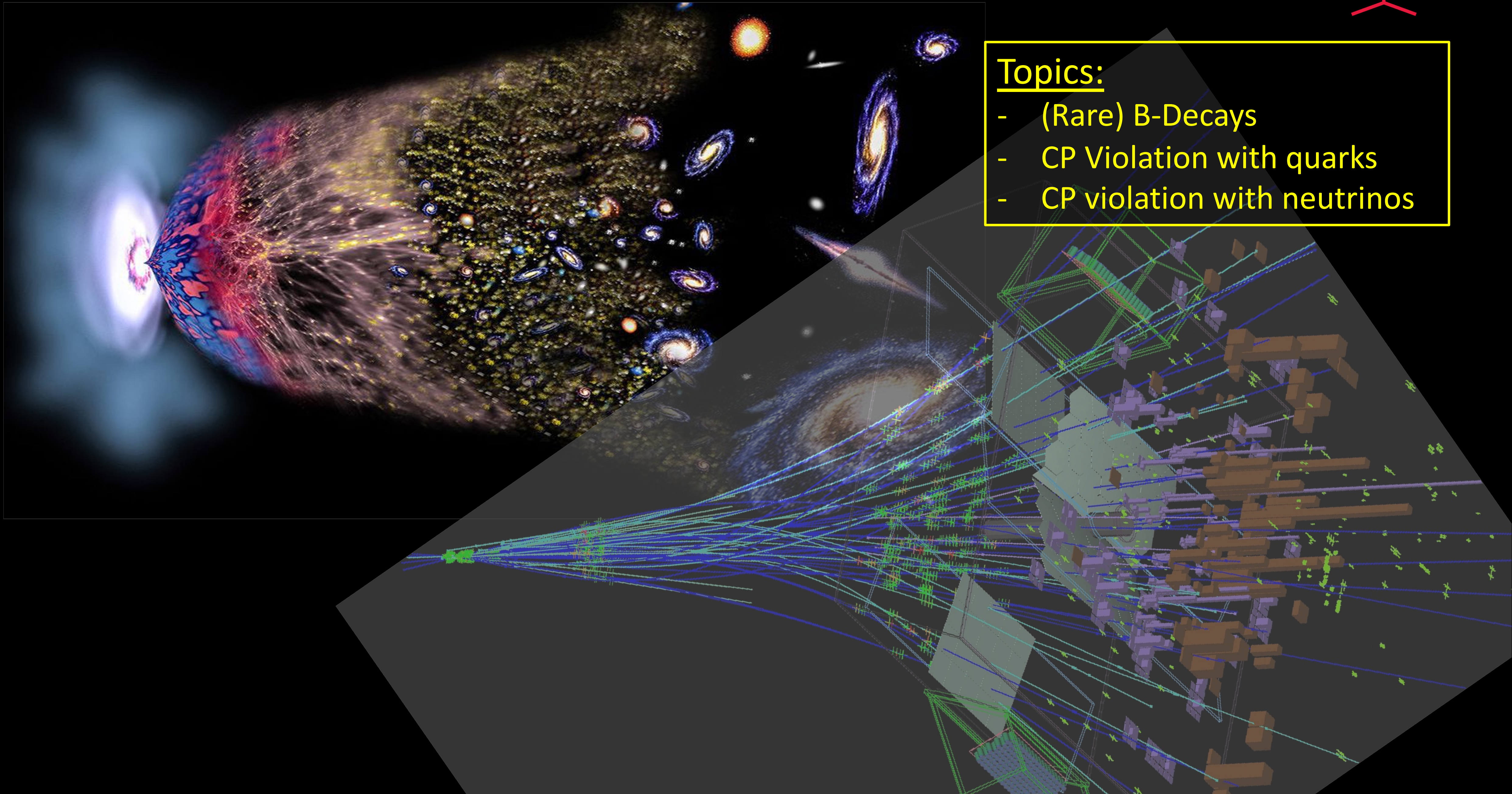
Topical Lectures: Flavour Physics and CP Violation

Nikhef



Topics:
- (Rare) B-Decays
- CP Violation with quarks
- CP violation with neutrinos

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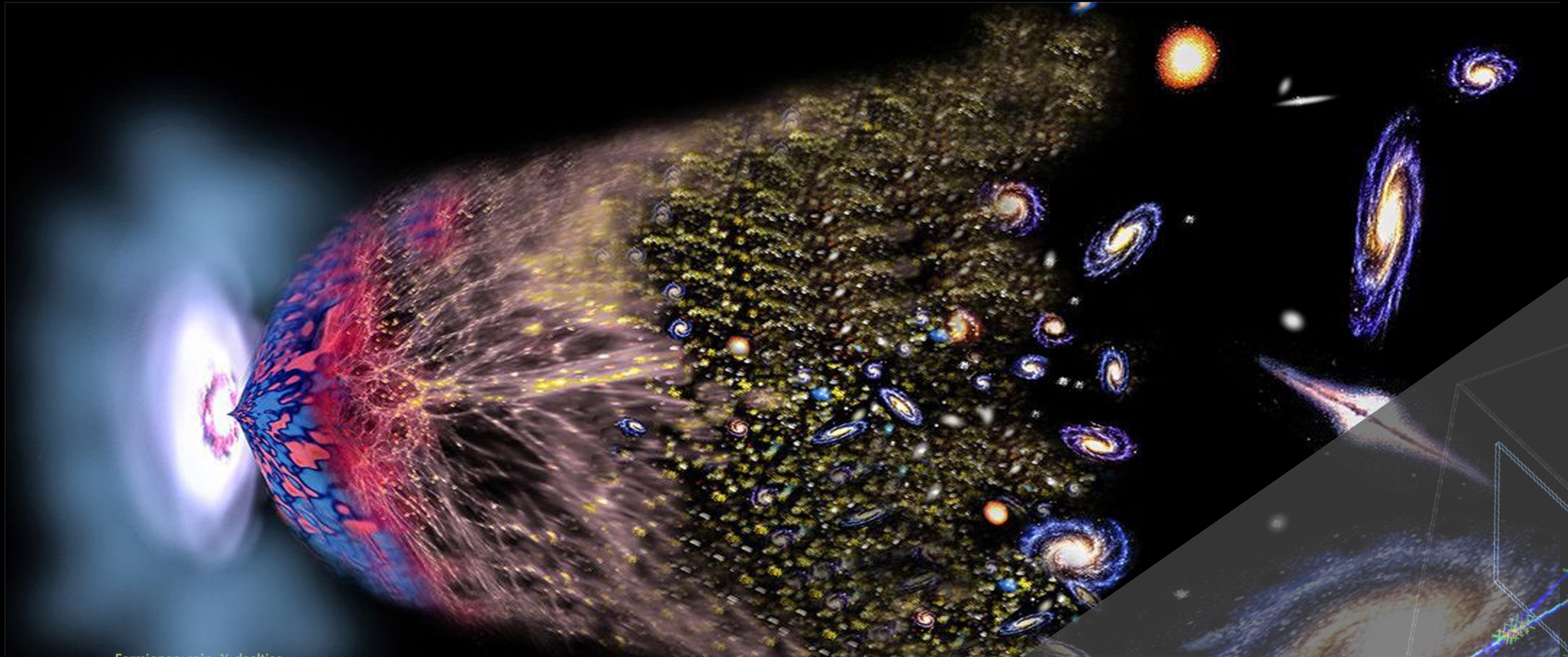
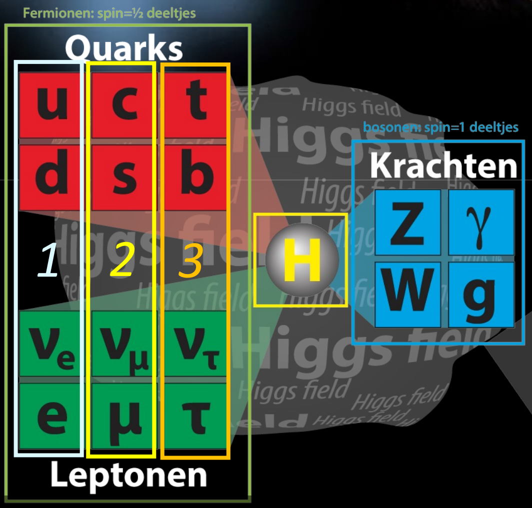
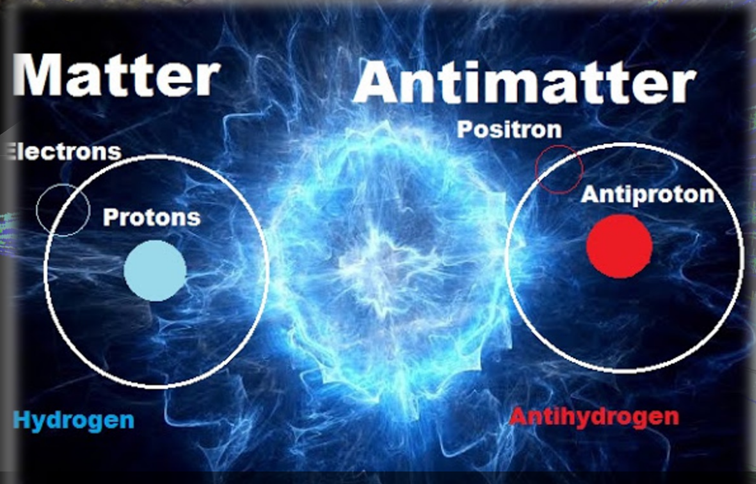
<u>Topics:</u>

- (Rare) B-Decays
- CP Violation with quarks
- CP violation with neutrinos

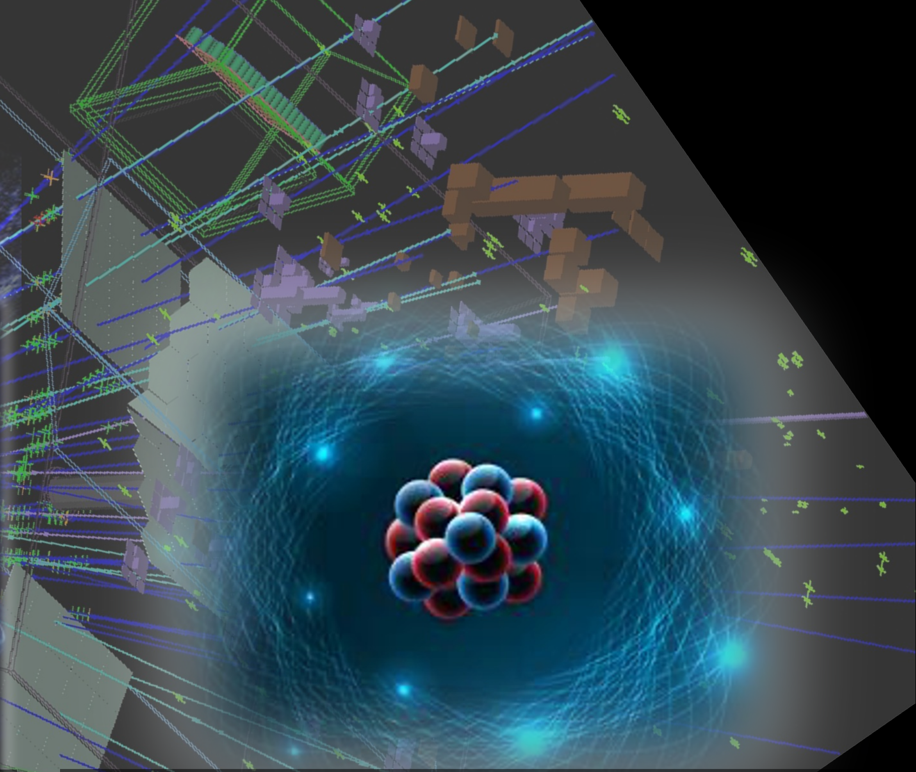




Why three generations of particles?



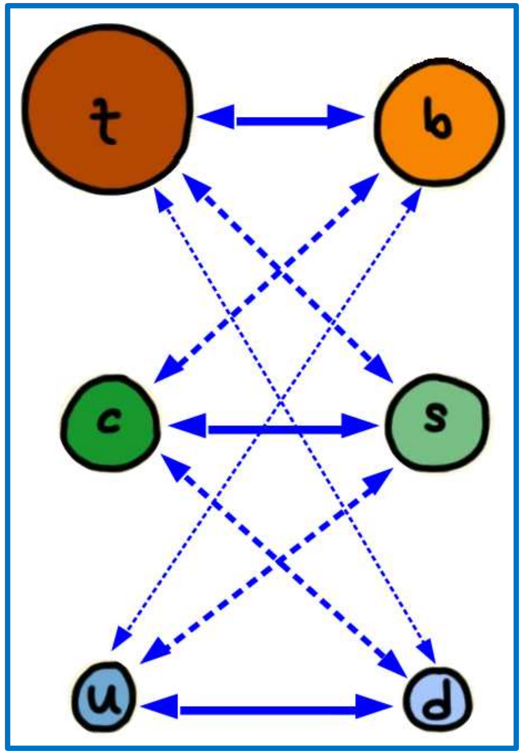
Why is there no antimatter?



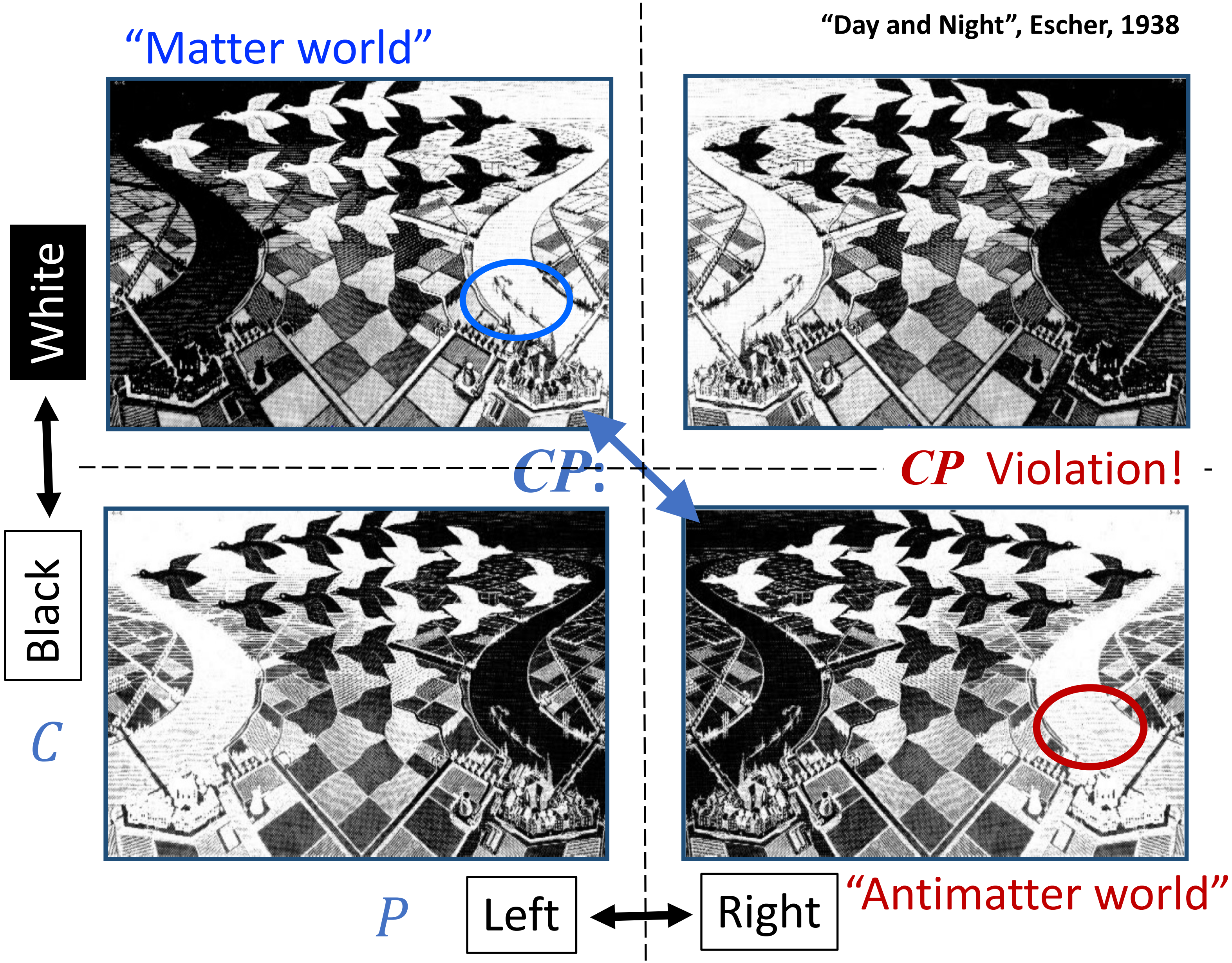
Why is an atom electric neutral?

The Antimatter Mystery

Flavour Physics and *CP* Violation

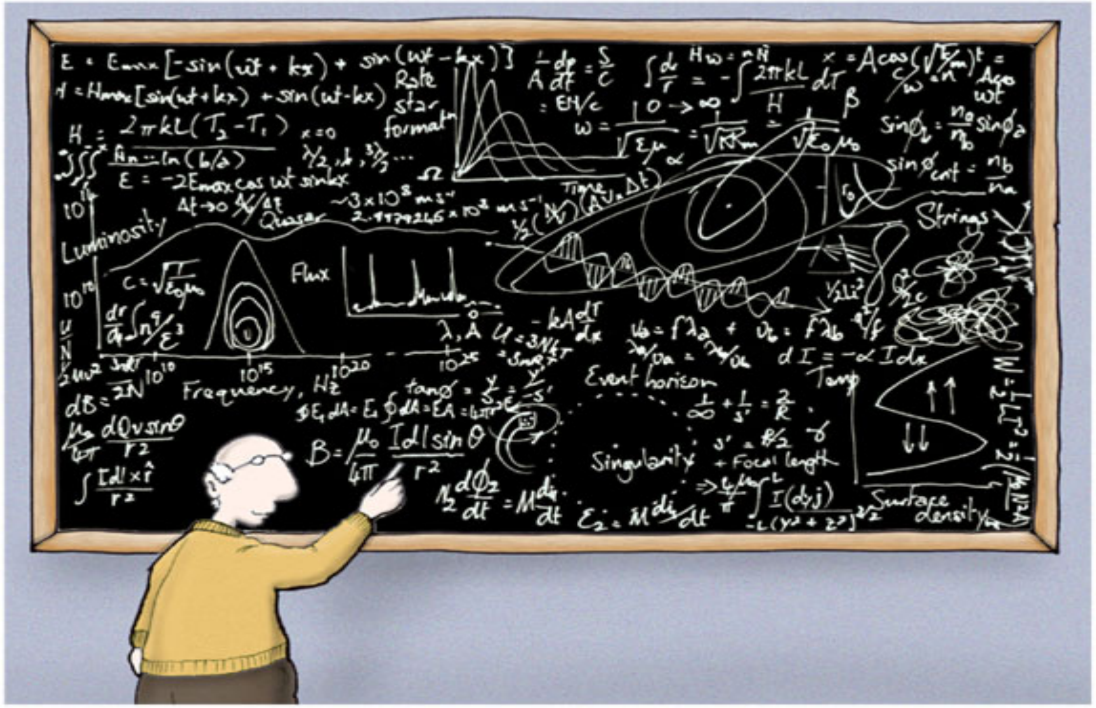


Complex amplitudes
in Weak interaction?!



Contents Today & Tomorrow:

1. CP Violation
   a) Discrete Symmetries
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
2. B-Mixing
   a) CP violation and Interference
   b) B-mixing and time dependent CP violation
   c) Experimental Aspects: LHC vs B-factory



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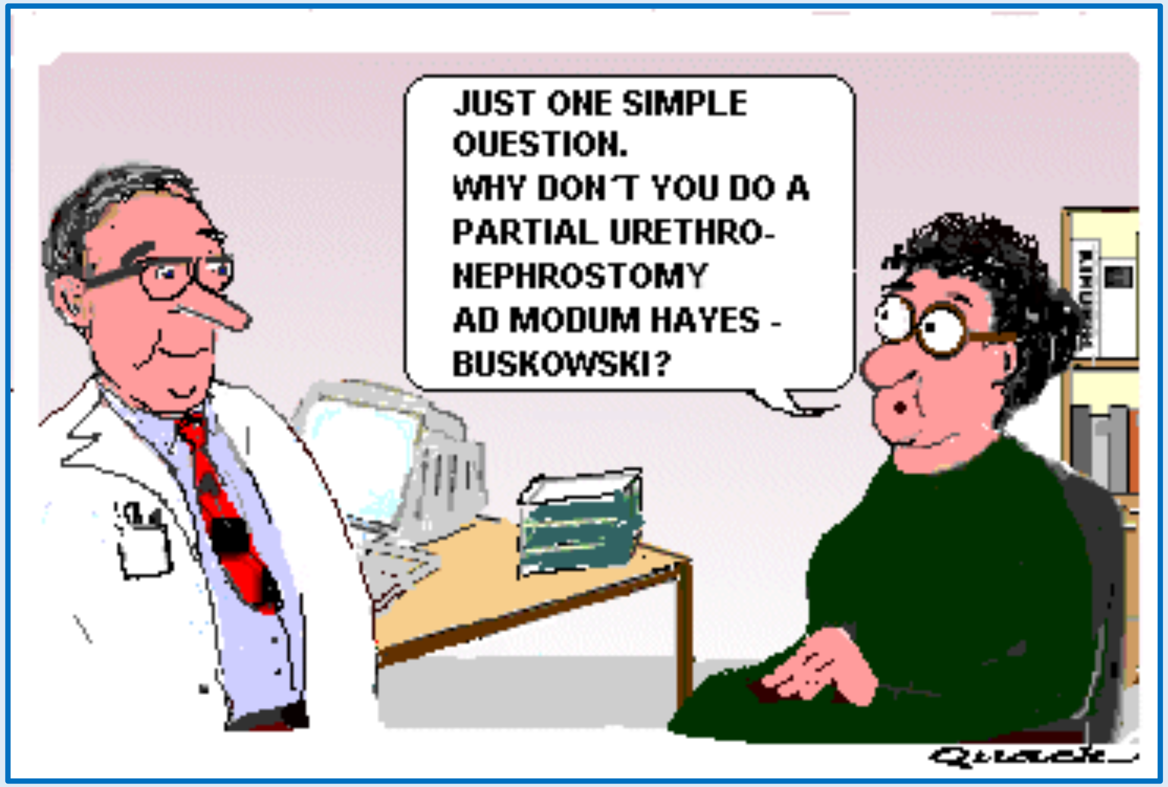
Don’t be afraid to ask questions…



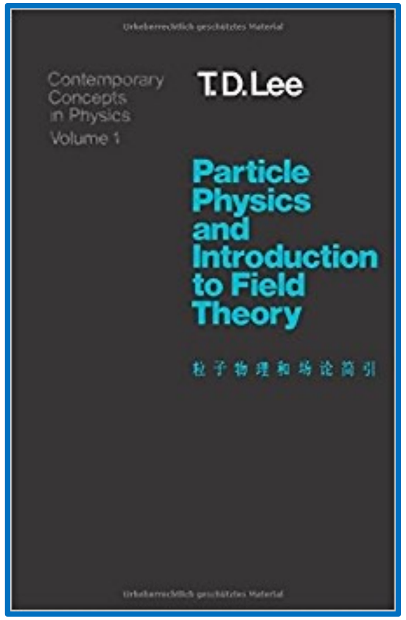
Contents Today & Tomorrow:

Symmetry and non-Observables

T.D.Lee: "The root to all *symmetry* principles lies in the assumption that it is impossible to observe certain basic quantities; the *non-observables*"

There are four main types of symmetry:

- Permutation symmetry:
  Bose-Einstein and Fermi-Dirac Statistics
- Continuous space-time symmetries:
  translation, rotation, velocity, acceleration,…
- Discrete symmetries:
  space inversion, time reversal, charge conjugation,…
- Unitary symmetries: gauge invariances:
  U_1(charge), SU_2(isospin), SU_3(color),…



$\Rightarrow$ If a quantity is fundamentally non-observable it is related to an *exact* symmetry

$\Rightarrow$ If it could in principle be observed by an improved measurement; the symmetry is said to be *broken*

Noether Theorem: symmetry $\Leftrightarrow$ conservation law

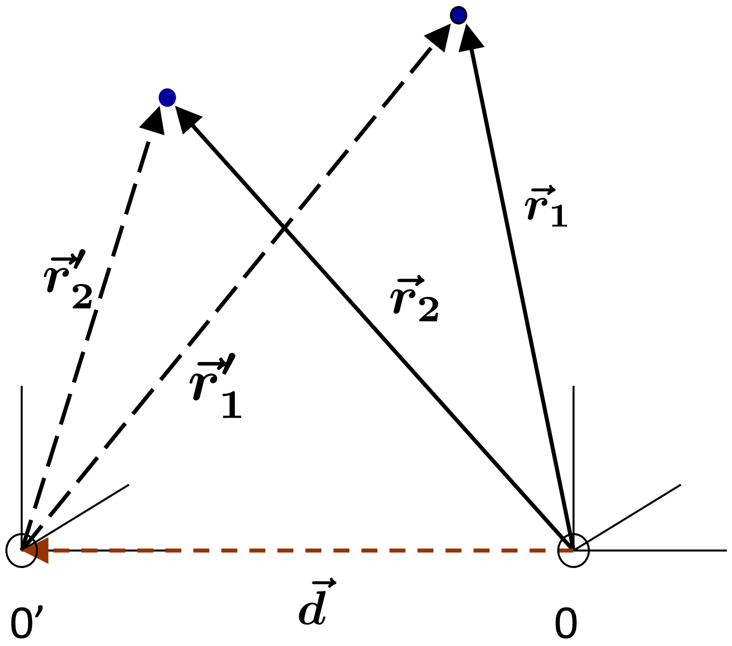
Symmetry and non-Observables

- Simple example: potential energy V between two charged particles:

Absolute position is a non-observable:
The interaction is independent on the choice of the origin 0.

Symmetry:
V is invariant under arbitrary space translations:

$$\vec{r_1} \rightarrow \vec{r}_1 + \vec{d} \qquad \vec{r_2} \rightarrow \vec{r}_2 + \vec{d}$$



Consequently:

$$V = V\left(\vec{r}_1 - \vec{r}_2\right)$$

Total momentum is conserved:

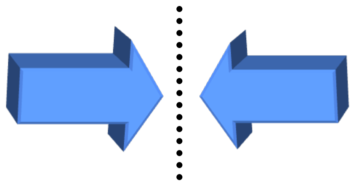
$$\frac{d}{dt}\underbrace{\left(\vec{p}_1 + \vec{p}_2\right)}_{\vec{p}_{\text{tot}}} = \vec{F}_1 + \vec{F}_2 = -\left(\vec{\nabla}_1 + \vec{\nabla}_2\right) V = 0$$

Symmetry and non-observables

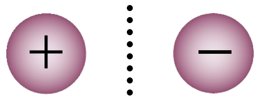
Non-observables	Symmetry Transformations	Conservation Laws or Selection Rule
Difference between identical particles	Permutation	B.-E. or F.-D. statistics
Absolute spatial position	Space translation: $\vec{r} \to \vec{r} + \vec{\Delta}$	momentum
Absolute time	Time translation: $t \to t + \tau$	energy
Absolute spatial direction	Rotation: $\vec{r} \to \vec{r}'$	angular momentum
Absolute velocity	Lorentz transformation	generators of the Lorentz group
Absolute right (or left)	$\vec{r} \to -\vec{r}$	parity
Absolute sign of electric charge	$e \to -e$	charge conjugation
Relative phase between states of different charge Q	$\psi \to e^{i\theta Q}\psi$	charge
Relative phase between states of different baryon number B	$\psi \to e^{i\theta N}\psi$	baryon number
Relative phase between states of different lepton number L	$\psi \to e^{i\theta L}\psi$	lepton number
Difference between different coherent mixture of p and n states	$\binom{p}{n} \to U\binom{p}{n}$	isospin

C, P, T Discrete Symmetries

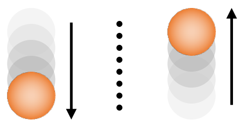
- **Parity, P:** *unobservable: (absolute handedness)*
  - Reflects a system through the origin.
    Converts right-handed to left-handed.
    - $\vec{x} \rightarrow -\vec{x}$, $\vec{p} \rightarrow -\vec{p}$ (vectors) but $\vec{L} = \vec{x} \times \vec{p}$ (axial vectors)



- **Charge Conjugation, C:** *unobservable: (absolute charge)*
  - Turns internal charges to opposite sign.
    - $e^+ \rightarrow e^-$, $K^- \rightarrow K^+$



- **Time Reversal, T:** *unobservable: (direction of time)*
  - Changes direction of motion of particles
    - $t \rightarrow -t$



- **CPT Theorem:**
  - All interactions are invariant under combined C, P and T operation
  - A particle ***is*** an antiparticle travelling backward in time
  - Implies e.g. particle and anti-particle have equal masses and lifetimes

Classical Mirror Worlds → Invariant!

- Parity operator P: $\vec{x} \rightarrow -\vec{x}$
  - Mass m — $P\,m = m$: scalar
  - Force $\vec{F}$ $(\vec{F} = d\vec{p}/dt)\,;\vec{p} = m d\vec{x}/dt$ — $P\,\vec{F} = P\,d\vec{p}/dt = -\,d\vec{p}/dt = -\vec{F}$: vector
  - Acceleration $\vec{a}$ $(\vec{a} = d^2\vec{x}/dt^2)$ — $P\,\vec{a} = -\,d^2x/dt^2 = -\vec{a}$: vector
  - Angular momentum $\vec{L},\vec{S},\vec{J}$ $(\vec{L} = \vec{x}\times\vec{p})$ — $P\,\vec{L} = -\vec{x}\times-\vec{p} = \vec{L}$: axial vector
- Parity: Newton's law is *invariant* under P-operation (i.e. the same in the mirror world):

$$\vec{F} = m\,\vec{a} \xrightarrow{P} -\vec{F} = -m\vec{a} \Leftrightarrow \vec{F} = m\vec{a}$$

- Charge: Lorentz Force in the C-mirror world is *invariant*:

$$\vec{F} = q\left[\vec{E} + \vec{v}\times\vec{B}\right] \xrightarrow{C} \vec{F} = -q\left[-\vec{E} + \vec{v}\times-\vec{B}\right]$$

- Time: laws of physics are also *invariant* unchanged under T-reversal, since:

$$\vec{F} = m\,\vec{a} = m\,\frac{d^2\vec{x}}{dt^2} \xrightarrow{T} \vec{F} = m\frac{d^2\vec{x}}{d(-t)^2} \Leftrightarrow \vec{F} = m\,\vec{a}$$

  - QM: Consider Schrodinger's equation $(t \rightarrow -t)$: $$ih\frac{\partial\psi}{\partial t} = -\frac{\vec{\nabla}^2\psi}{2m}$$

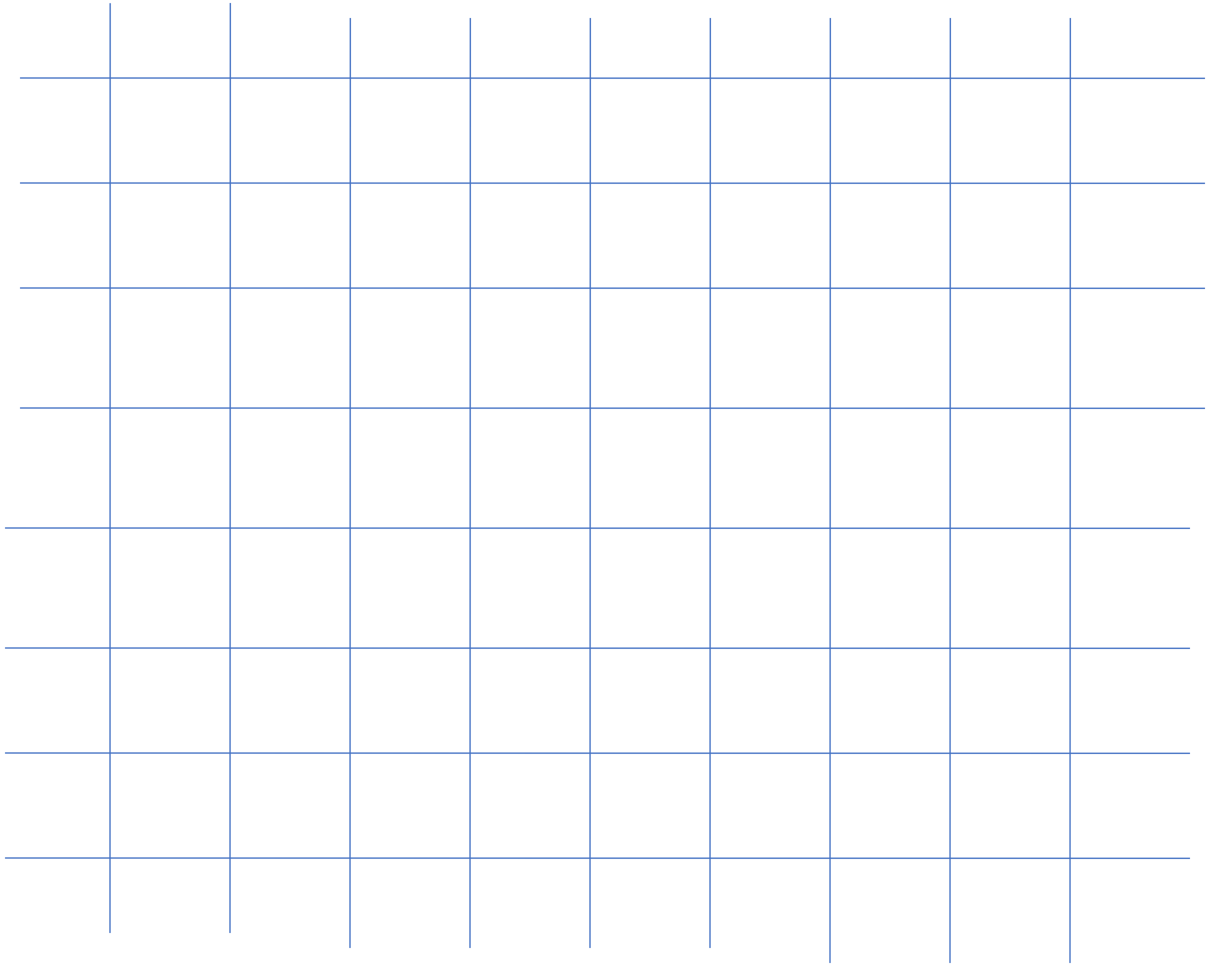
Complex conjugation of the equation is required to stay invariant: $\psi \xrightarrow{T} \psi^*$

C-, P-, T- Symmetry

- Classical Theory is invariant under C, P, T operations; i.e. they conserve C, P, T symmetry
  - Newton mechanics, Maxwell electrodynamics.

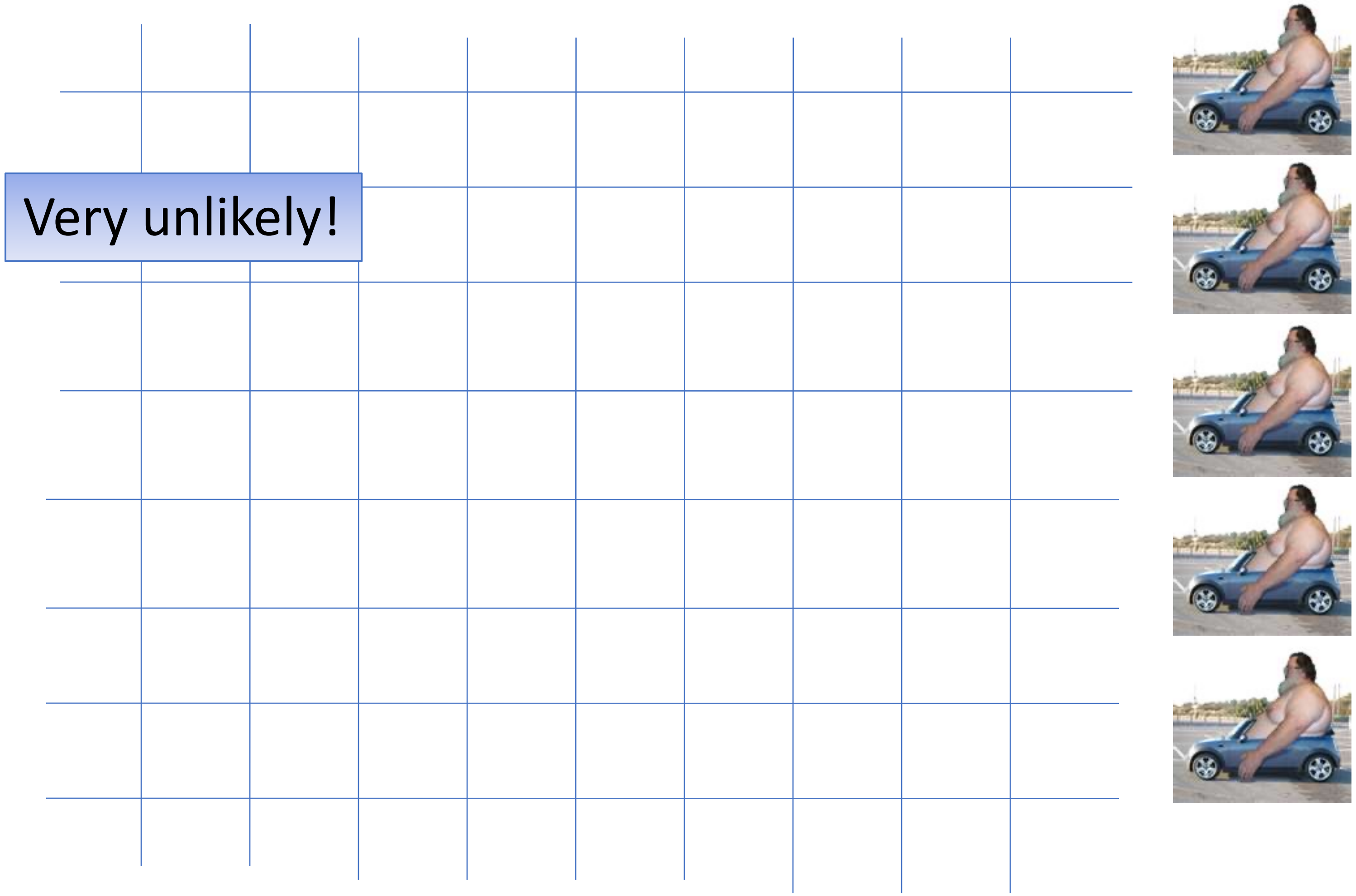
- Suppose we watch some physical event. Can we determine unambiguously whether:
  - We are watching the event where all ***charges are reversed*** or not?
  - We are watching the event ***in a mirror*** or not?
    - Macroscopic biological asymmetries are considered *accidents of evolution* rather than fundamental asymmetry in the laws of physics.
  - We are watching the event in a ***film running backwards*** or not?
    - The arrow of time is due to thermodynamics: i.e. the realization of a macroscopic final state is *statistically more probable* than the initial state

Macroscopic time reversal (T.D. Lee)



- At each crossing: 50% - 50% choice to go left or right
- After many decisions: reverse the velocity of the final state and return
- Do we end up with the initial state?

Macroscopic time reversal (T.D. Lee)



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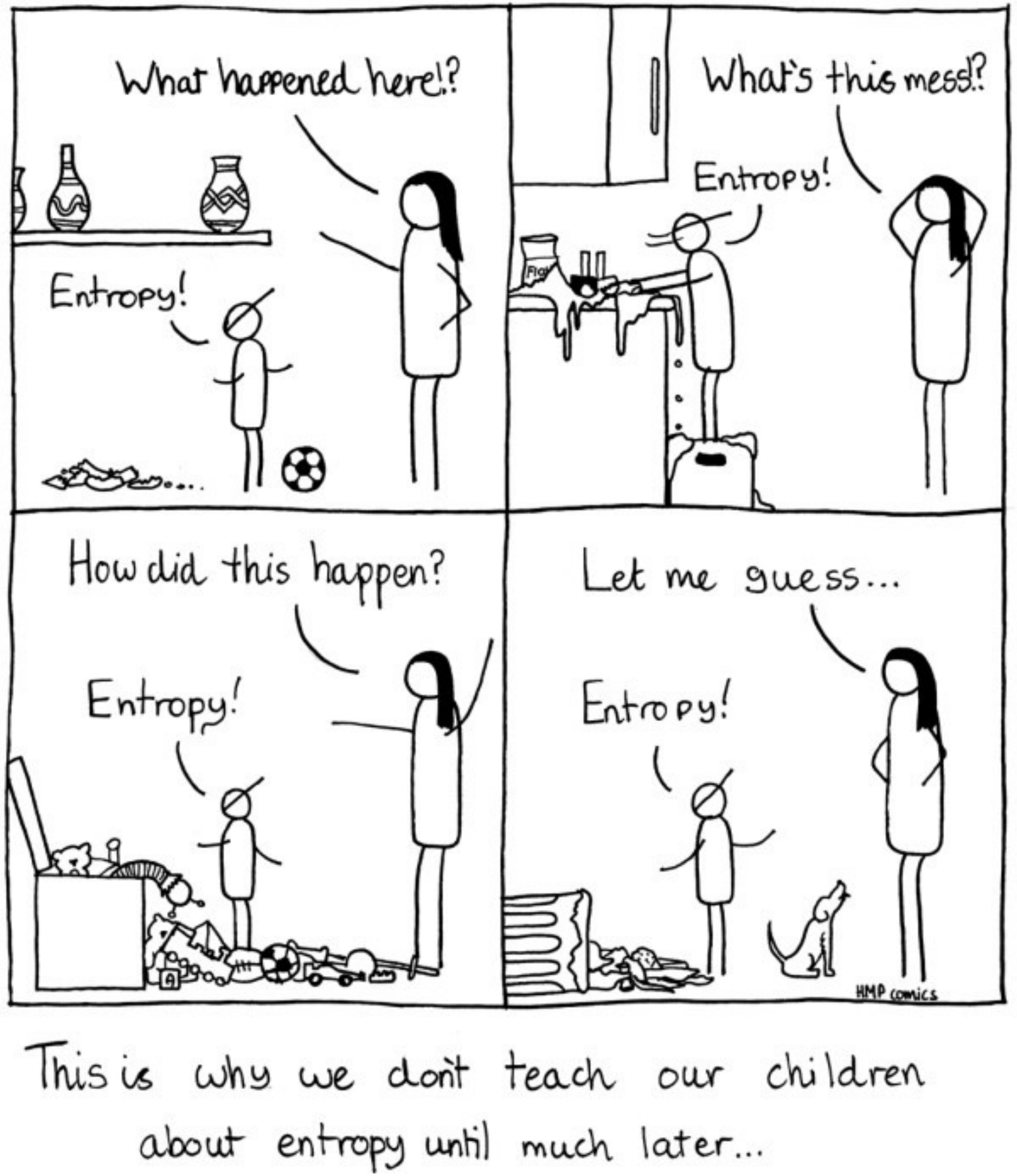
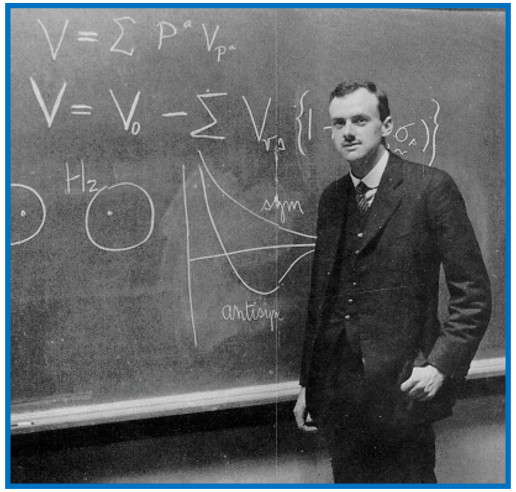
Macroscopic time reversal



C, P operations and Dirac theory (QED)

$(i\gamma^\mu \partial_\mu - m)\psi(\vec{x},t) = 0$



- In Dirac theory particles are represented as spinors

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

+1/2, -1/2 helicity solutions for the particle

+1/2, -1/2 helicity solutions for the antiparticle

Antimatter!

- Implementation of P and C operators in Dirac theory:

$$P: \quad \psi \to \psi' = \gamma^0 \psi(-\vec{x},t)$$

$$\left(\begin{matrix} [(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}) - m]\psi(\vec{x},t) = 0 \\ [(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}) - m]\psi'(-\vec{x},t) = 0 \end{matrix} \right)$$

$$C: \quad \psi \to \psi' = i\gamma^2 \psi^*(\vec{x},t)$$

$$\left(\begin{matrix} \text{Elect. } \psi: & [\gamma^\mu(i\partial_\mu + eA_\mu) - m]\psi = 0 \\ \text{Posit. } \psi': & [\gamma^\mu(i\partial_\mu - eA_\mu) - m]\psi' = 0 \end{matrix} \right)$$

- QED (Dirac theory) is symmetric under C, P conjugation. Reversing electric charges keeps electrodynamics invariant.

C, P operations and Dirac theory (QED)

$(i\gamma^\mu\partial_\mu - m)\psi(\vec{x},t) = 0$

$\gamma^{0*} = \gamma^0$
$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix},$$

$\gamma^{1*} = \gamma^1$
$$\gamma^1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix},$$

$\gamma^{2*} = -\gamma^2$
$$\gamma^2 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix},$$

$\gamma^{3*} = \gamma^3$
$$\gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

- In Dirac equation: $\left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}\right) - m\right]\psi(\vec{x},t) = 0$
- Implementation of P operator in Dirac: $\vec{x} \to -\vec{x}$; $\partial x_i \to -\partial x_i$

$P\ :\ \psi \to \psi' = \psi(-\vec{x},t)$?

$$\left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{-x_i}\right) - m\right]\psi(-\vec{x},t) = 0$$
$$\left[\left(i\gamma^0\partial_0 + i\gamma^i\partial_{x_i}\right) - m\right]\psi(-\vec{x},t) = 0$$

Does not work!

Multiply eq by γ^0:

$$\gamma^0\left[\left(i\gamma^0\partial_0 + i\gamma^i\partial_{x_i}\right) - m\right]\psi(-\vec{x},t) = 0$$

Instead: $\psi' = \gamma^0\psi(-\vec{x},t)$!

$$\left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}\right) - m\right]\gamma^0\psi(-\vec{x},t) = 0$$

OK!

- Implementation of C operator in Dirac: $C\ :q \to -q$; $\psi \to \psi' = i\gamma^2\psi^*(\vec{x},t)$

$\psi\ :\quad \left[\gamma^\mu\left(i\partial_\mu - qA_\mu\right) - m\right]\psi = 0$

$\psi'?:\quad \left[\gamma^\mu\left(i\partial_\mu - qA_\mu\right) - m\right]^*\psi^* = 0$

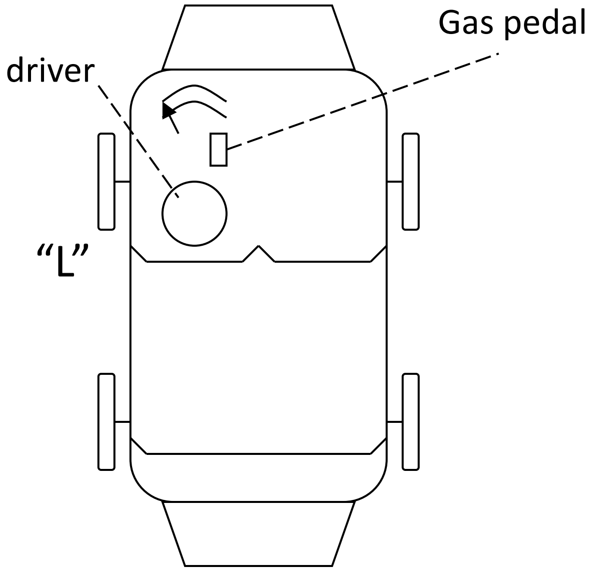
$\psi'\ :\quad i\gamma^2\left[-\gamma^{\mu*}\left(i\partial_\mu + qA_\mu\right) - m\right]\psi^* = 0$

$\psi'\ :\quad \left[\gamma^\mu\left(i\partial_\mu + qA_\mu\right) - m\right]i\gamma^2\psi^* = 0$ OK

Parity Violation

Before 1956 physicists were **convinced** that the laws of nature were left-right symmetric. Strange?

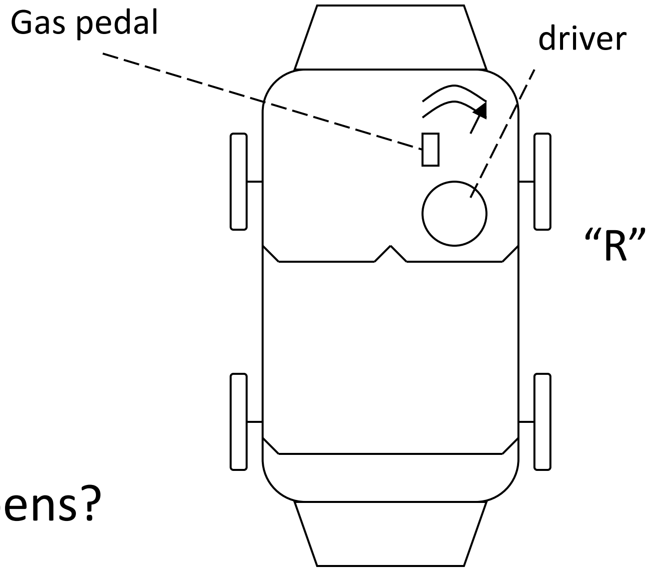
A "gedanken" experiment: consider two perfectly mirror symmetric cars:



"L" and "R" are fully symmetric,
Each nut, bolt, molecule etc.
However the engine is a black box

Person "L" gets in, starts, ….. 60 km/h

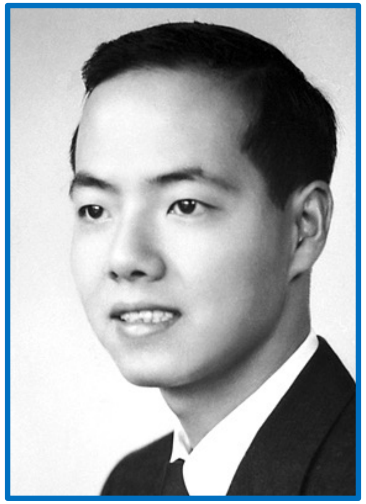
Person "R" gets in, starts, ….. What happens?



What happens in case the ignition mechanism uses, say, Co^{60} β decay?

Parity Violation

T.D. Lee



C.N. Yang

- First to pose Parity violation as a solution of the so-called theta-tau puzzle:
  - Two different particles with exactly same mass and spin but different decay modes?

$\theta^+ \rightarrow \pi^+\pi^0$ (Parity +)

$\tau^+ \rightarrow \pi^+\pi^+\pi^0$ (Parity –)

➢ One particle K^+ with parity violating decay

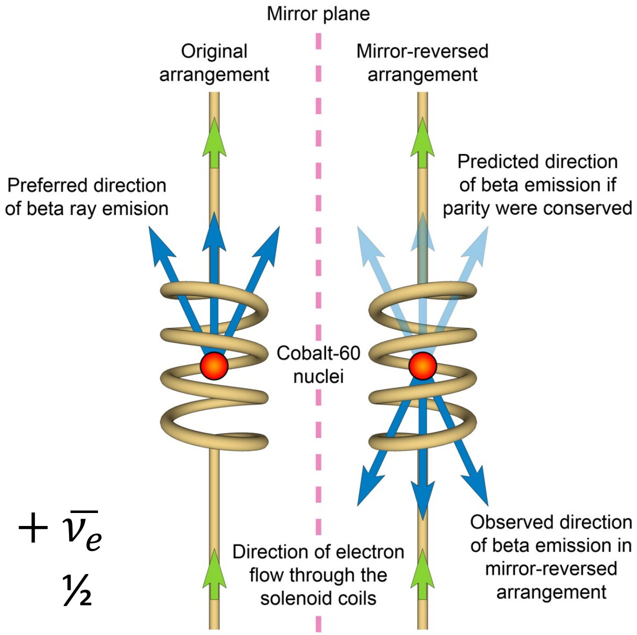
Wolfgang Pauli

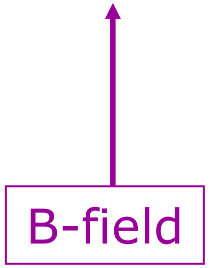
"I cannot believe God is a weak left-hander."

Discovery of Parity Violation

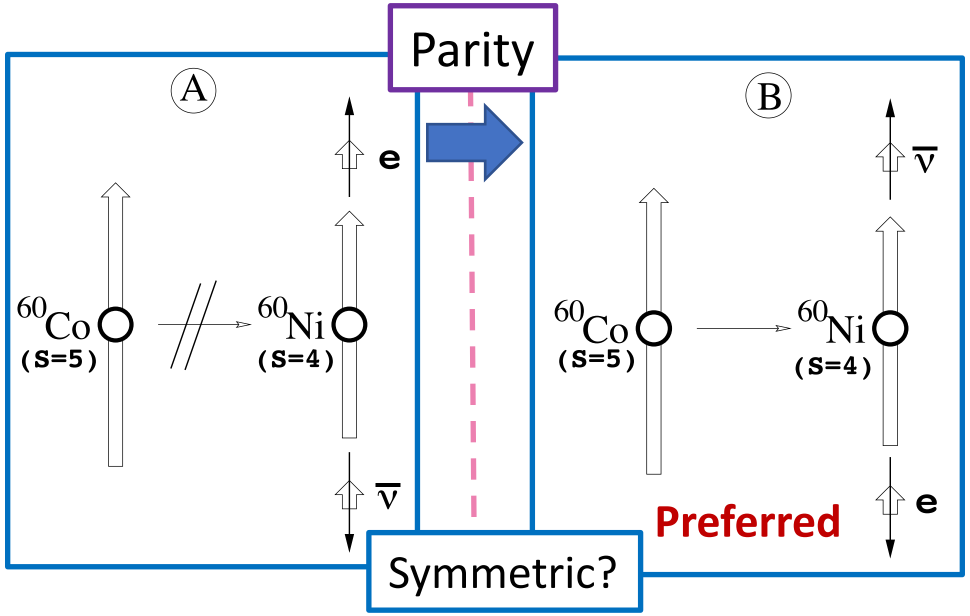
$$^{60}_{27}Co \rightarrow \, ^{60}_{28}Ni + e^- + \bar{\nu}_e$$

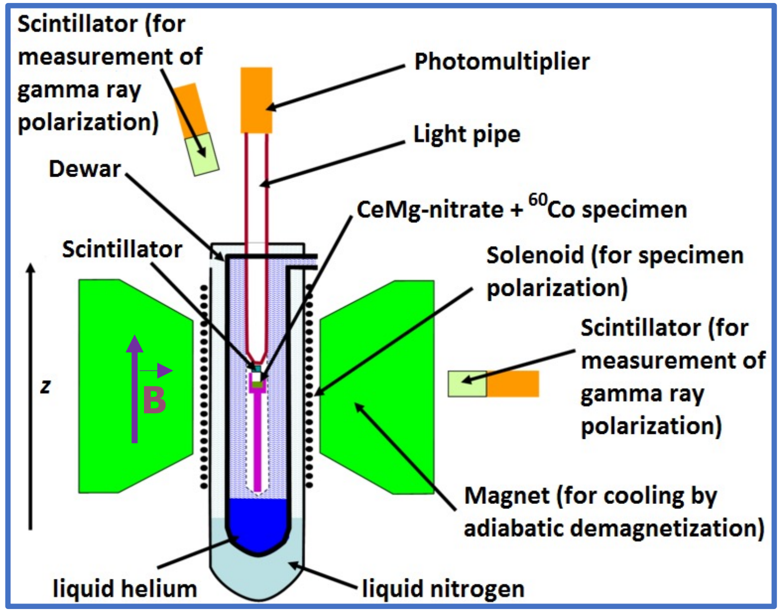
S: 5 4 ½ ½





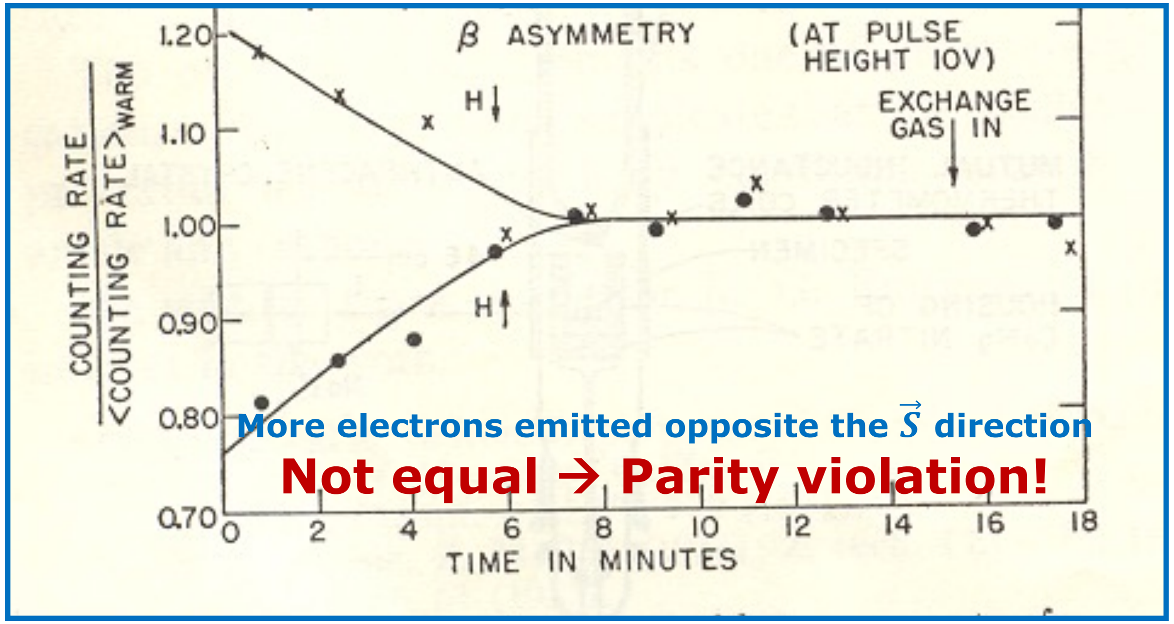
Spin is pseudoscalar, P: $\vec{S} \rightarrow \vec{S}$





Is physics is parity invariant?

Only if electron decay rate is symmetric wrt spin direction!

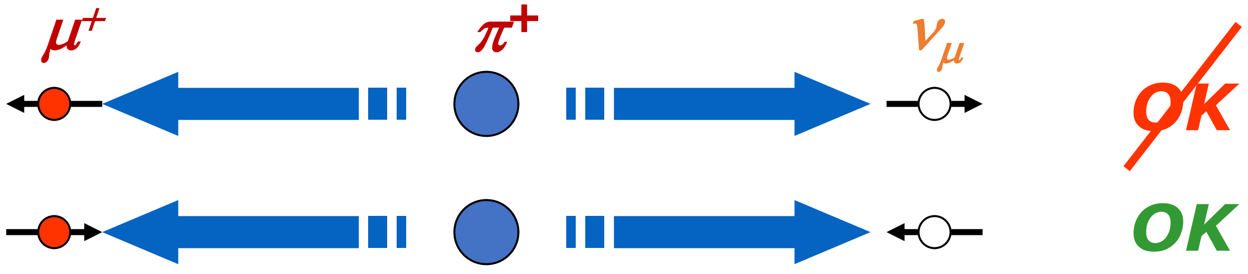


More electrons emitted opposite the $\vec{S}$ direction

Not equal → Parity violation!

So P is violated, what's next…?

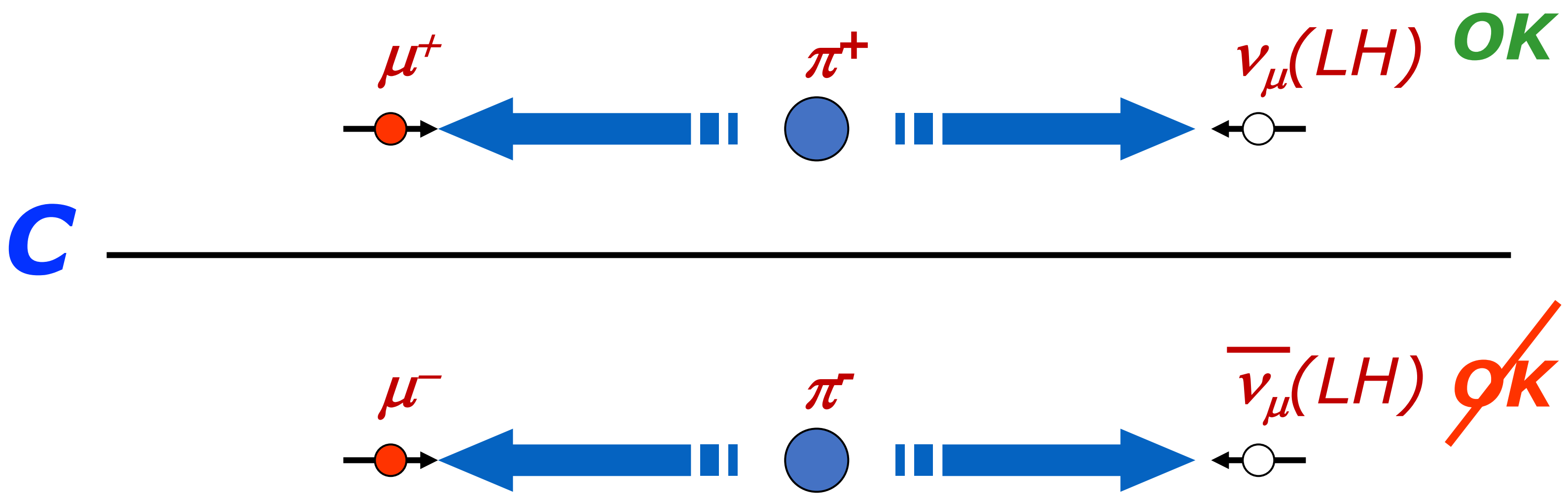
- Wu's experiment was shortly followed by another clever experiment by L. Lederman: Look at decay $\pi^+ \rightarrow \mu^+ \nu_\mu$
  - Pion has spin 0, while μ, ν_μ both have spin ½
    → spin of decay products must be oppositely aligned
    → Helicity of muon is same as that of neutrino.



- Ledermans result: All neutrinos are left-handed and all anti-neutrinos are right-handed

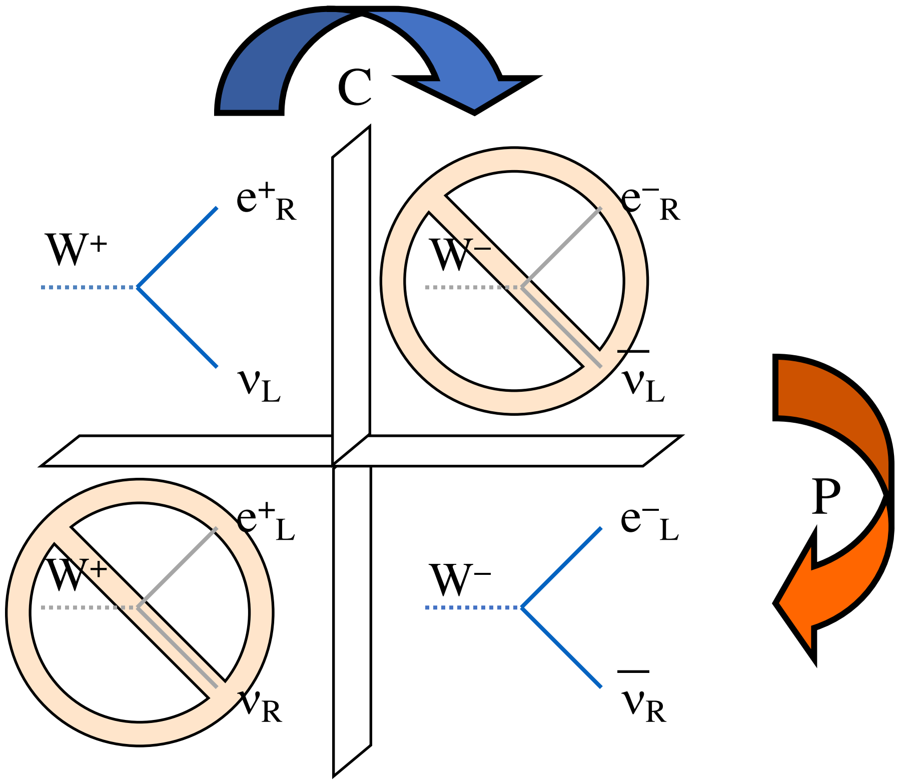
Charge conjugation symmetry?

- Introducing C-symmetry
  - The C(harge) conjugation is the operation which exchanges **particles and anti-particles** (not just electric charge)
  - It is a discrete symmetry, just like P, i.e. $C^2 = 1$



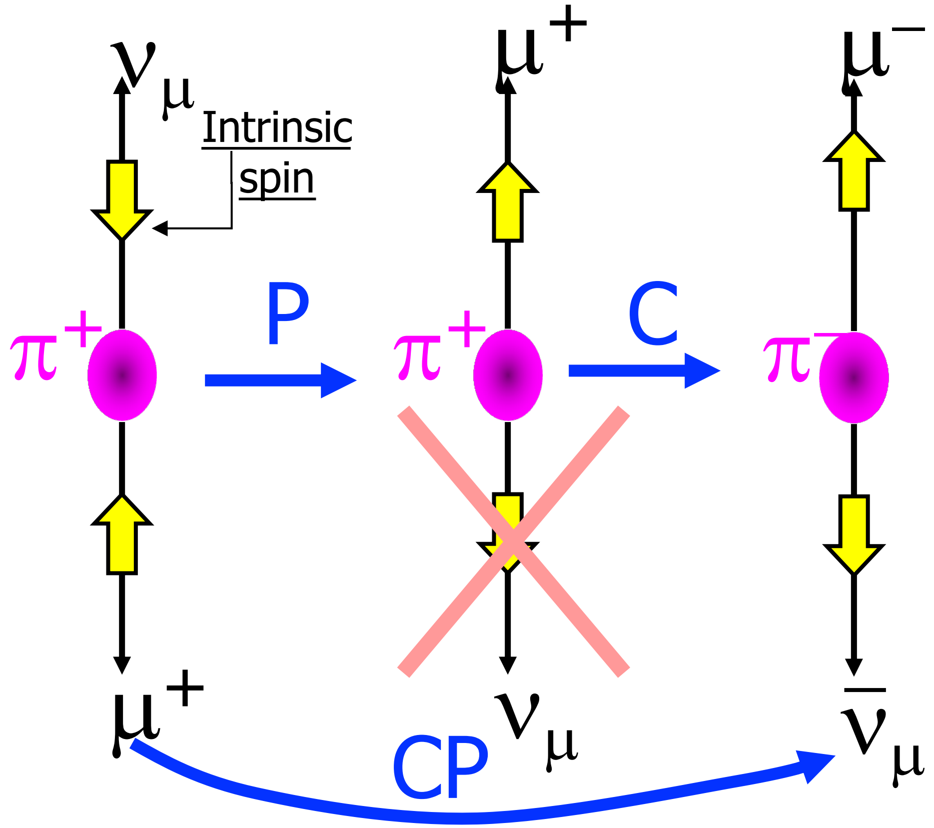
- C symmetry is broken by the weak interaction
  - Just like P

Weak Force breaks C and P, is CP really OK?



- Weak interaction breaks ***C*** and ***P*** symmetry maximally!
  - Nature is left-handed for matter and right-handed for antimatter.
- Despite *maximal* violation of ***C*** and ***P***, combined ***CP*** seems *conserved.*
- Is combined ***CP*** really exactly conserved?

The Weak force and CP violation

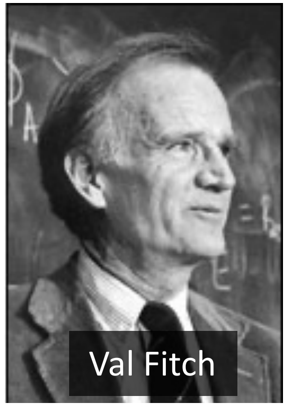


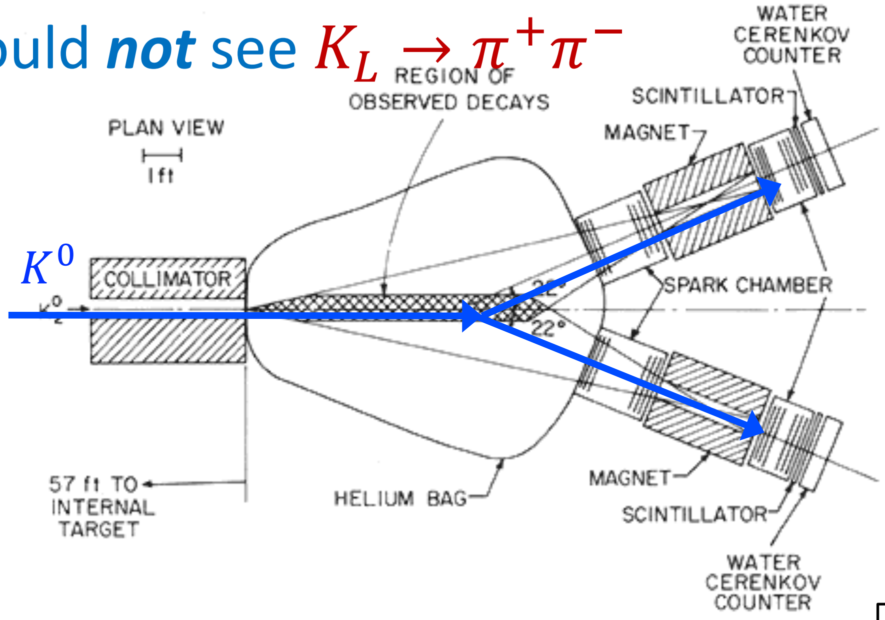
- Combined $C + P \equiv CP$ symmetry?
  - CP symmetry is parity conjugation: $(x, y, z \rightarrow -x, -y, -z)$ followed by charge conjugation: $(\psi \rightarrow \overline{\psi})$
- CP symmetry *appears* to be preserved in the weak interaction
- But in 1964, Christenson, Cronin, Fitch and Turlay observed CP *violation* in decays of neutral kaons…

Discovery of CP-Violation with K^0 decays

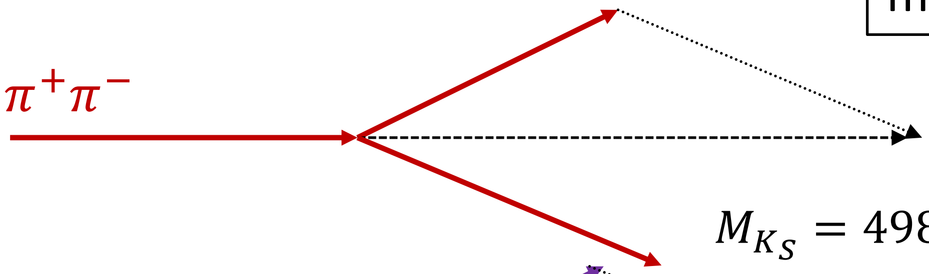
K_S: Short-lived is CP even:
$K_1^0 \to \pi^+\pi^-$ (fast)
K_L: Long-lived is CP odd:
$K_2^0 \to \pi^+\pi^-\pi^0$ (slow)

- Create a pure K_L beam ("wait" for K_S to decay)
- If CP is conserved, should ***not*** see $K_L \to \pi^+\pi^-$





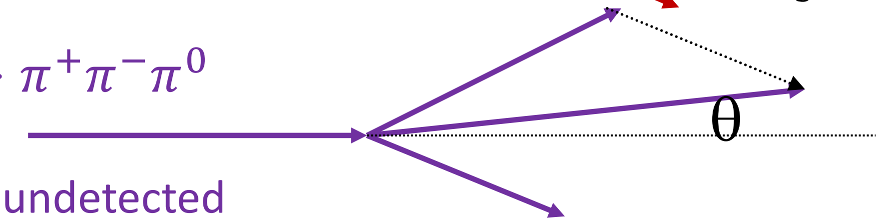
CP violating Signal: $K_L \to \pi^+\pi^-$



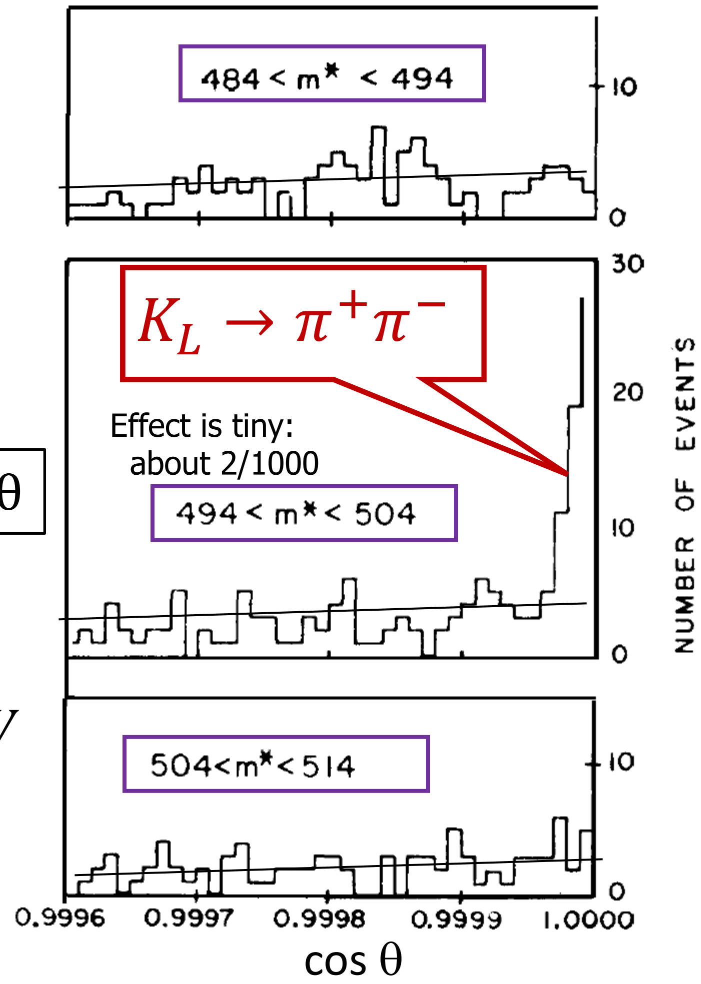
$M_{K_S} = 498\ MeV$

mass, θ

Background: $K_L \to \pi^+\pi^-\pi^0$



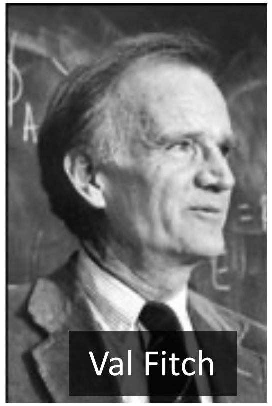
π^0 remains undetected



Discovery of CP-Violation with K^0 decays

- Create a pure K_L beam (“wait” for K to decay)
- If CP is conserved,

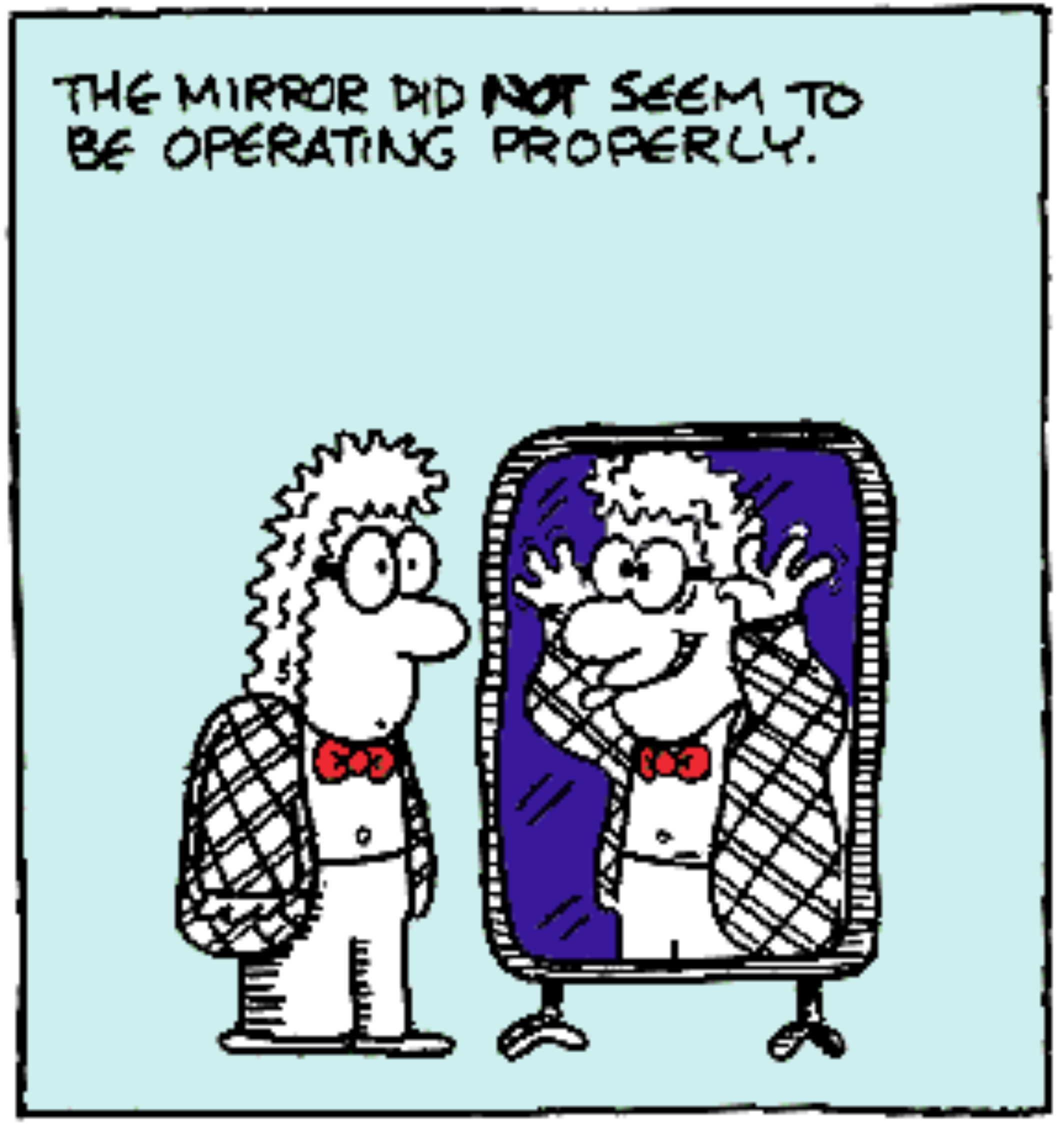
K_S: Short-lived is CP even:
$K_1^0 \to \pi^+\pi^-$ (fast)
K_L: Long-lived is CP odd:
$K_2^0 \to \pi^+\pi^-\pi^0$ (slow)

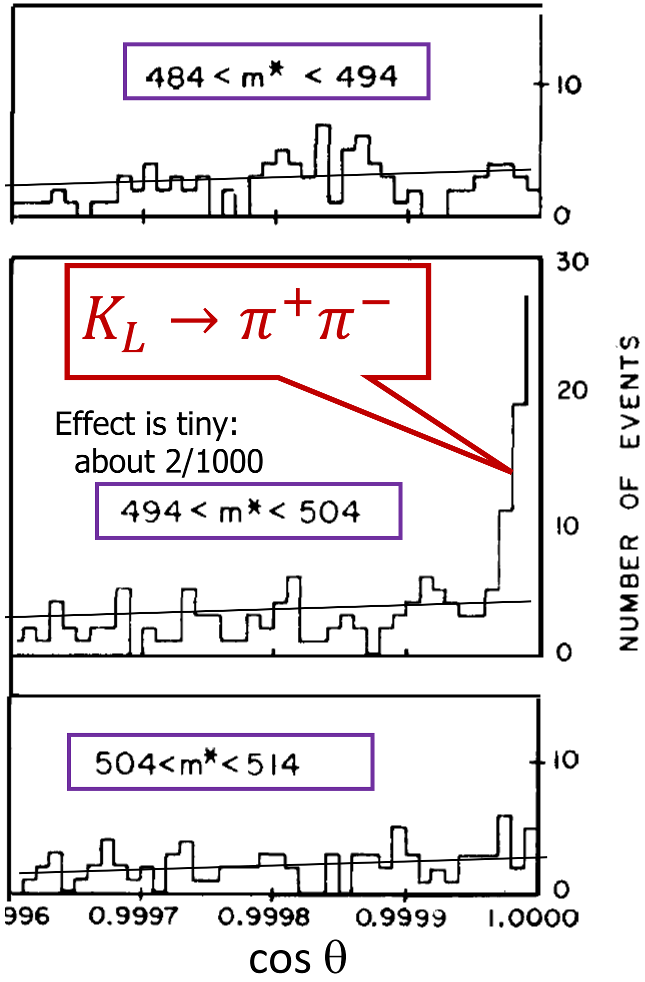


CP violating Signal: K

Background: K

π^0 remains undetected

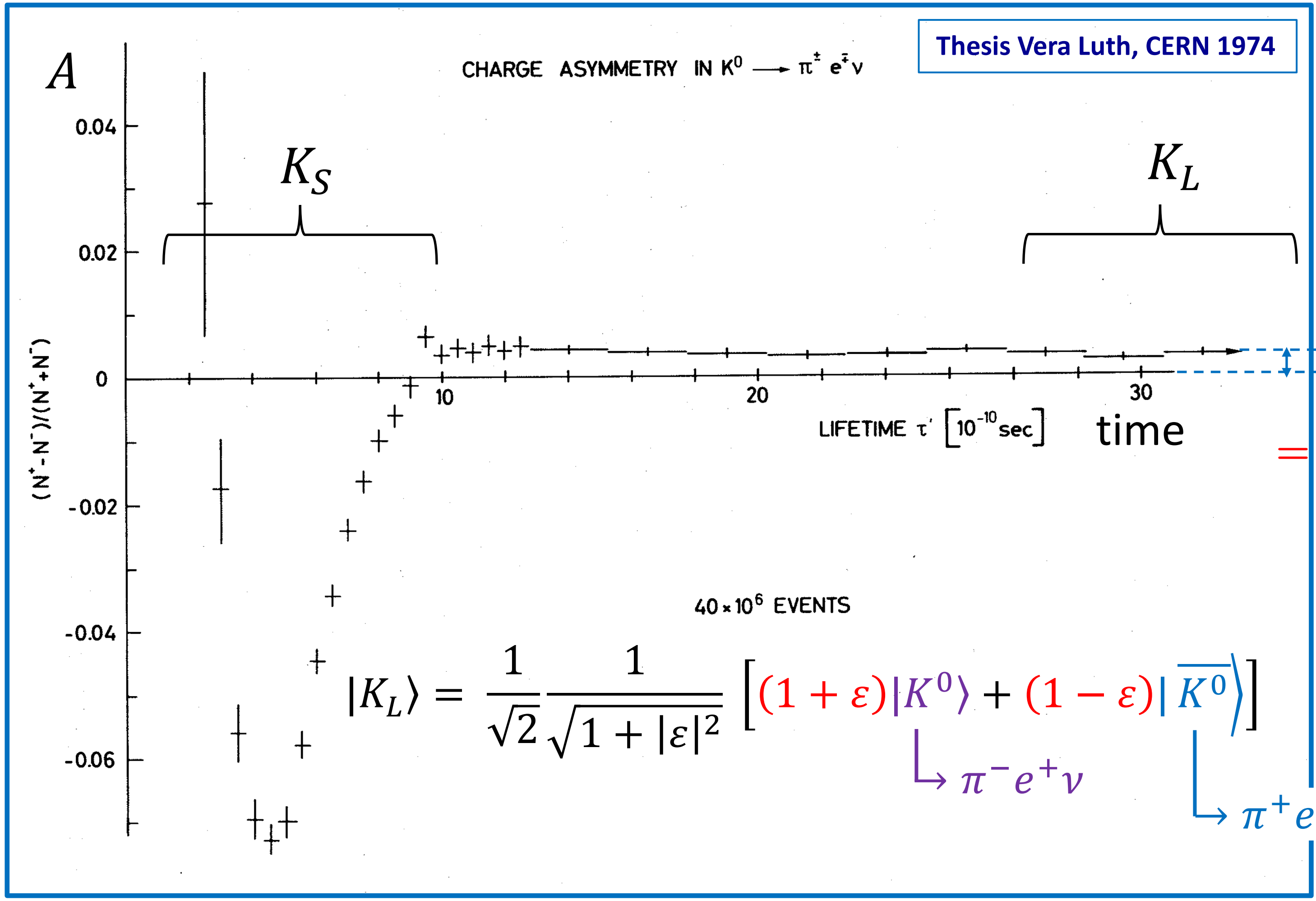




Alternative: Charge Asymmetry in K^0 decays

Measure $A = \frac{N^+ - N^-}{N^+ + N^-}$ with $N^+ = K^0 \to \pi^- e^+ \nu$, $N^- = \overline{K^0} \to \pi^+ e^- \bar{\nu}$ vs the K^0 decay time

$$\frac{N^+ - N^-}{N^+ + N^-} = A$$



$$|K_L\rangle = \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1+|\varepsilon|^2}} \left[(1+\varepsilon)|K^0\rangle + (1-\varepsilon)|\overline{K^0}\rangle\right]$$

$(1+\varepsilon)|K^0\rangle \to \pi^- e^+ \nu$

$(1-\varepsilon)|\overline{K^0}\rangle \to \pi^+ e^- \bar{\nu}$

$4\Re(\varepsilon)$

$$= \left|\frac{(1+\varepsilon)}{(1-\varepsilon)}\right|^2$$

Kaon has $J^P = 0^-$:

$$P|K^0\rangle = -|K^0\rangle$$

$$P|\overline{K^0}\rangle = -|\overline{K^0}\rangle$$

Two CP states:

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\overline{K^0}\rangle\right]$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\overline{K^0}\rangle\right]$$

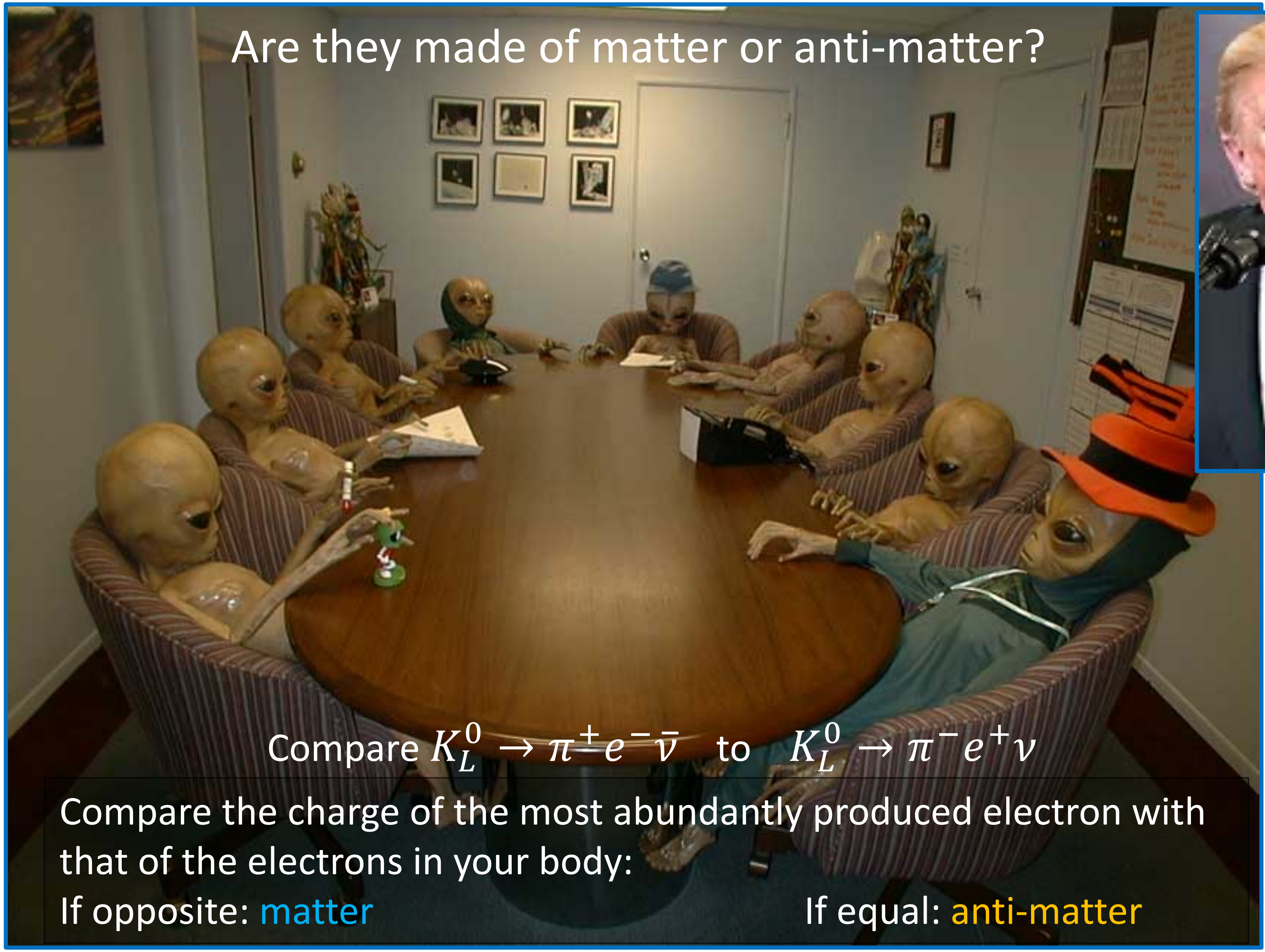
CP violation in meson mixing.

Two particles:

$$|K_S\rangle \simeq [|K_1\rangle + \varepsilon|K_2\rangle]$$

$$|K_L\rangle \simeq [|K_2\rangle + \varepsilon|K_1\rangle]$$

Contact with Aliens !



Are they made of matter or anti-matter?

Compare $K_L^0 \to \pi^+ e^- \bar{\nu}$ to $K_L^0 \to \pi^- e^+ \nu$

Compare the charge of the most abundantly produced electron with that of the electrons in your body:

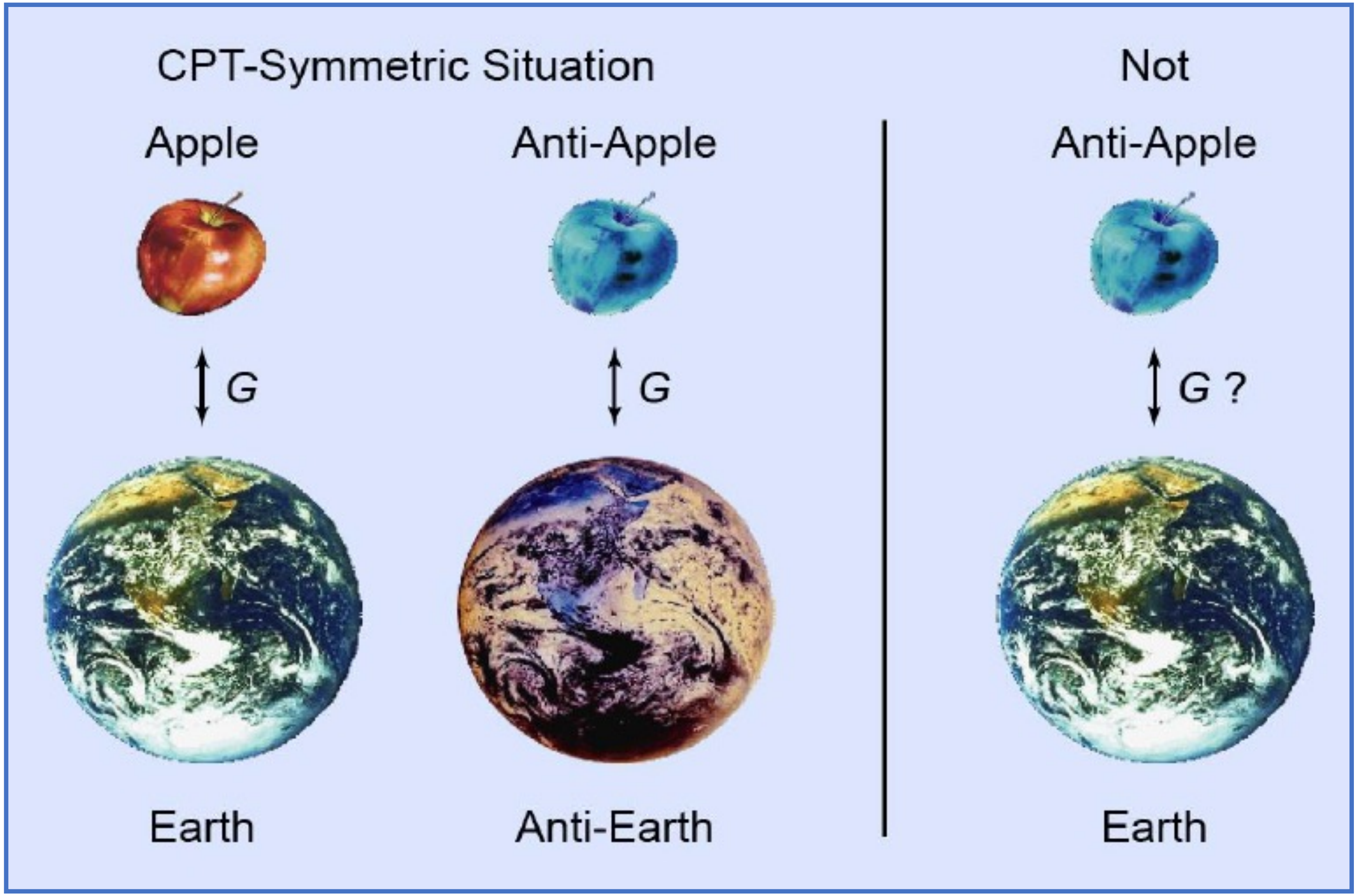
If opposite: matter

If equal: anti-matter

CPT Violation...

CPT symmetry implies that an antiparticle is ***identical*** to a particle travelling backwards in time.

CPT is conserved, but does anti-matter fall down?



Contents Today & Tomorrow:

1. CP Violation
   a) Discrete Symmetries
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
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   a) CP violation and Interference
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Weak interaction in three Flavour Generations

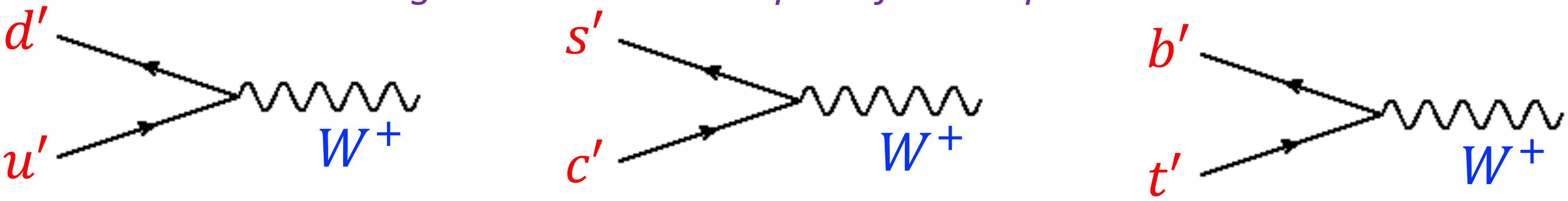
- Weak Interaction is 100% parity violating.
  - Wolfgang Pauli: *"I cannot believe God is a weak left-hander."*

- Implement an $SU(2)_L$ symmetry for *massless* particles:

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L \qquad \text{x3 !}$$

Note:
$$\psi_L = \frac{1}{2}(1-\gamma^5)\psi$$

- Flavour universality: *identical interactions* in three generations.
  - In fact: *how to distinguish a massless d' quark from s' quark?*



- There is *no CP violation* in these massless interactions
  - What happens when particles acquire mass?

Spontaneous Symmetry Breaking → Origin of Mass

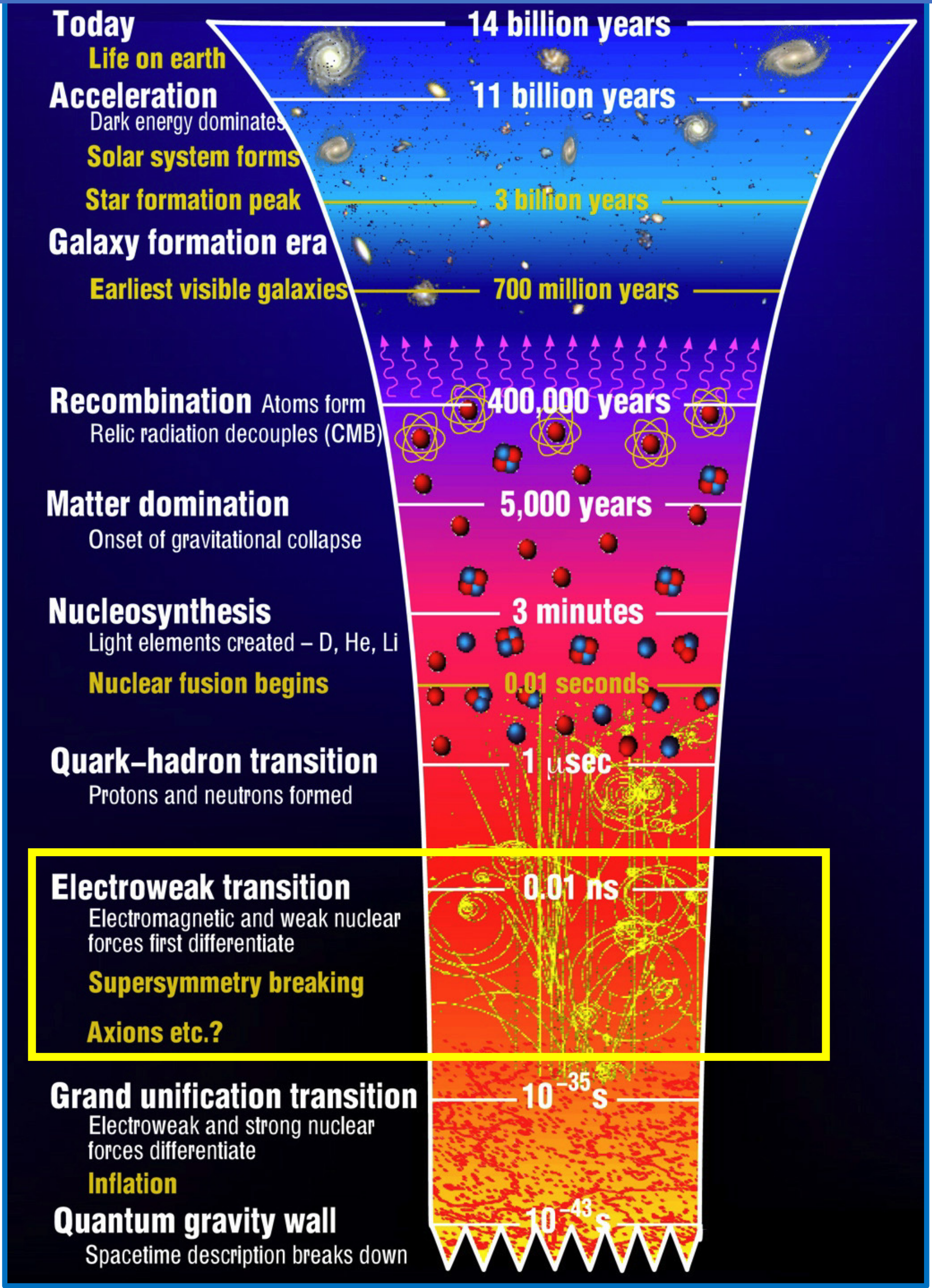
- Yukawa couplings to massless particles (Weinberg):

$$\mathcal{L}_Y = Y^d_{ij}\,\left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d'_{jR} + Y^u_{ij}\,\left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} u'_{jR}$$

- Yukawa interaction is *not* flavour universal!

→*Unknown origin of Yukawa matrix acting on generations "i" and "j"*

$$\begin{pmatrix} Y_{11}\overline{(u\ \ d)}^I_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{12}\overline{(u\ \ d)}^I_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{13}\overline{(u\ \ d)}^I_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} \\ Y_{21}\overline{(c\ \ s)}^I_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{22}\overline{(c\ \ s)}^I_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{23}\overline{(c\ \ s)}^I_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} \\ Y_{31}\overline{(t\ \ b)}^I_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{32}\overline{(t\ \ b)}^I_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} & Y_{33}\overline{(t\ \ b)}^I_L \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} \end{pmatrix} \cdot \begin{pmatrix} d^I_R \\ s^I_R \\ b^I_R \end{pmatrix}$$



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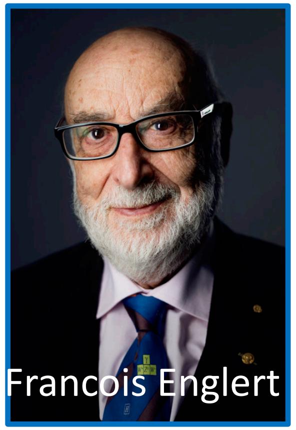
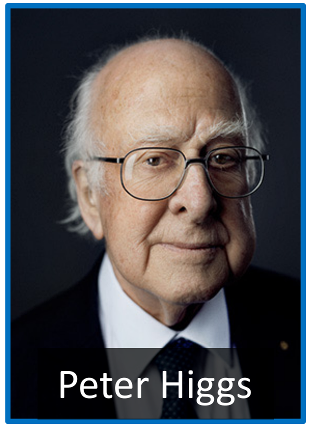
- SSB: B-E-H Mechanism:

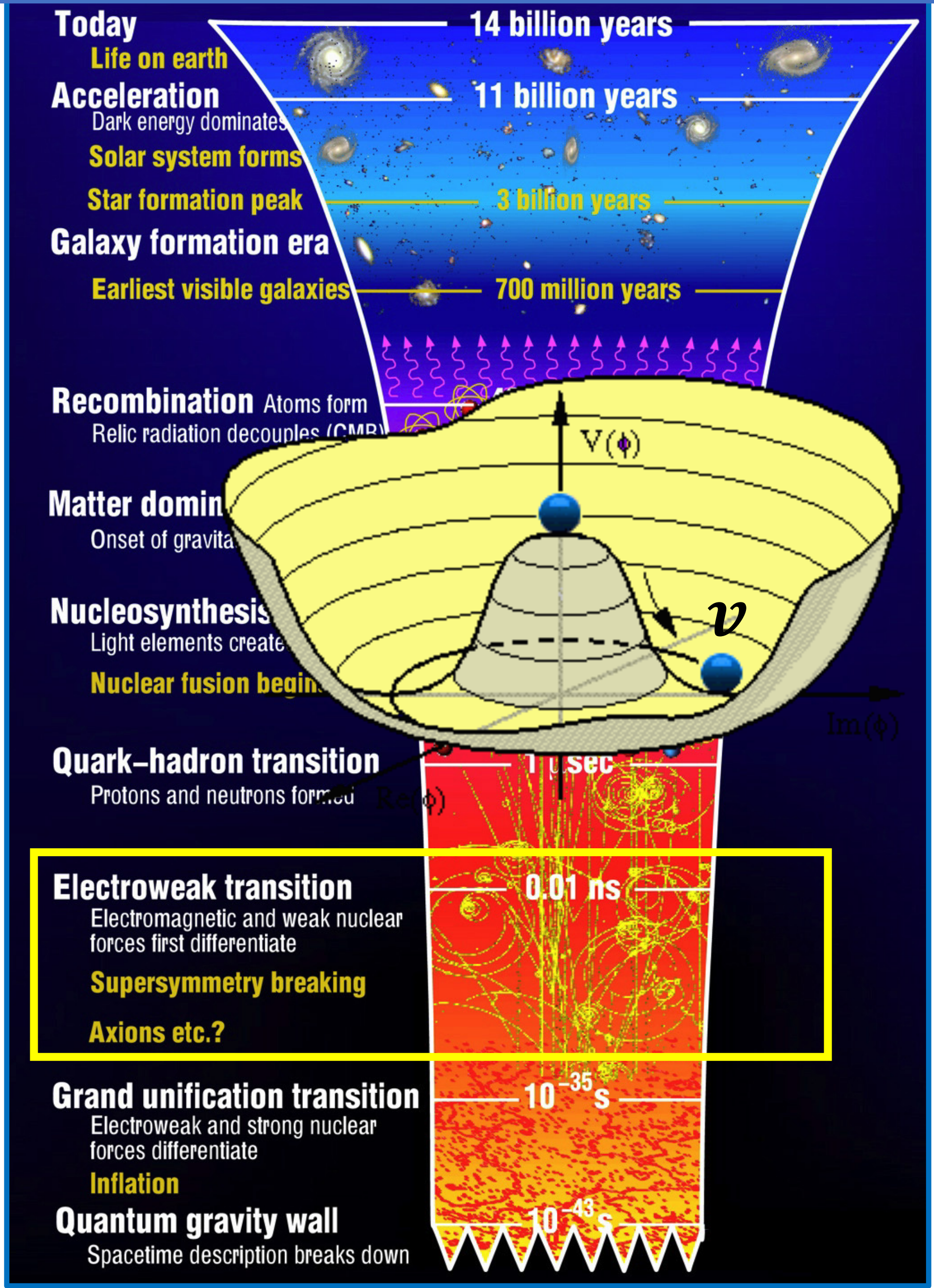

Robert Brout


Francois Englert


Peter Higgs

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

➔ Massive W- and Z- bosons



Spontaneous Symmetry Breaking→ Origin of Mass

- Yukawa couplings to massless particles (Weinberg):

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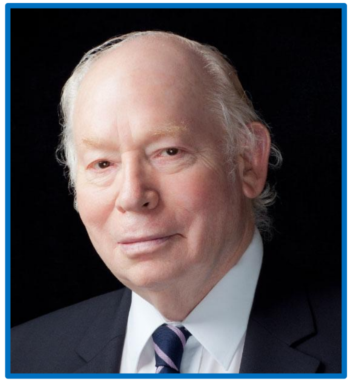
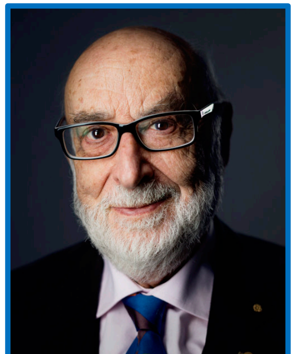


➔Massive fermions

- SSB: B-E-H Mechanism:

Robert Brout



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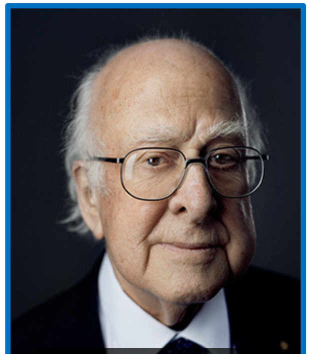

Peter Higgs

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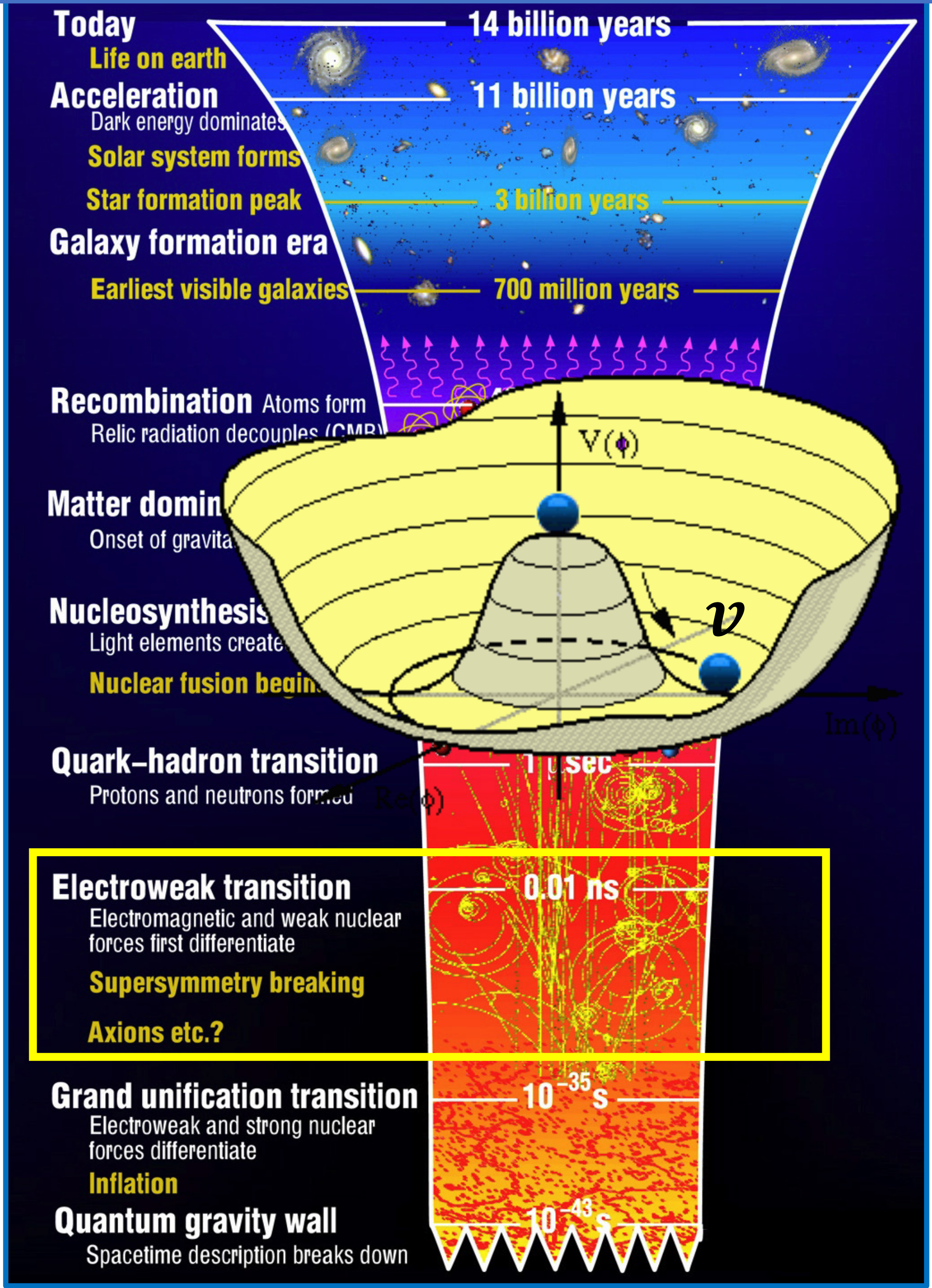
➔ Massive W- and Z- bosons



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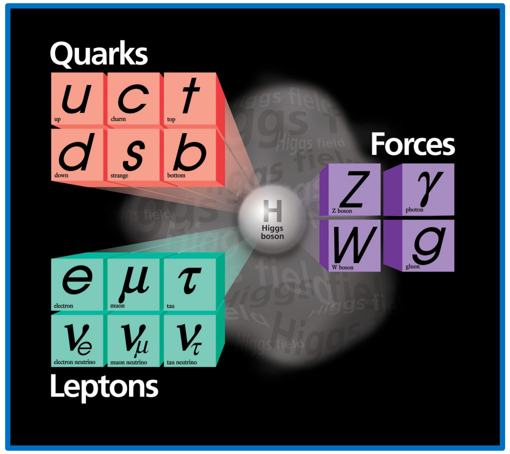
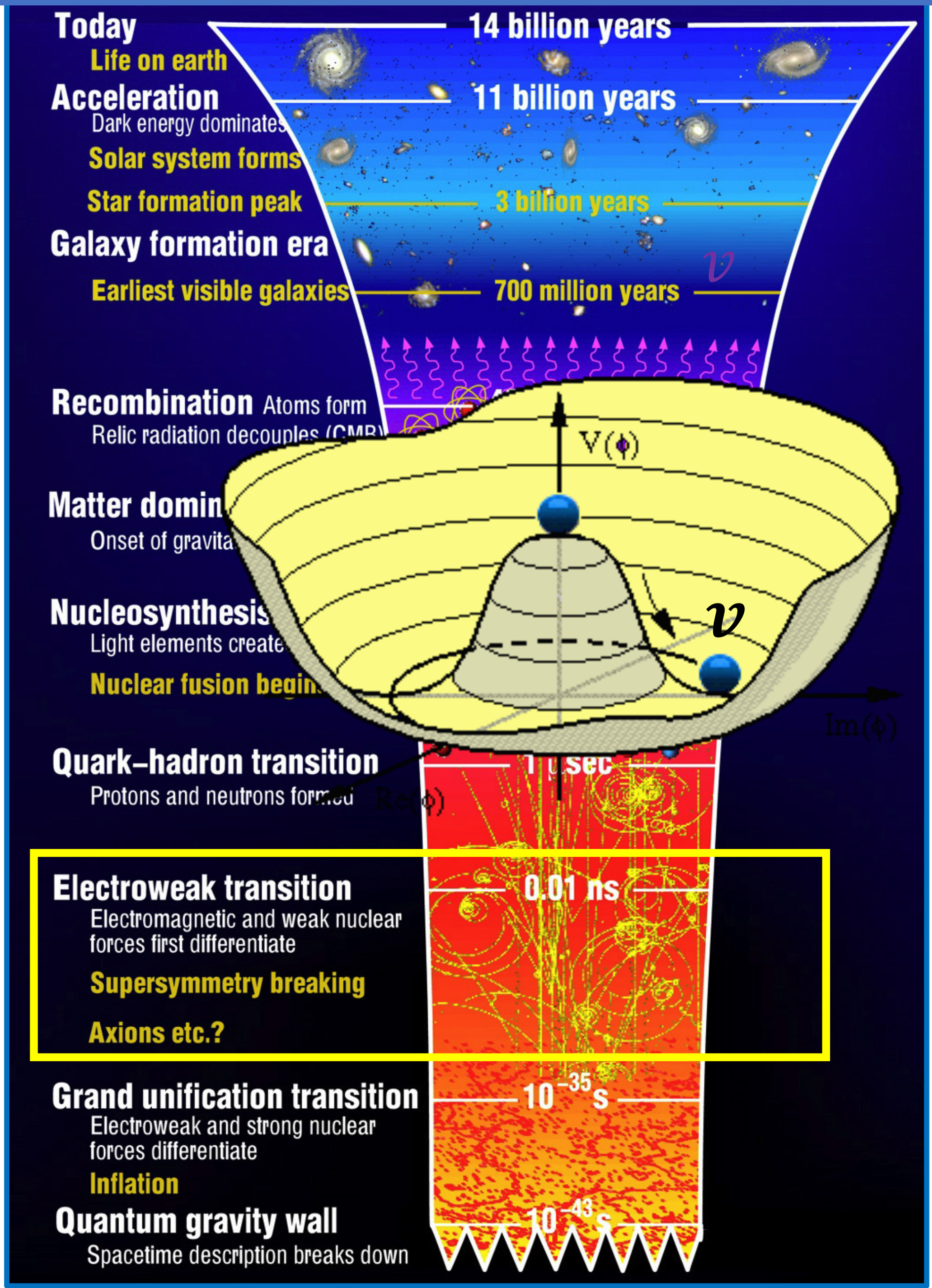
- Diagonalize Y_{ij} :

  $u_i = (V^u)_{ij}\, u'_j$ and $d_i = (V^d)_{ij}\, d'_j$

  → mass and flavour eigenstates





Spontaneous Symmetry Breaking → Origin of Mass

- Yukawa couplings to massless particles:

$$\mathcal{L}_Y = Y^d_{ii}\ (\bar{u}_i, \bar{d}_i)_L \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} d_{iR} + Y^u_{ii}\ (\bar{u}_i, \bar{d}_i)_L \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} u_{iR}$$

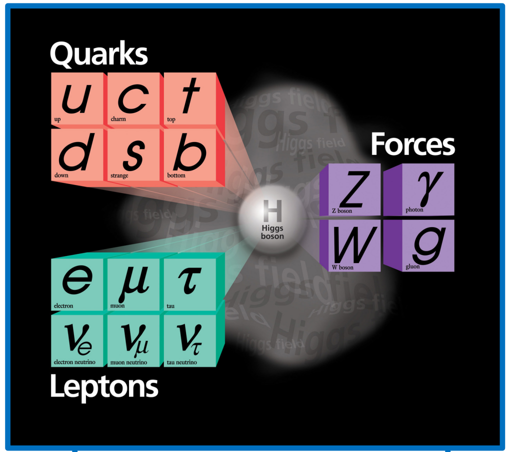
- Diagonalize Y_{ij} :

$u_i = (V^u)_{ij}\, u'_j$ and $d_i = (V^d)_{ij}\, d'_j$

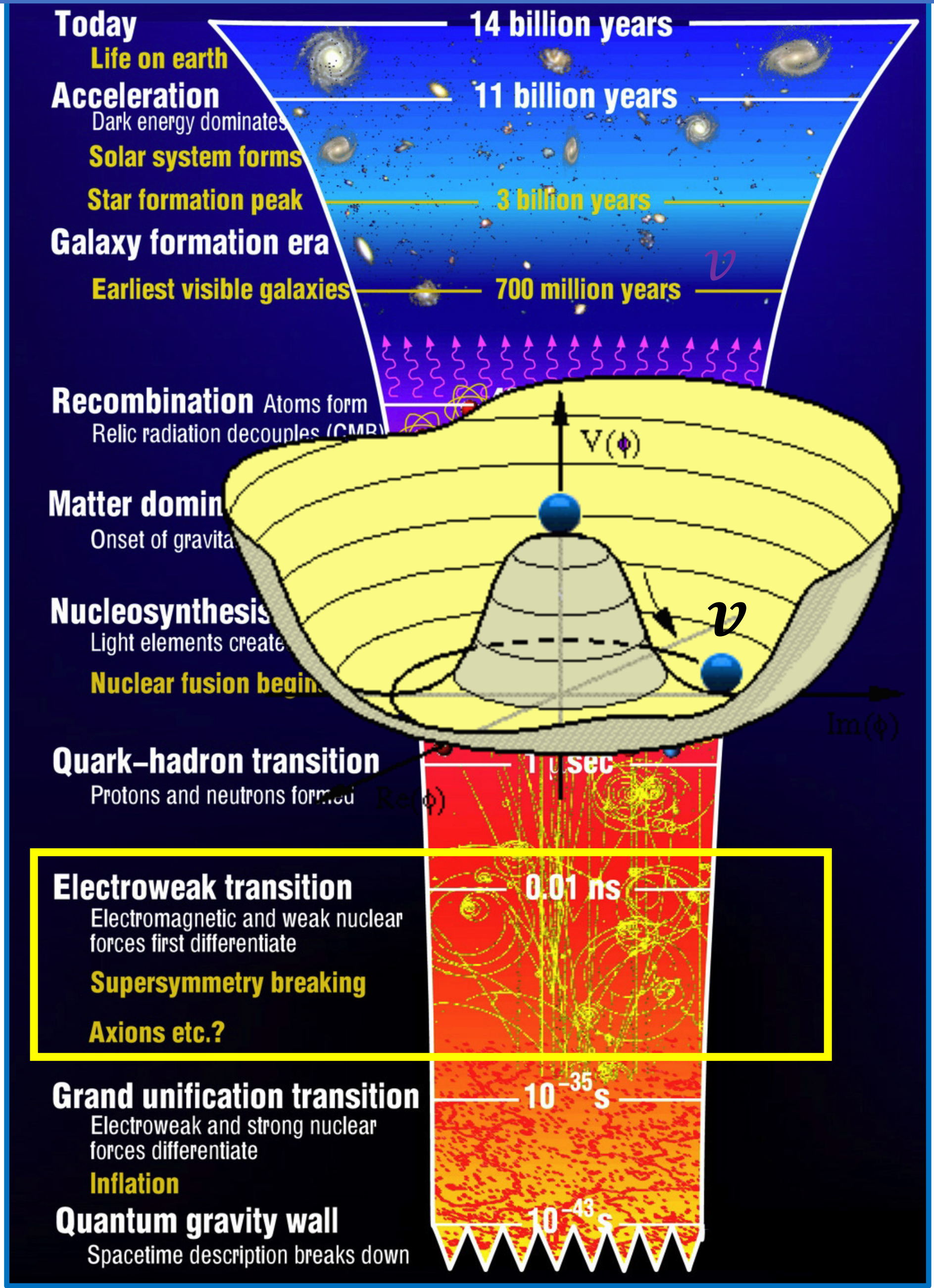
→ mass and flavour eigenstates

- Mass terms: $M_{ii} = Y_{ii}\, v/\sqrt{2}$

$$\mathcal{L}_Y \to \mathcal{L}_H = m_d\, \bar{d}_L\, d_R + m_u\, \bar{u}_L\, u_R$$



Physical particles



Spontaneous Symmetry Breaking→ Origin of Mass

- Yukawa couplings to massless particles:

$$\mathcal{L}_Y = Y_{ii}^d \left(\bar{u}_i, \bar{d}_i\right)_L \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} d_{iR} + Y_{ii}^u \left(\bar{u}_i, \bar{d}_i\right)_L \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} u_{iR}$$

- Diagonalize Y_{ij} :

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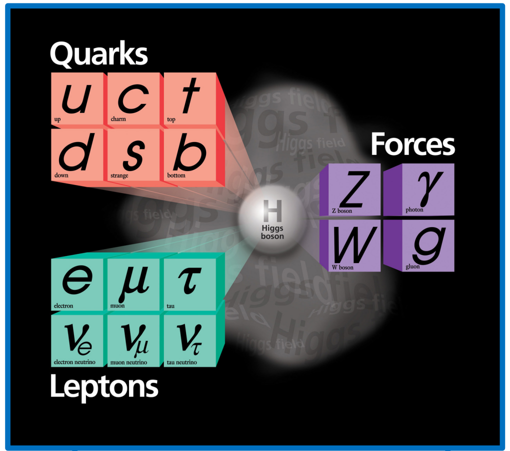
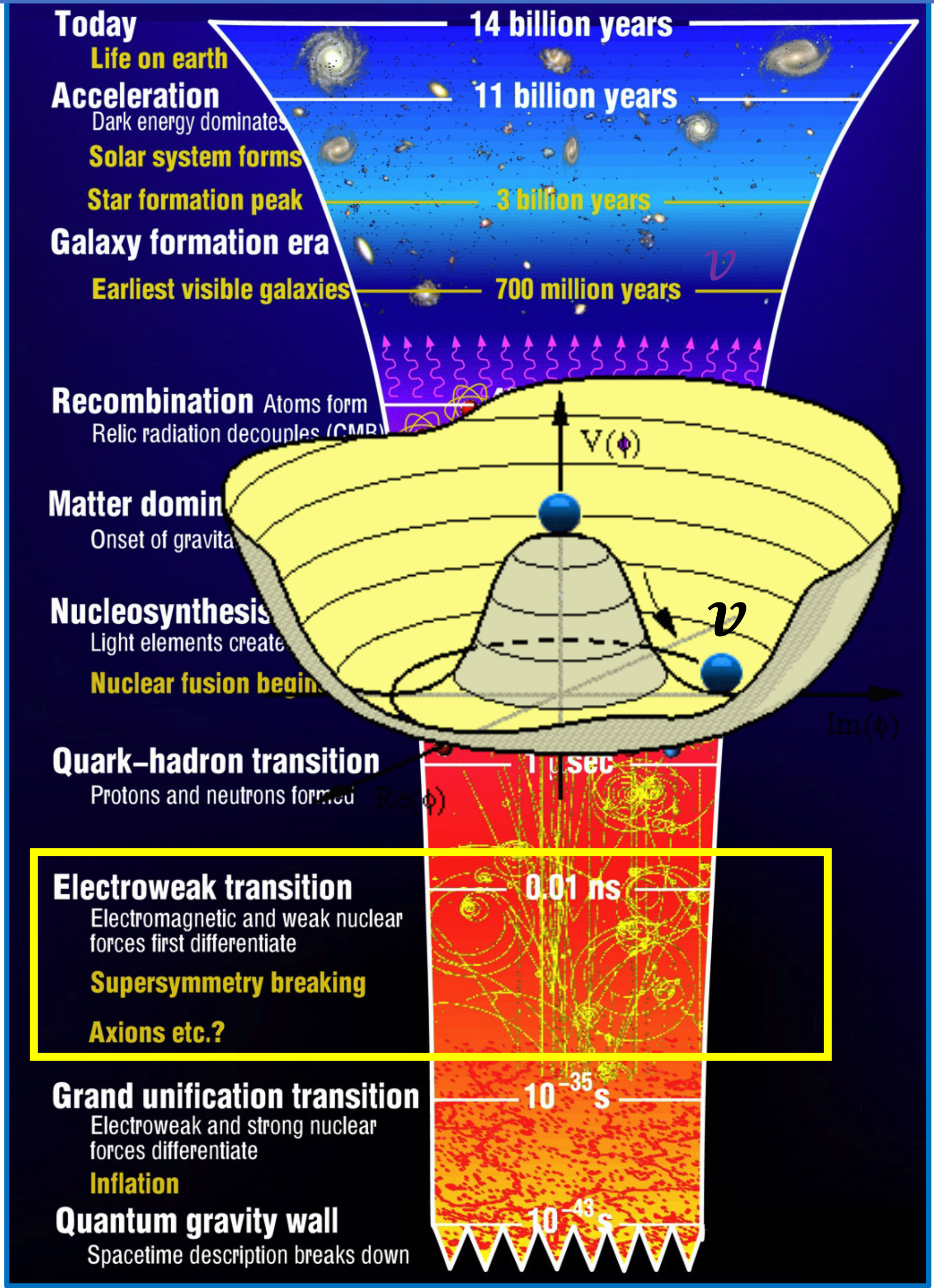


Physical particles

- Mass terms: $M_{ii} = Y_{ii}\, v/\sqrt{2}$

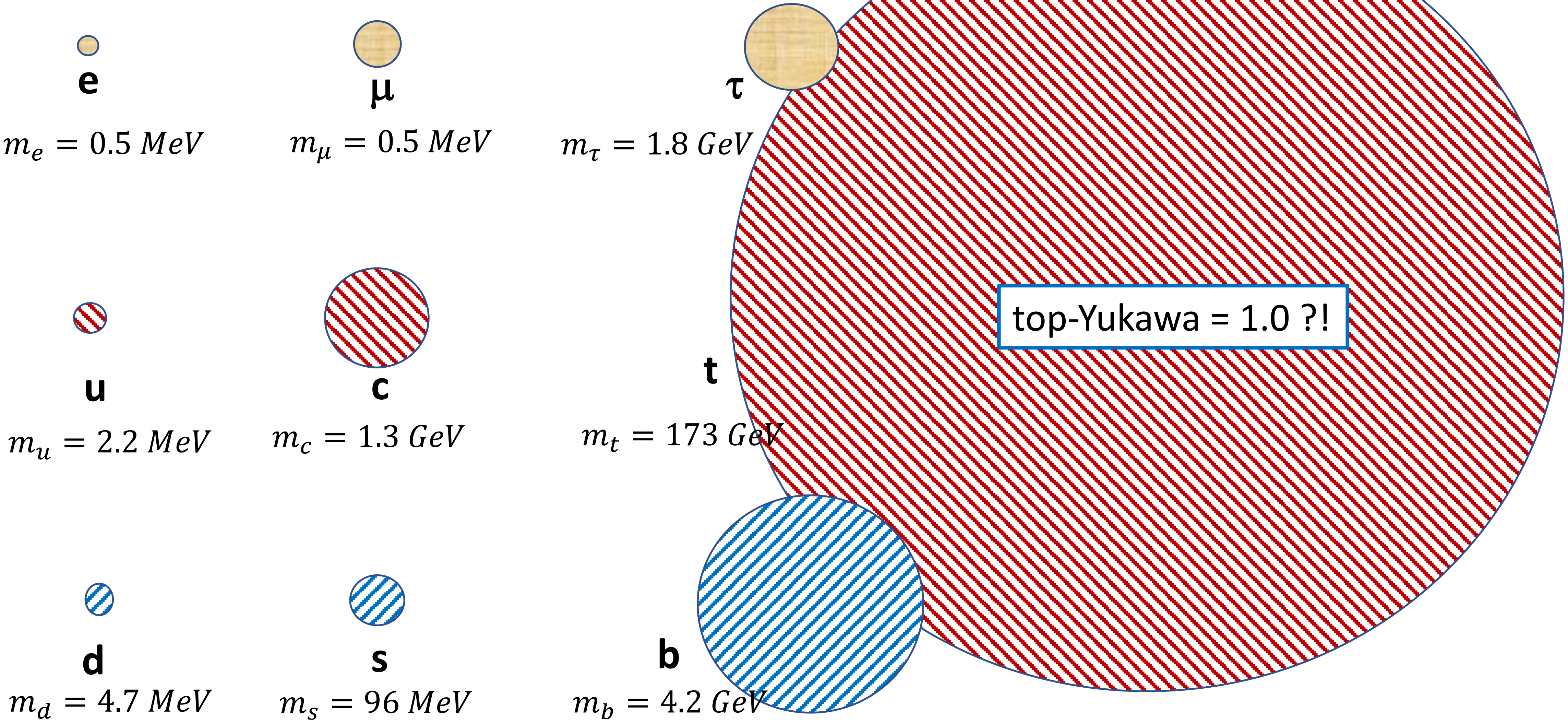
$$\mathcal{L}_Y \rightarrow \mathcal{L}_H = m_d\, \bar{d}\; d + m_u\, \bar{u}\; u$$

- Top quark mass: $m_{top} = 1.0\, v/\sqrt{2}$
  - *To first order Higgs couples only to top with coupling strength 1.0 !*
    - *Very* flavour non-universal



Flavour Puzzle: particle masses? Origin Yukawa couplings?

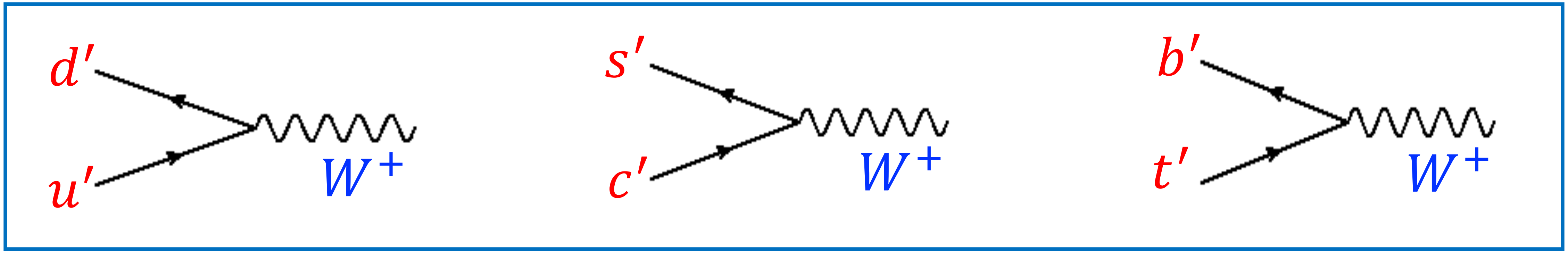
- Weak interaction flavour universal
- Higgs interaction almost purely 3rd generation



The Weak Interaction → Flavour Mixing

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L$$

- *No CP violation*



Redefine: $u'_i = (V^u)_{ij} u_i$ and: $d'_i = \left(V^d\right)^\dagger_{ij} d_i$, such that: $V_{CKM} = \left(V^u V^{d\dagger}\right)_{ij}$ …

The Weak Interaction → Flavour Mixing

(Interaction basis) (Mass basis)

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L \longrightarrow \mathcal{L}_W = \frac{g}{\sqrt{2}} V_{CKM}\, u_L \gamma_\mu W^\mu d_L$$

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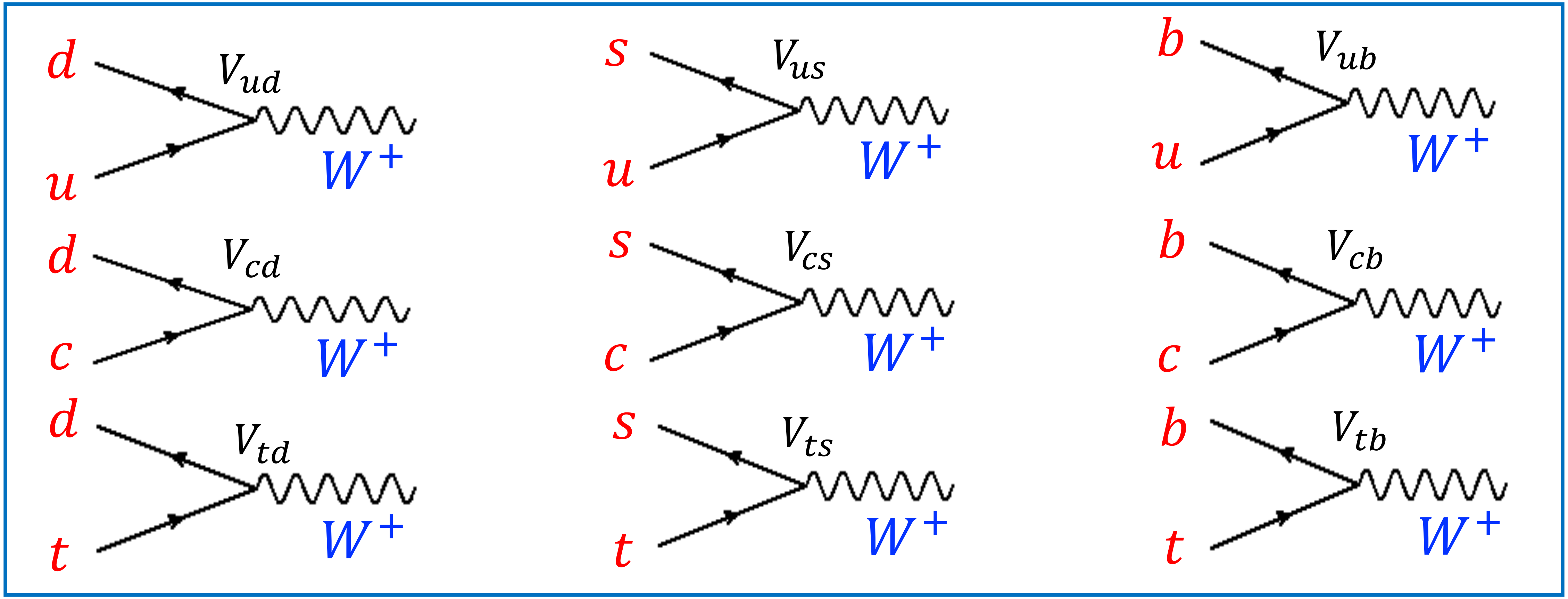
Generation structure of weak interaction, *now includes CP violation.*



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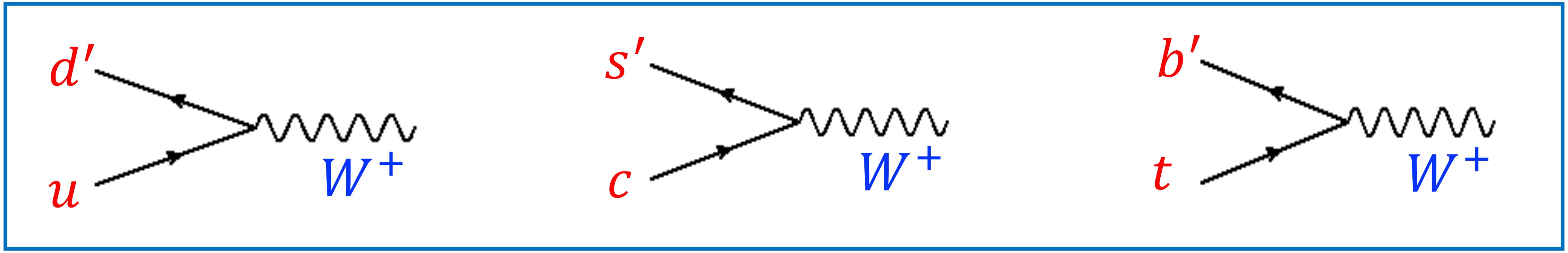
Generation structure of weak interaction, *now includes CP violation.*

Convention: instead, we do as if: $u'_i = u_i$ and $d'_i = (V_{CKM})_{ij}\, d_j$



$$|d'\rangle = V_{ud}\,|d\rangle + V_{us}\,|s\rangle + V_{ub}\,|b\rangle$$

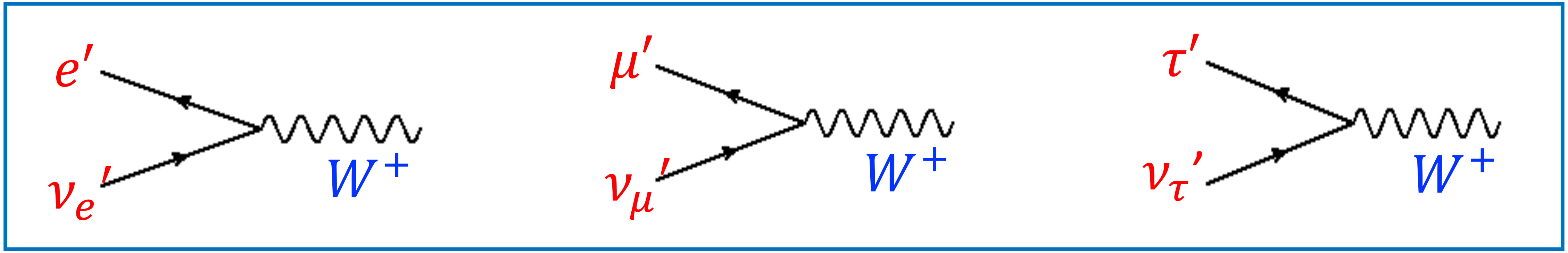
$$|s'\rangle = V_{cd}\,|d\rangle + V_{cs}\,|s\rangle + V_{cb}\,|b\rangle$$

$$|b'\rangle = V_{td}\,|d\rangle + V_{ts}\,|s\rangle + V_{tb}\,|b\rangle$$

How about leptons?

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \nu'_{e_L} \gamma_\mu W^\mu e'_L$$

- *No CP violation*



Redefine: $\nu_i' = (U^\nu)_{ij}\, \nu_i$ and: $l_i' = (U^l)^\dagger_{ij} l_i$, such that: $U_{MNS} = (U^\nu U^{l\dagger})_{ij}$ …

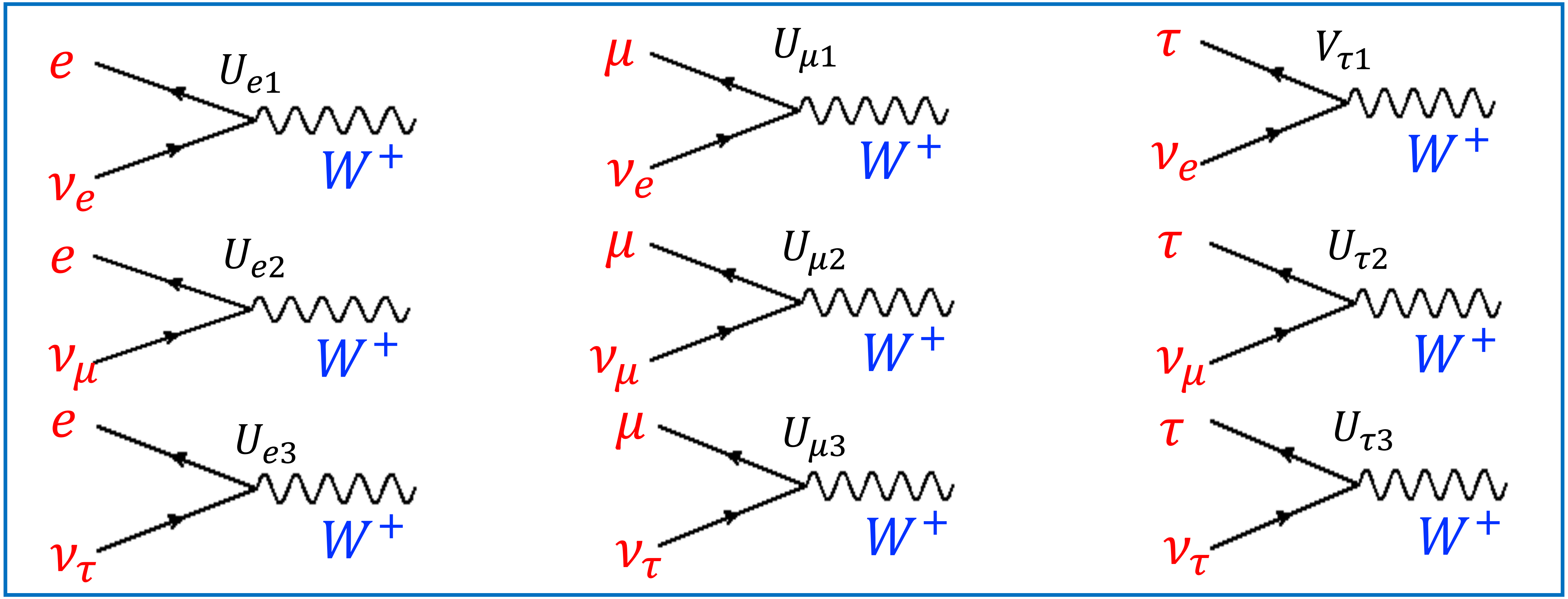
How about leptons?

(Interaction basis) (Mass basis)

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \nu'_L \gamma_\mu W^\mu e'_L \longrightarrow \mathcal{L}_W = \frac{g}{\sqrt{2}} U_{MNS} \nu_L \gamma_\mu W^\mu e_L$$

Redefine: $\nu'_i = (U)_{ij} \nu_i$ and: $l'_i = \left(U^d\right)^\dagger_{ij} l_i$, such that: $U_{MNS} = \left(U^u U^{d\dagger}\right)_{ij}$ …

Generation structure of weak interaction, *now includes CP violation.*



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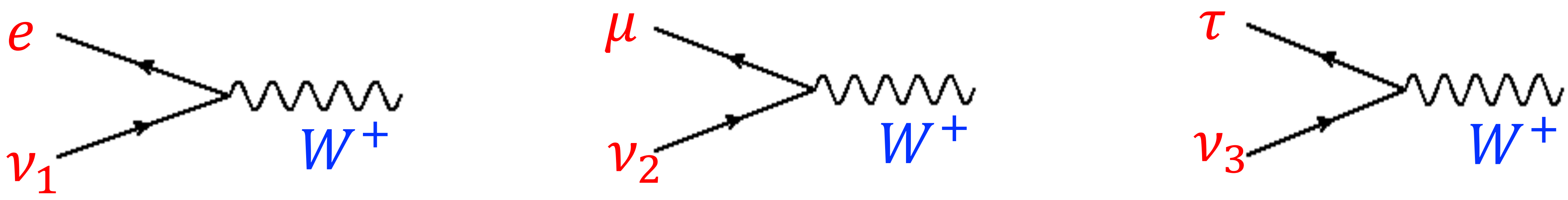
Generation structure of weak interaction, *now includes CP violation.*

Convention: instead we do as if: $\nu_{1,2,3} = (U_{MNS})_{ij} \nu_{e,\mu,\tau}$ and $l_i' = l_i$

For neutrinos we label the mass eigenstates as: 1, 2, 3 instead of e, μ, τ



$$|\nu_1\rangle = U_{e1}|\nu_e\rangle + U_{\mu 1}|\nu_\mu\rangle + U_{\tau 1}|\nu_\tau\rangle$$

$$|\nu_2\rangle = U_{e2}|\nu_e\rangle + U_{\mu 2}|\nu_\mu\rangle + U_{\tau 2}|\nu_\tau\rangle$$

$$|\nu_3\rangle = U_{e3}|\nu_e\rangle + U_{\mu 3}|\nu_\mu\rangle + U_{\tau 3}|\nu_\tau\rangle$$

Food for thought-1: which states mix?

- Quarks: $\binom{u}{d'} = \binom{u}{V_{ud}\, d + V_{us}\, s + V_{ub}\, b}$; We say "the down-type quarks mix".
- Leptons: $\binom{\nu_1}{e} = \binom{U_{e1}\, \nu_e + U_{\mu 1}\, \nu_\mu + U_{\tau 1}\, \nu_\tau}{e}$; We say "the neutrinos mix."

- Why the "down-types" in one case and the "up-types" in another?

- Answer: it is convention! Both mix individually (in an unknown way).
  - The interaction is always: $\mathcal{L}_W = \frac{g}{\sqrt{2}} V_{CKM}\, u_L\, \gamma_\mu\, W^\mu\, d_L$
  - i.e up and down-type combined!

- Paradox question: does this mean neutrino mixing is unphysical??

Food for thought-2: Where did the CP violation come from?

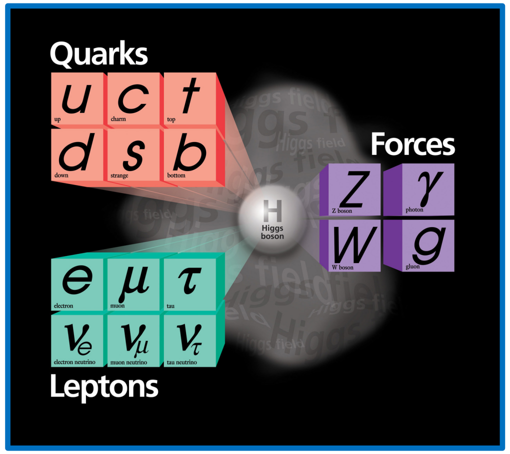
- Yukawa couplings to massless particles:

$$\mathcal{L}_Y = Y^d_{ij}\ (\overline{u'_i}, \overline{d'_i})_L \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} d'_{jR} + Y^u_{ij}\ (\overline{u'_i}, \overline{d'_i})_L \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} u'_{jR}$$

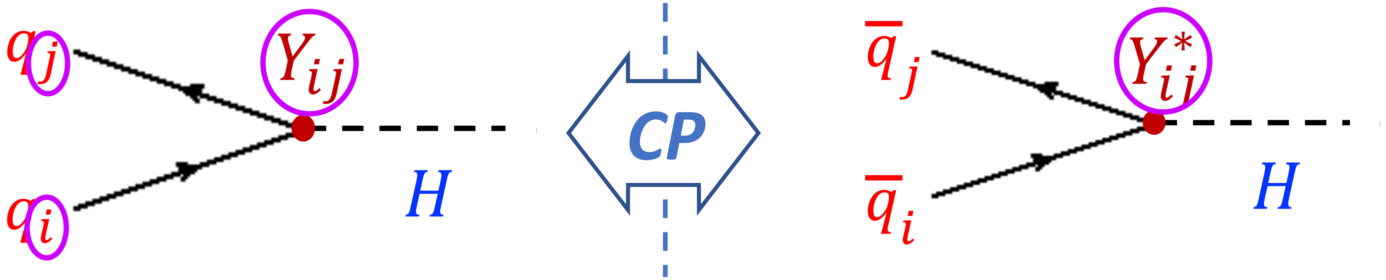
- Diagonalize Y_{ij} :

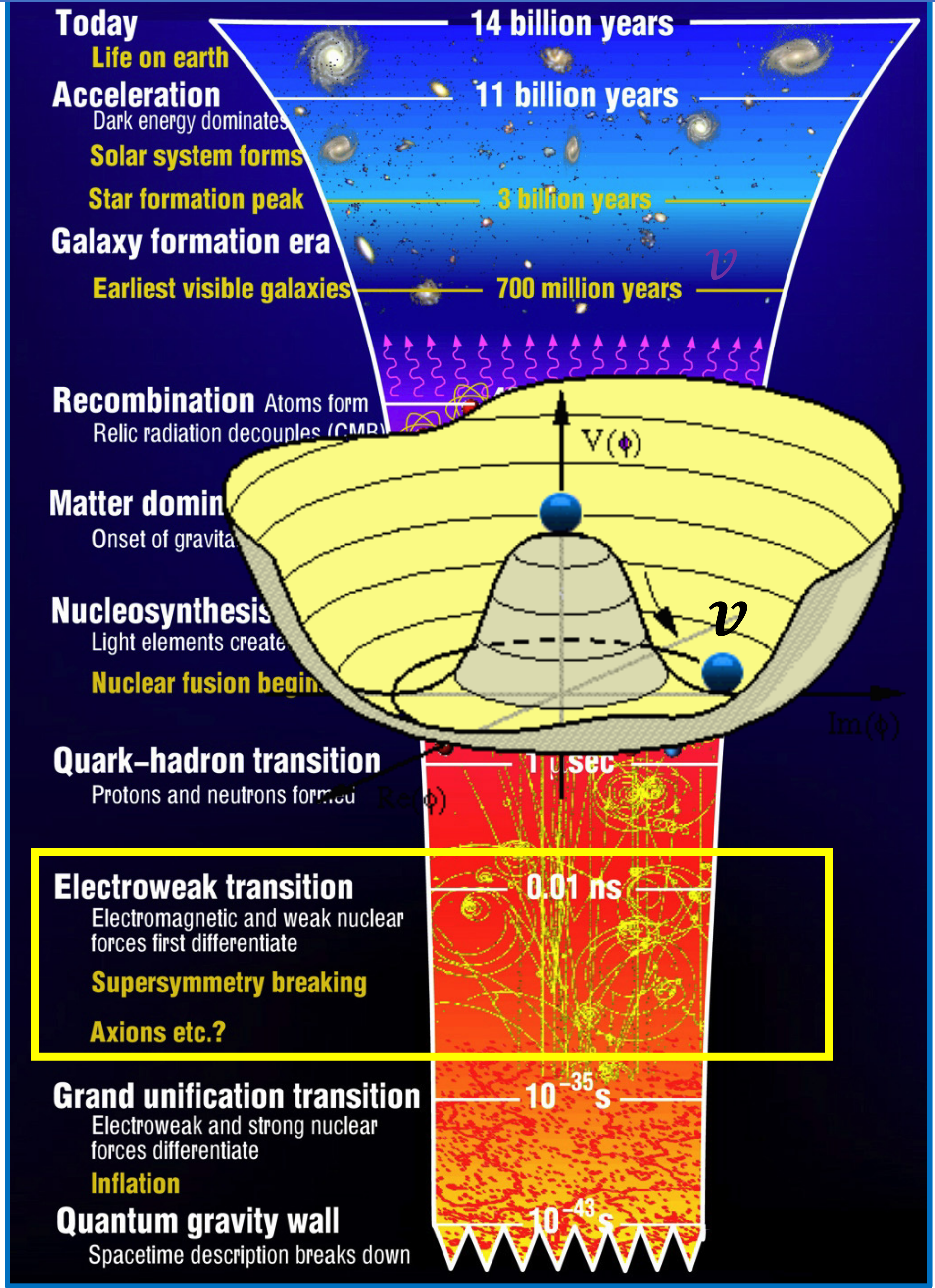
  $u_i = (V^u)_{ij}\, u'_j$ and $d_i = (V^d)_{ij}\, d'_j$

  → mass and flavour eigenstates



- Universality violation: Higgs !
  - Higgs coupling is *not universal*, and mixes generations
  - Complex couplings: allows for CP Violation!





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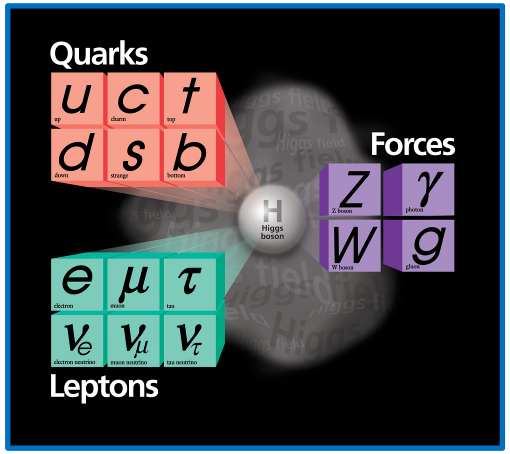
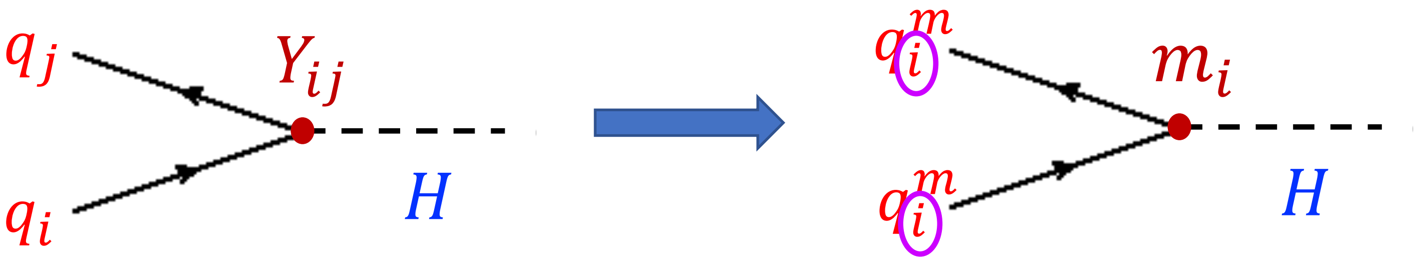
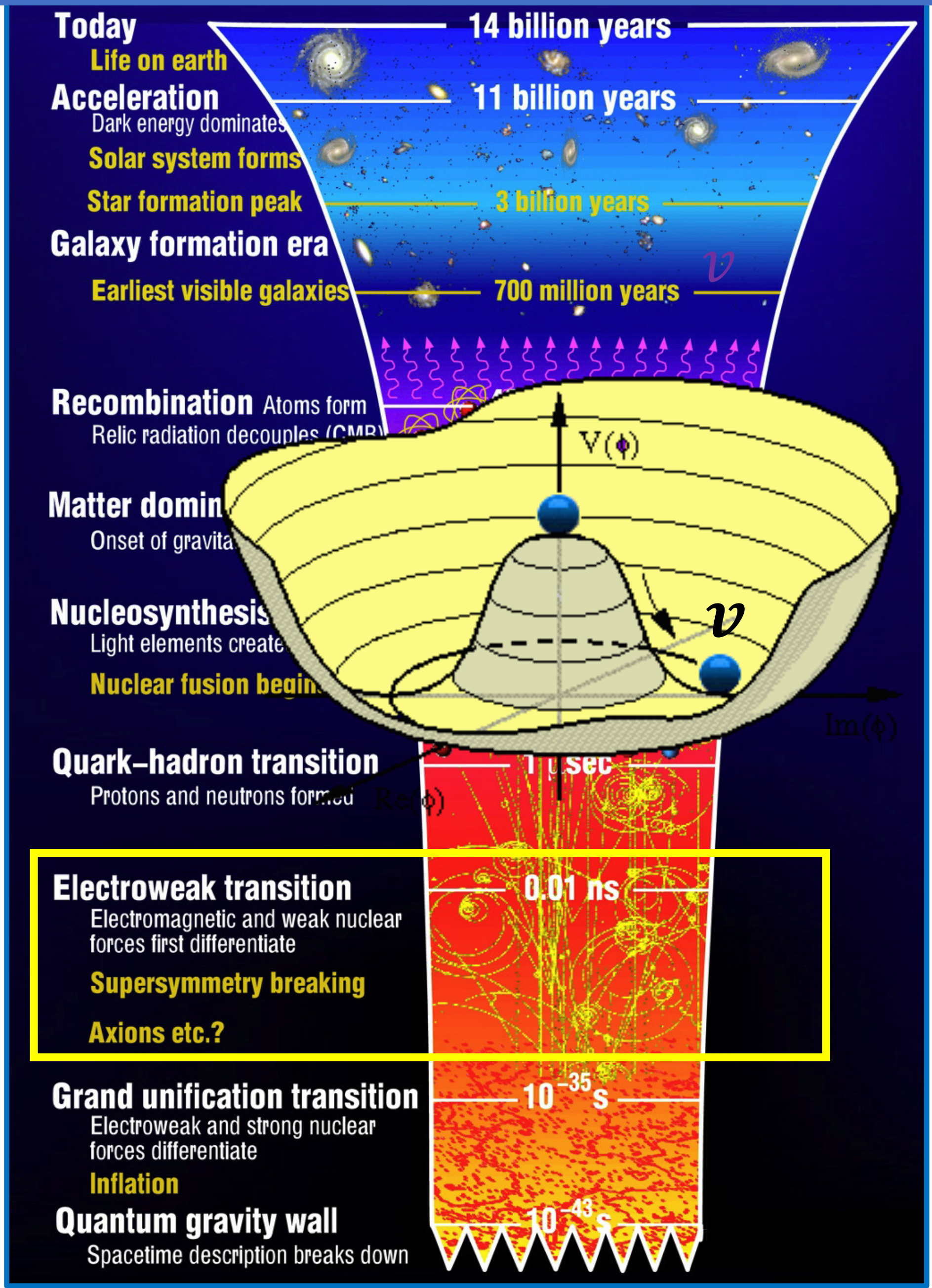


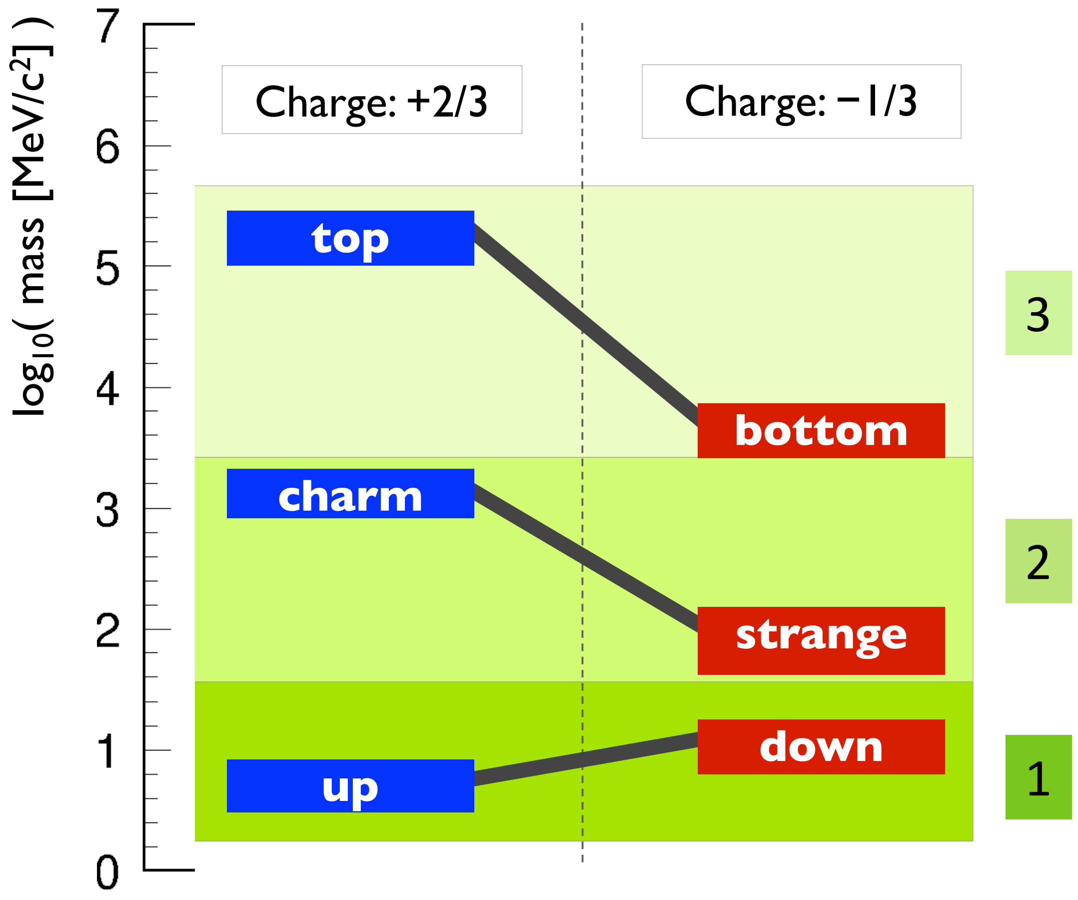
- Higgs: redefines quarks states in mass eigenstates $(i \leftrightarrow i)$

  m_i : Real couplings only! ➔ No CP violation

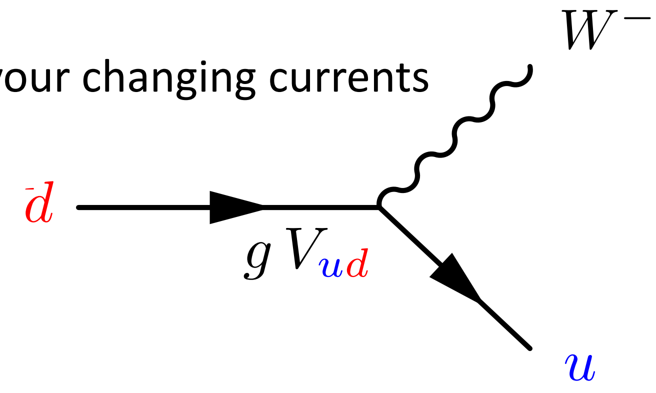




Flavour Changing Quark Interactions

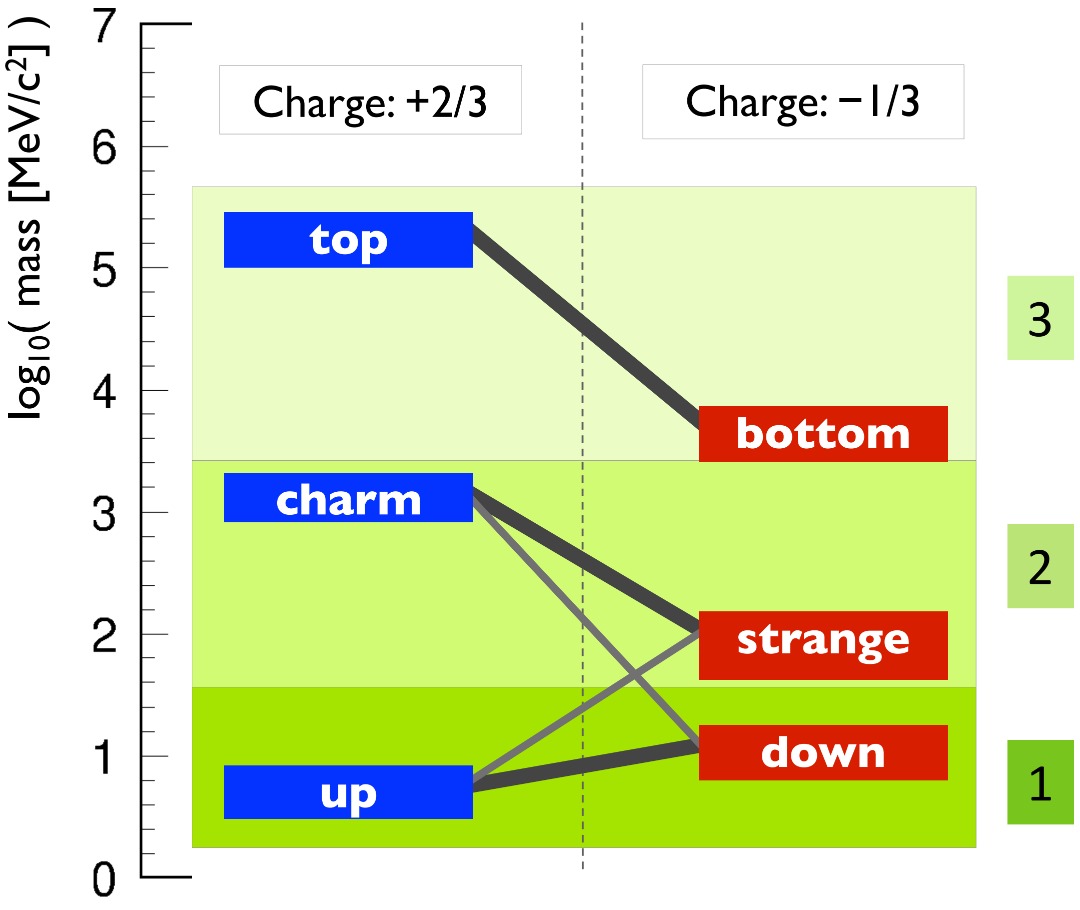


Flavour changing currents

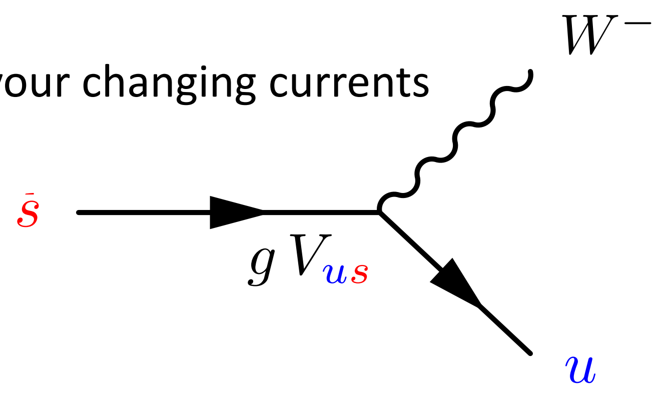


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & & \\ & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions

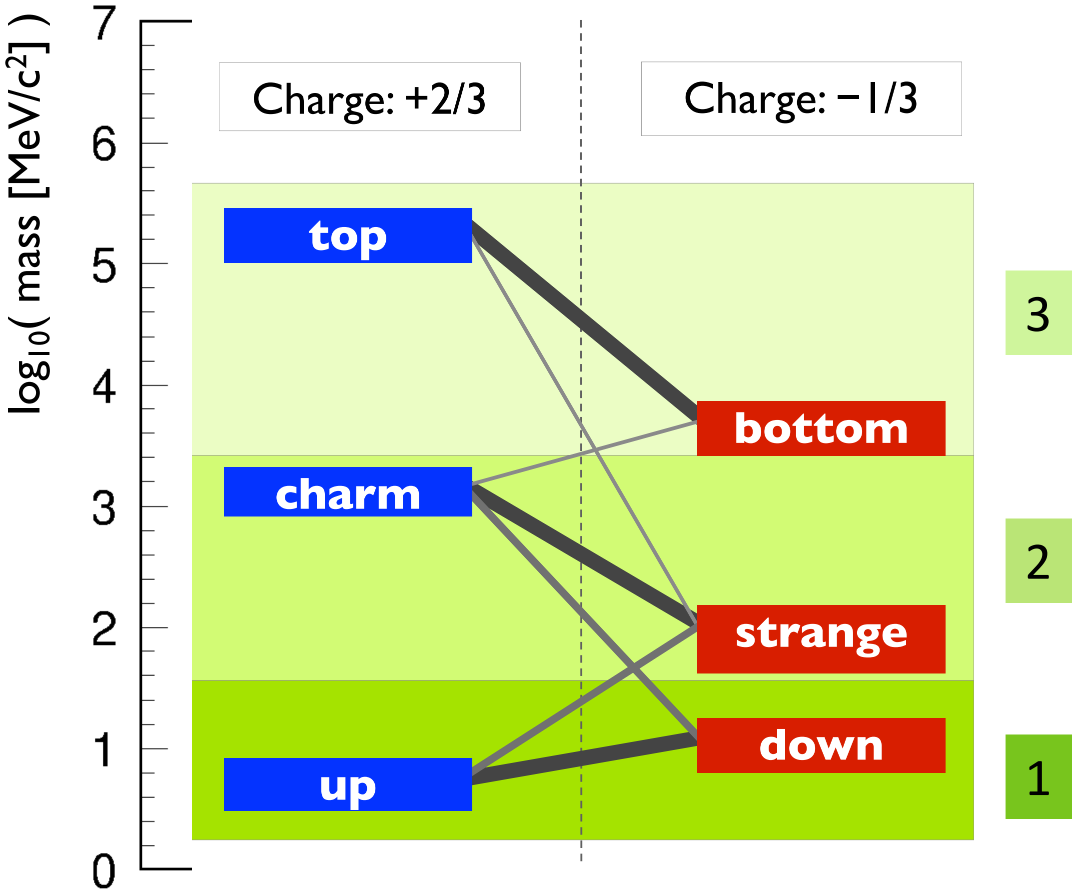


Flavour changing currents

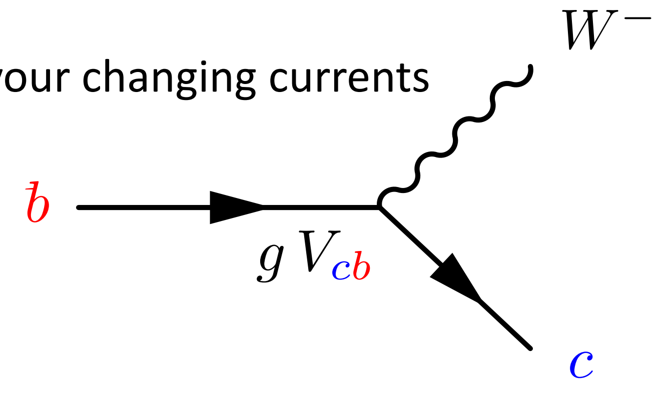


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions

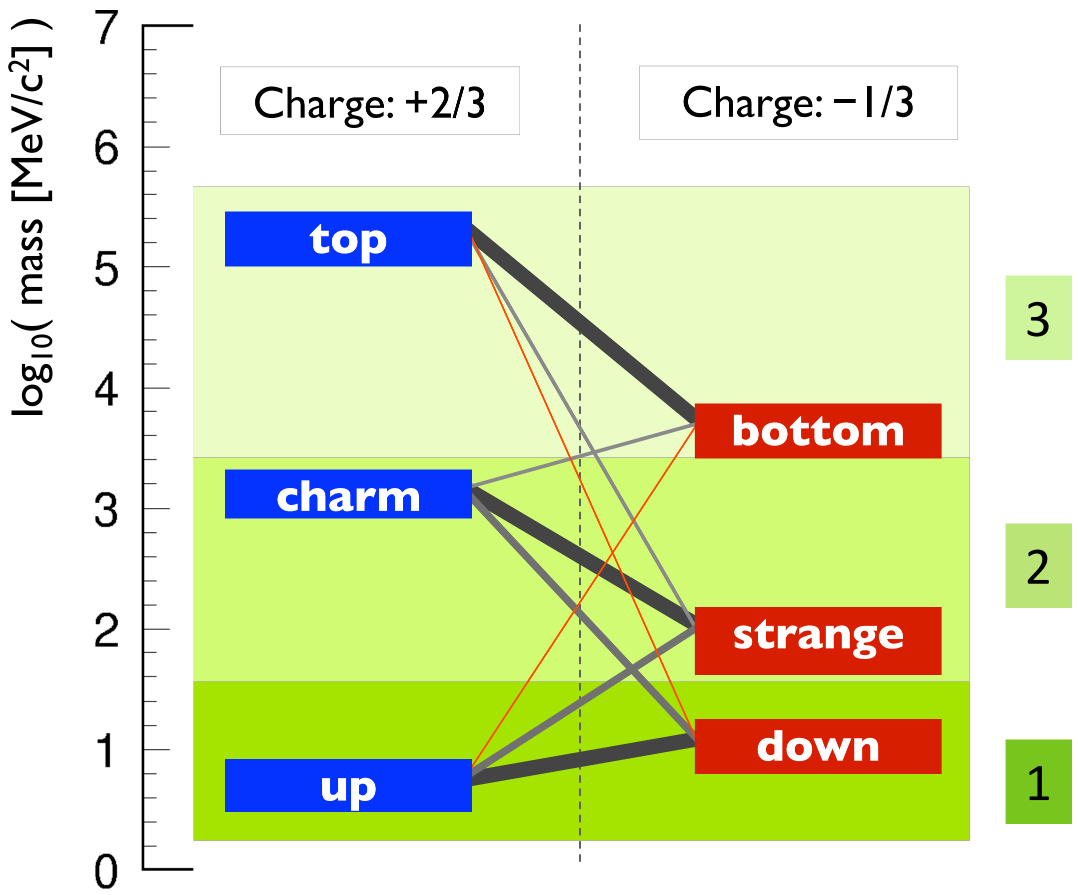


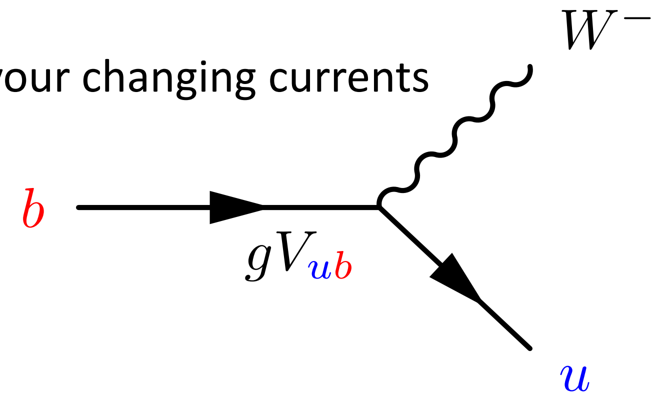
Flavour changing currents



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & V_{cb} \\ & V_{ts} & V_{tb} \end{pmatrix}$$

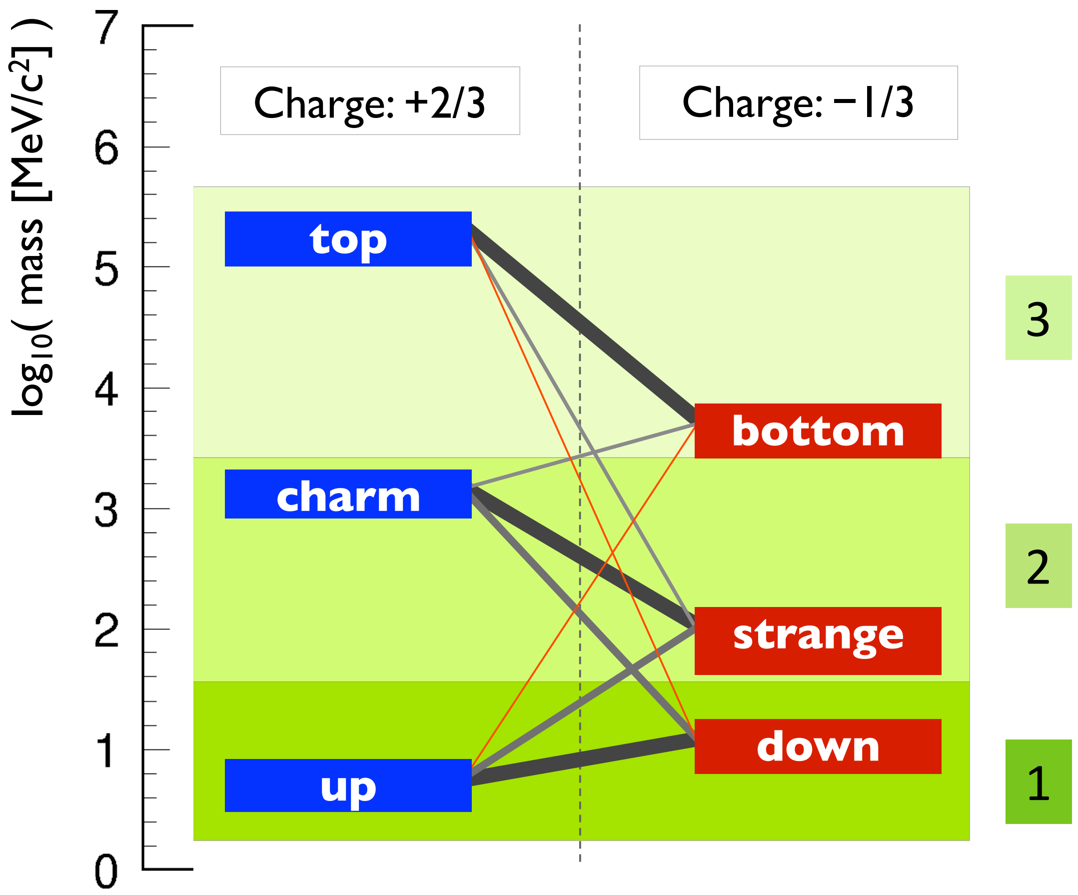
Flavour Changing Quark Interactions

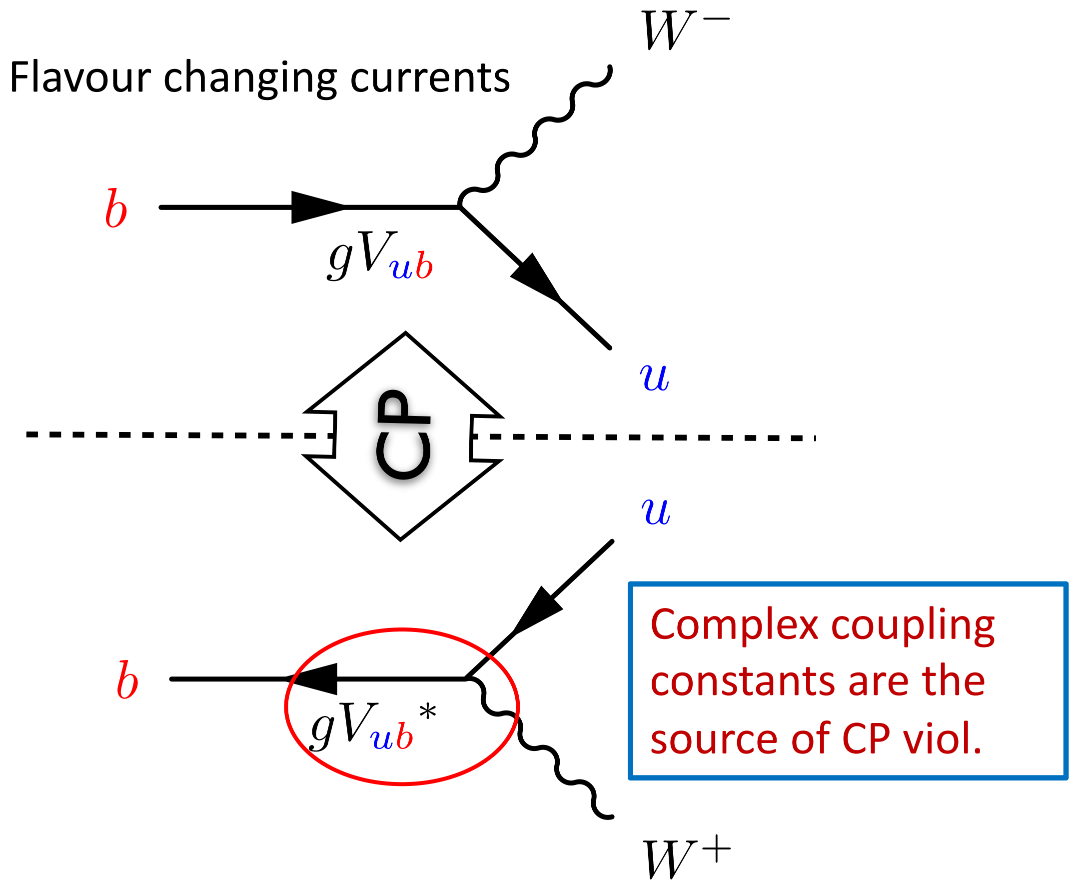




$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions – CP Violation





- Particles and antiparticles have complex conjugated coupling constants

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The CKM matrix V_{CKM} - 3 Generations

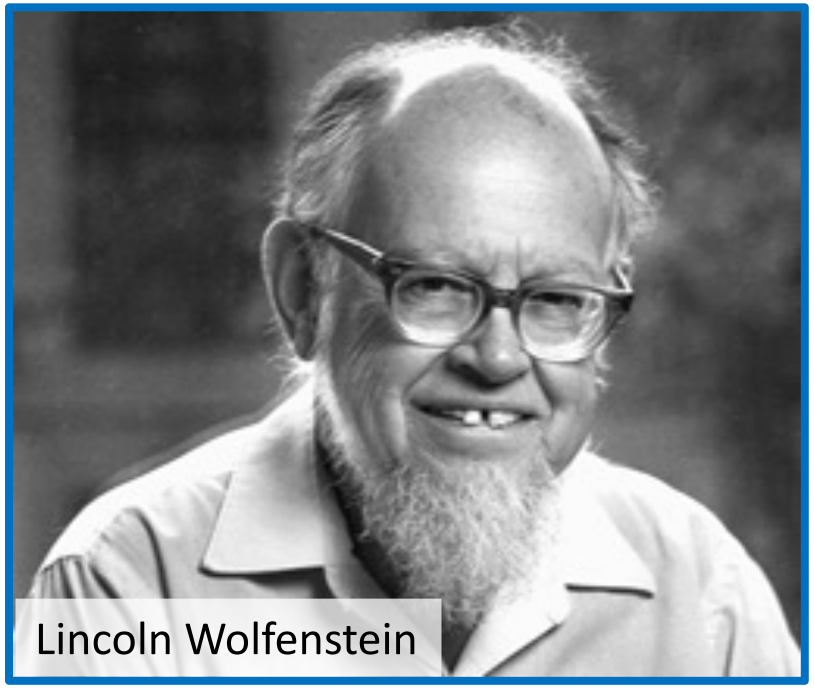
$$V_{CKM}: \quad \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{ccc} d & s & b \\ \end{array}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Wolfenstein parametrization: V_{CKM} =

$$\begin{pmatrix} 1 - {}^{1}/_{2}\,\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - {}^{1}/_{2}\,\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

➔ 1 complex degree of freedom
➔ CP violating phase



- It follows from unitarity:

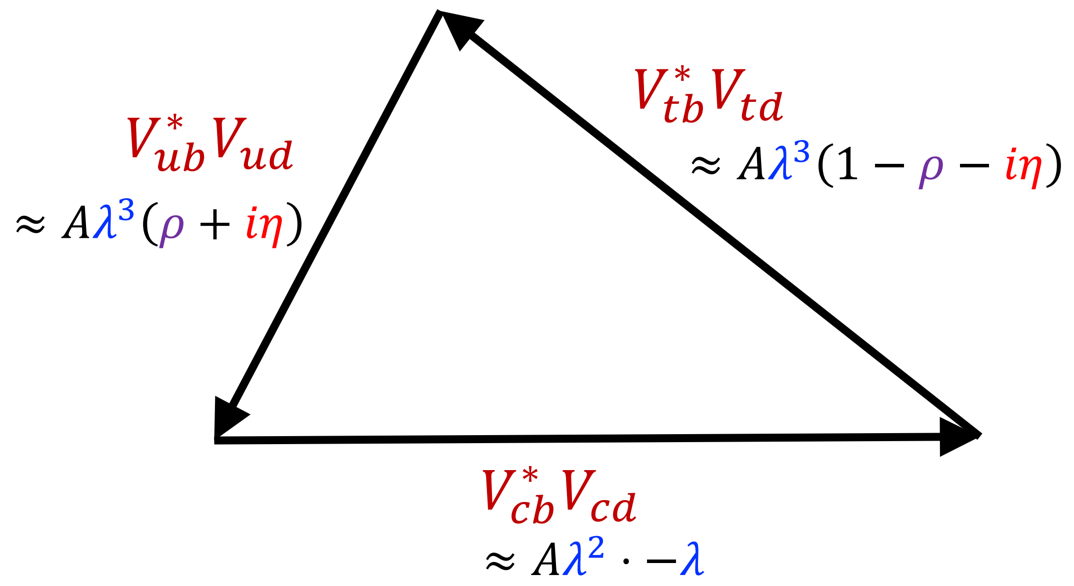
$$V_{CKM}^{\dagger}\, V_{CKM} = 1$$

The CKM matrix and unitarity triangle

- The CKM is a mixing matrix, ie. a complex rotation in 3x3 flavour space
  - This implies that the matrix is unitary: $V_{CKM}^{\dagger} V_{CKM} = 1$

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Triangle in the complex plane:



- There are 9 orthonormality equations
  - Example: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

- Wolfenstein parametrization:

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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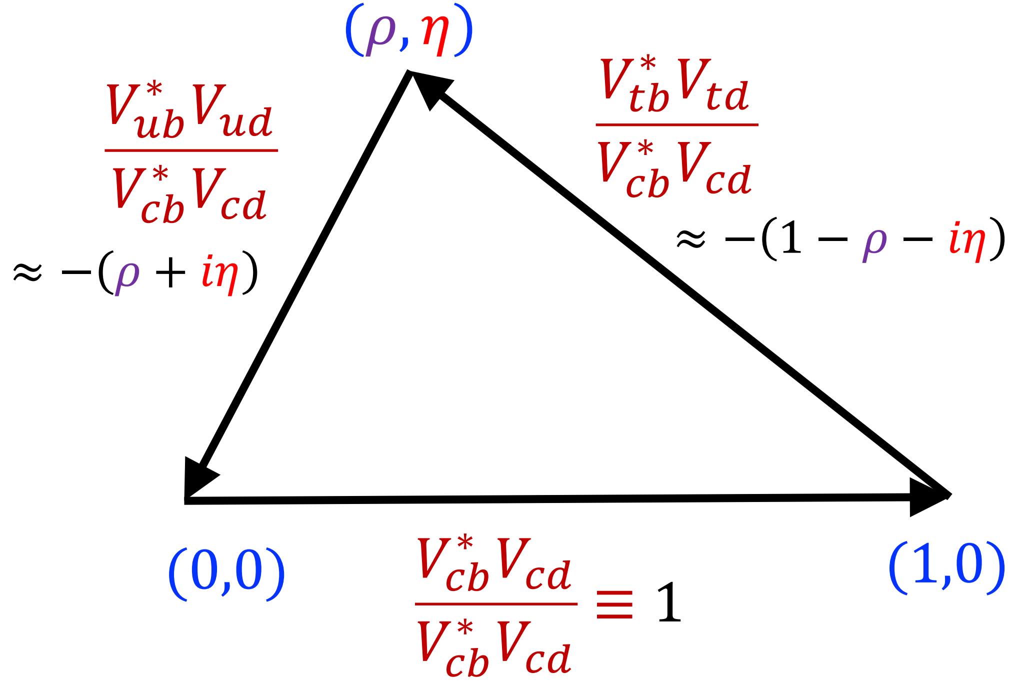


Renormalize horizontal scale to 1

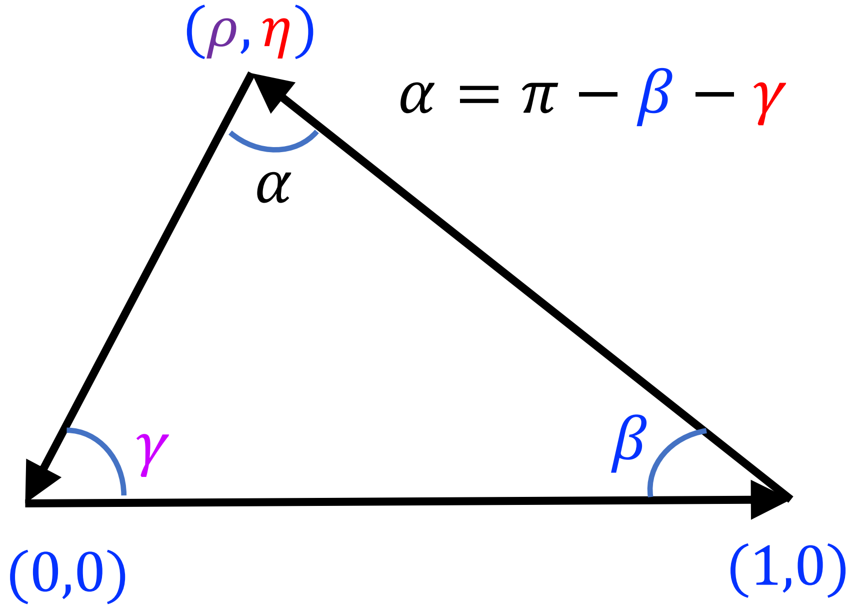
The CKM matrix and unitarity triangle

- CKM in terms of ***phases***:

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

$$V_{CKM}^{\dagger} V_{CKM} = 1$$

Triangle in the complex plane:



- There are 9 orthonormality equations
  - 9 complex numbers: 9 real + 9 imaginary
  - 5 unobservable *relative* quark phases: $\psi_i' \to e^{\phi_i}\psi_i$
  - 18 – 9 – 5 = 4 degrees of freedom

- Wolfenstein parametrization:

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- There are 4 degrees of freedom:
  - 3 real (Euler angles) and one phase

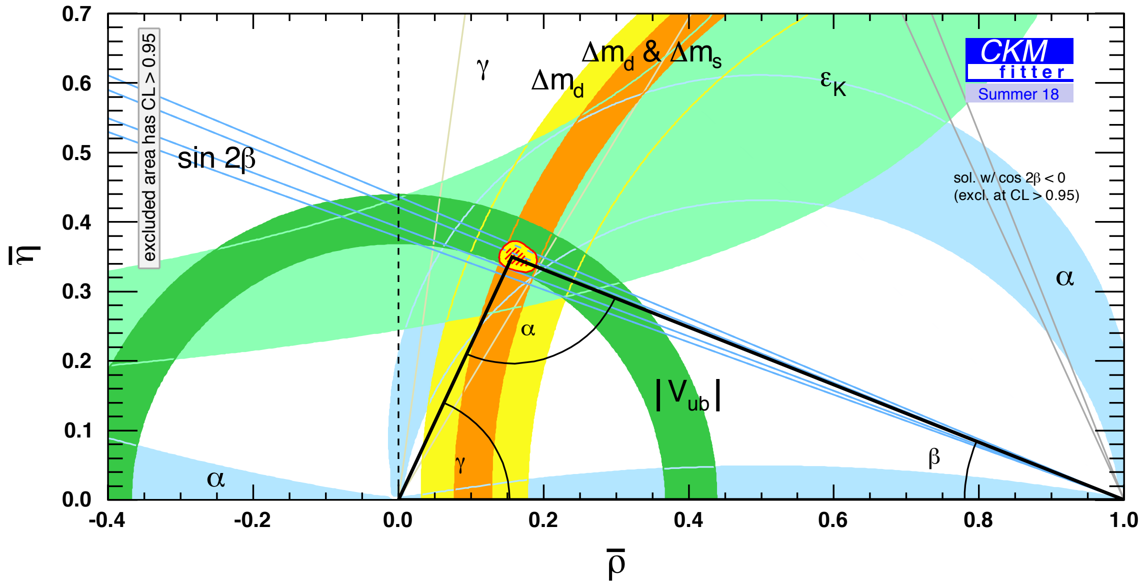
The CKM matrix and unitarity triangle

- CKM in terms of ***phases***:

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Triangle in the complex plane:

$$V_{CKM}^{\dagger} V_{CKM} = 1$$



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- CP Violation:
  - Non-zero unitary phases
  - Triangle surface $\neq 0$
    - Jarlskog invariant “J”

The CKM matrix V_{CKM} - 3 Generations

$$V_{CKM}: \quad \begin{matrix} & d & s & b \\ u & \\ c & \\ t & \end{matrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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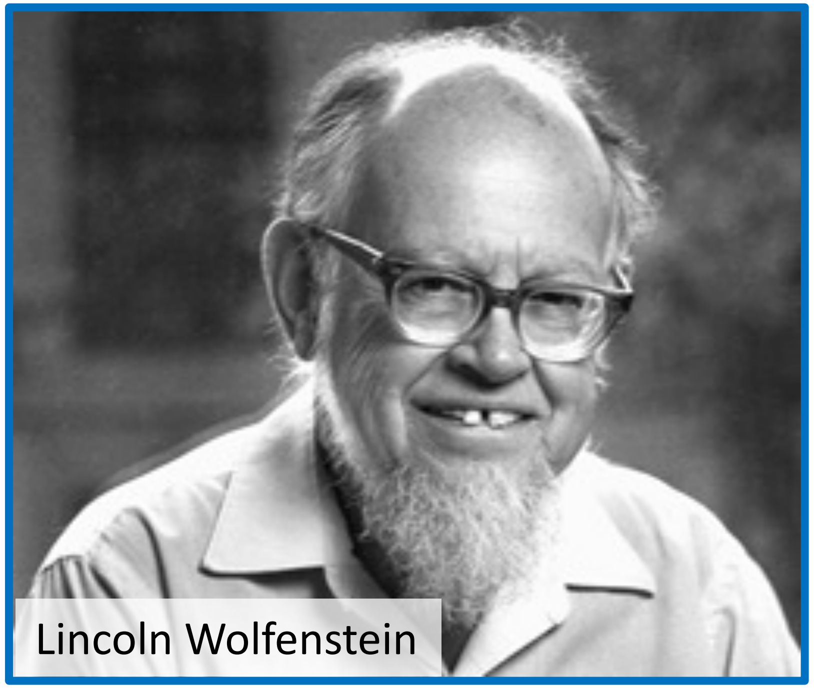
➔ 1 CP violating phase



Lincoln Wolfenstein

The CKM matrix V_{CKM} - 3 vs 2 Generations

$$V_{CKM}: \quad \begin{matrix} & d & s & b \\ u & V_{ud} & V_{us} & V_{ub} \\ c & V_{cd} & V_{cs} & V_{cb} \\ t & V_{td} & V_{ts} & V_{tb} \end{matrix}$$

- Wolfenstein parametrization: V_{CKM} =

$$\begin{pmatrix} 1-{}^1/_2\,\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-{}^1/_2\,\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

➔ 1 CP violating phase

$$V_{CKM}: \quad \begin{matrix} & d & s \\ u & V_{ud} & V_{us} \\ c & V_{cd} & V_{cs} \end{matrix}$$

1 free variable =
8 (4 complex)
– 4 orthonormality
– 3 quark phases

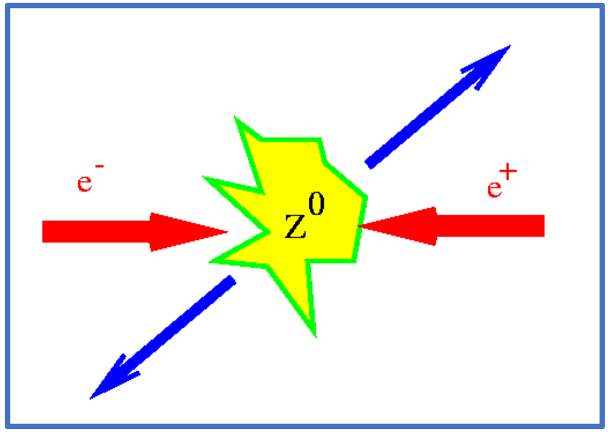
$$V_{CKM} = \begin{pmatrix} 1-{}^1/_2\,\lambda^2 & \lambda \\ -\lambda & 1-{}^1/_2\,\lambda^2 \end{pmatrix}$$

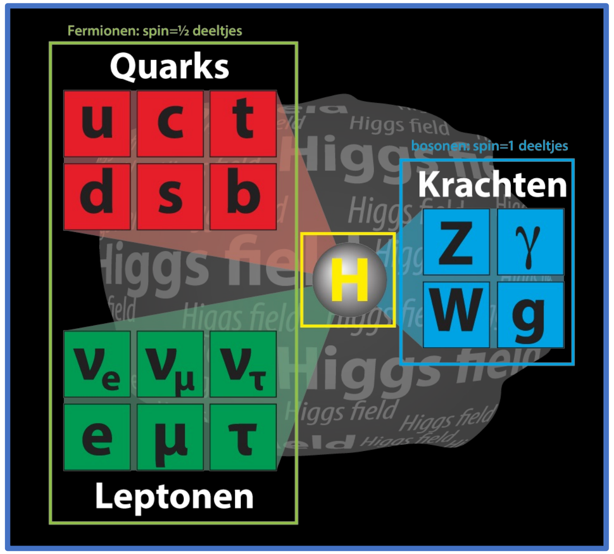
➔ No CP violation

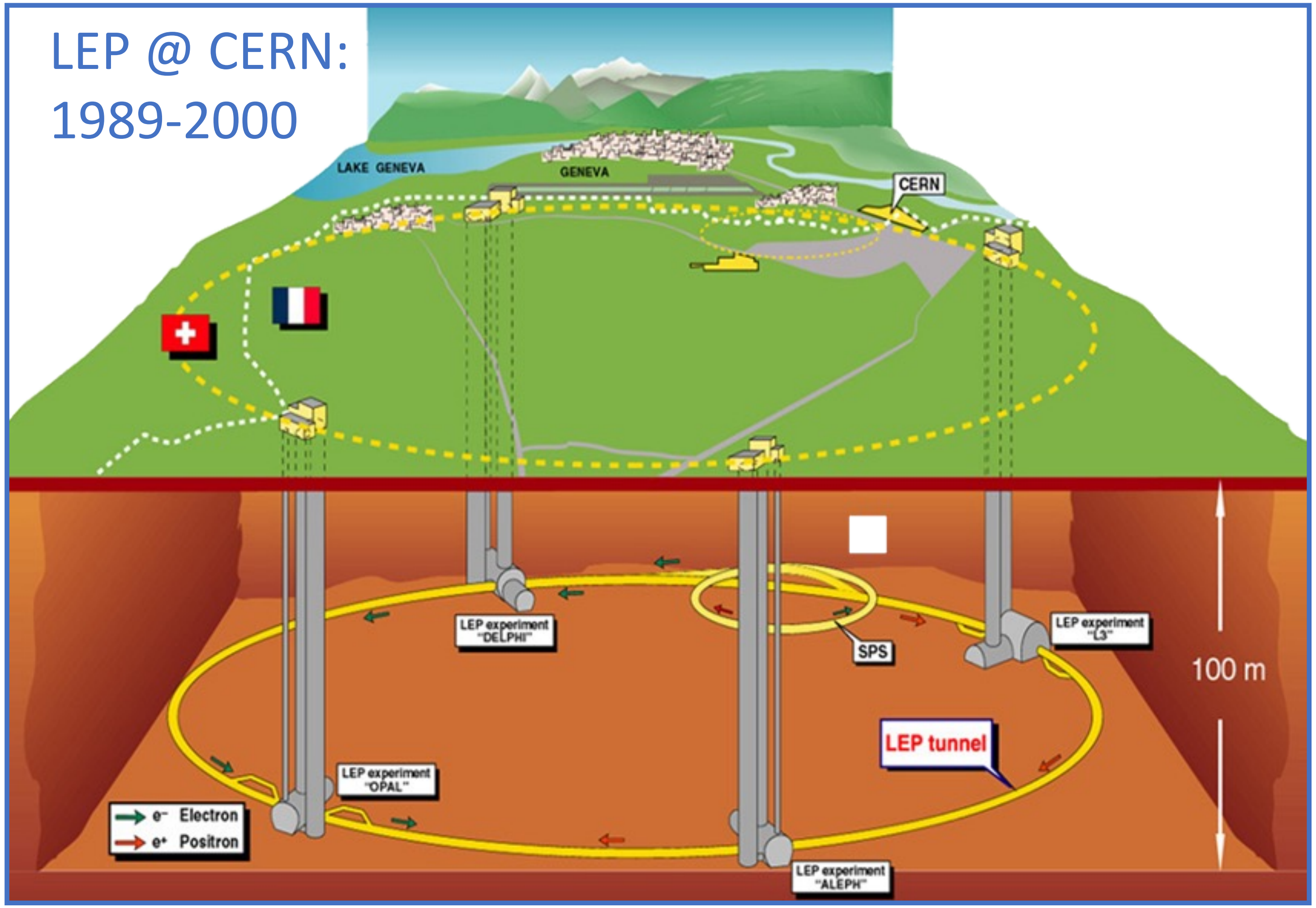
- *3 generations is the minimal particle content to generate CP violation* (In Standard Model).

3 Generations of particles – How do we know?

LEP: The heavy Z boson decays into 3 light neutrino types.







- *No additional weakly interacting **light fermion** generations.*

3 Generations of particles – How do we know?

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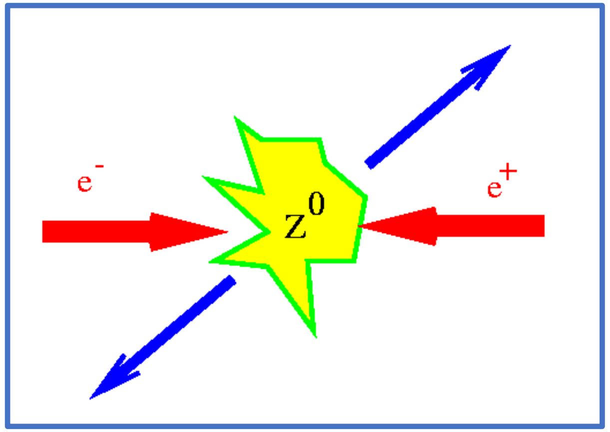
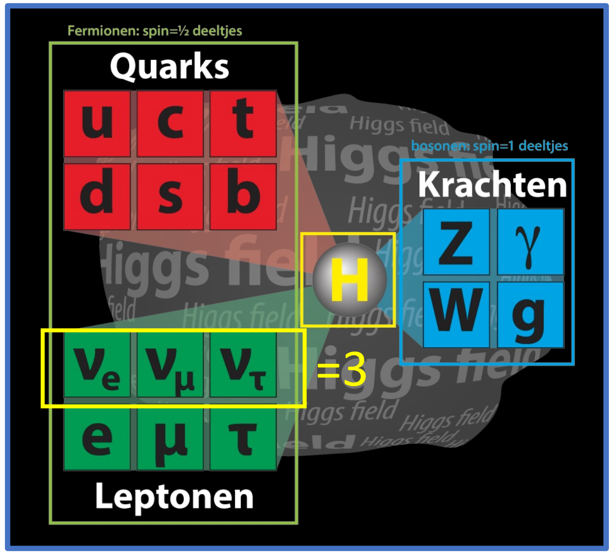
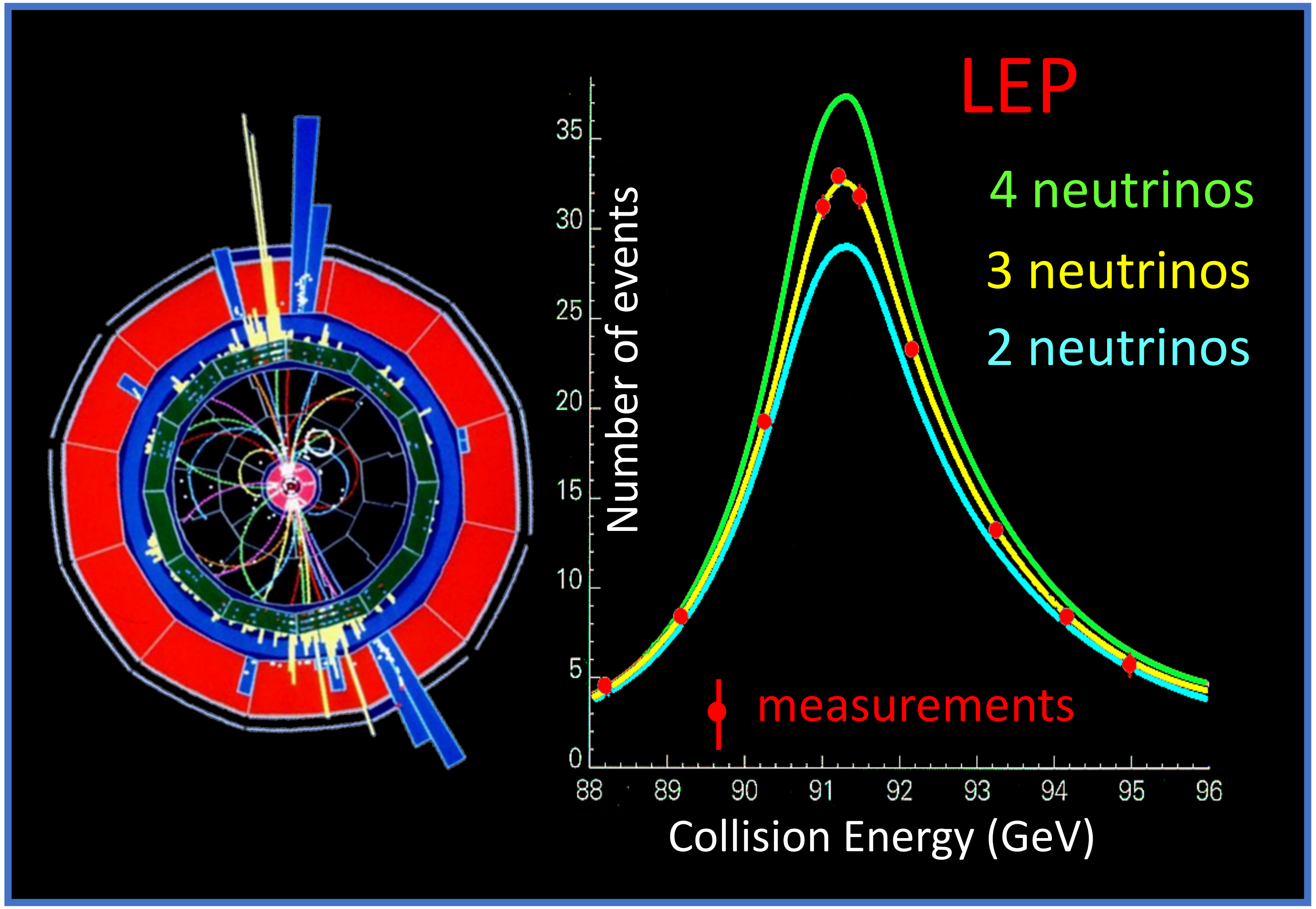




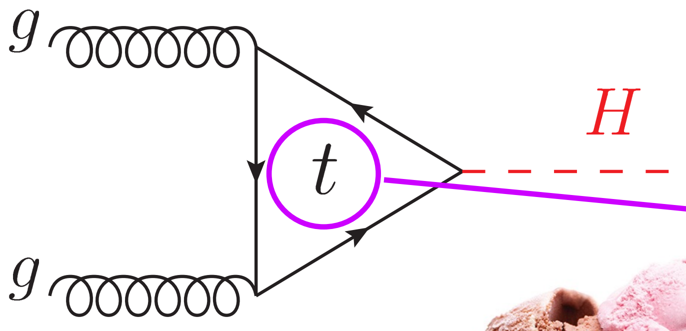


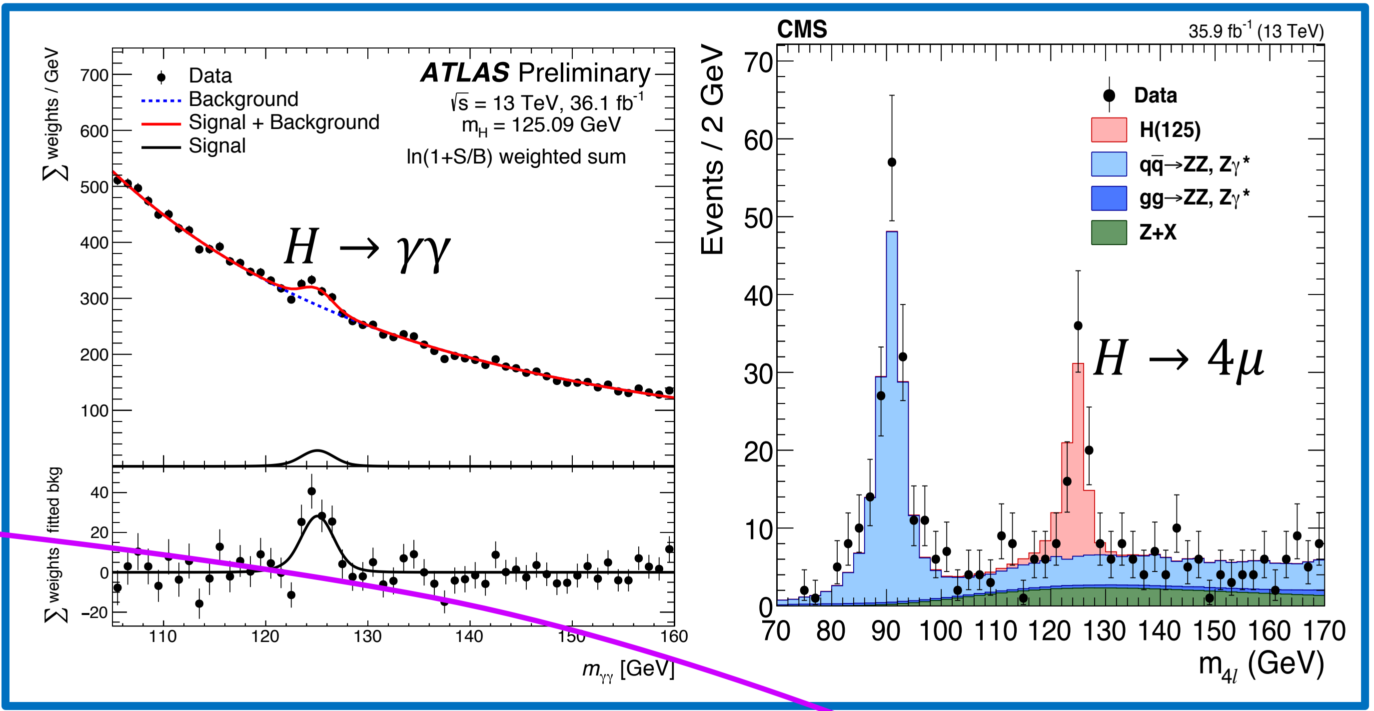
- *No additional weakly interacting **light fermion** generations.*

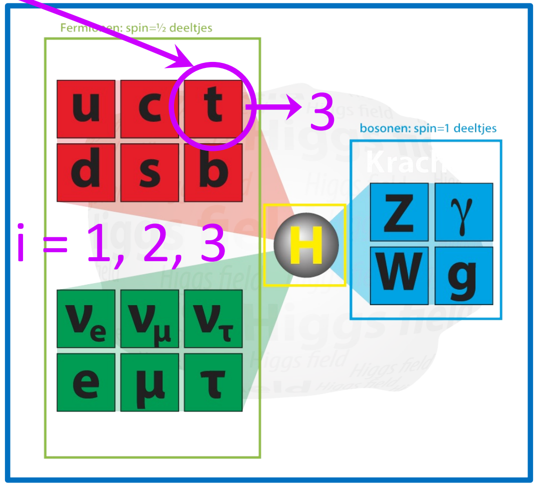
3 Generations of particles – How do we know?

LHC: Higgs production:

Loop diagram is proportional to the mass of the heaviest fermion.







- *Top is the **heaviest fermion** flavour.*
  - ➢ *3 Flavour generations*

How about leptons?

- Equivalent of CKM-Matrix V_{CKM} for leptons is PMNS-Matrix
  - Pontecorvo-Maki-Nakagawa-Sakata matrix: U_{PMNS}

- Neutrinos: U_{PMNS}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

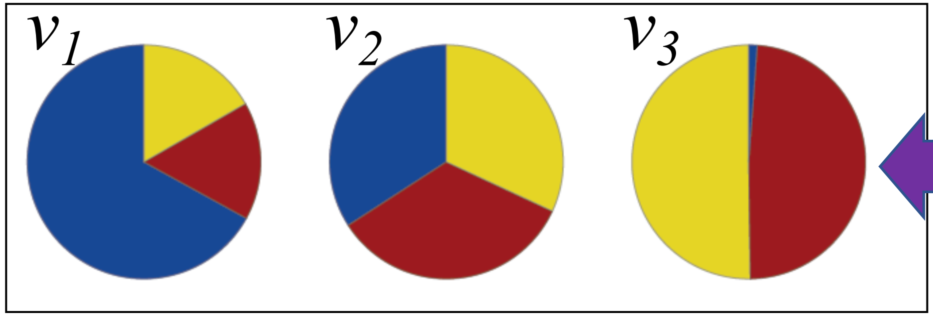
$$U_{MNSP} \approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.37 & 0.57 & 0.70 \\ 0.39 & 0.59 & 0.69 \end{pmatrix}$$

- Quarks: V_{CKM}

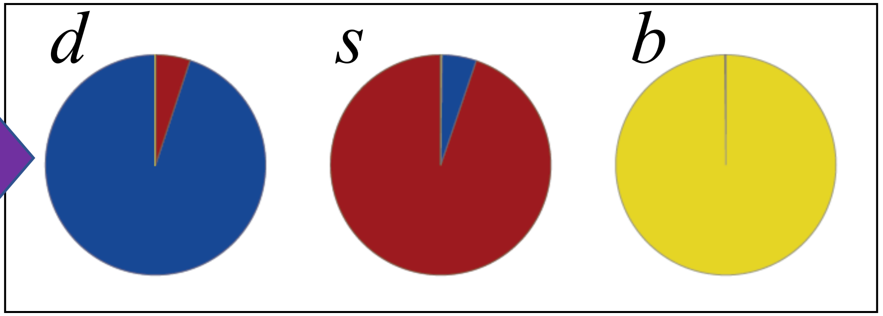
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

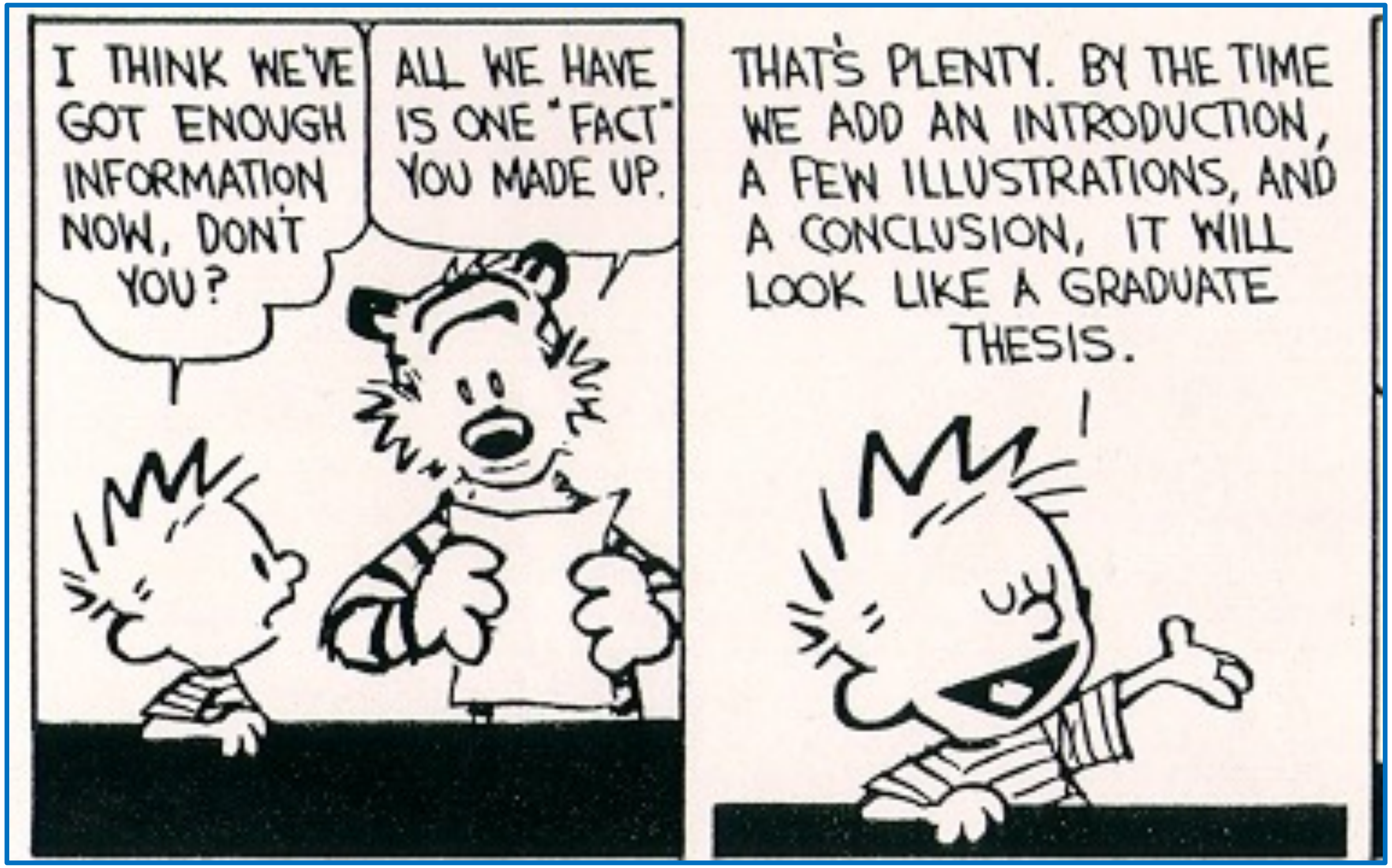
$$V_{CKM} = \begin{pmatrix} 0.97446 & 0.22452 & 0.00365 \\ 0.22438 & 0.97359 & 0.04214 \\ 0.00896 & 0.04133 & 0.99911 \end{pmatrix}$$

?



Completely different hiearchy

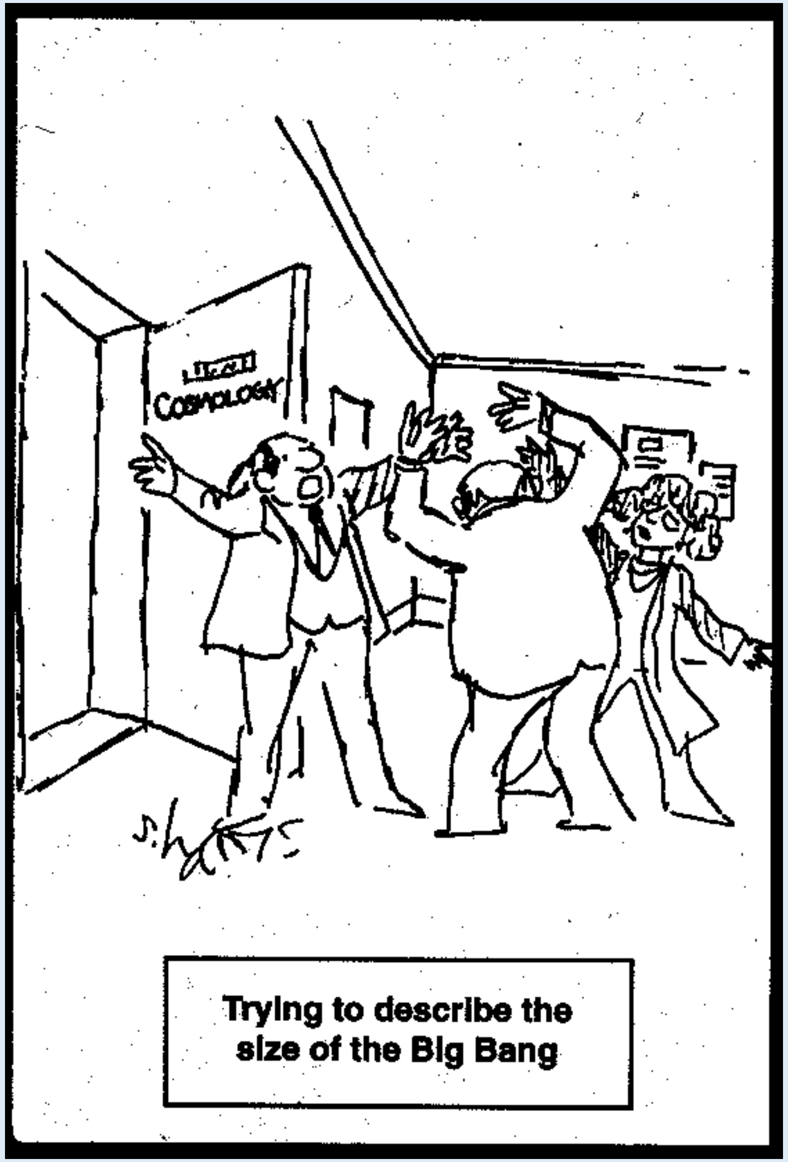



I THINK WE'VE GOT ENOUGH INFORMATION NOW, DON'T YOU?
ALL WE HAVE IS ONE "FACT" YOU MADE UP.
THAT'S PLENTY. BY THE TIME WE ADD AN INTRODUCTION, A FEW ILLUSTRATIONS, AND A CONCLUSION, IT WILL LOOK LIKE A GRADUATE THESIS.

Contents Today & Tomorrow:

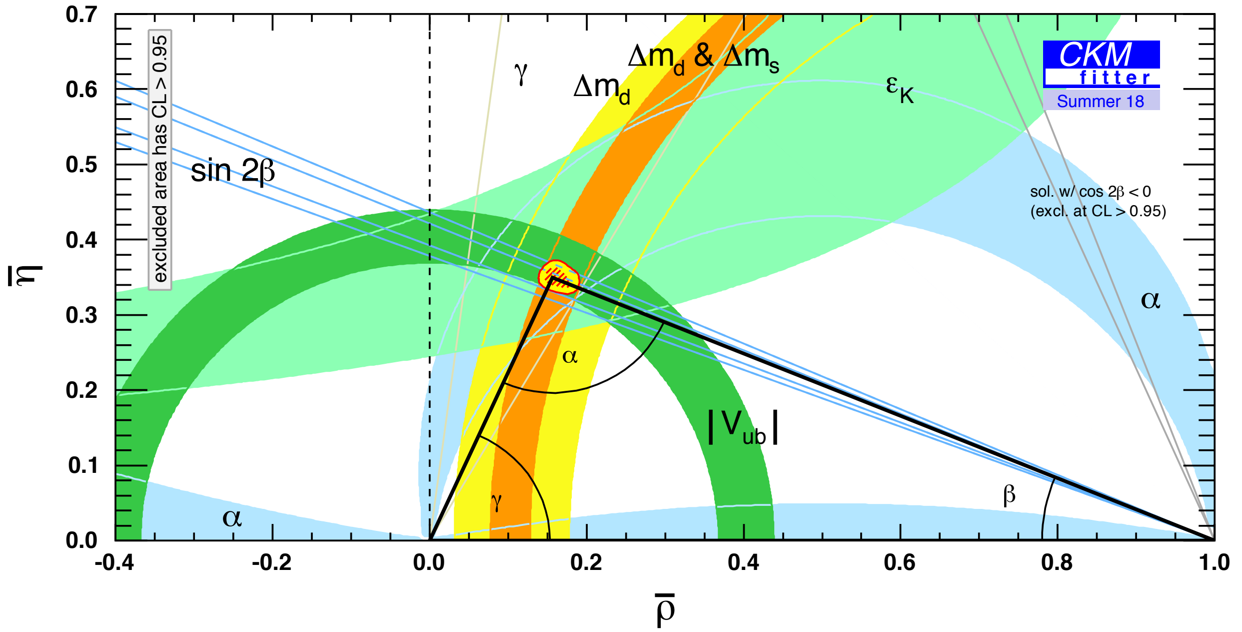
Contents Today & Tomorrow:

1. CP Violation
   a) Discrete Symmetries
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
2. B-Mixing
   a) CP violation and Interference
   b) B-mixing and time dependent CP violation
   c) Experimental Aspects: LHC vs B-factory



How large is CP violation?

- Large CP violation requires *large mixing* and *large phases* in the CKM matrix.
  - Surface of unitarity triangle
  - Jarlskog invariant: $J = 3 \times 10^{-5}$



- CP violation also requires three generations with non-zero quark masses
  - In fact, ***different*** masses are required:
    - $m_u \neq m_c$; $m_c \neq m_t$; $m_t \neq m_u$
    - $m_d \neq m_s$; $m_s \neq m_b$; $m_b \neq m_d$

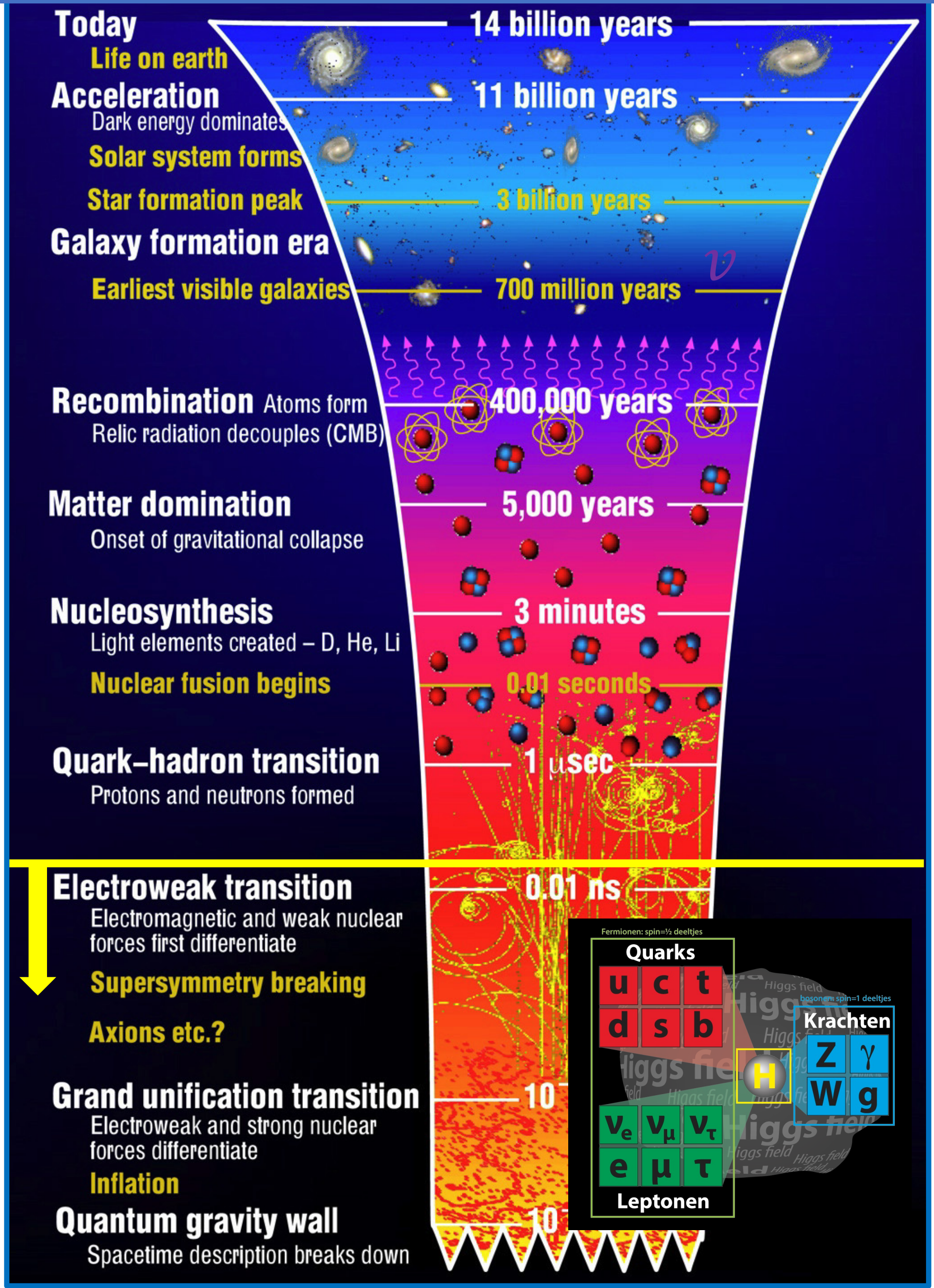
- Jarlskog criterion (1987) for amount of CP violation:
  - $\det[M_u M_u^\dagger, M_d M_d^\dagger] = 2\, i\, J\, (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2)$
    $\times\, (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$

$$M_{ij} = Y_{ij}\, v/\sqrt{2}$$

SU(2)

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L$$



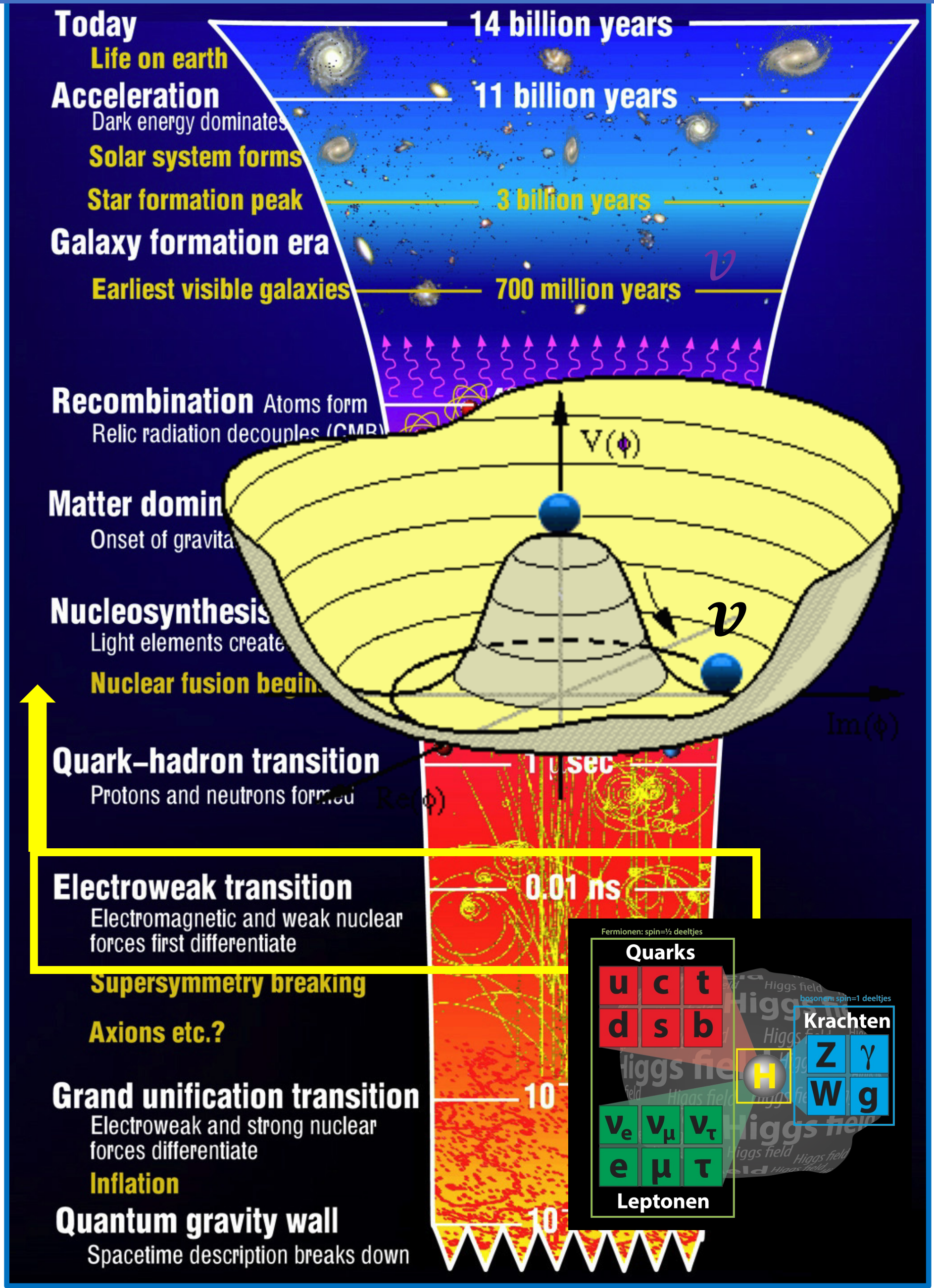
SU(2) → Higgs vev

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L$$

- Higgs interaction *not* flavour universal

$$\mathcal{L}_H = Y^d_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \binom{0}{v} d'_{jR} + Y^u_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \binom{v}{0} u'_{jR}$$



SU(2) → Higgs vev → Origin of Mass

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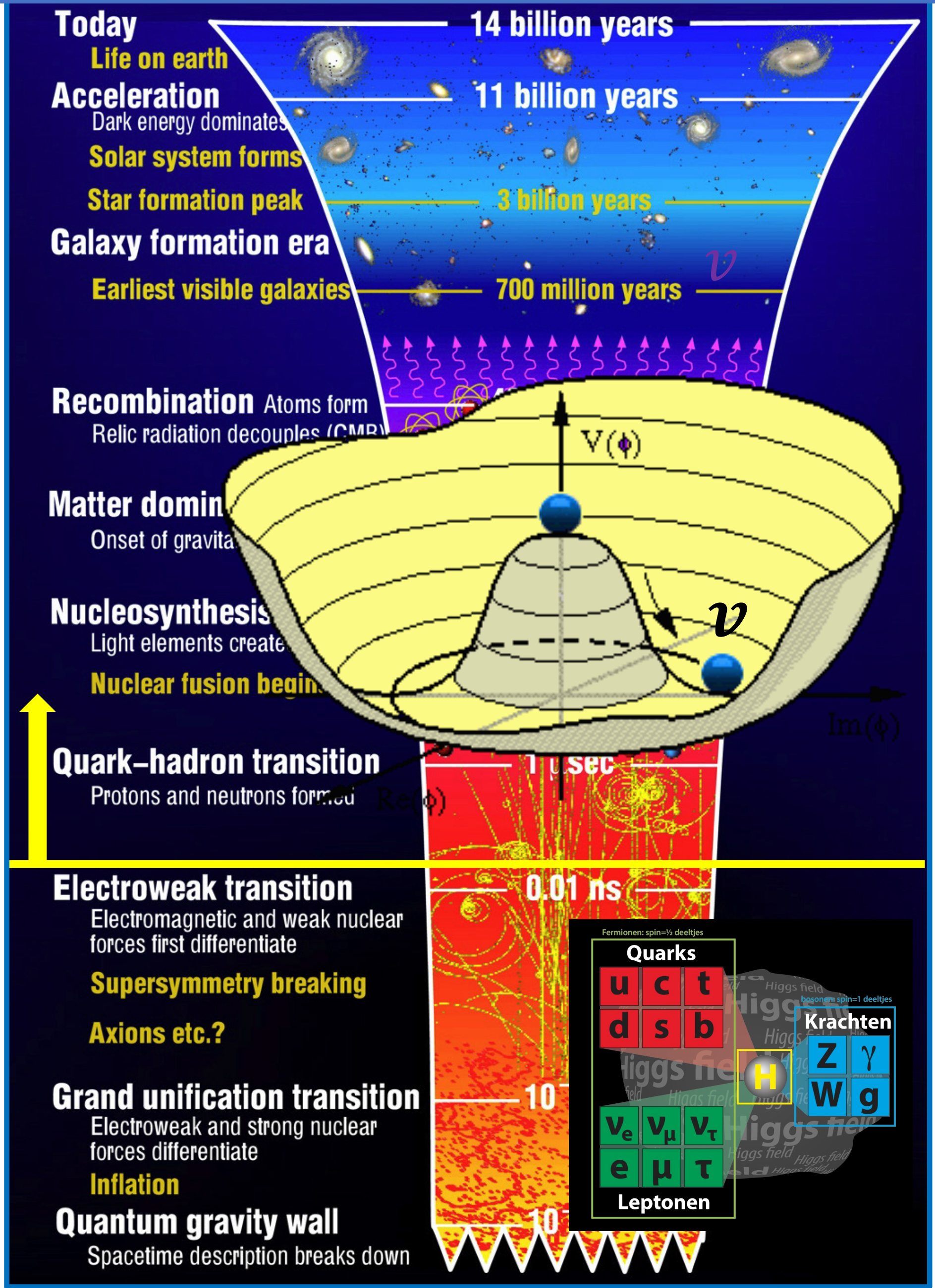
- Mass vs Interaction states:

$$u_i = (V^u)_{ij}\, u'_j \qquad\qquad d_i = (V^d)_{ij}\, d'_j$$

- Amount of CP violation:

$$\det\left[M_u M_u^\dagger, M_d M_d^\dagger\right] = 2\, i\, J\, (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$$



SU(2) → Higgs vev → Origin of Mass → Origin of CP violation?

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \, \gamma_\mu \, W^\mu \, d'_L$$

- Higgs interaction *not* flavour universal

$$\mathcal{L}_H = Y^d_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \binom{0}{v} d'_{jR} + Y^u_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \binom{v}{0} \; u'_{jR}$$

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$$u_i = (V^u)_{ij} \, u'_j \qquad\qquad d_i = \left(V^d\right)_{ij} d'_j$$

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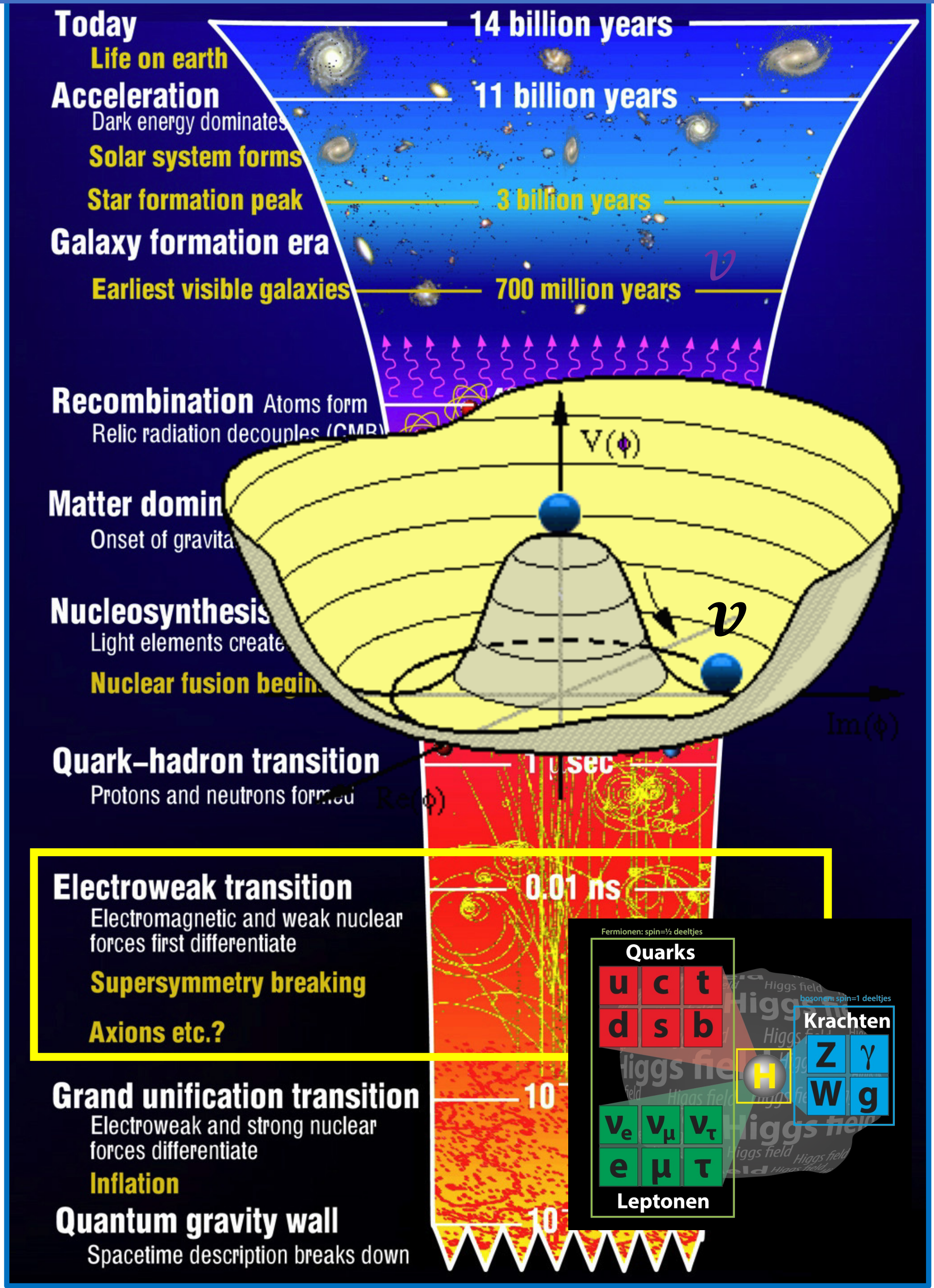
$$\det\left[M_u M_u^\dagger, M_d M_d^\dagger\right] = 2\, i\, J \, (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times \left(m_b^2 - m_s^2\right)\left(m_s^2 - m_d^2\right)\left(m_d^2 - m_b^2\right)$$

- *Does the Standard Model include CP violation **before** symmetry breaking?*
    - *Is CP violation perhaps an emergent phenomenon?*



The Baryogenesis Puzzle – Electroweak Baryogenesis?

- Sacharov Conditions
  - ✓ All present in S.M.

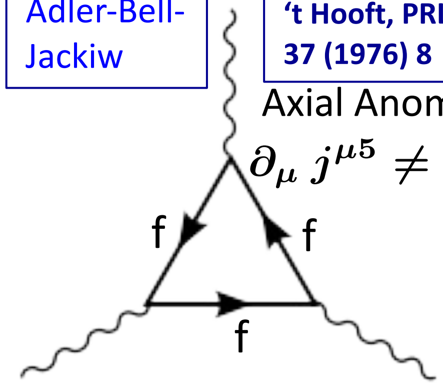
Baryon asymmetry

✓ Baryon Number Violation

Adler-Bell-Jackiw

't Hooft, PRL 37 (1976) 8

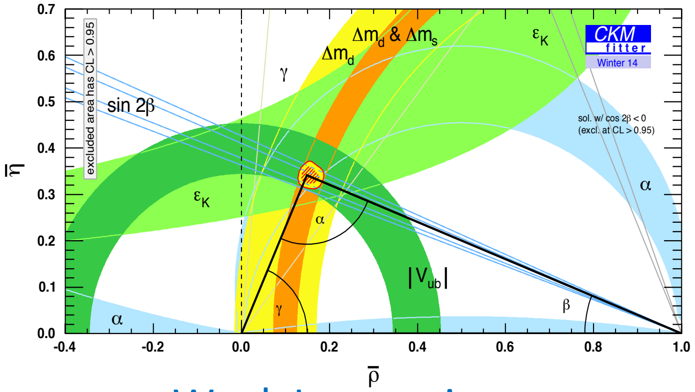
Axial Anomaly: $\partial_\mu j^{\mu 5} \neq 0$



Quantum anomaly

Matter - antimatter asymmetry

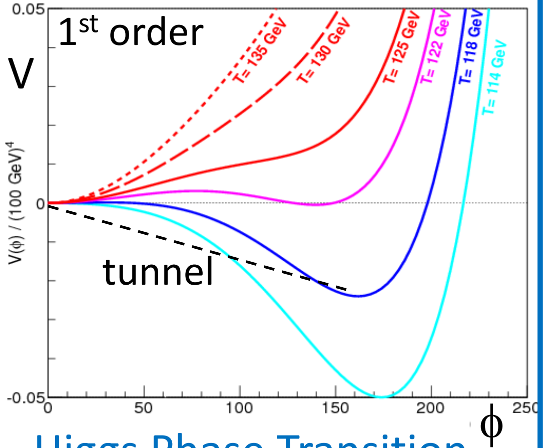
✓ C and CP Violation



Weak Interaction

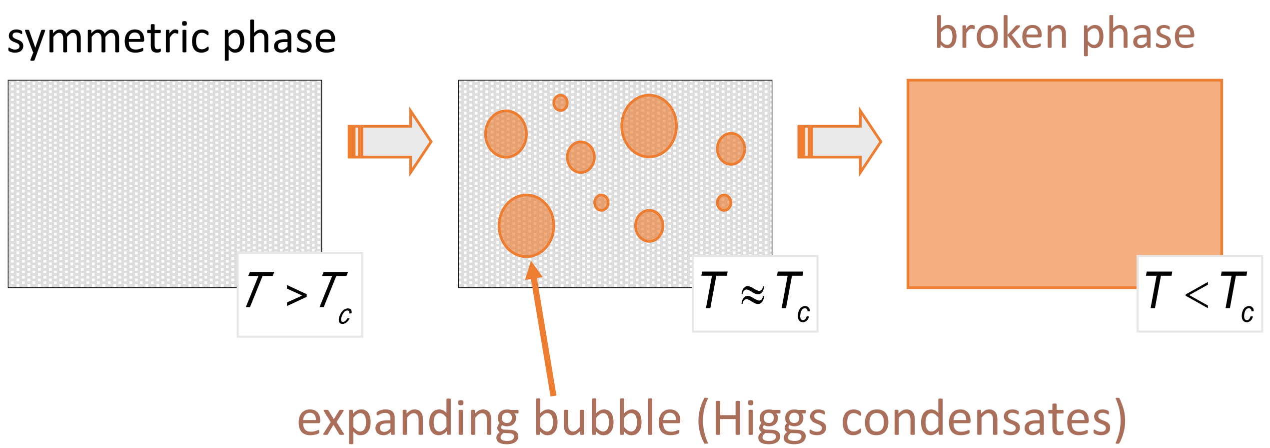
Non - reversal

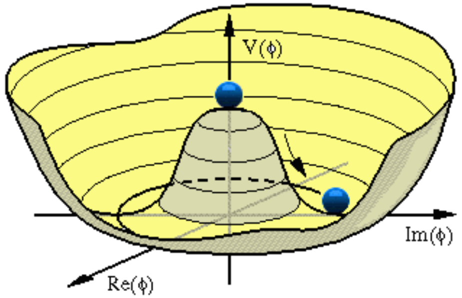
✓ Thermal non-equilibrium



Higgs Phase Transition

- Baryogenesis from Higgs symmetry breaking?





The Baryogenesis Puzzle – Electroweak Baryogenesis?

- Sacharov Conditions
  - ✓ All present in S.M.
  - ✗ Not Enough?

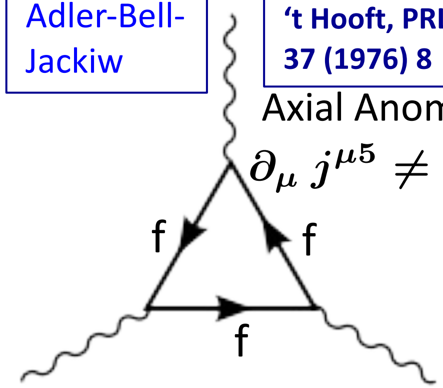
Baryon asymmetry

✓ Baryon Number Violation

Adler-Bell-Jackiw

'**t Hooft, PRL 37 (1976) 8**

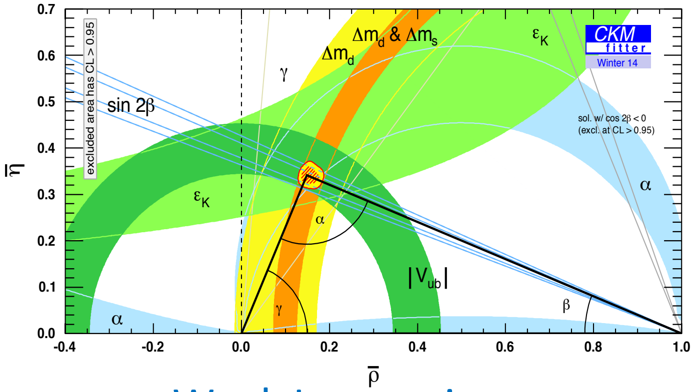
Axial Anomaly: $\partial_\mu j^{\mu 5} \neq 0$



Quantum anomaly

Matter - antimatter asymmetry

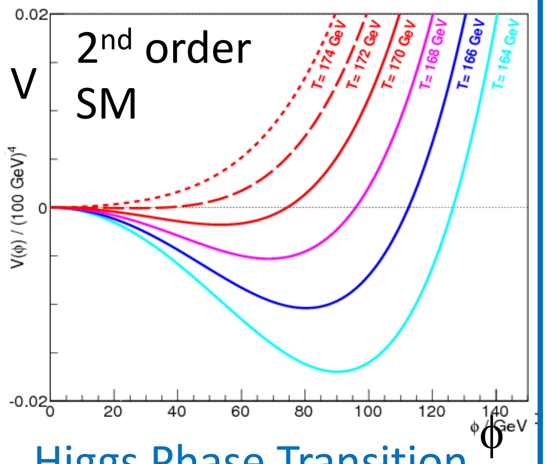
✗ C and CP Violation



Weak Interaction

Non - reversal

✗ Thermal non-equilibrium

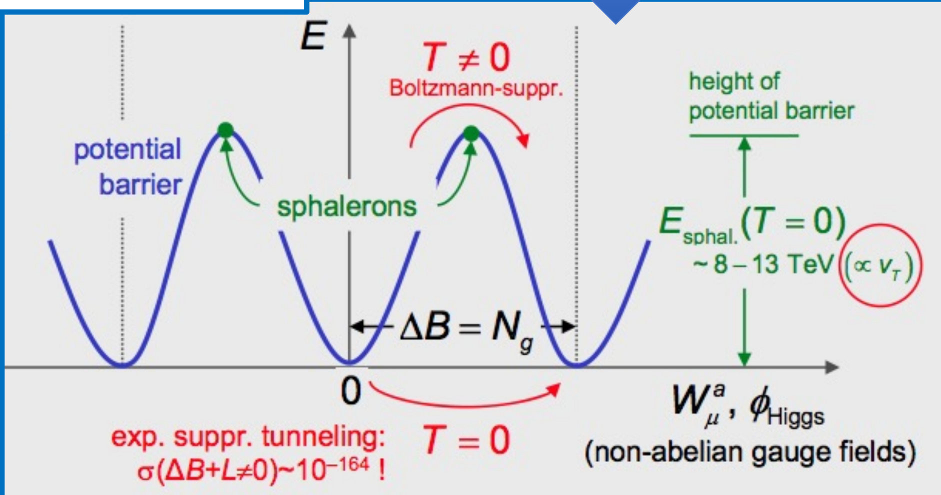


Higgs Phase Transition

✗ 1^{st} order?

- SM: M_H < ~70 GeV
- THDM: M_H ~ 125 OK

✓ Sphalerons

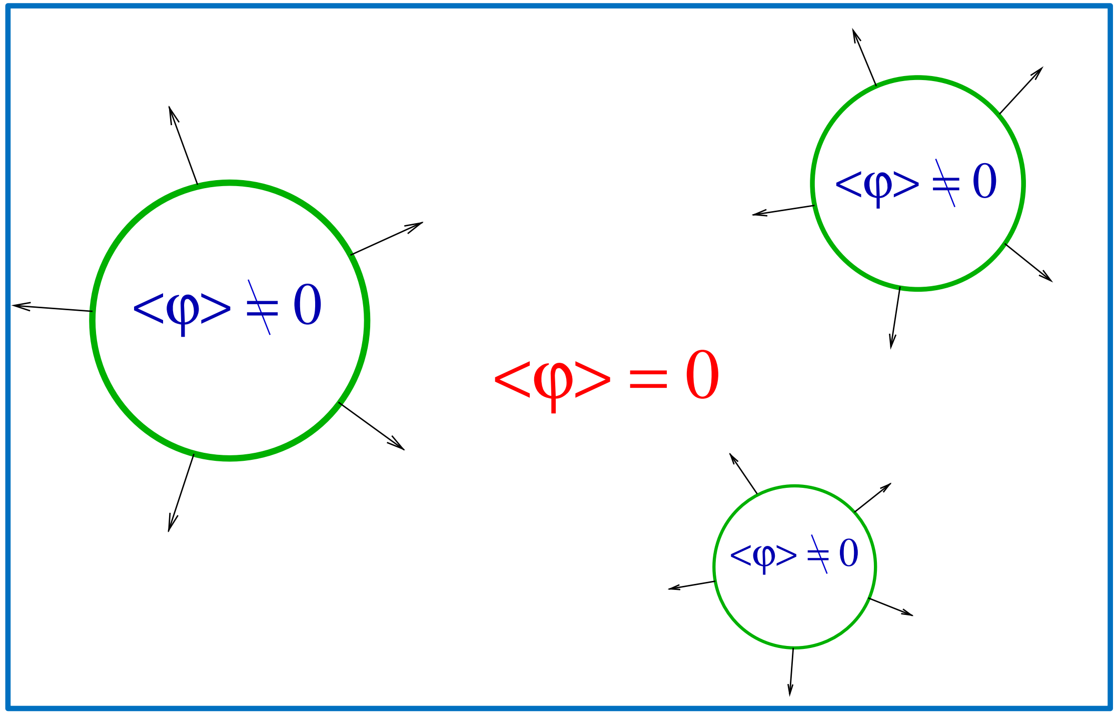


✗ CPV from CKM

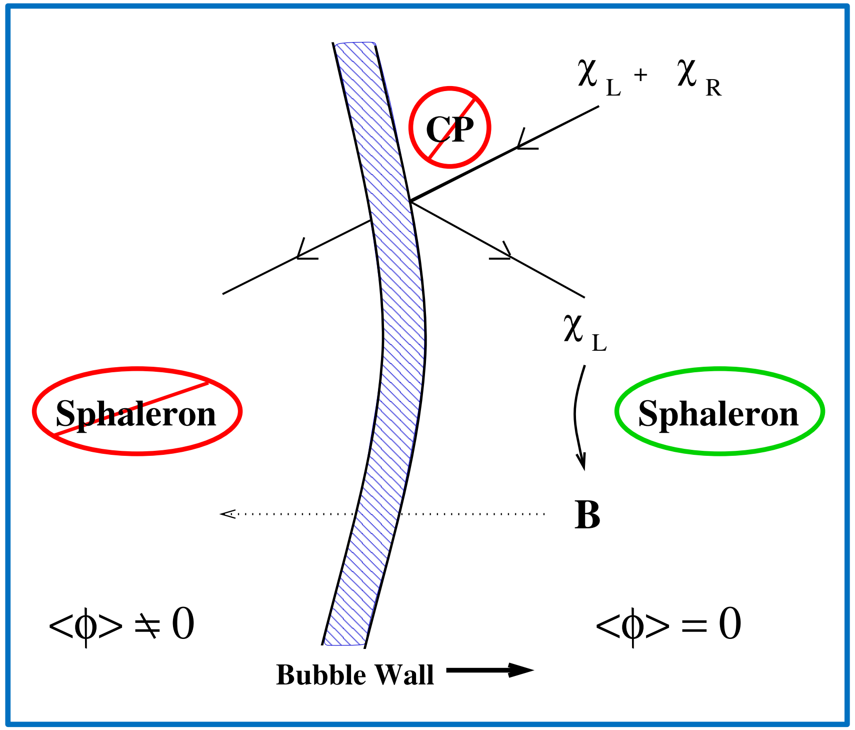
- BAU: $\frac{\Delta n_B}{n_\gamma} \approx 10^{-10}$
- $A_{CP} = J_{inv} \times (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$
  - From CKM: $A_{CP}/T_c^{12} \approx 10^{-20}$ → Too small
  - Used $T_c \sim 100$ GeV

The Baryogenesis Puzzle – Electroweak Baryogenesis?

Expanding bubbles of broken phase
In a medium of symmetric phase



Baryon production in front of bubble wall



➔ *Was the phase transition in the early universe of 1st order?*

➔ *Higgs potential?*

➔ *If new physics is abundant in thermal plasma of early universe:*

➔ *Likely to be of TeV energy scale.*

Alternative Explanation…

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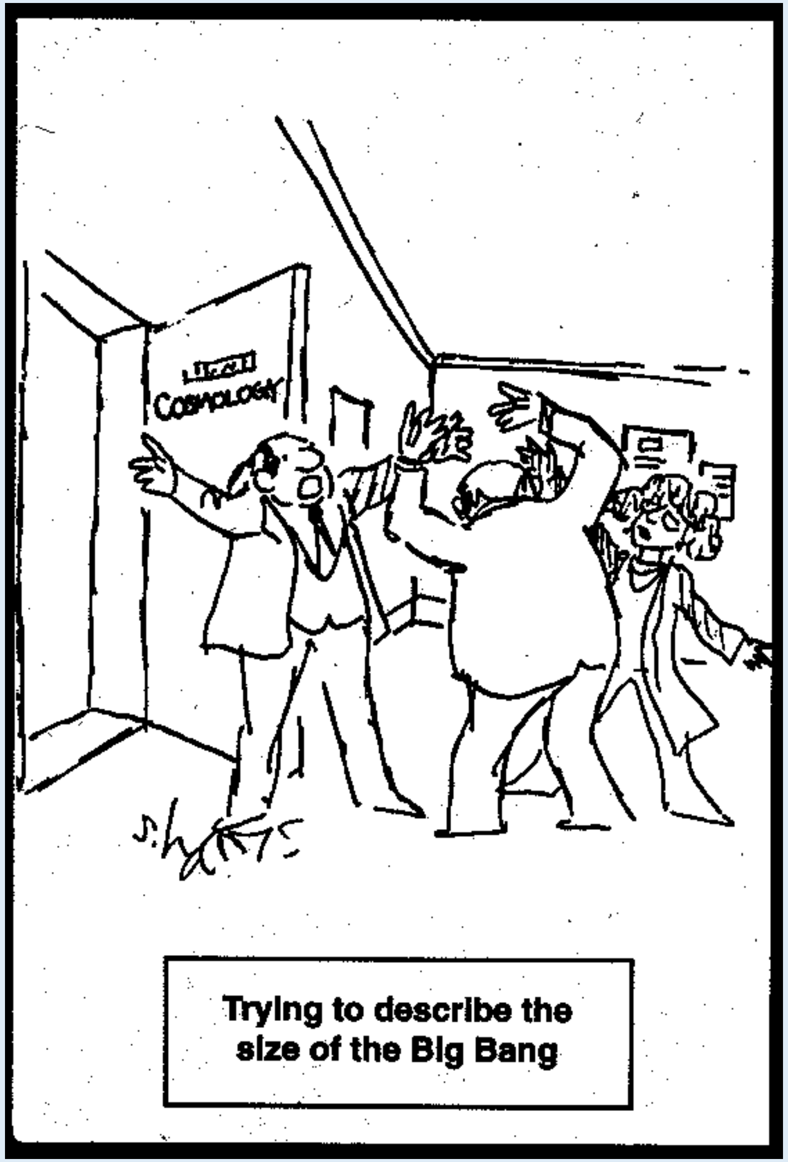

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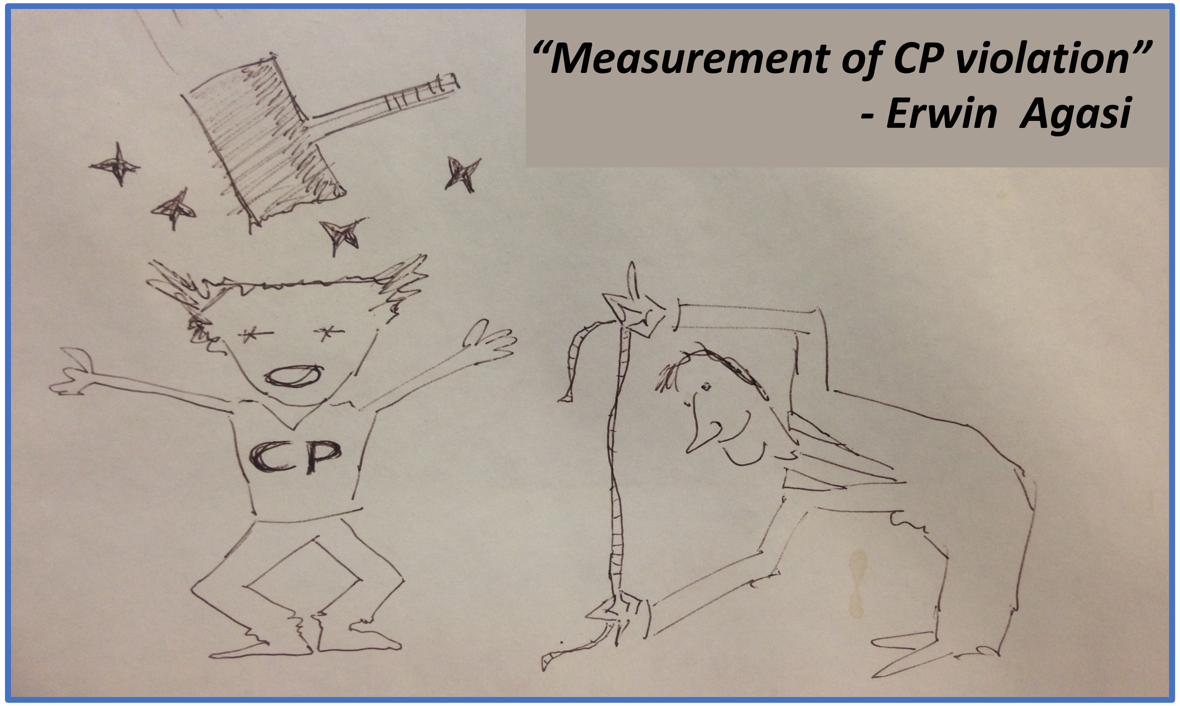
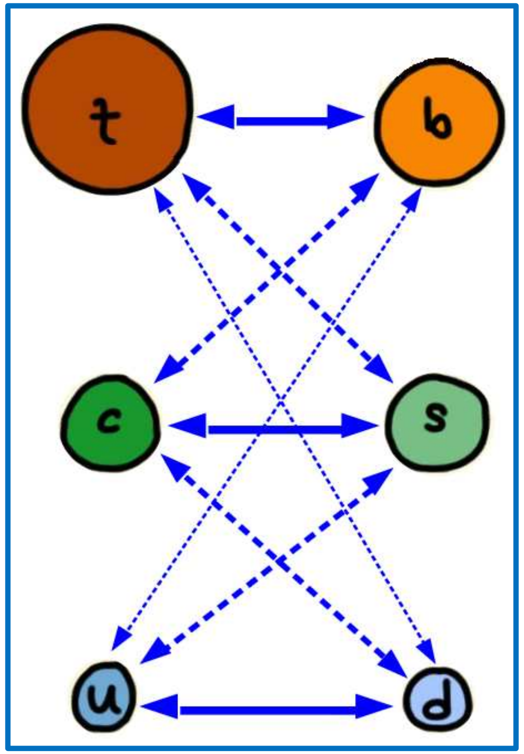
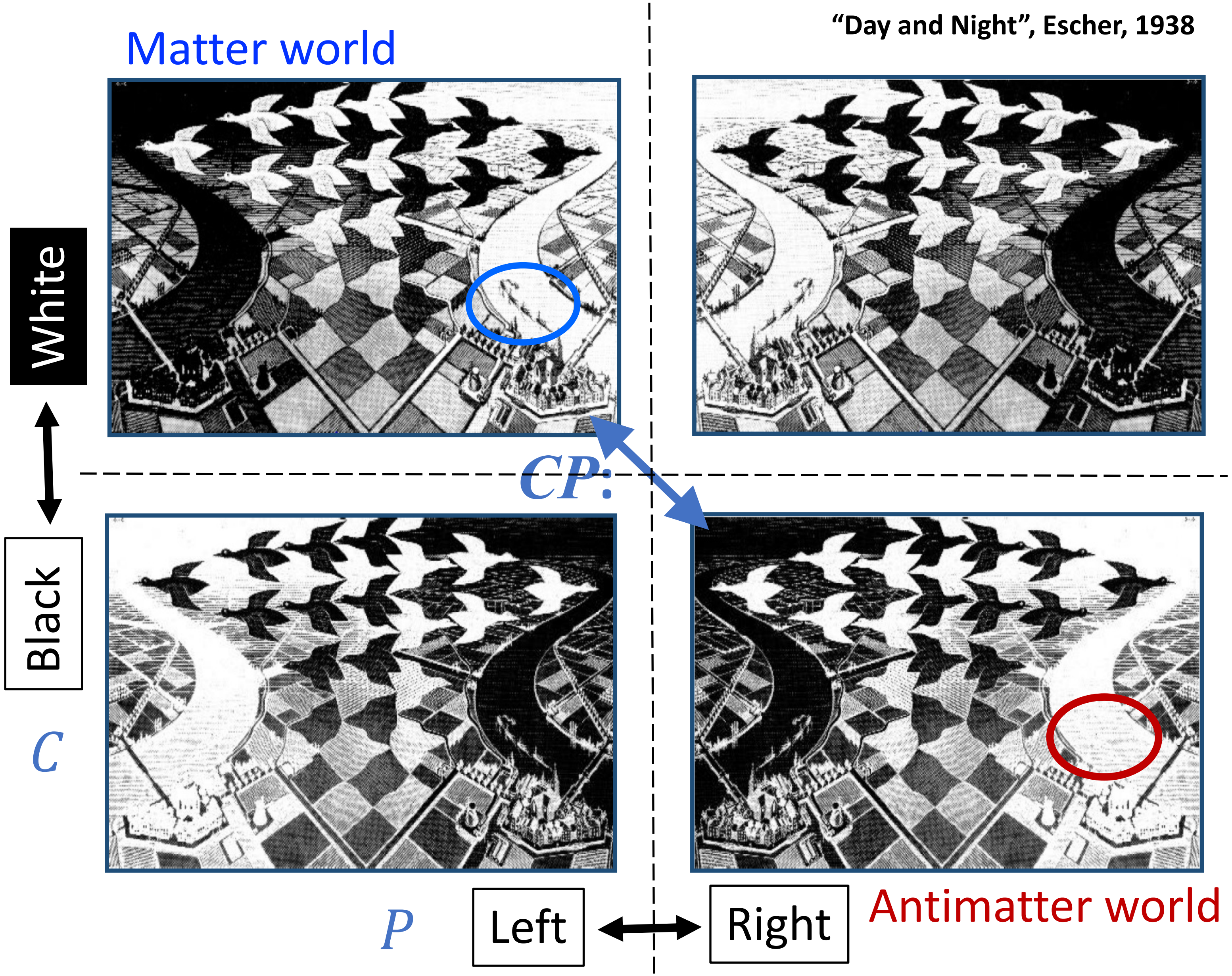


Recap: Flavour Physics and CP Violation

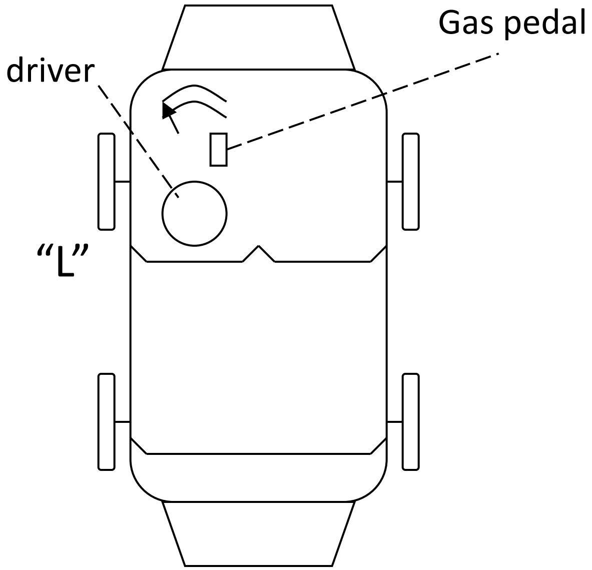




Recap: Broken Symmetry and Unobservables: Parity

Before 1956 physicists were **convinced** that the laws of nature were left-right symmetric.
Strange?

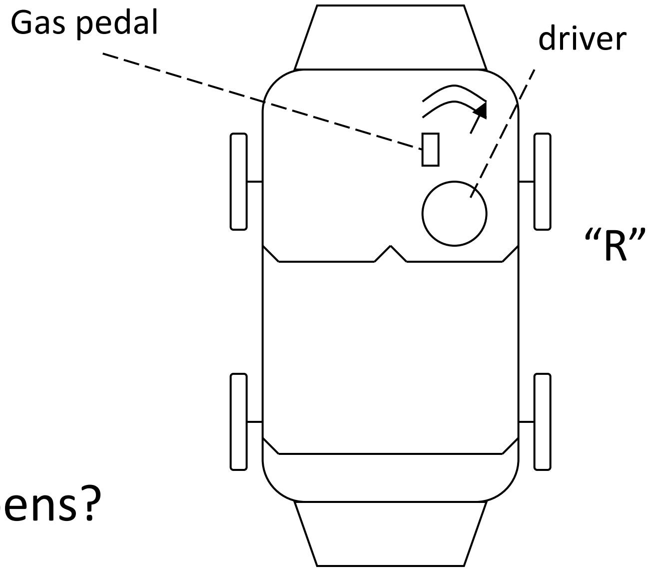
A "gedanken" experiment: consider two perfectly mirror symmetric cars:



"L" and "R" are fully symmetric,
Each nut, bolt, molecule etc.
However the engine is a black box

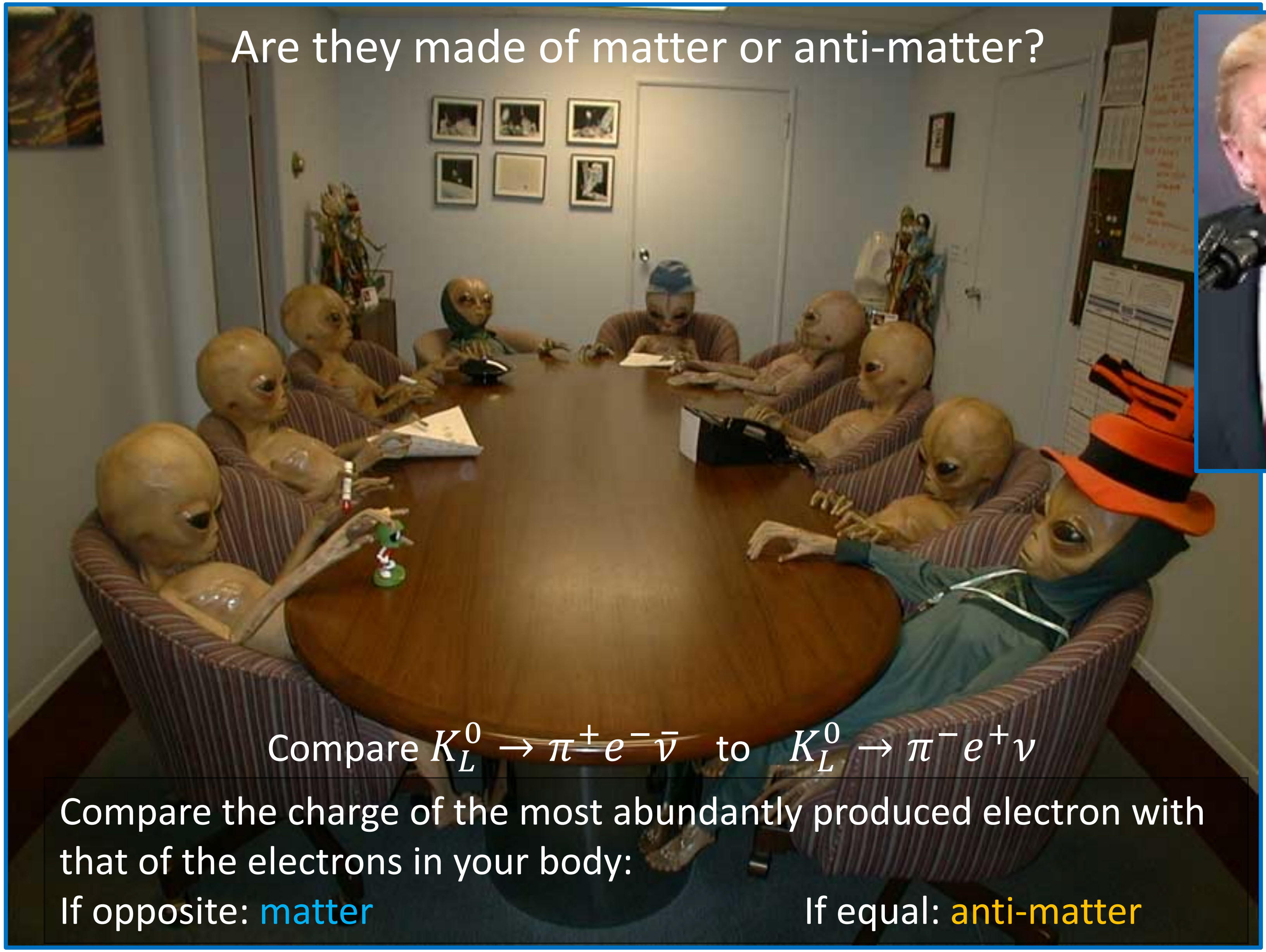
Person "L" gets in, starts, ….. 60 km/h

Person "R" gets in, starts, ….. What happens?



What happens in case the ignition mechanism uses, say, Co^{60} β decay?

Recap: Broken Symmetry and Unobservables: CP Violation



Are they made of matter or anti-matter?

Compare $K_L^0 \to \pi^+ e^- \bar{\nu}$ to $K_L^0 \to \pi^- e^+ \nu$

Compare the charge of the most abundantly produced electron with that of the electrons in your body:

If opposite: matter

If equal: anti-matter

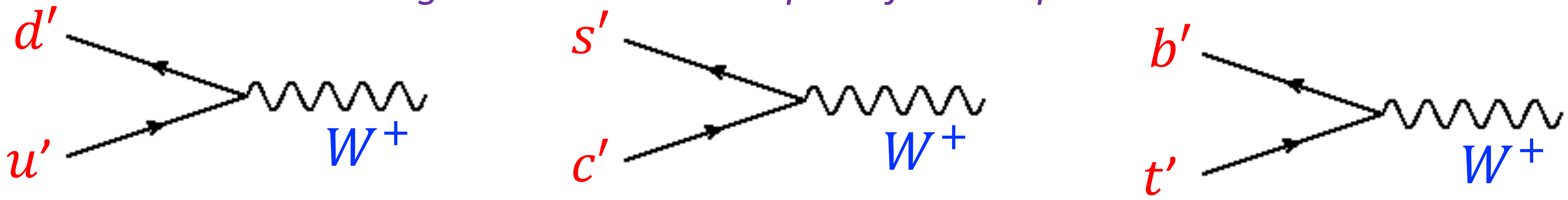
Recap: Weak interaction in three Flavour Generations

- Weak Interaction is 100% parity violating.
  - Wolfgang Pauli: *"I cannot believe God is a weak left-hander."*

- Implement an $SU(2)_L$ symmetry for *massless* particles:

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L$$ x3 !

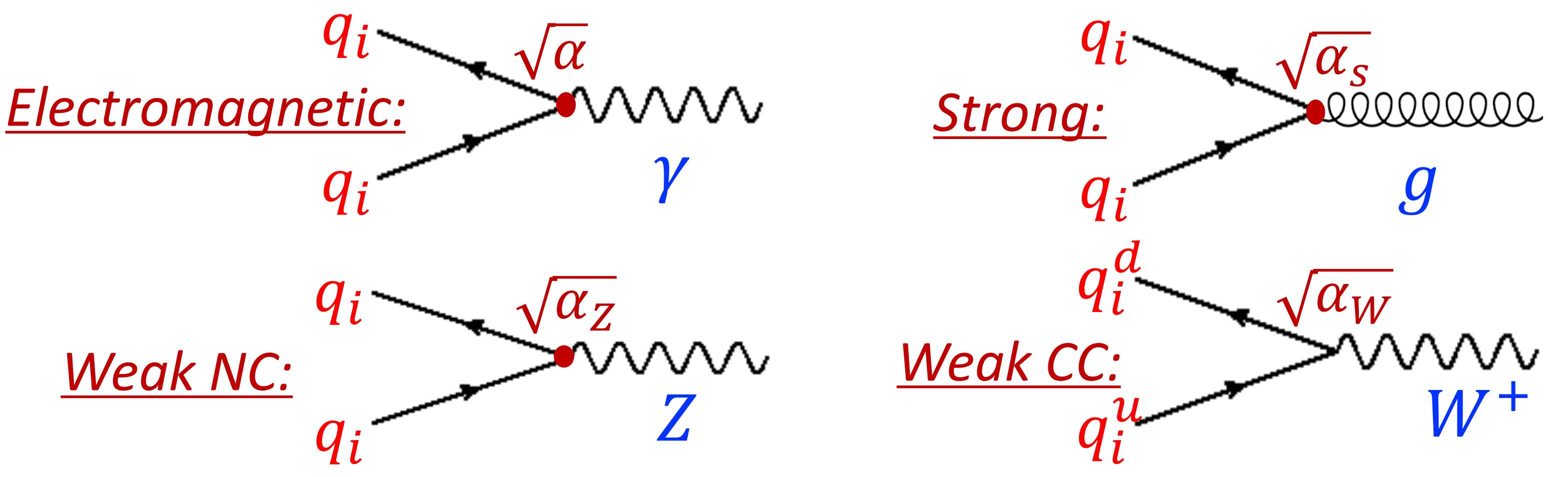
- Flavour universality: *identical interactions* in three generations.
  - In fact: *how to distinguish a massless d' quark from s' quark?*



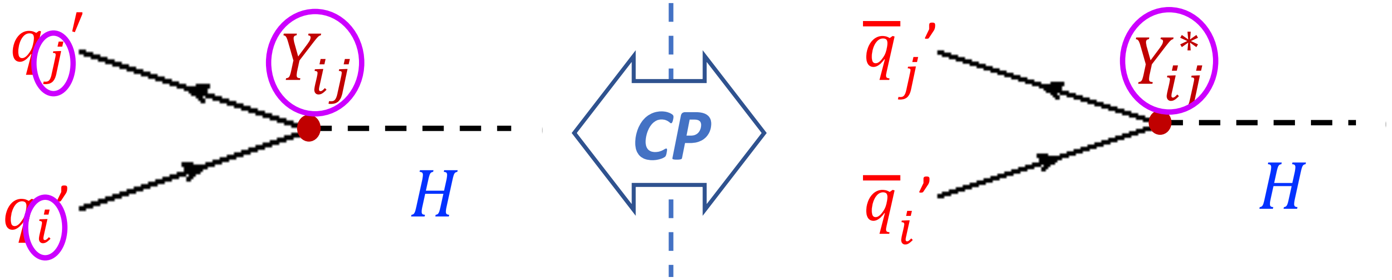
- There is *no CP violation* in these massless interactions
  - What happens when particles acquire mass?

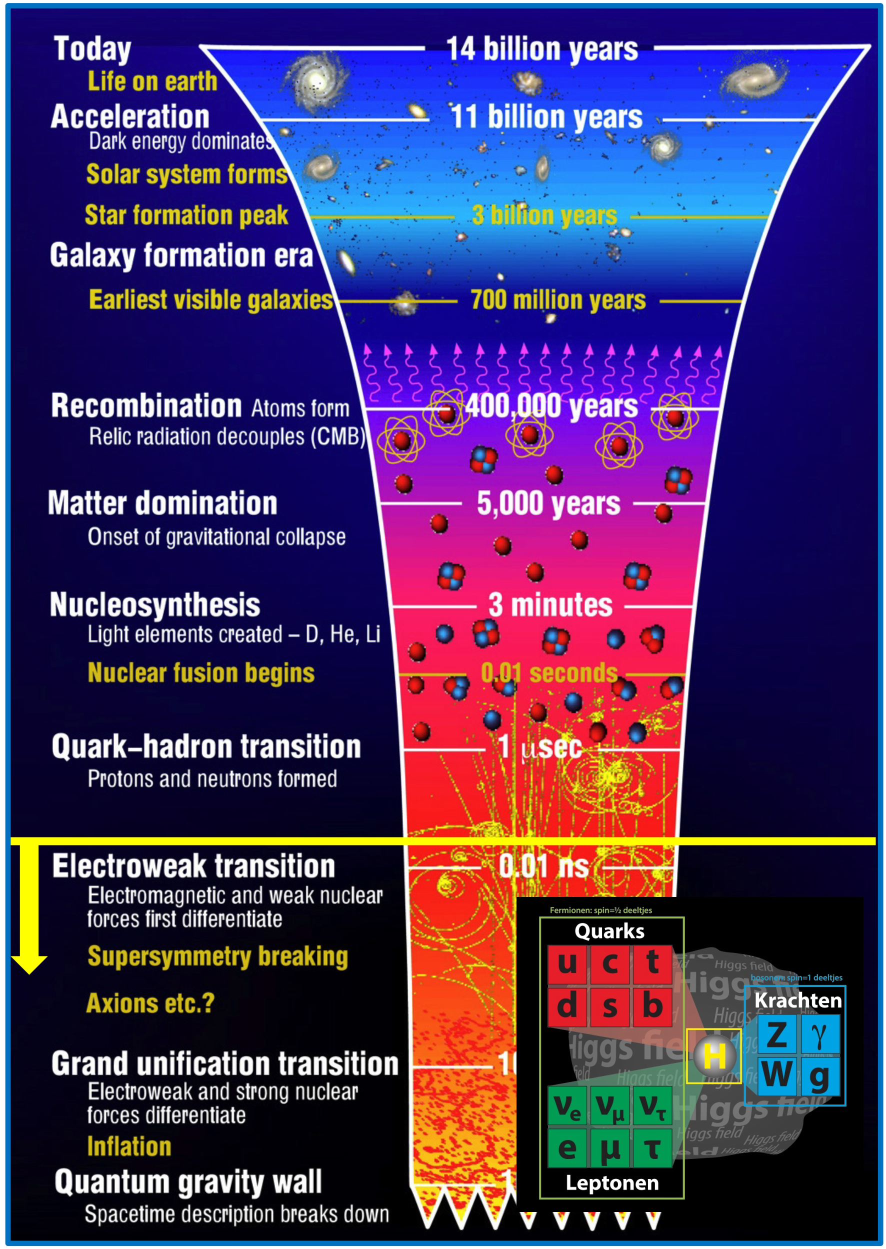
Recap: Flavour Universality in very Early Universe

- Quark and lepton generations interact identically
  - No difference between particles of different generation?
  - No matter – antimatter asymmetry (CP Violation)?



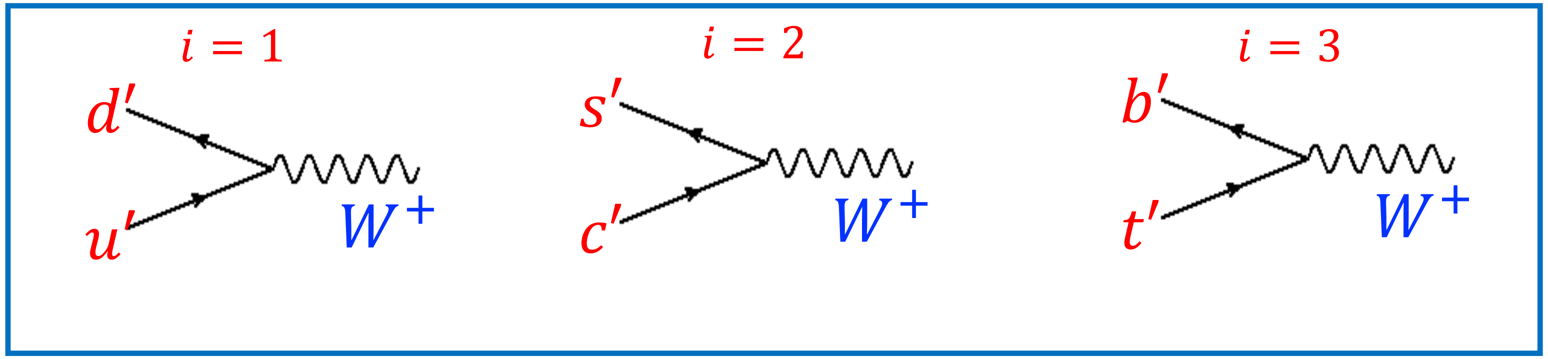
- Universality violation: Higgs !
  - Higgs coupling is *not universal*, and mixes generations
  - Complex couplings: allows for CP Violation!





Recap: Flavour Universality

- Weak charged current interaction: $(i \leftrightarrow i)$



- Universality violation: Higgs ! $(i \leftrightarrow j)$
  - Higgs coupling is *not universal*, and mixes generations
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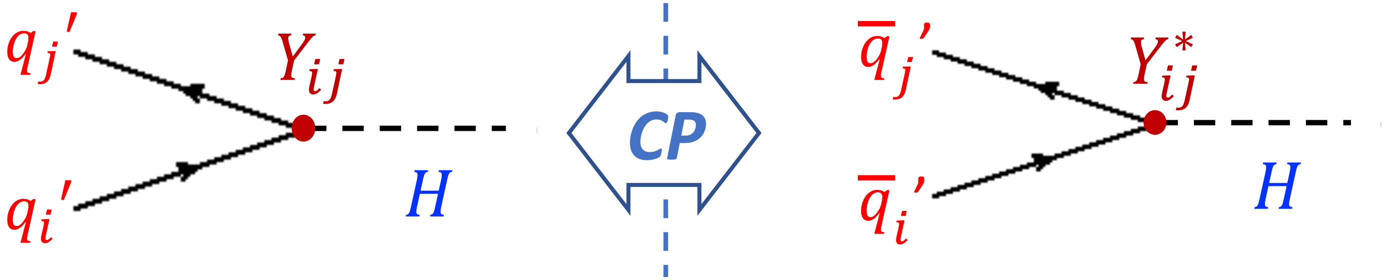
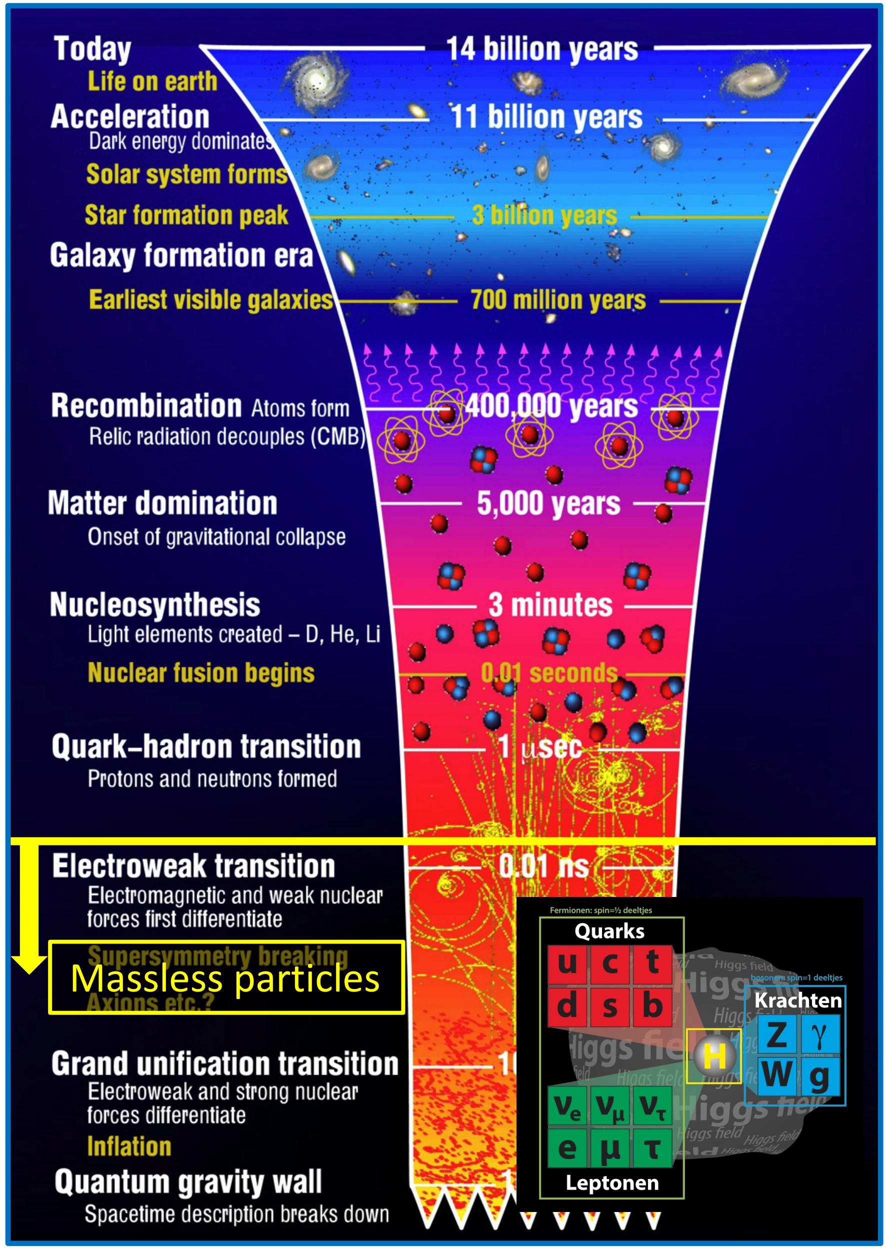
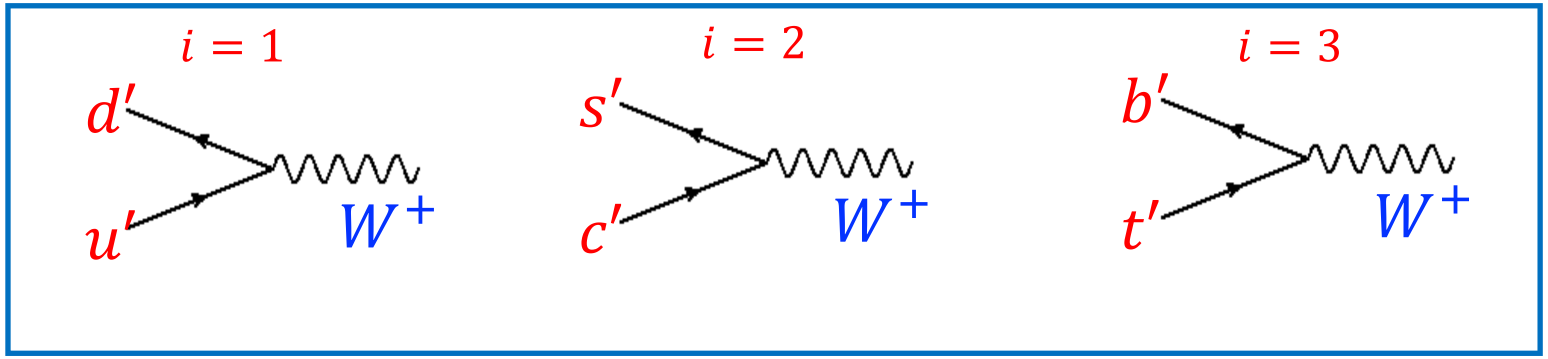


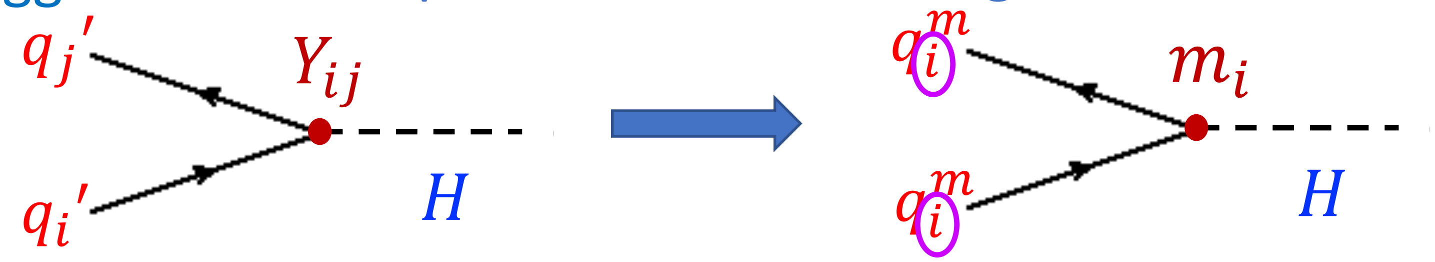


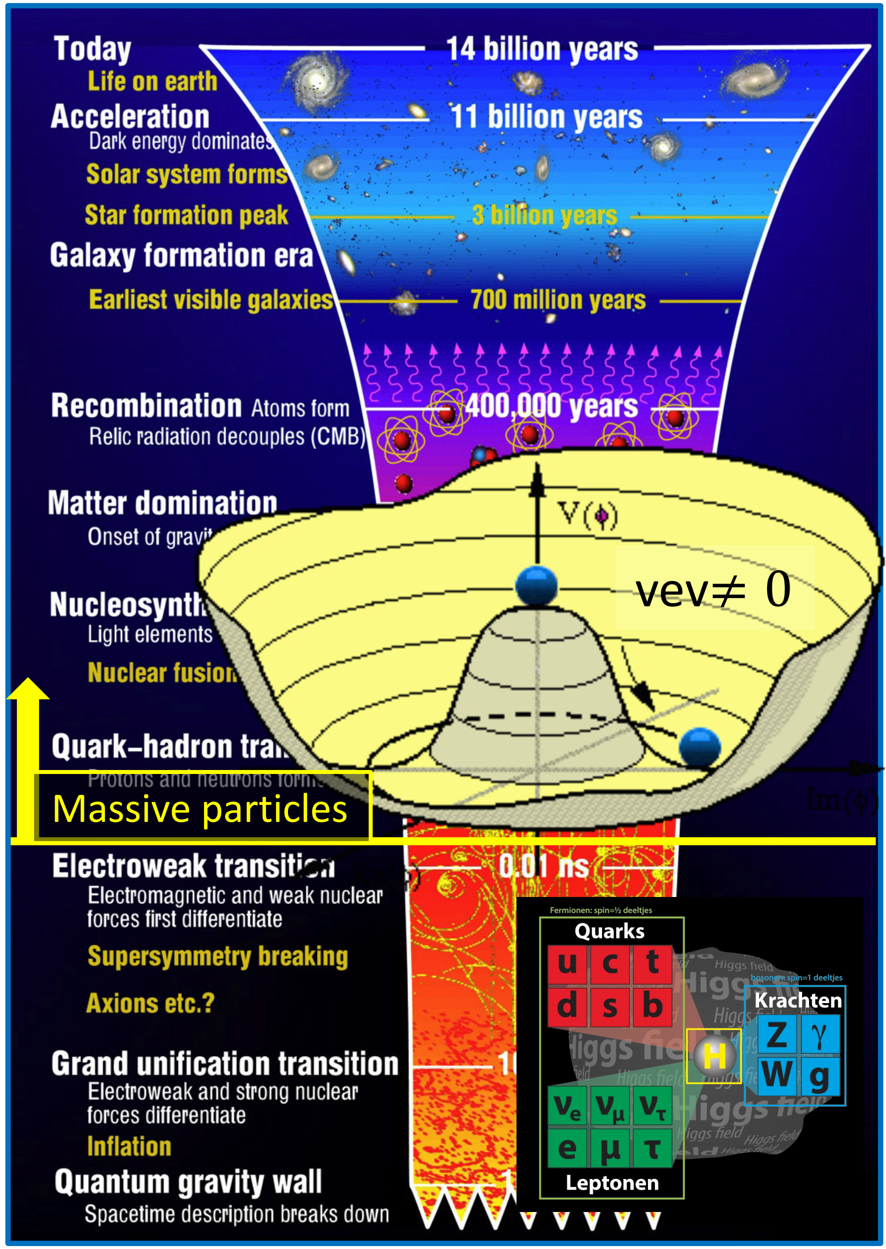
Recap: Flavour Universality → Symmetry Breaking

- Weak charged current interaction: $(i \leftrightarrow i)$



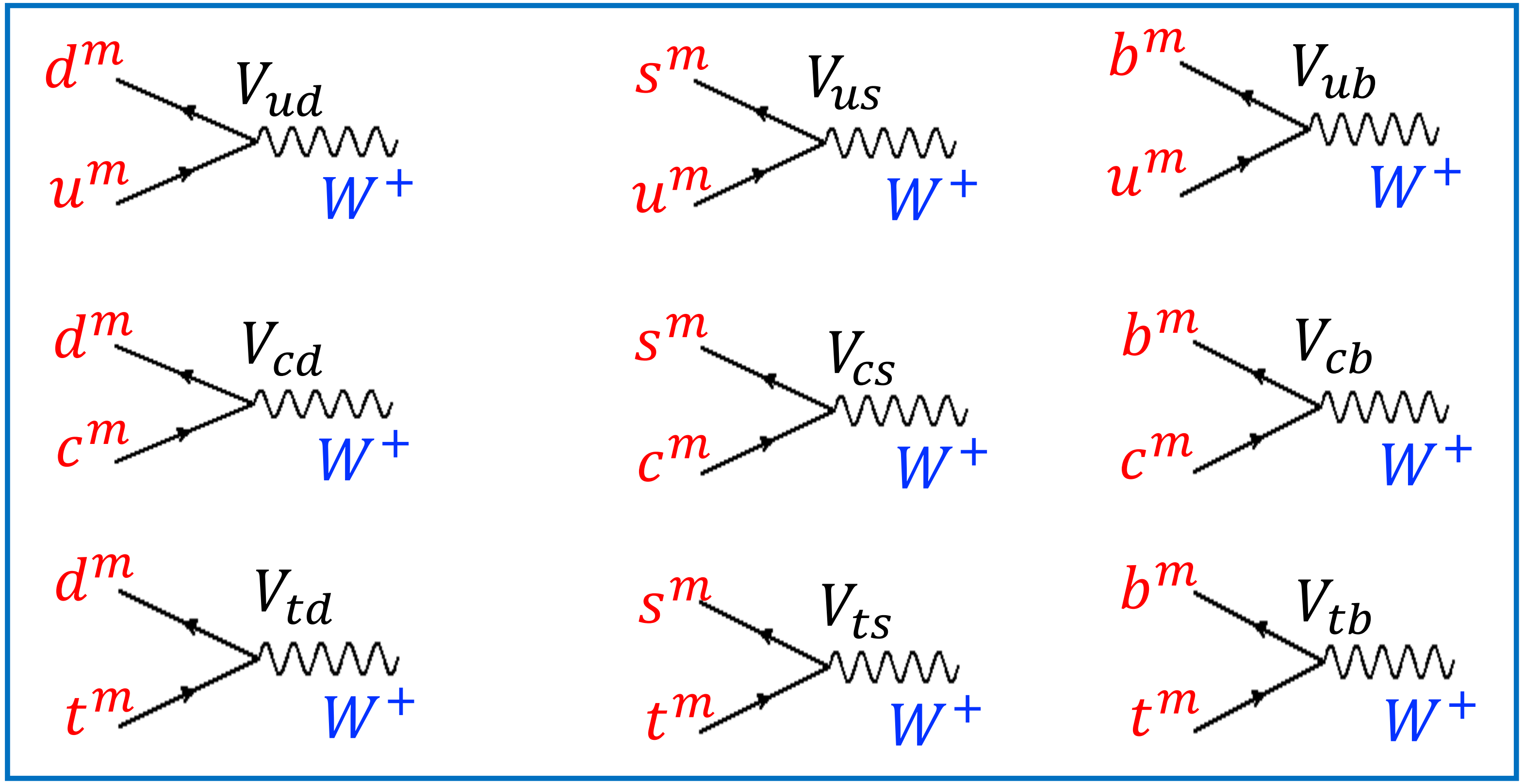
- Higgs: redefines quark states in mass eigenstates: $(i \leftrightarrow i)$





Recap: Flavour Universality → Symmetry Breaking → Flavour Mixing

- Weak charged current interaction: $(i \leftrightarrow j)$



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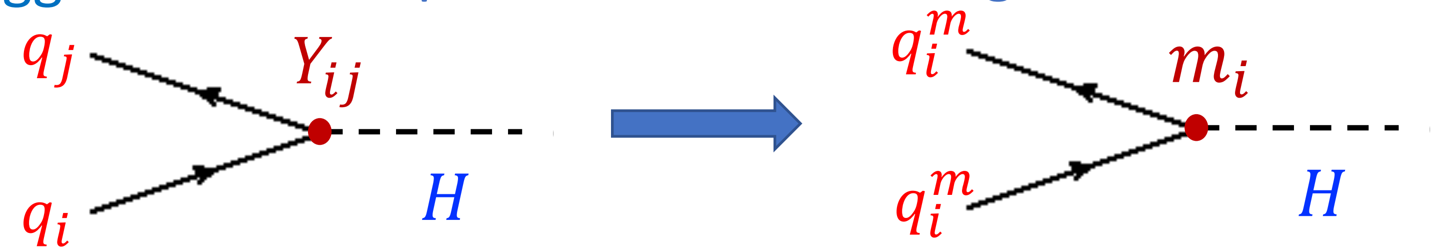
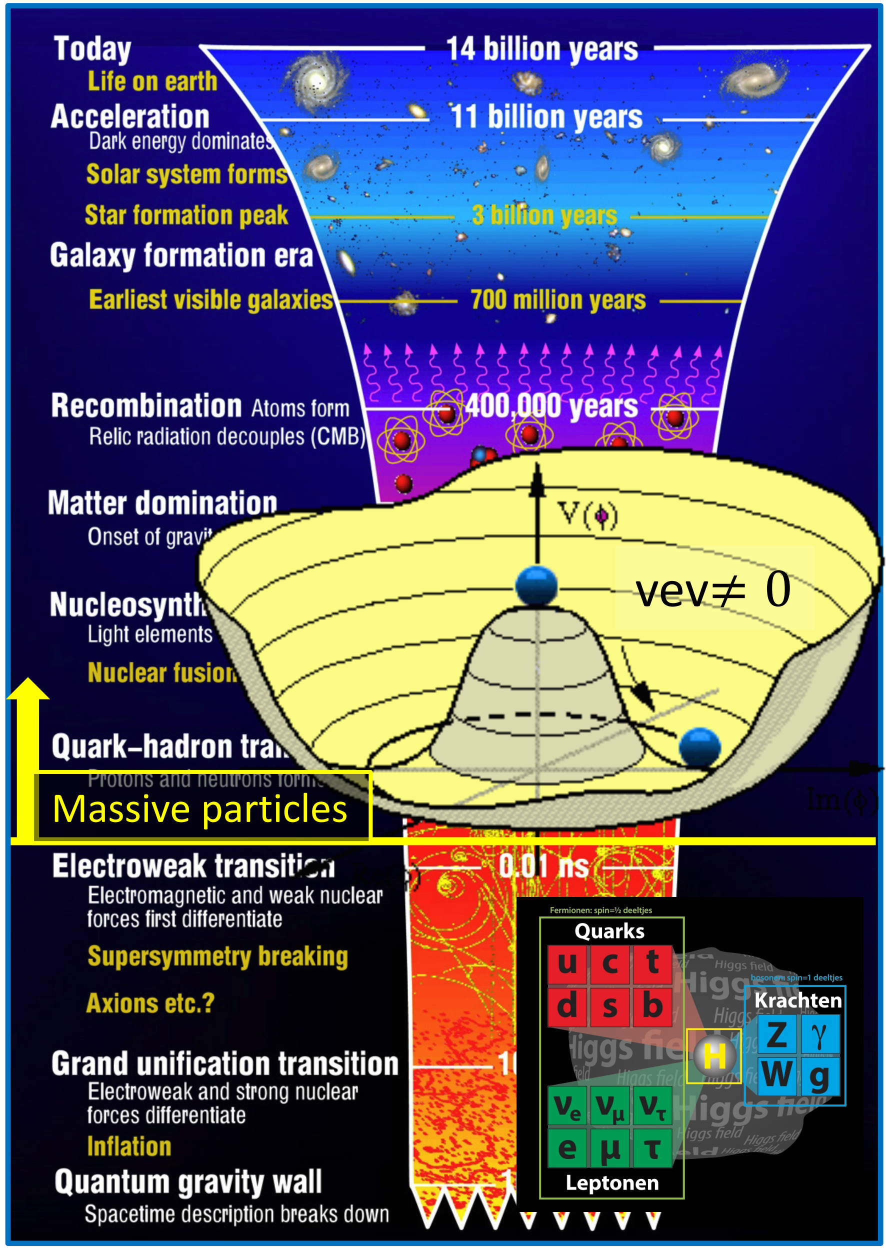
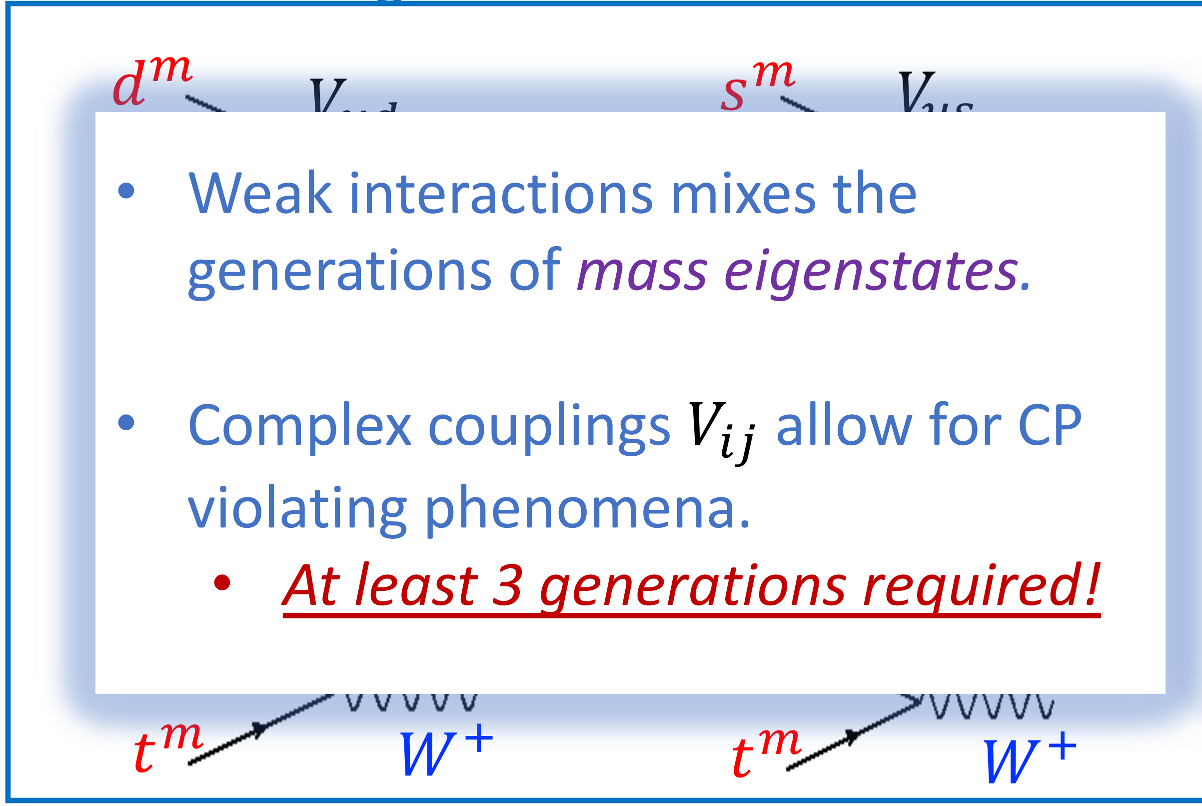
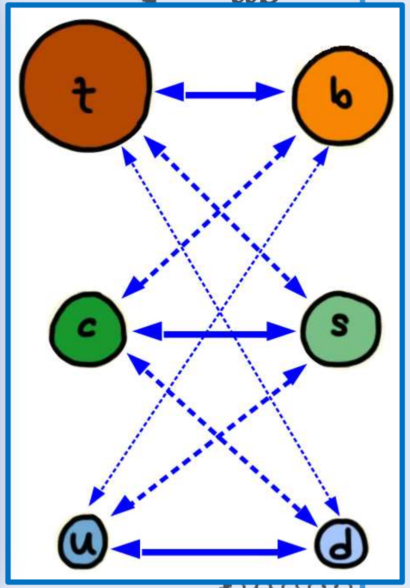


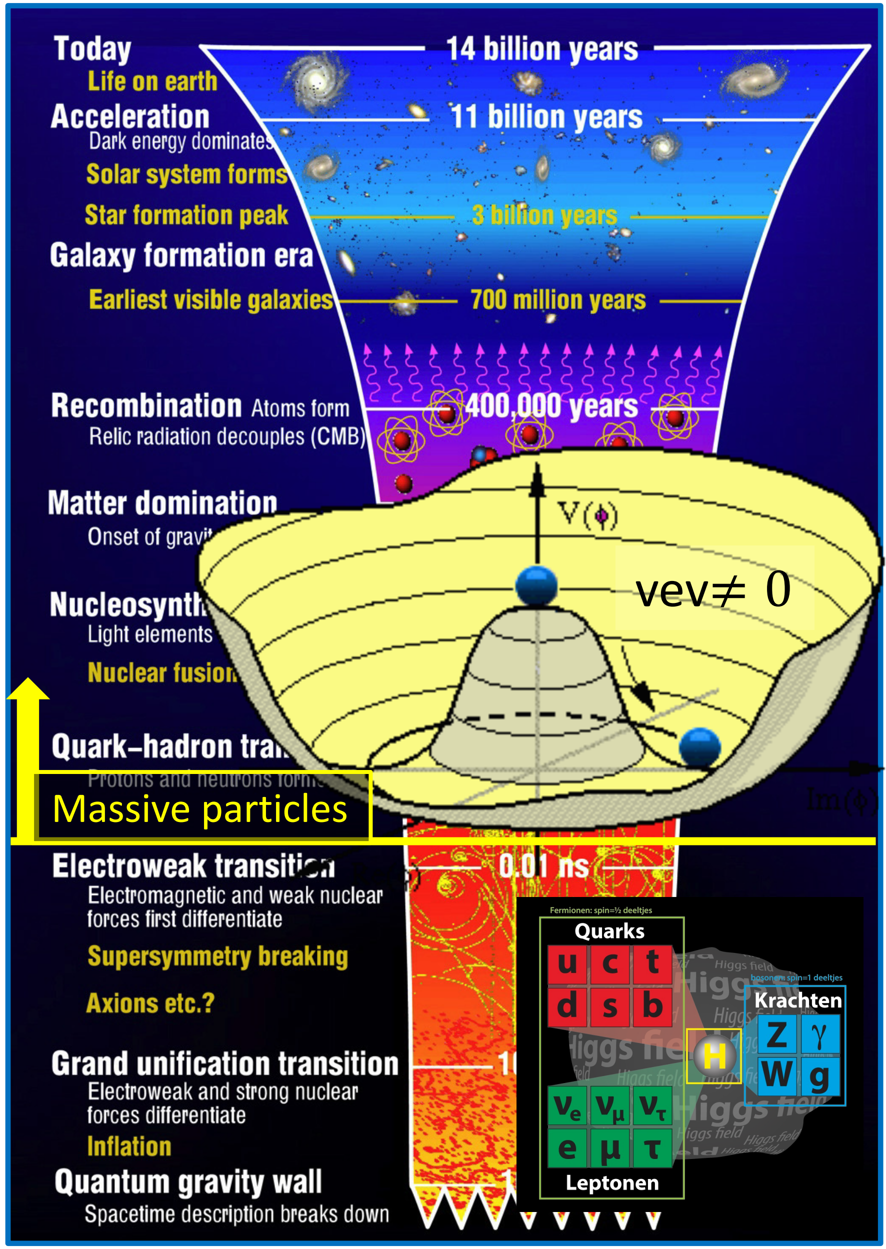


- Weak charged current interaction:



- Weak interactions mixes the generations of *mass eigenstates.*
- Complex couplings V_{ij} allow for CP violating phenomena.
  - ***At least 3 generations required!***





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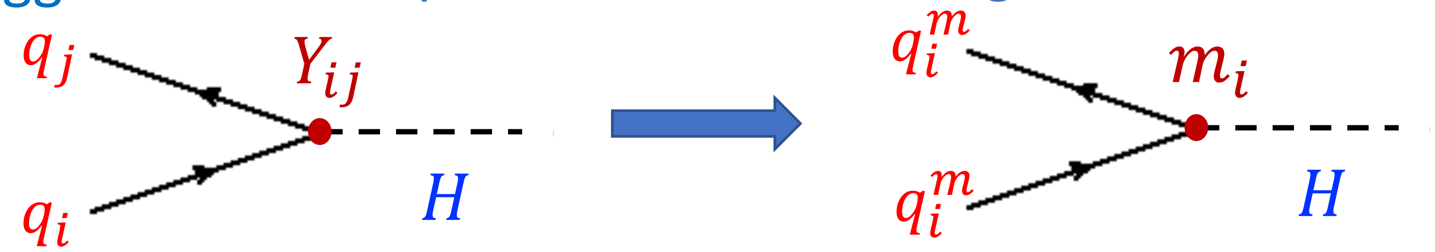


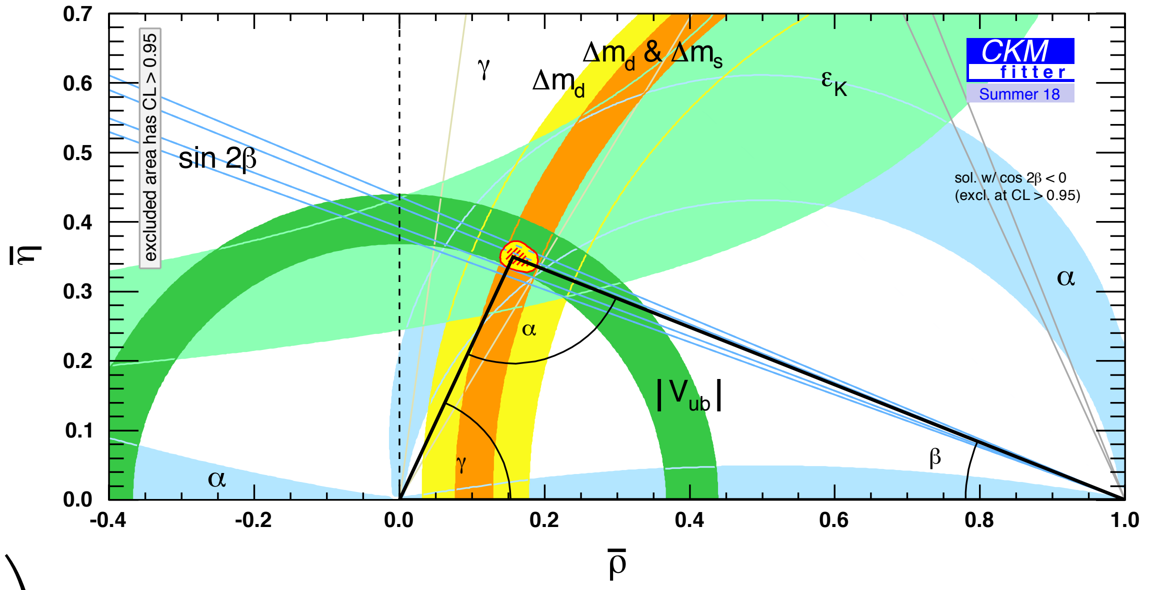
Recap: The CKM matrix and unitarity triangle

- CKM in terms of ***phases***:

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Triangle in the complex plane:

$$V^\dagger_{CKM} V_{CKM} = 1$$



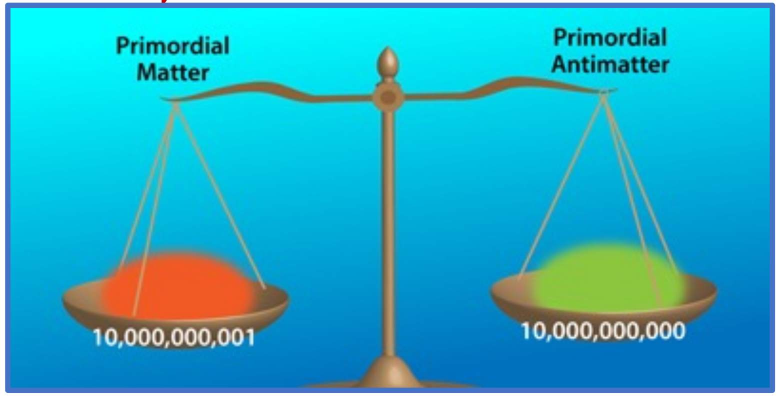
- Wolfenstein parametrization:

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- CP Violation:
  - ➢ Non-zero unitary phases
  - ➢ Triangle surface $\neq 0$
    - ❖ Jarlskog invariant

Recap: CP violation vs matter – antimatter asymmetry

- To explain the absence of antimatter in the universe ***requires*** a primordial baryon asymmetry of: $\frac{\Delta n_B}{n_\gamma} \approx \underline{10^{-10}}$

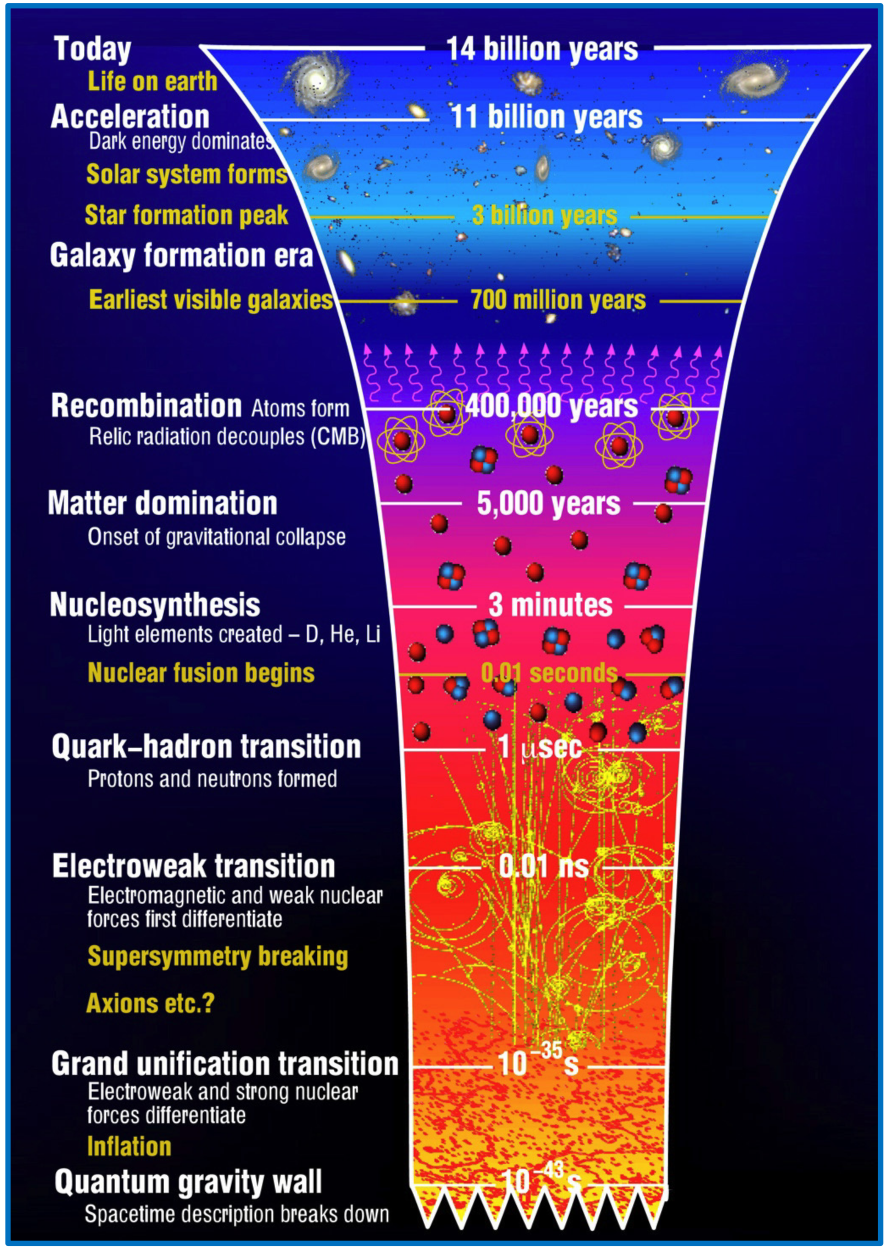


- Jarlskog criterion (1987) for ***amount of CP violation in SM***:

$$\det[M_u M_u^\dagger , M_d M_d^\dagger] = 2\, i\, J\, (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$$

From CKM: $A_{CP}/T_c^{12} \approx \underline{10^{-20}}$ → <u>**Too small**</u>

- *Explanation requires existence of **new massive** particles.*



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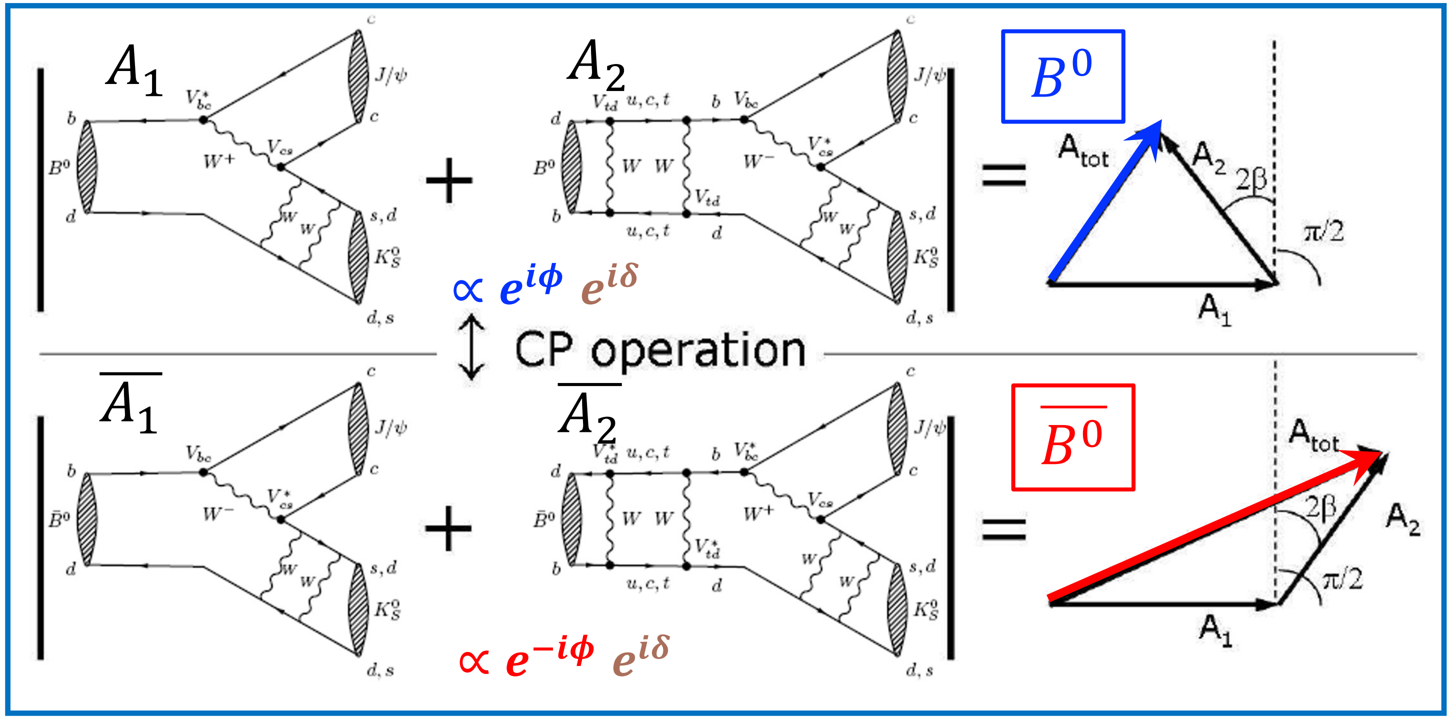
CP violation: a quantum interference experiment

- Quantum process with two amplitudes A_1 and A_2:
  - Eg.: $A_1 = B^0 \to J/\psi\, K_s$ and $A_2 = B^0 \to \overline{B^0} \to J/\psi\, K_s$



$|A_1| = |\overline{A_1}|$, $|A_2| = |\overline{A_2}|$,
but $|A_1 + A_2| \neq |\overline{A_1 + A_2}|$

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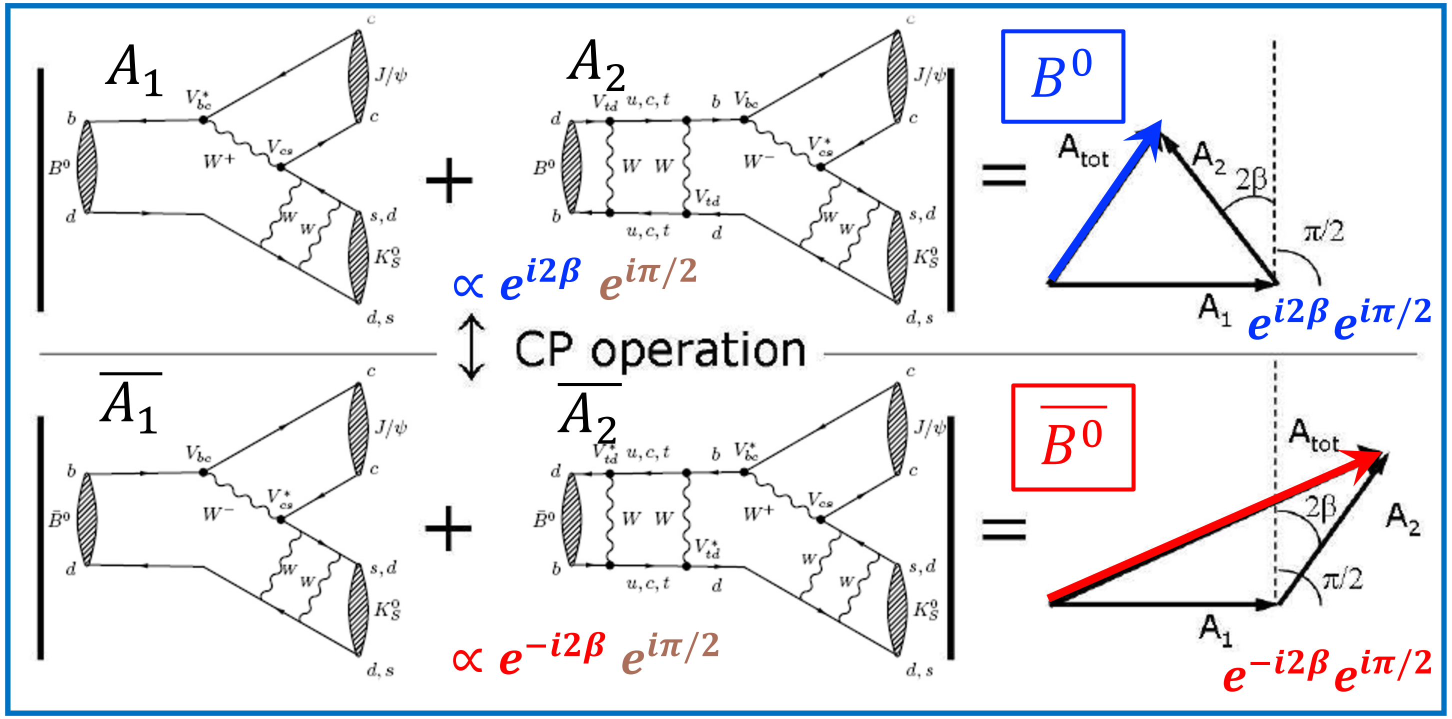

$|A_1| = |\overline{A_1}|$, $|A_2| = |\overline{A_2}|$,
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Weak phase from CKM: $e^{-i2\beta} \to e^{i2\beta}$
Strong phase from mixing process: $e^{i\pi/2} \to e^{i\pi/2}$

CP violation: a quantum interference experiment

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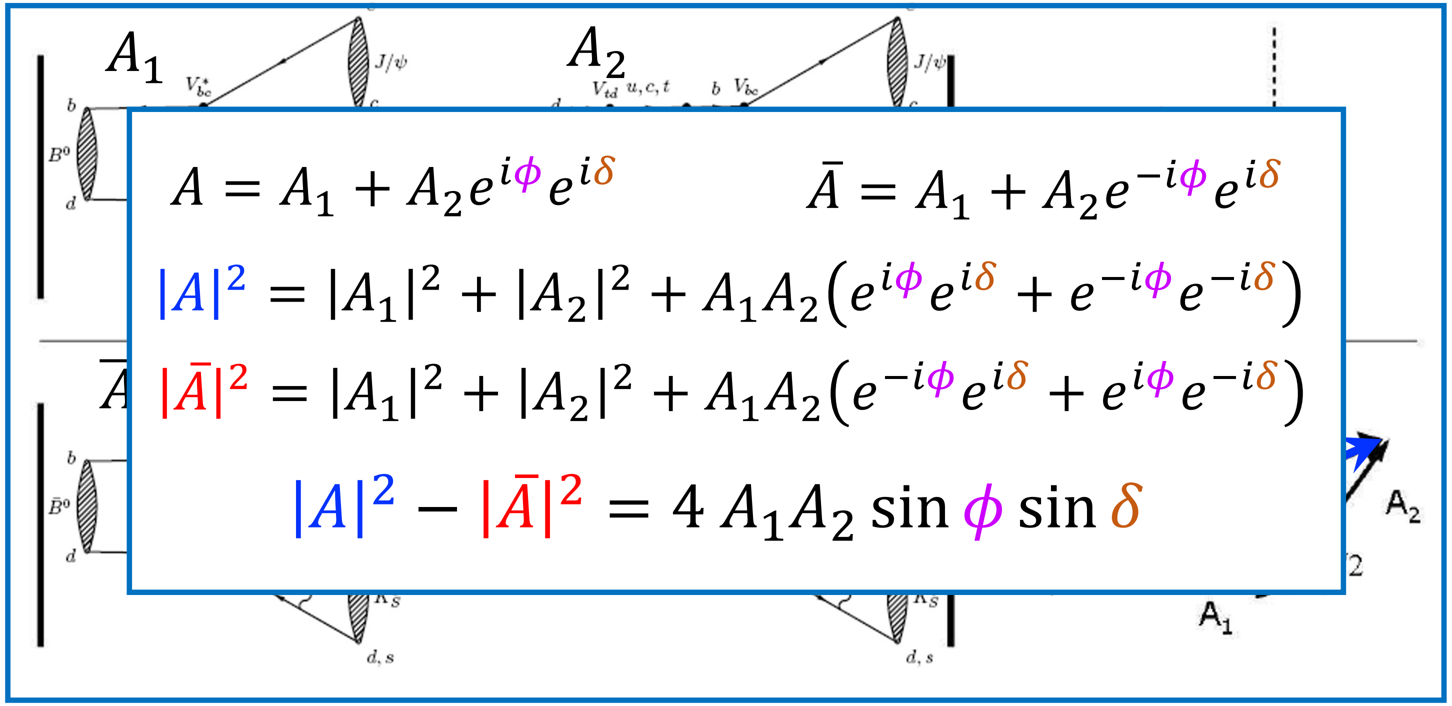
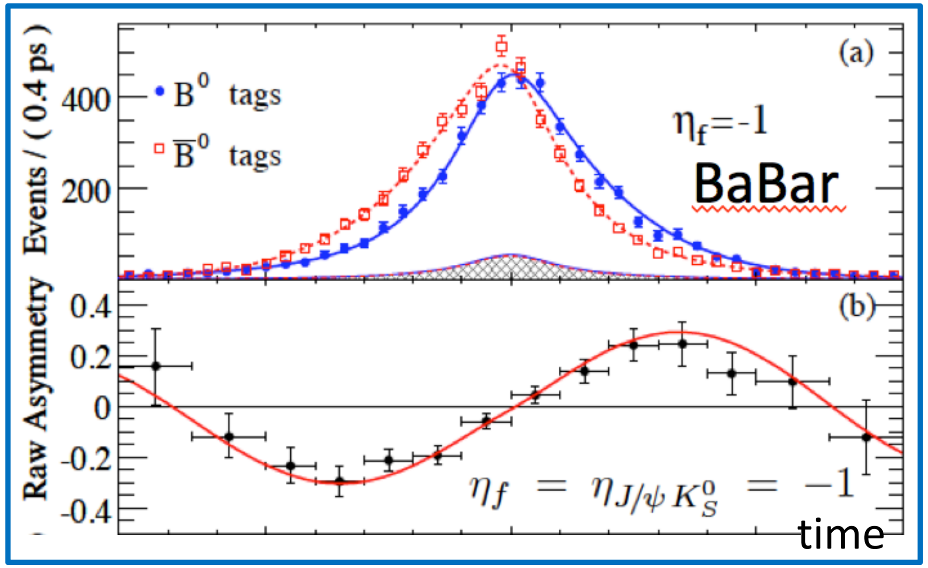


$$A = A_1 + A_2 e^{i\phi} e^{i\delta} \qquad \bar{A} = A_1 + A_2 e^{-i\phi} e^{i\delta}$$

$$|A|^2 = |A_1|^2 + |A_2|^2 + A_1 A_2 \left(e^{i\phi} e^{i\delta} + e^{-i\phi} e^{-i\delta}\right)$$

$$|\bar{A}|^2 = |A_1|^2 + |A_2|^2 + A_1 A_2 \left(e^{-i\phi} e^{i\delta} + e^{i\phi} e^{-i\delta}\right)$$

$$|A|^2 - |\bar{A}|^2 = 4\, A_1 A_2 \sin\phi \sin\delta$$



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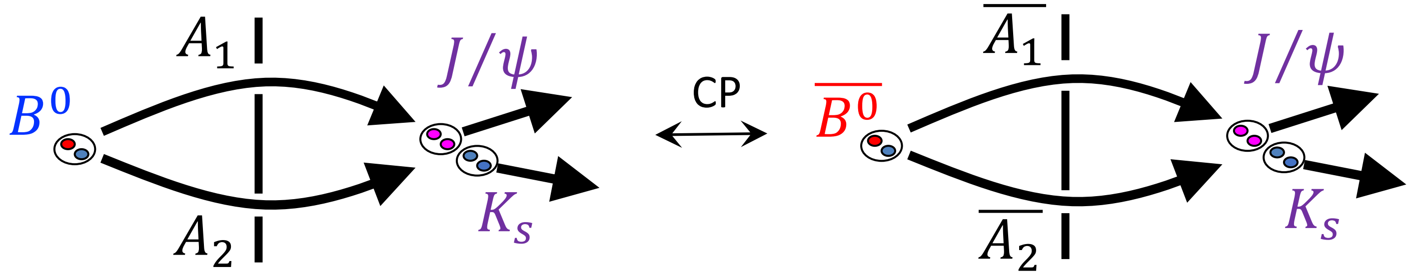
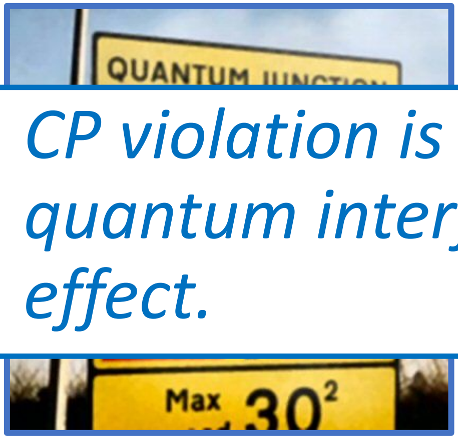
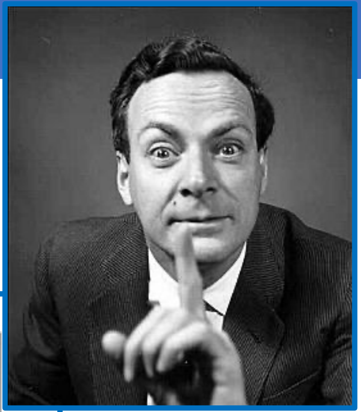


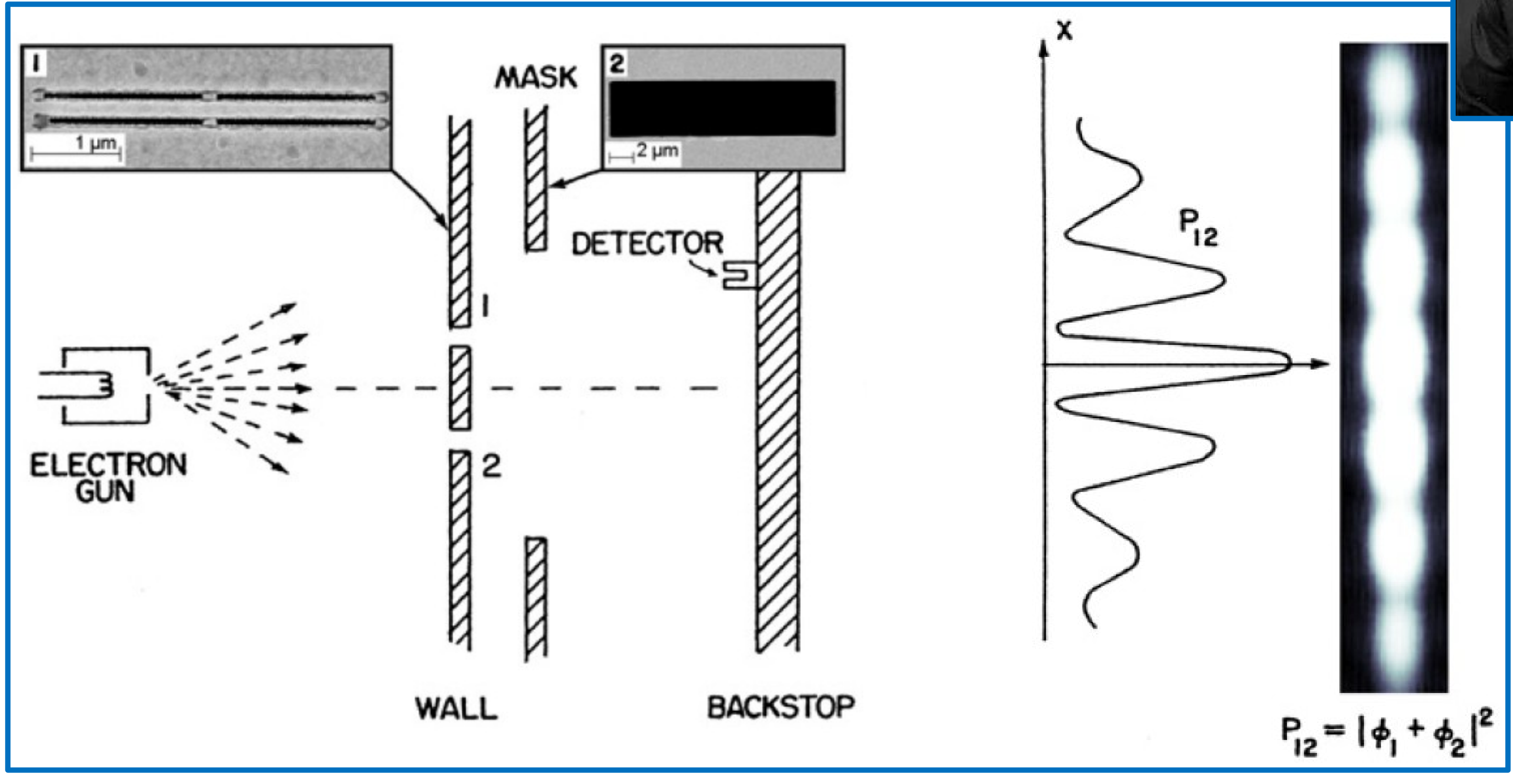


- *CP violation is a pure quantum interference effect.*

Intermezzo: CP violation and Interference



- Feynman: “In the end all quantum phenomena are manifestations of the double slit experiment.”



- *Thought: Assuming CPT symmetry, CP violation implies a quantum arrow of time*
  - *Quantum interference ←→ arrow of time?*

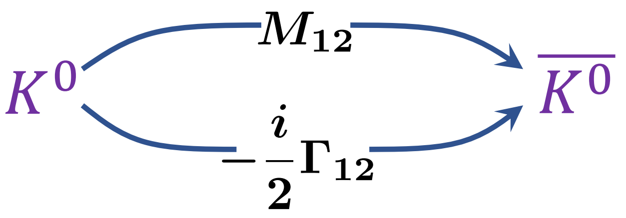
Three types of observable CP violation

a) *“indirect”* CP Violation: 1964 (CCFT)

- Prob$(K^0 \to \overline{K^0})$ $\neq$ Prob $(\overline{K^0} \to K^0)$

  $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$ (PDG)
- Also called: ***CPV in mixing***

Interfere *dispersive* and *absorptive*:



b) *“direct”* CP violation: 1999 (NA48 & KTeV):

- Decay rates $\Gamma(K^0 \to \pi^+\pi^-) \neq \Gamma(\overline{K^0} \to \pi^+\pi^-)$

  Re$(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$ (PDG)
- Also called: ***CPV in decay***

Interfere *Isospin amplitudes*:

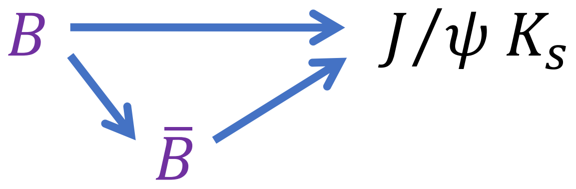
$$A = a_{0(K\to\pi\pi)} + a_{2(K\to\pi\pi)}$$

c) *“mixing induced”* CP violation: 2001 (Belle & Babar):

- Also: ***CPV in interference of mixing and decay***

  $\sin 2\beta = 0.682 \pm 0.019$ (PDG)

Interfere *direct and mixed*:



Observed CP violation in “Mixing”, “Decay”, “Induced”

1964
Strange particles: *CP* violation in K meson decays
J. W. Cronin, V. L. Fitch *et al.*
CPV in K^0 mixing

1999, 2001
Strange particles: *CP* violation in decay
KTeV and NA48 collaborations
CPV in K decay

2001
Beauty particles:Time-dependent *CP* violation in B^0 meson decays
BaBar and Belle collaborations
B^0 Mixing induced CPV

2004
Beauty particles: Time-integrated *CP* violation in B^0 meson decays
BaBar and Belle collaborations
CPV in B^0 decay

2012
Beauty particles: *CP* violation in B^+ meson decays
LHCb collaboration
CPV in B^+ decay

2013
Beauty-strange particles: Time-integrated *CP* violation in B_s^0 meson decays
LHCb collaboration
CPV in B_s decay

2019
Charm particles: *CP* violation in D^0 meson decays
LHCb collaboration
Primarily CPV in D^0 decay

TODAY

2020
Beauty-strange particles: Time-dependent *CP* violation in B_s^0 meson decays
LHCb collaboration
B_s Mixing induced CPV

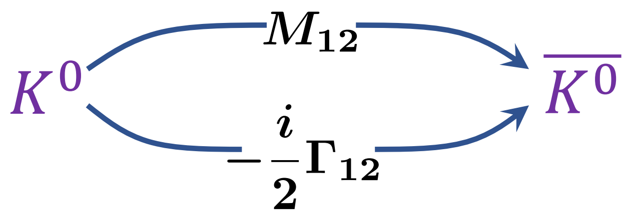
Three types of observable CP violation

a) *"indirect"* CP Violation: 1964 (CCFT)

- Prob($K^0 \to \overline{K^0}$) $\neq$ Prob ($\overline{K^0} \to K^0$)

  $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$ (PDG)
- Also called: ***CPV in mixing***

Interfere *dispersive* and *absorptive*:



b) *"direct"* CP violation: 1999 (NA48 & KTeV):

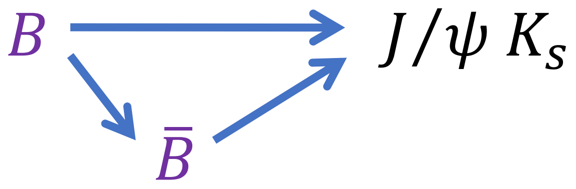
All CP violation processes result from quantum interference including three generations of fermions.

c) *"mixing induced"* CP violation: 2001 (Belle & Babar):

- Also: ***CPV in interference of mixing and decay***

  $\sin 2\beta = 0.682 \pm 0.019$ (PDG)

Interfere *direct* and *mixed*:



Whisky: Three types of Flavour Violation…

1. "In Mixing"

Blended

(Chivas Regal)

2. "Direct"

Single Malt

(Caol Ila)

3. "Mixing induced"

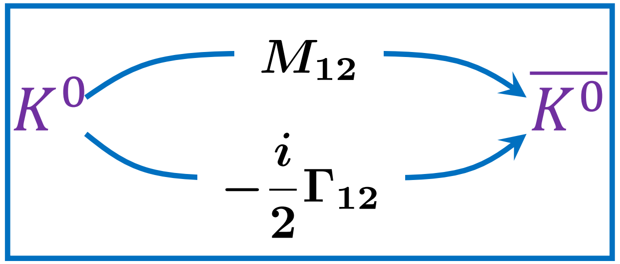
"WTF?"

Moonshine

→ Interference experiments lead to interesting effects! (Constructive or destructive??)

Type-1: CP violation in *mixing:* eg. K^0 decays

Measure $A = \frac{N^+ - N^-}{N^+ + N^-}$ with $N^+ = K^0 \to \pi^- e^+ \nu$, $N^- = \overline{K^0} \to \pi^+ e^- \bar{\nu}$ vs the K^0 decay time



Two CP states:

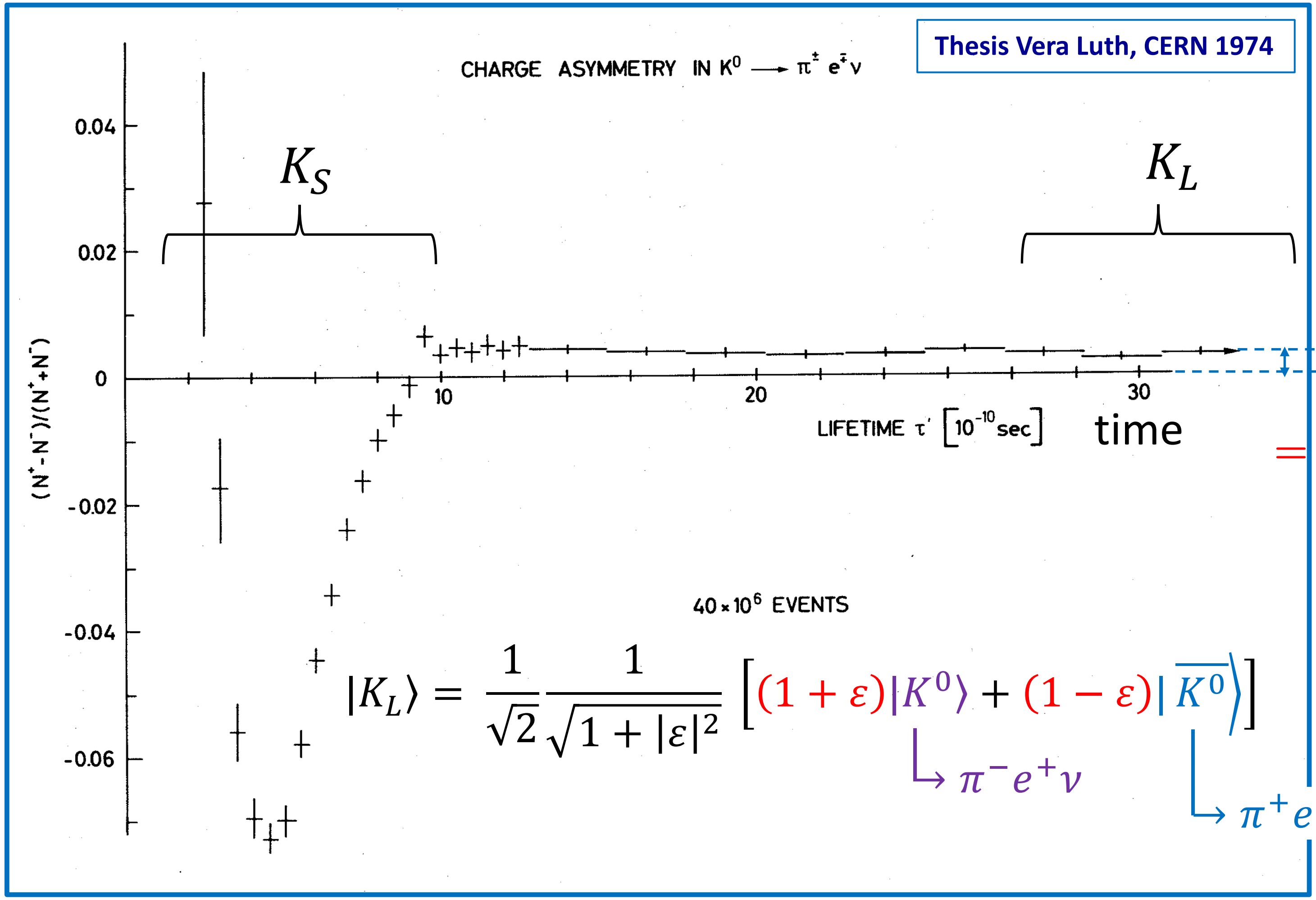
$$|K_1\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\overline{K^0}\rangle\right]$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\overline{K^0}\rangle\right]$$

Two particles:

$$|K_S\rangle \simeq [|K_1\rangle + \varepsilon|K_2\rangle]$$

$$|K_L\rangle \simeq [|K_2\rangle + \varepsilon|K_1\rangle]$$



$$|K_L\rangle = \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1+|\varepsilon|^2}} \left[(1+\varepsilon)|K^0\rangle + (1-\varepsilon)|\overline{K^0}\rangle\right]$$

$(1+\varepsilon)|K^0\rangle \to \pi^- e^+ \nu$

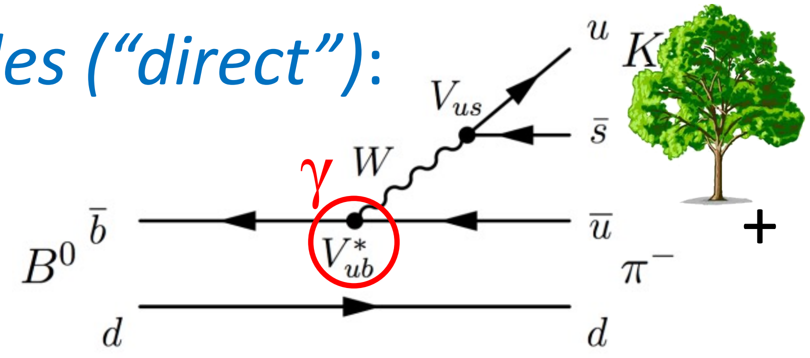
$(1-\varepsilon)|\overline{K^0}\rangle \to \pi^+ e^- \bar{\nu}$

$$4\Re(\varepsilon) = \left|\frac{(1+\varepsilon)}{(1-\varepsilon)}\right|^2$$

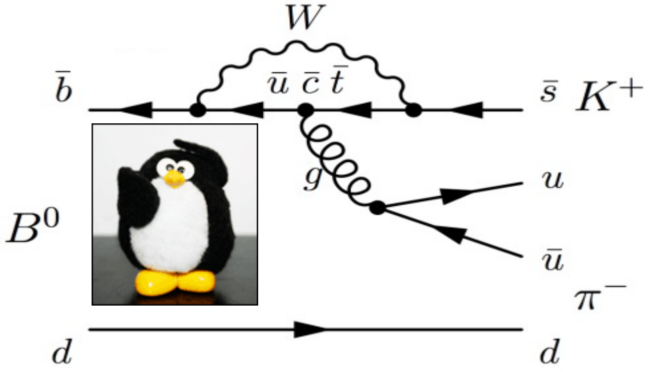
Type-2: CP violation in *decay*: $B_d^0 \to K\pi$ and $B_s^0 \to K\pi$

- Interfere *two decay amplitudes ("direct")*:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



+

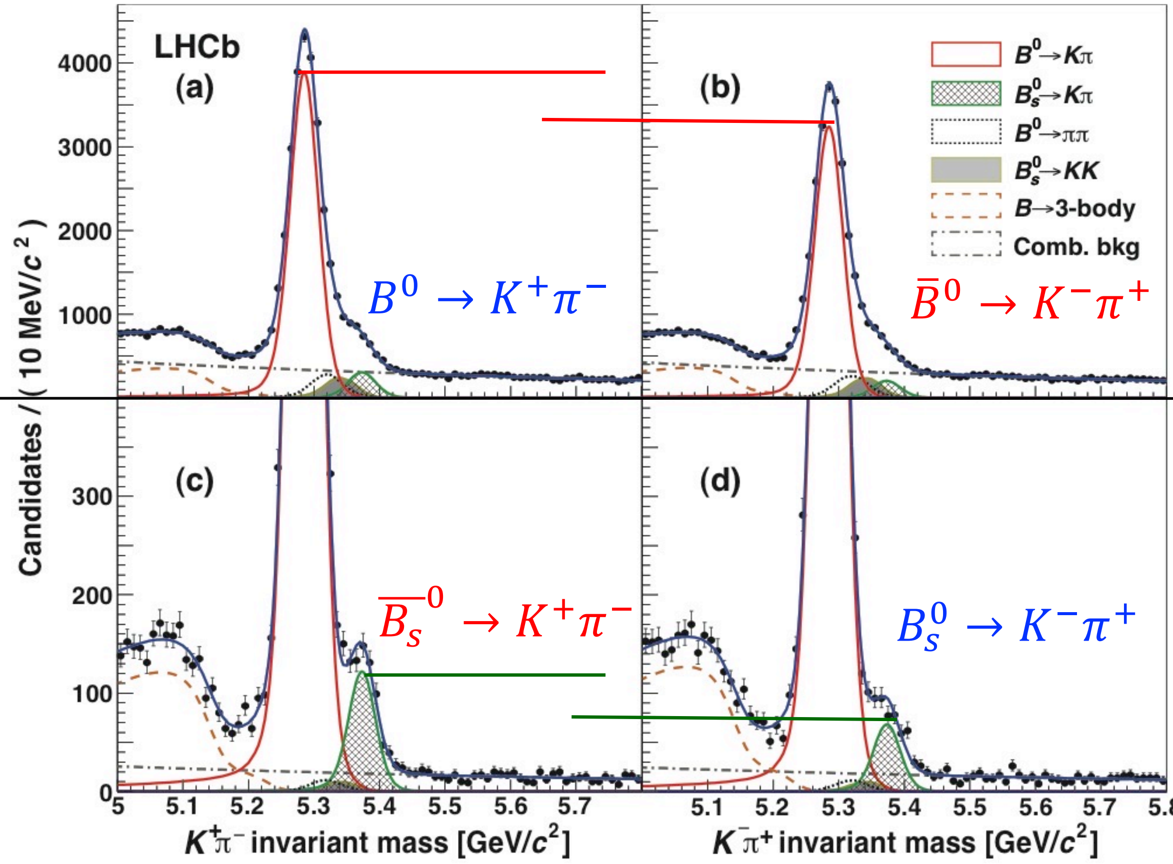


When there are ***multiple*** decay diagrams

$B_d^0 \to K\pi$

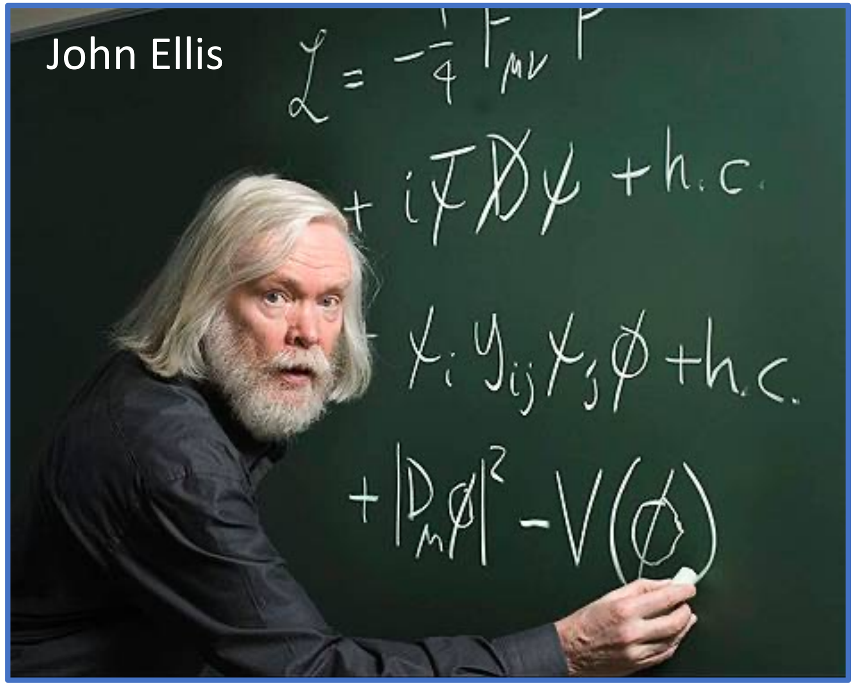
$B_s^0 \to K\pi$

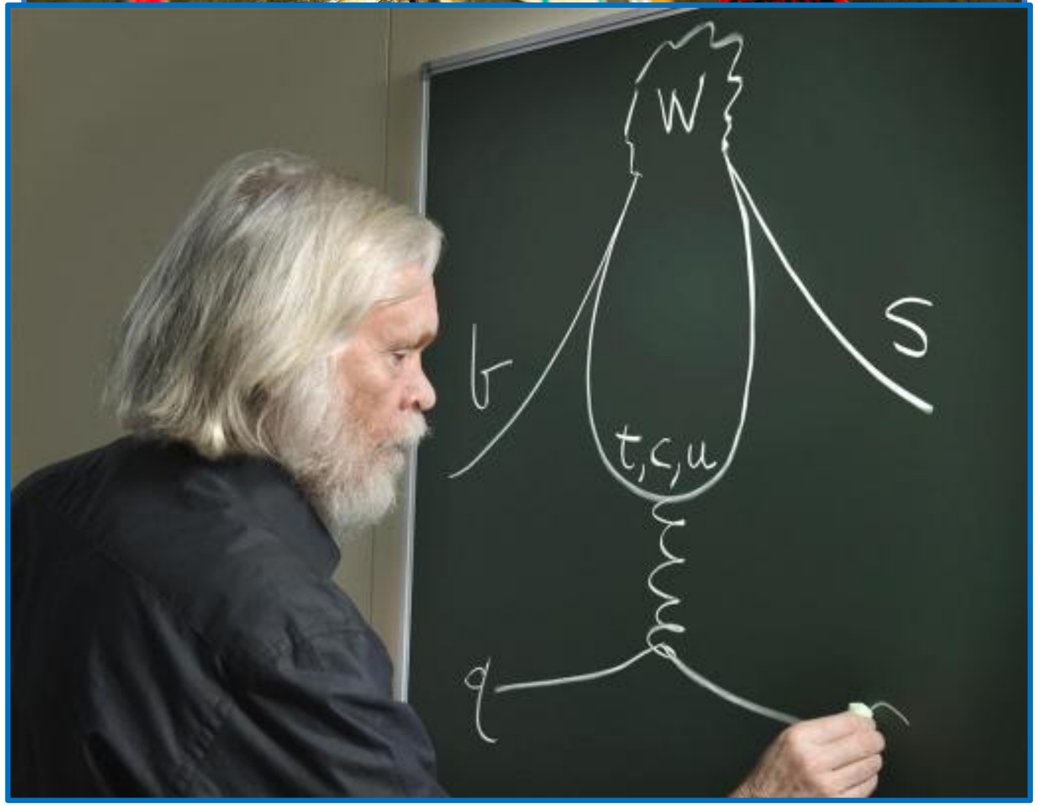
First observation of CP violation in B_s decays

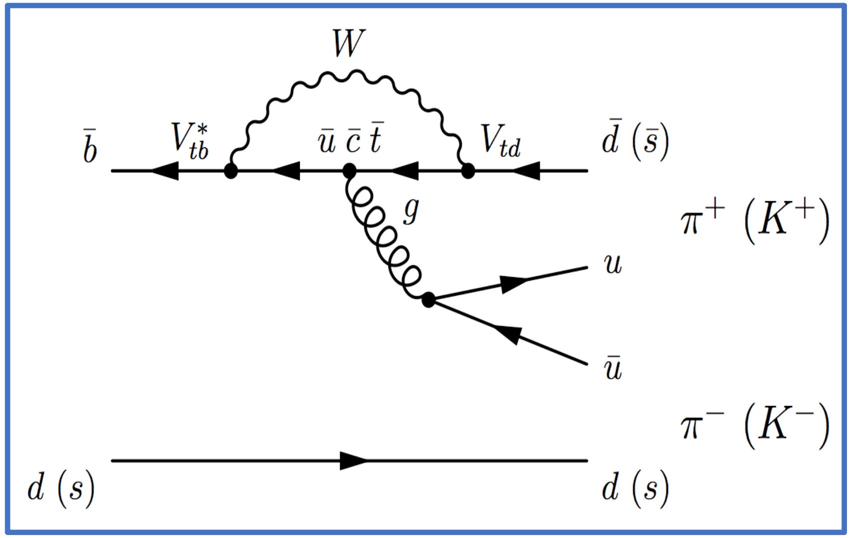


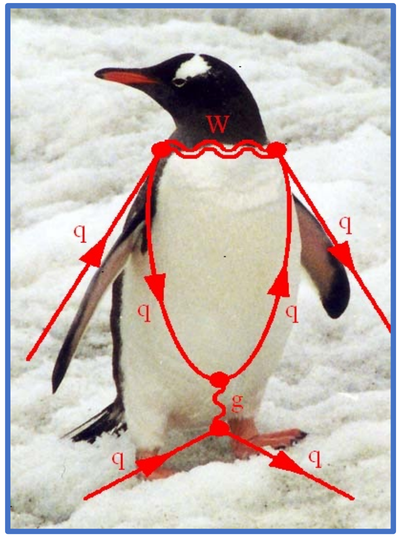
- Quarks from three generations involved
- Large interference
- Large CP violation!
  - Contrary to ϵ' in the kaon system

A story on darts and penguins





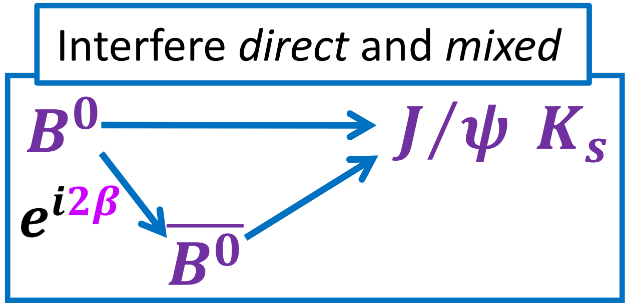




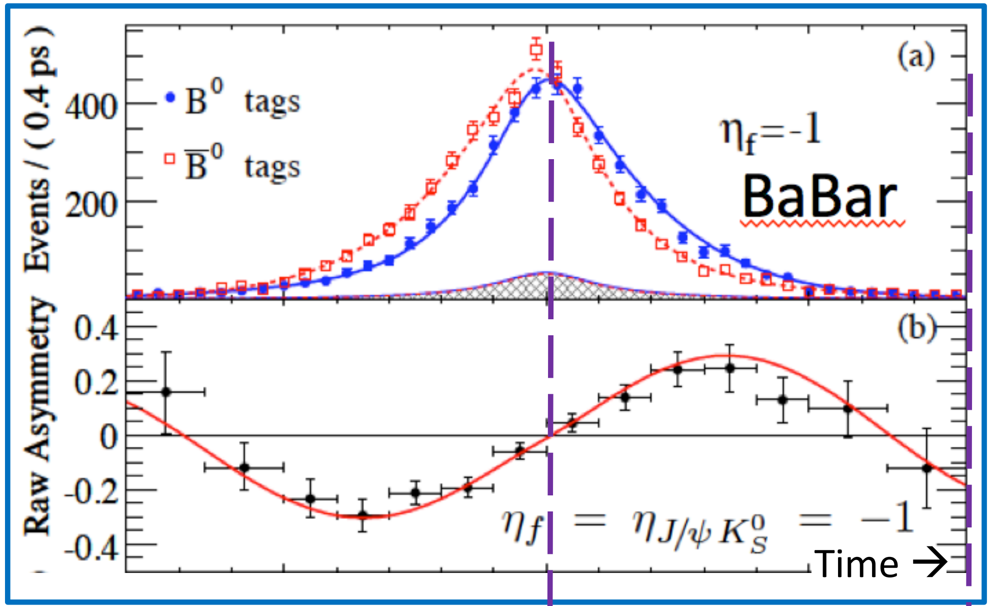
Type-3: CP violation in *interference of mixing and decay*

- Interfere *direct* with *mixed* decay ("mixing induced"):

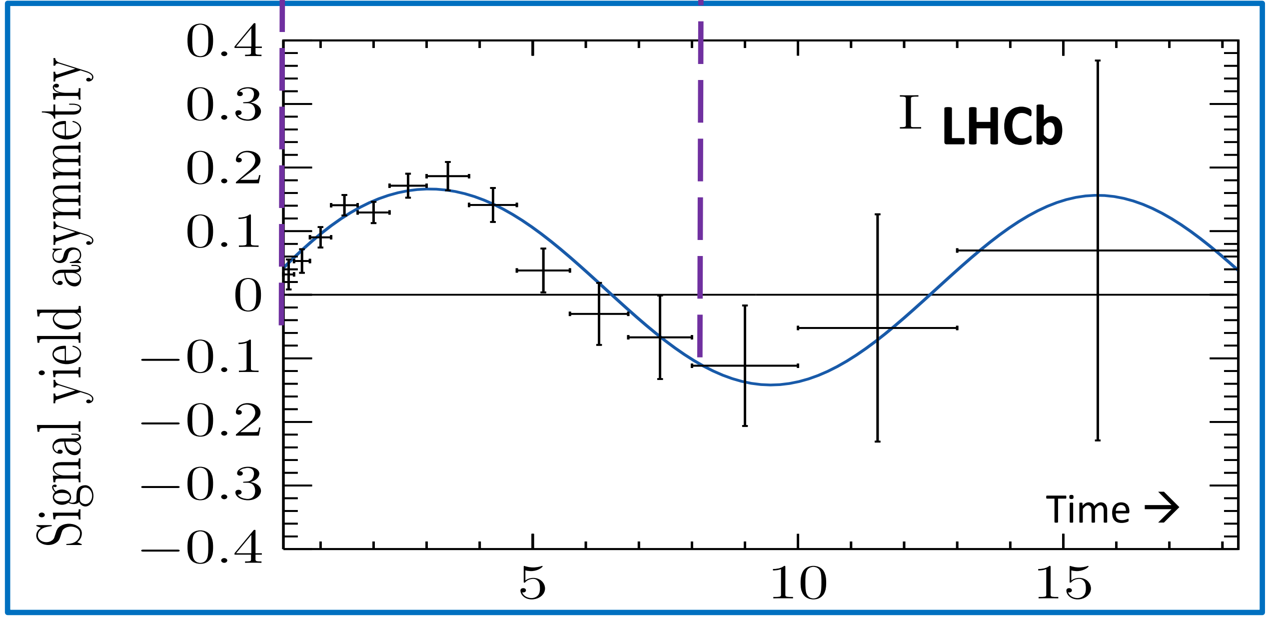
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$



$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



Decay-time dependent CP violation



Contents Yesterday & Today:

1. CP Violation
   a) Discrete Symmetries
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
2. B-Mixing
   a) CP violation and Interference
   b) B-mixing and time dependent CP violation
   c) Experimental Aspects: LHC vs B-factory

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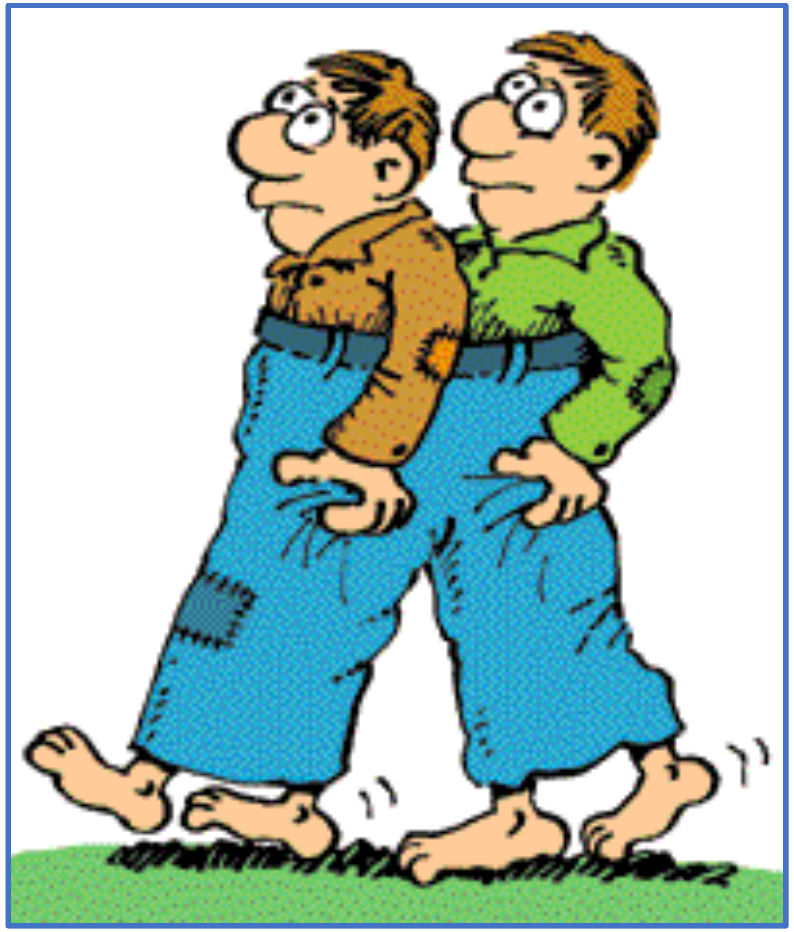
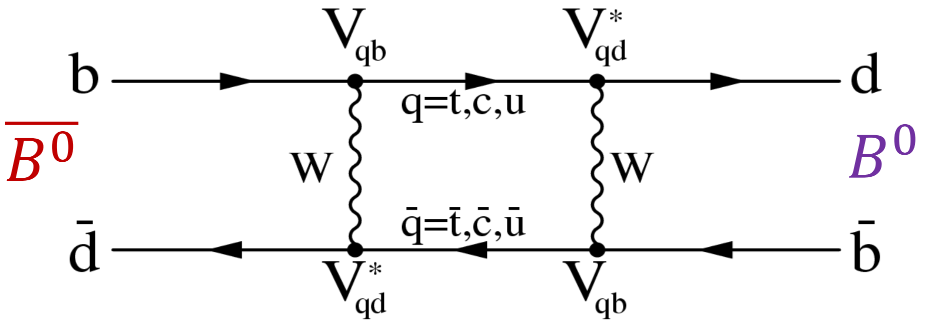


Flavor Oscillations

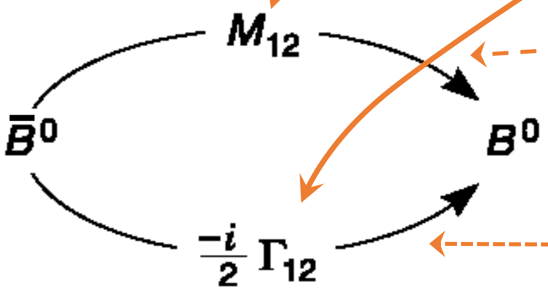
- Quantum mechanics with $\overline{B^0}$ and B^0 states: *"What is a particle?"*
  - Particle – antiparticle transitions $\overline{B^0} \leftrightarrow B^0$ mesons happen spontaneously.



- Time evolution of B^0 and $\overline{B^0}$ described by an effective Hamiltonian

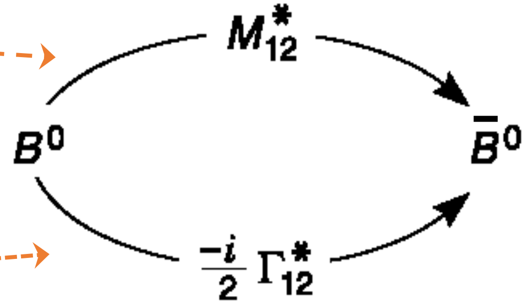
$$i\frac{\partial}{\partial t}\psi = H\psi \quad \rightarrow \quad \psi(t) = a(t)|B^0\rangle + b(t)|\overline{B^0}\rangle \quad \equiv \quad \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\text{Hermitean Mass-matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\text{Hermitean Decay-matrix}} \qquad H = H_{st} + H_{em} + H_{weak}$$



M_{12} describes $B^0 \leftrightarrow \overline{B^0}$ via *off-shell* states, e.g. the weak box diagram ("dispersive")

Γ_{12} describes $B^0 \leftrightarrow f \leftrightarrow \overline{B^0}$ via *on-shell* states, e.g. $f = \pi^+\pi^-$ ("absorptive")



Solving the Schrödinger Equation

$$i\frac{\partial}{\partial t}\psi(t) = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\psi(t)$$

Eigenvectors:

$$|B_H(t)\rangle = |B_H\rangle e^{-i\omega_+ t}$$

$$|B_L(t)\rangle = |B_L\rangle e^{-i\omega_- t}$$

B_H , B_L : *Mass* eigenstates

$$|B_H\rangle = p|B^0\rangle + q|\overline{B^0}\rangle$$

$$|B_L\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$$

B^0 , $\overline{B^0}$: *Flavour* eigenstates

From the eigenvalue calculation:

$$q/p = -\sqrt{\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)\Big/\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)}$$

Solution: (α and β are initial conditions):

$$\Rightarrow \quad \psi(t) = \alpha|B_H(t)\rangle + \beta|B_L(t)\rangle$$

$$\omega_\pm = m_\pm - \frac{i}{2}\Gamma_\pm \quad \begin{cases} m_\pm = M \pm \frac{1}{2}\Delta m & \text{Masses} \\ \Gamma_\pm = \Gamma \pm \frac{1}{2}\Delta\Gamma & \text{Lifetimes} \end{cases}$$

Δm and $\Delta\Gamma$ follow from the (weak) Hamiltonian:

$$\Delta m = 2\,\Re\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

$$\Delta\Gamma = 4\,\Im\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

Examples

B^0 : $\Delta\Gamma \approx 0$, $|q/p| = 1$

B_s^0 : $\Delta\Gamma/\Delta m \ll 1$, $|q/p| = 1$

K^0 : $\Delta\Gamma/\Delta m \simeq 1$, $|q/p| - 1 \simeq 10^{-3}$

B^0 Oscillation Amplitudes

For an initially ($t = 0$) produced B^0 or a $\overline{B^0}$ it follows:

using:

$$|B^0\rangle = \frac{1}{2p}(|B_H\rangle + |B_L\rangle)$$
$$|\overline{B^0}\rangle = \frac{1}{2q}(|B_H\rangle - |B_L\rangle)$$

$|\psi(t)\rangle$:

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)|\overline{B^0}\rangle$$

$$|\overline{B^0}(t)\rangle = g_+(t)|\overline{B^0}\rangle + \frac{p}{q}g_-(t)|B^0\rangle$$

with

$$g_{\pm(t)} = \frac{e^{-i\omega_+ t} \pm e^{-i\omega_- t}}{2}$$

$$\omega_\pm = m_\pm - \frac{i}{2}\Gamma_\pm$$

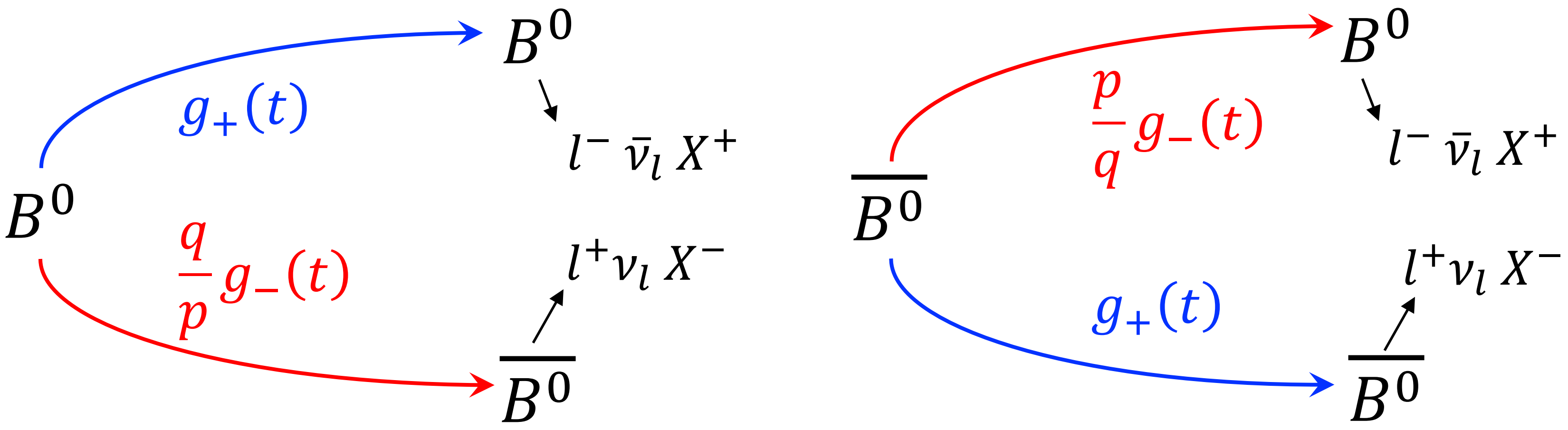
For B^0, expect:
$\Delta\Gamma \sim 0$,
$|q/p| = 1$

$$g_{\pm(t)} = e^{-iMt}e^{-\Gamma t/2}\left[\frac{e^{-\frac{1}{2}i\,\Delta mt} \pm e^{+\frac{1}{2}i\,\Delta mt}}{2}\right]$$

$$g_+(t) = e^{-iMt}e^{-\Gamma t/2}\cos\frac{\Delta mt}{2}$$

$$g_-(t) = e^{-iMt}e^{-\Gamma t/2}\,i\,\sin\frac{\Delta mt}{2}$$

B^0 Oscillations



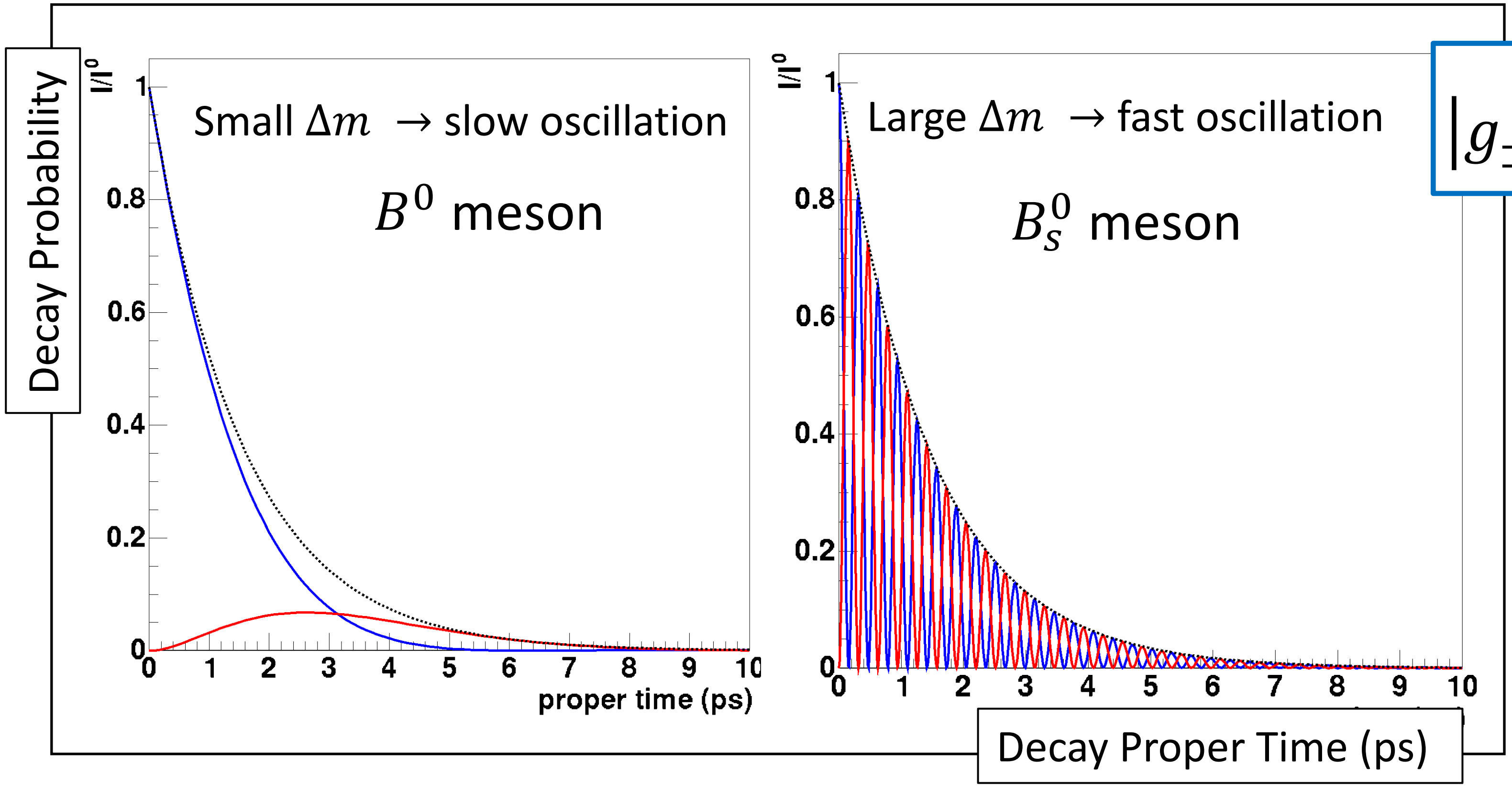
Calculate:

$|\langle B(t)|B^0\rangle|^2$

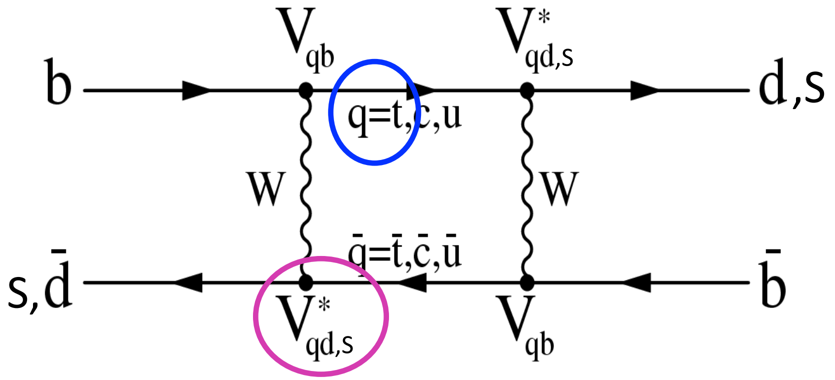
$|\langle \bar{B}(t)|B^0\rangle|^2$

For B^0, expect:
$\Delta\Gamma \sim 0$, $|q/p| = 1$

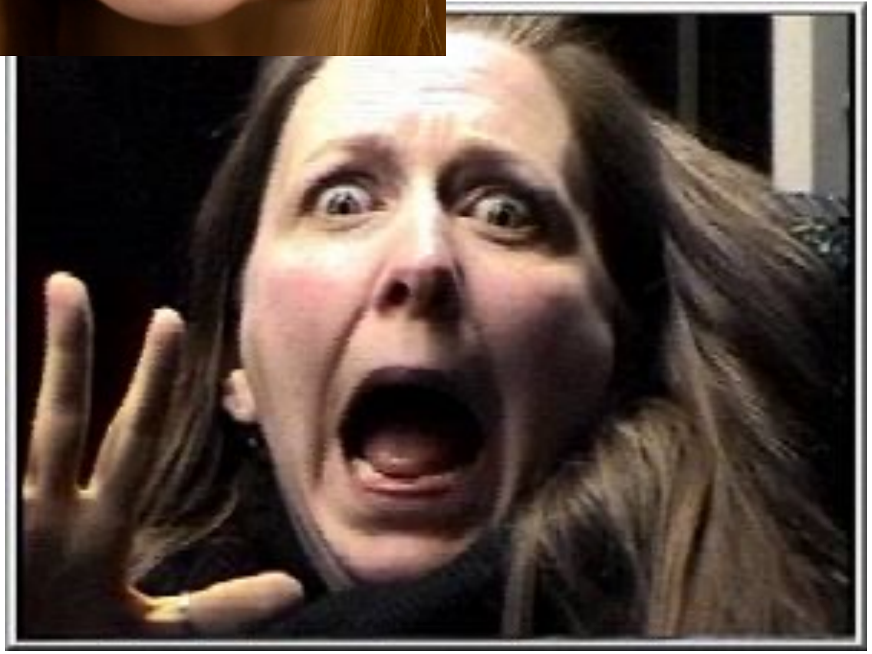
$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left[1 \pm \cos(\Delta m \cdot t)\right]$$



Flavour Oscillations!

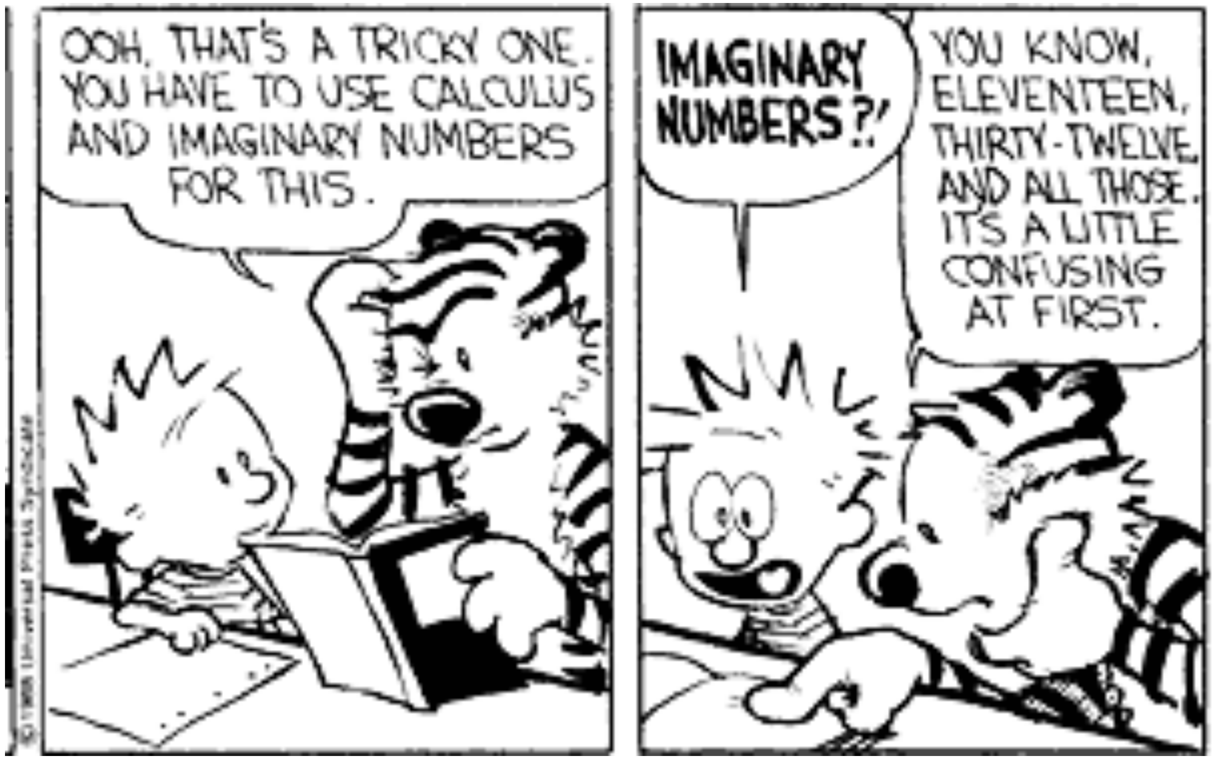


How are you? Hope not…

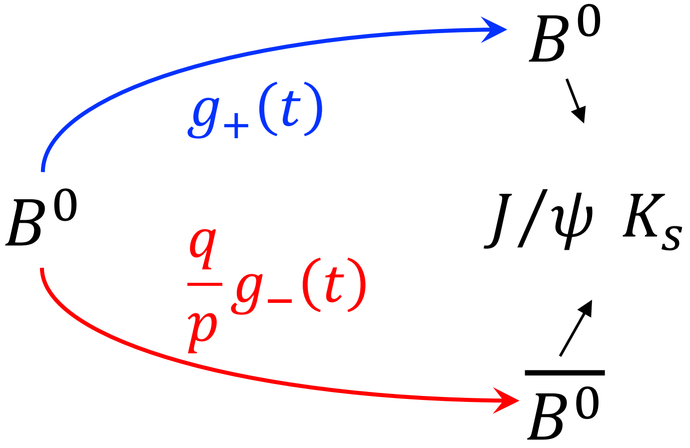


Observing CP Violation

- It's all about imaginary numbers…



B Decays to common final states: CP eigenstates



$B^0 \to J/\psi\, K_s$
+
$B^0 \to \overline{B^0} \to J/\psi\, K_s$

$\overline{B^0} \to J/\psi\, K_s$
+
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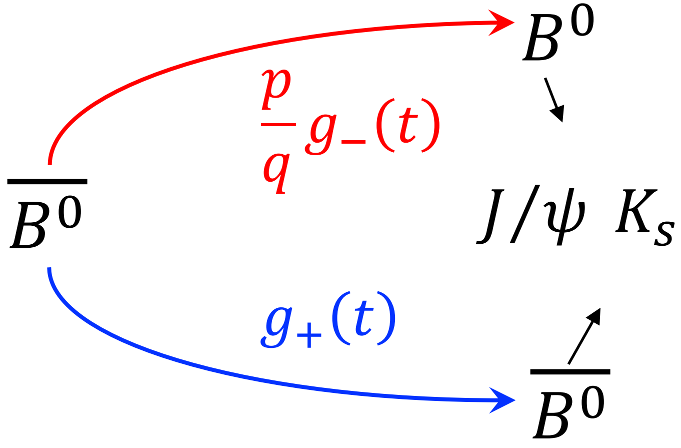
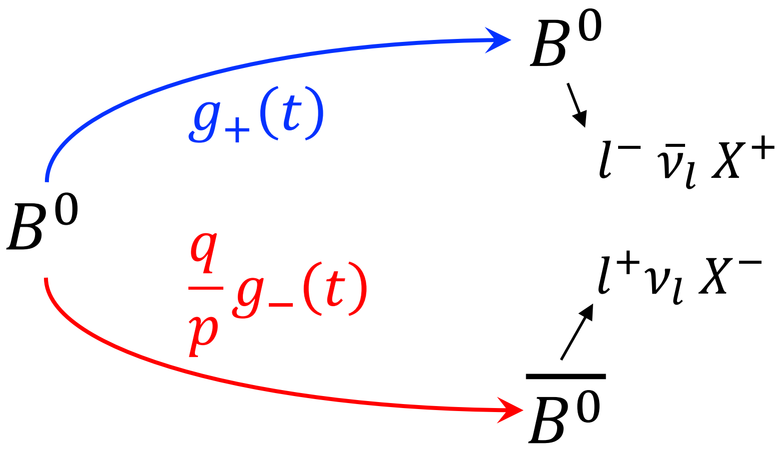
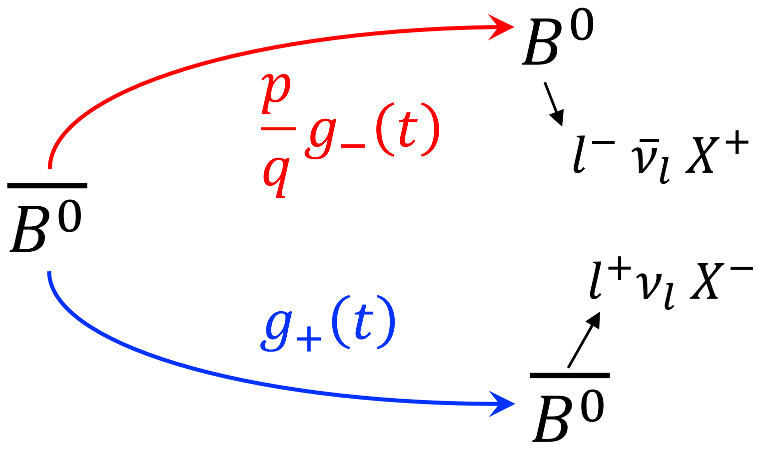


← CP →

Instead of (Flavour oscillations):



Instead of (Flavour oscillations):



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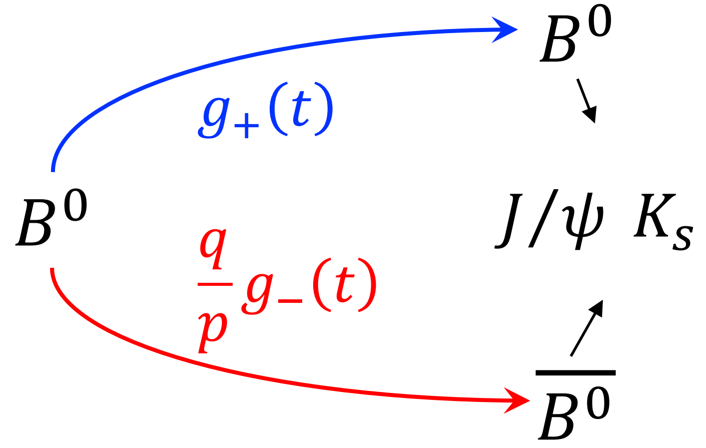
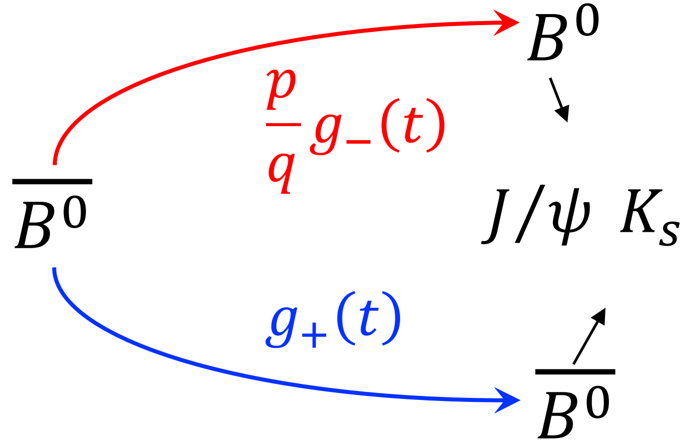


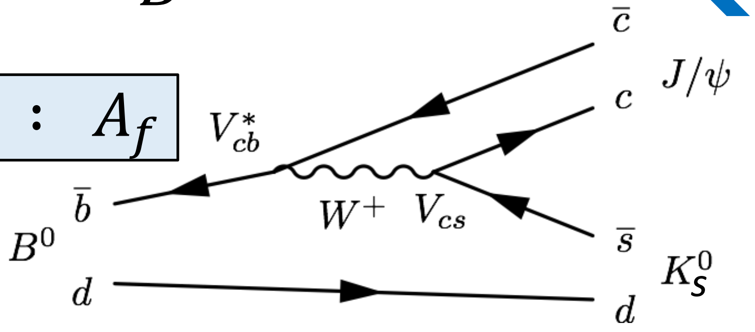
$B^0 \to J/\psi\, K_s$
+
$B^0 \to \overline{B^0} \to J/\psi\, K_s$

$\overline{B^0} \to J/\psi\, K_s$
+
$\overline{B^0} \to B^0 \to J/\psi\, K_s$



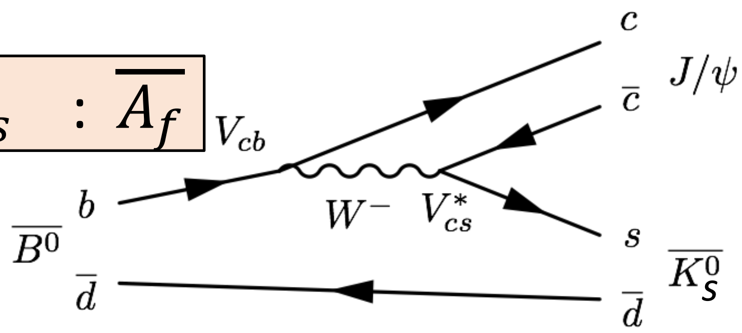
⟵ CP ⟶

$B^0 \to J/\psi\, K_s \quad : \quad A_f$



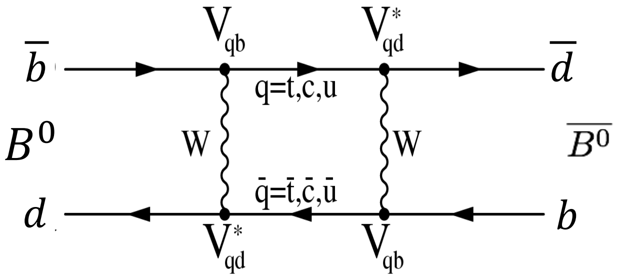
+

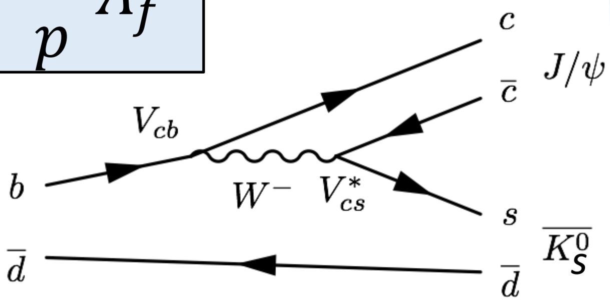
$\overline{B^0} \to J/\psi\, K_s \quad : \quad \overline{A_f}$



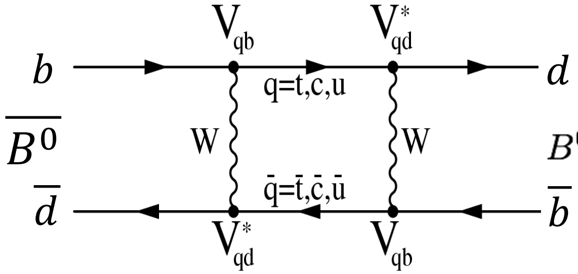
+

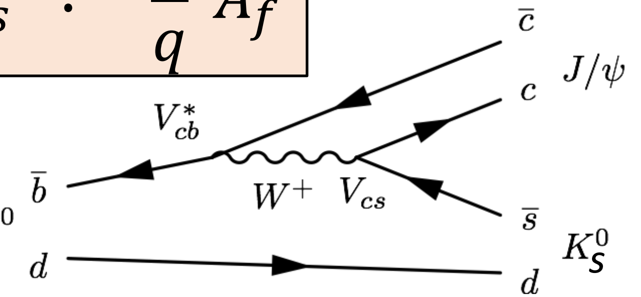
$B^0 \to \overline{B^0} \to J/\psi\, K_s \quad : \quad \frac{q}{p}\overline{A_f}$





$\overline{B^0} \to B^0 \to J/\psi\, K_s \quad : \quad \frac{p}{q} A_f$



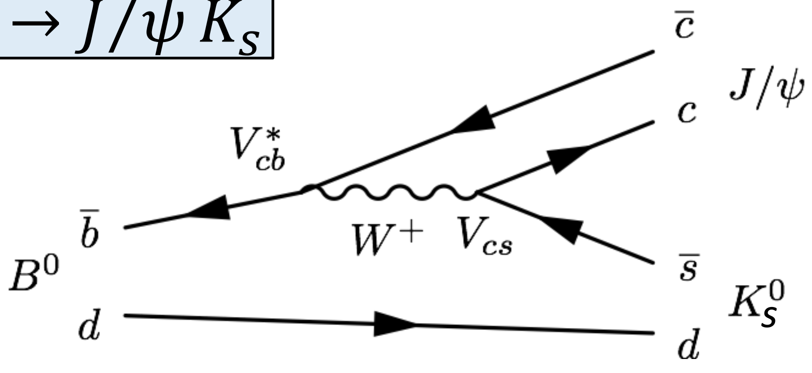


B Decays to common final states: CP eigenstates

$B^0 \to J/\psi\, K_s$

$$A_f \equiv \langle f | B^0 \rangle$$

$$\lambda \equiv \frac{q}{p}\frac{\overline{A_f}}{A_f}$$



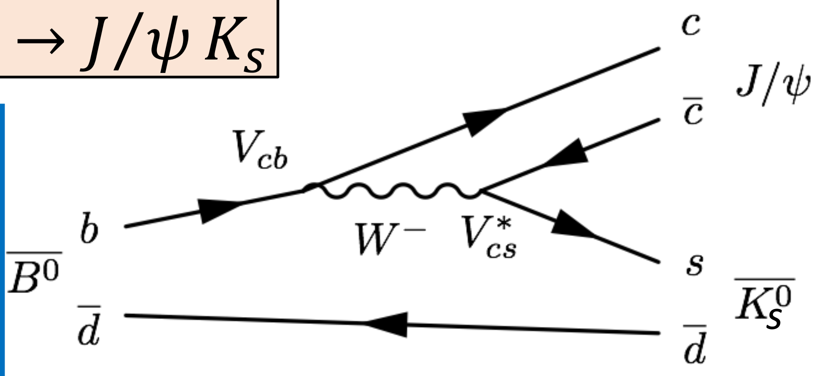
$\bar{\lambda} = 1/\lambda$

$f = \bar{f}$

$\overline{B^0} \to J/\psi\, K_s$

$$\overline{A_f} \equiv \langle f | \overline{B^0} \rangle$$

$$\bar{\lambda} \equiv \frac{p}{q}\frac{A_f}{\overline{A_f}}$$



- Calculate the decay rate of a B-meson into a final state f: $\Gamma_{(B(t)\to f)} = |\langle f | B^0(t) \rangle|^2$
- From solving Schrodinger's equation we already had:

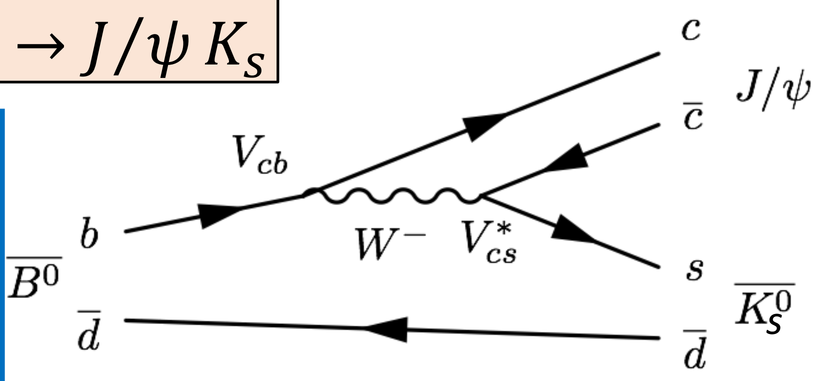
$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p} g_-(t)|\overline{B^0}\rangle$$

$$|\overline{B^0}(t)\rangle = g_+(t)|\overline{B^0}\rangle + \frac{p}{q} g_-(t)|B^0\rangle$$

$$g_\pm(t) = \frac{e^{-i\omega_+ t} \pm e^{-i\omega_- t}}{2}$$

with: $\omega_\pm = m_\pm - \frac{i}{2}\Gamma_\pm$, $m_\pm = M \pm \frac{1}{2}\Delta m$, $\Gamma_\pm = \Gamma \pm \frac{1}{2}\Delta\Gamma$

$\overline{0} \to J/\psi\, K_s$



$A_f \equiv \langle f |$ …

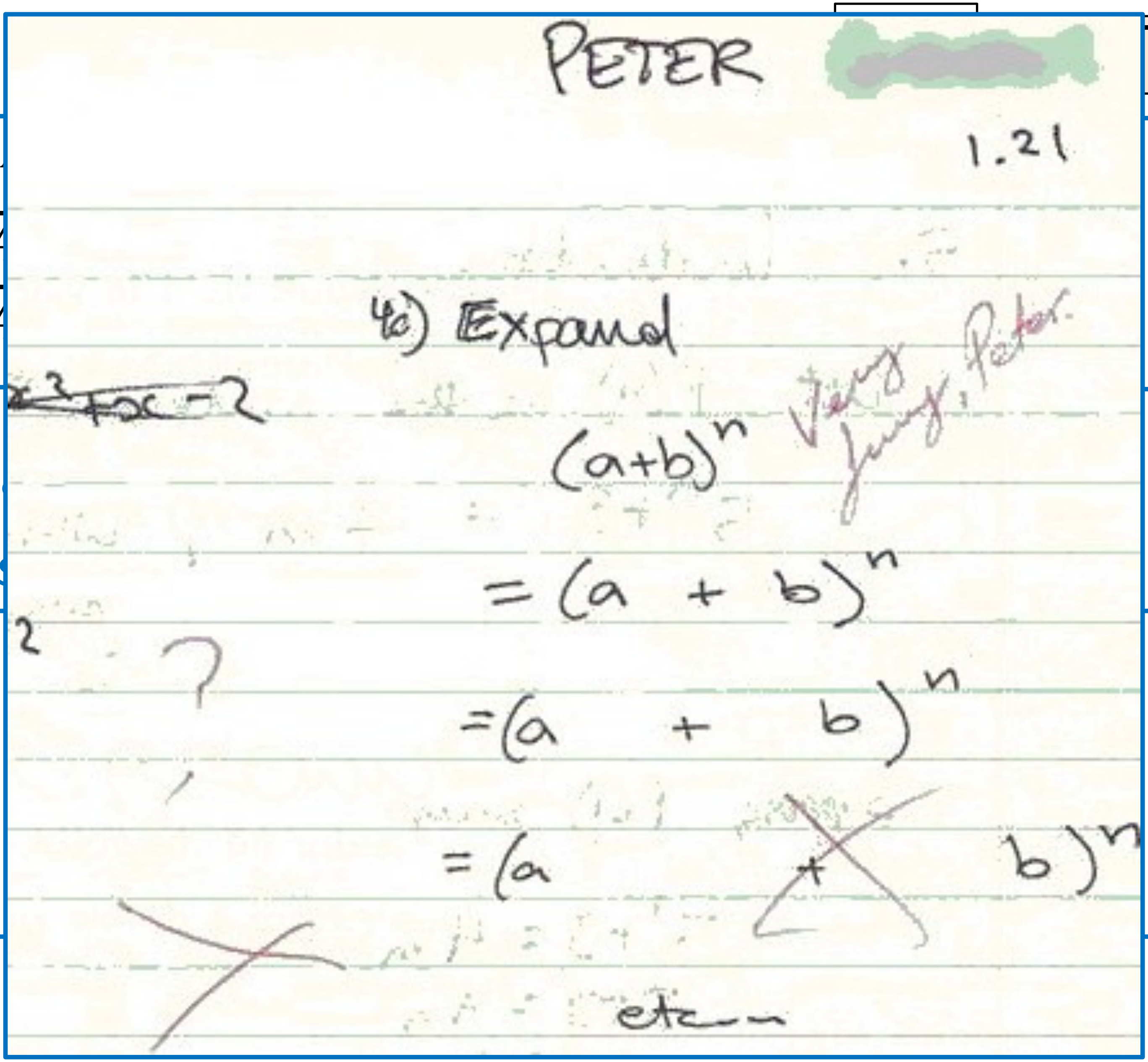
$\lambda \equiv \frac{q}{p} \frac{\overline{A}}{A}$ …

- Calcul… f: $\Gamma_{(B(t)\to f)} = |\langle f | B^0(t) \rangle|^2$
- From …

just expand by taking the square…

$$= \frac{e^{-i\omega_+ t} \pm e^{-i\omega_- t}}{2}$$

Δm , $\Gamma_\pm = \Gamma \pm \frac{1}{2}\Delta\Gamma$



Master formula for neutral B decays

- Just by (tediously) writing it out…

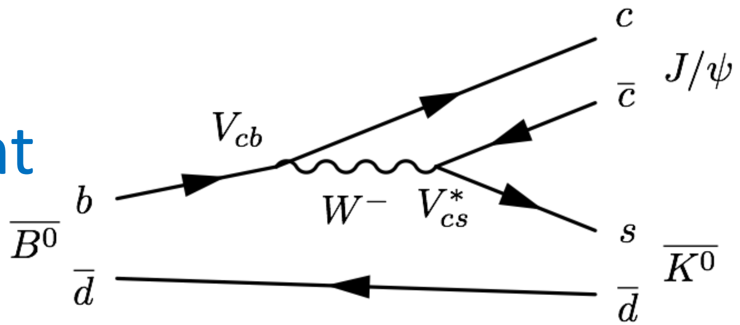
$$\Gamma_{(B\to f)}(t) = |A_f|^2 \left(1+|\lambda_f|^2\right)\frac{e^{-\Gamma t}}{2} \cdot \left(\cosh\frac{\Delta\Gamma t}{2} + D_f \sinh\frac{\Delta\Gamma t}{2} + C_f \cos\Delta m t - S_f \sin\Delta m\, t\right)$$

$$\Gamma_{(\overline{B}\to f)}(t) = |A_f|^2 \left|\frac{q}{p}\right|^2 \left(1+|\lambda_f|^2\right)\frac{e^{-\Gamma t}}{2} \cdot \left(\cosh\frac{\Delta\Gamma t}{2} + D_f \sinh\frac{\Delta\Gamma t}{2} - C_f \cos\Delta m t + S_f \sin\Delta m\, t\right)$$

with: $D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2}$, $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}$

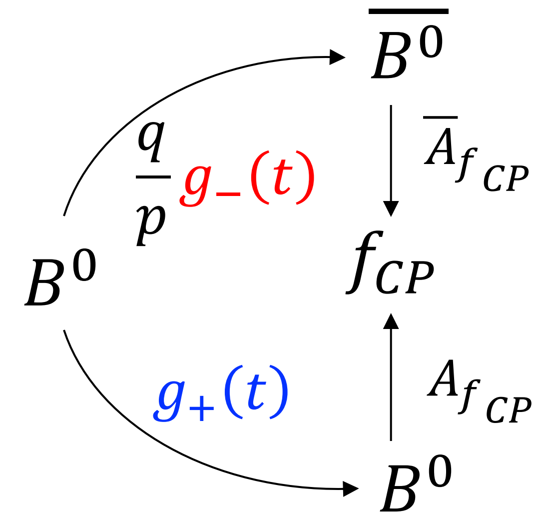
- Coefficients D_f, C_f and S_f are measured by experiment

➔ Measurement of CKM parameters via: $\lambda_f \equiv \frac{p}{q}\frac{\overline{A}_f}{A_f}$



How does it give CP violation?

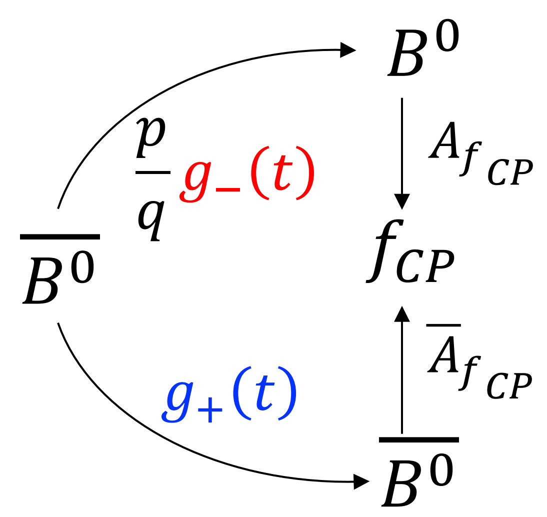
$t = 0$ | t | Amplitude



$$A_{f_{CP}}\left(g_+(t) + \lambda g_-(t)\right)$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

CP



$$\overline{A}_{f_{CP}}\left(g_+(t) + \frac{1}{\lambda} g_-(t)\right)$$

$$\overline{\lambda}_{f_{CP}} = \frac{p}{q}\frac{A_{f_{CP}}}{\overline{A}_{f_{CP}}} = \frac{1}{\lambda_{f_{CP}}}$$

$$g_\pm(t) = \frac{e^{-i\omega_1} \pm e^{-i\omega_2 t}}{2}$$

$$g_+(t) = e^{-imt}\, e^{-\Gamma t/2} \cos\frac{\Delta m t}{2}$$

$$g_-(t) = e^{-imt}\, e^{-\Gamma t/2}\, \boldsymbol{i} \sin\frac{\Delta m t}{2}$$

For neutral B mesons, g_- has a 90º (=i) phase difference wrt. g_+

Interfering Amplitudes

$t = 0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\left(g_+(t) + \lambda g_-(t)\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\bar{A}_{f_{CP}}\left(g_+(t) + \frac{1}{\lambda} g_-(t)\right)$

$$g_+ = e^{-imt}\, e^{-\Gamma t/2} \cos\frac{\Delta mt}{2}$$

$$g_- = e^{-imt}\, e^{-\Gamma t/2}\, \boldsymbol{i} \sin\frac{\Delta mt}{2}$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}} \qquad \text{(CKM)}$$

Interfering Amplitudes

$t = 0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\left(a_+ + a_-\, e^{-i\phi_w}\, e^{i\pi/2}\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\bar{A}_{f_{CP}}\left(a_+ + a_-\, e^{+i\phi_w}\, e^{i\pi/2}\right)$

$$g_+ = e^{-imt}\, e^{-\Gamma t/2} \cos\frac{\Delta mt}{2}$$

$$g_- = e^{-imt}\, e^{-\Gamma t/2}\, \boldsymbol{i} \sin\frac{\Delta mt}{2}$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}} \quad \text{(CKM)}$$

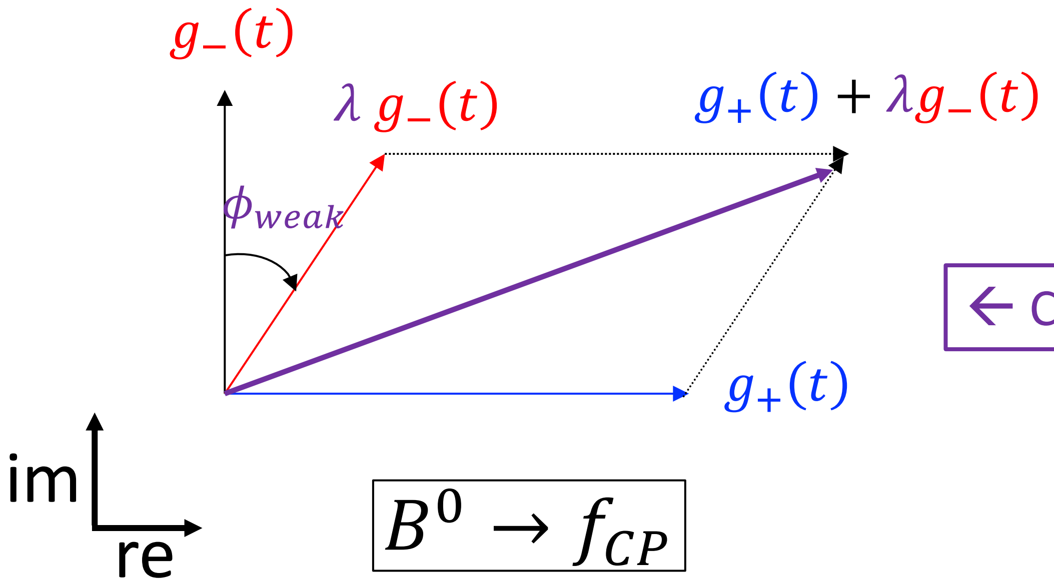
Interfering Amplitudes: CP violation!

$t=0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\left(g_+(t)+\lambda g_-(t)\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\overline{A}_{f_{CP}}\left(g_+(t)+\frac{1}{\lambda}g_-(t)\right)$

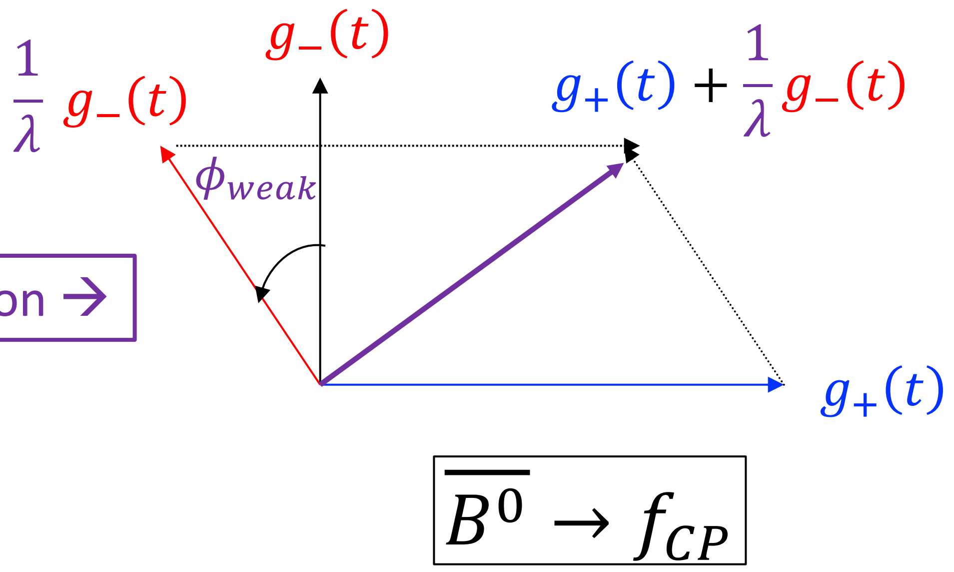
$$g_+ = e^{-imt}\, e^{-\Gamma t/2} \cos\frac{\Delta mt}{2}$$

$$g_- = e^{-imt}\, e^{-\Gamma t/2}\, i \sin\frac{\Delta mt}{2}$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}} \quad \text{(CKM)}$$

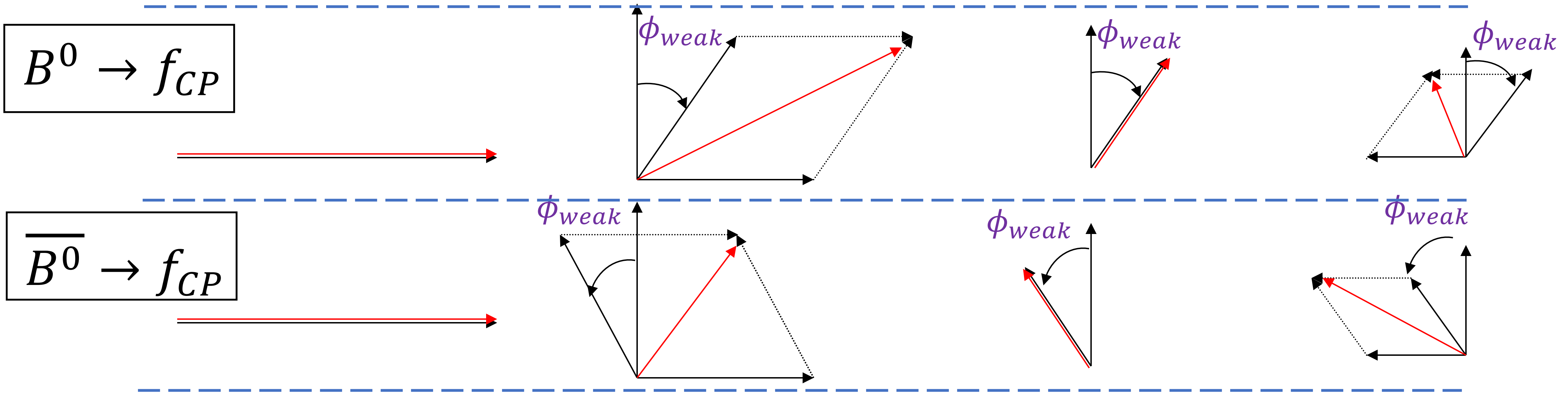


← CP-Violation →



Interfering Amplitudes: time dependent CP violation!

$t=0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\, e^{-iMt} e^{-i\Gamma t/2} \left(\cos\frac{\Delta m t}{2} + i\,\lambda\,\sin\frac{\Delta m t}{2}\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\bar{A}_{f_{CP}}\, e^{-iMt} e^{-i\Gamma t/2} \left(\cos\frac{\Delta m t}{2} + i\,\frac{1}{\lambda}\,\sin\frac{\Delta m t}{2}\right)$



$\Delta m t/2 = 0$ | $\Delta m t/2 = \pi/4$ | $\Delta m t/2 = \pi/2$ | $\Delta m t/2 = 3\pi/4$

No CPV | ***CPV!***

➔ Decay-Time Dependent CP Asymmetry!

From Amplitude to Decay rate

$t=0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\, e^{-iMt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta m t}{2} + i\,\lambda\,\sin\frac{\Delta m t}{2}\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\bar{A}_{f_{CP}}\, e^{-iMt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta m t}{2} + i\,\frac{1}{\lambda}\,\sin\frac{\Delta m t}{2}\right)$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

- Decay rate is the ***square*** of the amplitude (work it out):

$$B^0 \rightarrow f_{CP} \;:\quad \left|\cos\frac{\Delta m t}{2} + i\,\lambda\,\sin\frac{\Delta m t}{2}\right|^2 \propto 1 + \frac{(1-|\lambda|^2)}{(1+|\lambda|^2)}\cos\Delta m t - \frac{(2\Im\lambda)}{(1+|\lambda|^2)}\sin\Delta m t$$

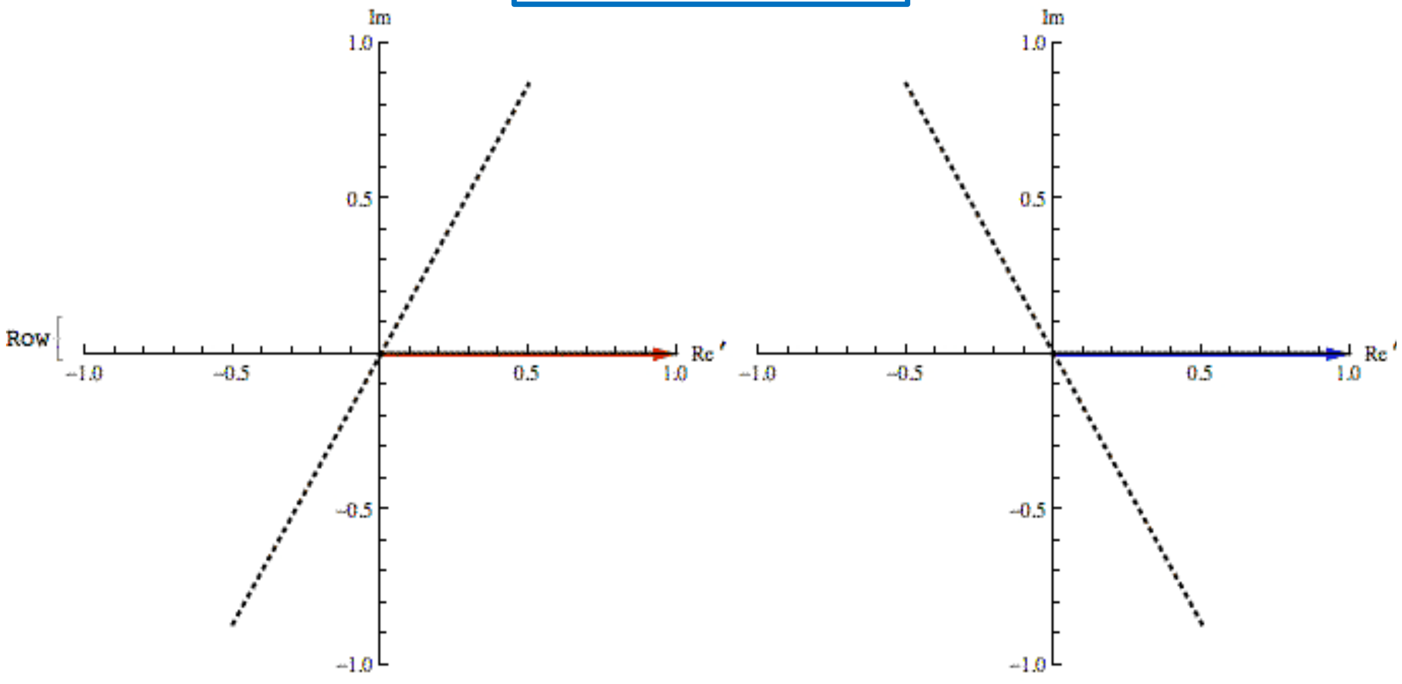
$$\overline{B^0} \rightarrow f_{CP} \;:\quad \left|\cos\frac{\Delta m t}{2} + i\,\frac{1}{\lambda}\sin\frac{\Delta m t}{2}\right|^2 \propto 1 - \frac{(1-|\lambda|^2)}{(1+|\lambda|^2)}\cos\Delta m t + \frac{(2\Im\lambda)}{(1+|\lambda|^2)}\sin\Delta m t$$

Time Dependent CP violation

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$t = 0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\, e^{-iMt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + i\, e^{-i\phi_{weak}}\, \sin\frac{\Delta mt}{2}\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\overline{A}_{f_{CP}}\, e^{-iMt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + i\, e^{+i\phi_{weak}}\, \sin\frac{\Delta mt}{2}\right)$

Decay Amplitudes

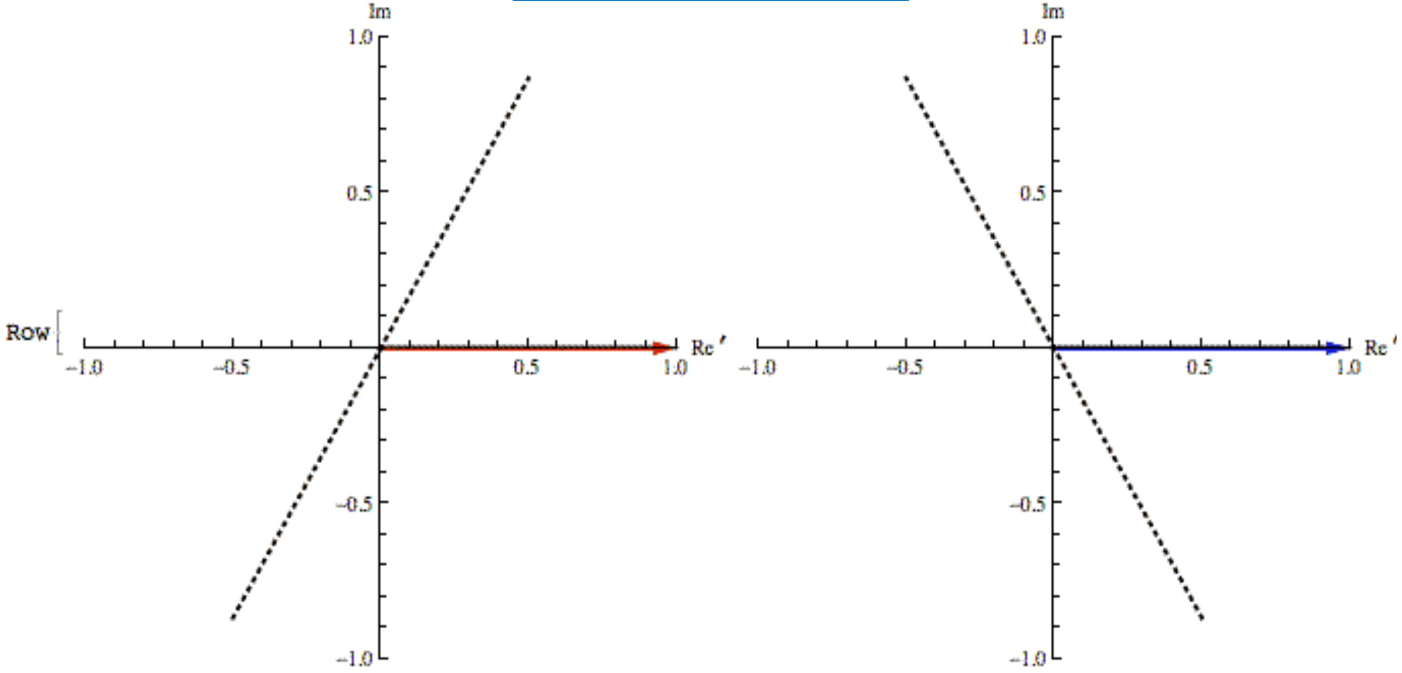


Time Dependent CP violation

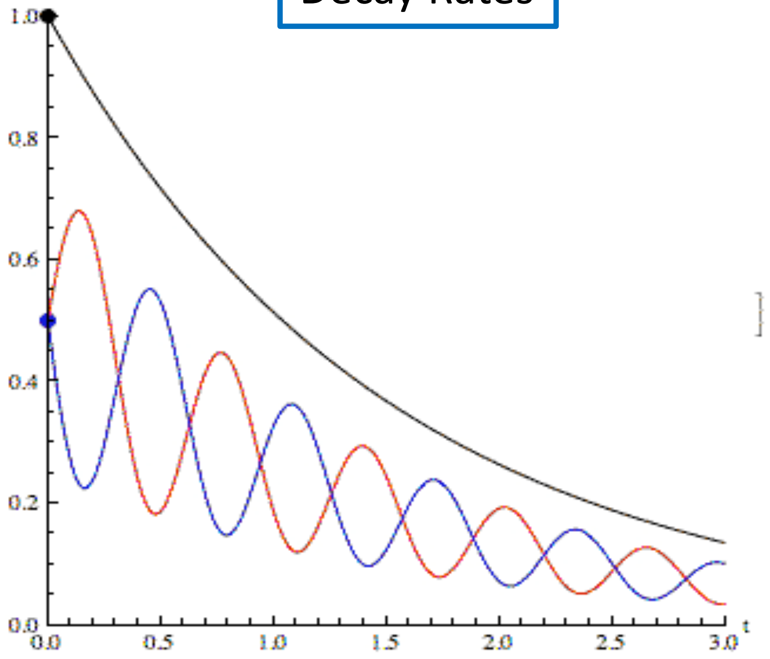
$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$t=0$		t	Decay Rate
B^0	$\rightarrow$	f_{CP}	$\propto\ e^{-\Gamma t}\,[1 + \sin\phi_{weak} \sin\Delta m t]$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\propto\ e^{-\Gamma t}\,[1 - \sin\phi_{weak} \sin\Delta m t]$

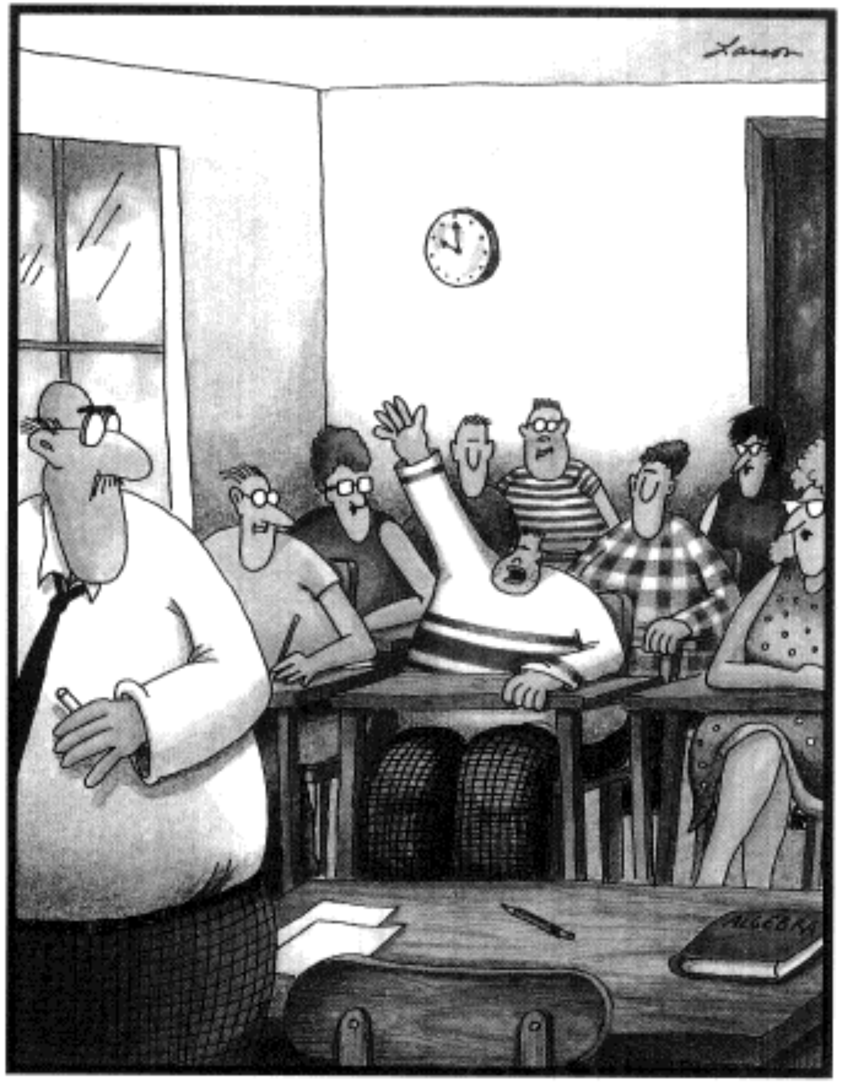
Decay Amplitudes



Decay Rates



Where were we?



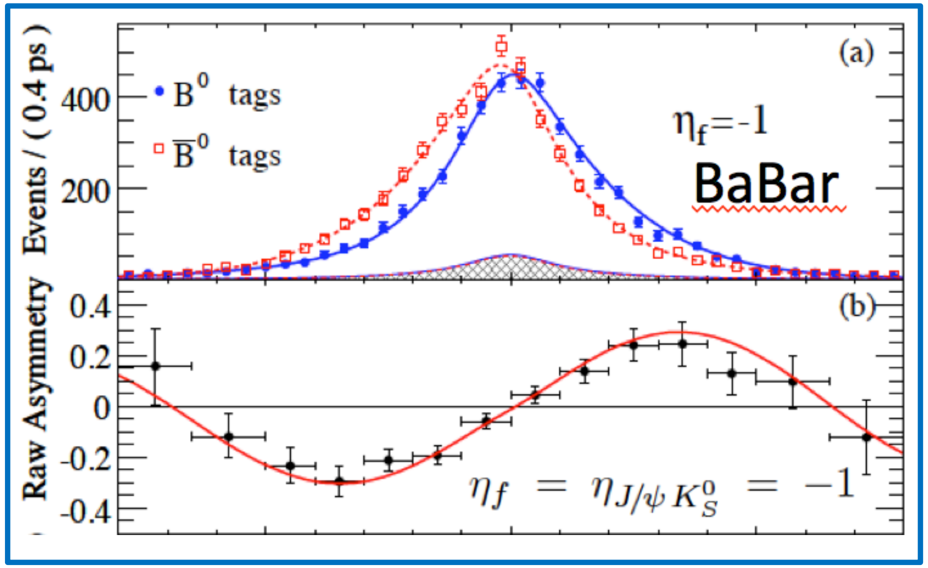
"Mr. Osborne, may I be excused?
My brain is full."

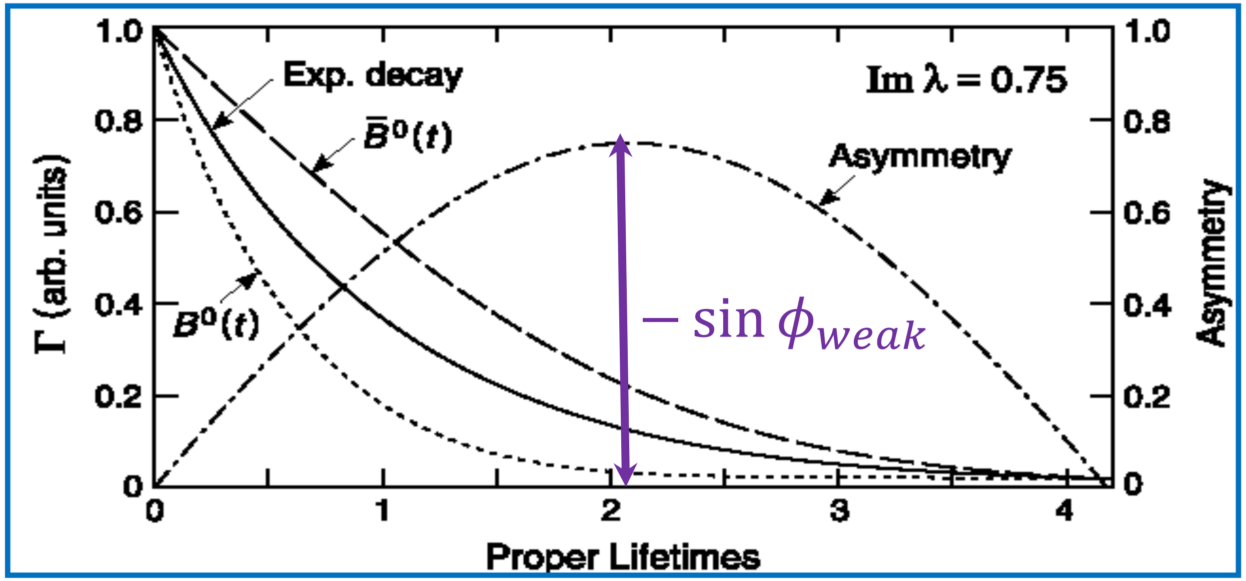
Time Dependent CP Asymmetry

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$t=0$		t	Decay Rate
B^0	$\rightarrow$	f_{CP}	$\propto e^{-\Gamma t}\ [1 + \sin\phi_{weak}\sin\Delta m t]$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\propto e^{-\Gamma t}\ [1 - \sin\phi_{weak}\sin\Delta m t]$

$$\mathcal{A}_{CP} = \frac{\Gamma\left(\overline{B^0}\rightarrow f_{CP}\right) - \Gamma(B^0\rightarrow f_{CP})}{\Gamma\left(\overline{B^0}\rightarrow f_{CP}\right) + \Gamma(B^0\rightarrow f_{CP})} = -\sin\phi_{weak}\ \sin\Delta m t$$



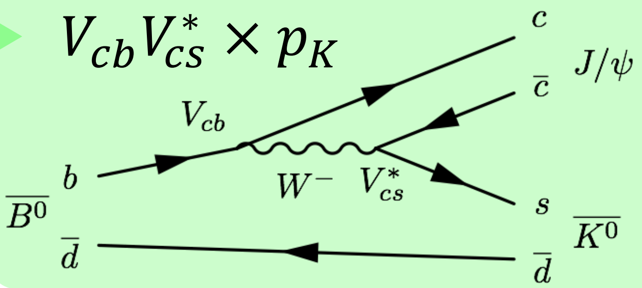


$\lambda_{J/\psi K_S}$ for "Golden" mode: $B^0 \to J/\psi K_S$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

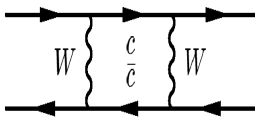
$$\lambda_{J/\psi K_S} \equiv -\frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$V_{cb}V_{cs}^* \times p_K$



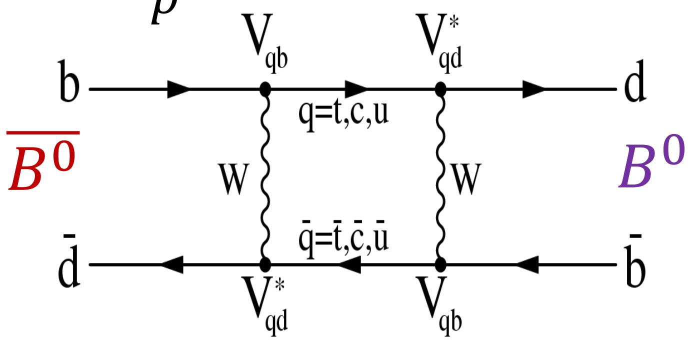
$\times \langle K_s|\overline{K^0}\rangle$

p_{K_S}



$$\lambda_{J/\psi K_S} = -\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\frac{p_{K_S}}{q_{K_S}}$$

$\frac{q}{p}$

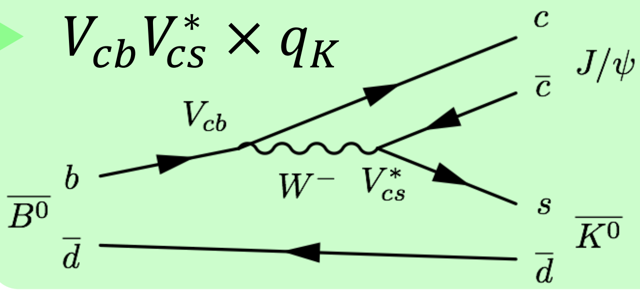


$\lambda_{J/\psi K_S}$ for "Golden" mode: $B^0 \to J/\psi K_S$

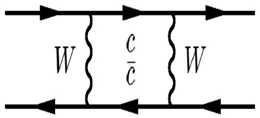
$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$$\lambda_{J/\psi K_S} \equiv -\frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$$V_{cb}V_{cs}^* \times q_K$$



$$\times \langle K_s|\overline{K^0}\rangle$$



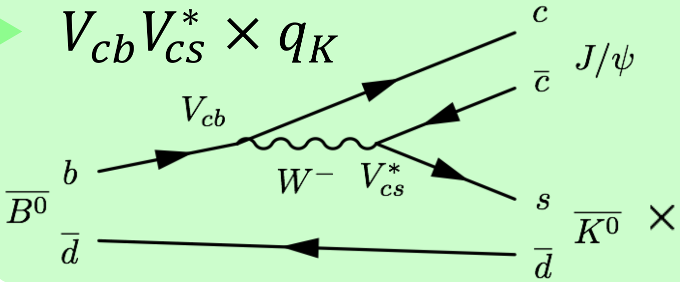
$$\lambda_{J/\psi K_S} = -\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}$$

$\lambda_{J/\psi K_S}$ for "Golden" mode: $B^0 \to J/\psi K_S$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$$\lambda_{J/\psi K_S} \equiv -\frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$V_{cb}V_{cs}^* \times q_K$

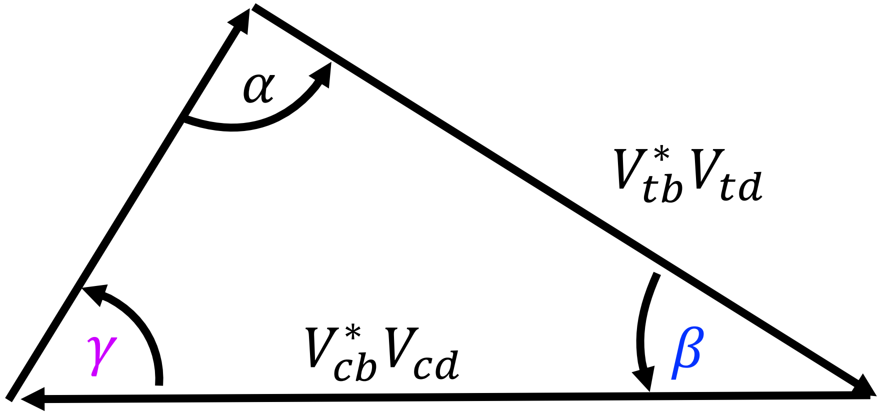


$\overline{K^0} \times \langle K_s | \overline{K^0} \rangle$

$$\phi_{weak} = 2\beta$$

$$\lambda_{J/\psi K_S} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb}}{V_{cb}^*}\frac{V_{cd}^*}{V_{cd}} = -e^{-2i\beta}$$

$$\mathrm{V_{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



- Similarly with this method of time dependent CP violation:

$B^0 \to J/\psi K_S \to 2\beta$; $B^0 \to \pi^+\pi^- \to 2\beta + 2\gamma$

$B_s \to J/\psi\,\phi \to 2\beta_s$; $B_s^0 \to K^+K^- \to 2\beta_s + 2\gamma$; $B_s^0 \to D_s^{\mp}K^{\pm} \to 2\beta + \gamma$

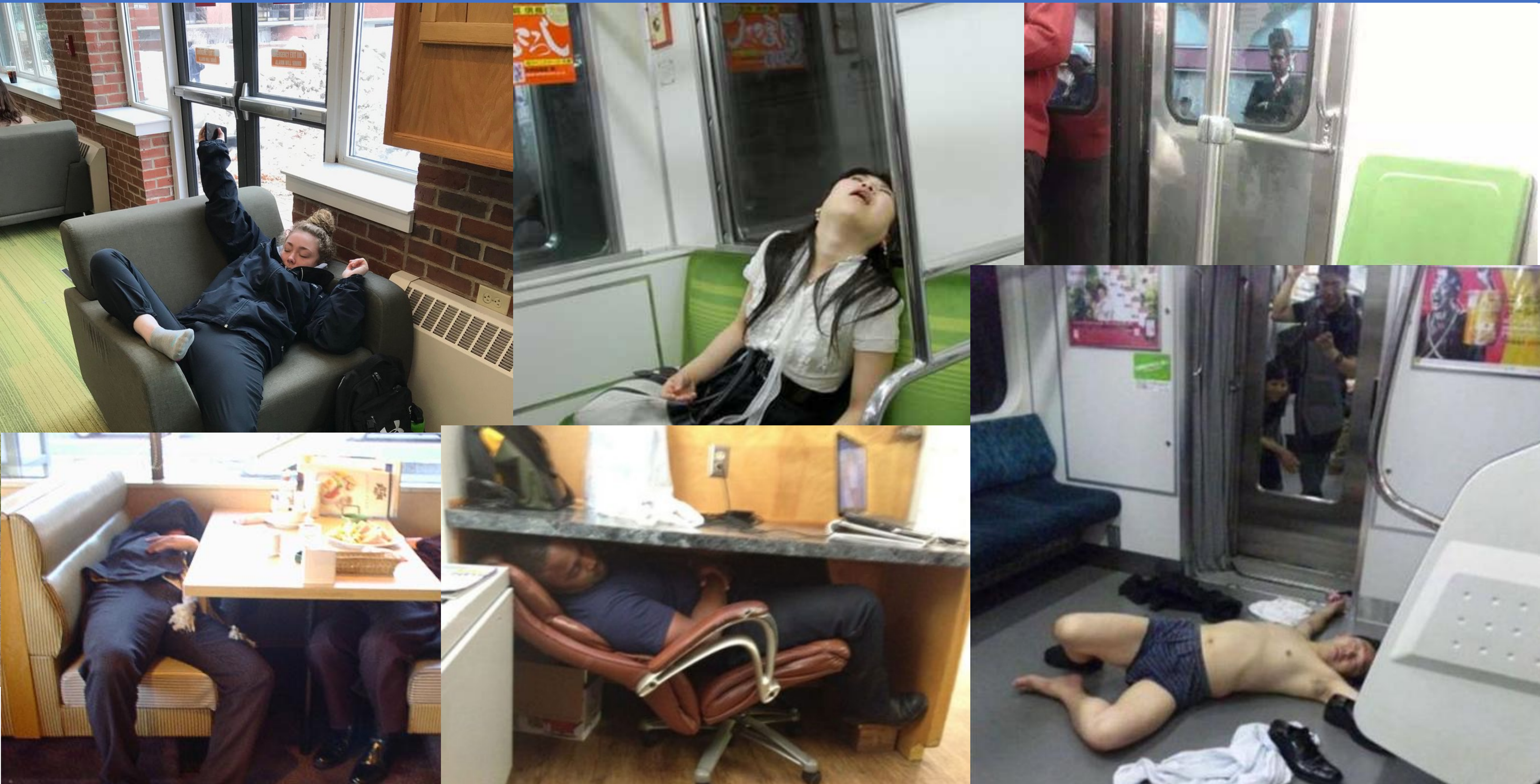
➔ B_s physics is mainly done at the LHC …

How are you doing?

How are you doing?

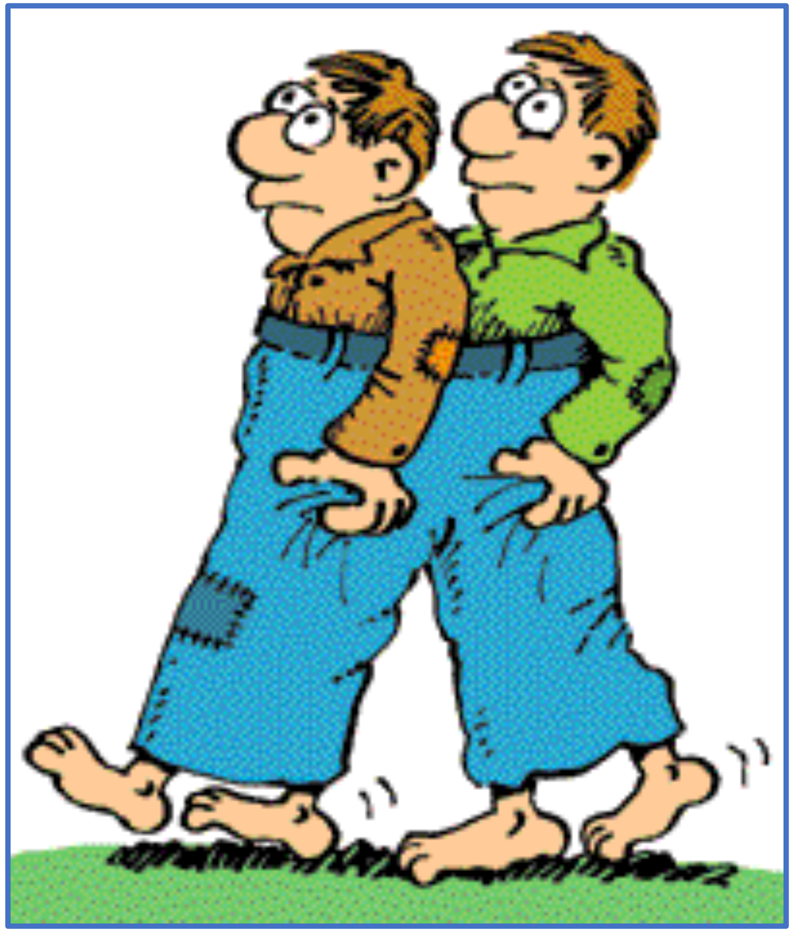


How are you doing?

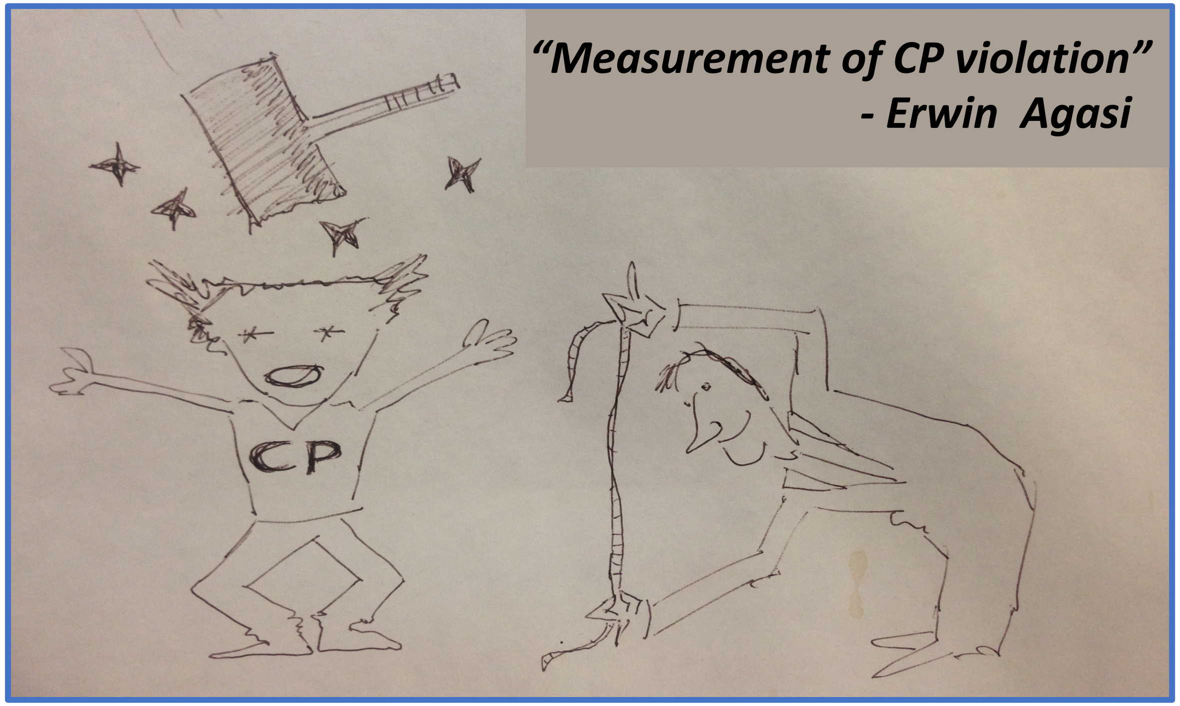


Contents Yesterday & Today:

1. CP Violation
   a) Discrete Symmetries
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
2. B-Mixing
   a) CP violation and Interference
   b) B-mixing and time dependent CP violation
   c) Experimental Aspects: LHC vs B-factory

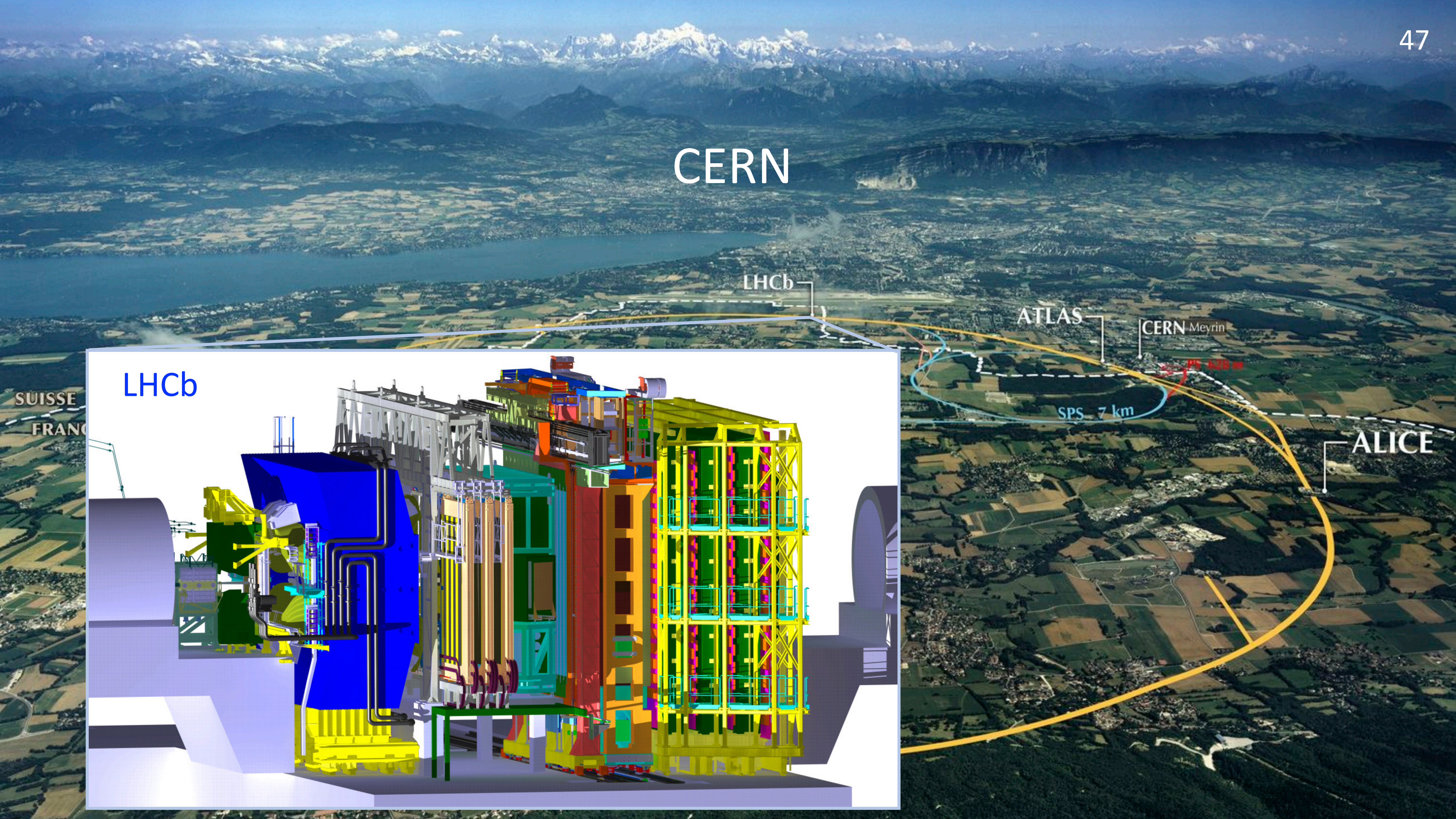


Contents Yesterday & Today:

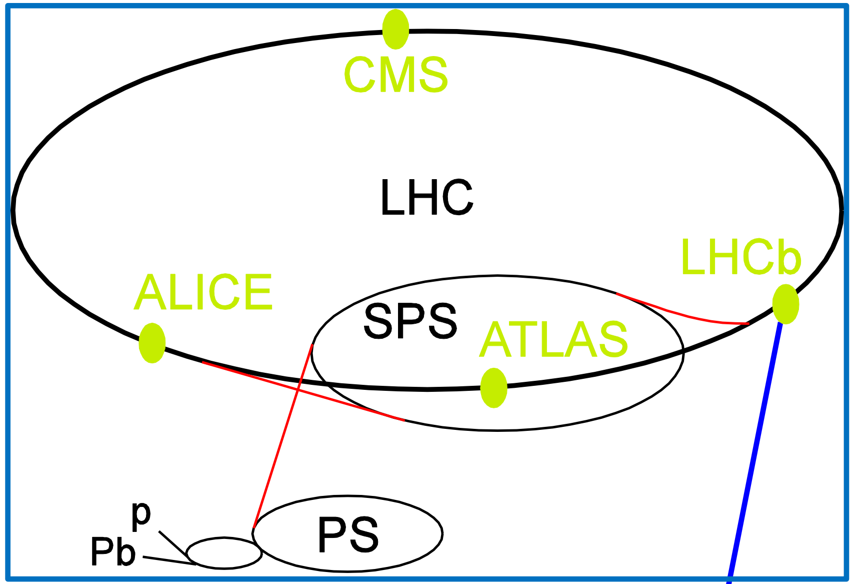


"Measurement of CP violation"
- Erwin Agasi

CERN



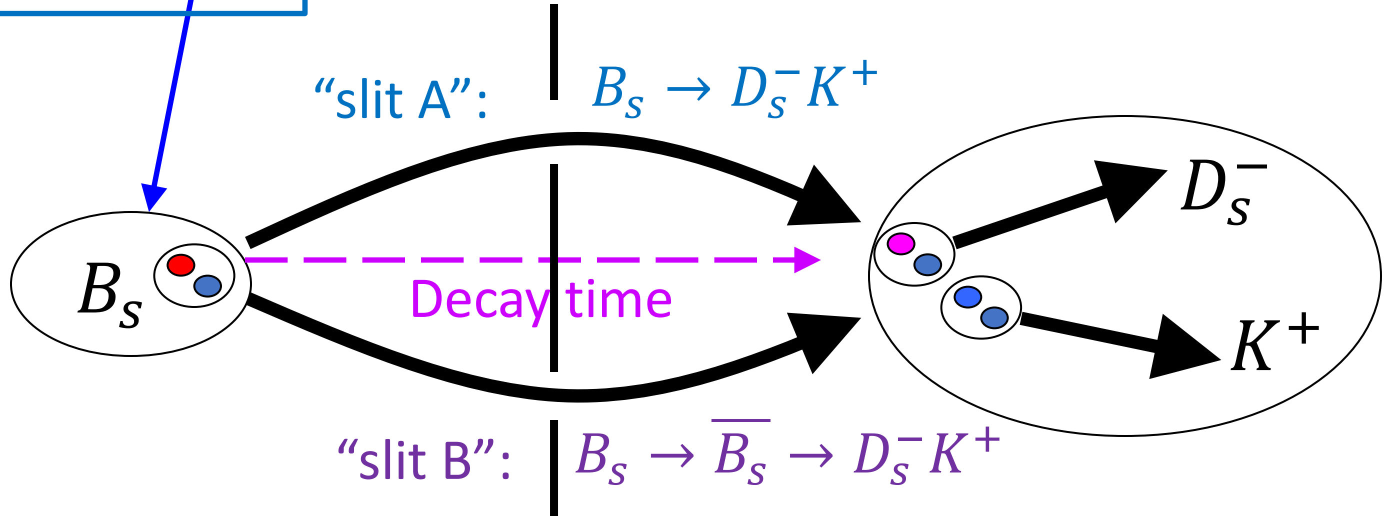
$B_s \to D_s K$: Quantum Interference Experiment @ LHCb



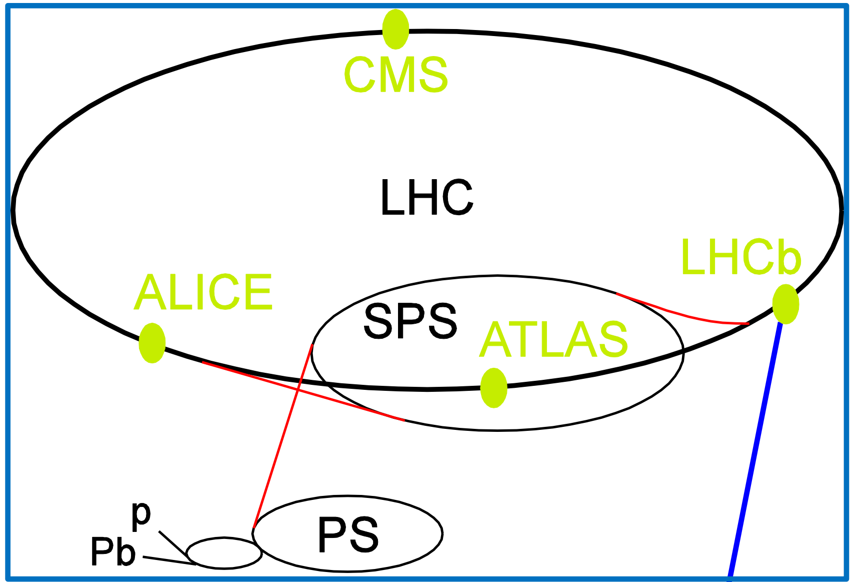
Measure:

$$B_s \to \left(\overline{B_s} \to\right) D_s^- K^+$$

$$\overline{B_s} \to (B_s \to) D_s^- K^+$$



$B_s \to D_s K$: Quantum Interference Experiment @ LHCb

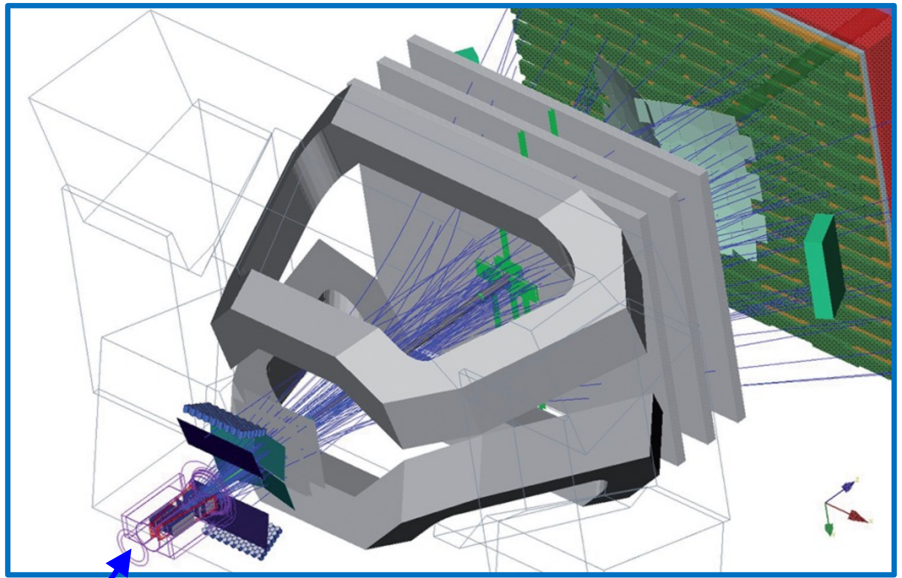


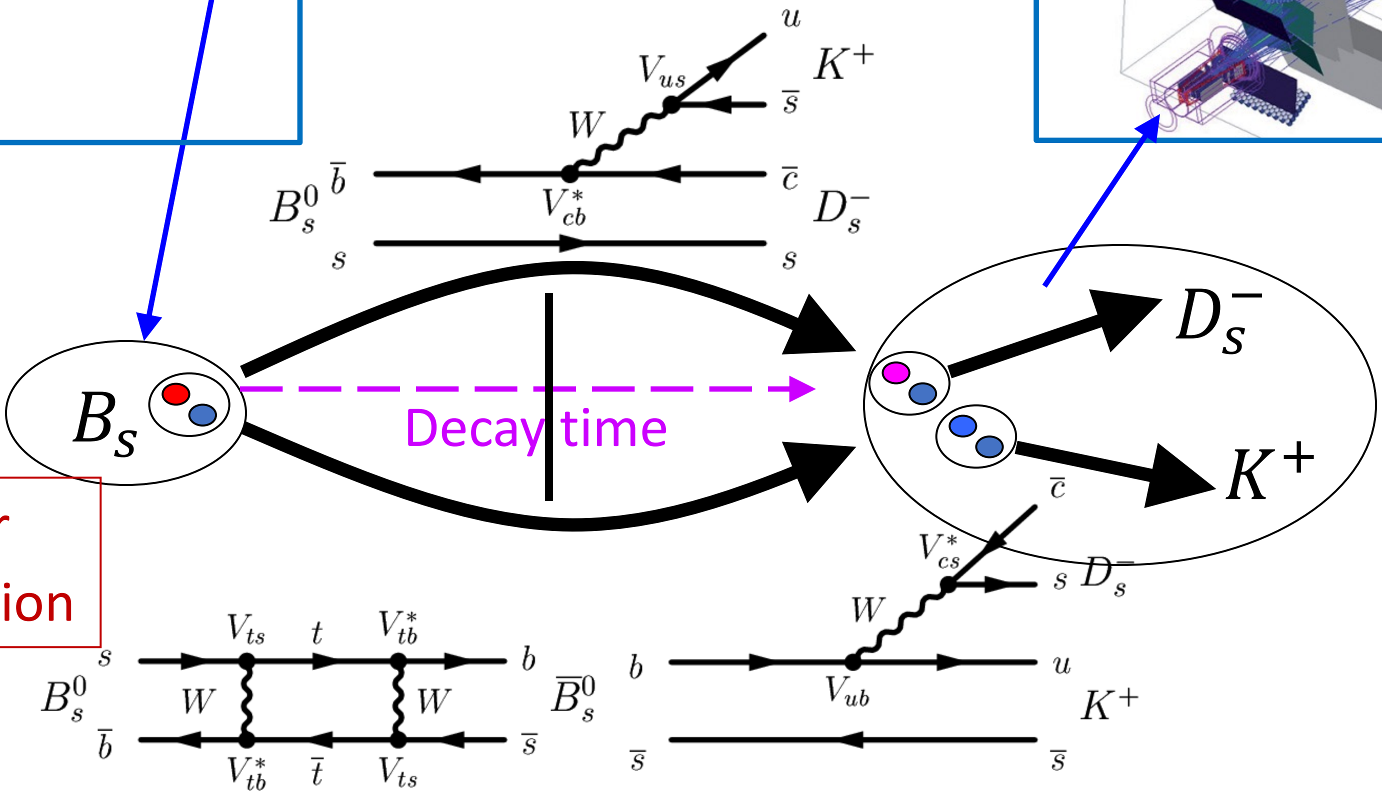
Measure:

$B_s \to (\overline{B_s} \to)\ D_s^- K^+$

$\overline{B_s} \to (B_s \to)\ D_s^- K^+$

Repeat for $D_s^+ K^-$

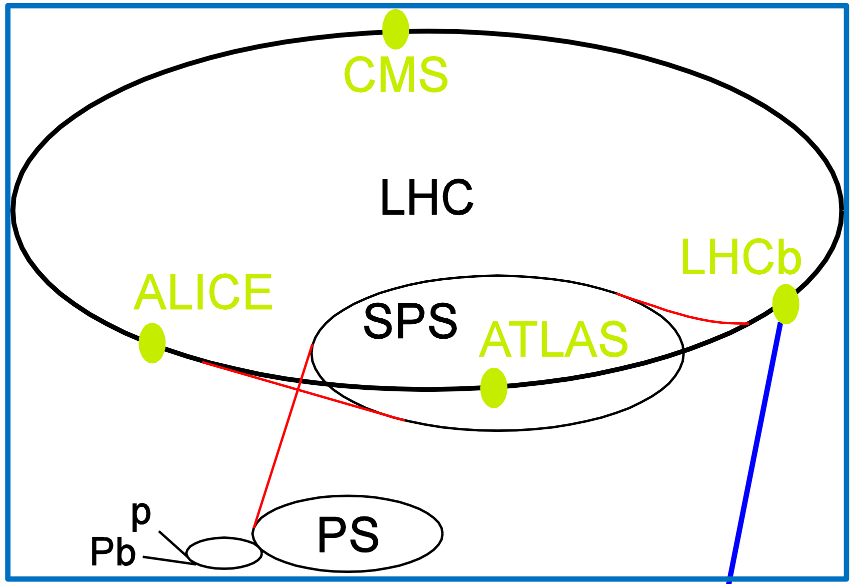




2) Measure decay rate as function of decay-time

1) Determine whether B_s or $\overline{B_s}$ at production

$B_s \to D_s K$: Quantum Interference Experiment @ LHCb

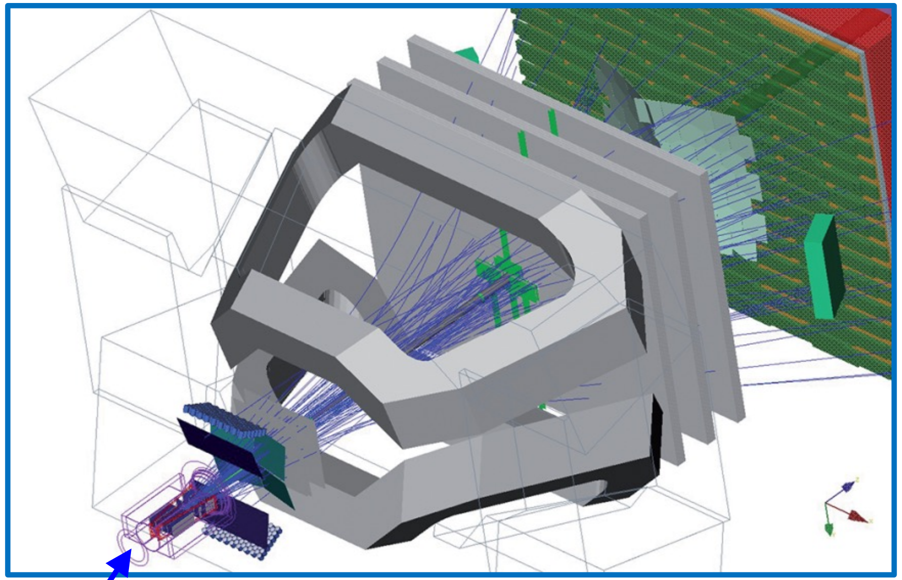


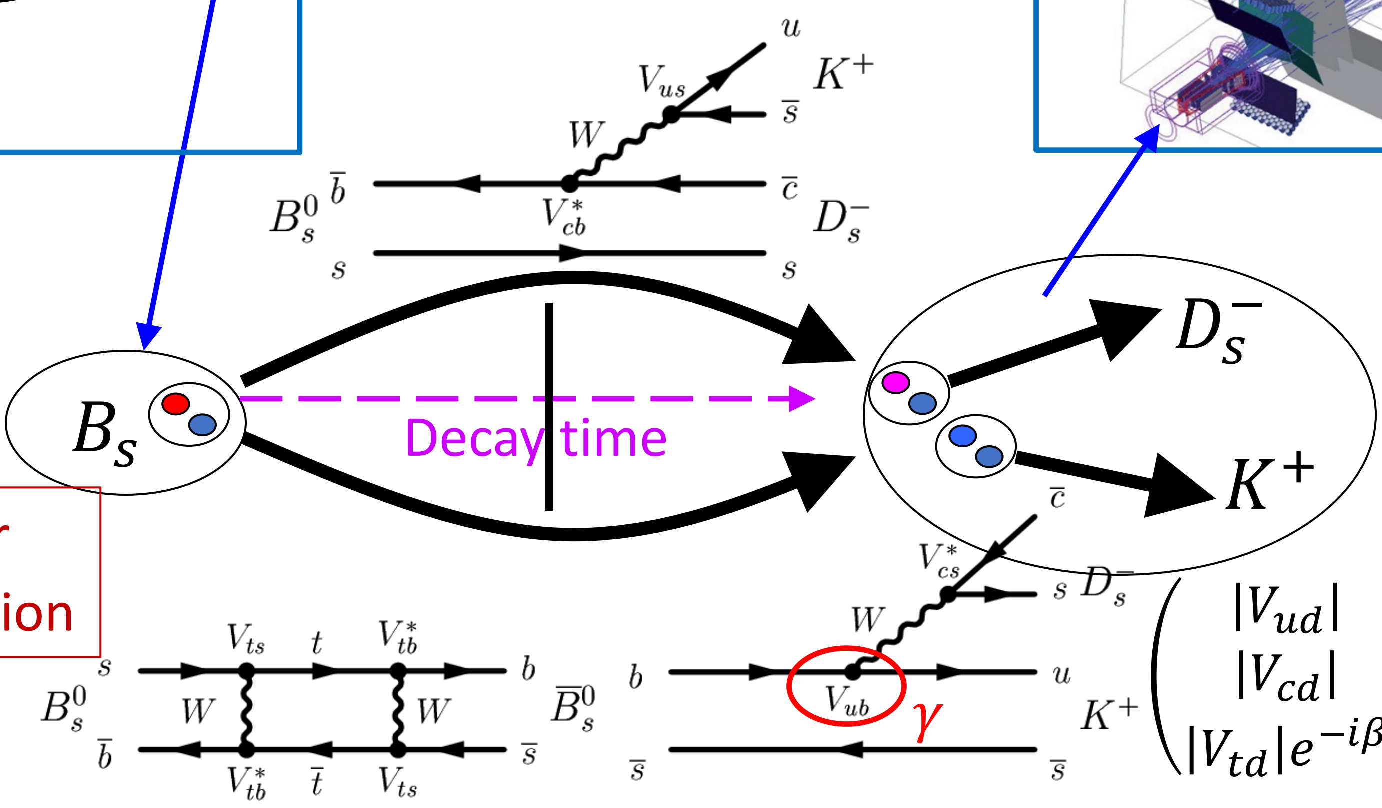
Measure:

$B_s \to (\overline{B_s} \to)\ D_s^- K^+$

$\overline{B_s} \to (B_s \to)\ D_s^- K^+$

Repeat for $D_s^+ K^-$



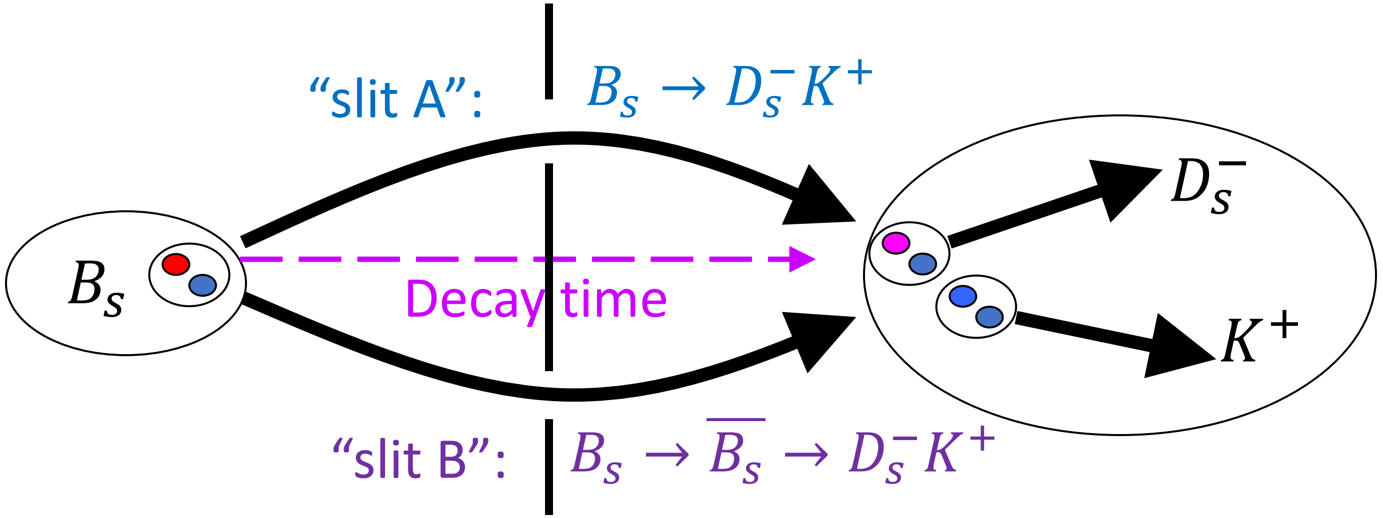


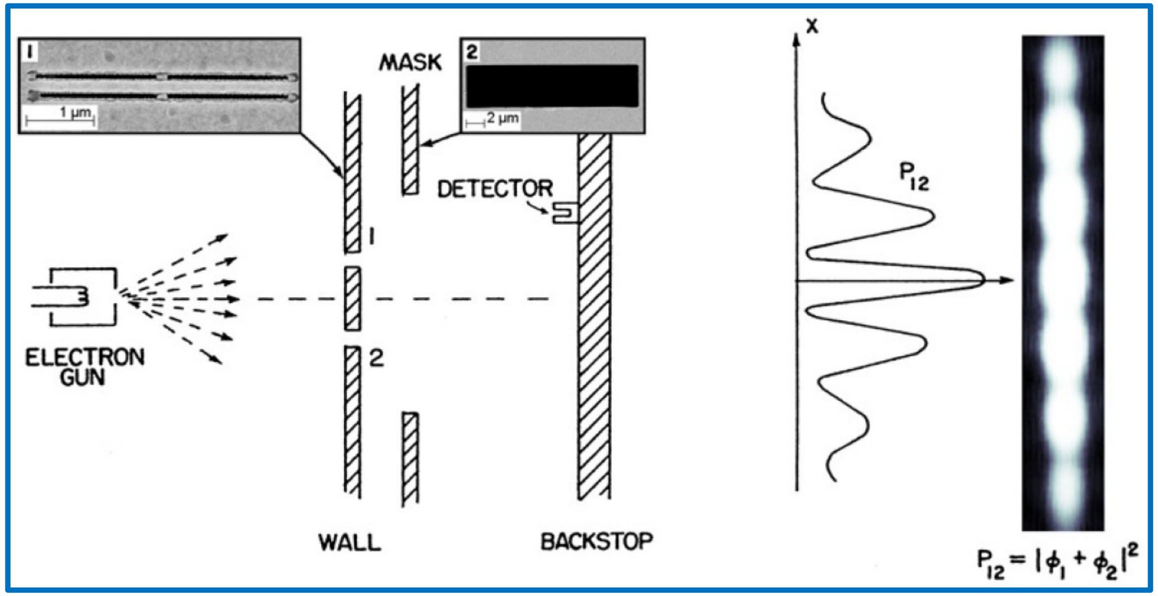
2) Measure decay rate as function of decay-time

1) Determine whether B_s or $\overline{B_s}$ at production

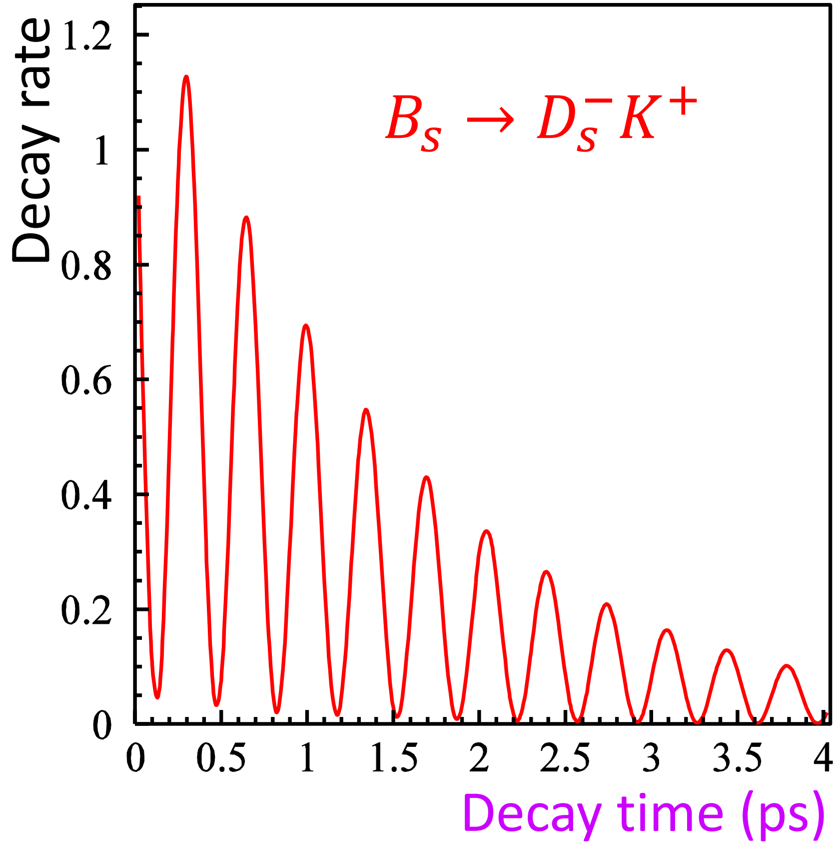
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

$B_s \to D_s K$: Quantum Interference Experiment @ LHCb

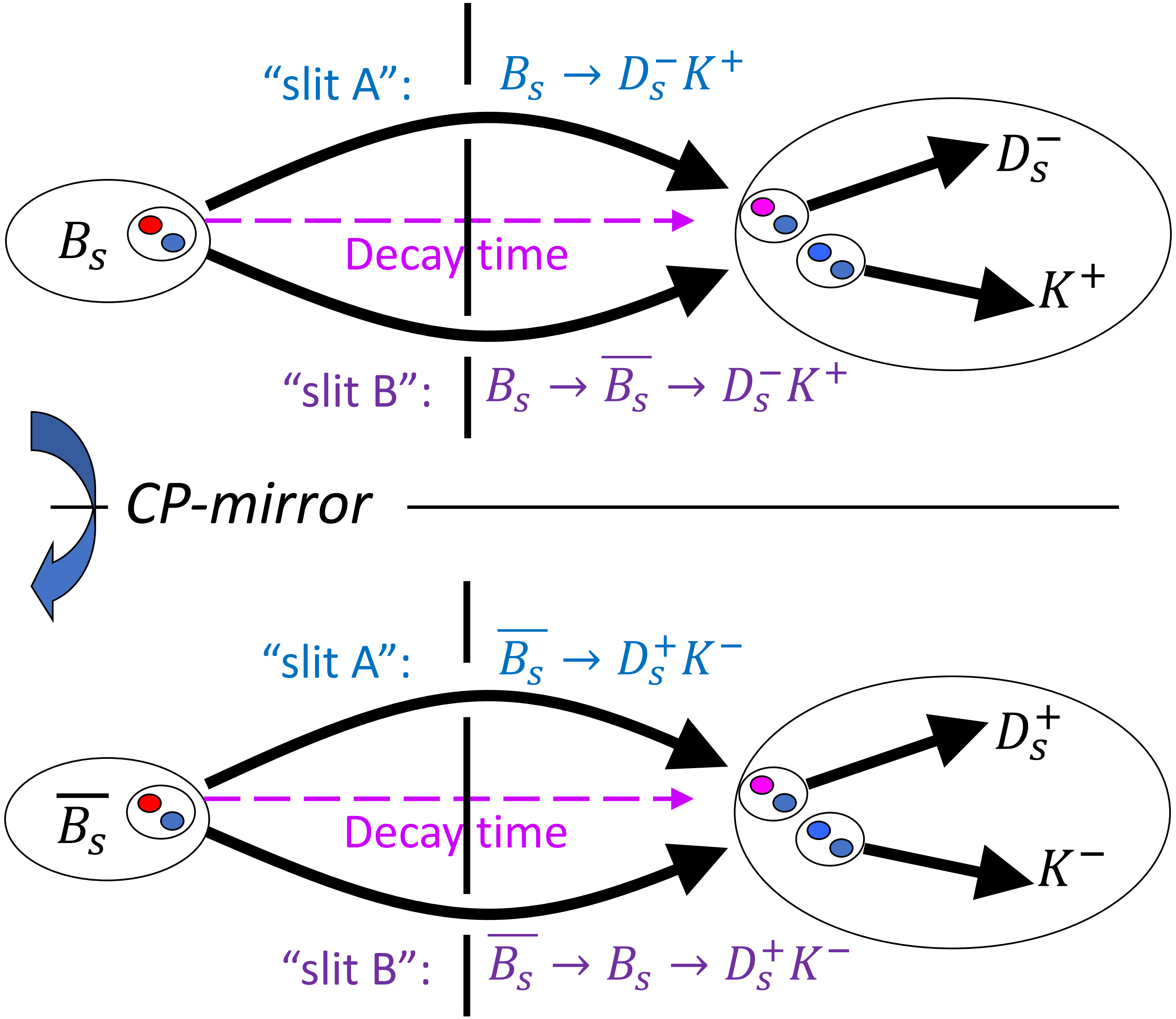




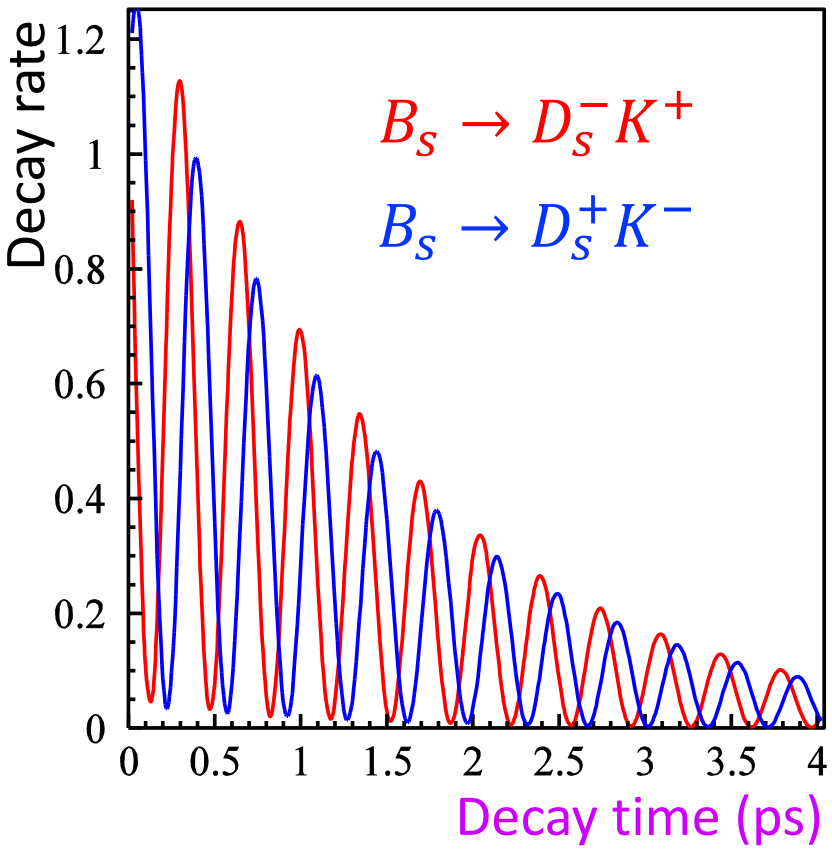
An interference pattern:



$B_s \rightarrow D_s K$: Quantum Interference Experiment @ LHCb

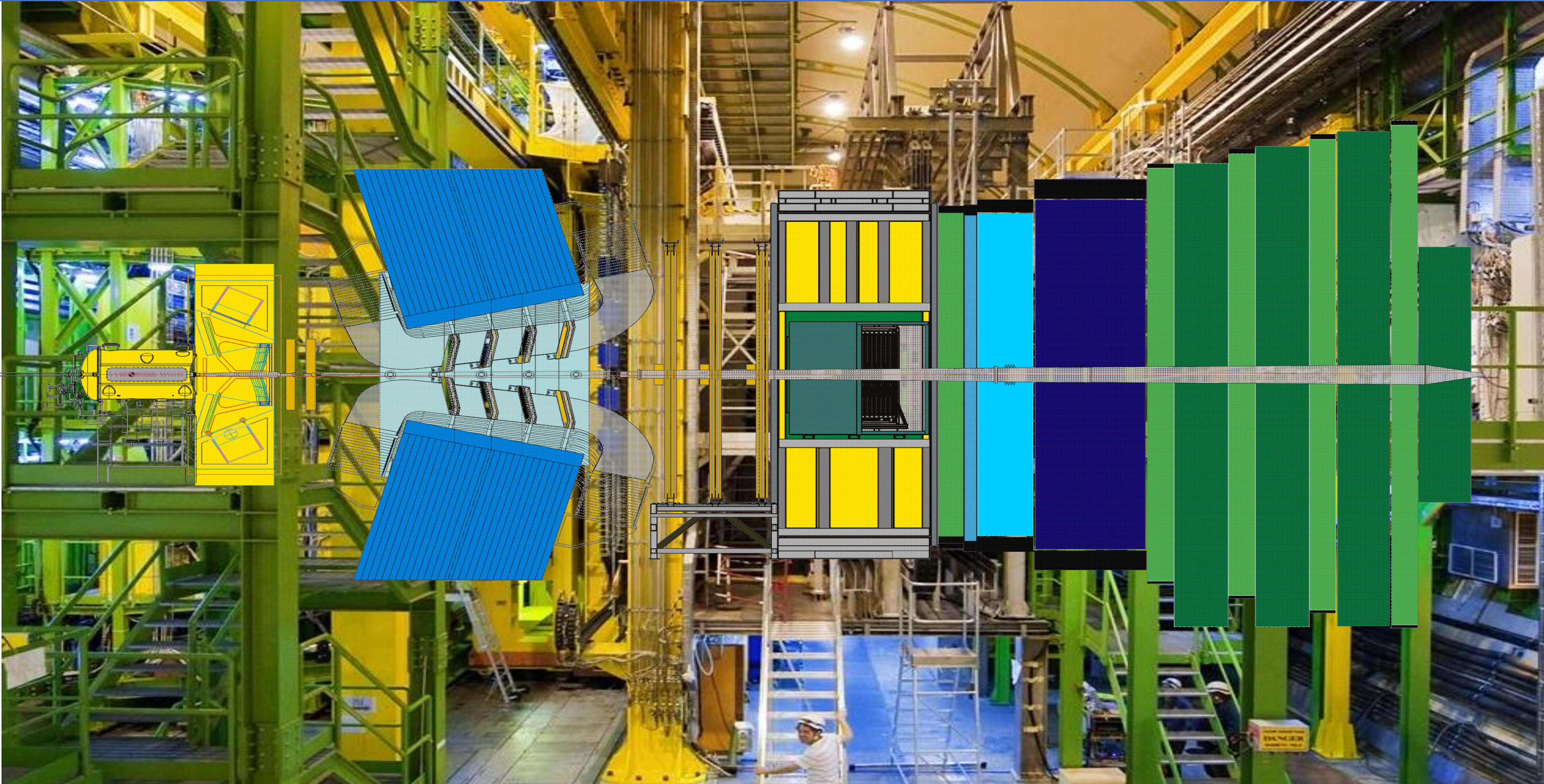


An interference pattern:

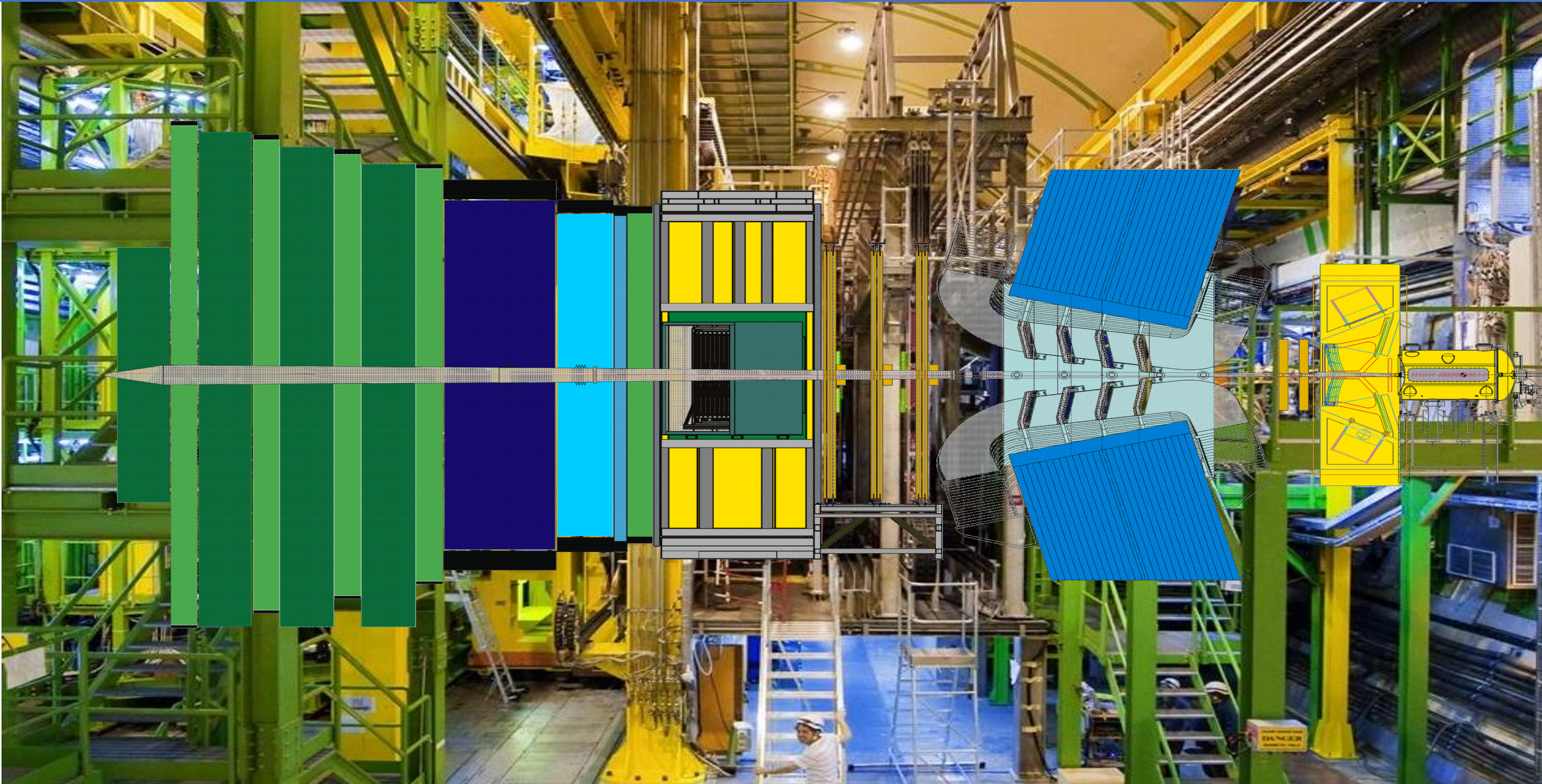


Time dependent CP violation!

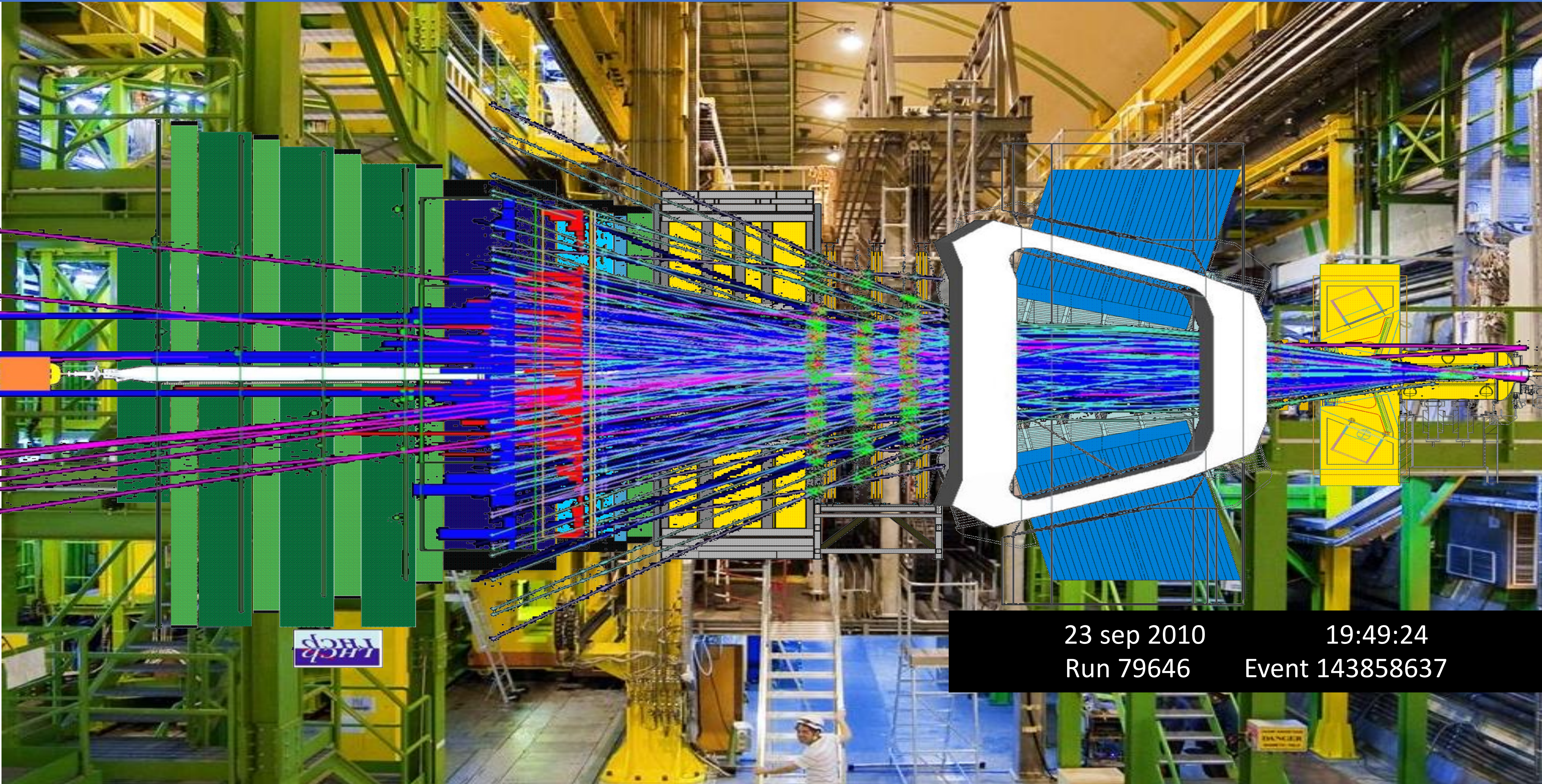
The LHCb Detector? dƆHꞀ



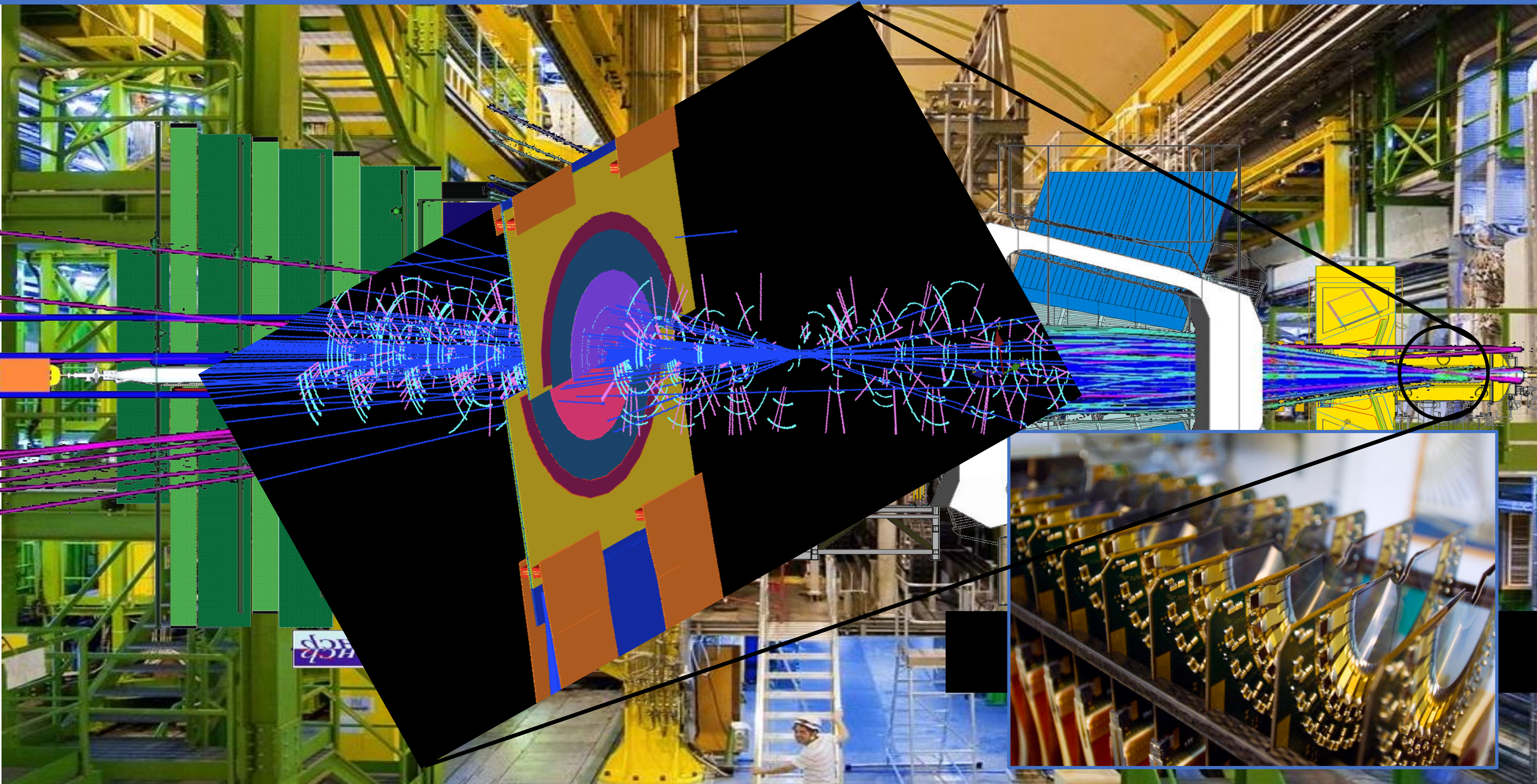
The LHCb Detector!



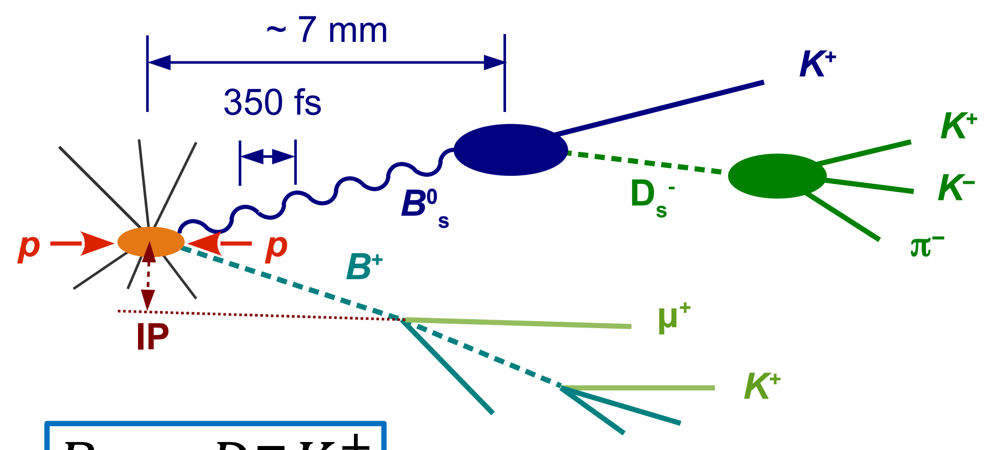
The LHCb Detector



Measure time dependent B and $\overline{B}$ decay rates



B_s Physics at LHCb



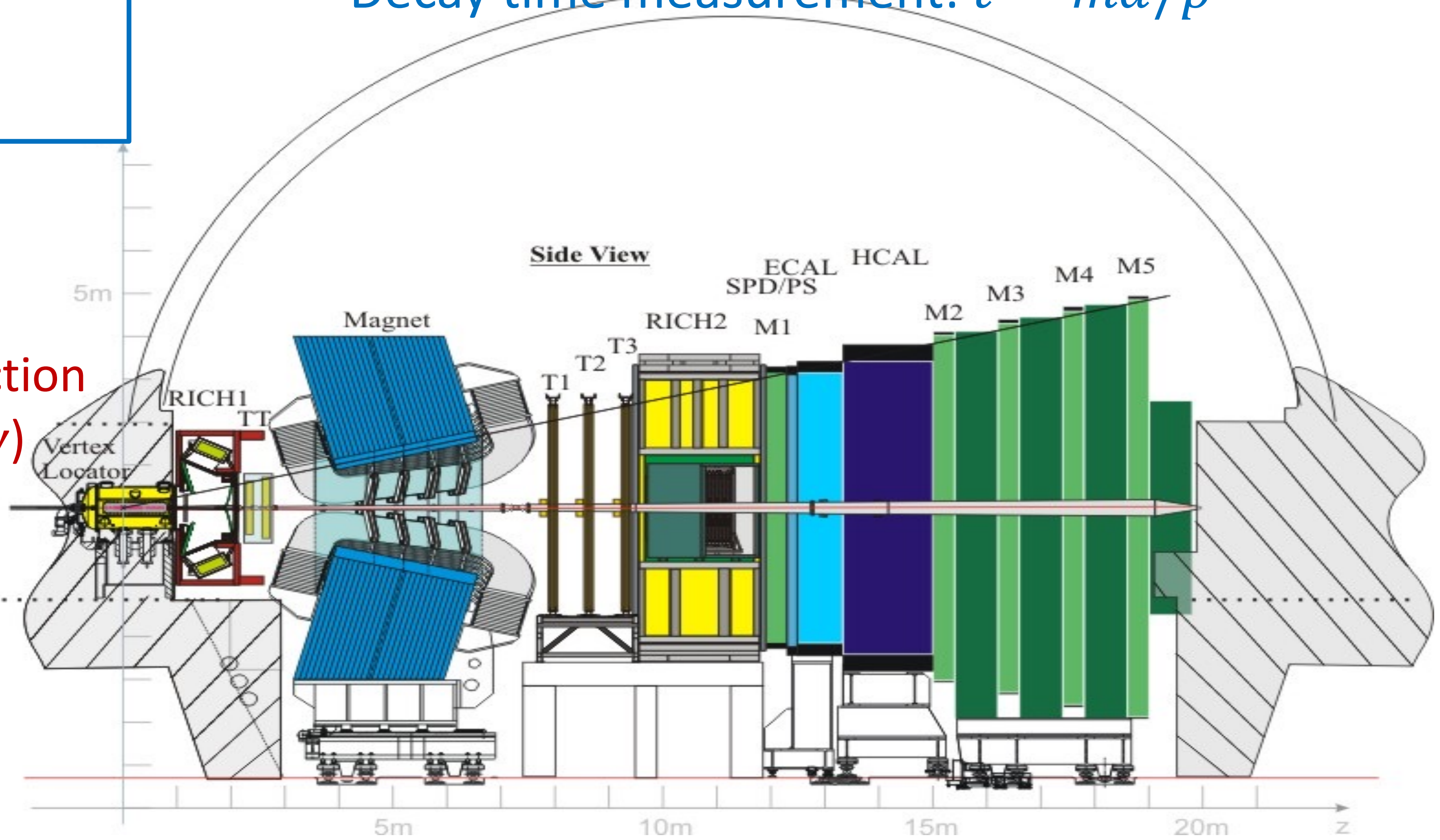
$B_s \to D_s^- K^+$

Physics Requirements:

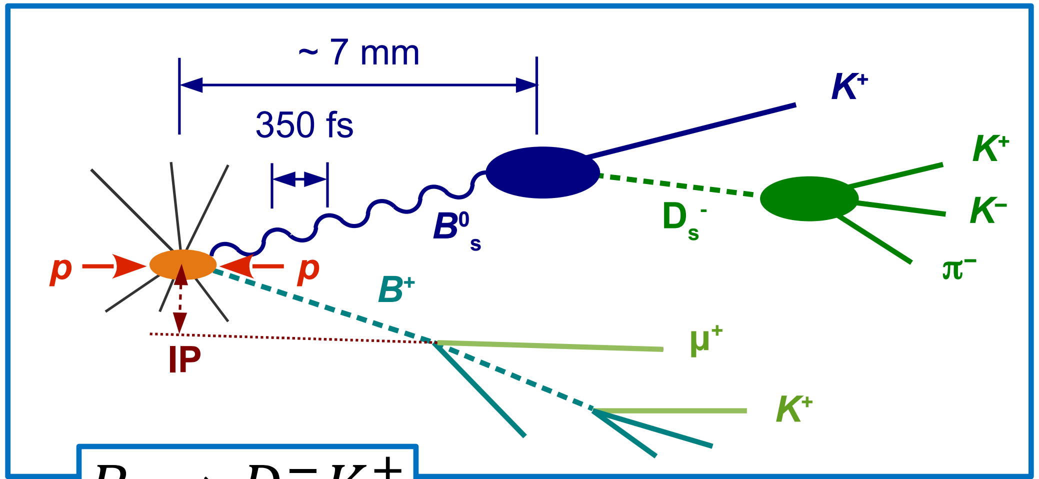
- Signal selection and background suppression
- Flavour tagging: B or $\overline{B}$ at production
- Decay time measurement: $t = md/p$

Detector Requirements:

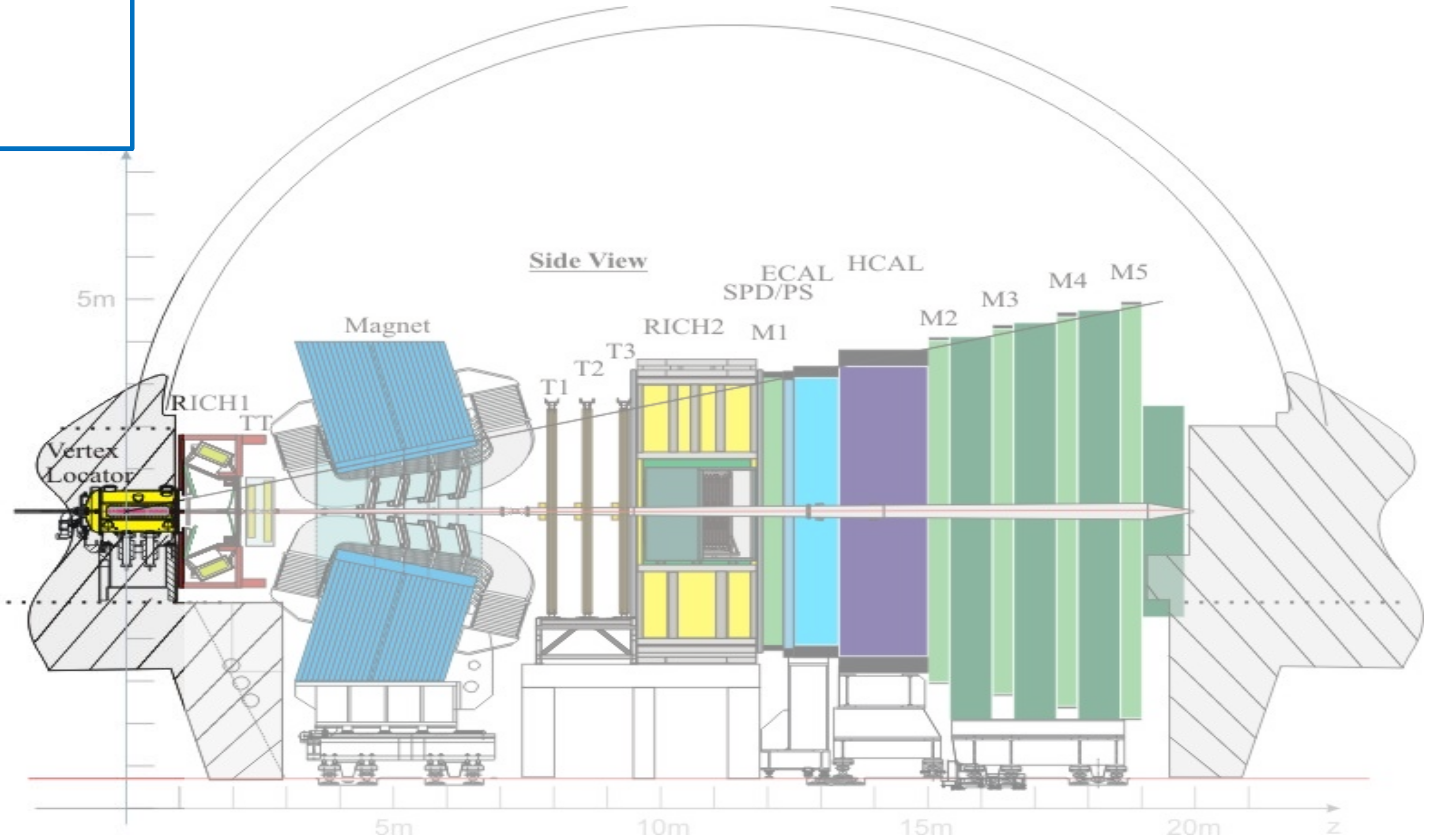
- Vertex reconstruction
- Momentum and mass reconstruction
- Particle identification (π, K, μ, e, γ)
- Trigger (Online reconstruction)



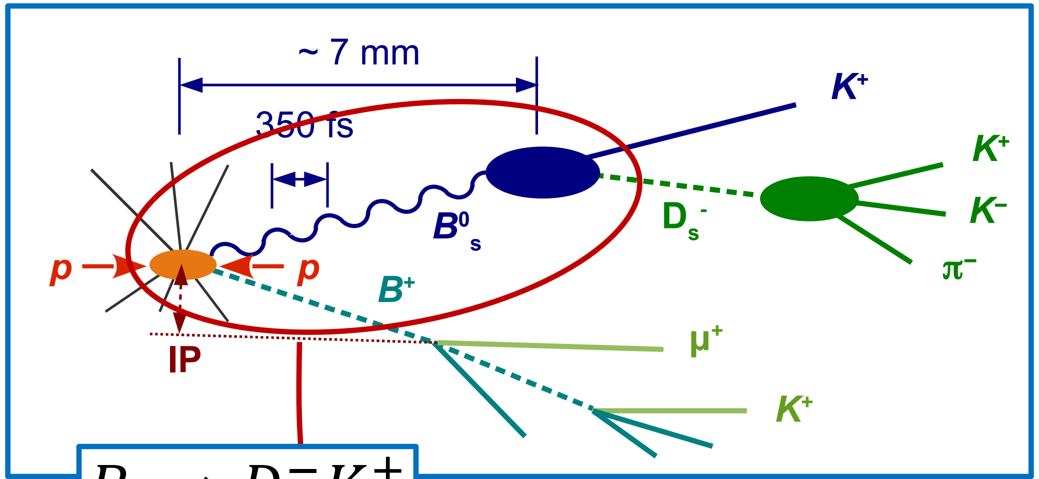
B_s Physics at LHCb - Vertex reconstruction



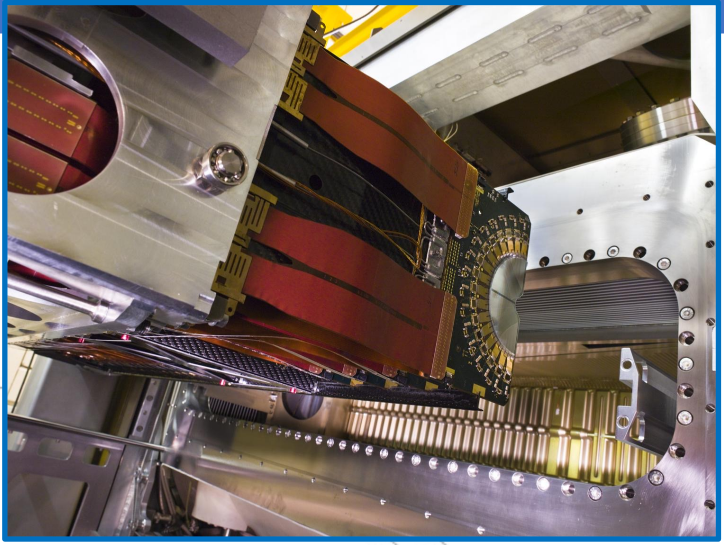
$B_s \to D_s^- K^+$

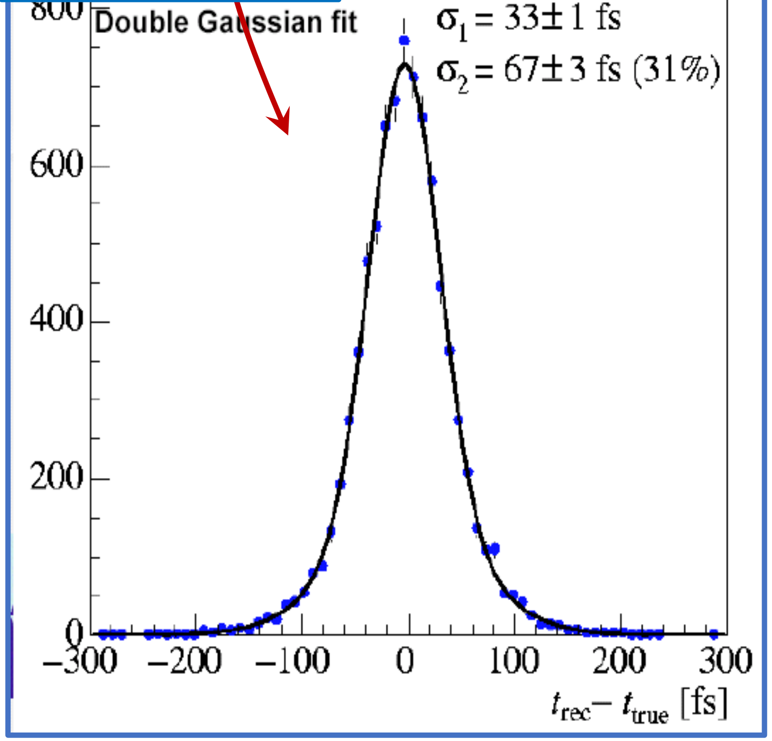


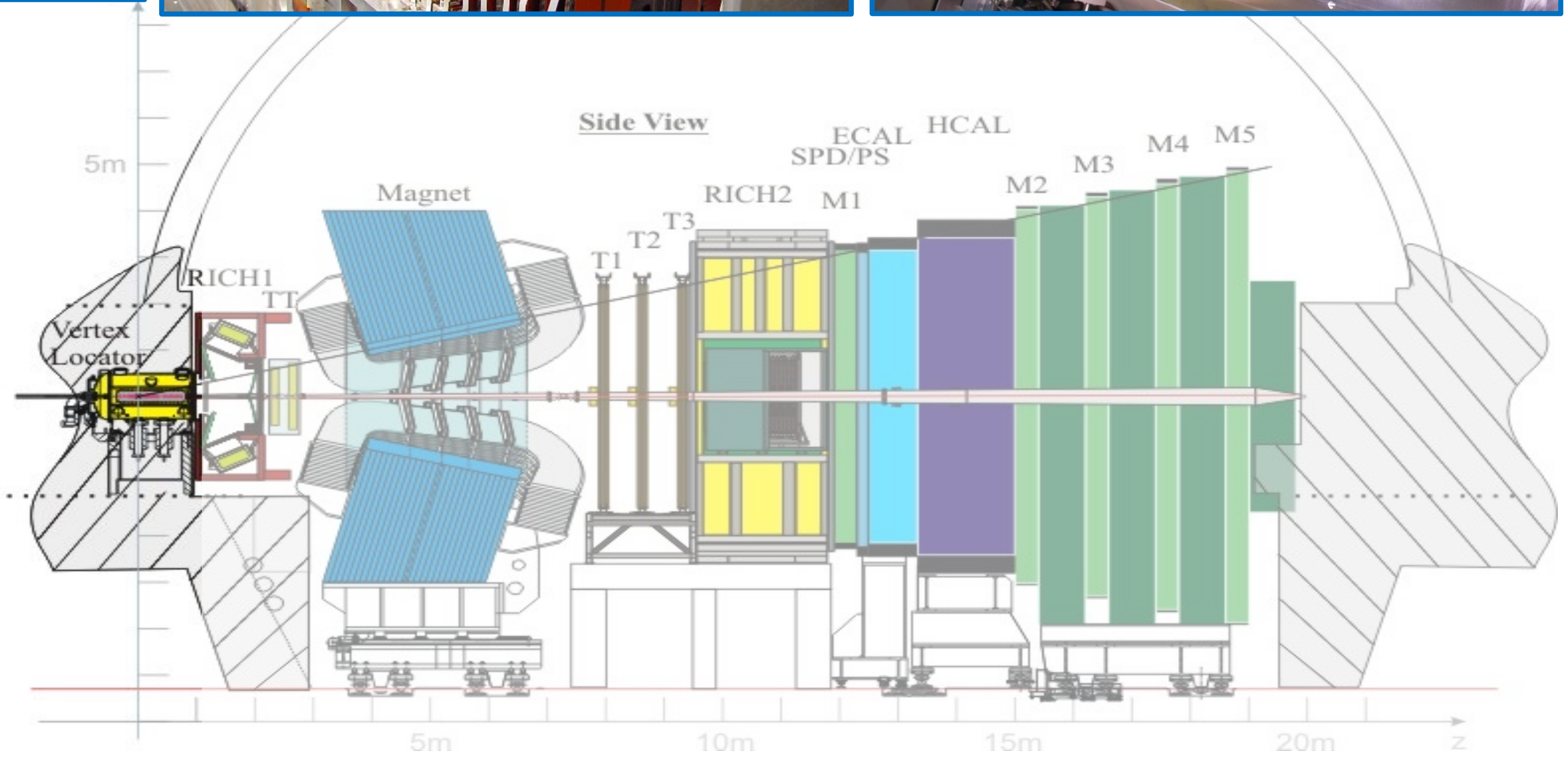
B_s Physics at LHCb - Vertex reconstruction



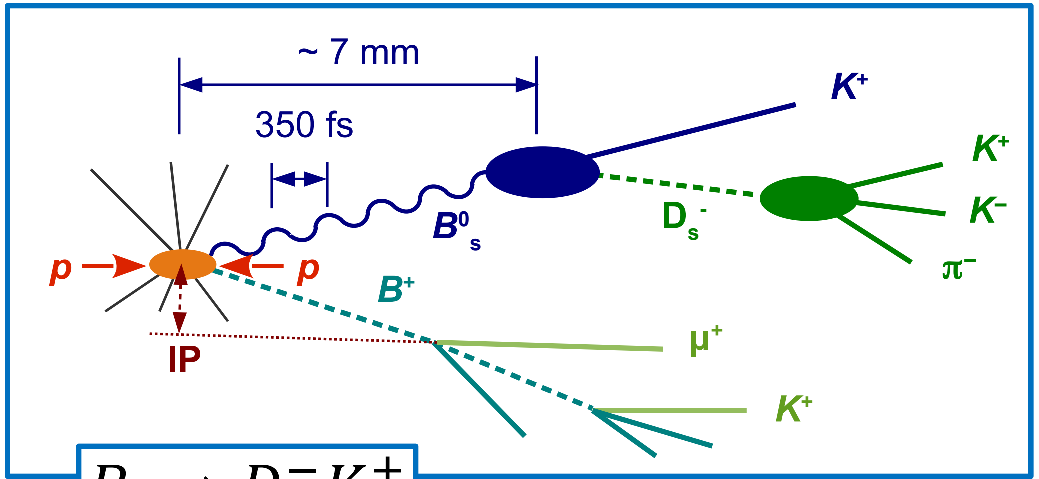
$B_s \to D_s^- K^+$



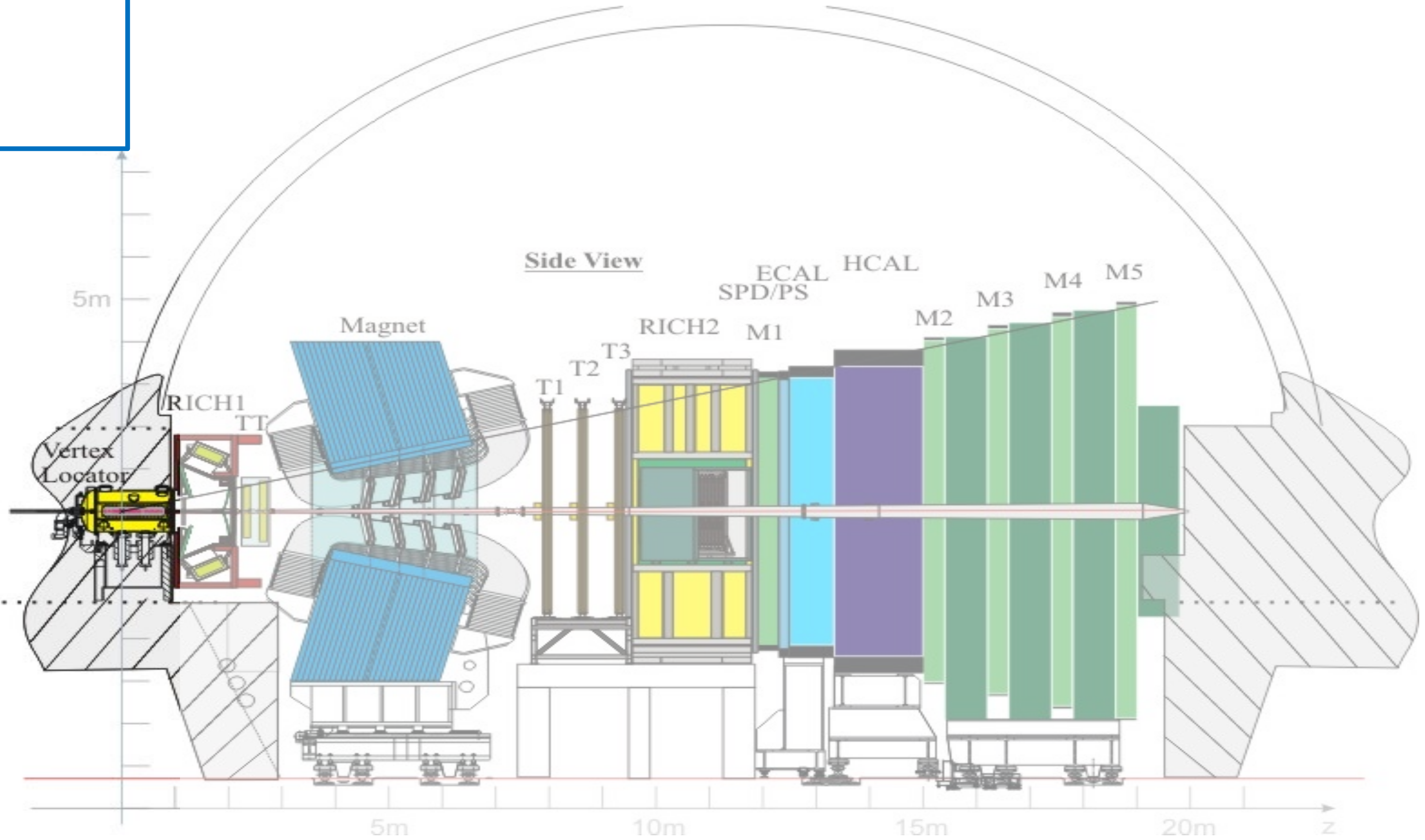




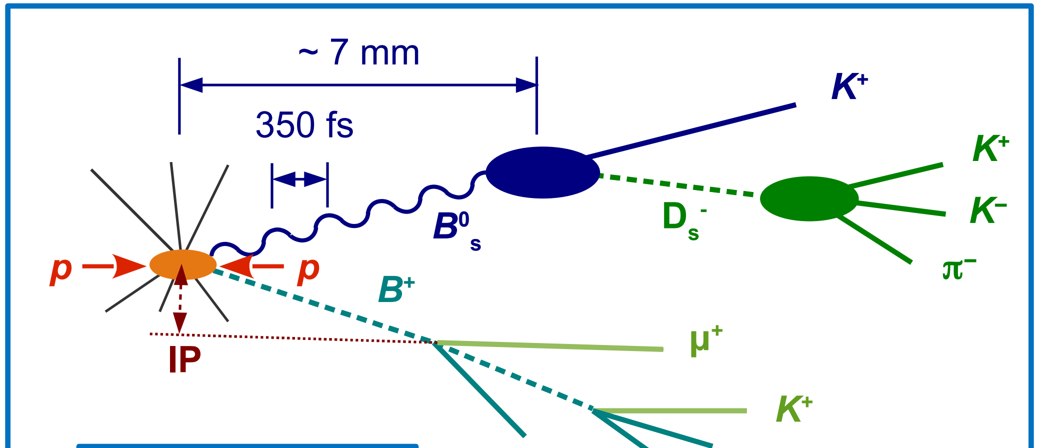
B_s Physics at LHCb



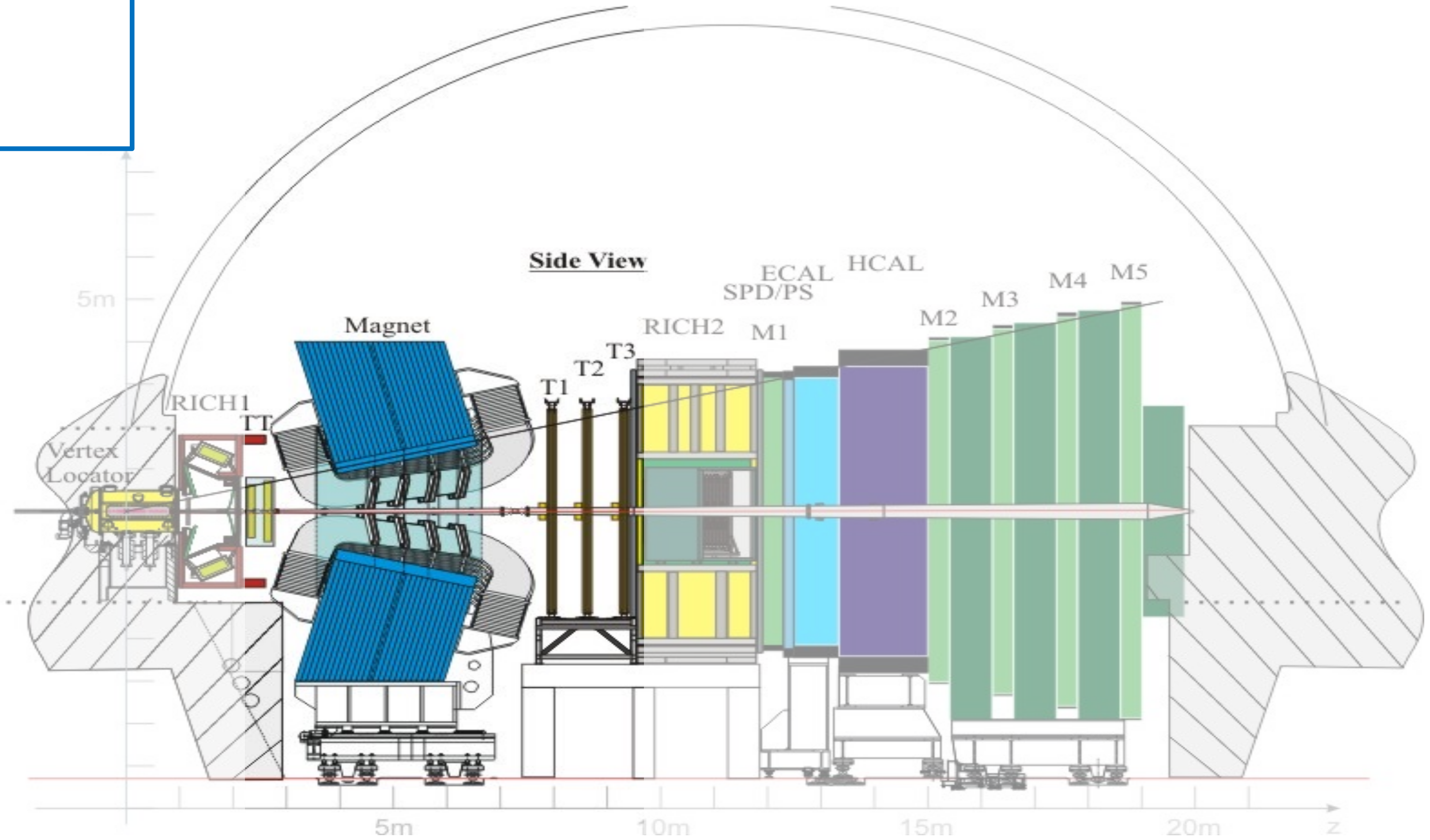
$B_s \rightarrow D_s^- K^+$



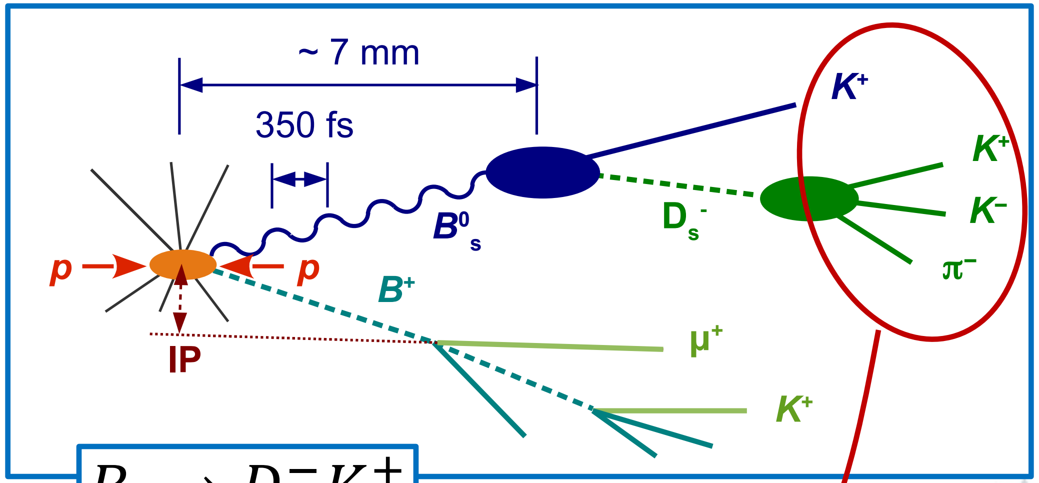
B_s Physics at LHCb – momentum and mass determination



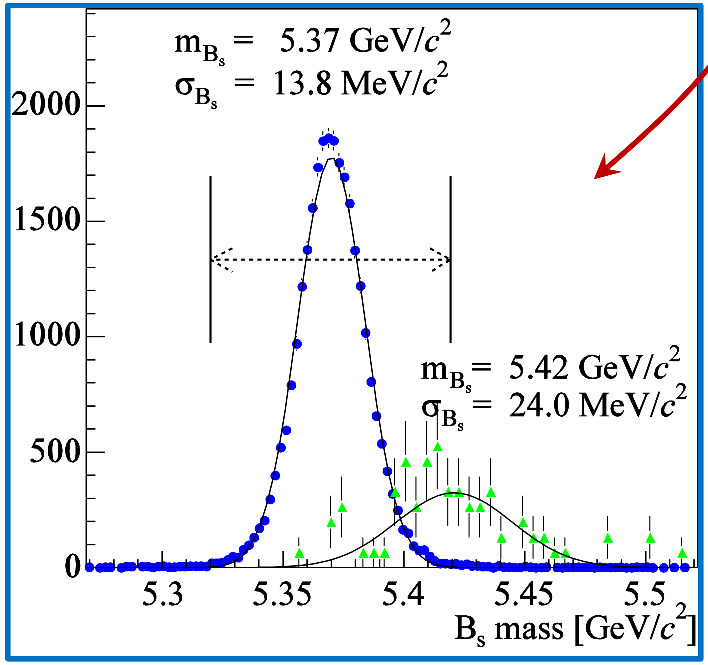
$B_s \to D_s^- K^+$

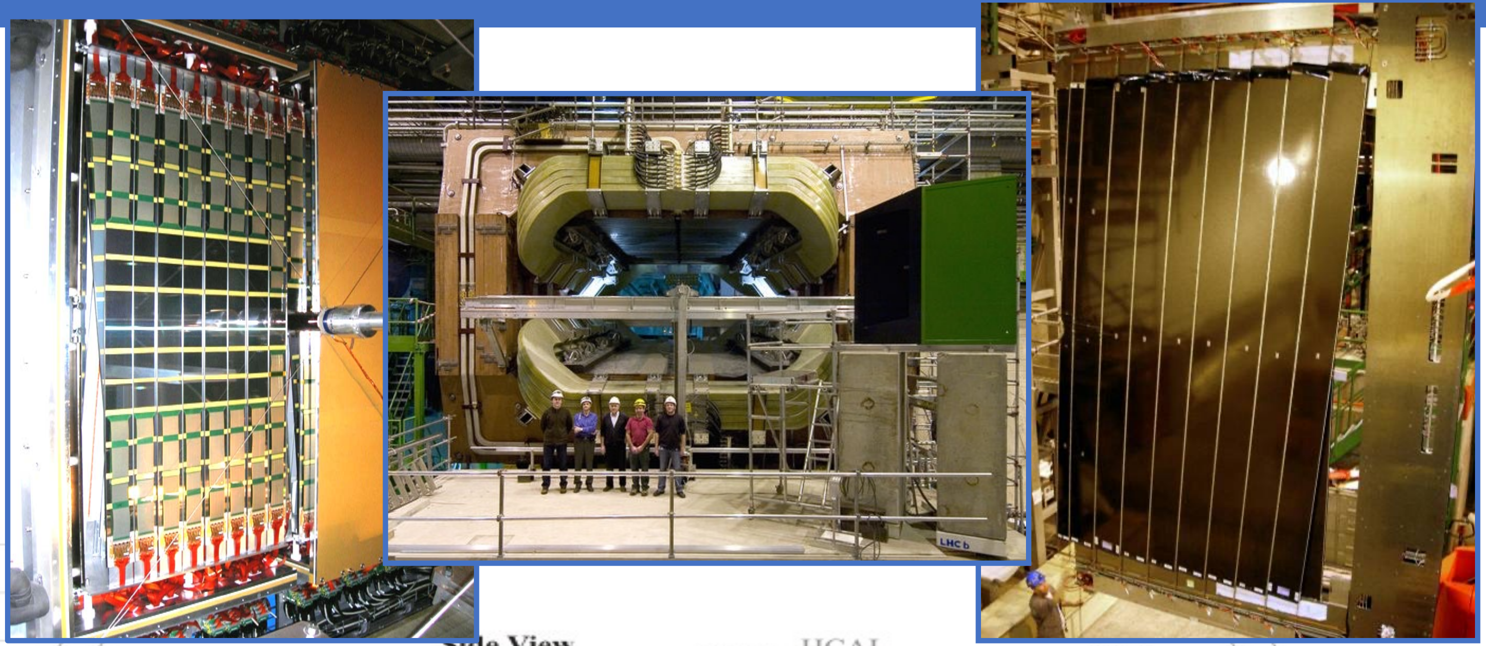


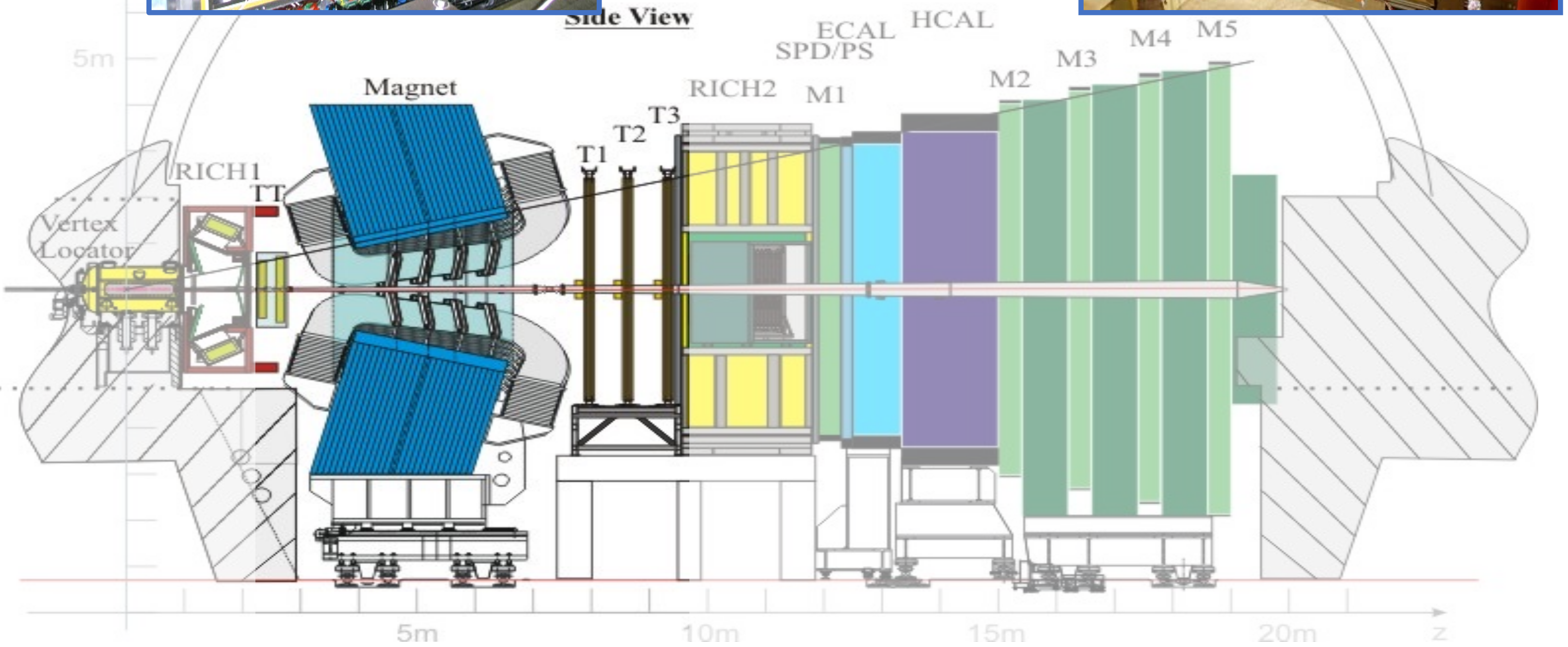
B_s Physics at LHCb – momentum and mass determination



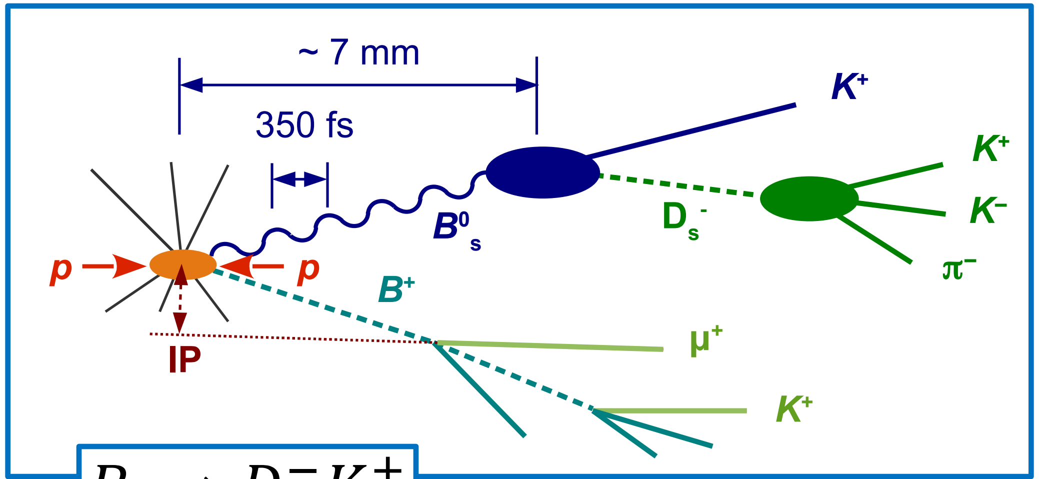
$B_s \to D_s^- K^+$



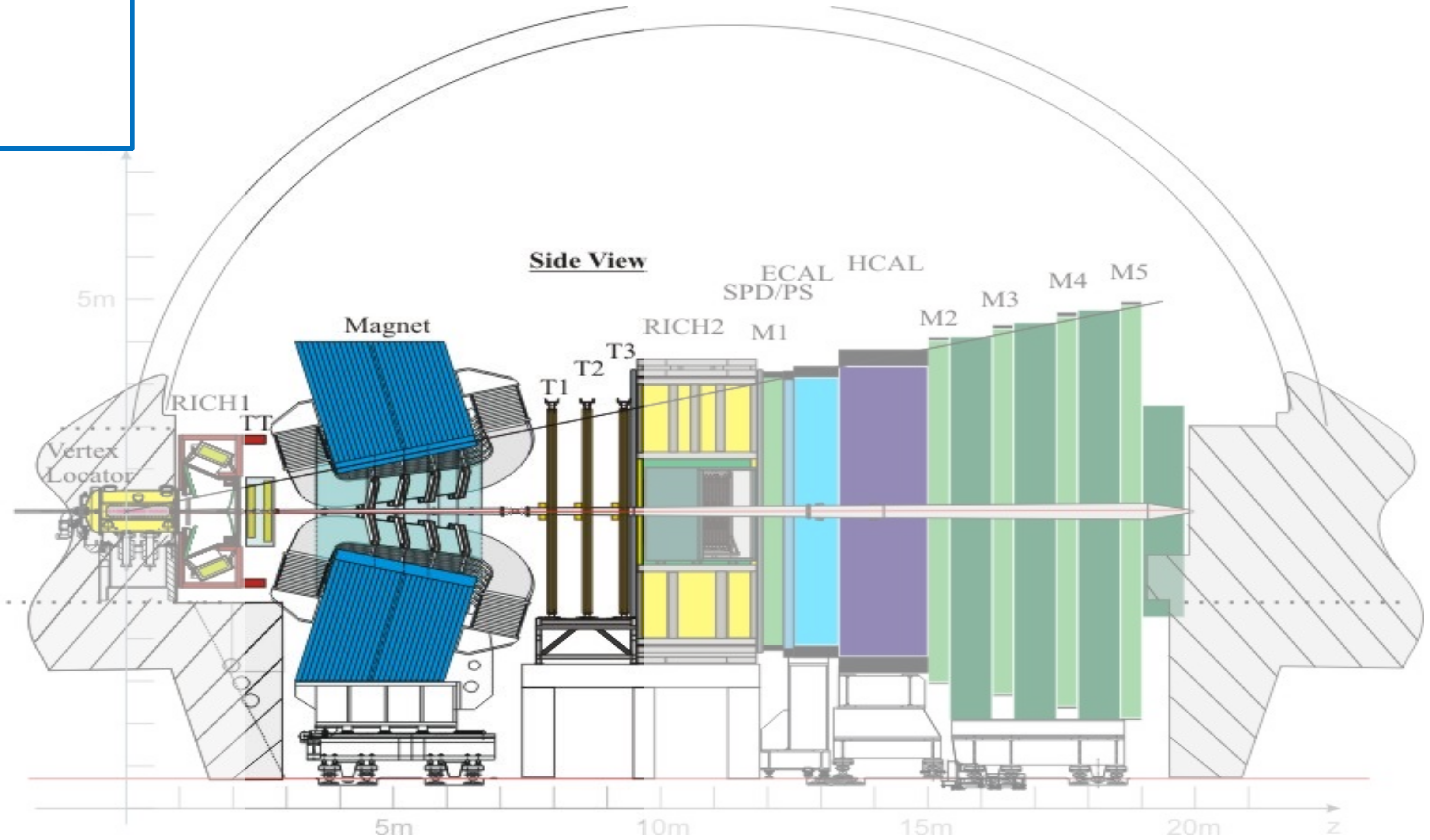




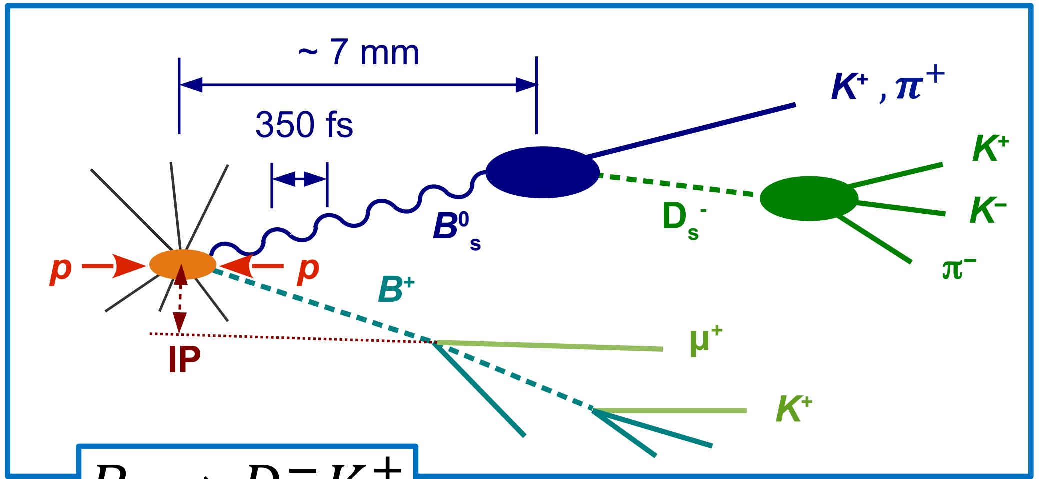
B_s Physics at LHCb



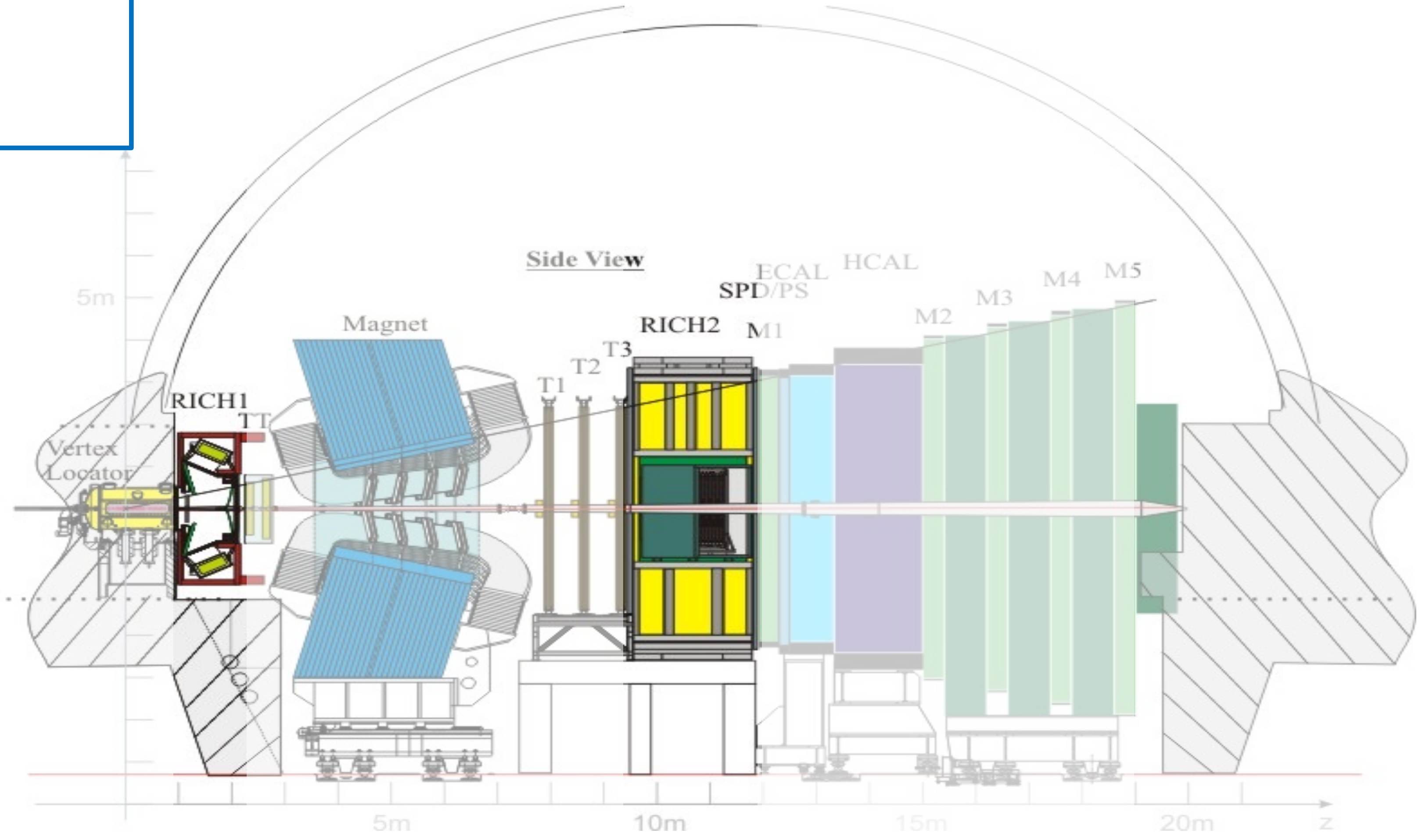
$B_s \to D_s^- K^+$



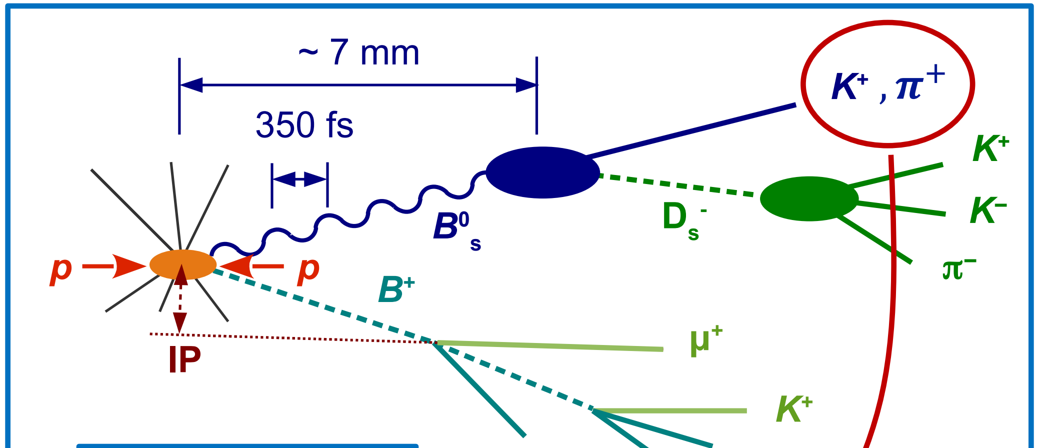
B_s Physics at LHCb – Particle Identification with RICH



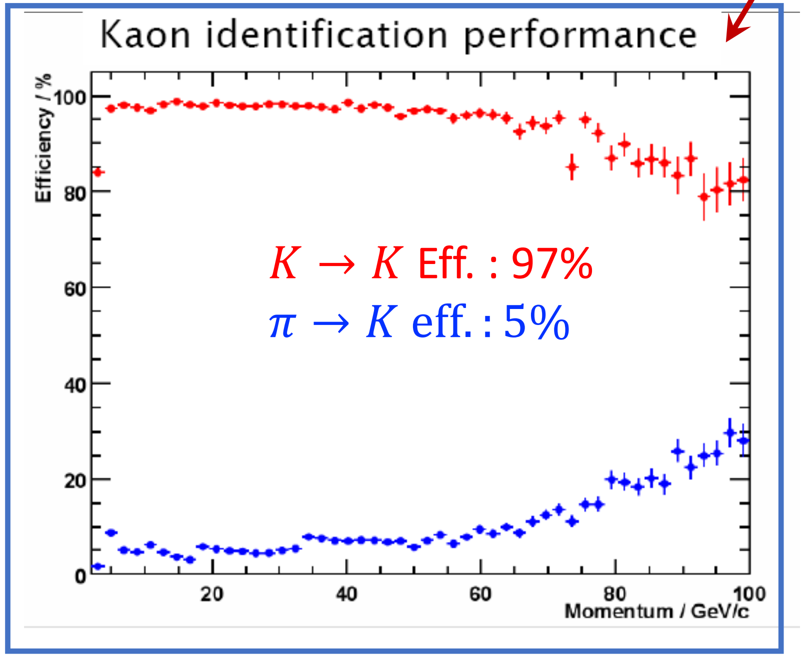
$B_s \to D_s^- K^+$

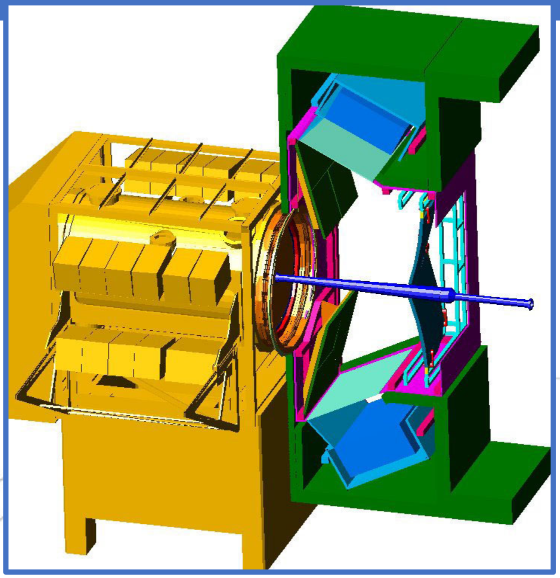


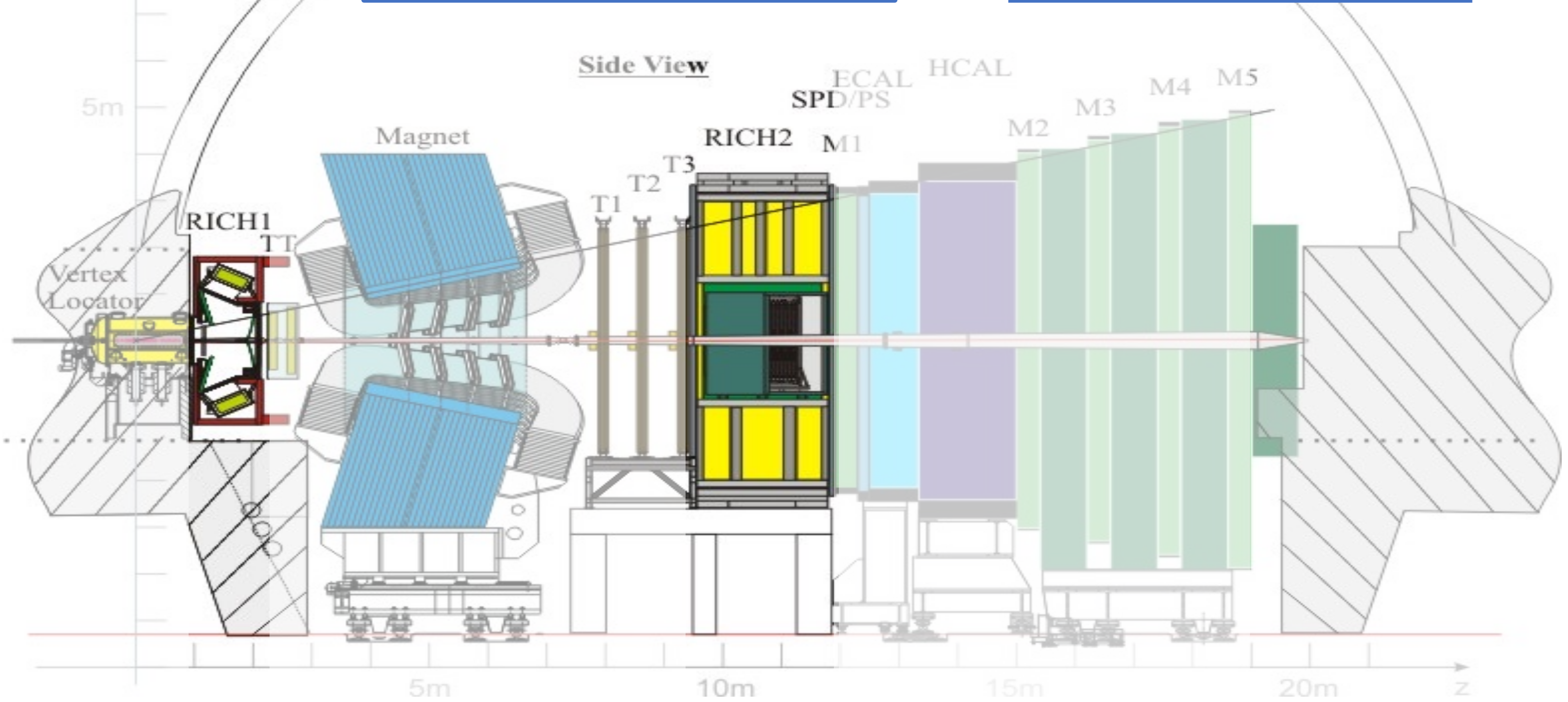
B_s Physics at LHCb – Particle Identification with RICH



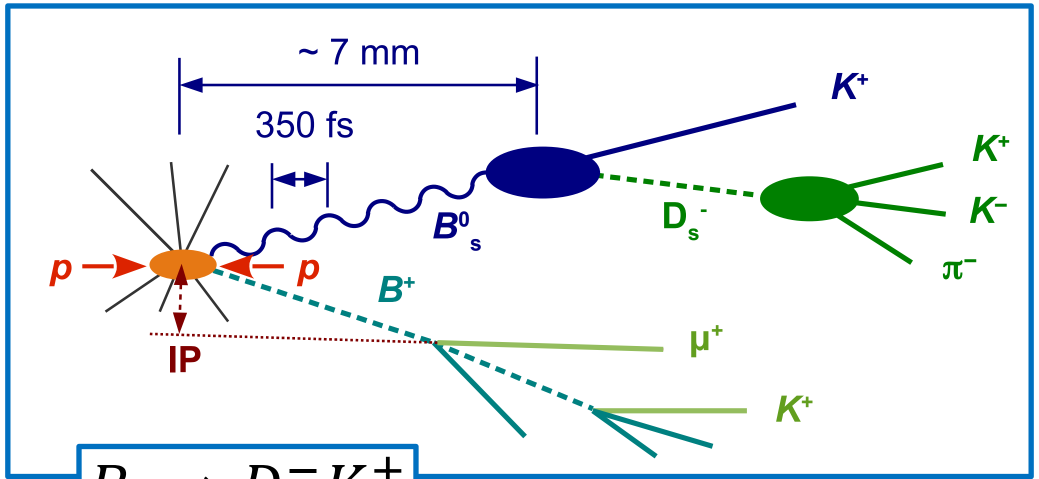
$B_s \rightarrow D_s^- K^+$



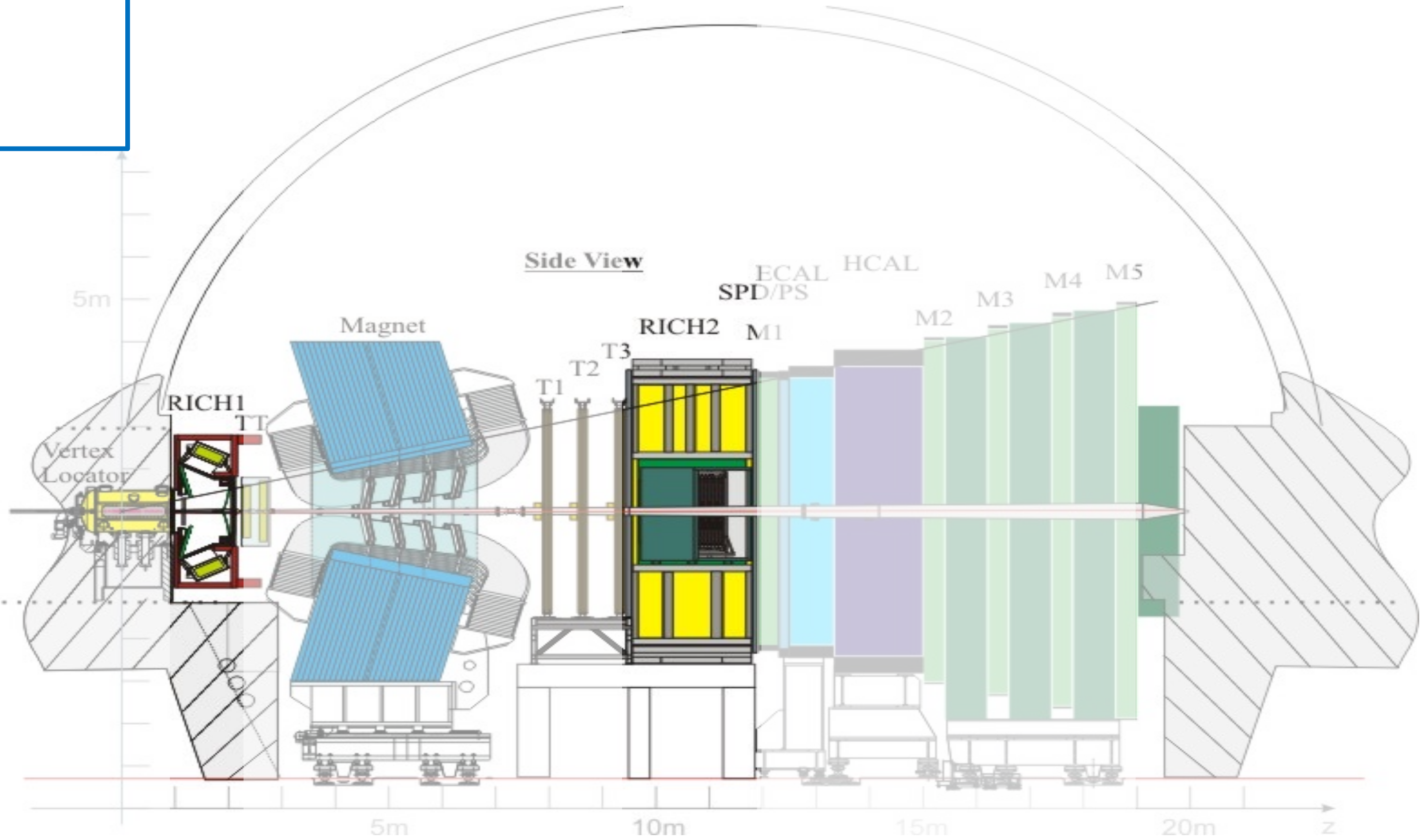




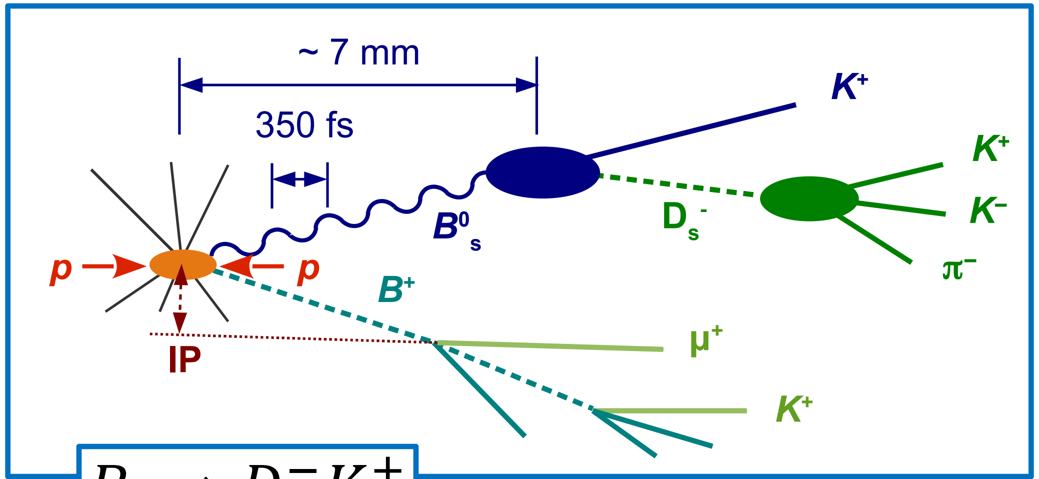
B_s Physics at LHCb



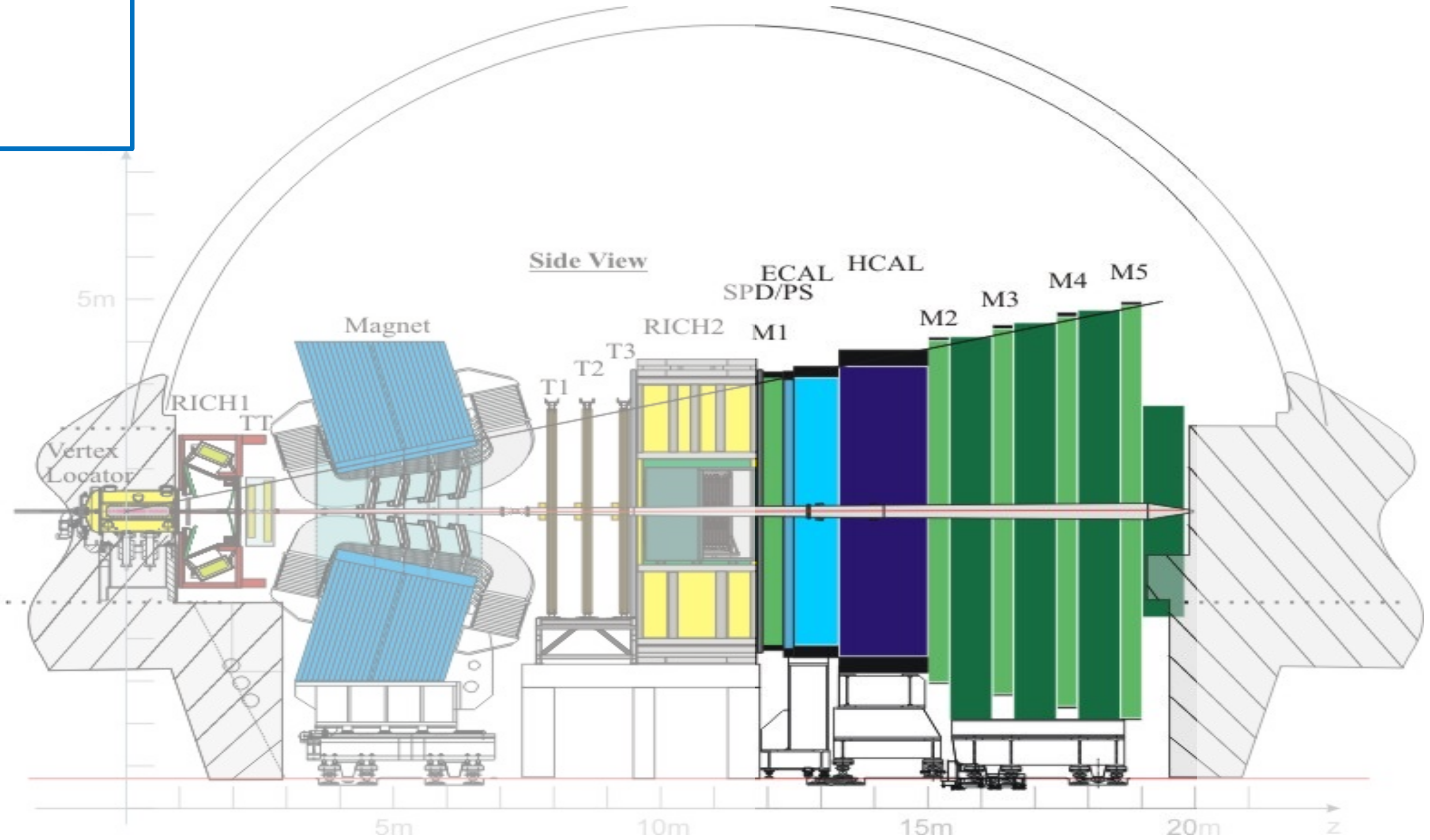
$B_s \to D_s^- K^+$



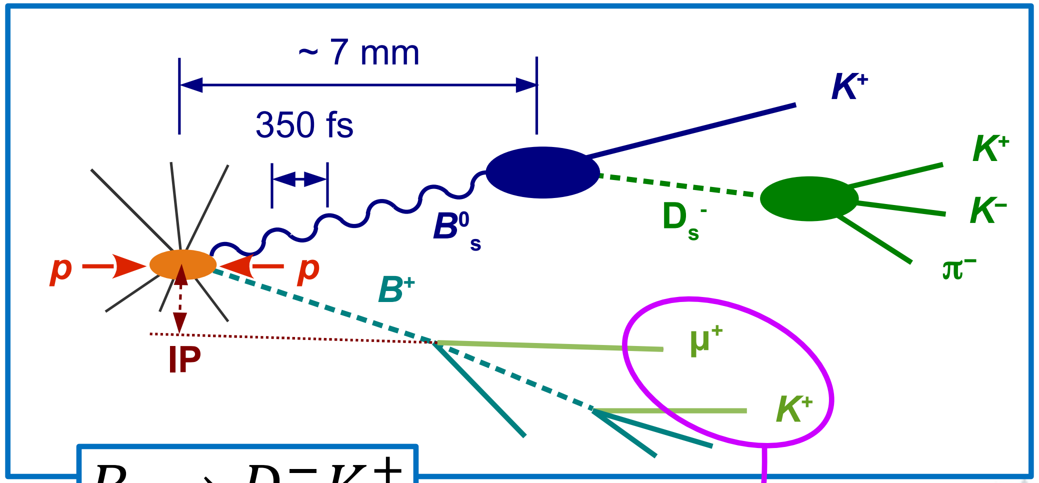
B_s Physics at LHCb – Trigger/Tag with Calorimeters and Muon



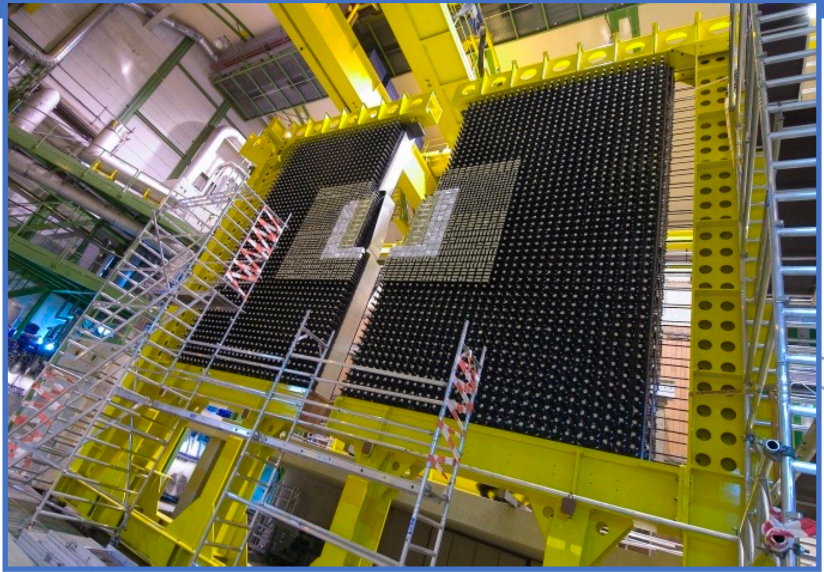
$B_s \rightarrow D_s^- K^+$



B_s Physics at LHCb – Trigger/Tag with Calorimeters and Muon

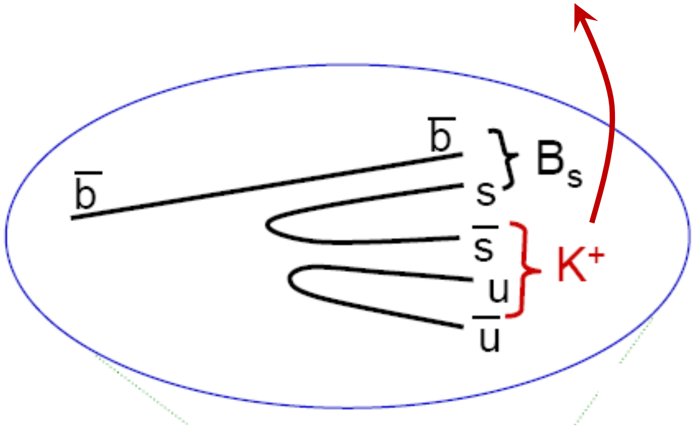


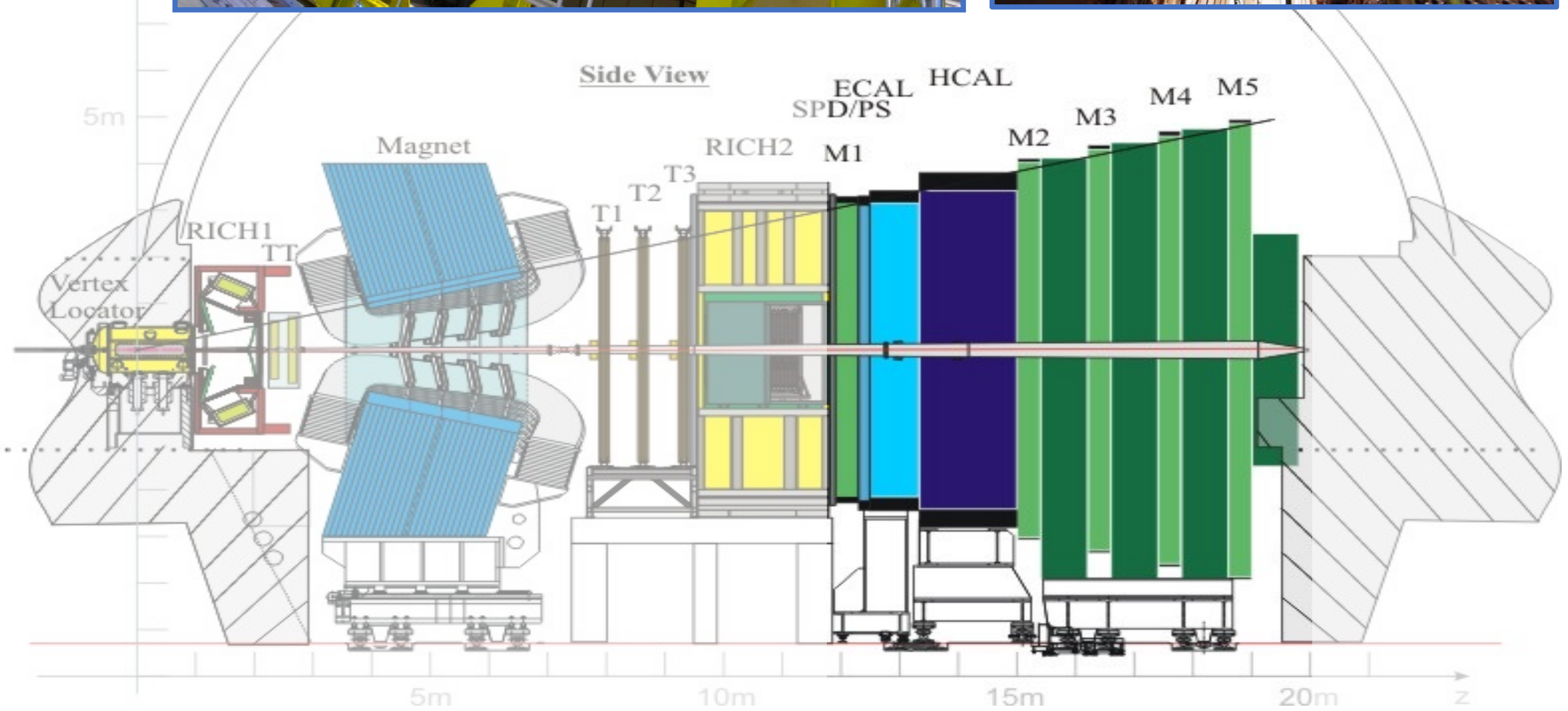
$B_s \to D_s^- K^+$



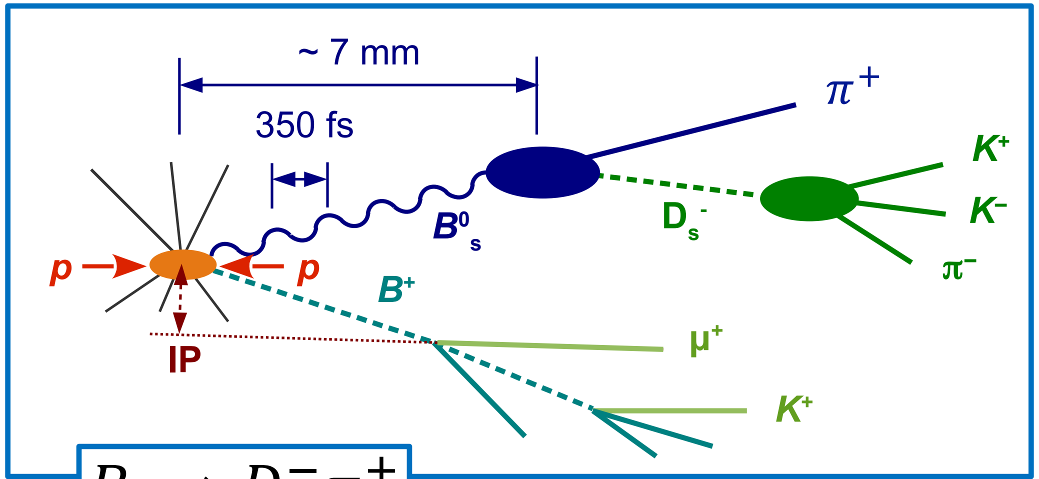
Identification of γ, e , μ:

- Triggering
- Flavour tagging:
  - Opposite or same side





Measuring B_s - $\overline{B_s}$ Oscillations (Self tagging $B_s \to D_s\pi$)

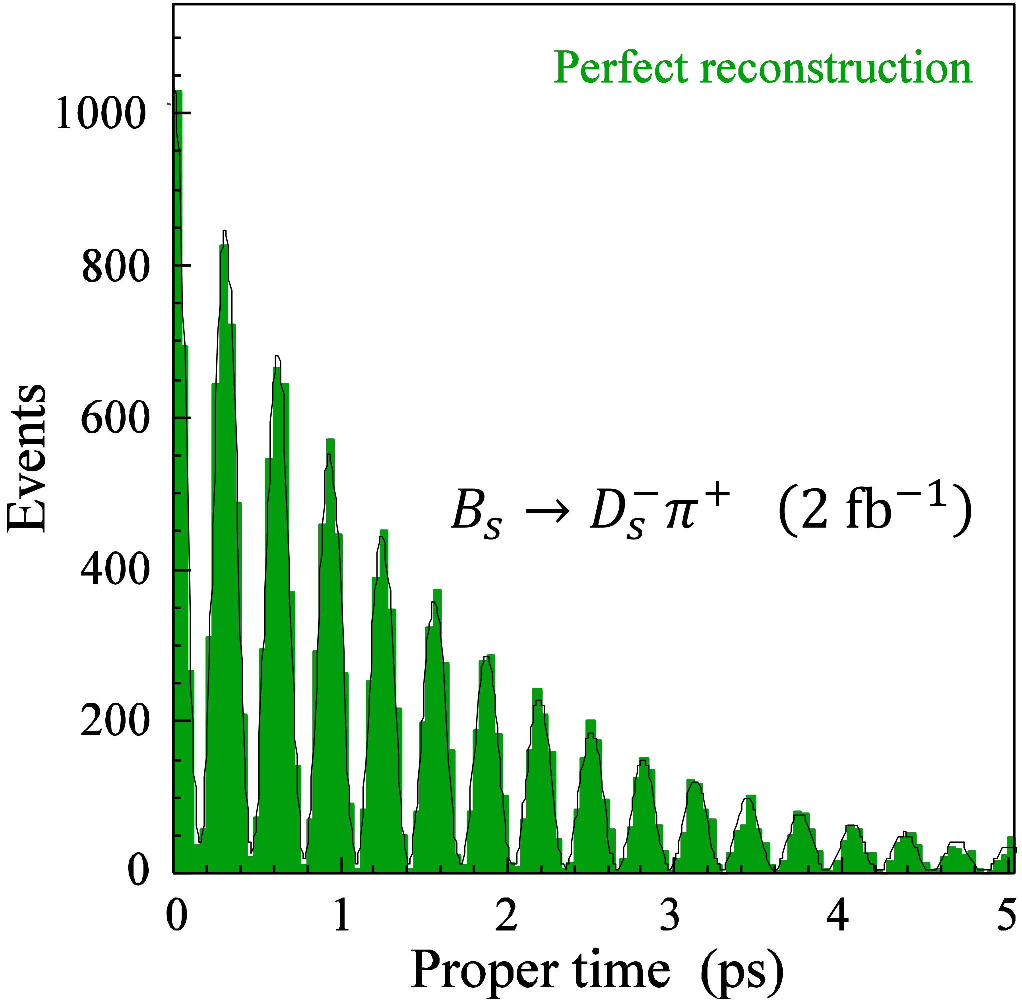


$B_s \to D_s^- \pi^+$

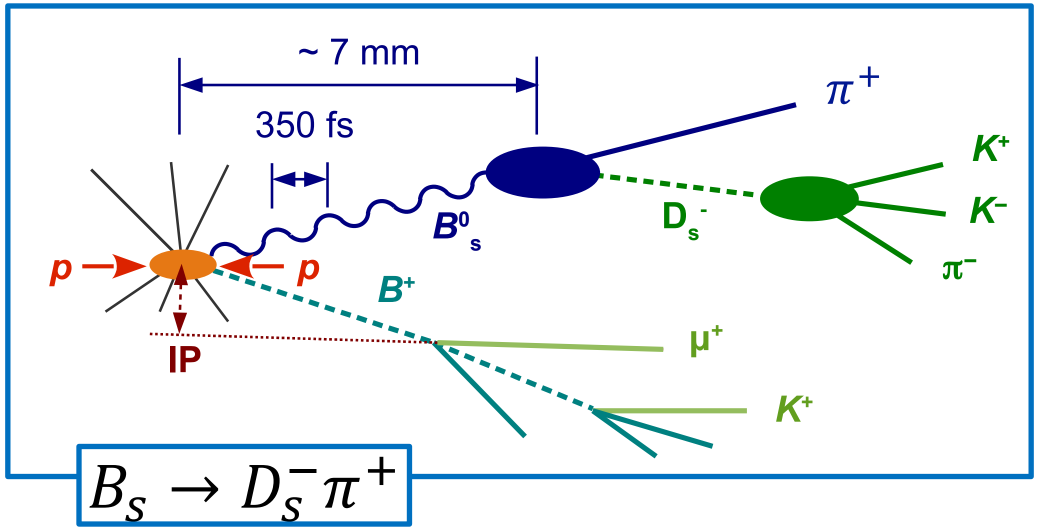
Experimental Situation:

Ideal measurement (no dilutions)

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations

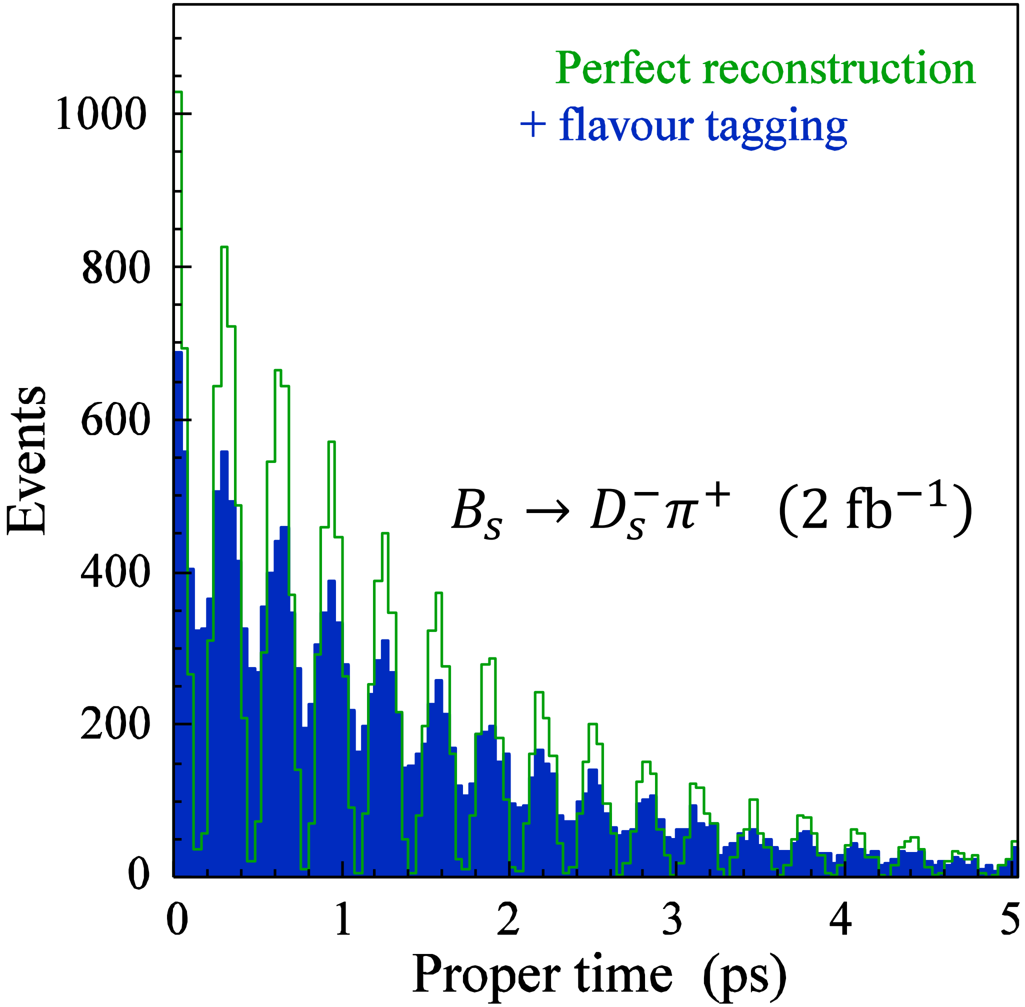


Experimental Situation:

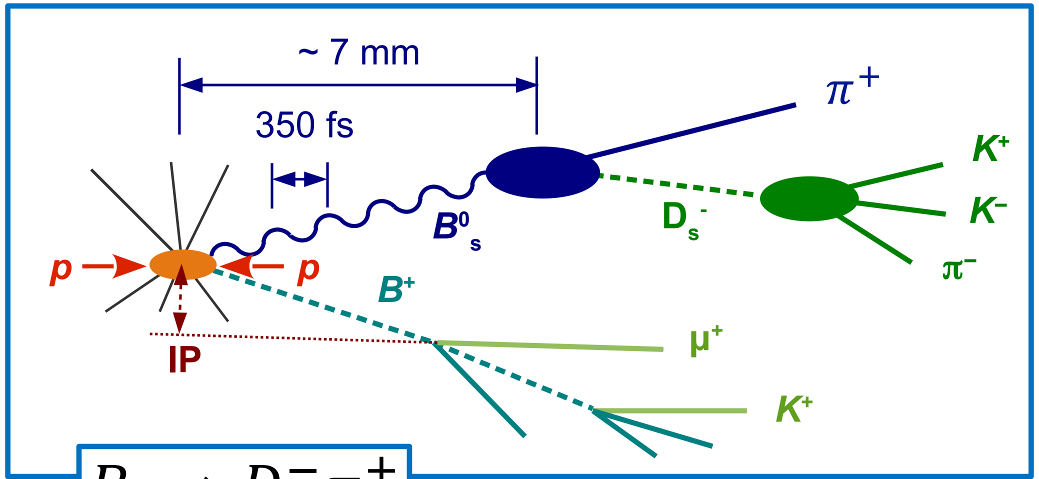
Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



$B_s \to D_s^- \pi^+$

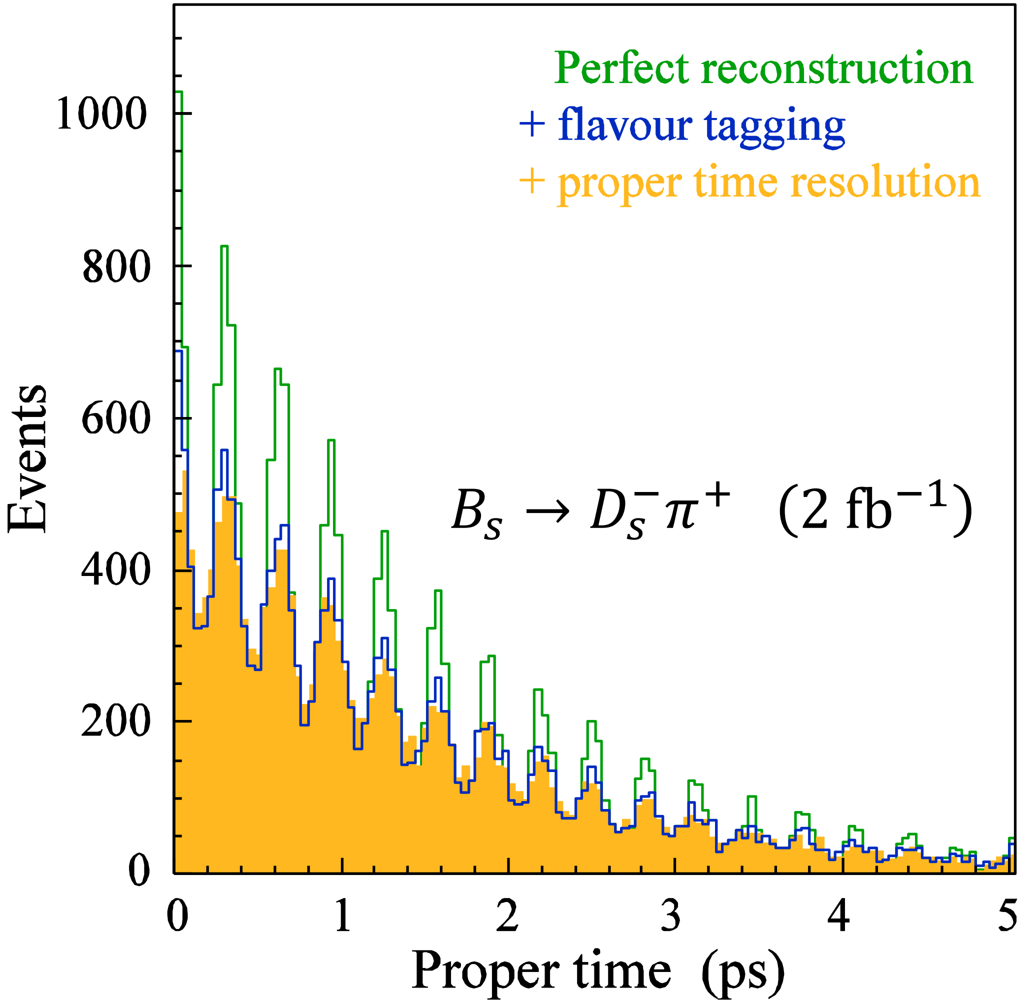
__Experimental Situation:__

Ideal measurement (no dilutions)

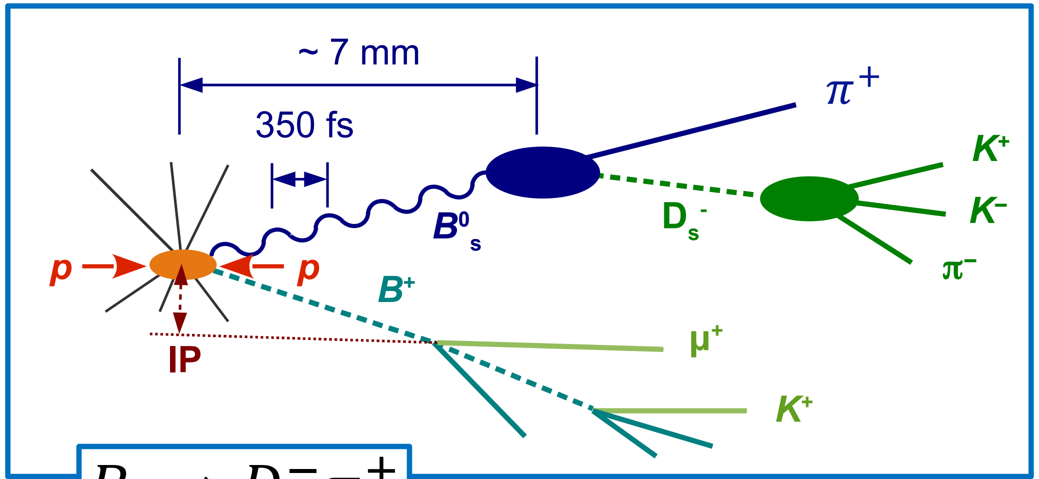
+ Realistic flavour tagging dilution

+ Realistic decay time resolution

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



$B_s \to D_s^- \pi^+$

Experimental Situation:

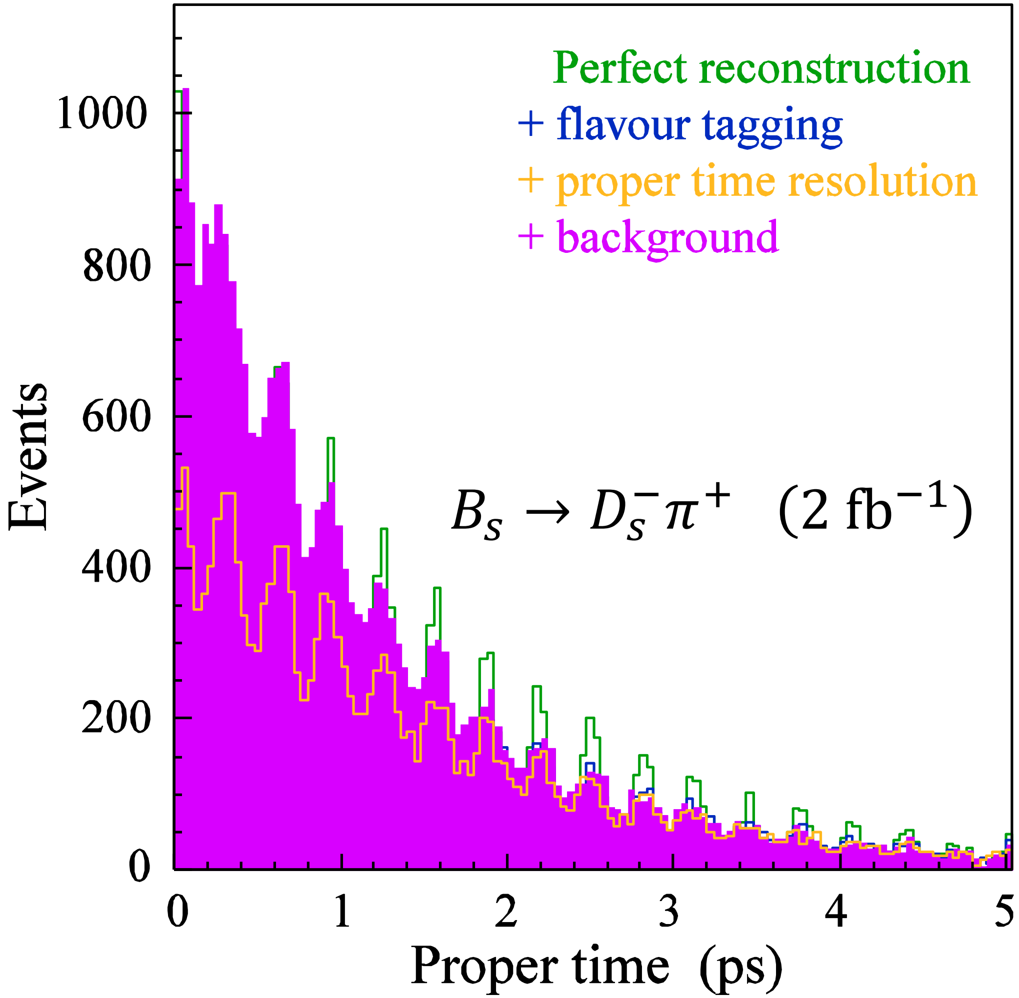
Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution

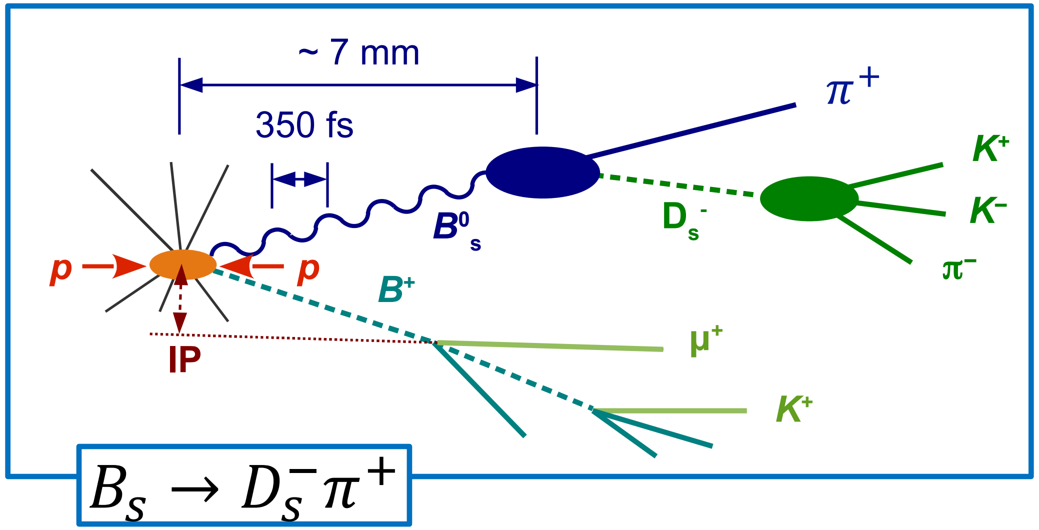
+ Realistic decay time resolution

+ Background events

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations

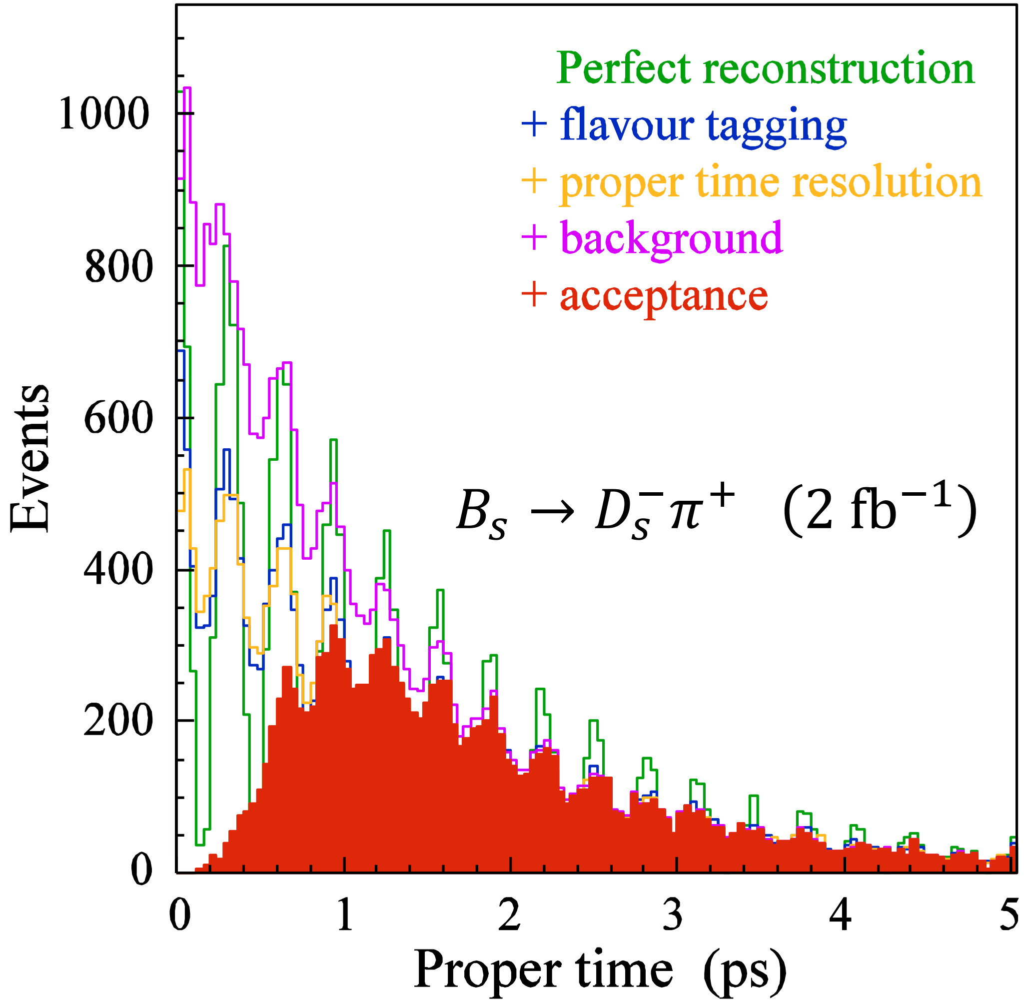


Experimental Situation:

Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution
+ Realistic decay time resolution
+ Background events
+ Trigger and selection acceptance

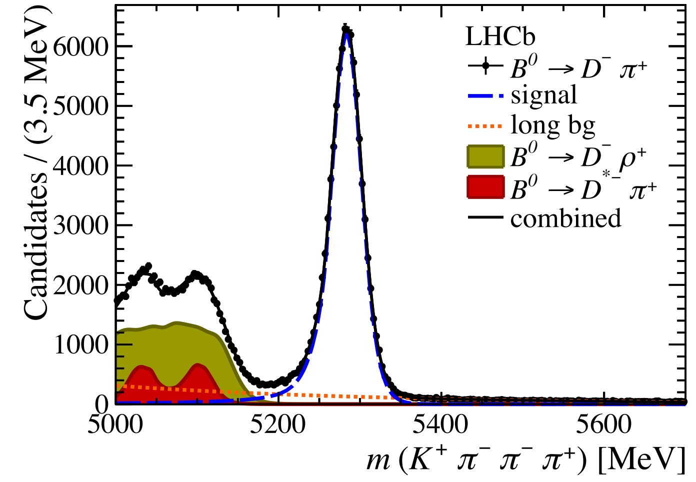
Proper-time dependent decay rate:

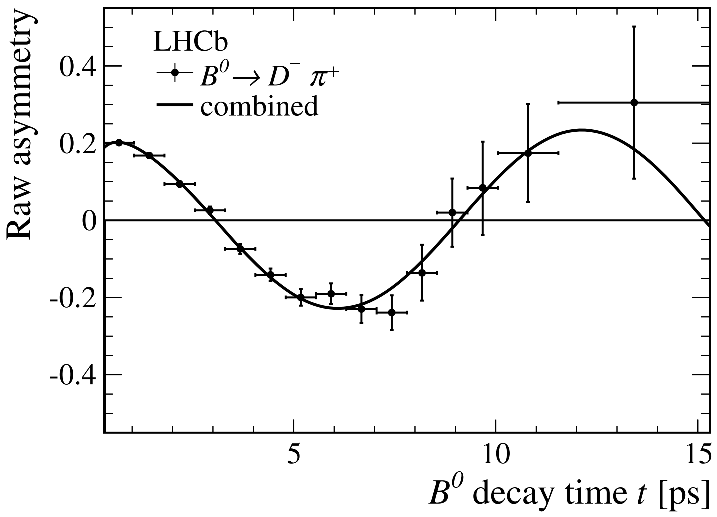


Meson mixing in LHCb: does is actually work?

$B^0 - \overline{B^0}$ mixing

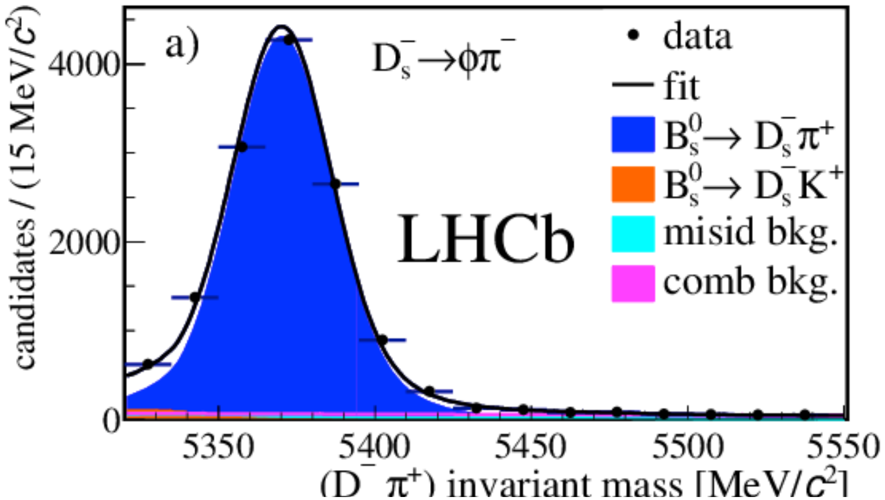
$B^0 \to D^- \pi^+$ **Phys.Lett.B719 (2013) 318**

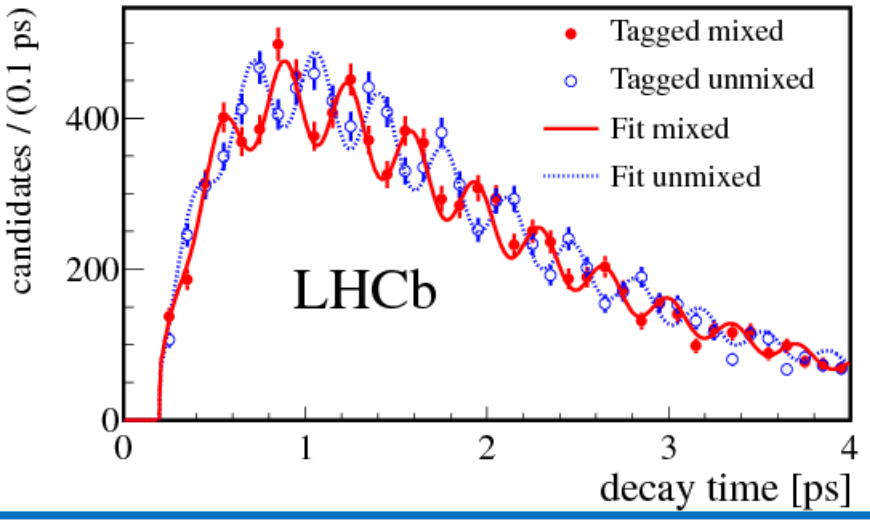




$B_s^0 - \overline{B_s^0}$ mixing

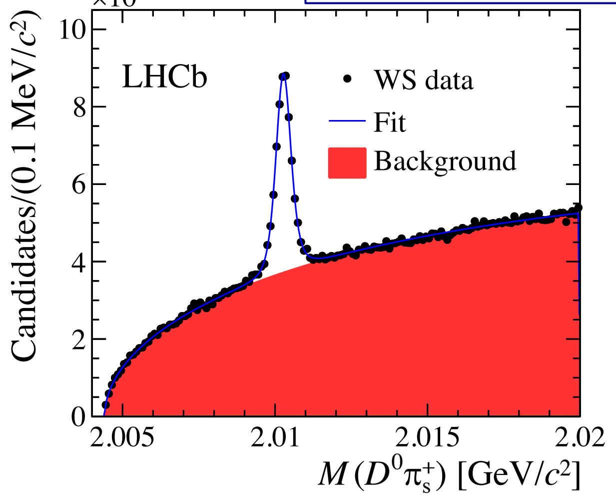
$B_s^0 \to D_s^- \pi^+$ **New.J.Phys.15 (2013) 053021**

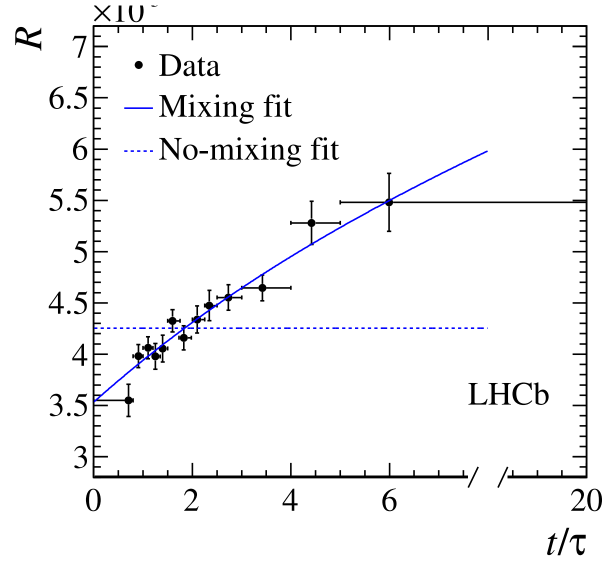




$D^0 \to \overline{D^0}$ mixing

$D^0 \to K^+ \pi^-$ **PRL.110 (2013) 101802**

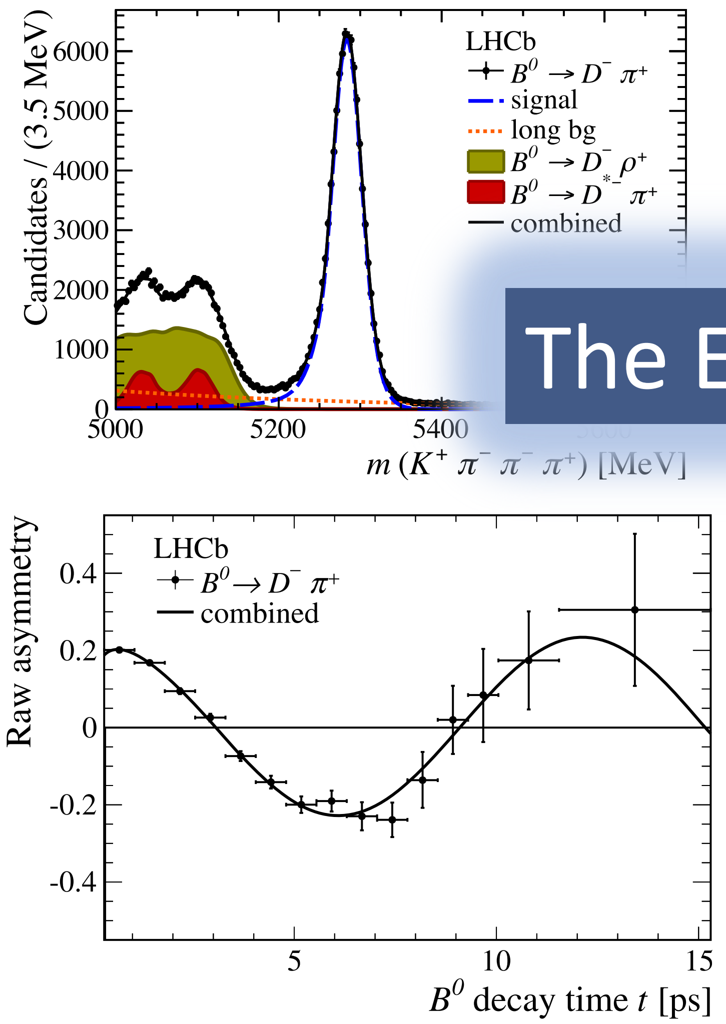




Meson mixing in LHCb: does is actually work?

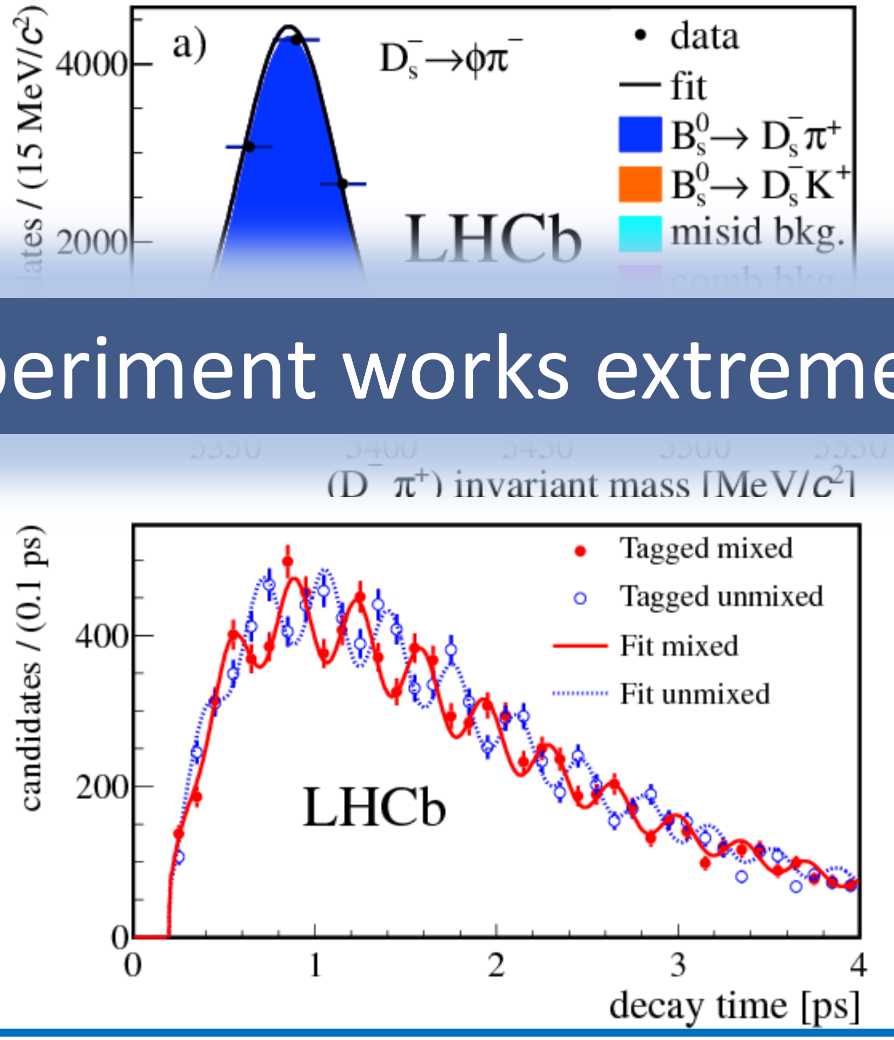
$B^0 - \overline{B^0}$ mixing

$B^0 \to D^-\pi^+$ **Phys.Lett.B719 (2013) 318**



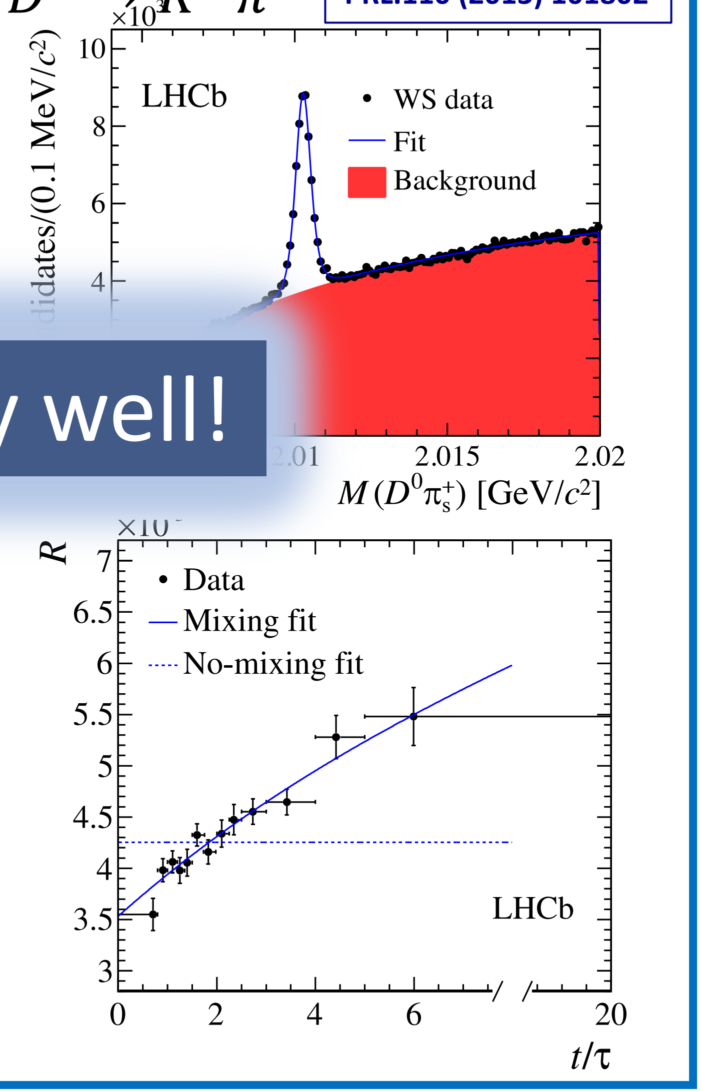
$B^0_s - \overline{B^0_s}$ mixing

$B^0_s \to D^-_s\pi^+$ **New.J.Phys.15 (2013) 053021**

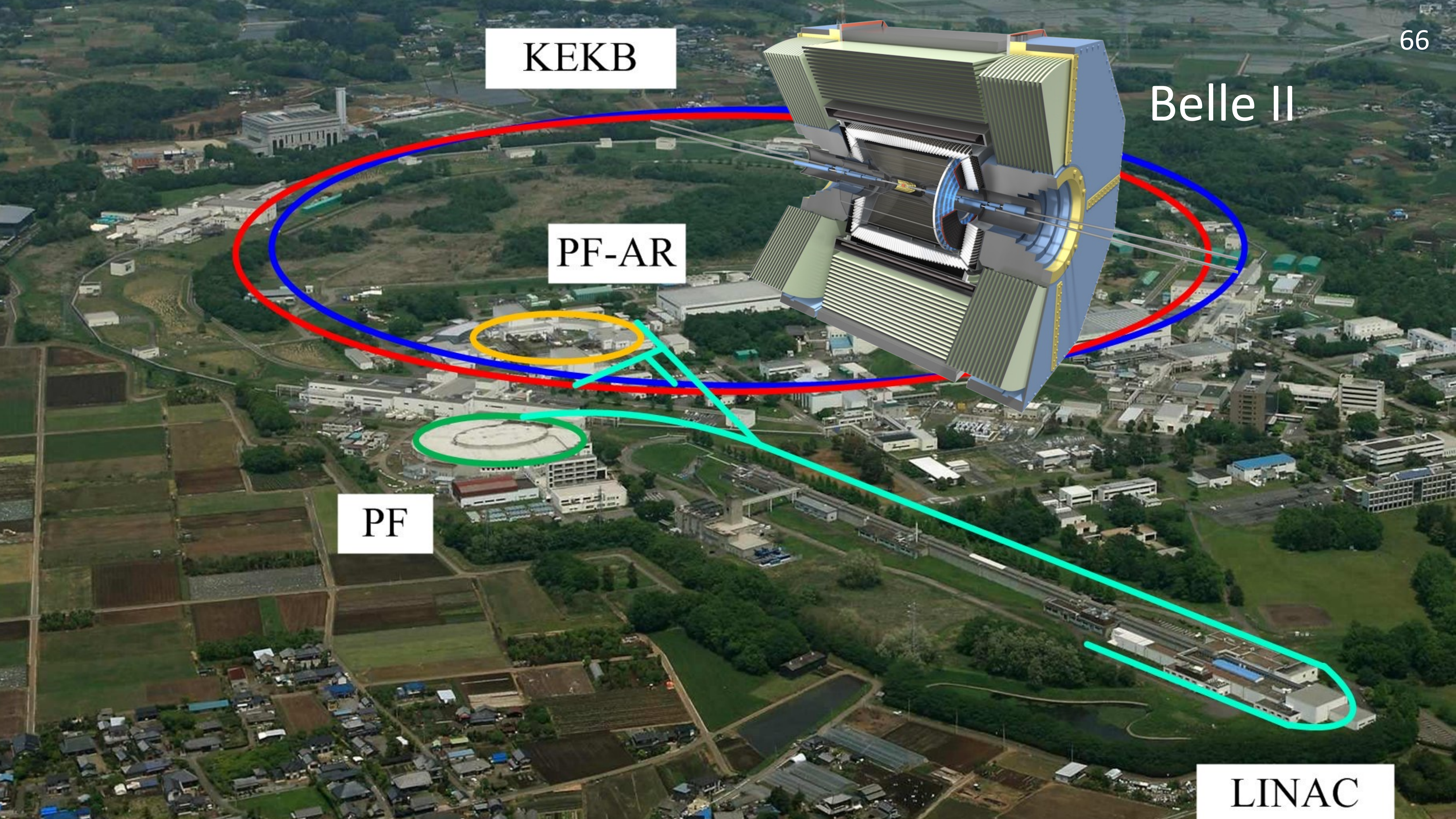


$D^0 \to \overline{D^0}$ mixing

$D^0 \to K^+\pi^-$ **PRL.110 (2013) 101802**



The Experiment works extremely well!

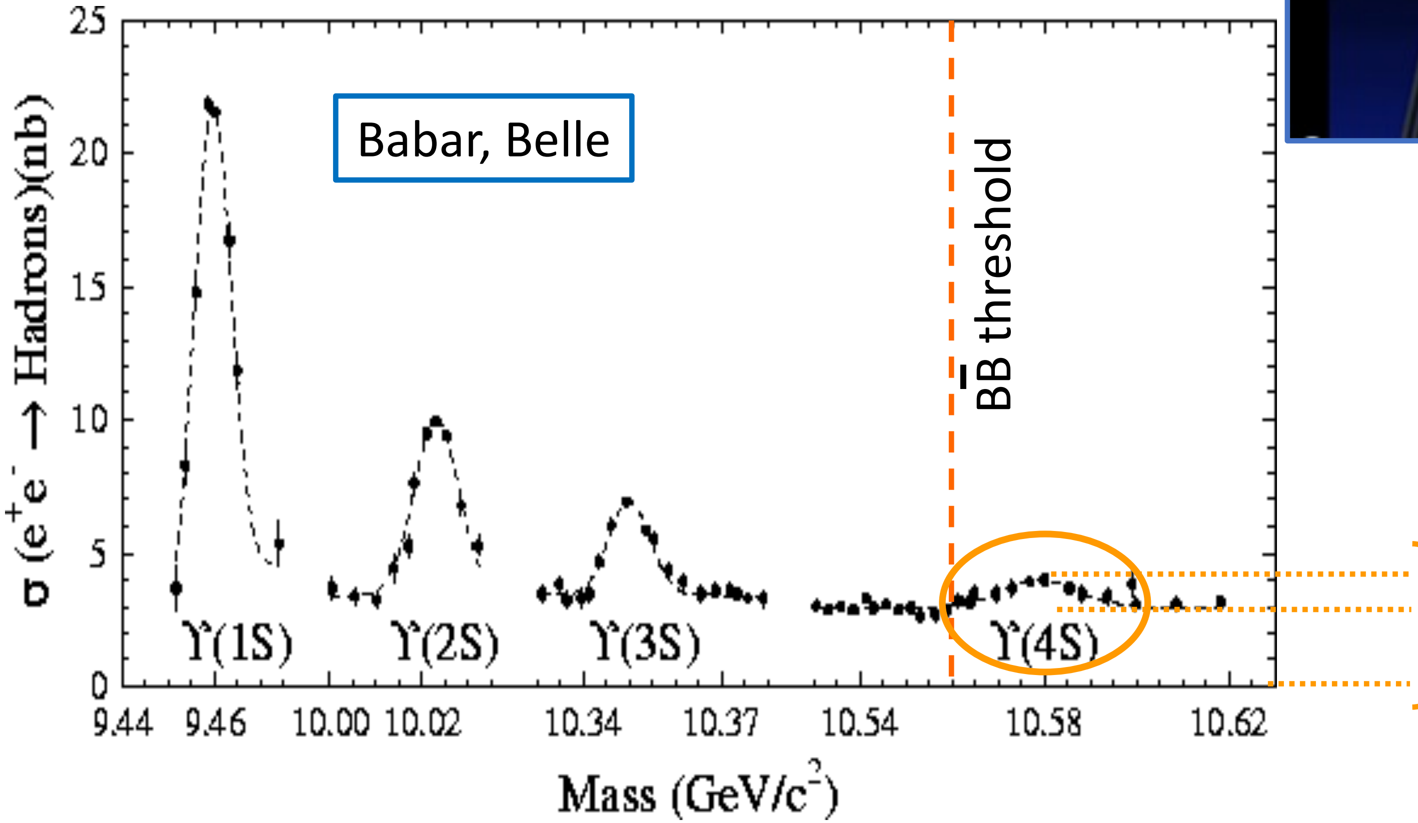

KEKB
Belle II
PF-AR
PF
LINAC

B meson production in e^+e^- Collisions

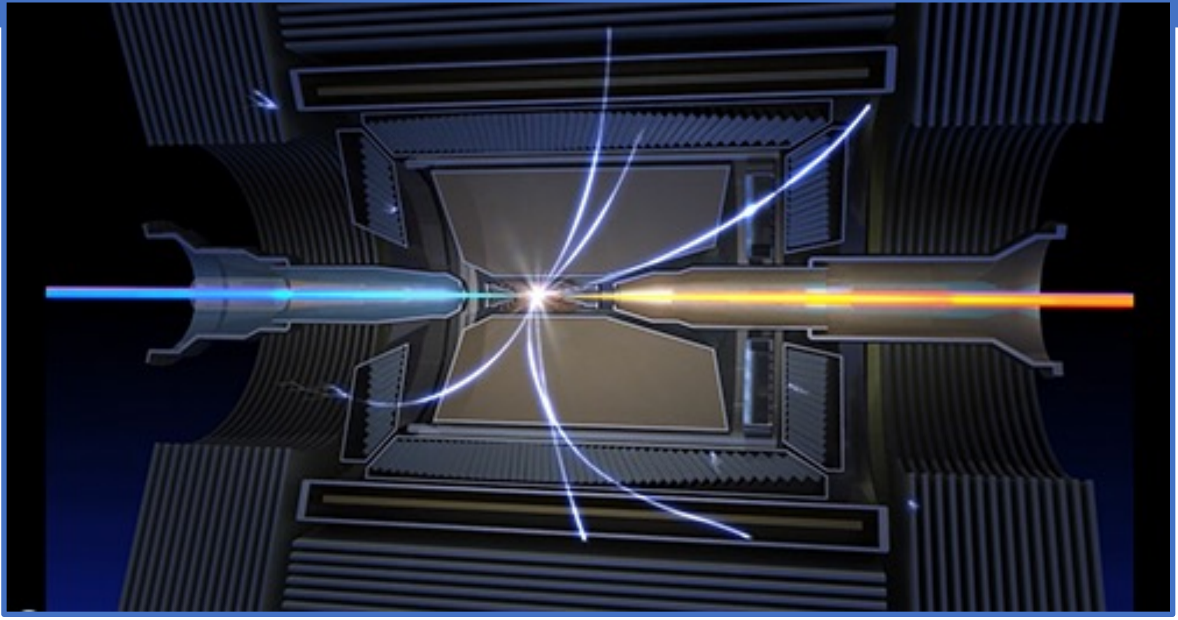
- Electron-Positron collider:

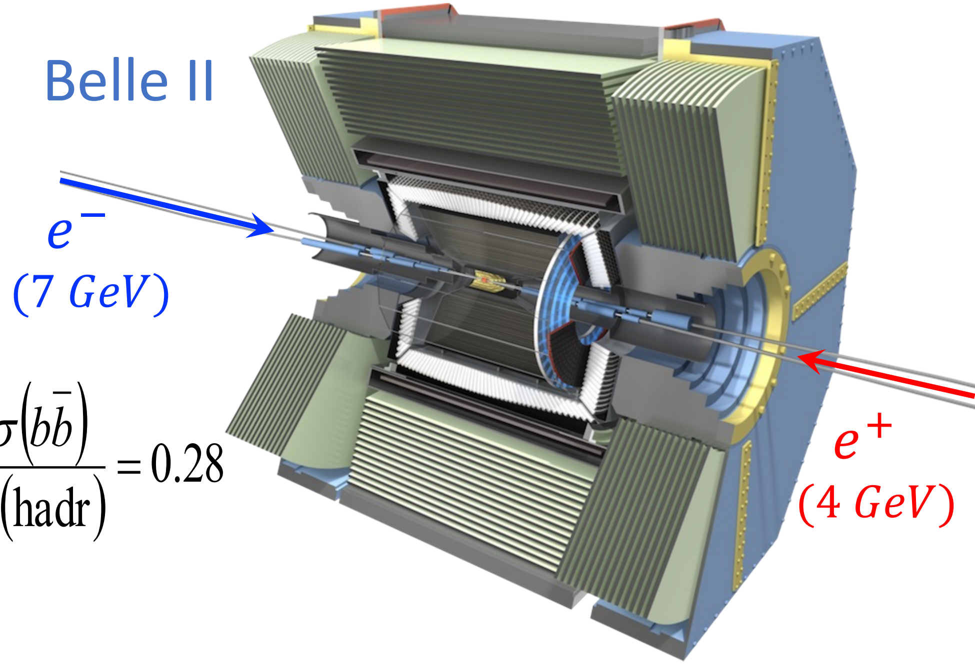
  $e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\overline{B^0}$

  - Only 4S resonance or higher produces B meson pair
  - Low B production cross-section: ~1 nb
  - Clean environment, *coherent* $B^0\overline{B^0}$ production



$$\frac{\sigma(b\bar{b})}{\sigma(\text{hadr})} = 0.28$$





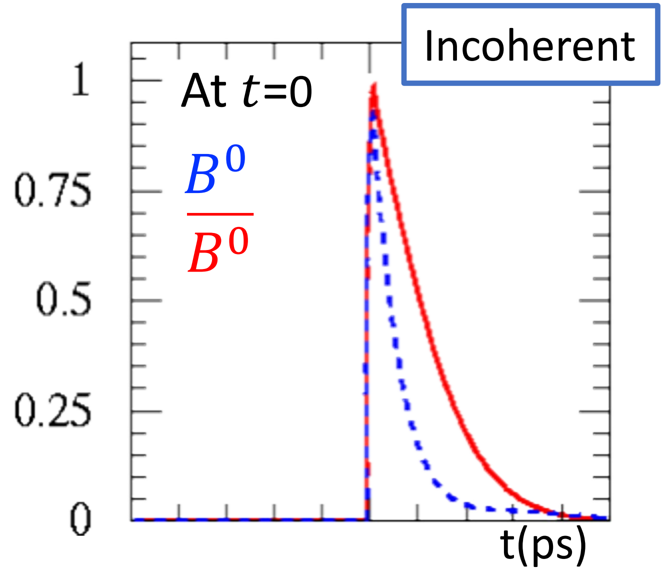
$\Upsilon(4S)$: Coherent B - $\overline{B}$ production

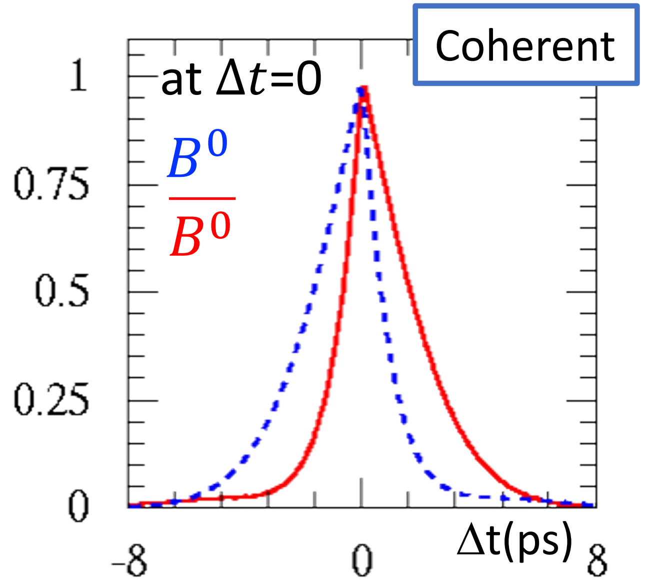
- Production at $\Upsilon(4S)$ $J^{PC} = 1^{--}$:

  $B^0\overline{B^0}$ system evolves coherently until one B decays (EPR!)

$$|\left(B^0\overline{B^0}\right)_{P=-}(t)\rangle = e^{-\Gamma_B t/2}\ \frac{1}{\sqrt{2}}\ |B^0(\vec{k})\,\overline{B^0}(-\vec{k})\rangle - |B^0(-\vec{k}\,)\,\overline{B^0}(\vec{k})\rangle$$

  - $P = -1$: Wave function is odd under particle exchange.
  - The first decay of the two B's "starts the clock".
  - Instead of flavour tag at production, B mesons have opposite flavour at the time the first meson decays.
    - Work with Δt
    - Half of the time the signal B *decays first* ($\Delta t < 0$)
  - Coherent production improves flavour tagging performance



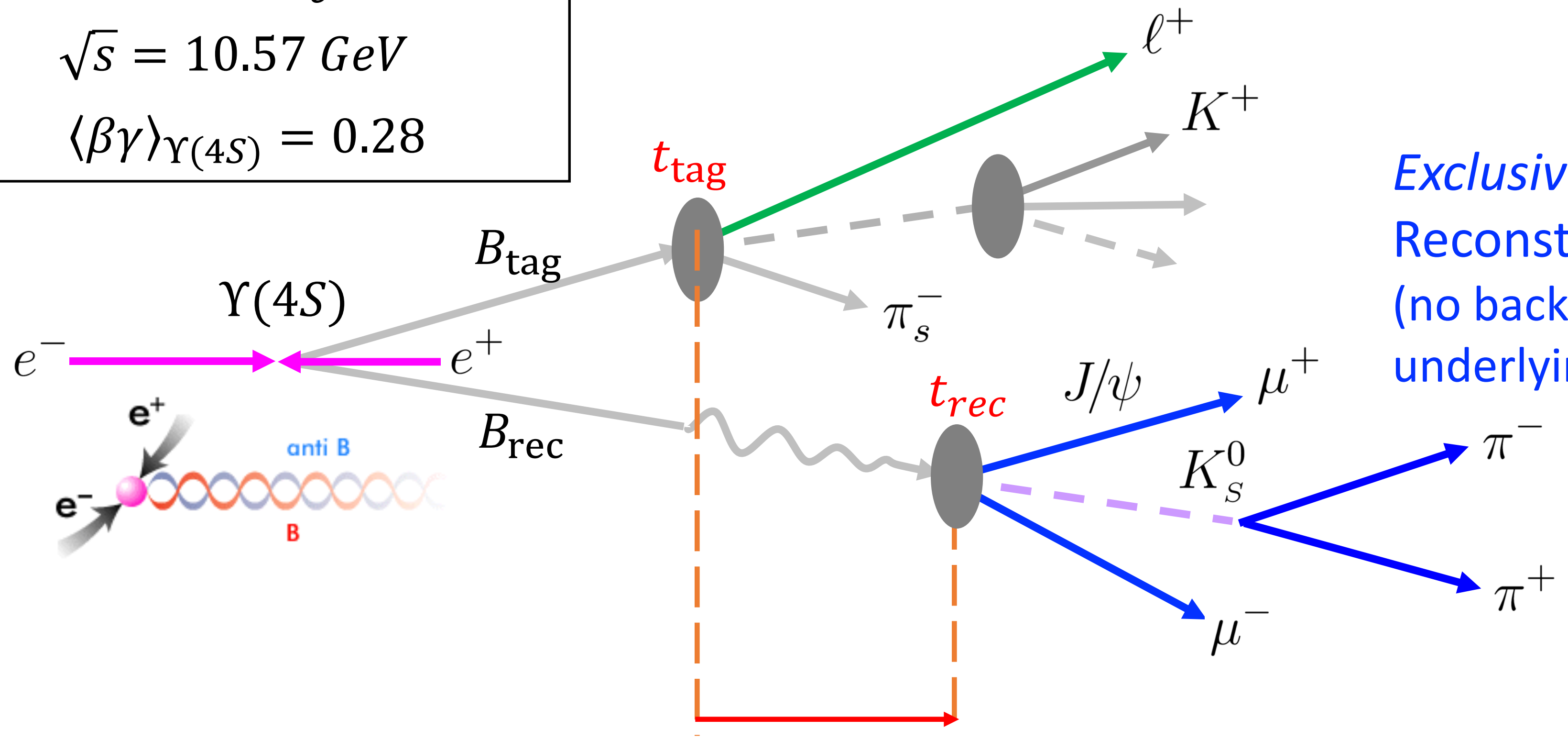


$\Upsilon(4S)$: Coherent B - $\overline{B}$ production (Babar & Belle)

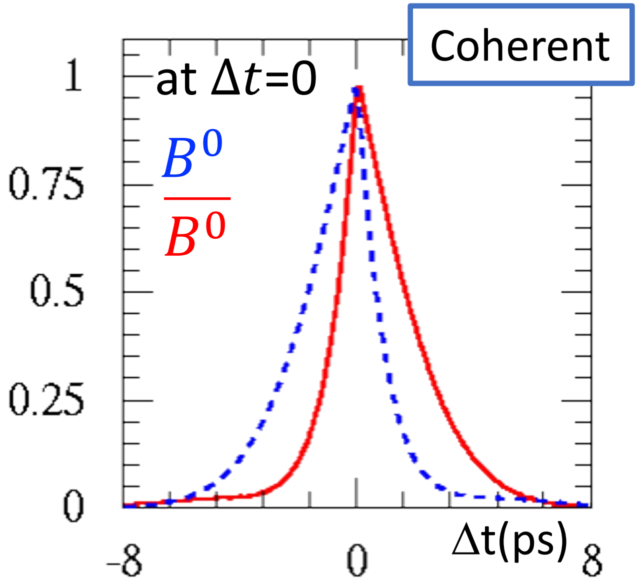
Belle II @ Super KEKB

$$E_{e^-} = 7\ GeV \quad ; \quad E_{e^-} = 4\ GeV$$
$$\sqrt{s} = 10.57\ GeV$$
$$\langle \beta\gamma \rangle_{\Upsilon(4S)} = 0.28$$

Flavour tagging of *other B*
(can be 100% pure)



Exclusive B meson
Reconstruction
(no backgrounds from
underlying event)

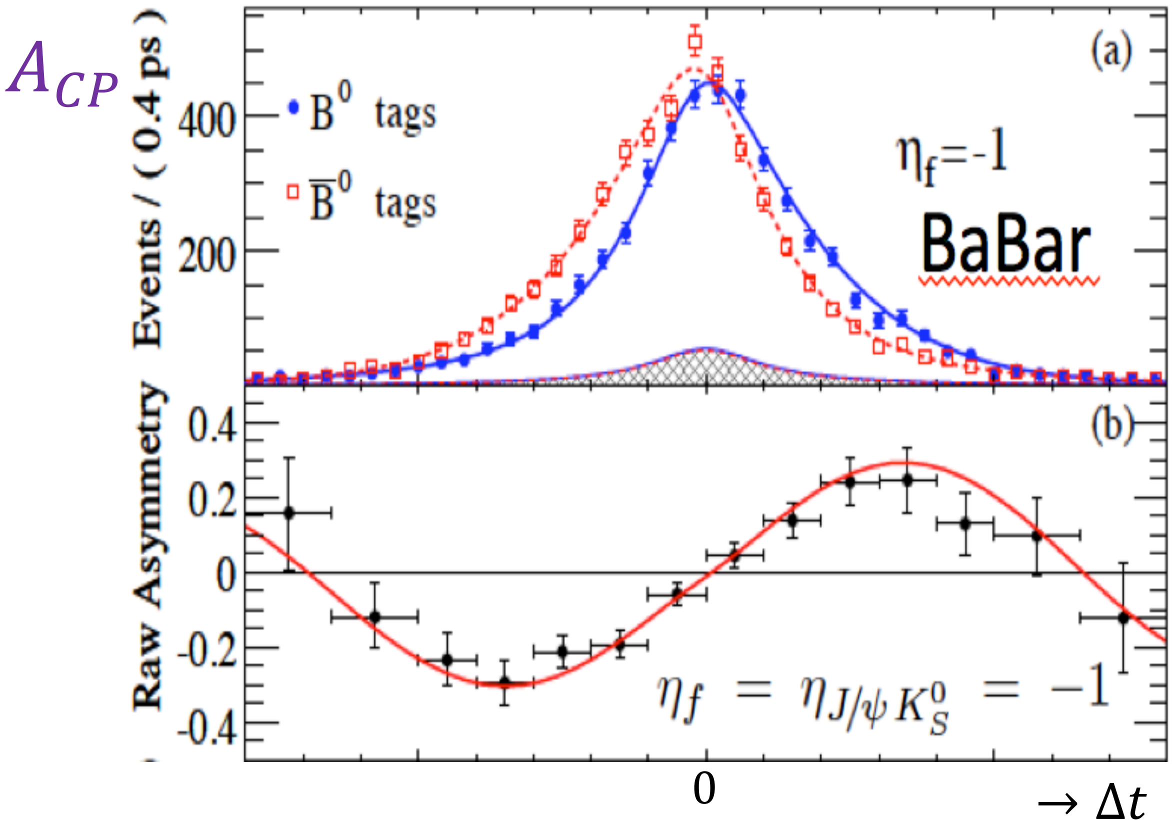


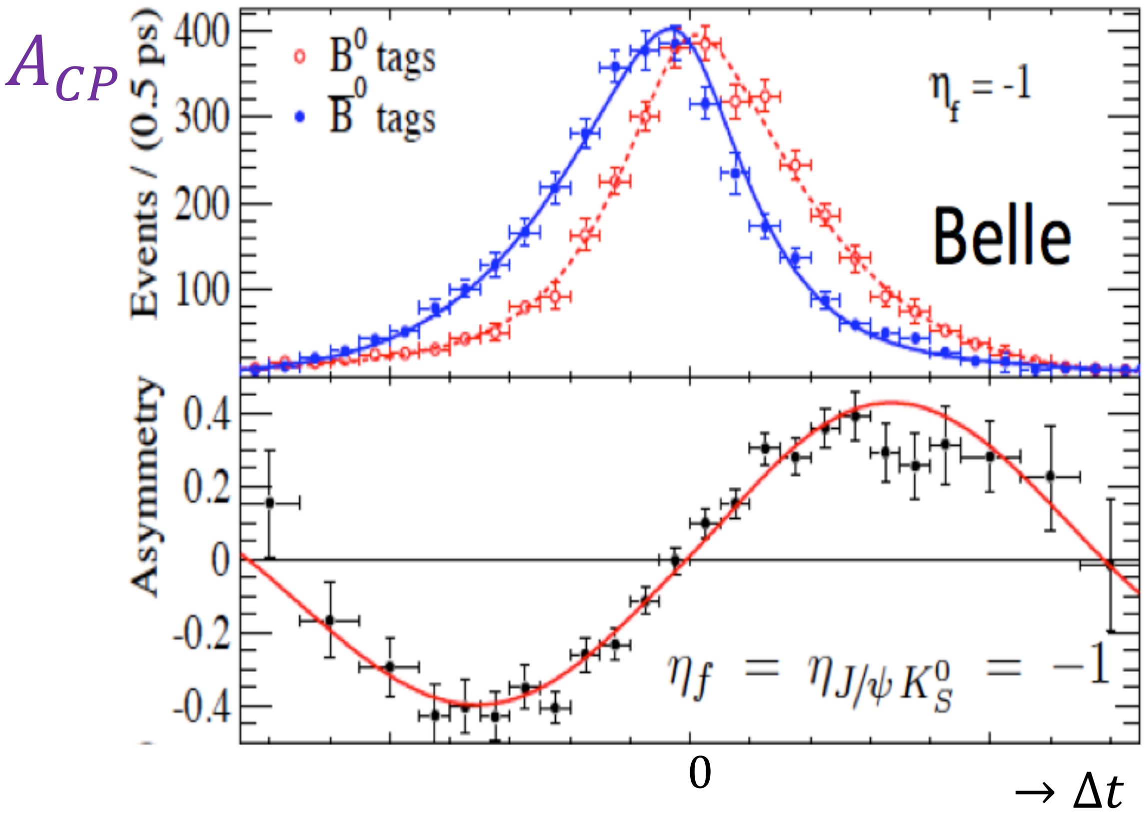
$$\Delta t \equiv t_{\text{rec}} - t_{\text{tag}}$$

Vertexing and time reconstruction

$\Delta t \approx {}^{\Delta z}/_{c\ \beta\gamma\Upsilon(4S)}$; $(\langle \Delta z \rangle \approx 130\ \mu\text{m})$

CP Asymmetry for "Golden" mode: $B^0 \to J/\psi\ K_S$





$$A_{CP}(t) = \sin 2\beta \sin \Delta m t$$

Babar: $\sin 2\beta = 0.657 \pm 0.036\ (\text{stat}) \pm 0.012\ (\text{syst})$

Belle: $\sin 2\beta = 0.670 \pm 0.029\ (\text{stat}) \pm 0.013\ (syst)$

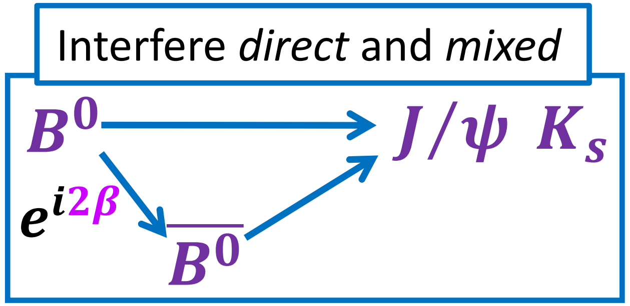
Babar & Belle

Compare LHC with B-factory for $B^0 \to J/\psi\ K_S$

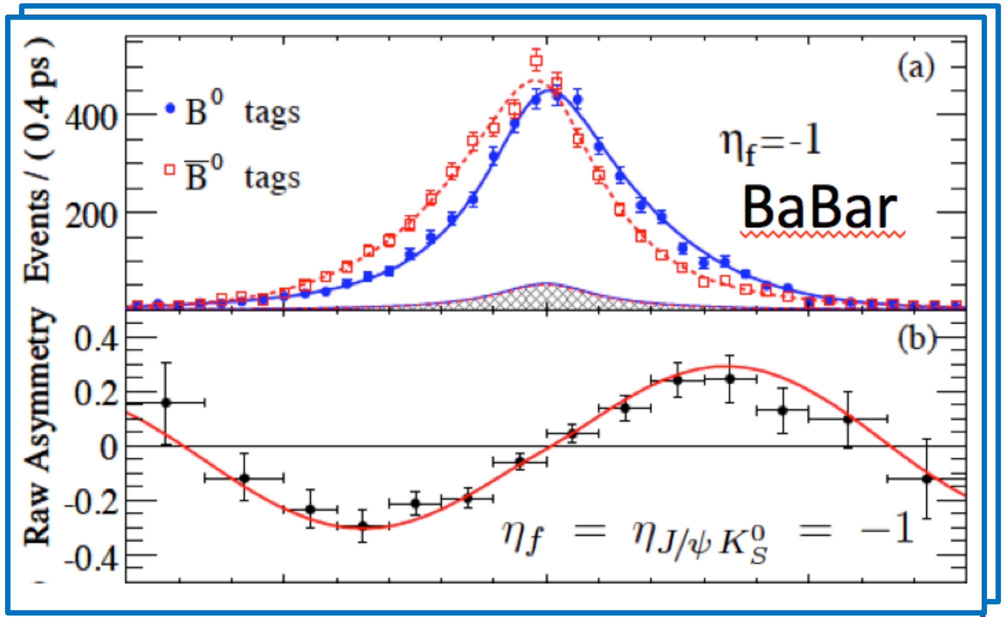
- *Decay-time dependent*

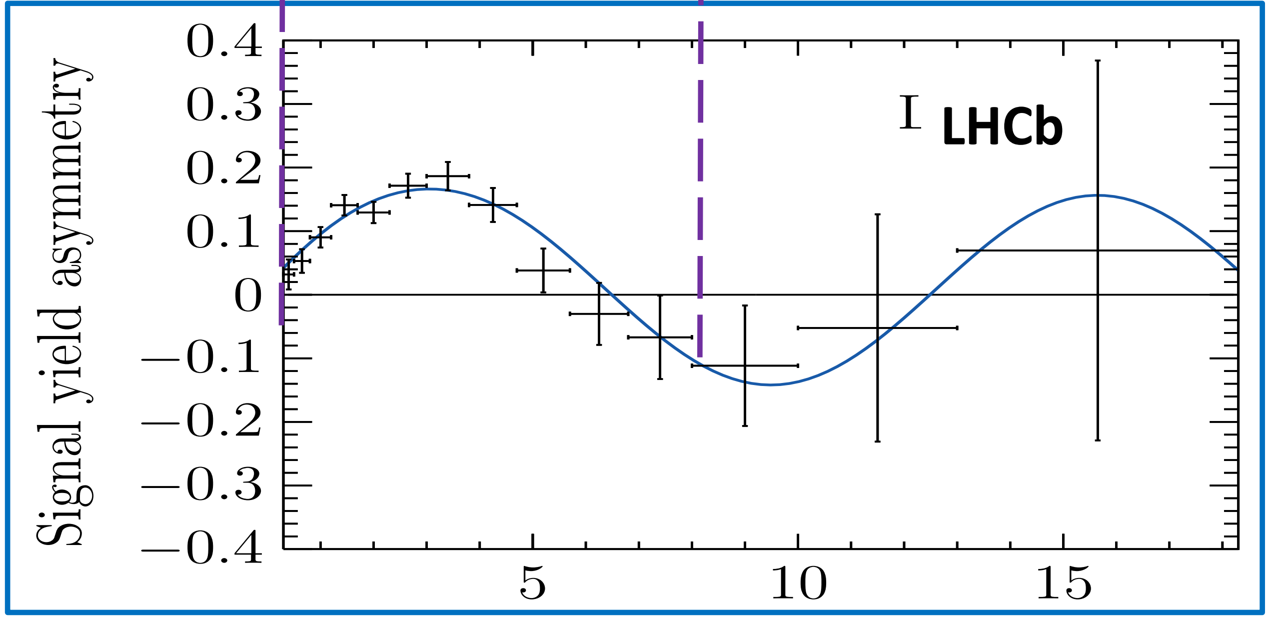
  CP violation:

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$



$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

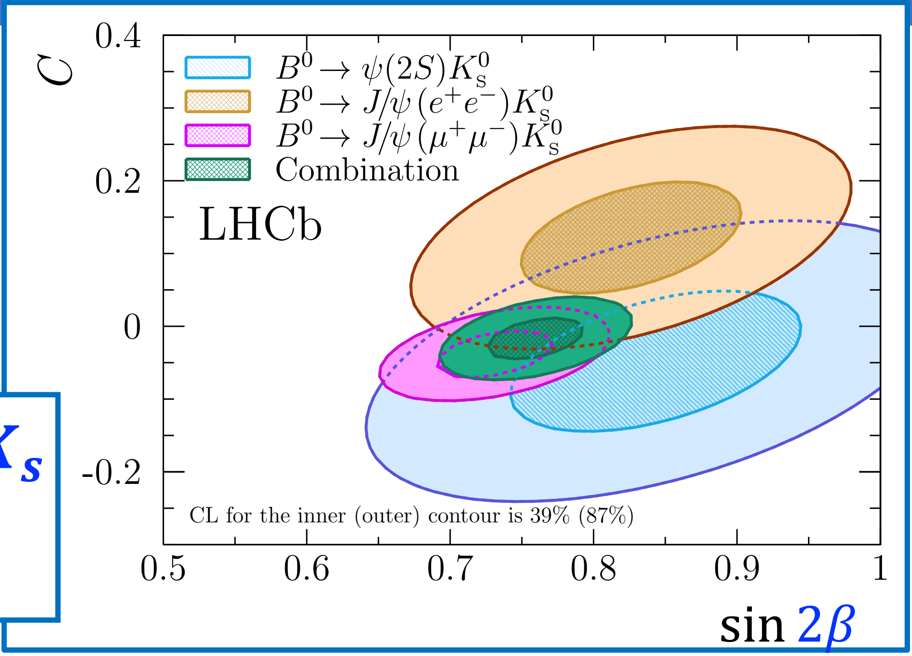


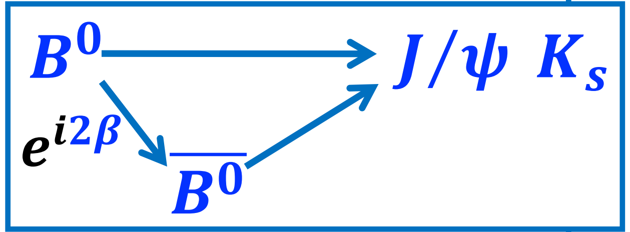


Decay time dependent CP violation

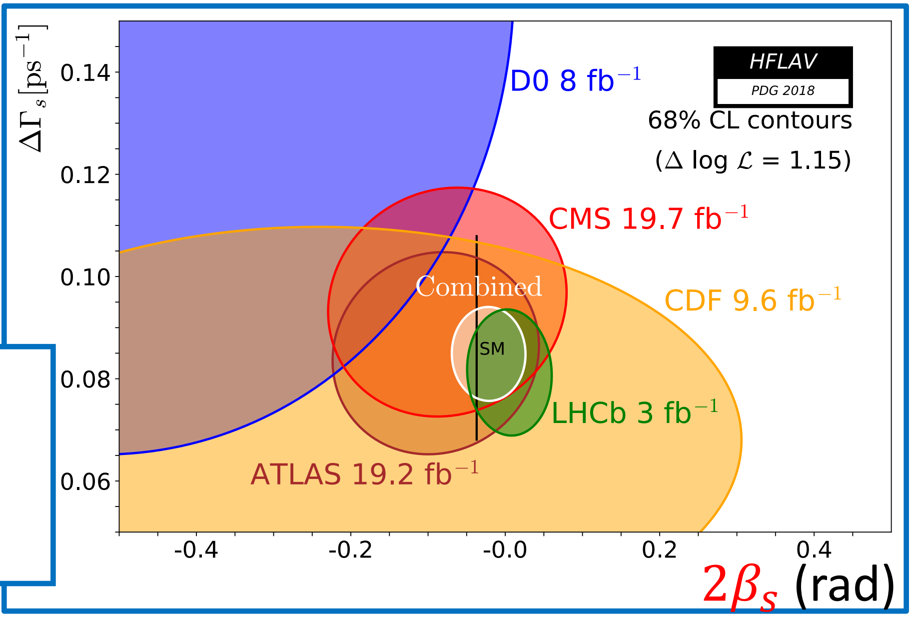
- $B^0 \to J/\psi\, K_s$ and $B_s^0 \to J/\psi\, \phi$

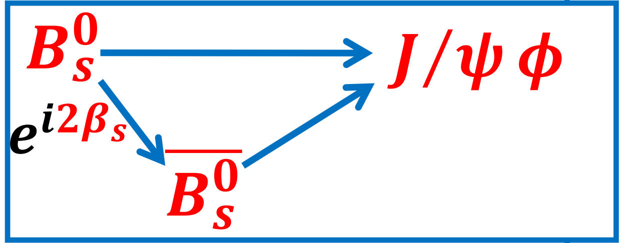
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_{(s)}\to f}(t) - \Gamma_{B_{(s)}\to f}(t)}{\Gamma_{B_{(s)}\to f}(t) + \Gamma_{B_{(s)}\to f}(t)}$$





$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



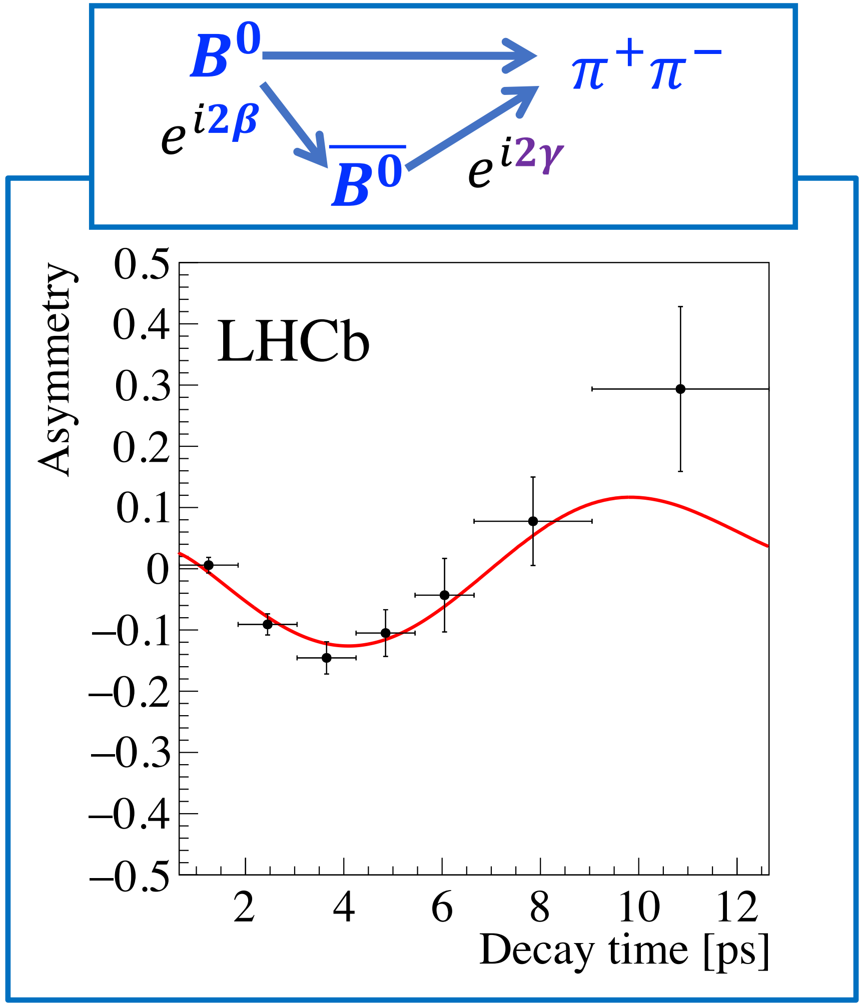


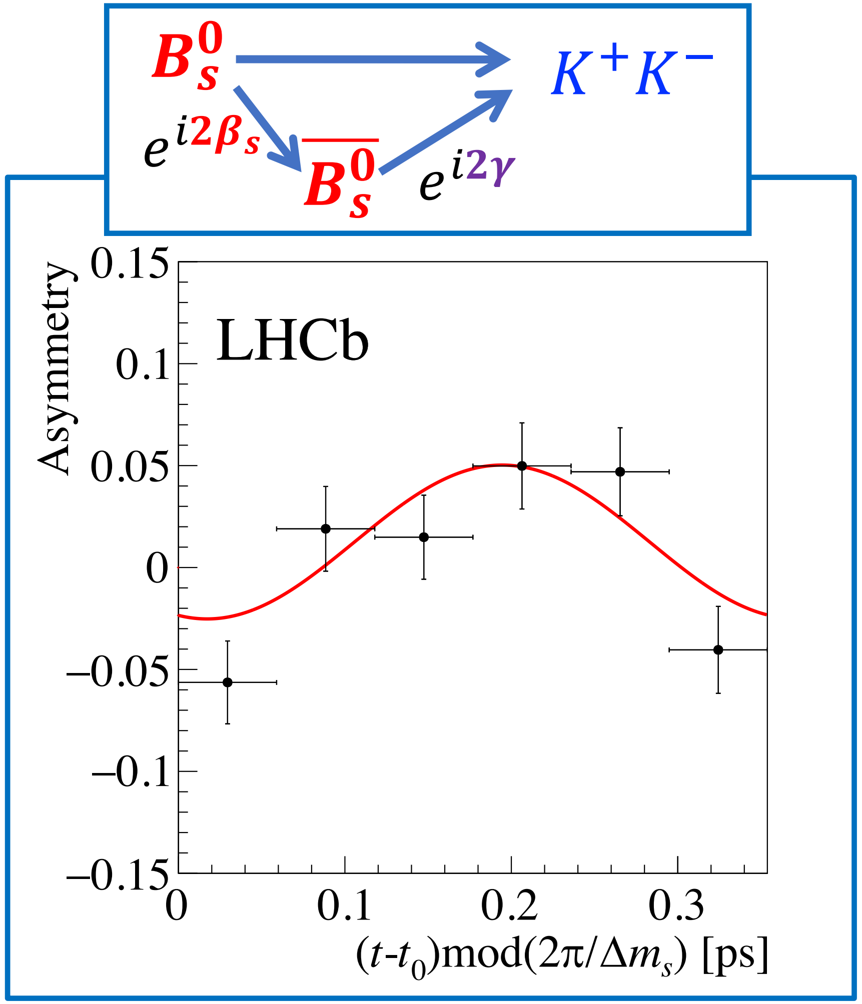
Decay time dependent CP violation

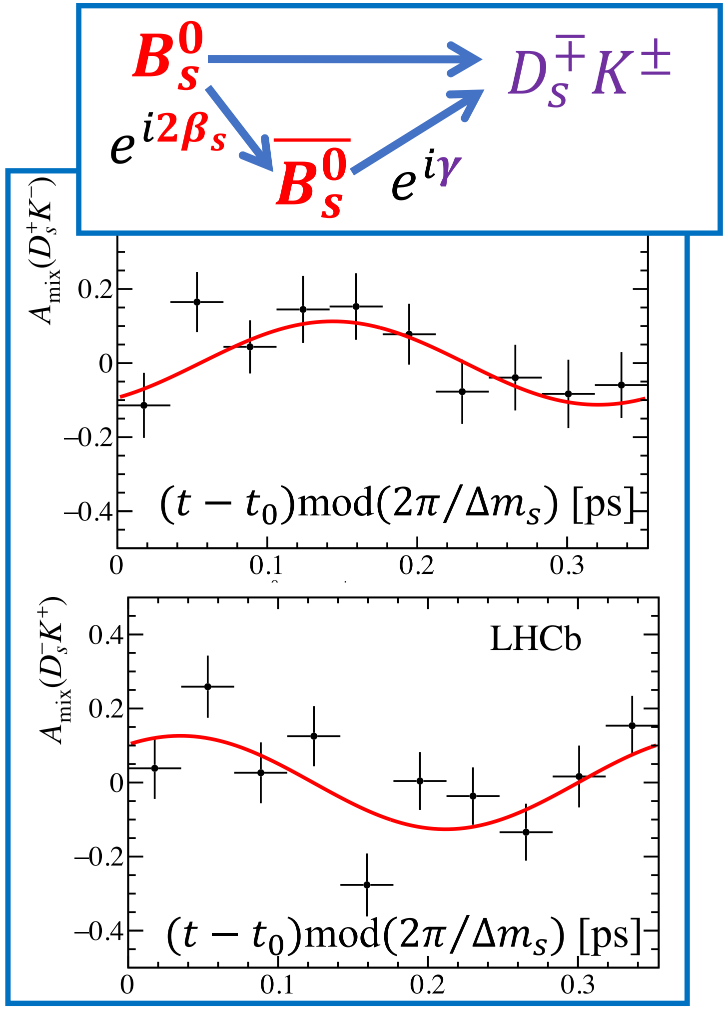
- *Hadronic decay modes (LHCb)*:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Note: $\alpha = \pi - (\beta + \gamma)$



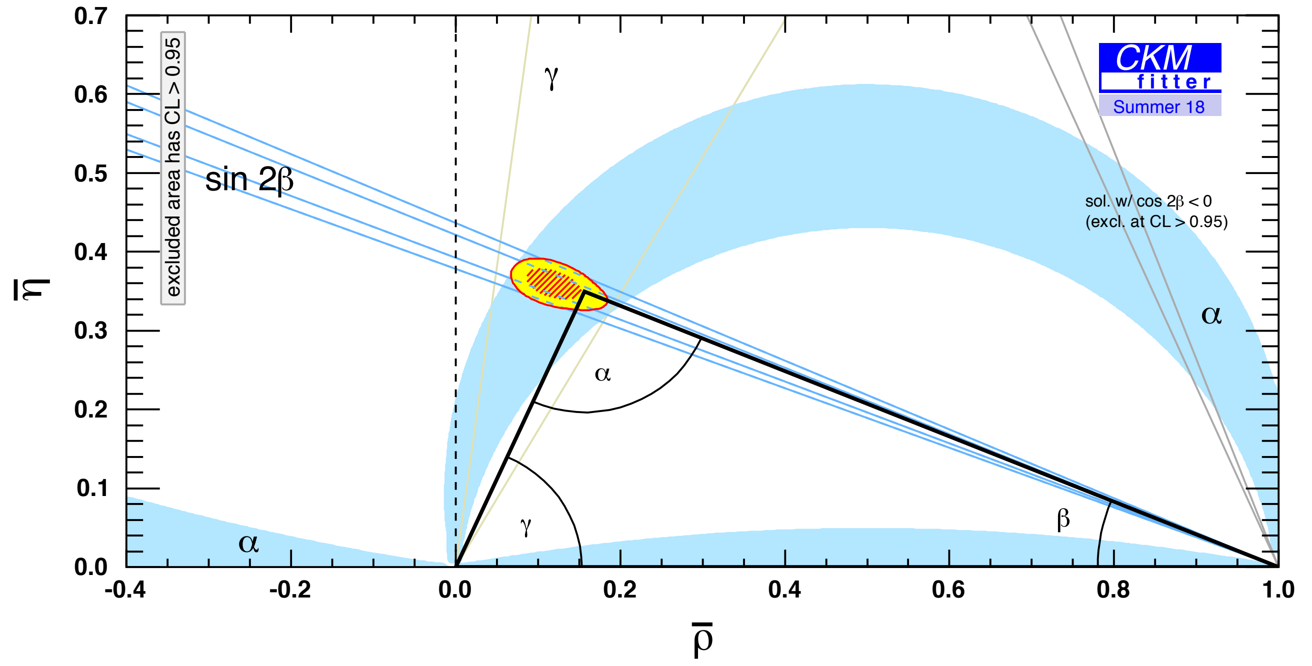


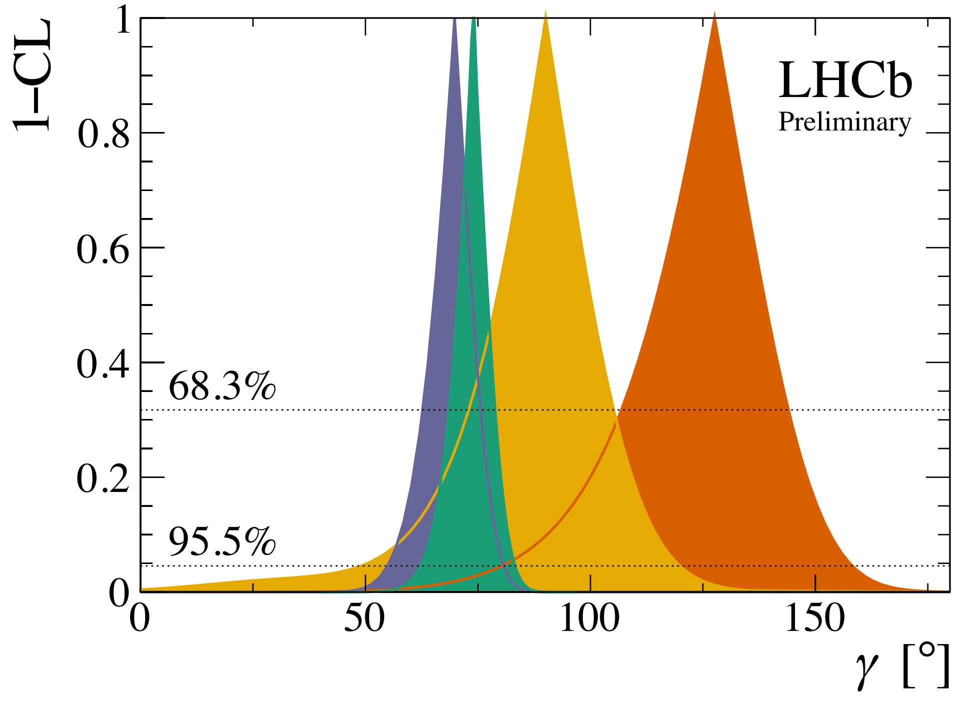


Current situation on angle γ

- The situation for angle γ :

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$





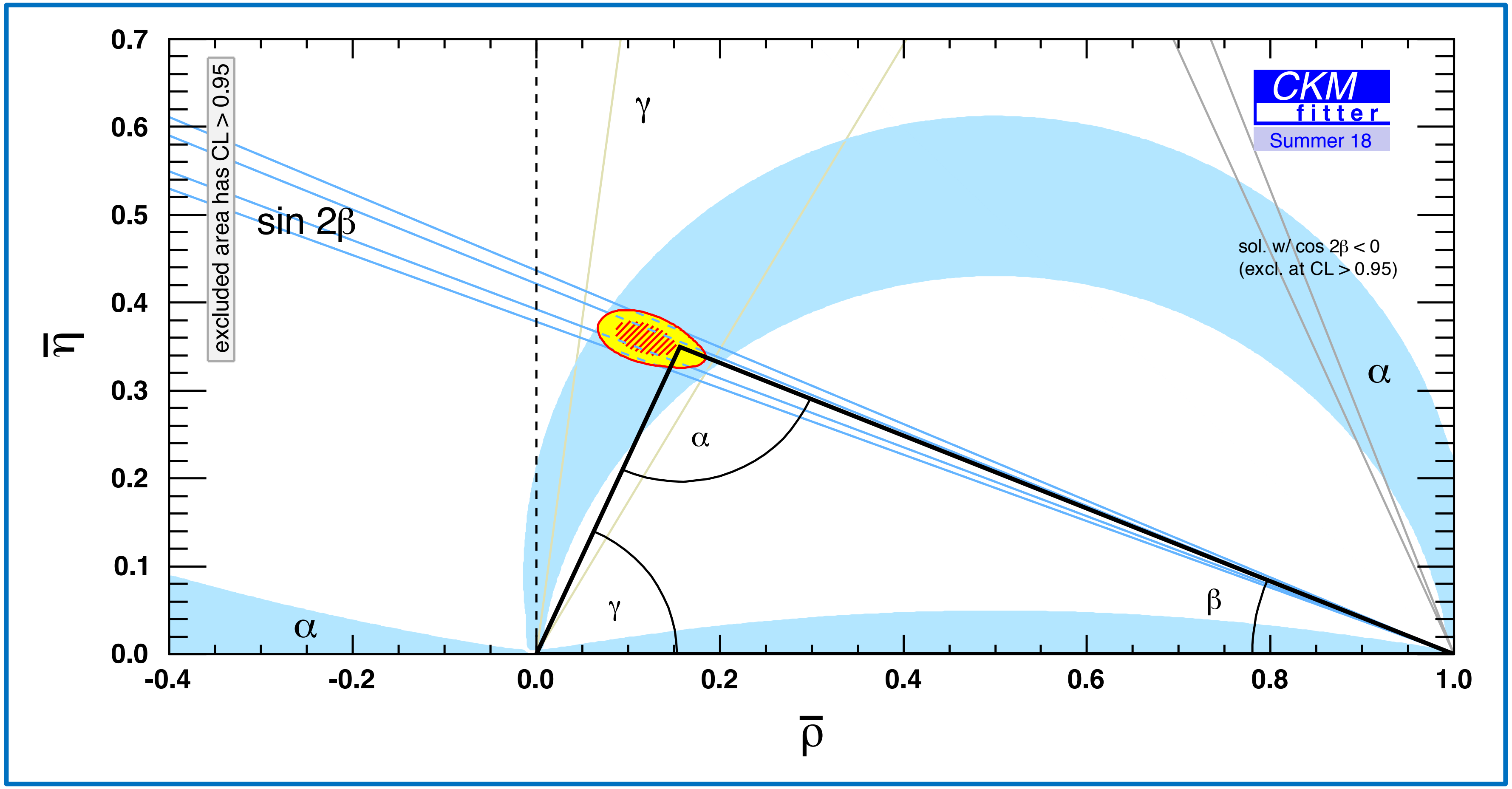
	B_s^0 decays
	B^0 decays
	B^+ decays
	Combination

Average:

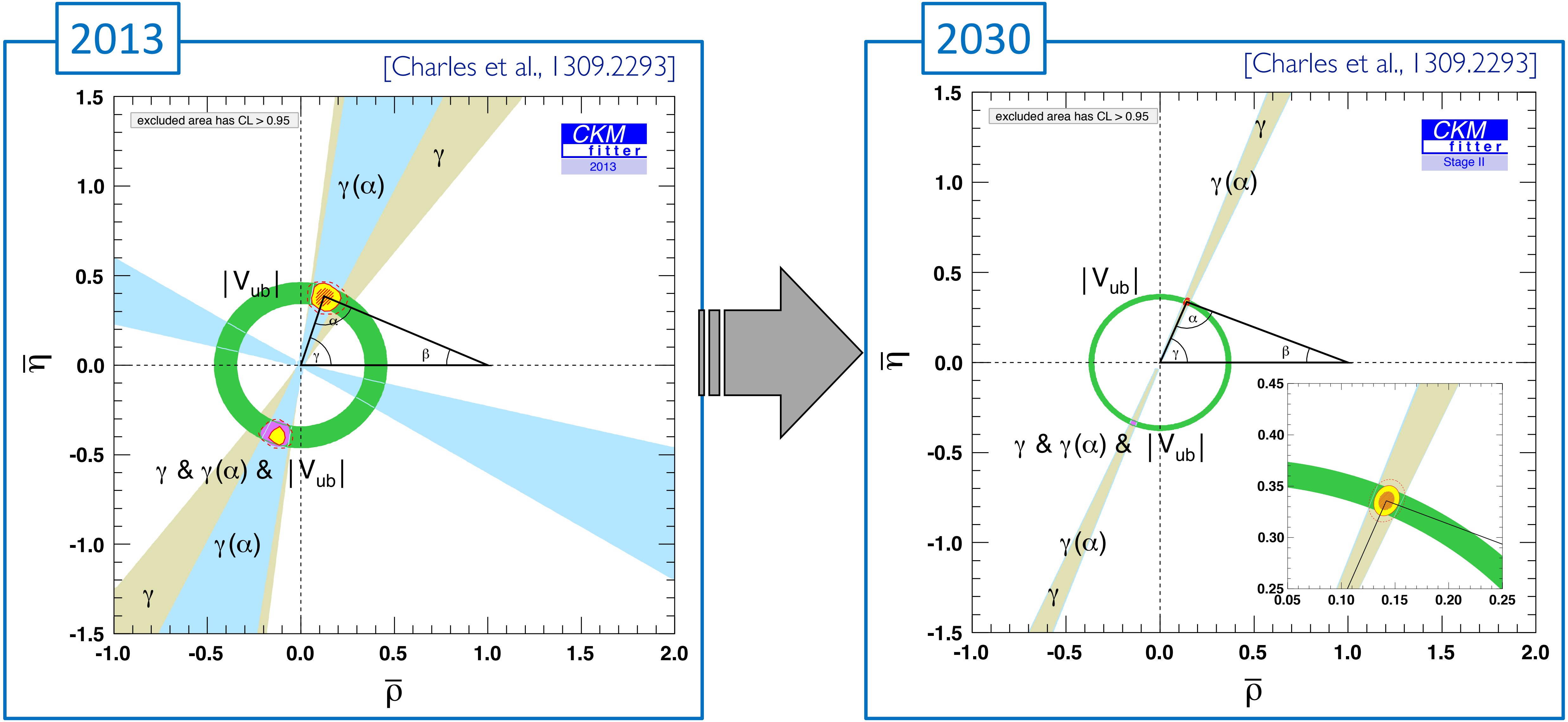
$$\gamma = \left(74.0^{+5.0}_{-5.8}\right)^o$$

CKM triangle: putting all measurements together

	Measured	CKMfitter prediction	UTfit prediction
β	22.7 ± 0.7	$23.7^{+1.1}_{-1.0}$	23.8 ± 1.4
γ	70.0 ± 4.2	$65.3^{+1.0}_{-2.5}$	65.8 ± 2.2
α	93.1 ± 5.6	$92.1^{+1.5}_{-1.1}$	90.1 ± 2.2

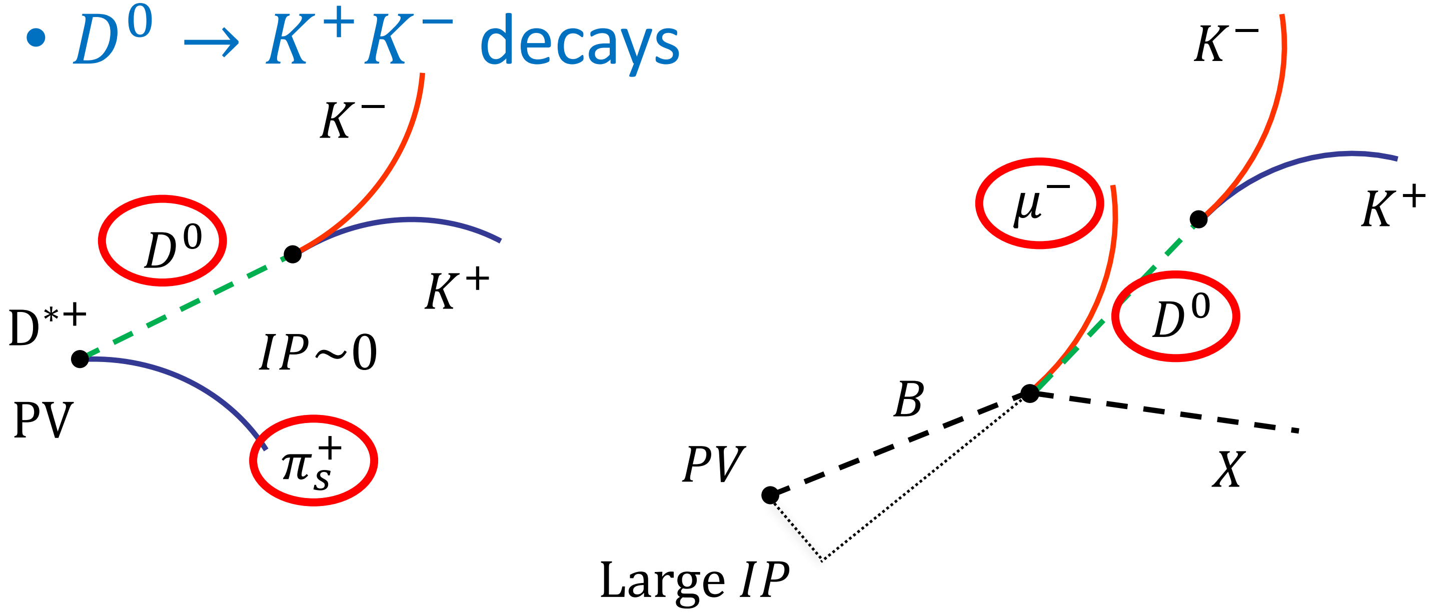


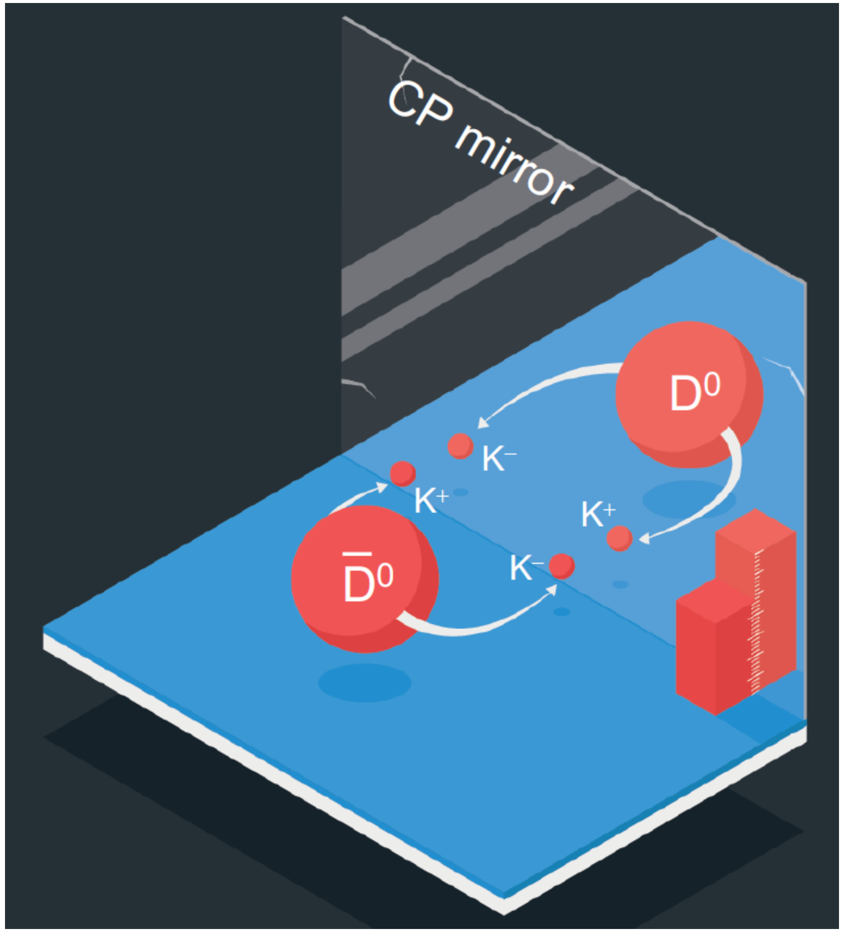
LHCb: Future sensitivity for CP violation



CPV in Kaons (K) and Beauty (B): How about Charm (D)?

- $D^0 \to K^+K^-$ decays



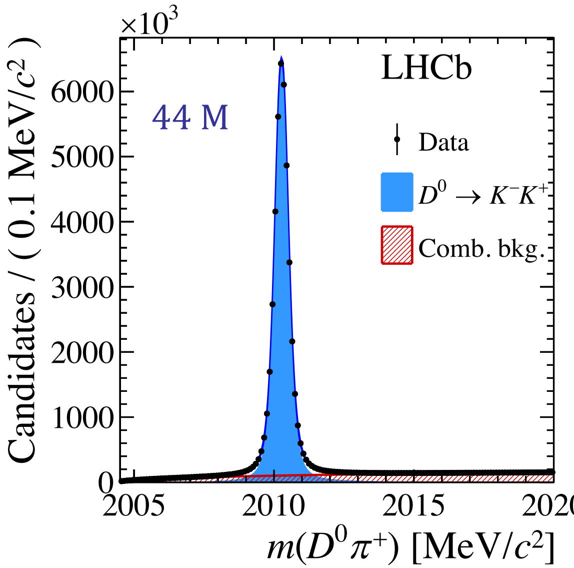


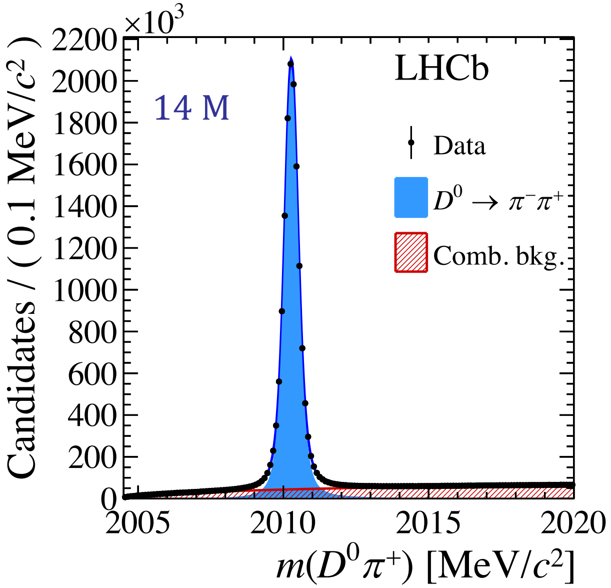
$$A_{raw}(K^+K^-) = \frac{N(D^0 \to K^+K^-) - N(\bar{D}^0 \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\bar{D}^0 \to K^+K^-)}$$

$$A_{raw}(K^+K^-) = A_{CP}(K^+K^-) + A_D(K^+K^-) + A_D(\pi_s) + A_P(D^{*+})$$

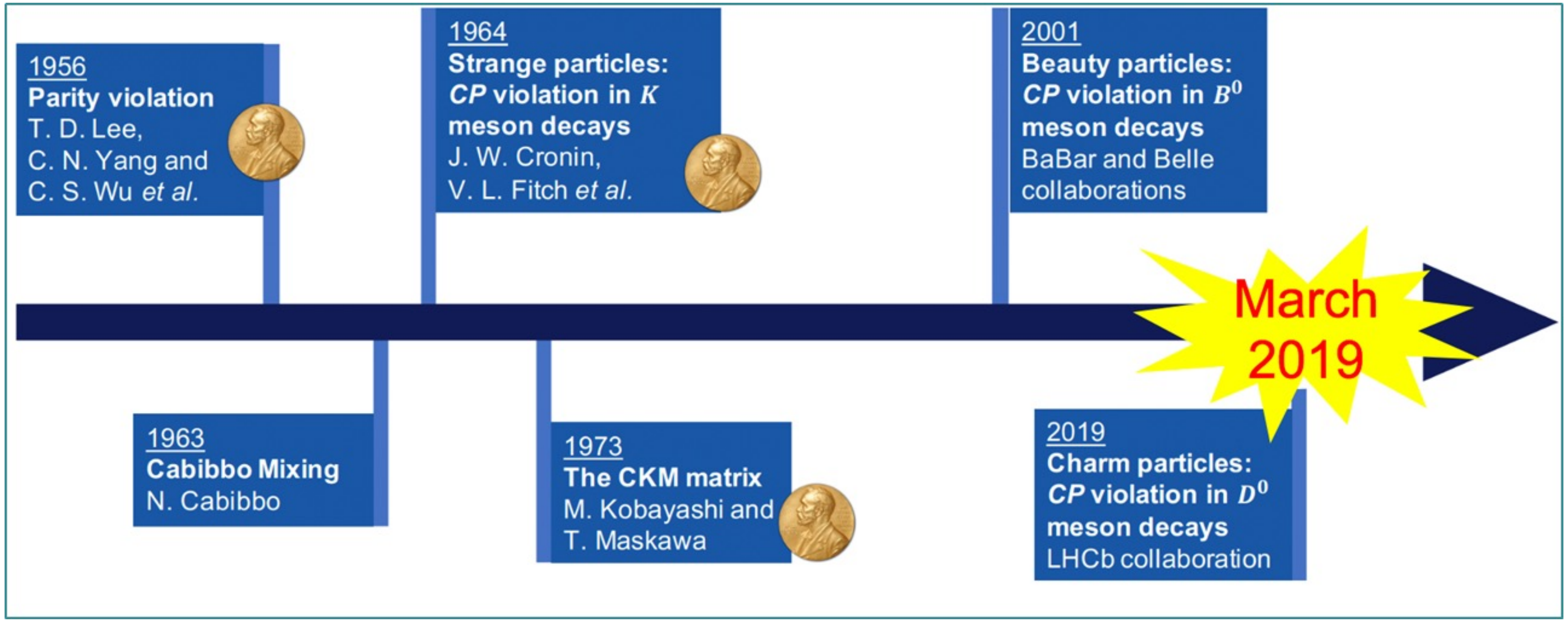
- Look at: $\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$
  - ⇒ All detection and production asymmetries cancel
  - ⇒ Directly observe CP asymmetry!

2019: Discovery of CP violation in charm mesons!





- Result: $\Delta A_{CP} = (-15.8 \pm 2.9)\times 10^{-4}$
- 5.3σ Observation!
- Is it consistent with CKM in Standard Model?



Design your own B-meson CP Violation Experiment

- Which type of machine would you use?
  - e^+e^- or pp , pp or $p\overline{p}$ collider or fixed target? Why?
- At which energy do you want to run this machine?
- You will measure CP asymmetry in $B_s \to D_s^{\mp}K^{\pm}$with BR=10^{-4}
  - Estimate how many collisions you need for a precision of γ=1^{o}
- You measure $B_s \to D_s^{\mp}K^{\pm}$ and $\overline{B_s} \to D_s^{\mp}K^{\pm}$
  - How do you determine the flavour of the B_s at production?
  - Are there intrinsic limits to this precision?
  - How would you calibrate the wrong tag fraction?
- There is a potential large background from another B_s-decay.
  - Do you know which it could be?
  - With which detector technology would you remove this background?
- What is the formula to reconstruct the B_s meson decay time in an event in observable quantities?
  - Which subdetectors would you require to measure it?

Design your own B-meson CP Violation Experiment

- Which type of machine would you use?
- e^+e^- or pp , pp or $p\overline{p}$ collider or fixed target? Why?
- At which energy do you want to run this machine?

- Points to consider:
  - e^+e^- at $\Upsilon(4S)$: electromagnetic production, clean, *no* B_s, coherent production: B^0 only time dependent CPV, requires asymmetric beams, good flavor tagging.
  - e^+e^- at $\Upsilon(5S)$: B_s, lower cross section, no resolution for time dependent CPV.
  - e^+e^- at Z-peak. Weak production, not coherent, interesting…?
  - pp collisions: Strong production and lots of stat's, "messy" events, large backgrounds requiring excellent detectors.
  - Fixed target vs collider: low cross section vs long decay distance.
    - b-quark cross section increases with high energy
  - pp vs $p\overline{p}$: "colour drag" asymmetry. Extra cross check for pp.

Design your own B-meson CP Violation Experiment

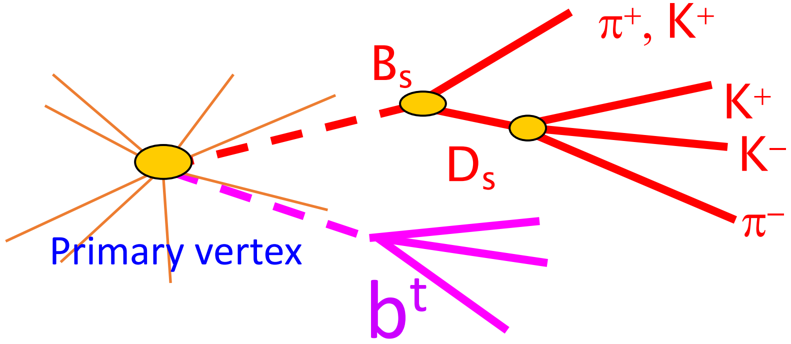
- You will measure CP asymmetry in $B_s \to D_s^{\mp} K^{\pm}$ with BR=10^{-4}.
  - Estimate how many collisions you need for a precision of γ=1°
  - B_s mesons: Let's assume pp collisions at LHC using LHCb

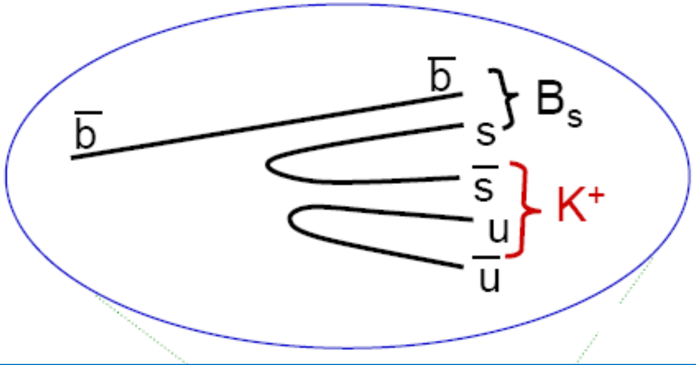
- For ~1% measurement precision (0.01) on asymmetry:
  - Number of perfectly measured $B_s \to D_s^{\mp} K^{\pm}$ events:
    - N ~ 10.000
  - Fraction of collisions that produce b-quarks:
    - ~ 1 in 100
  - Fraction of events where B_s meson is produced from b-quark:
    - 1 in 10
  - Fraction of B_s that decay into $B_s \to D_s^{\mp} K^{\pm}$ channel
    - 1 in 5000 (BR = 2 x 10^{-4})
- ➔ So in total ~ 10.000 x 100 x 10 x 5000 = 5 x 10^{10} perfectly reconstructed events required

- Next, assumed measured by the LHCb experiment:
  - Acceptance x Reconstruction (background, resolution):
    - 1 in 40
  - Trigger:
    - 1 in 3
  - Tagging Power:
    - 4% → 1 in 25
- In total 5 x 10^{10} x 40 x 3 x 25 = 1.5 x 10^{14} pp collisions must be collected
- Assume ~10 MHz collisions, 3 x 10^{6} s/year running time: ~ 5 years of running.

Design your own B-meson CP Violation Experiment

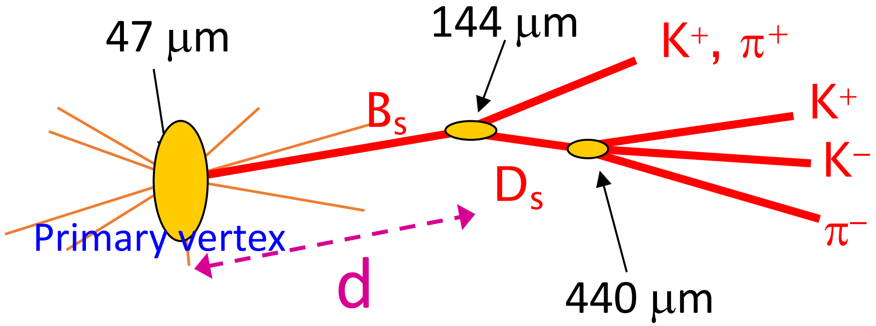
- You measure $B_s \to D_s^{\mp} K^{\pm}$ and $\overline{B_s} \to D_s^{\mp} K^{\pm}$
  - How do you determine the flavour of the B_s at production?
    - Opposite side tag:
      - charge of lepton from b-decay, charge of kaon from b-decay, vertex charge.
    - Same side tag: “closest” kaon in the color string.
  - Are there intrinsic limits to this precision?
    - B-mixing of neutral B:
      - Charged B^+, B^- =perfect, B_d^0= ok-ish, B_s^0 = no information
  - How would you calibrate the wrong tag fraction?
    - Use $B_s \to D_s^- \pi^+$ and $\overline{B_s} \to D_s^+ \pi^-$ Mixing asymmetry has amplitude 1 → calibrate.





Design your own B-meson CP Violation Experiment

- There is a potential large background from another B_s-decay.
  - Do you know which it could be?
    - $B_s \to D_s\pi$
  - With which detector technology would you remove this background?
    - π – K seperation using RICH particle identification
- What is the formula to reconstruct the B_s meson decay time in an event in observable quantities?
    - $t = md/p$
  - Which subdetectors would you require to measure it?
    - $d \;\to$ Vertex detector
    - $p \;\to$ Magnet Tracker
    - $m \to B$ meson mass



Decay time resolution = 40 fs

Contents Yesterday & Today:

1. CP Violation
   a) Discrete Symmetries
   b) CP Violation in the Standard Model
   c) Jarlskog Invariant and Baryogenesis
2. B-Mixing
   a) CP violation and Interference
   b) B-mixing and time dependent CP violation
   c) Experimental Aspects: LHC vs B-factory