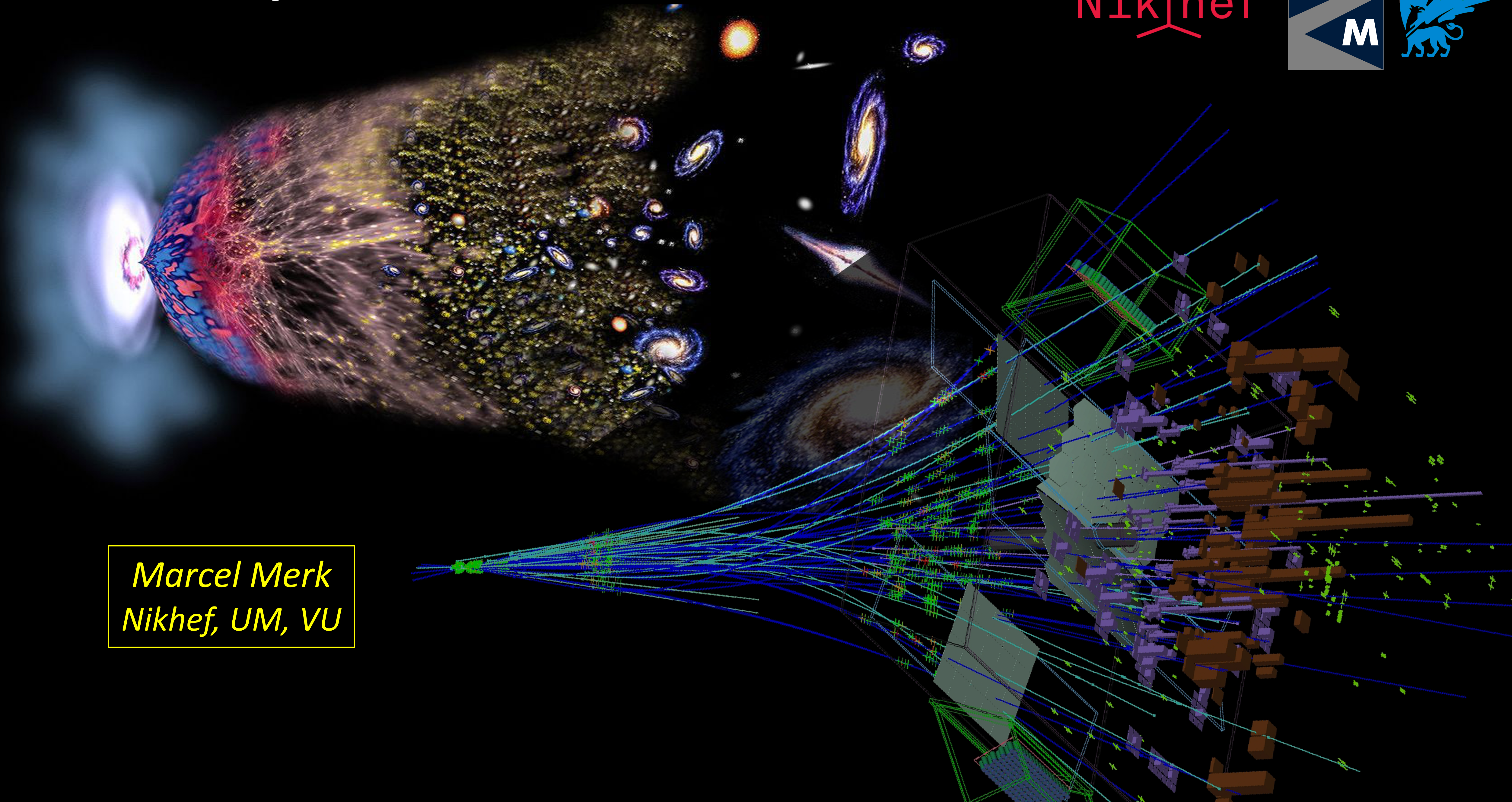
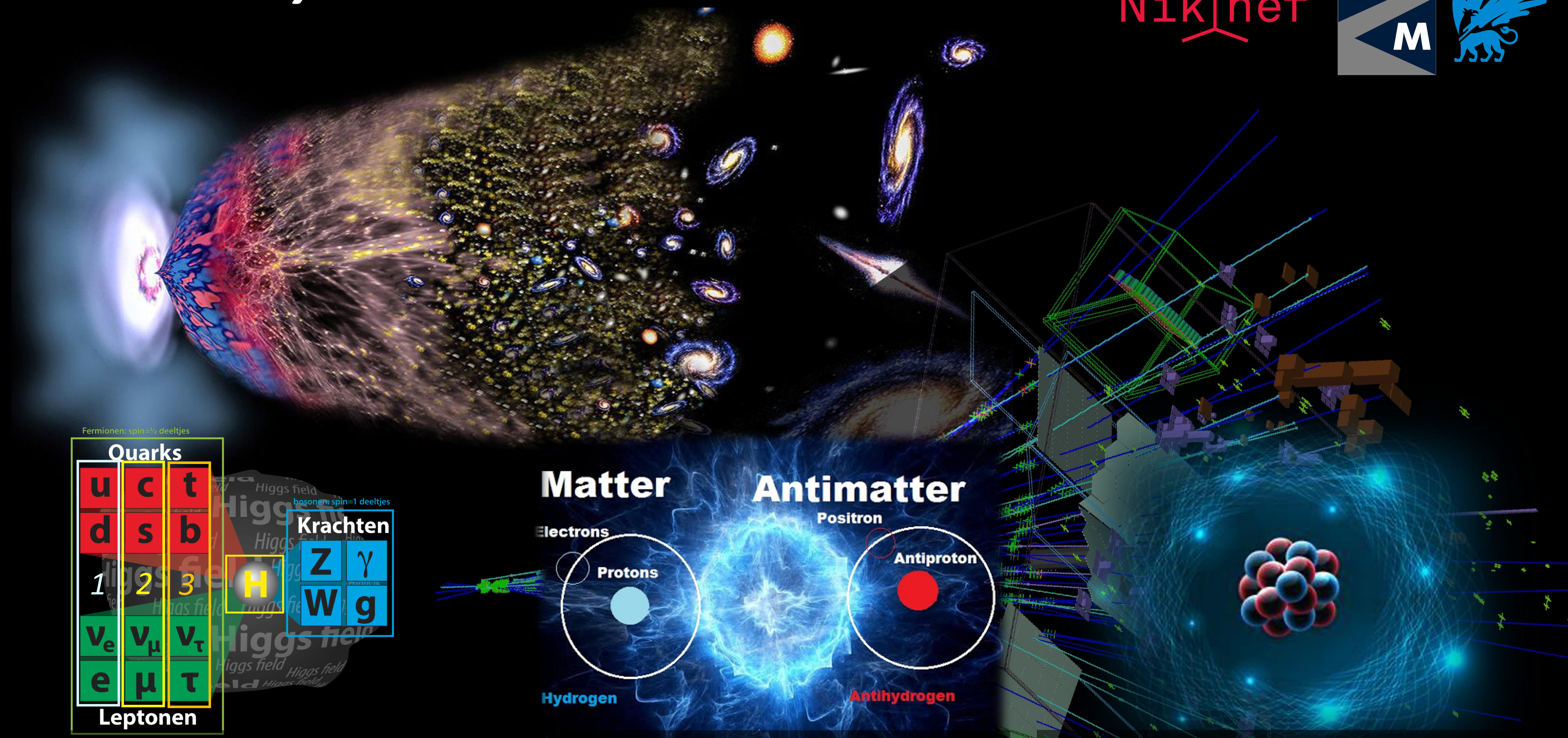
Flavour Physics and CP Violation



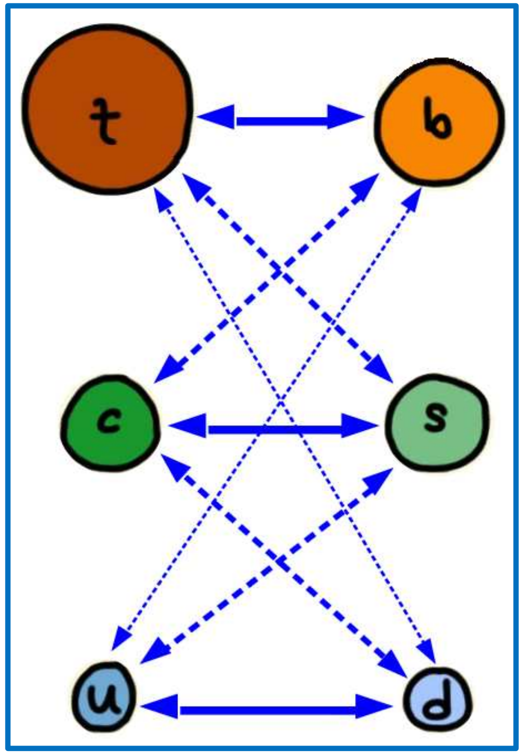
Marcel Merk
Nikhef, UM, VU

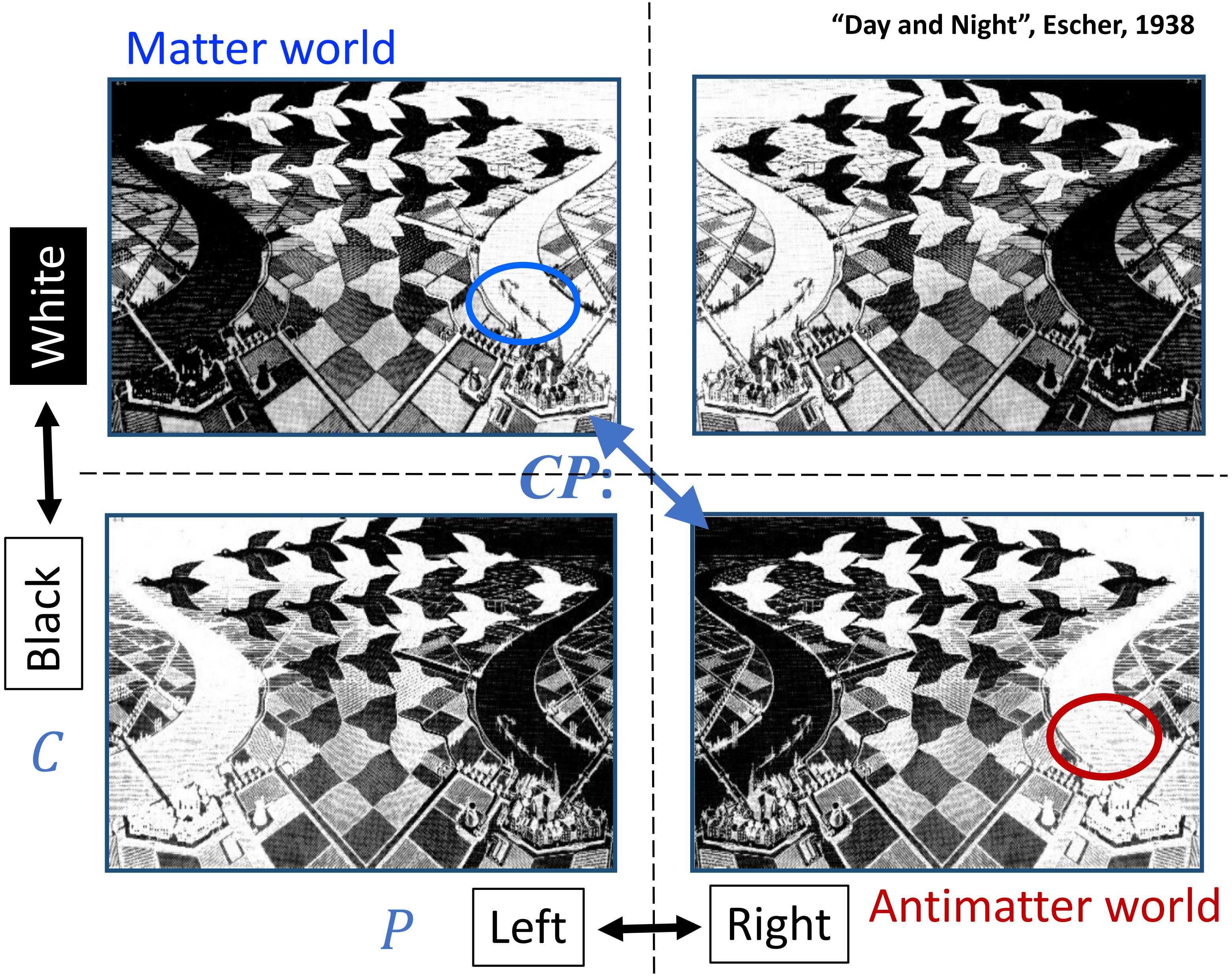
Flavour Physics and CP Violation



Why three generations of particles? ***Why is there no antimatter?*** ***Why is an atom electric neutral?***

Recap: Flavour Physics and CP Violation

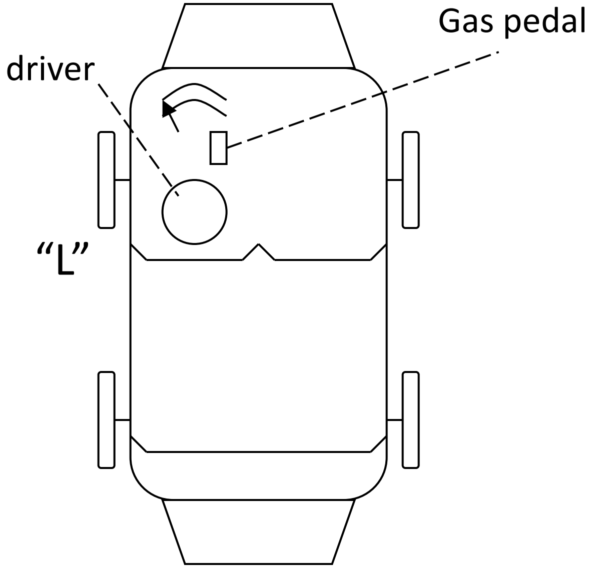




Recap: Broken Symmetry and Unobservables: Parity

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

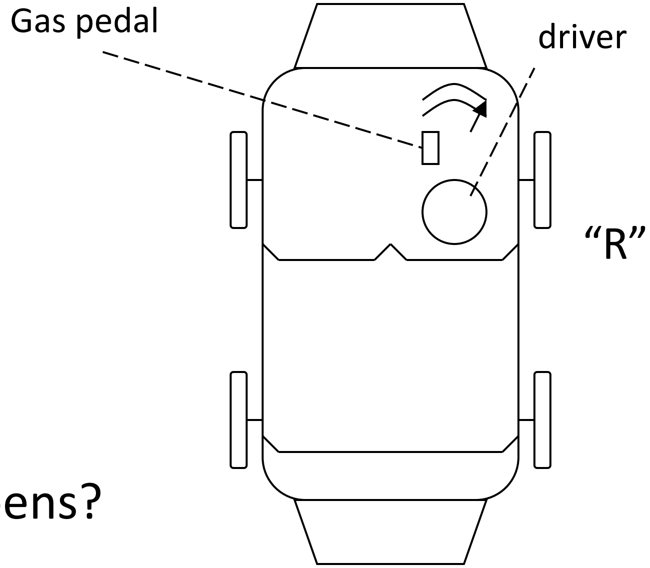
A "gedanken" experiment: consider two perfectly mirror symmetric cars:



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

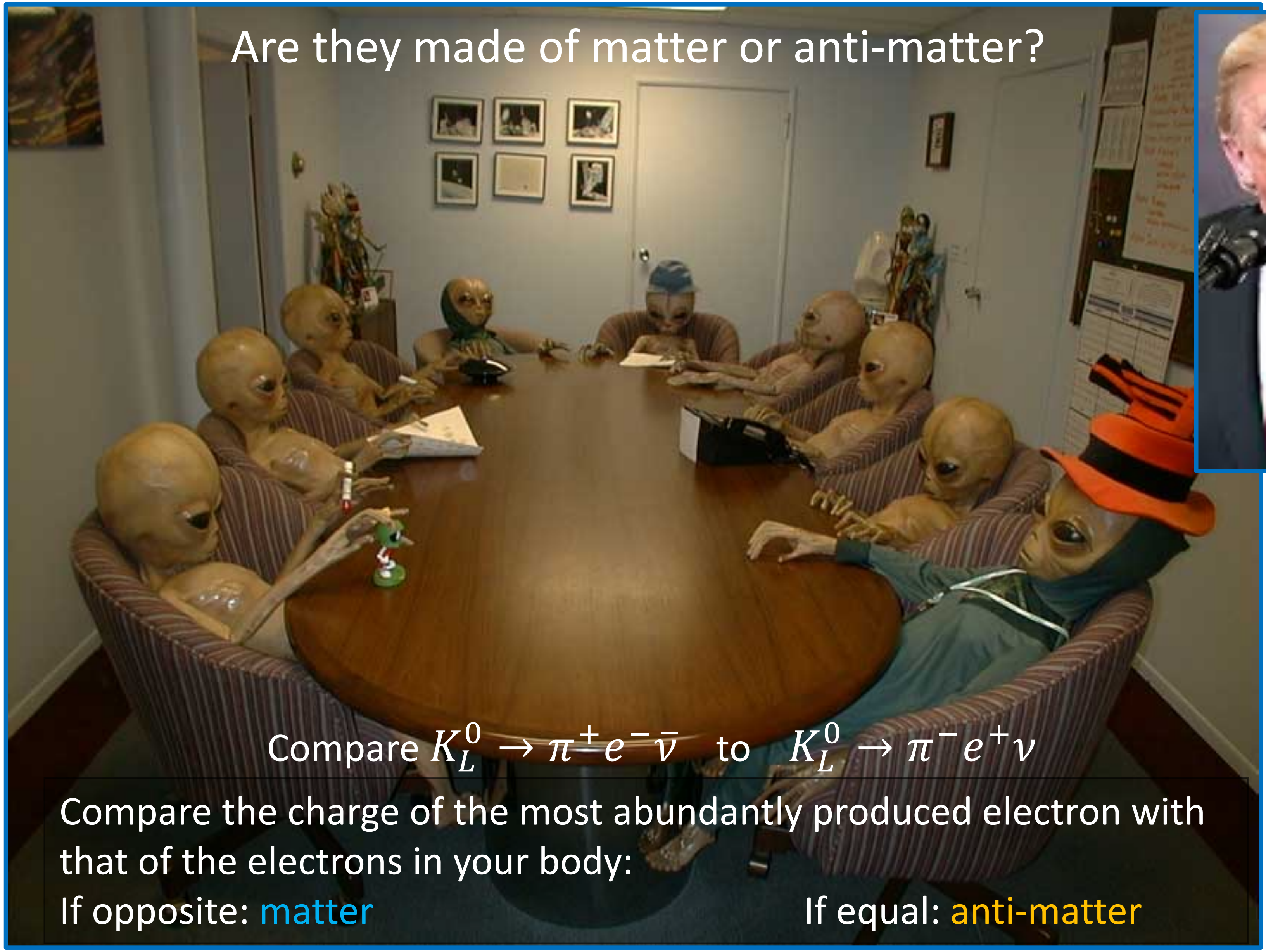
Person "L" gets in, starts, ….. 60 km/h

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

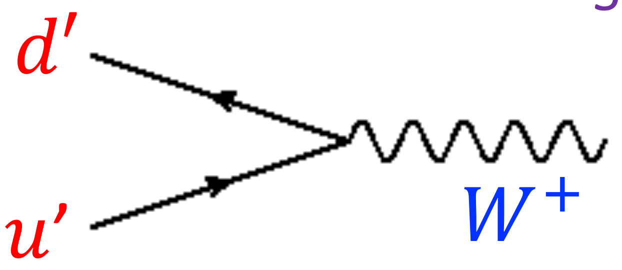
If equal: anti-matter

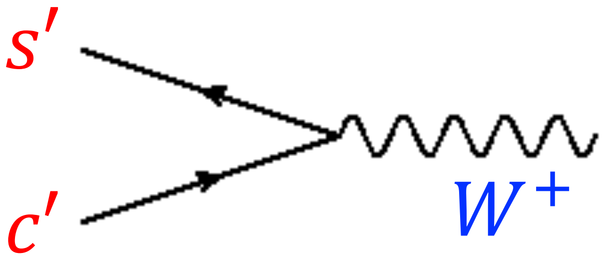
Recap: Weak interaction in three Flavour Generations

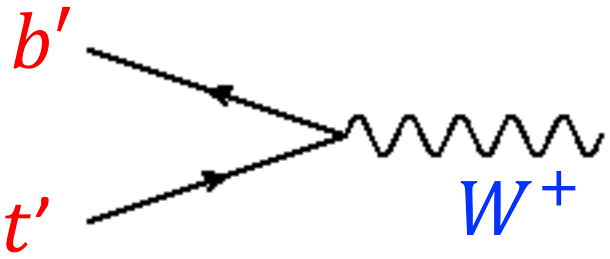
- Weak Interaction is 100% parity violating.
  - Wolfgang Pauli: *"I cannot believe God is a weak left-hander."*
- Implement an $SU(2)_L$ symmetry for *massless* particles:

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

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



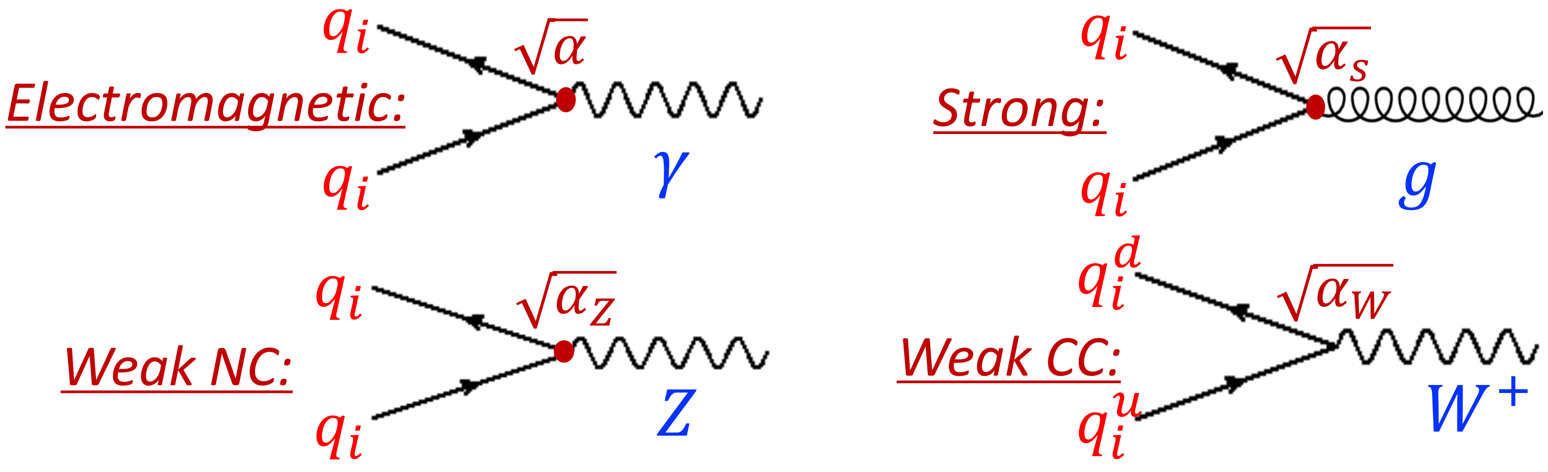




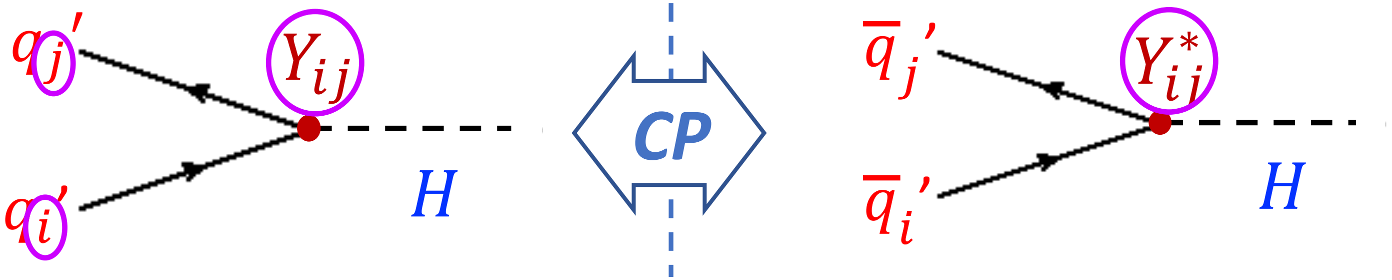
- There is *no CP violation* in these massless interactions
  - What happens when particles acquire mass?

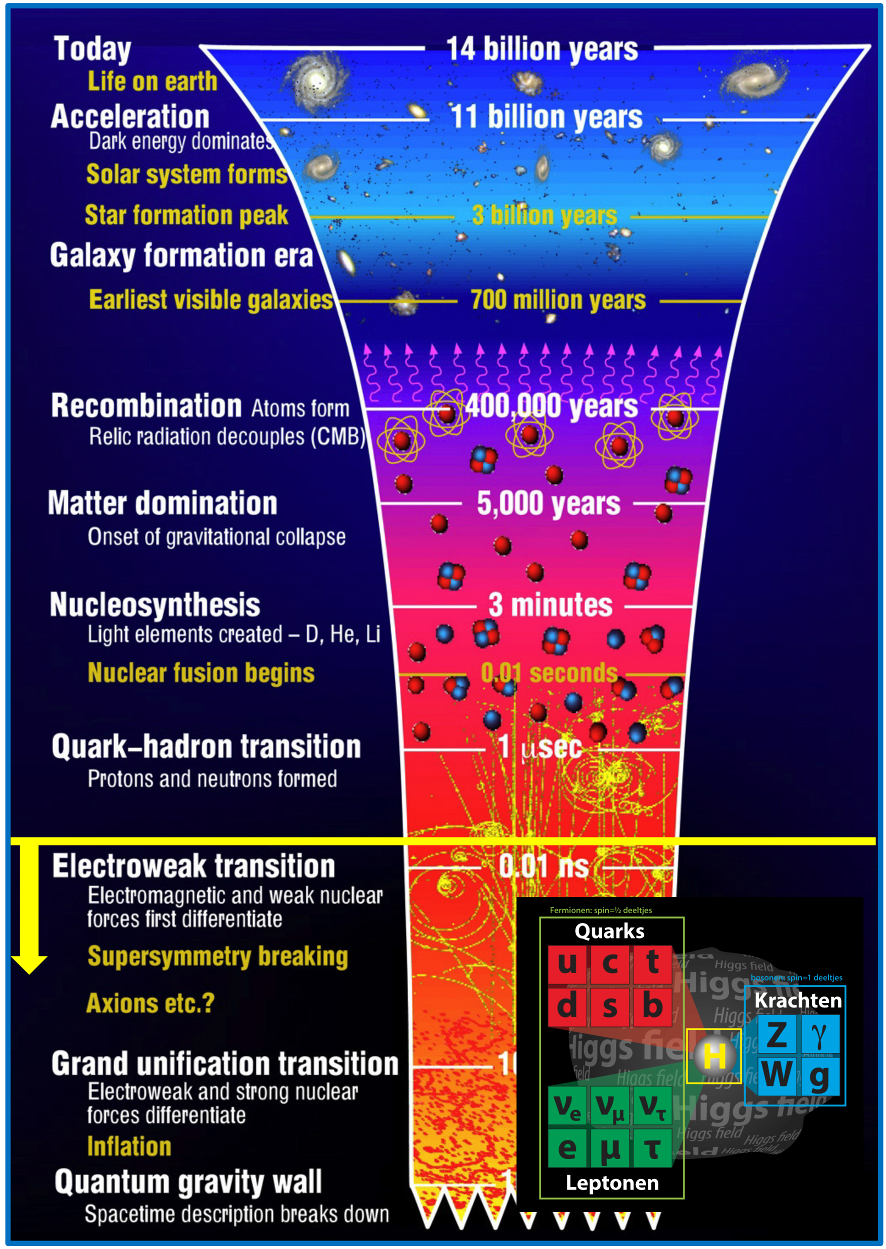
Recap: Flavour Universality in very Early Universe

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



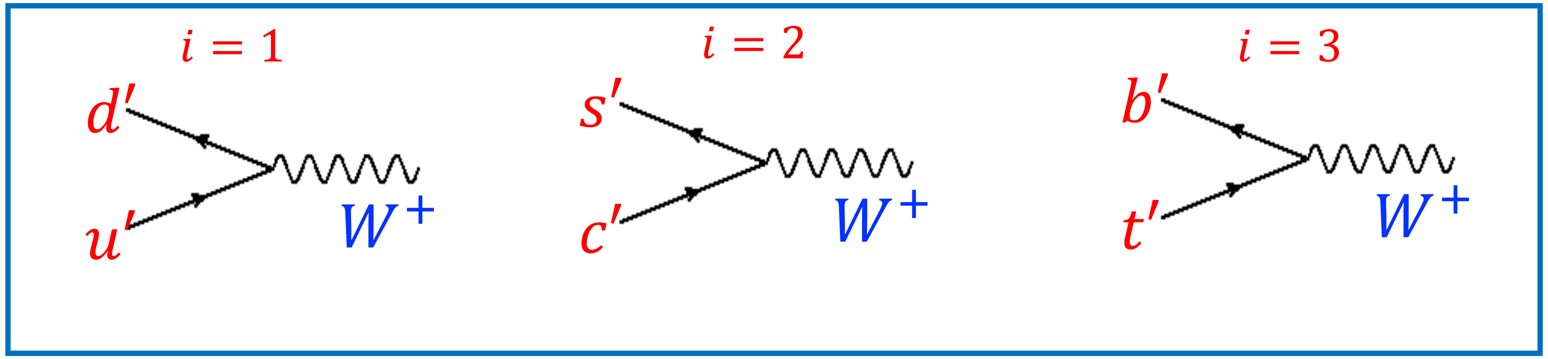
- Universality violation: Higgs !
  - Higgs coupling is *not universal*, and mixes generations
  - Complex couplings: allows for CP Violation!





Recap: Flavour Universality

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



- Universality violation: Higgs ! $(i \leftrightarrow j)$
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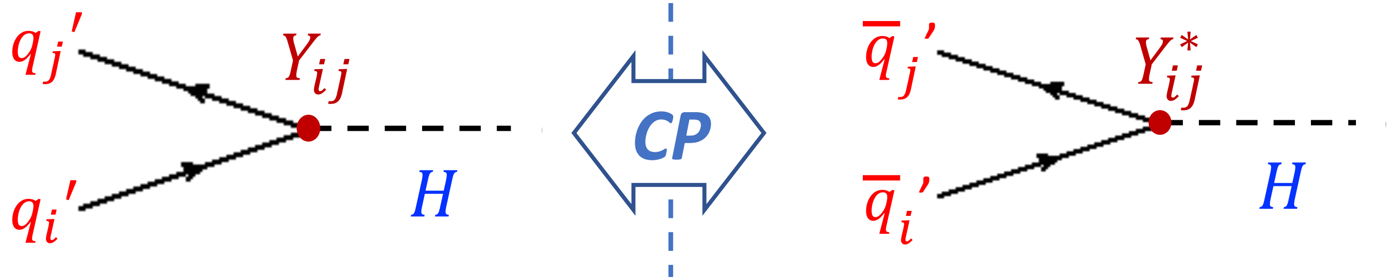
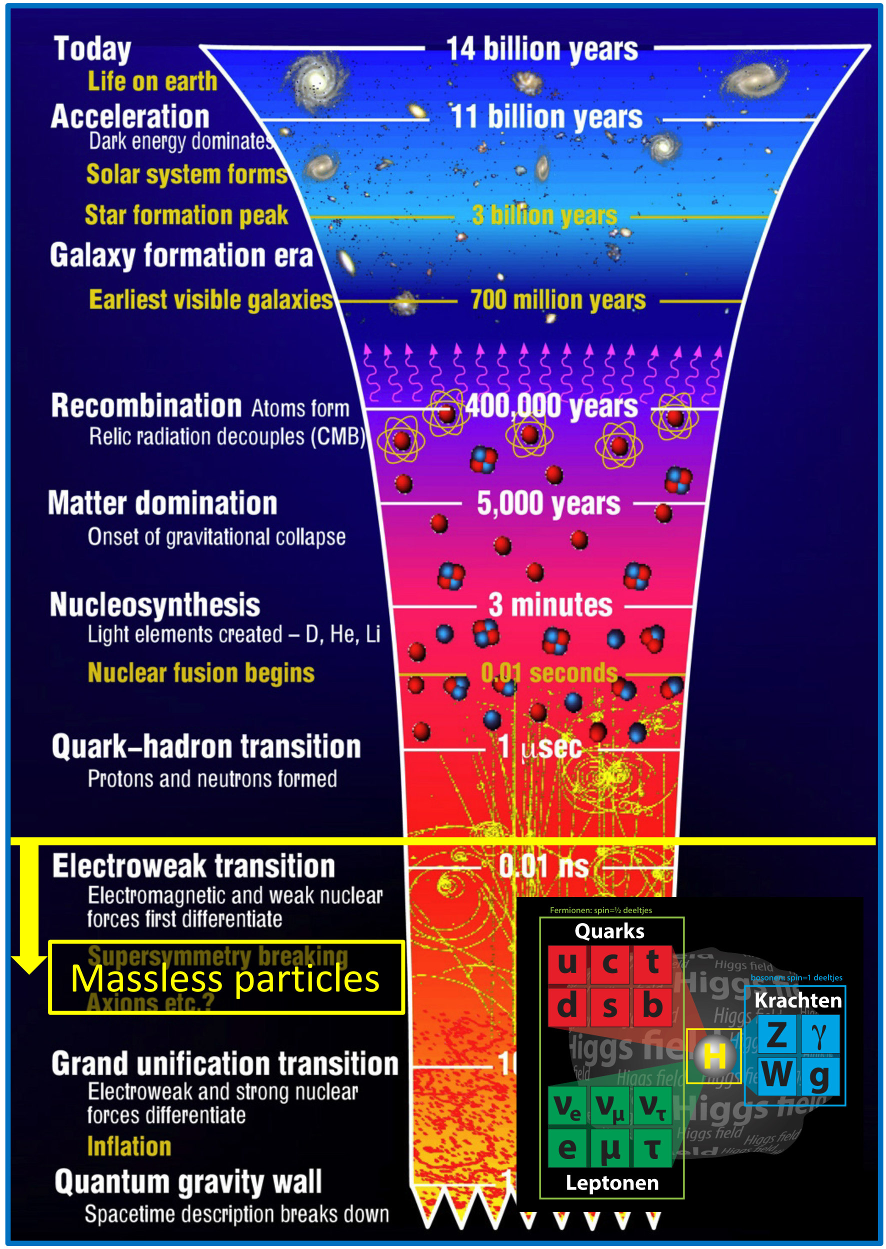
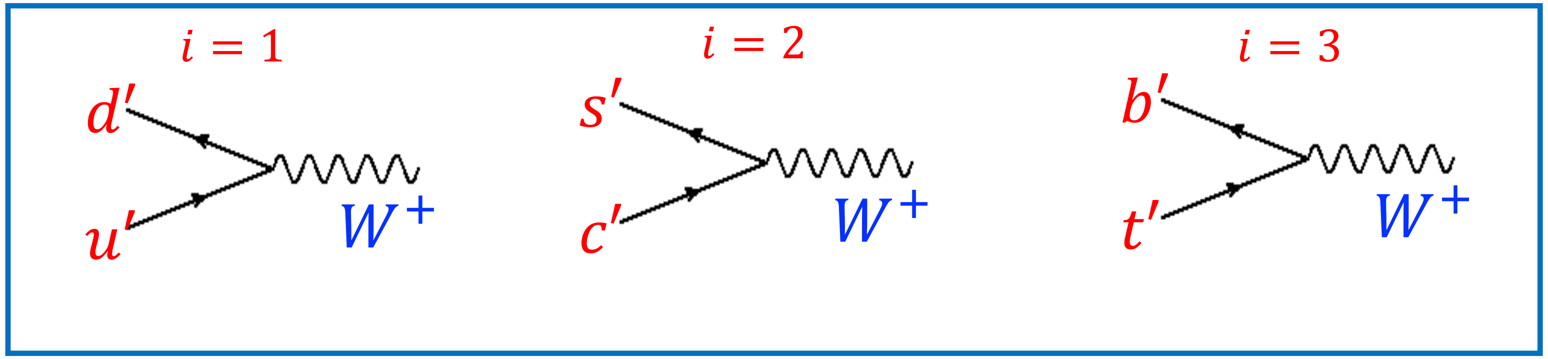
  - Complex couplings: allows for CP Violation!



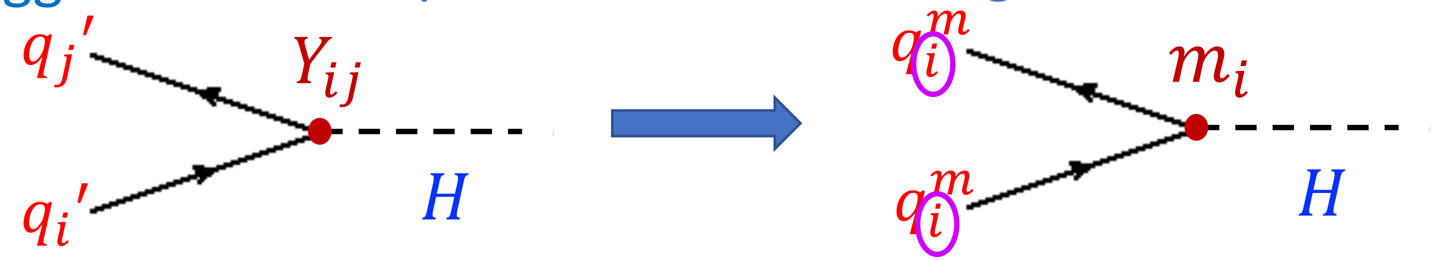


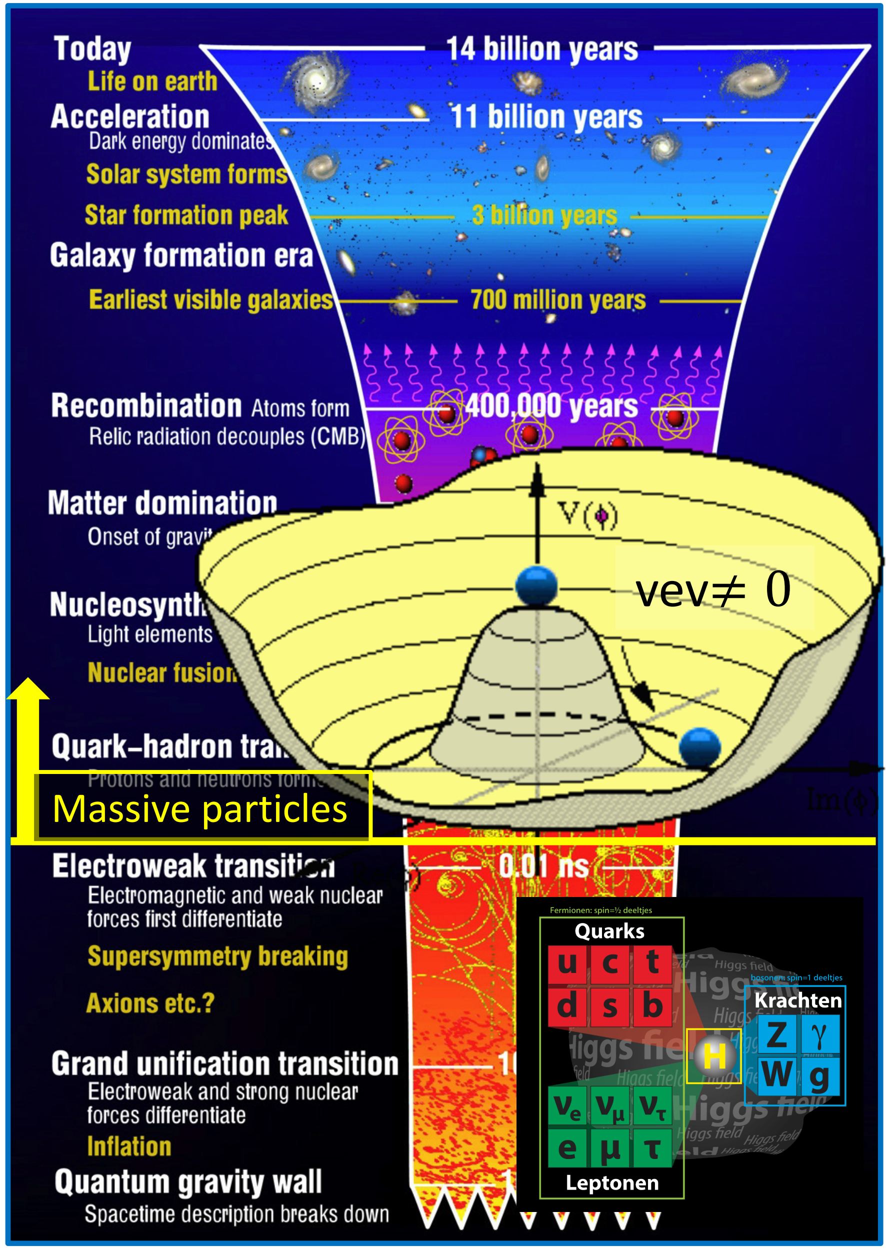
Recap: Flavour Universality → Symmetry Breaking

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

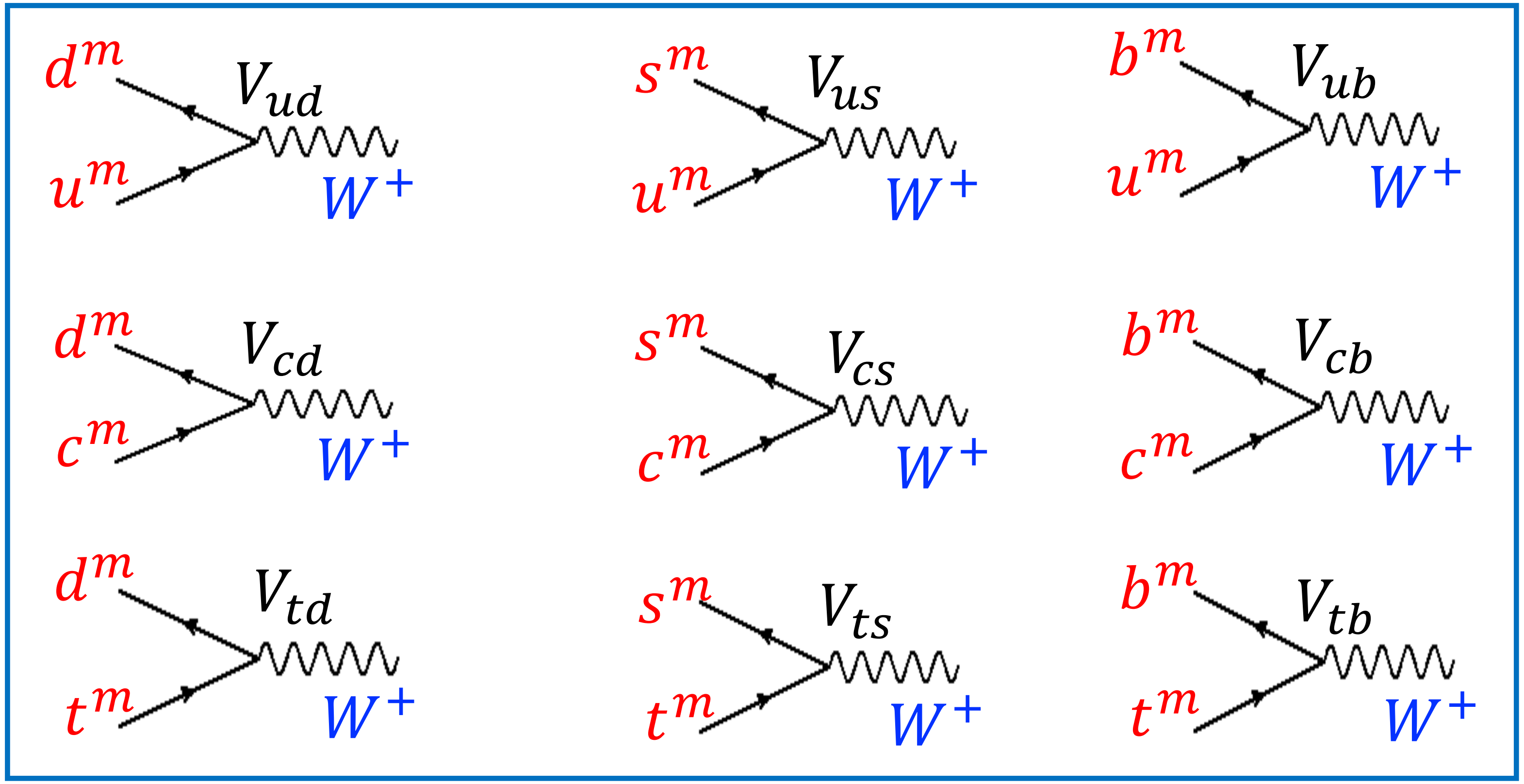


- Higgs: redefines quark states in mass eigenstates: $(i \leftrightarrow i)$

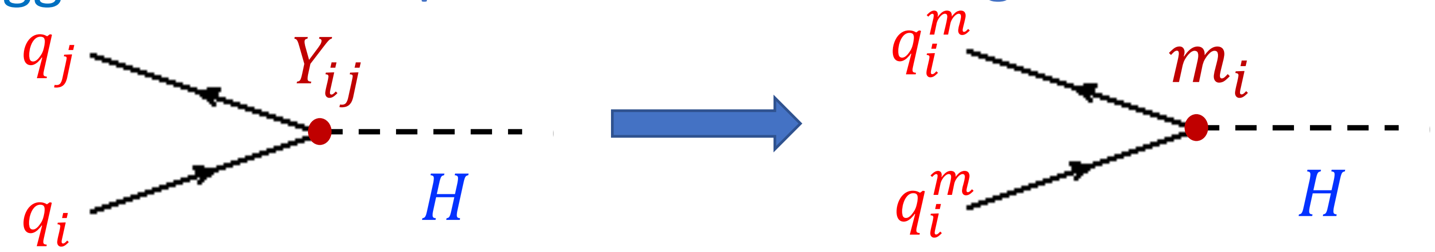


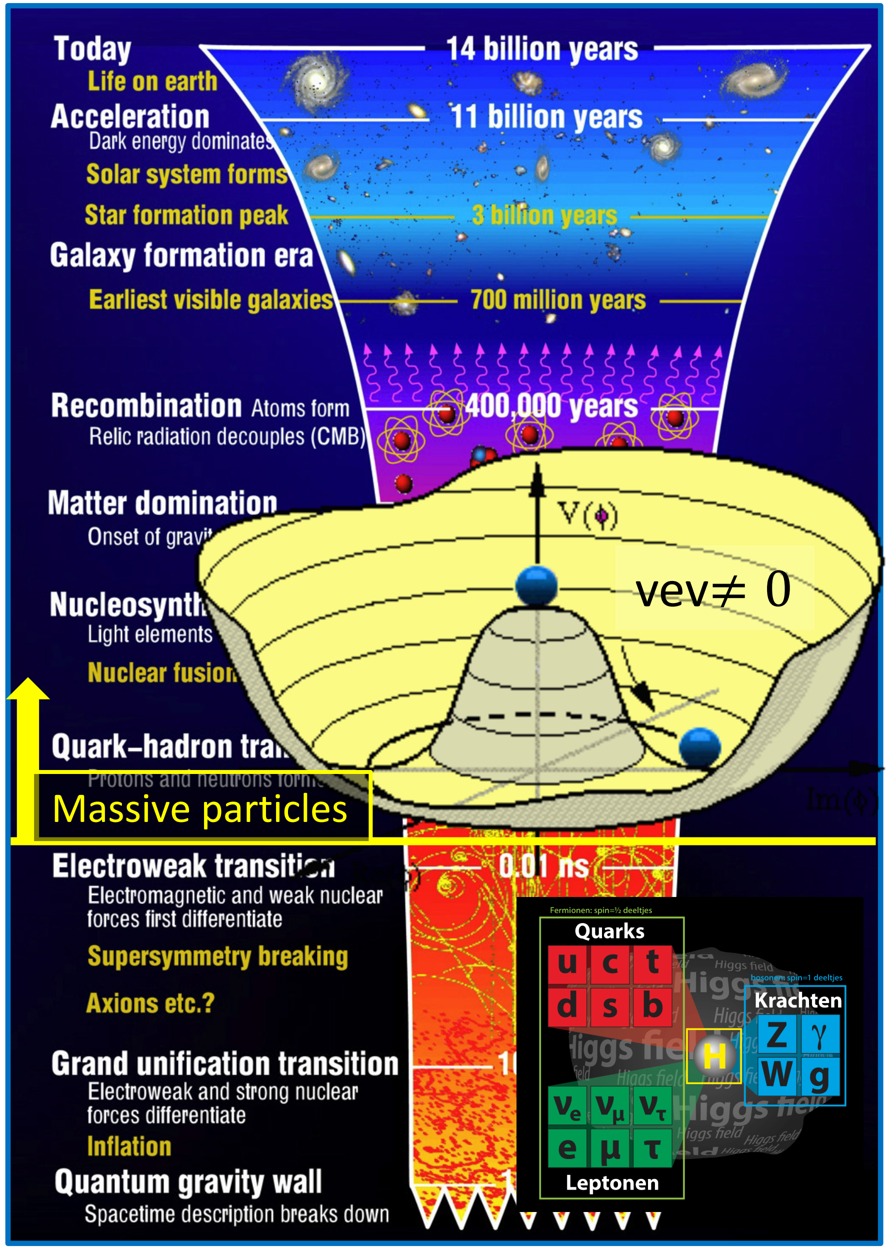


- Weak charged current interaction: $(i \leftrightarrow j)$

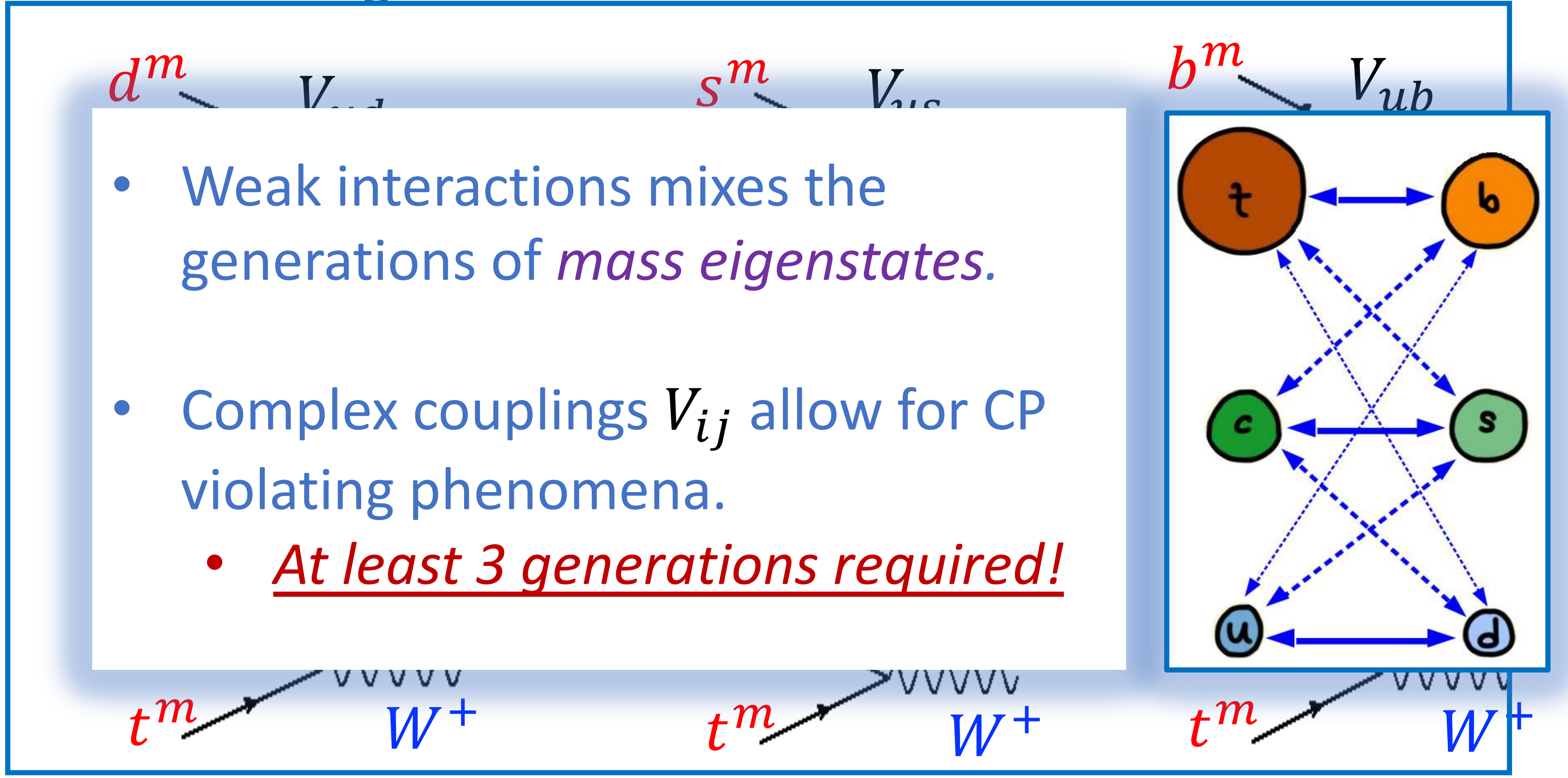


- Higgs: redefines quark states in mass eigenstates: $(i \leftrightarrow i)$



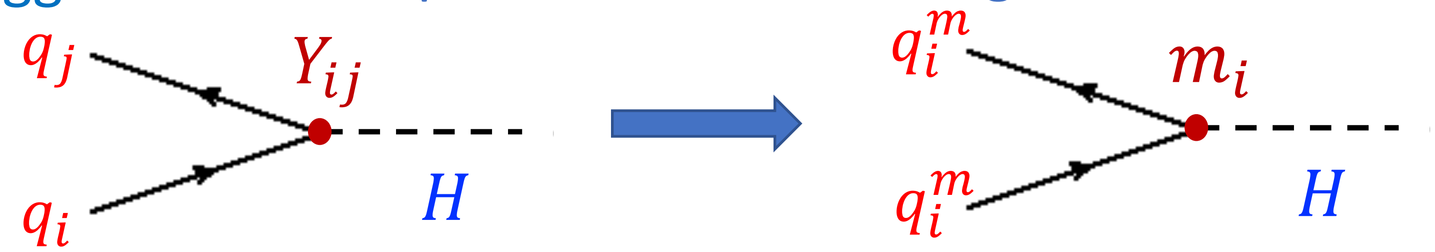


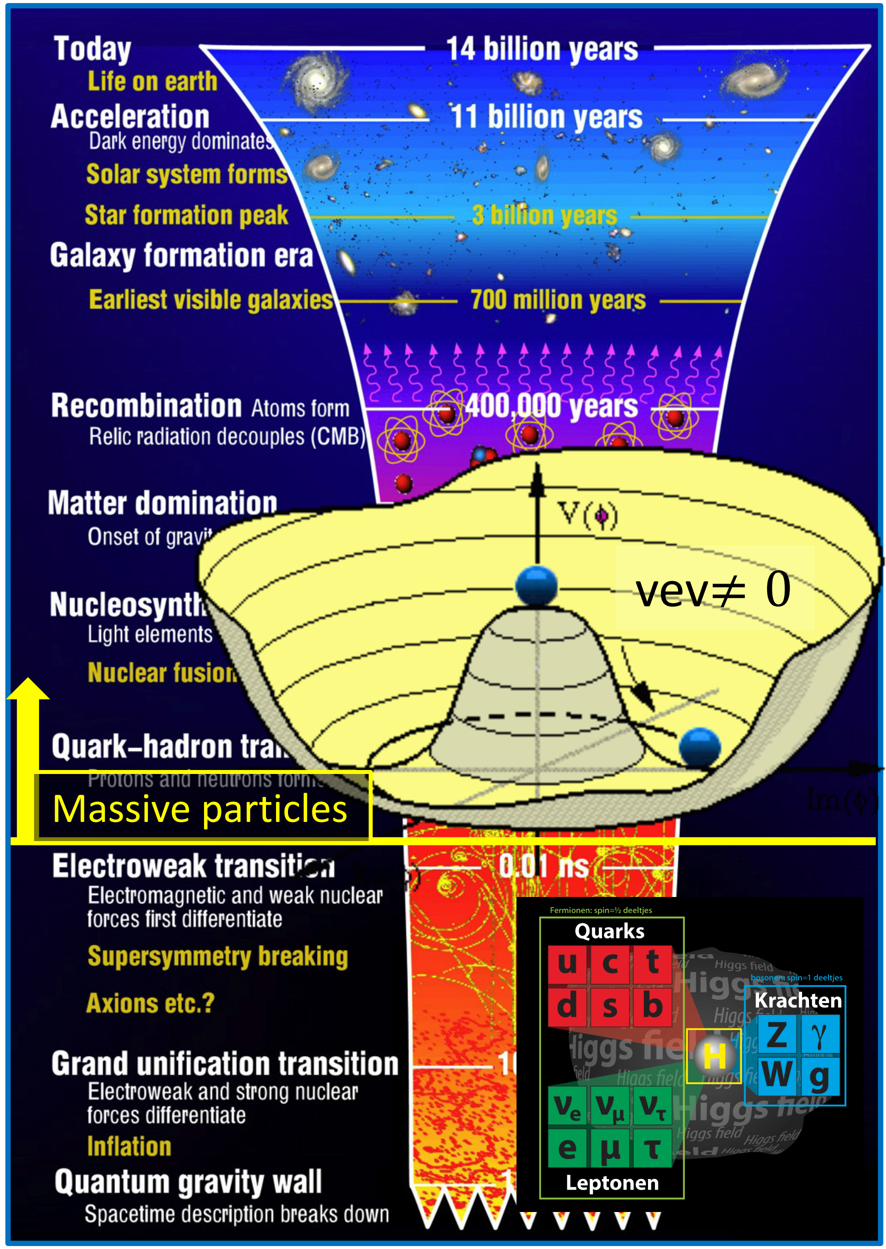
- Weak charged current interaction:



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

- Higgs: redefines quark states in mass eigenstates:





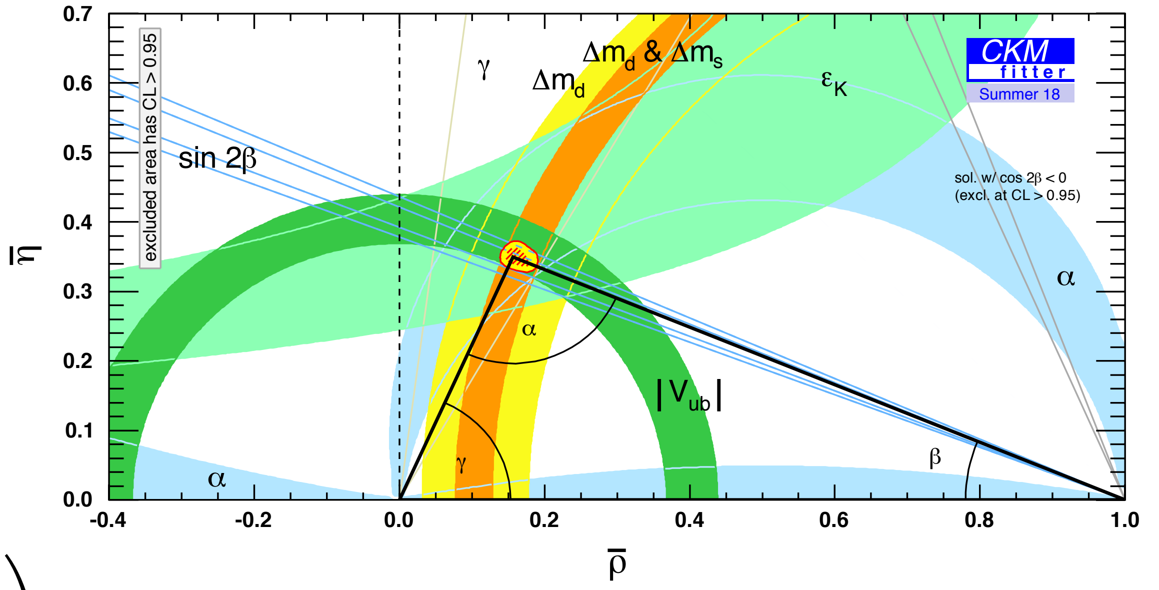
Recap: The CKM matrix and unitarity triangle

- 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:

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

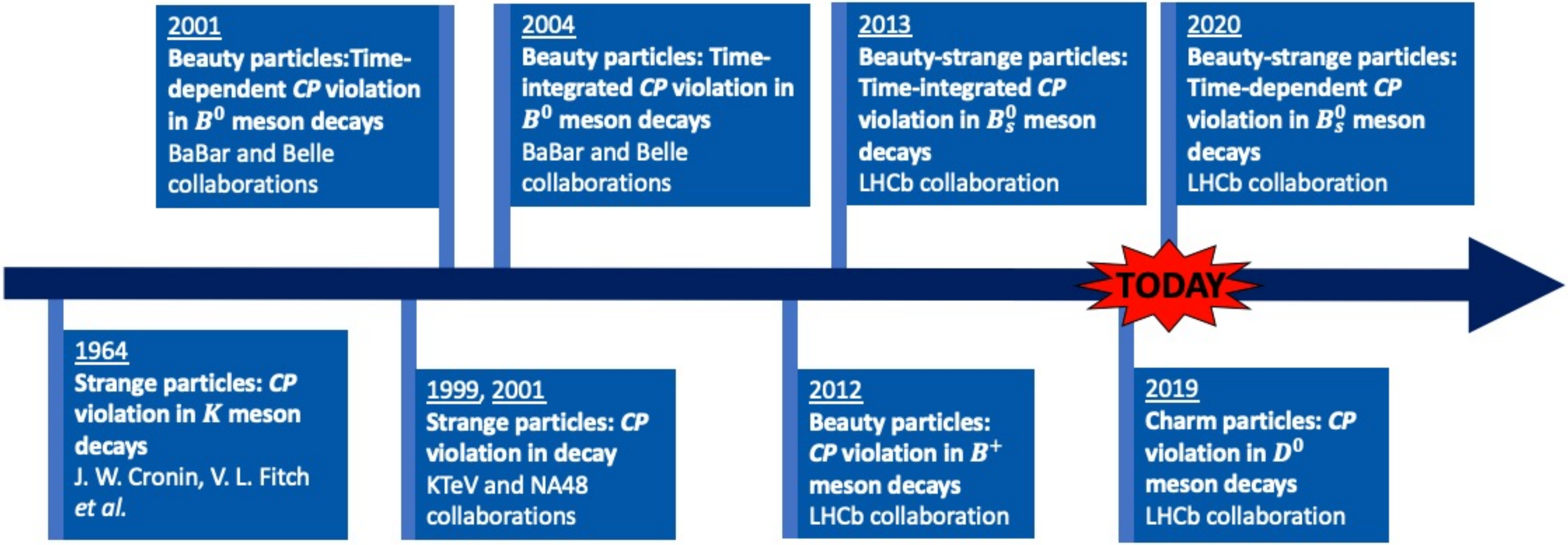


- Wolfenstein parametrization:

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

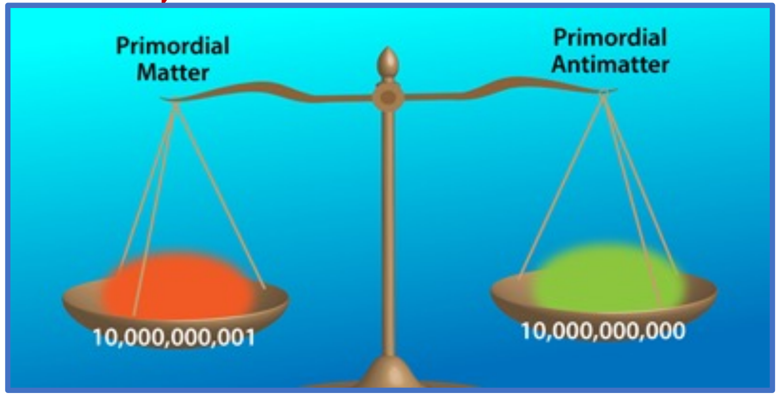
- CP Violation:
  - Non-zero unitary phases
  - Triangle surface $\neq 0$
    - Jarlskog invariant

Recap: CP violating phenomena have been well established



Recap: CP violation vs matter – antimatter asymmetry

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

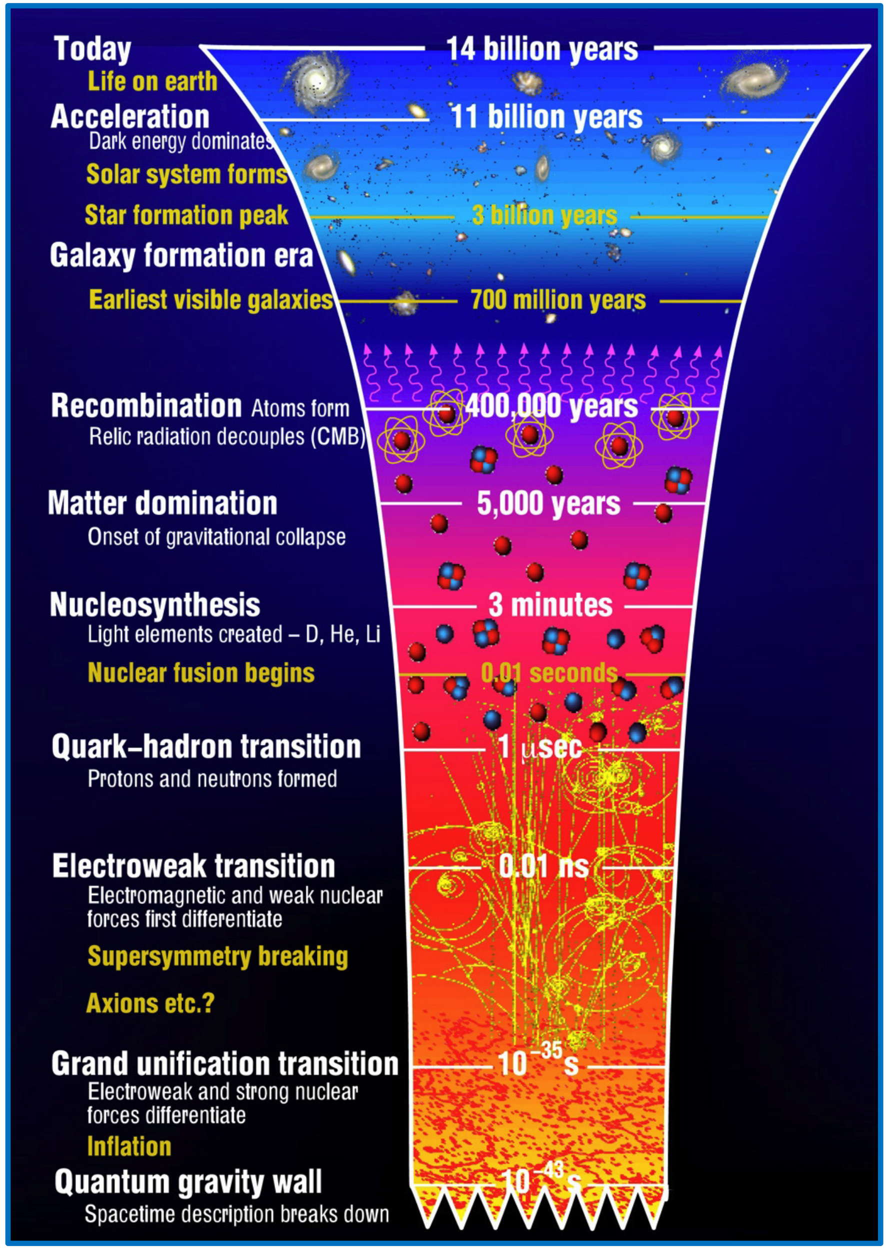


- Jarlskog criterion (1987) for ***amount of CP violation in SM***:

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

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

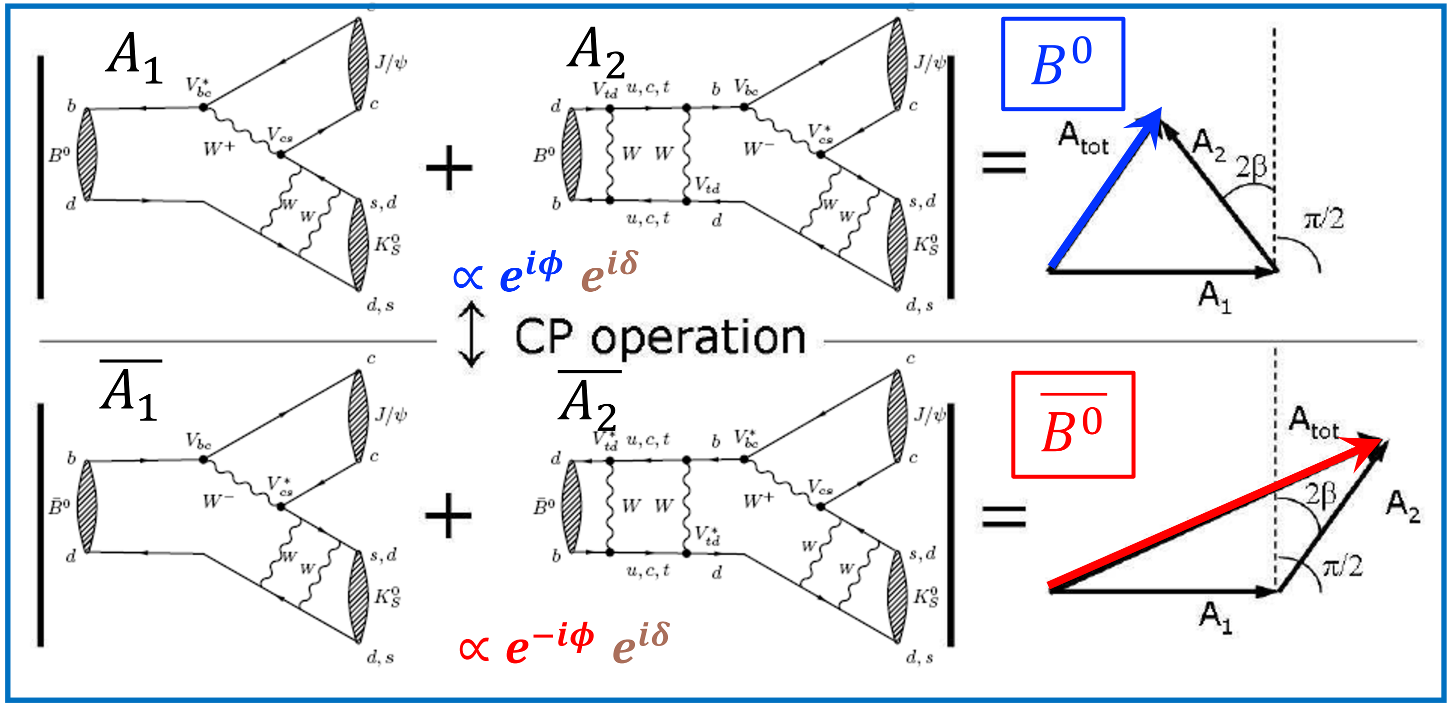
- *Explanation requires existence of **new massive** particles.*



Contents:

CP violation: a quantum interference experiment

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



$|A_1| = |\overline{A_1}|$, $|A_2| = |\overline{A_2}|$,

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

CP violation: a quantum interference experiment

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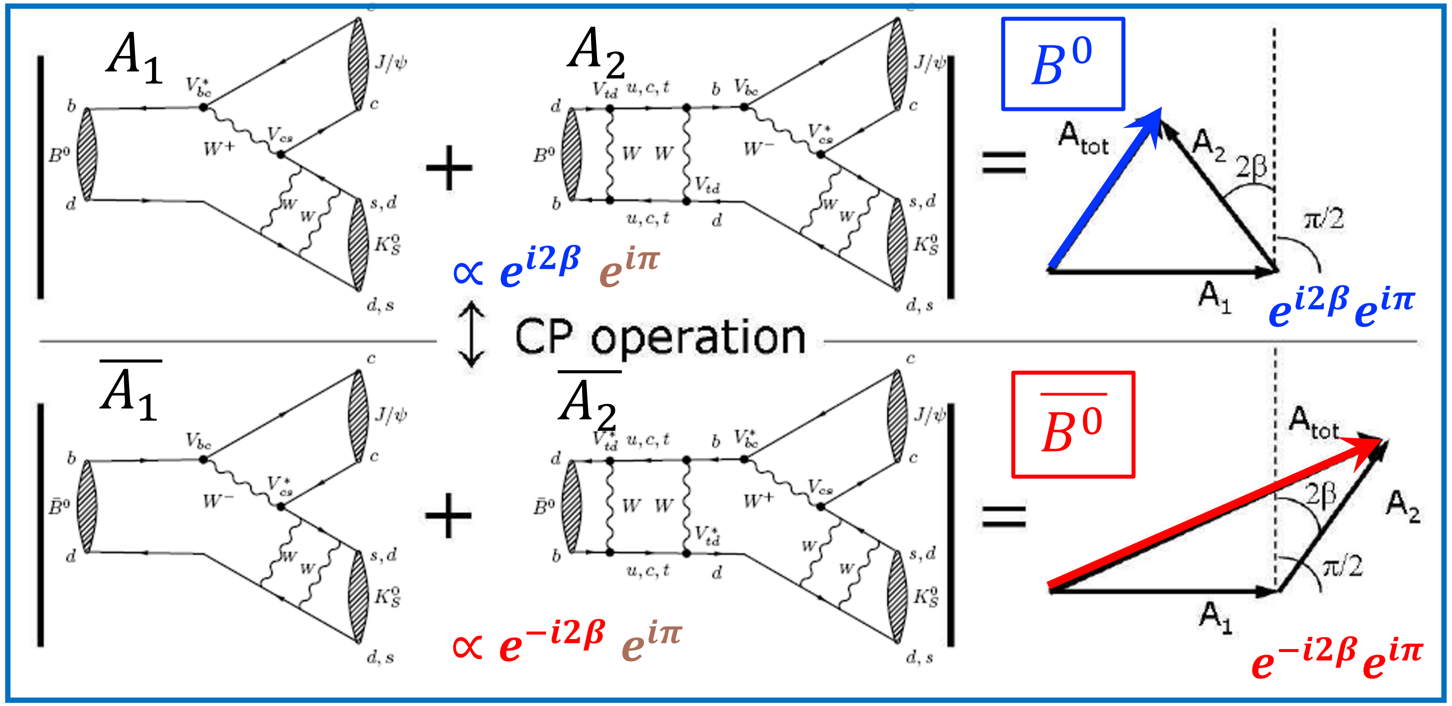

$|A_1| = |\overline{A_1}|$, $|A_2| = |\overline{A_2}|$,
but $|A_1 + A_2| \neq |\overline{A_1 + A_2}|$

Weak phase from CKM: $e^{-i2\beta} \to e^{i2\beta}$
Strong phase from mixing process: $e^{i\pi} \to e^{i\pi}$

CP violation: a quantum interference experiment

- Quantum process with two amplitudes A_1 and A_2:
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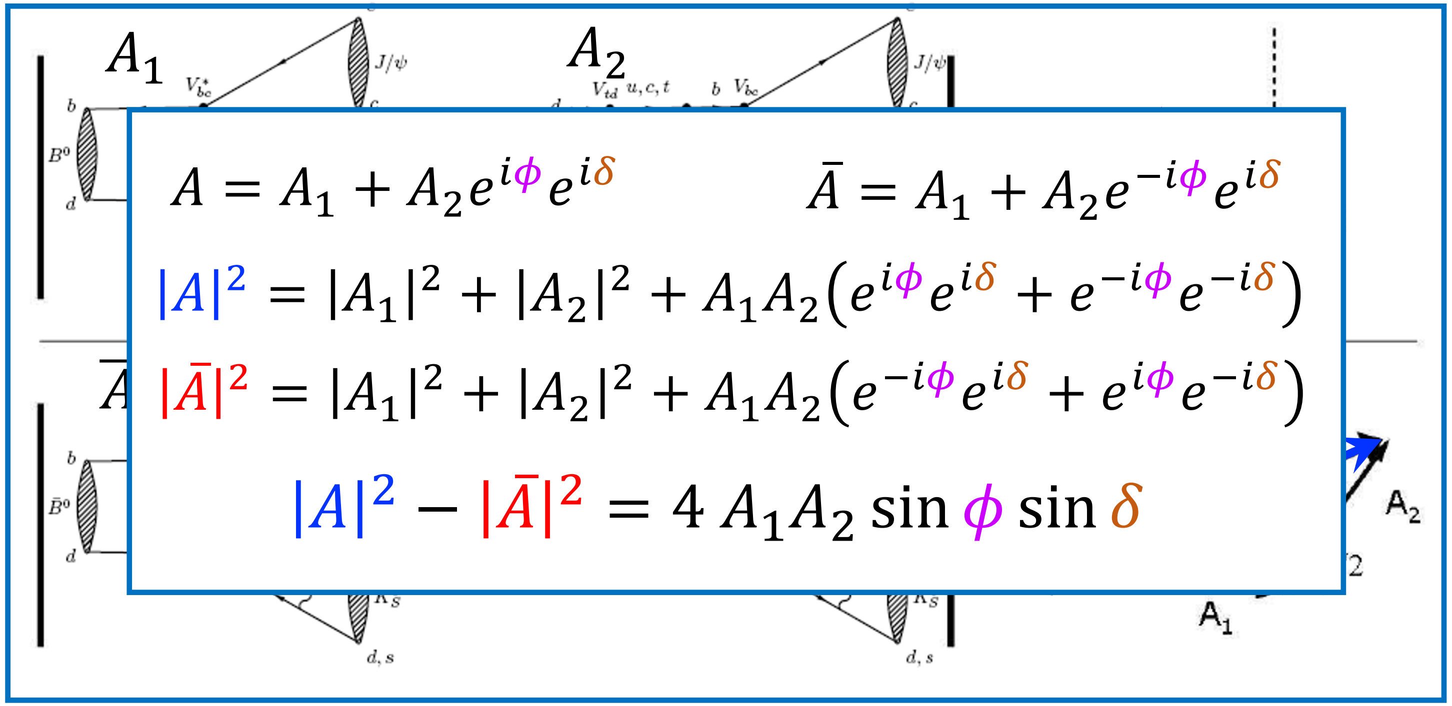
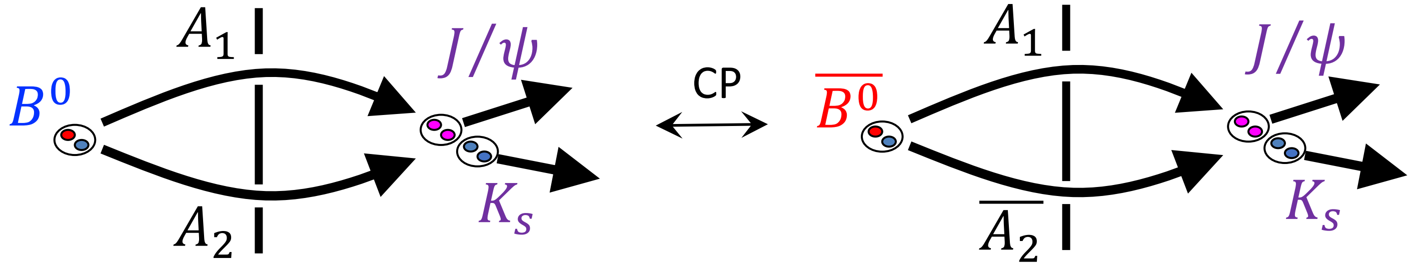


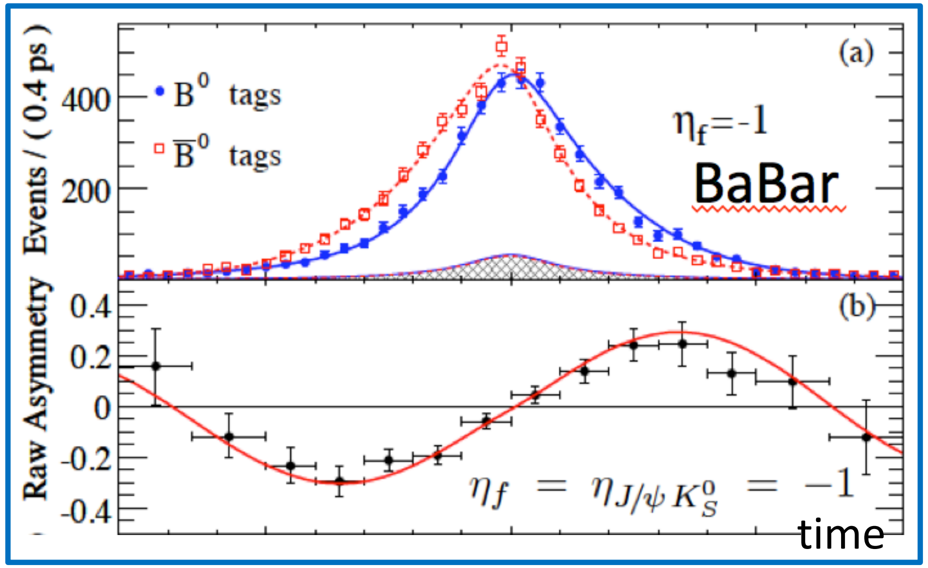
$$A = A_1 + A_2 e^{i\phi} e^{i\delta} \qquad \bar{A} = A_1 + A_2 e^{-i\phi} e^{i\delta}$$

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

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

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





$|A_1| = |\overline{A_1}|$, $|A_2| = |\overline{A_2}|$,
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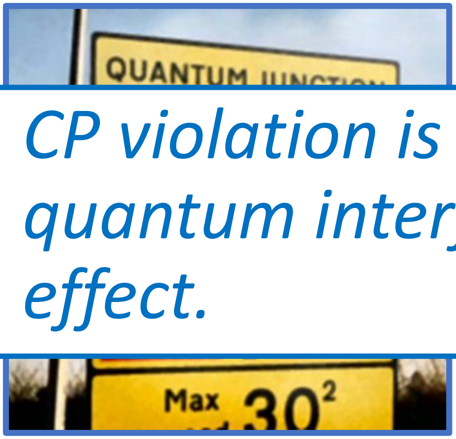
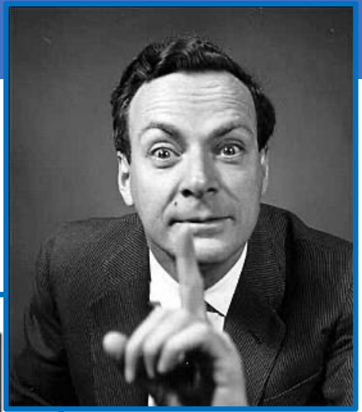
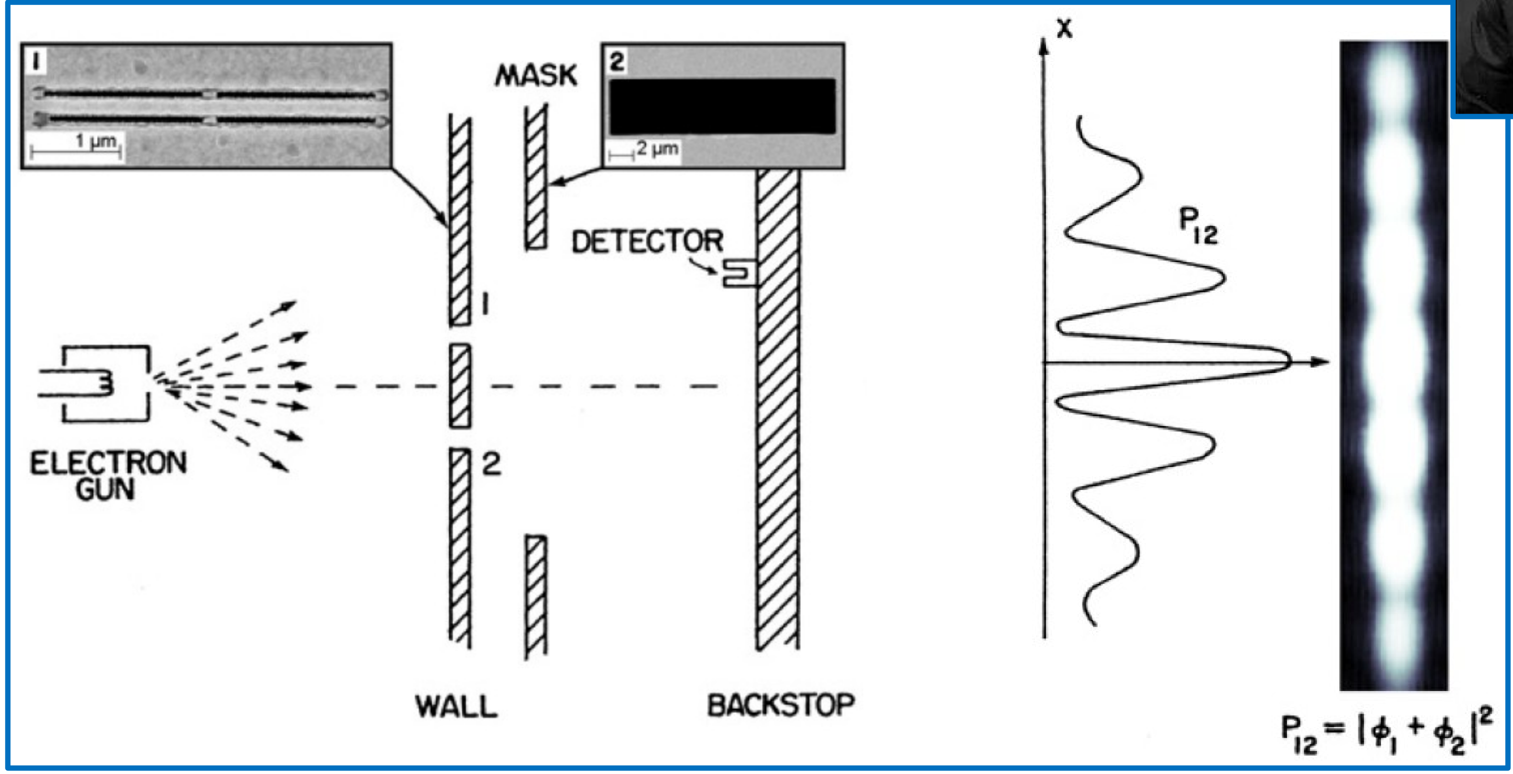


- *CP violation is a pure quantum interference effect.*

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?*

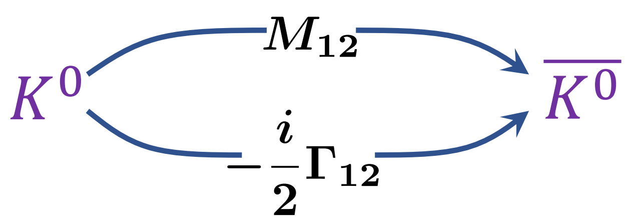
Three types of observable CP violation

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

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

  $|\varepsilon|$ = (2.228 ± 0.011) x 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(ε'/ε) = (1.65 ± 0.26) x 10^{-3} (PDG)
- Also called: ***CPV in decay***

Interfere *Isospin amplitudes*:

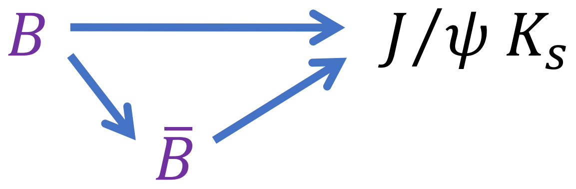
$$A = a_{0(K\to\pi\pi)} + a_{2(K\to\pi\pi)}$$

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

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

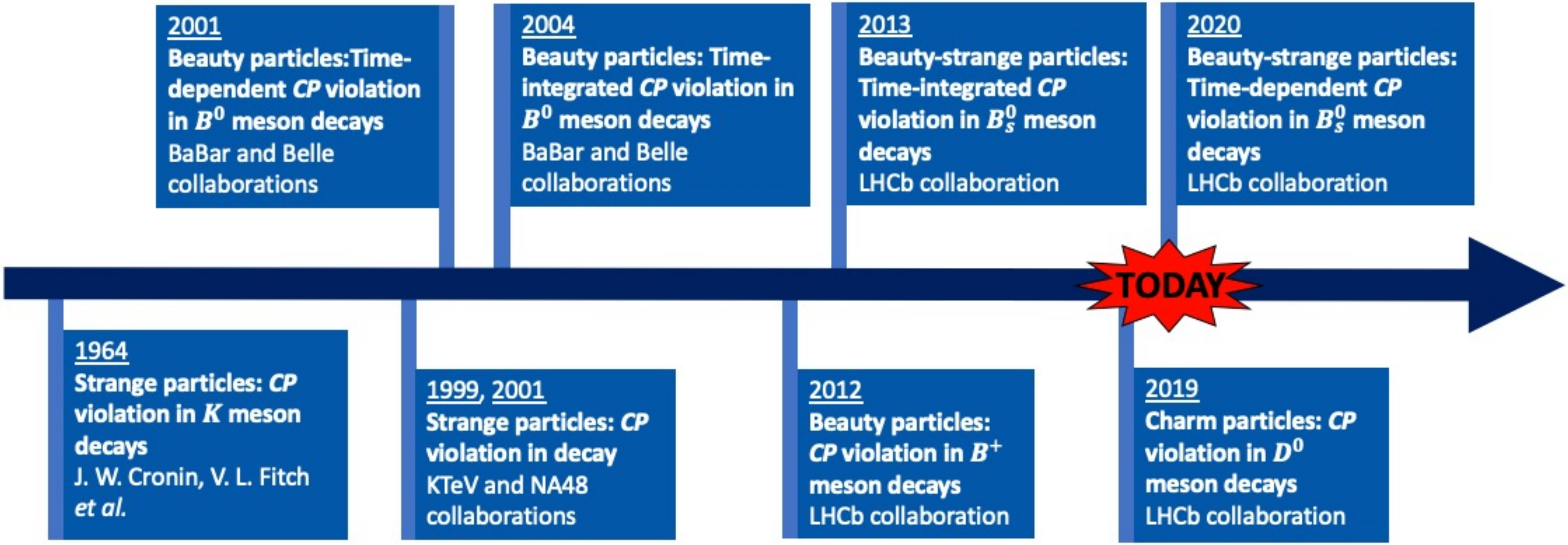
  sin 2β = 0.682 ± 0.019 (PDG)

Interfere *direct* and *mixed*:



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

B^0 Mixing induced CPV — *CPV in B^0 decay* — *CPV in B_s decay* — *B_s Mixing induced CPV*



CPV in K^0 mixing — *CPV in K decay* — *CPV in B^+ decay* — *Primarily CPV in D^0 decay*

Three types of observable CP violation

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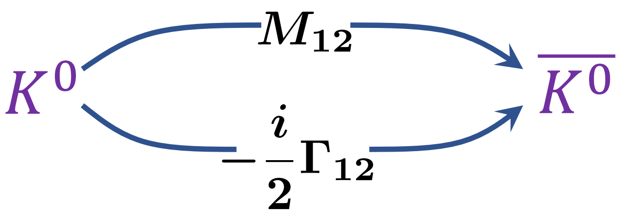
- Also called: ***CPV in mixing***

Interfere *dispersive* and *absorptive*:



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

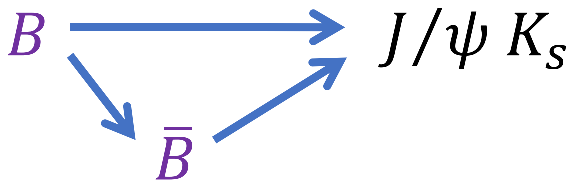
All CP violation processes result from quantum interference including three generations of fermions.

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

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

  sin 2β = 0.682 ± 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”

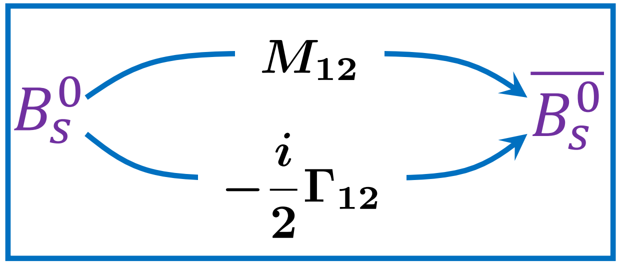
“WTF?”

Moonshine

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

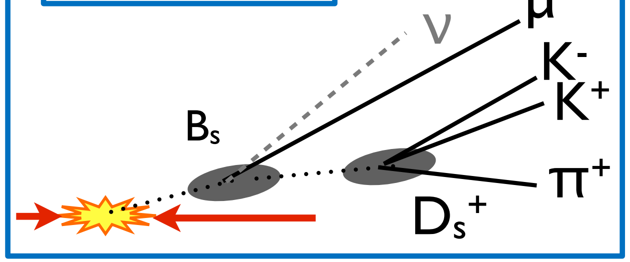
Type-1: CP violation *in mixing*: $a_{SL}(B_d)$ en $a_{SL}(B_s)$

- Interfere *dispersive* and *absorptive* amplitudes ("indirect"):

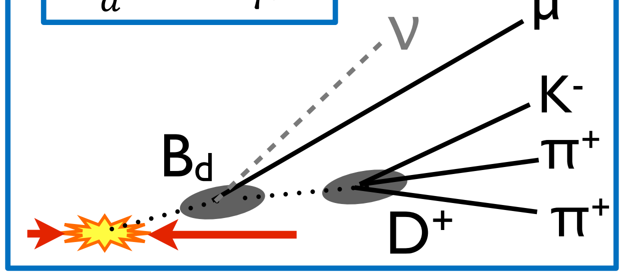


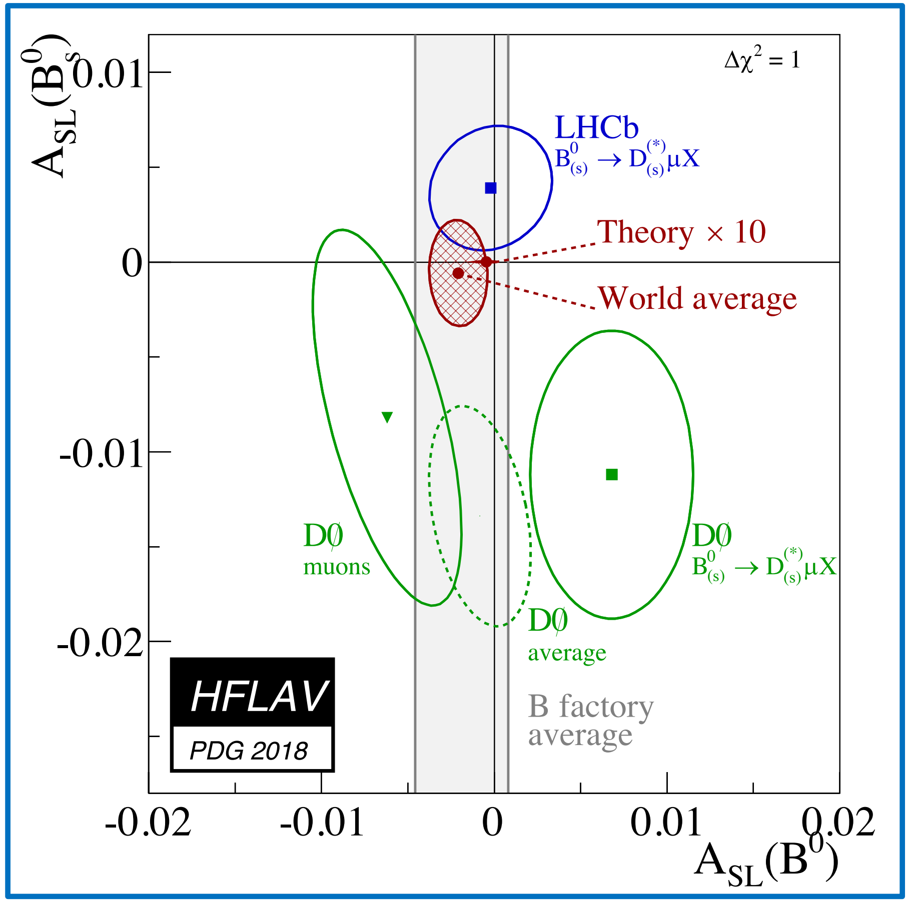
$$\mathcal{A}_{meas} = \frac{\Gamma_{(B_s^0 \to D_s^- \mu^+)} - \Gamma_{(B_s^0 \to D_s^+ \mu^-)}}{\Gamma_{(B_s^0 \to D_s^- \mu^+)} + \Gamma_{(B_s^0 \to D_s^+ \mu^-)}}$$

$B_s^0 \to D_s^+ \mu^-$

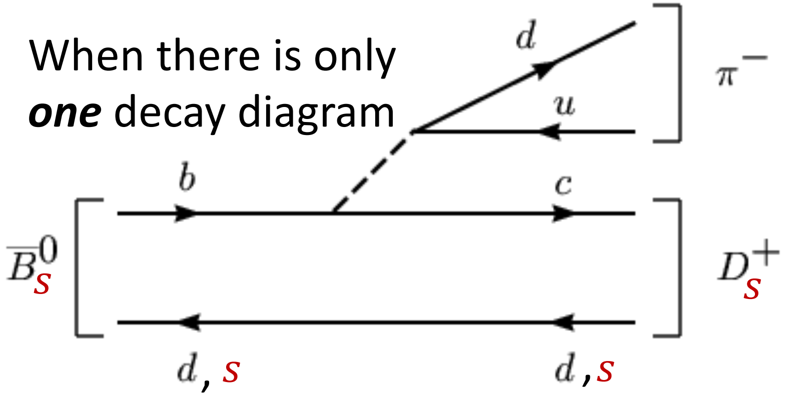


$B_d^0 \to D^+ \mu^-$





When there is only *one* decay diagram



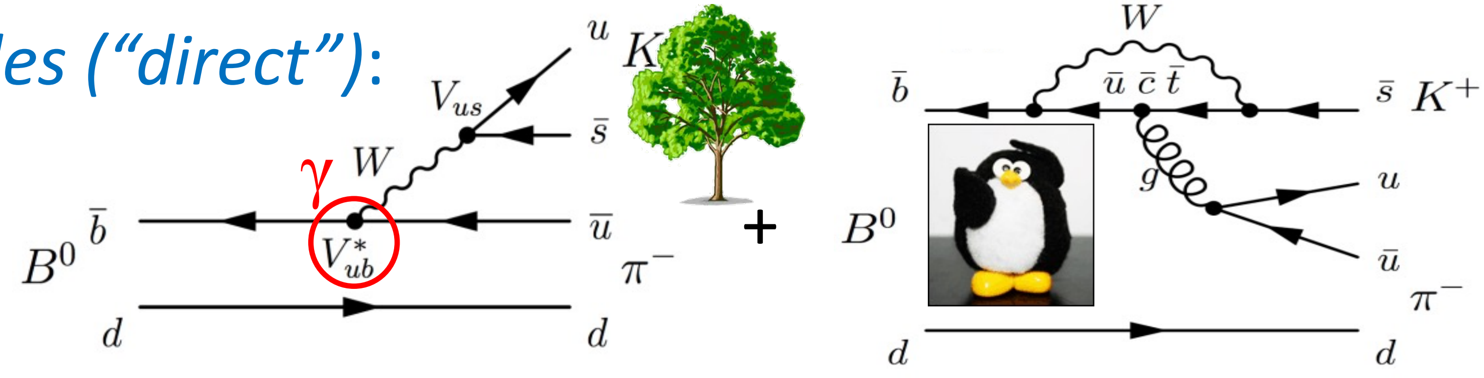
CP violation in mixing *does not happen* in B_d^0 and B_s^0 mesons:

- $B \to \bar{B}$ goes at same rate as $\bar{B} \to B$
- Contrary to ϵ in kaons!

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

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

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

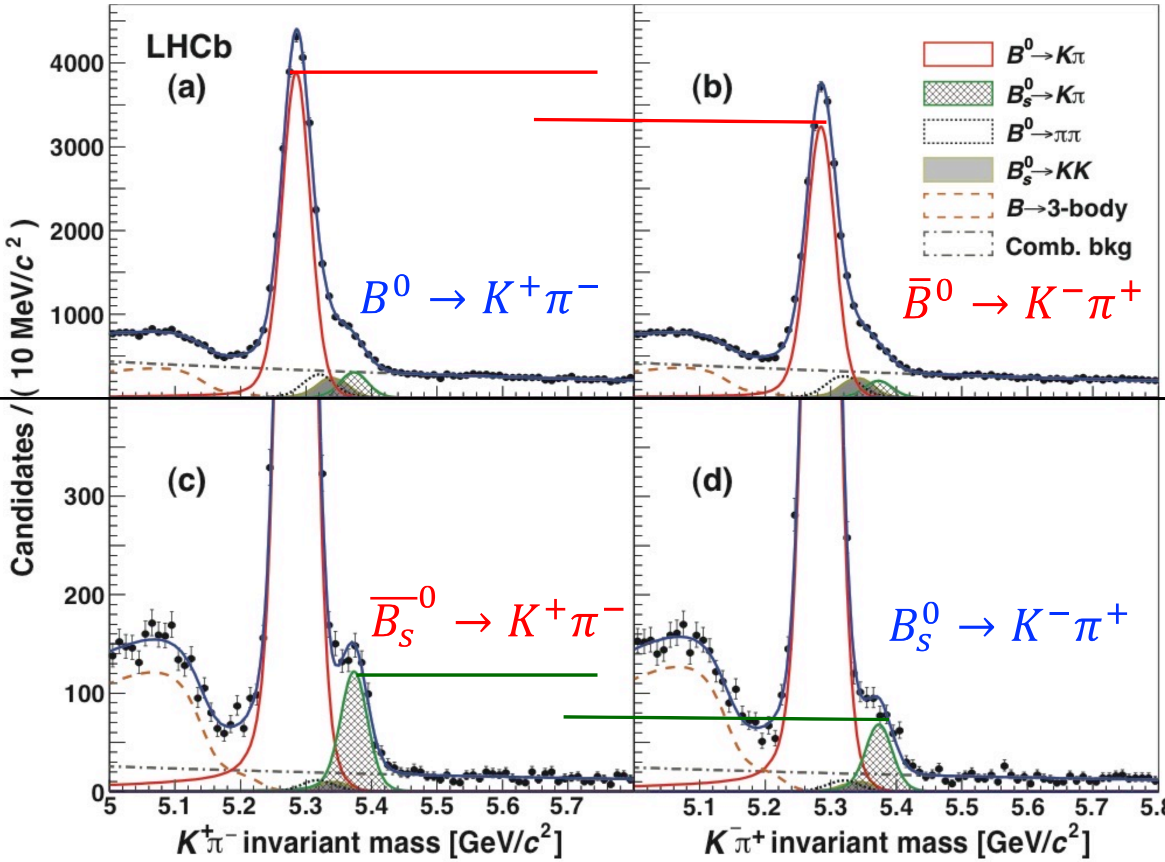


When there are *multiple* decay diagrams

$B_d^0 \to K\pi$

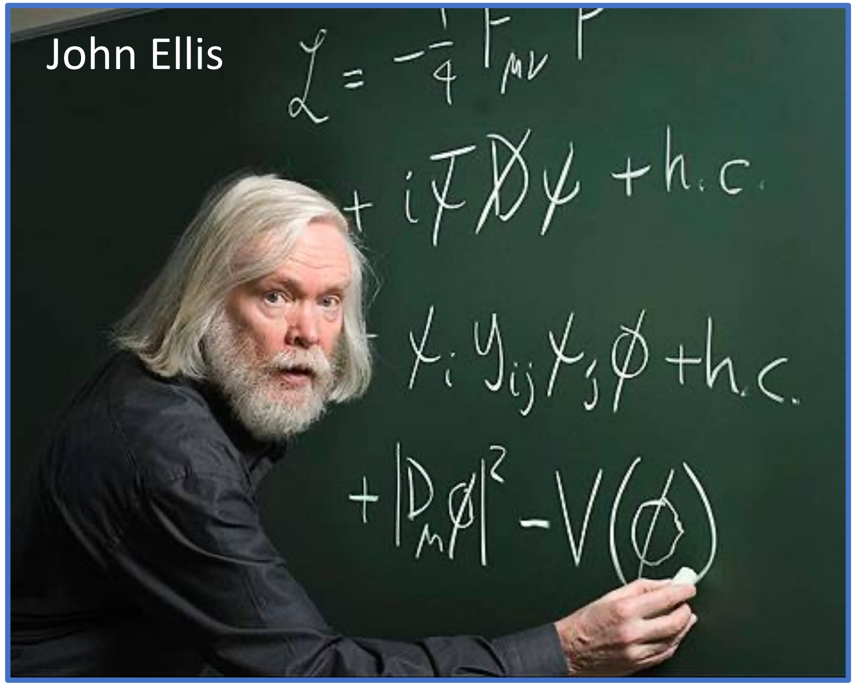
$B_s^0 \to K\pi$

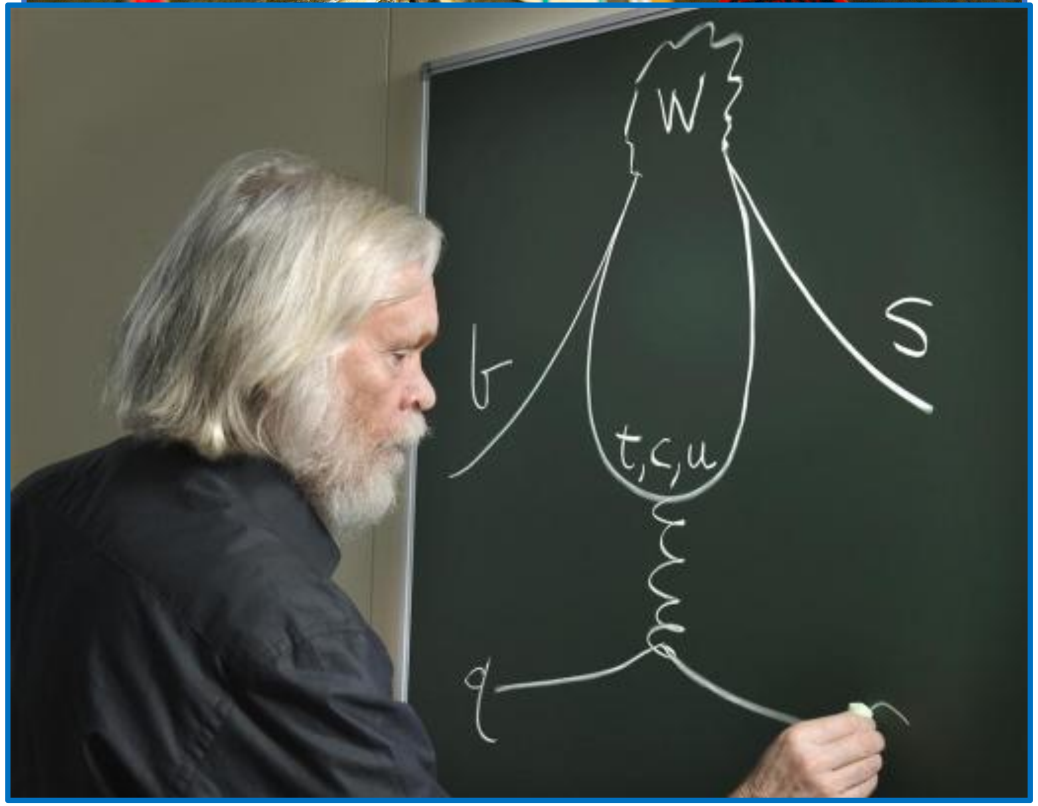
First observation of CP violation in B_s decays

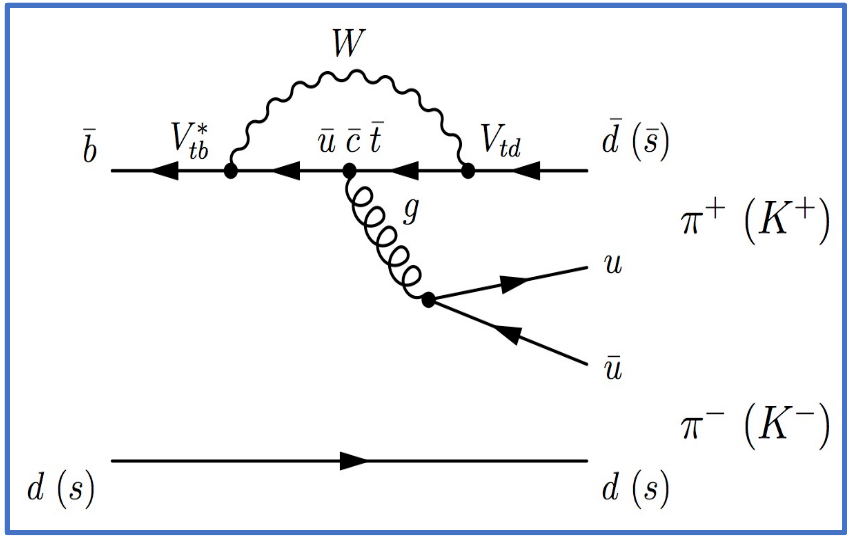


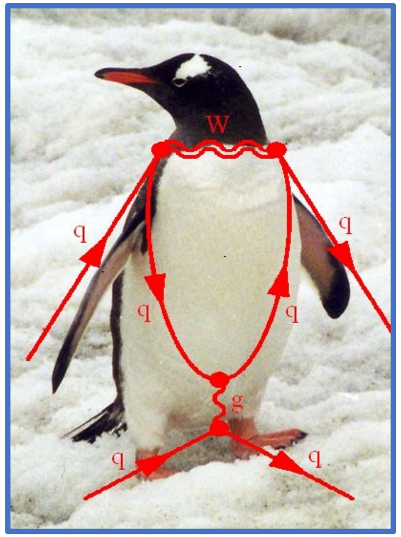
- Quarks from three generations involved
- Large interference
- Large CP violation!
  - Contrary to ϵ' in the kaon system

A story on darts and penguins





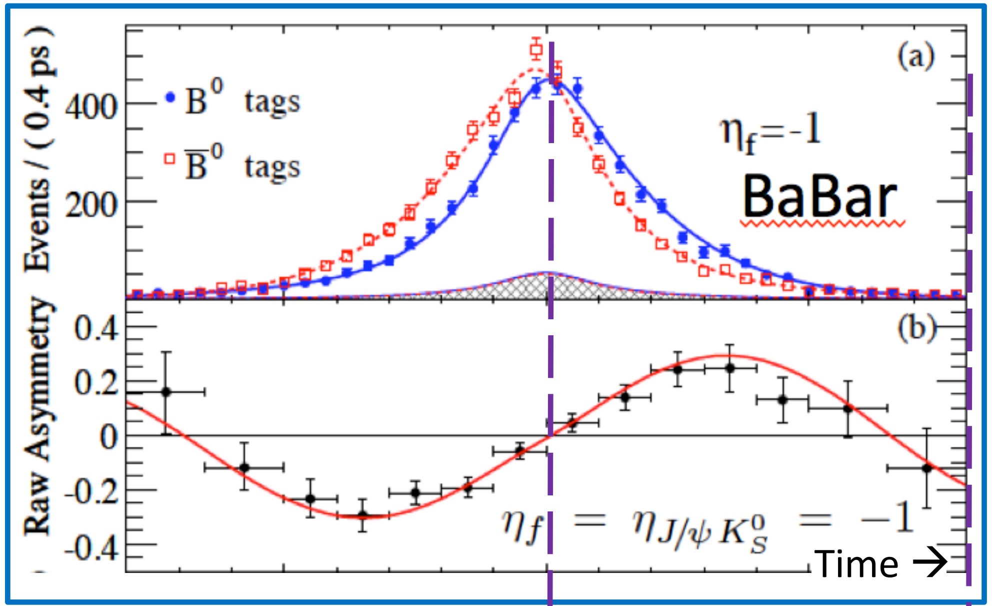




Type-3: CP violation in *interference of mixing and decay*

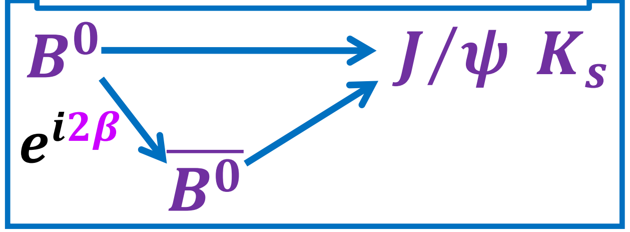
- Interfere *direct* with *mixed* decay ("mixing induced"):

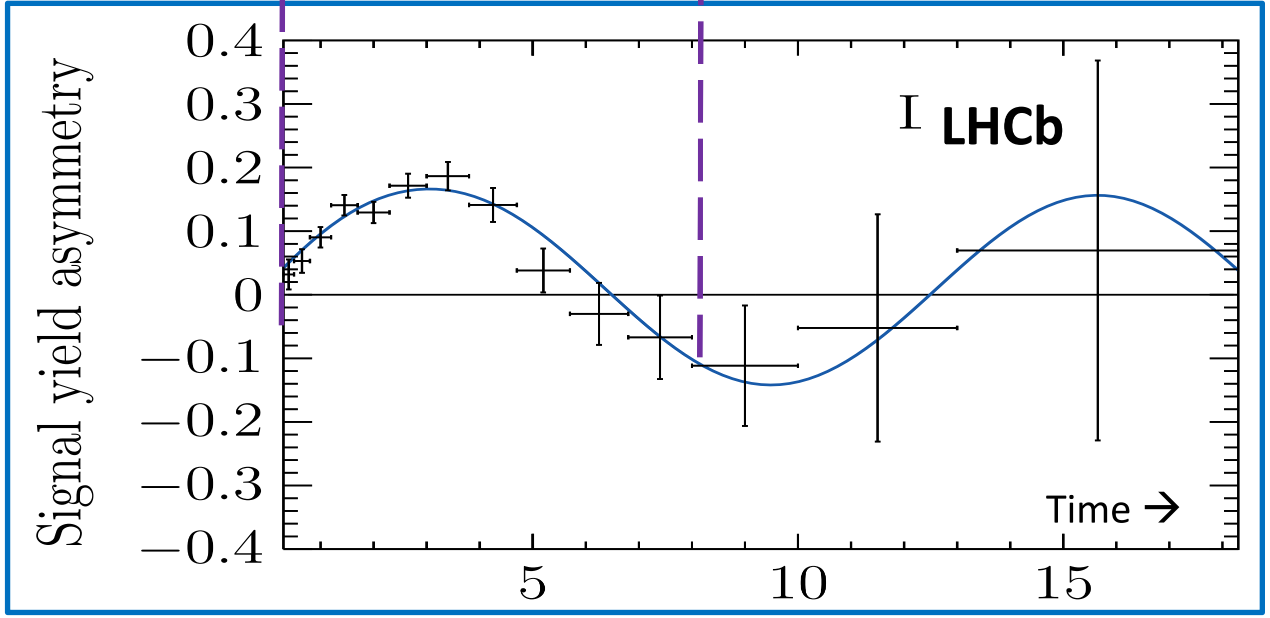
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$



Decay-time dependent CP violation

Interfere *direct* and *mixed*



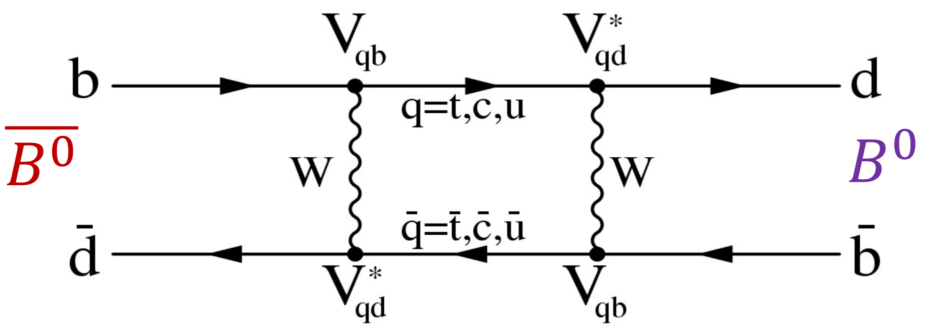


$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Contents:

Contents:

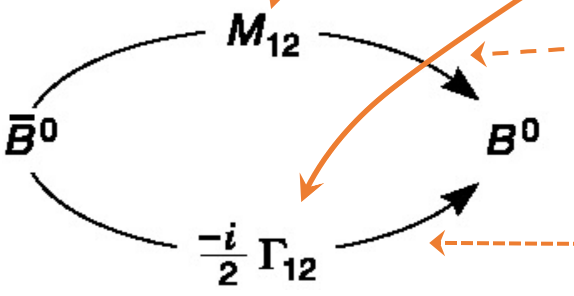
- Quantum mechanics with $\overline{B^0}$ and B^0 states: *"What is a particle?"*
  - Particle – antiparticle transitions $\overline{B^0} \leftrightarrow B^0$ mesons happen spontaneously.



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

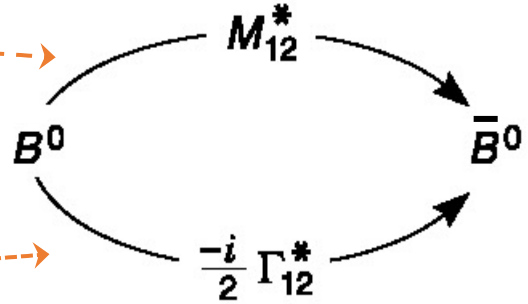
$$i\frac{\partial}{\partial t}\psi = H\psi \quad \rightarrow \quad \psi(t) = a(t)|B^0\rangle + b(t)|\overline{B^0}\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

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



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

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

Solution: (α and β are initial conditions):

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

Eigenvectors:

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

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

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

Masses

Lifetimes

B_H , B_L : *Mass* eigenstates

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

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

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

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

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

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

From the eigenvalue calculation:

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

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

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

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

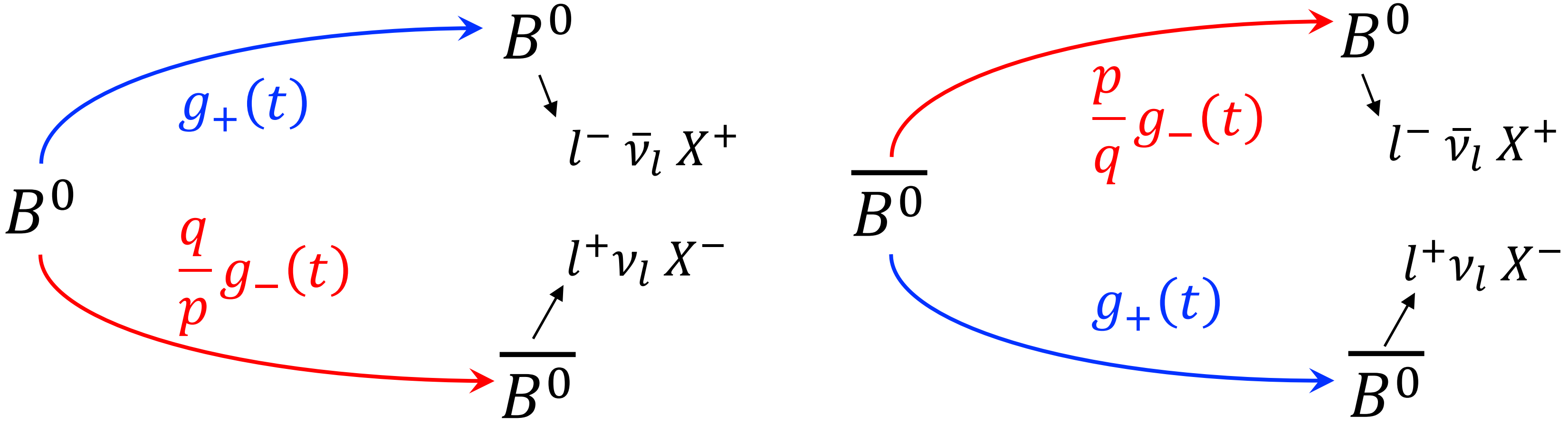
For B^0, expect:
$\Delta\Gamma \sim 0$,
$|q/p| = 1$

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

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

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

B^0 Oscillations



Calculate:

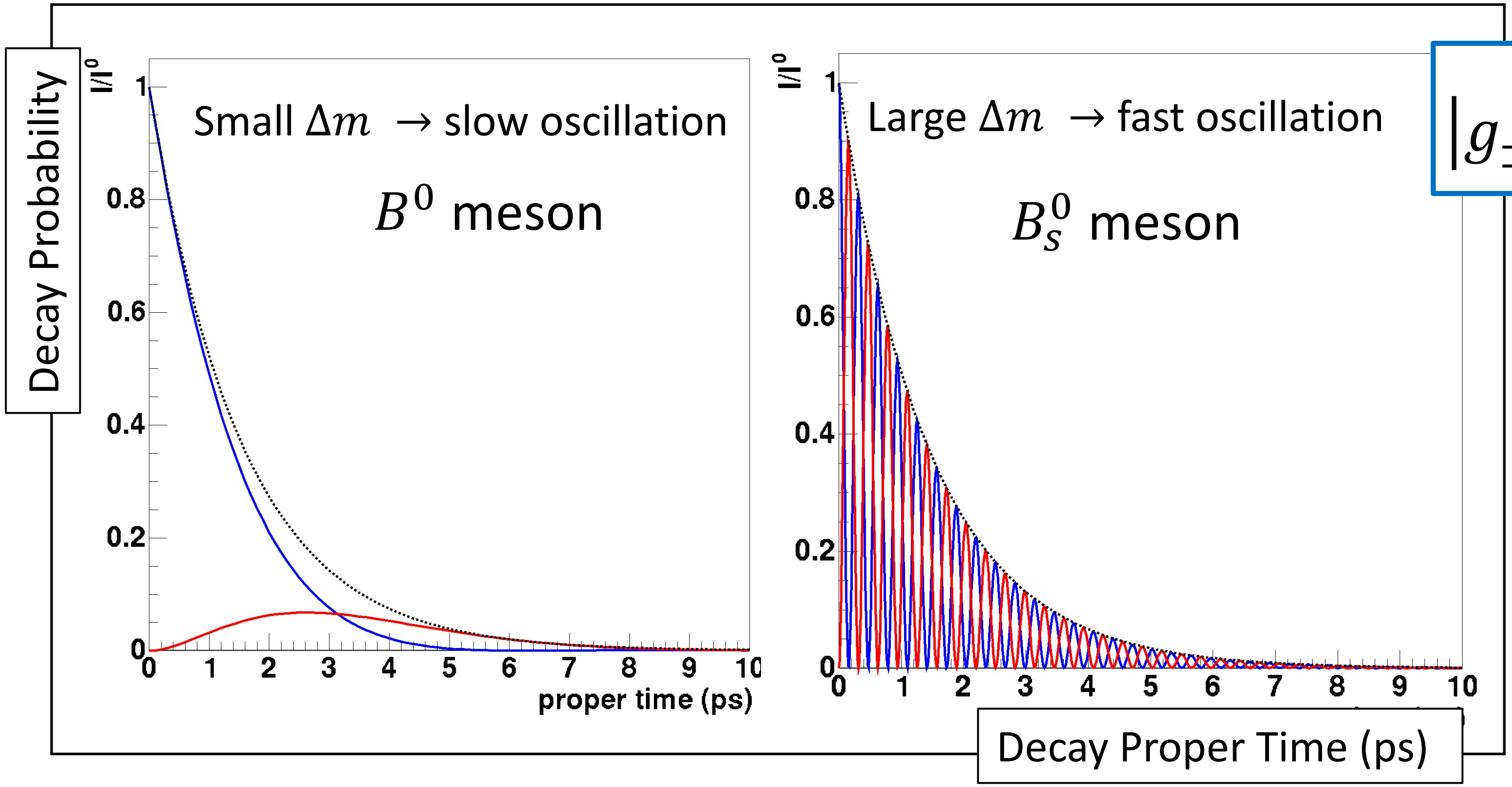
$|\langle B(t)|B^0\rangle|^2$

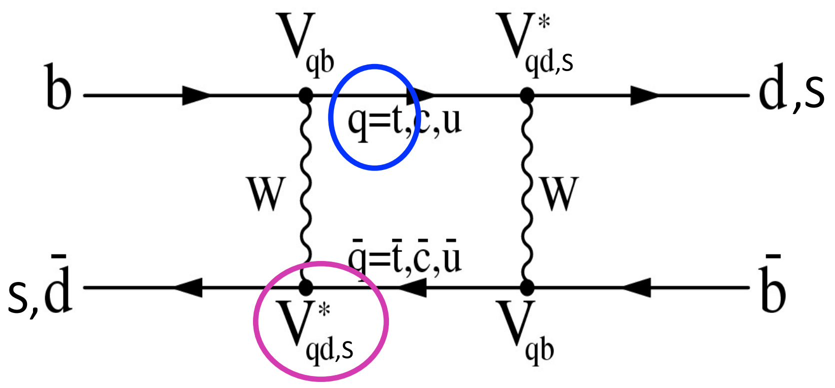
$|\langle \bar{B}(t)|B^0\rangle|^2$

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

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

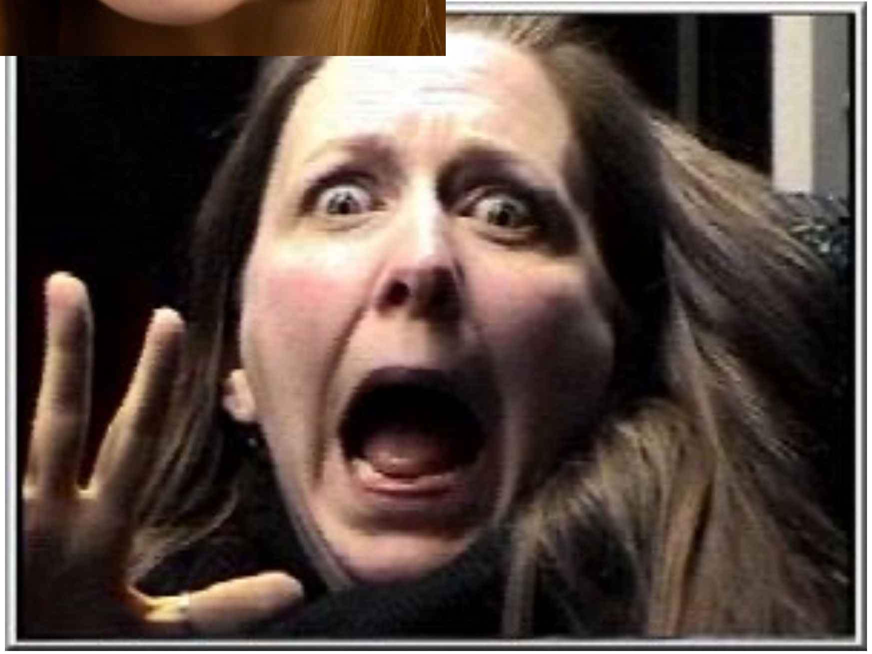
Flavour Oscillations!





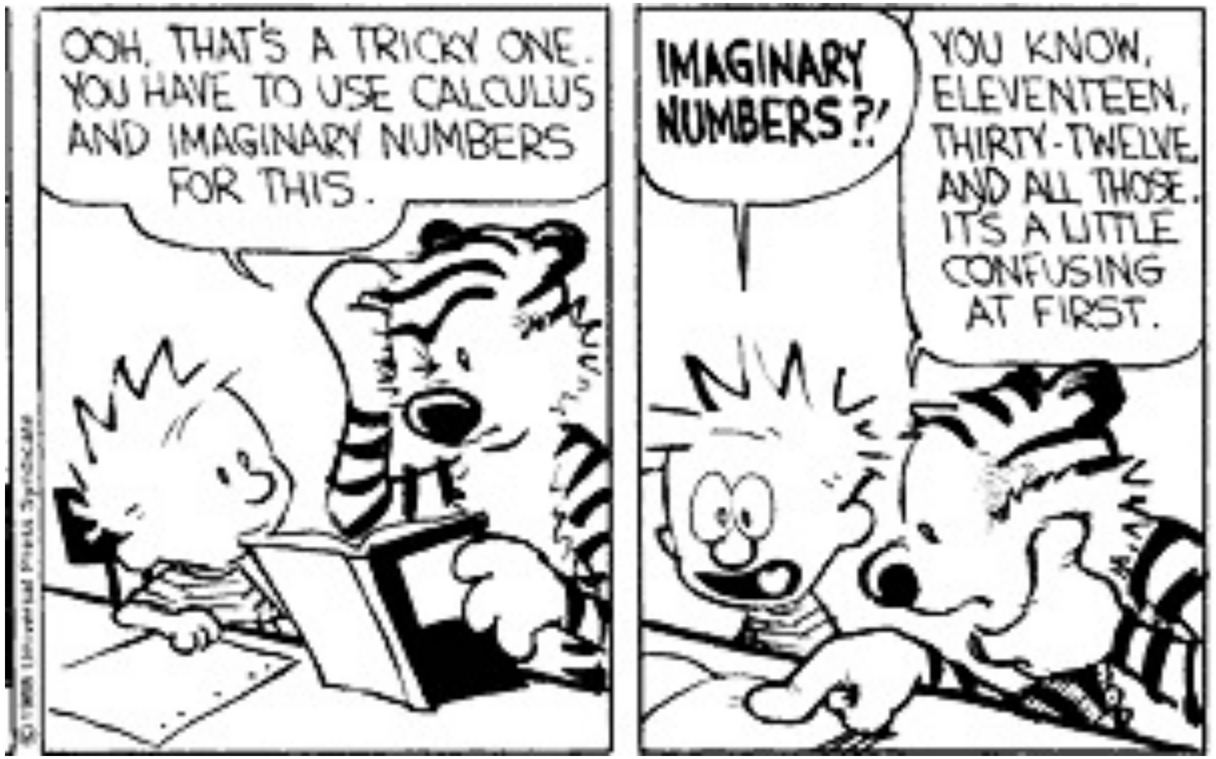
So far, so good...?

Hope not...

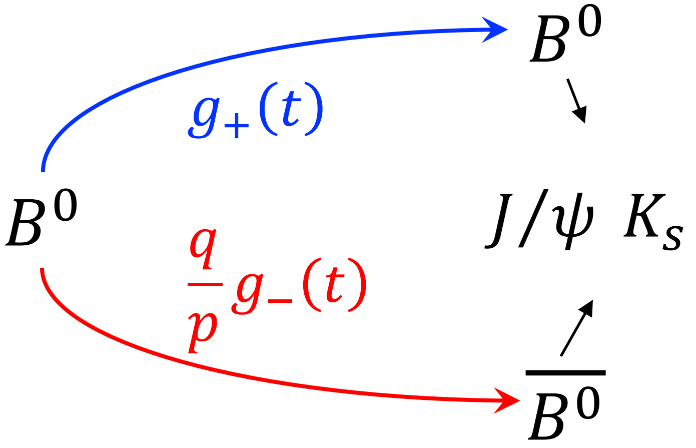


Observing CP Violation

- It's all about imaginary numbers…



B Decays to common final states: CP eigenstates



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

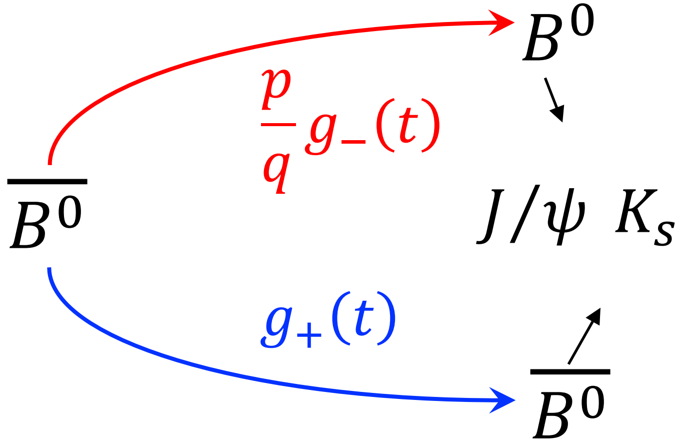
+

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

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

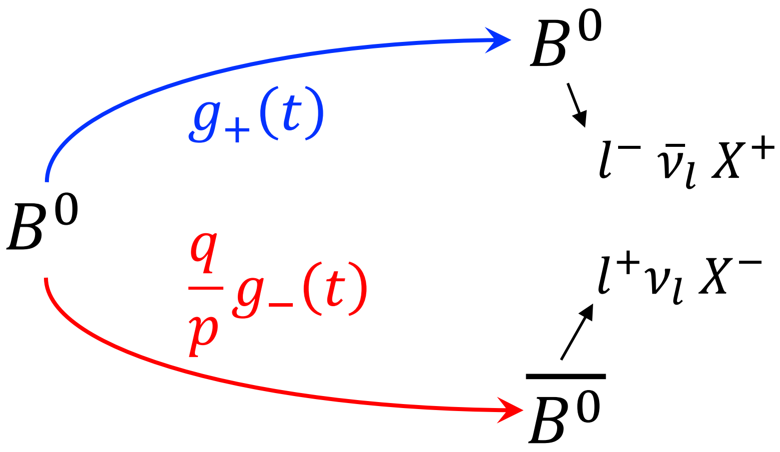
+

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

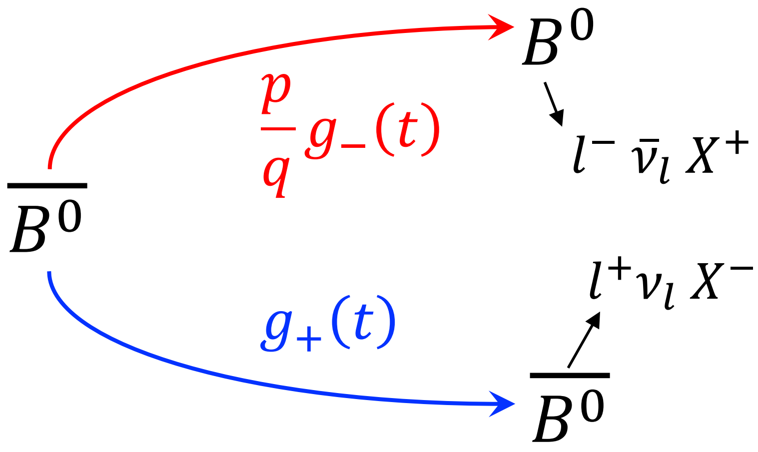


←CP→

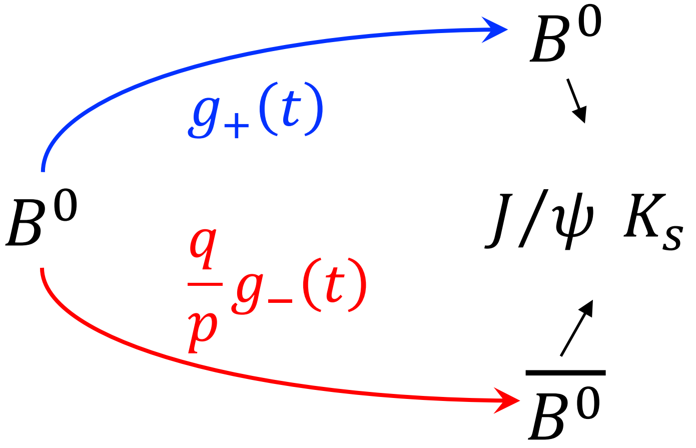
Instead of (Flavour oscillations):



Instead of (Flavour oscillations):

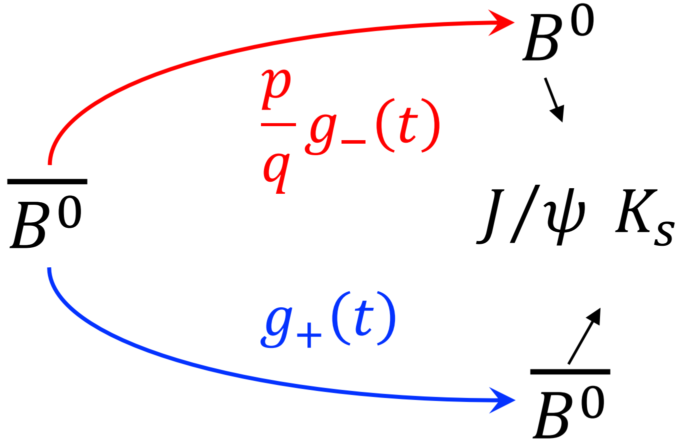


B Decays to common final states: CP eigenstates



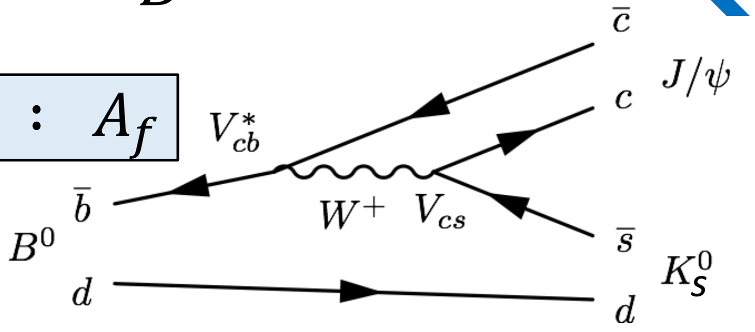
$B^0 \to J/\psi\, K_s$
$+$
$B^0 \to \overline{B^0} \to J/\psi\, K_s$

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



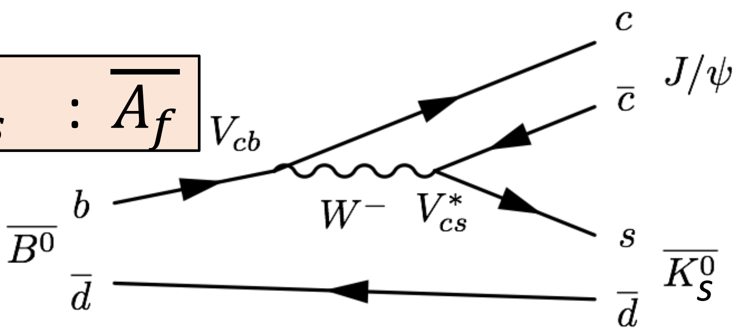
CP

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



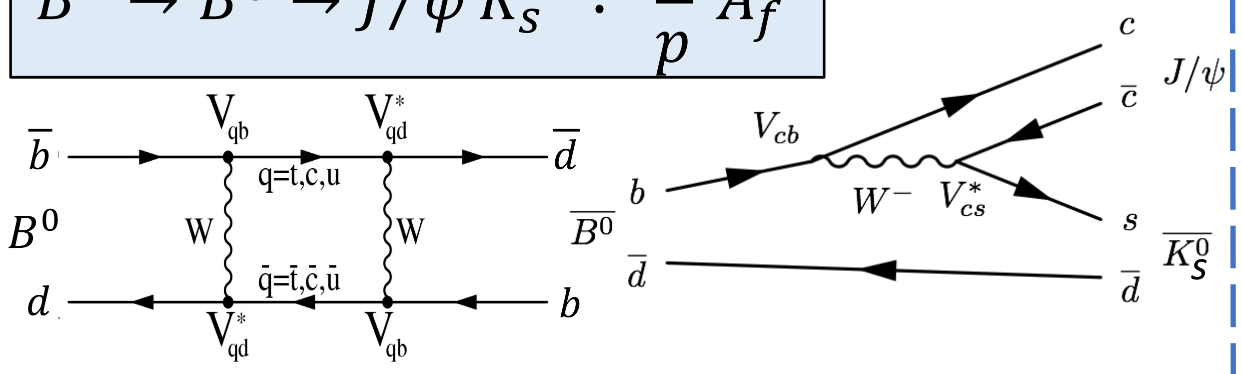
$+$

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

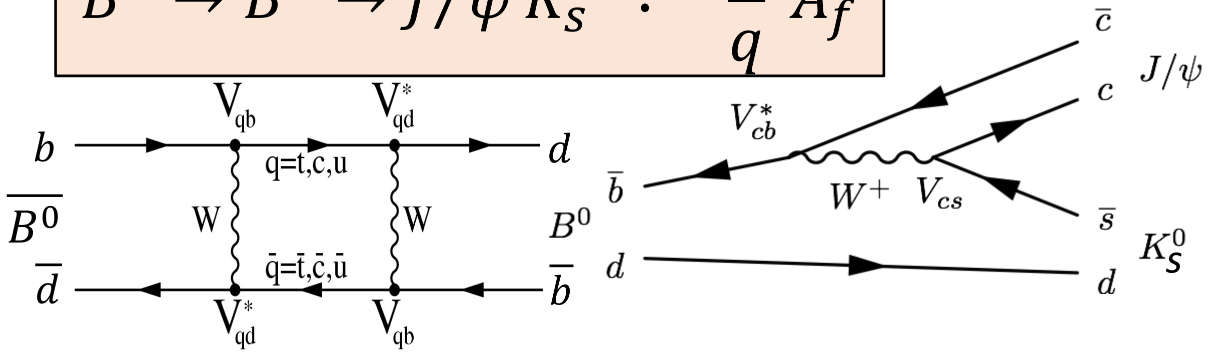


$+$

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



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

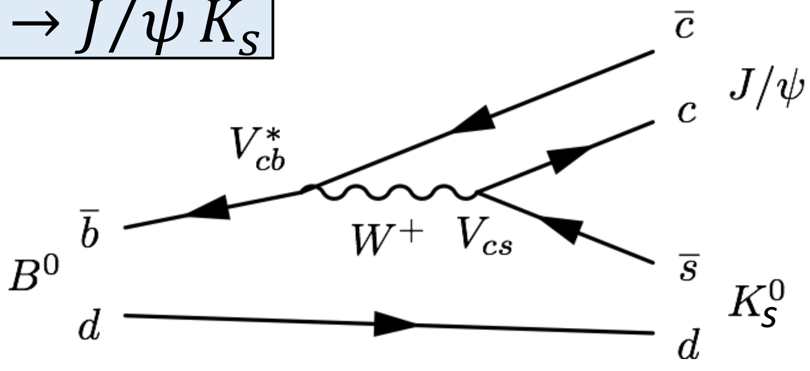


B Decays to common final states: CP eigenstates

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

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

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



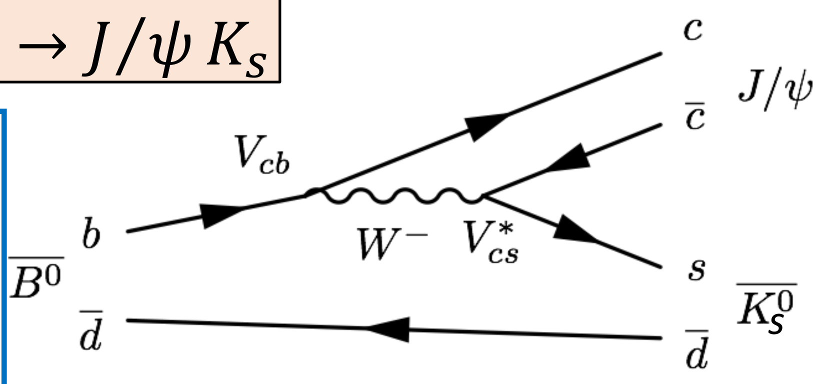
$\bar{\lambda} = 1/\lambda$

$f = \bar{f}$

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

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

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



- 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:

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

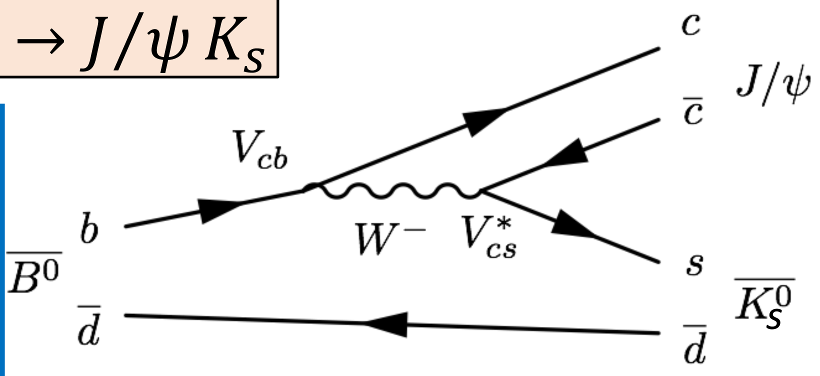
$$|\overline{B^0}(t)\rangle = g_+(t)|\overline{B^0}\rangle + \frac{p}{q}g_-(t)|B^0\rangle$$

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

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

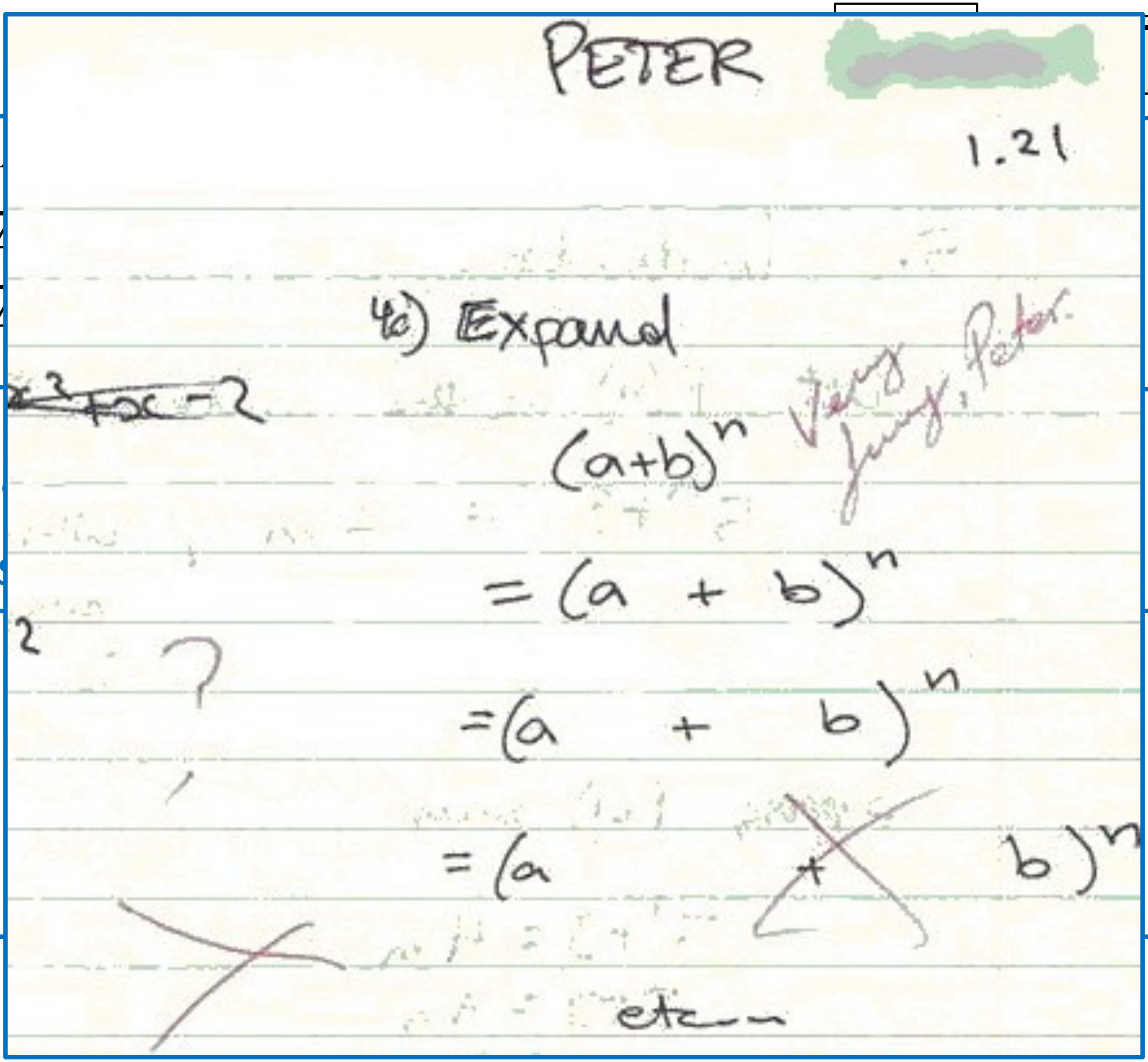
B Decays to common final states: CP eigenstates

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



$A_f \equiv \langle f|$ …

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



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

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…

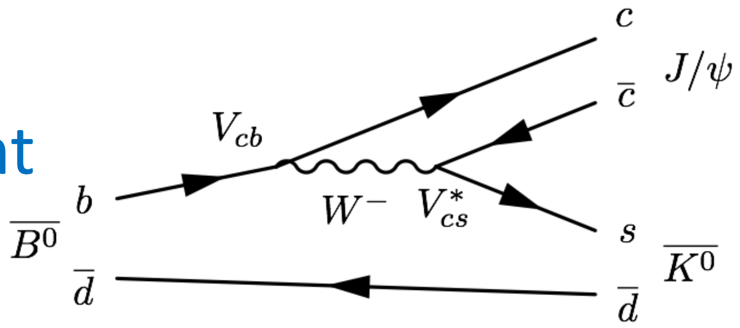
$$\Gamma_{(B\to f)}(t) = |A_f|^2\left(1+|\lambda_f|^2\right)\frac{e^{-\Gamma t}}{2}\cdot$$
$$\left(\cosh\frac{\Delta\Gamma t}{2} + D_f\sinh\frac{\Delta\Gamma t}{2} + C_f\cos\Delta m t - S_f\sin\Delta m\, t\right)$$

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

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

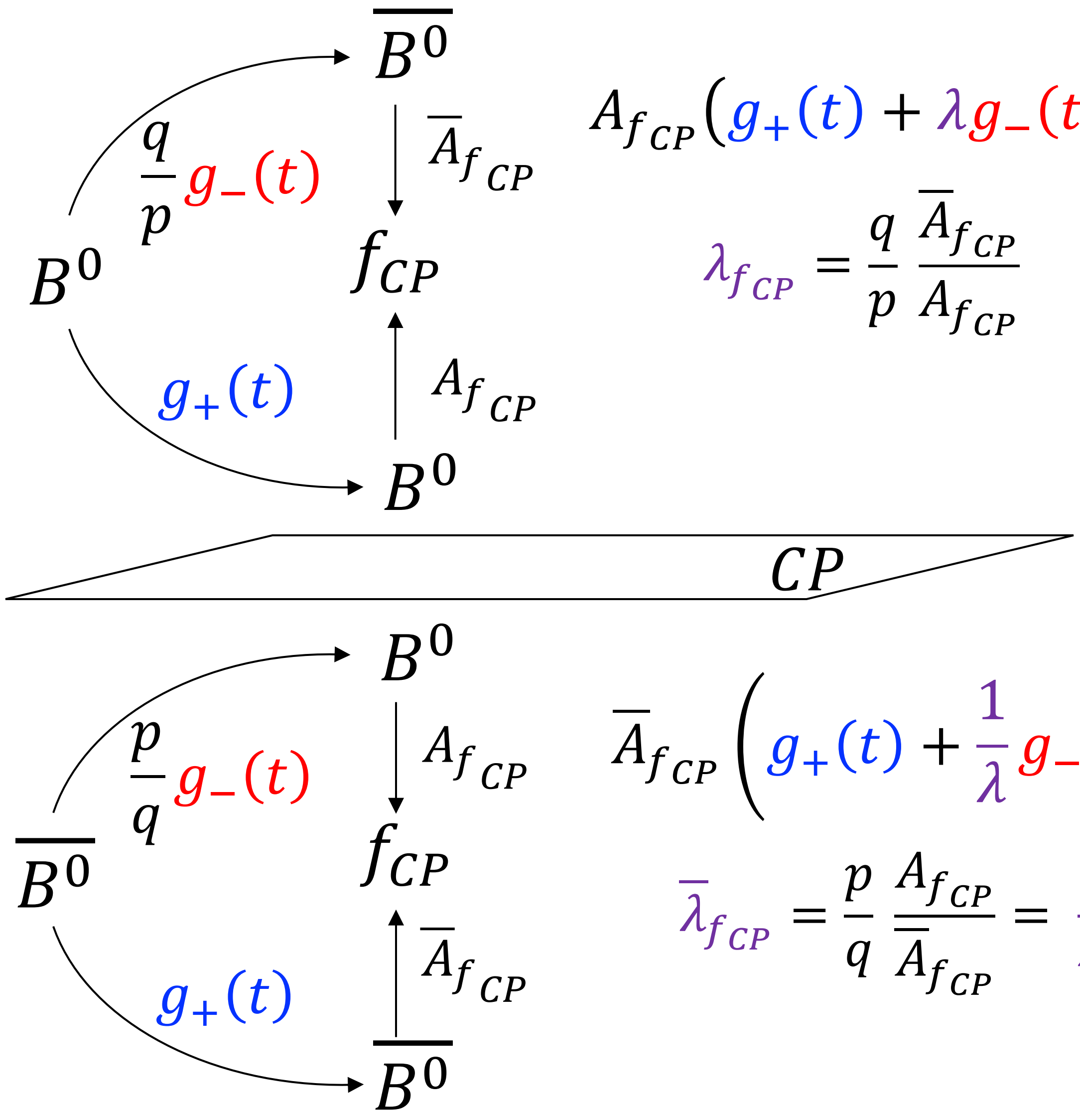
- Coefficients D_f, C_f and S_f are measured by experiment

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



How does it give CP violation?

<u>$t=0$ $\quad$ t $\quad$ Amplitude</u>



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

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

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

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

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

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

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

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

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

For neutral B mesons, g_- has a 90° (= 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}	$\bar{A}_{f_{CP}}\left(g_+(t) + \frac{1}{\lambda} g_-(t)\right)$

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

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

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

Interfering Amplitudes

$t = 0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}(a_1 + a_2\, e^{-i\phi_w}\, e^{i\pi/2})$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\bar{A}_{f_{CP}}(a_1 + a_2\, e^{+i\phi_w}\, e^{i\pi/2})$

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

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

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

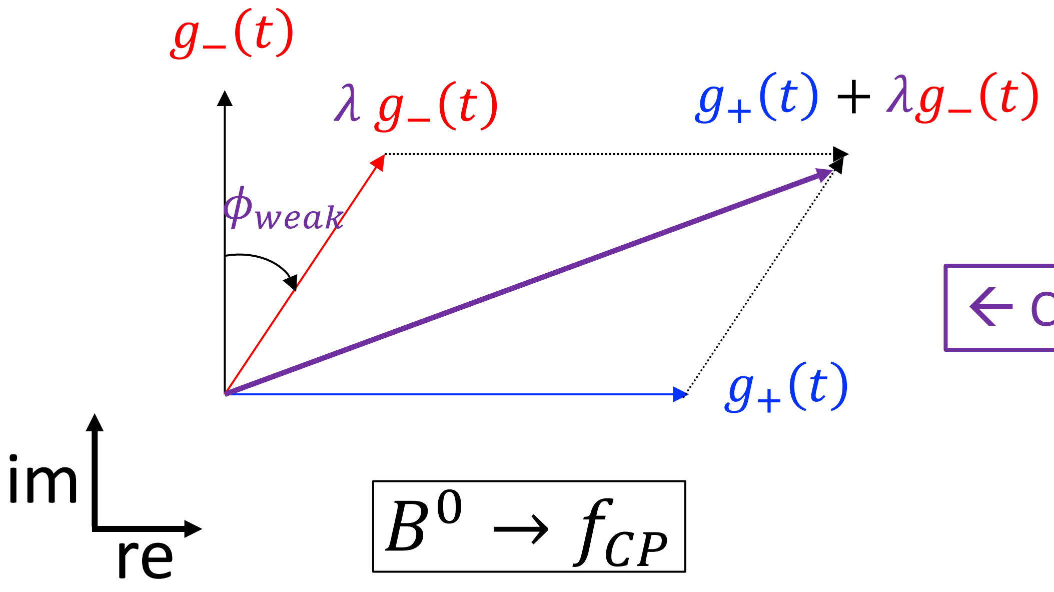
Interfering Amplitudes: CP violation!

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

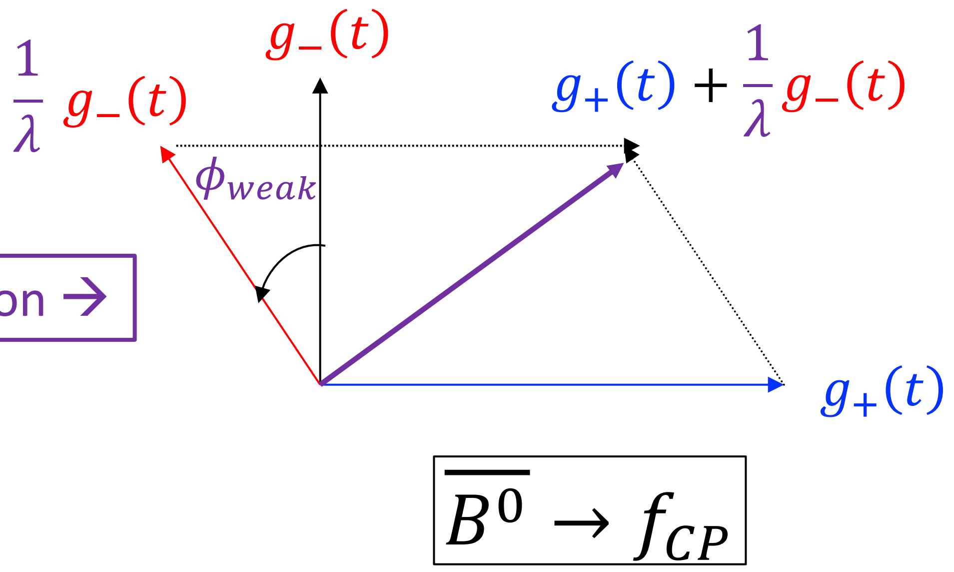
$$g_+ = e^{-imt}\, e^{-\Gamma t/2} \cos\frac{\Delta mt}{2}$$

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

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



← CP-Violation →

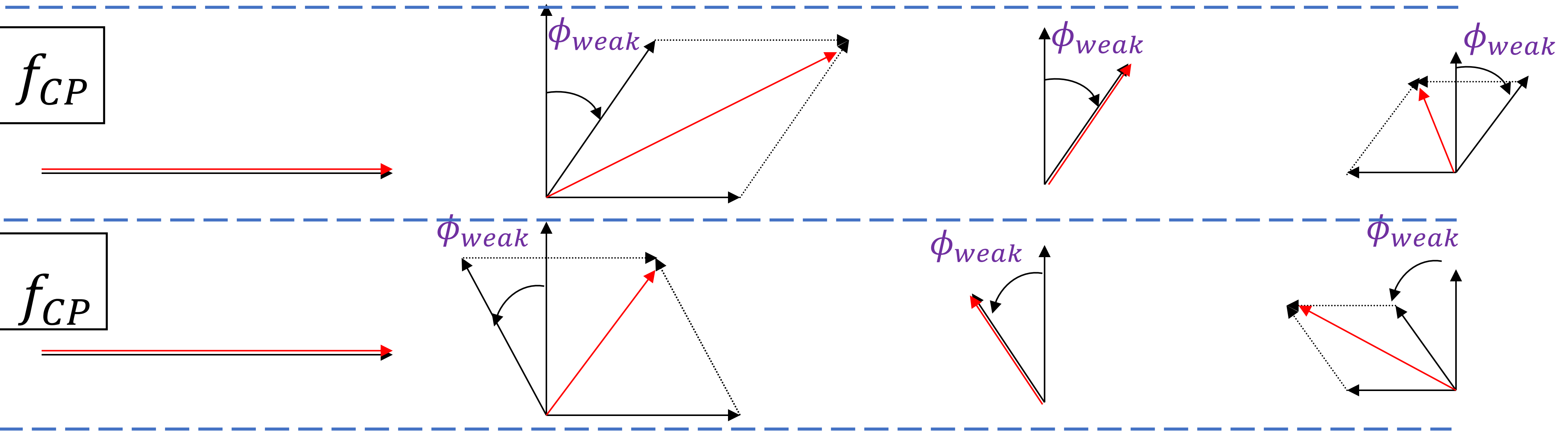


Interfering Amplitudes: time dependent CP violation!

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

$B^0 \rightarrow f_{CP}$

$\overline{B^0} \rightarrow f_{CP}$



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

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}	$\overline{A}_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta m t}{2} + i\,\frac{1}{\lambda}\,\sin\frac{\Delta m t}{2}\right)$

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

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

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

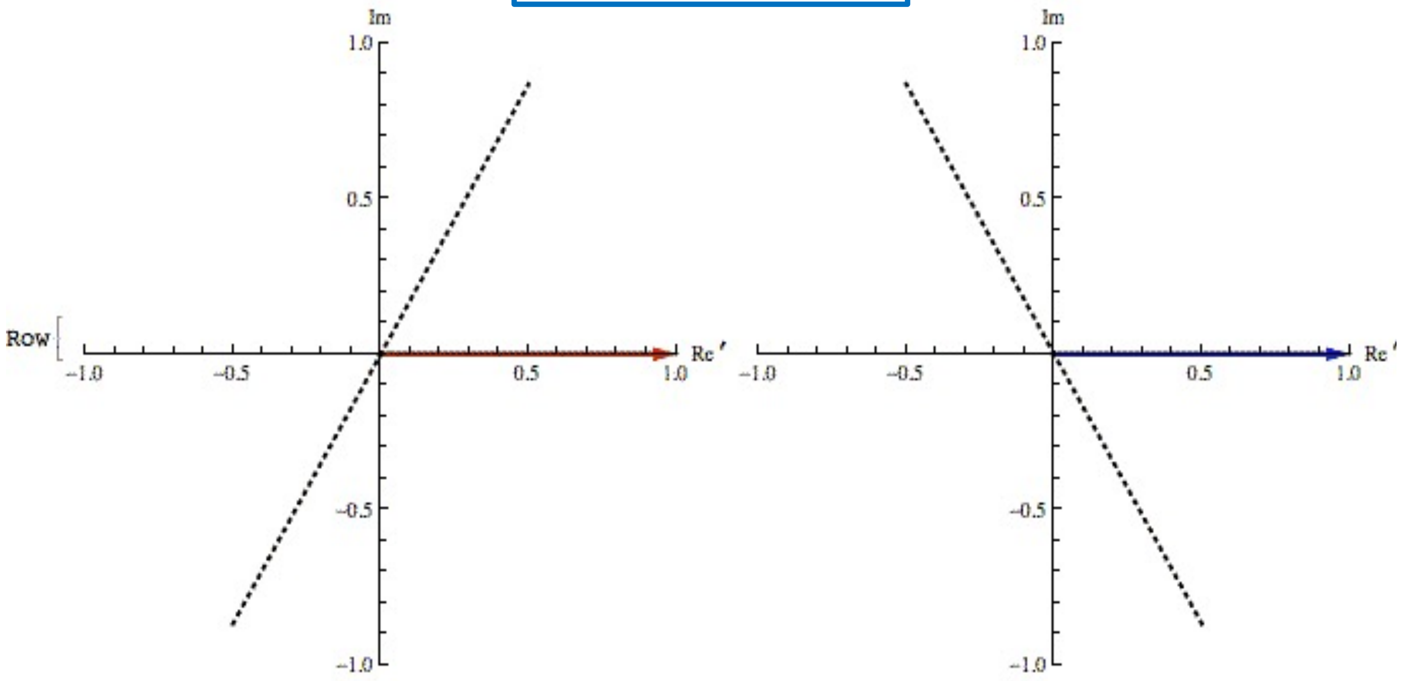
$$\overline{B^0} \rightarrow f_{CP} \;:\quad \left|\cos\frac{\Delta m t}{2} + i\,\frac{1}{\lambda}\sin\frac{\Delta m t}{2}\right|^2 \propto 1 - \frac{(1-|\lambda|^2)}{(1+|\lambda|^2)}\cos\Delta m t + \frac{(2\Im\lambda)}{(1+|\lambda|^2)}\sin\Delta m t$$

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

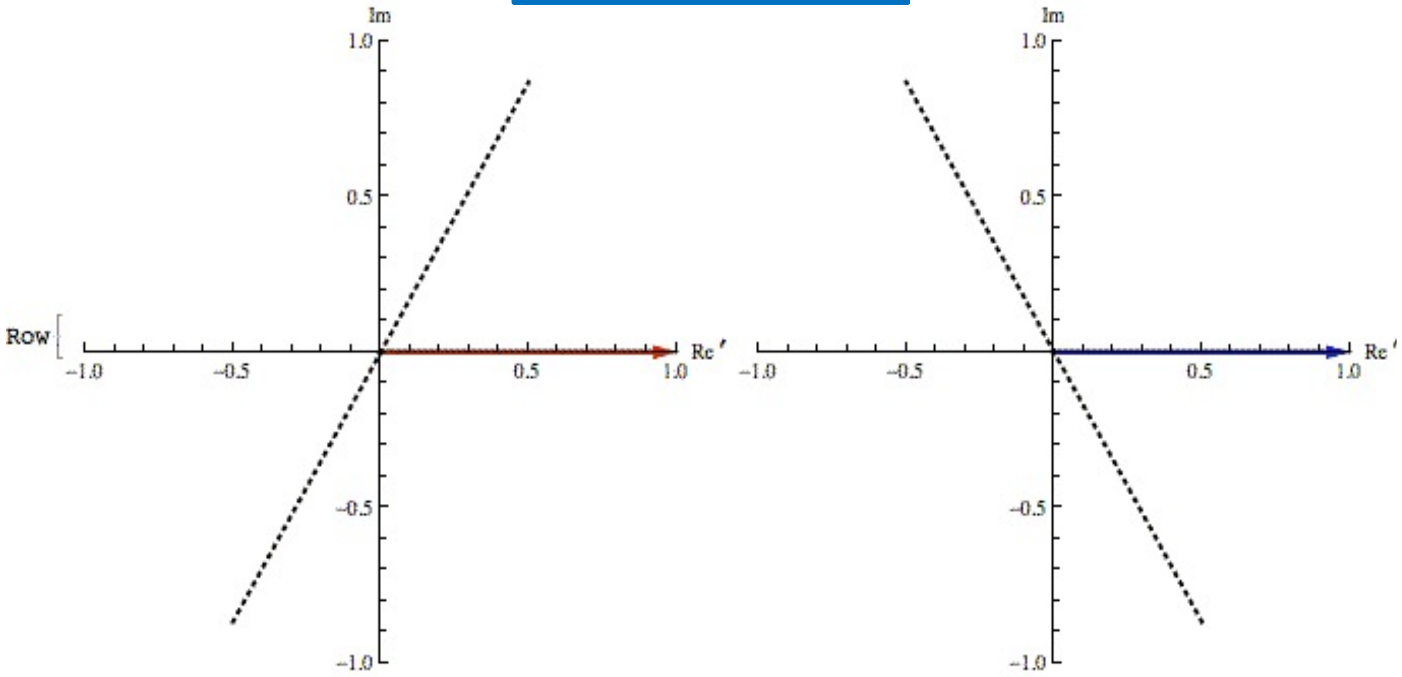


Time Dependent CP violation

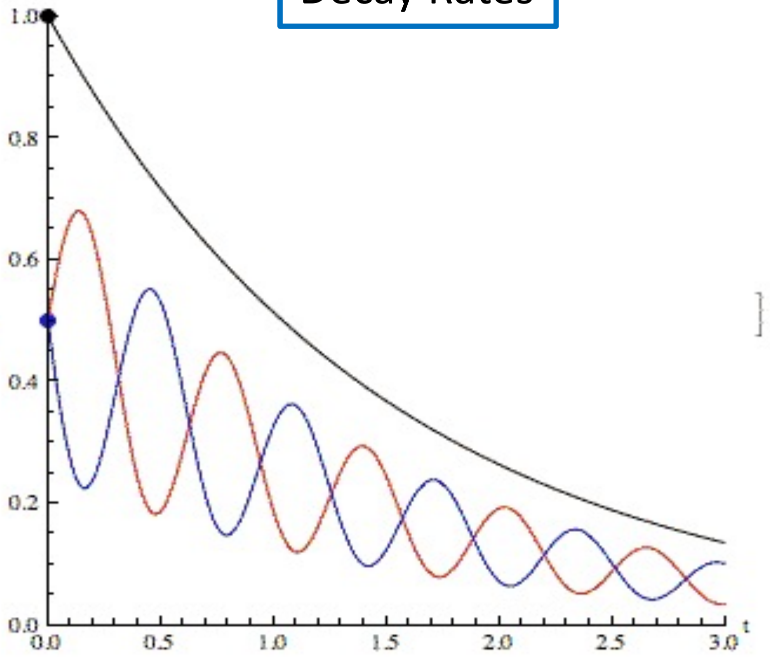
$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$t = 0$		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}	$\propto e^{-\Gamma t}\,[1 - \sin\phi_{weak}\sin\Delta m t]$

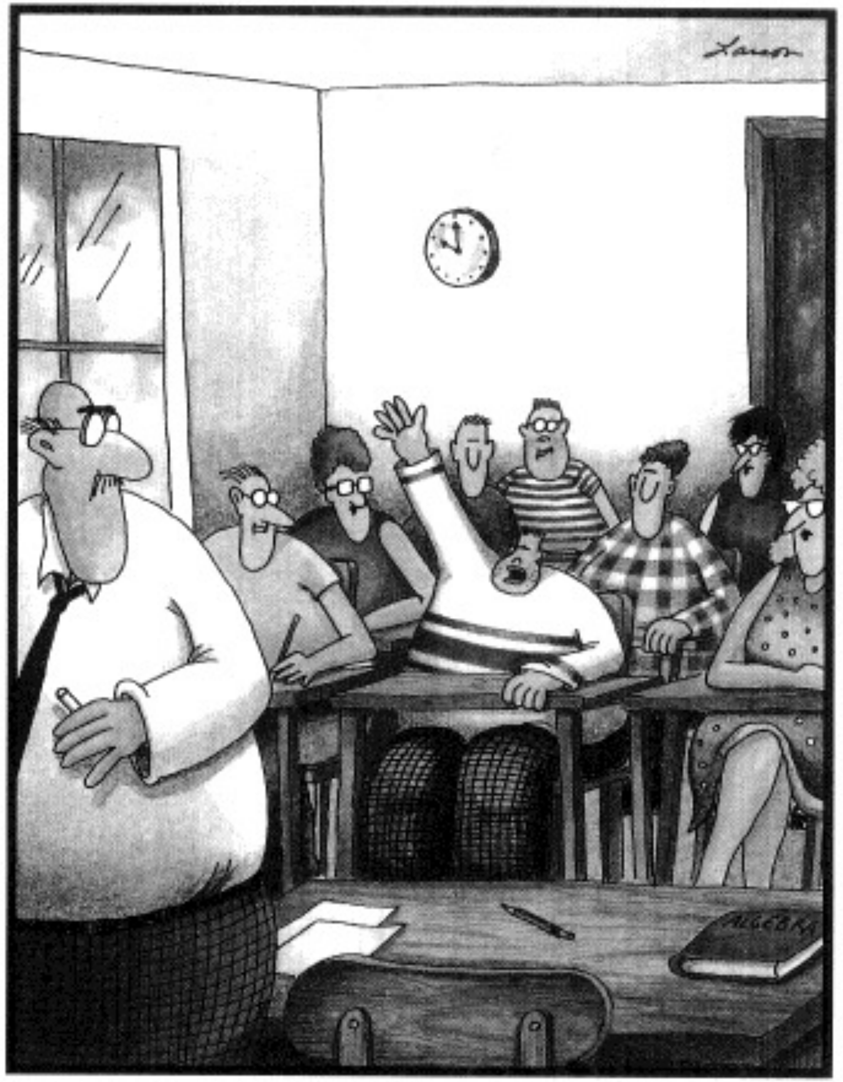
Decay Amplitudes



Decay Rates



Where were we?



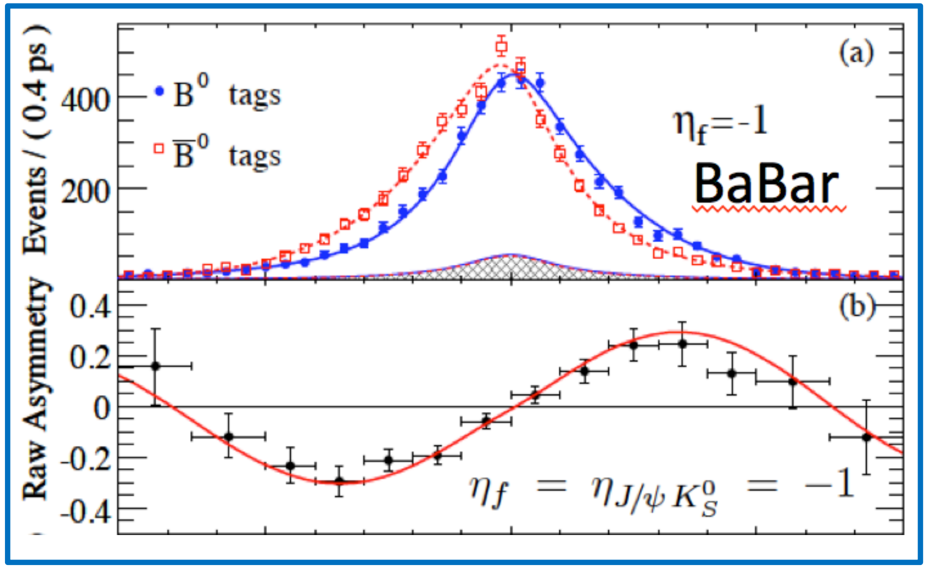
"Mr. Osborne, may I be excused? My brain is full."

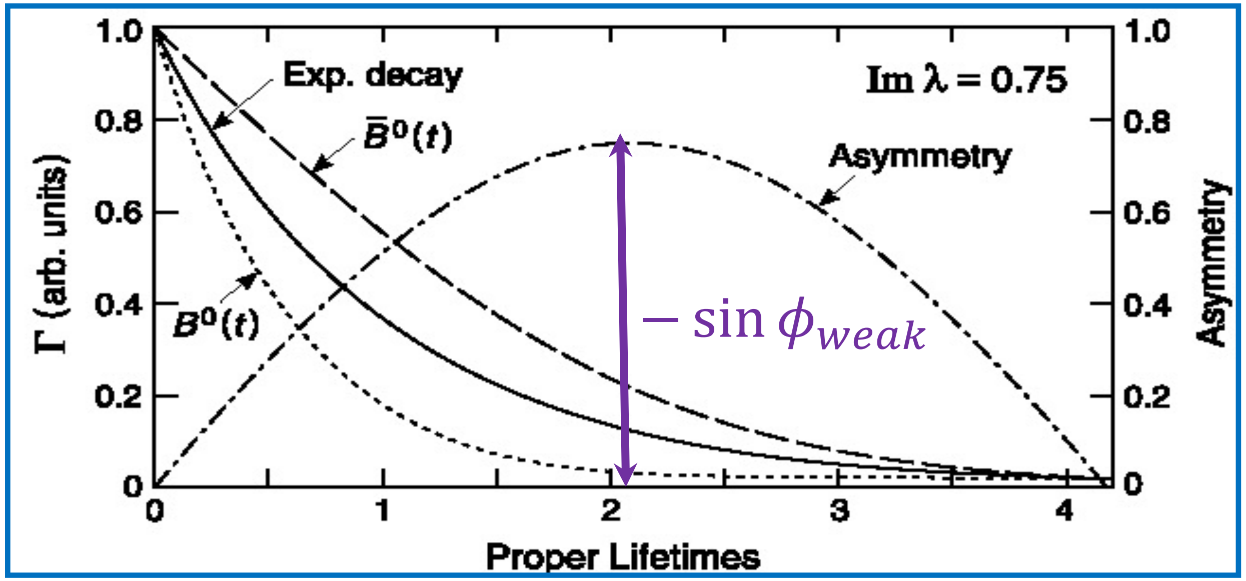
Time Dependent CP Asymmetry

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

$t=0$		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}	$\propto e^{-\Gamma t}\ [1-\ \sin\phi_{weak}\sin\Delta m t]$

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



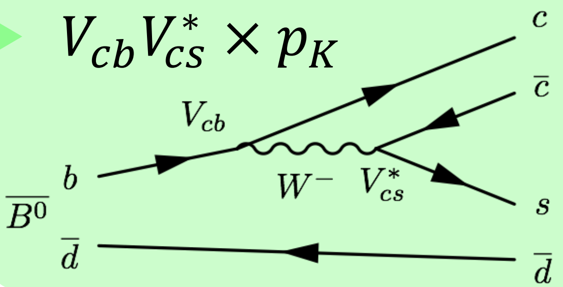


$\lambda_{J/\psi K_S}$ for "Golden" mode: $B^0 \to J/\psi K_S$

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

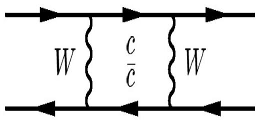
$$\lambda_{J/\psi K_S} \equiv -\frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

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



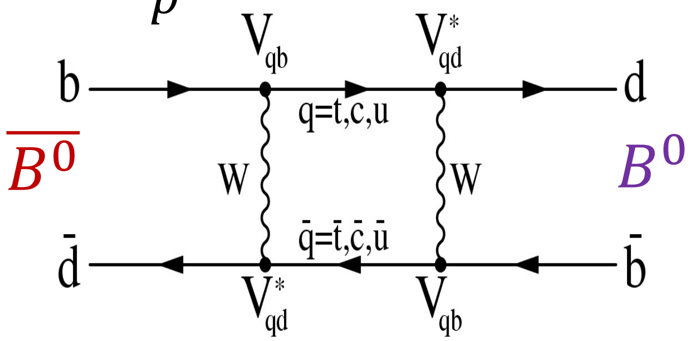
$\overline{K^0} \times \langle K_s|\overline{K^0}\rangle$

p_{K_S}



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

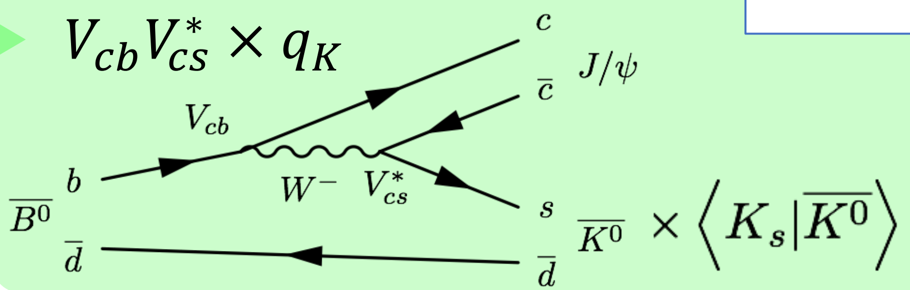
$\frac{q}{p}$

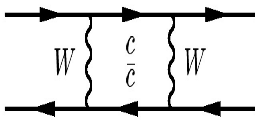


$\lambda_{J/\psi K_S}$ for "Golden" mode: $B^0 \to J/\psi K_S$

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

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





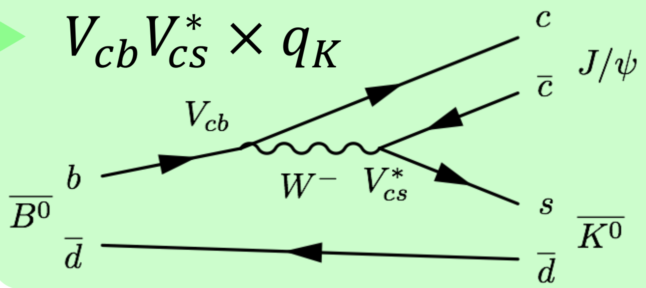
$$\lambda_{J/\psi K_S} = -\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}$$

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

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

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

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

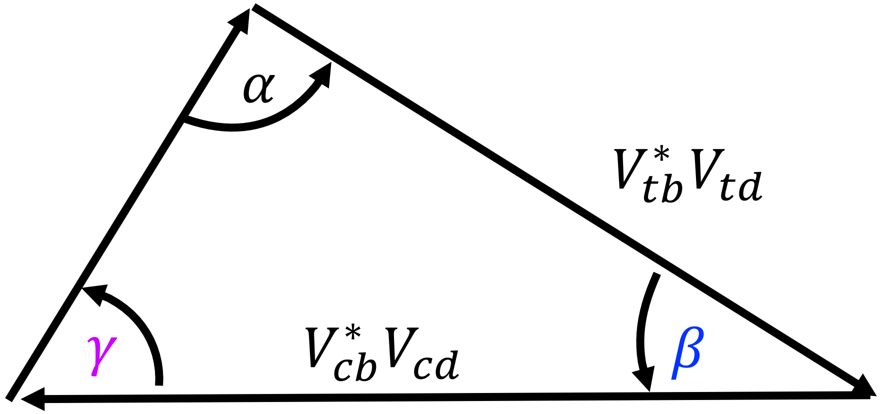


$\overline{K^0} \times \langle K_s | \overline{K^0} \rangle$

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

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

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



- 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 …

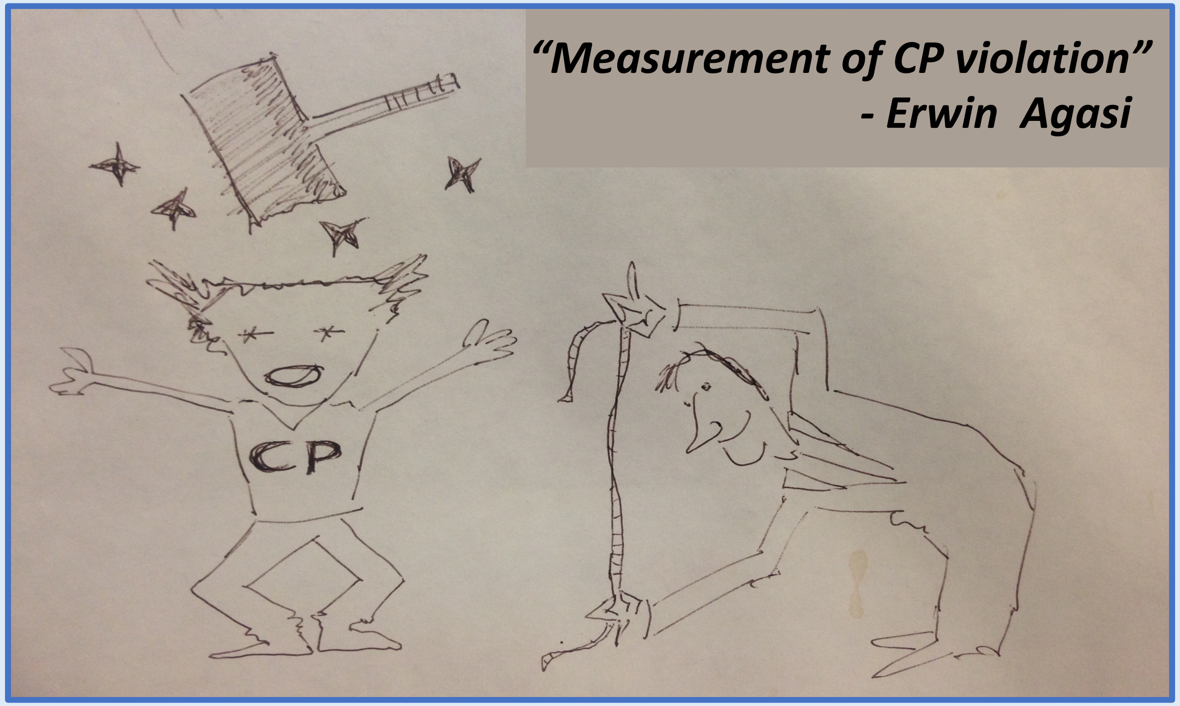
How are you doing?

How are you doing?

How are you doing?

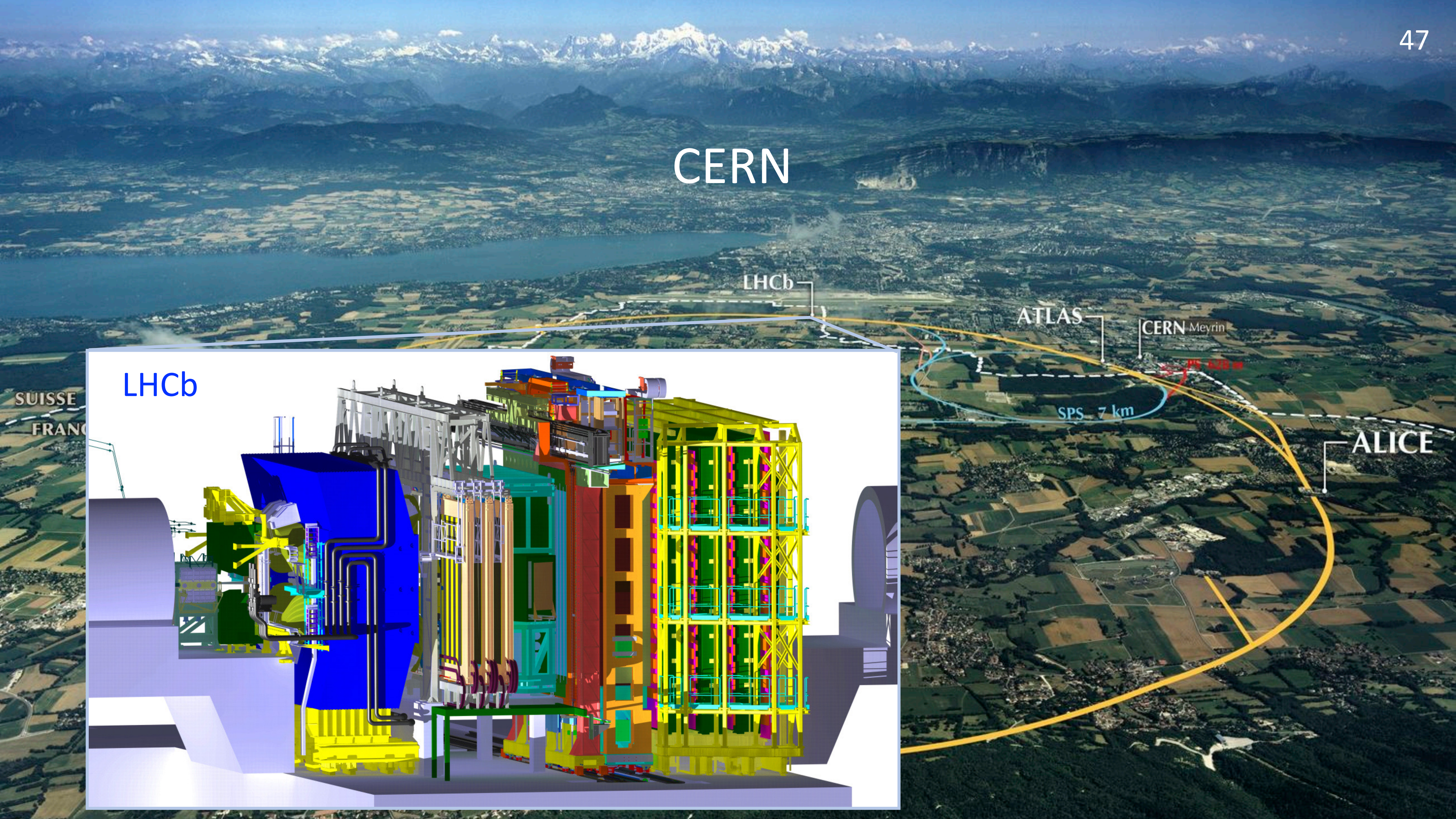
Contents:

Contents:

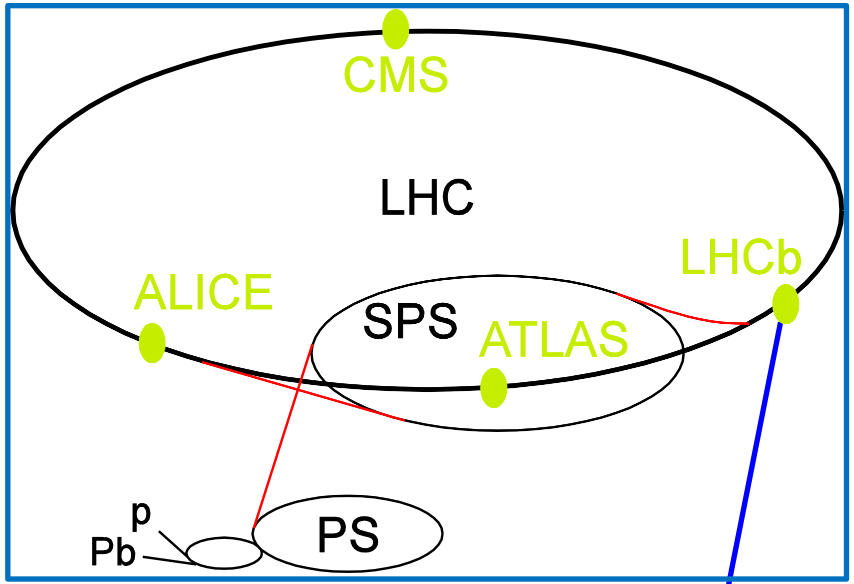


"Measurement of CP violation"
- Erwin Agasi

CERN



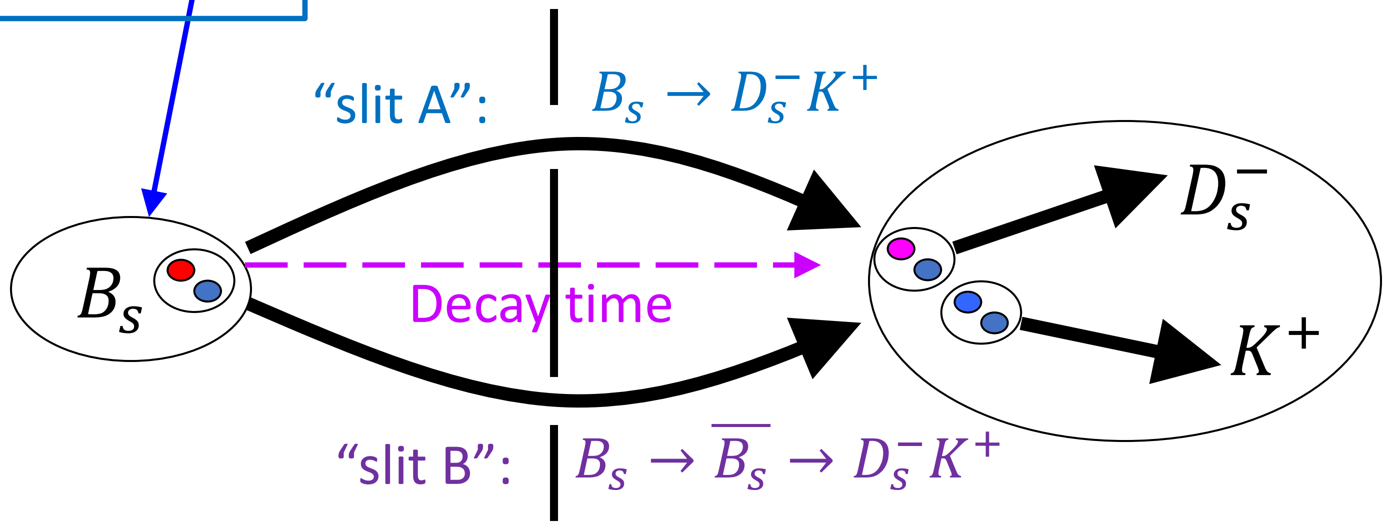
$B_s \to D_s K$: Quantum Interference Experiment @ LHCb



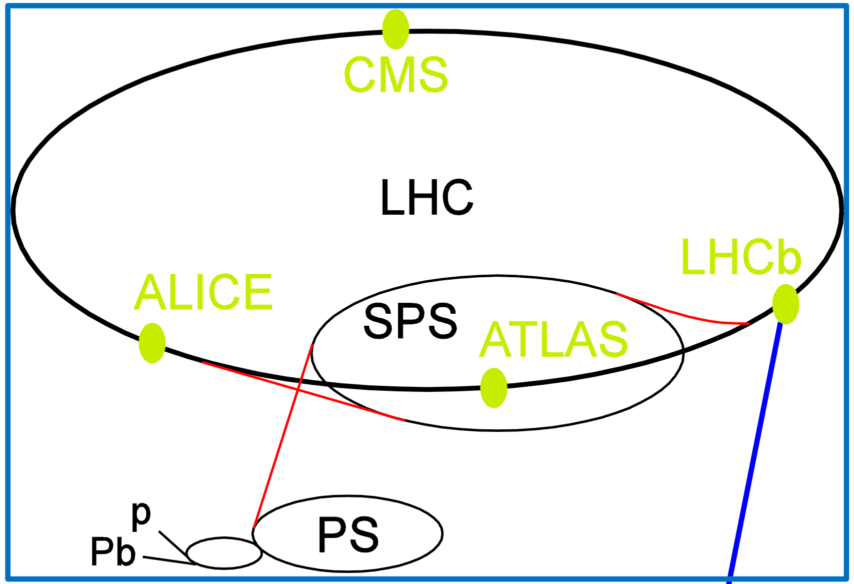
Measure:

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

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



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

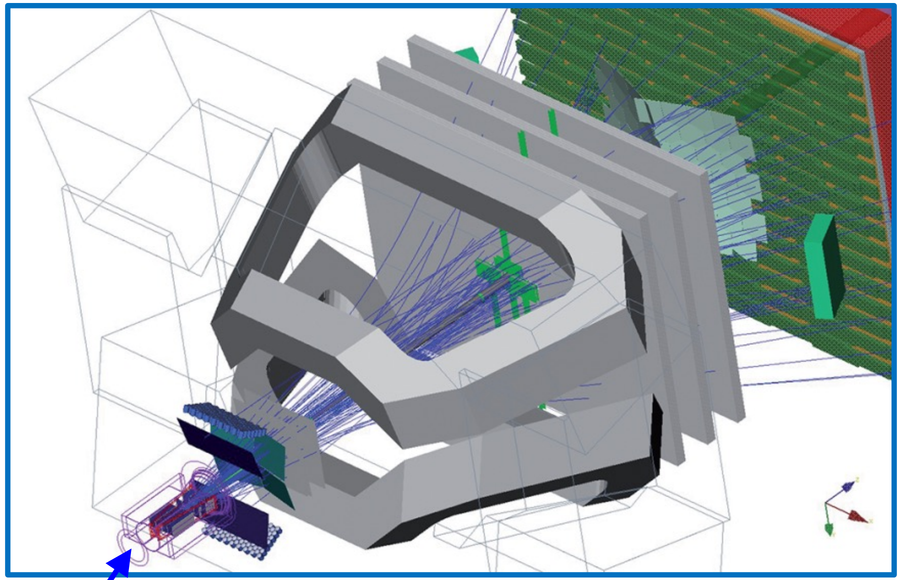


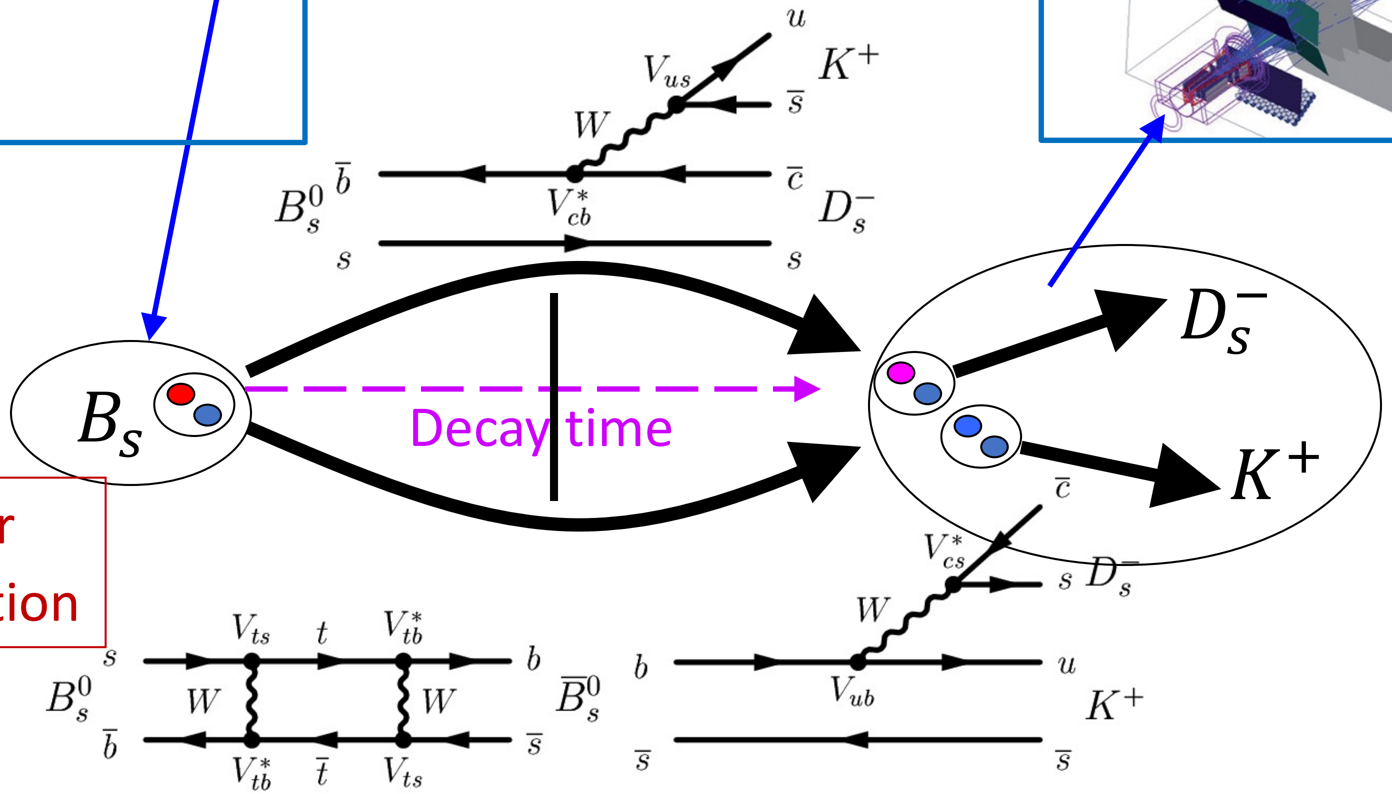
Measure:

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

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

Repeat for $D_s^+ K^-$

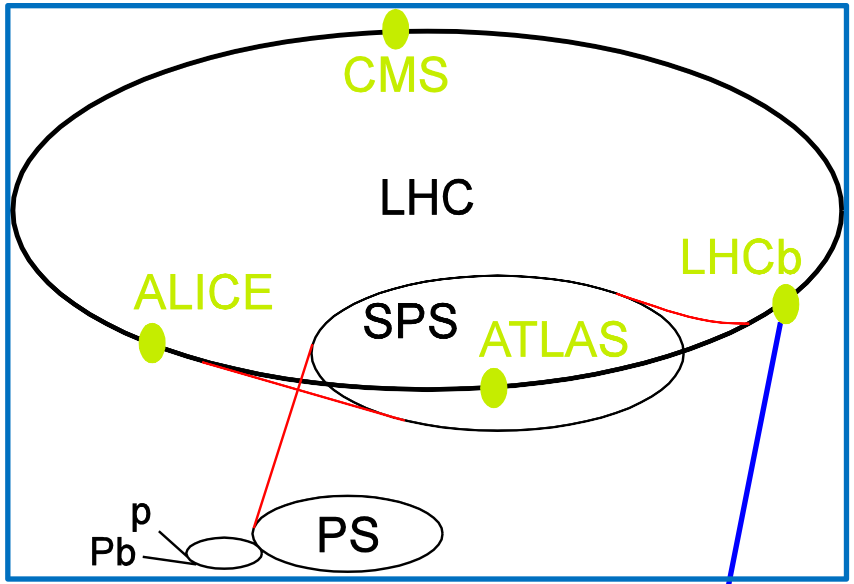




2) Measure decay rate as function of decay-time

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

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

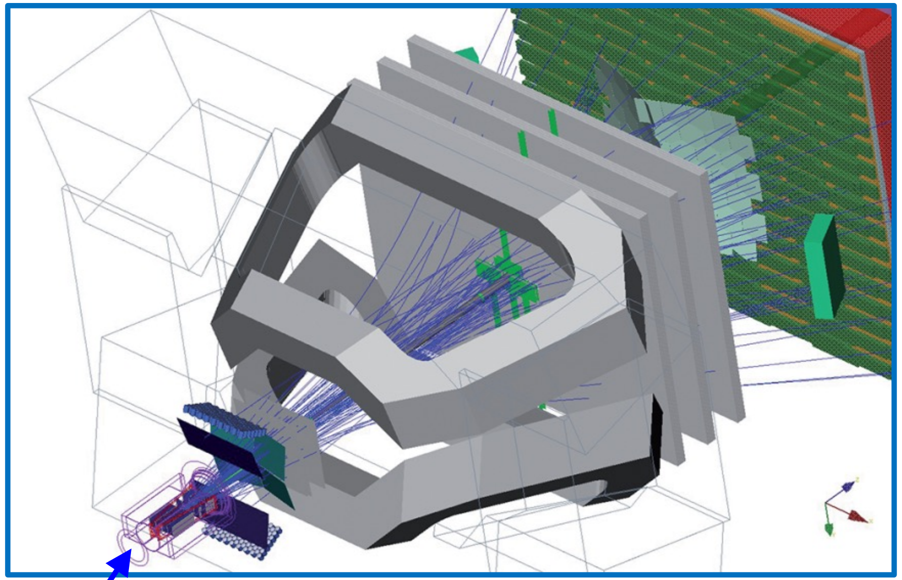


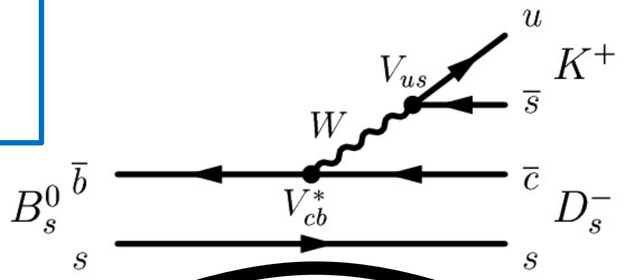
Measure:

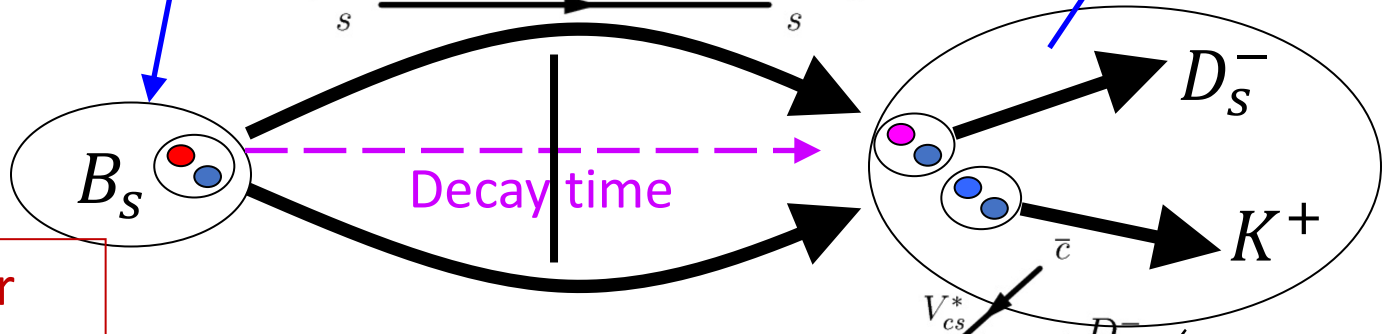
$B_s \to (\overline{B_s} \to) D_s^- K^+$

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

Repeat for $D_s^+ K^-$







2) Measure decay rate as function of decay-time

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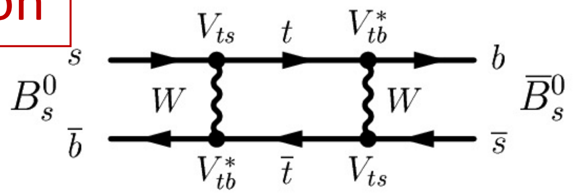
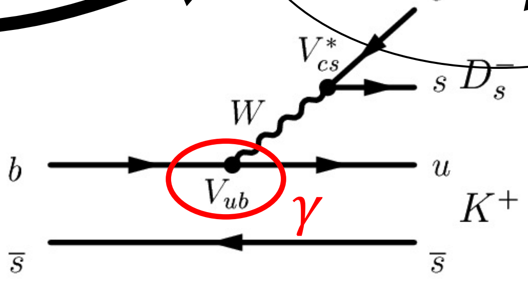
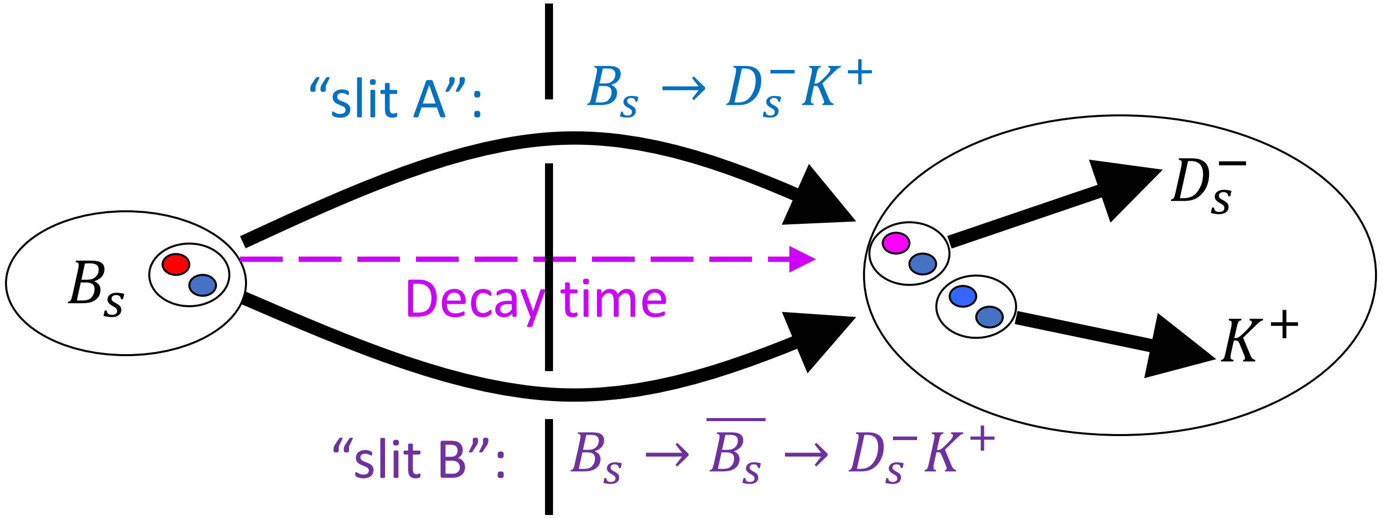
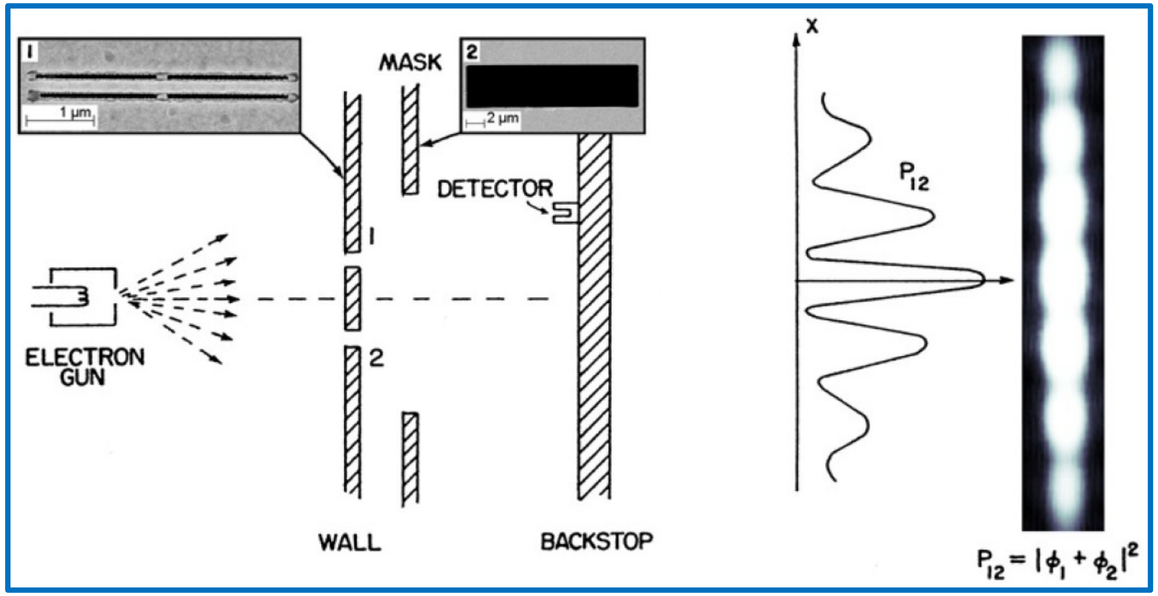




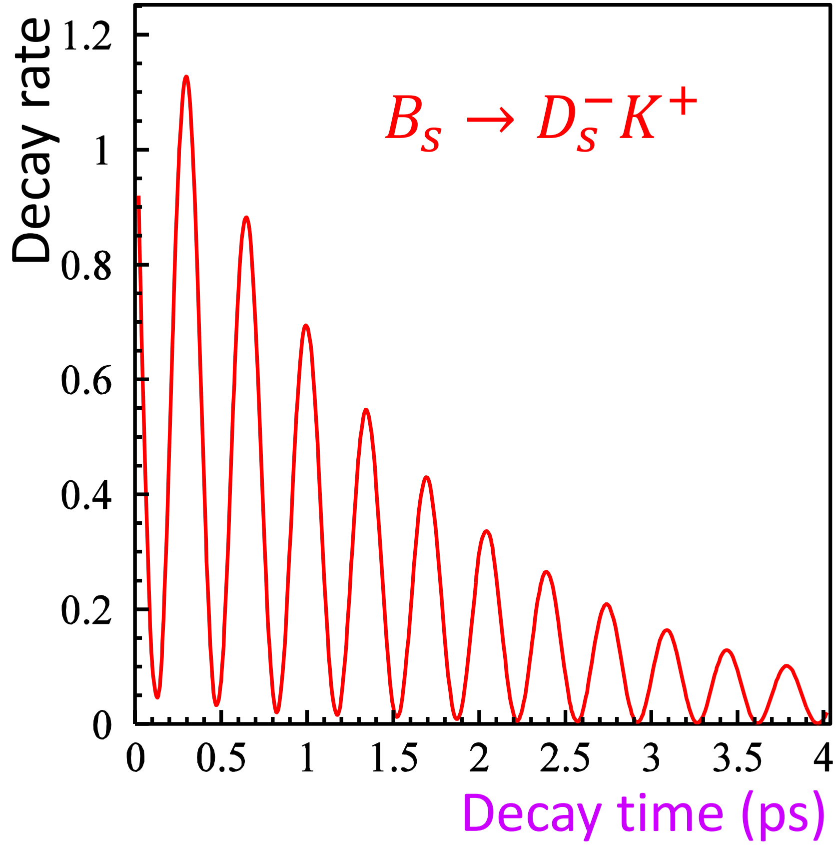
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

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

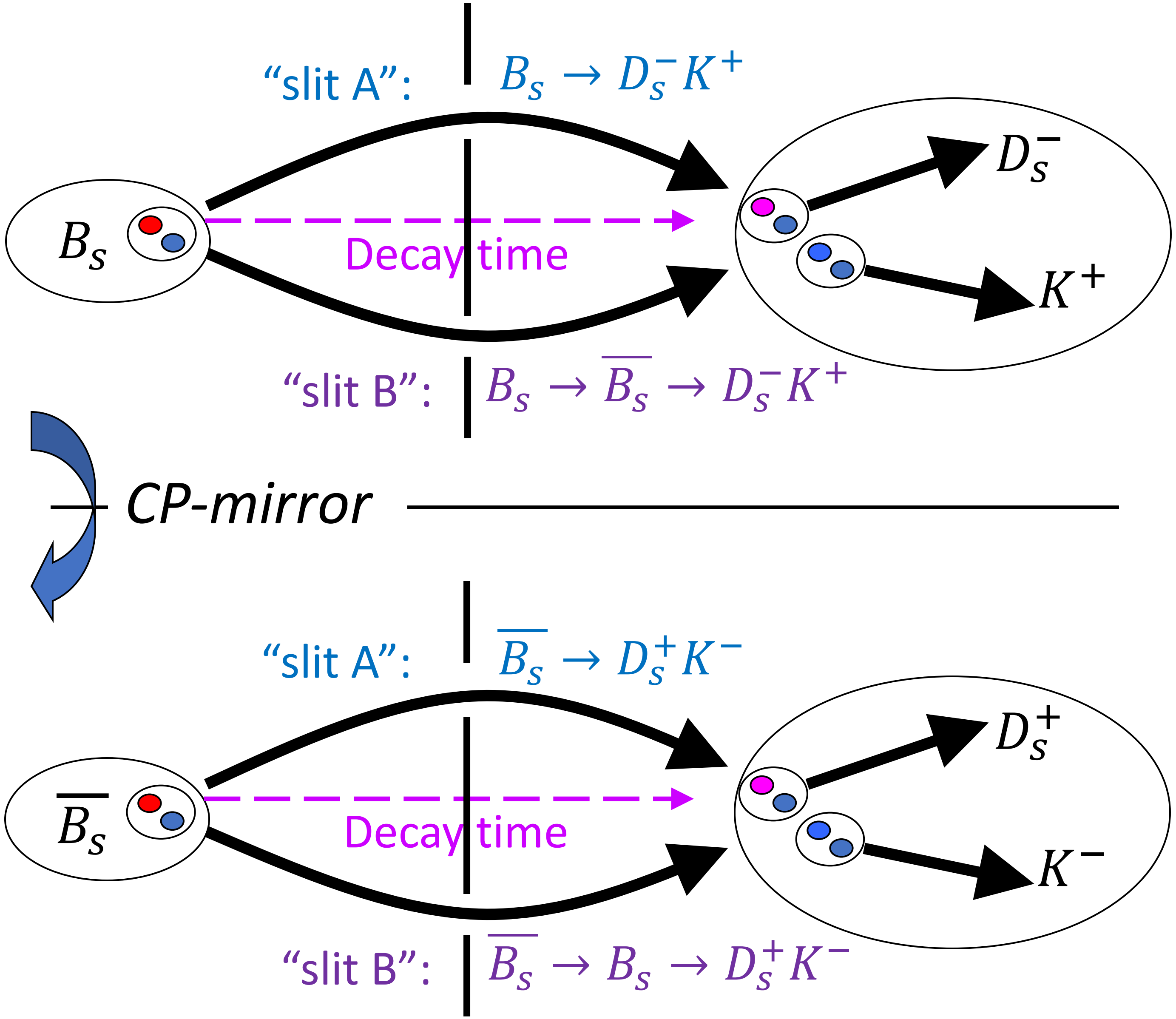




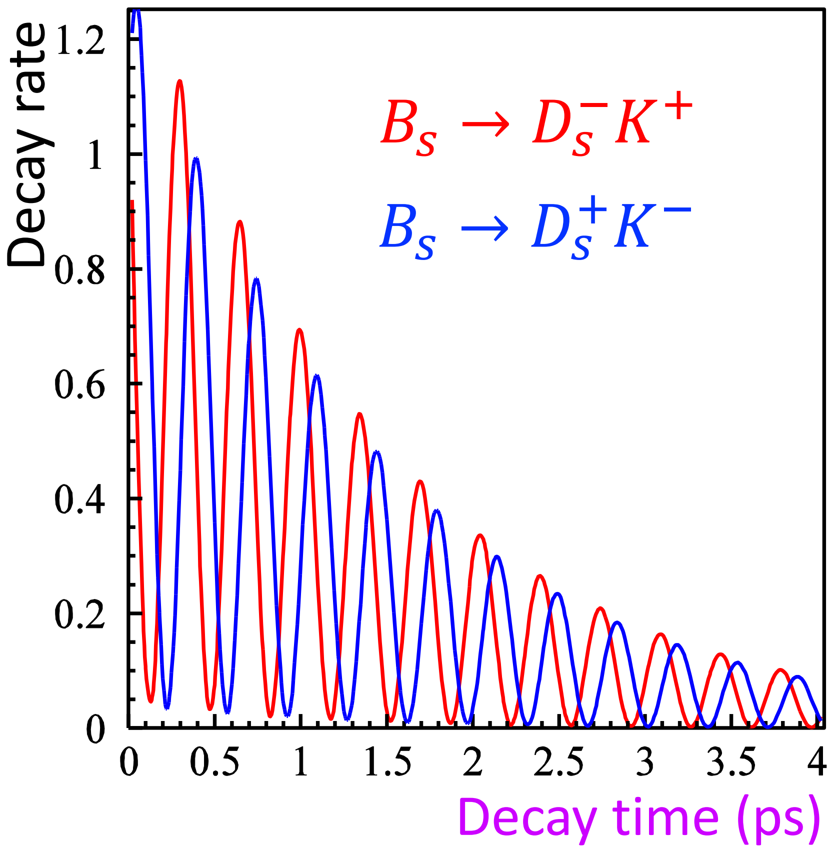
An interference pattern:



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

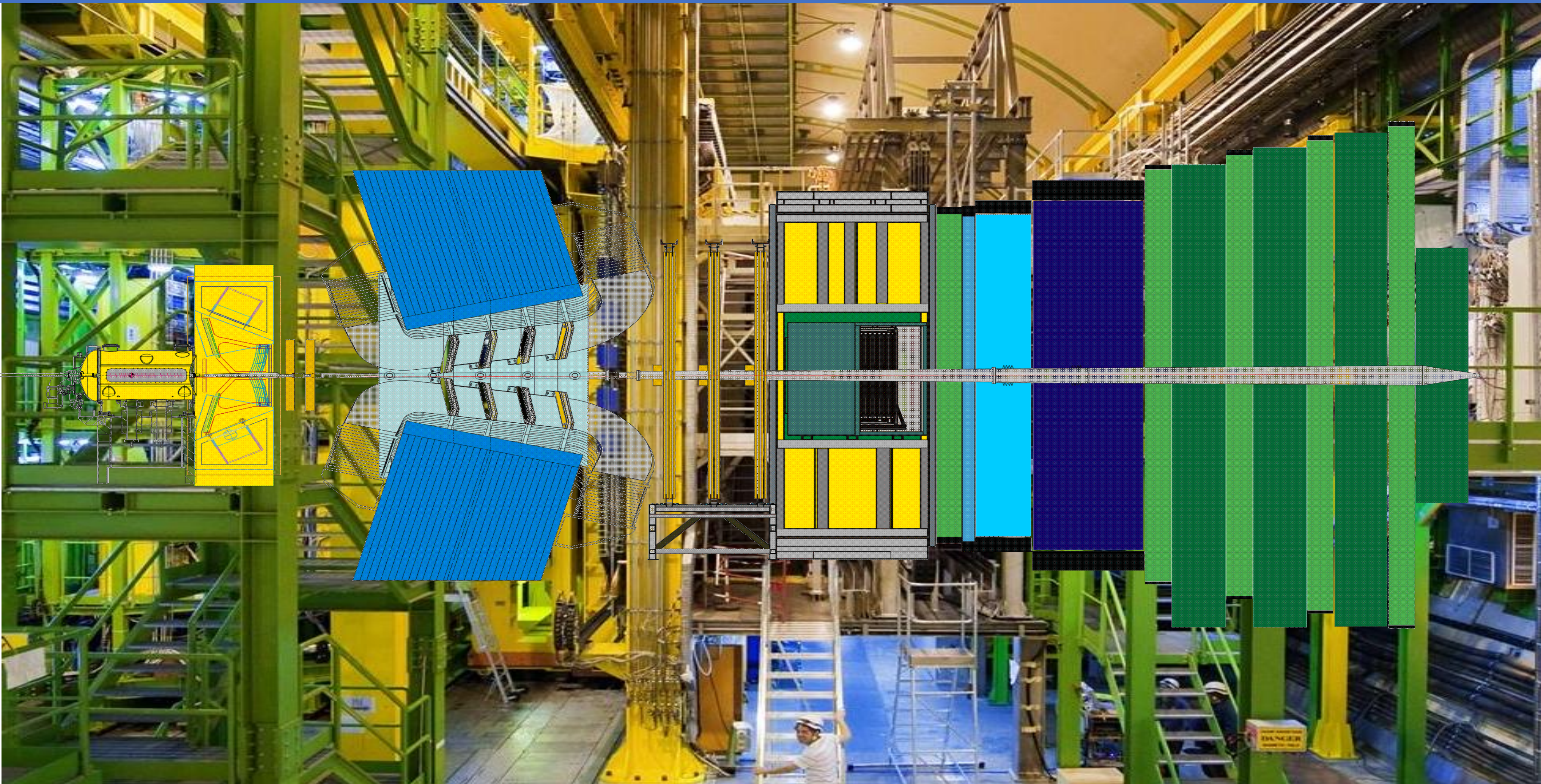


An interference pattern:

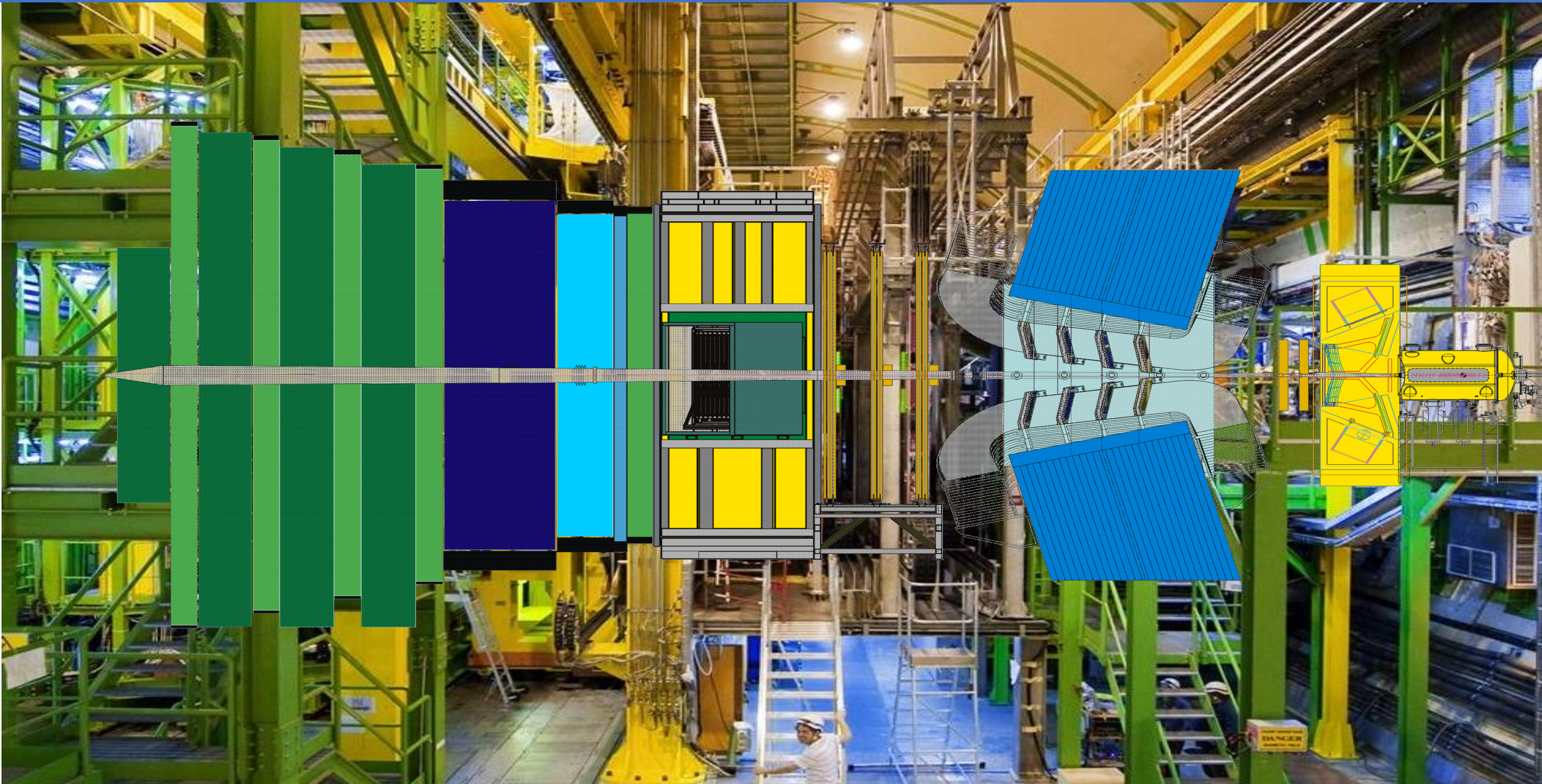


Time dependent CP violation!

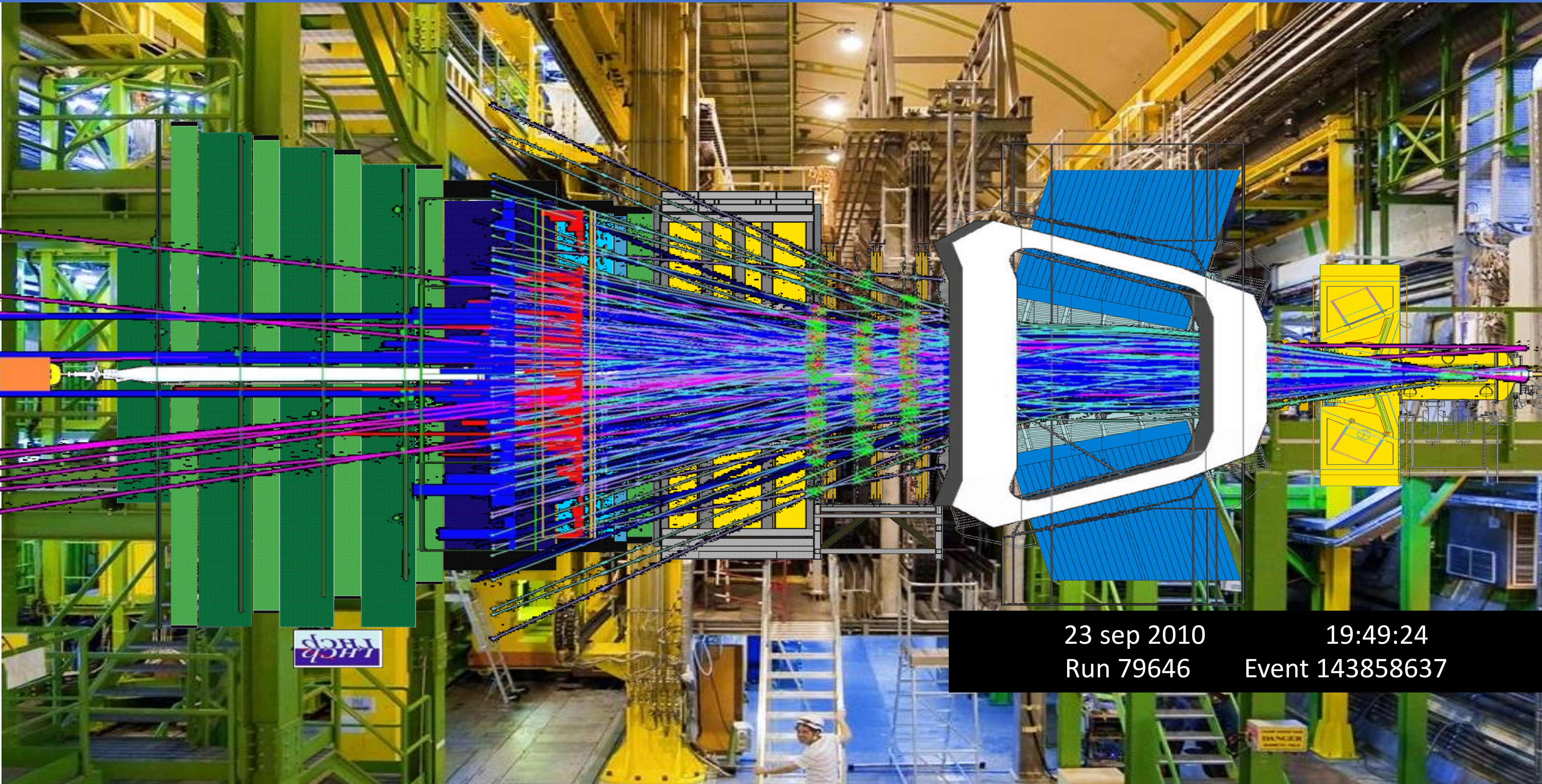
The LHCb Detector?



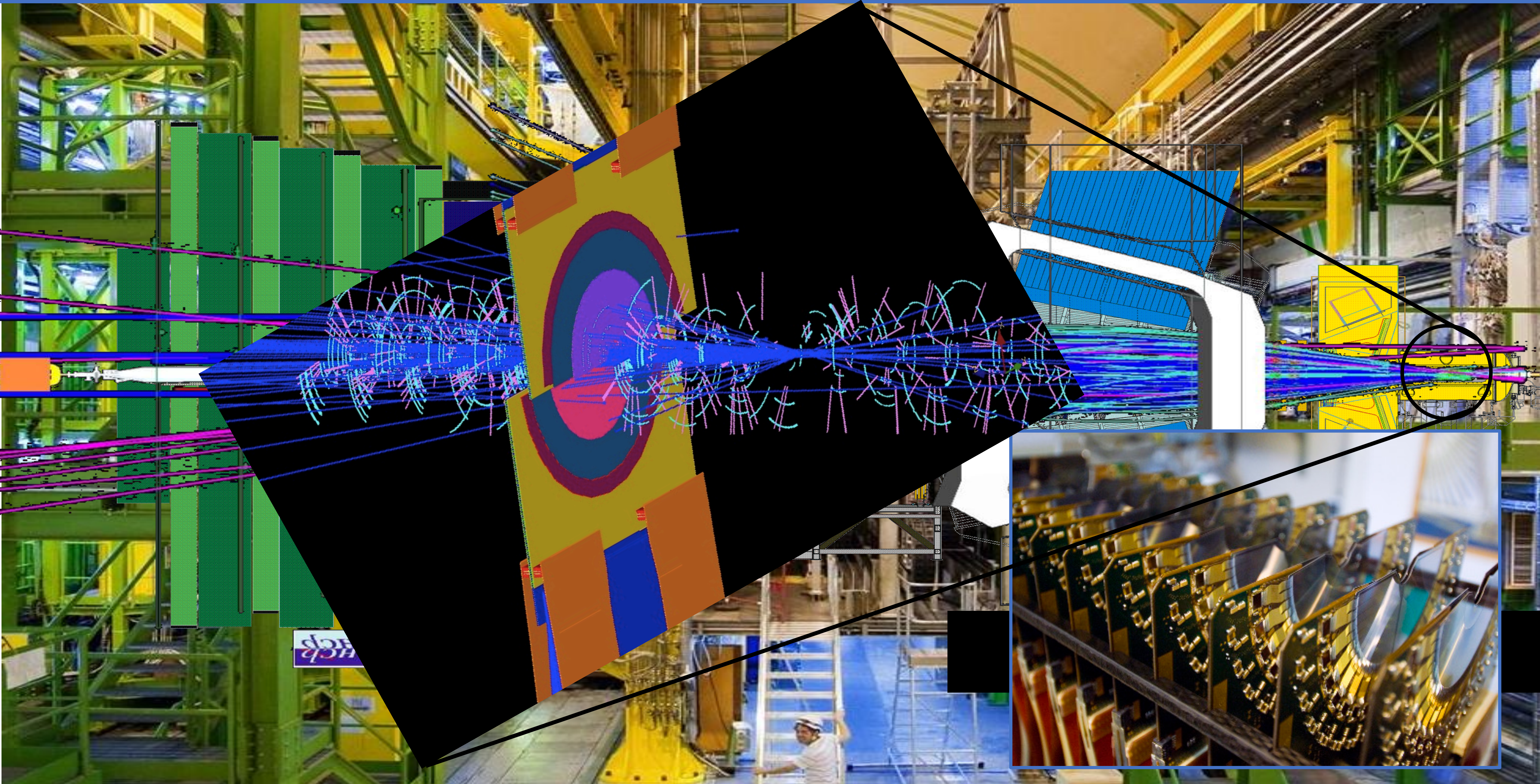
The LHCb Detector!

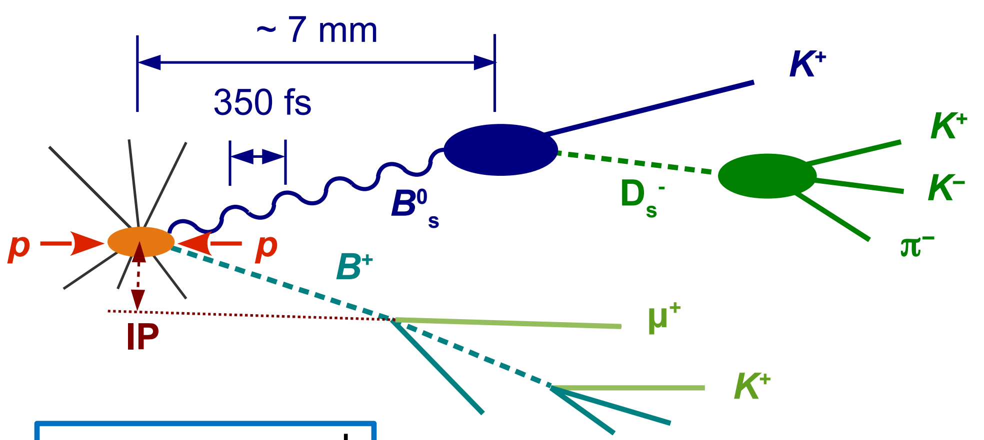


The LHCb Detector



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





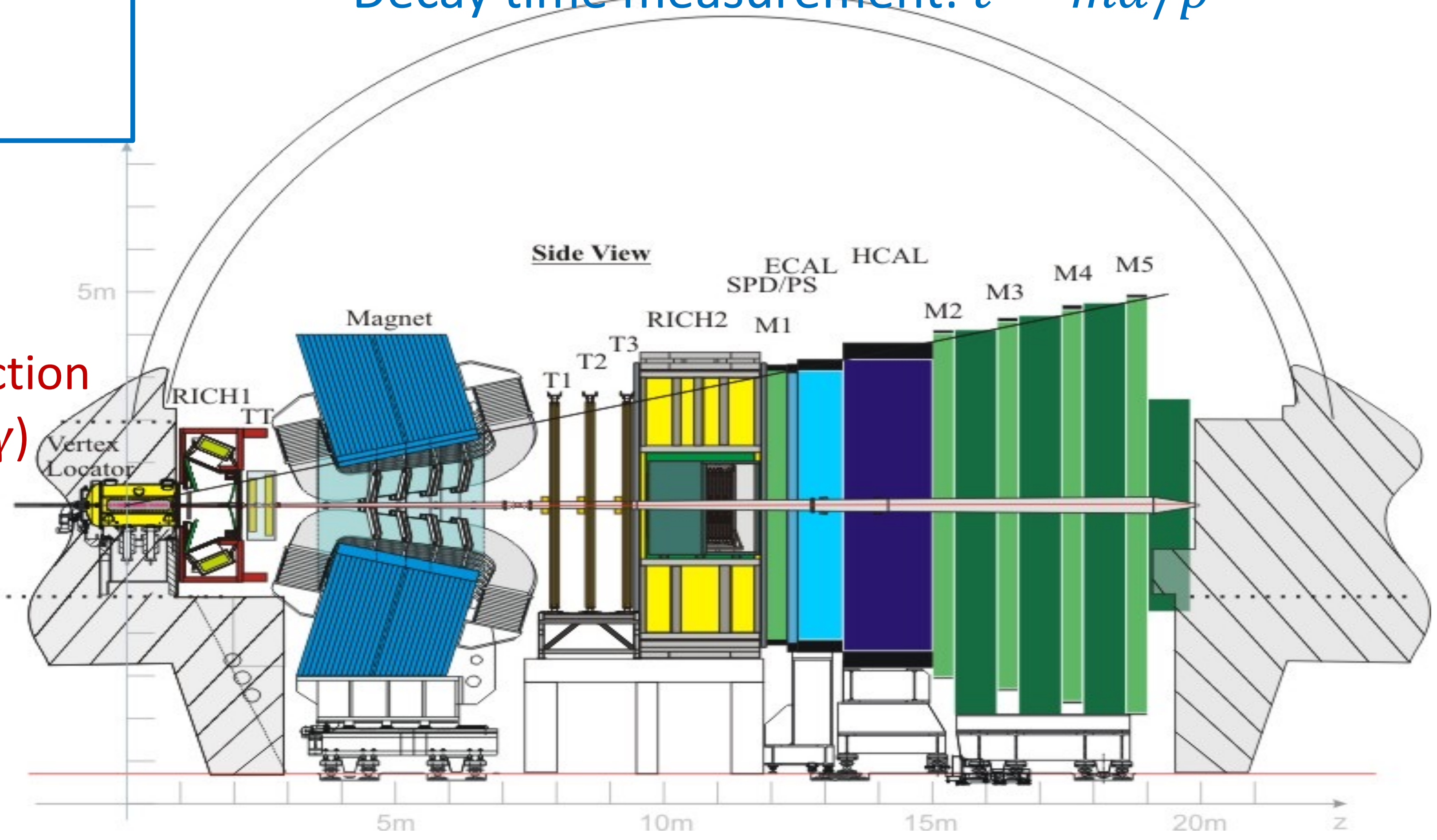
$B_s \to D_s^- K^+$

Physics Requirements:

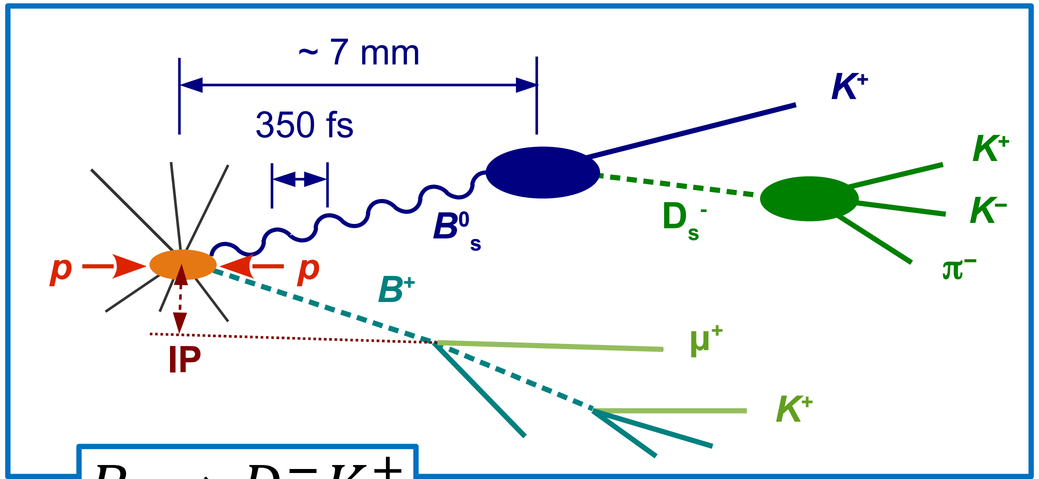
- Signal selection and background suppression
- Flavour tagging: B or $\overline{B}$ at production
- Decay time measurement: $t = md/p$

Detector Requirements:

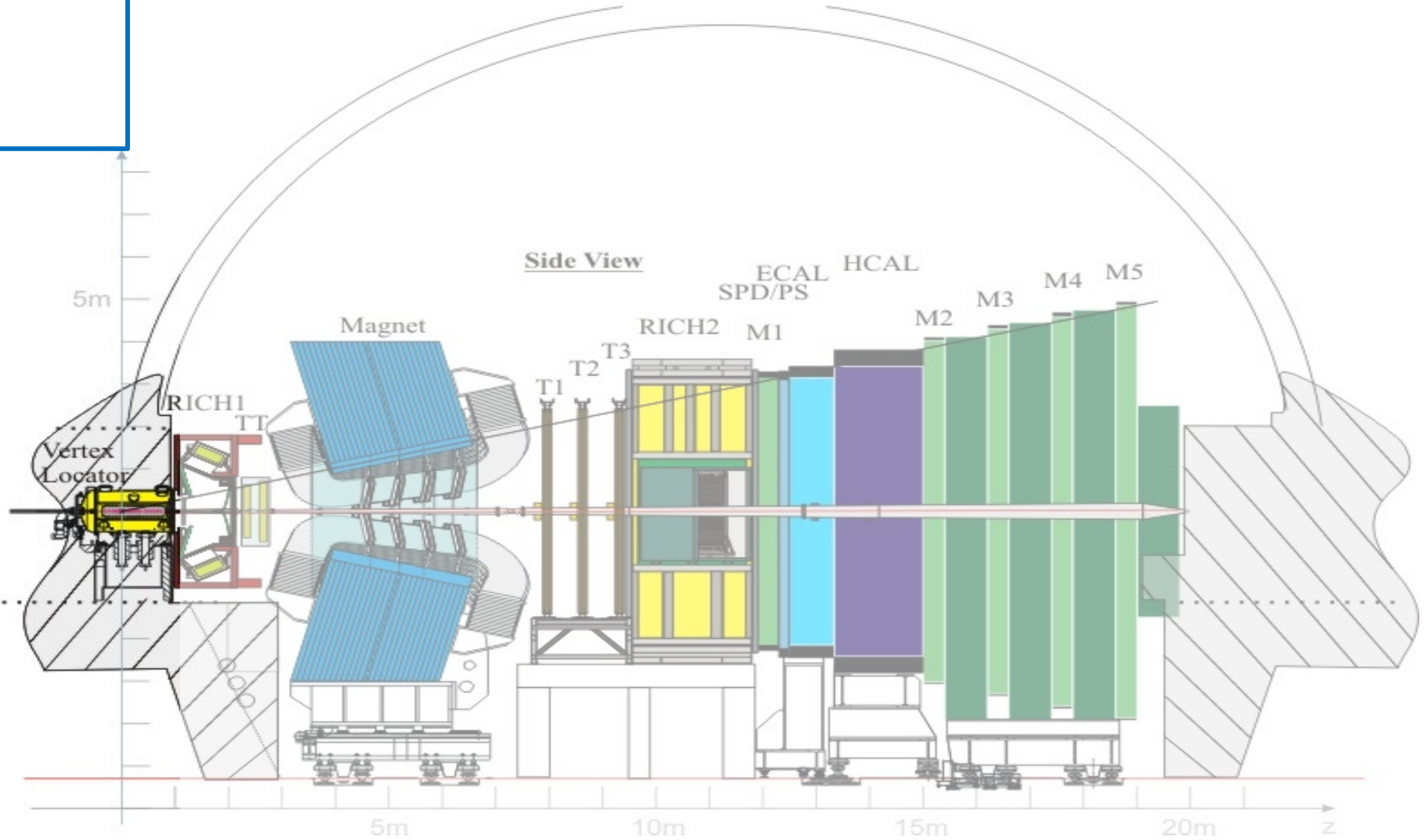
- Vertex reconstruction
- Momentum and mass reconstruction
- Particle identification (π, K, μ, e, γ)
- Trigger (Online reconstruction)



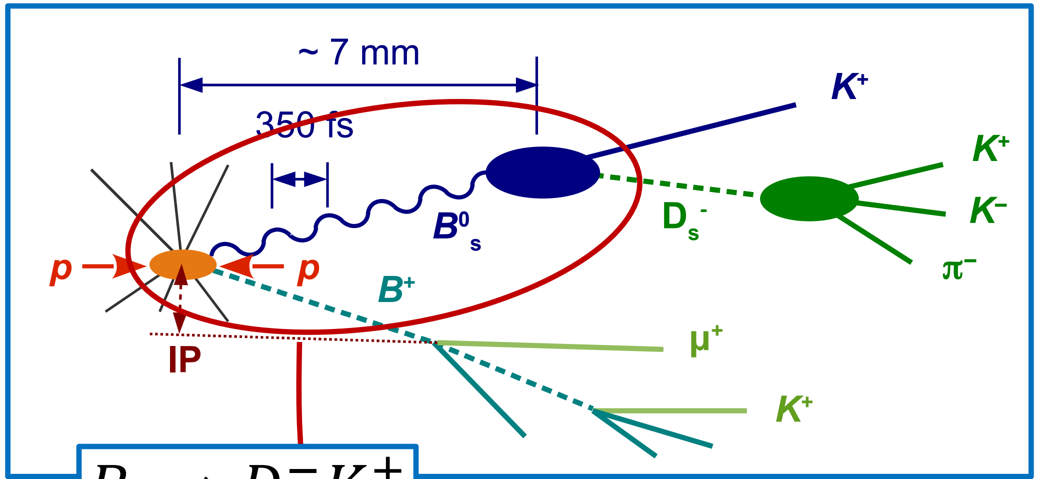
B_s Physics at LHCb - Vertex reconstruction



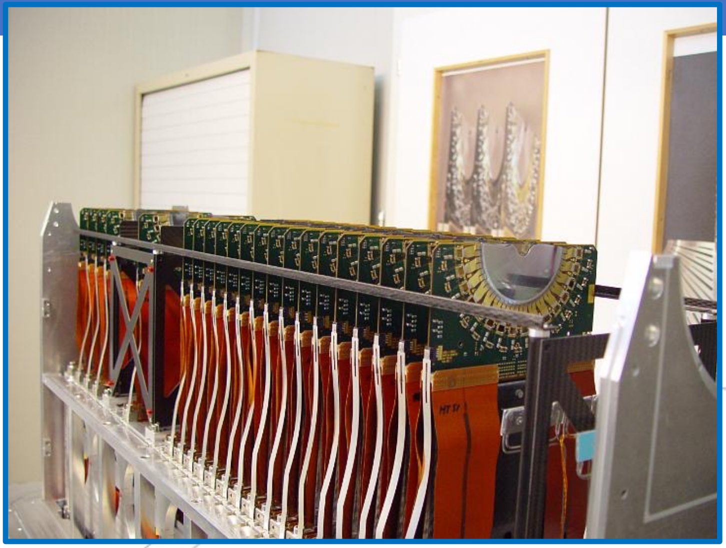
$B_s \rightarrow D_s^- K^+$

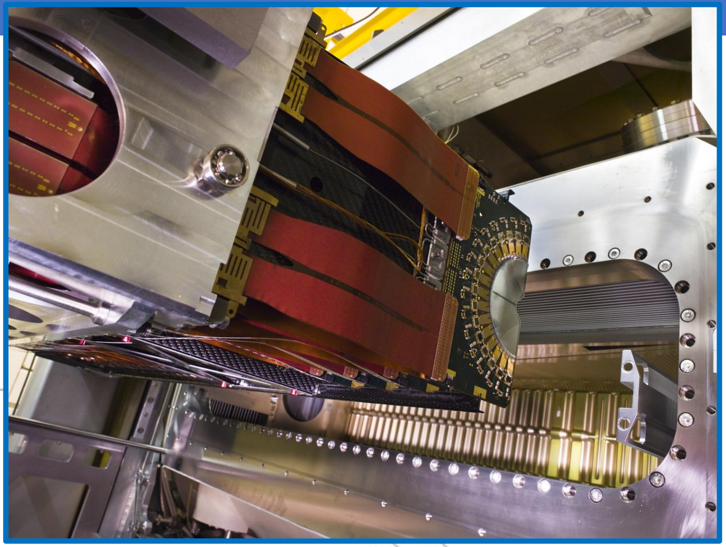


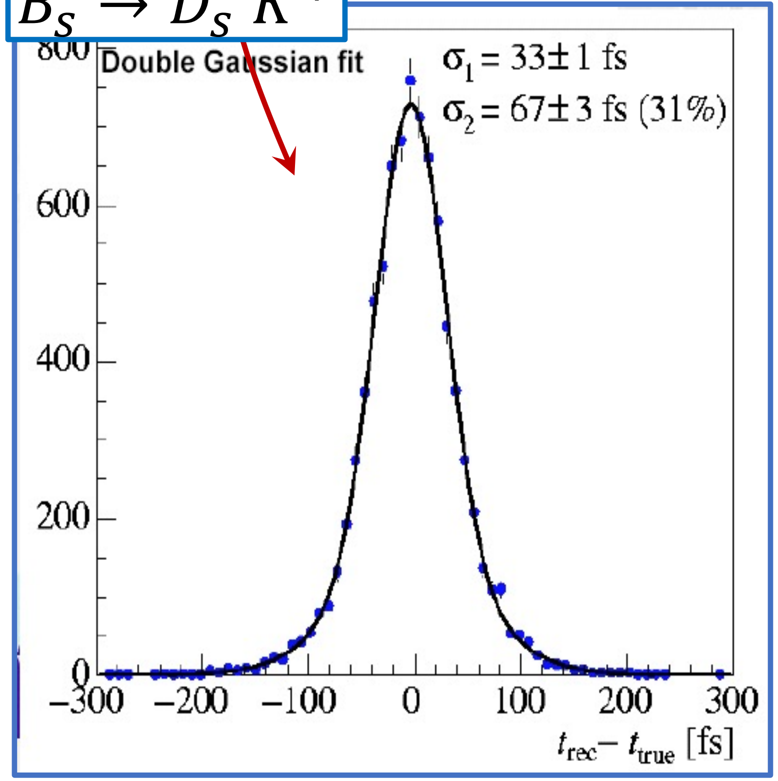
B_s Physics at LHCb - Vertex reconstruction

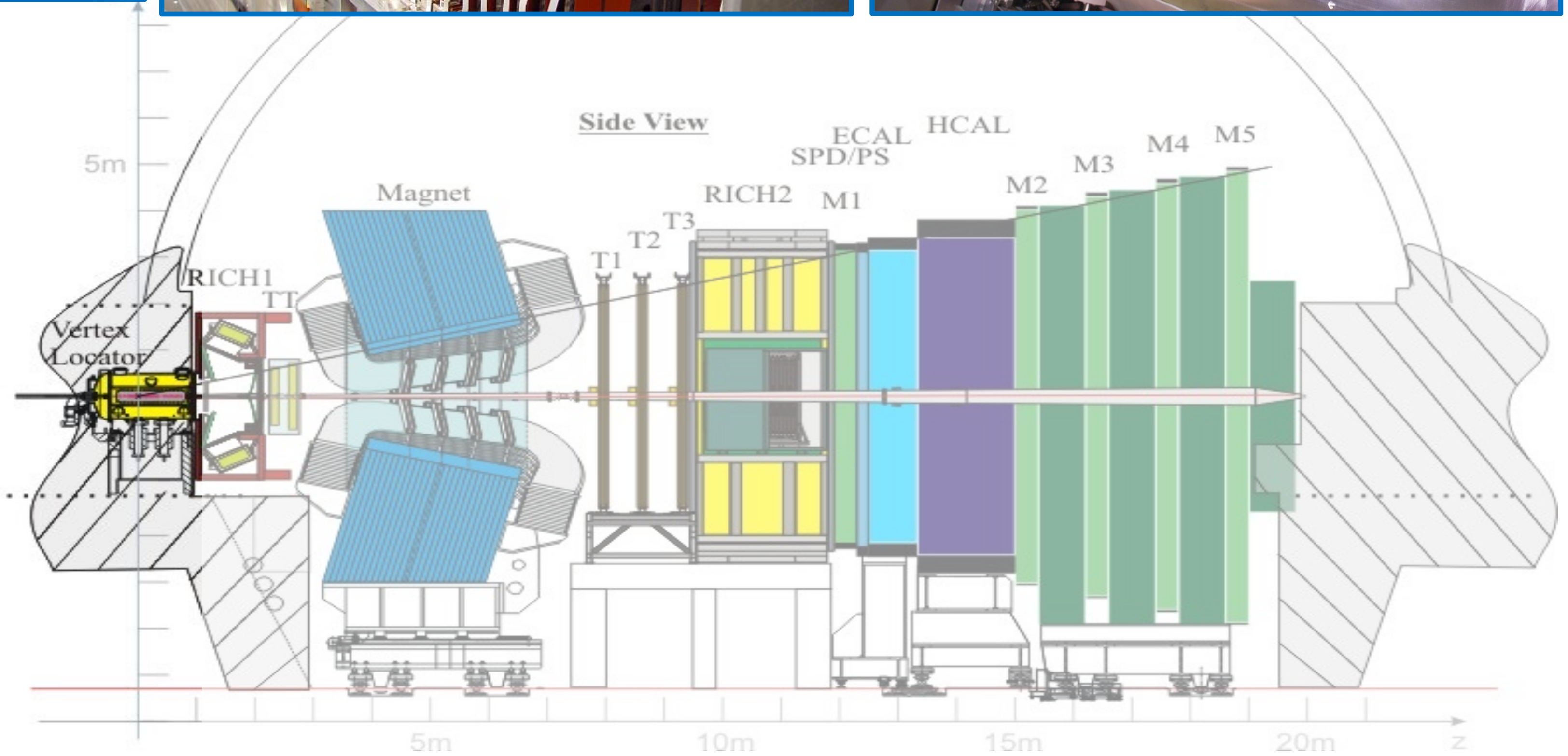


$B_s \to D_s^- K^+$

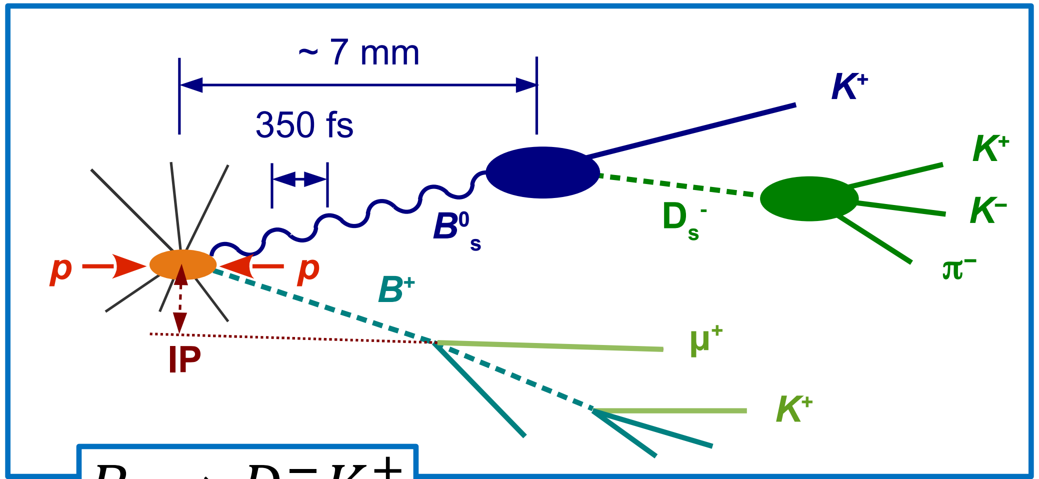




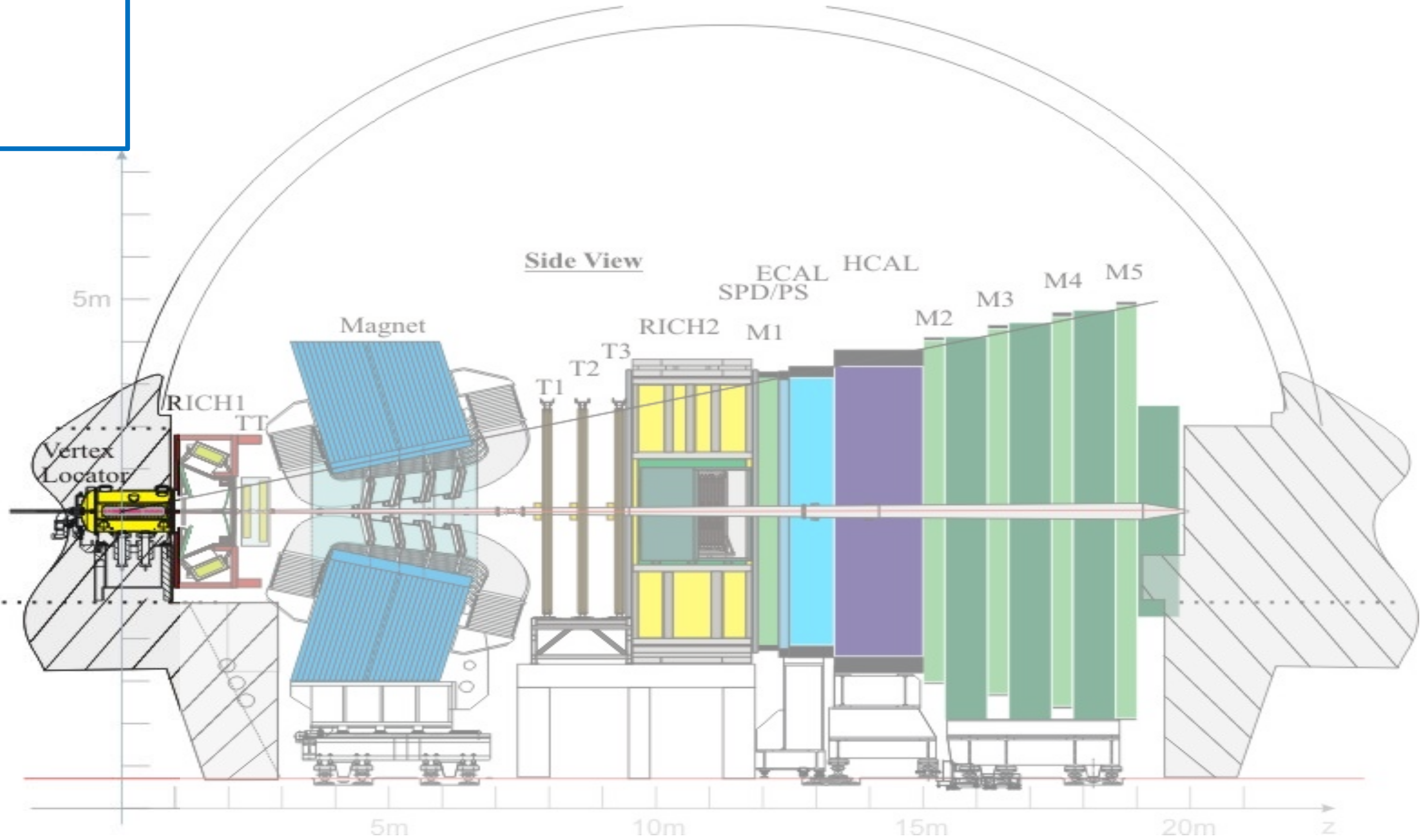




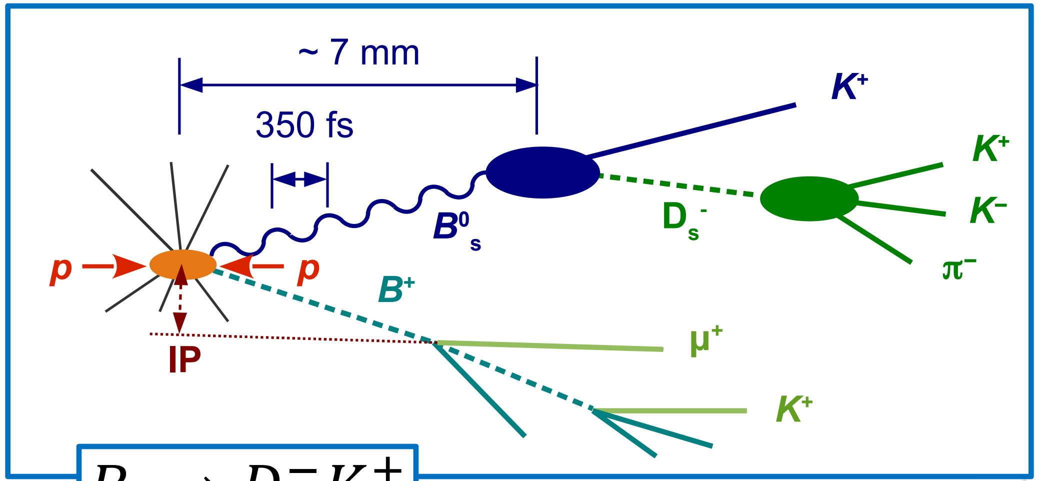
B_s Physics at LHCb



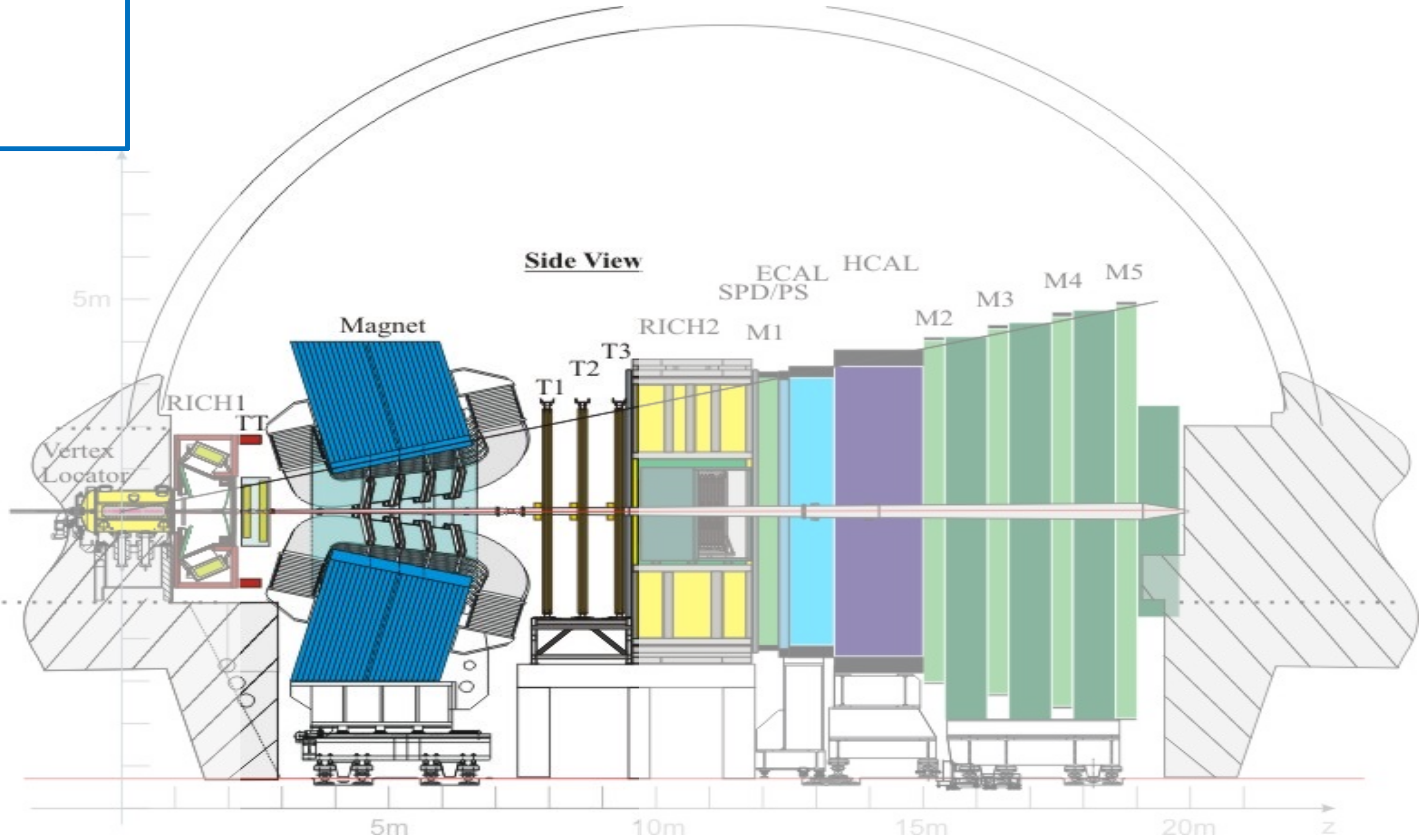
$B_s \to D_s^- K^+$



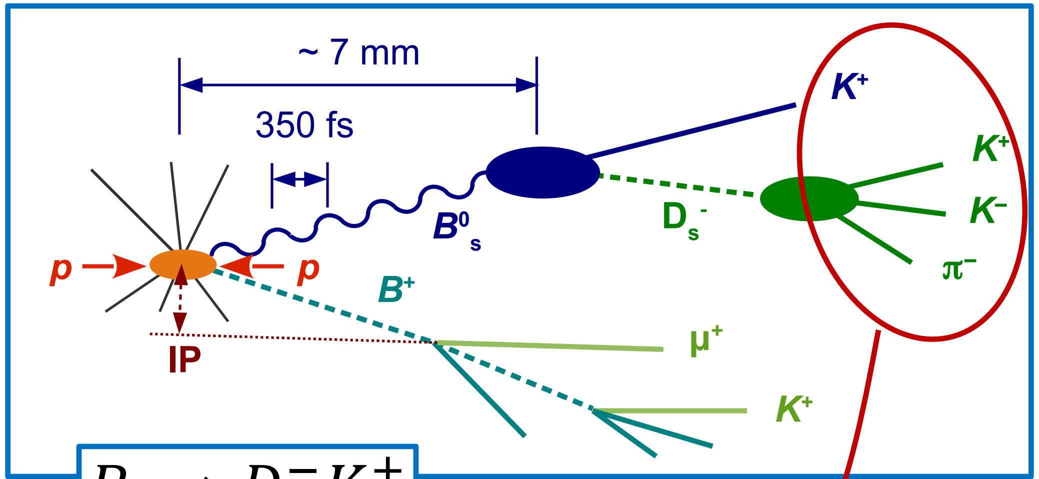
B_s Physics at LHCb – momentum and mass determination



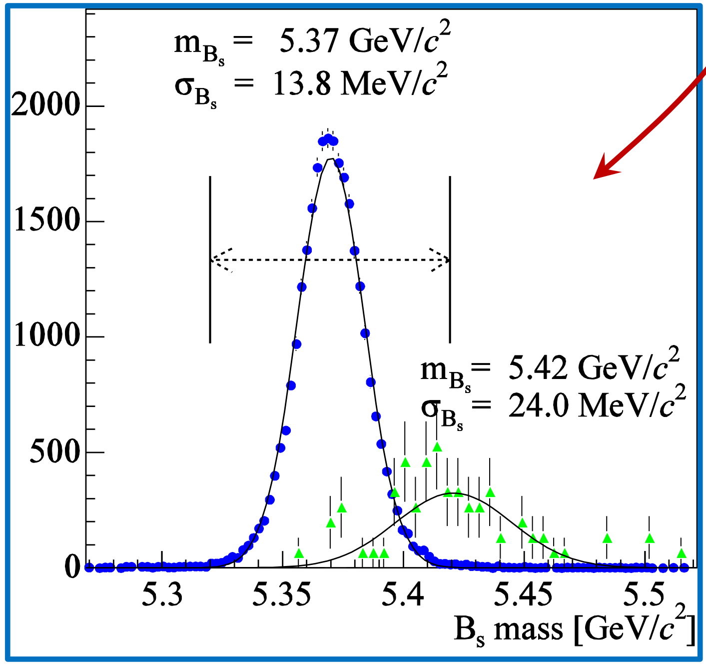
$B_s \to D_s^- K^+$

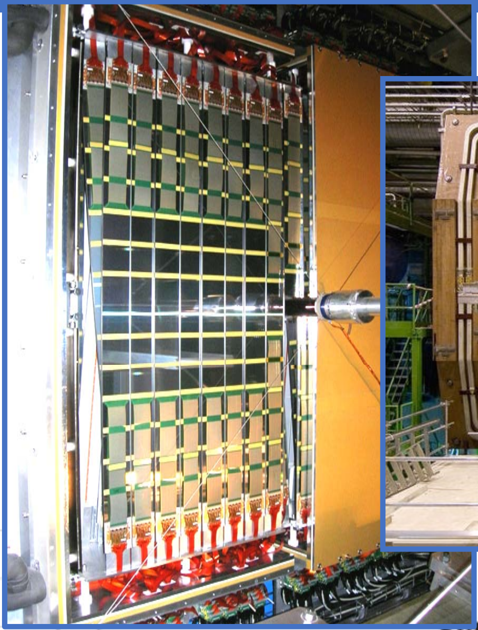


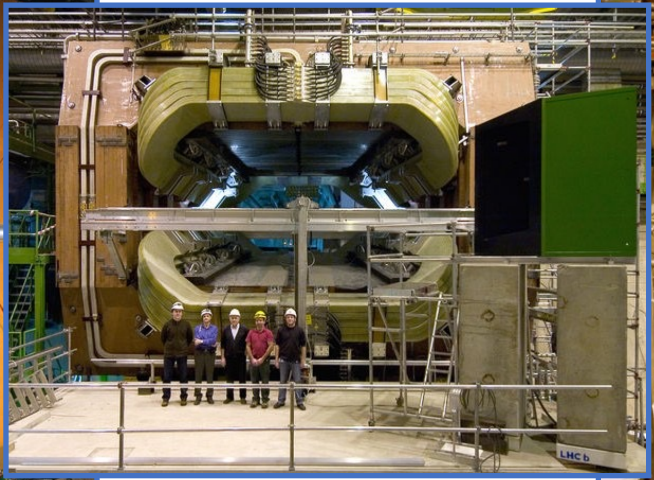
B_s Physics at LHCb – momentum and mass determination

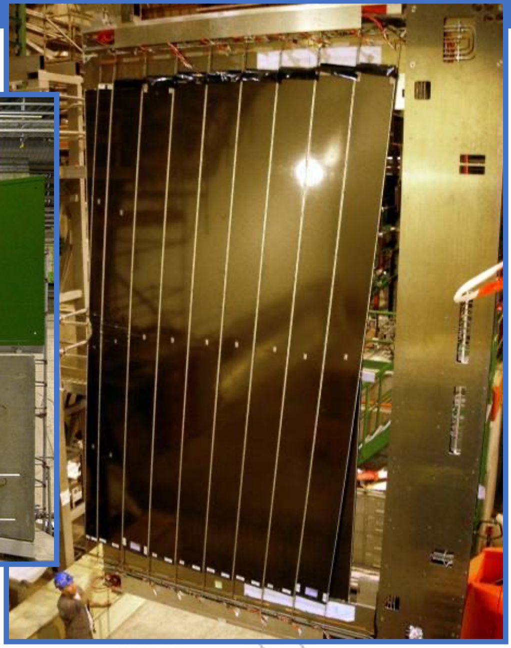


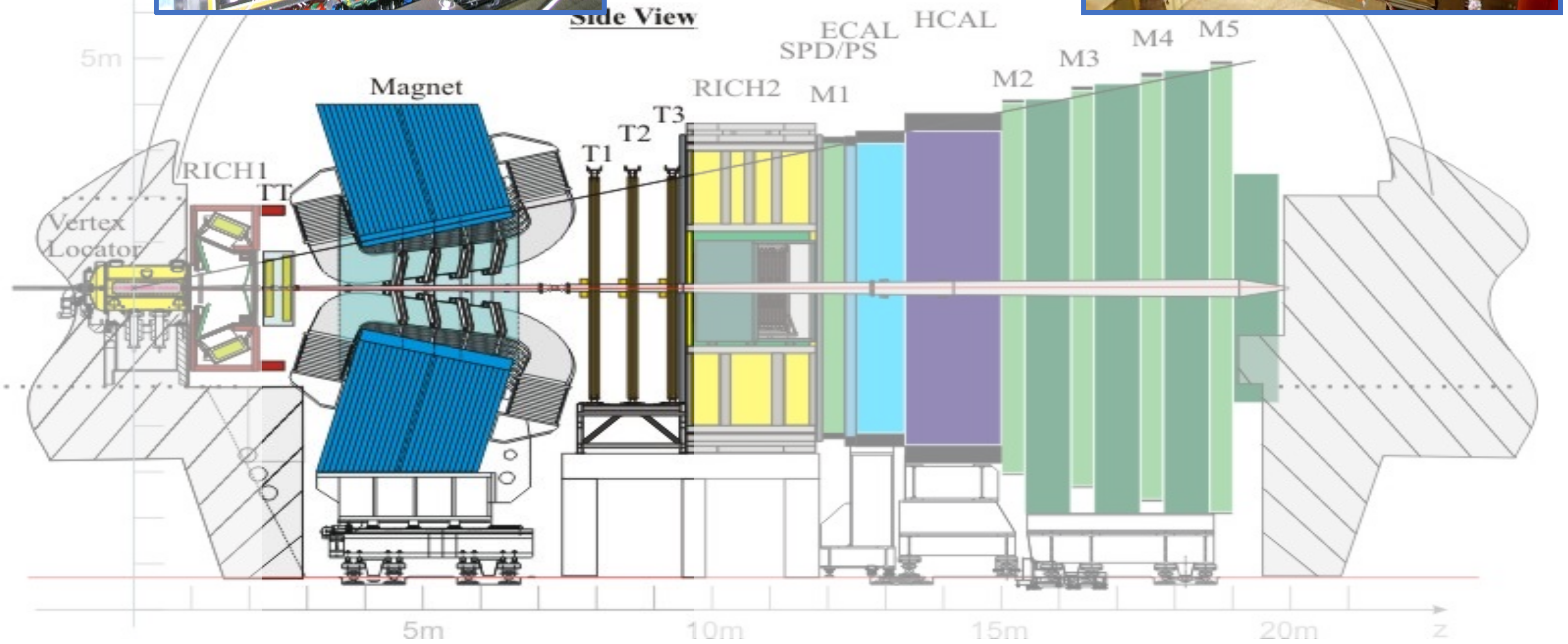
$B_s \to D_s^- K^+$



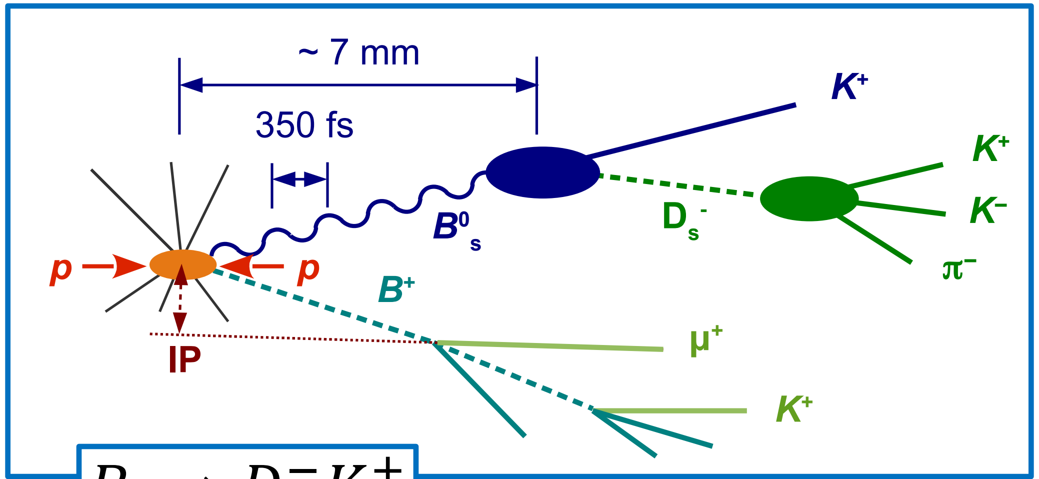




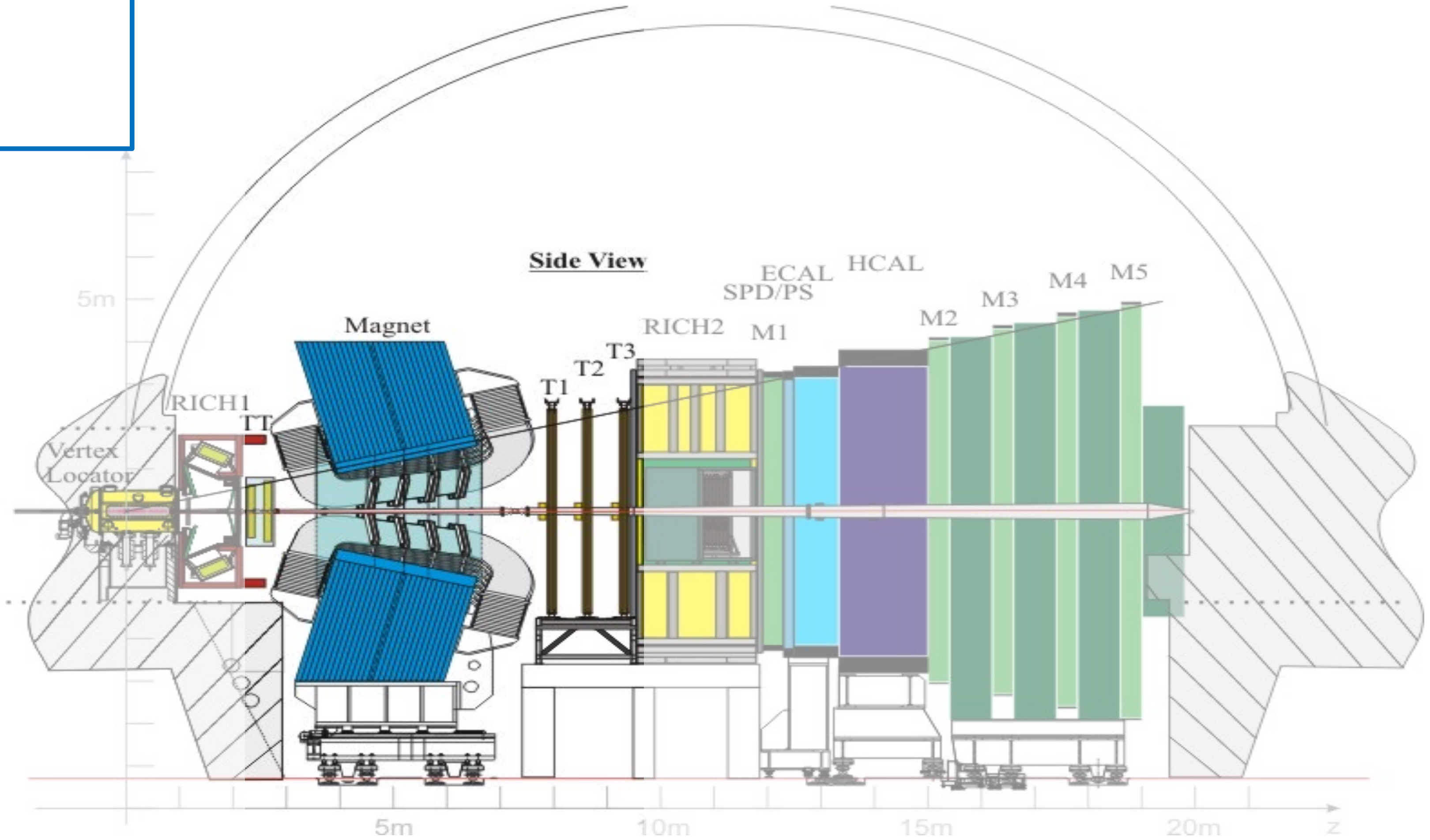




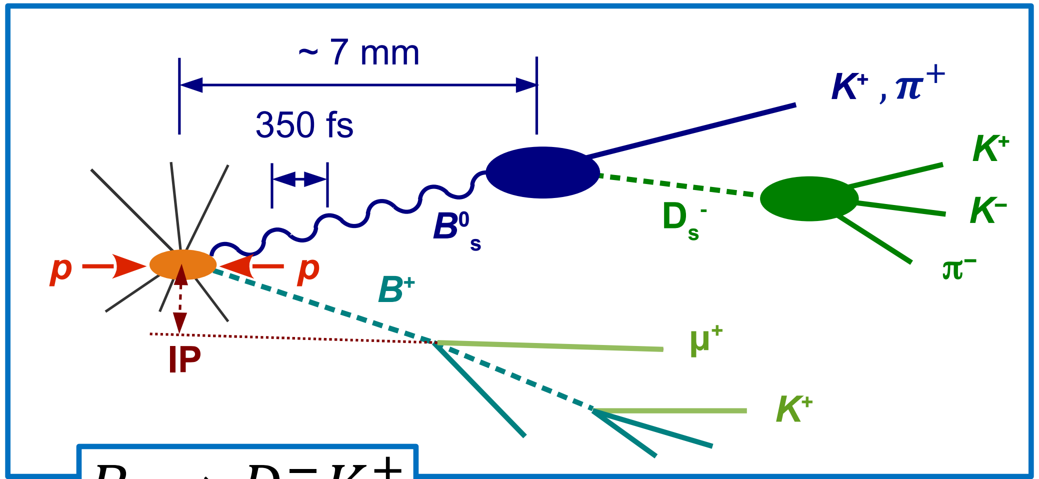
B_s Physics at LHCb



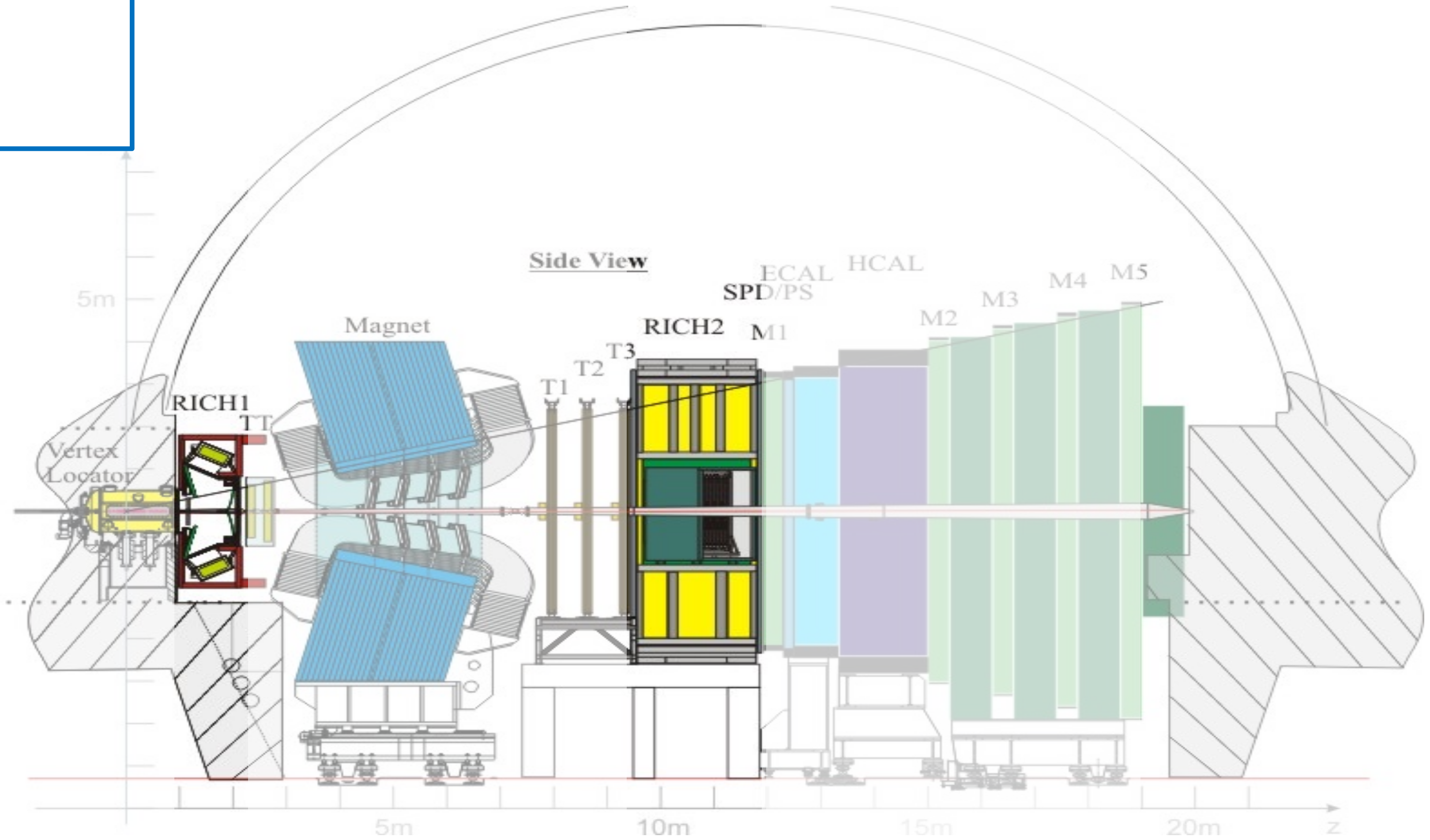
$B_s \to D_s^- K^+$



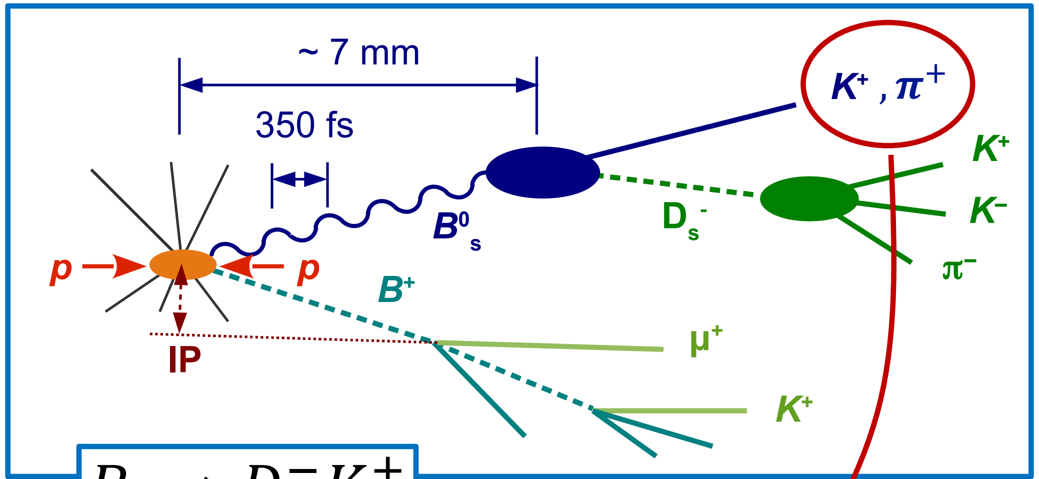
B_s Physics at LHCb – Particle Identification with RICH



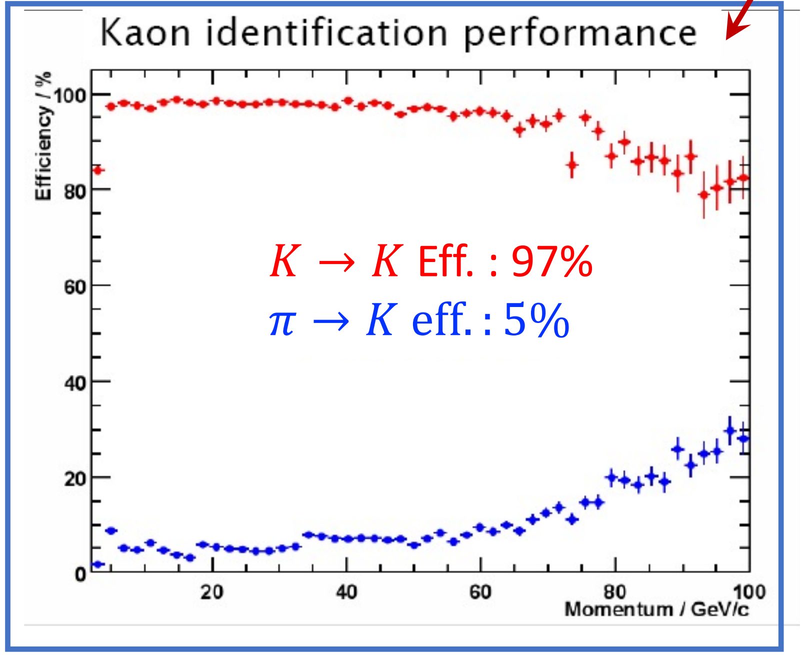
$B_s \to D_s^- K^+$



B_s Physics at LHCb – Particle Identification with RICH

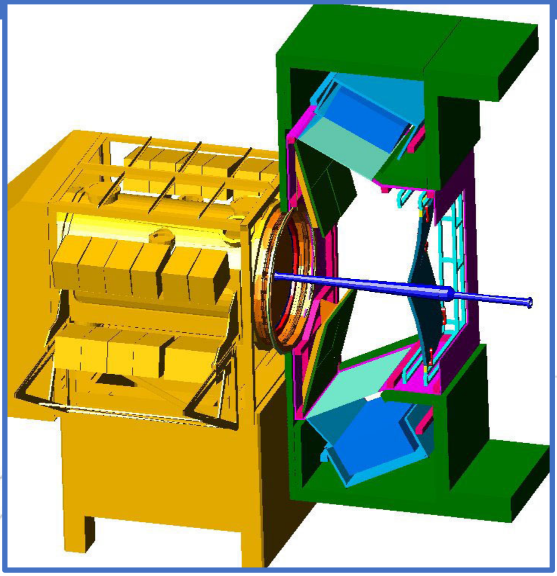


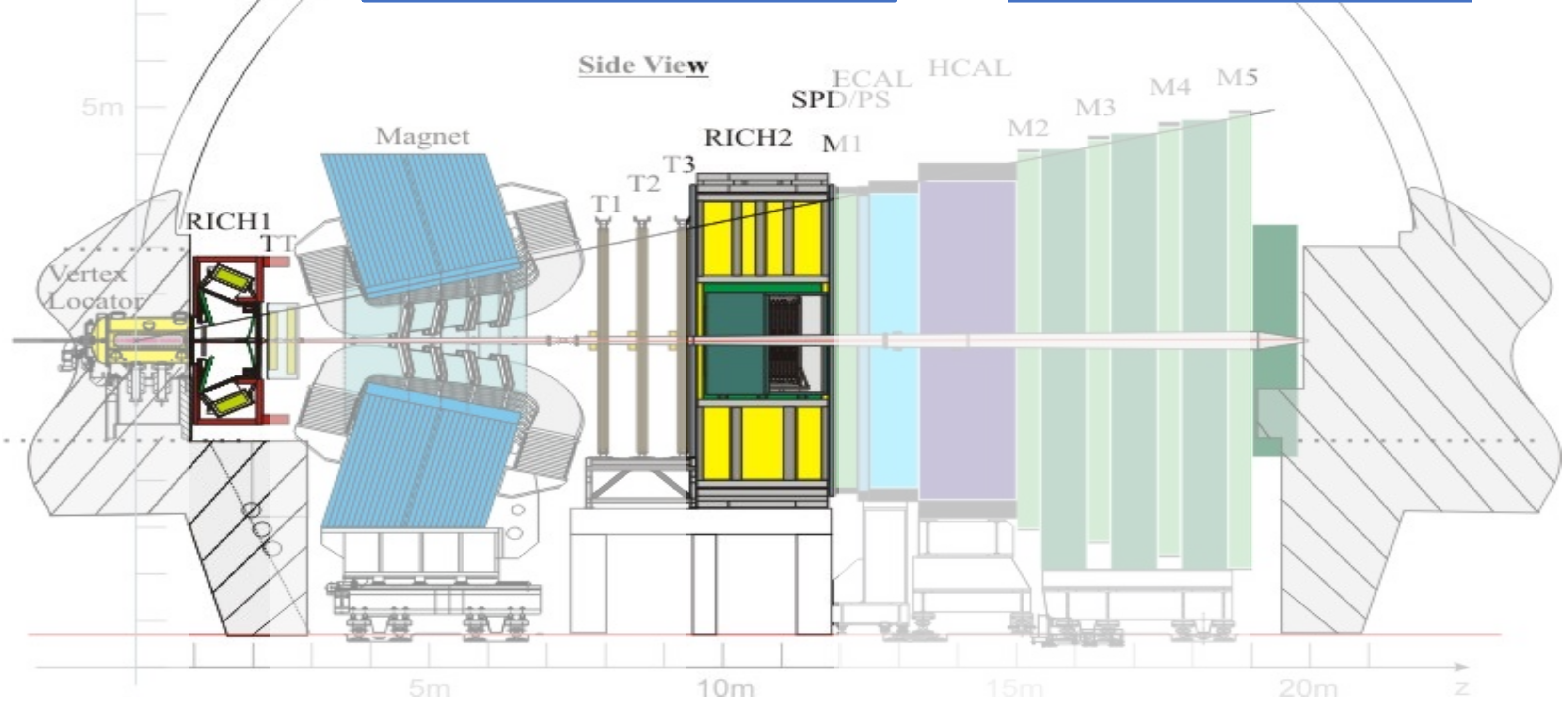
$B_s \rightarrow D_s^- K^+$



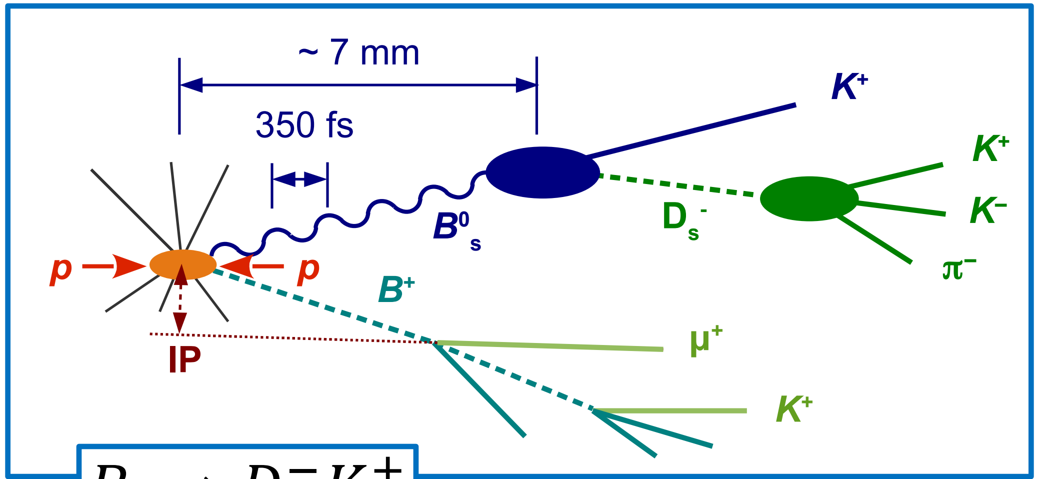
$K \rightarrow K$ Eff. : 97%

$\pi \rightarrow K$ eff. : 5%

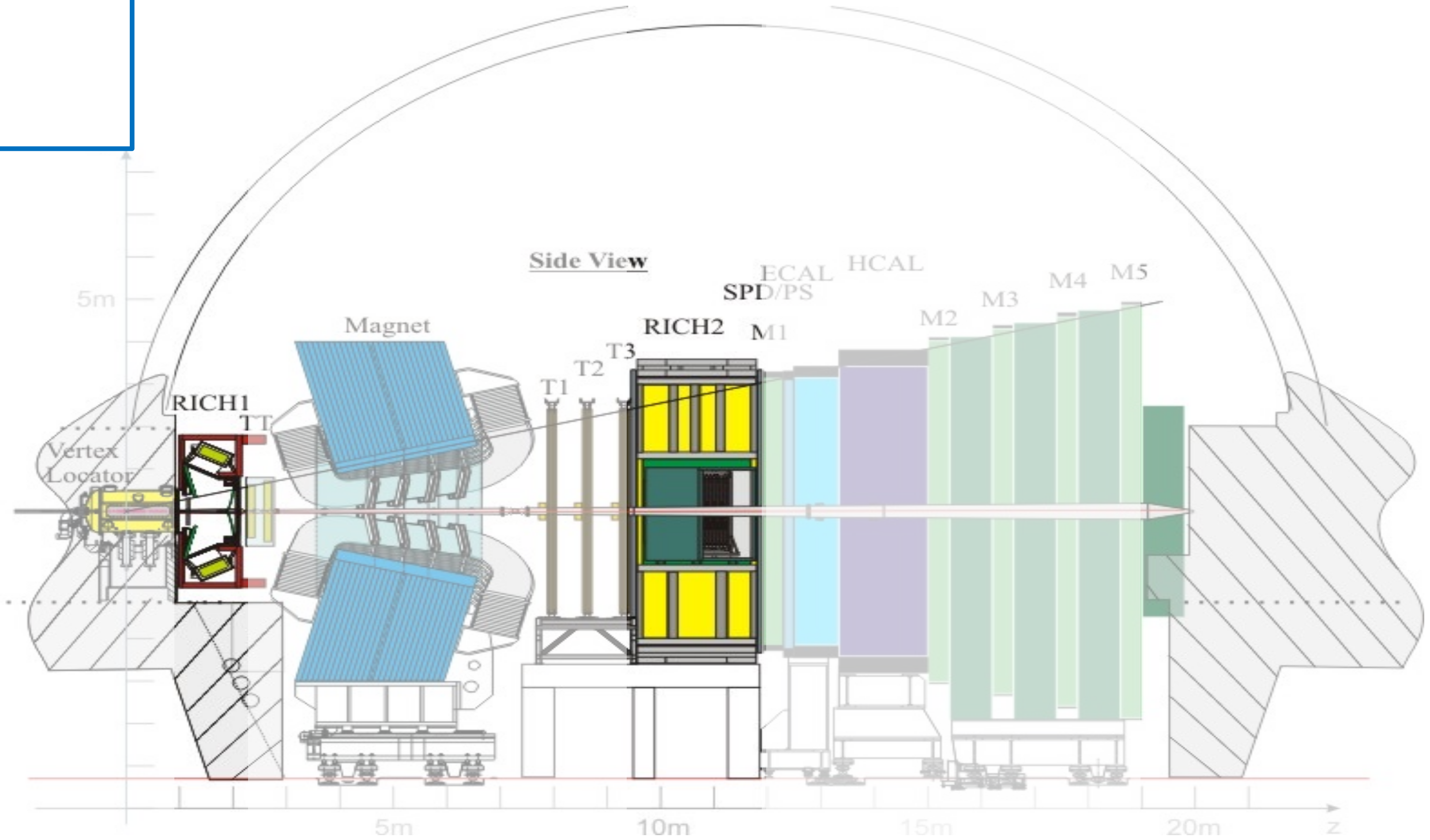


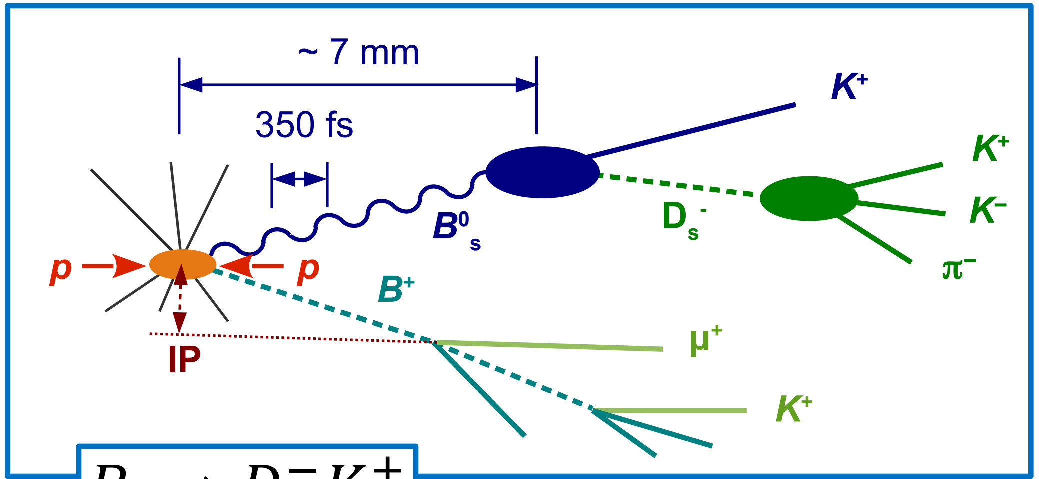


B_s Physics at LHCb



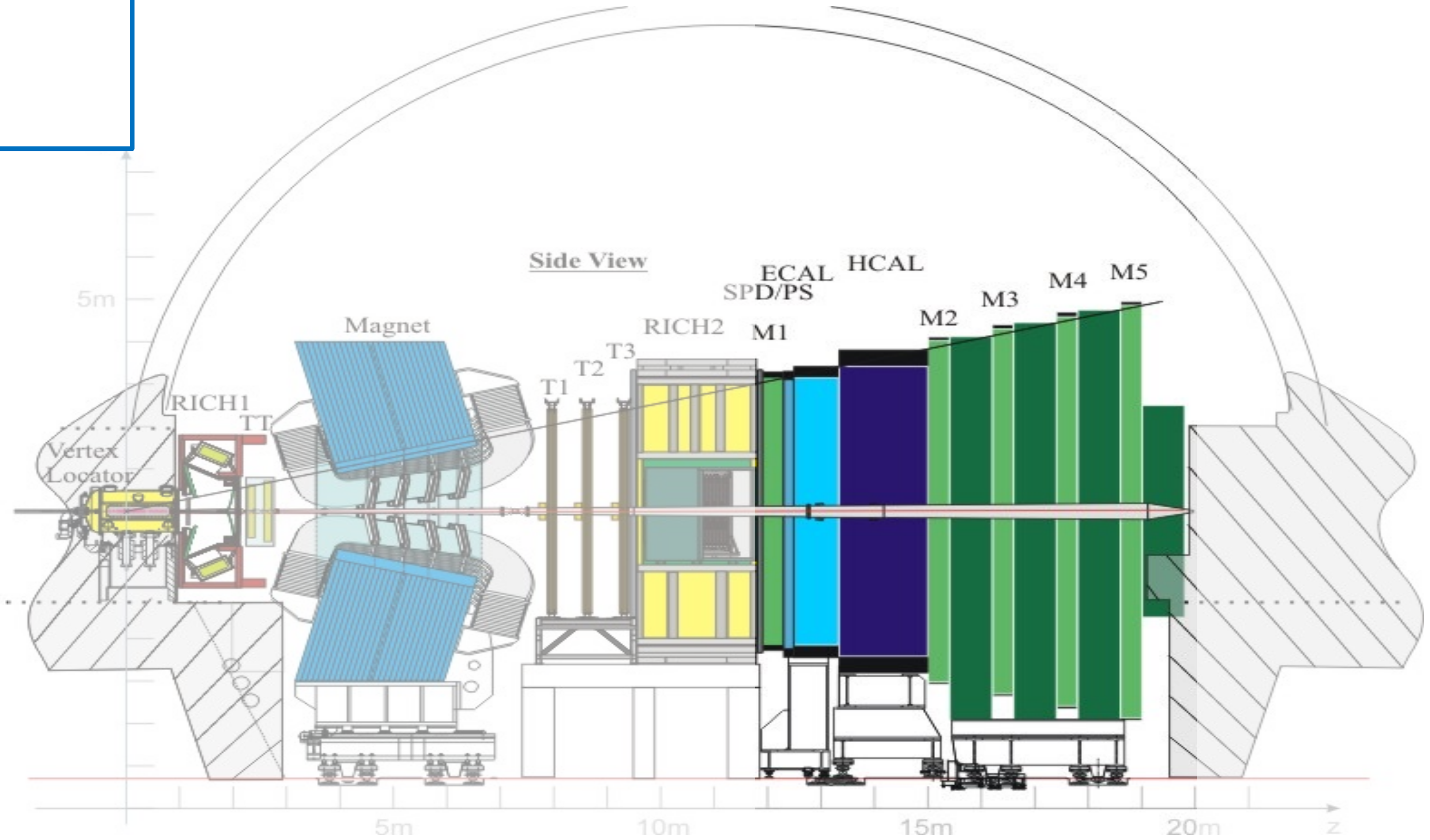
$B_s \to D_s^- K^+$





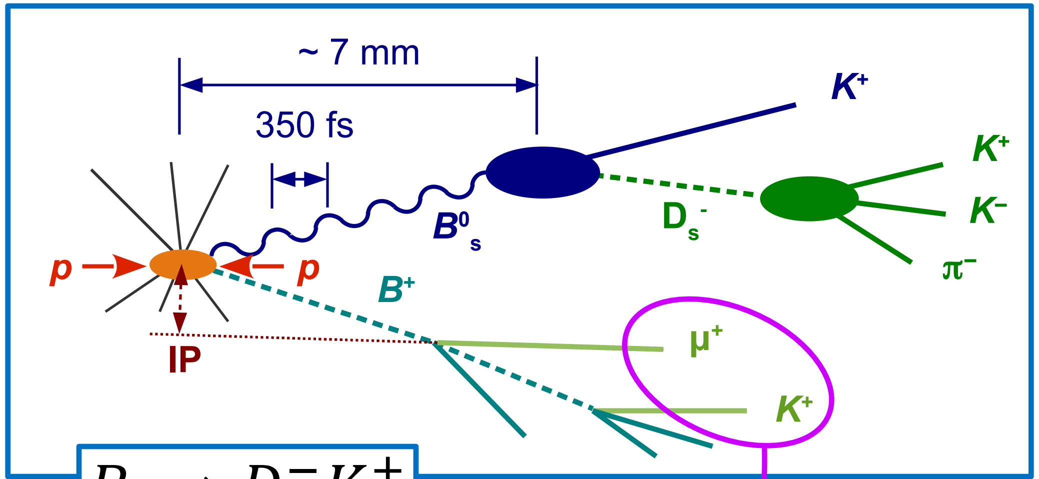
~ 7 mm
350 fs
K+
K+
K−
π−
Ds-
B0s
p
p
B+
IP
μ+
K+

$B_s \to D_s^- K^+$

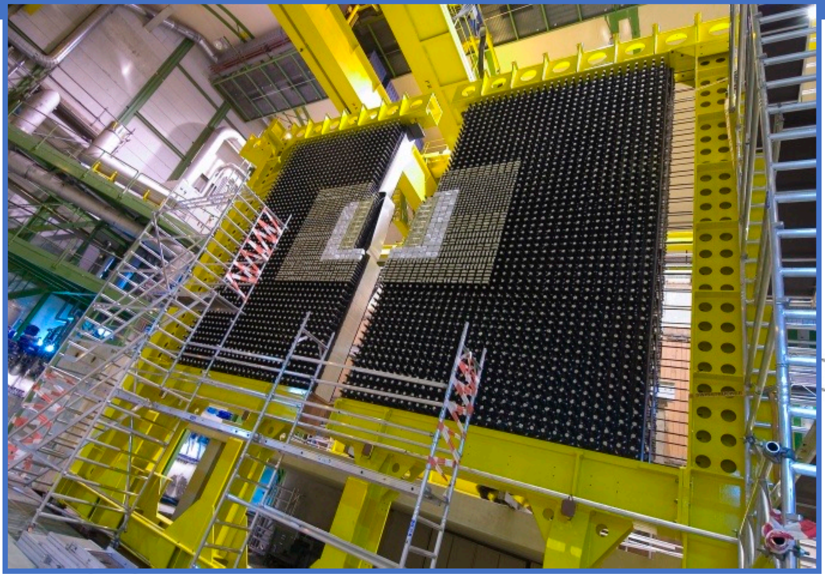


Side View
ECAL
HCAL
SPD/PS
M1
M2
M3
M4
M5
Magnet
RICH2
T1
T2
T3
RICH1
TT
Vertex
Locator
5m
5m
10m
15m
20m
z

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

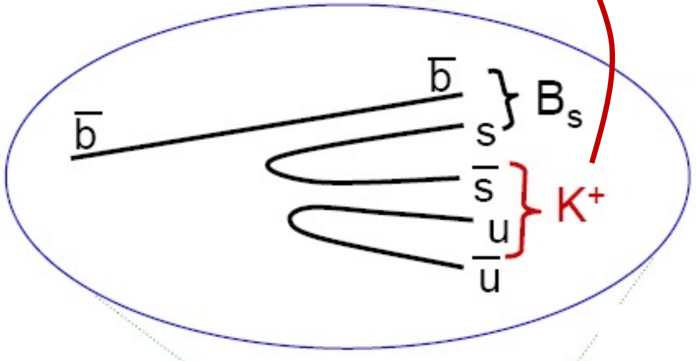


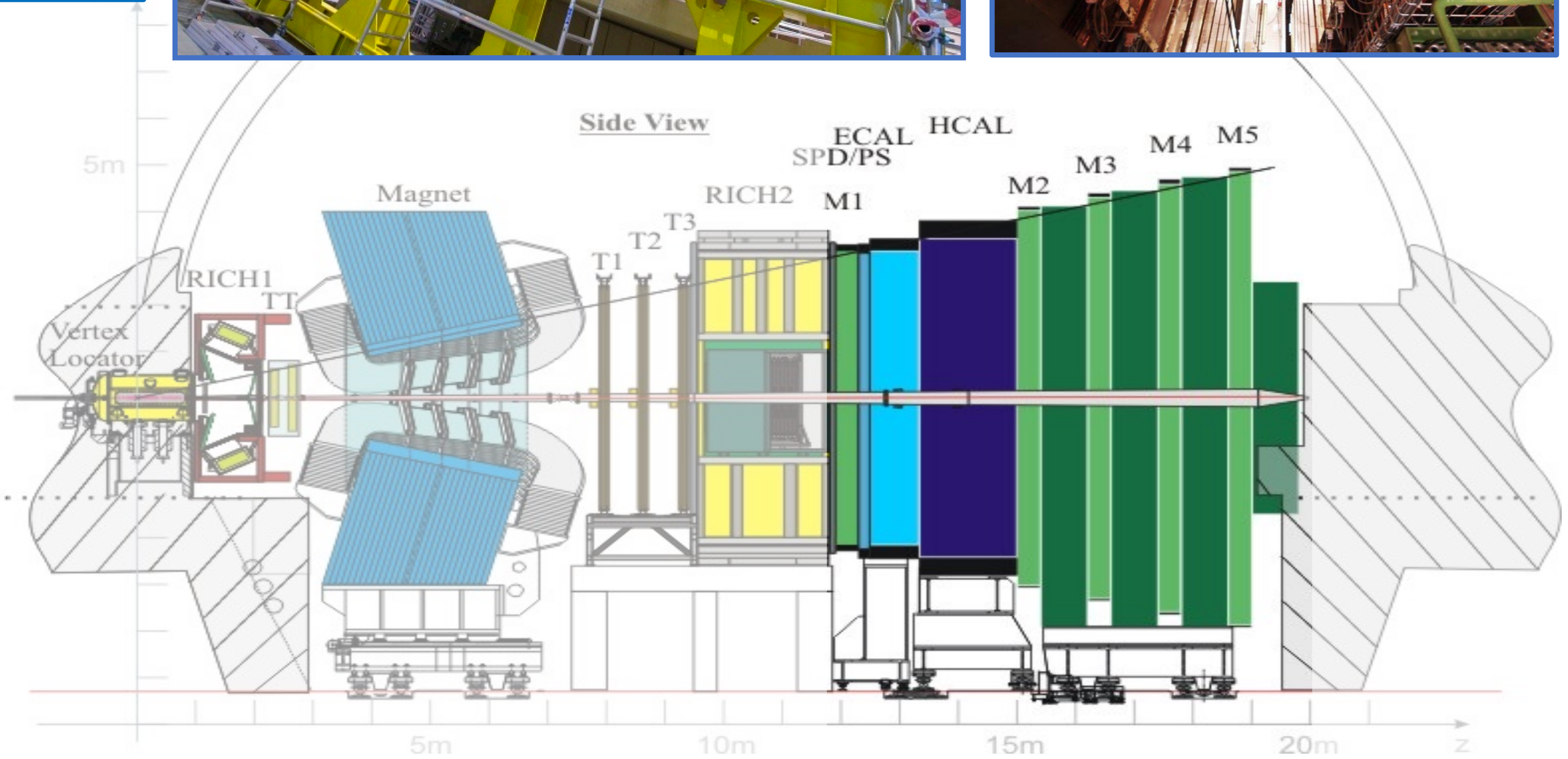
$B_s \to D_s^- K^+$



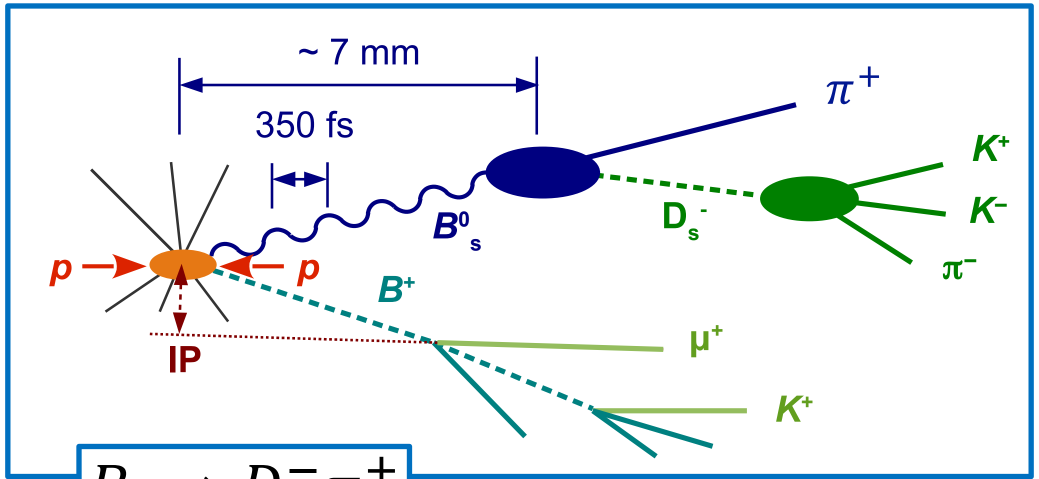
Identification of γ, e , μ:

- Triggering
- Flavour tagging:
  - Opposite or same side





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

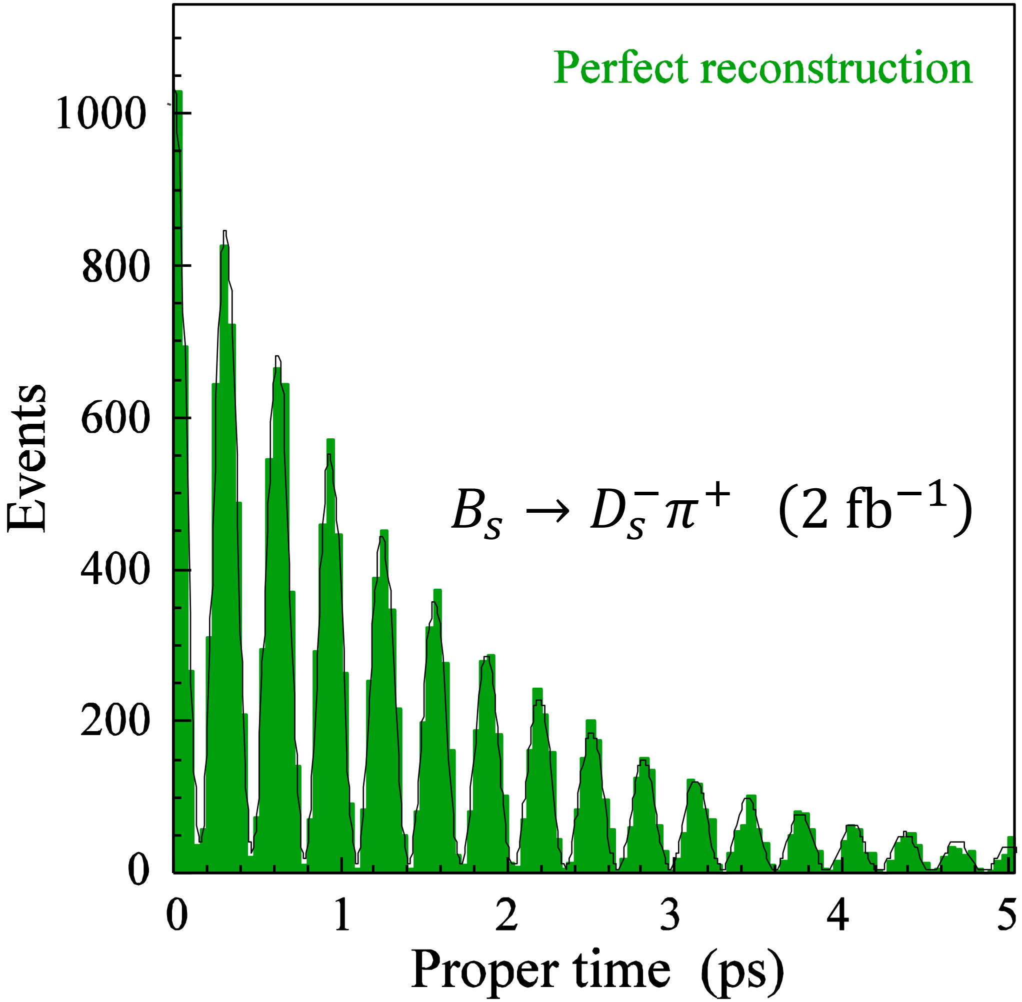


$B_s \to D_s^- \pi^+$

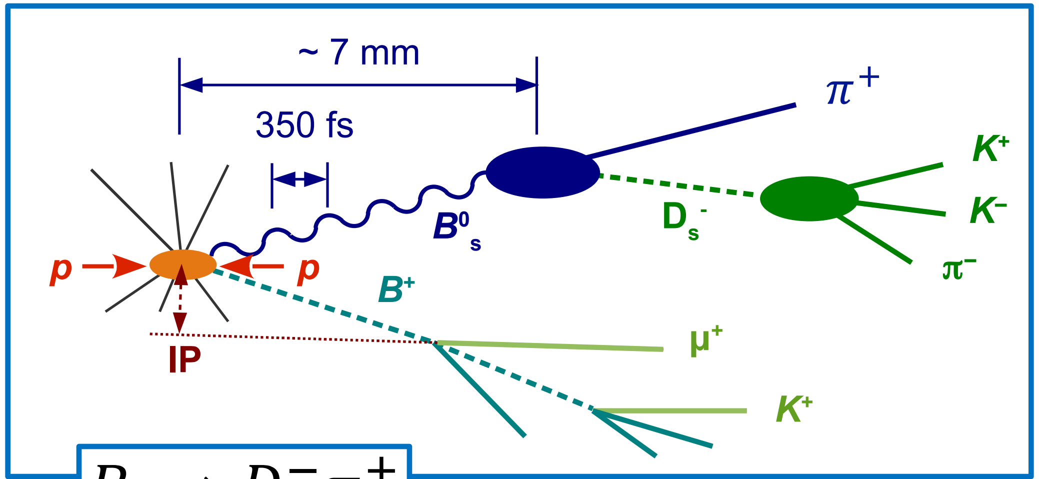
Experimental Situation:

Ideal measurement (no dilutions)

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



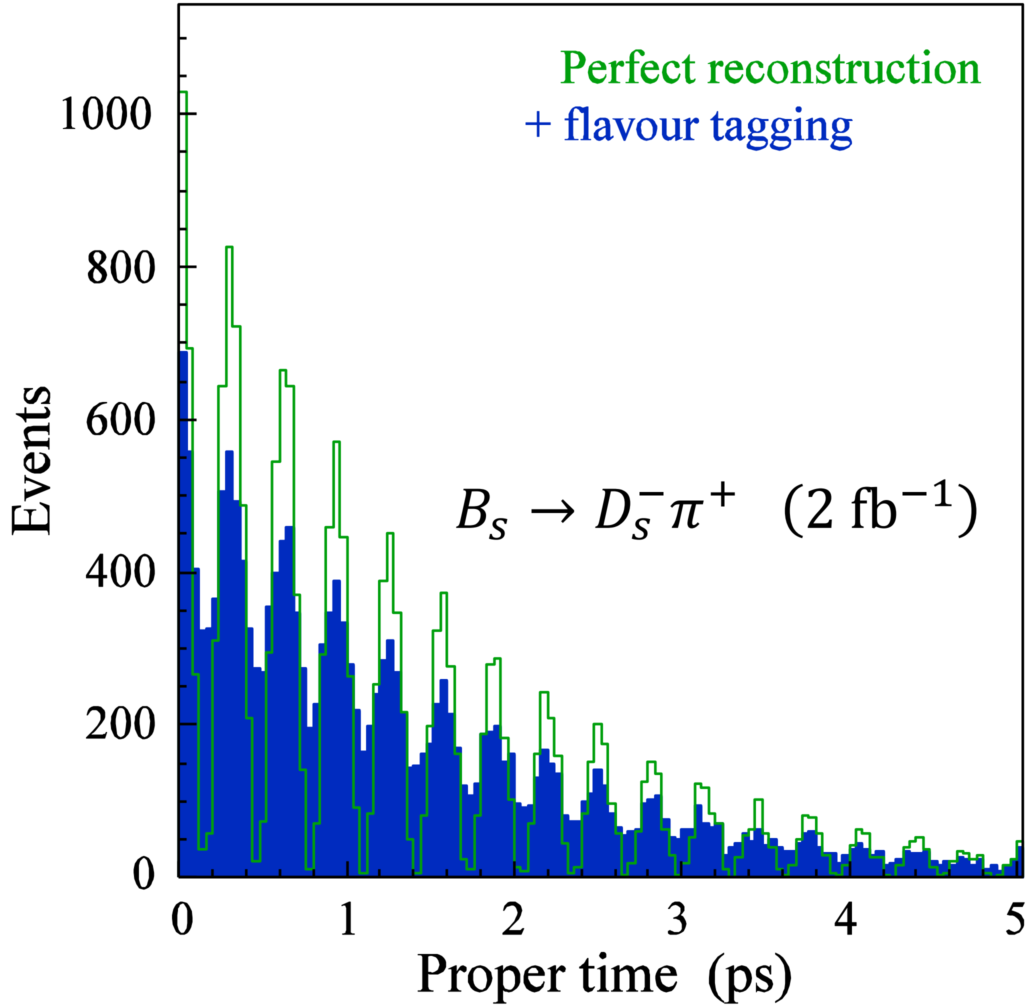
$B_s \to D_s^- \pi^+$

__Experimental Situation:__

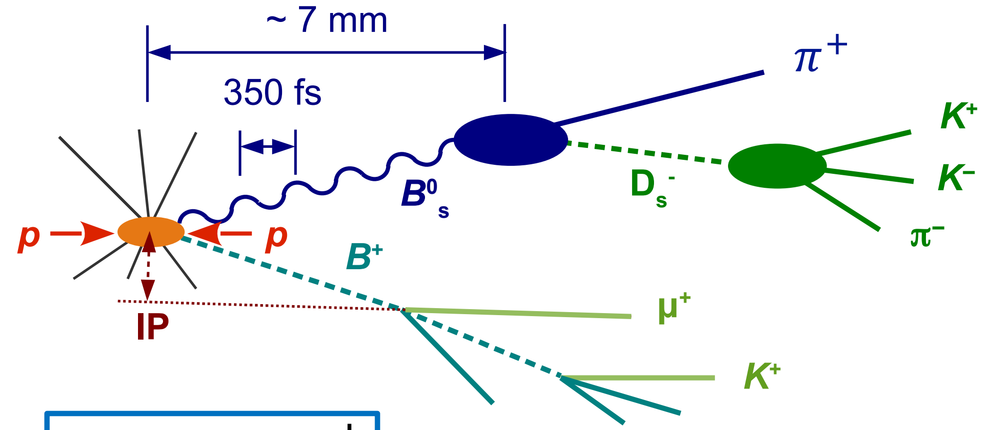
Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



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

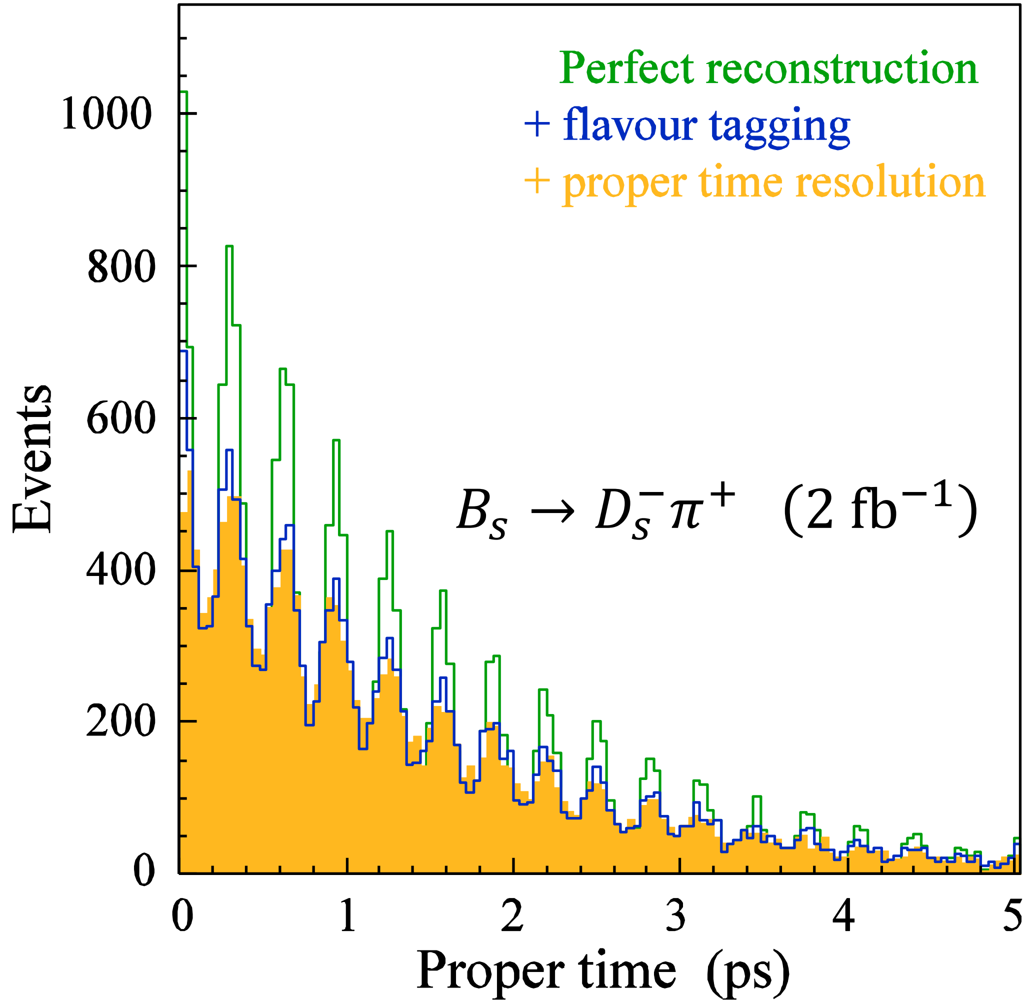
Experimental Situation:

Ideal measurement (no dilutions)

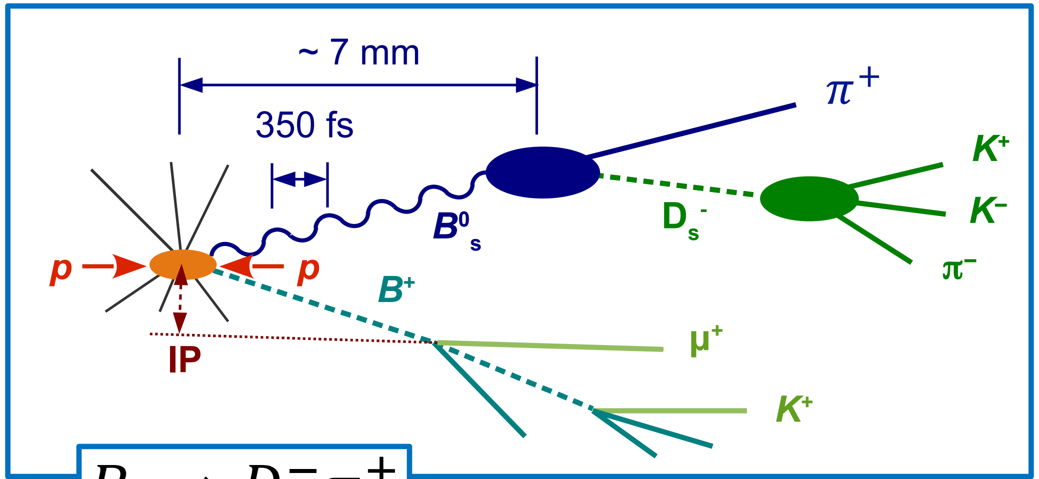
+ Realistic flavour tagging dilution

+ Realistic decay time resolution

Proper-time dependent decay rate:

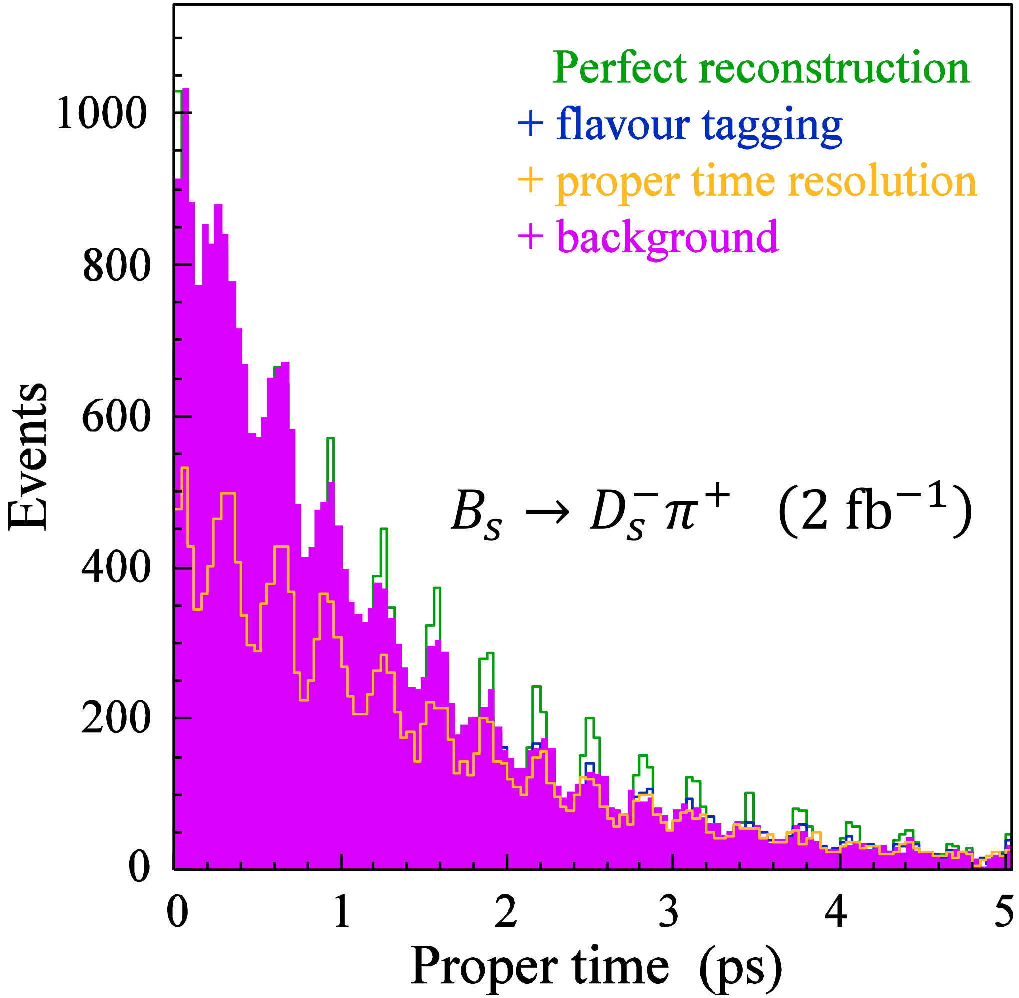


Measuring B_s - $\overline{B_s}$ Oscillations



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

Proper-time dependent decay rate:



Experimental Situation:

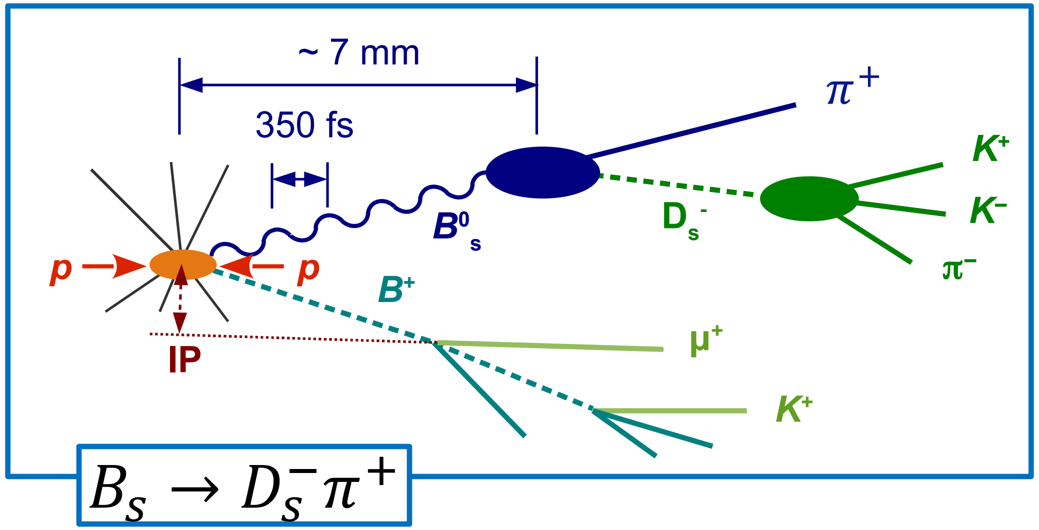
Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution

+ Realistic decay time resolution

+ Background events

Measuring B_s - $\overline{B_s}$ Oscillations



Experimental Situation:

Ideal measurement (no dilutions)

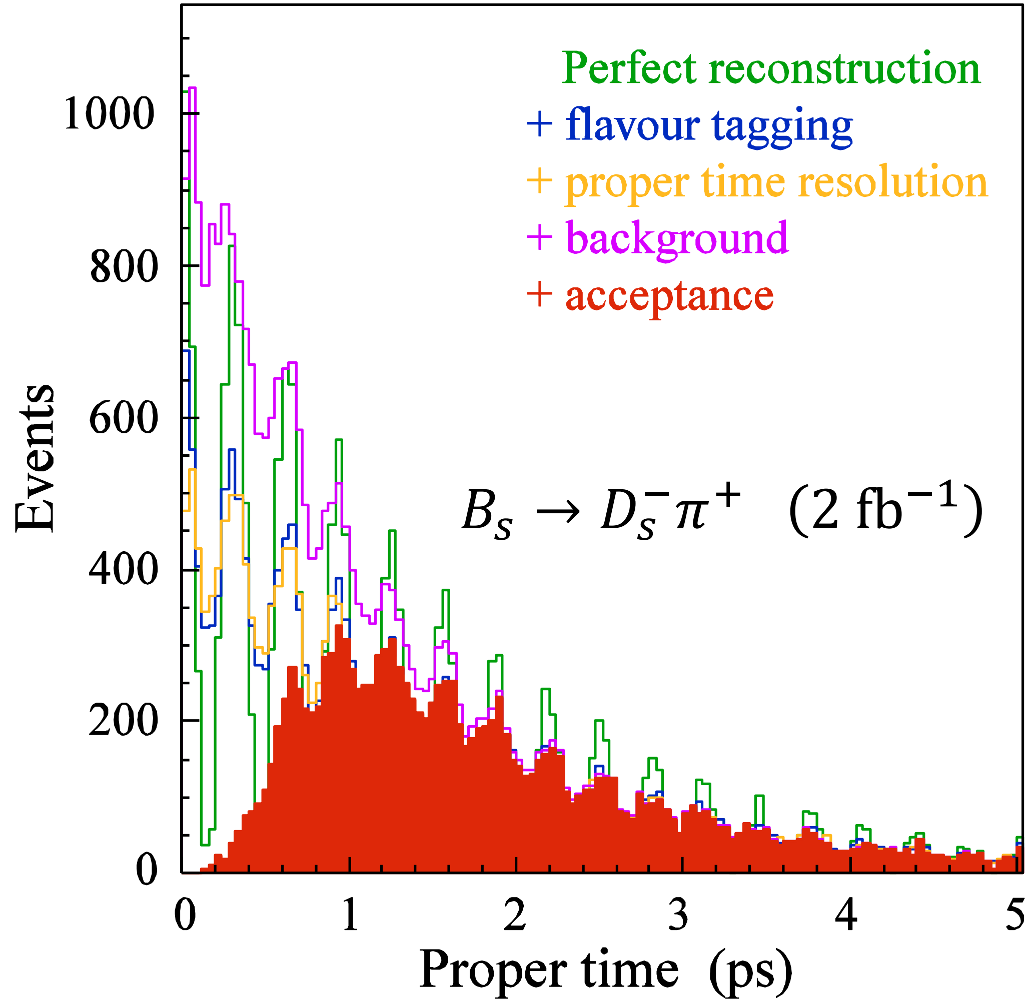
+ Realistic flavour tagging dilution

+ Realistic decay time resolution

+ Background events

+ Trigger and selection acceptance

Proper-time dependent decay rate:

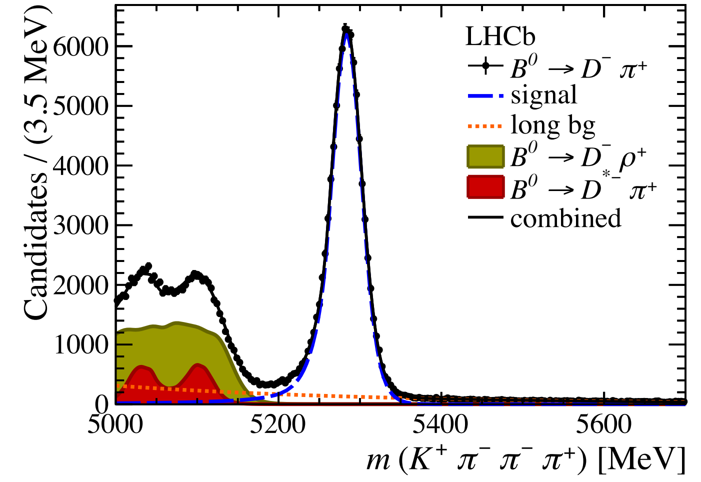


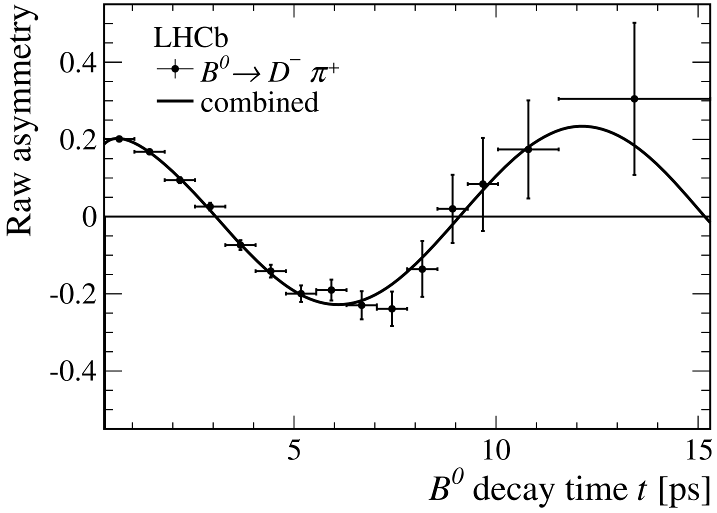
Meson mixing in LHCb: does is actually work?

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

$B^0 \rightarrow D^- \pi^+$

Phys.Lett.B719 (2013) 318

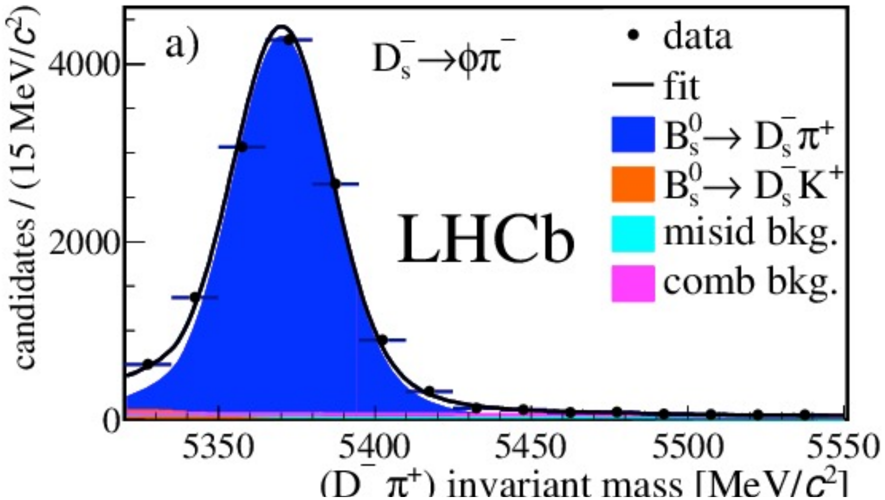


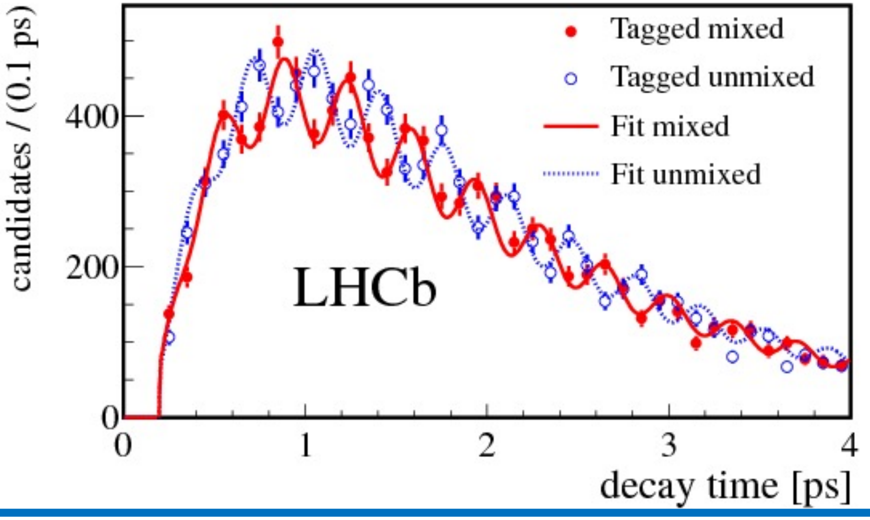


$B_s^0 - \overline{B_s^0}$ mixing

$B_s^0 \rightarrow D_s^- \pi^+$

New.J.Phys.15 (2013) 053021

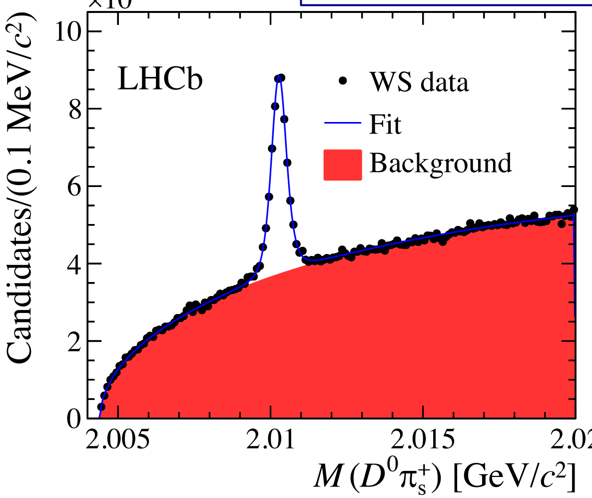


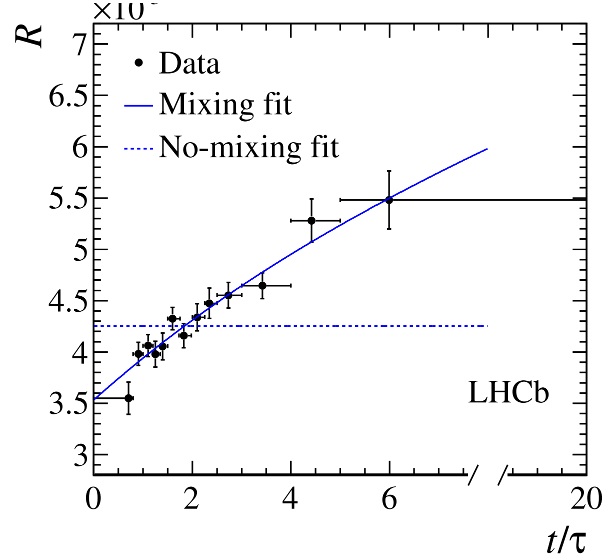


$D^0 \rightarrow \overline{D^0}$ mixing

$D^0 \rightarrow K^+ \pi^-$

PRL.110 (2013) 101802

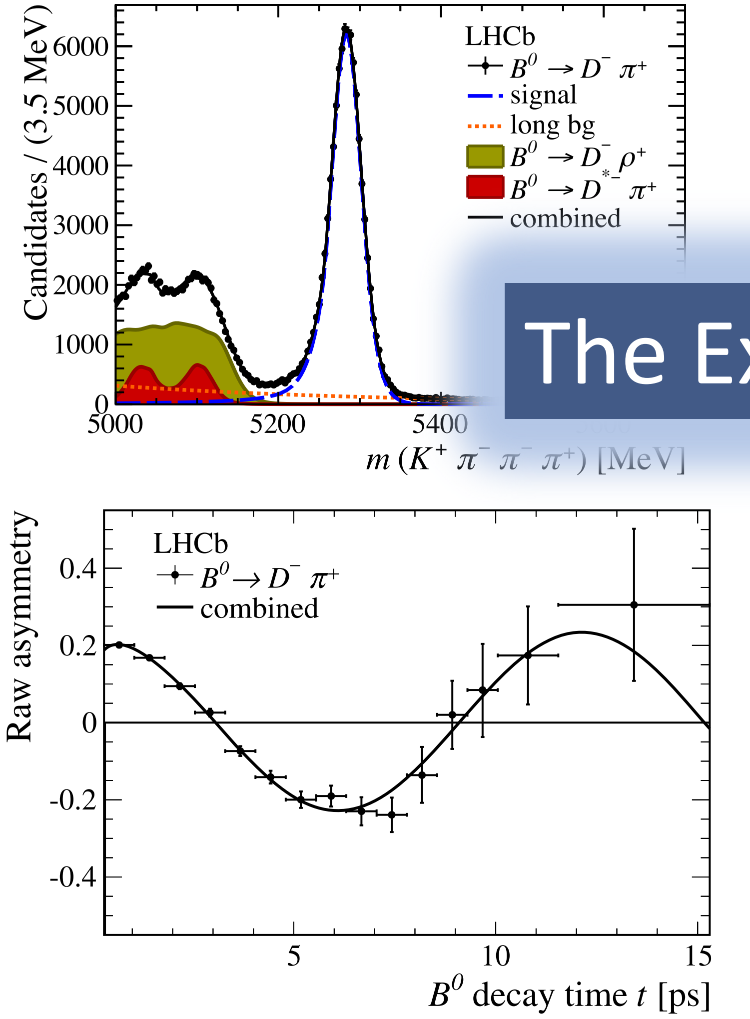




Meson mixing in LHCb: does is actually work?

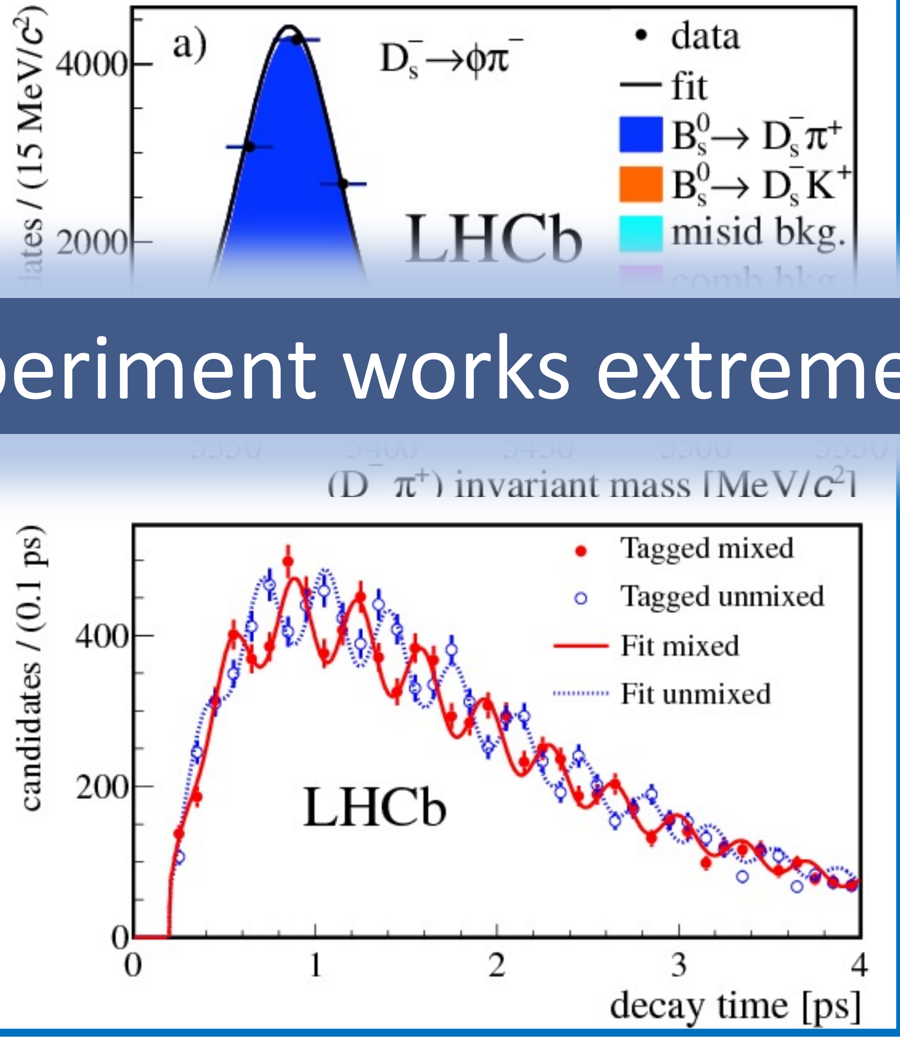
$B^0 - \overline{B^0}$ mixing

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



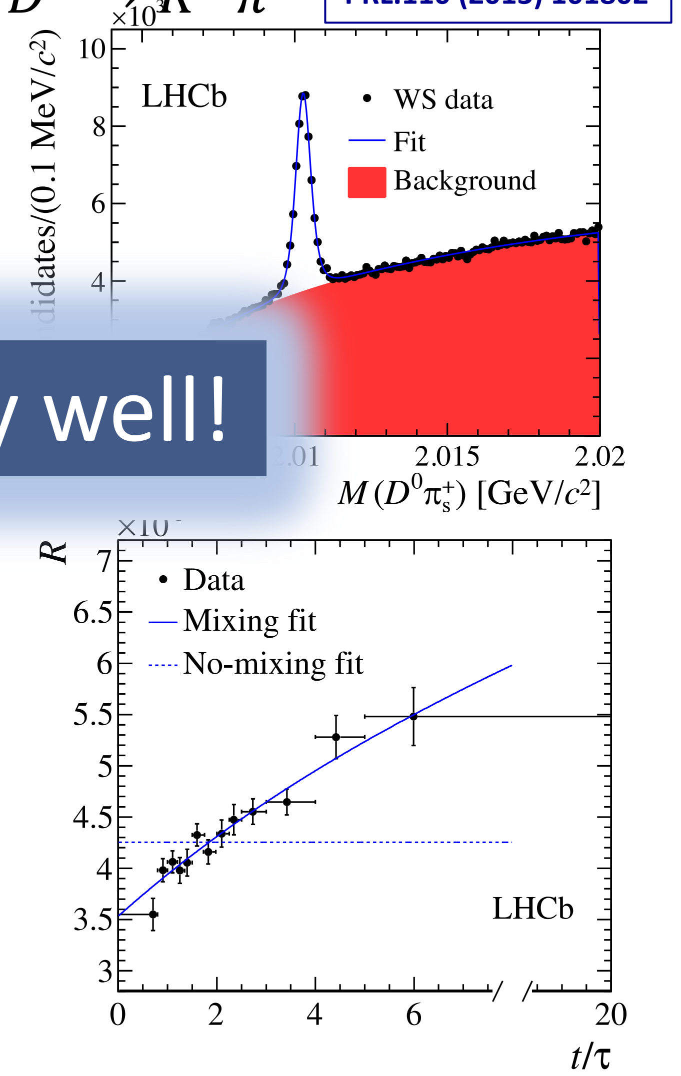
$B^0_s - \overline{B^0_s}$ mixing

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

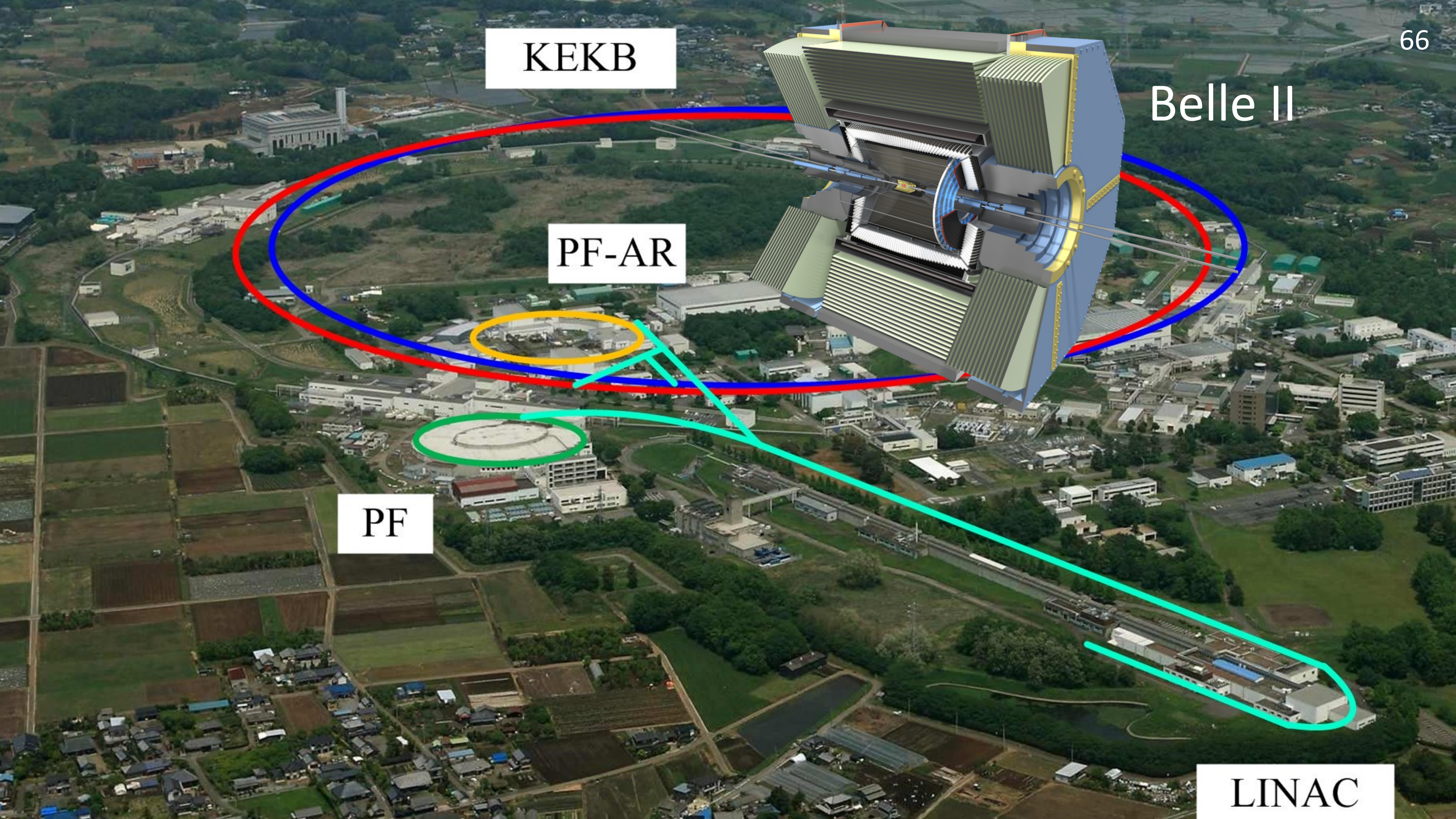


$D^0 \to \overline{D^0}$ mixing

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



The Experiment works extremely well!

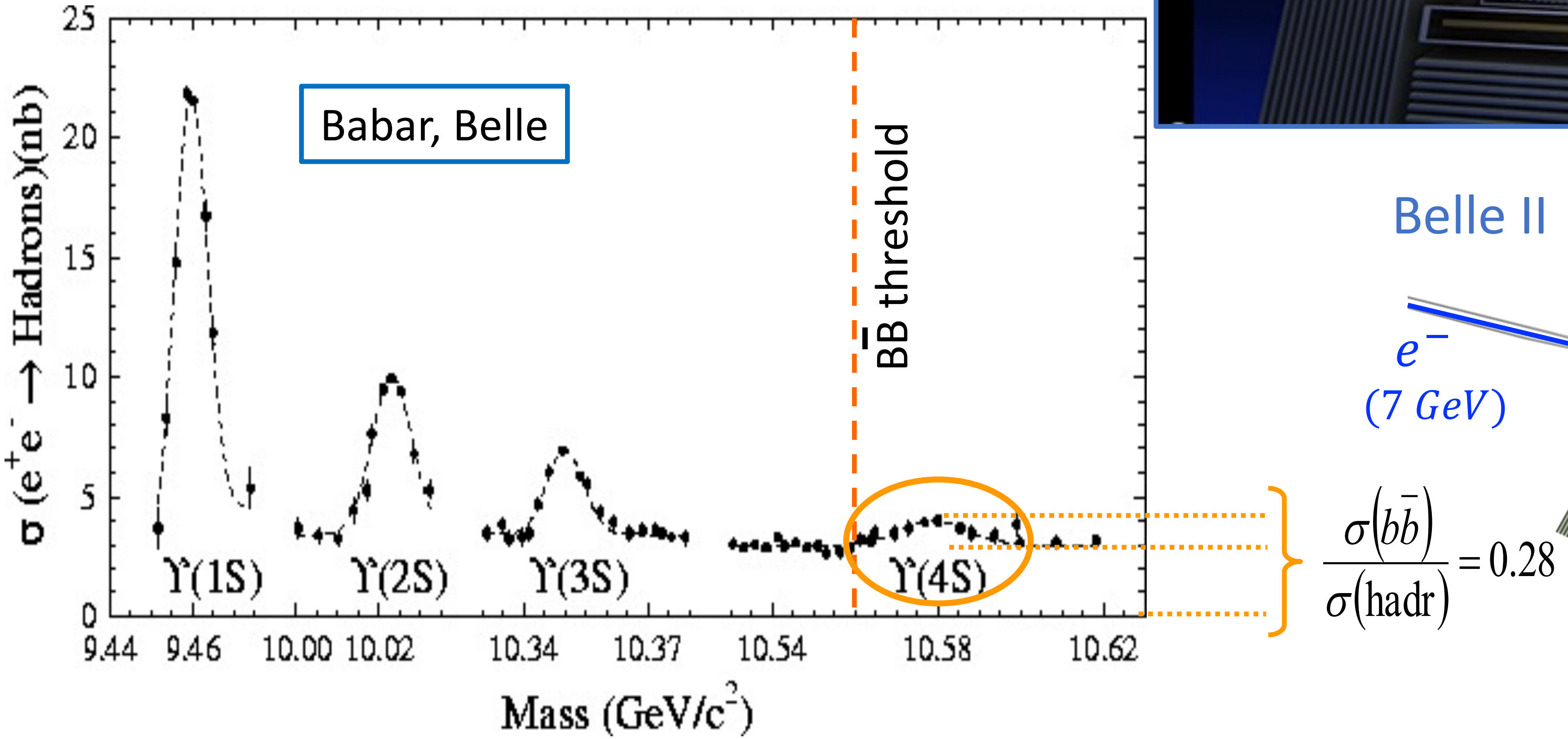

KEKB
Belle II
PF-AR
PF
LINAC

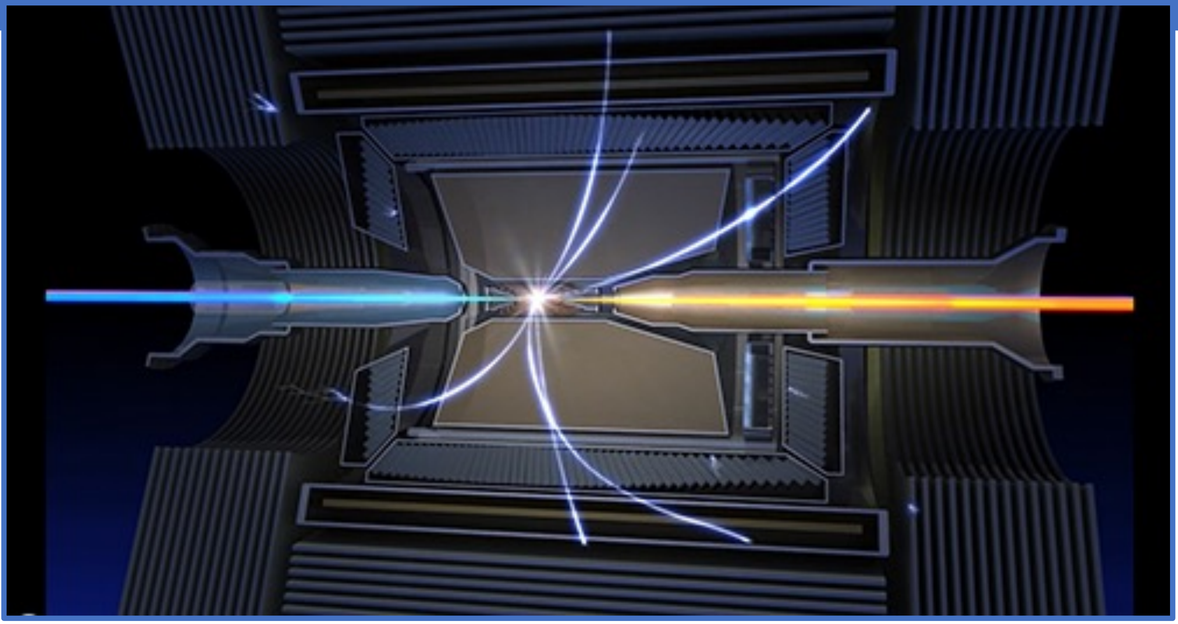
B meson production in e^+e^- Collisions

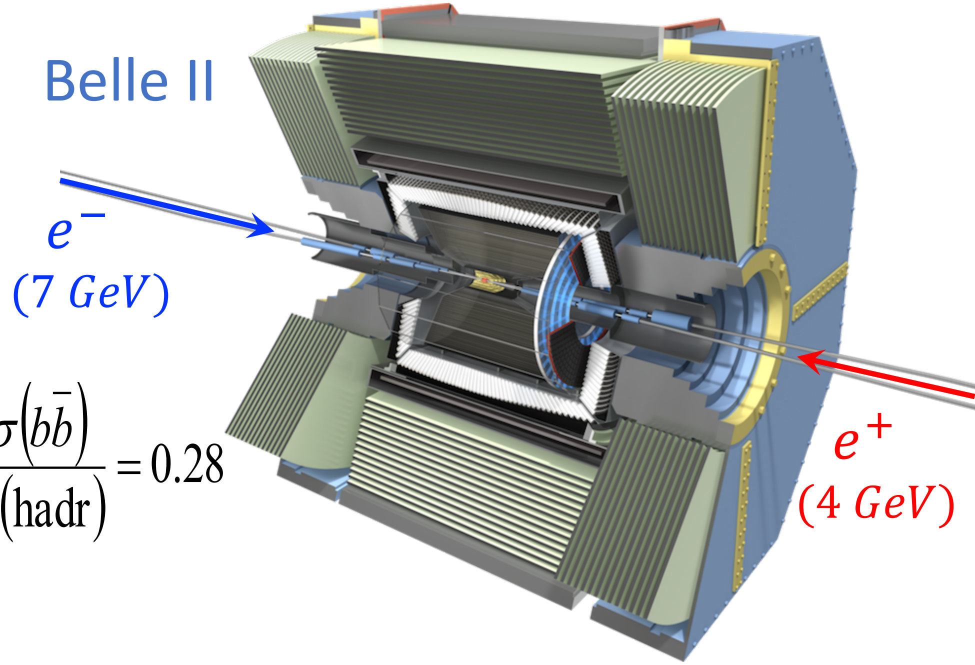
- Electron-Positron collider:

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

  - 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







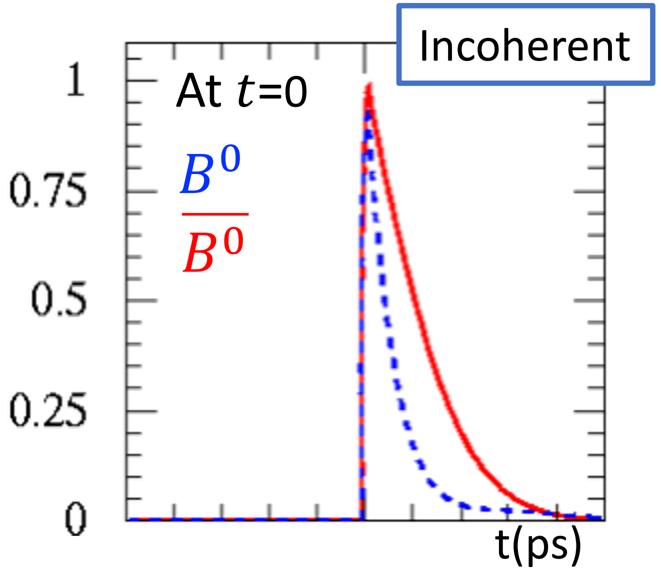
$\Upsilon(4S)$: Coherent B - $\overline{B}$ production

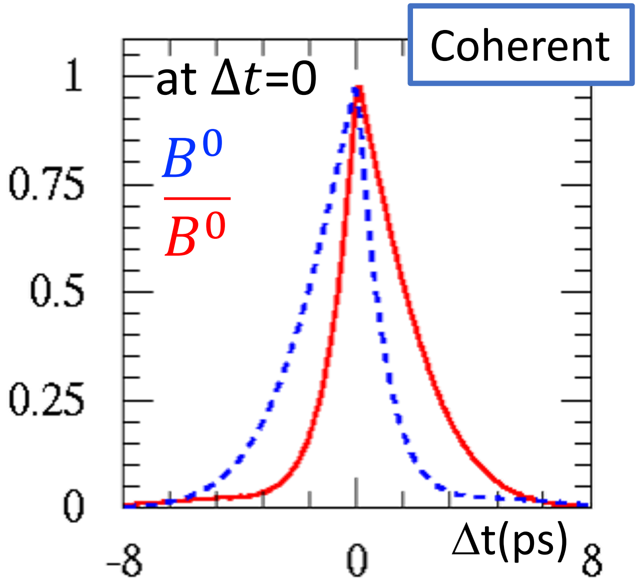
- Production at $\Upsilon(4S)\ J^{PC} = 1^{--}$:

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



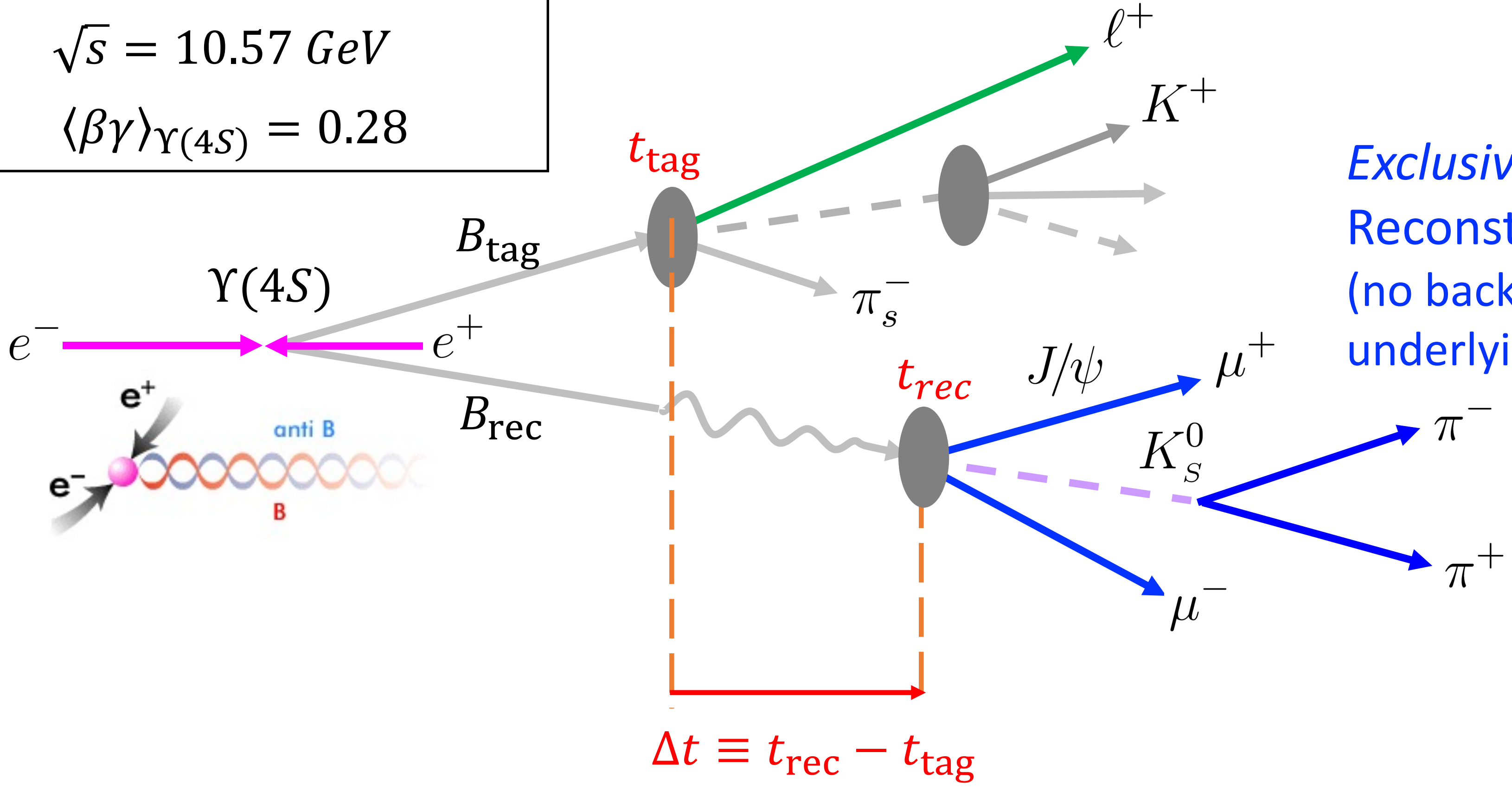


$\Upsilon(4S)$: Coherent B - $\overline{B}$ production (Babar & Belle)

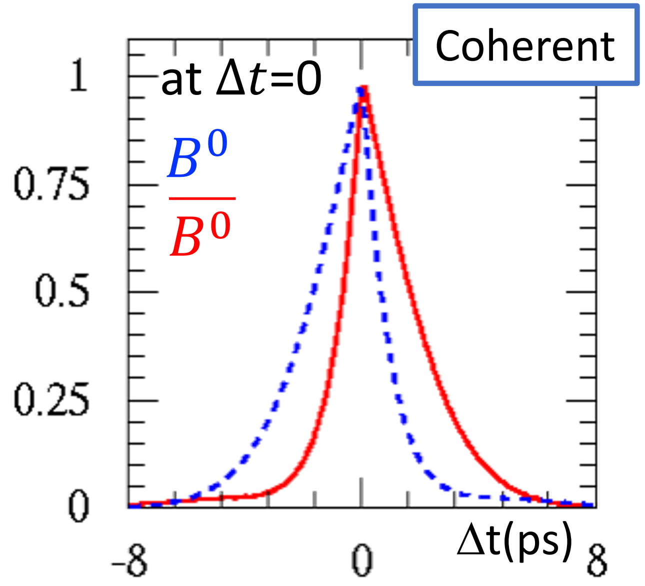
Belle II @ Super KEKB

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

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



Exclusive B meson
Reconstruction
(no backgrounds from
underlying event)

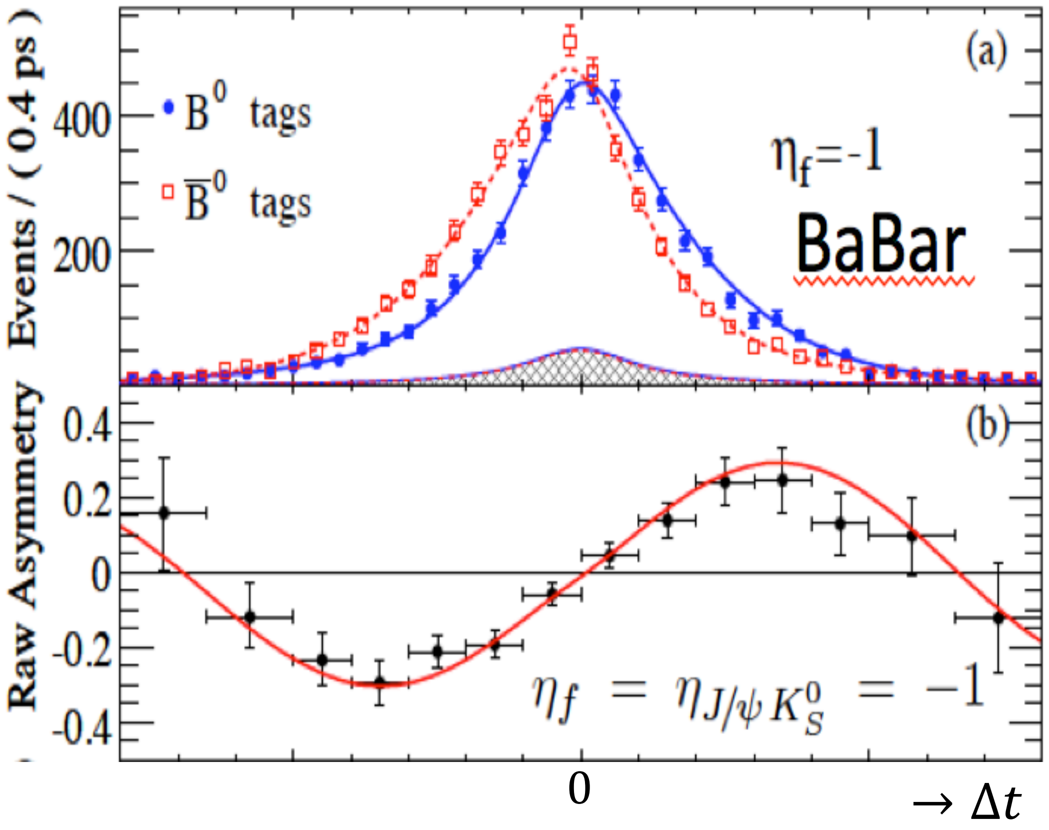


Vertexing and time reconstruction

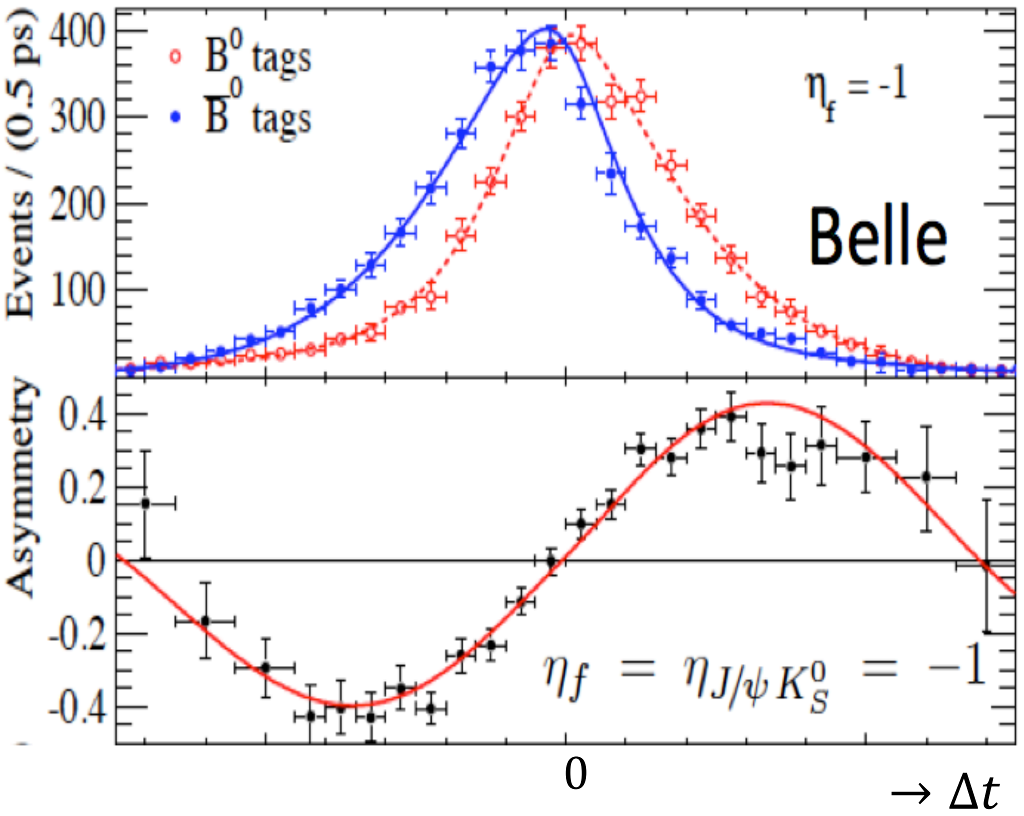
$$\Delta t \approx {}^{\Delta z}/_{c\ \beta\gamma\Upsilon(4S)} \qquad ; \qquad (\langle\Delta z\rangle \approx 130\ \mu m)$$

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

A_{CP}



A_{CP}



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

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

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

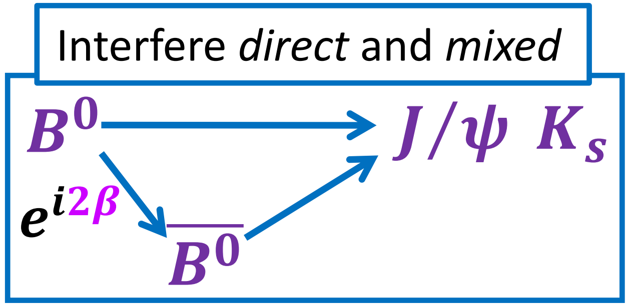
Babar & Belle

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

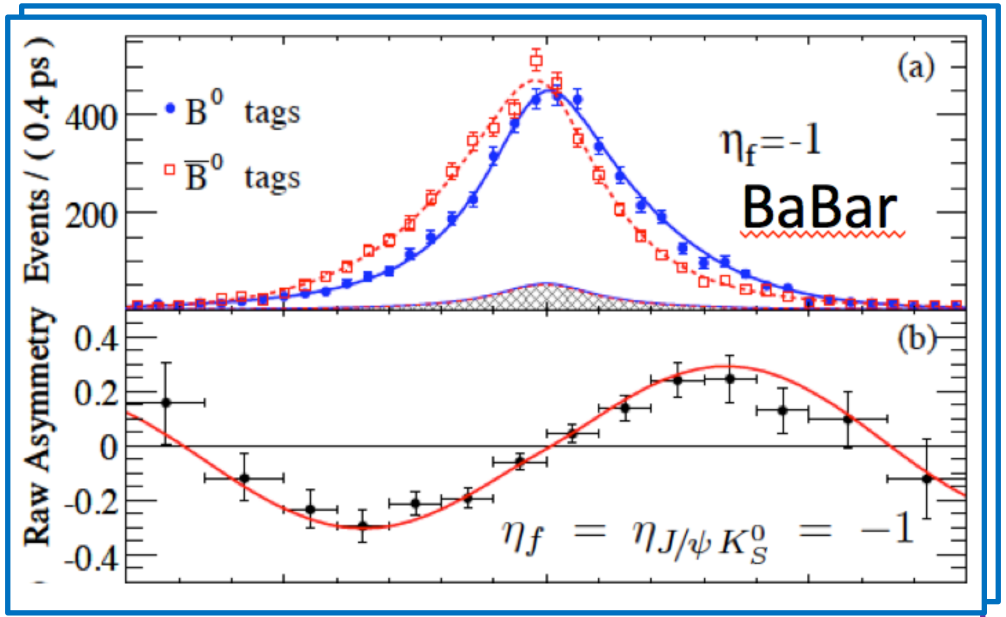
- *Decay-time dependent*

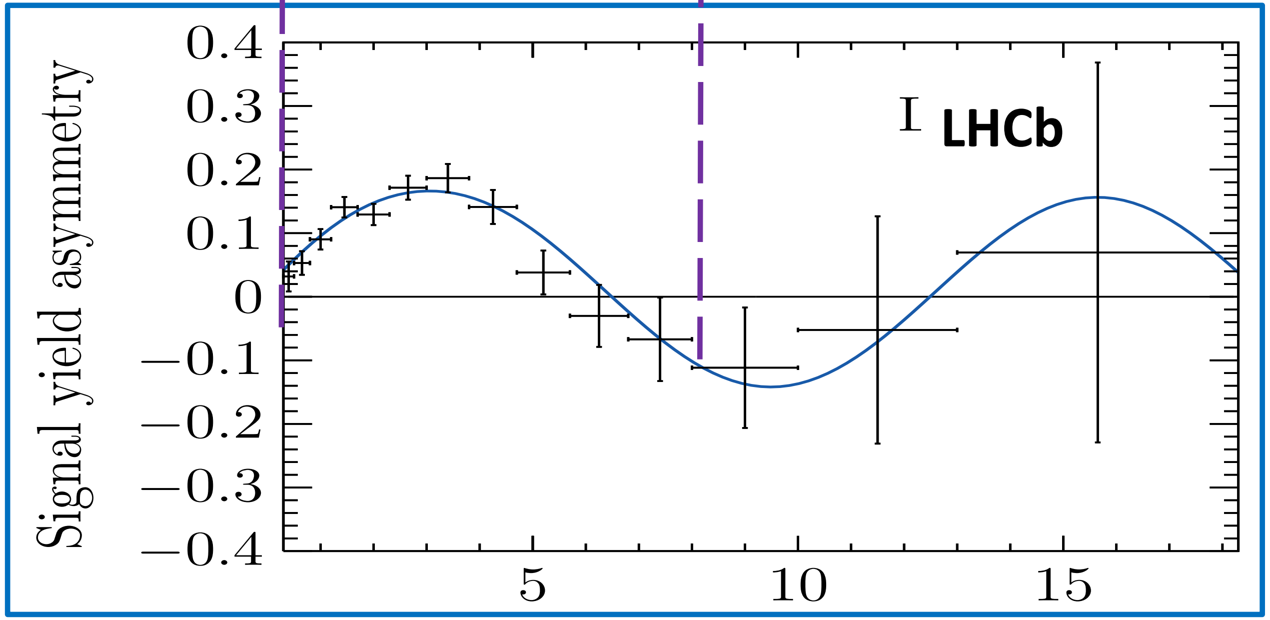
  CP violation:

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



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

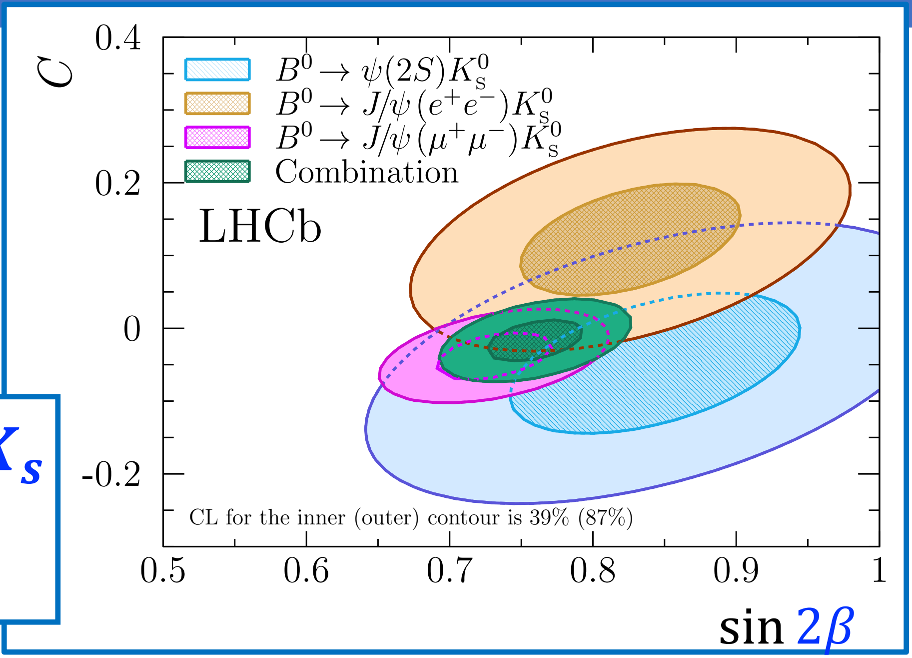


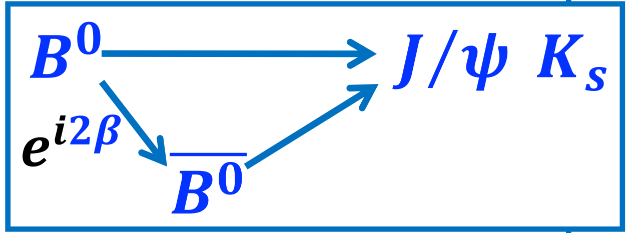


Decay time dependent CP violation

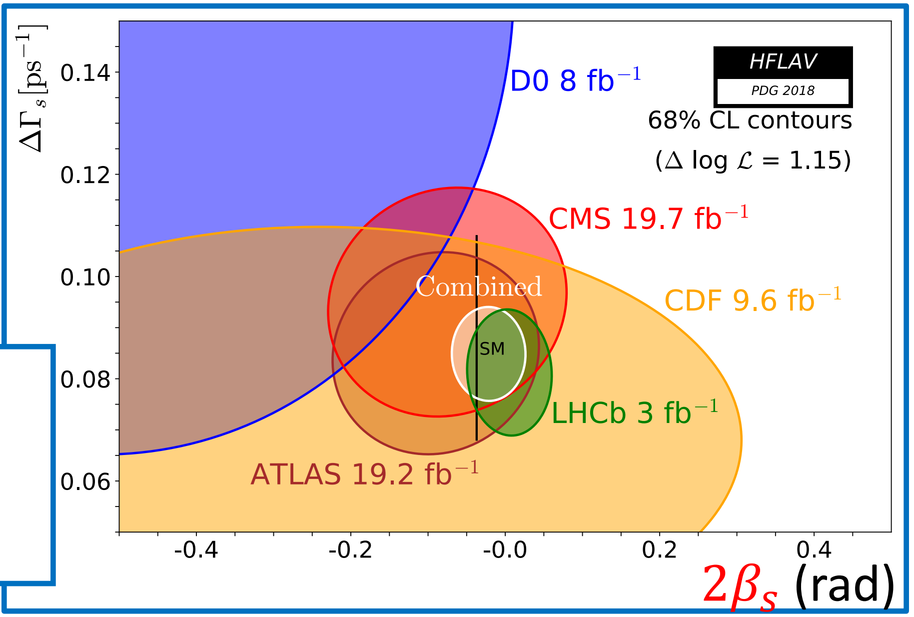
- $B^0 \rightarrow J/\psi\, K_s$ and $B_s^0 \rightarrow J/\psi\, \phi$

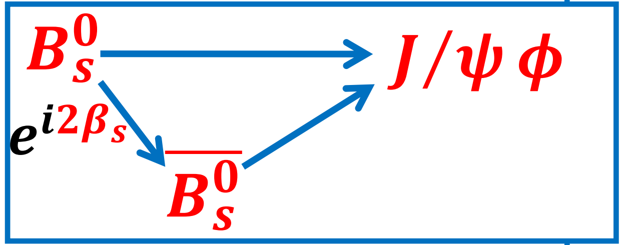
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_{(s)}\rightarrow f}(t) - \Gamma_{B_{(s)}\rightarrow f}(t)}{\Gamma_{B_{(s)}\rightarrow f}(t) + \Gamma_{B_{(s)}\rightarrow f}(t)}$$





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



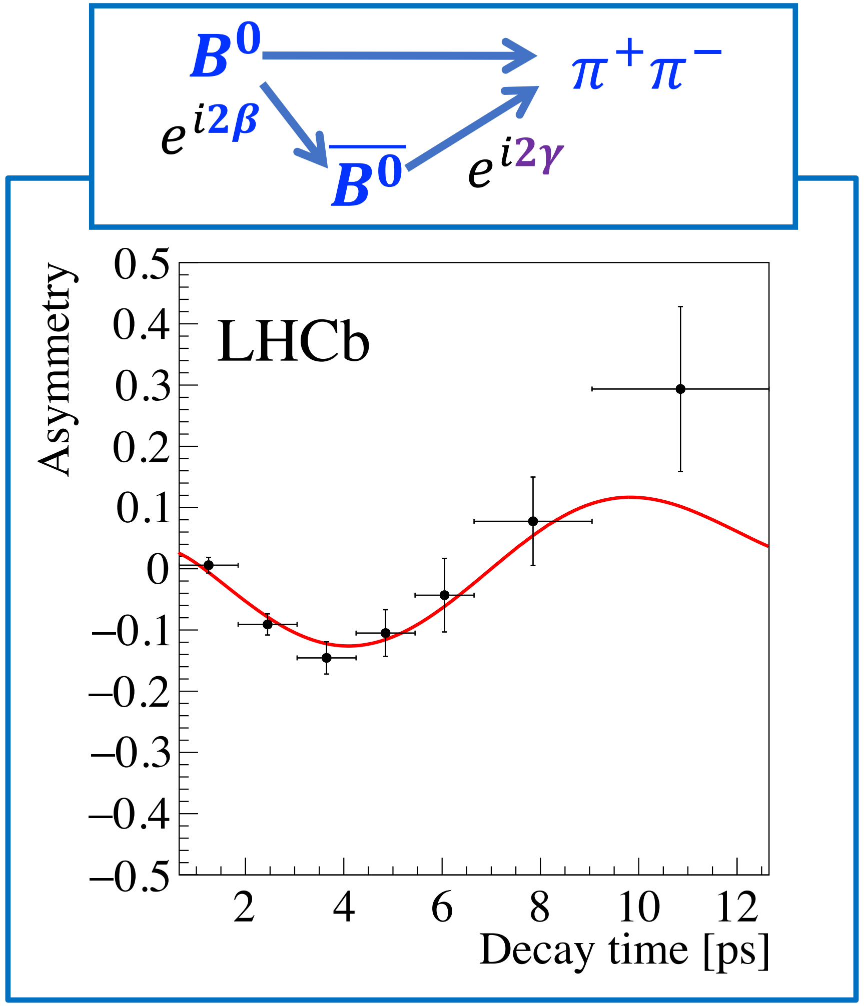


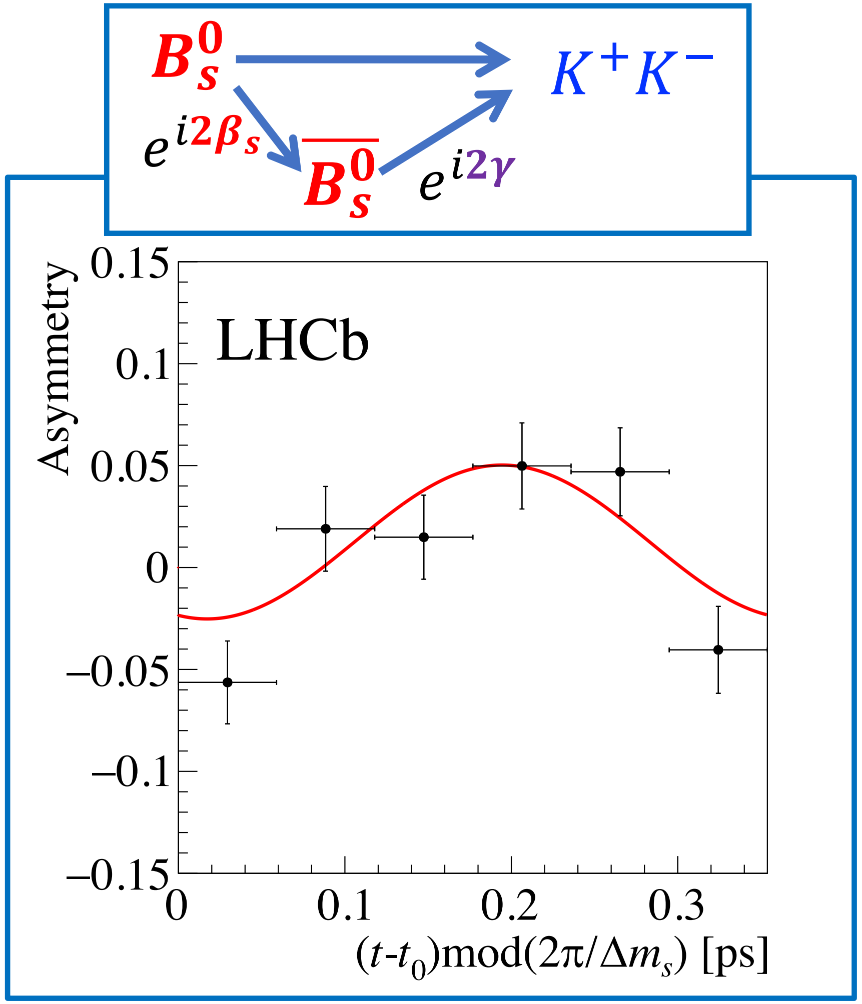
Decay time dependent CP violation

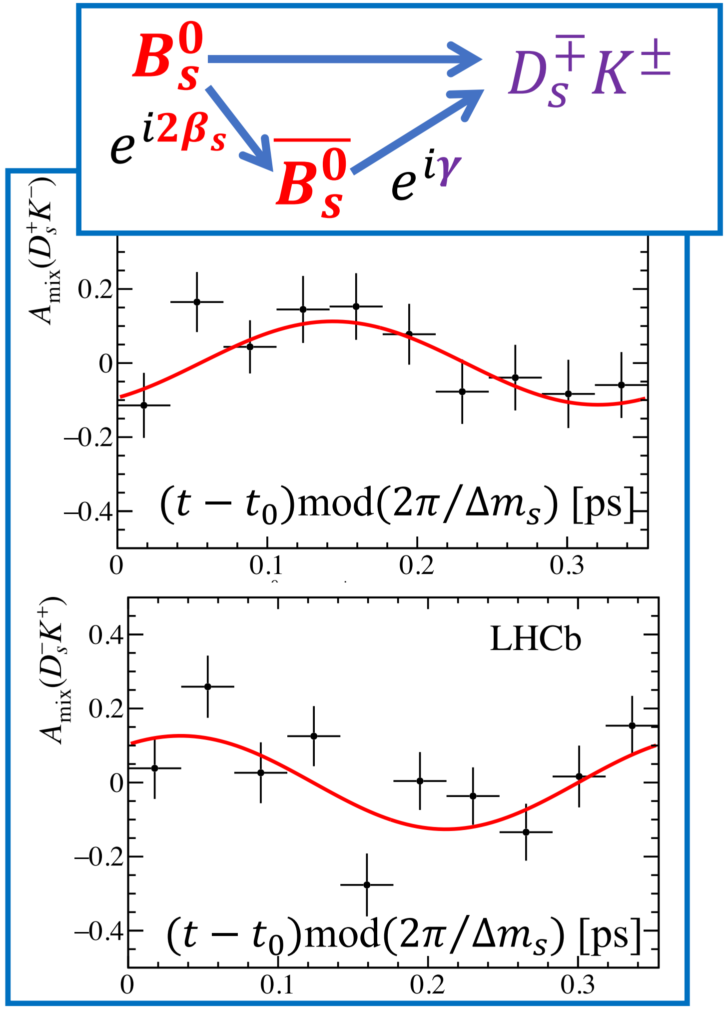
- *Hadronic decay modes (LHCb)*:

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

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



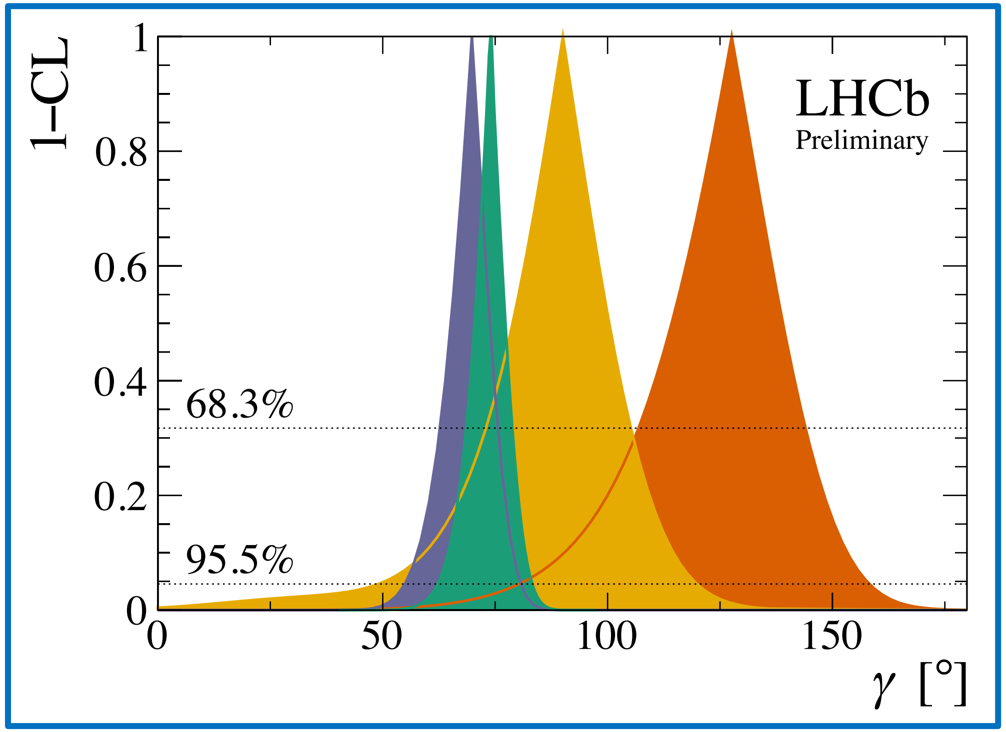


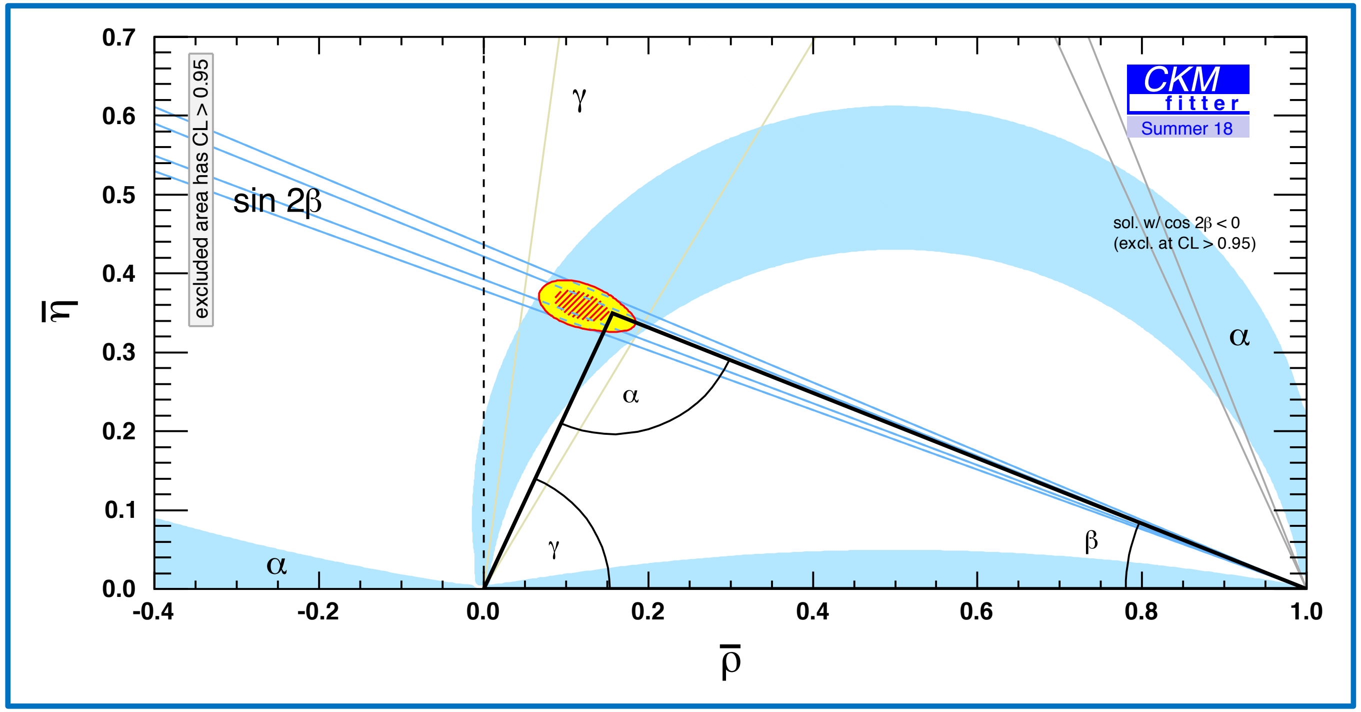


Current situation on angle γ

- The situation for angle γ :

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





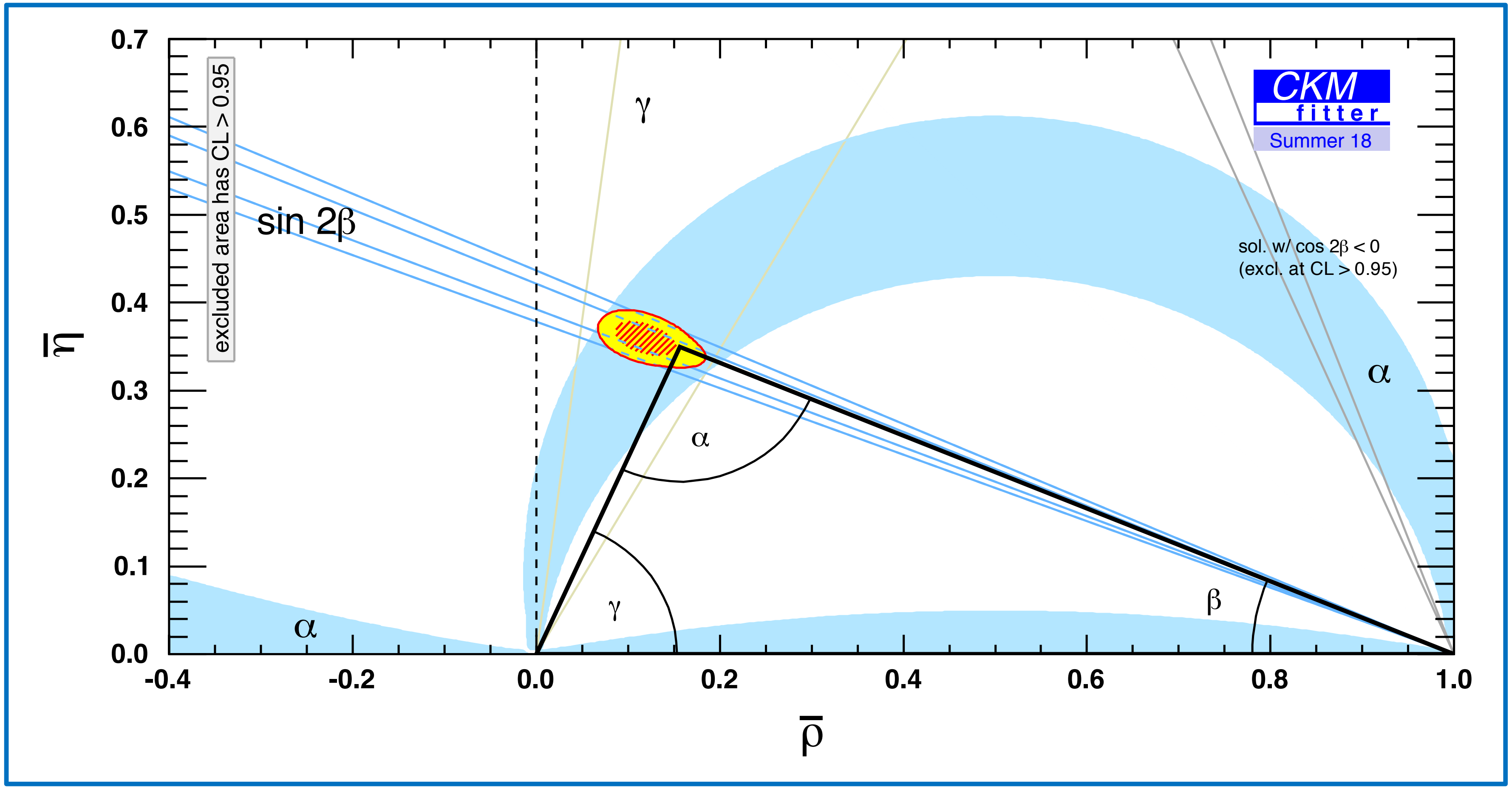
- B_s^0 decays
- B^0 decays
- B^+ decays
- Combination

Average:

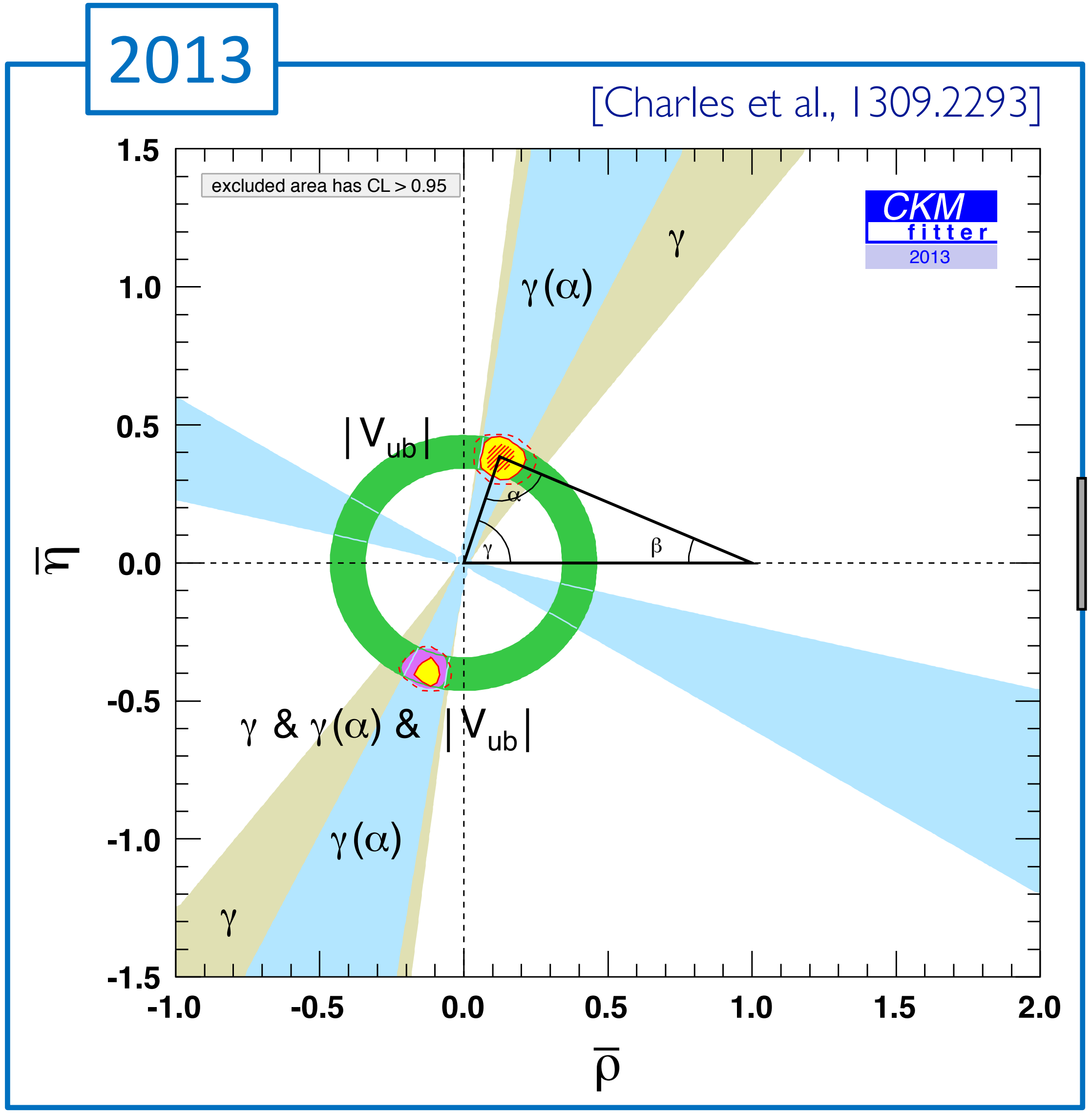
$$\gamma = \left(74.0^{+5.0}_{-5.8}\right)^o$$

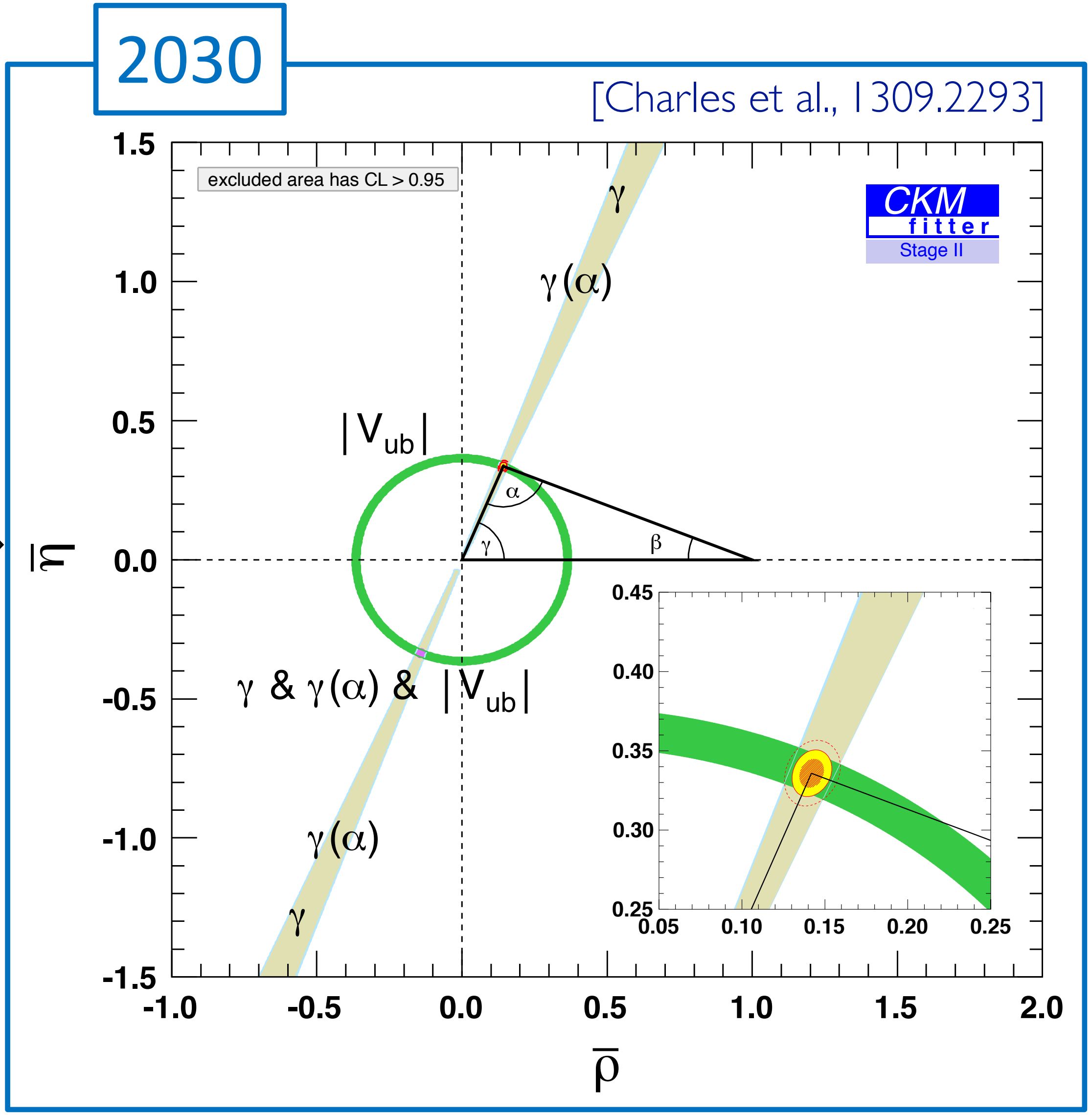
CKM triangle: putting all measurements together

	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



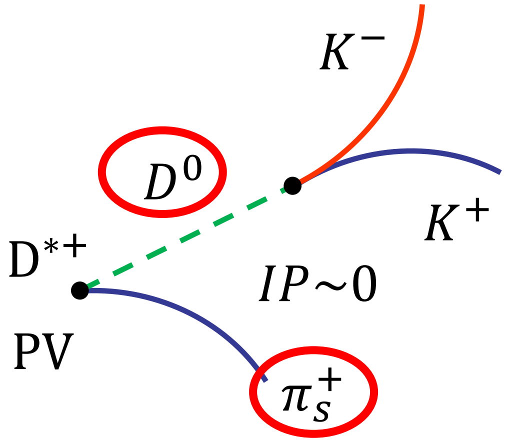
LHCb: Future sensitivity for CP violation

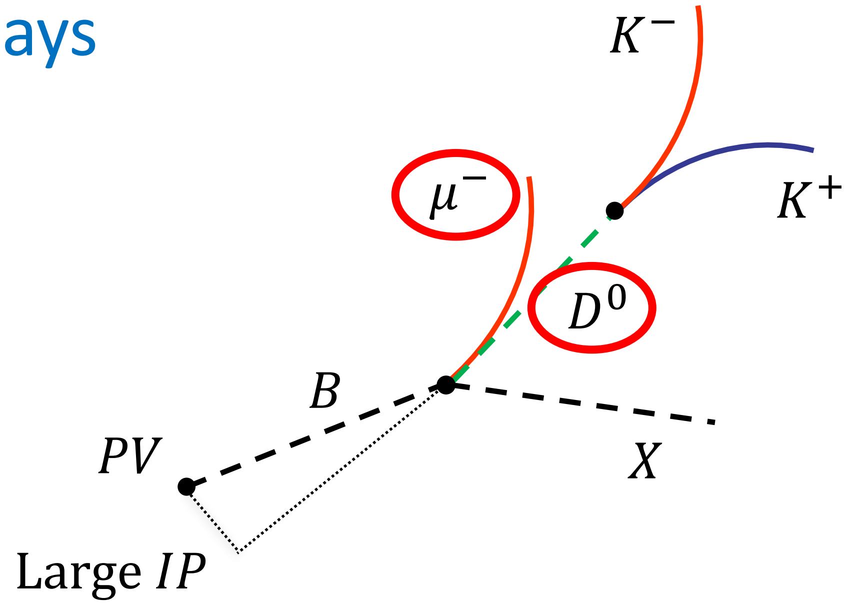


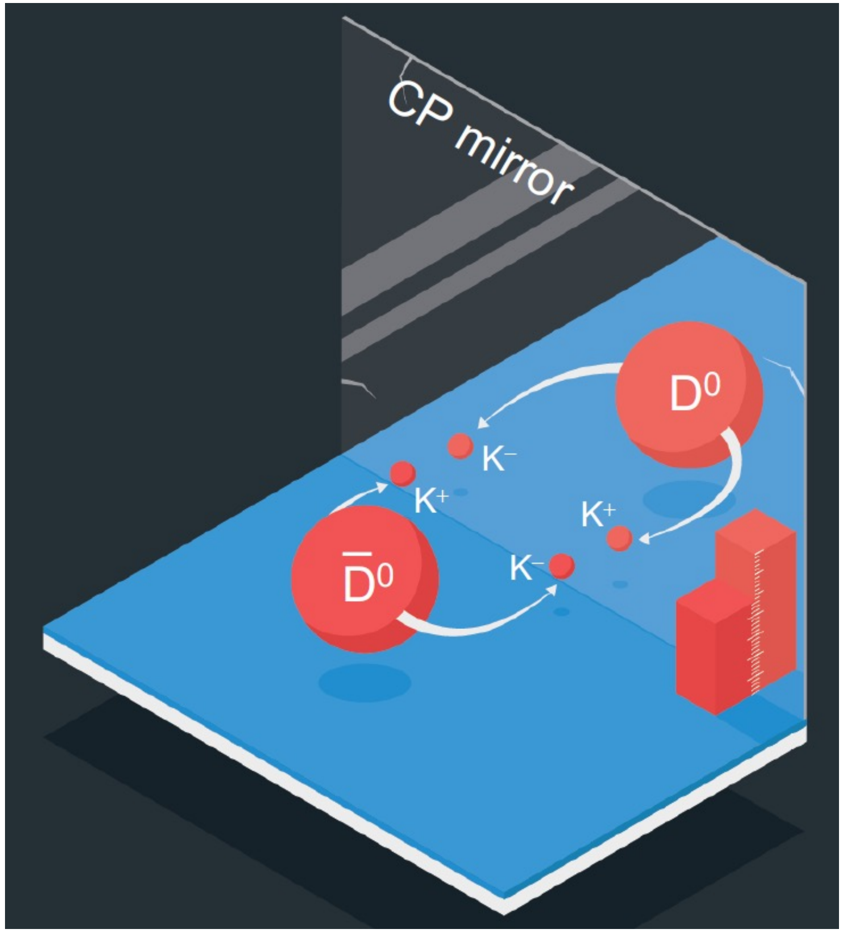


CPV in Kaons (K) and Beauty (B): How about Charm (D)?

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





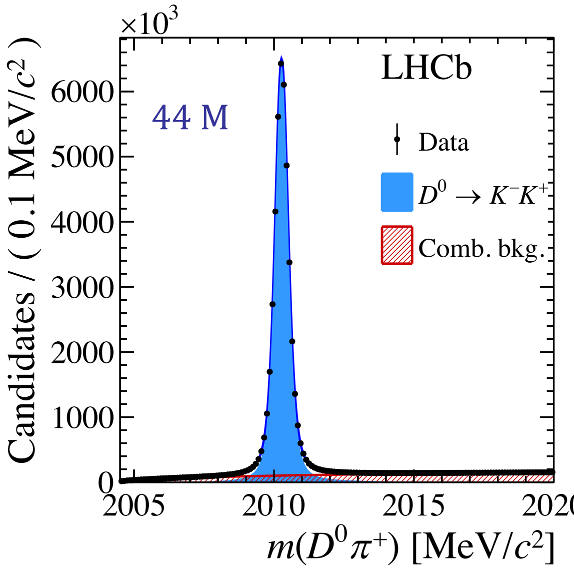


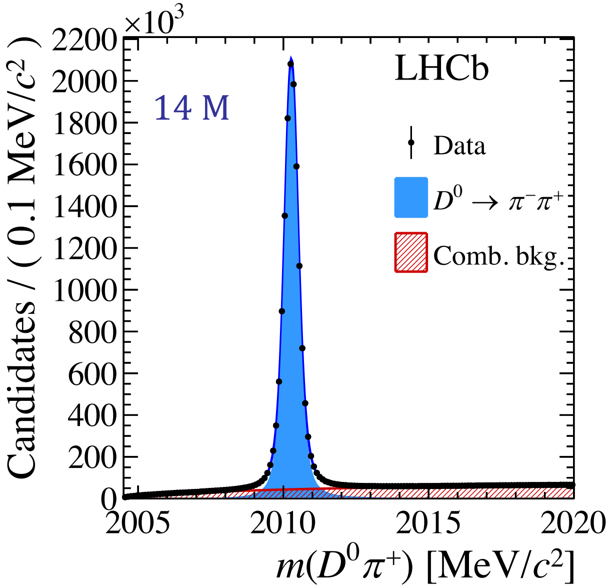
$$A_{raw}(K^+K^-) = \frac{N(D^0 \to K^+K^-) - N(\bar{D}^0 \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\bar{D}^0 \to K^+K^-)}$$

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

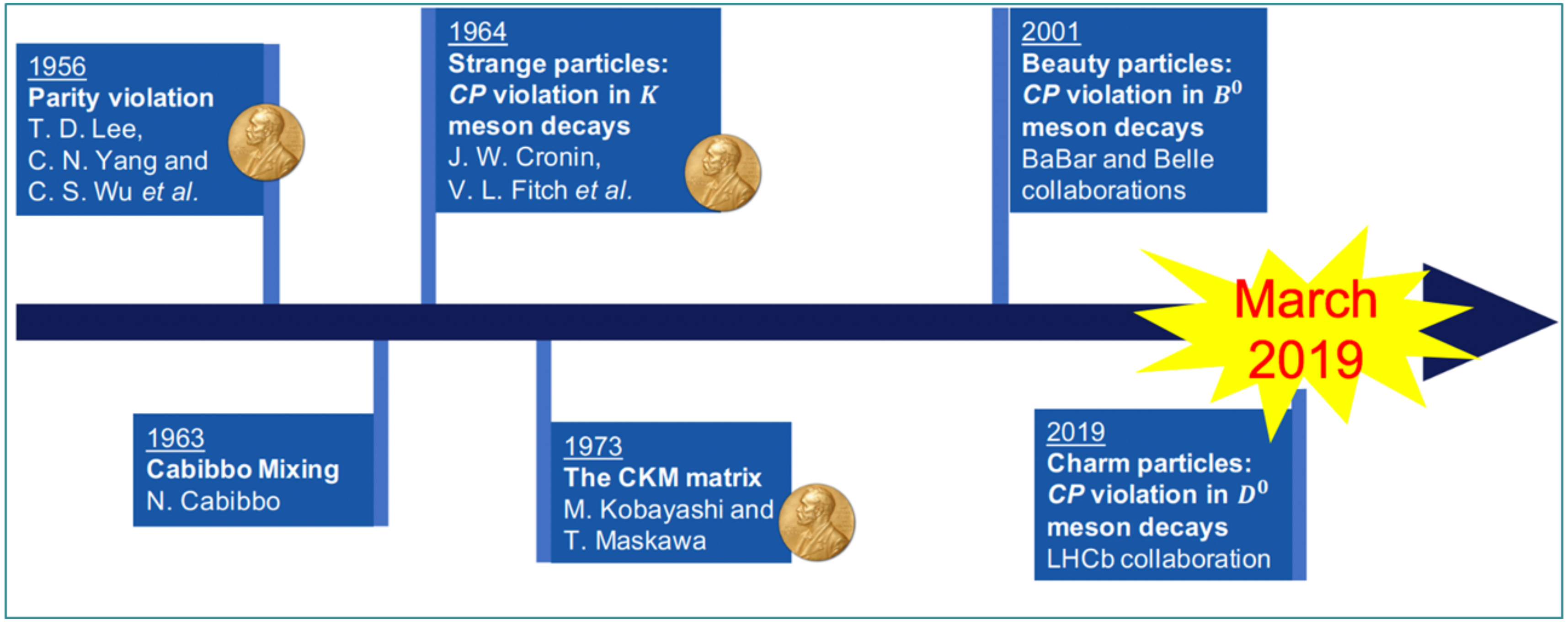
- Look at: $\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$
  - ⇒ All detection and production asymmetries cancel
  - ⇒ Directly observe CP asymmetry!

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 $\gamma=1^{o}$
- 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:
  - Fraction of collisions that produce b-quarks:
  - Fraction of events where B_s meson is produced from b-quark:
  - Fraction of B_s that decay into $B_s \to D_s^{\mp} K^{\pm}$ channel
- ➔ So in total perfectly reconstructed events required
- Next, assumed measured by the LHCb experiment:
  - Acceptance x Reconstruction (background, resolution):
  - Trigger:
  - Tagging Power:
- In total pp collisions must be collected
- Assume ~10 MHz collisions, 3 x 10^6 s/year running time: of running.

Design your own B-meson CP Violation Experiment

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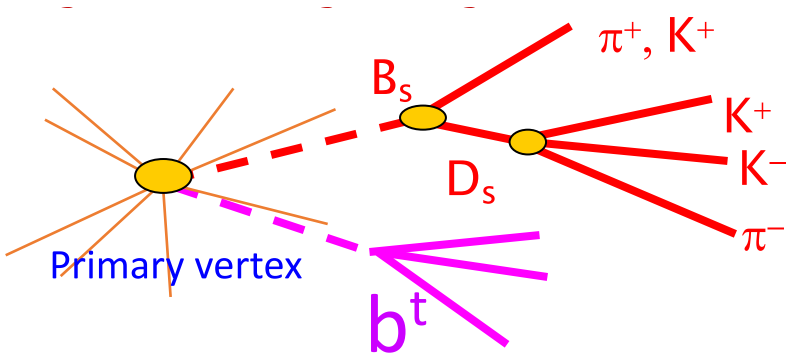

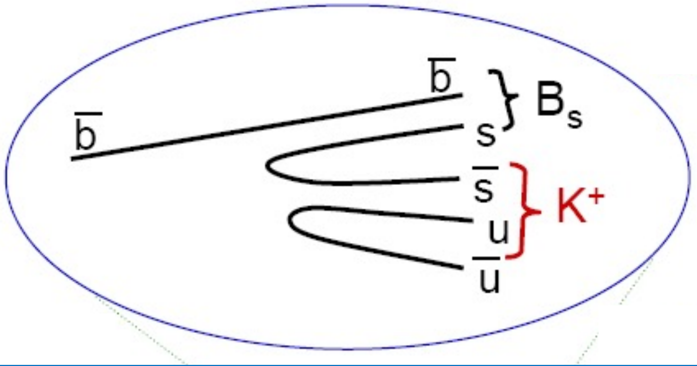

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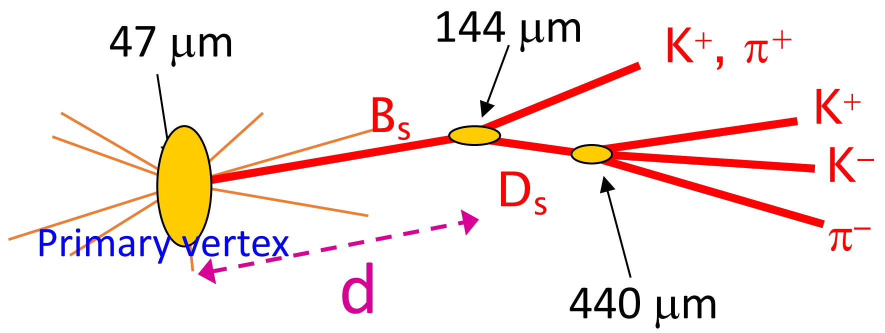

Decay time resolution = 40 fs

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