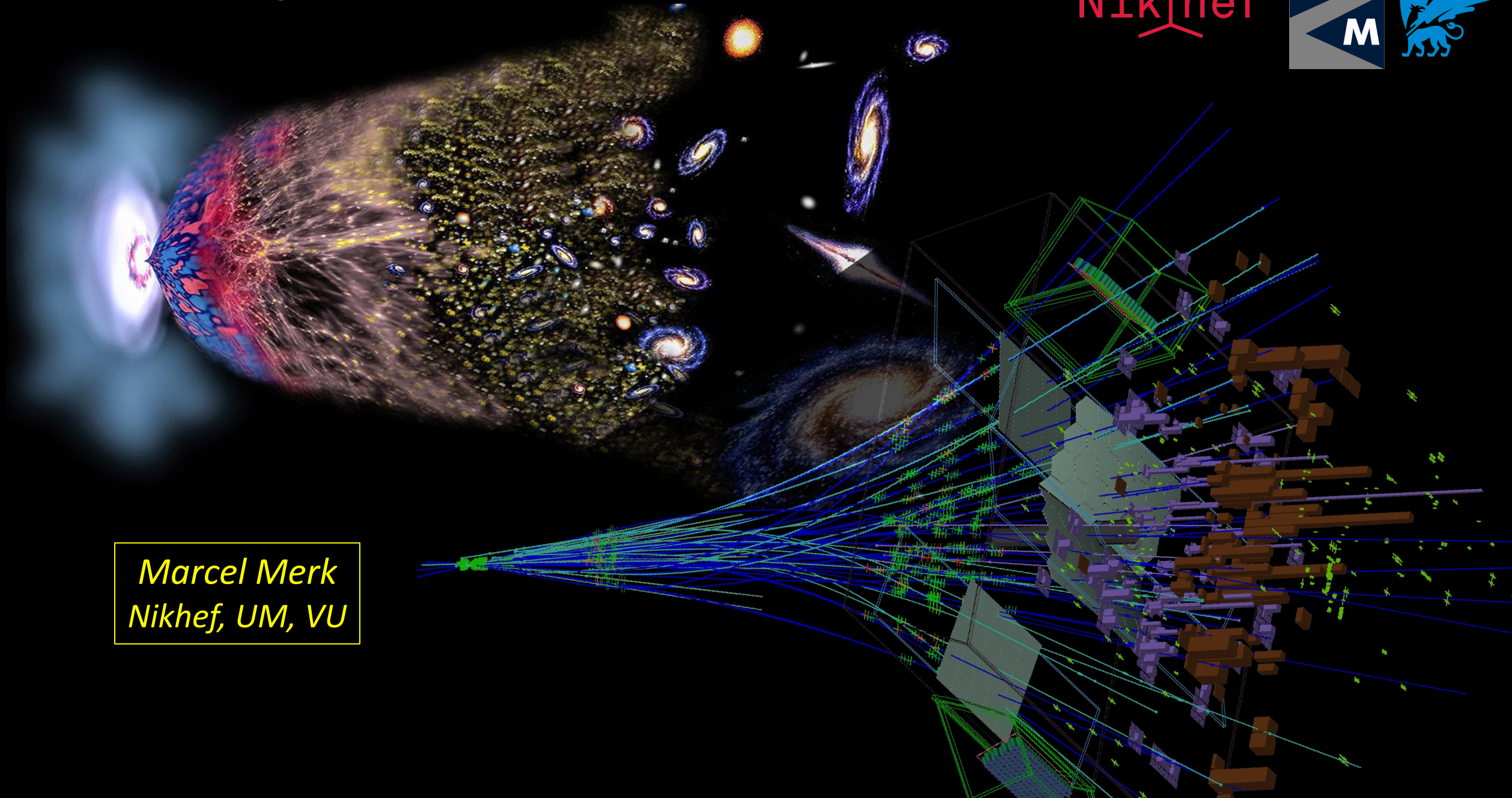
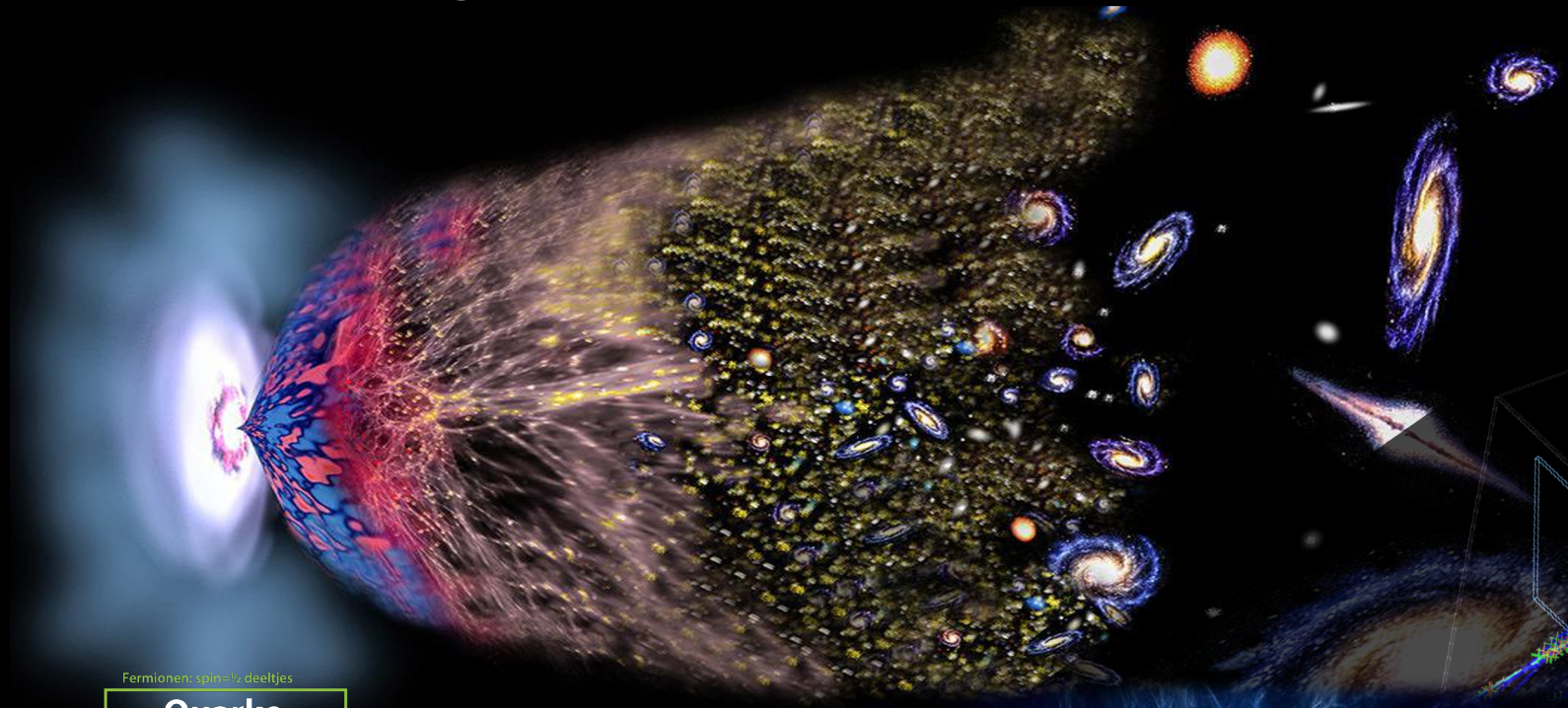
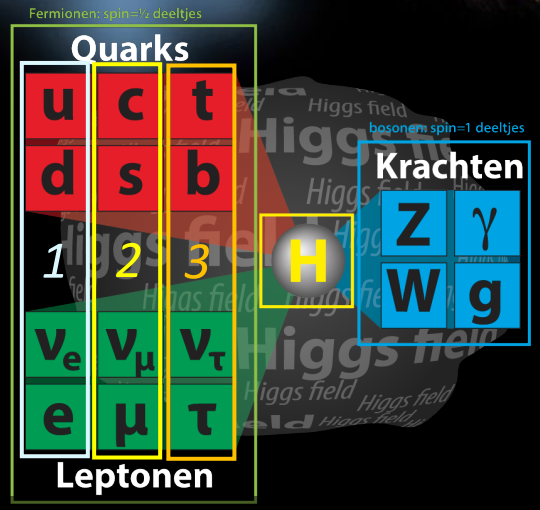
Flavour Physics and CP Violation

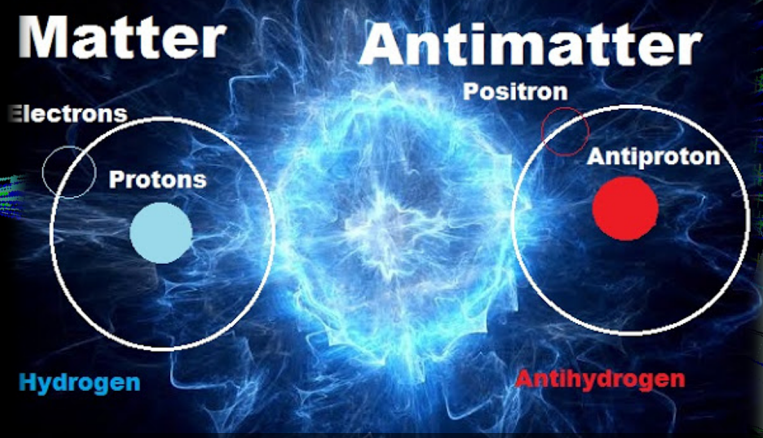


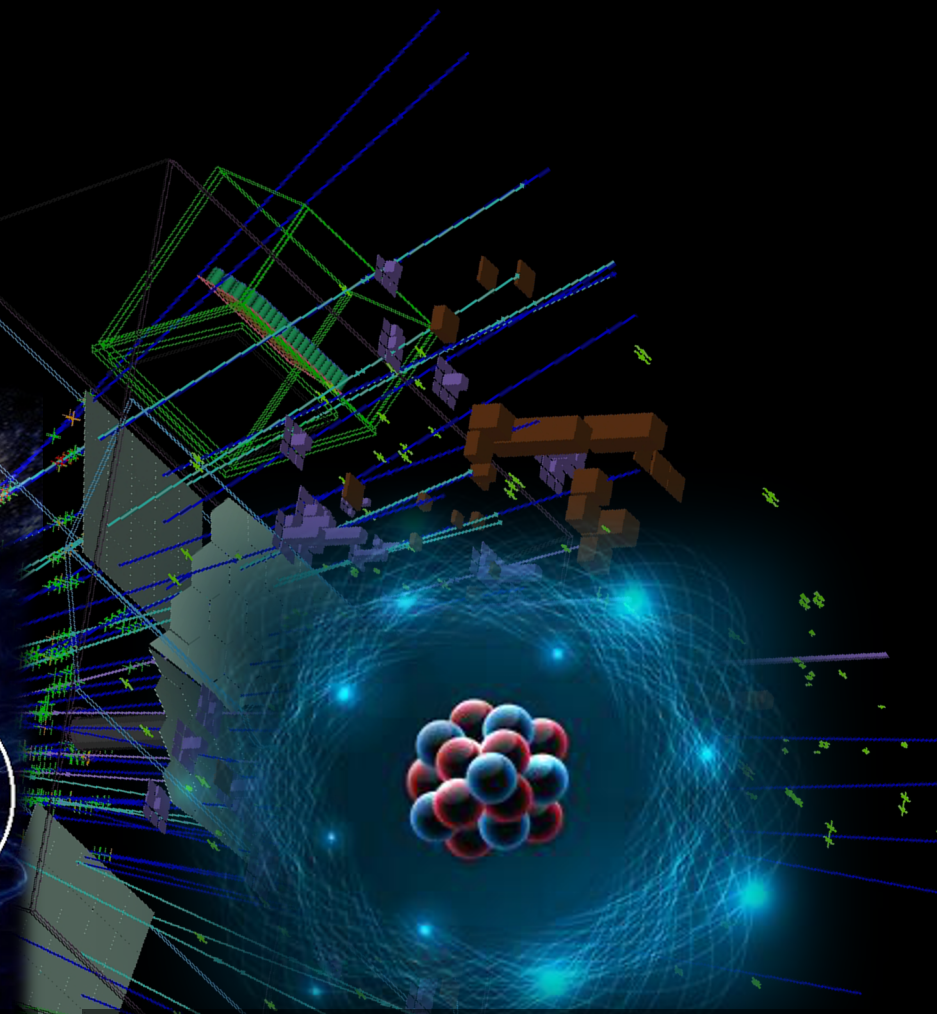
Marcel Merk
Nikhef, UM, VU

Flavour Physics and CP Violation







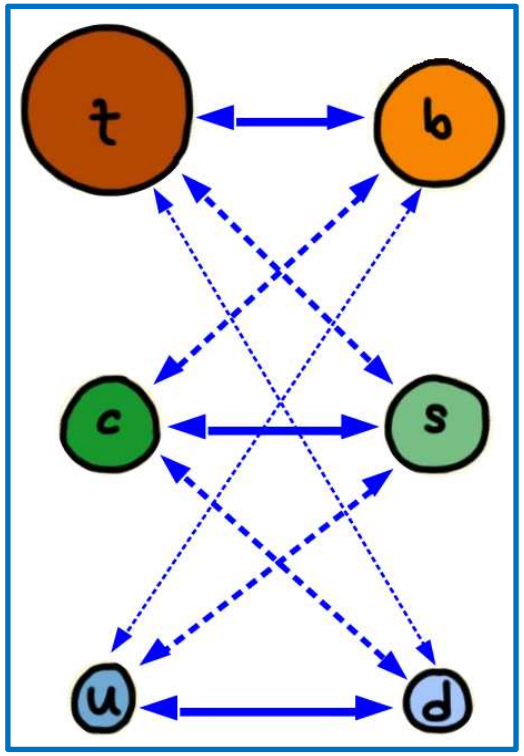


Why three generations of particles?

Why is there no antimatter?

Why is an atom electric neutral?

Recap: Flavour Physics and CP Violation



"Day and Night", Escher, 1938

Matter world

White

Black

C

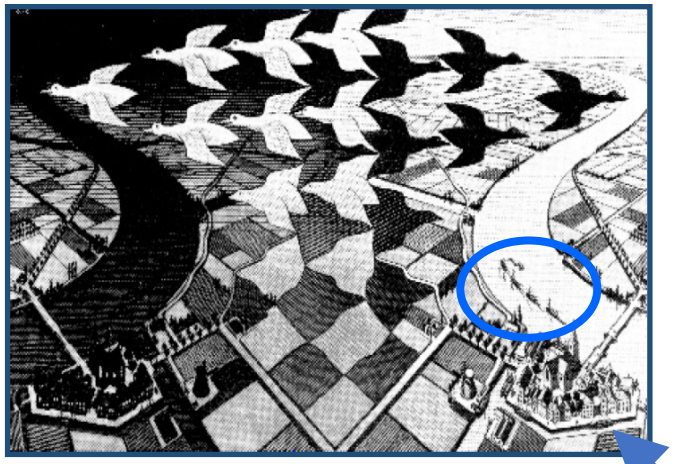
CP:

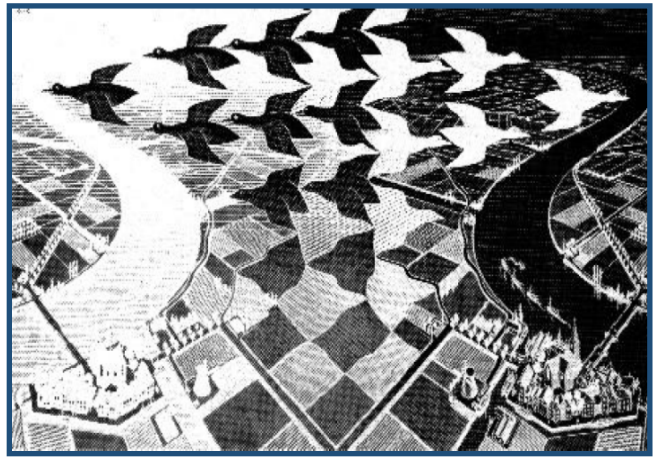
P

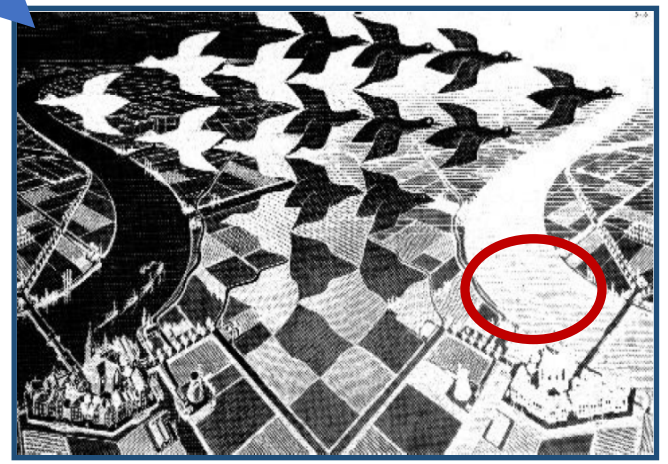
Left

Right

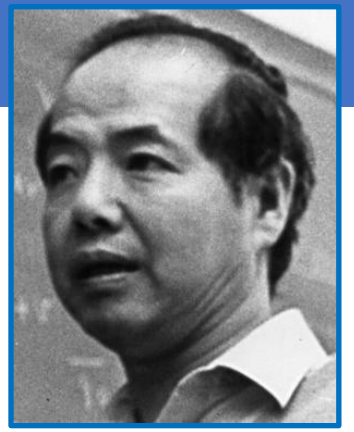
Antimatter world





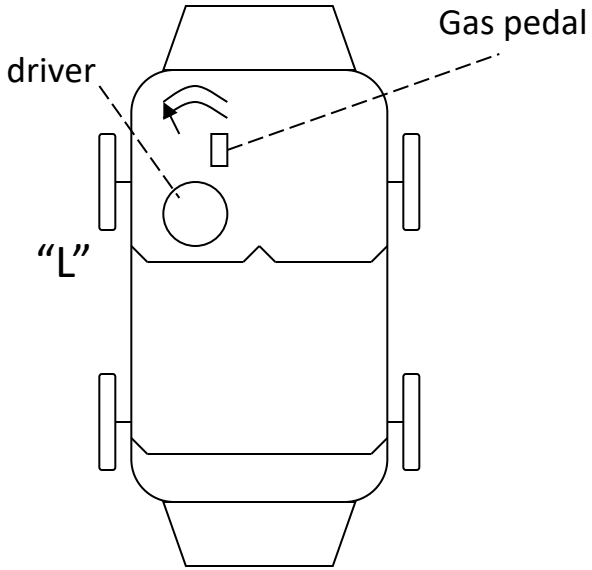


Recap: Broken Symmetry and Unobservables: Parity



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

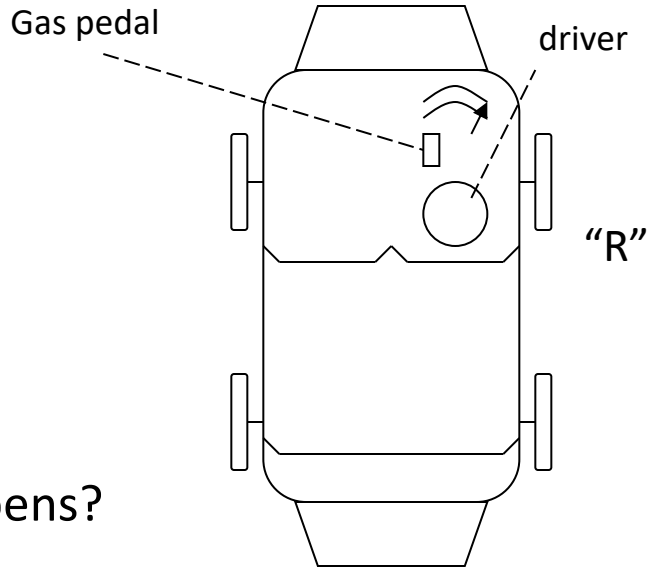
A "gedanken" experiment: consider two perfectly mirror symmetric cars:



"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

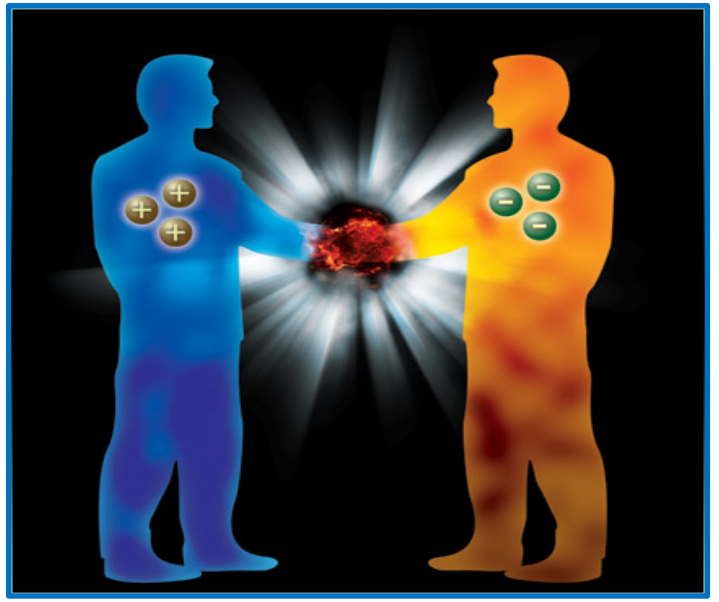
Person "R" gets in, starts, ….. What happens?



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

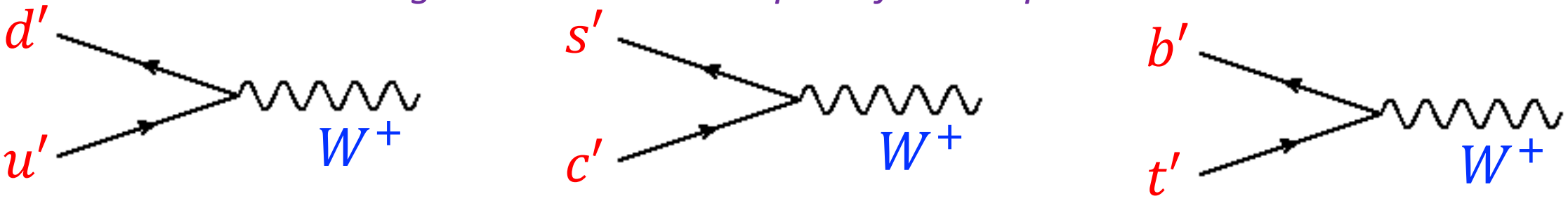
- Weak Interaction is 100% parity violating.
  - Wolfgang Pauli: *"I cannot believe God is a weak left-hander."*


Wolfgang Pauli

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

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

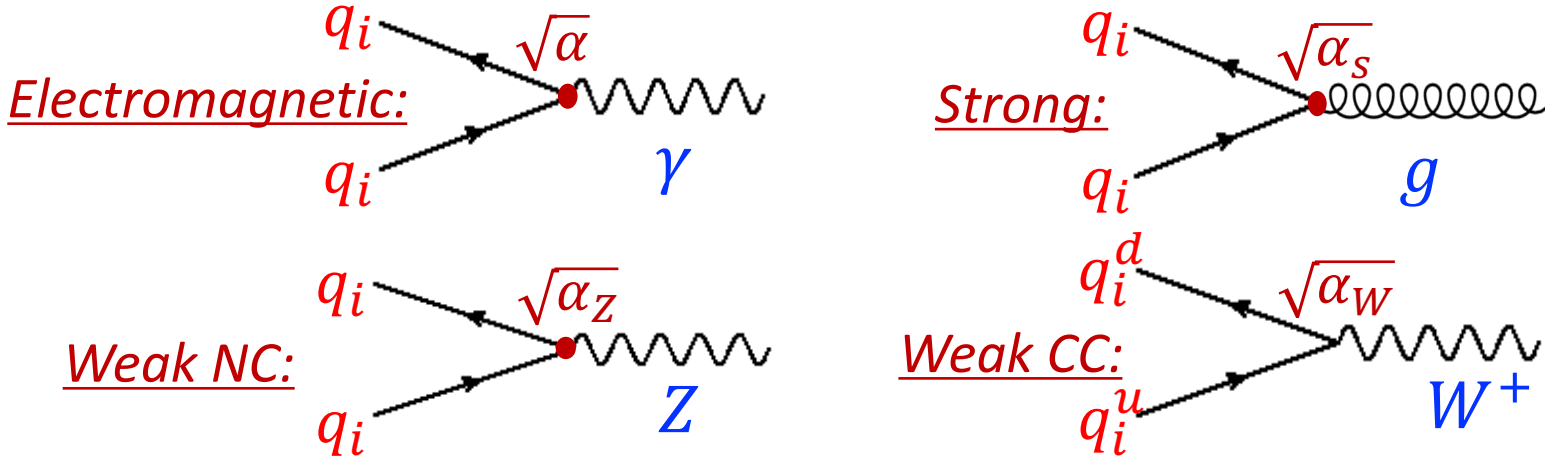
- Flavour universality: *identical interactions* in three generations.
  - In fact: *how to distinguish a massless d' quark from s' quark?*



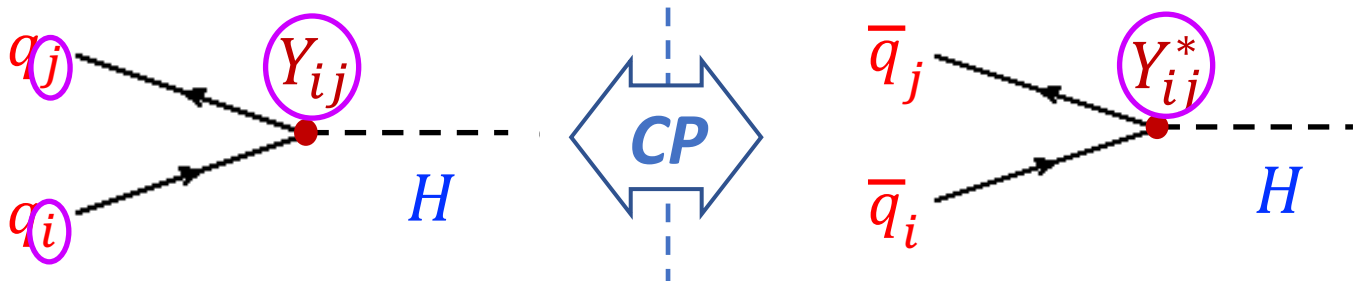
- There is *no CP violation* in these massless interactions
  - What happens when particles acquire mass?

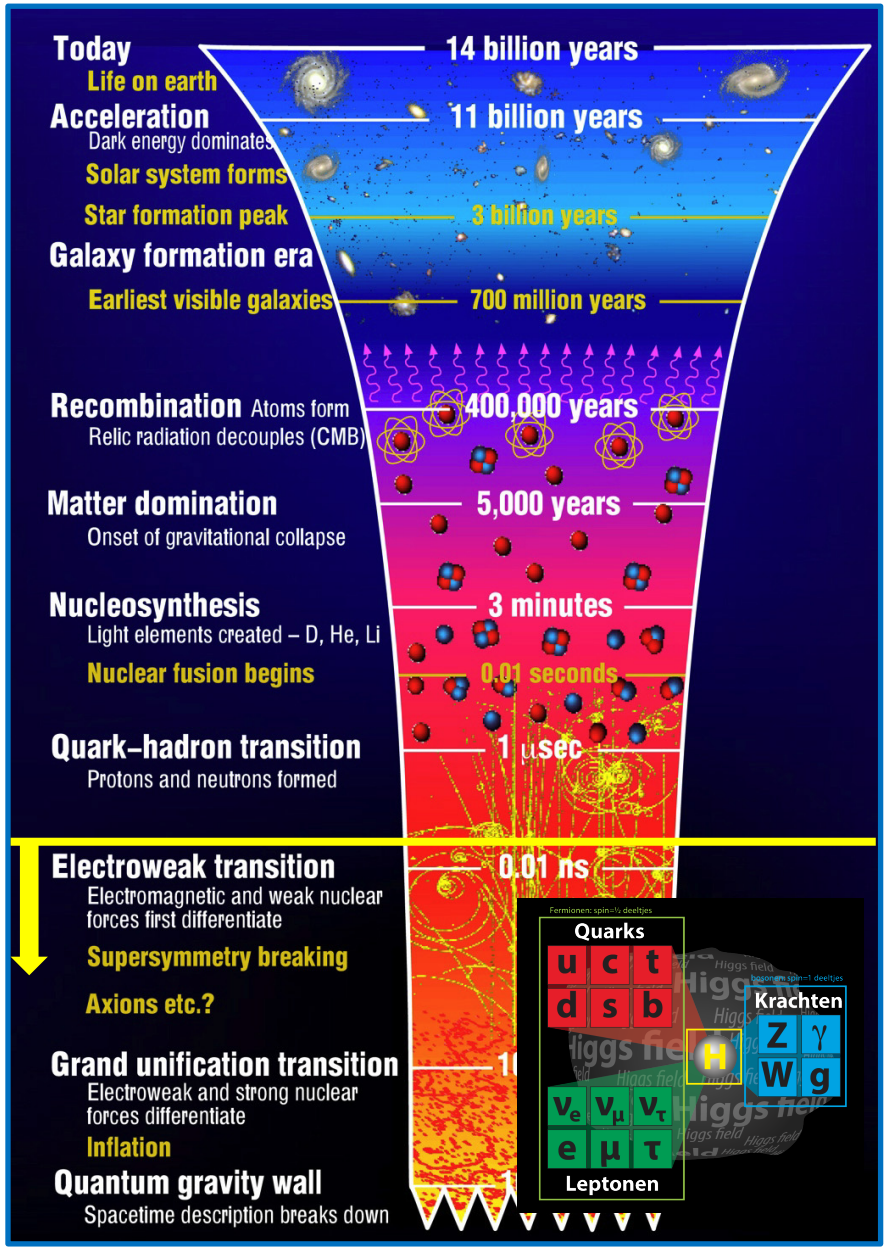
Recap: Flavour Universality in very Early Universe

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



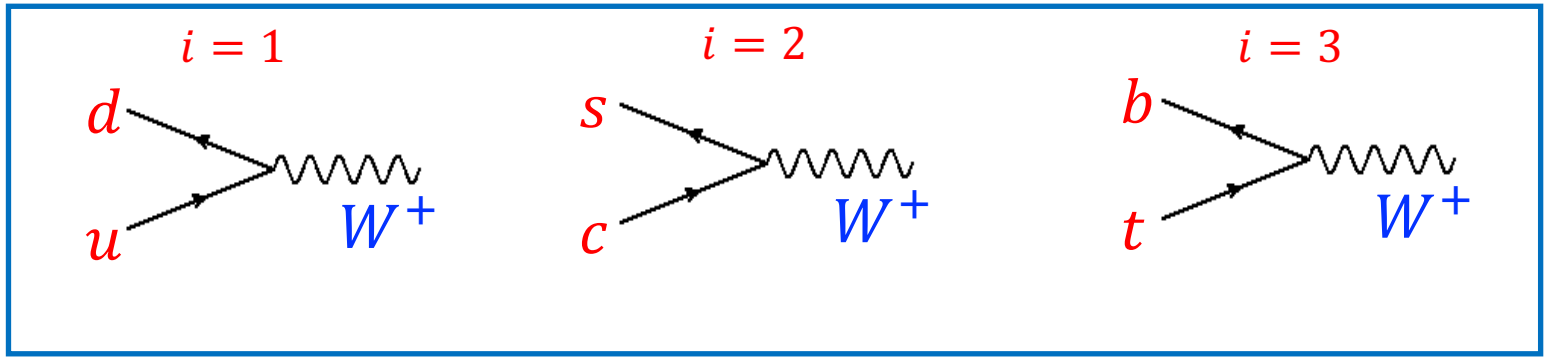
- Universality violation: Higgs !
  - Higgs coupling is *not universal*, and mixes generations
  - Complex couplings: allows for CP Violation!





Recap: Flavour Universality

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



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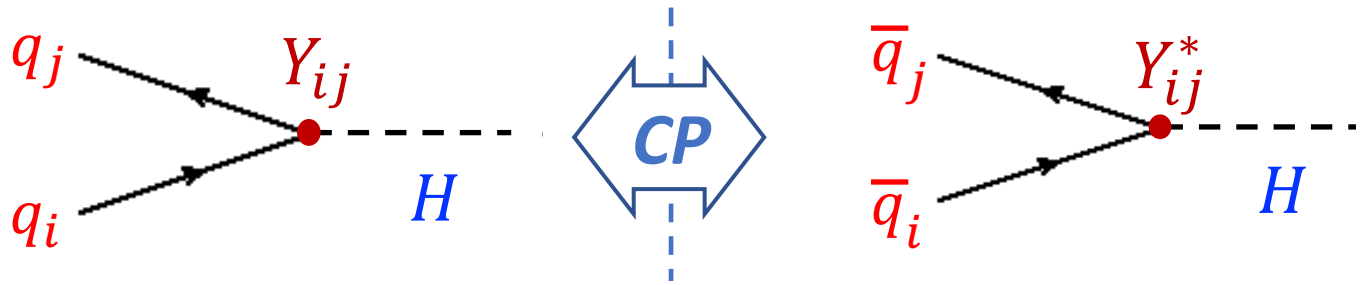
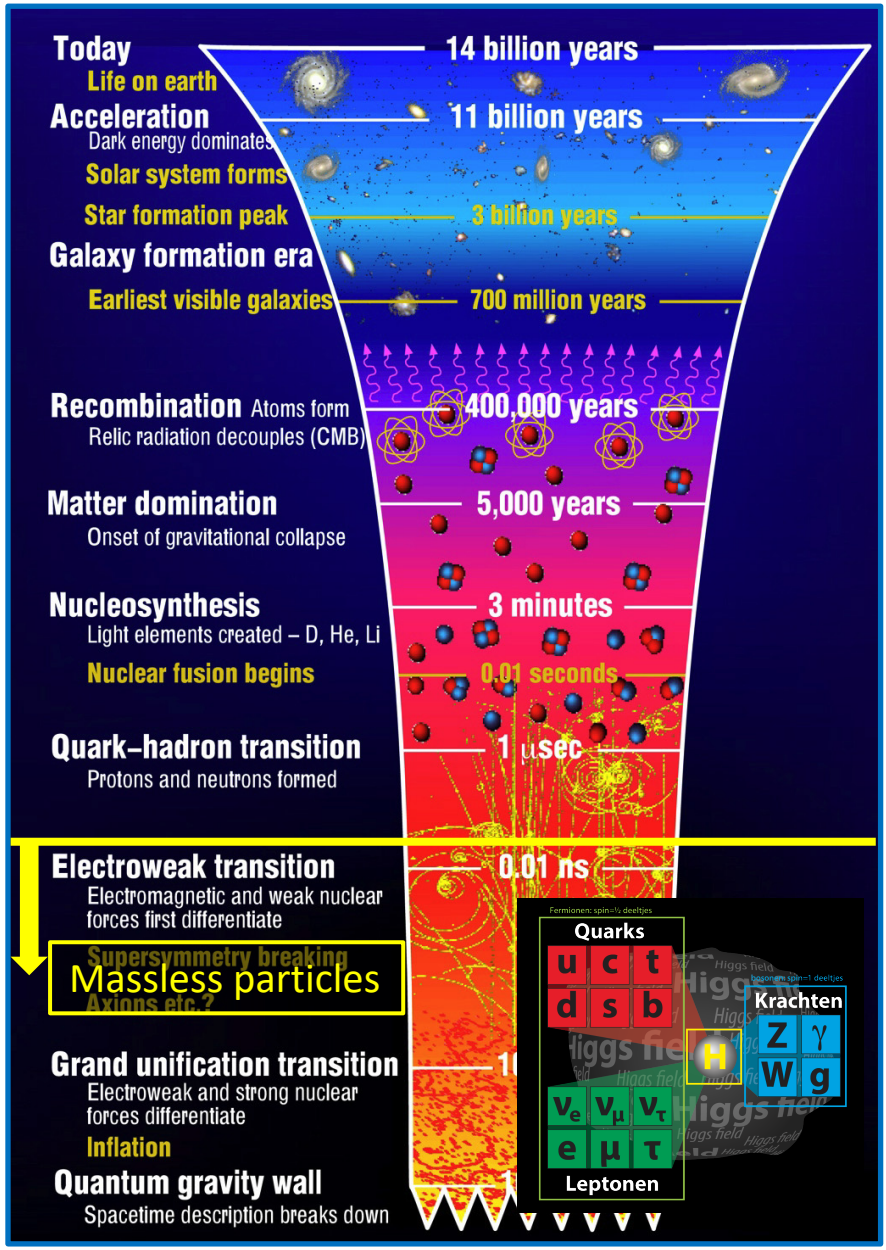
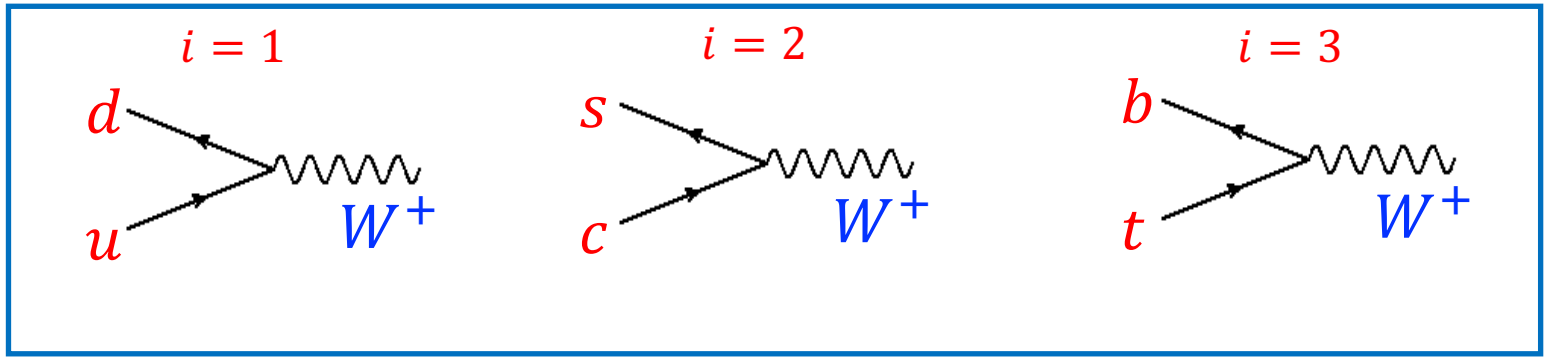


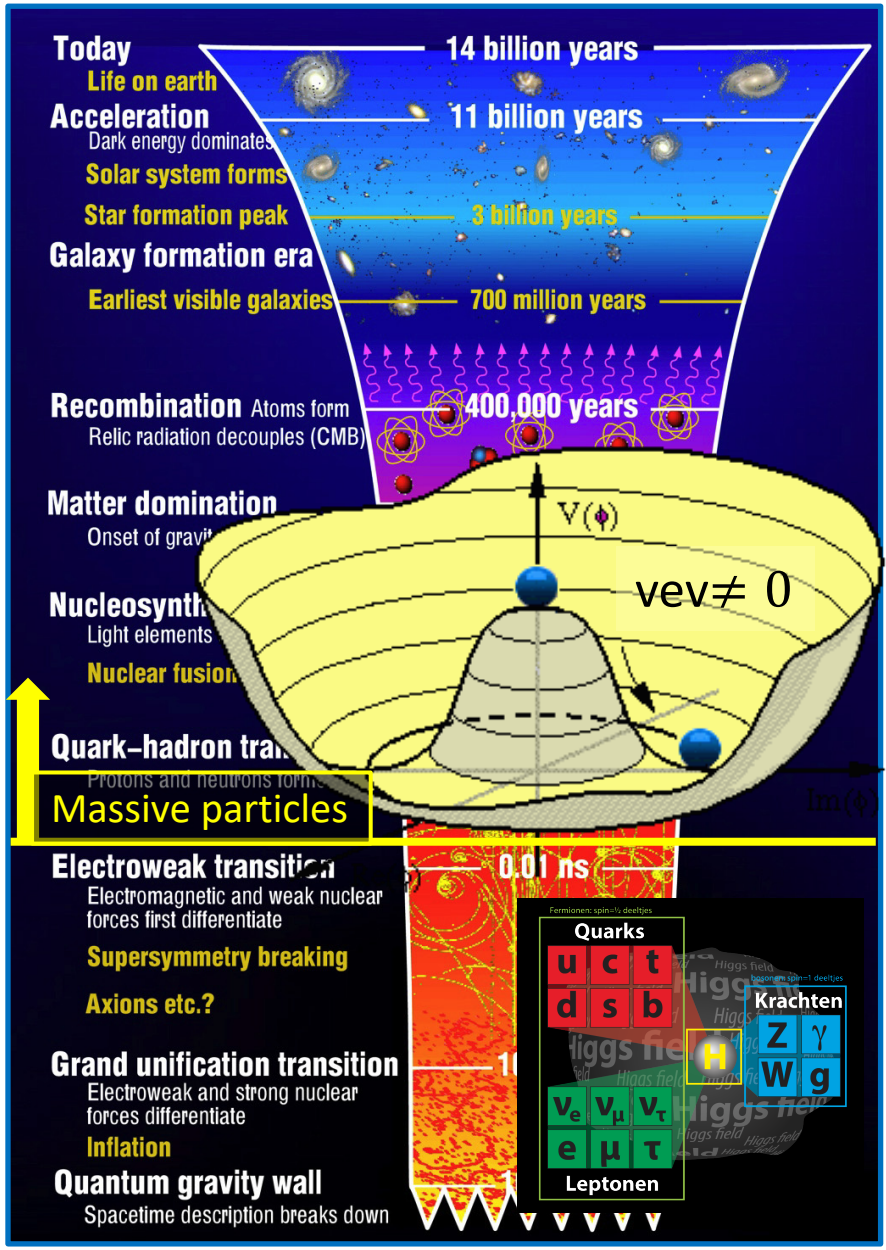


Recap: Flavour Universality → Symmetry Breaking

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

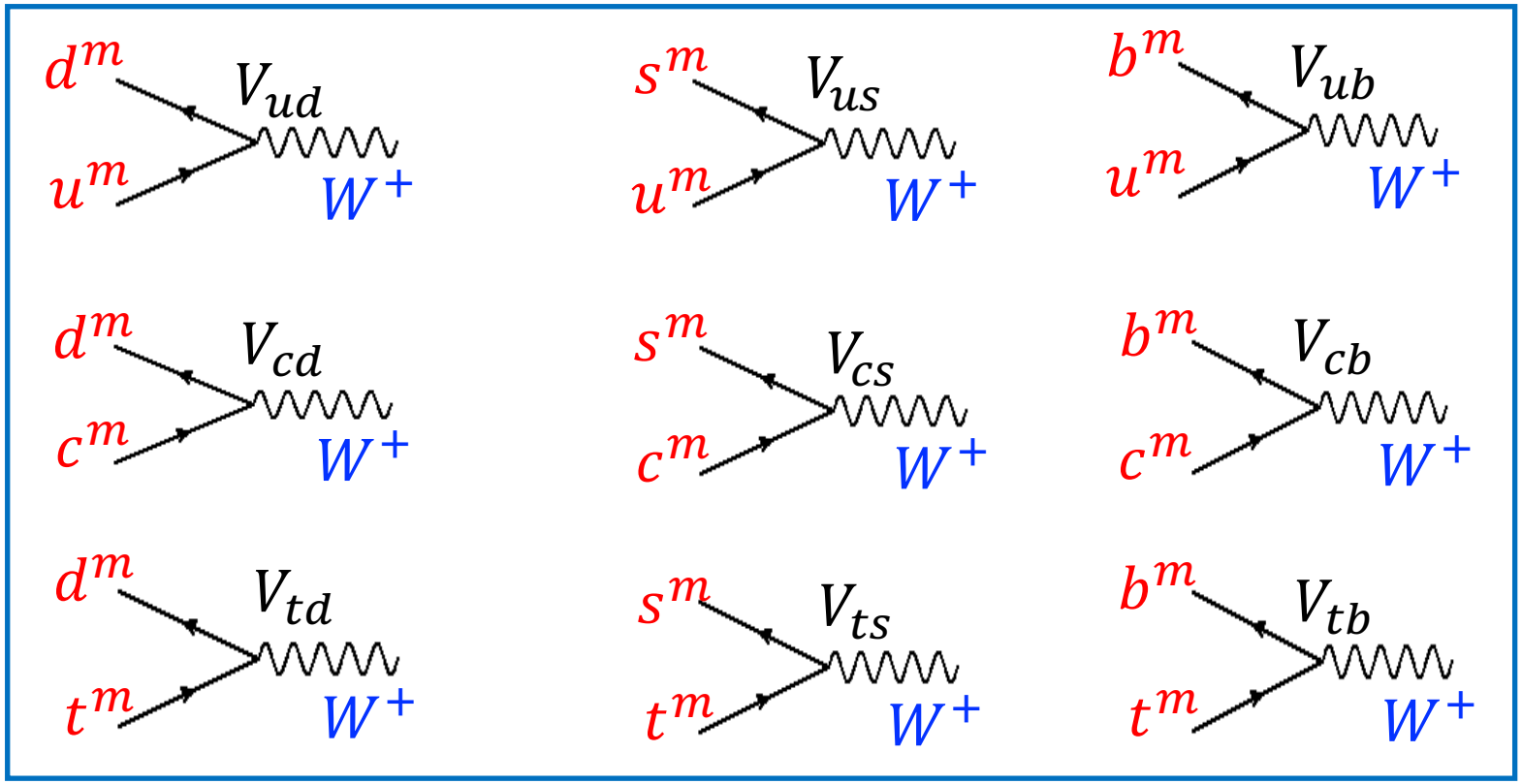


- Higgs: redefines quark states in mass eigenstates: $(i \leftrightarrow i)$



Recap: Flavour Universality → Symmetry Breaking → Flavour Mixing

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



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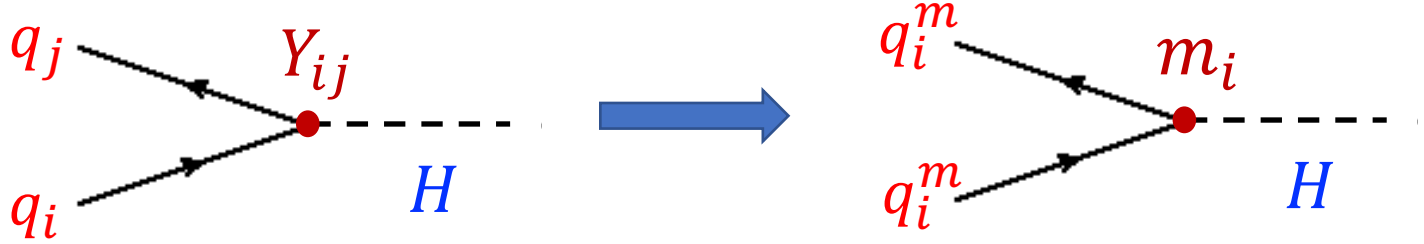
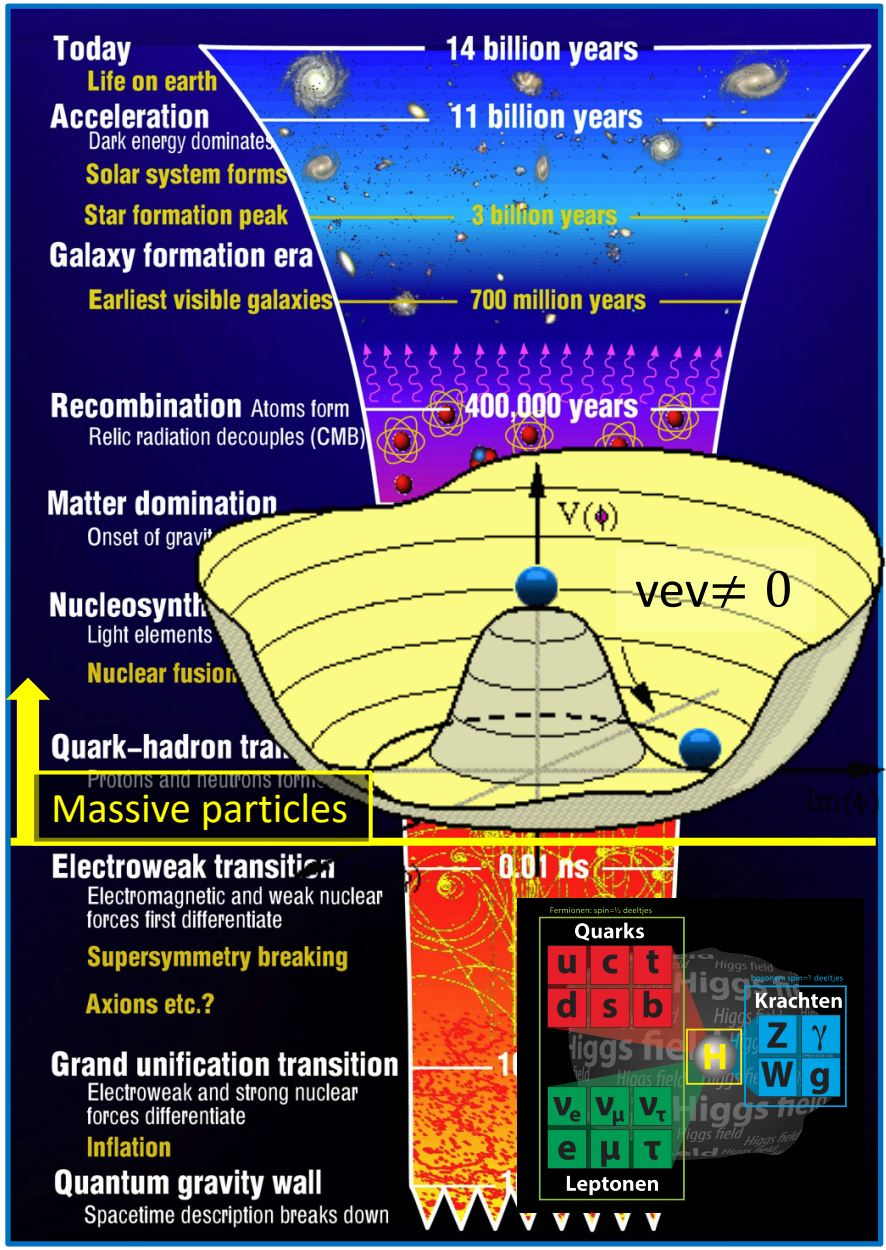
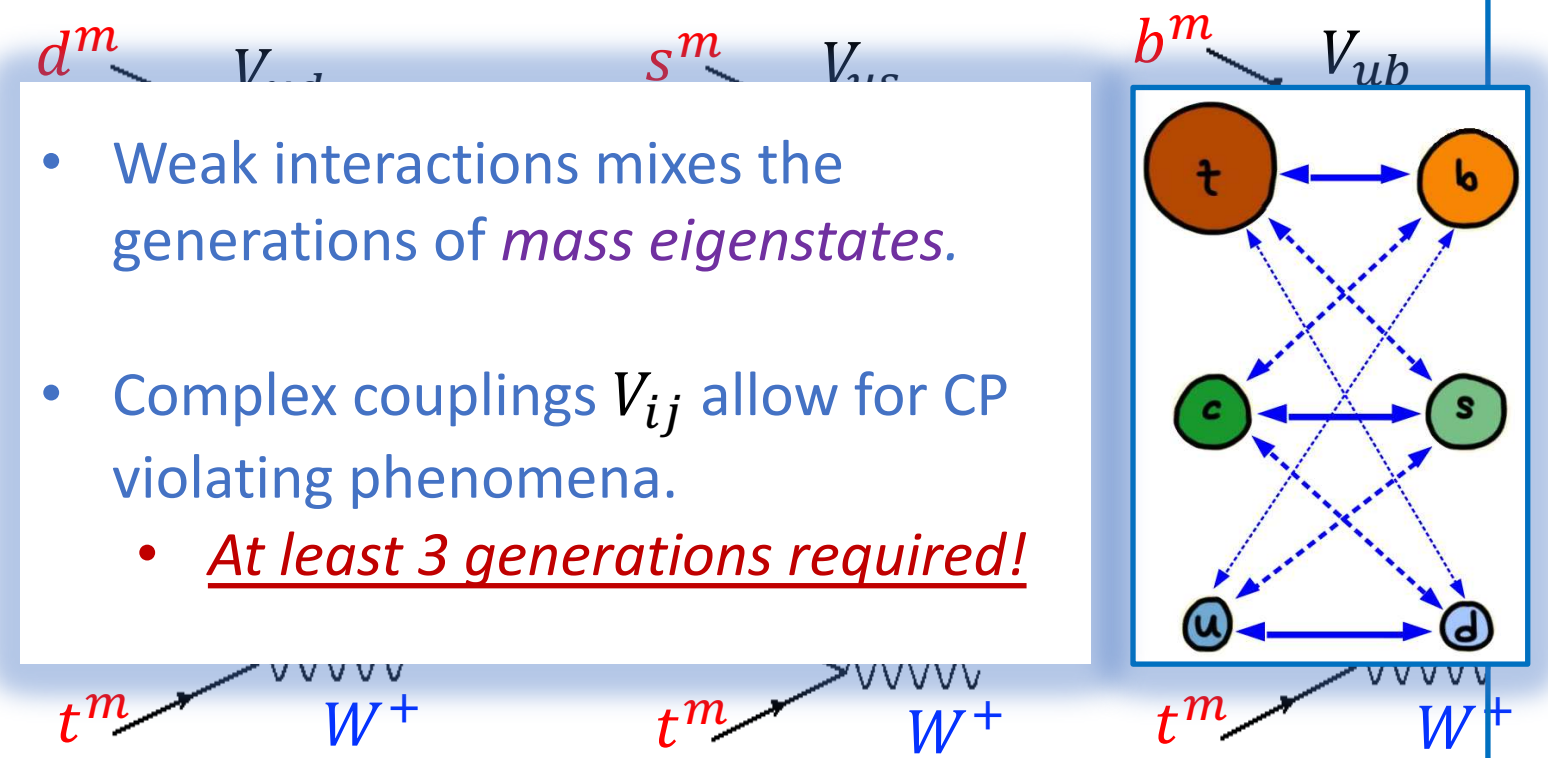




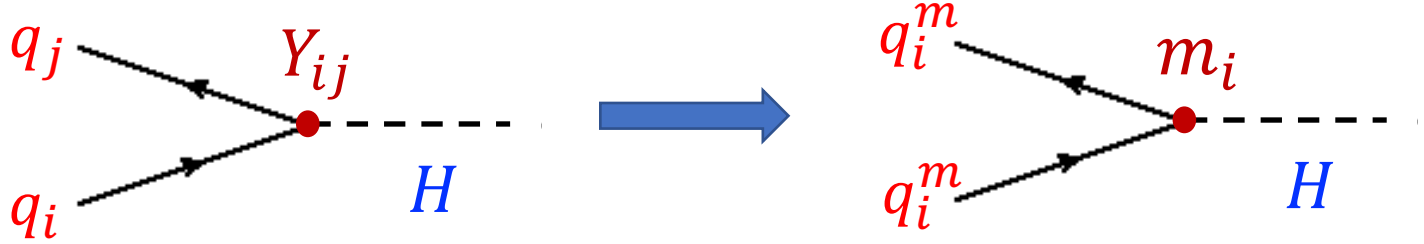
Recap: Flavour Universality → Symmetry Breaking → Flavour Mixing

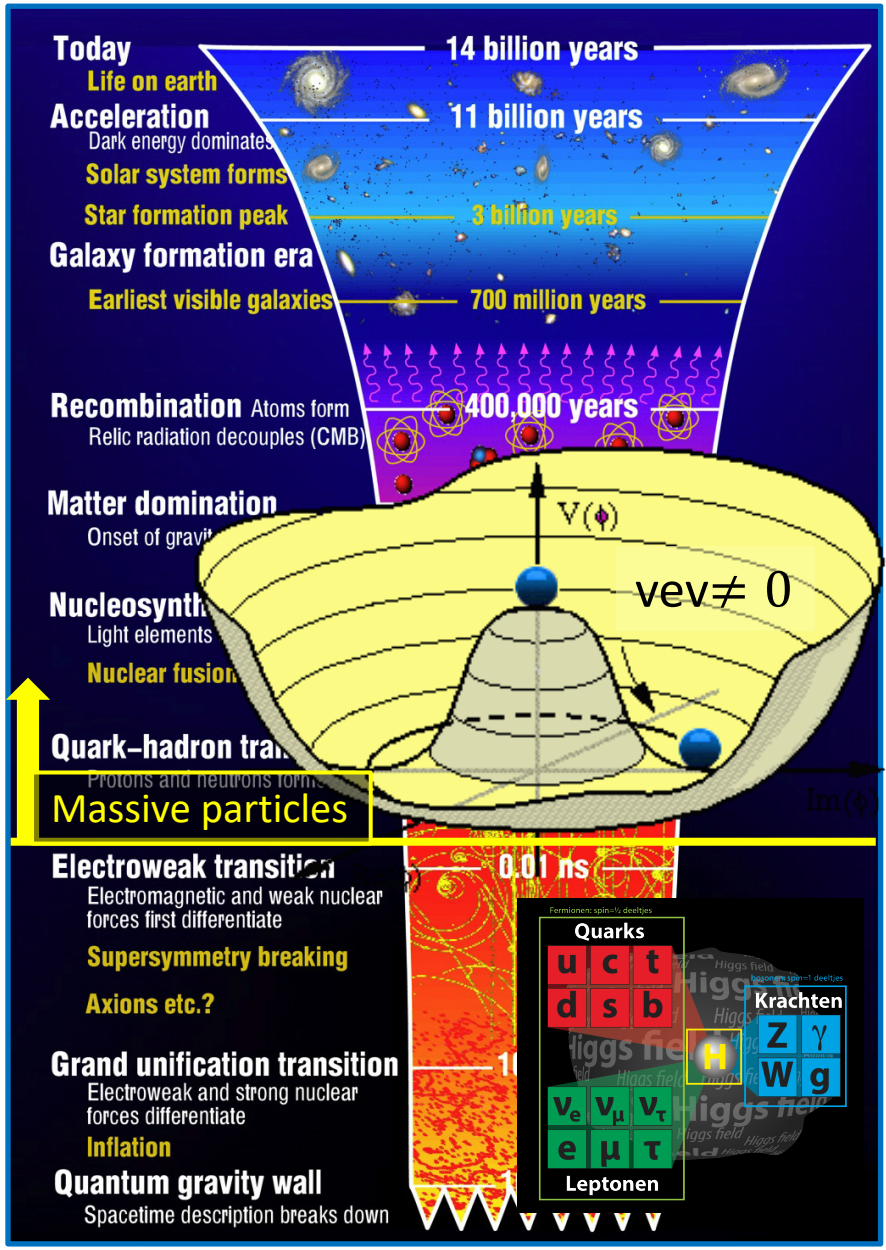
- Weak charged current interaction:



- 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:





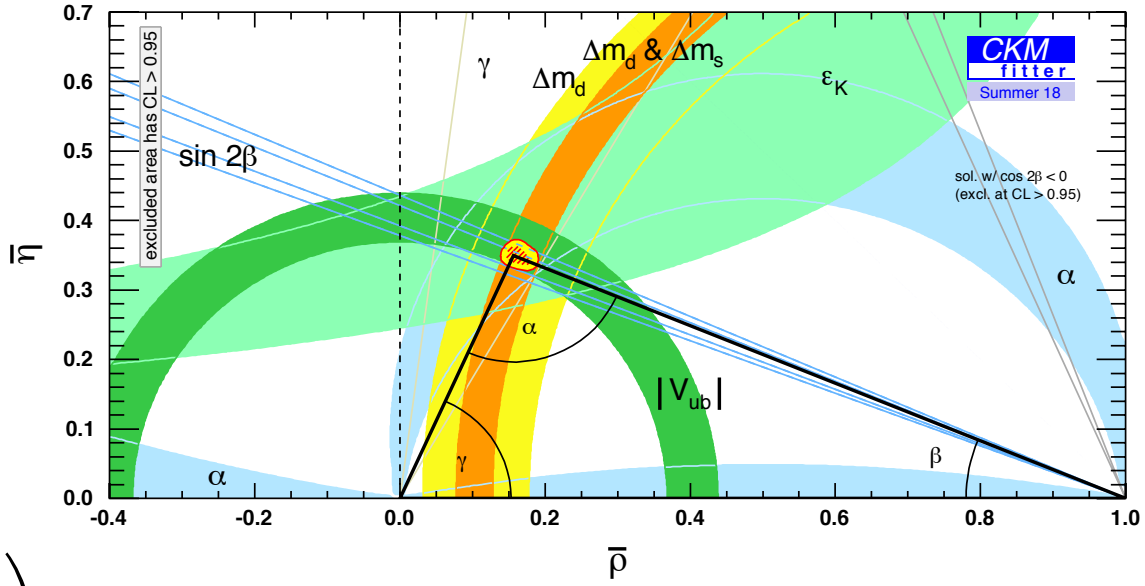
Recap: The CKM matrix and unitarity triangle

- 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:

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

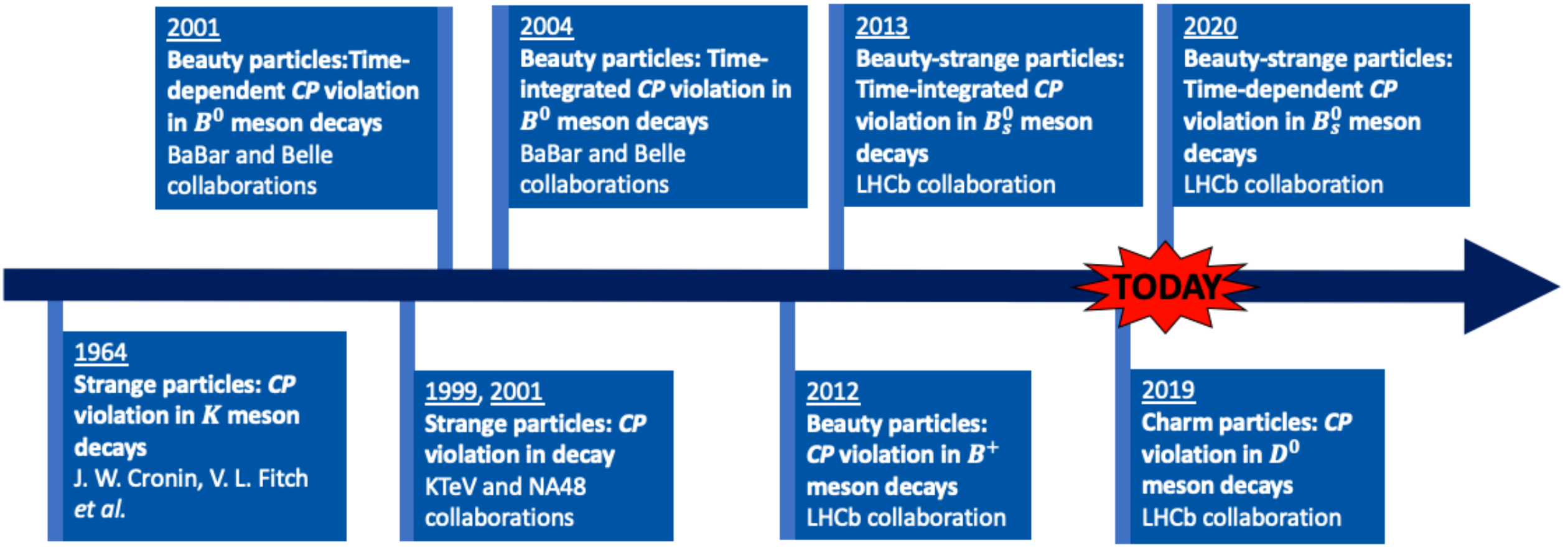


- Wolfenstein parametrization:

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

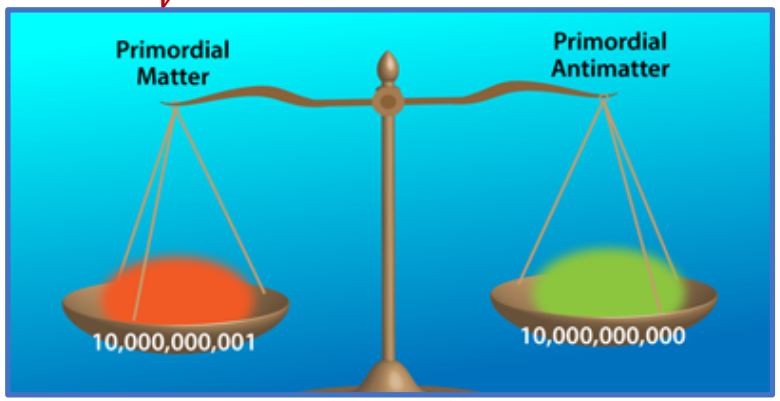
- CP Violation:
  - Non-zero unitary phases
  - Triangle surface ≠ 0
    - Jarlskog invariant

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: $\frac{\Delta n_B}{n_\gamma} \approx \underline{10^{-10}}$

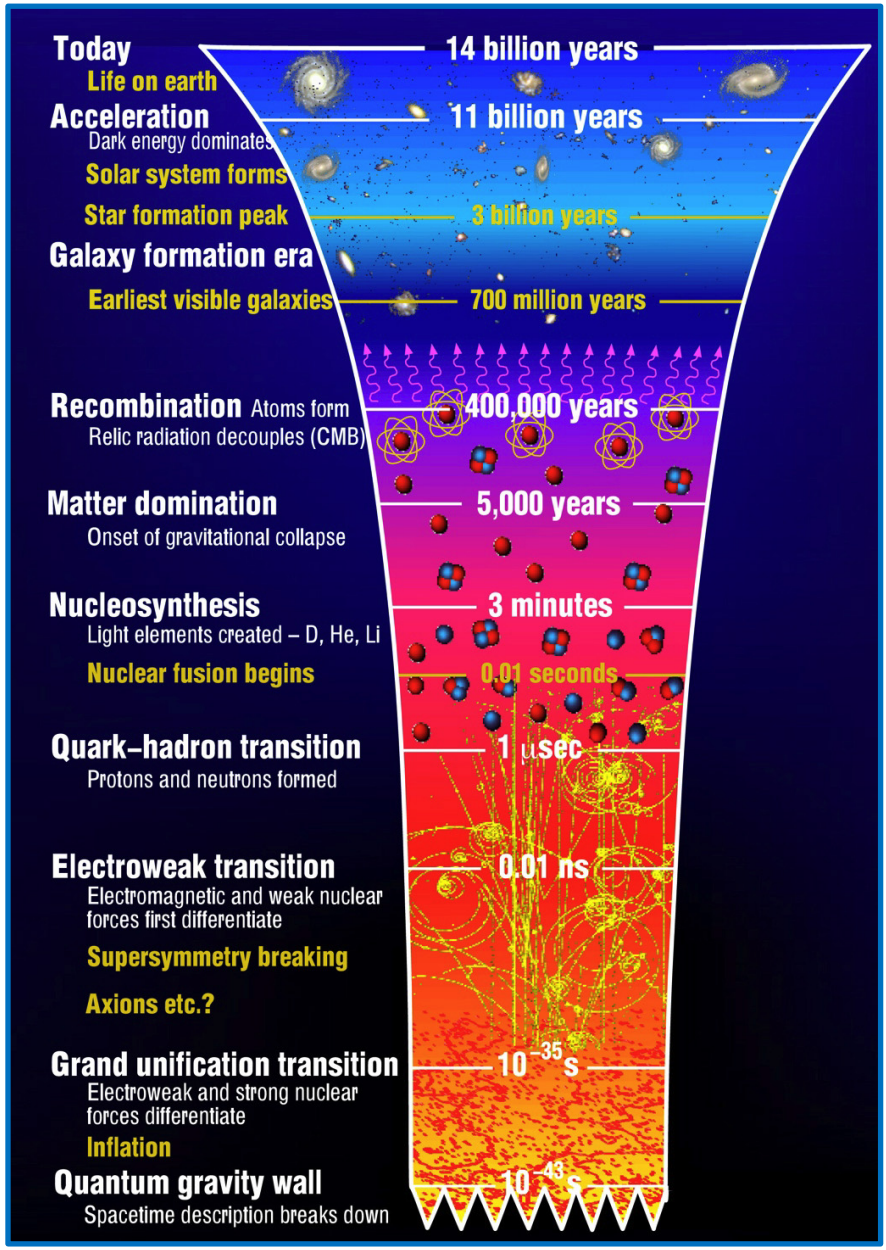


- Jarlskog criterion (1987) for ***amount of CP violation in SM***:

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

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

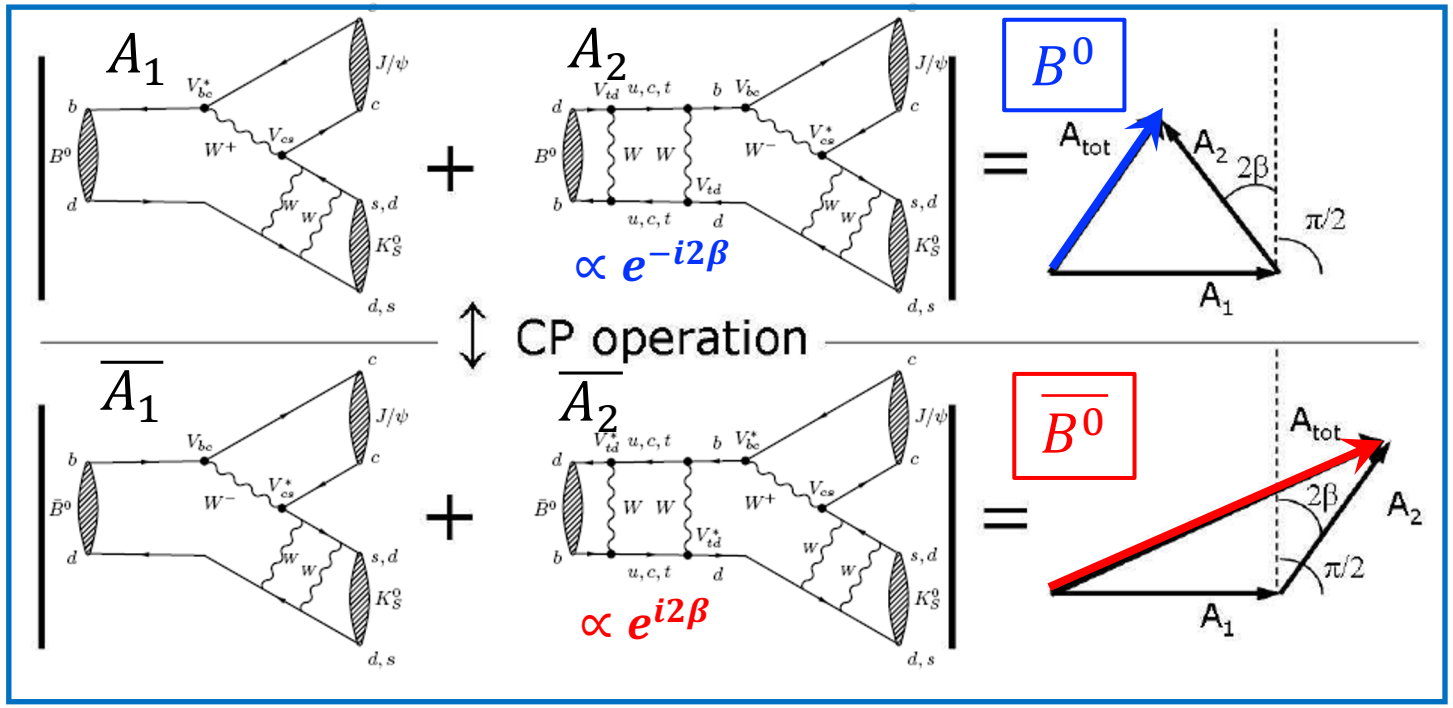
- *Explanation requires existence of **new massive** particles.*

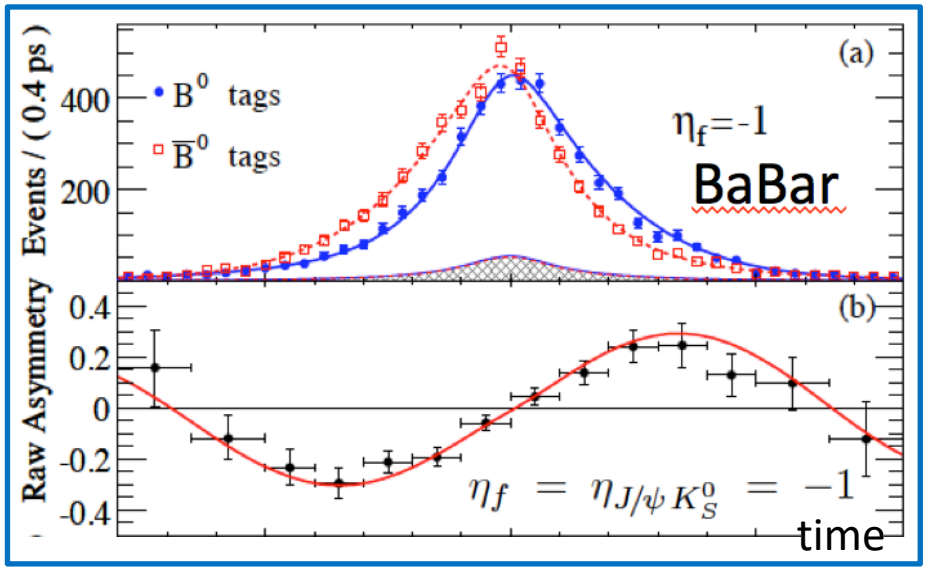


Contents:

CP violation: a quantum interference experiment

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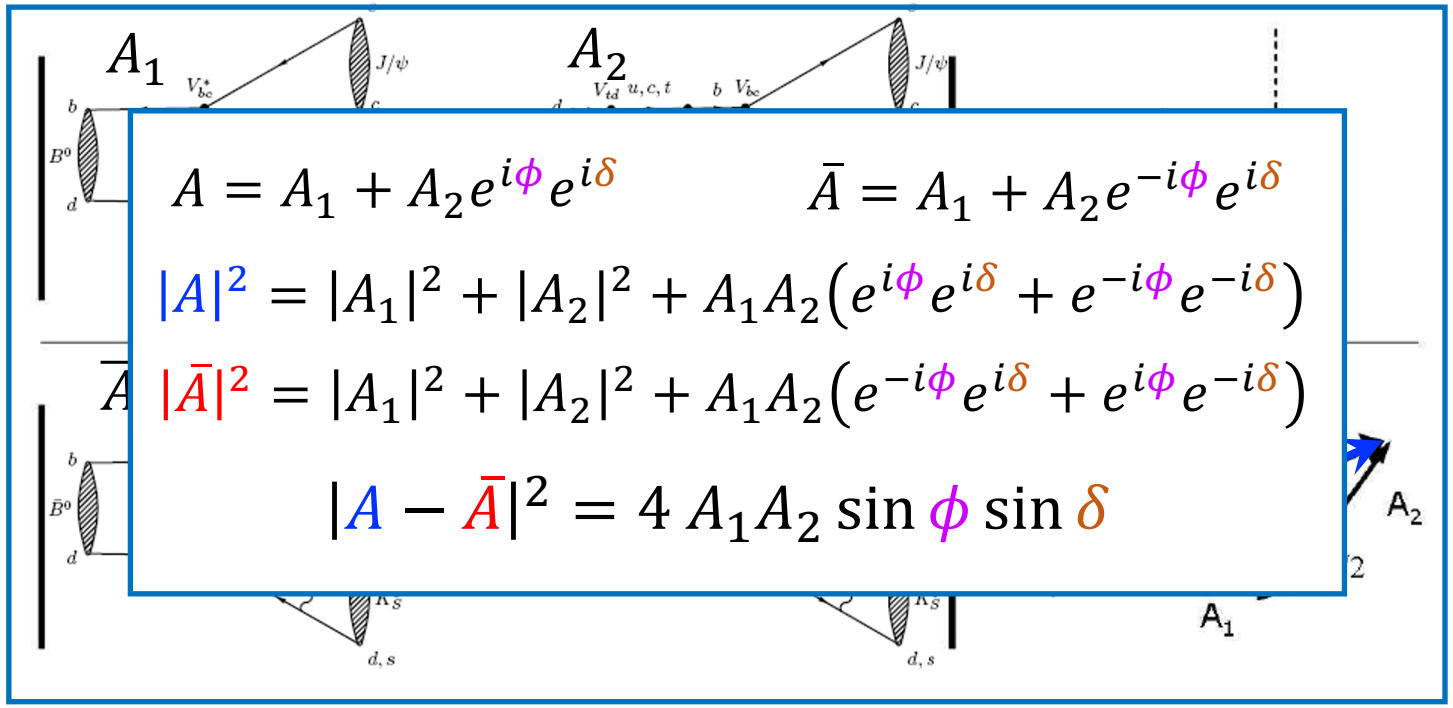
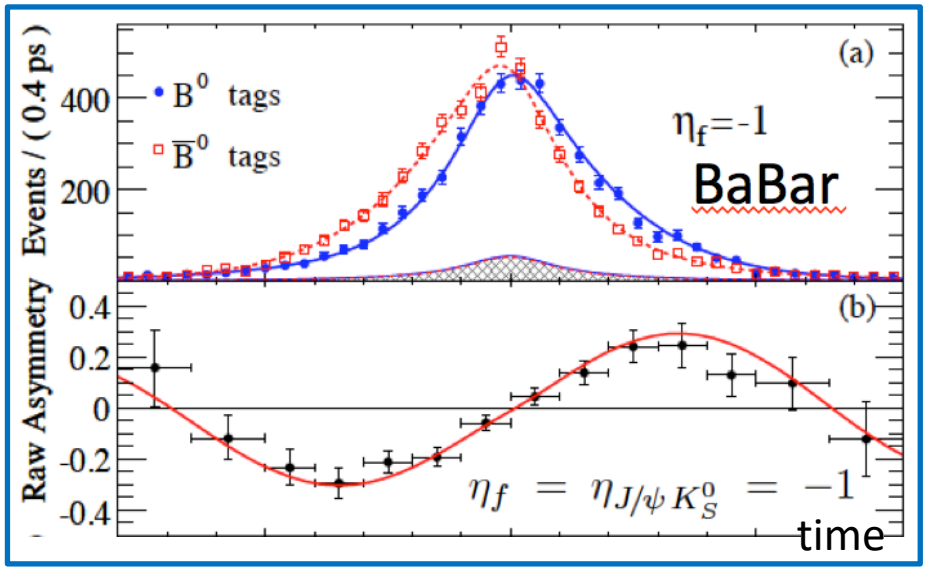


$$A = A_1 + A_2 e^{i\phi} e^{i\delta} \qquad \bar{A} = A_1 + A_2 e^{-i\phi} e^{i\delta}$$

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

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

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



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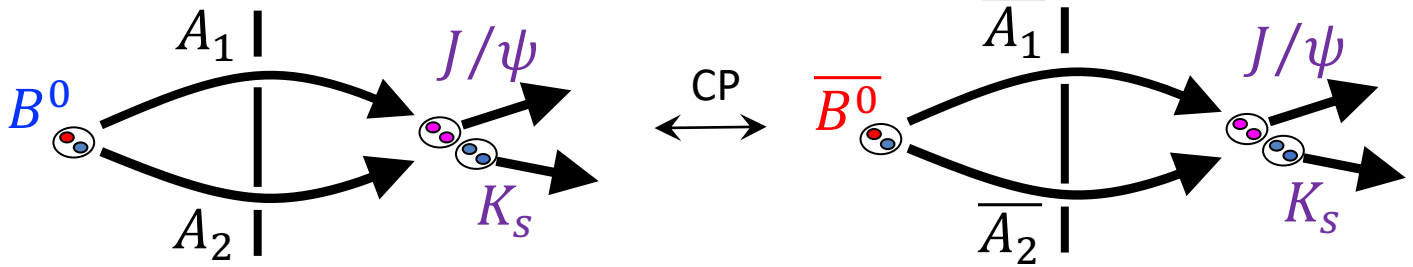
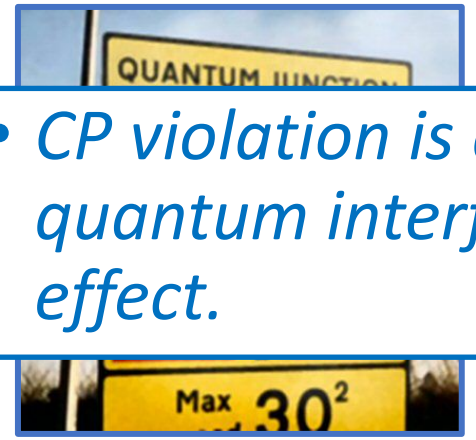
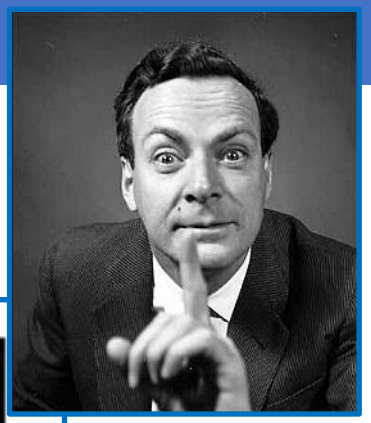


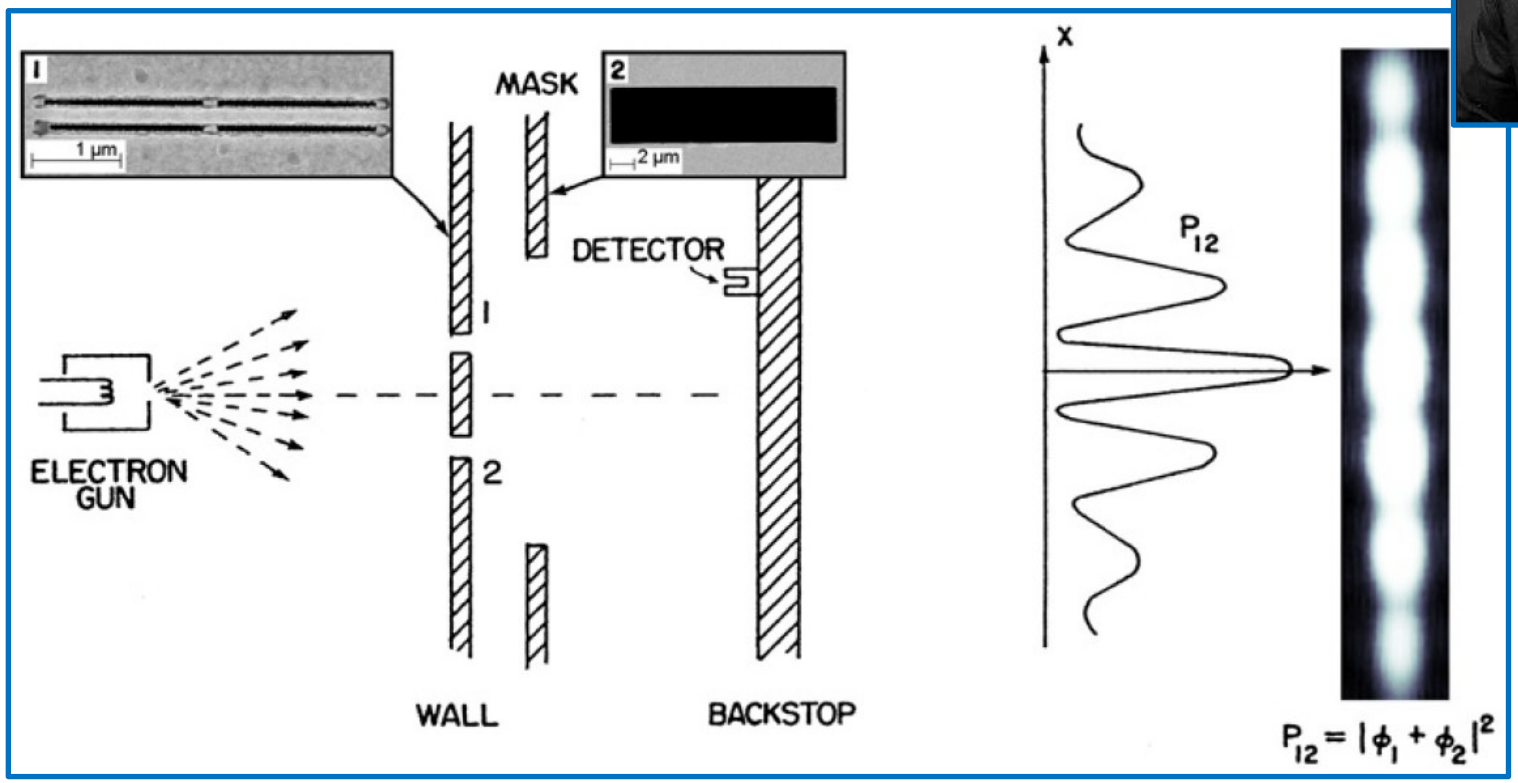


- *CP violation is a pure quantum interference effect.*

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 ± 0.011) x 10^{-3} (PDG)
- Also called: ***CPV in mixing***

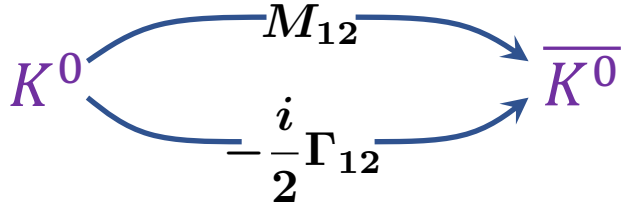
b) *"direct"* CP violation: 1999 (NA48 & KTeV):

- 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***

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

- Also: ***CPV in interference of mixing and decay***
  sin 2β = 0.682 ± 0.019 (PDG)

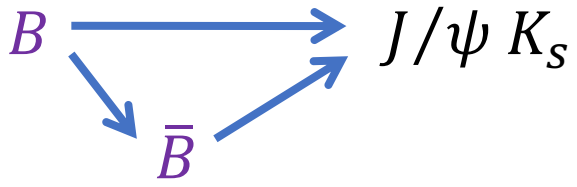
Interfere *dispersive* and *absorptive*:



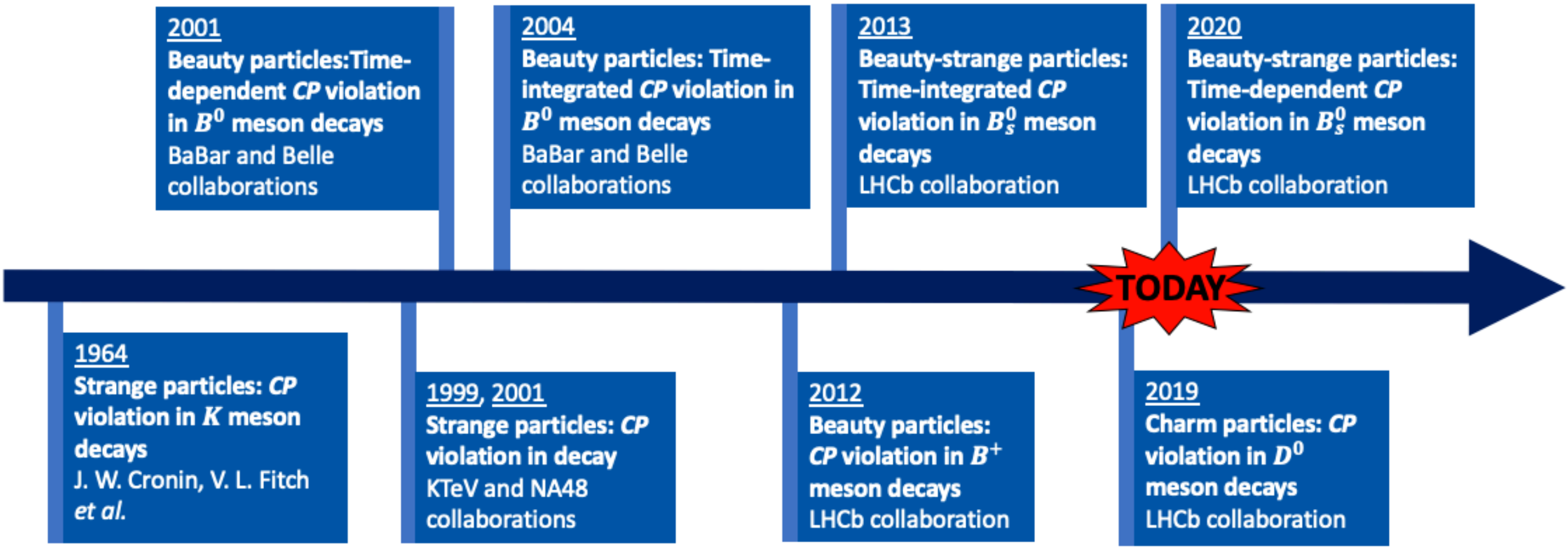
Interfere *Isospin amplitudes*:

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

Interfere *direct and mixed*:



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



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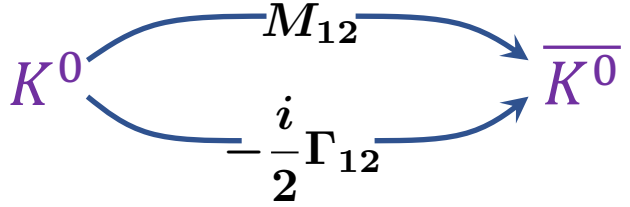


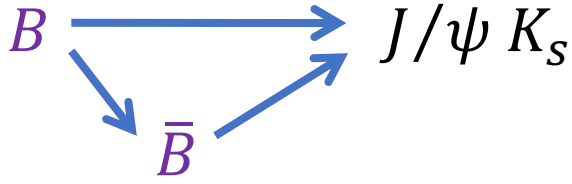
All CP violation processes result from quantum interference including three generations of fermions.

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”

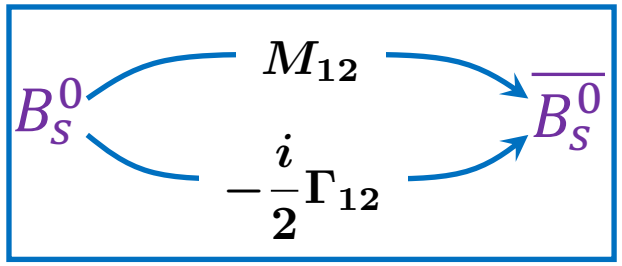
“WTF?”

Moonshine

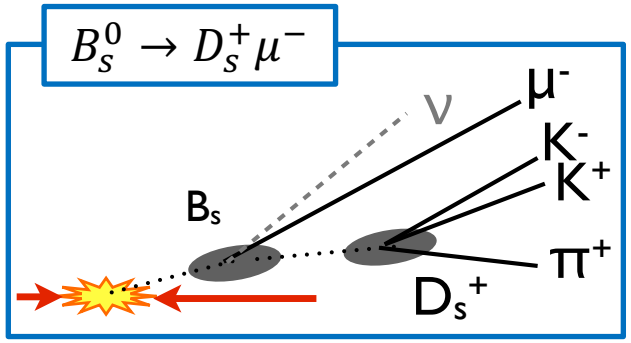
→ Interference experiments lead to interesting effects! (Constructive or destructive??)

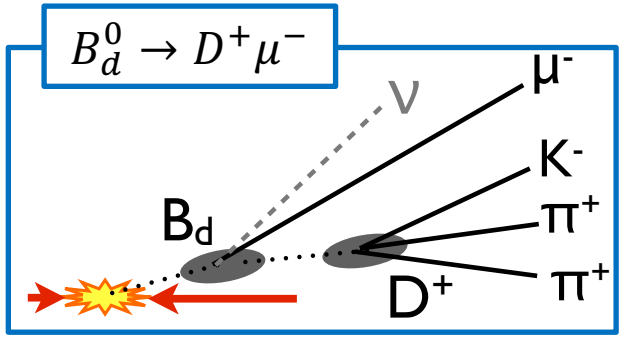
Type-1: CP violation *in mixing*: $a_{SL}(B_d)$ en $a_{SL}(B_s)$

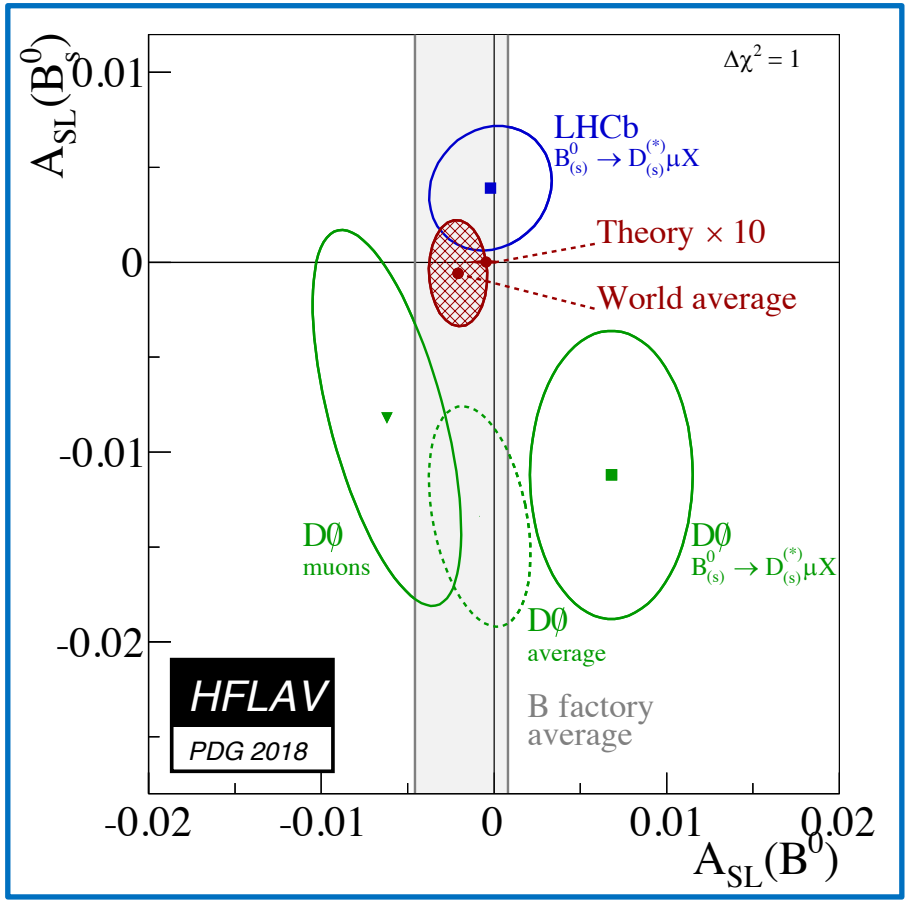
- Interfere *dispersive* and *absorptive* amplitudes ("indirect"):



$$\mathcal{A}_{meas} = \frac{\Gamma_{(B_s^0 \to D_s^- \mu^+)} - \Gamma_{(B_s^0 \to D_s^+ \mu^-)}}{\Gamma_{(B_s^0 \to D_s^- \mu^+)} + \Gamma_{(B_s^0 \to D_s^+ \mu^-)}} = \frac{1}{2}\, a_{SL}(B_s^0)$$







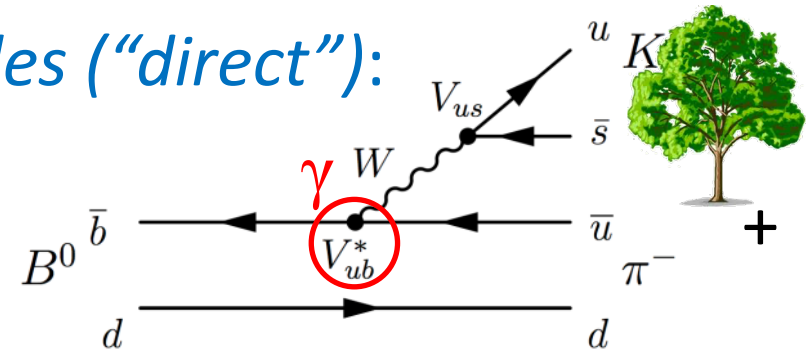
CP violation in mixing *does not happen* in B_d^0 and B_s^0 mesons:

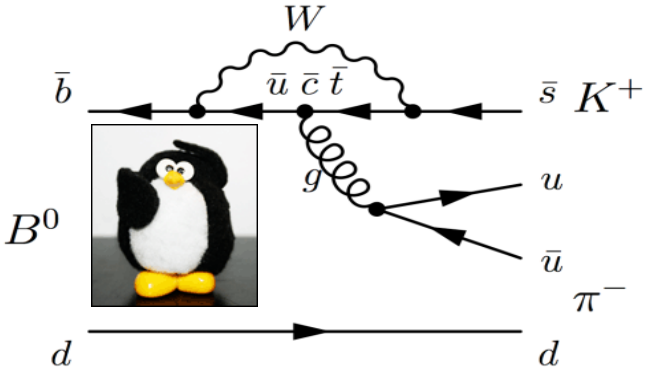
- $B \to \bar{B}$ goes at same rate as $\bar{B} \to B$
- Contrary to ϵ in kaons.

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

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

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

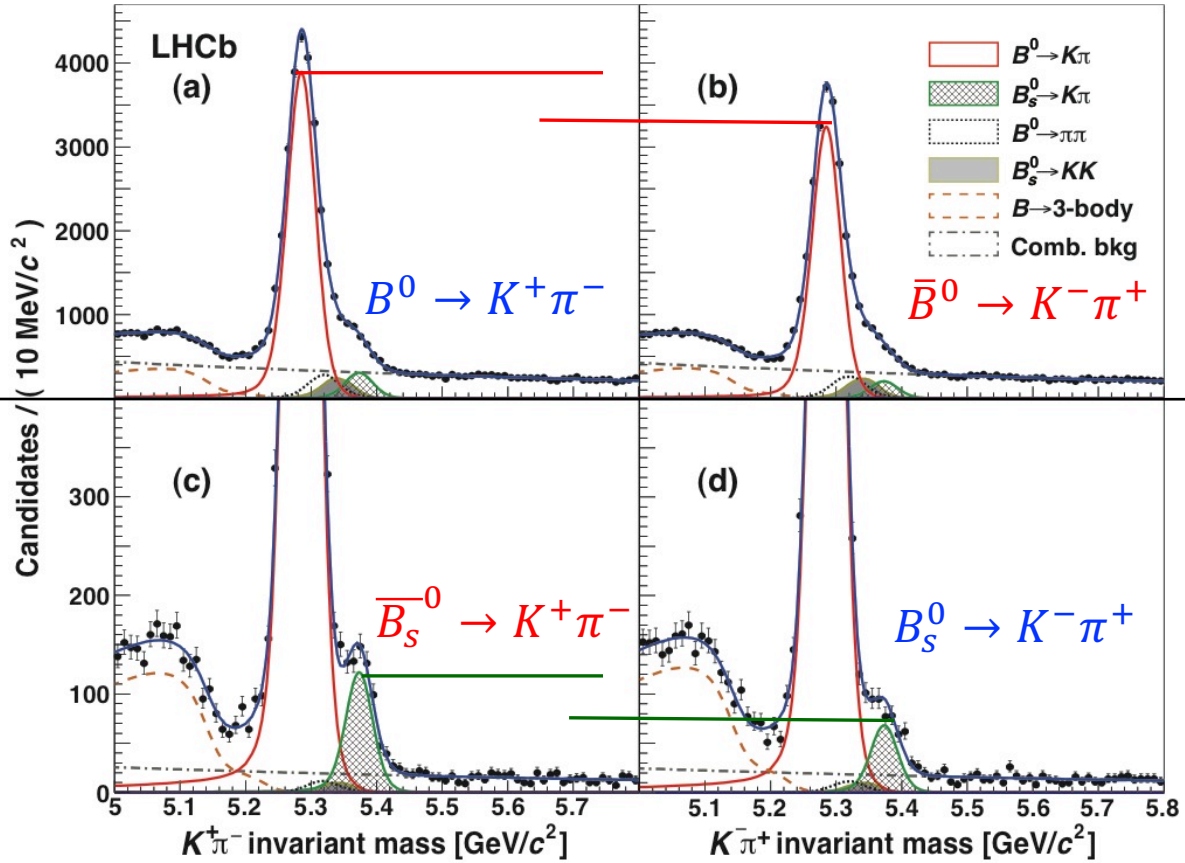




$B_d^0 \to K\pi$

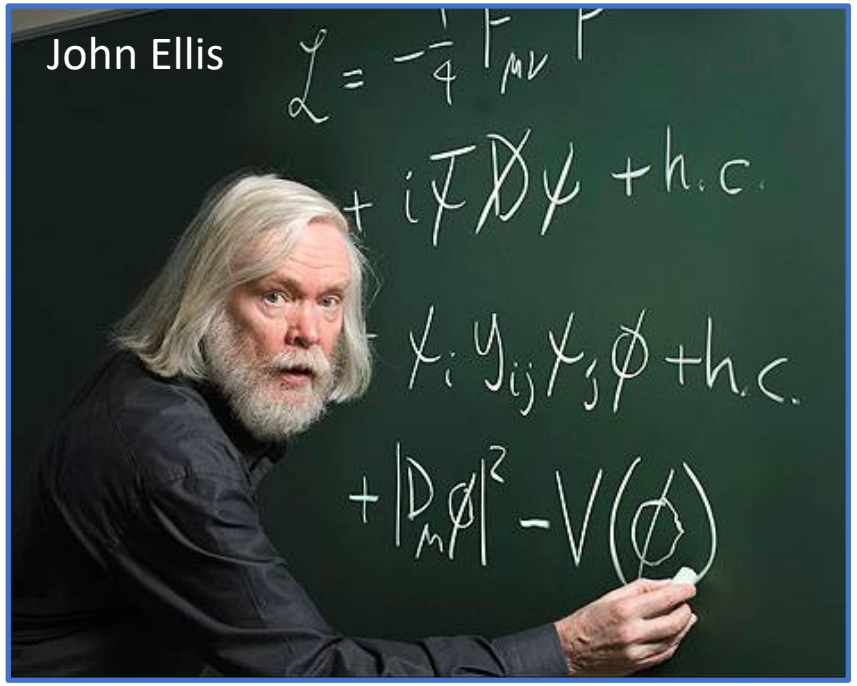
$B_s^0 \to K\pi$

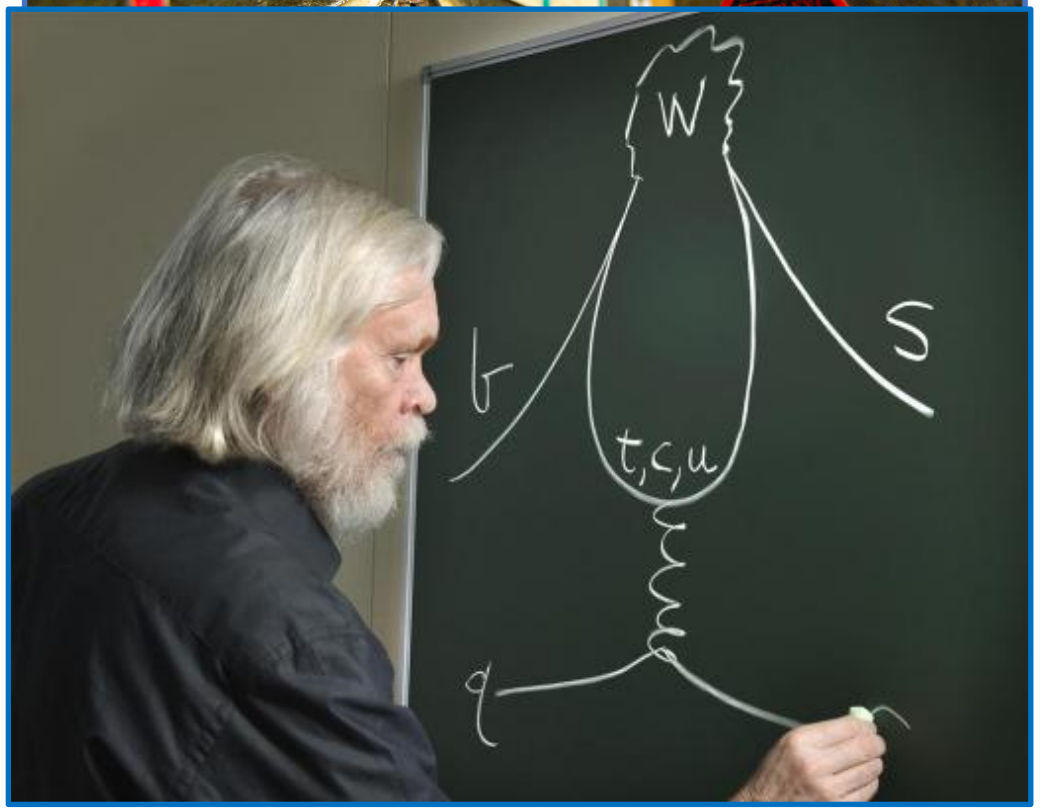
First observation of CP violation in B_s decays

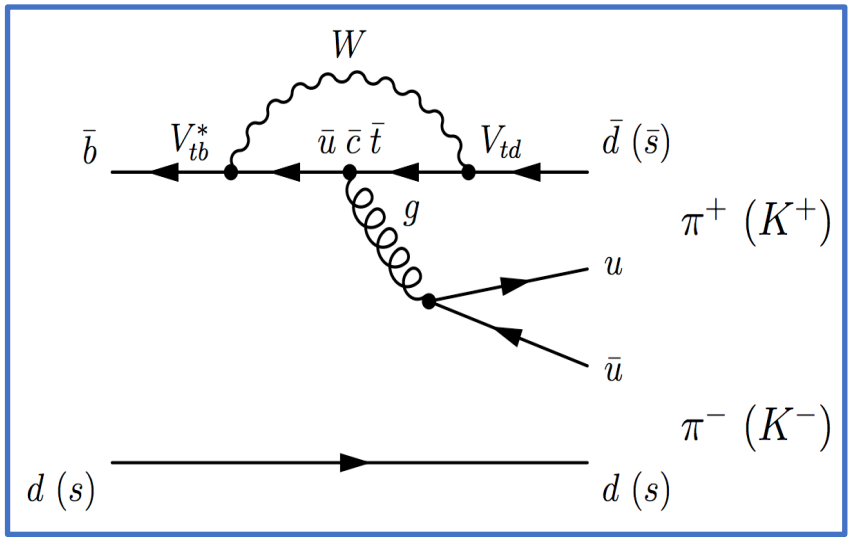


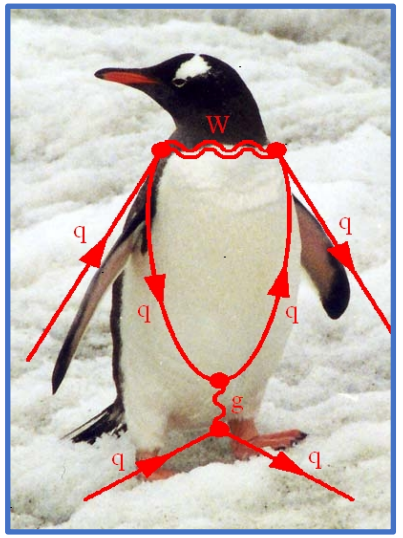
- Quarks from three generations involved
- Large interference
- Large CP violation!
  - Contrary to ϵ' in the kaon system

A story on darts and penguins









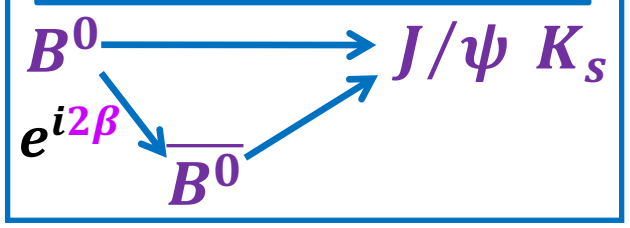
A story on darts and penguins

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

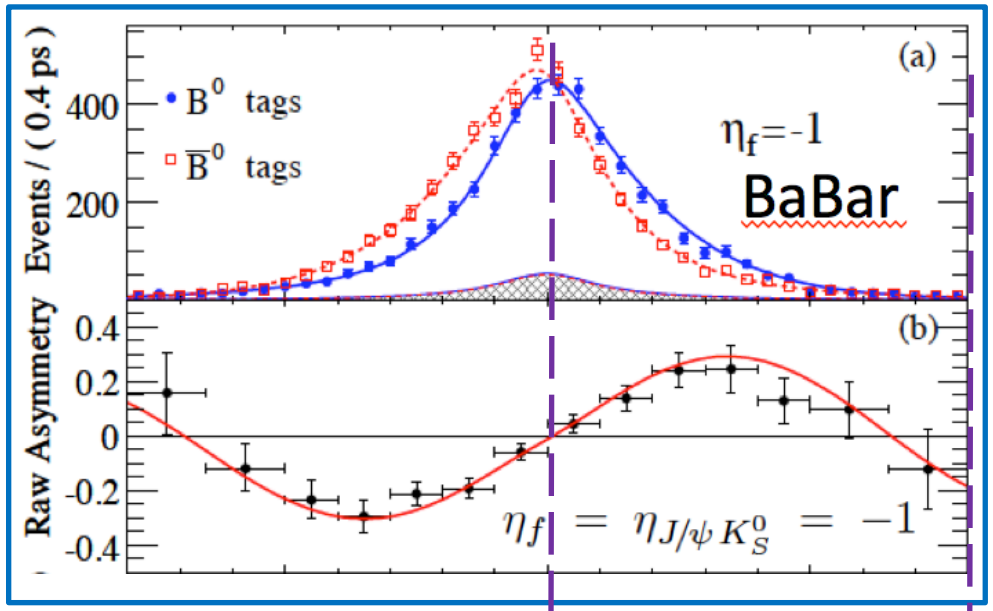
- Interfere *direct* with *mixed* decay ("mixing induced"):

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

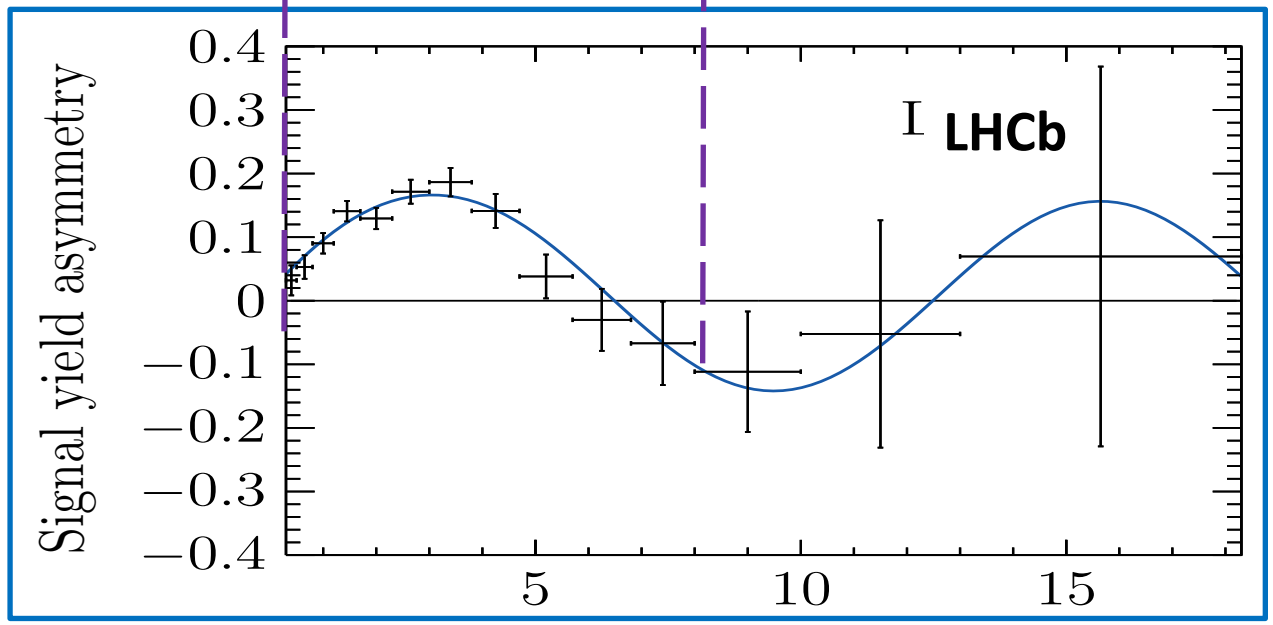
Interfere *direct* and *mixed*



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

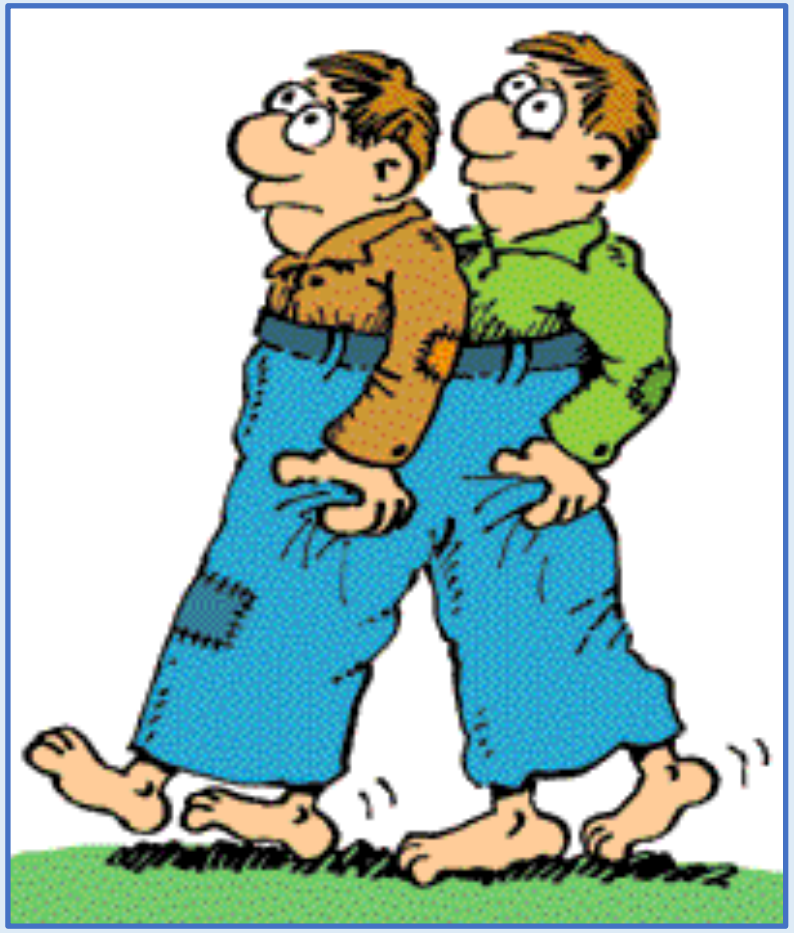


Decay-time dependent CP violation

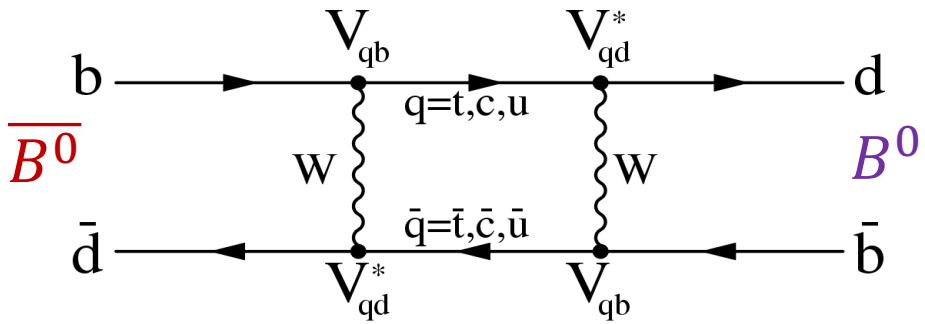


Contents:

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.

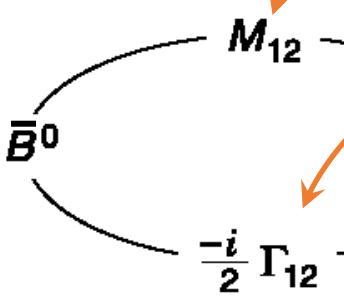


- Time evolution of B^0 and $\overline{B^0}$ described by an effective Hamiltonian

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

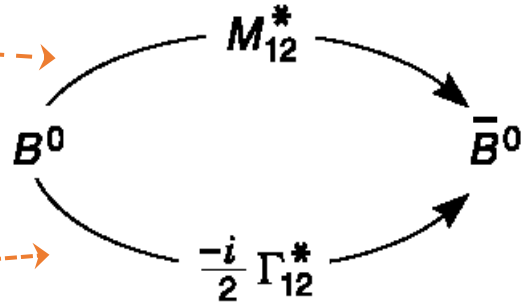
$$H = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

Hermitean Mass-matrix *Hermitean Decay-matrix*



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):

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

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

Masses

Lifetimes

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

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

B^0 Oscillation Amplitudes

For an initially produced B^0 or a $\overline{B^0}$ it then 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 $$g_{\pm(t)} = \frac{e^{-i\omega_+ t} \pm e^{-i\omega_- t}}{2}$$

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

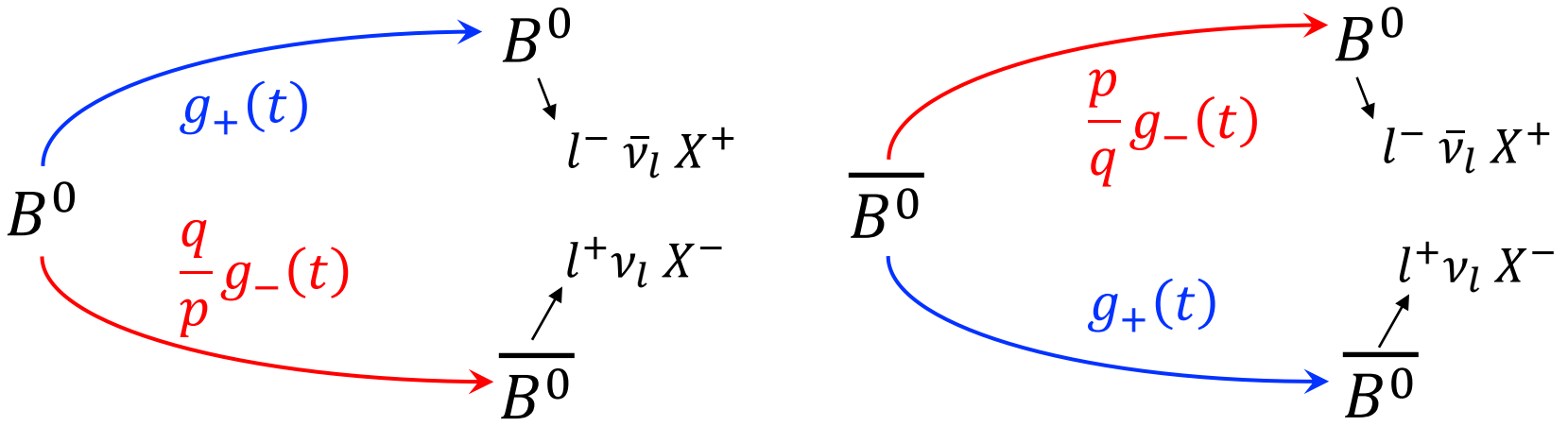
For B^0, expect:
$\Delta\Gamma \sim 0$,
$|q/p| = 1$

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

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

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

B^0 Oscillations



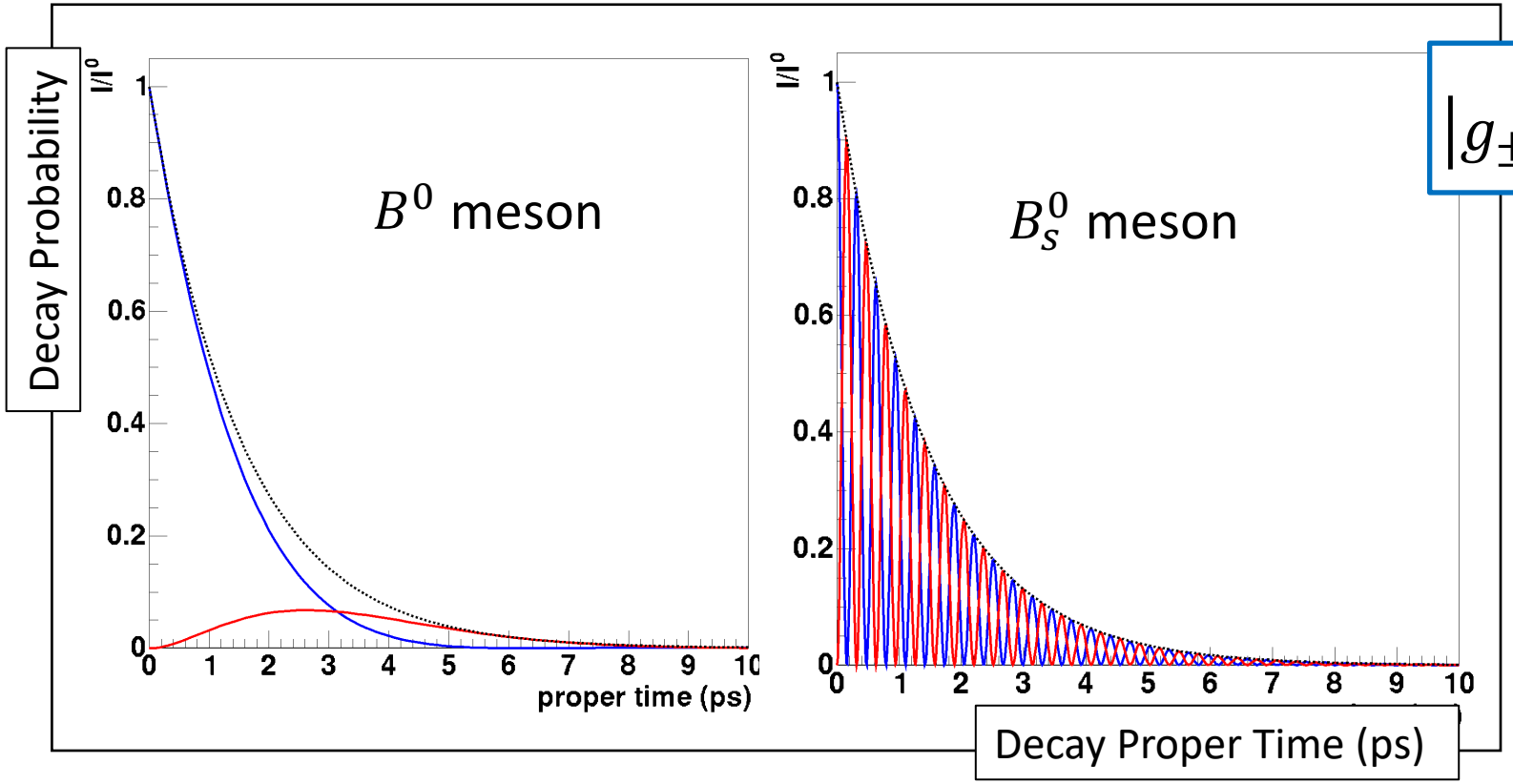
Calculate:

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

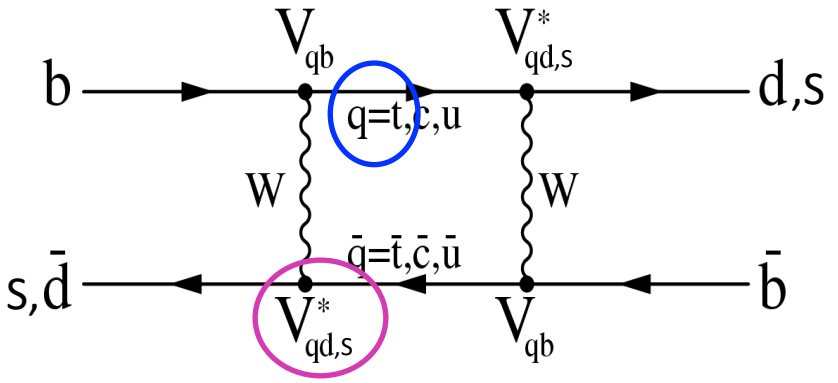
$|\langle \bar{B}(t)|B^0\rangle|^2$

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

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

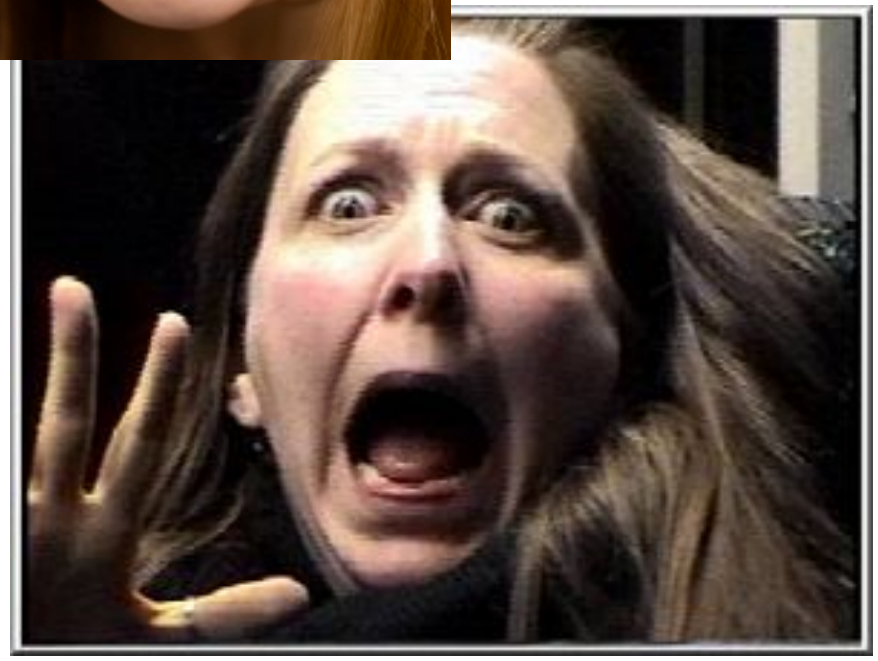


Flavour Oscillations!



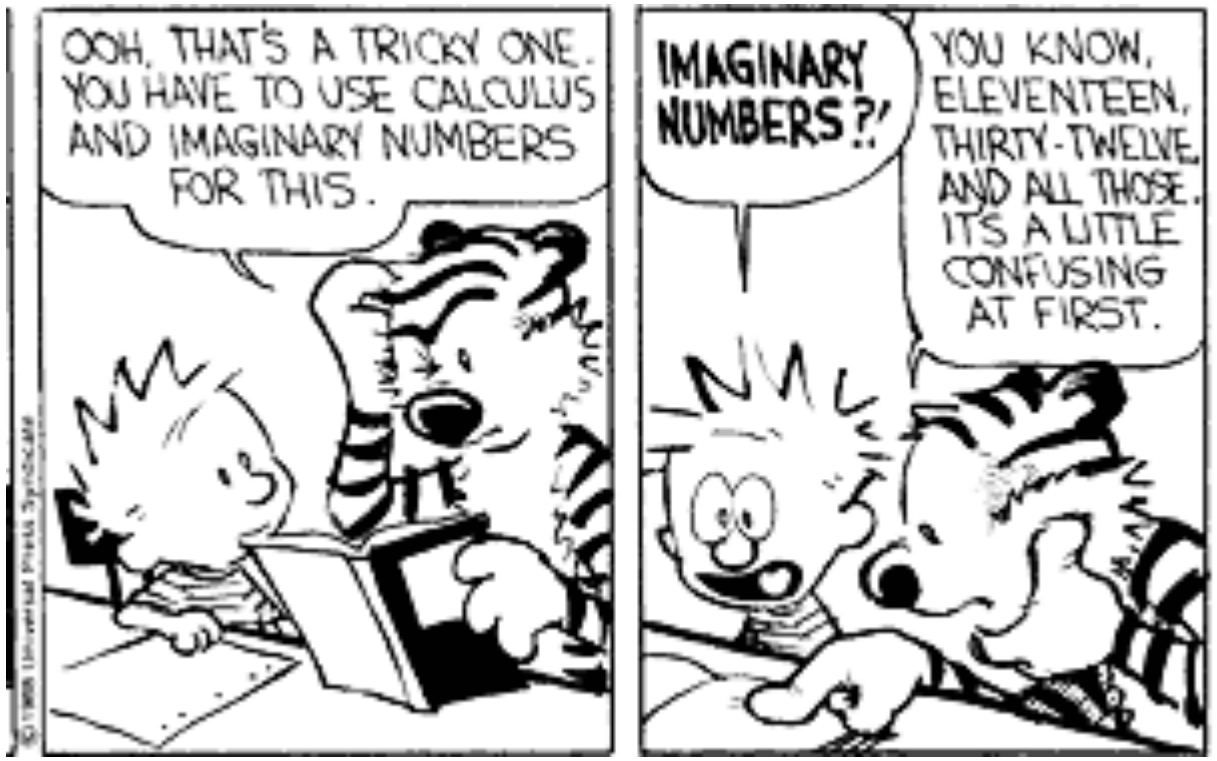
So far, so good…?

Hope not…

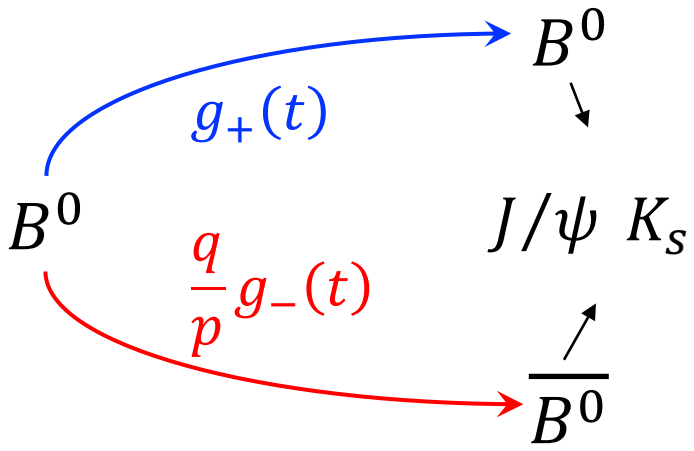


Observing CP Violation

- It's all about imaginary numbers…

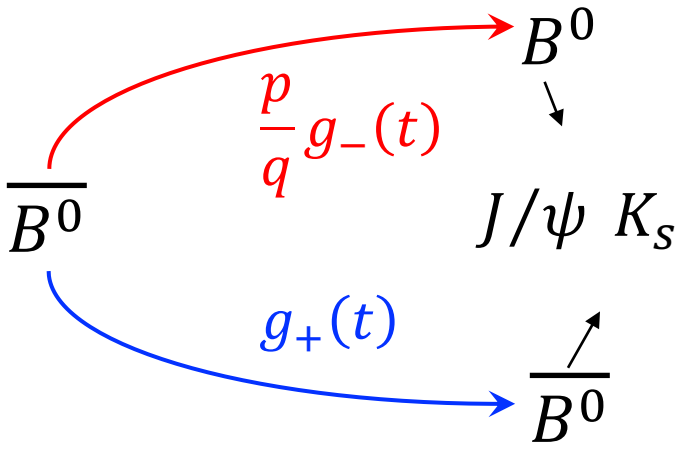


B Decays to common final states: CP eigenstates



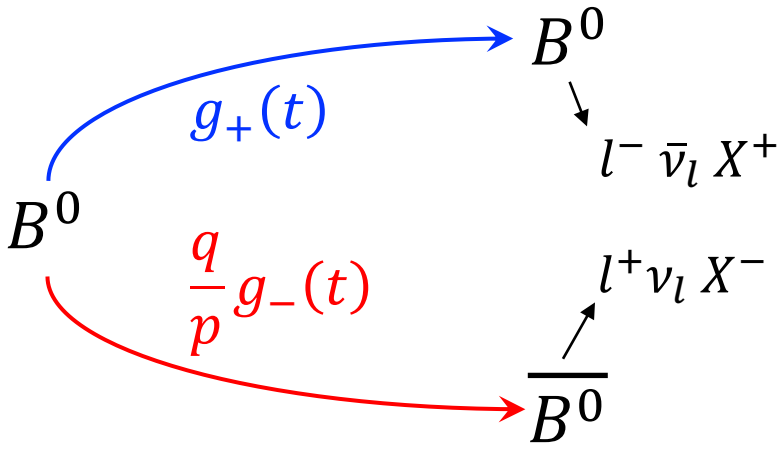
$B^0 \to J/\psi\, K_s$
+
$B^0 \to \overline{B^0} \to J/\psi\, K_s$

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

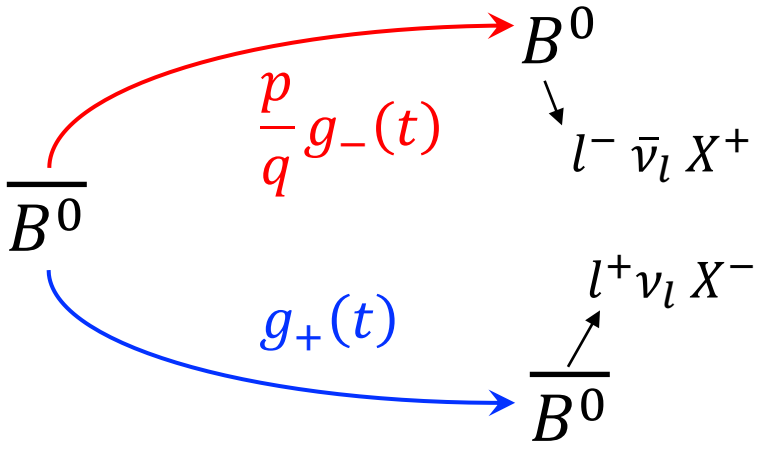


CP

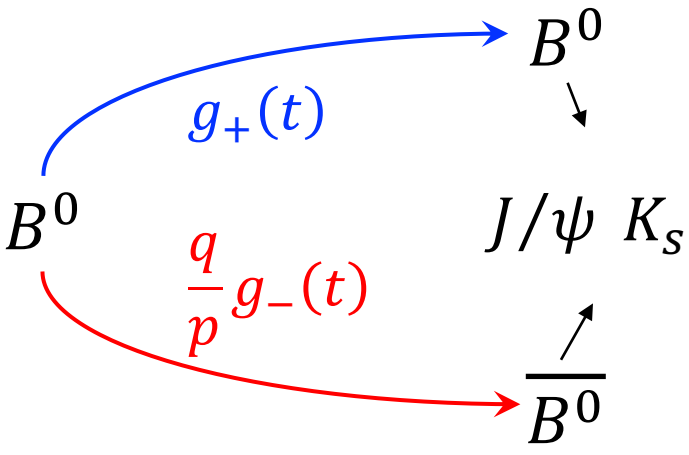
Instead of (Flavour oscillations):



Instead of (Flavour oscillations):

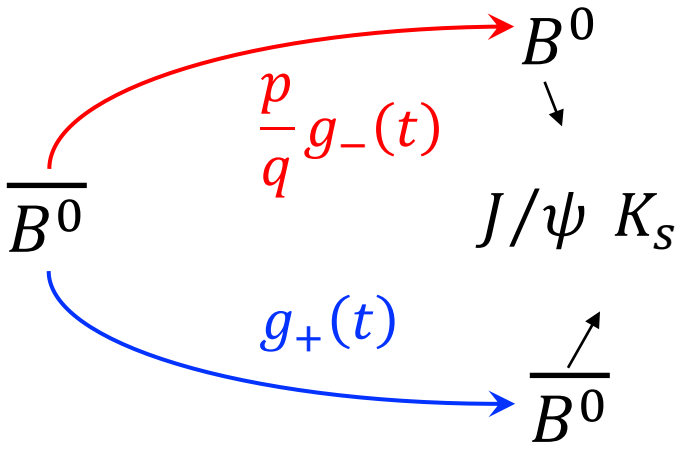


B Decays to common final states: CP eigenstates



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

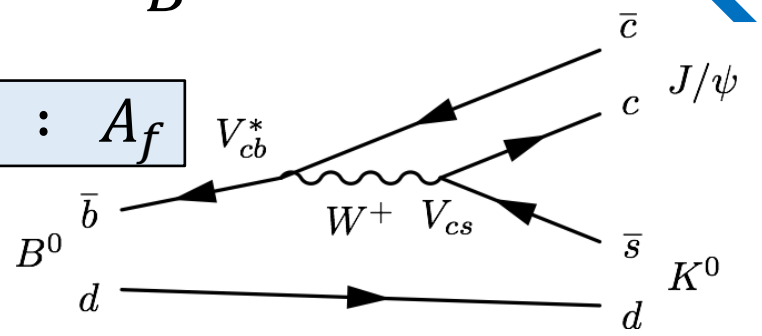
$\overline{B^0} \to J/\psi\, K_s$
+
$\overline{B^0} \to B^0 \to J/\psi\, K_s$



$\Leftarrow CP \Rightarrow$

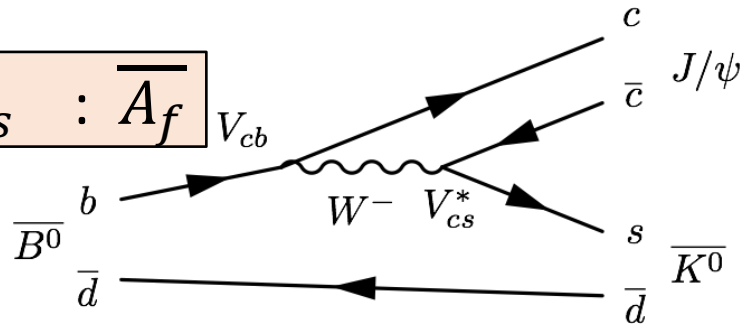
$B^0 \to J/\psi\, K_s \;:\; A_f$

+

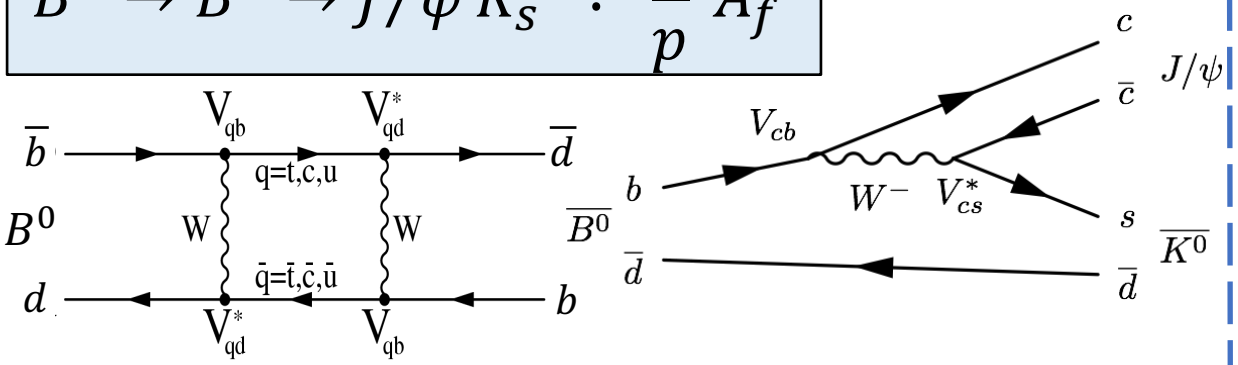


$\overline{B^0} \to J/\psi\, K_s \;:\; \overline{A_f}$

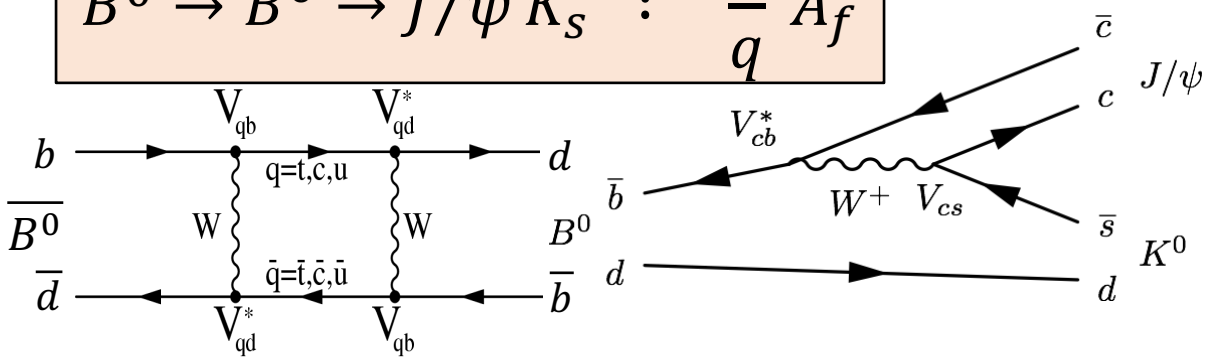
+



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



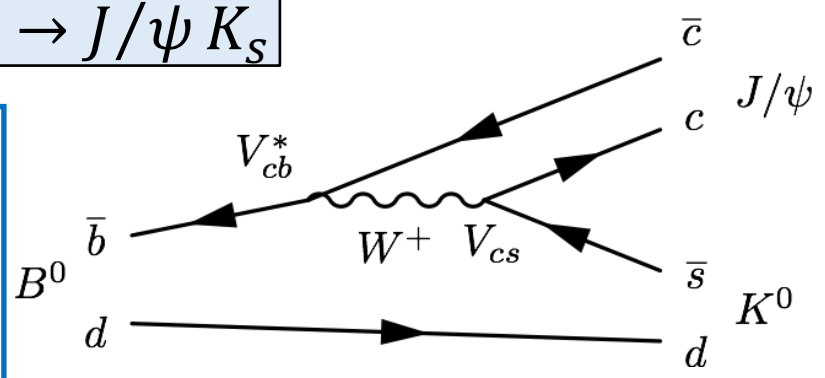
$\overline{B^0} \to B^0 \to J/\psi\, K_s \;:\; \frac{p}{q}\, A_f$



B Decays to common final states: CP eigenstates

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

$$A_f \equiv \langle f|B^0\rangle \qquad \lambda \equiv \frac{q}{p}\frac{\overline{A_f}}{A_f}$$

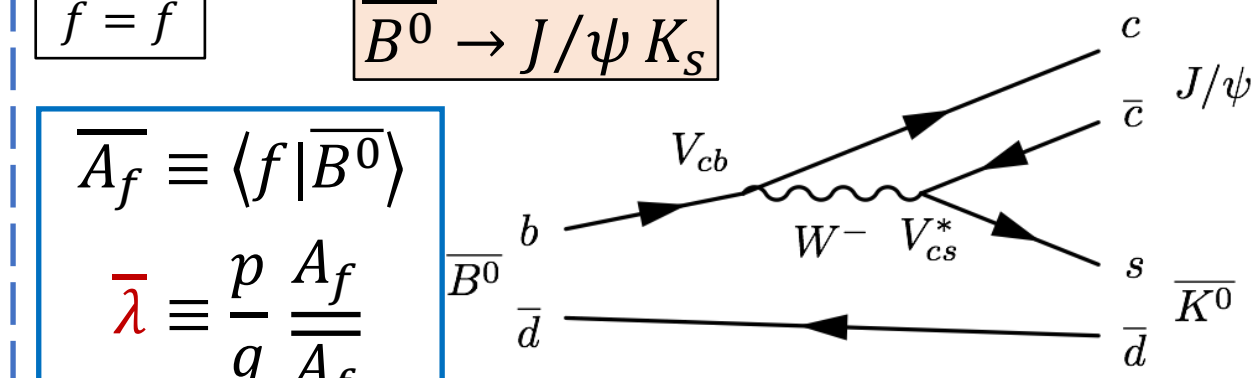


$\bar{\lambda} = 1/\lambda$

$f = \bar{f}$

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

$$\overline{A_f} \equiv \langle f|\overline{B^0}\rangle \qquad \bar{\lambda} \equiv \frac{p}{q}\frac{A_f}{\overline{A_f}}$$



- 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:

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

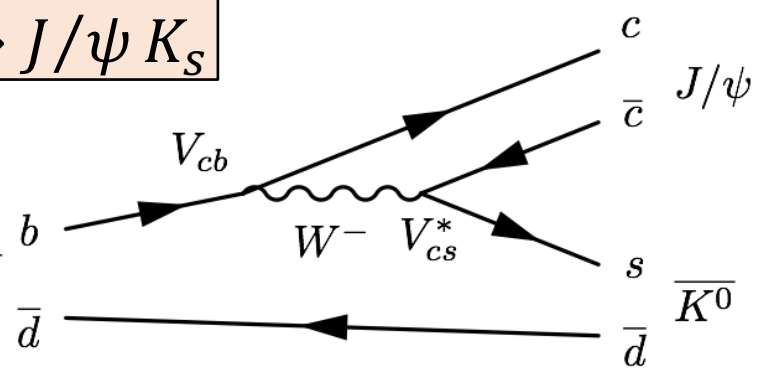
$$\left|\overline{B^0}(t)\right\rangle = \mathrm{g}_+(\mathrm{t})\left|\overline{B^0}\right\rangle + \frac{p}{q}g_-(t)|B^0\rangle$$

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

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

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



$A_f \equiv \langle f |$

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

- Calcul
- From

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

just expand by taking the square…

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

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

PETER

1.21

4c) Expand

$(a+b)^n$ Very funny, Peter.

$= (a + b)^n$

$= (a + b)^n$

$= (a \quad + \quad b)^n$

etc.

Master formula for neutral B decays

- Just by (tediously) writing it out…

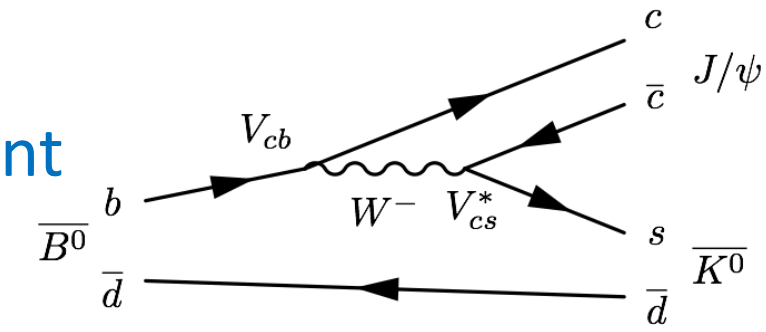
$$\Gamma_{(B\to f)}(t) = |A_f|^2 \left(1+|\lambda_f|^2\right)\frac{e^{-\Gamma t}}{2} \cdot \left(\cosh\frac{\Delta\Gamma t}{2} + D_f \sinh\frac{\Delta\Gamma t}{2} + C_f \cos\Delta m t - S_f \sin\Delta m\, t\right)$$

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

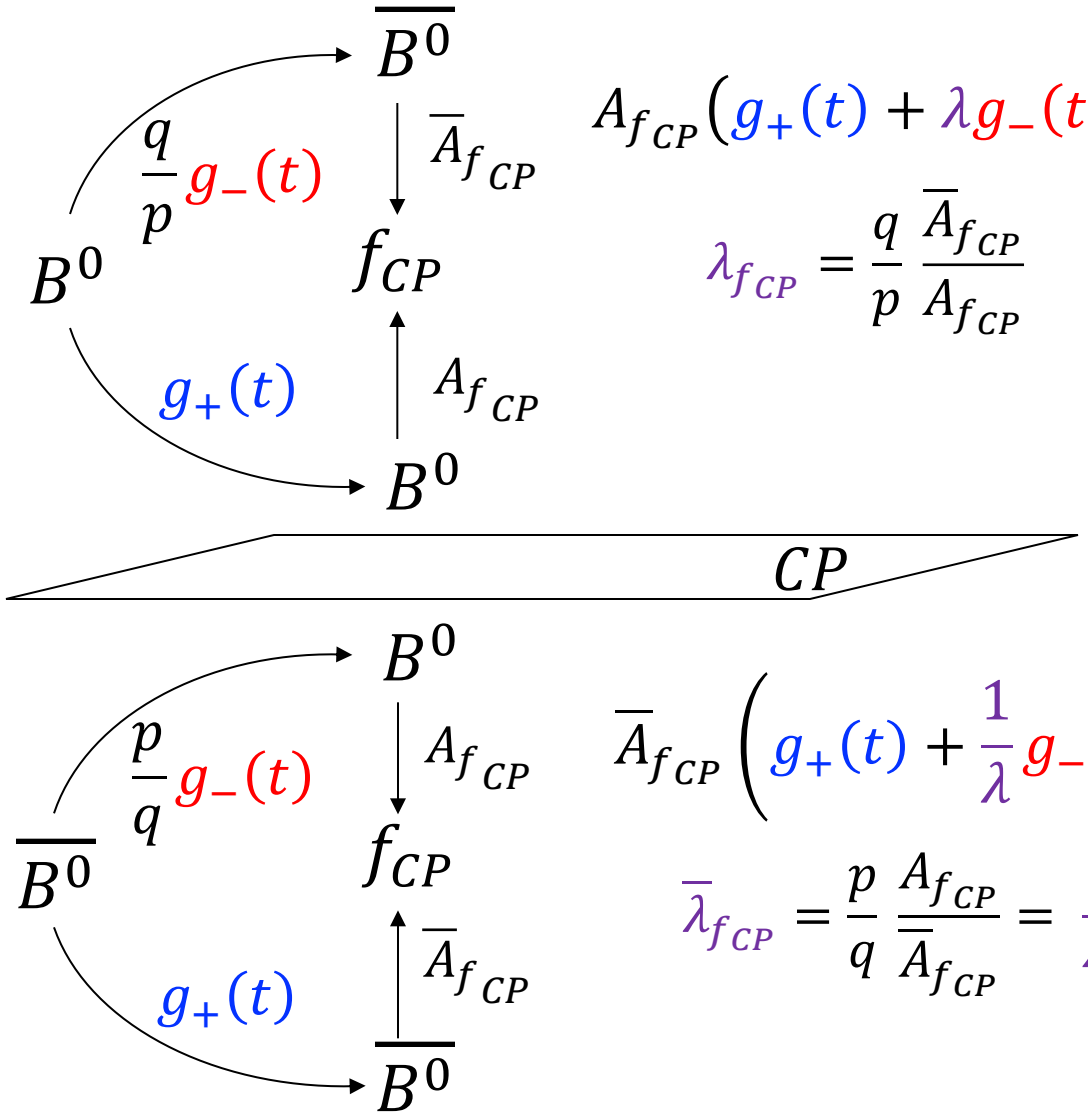
with: $D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2}$, $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}$

- 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?



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

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

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

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

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

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

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

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

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

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

Interfering Amplitudes

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

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

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

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

Interfering Amplitudes

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

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

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

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

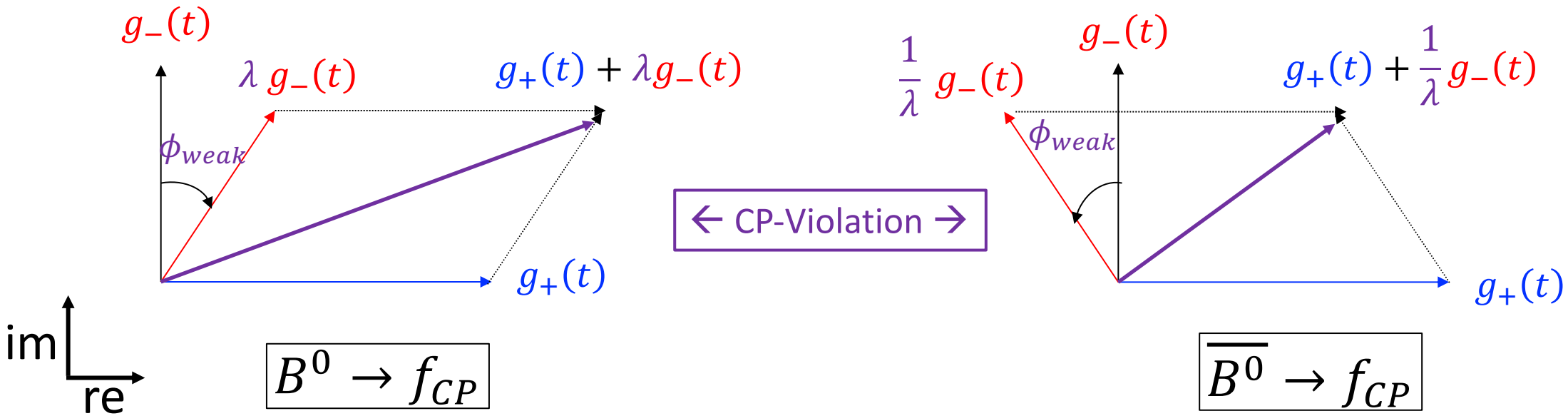
Interfering Amplitudes: CP violation!

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

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

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

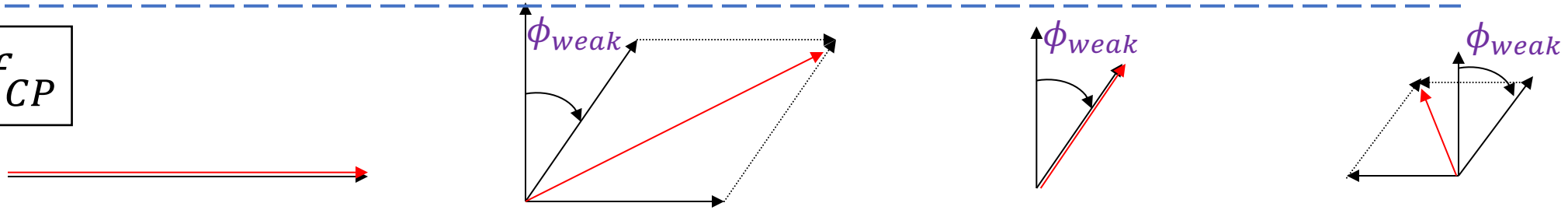
$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}} \quad \text{(CKM)}$$



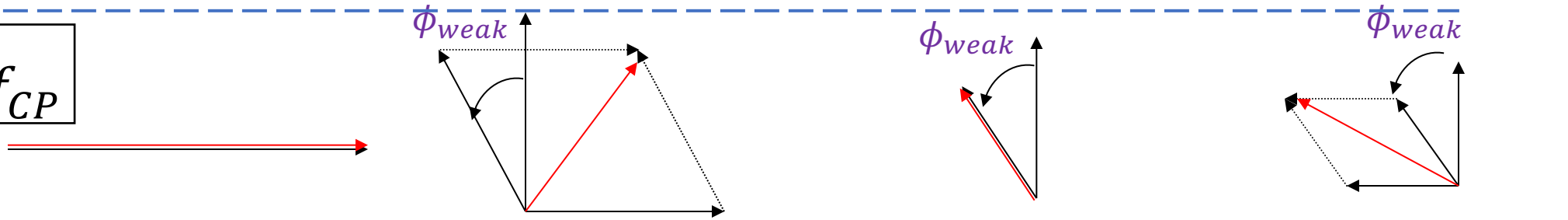
Interfering Amplitudes: time dependent CP violation!

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

$B^0 \rightarrow f_{CP}$



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



$\Delta mt/2 = 0$ $\quad$ $\Delta mt/2 = \pi/4$ $\quad$ $\Delta mt/2 = \pi/2$ $\quad$ $\Delta mt/2 = 3\pi/4$

No CPV $\quad$ ***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):

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

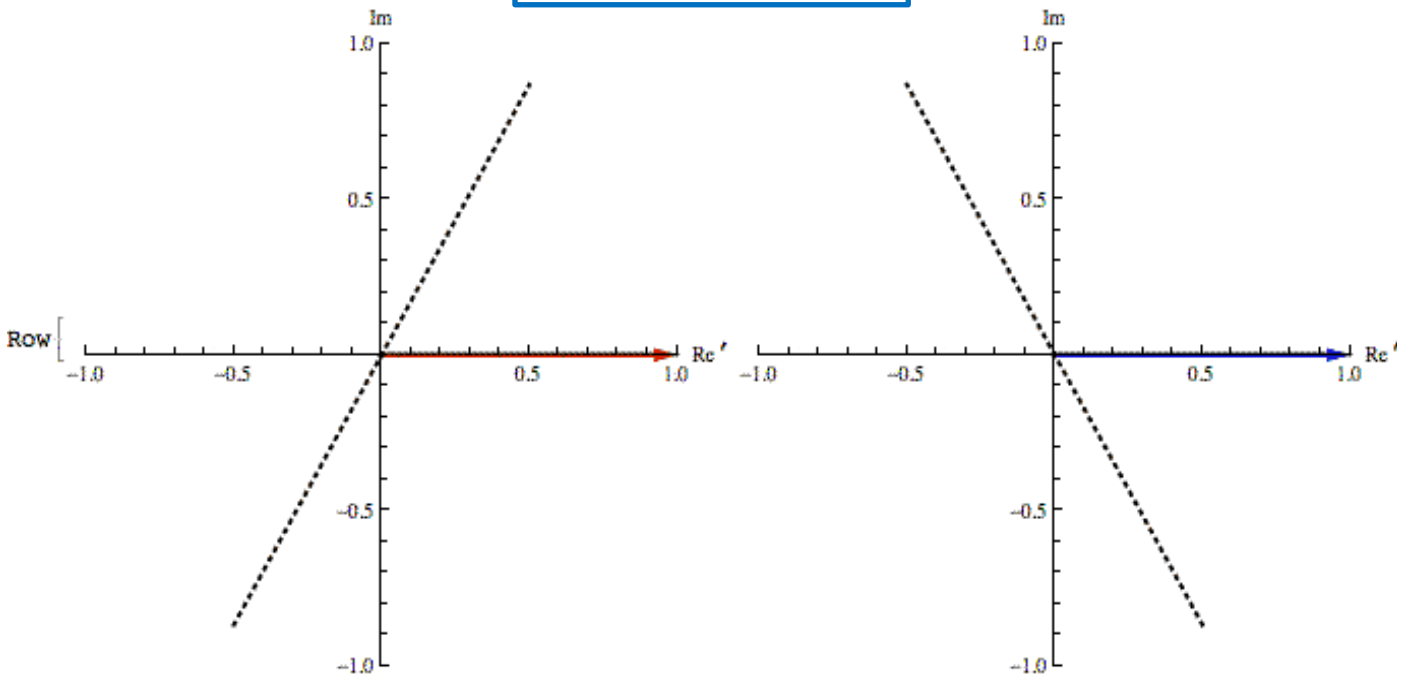
$$\overline{B^0} \rightarrow f_{CP} \;:\quad \left|\cos\frac{\Delta m t}{2} + i\,\frac{1}{\lambda}\sin\frac{\Delta m t}{2}\right|^2 \propto 1 - \frac{(1-|\lambda|^2)}{(1+|\lambda|^2)}\cos\Delta m t + \frac{(2\Im\lambda)}{(1+|\lambda|^2)}\sin\Delta m t$$

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

Decay Amplitudes

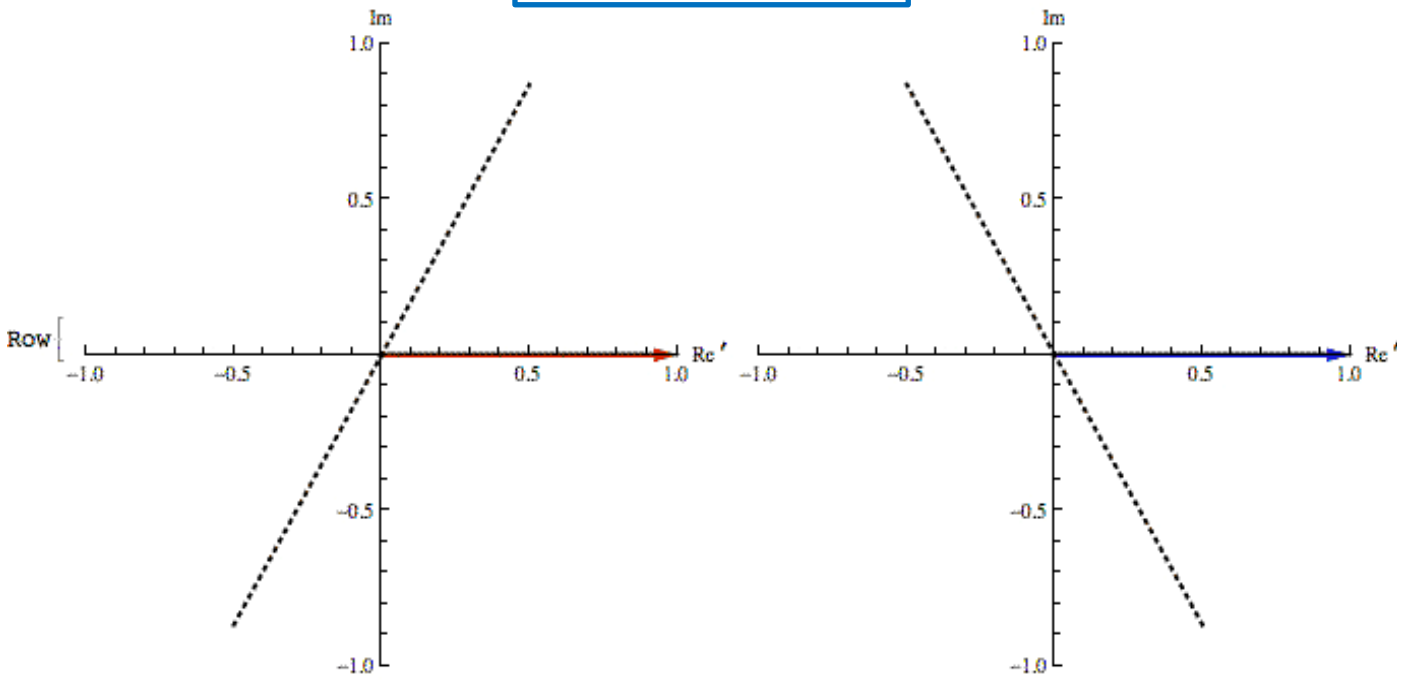


Time Dependent CP violation

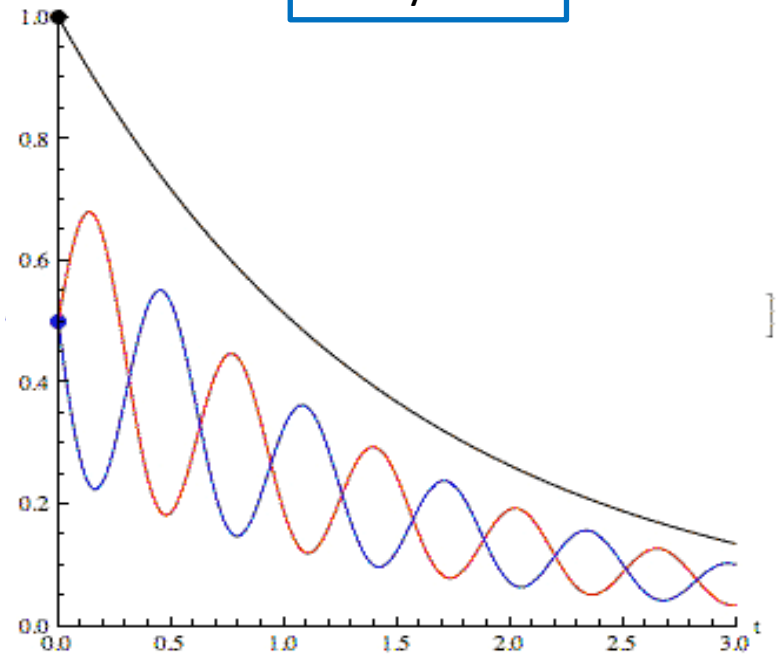
$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

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

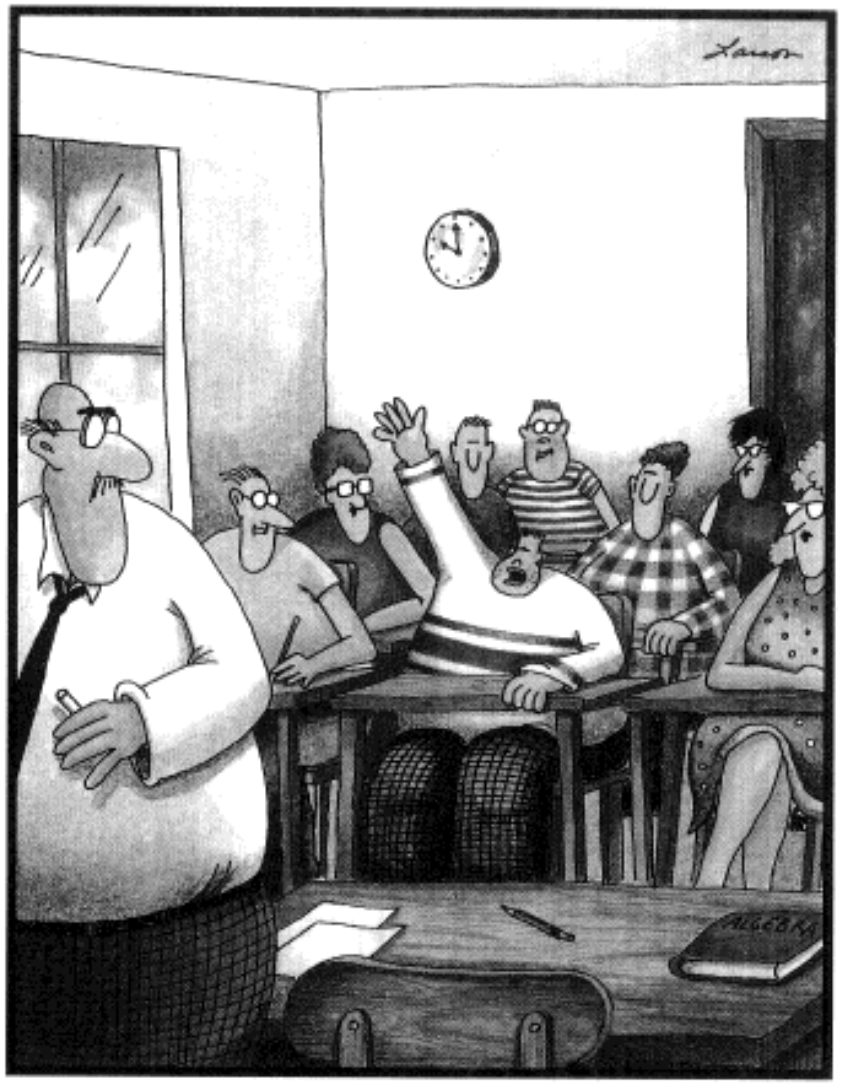
Decay Amplitudes



Decay Rates



Where were we?



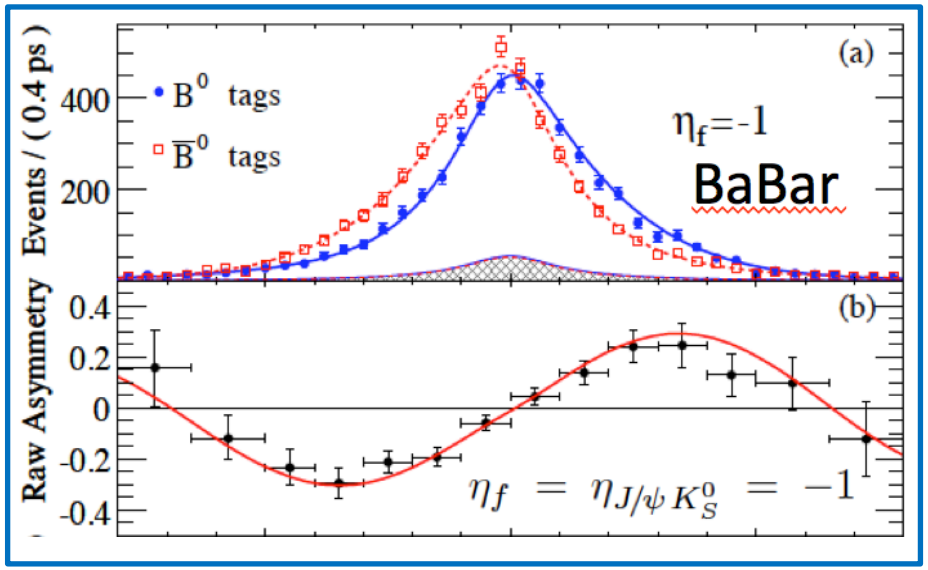
"Mr. Osborne, may I be excused?
My brain is full."

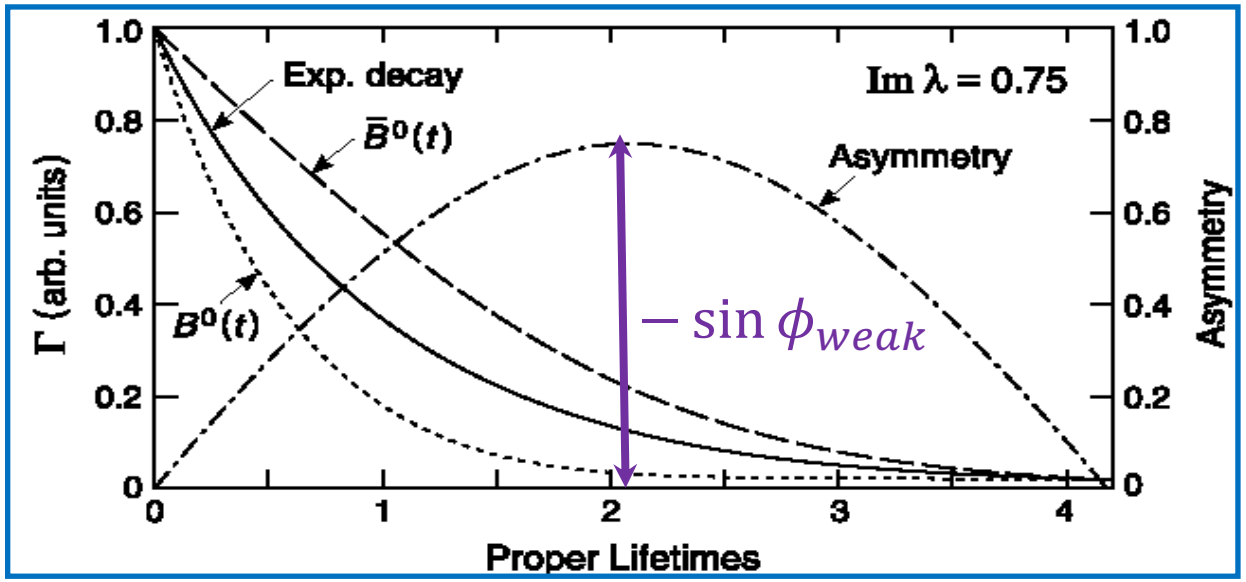
Time Dependent CP Asymmetry

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

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

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

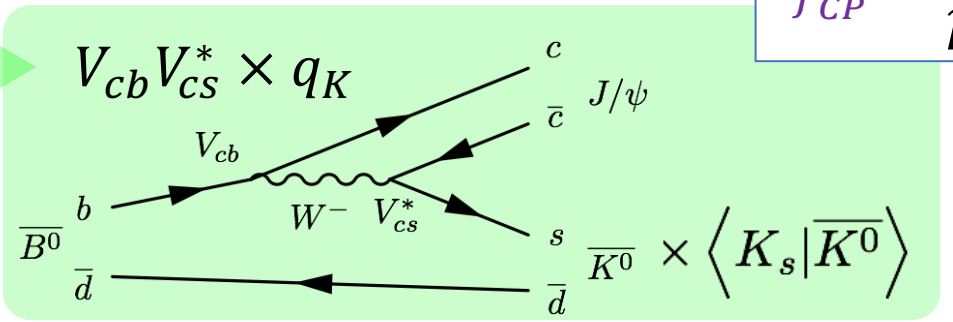




$\lambda_{J/\psi K_S}$ for "Golden" mode: $B^0 \to J/\psi K_S$

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

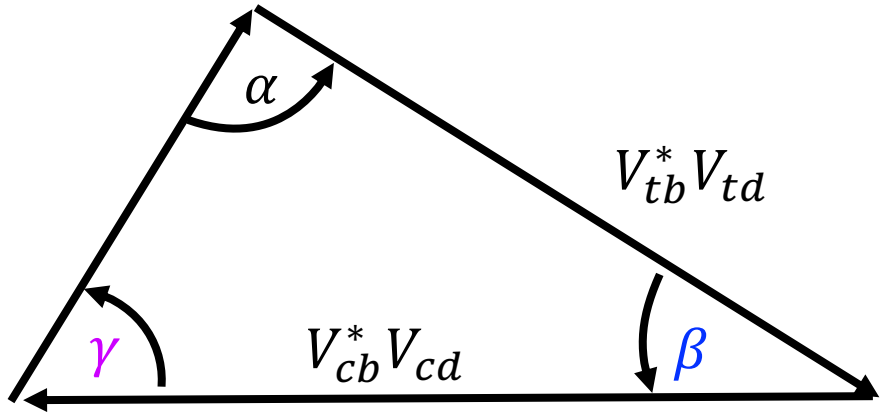
$$\lambda_{J/\psi K_S} \equiv -\frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$



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

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

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



- Similarly with this method of time dependent CP violation:

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

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

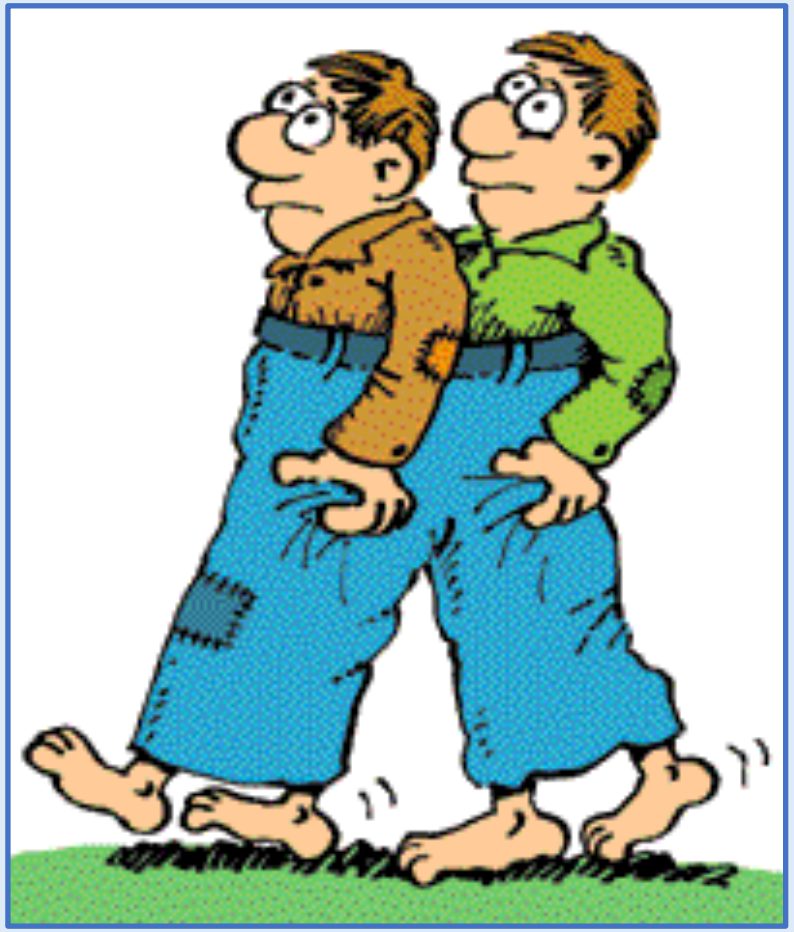
➔ B_s physics is mainly done at the LHC …

How are you doing?

How are you doing?

How are you doing?

Contents:



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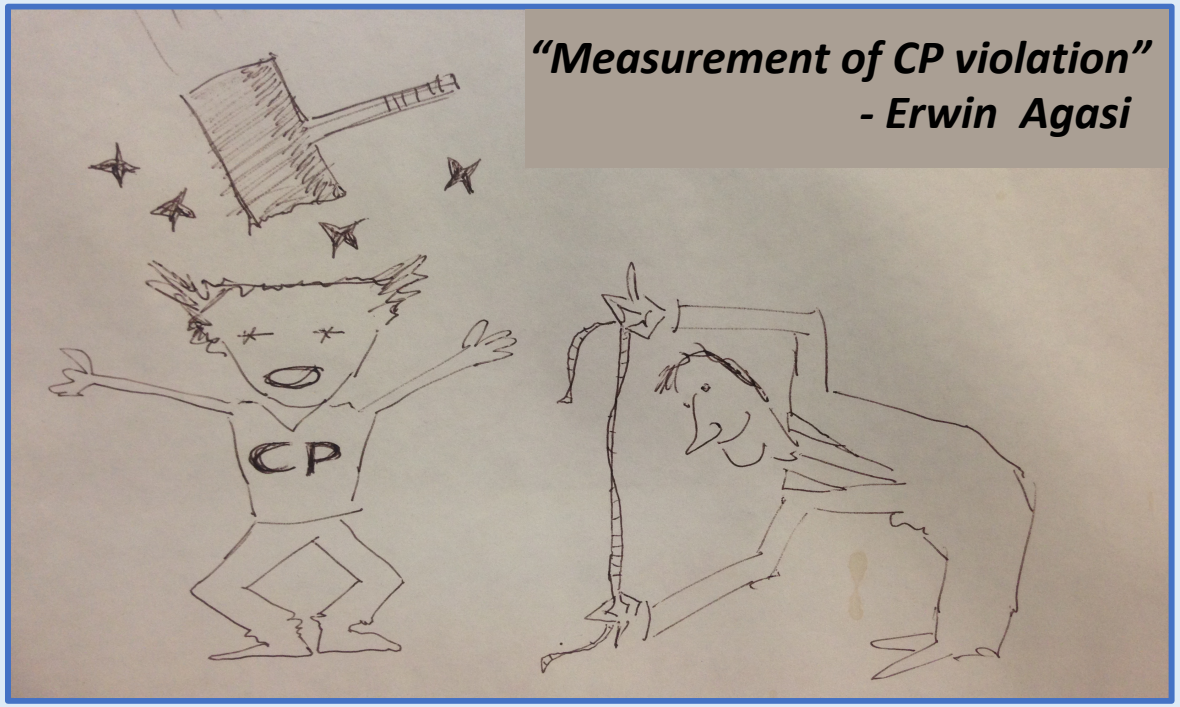
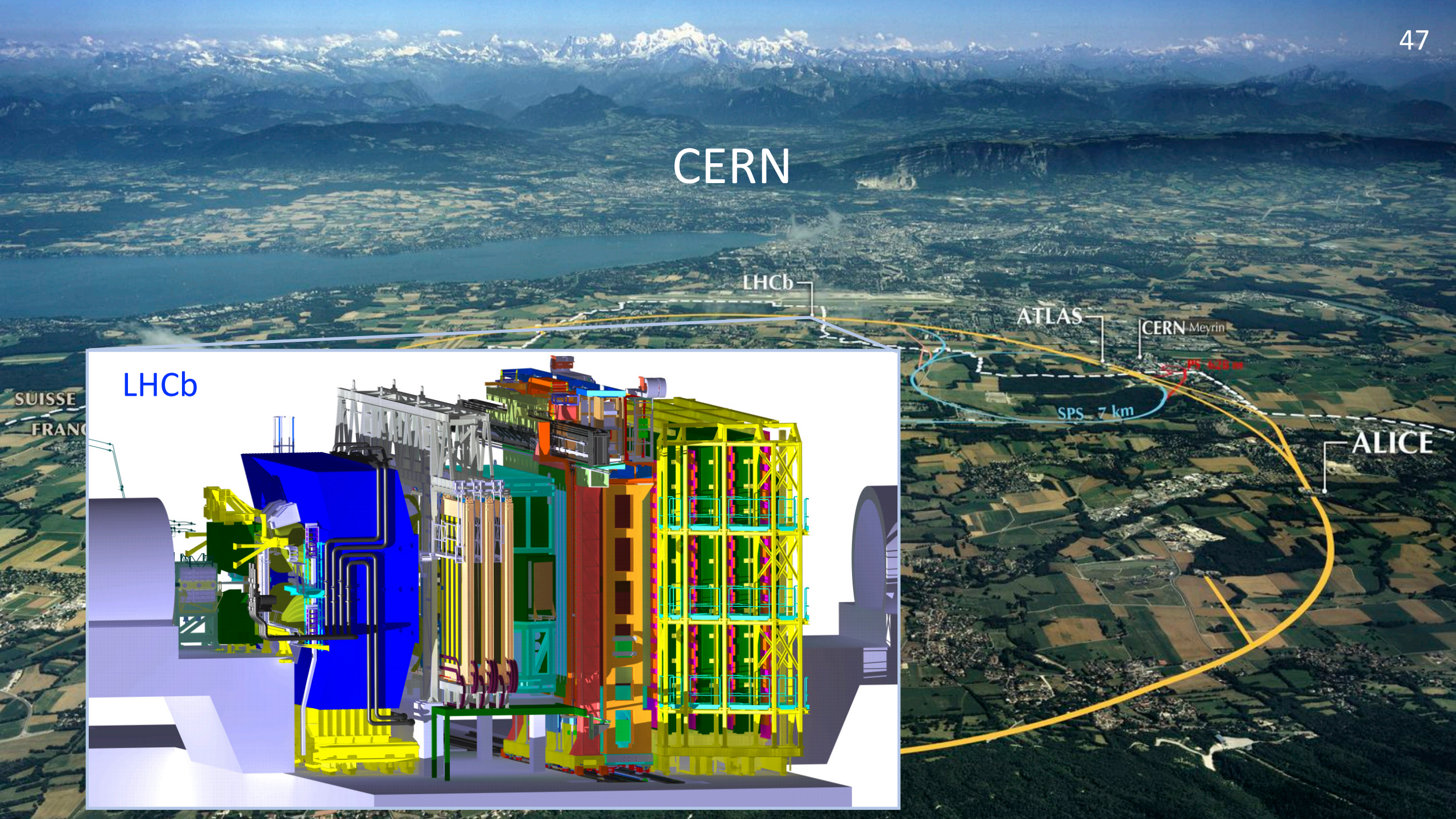
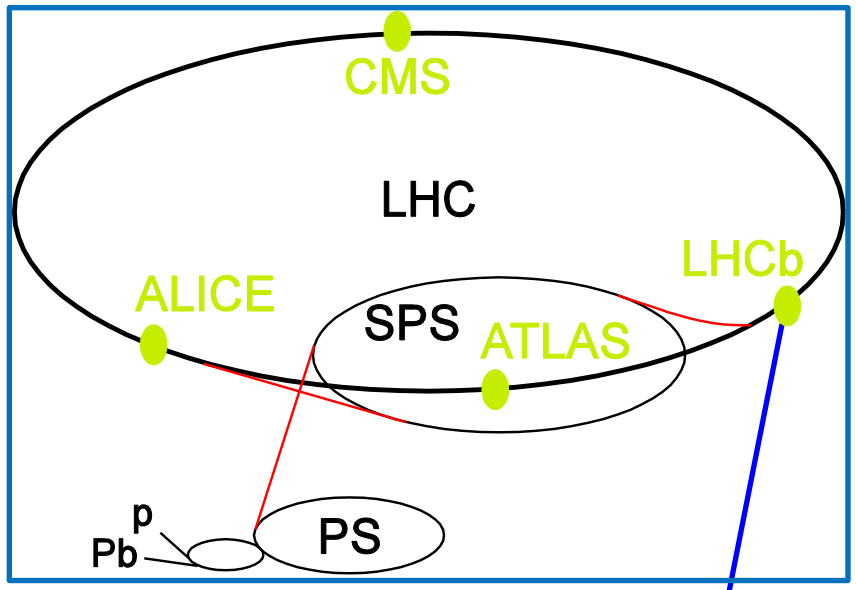


CERN



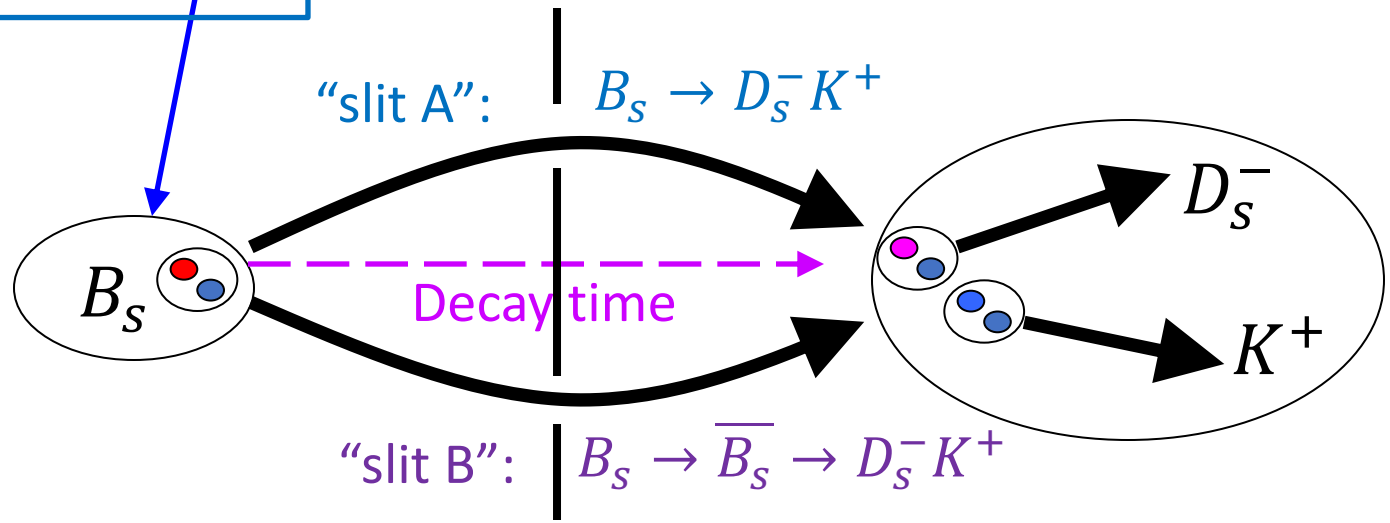
$B_s \to D_s K$: Quantum Interference Experiment @ LHCb



Measure:

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

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



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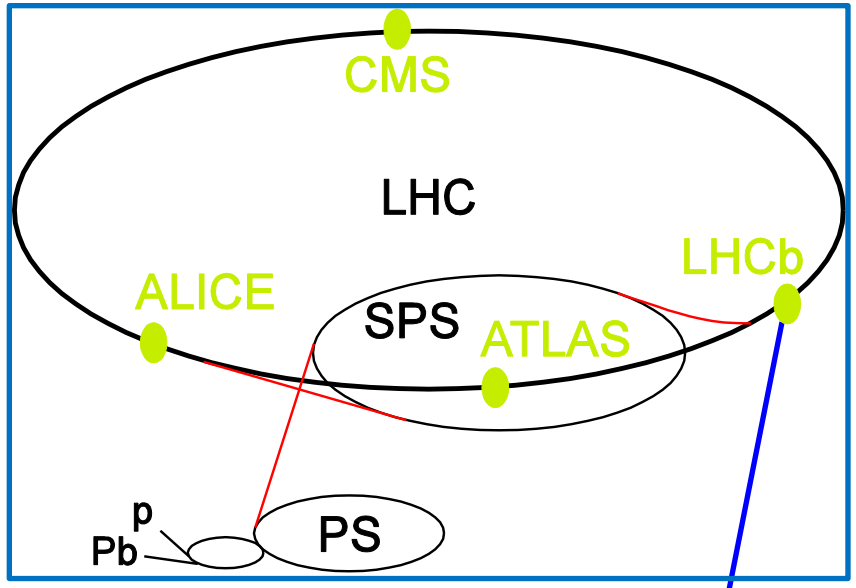
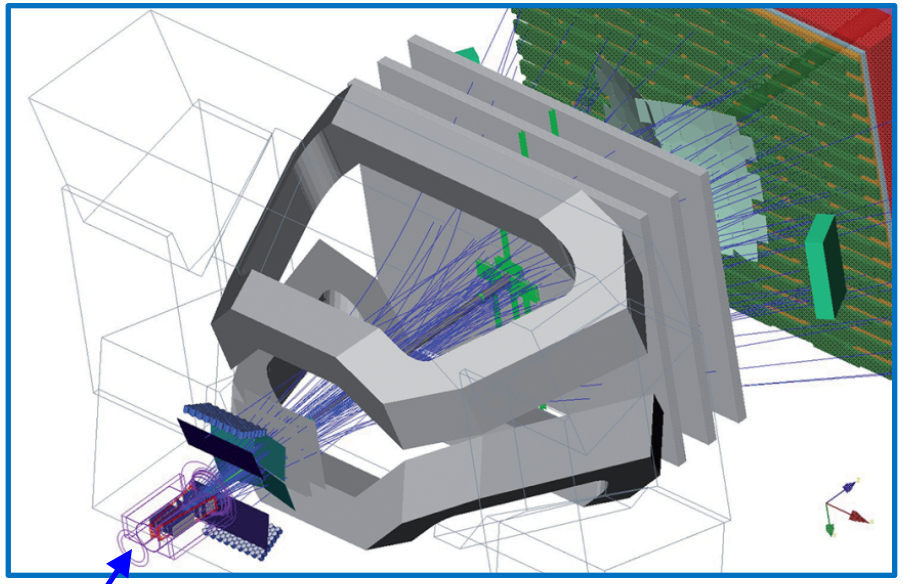


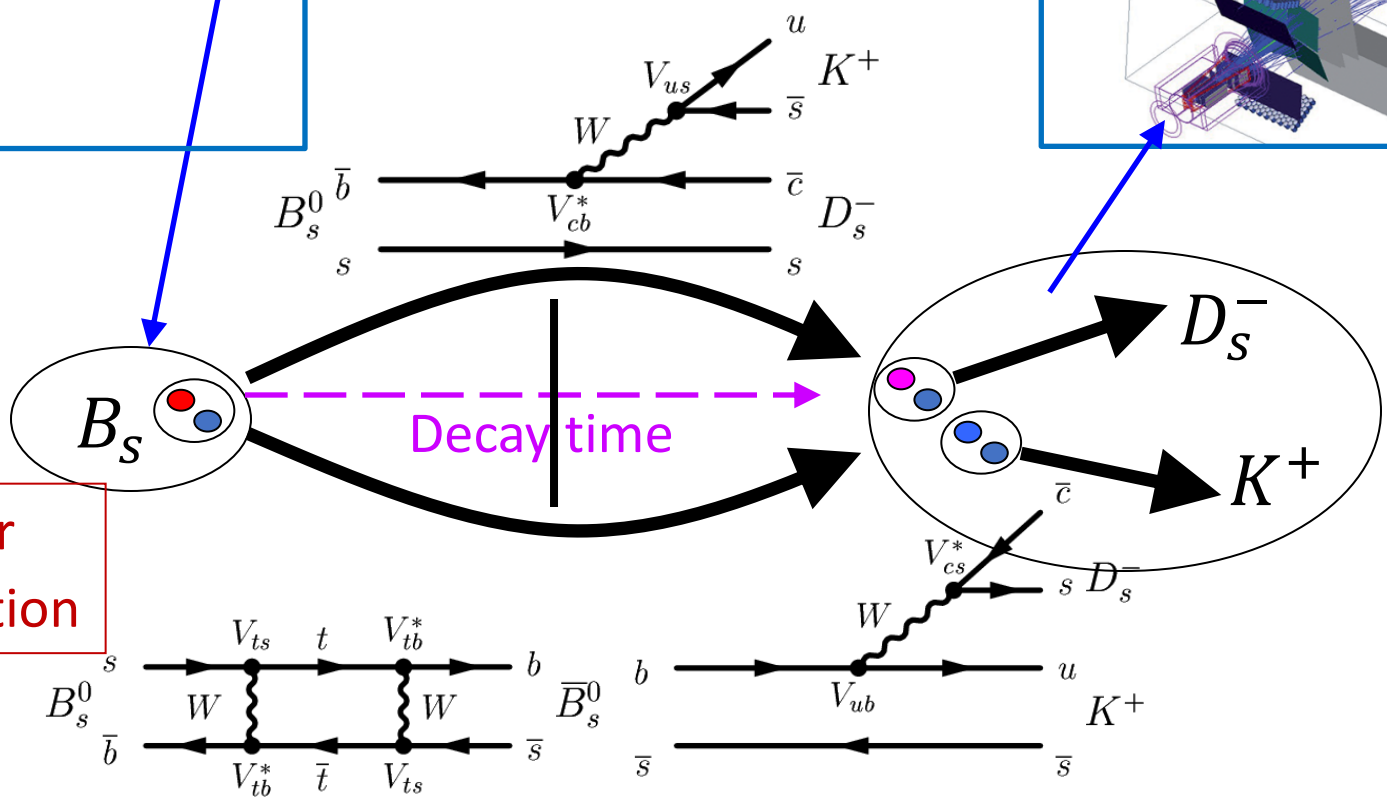
Measure:

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

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

Repeat for $D_s^+ K^-$

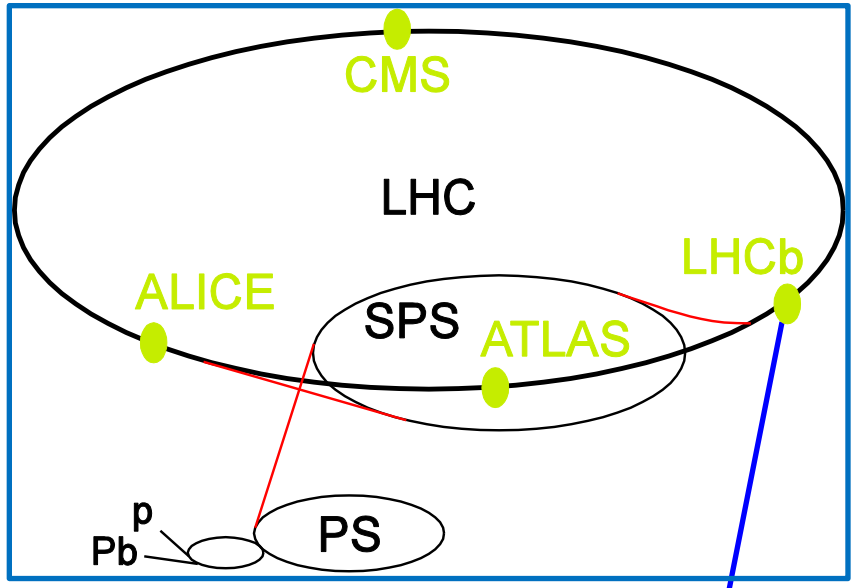




1) Determine whether B_s or $\overline{B_s}$ at production

2) Measure decay rate as function of decay-time

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

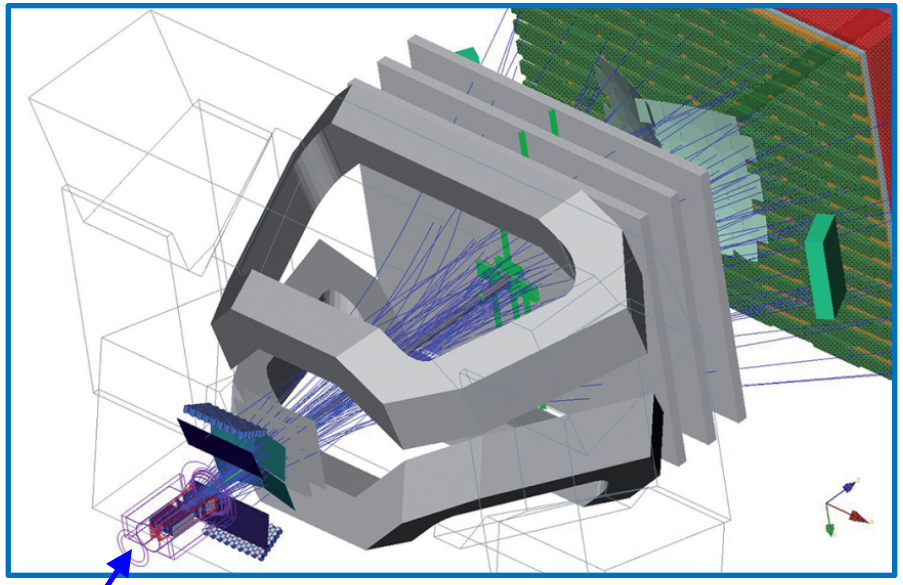


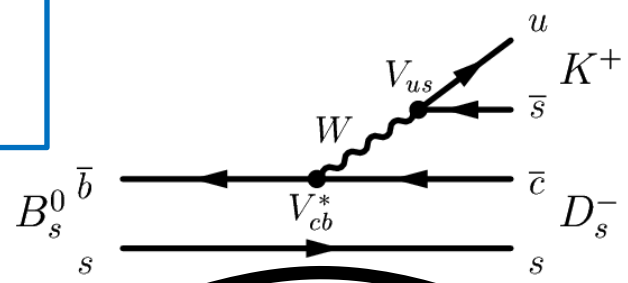
Measure:

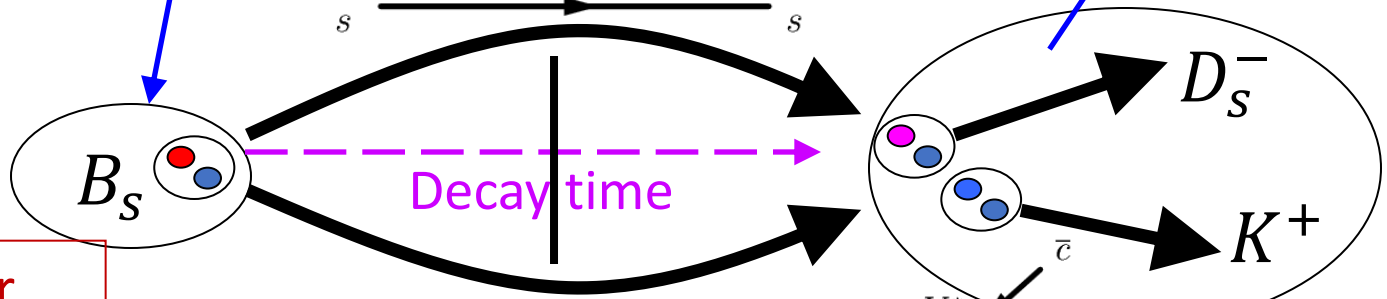
$B_s \to (\overline{B_s} \to) D_s^- K^+$

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

Repeat for $D_s^+ K^-$

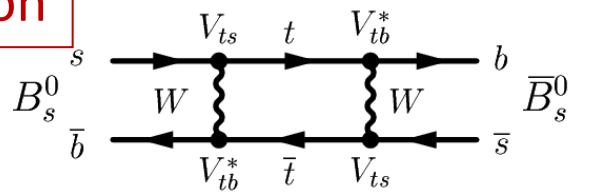


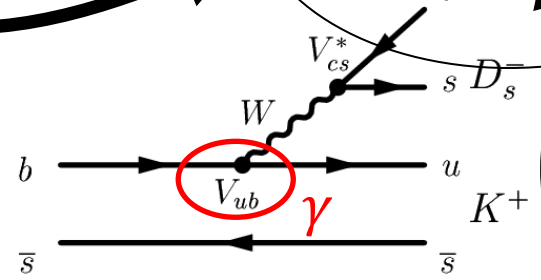




2) Measure decay rate as function of decay-time

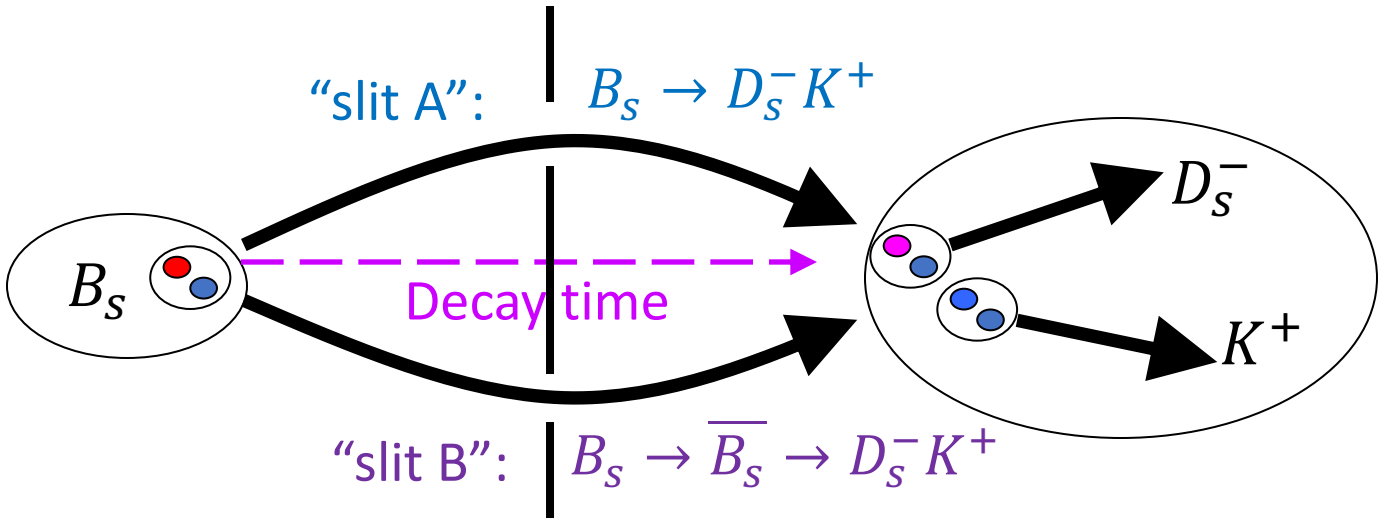
1) Determine whether B_s or $\overline{B_s}$ at production

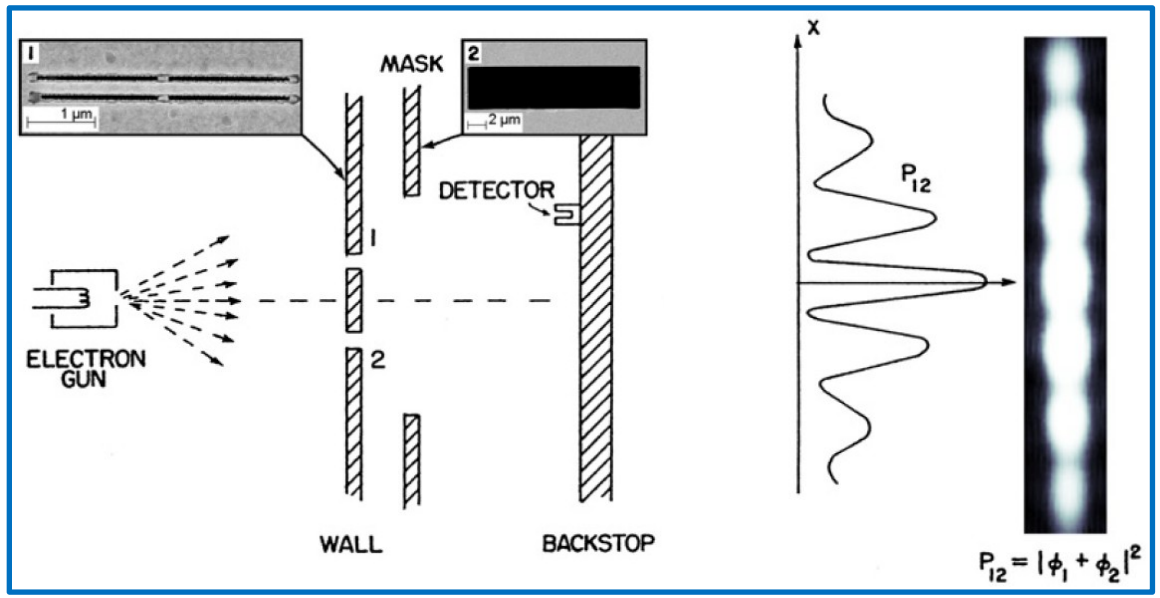




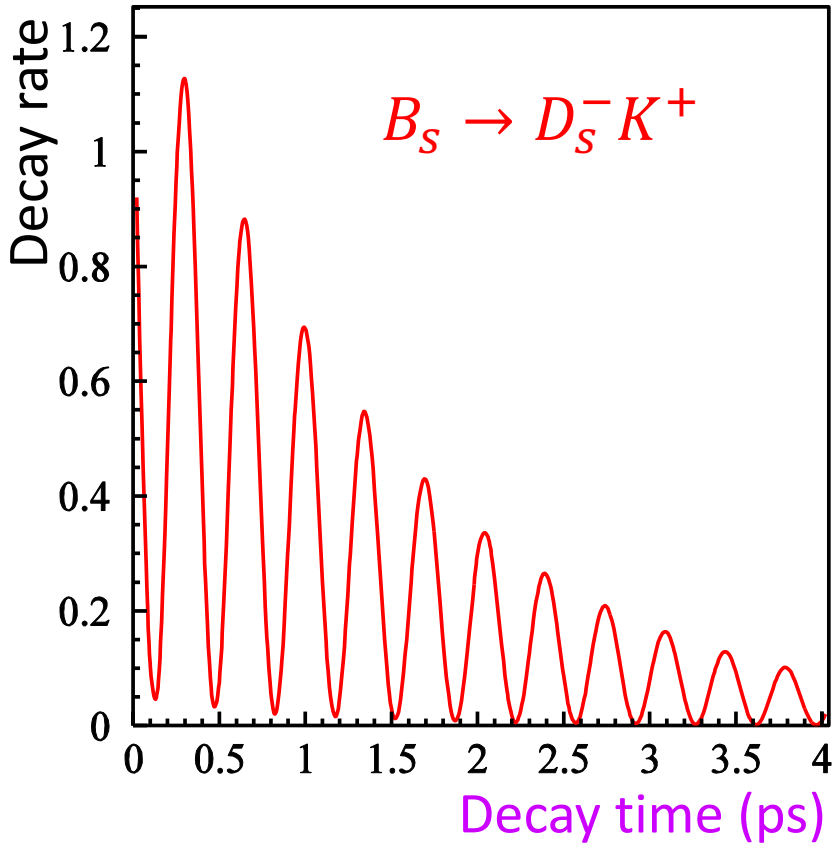
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

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

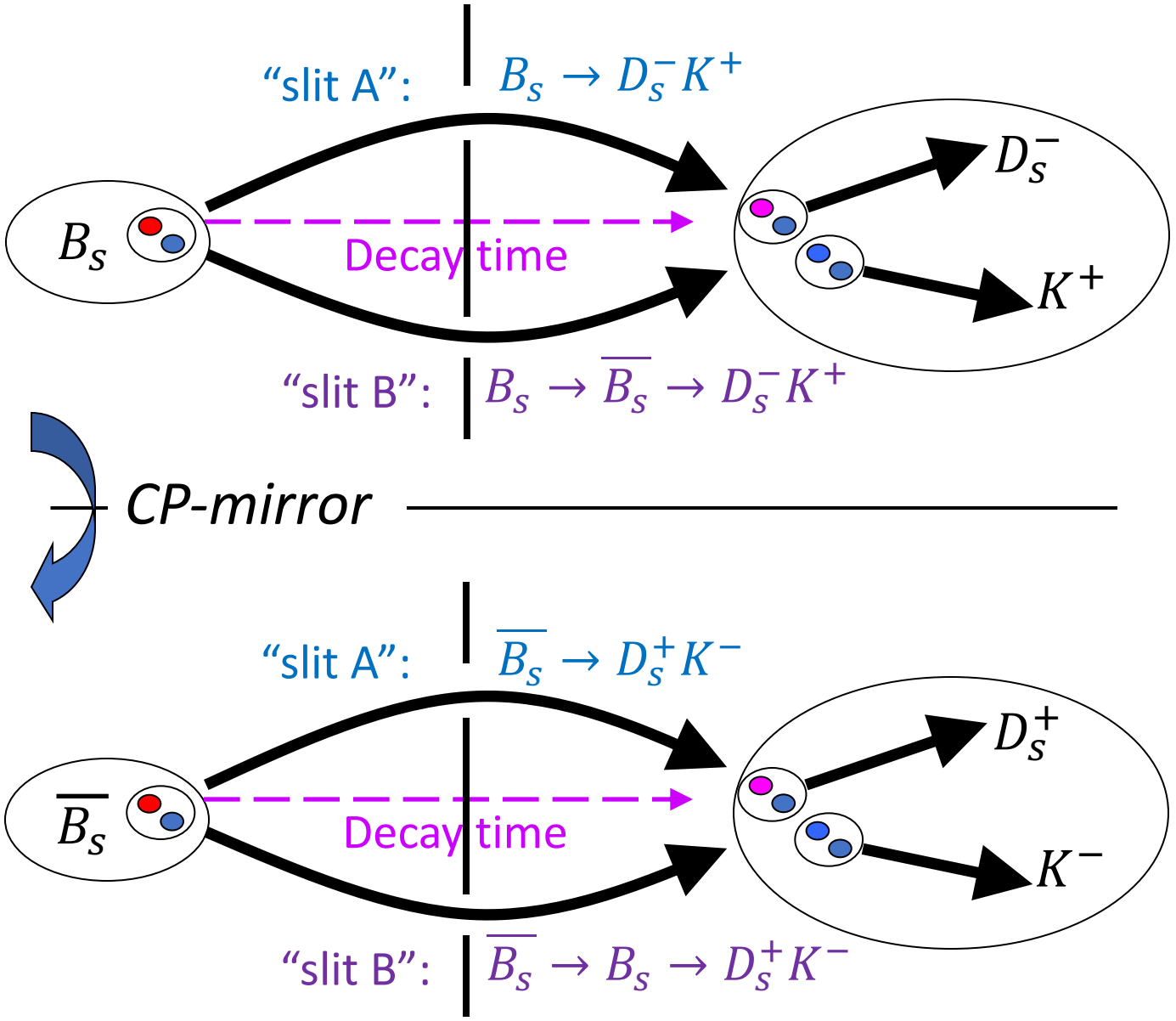




An interference pattern:



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



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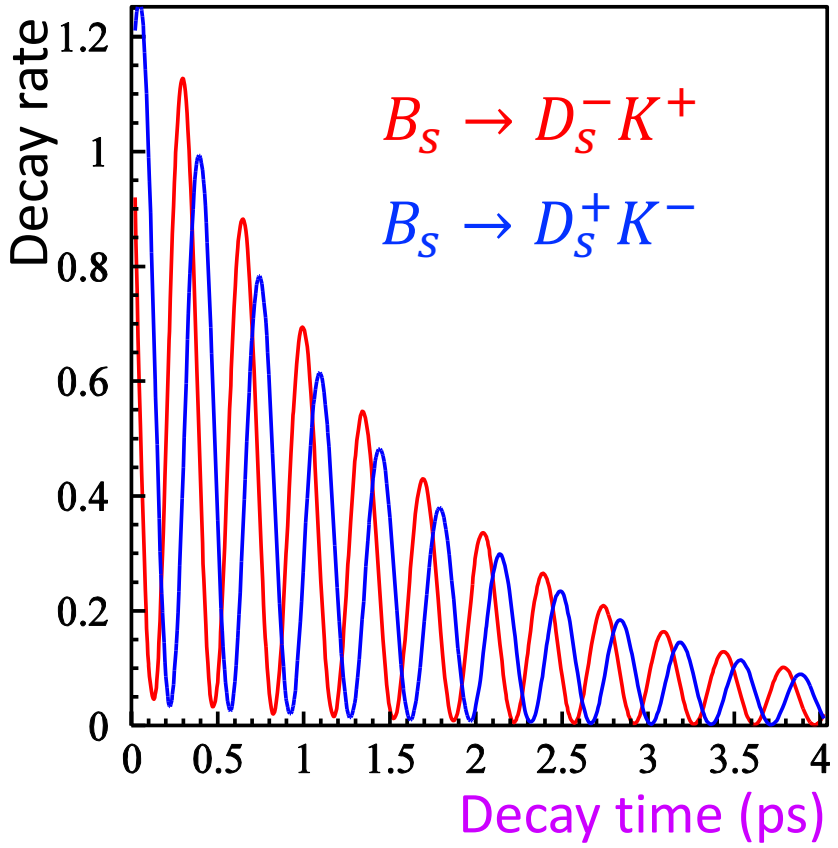
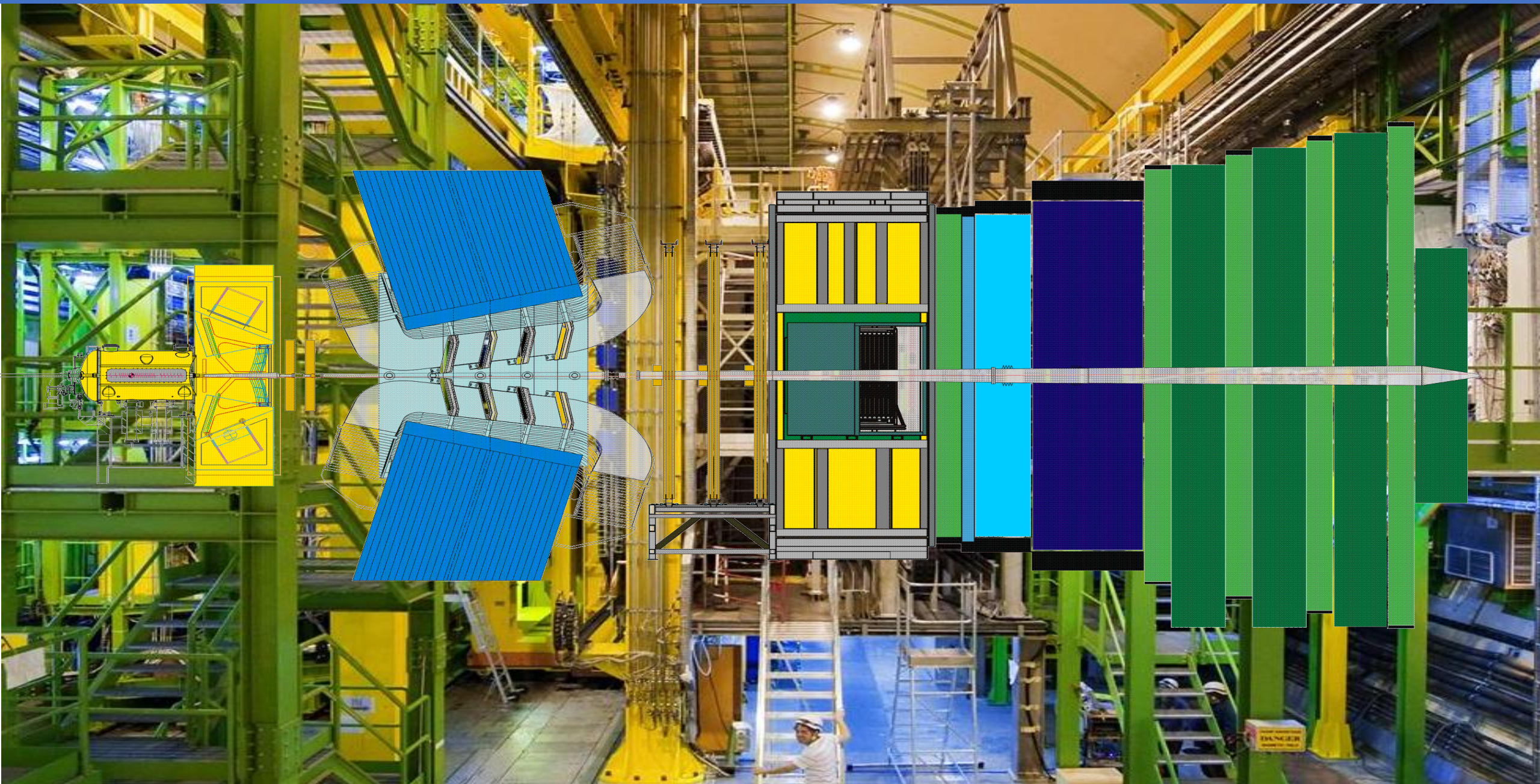
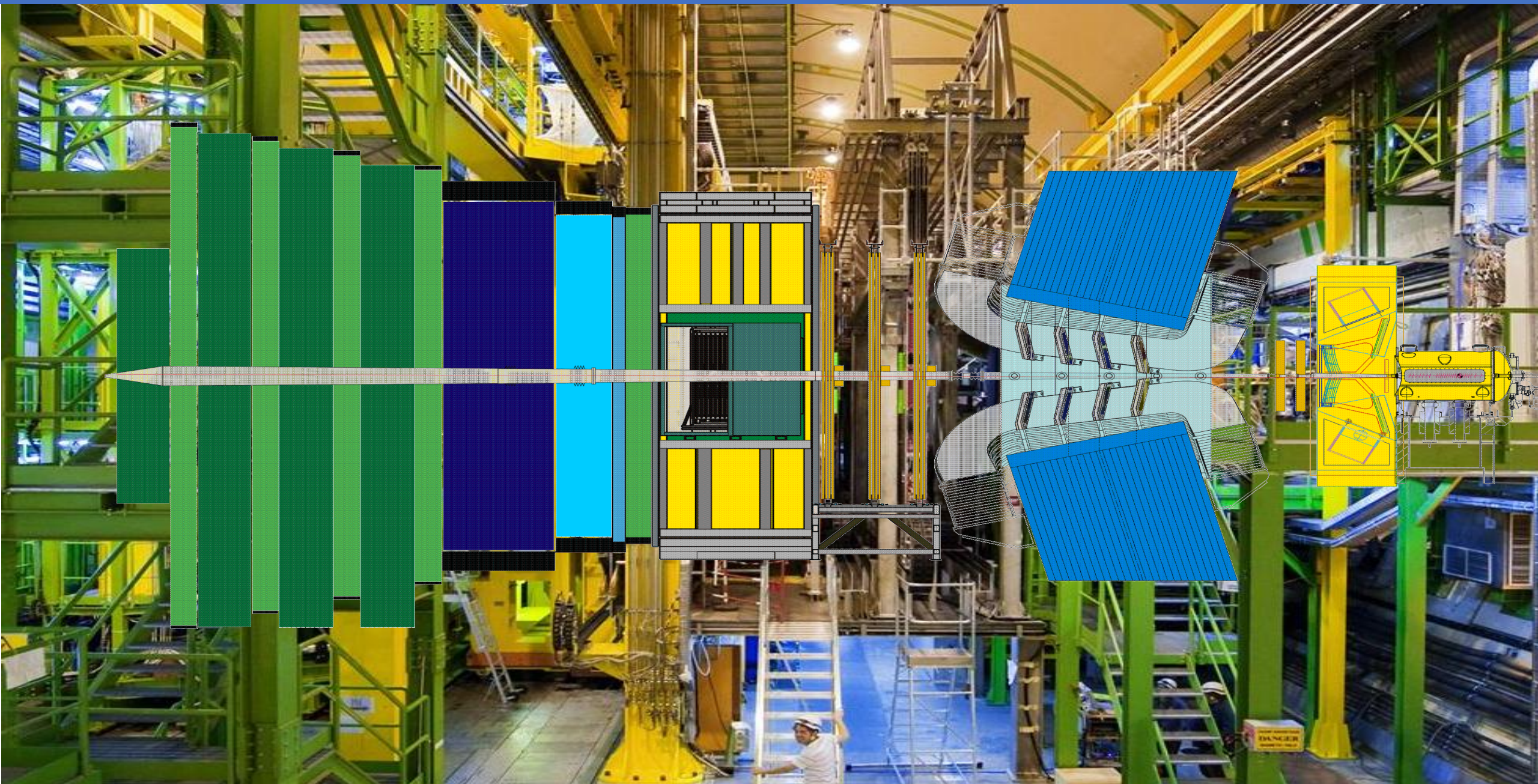


Time dependent CP violation!

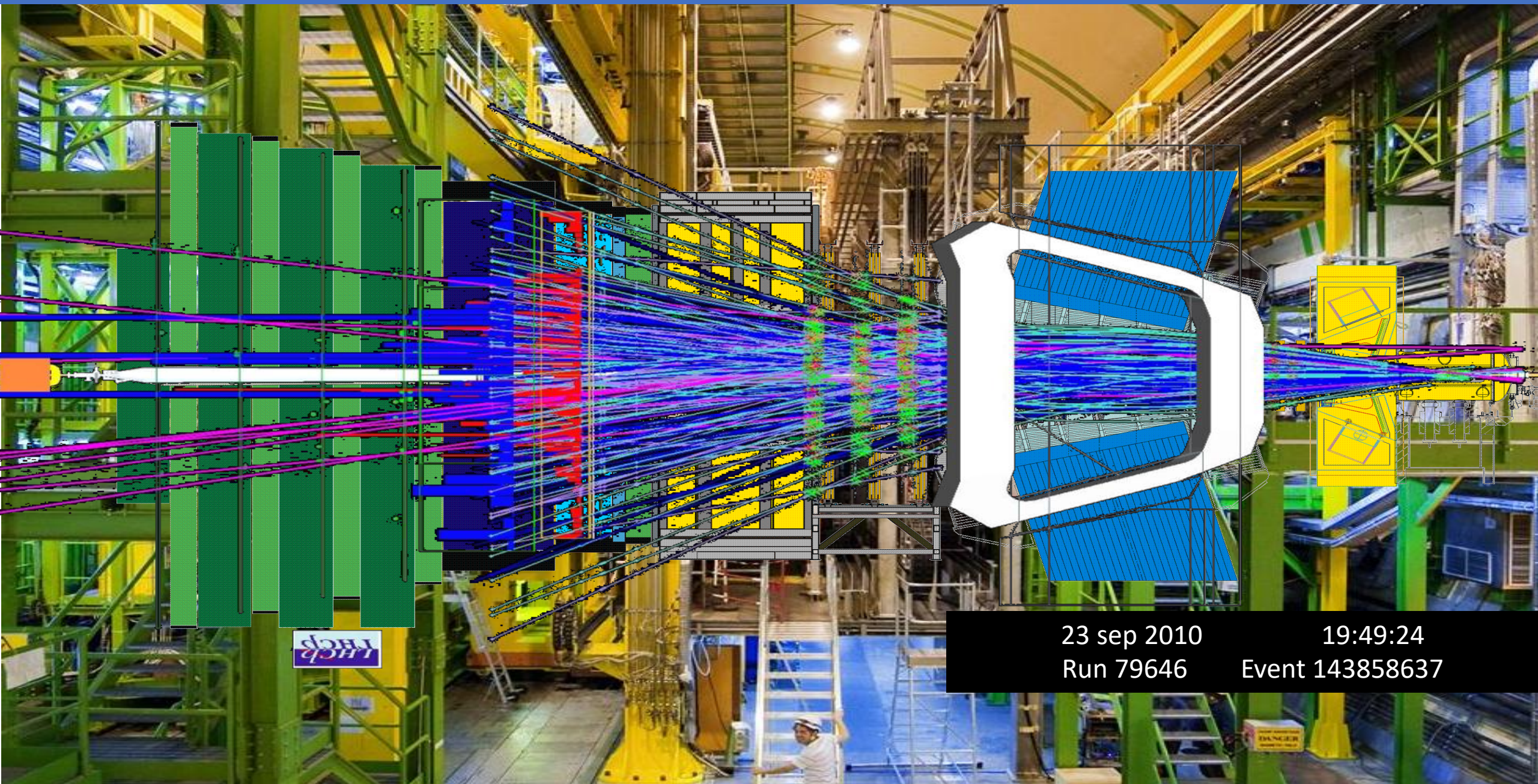
The LHCb Detector?



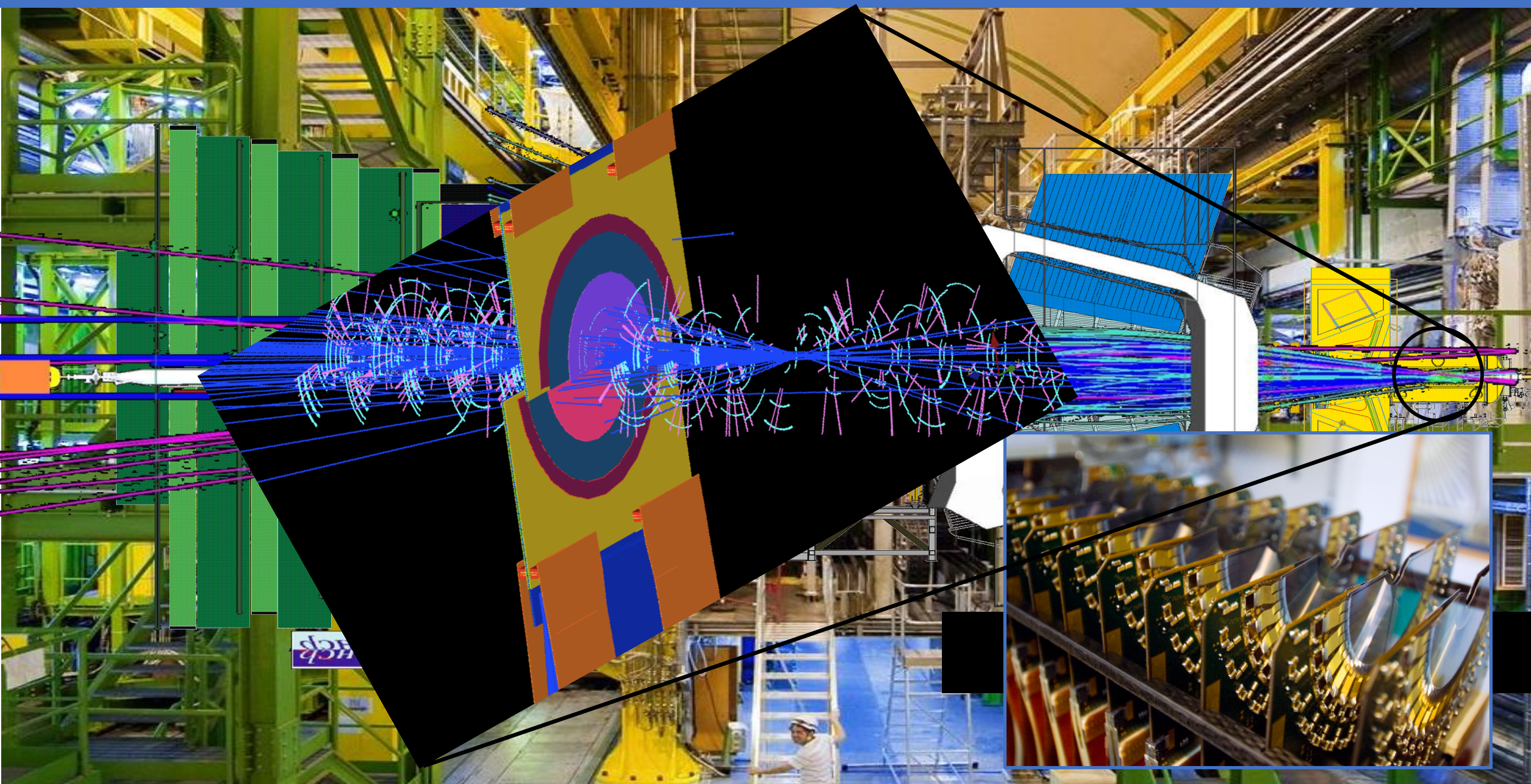
The LHCb Detector!



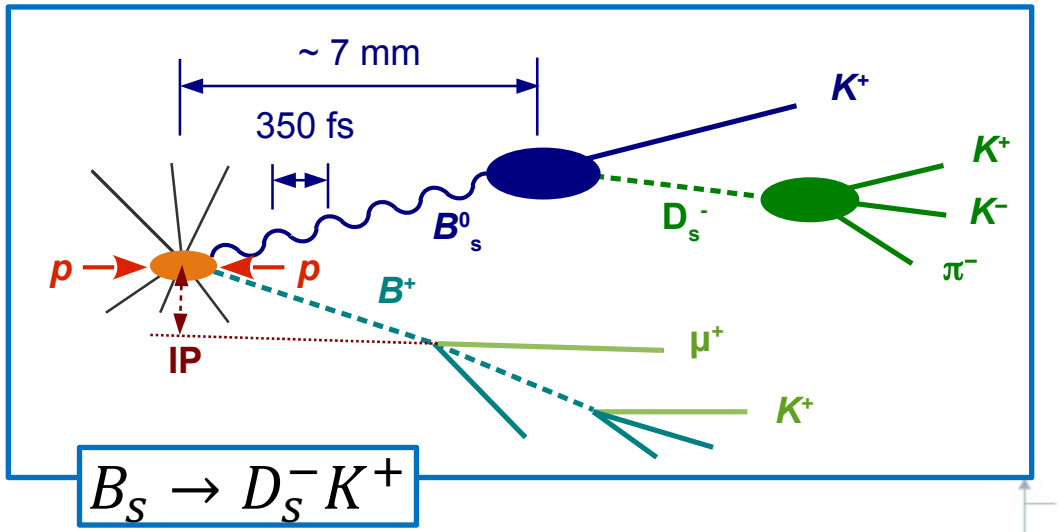
The LHCb Detector



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



B_s Physics at LHCb

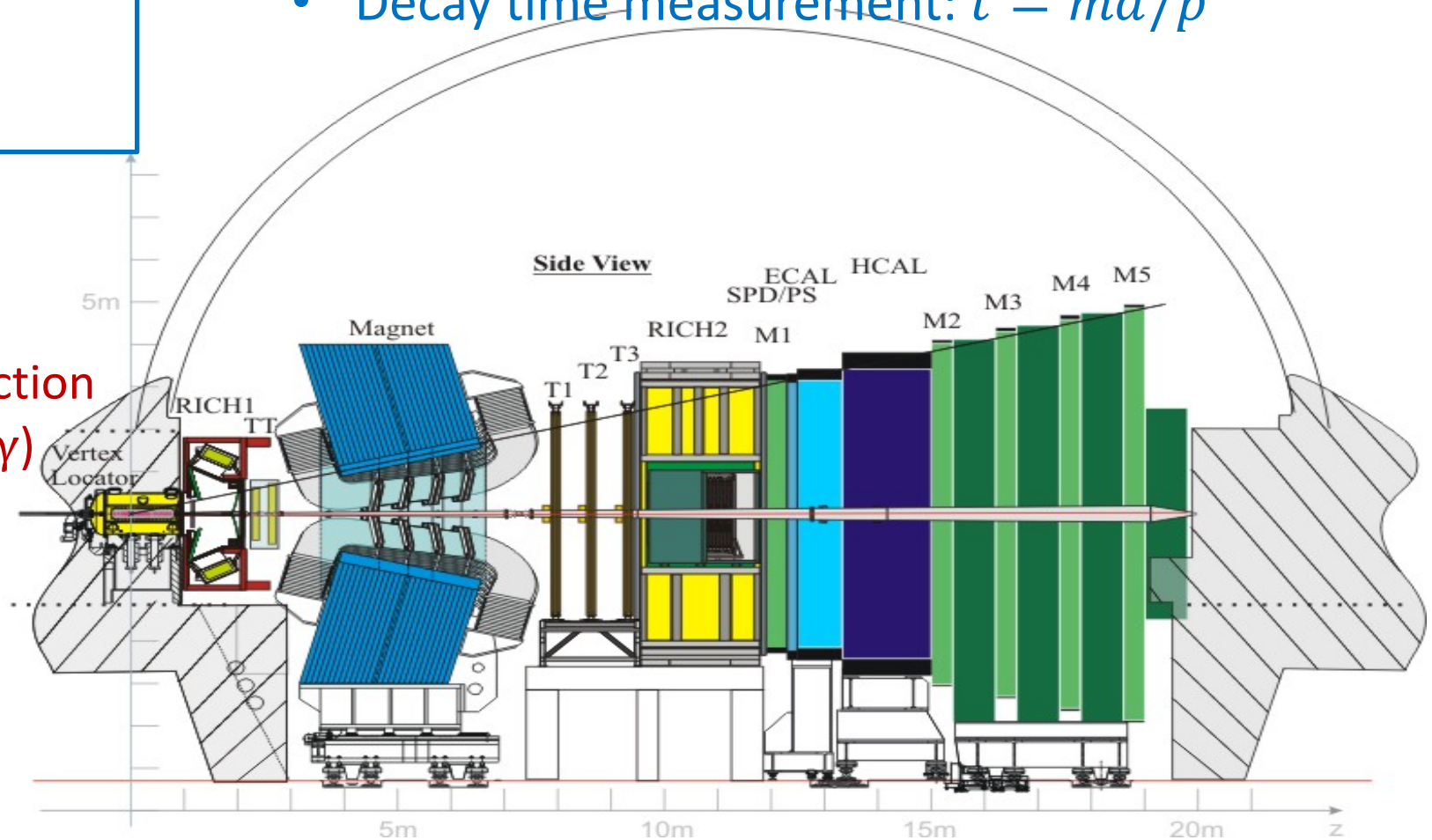


Physics Requirements:

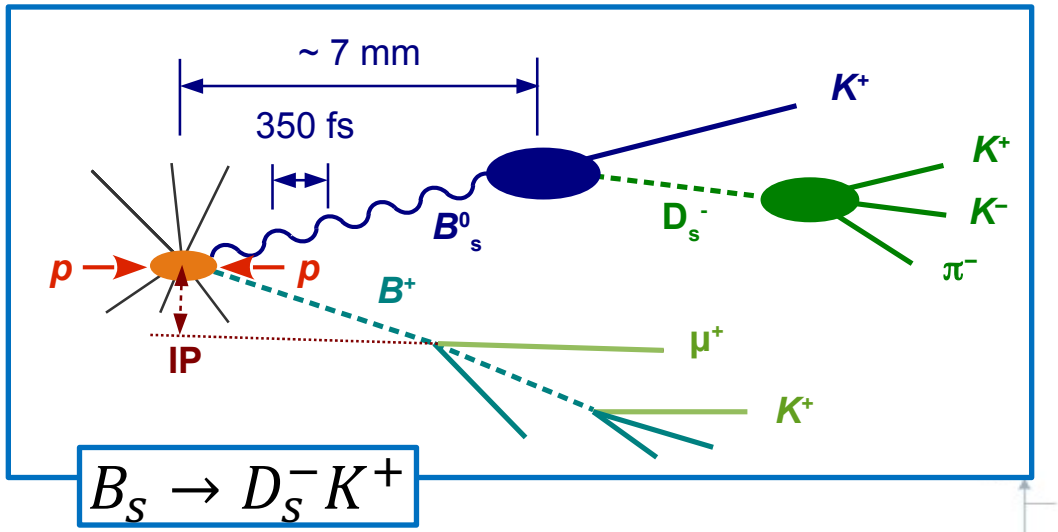
- Signal selection and background suppression
- Flavour tagging: B or $\overline{B}$ at production
- Decay time measurement: $t = md/p$

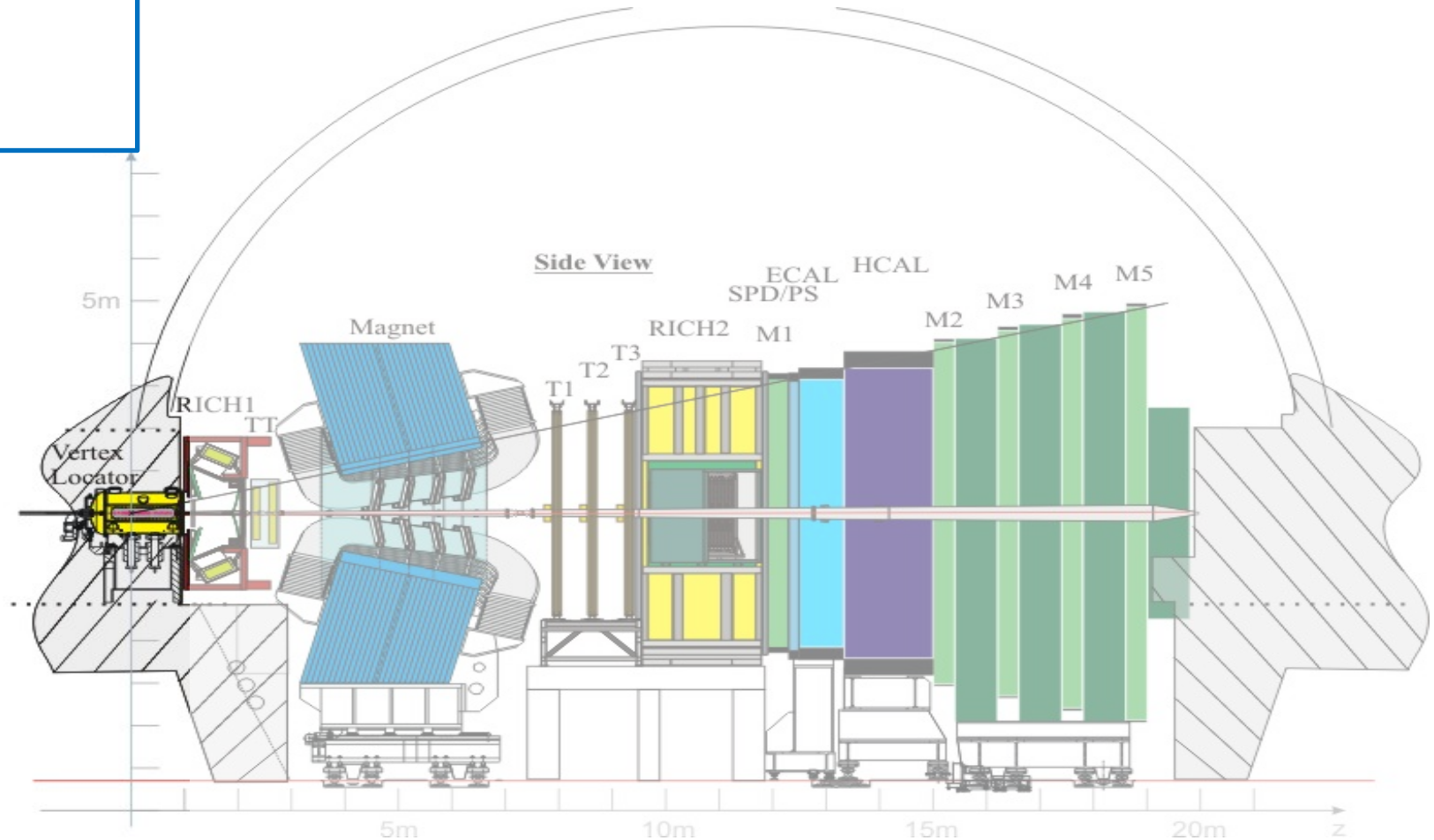
Detector Requirements:

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

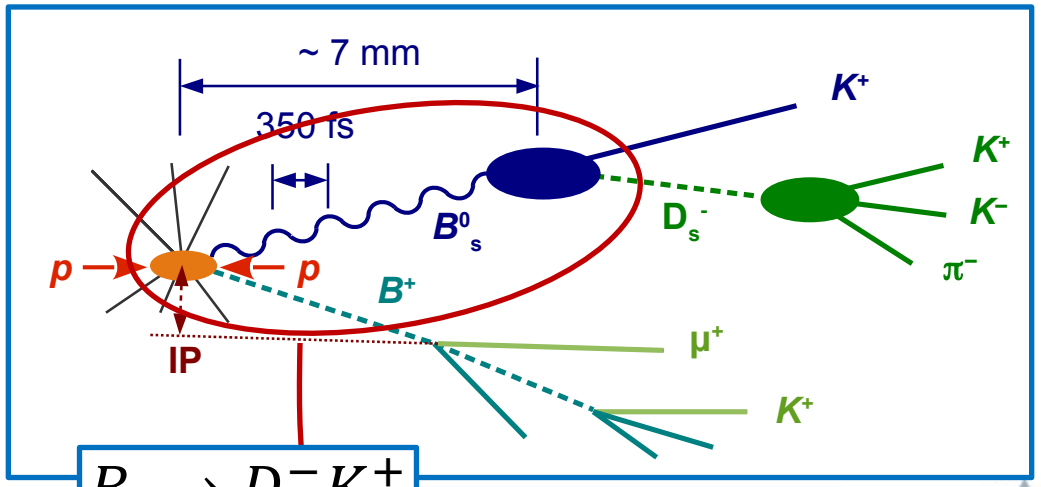


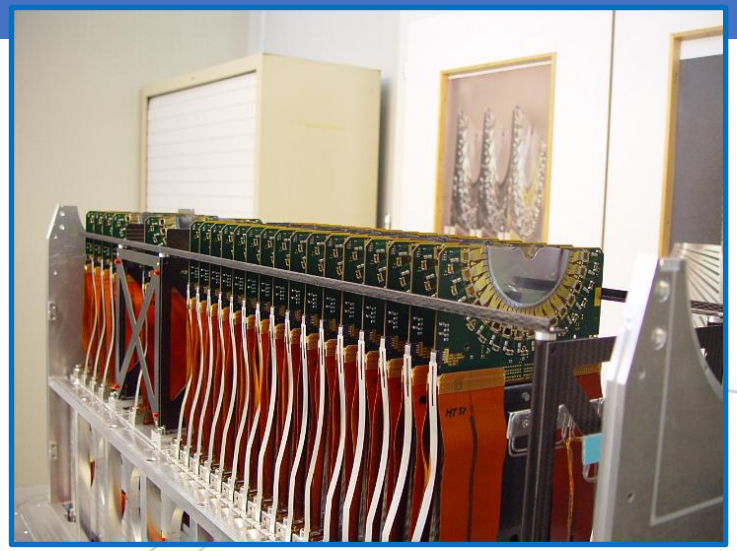
B_s Physics at LHCb - Vertex reconstruction

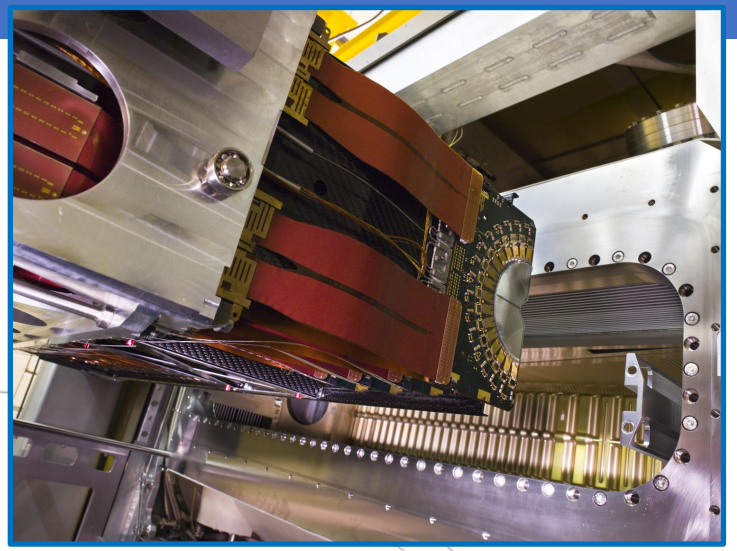




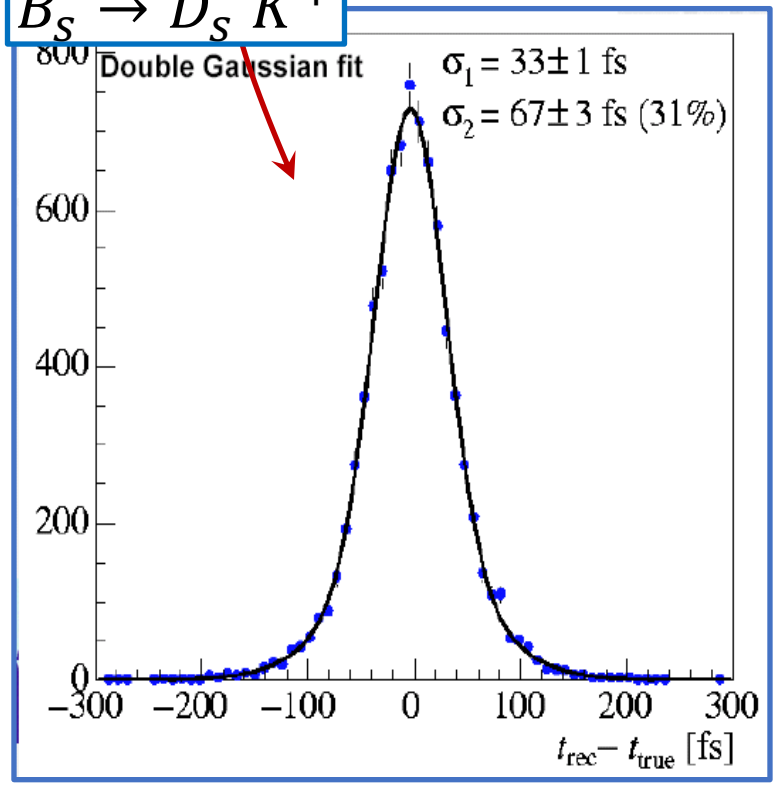
B_s Physics at LHCb - Vertex reconstruction

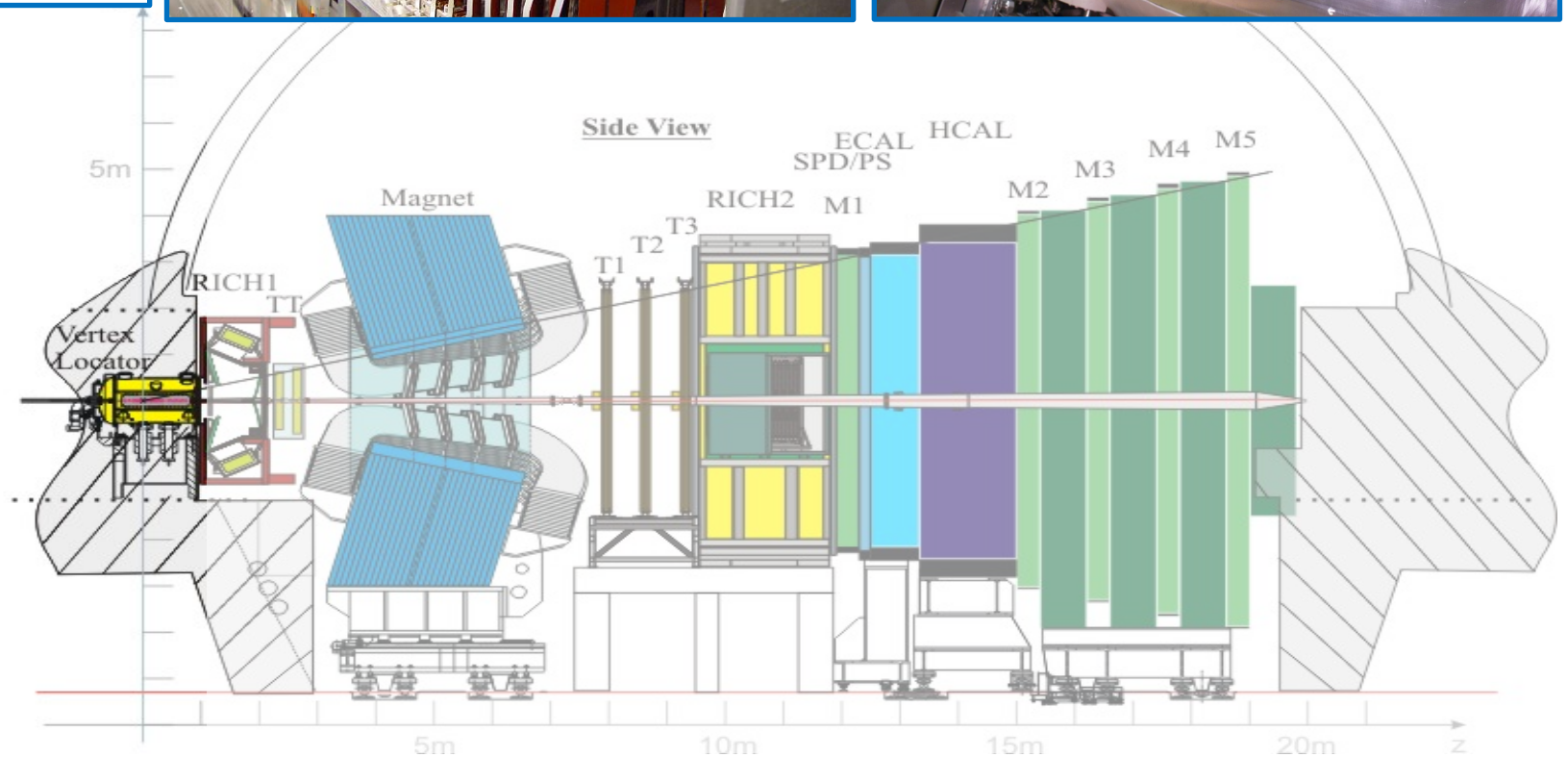




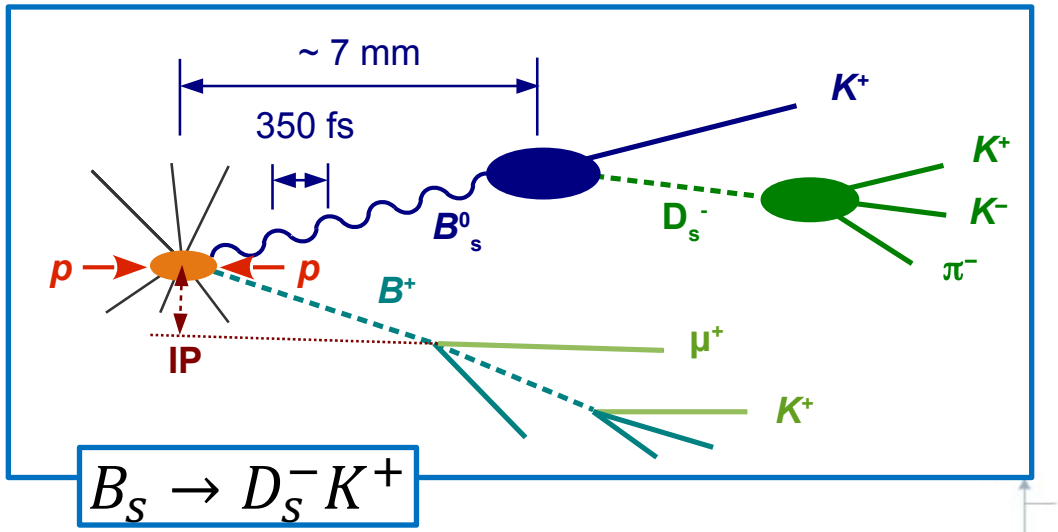


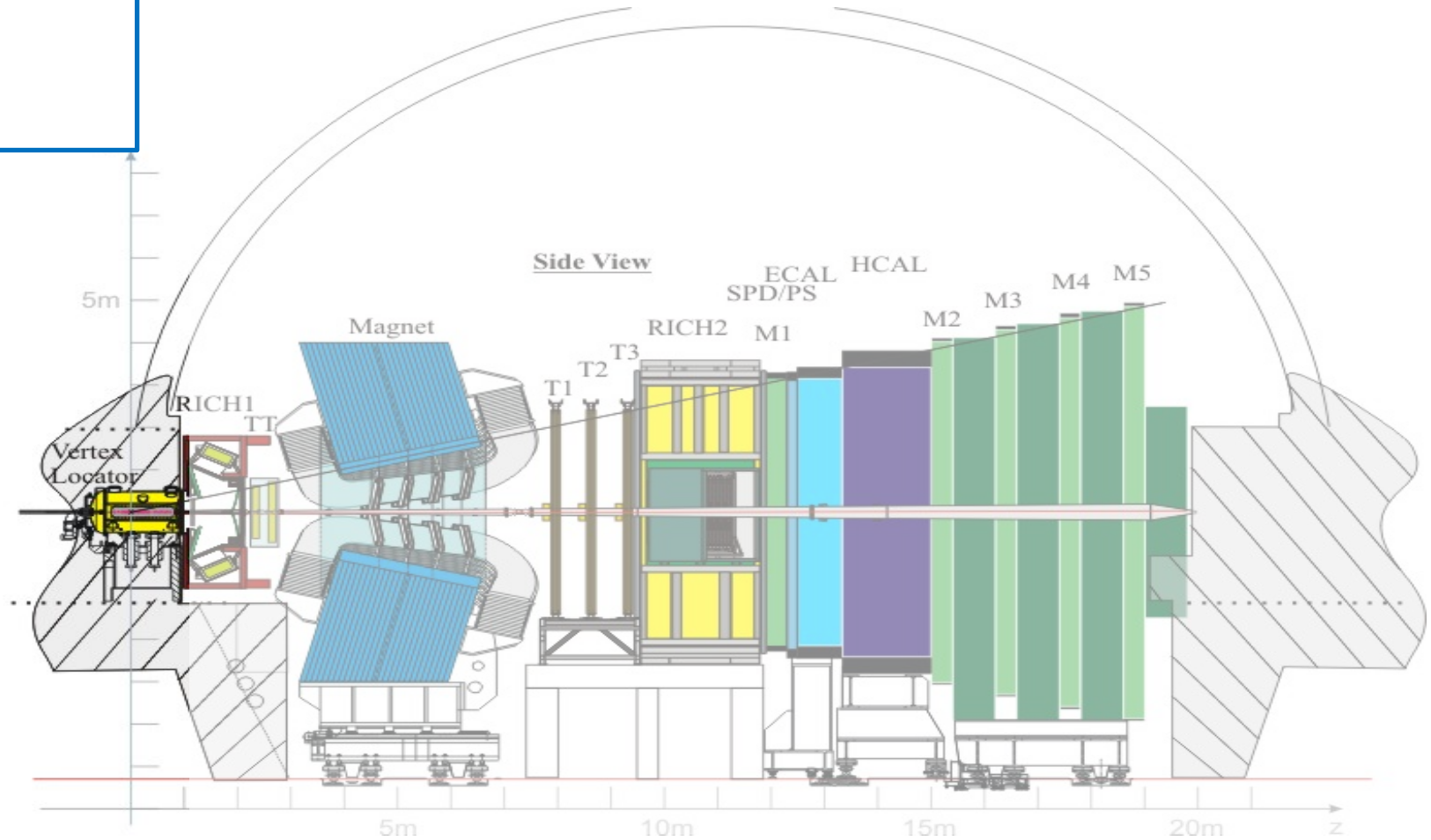
$B_s \to D_s^- K^+$



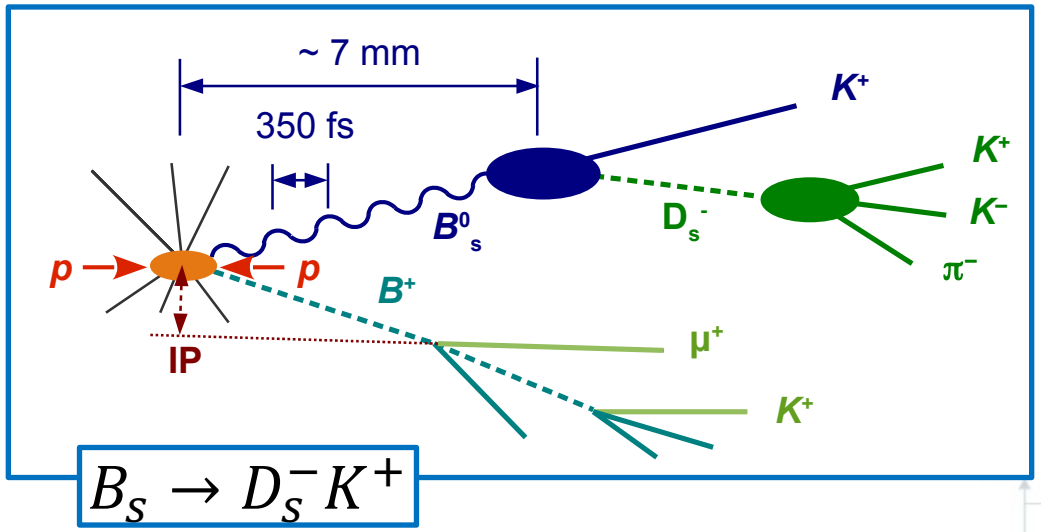


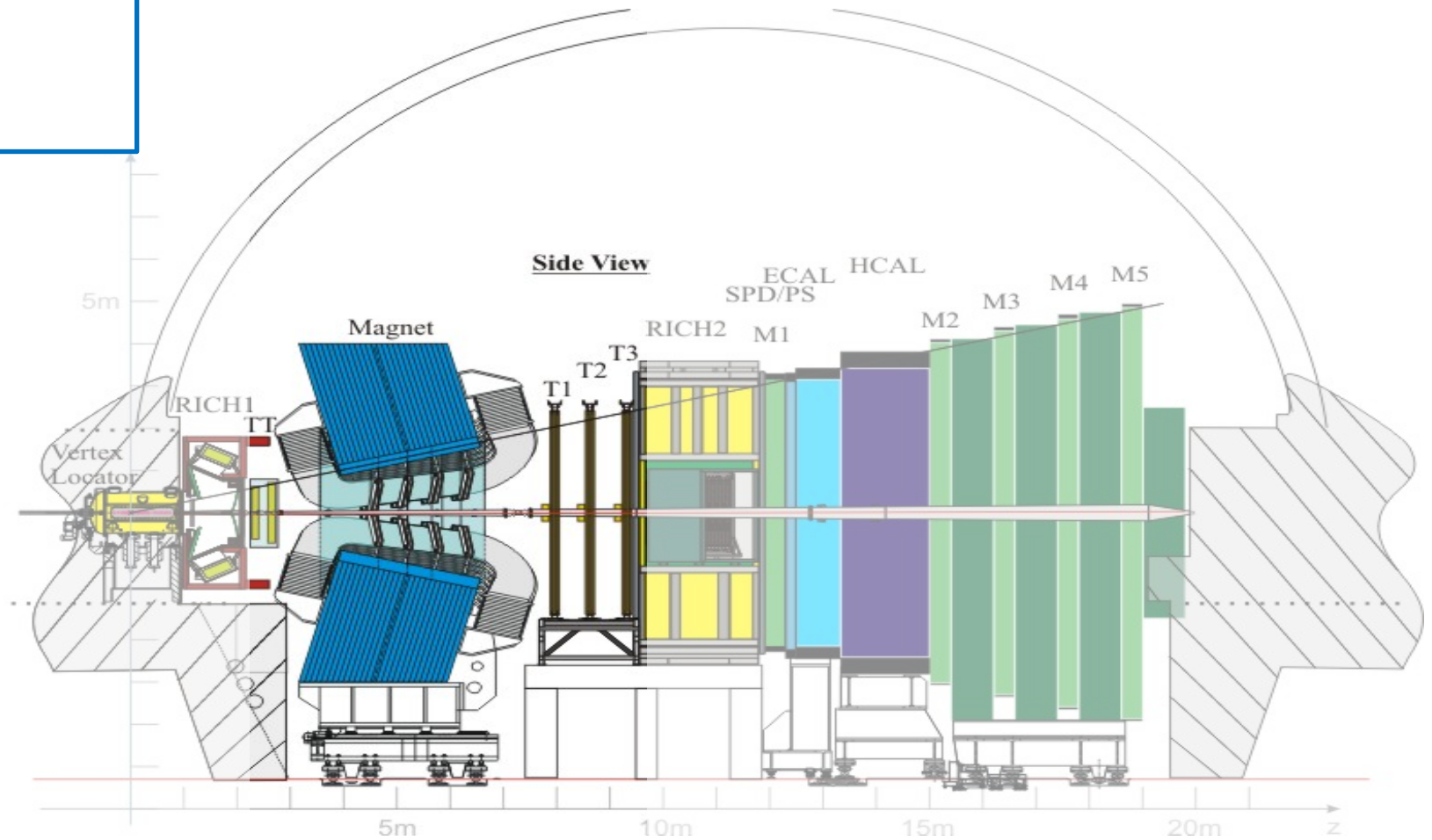
B_s Physics at LHCb



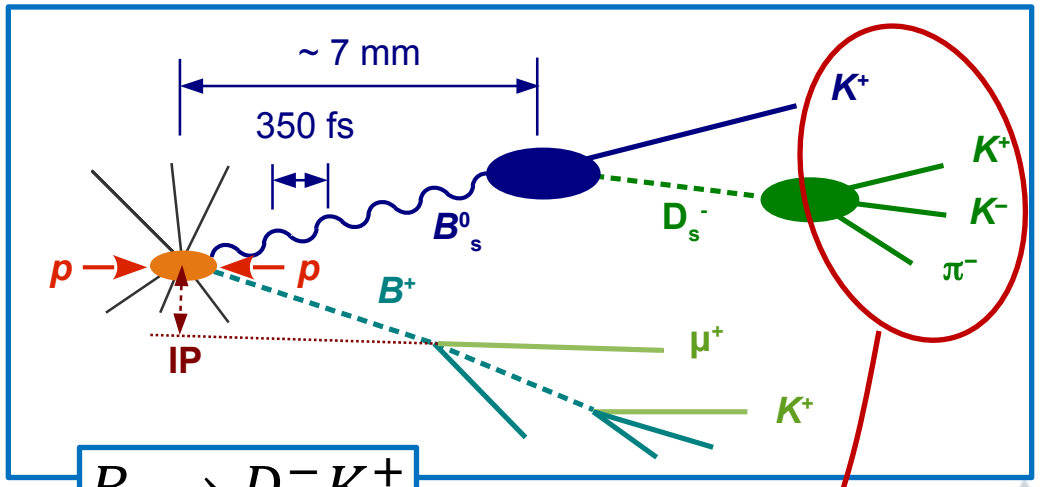


B_s Physics at LHCb – momentum and mass determination

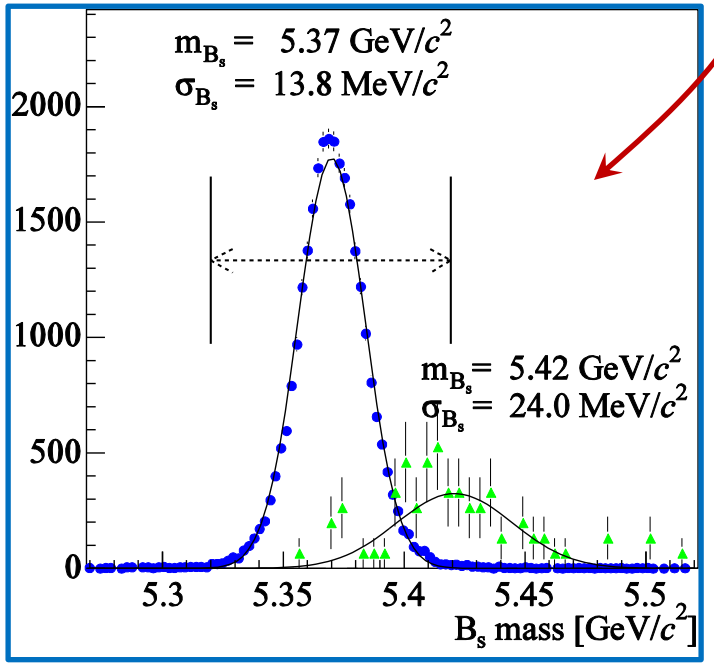


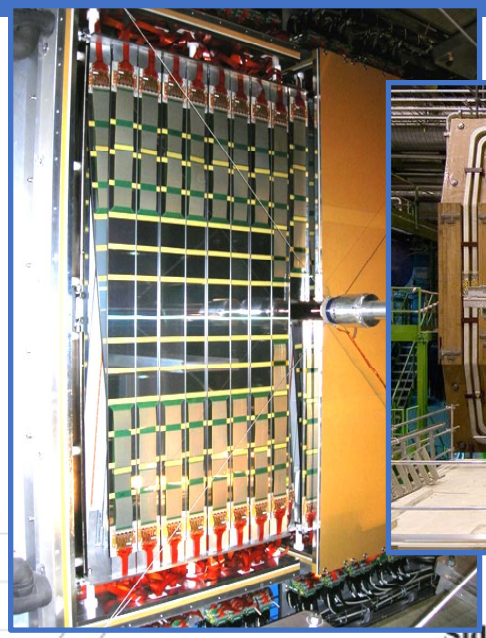


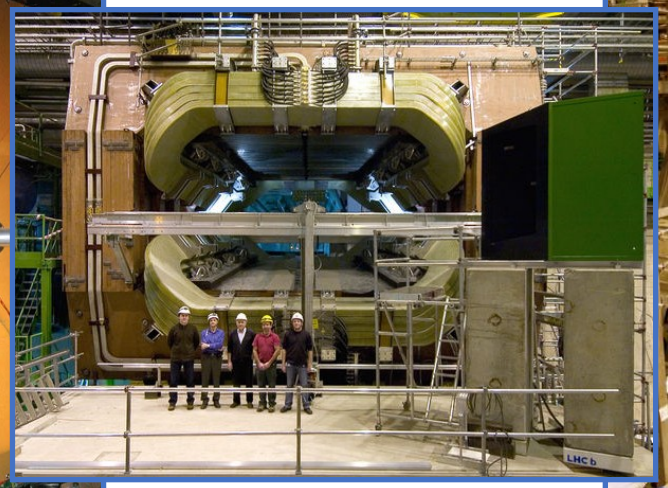
B_s Physics at LHCb – momentum and mass determination

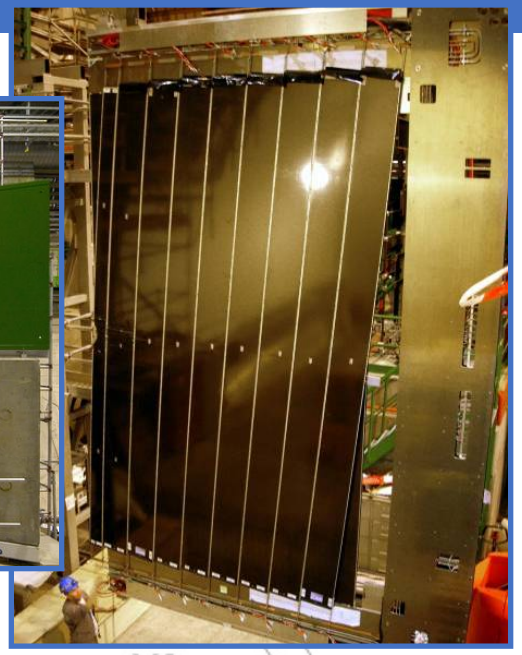


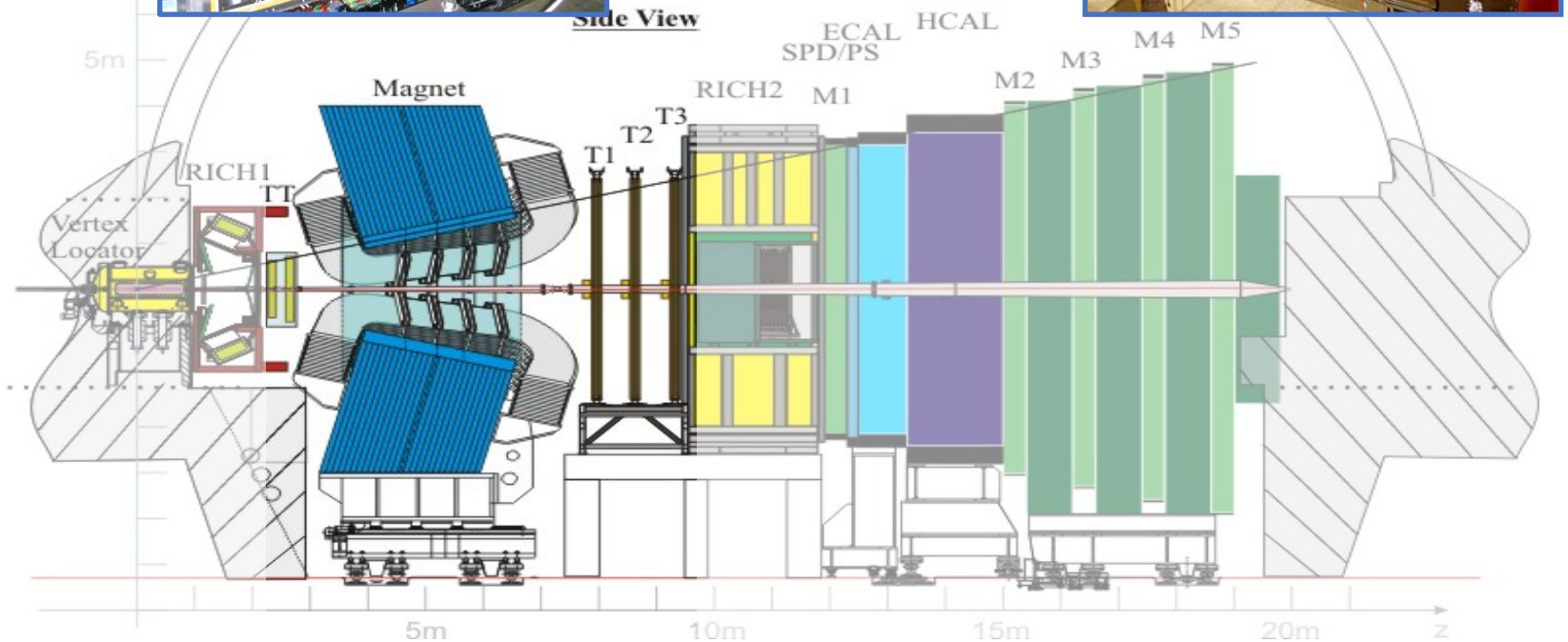
$B_s \to D_s^- K^+$



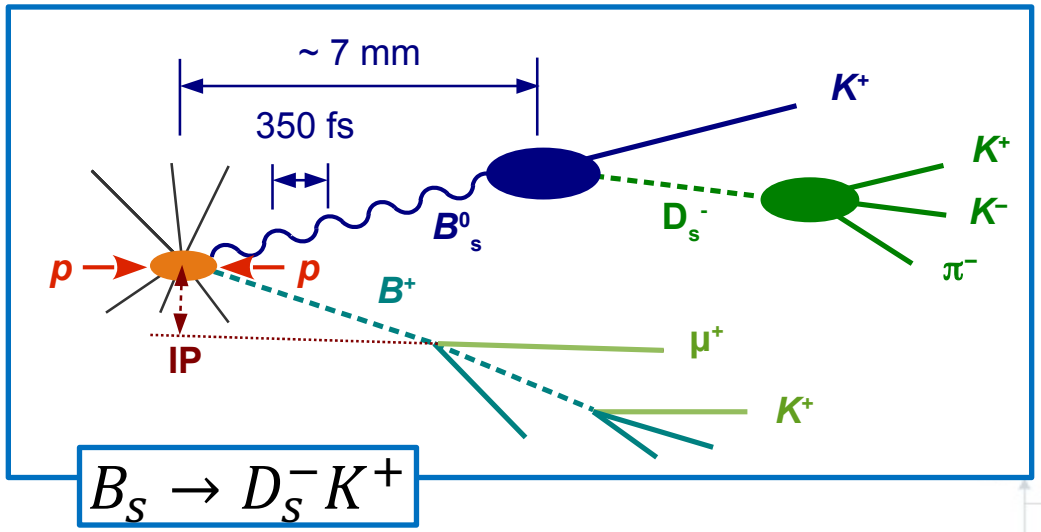


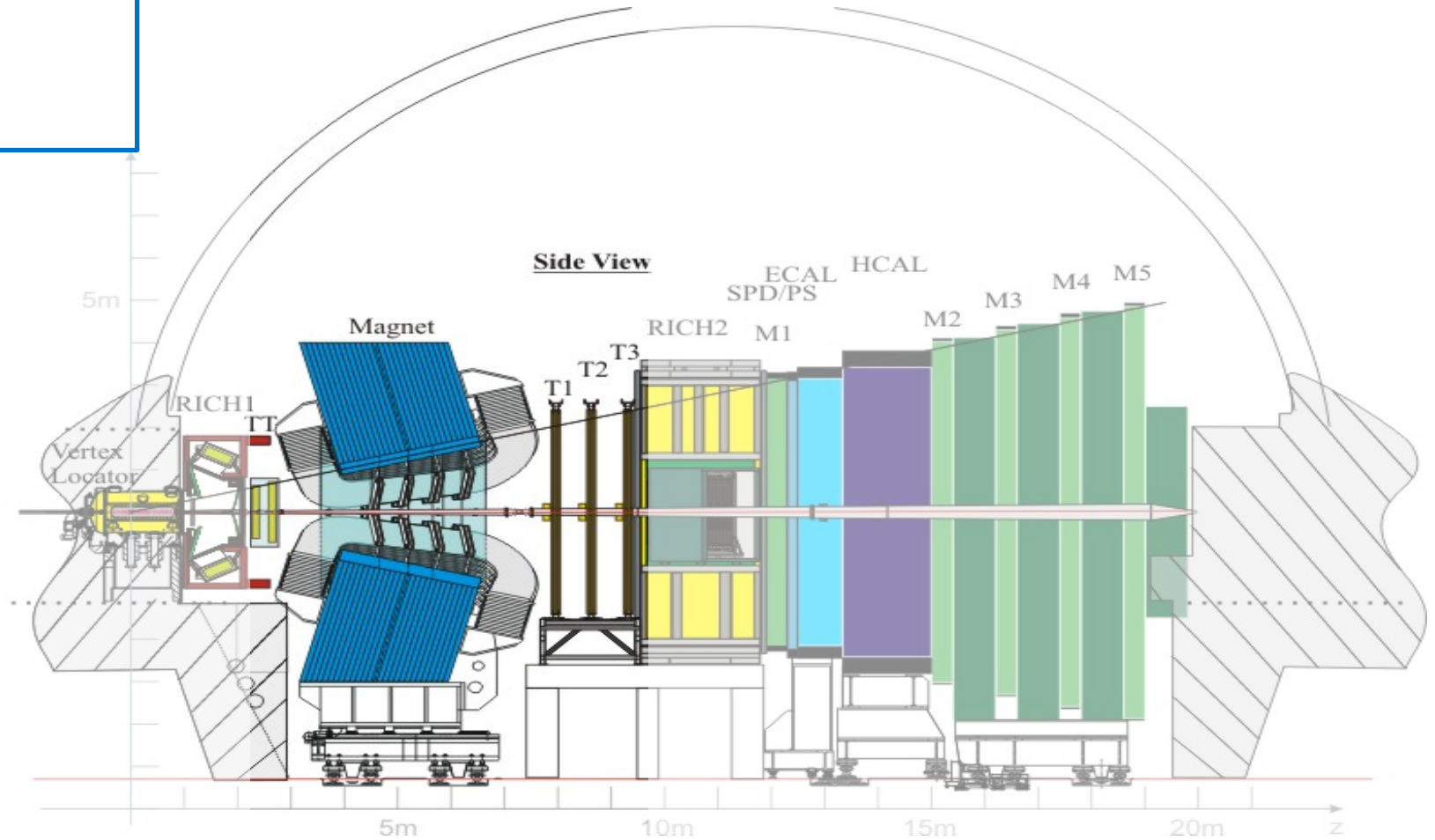




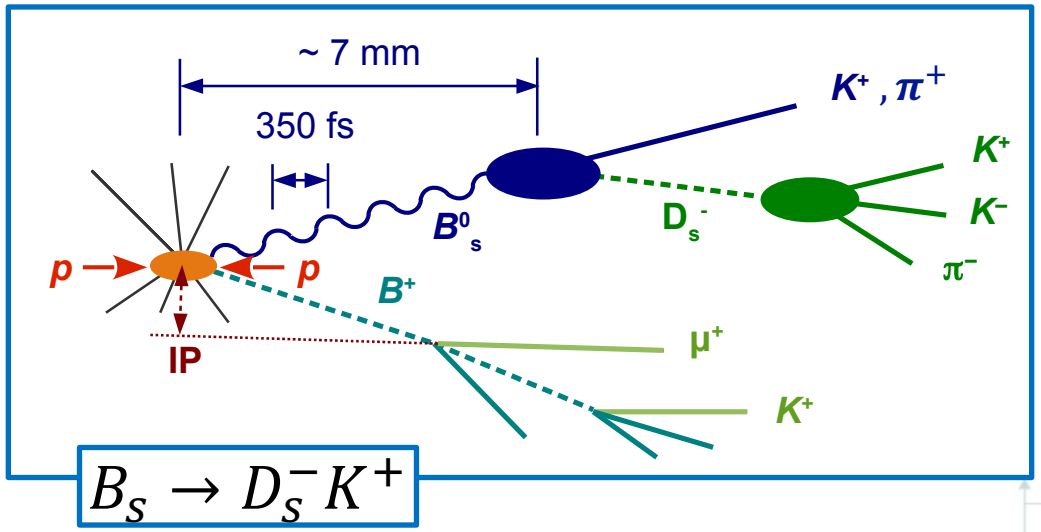


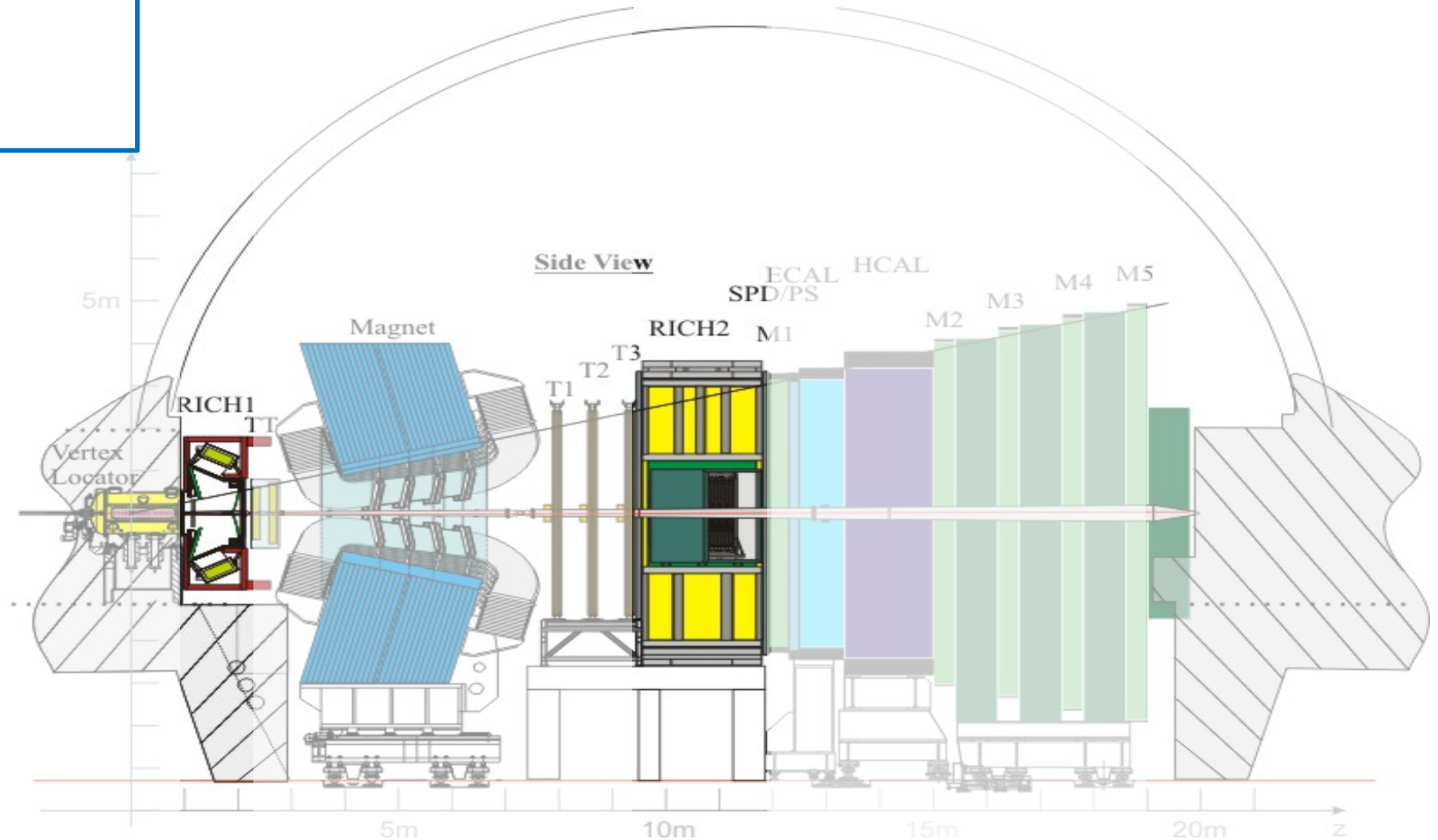
B_s Physics at LHCb



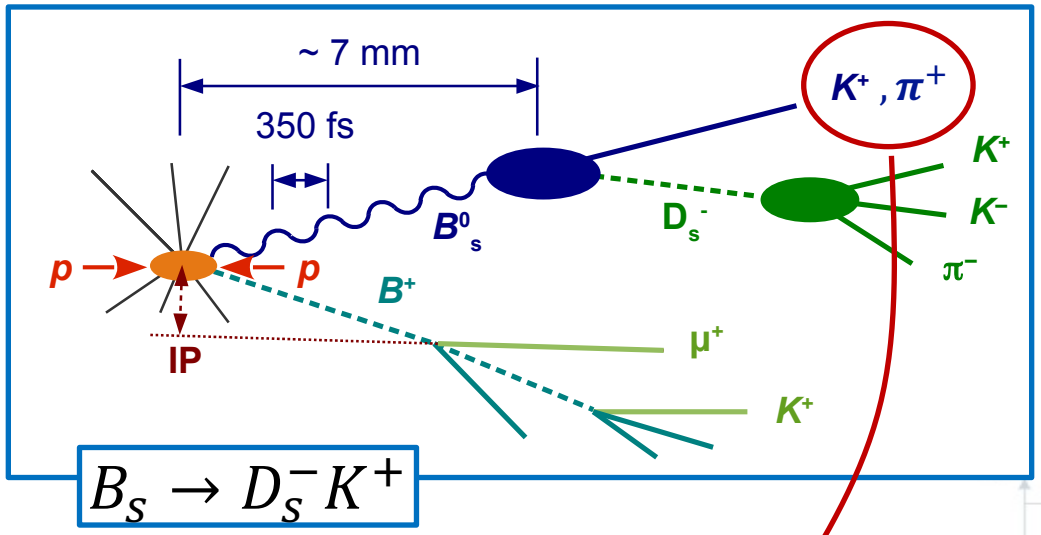


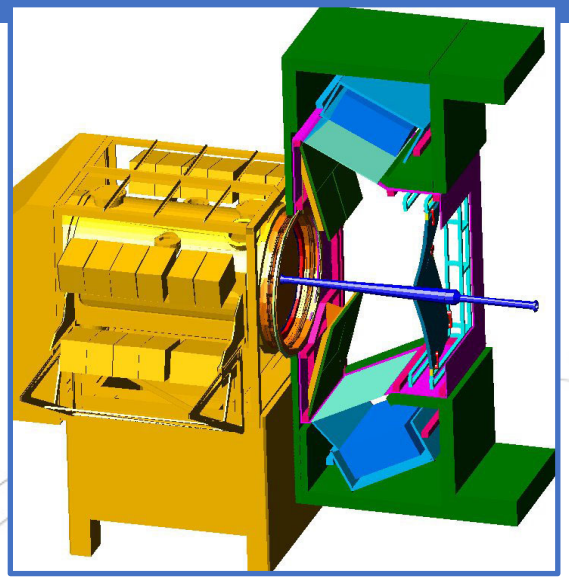
B_s Physics at LHCb – Particle Identification with RICH

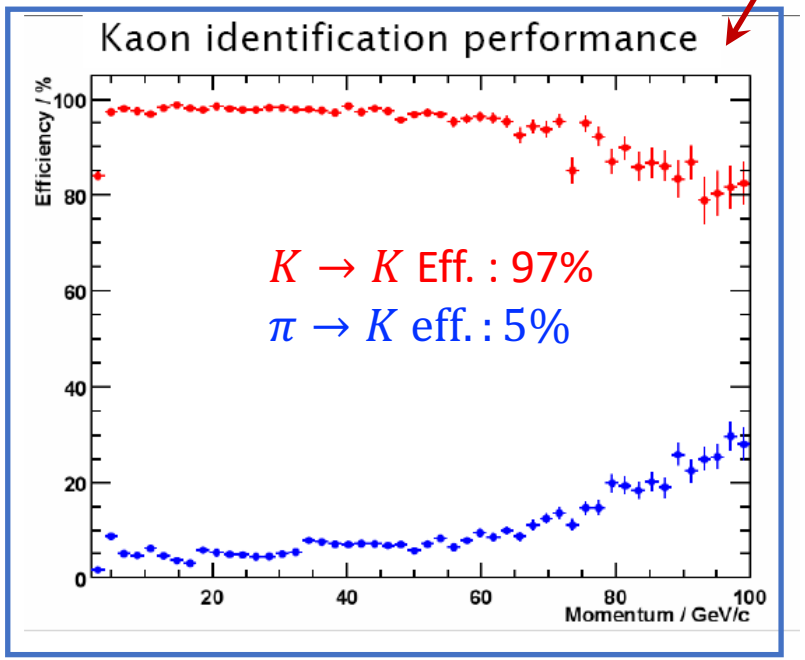


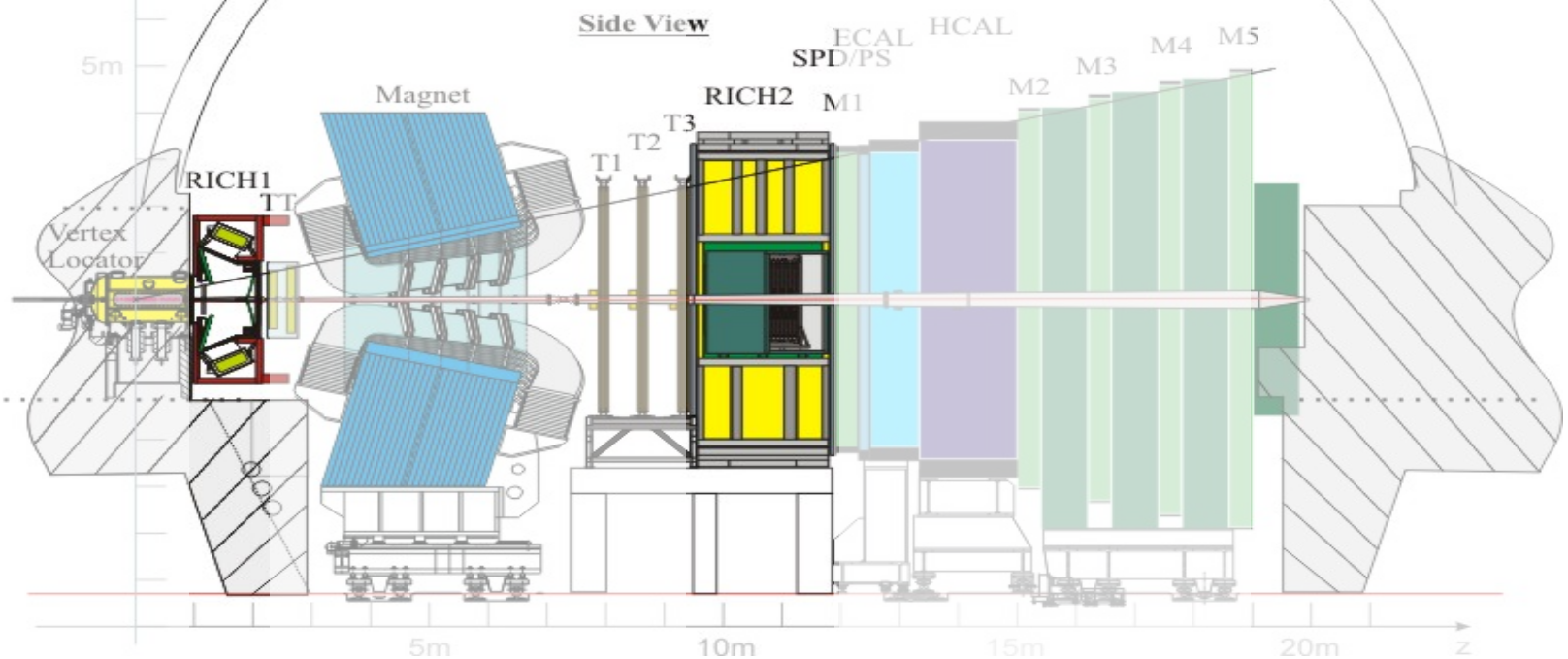


B_s Physics at LHCb – Particle Identification with RICH

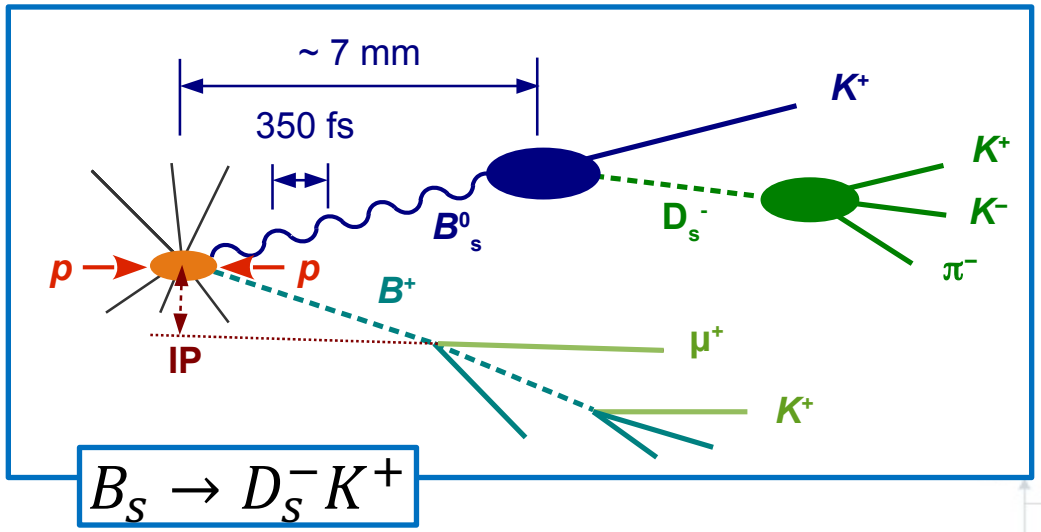


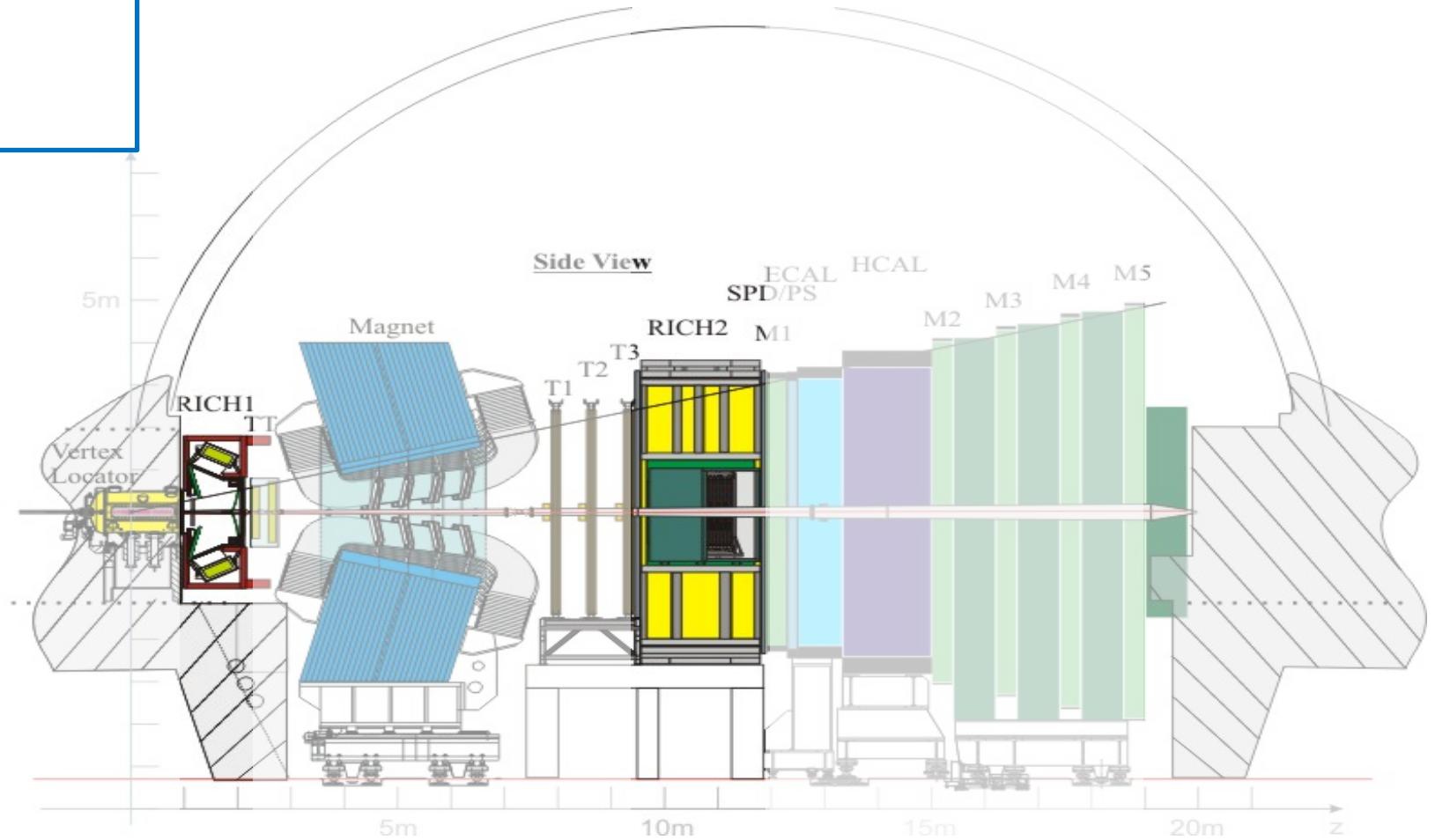




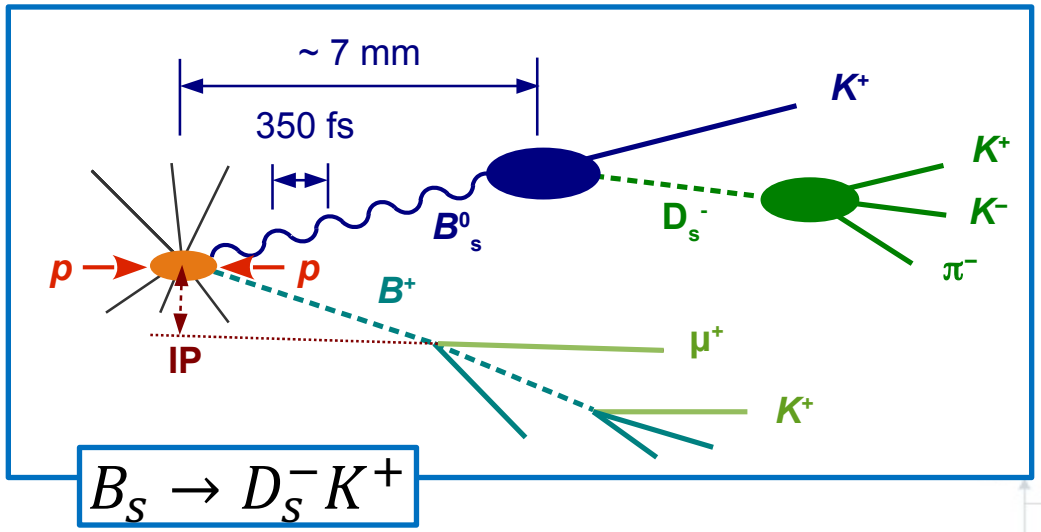


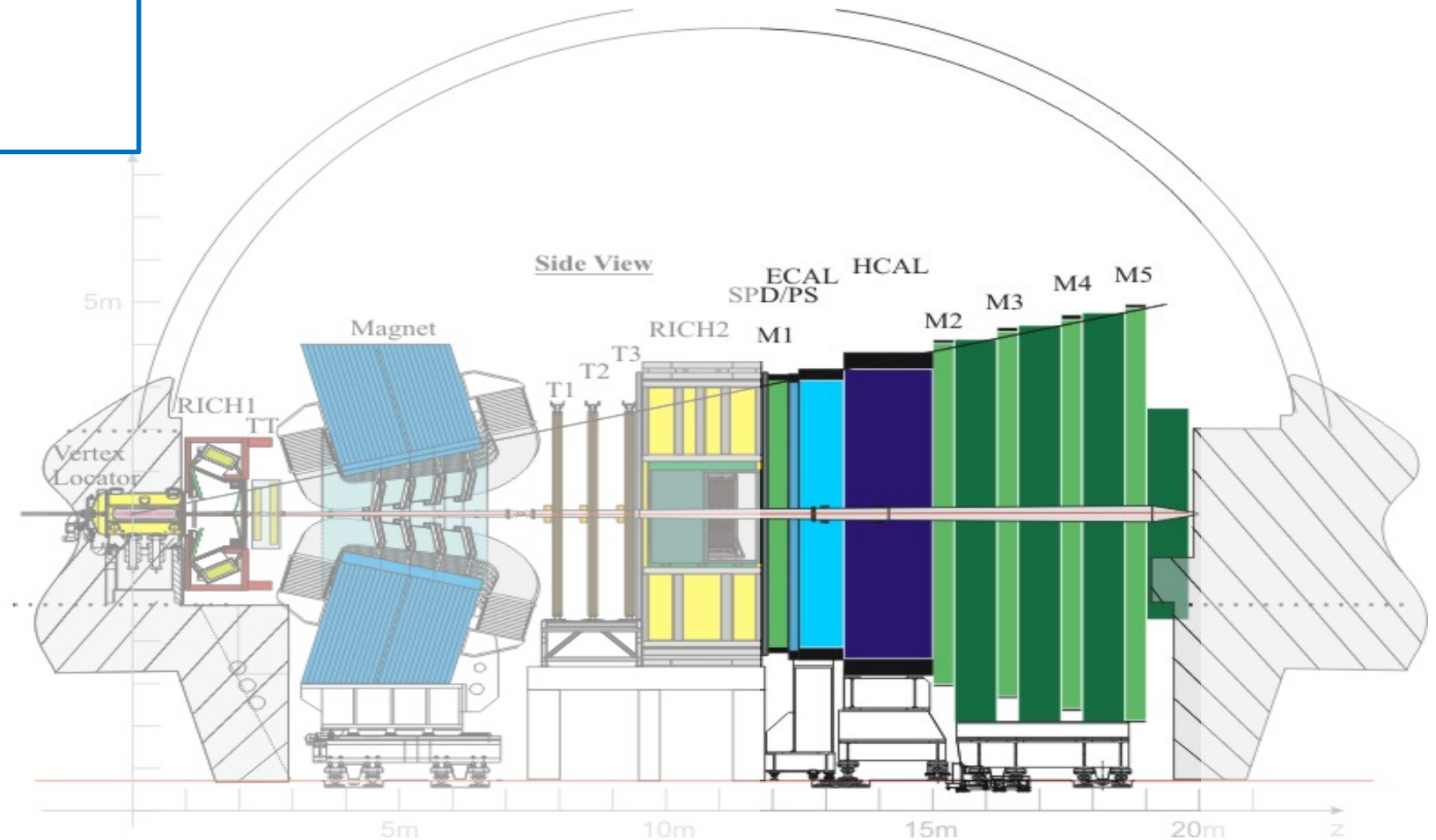
B_s Physics at LHCb



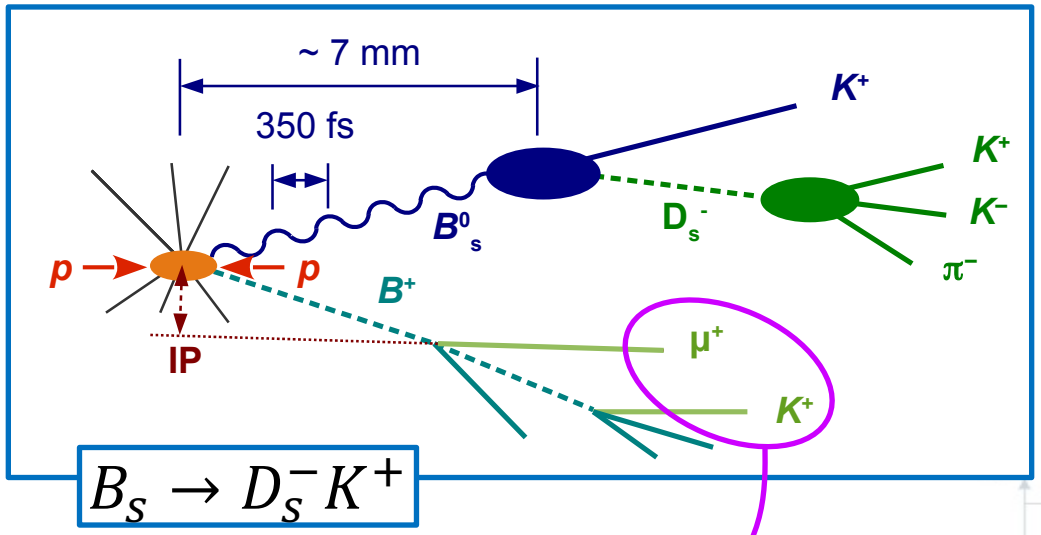


B_s Physics at LHCb – Trigger/Tag with Calorimeters and Muon

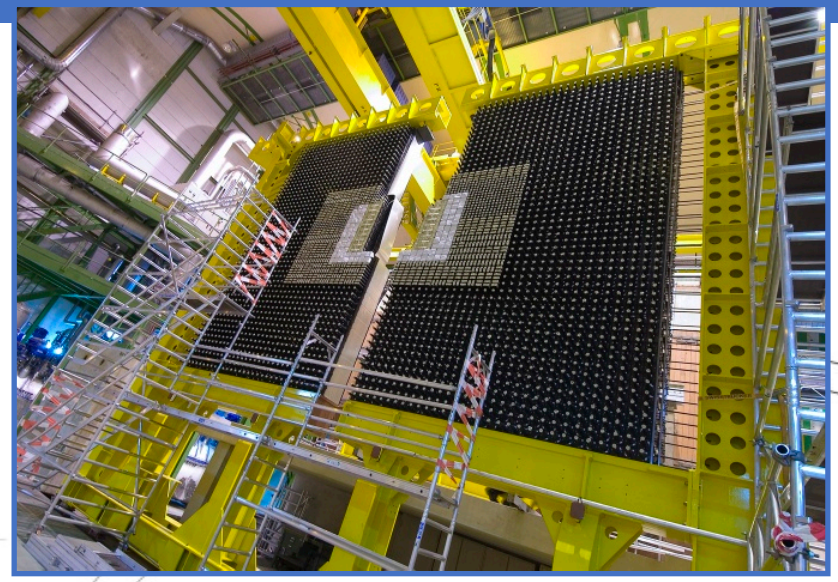


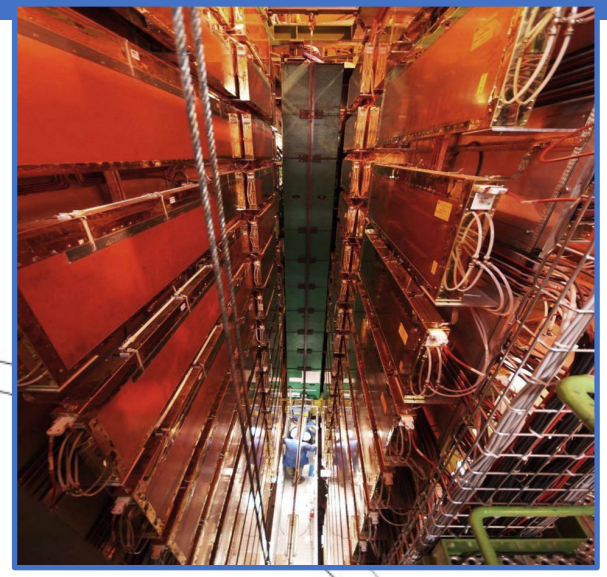


B_s Physics at LHCb – Trigger/Tag with Calorimeters and Muon



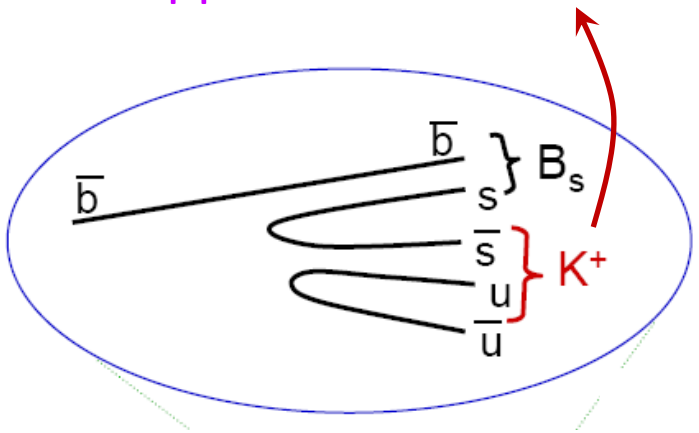
$B_s \to D_s^- K^+$

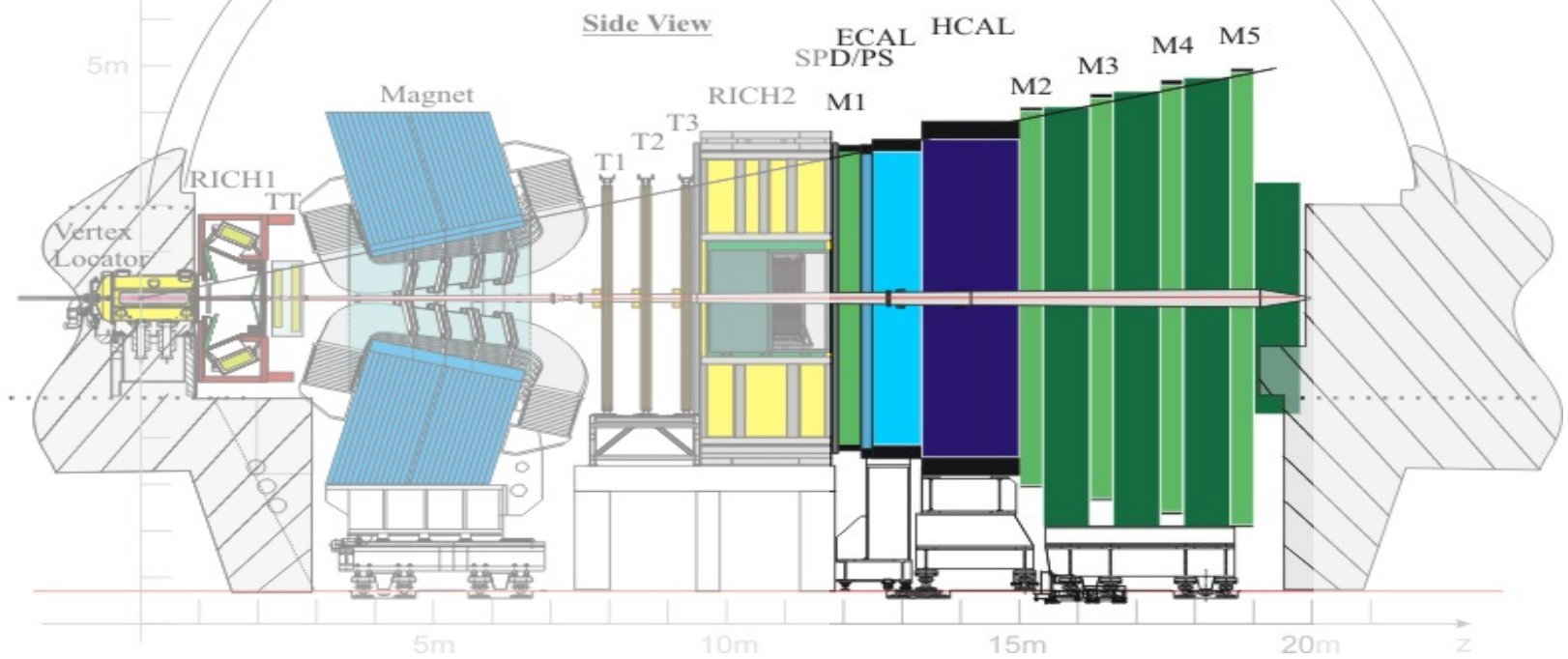




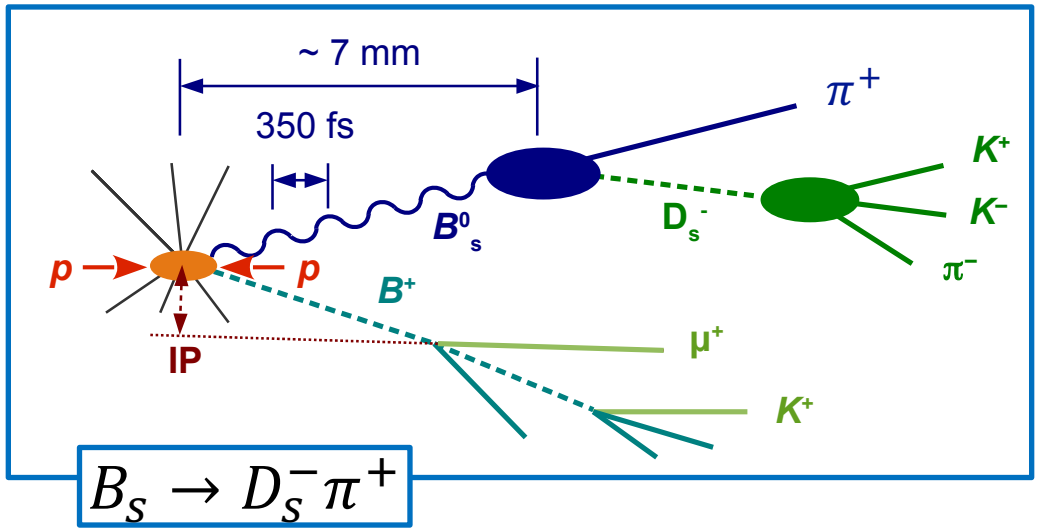
Identification of γ, e , μ:

- Triggering
- Flavour tagging:
  - Opposite or same side





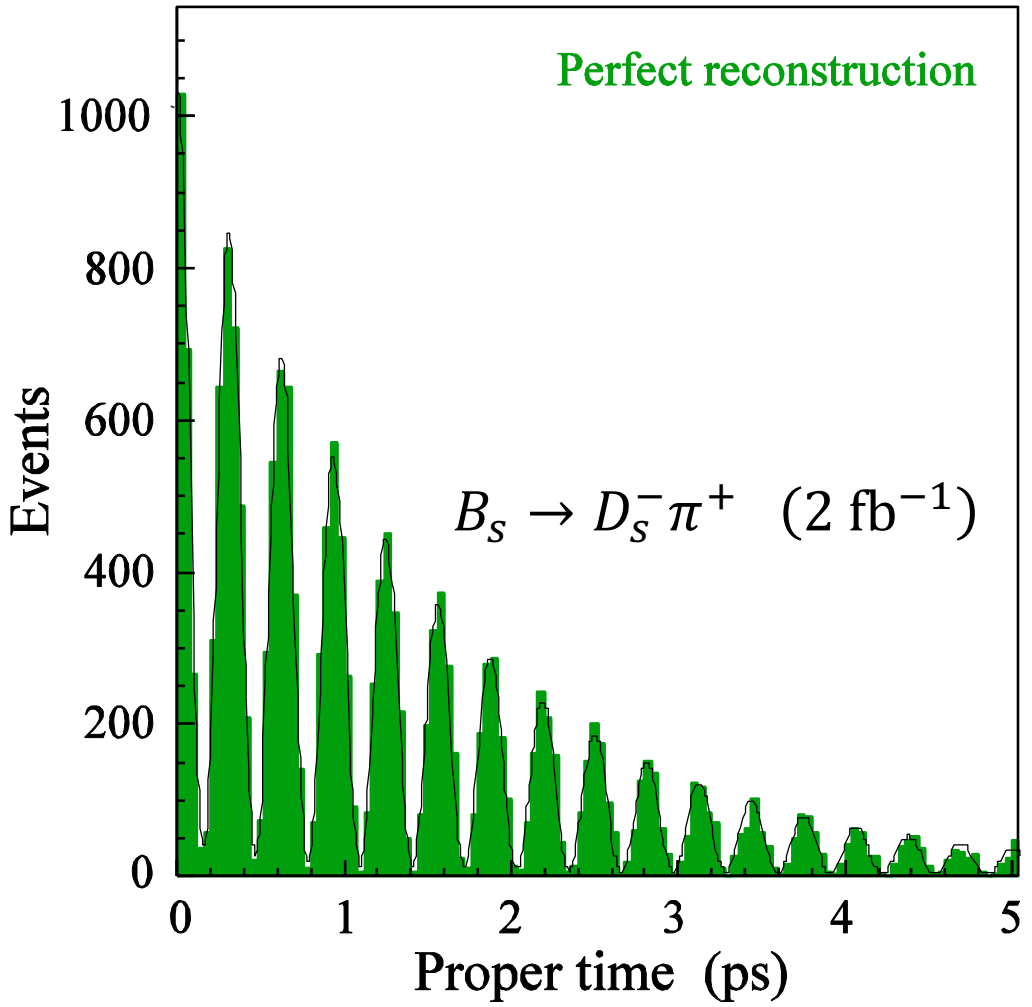
Measuring B_s - $\overline{B_s}$ Oscillations (Self tagging $B_s \to D_s\pi$)



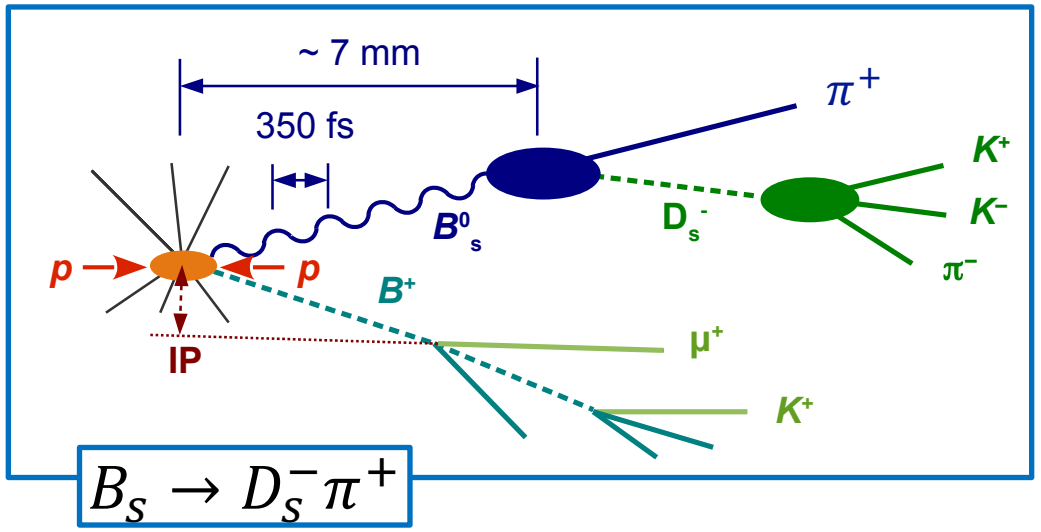
Experimental Situation:

Ideal measurement (no dilutions)

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations

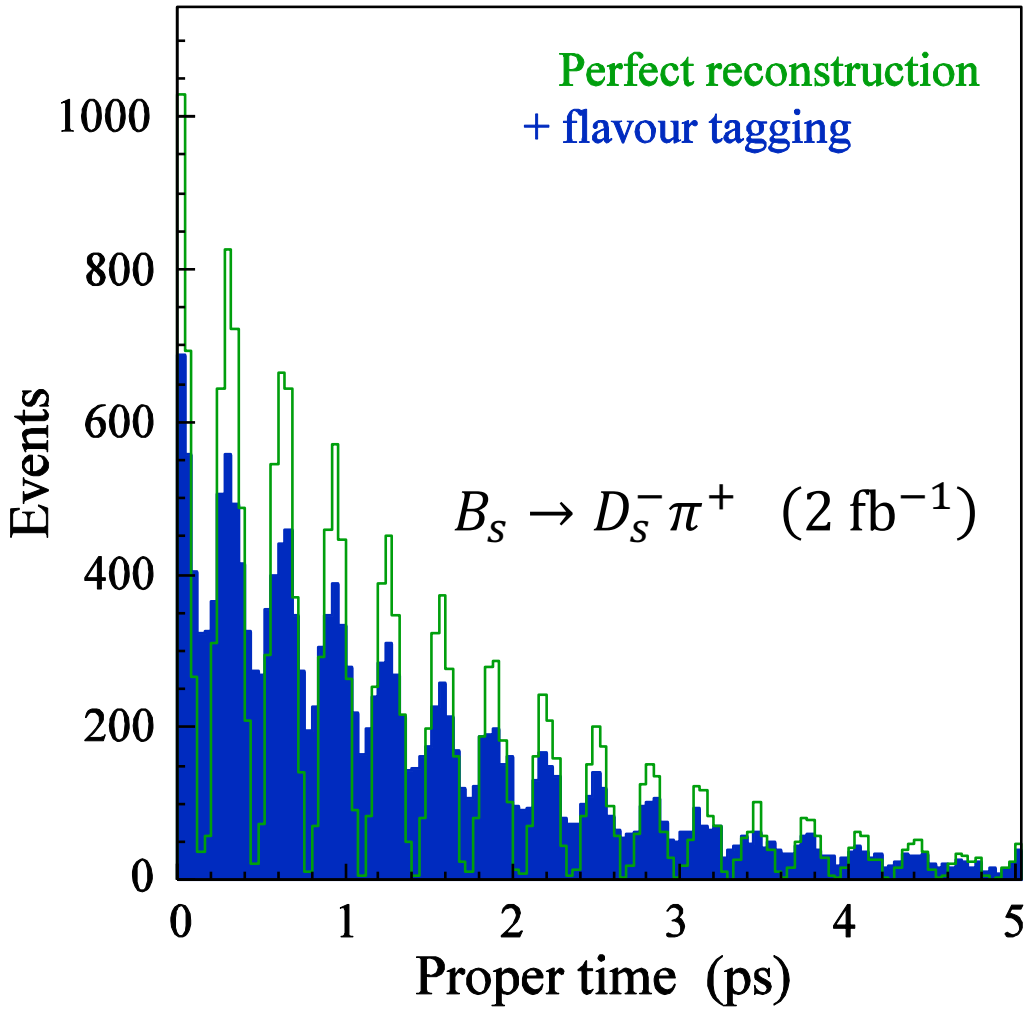


Experimental Situation:

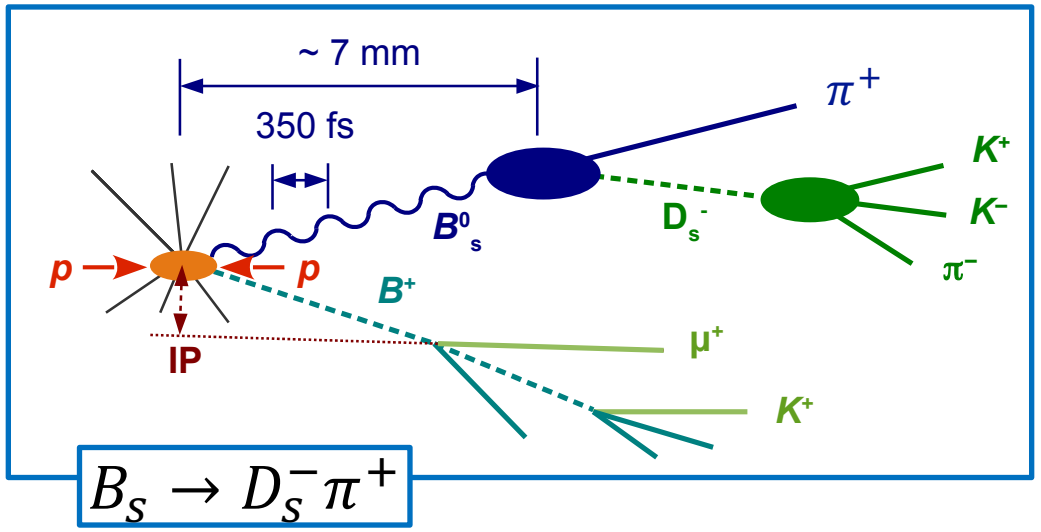
Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



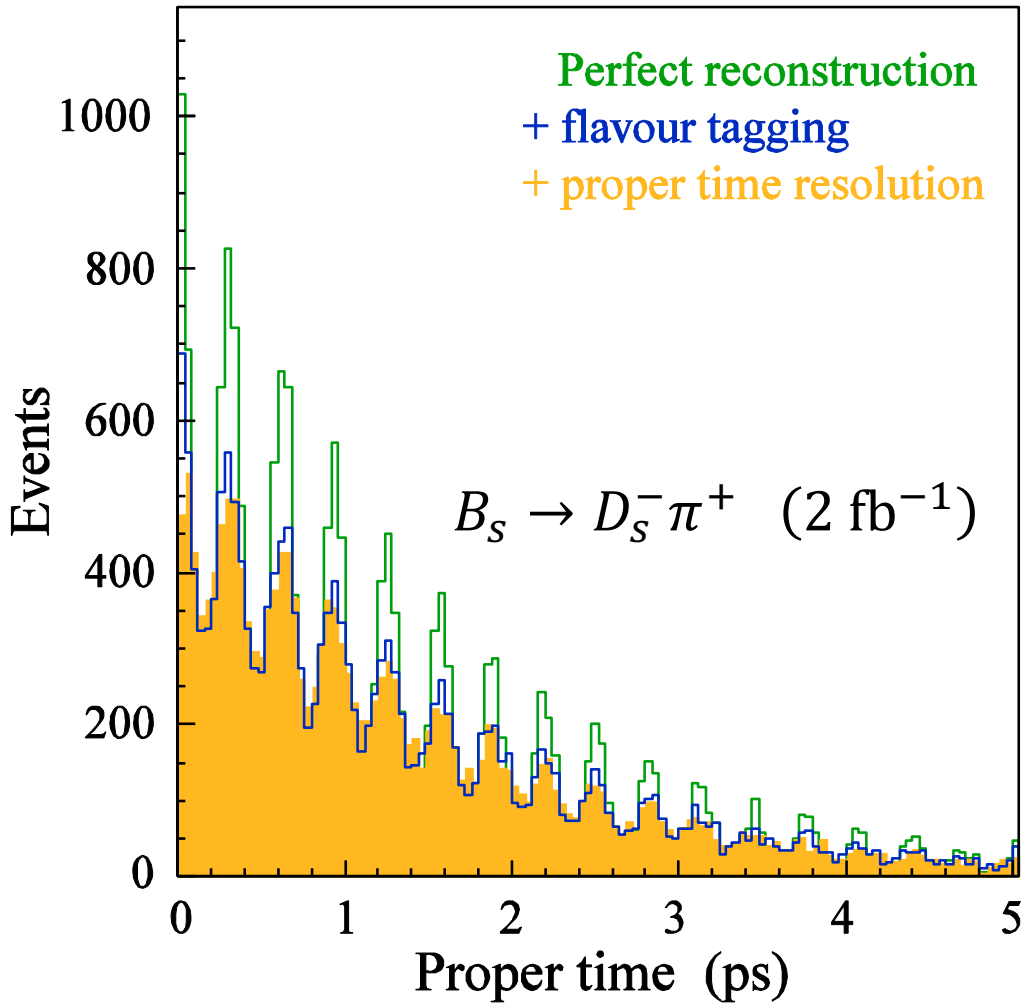
Experimental Situation:

Ideal measurement (no dilutions)

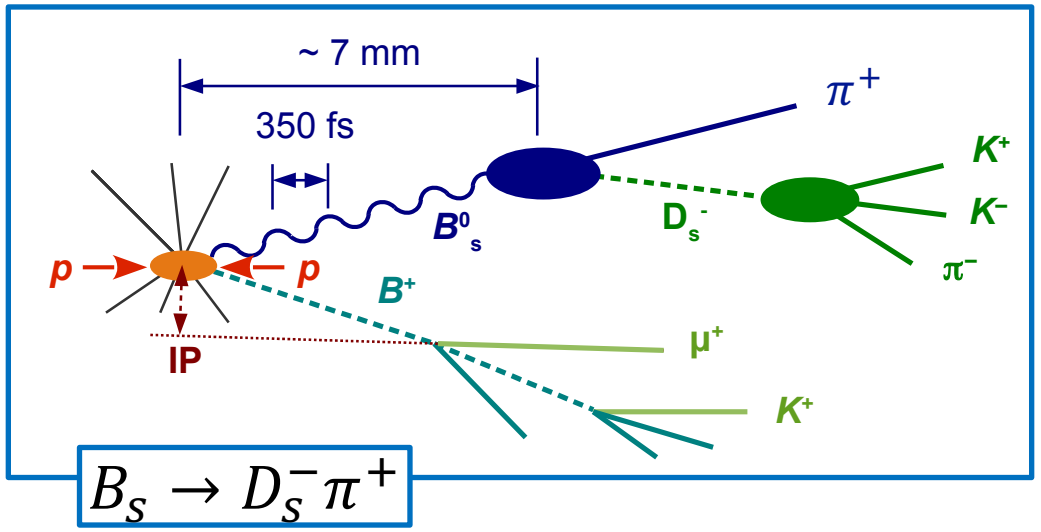
+ Realistic flavour tagging dilution

+ Realistic decay time resolution

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



Experimental Situation:

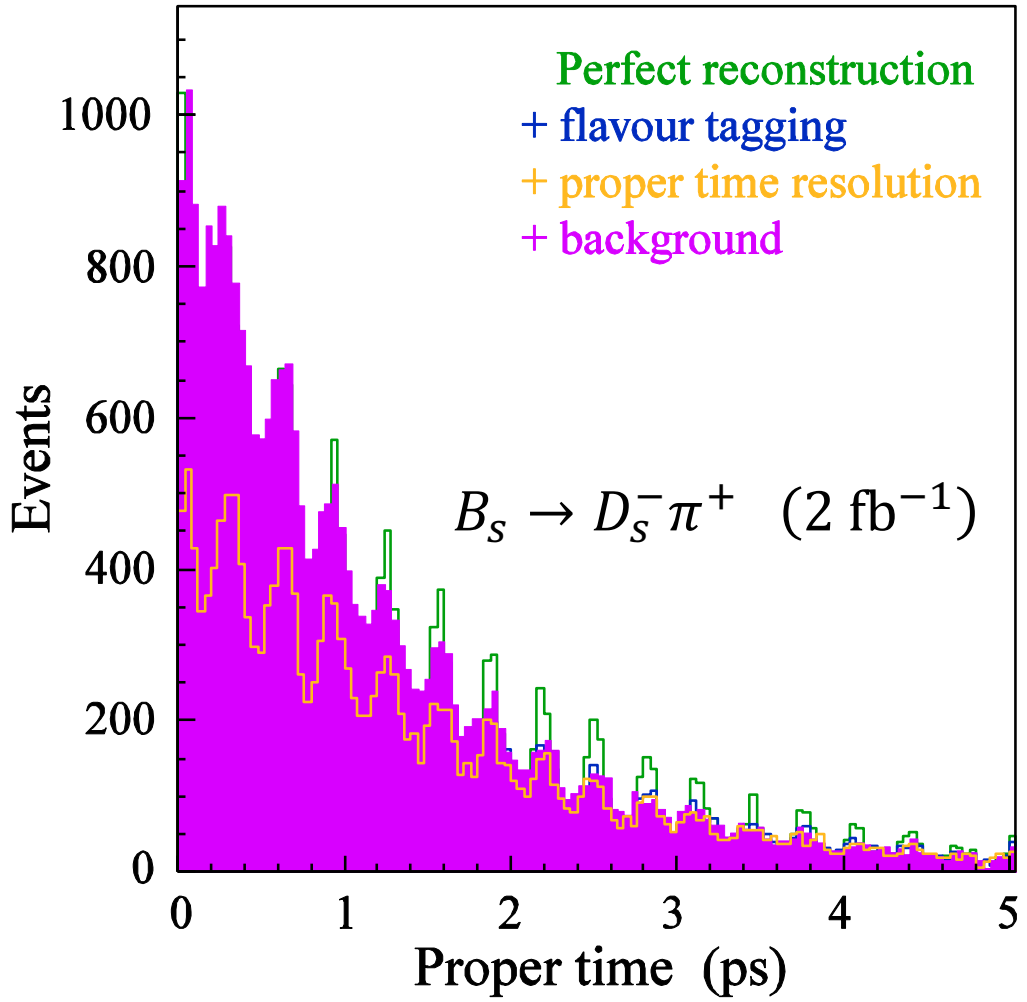
Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution

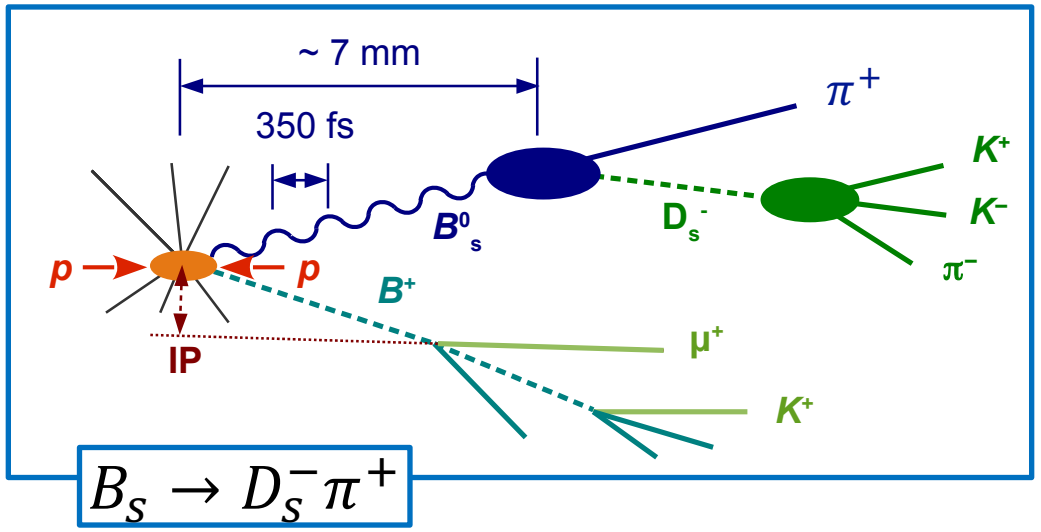
+ Realistic decay time resolution

+ Background events

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



Experimental Situation:

Ideal measurement (no dilutions)

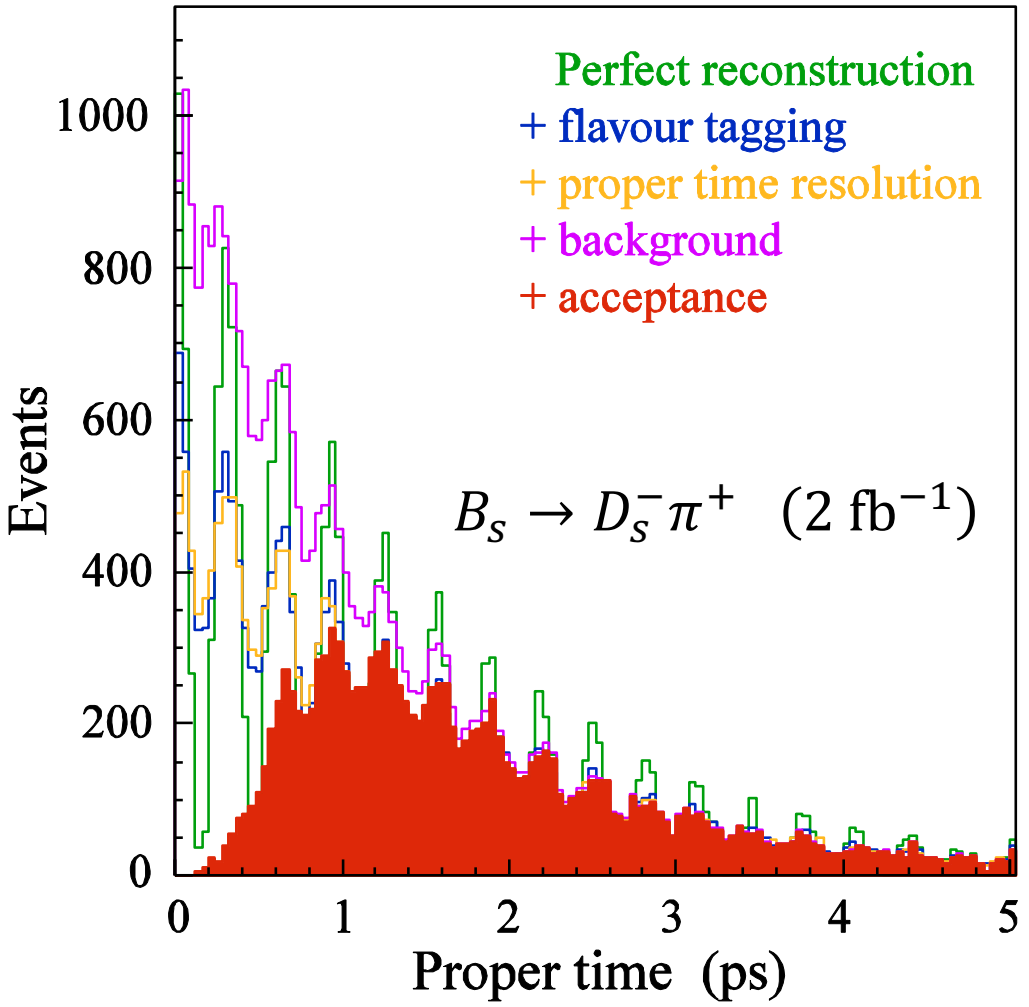
+ Realistic flavour tagging dilution

+ Realistic decay time resolution

+ Background events

+ Trigger and selection acceptance

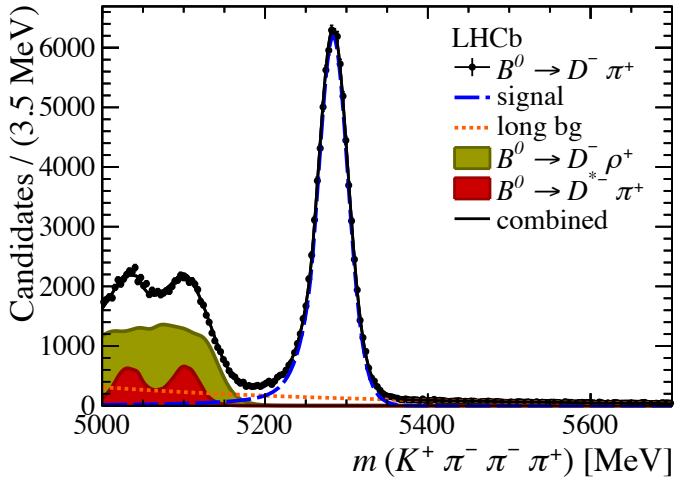
Proper-time dependent decay rate:

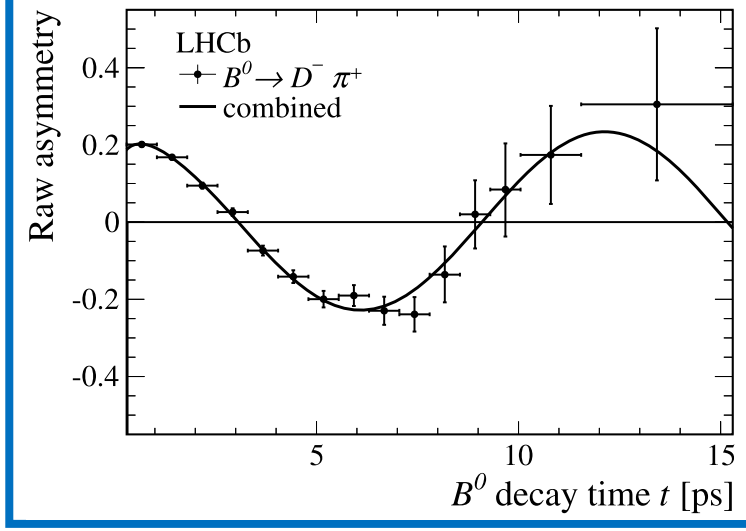


Meson mixing in LHCb: does is actually work?

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

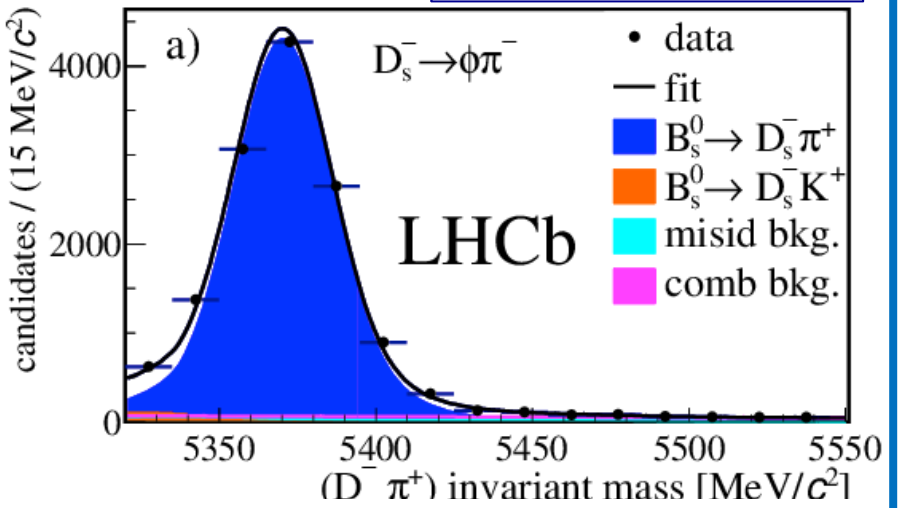
$B^0 \to D^- \pi^+$ Phys.Lett.B719 (2013) 318

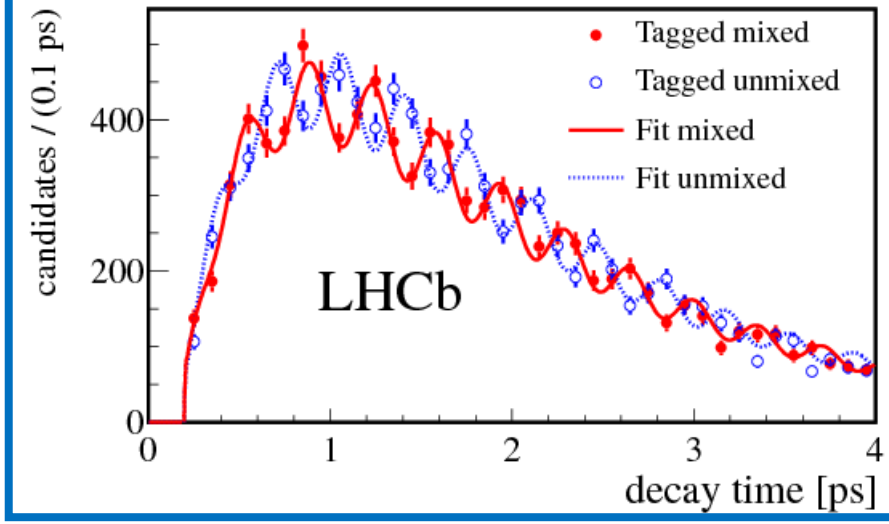




$B_s^0 - \overline{B_s^0}$ mixing

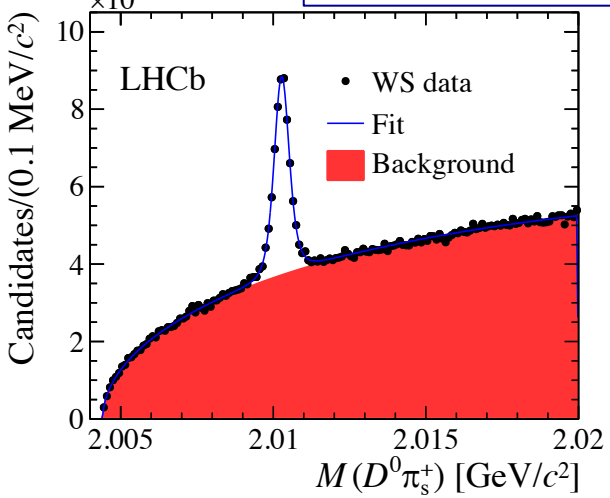
$B_s^0 \to D_s^- \pi^+$ New.J.Phys.15 (2013) 053021

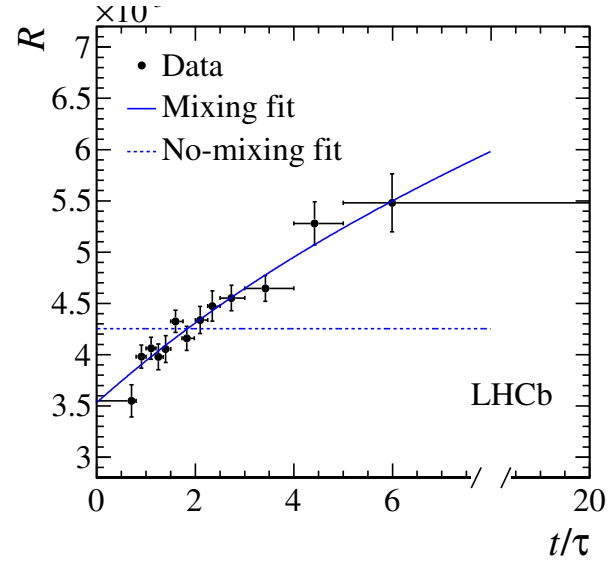




$D^0 \to \overline{D^0}$ mixing

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

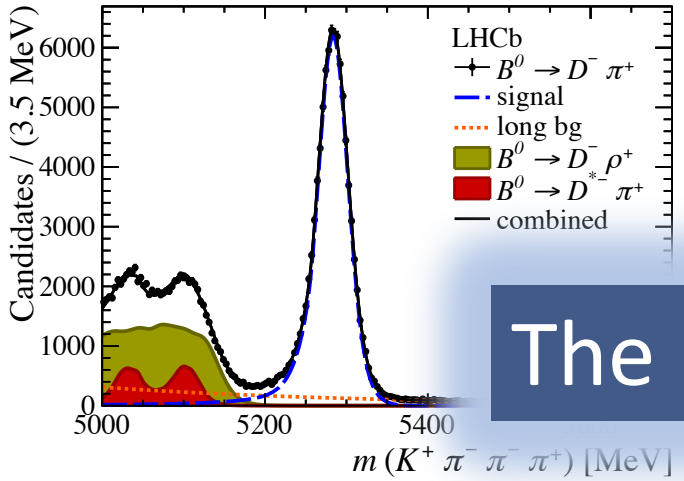


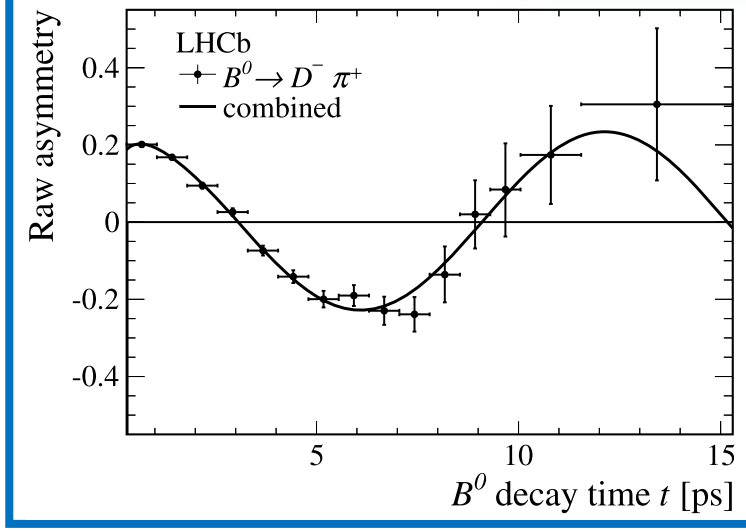


Meson mixing in LHCb: does is actually work?

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

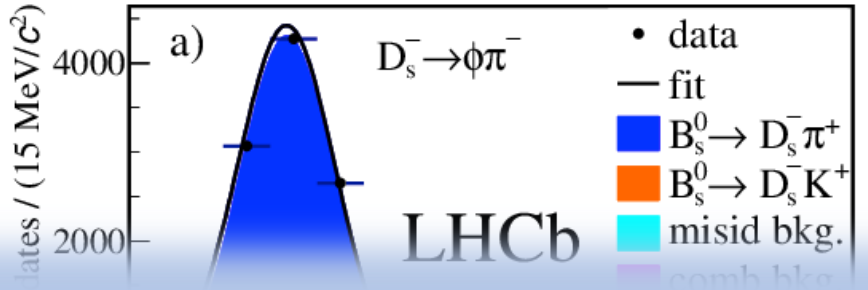
$B^0 \to D^-\pi^+$ Phys.Lett.B719 (2013) 318

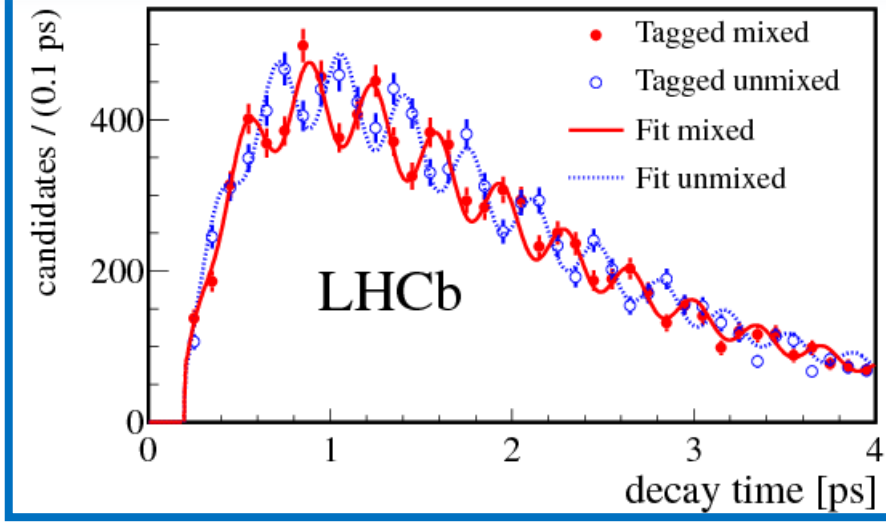




$B_s^0 - \overline{B_s^0}$ mixing

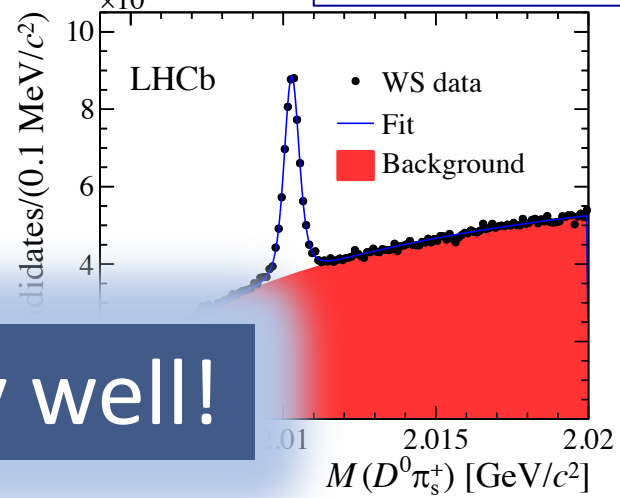
$B_s^0 \to D_s^-\pi^+$ New.J.Phys.15 (2013) 053021

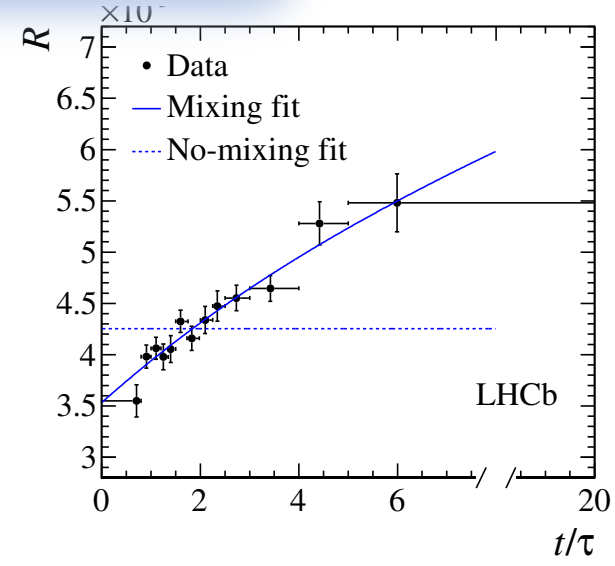




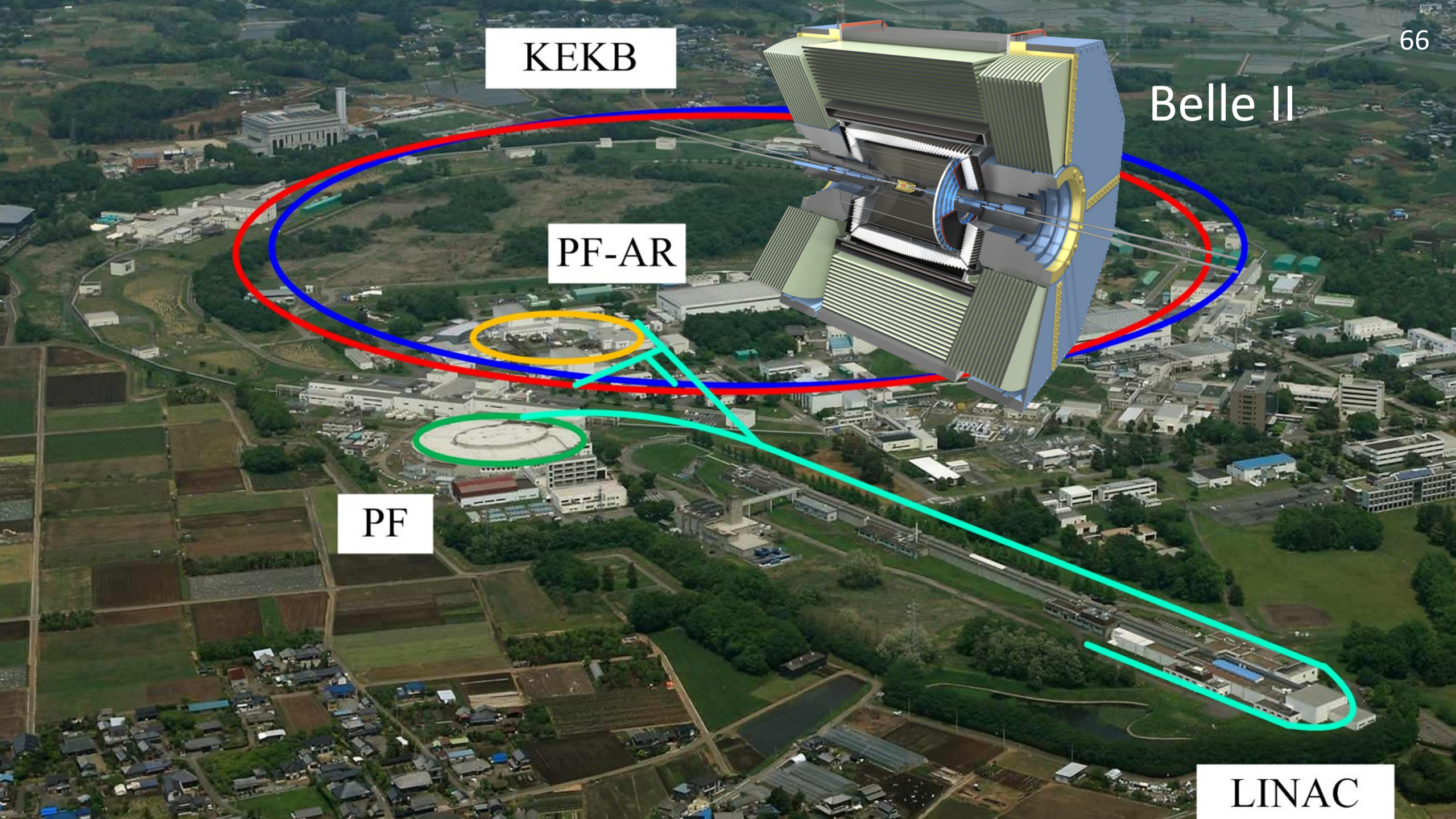
$D^0 \to \overline{D^0}$ mixing

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





The Experiment works extremely well!

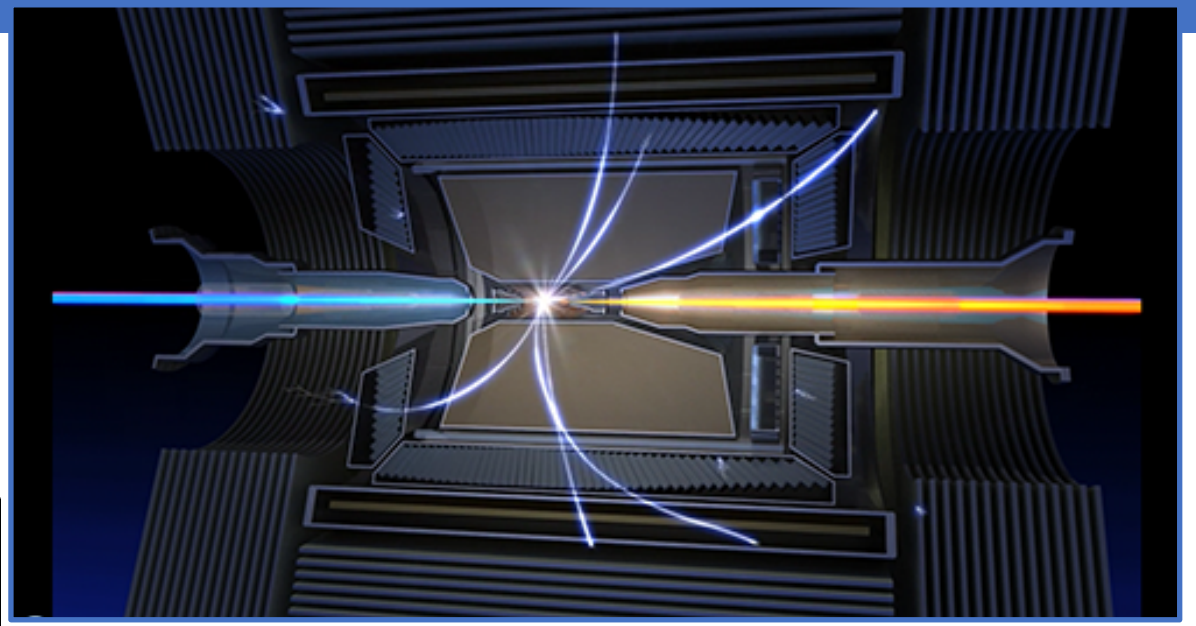

KEKB
Belle II
PF-AR
PF
LINAC

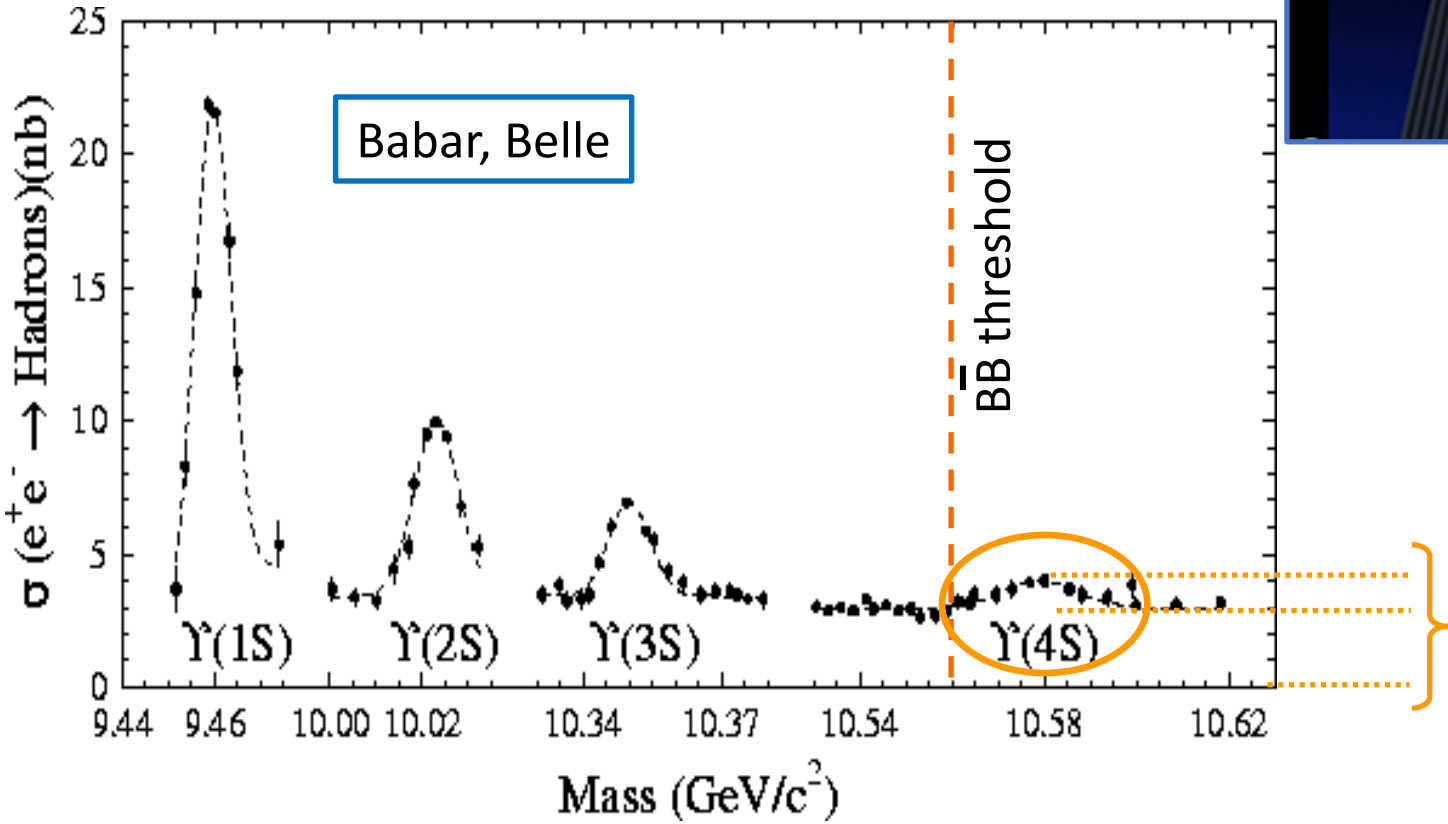
B meson production in e^+e^- Collisions

- Electron-Positron collider:

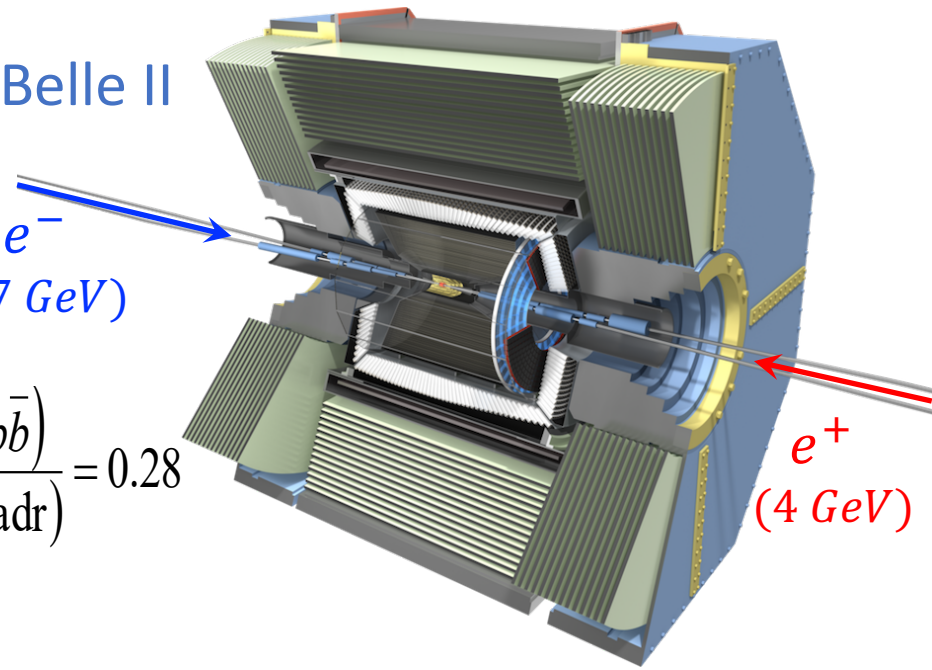
  $e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\overline{B^0}$

  - 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





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



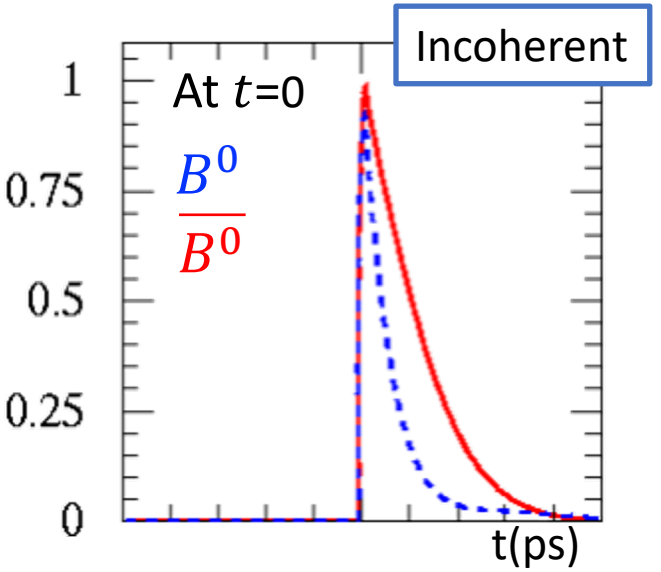
$\Upsilon(4S)$: Coherent B - $\overline{B}$ production

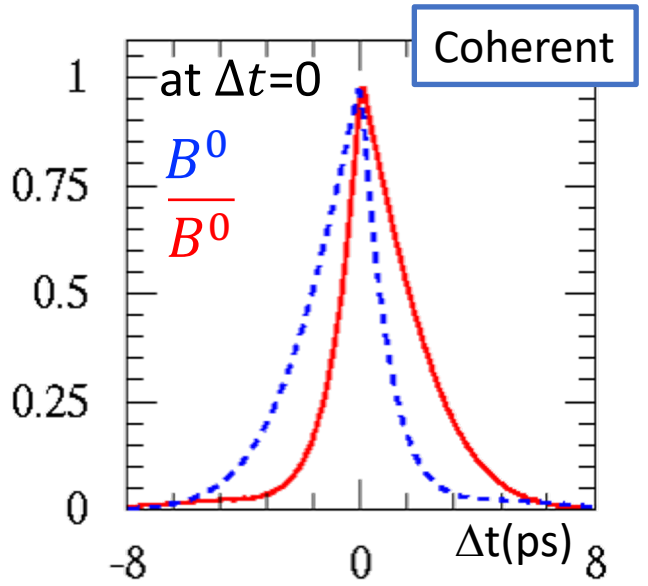
- Production at $\Upsilon(4S)$ $J^{PC} = 1^{--}$:

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

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

  - $P = -1$: 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)

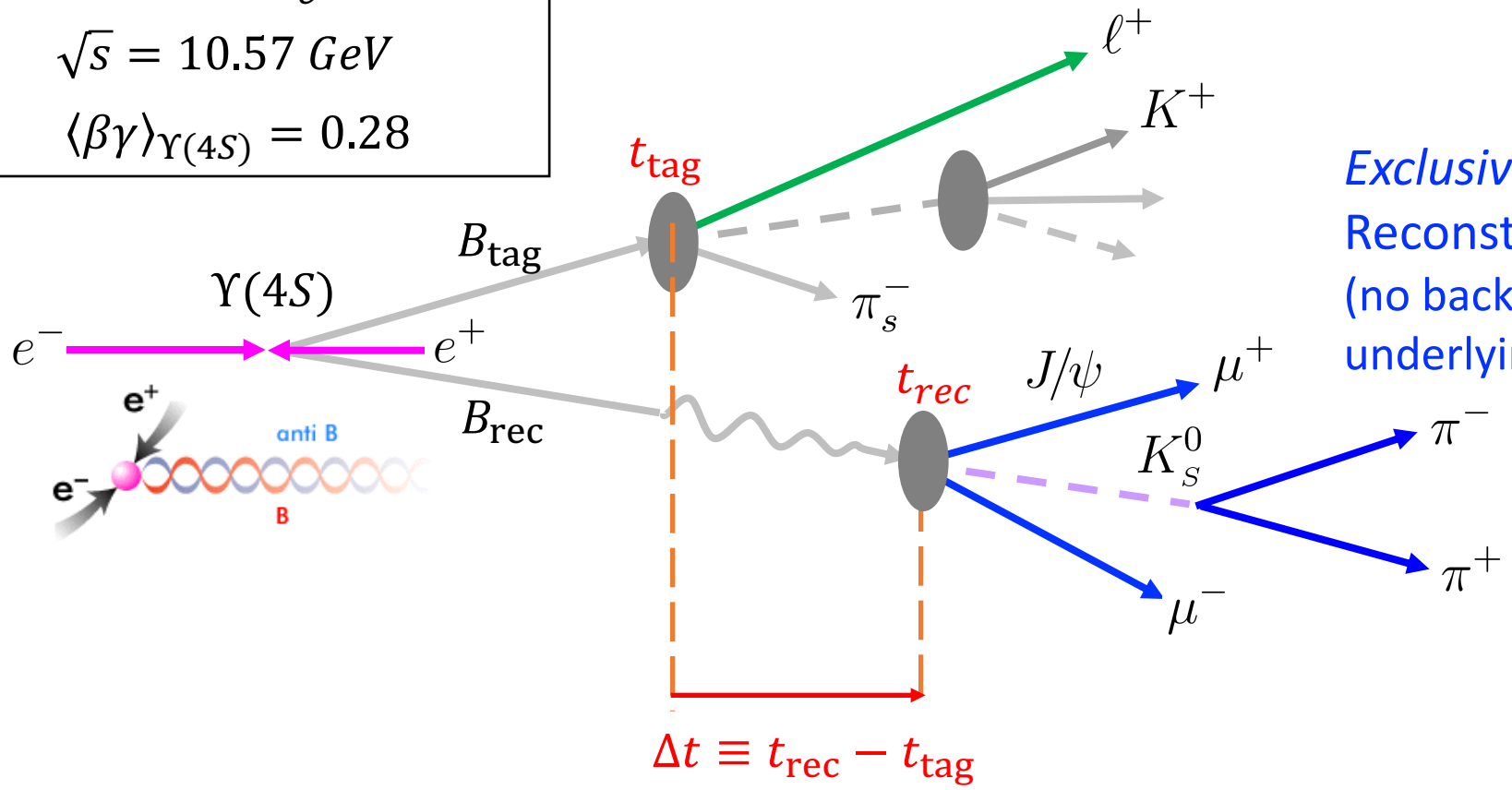
Belle II @ Super KEKB

$E_{e^-} = 7\ GeV \quad ; \quad E_{e^-} = 4\ GeV$

$\sqrt{s} = 10.57\ GeV$

$\langle \beta\gamma \rangle_{\Upsilon(4S)} = 0.28$

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

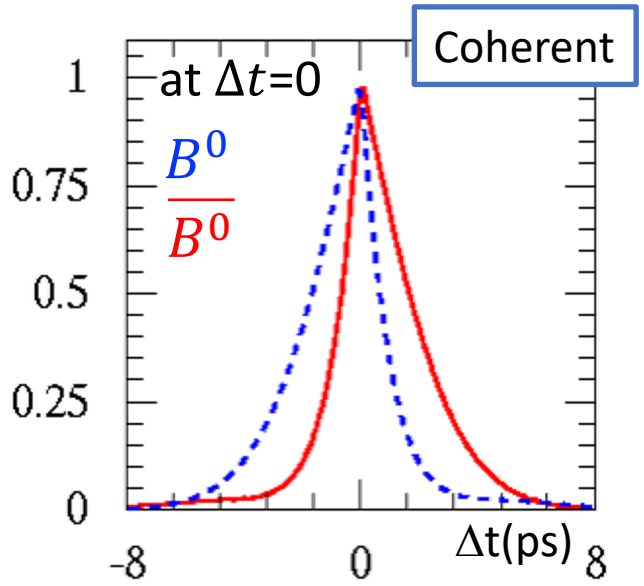


Exclusive B meson Reconstruction
(no backgrounds from underlying event)

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

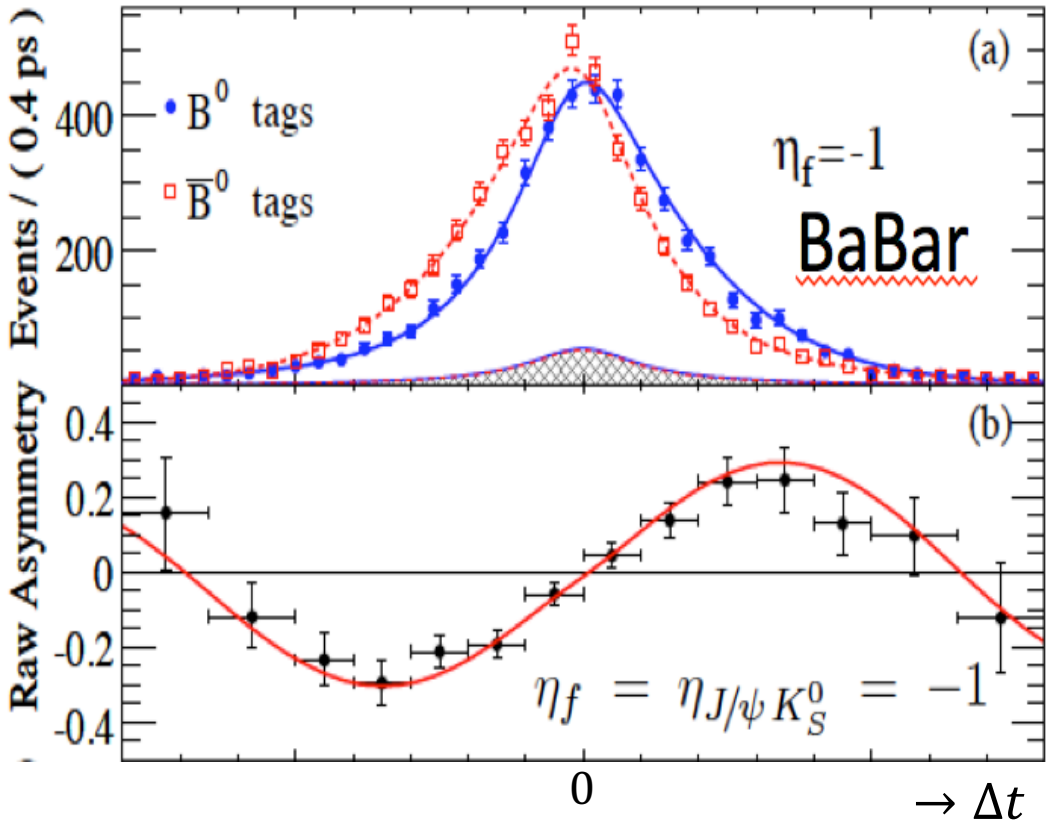
Vertexing and time reconstruction

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

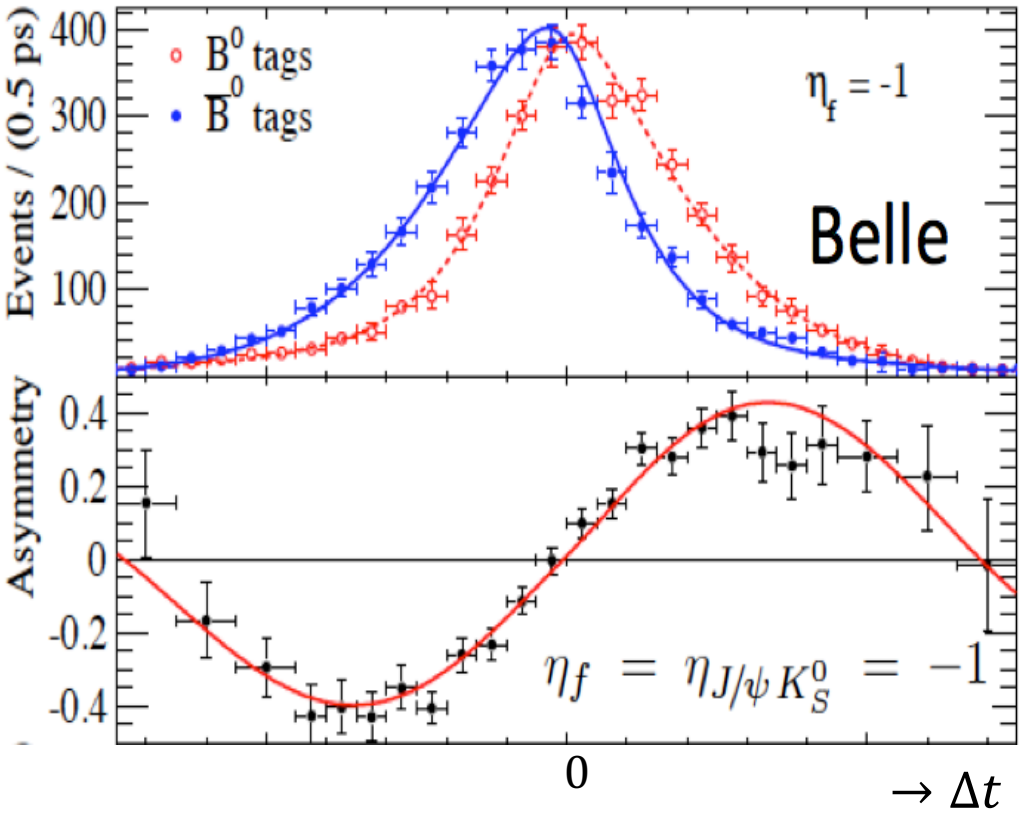


CP Asymmetry for "Golden" mode: $B^0 \to J/\psi\ K_S$

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

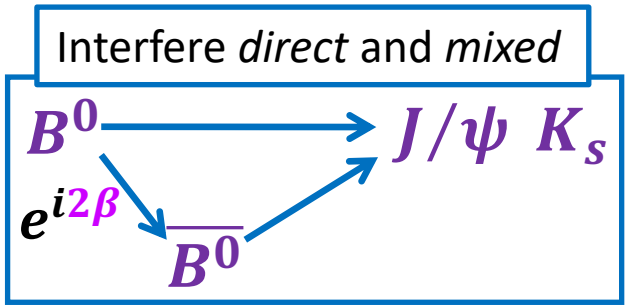
Compare LHC with B-factory for $B^0 \to J/\psi\ K_S$

- *Decay-time dependent*

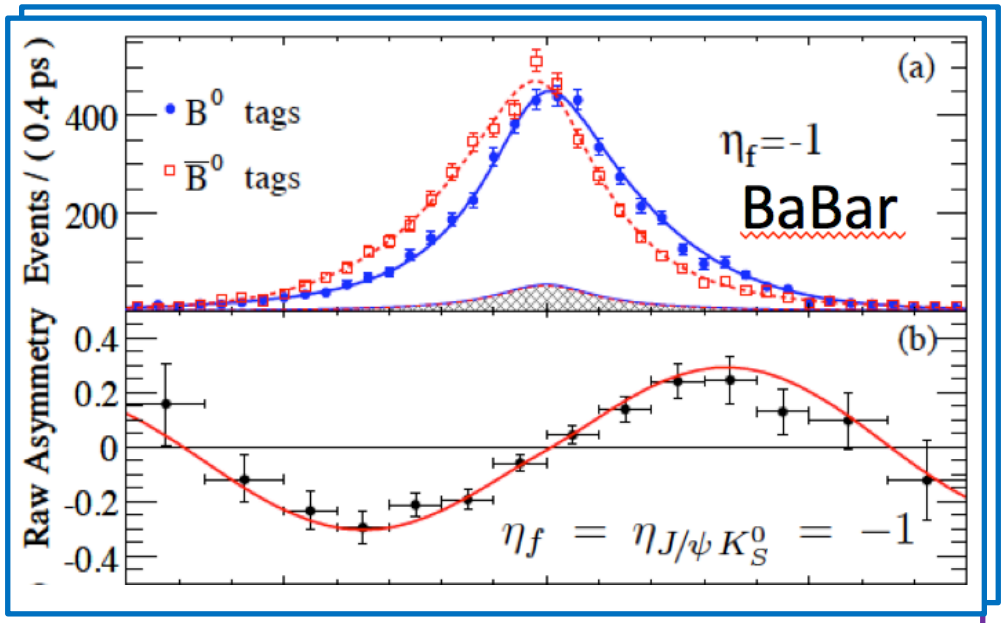
  CP violation:

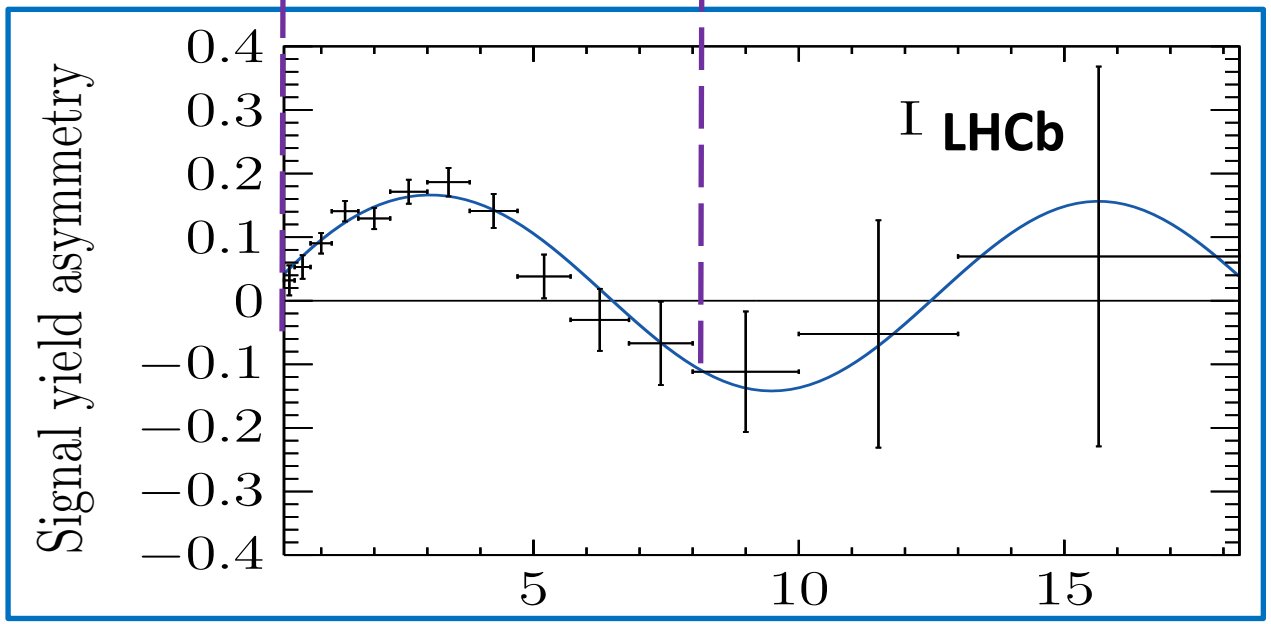
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$

Interfere *direct* and *mixed*



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

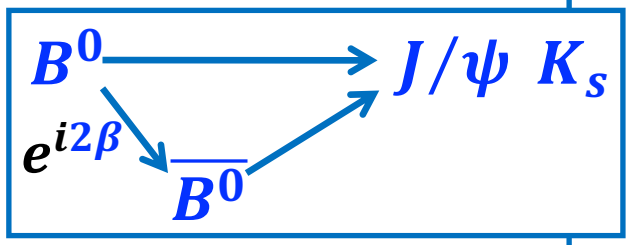


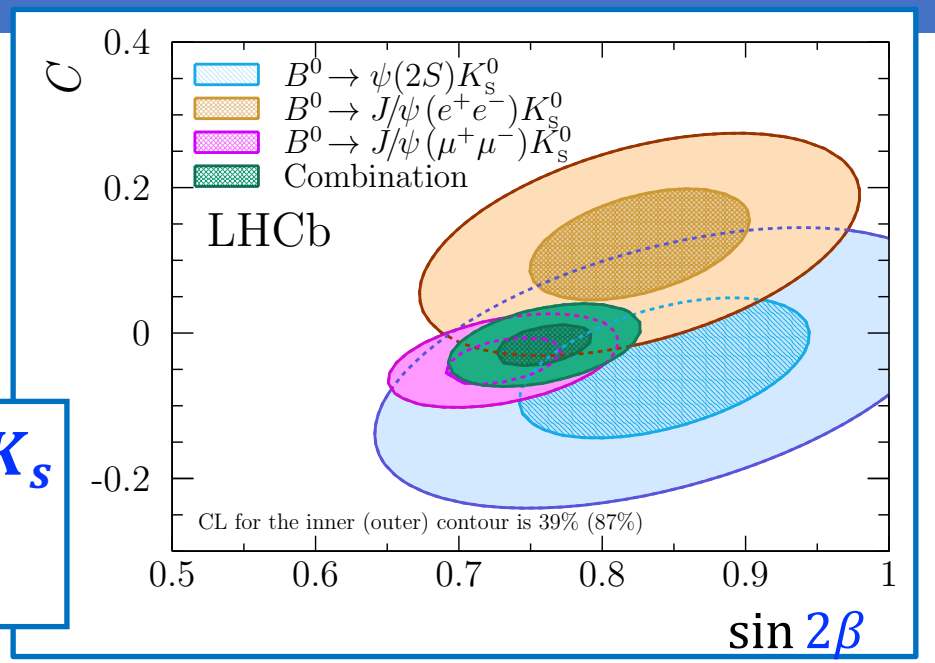


Decay time dependent CP violation

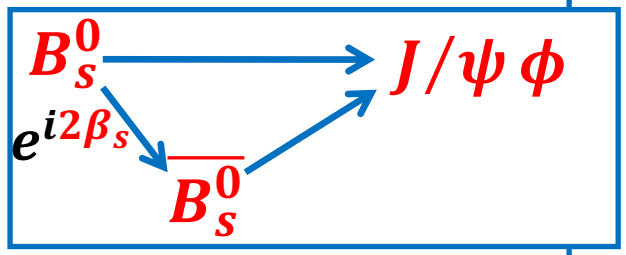
- $B^0 \to J/\psi\, K_s$ and $B_s^0 \to J/\psi\, \phi$

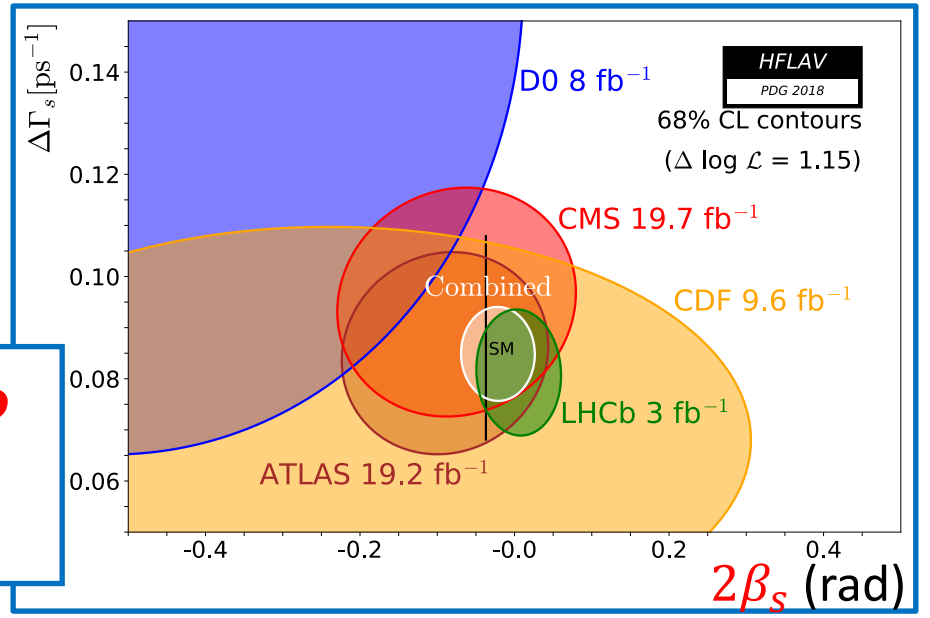
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_{(s)}\to f}(t) - \Gamma_{B_{(s)}\to f}(t)}{\Gamma_{B_{(s)}\to f}(t) + \Gamma_{B_{(s)}\to f}(t)}$$





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



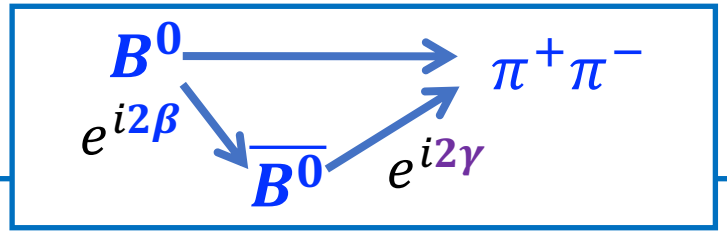


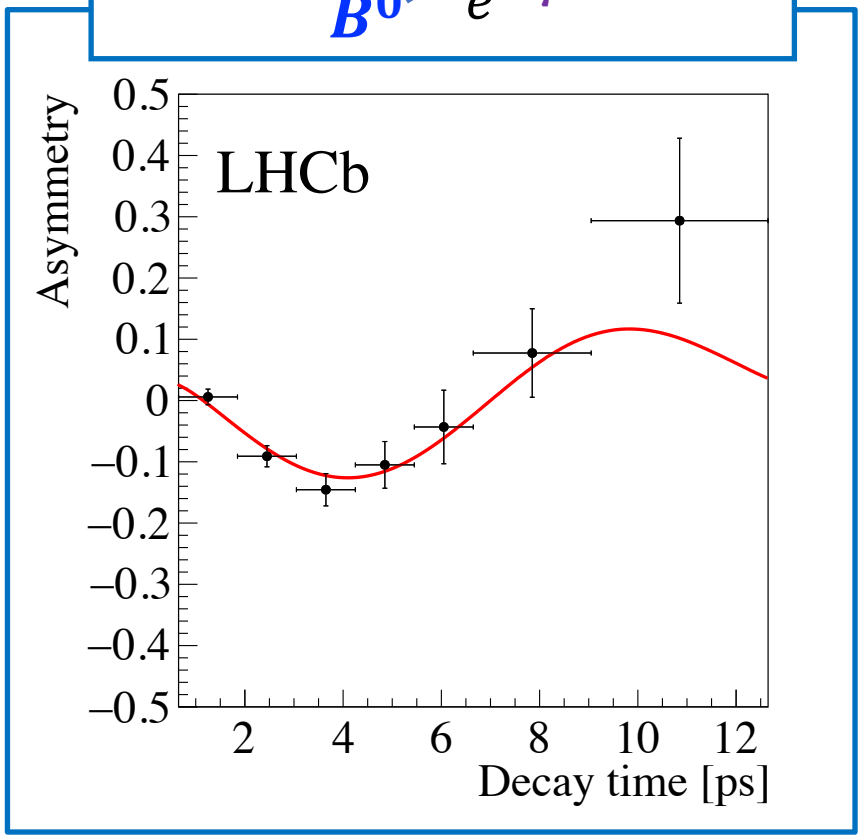
Decay time dependent CP violation

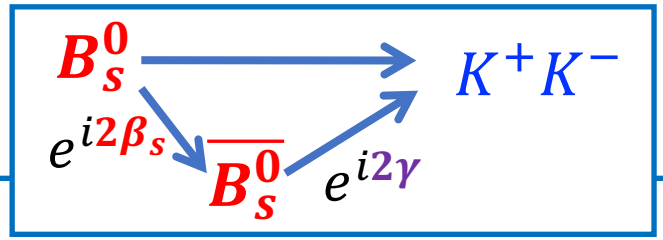
- *Hadronic decay modes (LHCb)*:

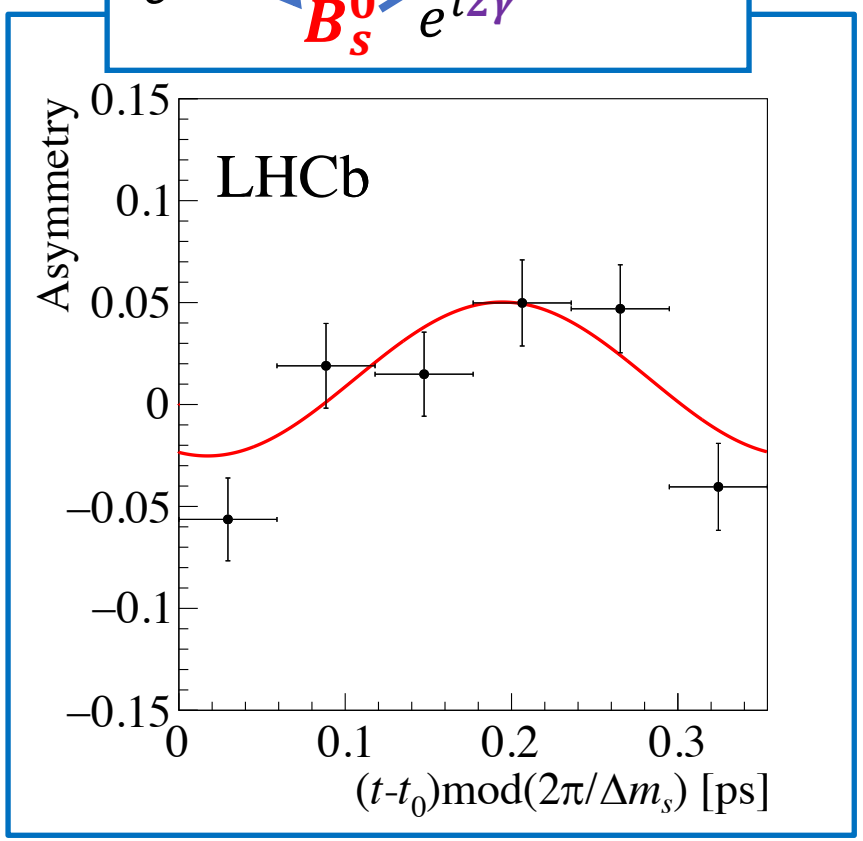
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

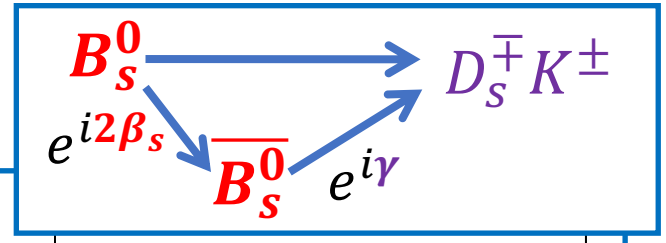
Note: $\alpha = \pi - (\beta + \gamma)$

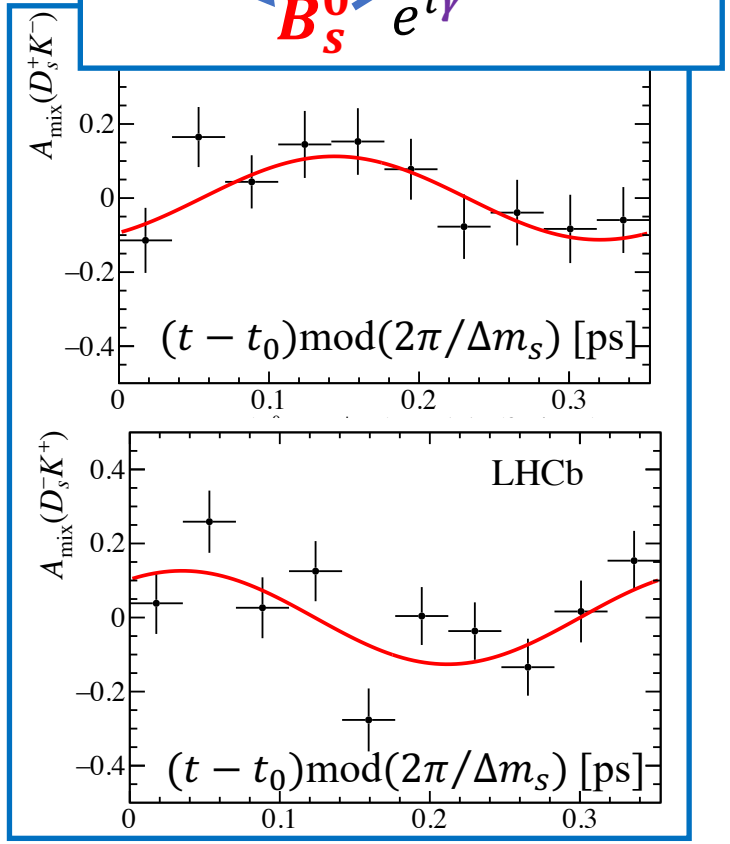








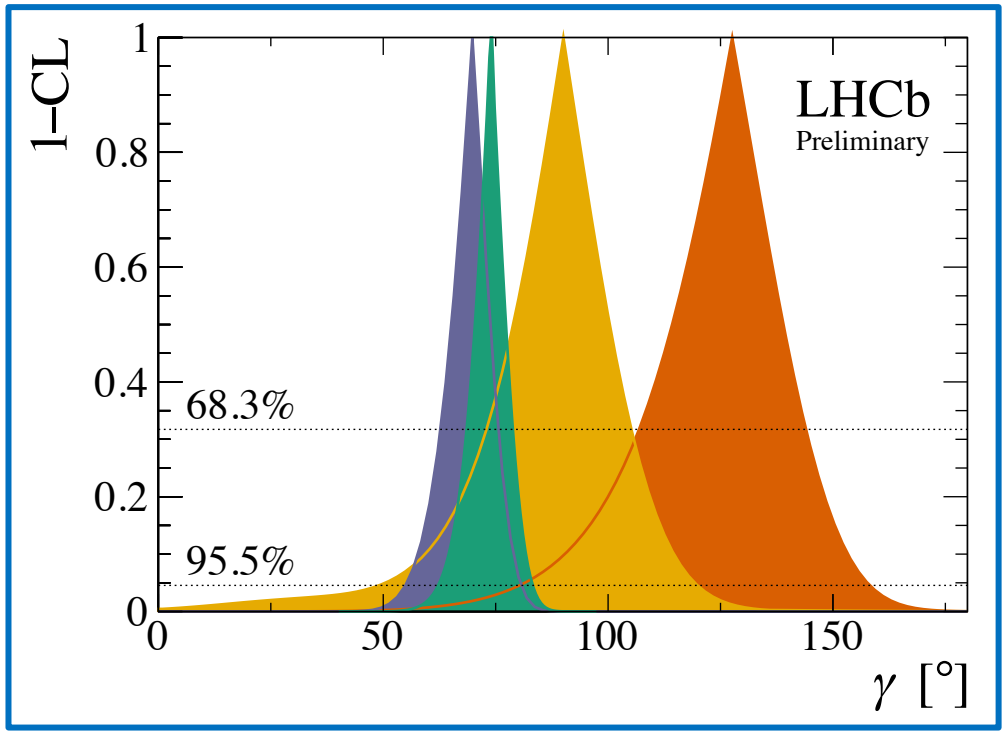


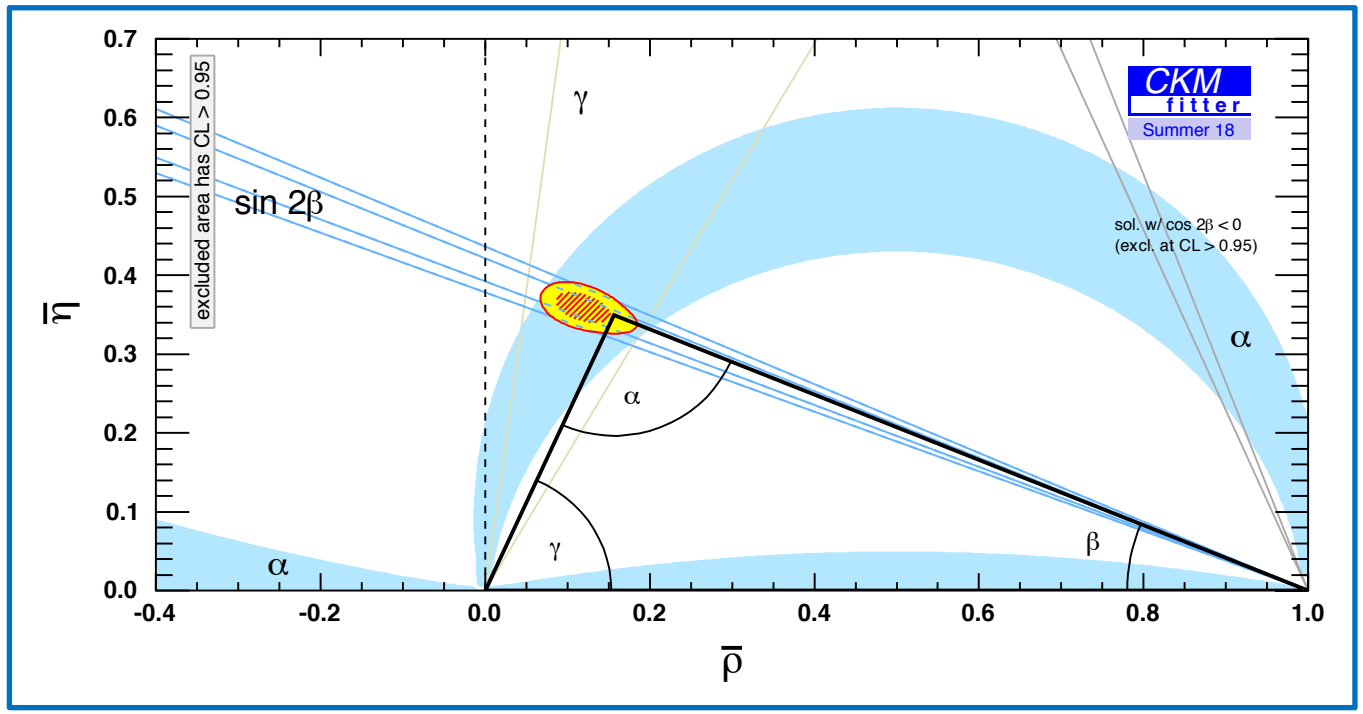


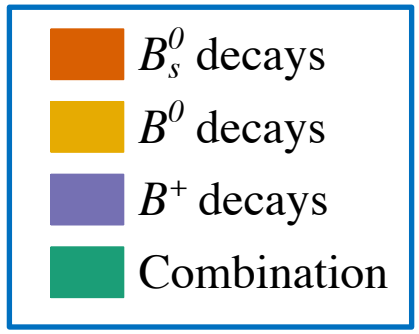
Current situation on angle γ

- The situation for angle γ :

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





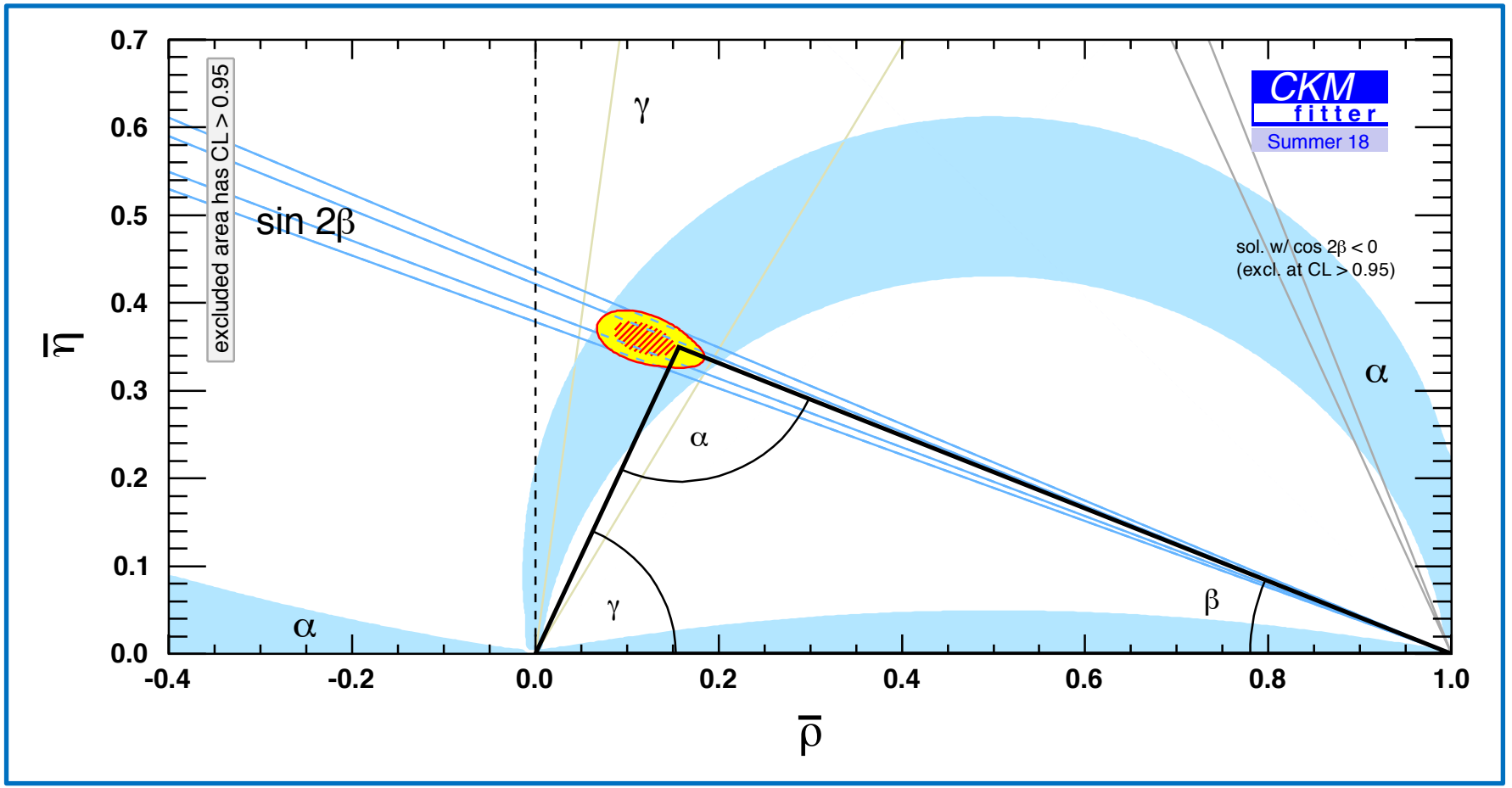


Average:

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

CKM triangle: putting all measurements together

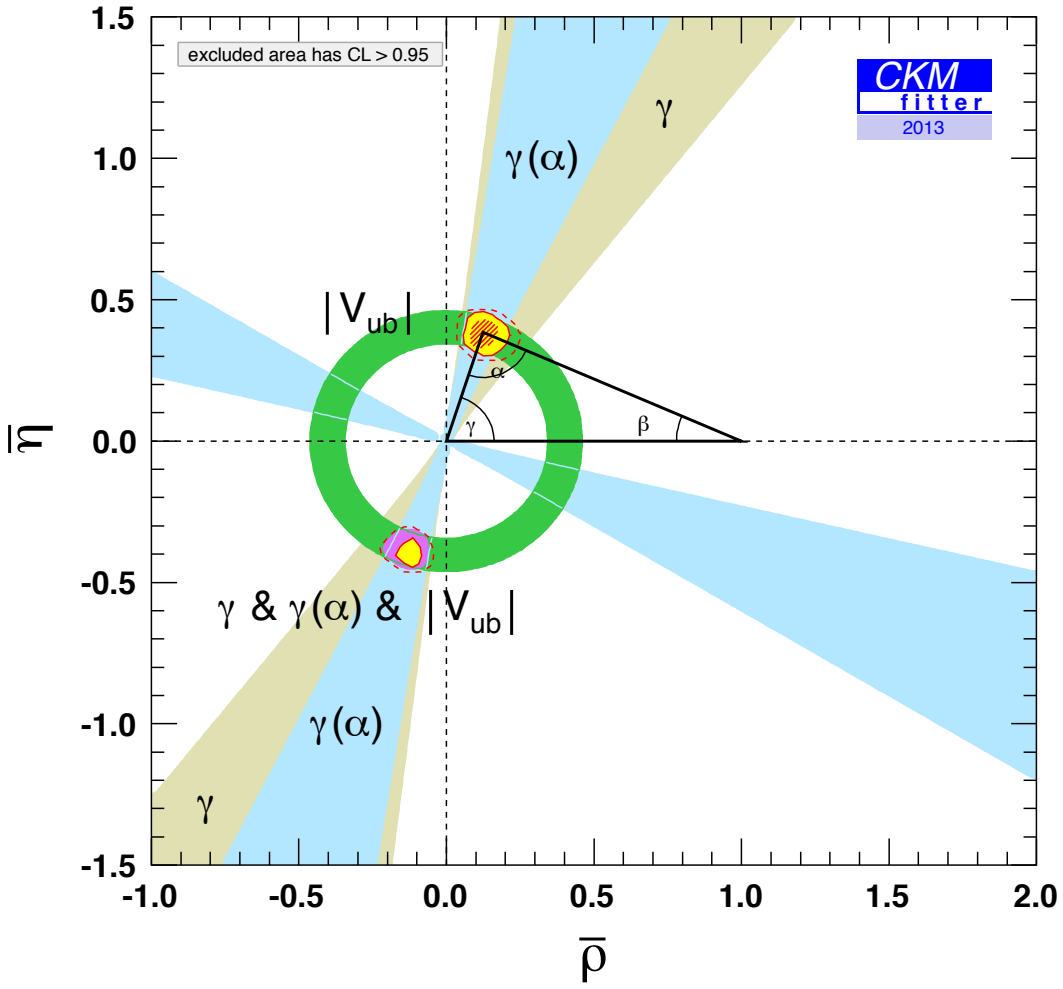
	Measured	CKMfitter prediction	UTfit prediction
β	22.7 ± 0.7	$23.7\ ^{+1.1}_{-1.0}$	23.8 ± 1.4
γ	70.0 ± 4.2	$65.3\ ^{+1.0}_{-2.5}$	65.8 ± 2.2
α	93.1 ± 5.6	$92.1\ ^{+1.5}_{-1.1}$	90.1 ± 2.2



LHCb: Future sensitivity for CP violation

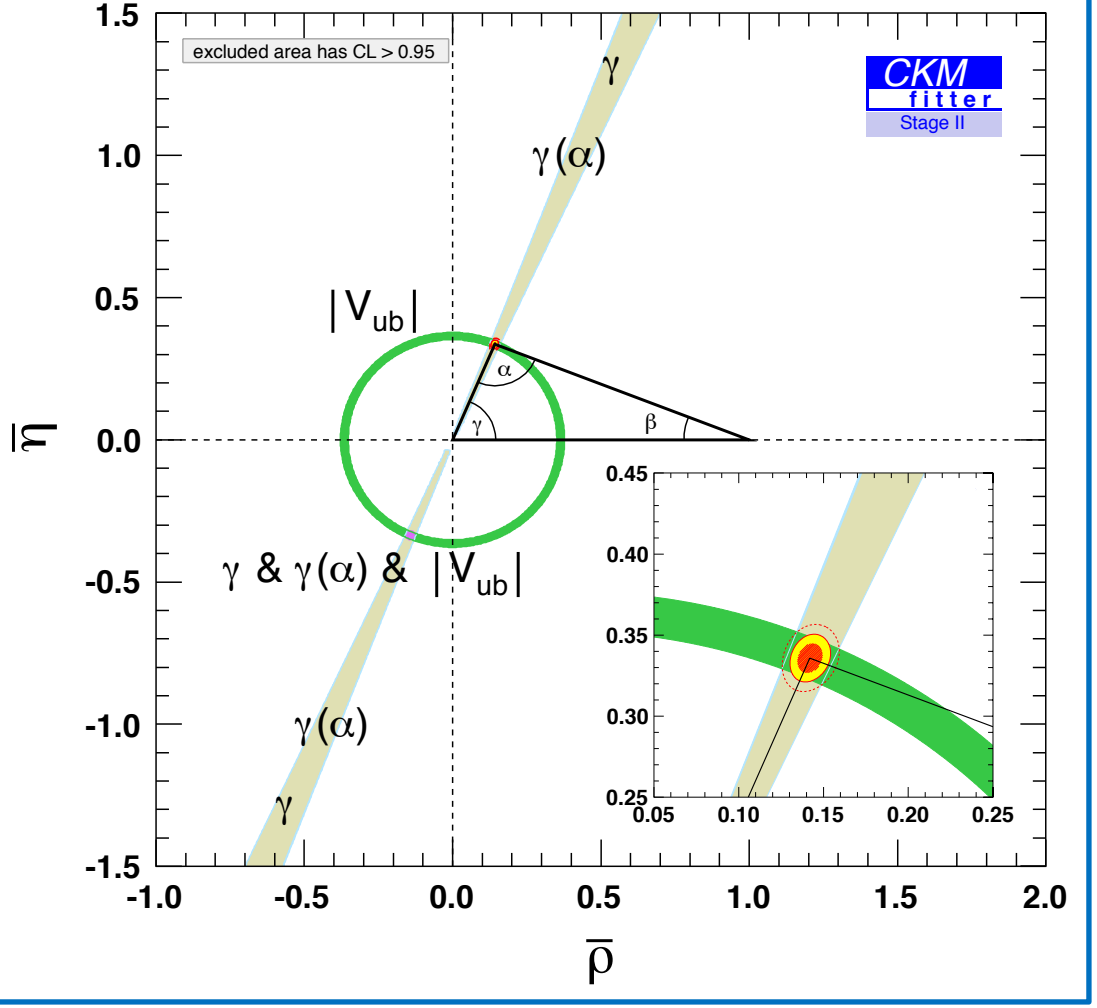
2013

[Charles et al., 1309.2293]



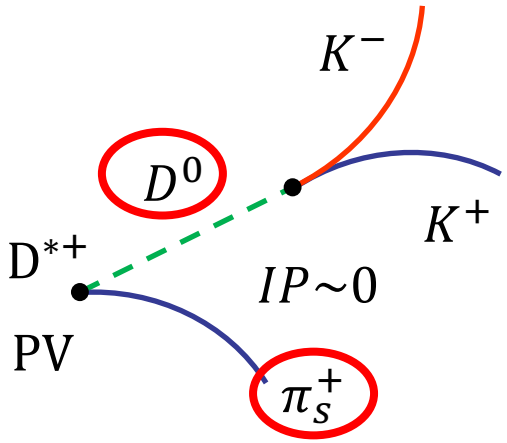
2030

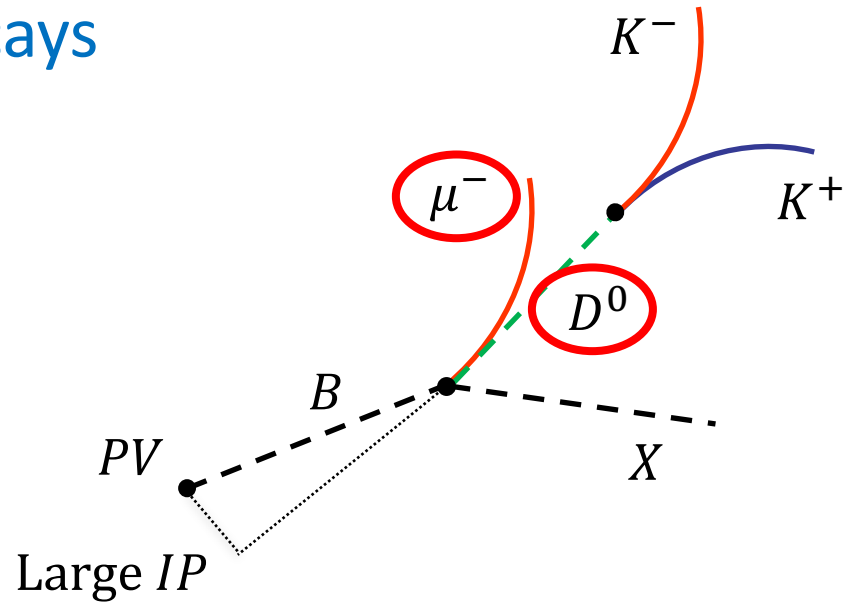
[Charles et al., 1309.2293]

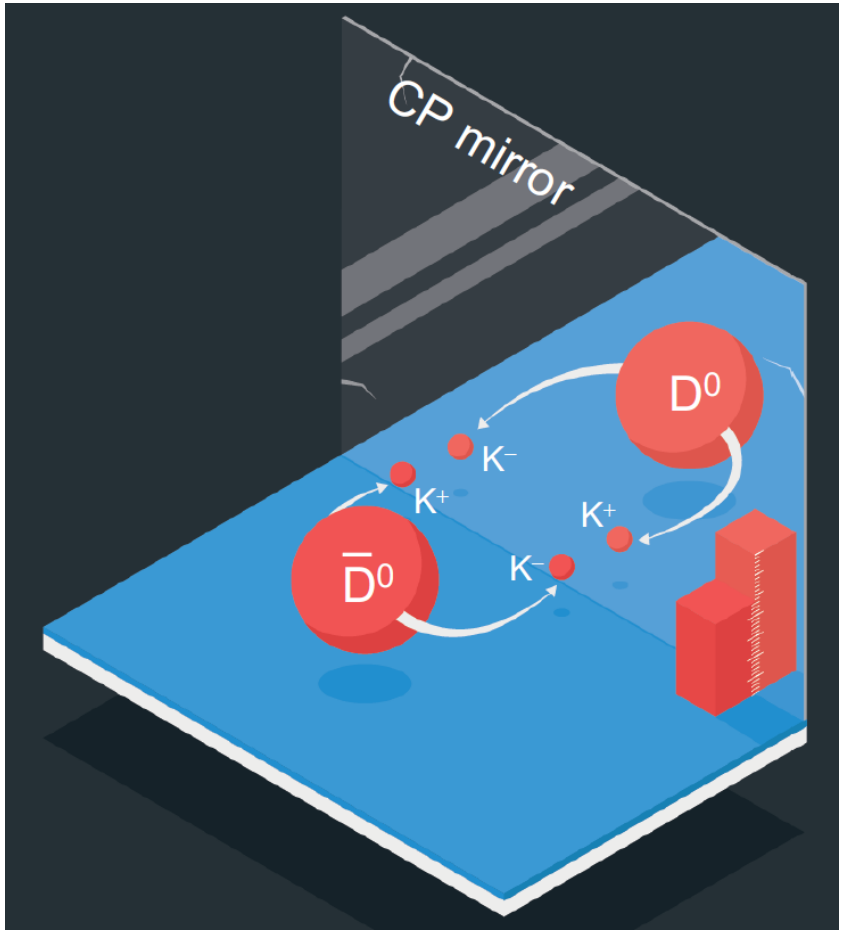


CPV in Kaons (K) and Beauty (B): How about Charm (D)?

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







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

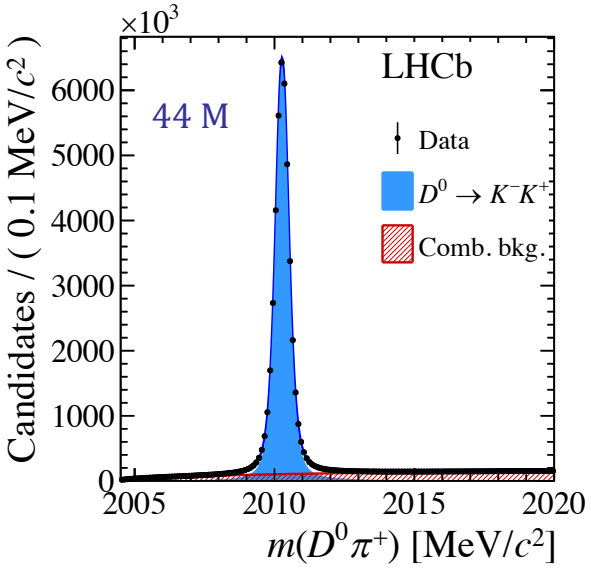
$$A_{raw}(K^+K^-) = A_{CP}(K^+K^-) + A_D(K^+K^-) + A_D(\pi_s) + A_P(D^{*+})$$

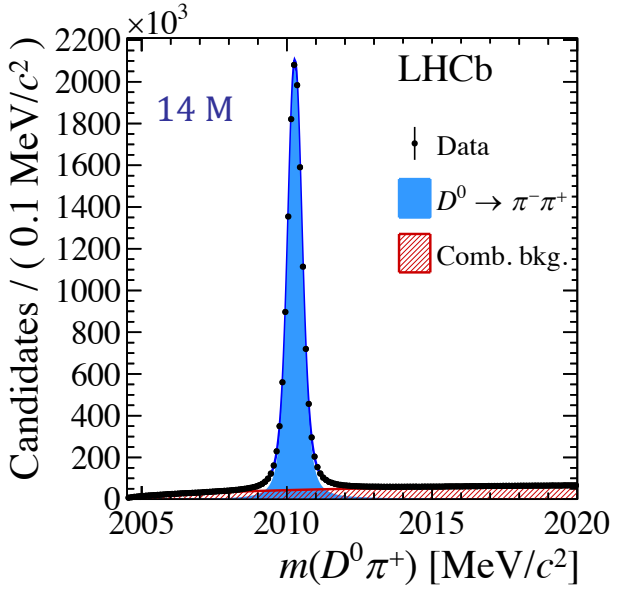
- Look at: $\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$

  ⇒ All detection and production asymmetries cancel

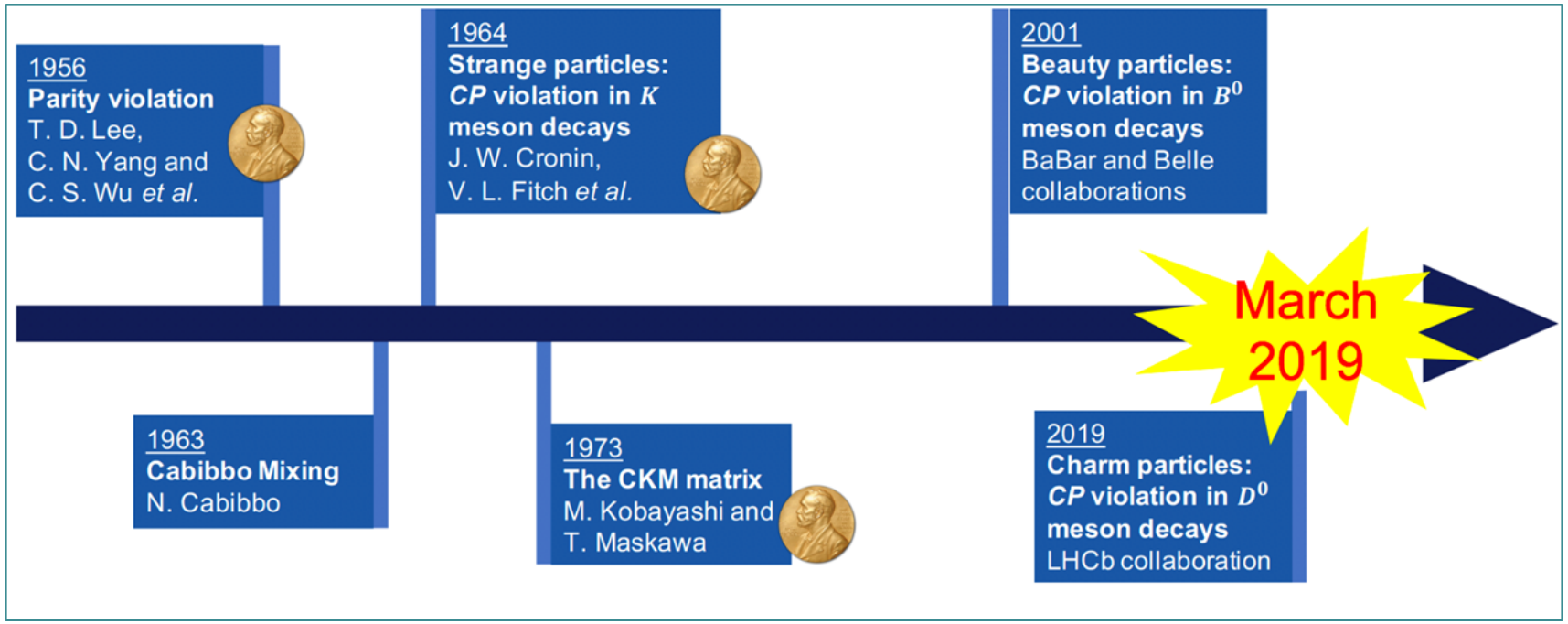
  ⇒ Directly observe CP asymmetry!

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 $p\bar{p}$ 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°
- 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?

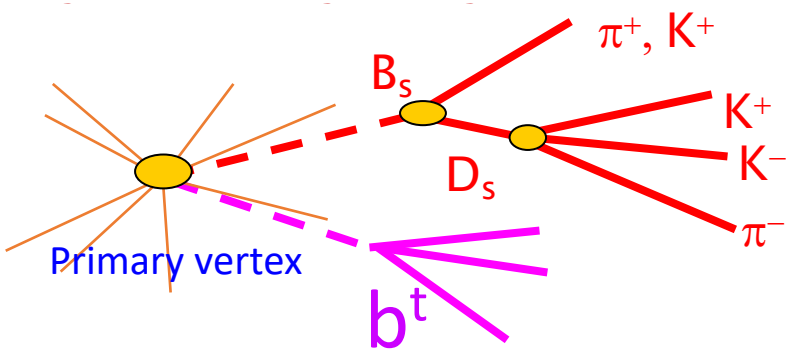
- Points to consider:
  - e^+e^- at $\Upsilon(4S)$: electromagnetic production, clean, *no* B_s, coherent production: B^0 only time dependent CPV, requires asymmetric beams, good flavor tagging.
  - e^+e^- at $\Upsilon(5S)$: B_s, lower cross section, no resolution for time dependent CPV.
  - e^+e^- at 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.

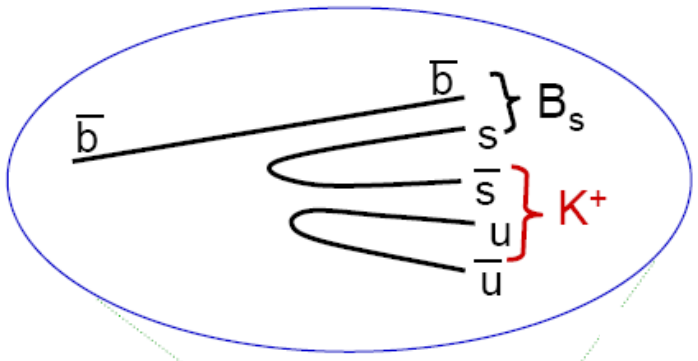
Design your own B-meson CP Violation Experiment

- 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

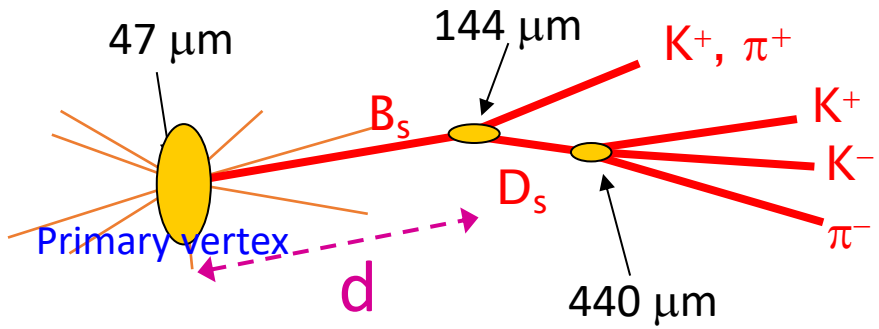
- You measure $B_s \to D_s^{\mp} K^{\pm}$ and $\overline{B_s} \to D_s^{\mp} K^{\pm}$
  - How do you determine the flavour of the B_s at production?
  - Are there intrinsic limits to this precision?
  - How would you calibrate the wrong tag fraction?





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?
  - 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?



Decay time resolution = 40 fs

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