An introduction to Quark Flavour Physics

Part 2

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Warwick Week 2019

An introduction to Flavour Physics

- What's covered in these lectures:

1. An introduction to flavour in the SM.
2. **CP violation (part 1).**
   ➡ **Types of CP violation and neutral meson mixing.**
3. CP violation (part 2).
4. Flavour changing neutral current processes.

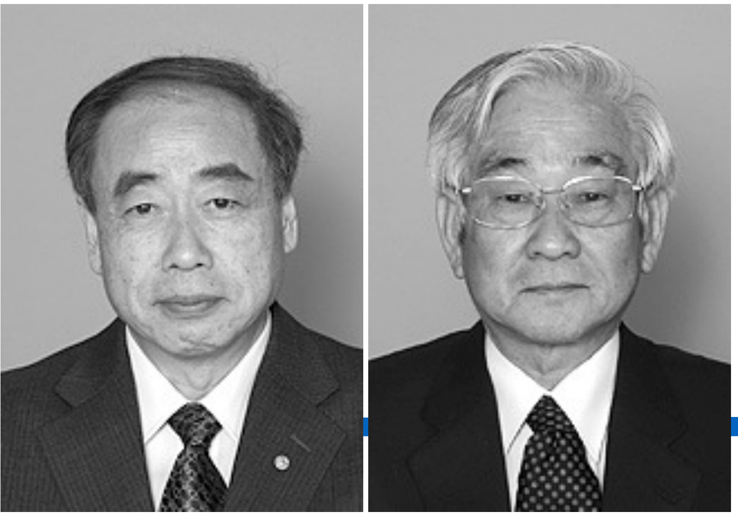
Recap: CKM matrix

- Standard form is to express the CKM matrix in terms of three rotation matrices and one CP violating phase,

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where

$$c_{ij} = \cos\theta_{ij} \text{ and } s_{ij} = \sin\theta_{ij}$$



Wolfenstein parameterisation

- Can also exploit the hierarchy of the CKM matrix to write

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

where

$$\lambda \simeq 0.22, \quad A \simeq 0.82, \quad \bar{\rho} \simeq 0.13, \quad \bar{\eta} \simeq 0.35$$

Wolfenstein parameterisation

- Can also exploit the hierarchy of the CKM matrix to write

CP violating phase associated with V_{ub}

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \boxed{A\lambda^3(\rho - i\eta)} \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ \boxed{A\lambda^3(1-\rho-i\eta)} & \boxed{-A\lambda^2} & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

B_d system CP violating phase enters at λ^3 in mixing

B_s system CP violating phases enters at λ^4 in mixing

Wolfenstein parameterisation

- Can also exploit the hierarchy of the CKM matrix to write

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ \boxed{-\lambda} & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

CP violation in charm is highly suppressed (phase enters at λ^5)

… sensitivity to complex phases requires interference

CP violation

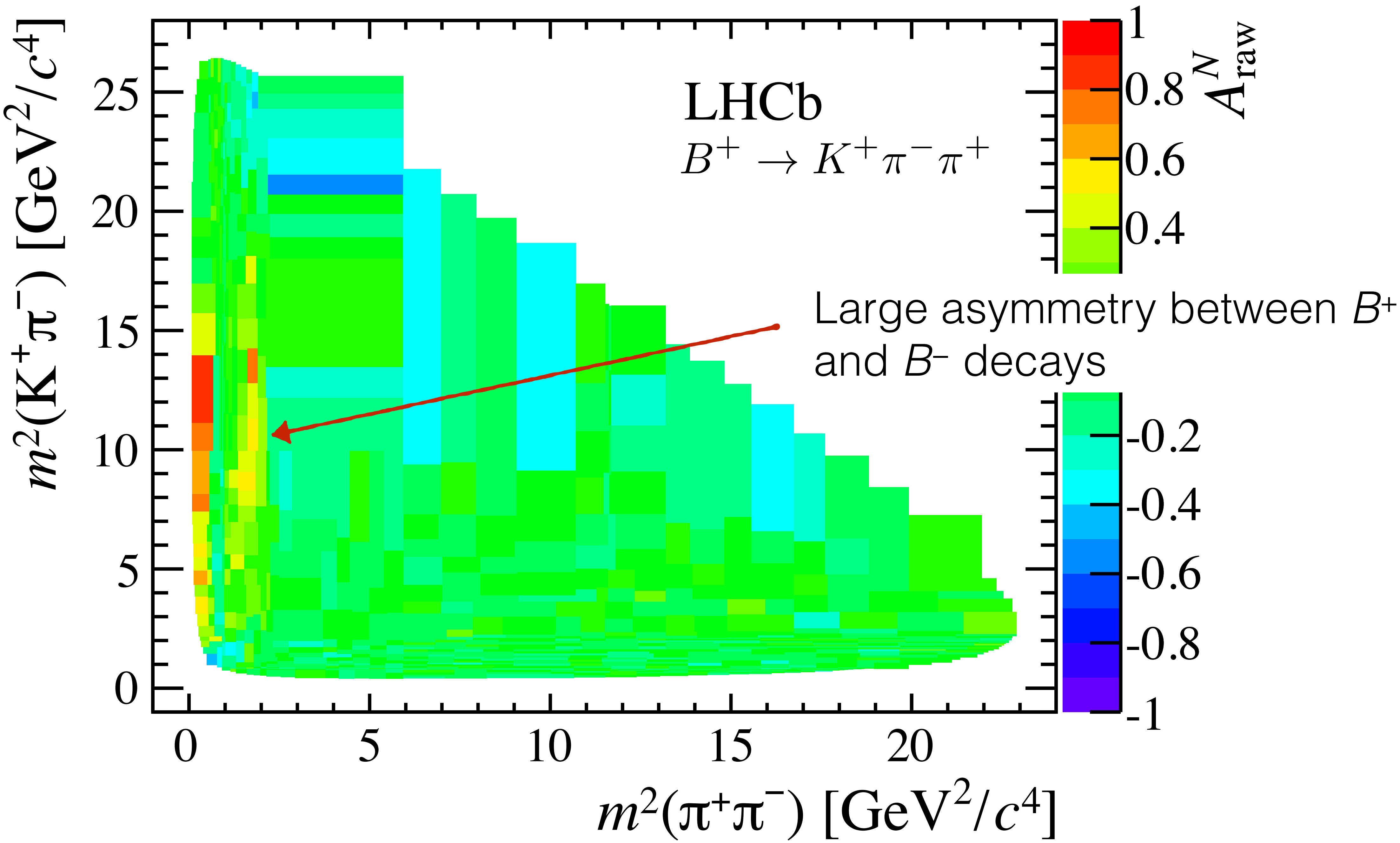
- Three ways to observe CP violating effects:

1. Direct CP violation $$\left|\frac{\mathcal{A}(\bar{B}\to\bar{f})}{\mathcal{A}(B\to f)}\right| \neq 1$$

2. Mixing induced CP violation

3. CP violation in the interference between mixing and decay

Direct CP violation



Direct CP violation

- If there is only a single "path" to a final state *f*, then cannot get direct CP violation.
- Starting from

$$\mathcal{A}(B \to f) = A_1 e^{i(\delta_1 + \phi_1)}$$
$$\mathcal{A}(\bar{B} \to \bar{f}) = A_1 e^{i(\delta_1 - \phi_1)}$$

- Gives

$$\mathcal{A}_{\rm CP} = \frac{|\mathcal{A}(B \to f)|^2 - |\mathcal{A}(\overline{B} \to \bar{f})|^2}{|\mathcal{A}(B \to f)|^2 + |\mathcal{A}(\overline{B} \to \bar{f})|^2} = 0$$

- Solution
  - ➡ Introduce a second amplitude. Often realised by having interfering tree and penguin amplitudes.

Direct CP violation

- Introducing a second amplitude

$$\mathcal{A}(B \to f) = A_1 e^{i(\delta_1+\phi_1)} + A_2 e^{i(\delta_2+\phi_2)}$$
$$\mathcal{A}(\bar{B} \to \bar{f}) = A_1 e^{i(\delta_1-\phi_1)} + A_2 e^{i(\delta_2-\phi_2)}$$

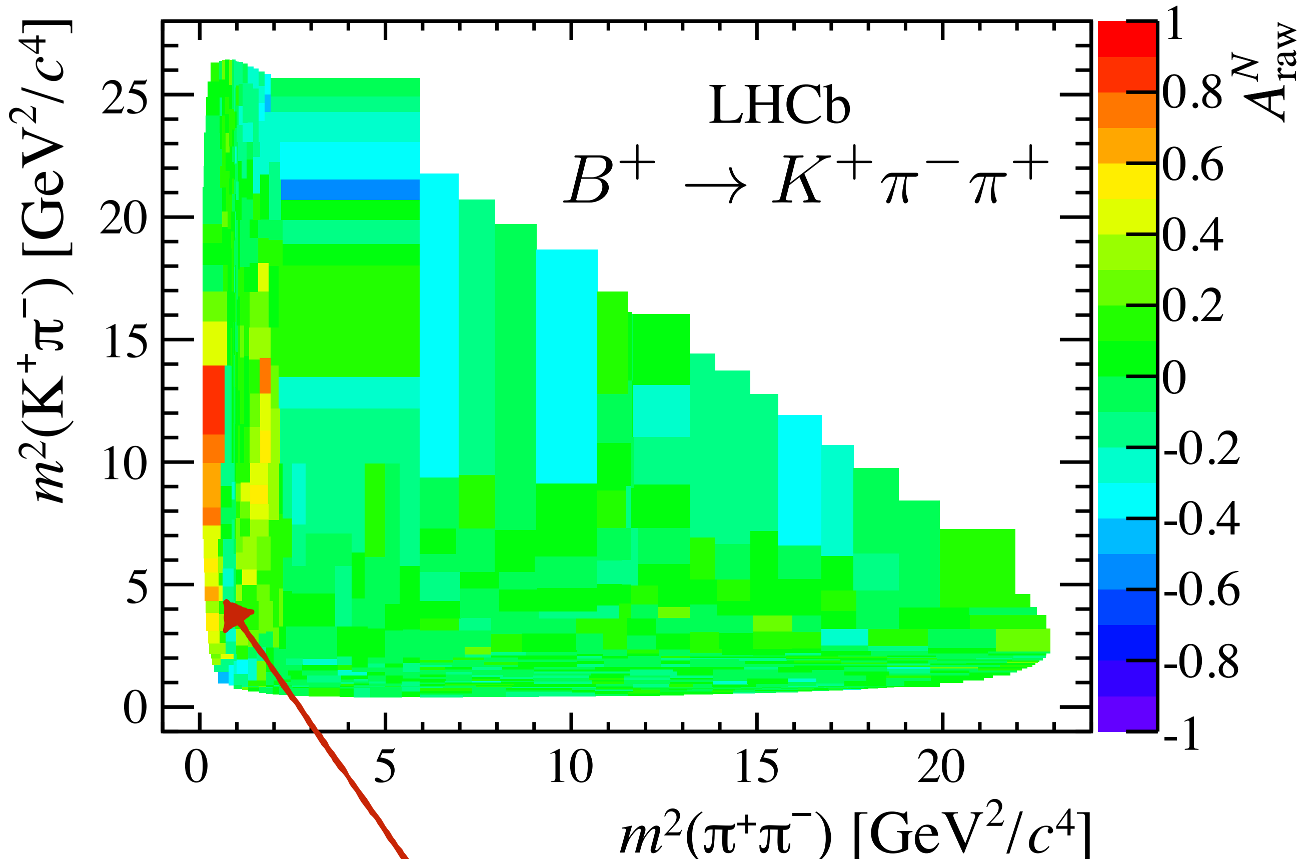
- The direct CP asymmetry is

$$-2A_1A_2\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)$$

which is non-zero only if the amplitudes have different weak **and** strong phases.

CP violation in charmless B decays

- For direct CP violation we need interference between amplitudes with different weak and strong phases.
- Weak phase differences can come from from interference between tree and penguin processes with different phases.
- Strong phase differences can come from re-scattering of final-state particles or regions with interference between intermediate resonances.



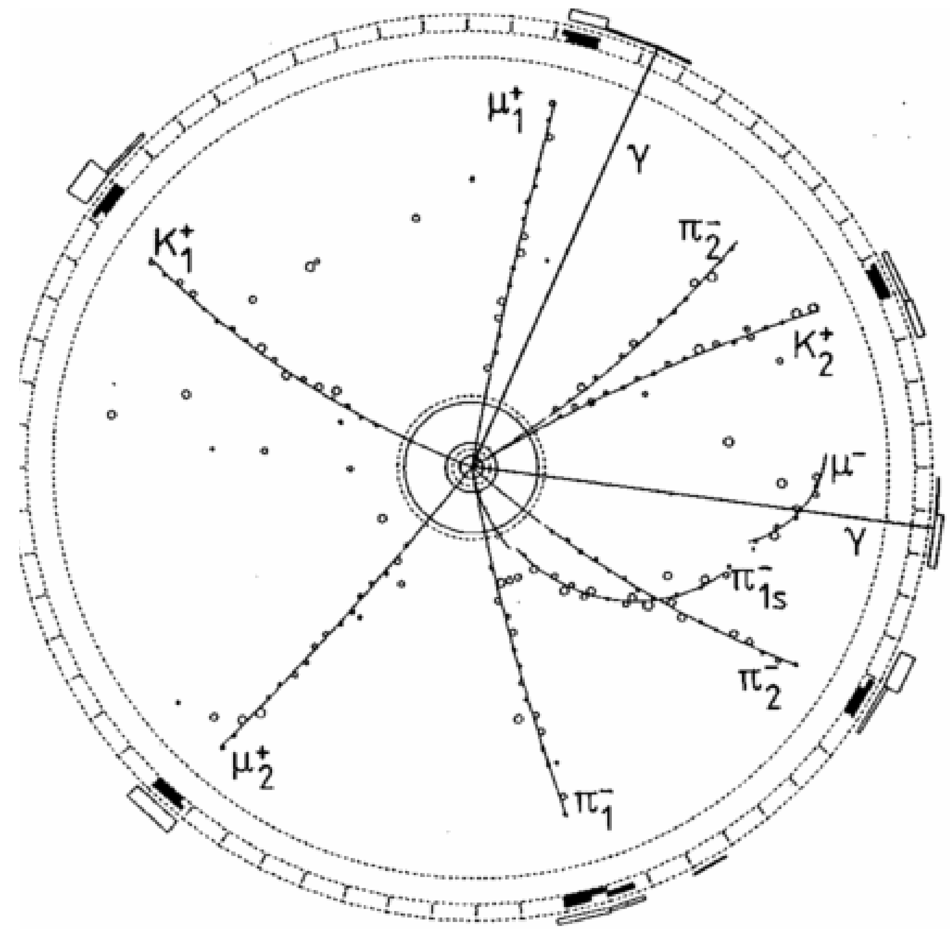
Large asymmetry between B^+ and B^- decays in the region where ρK interferes with other contributions in the Dalitz plot.

Neutral meson mixing

Formalism and experimental results

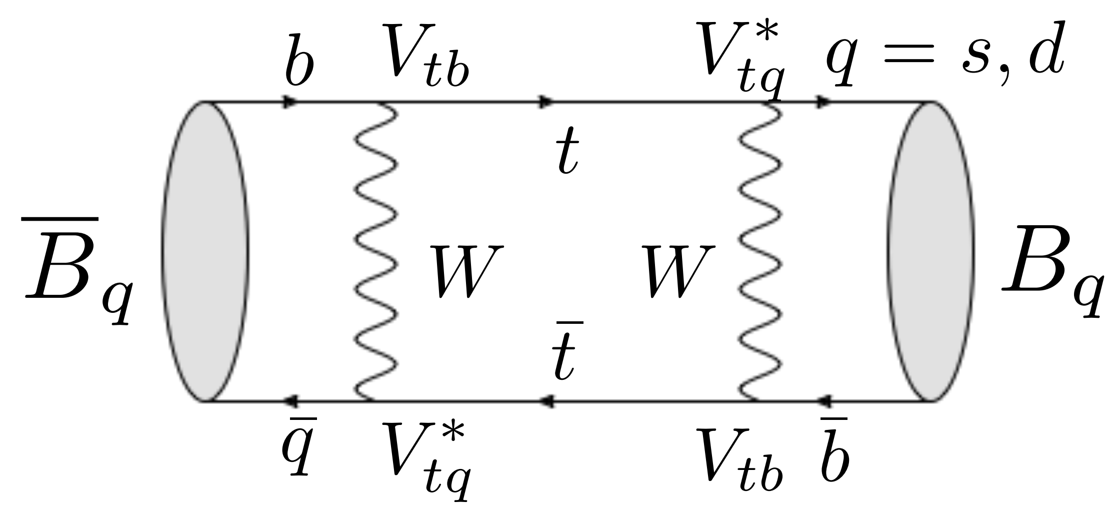
Observation of B "mixing"

- The ARGUS experiment observed that pair of $B^0\overline{B}^0$ mesons could decay to a final-state with like-sign leptons.
- How is this possible?



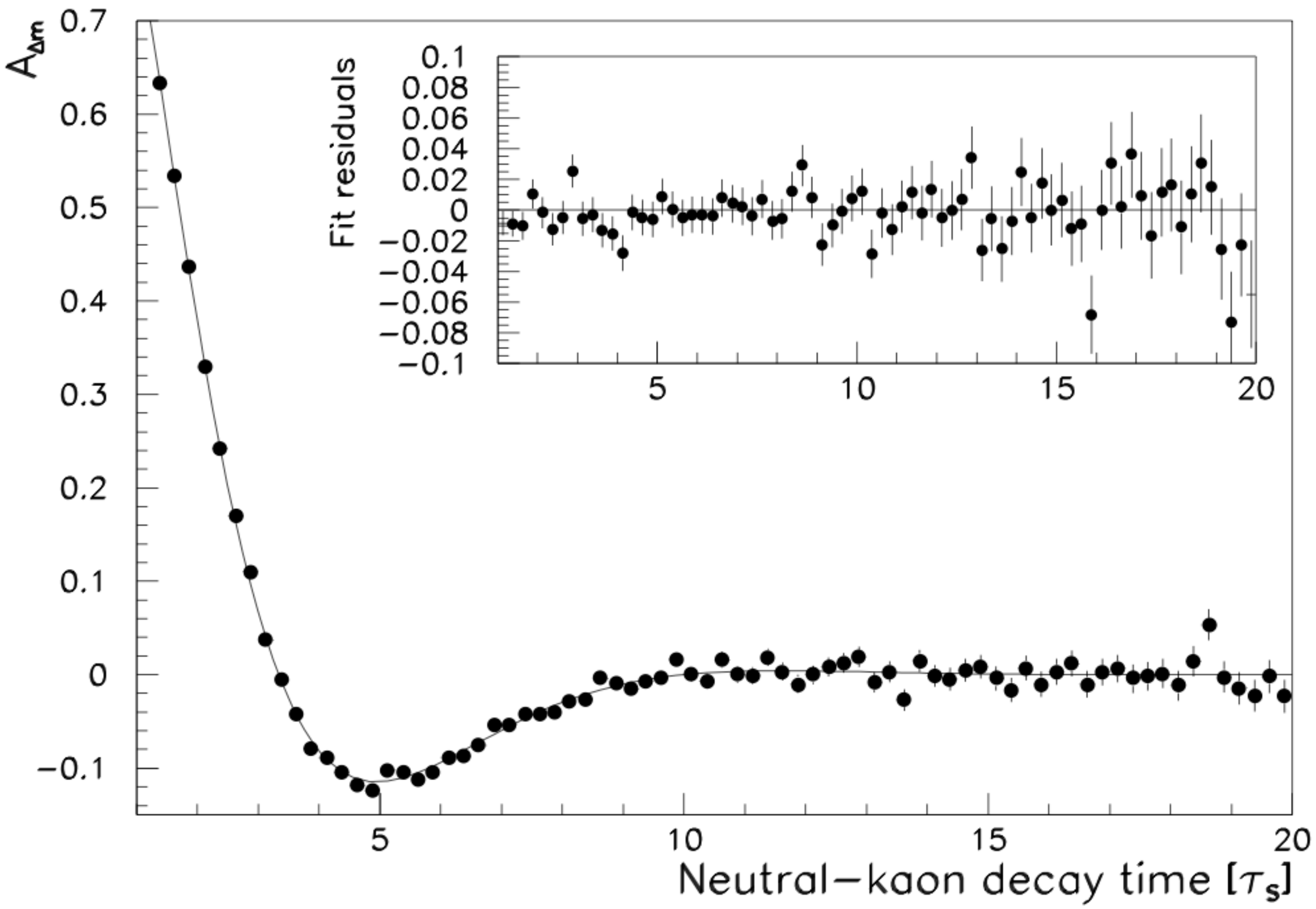
Neutral meson mixing

- In SM generate meson anti-meson mixing via box diagrams involving charged current interaction.
- Weak eigenstates are not the same as physical mass eigenstates of the system.



CPLEAR

- Produce pure beam of K^0 at production. Use semileptonic decays, $K^0 \to \pi^- \ell^+ \nu$ to tag the flavour at decay.



- Time evolution:

$$|K_1(t)\rangle = e^{-im_1 t} e^{-\Gamma_1 t/2} |K_1\rangle$$

$$|K_2(t)\rangle = e^{-im_2 t} e^{-\Gamma_2 t/2} |K_2\rangle$$

- At a later time, t

$$\begin{aligned} 2\langle K_0|K_0\rangle &= \langle K_1^*|K_1\rangle + \langle K_2^*|K_2\rangle + \langle K_1^*|K_2\rangle + \langle K_2^*|K_1\rangle \\ &= e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + e^{(\Gamma_1+\Gamma_2)t/2}\cos[(m_1 - m_2)t] \end{aligned}$$

Coupled meson systems

- Single particle system evolves according to the Schrödinger equation

$$i\frac{\partial}{\partial t}|M(t)\rangle = \mathcal{H}|M(t)\rangle = \left(M - i\frac{\Gamma}{2}\right)|M(t)\rangle$$

- For neutral mesons, mixing leads to a coupled system

$$i\frac{\partial}{\partial t}\begin{pmatrix}|B^0\rangle\\|\overline{B}^0\rangle\end{pmatrix} = \mathcal{H}\begin{pmatrix}|B^0\rangle\\|\overline{B}^0\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|B^0\rangle\\|\overline{B}^0\rangle\end{pmatrix}$$
$$= \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M_{22} - i\frac{\Gamma_{22}}{2}\end{pmatrix}\begin{pmatrix}|B^0\rangle\\|\overline{B}^0\rangle\end{pmatrix}$$

where

$$M_{12} = \frac{1}{2M}\mathcal{A}(B^0 \to \overline{B}^0) = \langle \overline{B}^0|\mathcal{H}(\Delta B = 2)|B^0\rangle$$

Coupled meson systems

- Neglecting CP violation, the physical states are an equal admixture of the weak eignenstates,

$$|B_{\rm L}\rangle = \frac{|B^0\rangle + |\overline{B}^0\rangle}{\sqrt{2}} \;,\; |B_{\rm H}\rangle = \frac{|B^0\rangle - |\overline{B}^0\rangle}{\sqrt{2}}$$

with mass and width differences

$$|\Delta\Gamma| = |\Gamma_{\rm H} - \Gamma_{\rm L}| = 2|\Gamma_{12}| \;,\; \Delta M = M_{\rm H} - M_{\rm L} = 2|M_{12}|$$

such that the system evolves as

$$\begin{aligned} i\frac{\partial}{\partial t}\begin{pmatrix}|B_{\rm L}\rangle \\ |\bar{B}_{\rm H}\rangle\end{pmatrix} &= \mathcal{H}\begin{pmatrix}|B_{\rm L}\rangle \\ |\bar{B}_{\rm H}\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|B_{\rm L}\rangle \\ |B_{\rm H}\rangle\end{pmatrix} \\ &= \begin{pmatrix} M_{\rm L} - i\frac{\Gamma_{\rm L}}{2} & 0 \\ 0 & M_{\rm H} - i\frac{\Gamma_{\rm H}}{2}\end{pmatrix}\begin{pmatrix}|B_{\rm L}\rangle \\ |\bar{B}_{\rm H}\rangle\end{pmatrix}\end{aligned}$$

Time evolution

- Solving the Schrödinger equation for the time evolution of the system an initially pure flavour eigenstate evolves as

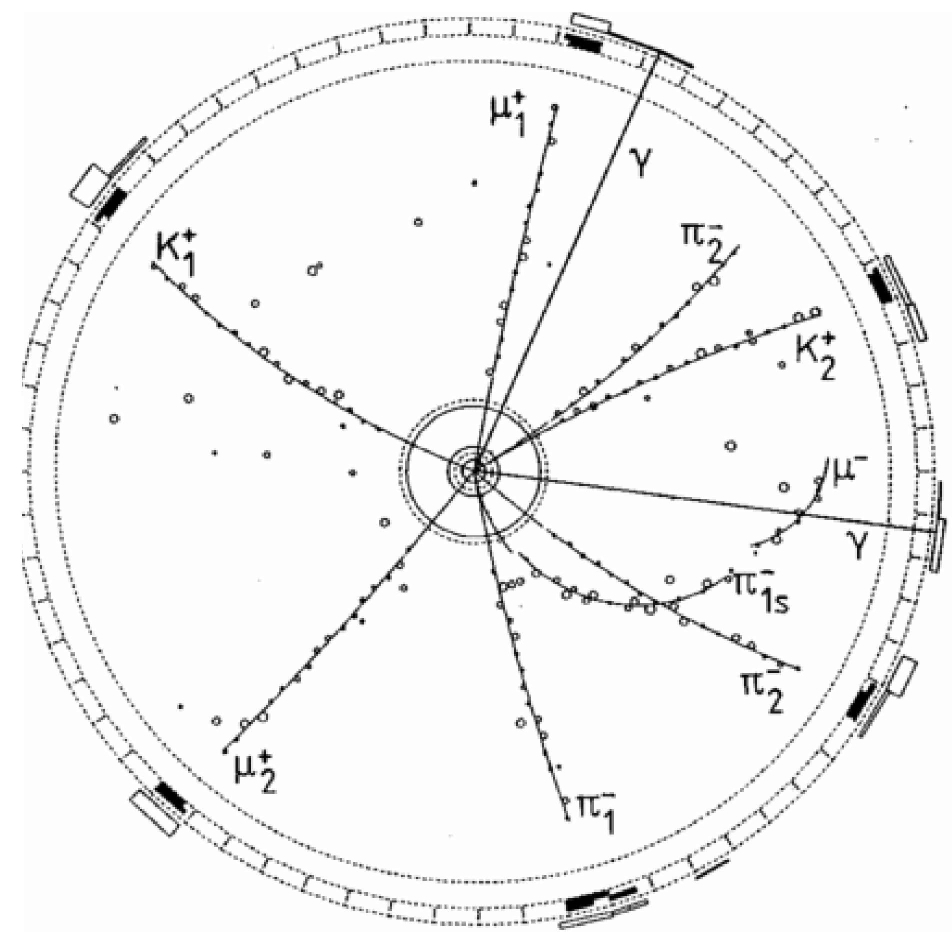
$$|B(t)\rangle = e^{-iMt}e^{-\Gamma t/2}(\alpha(t)|B^0\rangle + \beta(t)|\overline{B}^0\rangle)$$

where

$$\begin{aligned}\alpha(t) &= \cosh\left(\frac{\Delta\Gamma t}{4}\right)\cos\left(\frac{\Delta m t}{2}\right) - i\sinh\left(\frac{\Delta\Gamma t}{4}\right)\sin\left(\frac{\Delta m t}{2}\right)\\ \beta(t) &= -\sinh\left(\frac{\Delta\Gamma t}{4}\right)\cos\left(\frac{\Delta m t}{2}\right) + i\cosh\left(\frac{\Delta\Gamma t}{4}\right)\sin\left(\frac{\Delta m t}{2}\right)\end{aligned}$$

Observation of *B* mixing

- Neutral B meson mixing observed by the ARGUS experiment in 1987.
- Coherent pairs of $B^0\overline{B}^0$ produced. Observed decay to same sign leptons.
  - ➡ Evidence for mixing.
- Rate of mixing is large.
  - ➡ Top quark must be heavy.



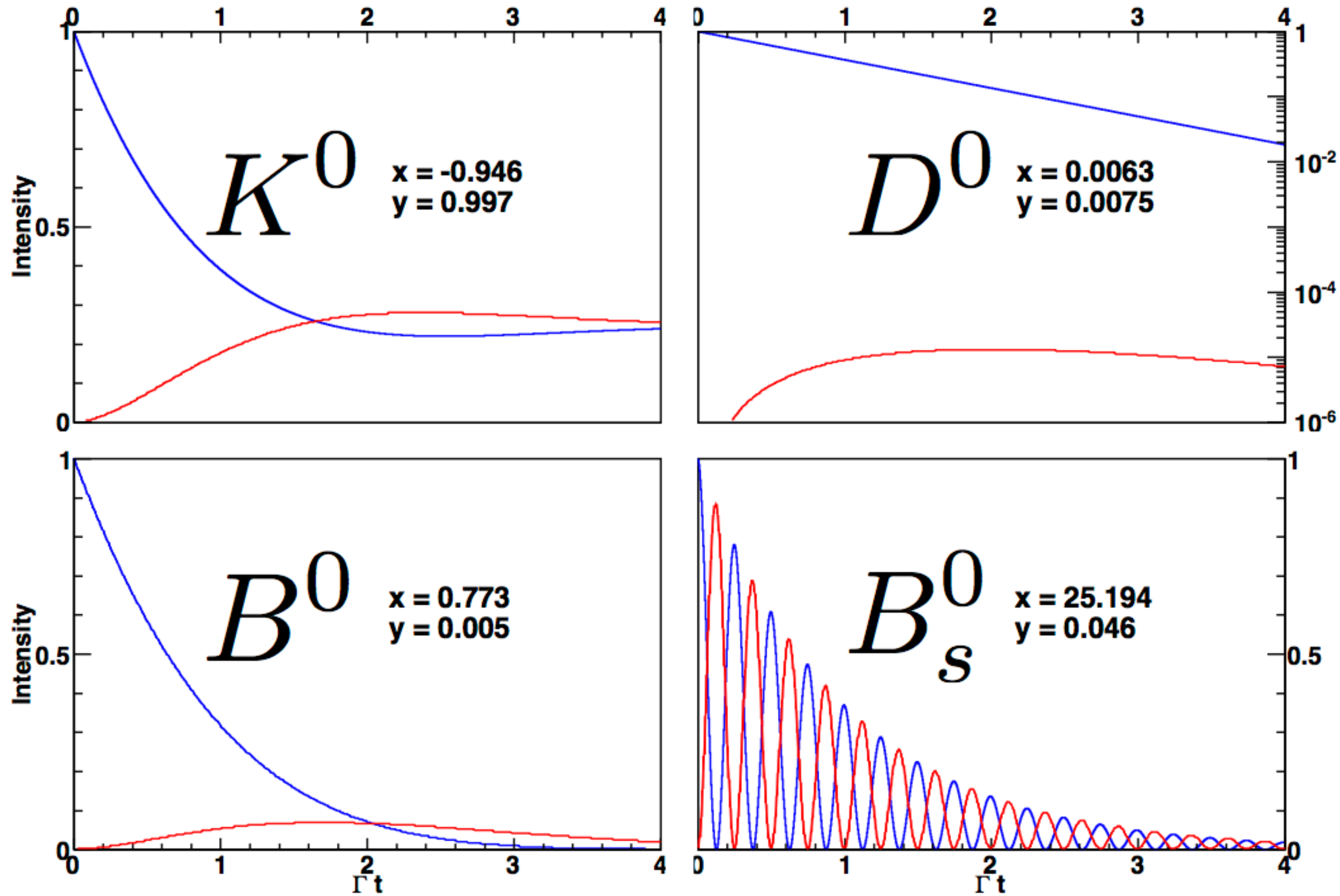
Time evolution

- Time evolution is very different for different neutral meson systems.

From [arXiv:1209.5806]

$P(X^0(0) \to X^0(t))$

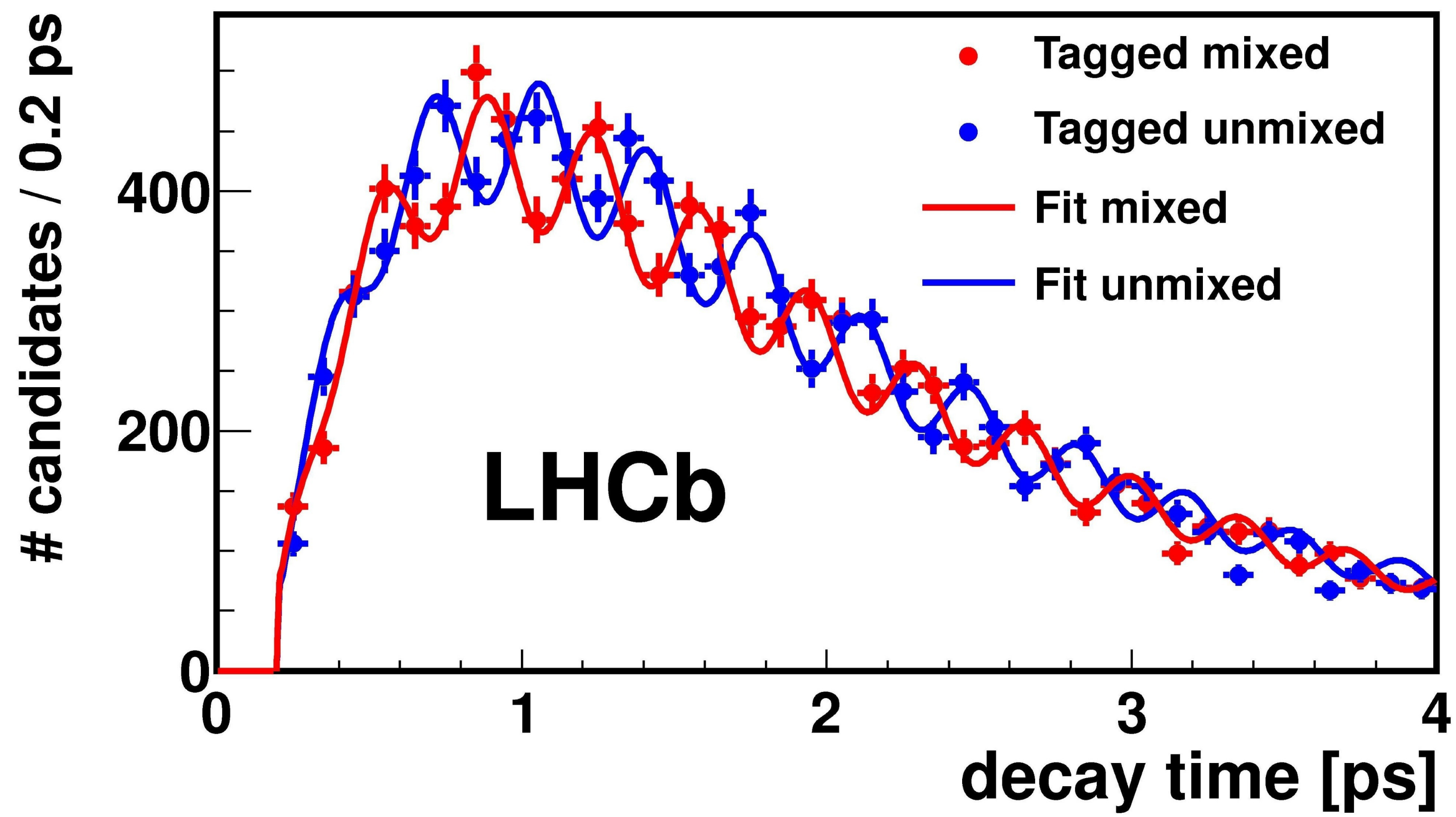
$P(X^0(0) \to \overline{X^0}(t))$



Time evolution

- Nice demonstration of this oscillation performed for the *B*s system by LHCb using $B_s^0 \to D_s^- \pi^+$ decays.

  (Tagging flavour at production and looking at flavour at decay)

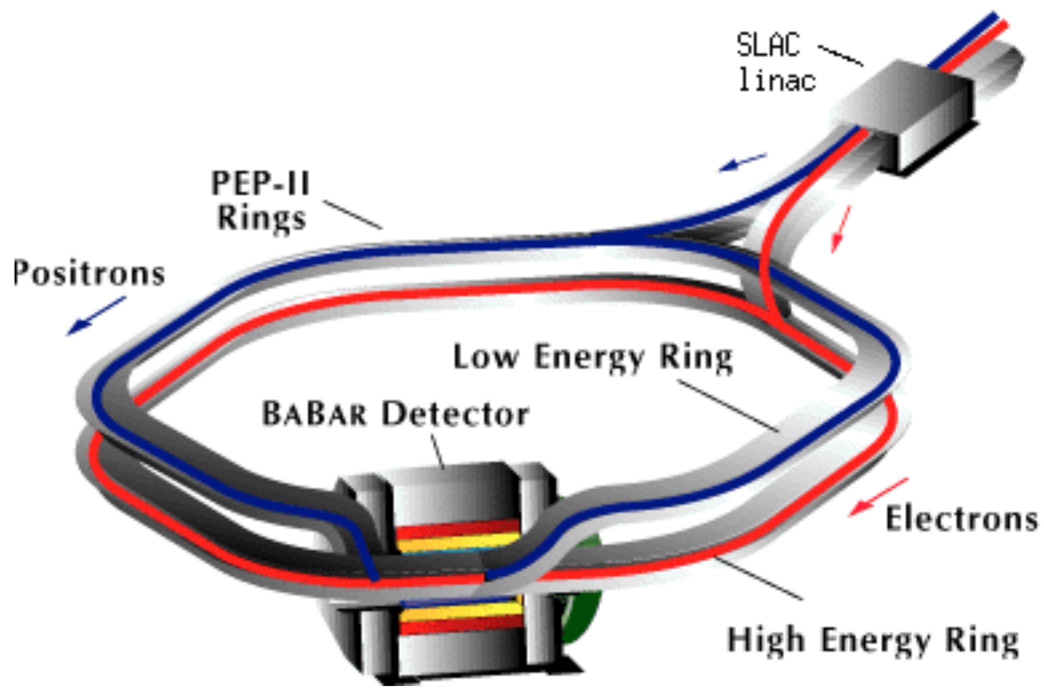


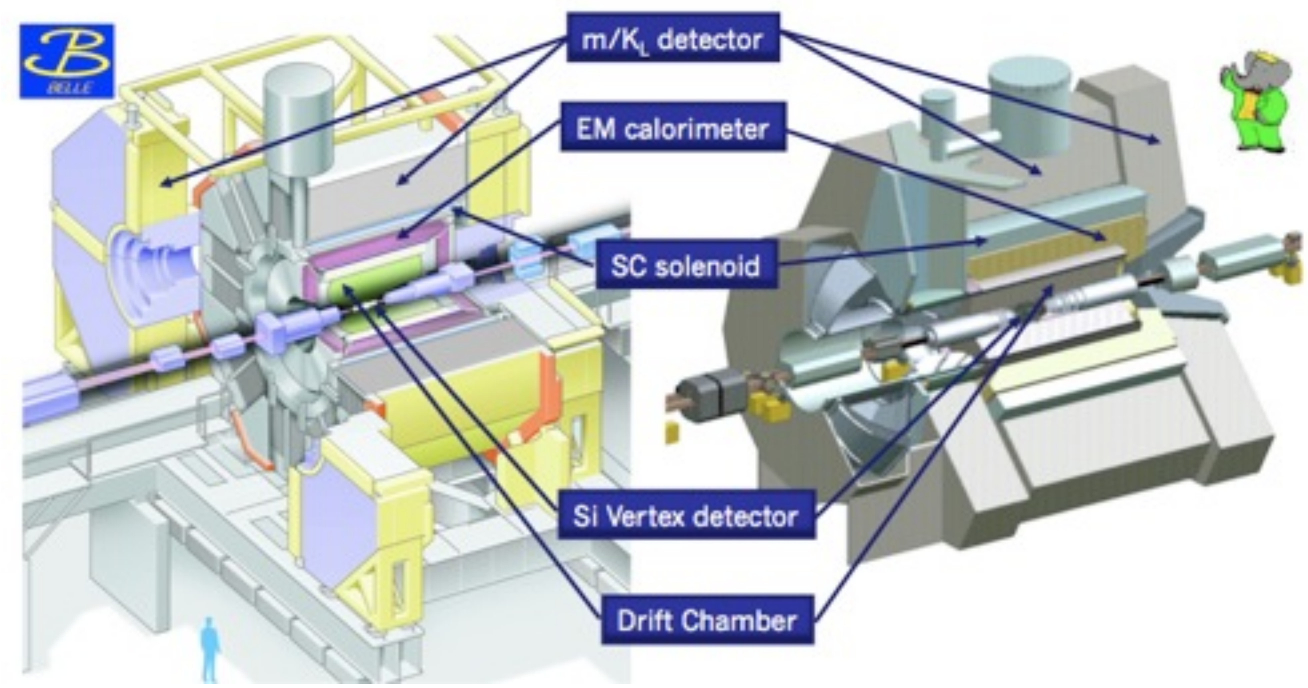
Amplitude of the oscillation is damped by the experiments ability to correctly “tag” the flavour of the *B*s at production.

B meson production

Production and flavour tagging

B-factories at $\Upsilon(4S)$

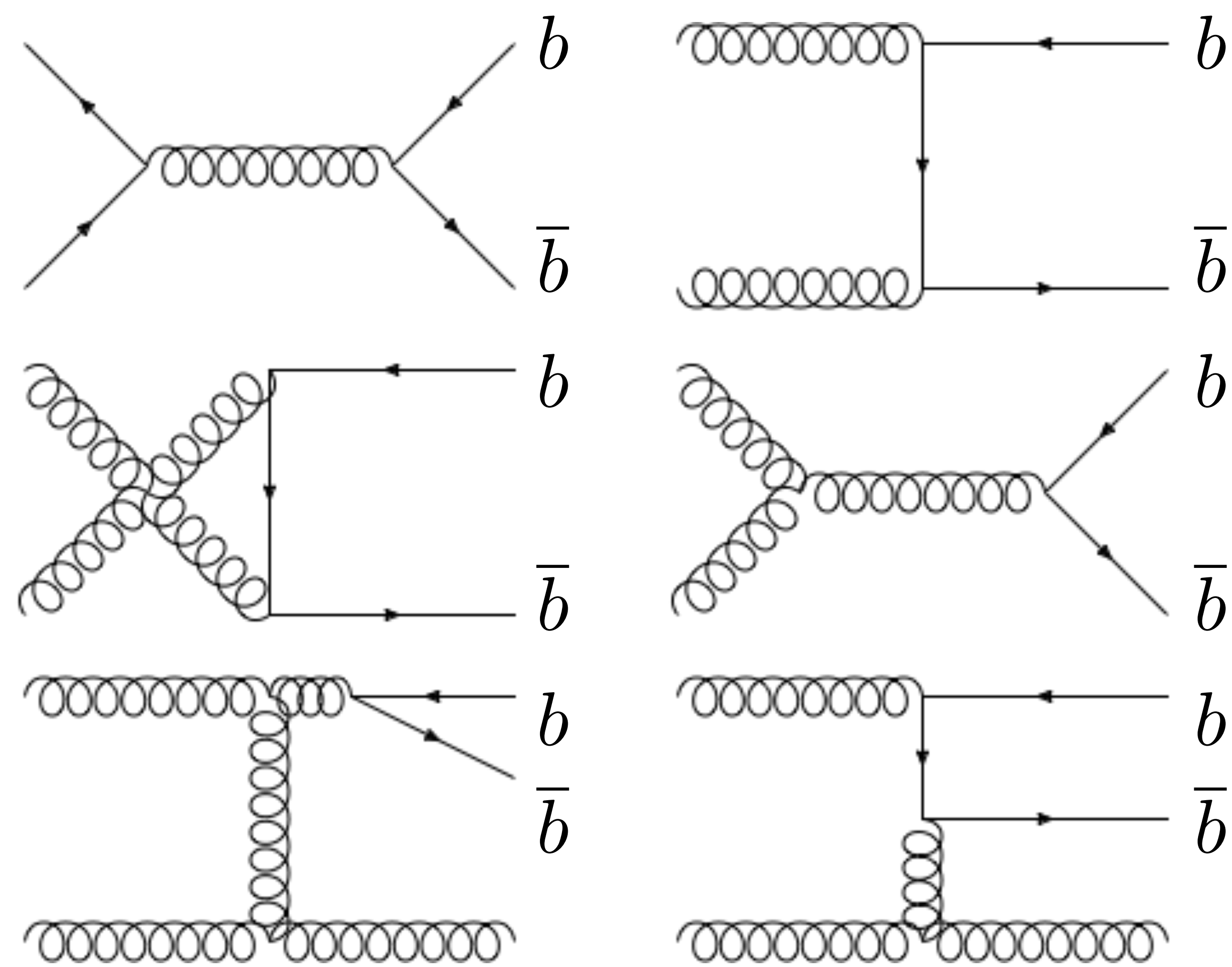




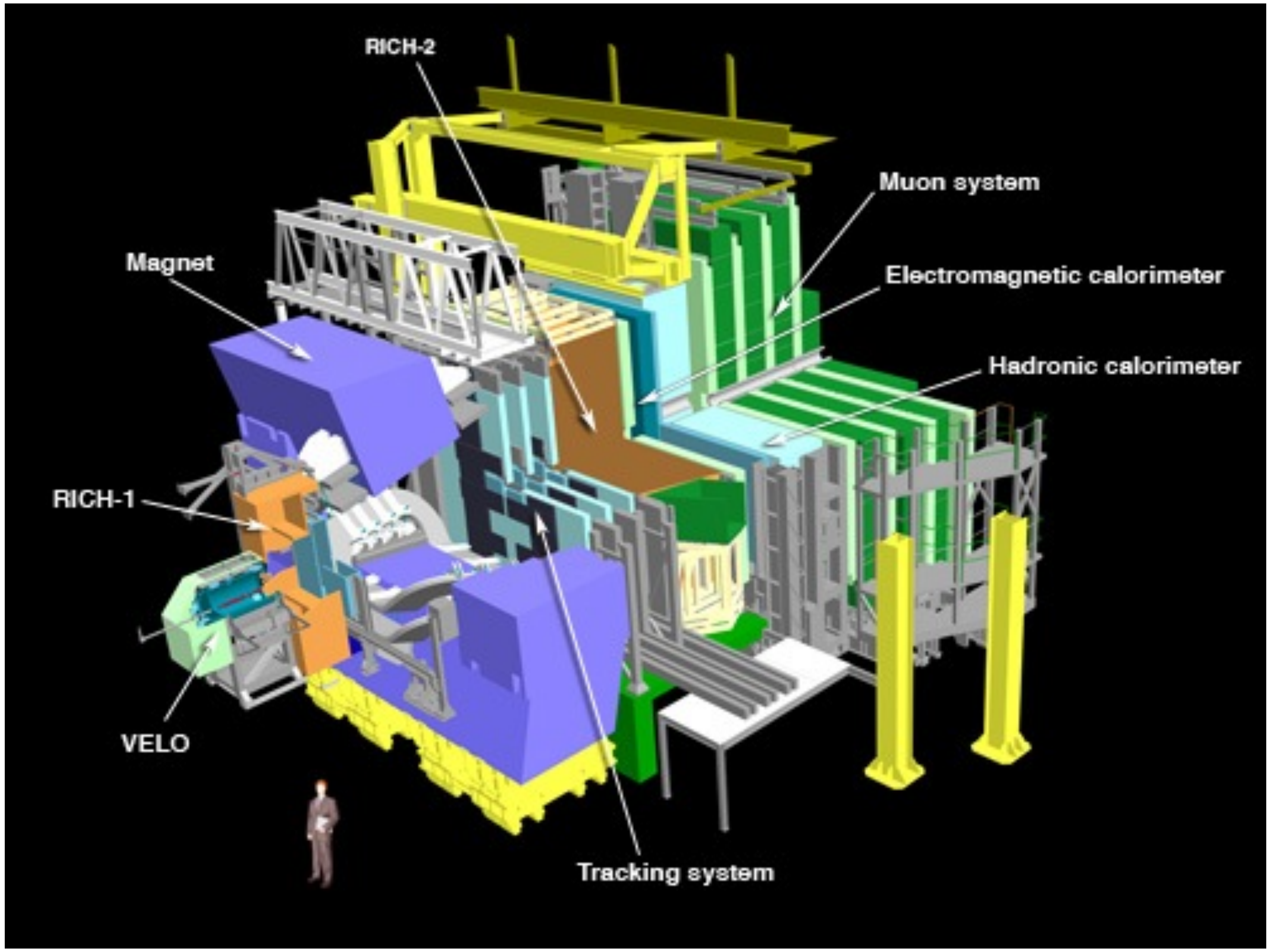
- Asymmetric e- e+ colliders:
  - ➡ PEP-II at SLAC is 9 GeV on 3.1 GeV
  - ➡ KEKB at KEK is 8 GeV on 3.5 GeV
- Produces a coherent $B^0\overline{B}^0$ or B^+B^- system that is moving in lab-frame (needed for decay time measurements).

b-production at the LHC

- LHC is predominantly a gluon collider.
- b-quarks produced in the forward direction with large boost → forward geometry of LHCb.
- Large boost and excellent vertexing makes decay time measurements much easier at the LHC → can resolve the fast B_s oscillations.

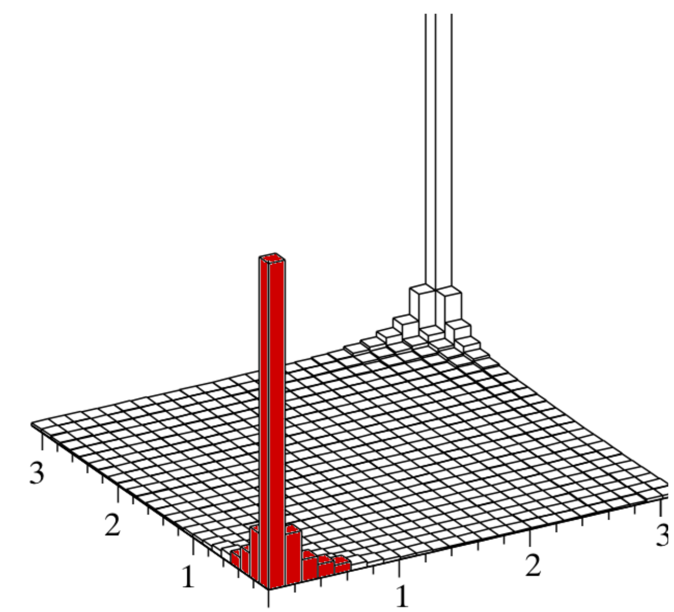


LHCb experiment

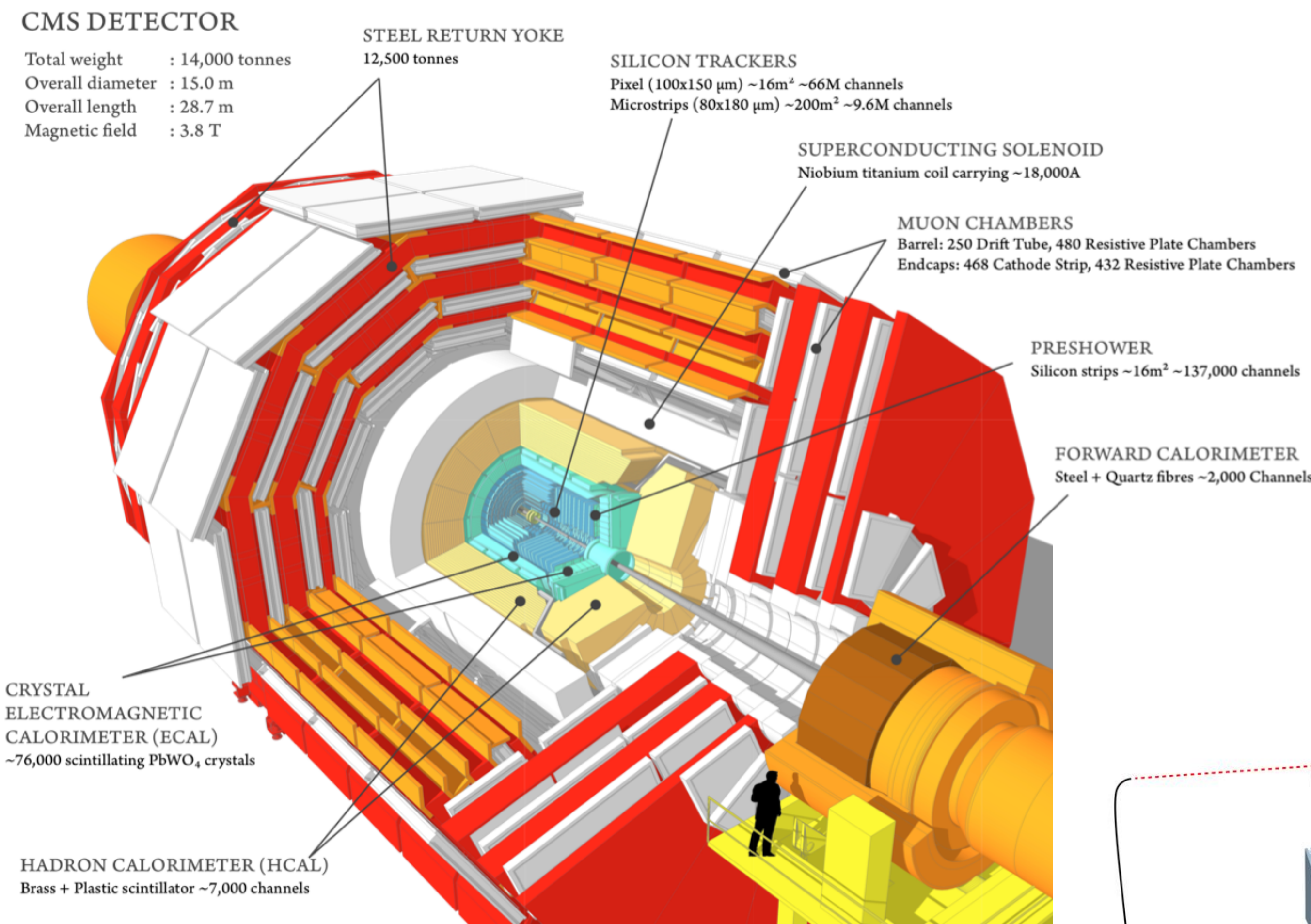


LHCb is a dedicated for experiment *b*- and *c*-hadron studies in the forward direction at the LHC.

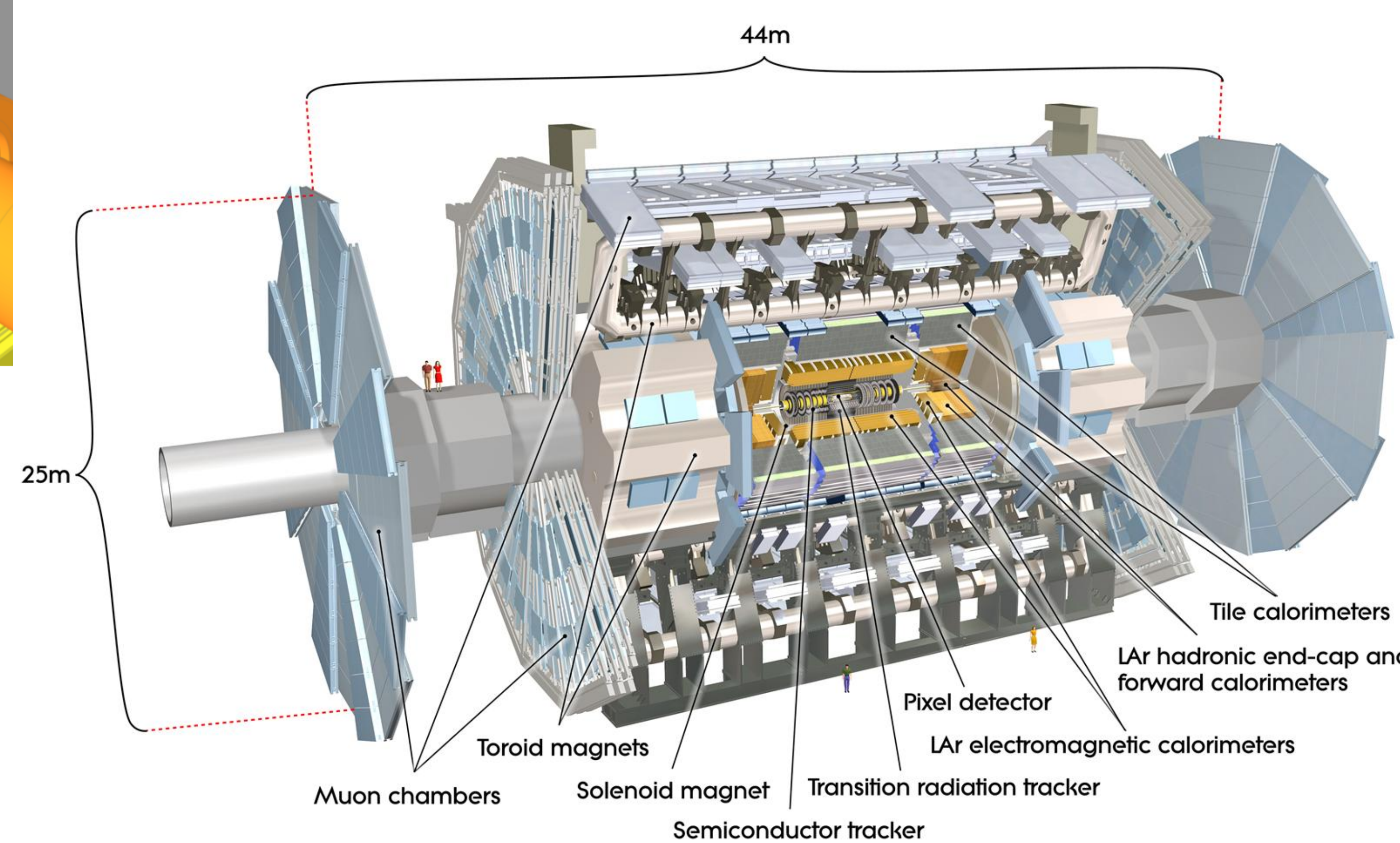
$b\bar{b}$ production predominantly in same direction and at small angles to the beam line (collisions between one hard and one soft parton).



LHC experiments

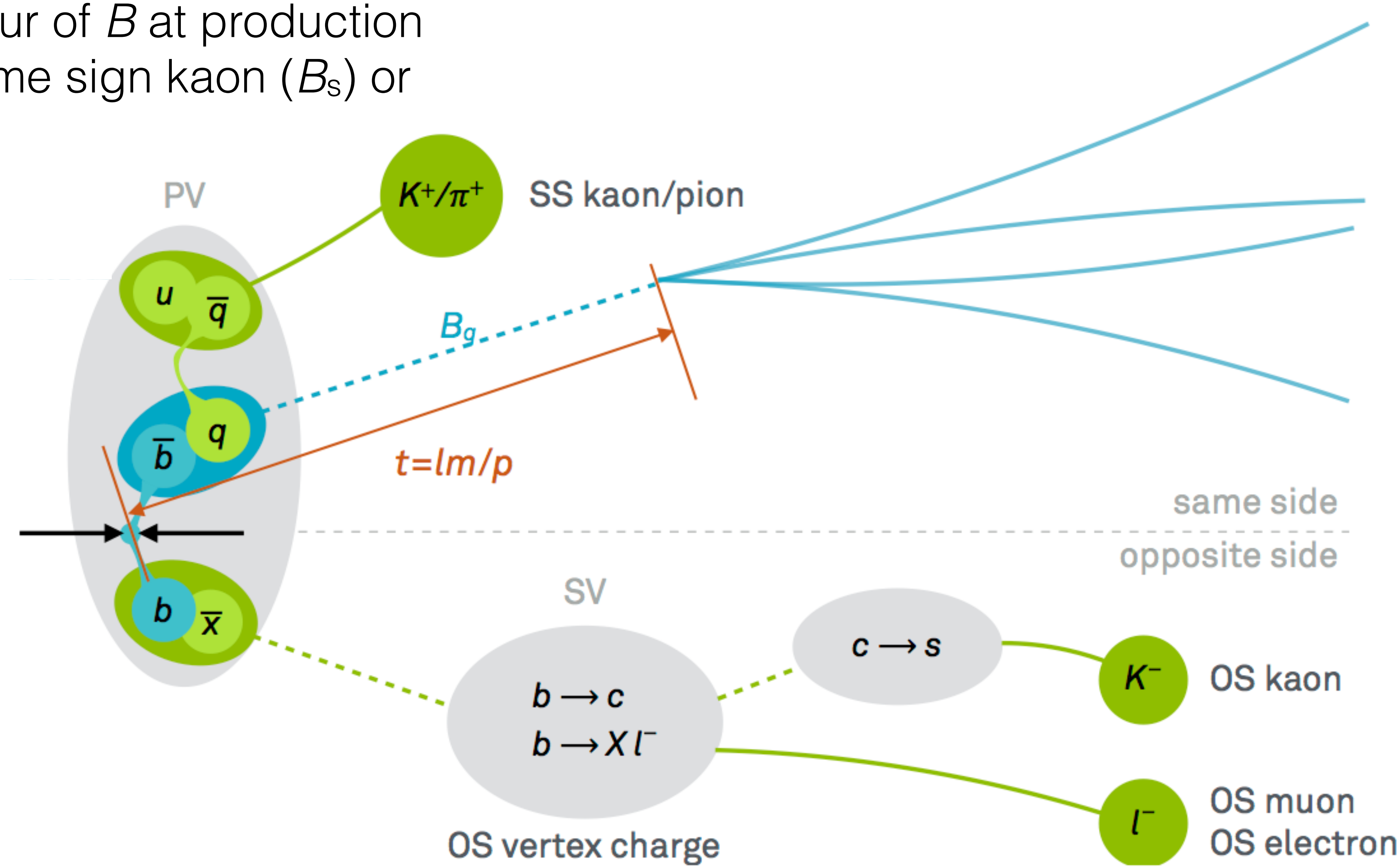


There are also significant contributions from ATLAS and CMS to heavy flavour measurements
(large rate, but limited hadron ID)



Flavour tagging at the LHC

Tag flavour of B at production using same sign kaon (B_s) or pion (B^0)



or flavour of B using the flavour of the other B in the event

Neutral meson mixing

Formalism and experimental results

CP violation?

- Allowing for CP violation, $M_{12} \neq M_{12}^{*} \quad \text{and} \quad \Gamma_{12} \neq \Gamma_{12}^{*}$
- The physical states are combinations

$$|B_{\rm L}\rangle = p|B^{0}\rangle + q|\overline{B}^{0}\rangle \ , \ |B_{\rm H}\rangle = p|B^{0}\rangle - q|\overline{B}^{0}\rangle$$

$$|p|^{2} + |q|^{2} = 1$$

- The states have mass and width differences

$$|\Delta\Gamma| \approx 2|\Gamma_{12}|\cos\phi \ , \ \Delta M \approx 2|M_{12}| \ , \ \phi = \arg(-M_{12}/\Gamma_{12})$$

Neutral kaon system

- Ignoring CP violation, the two physical states in the neutral kaon system are

$$|K_1\rangle = \frac{|K^0\rangle - |\overline{K}^0\rangle}{\sqrt{2}} \quad \text{and} \quad |K_2\rangle = \frac{|K^0\rangle + |\overline{K}^0\rangle}{\sqrt{2}}$$

under Parity and Charge Conjugation

$$\mathcal{P}|K^0\rangle = -|K^0\rangle \quad , \quad \mathcal{C}|K^0\rangle = |\overline{K}^0\rangle \quad \text{and} \quad \mathcal{CP}|K^0\rangle = -|\overline{K}^0\rangle$$

- For the physical states

$$\mathcal{P}|K_{1,2}\rangle = -|K_{1,2}\rangle \quad , \quad \mathcal{C}|K_{1,2}\rangle = \mp|K_{1,2}\rangle \quad \text{and} \quad \mathcal{CP}|K_{1,2}\rangle = \pm|K_{1,2}\rangle$$

i.e. they are P, C and CP eigenstates as well.

Neutral kaon system

- What does this tell us about their decays?

$\pi^+\pi^-$

➡ P = +1, C = +1 and CP = +1 $\Big\}$ shorter lived K_1

$\pi^+\pi^-\pi^0$

➡ P = -1, C = + 1 and CP = -1 $\Big\}$ longer lived K_2

- K_2 decays to 3π but the 2π decay would be forbidden if CP is conserved.

CP violation in kaon system

- Two possible explanations for CP violation in the kaon system, the K_S and K_L are not pure K_1 and K_2 states ($p \neq q$)

$$|K^0_{\rm S}\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}(|K_1\rangle + \varepsilon|K_2\rangle)$$

$$|K^0_{\rm L}\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}(|K_2\rangle + \varepsilon|K_1\rangle)$$

decays to 3π

decays to 2π

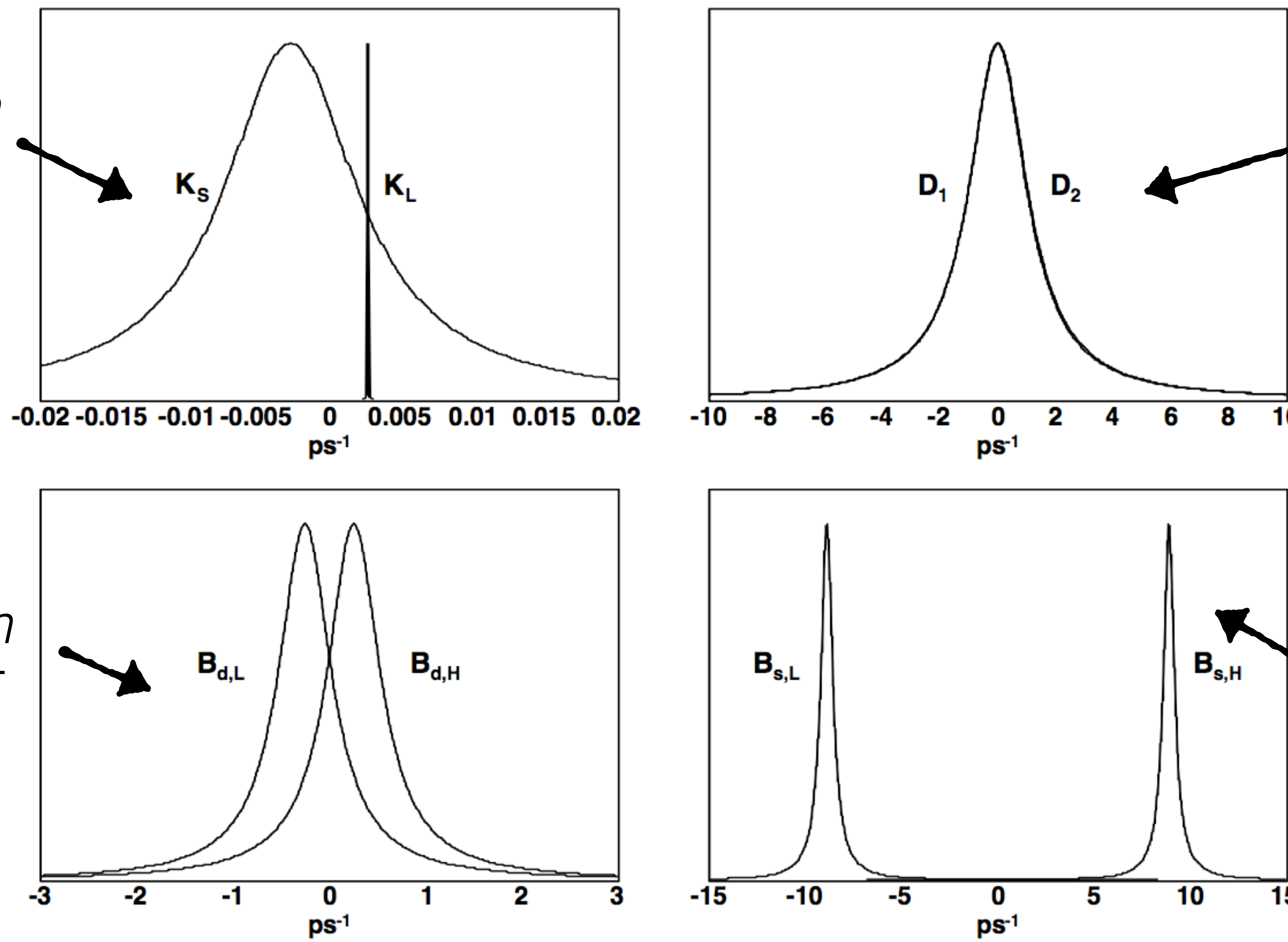
$$|\varepsilon| \approx 2 \times 10^{-3}$$

- Can also have CP violation in the decay (discussed in lecture 3).

Mass and width differences

large Δm
and $\Delta\Gamma$

small Δm
and $\Delta\Gamma$



moderate Δm
and small $\Delta\Gamma$

large Δm and
moderate $\Delta\Gamma$

$|q/p| \sim 1$ for every meson system

CP violation

- Three types of CP violation

1. Direct CP violation $$\left|\frac{\mathcal{A}(\bar{B} \to \bar{f})}{\mathcal{A}(B \to f)}\right| \neq 1$$

2. Mixing induced CP violation $$\left|\frac{q}{p}\right| \neq 1$$

3. CP violation in the interference between mixing and decay $$\mathrm{Im}\left(\frac{q}{p}\frac{\mathcal{A}(\overline{B} \to f)}{\mathcal{A}(B \to f)}\right) \neq 0$$

CP violation

- Three ways to observe CP violating effects:

1. Direct CP violation

charged and neutral mesons/baryons

2. Mixing induced CP violation

3. CP violation in the interference between mixing and decay

neutral mesons

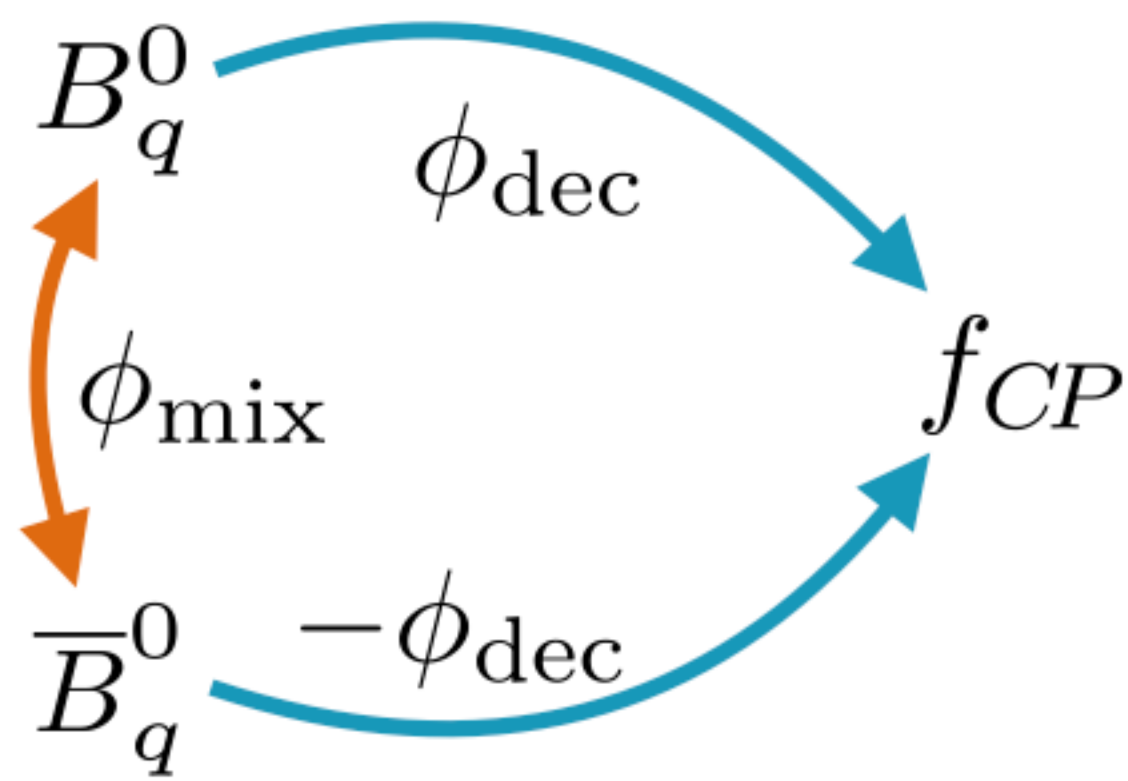
CP violation and mixing

- Need two interfering contributions,

  eg interference between decays to a common final state, with and without mixing.

- Experimental complication:

  ➡ Need to “tag” the flavour of the *B* at production.



Time evolution

direct CP violation

$$\boxed{\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}}$$

$$\boxed{C = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}$$

$$\Gamma[B \to f] = |A_f|^2 e^{-\Gamma t}\left(\frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma}{2}t + \frac{1-|\lambda_f|^2}{2}\cos\Delta M t\right.$$
$$\left. -\mathrm{Re}\lambda_f \sinh\frac{\Delta\Gamma}{2}t - \mathrm{Im}\lambda_f \sin\Delta M t\right)$$

known to be B^0 at t = 0

$$\Gamma[\overline{B} \to f] = |A_f|^2 e^{-\Gamma t}\left(\frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma}{2}t - \frac{1-|\lambda_f|^2}{2}\cos\Delta M t\right.$$
$$\left. -\mathrm{Re}\lambda_f \sinh\frac{\Delta\Gamma}{2}t + \mathrm{Im}\lambda_f \sin\Delta M t\right)$$

known to be $\overline{B}^0$ at t = 0

$$\boxed{\mathcal{A}^{\Delta\Gamma} = \frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2}}$$

$$\boxed{S = \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}}$$

Time evolution

B^0 system $\Delta\Gamma \sim 0$

$$\Gamma[B \to f] = |A_f|^2 e^{-\Gamma t} \left(\frac{1+|\lambda_f|^2}{2} + \frac{1-|\lambda_f|^2}{2} \cos \Delta M t - \mathrm{Im}\lambda_f \sin \Delta M t \right)$$

$$\Gamma[\overline{B} \to f] = |A_f|^2 e^{-\Gamma t} \left(\frac{1+|\lambda_f|^2}{2} - \frac{1-|\lambda_f|^2}{2} \cos \Delta M t + \mathrm{Im}\lambda_f \sin \Delta M t \right)$$

Time evolution

no tagging of the flavour

$$\Gamma[B \to f] = |A_f|^2 e^{-\Gamma t} \left(\frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta\Gamma}{2} t \right.$$
$$\left. - \mathrm{Re}\lambda_f \sinh \frac{\Delta\Gamma}{2} t \right)$$

$$\Gamma[\overline{B} \to f] = |A_f|^2 e^{-\Gamma t} \left(\frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta\Gamma}{2} t \right.$$
$$\left. - \mathrm{Re}\lambda_f \sinh \frac{\Delta\Gamma}{2} t \right)$$

i.e. only see sum of two contributions.

Time evolution

$\Delta\Gamma$ and Δm small (D system)

$$\Gamma[B \to f] = |A_f|^2 e^{-\Gamma t} \left(\frac{1+|\lambda_f|^2}{2} + \frac{1-|\lambda_f|^2}{2} - \mathrm{Re}\lambda_f \frac{\Delta\Gamma}{2} t - \mathrm{Im}\lambda_f \, \Delta m t \right)$$

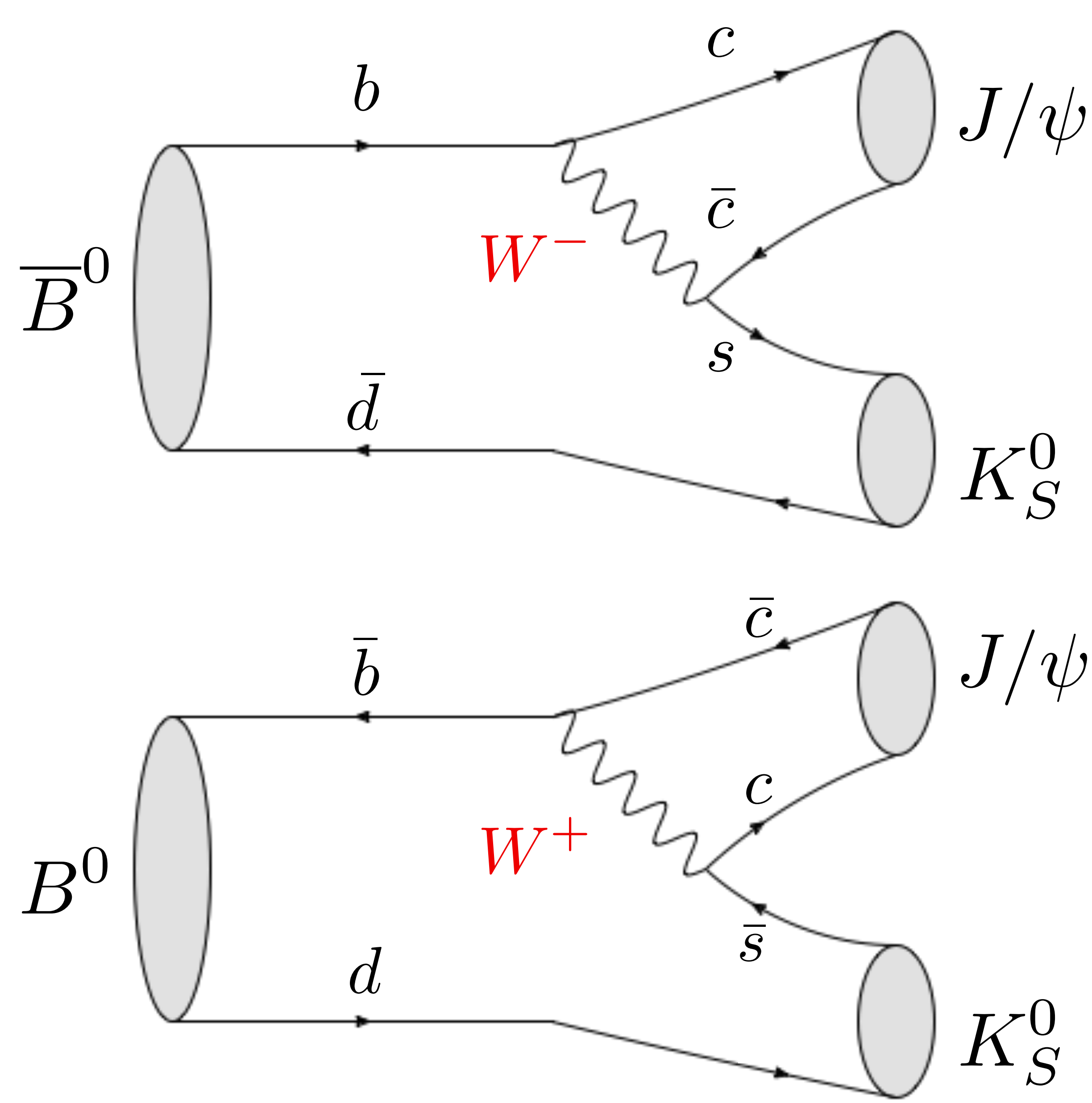
$$\Gamma[\overline{B} \to f] = |A_f|^2 e^{-\Gamma t} \left(\frac{1+|\lambda_f|^2}{2} - \frac{1-|\lambda_f|^2}{2} - \mathrm{Re}\lambda_f \frac{\Delta\Gamma}{2} t + \mathrm{Im}\lambda_f \, \Delta m t \right)$$

β and β_s

Experimental results

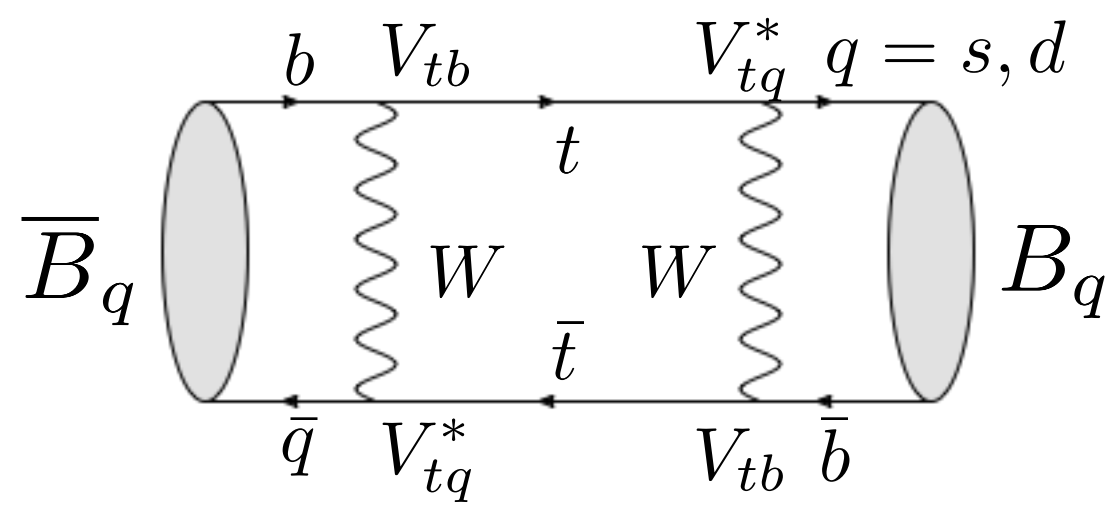
Golden mode

- Look at tree level $b \to c\bar{c}s$ decays to a common final state.
- Higher order, penguin diagrams, have (mostly) the same weak phase.
    - ➡ No direct CP violation. Just sensitive to CP violation in mixing.



Golden mode

- Look at tree level $b \to c\bar{c}s$ decays to a common final state.
- Higher order, penguin diagrams, have (mostly) the same weak phase.
    - ➡ No direct CP violation (CP violation in the decay).
    - ➡ Sensitive to CP violation in mixing.



- Mixing phase is $$\frac{q}{p} = \frac{V_{tb}^* V_{td} V_{tb}^* V_{td}}{|V_{tb}^* V_{td} V_{tb}^* V_{td}|} = e^{-2i\beta}$$

- Therefore $C \approx 0 \quad S \approx -\eta_{\rm CP} \sin 2\beta$

Time dependent CP violation in B^0 system

- Time dependent CP violation with $\Delta\Gamma \approx 0$

$$\Gamma[\overline{B}^0 \to f](t) \propto e^{-\Gamma t}(1 + S\sin(\Delta m t) - C\cos(\Delta m t))$$

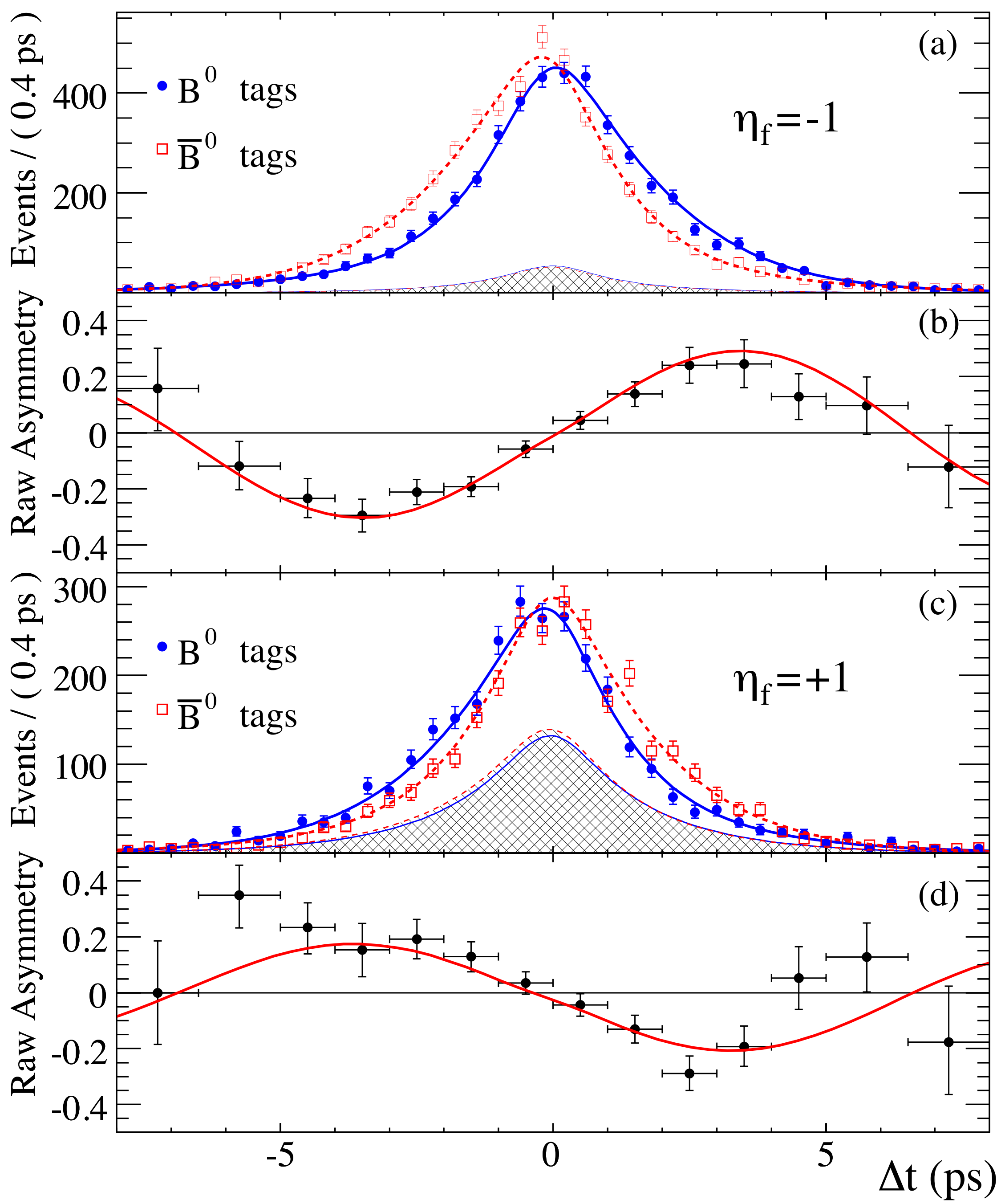
$$\Gamma[B^0 \to f](t) \propto e^{-\Gamma t}(1 - S\sin(\Delta m t) + C\cos(\Delta m t))$$

where

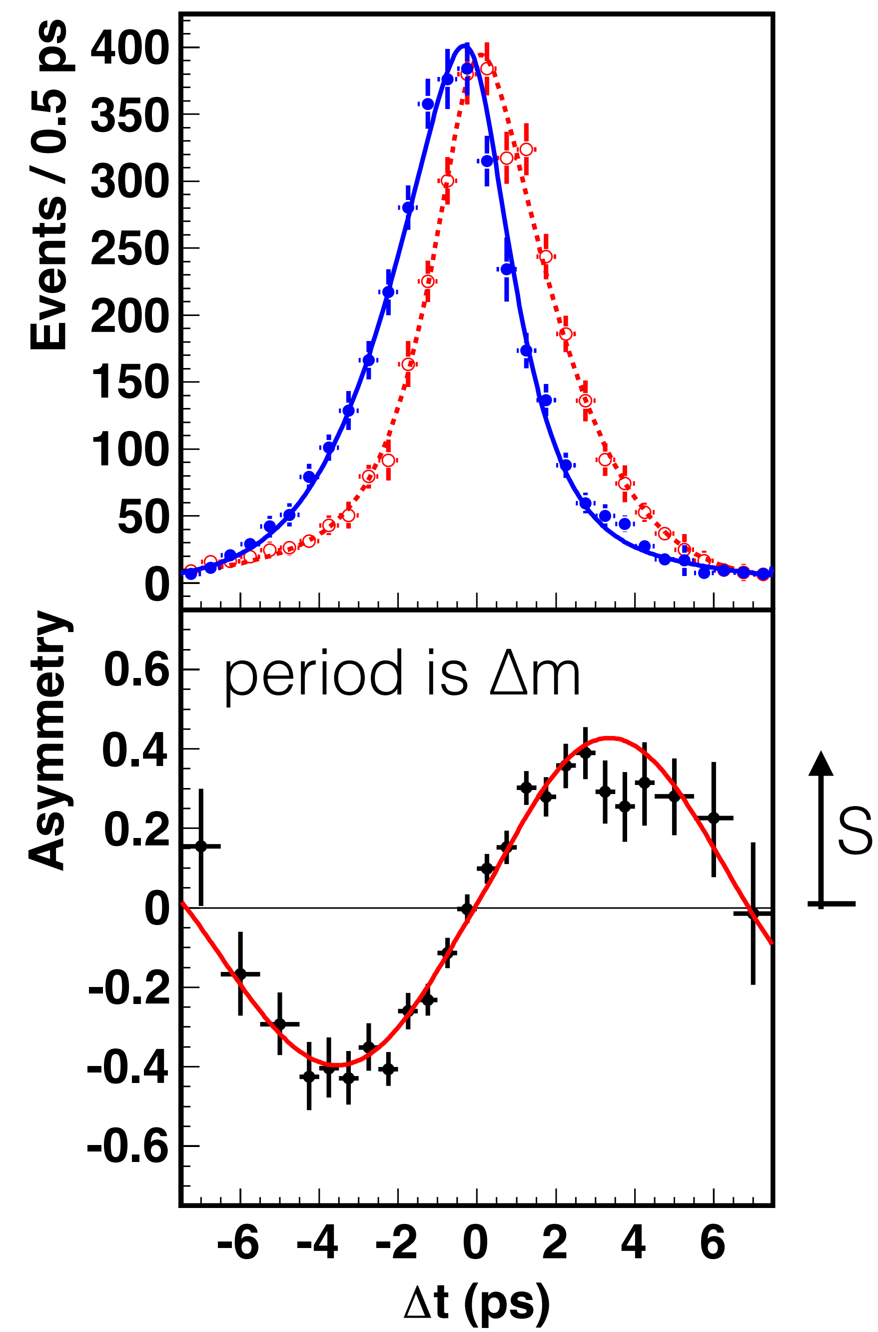
$$S = \frac{2\mathrm{Im}\left(\frac{q}{p}\frac{\bar{\mathcal{A}}}{\mathcal{A}}\right)}{1 + \left|\frac{q}{p}\frac{\bar{\mathcal{A}}}{\mathcal{A}}\right|^2} \qquad C = \frac{1 - \left|\frac{q}{p}\frac{\bar{\mathcal{A}}}{\mathcal{A}}\right|^2}{1 + \left|\frac{q}{p}\frac{\bar{\mathcal{A}}}{\mathcal{A}}\right|^2}$$

Golden mode

BaBar PRDD79 072009 (2009) [arXiv:0902.1708]



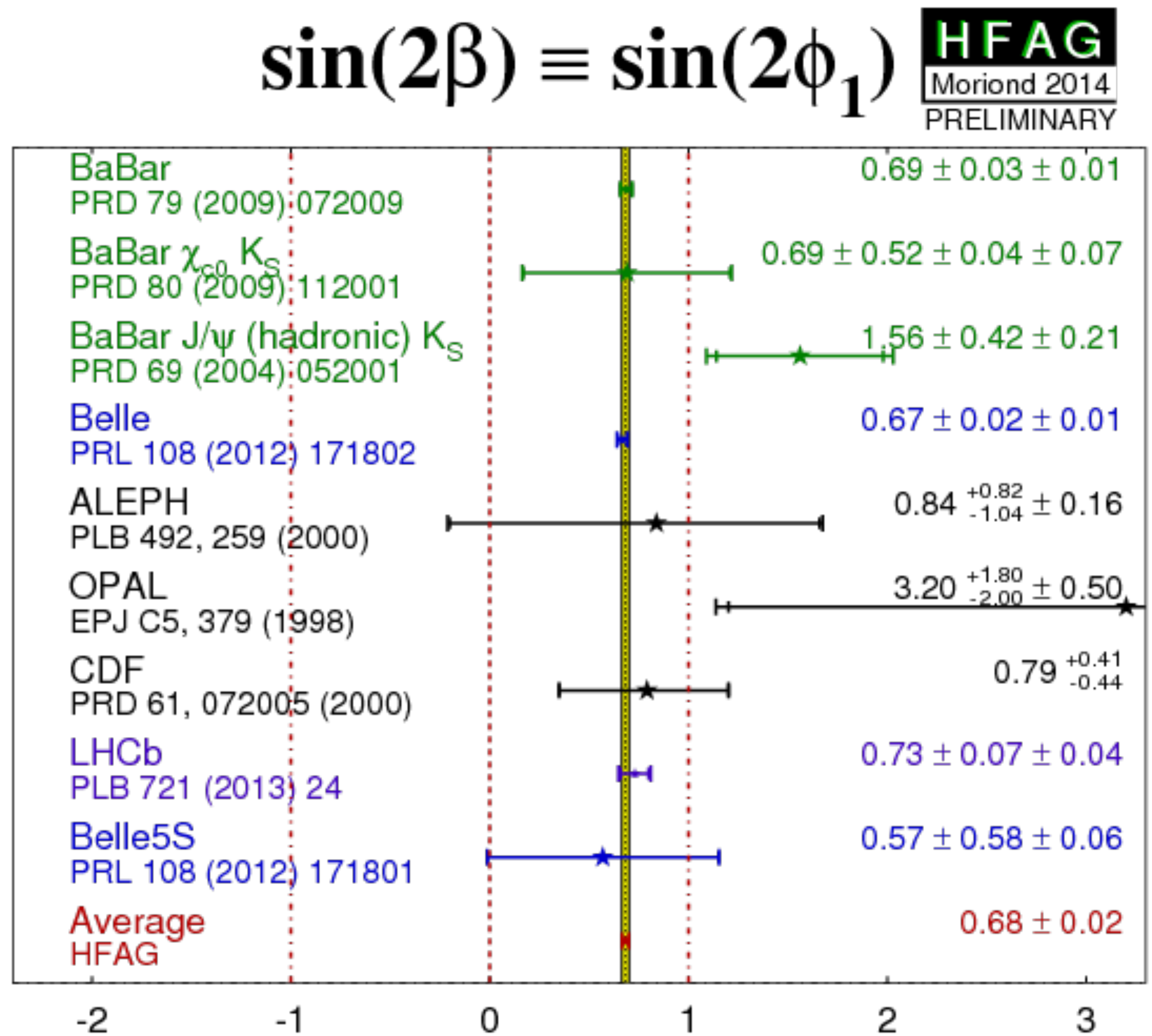
Belle PRL 108 171802 (2012) [arXiv:1201.4643]



tag flavour at time t_1 reconstruct decay at t_2 ($\Delta t = t_2 - t_1$)

Golden mode

- The angle β is very precisely known from measurements at the B-factories.

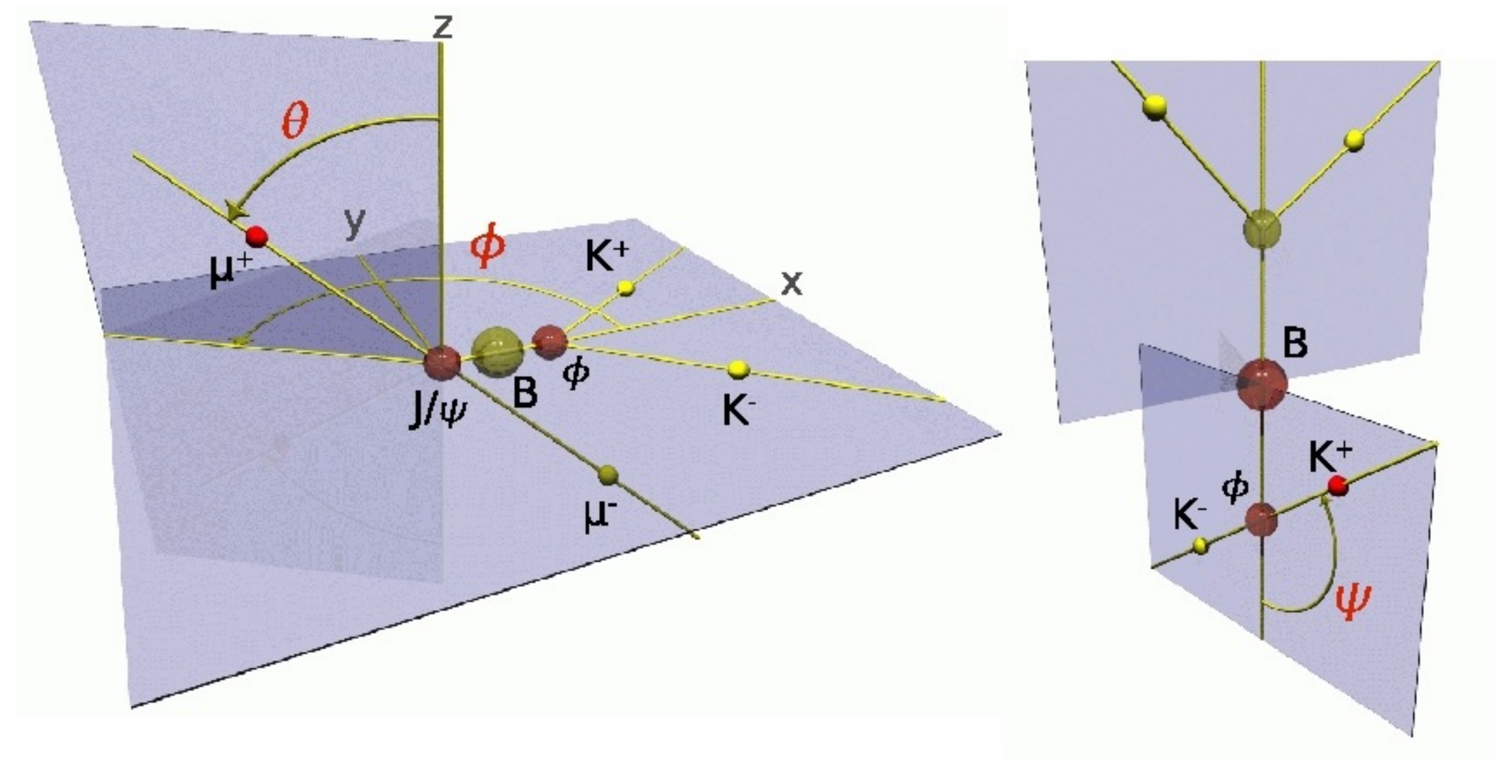


B_s mixing phase

- Can also look at equivalent processes in the B_s system,
  - ➡ Sensitive to the Bs mixing phase, $\phi_s = 2\beta_s$.
- Cleanest experimental signature is $B_s^0 \to J/\psi\,\phi$
  - ➡ 4 charged particles in the final state.
- However, now have a pseudoscalar B meson decaying to two vector (J = 1) particles.
  - ➡ The final state is a mix of CP-odd and CP-even.
  - ➡ Need to perform a time-dependent angular analysis to separate the CP-odd and CP-even components and determine ϕ_s.

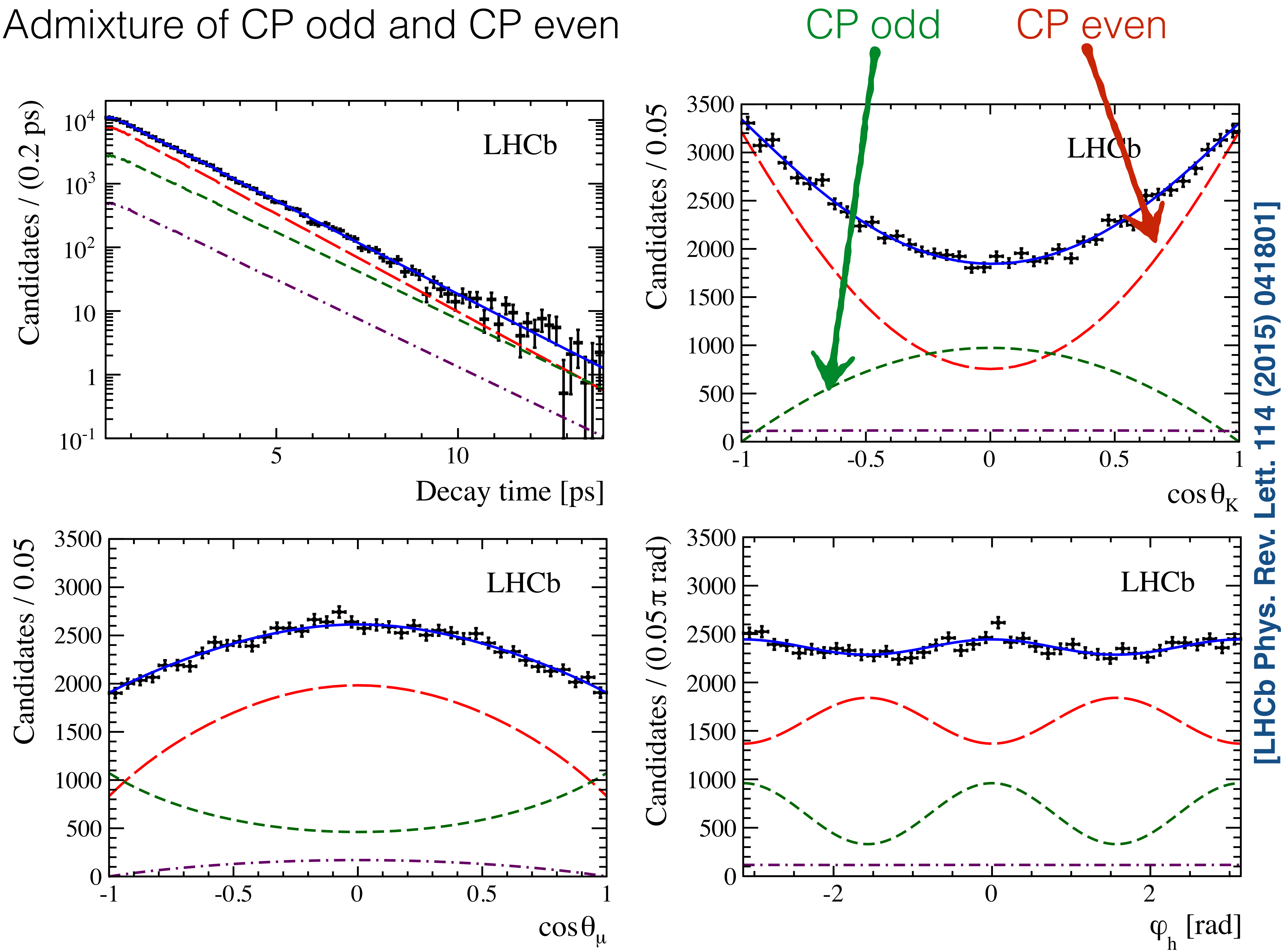
B_s mixing phase

- P → VV decay has a final state that is a mixture of CP odd and CP even.
- Separated using angular information.

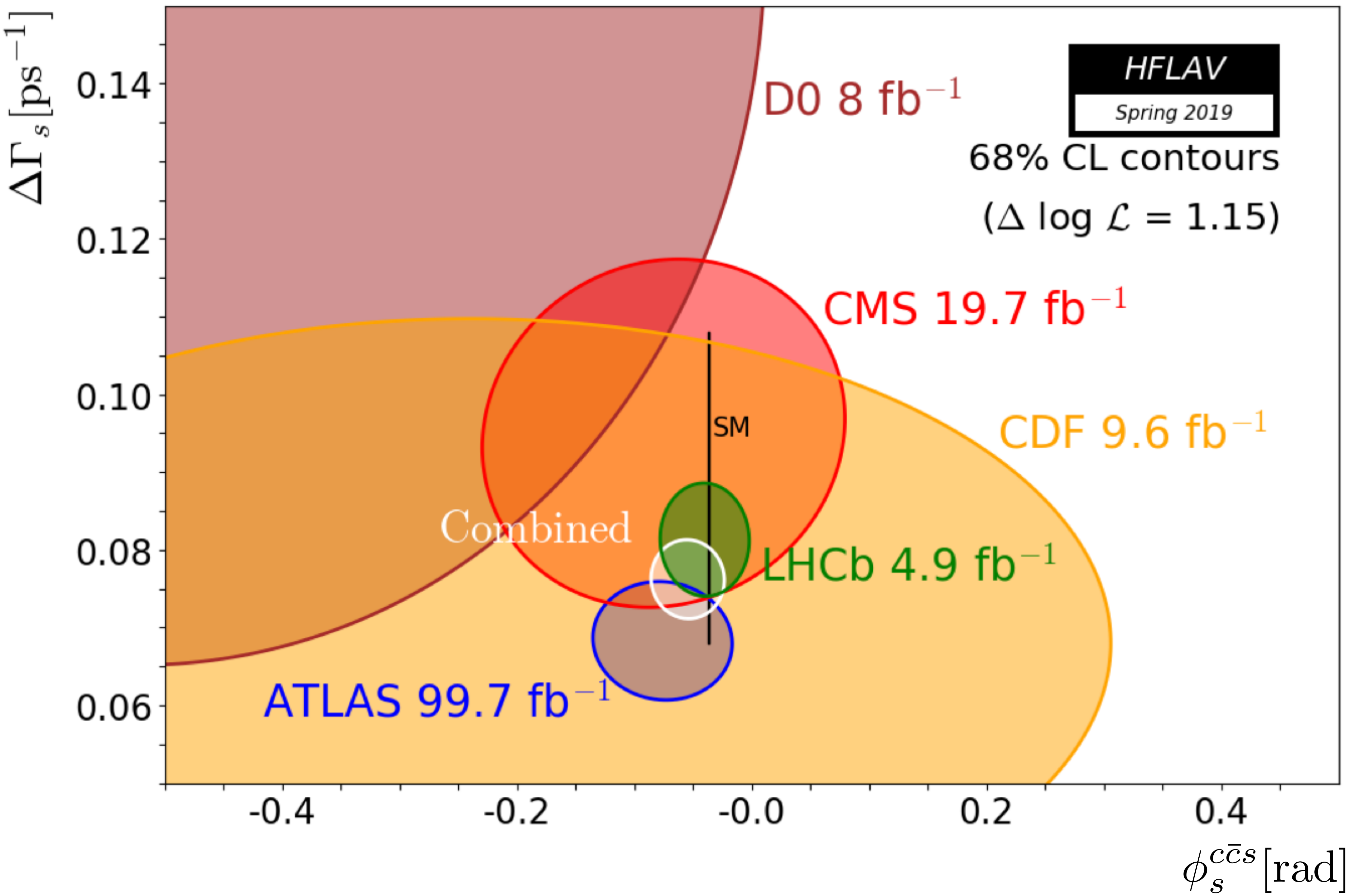


- Analyse decay in terms of polarisation of the ϕ meson, which can be longitudinally polarised or transversely polarised (there two transverse states with different CP).

Admixture of CP odd and CP even



ϕ_s



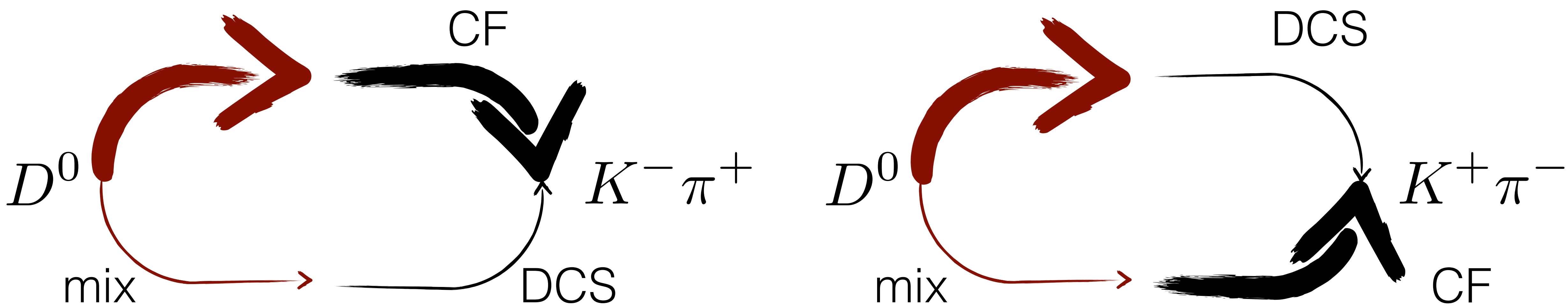
CP violating phase is small for fast B_s oscillations (consistent with SM)

Charm mixing and CP violation

Experimental results

Charm mixing

- Can probe mixing in Charm using "wrong sign" *D* decays.
  - ➡ Tagging the flavour of the *D* at production using $D^{*\pm}$ decays.



- Ratio of wrong-to-right sign decays:

$$R(t) = \frac{N_{\rm WS}}{N_{\rm RS}} \approx R_d + \underbrace{\boxed{\sqrt{R_D} y' \left(\frac{t}{\tau}\right)}}_{\text{interference}} + \underbrace{\boxed{\frac{(x')^2 + (y')^2}{4} \left(\frac{t}{\tau}\right)^2}}_{\text{mixing}}$$

Mixing formalism

- Ratio of wrong-to-right sign decays:

$$R(t) = \frac{N_{\rm WS}}{N_{\rm RS}} \approx R_d + \underbrace{\boxed{\sqrt{R_D}y'\left(\frac{t}{\tau}\right)}}_{\text{interference}} + \underbrace{\boxed{\frac{(x')^2+(y')^2}{4}\left(\frac{t}{\tau}\right)^2}}_{\text{mixing}}$$

- Uses a slightly different notation to before:

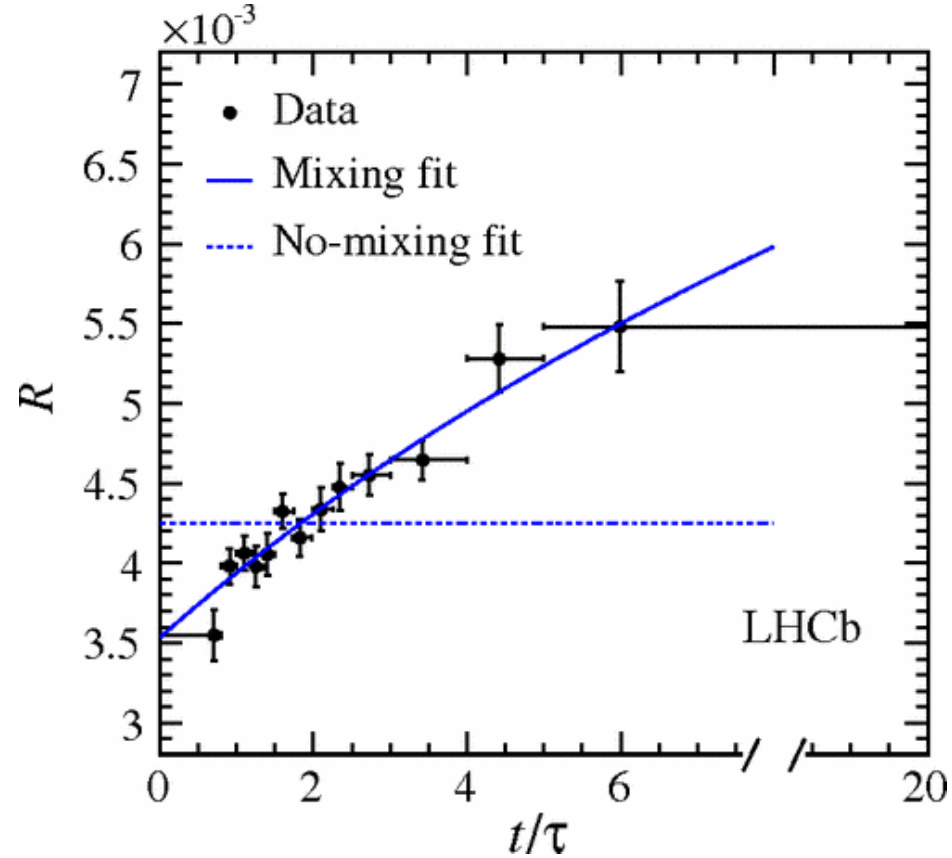
$$x = \frac{\Delta m}{\Gamma} \quad , \quad y = \frac{\Delta\Gamma}{2\Gamma}$$

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

strong phase difference
between WS and RS

Charm mixing

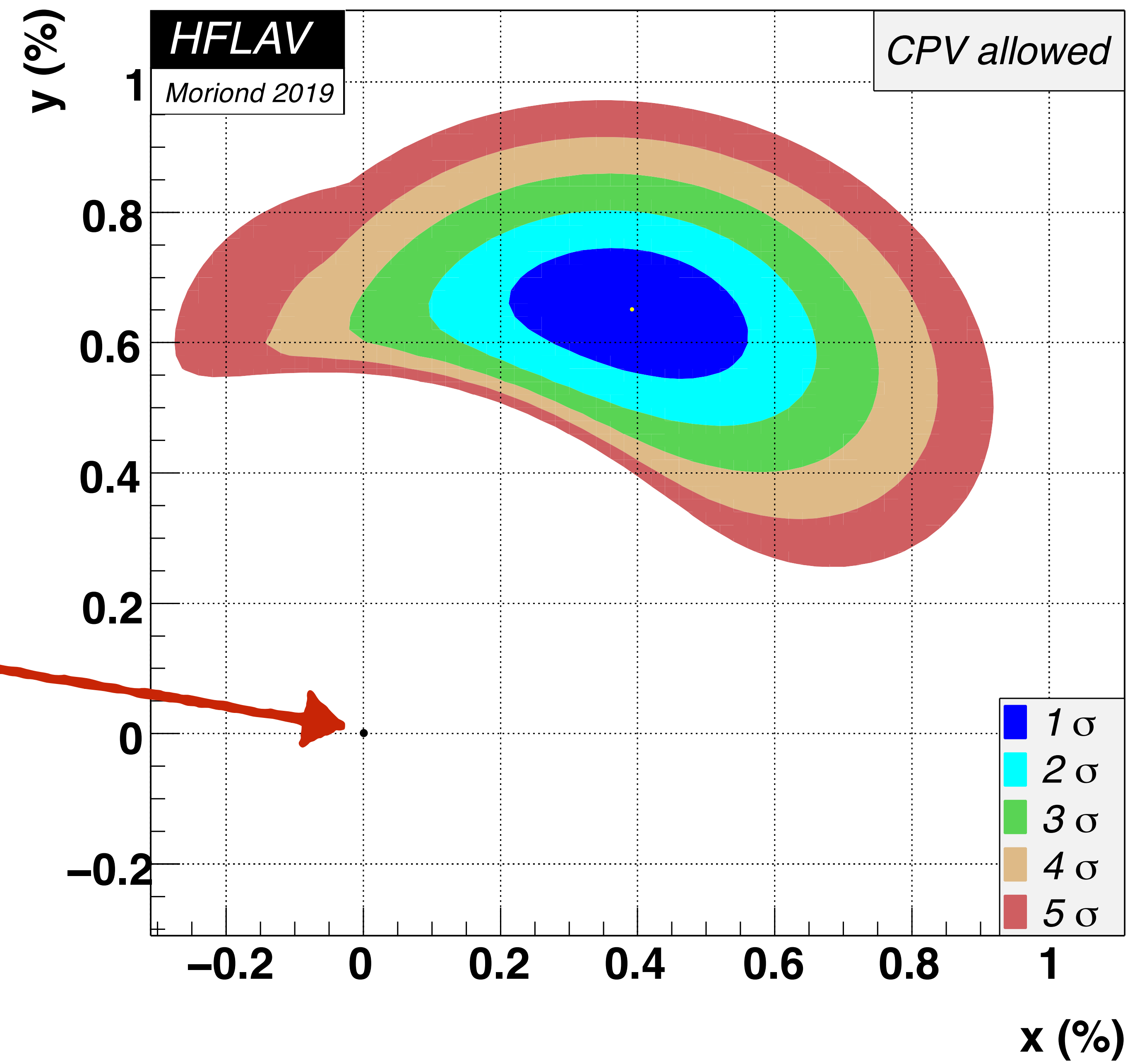
- Gradient with proper time arises from *D* mixing/interference.
- Can exclude no mixing hypothesis at more than 5σ.



Charm mixing

- Can exclude no mixing hypothesis at more than 5σ.

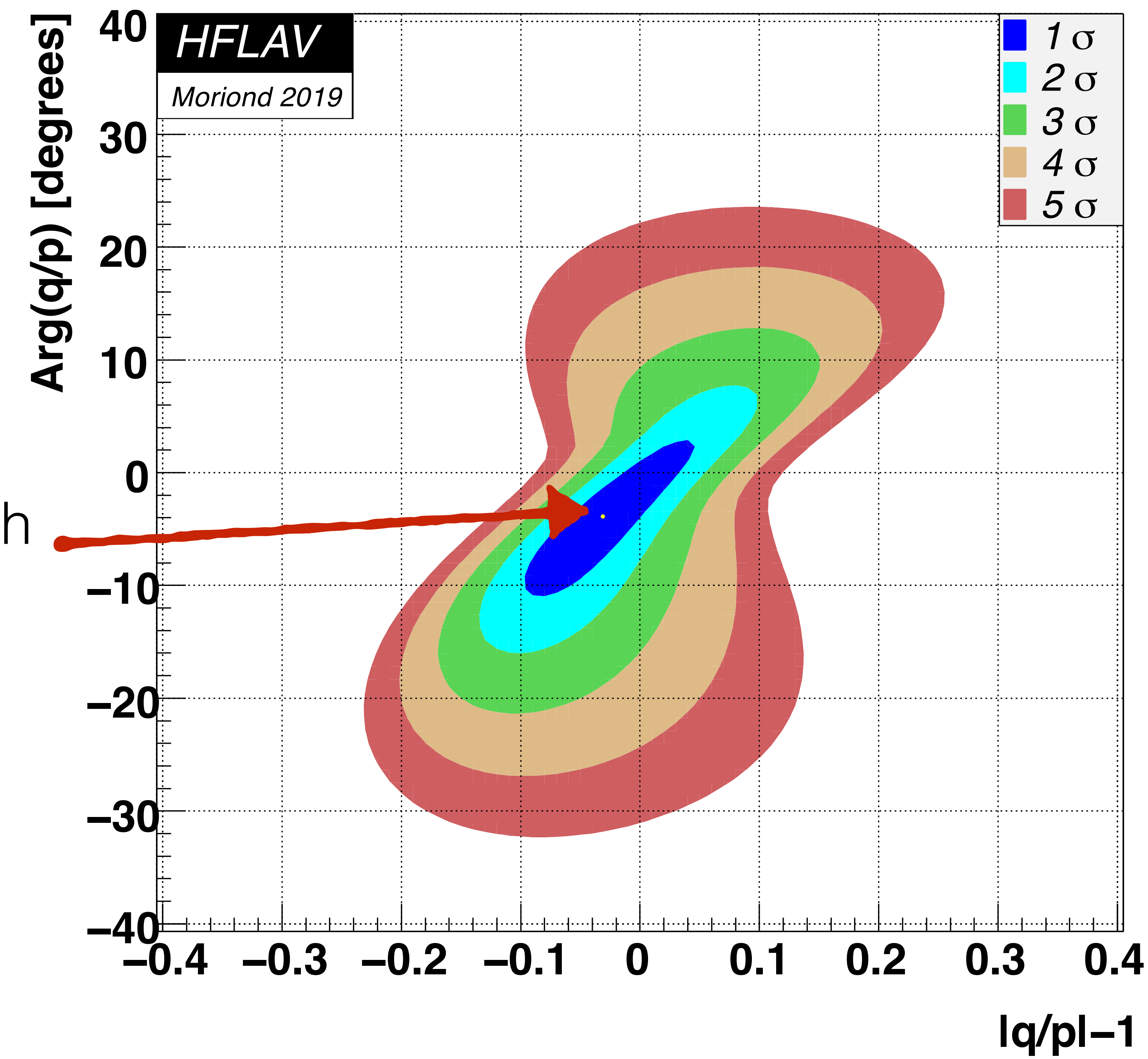
No mixing



Charm CP violation

- No evidence (yet) for CP violation in mixing in *D* mesons.

Consistent with $|q/p| = 1$ and $\mathrm{Arg}(q/p) = 0$



Charm CP violation

- Direct CP violation in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$
- Tag the initial flavour of the *D* using $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \bar{D}^0\pi^-$ decays or semileptonic *B* meson decays.
- Resulting asymmetry:

physical asymmetry

production asymmetry

$$A_{\rm raw}(f) \approx A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}({\rm tag}) + A_P(D)$$

detection asymmetries

- Can cancel many experimental uncertainties by measuring

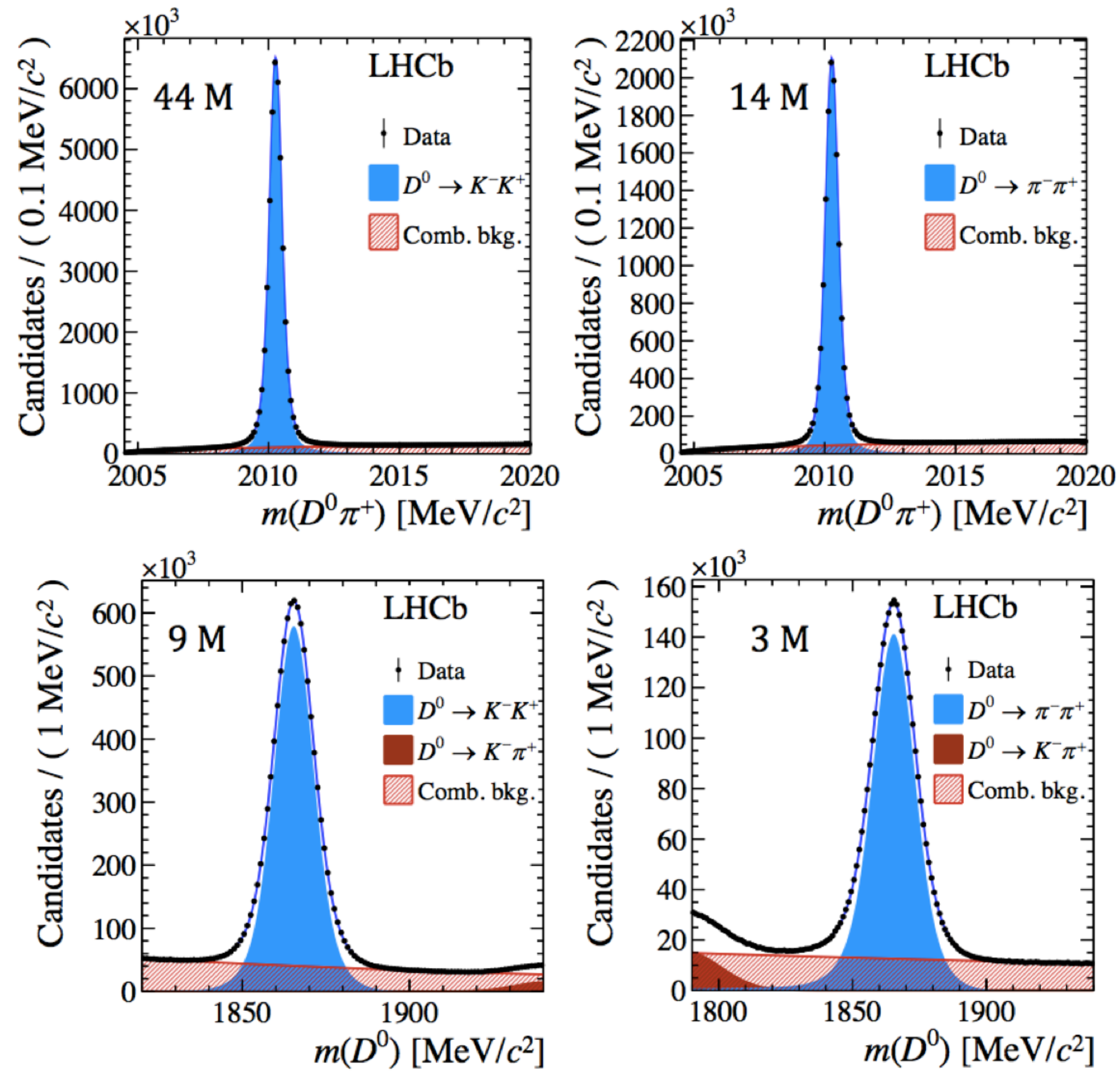
$$\Delta A_{CP} = A_{\rm raw}(KK) - A_{\rm raw}(\pi\pi) \approx A_{CP}(KK) - A_{CP}(\pi\pi)$$

ΔA_{CP}

- At the LHC we are able to record huge samples of D meson decays.
- LHCb measures:

$$\Delta A_{CP} = (-15.5 \pm 2.9) \times 10^{-4}$$

- First observation of CP violation in charm decays at 5.3σ.



Recap

- In this lecture we discussed:
  - ➡ The three different types of CP violation:
    1. Direct CP violation,
    2. CP violation in mixing,
    3. CP violation in interference between mixing and decay.
  - ➡ Mixing in the K, B^0, B_s and D^0 systems.
  - ➡ The CKM angle β.

Fin

Flavour specific decays

- Probe CP violation through "wrong flavour" decays to a flavour specific final state, e.g. semileptonic decays where the charge of the lepton identifies the flavour of the B.

$$a_{\rm fs} = \frac{\Gamma[\overline{M} \to M \to f] - \Gamma[M \to \overline{M} \to \bar{f}]}{\Gamma[\overline{M} \to M \to f] + \Gamma[M \to \overline{M} \to \bar{f}]}$$

$$\approx \frac{\Delta\Gamma}{\Delta M} \tan\phi$$

e.g M at production
and $\overline{M}$ at decay

Flavour specific decays

- In practice easier not to tag the flavour at production and then to look at the time dependence of the flavour specific asymmetry

$$a_{\rm fs}(t) = \frac{a_{\rm fs}}{2}\left(1 - \frac{\cos\Delta M t}{\cosh\dfrac{\Delta\Gamma t}{2}}\right)$$

washed out in time integrated asymmetry by the fast B_s oscillation.

A_{sl}

- Results consistent with SM

$A_{sl(s,d)}$ consistent with SM

D0 like-sign result in tension with SM