Results in Experimental Heavy Flavor Physics and CP violation

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There must be Physics beyond the Standard Model:

1) neutrinos have mass.

2) baryonic matter corresponds to only ~4%
   of the mass of the Universe;

3) us: matter and antimatter are not symmetric.

The high-energy approach: ATLAS & CMS
direct searches for new, heavy particles up to few TeV

The high-intensity approach: LHCb and B-factories
probe high energy scales using loop-induced transitions

Flavour Physics in the quark sector is a route to NP:
mixing, **CP** violation and rare decays

OUTLINE

1. Formalism and notation

2. Mixing and **CP** violation in the beauty sector

3. Mixing and **CP** violation in the charm sector

4. Rare decays

5. The pentaquark

6. Summary and prospects

Formalism and notation

Neutral meson oscillations

- K^0, D^0, B^0, B_s^0 : flavour and mass eigenstates are not the same. Common decay modes allow $\Delta F = 2$ transitions

$$i\frac{\partial}{\partial t}|\psi(t)\rangle = \mathcal{H}|\psi(t)\rangle \quad \longrightarrow \quad i\frac{\partial}{\partial t}\begin{pmatrix} P^0(t) \\ \overline{P}^0(t) \end{pmatrix} = \mathcal{H}\begin{pmatrix} P^0(t) \\ \overline{P}^0(t) \end{pmatrix}$$

Effective Hamiltonian: combination of mass and decay matrix

$$\mathcal{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix} \qquad \begin{aligned} \langle M^0|\mathcal{H}|\overline{M}^0\rangle &= M_{12} - \frac{i}{2}\Gamma_{12} \\ \langle \overline{M}^0|\mathcal{H}|M^0\rangle &= M_{12}^* - \frac{i}{2}\Gamma_{12}^* \end{aligned}$$

Mass and flavour eigenstates are related by

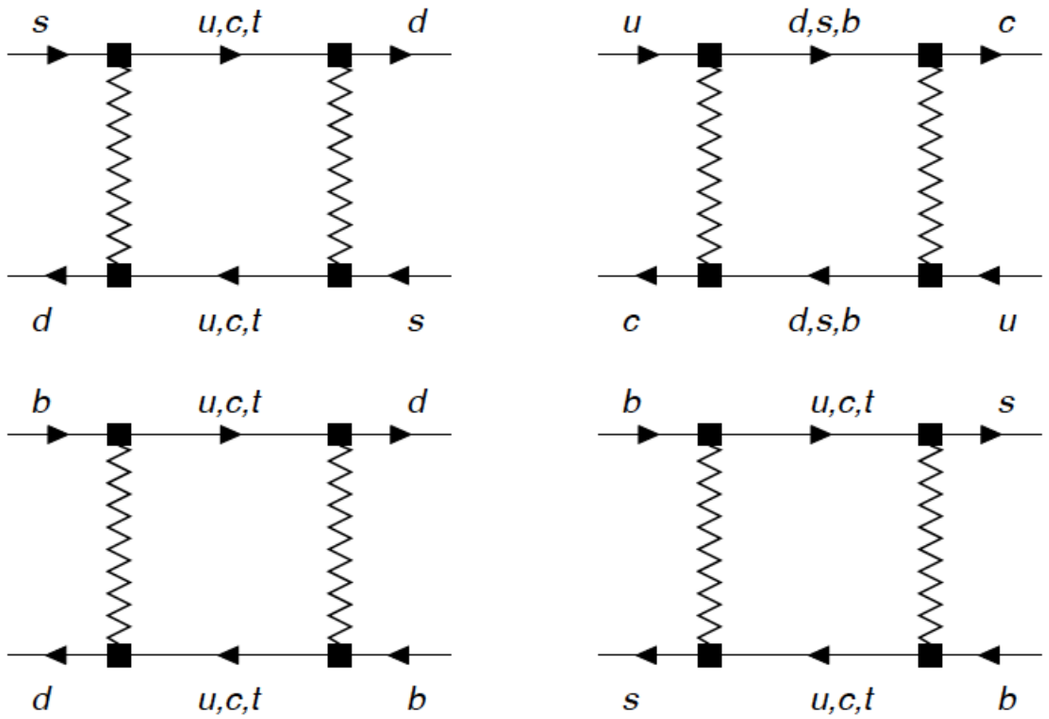
$$|P_1\rangle = p|P^0\rangle + q|\overline{P}^0\rangle, \qquad |P_2\rangle = p|P^0\rangle - q|\overline{P}^0\rangle, \qquad |q|^2 + |p|^2 = 1.$$

$$p = \langle P^0|P_1\rangle, \;\; q = \langle \overline{P}^0|P_1\rangle \quad \text{assuming } m(P_2) > m(P_1)$$

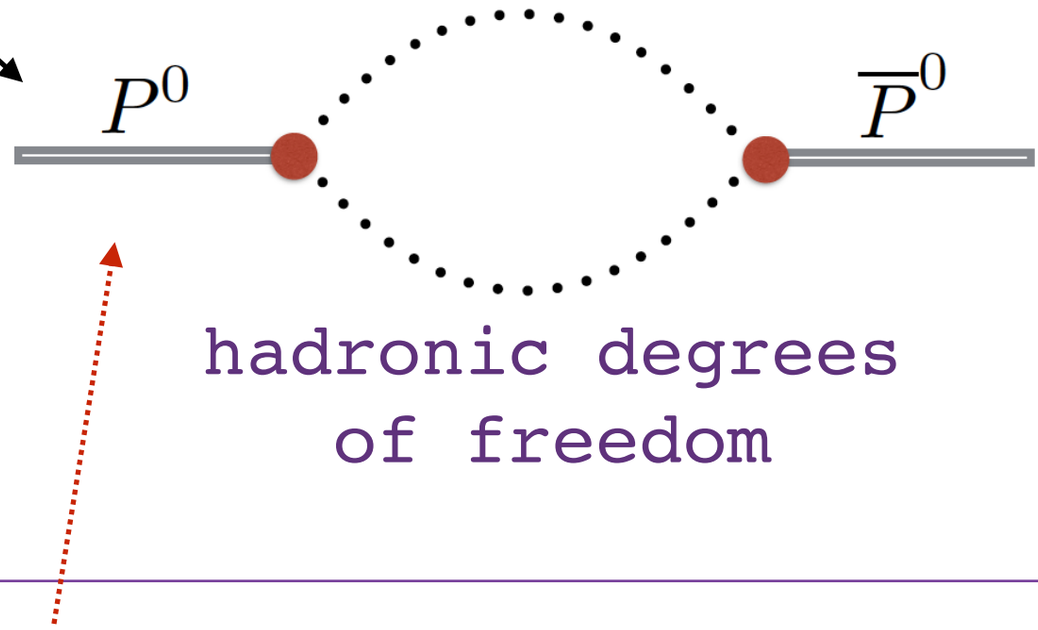
$$\Delta M = m_2 - m_1 \qquad \Delta\Gamma = \Gamma_2 - \Gamma_1$$

Flavour oscillations, or meson mixing: contributions from short- and long-distance processes:

$$M_{12} = M_{12}^* = \langle P^0|H_{\Delta F=2}|\overline{P}^0\rangle + \sum_n \mathcal{P}\left[\frac{\langle P^0|H_{\Delta F=1}|n\rangle\langle n|H_{\Delta F=1}|\overline{P}^0\rangle}{M_P - M_n}\right]$$



sensitive to new Physics



hadronic degrees of freedom

ΔM: dominated by short-distance processes

$\Delta\Gamma$: only long-distance contributions

$$\Gamma_{12} = \Gamma_{12}^* = \sum_n \delta(M_P - M_n)\langle P^0|H_{\Delta F=1}|n\rangle\langle n|H_{\Delta F=1}|\overline{P}^0\rangle$$

Mixing is governed by two dimensionless parameters

$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}.$$

The time evolution of a meson with known initial flavour:

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

where $\quad g_\pm(t) \equiv \frac{1}{2}\left[e^{-im_1 t - \frac{1}{2}\Gamma_1 t} \pm e^{-im_2 t - \frac{1}{2}\Gamma_2 t}\right].$

In the decay $P^0 \to f$ one can define up to 4 amplitudes:

$A_f \equiv \langle f|\mathcal{H}|P^0\rangle$, $\overline{A}_f \equiv \langle f|\mathcal{H}|\overline{P}^0\rangle$, $\overline{A}_{\bar{f}} \equiv \langle \bar{f}|\mathcal{H}|\overline{P}^0\rangle$ and $A_{\bar{f}} \equiv \langle \bar{f}|\mathcal{H}|P^0\rangle$

$D^0 \to K^-\pi^+$ $\qquad$ $\overline{D}^0 \to K^-\pi^+$ $\qquad$ $\overline{D}^0 \to K^+\pi^-$ $\qquad$ $D^0 \to K^+\pi^-$

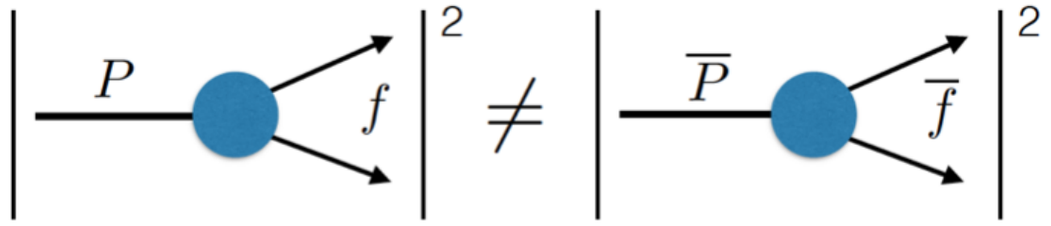
DCS $\qquad$ DCS

If $f = \bar{f} = f_{\rm CP}$ $(f = K^+K^-,\ \pi^+\pi^-, \rho^+\rho^-,\ ...)$, $A_f = A_{\bar{f}},\ \overline{A}_{\bar{f}} = \overline{A}_f$

The three types of **CP** violation

1) **CP** violation in decay:

$$|A_f| \neq |\overline{A}_{\bar{f}}|$$



The observable is the time-integrated asymmetry

$$A_{CP} \equiv \frac{\Gamma(A \to f) - \Gamma(\overline{A} \to \bar{f})}{\Gamma(A \to f) + \Gamma(\overline{A} \to \bar{f})} = \frac{|A_f|^2 - |\overline{A}_{\bar{f}}|^2}{|A_f|^2 + |\overline{A}_{\bar{f}}|^2}$$

$$A_f = |a_1|e^{i(\delta_1+\phi)} + |a_2|e^{i\delta_2}, \quad \overline{A}_{\bar{f}} = |a_1|e^{i(\delta_1-\phi)} + |a_2|e^{i\delta_2}$$

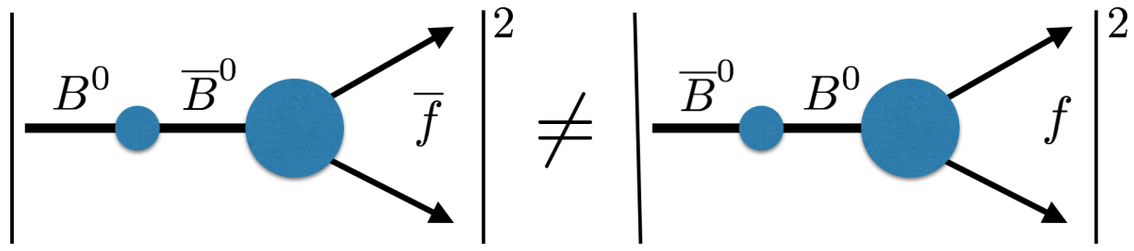
$\delta_1, \delta_2 \to$ strong phases (**CP**-even), $\quad \phi \to$ weak phase (**CP**-odd)

$$A_{CP} = \frac{2|a_1 a_2| \sin(\delta_2 - \delta_1) \sin\phi}{|a_1|^2 + |a_2|^2 + 2|a_1 a_2| \cos(\delta_2 - \delta_1) \cos\phi}$$

$\delta_1 \neq \delta_2$
$\phi \neq 0$
necessary for CP violation in decay.

The three types of **CP** violation

2) CP violation in mixing: difference in oscillation frequency



Theoretically clean method uses flavour-specific decays:

$$B^0 \to \ell^+ + X \nleftarrow \overline{B}^0, \quad B^0 \nrightarrow \ell^- + X \leftarrow \overline{B}^0$$

"Wrong sign" leptons can only occur through mixing.

$$A(\ell^+) \equiv A(B^0 \to \ell^+ X) = \overline{A}(\ell^-) \equiv A(\overline{B}^0 \to \ell^- X), \qquad A(\ell^-) = \overline{A}(\ell^+) = 0$$

In semi-leptonic modes there is no **CP** violation in decay.

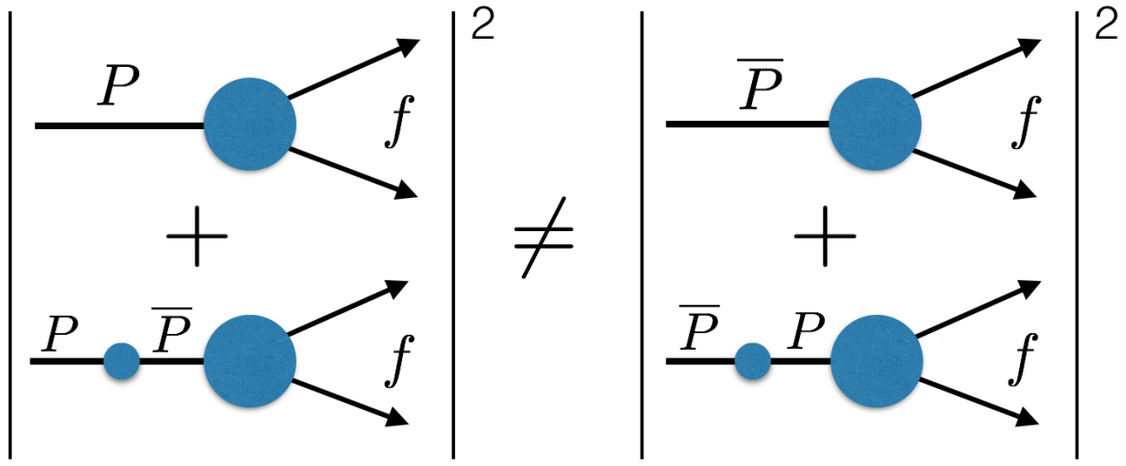
Time-dependent asymmetry:

$$\mathcal{A}_{\rm SL} = \frac{\Gamma(B^0(t) \to \ell^- X) - \Gamma(\overline{B}^0(t) \to \ell^+ X)}{\Gamma(B^0(t) \to \ell^- X) + \Gamma(\overline{B}^0(t) \to \ell^+ X)} = \frac{1 - |p/q|^4}{1 + |p/q|^4},$$

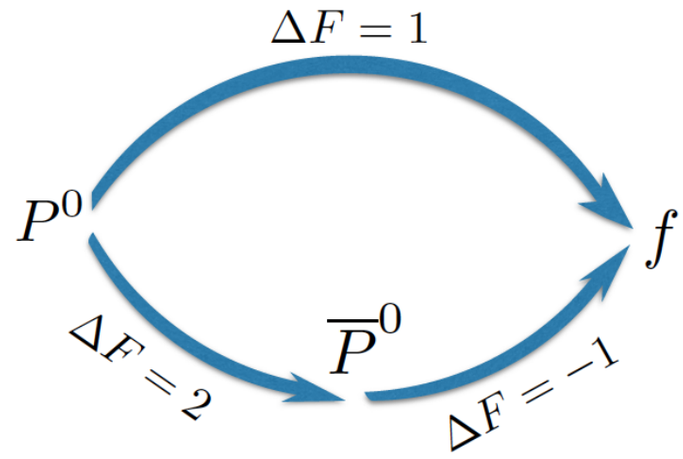
The condition for CP violation in mixing: $\boxed{|p| \neq |q|}$

The three types of **CP** violation

3) **CP** violation in the interference between decays with and without mixing. Only for $f = \bar{f}$.



Two ways for $P^0 \to f$. **CP** violation effect: different relative phases between the two paths for P^0 and $\overline{P}^0$.



All types of **CP** violation contained in $\lambda_f \equiv \eta_f \dfrac{q}{p}\dfrac{\overline{A}_f}{A_f}.$

mixing: $\dfrac{q}{p} = \left|\dfrac{q}{p}\right| e^{-i\phi_M}.$ decay: $\dfrac{\overline{A}_f}{A_f} = \left|\dfrac{\overline{A}_f}{A_f}\right| e^{-i(\Delta\phi_f + \Delta\delta_f)}.$

$$\lambda_f = \eta_f \left|\frac{q}{p}\right| \left|\frac{\overline{A}_f}{A_f}\right| e^{-i(\phi_M + \Delta\phi_f + \Delta\delta_f)}$$

$\left|\dfrac{\overline{A}_f}{A_f}\right| \neq 1$ **CP** violation in decay

$\left|\dfrac{q}{p}\right| \neq 1$ **CP** violation in mixing

$\arg \lambda_f \neq 0$ **CP** violation in interference between mixing and decay

The time-dependent decay rates:

$$\frac{d\Gamma_{B\to f}(t)}{dt} \propto e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right) + C_f\cos(\Delta m t) - S_f\sin(\Delta m t)\right]$$

$$\frac{d\Gamma_{\overline{B}\to f}(t)}{dt} \propto e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right) - C_f\cos(\Delta m t) + S_f\sin(\Delta m t)\right]$$

The time-dependent **CP** asymmetry is

$$\mathcal{A}_f(t) = \frac{\Gamma[\overline{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\overline{B}^0(t) \to f] + \Gamma[B^0(t) \to f]}.$$

Defining $S_f \equiv A_{CP}^{\rm int},\ C_f \equiv A_{CP}^{\rm dir}$ and the approximation $|q/p| = 1$ (no **CP**V in mixing)

$$\mathcal{A}_f(t) = \frac{A_{CP}^{\rm int}\sin(\Delta m t) - A_{CP}^{\rm dir}\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)},$$

$$A_{CP}^{\rm dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad A_{CP}^{\rm int} = \frac{2{\rm Im}\lambda_f}{1+|\lambda_f|^2}, \qquad A_{\Delta\Gamma} = -\frac{2{\rm Re}\lambda_f}{1+|\lambda_f|^2}.$$

For the B^0 mesons $\Delta\Gamma \approx 0$. The asymmetry becomes

$$\mathcal{A}_f(t) = A_{CP}^{\rm int}\sin(\Delta m t) - A_{CP}^{\rm dir}\cos(\Delta m t).$$

The Cabibbo-Kobayashi-Maskawa matrix

Charged currents are the only flavour-changing processes at tree level: $\mathcal{L}_{\rm W} = \frac{g_W}{\sqrt{2}} \sum_{j,k=1,2,3} \left[V_{jk} \overline{u}_{jL} \gamma^\mu d_{kL} W^+_\mu + V^*_{jk} \overline{d}_{kL} \gamma^\mu u_{jL} W^-_\mu \right],$

CKM: unitary matrix connecting weak and mass eigenstates,

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

The standard parameterization:

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Three angles: $\theta_{12}, \theta_{13}, \theta_{23}$ $\qquad c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij},$

One complex phase: $\delta \rightarrow$ **CP** violation in SM

The most sensitive processes to determine the the CKM matrix:

$$V_{\rm CKM} \Rightarrow \begin{pmatrix} n \to p e^- \overline{\nu} & K \to \pi \ell^- \overline{\nu} & B \to \pi \ell^- \overline{\nu} \\ D \to \pi \ell^- \overline{\nu} & D \to K \ell^- \overline{\nu} & B \to D \ell^- \overline{\nu} \\ B^0 - \overline{B}^0 & B_s^0 - \overline{B}_s^0 & t \to W b \end{pmatrix}$$

$$V_{\rm CKM} = \begin{pmatrix} 0.97425 \pm 0.00022 & 0.2253 \pm 0.0008 & 0.00413 \pm 0.00049 \\ 0.225 \pm 0.008 & 0.986 \pm 0.016 & 0.0411 \pm 0.0013 \\ 0.0084 \pm 0.0006 & 0.0400 \pm 0.0027 & 1.021 \pm 0.032 \end{pmatrix}$$

The Wolfenstein parameterization

$$V_{\rm CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda + \mathcal{O}(\lambda^7) & A\lambda^3(\rho - i\eta) \\ \lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 + \mathcal{O}(\lambda^8) \\ A\lambda^3(1 - \overline{\rho} - i\overline{\eta}) & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^4 \end{pmatrix}$$

$$\lambda \equiv s_{12} \approx 0.22, \quad A\lambda^2 \equiv s_{23}, \quad A\lambda^3(\rho - i\eta) \equiv s_{13} e^{i\delta}$$

$$\overline{\rho} \simeq \rho(1 - \frac{\lambda^2}{2}) + \mathcal{O}(\lambda^4), \quad \overline{\eta} = \eta(1 - \frac{\lambda^2}{2}) + \mathcal{O}(\lambda^4)$$

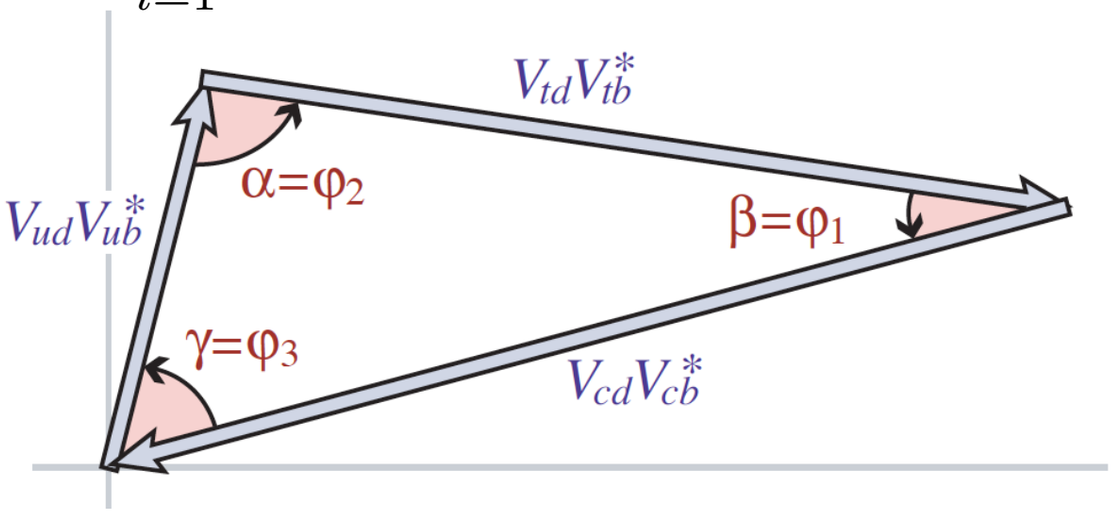
Unitarity triangles

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

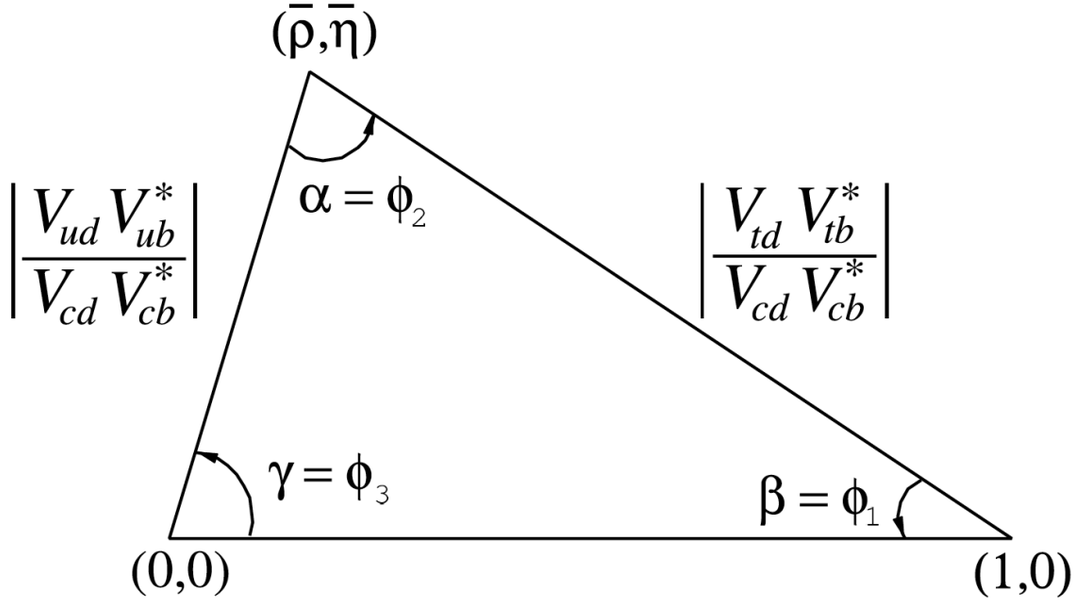
leads to 6 relations: $\sum_{i=1}^{3} V_{ij} V_{ik}^* = \sum_{i=1}^{3} V_{ji} V_{ki}^* = 0, \quad j,k = 1,2,3, \quad j \neq k$

The usefulness of B mesons for CP violation studies:

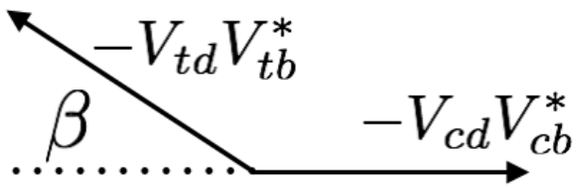
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0,$$



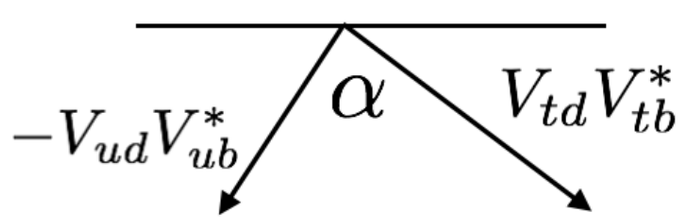
Dividing all sides by the best known one, $V_{cd}V_{cb}^*$ →



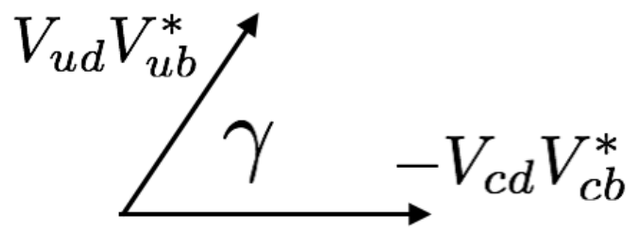
The angles of the Unitarity Triangle:



$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$



$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Another unitarity triangle is relevant for the B_s^0 meson:

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

The angle $\beta_s \equiv \left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$: particularly relevant for **CP** violation in the B_s^0 sector.

The precise measurement of the UTs angles is crucial for the understanding of CP violation in the B system.

The basic strategy: measure the angles using different processes and check whether the results are consistent.

Flavour tagging

In the B-factories: mesons are produced in a **C=-1** state,

$$|[B^0\overline{B}^0](t)\rangle = e^{-\Gamma t}\frac{1}{\sqrt{2}}\left[|B^0(\mathbf{k})\rangle|\overline{B}^0(-\mathbf{k})\rangle - |B^0(-\mathbf{k})\rangle|\overline{B}^0(\mathbf{k})\rangle\right]$$

One of the B mesons decays to a flavour specific mode: the flavour of the other B at that moment is determined.

$$\frac{d\Gamma_\eta(t)}{dt} \propto e^{-\Gamma|\Delta t|}\left[1+\eta\mathcal{D}\left(S_f\sin(\Delta m\Delta t) - C_f\cos(\Delta m\Delta t)\right)\right]\otimes\mathcal{R}(\Delta t-\Delta t')$$

$$-\infty < \Delta t < \infty \qquad\qquad \eta = 1 \;\rightarrow\; B^0, \quad \eta = -1 \;\rightarrow\; \overline{B}^0$$

$\mathcal{D}$ $\rightarrow$ tagging dilution

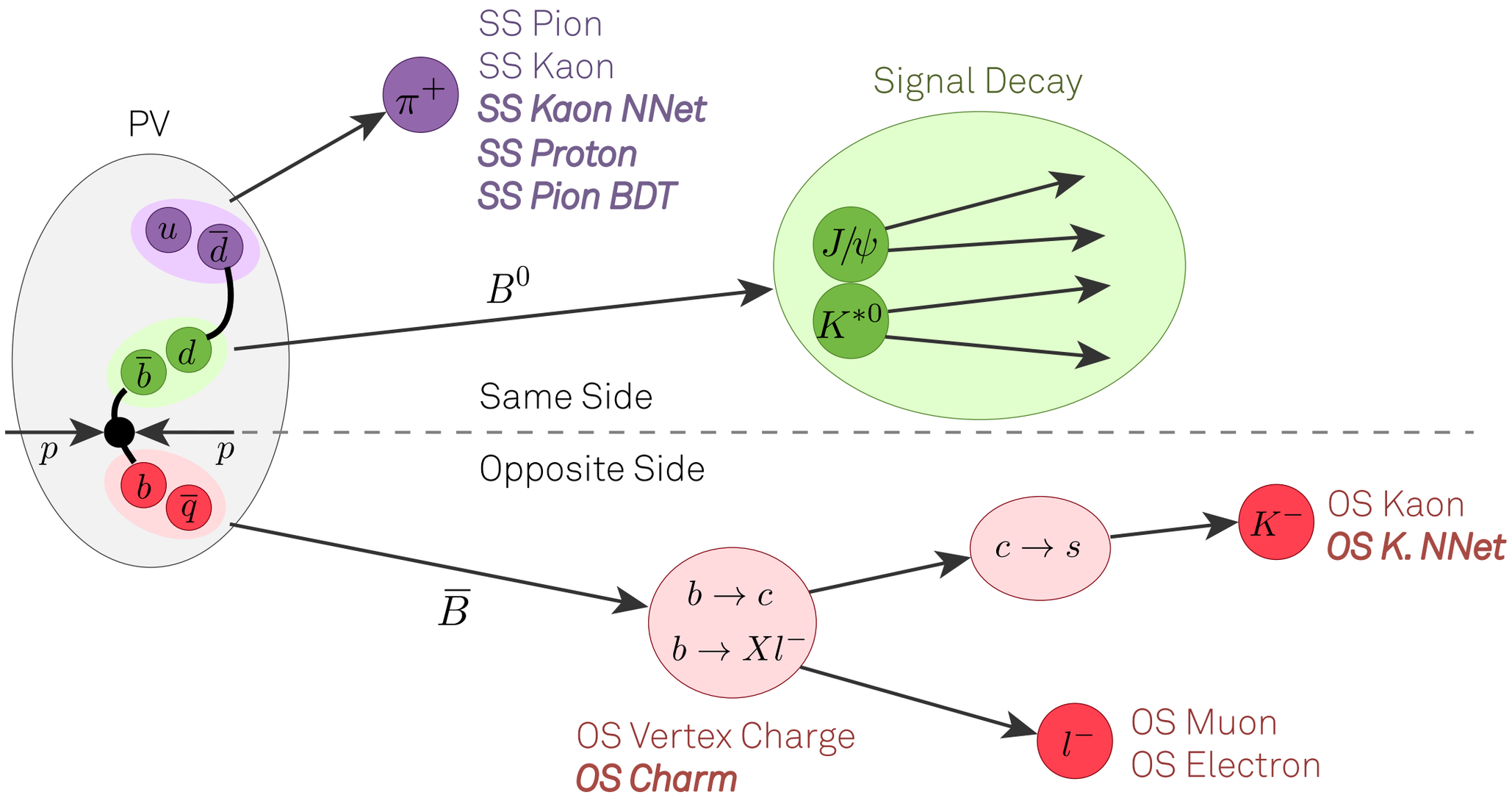
ω $\rightarrow$ probability of incorrect tagging

$\varepsilon_{\rm tag}$ $\rightarrow$ fraction of events for which a flavour tag exists

Effective tagging power: $\varepsilon_{\rm eff} = \varepsilon_{\rm tag}\mathcal{D}^2 = \varepsilon_{\rm tag}(1-2\omega)^2$

Flavour tagging

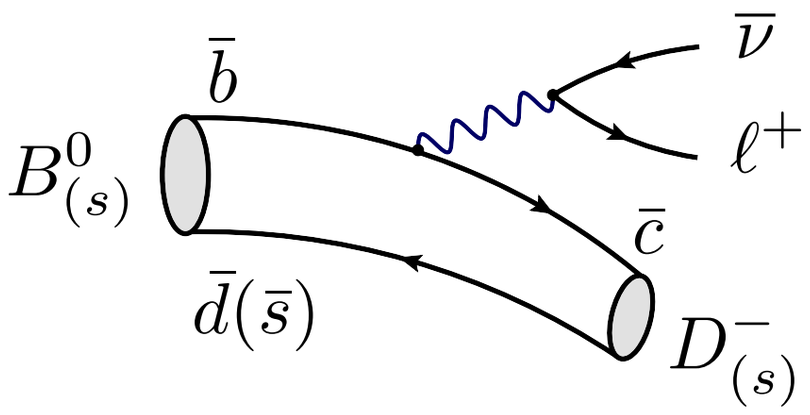
In hadron colliders different algorithms are combined



CP violation in the B system

CP violation in mixing

The most sensitive process: $b \to c\ell^+\overline{\nu} \quad (B \to D\ell^+\overline{\nu}X)$



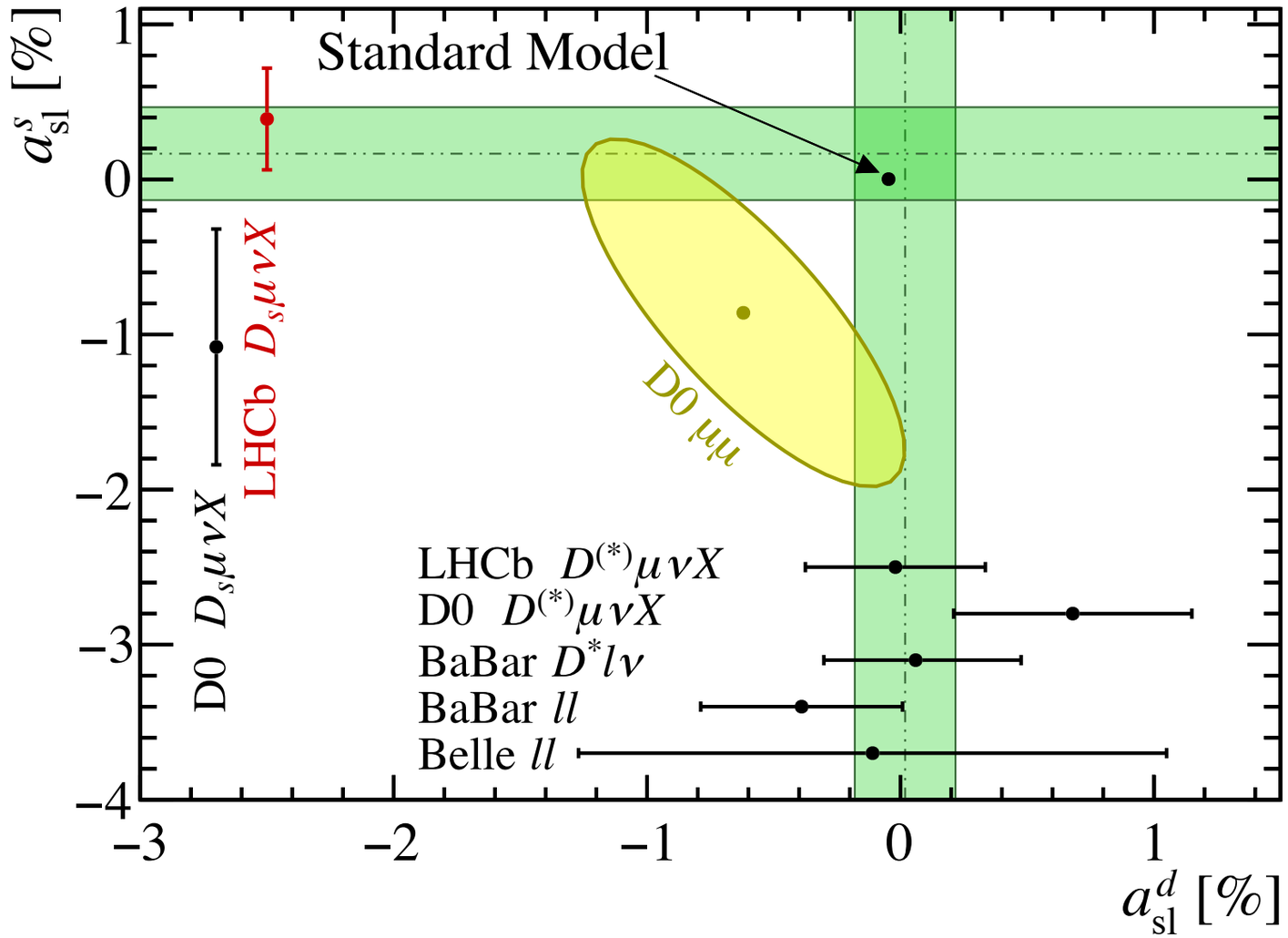
A flavour-specific decay, with one single possible amplitude: no **CP** violation in decay

The observable: time-dependent asymmetry,

$$a_{\rm SL}^{d,s} = \frac{\Gamma(\overline{B}(t) \to \ell^+ DX) - \Gamma(B(t) \to \ell^- DX)}{\Gamma(\overline{B}(t) \to \ell^- DX) + \Gamma(B(t) \to \ell^+ DX)} = \frac{1 - |p/q|^4}{1 + |p/q|^4},$$

is actually independent of the decay time!

CP is violated in mixing if $a_{\rm SL}^{d,s} \neq 0$ **CP** in conserved in mixing if $\left|\frac{p}{q}\right| = 1$



arXiv:1607.06746

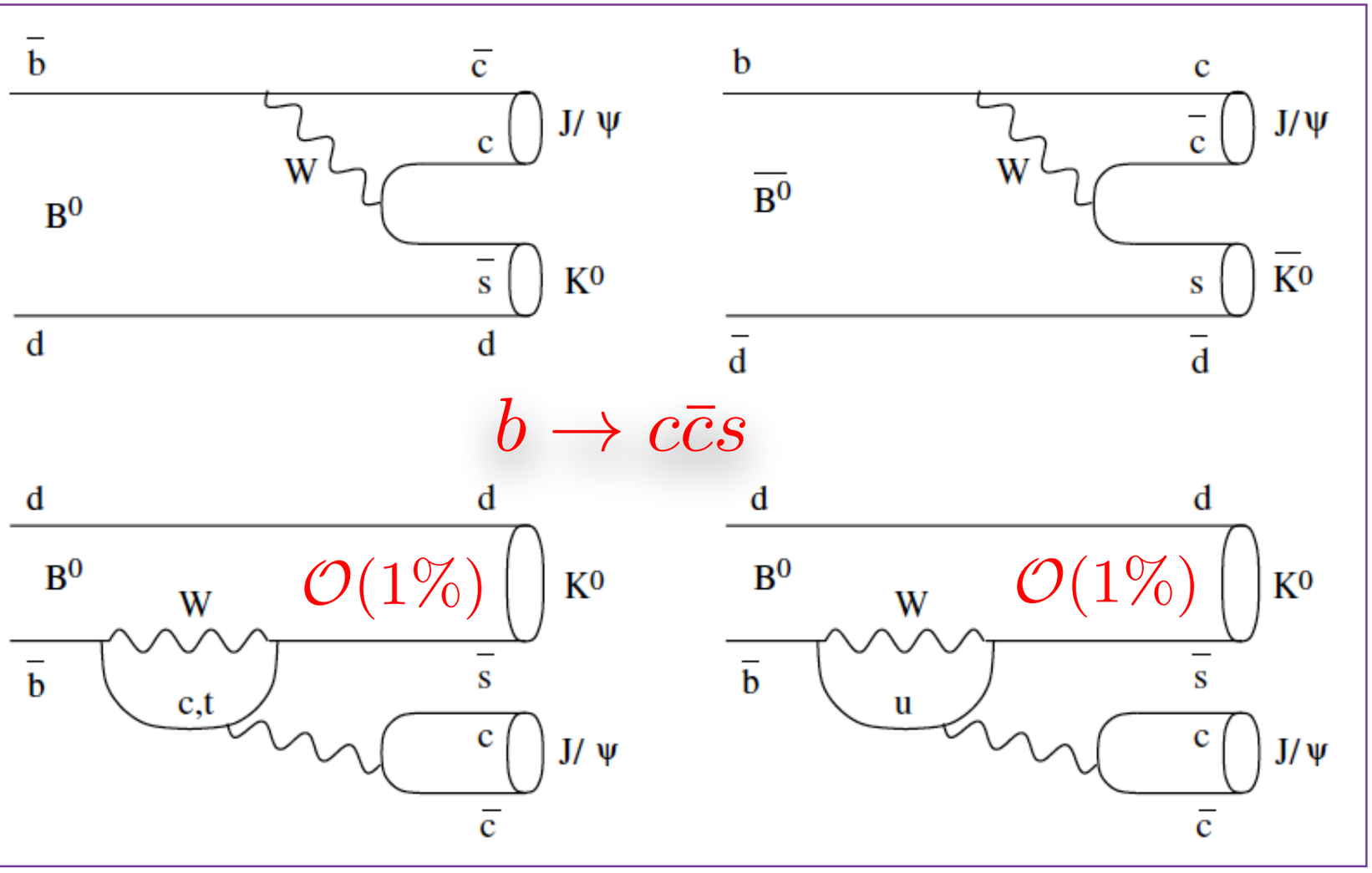
		$a^d_{\rm SL}$ (%)	$a^s_{\rm SL}$ (%)	
PRL **111,**101802	BaBar	$0.06 \pm 0.17^{+0.38}_{-0.32}$	-	
PRD **73,**112002	Belle	$-0.11 \pm 0.79 \pm 0.70$	-	
PRL **114,**041601	LHCb	$-0.02 \pm 0.19 \pm 0.70$	$0.39 \pm 0.26 \pm 0.20$	PRL **117,**061803
PRD **92,**033002	SM	-0.00047 ± 0.00006	0.0000222 ± 0.0000027	

CP violation in mixing: a very small effect!

Measurement of the angle $\beta(\phi_1)$

The "golden channels": $B^0 \to \psi K^0_S$ ("ψ" $= J/\psi,\ \psi(2S),\ \chi_{c1},\ \eta_c$)

Very small contribution from penguins: no **CP**V in decay,



$$\left|\frac{\overline{A}_f}{A_f}\right| = 1$$

No CPV in mixing,

$$\left|\frac{q}{p}\right| = 1$$

Therefore

$$|\lambda_f| = 1$$

Time-dependent **CP** asymmetry becomes

$$\mathcal{A}_f(t) = A^{\rm int}_{CP} \sin(\Delta m t).$$

The coefficient $A_{CP}^{\rm int} = \dfrac{2{\rm Im}\lambda_f}{1+|\lambda_f|^2} \approx \arg\lambda_f$ can be related to the CKM matrix elements. Recall that

$$\mathcal{H}|P_{1,2}\rangle = \lambda_{1,2}|P_{1,2}\rangle\ , \qquad |P_1\rangle = p|P^0\rangle + q|\overline{P}^0\rangle, \qquad |P_2\rangle = p|P^0\rangle - q|\overline{P}^0\rangle,$$

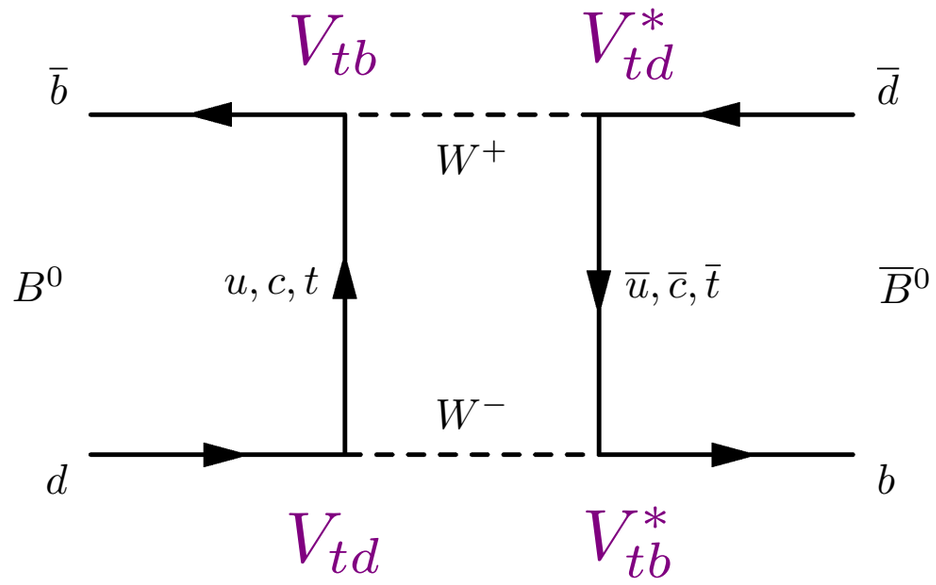
$$\mathcal{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$$

The eigenvalues are

$$\lambda_1 = M_{11} - \frac{i}{2}\Gamma_{11} + \frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right), \quad \lambda_2 = M_{11} - \frac{i}{2}\Gamma_{11} - \frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)$$

For B^0: $|\Gamma_{12}| \ll |M_{12}|$

$$\frac{q}{p} \simeq \sqrt{\frac{M_{12}^*}{M_{12}}} = \frac{M_{12}^*}{|M_{12}|} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$



The ratio of decay amplitudes:

$$\frac{\overline{A}}{A}(\psi K_S^0) = \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \frac{V_{ud}^* V_{us}}{V_{ud} V_{us}^*}$$

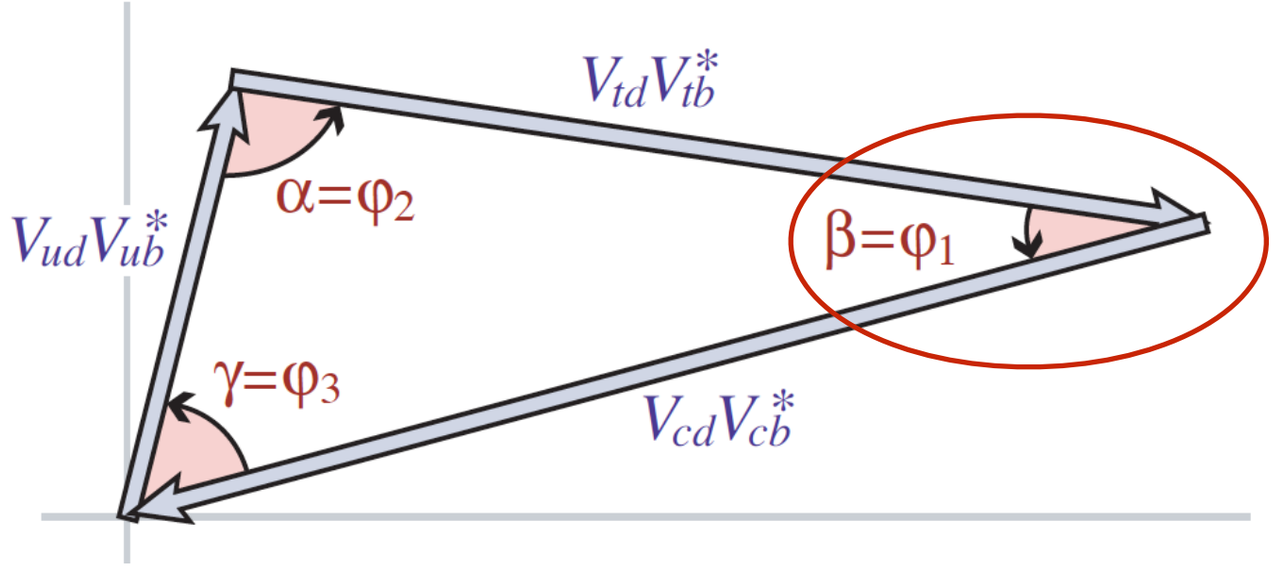
B decay

$K^0 - \overline{K}^0$

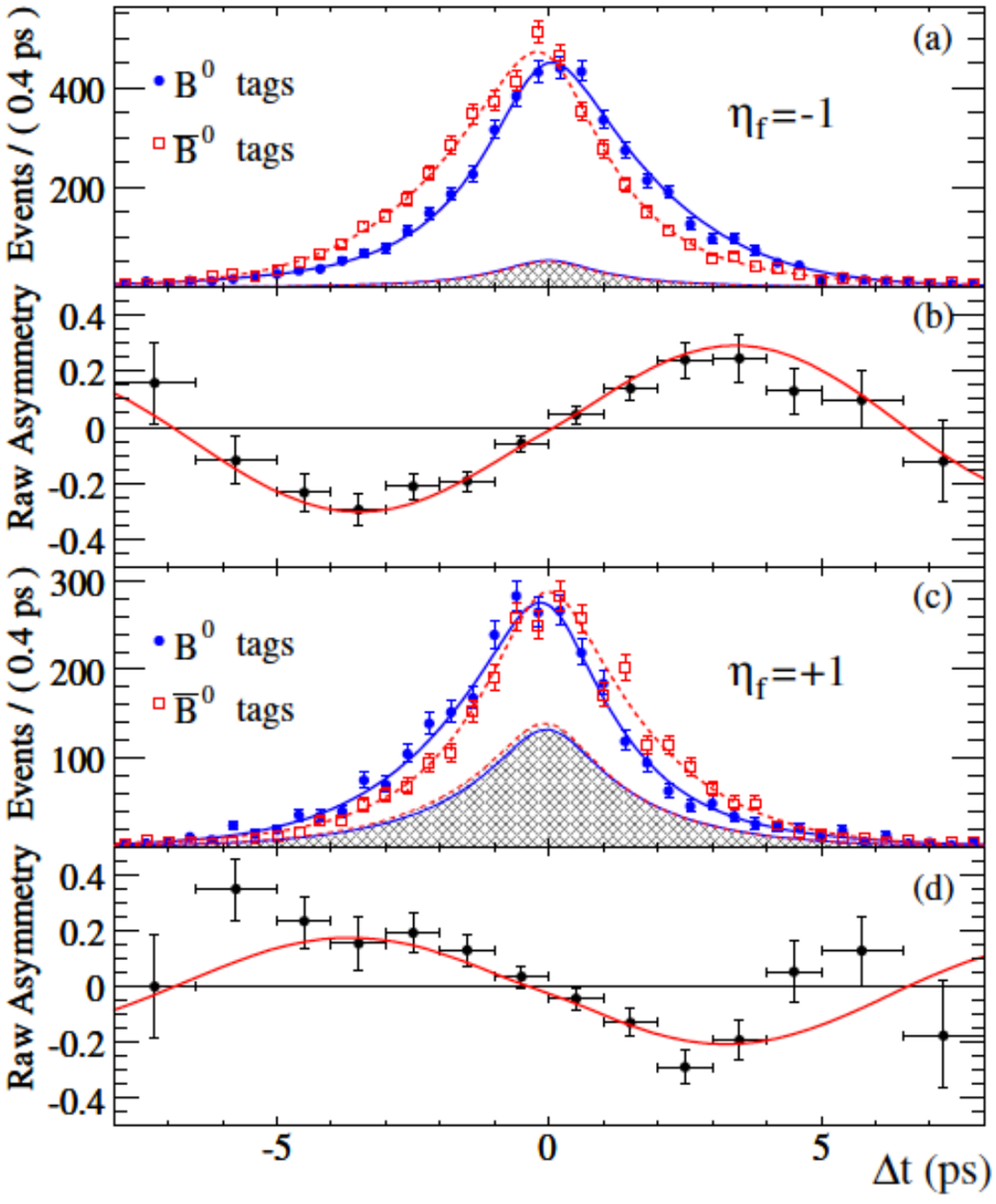
Putting the mixing and decay part together:

$$\lambda_f = \left|\frac{q}{p}\right| \left|\frac{\overline{A}_f}{A_f}\right| e^{-i(\phi_d)}, \quad \lambda_{\psi K_S^0} \simeq \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \frac{V_{ud}^* V_{us}}{V_{ud} V_{us}^*} = -e^{-2i\beta}$$

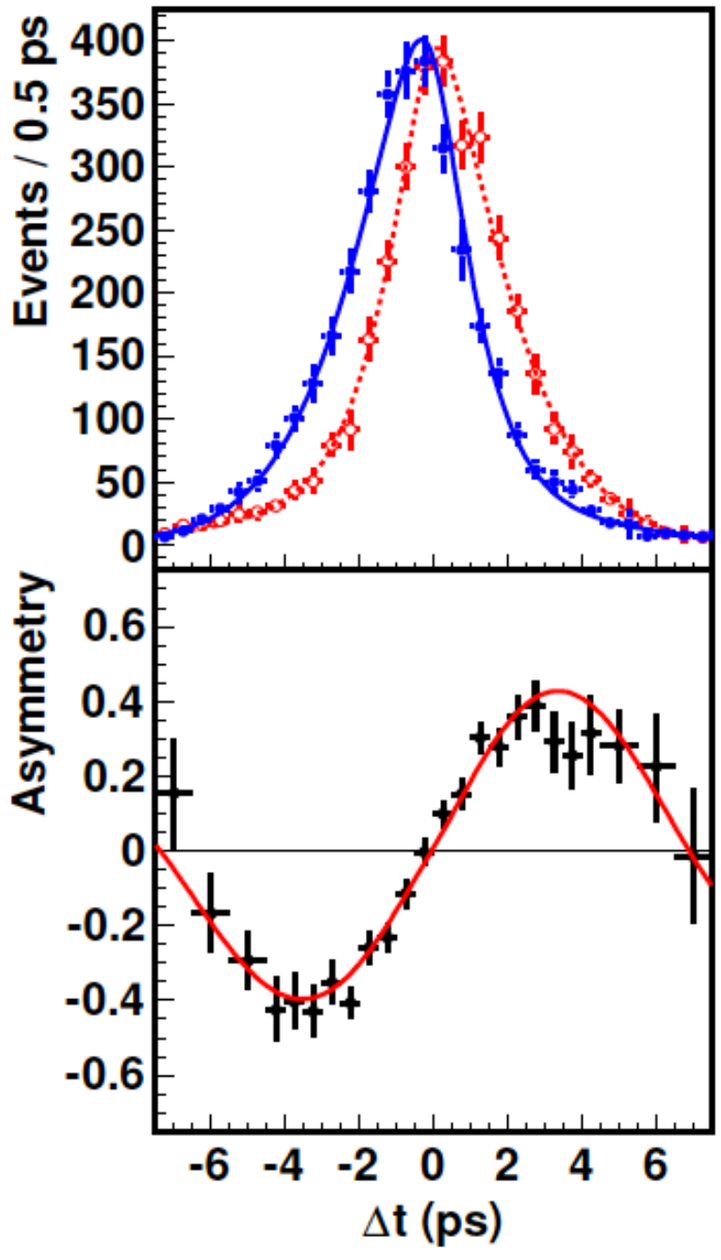
$$\text{Im } \lambda_{\psi K_S^0} \simeq \sin 2\beta$$



BaBar (PRD79, 072009)



Belle (PRL 108, 171802)



Most recent world average:

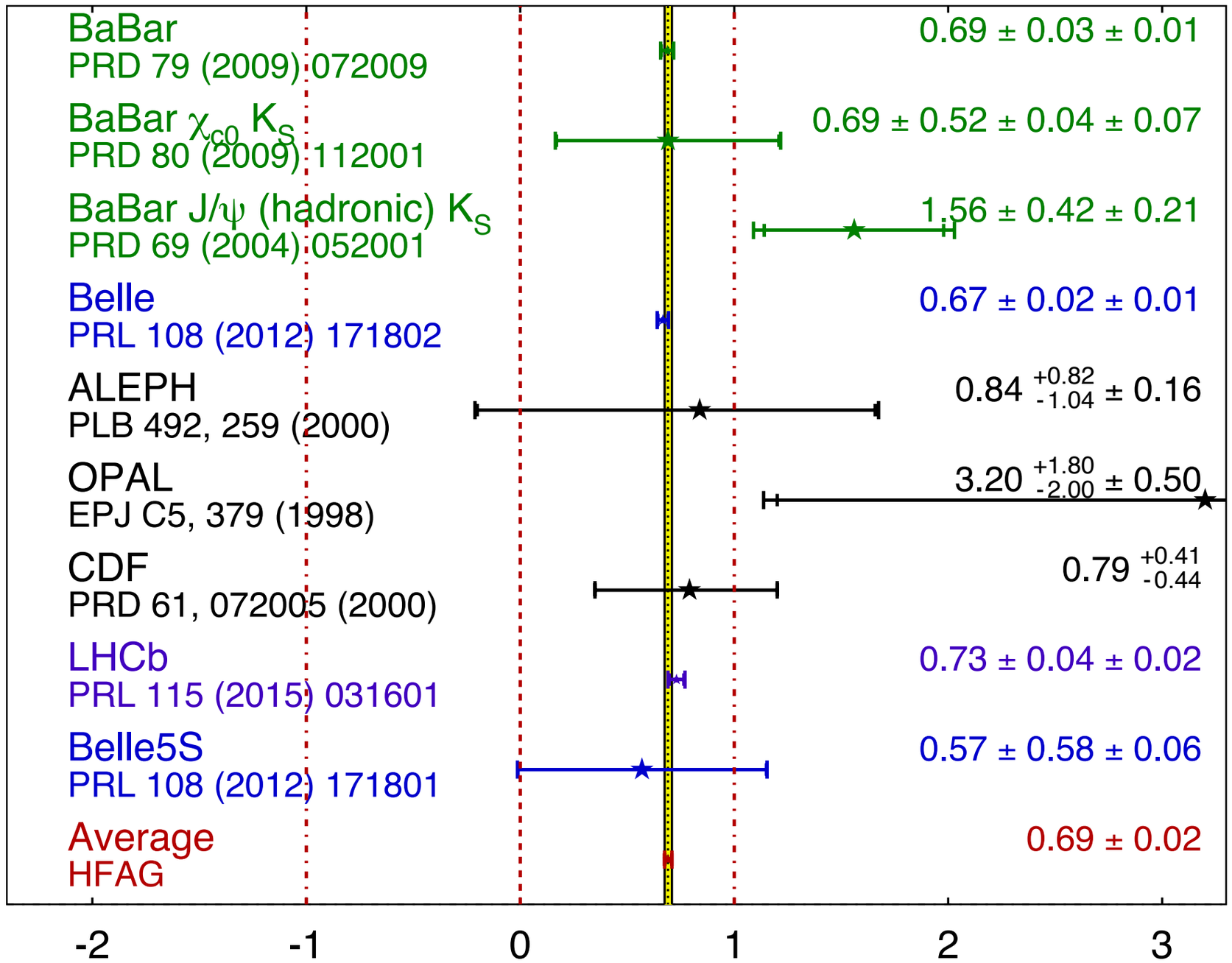
HFAG 2015

$$\sin 2\beta = 0.682 \pm 0.019$$

$$\beta = (21.5 \pm 0.8)^\circ$$

$\sin(2\beta) \equiv \sin(2\phi_1)$

HFAG
Moriond 2015
PRELIMINARY



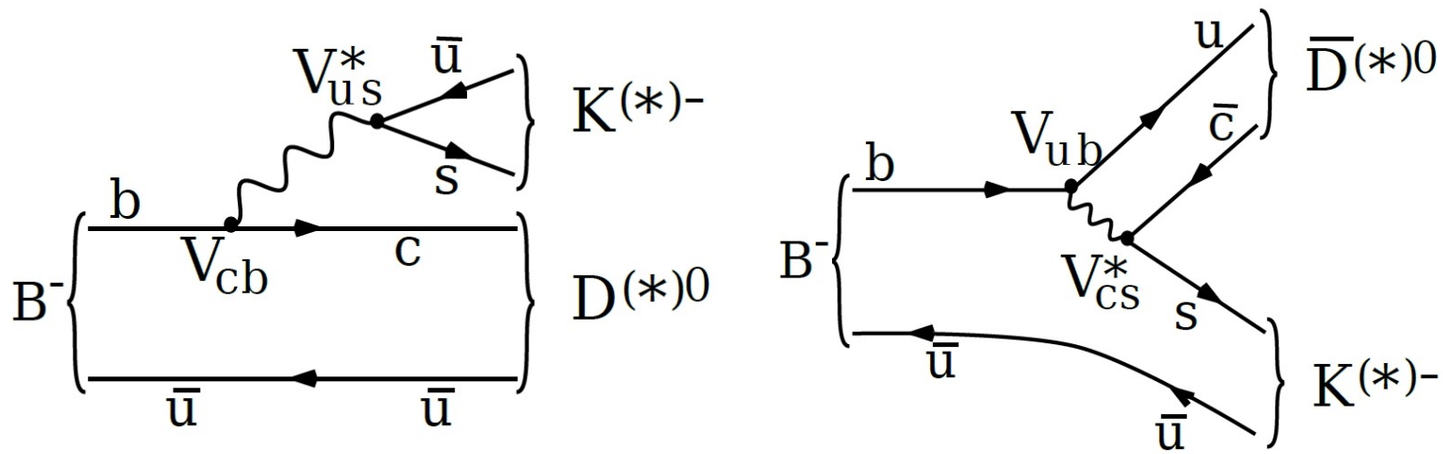
Measurement of the angle γ (ϕ_3)

$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$:the least well constrained angle of the UT

The only **CP** violating parameter that can be measured using only tree-level decays: an essential benchmark!

$B \to DK$

negligible theoretical uncertainty, $\mathcal{O}(10^{-6})$



γ determined from interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$

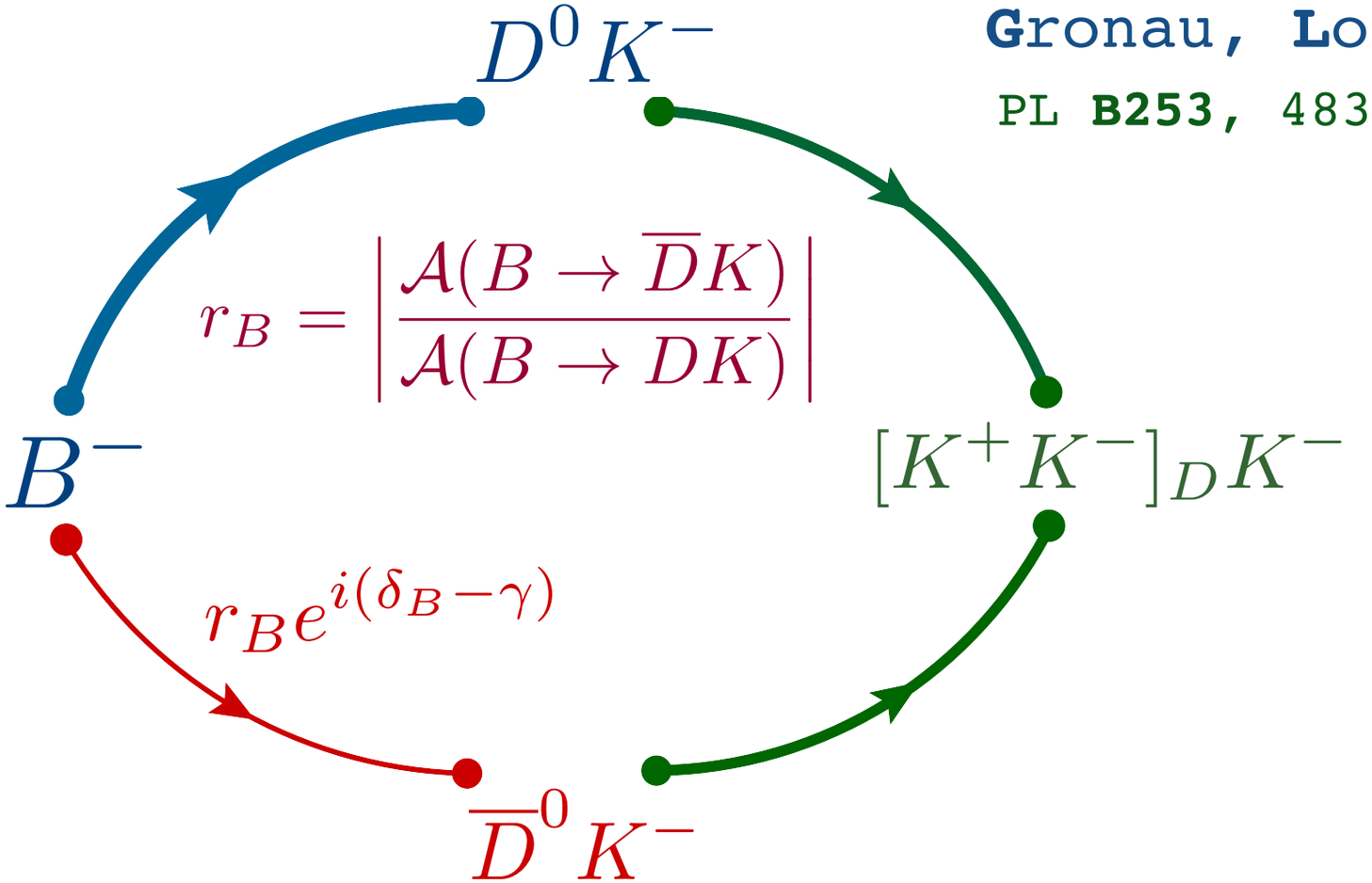
several different methods, depending on D decay:

$D^0 \to \underbrace{K^-K^+,\ \pi^-\pi^+,\ \pi^-\pi^+\pi^-\pi^+}, \underbrace{K^+\pi^-,\ K^+\pi^-\pi^+\pi^-}, \underbrace{K_S^0\pi^+\pi^-, K_s^0K^+K^-}$

GLW: **CP** eigenstates | ADS: DCS | GGSZ: Dalitz

Gronau, London, Wyler - GLW

PL **B253,** 483 and PL **B265,** 172

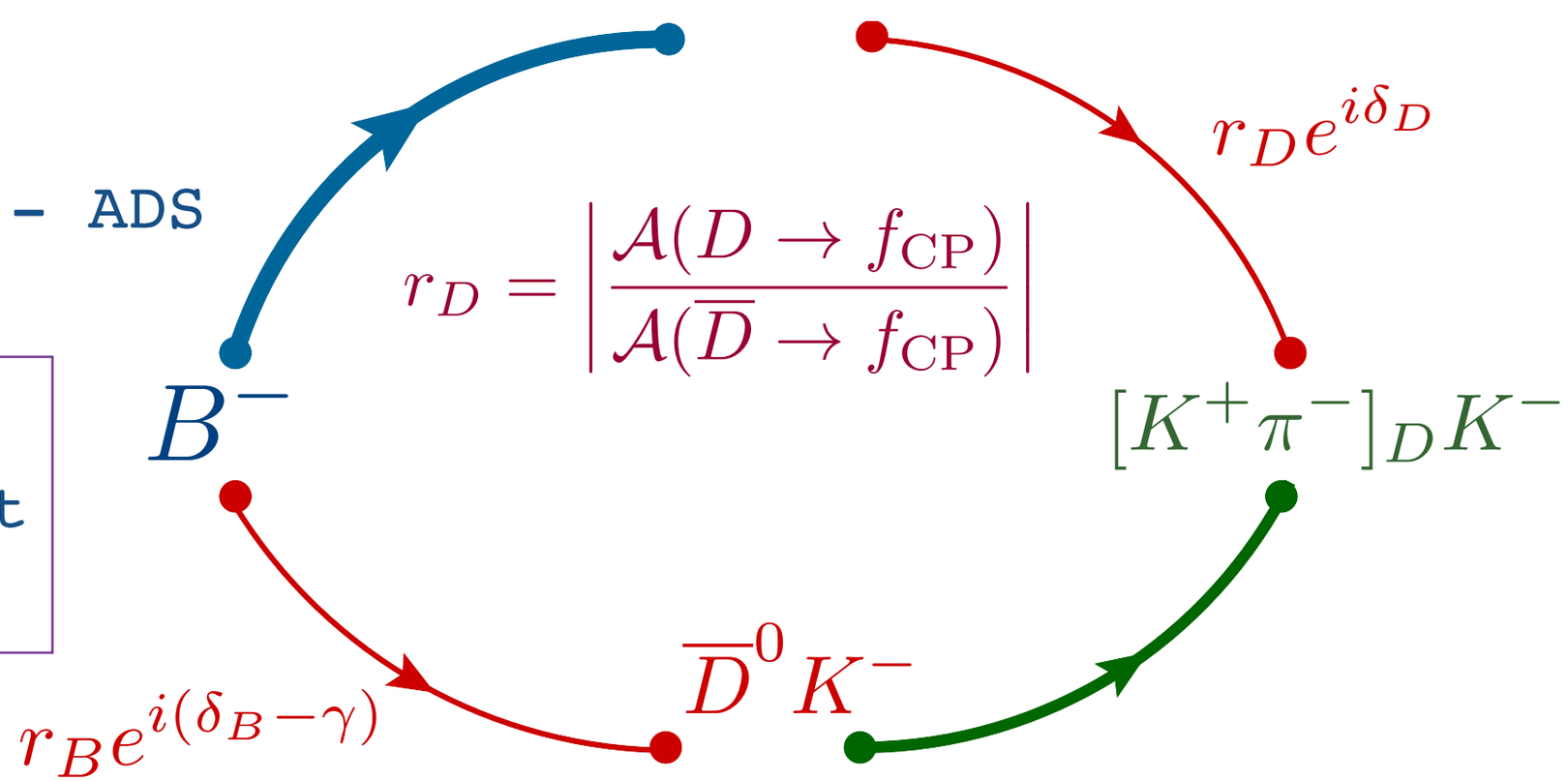


$r_B(\sim 0.1)$, δ_B :
hadronic parameters to be determined alongside γ

Atwood, Dunietz, Soni - ADS

PRL **78,** 3257

Larger interference, requires external input
r_D, δ_D



Best sensitivity obtained combining different decays:

$$B^- \to DK^-, \quad B^0 \to D^{(*)\mp}\pi^\pm, \quad B_s^0 \to D_s^\mp K^\pm, \quad B^0 \to DK^{*0}$$

External inputs from charm factories are necessary:

$$r_D^{KK},\ \delta_D^{KK},\ r_D^{\pi\pi},\ \delta_D^{\pi\pi},\ r_D^{K\pi},\ \delta_D^{K\pi},\ r_D^{K3\pi},\ \delta_D^{K3\pi},\ \ldots$$

Several observables needed to measure all parameters.
In the simplest case (GLW), where $D \to f_{\rm CP} \equiv D_{\rm CP}$:

$$\Gamma(B^- \to D_{\rm CP\pm}K^-) \propto 1 + r_B^2 \pm 2r_B^2\cos(\delta_B - \gamma)$$

$$\Gamma(B^+ \to D_{\rm CP\pm}K^+) \propto 1 + r_B^2 \pm 2r_B^2\cos(\delta_B + \gamma)$$

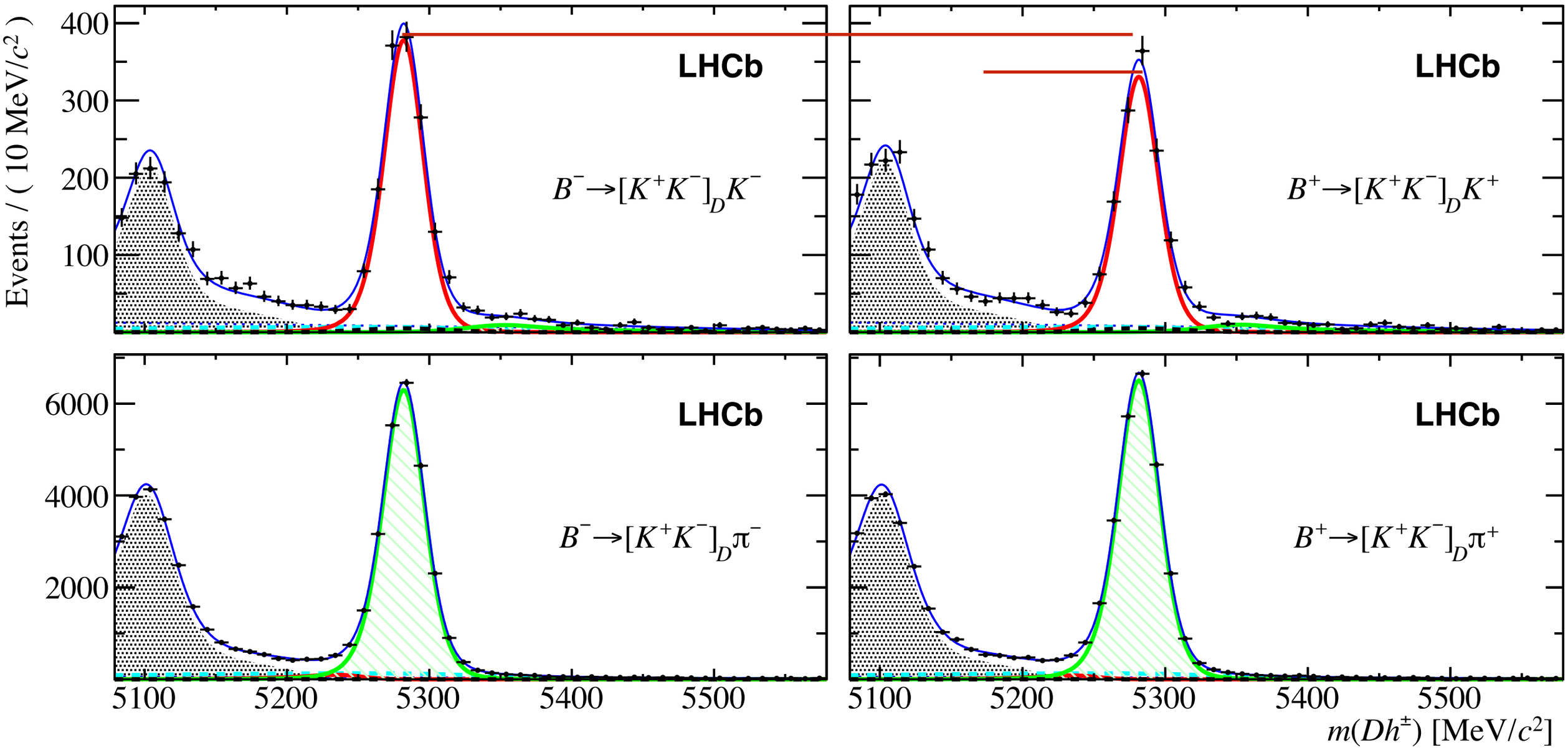
decay rates combined in double ratios

$$R_{\rm CP\pm} = 2\frac{\Gamma[B^- \to D_{\rm CP\pm}K^-] + \Gamma[B^+ \to D_{\rm CP\pm}K^+]}{\Gamma[B^- \to D^0(K^-\pi^+)\pi^-] + \Gamma[B^+ \to \overline{D}^0(K^+\pi^-)\pi^+]}$$

$$R_{\rm CP\pm} = 1 + r_B^2 \pm 2r_B\cos\delta_B\cos\gamma$$

$$A_{\rm CP\pm} = \pm\frac{2r_B\sin\delta_B\sin\gamma}{1 + r_B^2 + 2r_B\cos\delta_B\cos\gamma} = \pm 2r_B\sin\delta_B\sin\gamma/R_{\rm CP\pm}$$

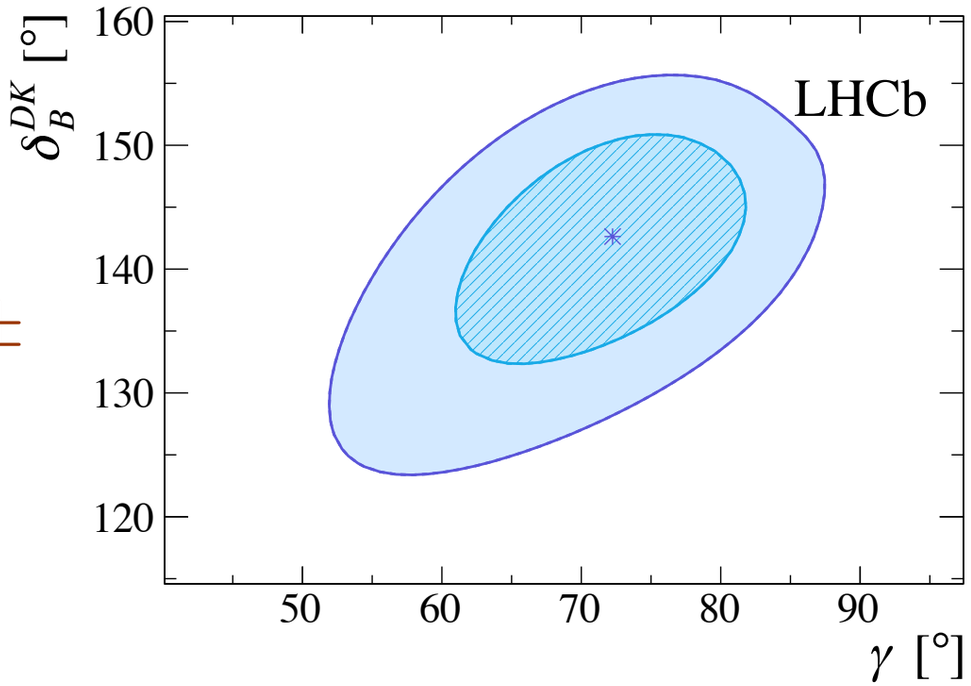
$B \to DK, \;\; B \to D\pi, \;\;\; D^0 \to K^+K^-$

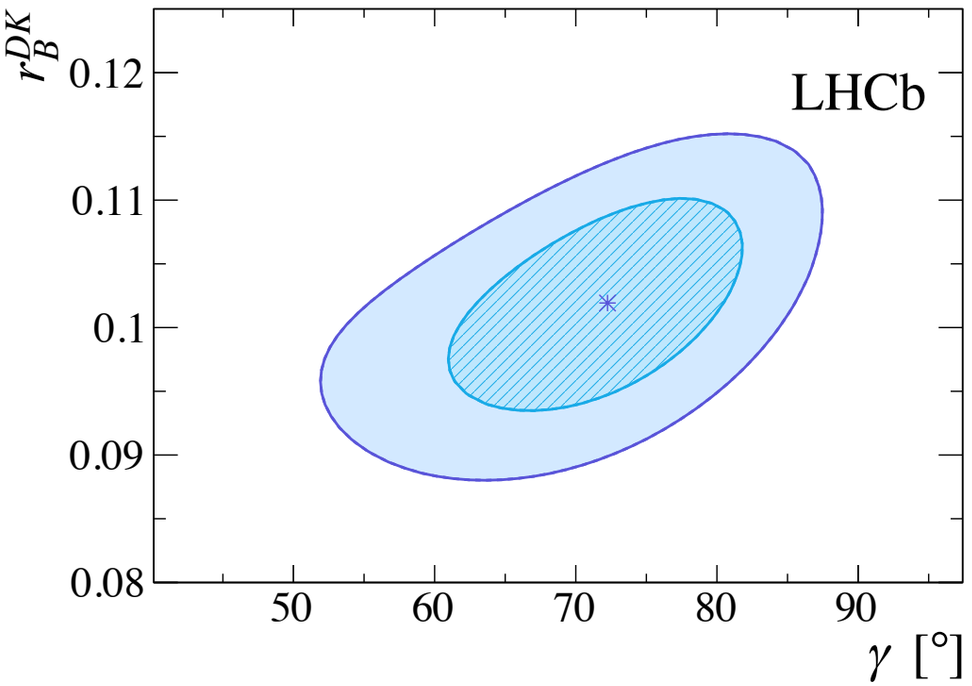


LHCb: $A_{\rm CP}(B^\pm \to [h^+h^-]_D K^\pm) = +0.097 \pm 0.018 \pm 0.009$

World average: $A_{\rm CP}(B^\pm \to [K^+\pi^-]_D K^\pm) = -0.41 \pm 0.06$

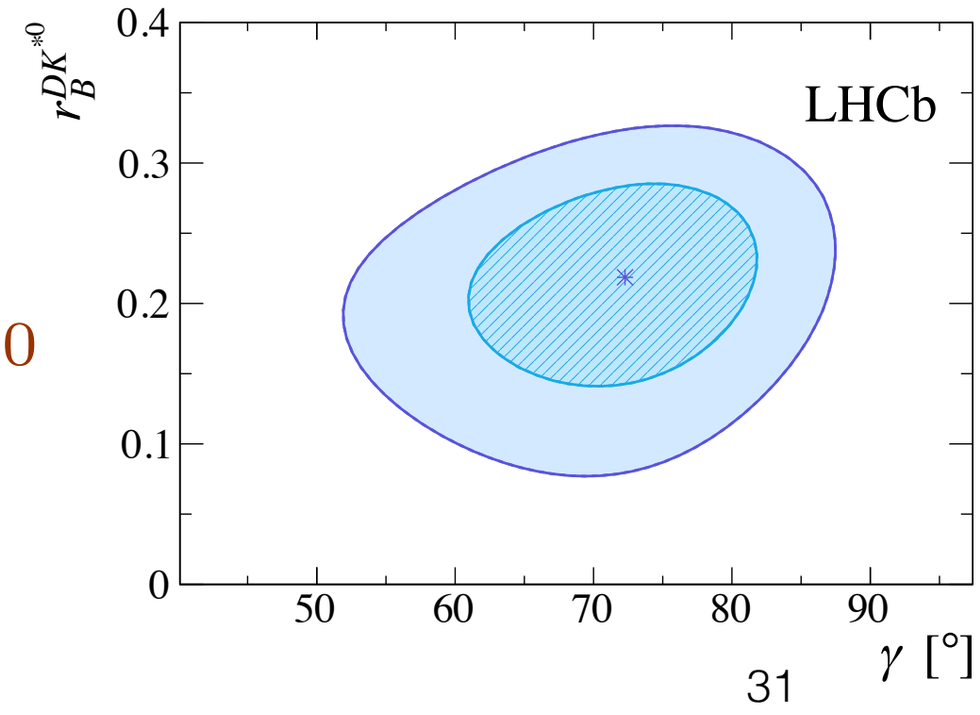
$B^{\pm} \to DK^{\pm}$

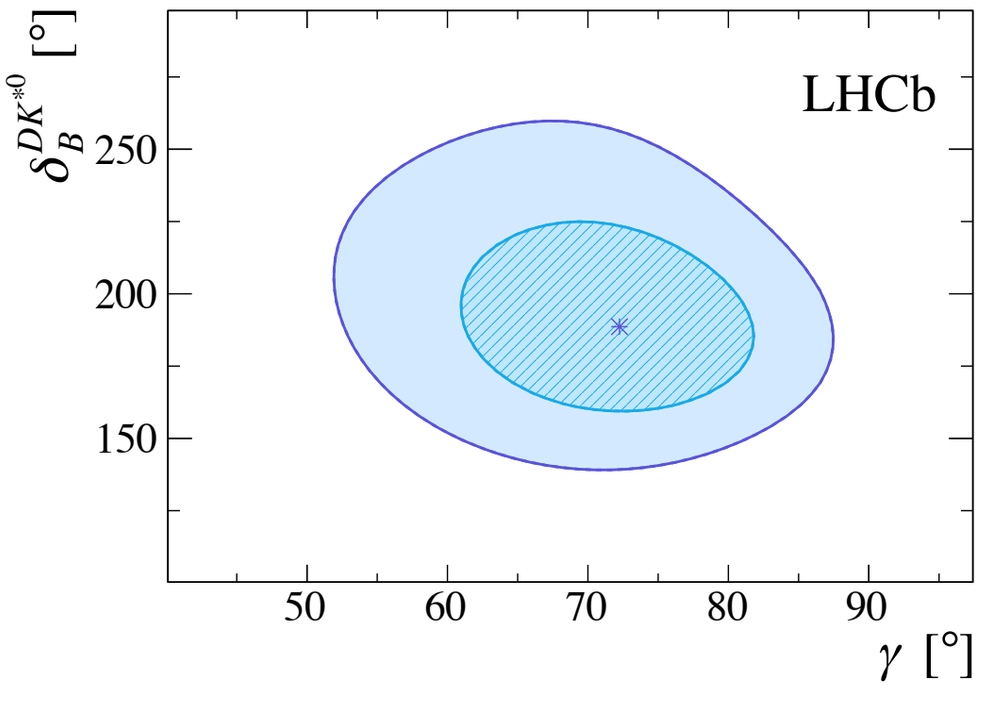




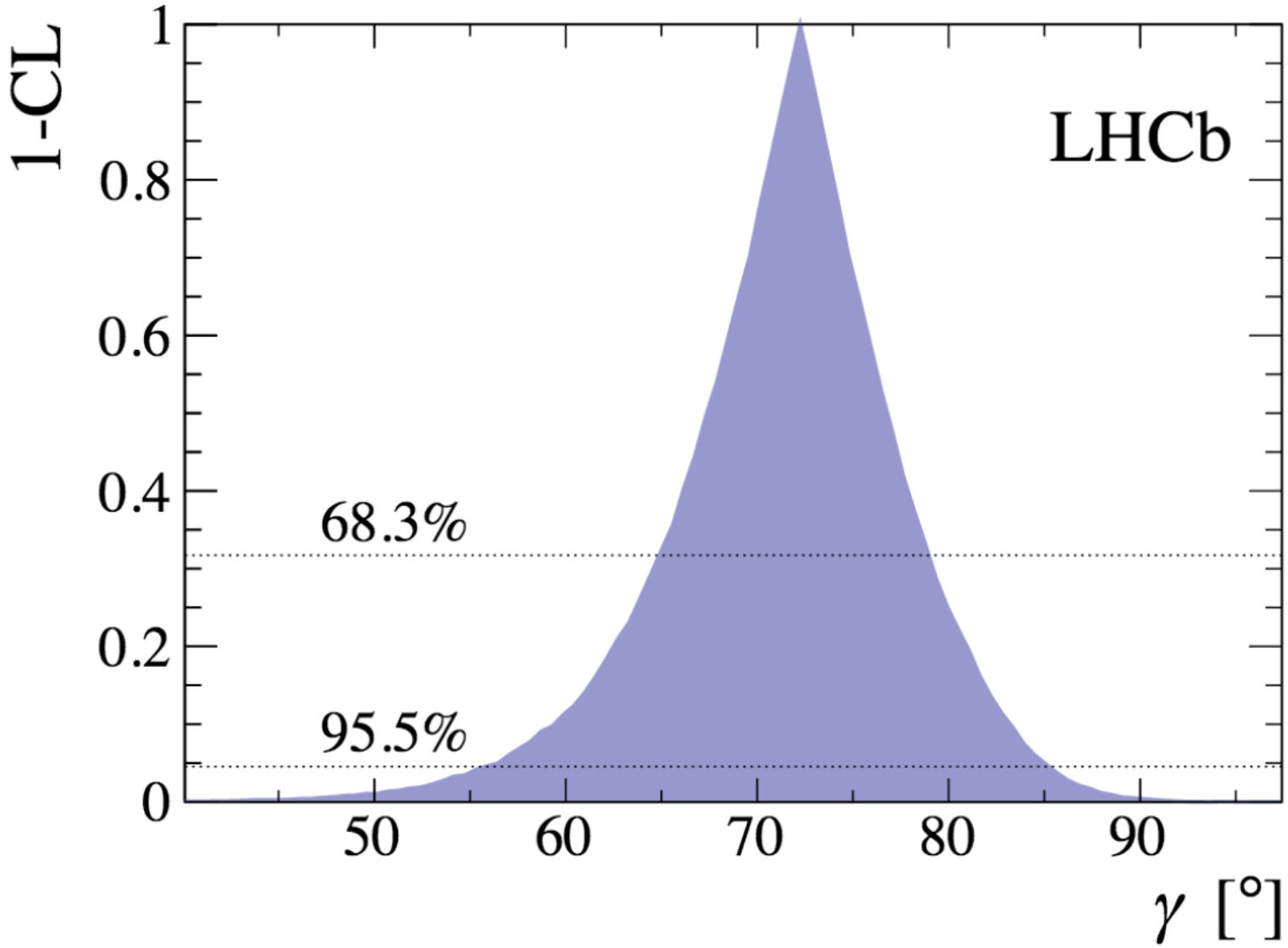
$\gamma,\ \delta_B,\ r_B$ are less correlated in $B^0 \to DK^{*0}$

$B^0 \to DK^{*0}$





Combination of all methods and decay modes:



LHCb: $\gamma = (72.2^{+6.8}_{-7.3})^\circ$

World average: $\gamma = (73.2^{+6.3}_{-7.0})^\circ$

All measurements are still statistically limited

Measurement of the angle ϕ_s

The **CP**-violating phase ϕ_s :

relative phase between mixing and decay amplitudes:

$$\lambda_f = \eta_f \frac{q}{p} \frac{\overline{A}_f}{A_f} = \eta_f \left|\frac{q}{p}\right| \left|\frac{\overline{A}_f}{A_f}\right| e^{-i\phi_s},$$

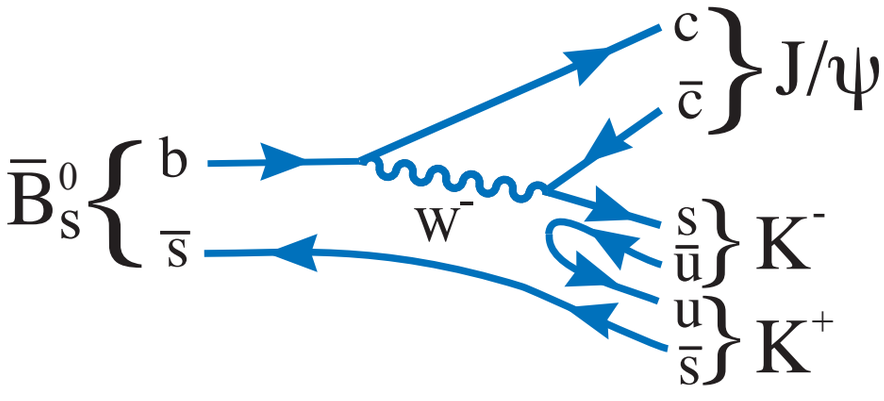
penguins, $\mathcal{O}(1^\circ)$

$$\phi_s = -2\beta_s + \Delta\phi_s + \delta_s^{\rm NP}, \qquad \beta_s = \arg\left[\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$

tree — new physics, $\mathcal{O}(?)$

If penguin contributions are small and no NP, $\phi_s \approx -2\beta_s$

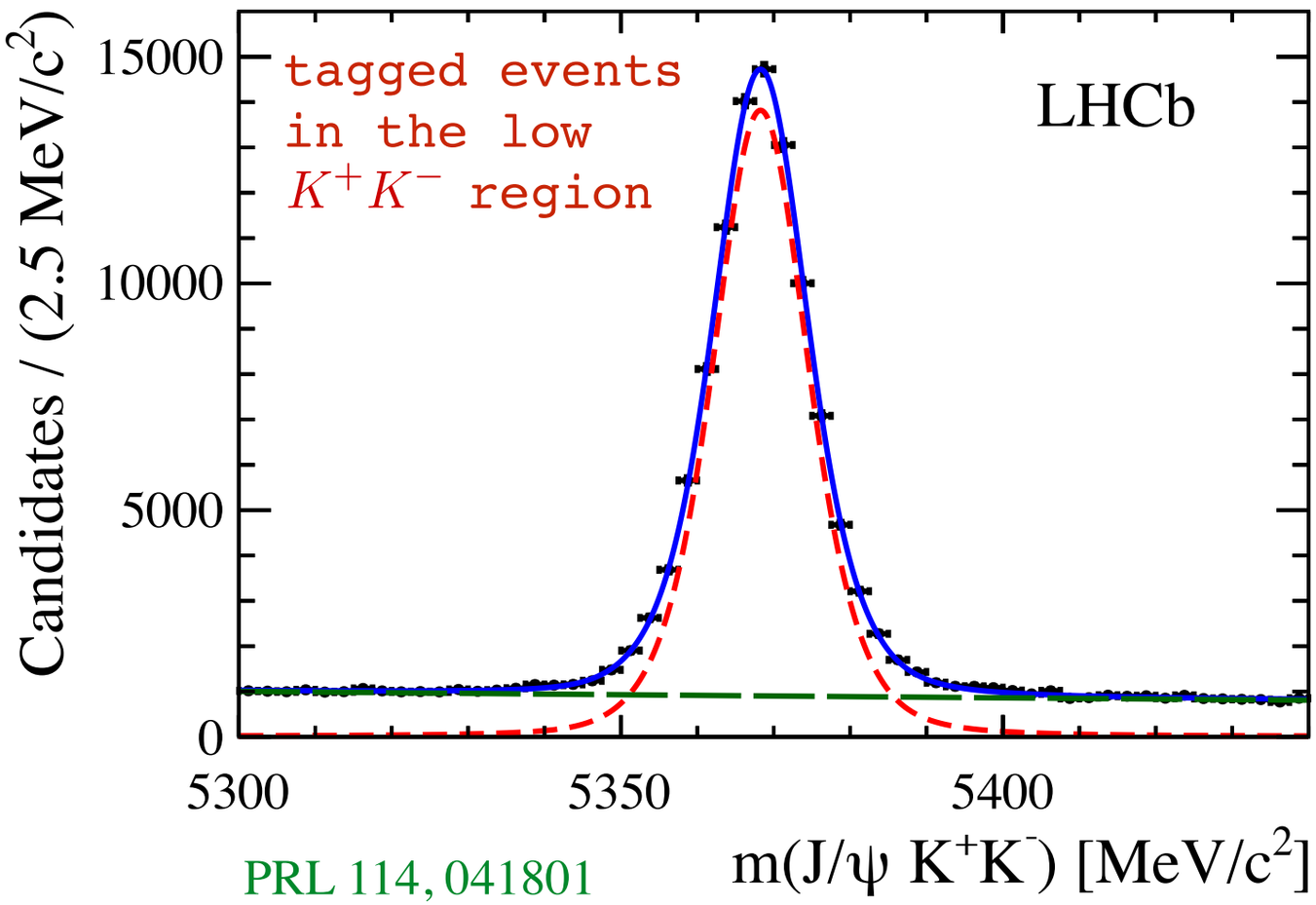
The SM prediction: $-2\beta_s = -0.0363 \pm 0.0013$



"Golden modes": $b \to c\bar{c}s$ transitions,

$$B_s^0 \to J/\psi\, K^+K^-$$
$$B_s^0 \to J/\psi\, \pi^+\pi^-$$
$$B_s^0 \to D_s^+ D_s^-$$

$B_s^0 \to J/\psi\,\phi$ decay ($P \to VV$): full angular analysis needed to disentangle **CP**-even and **CP**-odd components



PRL 114, 041801

3 helicity states,

$h_0,\ h_-,\ h_+$

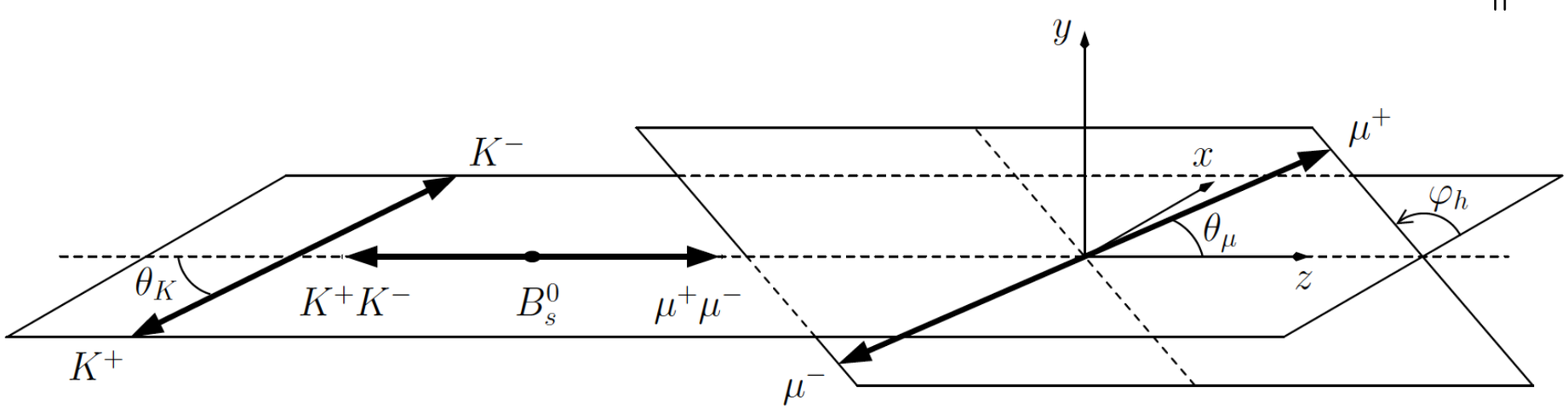
C but not **P** eigenstates

Transversity basis

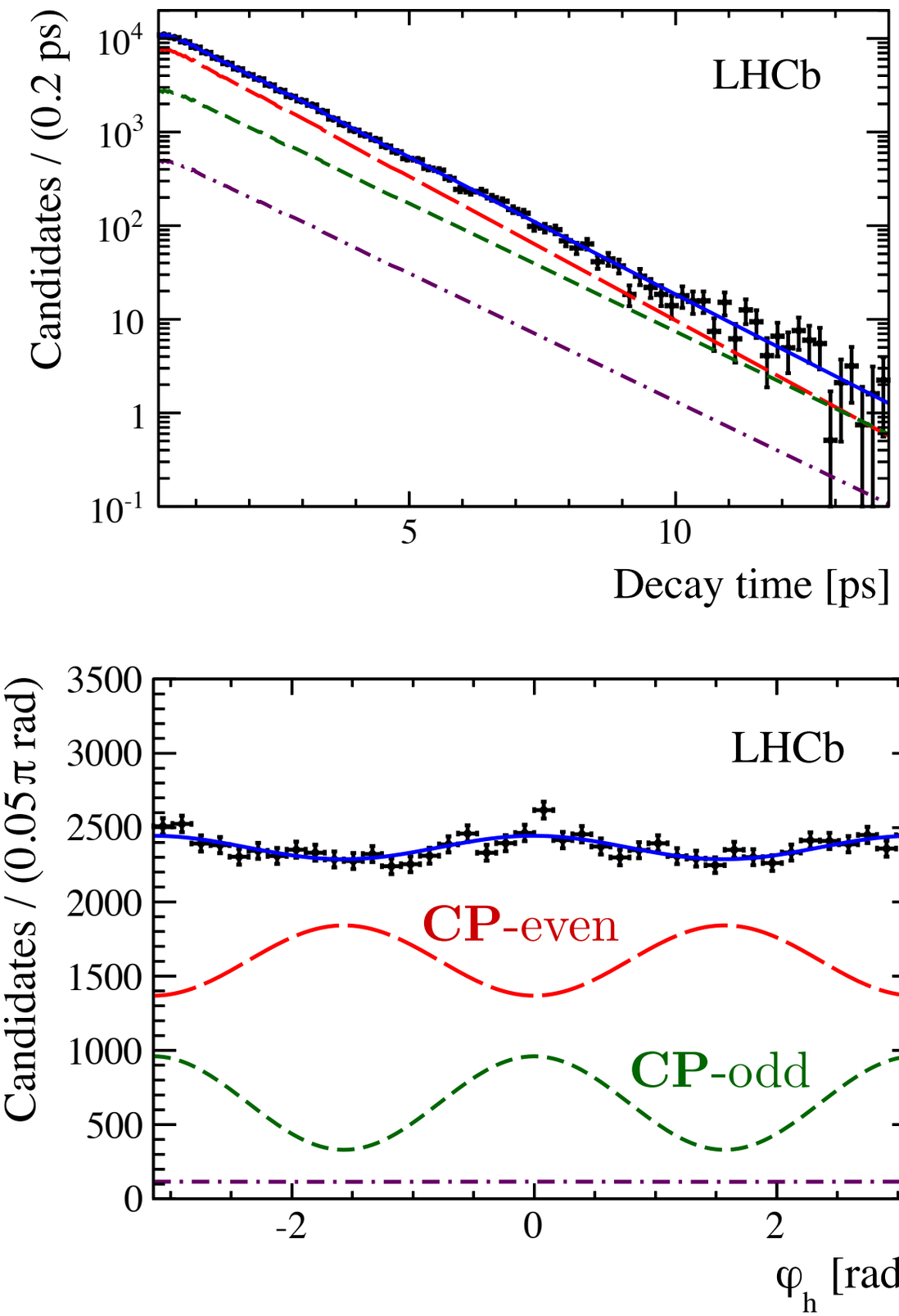
$$A_0 = h_0$$

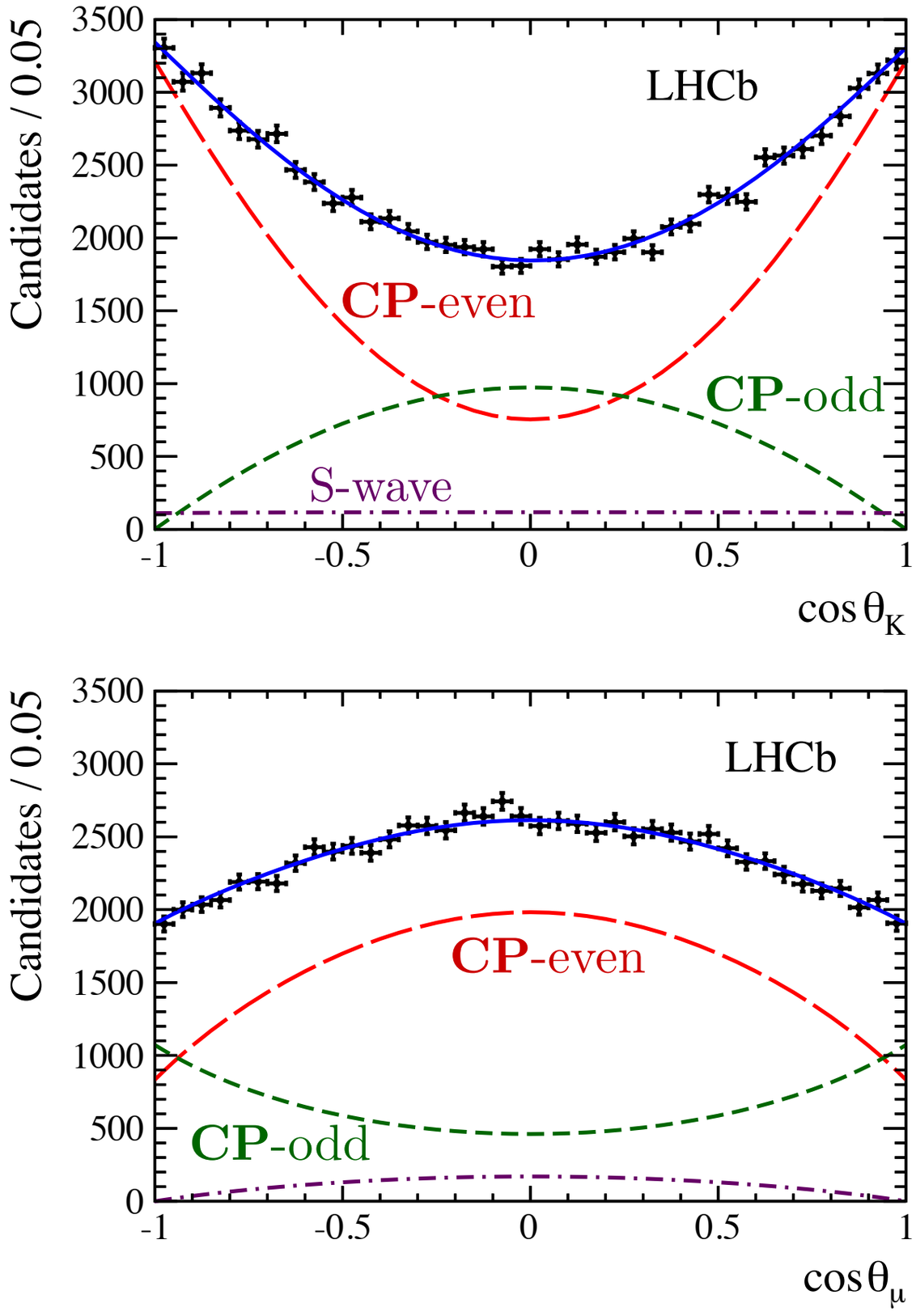
$$A_\perp = \frac{1}{\sqrt{2}}(h_- - h_+)$$

$$A_\parallel = \frac{1}{\sqrt{2}}(h_- + h_+)$$



Background subtracted decay time and angular distributions, with result from the 4D fit overlaid





LHCb

Parameter	Value
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0032$
$\lvert A_\perp \rvert^2$	$0.2504 \pm 0.0049 \pm 0.0036$
$\lvert A_0 \rvert^2$	$0.5241 \pm 0.0034 \pm 0.0067$
$\delta_\parallel$ [rad]	$3.26\ ^{+0.10}_{-0.17}\ ^{+0.06}_{-0.07}$
$\delta_\perp$ [rad]	$3.08\ ^{+0.14}_{-0.15} \pm 0.06$
ϕ_s [rad]	$-0.058 \pm 0.049 \pm 0.006$
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$
Δm_s [ps^{-1}]	$17.711\ ^{+0.055}_{-0.057} \pm 0.011$

PRL 114, 041801

$$B_s^0 \to J/\psi\, K^+ K^-$$

$$\phi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad}$$

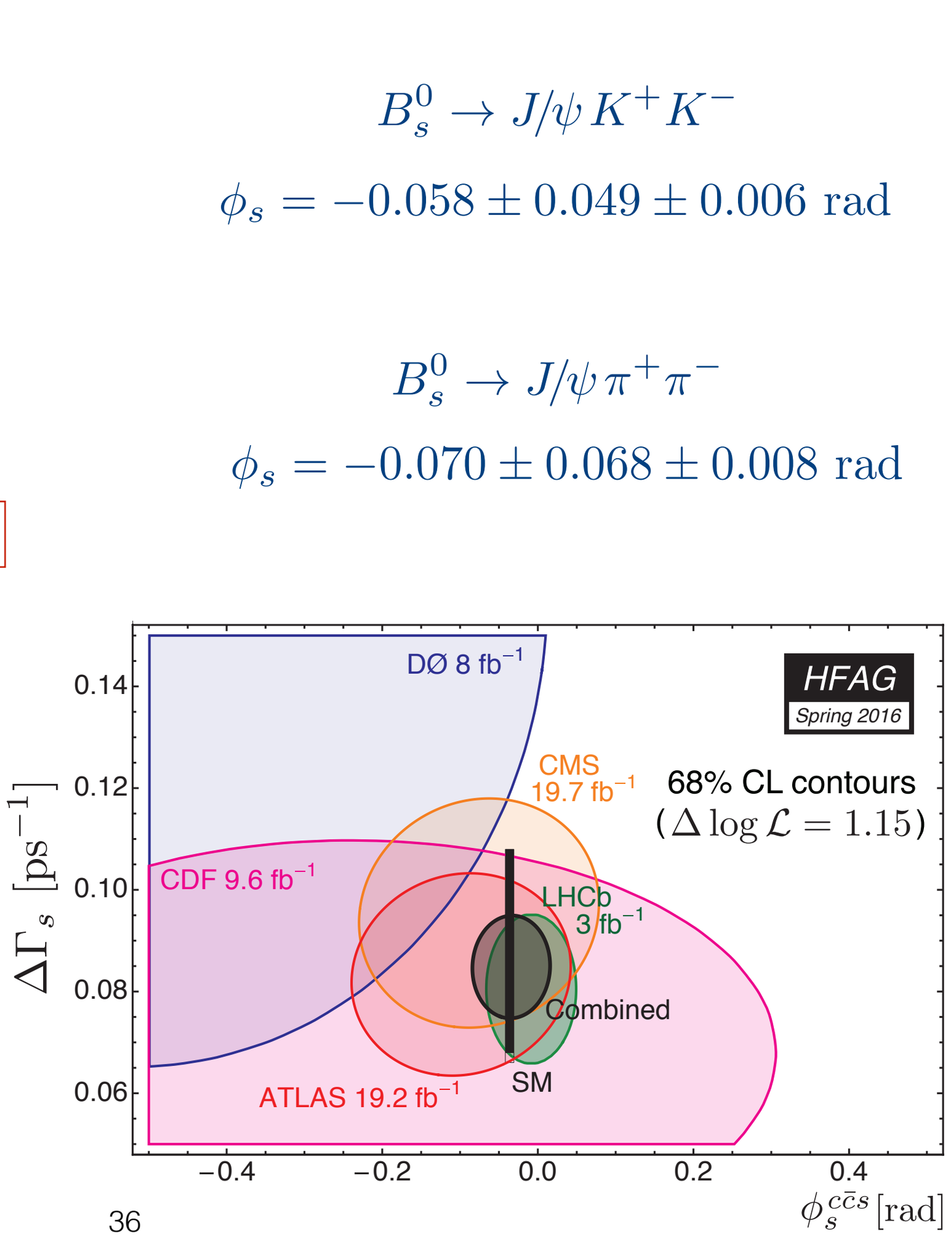
$$B_s^0 \to J/\psi\, \pi^+ \pi^-$$

$$\phi_s = -0.070 \pm 0.068 \pm 0.008 \text{ rad}$$

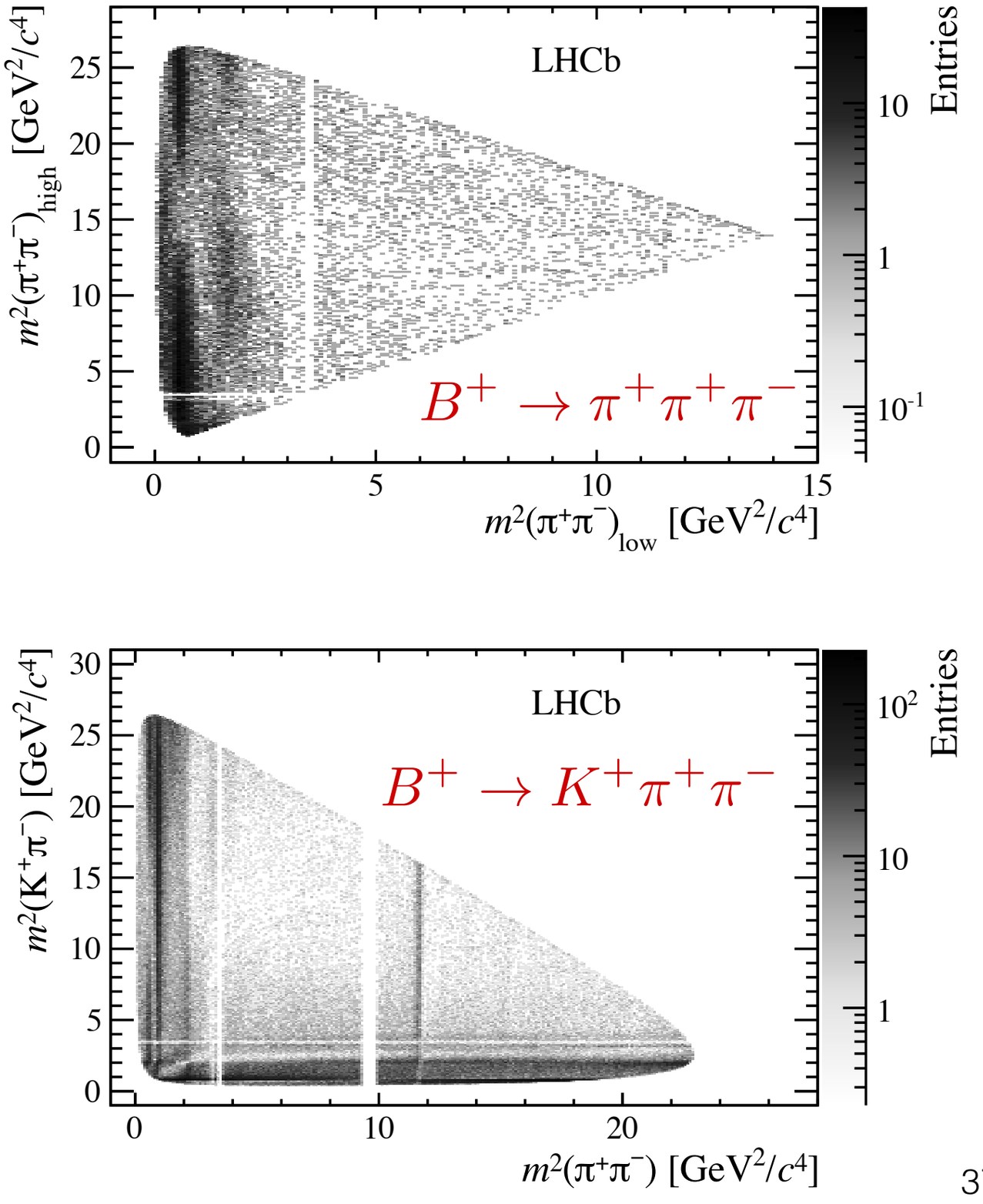
World average:

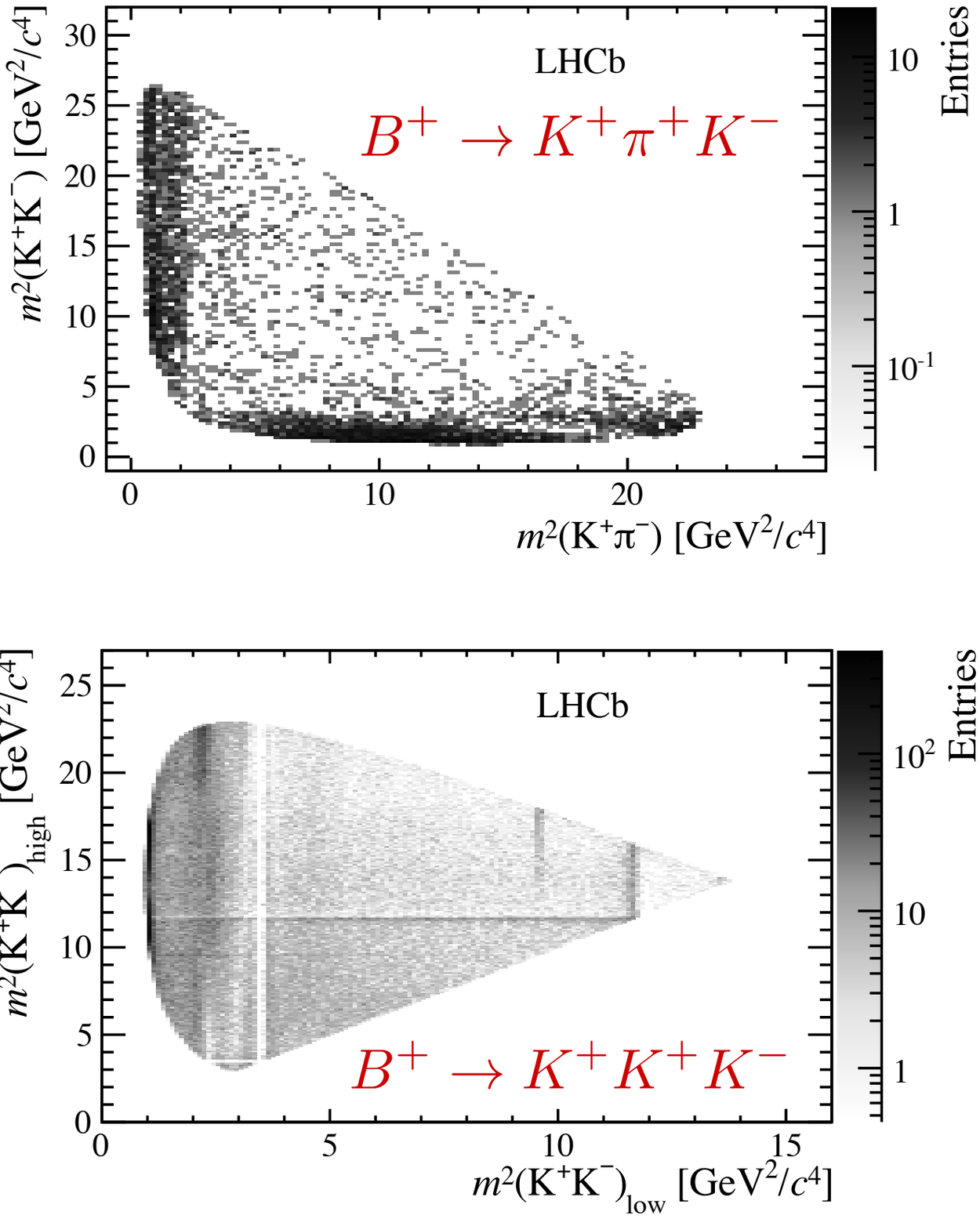
$$\phi_s = -0.033 \pm 0.033 \text{ rd}$$

Still statistically limited



Direct CP violation in charmless B^+ decays



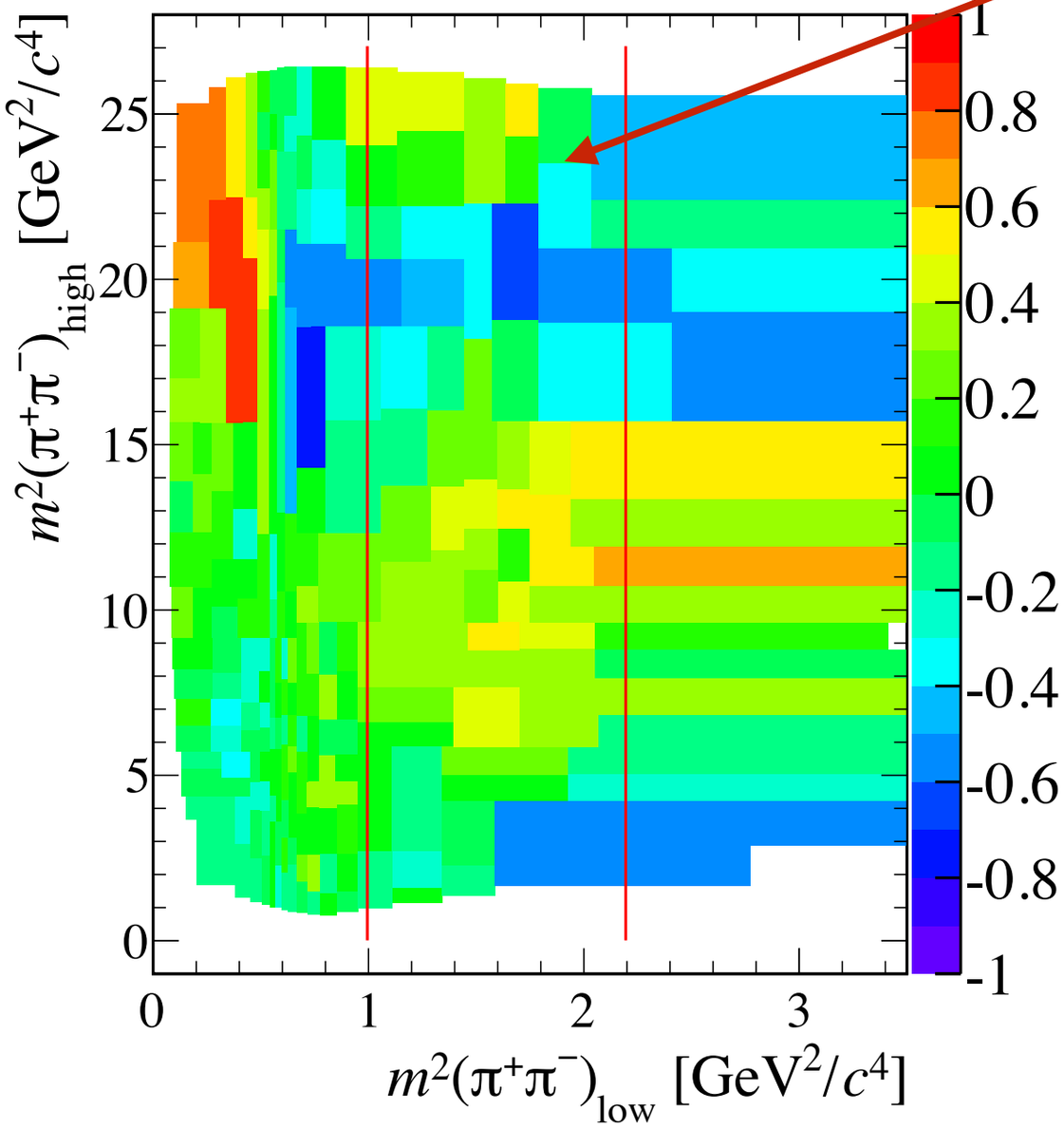


- The Dalitz plots into bins of equal population
- In each bin compute the **CP** asymmetry

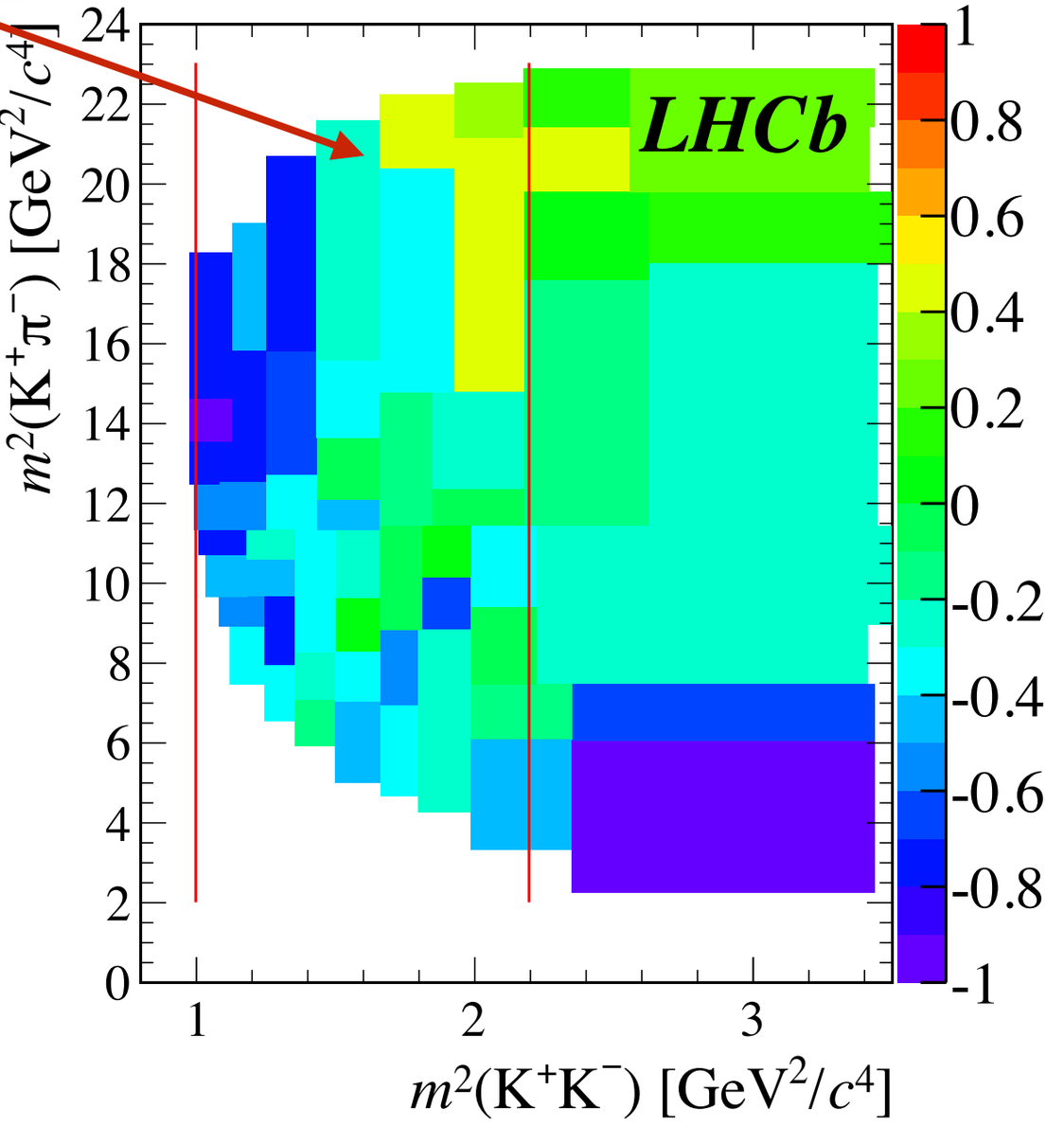
$$A_{\rm CP} = \frac{\Gamma(B^- \to f) - \Gamma(B^+ \to \bar{f})}{\Gamma(B^- \to f) + \Gamma(B^+ \to \bar{f})} \approx \frac{N_{\rm obs}(B^-) - N_{\rm obs}(B^+)}{N_{\rm obs}(B^-) + N_{\rm obs}(B^+)}$$

$\pi^+\pi^- \rightleftarrows K^+K^-$

$B^+ \to \pi^+\pi^+\pi^-$

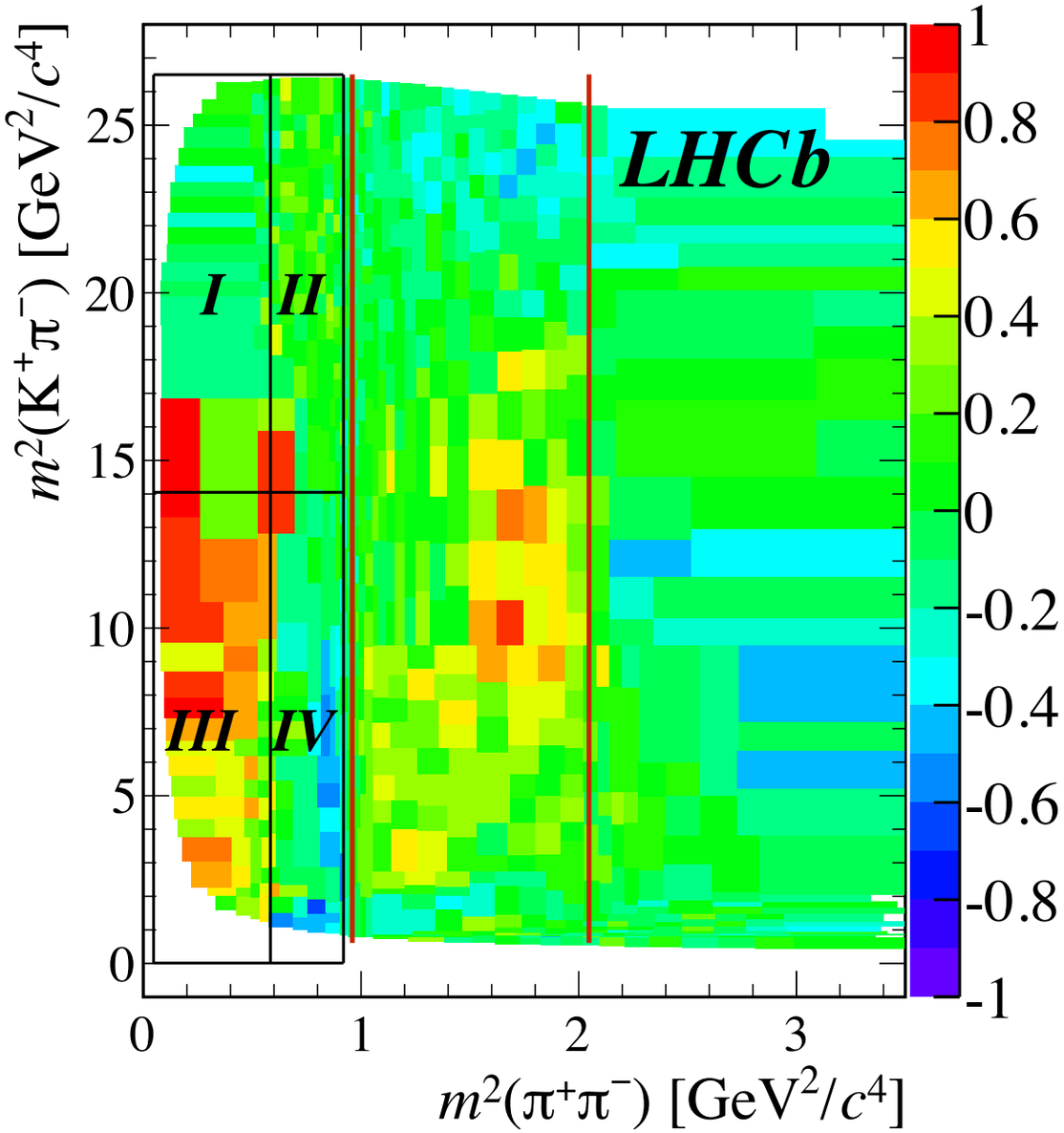


$B^+ \to K^+\pi^+K^-$

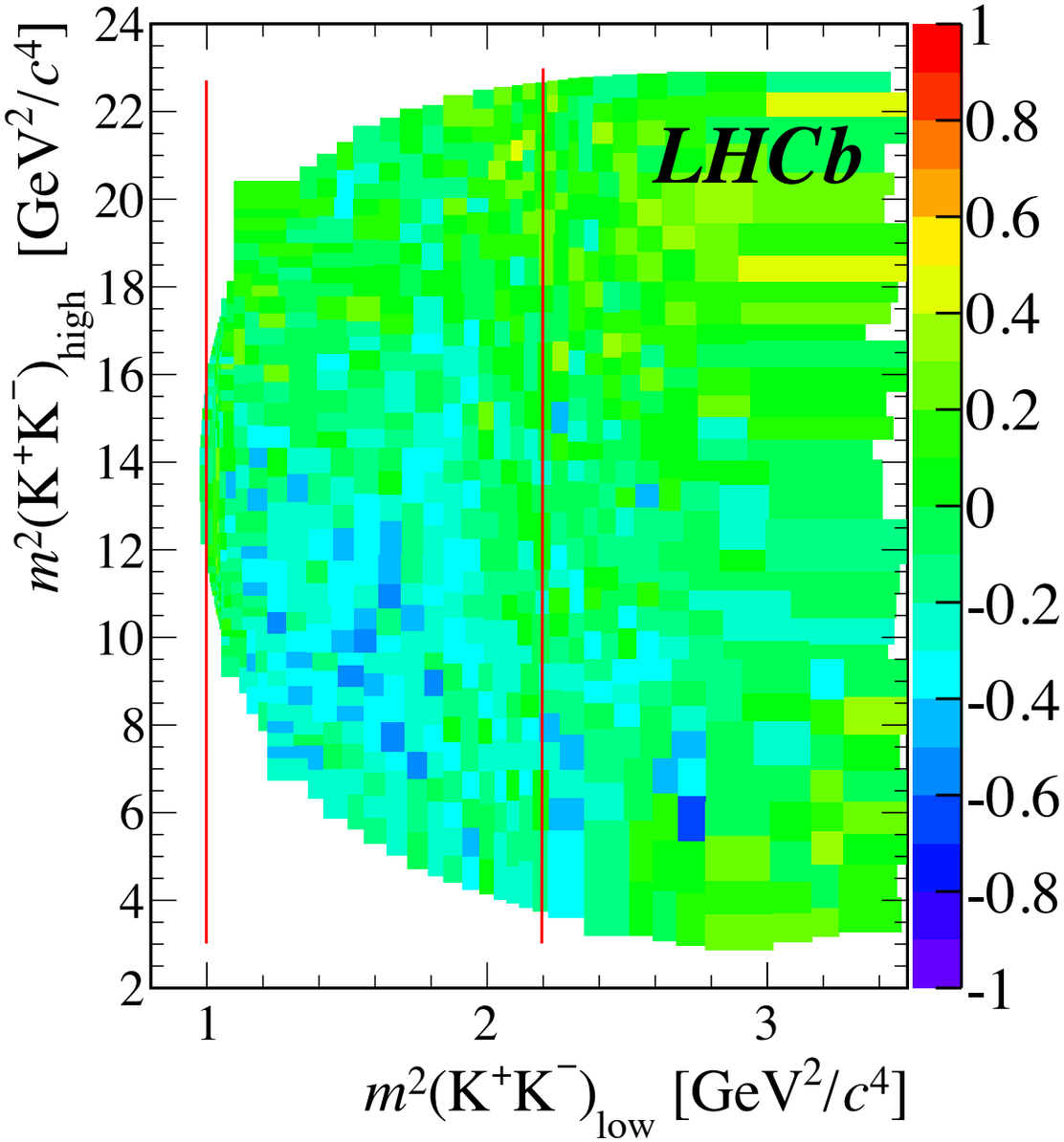


- A very rich pattern of **CP** asymmetries
- Different mechanisms for strong phase difference
- **CP** asymmetries up to 80%!
- Can this be explained by the SM CP violation alone?

$B^+ \to K^+\pi^+\pi^-$



$B^+ \to K^+K^+K^-$

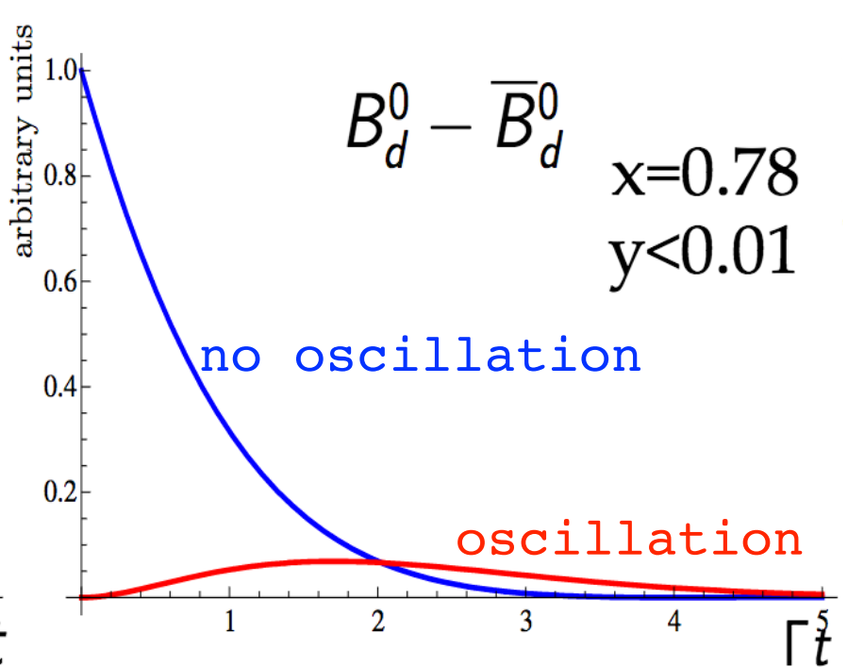


charm mixing and CP violation

$D^0 - \overline{D}^0$ mixing is well established. Very low oscillation frequency: difficult to measure mixing parameters

Parameters governing mixing:

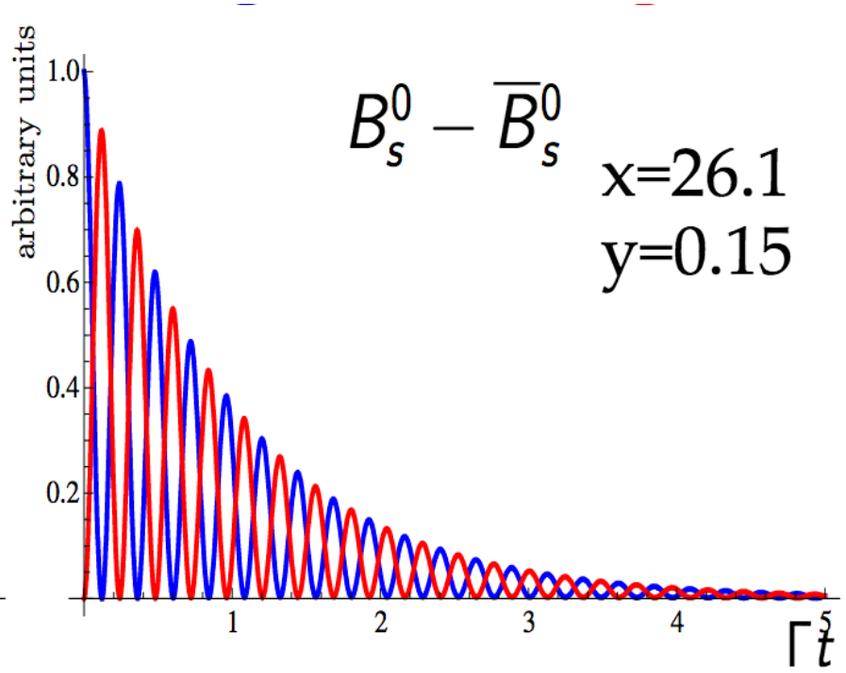
$$x = \frac{\Delta m}{\Gamma}, \qquad y = \frac{\Delta\Gamma}{2\Gamma}, \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{\Gamma}$$



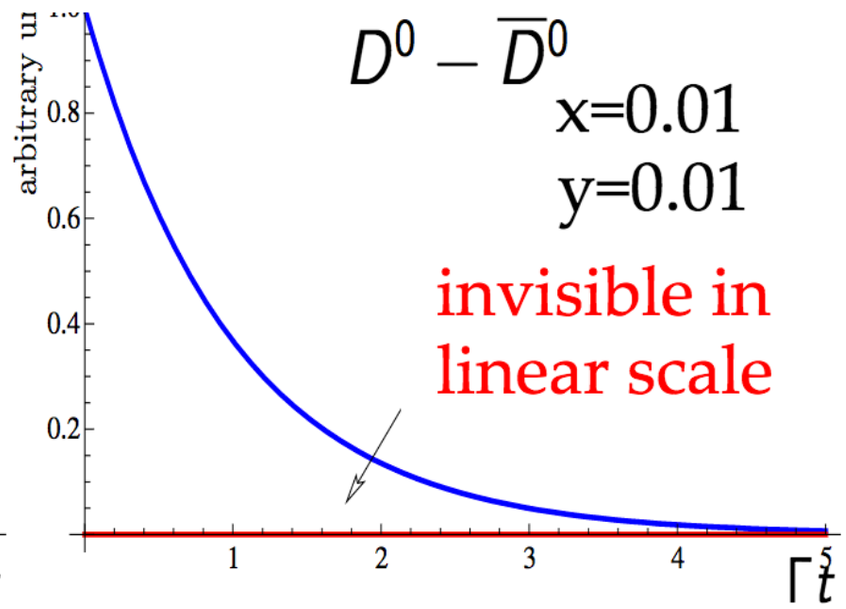
$B_d^0 - \overline{B}_d^0$ x=0.78 y<0.01

no oscillation

oscillation



$B_s^0 - \overline{B}_s^0$ x=26.1 y=0.15



$D^0 - \overline{D}^0$ x=0.01 y=0.01

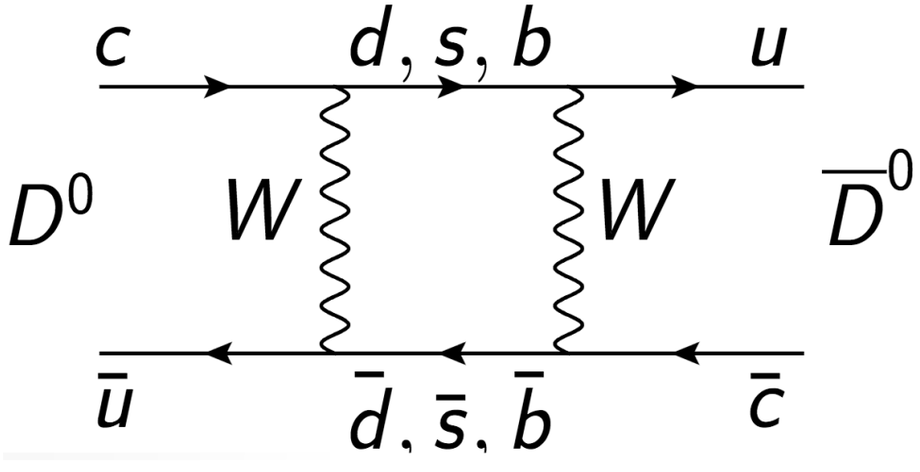
invisible in linear scale

Time evolution: $\mathcal{P}[D^0(t) \to D^0] \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$

no oscillation

oscillation

short-distance: contribute only to x



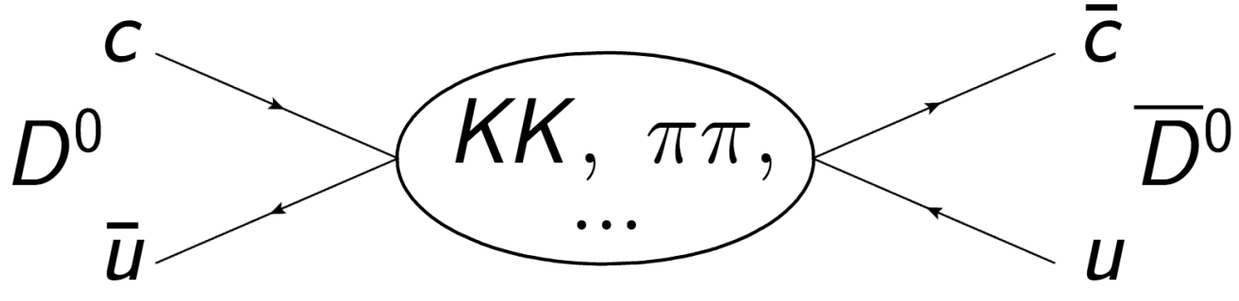
strong suppression of box diagram in SM:

GIM CKM

$$\left(\frac{m_{d,s,b}}{m_W}\right)^2 \quad , \quad \left|\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right|^2 = \mathcal{O}(10^{-6})$$

That's where New Physics could manifest!

Long-distance: contribute to both x and y

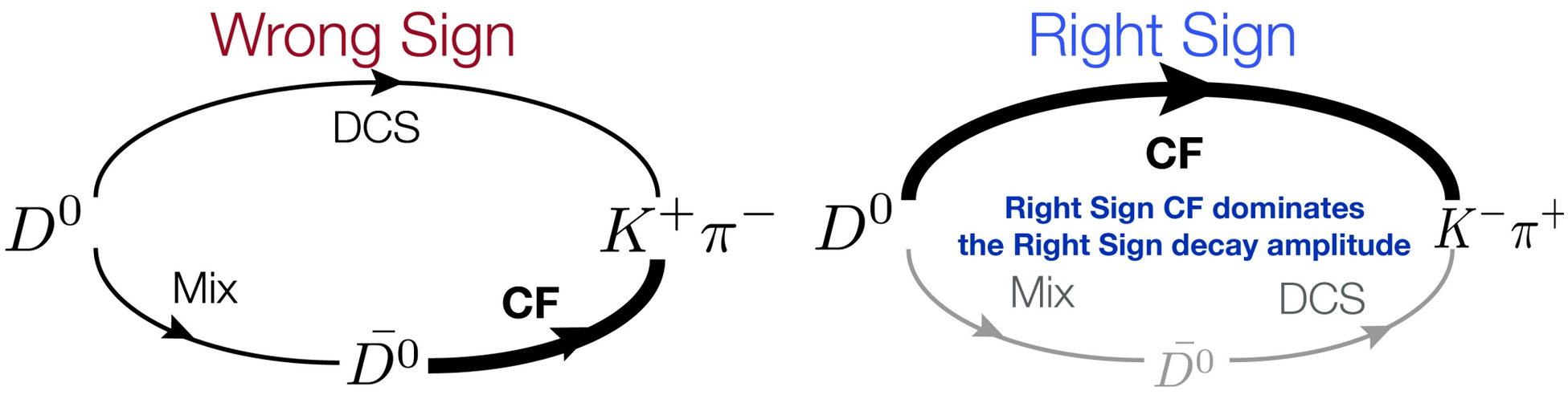


$$x, y \sim \sin^2\theta_C \times [\mathrm{SU}(3)\ \mathrm{breaking}]^2$$

SM predictions suffer from large uncertainties: charm is not so heavy, and not so light.

Interpretation of experimental results is not straightforward

The most sensitive technique: time-dependent ratio of "wrong-sign" to "right sign" $D^0 \to K\pi$ decays



Assuming $|x|, |y| \ll 1$ and no CP violation, and defining

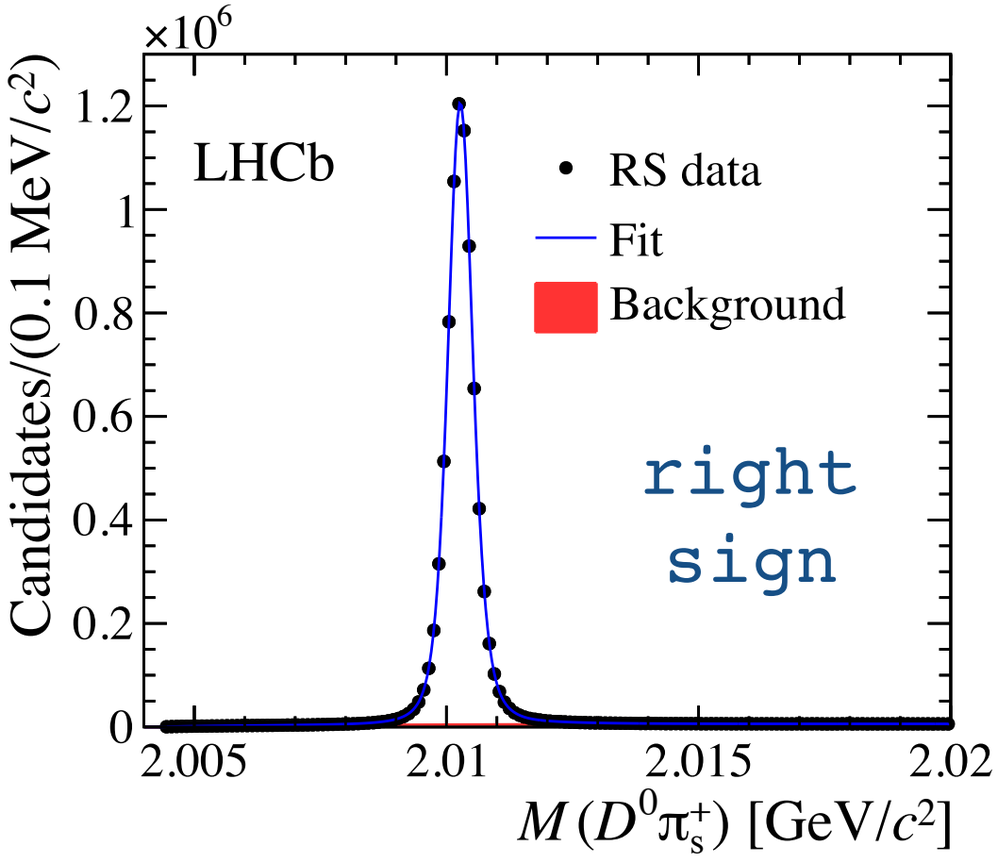
$$\frac{A_{K^+\pi^+}}{\overline{A}_{K^+\pi^+}} = -\sqrt{R_D}\, e^{-i\delta_{K\pi}}, \quad y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi} \qquad x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$

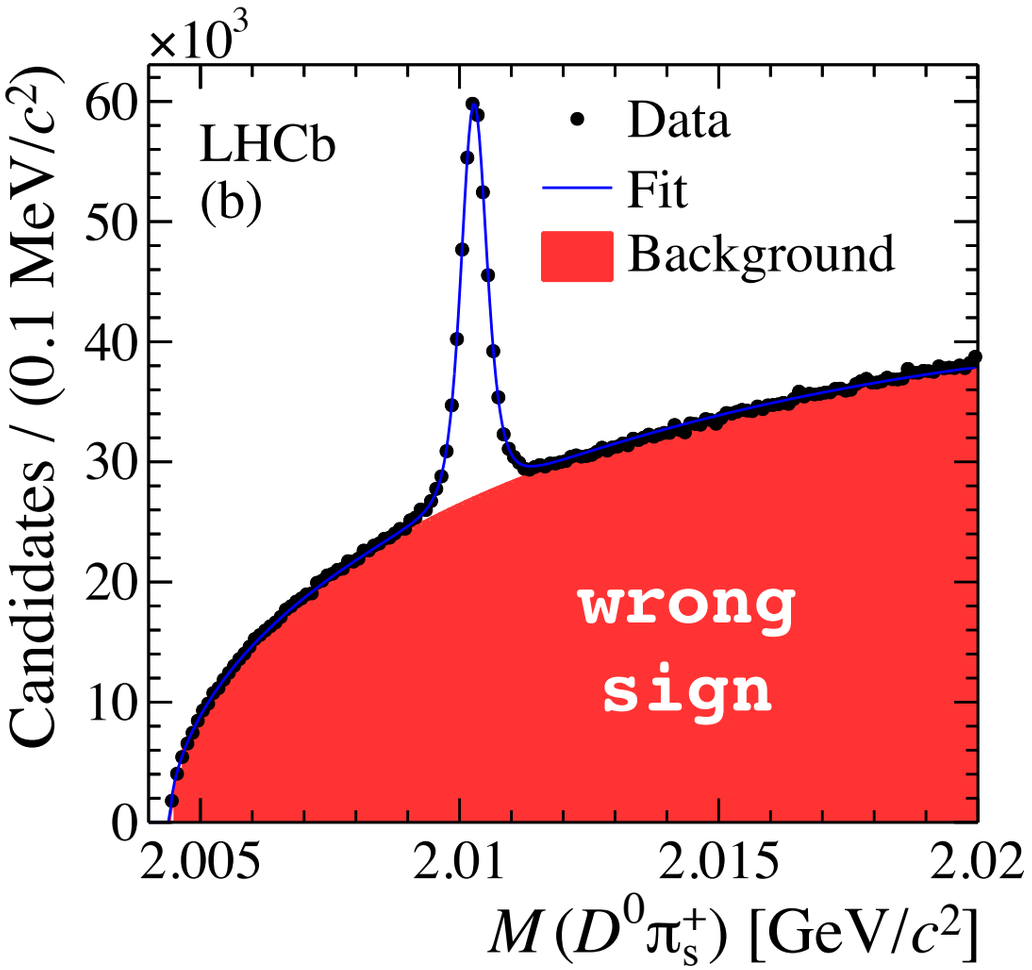
the time-dependent WS/RS ratio, assuming no **CP** violation

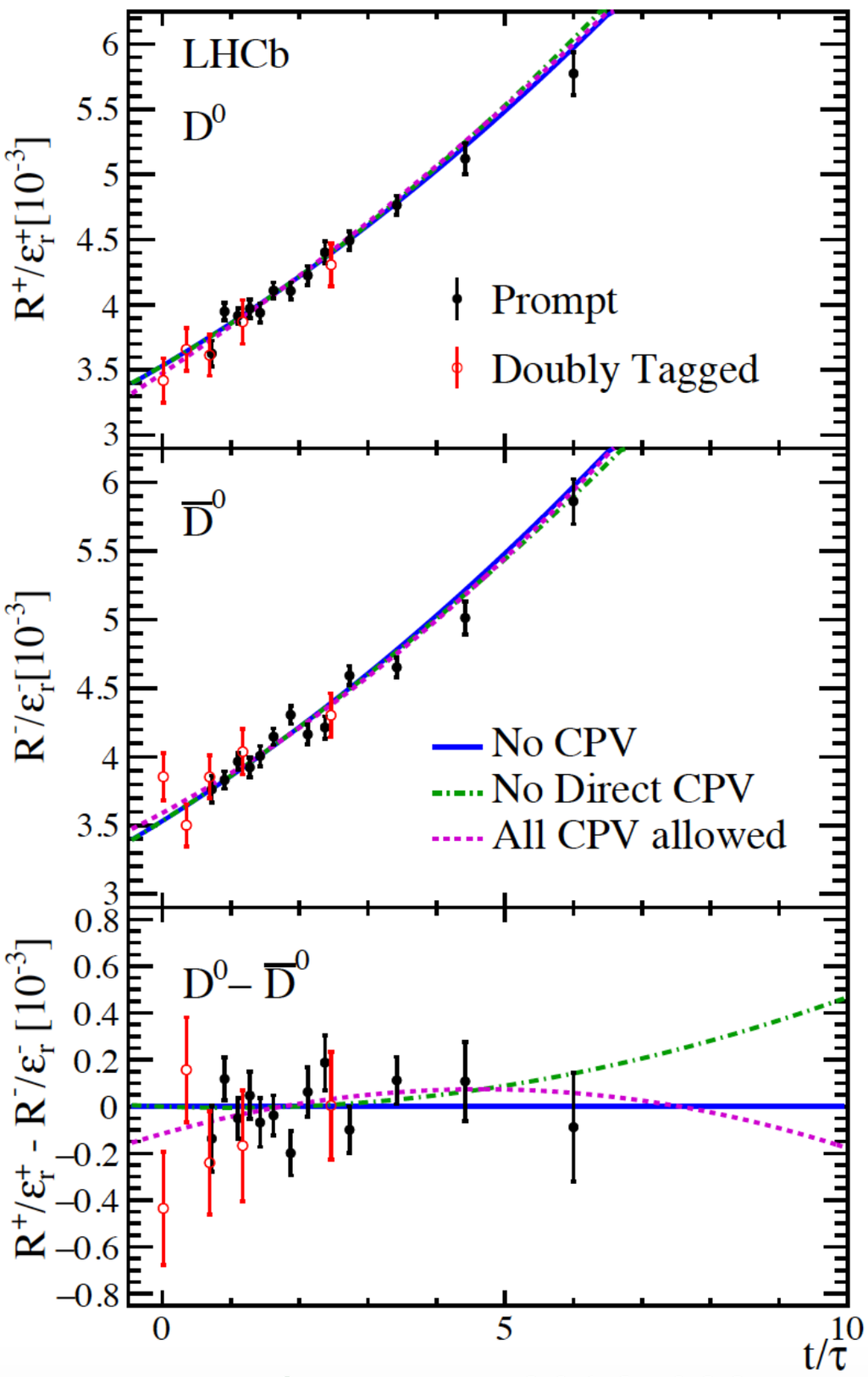
$$R(t) = \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-} \approx R_D + \sqrt{R_D}\, y'\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2$$

DCS interf. mixing

$D^{*+} \to D^0\pi^+,\ D^0 \to K\pi$

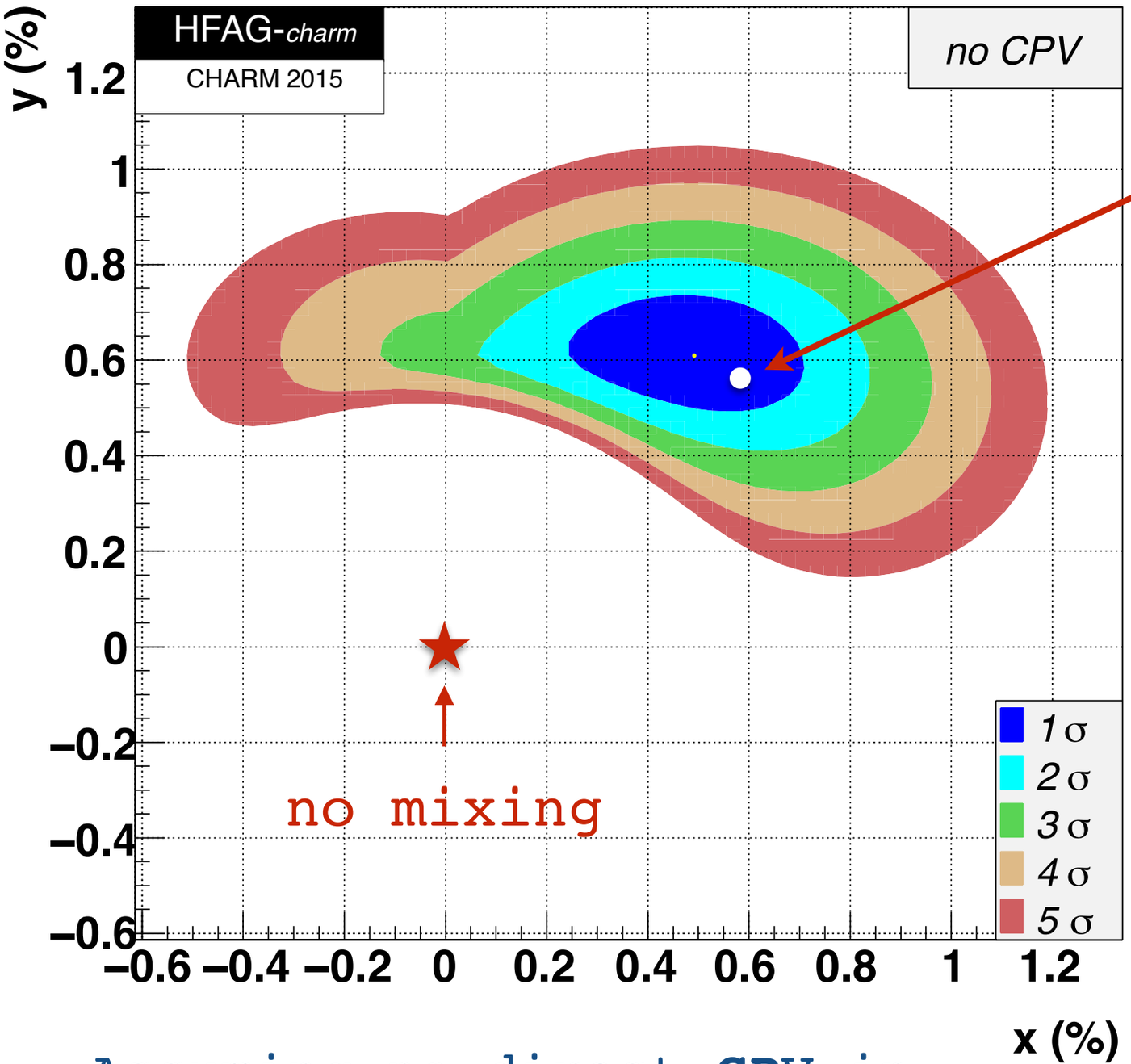






LHCb-PAPER-2016-033

LHCb: $x'^2[10^{-5}] = 3.6 \pm 4.3$, $y'^2[10^{-3}] = 5.23 \pm 0.84$ LHCb-PAPER-2016-033



Assuming no direct **CP**V in DCS decays - $R_D^+ = R_D^-$

$|q/p| = 1.002 \pm 0.014$ $\phi(^\circ) = -0.07 \pm 0.6$

World average:

$$x(\%) = 0.49^{+0.14}_{-0.15}$$

$$y(\%) = 0.61 \pm 0.08$$

Mixing in the charm sector is firmly established: $11\,\sigma$

A precise measurement of x is one of the main challenges for LHCb and Belle II.

Search for CP violation in charm

SM **CP** violation in charm is expected to be very small.

Direct **CP**V possible only in Cabibbo-suppressed decays:

$$D^0 \to K^+K^-,\ \pi^+\pi^-;\ \ D^+ \to K^-K^+\pi^+,\ \pi^-\pi^+\pi^+$$

The most stringent limits are from $D^0 \to K^+K^-,\ \pi^+\pi^-$

Main observable is the time-integrated **CP** asymmetry.

U-spin symmetry: $A_{\rm CP}(D^0 \to K^+K^-) = -A_{\rm CP}(D^0 \to \pi^+\pi^-)$

$$\Delta A_{\rm CP} \equiv A_{\rm CP}(D^0 \to K^+K^-) - A_{\rm CP}(D^0 \to \pi^+\pi^-)$$

- enhance small **CP** asymmetries
- cancellation of systematic effects

Independent samples: $pp \to D^{*+}X,\ D^{*+} \to D^0\pi_s^+$ and $B \to D^0\mu X$

For "prompt" sample: $A_{\rm raw}(f) \approx A_{\rm CP} + A_D(f) + \underbrace{A_D(\pi_s^+) + A_P(D^{*+})}_{\text{common factors}}$

The time-integrated CP asymmetry has a small indirect component

mode specific

average decay time

universal

$$A_{CP}(f) \approx a_{CP}^{dir}(f) + \frac{\langle t \rangle}{\tau_{D^0}} a_{CP}^{ind}$$

A_Γ

For decays to **CP**-eigenstates ($x, y \ll 1$):

$$\Gamma(D^0(t) \to f) \propto \exp[-\hat{\Gamma}_{D^0 \to f} t], \quad \Gamma(\overline{D}^0(t) \to f) \propto \exp[-\hat{\Gamma}_{\bar{D}^0 \to f} t]$$

$$\hat{\Gamma}_{D^0} = \Gamma_D \left[1 + \eta_{CP}^f \left| \frac{q}{p} \right| (y \cos\phi - x \sin\phi) \right], \quad \Gamma_{\overline{D}^0} = \Gamma_D \left[1 + \eta_{CP}^f \left| \frac{q}{p} \right| (y \cos\phi + x \sin\phi) \right]$$

Assuming $\left| \frac{\overline{A}_f}{A_f} \right| = 1$ and $\left| \frac{q}{p} \right| = 1$, $\lambda_f = \eta_C e^{i\phi}$

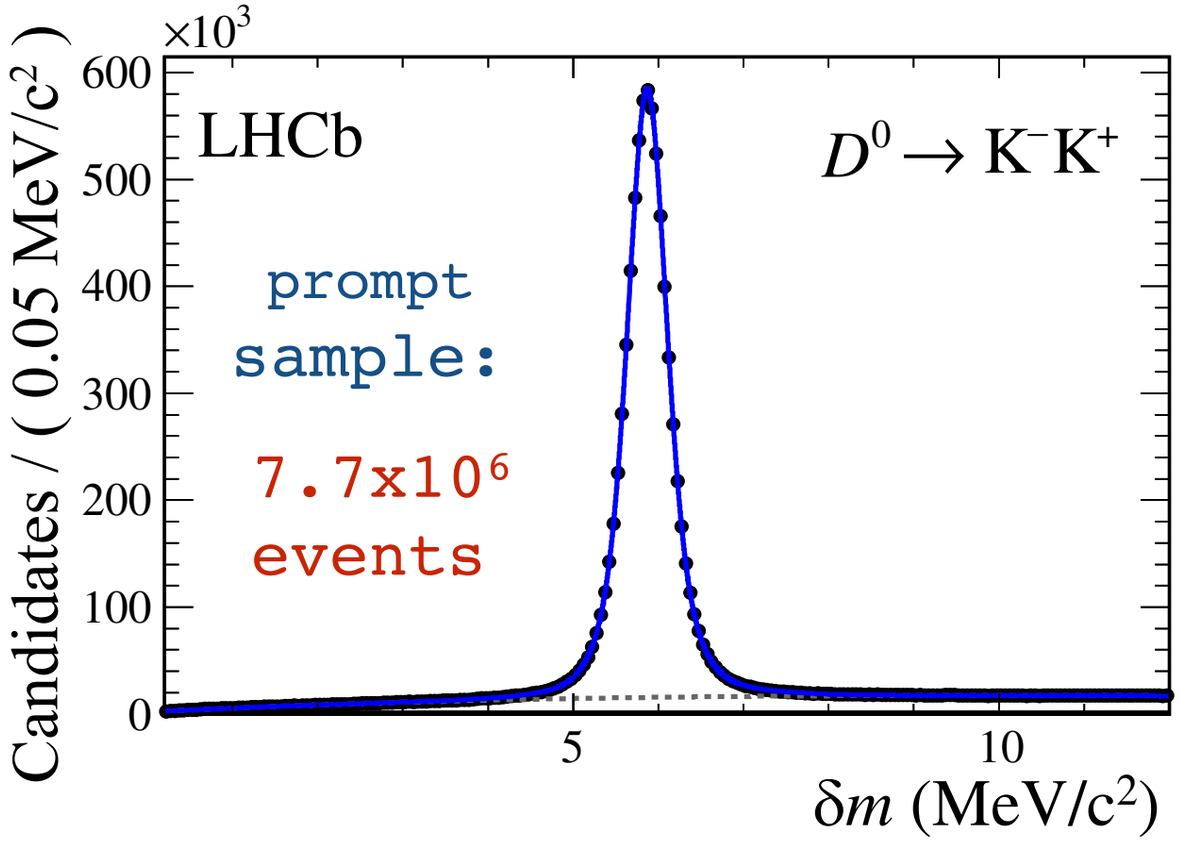
no **CP**V in decay

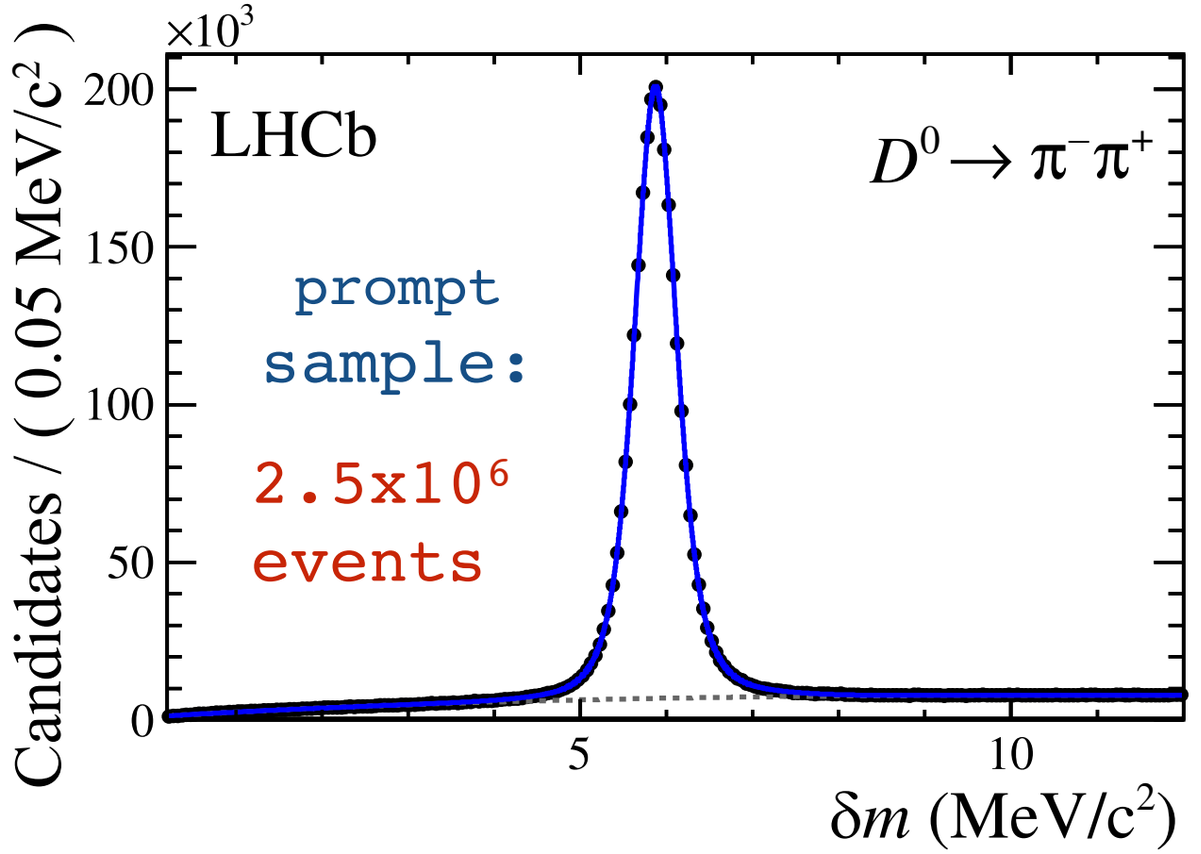
no **CP**V in mixing

relative phase between mixing and decay

$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0(t) \to f} - \hat{\Gamma}_{\bar{D}^0(t) \to f}}{\hat{\Gamma}_{D^0(t) \to f} + \hat{\Gamma}_{\bar{D}^0(t) \to f}} = a_{CP}^{int}$$

$$a_{CP}^{int} = \eta_{CP} \frac{x}{2} \sin\phi \left(\left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right)$$

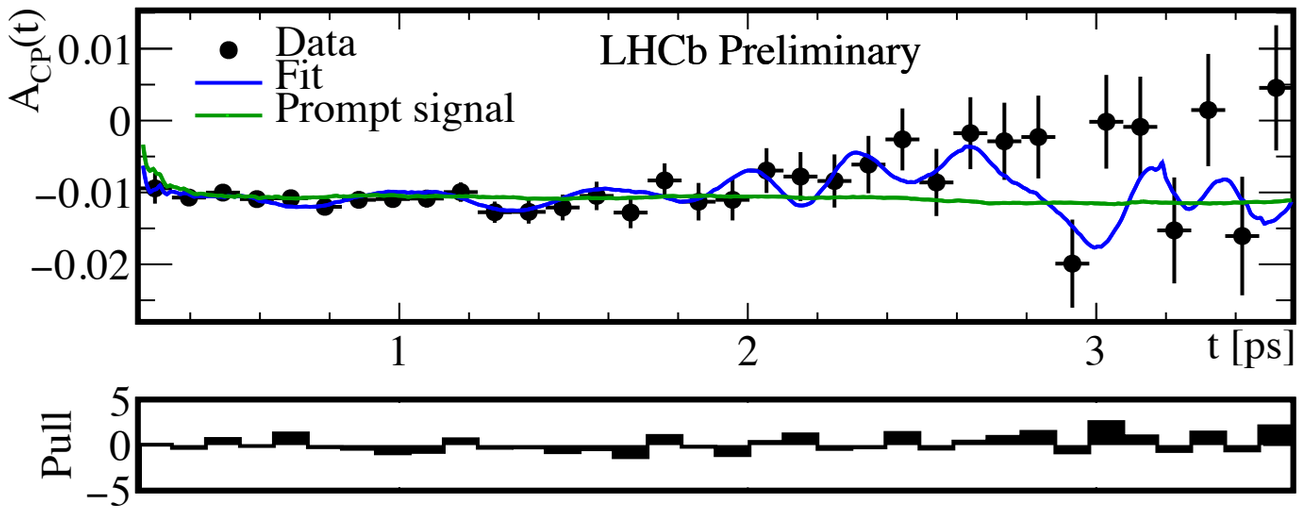




PRL 116, 191601 ; LHCb-CONF-2016-009/010

- Divide tagged sample in bins of decay time
- Compute $A_{\rm CP}$ in each bin
- Fit distribution to a straight line,

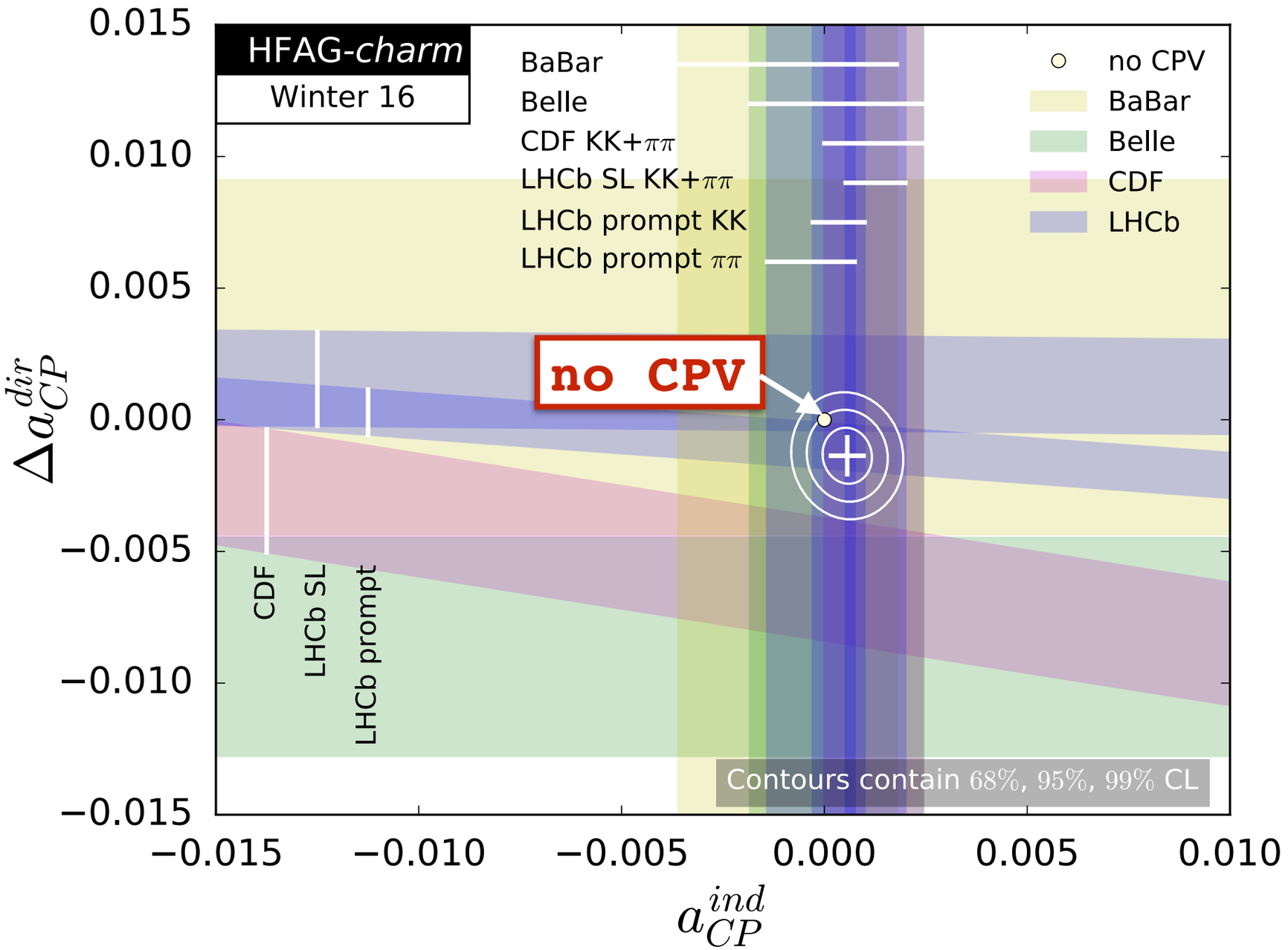
$$A_{\rm CP}(t) = a^{\rm dir}_{\rm CP} + A_\Gamma \frac{t}{\tau_{D^0}}$$



$$A_\Gamma = (-0.012 \pm 0.030)\%$$

$$\Delta A_{\rm CP} = [-0.10 \pm 0.08 \pm 0.03]\%$$

HFAG average (not including latest A_Γ from LHCb)



$$a_{\rm CP}^{\rm ind} = (0.056 \pm 0.040)\%$$

$$\Delta a_{\rm CP}^{\rm dir} = (-0.137 \pm 0.070)\%$$

$\sigma \sim \mathcal{O}(10)^{-4}$!

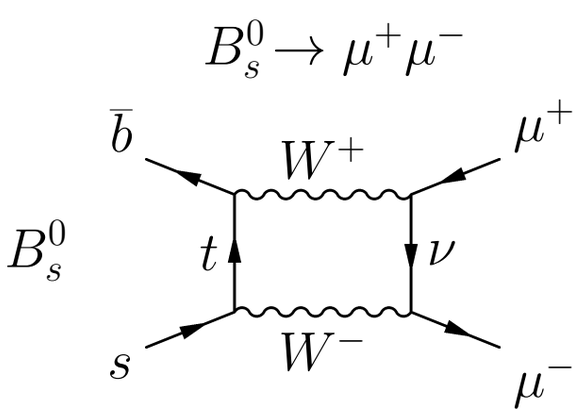
Still limited by statistics

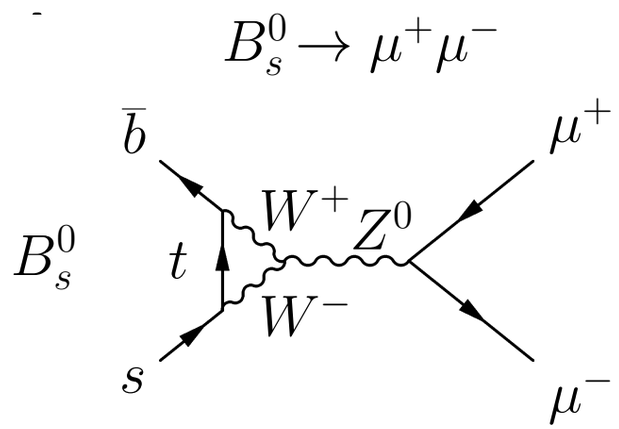
Rare decays

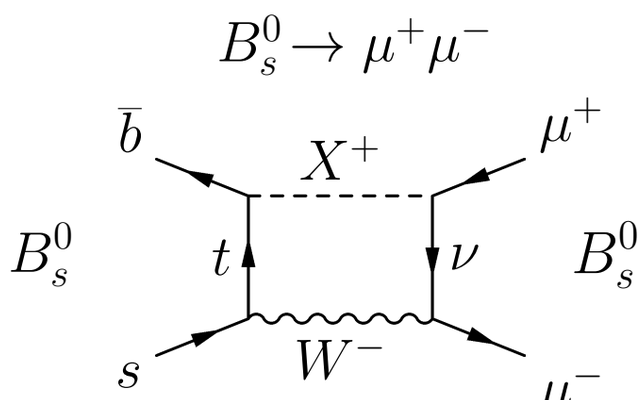
$B^0_{(s)} \to \mu^+\mu^-$

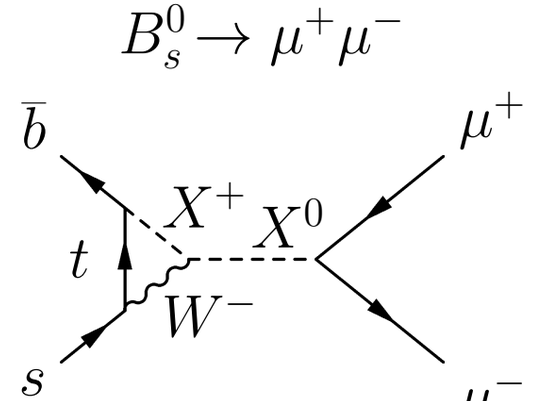
In the SM, FCNC can only occur via diagrams with quantum loops

New particles contributing to the loops could increase the branching ratios









SM branching ratio is predicted with good accuracy:

$$\mathcal{A}(B^0_{(s)} \to \mu^+\mu^-) = \langle \mu^+\mu^- | \mathcal{H}_{\rm eff} | B^0_{(s)} \rangle, \quad \mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V^*_{tq} \sum_i \mathcal{C}_i O_i + \text{h.c.}$$

$$\langle \ell\ell | j_\ell \cdot j_{d,s} | B^0_{d,s} \rangle = \langle \ell\ell | j_\ell | 0 \rangle \cdot \langle 0 | j_{d,s} | B^0_{d,s} \rangle \; \langle \ell\ell | j_\ell | 0 \rangle \cdot f_{B_{d,s}}$$ ← from LQCD

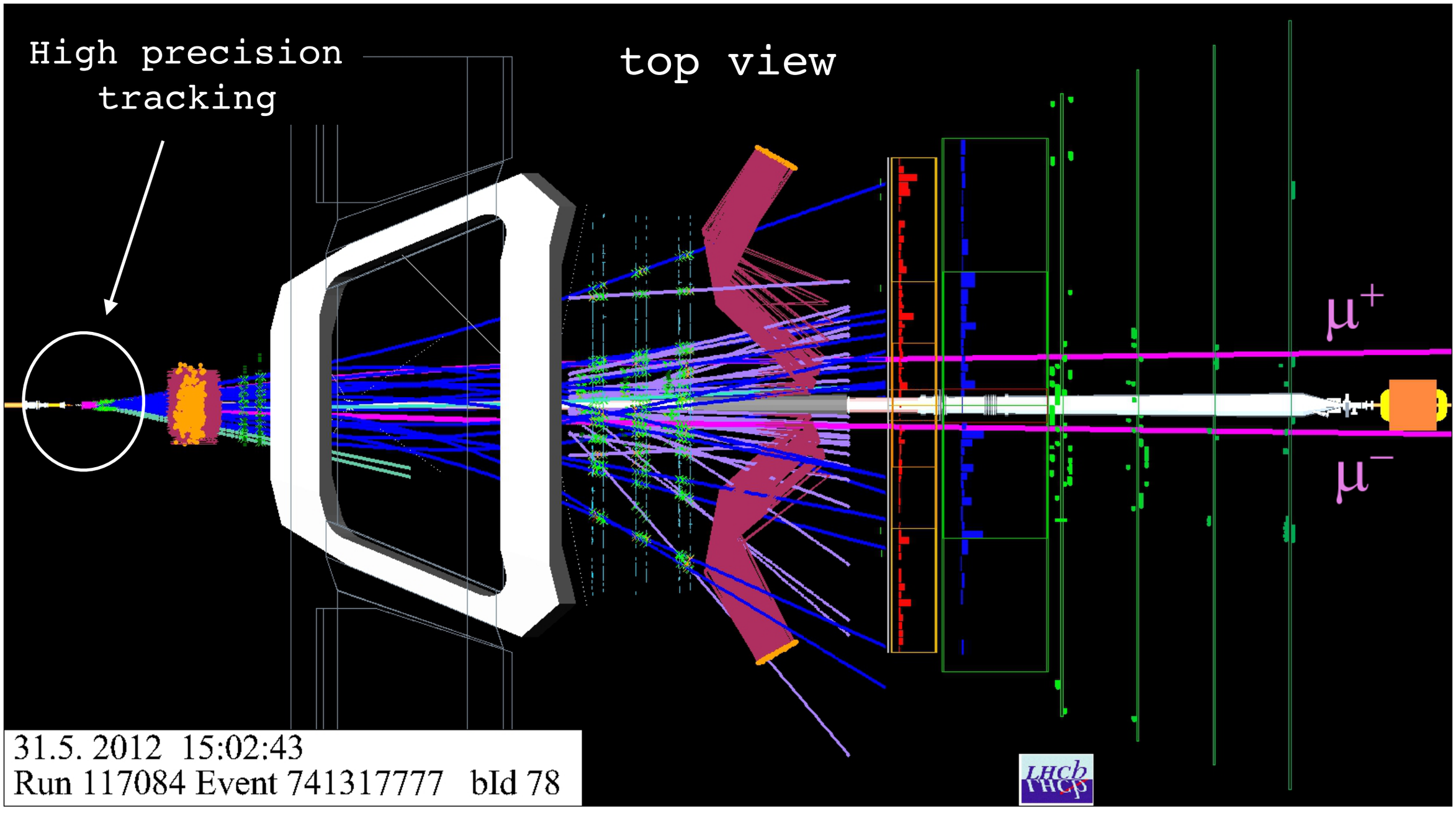
$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$, $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.12 \pm 0.12) \times 10^{-10}$

~4 decays per billion B^0_s ! 1 decay per 10 billions B^0 !

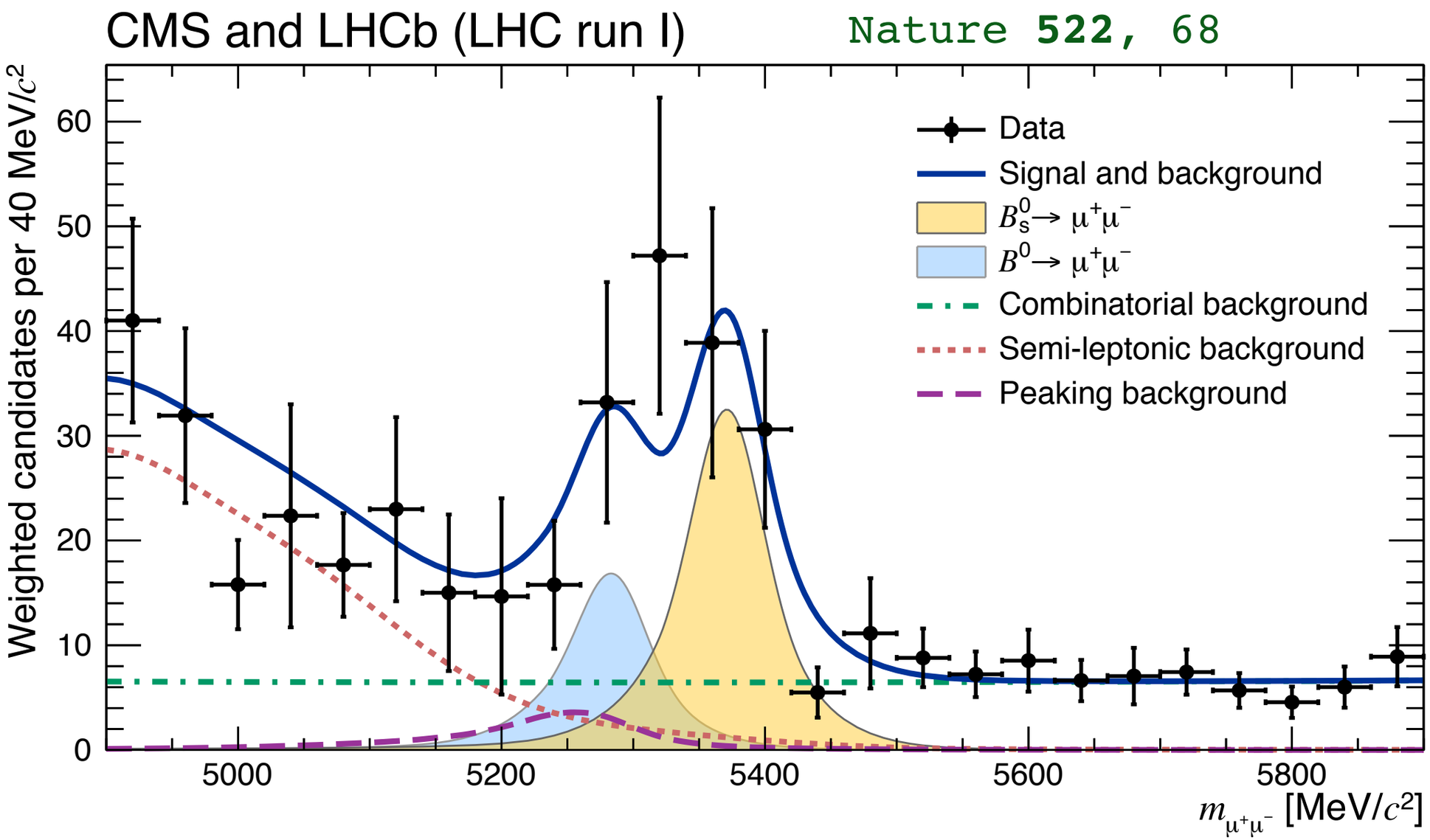
arXiv:1208.0934, PRL **109**,041801

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N^{B^0_{(s)}\to\mu^+\mu^-}_{\rm prod}}{N^{B}_{\rm prod}} = \frac{\mathcal{B}_{\rm norm}\varepsilon_{\rm norm} f_{\rm norm}}{N_{\rm norm}\varepsilon_{\rm sig} f_{d(s)}} \times N^{\rm obs}_{B^0_{(s)}\to\mu^+\mu^-}$$

normalization channel is $B^+ \to J/\psi\, K^+$, assuming $f_d = f_u$



Simultaneous fit to LHCb and CMS data

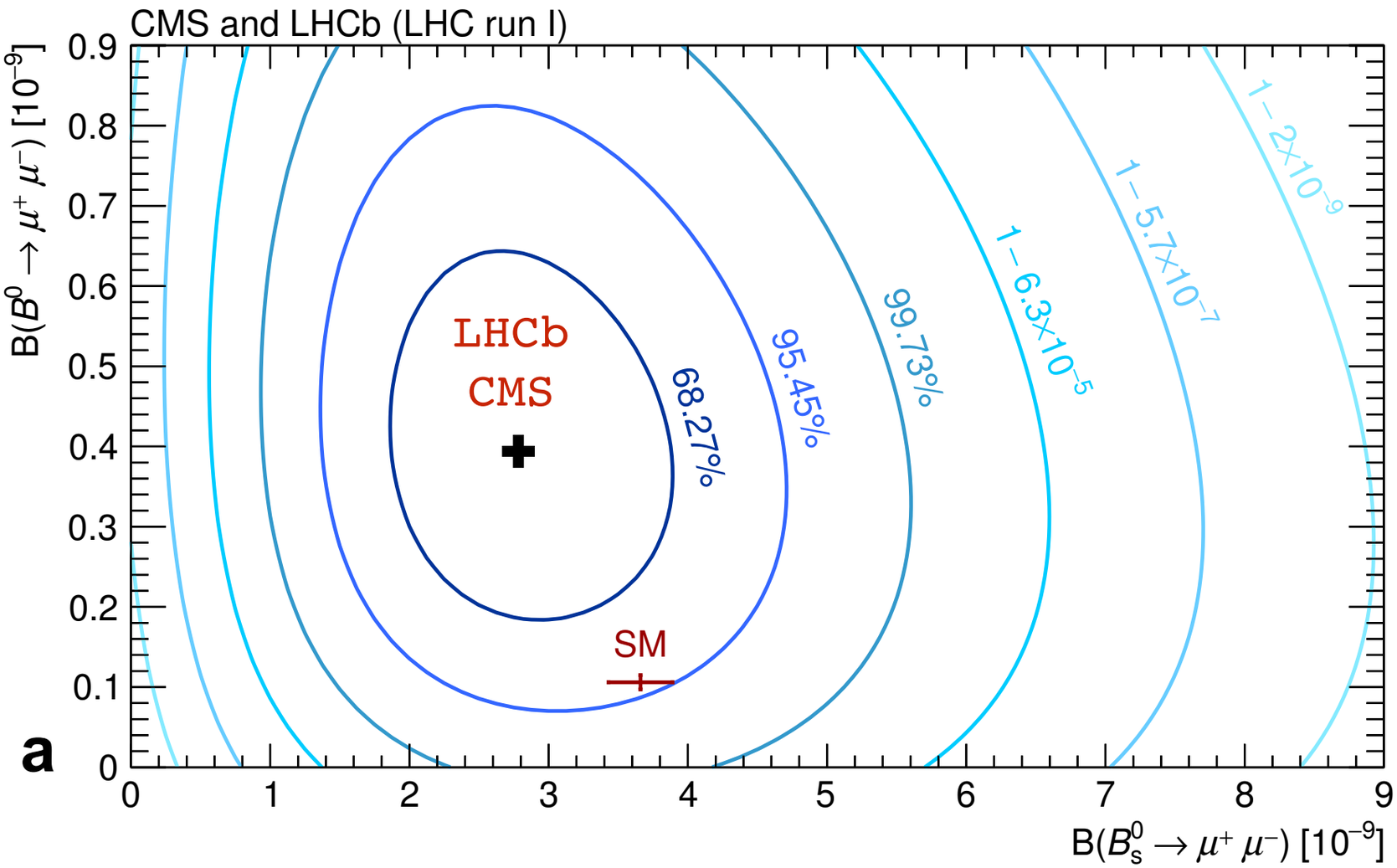


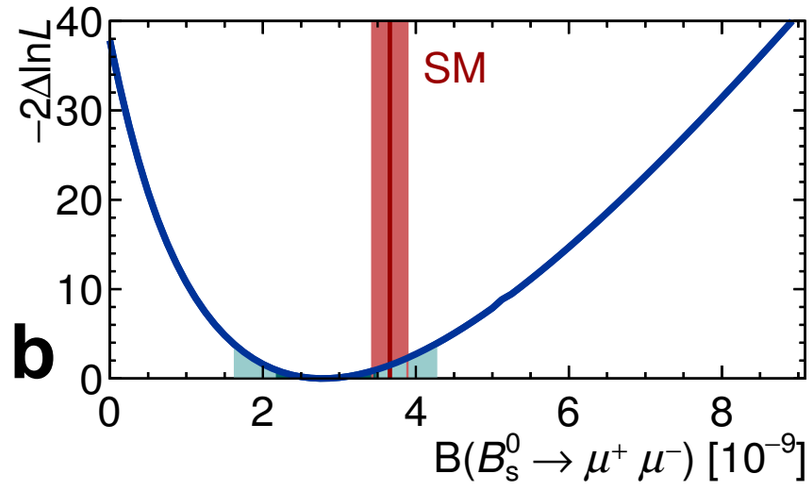
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

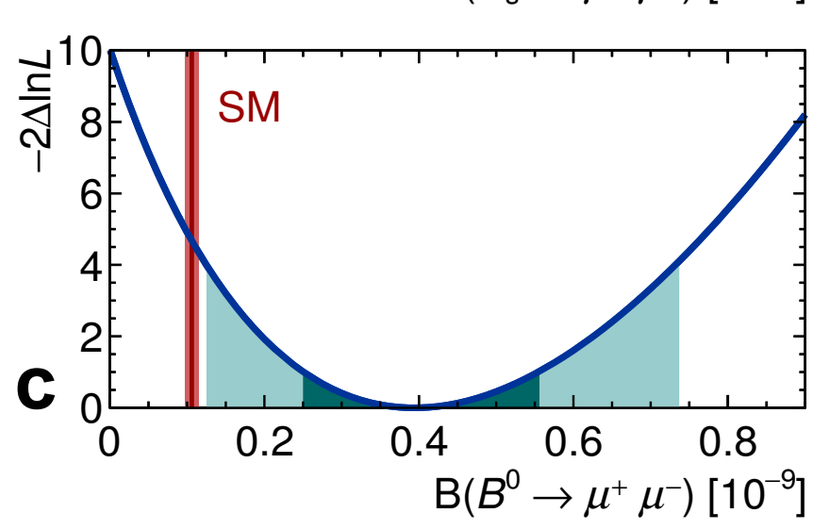
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.8}) \times 10^{-9}$$

Likelihood contours in the $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ vs. $\mathcal{B}(B^0 \to \mu^+\mu^-)$ plane

$-2\Delta \ln \mathcal{L}$ for $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$





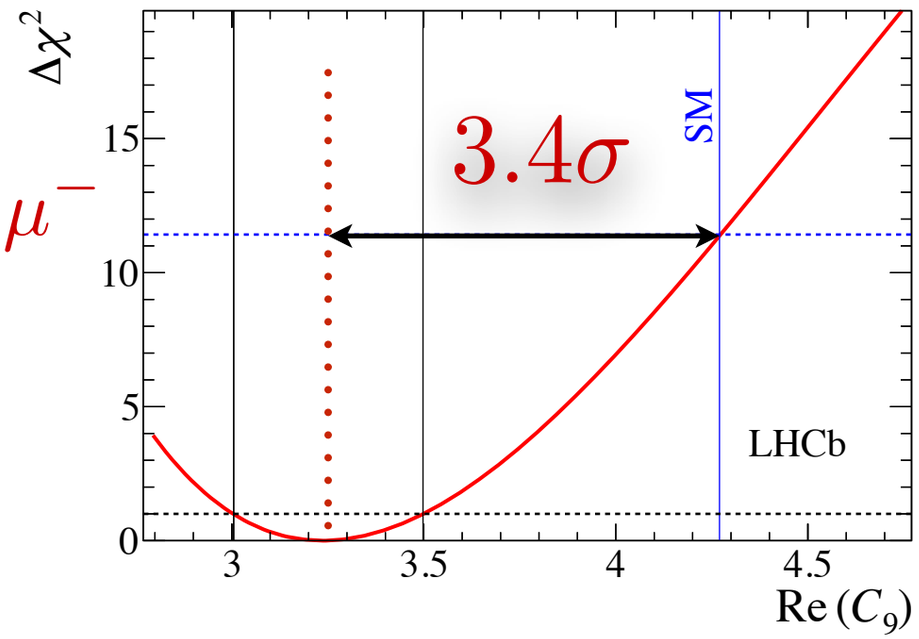


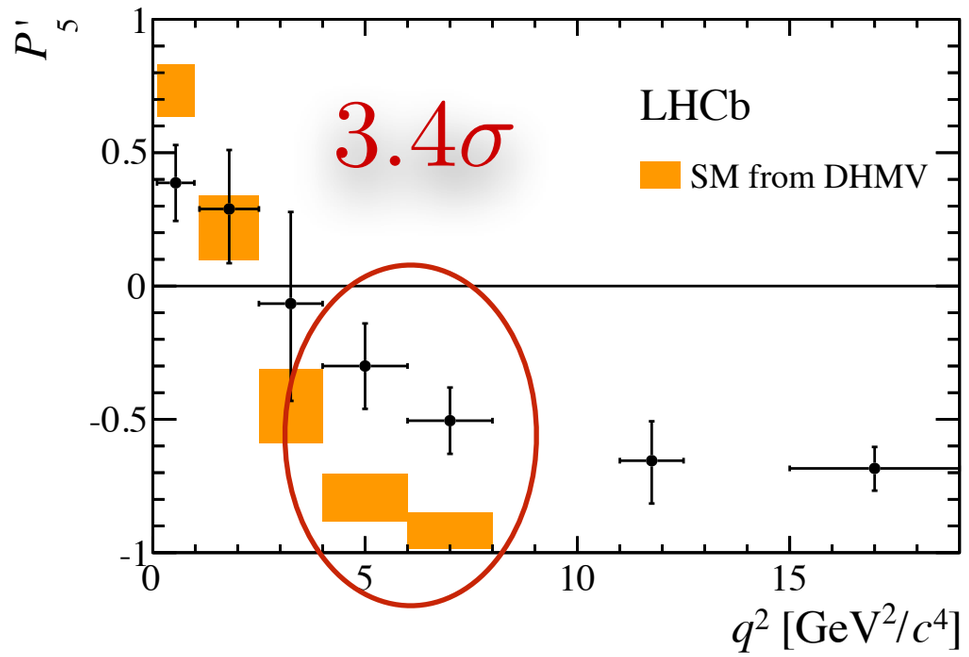
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ over 2σ tension with SM

$-2\Delta \ln \mathcal{L}$ for $\mathcal{B}(B^0 \to \mu^+\mu^-)$

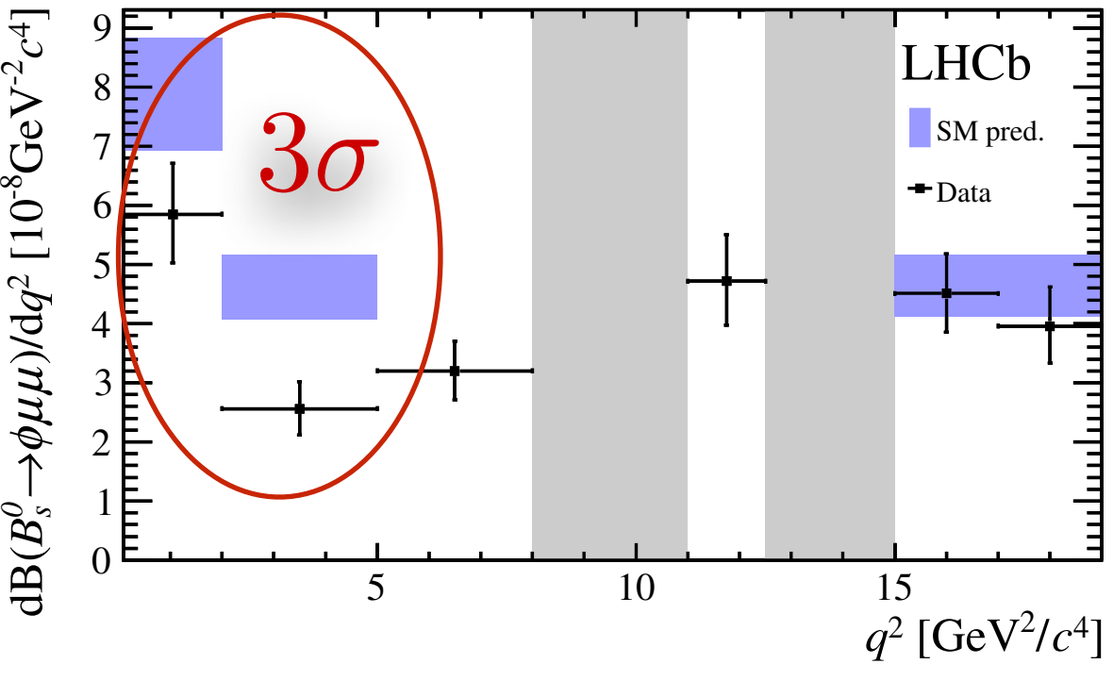
Other discrepancies with the SM predictions in $b \to s\ell^+\ell^-$ transitions

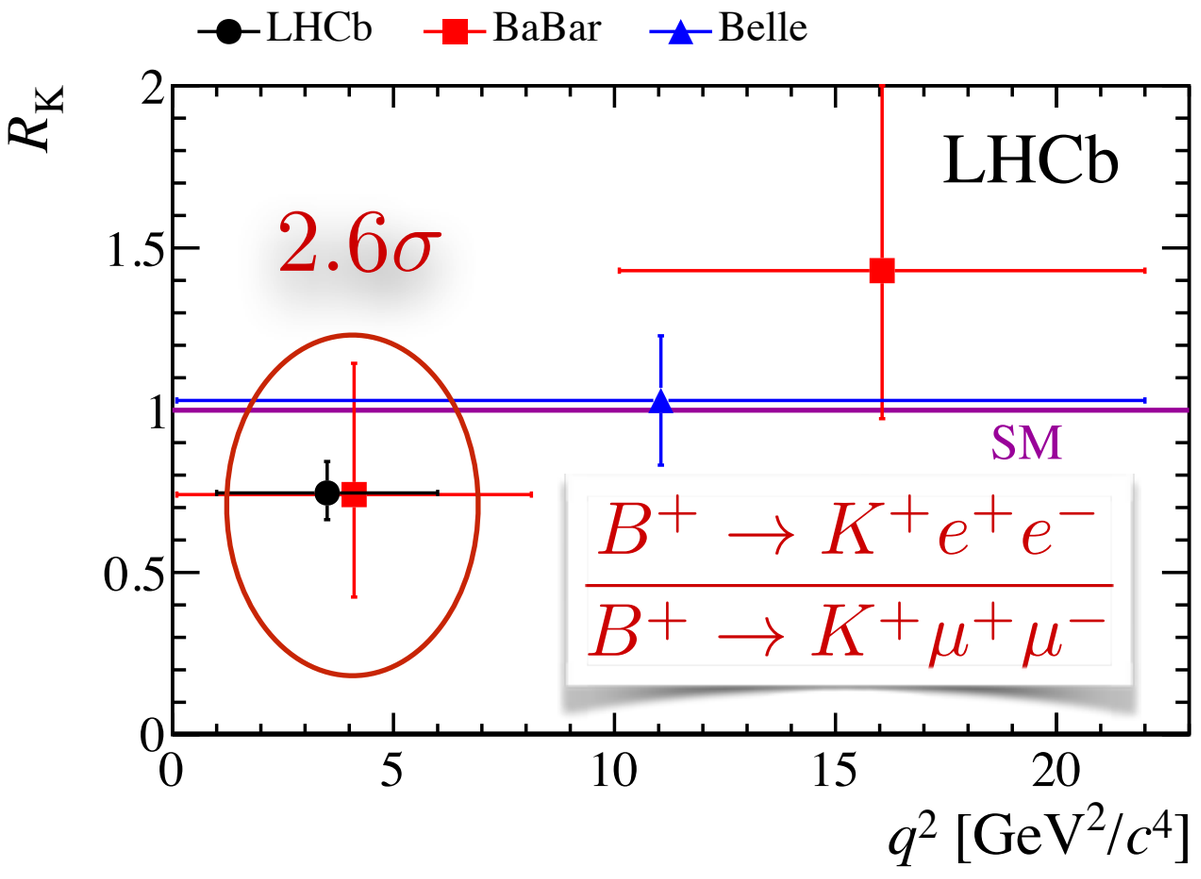
$B^0 \to K^{*0}\mu^+\mu^-$





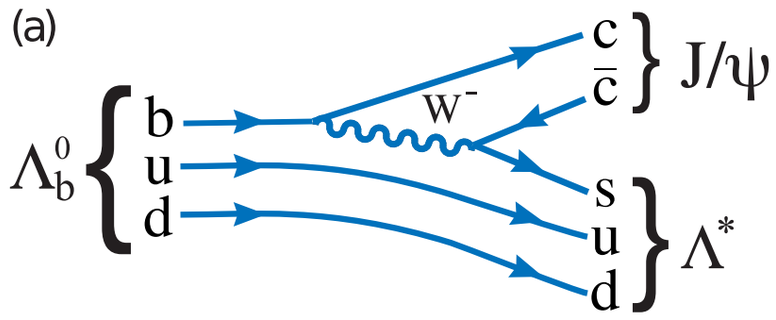
$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$

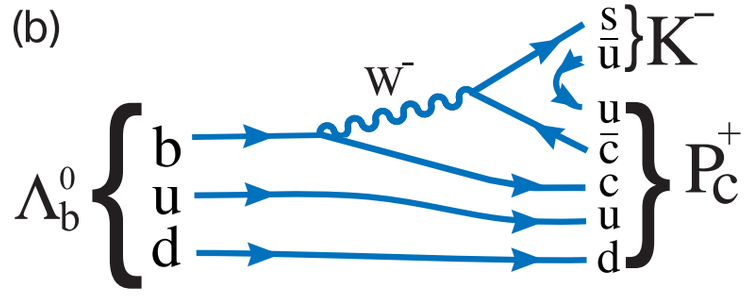




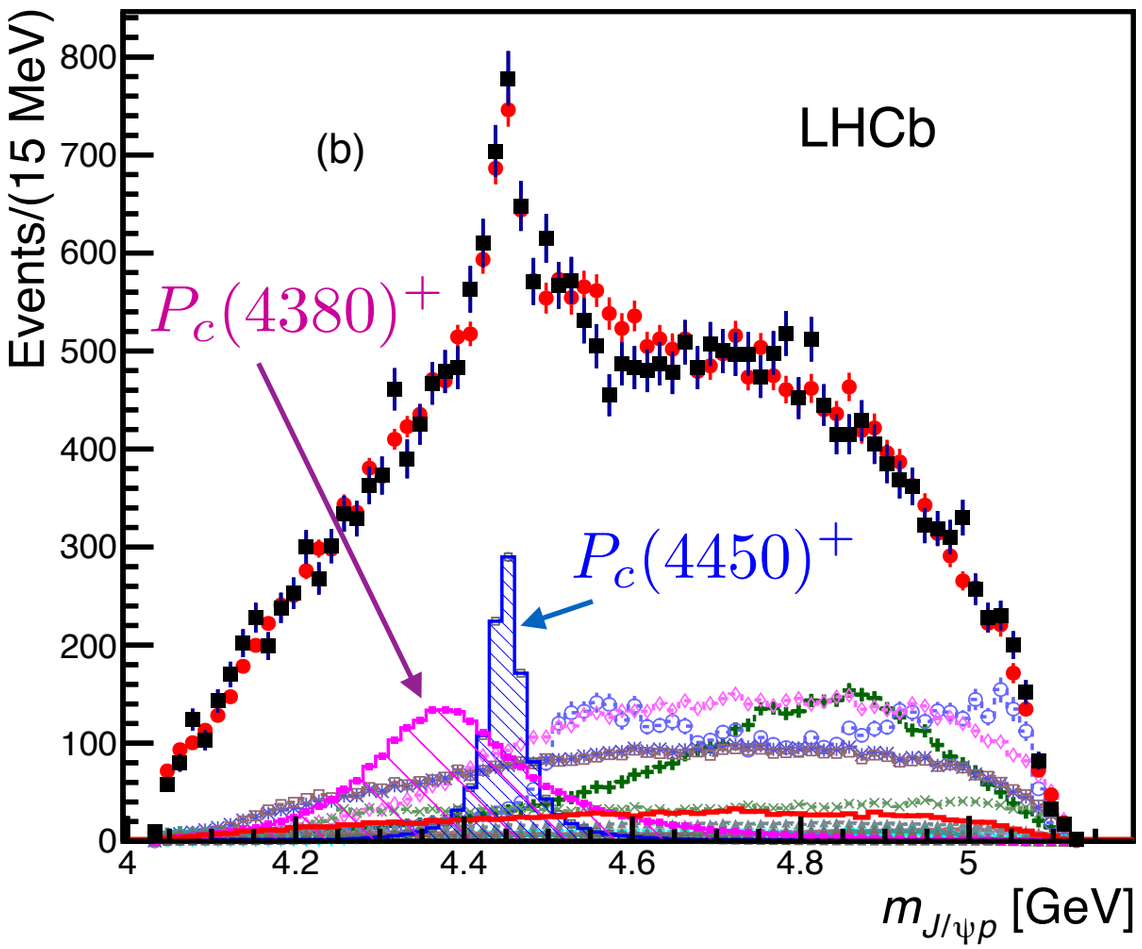
The pentaquark

"Exotic" structures observed in $J/\psi\, p$ channel from the $\Lambda_b^0 \to J/\psi\, K^- p$ and $\Lambda_b^0 \to J/\psi\, \pi^- p$ decays

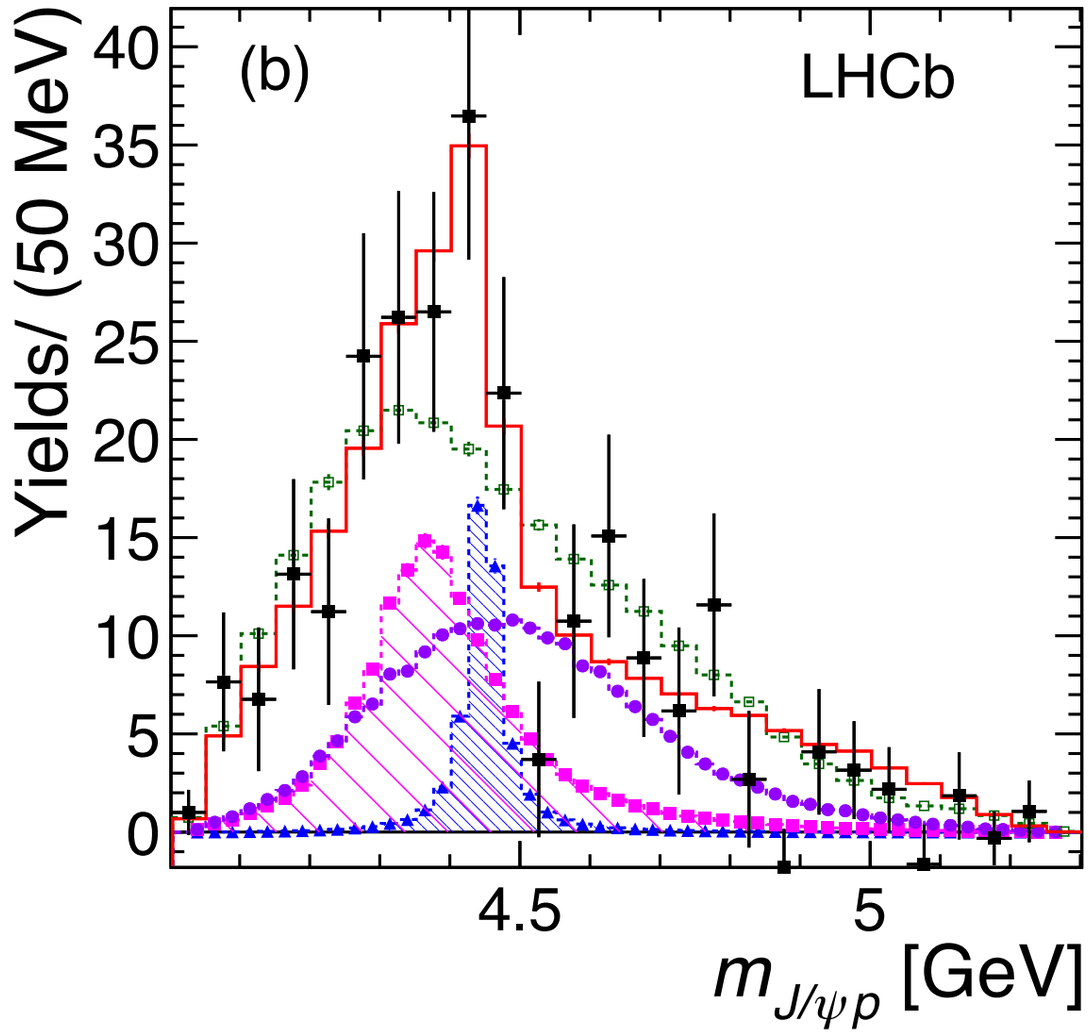




PRL **115,** 072001



PRL **117,** 082003



A six-dimensional, model-dependent fit: data cannot be explained by pK^- and $p\pi^-$ resonances alone

Two new $J/\psi\, p$ states (quark content = $uudc\bar{c}$) needed:

$$P_c(4380)^+, \quad P_c(4450)^+$$

$m = 4380 \pm 8 \pm 29$ MeV

$\Gamma = 205 \pm 18 \pm 86$ MeV

$m = 4450 \pm 2 \pm 3$ MeV

$\Gamma = 39 \pm 5 \pm 19$ MeV

Results from amplitude fit confirmed by model-independent statistical test:

significance $\approx 10\sigma$

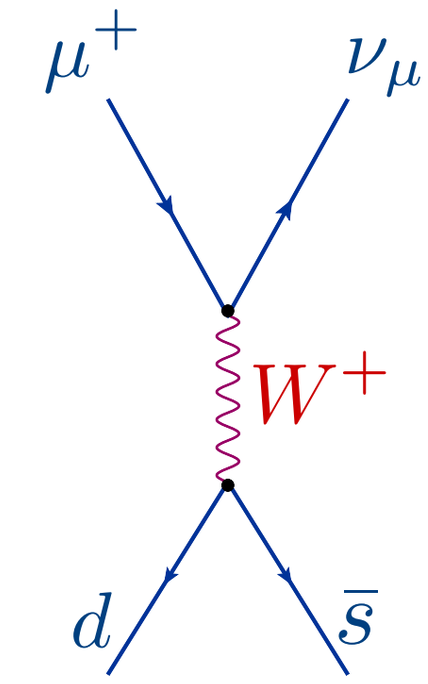
PRL **117,** 082002

Summary and prospects

Flavour Physics is at the heart of the SM

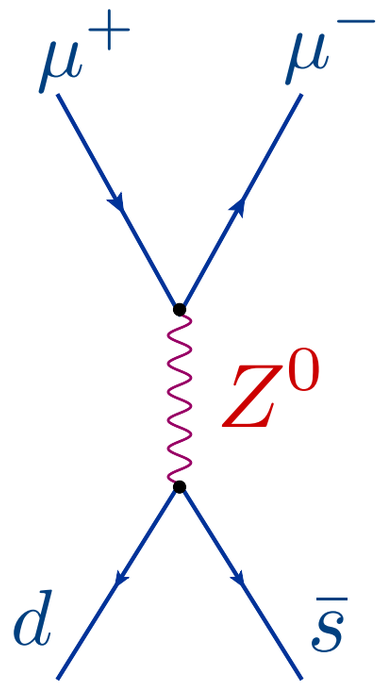
Sensitivity to New Physics through loop diagrams!

GIM mechanism



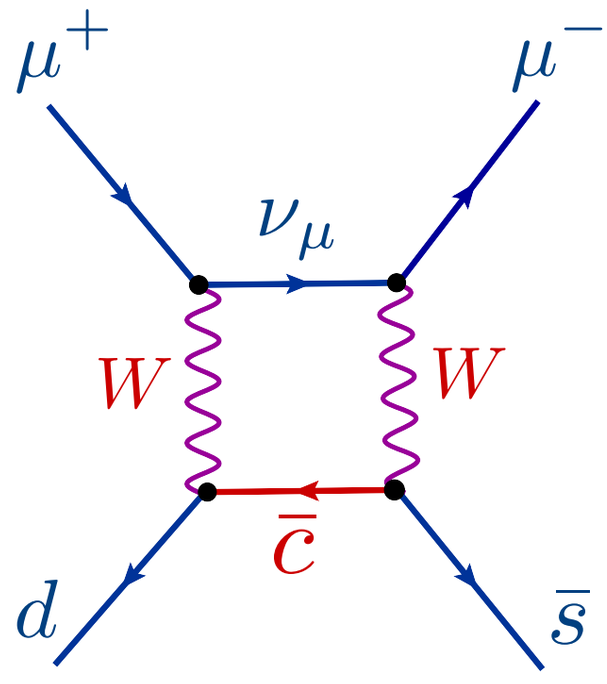
$K^+ \to \mu^+\nu_\mu$

YES



$K^0 \to \mu^+\mu^-$

NO



$K^0 \to \mu^+\mu^-$

YES

$$\frac{\mathcal{B}(K^0 \to \mu^+\mu^-)}{\mathcal{B}(K^+ \to \mu^+\nu_\mu)} \approx 10^{-8}$$

CP violation, mixing and rare decays:
probing the TeV scales with virtual processes

The near future timeline

- LHC Run II: 2015-2018 ⟶ 5 fb^{-1} (~5 times Run I)
- BESIII : 2018-? (> 5 fb^{-1})
- Belle II: 2019-2024 ⟶ 50 ab^{-1} (40 times Belle I)
- LHC Run III and IV: 2021-2023, 2026-2029 ⟶ 300 fb^{-1}

In the next decade the SM will be probed with an amazing precision

Intriguing anomalies will be clarified:

- Statistical fluctuations?
- Unaccounted systematics?
- New Physics?

Flavour physics: field plenty of opportunities for young scientists!!

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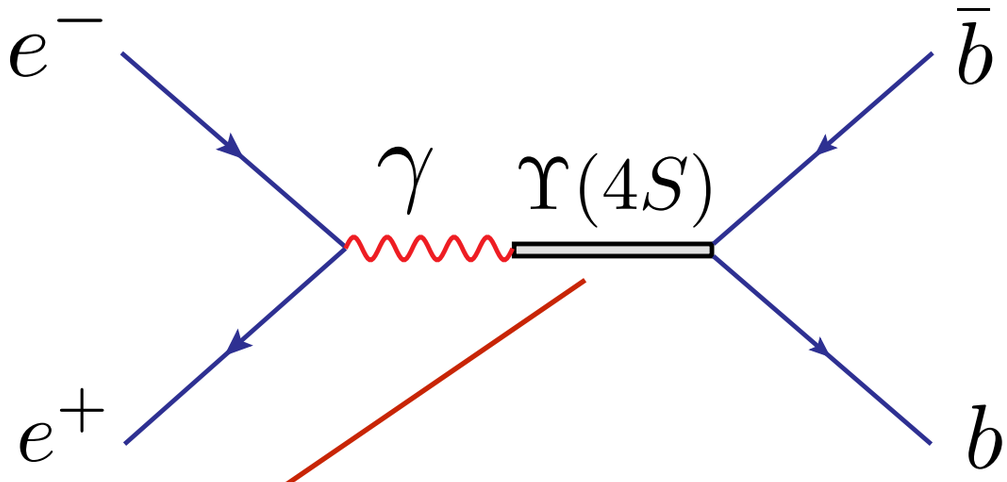
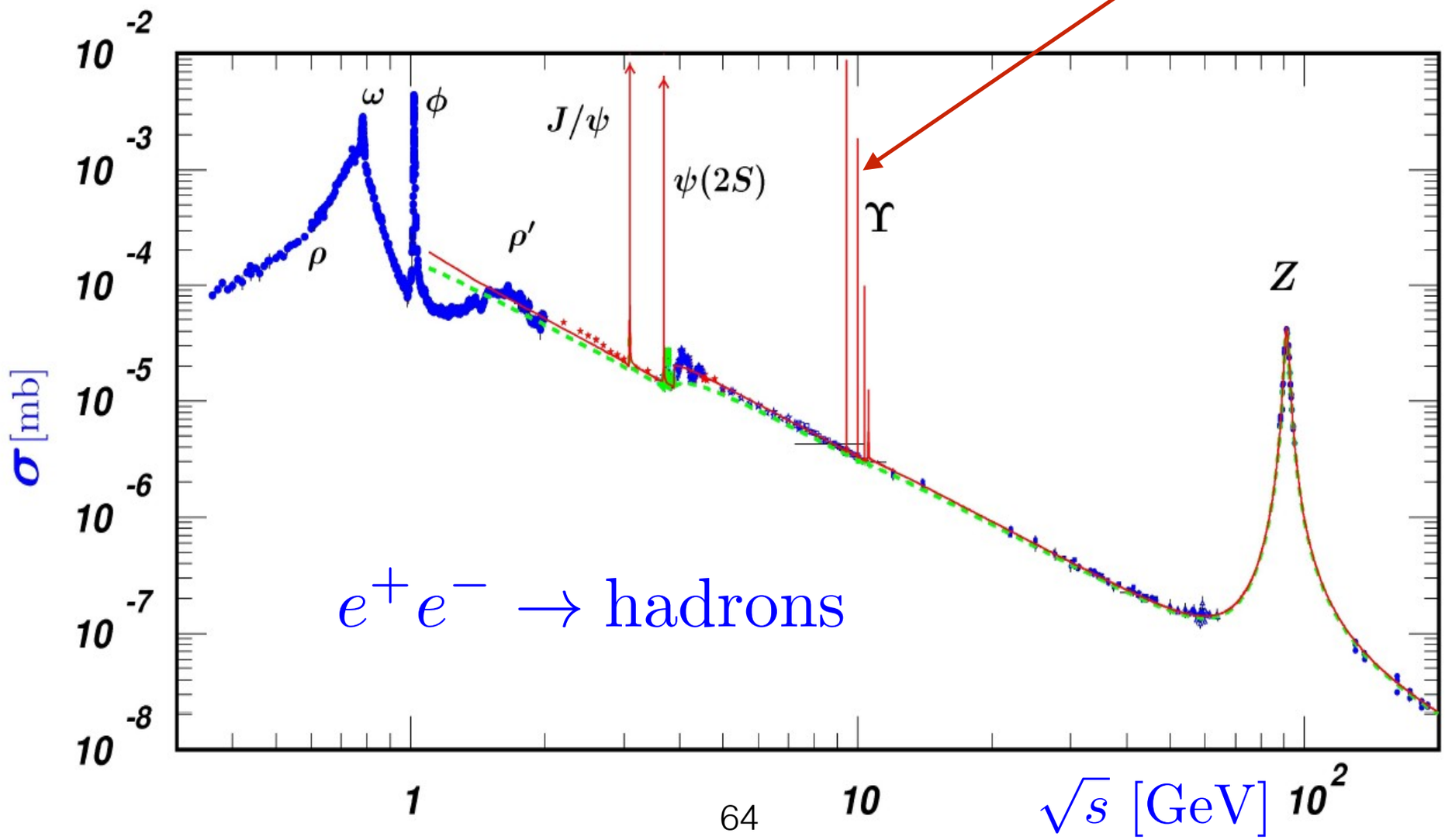
Backup

The B factories

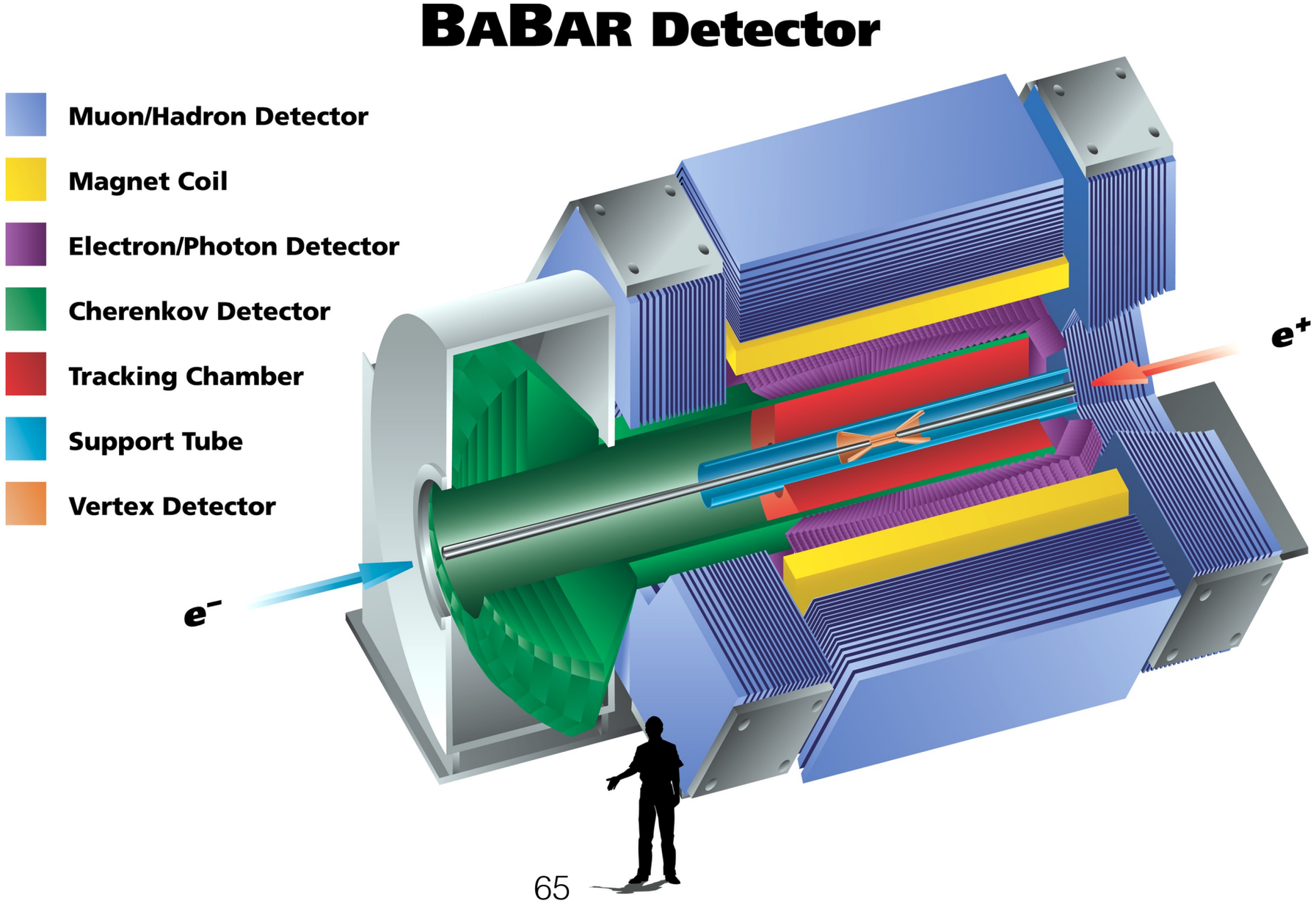
BaBar and Belle: very successful experiments, but ended in 2010 (Belle).

Belle II under construction, start data taking in 2018.



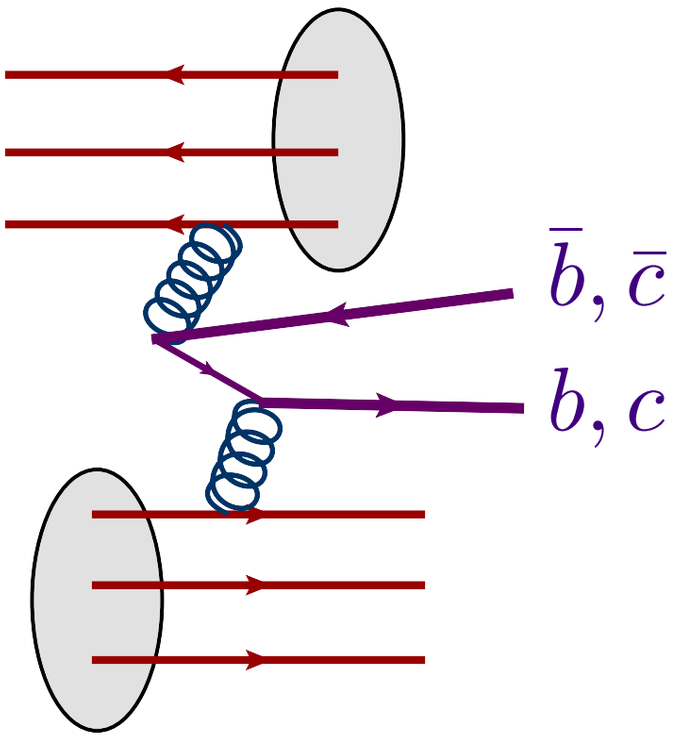


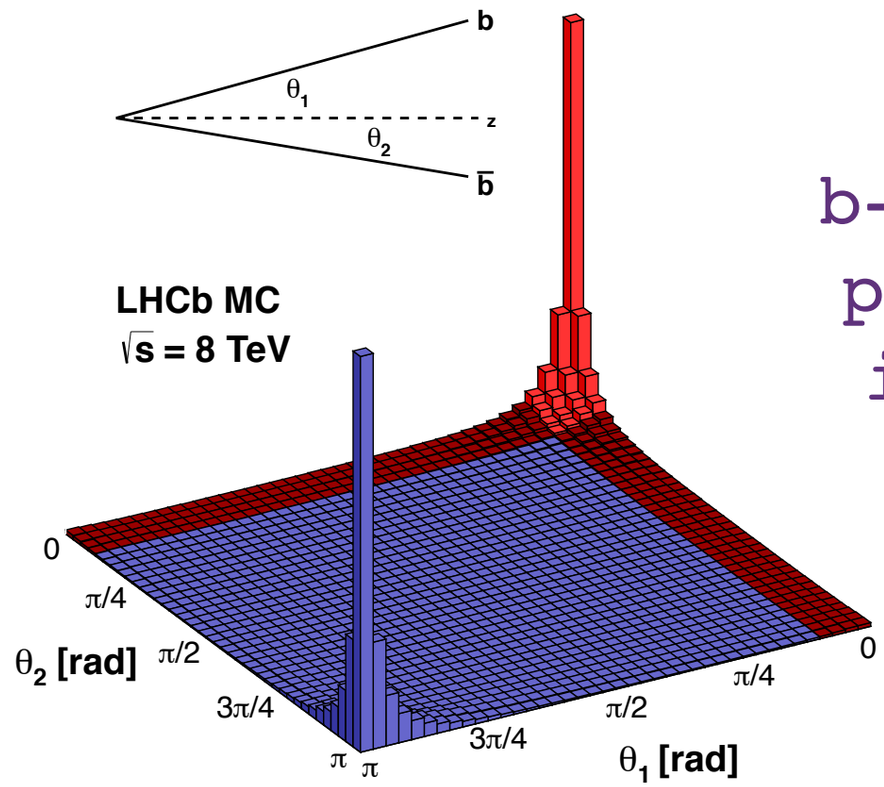
- Asymmetric beam energies;
- 4π coverage;
- excellent efficiency for neutrals;
- low background;
- coherent production of B pairs: efficient tagging.



Hadron collider - LHCb

- pp collisions: $b\bar{b}$, $c\bar{c}$ pairs via gluon-gluon fusion.



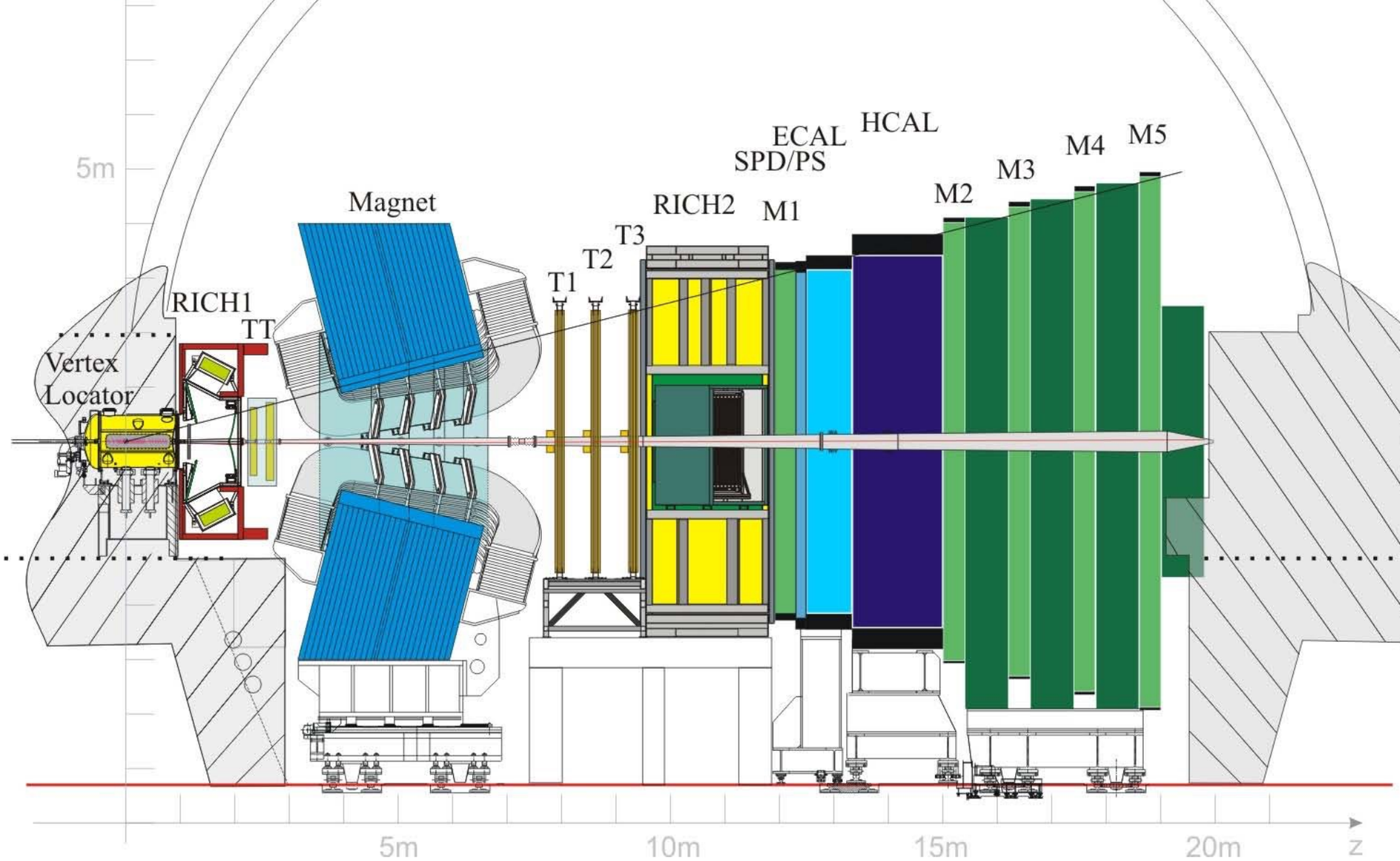
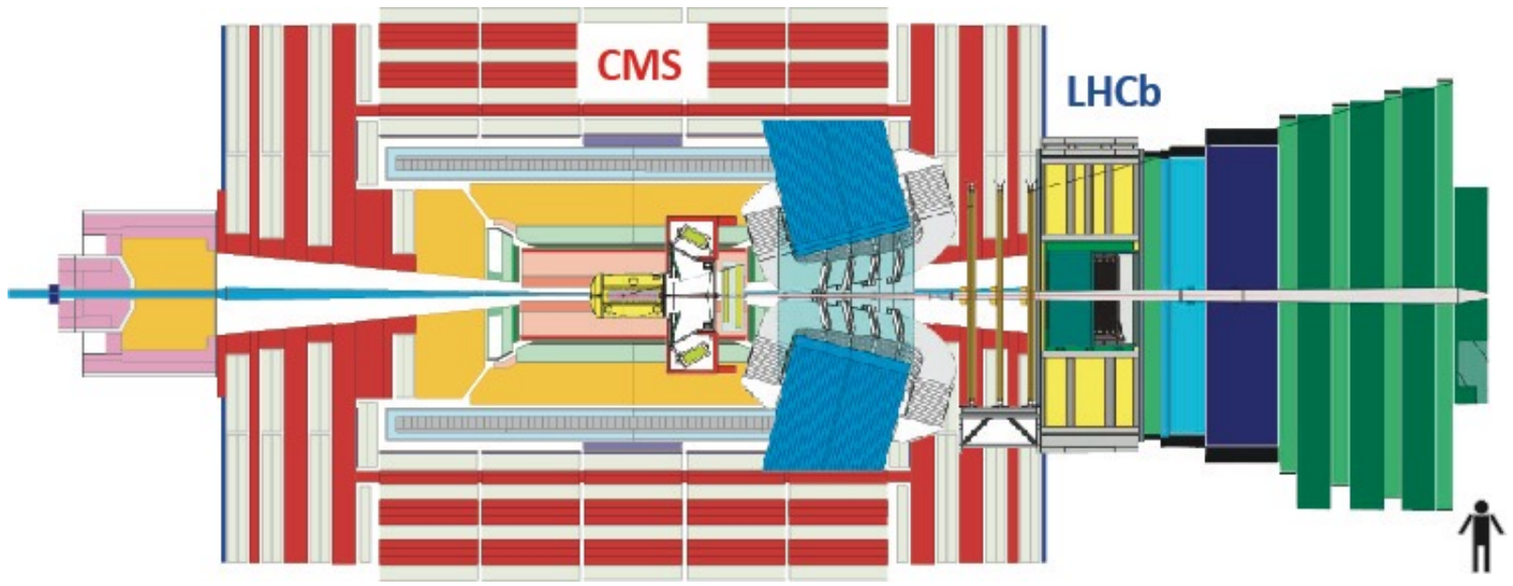


b- and c—hadrons produced mostly in the forward direction.

Compared to the B factories:

- much higher rates due to very large cross-sections;
- larger backgrounds;
- incoherent production: less efficient tagging;
- not so efficient for neutrals.

The LHCb detector



LHCb geometry is complementary to ATLAS and CMS