CP violation and mixing in charm and beauty hadrons

Malcolm John

for the LHCb Collaboration

LS LOWRY, Peel Park, Salford (1944)

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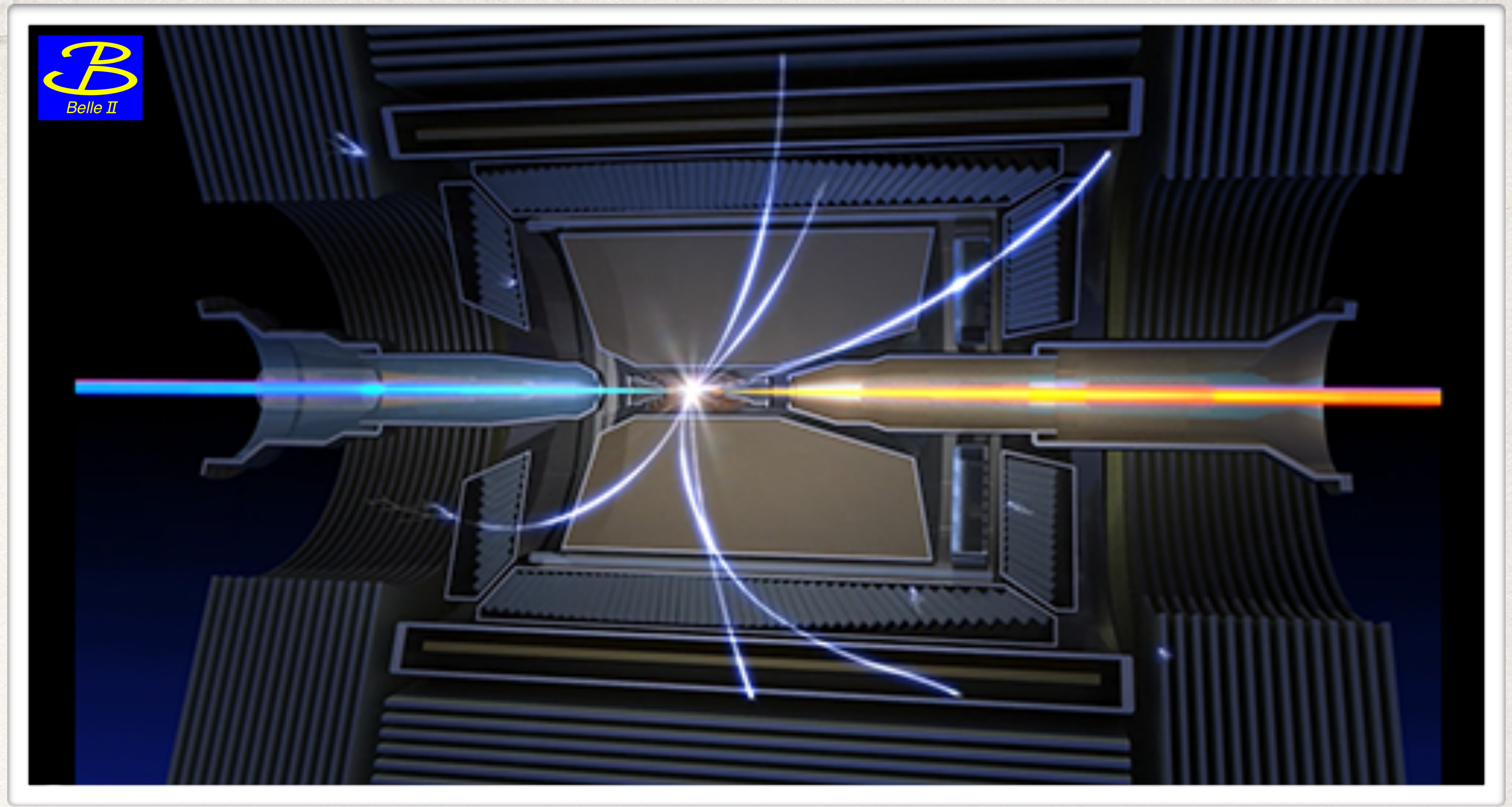
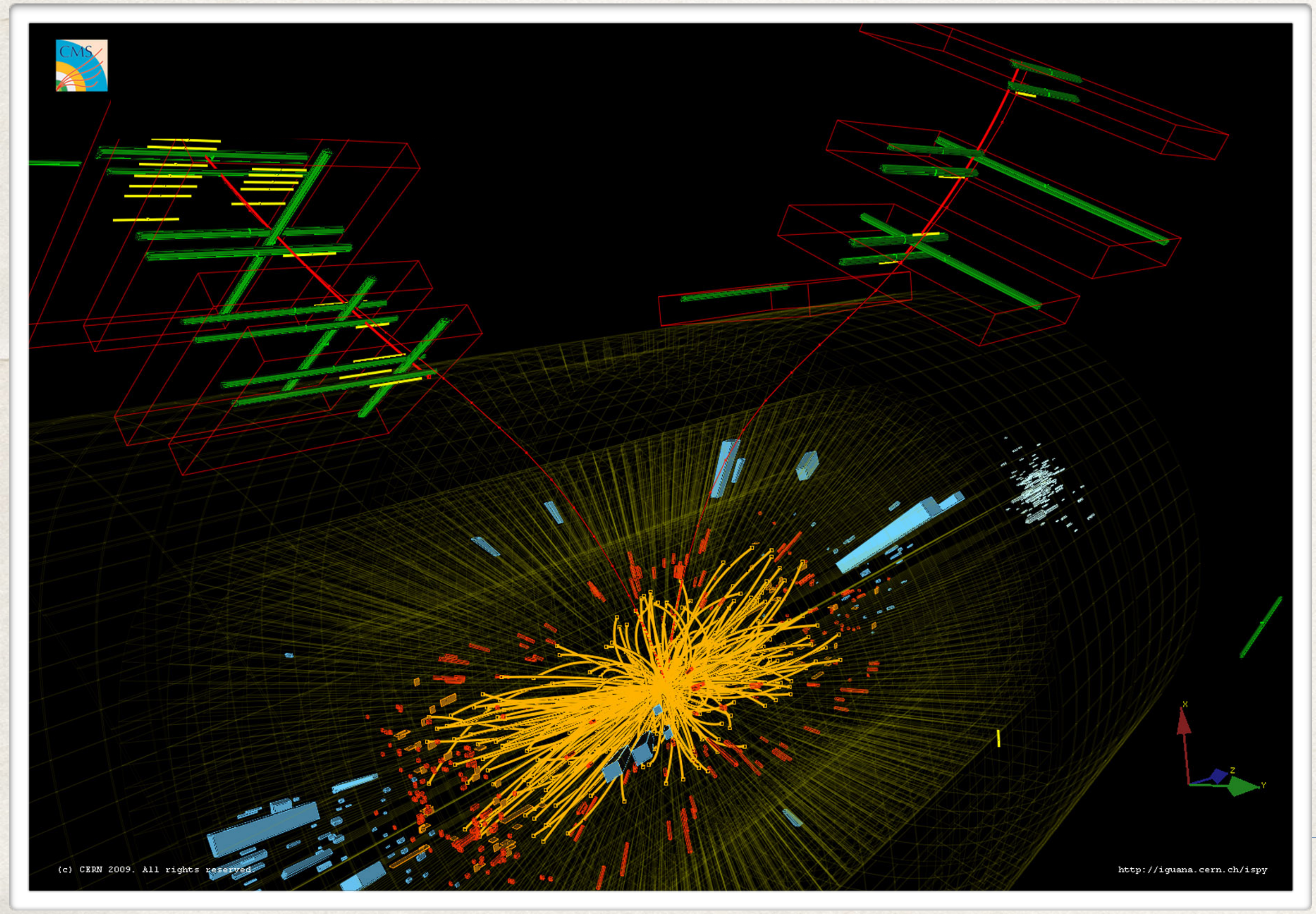
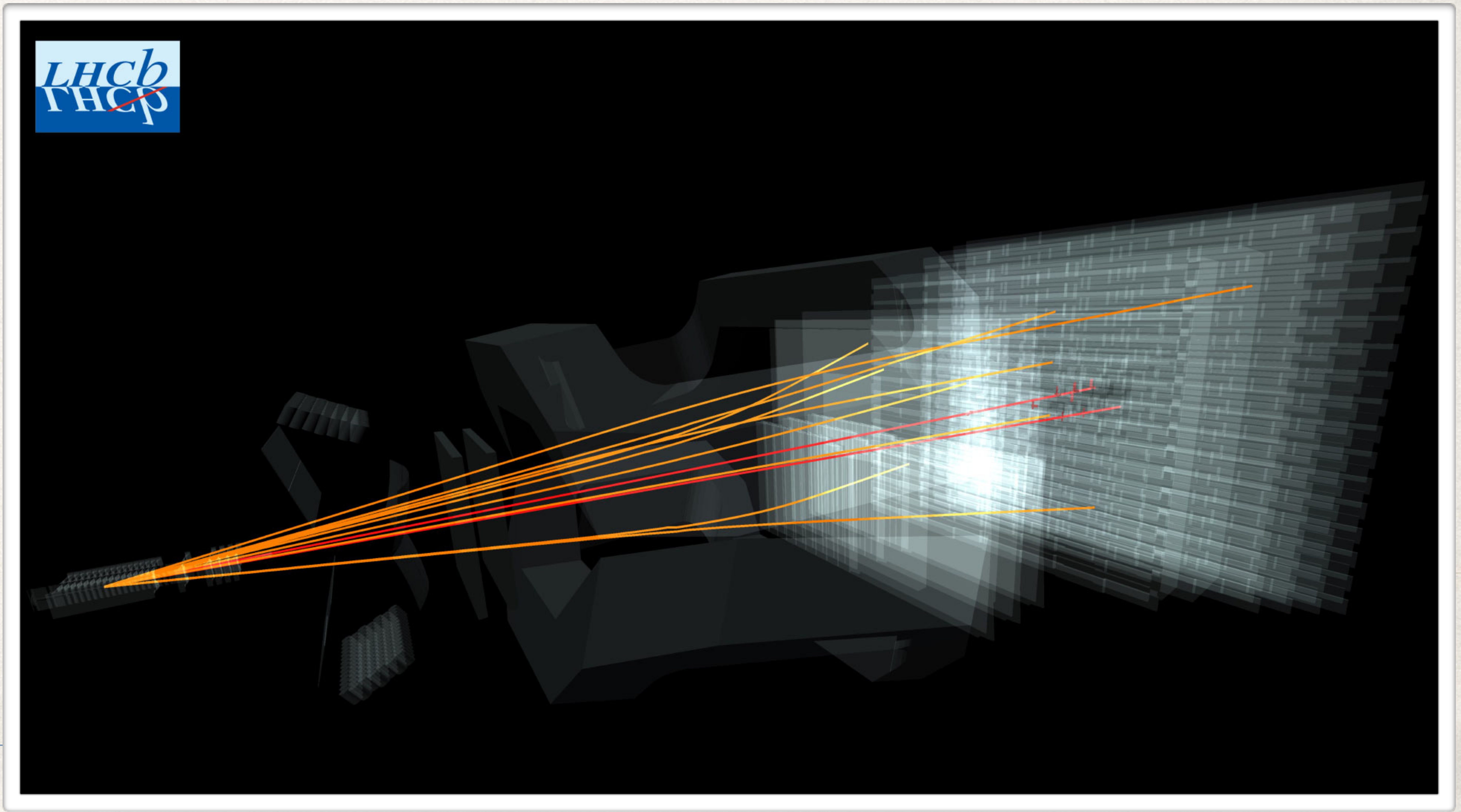
CP violation experiments

- $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ or: $\to \psi(3770) \to D\overline{D}$
  - Known initial state but comparatively low cross section
- $pp \to gg \to b\overline{b}$ with general-purpose detectors
  - Huge cross section but messy. Not what they're built for.
- or dedicated detector with tuned-down pile-up: LHCb.
  - Optimised vertexing, hadron PID and a software trigger







Topics and parallel sessions

- Precision measurement of B_s meson oscillations
- Observation of D^0 meson mass difference
- Observation of direct CP violation with D^0 mesons
- Time-dependent CP violation search with D^0 mesons
- CP violation searches with $D^+_{(s)}$ mesons
- CP violation in charmless B^+ decays
- Unitarity Triangle: β
- Unitarity Triangle: γ
- CP violating phase with B_s mesons

Wed 11:20: Yu Zhang
"Hadronic charm decays at BESIII"

Wed 11:40: Joan Ruiz Vidal
"CPV and mixing in charm at LHCb"

Wed 10:00: Markus Reif
"Hadronic B decays at Belle II"

Wed 12:00: Radek Zlebcik
"Charm and TDCPV in B decays at Belle II"

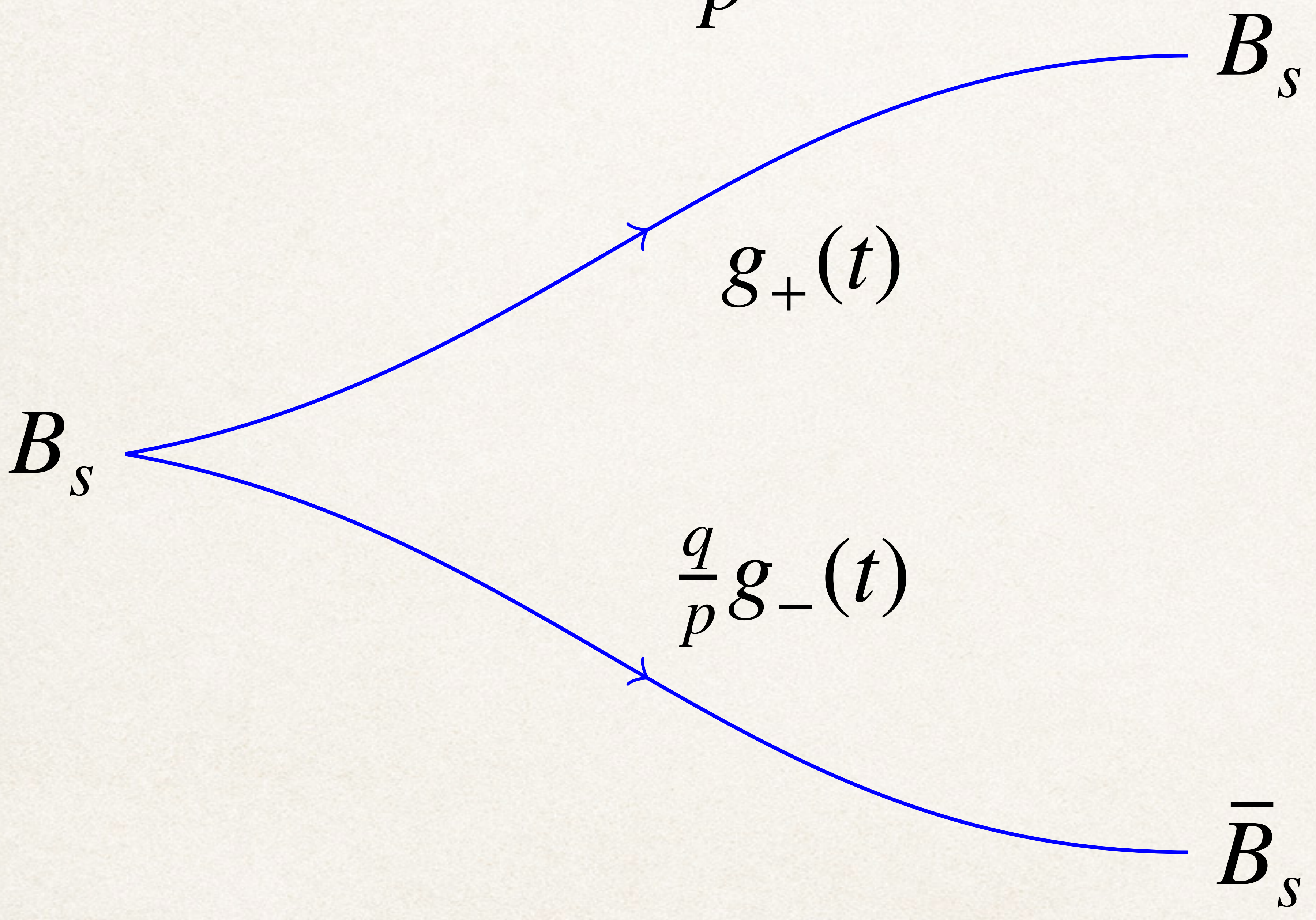
Wed 10:40: Jordy Butter
"CPV and CKM measurements with beauty decays at LHCb"

$B_s \leftrightarrow \bar{B}_s$ mixing frequency: Δm_s

- Mixing occurs if the eigenstates of the hamiltonian are not aligned with the interactions eigenstates:

$$|B_{sH}\rangle = p\,|B_s\rangle - q\,|\bar{B}_s\rangle$$
$$|B_{sL}\rangle = p\,|B_s\rangle + q\,|\bar{B}_s\rangle$$

$$|B_s(t)\rangle = g_+\,|B_s\rangle + \frac{q}{p} g_-\,|\bar{B}_s\rangle$$



$$g_\pm = \frac{1}{2}\left[e^{-iM_L t - \Gamma_L t/2} \pm e^{-iM_H t - \Gamma_H t/2}\right]$$

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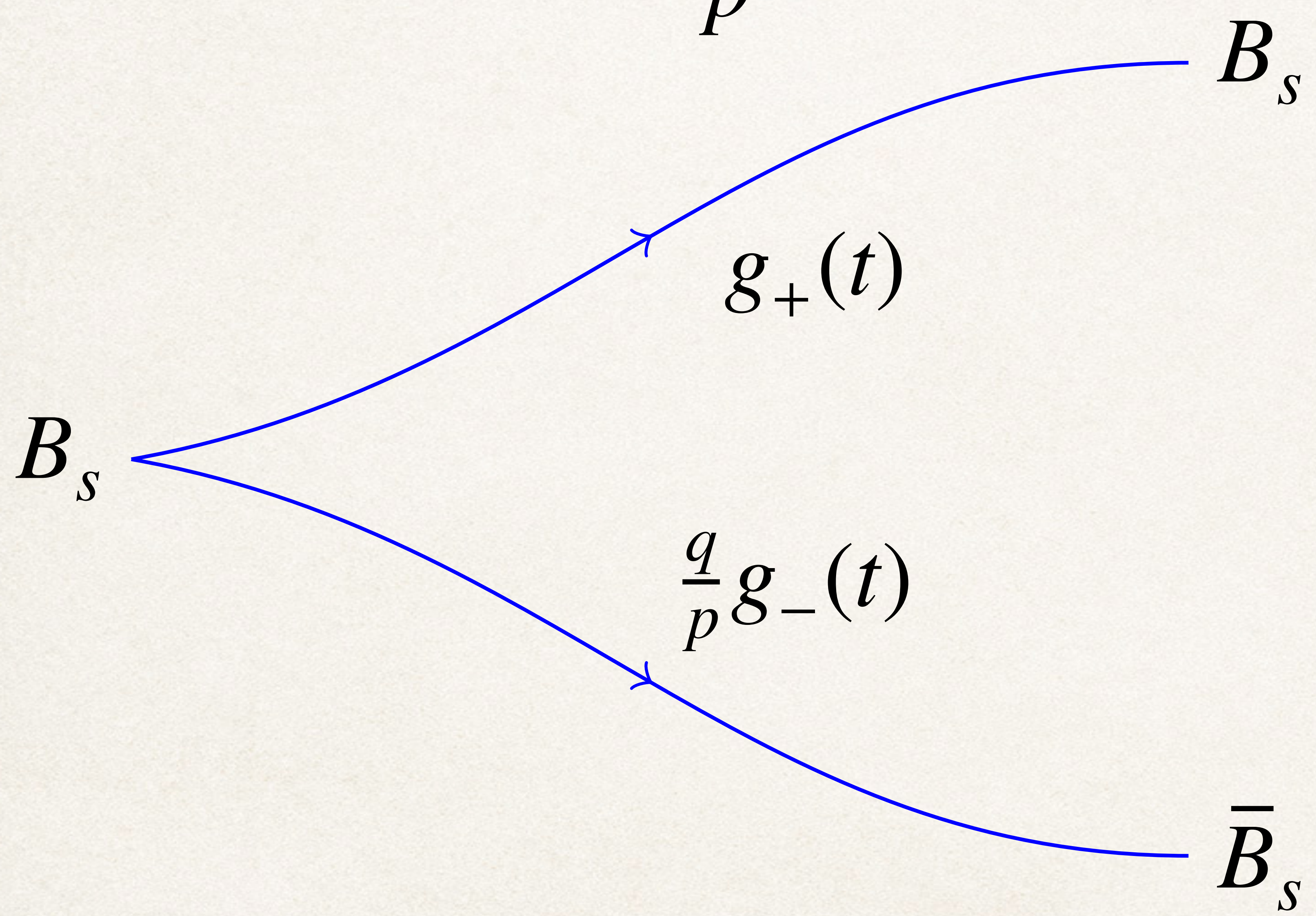


$$g_\pm = \frac{1}{2}\left[e^{-iM_Lt-\Gamma_Lt/2} \pm e^{-iM_Ht-\Gamma_Ht/2}\right]$$

$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cdot\cos(\Delta m_s t)\right]$$

Probability to observe [un]mixed B_s meson

average decay width
$\Gamma_s = (\Gamma_H + \Gamma_L)/2$

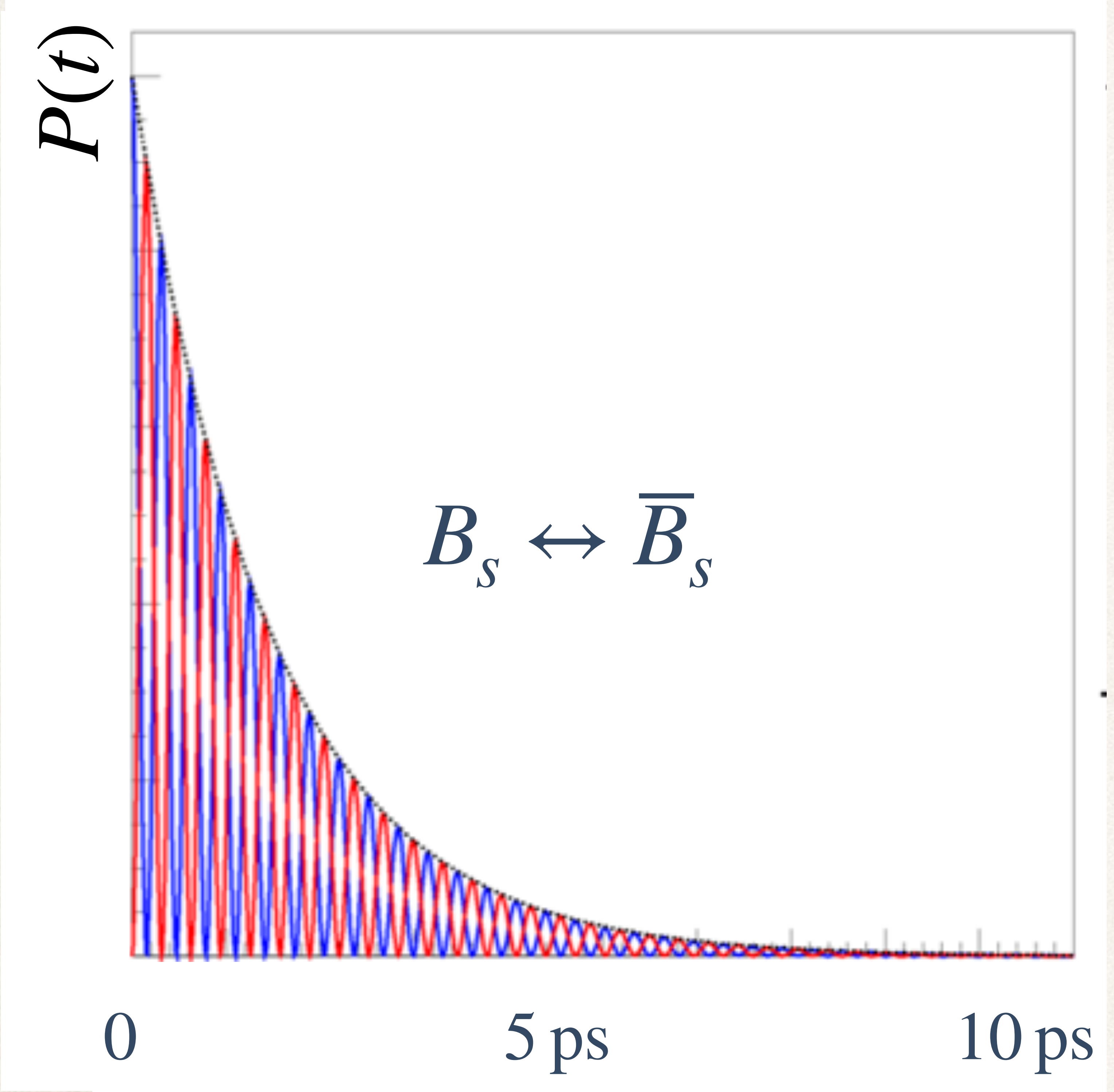
decay width difference
$\Delta\Gamma_s = \Gamma_H - \Gamma_L$

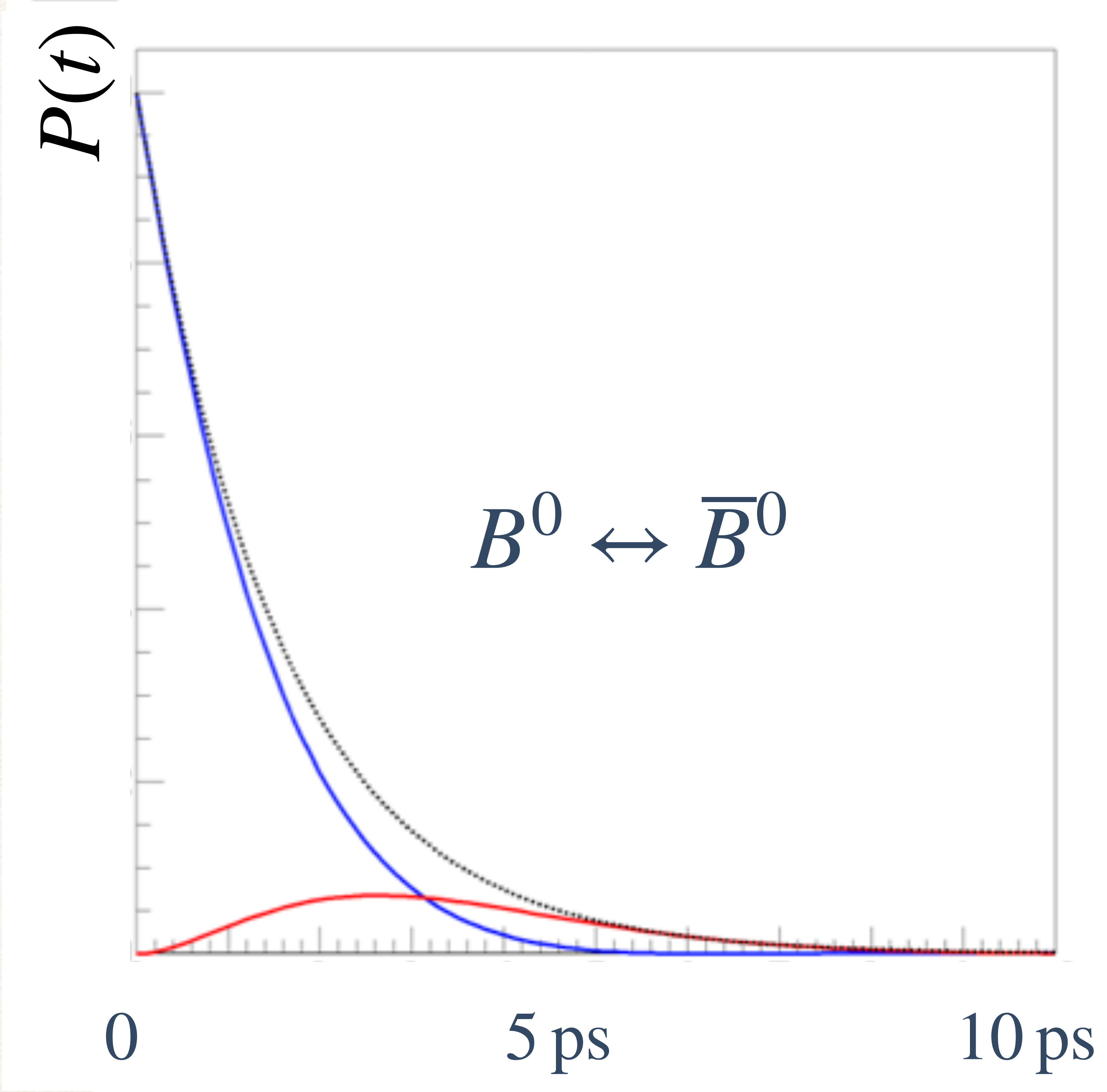
Constant $C = -1$ $(+1)$ for mixed (unmixed) B_s meson

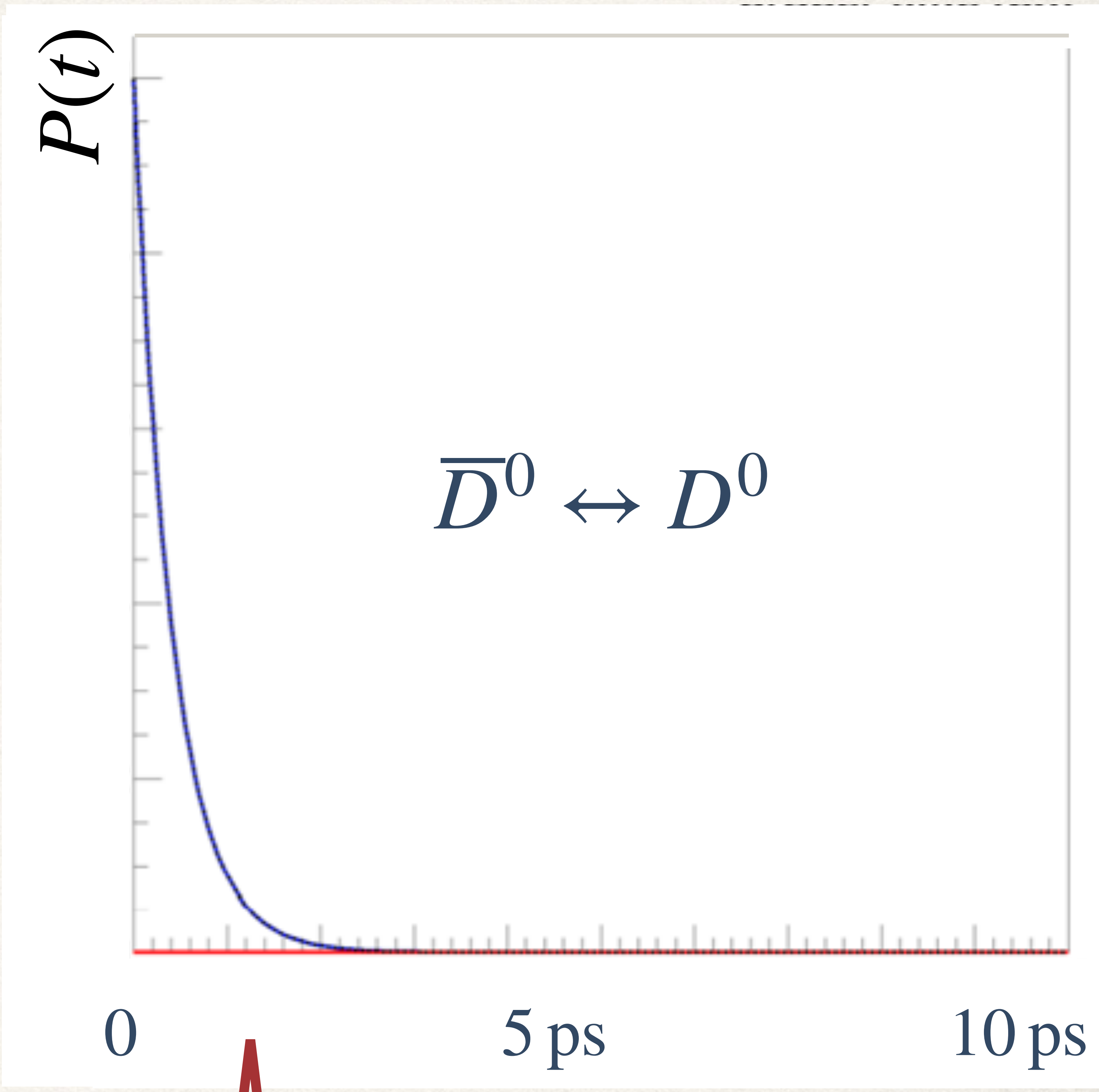
$\Delta m_s = m_H - m_L$
mass difference

Illustration: initial → mixed → mix back → mix again …

Flavour tagging vital to identify initial flavour







$\sim$ 1 cm
at LHCb

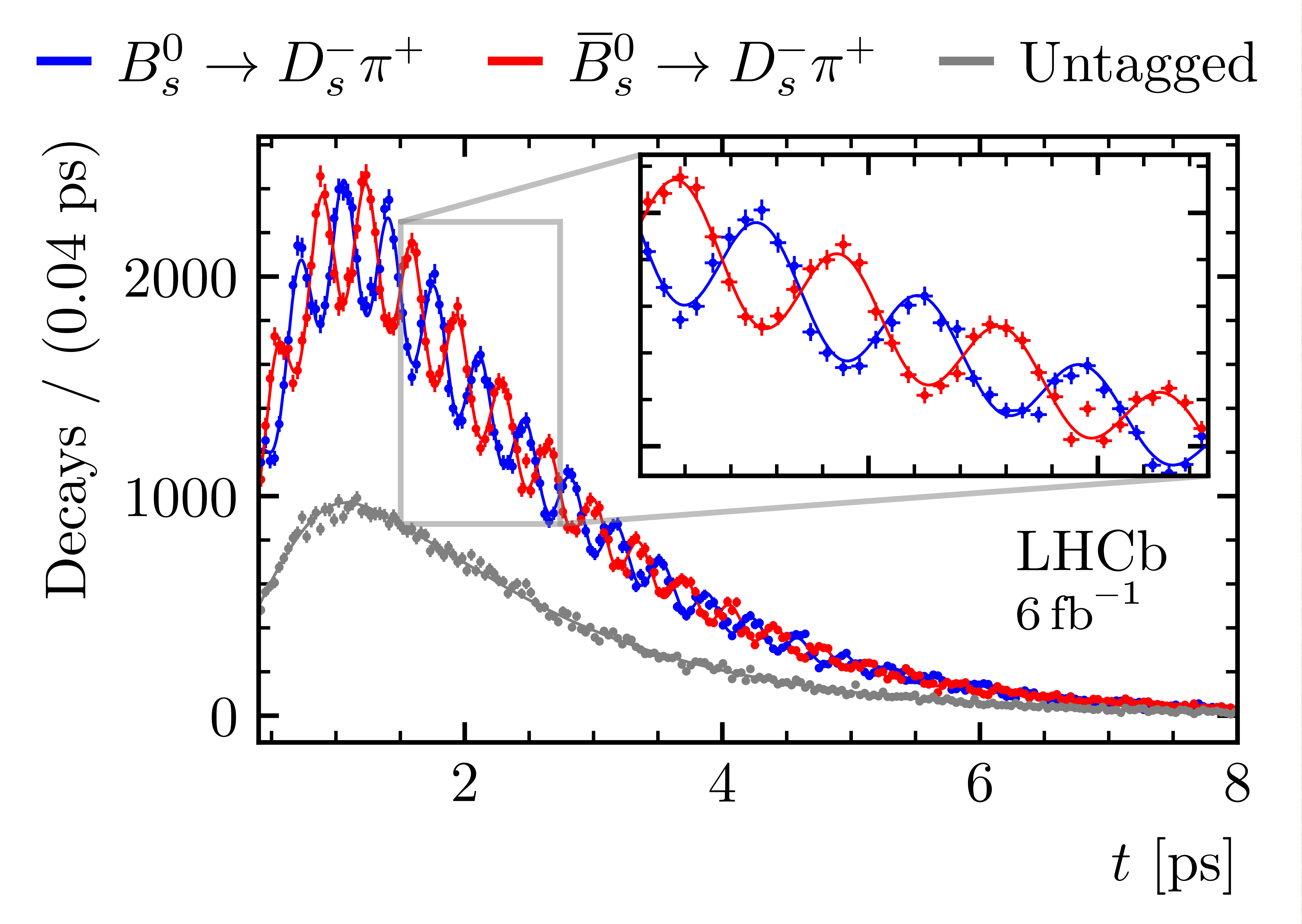
Small mixing probability

Δm_s with $B_s \to D_s^{\pm}\pi^{\mp}$

arXiv:2104.04421 (accepted by Nat. Phys.)

- Identify decay flavour with Cabibbo-favoured $b \to c\pi^-$ vs. $\bar{b} \to \bar{c}\pi^+$ transition
  - DCS contribution negligible
- Identify initial flavour with flavour tagging.
  - Effecting performance at LHCb: **6.1%** of ideal.

c.f. ~ 31% at Belle(II)



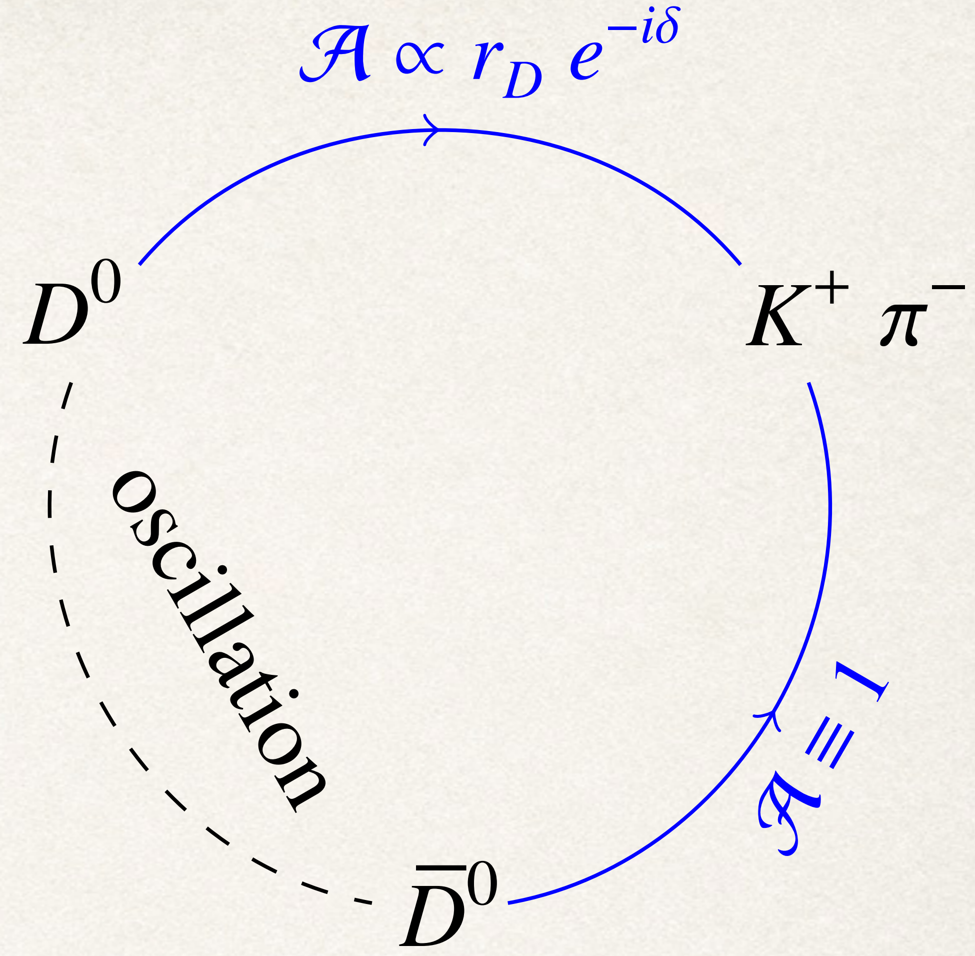
- An initial mass fit identifies **379k** signal events
- Result with $B_s \to D_s\pi$ combined with earlier result using $B_s \to D_s\pi\pi\pi$ (JHEP 03 (2021) 137)

$$\Delta m_s = 17.7656 \pm 0.0057\,\mathrm{ps}^{-1}$$

- Consistent with, but far more precise than, SM prediction (due to QCD calculation limitations)

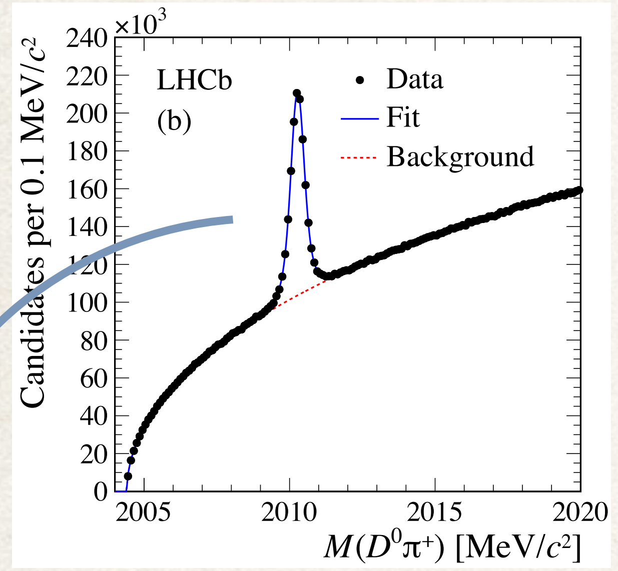
Pioneered by Babar Phys. Rev. Lett. 98 (2007) 211802, and Belle Phys. Rev. Lett. 98 (2007) 211803, LHCb shown Phys. Rev. D97 (2018) 031101

On the other hand, charm mixing is slow

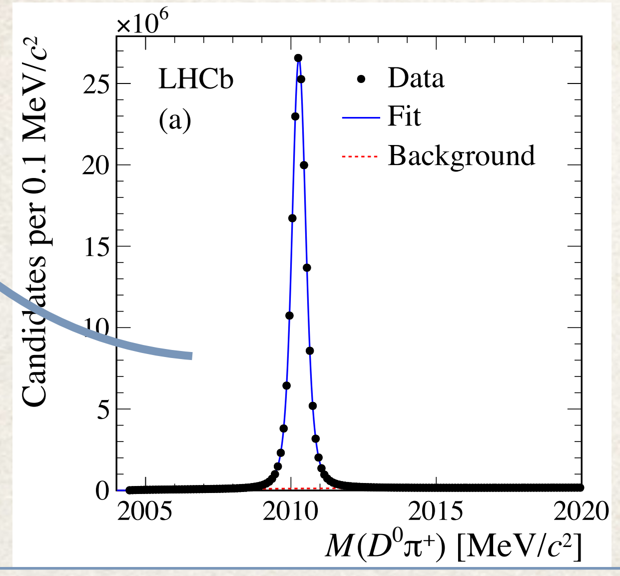


- Probability of mixing too small to measure complete oscillations
  - Though flavour tagging is near-perfect: $D^{*+} \to D^0\pi^+$ or $B^- \to D^0\mu^-\nu$
- Instead, look for a time-dependant change in the rate of DCS decays

$$\Gamma(D^0 \to K^+\pi^-) = \left| g_+(t)\, r_D e^{-i\delta_D} + g_-(t) \right|^2$$



$$R = \frac{D^0 \to K^+\pi^-}{\overline{D}^0 \to K^+\pi^-}$$



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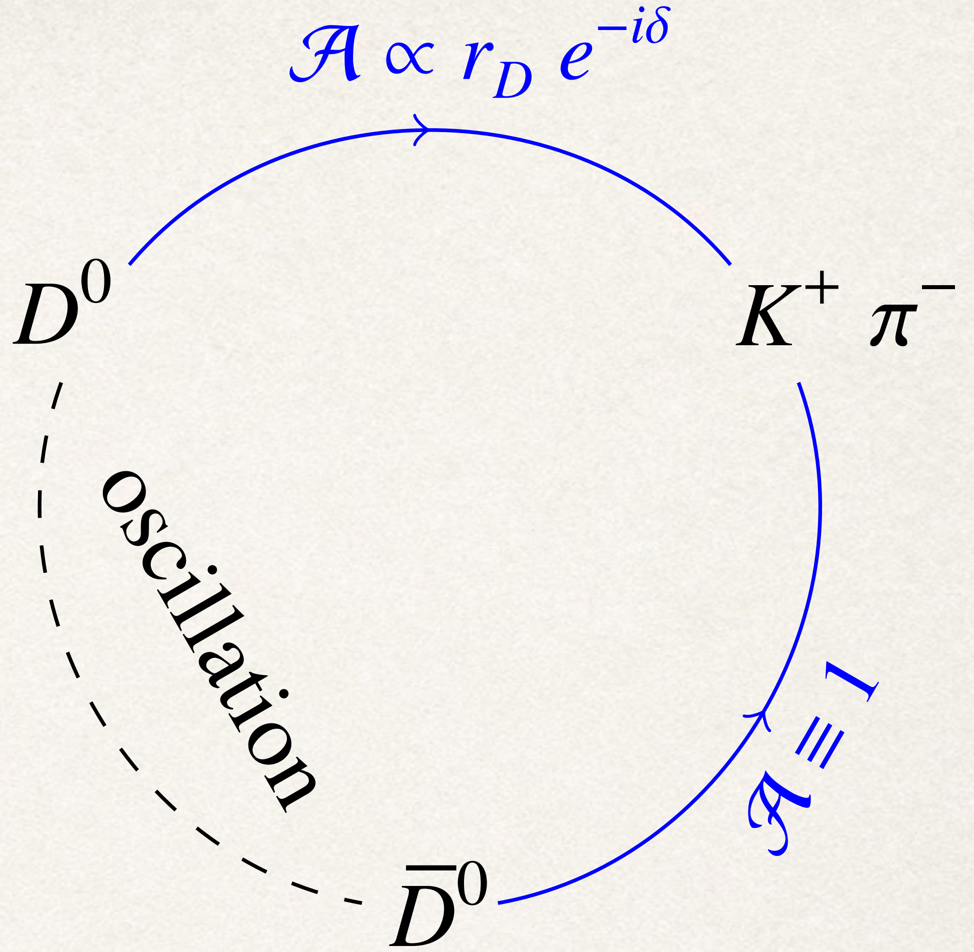

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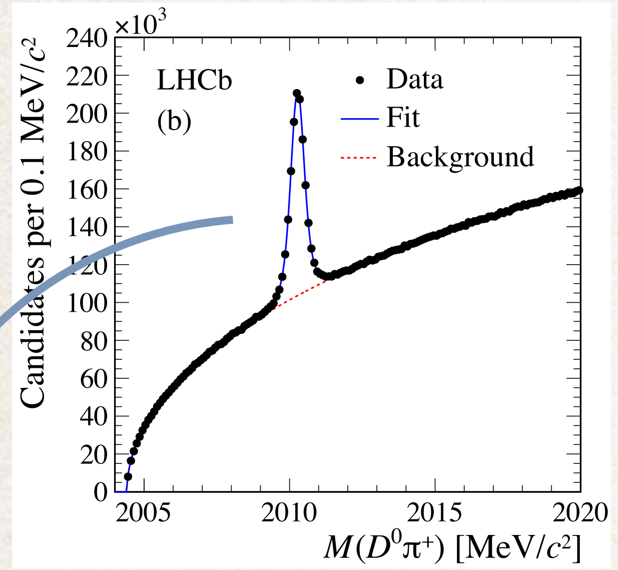
$$= e^{-\Gamma t}\left[\frac{1}{2} r_D^2 \left(\cosh(y\Gamma t) + \cos(x\Gamma t)\right) + \frac{1}{2}\left(\cosh(y\Gamma t) - \cos(x\Gamma t)\right) + r_D\left(\cos\delta_D \sinh(y\Gamma t) - \sin\delta_D \sin(x\Gamma t)\right)\right]$$

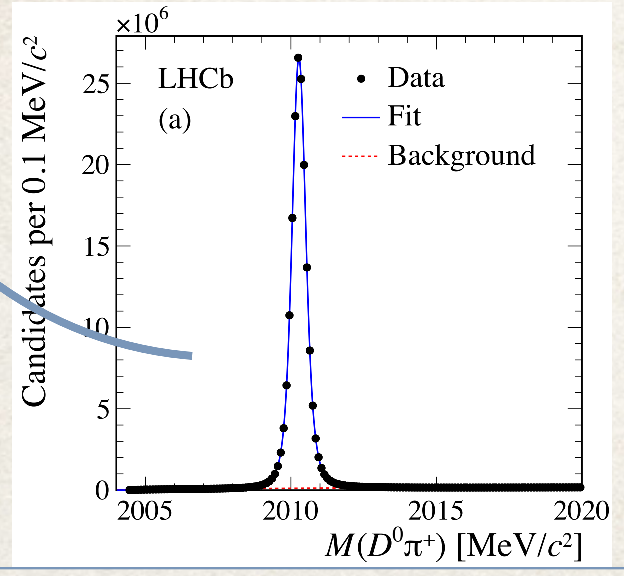
as before *neglected before* *new term*

$$x \equiv \Delta m/\Gamma \qquad y \equiv \Delta\Gamma/2\Gamma$$

dimensionless parameters O(1%)



$$R = \frac{D^0 \to K^+\pi^-}{\overline{D}^0 \to K^+\pi^-} \simeq r_D^2 + r_D\left(y\cos\delta_D - x\sin\delta_D\right)\left(\frac{t}{\tau}\right) + \frac{y^2 + x^2}{4}\left(\frac{t}{\tau}\right)^2$$



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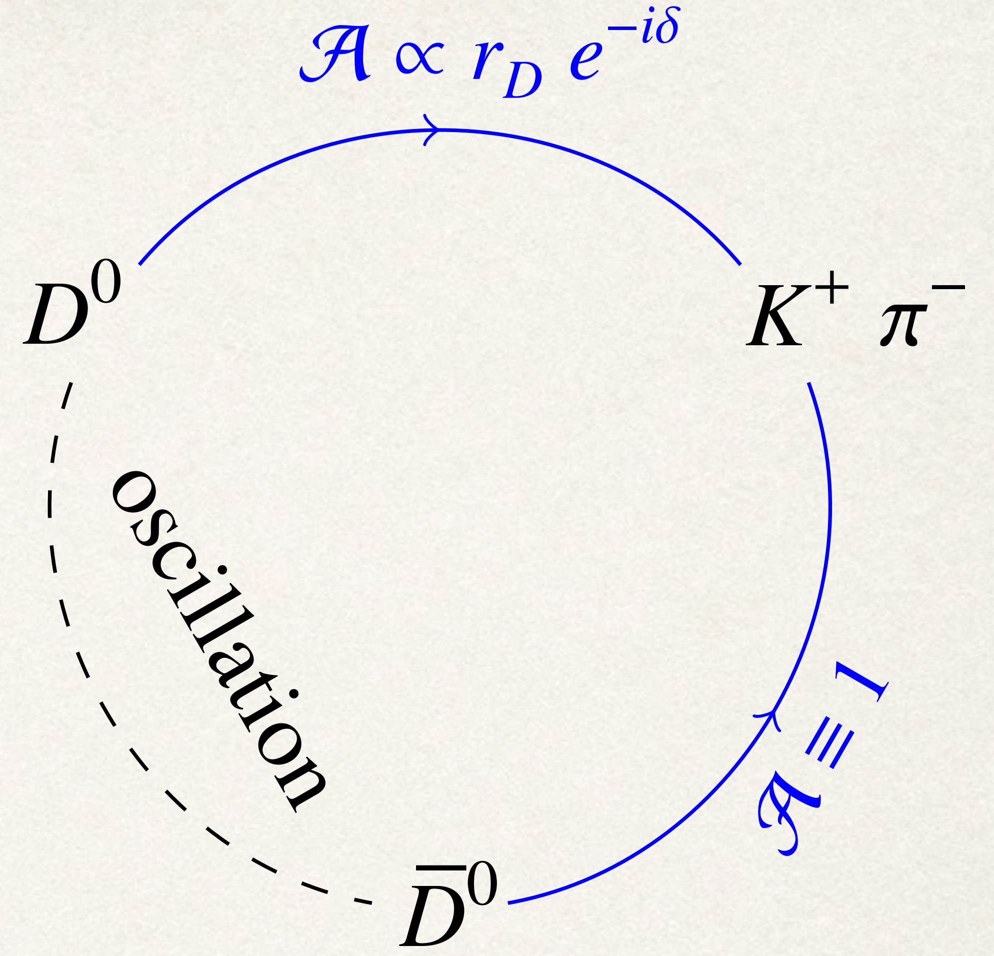

$$\Gamma(D^0 \to K^+\pi^-) = \left| g_+(t)\, r_D e^{-i\delta_D} + g_-(t) \right|^2$$

$$= e^{-\Gamma t}\left[\frac{1}{2}r_D^2\left(\cosh(y\Gamma t) + \cos(x\Gamma t)\right) + \frac{1}{2}\left(\cosh(y\Gamma t) - \cos(x\Gamma t)\right) + r_D\left(\cos\delta_D \sinh(y\Gamma t) - \sin\delta_D \sin(x\Gamma t)\right)\right]$$

neglected before — *as before* — *new term*

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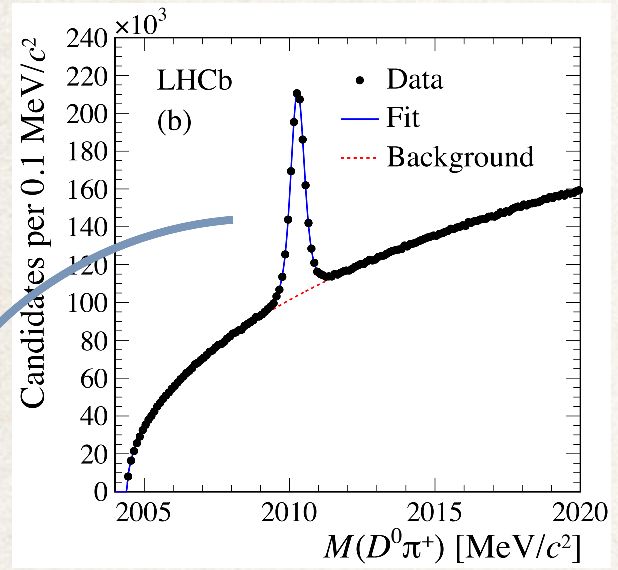
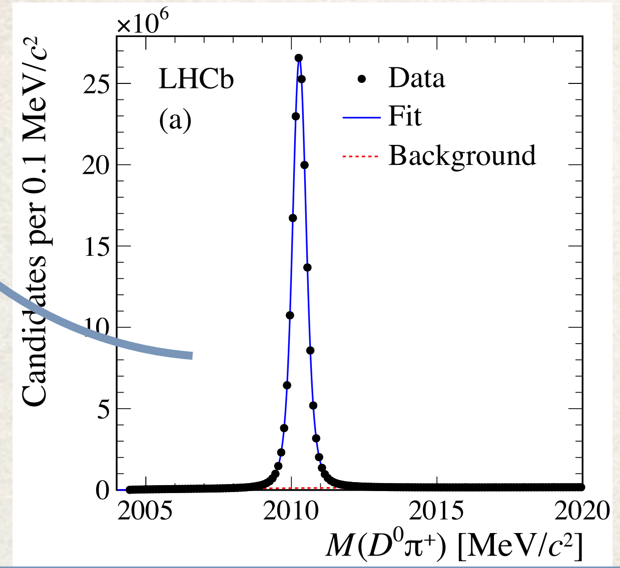
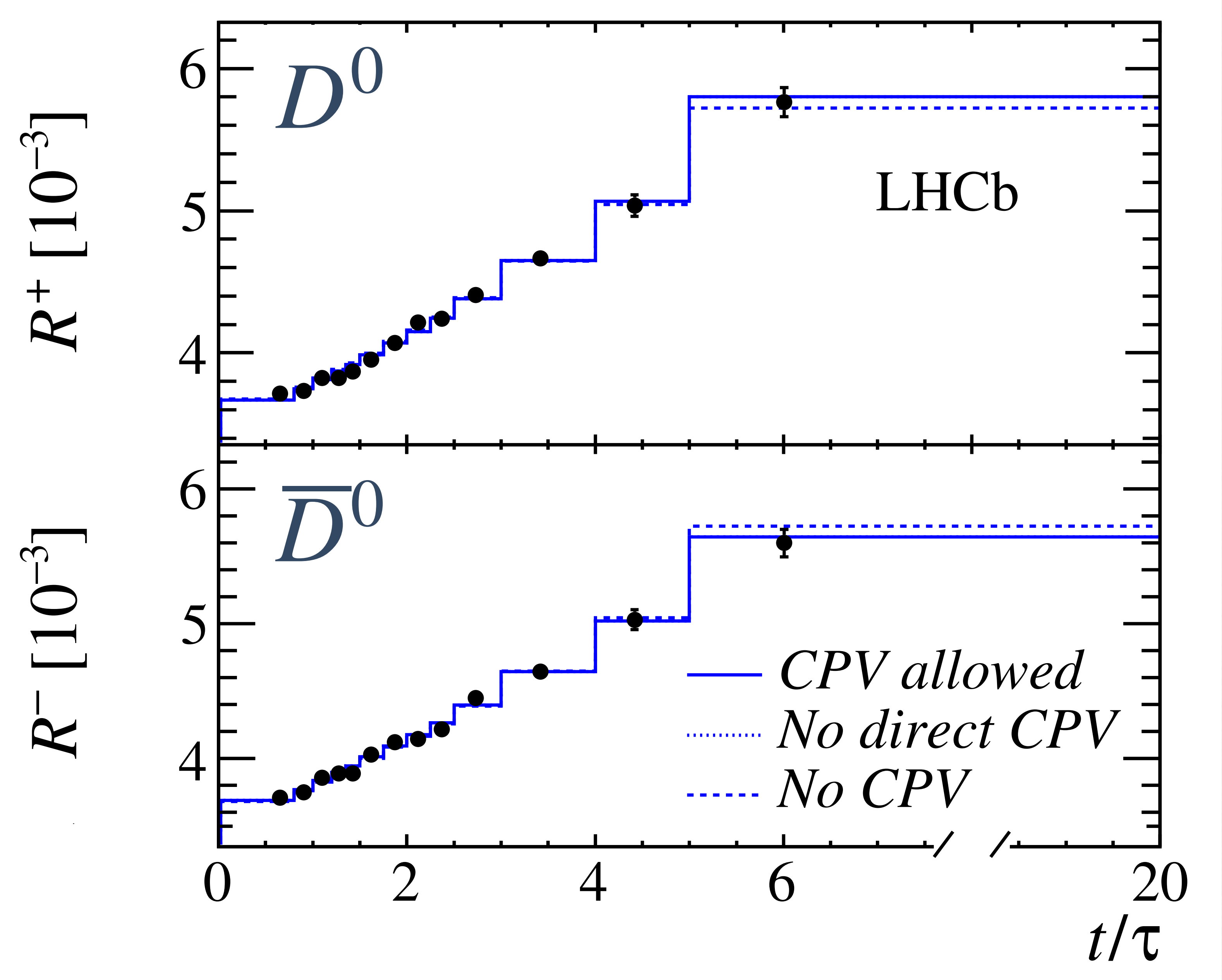


$$R = \frac{D^0 \to K^+\pi^-}{\overline{D}^0 \to K^+\pi^-} \simeq r_D^2 + r_D\left(y\cos\delta_D - x\sin\delta_D\right)\left(\frac{t}{\tau}\right) + \frac{y^2 + x^2}{4}\left(\frac{t}{\tau}\right)^2$$



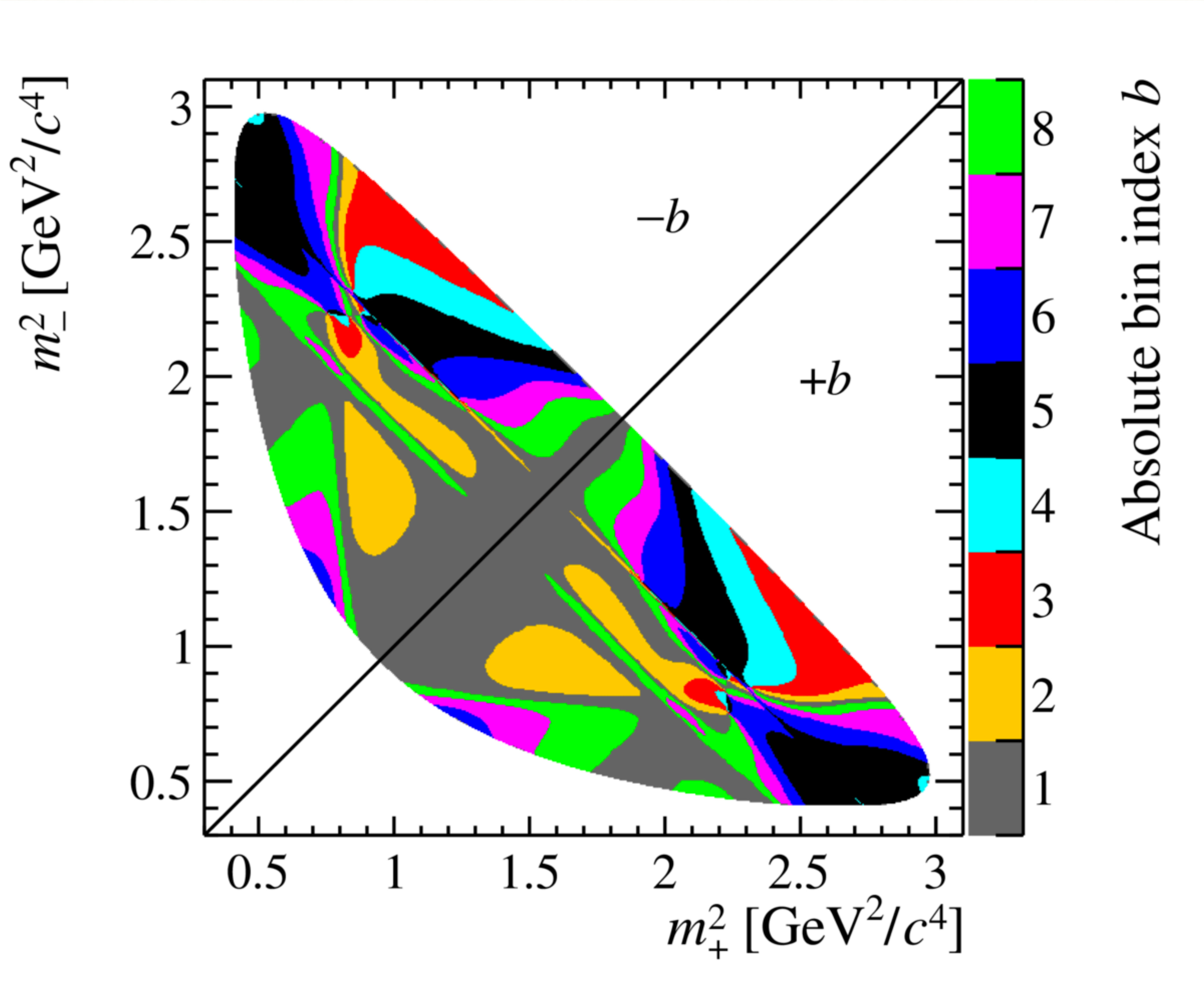
Problem: need a precise δ_D for precision x & y

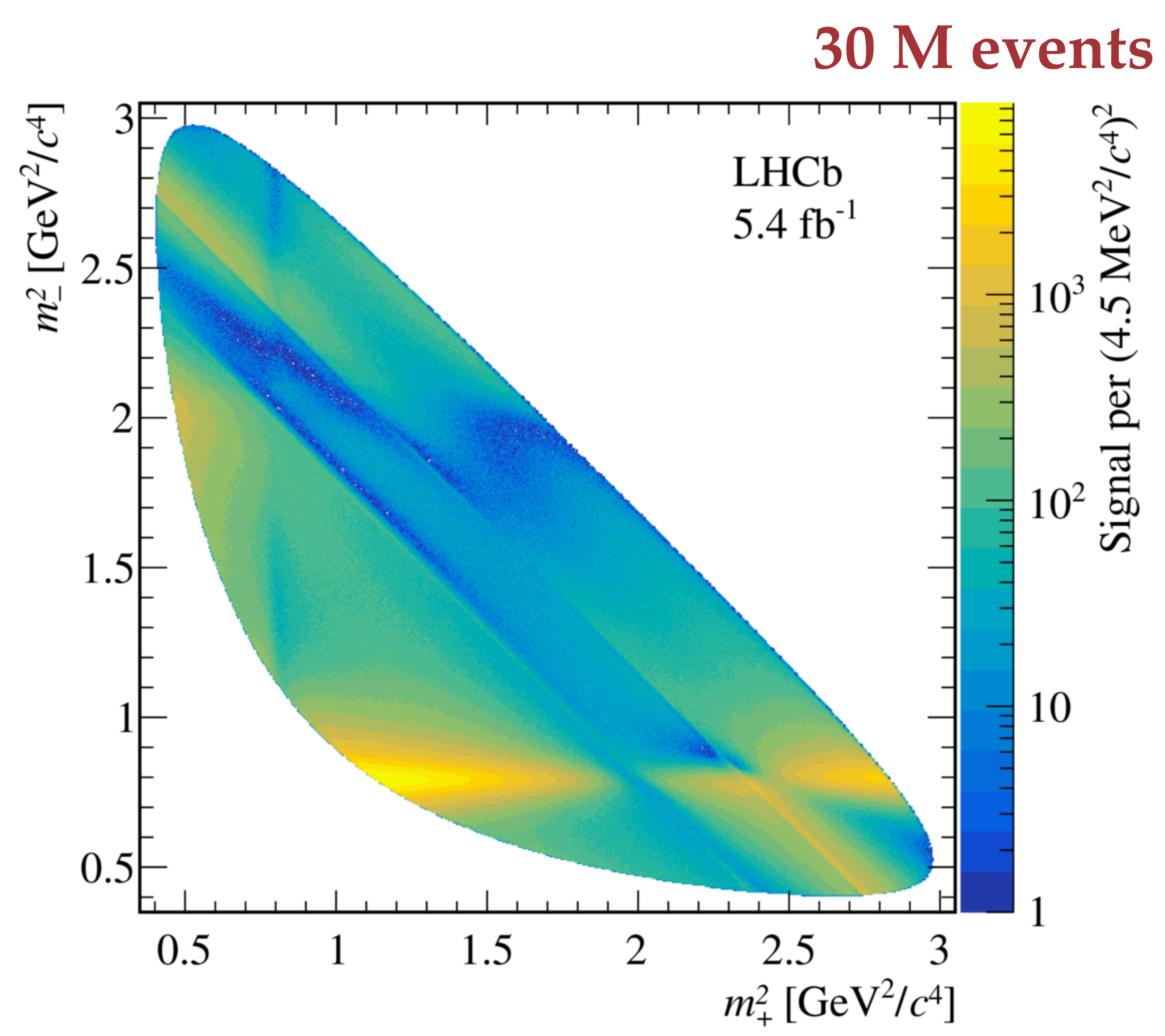


Bin-flip method with $D \to K^0_S \pi^+ \pi^-$

Method: Phys. Rev. D99 (2019) 012007
BESIII: Phys. Rev. D101 (2020) 112002
LHCb: Phys. Rev. Lett. 127, (2021) 111801

- Use charge-conjugate multi-body decay. Subdivided into bins with a variety of δ_D (called X_b here)
- Measure the relative phases between bin $+b$ and $-b$, X_b using quantum-correlated $D^0\overline{D}^0$ pairs in a $e^+e^- \to \psi(3770)$ dataset ( ). At LHCb, measure time-dependent "DCS" ratio R_b in each bin-pair.





Observation of the neutral charm Δm

Method: Phys. Rev. D99 (2019) 012007
BESIII: Phys. Rev. D101 (2020) 112002
LHCb: Phys. Rev. Lett. 127, (2021) 111801

- Formalism expanded and generalised to include the binning scheme and CP violation

$$R_{bj}^{\pm} \approx \frac{r_b + r_b\frac{\langle t^2\rangle_j}{4}\,\mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{\langle t^2\rangle_j}{4}\,|z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j\,\mathrm{Re}[X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{\langle t^2\rangle_j}{4}\,\mathrm{Re}(z_{CP}^2 - \Delta z^2) + r_b\frac{\langle t^2\rangle_j}{4}\,|z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j\,\mathrm{Re}[X_b(z_{CP} \pm \Delta z)]}.$$

for Dalitz bin b and decay-time bin j

$r_b = R_{bj}$ at $t = 0$

$X_b = \exp\left(i\delta_D(b)\right)$ where $\delta_D(b)$ is the strong-phase difference between $+b$ and $-b$

$$z_{CP} \pm \Delta z \equiv -\,(q/p)^{\pm 1}\,(y + ix) \qquad x \equiv \Delta m/\Gamma \qquad y \equiv \Delta\Gamma/2\Gamma$$

dimensionless parameters O(1%)

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for Dalitz bin b and decay-time bin j

$r_b = R_{bj}$ at $t = 0$

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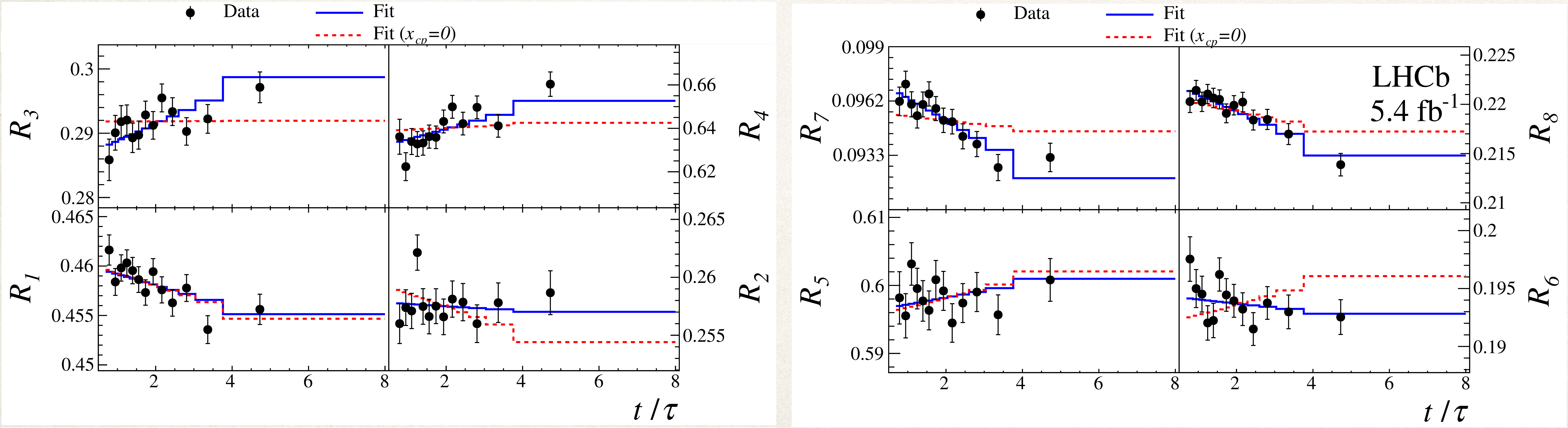
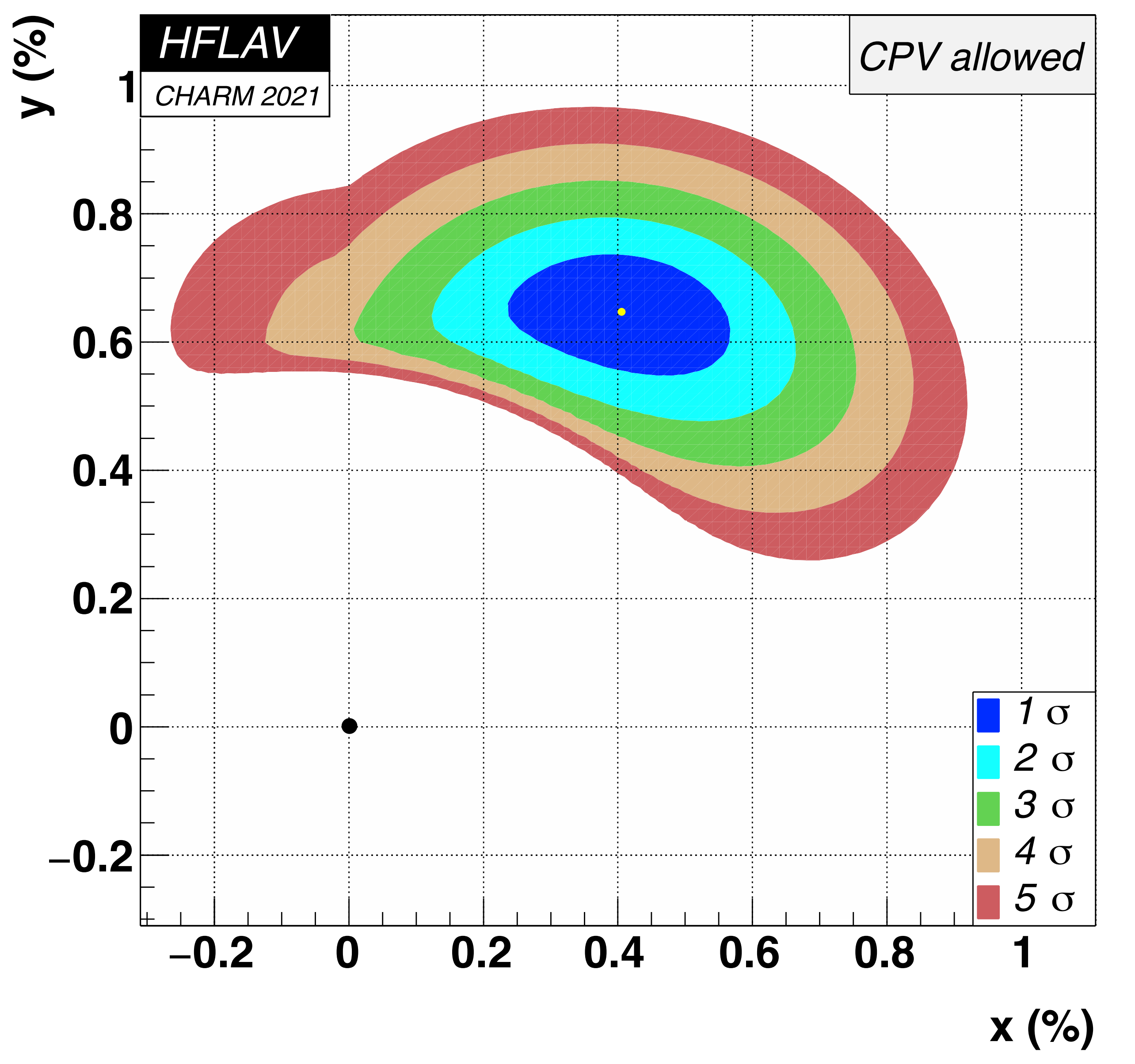


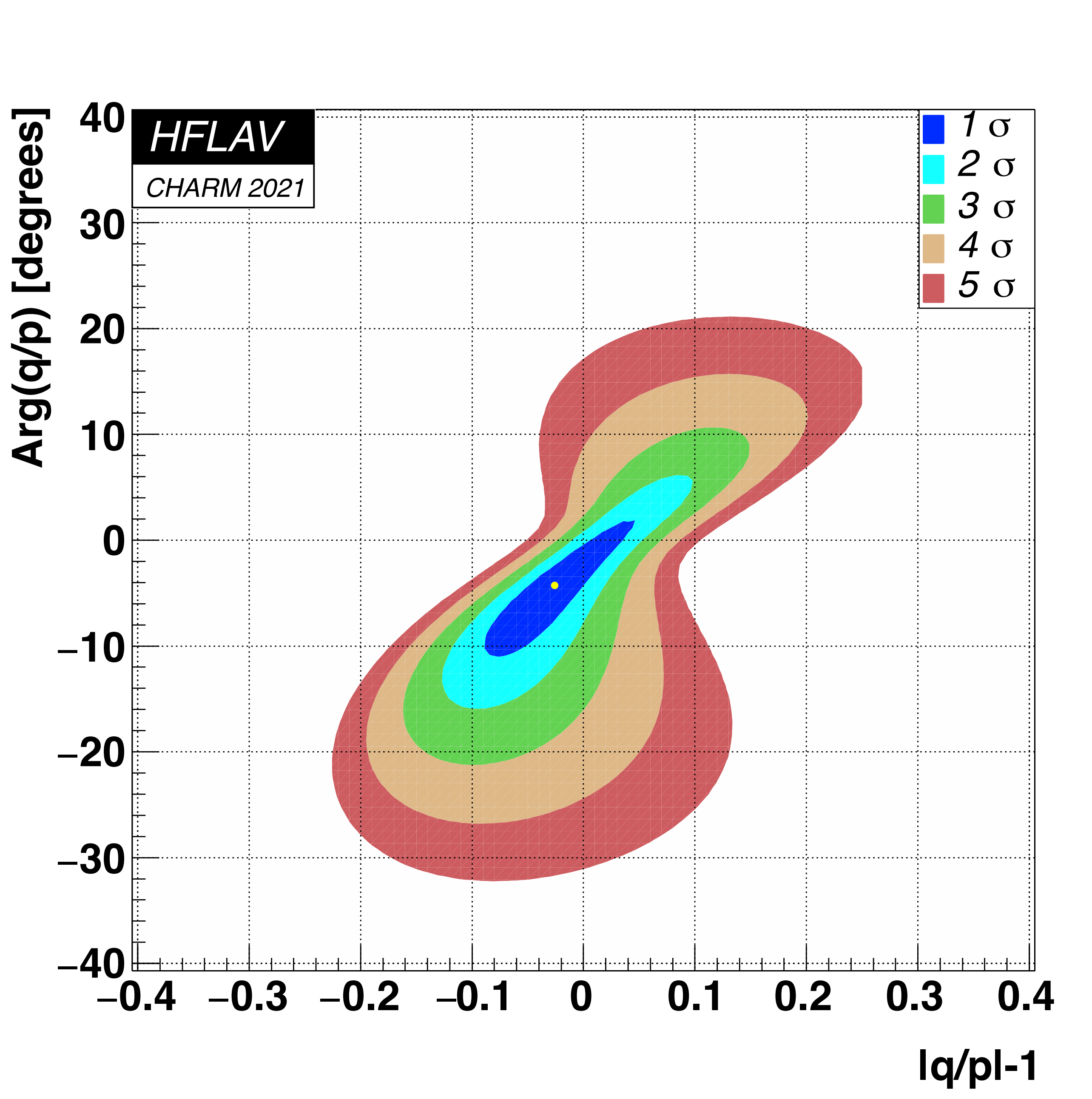
$> 7\sigma$

$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (4.6^{+1.5}_{-1.4}) \times 10^{-3},$$
$$|q/p| = 0.996 \pm 0.052,$$
$$\arg(q/p) = 0.056^{+0.047}_{-0.051}.$$

https://hflav-eos.web.cern.ch/hflav-eos/charm/CKM21/results_mix_cpv.html

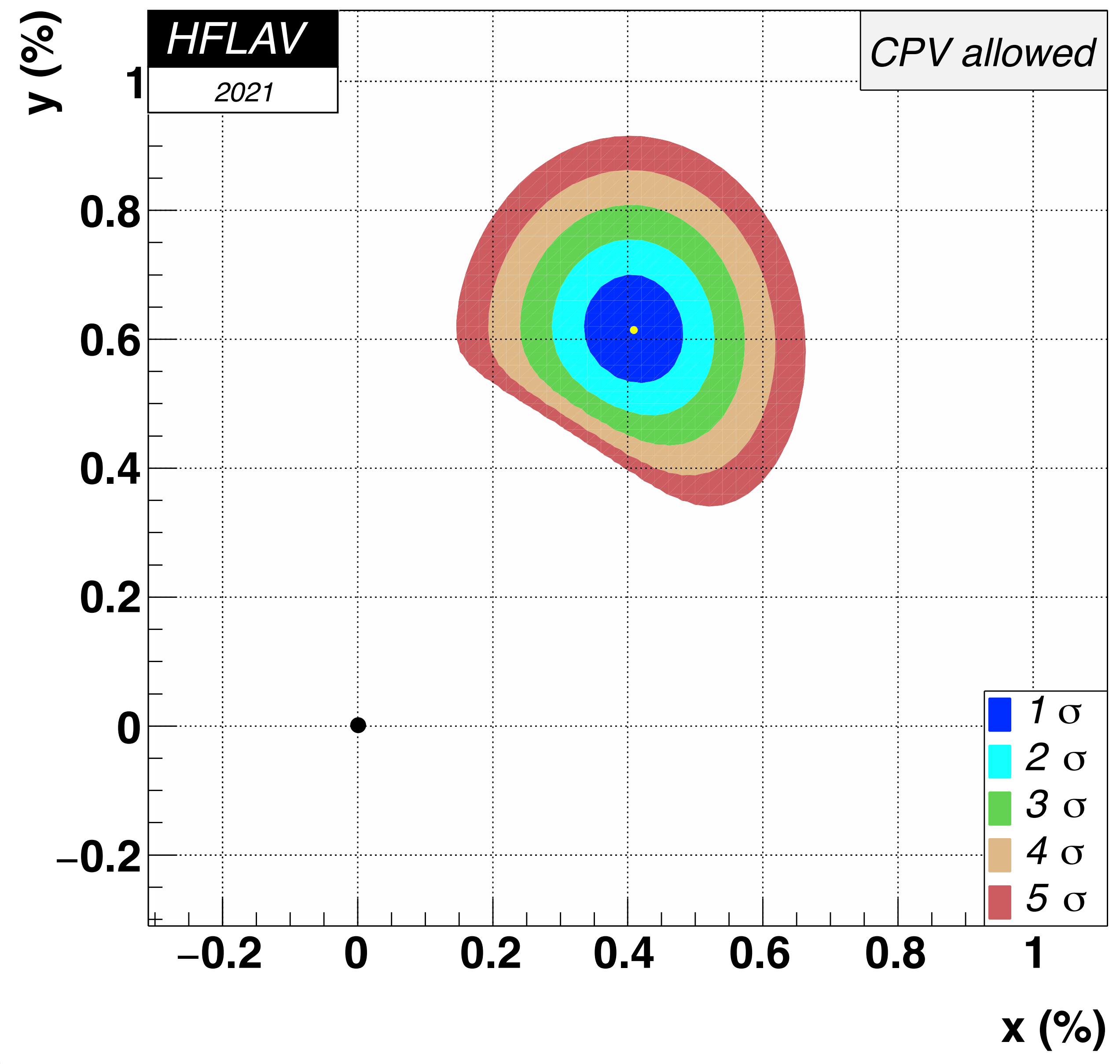
Impact

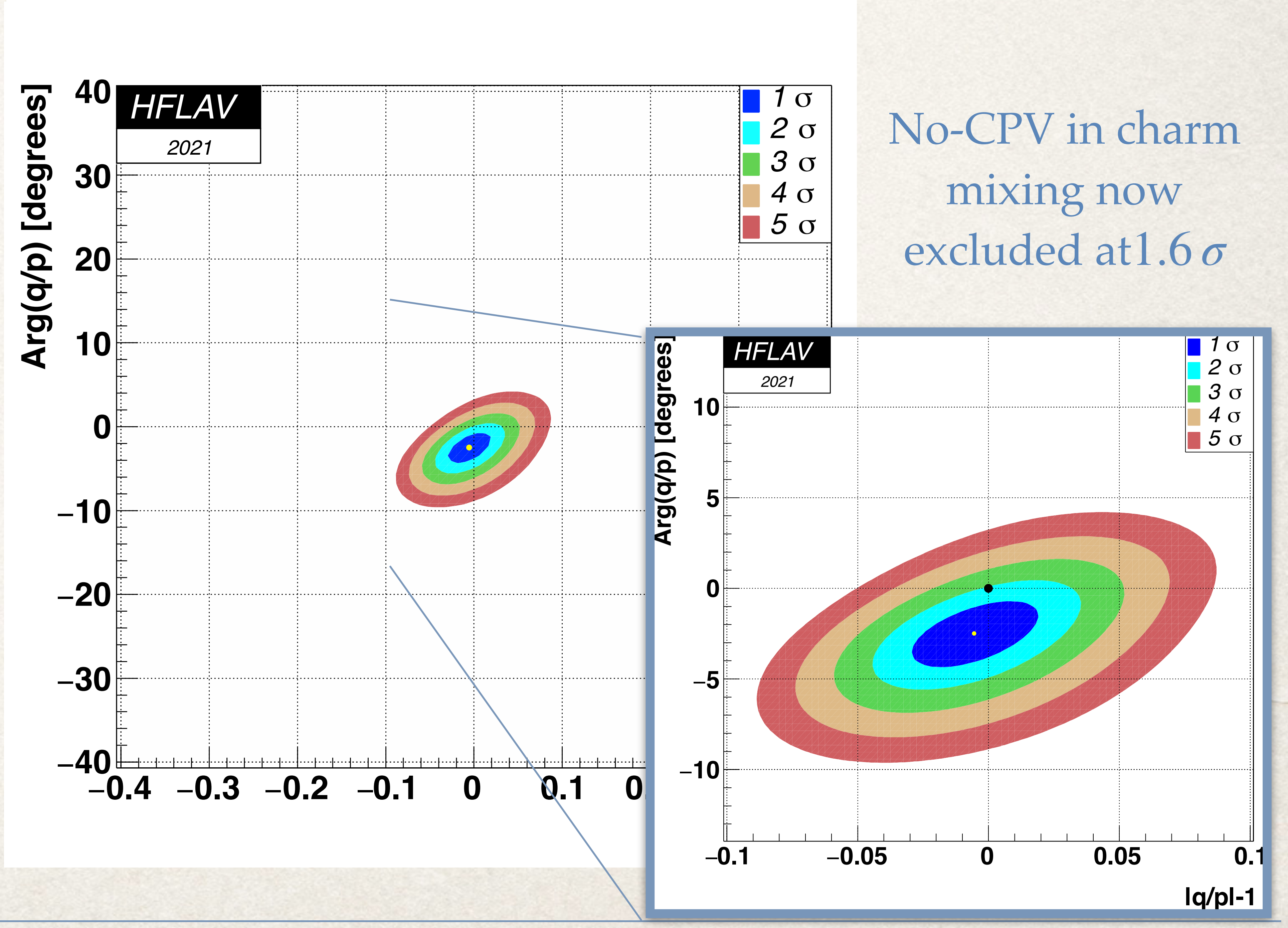




New global combination

$$x = (0.409 \pm 0.049) \times 10^{-3}$$
$$y = (0.615 \pm 0.056) \times 10^{-3}$$
$$|q/p| - 1 = -0.005 \pm 0.016$$
$$\arg(q/p) = (-2.5 \pm 1.2)^{\circ}$$





No-CPV in charm mixing now excluded at1.6 σ

Time dependant CPV in charm

- Lifetime asymmetry of D^0 and $\overline{D}^0$ to a CP eigenstate, $f = K^+K^-$, $\pi^+\pi^-$ expected to be $\mathcal{O}\left(10^{-5}\right)$

$$A_{CP}(f,t) \equiv \frac{\Gamma(D^0 \to f,t) - \Gamma(\overline{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\overline{D}^0 \to f,t)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}$$

slope measurement only

$$\Delta Y_f \approx -\frac{\hat{\Gamma}_{D^0 \to f} - \hat{\Gamma}_{\overline{D}^0 \to f}}{\hat{\Gamma}_{D^0 \to f} + \hat{\Gamma}_{\overline{D}^0 \to f}}$$

Asymmetry of the effective decay widths

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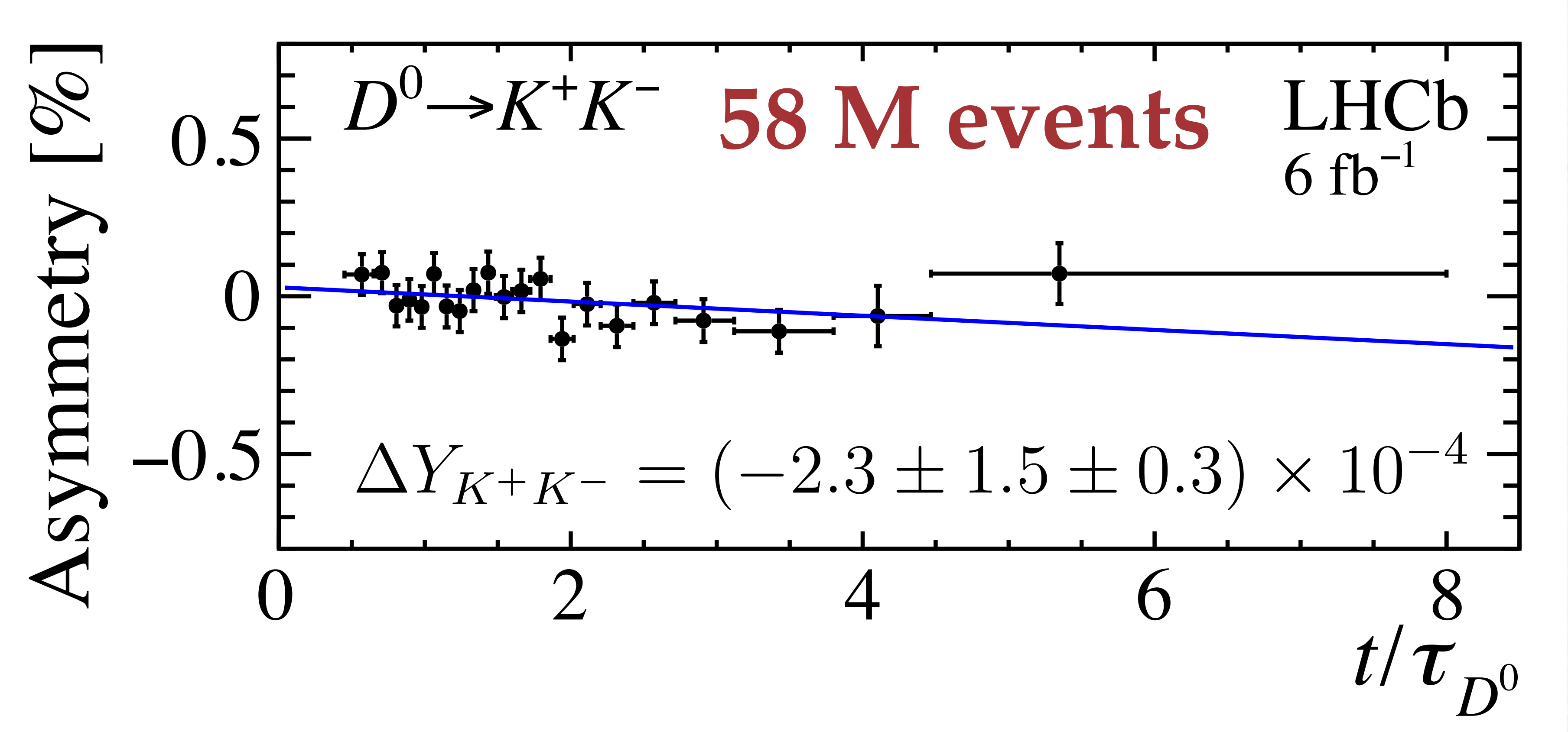
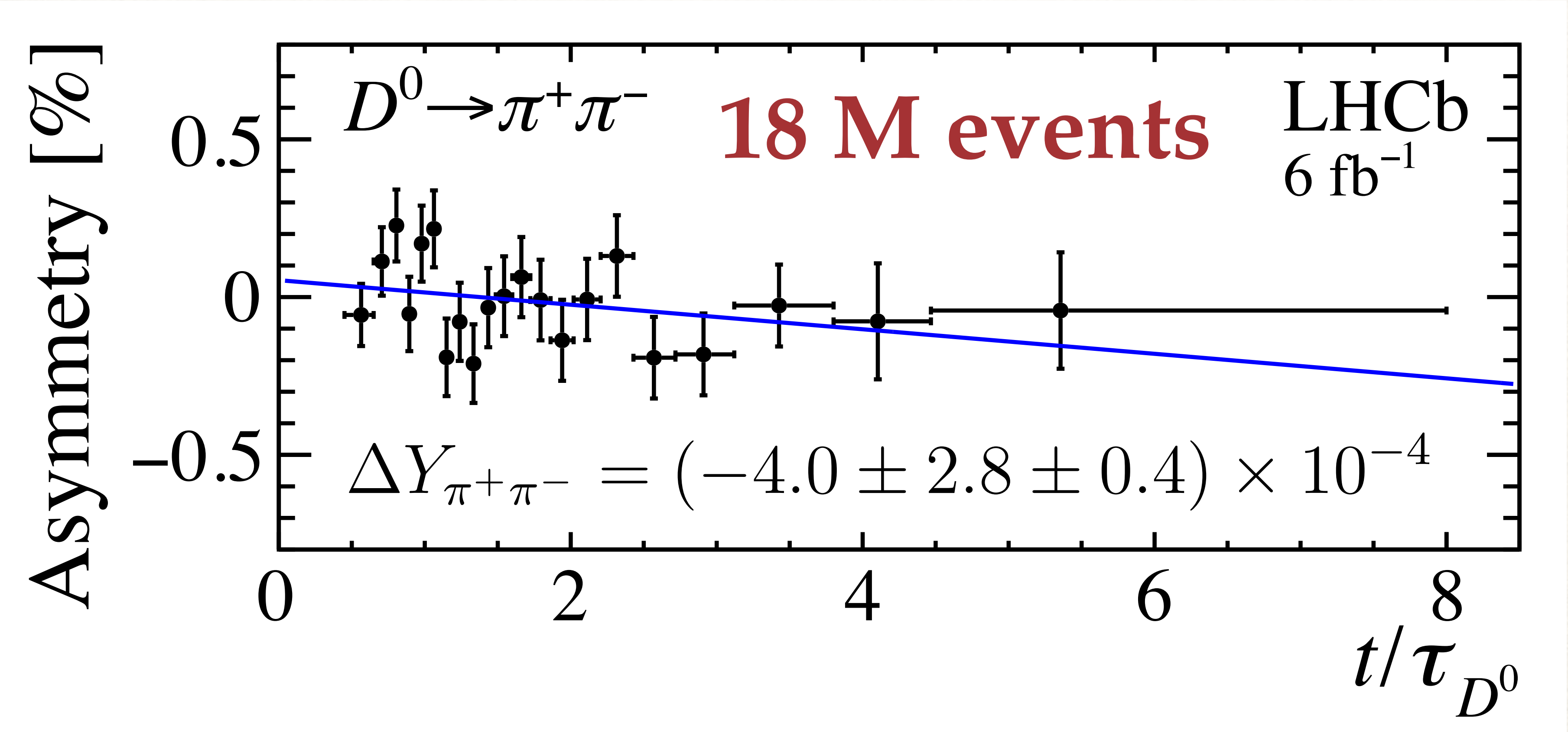
$$\Delta Y_f = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| + \left|\frac{p}{q}\right|\left|\frac{A_f}{\bar{A}_f}\right|\right) x \sin\phi_{\lambda_f} - \left(\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| - \left|\frac{p}{q}\right|\left|\frac{A_f}{\bar{A}_f}\right|\right) y \cos\phi_{\lambda_f}\right]$$

slope measurement only





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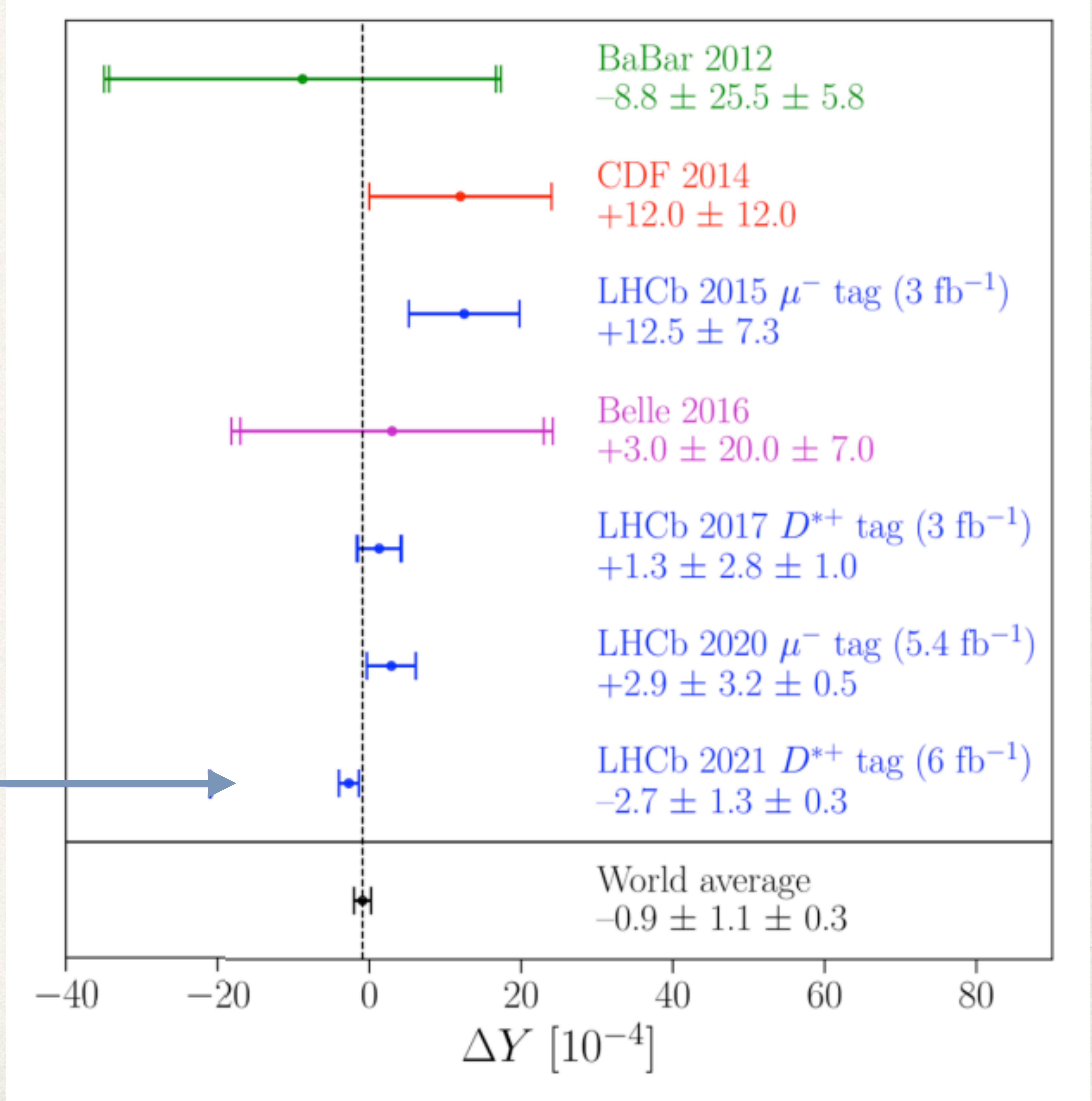
Asymmetry of the effective decay widths



This measurement

Observation of a direct *CP* violating effect in charm

- *A*chieved using a difference method to cancel common systematics

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$\approx \Delta a_{CP}^{\text{dir}} + \frac{\Delta\langle t\rangle}{\tau_{D^0}}\Delta Y$$

dominates

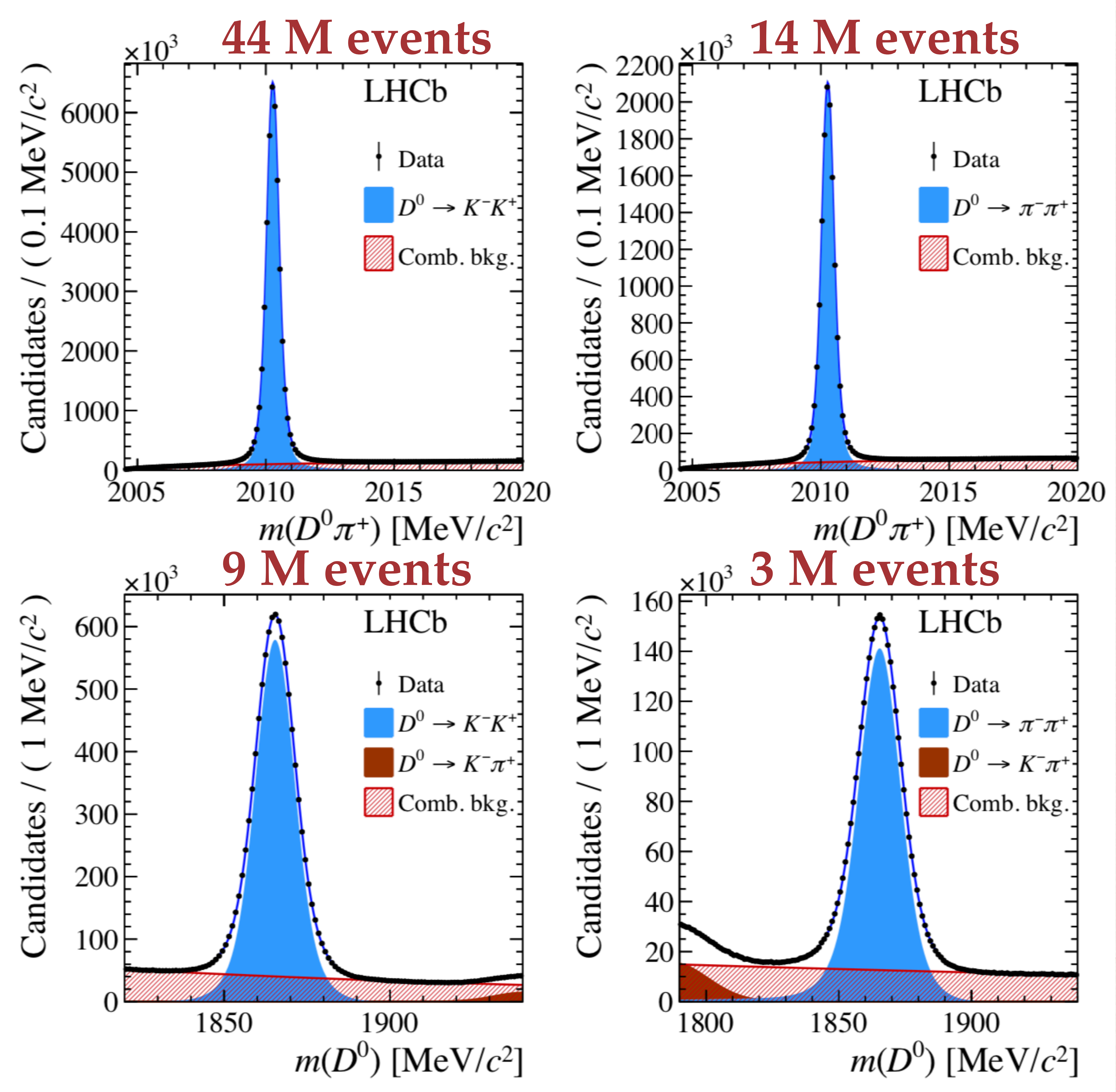
$\approx +3 \times 10^{-5}$, with earlier ΔY result

- Using both $D^{*+} \to D^0\pi^+$ (top) and $B^- \to D^0\mu^-\nu$ self-tagging sources of D^0 decays,

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

5.3σ from zero

To be determined if *KK* or $\pi\pi$ or neither are consistent with zero



Other direct CPV searches with charm

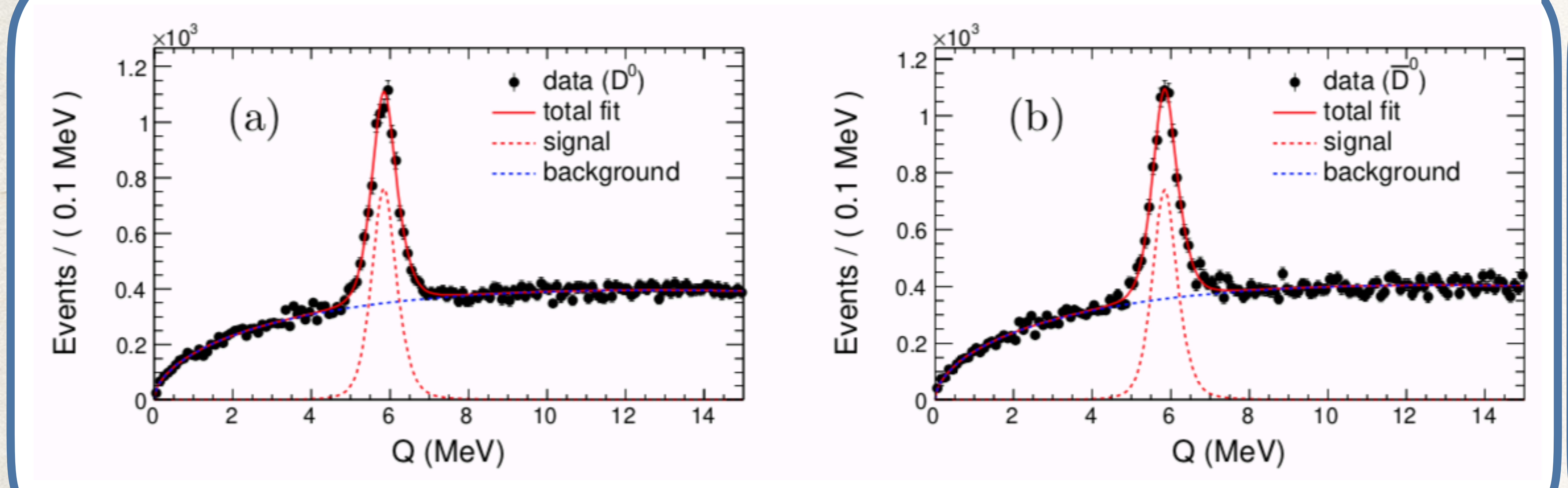
Belle: JHEP 2021, 75

Belle: Phys. Rev. D 103, 112005

- Belle dataset ($0.98\,\mathrm{ab}^{-1}$) used to improve branching fractions and search for CP asymmetries

With D^0 mesons,

$D^0 \to \pi^+\pi^-\eta$ shown. ($Q \equiv \Delta m$)



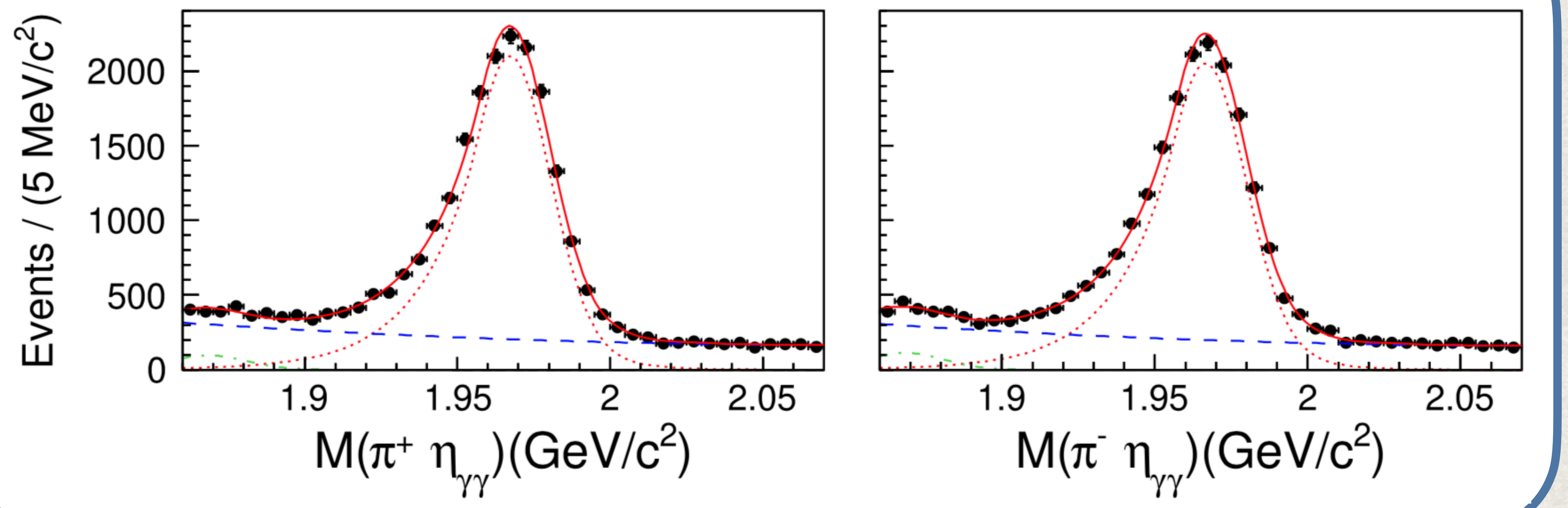
$$A_{CP}(D^0 \to \pi^+\pi^-\eta) = [0.9 \pm 1.2\,(\mathrm{stat}) \pm 0.5\,(\mathrm{syst})]\%\,,$$ 13k events

$$A_{CP}(D^0 \to K^+K^-\eta) = [-1.4 \pm 3.3\,(\mathrm{stat}) \pm 1.1\,(\mathrm{syst})]\%\,,$$ 1462 events

$$A_{CP}(D^0 \to \phi\eta) = [-1.9 \pm 4.4\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst})]\%\,.$$ 728 events

With D_s^+ mesons,

$D_s^+ \to \pi^+\eta$ shown.



$$A_{CP}(D_s^+ \to K^+\pi^0) = 0.064 \pm 0.044 \pm 0.011$$ 12k events

$$A_{CP}(D_s^+ \to K^+\eta) = 0.021 \pm 0.021 \pm 0.004$$ 14k events

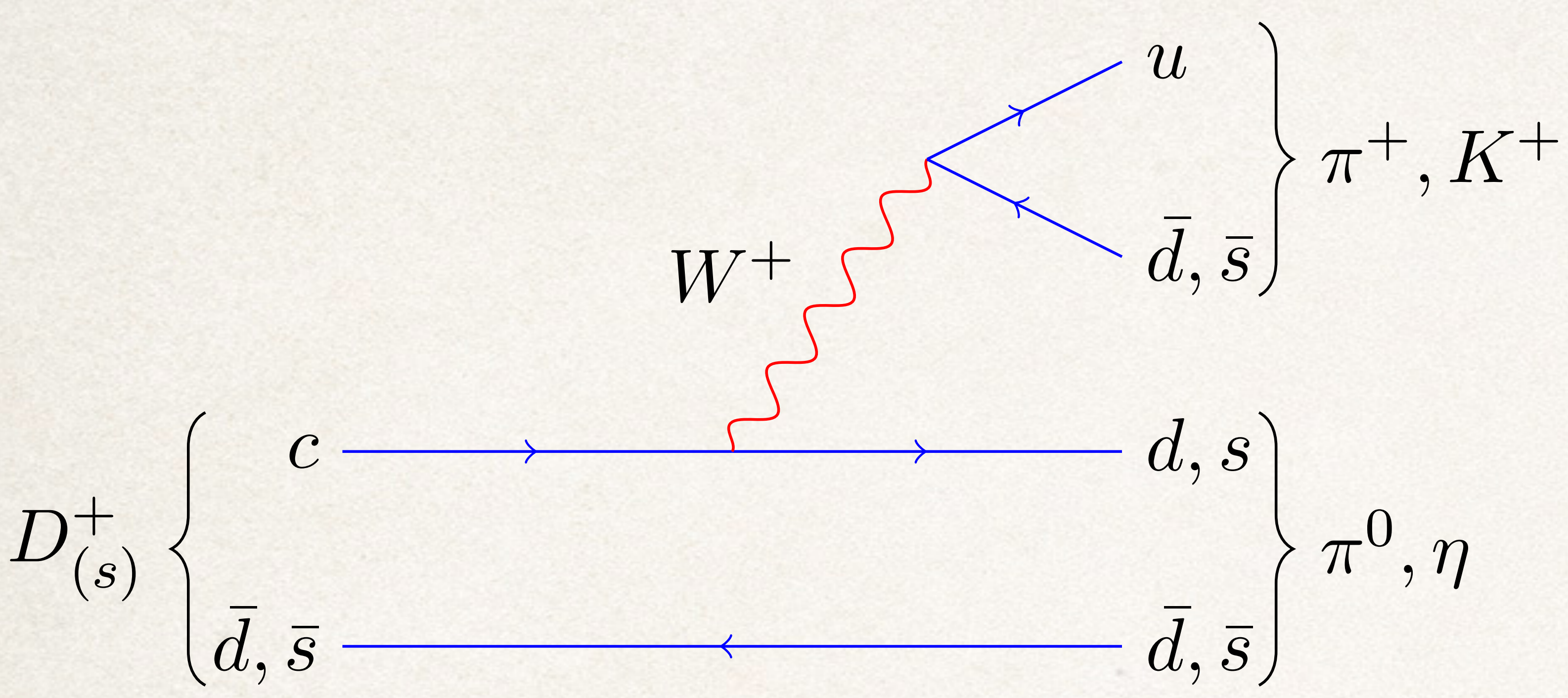
$$A_{CP}(D_s^+ \to \pi^+\eta) = 0.002 \pm 0.003 \pm 0.003.$$ 223k events

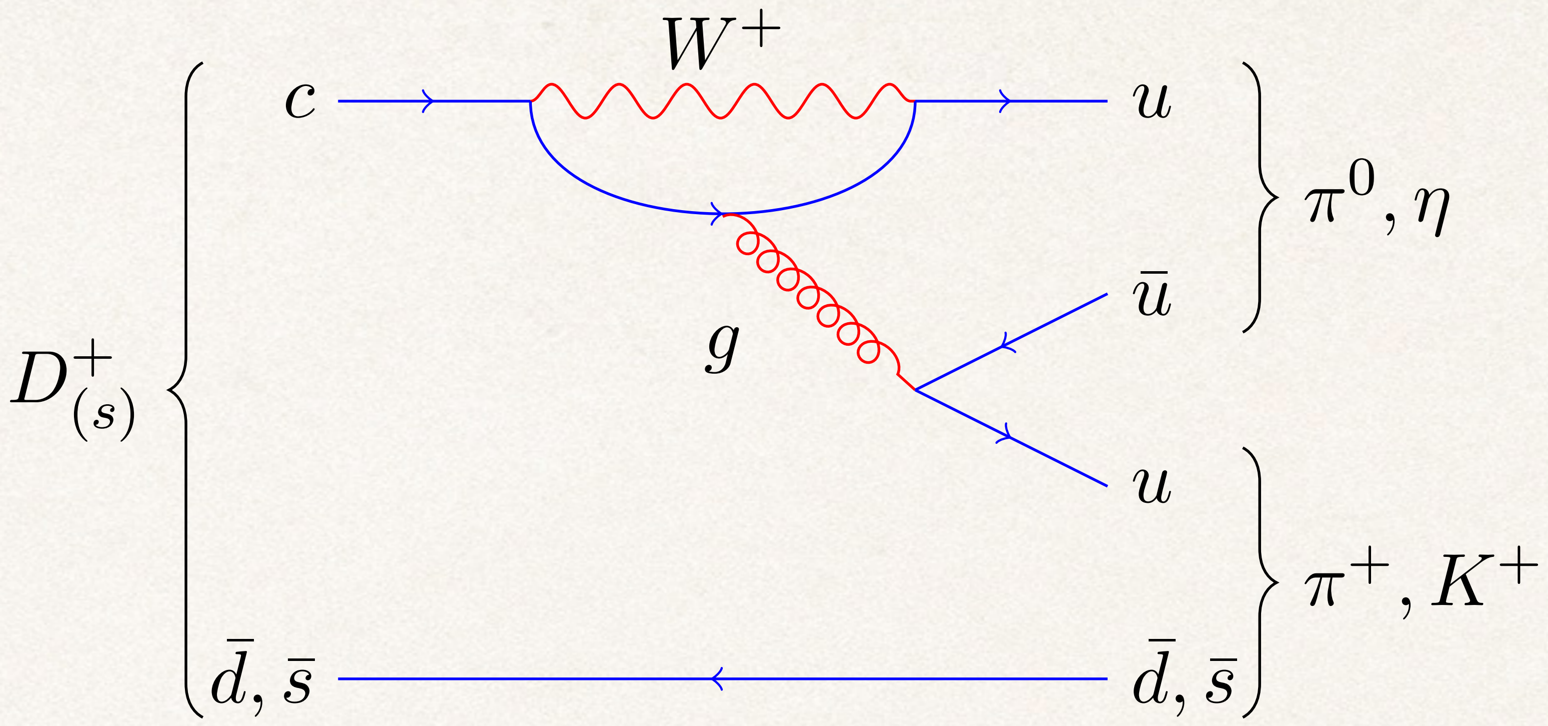
All consistent with zero

CPV search with $D^+ \to \pi^+\pi^0$

LHCb: JHEP 06 (2021) 019

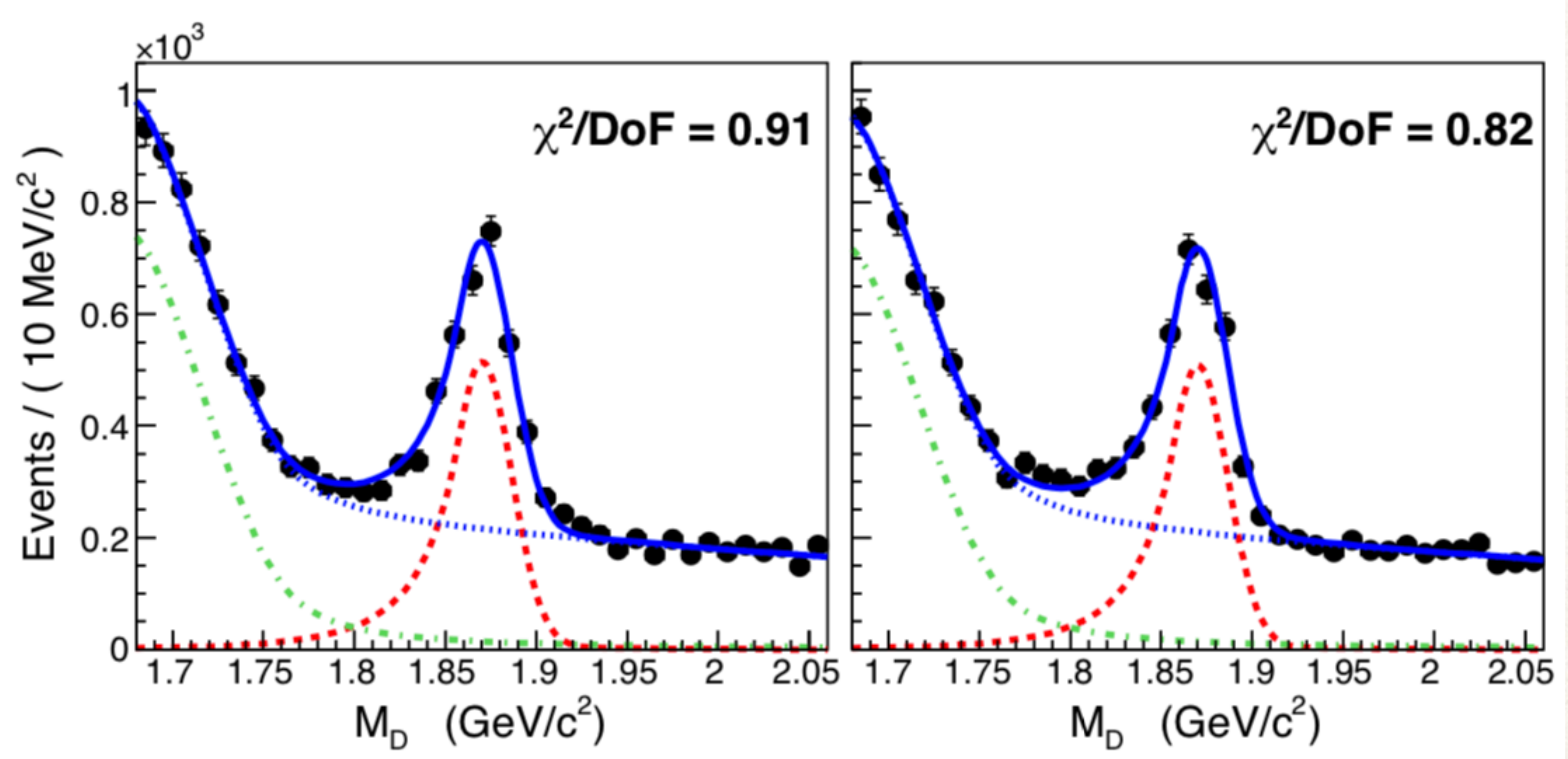
Belle: Phys. Rev. D 97, 011101 (2018)

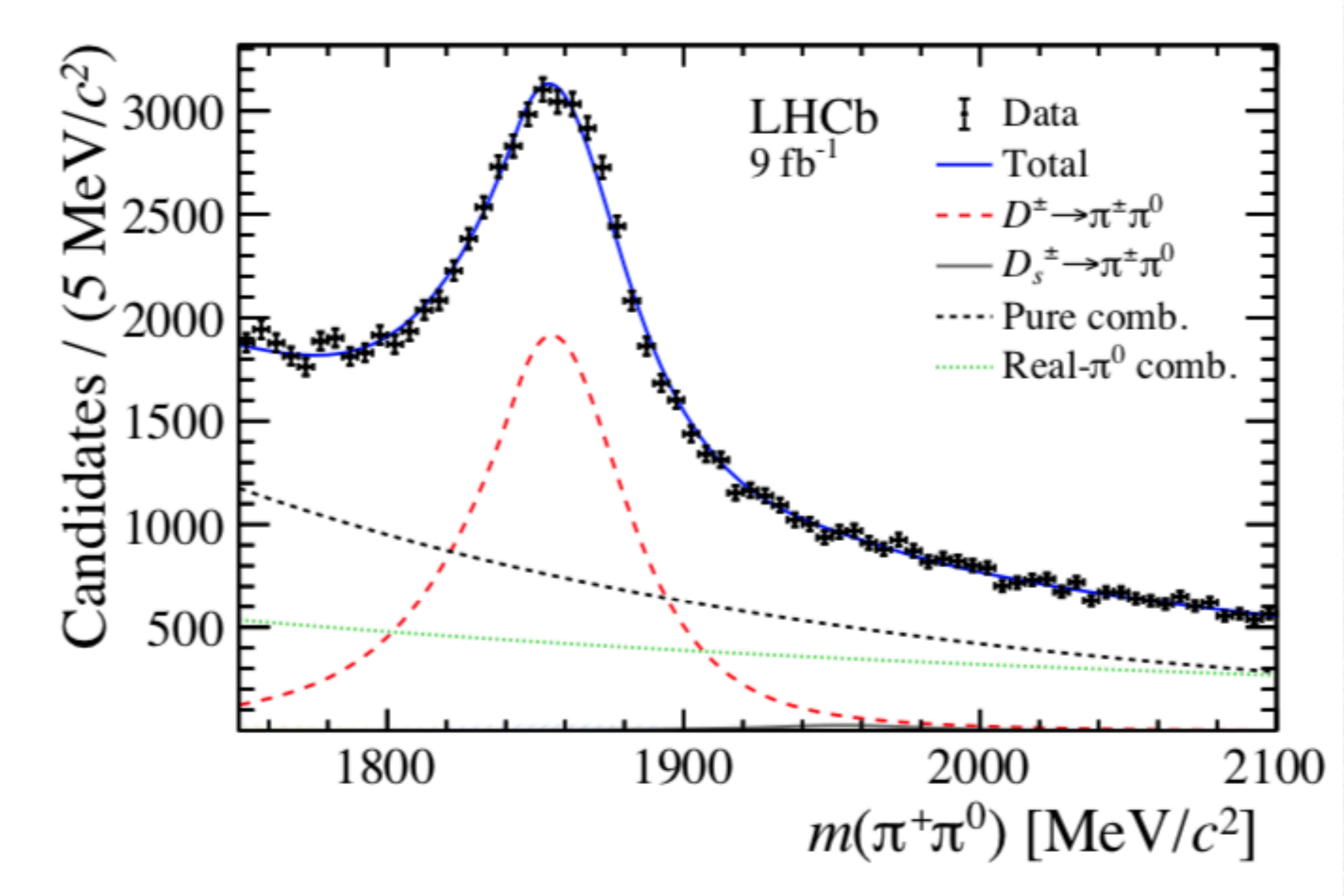


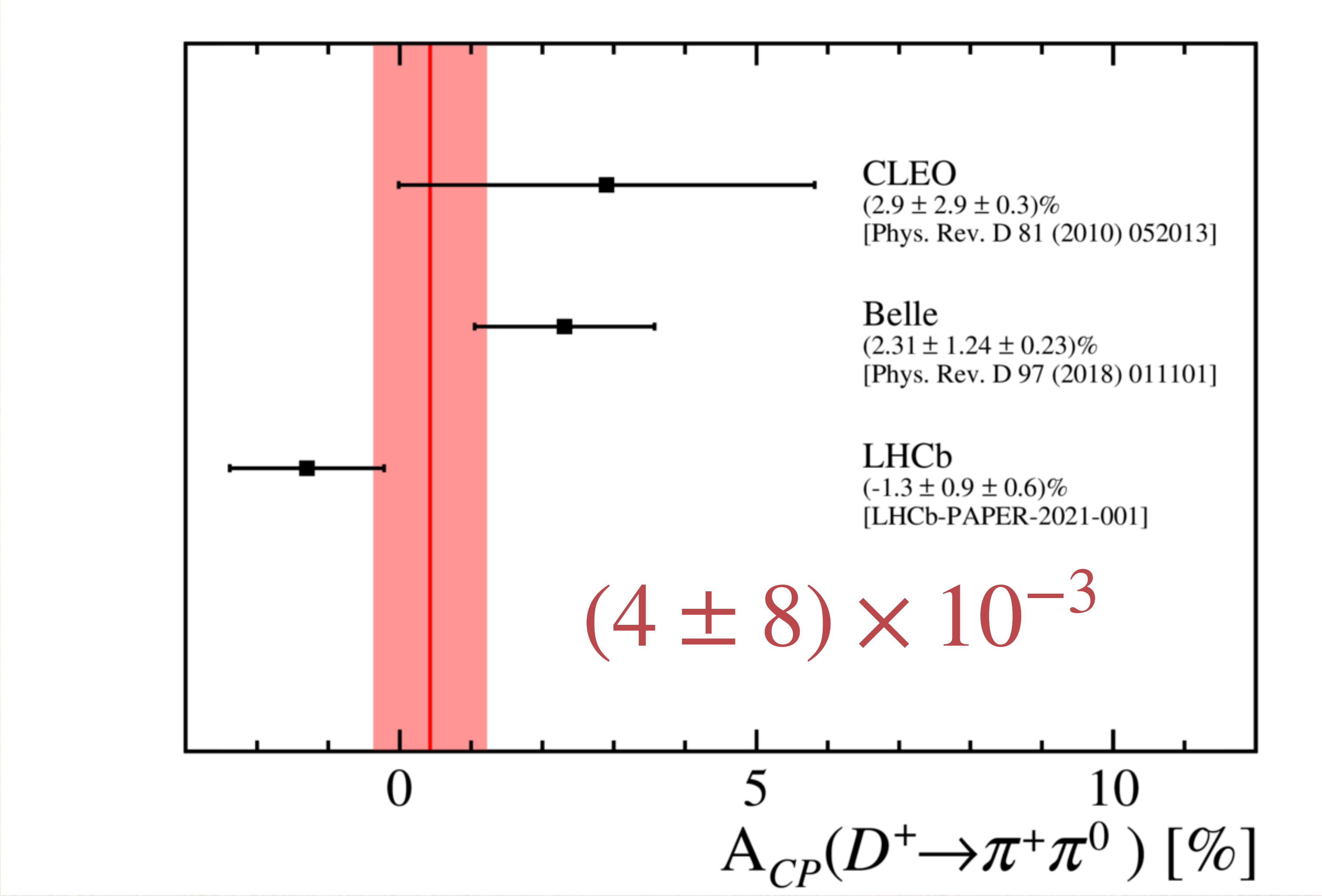


- Final state should symmetric in flavour.
- So must be a $I = 2$ as $I_3 = 1$.
- Thus $\Delta I = \frac{3}{2}$. ($\Delta I = \frac{1}{2}$ in W^+ exchange)
- $\Delta I = 1$ in gluon line would be a flavour change, so second diagram forbidden.
- So one set of CKM factors contributes.
- Thus: zero *CP* violation.

- Very challenging reconstruction for LHCb. Trick: use $\pi^0 \to \gamma e^+ e^-$, including conversions







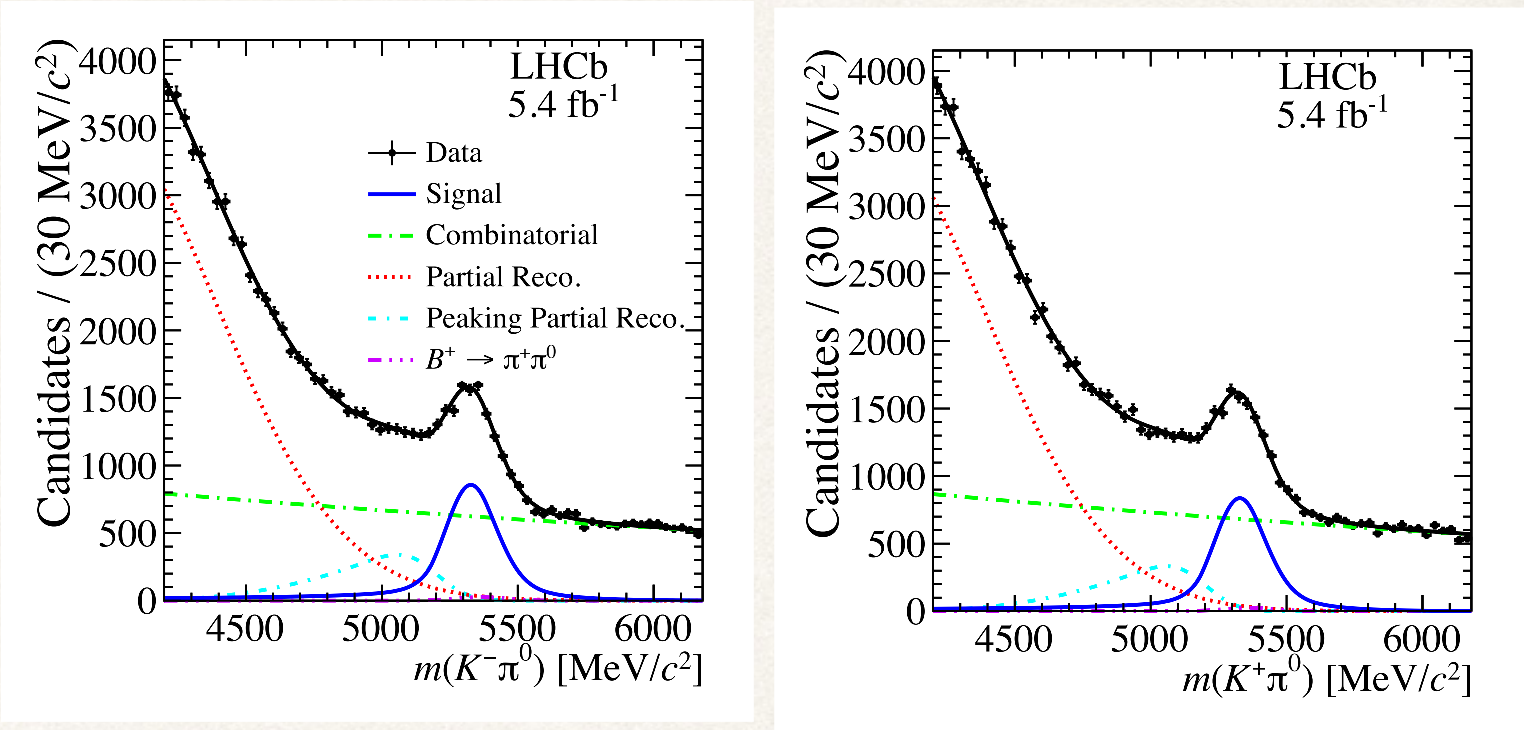
- Belle: 6.6k events ($0.92\,\mathrm{ab}^{-1}$)
- LHCb 26k events ($6\,\mathrm{fb}^{-1}$)

LHCb: Phys. Rev. Lett. 126 (2021) 091802
Belle II ($K^+\pi^0$): https://arxiv.org/abs/2105.04111
Belle II ($K^0\pi^0$): https://arxiv.org/abs/2104.14871

$B \to K\pi$

- Long-standing puzzle. Assuming isospin symmetry of the spectator quark, expect $I_{K\pi} = 0$.

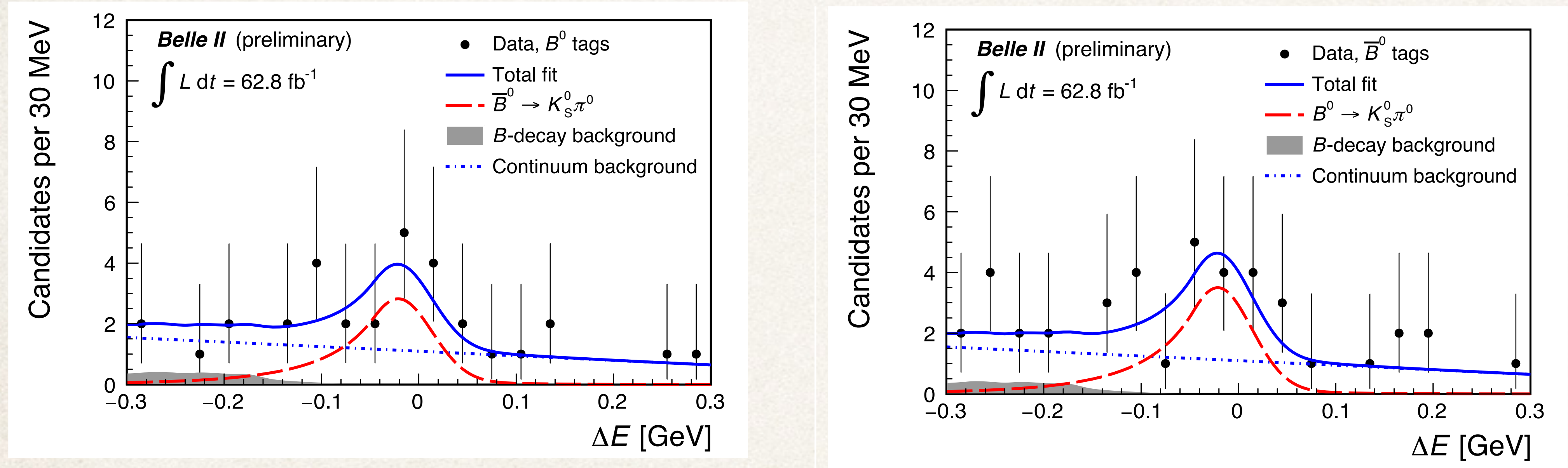
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$



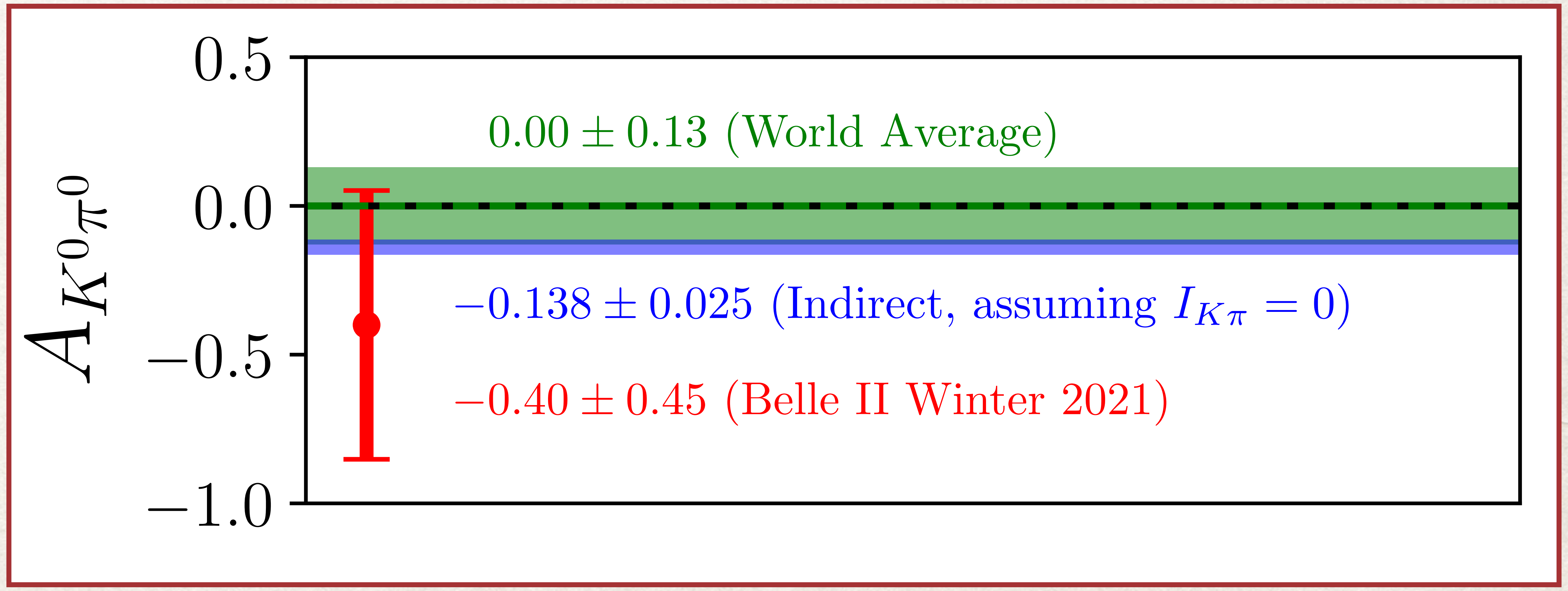
- LHCb now provide new information with 16.7k events.

$$A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$$

- First measurement of $A_{K^0\pi^0}$ by Belle II



- Belle II predict $\sigma\left(A_{K^0\pi^0}\right)$ reach 0.025 with 50 ab^{-1}



Progress likely to be dominated by Belle II

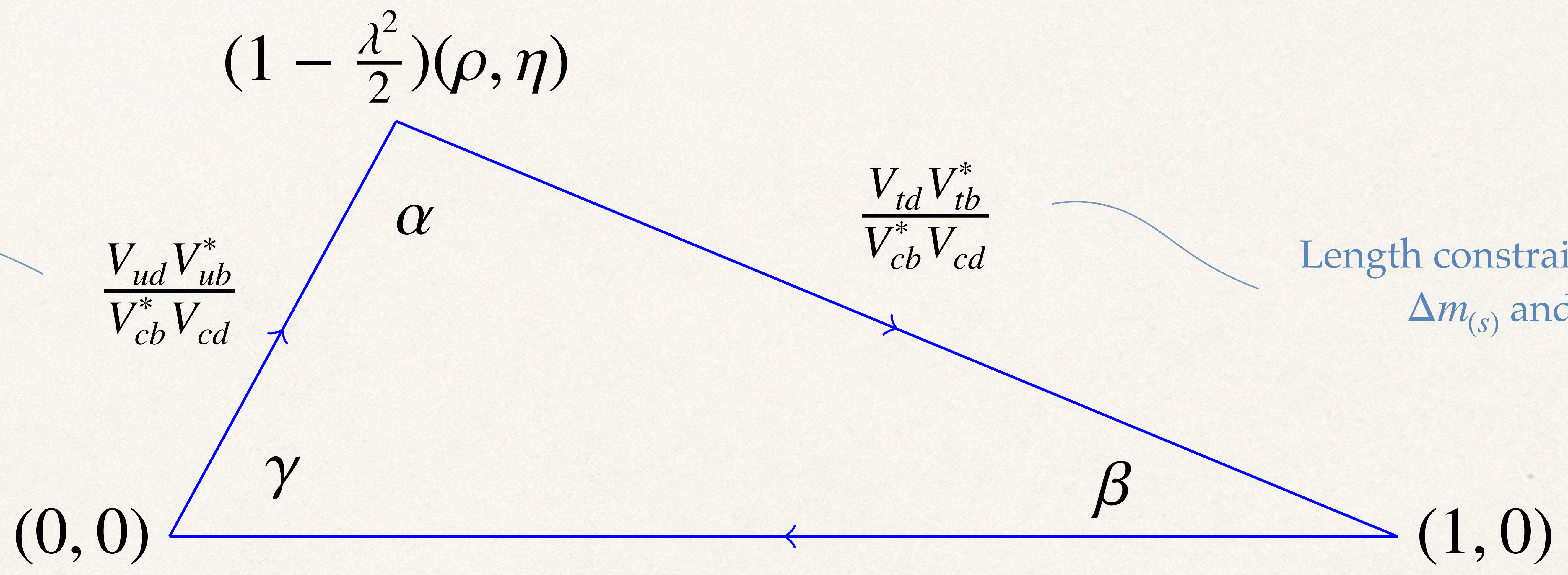
Unitarity triangle, β, γ

Little progress on α in the last decade but Belle II will lead here with $B \to \pi\pi$ & $\rho\rho$

arxiv/2104.06224

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2-\lambda^4/8(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2+\frac{\lambda^4}{2}A\,(1-2(\rho+i\eta)) & 1-\lambda^4/2A^2 \end{pmatrix} + \mathcal{O}(\lambda^5)$$

Forming inner product of 1st and 3rd columns gives the UT



Length constrained by measurements of semileptonic $b \to u$ decays and QCD calculations

Length constrained by measurements of $\Delta m_{(s)}$ and QCD calculations

$$\gamma = \arg\left(-\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}}\right) \qquad \beta = \arg\left(-\frac{V_{cb}^*V_{cd}}{V_{tb}^*V_{td}}\right)$$

Similarly (but smaller) :

$$\beta_s = \arg\left(-\frac{V_{cb}^*V_{cs}}{V_{tb}^*V_{ts}}\right)$$

JHEP 11 (2017) 170

$\sin 2\beta$: the *CP*-violating phase of B^0 mixing

- Flagship result of the *B*-factories. LHCb has become, and should remain, competitive.

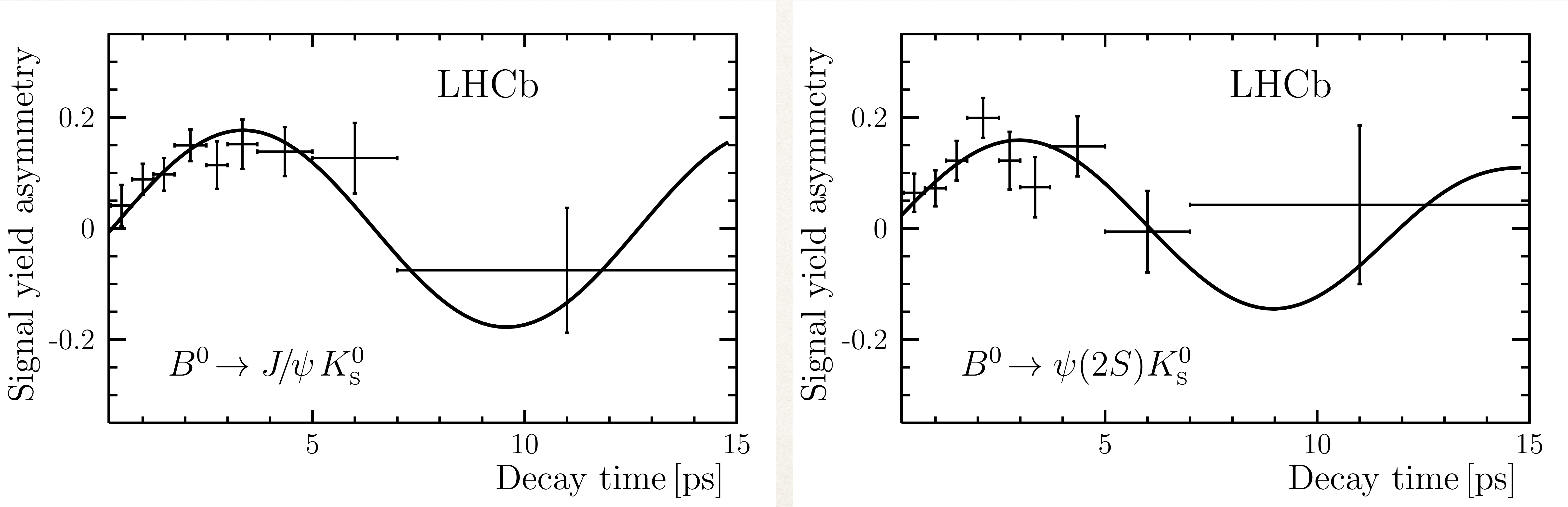
$$\mathcal{A}_{[c\bar{c}]K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t)\to[c\bar{c}]K^0_S) - \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}{\Gamma(\overline{B}^0(t)\to[c\bar{c}]K^0_S) + \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}$$

$$= \frac{S\sin(\Delta m\, t) - C\cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)} \approx S\sin(\Delta m\, t) - C\cos(\Delta m\, t)$$

$C_{\mathrm{SM}} \simeq 0$

$S_{\mathrm{SM}} = \sin 2\beta$

(the amplitude of the sine wave after correction for mis-tagging)

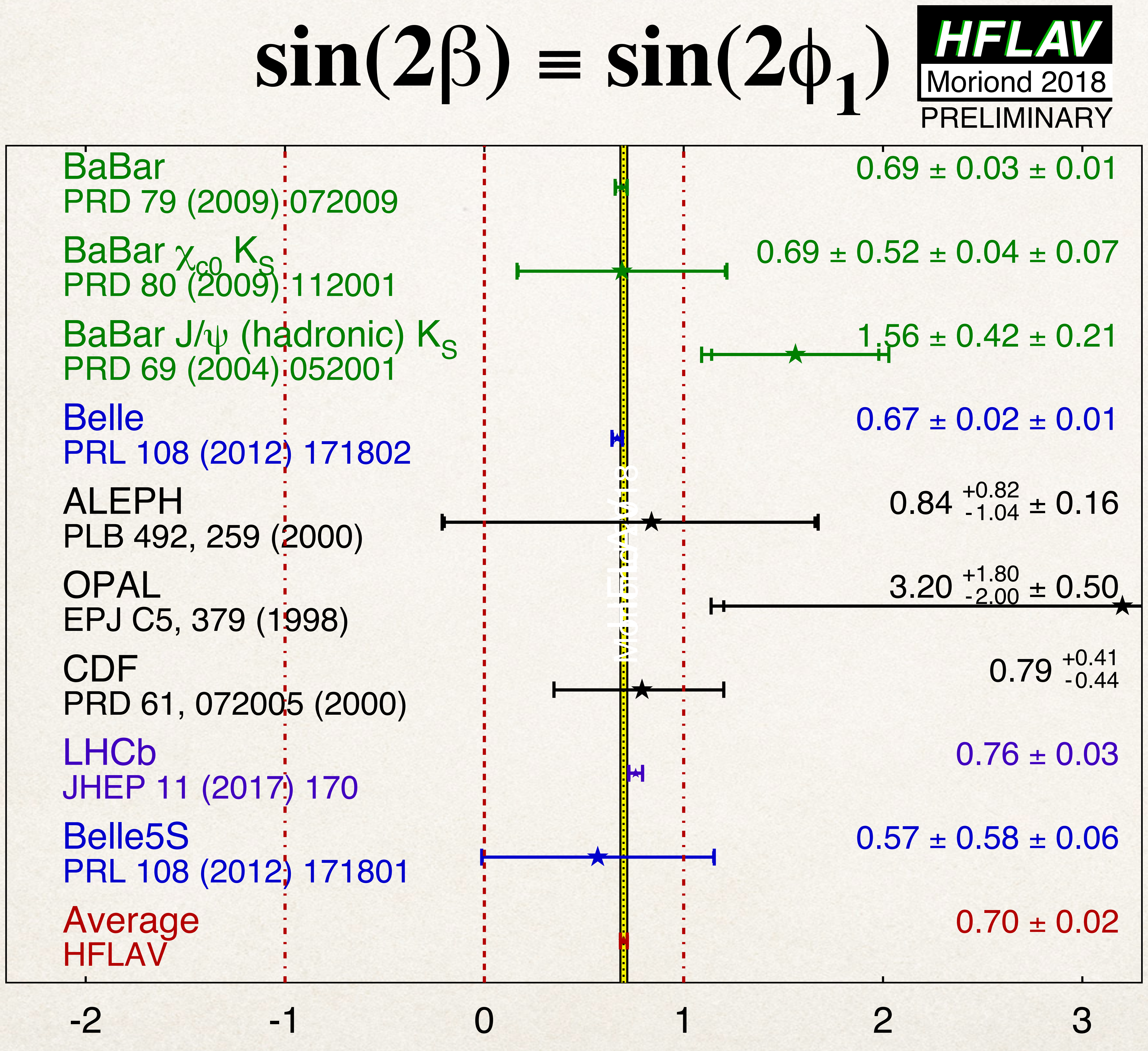


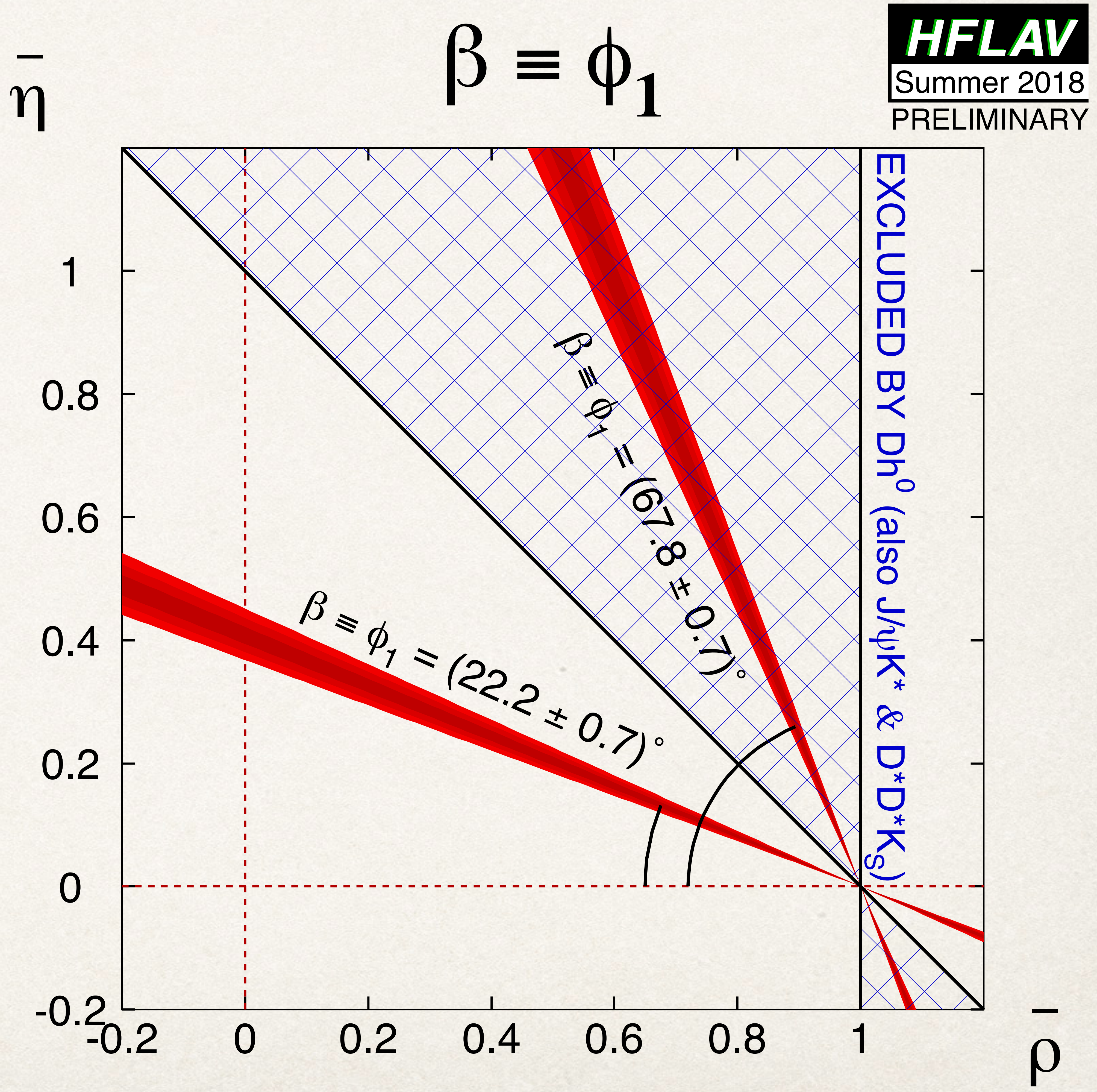
$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$

https://hflav-eos.web.cern.ch/hflav-eos/triangle/pdg2021/index.shtml#sin2b

sin 2β : world average

- Should remain the most precise UT angle throughout the BelleII / LHCb era.



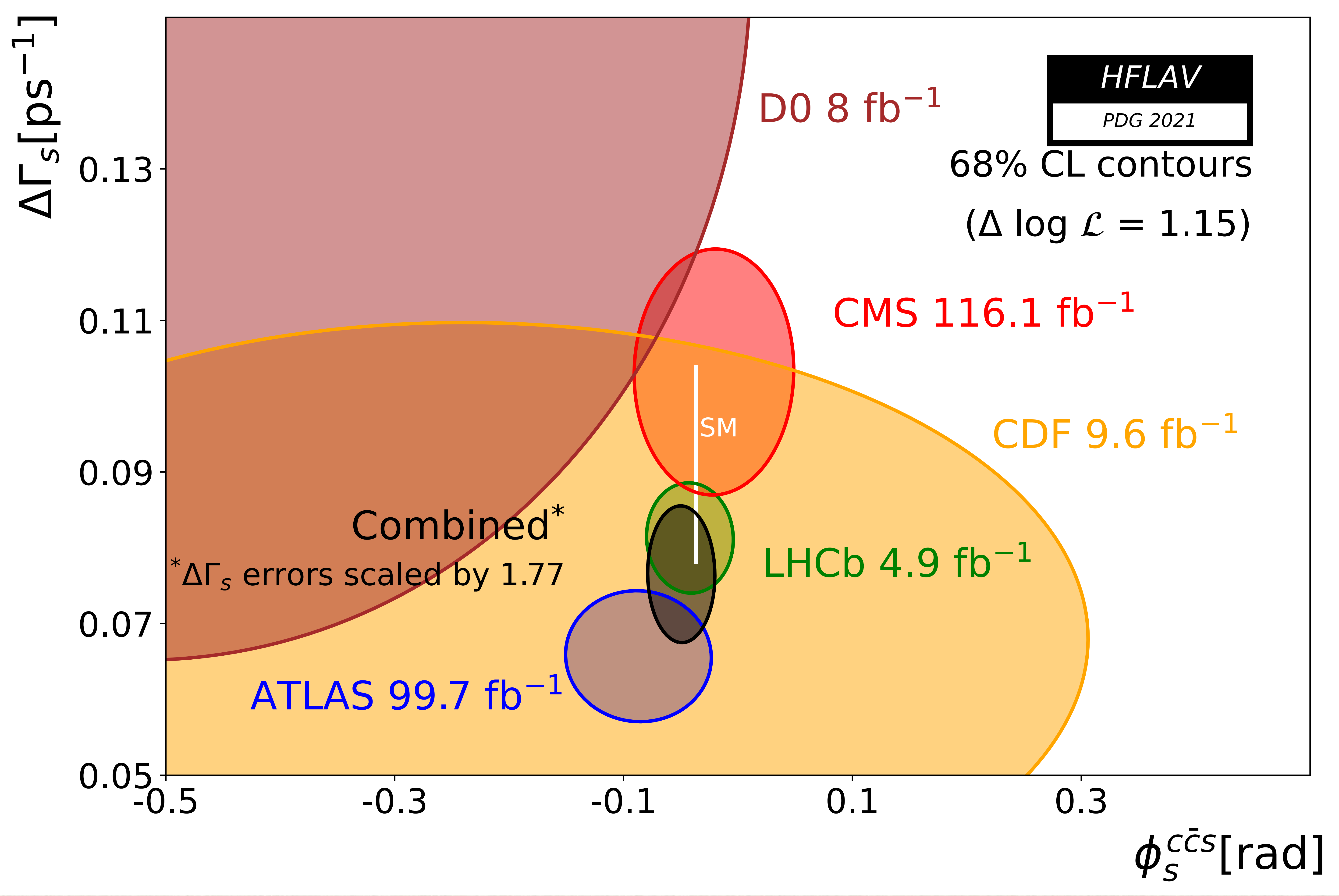


$\phi_s = -2\beta_s$: the CP-violating phase of B_s^0 mixing

- β_s is analogous to β but is much smaller in the SM due to smallness of the complex phase in V_{ts}
- LHCb / ATLAS / CMS use time-dependent analysis of $B_s \to J/\psi \left(K^+K^-\right)_\phi$ (LHCb also $B_s \to J/\psi\pi^+\pi^-$)

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})
CDF	$J/\psi\,\phi$	9.6 fb^{-1}	$[-0.60,\ +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$
D0	$J/\psi\,\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$
ATLAS	$J/\psi\,\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$
ATLAS	$J/\psi\,\phi$	14.3 fb^{-1}	$-0.110 \pm 0.082 \pm 0.042$	$+0.101 \pm 0.013 \pm 0.007$
ATLAS	$J/\psi\,\phi$	80.5 fb^{-1}	$-0.081 \pm 0.041 \pm 0.022$	$+0.0607 \pm 0.0047 \pm 0.0043$
ATLAS	above 3 combined	(99.7 fb^{-1})	$-0.087 \pm 0.036 \pm 0.021$	$+0.0657 \pm 0.0043 \pm 0.0037$
CMS	$J/\psi\,\phi$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$
CMS	$J/\psi\,\phi$	96.4 fb^{-1}	$-0.011 \pm 0.050 \pm 0.010$	$+0.114 \pm 0.0014 \pm 0.0007$
CMS	above 2 combined	(116.1 fb^{-1})	$-0.021 \pm 0.044 \pm 0.010$	$+0.1032 \pm 0.0095 \pm 0.0048$
LHCb	$J/\psi\,K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0032$
LHCb	$J/\psi\,\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—
LHCb	$J/\psi\,K^+K^-$ [a]	3.0 fb^{-1}	$+0.119 \pm 0.107 \pm 0.034$	$+0.066 \pm 0.018 \pm 0.010$
LHCb	$\psi(2S)\phi$	3.0 fb^{-1}	$+0.23^{+0.29}_{-0.28} \pm 0.02$	$+0.066^{+0.41}_{-0.44} \pm 0.007$
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—
LHCb	$J/\psi\,\pi^+\pi^-$	1.9 fb^{-1} [b]	$-0.057 \pm 0.060 \pm 0.011$	—
LHCb	$J/\psi\,K^+K^-$	1.9 fb^{-1} [b]	$-0.083 \pm 0.041 \pm 0.006$	$+0.077 \pm 0.008 \pm 0.003$
LHCb		above 7 combined	-0.042 ± 0.025(tot)	$+0.0813 \pm 0.0048$(tot)
All combined			-0.050 ± 0.019	$+0.082 \pm 0.005$

[a] $m(K^+K^-) > 1.05$ GeV/c^2. [b] Run 2.



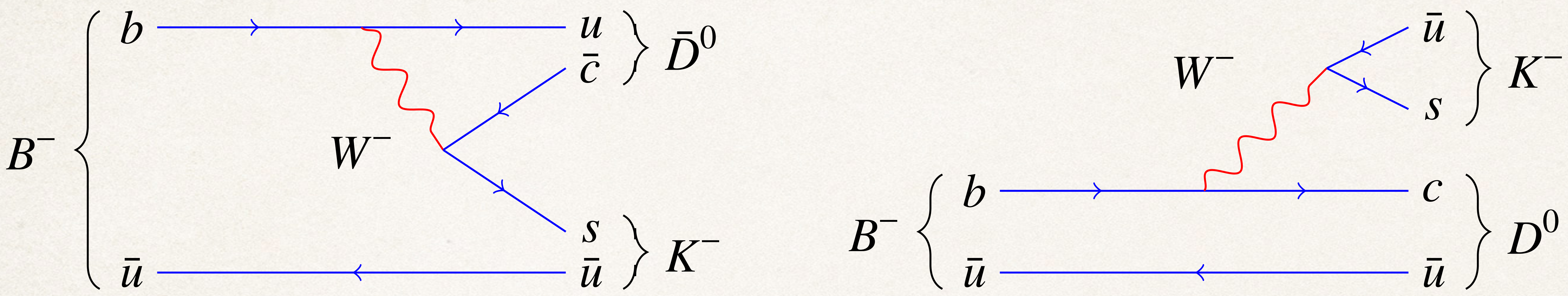
HFLAV: $\phi_s = -0.050 \pm 0.019$

SM: $-2\beta_s = -0.037 \pm 0.001$

JHEP 04 (2021) 081

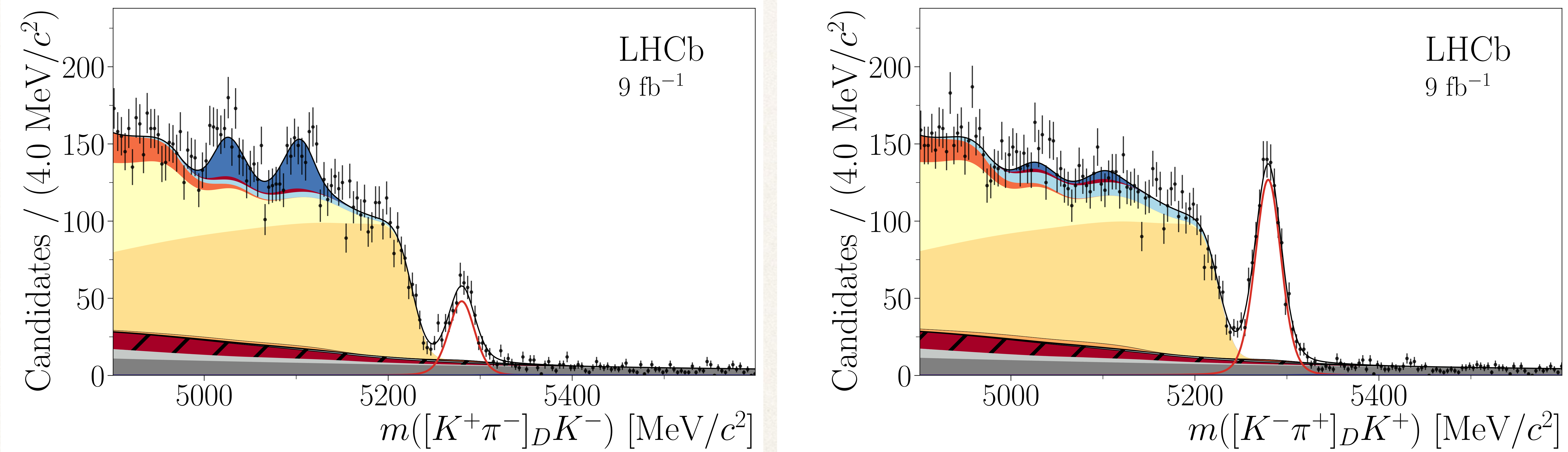
Unitarity angle γ : ADS/GLW

- The CP-violating phase in <u>tree-level</u> $b \to u \oplus b \to c$ transitions is γ. Negligible penguin/theory error



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

- Gives rise to large, direct asymmetries $\Gamma(B^\mp \to [[f]_D h^\mp]_X) \propto (r_D^f)^2 + (r_B^X)^2 + 2 r_D^f r_B^X \cos(\delta_B^X + \delta_D^f \mp \gamma)$



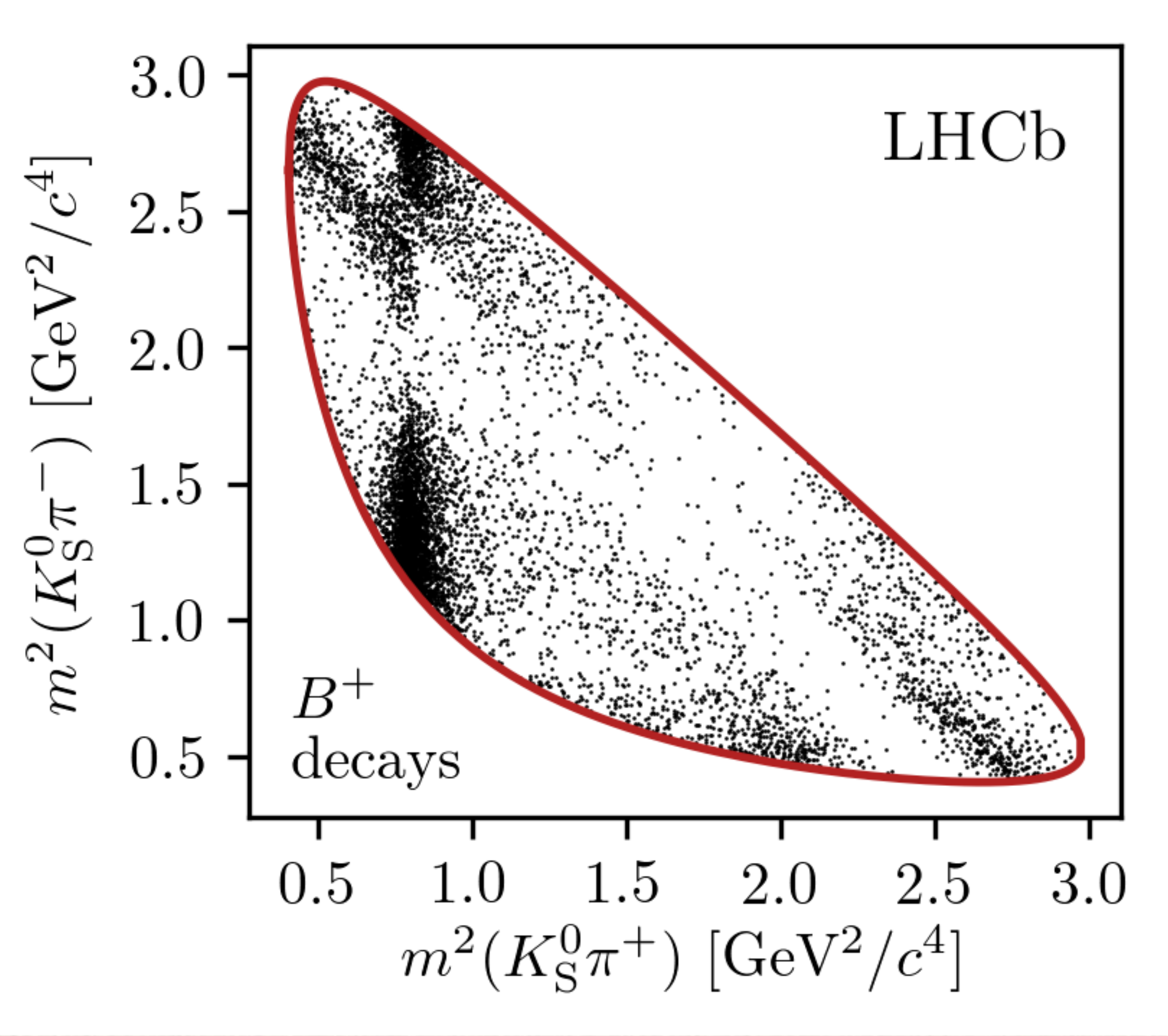
- γ not measured directly, but must be inferred along with other nuisance parameters, r_B, δ_B, δ_D, r_D

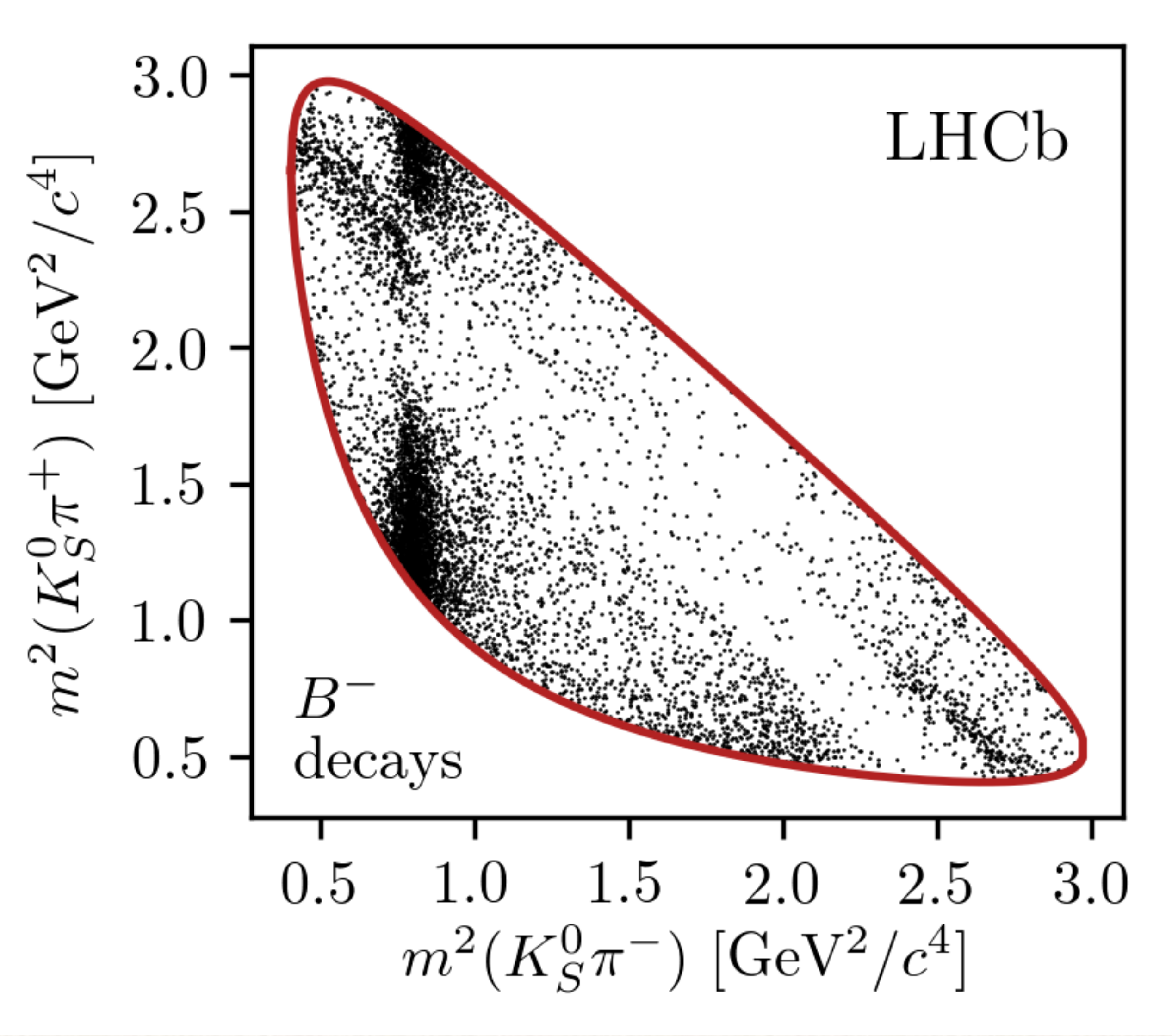
Unitarity angle $\gamma : K^0_S h^+ h^-$

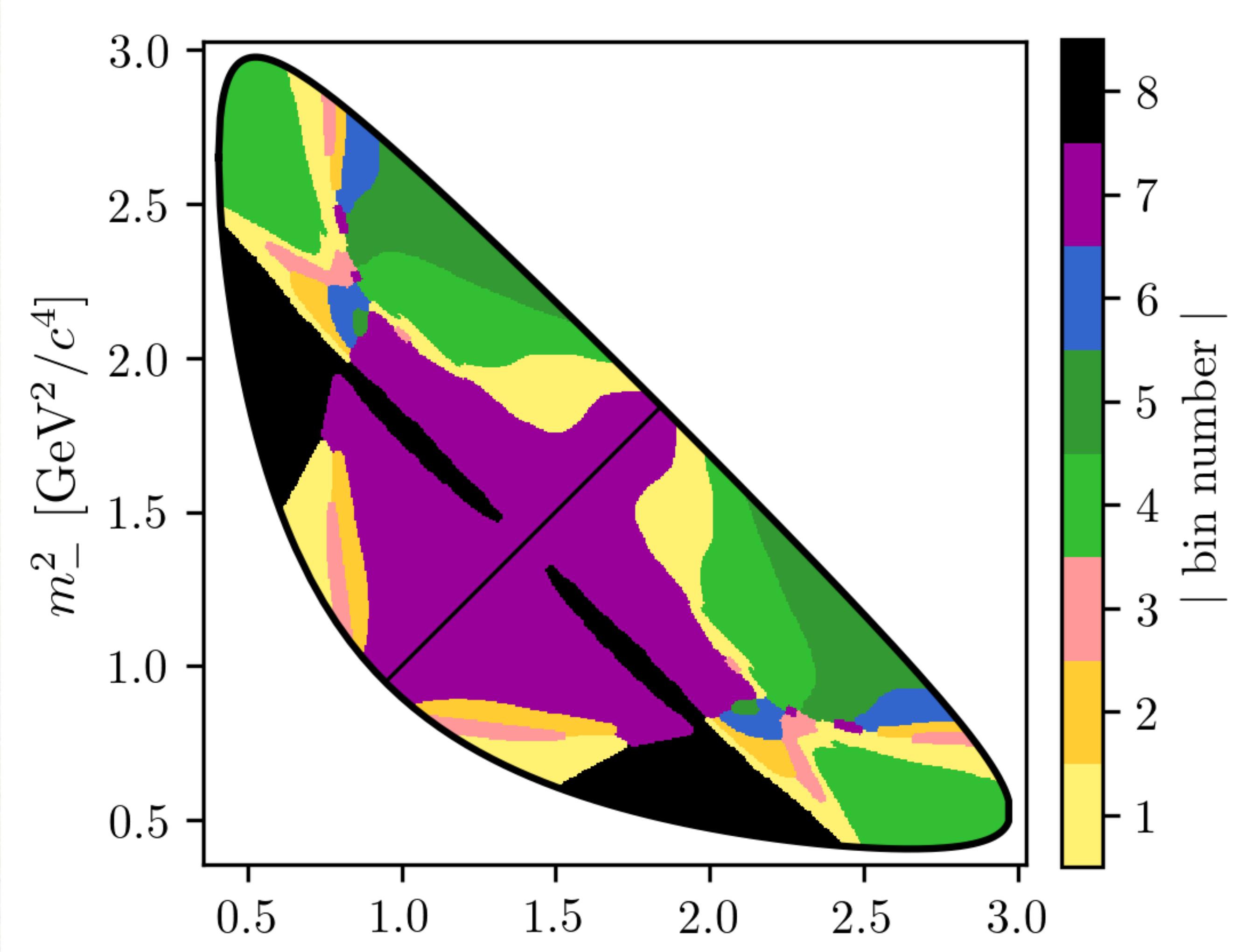
BESIII: Phys. Rev. D101 (2020) 112002

LHCb: JHEP 02 (2021) 169

- Recent work at BESIII has ensured c_i, s_i systematics remain 'small' for LHCb throughout 2020s

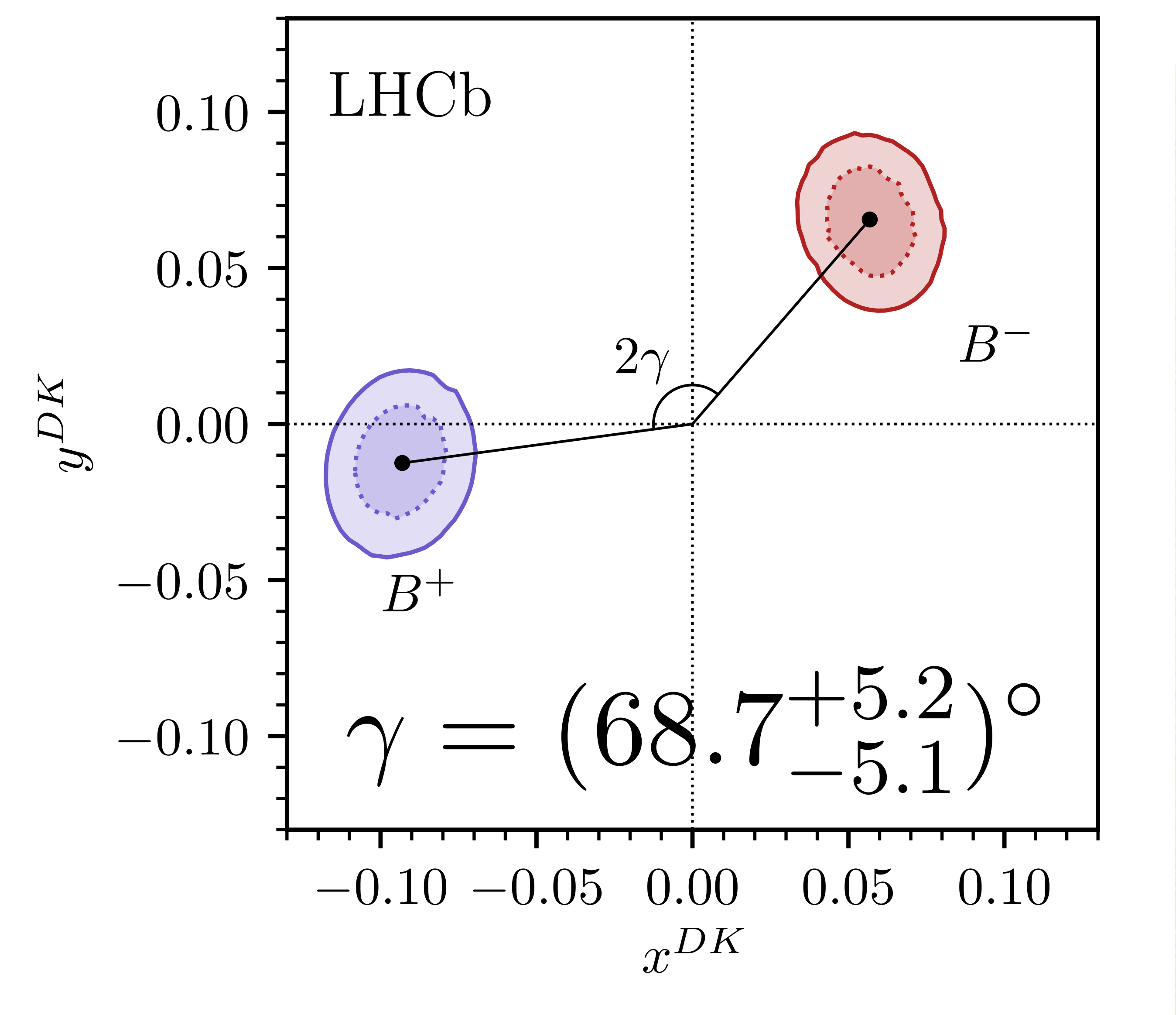






$$N^+_{+i} = h_{B^+}\left[F_{-i} + \left(\left(x^{DK}_+\right)^2 + \left(y^{DK}_+\right)^2\right)F_{+i} + 2\sqrt{F_i F_{-i}}\left(x^{DK}_+ c_{+i} - y^{DK}_+ s_{+i}\right)\right]$$
$$N^+_{-i} = h_{B^+}\left[F_{+i} + \left(\left(x^{DK}_+\right)^2 + \left(y^{DK}_+\right)^2\right)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x^{DK}_+ c_{+i} + y^{DK}_+ s_{+i}\right)\right]$$
$$N^-_{+i} = h_{B^-}\left[F_{+i} + \left(\left(x^{DK}_-\right)^2 + \left(y^{DK}_-\right)^2\right)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x^{DK}_- c_{+i} + y^{DK}_- s_{+i}\right)\right]$$
$$N^-_{-i} = h_{B^-}\left[F_{-i} + \left(\left(x^{DK}_-\right)^2 + \left(y^{DK}_-\right)^2\right)F_{+i} + 2\sqrt{F_i F_{-i}}\left(x^{DK}_- c_{+i} - y^{DK}_- s_{+i}\right)\right]$$

$$x^{DK}_\pm \equiv r^{DK}_B \cos(\delta^{DK}_B \pm \gamma) \quad \text{and} \quad y^{DK}_\pm \equiv r^{DK}_B \sin(\delta^{DK}_B \pm \gamma).$$



Unitarity angle $\gamma : K_S^0 h^+ h^-$

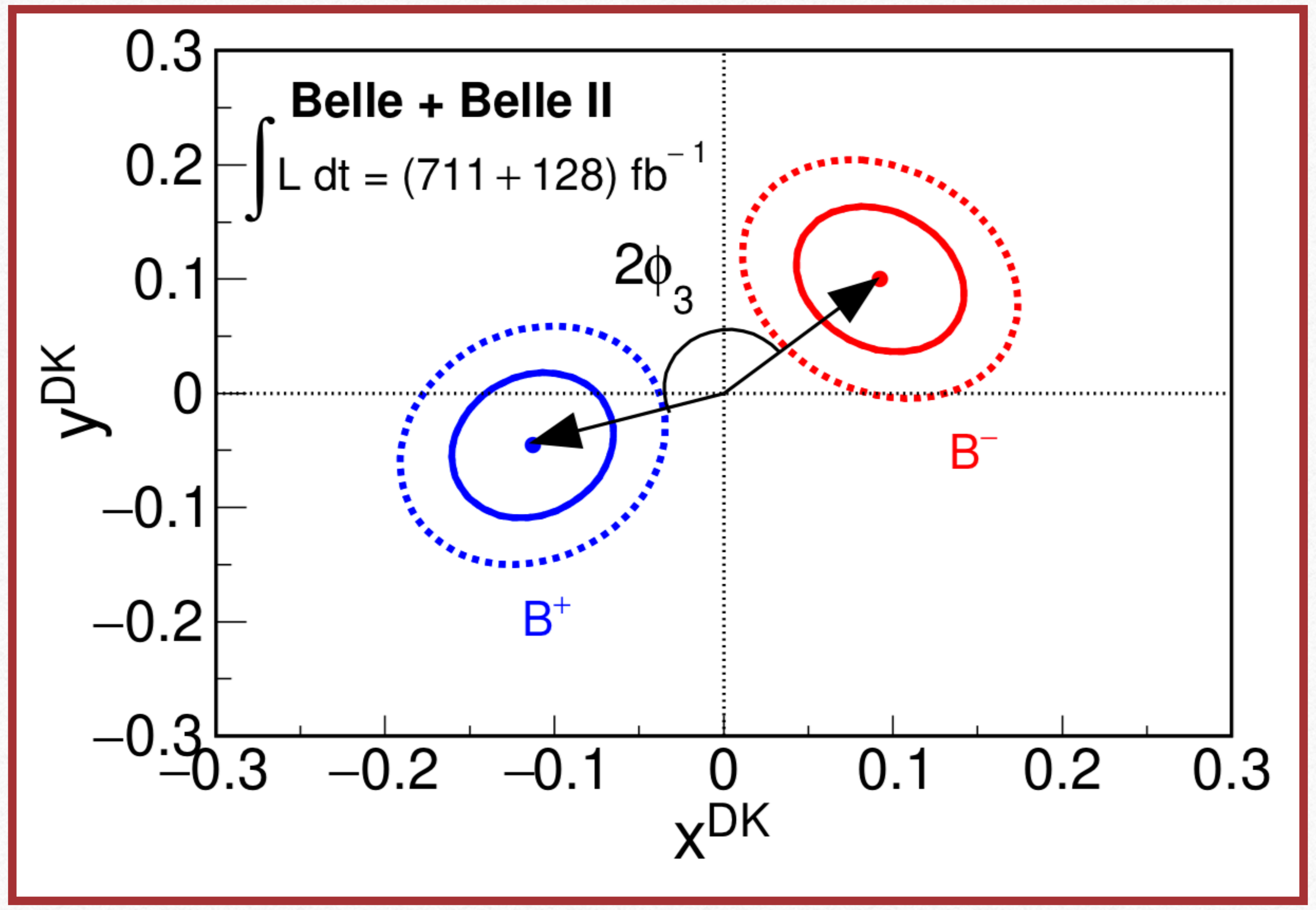
BESIII: Phys. Rev. D101 (2020) 112002

LHCb: JHEP 02 (2021) 169

Belle + Belle II https://arxiv.org/abs/2110.12125

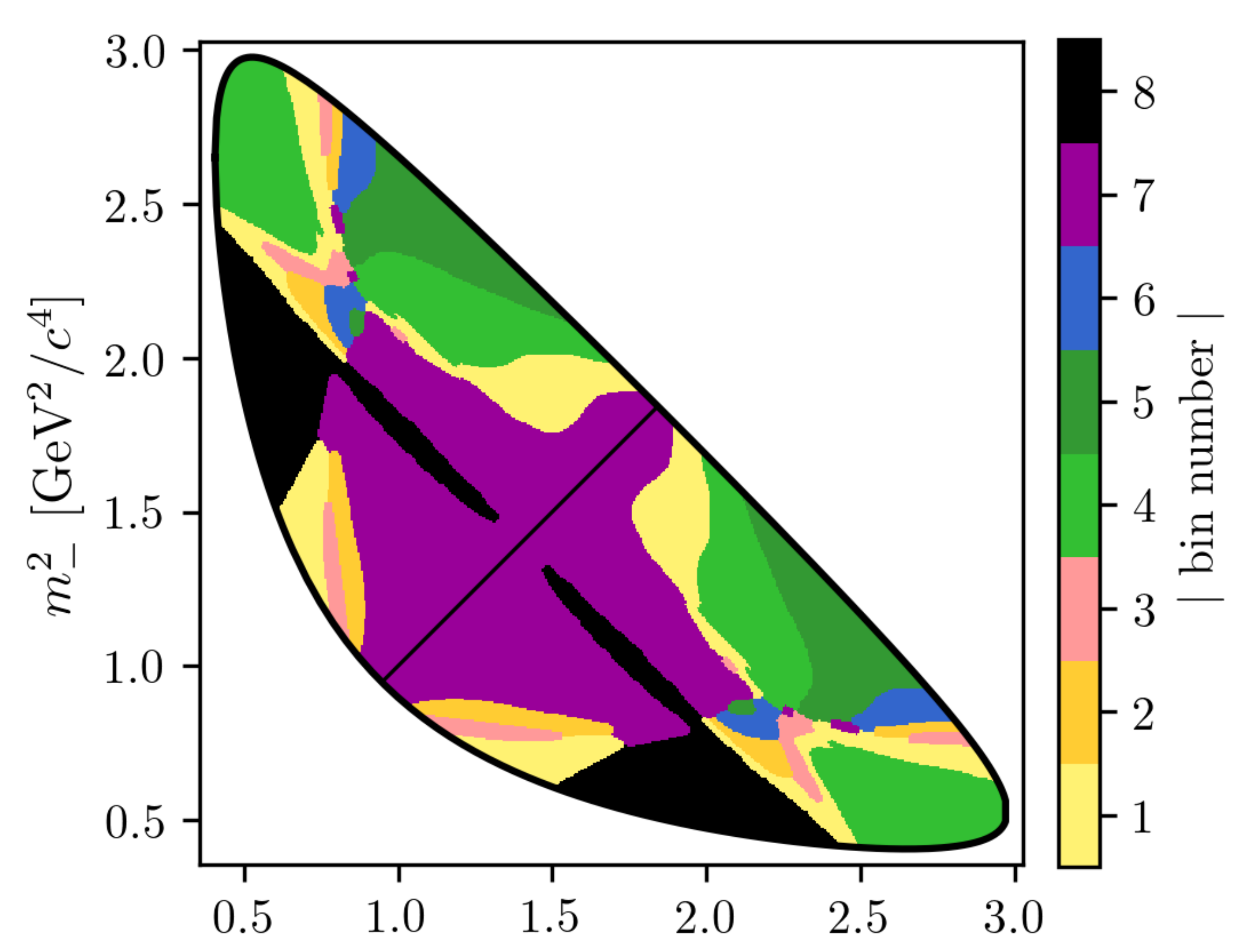
- Recent work at BESIII has ensured c_i, s_i systematics remain 'small' for LHCb throughout 2020s

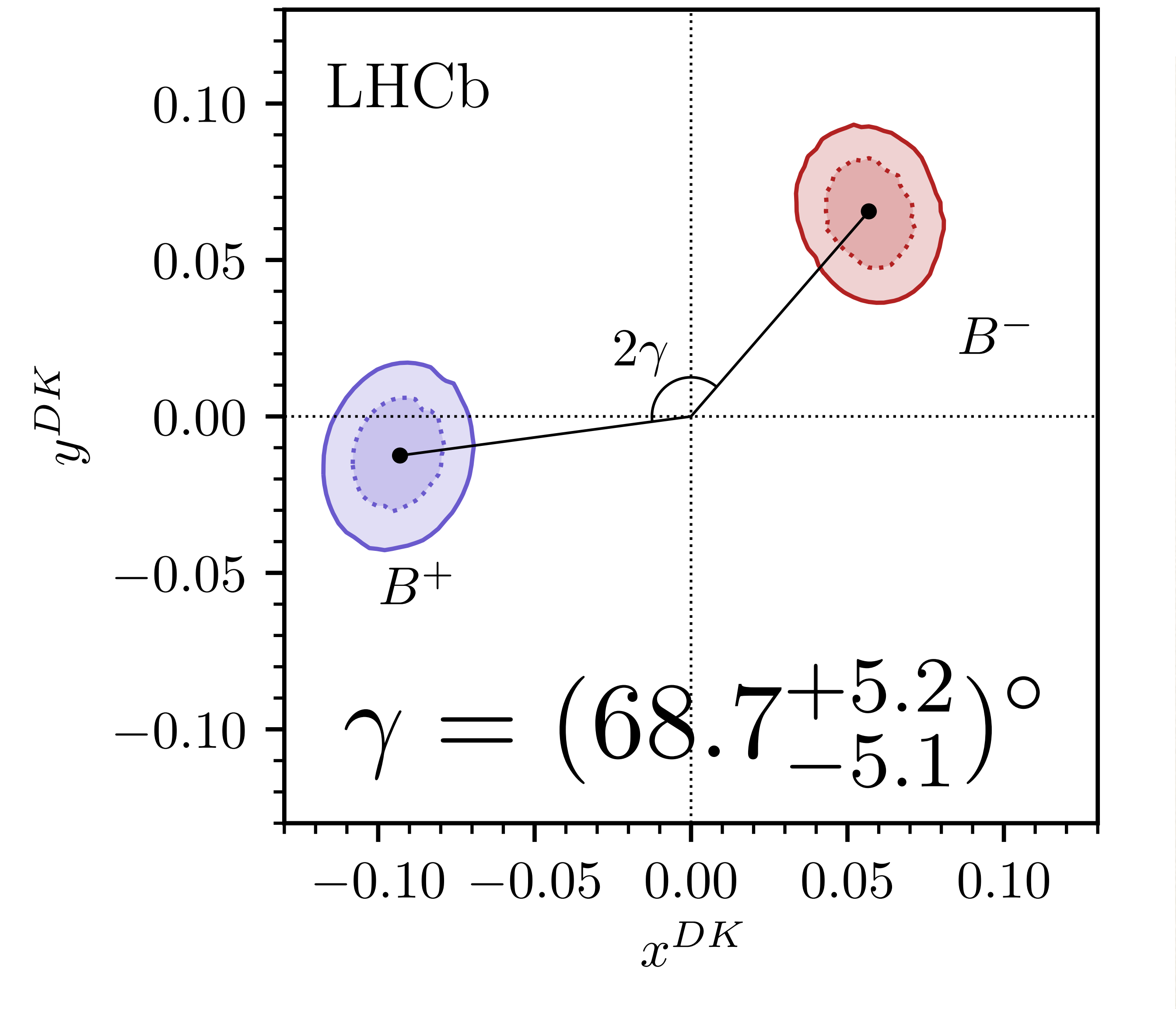
  - First major result on γ using Belle + BelleII data



$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$$

expect ~1° with 50 ab⁻¹



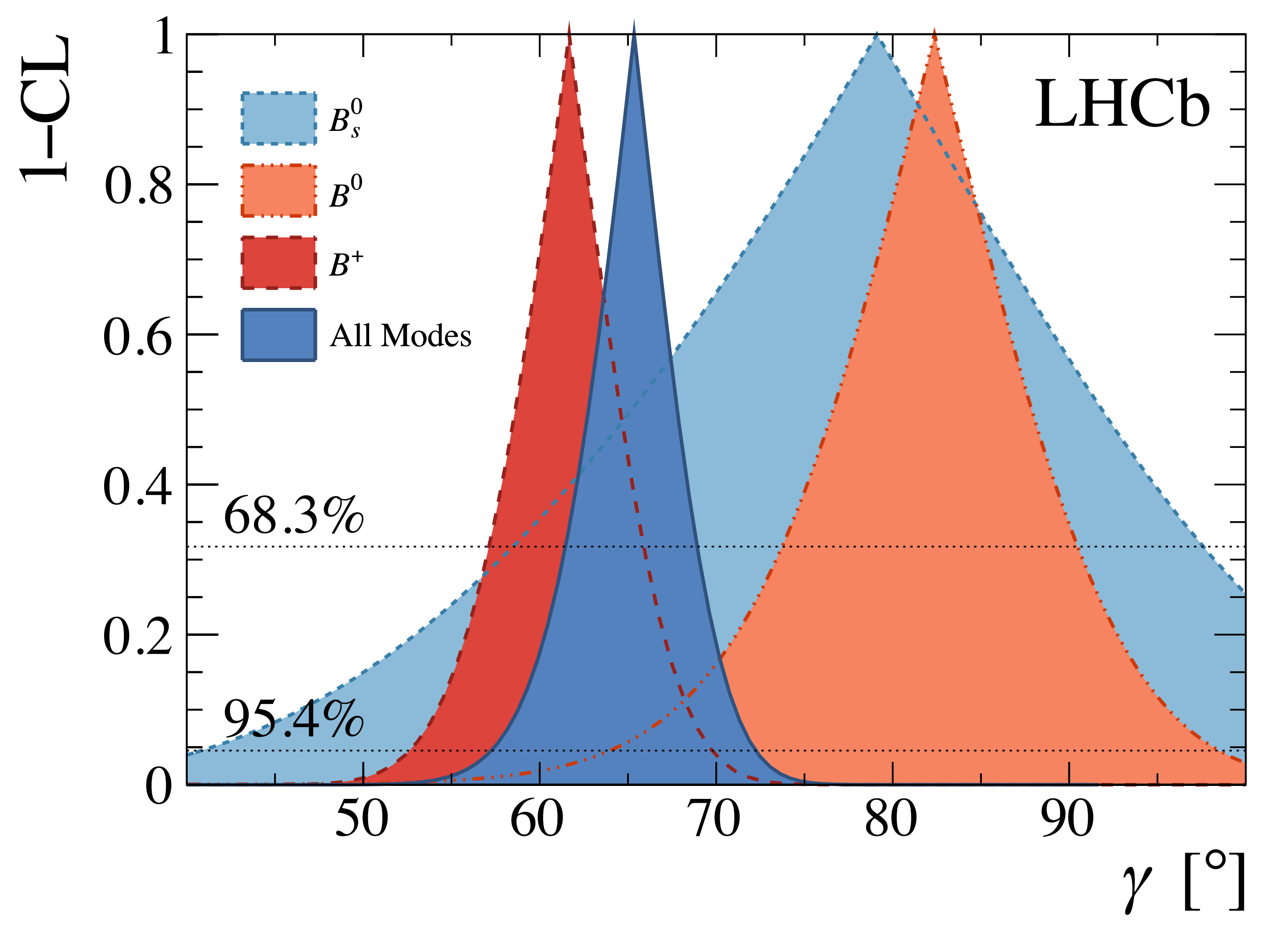


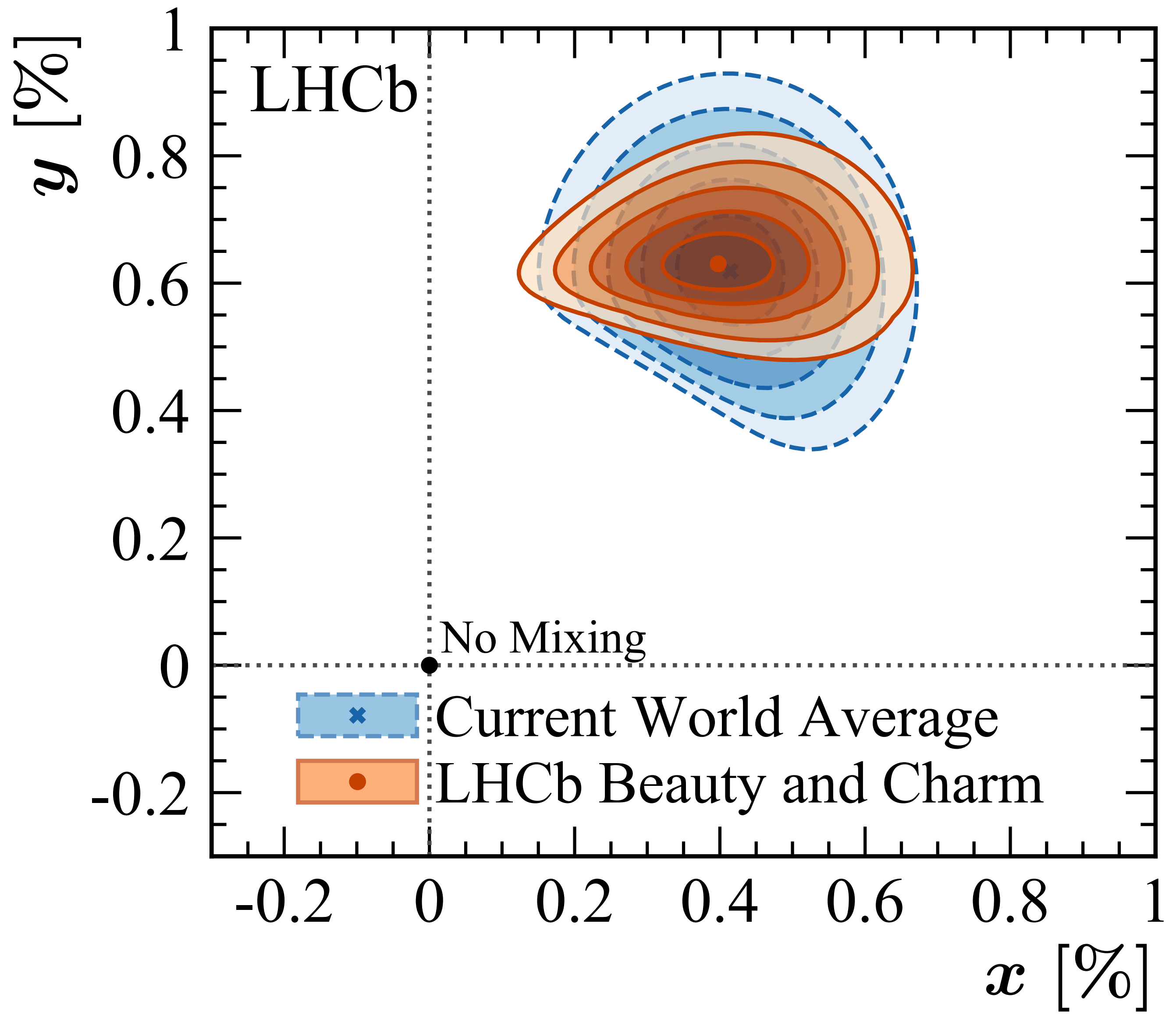
Unitarity angle γ extracted in combination

LHCb: JHEP 12 (2021) 141
UTFit: 2018 update
CKMFitter: 2019 update

- All $B \to DX$ results are combined with time-dependent charm results

B decay	D decay	Ref.	Dataset	Status since Ref. [24]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[28]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[29]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K_S^0 h^+h^-$	[26]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K_S^0 K^\pm\pi^\mp$	[30]	Run 1&2	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[31]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[31]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[32]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[33]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	[34]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[35]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[36]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[37]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[38–40]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[41]	Run 1	**New**
–	$D^0 \to h^+h^-$	[42–45]	Run 1&2	**New**
–	$D^0 \to K^+\pi^-$	[46]	Run 1	**New**
–	$D^0 \to K^+\pi^-$	[47]	Run 1&2(*)	**New**
–	$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	[48]	Run 1	**New**
–	$D^0 \to K_S^0\pi^+\pi^-$	[49, 50]	Run 1&2	**New**
–	$D^0 \to K_S^0\pi^+\pi^-$	[51]	Run 1	**New**





$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

CKMfitter expectation
$(65.7^{+0.9}_{-2.7})^\circ$

UTFit expectation
$(65.8 \pm 2.2)^\circ$

$$x = (0.400^{+0.052}_{-0.053})\%$$
$$y = (0.630^{+0.033}_{-0.030})\%$$

CP violation and mixing in charm and beauty hadrons

Conclusion

- LHCb is delivering a wealth of measurements on heavy-flavour *CP* violation and mixing
- All major results are compatible with the SM expectation
- But the search goes on. LHCb upgrade will provide a factor 5-10 more statistics
- And BelleII aims to improve B-factory statistics by a factor ~50
- No time to be playing football in the park.

LS LOWRY, Peel Park, Salford (1944)