Flavour Physics - Chapter II

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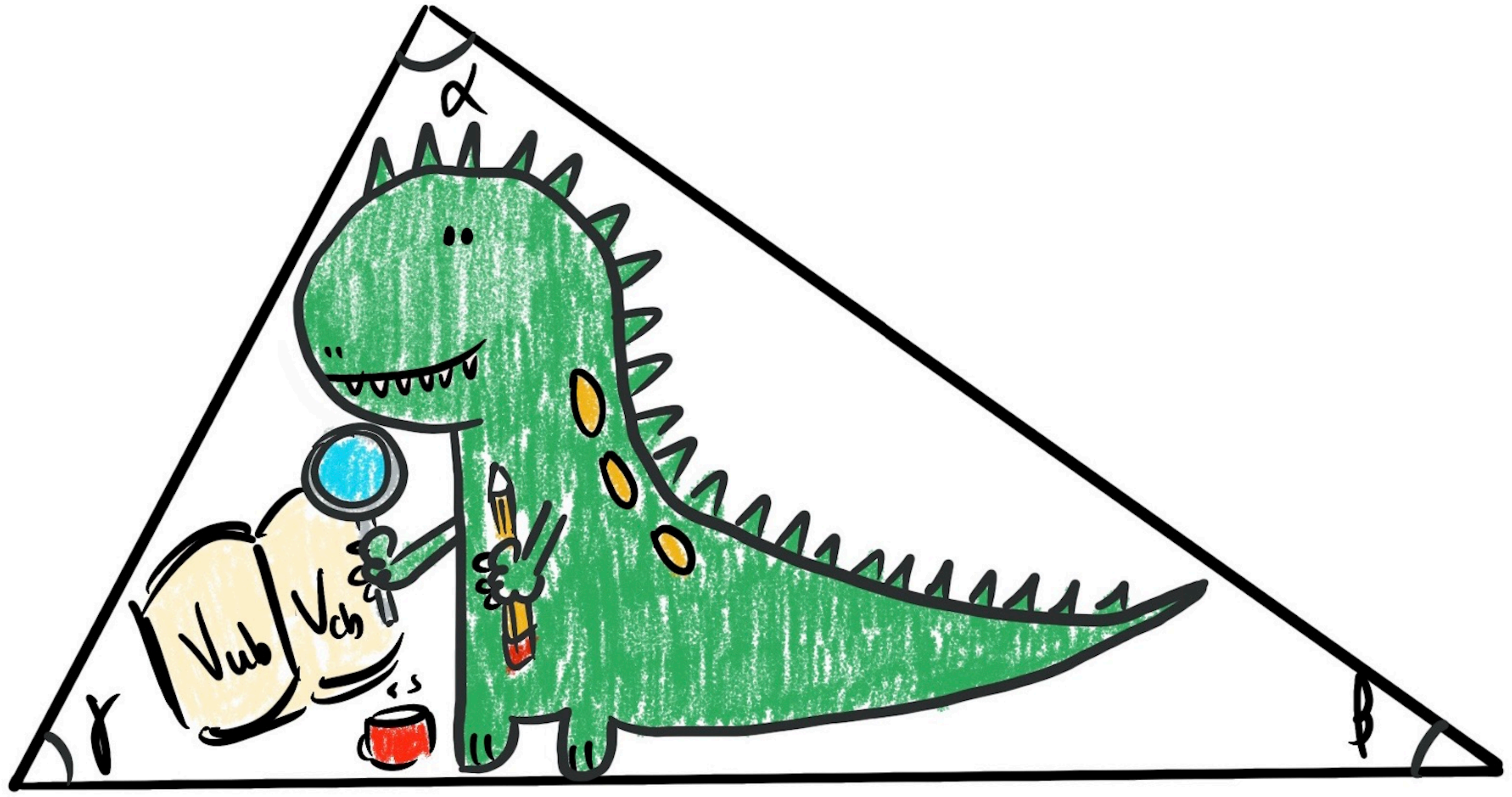
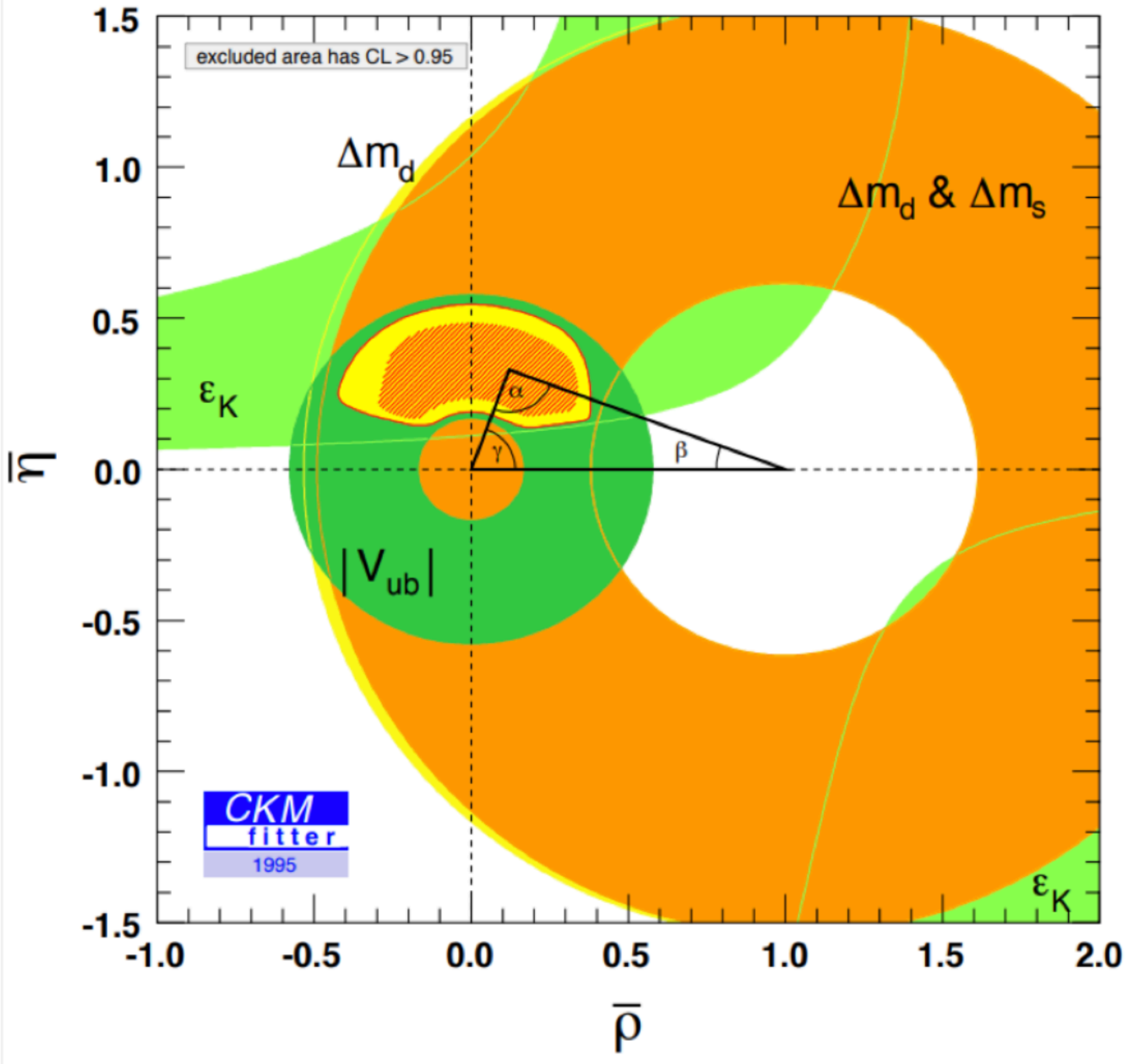
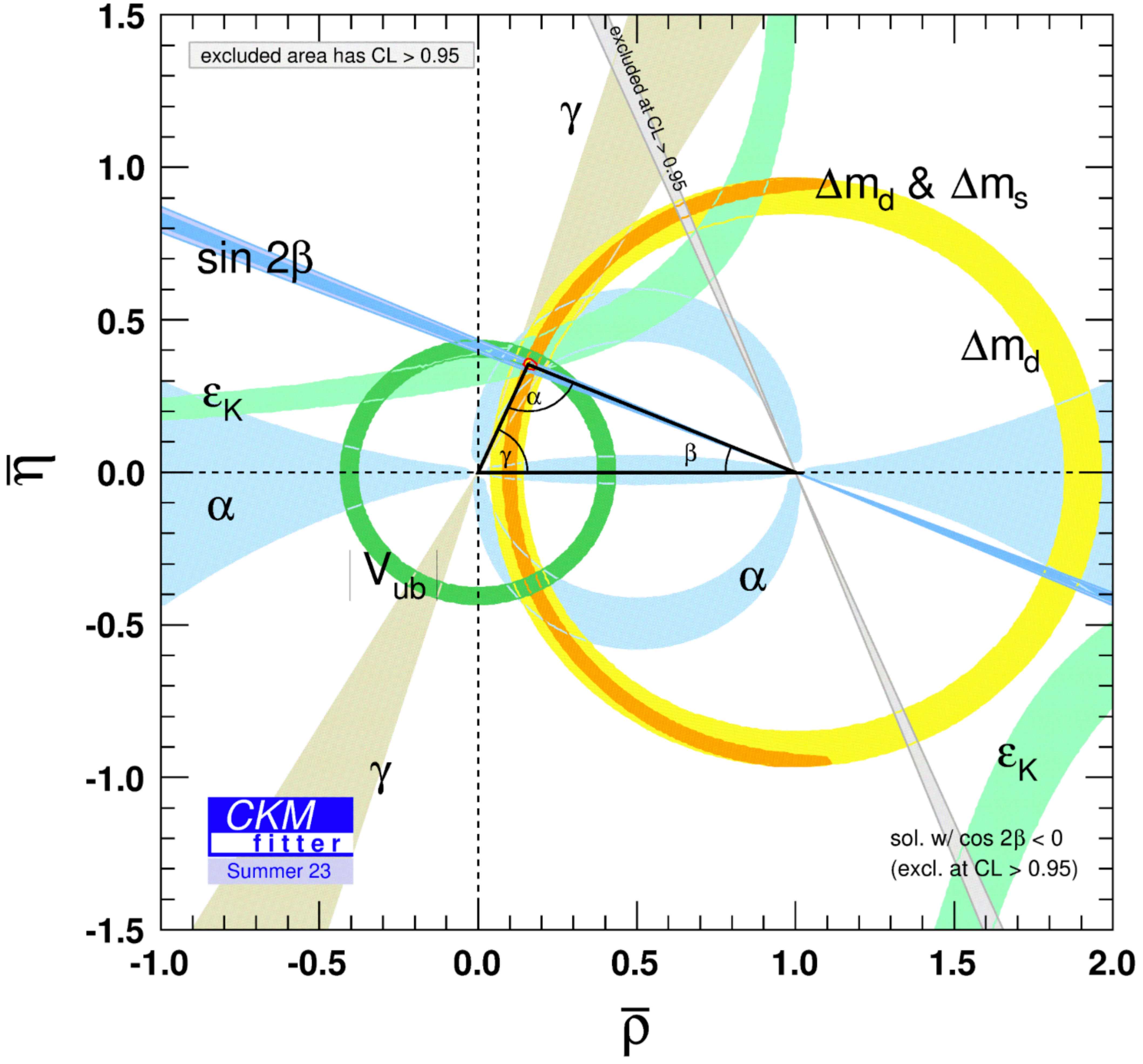
CERN Summer School



July/August 2024

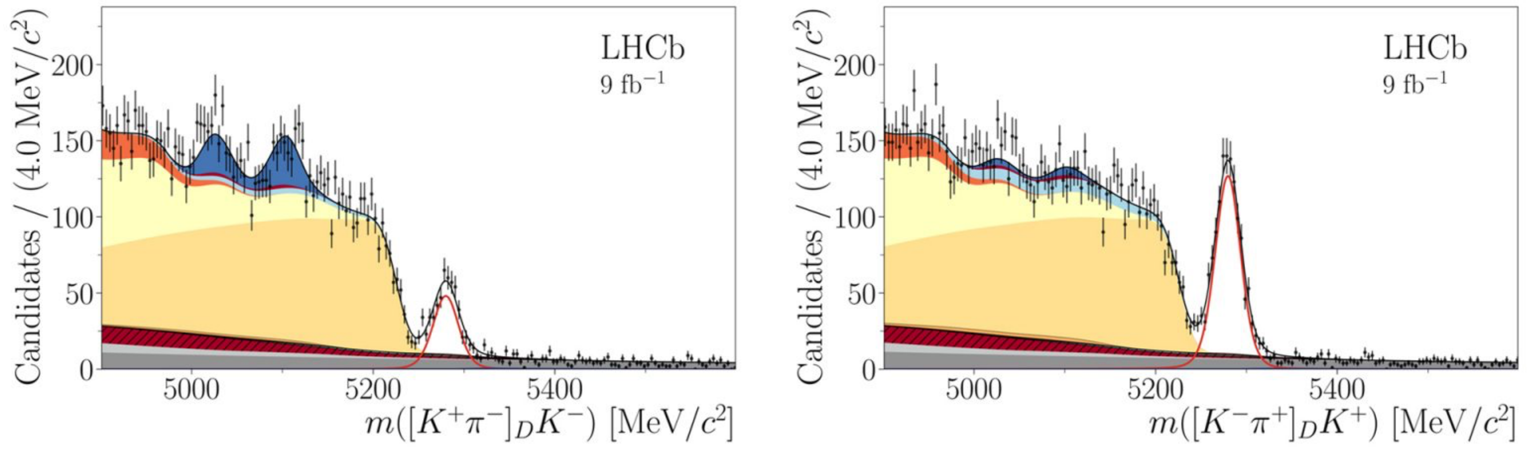
Next steps

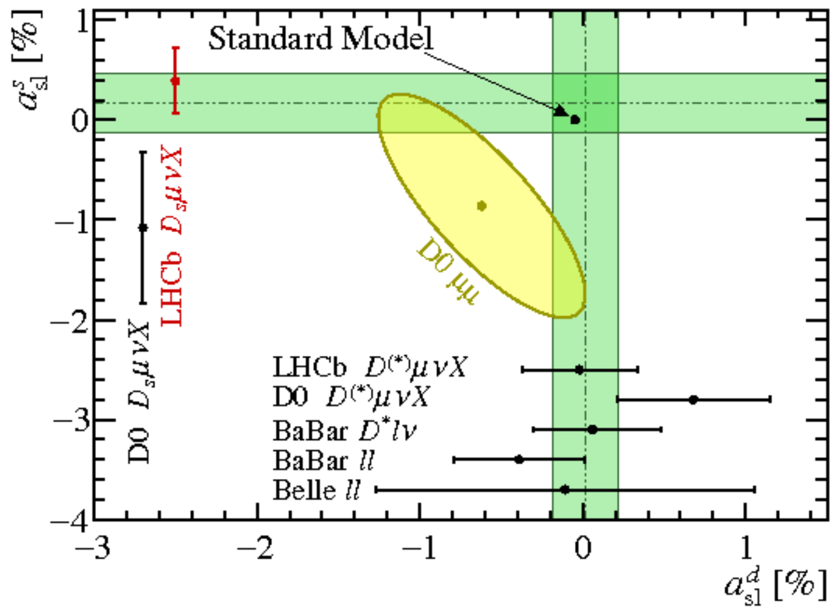


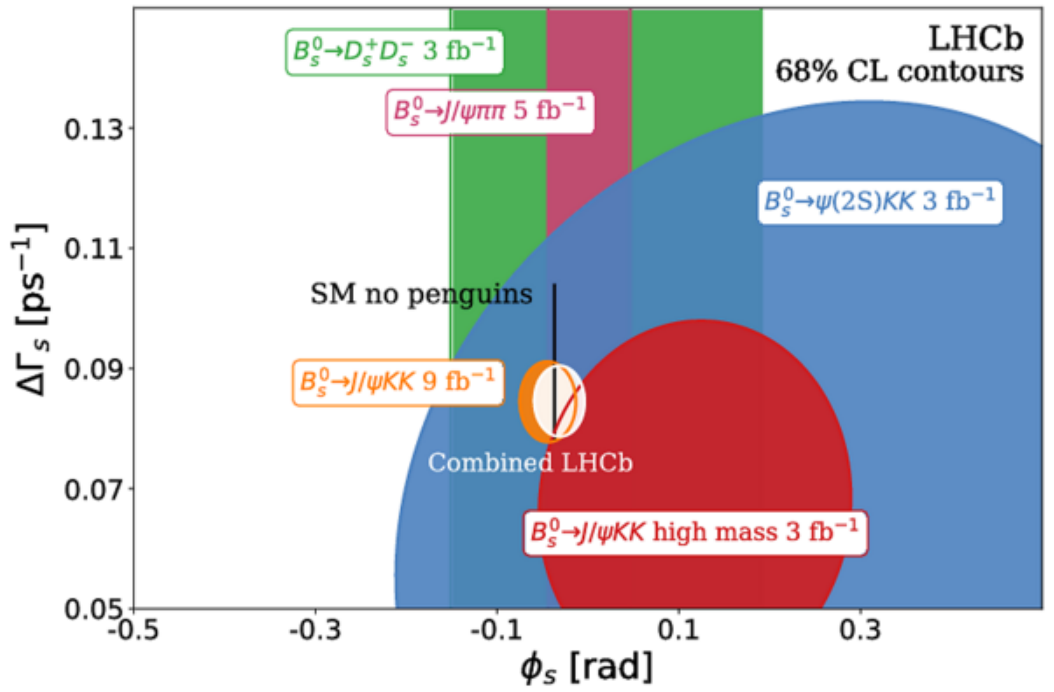


http://ckmfitter.in2p3.fr/

Types of CP violation





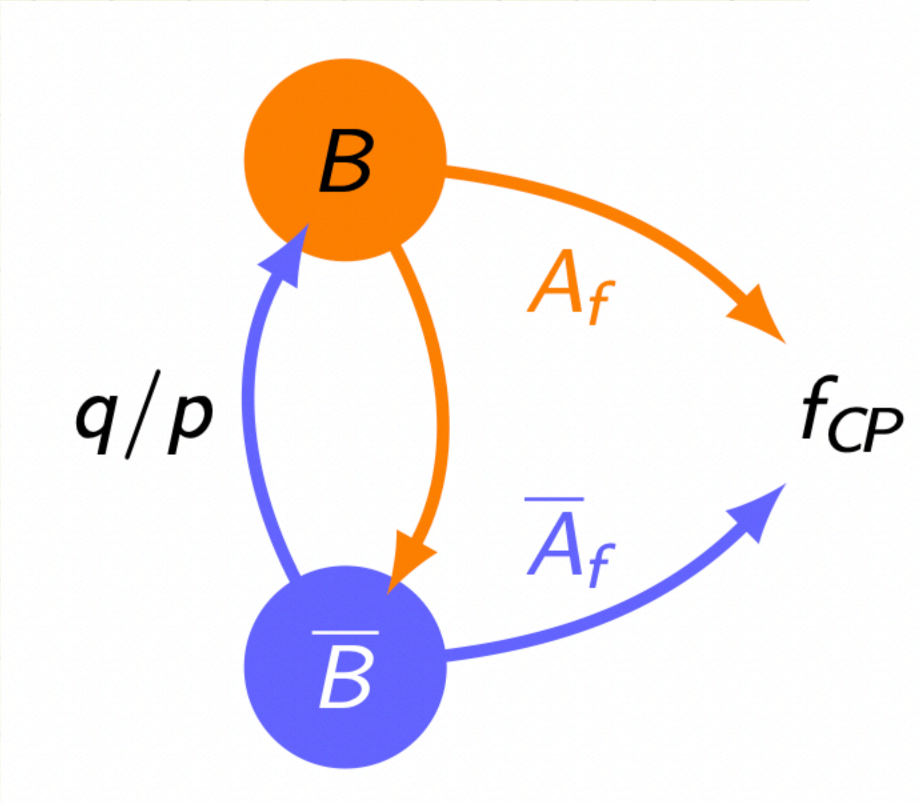


CP Violation in Decay

- $\left|\frac{A_f}{\bar{A}_f}\right| \neq 1$

A_f Amplitude $B \to f$

$\bar{A}_f$ Amplitude $\bar{B} \to \bar{f}$



CP Violation in mixing

- $\left|q/p\right| \neq 1$

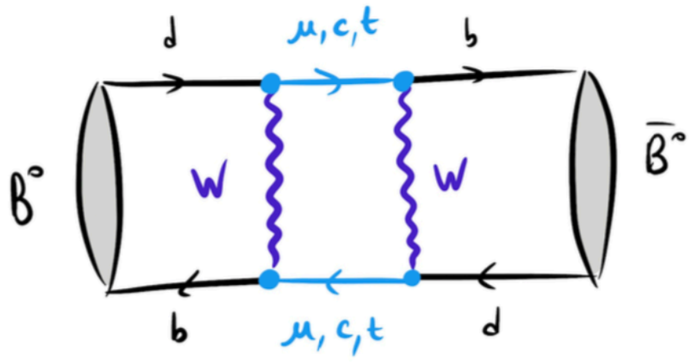
CP violation in the interference between mixing and decay

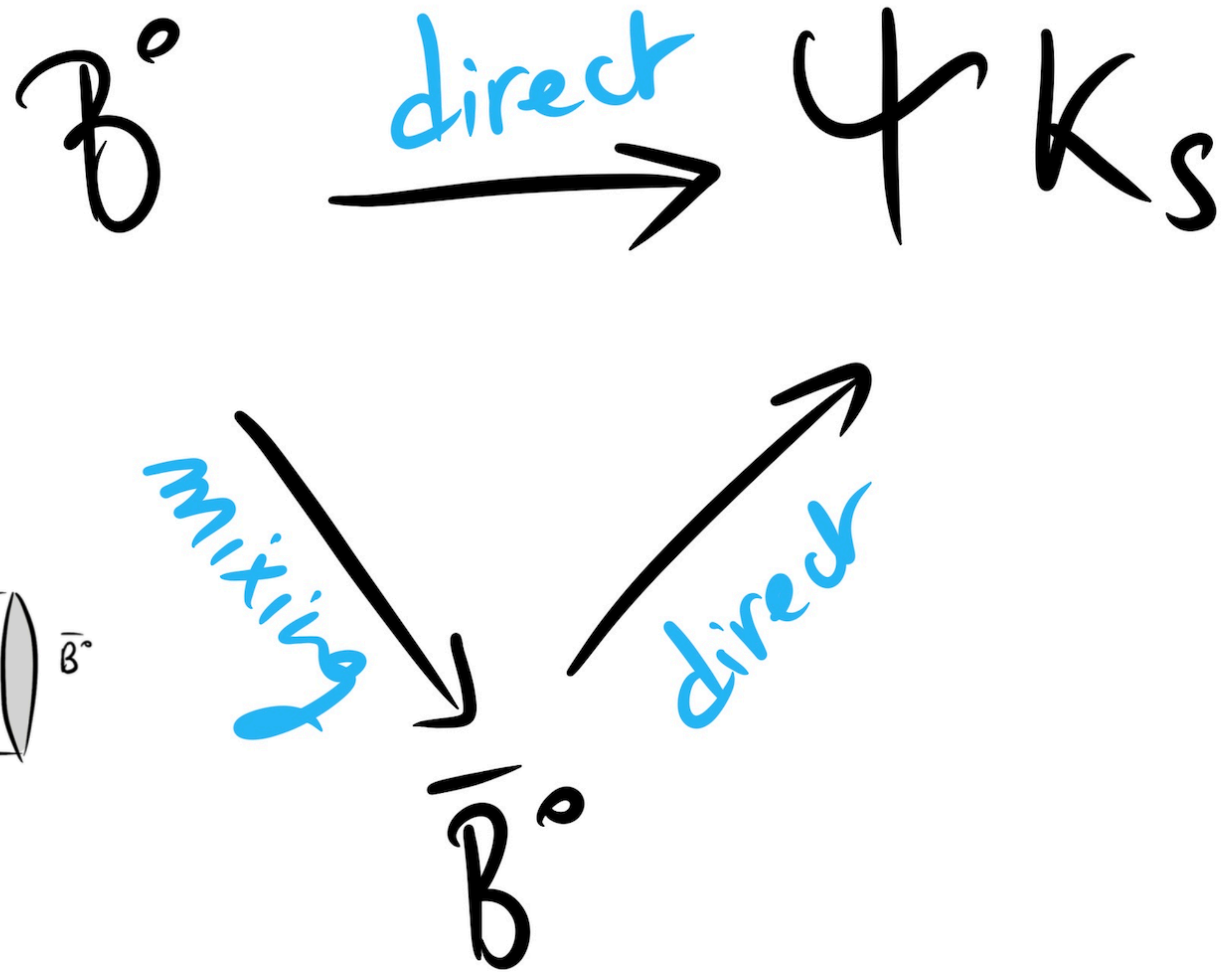
- $\mathrm{Im}(\lambda_f) = \mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$

λ_f = parameter that quantifies CP violation

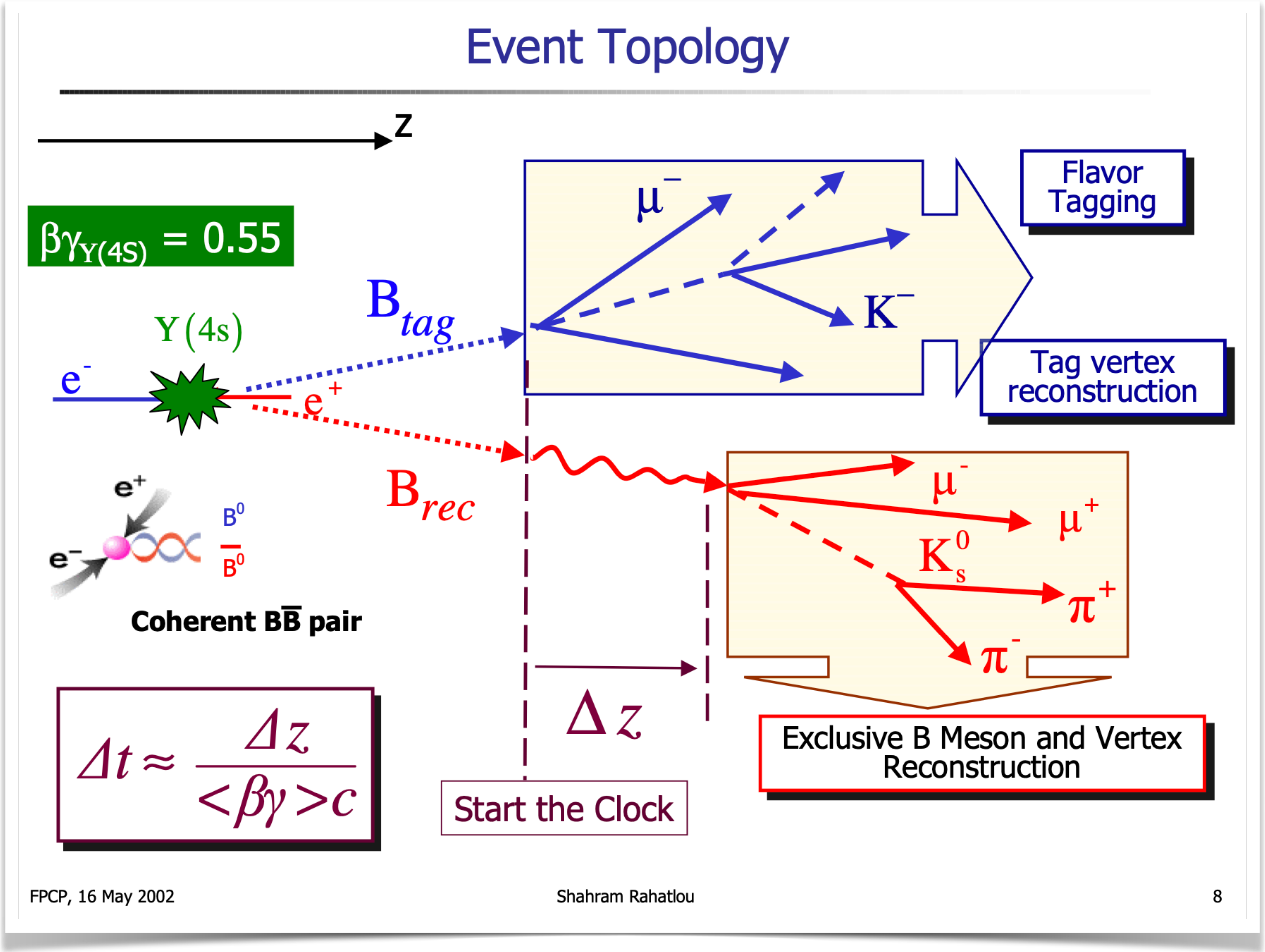
$CP\,|f_{cp}\rangle = \eta_f^{CP}\,|f_{cp}\rangle$ with $\eta_{cp} = \pm 1$

Let's start with sin2beta With the “golden” mode $B^0 \to J/\Psi\ (\to \mu^+\mu^+)\ K_S\ (\pi^-\pi^-)$





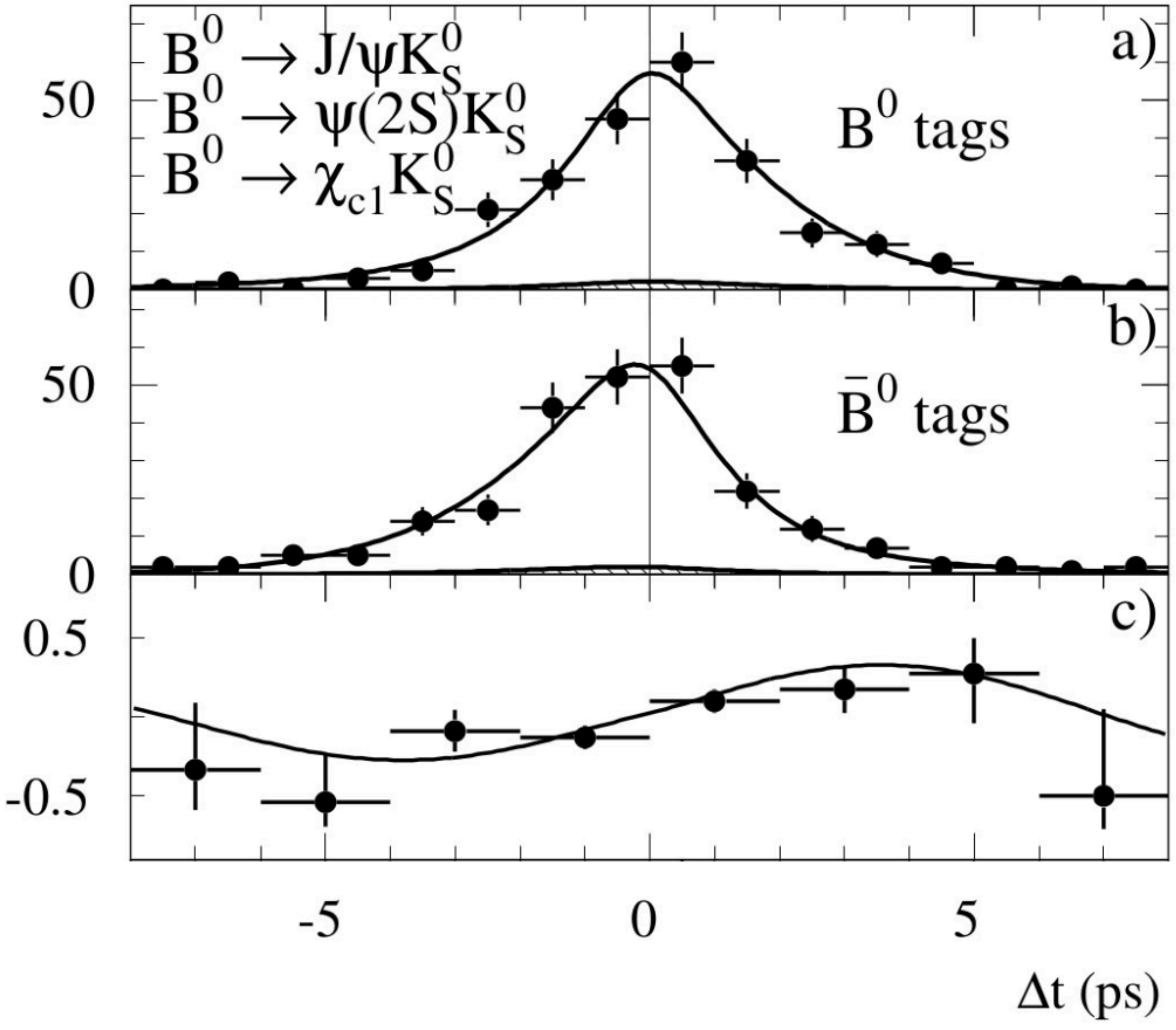
$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to \psi K^0_S) - \Gamma(B^0(t) \to \psi K^0_S)}{\Gamma(\bar{B}^0(t) \to \psi K^0_S) + \Gamma(B^0(t) \to \psi K^0_S)} \approx \underbrace{D_{\Delta t} D_{FT}}_{\text{Experimental dilution factors}} S \sin(\Delta m_d t)$$



Time dependent analysis → requires flavour tagging

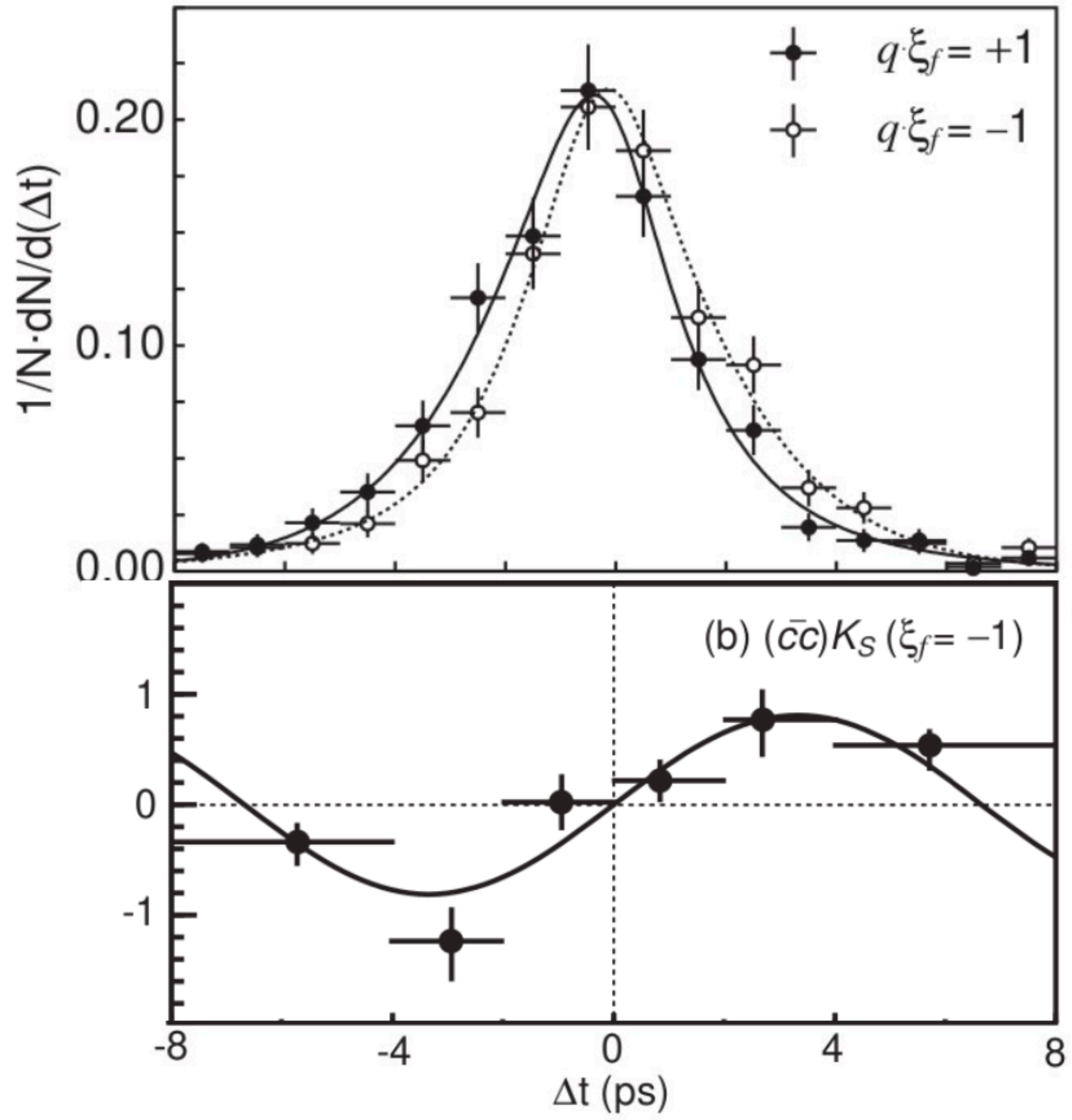
sin 2β aka the raison d’être of B-factories - 2001

BaBar, PRL 87 (2001) 091801



$$\sin 2\beta = 0.59 \pm 0.14\ (\text{stat}) \pm 0.05\ (\text{syst}).$$

Belle, PRL 97 (2001) 091802

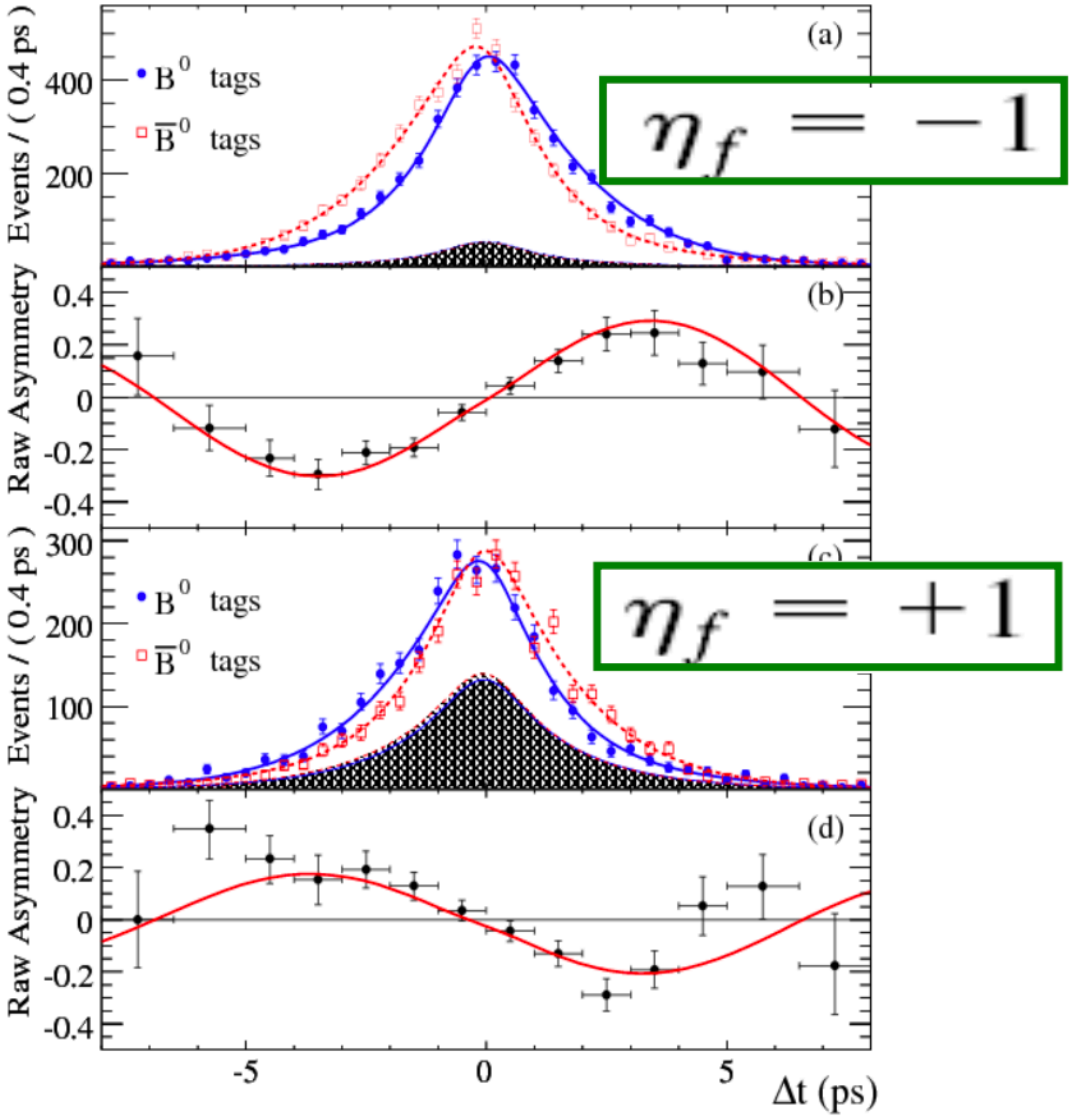


$$\sin 2\phi_1 = 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst}).$$

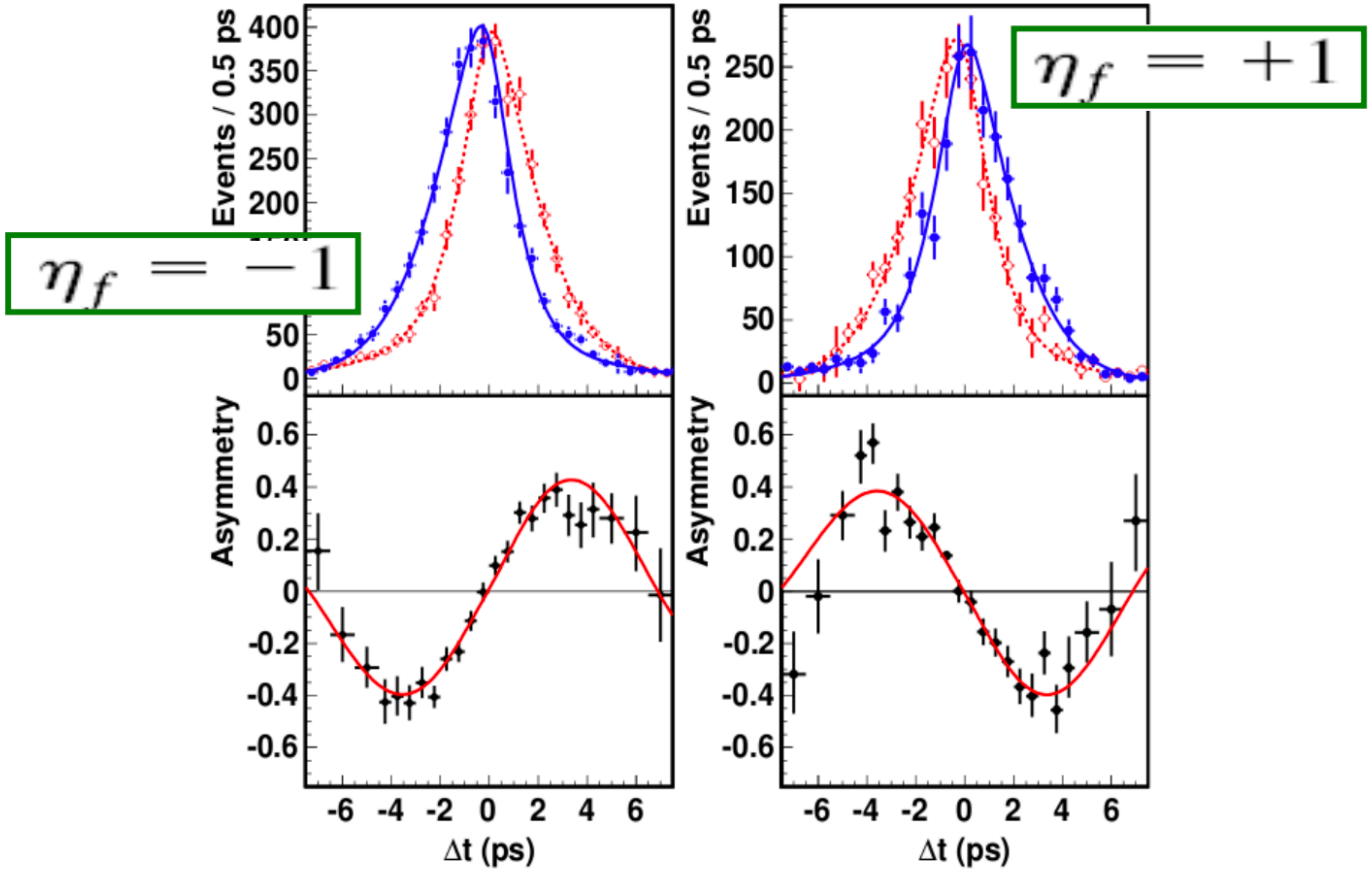
Different conventions on each side of the pacific

Legacy from B-Factories

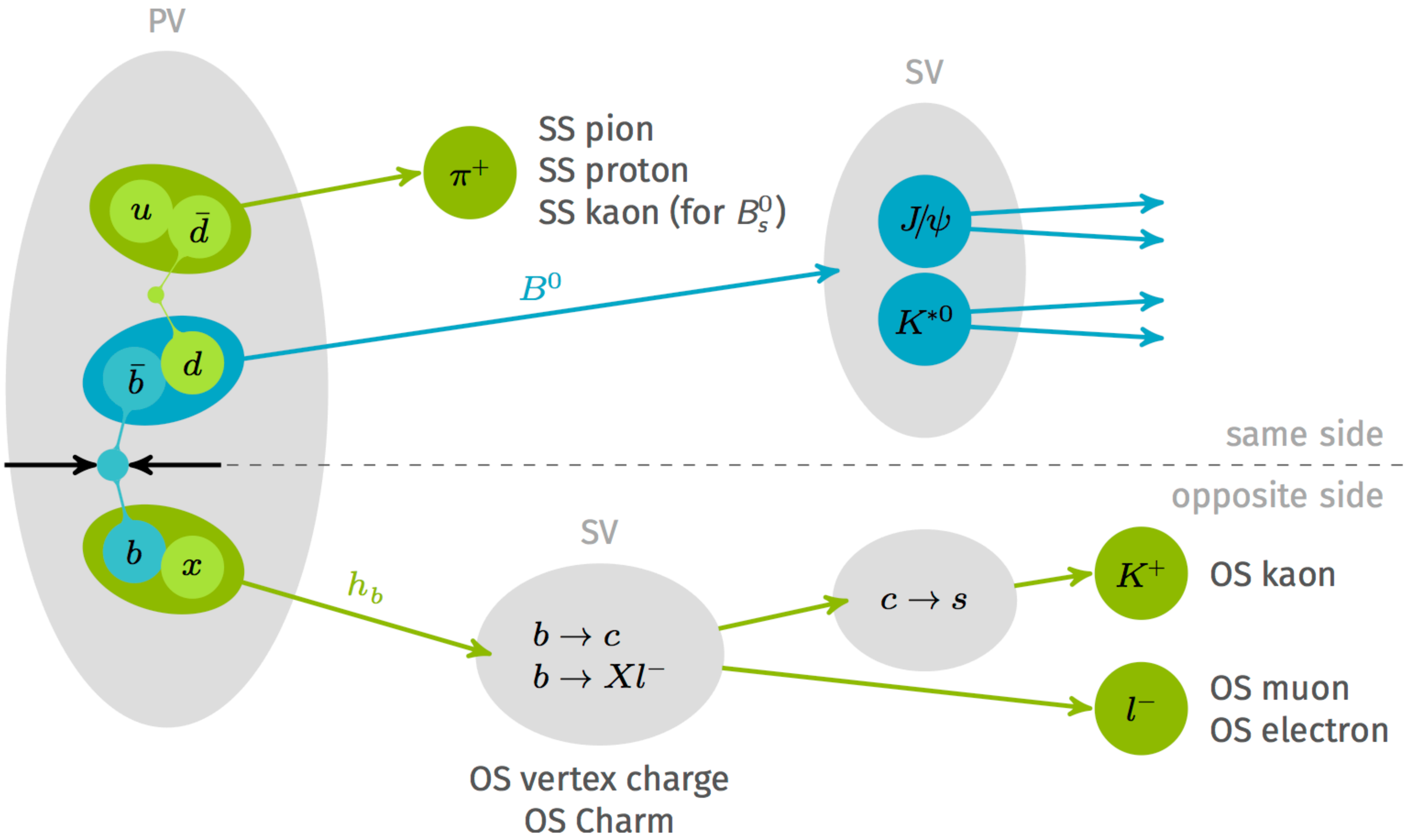
BaBar, PRD 79 (2009) 072009



Belle, PRL 108 (2012) 171802

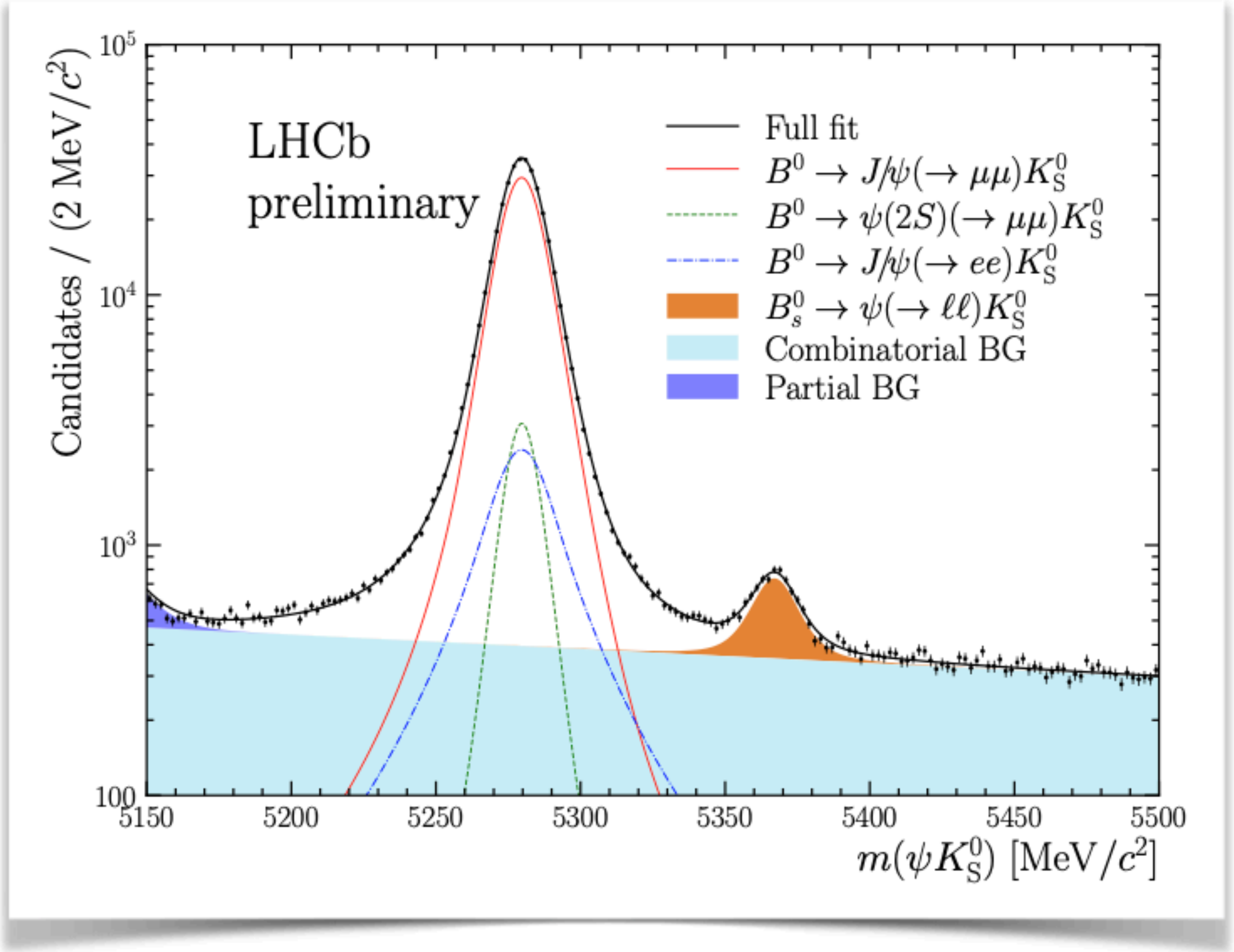


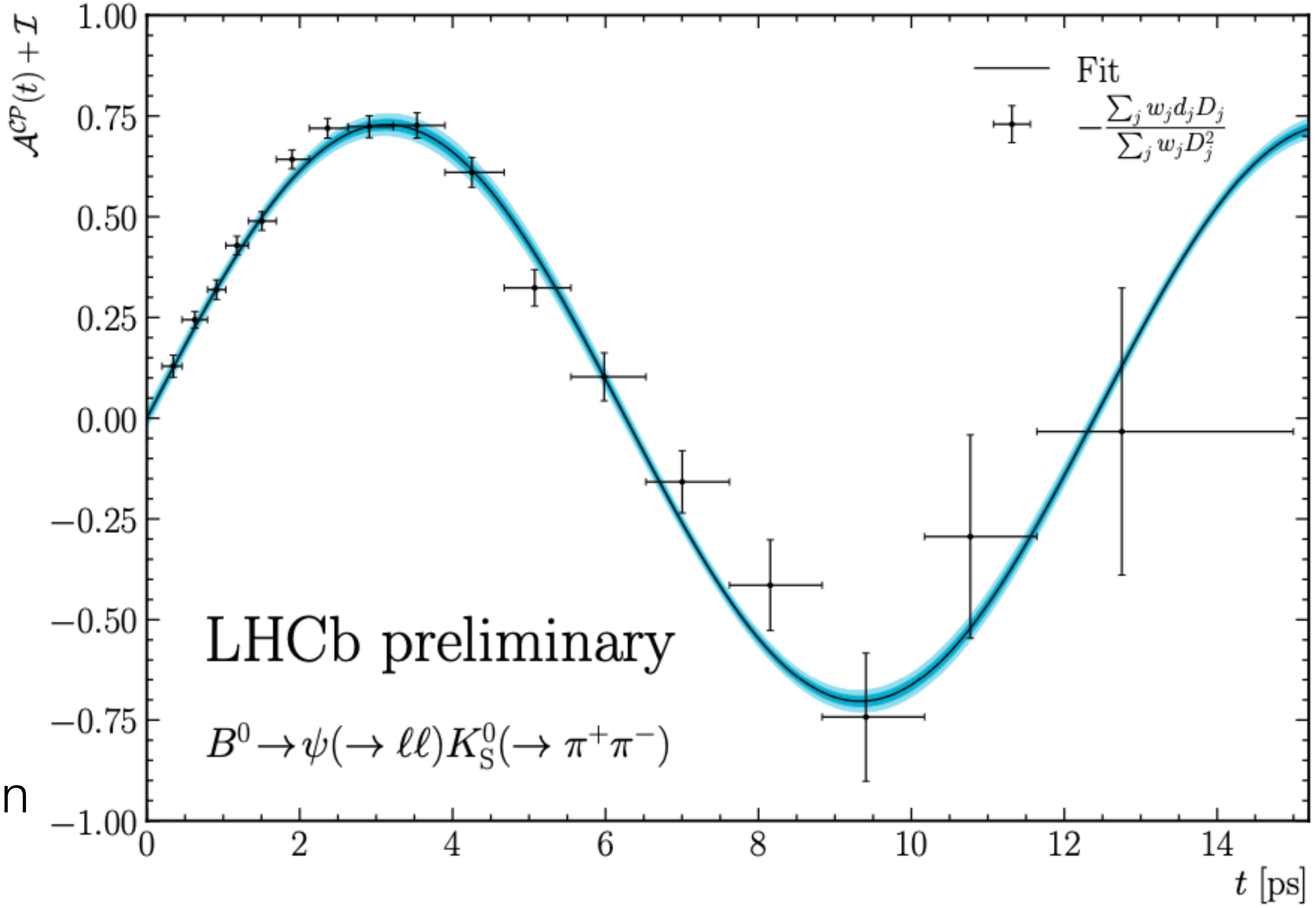
Flavour Tagging @ LHCb



Combination of a few decay channels

Text book like result !





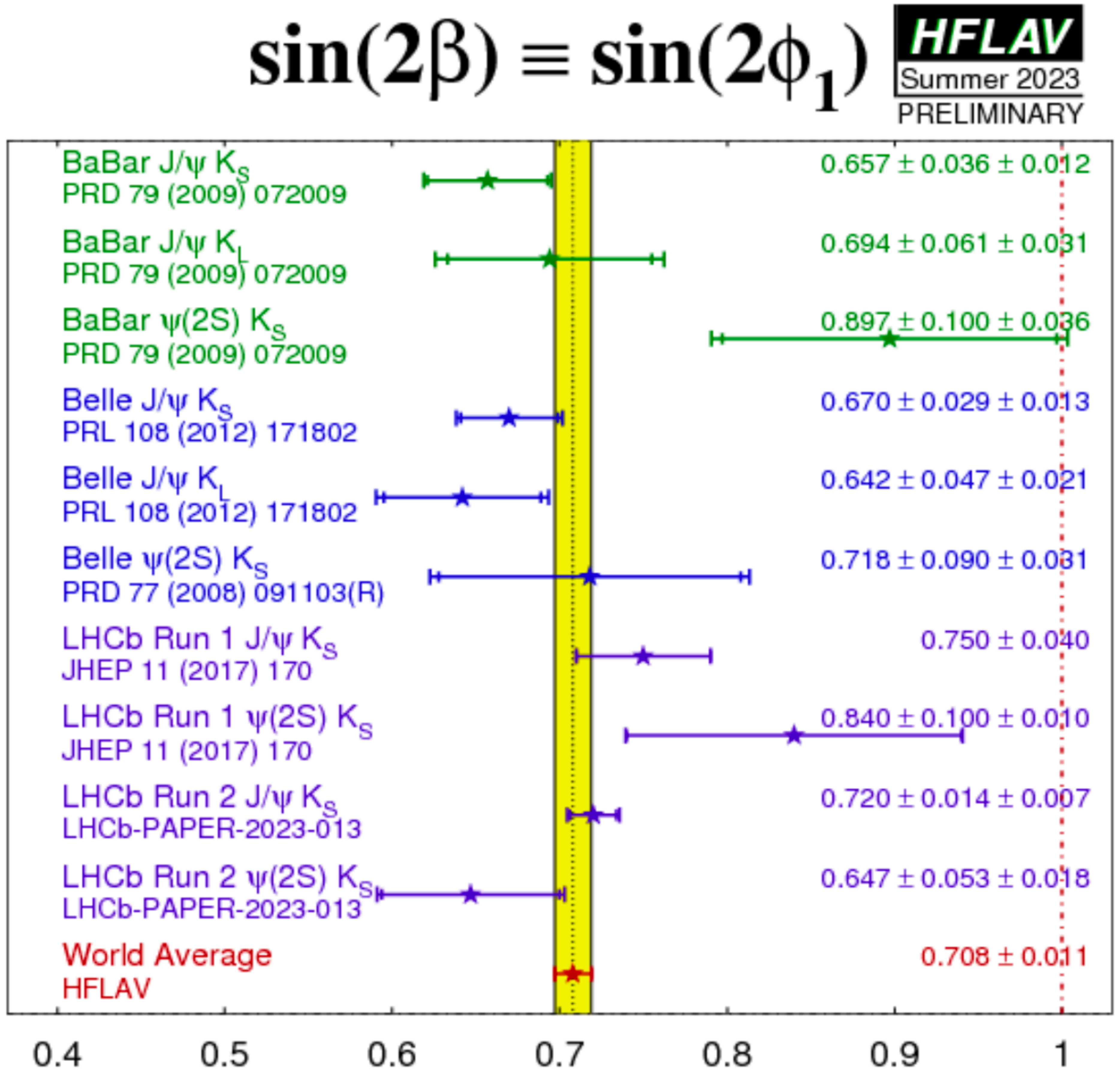
Flavour tagging

Importance of efficient reconstruction

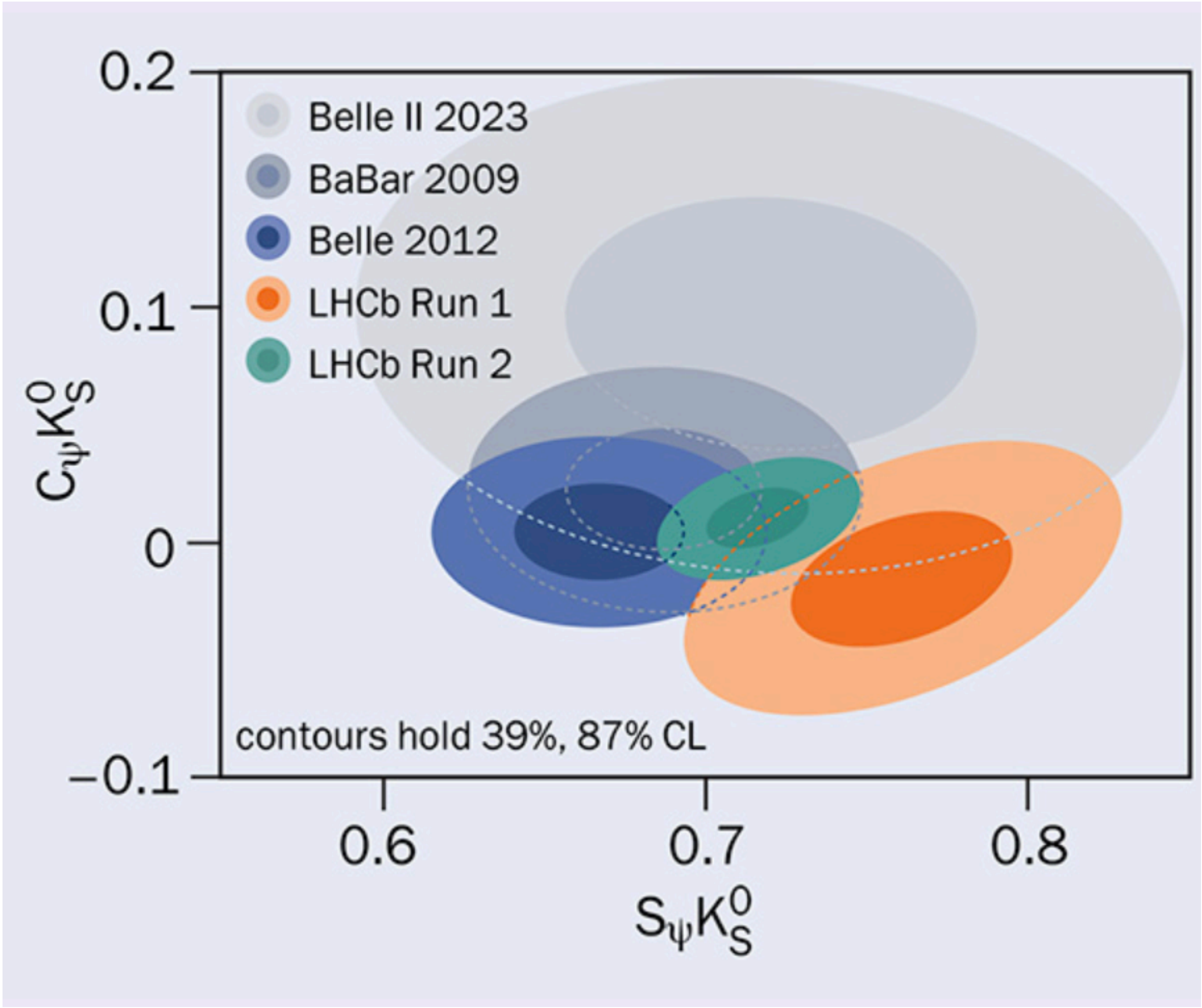
Understanding tiny effects

Trigger wise dilepton decays are a day at the beach

Summary plot

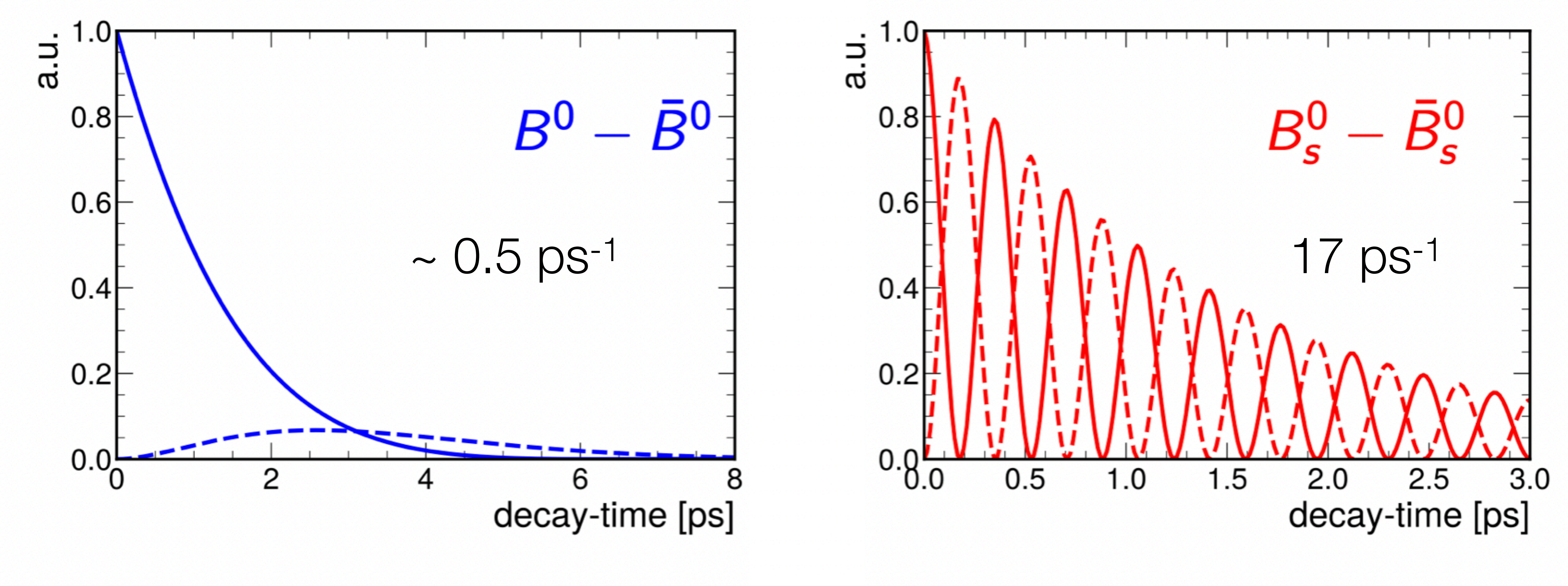


Is there room for NP in this corner ?



A nice read https://cerncourier.com/a/lhcb-sets-record-precision-on-cp-violation/

It's interesting to see what a "just" a difference in the spectator quark can do



An other fascinating topic is simple lifetime measurements.
If you are interested in this Google my dear colleague Alex Lenz

A few lines about the mixing formalism

- $$i \frac{d}{dt} \begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix} = \mathcal{H} \begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix}$$

where $\mathcal{H} = \left(M - \frac{i}{2}\Gamma\right) = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$

M → Mass Matrix (Dispersive)

Γ → Decay Matrix (Absorptive)

$M = M^\dagger$ and $\Gamma = \Gamma^\dagger$, CPT $\Rightarrow M_{11} = M_{22} = m_q$ and $\Gamma_{11} = \Gamma_{22} = \Gamma_q$

in case of mixing: M_{12} and Γ_{12} are non-zero

A few lines about the mixing formalism

The mass eigenstates:

$$|B_H\rangle \propto p\,|B_q^0\rangle + q\,|\bar{B}_q^0\rangle$$

$$|B_L\rangle \propto p\,|\bar{B}_q^0\rangle - q\,|\bar{B}_q^0\rangle$$

The time evolution:

$$|B_{H/L}(t)\rangle = e^{-i m_{H/L} t}\, e^{-i \Gamma_{H/L} t/2}\, |B_{H/L}\rangle$$

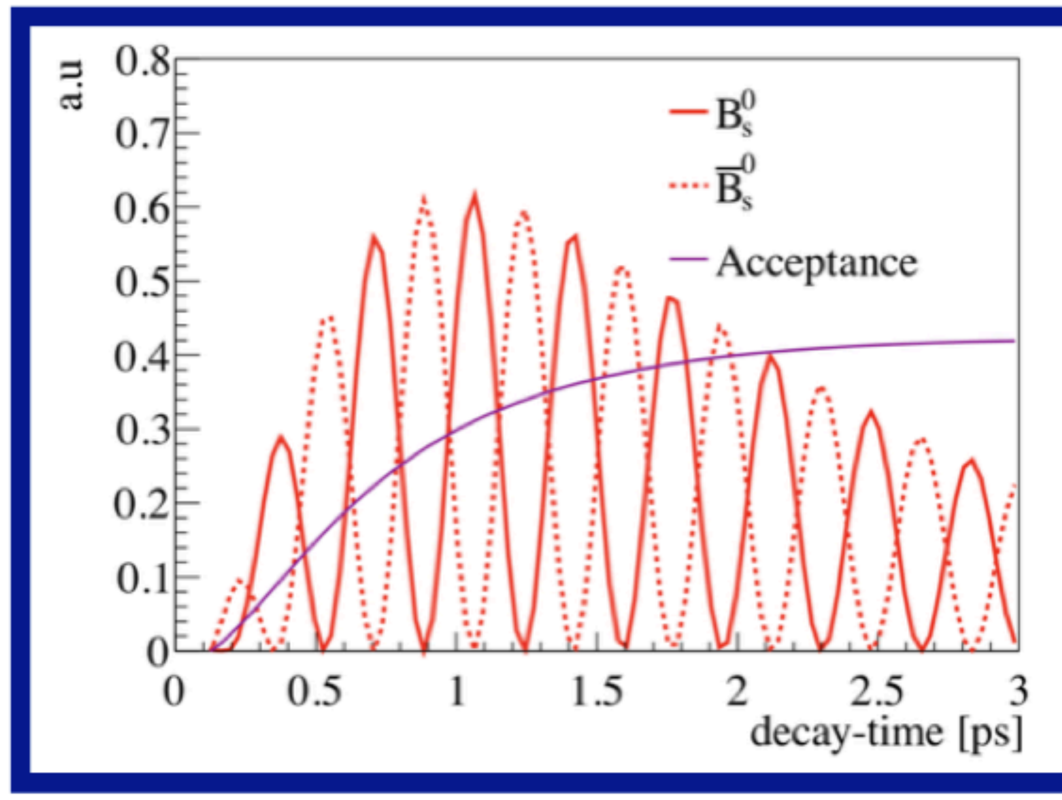
$$m_q = \frac{m_H - m_L}{2}, \quad \Gamma_q = \frac{\Gamma_L + \Gamma_H}{2} = \frac{1}{2}$$

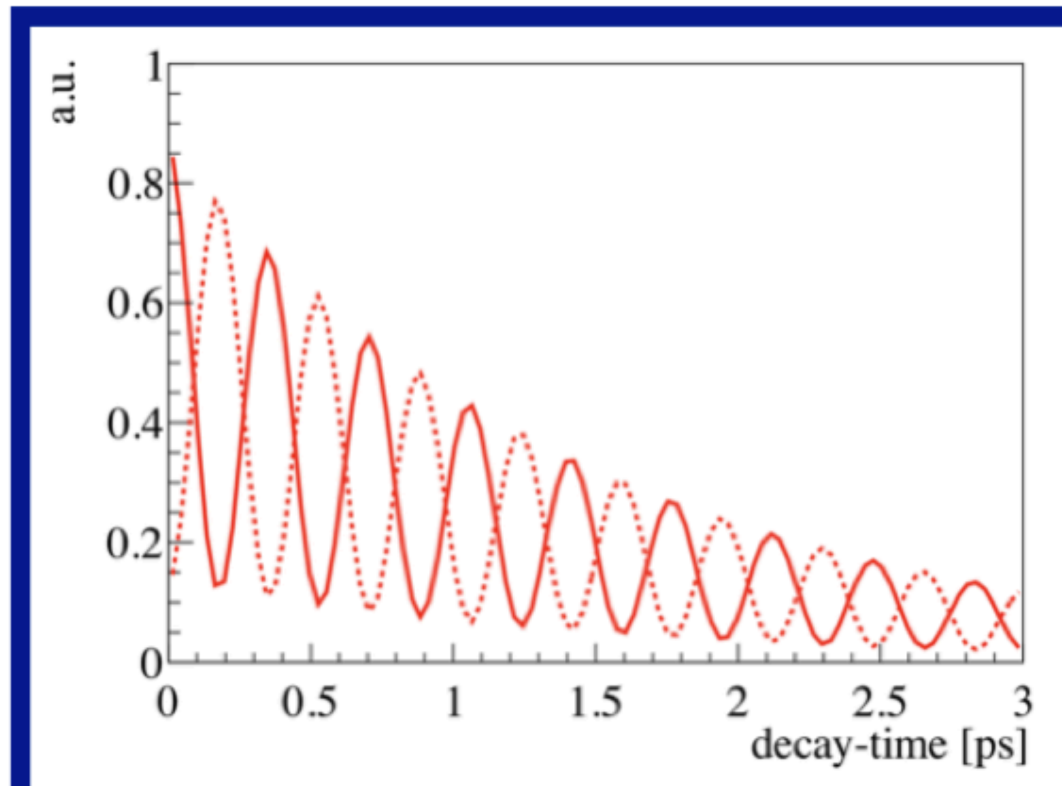
$$\Delta m_q = m_H - m_L, \quad \Delta\Gamma_q = \Gamma_L - \Gamma_H$$

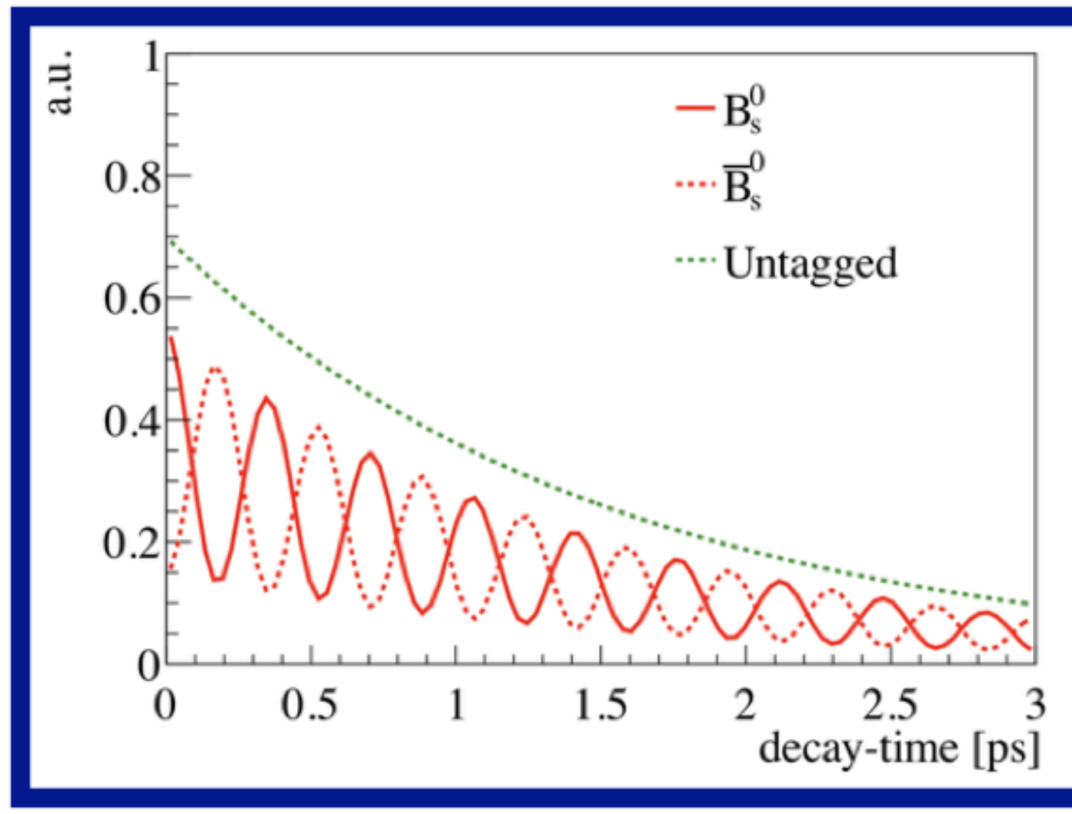
CERN-THESIS-2014-361 a very pedagogical reference.

We have to make the actual omelette

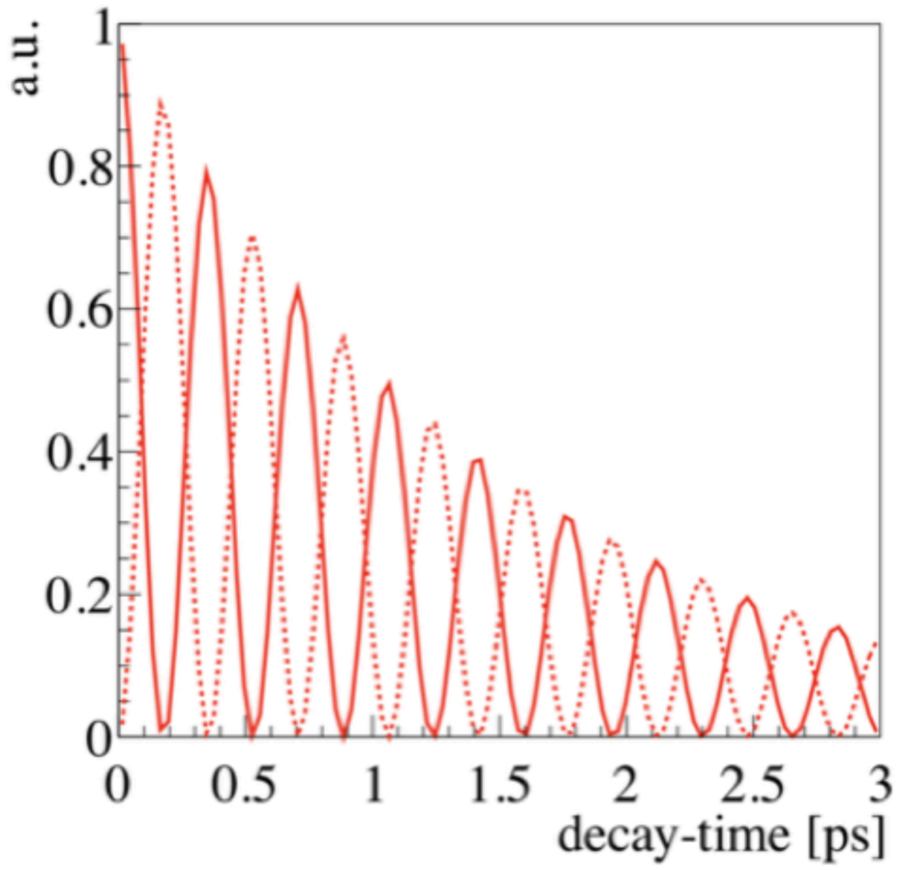
Detector effects





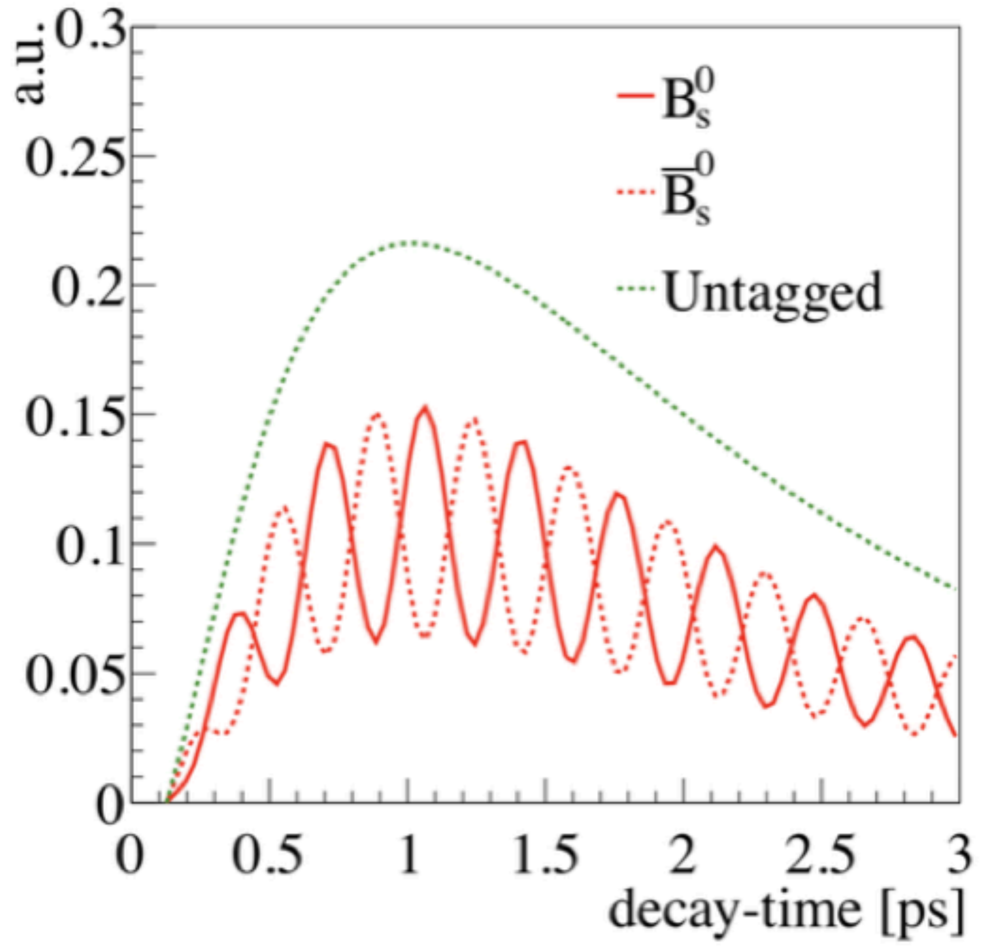


Perfect



$$P(t) \sim e^{-\Gamma_s t}(\cosh(\frac{\Delta\Gamma_s t}{2}) \pm \cos(\Delta m_s t))$$

Data



If you'll indulge me a little parenthesis

From my PhD 2006-2009

The channels in question

$B^0 \rightarrow D^- \rho^+(770)$ → Gamma Extraction:U-spin modes

$B^0{}_s \rightarrow D^-{}_s \rho^+$ → Bs Oscillations measurement.

You can tell I was young, I was using ComicSense

[Submitted on 22 Sep 2006]

Observation of Bs-Bsbar Oscillations

22 days after the start of my thesis

CDF Collaboration

We report the observation of Bs-Bsbar oscillations from a time-dependent measurement of the Bs-Bsbar oscillation frequency Delta ms. Using a data sample of 1 fb^-1 of p-pbar collisions at sqrt{s}=1.96 TeV collected with the CDF II detector at the Fermilab Tevatron, we find signals of 5600 fully reconstructed hadronic Bs decays, 3100 partially reconstructed hadronic Bs decays, and 61500 partially reconstructed semileptonic Bs decays. We measure the probability as a function of proper decay time that the Bs decays with the same, or opposite, flavor as the flavor at production, and we find a signal for Bs-Bsbar oscillations. The probability that random fluctuations could produce a comparable signal is 8 X 10^-8, which exceeds 5 sigma significance. We measure
Delta ms = 17.77 +- 0.10 (stat) +- 0.07 (syst) ps^-1
and extract
|Vtd/Vts| = 0.2060 +- 0.0007 (exp) + 0.0081 - 0.0060 (theor).

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CERN releases analysis of LHC incident

One year after the start of my thesis

16 OCTOBER, 2008

Geneva, 16 October 2008. Investigations at CERN following a large helium leak into sector 3-4 of the Large Hadron Collider (LHC) tunnel have confirmed that cause of the incident was a faulty electrical connection between two of the accelerator's magnets. This resulted in mechanical damage and release of helium from the magnet cold mass into the tunnel.

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The end of the universe if not something very close

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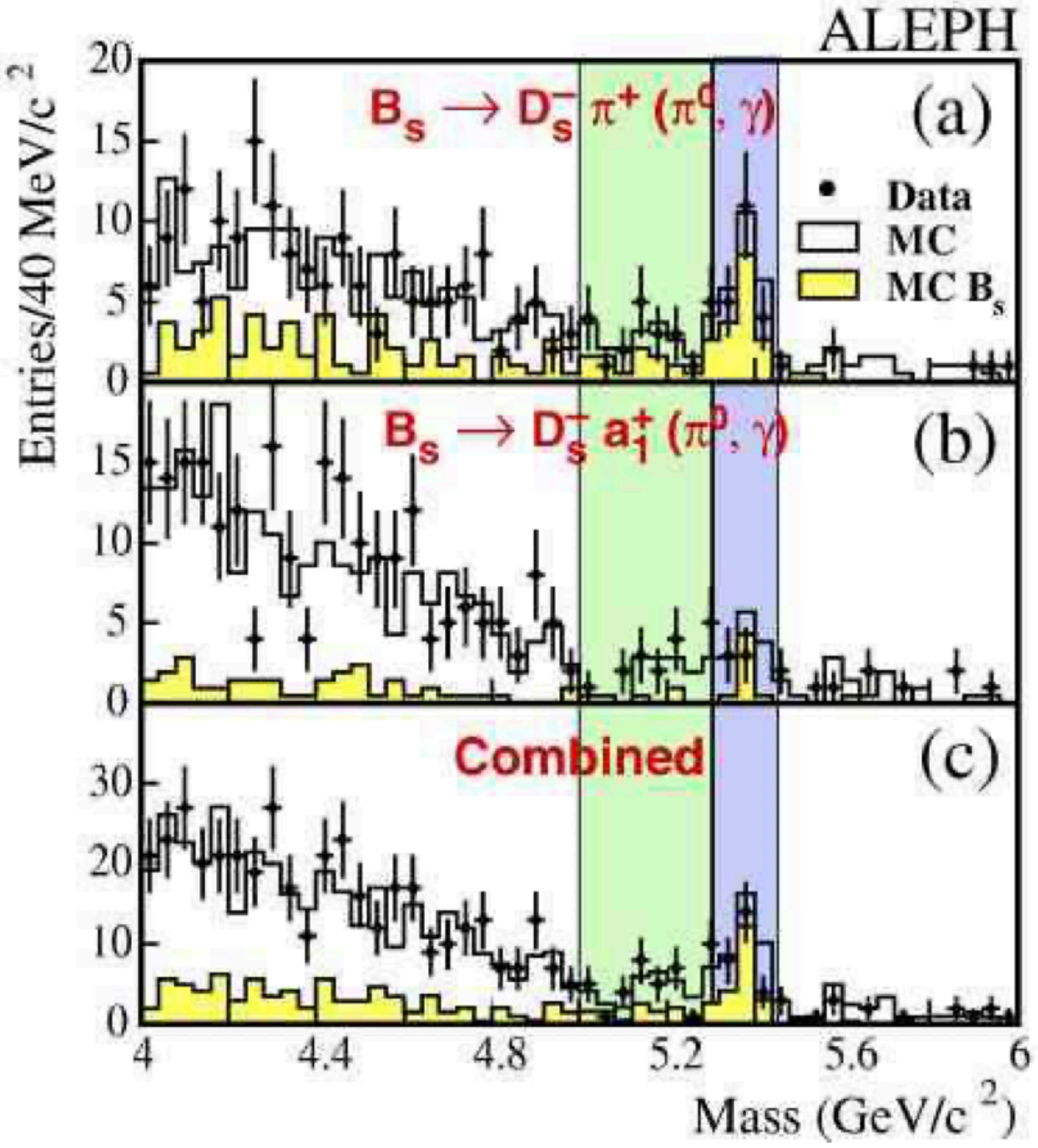
In 2008

B factories and Tevratron students

LHC students

These were dark days for us



https://arxiv.org/pdf/hep-ex/0209007

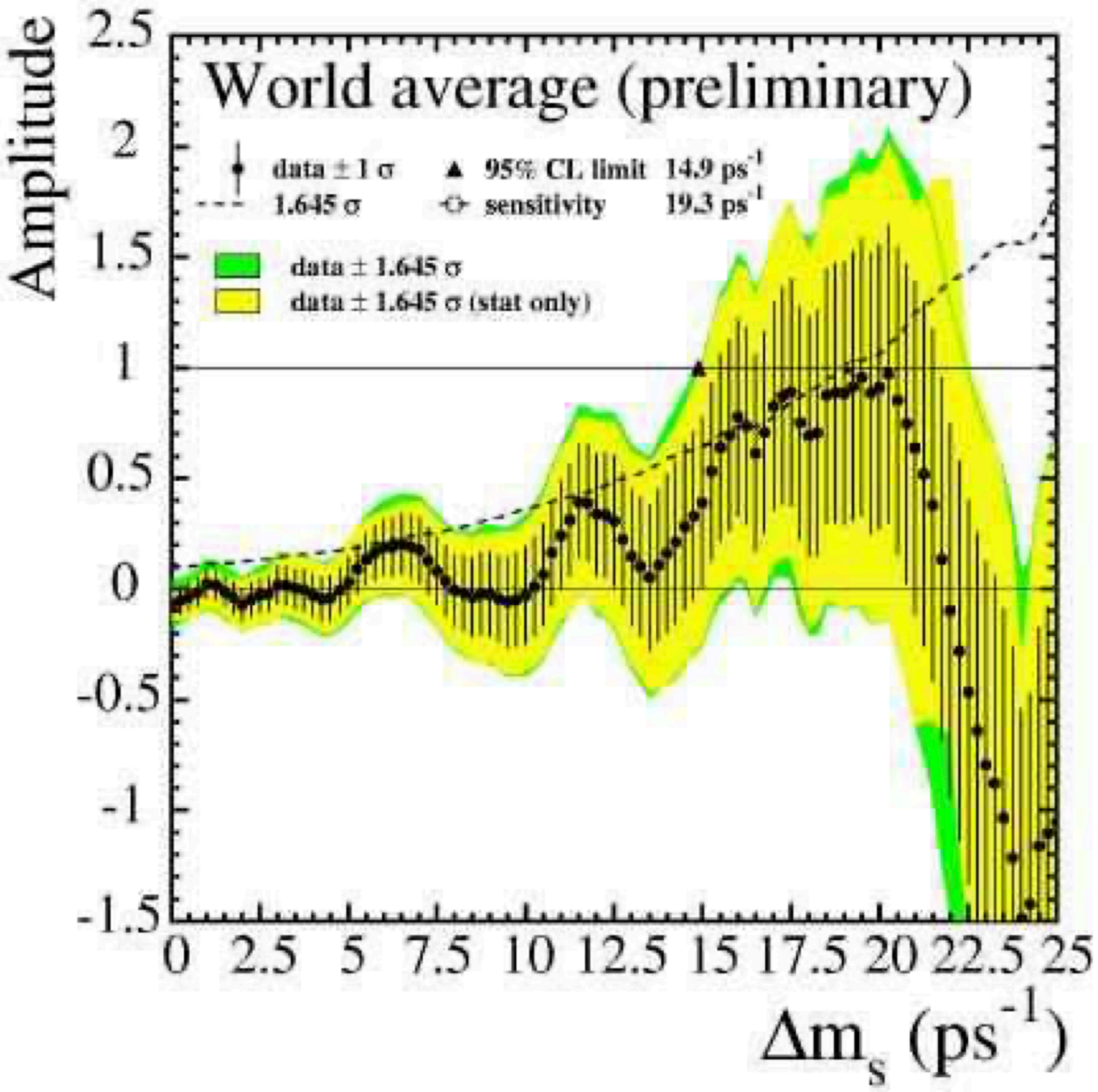
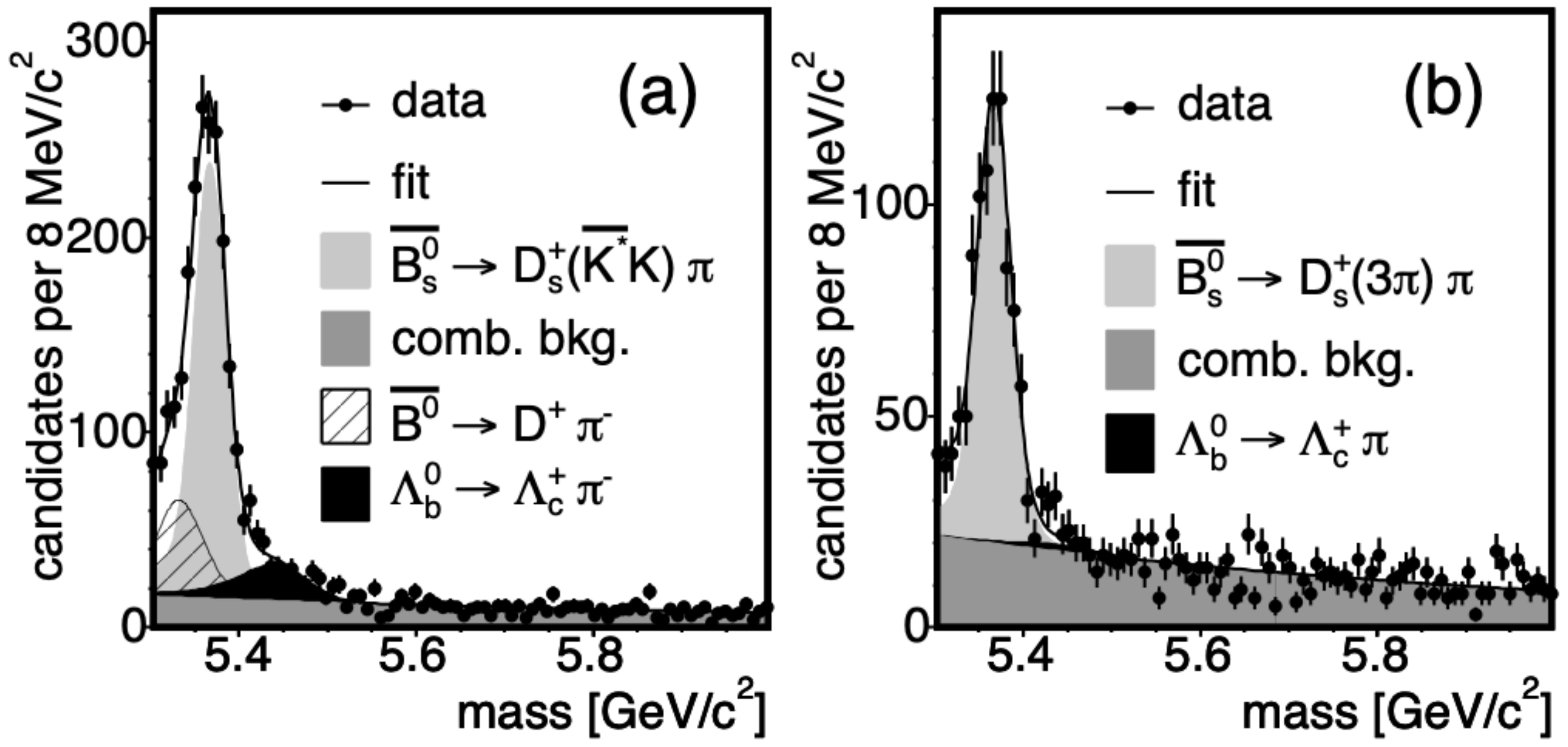


Figure 7: The combined B_s^0 oscillation results from ALEPH, CDF, DELPHI, OPAL, and SLD shown as amplitude versus hypothesized Δm_s [11]. The dots with error bars show the fitted aplitude values and uncertainties. An observed (expected) 95% C.L. lower limit on Δm_s of 14.9 ps^{-1} (19.3 ps^{-1}) is obtained.

My personal end of the universe at the time



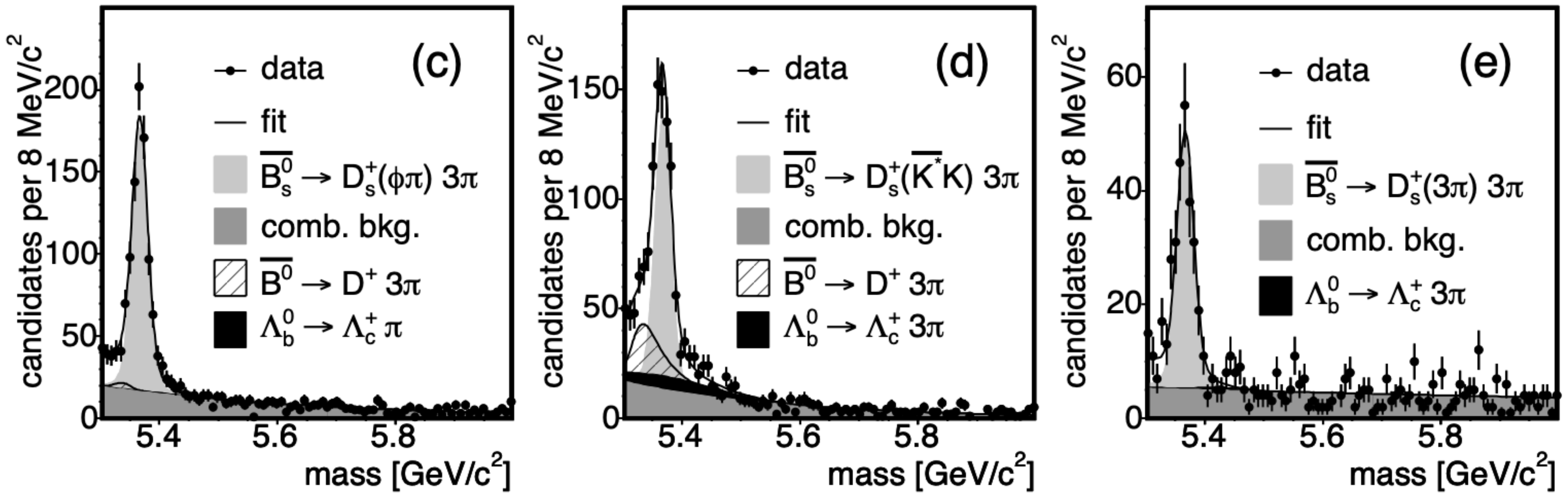
(a) $\overline{B^0_s} \rightarrow D^+_s(\overline{K^*}K)\,\pi$

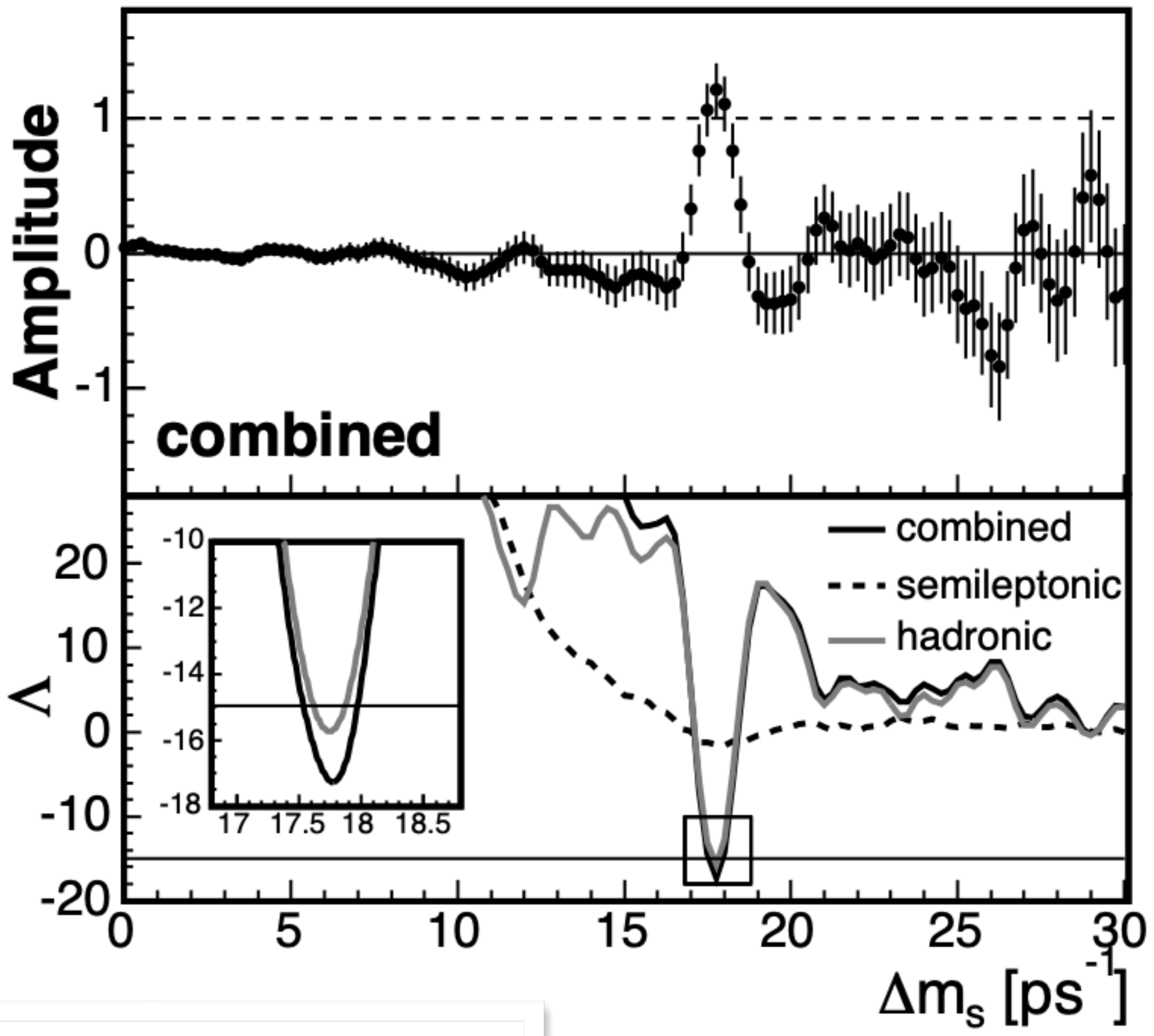
(b) $\overline{B^0_s} \rightarrow D^+_s(3\pi)\,\pi$

(c) $\overline{B^0_s} \rightarrow D^+_s(\phi\pi)\,3\pi$

(d) $\overline{B^0_s} \rightarrow D^+_s(\overline{K^*}K)\,3\pi$

(e) $\overline{B^0_s} \rightarrow D^+_s(3\pi)\,3\pi$





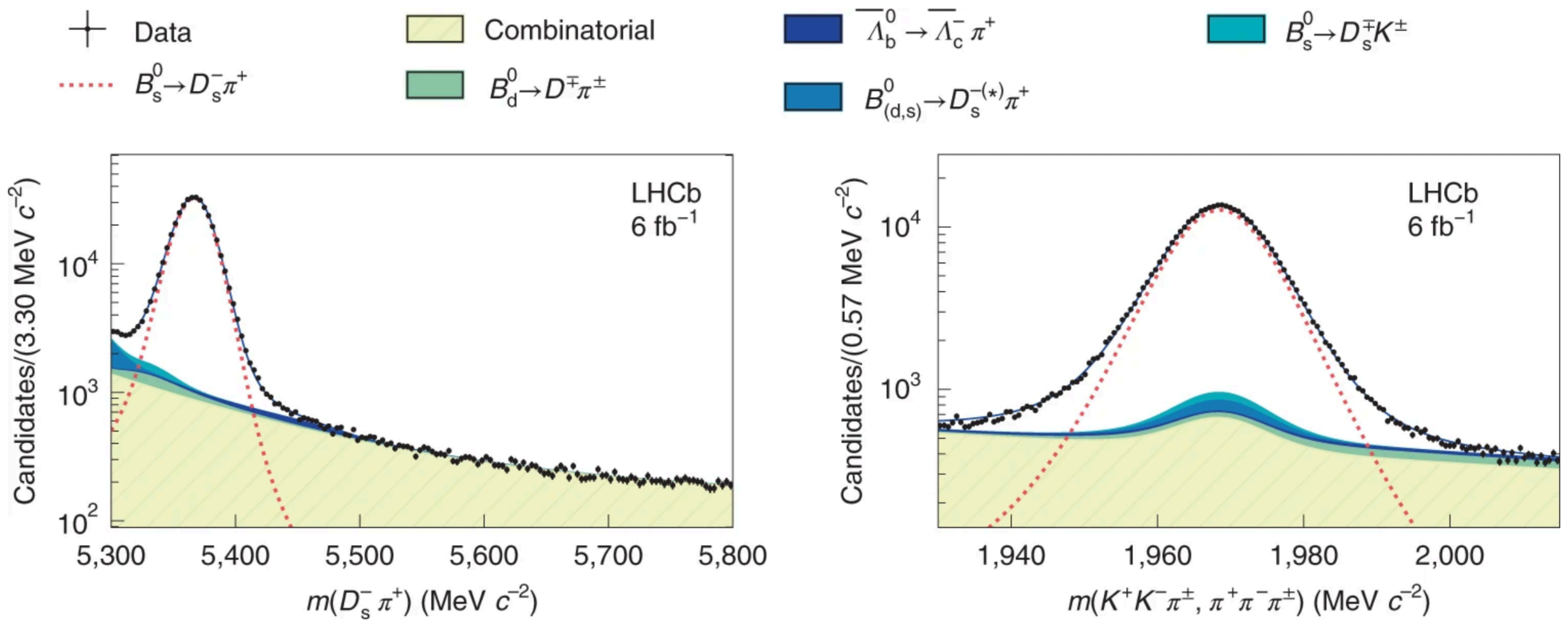
Observation of B^0_s-$\bar{B}^0_s$ Oscillations

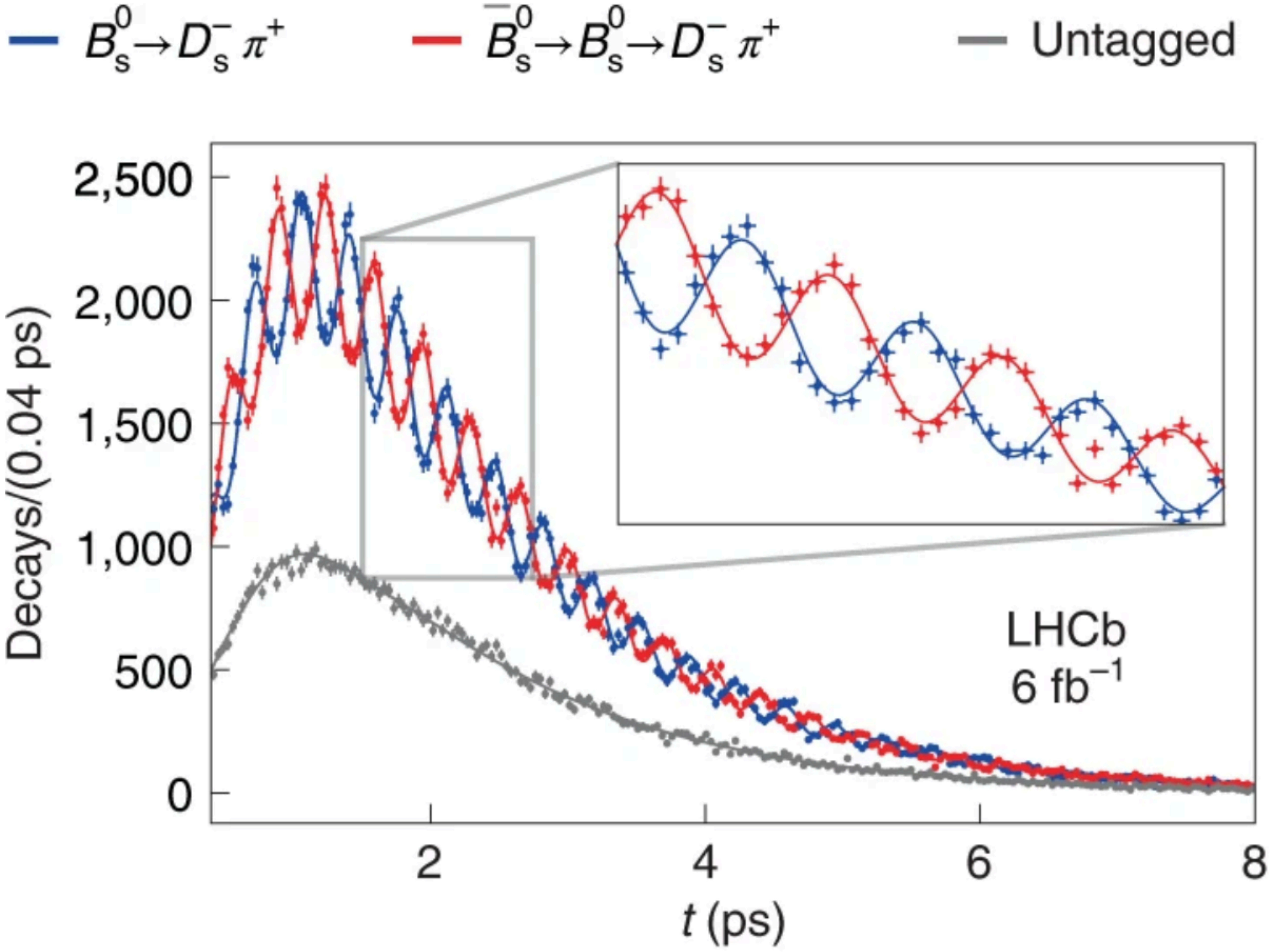
arXiv:hep-ex/0609040v1 22 Sep 2006

Finally…

A counting experiment

$$A(t) = \frac{N(B_s^0 \to D_s^- \pi^+, t) - N(\overline{B}_s^0 \to D_s^- \pi^+, t)}{N(B_s^0 \to D_s^- \pi^+, t) + N(\overline{B}_s^0 \to D_s^- \pi^+, t)},$$



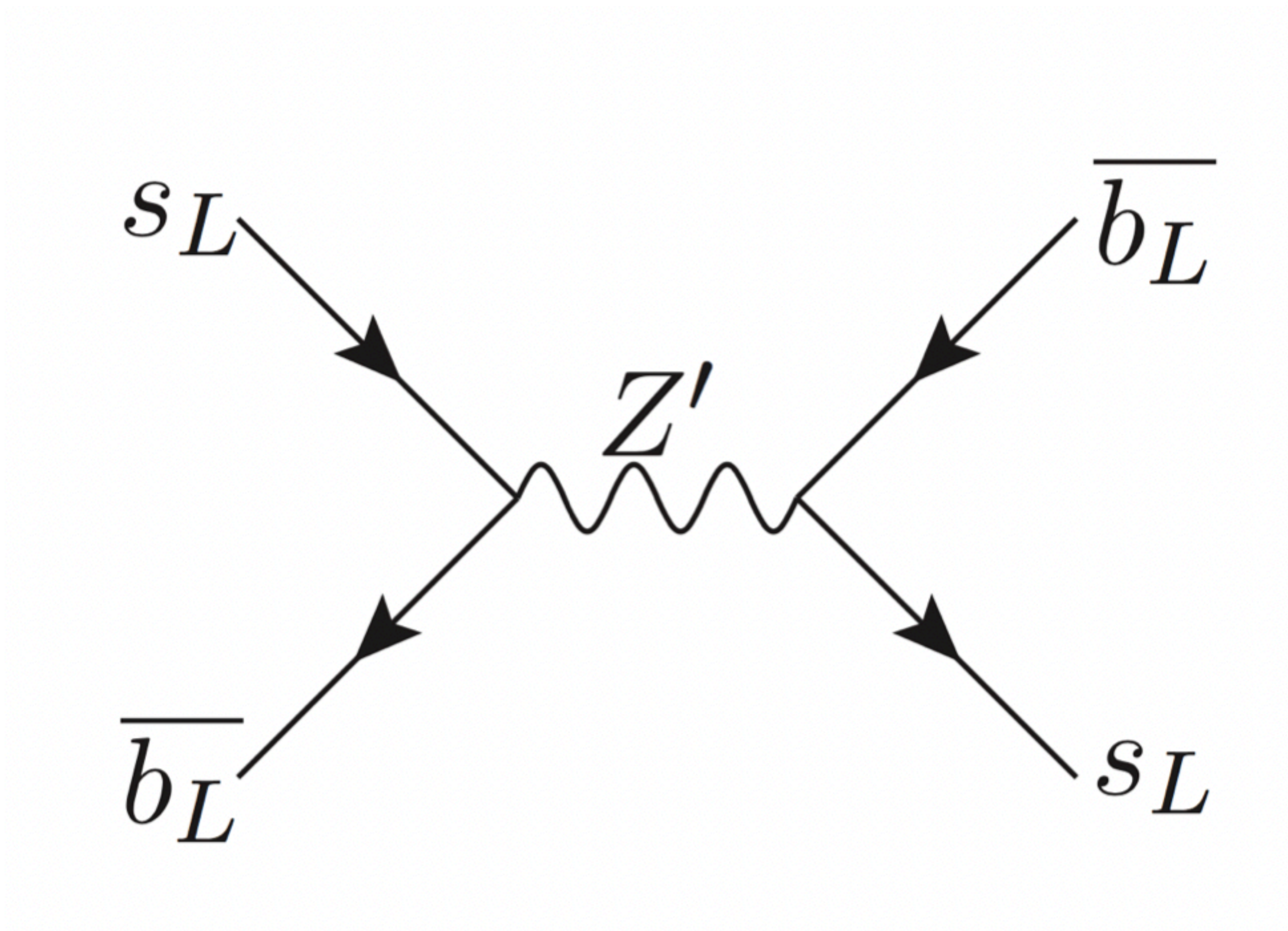


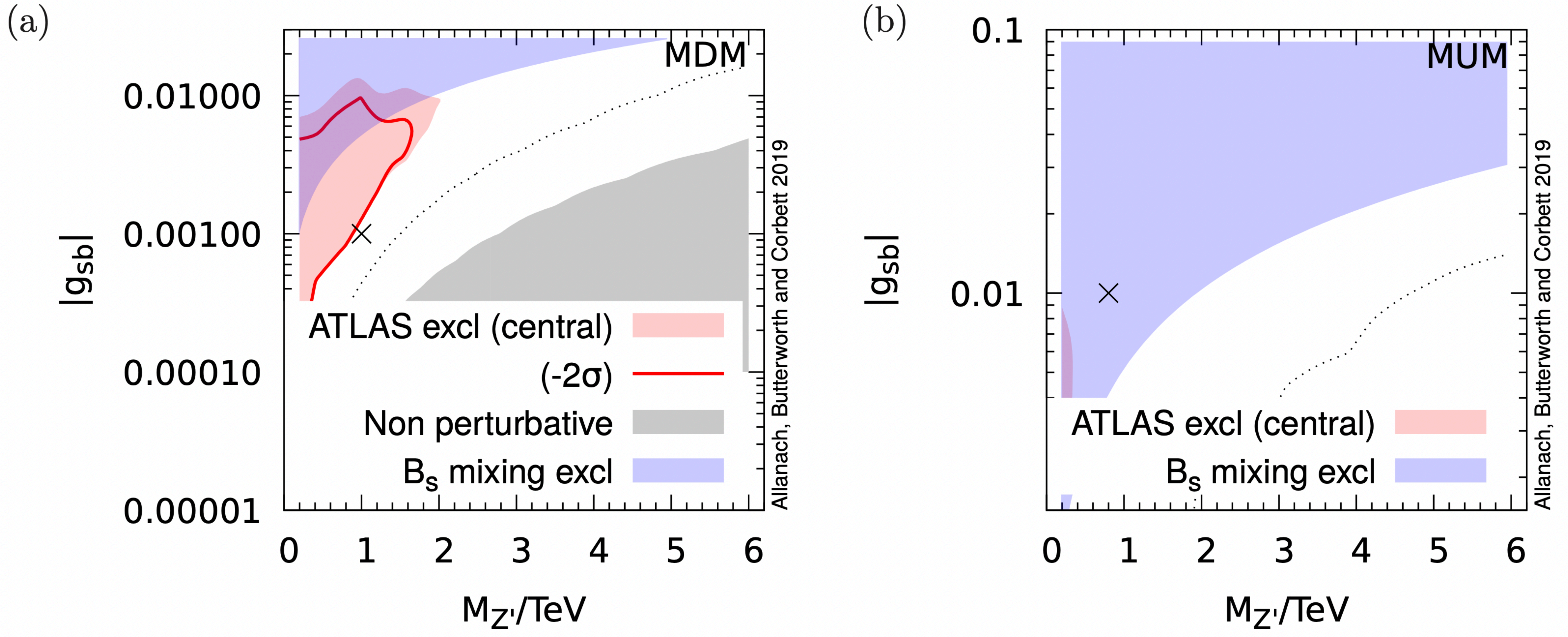
Decay mode	Data sample	Δm_s ps^{-1}
$B_s^0 \to D_s^- \pi^+$	2011	$17.768 \pm 0.023 \pm 0.006$
$B_s^0 \to D_s^- \pi^- \pi^+ \pi^+$	2011-2018	$17.757 \pm 0.007 \pm 0.008$
$B_s^0 \to D_s^- \pi^+$	2015-2018	$17.7683 \pm 0.0051 \pm 0.0032$
Average		17.7666 ± 0.0057

Importance of PID, proper time resolution, flavour tagging

Loop back to the models

$$\text{SM} \quad \Delta m_q = \frac{G_f^2}{6\pi^2} m_{B_q} M_W^2 f\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD} B_{B_q} f_{B_q}^2 |V_{tb}^* V_{tq}|^2 \qquad q = d, s$$



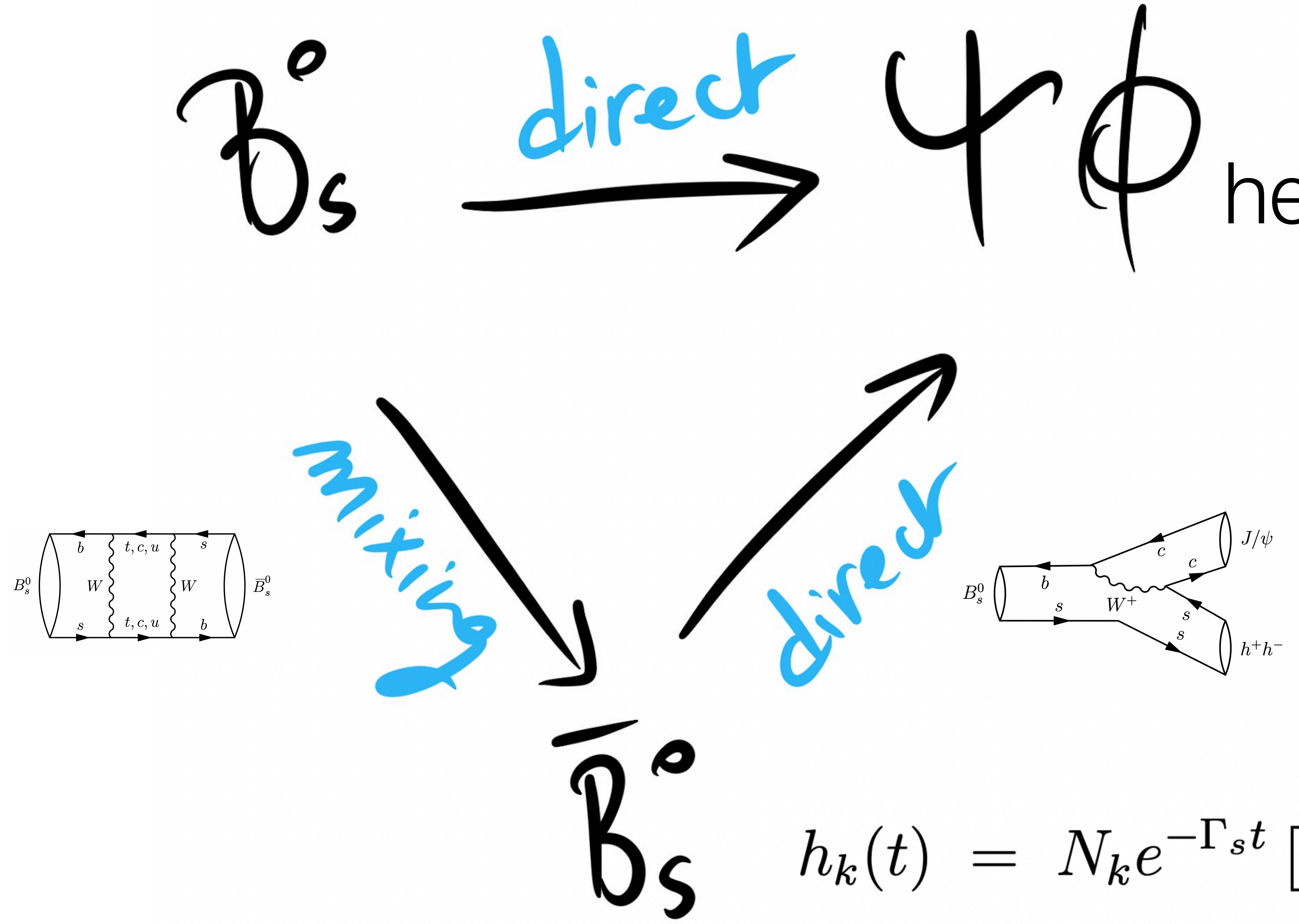


arXiv:1904.10954 one example out of the billion out there.

Let’s us add complexity - $B_s \rightarrow J/\Psi\ (\rightarrow \mu^+\mu^+)\ \Phi\ (K^+K^-)$

Mixture of CP odd and CP even eigenstates

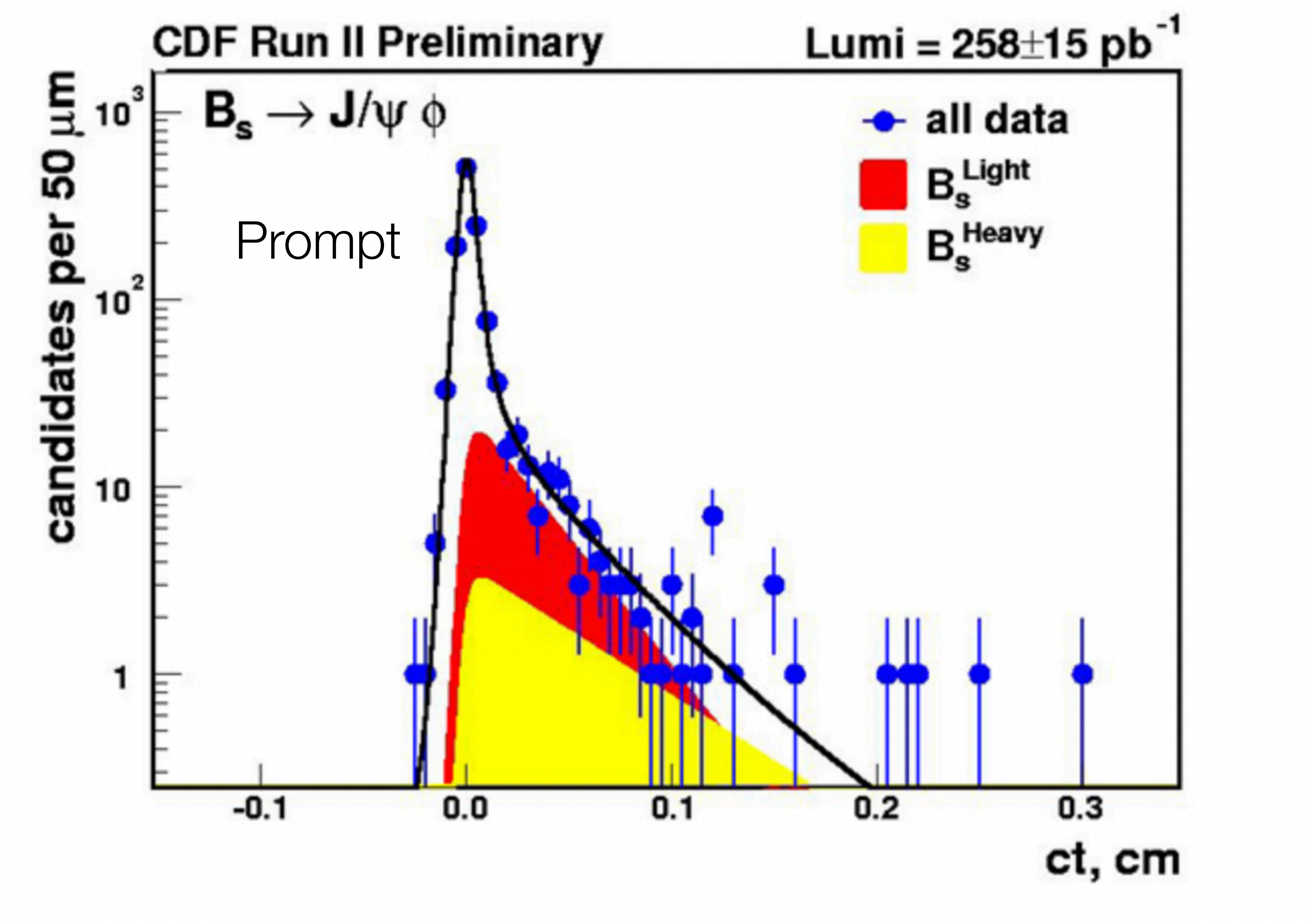
None negligible difference between the heavy and the light state of your the B_s mesons $\Delta\Gamma_s$

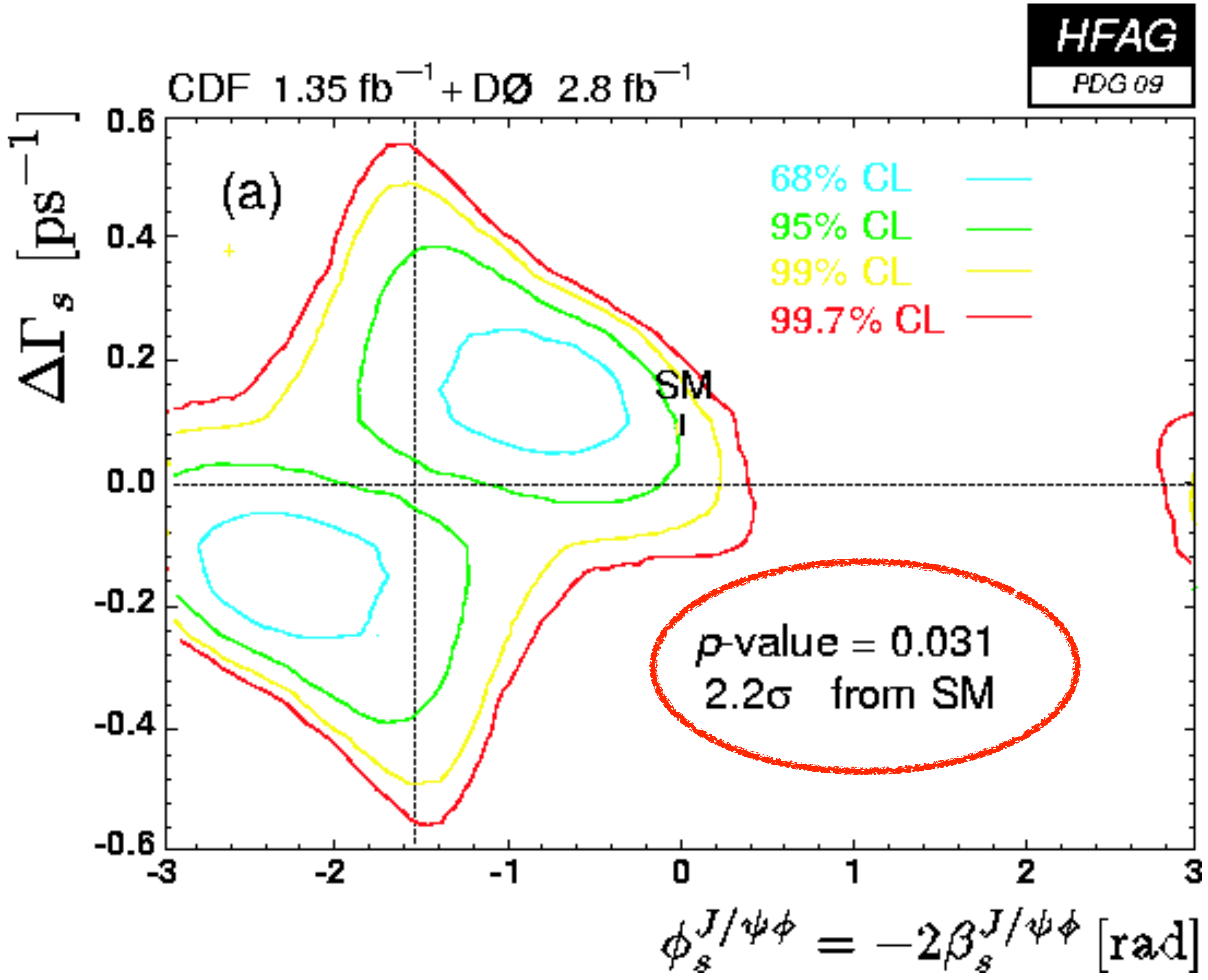


$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\ d\Omega} \propto \sum_{k=1}^{10} h_k(t)\ f_k(\Omega)\,.$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right],$$

Fermilab paved the path of B_s physics

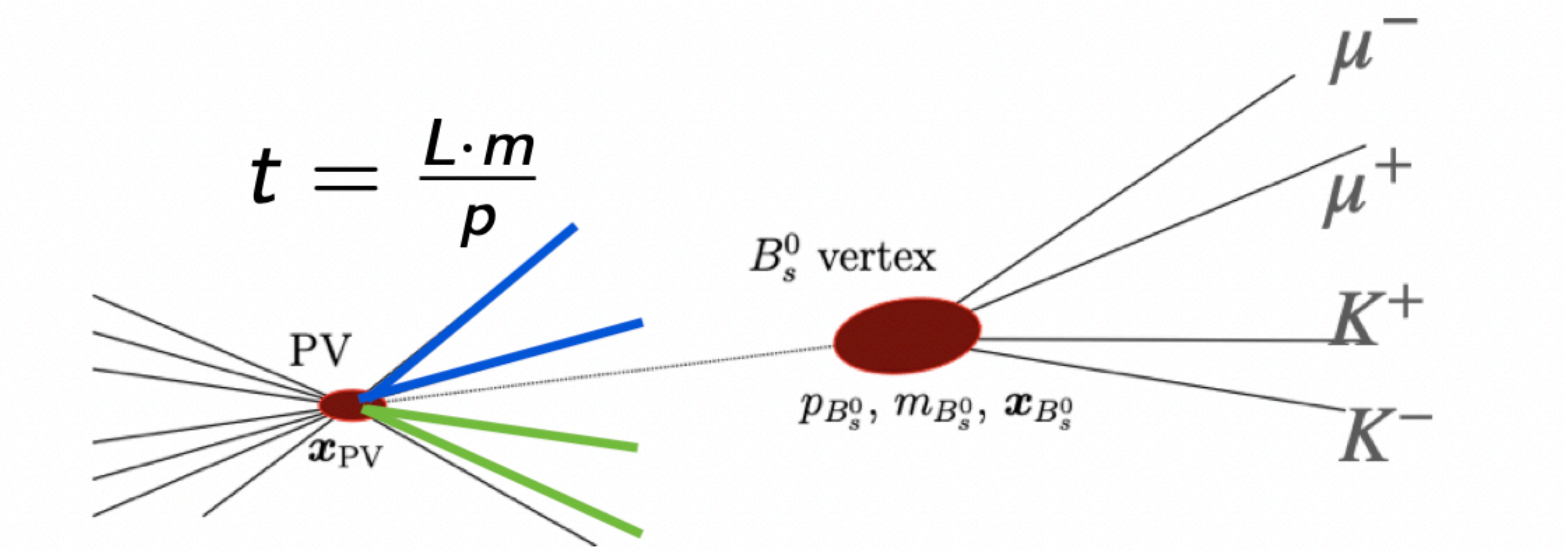




Time dependent angular analysis

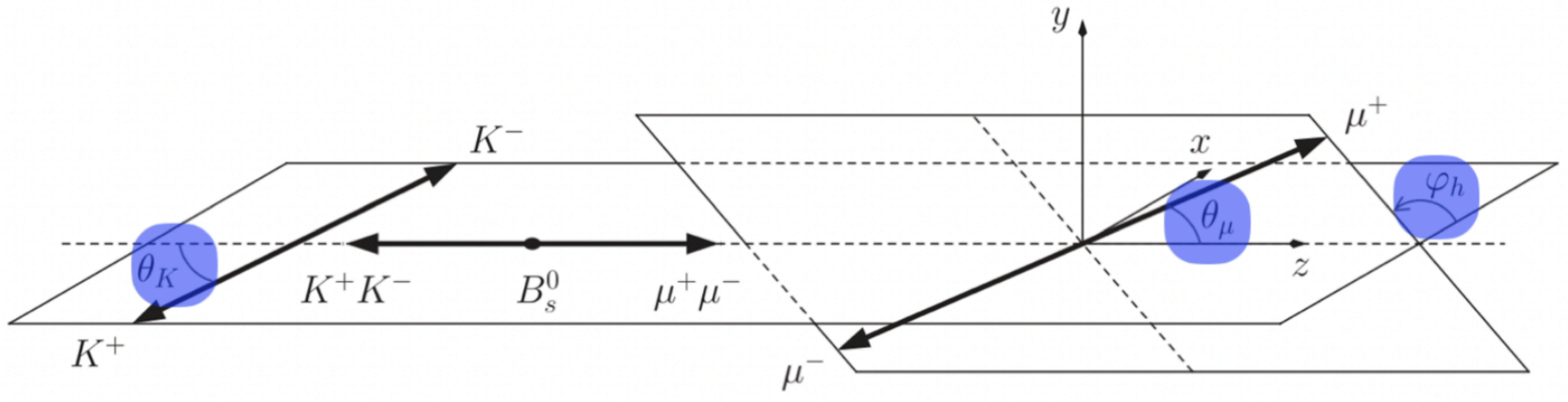
We will come back to the to angular analyses in the second lecture

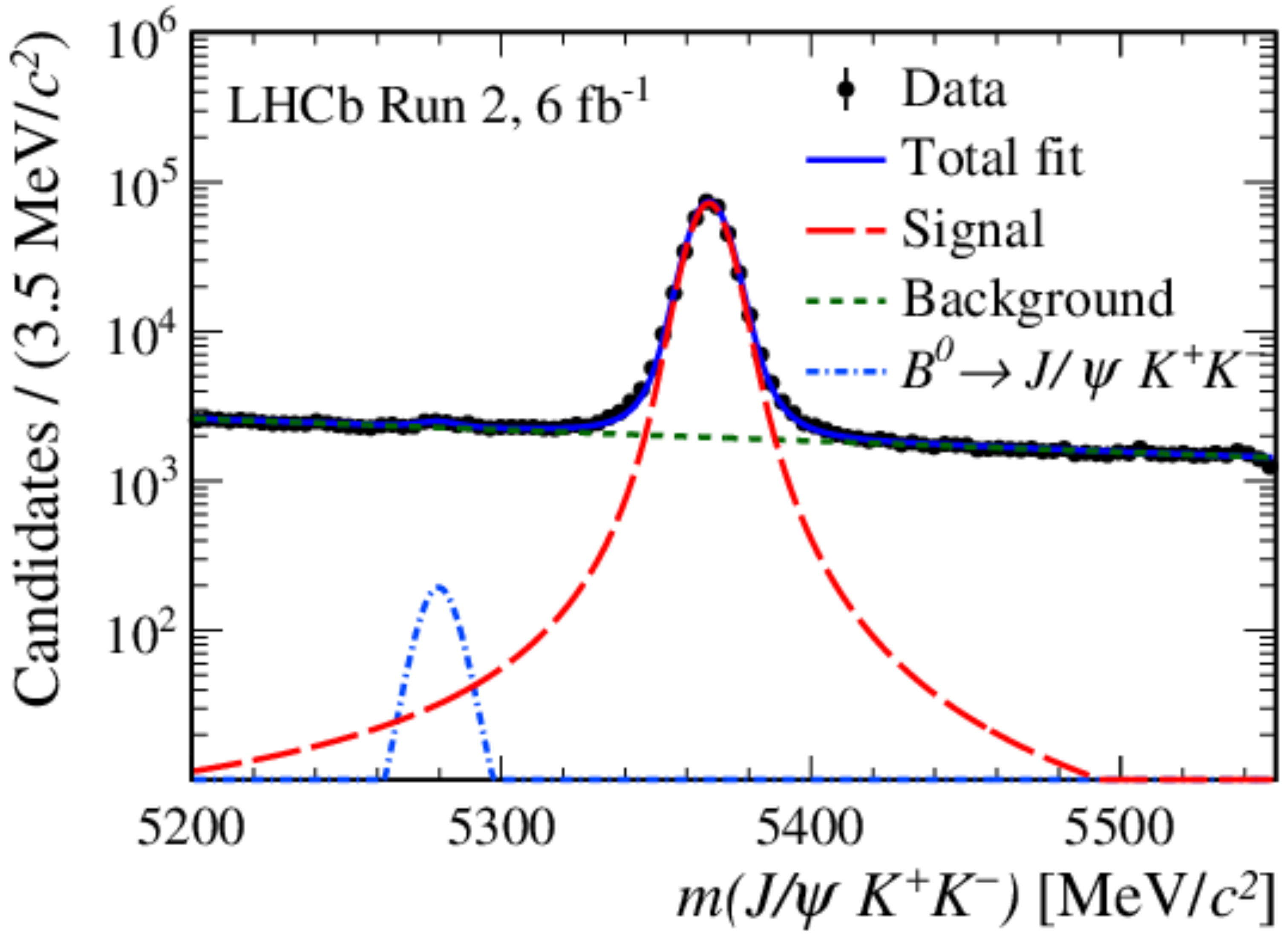
It's just a counting experiment

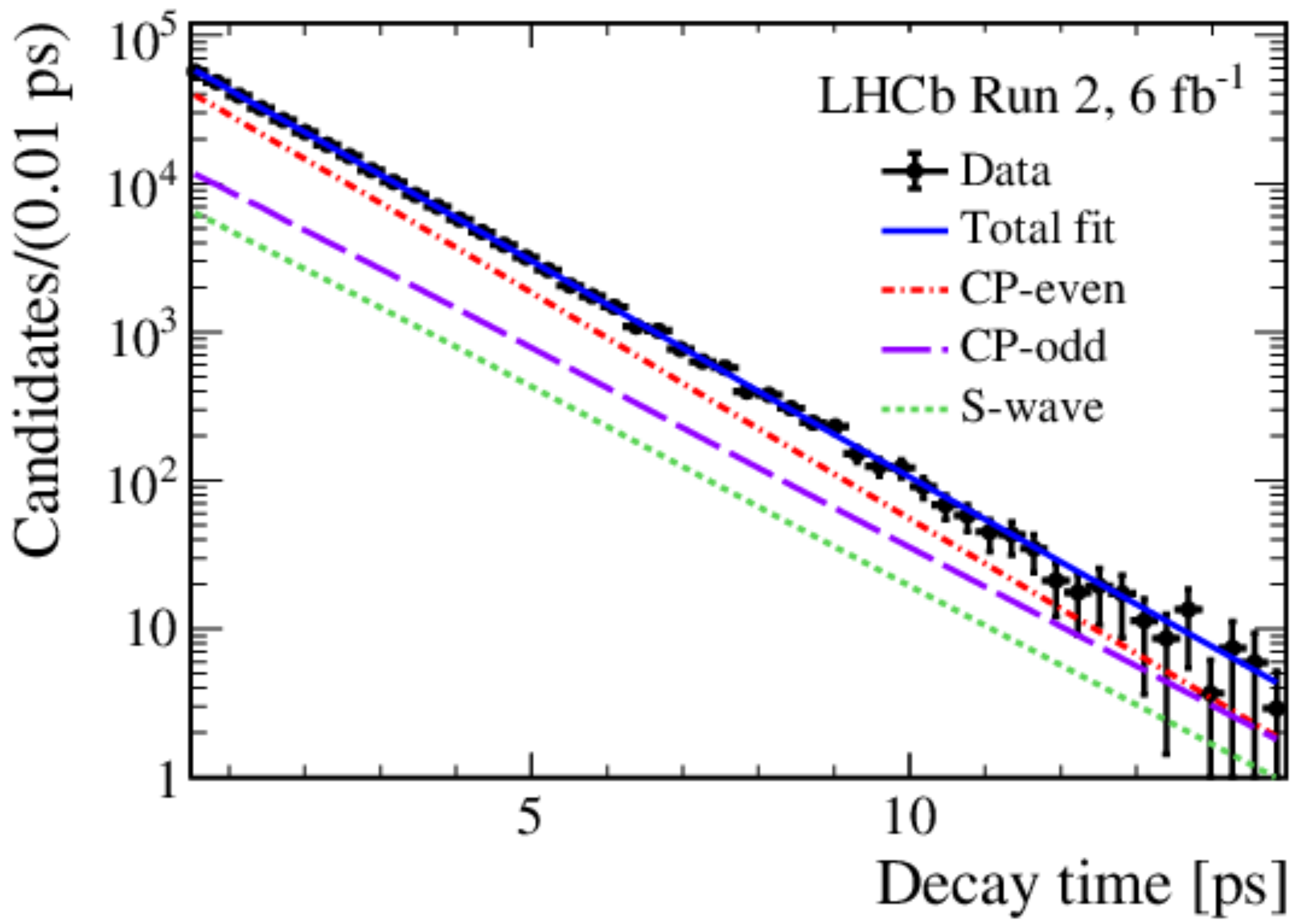


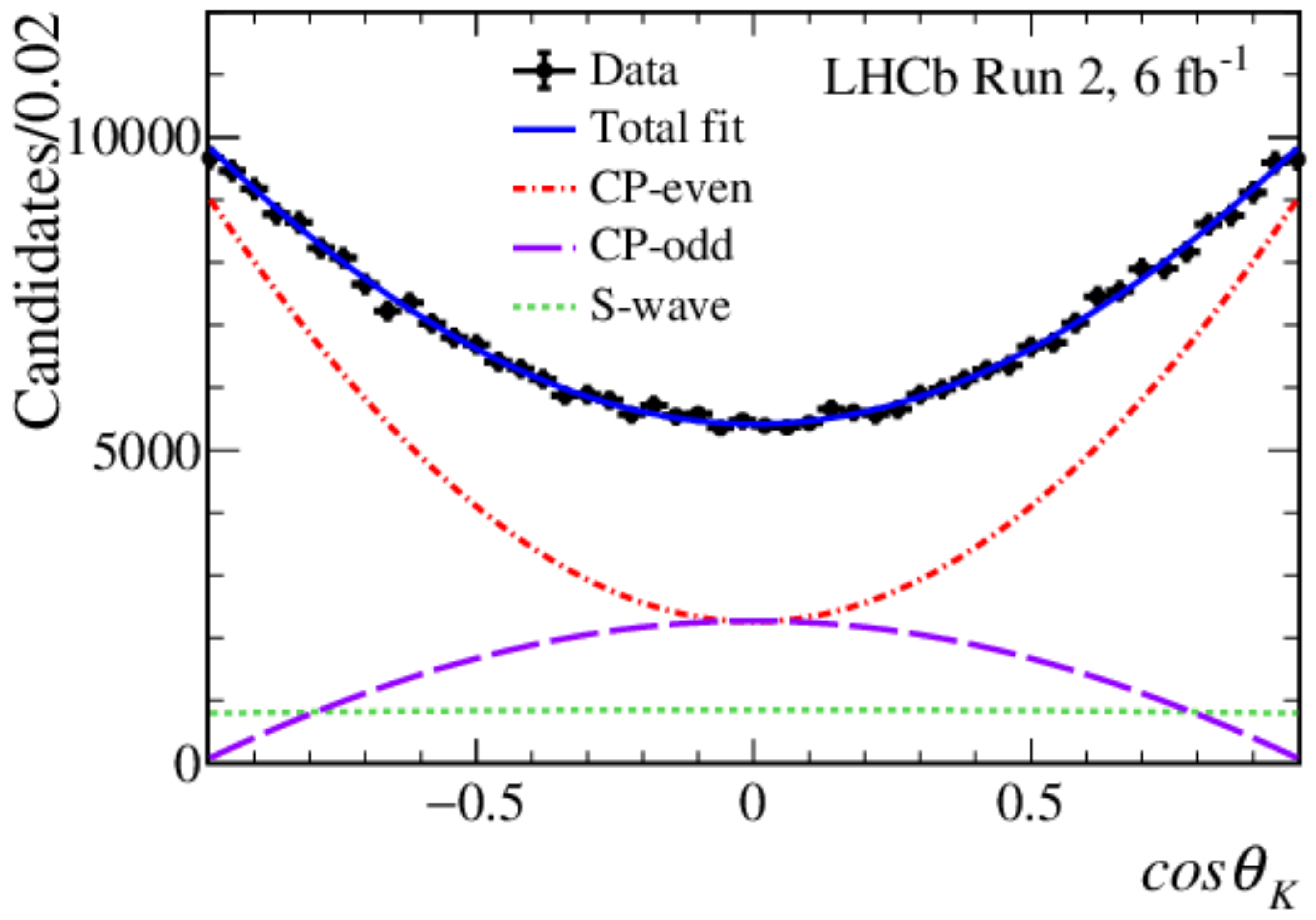
$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to J/\psi KK) - \Gamma(B_s^0 \to J/\psi KK)}{\Gamma(\bar{B}_s^0 \to J/\psi KK) + \Gamma(B_s^0 \to J/\psi KK)} = \eta_f \cdot \sin \phi_s^{\mathrm{obs}} \cdot \sin(\Delta m_s t)$$

- CP eigenvalue of the final state $\eta_f = (-1)^L$
- A mixture of CP-even & CP-odd components $\to$ angular analysis

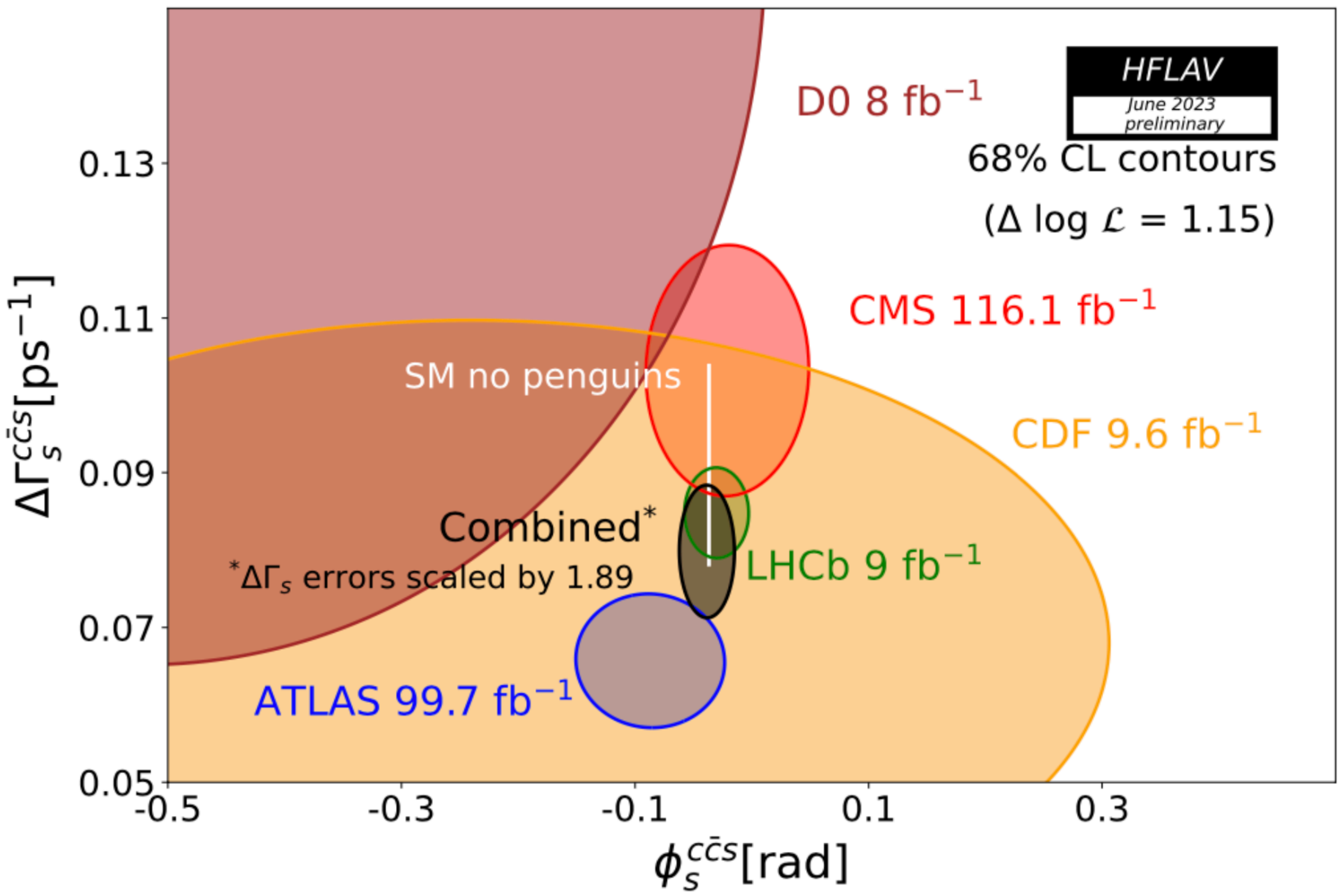








Very similar experimental techniques between the LHC three collaborations



arXiv:2308.01468

An example of NP interpretations

$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\rm eff}^{\rm full} | \bar{B}_q \rangle}{\langle B_q | H_{\rm eff}^{\rm SM} | \bar{B}_q \rangle} = 1 + \frac{A_q^{\rm NP}}{A_q^{\rm SM}} e^{2i\phi_q^{\rm NP}}$$

Let us first consider MFV models and update our results presented in Ref. [11, 12]. In practice, the most convenient strategy in this case is to fit the shift in the Inami-Lim top-quark function entering B_d, B_s and K^0 mixing. We fit for this shift using the experimental measurements of Δm_d, Δm_s and ϵ_K, after determining the parameters of the CKM matrix with the universal unitarity triangle analysis [17].[7] We obtain the following lower bounds at 95% probability:

$$\Lambda > 5.5\,\text{TeV} \quad (\text{small} \tan\beta)\,, \tag{13}$$

$$\Lambda > 5.1\,\text{TeV} \quad (\text{large} \tan\beta)\,. \tag{14}$$

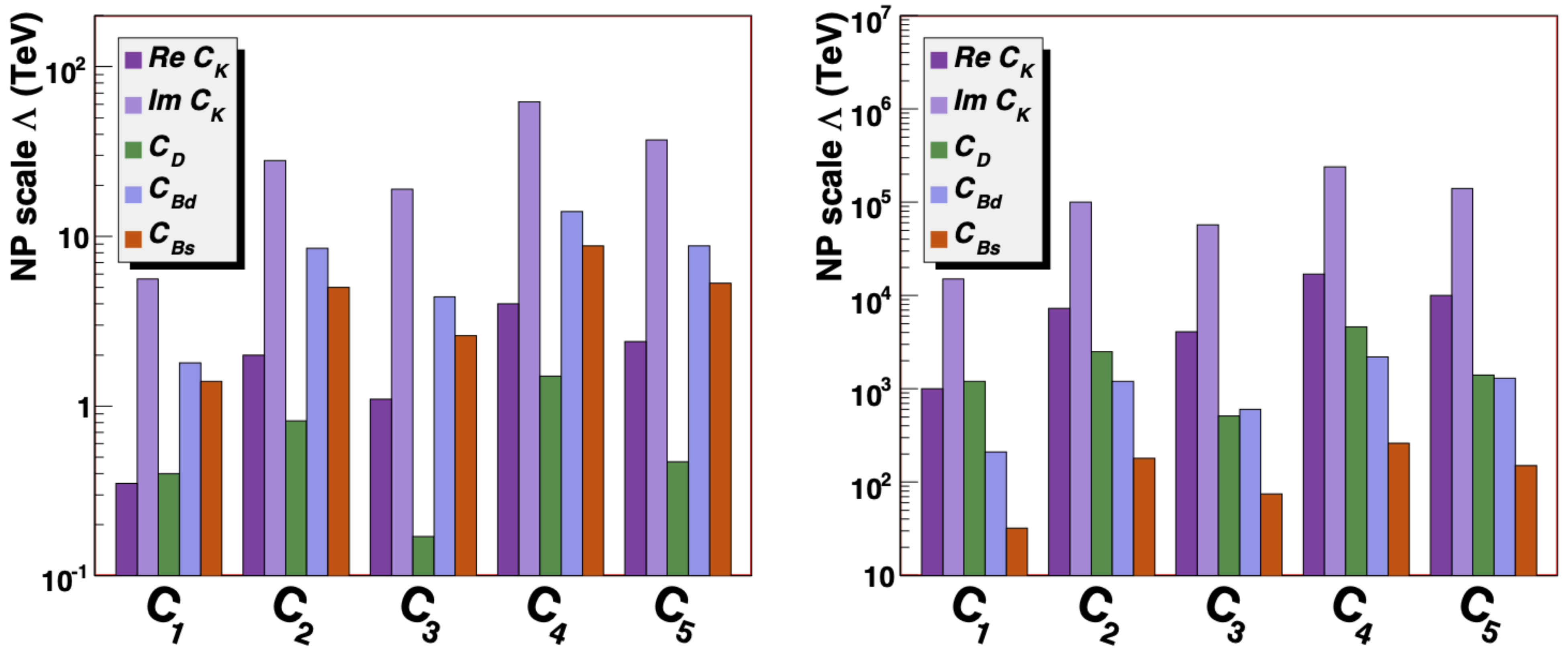


FIG. 7: Summary of the 95% probability lower bound on the NP scale Λ for strongly-interacting NP in NMFV (left) and general NP (right) scenarios.

https://arxiv.org/pdf/0707.0636

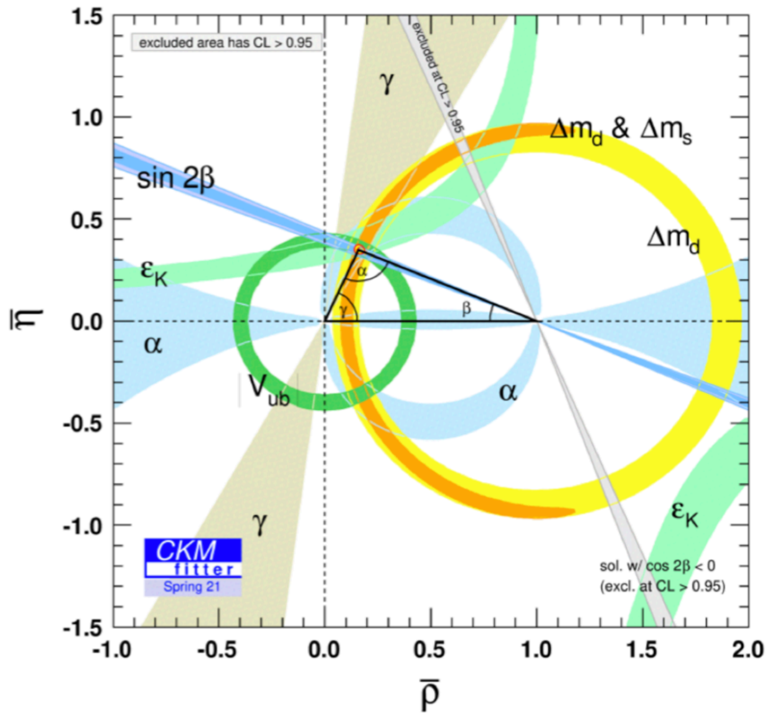
sin 2β & ϕ_s

Typically dominated by a few “Golden modes”

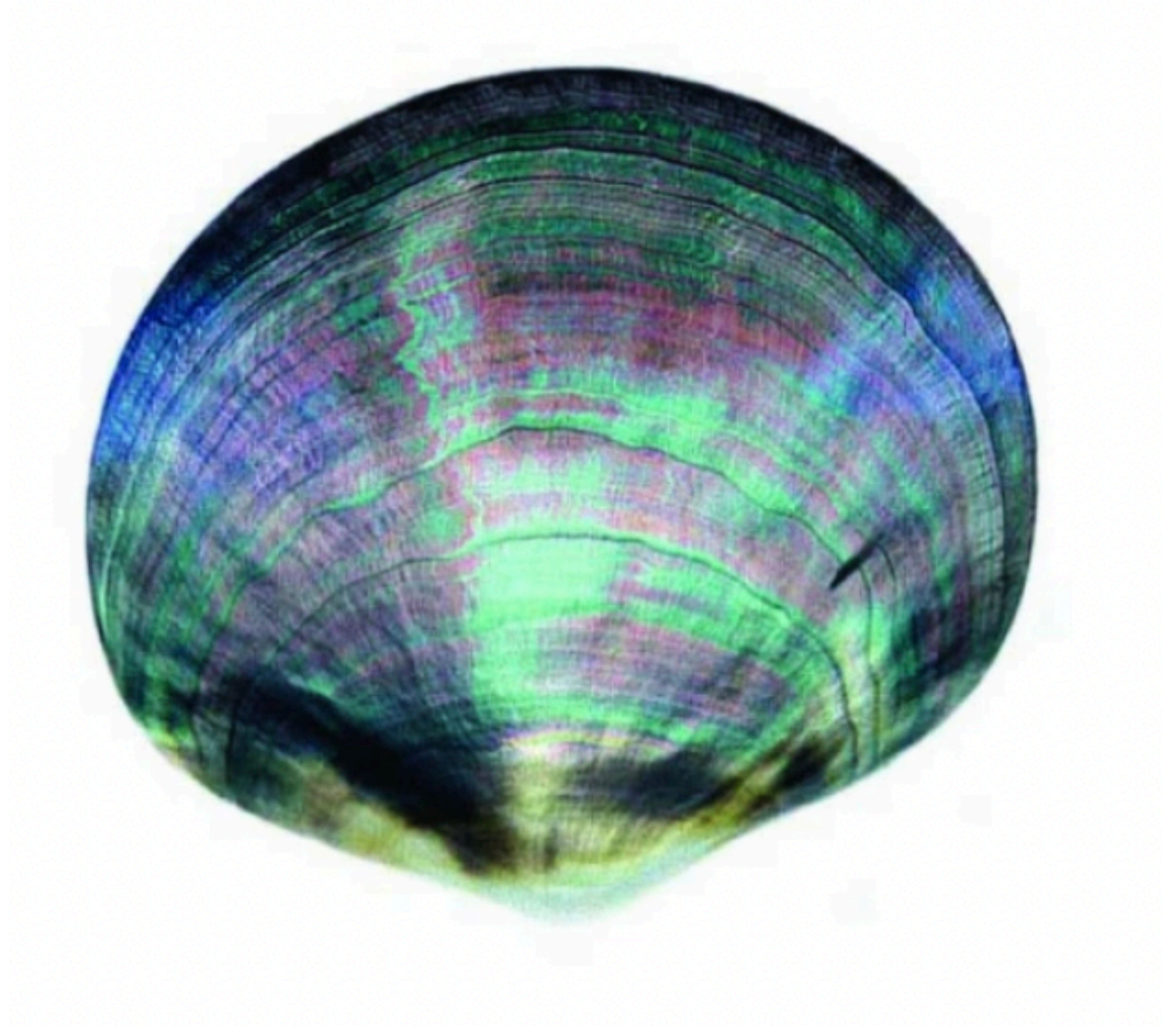
γ measurements have somewhat of a “commune spirit ”

How to measure γ ?

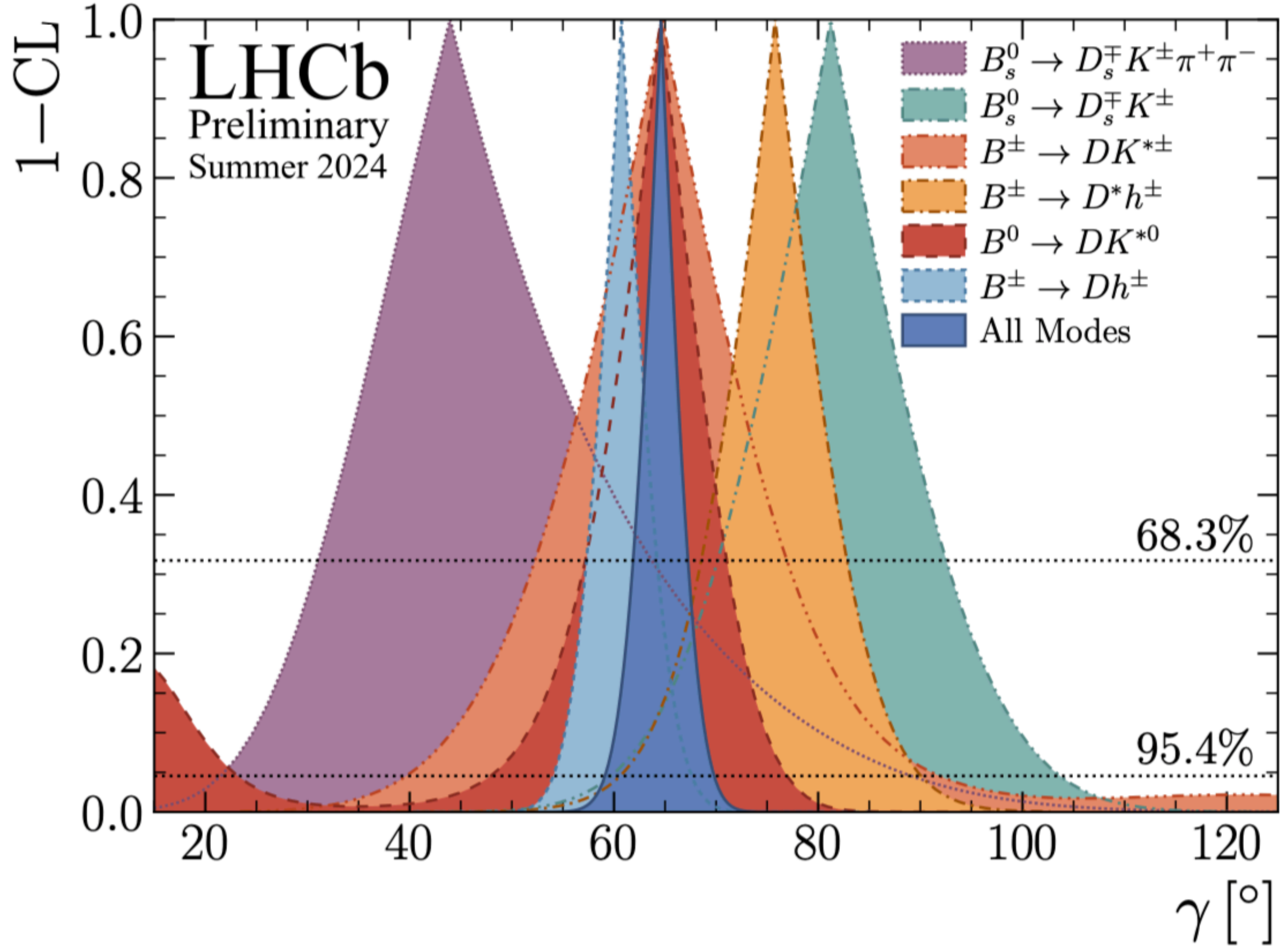
$$\gamma \equiv \varphi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \simeq \arg\left(\rho + i\eta\right) \ .$$



It's all about interferences !



< Beautiful Mont-Blanc analogy >



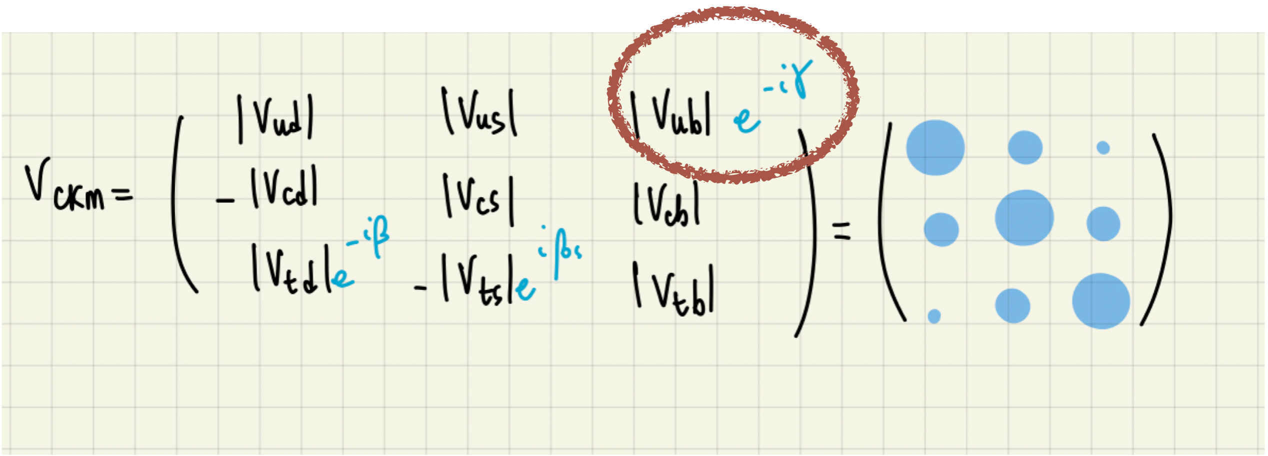
CONF-2024-004

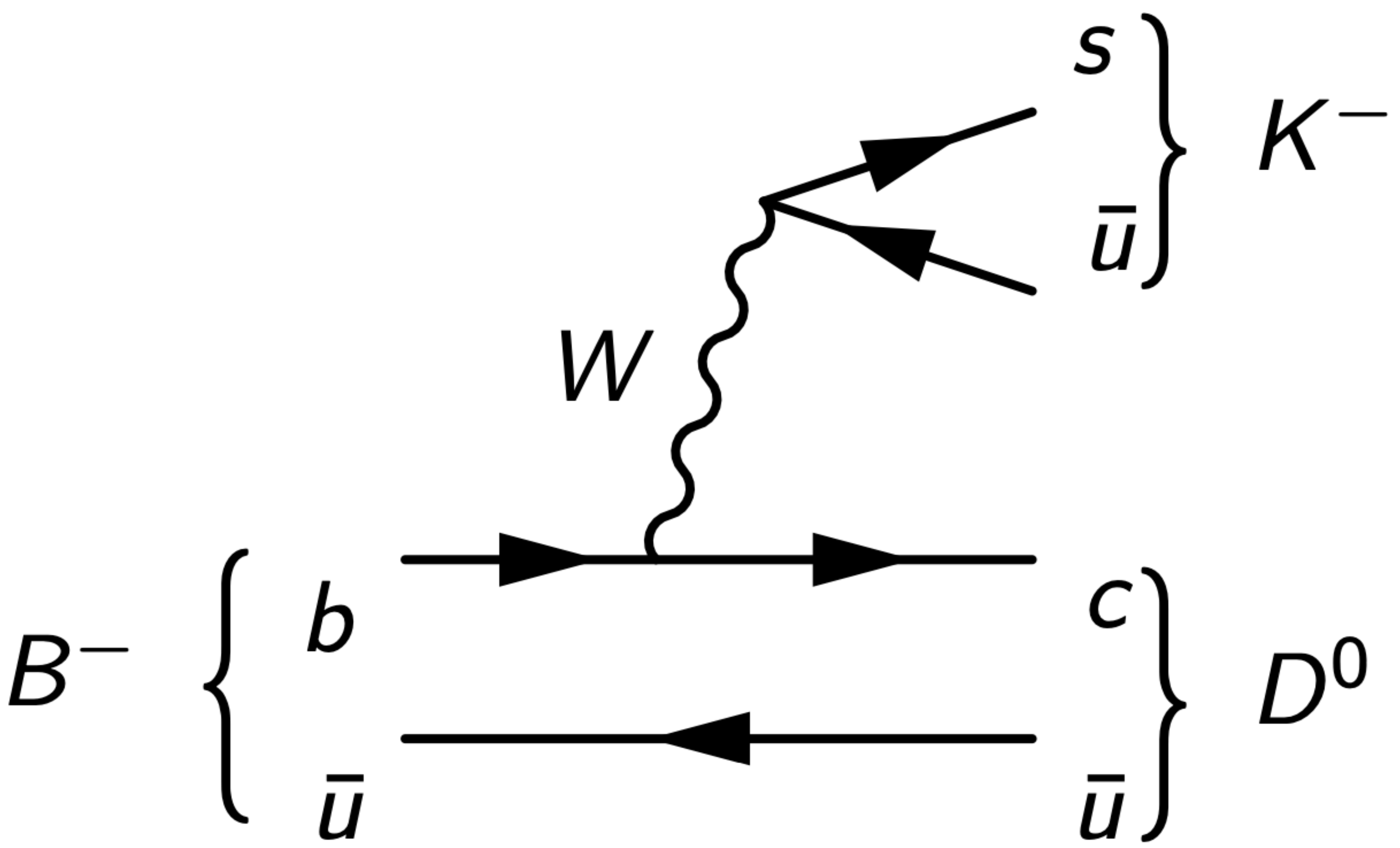
There is a myriad of techniques to measure this angle

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^{\pm} \to Dh^{\pm}$	$D \to h^{\pm} h'^{\mp}$	[35]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to h^+ h^- \pi^+ \pi^-$	[19]	Run 1&2	**New**
$B^{\pm} \to Dh^{\pm}$	$D \to K^{\pm} \pi^{\mp} \pi^+ \pi^-$	[36]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to h^{\pm} h'^{\mp} \pi^0$	[37]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to K_S^0 h^+ h^-$	[38]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to K_S^0 K^{\pm} \pi^{\mp}$	[39]	Run 1&2	*As before*
$B^{\pm} \to D^* h^{\pm}$	$D \to h^{\pm} h'^{\mp}$ (PR)	[35]	Run 1&2	*As before*
$B^{\pm} \to D^* h^{\pm}$	$D \to K_S^0 h^+ h^-$ (PR)	[20]	Run 1&2	**New**
$B^{\pm} \to D^* h^{\pm}$	$D \to K_S^0 h^+ h^-$ (FR)	[21]	Run 1&2	**New**
$B^{\pm} \to D K^{*\pm}$	$D \to h^{\pm} h'^{\mp}$	[22]†	Run 1&2	**Updated**
$B^{\pm} \to D K^{*\pm}$	$D \to h^{\pm} \pi^{\mp} \pi^+ \pi^-$	[22]†	Run 1&2	**Updated**
$B^{\pm} \to D K^{*\pm}$	$D \to K_S^0 h^+ h^-$	[22]†	Run 1&2	**New**
$B^{\pm} \to D h^{\pm} \pi^+ \pi^-$	$D \to h^{\pm} h'^{\mp}$	[40]	Run 1	*As before*
$B^0 \to D K^{*0}$	$D \to h^{\pm} h'^{\mp}$	[23]	Run 1&2	**Updated**
$B^0 \to D K^{*0}$	$D \to h^{\pm} \pi^{\mp} \pi^+ \pi^-$	[23]	Run 1&2	**Updated**
$B^0 \to D K^{*0}$	$D \to K_S^0 h^+ h^-$	[24]	Run 1&2	**Updated**
$B^0 \to D^{\mp} \pi^{\pm}$	$D^+ \to K^- \pi^+ \pi^+$	[41]	Run 1	*As before*
$B_s^0 \to D_s^{\mp} K^{\pm}$	$D_s^+ \to h^+ h^- \pi^+$	[25, 42]†	Run 1&2	**Updated**
$B_s^0 \to D_s^{\mp} K^{\pm} \pi^+ \pi^-$	$D_s^+ \to h^+ h^- \pi^+$	[43]	Run 1&2	*As before*

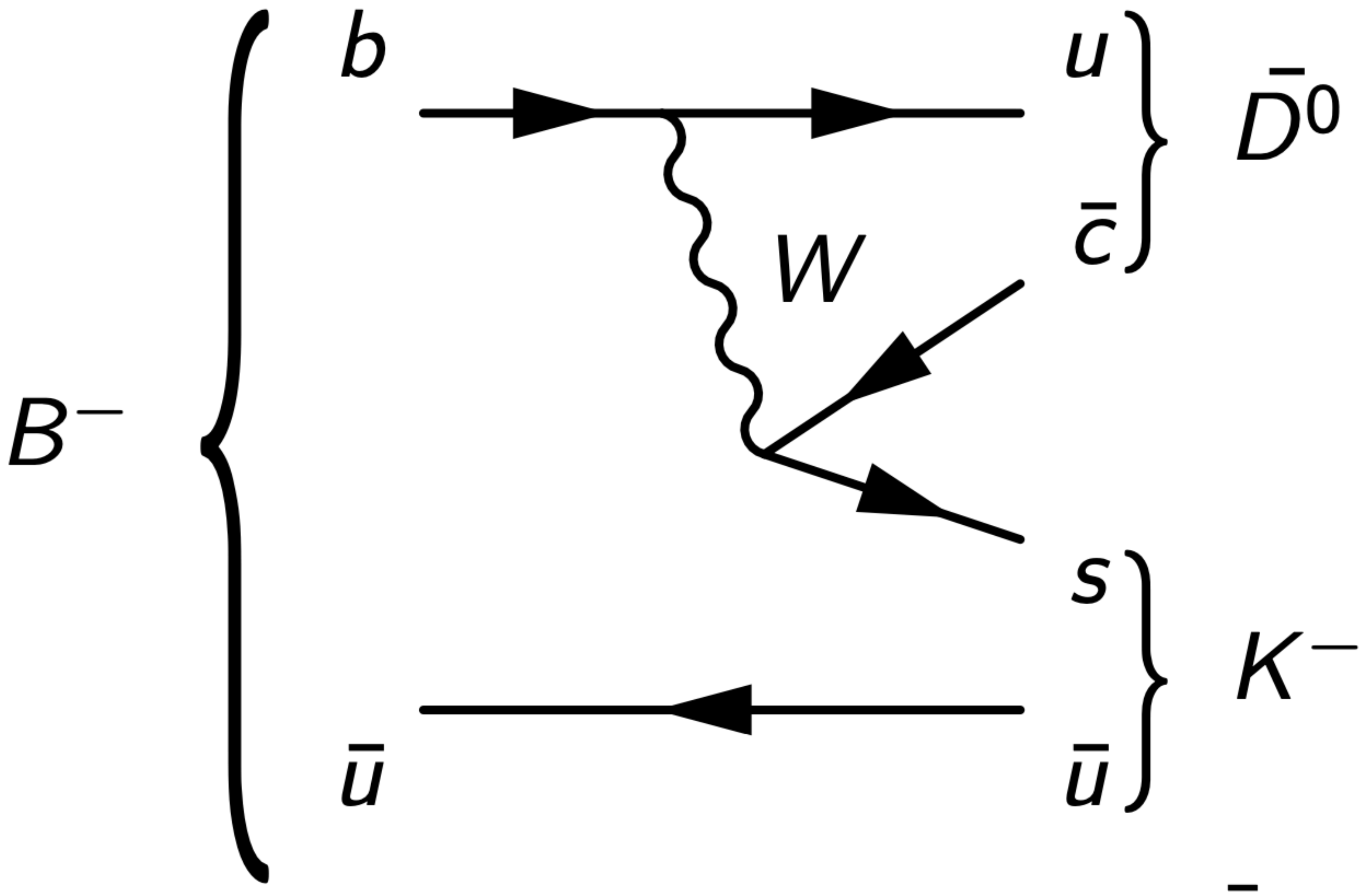
ADS, GLW, BPGGSZ, etc.

Which interference are we talking about ?

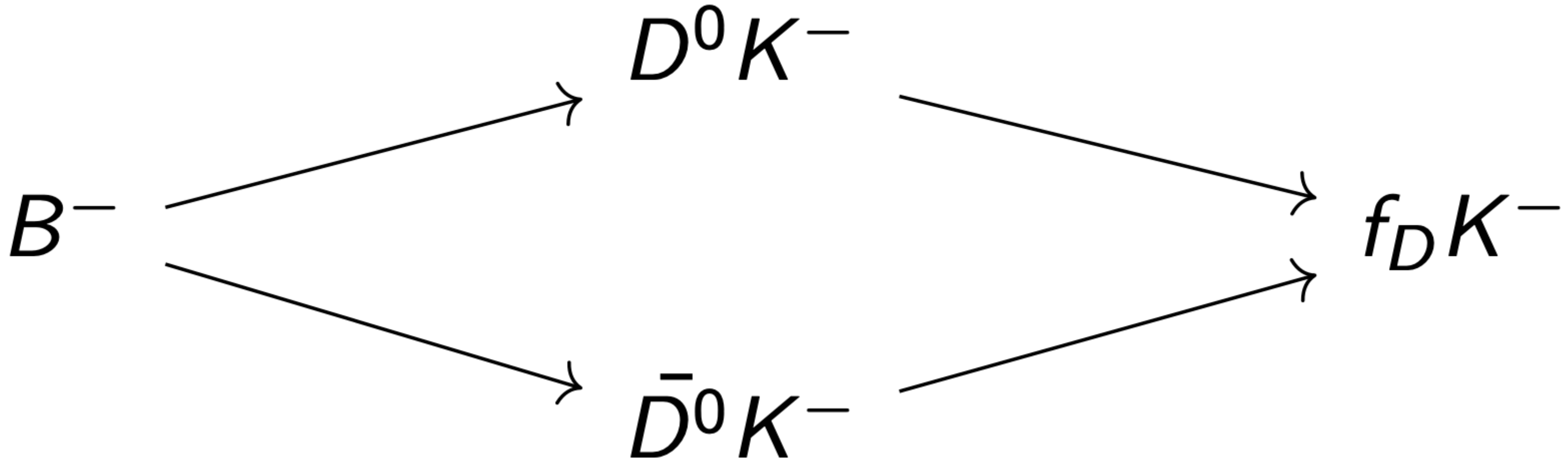




Favoured $B^- \to D^0 K^-$



CKM+colour suppressed $B^- \to \bar{D}^0 K^-$



We can write down the amplitudes

$$\mathcal{A}(B^-) = \mathcal{A}_B\big(\mathcal{A}_{D^0} + \ r_B\ e^{i(\ \delta_B\ -\ \gamma\ )}\mathcal{A}_{\bar{D}^0}\big)$$

$$\mathcal{A}(B^+) = \mathcal{A}_B\big(\mathcal{A}_{\bar{D}^0} + \ r_B\ e^{i(\ \delta_B\ +\ \gamma\ )}\mathcal{A}_{D^0}\big)$$

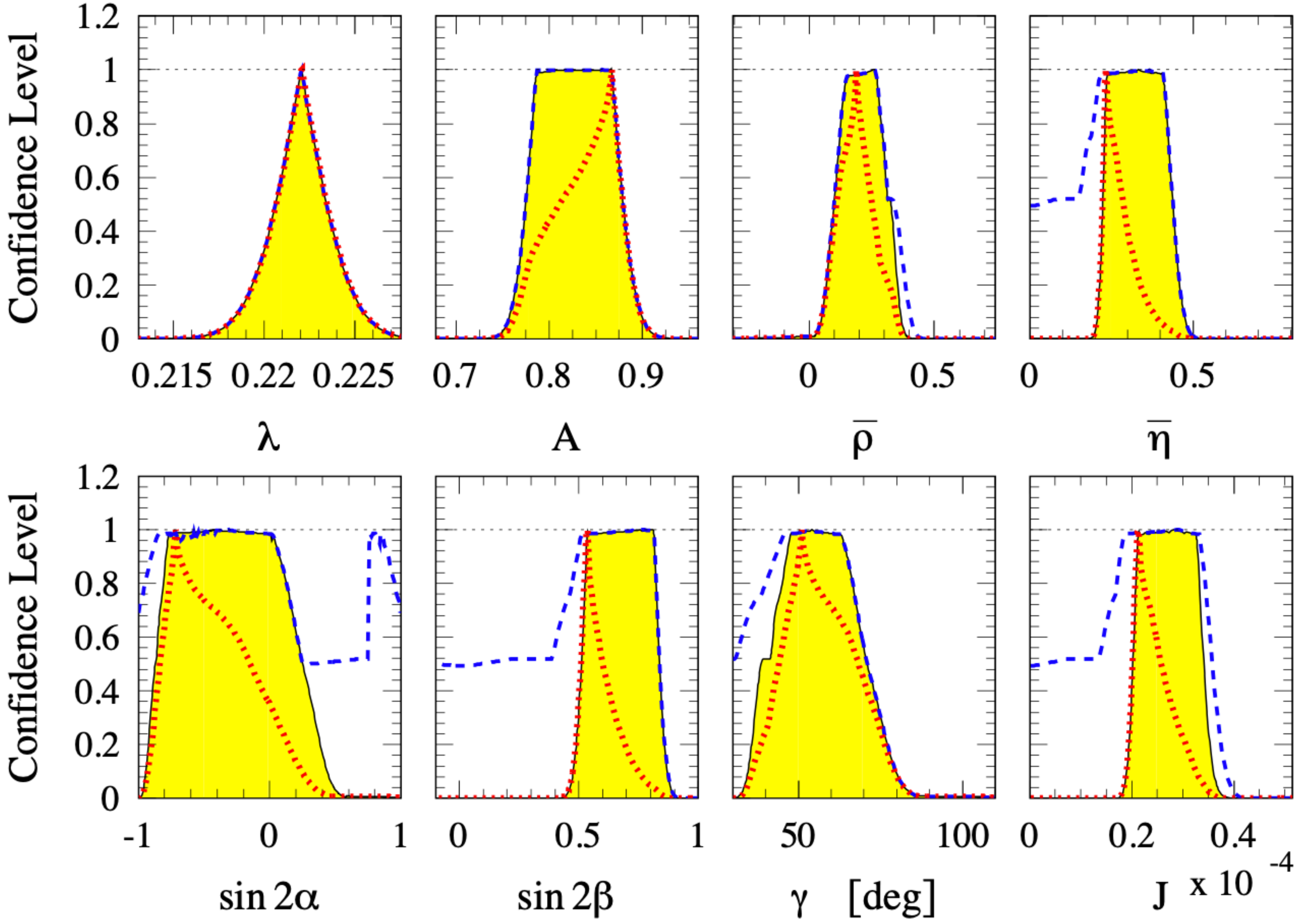
- r_B : The magnitude of the interferences

  δ_B: Strong phase difference, accounts for all unknown QCD phases

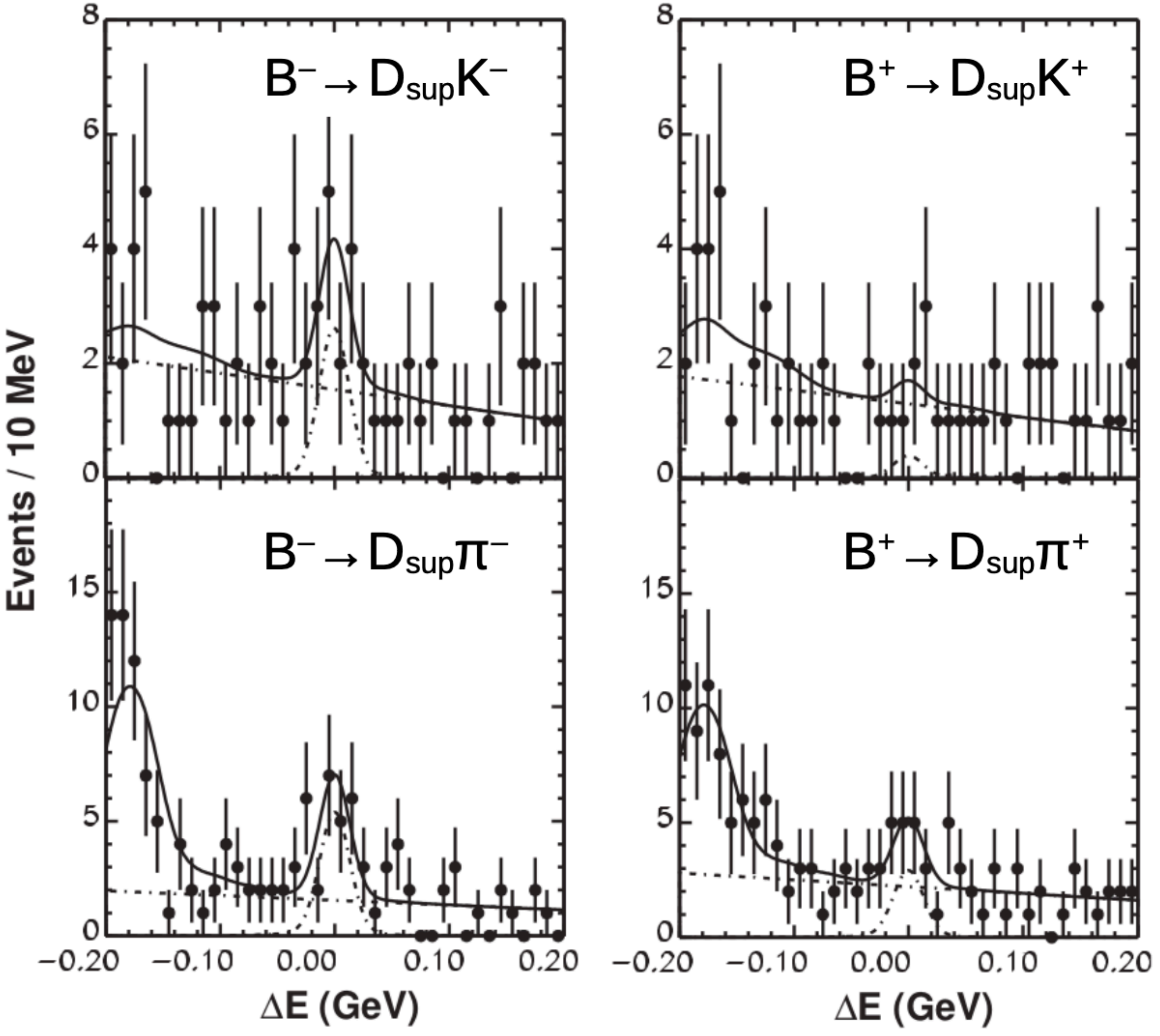
  γ : The weak phase, swaps under CP

Parameter	$\geq 32\%$ CL	half width	$\geq 5\%$ CL	half width	δ_{32}	δ_5
λ	0.2221 ± 0.0021		0.2221 ± 0.0041		0	0
A	0.782 - 0.888	0.053	0.758 - 0.906	0.074	10	3
$\bar{\rho}$	0.09 - 0.29	0.10	0.04 - 0.37	0.16	29	6
$\bar{\eta}$	0.22 - 0.32	0.05	0.21 - 0.42	0.11	58	21
J (10^{-5})	2.0 - 2.9	0.5	1.9 - 3.5	0.8	38	11
$\sin 2\alpha$	-0.88 - 0.04	0.46	-0.95 - 0.33	0.64	27	12
$\sin 2\beta$	0.50 - 0.67	0.09	0.47 - 0.81	0.17	50	19
α	89° - 121°	16°	80° - 126°	23°	27	12
β	15.0° - 21.0°	3.0°	14.0° - 27.0°	6.5°	59	25
$\gamma = \delta$	42° - 74°	16°	34° - 82°	24°	16	0
$\sin\theta_{12}$	0.2221 ± 0.0021		0.2221 ± 0.0041		0	0
$\sin\theta_{13}$ (10^{-3})	2.70 - 4.03	0.67	2.49 - 4.38	0.95	17	8
$\sin\theta_{23}$ (10^{-3})	38.4 - 43.2	2.4	38.0 - 43.6	2.8	0	0
$\lvert V_{ud}\rvert$	0.97504 ± 0.00049		0.97504 ± 0.00094		0	0
$\lvert V_{us}\rvert$	0.2221 ± 0.0021		0.2221 ± 0.0042		0	0
$\lvert V_{ub}\rvert$ (10^{-3})	2.70 - 3.71	0.51	2.45 - 4.38	0.96	37	7
$\lvert V_{cd}\rvert$	0.2220 ± 0.0021		0.2220 ± 0.0042		0	0
$\lvert V_{cs}\rvert$	0.97414 ± 0.00049		0.97414 ± 0.00098		13	4
$\lvert V_{cb}\rvert$ (10^{-3})	38.7 - 43.2	2.3	38.1 - 43.6	2.8	4	0
$\lvert V_{td}\rvert$ (10^{-3})	7.2 - 9.2	1.0	6.6 - 9.6	1.5	23	6
$\lvert V_{ts}\rvert$ (10^{-3})	38.0 - 42.7	2.4	37.4 - 43.1	2.9	8	3
$\lvert V_{tb}\rvert$	0.99907 - 0.99926	9×10^{-5}	0.99905 - 0.99928	11×10^{-5}	10	8
Δm_s (ps^{-1})	15.5 - 33.7	9.1	15.0 - 41.3	13.1	0	3
$\mathrm{BR}(K_L^0 \to \pi^0 \nu\bar{\nu})$ (10^{-11})	1.2 - 2.6	0.7	1.1 - 3.8	1.4	50	13
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$ (10^{-11})	6.6 - 9.5	1.5	5.4 - 10.4	2.5	35	14
$\mathrm{BR}(B^+ \to \tau^+ \nu_\tau)$ (10^{-5})	4.6 - 12.4	3.9	3.6 - 21.0	8.7	49	13
$\mathrm{BR}(B^+ \to \mu^+ \nu_\mu)$ (10^{-7})	1.8 - 4.9	1.6	1.4 - 8.3	3.5	48	10
$f_{B_d}\sqrt{B_d}$ (MeV)	194 - 246	26	185 - 272	44	33	12
B_K	> 0.72		> 0.55		31	10
m_t (GeV)	124 - 406	141	102 - 550	224	6	5

Table 3: *Fit results including the world average on* $\sin 2\beta_{\mathrm{WA}}$. *As in Table 2, ranges are given for the quantities that are limited by systematic theoretical errors. The two right columns give the relative improvements (in percent) of the* $\geq 32\%$ CL *and* $\geq 5\%$ CL *half widths with respect to the fit results without* $\sin 2\beta$ *given in Tab. 2. The last three lines give the ranges obtained for chosen theoretical parameters when removing their respective bounds in the fit.*



https://arxiv.org/pdf/hep-ph/0104062



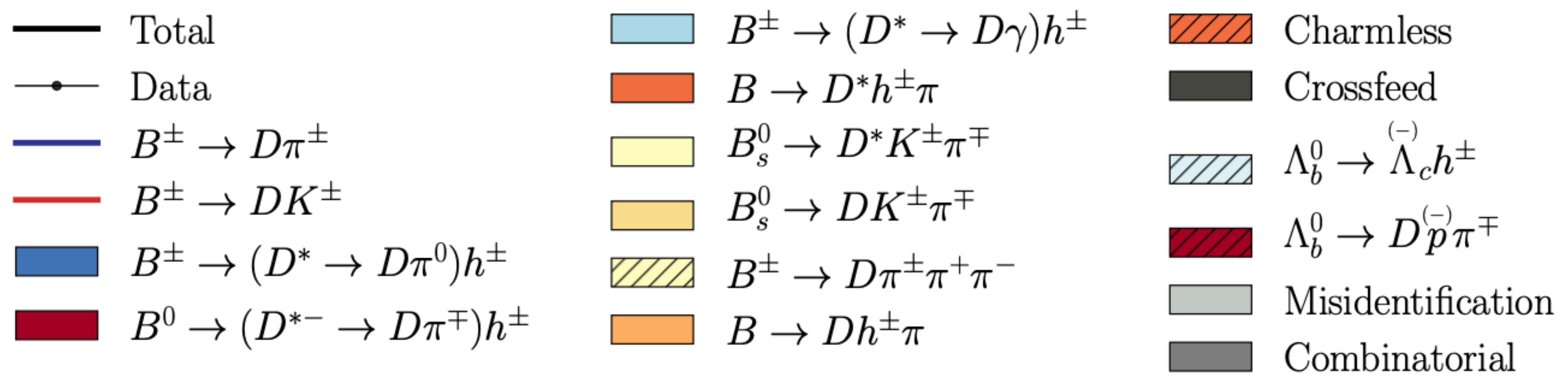
ADS technique

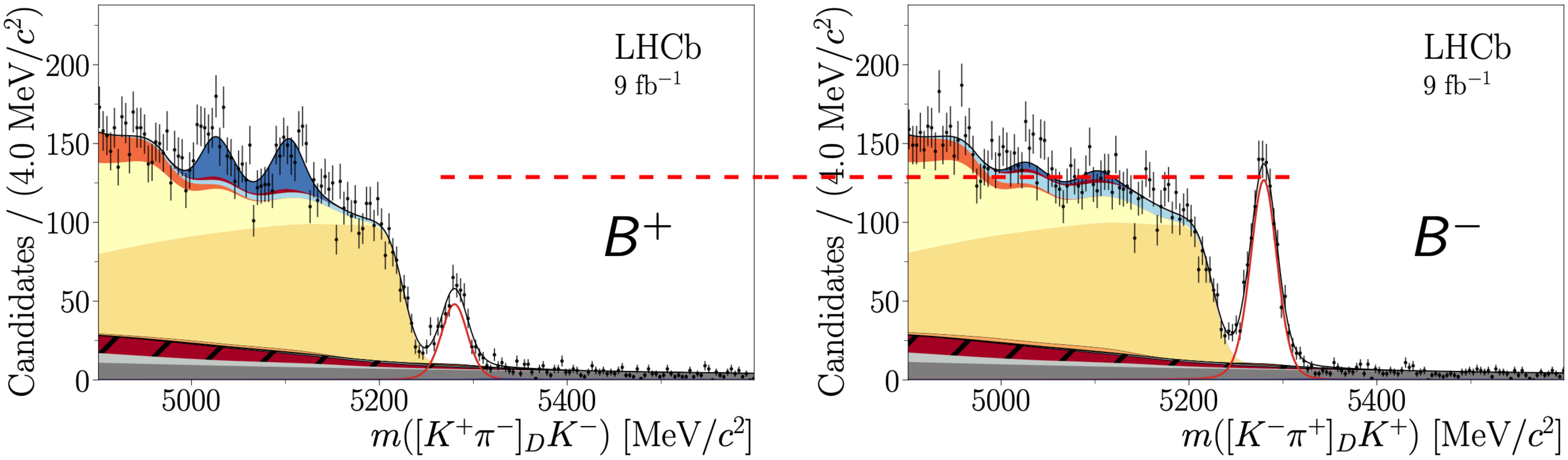
$$\mathcal{A}_{DK} = 0.88\,^{+0.77}_{-0.62}(\mathrm{stat}) \pm 0.06(\mathrm{syst}),$$
$$\mathcal{A}_{D\pi} = 0.30\,^{+0.29}_{-0.25}(\mathrm{stat}) \pm 0.06(\mathrm{syst}),$$

Here, both B➞Dh peak at 0 when correctly identified

Belle, PRL 94 (2005) 091601

Example of a very spectacular asymmetry

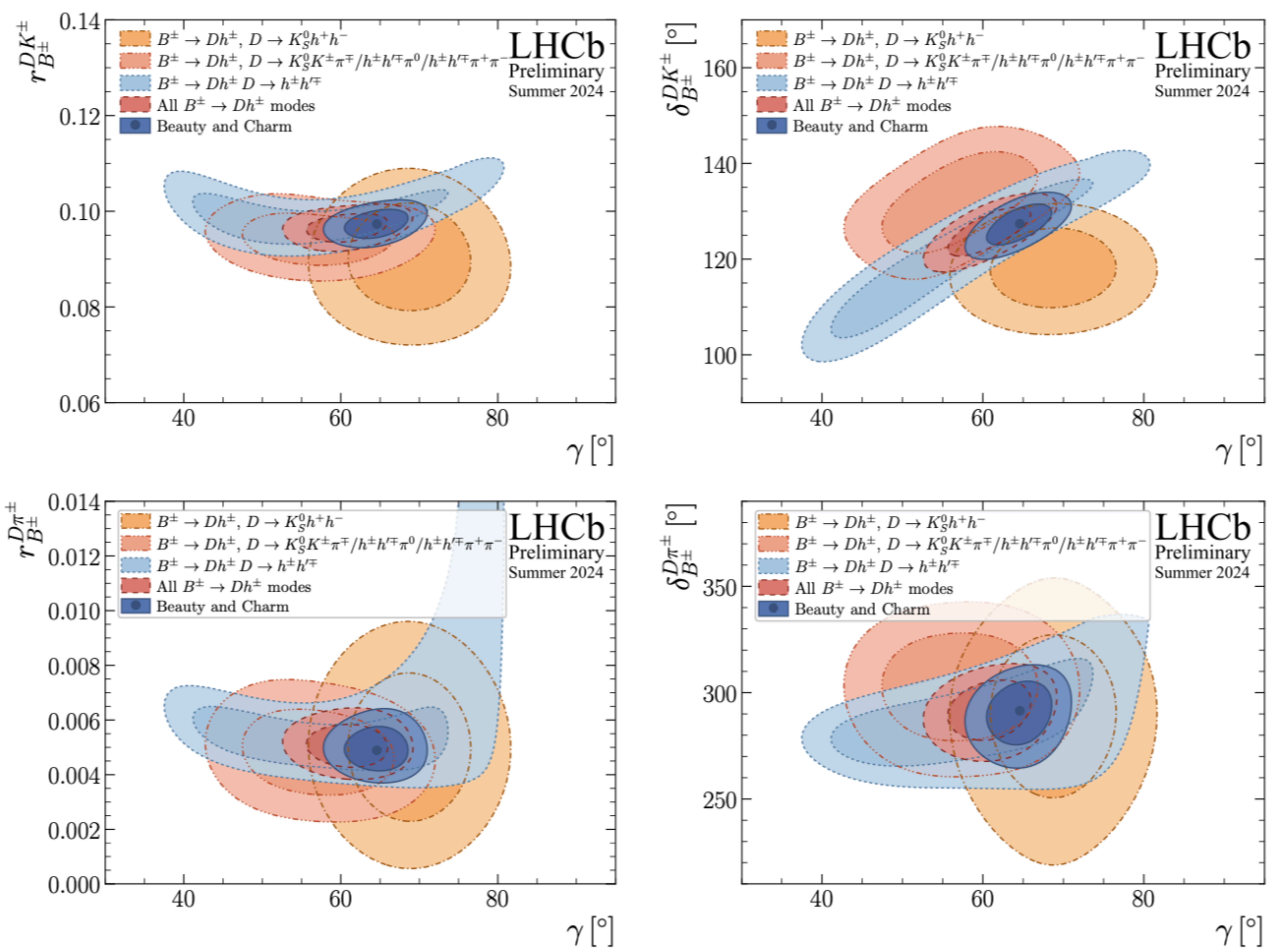


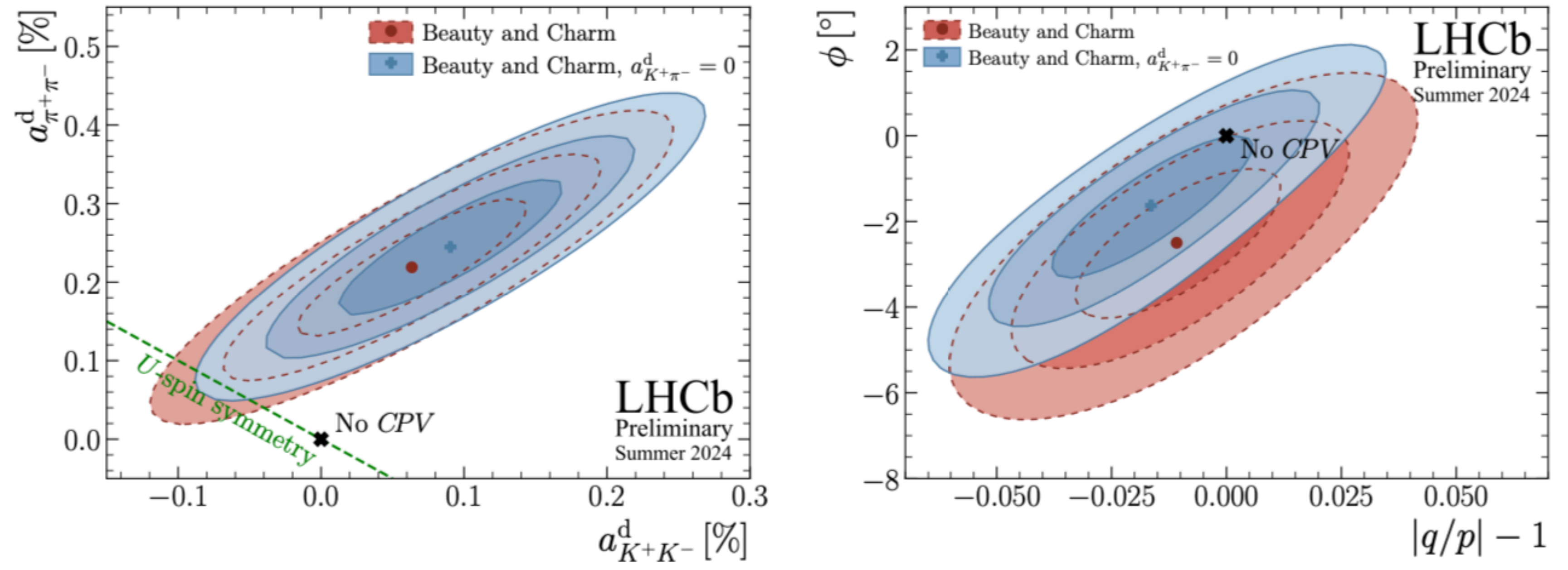


LHCb, JHEP 04 (2021) 081

Just drawing a line does not do justice to this work

Putting everything together





Importance of charm inputs

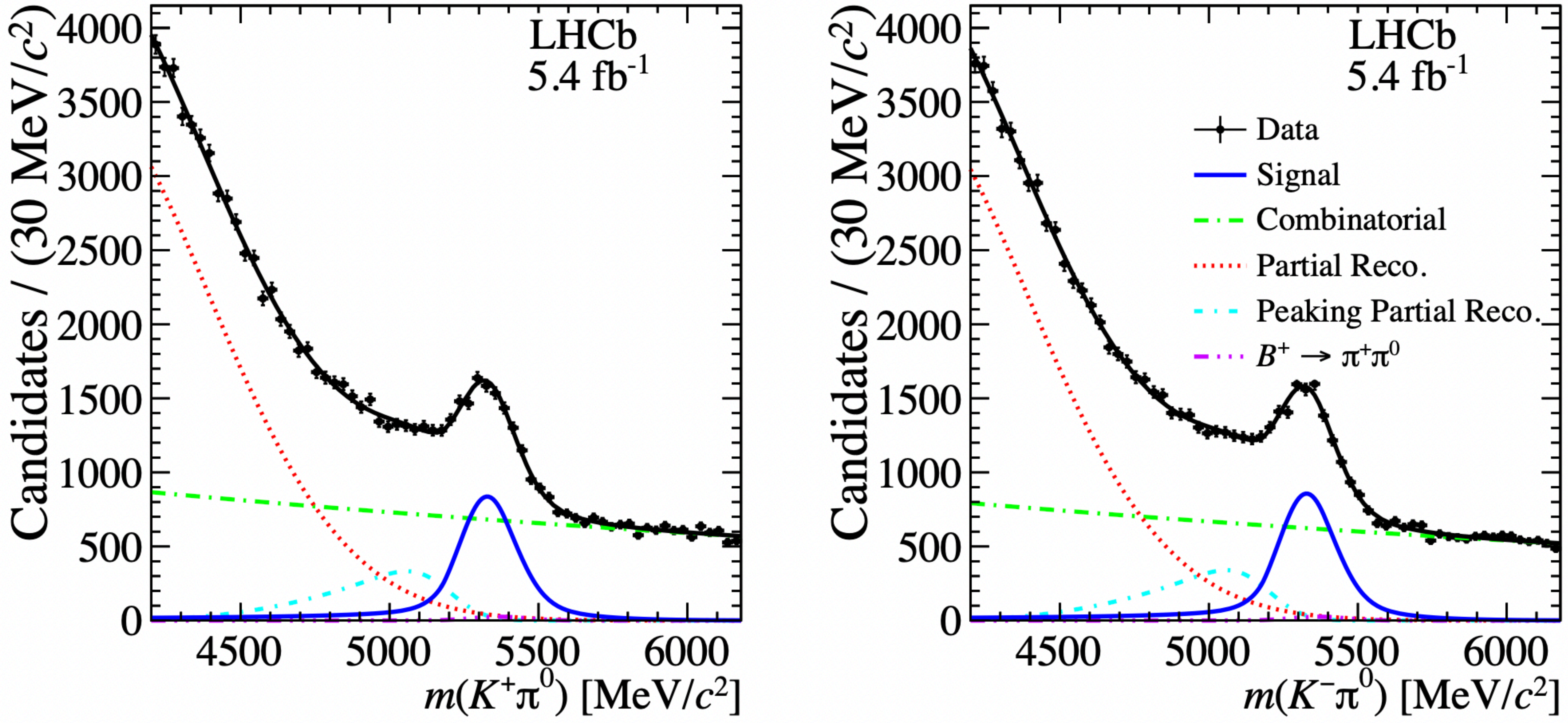
	γ	$r_{B^\pm}^{DK^\pm}$	$\delta_{B^\pm}^{DK^\pm}$	$r_{B^\pm}^{D\pi^\pm}$	$\delta_{B^\pm}^{D\pi^\pm}$	$r_D^{K\pi}$	$\delta_D^{K\pi}$	x	y	$\|q/p\|$	ϕ	$a^{d}_{K^+K^-}$	$a^{d}_{\pi^+\pi^-}$	$a^{d}_{K^+\pi^-}$
γ	1.00	0.36	0.62	–0.02	0.19	-	-	-	-	-	-	-	-	-
$r_{B^\pm}^{DK^\pm}$		1.00	0.21	-	0.07	–0.04	–0.10	0.02	–0.08	-	-	-	-	-
$\delta_{B^\pm}^{DK^\pm}$			1.00	–0.04	0.18	–0.11	–0.39	0.06	–0.32	-	–0.01	-	-	0.02
$r_{B^\pm}^{D\pi^\pm}$				1.00	0.57	0.04	0.02	-	0.01	-	-	-	-	-
$\delta_{B^\pm}^{D\pi^\pm}$					1.00	0.01	–0.13	0.02	–0.11	-	-	-	-	-
$r_D^{K\pi}$						1.00	0.29	0.18	–0.07	–0.04	0.01	-	-	–0.02
$\delta_D^{K\pi}$							1.00	–0.05	0.84	-	0.04	–0.02	–0.02	–0.05
x								1.00	0.22	–0.09	0.09	0.01	-	-
y									1.00	–0.04	0.04	–0.01	–0.01	–0.06
$\|q/p\|$										1.00	0.72	0.11	0.10	–0.16
ϕ											1.00	–0.04	–0.04	0.33
$a^{d}_{K^+K^-}$												1.00	0.87	0.22
$a^{d}_{\pi^+\pi^-}$													1.00	0.20
$a^{d}_{K^+\pi^-}$														1.00

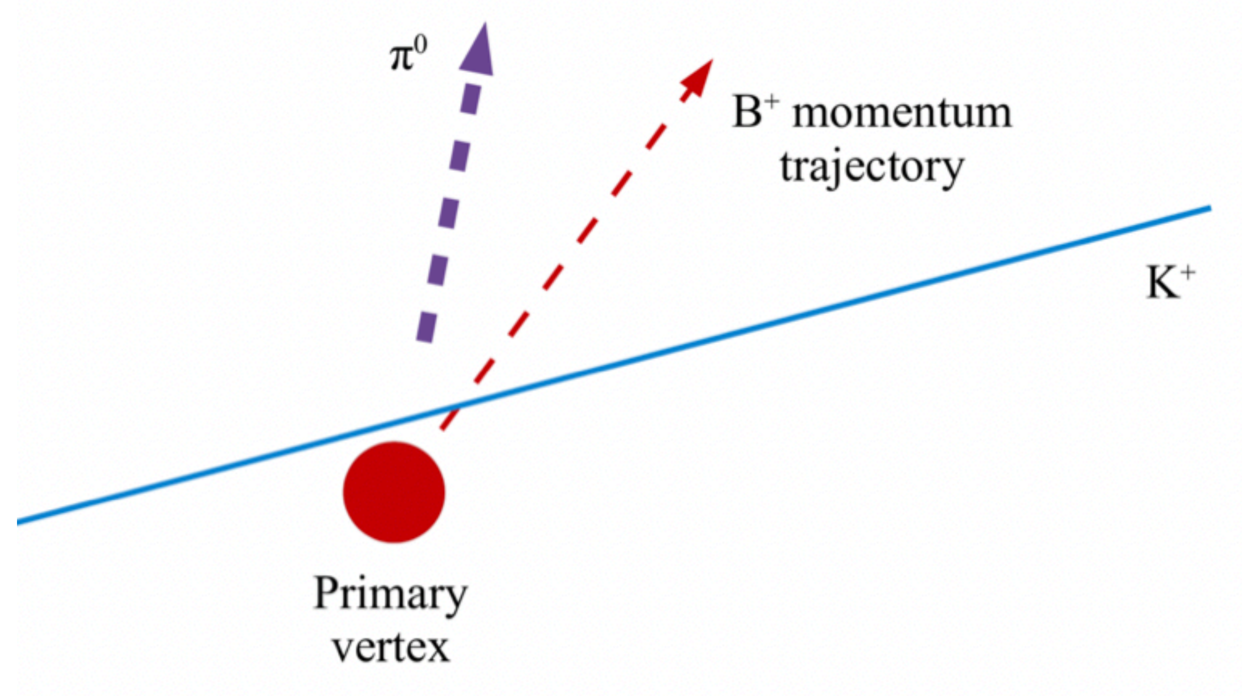
LHCb-CONF-2024-004

Consistent analyses

An other example of a direct CP violation measurement

$$A_{CP} = \frac{\Gamma(B^- \to K^-\pi^0) - \Gamma(B^+ \to K^+\pi^0)}{\Gamma(B^- \to K^-\pi^0) + \Gamma(B^+ \to K^+\pi^0)}$$





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

Consistent with the world average

ARXIV:2012.12789

Part of the Kπ puzzle expressed via this sum rule

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

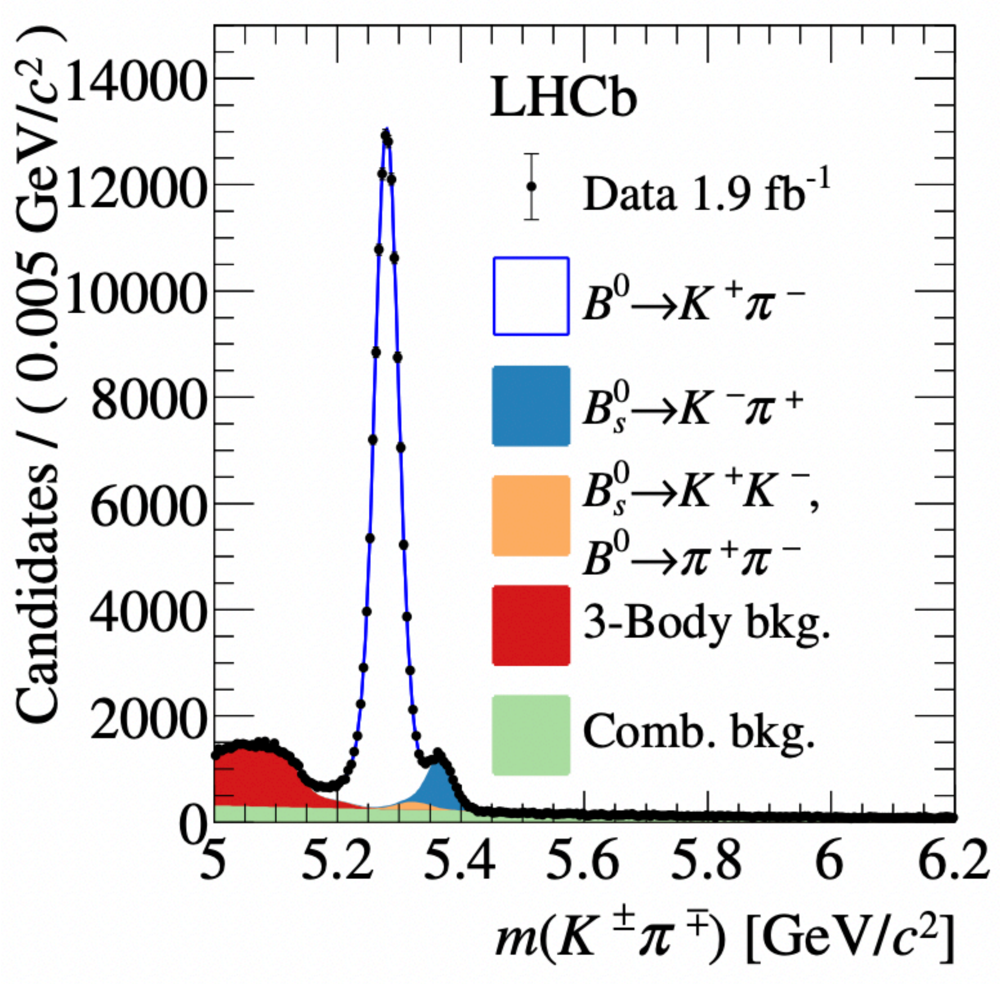
B→hh

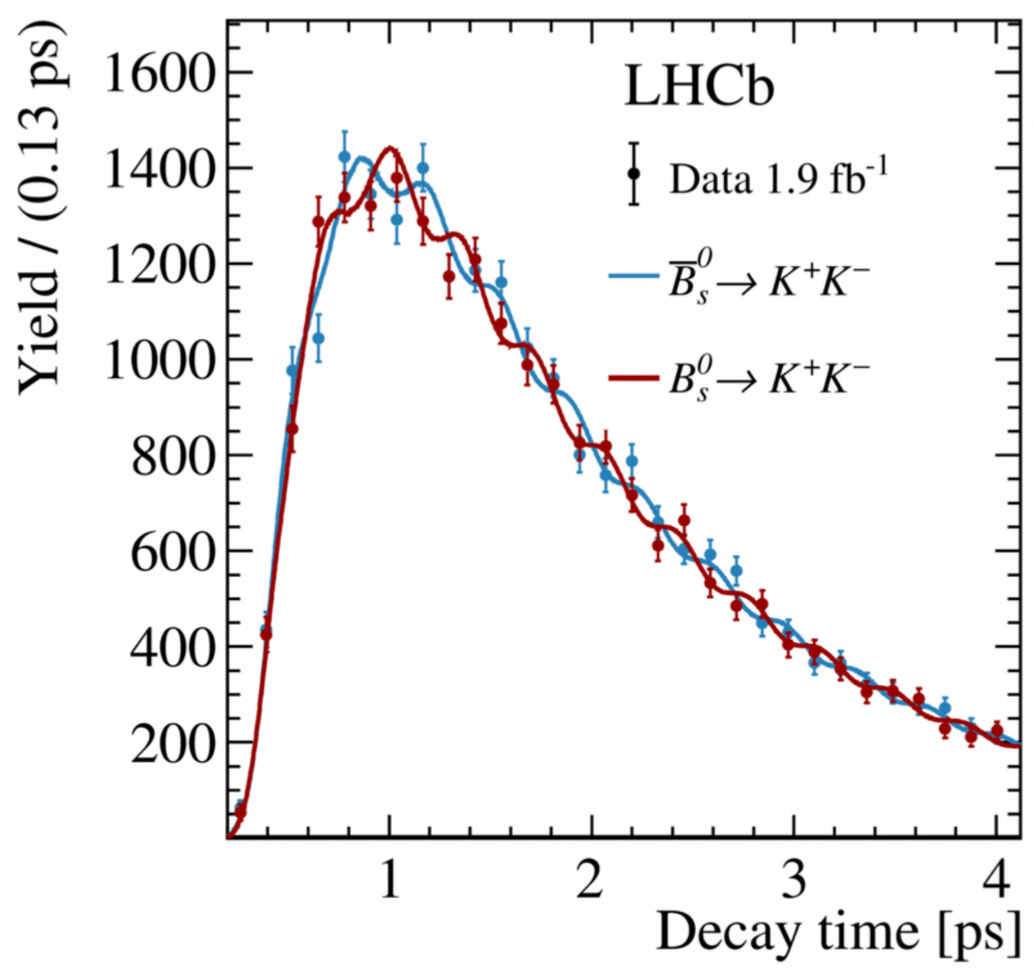
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)},$$

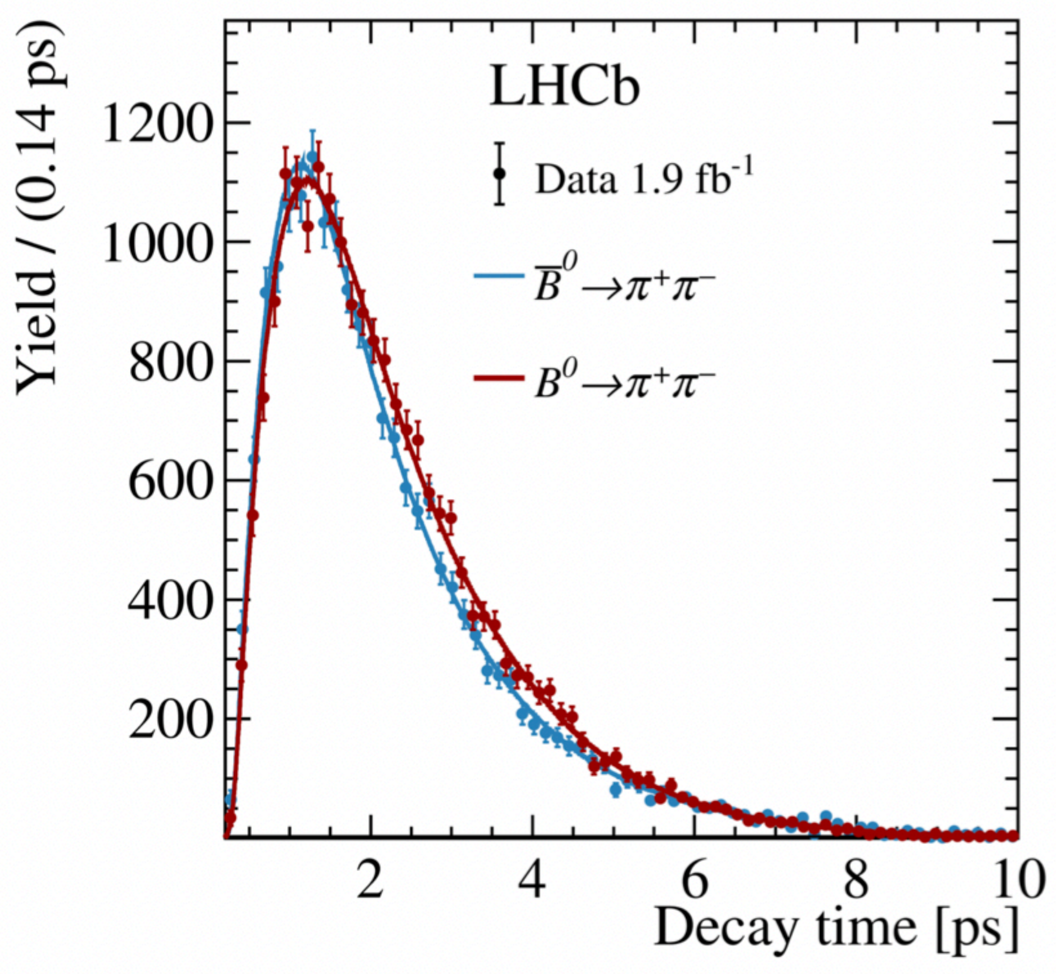
An important quantity to control is detector asymmetries

$$A_{\rm det}^{K\pi} = A_{\rm RAW}^{K\pi\pi} - A_{\rm RAW}^{\bar{K}^0\pi} - A_{\rm det}^{K^0}.$$

Analyses that explore U spin symmetry

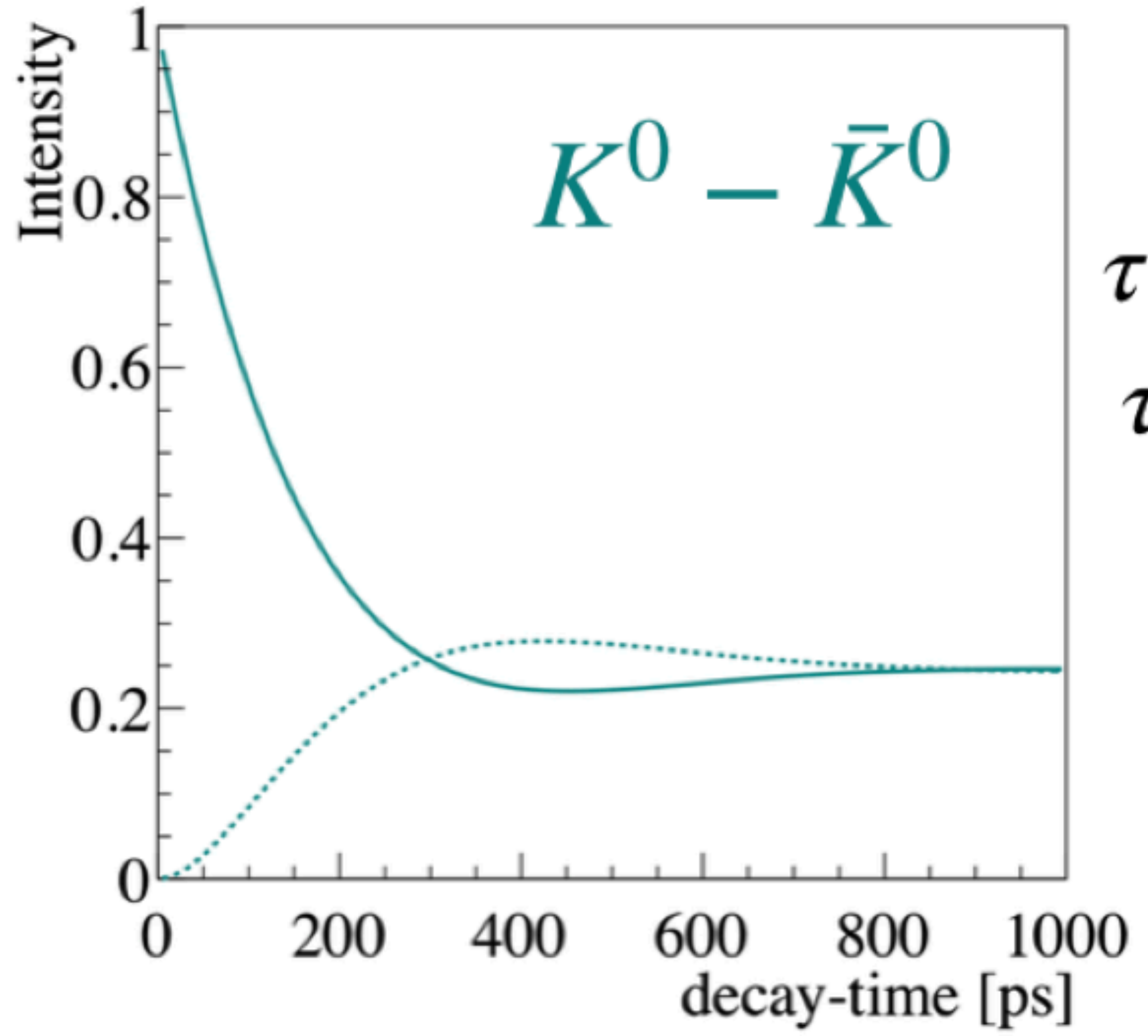






$$\begin{aligned}
C_{\pi\pi} &= -0.320 \pm 0.038,\\
S_{\pi\pi} &= -0.672 \pm 0.034,\\
A_{CP}^{B^0} &= -0.0831 \pm 0.0034,\\
A_{CP}^{B_s^0} &= 0.225 \pm 0.012,\\
C_{KK} &= 0.172 \pm 0.031,\\
S_{KK} &= 0.139 \pm 0.032,\\
A_{KK}^{\Delta\Gamma} &= -0.897 \pm 0.087
\end{aligned}$$

This constitutes the first observation of time-dependent CP violation in decays of the B_s meson.

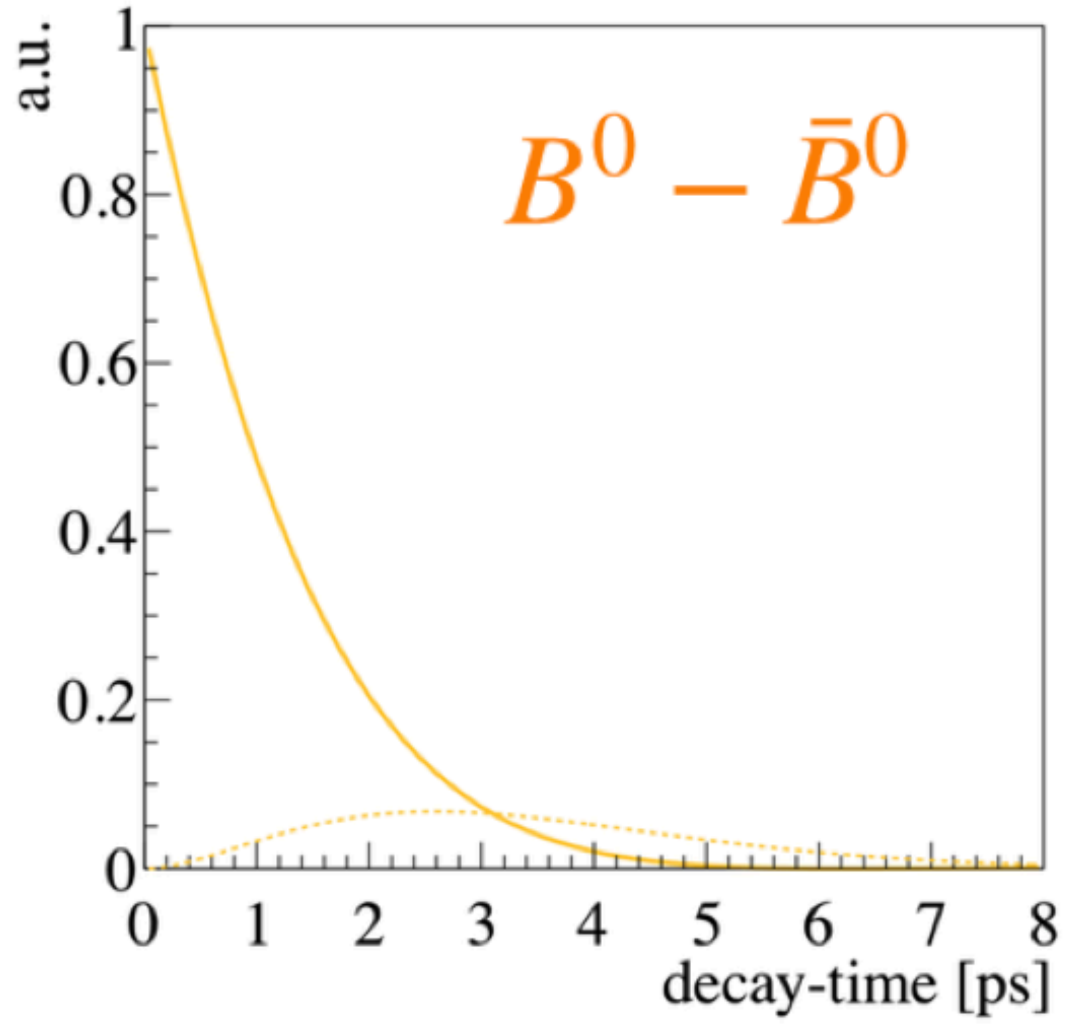


Very different lifetime:

$\tau(K_S^0) \sim 0.9 \times 10^{-10}$

$\tau(K_L^0) \sim 0.5 \times 10^{-7}$

the oscillation period longer than the K_S lifetime, but K_L^0 exceptionally long



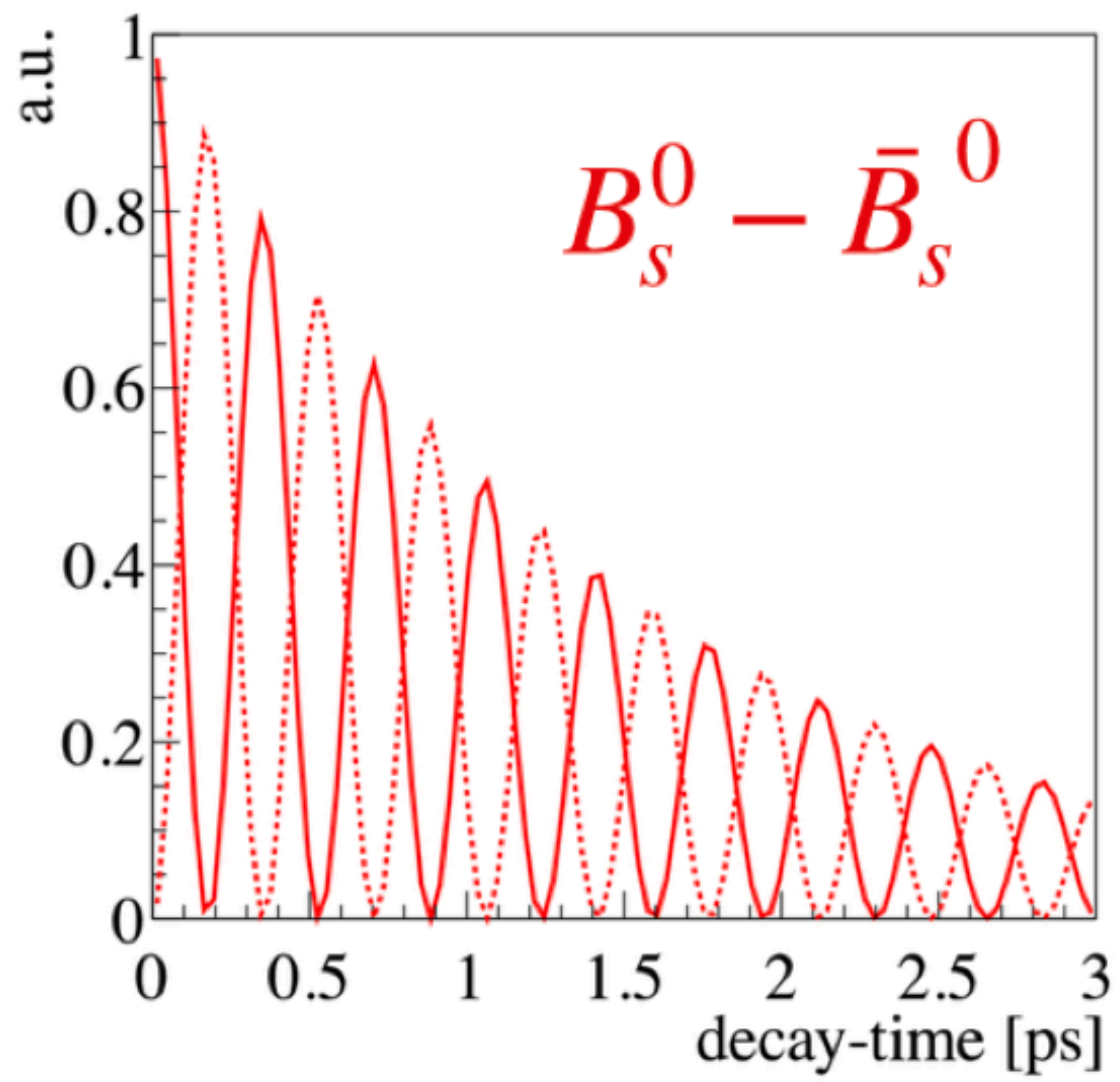
Oscillations

$\Delta m \sim 0.5\ ps^{-1}$

Lifetime

$\tau(B^0) \sim 1.5\ ps$

The same order of magnitudes

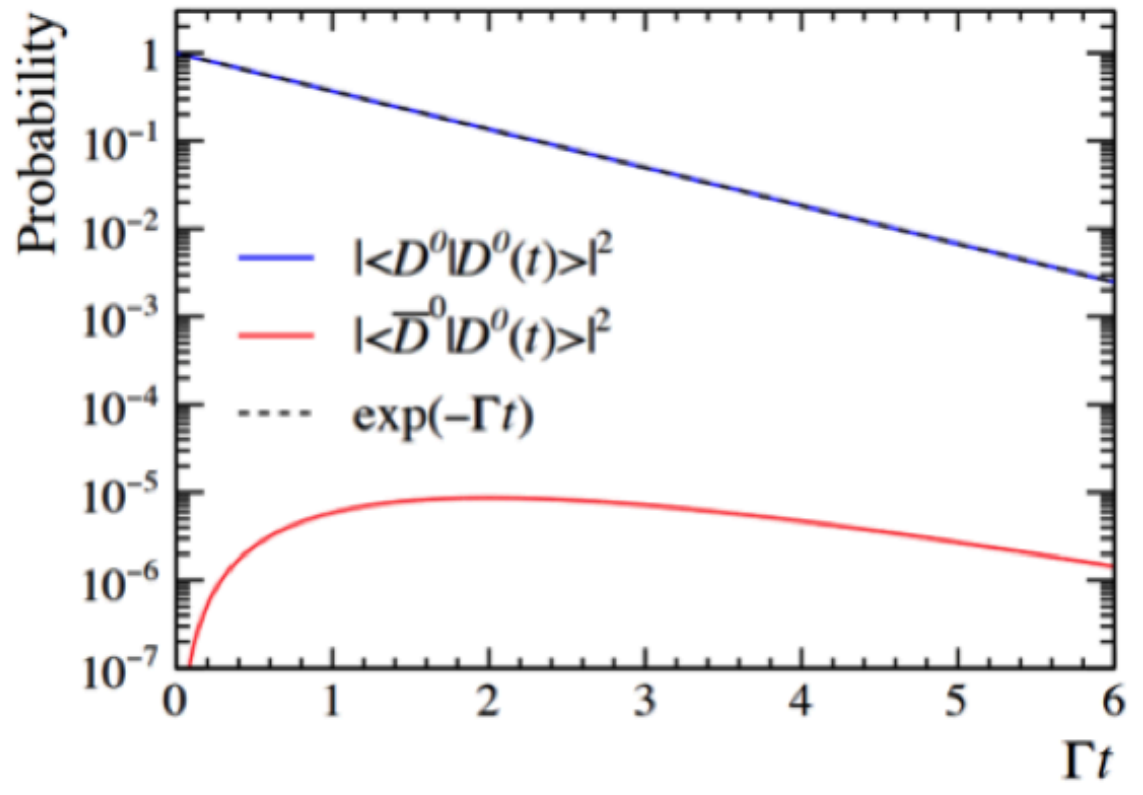


Very fast oscillations

$\Delta m_s > 15\ ps^{-1}$

$\tau(B_s^0) \sim 1.5\ ps$

Non-zero $\Delta\Gamma_s$



$D^0 - \bar{D}^0$

Very slow oscillations

$\Delta m \sim 10^{-3}\ ps^{-1}$

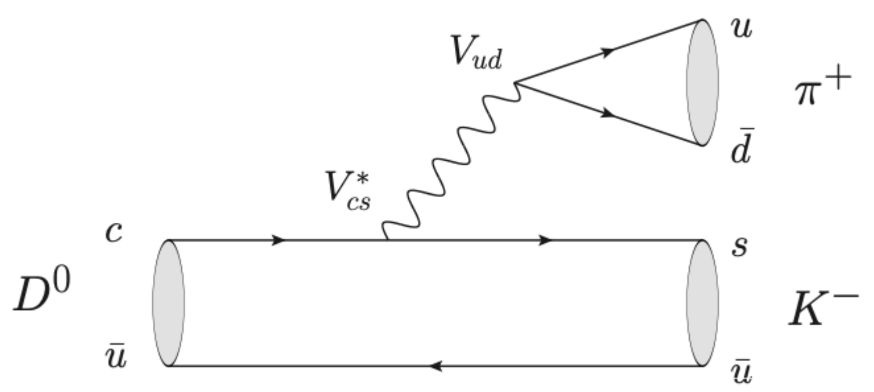
Very short lifetime

$\tau(D^0) \sim 0.4\ ps$

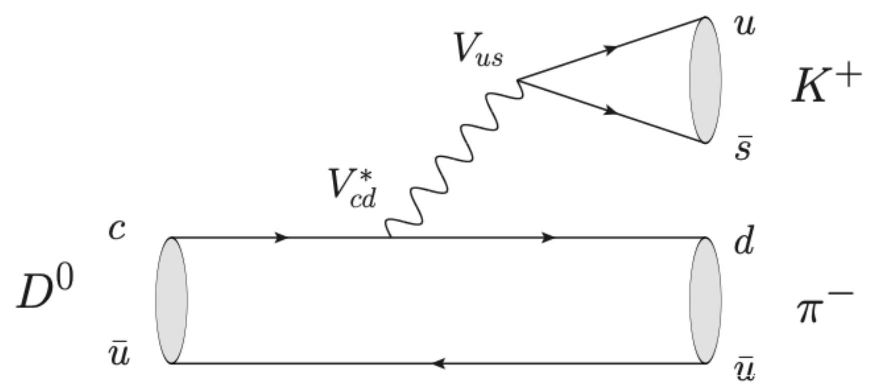
D^0 decays before has a chance to oscillate

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

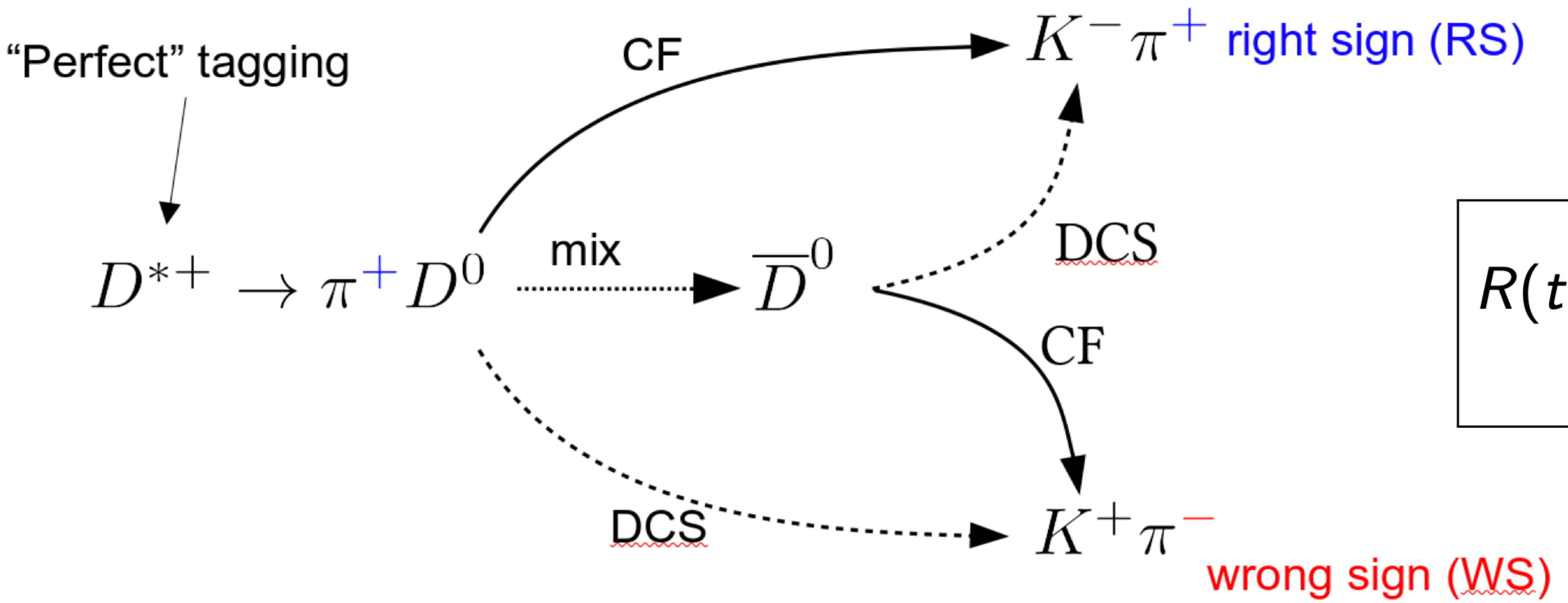
Mixing in charm land



Cabbibo-favoured (CF)
$(|V_{cs}^* V_{ud}|^2 \approx 1)$



Doubly-Cabbibo suppressed (DCS)
$(|V_{cd}^* V_{us}|^2 \approx 2 \times 10^{-3})$



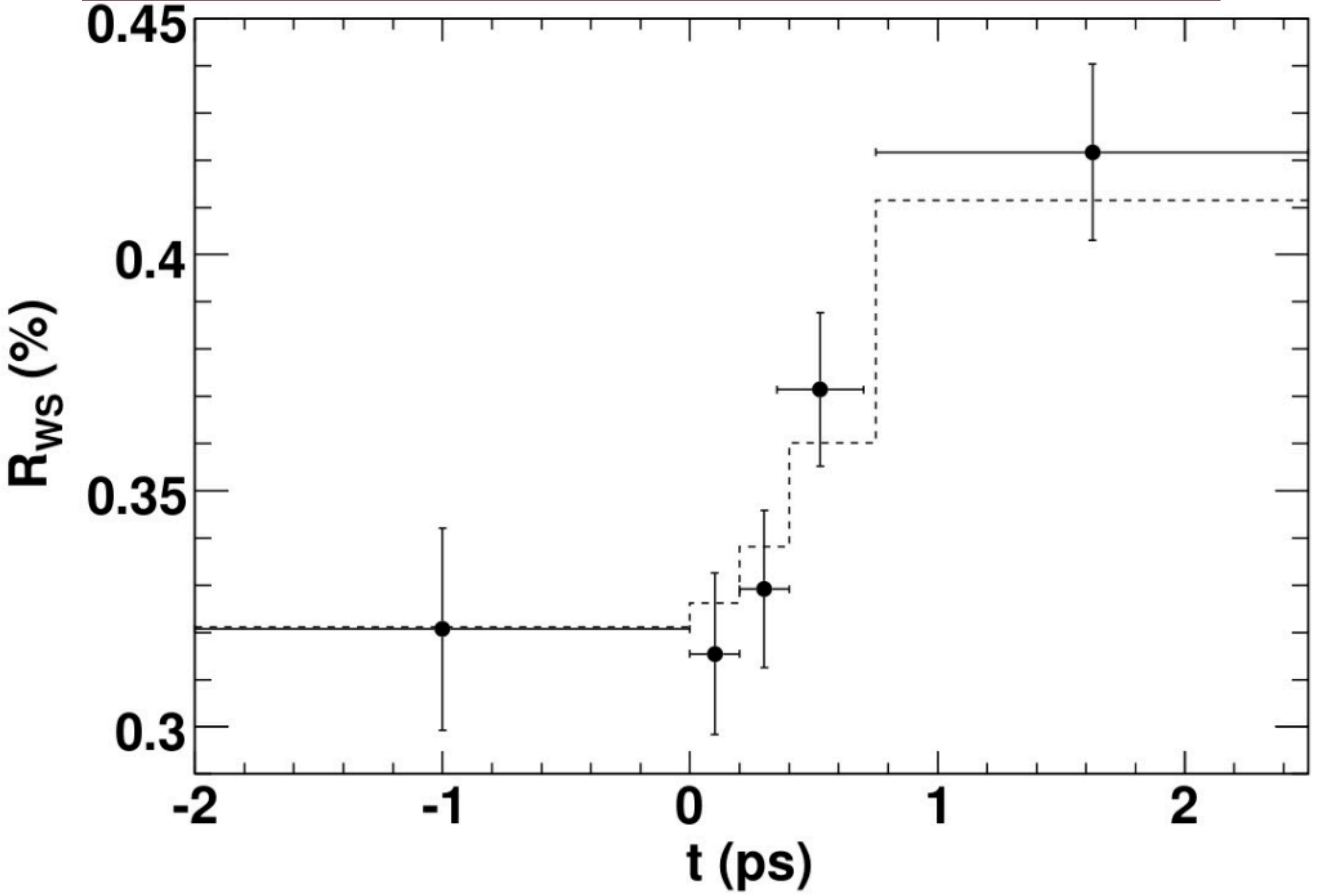
$$R(t) = \frac{N(\text{wrong})(t)}{N(\text{right})(t)}$$

$$R(t) \approx r_D + \underbrace{\sqrt{r_D}\, y' \frac{t}{\tau}}_{\text{(Interference)}} + \underbrace{\frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2}_{\text{(Pure mixing)}}$$

I warned you there is a lot of Jargon

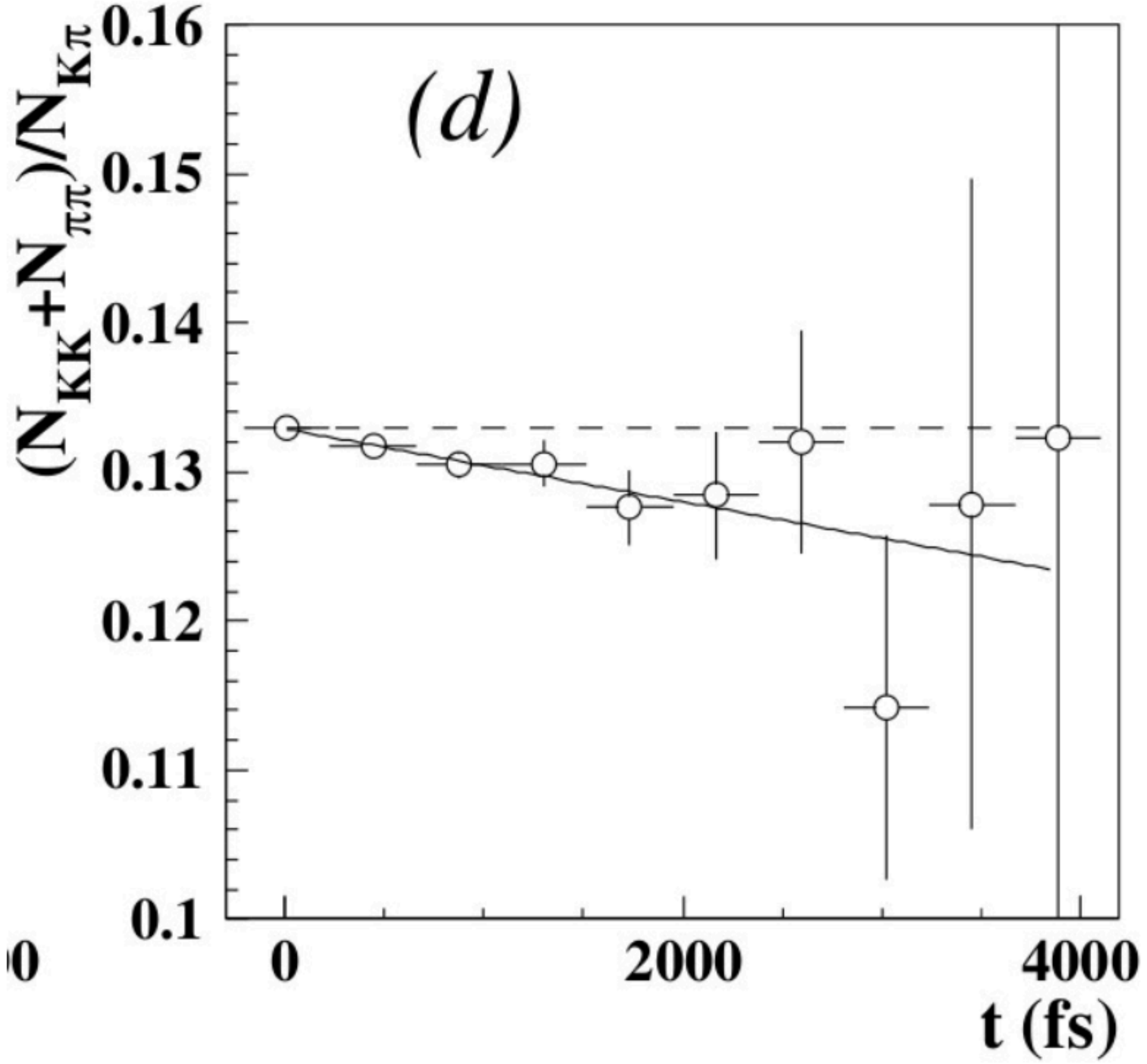
Charm Mixing 2007

BaBar, PRL 98 (2007) 211802



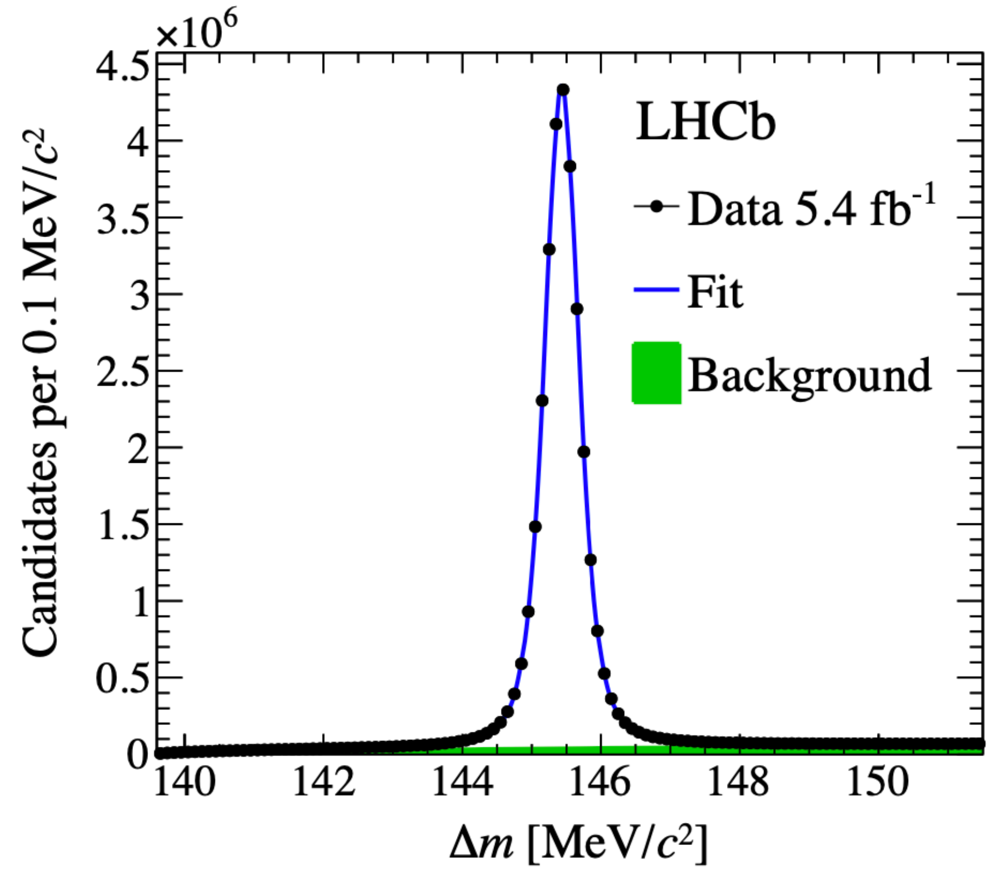
$D^0 \to K^+\pi^-$

Belle, PRL 98 (2007) 211803

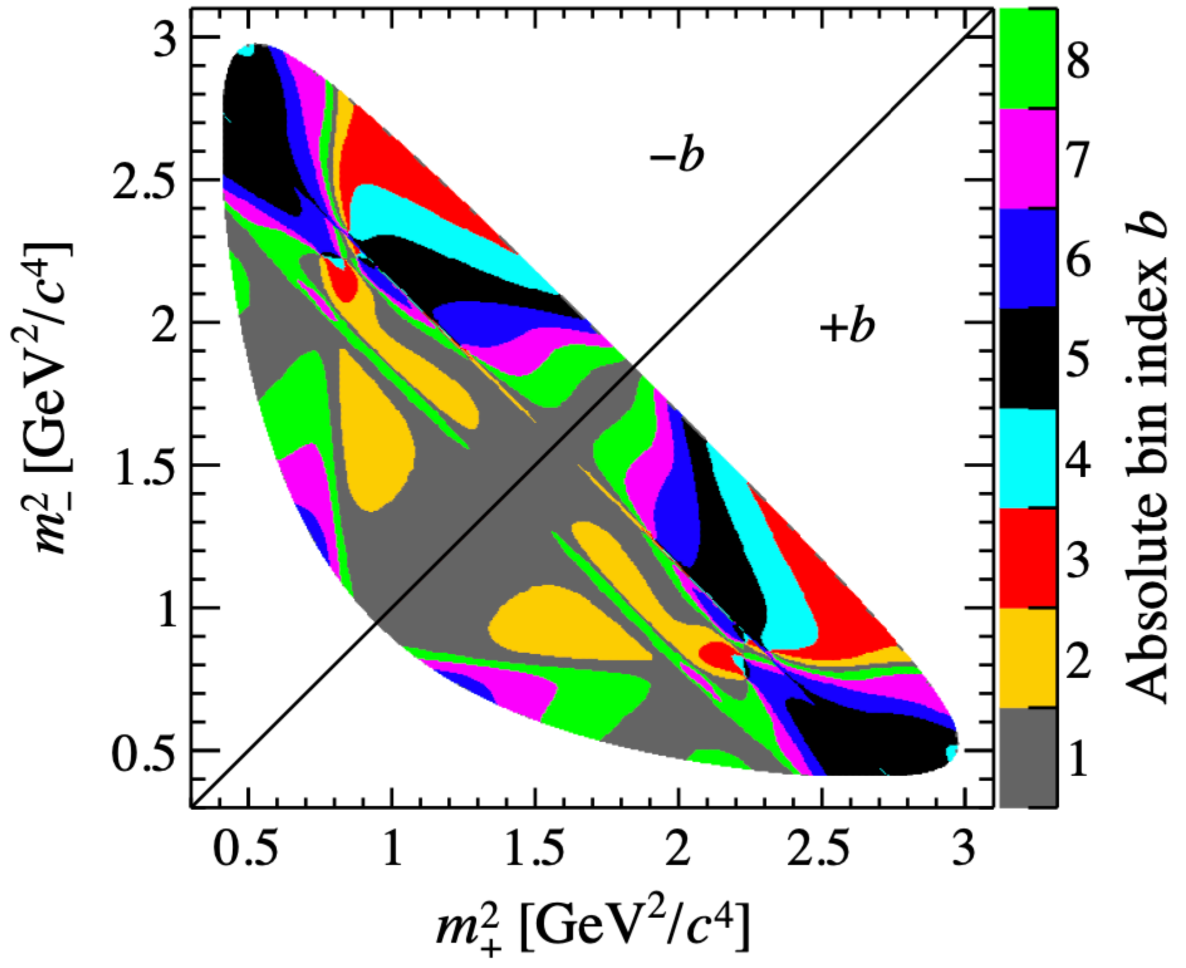


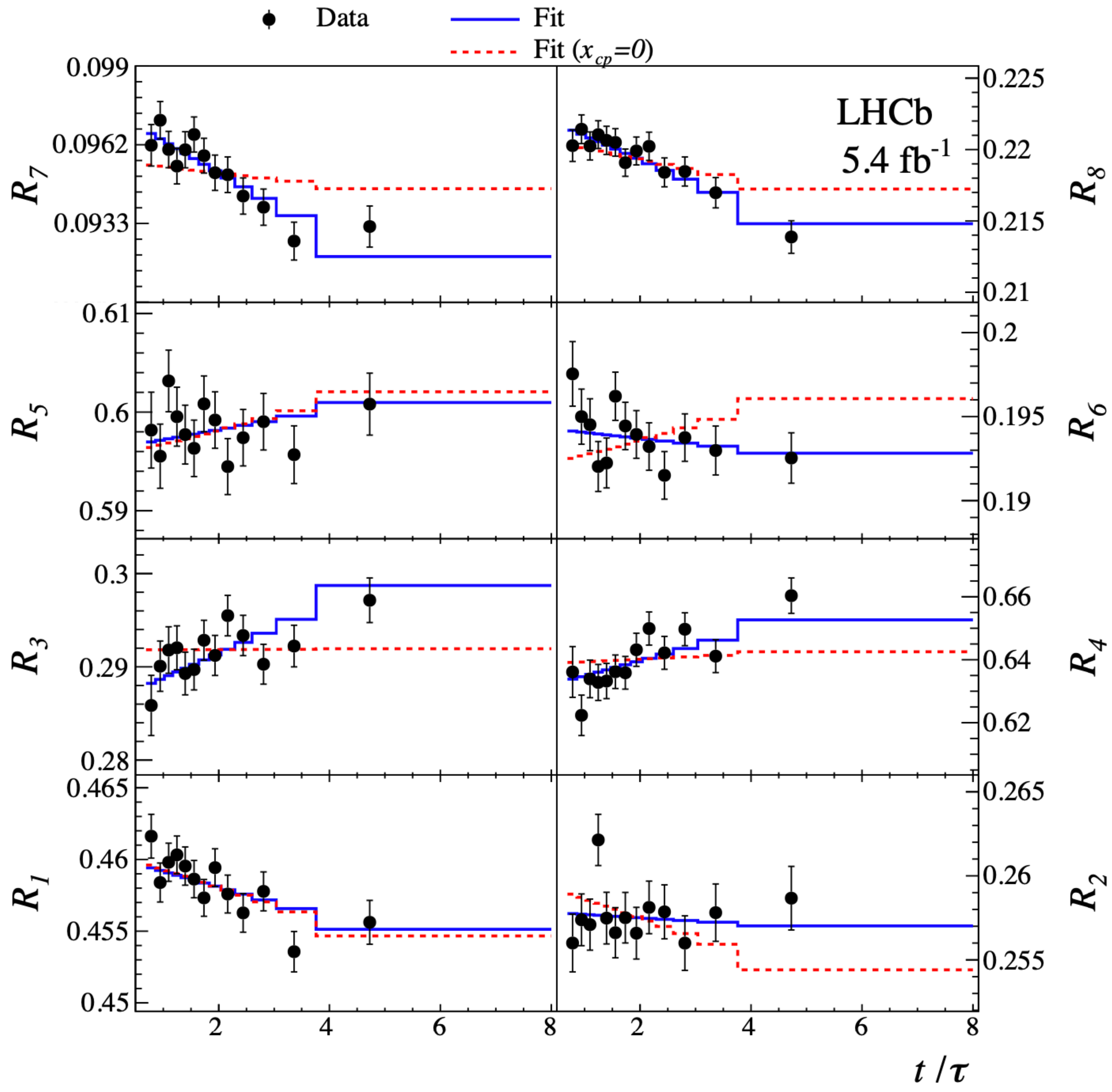
$D^0 \to K^+K^-, \pi^+\pi^-$

Today … first observation of nonzero mass difference of D^0 meson mass eigenstates!

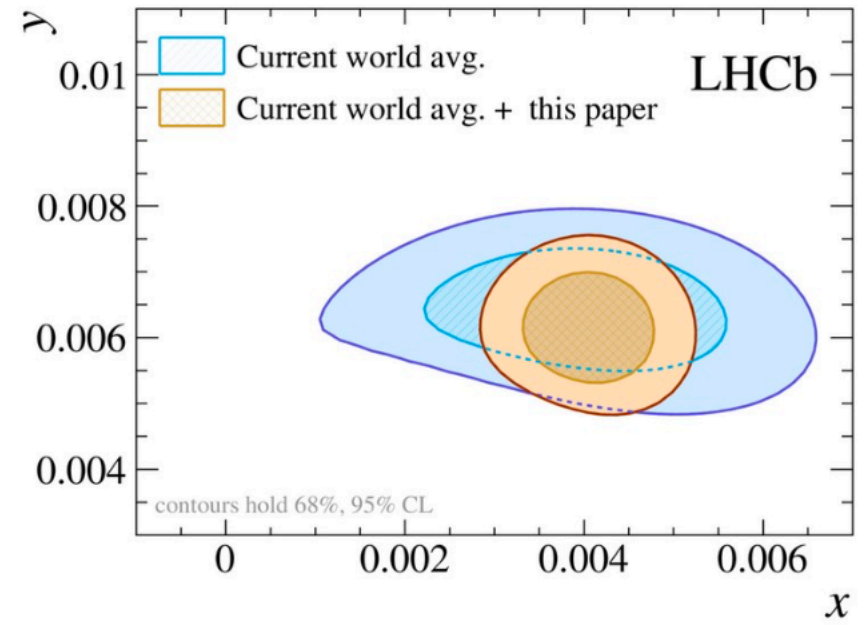


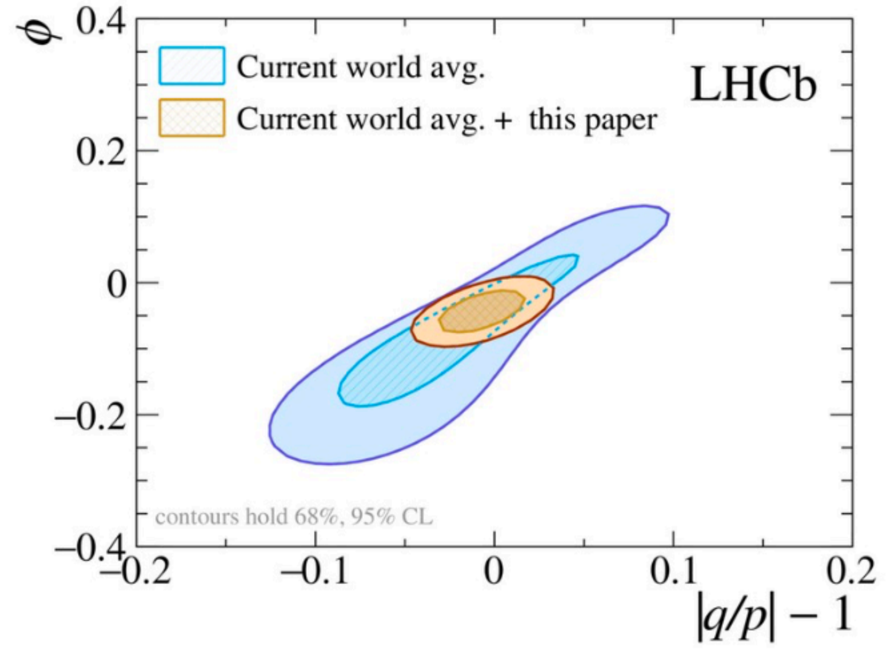
Bin flip method





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





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Loop back to beauty !

Giving one lecture on CP Violation

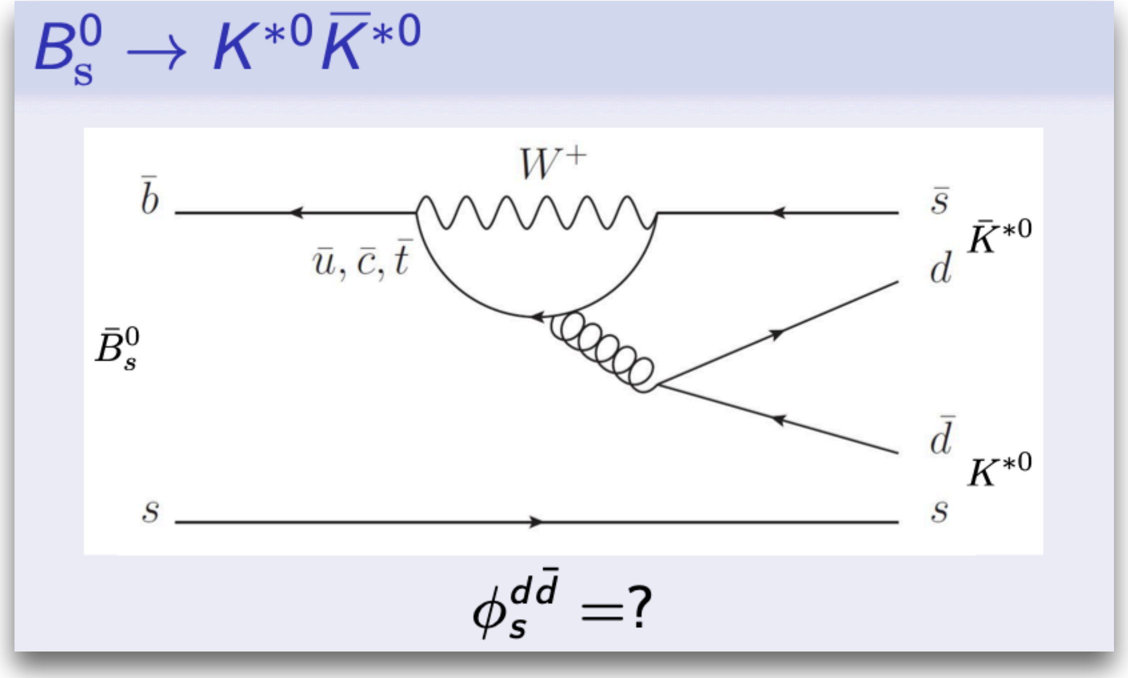
- Pros: it's only ~50-40 slides.

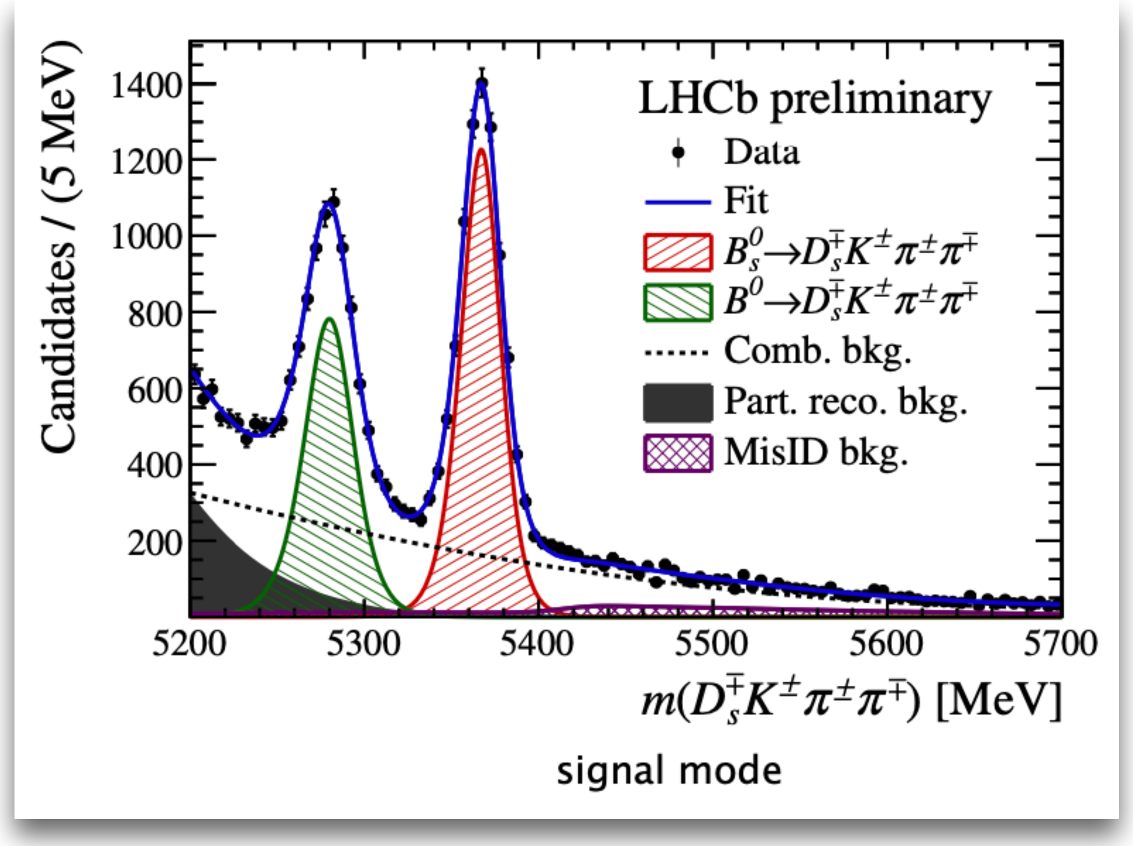
- Cons: it's impossible to do justice to the topic.

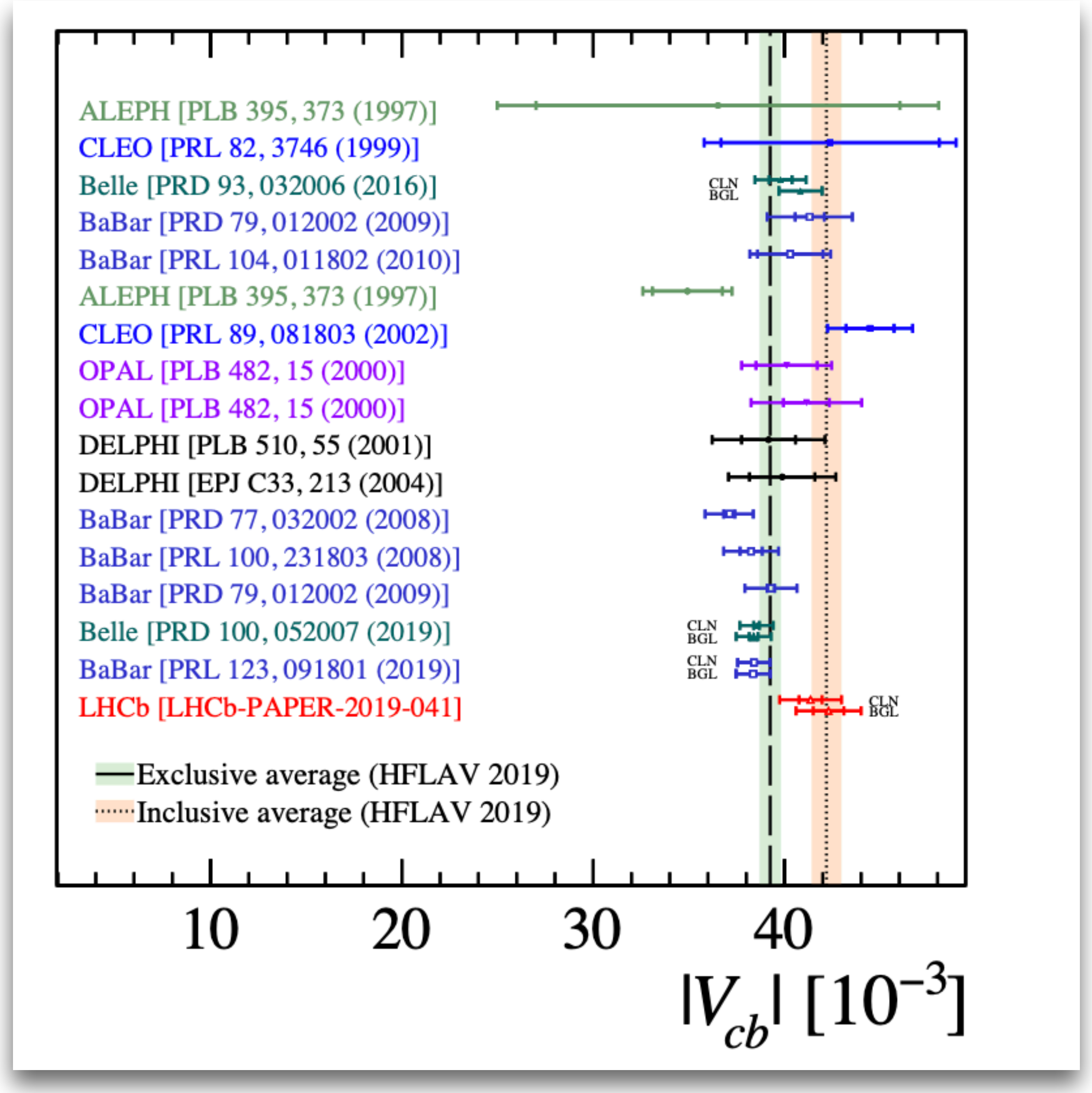
$A_{CP}(D^0 \to K^0_S K^0_S)$

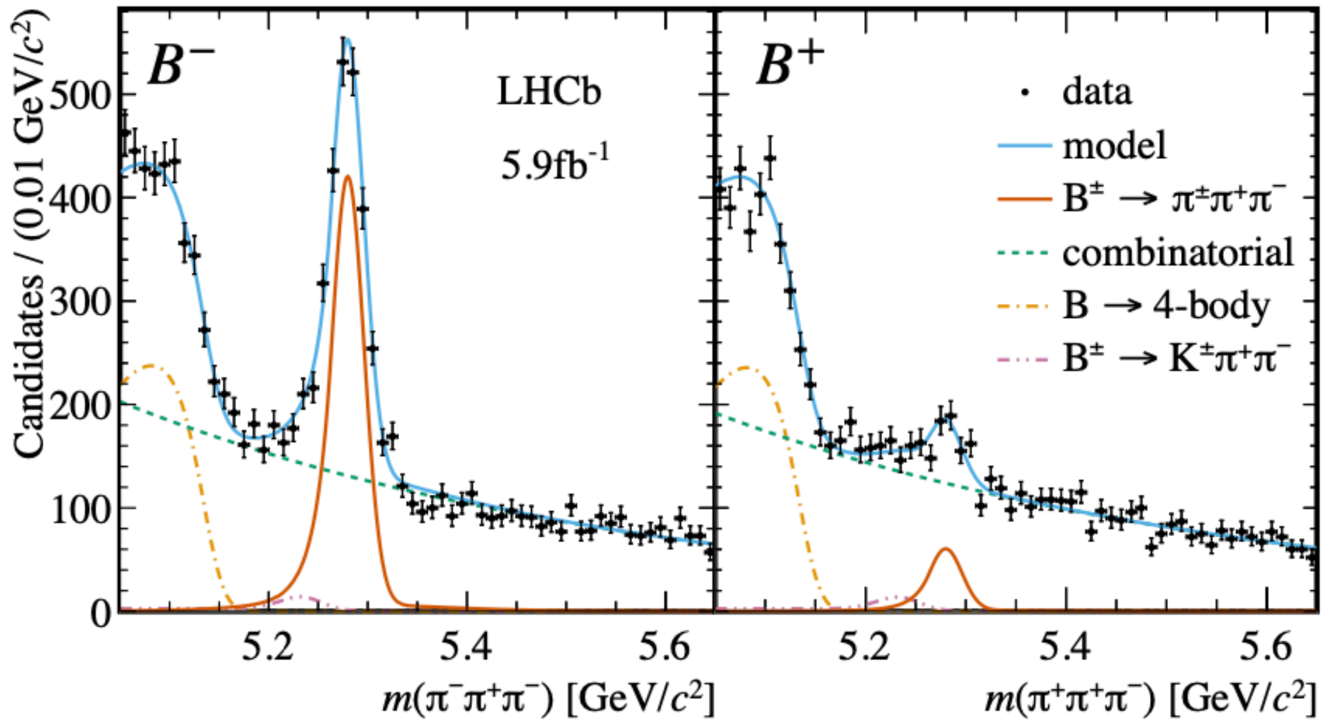
$A_{CP}(D^+_{(s)} \to h^+\pi^0, h^+\eta)$

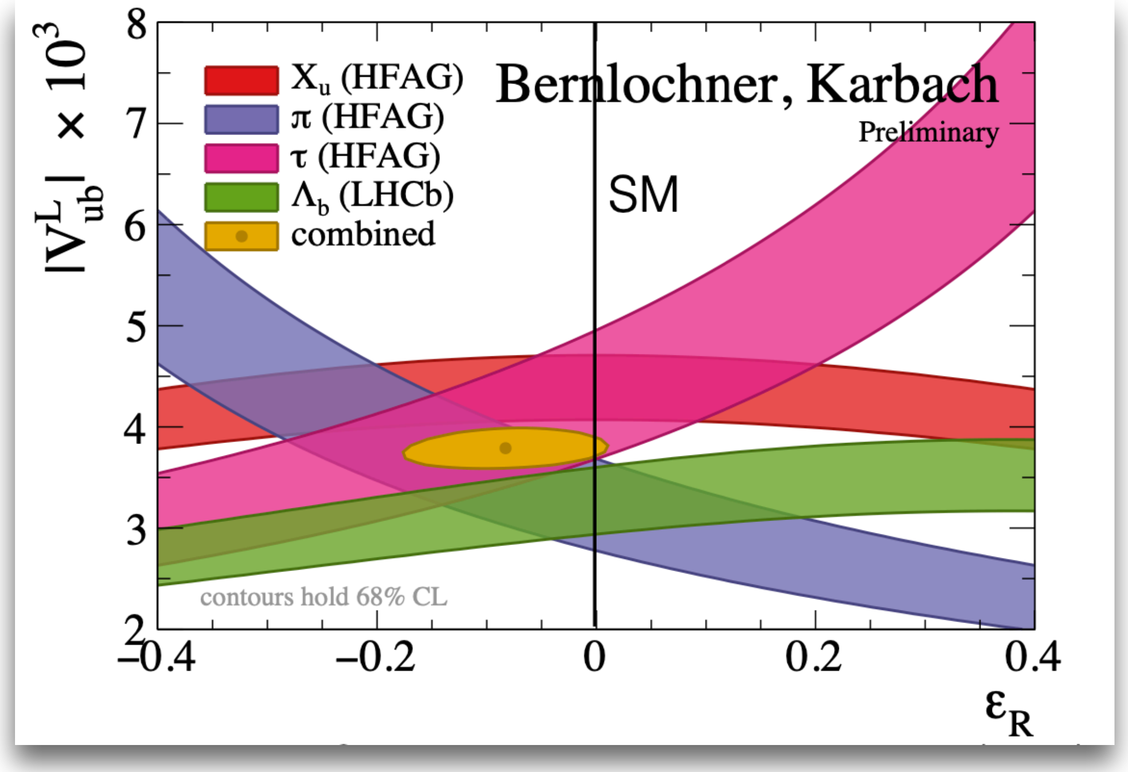
$\Delta Y_{D^0 \to K^+K^-}$ and $\Delta Y_{D^0 \to \pi^+\pi^-}$



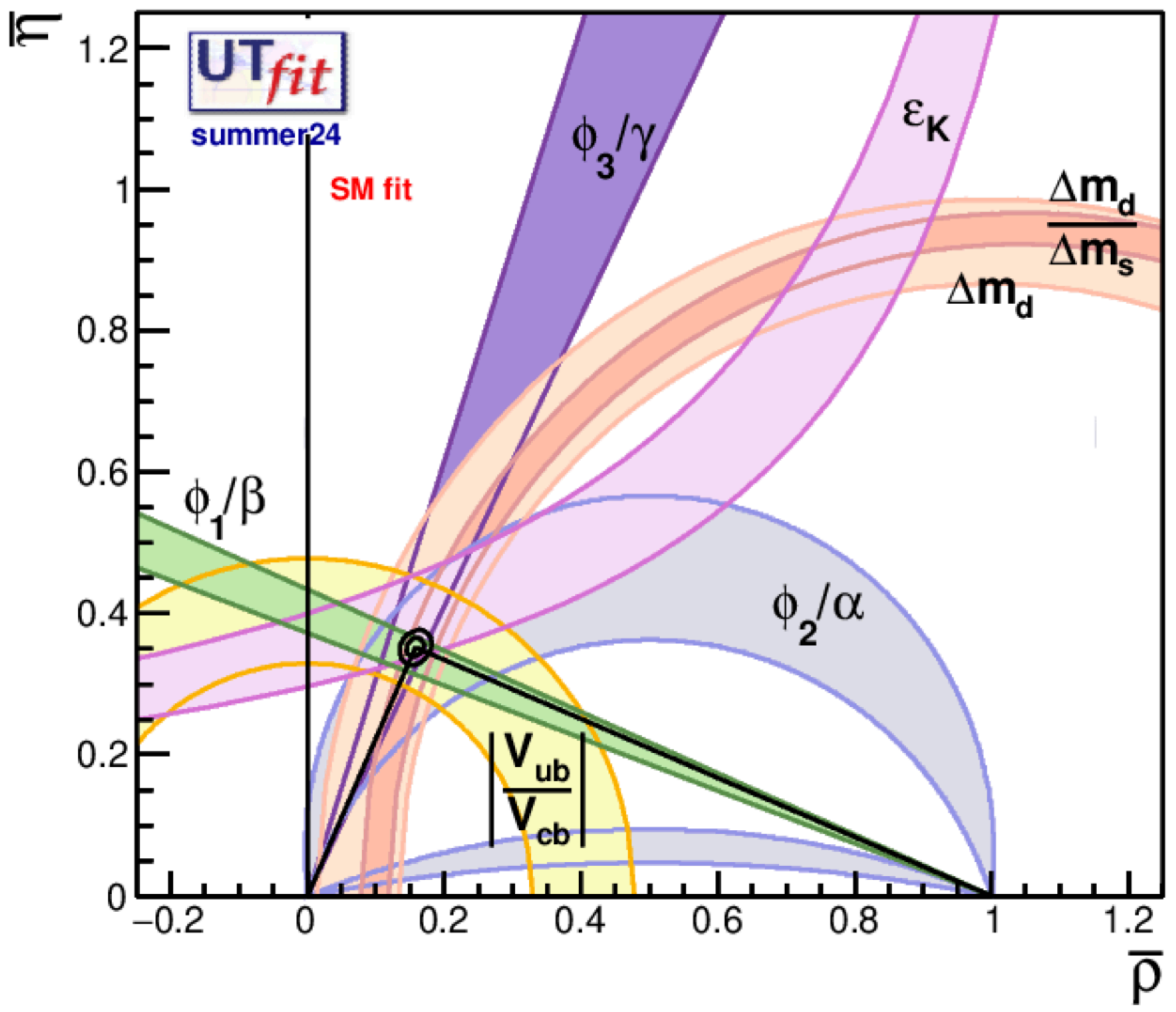








Overall, we see a very consistent picture, if there is New Physics it must be at pretty high energies and there were to be this New Physics we would need it to carry extra sources of CP Violation



levels @
95% Prob

To illustrate the level of suppression required for BSM contributions, consider a class of models in which the unitarity of the CKM matrix is maintained, and the dominant BSM effects modify the neutral meson mixing amplitudes [134] by $(z_{ij}/\Lambda^2)(\bar{q}_i\gamma^\mu P_L q_j)^2$, where z_{ij} is an unknown coefficient and Λ is the scale suppressing this BSM contribution (see, [135, 136]). It is only known since the first measurements of γ and α that the SM gives the leading contribution to $B^0-\bar{B}^0$ mixing [6, 137]. Nevertheless, new physics with a generic weak phase may still contribute to neutral meson mixings at a significant fraction of the SM [131, 138, 139]. The existing data imply that $\Lambda/|z_{ij}|^{1/2}$ has to exceed about 10^4 TeV for $K^0-\bar{K}^0$ mixing, 10^3 TeV for $D^0-\bar{D}^0$ mixing, 500 TeV for $B^0-\bar{B}^0$ mixing, and 100 TeV for $B_s^0-\bar{B}_s^0$ mixing [131, 136]. (Some other operators are even better constrained [131].) The constraints are the strongest in the kaon sector, because the CKM suppression is the most severe. Thus, if there is new physics at the TeV scale, $|z_{ij}| \ll 1$ is required. Even if $|z_{ij}|$ are suppressed by a loop factor and $|V_{ti}^* V_{tj}|^2$ (in the down quark sector), similar to the SM, one expects percent-level effects, which may be observable in forthcoming flavor physics experiments. To constrain such extensions of the SM, many measurements irrelevant for the SM-CKM fit, such as the CP asymmetry in semileptonic $B^0_{d,s}$ decays, $A^{d,s}_{\mathrm{SL}}$, are important [140]. The current world averages [24] are consistent with the SM, with experimental uncertainties far greater than those of the theory predictions.

https://pdg.lbl.gov/2024/web/viewer.html?file=../reviews/rpp2024-rev-ckm-matrix.pdf

We take a break here for today !

Tomorrow we discuss penguins, EFTs and all the good stuff.