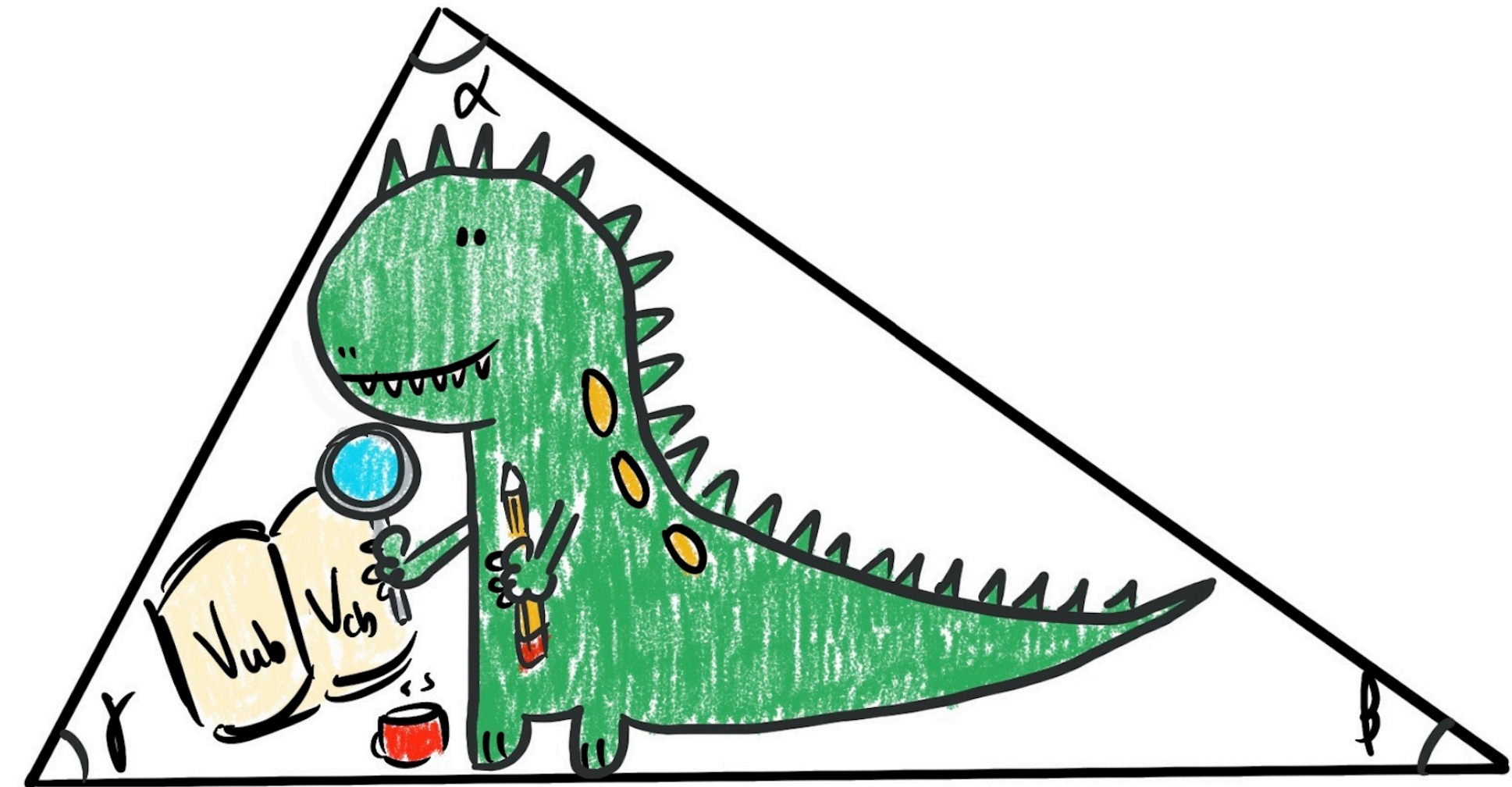
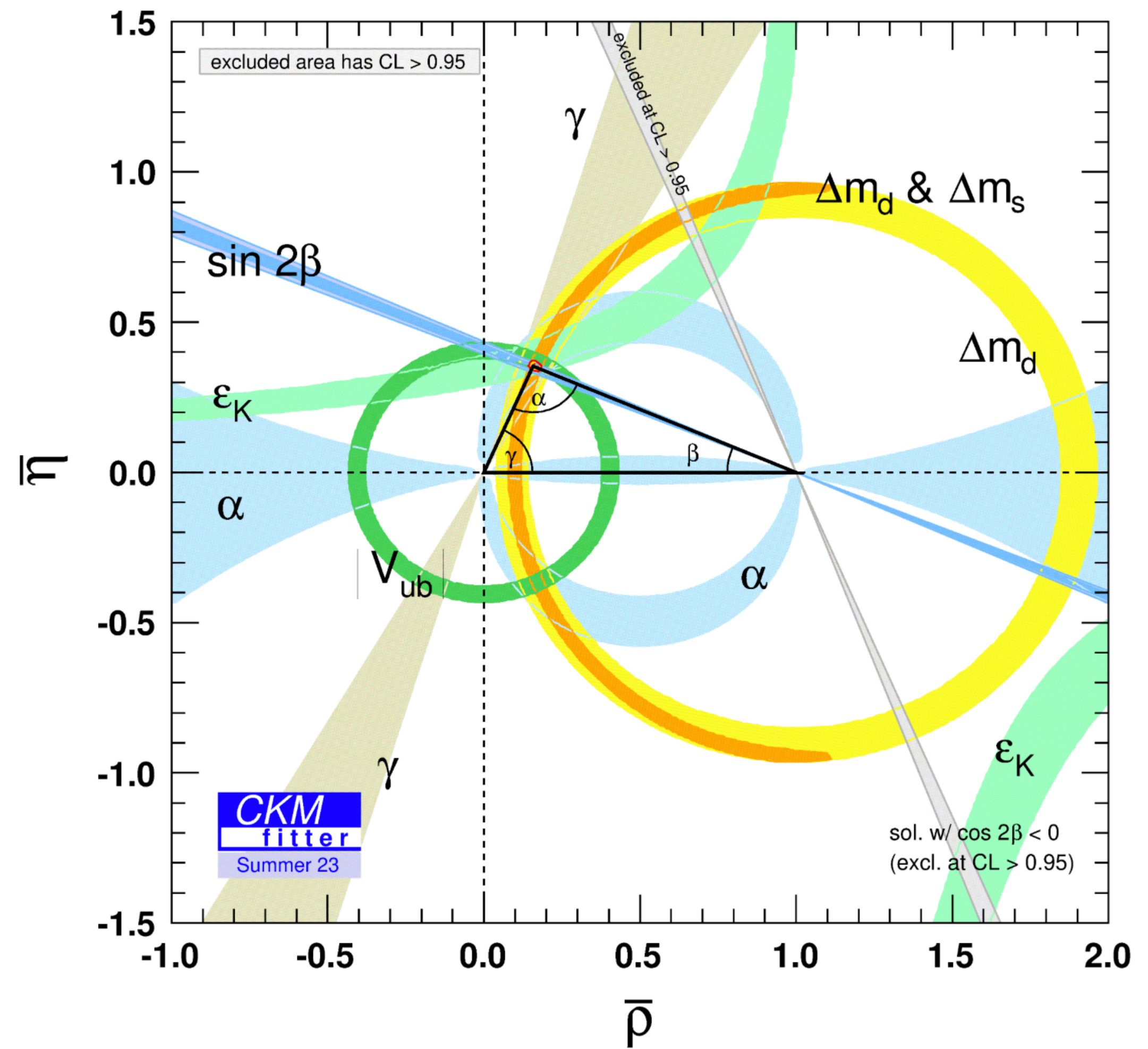
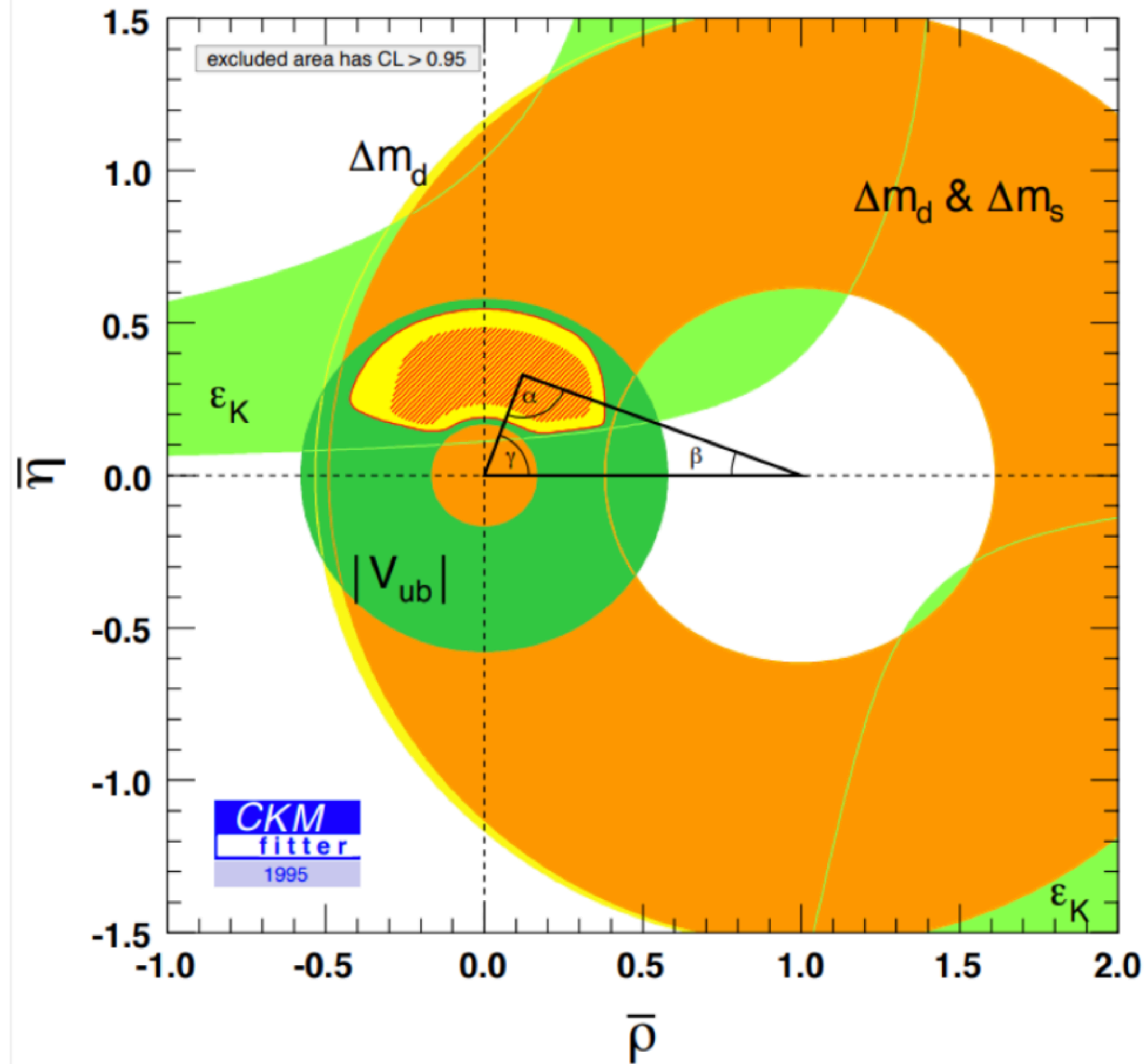


Flavour Physics - Chapter II

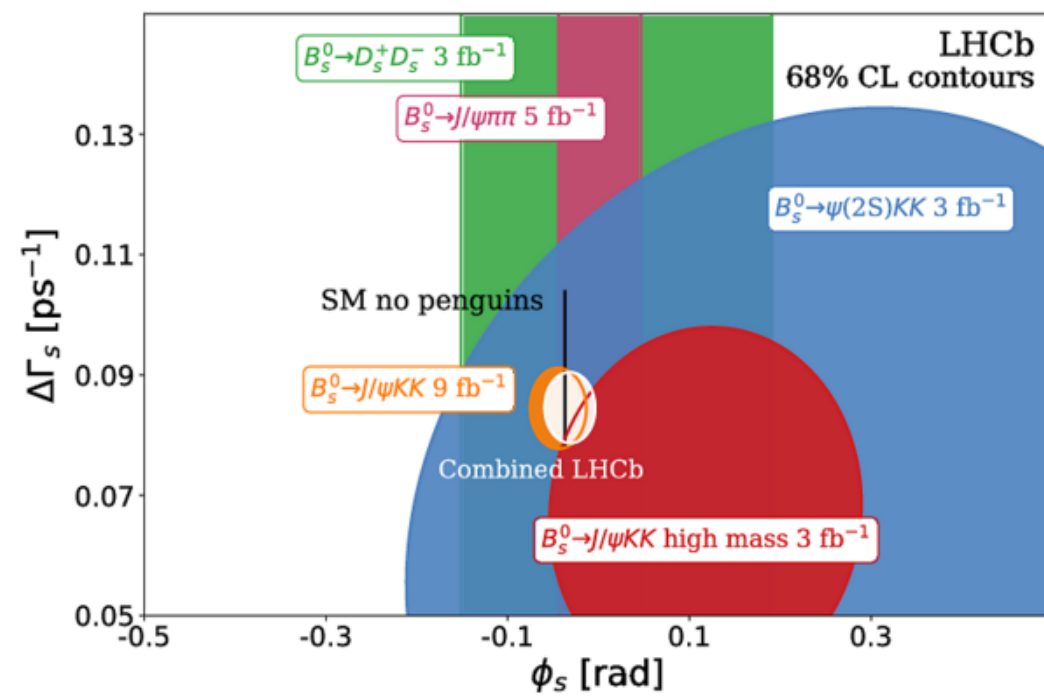
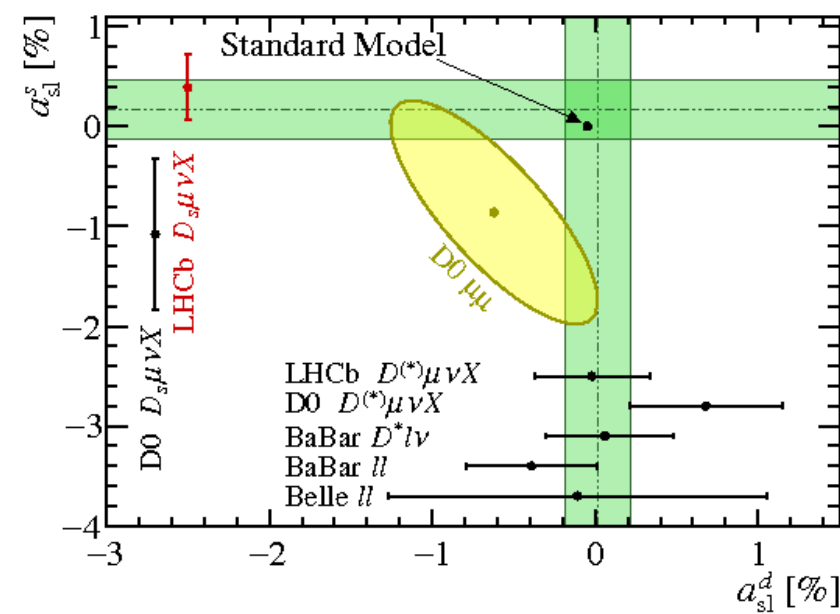
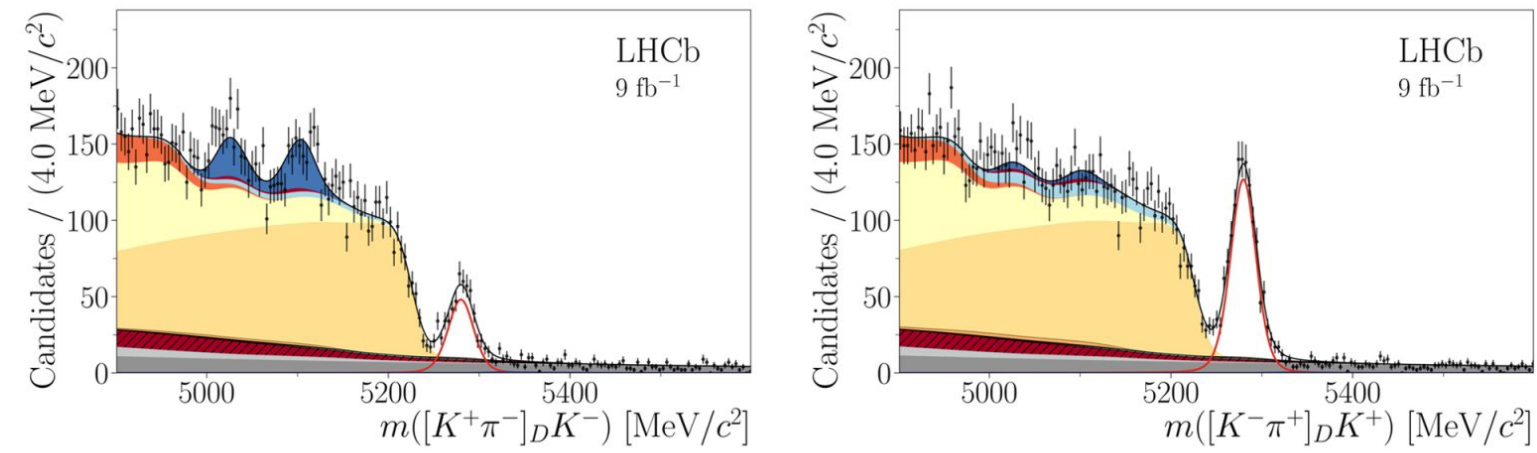
Yasmine Amhis
CERN Summer School



Next steps



Types of CP violation



CP Violation in Decay

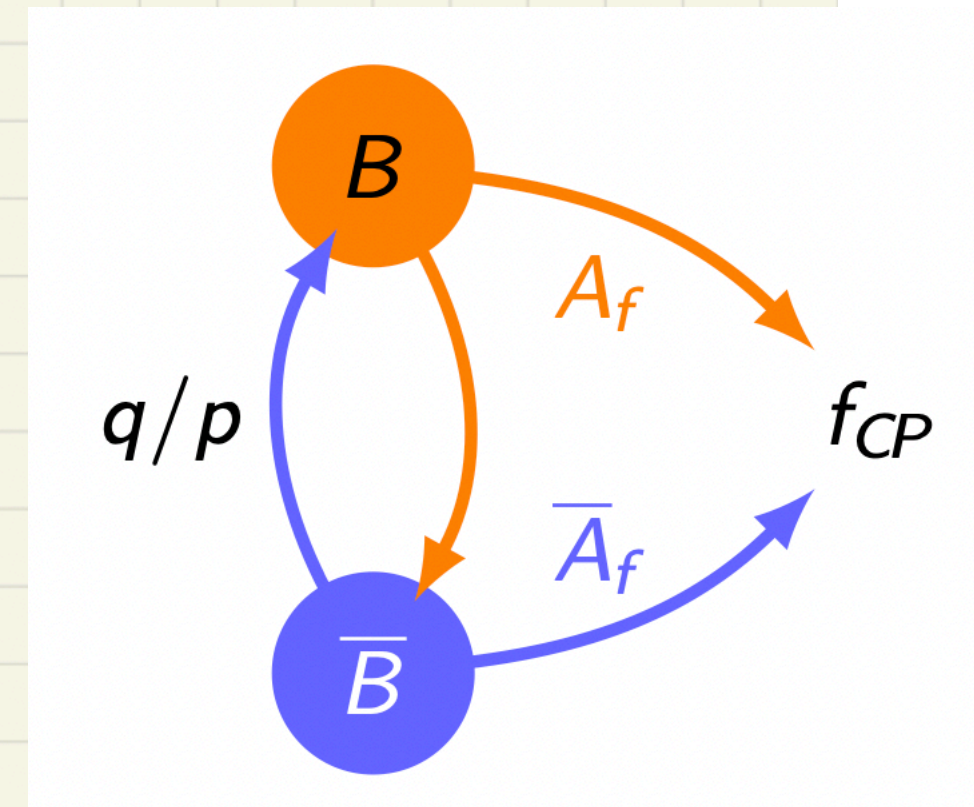
- $\left| \frac{A_f}{\bar{A}_f} \right| \neq 1$

A_f Amplitude $b \rightarrow f$

\bar{A}_f Amplitude $\bar{b} \rightarrow \bar{f}$

CP Violation in mixing

- $\left| \frac{q}{p} \right| \neq 1$



CP violation in the interference between mixing and decay

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

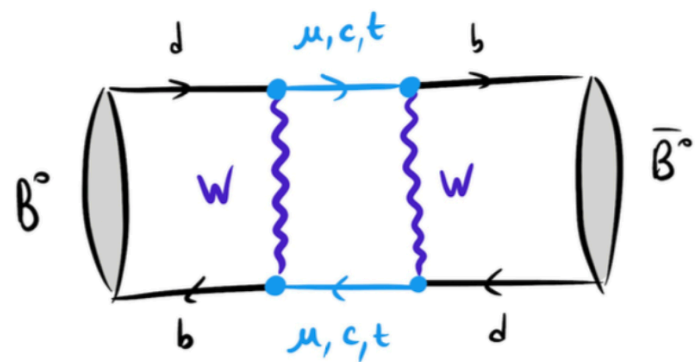
λ_f = parameter that quantifies CP violation

$$\text{CP} |f_{CP}\rangle = \eta_f^{\text{CP}} |f_{CP}\rangle \quad \text{with} \quad \eta_f^{\text{CP}} = \pm 1$$

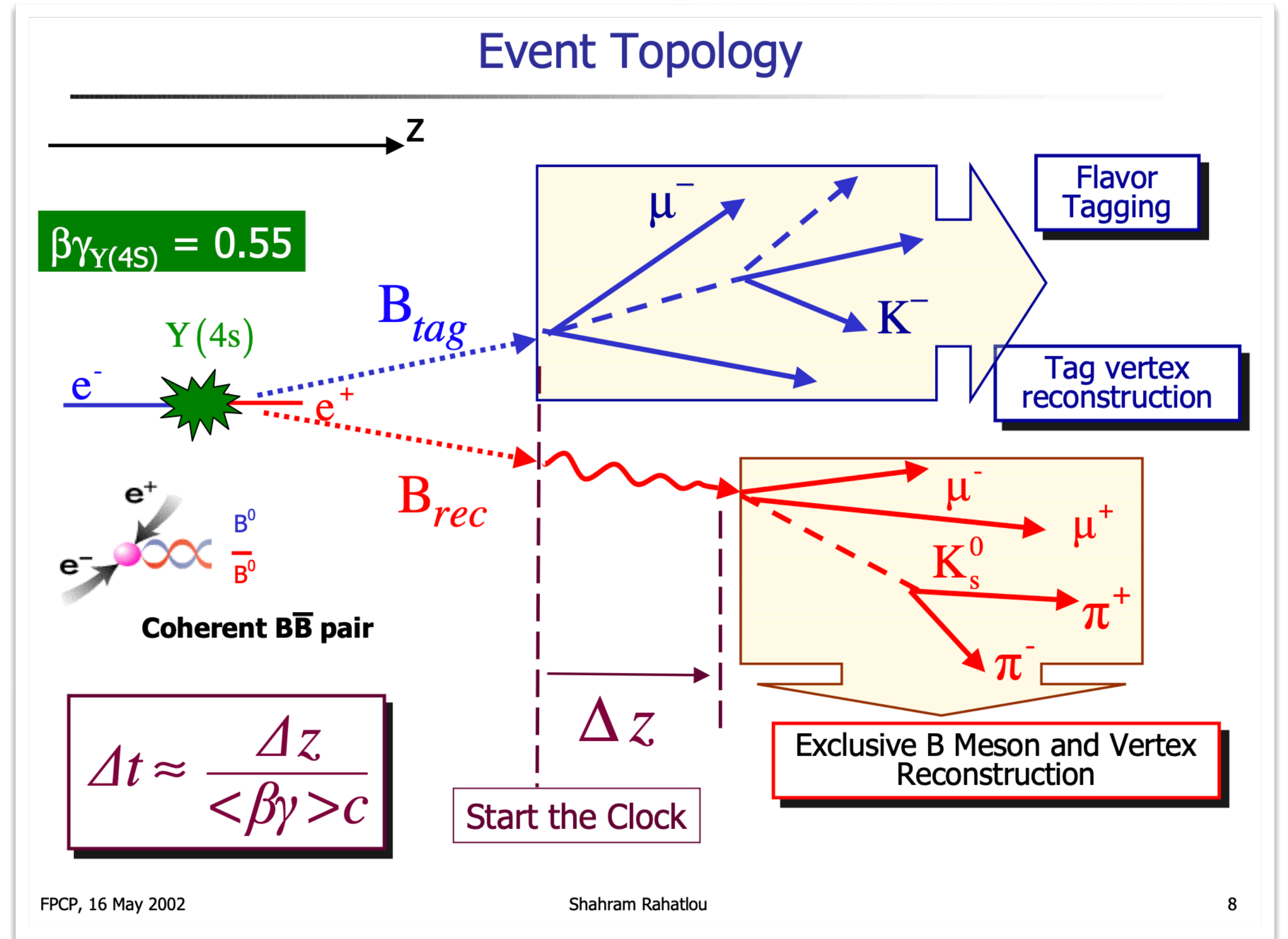
Let's start with sin2beta With the "golden" mode $B^0 \rightarrow J/\psi (\rightarrow \mu^+\mu^-) K_S (\pi^+\pi^-)$

B^0 *direct* ψK_S

mixing $B^0 \leftrightarrow \bar{B}^0$ *direct*



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

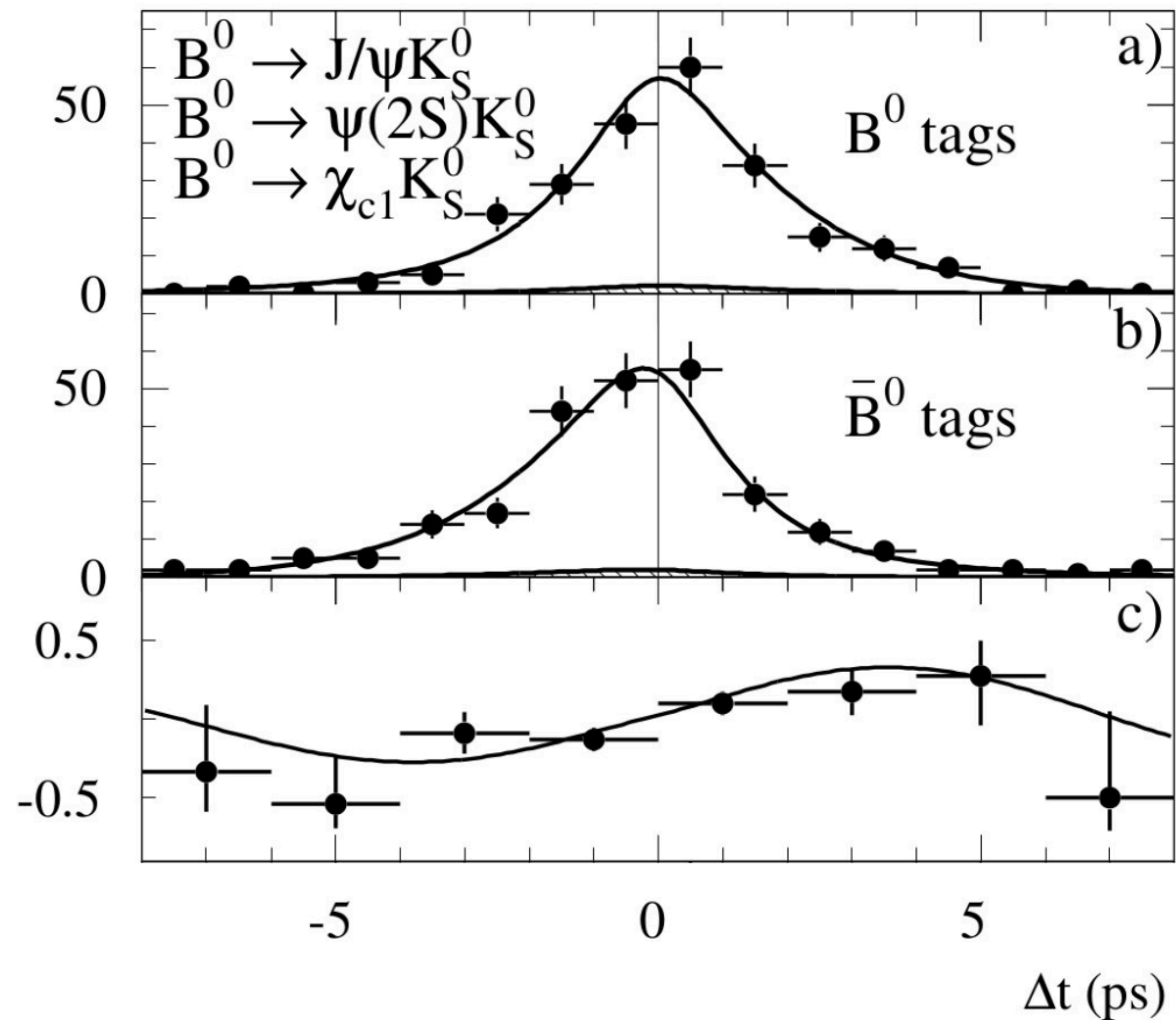


Time dependent analysis \rightarrow requires flavour tagging

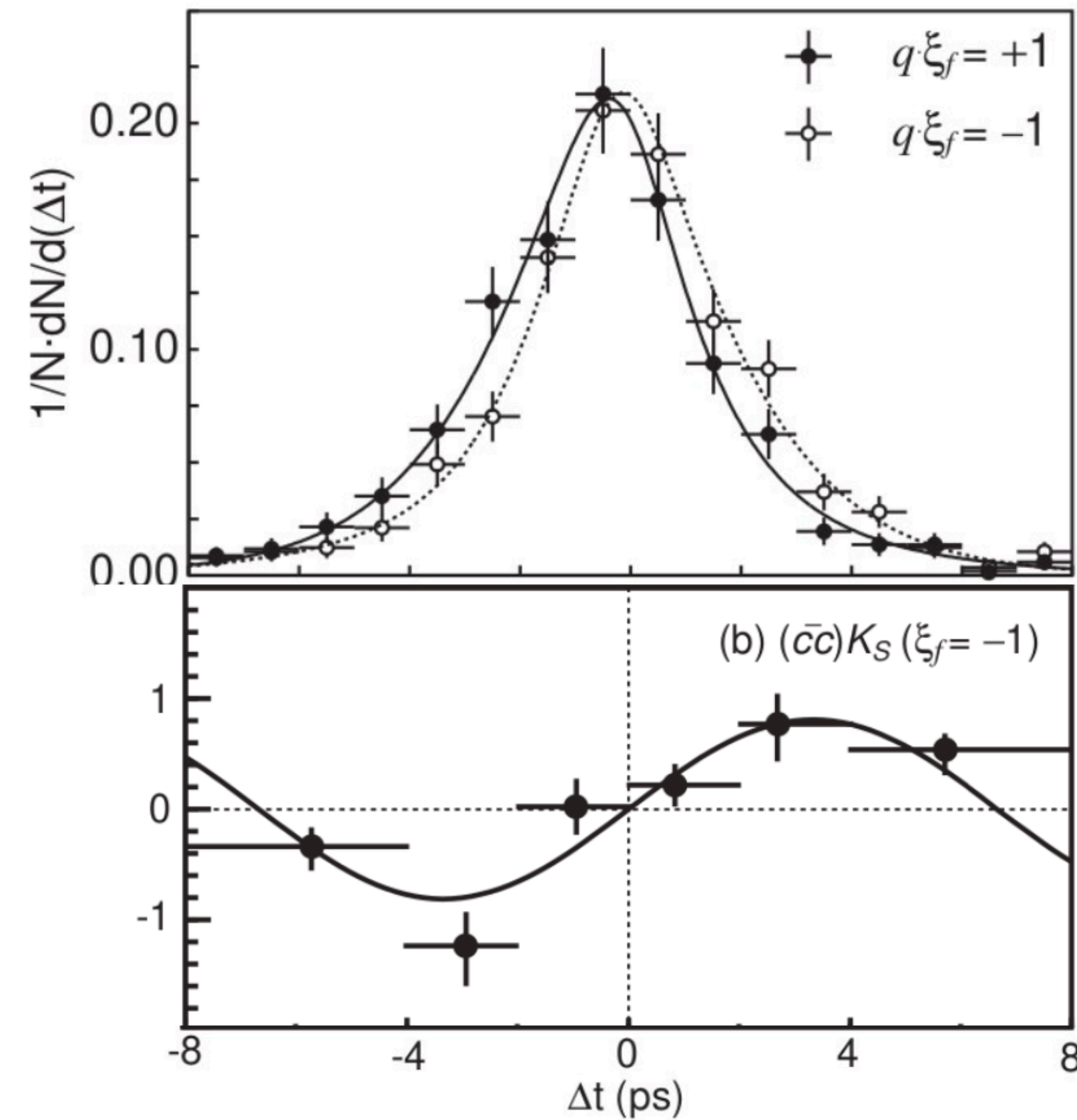
sin 2β aka the raison d'être of B-factories - 2001

BaBar, PRL 87 (2001) 091801

Belle, PRL 97 (2001) 091802



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

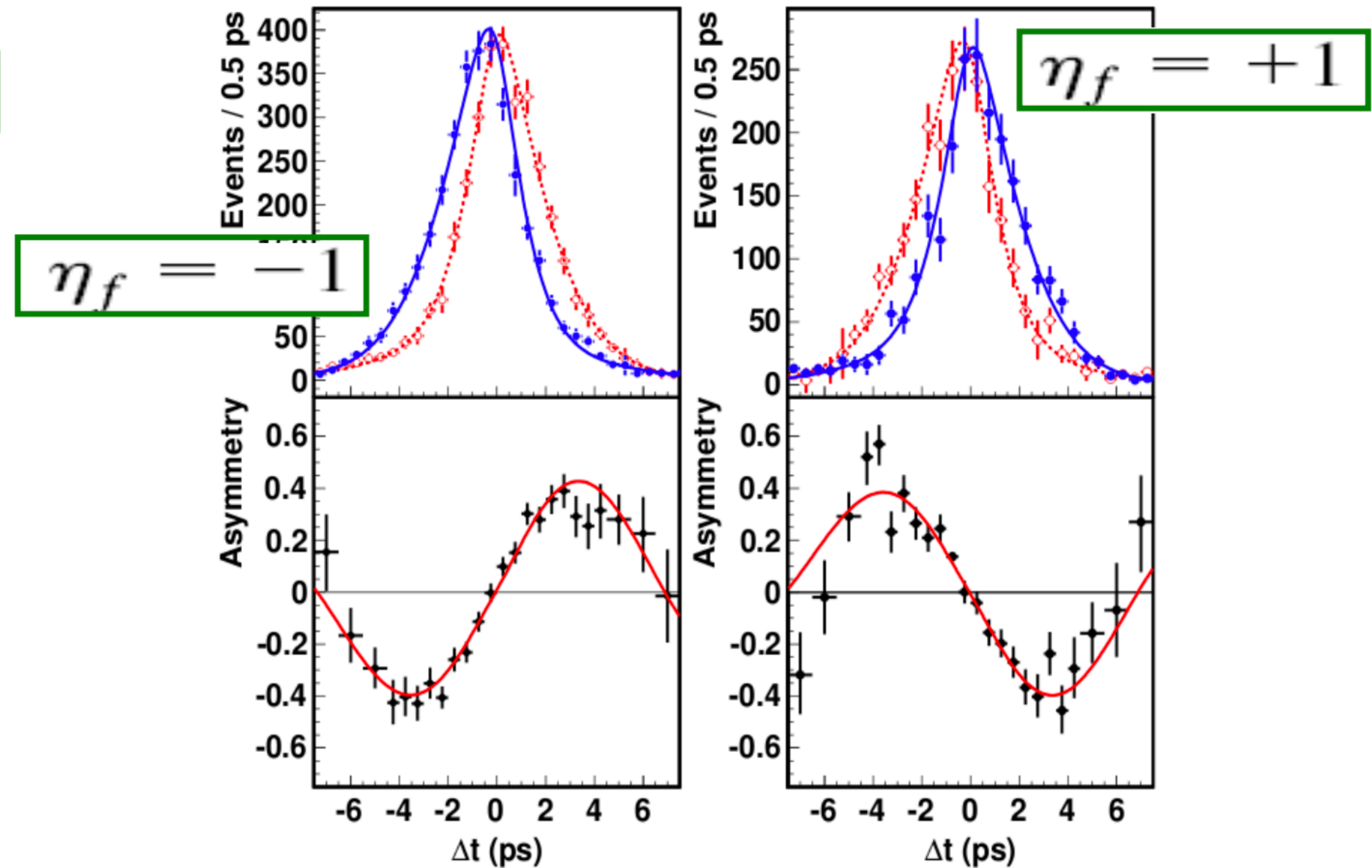
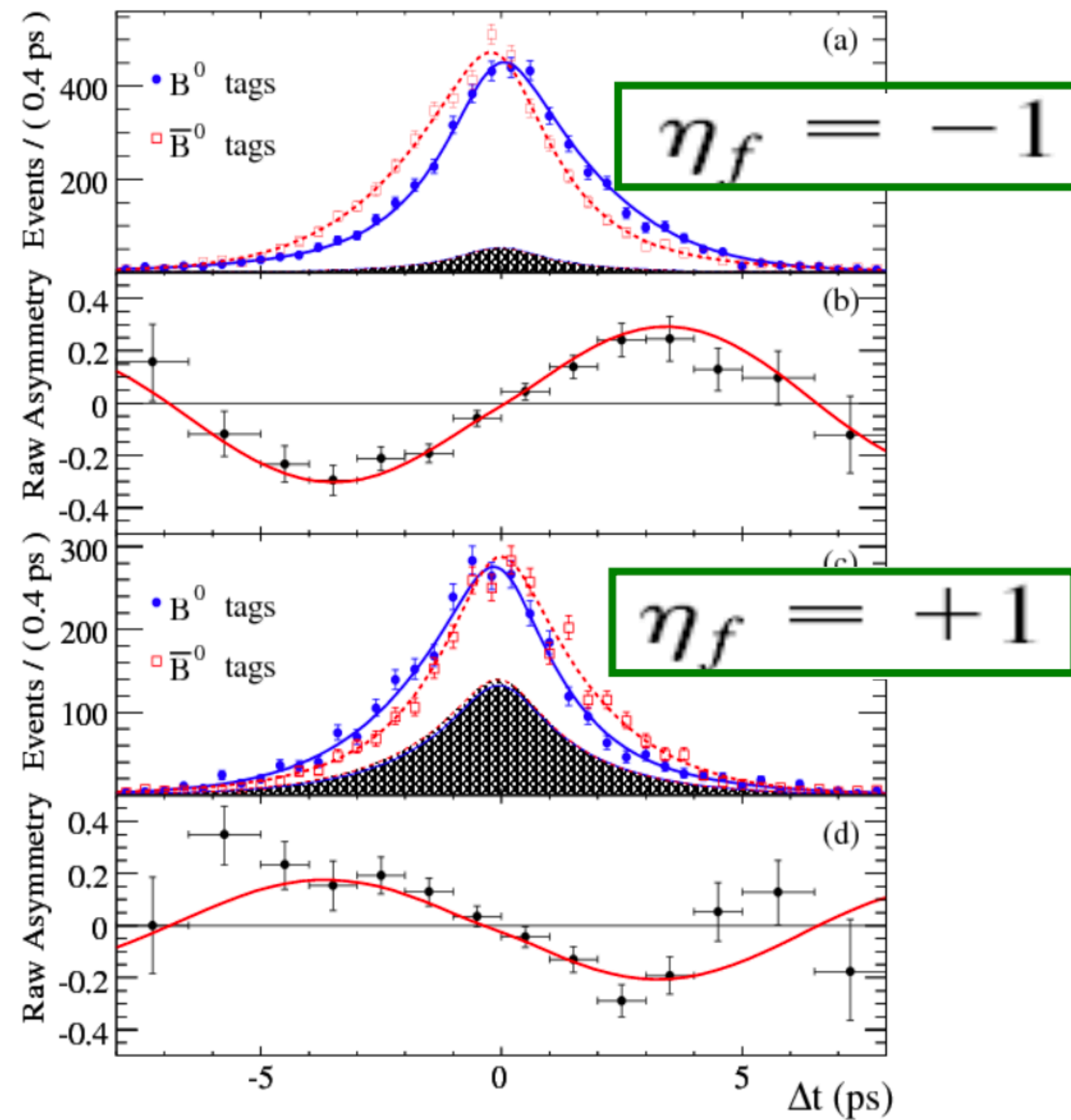


$$\sin 2\phi_1 = 0.99 \pm 0.14 \text{ (stat)} \pm 0.06 \text{ (syst)}.$$

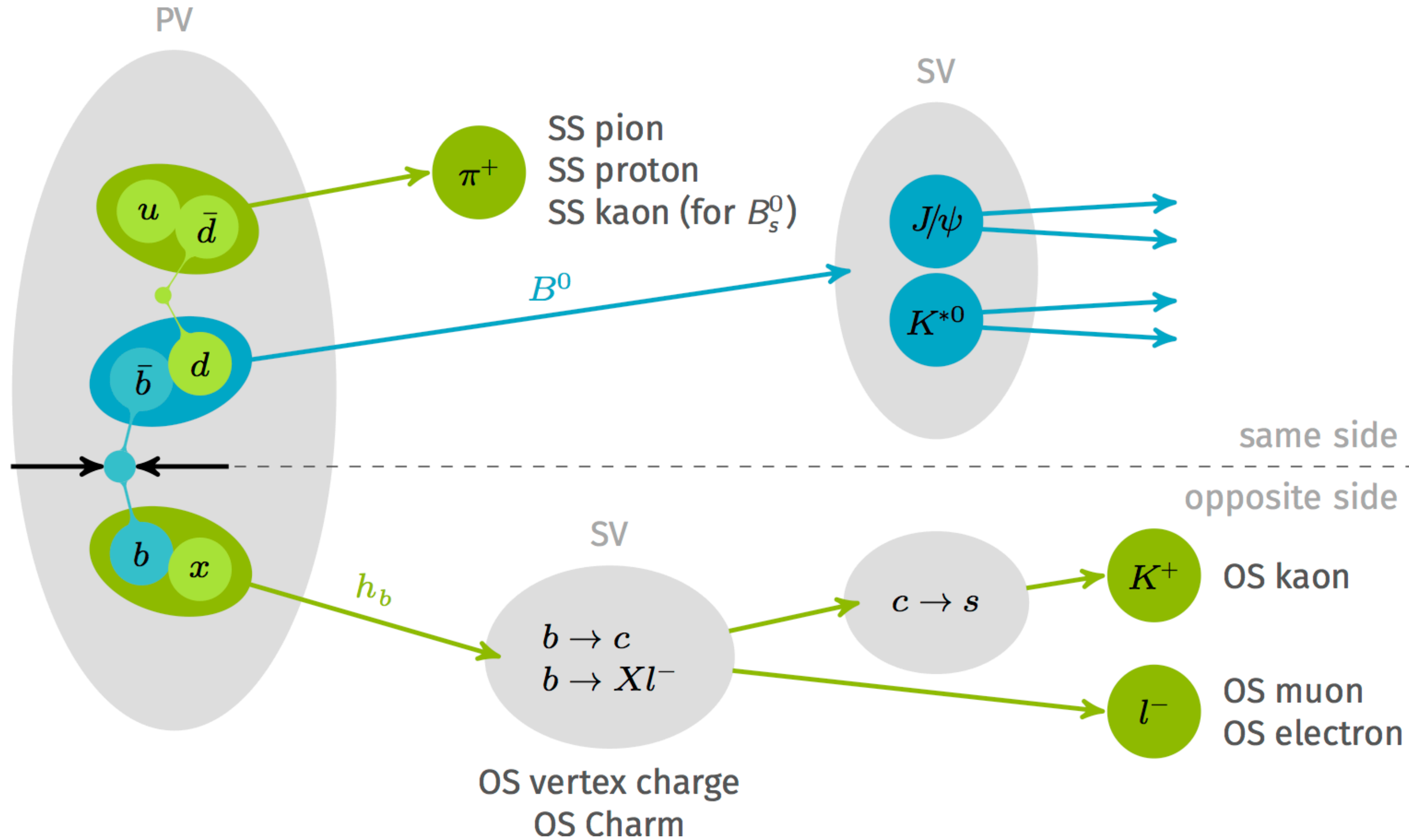
Legacy from B-Factories

BaBar, PRD 79 (2009) 072009

Belle, PRL 108 (2012) 171802

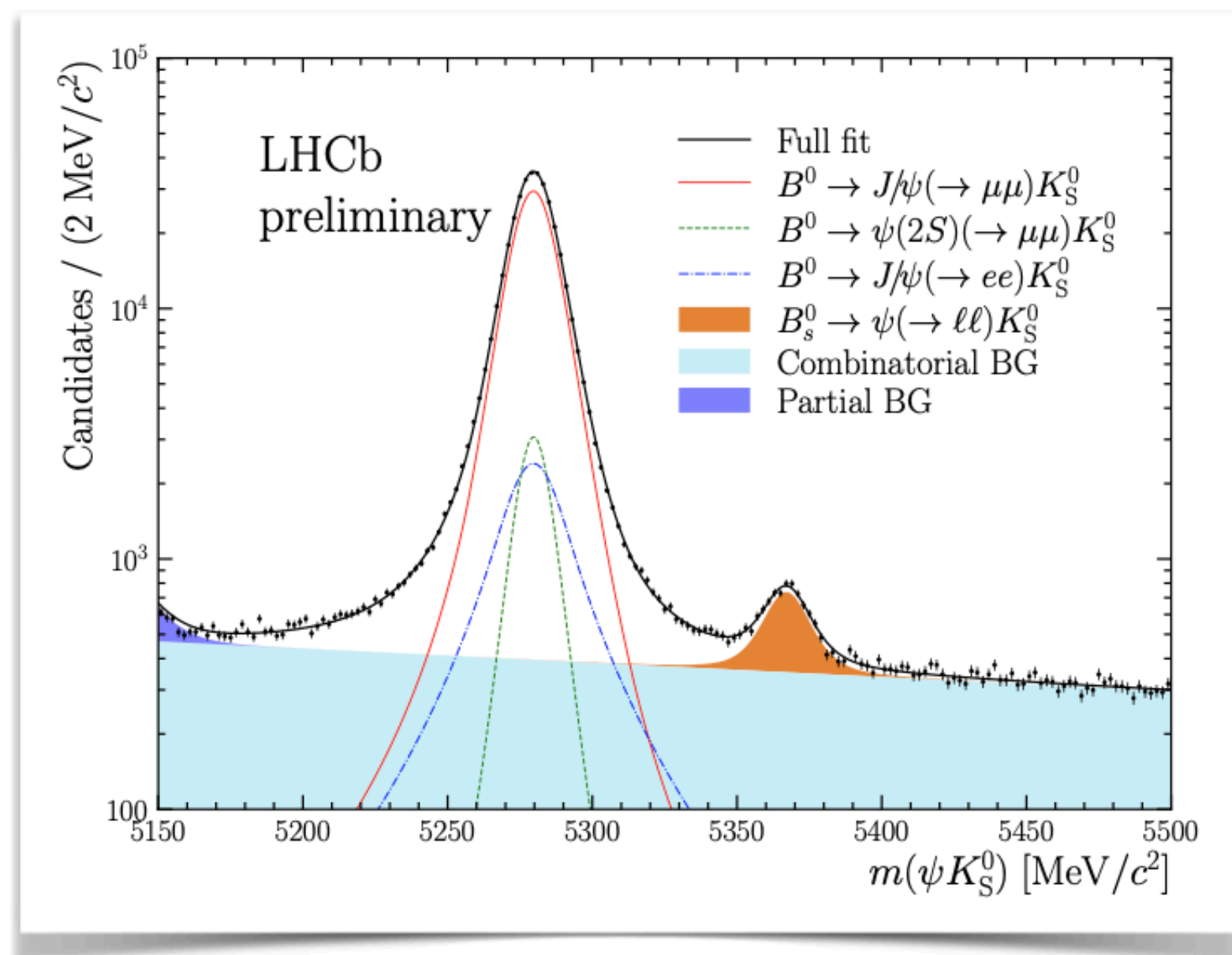


Flavour Tagging @ LHCb



Combination of a few decay channels

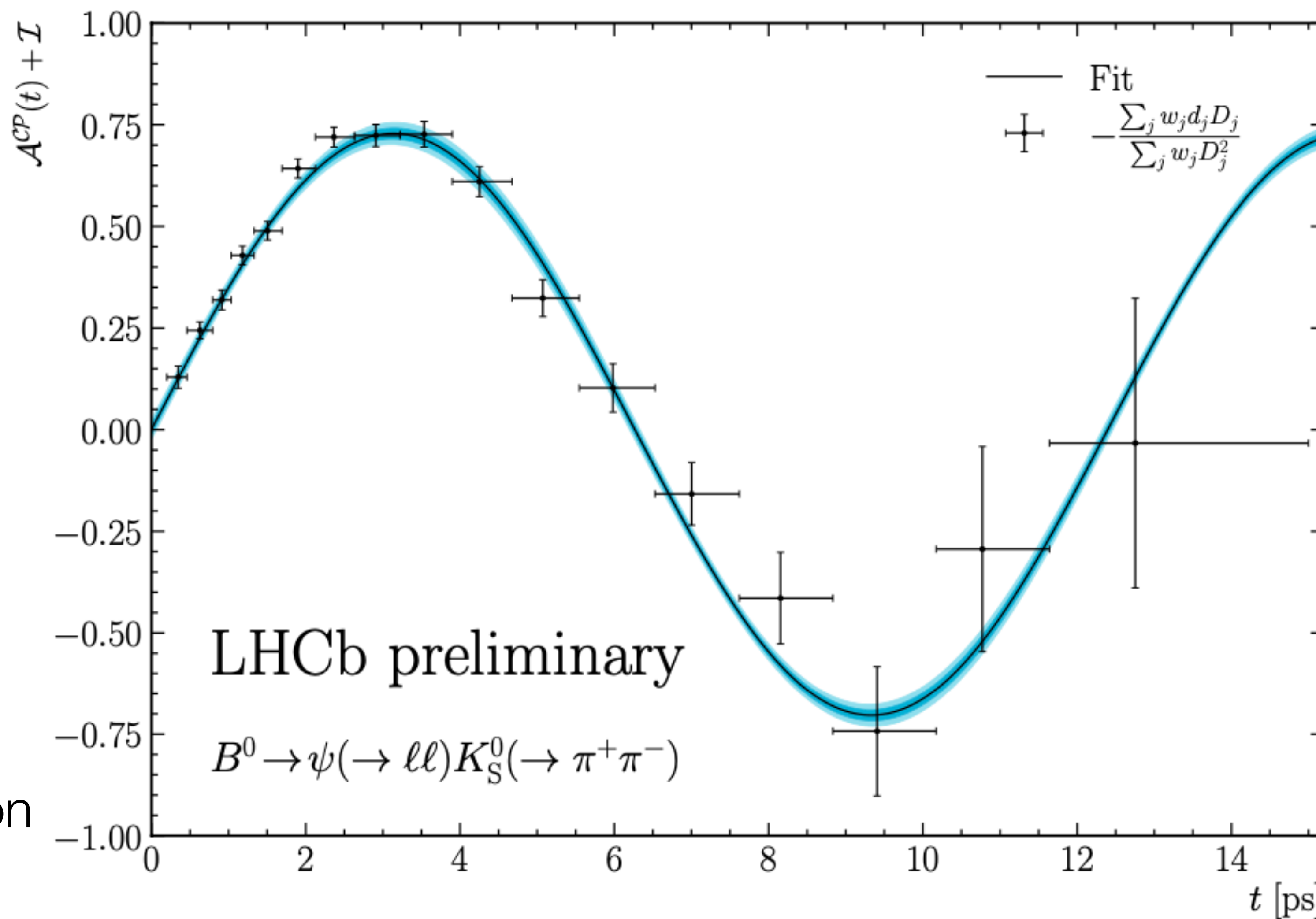
Text book like result !



Flavour tagging

Importance of efficient reconstruction

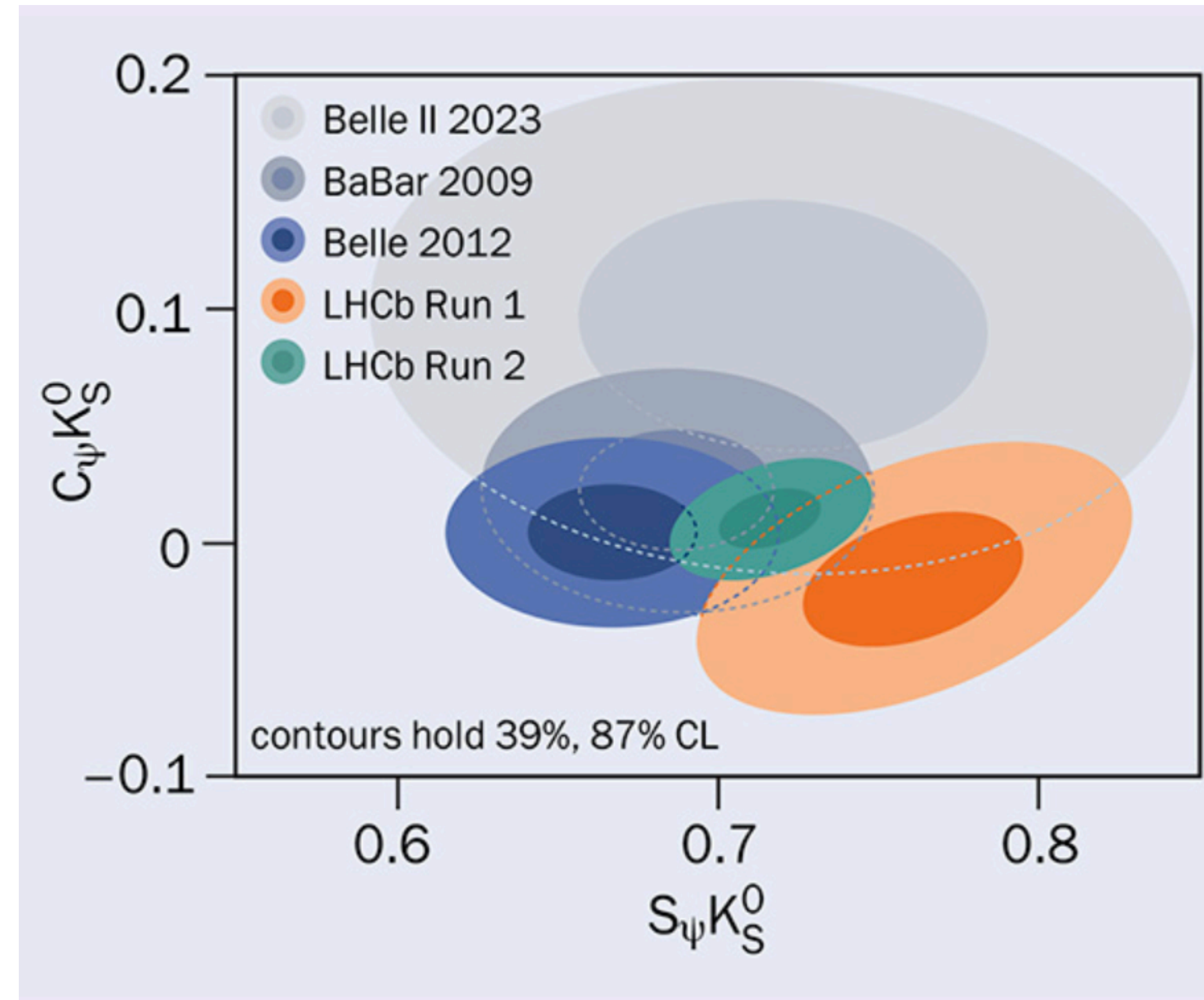
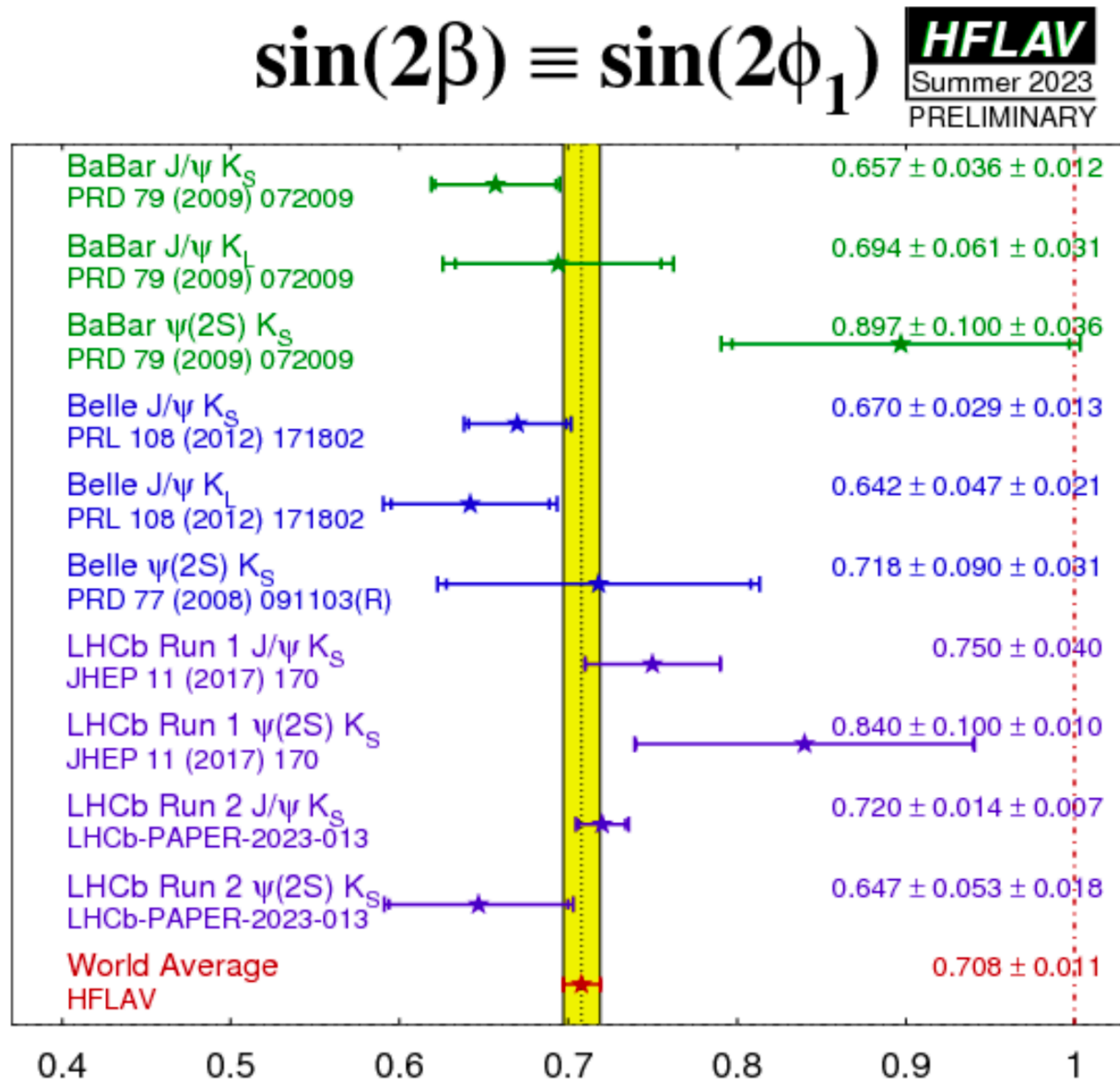
Understanding tiny effects



Trigger wise dilepton decays are a day at the beach

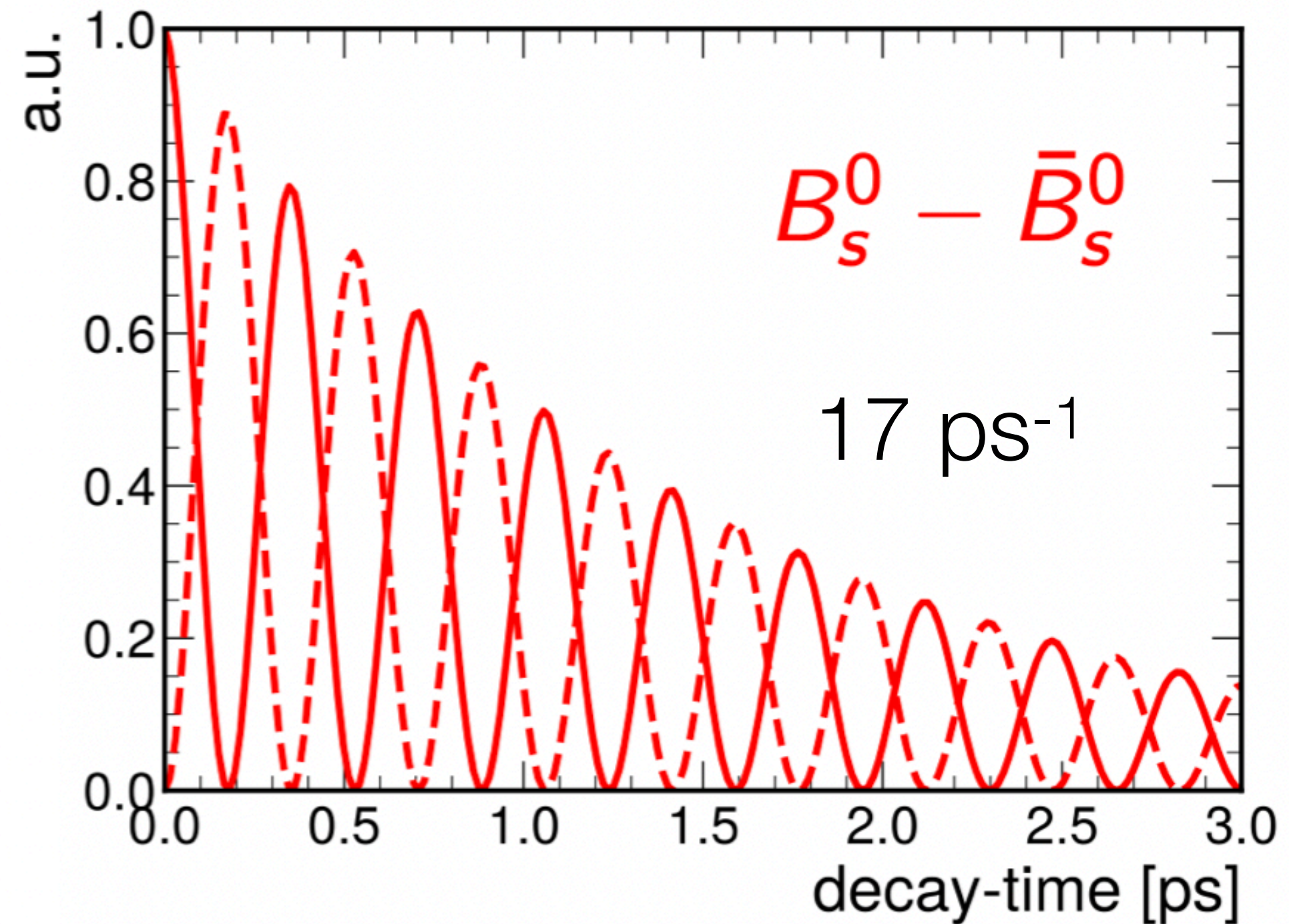
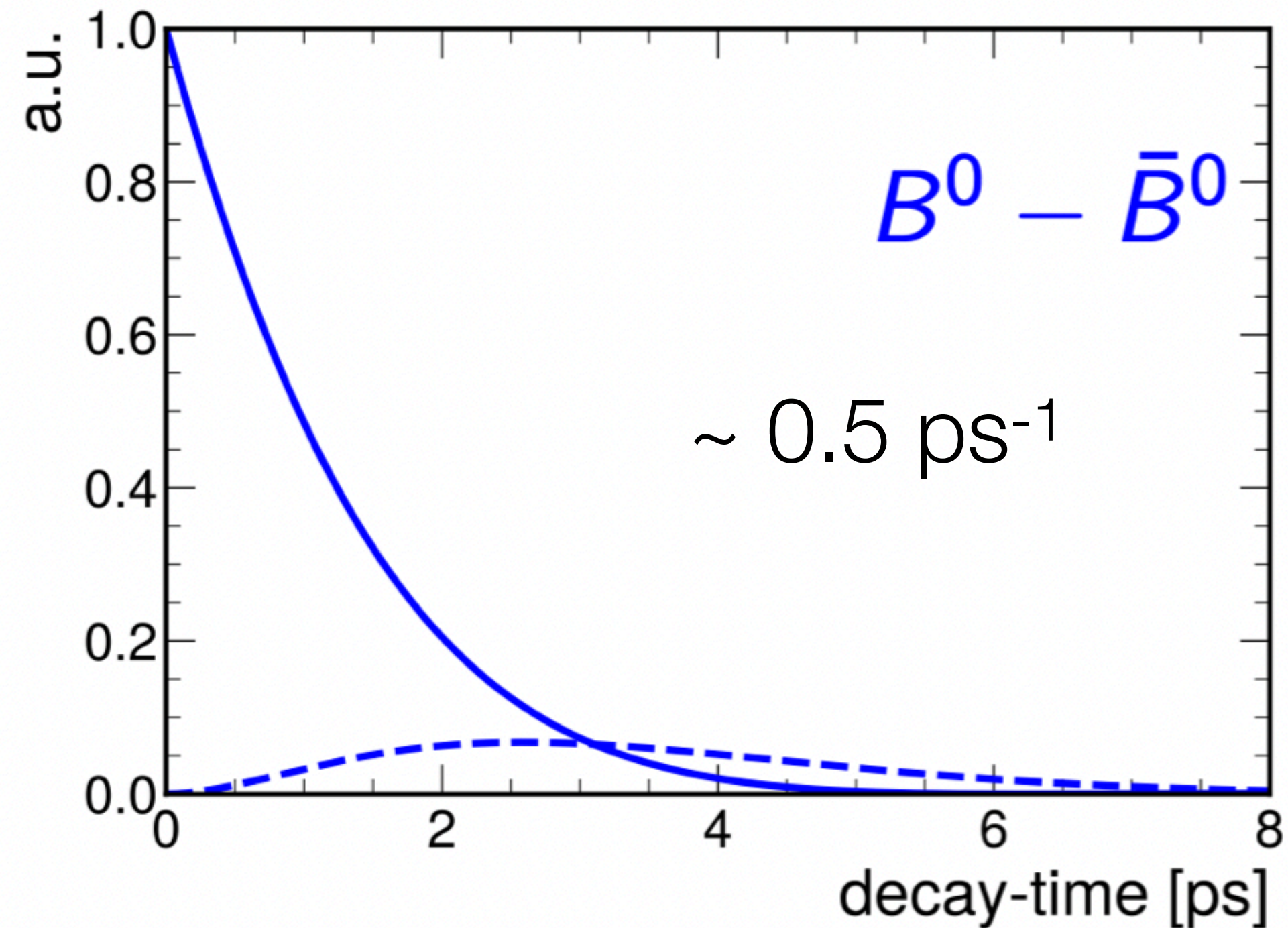
Summary plot

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

Mass Matrix
Dispersive

Decay Matrix
Absorptive

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

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

A few lines about the mixing formalism

The mass eigenstates =

$$|B_H\rangle \propto p |B_q'\rangle + q |\bar{B}_q\rangle$$

$$|B_L\rangle \propto p |\bar{B}_q'\rangle - q |\bar{B}_q\rangle$$

The time evolution =

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

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

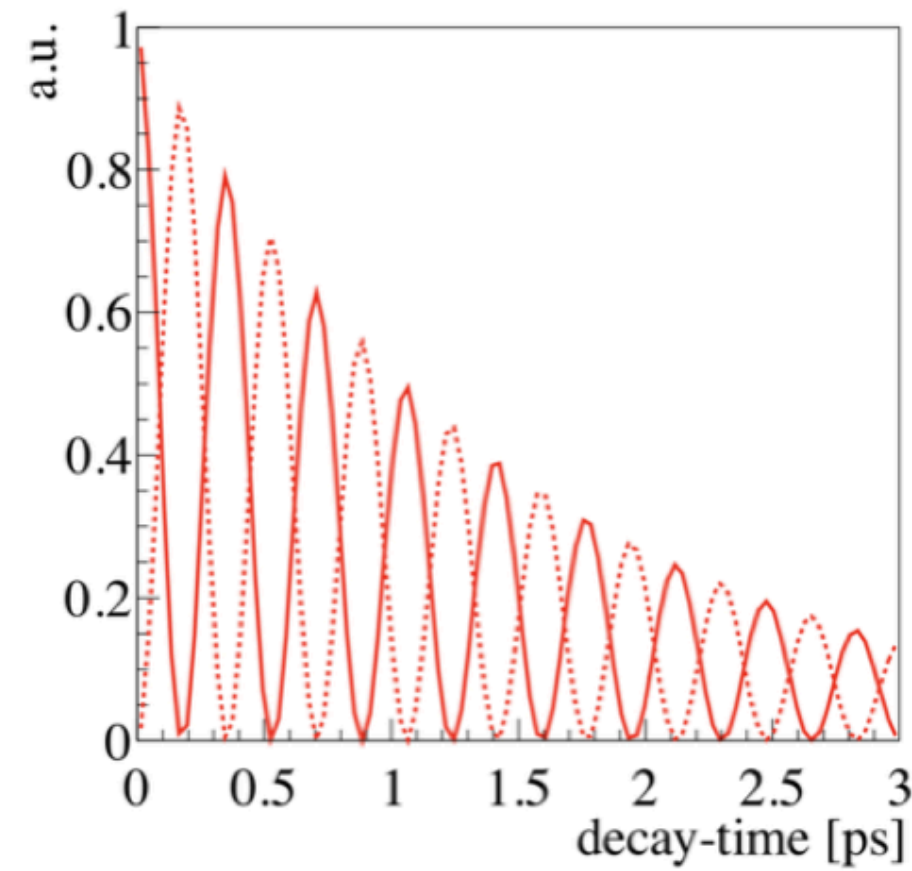
$$\Delta m_q = m_H - m_L, \quad \Delta\Gamma_q = \Gamma_L - \Gamma_H$$

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

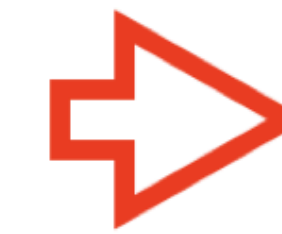
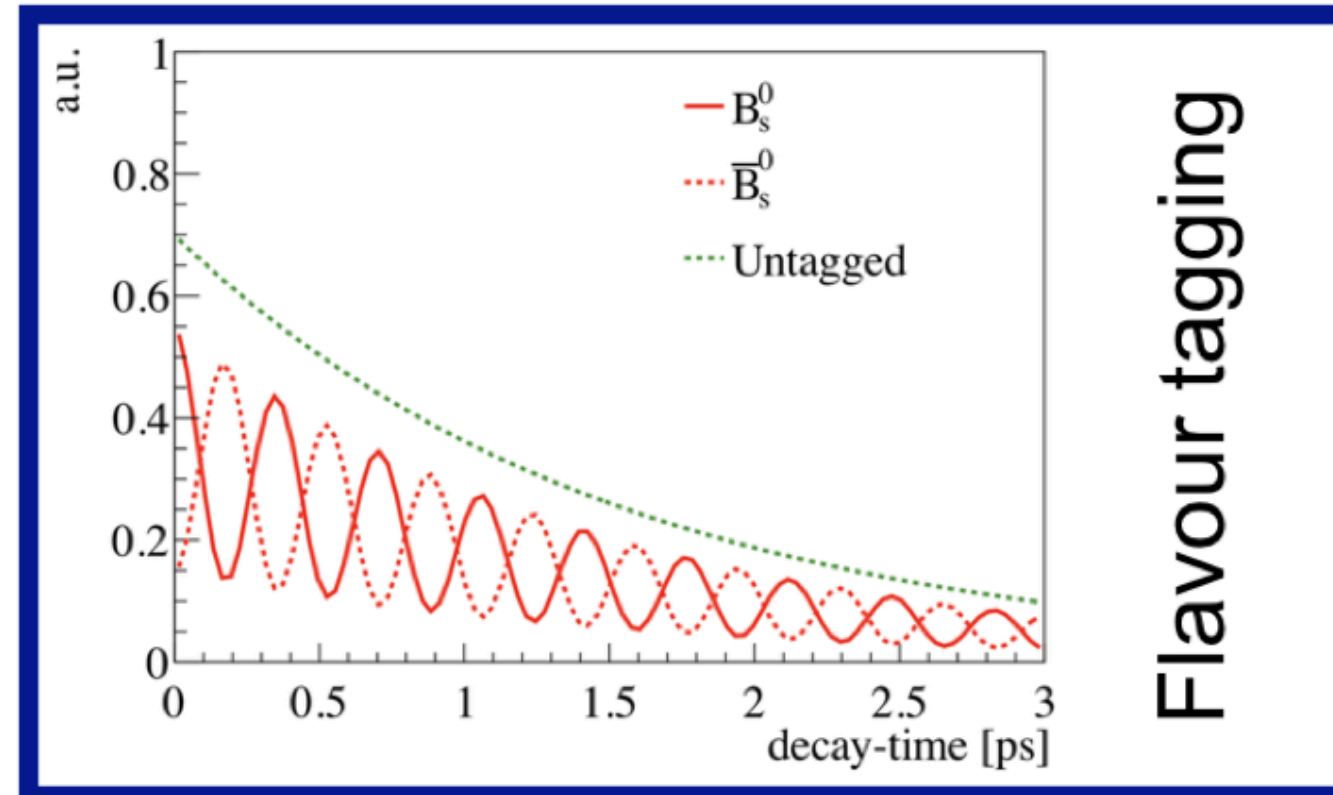
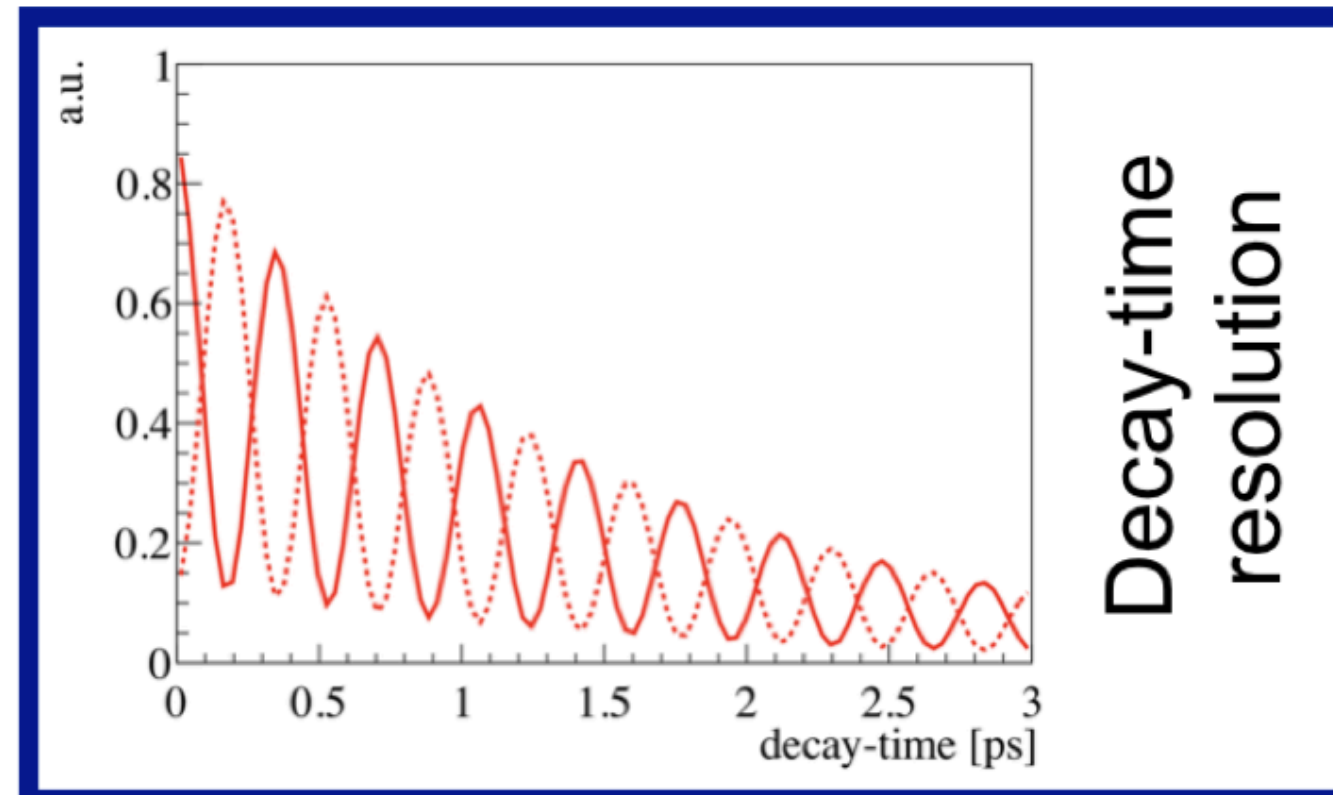
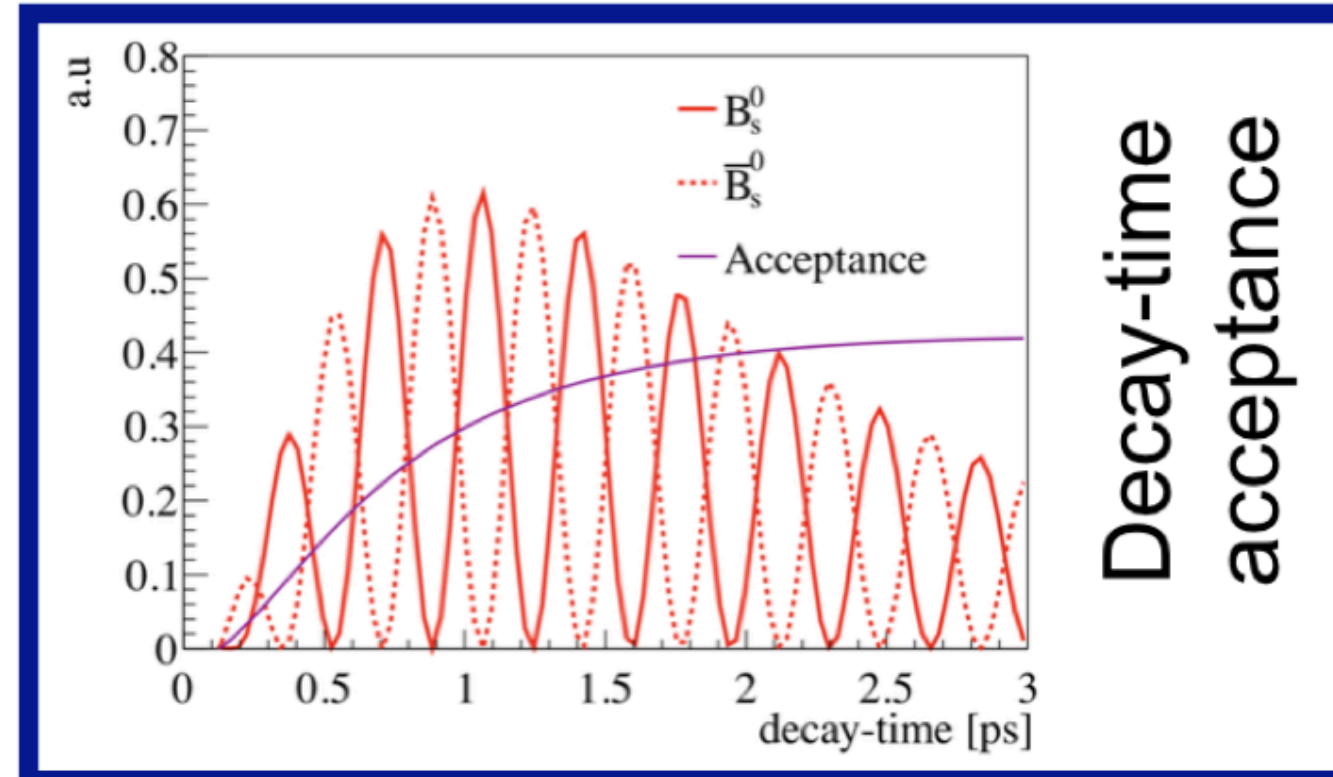
We have to make the actual omelette

Detector effects

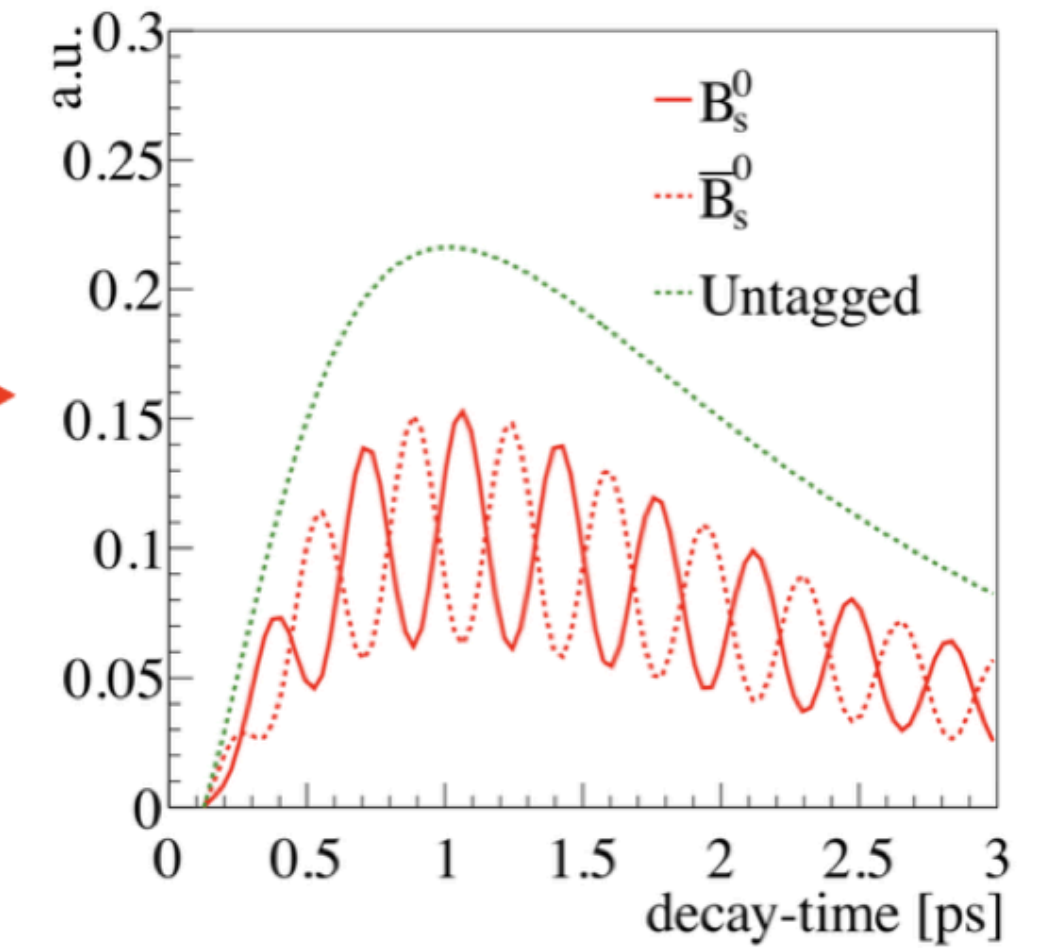
Perfect



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



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

$B_s^0 \rightarrow D_s^- \rho^+$  Bs Oscillations measurement.

[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 Δm_s . Using a data sample of 1 fb^{-1} of p–pbar collisions at $\sqrt{s}=1.96 \text{ TeV}$ 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 8×10^{-8} , which exceeds 5 sigma significance. We measure

$\Delta m_s = 17.77 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ ps}^{-1}$

and extract

$|\text{Vtd}/\text{Vts}| = 0.2060 \pm 0.0007 \text{ (exp)} + 0.0081 - 0.0060 \text{ (theor)}.$

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The end of the universe if not something very close



In 2008

B factories and Tevatron students



LHC students



These were dark days for us

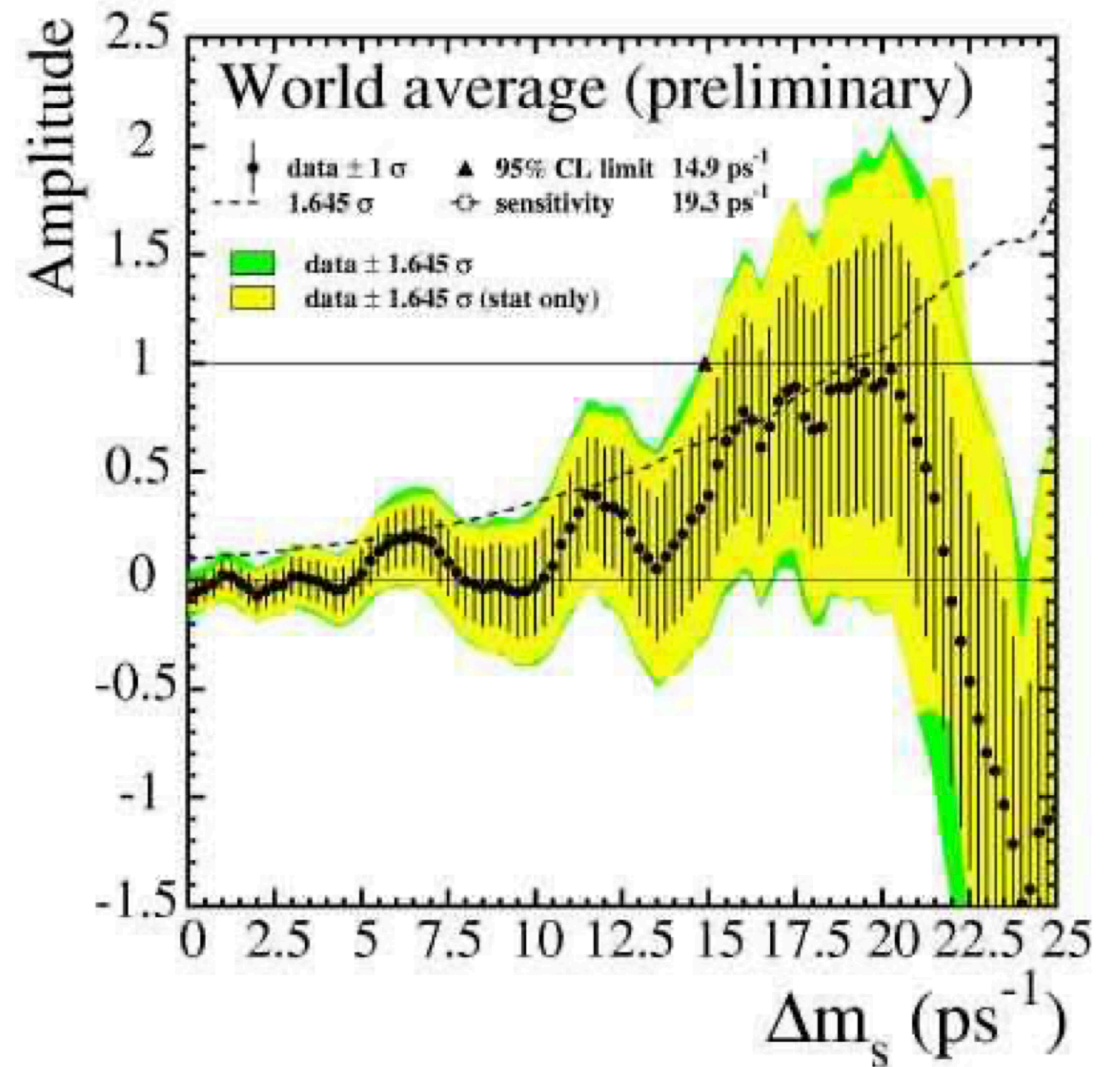
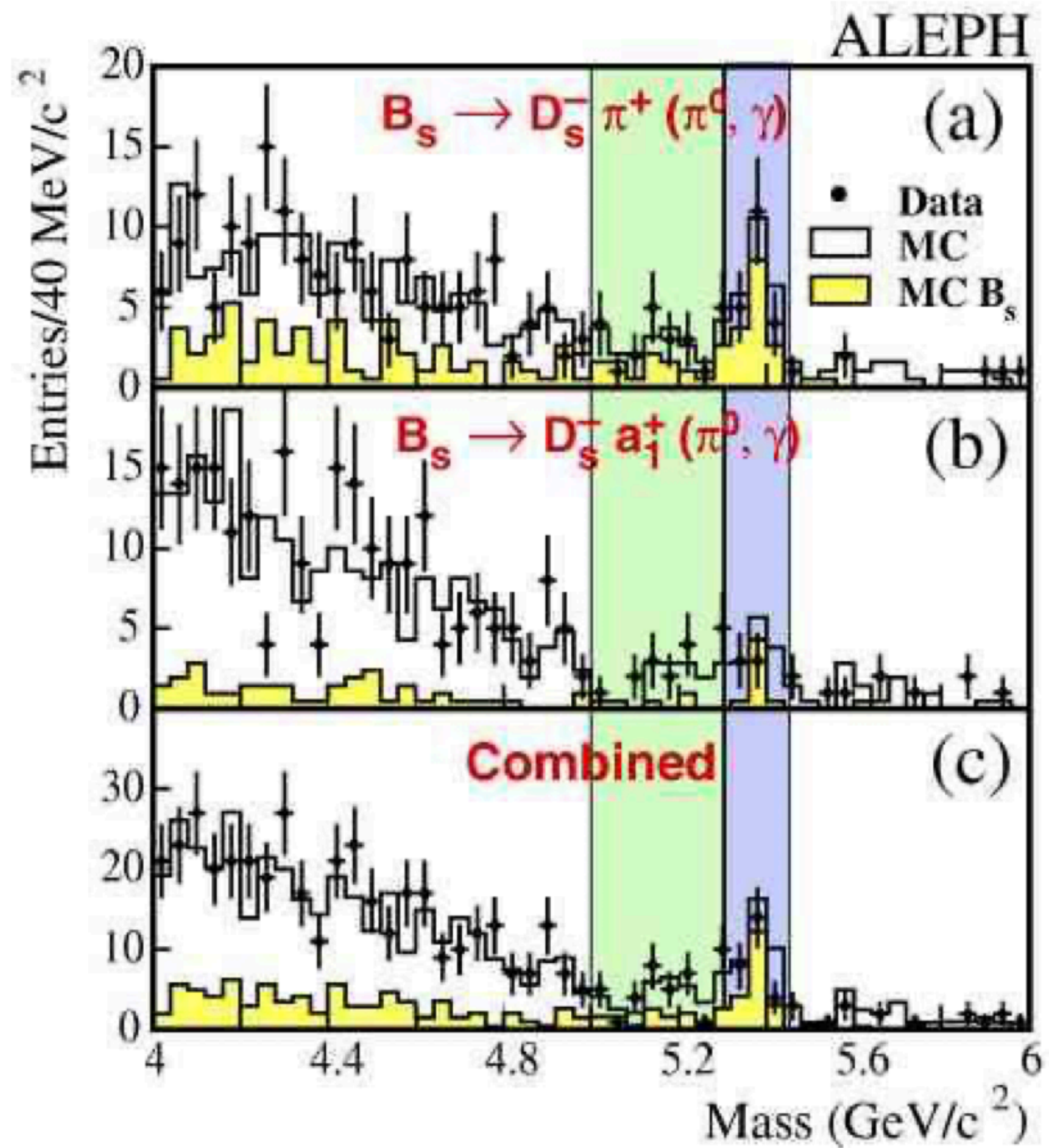
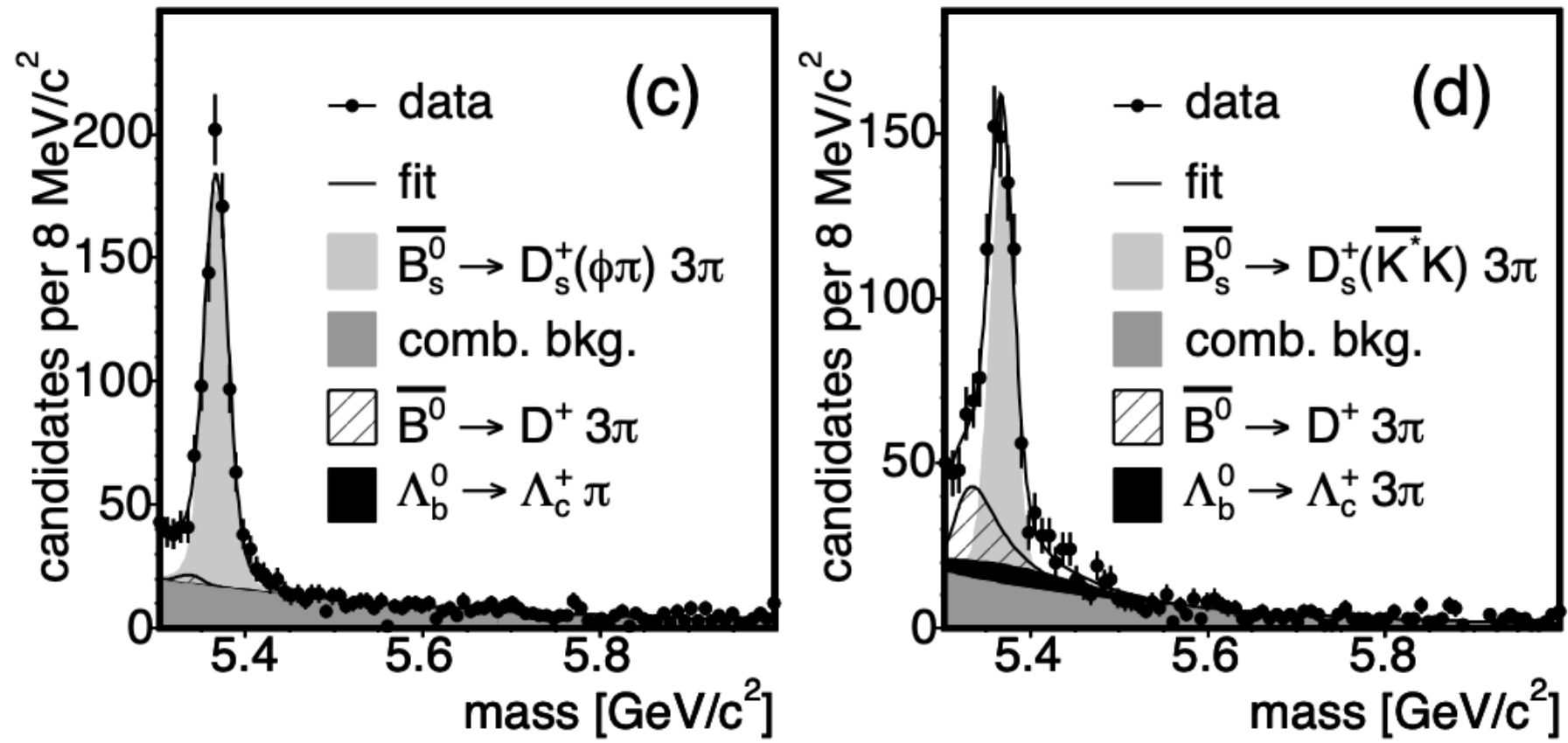
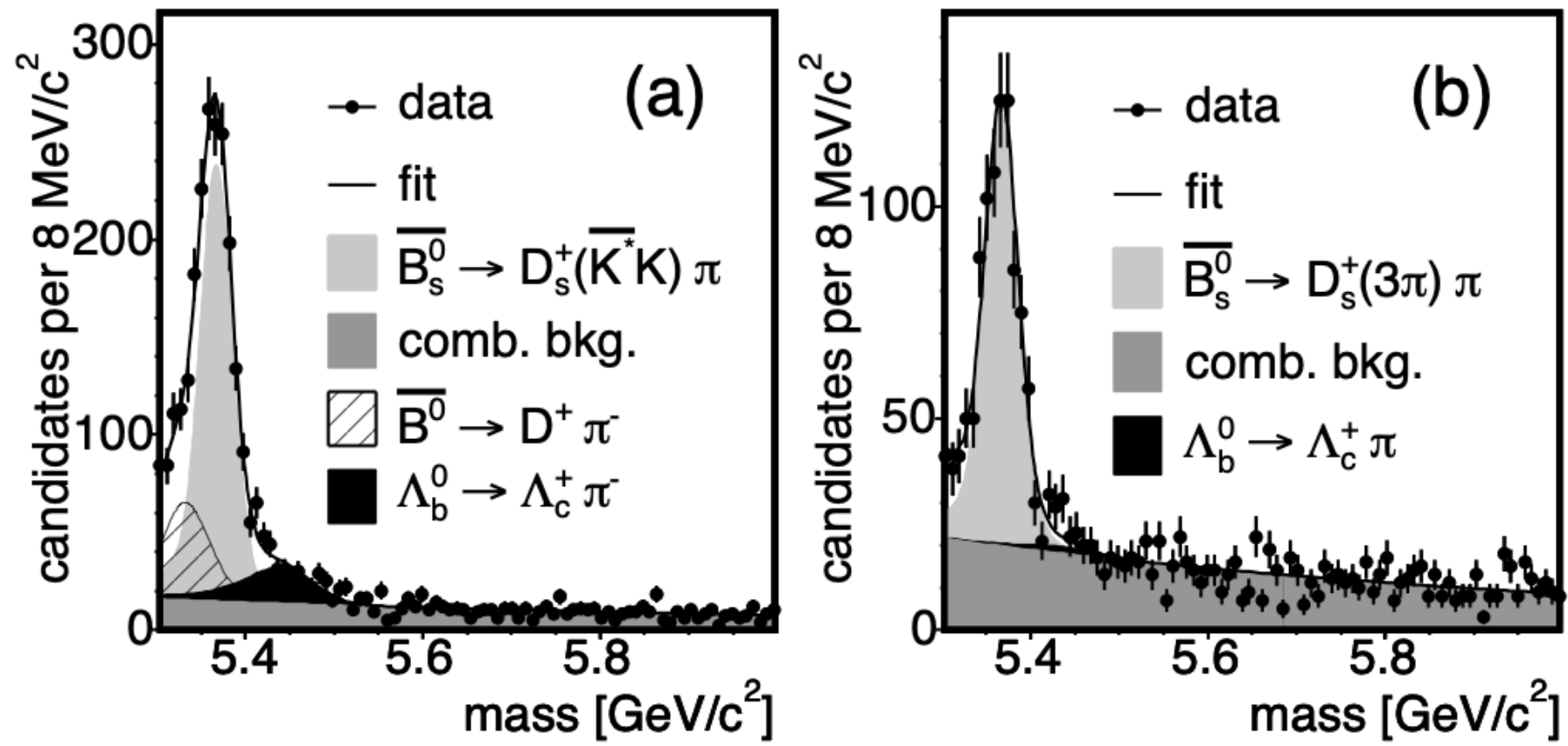


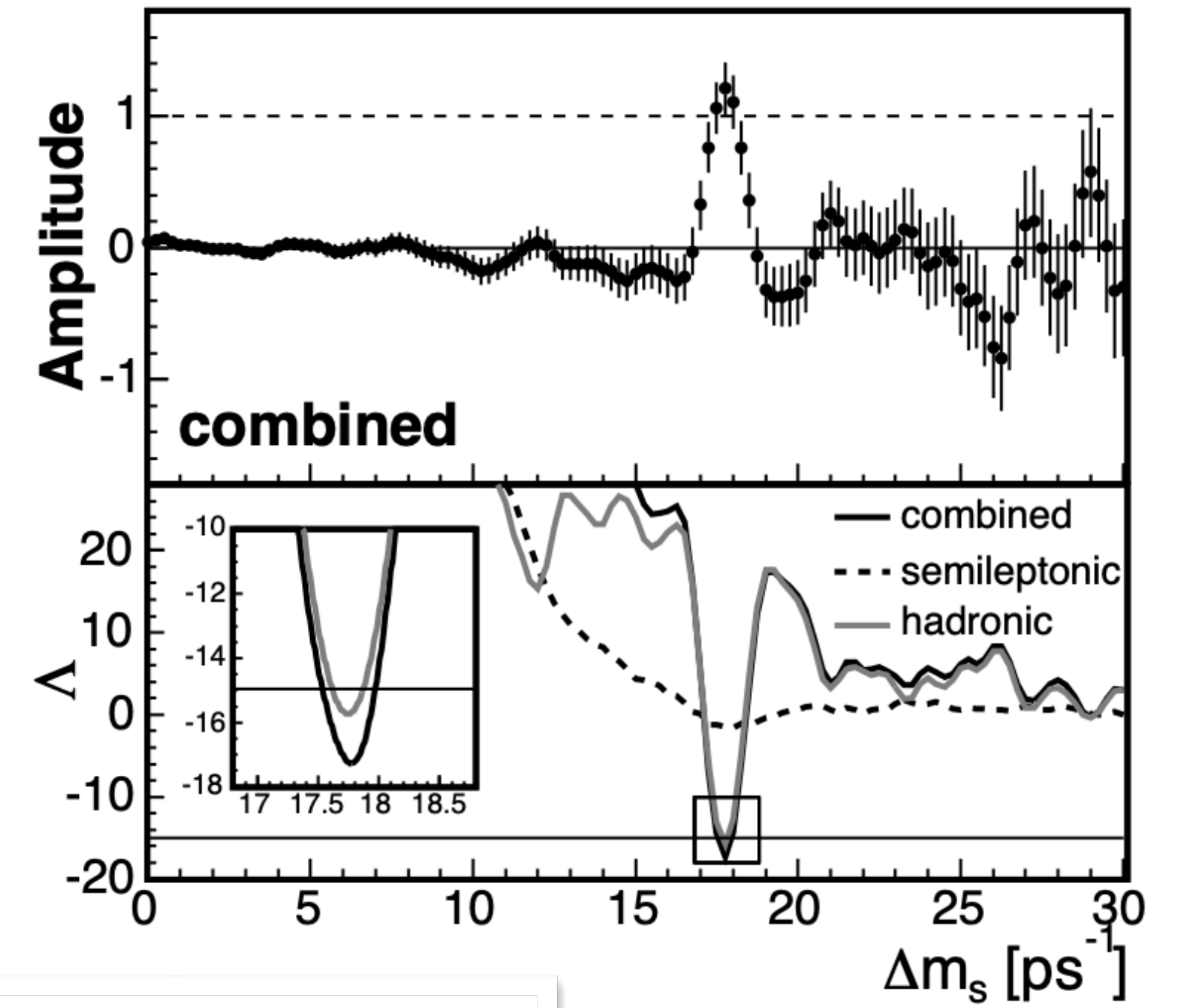
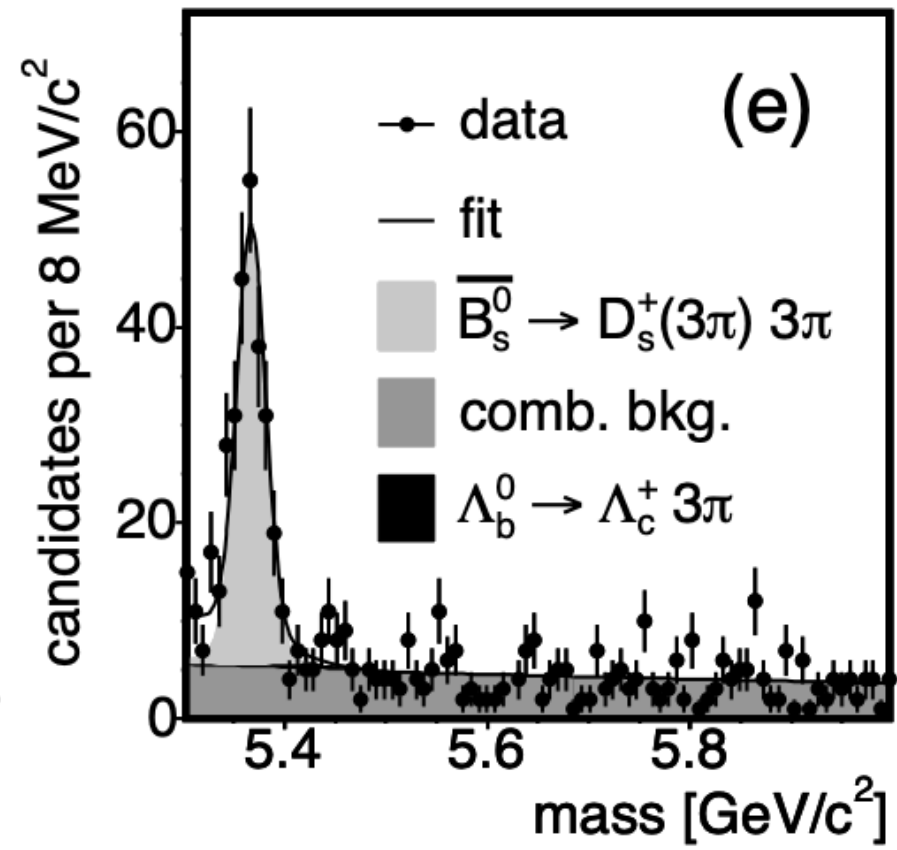
Figure 7: The combined B_s^0 oscillation results from ALEPH, CDF, DELPHI, OPAL, and SLD shown as amplitude versus hypothesized Δm_s [11]. The dots with error bars show the fitted amplitude values and uncertainties. An observed (expected) 95% C.L. lower limit on Δm_s of 14.9 ps⁻¹ (19.3 ps⁻¹) is obtained.

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

My personal end of the universe at the time



- (a) $\overline{B}_s^0 \rightarrow D_s^+(\overline{K}^+K^-) \pi$
- (b) $\overline{B}_s^0 \rightarrow D_s^+(3\pi) \pi$
- (c) $\overline{B}_s^0 \rightarrow D_s^+(\phi\pi) 3\pi$
- (d) $\overline{B}_s^0 \rightarrow D_s^+(\overline{K}^+K^-) 3\pi$
- (e) $\overline{B}_s^0 \rightarrow D_s^+(3\pi) 3\pi$



arXiv:hep-ex/0609040v1 22 Sep 2006

Observation of B_s^0 - \overline{B}_s^0 Oscillations

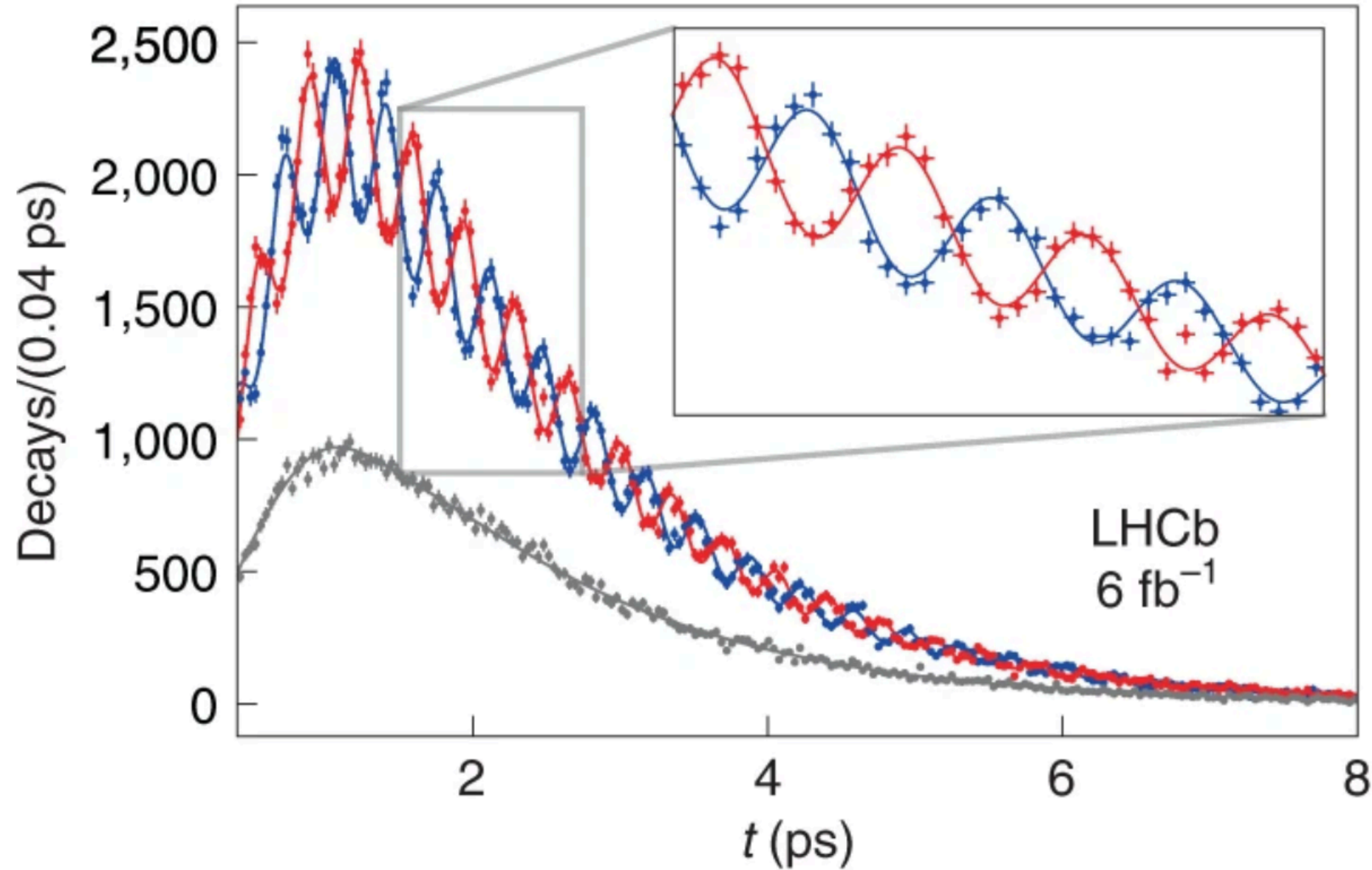
A. Abulencia,²³ J. Adelman,¹³ T. Affolder,¹⁰ T. Akimoto,⁵⁵ M.G. Albrow,¹⁶ D. Ambrose,¹⁶ S. Amerio,⁴³ D. Amidei,³⁴ A. Anastassov,⁵² K. Anikeev,¹⁶ A. Annovi,¹⁸ J. Antos,¹ M. Aoki,⁵⁵ G. Apollinari,¹⁶ J.-F. Arguin,³³ T. Arisawa,⁵⁷ A. Artikov,¹⁴ W. Ashmanskas,¹⁶ A. Attal,⁸ F. Azfar,⁴² P. Azzi-Bacchetta,⁴³ P. Azzurri,⁴⁶ N. Bacchetta,⁴³ W. Badgett,¹⁶ A. Barbaro-Galtieri,²⁸ V.E. Barnes,⁴⁸ B.A. Barnett,²⁴ S. Baroiian,⁷ V. Bartsch,³⁰ G. Bauer,³⁹ F. Bealeschi,⁴⁶ S. Behari,²⁴ S. Bellocq,³⁴ G. Bellizzi,⁴⁶ J. Bellinger,⁵⁰ A. Belloni,⁵² D. Benjamin,¹⁵ A. Berevas,¹⁶ J. Beringer,²⁸ T. Berry,²⁹ A. Bhatti,⁵⁰ M. Binkley,¹⁶ D. Bisello,⁴⁸ R.E. Blair,⁷ C. Blocker,⁹ B. Blumenfeld,²⁴ A. Bocci,¹⁵ A. Bodek,⁴⁹ V. Boisvert,⁴⁹ G. Bolli,⁴⁸ A. Bolshov,³² D. Bortoletto,⁴⁸ J. Bondreau,⁴⁷ A. Boveia,¹⁰ B. Braun,¹⁰ L. Brigliadori,² C. Bromberg,³⁵ E. Brubaker,¹³ J. Budagov,¹⁴ H.S. Budd,⁴⁹ S. Budd,²³ S. Budroni,⁴⁶ K. Burkett,¹⁶ G. Busetto,⁴³ P. Bussey,²⁰ K. L. Byrum,² S. Cabrera,¹⁵ M. Campanelli,¹⁹ M. Campbell,³⁴ F. Canelli,¹⁶ A. Canepa,⁴⁸ S. Carrillo,¹⁷ D. Carlsmith,⁵⁰ R. Carosi,⁴⁶ S. Carron,³³ B. Casal,¹¹ M. Casarsa,⁵⁴ A. Castro,⁵ P. Catastini,⁴⁶ D. Cauz,⁵⁴ M. Cavalli-Sforza,³ A. Cerri,²⁸ L. Cerrito,³⁰ S.H. Chang,²⁷ Y.C. Chen,¹ M. Chertok,⁷ G. Chiarelli,⁴⁶ G. Chlachidze,¹⁴ F. Chlebana,¹⁶ I. Cho,²⁷ K. Cho,²⁷ D. Chokheli,¹⁴ J.P. Chou,²¹ G. Choudalakis,³² S.H. Chuang,⁵⁹ K. Chung,¹³ W.H. Chung,⁵⁹ Y.S. Chung,⁴⁹ M. Cijlak,⁴⁶ C.I. Ciobanu,²³ M.A. Ciocci,⁴⁶ A. Clark,¹⁹ D. Clark,⁶ M. Coca,¹⁹ G. Compostella,⁴³ M.E. Convery,³⁰ J. Conway,⁷ B. Cooper,²³ K. Copie,²⁴ M. Cordelli,¹⁸ G. Cortiana,⁴³ F. Crescioli,⁴⁶ C. Cuenca Almenar,⁷ J. Cuevas,¹¹ R. Culbertson,³⁶ J.C. Cully,²⁴ D. Cyr,³⁹ S. DaRanco,²³ S. D'Auria,²⁰ T. Davies,²⁰ M. D'Onofrio,⁷ D. Dagenhart,⁶ P. de Barbaro,⁴⁹ S. De Cecco,⁵¹ A. Delaisé,²⁹ G. De Lentdecker,⁴⁹ M. Dell'Orso,⁴⁶ E. Delli Paoli,⁶³ L. Demortier,⁵⁰ J. Deng,¹⁵ M. Deninno,⁵ D. De Pedis,⁵¹ P.F. Derwent,¹⁶ G.P. Di Giovanni,¹⁴ C. Dionisi,⁵³ B. Di Ruzza,⁴⁹ J.R. Dittmann,⁴ P. DiToro,⁵² C. Dörz,²⁵ S. Donati,⁴⁶ M. Donega,¹⁹ P. Dong,² J. Douin,⁴³ T. Dorigo,⁴³ S. Dube,⁵² J. Efron,³⁹ R. Erbacher,⁷ D. Errede,²³ S. Errede,²³ R. Eusebi,¹⁶ H.C. Fang,²⁸ S. Farrington,²⁹ I. Fedorko,⁴⁶ W.T. Fedorko,¹³ R.G. Feild,¹⁴ M. Feindt,²⁵ J.P. Fernandez,³¹ R. Field,¹⁷ G. Flanagan,⁴⁸ A. Foland,²¹ S. Forrester,⁷ G.W. Foster,¹⁶ M. Franklin,¹² J.C. Freeman,²⁸ H. J. Frisch,¹³ I. Furic,¹³ M. Gallinaro,⁵⁰ J. Galyardt,¹² J.E. Garcia,⁴⁶ F. Garberon,¹⁰ A.F. Garfinkel,⁴⁸ C. Gay,⁶⁰ H. Gerberich,²³ D. Gerdes,³⁴ S. Giagu,⁵¹ P. Giannetti,⁴⁶ A. Gibson,²⁸ K. Gibson,⁴⁷ J.L. Gimmelli,⁴⁹ C. Ginsburg,¹⁶ N. Gioularis,¹⁴ M. Giordani,⁵⁴ P. Giromini,¹⁸ M. Giunta,⁴⁶ G. Giurgiu,¹² V. Glagolev,¹⁴ D. Glezinski,¹⁶ M. Gold,³⁷ N. Goldschmidt,¹⁷ J. Goldstein,⁴² G. Gomez,¹¹ G. Gomez-Ceballos,¹¹ M. Goncharov,⁵³ O. González,³¹ I. Gorelov,³⁷ A.T. Goshaw,¹⁵ K. Goulianos,³⁰ A. Gresse,⁴³ M. Griffiths,²⁹ S. Grinstein,²¹ C. Grosso-Pilcher,¹³ R.C. Group,¹⁷ U. Grundler,²³ J. Guimaraes da Costa,²¹ Z. Gunay-Unalan,²⁹ C. Haber,²⁹ K. Hahn,³⁷ S.R. Hahn,¹⁹ E. Halkiadakis,⁵² A. Hamilton,²¹ B.-Y. Han,⁴⁹ J.Y. Han,⁴⁹ R. Handerl,³⁹ F. Happacher,¹⁸ K. Hara,⁵⁵ M. Hase,⁵⁶ S. Harper,⁴² R.F. Harr,³⁸ R.M. Harris,¹⁶ M. Hartz,⁴⁷ K. Hatakeyama,³⁰ J. Hauser,⁸ A. Heijboer,⁵ B. Heinemann,²⁹ J. Heinrich,⁴⁵ C. Henderson,³² M. Herndon,⁵⁹ J. Heuser,²⁵ D. Hidas,¹⁵ C.S. Hill,¹⁹ D. Hirschbuhl,²⁵ A. Hocker,¹⁶ A. Holloway,²¹ S. Hou,¹ M. Houlden,²⁹ S.-C. Hsu,⁹ B.T. Huffman,⁴² R.E. Hughes,³⁹ U. Husemann,⁴⁹ J. Huston,²¹ S. Incandella,¹⁰ G. Introzzi,⁴⁶ M. Iori,⁵¹ Y. Ishizawa,⁵⁵ A. Ivanov,⁷ B. Iyutin,³² E. James,¹⁶ D. Jang,⁵² B. Jayatilaka,³⁴ D. Jeans,⁵¹ H. Jensen,¹⁶ E.J. Jeon,²⁷ S. Jindariani,¹⁷ M. Jones,⁴⁸ K.K. Joo,²⁷ S.Y. Jun,¹² J.E. Jung,²⁷ T.R. Junk,²³ T. Kamon,⁵³ P.E. Karchin,⁵⁸ Y. Kato,⁴¹ Y. Kemp,²⁵ R. Kephart,¹⁶ U. Kerzel,²⁵ V. Khotilovich,⁵³ B. Kilminster,³⁹ D.H. Kim,²⁷ H.S. Kim,²⁷ J.E. Kim,²⁷ M.J. Kim,¹² S.B. Kim,²⁷ S.H. Kim,⁵⁵ Y.K. Kim,¹⁵ N. Kimura,⁵⁵ L. Kirsch,⁵ S. Klimentenko,¹⁷ M. Klute,³² B. Knuteson,³² B.R. Ko,¹⁹ K. Kondo,⁵⁷ D.J. Kong,²⁷ J. Konigsberg,¹⁷ A. Korytov,¹⁷ A.V. Kotwal,¹⁵ A. Kovalev,⁴⁵ A.C. Kraan,⁴⁵ J. Kraus,²³ I. Kravchenko,³² M. Kreps,²⁵ J. Kroll,⁴⁵ N. Krumnack,⁴ M. Kruse,¹⁵ V. Krutelyov,¹⁰ T. Kubo,³⁵ S. E. Kuhlmann,² T. Kühr,²⁵ Y. Kuskabe,²¹ S. Kwang,⁵³ A.T. Laasanen,⁴⁸ S. Lai,⁵³ S. Lami,⁴⁹ S. Lammi,⁴⁹ M. Lancaster,²⁰ R.L. Lander,⁷ K. Lannon,³⁹ A. Latt,⁵² G. Latino,⁴⁹ I. Lazizzera,⁴³ T. LeCompte,² J. Lee,⁴⁹ J. Lee,²⁷ V.J. Lee,²⁷ S.W. Lee,⁵⁹ R. Lefebre,³ N. Leonardo,³² S. Leone,⁴⁸ S. Levy,¹³ J.D. Lewis,¹⁶ C. Lin,⁶⁰ C.S. Lin,¹⁶ M. Lindgren,¹⁶ E. Lipin,⁹ T.M. Liss,²³ A. Lister,⁷ D.O. Litvintsev,¹⁶ T. Liu,¹⁴ N.S. Lockyer,⁴⁵ A. Logunov,³⁶ M. Loret,⁴³ P. Loverre,⁵¹ R.-S. Lu,¹ D. Lucchesi,⁴³ P. Lujan,²⁸ P. Lukens,¹⁶ G. Lungu,¹⁷ L. Lyons,⁴² J. Lys,²⁸ R. Lysak,¹ E. Lytkin,⁴⁸ P. Mack,²⁵ D. MacQueen,³³ R. Madrak,¹⁶ K. Maeshima,¹⁶ K. Makhoul,³² T. Maki,²² P. Maksimovic,²⁴ S. Malde,⁴² G. Manca,²⁹ F. Margaroli,⁵ R. Marginean,¹⁶ C. Marino,²⁵ C.P. Marino,²³ A. Martin,⁶⁰ M. Martin,²⁴ V. Martin,²⁰ M. Martinez,³ T. Maruyama,⁵⁵ P. Mastrandrea,⁵¹ T. Masubuchi,⁵⁵ H. Matsunaga,⁵⁵ M.E. Mattson,²⁸ R. Mazini,³³ P. Mazzanti,⁵ K.S. McFarland,⁴⁹ P. McIntyre,⁵³ R. McNulty,²⁹ A. Mehta,²⁹ P. Mehtala,²² S. Menzemer,¹¹ A. Menzione,⁴⁶ P. Merkel,⁴⁸ C. Mesropian,⁵⁰ A. Messina,⁵¹ T. Miaou,¹⁶ N. Miladinovic,⁶ J. Miles,³² R. Miller,³⁵ C. Mills,¹⁰ M. Milnik,²⁵ A. Mitra,¹ G. Mitselmakher,¹⁷ A. Miyamoto,²⁶ S. Moed,¹⁹ N. Moggi,⁵ B. Mohr,⁵

Finally...

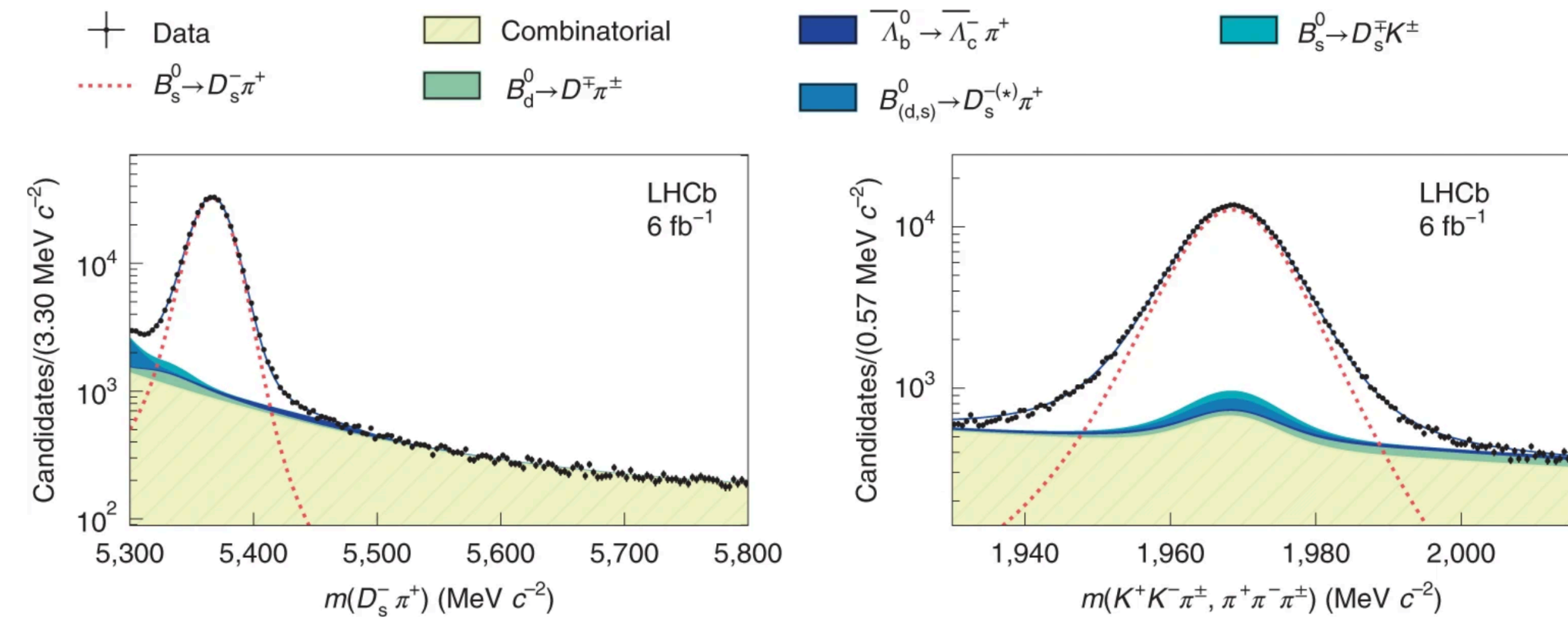
A counting experiment

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

— $B_s^0 \rightarrow D_s^- \pi^+$ — $\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+$ — Untagged



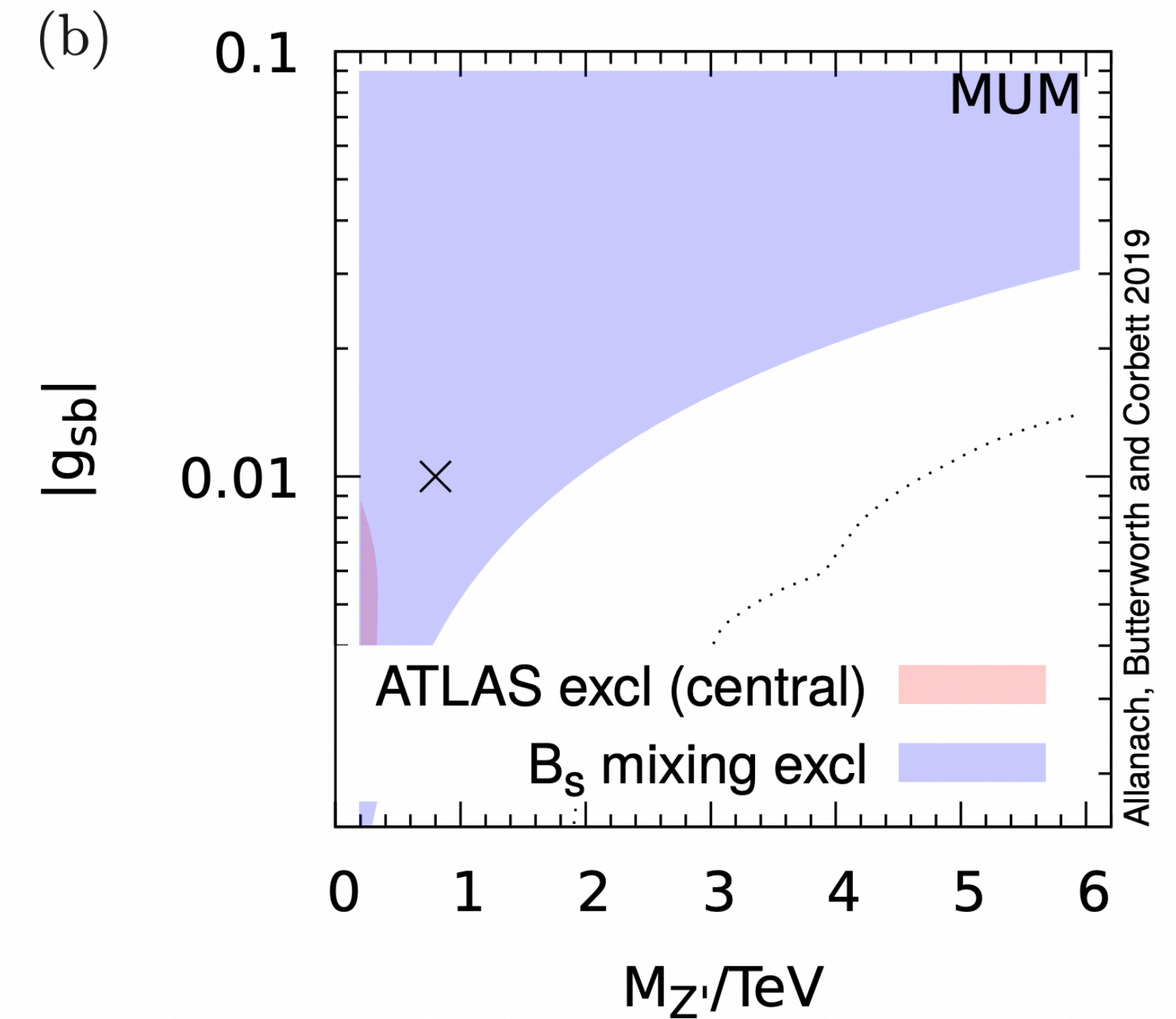
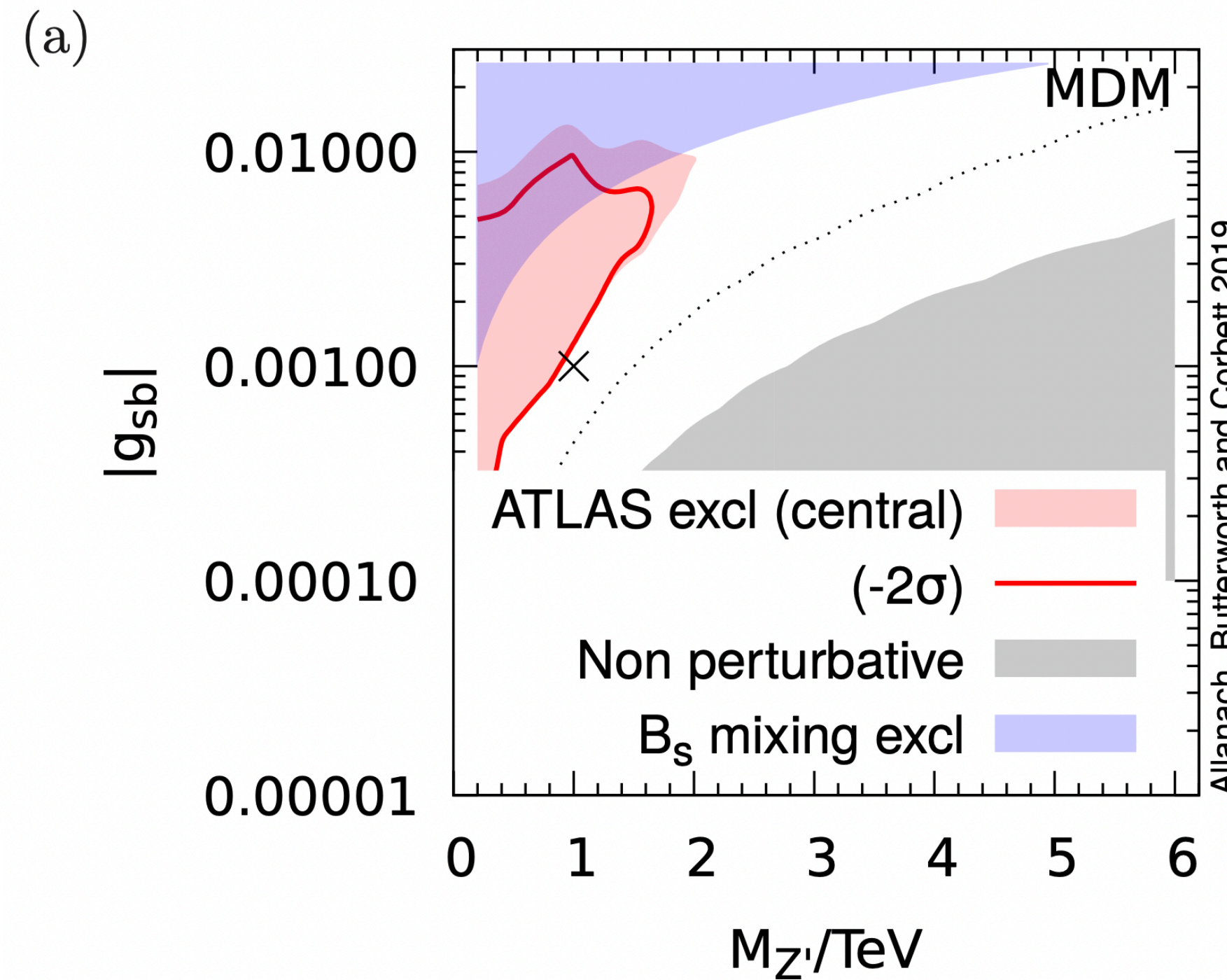
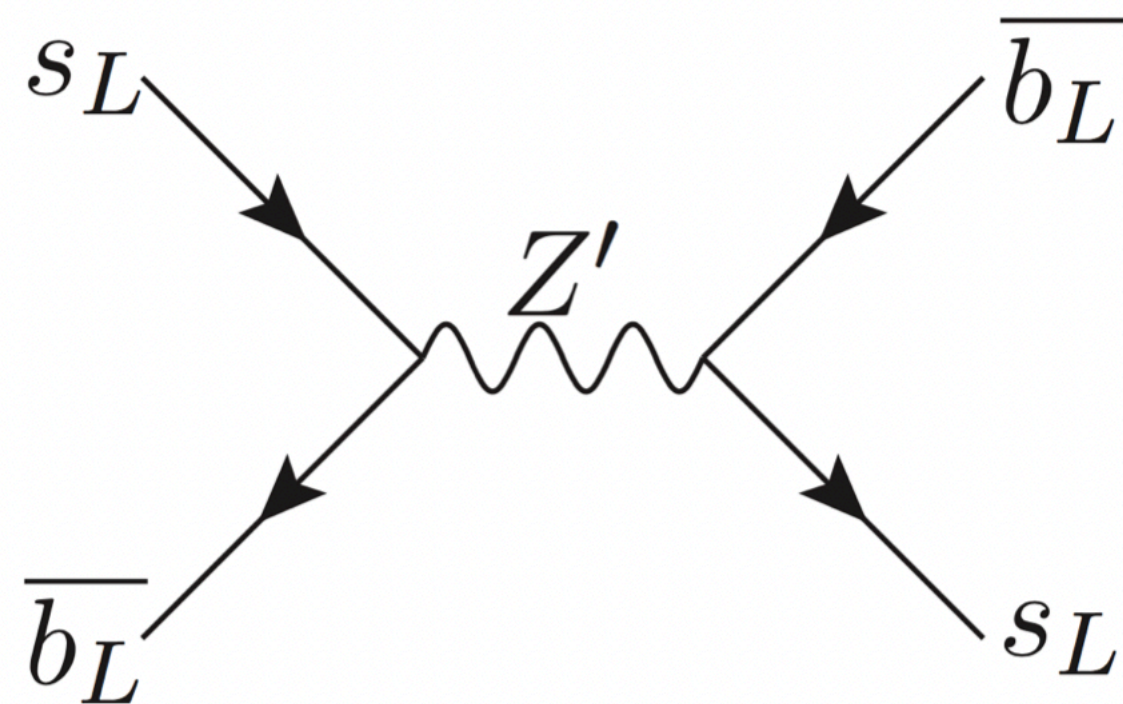
Decay mode	Data sample	$\Delta m_s \text{ ps}^{-1}$
$B_s^0 \rightarrow D_s^- \pi^+$	2011	$17.768 \pm 0.023 \pm 0.006$
$B_s^0 \rightarrow D_s^- \pi^- \pi^+ \pi^+$	2011-2018	$17.757 \pm 0.007 \pm 0.008$
$B_s^0 \rightarrow D_s^- \pi^+$	2015-2018	$17.7683 \pm 0.0051 \pm 0.0032$
Average		17.7666 ± 0.0057



Importance of PID, proper time resolution, flavour tagging

Loop back to the models

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



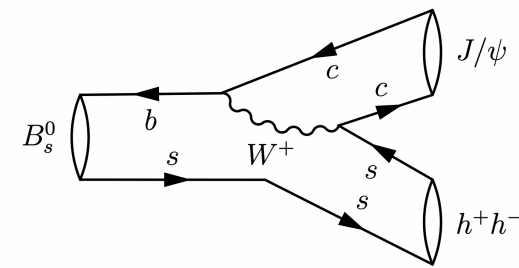
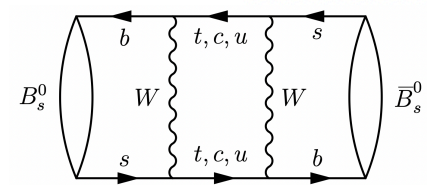
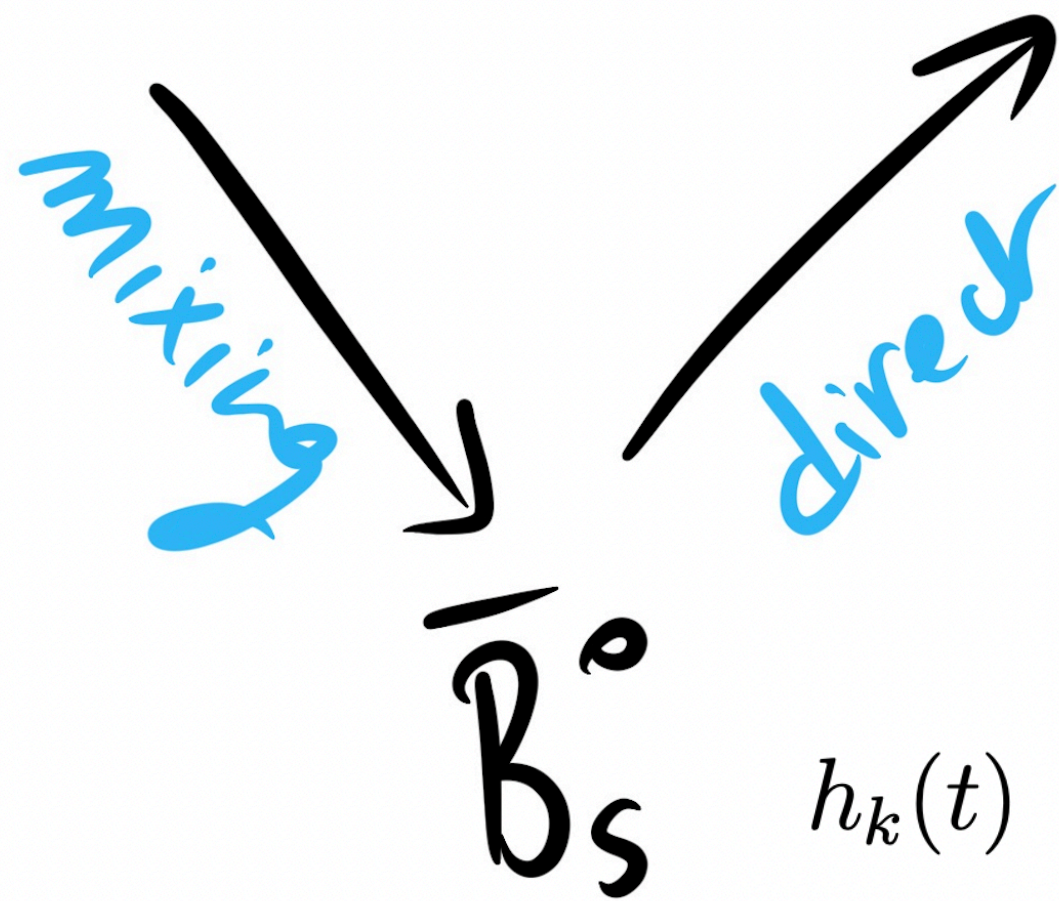
arXiv:1904.10954 one example out of the billion out there.

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

Mixture of CP odd and CP even eigenstates



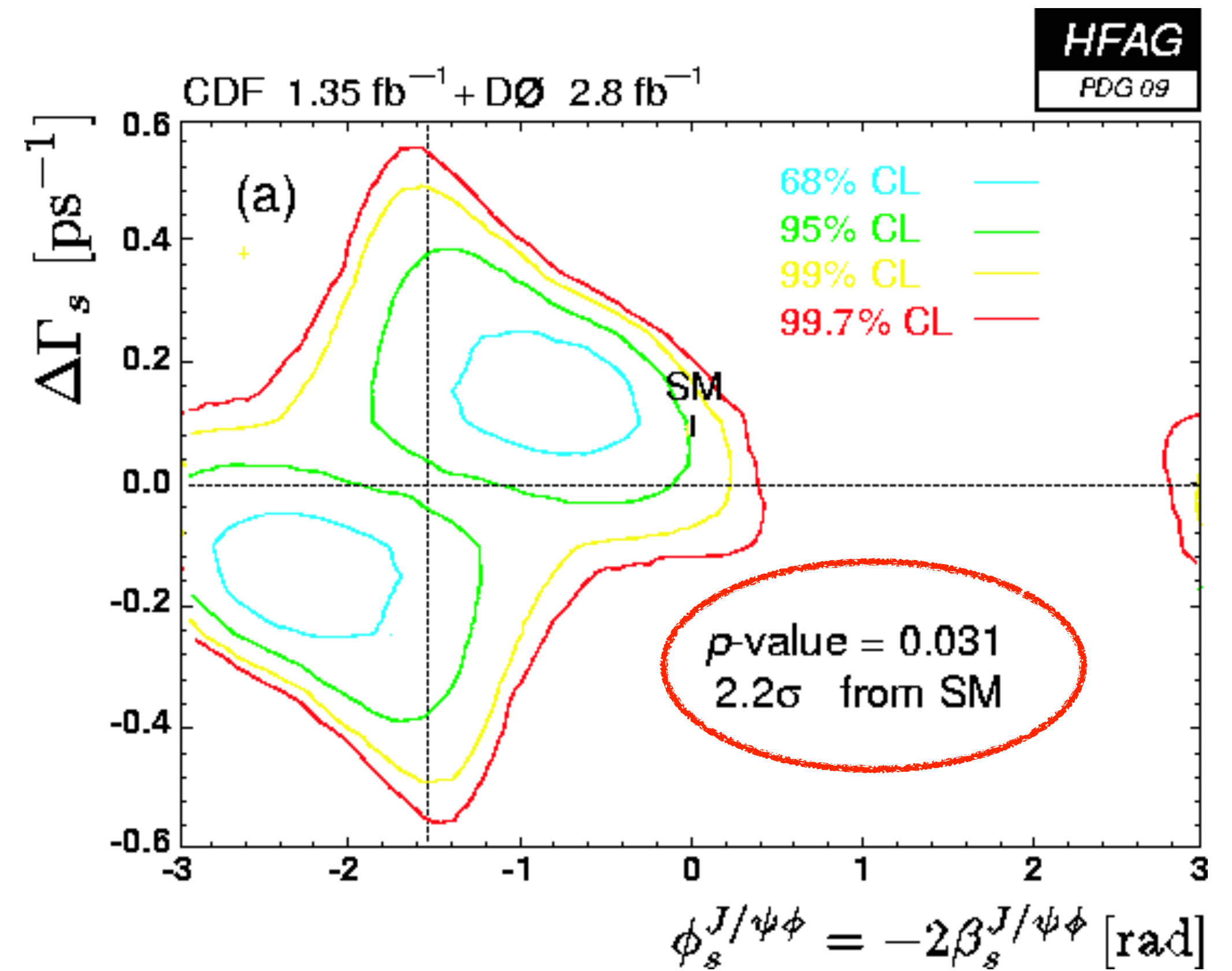
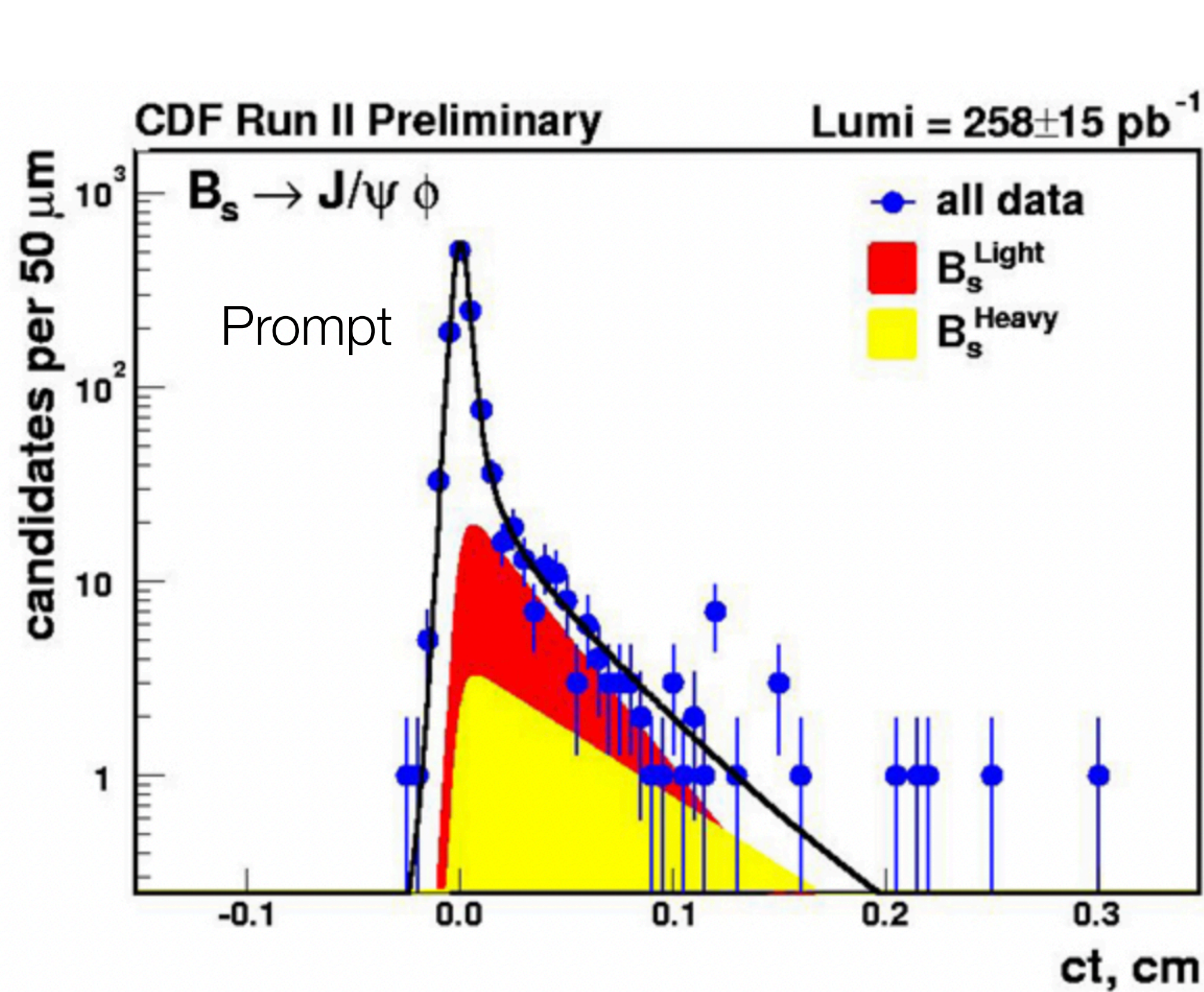
None negligible difference between the heavy and the light state of your the B_s mesons $\Delta\Gamma_s$



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

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

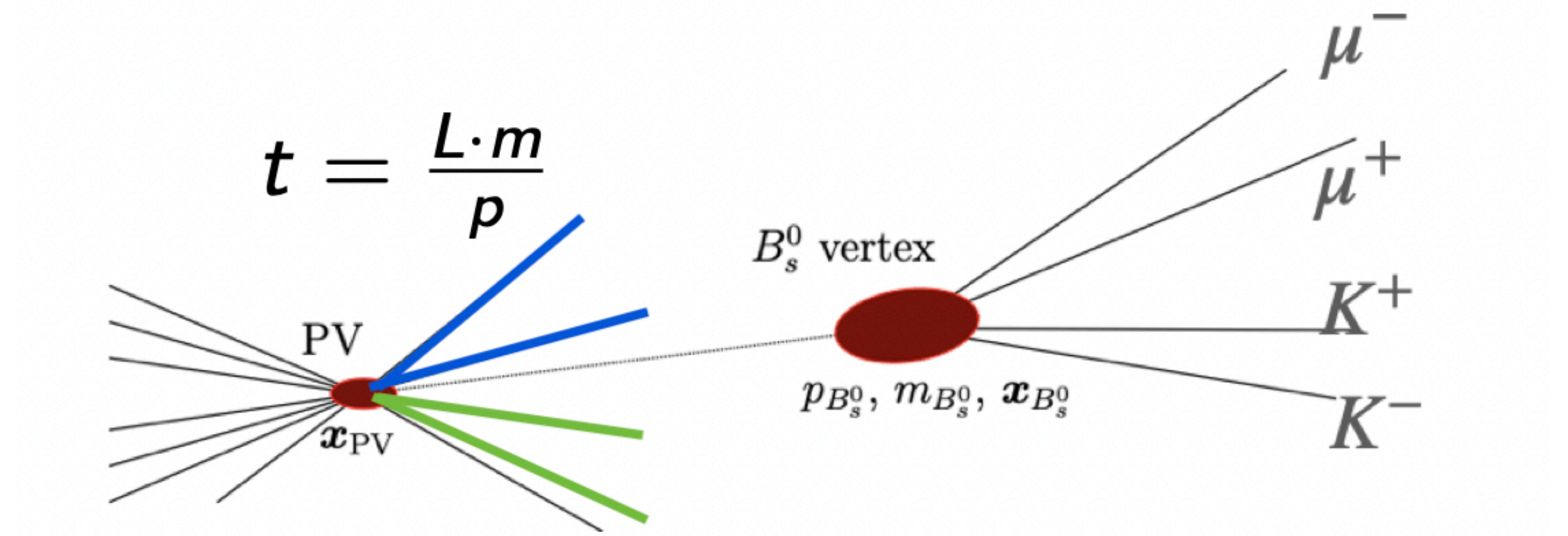
Fermilab paved the path of B_s physics



Time dependent angular analysis

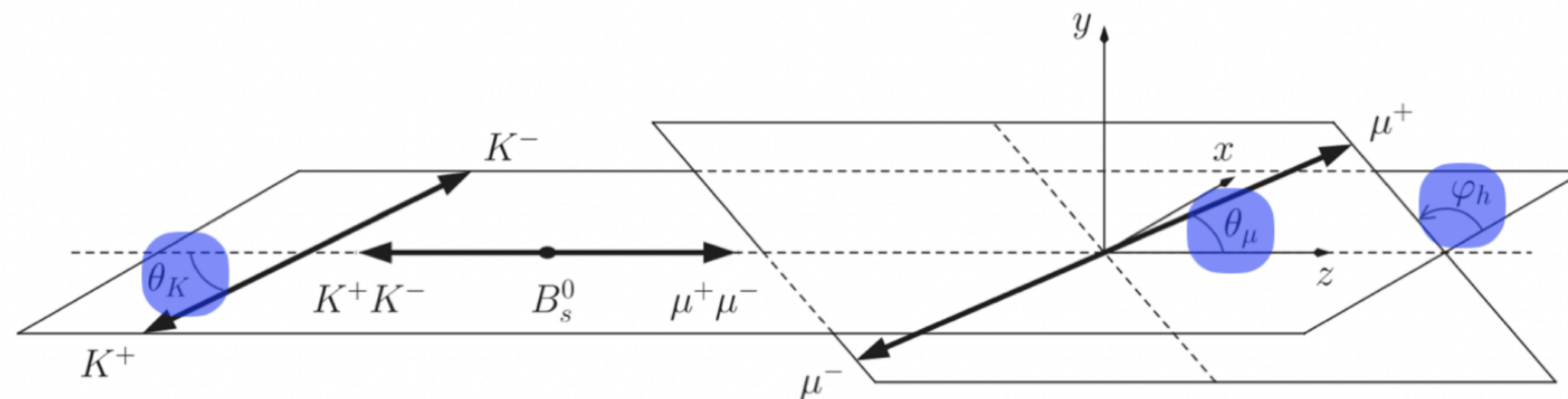
We will come back to the to angular analyses in the second lecture

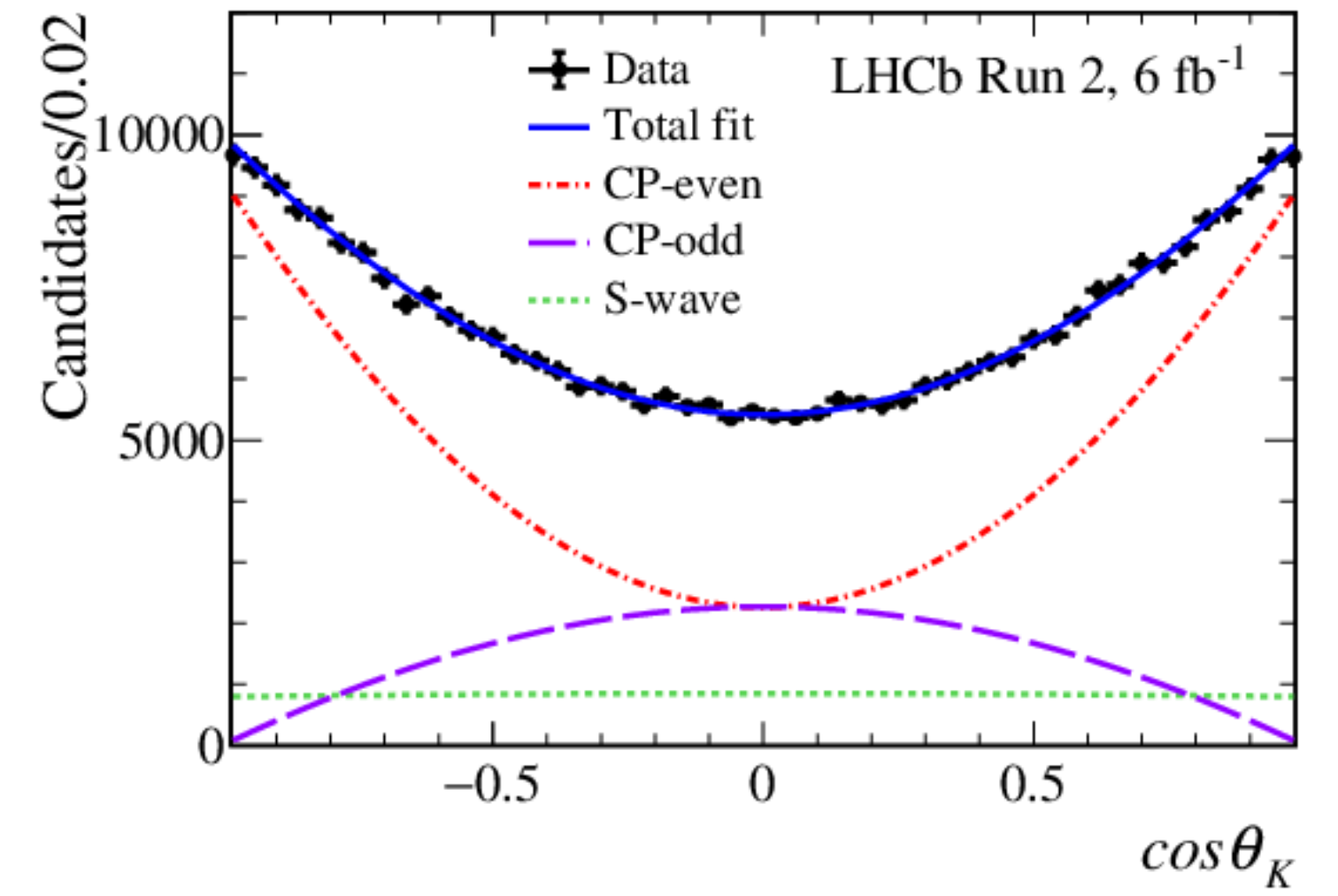
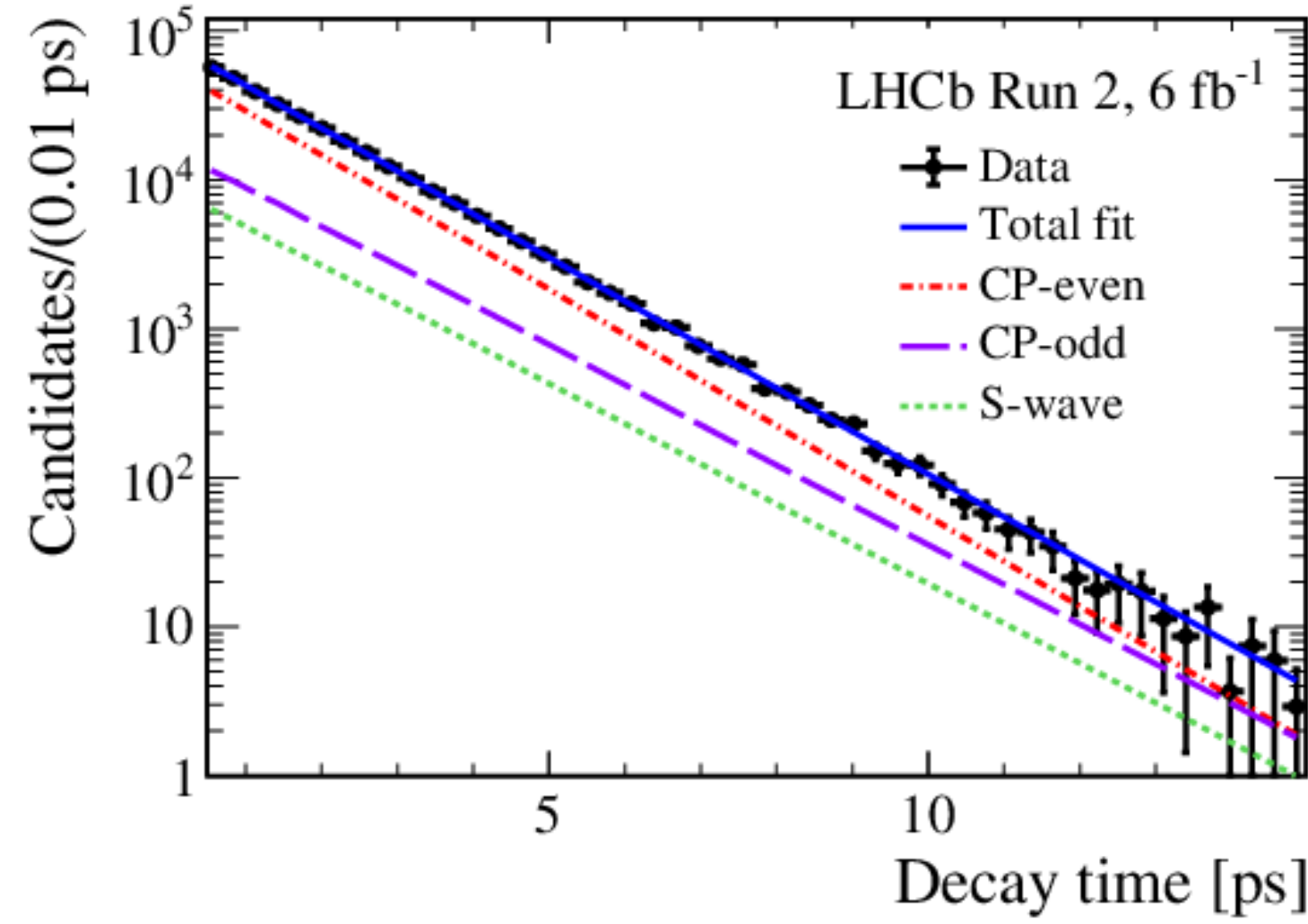
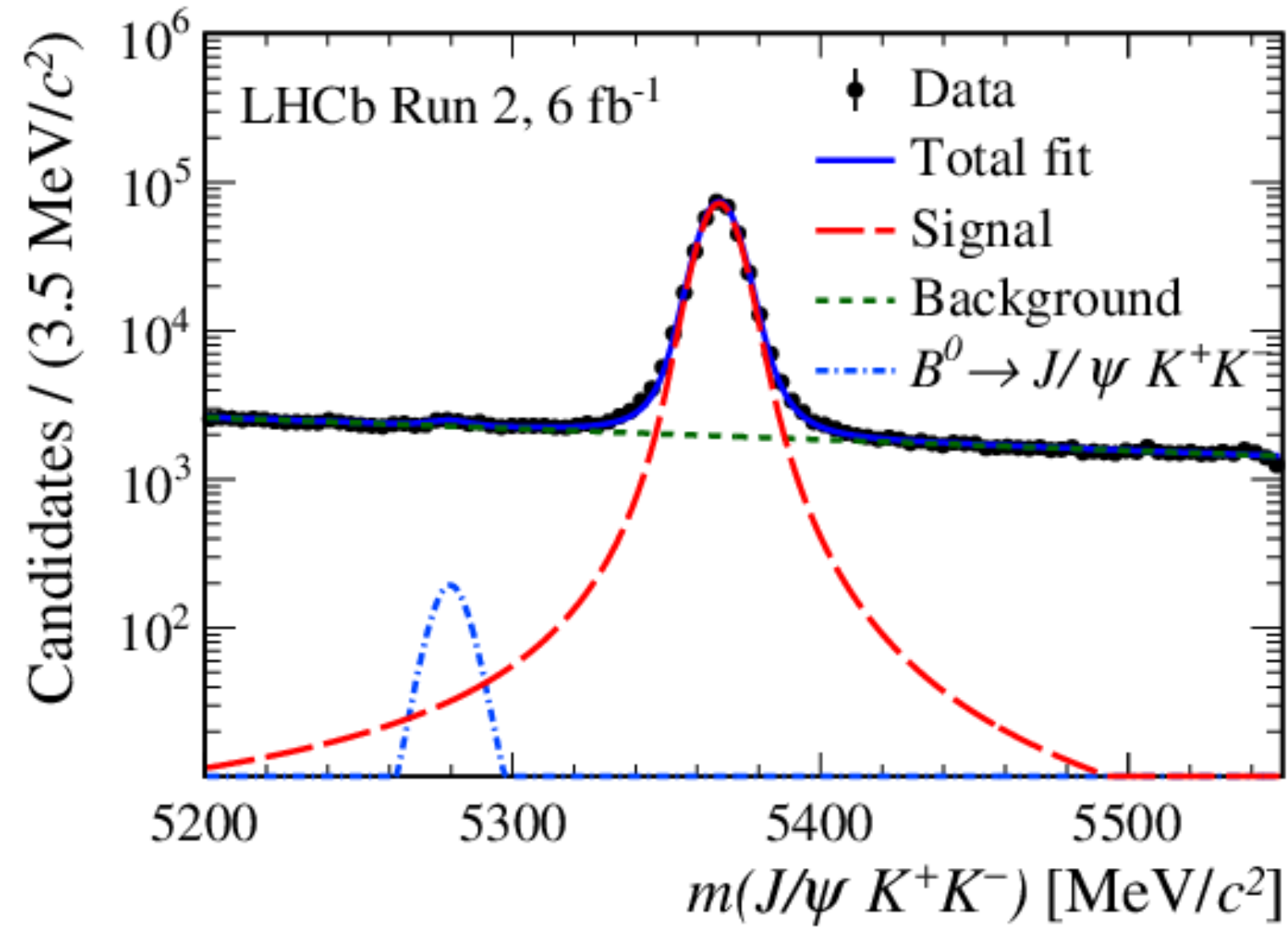
It's just a counting experiment



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

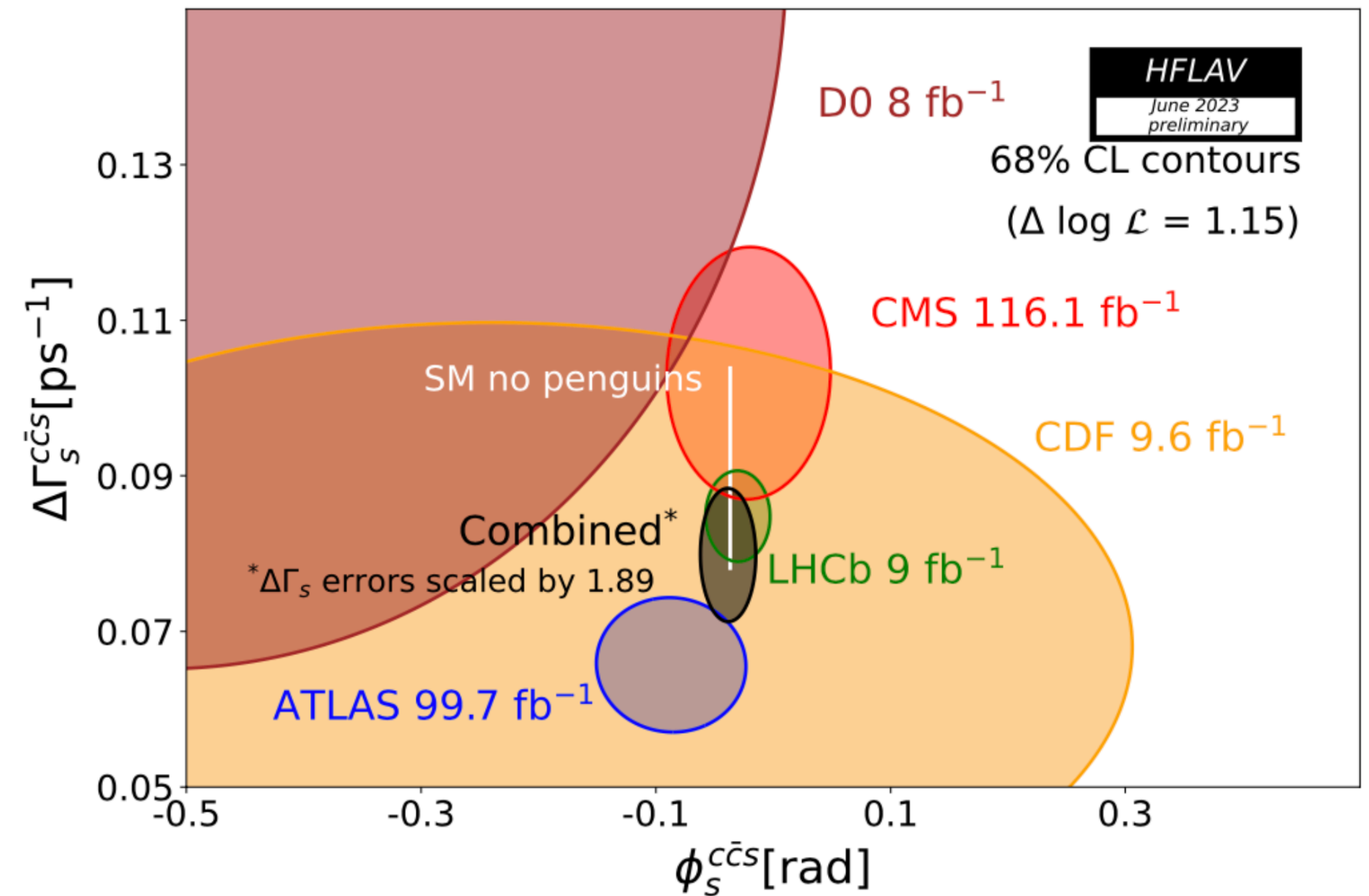
- CP eigenvalue of the final state $\eta_f = (-1)^L$
- A mixture of CP -even & CP -odd components \rightarrow angular analysis





Very similar experimental techniques between the LHC three collaborations

arXiv:2308.01468



An example of NP interpretations

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

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:

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

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

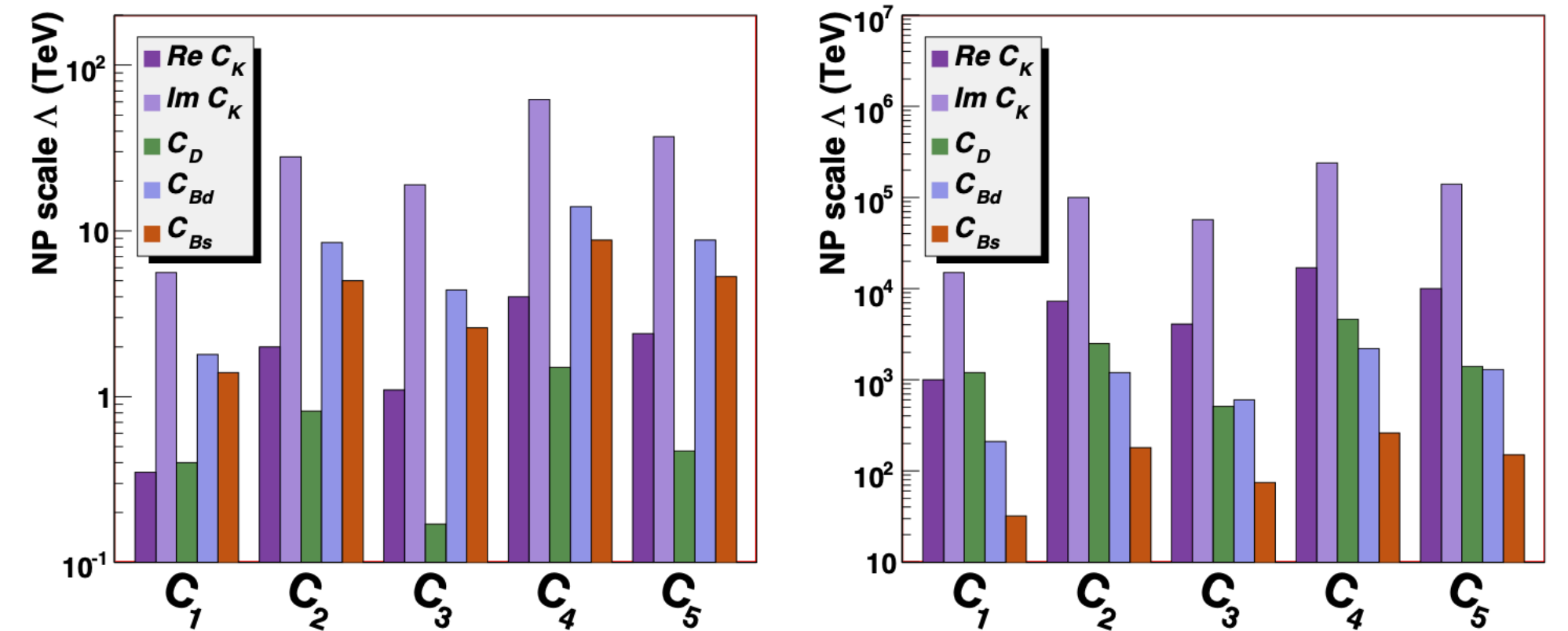


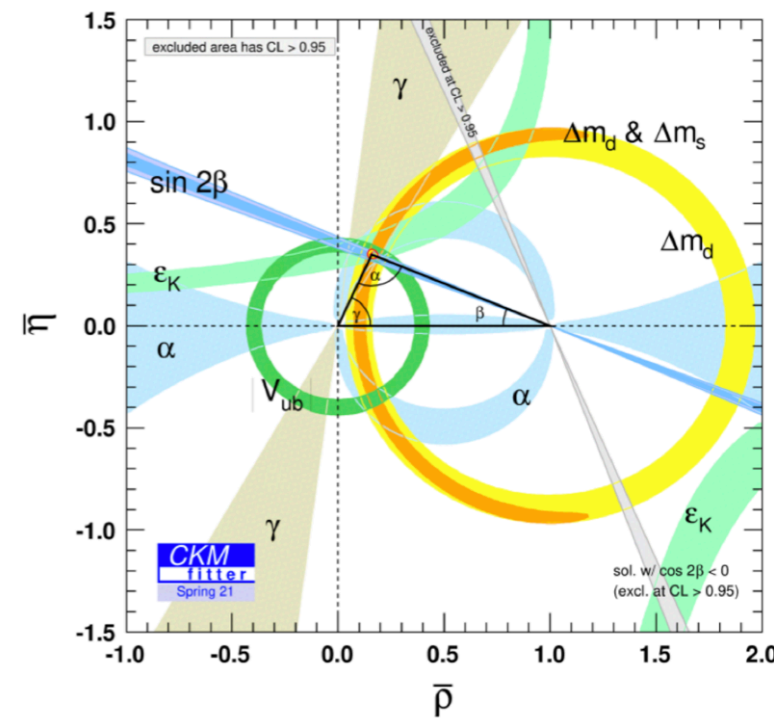
FIG. 7: Summary of the 95% probability lower bound on the NP scale Λ for strongly-interacting NP in NMFV (left) and general NP (right) scenarios.

$\sin 2\beta$ & ϕ_s

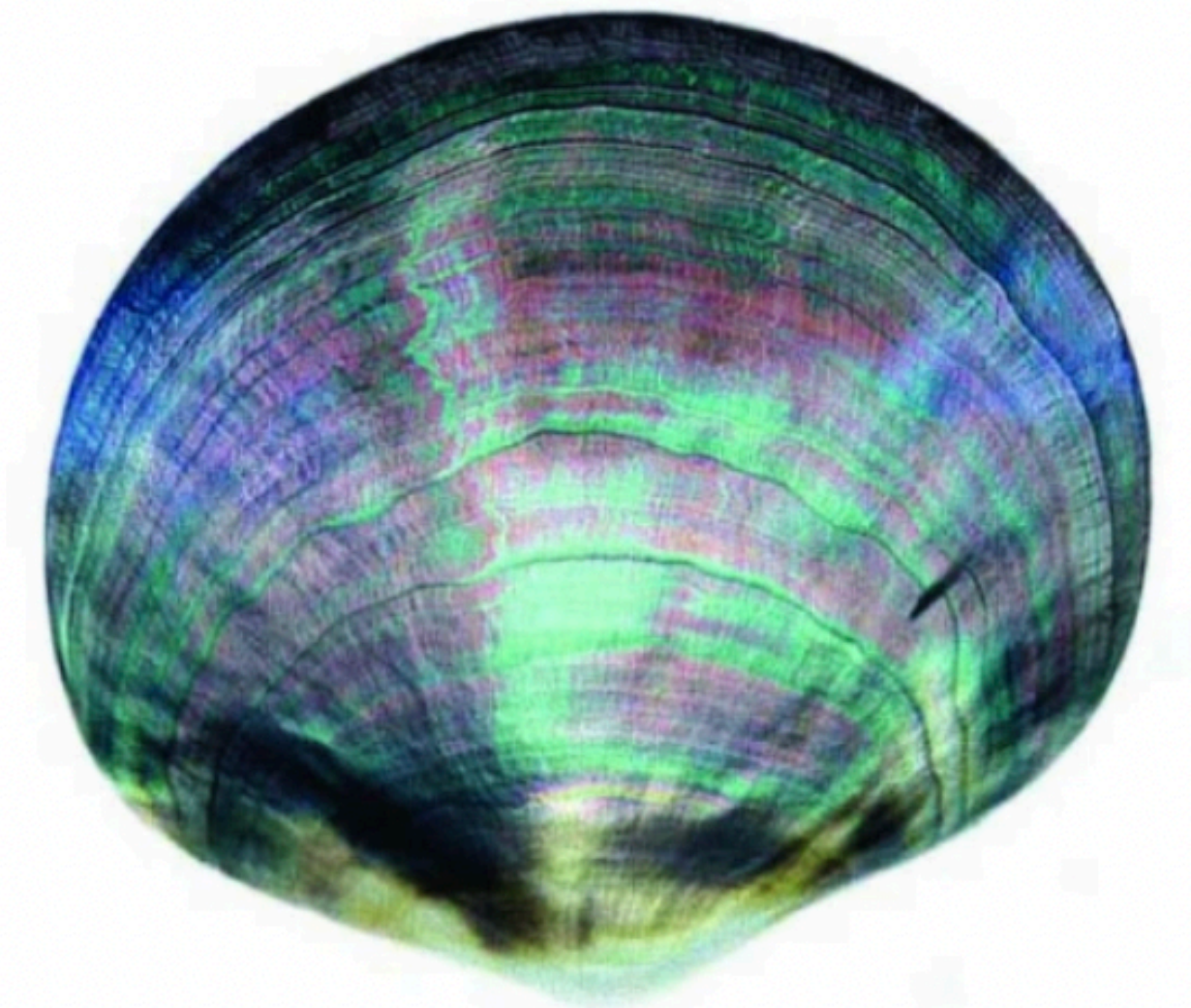
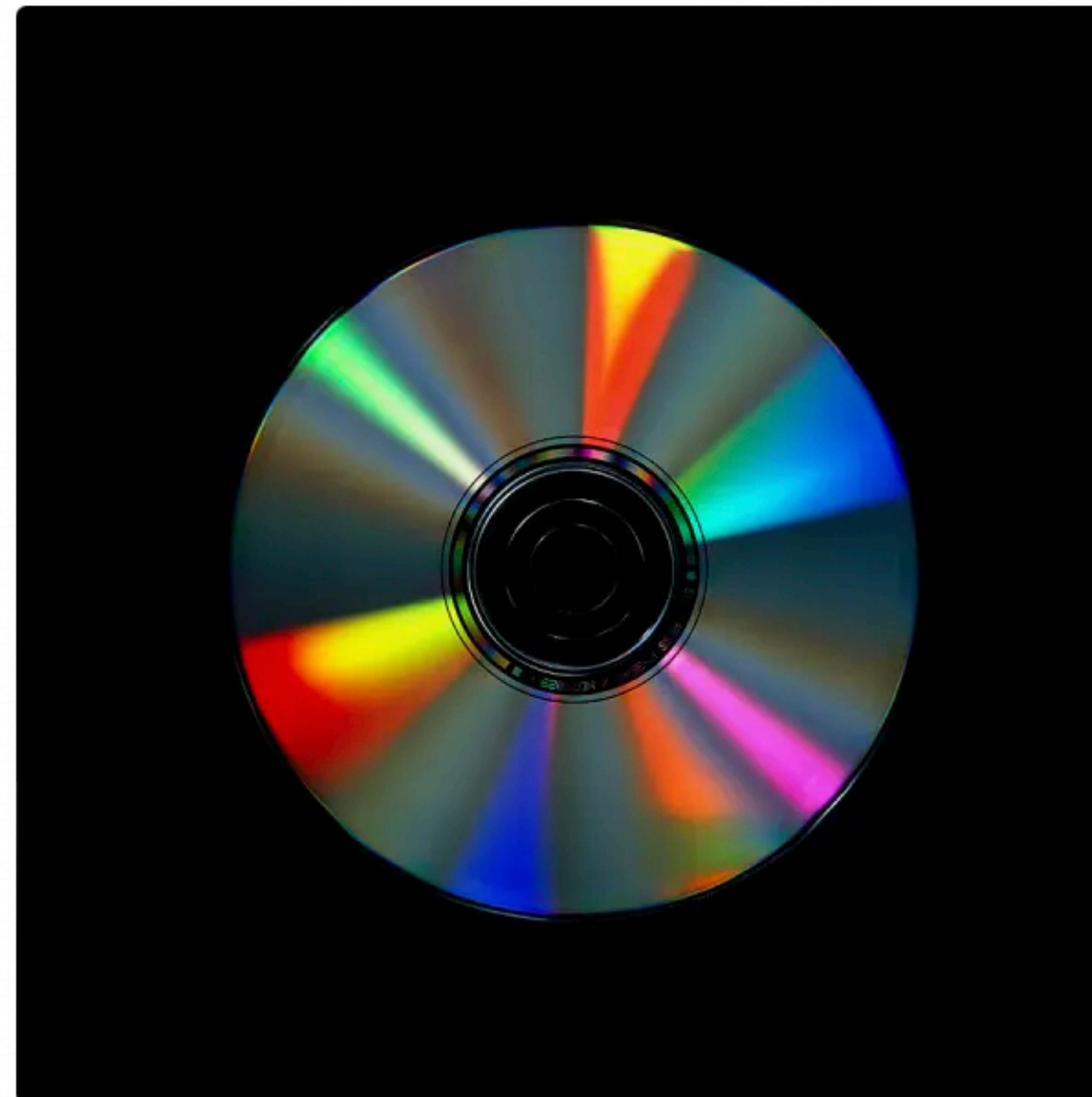
Typically dominated by a
few “Golden modes”

γ measurements have somewhat of a
“commune spirit ”

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

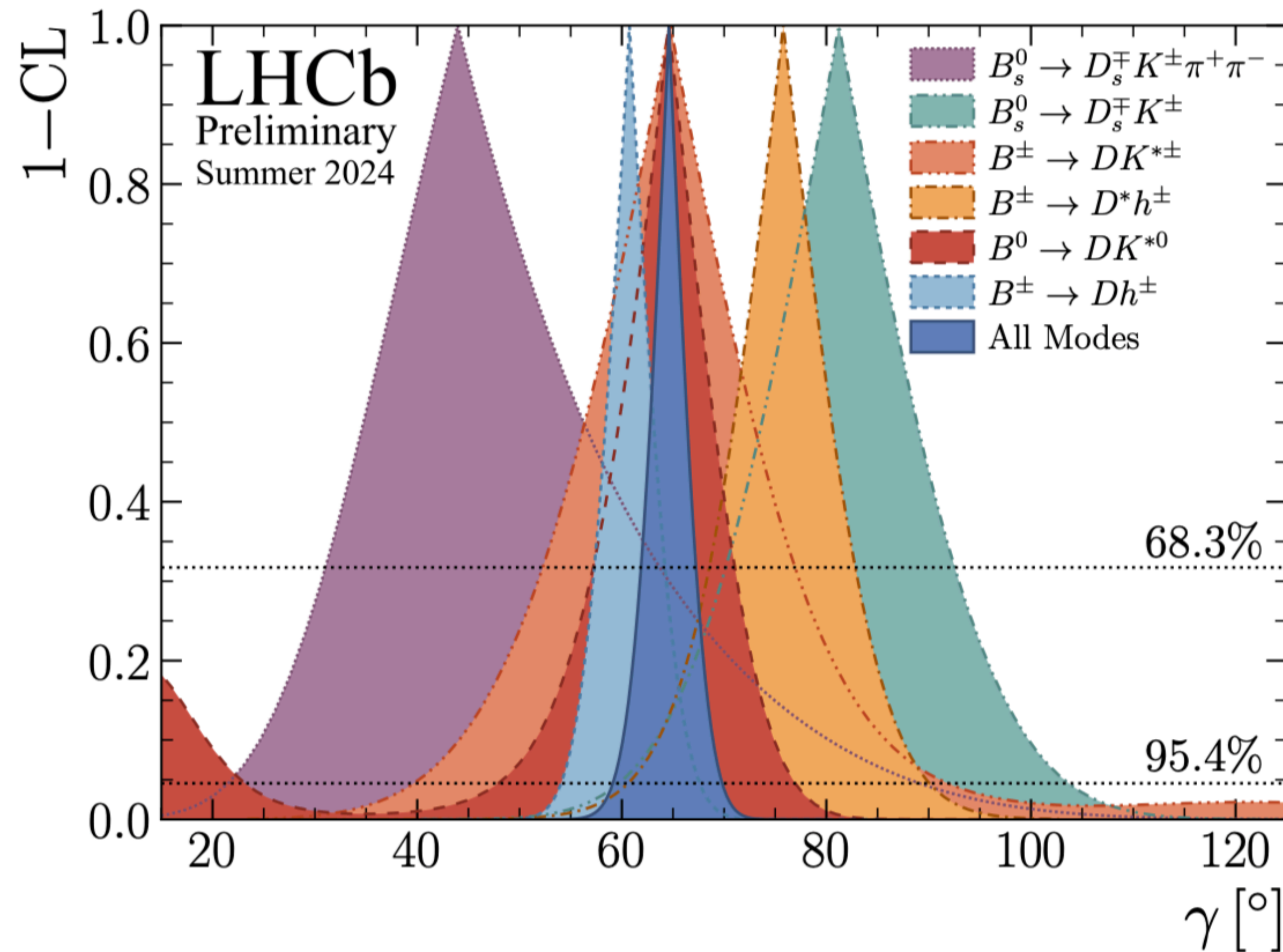


It's all about interferences !



< Beautiful Mont-Blanc analogy >

There is a myriad of techniques to measure this angle

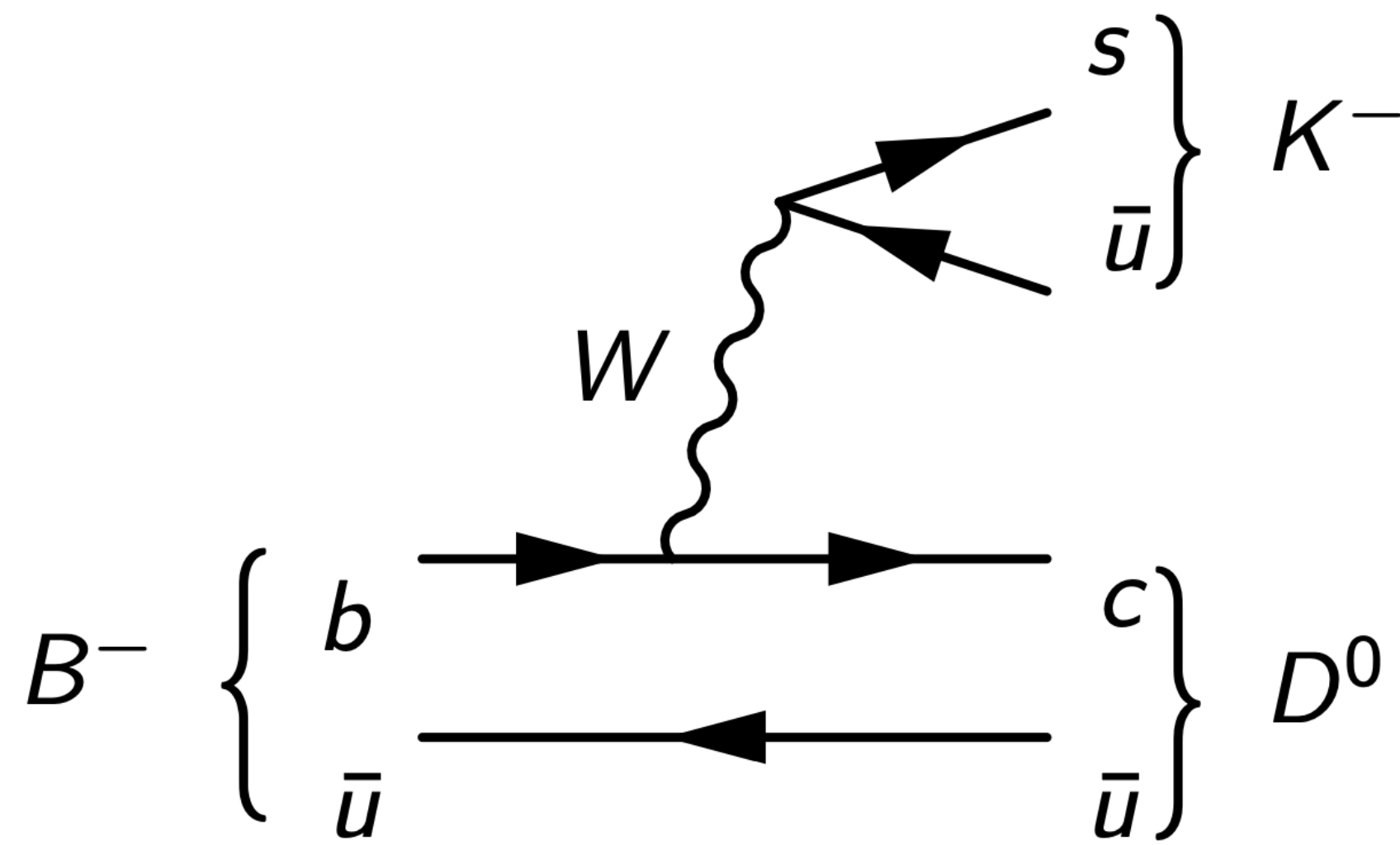


B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^\pm h'^\mp$	[35]	Run 1&2	As before
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow h^+ h^- \pi^+ \pi^-$	[19]	Run 1&2	New
$B^\pm \rightarrow Dh^\pm$	$D \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$	[36]	Run 1&2	As before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

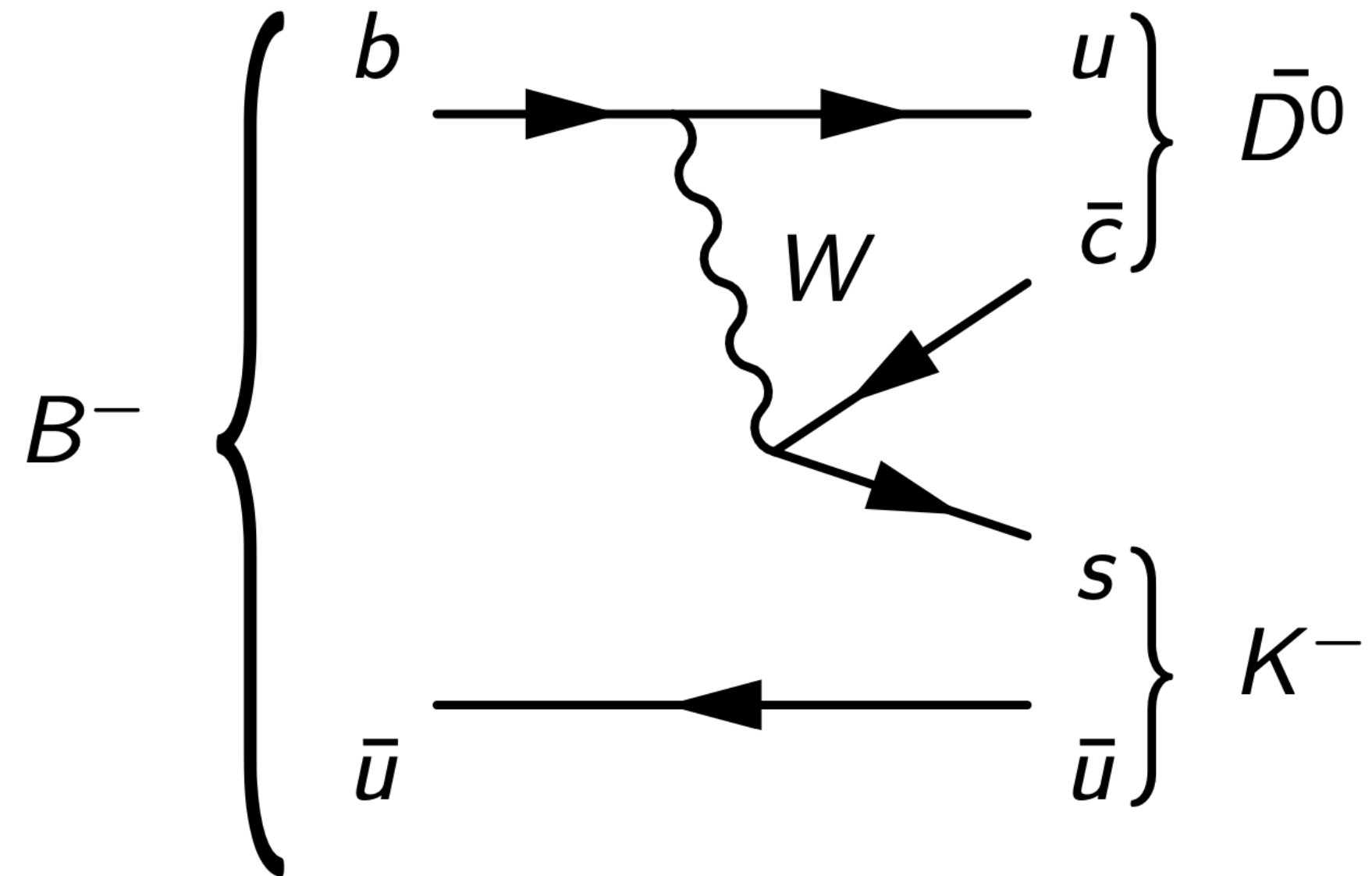
ADS, GLW, BPGGSZ, etc.

Which interference are we talking about ?

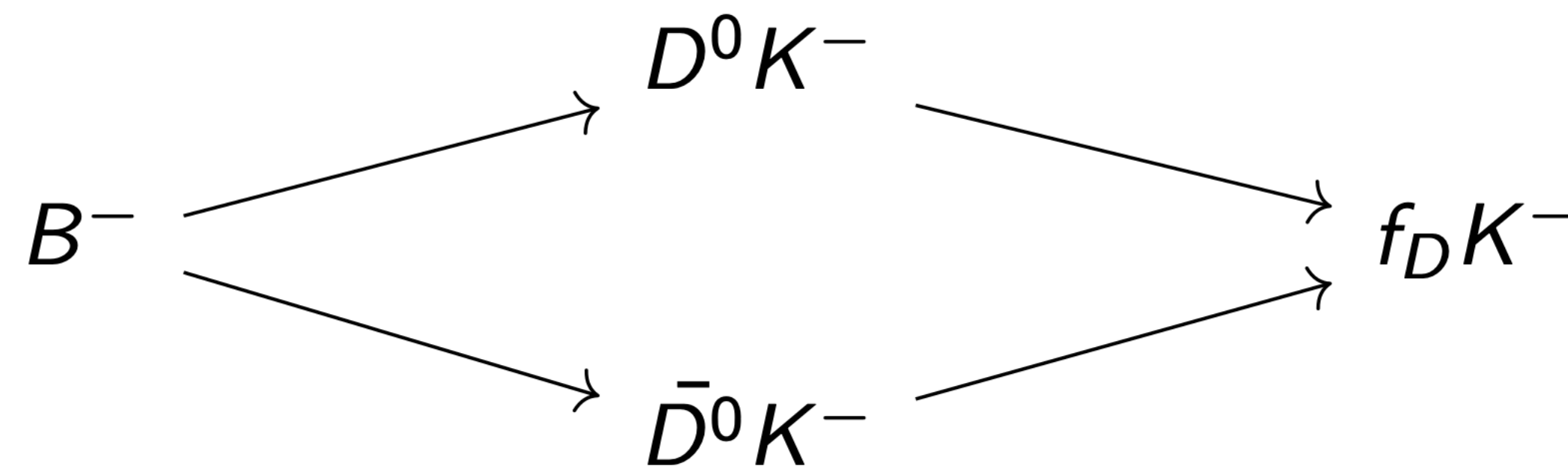
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| e^{-i\beta} & -|V_{ts}| e^{i\beta_s} & |V_{tb}| \end{pmatrix} = \begin{pmatrix} \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \end{pmatrix}$$



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



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



We can write down the amplitudes

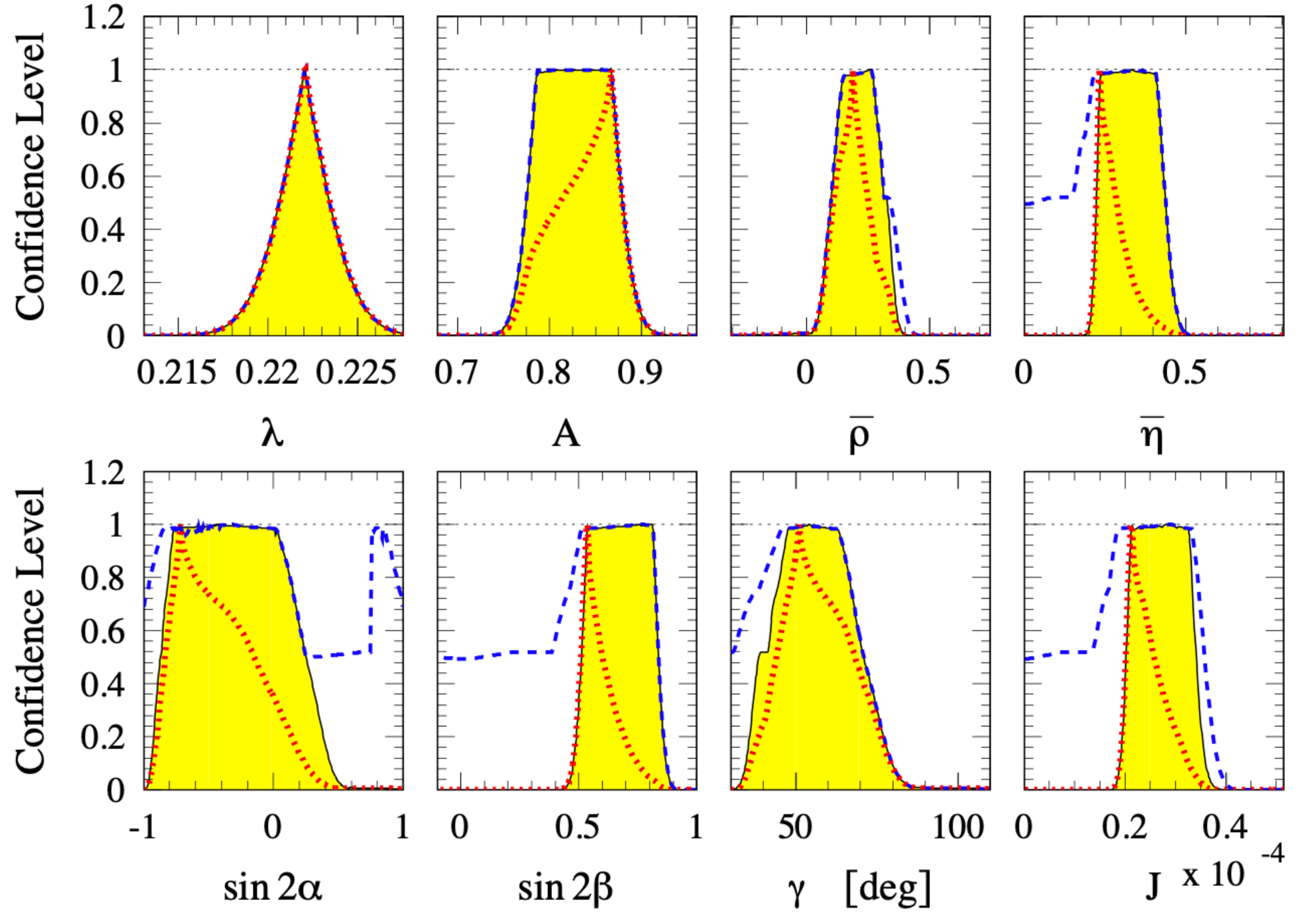
$$\mathcal{A}(B^-) = \mathcal{A}_B (\mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)} \mathcal{A}_{\bar{D}^0})$$

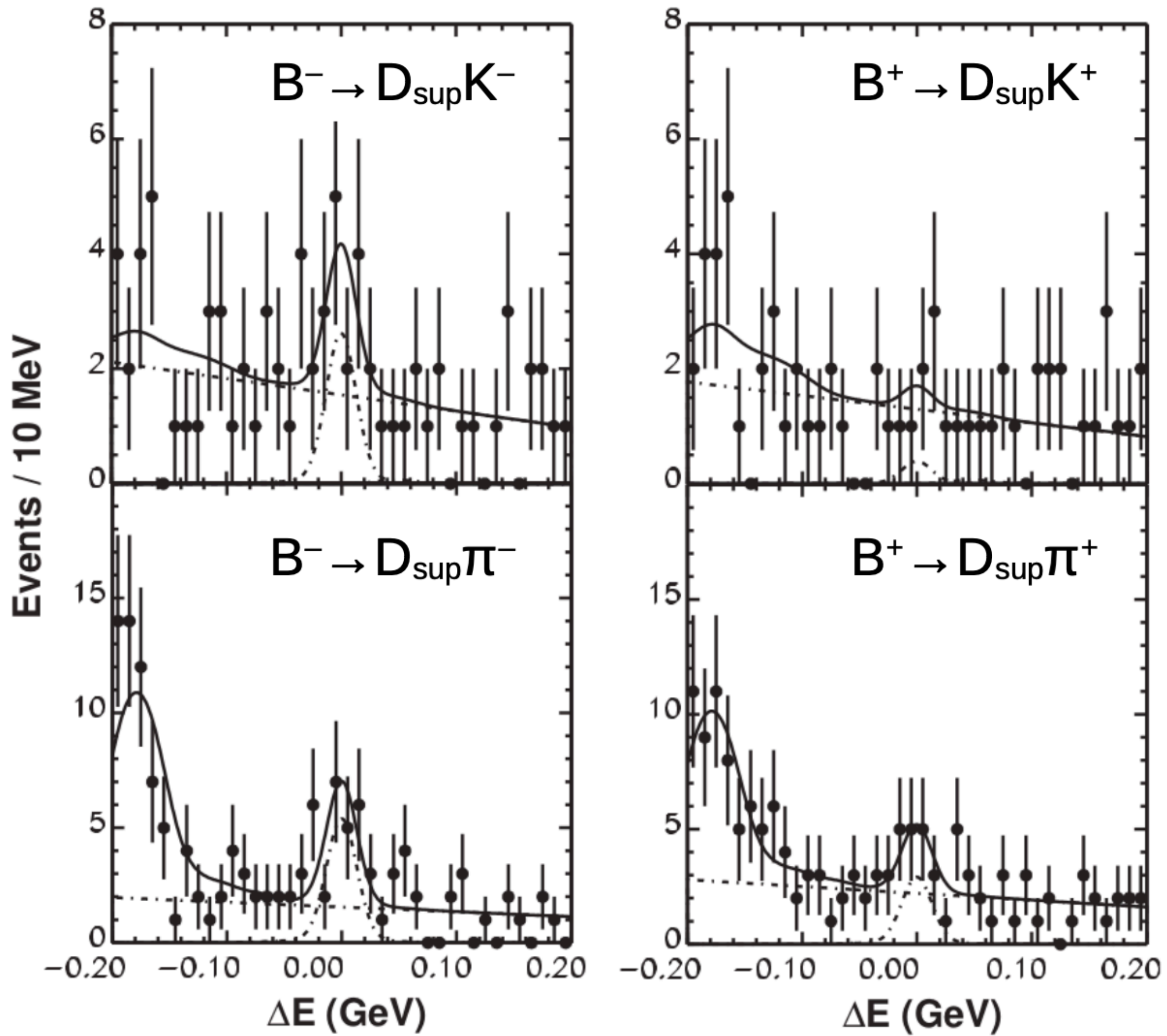
$$\mathcal{A}(B^+) = \mathcal{A}_B (\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)} \mathcal{A}_{D^0})$$

- 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	$89^\circ - 121^\circ$	16°	$80^\circ - 126^\circ$	23°	27	12
β	$15.0^\circ - 21.0^\circ$	3.0°	$14.0^\circ - 27.0^\circ$	6.5°	59	25
$\gamma = \delta$	$42^\circ - 74^\circ$	16°	$34^\circ - 82^\circ$	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
$ V_{ud} $	0.97504 ± 0.00049		0.97504 ± 0.00094		0	0
$ V_{us} $	0.2221 ± 0.0021		0.2221 ± 0.0042		0	0
$ V_{ub} $ (10^{-3})	2.70 - 3.71	0.51	2.45 - 4.38	0.96	37	7
$ V_{cd} $	0.2220 ± 0.0021		0.2220 ± 0.0042		0	0
$ V_{cs} $	0.97414 ± 0.00049		0.97414 ± 0.00098		13	4
$ V_{cb} $ (10^{-3})	38.7 - 43.2	2.3	38.1 - 43.6	2.8	4	0
$ V_{td} $ (10^{-3})	7.2 - 9.2	1.0	6.6 - 9.6	1.5	23	6
$ V_{ts} $ (10^{-3})	38.0 - 42.7	2.4	37.4 - 43.1	2.9	8	3
$ V_{tb} $	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
$\text{BR}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ (10^{-11})	1.2 - 2.6	0.7	1.1 - 3.8	1.4	50	13
$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ (10^{-11})	6.6 - 9.5	1.5	5.4 - 10.4	2.5	35	14
$\text{BR}(B^+ \rightarrow \tau^+ \nu_\tau)$ (10^{-5})	4.6 - 12.4	3.9	3.6 - 21.0	8.7	49	13
$\text{BR}(B^+ \rightarrow \mu^+ \nu_\mu)$ (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 $\sin 2\beta_{\text{WA}}$. 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.





ADS technique

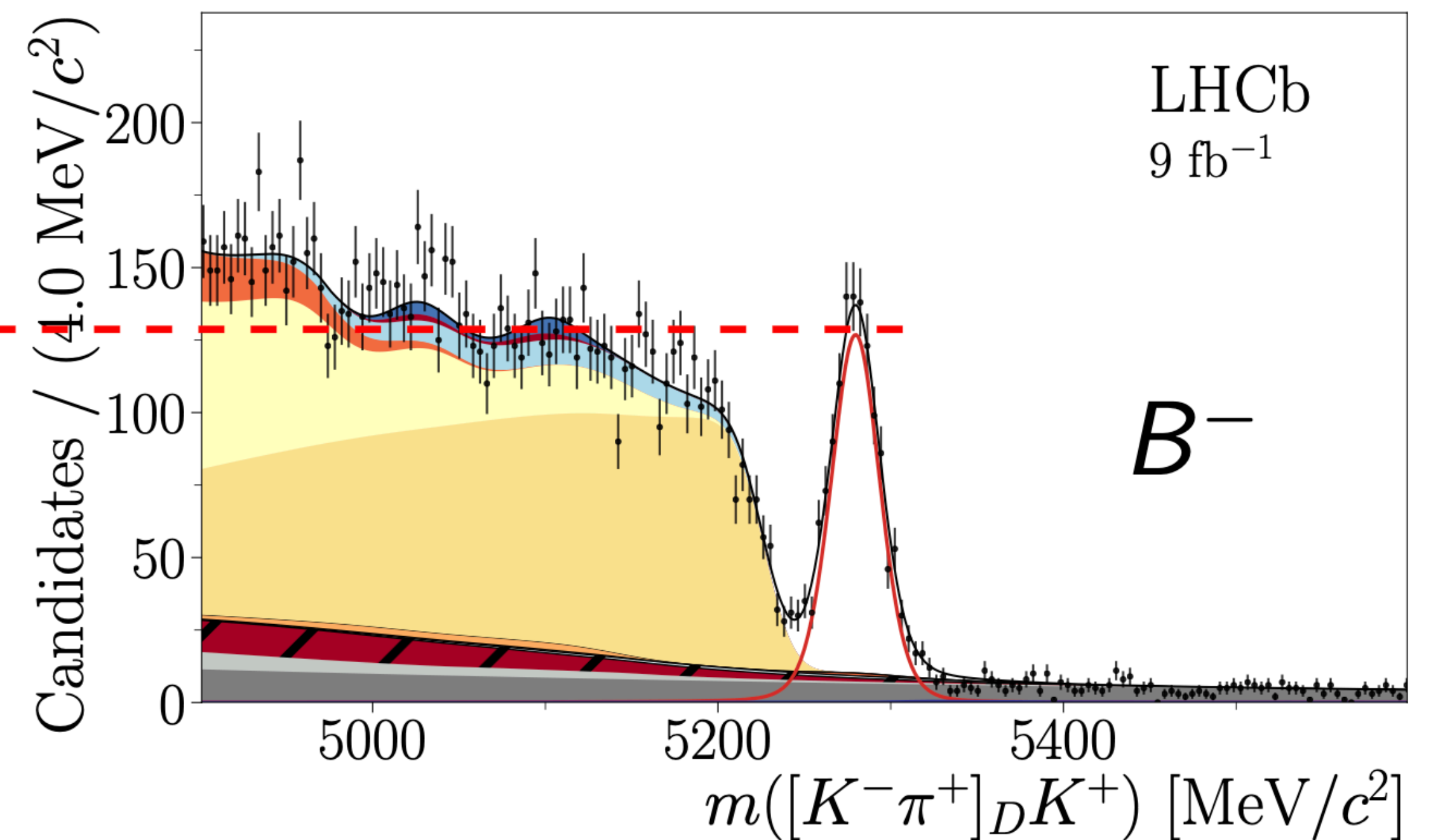
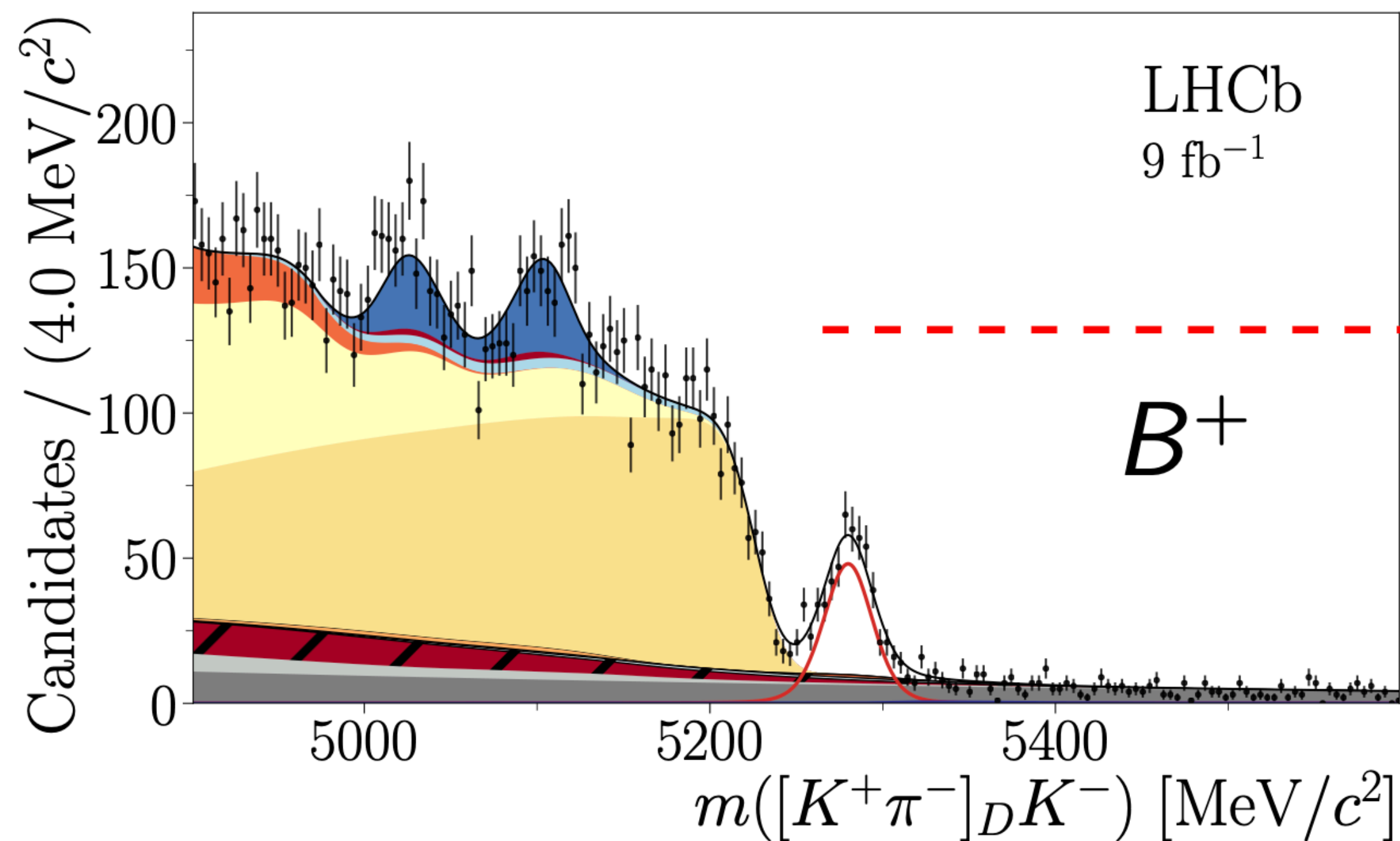
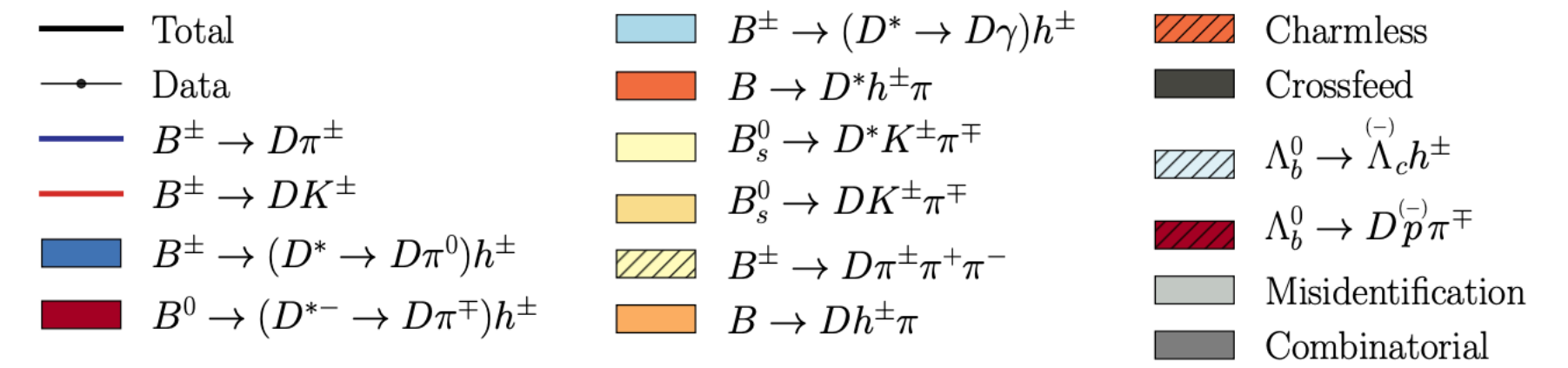
$$\mathcal{A}_{DK} = 0.88^{+0.77}_{-0.62}(\text{stat}) \pm 0.06(\text{syst}),$$

$$\mathcal{A}_{D\pi} = 0.30^{+0.29}_{-0.25}(\text{stat}) \pm 0.06(\text{syst}),$$

Here, both $B \rightarrow Dh$ peak at 0 when correctly identified

Belle, PRL 94 (2005) 091601

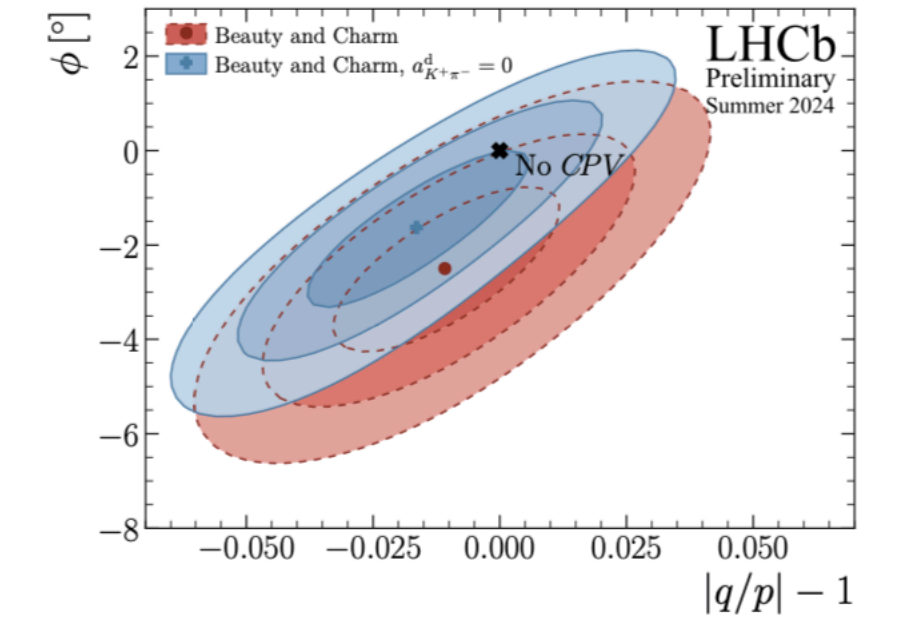
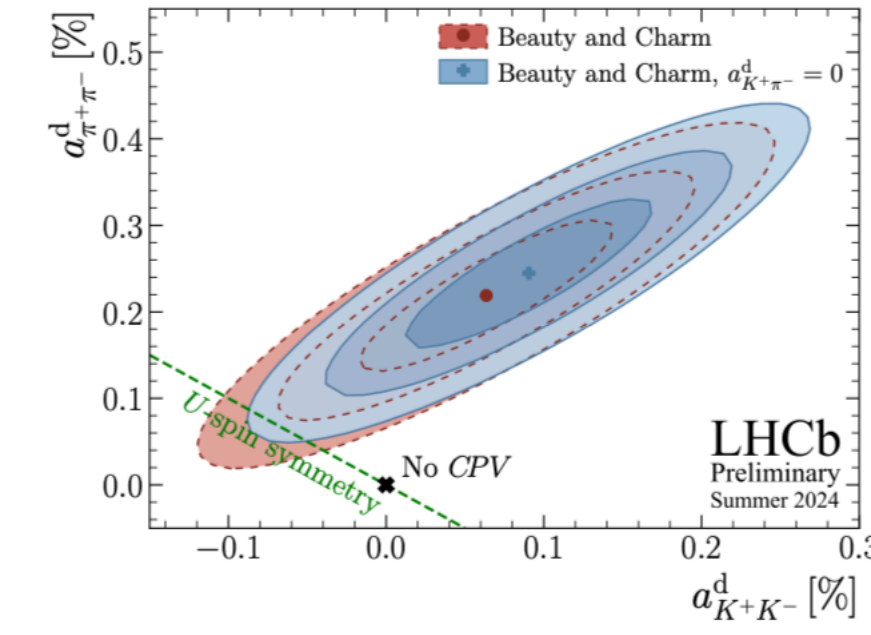
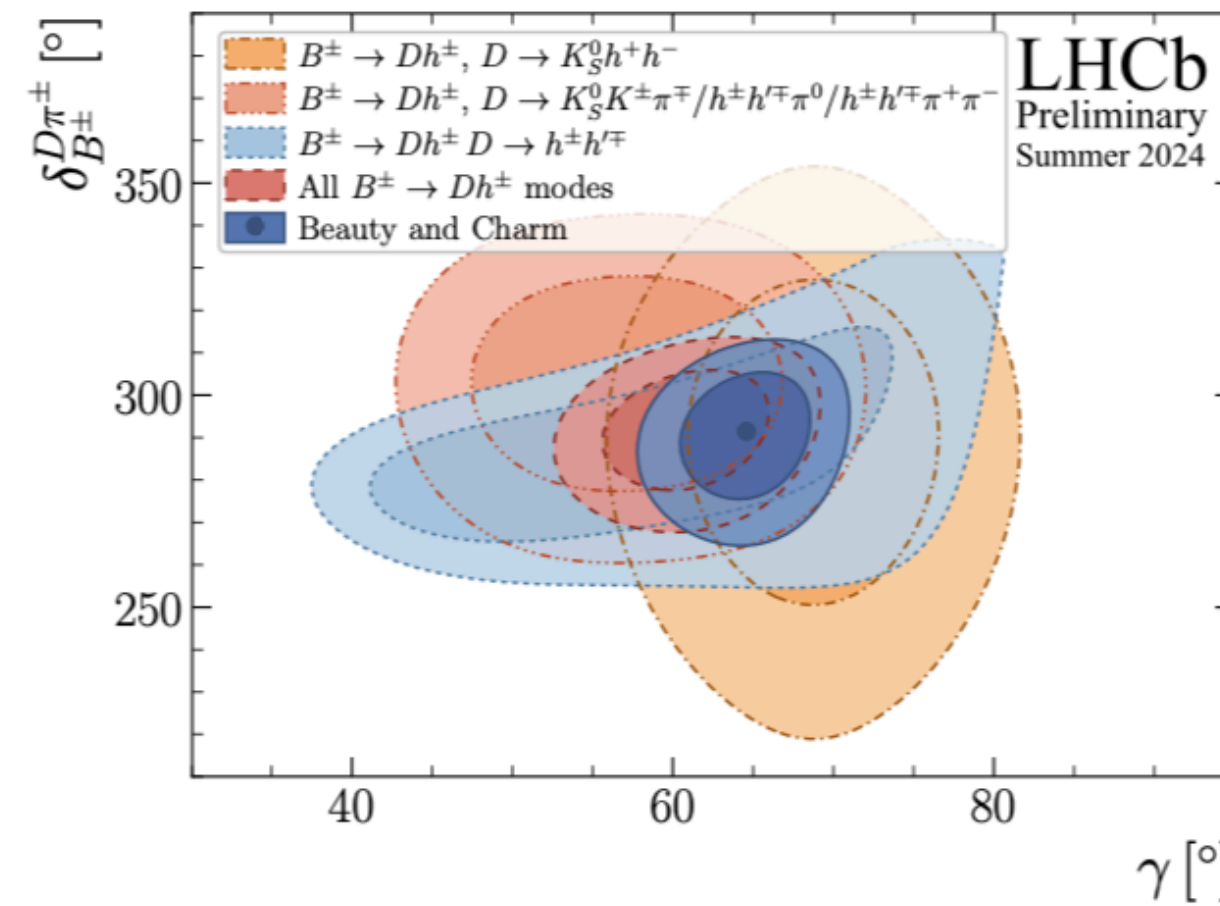
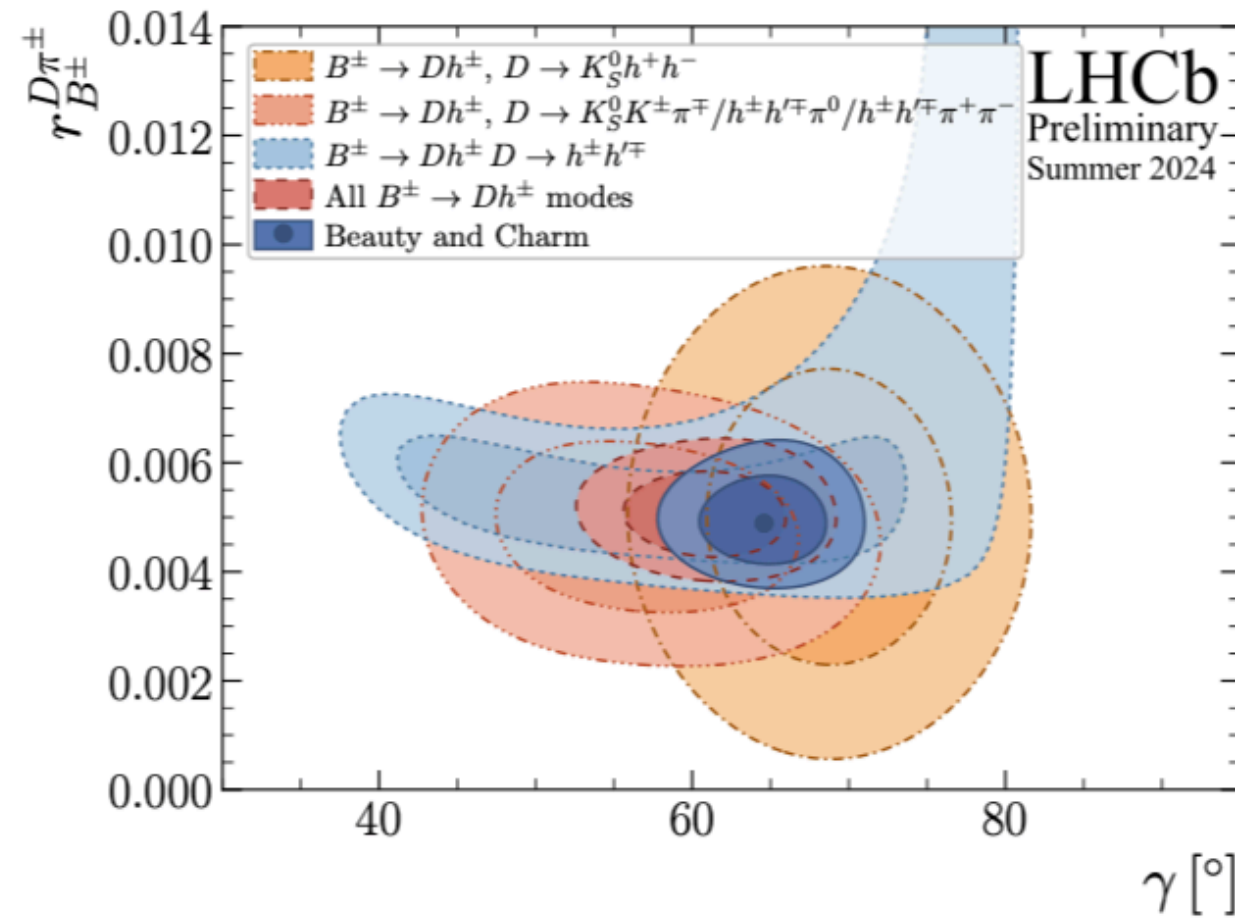
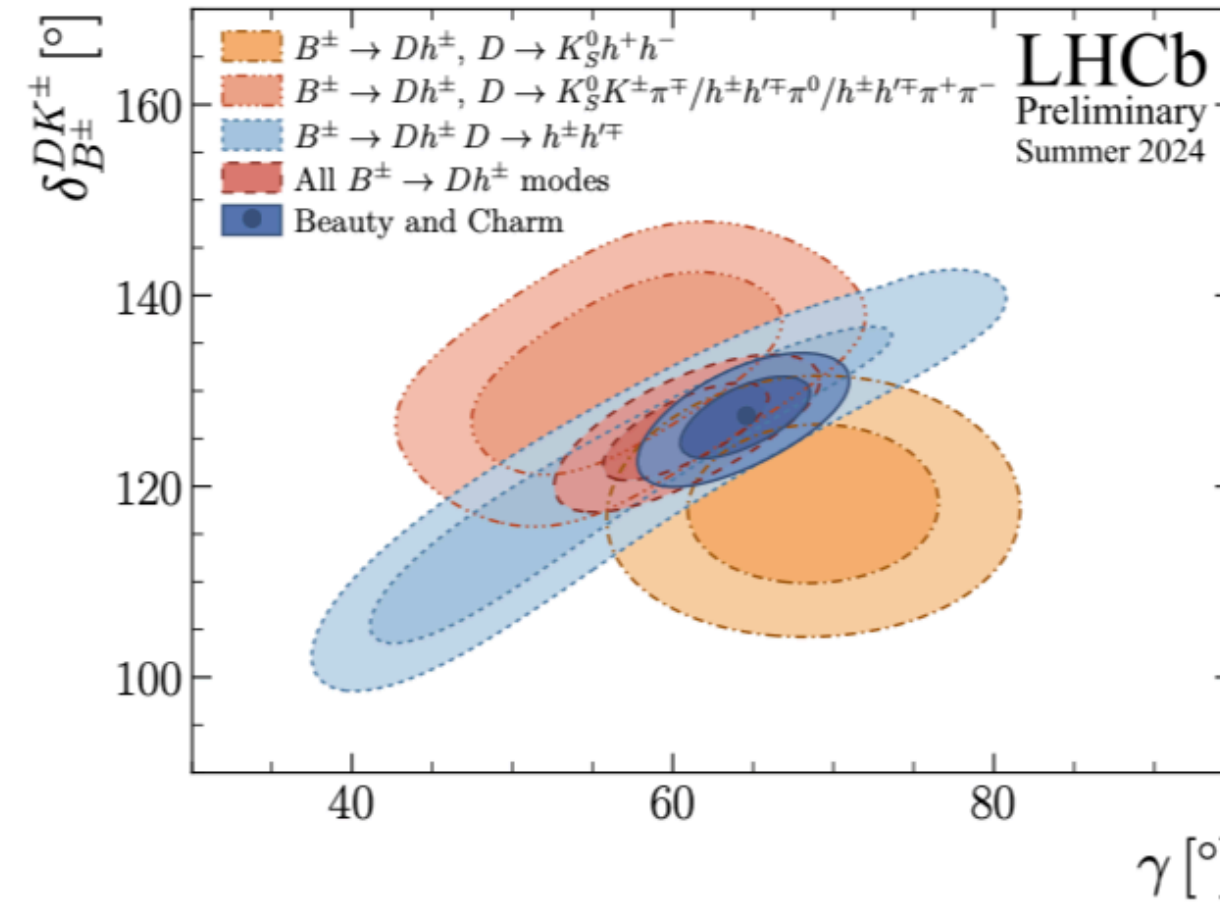
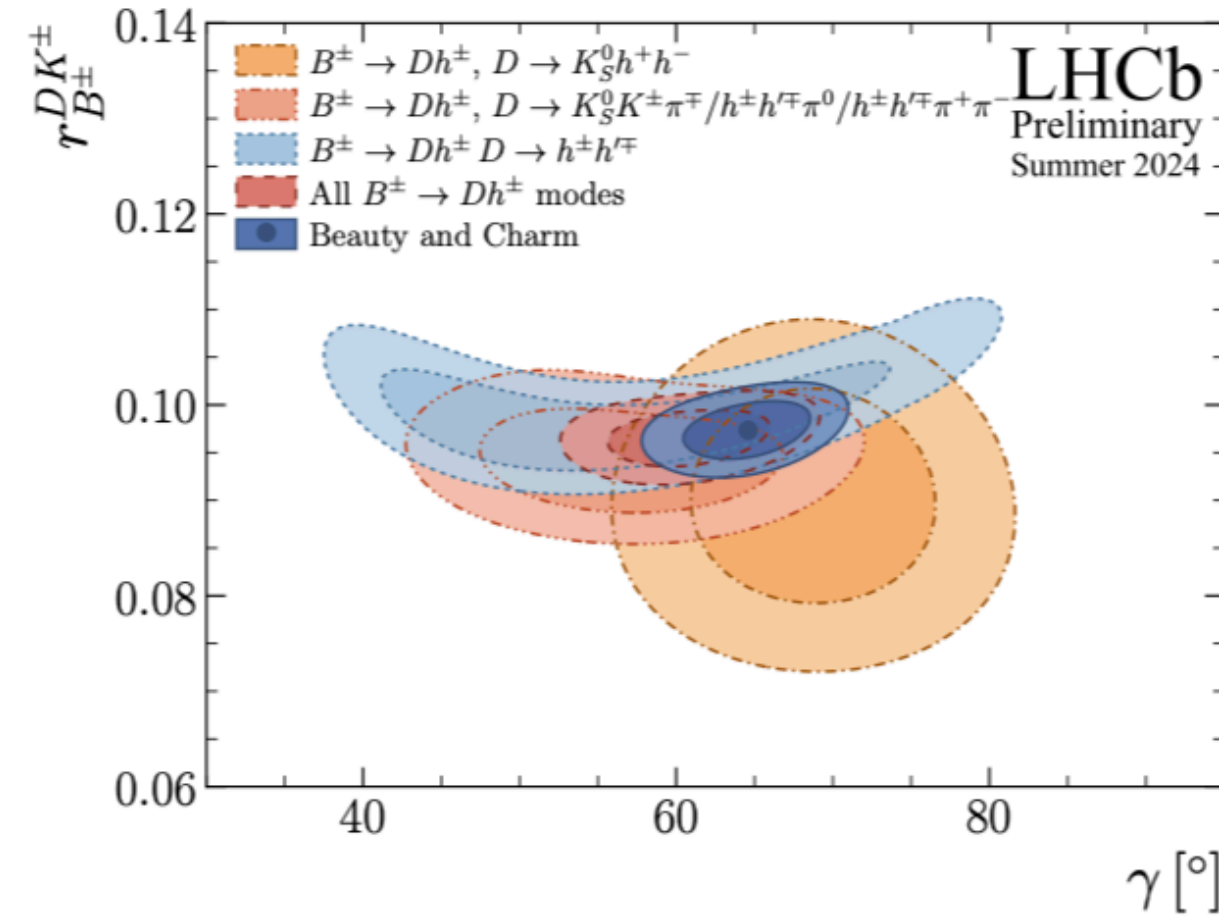
Example of a very spectacular asymmetry



LHCb, JHEP 04 (2021) 081

Just drawing a line does not do justice to this work

Putting everything together

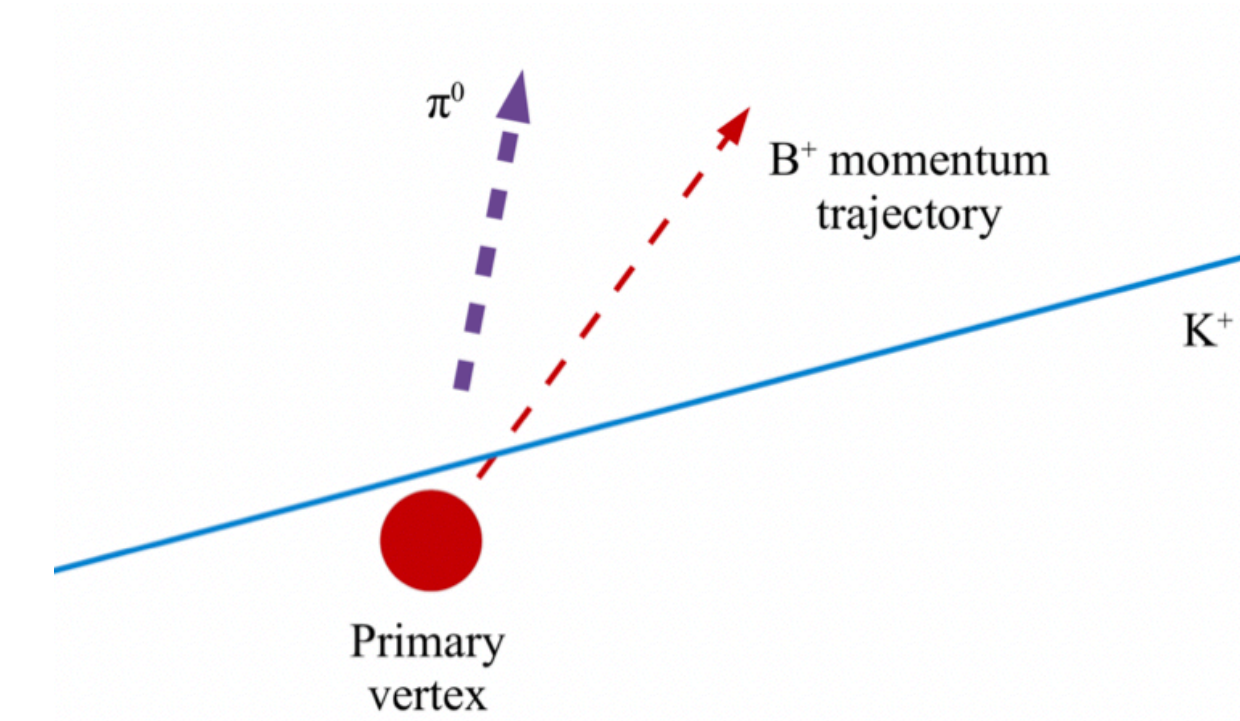
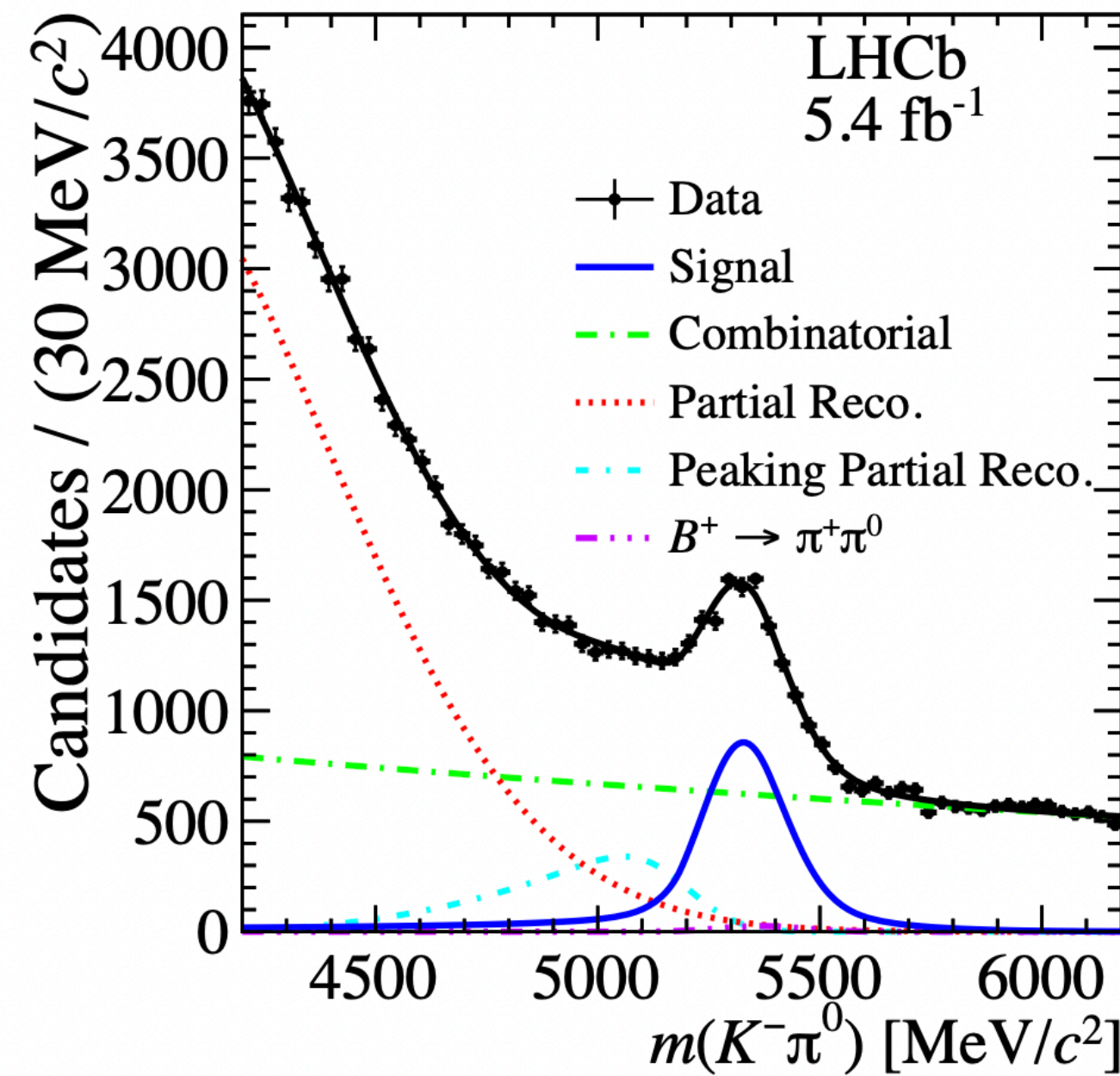
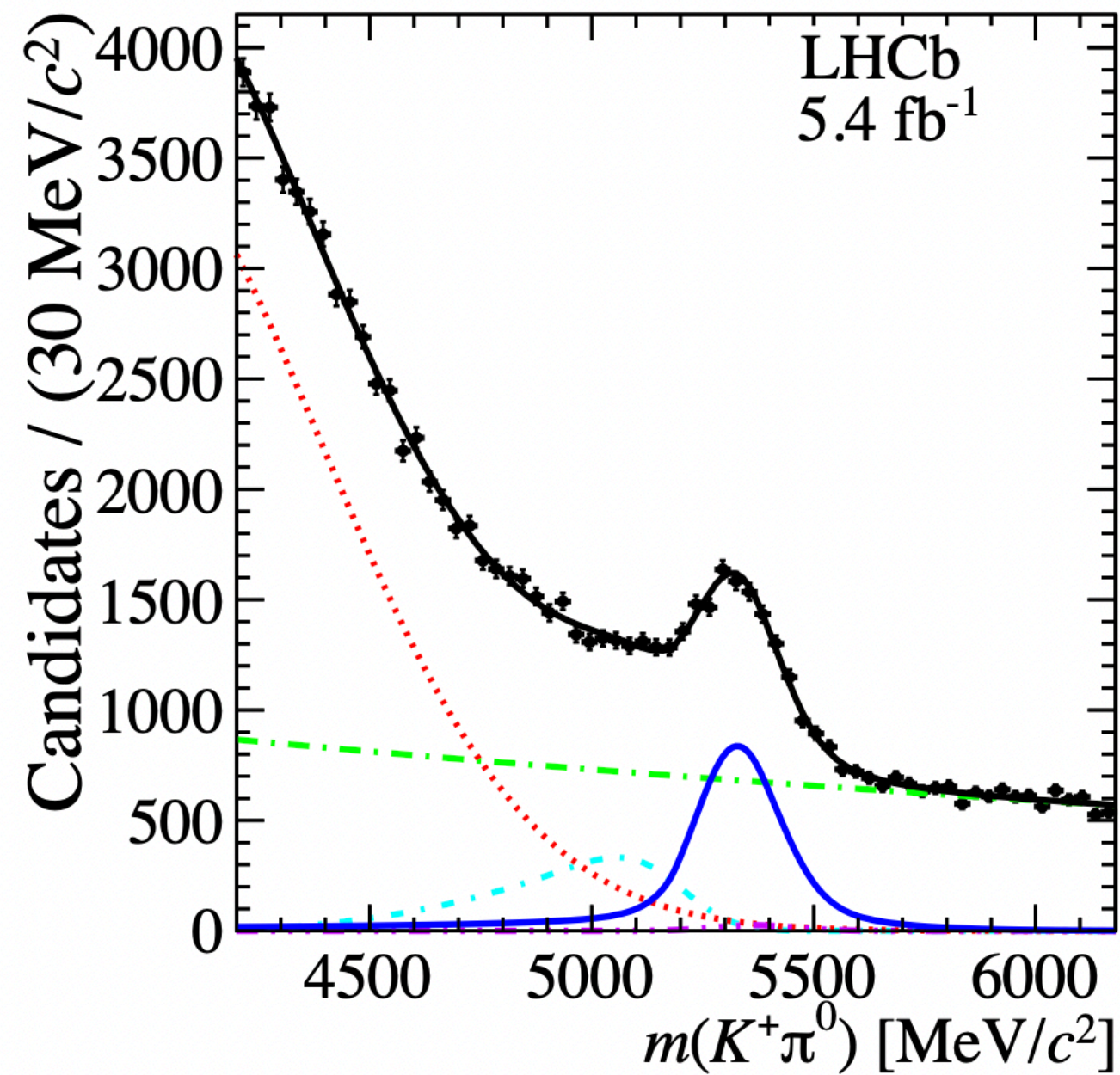


Importance of charm inputs

	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	$a_{K^+K^-}^d$	$a_{\pi^+\pi^-}^d$	$a_{K^+\pi^-}^d$
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
$a_{K^+K^-}^d$												1.00	0.87	0.22
$a_{\pi^+\pi^-}^d$													1.00	0.20
$a_{K^+\pi^-}^d$														1.00

An other example of a direct CP violation measurement

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



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

Consistent with the world average

ARXIV:2012.12789

Part of the $K\pi$ puzzle expressed via this sum rule

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

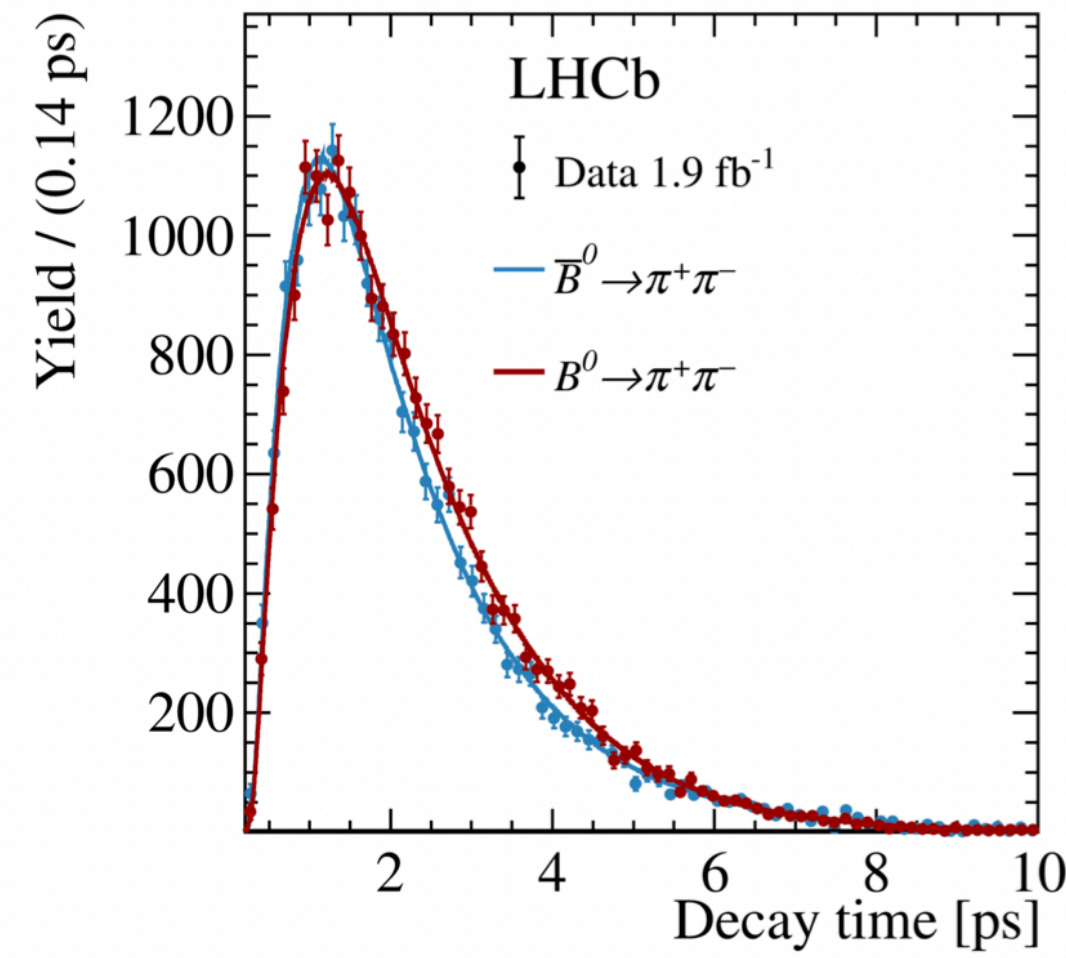
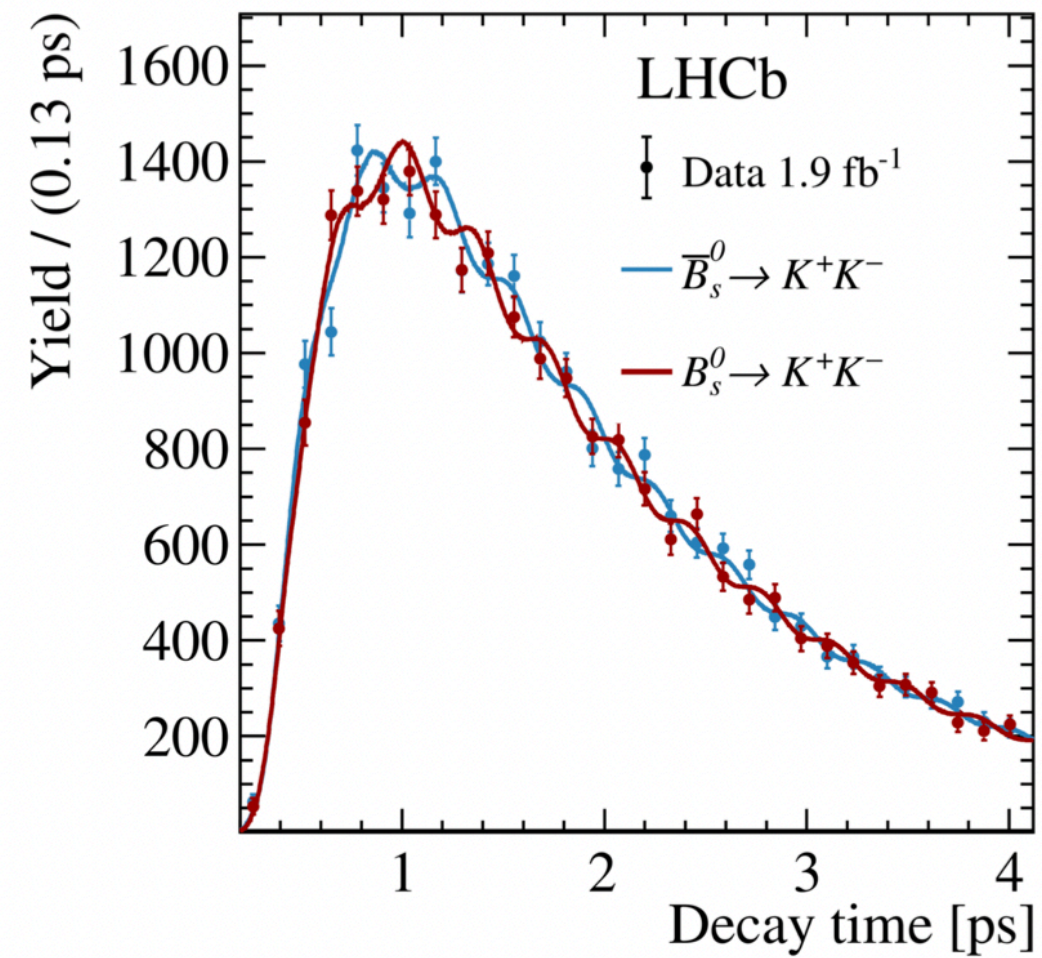
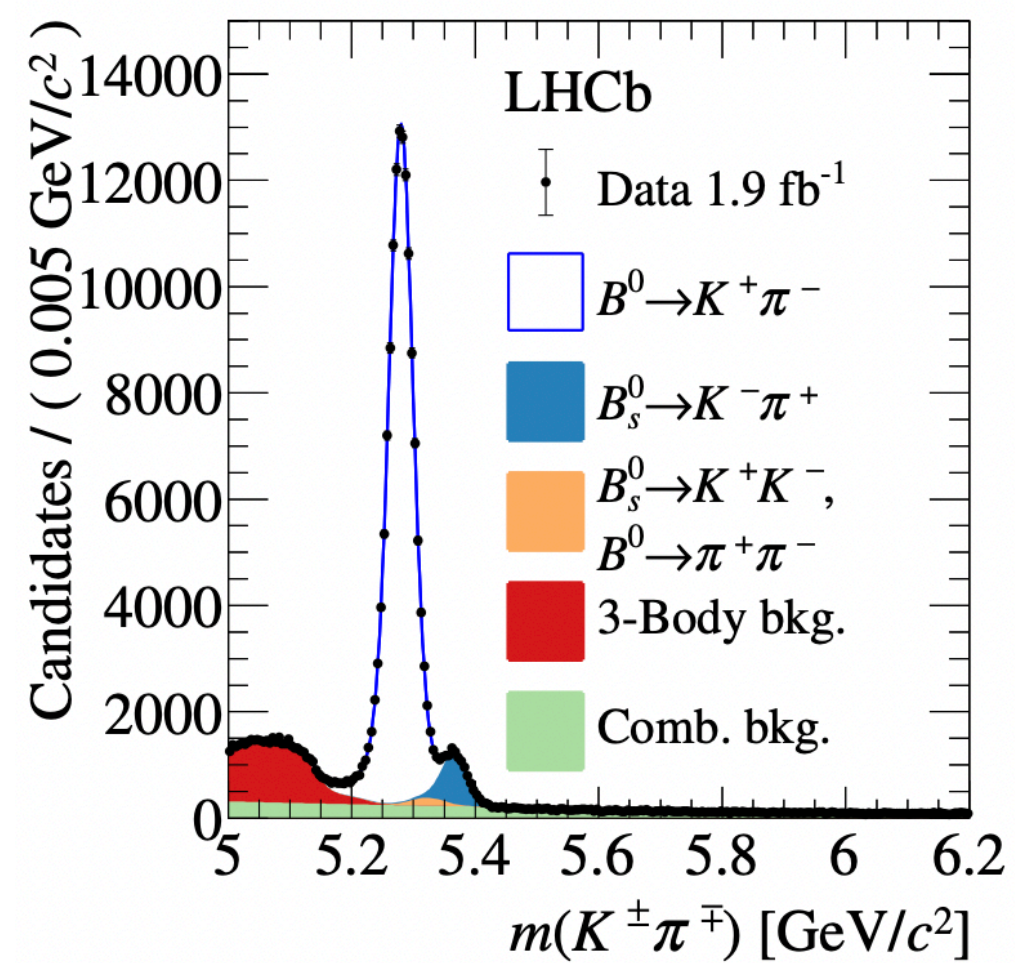
B → hh

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

An important quantity to control is detector asymmetries

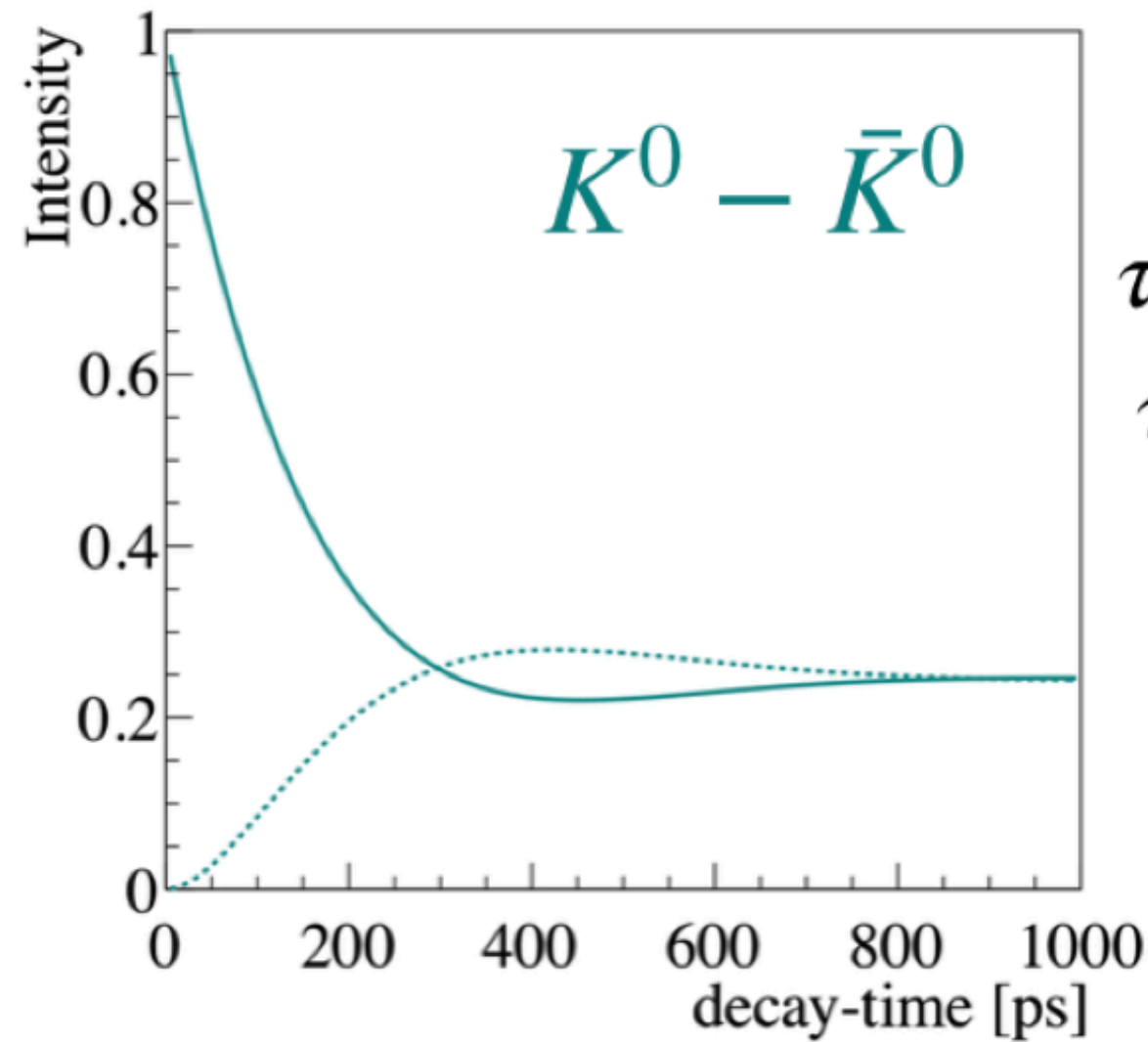
$$A_{\text{det}}^{K\pi} = A_{\text{RAW}}^{K\pi\pi} - A_{\text{RAW}}^{\bar{K}^0\pi} - A_{\text{det}}^{K^0}.$$

Analyses that explore U spin symmetry



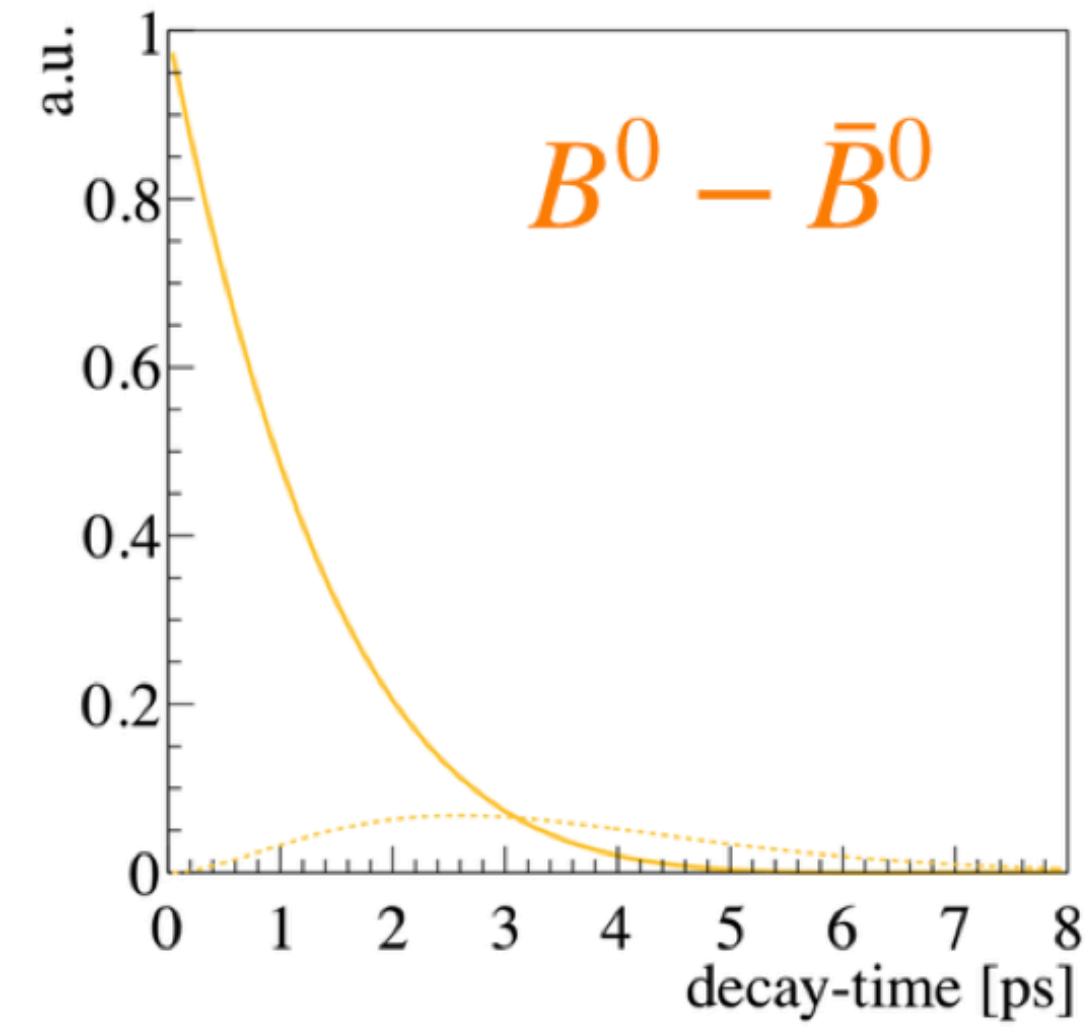
$$\begin{aligned} C_{\pi\pi} &= -0.320 \pm 0.038, \\ S_{\pi\pi} &= -0.672 \pm 0.034, \\ A_{CP}^{B^0} &= -0.0831 \pm 0.0034, \\ A_{CP}^{B_s^0} &= 0.225 \pm 0.012, \\ C_{KK} &= 0.172 \pm 0.031, \\ S_{KK} &= 0.139 \pm 0.032, \\ \mathcal{A}_{KK}^{\Delta\Gamma} &= -0.897 \pm 0.087 \end{aligned}$$

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



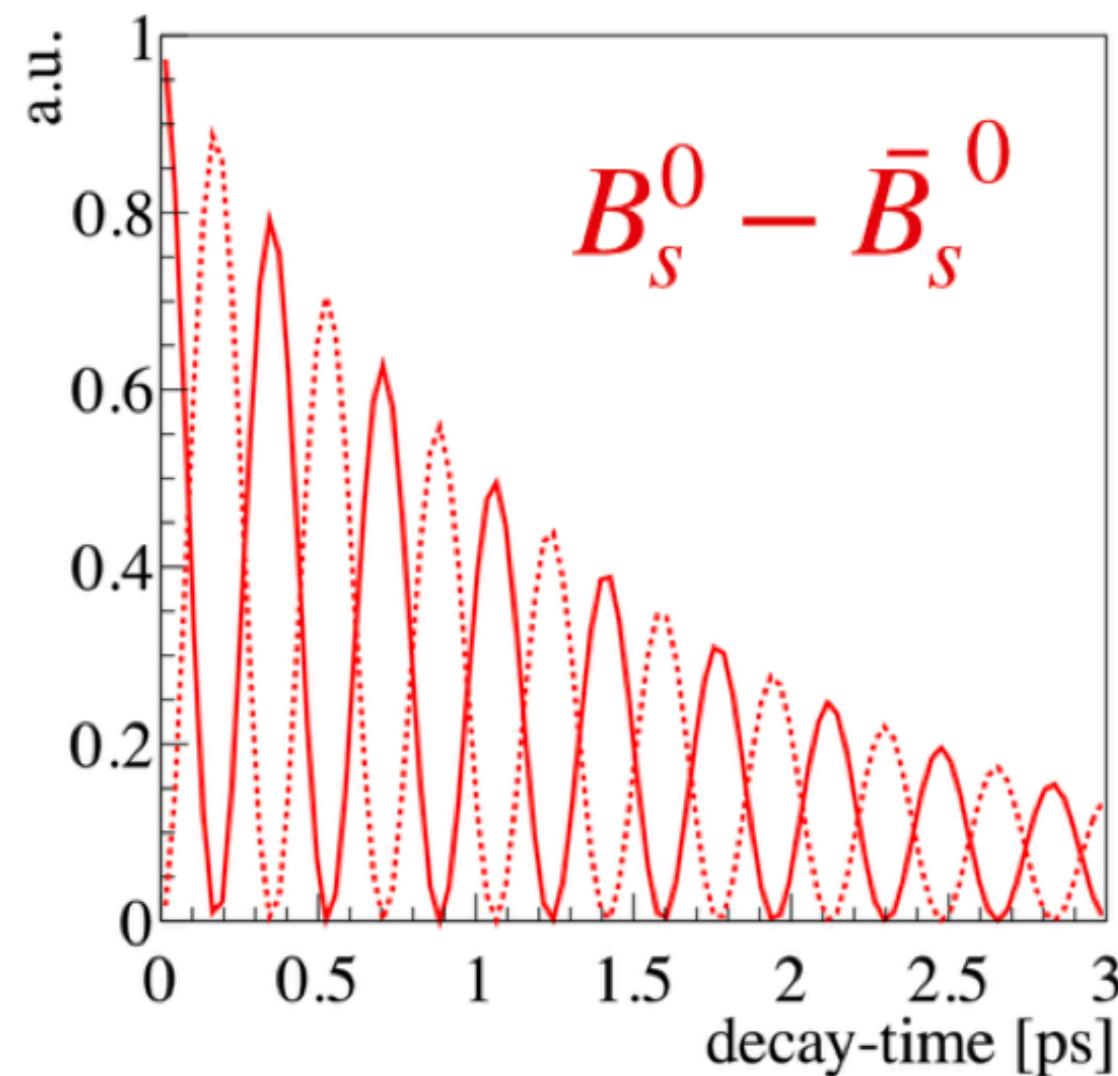
$K^0 - \bar{K}^0$

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



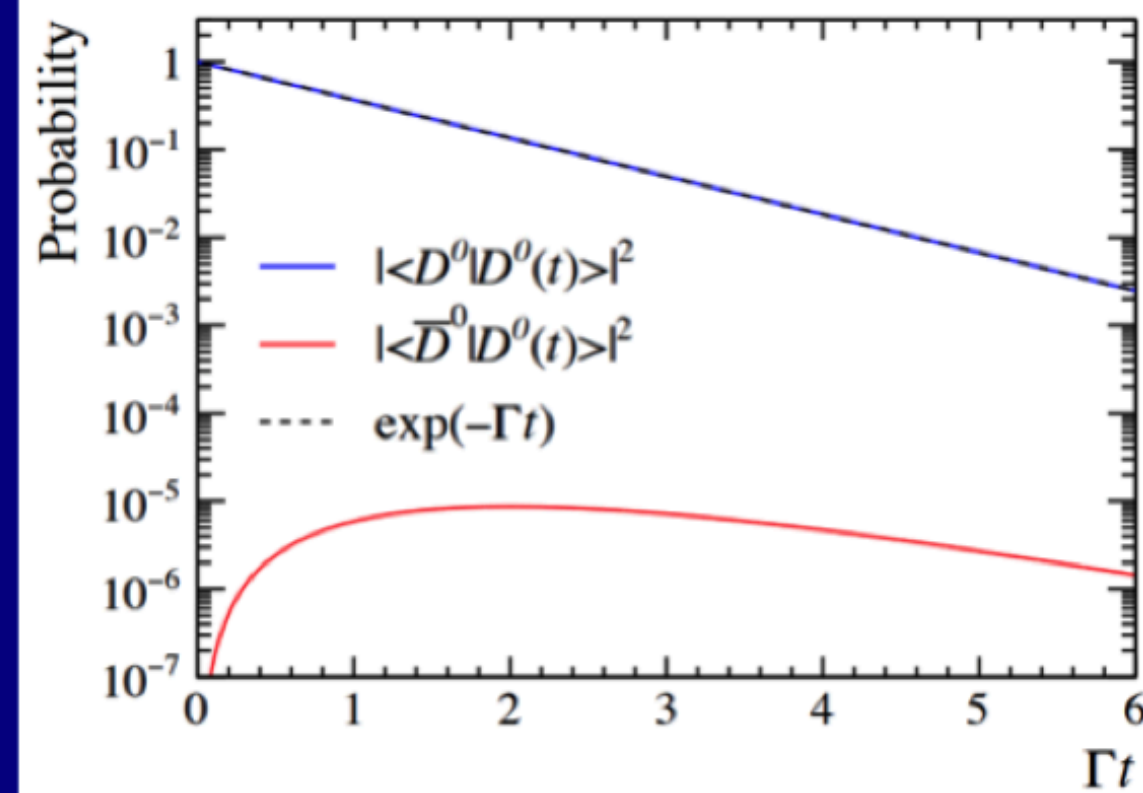
$B^0 - \bar{B}^0$

Oscillations
 $\Delta m \sim 0.5 \text{ ps}^{-1}$
 Lifetime
 $\tau(B^0) \sim 1.5 \text{ ps}$
 The same order of magnitudes



$B_s^0 - \bar{B}_s^0$

Very fast oscillations
 $\Delta m_s > 15 \text{ ps}^{-1}$
 $\tau(B_s^0) \sim 1.5 \text{ ps}$
 Non-zero $\Delta\Gamma_s$

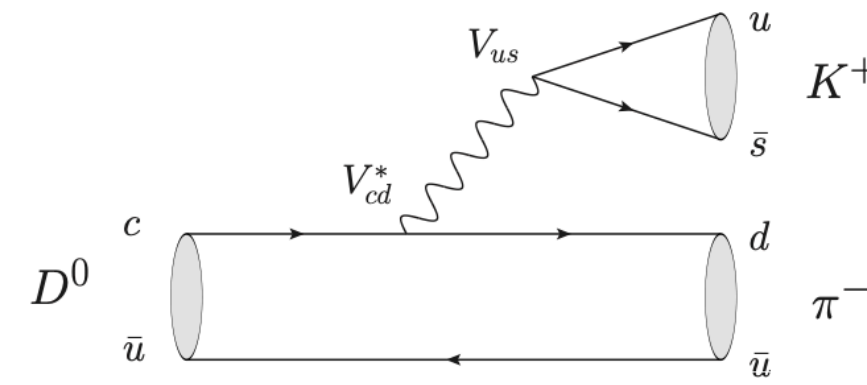
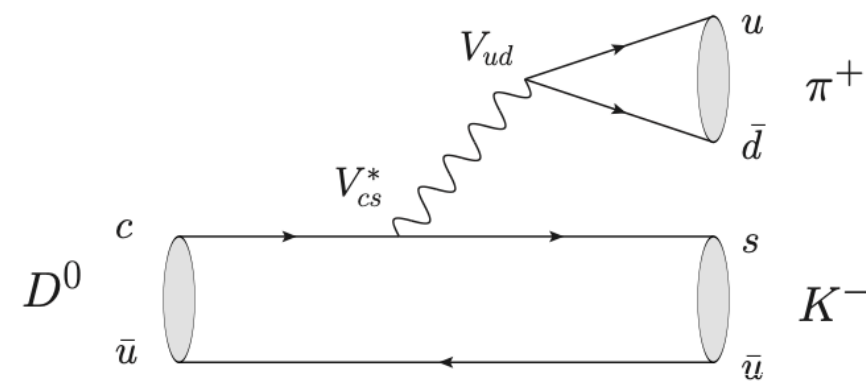


$D^0 - \bar{D}^0$

Very slow oscillations
 $\Delta m \sim 10^{-3} \text{ ps}^{-1}$
 Very short lifetime
 $\tau(D^0) \sim 0.4 \text{ ps}$
 D^0 decays before has a chance to oscillate

Mixing in charm land

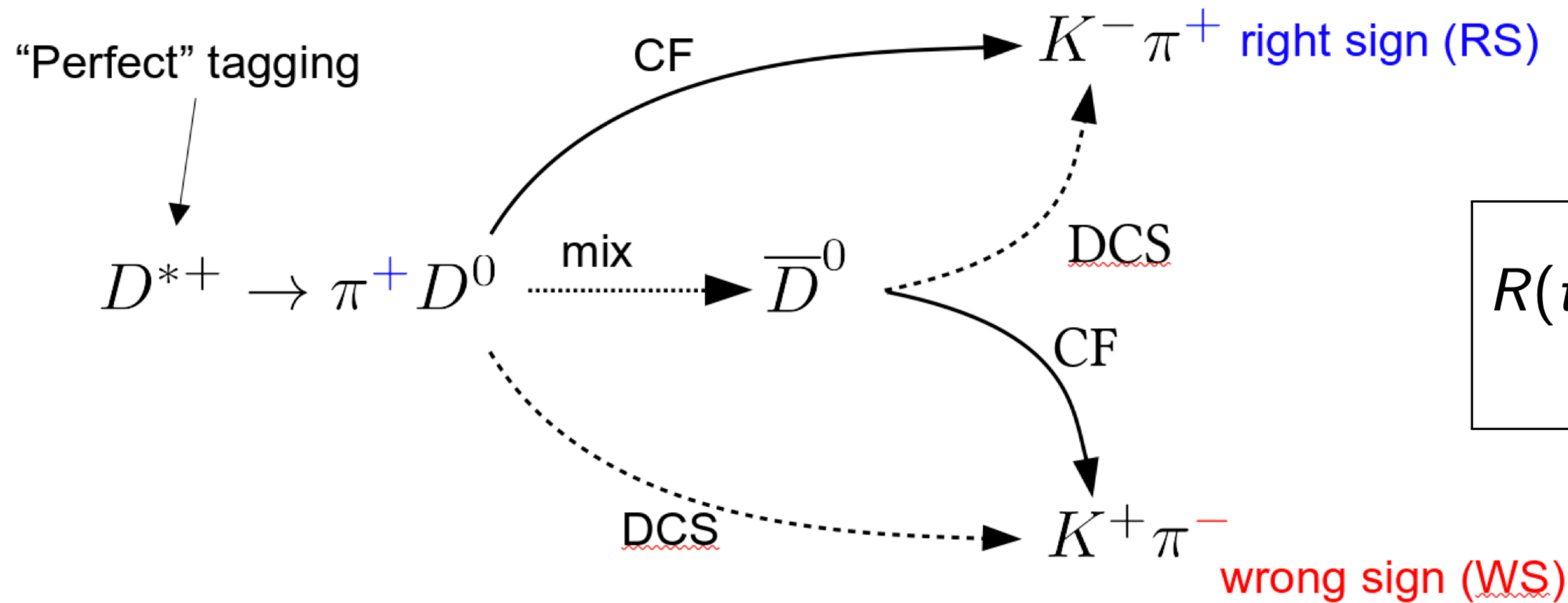
$$x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2\Gamma}$$



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

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

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

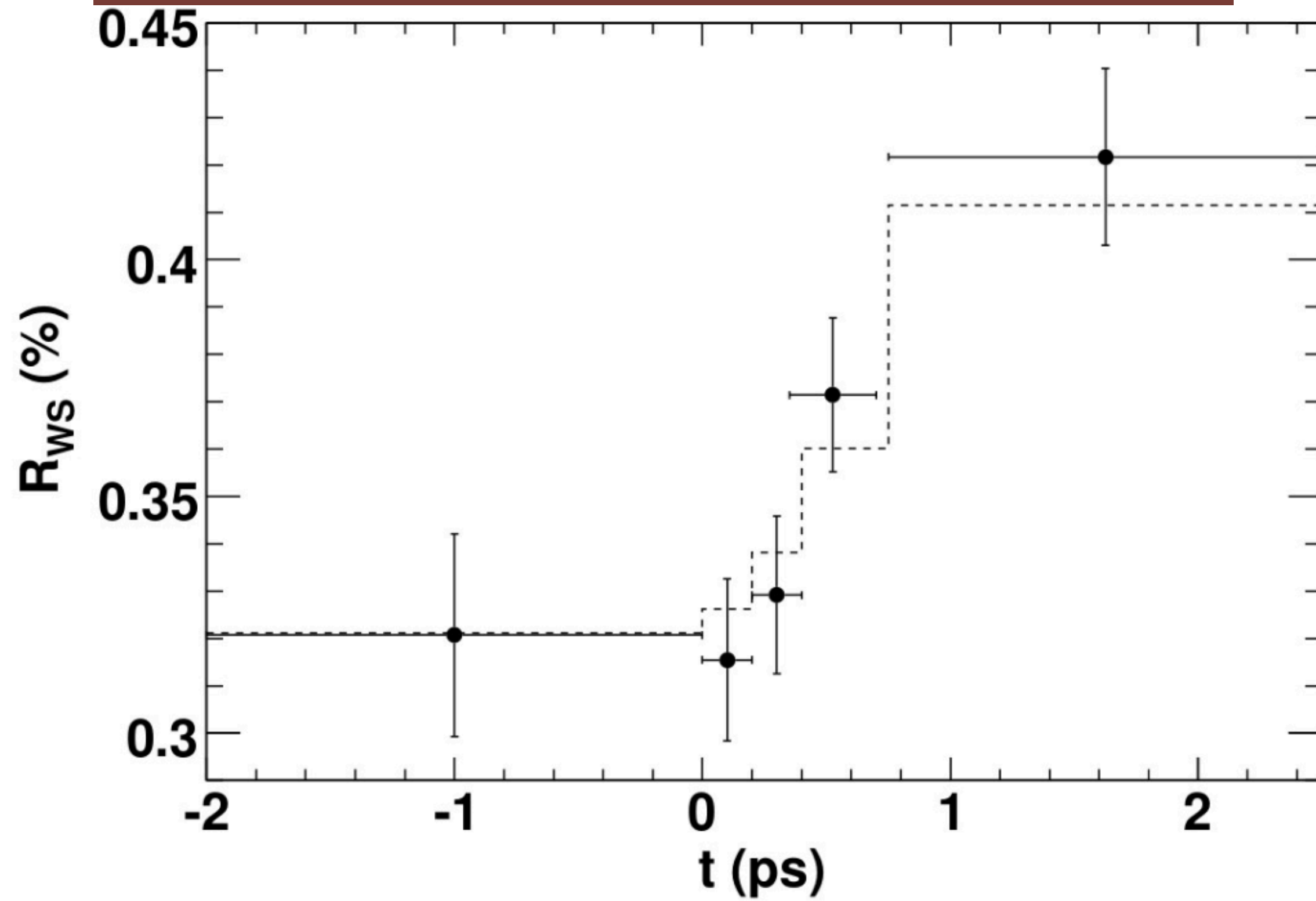


$$R(t) \approx r_D + \underbrace{\sqrt{r_D} y' \frac{t}{\tau}}_{\text{(Interference)}} + \underbrace{\frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2}_{\text{(Pure mixing)}}$$

I warned you there is a lot of Jargon

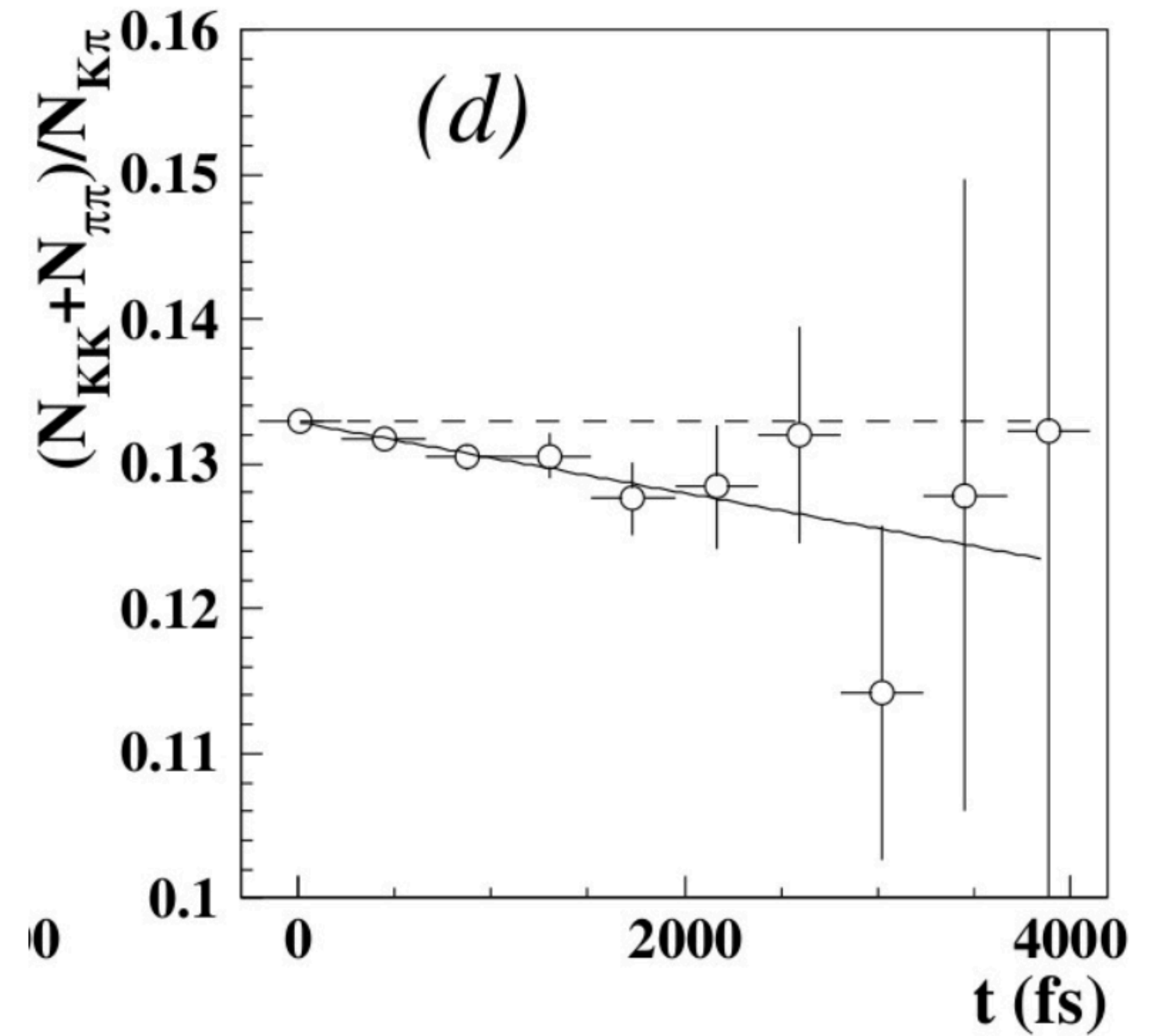
Charm Mixing 2007

BaBar, PRL 98 (2007) 211802



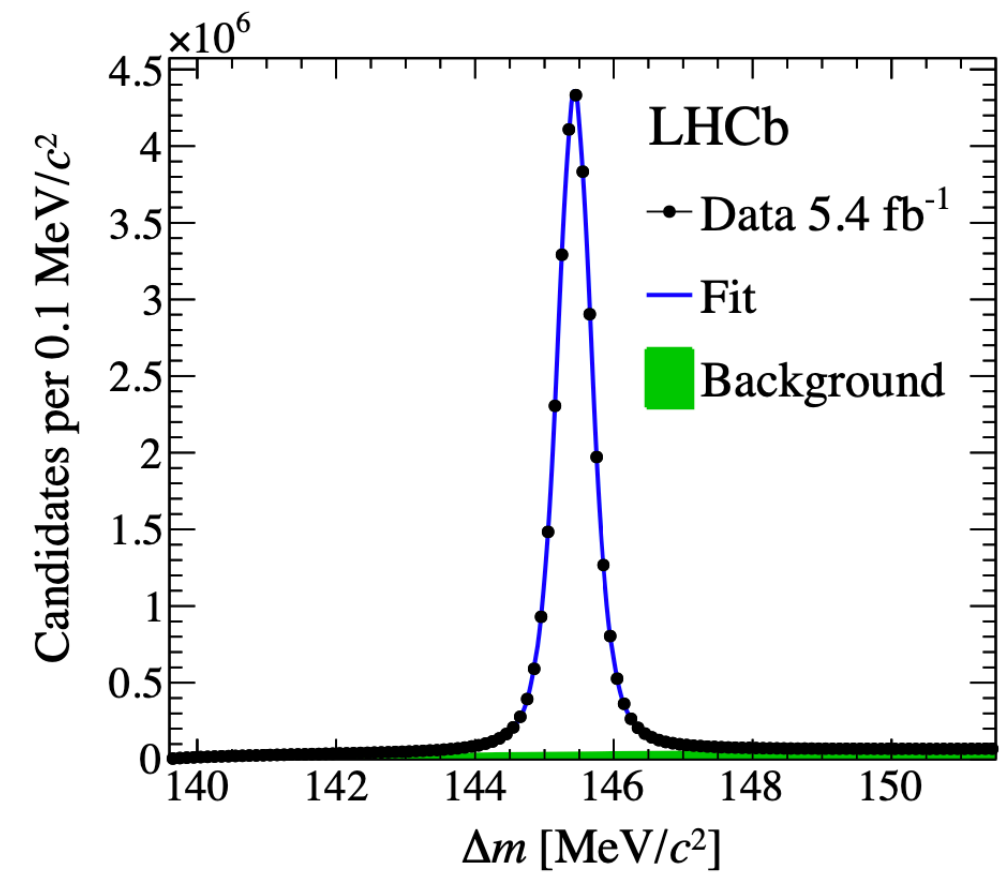
$D^0 \rightarrow K^+ \pi^-$

Belle, PRL 98 (2007) 211803

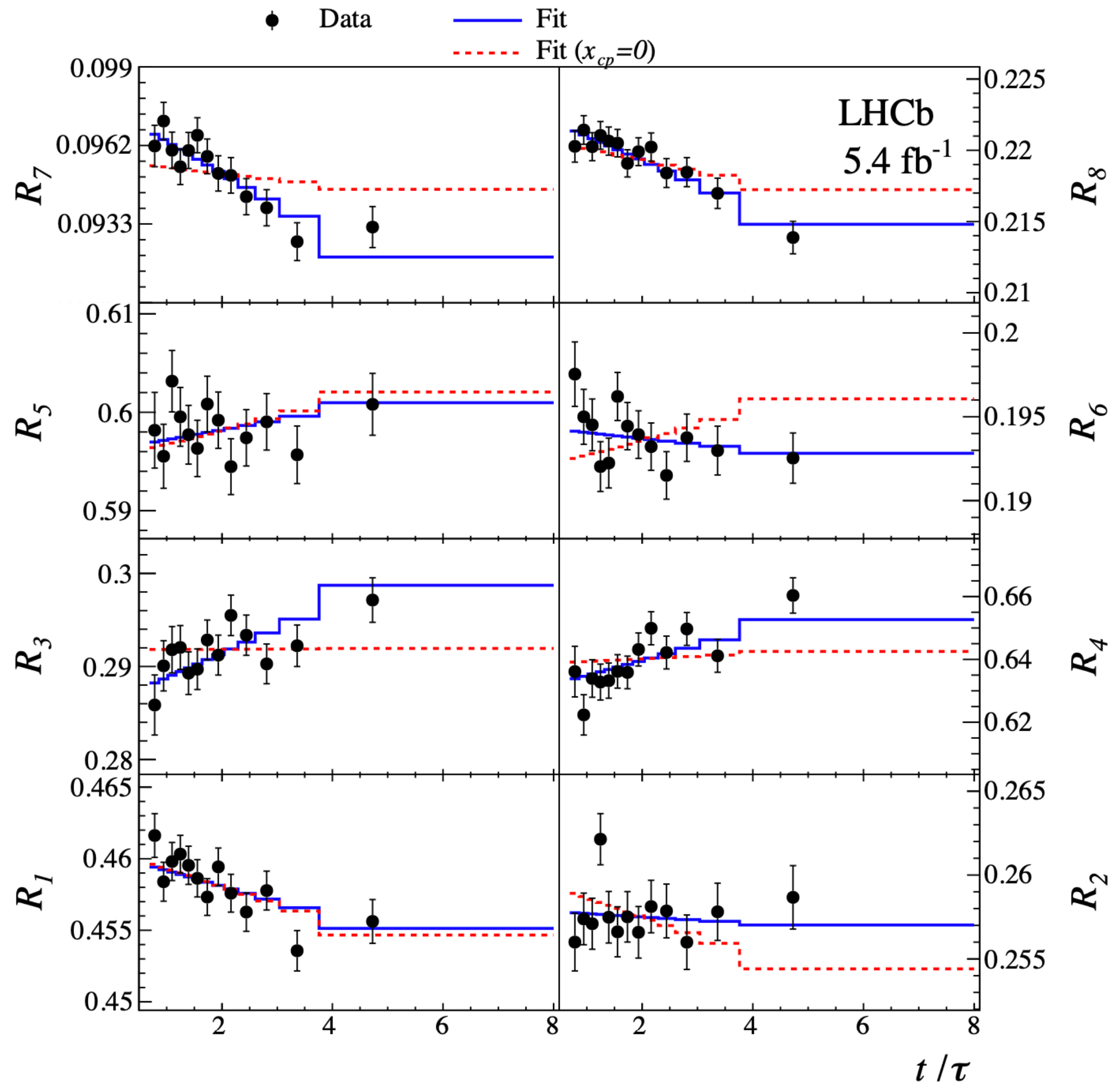
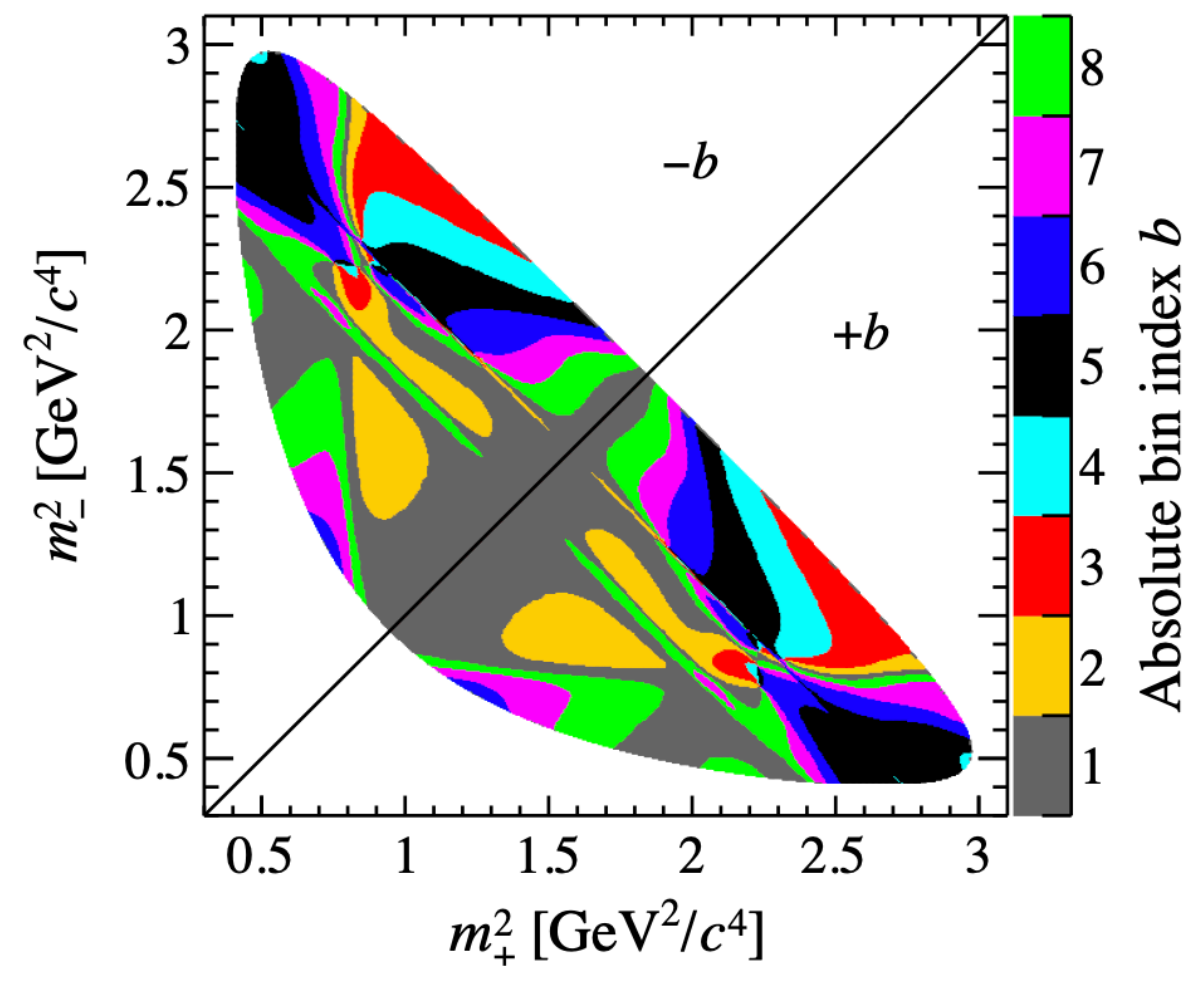


$D^0 \rightarrow K^+ K^-, \pi^+ \pi^-$

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



Bin flip method

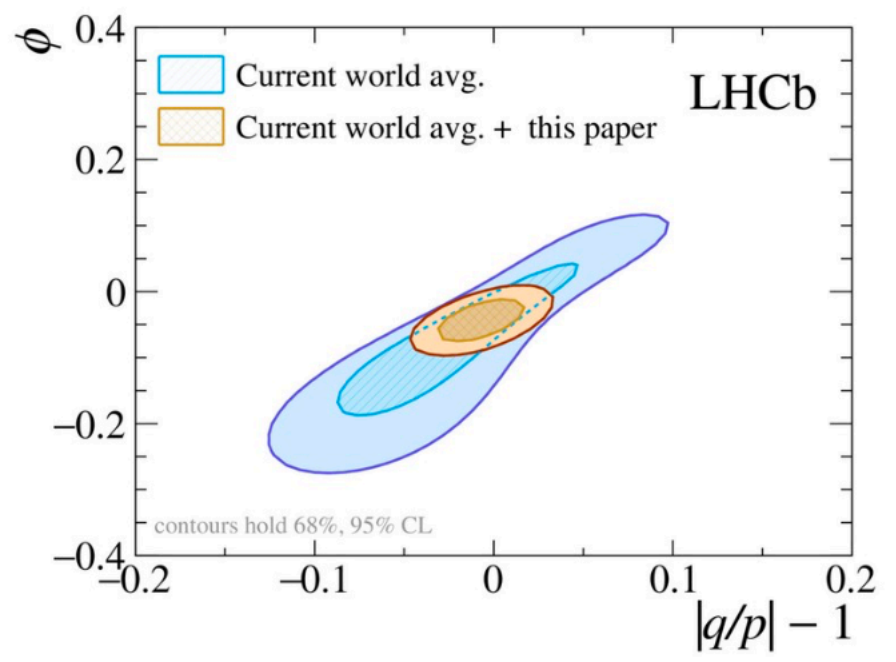
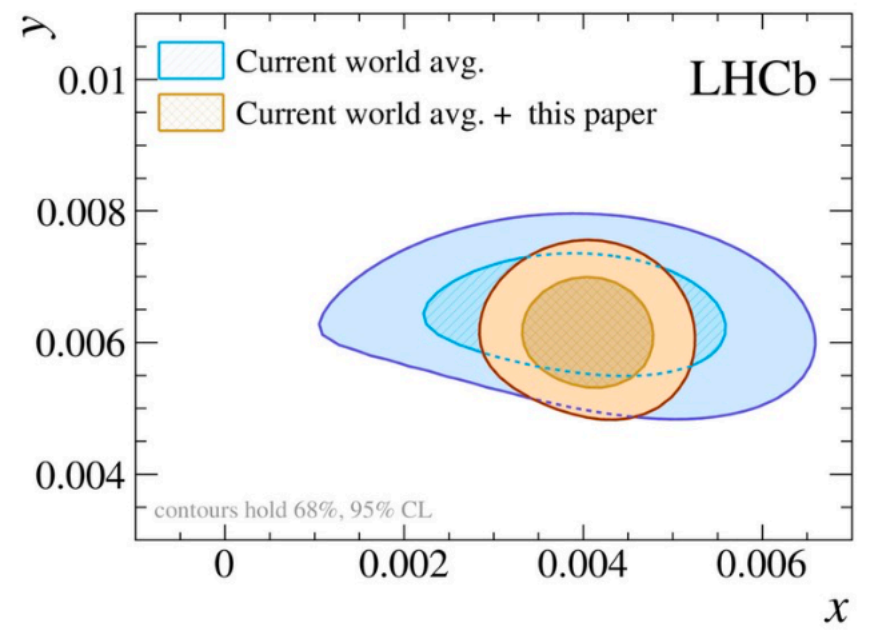


$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$

$$y = (4.6^{+1.5}_{-1.4}) \times 10^{-3},$$

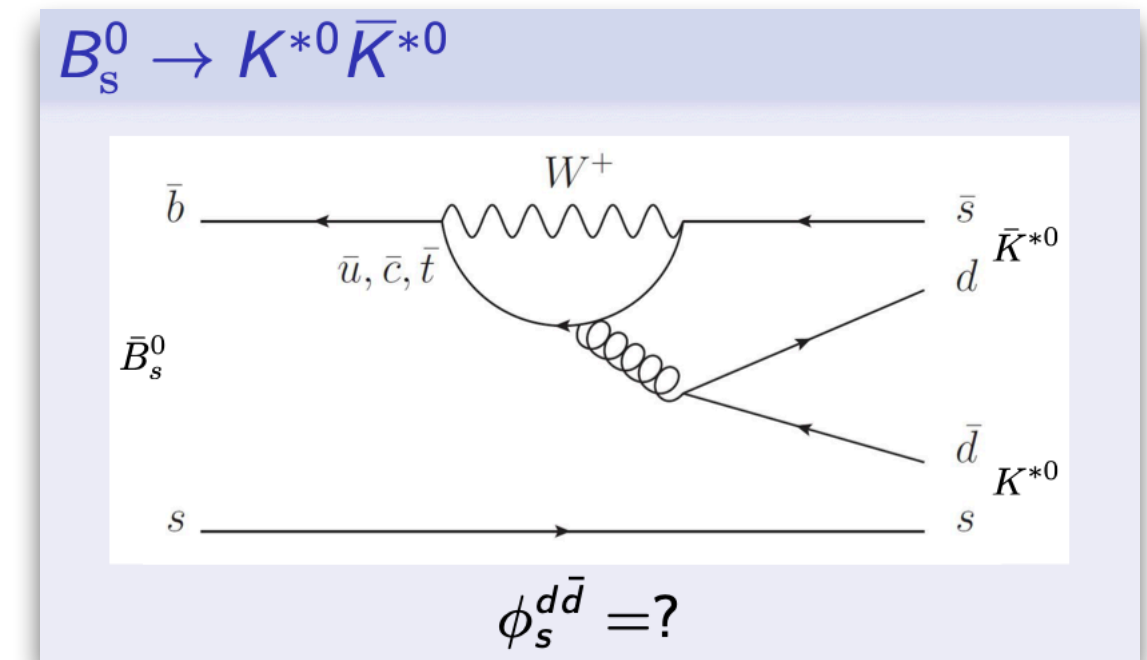
$$|q/p| = 0.996 \pm 0.052,$$

$$\phi = 0.056^{+0.047}_{-0.051}.$$



Giving one lecture on CP Violation

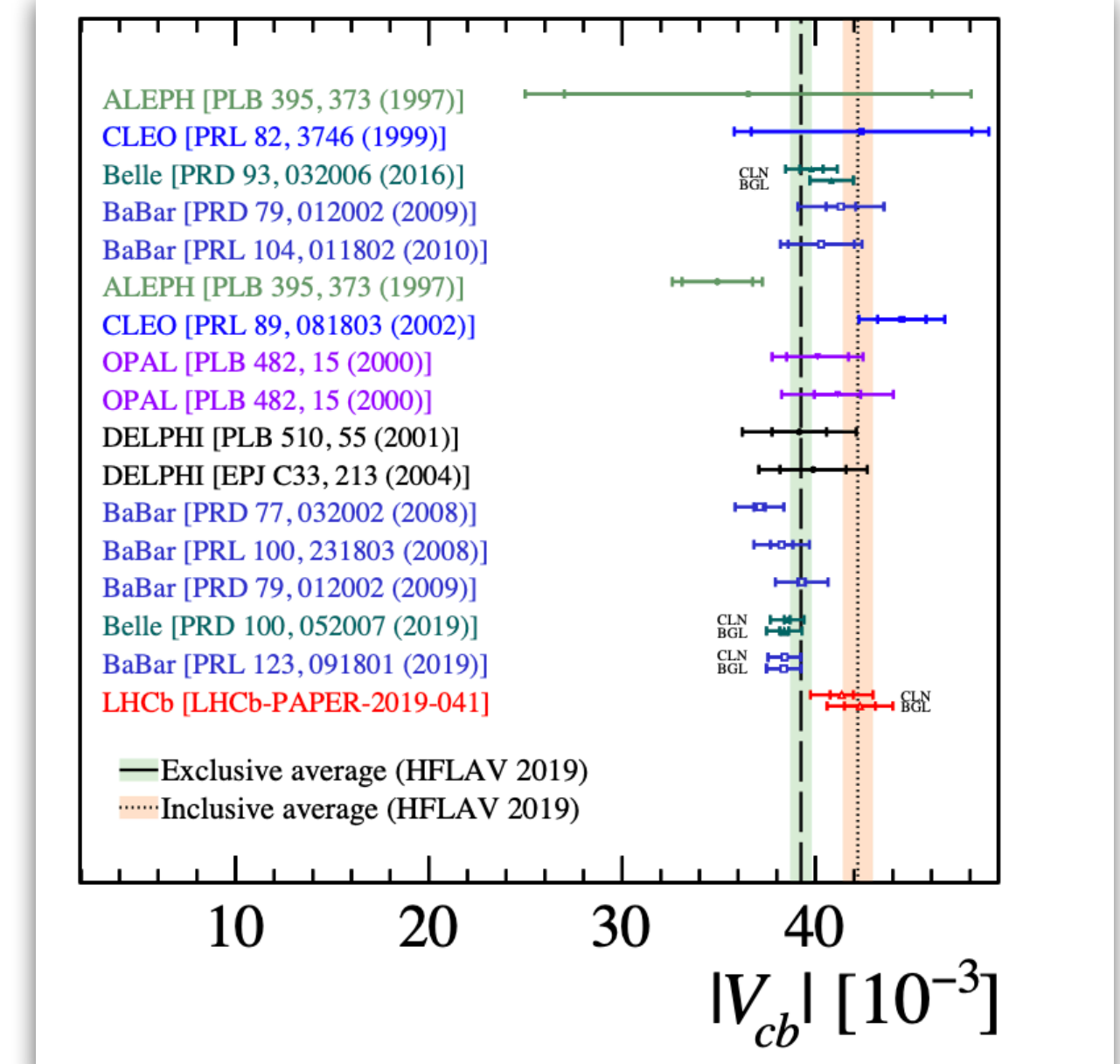
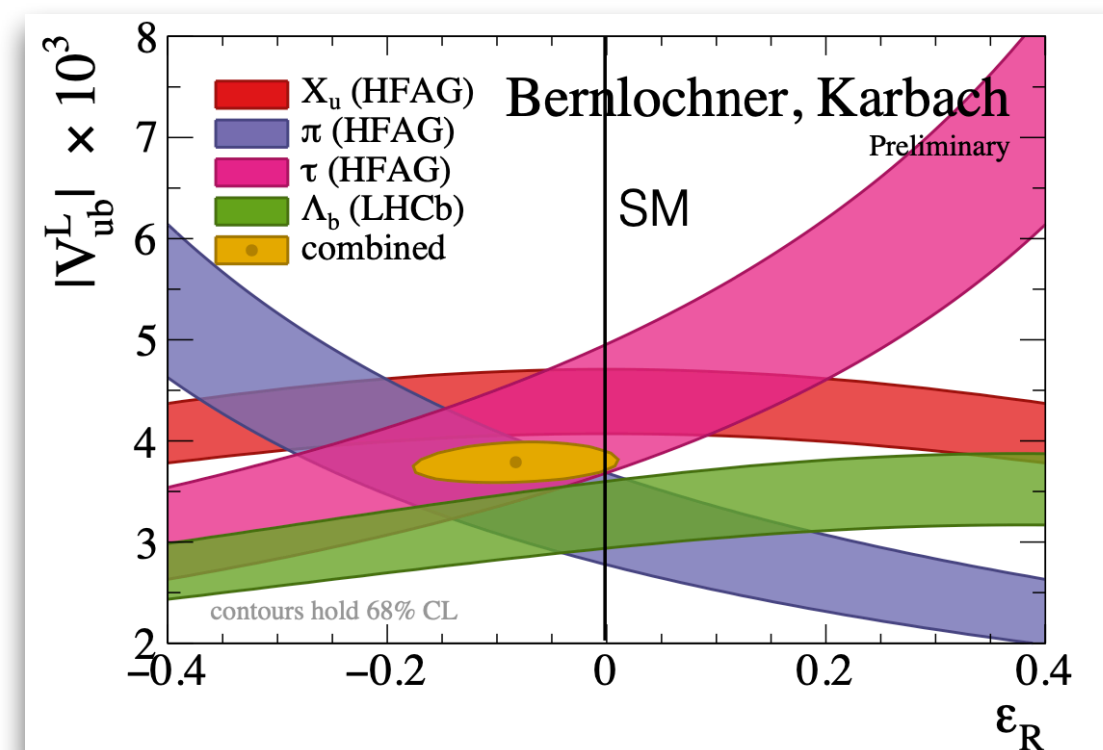
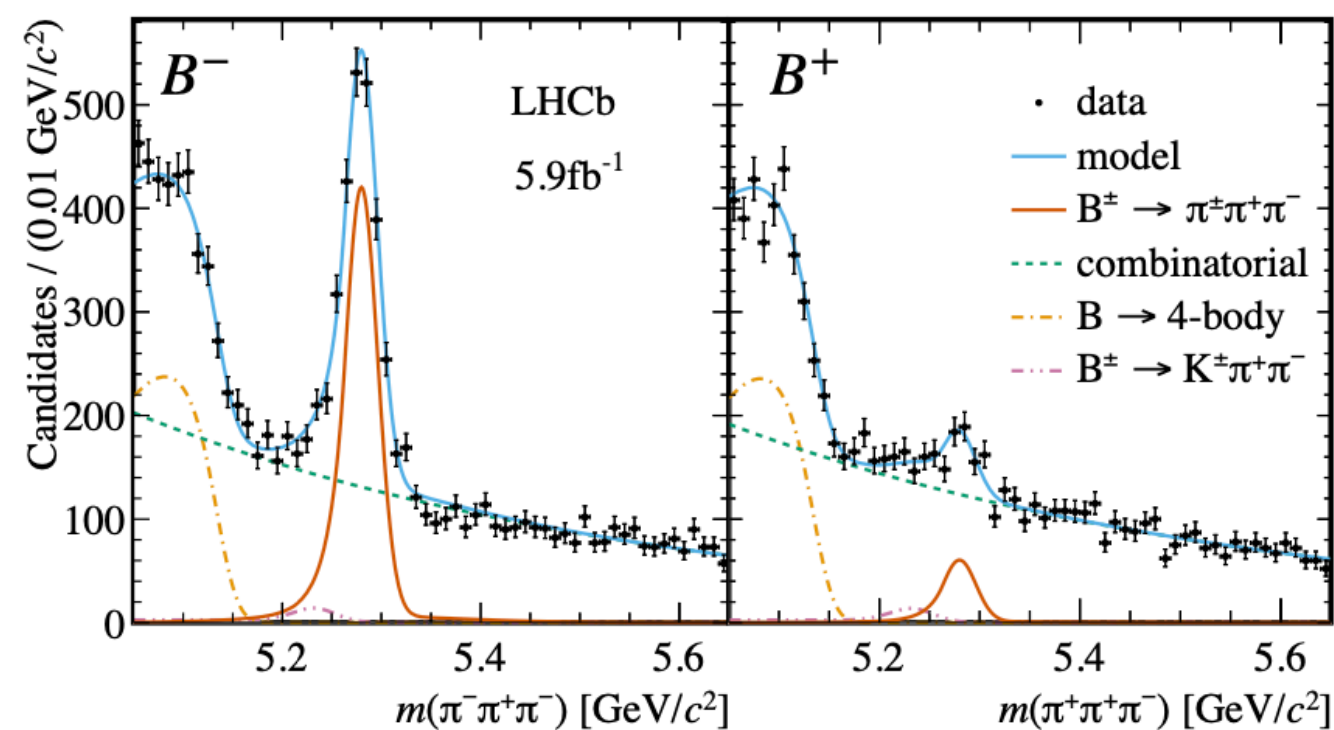
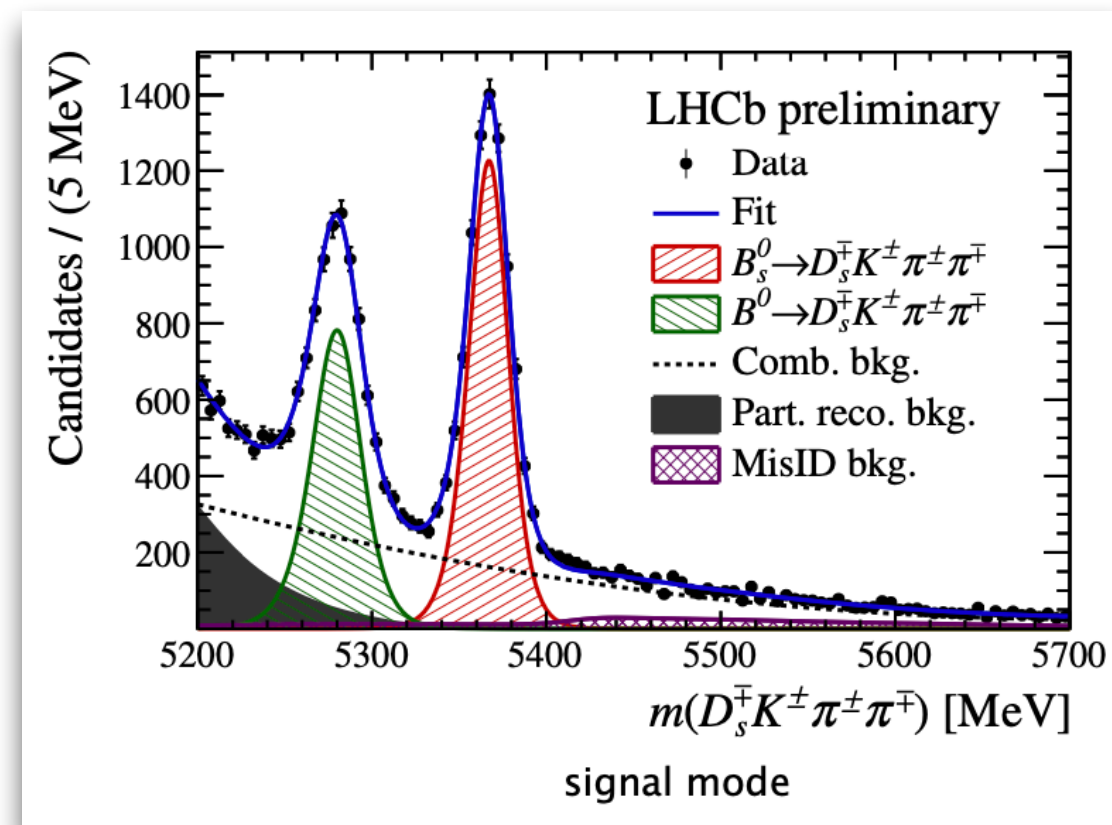
- Pros: it's only ~50-40 slides.
- Cons: it's impossible to do justice to the topic.



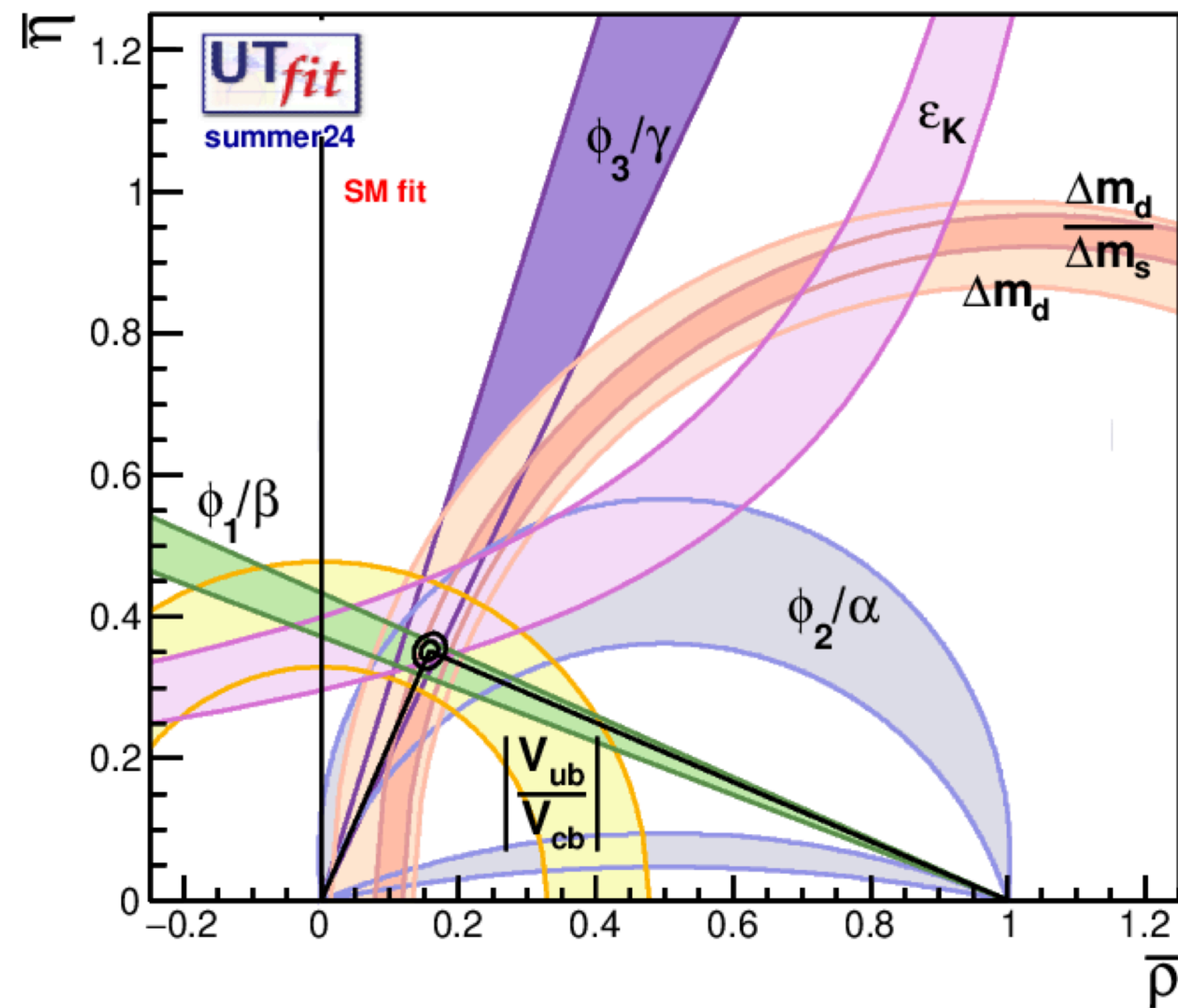
$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$$

$$A_{CP}(D_{(s)}^+ \rightarrow h^+ \pi^0, h^+ \eta)$$

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



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 $B_{d,s}^0$ decays, $A_{SL}^{d,s}$, are important [140]. The current world averages [24] are consistent with the SM, with experimental uncertainties far greater than those of the theory predictions.

We take a break here for today !
Tomorrow we discuss penguins, EFTs and all the good stuff.

