Flavour Physics - Chapter I

Yasmine Amhis
CERN Fermilab Summer School

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

CERN

August 2023

Let's see how Flavour Physics can help us go Beyond the SM ?

Beyond the SM

12

* Need to add neutrino mass (Majorana or Dirac?)

Motivation for BSM

Plausable EFT Solutions

- Dark matter
- Baryon asymmetry
- Strong CP
- Fermion masses and mixings
- Grand unification

Challenge EFT Paradigm

- Hierarchy problem
- Cosmological constant
- Initial conditions for inflation / Eternal inflation
- UV completion of gravity

Tim Cohen

Disclaimer

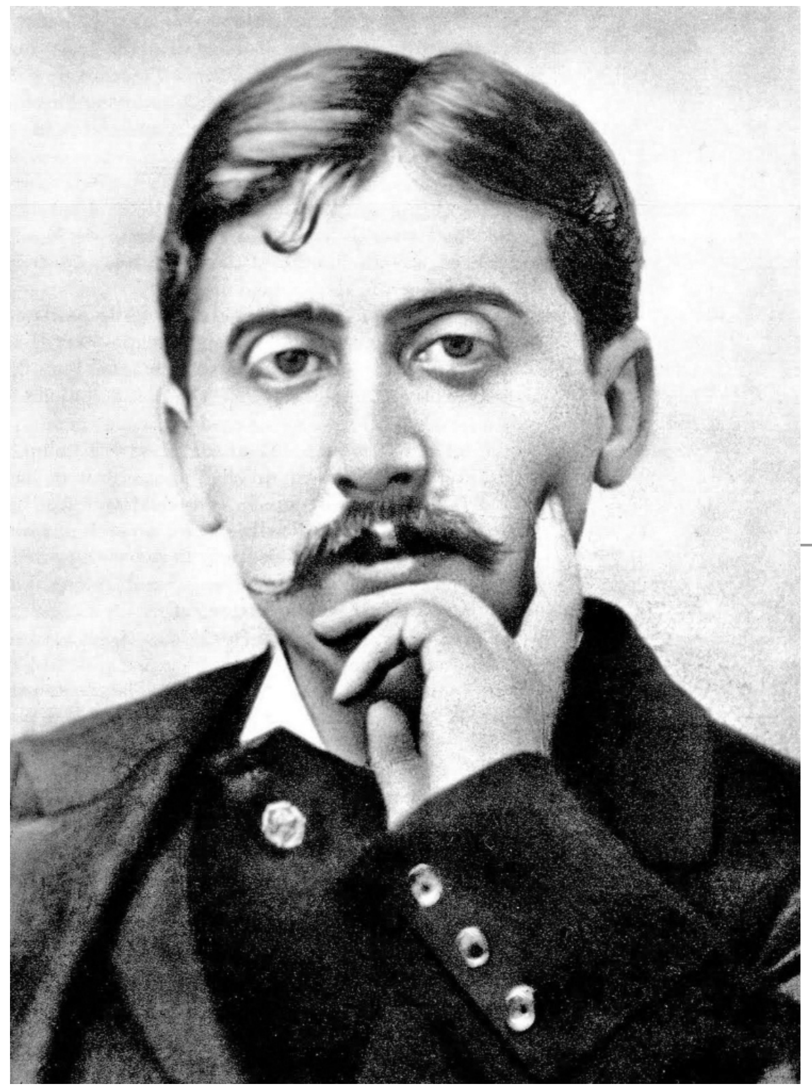
Flavour Physics is packed with Jargon (K, π, D*, K*, ADS, C9, OS etc.)

However the underlying physics is fascinating

Rich phenomenology and experimental techniques

Exciting implications !

Please bare with me

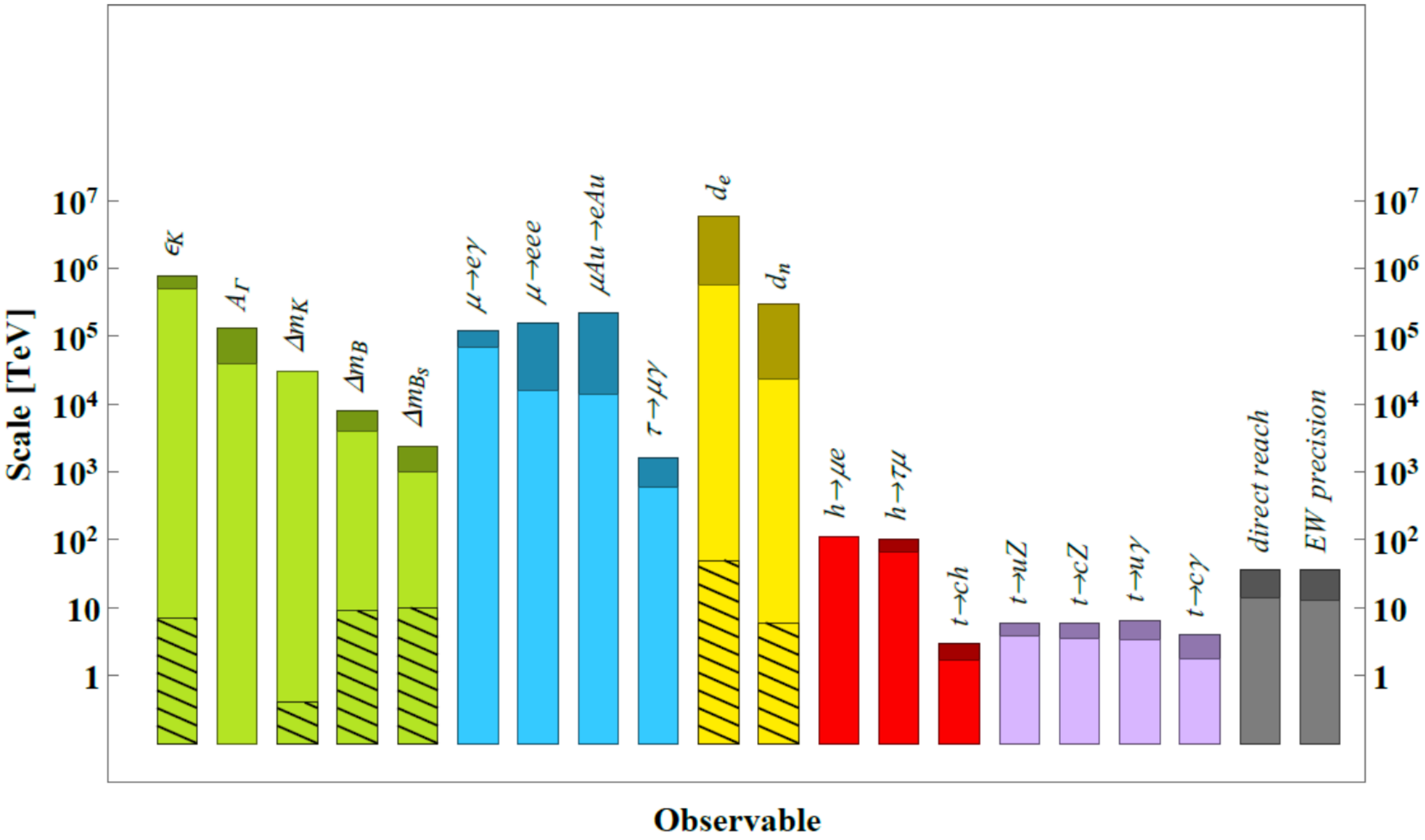


A hitchhiker guide to flavour physics
Questionnaire de Proust

What is the observable?
A branching ratio? An angle?
What is the process? A penguin? A tree?
What are we testing/measuring? NP? SM?
What is the statistics? Rare decay? Normalisation ?
What is the topology of the decay?
Are we ever going to see it?
What about the systematics?
Do we really care about it?

If you are lost go back to these questions

Oldie but goodie - an indirect road to discoveries and high scales



Examples of Flavored Discoveries

- The smallness of $\Gamma(K_L \to \mu^+\mu^-)/\Gamma(K^+ \to \mu^+\nu)$
  $\Longrightarrow$ Predicting the charm quark
- The size of Δm_K
  $\Longrightarrow m_c$
- The size of Δm_B
  $\Longrightarrow m_t$
- The measurement of ϵ_K
  $\Longrightarrow$ Third generation
- The measurement of ν flavor transitions
- $\Longrightarrow m_\nu \neq 0$

Y. Nir

The strength of flavour physics and indirect searches

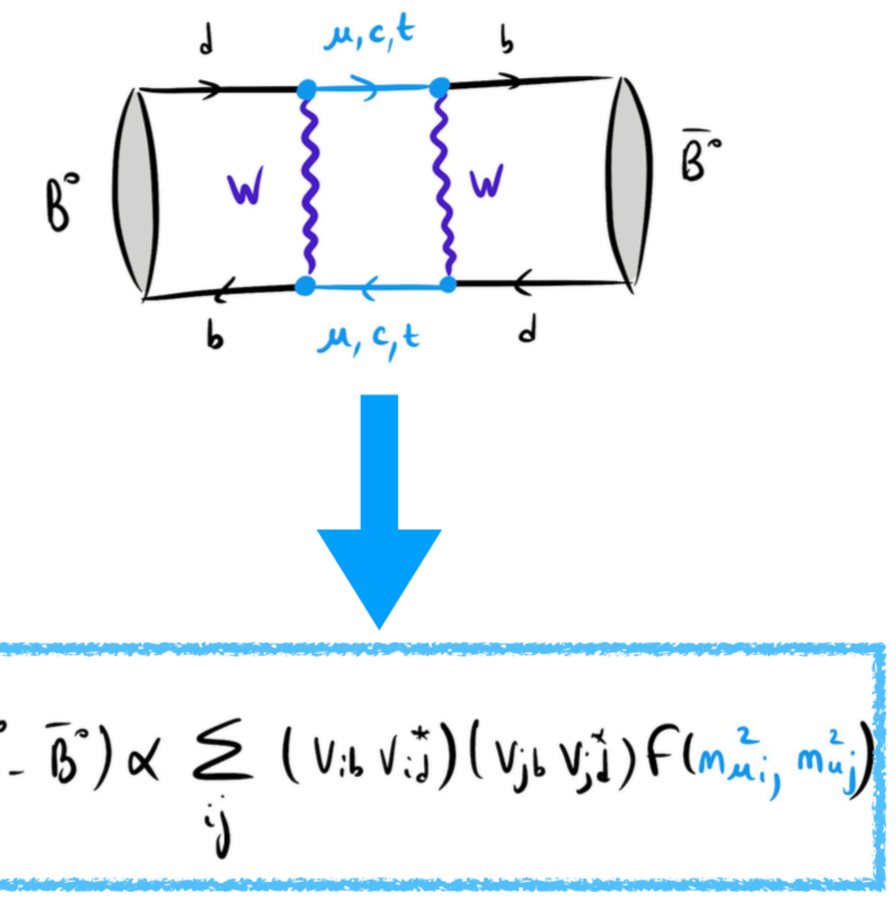
PLB 192 (1987)

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson–lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0–$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a]
$m_t > 50$ GeV/c^2	t quark mass

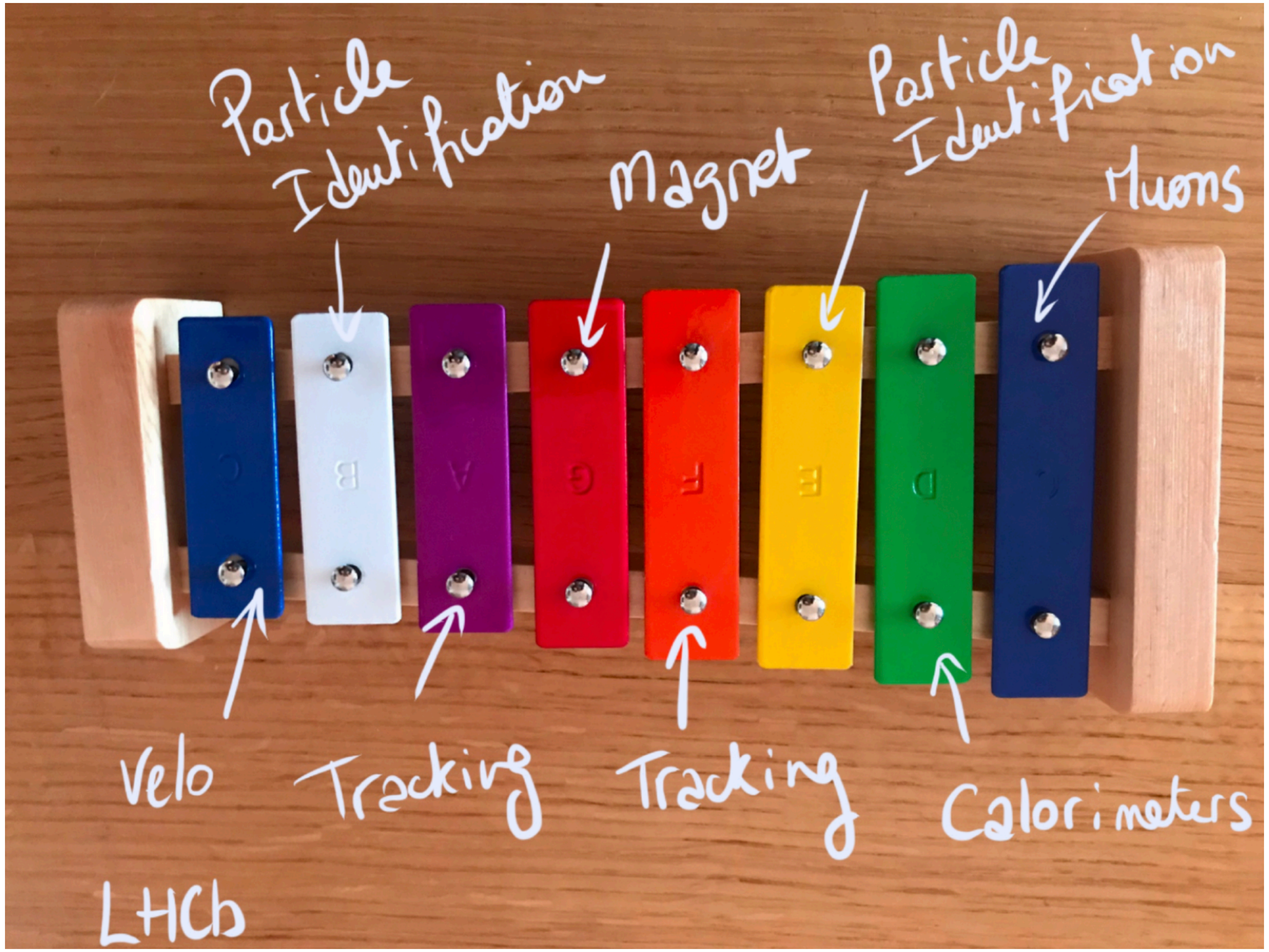


Emphasis the complementarity of direct vs indirect searches

Structure of these lectures

- Examples of historical/recent measurements.
- What makes them experimentally challenging? Blood sweat & tears.
- How do we loop back to the underlying phenomenology ?

You can't make an omelette without breaking a few eggs

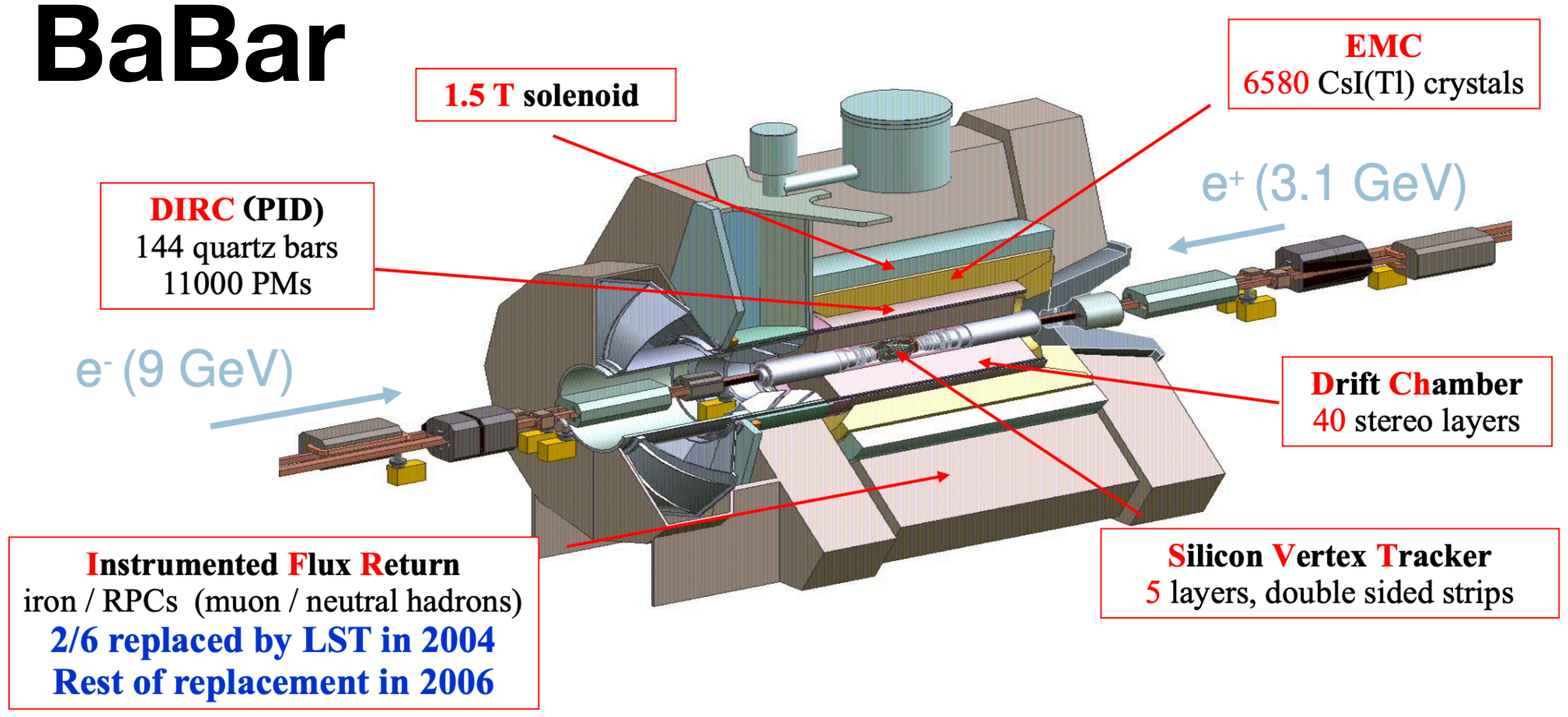


Need a collider

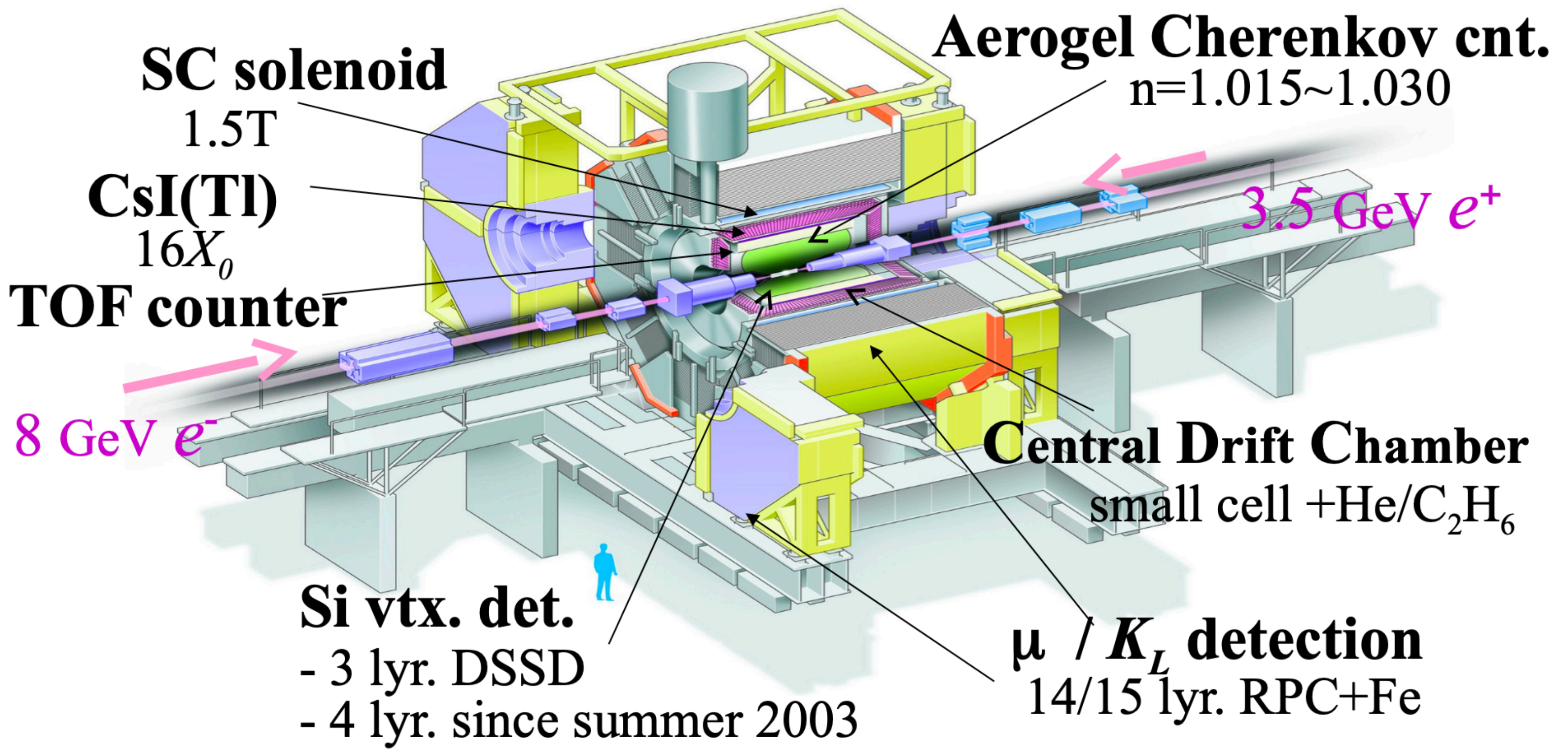
Need excellent:
Vertexing
Tracking
PID
Calorimetry
Versatile triggers

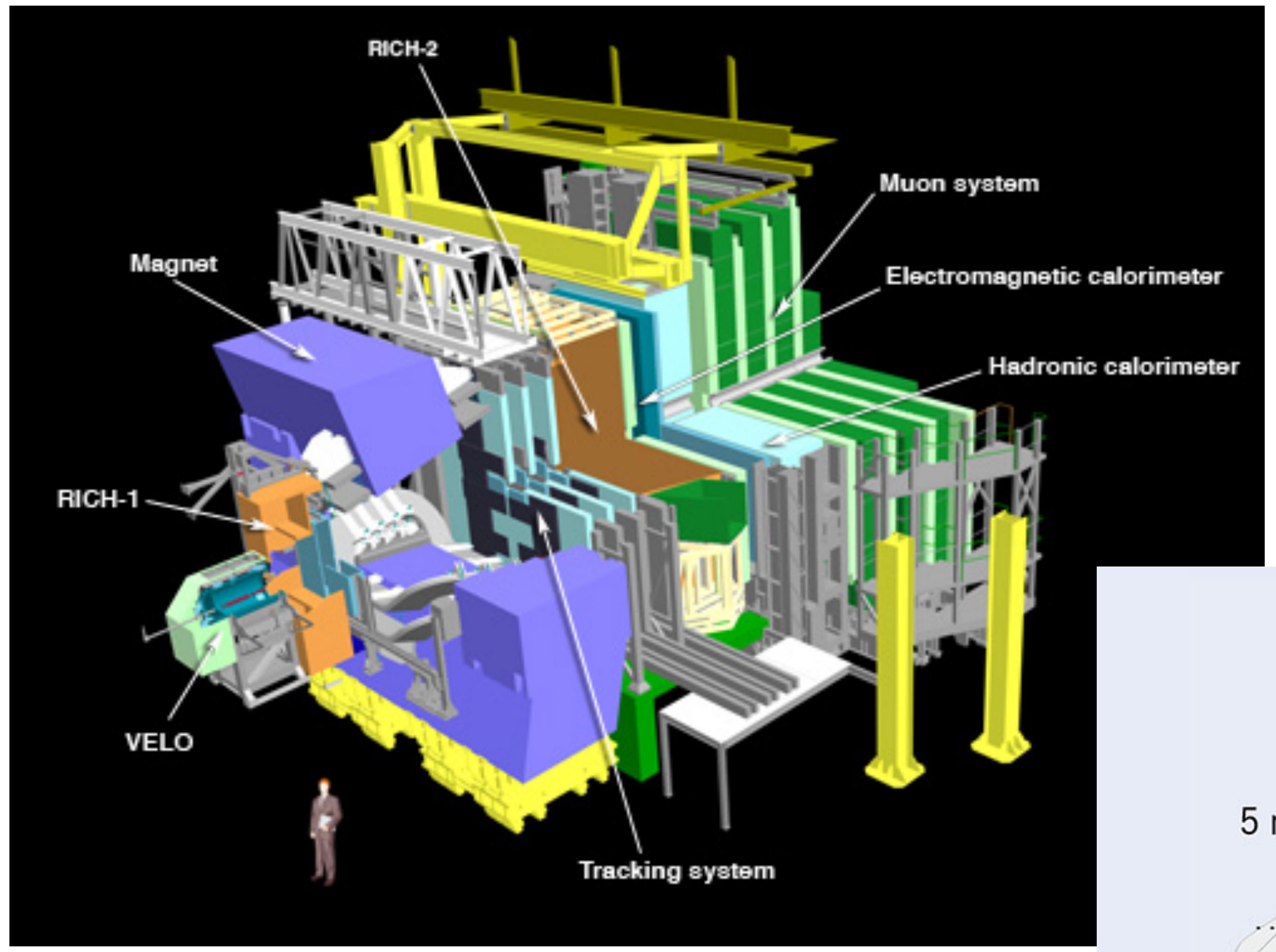
Often we can't have everything at the same time
…decisions decisions…

BaBar

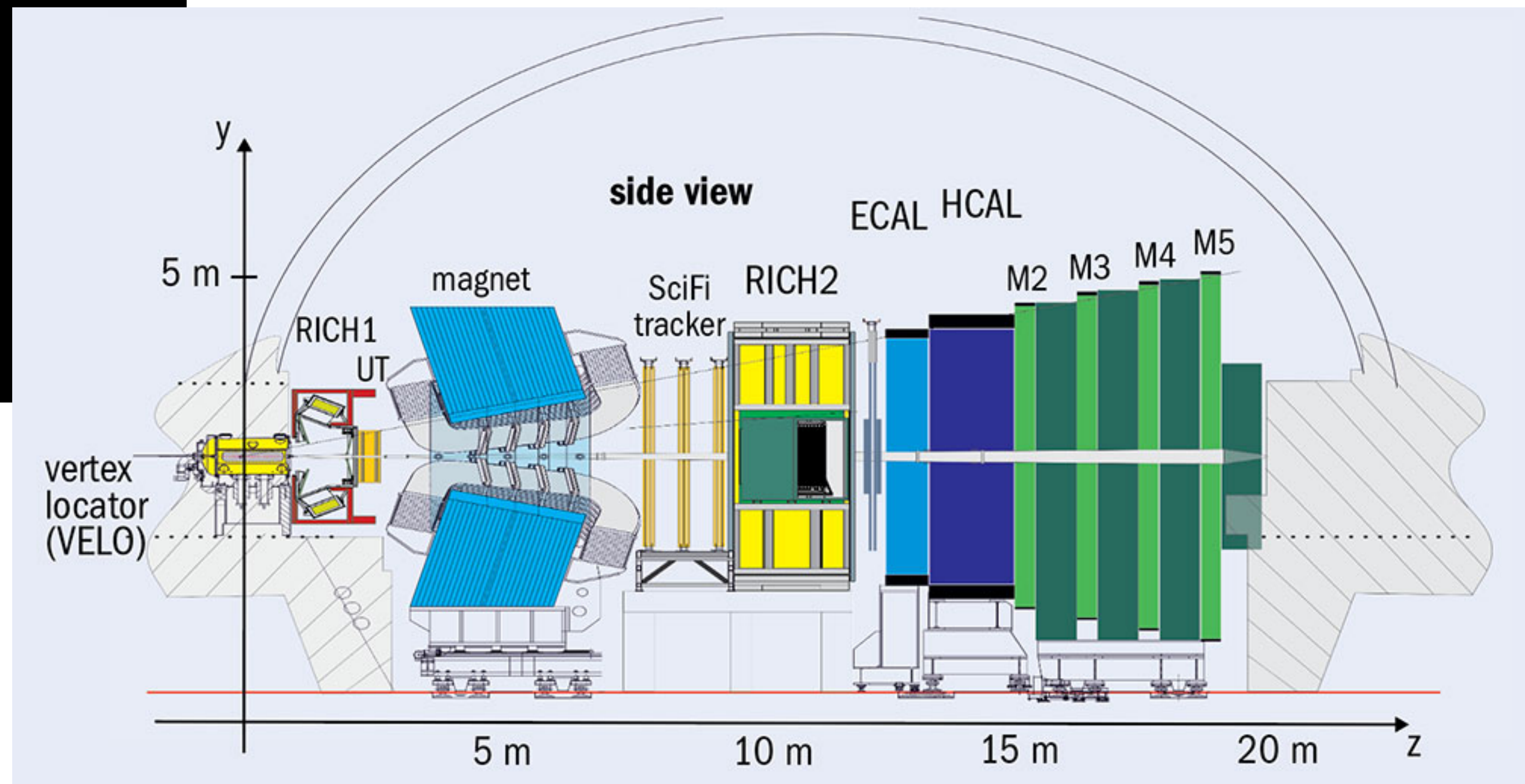


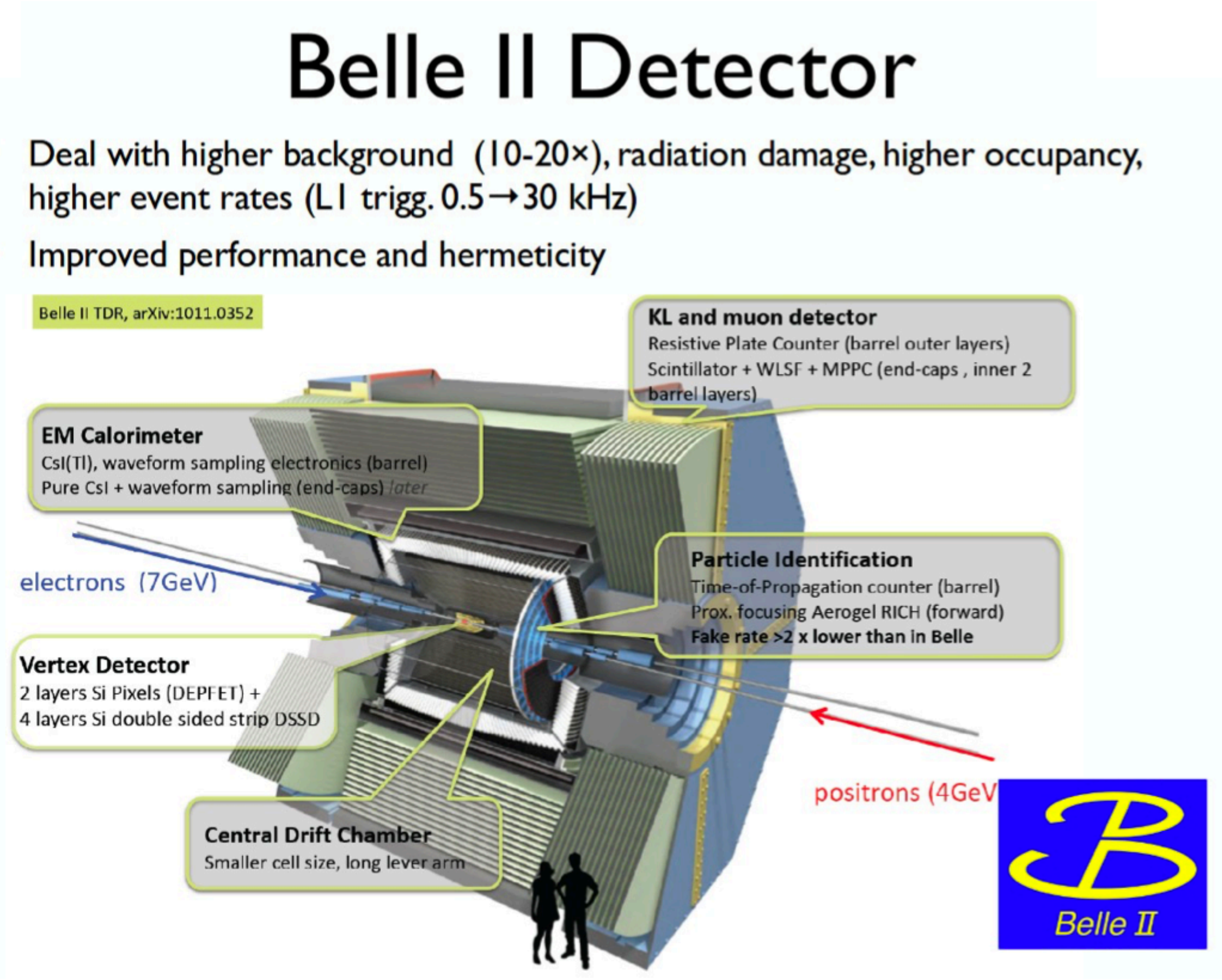
Belle





LHCb & its Upgrades

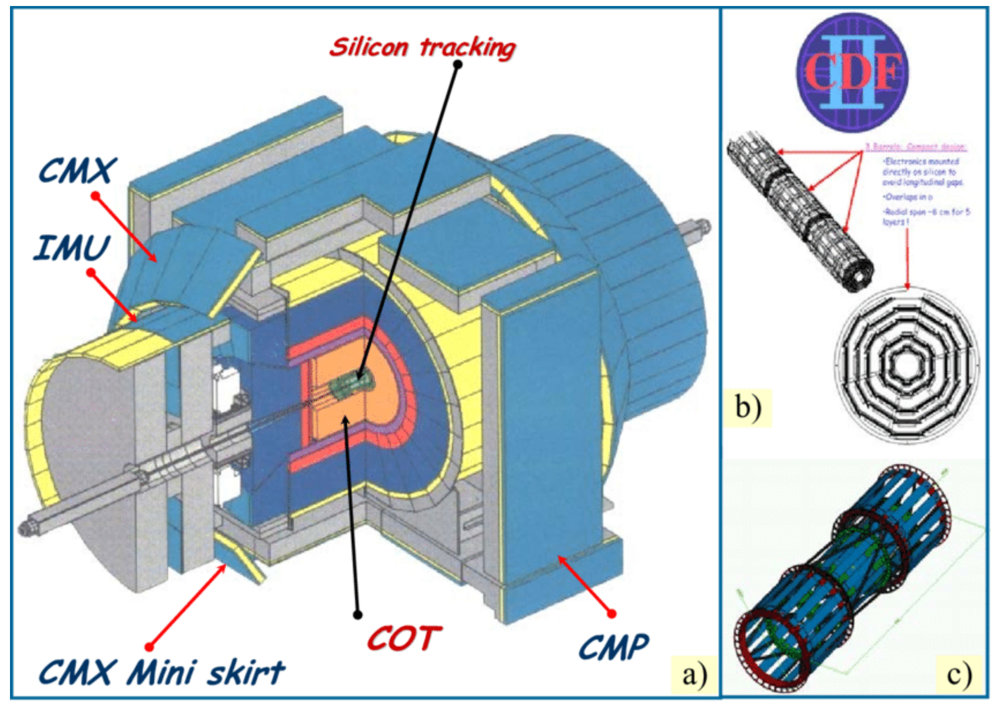


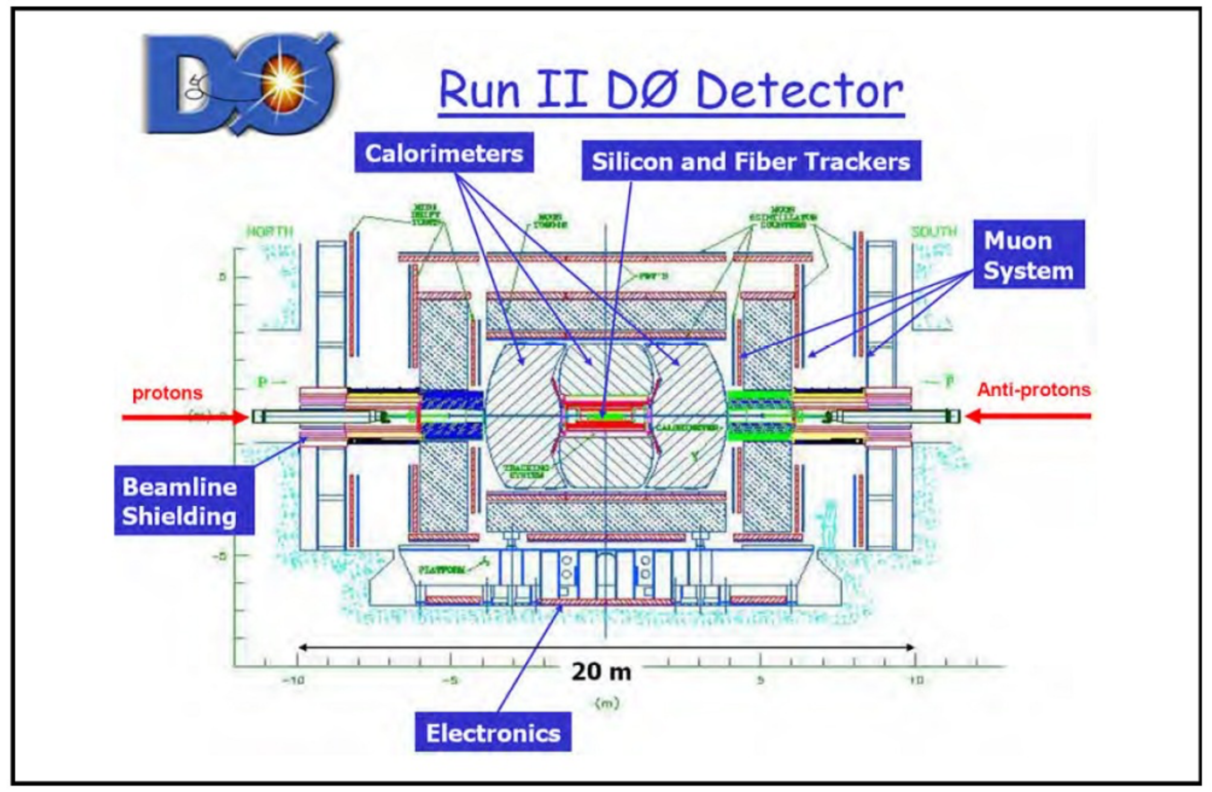


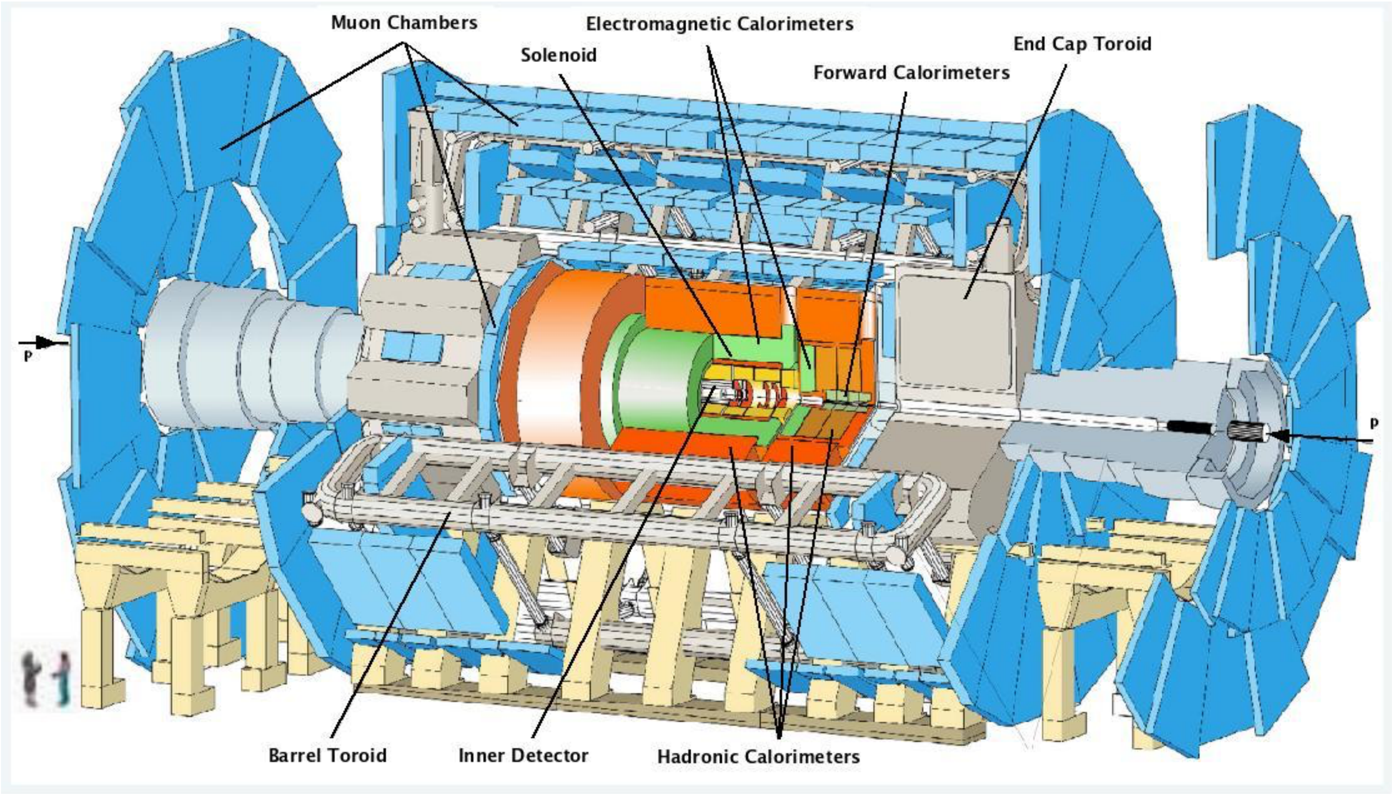
Have a look at all the TDRs

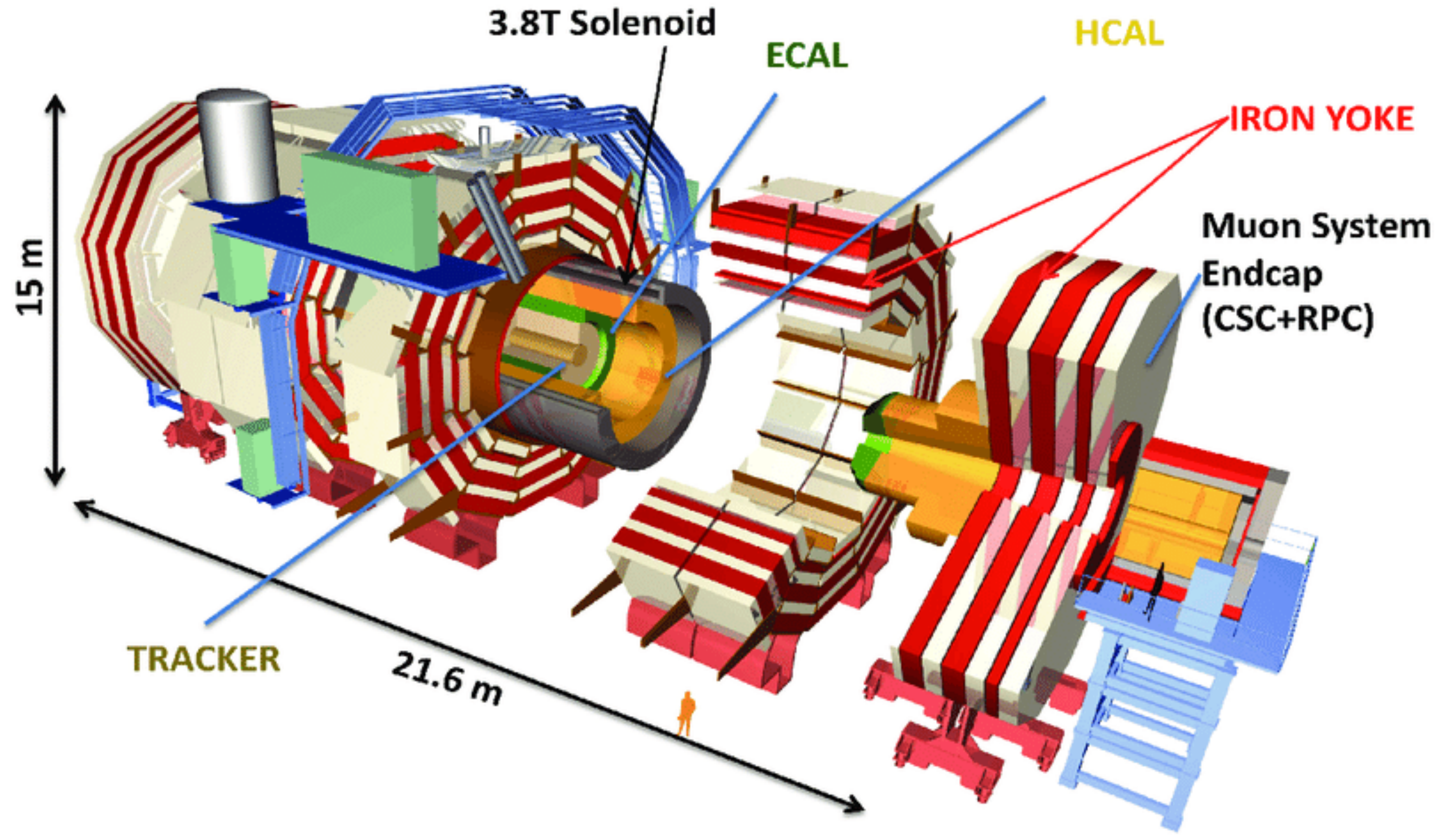
But also …

On the other side of the Ocean





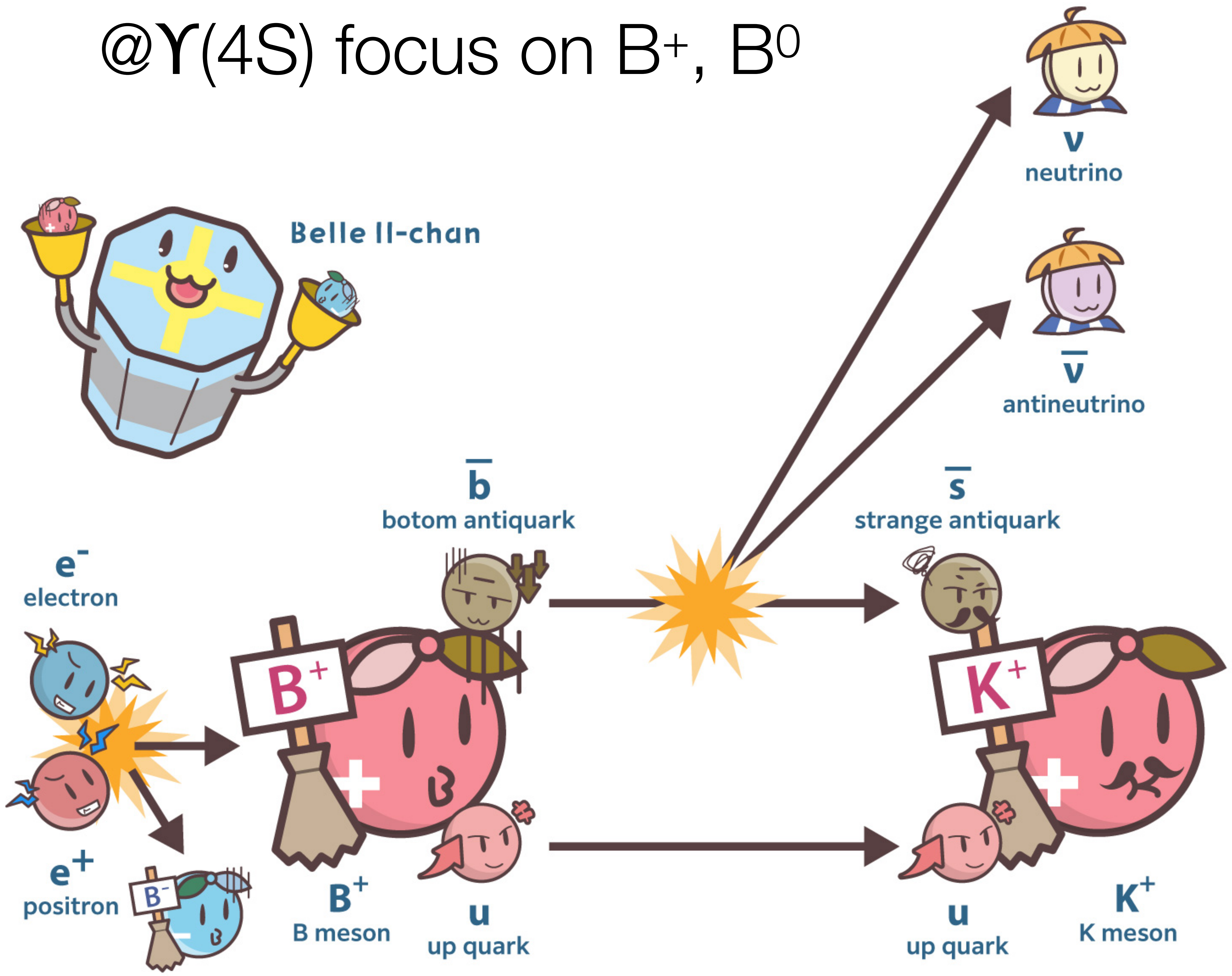




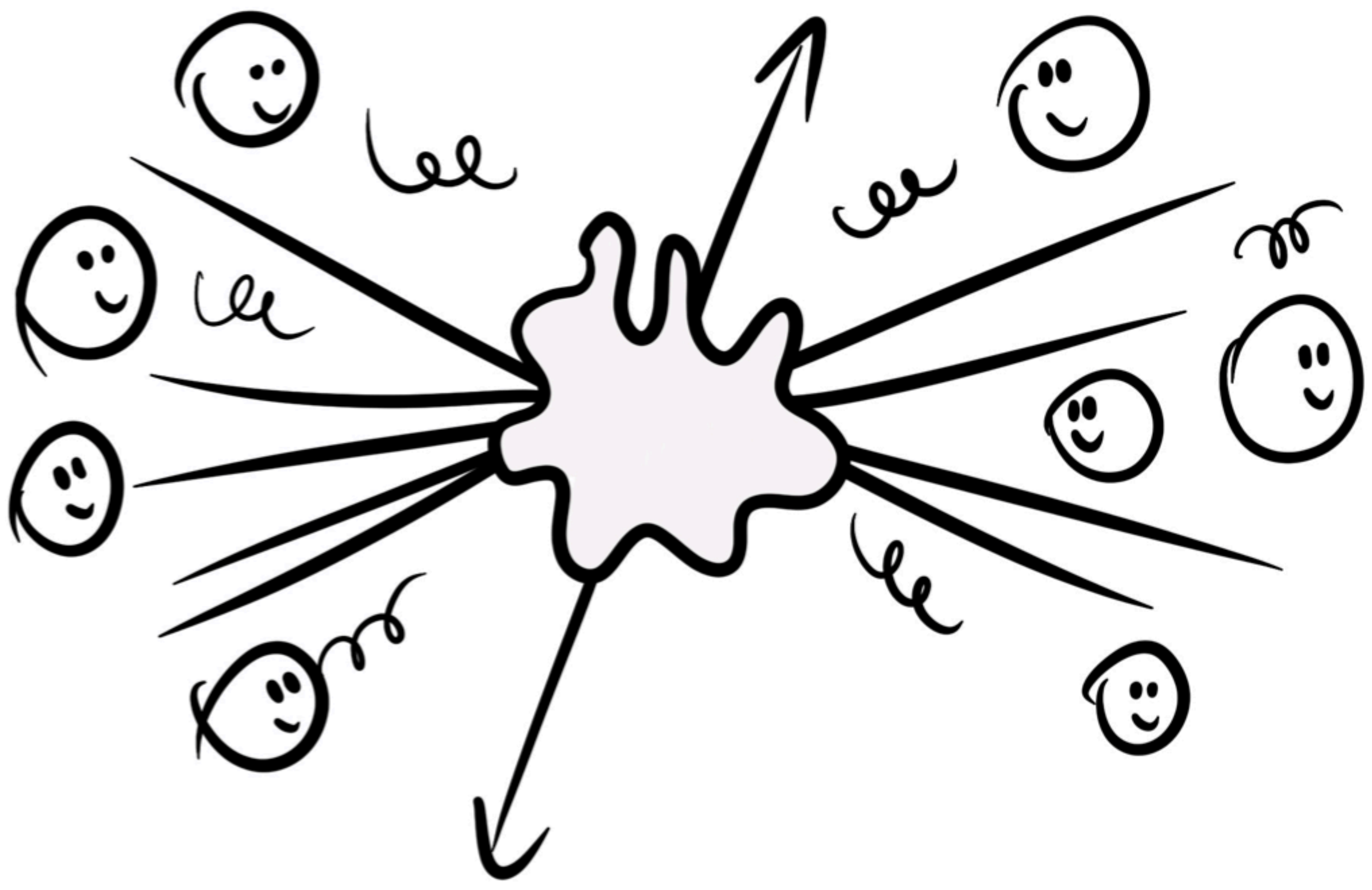
On the other side of the ring

Leptons or Hadrons

@Υ(4S) focus on B^+, B^0

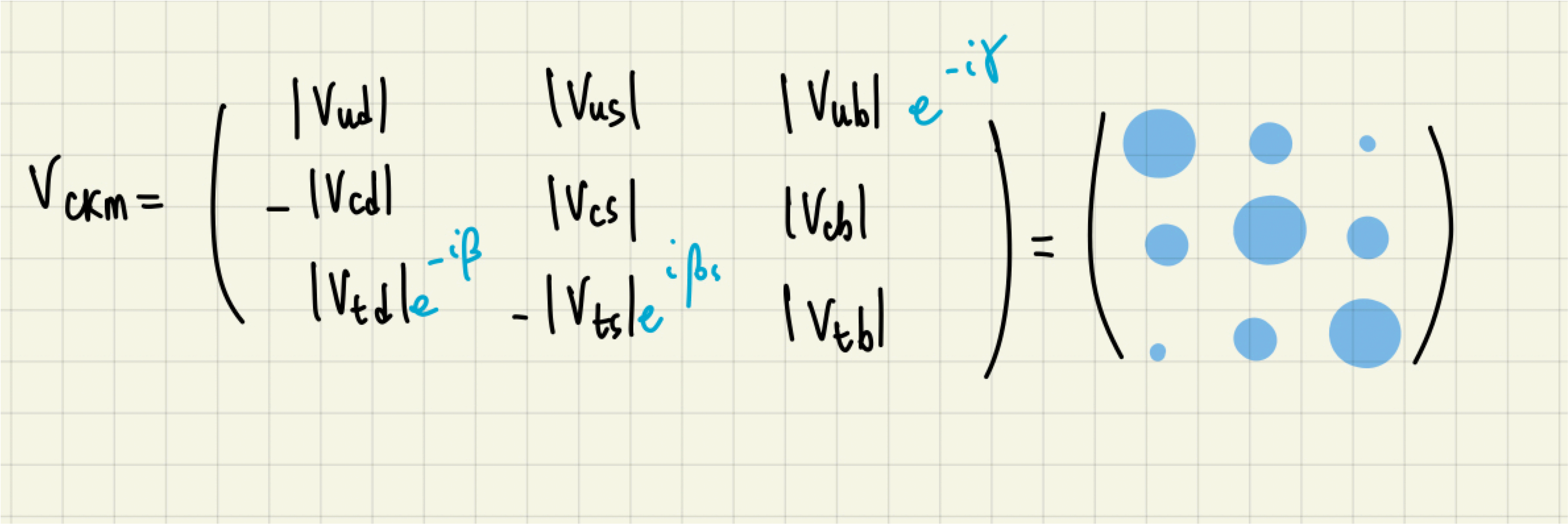


All specifies are created $B_{,u,d,s,c}$ baryons etc.



Naturally there are different challenges/advantages to each

We will start by discussing these angles

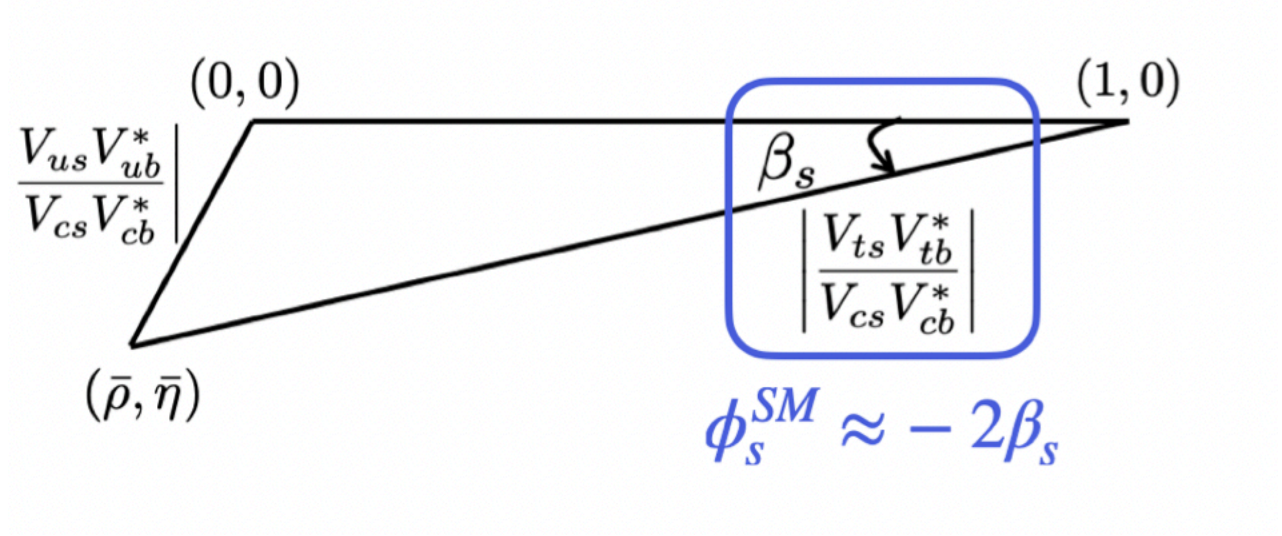


Unitarity

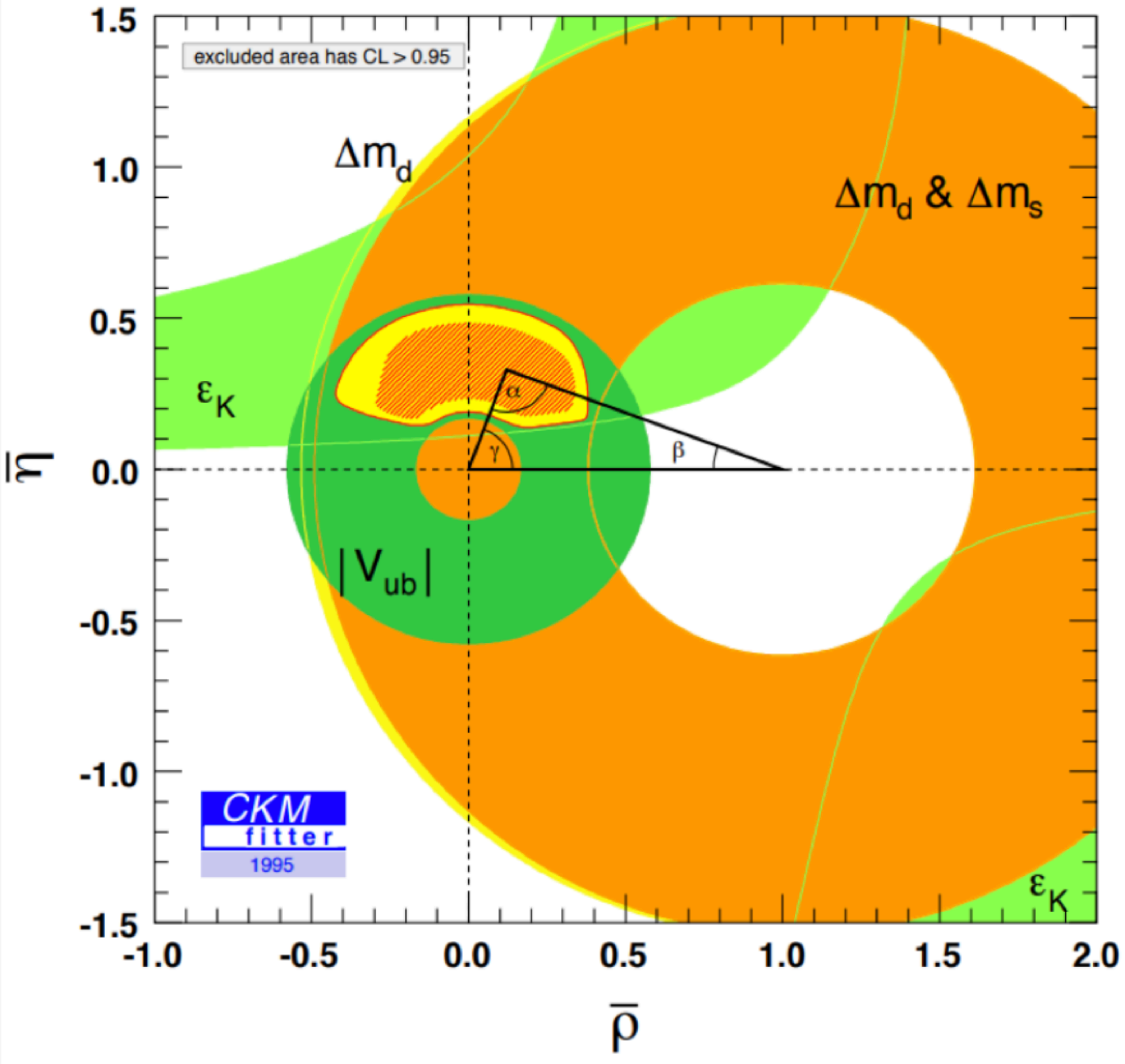
Can construct many triangles

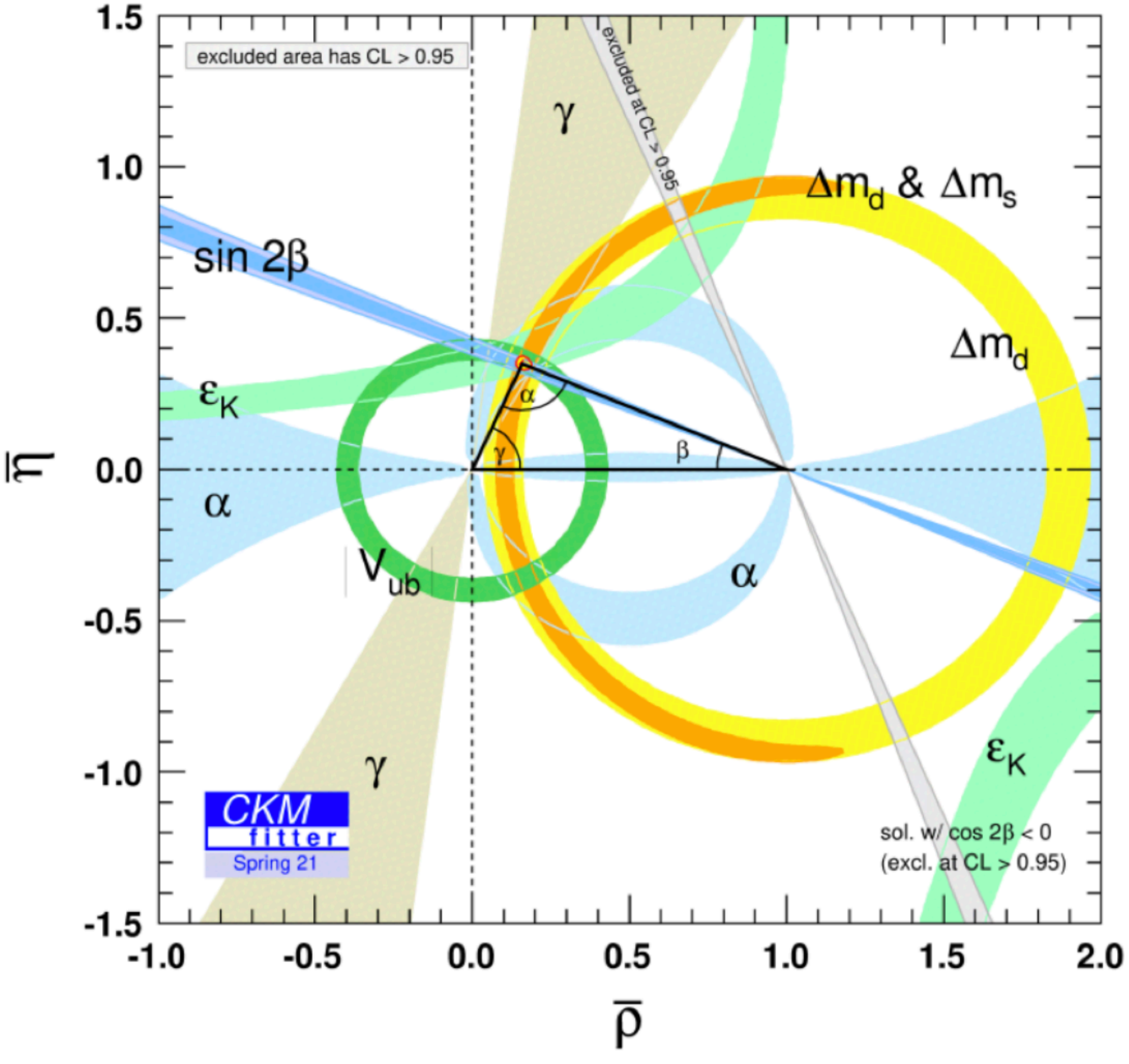
$$\sin(2\beta) = \mathrm{Im}\left(\frac{q}{p}\frac{\overline{A}_{J/\psi K^0_S}}{A_{J/\psi K^0_S}}\right)$$

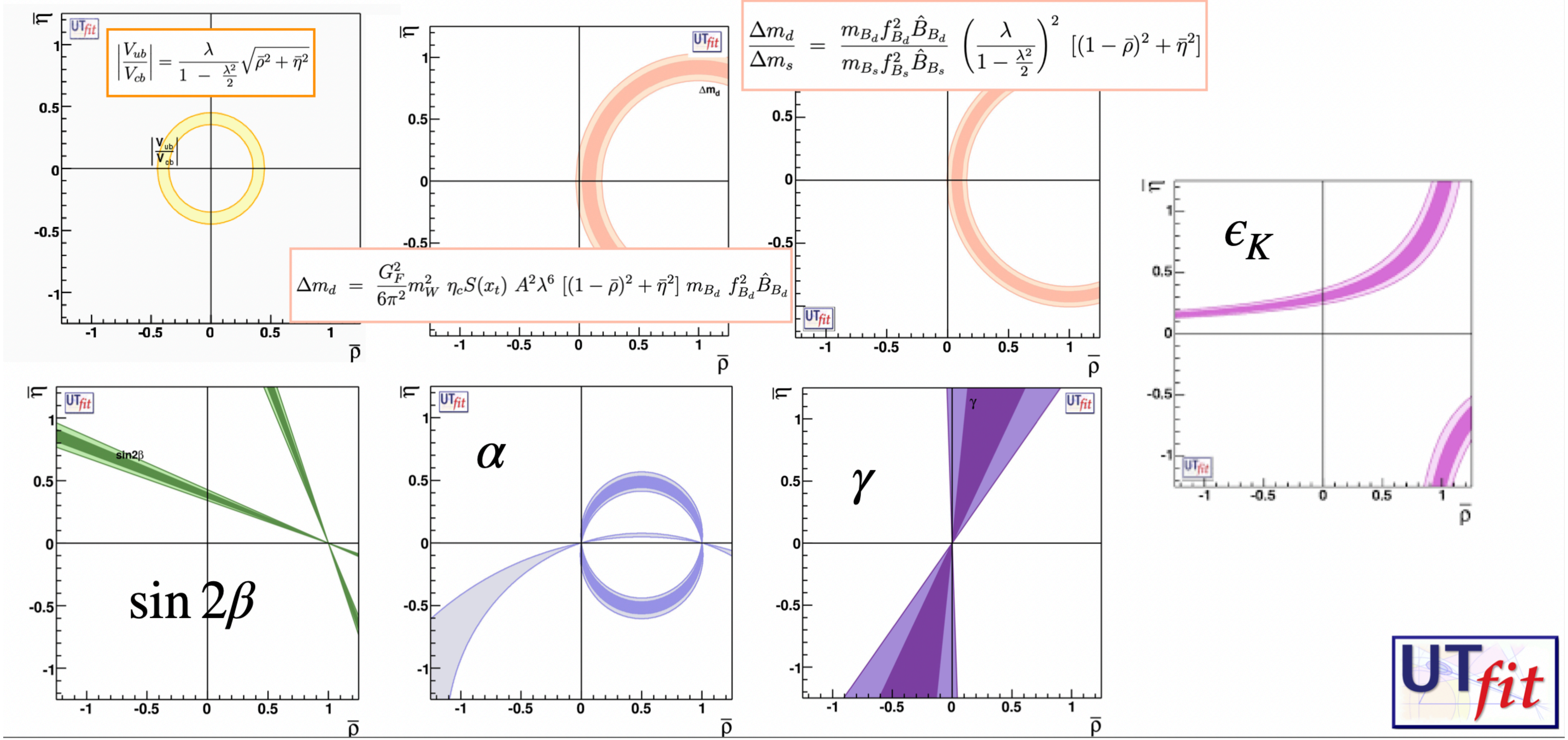
$$\beta = \arg\left(-\frac{V^*_{cb}V_{cd}}{V^*_{tb}V_{td}}\right)$$



1995 to 2021


excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
ε_K
|V_ub|
α
β
γ
ε_K
CKM fitter
1995
η̄
ρ̄


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
V_ub
α
β
γ
ε_K
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
CKM fitter
Spring 21
η̄
ρ̄

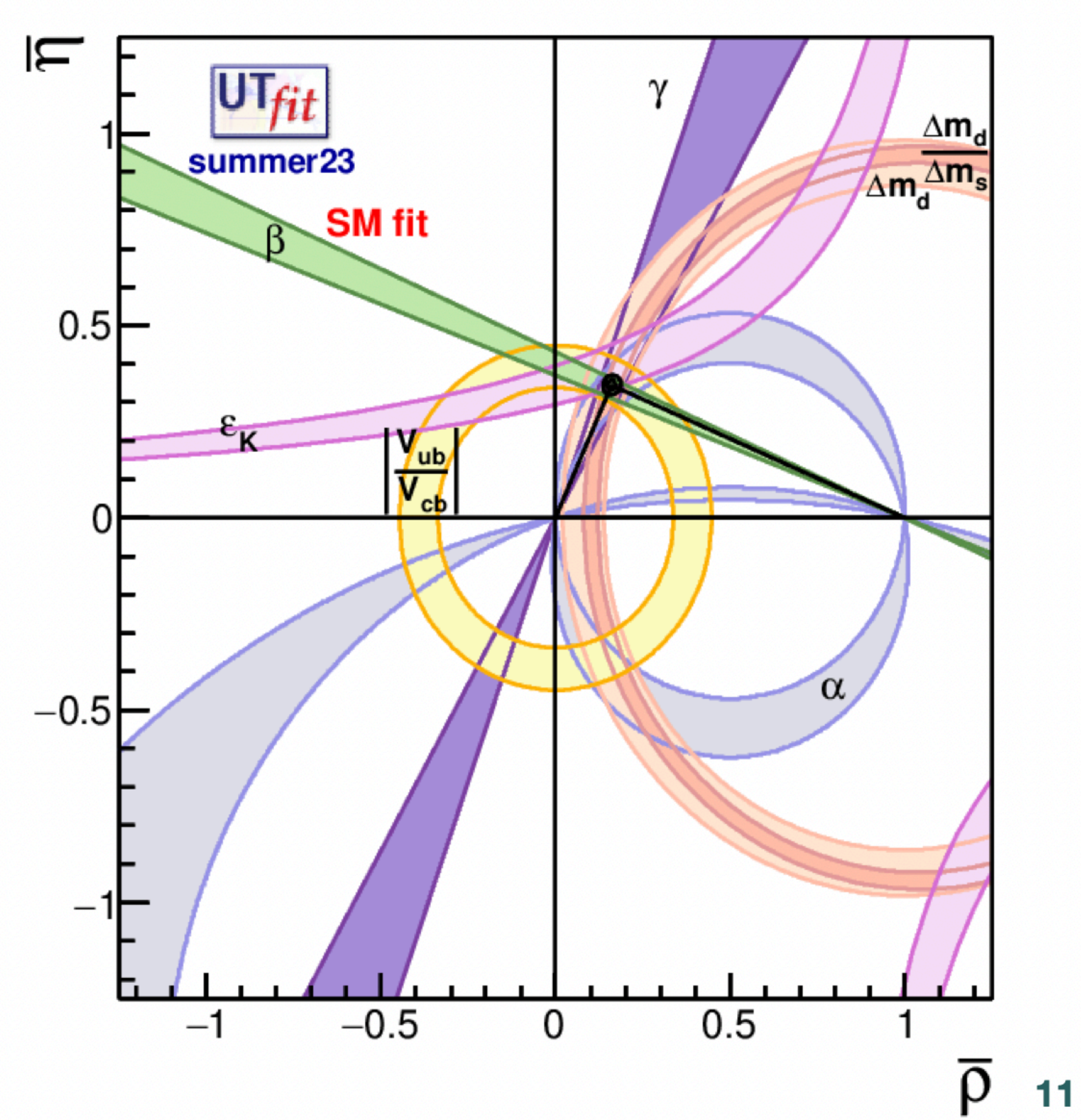


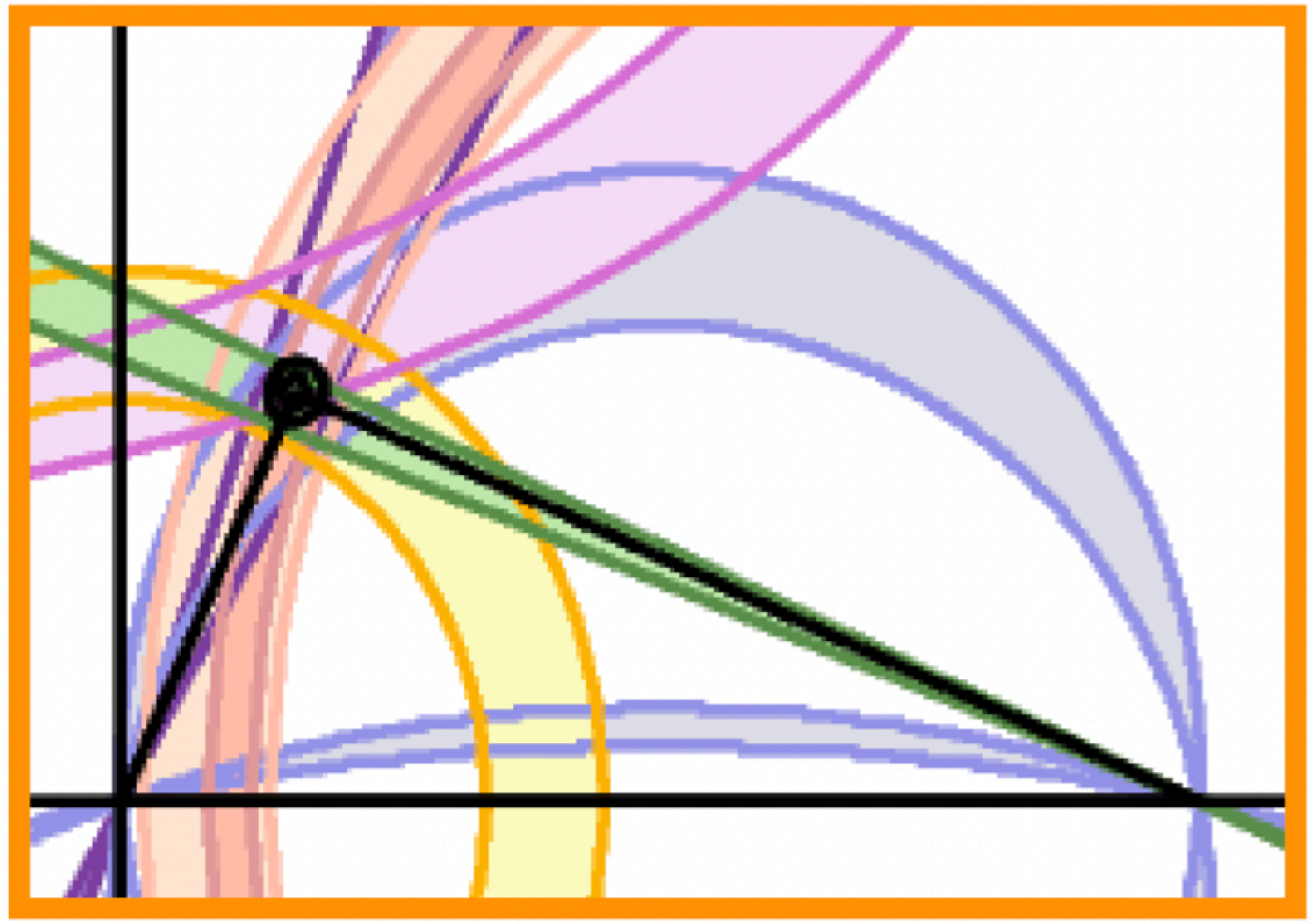
$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1-\frac{\lambda^2}{2}}\sqrt{\bar\rho^2+\bar\eta^2}$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 [(1-\bar\rho)^2+\bar\eta^2]$$

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\ \eta_c S(x_t)\ A^2\lambda^6\ [(1-\bar\rho)^2+\bar\eta^2]\ m_{B_d}\ f_{B_d}^2 \hat{B}_{B_d}$$

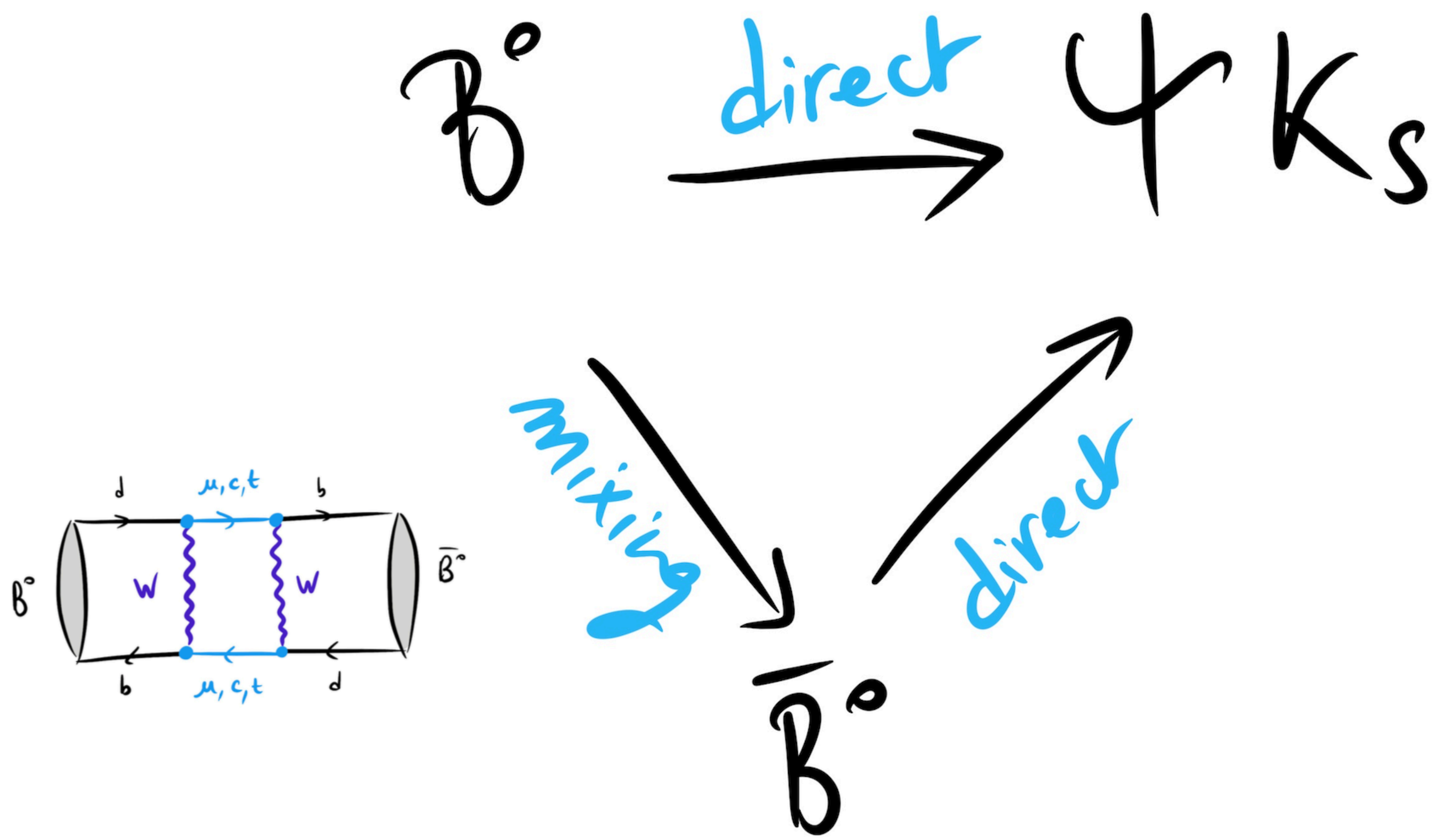
Overall, we see a very consistent picture…this could be the end of the lecture ?

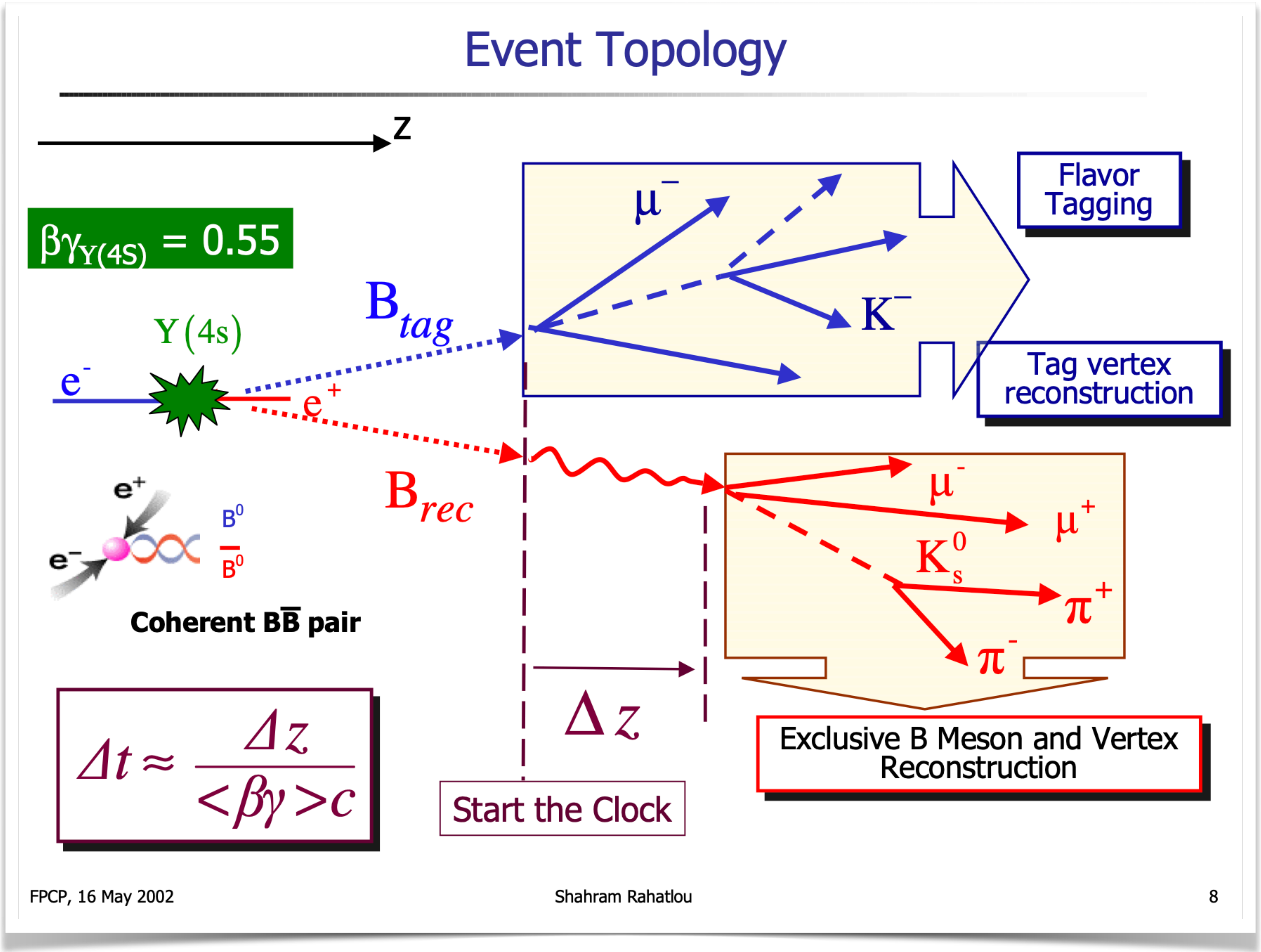




$$\bar{\rho} = 0.160 \pm 0.009$$
$$\bar{\eta} = 0.345 \pm 0.011$$

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



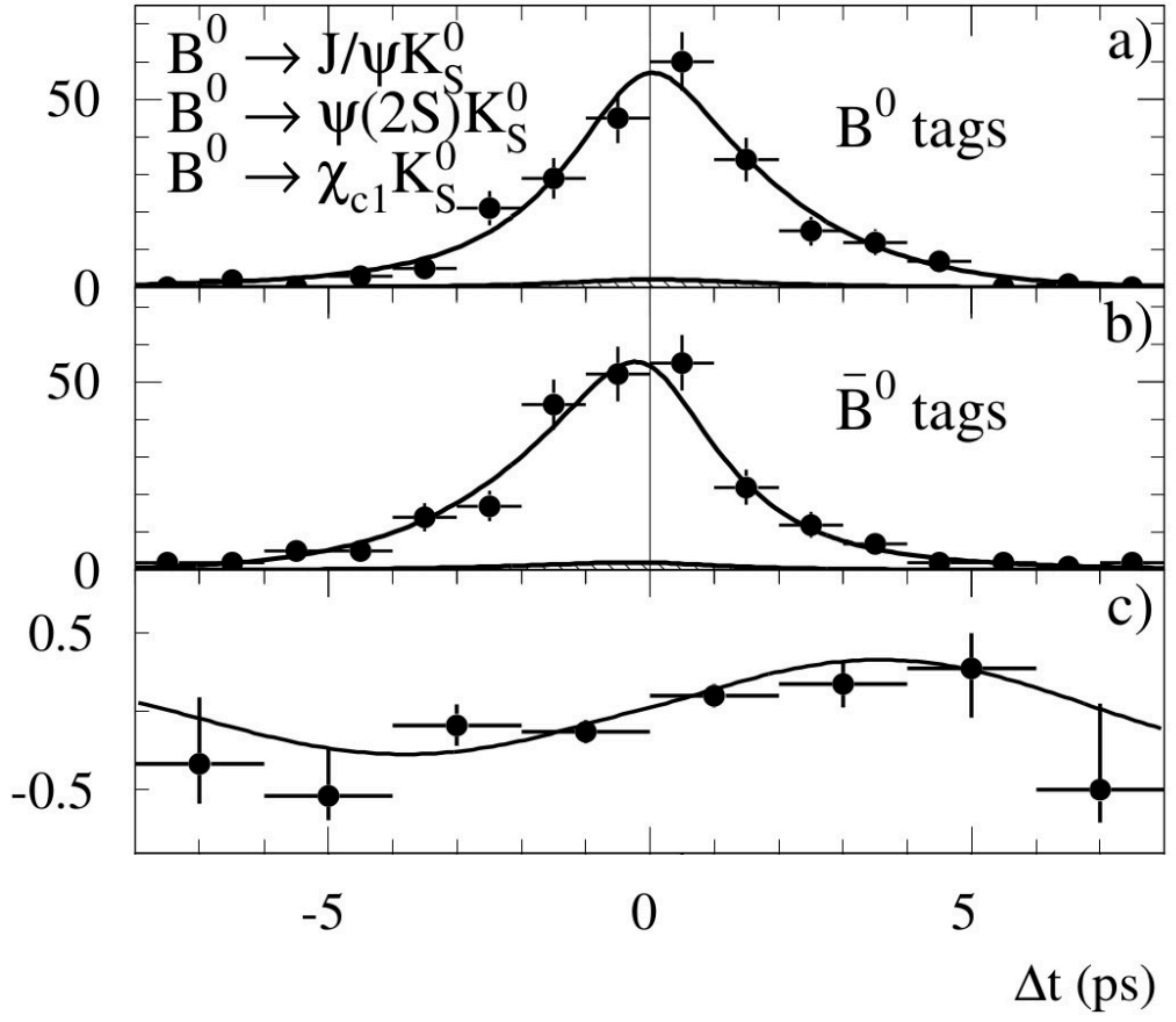


$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\bar{B}^0(t)\to\psi K^0_S) - \Gamma(B^0(t)\to\psi K^0_S)}{\Gamma(\bar{B}^0(t)\to\psi K^0_S) + \Gamma(B^0(t)\to\psi K^0_S)} \approx \underbrace{D_{\Delta t} D_{FT}}_{\text{Experimental dilution factors}} S \sin(\Delta m_d t)$$

Time dependent analysis → requires flavour tagging

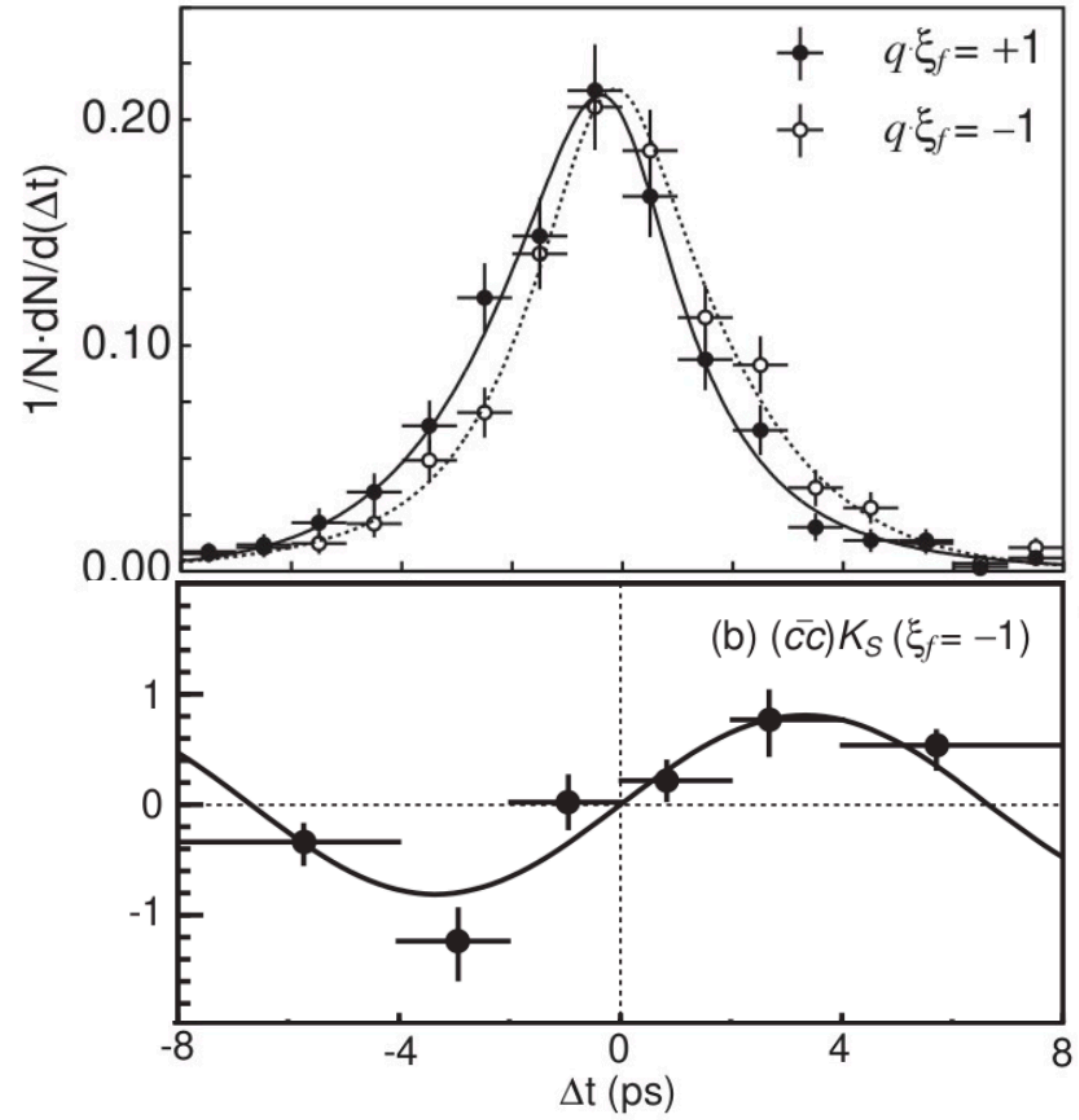
sin 2β aka the raison d’être of B-factories - 2001

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

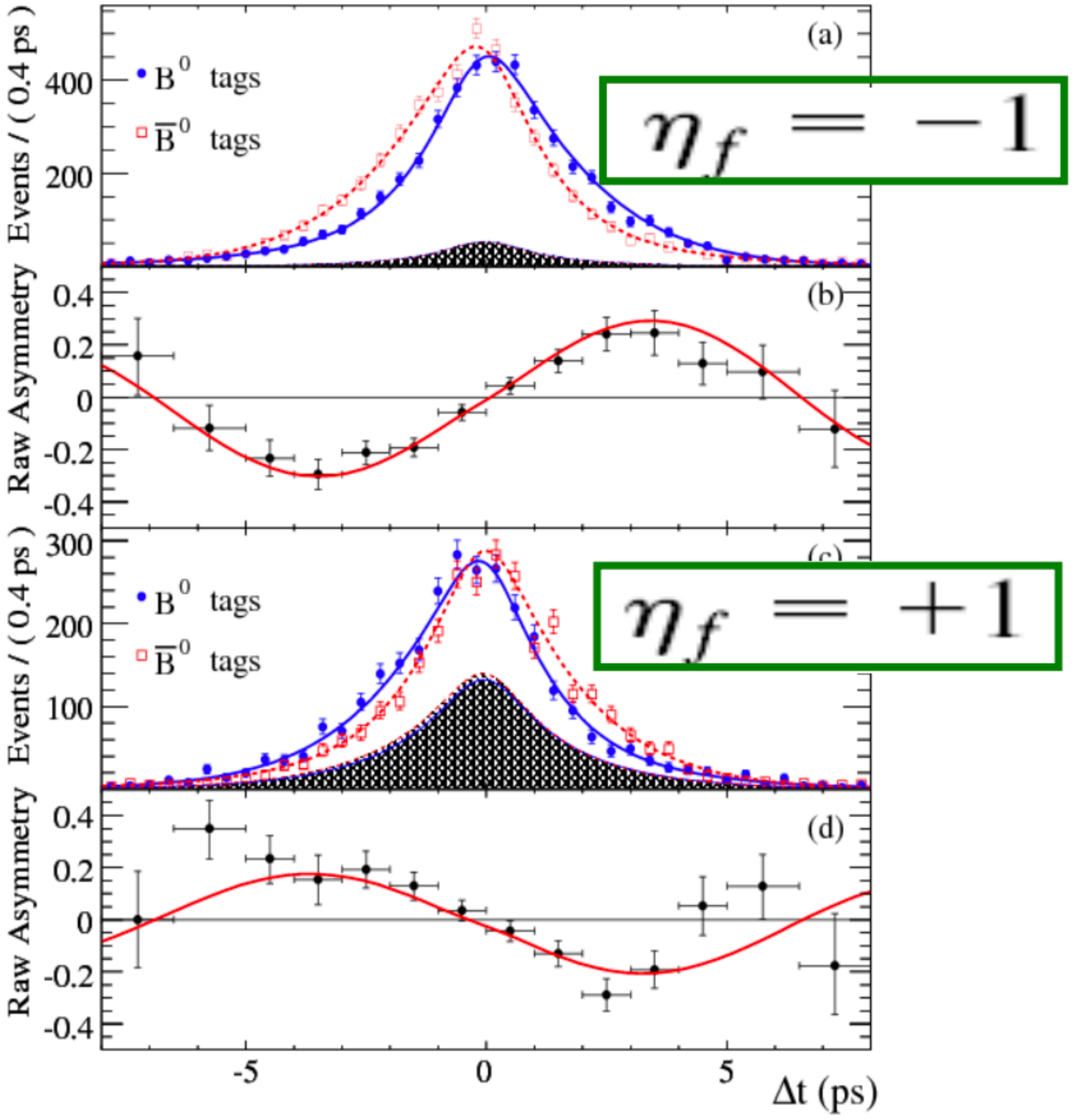


$$\sin 2\phi_1 = 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst}).$$

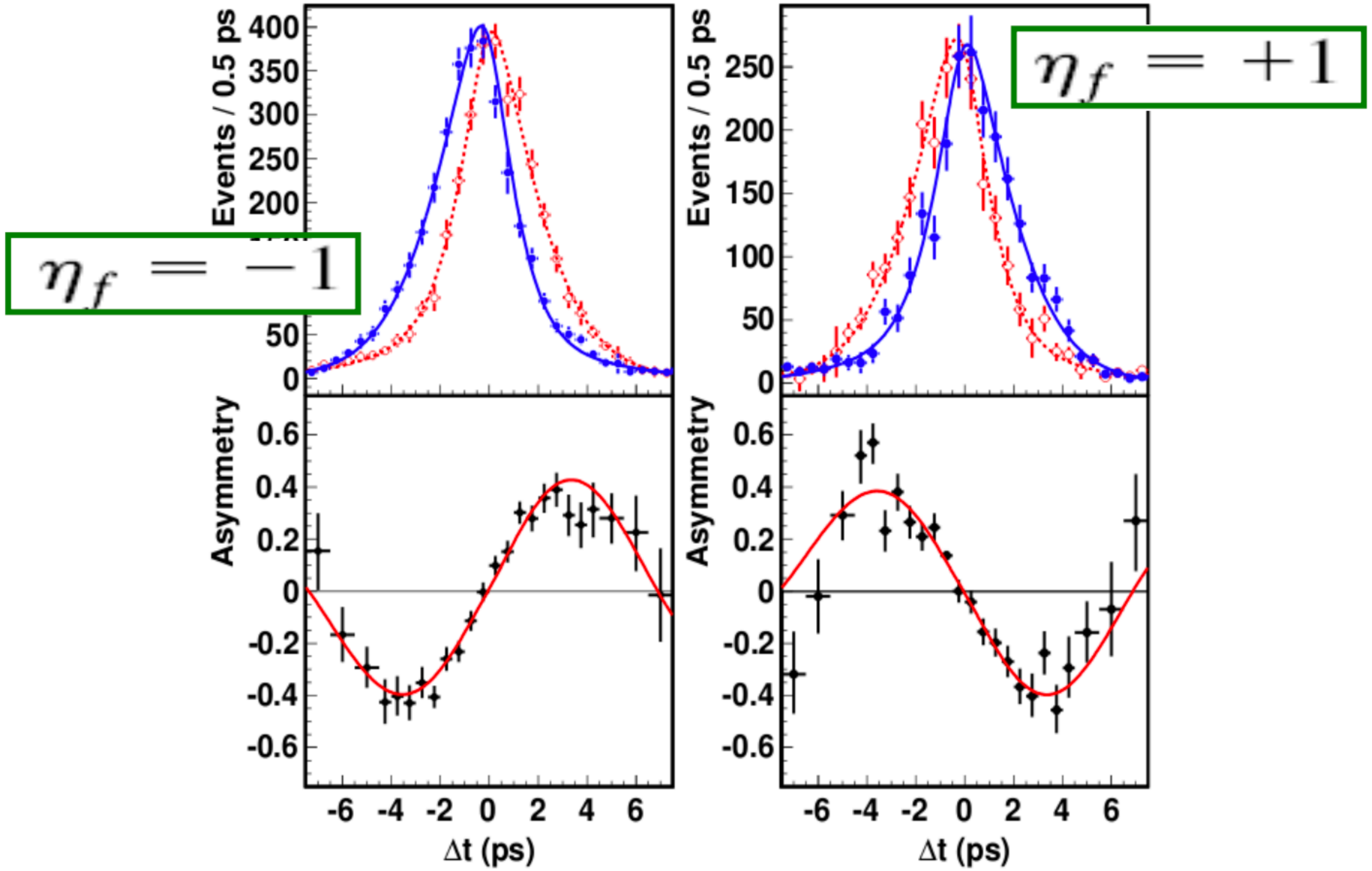
Different conventions on each side of the pacific

Legacy from B-Factories

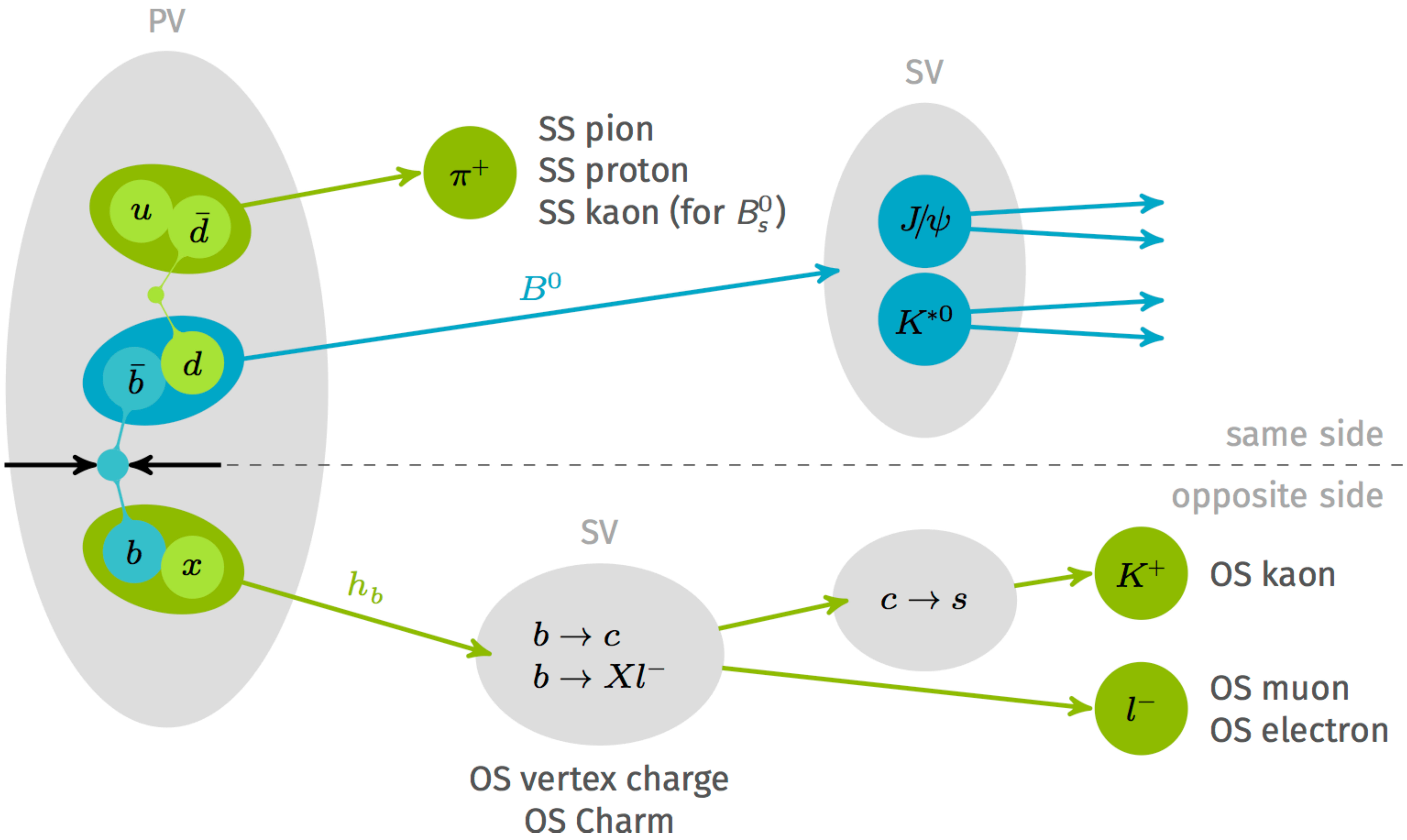
BaBar, PRD 79 (2009) 072009



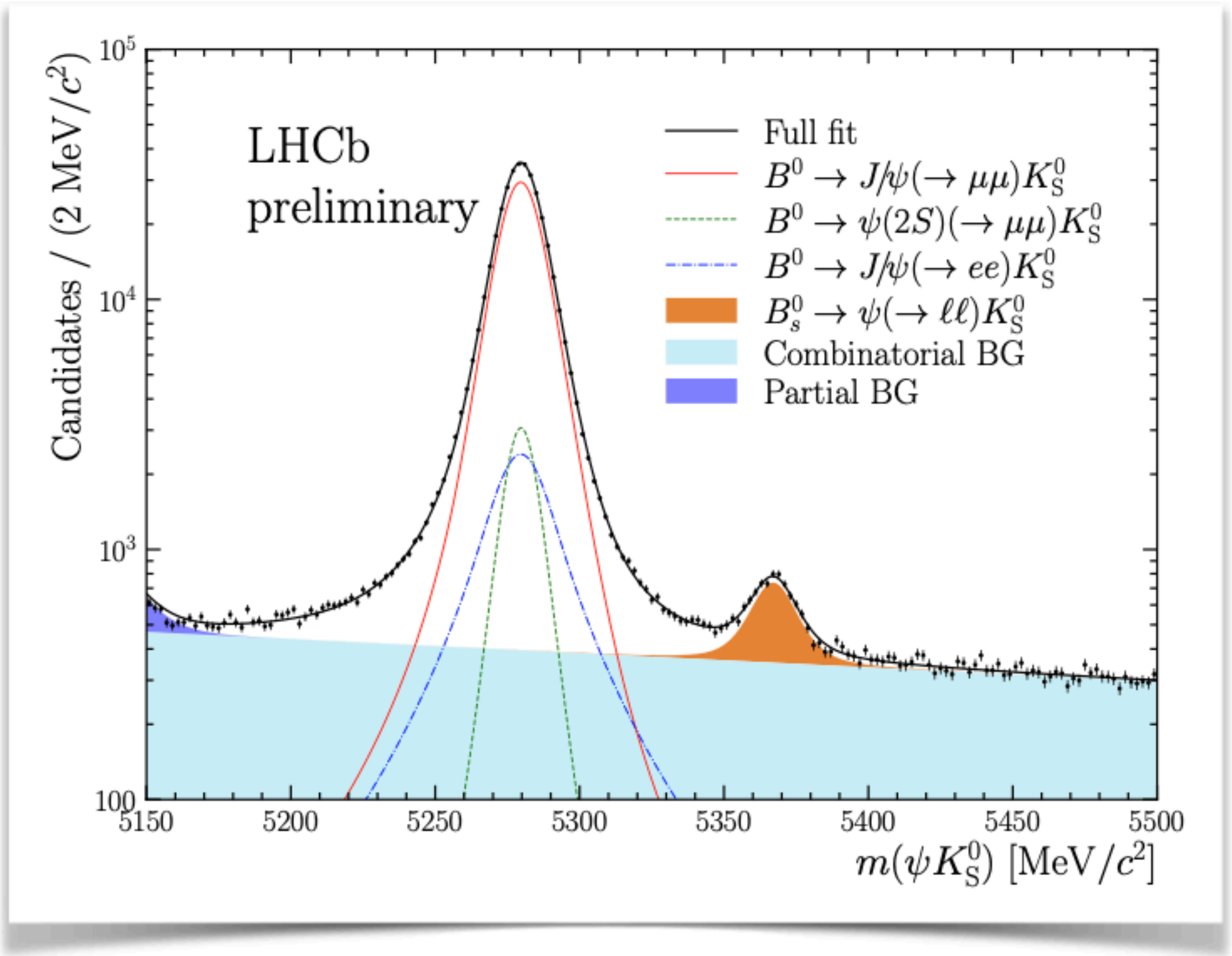
Belle, PRL 108 (2012) 171802



Flavour Tagging @ LHCb



Text book like result !

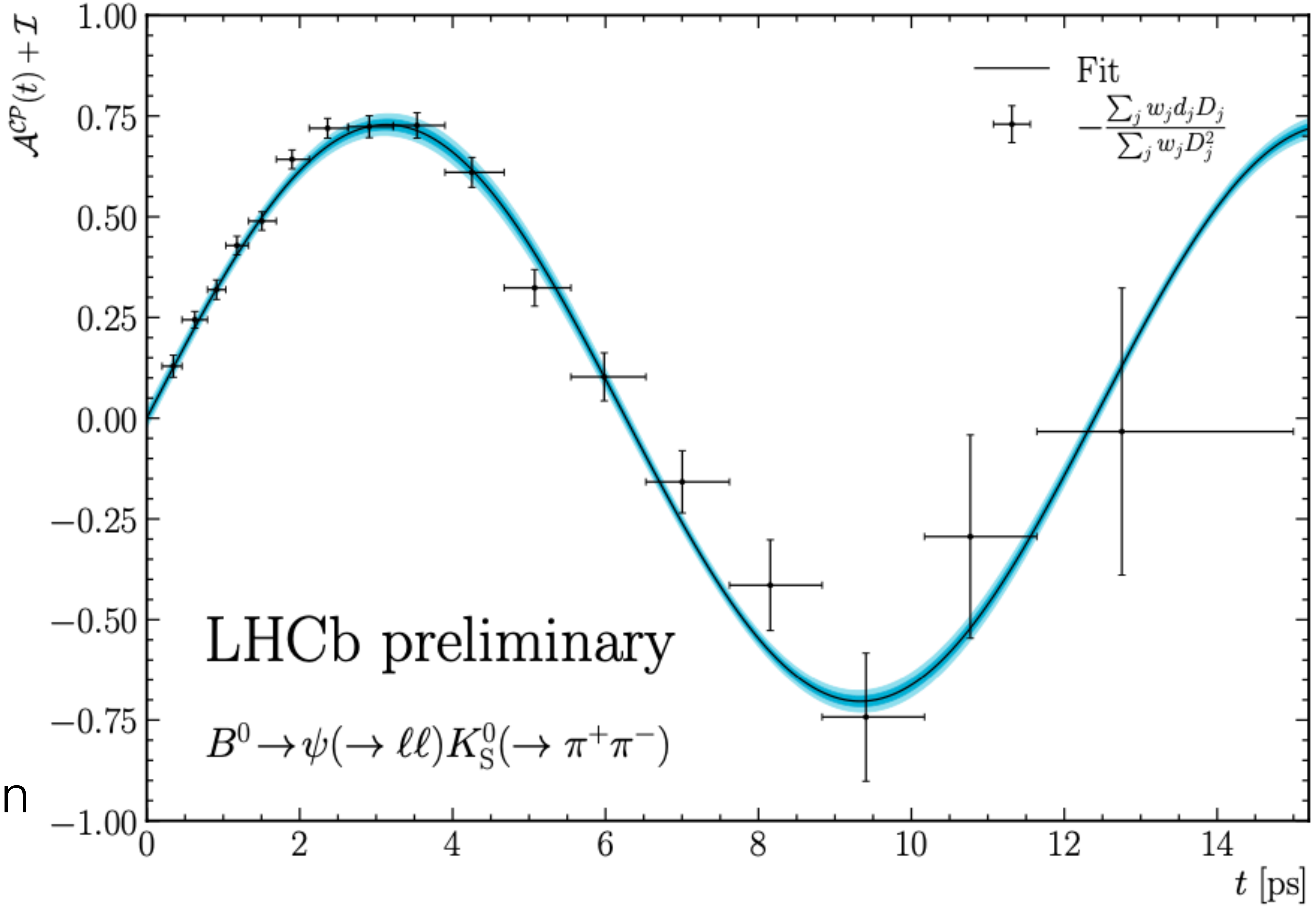


Flavour tagging

Importance of efficient reconstruction

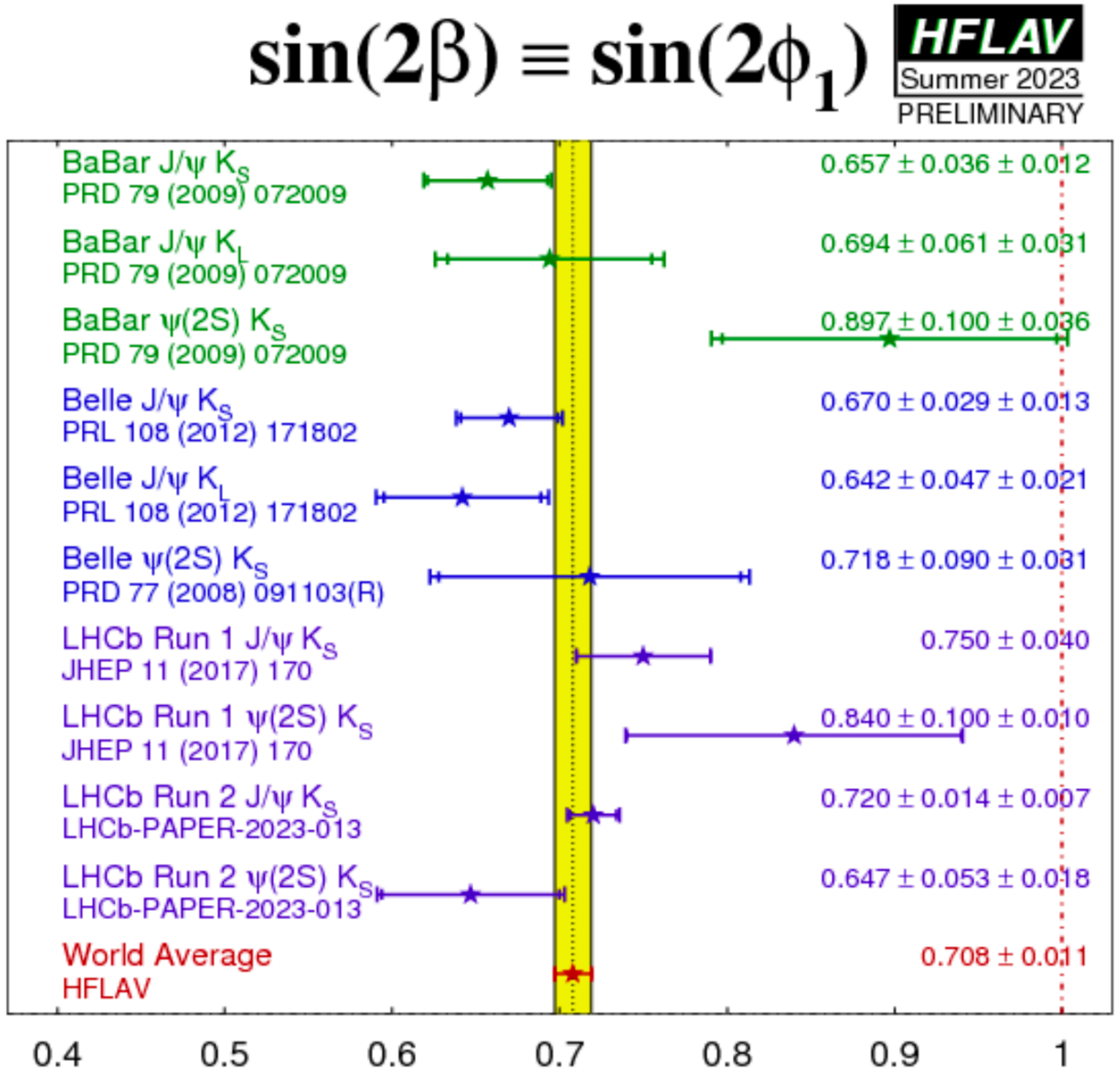
Understanding tiny effects

Combination of a few decay channels

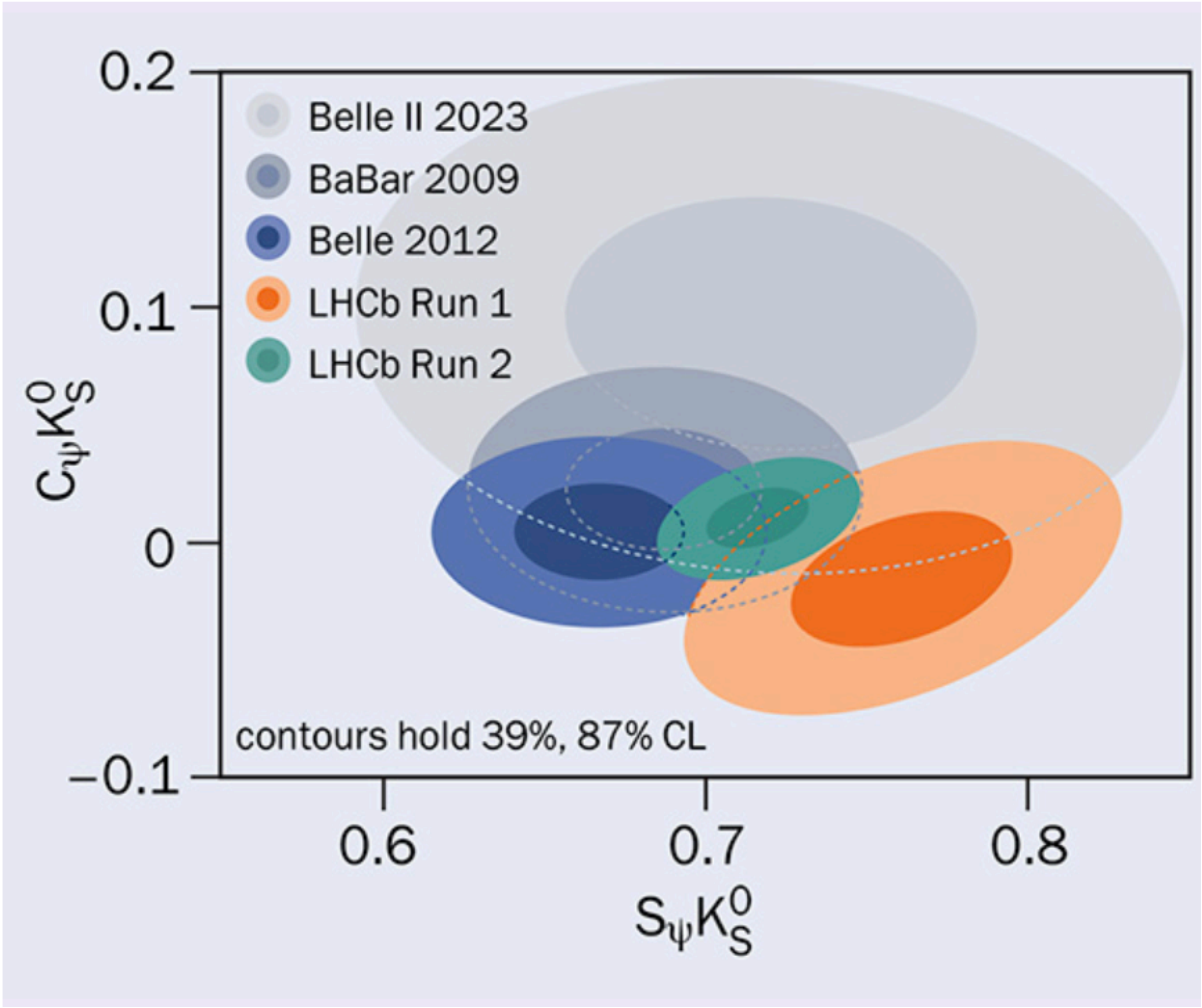


Trigger wise dilepton decays are a day at the beach

Summary plot

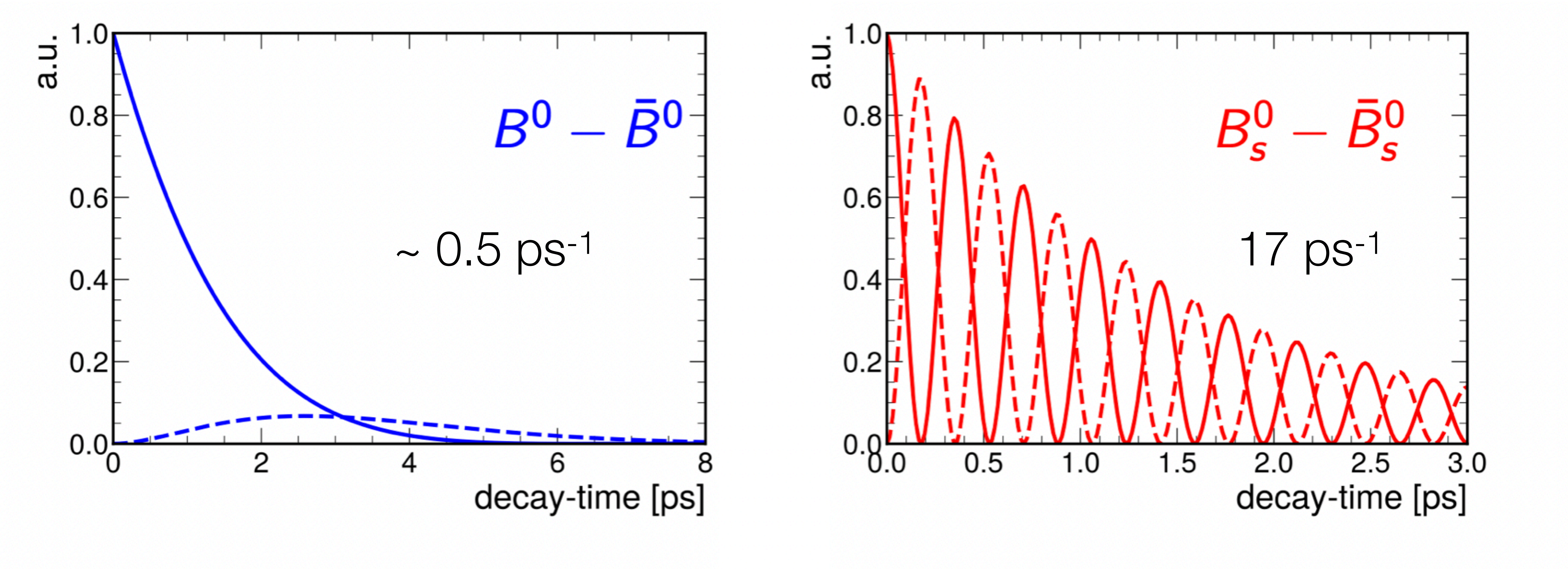


Is there room for NP in this corner ?



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:

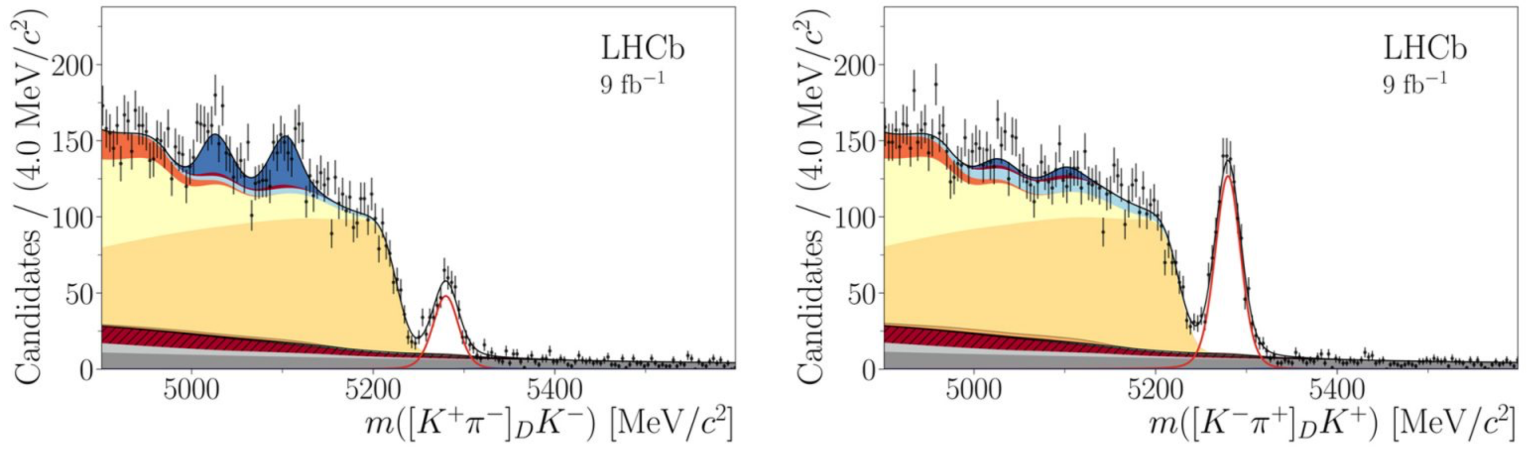
$$|B_{H/L}(t)\rangle = e^{-i M_{H/L} t}\, e^{-i \Gamma_{H/L} t/2}\, |B_{H/L}\rangle$$

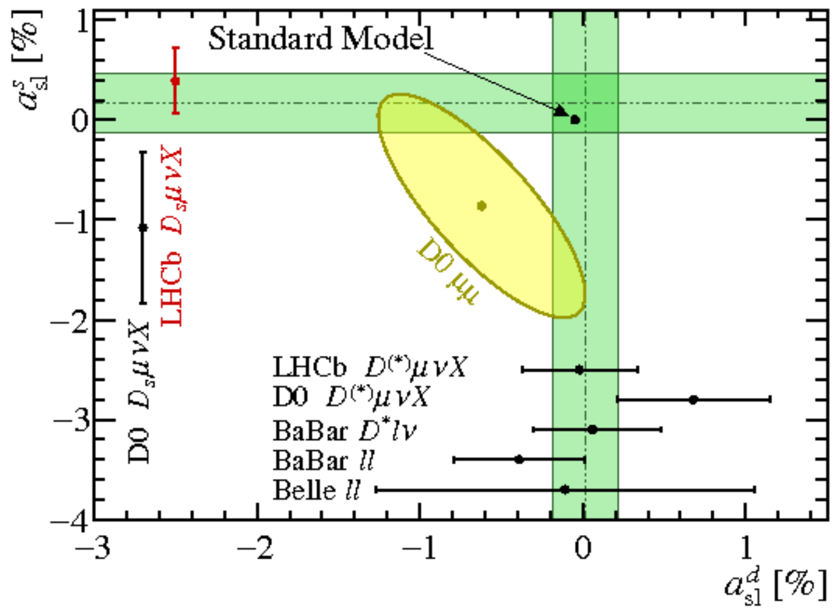
$$m_q = \frac{M_H - M_L}{2}, \quad \Gamma_q = \frac{\Gamma_L + \Gamma_H}{2} = \frac{1}{2}$$

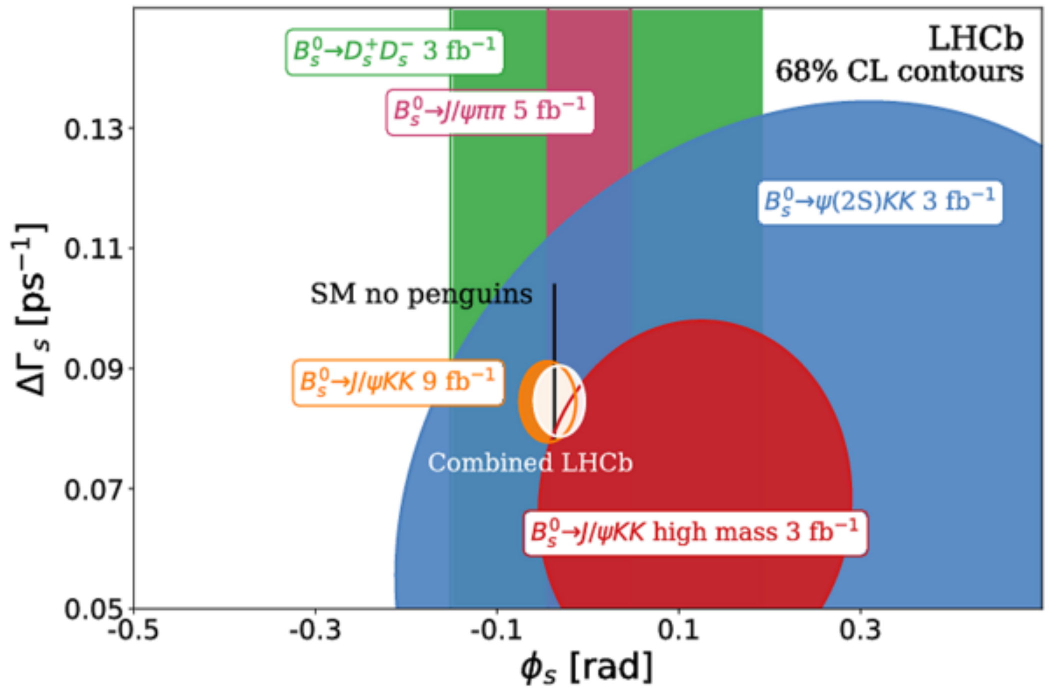
$$\Delta m_q = M_H - M_L, \quad \Delta\Gamma_q = \Gamma_L - \Gamma_H$$

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

Types of CP violation





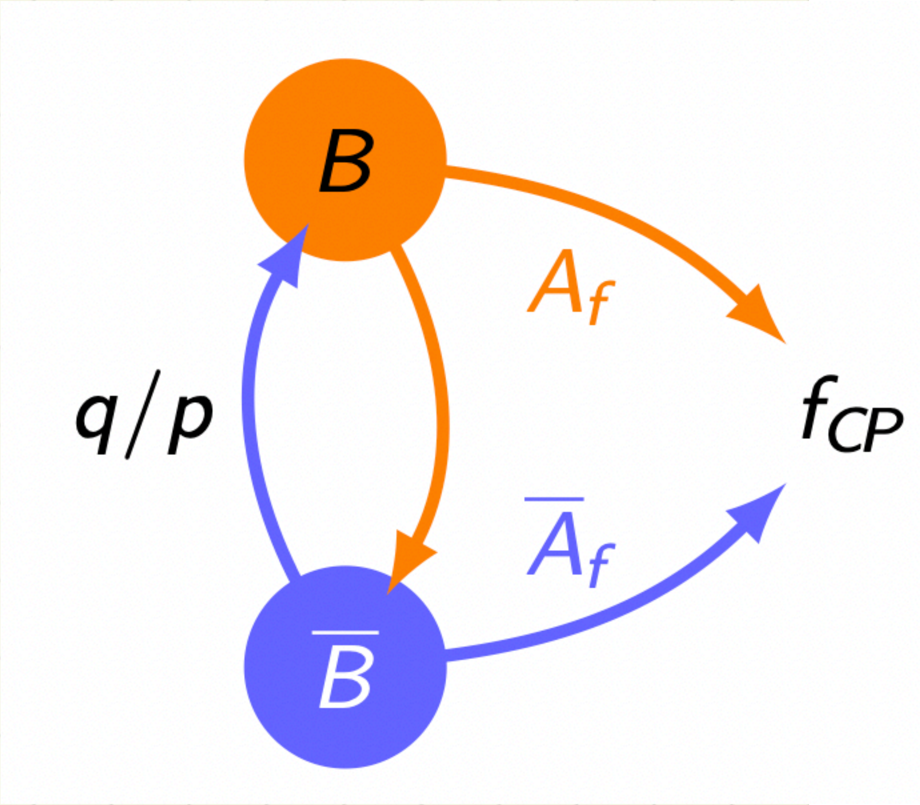


CP Violation in Decay

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

A_f Amplitude $B \to f$

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



CP Violation in mixing

- $|q/p| \neq 1$

CP violation in the interference between mixing and decay

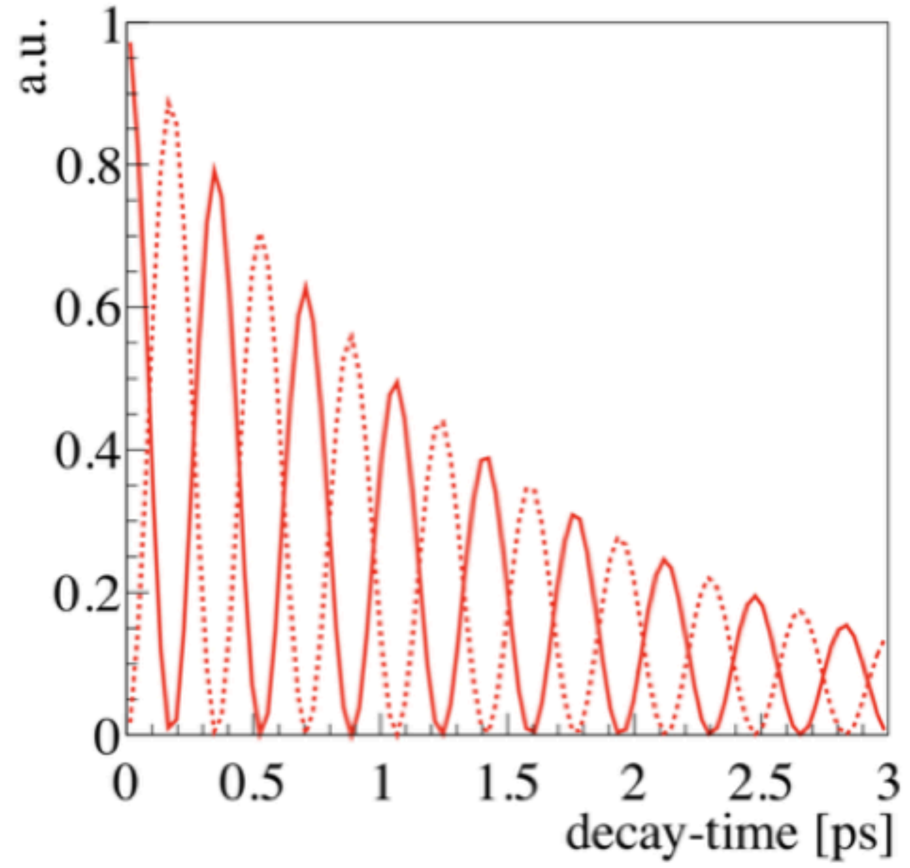
- $\mathrm{Im}(\lambda_f) = \mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$

λ_f = parameter that quantifies CP violation

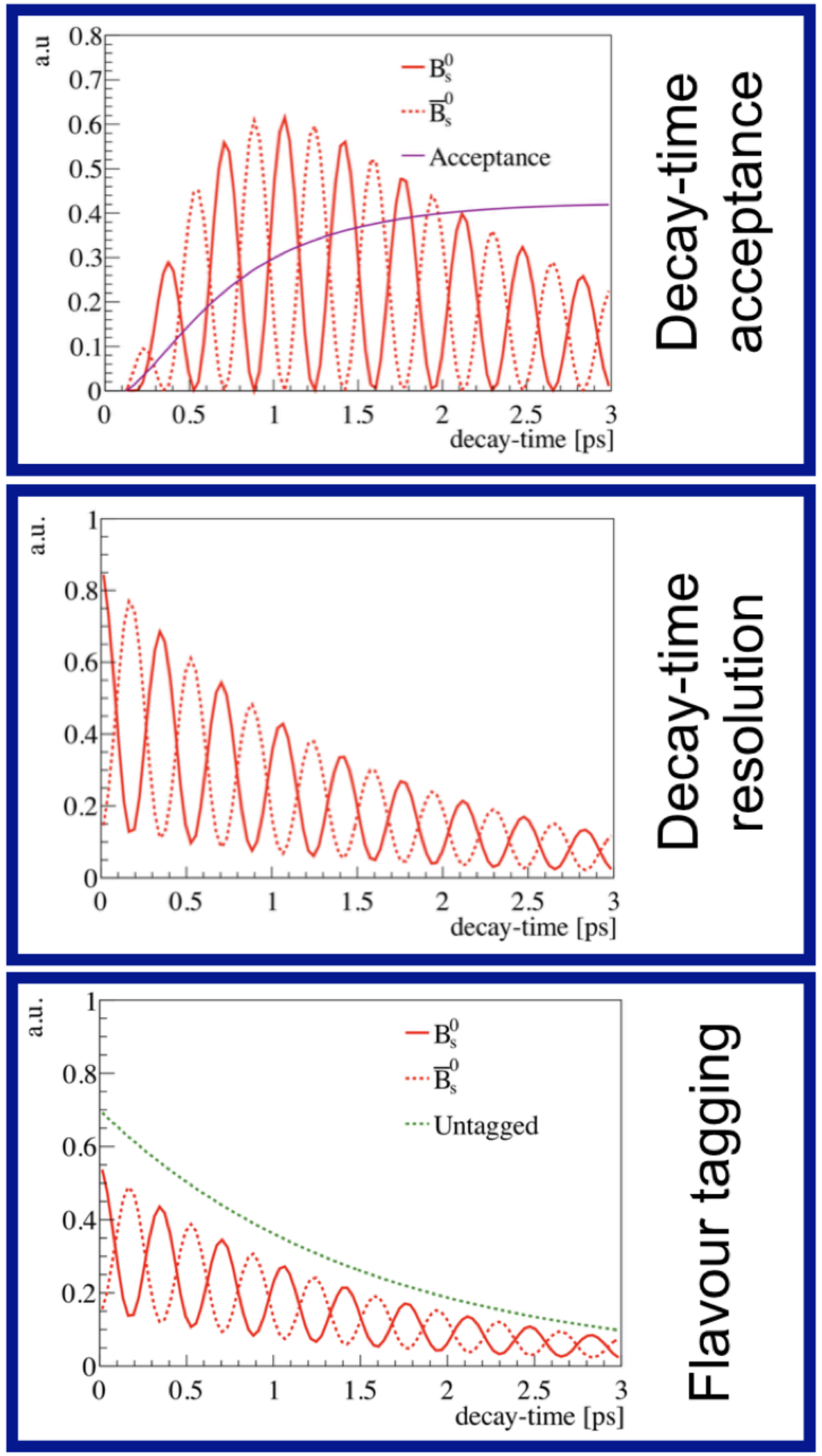
$CP\,|f_{cp}\rangle = \eta_f^{cp}\,|f_{cp}\rangle$ with $\eta_{cp} = \pm 1$

Detector effects

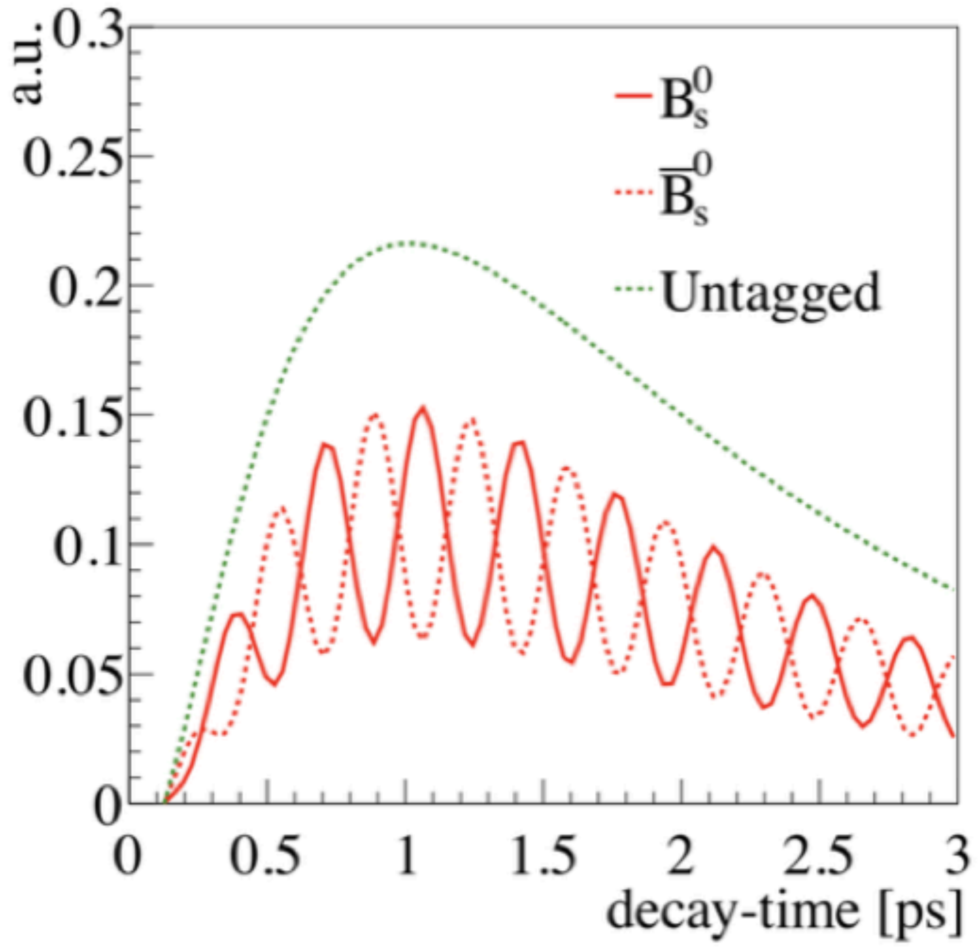
Perfect



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



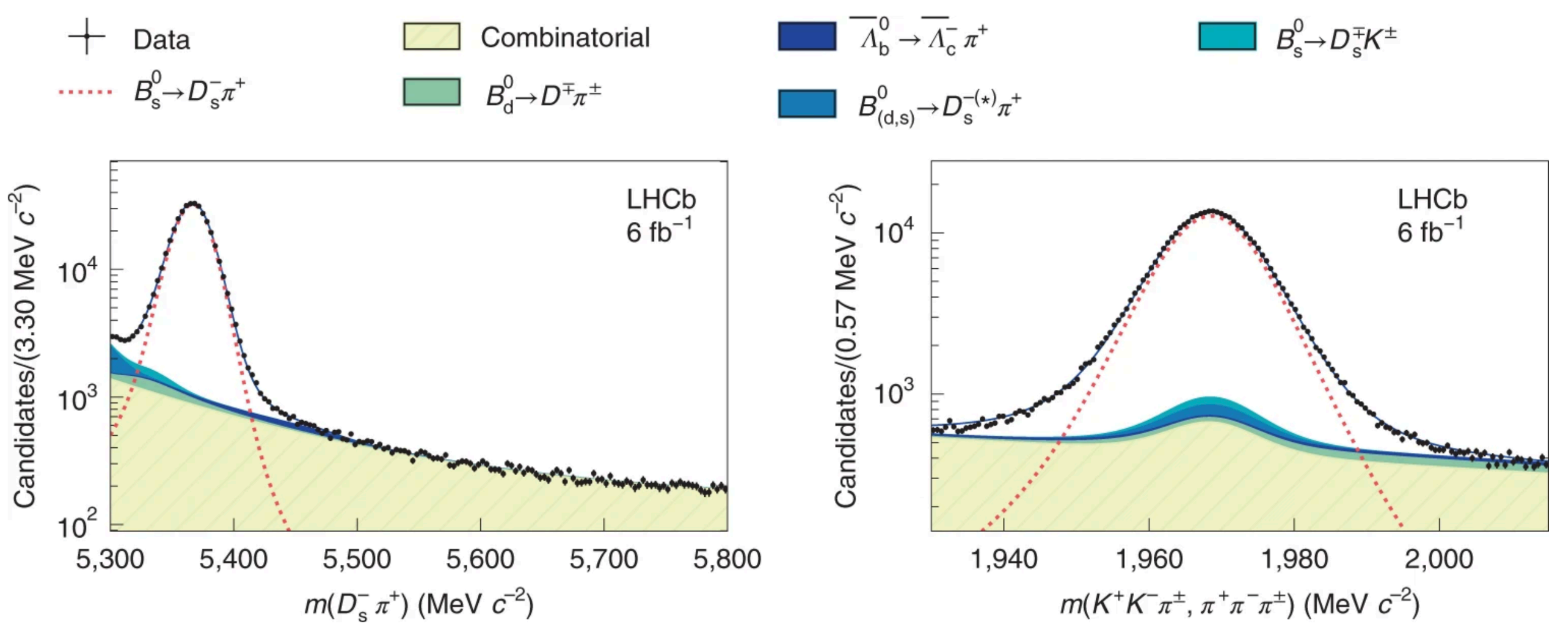
Data

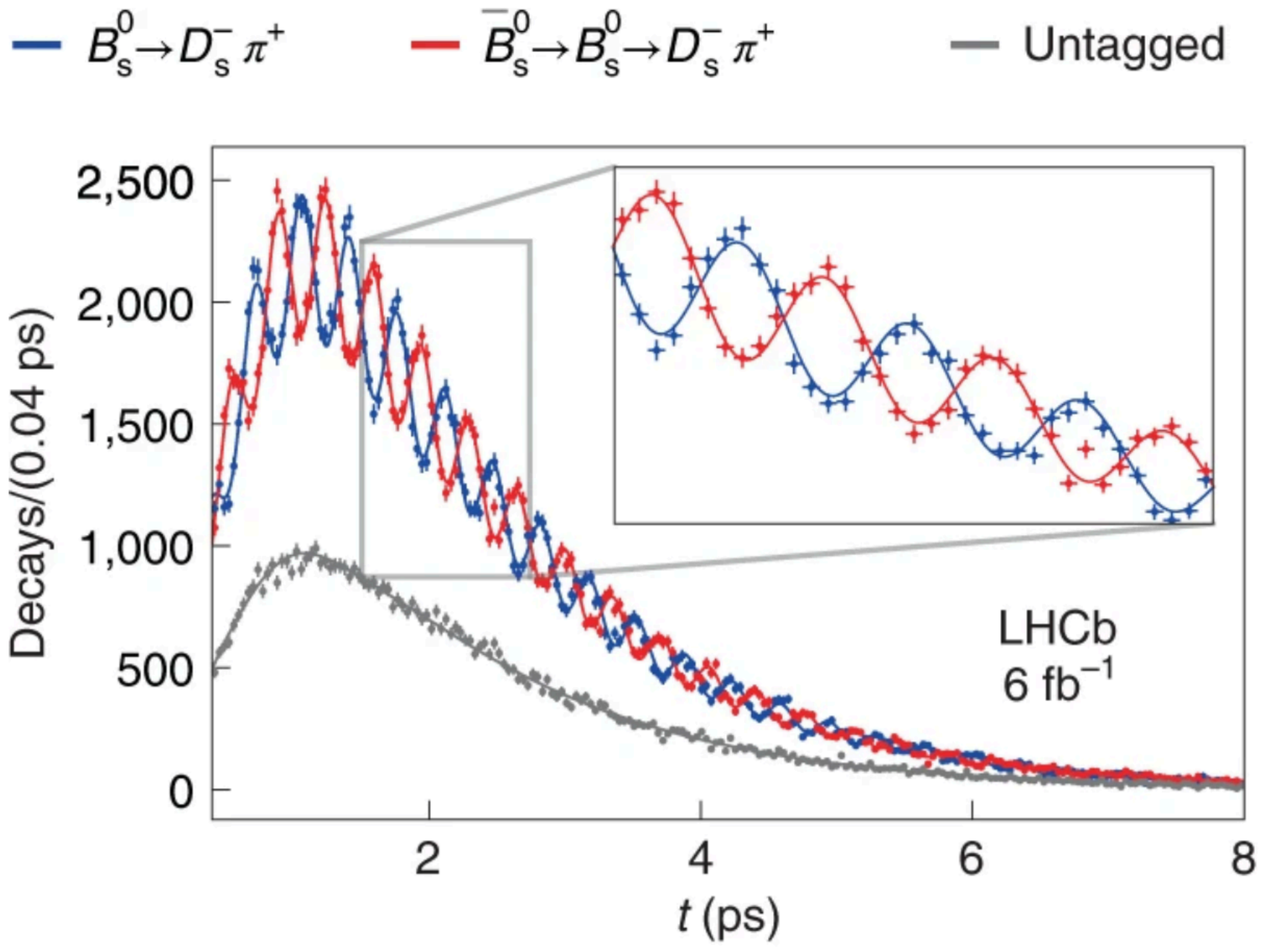


An other text book result

A counting experiment

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



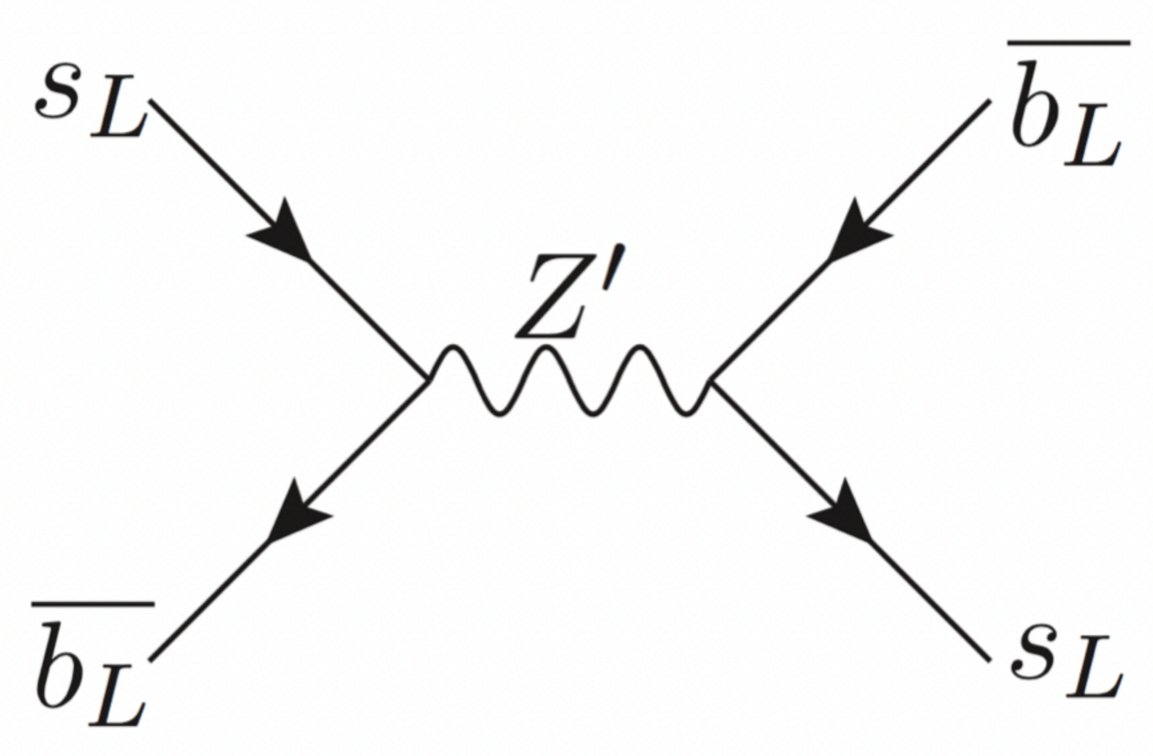


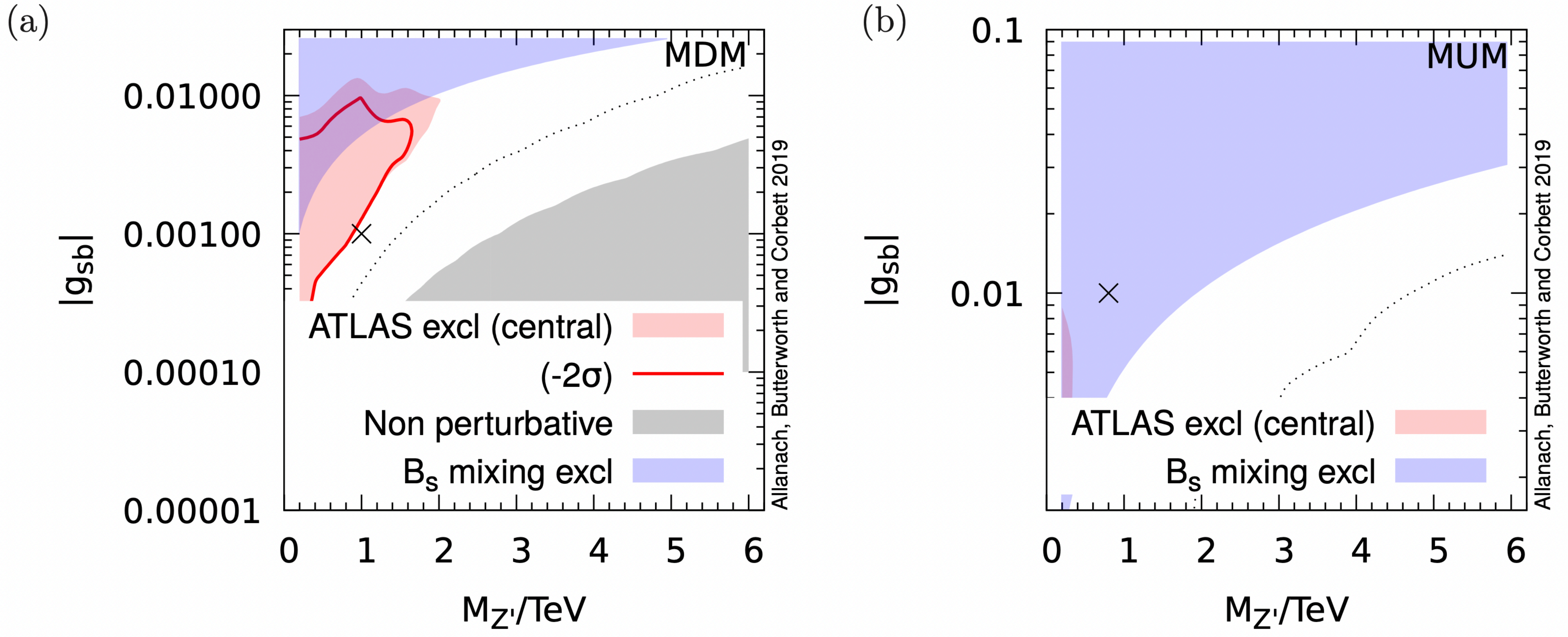
Decay mode	Data sample	Δm_s ps^{-1}
$B_s^0 \to D_s^- \pi^+$	2011	$17.768 \pm 0.023 \pm 0.006$
$B_s^0 \to D_s^- \pi^- \pi^+ \pi^+$	2011-2018	$17.757 \pm 0.007 \pm 0.008$
$B_s^0 \to D_s^- \pi^+$	2015-2018	$17.7683 \pm 0.0051 \pm 0.0032$
Average		17.7666 ± 0.0057

Importance of PID, proper time resolution, flavour tagging

Loop back to the models

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



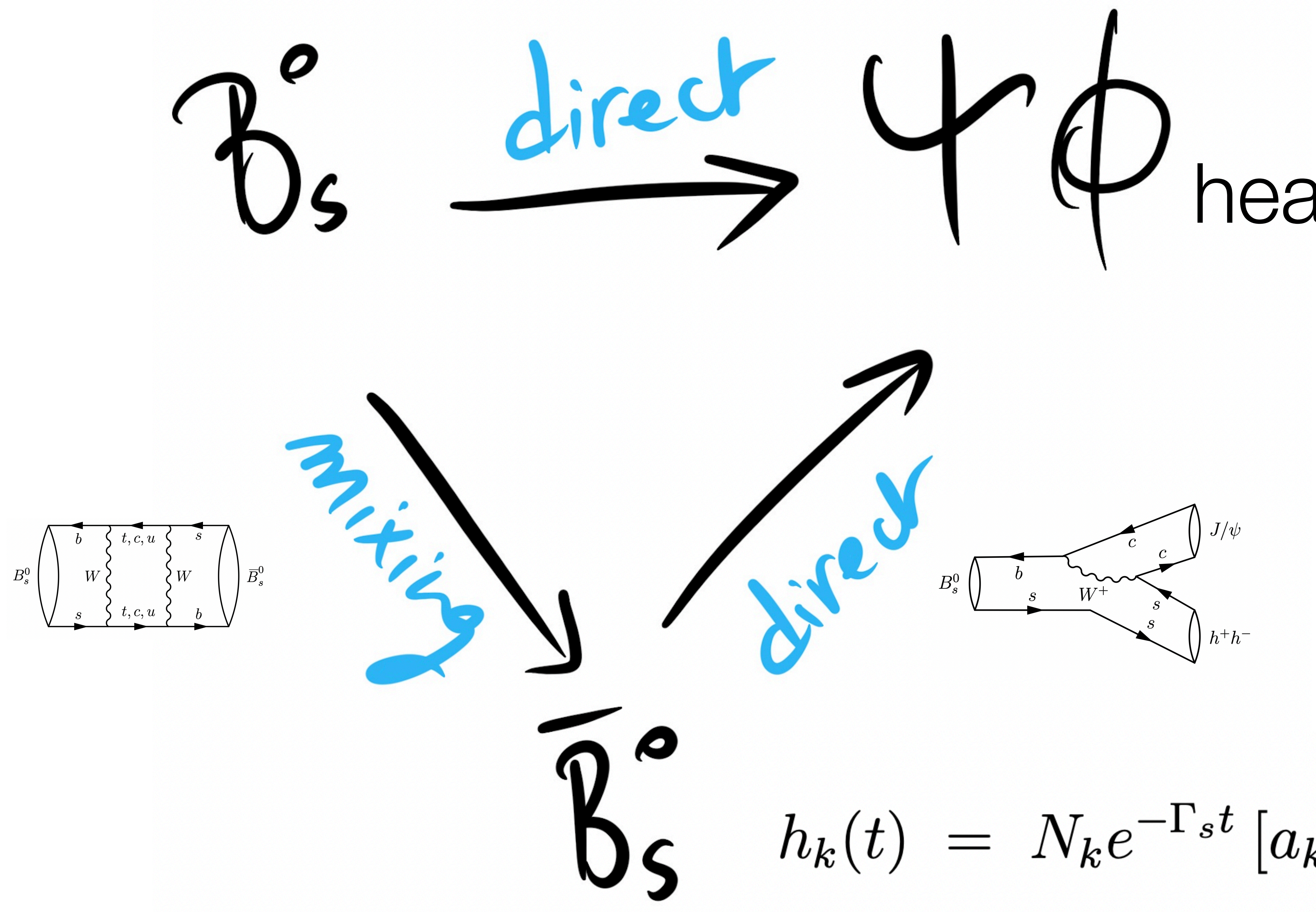


arXiv:1904.10954 one example out of the billion out there.

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

Mixture of CP odd and CP even eigenstates

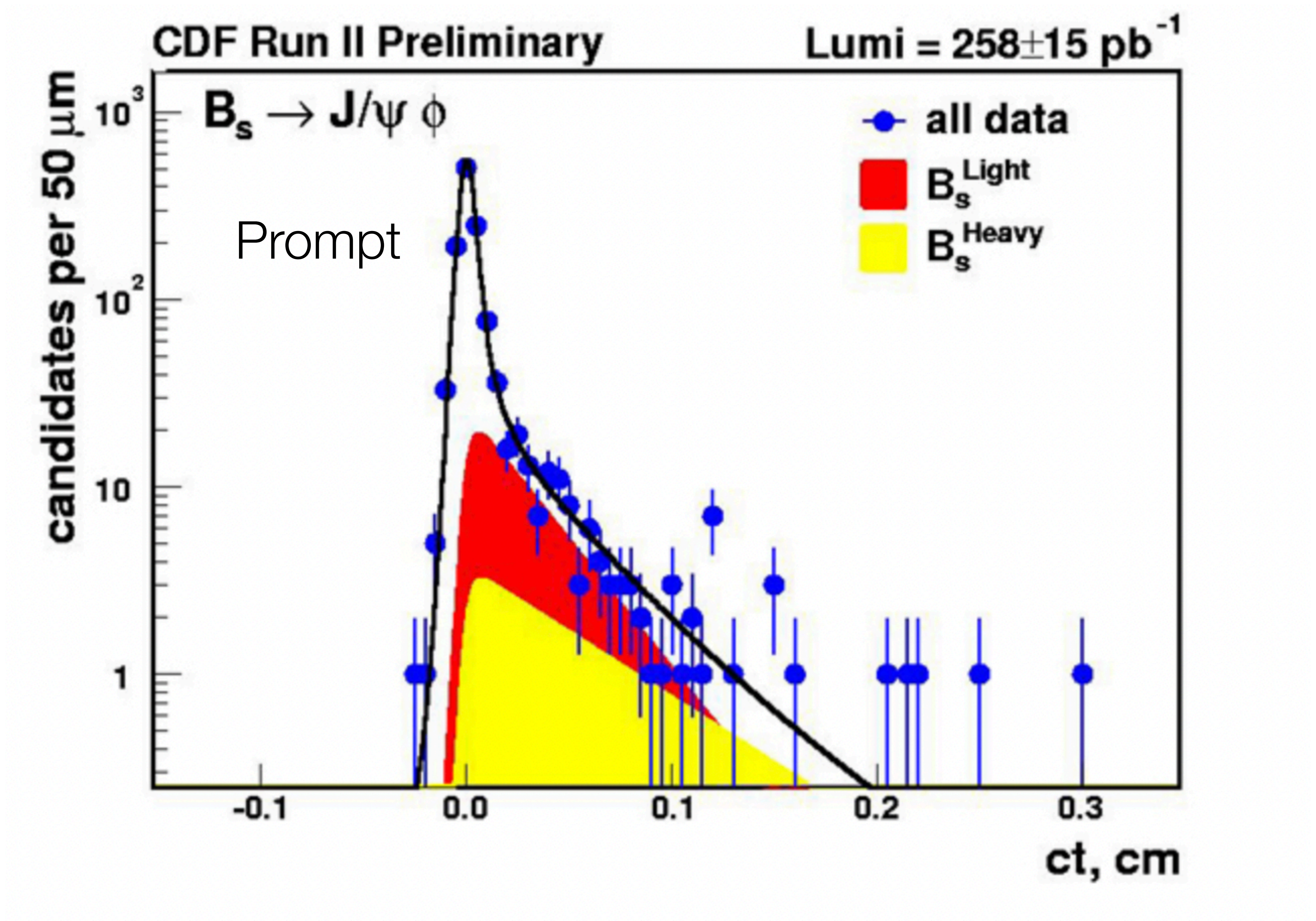
None negligible difference between the heavy and the light state of your the B_s mesons $\Delta\Gamma_s$

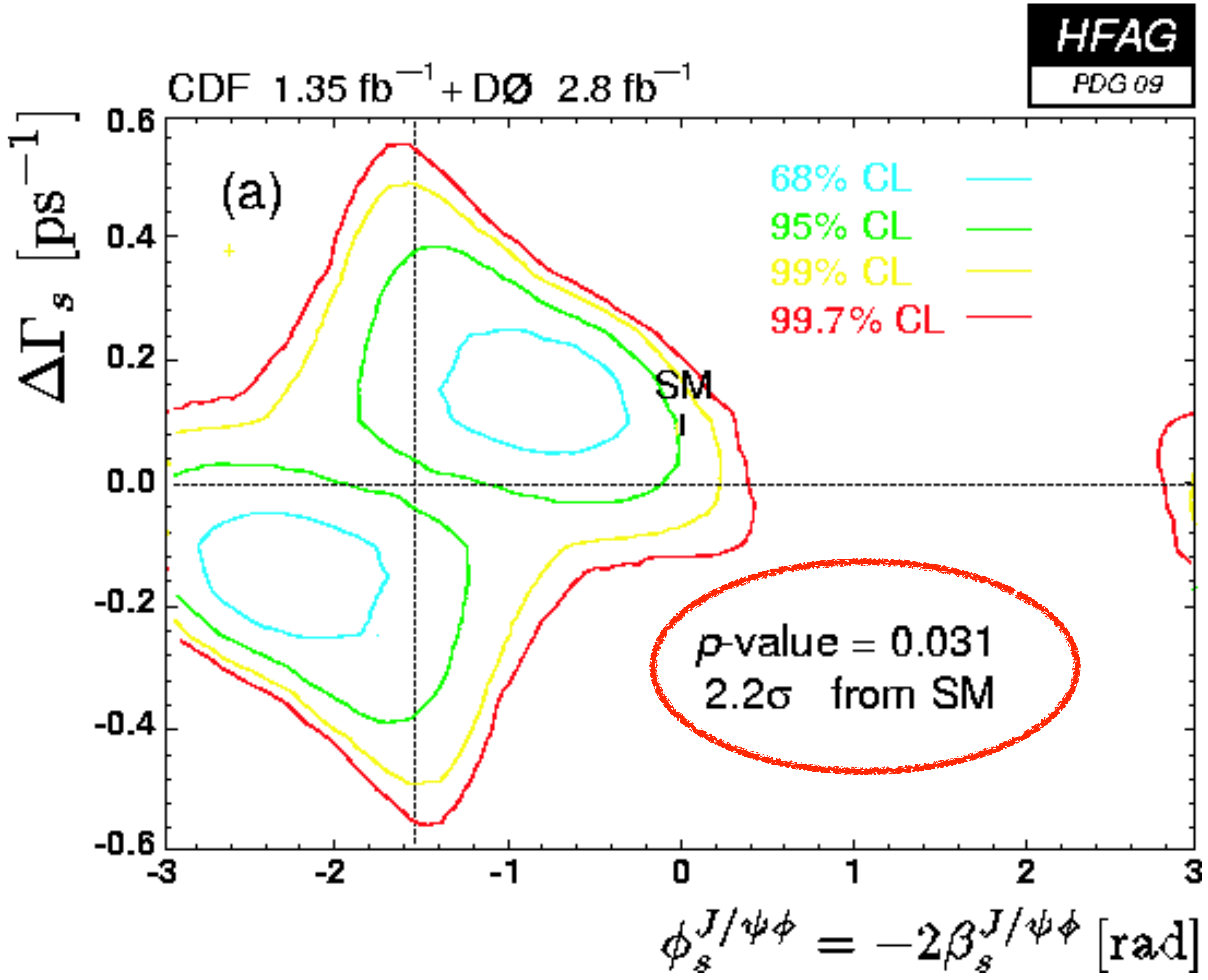


$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)\,.$$

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

Fermilab paved the path of B_s physics

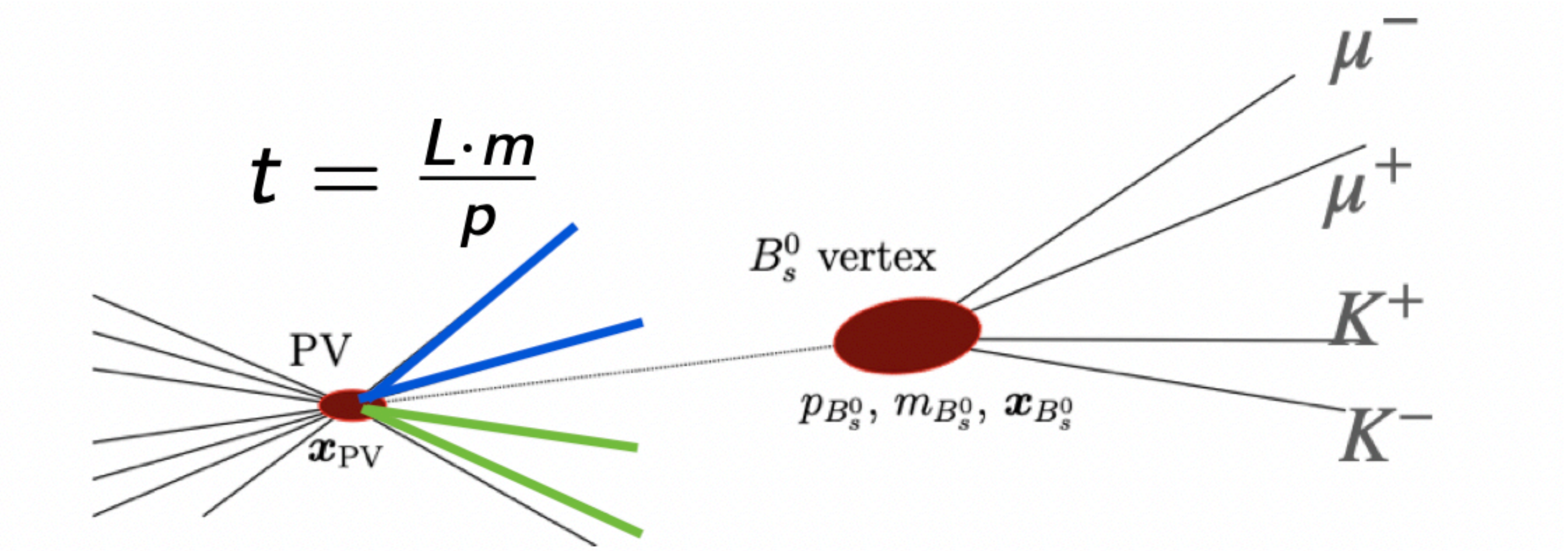




Time dependent angular analysis

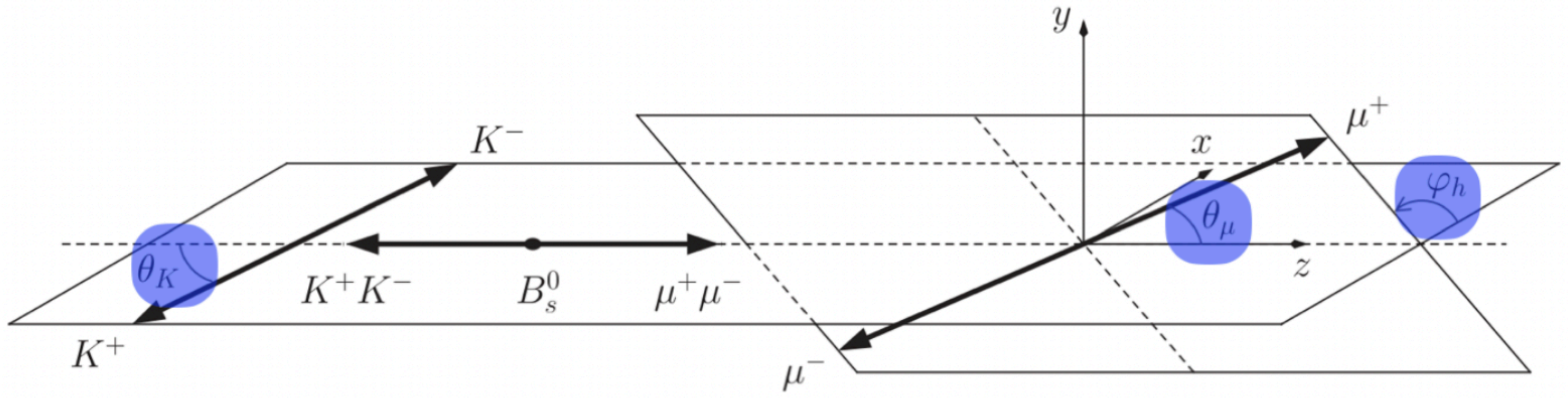
We will come back to the to angular analyses in the second lecture

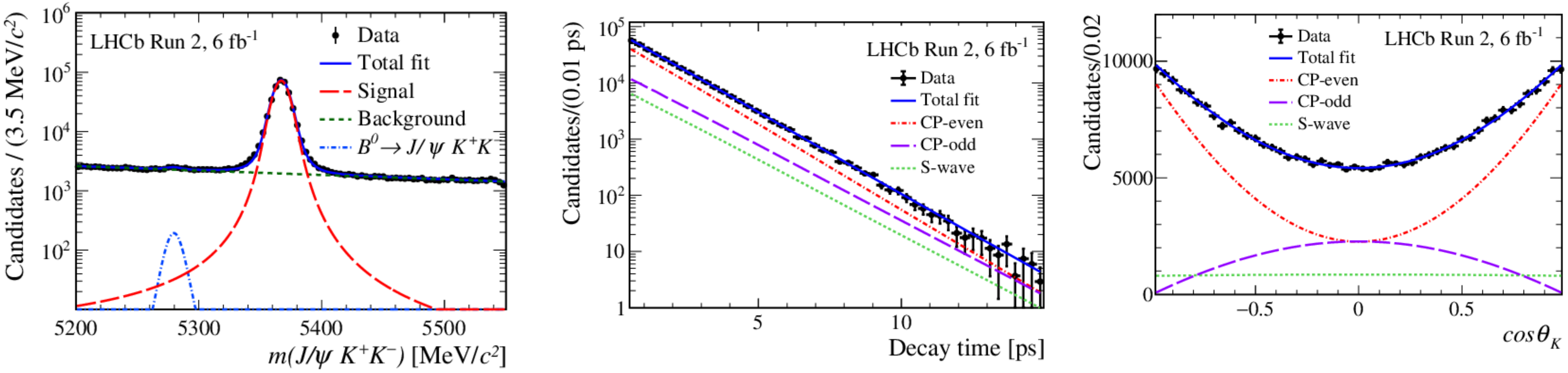
It's just a counting experiment



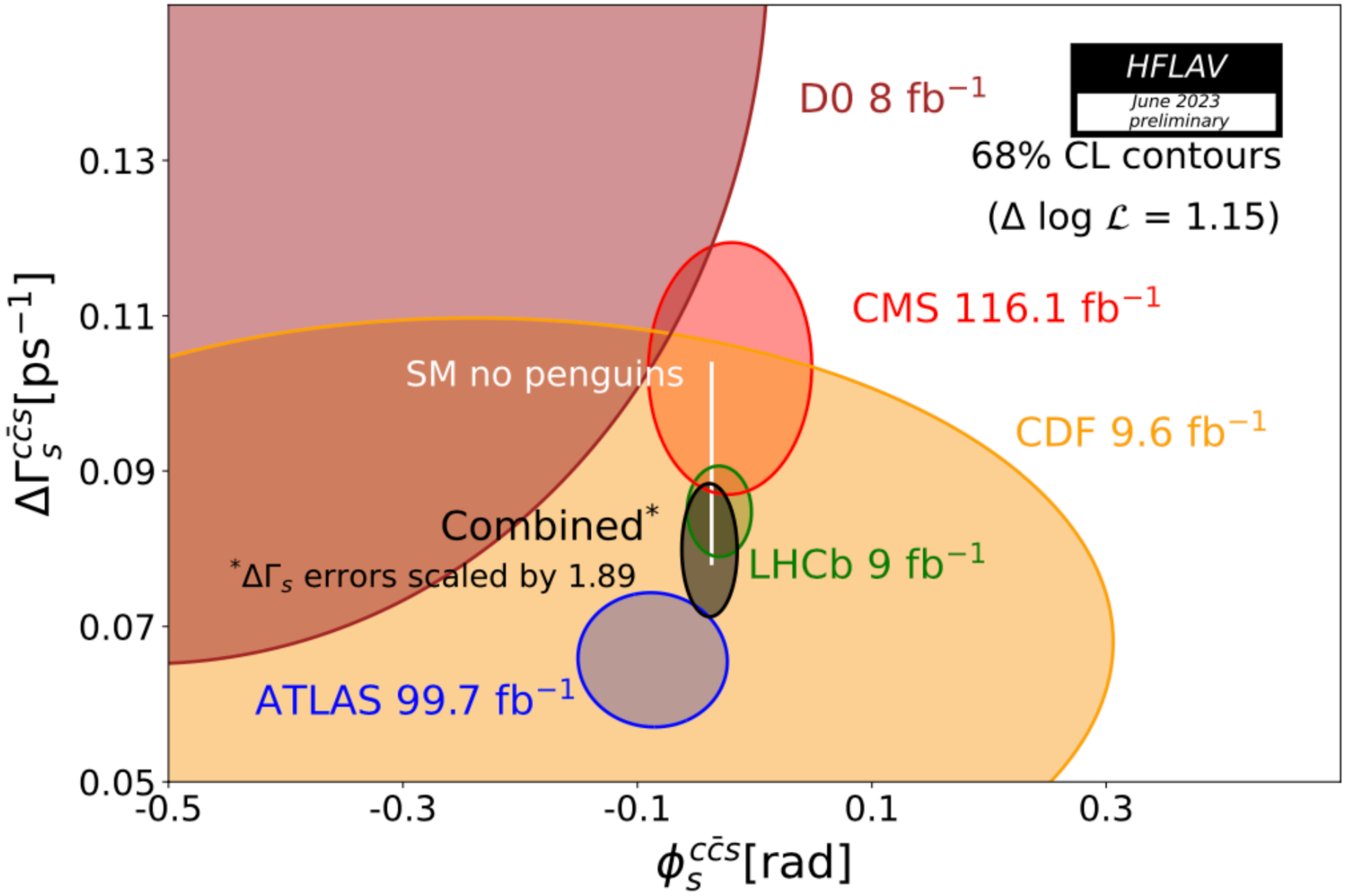
$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to J/\psi KK) - \Gamma(B_s^0 \to J/\psi KK)}{\Gamma(\bar{B}_s^0 \to J/\psi KK) + \Gamma(B_s^0 \to J/\psi KK)} = \eta_f \cdot \sin \phi_s^{\mathrm{obs}} \cdot \sin(\Delta m_s t)$$

- *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



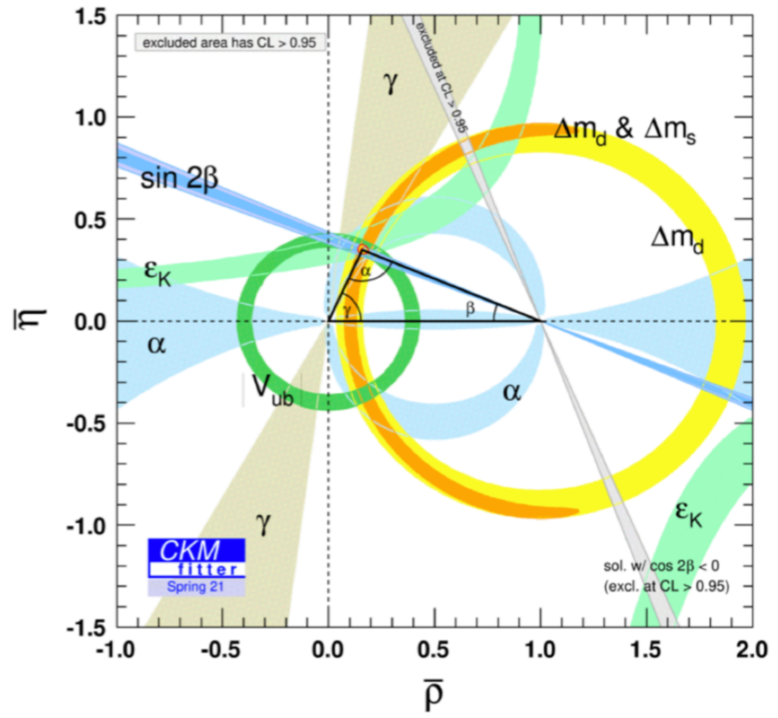
arXiv:2308.01468

$\sin 2\beta$ & ϕ_s

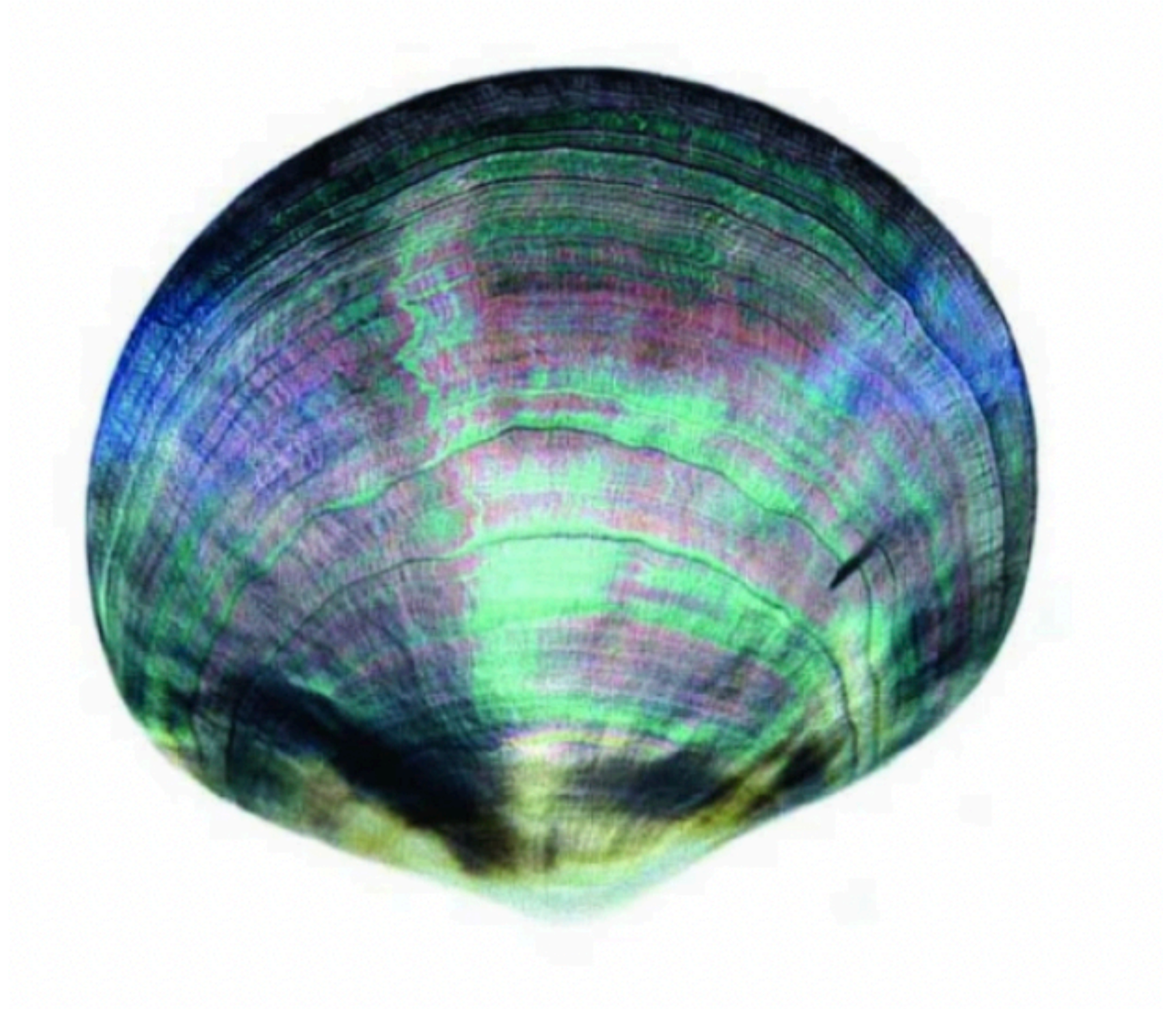
Typically dominated by a few “Golden modes”

γ measurements have somewhat of a “commune spirit ”

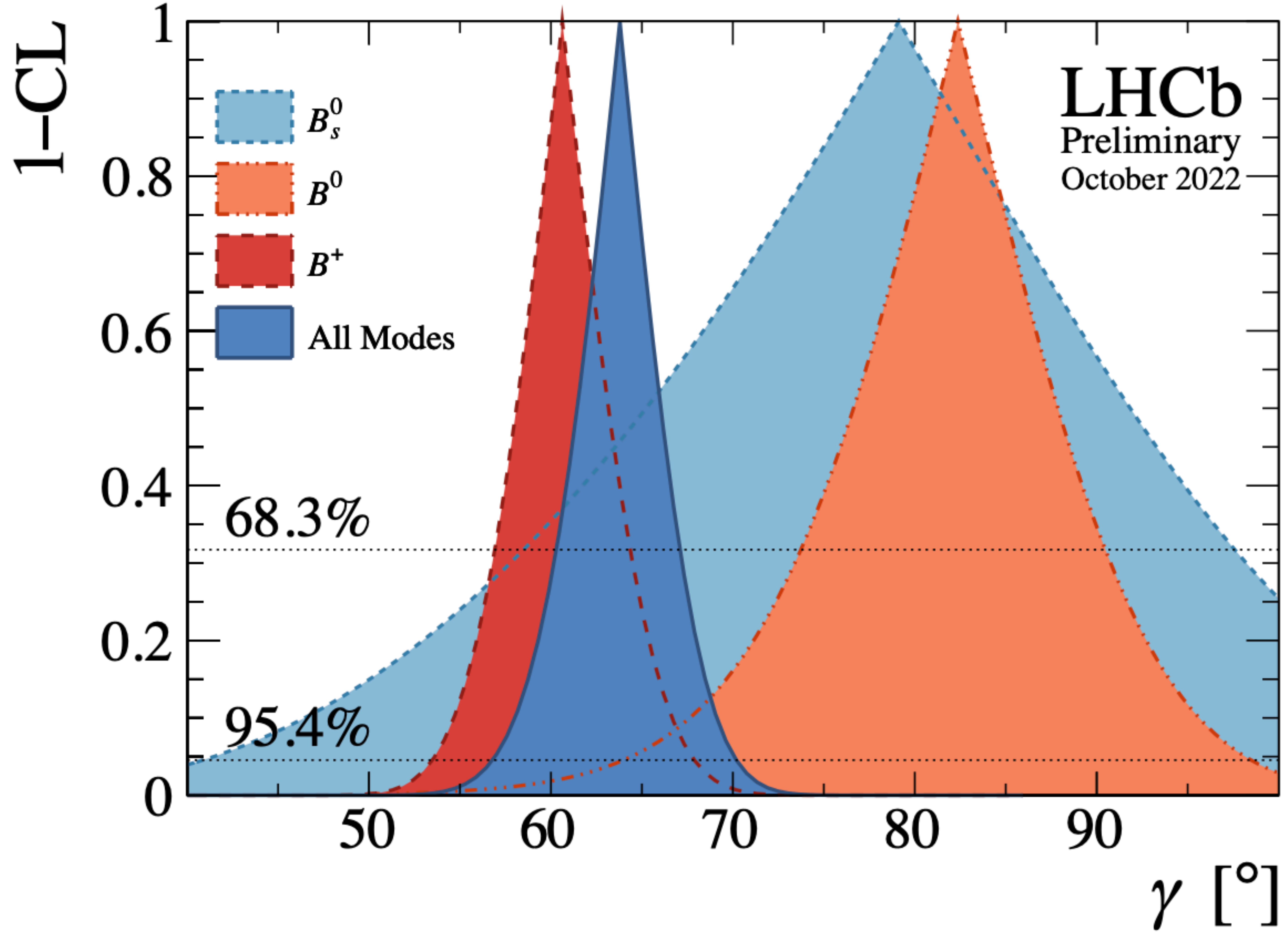
How to measure γ ?



It's all about interferences !



< Beautiful Mont-Blanc analogy >



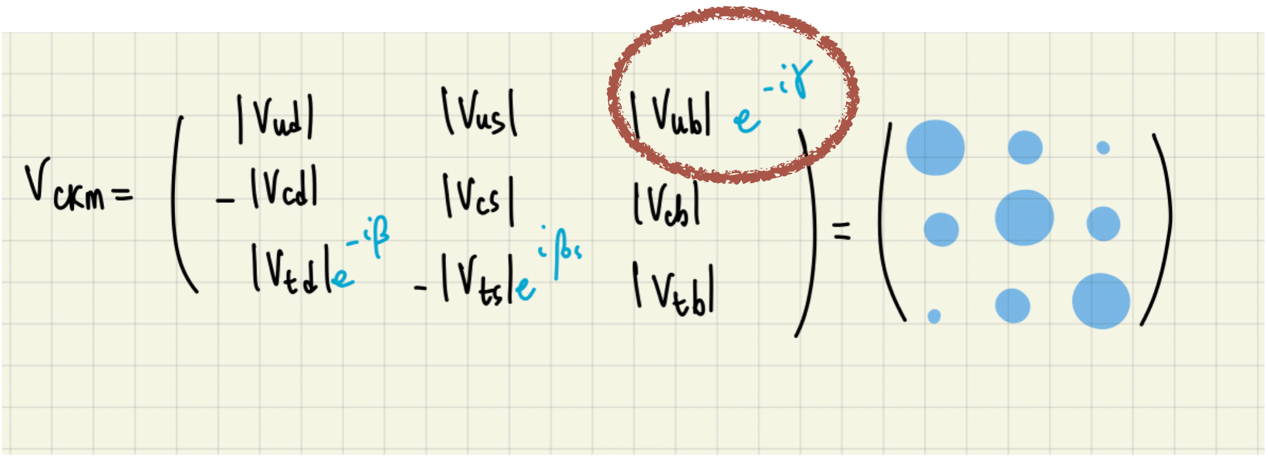
LHCb-CONF-2022-003

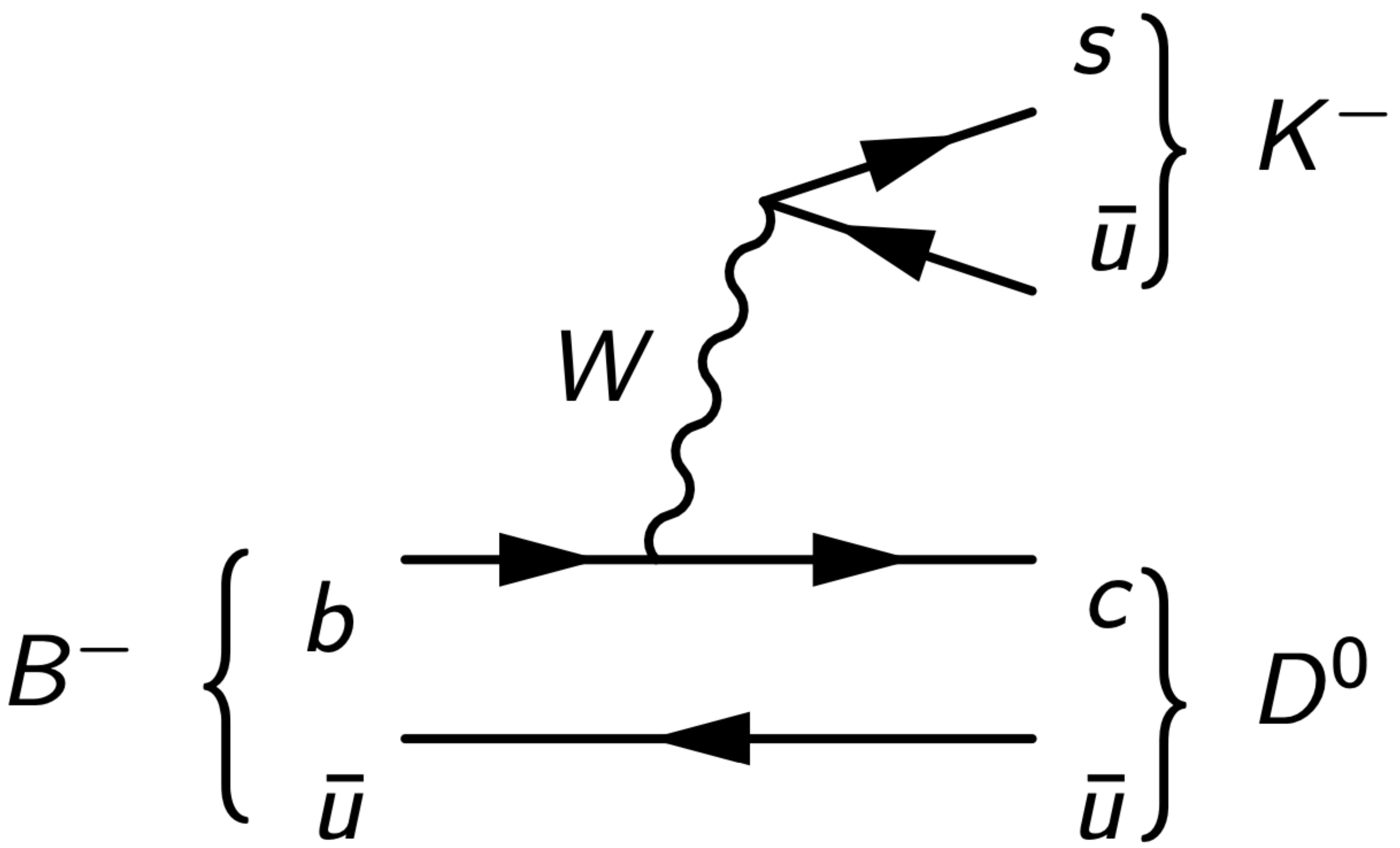
There is a myriad of techniques to measure this angle

B decay	D decay
$B^\pm \to Dh^\pm$	$D \to h^+h^-$
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$
$B^\pm \to Dh^\pm$	$D \to K_S^0h^+h^-$
$B^\pm \to Dh^\pm$	$D \to K_S^0K^\pm\pi^\mp$
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$
$B^0 \to DK^{*0}$	$D \to h^+h^-$
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$
$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$

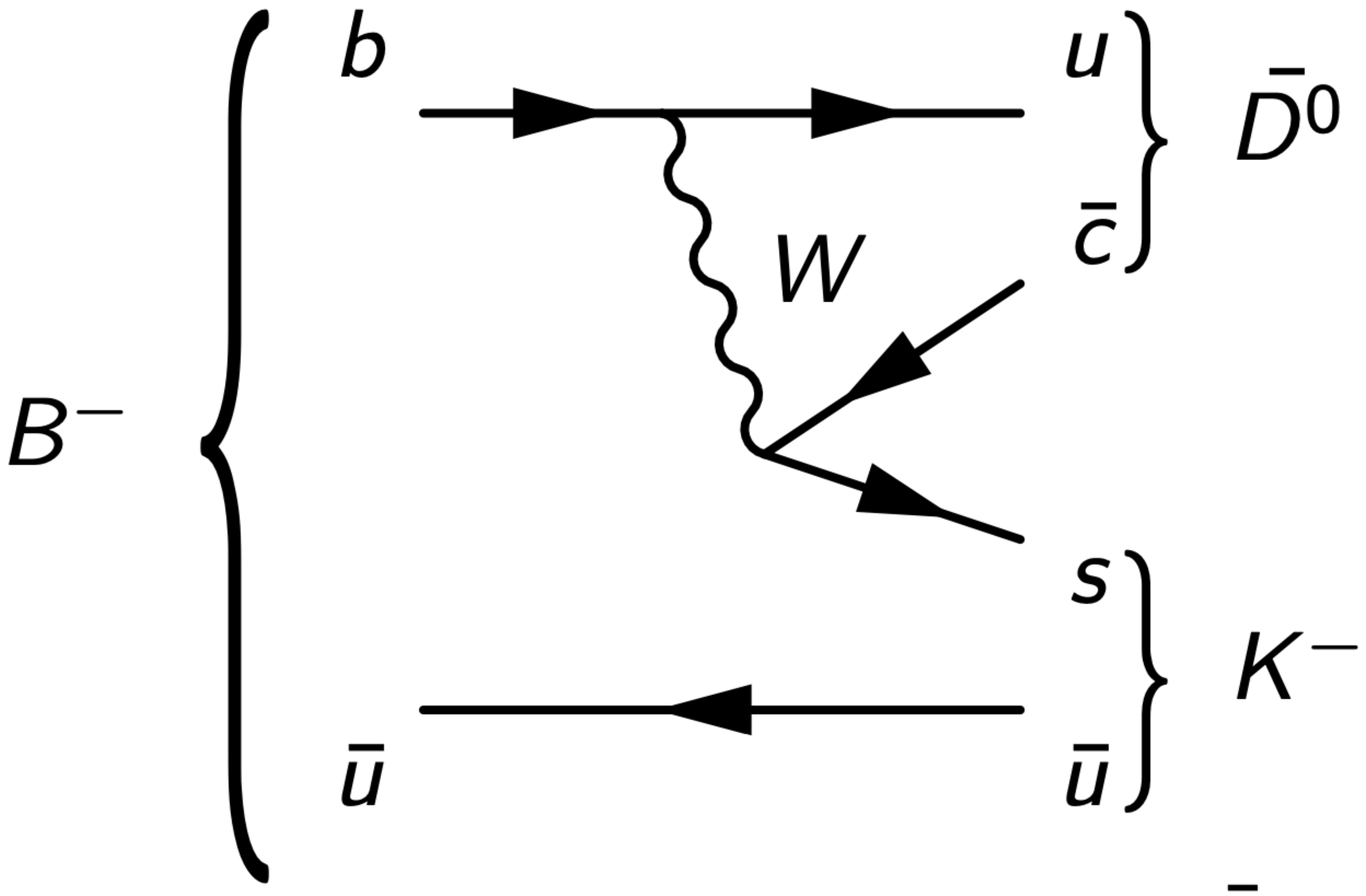
ADS, GLW, BPGGSZ, etc.

Which interference are we talking about ?

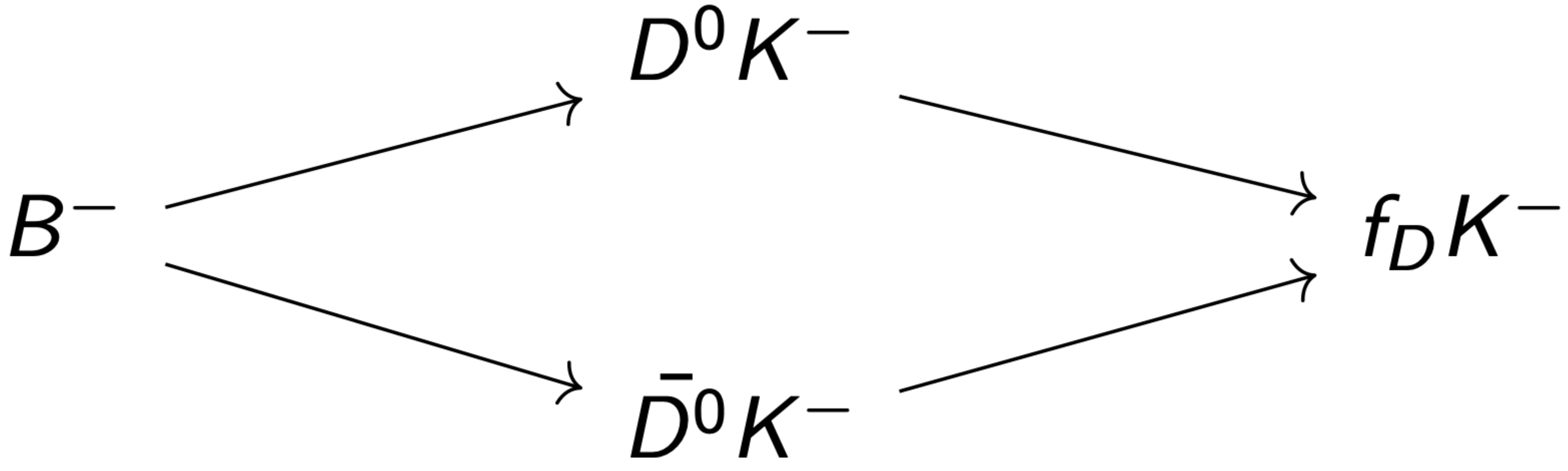




Favoured $B^- \to D^0 K^-$



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



We can write down the amplitudes

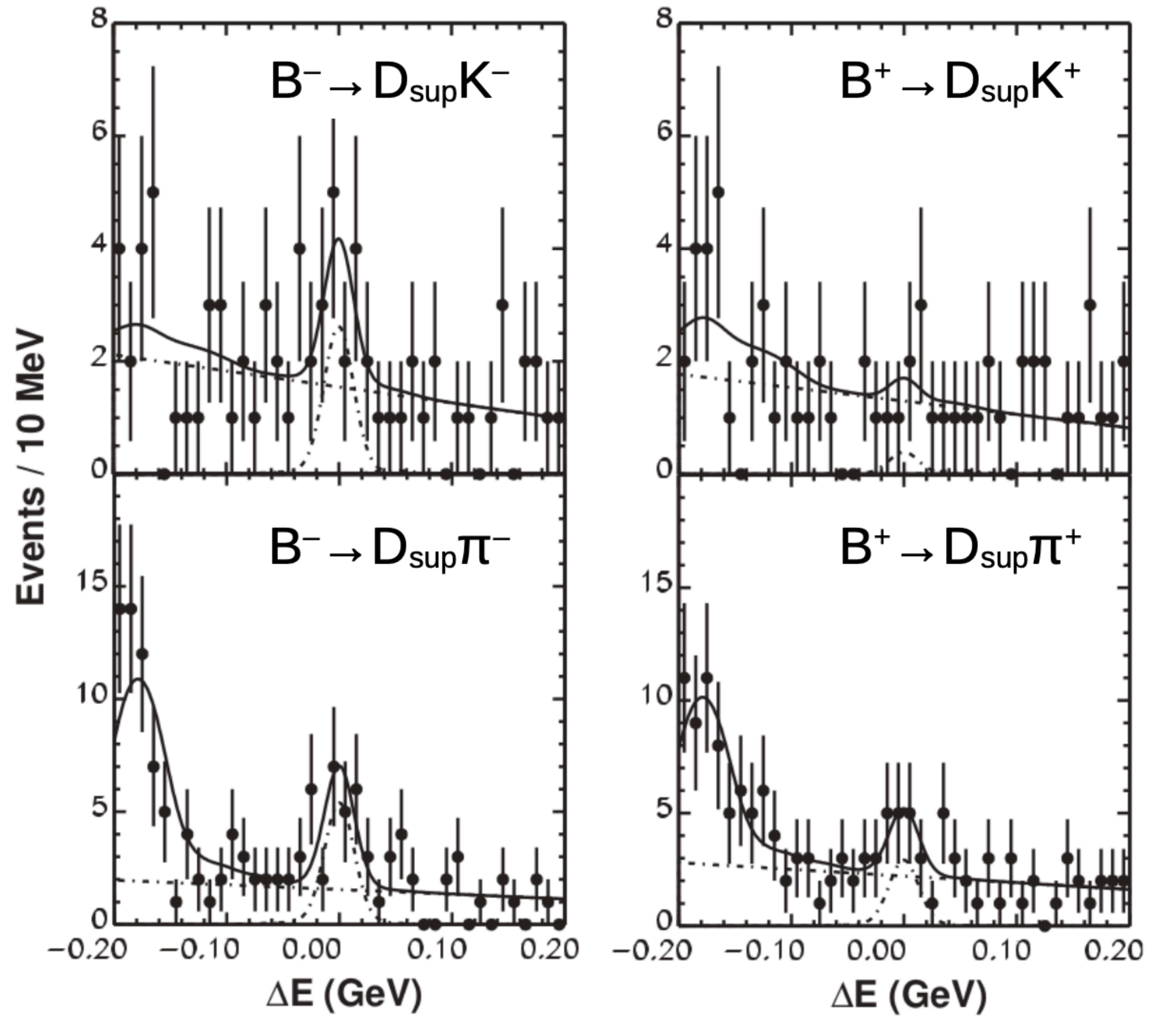
$$\mathcal{A}(B^-) = \mathcal{A}_B\left(\mathcal{A}_{D^0} + \ r_B\ e^{i(\ \delta_B\ -\ \gamma\ )}\mathcal{A}_{\bar{D}^0}\right)$$

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

- 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



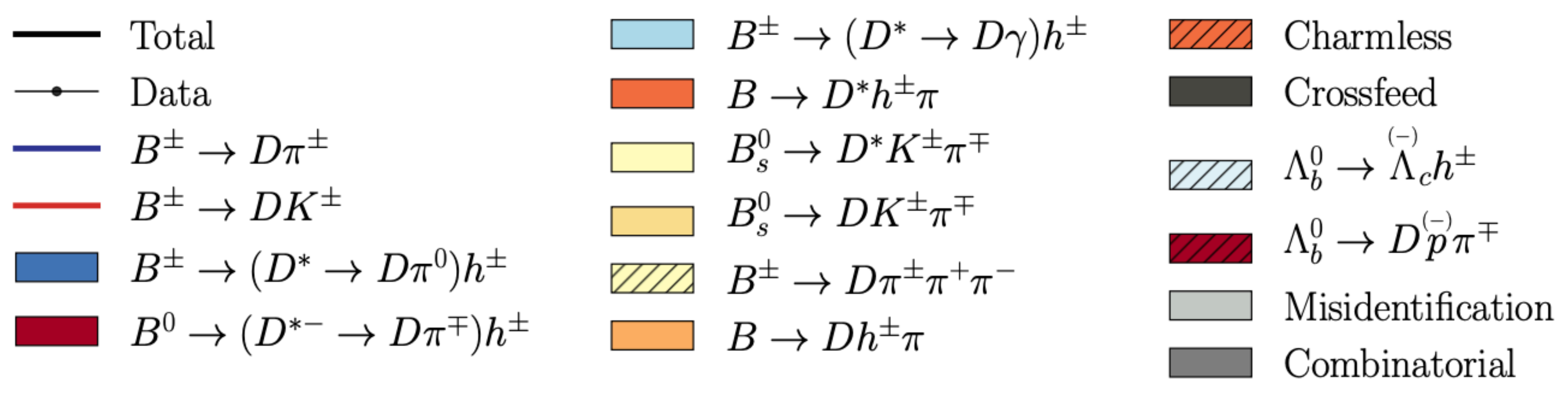
Belle, PRL 94 (2005) 091601

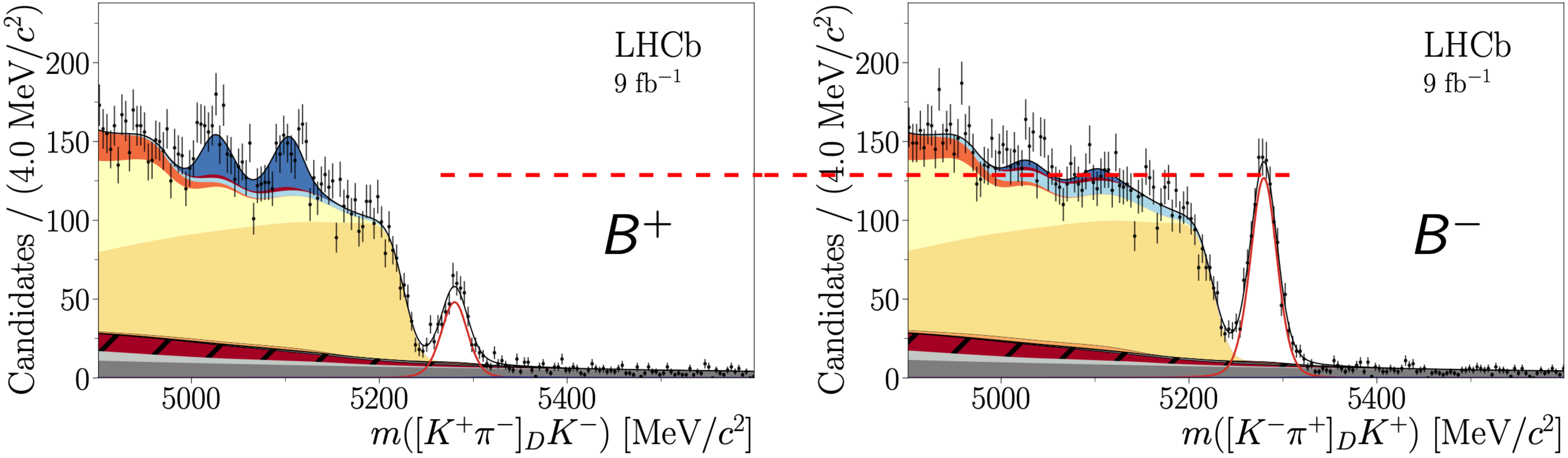
ADS technique

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

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

Example of a very spectacular asymmetry

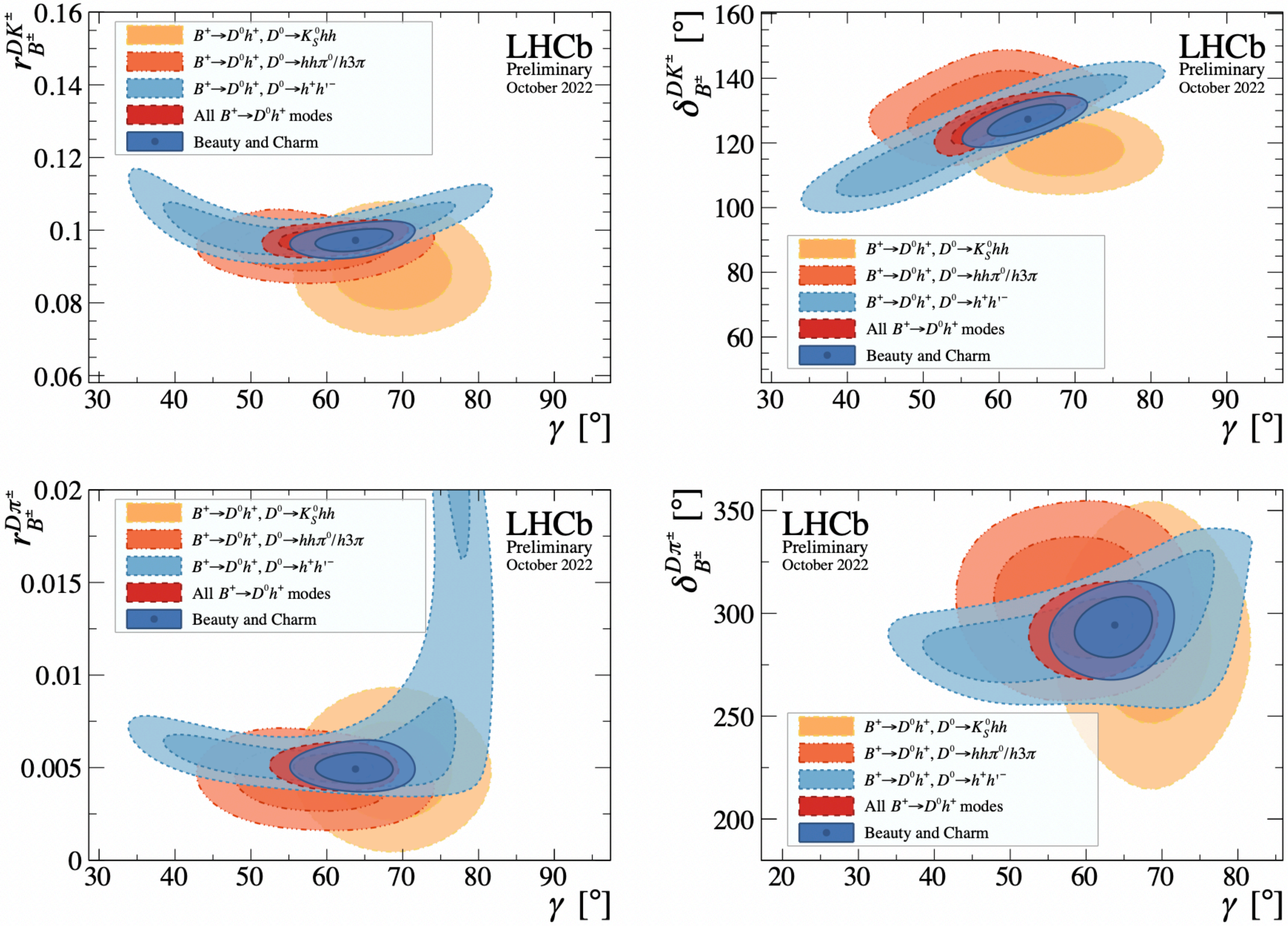


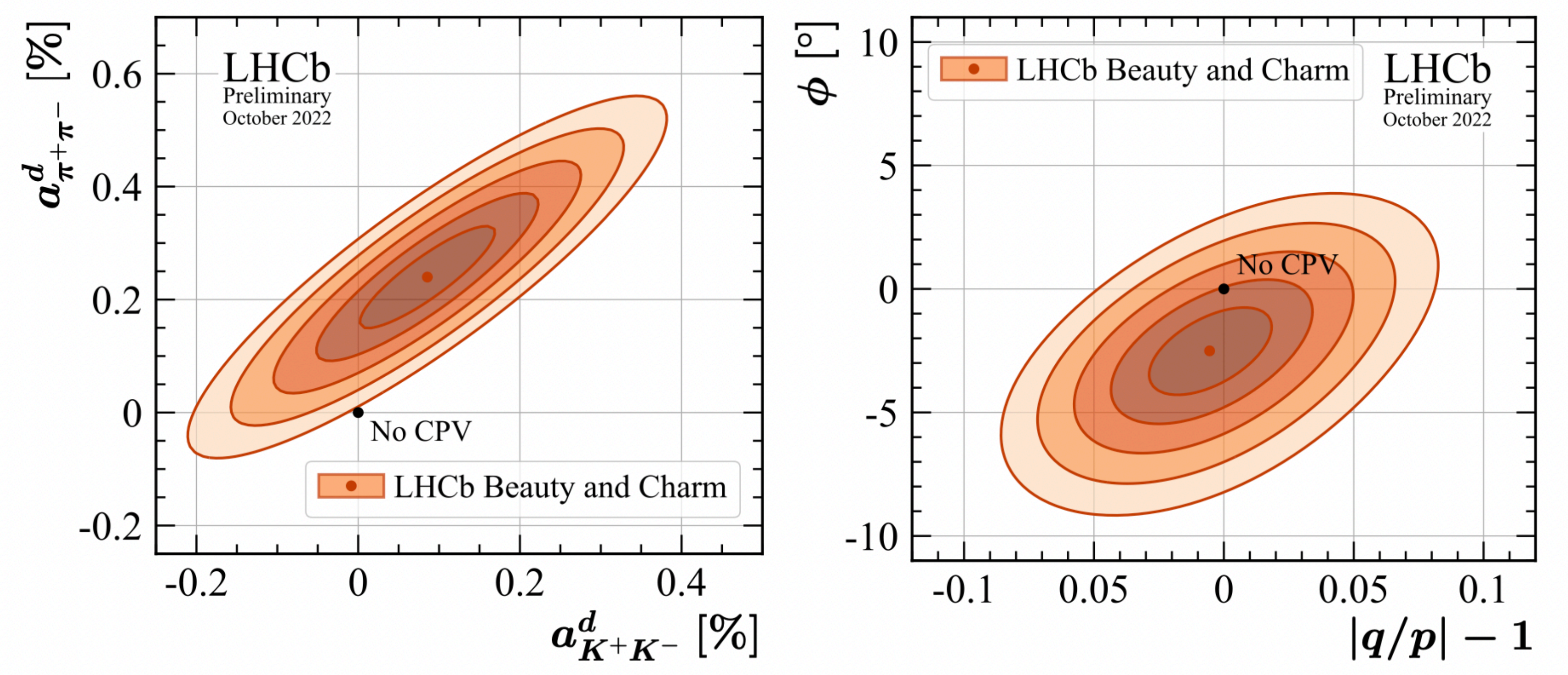


LHCb, JHEP 04 (2021) 081

Just drawing a line does not do justice to this work

Putting everything together





Importance of charm inputs

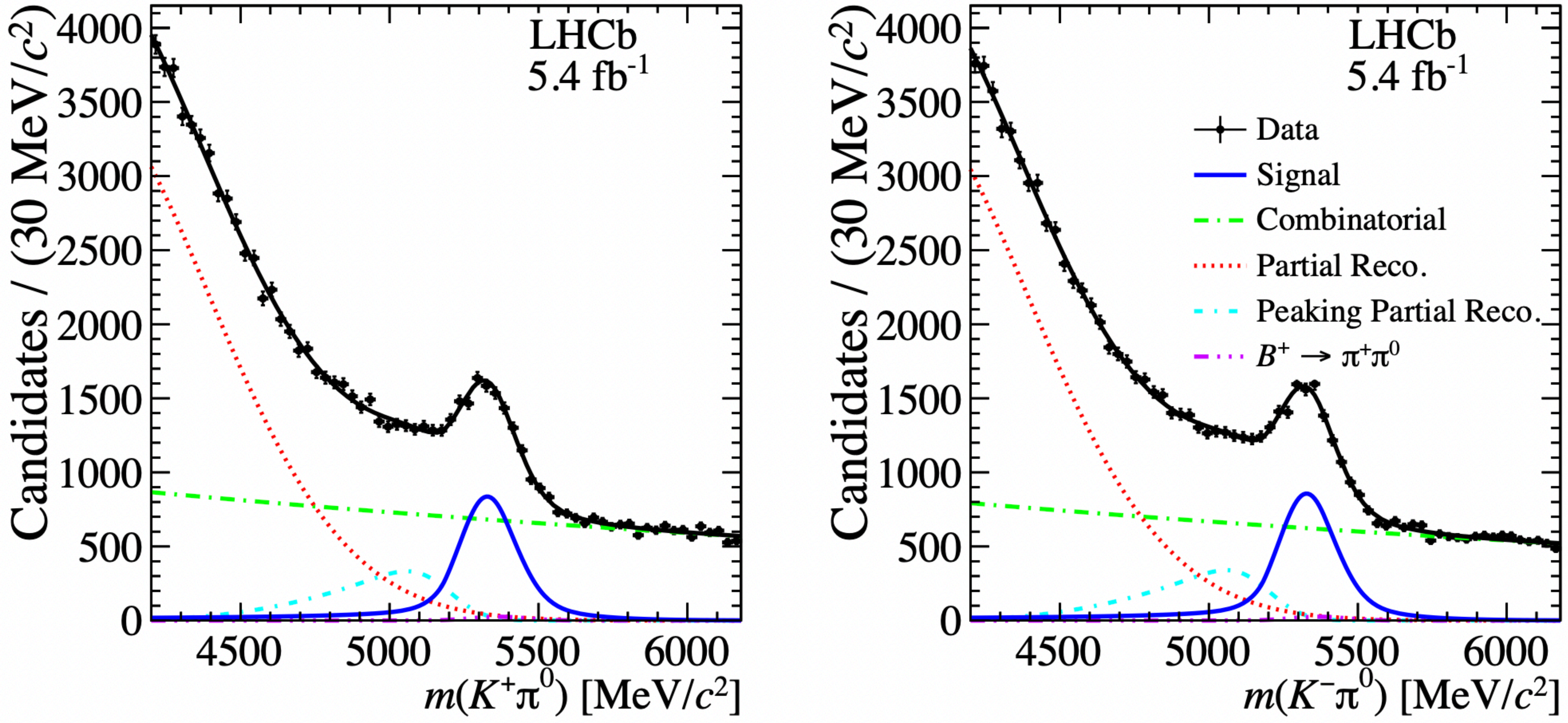
	γ	$r_{B^\pm}^{DK^\pm}$	$\delta_{B^\pm}^{DK^\pm}$	$r_{B^\pm}^{D\pi^\pm}$	$\delta_{B^\pm}^{D\pi^\pm}$	$r_D^{K\pi}$	$\delta_D^{K\pi}$	x	y	$\lvert q/p \rvert$	ϕ	$a^d_{K^+K^-}$	$a^d_{\pi^+\pi^-}$
γ	1.00	0.41	0.70	-0.03	0.23	-	0.02	-	0.02	-	-	-	-
$r_{B^\pm}^{DK^\pm}$		1.00	0.26	-0.01	0.10	-0.05	-0.09	-	-0.06	-	-	-	-
$\delta_{B^\pm}^{DK^\pm}$			1.00	-0.04	0.23	-0.16	-0.37	-	-0.28	-	-	-	-
$r_{B^\pm}^{D\pi^\pm}$				1.00	0.57	0.06	0.02	-	-	-	-	-	-
$\delta_{B^\pm}^{D\pi^\pm}$					1.00	-	-0.16	-	-0.15	-	-	-	-
$r_D^{K\pi}$						1.00	0.44	0.30	-0.13	-0.07	0.02	-	-
$\delta_D^{K\pi}$							1.00	0.08	0.77	-0.03	0.03	-0.02	-0.01
x								1.00	0.05	-0.12	0.09	-	-
y									1.00	-0.03	-	-	-
$\lvert q/p \rvert$										1.00	0.55	0.16	0.14
ϕ											1.00	-0.08	-0.06
$a^d_{K^+K^-}$												1.00	0.88
$a^d_{\pi^+\pi^-}$													1.00

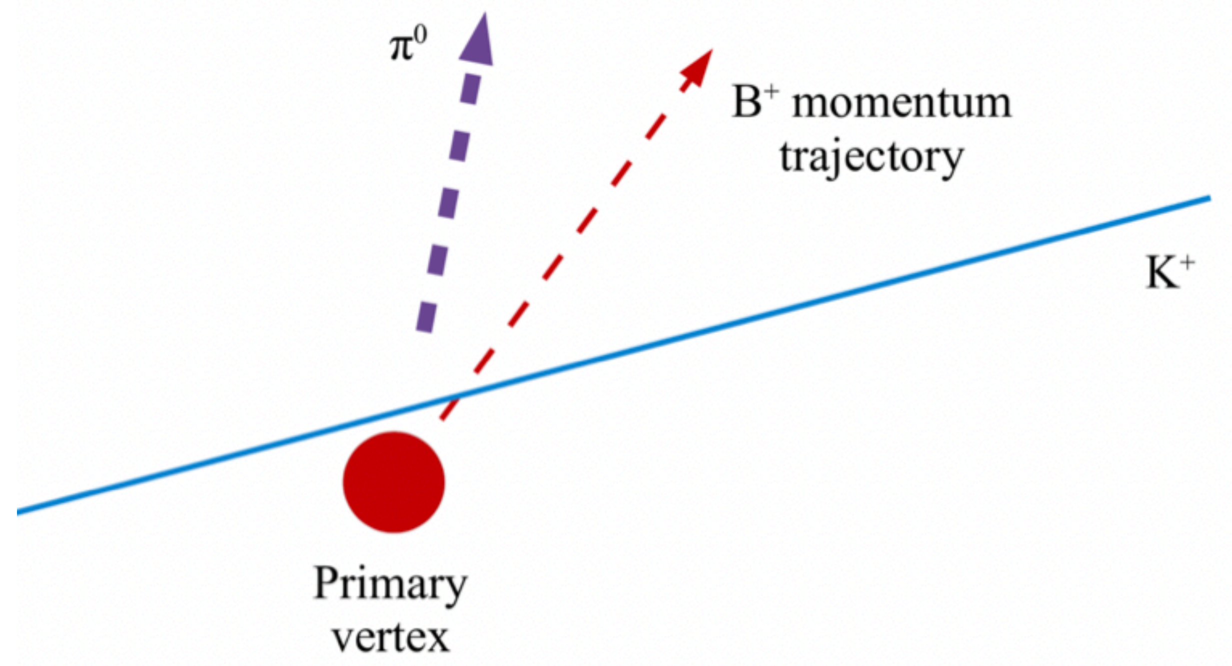
Consistent analyses

LHCb-CONF-2022-003

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

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

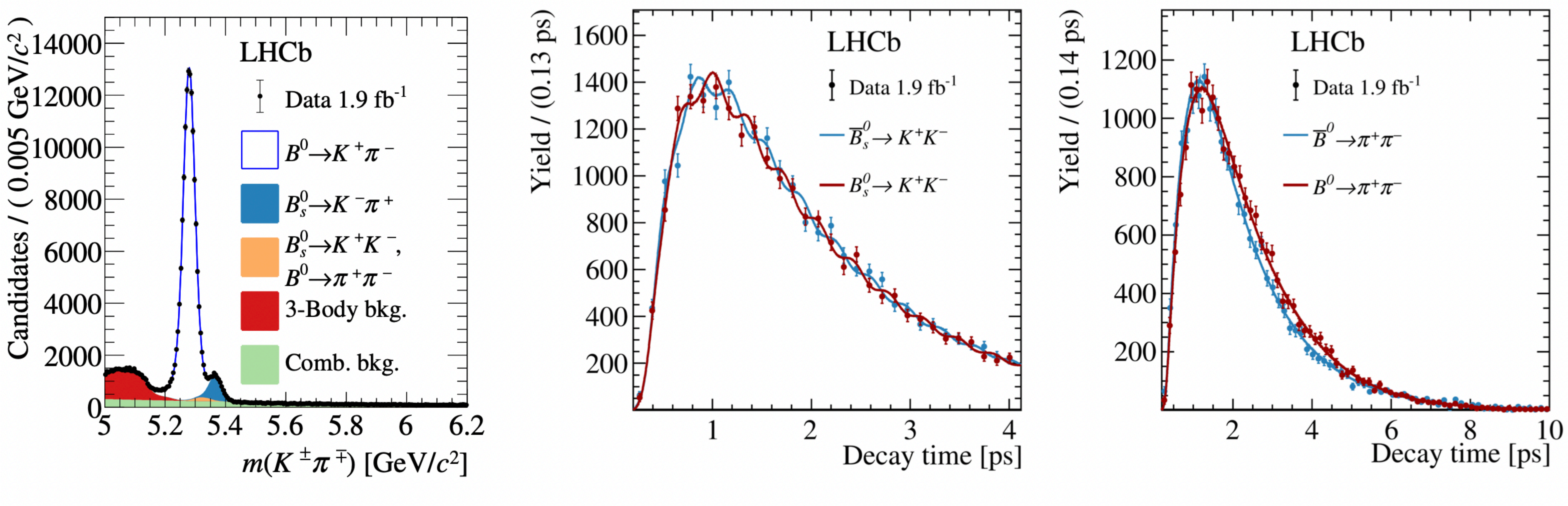
B→hh

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

An important quantity to control is detector asymmetries

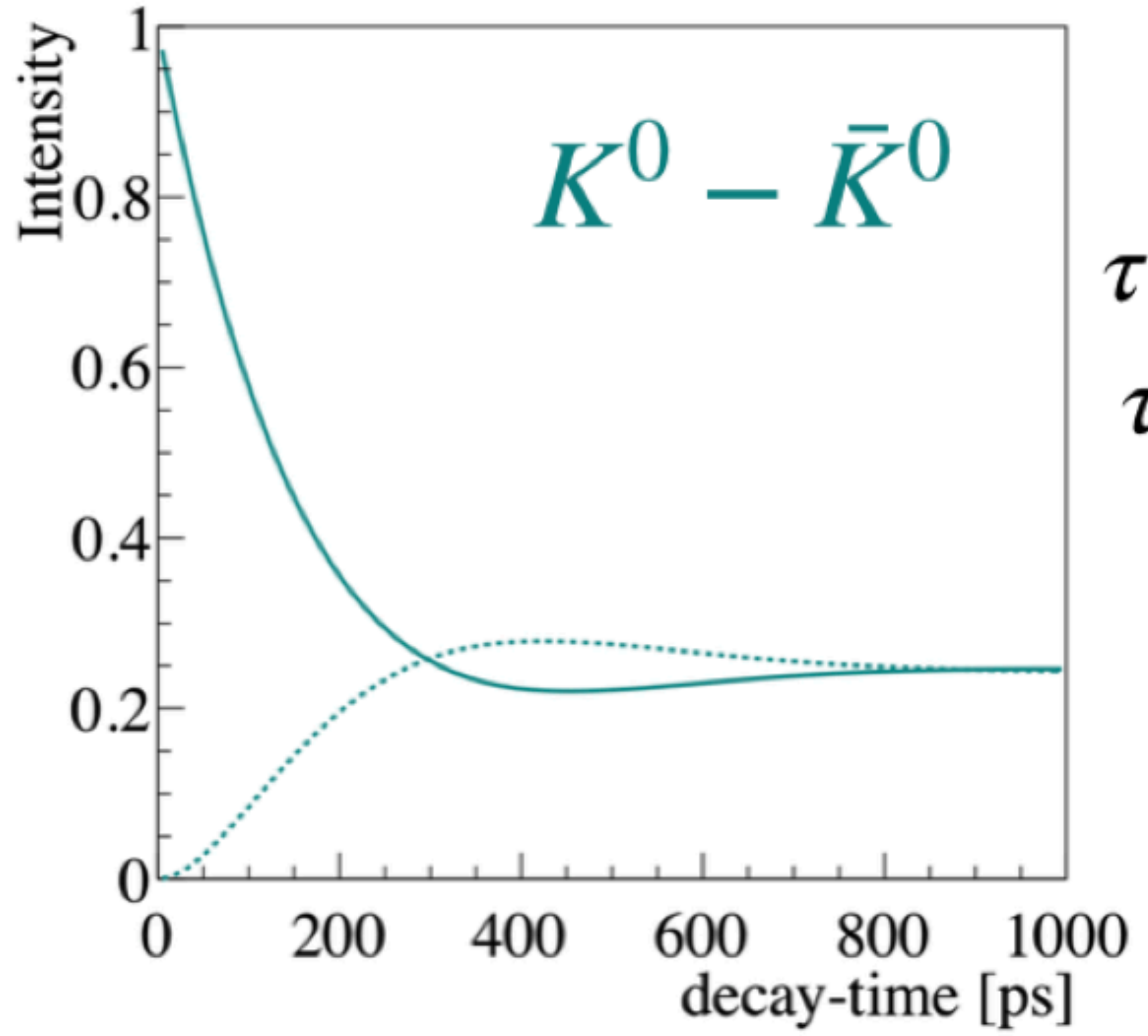
$$A_{\rm det}^{K\pi} = A_{\rm RAW}^{K\pi\pi} - A_{\rm RAW}^{\bar{K}^0\pi} - A_{\rm det}^{K^0}.$$

Analyses that explore U spin symmetry



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

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

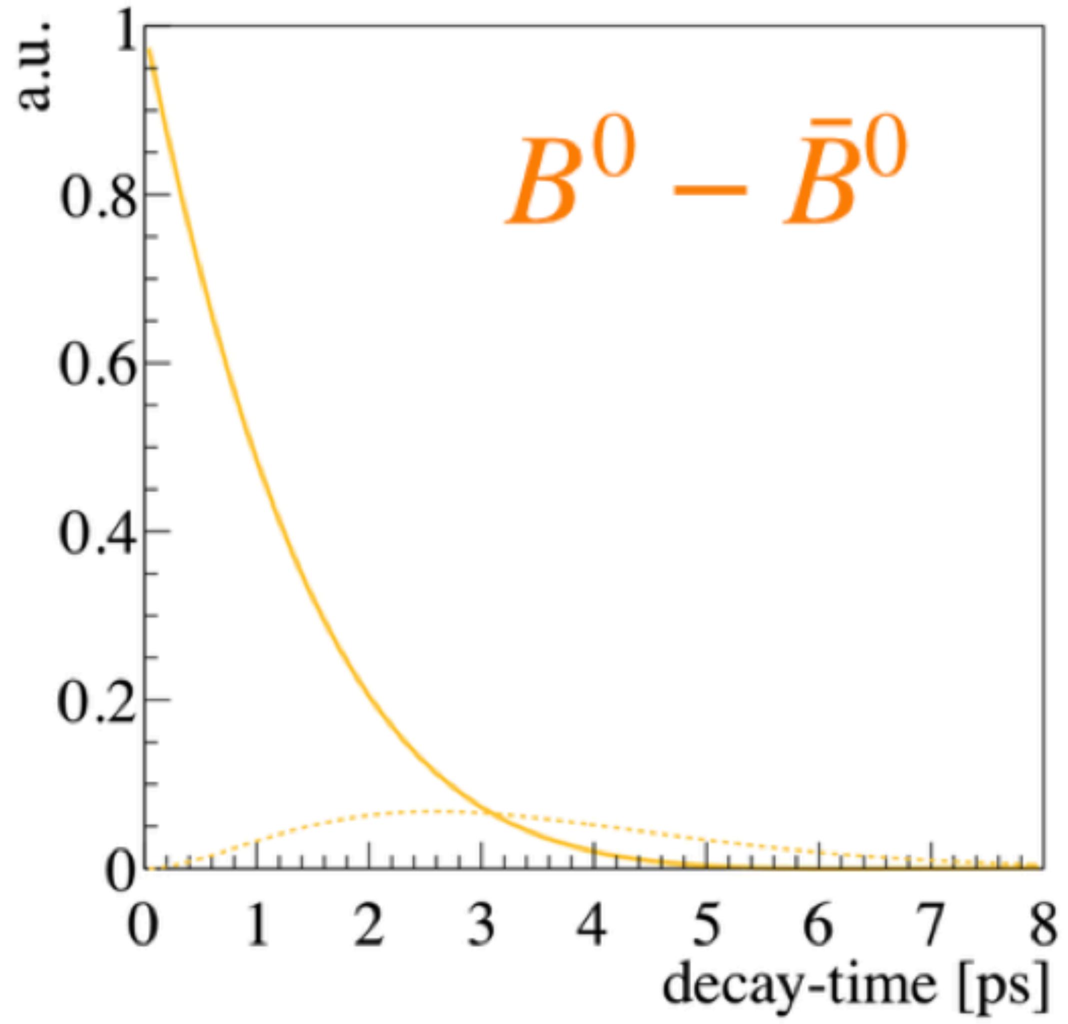


Very different lifetime:

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

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

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



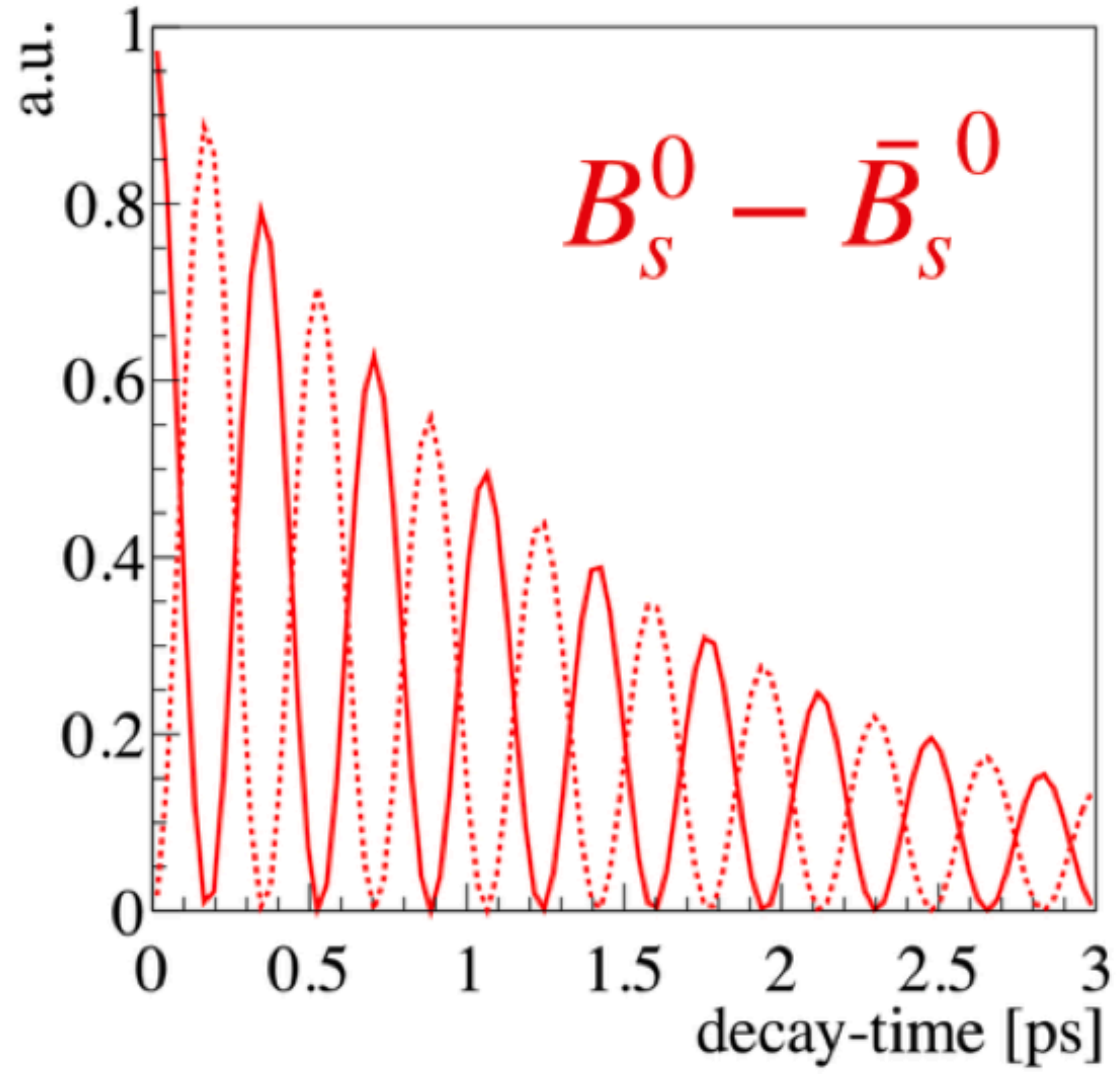
Oscillations

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

Lifetime

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

The same order of magnitudes

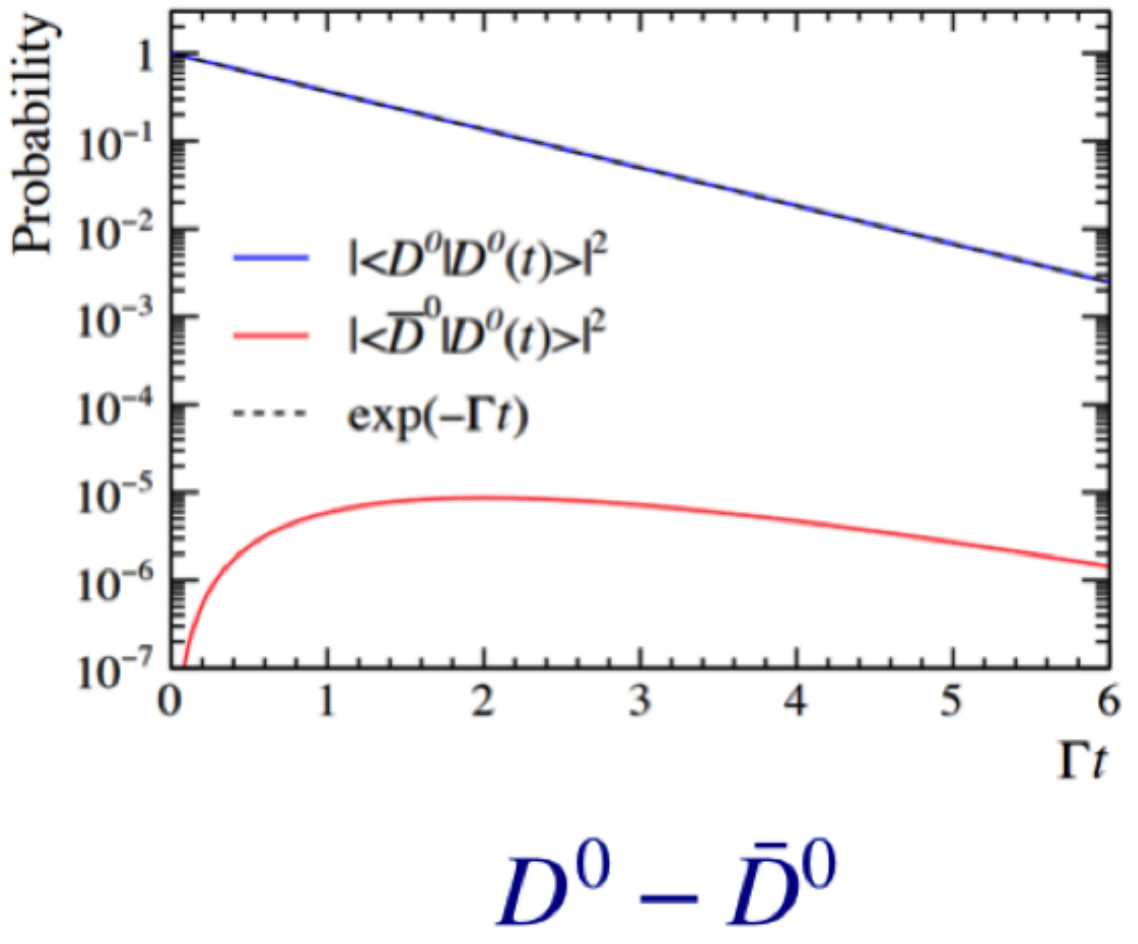


Very fast oscillations

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

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

Non-zero $\Delta\Gamma_s$



Very slow oscillations

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

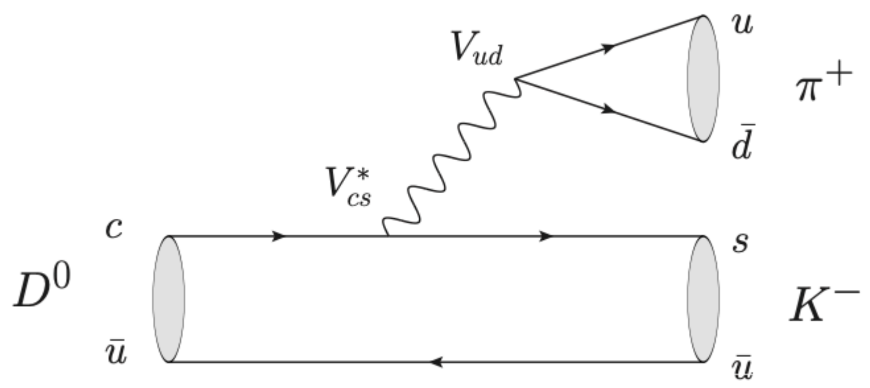
Very short lifetime

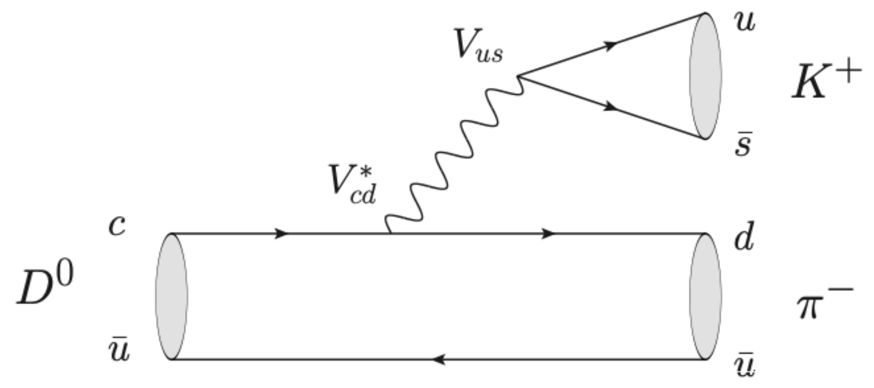
$\tau(D^0) \sim 0.4\ ps$

D^0 decays before has a chance to oscillate

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

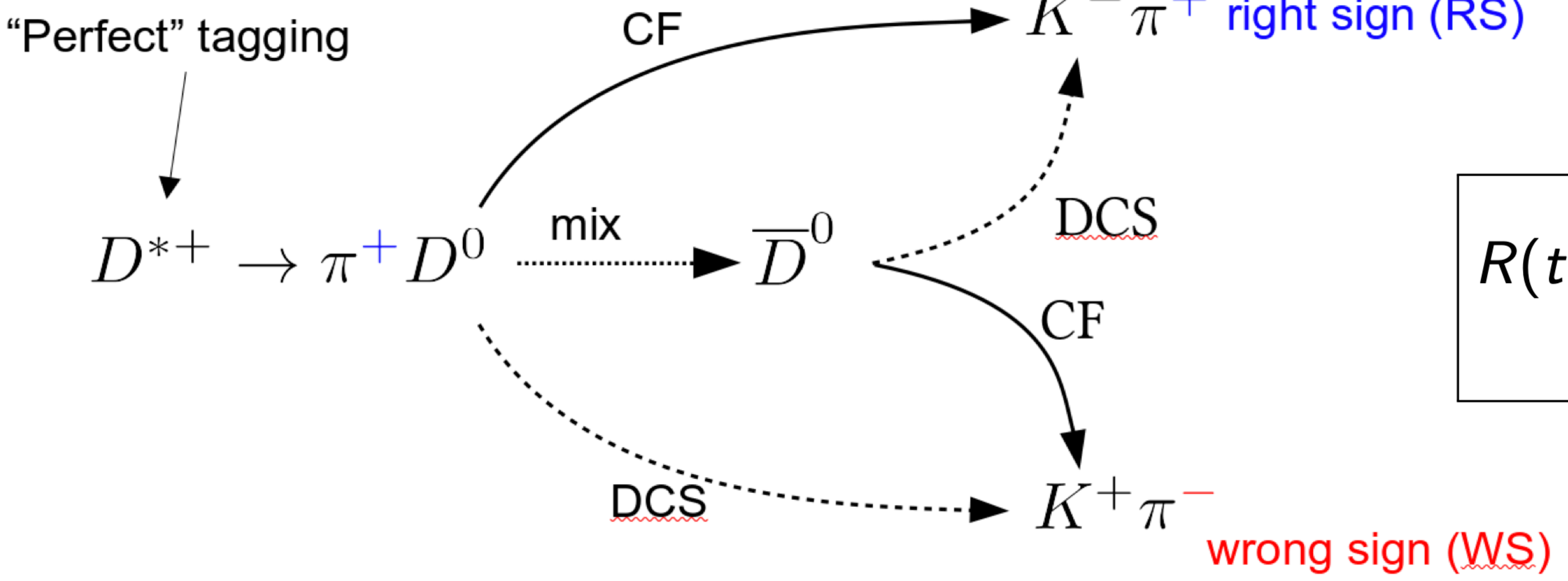
Mixing in charm land





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

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



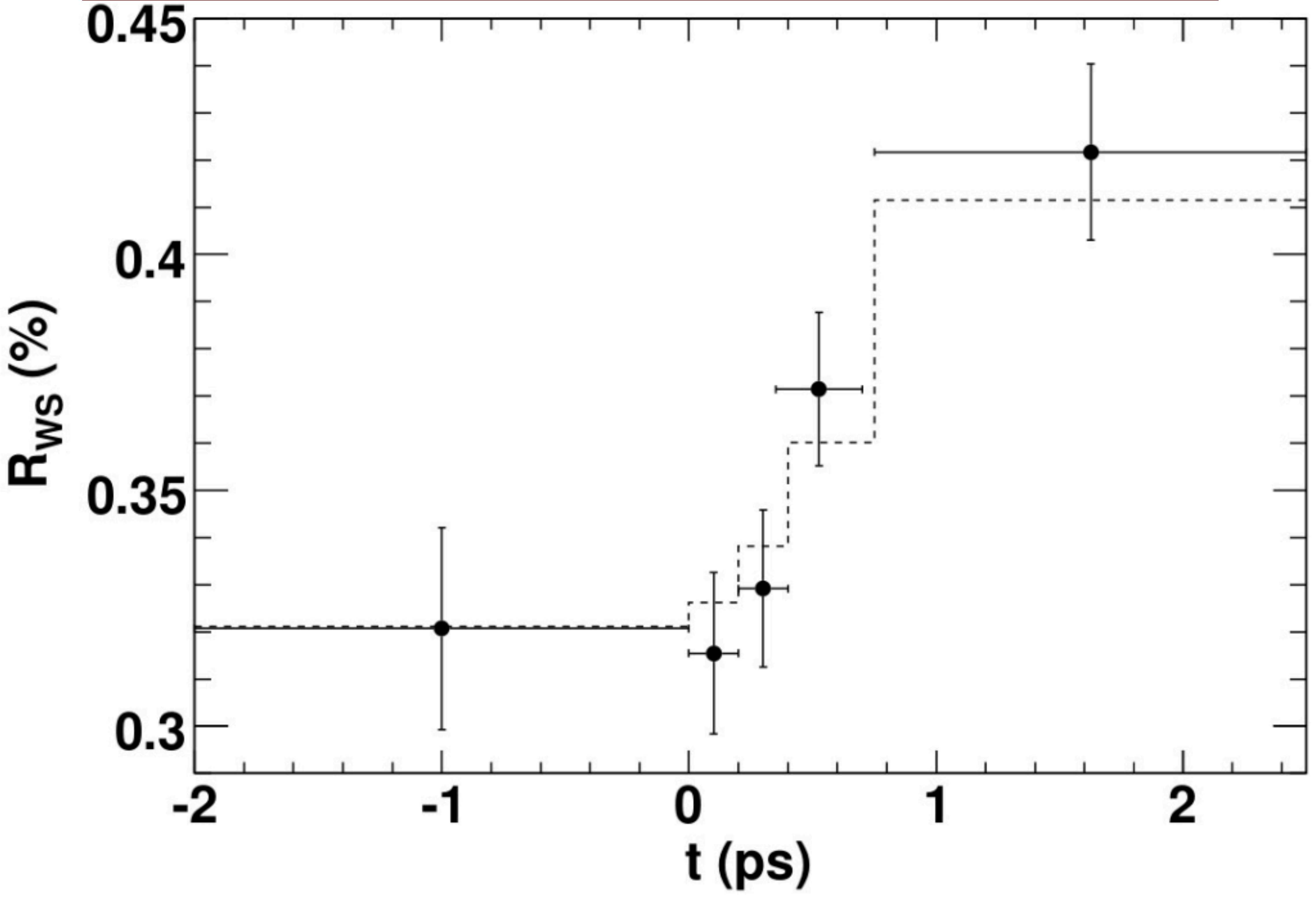
$$R(t) = \frac{N(\text{wrong})(t)}{N(\text{right})(t)}$$

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

I warned you there is a lot of Jargon

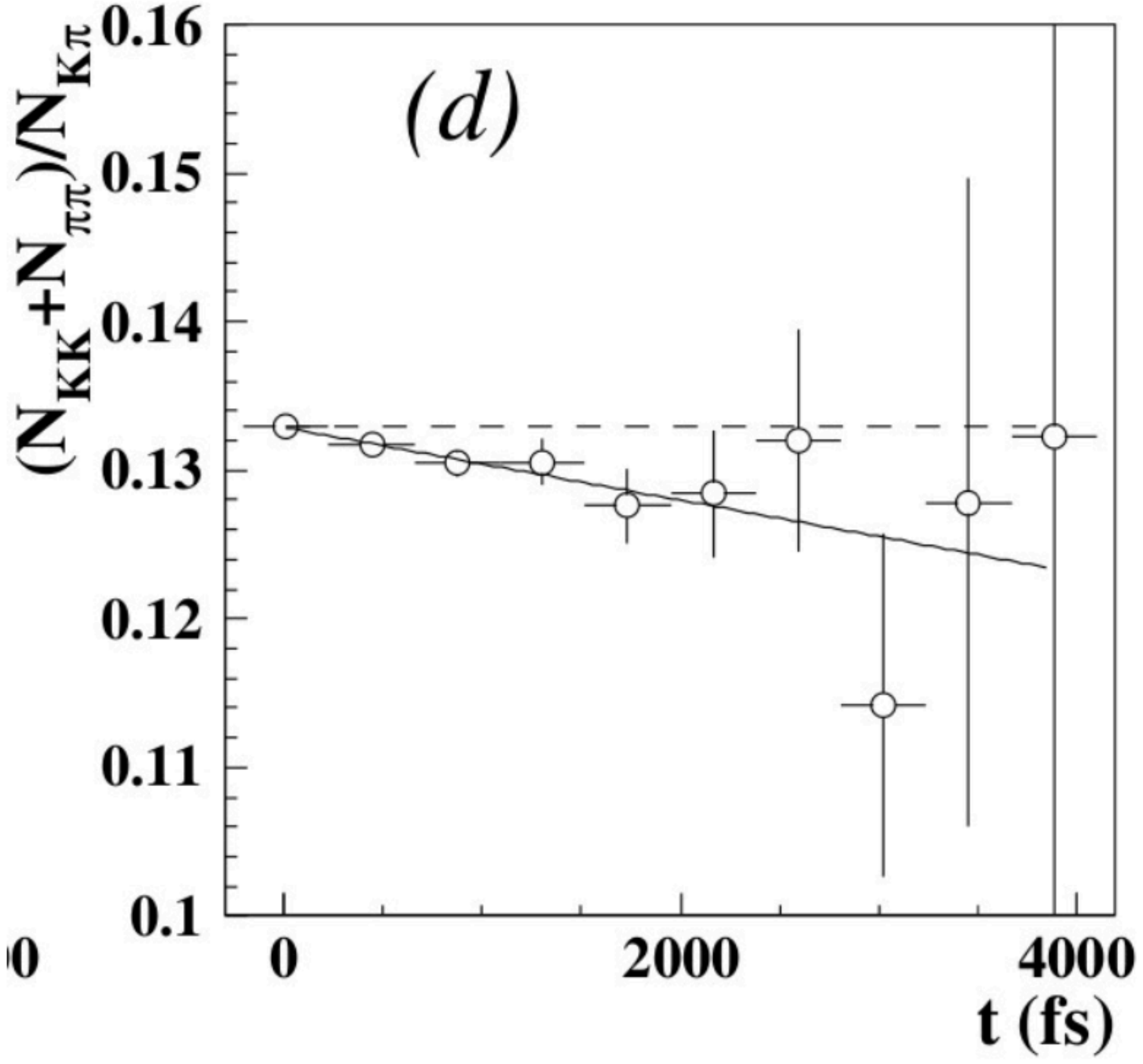
Charm Mixing 2007

BaBar, PRL 98 (2007) 211802



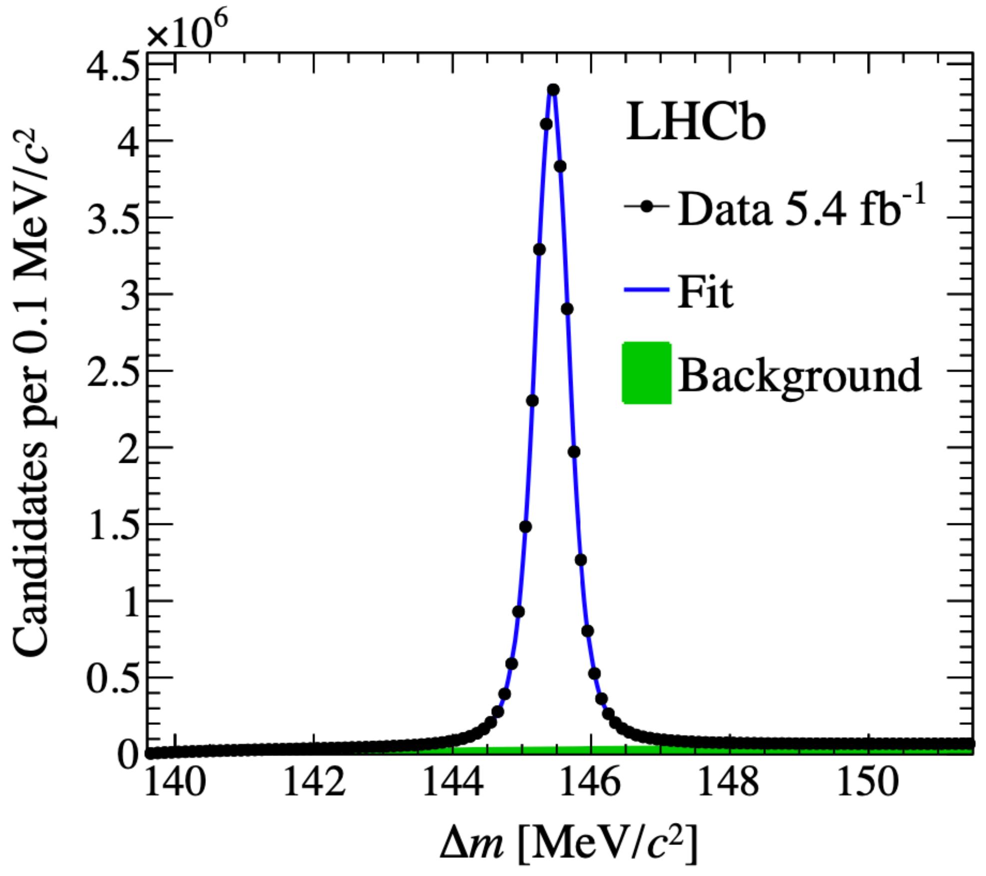
$D^0 \to K^+\pi^-$

Belle, PRL 98 (2007) 211803

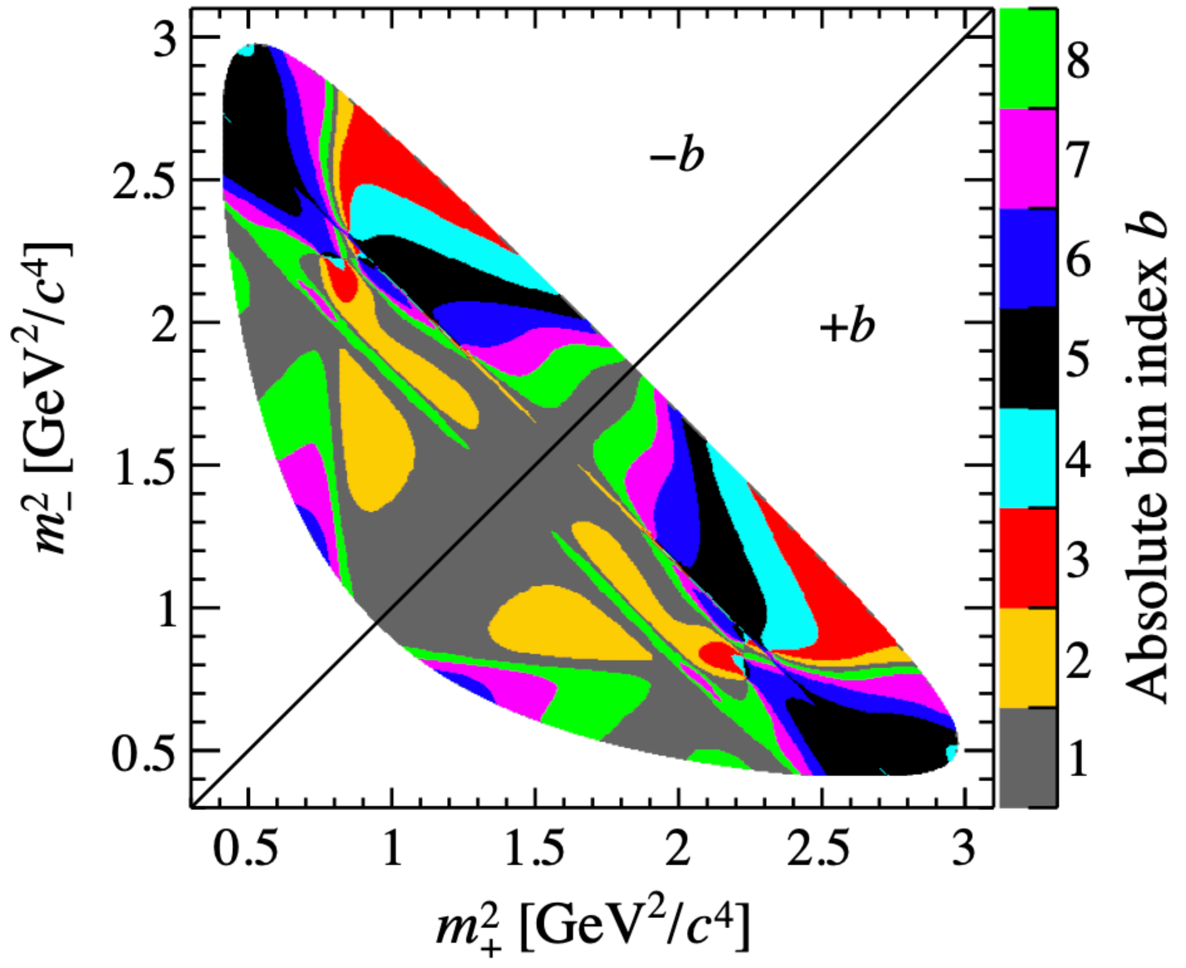


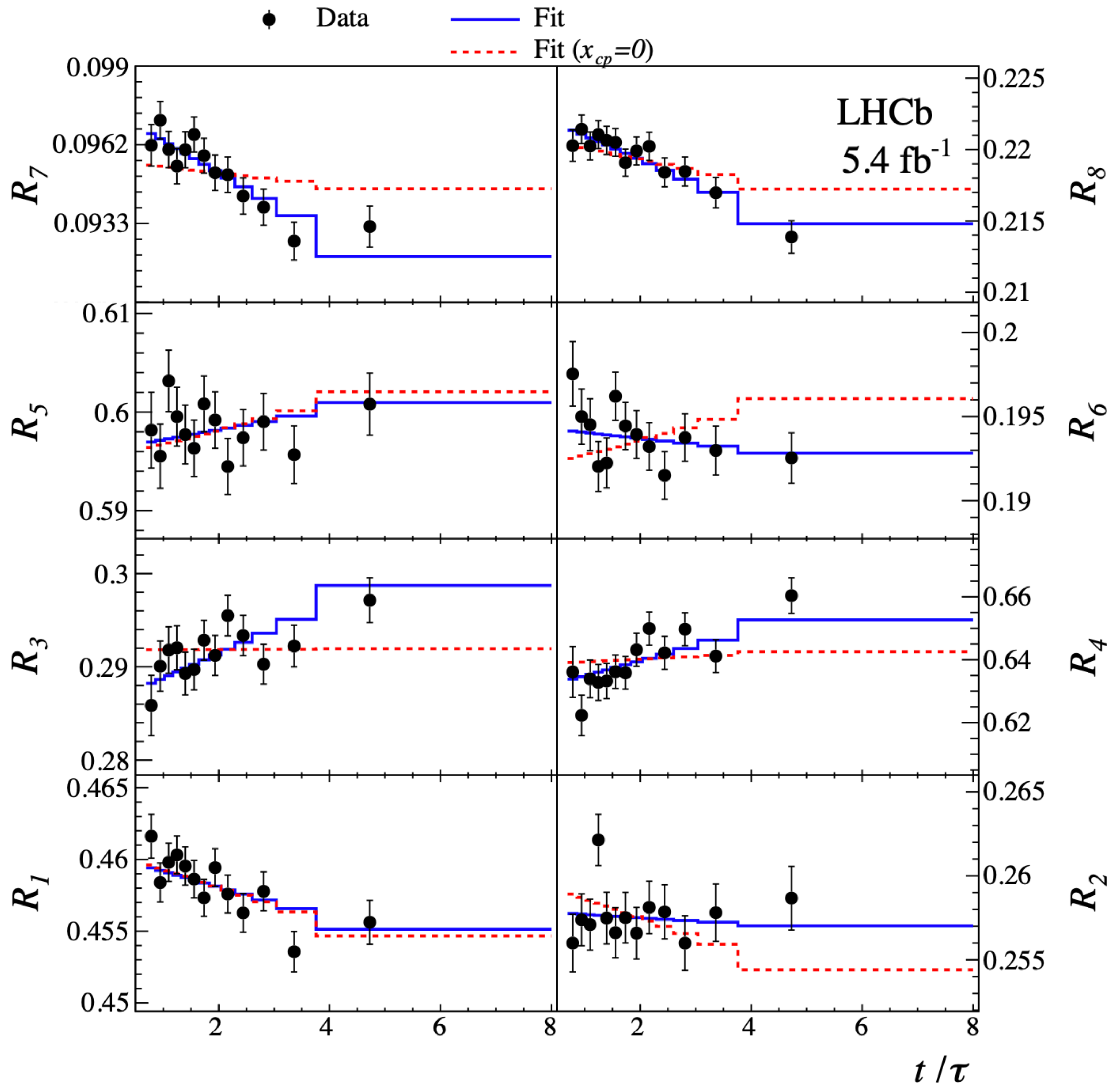
$D^0 \to K^+K^-, \pi^+\pi^-$

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

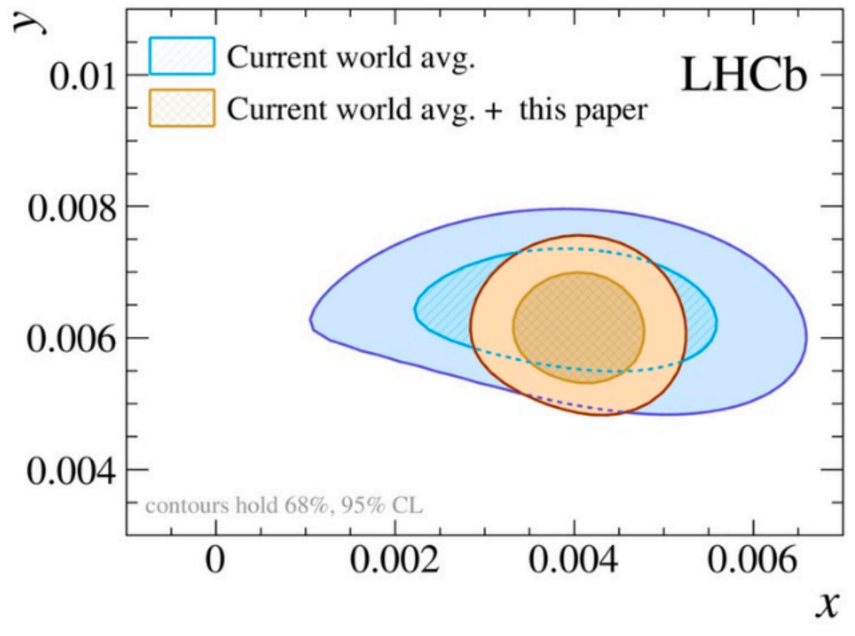


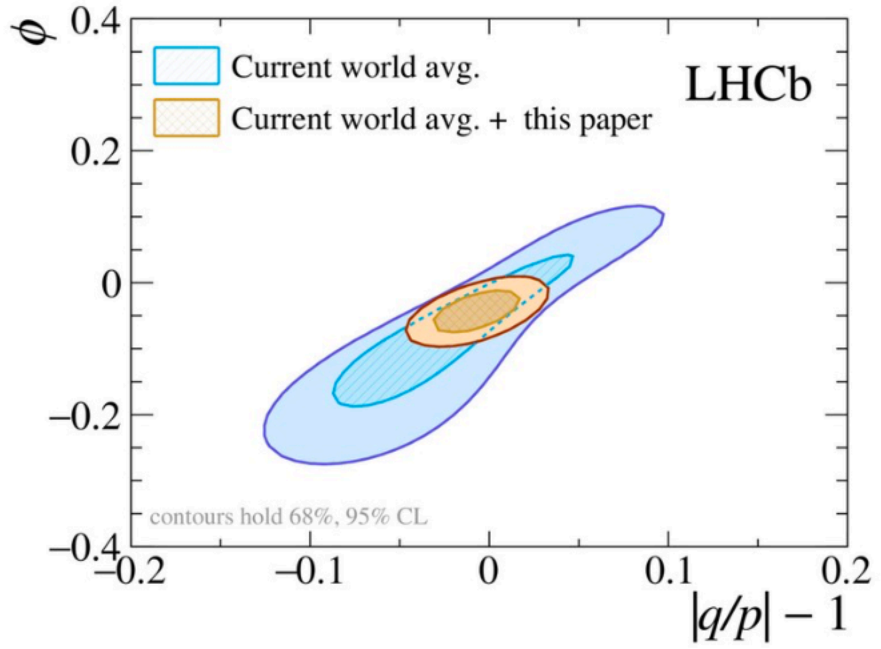
Bin flip method





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





LHCb, PRL 127 (2021) 111801

Loop back to beauty !

arXiv:2001.07207v3 [hep-ph] 12 Feb 2021

Dispersive and Absorptive CP Violation in $D^0 - \overline{D}^0$ Mixing

Alexander L. Kagan[1,*] and Luca Silvestrini[2,3,†]

[1]*Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221,USA*
[2]*CERN, 1211 Geneva 23, Switzerland*
[3]*INFN, Sezione di Roma, Piazzale A. Moro 2, I-00185 Roma, Italy*

CP violation (CPV) in $D^0-\overline{D}^0$ mixing is described in terms of the dispersive and absorptive 'weak phases' ϕ_f^M and ϕ_f^Γ. They parametrize CPV originating from the interference of D^0 decays with and without dispersive mixing, and with and without absorptive mixing, respectively, for CP conjugate hadronic final states f, $\bar{f}$. These are distinct and separately measurable effects. For CP eigenstate final states, indirect CPV only depends on ϕ_f^M (dispersive CPV), whereas ϕ_f^Γ (absorptive CPV) can only be probed with non-CP eigenstate final states. Measurements of the final state dependent phases ϕ_f^M, ϕ_f^Γ determine the intrinsic dispersive and absorptive mixing phases ϕ_2^M and ϕ_2^Γ. The latter are the arguments of the dispersive and absorptive mixing amplitudes M_{12} and Γ_{12}, relative to their dominant ($\Delta U = 2$) U-spin components. The intrinsic phases are experimentally accessible due to *approximate universality*: in the SM, and in extensions with negligible new CPV phases in Cabibbo favored/doubly Cabibbo suppressed (CF/DCS) decays, the deviation of $\phi_f^{M,\Gamma}$ from $\phi_2^{M,\Gamma}$ is negligible in CF/DCS decays $D^0 \to K^\pm X$, and below 10% in CF/DCS decays $D^0 \to K_{S,L}X$ (up to precisely known $O(\epsilon_K)$ corrections). In Singly Cabibbo Suppressed (SCS) decays, QCD pollution enters at $O(\epsilon)$ in U-spin breaking and can be significant, but is $O(\epsilon^2)$ in the average over $f = K^+K^-$, $\pi^+\pi^-$. SM estimates yield $\phi_2^M, \phi_2^\Gamma = O(0.2\%)$. A fit to current data allows $O(10)$ larger phases at 2σ, from new physics. A fit based on naively extrapolated experimental precision suggests that sensitivity to ϕ_2^M and ϕ_2^Γ in the SM may be achieved at the LHCb Phase II upgrade.

I. INTRODUCTION

In the Standard Model (SM), CP violation (CPV) enters $D^0 - \overline{D}^0$ mixing and D decays at $O(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$, due to the weak phase γ. Consequently, all three types of CPV [1] are realized: (i) direct CPV, (ii) CPV in pure mixing (CPVMIX), which is due to interference of the dispersive and absorptive mixing amplitudes, and (iii) CPV due to the interference of decay amplitudes with and without mixing (CPVINT). In this work, we are particularly interested in the latter two, which result from $D^0 - \overline{D}^0$ mixing, and which we collectively refer to as "indirect CPV". We would like to answer the following questions: How large are the indirect CPV asymmetries in the SM? What is the minimal parametrization appropriate for the LHCb/Belle-II precision era? How large is the current window for new physics (NP)? Can this window be closed by LHCb and Belle-II?

In order to address these questions we first develop the description of indirect CPV in terms of the CP violating (CP-odd) and final state dependent dispersive and absorptive "weak phases". These phases, which we denote as ϕ_f^M and ϕ_f^Γ, respectively, for CP conjugate final states f and $\bar{f}$, parametrize CPVINT contributions originating from the interference of D^0 decays with and without dispersive (absorptive) mixing, respectively. These are distinct measurable effects, as we will see below. Their difference equals the CPVMIX weak phase.

An immediate consequence of our approach is that it yields simplified expressions for the indirect CP asymmetries, which have a transparent physical interpretation (unlike the more familiar description in terms of the mixing parameter $|q/p|$, and the weak phase ϕ_{λ_f}). In particular, the requirement that the underlying interfering amplitudes possess non-trivial CP-even "strong-phase" differences is manifest, and accounts for the differences between the ϕ_f^M and ϕ_f^Γ dependence of the CP asymmetries. For example, we will see that the time-dependent CPVINT asymmetries in decays to CP eigenstate final states are purely dispersive, i.e. they only depend on ϕ_f^M (apart from subleading direct CPV effects).

In the SM, the dispersive and absorptive $D^0-\overline{D}^0$ mixing amplitudes are due to the long distance exchanges of all off-shell and on-shell intermediate states, respectively (short distance dispersive mixing is negligible). The CPVINT asymmetries are due to the CP-odd contributions of the subleading $\Delta C = 1$ transitions to the mixing amplitudes (via intermediate states) and the decay amplitudes (via final states). The combined effects of these two CPV contributions can be expressed in terms of the underlying final state dependent phases $\phi_f^{M,\Gamma}$, as noted above. Unfortunately, due to their non-perturbative nature, these phases can not currently be calculated from first principles QCD. However, we will be able to make meaningful statements using $SU(3)_F$ flavor symmetry arguments.

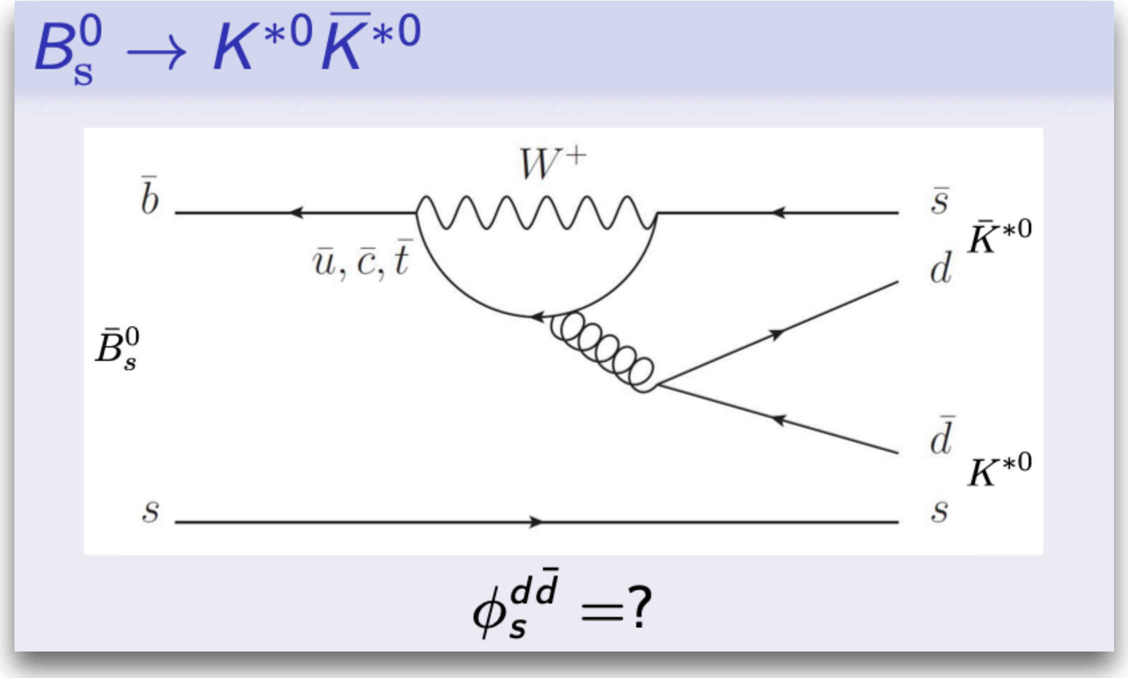
In order to estimate the magnitudes and final state dependence of $\phi_f^{M,\Gamma}$ in the different classes of decays, we compare them to a theoretical pair of dispersive and absorptive phases. The latter are intrinsic to the mixing amplitudes, and follow from their U-spin decomposition. In general, they are defined as the arguments of the

*kaganalexander@ucmail.uc.edu
†luca.silvestrini@roma1.infn.it

A very nice reference for the charm mixing formalism

Giving one hour lecture on CP Violation

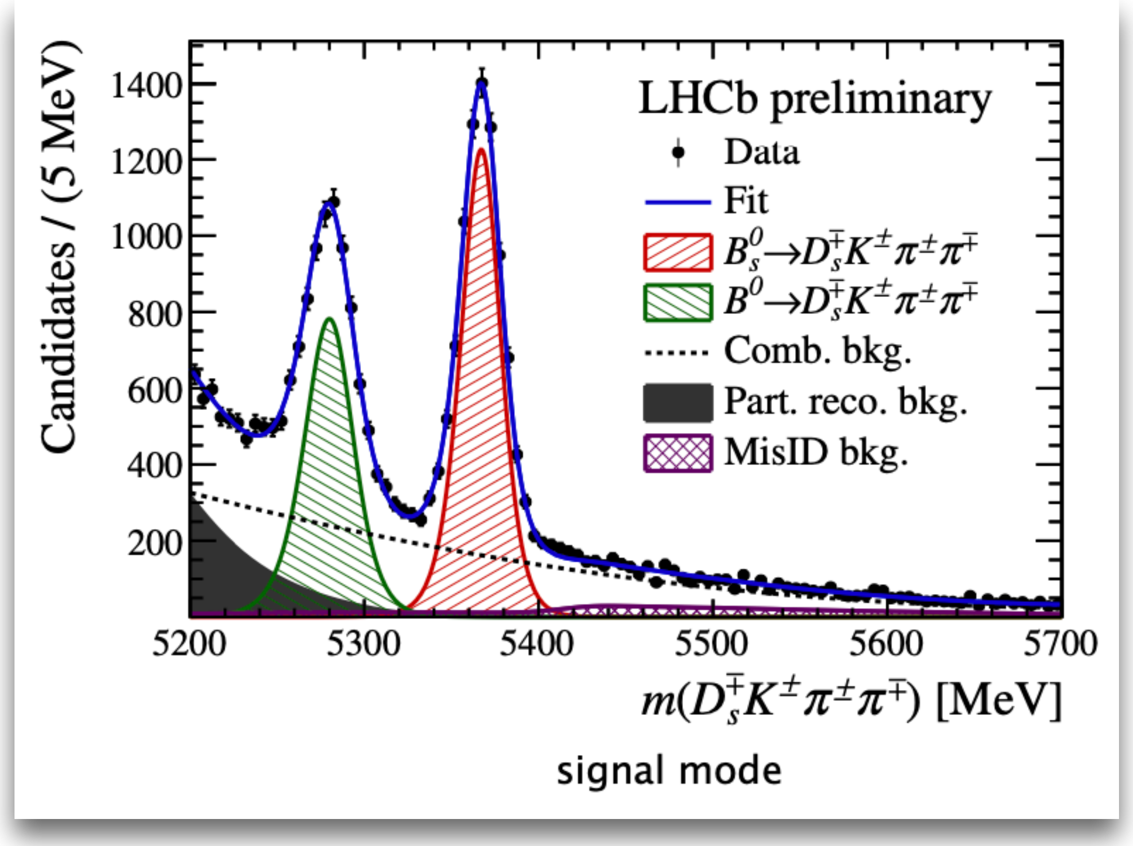
- Pros: it's only ~50 slides.
- Cons: it's impossible to do justice to the topic.

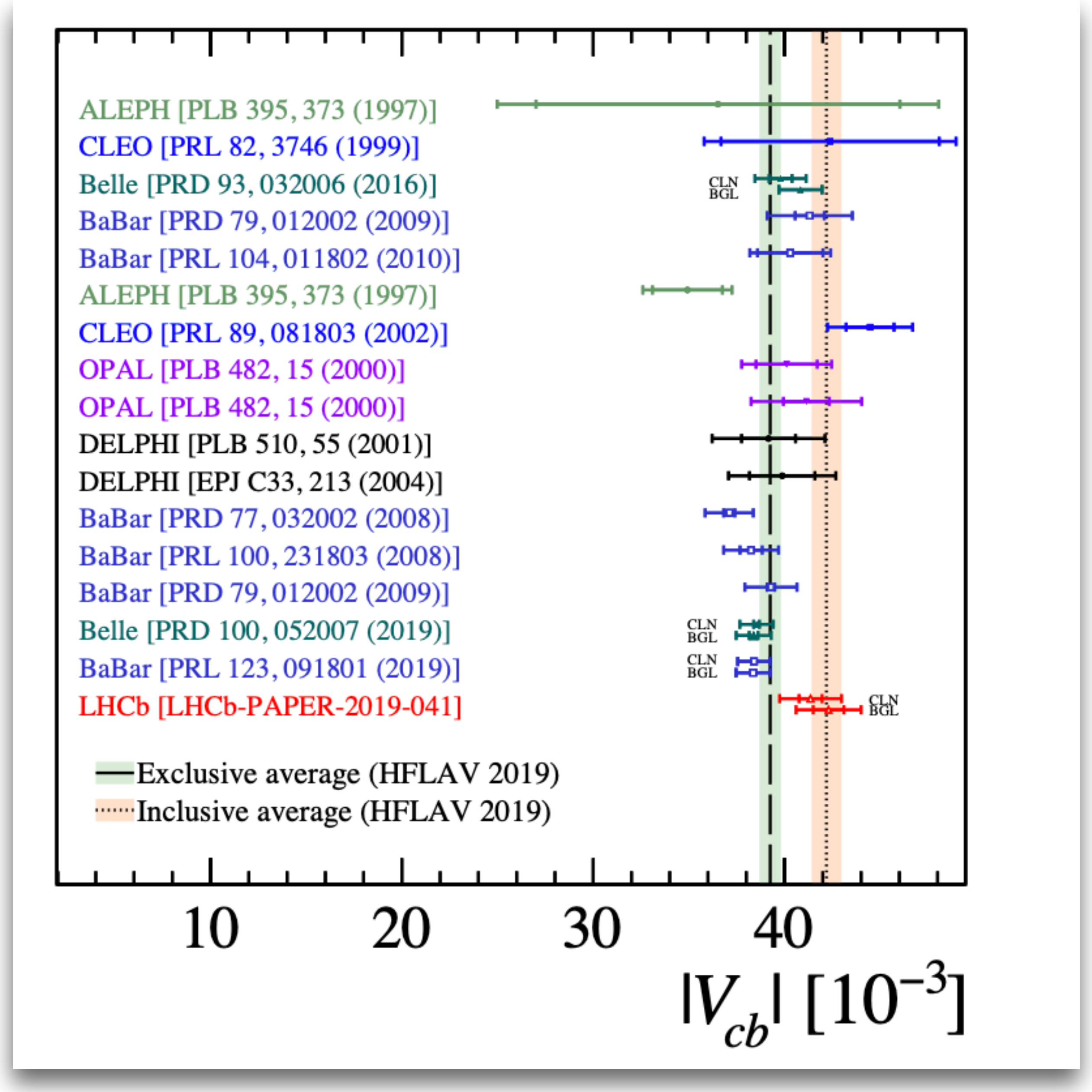


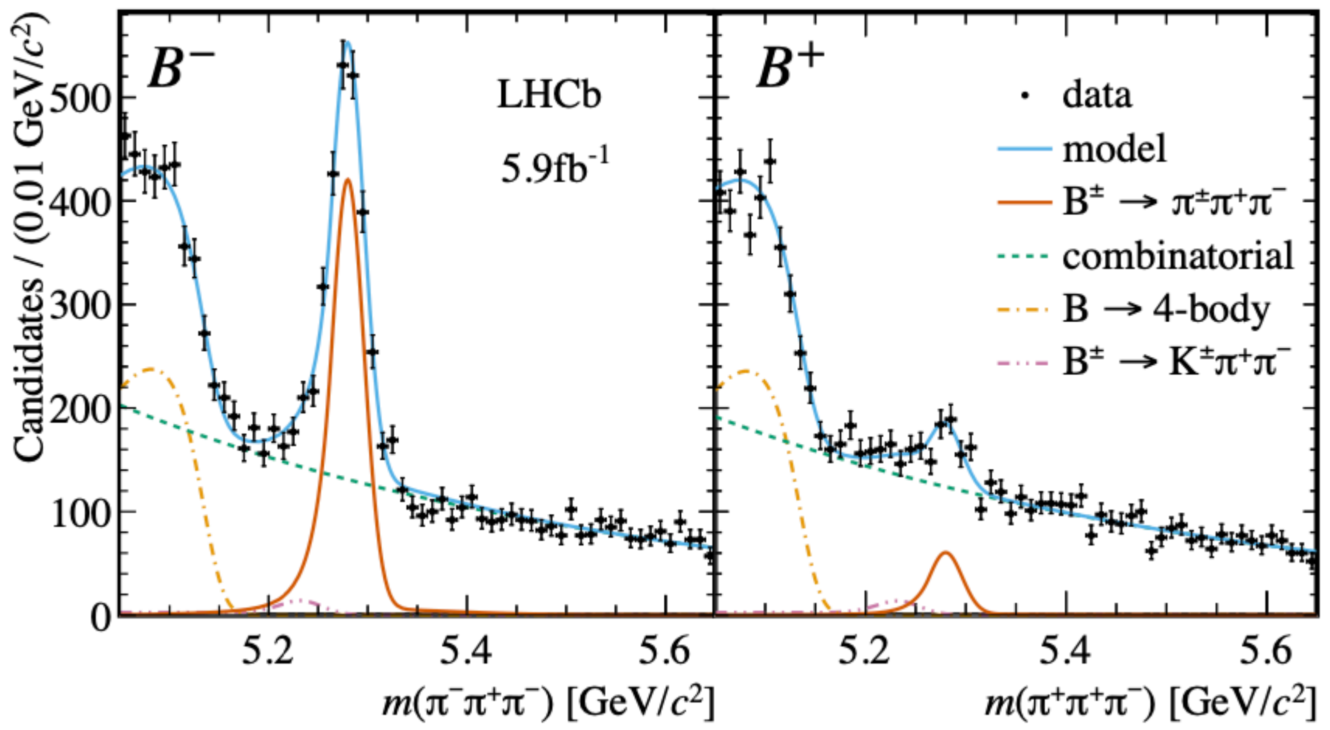
$A_{CP}(D^0 \to K_S^0 K_S^0)$

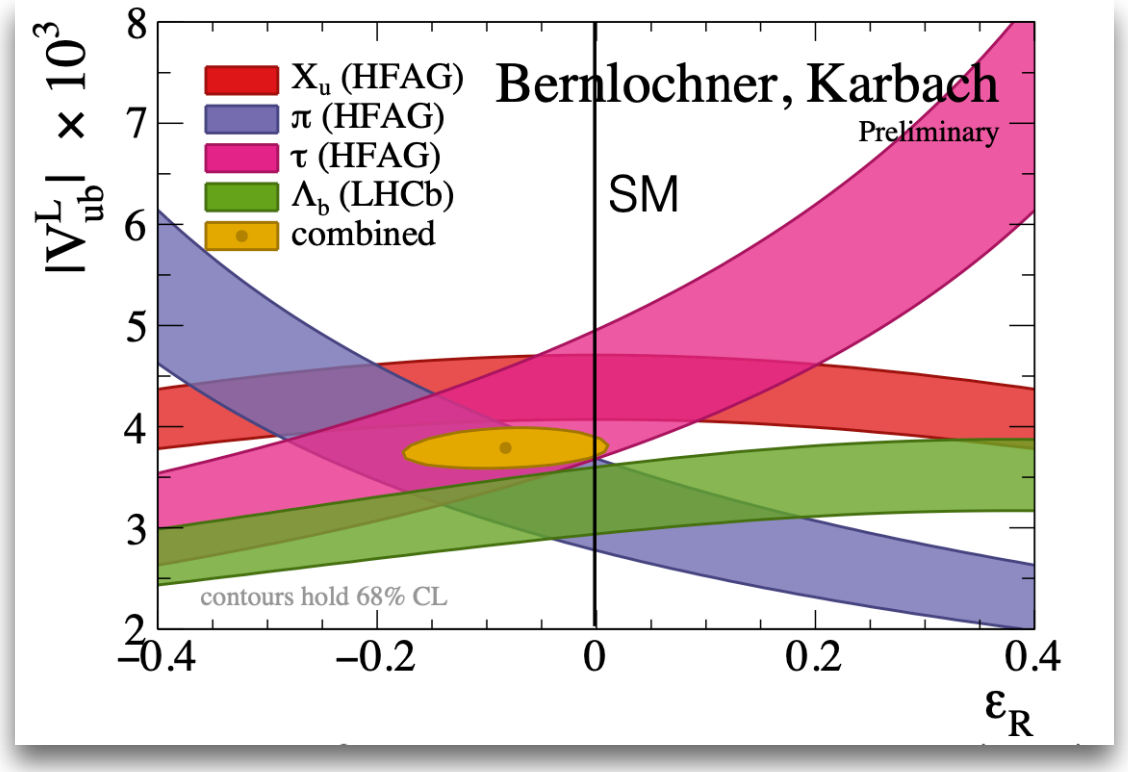
$A_{CP}(D_{(s)}^+ \to h^+\pi^0, h^+\eta)$

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



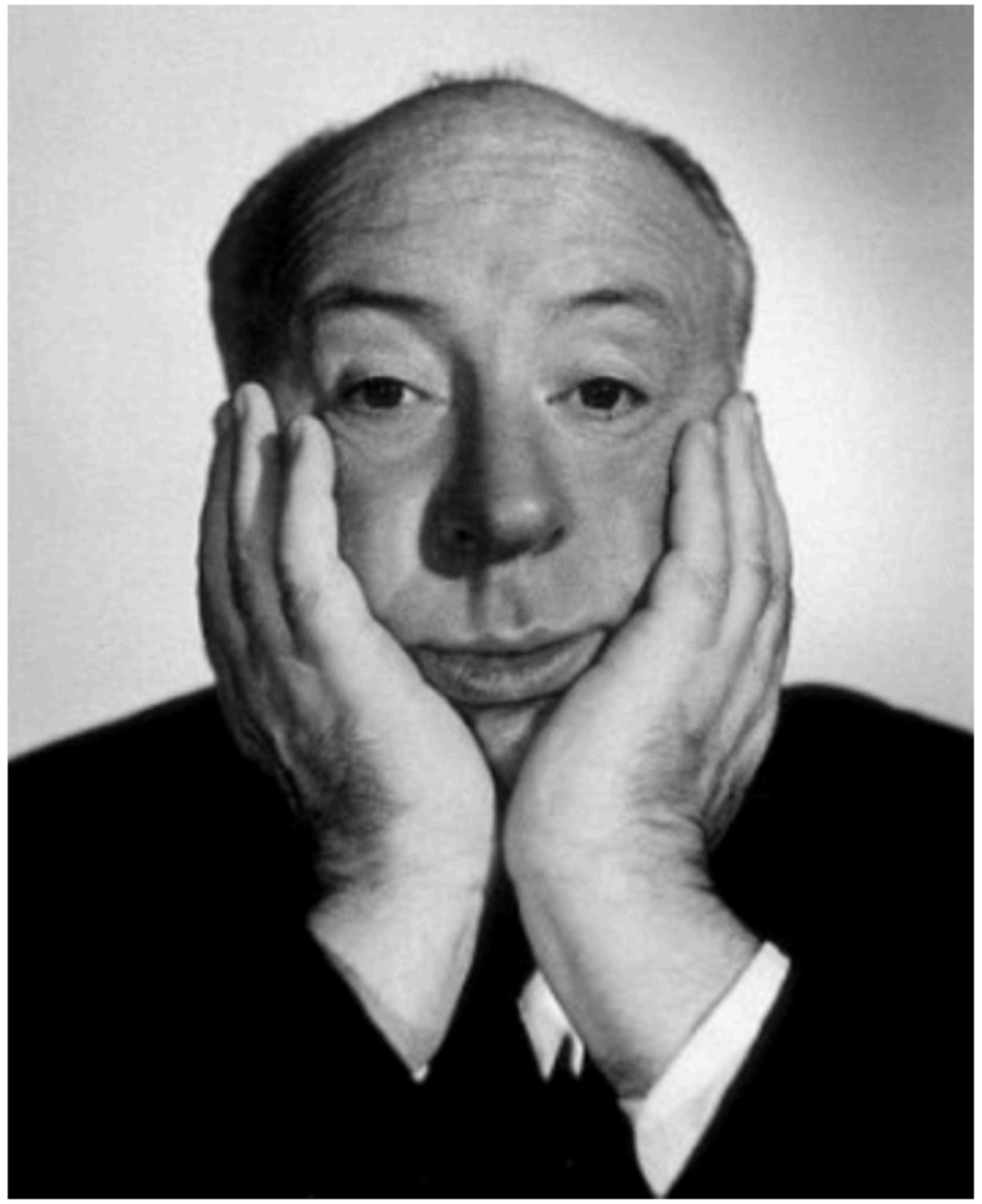






To conclude

CP violation is a fascinating topic, we are still learning a lot.



If you have questions yasmine.sara.amhis@cern.ch

A colouring book for children will soon be available at the CERN Science Gateway

More information yasmineamhis.com