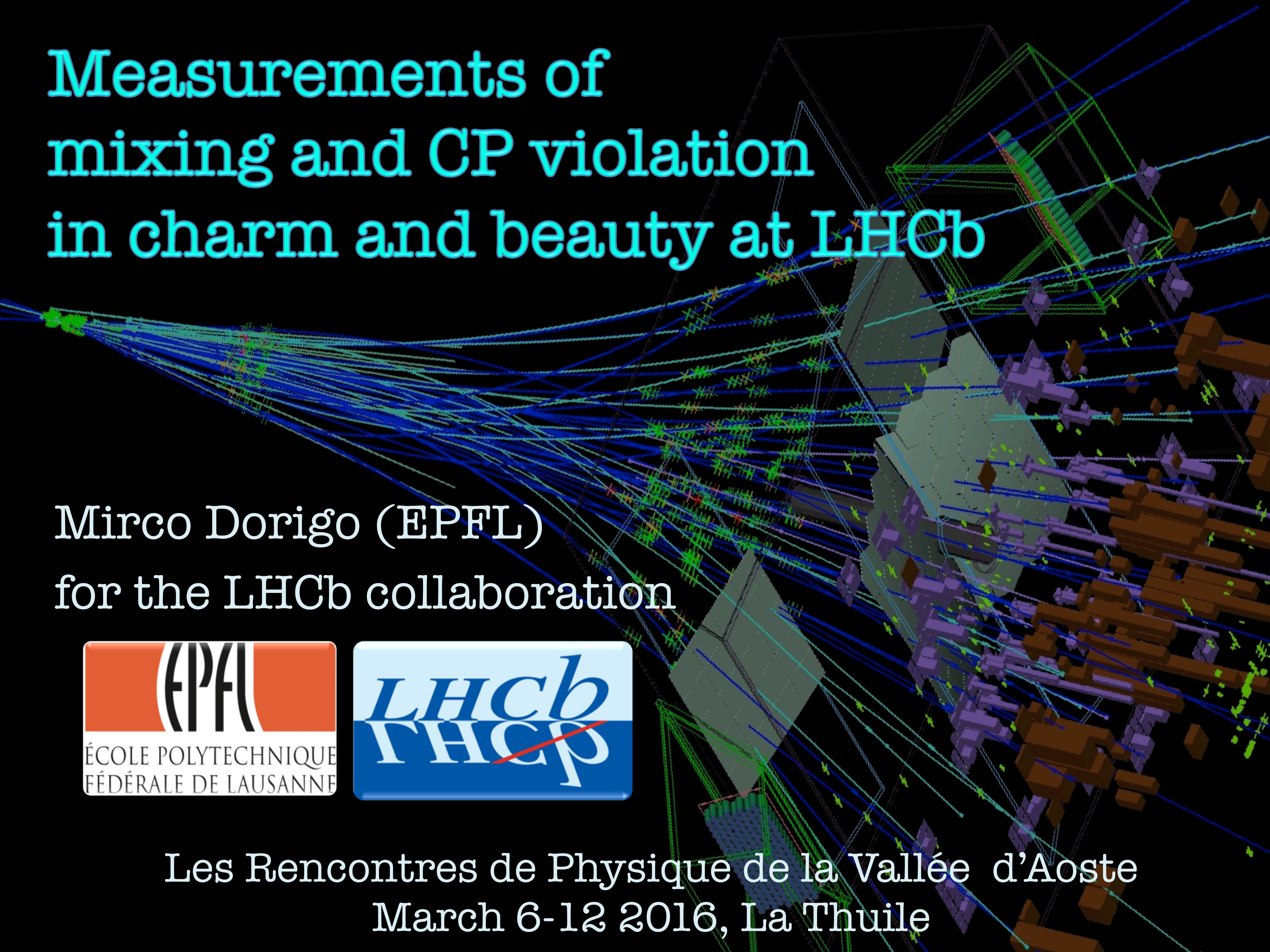
Measurements of mixing and CP violation in charm and beauty at LHCb

Mirco Dorigo (EPFL)
for the LHCb collaboration



Les Rencontres de Physique de la Vallée d'Aoste
March 6-12 2016, La Thuile

Accessing the next scale

Direct way

High energy production of new particles.
Probe directly structure of matter and its interactions

Indirect way (Flavour)

Low-energy precision measurements.
- NP can alter mixing dynamics
- NP can introduce new sources of CP violation

Mixing formalism

Neutral K (D, B and B_s) system:
"particle mixture",
time-evolution governed by
2x2 Schroedinger's equation

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \to \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

Phys. Rev. 97 (1955) 1387

$$i\frac{\partial}{\partial t}\begin{pmatrix}|P^0(t)\rangle \\ |\overline{P}^0(t)\rangle\end{pmatrix} = \left[\begin{pmatrix}M_{11} & M_{12} \\ M_{12}^* & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|P^0(t)\rangle \\ |\overline{P}^0(t)\rangle\end{pmatrix}$$

Eigenstates superposition of flavour states,
can have different masses and decay widths

$$|P_{L,H}\rangle = p|P^0\rangle \pm q|\overline{P}^0\rangle$$

$$x = \frac{\Delta m}{\Gamma} = \frac{m_H - m_L}{(\Gamma_H + \Gamma_L)/2}$$

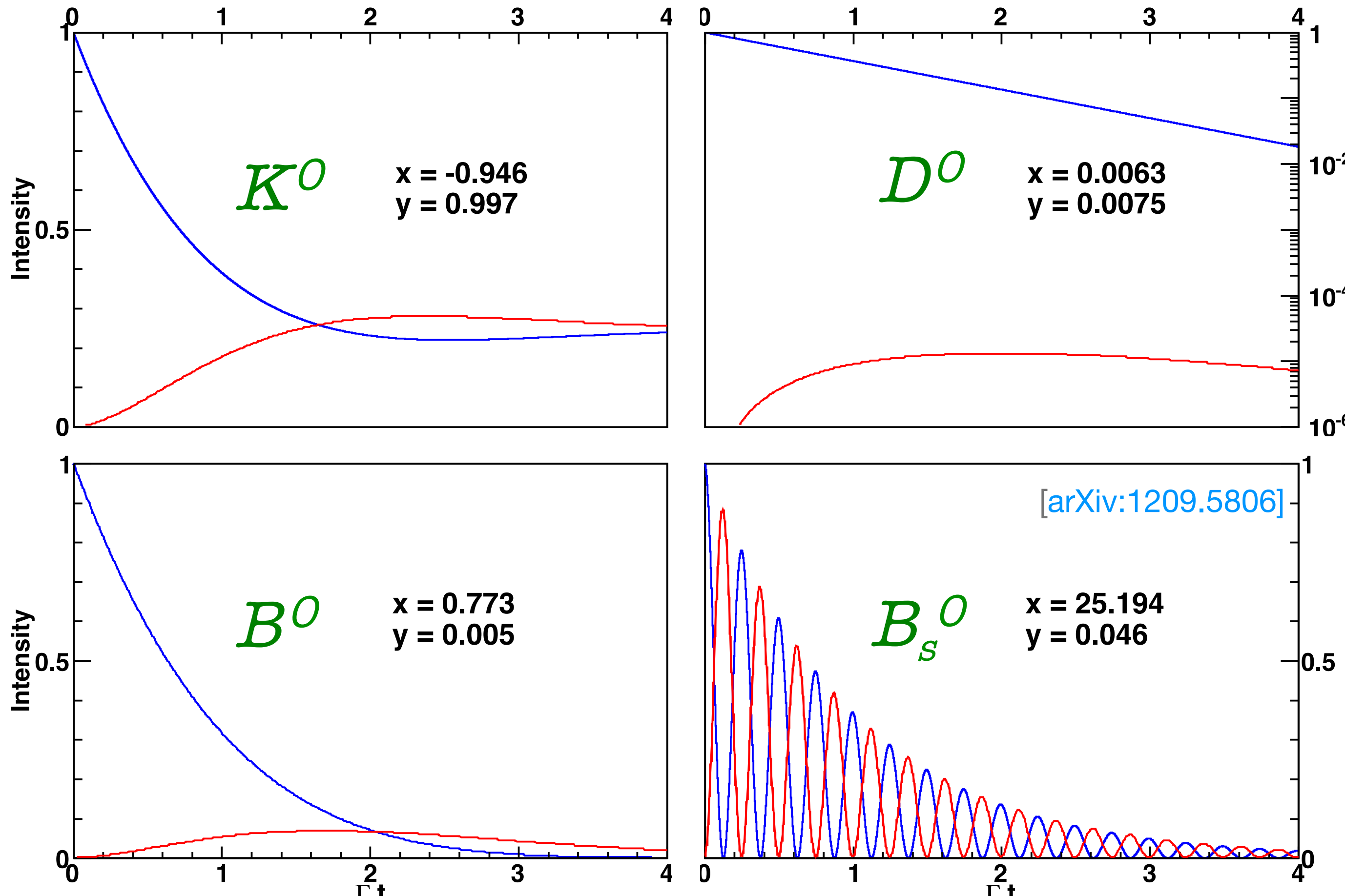
$$y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L}$$

If CP is conserved, q and p are real, i.e. $|q/p| = 1$ and $\varphi = \arg(q/p) = 0$

Phenomenology

Blue line:
given a P^0, at t=0,
the probability of
finding a P^0 at t

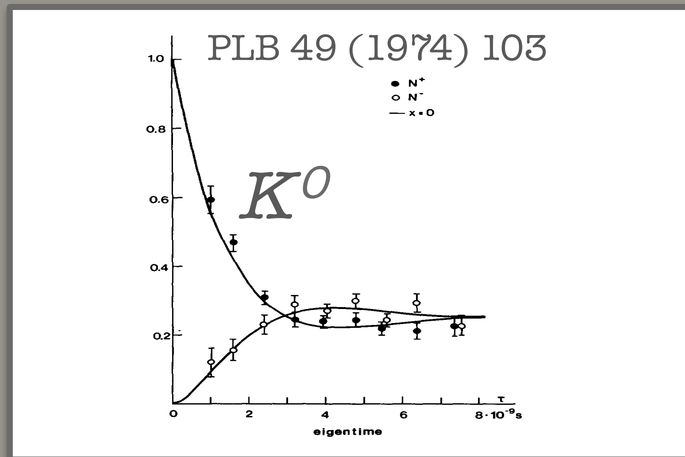
Red Line:
given a P^0, at t=0,
the probability of
finding a $\overline{P}^0$ at t

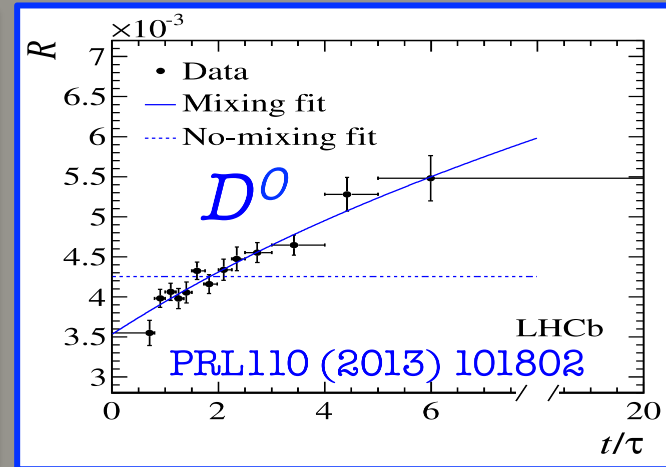


$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

$$|\langle P^0(0)|\overline{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

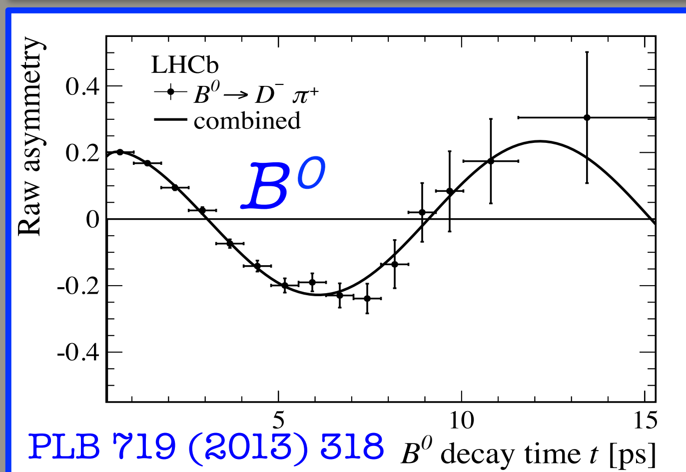
Phenomenology

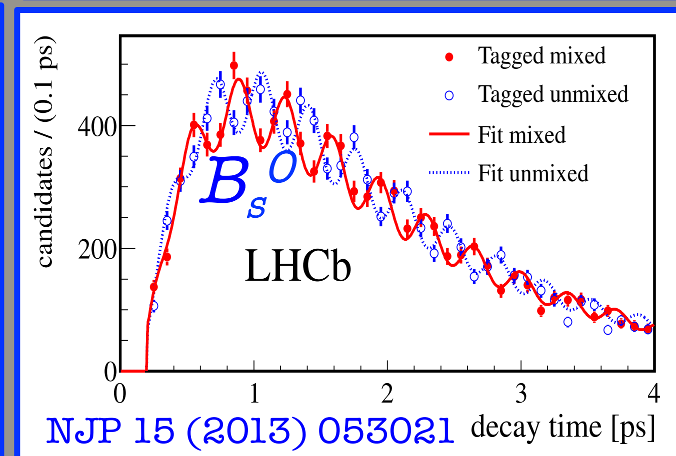




Blue line:
given a P⁰, at t=0, the probability of finding a P⁰ at t

Red Line:
given a P⁰, at t=0, the probability of finding a P̄⁰ at t

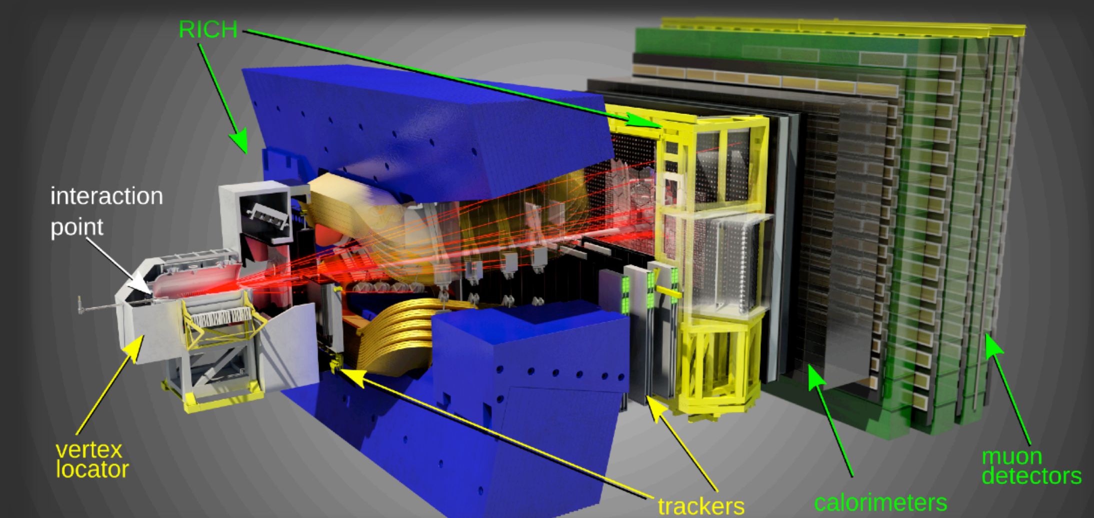




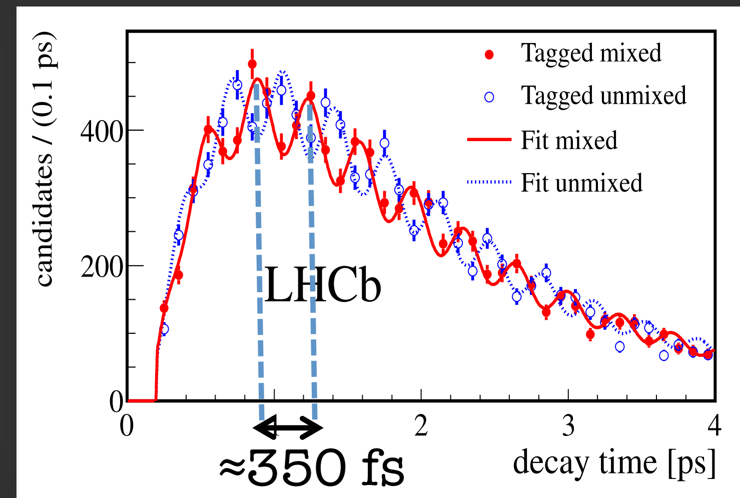
$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

$$|\langle P^0(0)|\overline{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

Experimentally



IJMP A30 (2015) 1530022

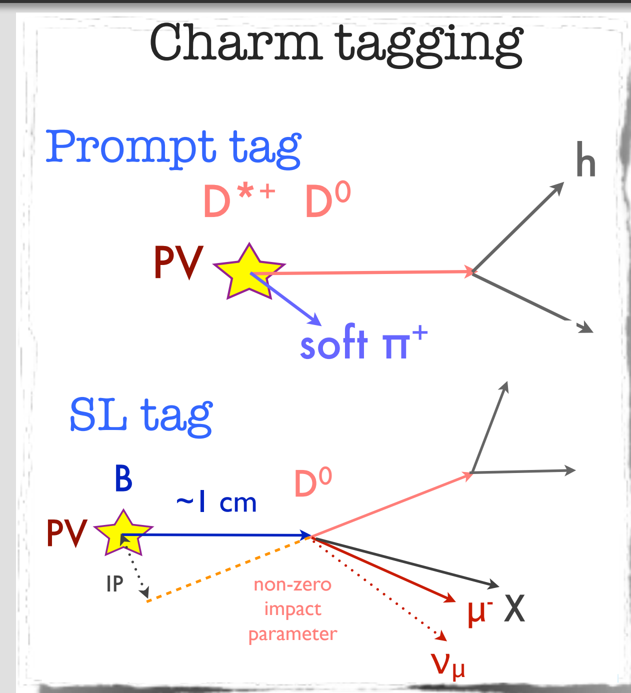


Crucial tracking and vertexing

- $\Delta p/p$ = 0.4-0.6% at 5-100 GeV/c
- O(20) µm IP resolution on tracks
- O(50) fs decay-time resolution

Flavour at decay from final-state particles.
Initial flavour:

- use D^0 coming from, $D^{*+} \to D^0 \pi^+$ or $B \to D^0 \mu^- X$
- for B^0 and $B_s{}^0$ more complicated...



Identifying the initial B flavour

Hadron collisions represent a challenging environments for B tagging

Don't miss Vincenzo Battista's talk at YSF!

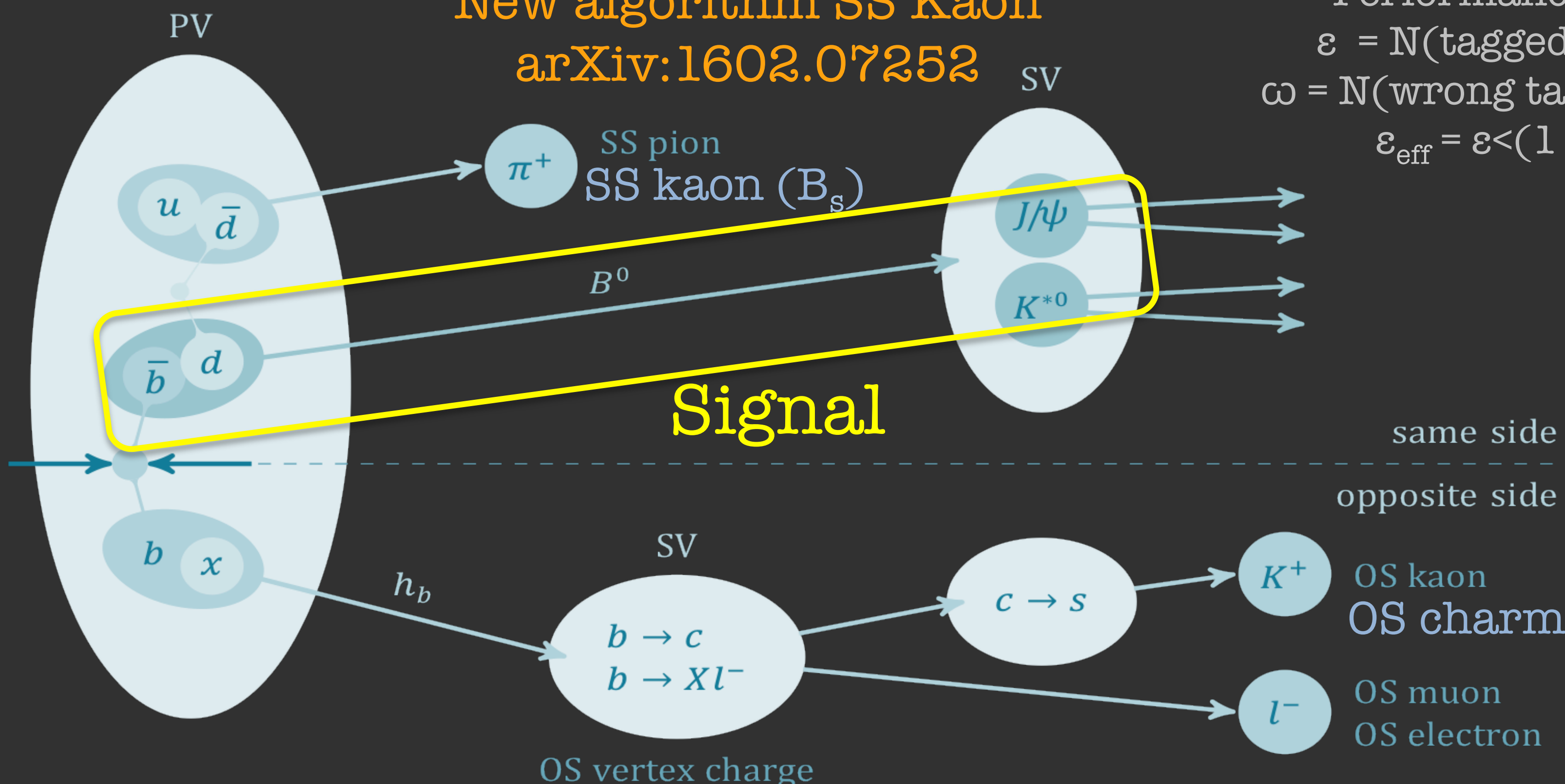
New algorithm SS Kaon
arXiv:1602.07252

Performance metrics

ε = N(tagged)/N(total)

ω = N(wrong tag)/N(tagged)

$\varepsilon_{eff} = \varepsilon\langle(1 - 2\omega)^2\rangle$



OS algorithms in EPJC 72 (2012) 2022

New OS Charm algorithm
JINST 10 (2015) 10005

Identifying the initial B flavour

Hadron collisions represent a challenging environments for B tagging

Don't miss Vincenzo Battista's talk at YSF!

New algorithm SS Kaon

Performance metrics

Tagging power [%]

	2011	Run I	Improvement	Ref.
$B^0 \to J/\psi K_S$	2.38	3.03	+27%	PRL 115 (2015) 031601
$B_s^0 \to J/\psi KK$	3.13	3.73	+19%	PRL 114 (2015) 041801
$B_s^0 \to J/\psi \pi\pi$	2.43	3.89	+60%	PLB 736 (2014) 186
$B_s^0 \to \varphi\varphi$		5.33		PRD 90 (2014) 052011
$B_s^0 \to D_s K$		5.07		JHEP 11 (2014) 060

Impressive improvements

Δm_d with high precision

Tagged $B^0 \to D^-(\to K^+\pi^-\pi^-)\mu^+ X$ (1.6M)
and $B^0 \to D^{*-}(\to D^0_{[K\pi]}\pi^-)\mu^+ X$ (0.8M)
decays reconstructed in the Run I dataset

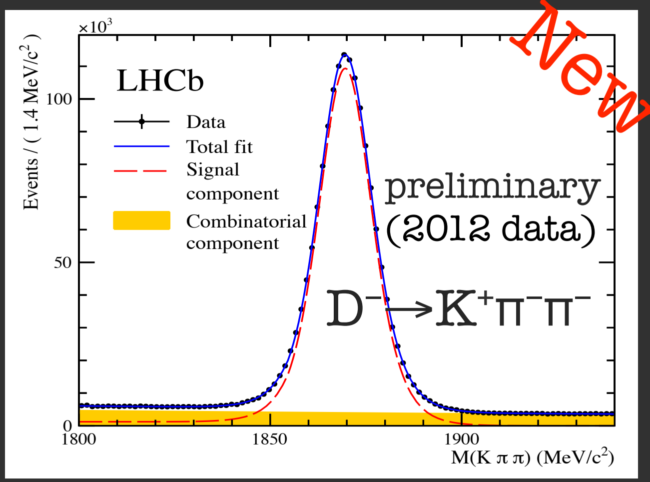
$B^+ \to D^{(*)-}\mu^+ X$ major offending background.
Develop a multivariate classifier to distinguish it from signal.

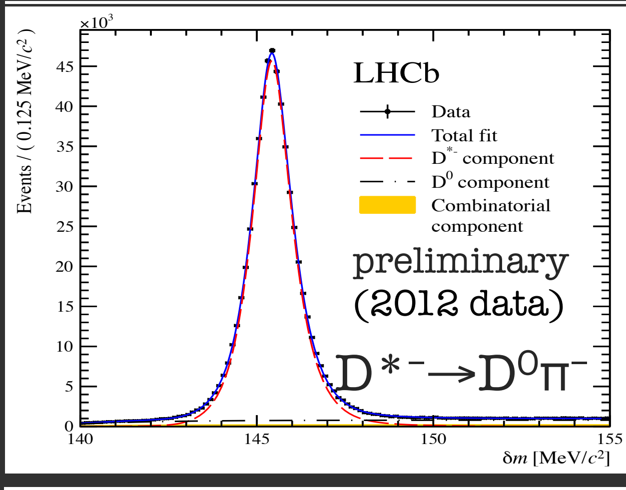
Use of OS tagging algorithm,
tagging power of about 2.5%.

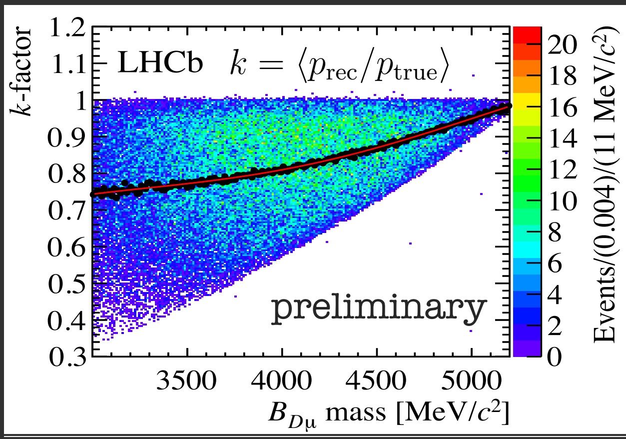
Biased estimate of the decay time,
due to the unreconstructed neutrino
(B momentum partially reconstructed).

$$t = \frac{ML}{p_{\rm rec}c} k(m_{D\mu})$$

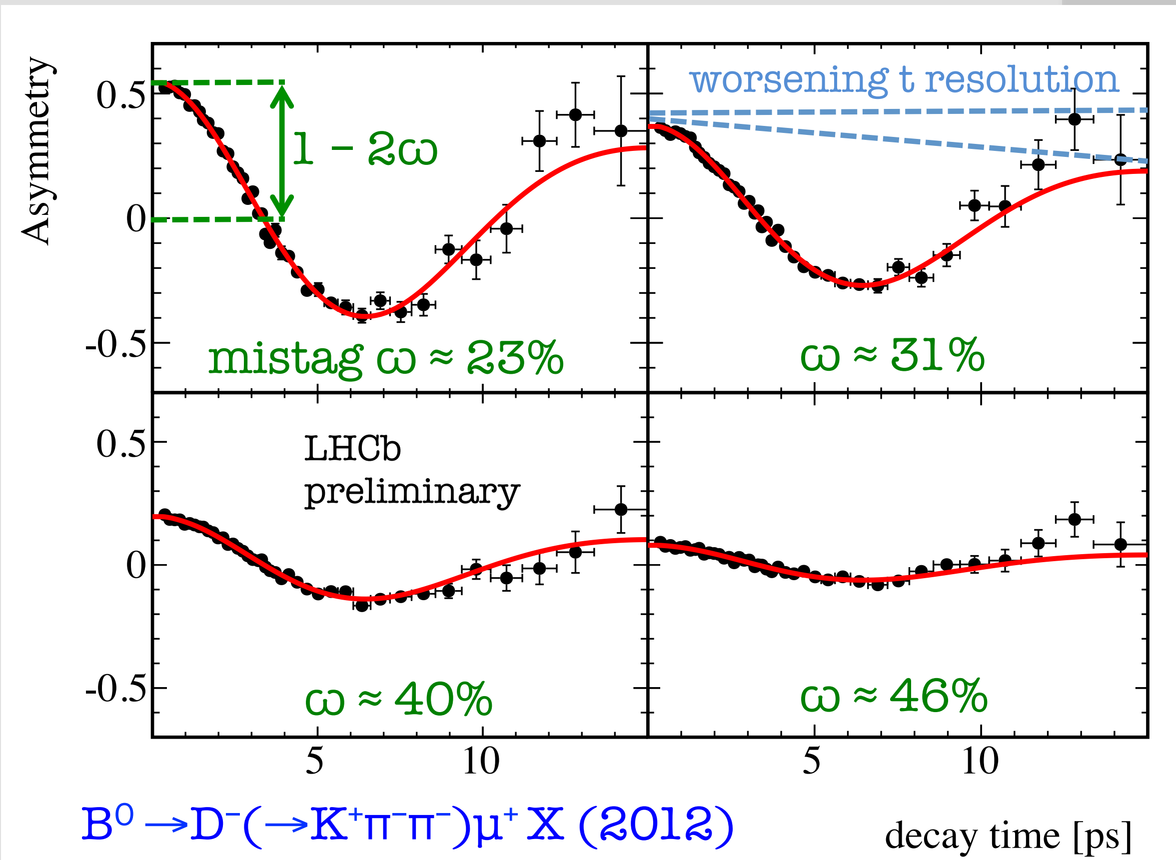
Statistically correct by using simulation (k-factor). Decrease of the time resolution.





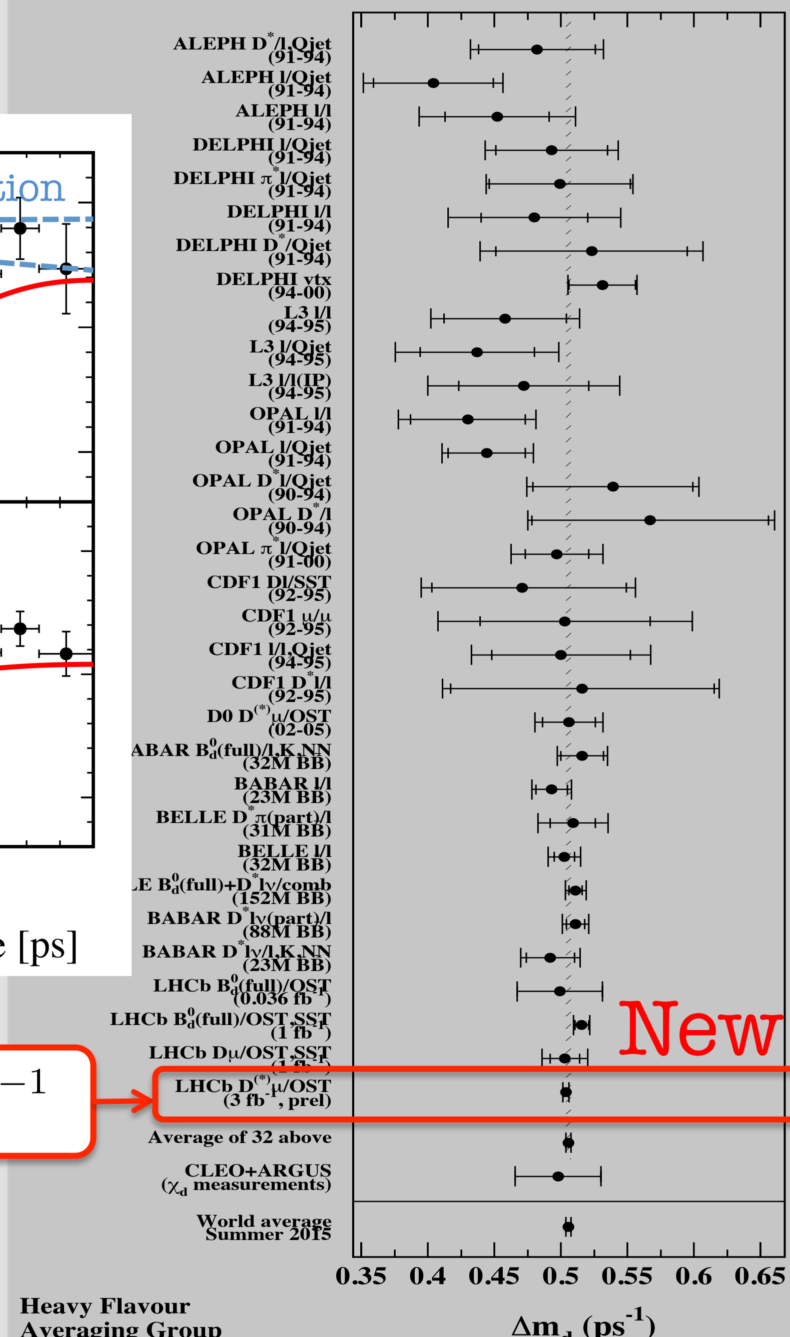


Δm_d with high precision



World's best measurement

$$\Delta m_d = (505.0 \pm 2.1\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst}))\ \mathrm{ns}^{-1}$$



Main sources of systematic related to the k-factor correction.

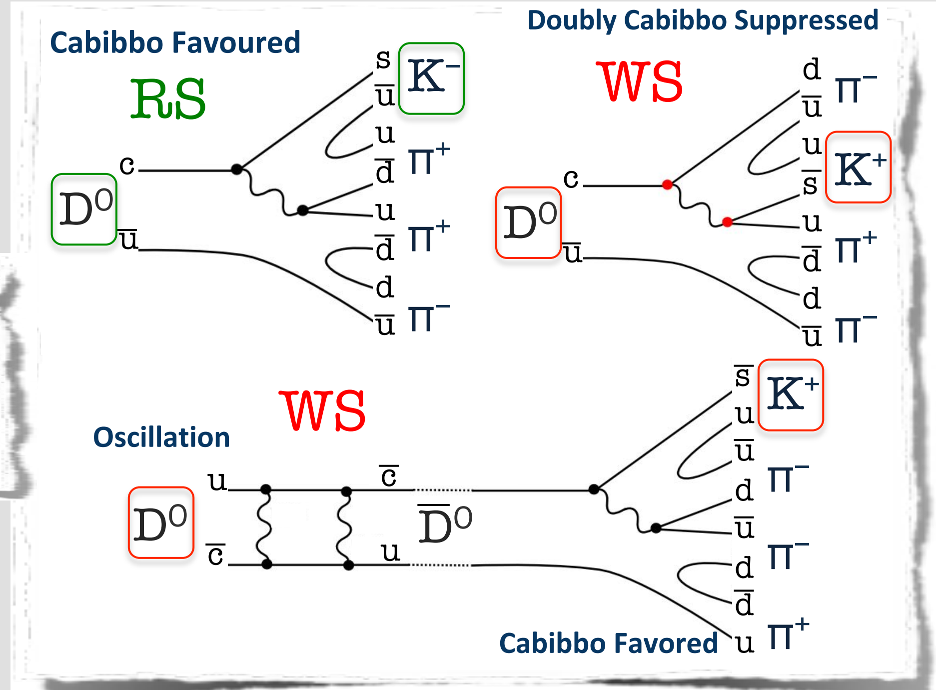
LHCb-PAPER-2015-031

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

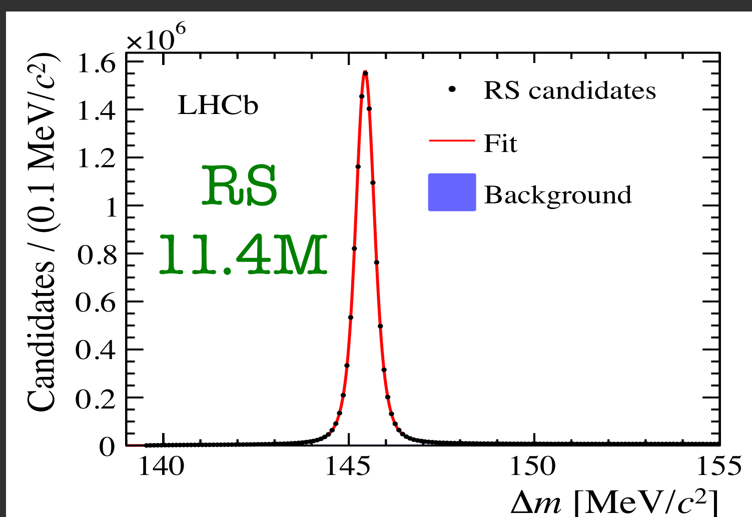
Prompt-tagged decays from Run I data.
4-body final state, very challenging.
Measure the ratio of WS to RS decays in bins of decay time.

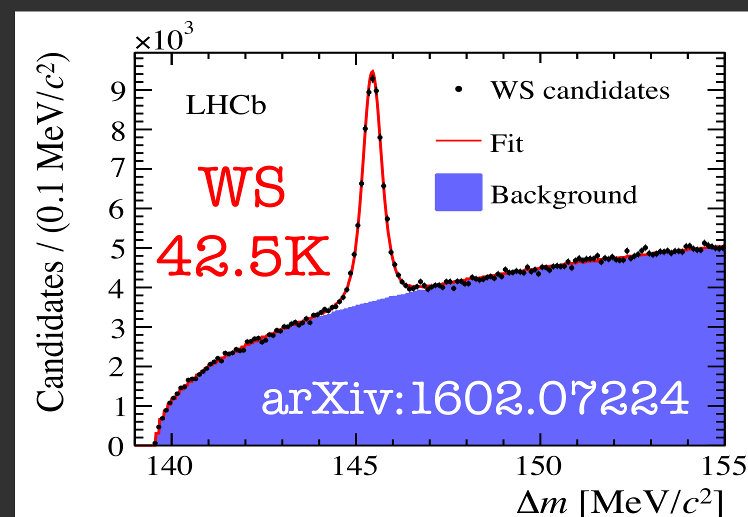
$$R(t) \approx \left(r_D^{K3\pi}\right)^2 - r_D^{K3\pi} R_D^{K3\pi} \cdot y'_{K3\pi} \frac{t}{\tau} + \frac{x^2 + y^2}{4} \left(\frac{t}{\tau}\right)^2$$

$$y'_{K3\pi} \equiv y \cos \delta_D^{K3\pi} - x \sin \delta_D^{K3\pi}$$

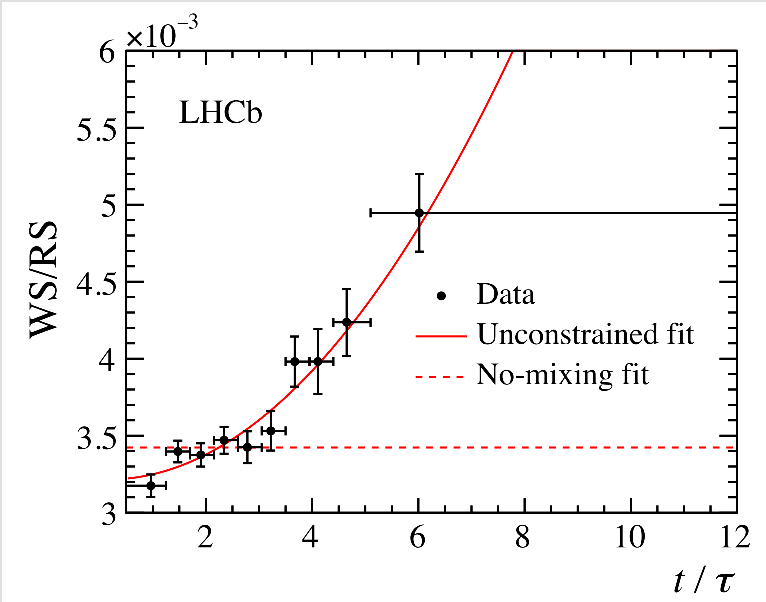


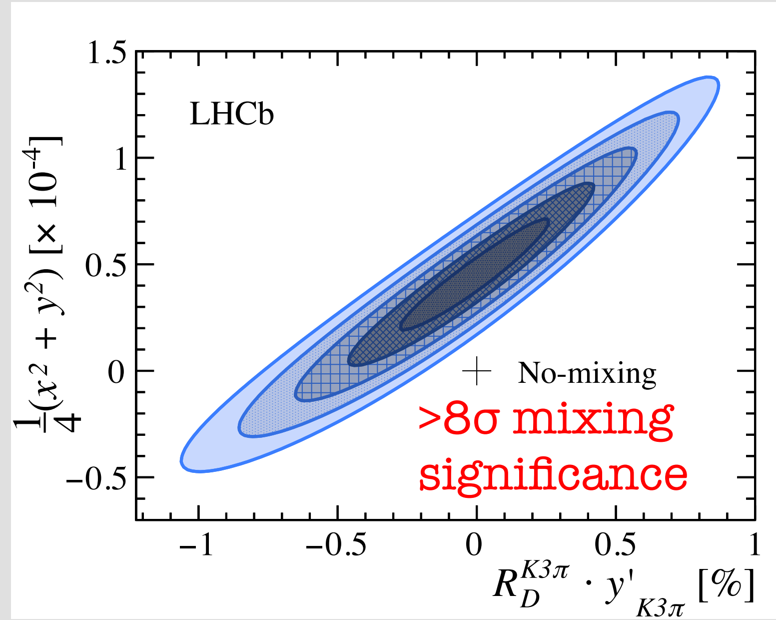
Sensitive to mixing, interference between CF and DCS amplitudes and their relative strength.

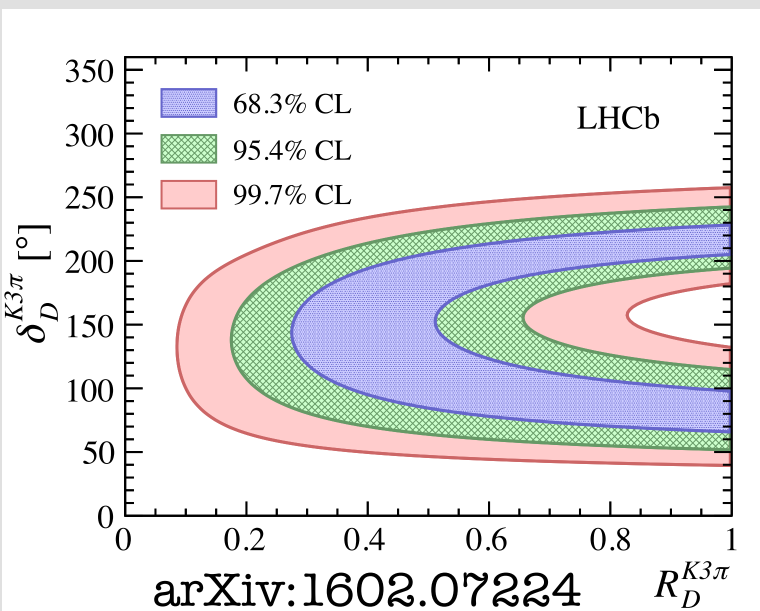




New mixing observation







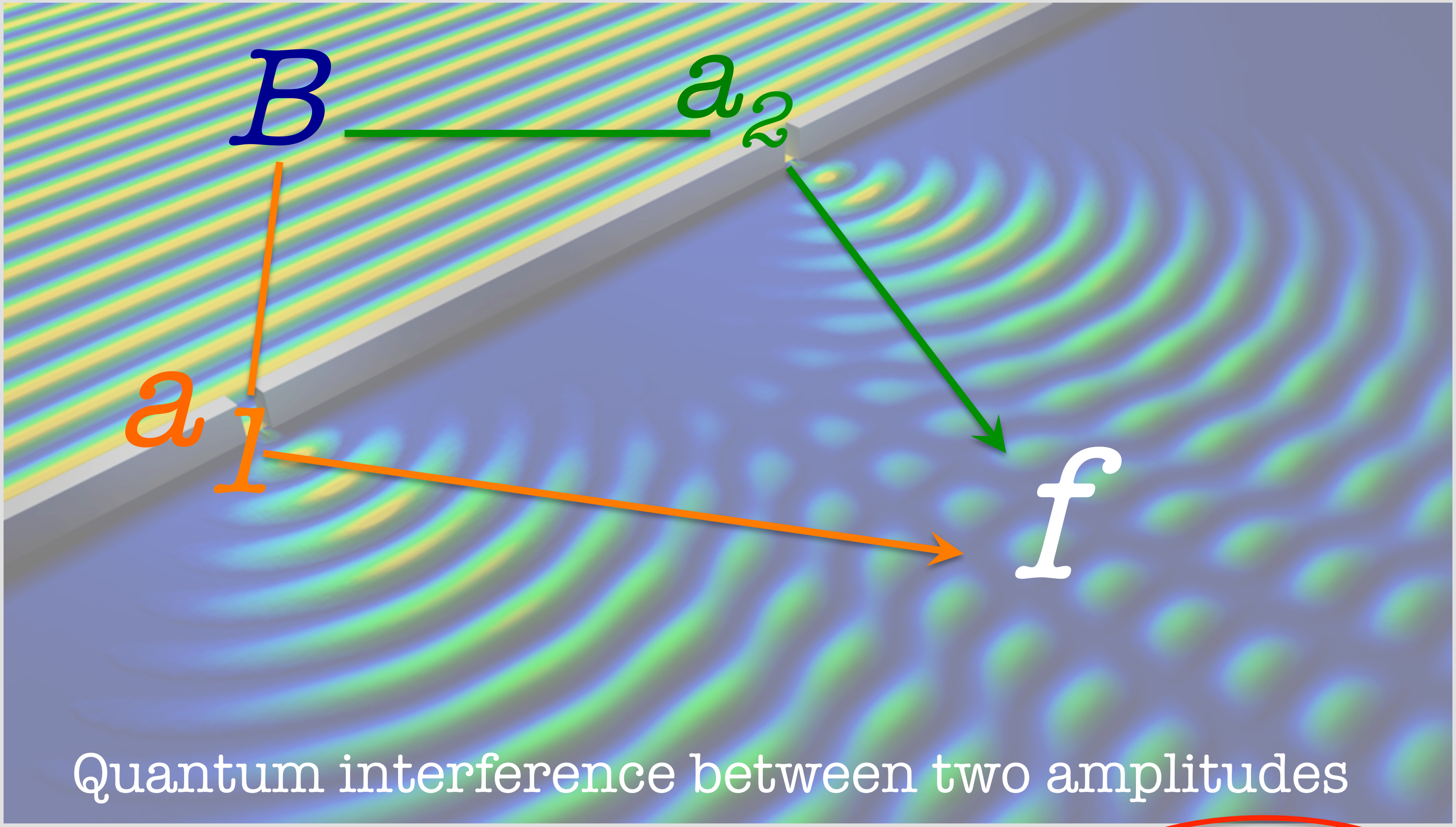
Constraining x and y in the fit to known values (HFAG), measure

$$r_D^{K3\pi} \quad (5.50 \pm 0.07) \times 10^{-2}$$
$$R_D^{K3\pi} \cdot y'_{K3\pi} \quad (-3.0 \pm 0.7) \times 10^{-3}$$

World's best results.

Important input for γ measurement in $B \to D(\to K^-\pi^+\pi^-\pi^+)K$ decay.

CPV: a two slits experiment



$$A_{CP} \approx 2|a_1 a_2| \sin(\delta_1 - \delta_2) \sin(\varphi_1 - \varphi_2)$$

CKM phase(s)

$$
\begin{array}{c|ccc}
 & d & s & b \\
\hline
u & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\
c & -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\
t & A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4
\end{array}
$$

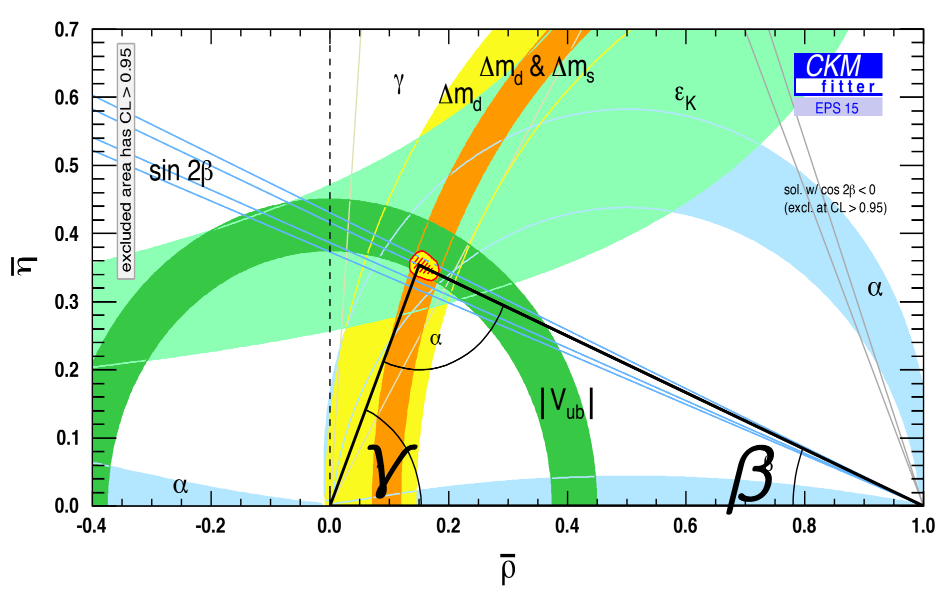
$\lambda \approx 0.23$

γ less constrained angle

β mixing-induced CPV in B^0

β_s mixing-induced CPV in B_s^0
[very small]

Charm CPV suppressed
[extremely small]



γ with $B^0 \to D^0 K^+ \pi^-$

New

γ constraints from pure tree $B \to Dh$ decays are robustly free from NP.

γ uncertainty mainly statistical. Benefit from combining several inputs. Latest LHCb combination:

$$\gamma = \left(73^{+9}_{-10}\right)^\circ$$

[LHCb-CONF-2014-004]

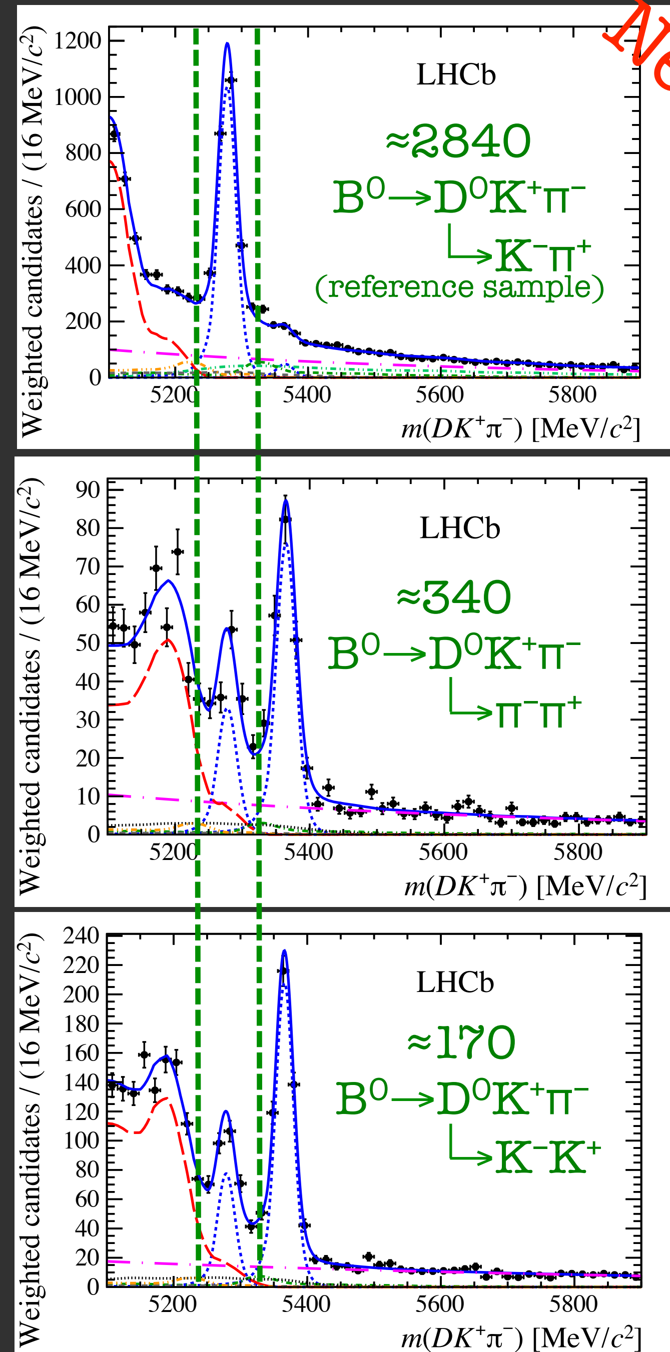
Will be updated very soon!

using $B^+ \to Dh^+ (h^- h^+)$ with

- $D \to f_{CP}$ (GLW method)
- $D \to f_{sup}$ (ADS method)
- $D \to$ 3-body (GGSZ method)

and time-dependent $B_s^0 \to D_s^- K^+$.

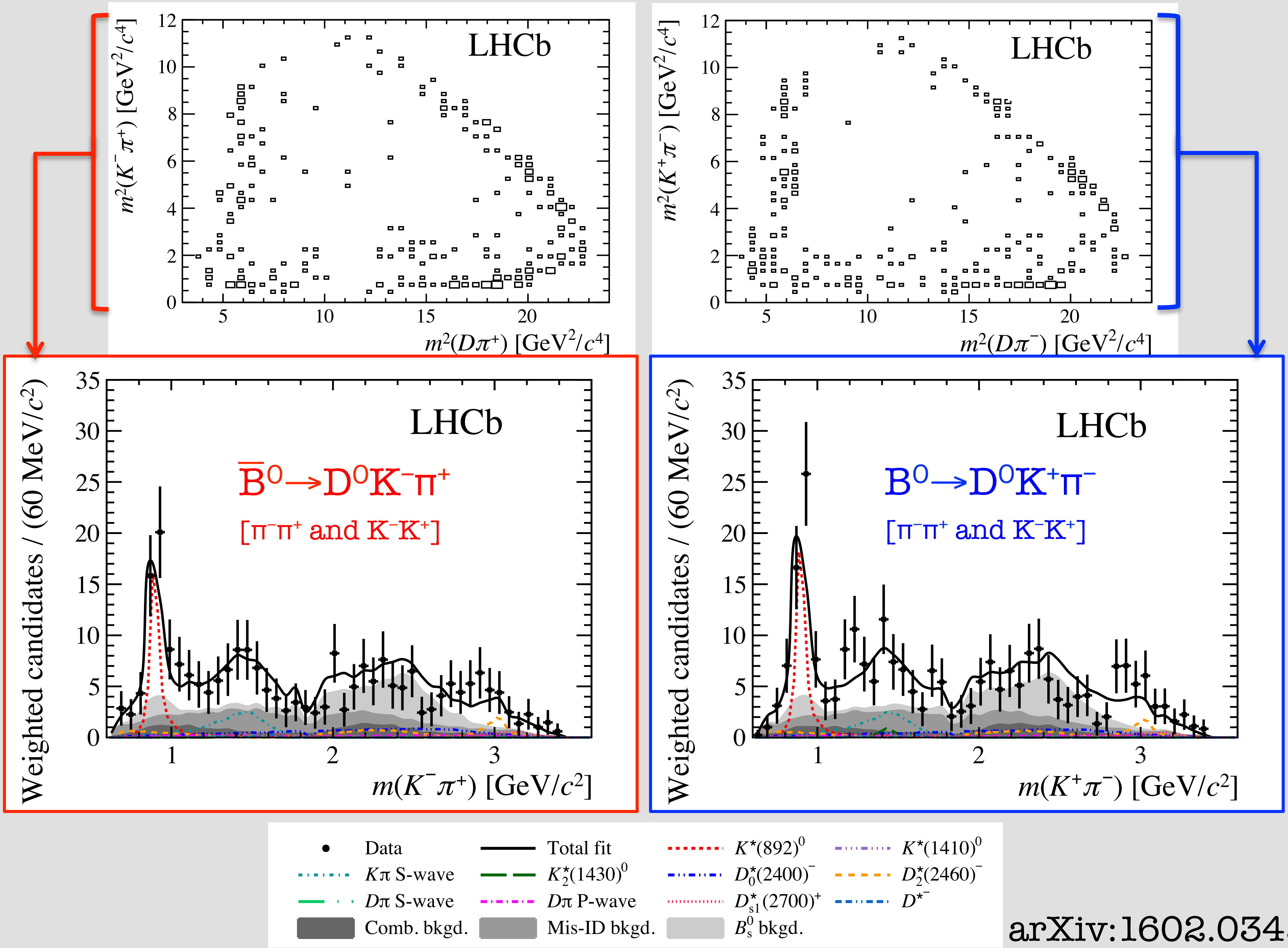
First $B^0 \to D^0 K^+ \pi^-$ Dalitz-plot analysis. Despite low statistics, a new opportunity to access γ from interference of resonances in the DP.



arXiv:1602.03455

γ with $B^0 \to D^0 K^+ \pi^-$

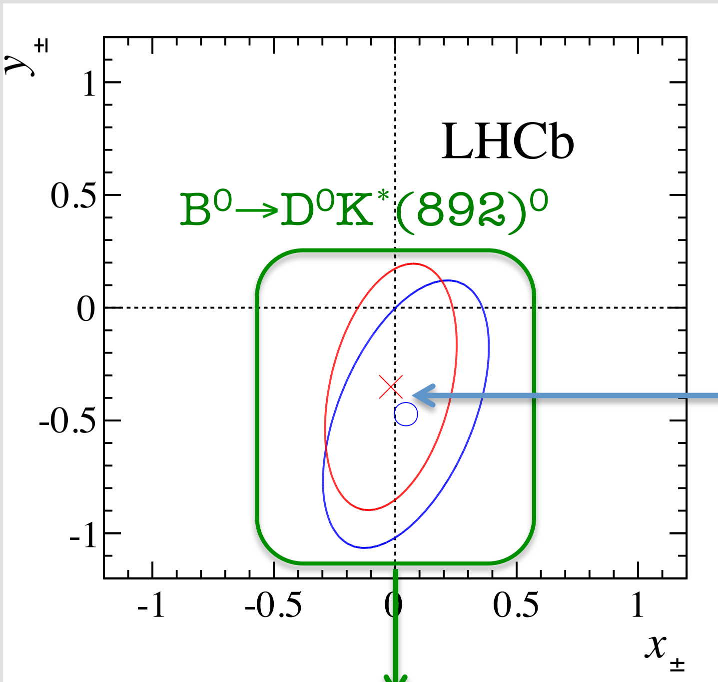
New



arXiv:1602.03455

γ with $B^0 \to D^0 K^+ \pi^-$

New

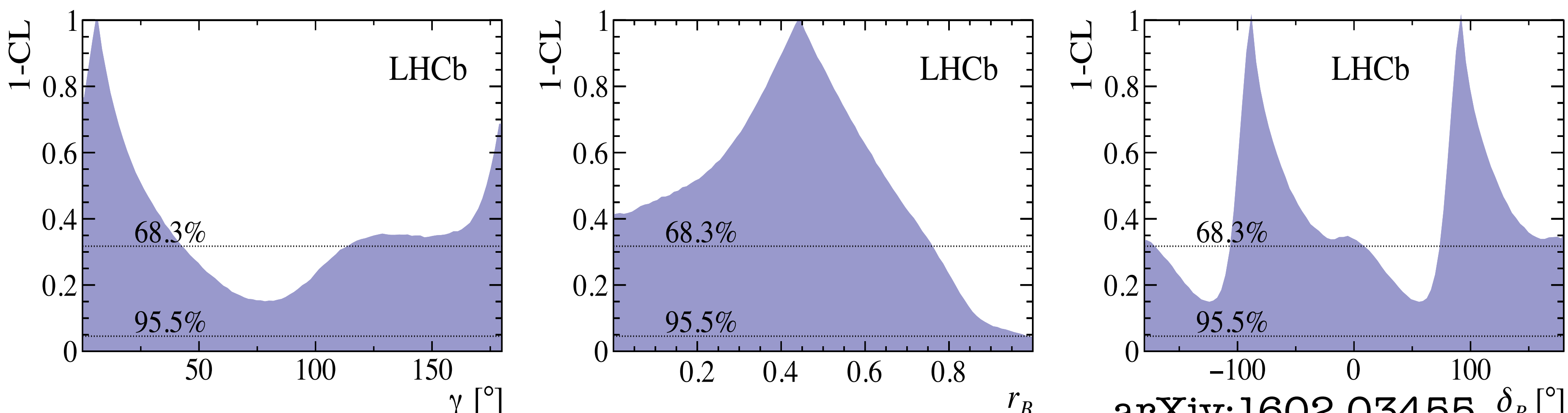


From $B^0 \to D^0 K^*(892)^0$ extract the CP asymmetries

$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$

No evidence of CP violation.

While no value of is excluded at 95% C.L., this is a powerful new method which will be very important in Run 2 and beyond!



arXiv:1602.03455

ΔA_{CP} in $D^0 \to h^+h^-$

Probe CPV in charm with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$.

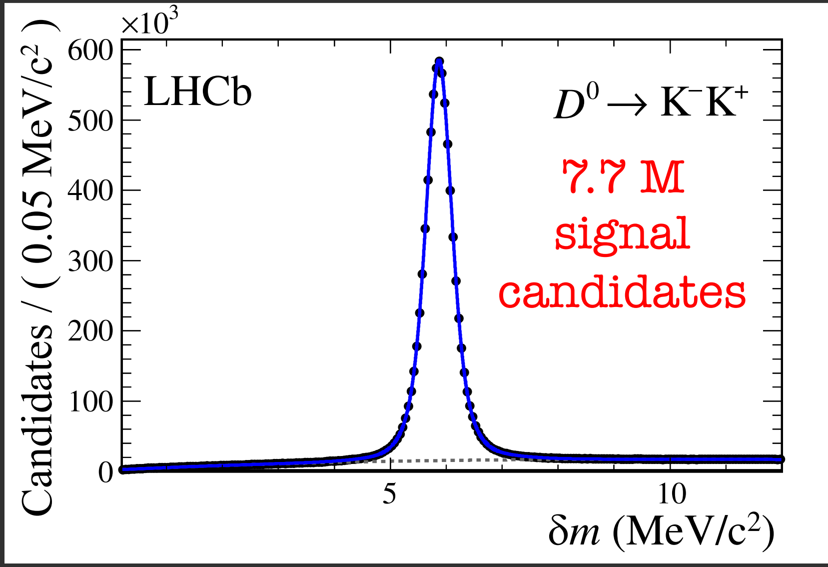
Prompt-tagged decays from full Run I dataset. Measure:

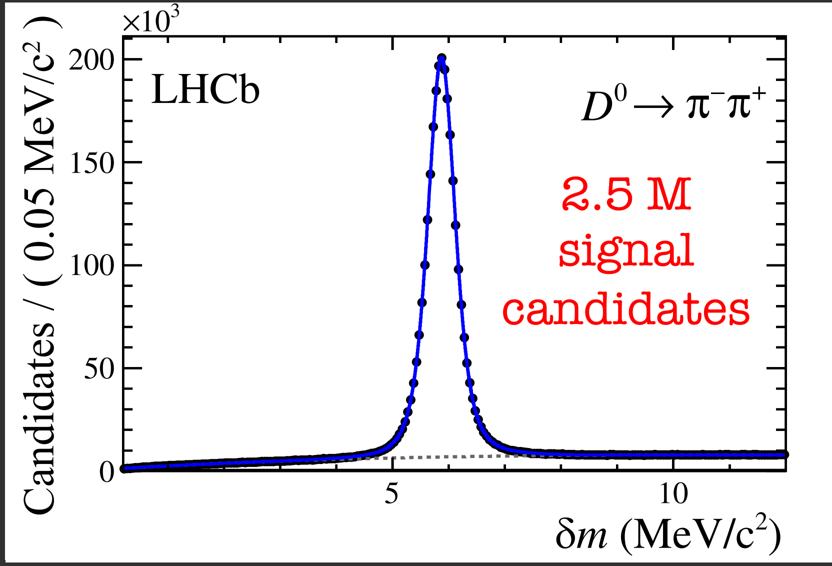
$$A_{\text{raw}}[hh] \equiv \frac{N(D^{*+} \to D^0_{[hh]}\pi_s^+) - N(D^{*-} \to \overline{D}^0_{[hh]}\pi_s^-)}{N(D^{*+} \to D^0_{[hh]}\pi_s^+) + N(D^{*-} \to \overline{D}^0_{[hh]}\pi_s^-)}$$

$$\approx A_{CP}[hh] + A_{\text{prod}}[D^*] + A_{\text{det}}[\pi_s]$$

Provided equal kinematic distributions for decays to K^+K^- and $\pi^+\pi^-$ decays, spurious asymmetries cancel in the difference

$$\Delta A_{CP} = A_{\text{raw}}(K^-K^+) - A_{\text{raw}}(\pi^-\pi^+)$$



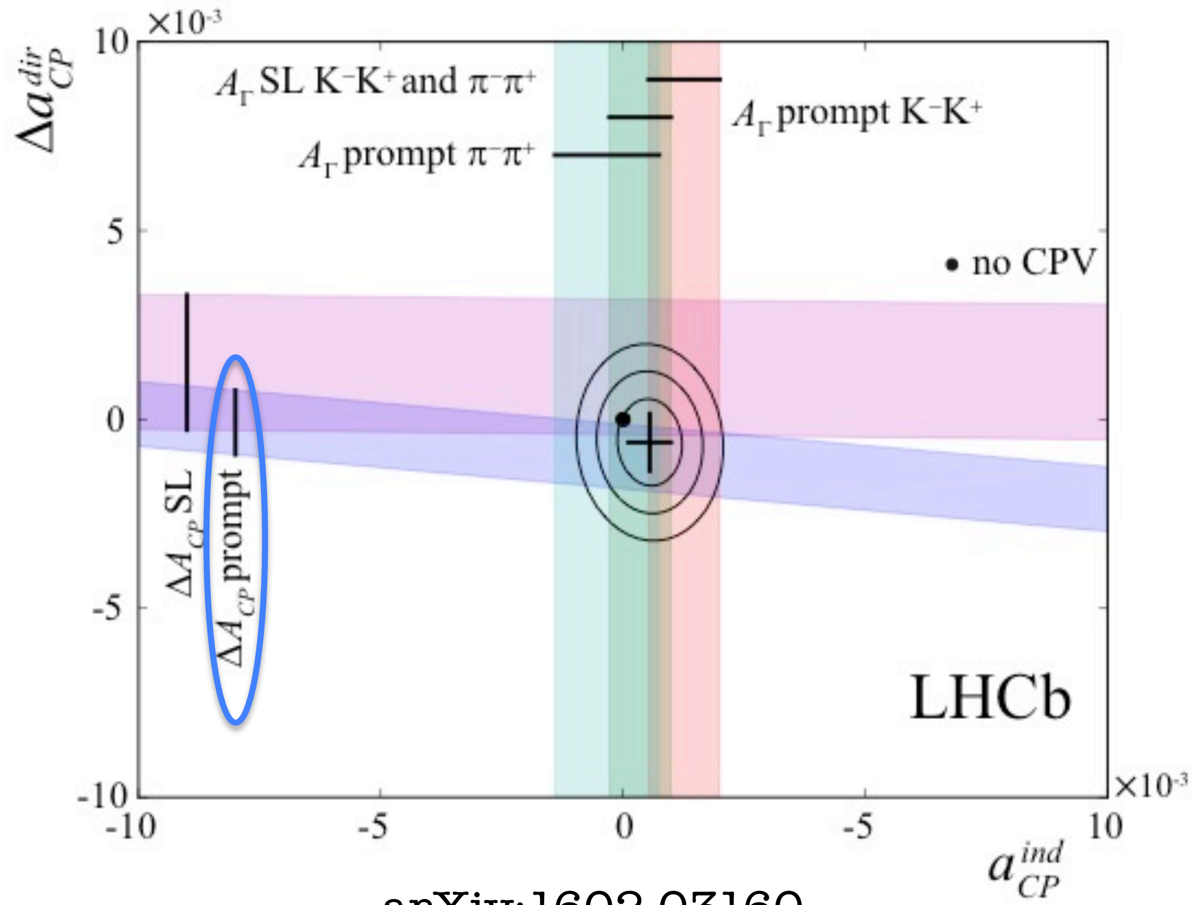


arXiv:1602.03160

ΔA_{CP} in $D^0 \to h^+h^-$

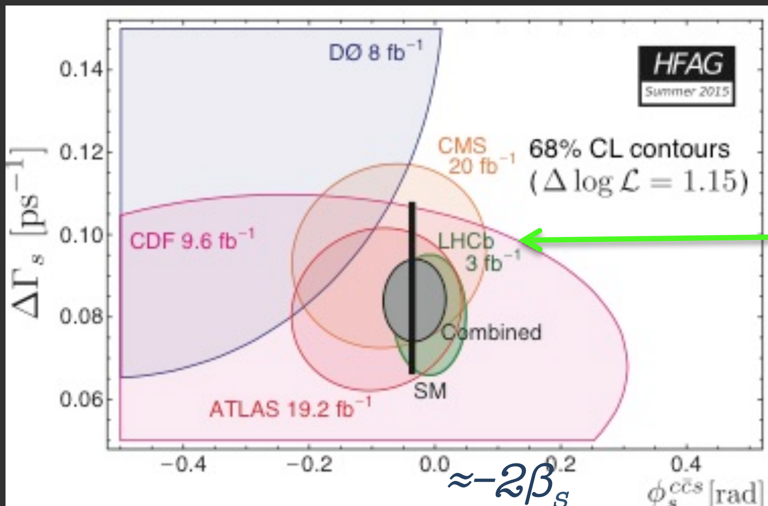
$$\Delta A_{CP} = (-0.10 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst}))\ \%$$

No CPV violation observed. Supersedes PRL 108 (2012) 11162.
Compatible with SL-tagged analysis [PLB 723 (2013) 23].



arXiv:1602.03160

$2\beta_s$ and 2β quick reminder

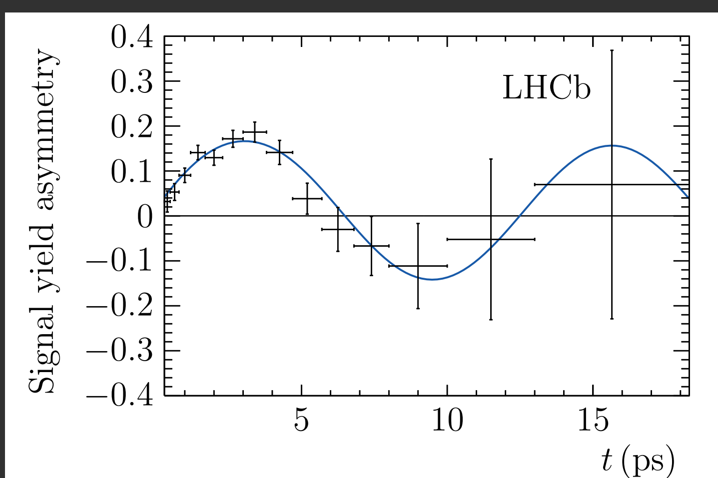


$2\beta_s$

- $B_s^0 \to J/\psi KK$ PRL 114 (2015) 041801
- $B_s^0 \to J/\psi \pi\pi$ PLB 736 (2014) 186
- $B_s^0 \to D_s^- D_s^+$ PRL 114 (2015) 041801

$2\beta_s^{eff}$ $B_s^0 \to \phi\phi$ PRD 90 (2014) 052011

$\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$ with $B^0 \to J/\psi K_S$ PRL 115 (2015) 031601



+ Control of penguin pollution

$2\beta^{eff}$ $B^0 \to J/\psi \rho$ PLB 742 (2015) 38

CPV in $B_s^0 \to J/\psi K^*$ JHEP 11 (2015) 082

CPV in $B_s^0 \to J/\psi K_S$ JHEP 06 (2015) 131

Conclusions

- ✧ LHCb continues to harvest rich results from Run I.

  High precision measurements of mixing of neutral B mesons.
  Continuing the exploration of the D mixing dynamics.

  Measurements of CPV in B and D mesons in good agreement with the SM, but (almost all) limited by statistics.

  Full data sample not (yet) completely exploited, many important results foreseen very soon (e.g. new γ measurements, CPV in b baryons)

- ✧ LHCb ready and fully operational for Run II.

  Eager to exploit the physics potential of new data!

Backup

ΔA_{CP} in $D^0 \to h^+h^-$

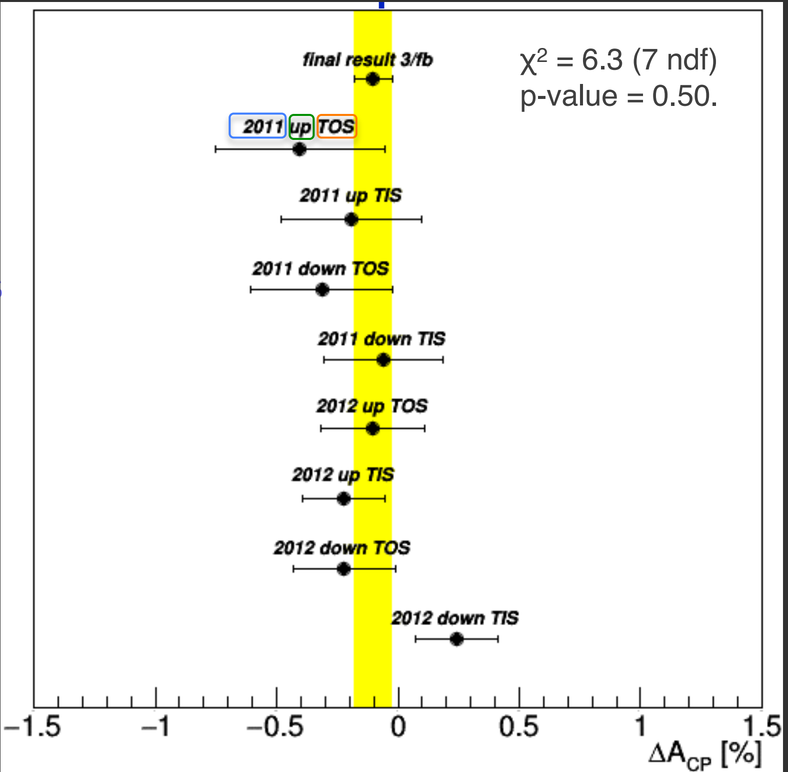
Going to sub-per-mill precision.

Analysis of 8 disjoint subsamples
Split by:

- magnet polarity: test cancellation of detector-related asymmetries
- year: data taking condition
- L0 trigger: different kinematic of the decays

Numerous stability checks.
Asymmetries as a function of

number of primary vertices
quality of the D^* vertex
π soft kinematics
D^0 kinematics
PID requirements
D^0 mass
time (run numbers)
…



arXiv:1602.03160

β angle

Indirect determination:

$\sin 2\beta_{SM} = 0.771^{+0.017}_{-0.041}$

[CKMFitter arXiv:1501.05013]

A long history of sin 2β measurements at the B factories, started in 1999.

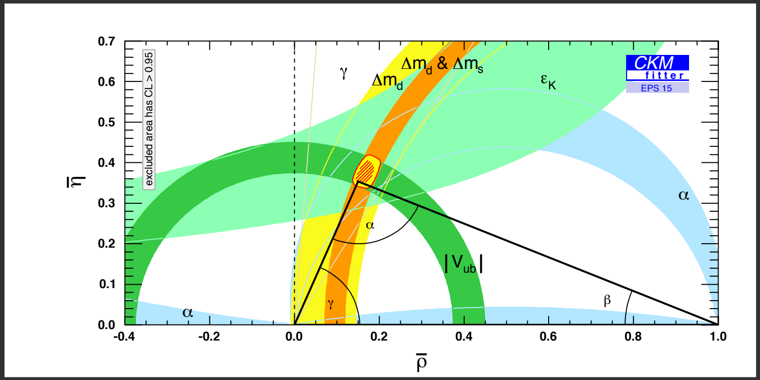
BaBar: 0.687 ± 0.028 ± 0.012

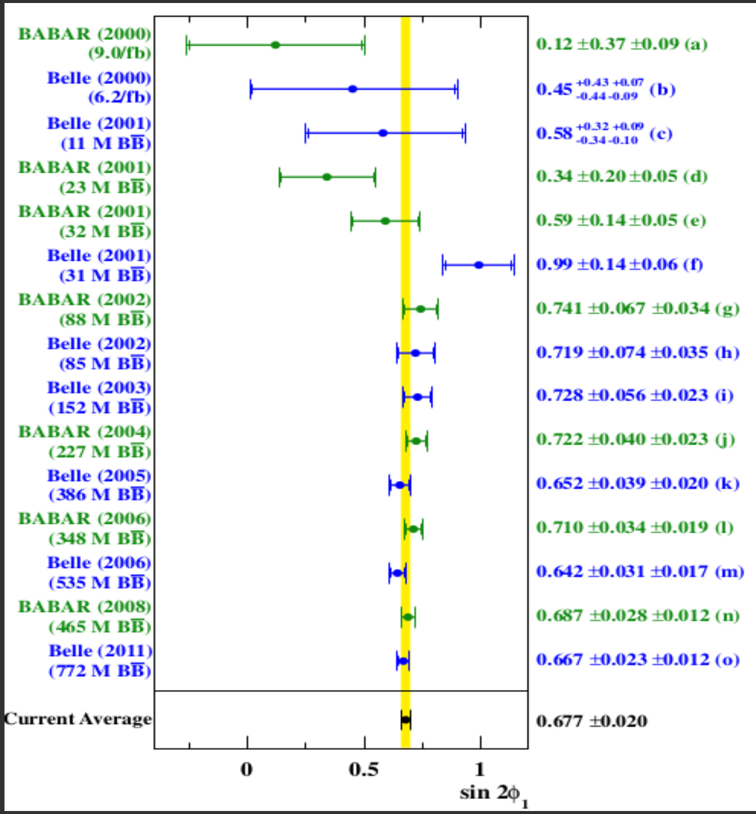
[PRD 79, 072009 (2009)]

Belle: 0.667 ± 0.023 ± 0.012

[PRL 108, 171802 (2012)]

Intriguing tension between direct and indirect determinations





β_s angle

Another unitary relation of CKM matrix, concerning B_s

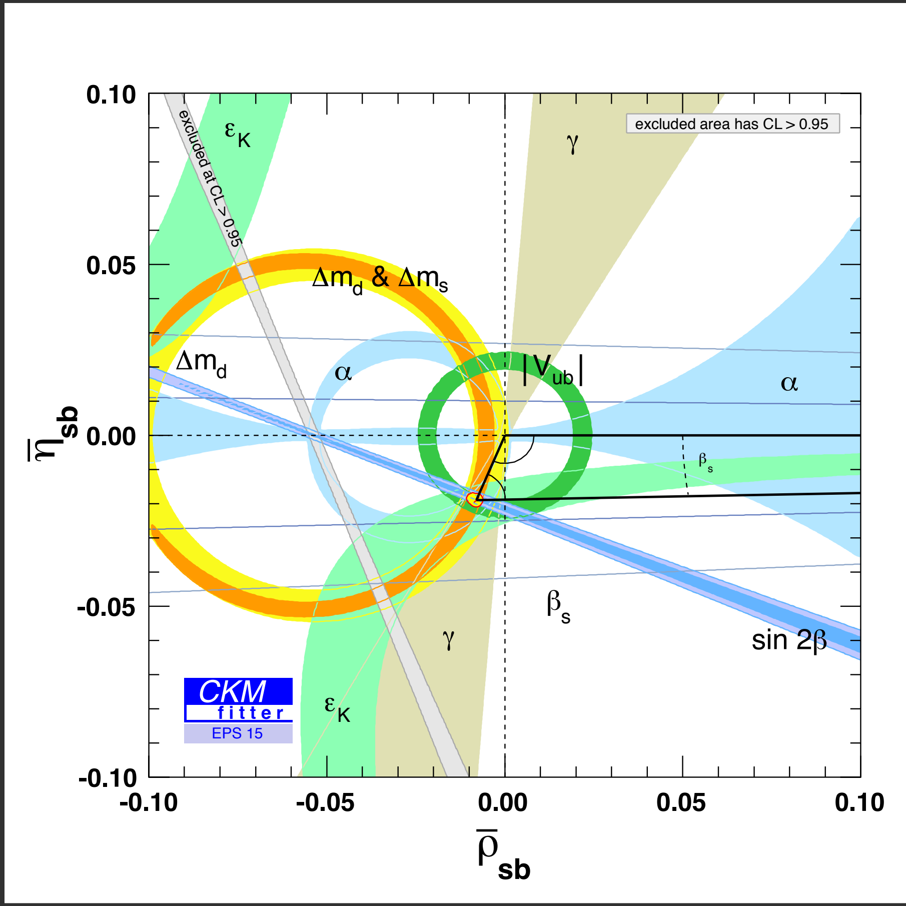
Indirect determination:

$2\beta_s^{SM} = 0.0363 \pm 0.0013$ rad

[CKMFitter arXiv:1501.05013]

Early measurements by Tevatron experiments showed interesting 2σ deviation from indirect determination, but large uncertainties.

Moved to high precision era with LHC "B_s factory".



Outlooks

We expect a huge increase in precision in the LHCb upgrade!

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–