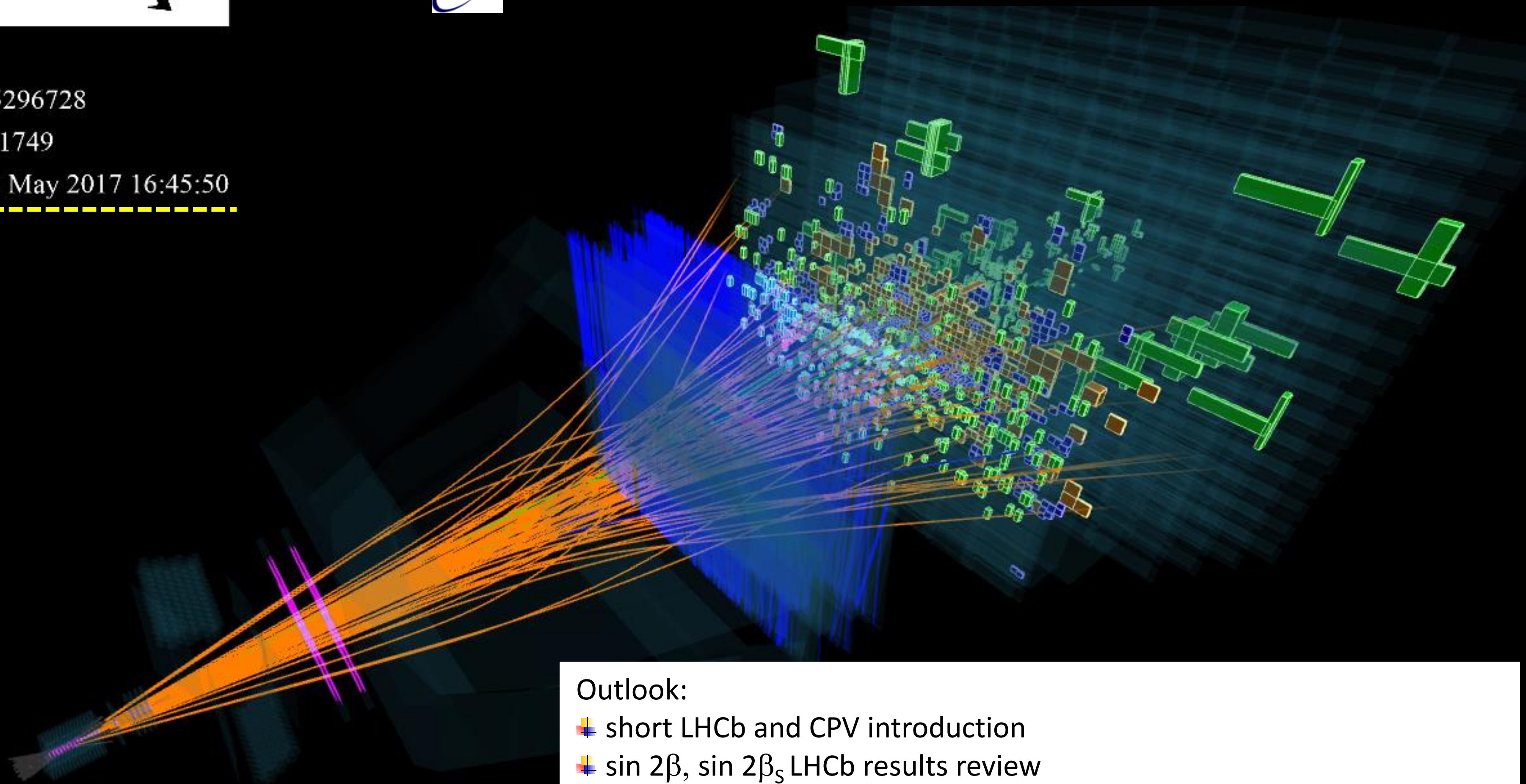
Status of mixing and CP-violation measurements at LHCb

A. Bertolin INFN **on behalf of the LHCb collaboration**



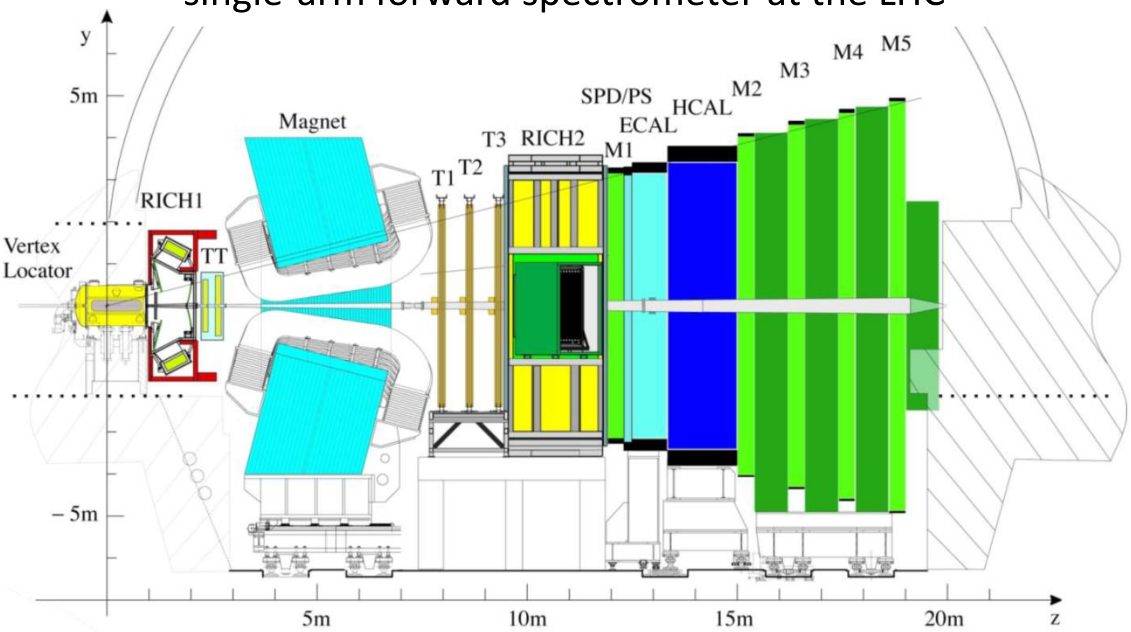
Outlook:

- short LHCb and CPV introduction
- sin 2β, sin 2β_S LHCb results review
- LHCb γ results:
  - a time-integrated γ measurement (used in the latest LHCb γ combination)
  - the latest LHCb γ combination results
- an updated time-dependent γ measurement
- matter antimatter differences in beauty baryon decays
- summary and future prospects

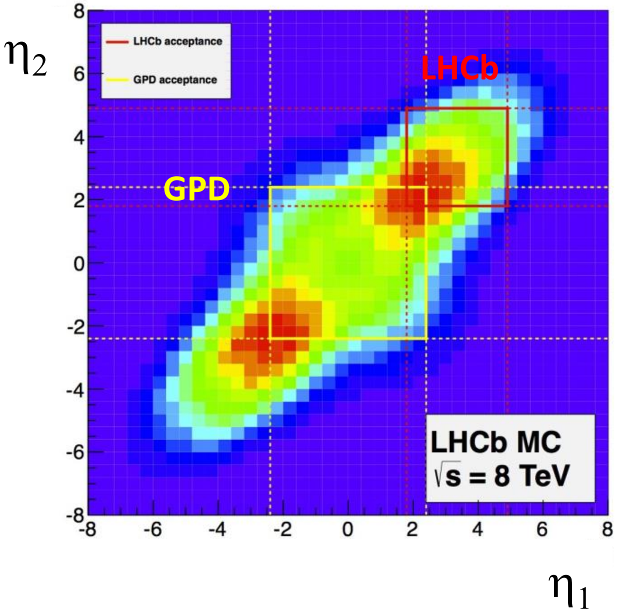
LHCb: the detector and the story so far

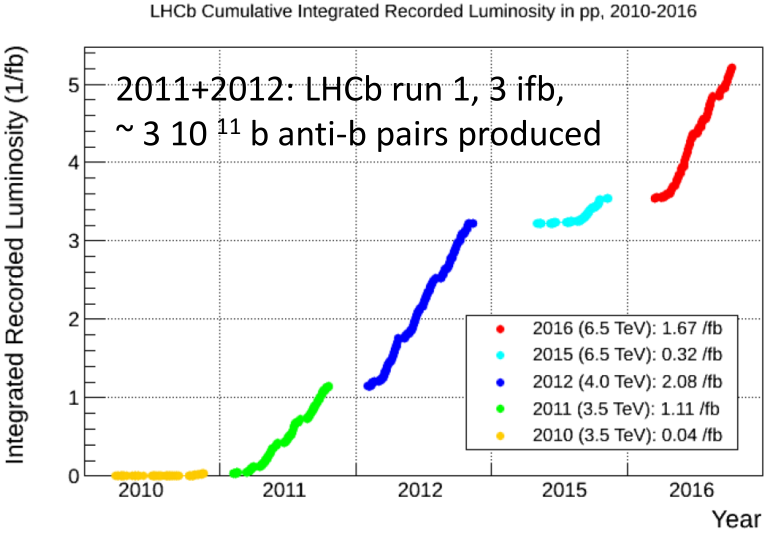
JINST 3 (2008) S08005
Int.J.Mod.Phys. A30 (2015) 1530022

single-arm forward spectrometer at the LHC



b anti-b pairs produced





2011+2012: LHCb run 1, 3 ifb,
~ 3 10^{11} b anti-b pairs produced

optimized for beauty and charm physics at $2 < \eta < 5$:

- momentum resolution ($\sigma(p)/p \approx 0.5 - 0.8$ %, $p < 100$ GeV/c)
- impact parameter resolution ($\sigma(IP) \approx 20$ μm at high p_T)
- primary and secondary vertices reconstruction
- decay time resolution ($\sigma(t) \approx 50$ fs)
- 'global' PID: e / μ / π / K

(K id ≈ 95 % π mis-id ≈ 5 %, p < 100 GeV/c)

- γ and π^0 reconstruction

CP violation

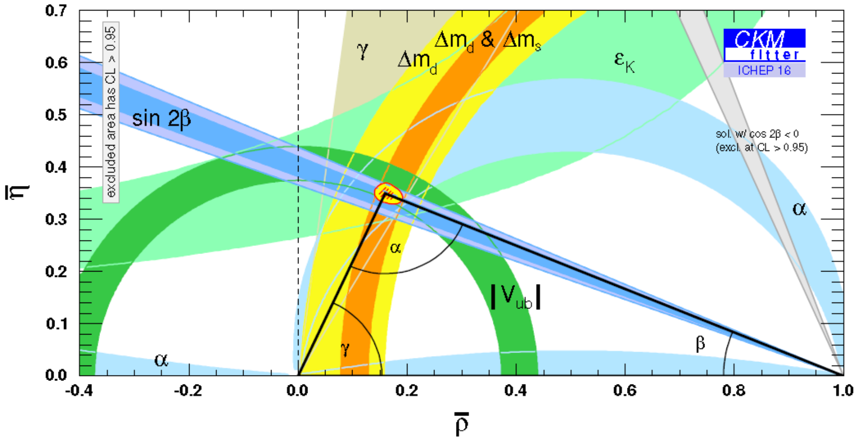
CP violation is one requirement for explaining the baryon asymmetry we observe today
a process must have been in place that took us from the equal amounts of matter - anti-matter produced in the Big Bang to the matter dominated Universe we are leaving in

charged current weak interactions between quarks are described by a matrix: 3 x 3, unitary (⇔ 3 angles and 1 phase), the **CKM matrix**

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$

CKM expansion in $\lambda \approx 0.22$ up to $\mathcal{O}(\lambda^3)$

$\rho - i\,\eta$: gives the **CKM phase**, only source of CP violation in the SM quark sector



$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

multiple measurements allow to over constrain the few ‘free’ parameters of the SM and hence allow to look for new physics effects distorting their values … due for example to new particles / mediators being exchanged in loops …

why B mesons / hadrons ? related unitary triangles are less squeezed hence expect larger sensitivity to any CP violation effect

PRL 115 (2015) 031601

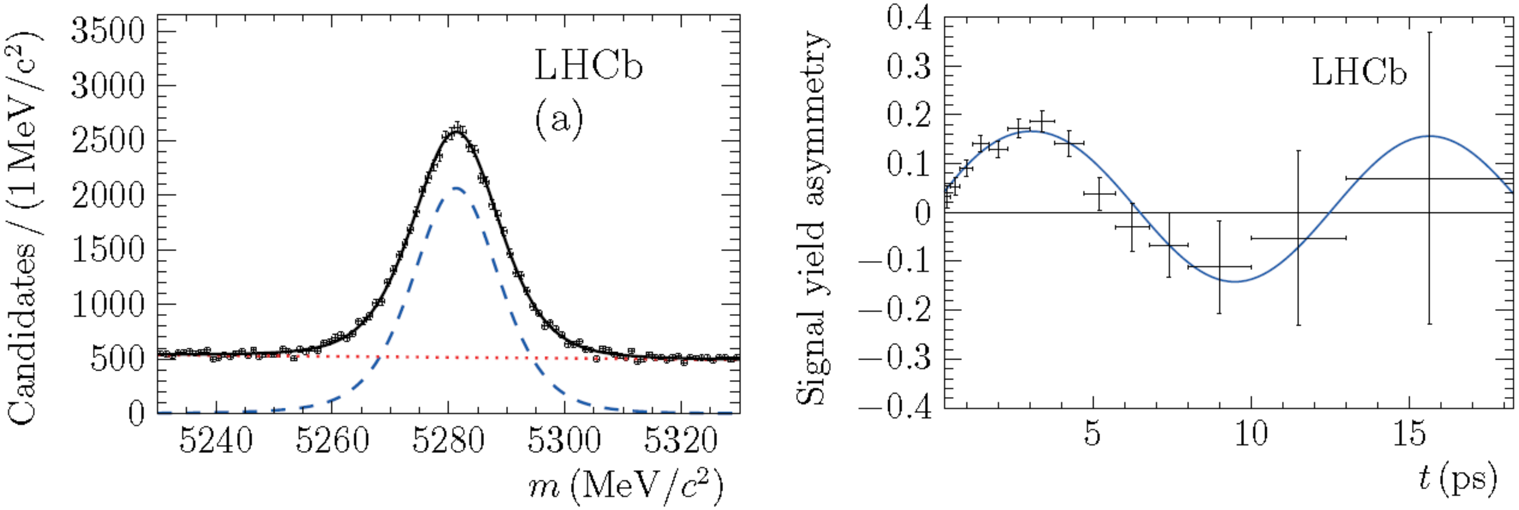
LHCb sin 2β measurement, 3 ifb

$$\beta \equiv \arg[-(V_{cd}V_{cb}^{*})/(V_{td}V_{tb}^{*})]$$

$B^0 \to J/\psi\, K^0_s$ "golden mode" for this measurement

$$\mathcal{A}(t) = \frac{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_S) - \Gamma(B^0(t) \to J/\psi\, K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_S) + \Gamma(B^0(t) \to J/\psi\, K^0_S)} = \frac{S\sin(\Delta m\, t) - C\cos(\Delta m\, t)}{\underbrace{\cosh(\frac{\Delta\Gamma\, t}{2}) + A_{\Delta\Gamma}\sinh(\frac{\Delta\Gamma\, t}{2})}_{\approx 1}}$$

S = sin 2β



$$S = \quad 0.731 \pm 0.035\,(\text{stat}) \pm 0.020\,(\text{syst})$$ (δβ ≈ 1.16°)

- time dependent
- flavor tagging

BaBar [PRD 79 (2009) 072009] = 0.69 ± 0.03 (stat) ± 0.01 (syst)
Belle [PRL 108 (2012) 171802] = 0.67 ± 0.02 (stat) ± 0.01 (syst)

overall result as good as BaBar and Belle

LHCb sin 2β_S measurements

$$\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$$

interference between the amplitudes of decays of B^0_s mesons to c cbar X(s) CP eigenstates directly or via mixing

$\phi_s \approx -2\beta_S$ (SM+ ignoring subleading penguin contributions)

LHCb analyses, all updated to 3 ifb, give the most precise results:

$B^0_s \rightarrow J/\psi\ \pi^+ \pi^-$ [PLB 736 (2014) 186]

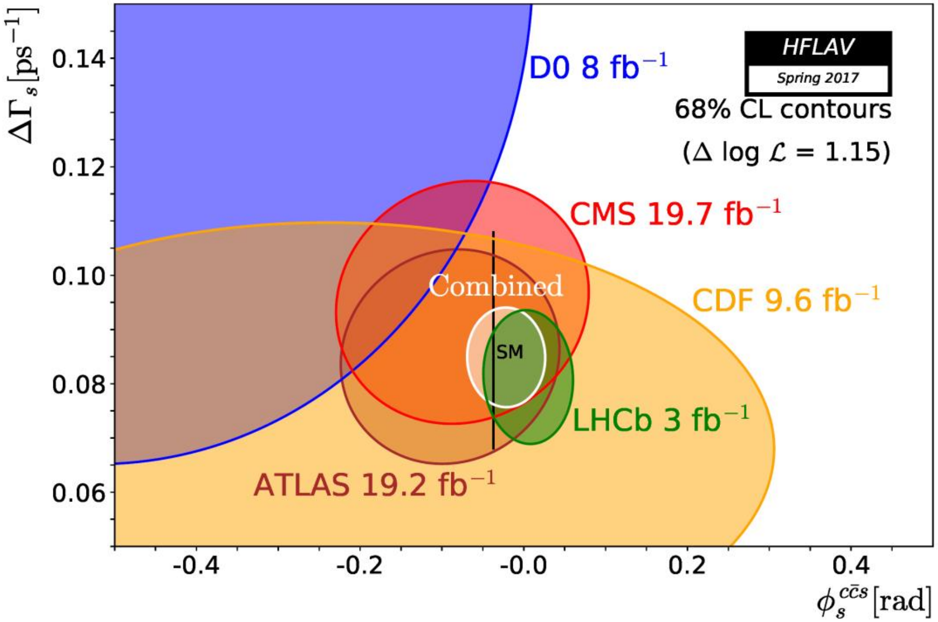
$B^0_s \rightarrow D_s^+ D_s^-$ [PRL 113 (2014) 211801]

$B^0_s \rightarrow J/\psi\ K^+ K^-$, $m(K^+ K^-)$ in the ϕ region [PRL 114 (2015) 041801]

$B^0_s \rightarrow \psi(2S)\ \phi$ [PLB 762 (2016) 253-262]

$B^0_s \rightarrow J/\psi\ K^+ K^-$, $m(K^+,K^-) > m(\phi)$ [https://arxiv.org/abs/1704.08217]

- time dependent
- flavor tagging

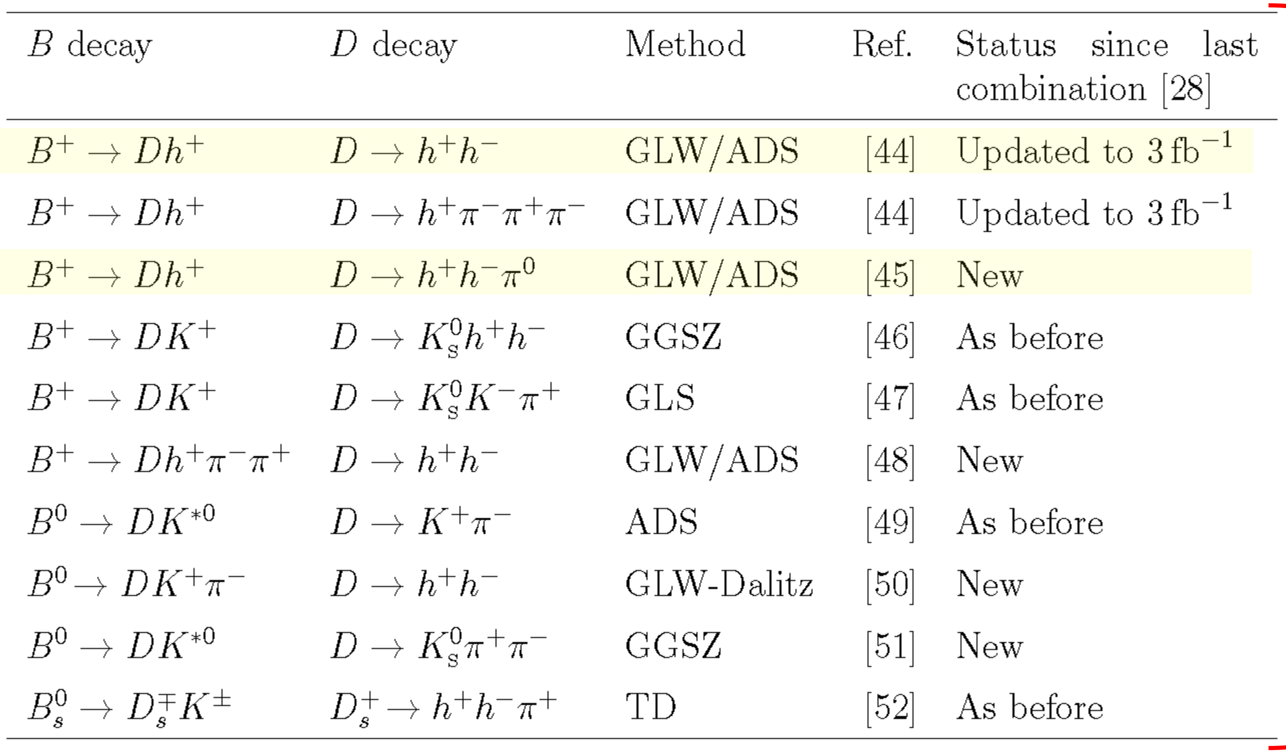


JHEP 12 (2016) 087

LHCb γ combination

$$\gamma \equiv \arg[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}]$$

- can be measured using only tree-level processes
- assuming new physics is not present in tree-level decays, negligible theoretical uncertainty
- disagreement between direct measurements and the value inferred from global CKM fits would spot new physics beyond the SM
- can be determined by exploiting the interference between favored b → c W (V_{cb}) and suppressed b → u W (V_{ub}) transition amplitudes



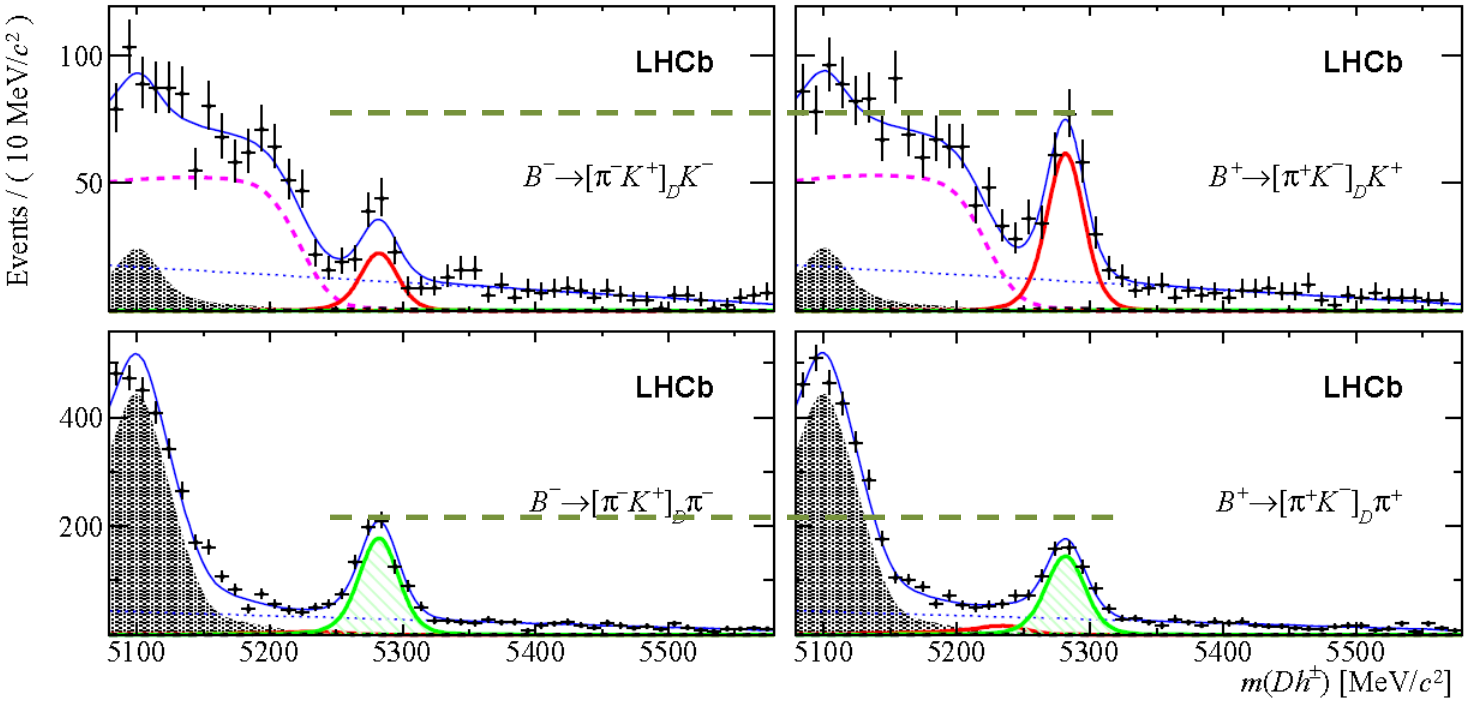
B decay	D decay	Method	Ref.	Status since last combination [28]
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS	[44]	Updated to 3 fb^{-1}
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[44]	Updated to 3 fb^{-1}
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[45]	New
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[46]	As before
$B^+ \to DK^+$	$D \to K^0_S K^-\pi^+$	GLS	[47]	As before
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS	[48]	New
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[49]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[50]	New
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[51]	New
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[52]	As before

LHCb inputs for the γ combination:

- D K: excludes
  - $B^+ \to D\pi^+$
  - $B^+ \to D\pi^+\pi^-\pi^+$
- D h: full list

Phys. Lett. B760 (2016) 117

γ from B± → [h h’] K / π, 3 ifb, time integrated

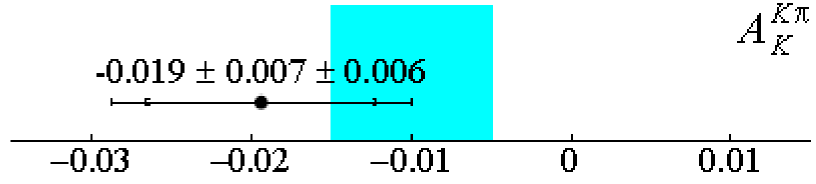


- blue: fit result
- red: [π K] K i.e. signal
- dashed pink: [π K] K π when the last π is missed
- dotted blue: combinatorial
- shaded: other partially reco. backgrounds

- blue: fit result
- green: [π K] π i.e. signal
- red: [π K] K
- dotted blue: combinatorial
- shaded: partially reco. backgrounds

from the two upper plots:

$$A_h^f = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [\bar{f}]_D h^+)}{\Gamma(B^- \to [f]_D h^-) + \Gamma(B^+ \to [\bar{f}]_D h^+)}$$

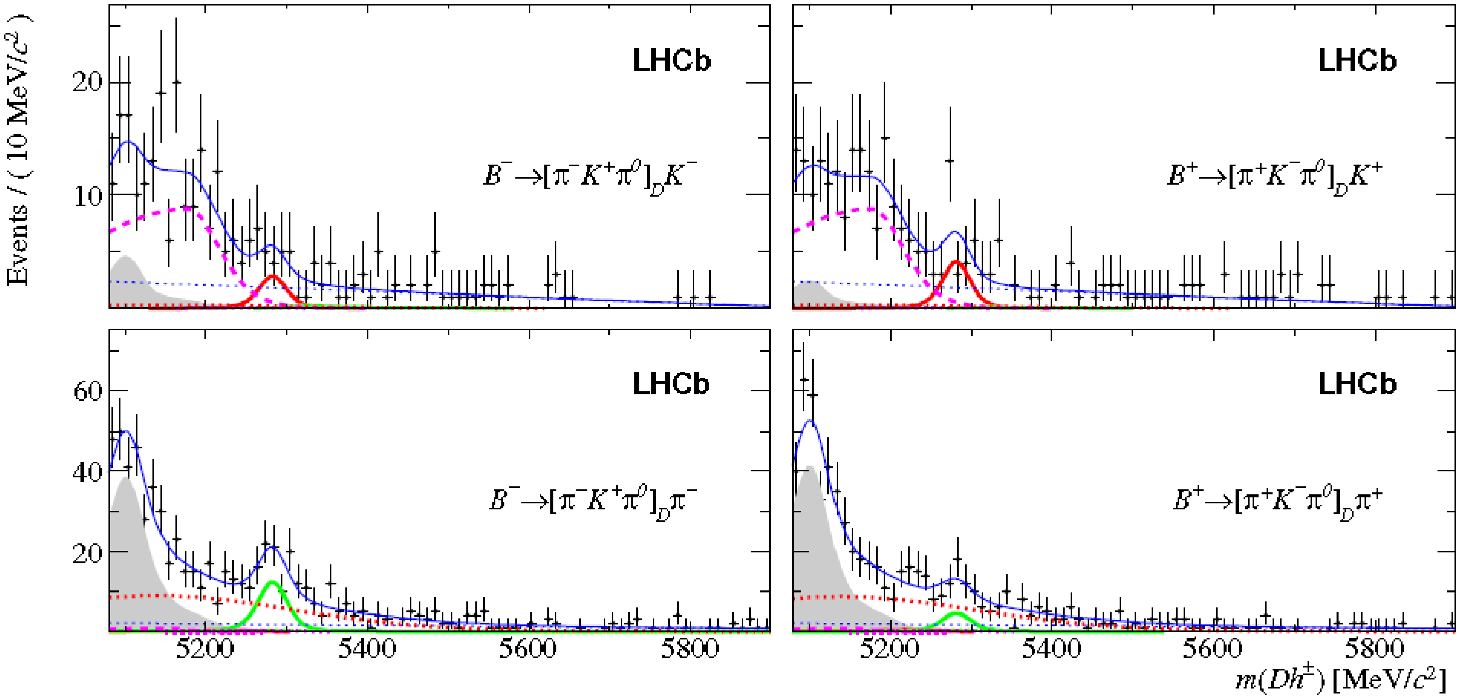


Decay mode	Yield
$B^{\pm} \to [K^{\pm}\pi^{\mp}]_D\,\pi^{\pm}$	378,050 ± 650
$B^{\pm} \to [K^{\pm}\pi^{\mp}]_D\,K^{\pm}$	29,470 ± 230
$B^{\pm} \to [K^{+}K^{-}]_D\,\pi^{\pm}$	50,140 ± 270
$B^{\pm} \to [K^{+}K^{-}]_D\,K^{\pm}$	3816 ± 92
$B^{\pm} \to [\pi^{+}\pi^{-}]_D\,\pi^{\pm}$	14,680 ± 130
$B^{\pm} \to [\pi^{+}\pi^{-}]_D\,K^{\pm}$	1162 ± 48
$B^{\pm} \to [\pi^{\pm}K^{\mp}]_D\,\pi^{\pm}$	1360 ± 44
$B^{\pm} \to [\pi^{\pm}K^{\mp}]_D\,K^{\pm}$	553 ± 34

the significance of CP violation in $B^- \to [\pi^- K^+]_D K^-$ is 8.0 σ

Phys. Rev. D91 (2015) 112014

γ from $B^{\pm} \rightarrow [h\, h'\, \pi^0]\, K / \pi$, 3 ifb, time integrated



- blue: fit result
- red: $[\pi\ K\ \pi^0]$ K i.e. signal
- dashed pink: $[\pi\ K\ \pi^0]$ K π when the last π is missed
- dotted blue: combinatorial
- shaded: other partially reco. backgrounds
- **dotted red: wrongly associated π^0**

- blue: fit result
- green: $[\pi\ K\ \pi^0]$ π i.e. signal
- dashed pink: $[\pi\ K\ \pi^0]$ K π when the last π is missed
- dotted blue: combinatorial
- shaded: other partially reco. Backgrounds
- **dotted red: wrongly associated π^0**

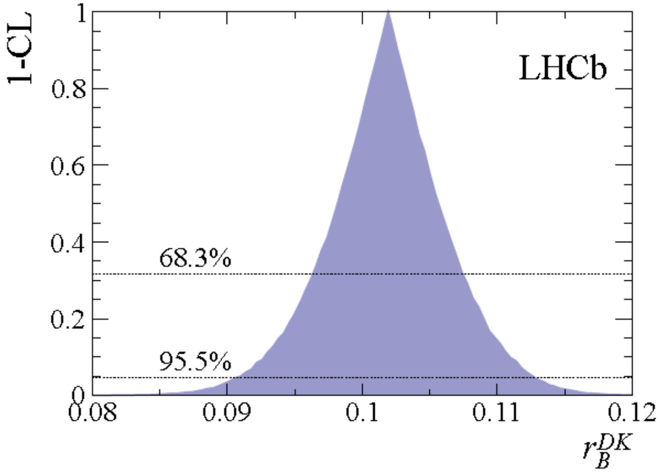
LHCb can cope with this π^0 'challenge'
additional inputs for the combined measurement

JHEP 12 (2016) 087

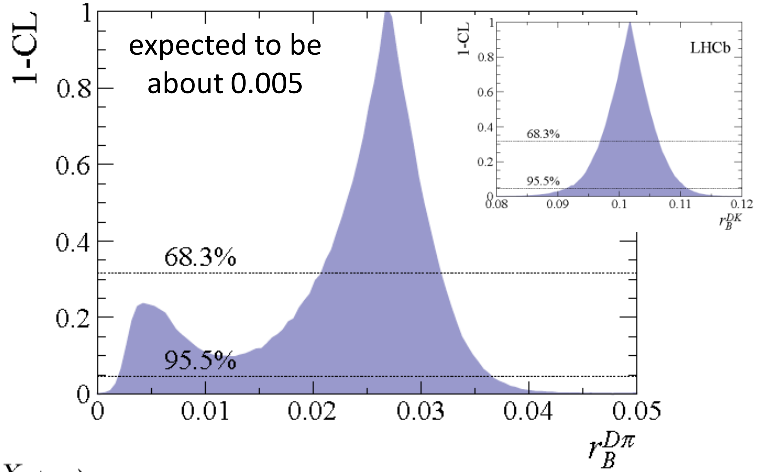
LHCb γ combination: D K (D h) combination results, freq. approach

- 71 (89) observables, 32 (38) parameters for D K (D h)
- from the χ^2 value at the minimum and the n.d.f., goodness of fit is *p* = (72.9) % for D h (D K)

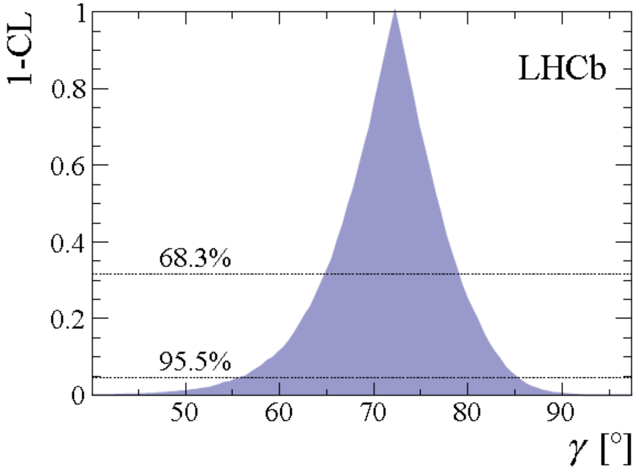
D K combination

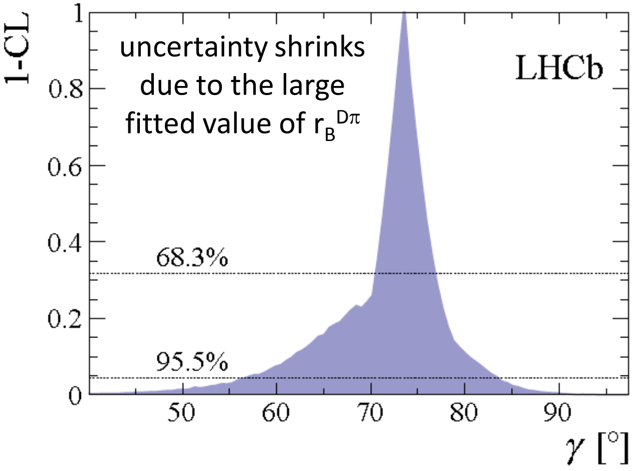


D h combination


expected to be about 0.005

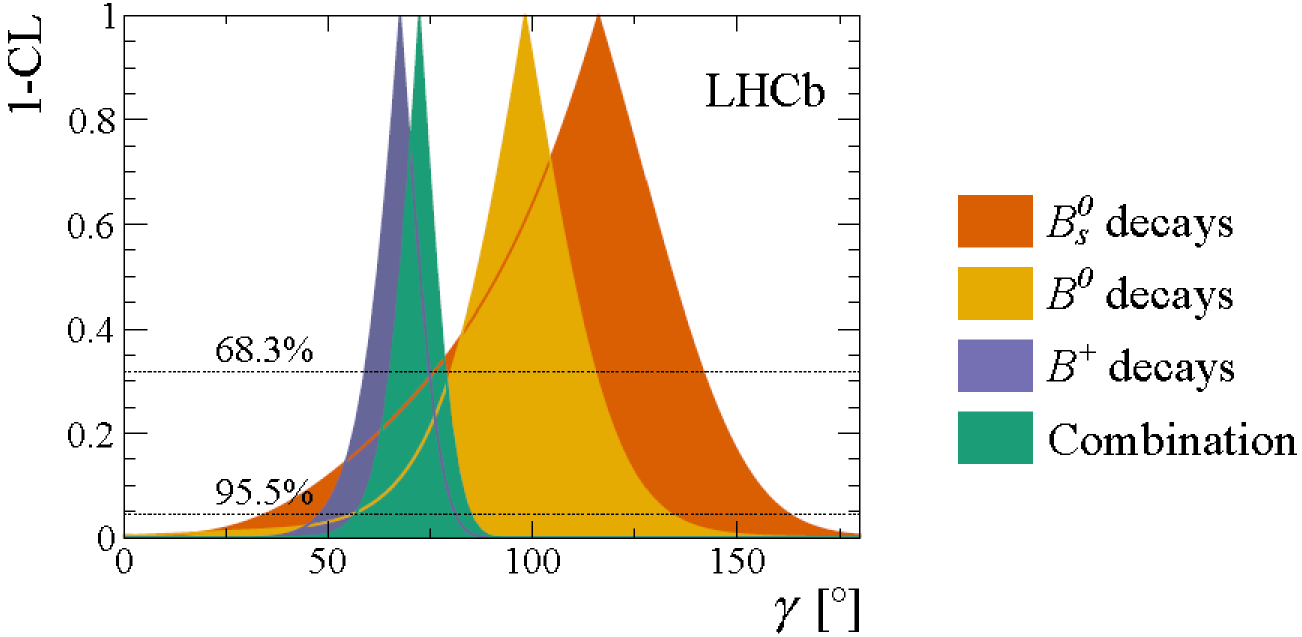
$$\mathcal{A}_{\rm sup}/\mathcal{A}_{\rm fav} = r_B^X e^{i(\delta_B^X \pm \gamma)}$$



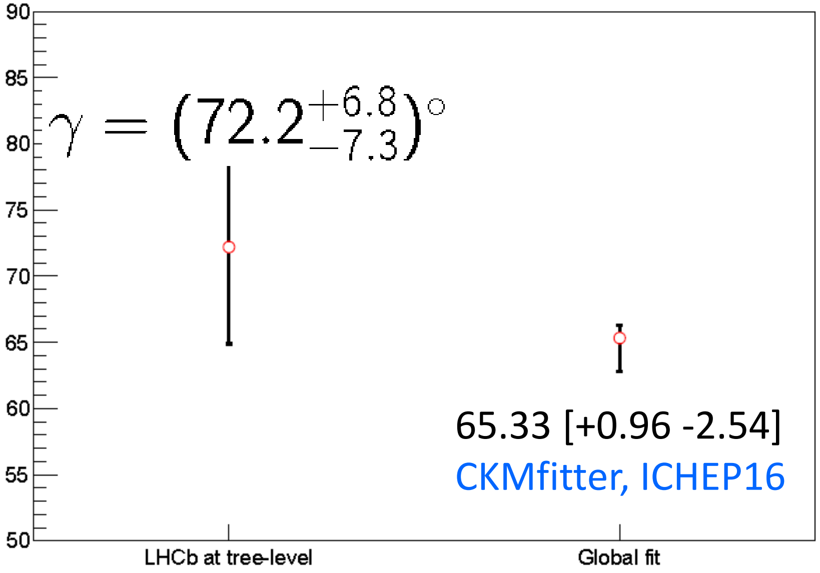

uncertainty shrinks due to the large fitted value of $r_B^{D\pi}$

JHEP 12 (2016) 087

LHCb γ combination: result by B decay mode (for D K) and final outcome



even if B$^+$ is dominant should continue to use both B$^+$ B^0 and B^0_s modes to further access the robustness of the measurement



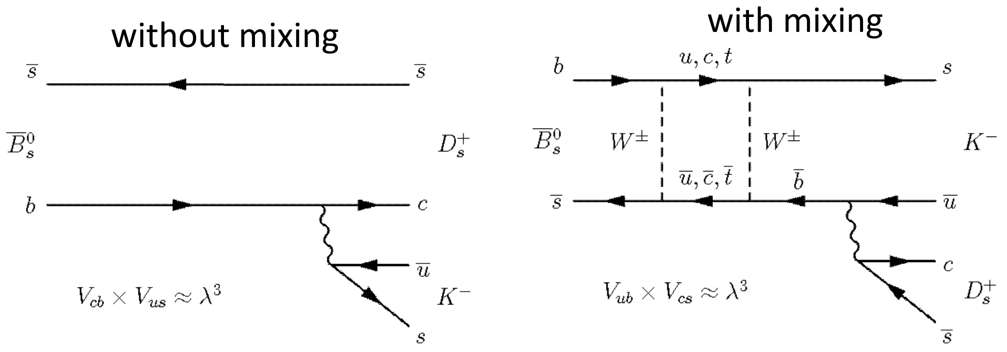
65.33 [+0.96 -2.54]

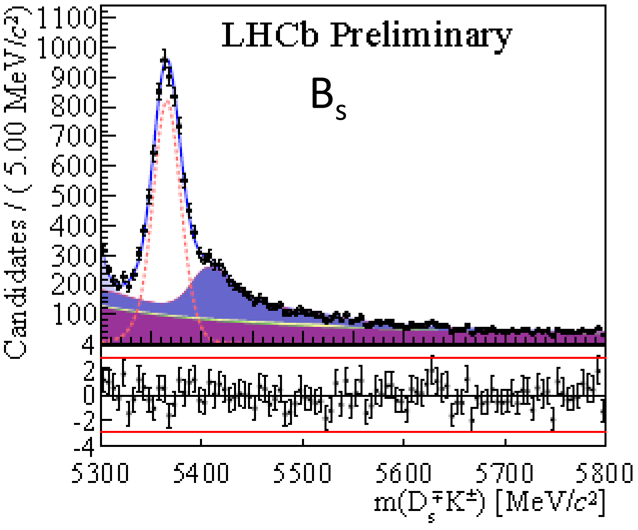
CKMfitter, ICHEP16

final outcome: quote for γ the value obtained from the D K combination

γ from $B_s \to D_s$ K, 3 ifb, time dependent

(will be included in the next D K LHCb γ combination)

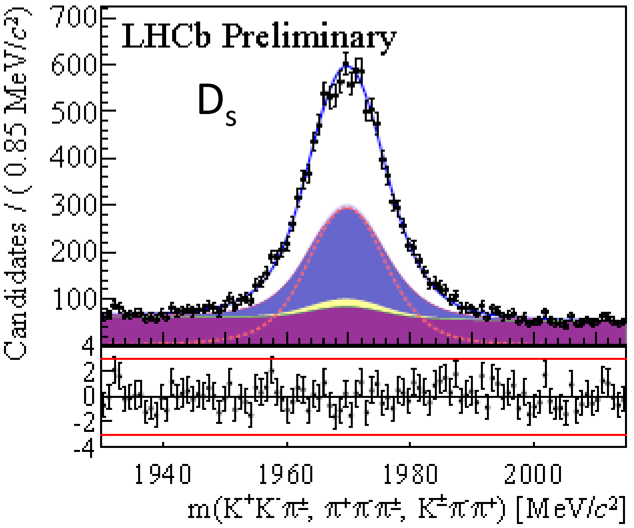


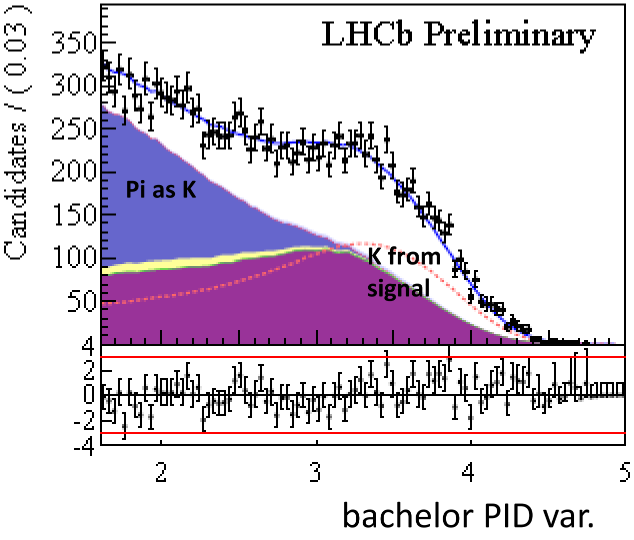


decay time distributions

$$\frac{\mathrm{d}\Gamma_{B_s^0\to f}(t)}{\mathrm{d}t} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos\left(\Delta m_s t\right) - S_f\sin\left(\Delta m_s t\right)\right]$$

$$\frac{\mathrm{d}\Gamma_{\overline{B}{}_s^0\to f}(t)}{\mathrm{d}t} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f\cos\left(\Delta m_s t\right) + S_f\sin\left(\Delta m_s t\right)\right]$$

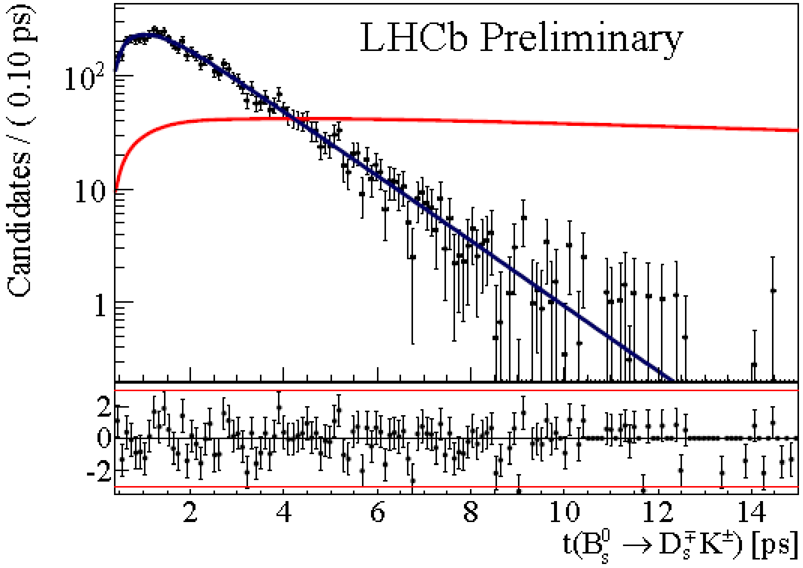




- blue line: fit
- dashed red: signal
- dark pink: combinatorial
- violet: $B_s \to D_s \pi$
- yellow: $\Lambda_b \to \Lambda_c K$

LHCb-CONF-2016-015

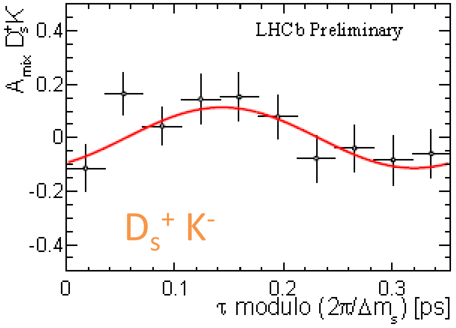
γ from $B_s \rightarrow D_s K$, 3 ifb, time dependent (cont.)

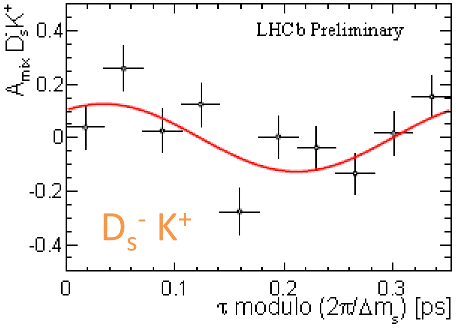


red curve: time acceptance obtained from $B_s \rightarrow D_s$ Pi DATA and corrected for the $B_s \rightarrow D_s$ K to $B_s \rightarrow D_s$ Pi MC time acceptance ratio

black curve: fit to the decay time distribution

$$\left\{\begin{array}{l} C_f \\ A_f^{\Delta\Gamma} \\ A_{\bar{f}}^{\Delta\Gamma} \\ S_f \\ S_{\bar{f}} \end{array}\right.$$





folded asymmetry plots for $D_s^+ K^-$ and $D_s^- K^+$

red curve: fit result

CP violation: different phase for $\tau = 0$ ps

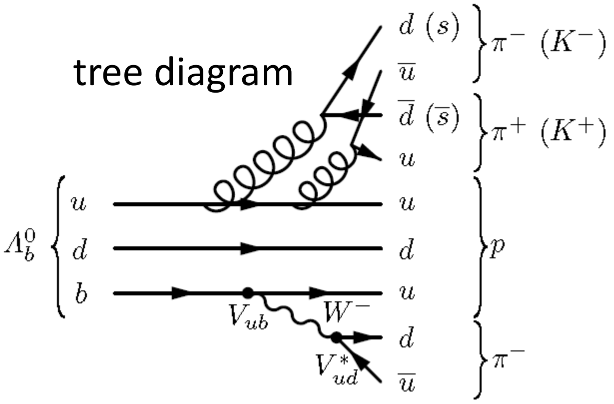
strictly speaking probing $\gamma - 2\beta_s$, using in addition $\phi_s = -2\beta_s$ and ϕ_s from $B_s \rightarrow J/\psi$ KK / $\pi\pi$

$$\gamma = (127^{+17}_{-22})^\circ \qquad \delta = (358^{+15}_{-16})^\circ \quad r_{D_sK} = 0.37^{+0.10}_{-0.09}$$

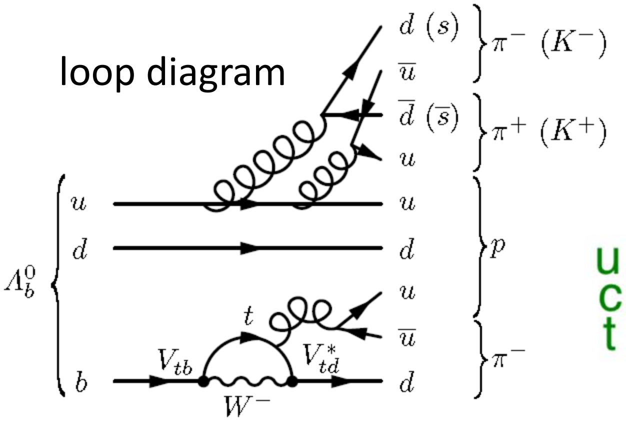
Matter antimatter differences in beauty baryon decays, 3 ifb

arXiv.1609:05216
submitted to Nature Physics

tree diagram



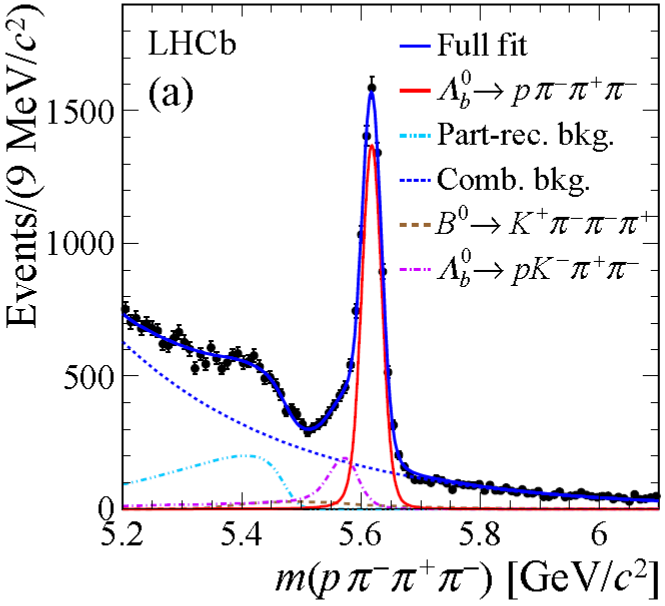
loop diagram



$$\begin{array}{c|ccc} & d & s & b \\ u & 1-\lambda^2/2 & \lambda & \boxed{A\lambda^3(\rho-i\eta)} \\ c & -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ t & \boxed{A\lambda^3(1-\rho-i\eta)} & -A\lambda^2 & 1 \end{array}$$

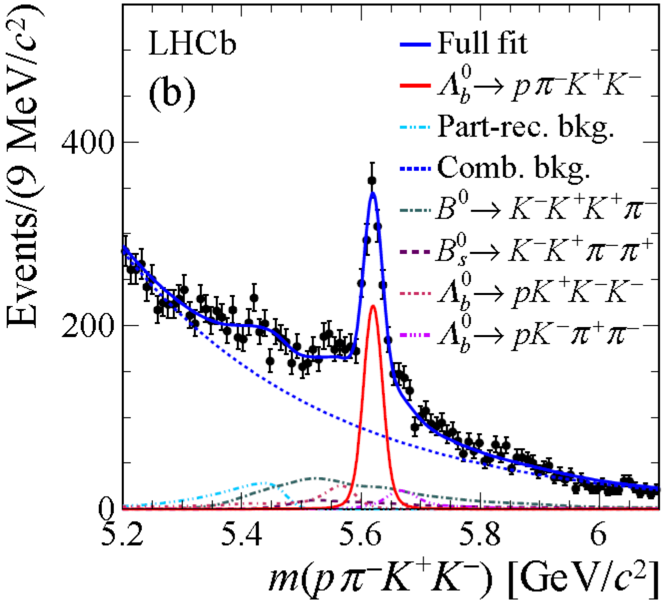
CKM expansion in $\lambda \approx 0.22$ up to $\mathcal{O}(\lambda^3)$

first observation of this decay mode



yield: 6646 ± 105

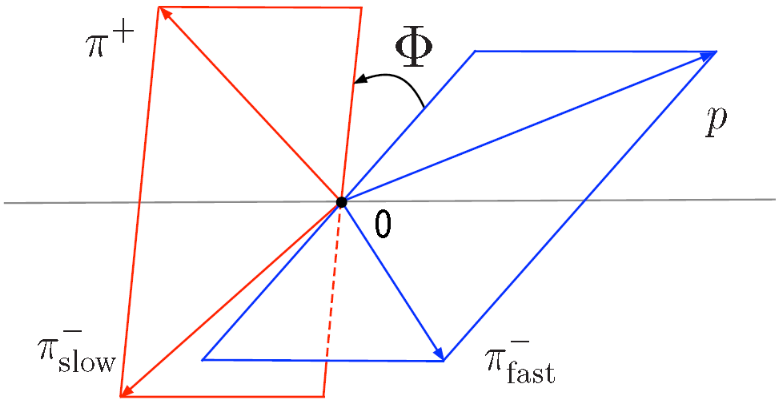
first observation of this decay mode



yield: 1030 ± 56

Matter antimatter differences in beauty baryon decays (cont.)

arXiv.1609:05216
submitted to Nature Physics



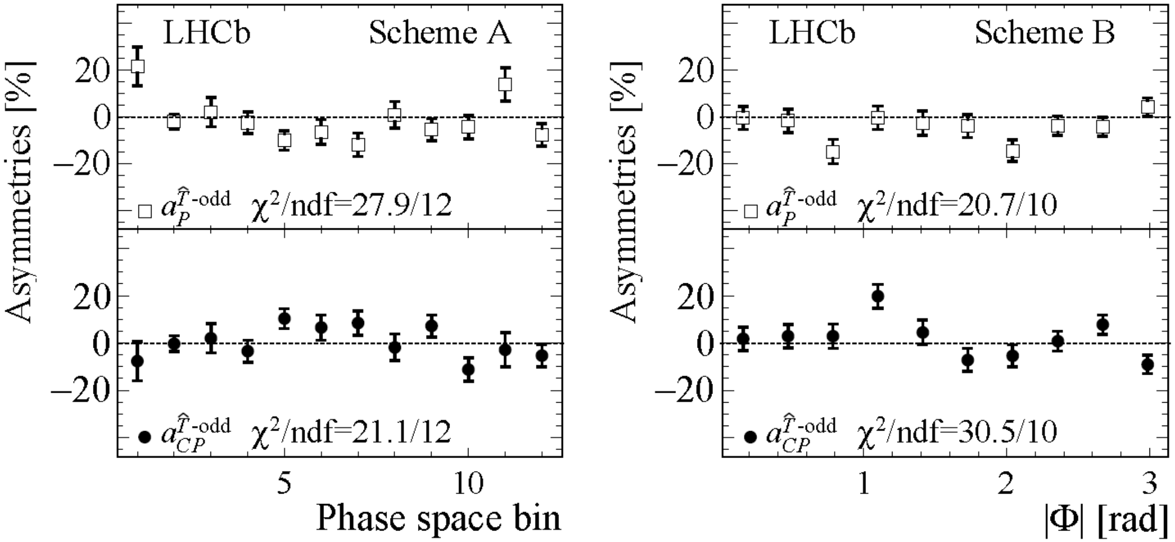
$$C_{\widehat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \quad \overline{C}_{\widehat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})$$

$$A_{\widehat{T}}(C_{\widehat{T}}) = \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)},$$

$$\overline{A}_{\widehat{T}}(\overline{C}_{\widehat{T}}) = \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)}$$

$$a_P^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} + \overline{A}_{\widehat{T}}\right) \quad a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} - \overline{A}_{\widehat{T}}\right)$$

$\Lambda^0_b \to p\,\pi\,\pi\,\pi$



the χ^2/ndf are quoted for the P and CP conserving hypotheses

searches for localized P or CP violation

1. p π K K: no significant P or CP violation (not shown)
2. p π π π:

- no significant P violation (white boxes)
- CP violation at the 3.3 σ level (black dots)

- first evidence of CP violation in the baryon sector
- indicates an asymmetry between baryonic matter and antimatter

EPJ C 73 (2013) 2373

Summary and future prospects

current LHCb sensitivities and expected ones in 2018 and beyond

Observable	LHCb Run I	LHCb Run II	Upgrade ($50\ \mathrm{fb}^{-1}$)	Theory uncertainty
$\gamma(B \to D^{(*)}K^{(*)})$	$\sim 7^\circ$	4°	0.9°	negligible
$\gamma(B_s^0 \to D_s K)$	$\sim 20^\circ$	11°	2°	negligible
$\beta(B^0 \to J/\psi K_S)$	1.16°	0.6°	0.2°	negligible
$2\beta_s(B_s^0 \to J/\psi \phi)$	0.049	0.025	0.008	~ 0.003

✓ achieved

2011-2012
- 3 ifb
- 3.5 / 4.0 TeV

2015-2018
- + 5 ifb
- 6.5 TeV

(factor 2 increase of σ for beauty)

2020-2023
- + 50 ifb
- 6.5 TeV
- improved detector, for flavor physics (PID, tagging, …)
- software trigger (significant improvement of hadronic trigger efficiency, expect a factor 2)

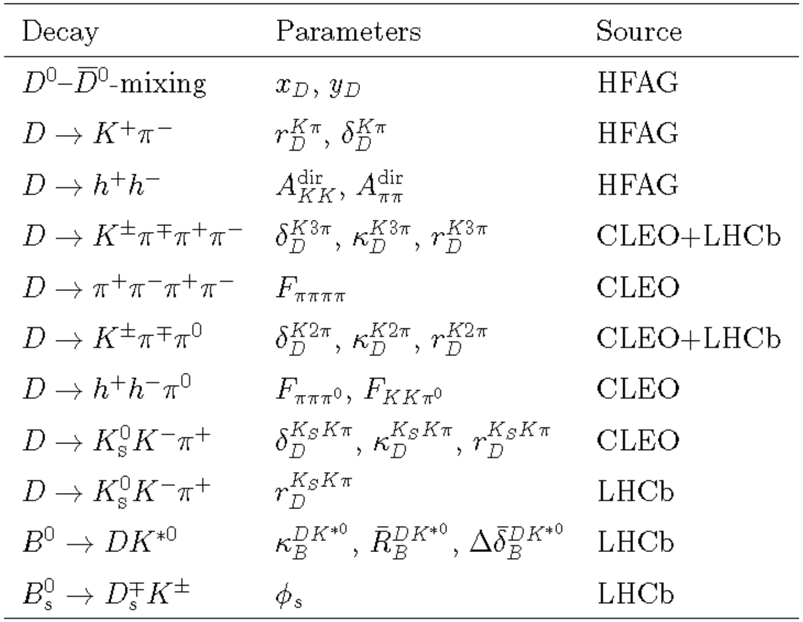
γ[CKMfitter, ICHEP16] = 65.33 [+0.96 -2.54]
- expect to be close when integrating up to 2018 data
- at the same level with the upgrade

+ start to see CPV also for baryons

+ if you add also Belle 2 in this game I really feel we have exciting times ahead of us

Backup

LHCb γ combination: auxiliary inputs

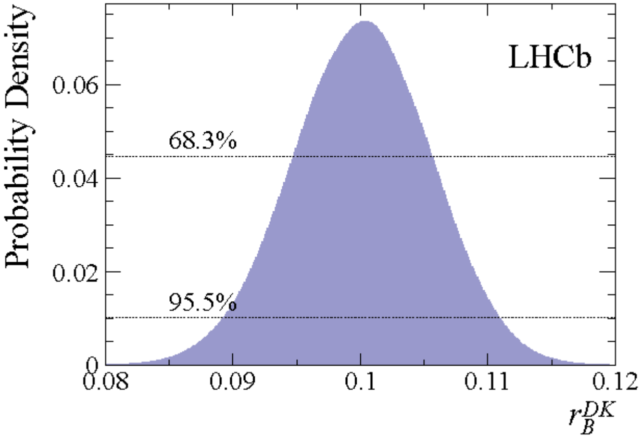


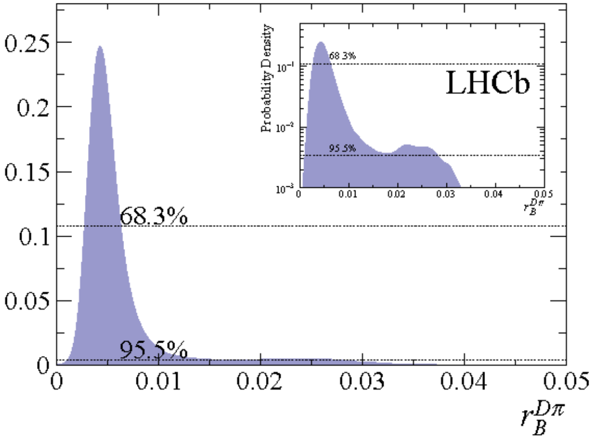
Decay	Parameters	Source
D^0–$\overline{D}^0$-mixing	$x_D,\, y_D$	HFAG
$D \to K^+\pi^-$	$r_D^{K\pi},\, \delta_D^{K\pi}$	HFAG
$D \to h^+h^-$	$A_{KK}^{\rm dir},\, A_{\pi\pi}^{\rm dir}$	HFAG
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$\delta_D^{K3\pi},\, \kappa_D^{K3\pi},\, r_D^{K3\pi}$	CLEO+LHCb
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{\pi\pi\pi\pi}$	CLEO
$D \to K^\pm\pi^\mp\pi^0$	$\delta_D^{K2\pi},\, \kappa_D^{K2\pi},\, r_D^{K2\pi}$	CLEO+LHCb
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0},\, F_{KK\pi^0}$	CLEO
$D \to K_{\rm s}^0K^-\pi^+$	$\delta_D^{K_SK\pi},\, \kappa_D^{K_SK\pi},\, r_D^{K_SK\pi}$	CLEO
$D \to K_{\rm s}^0K^-\pi^+$	$r_D^{K_SK\pi}$	LHCb
$B^0 \to DK^{*0}$	$\kappa_B^{DK^{*0}},\, \bar{R}_B^{DK^{*0}},\, \Delta\bar{\delta}_B^{DK^{*0}}$	LHCb
$B_s^0 \to D_s^\mp K^\pm$	ϕ_s	LHCb

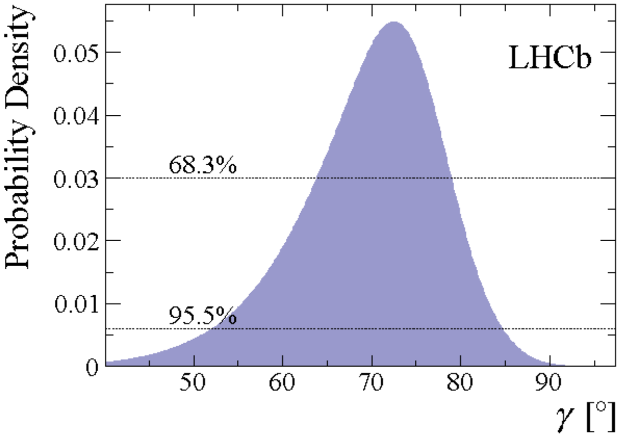
- taken from HFAG or other experiments
- more and more often taken from LHCb itself

LHCb γ combination: D h vs D K combination results (Bayesian analysis)

D h combination

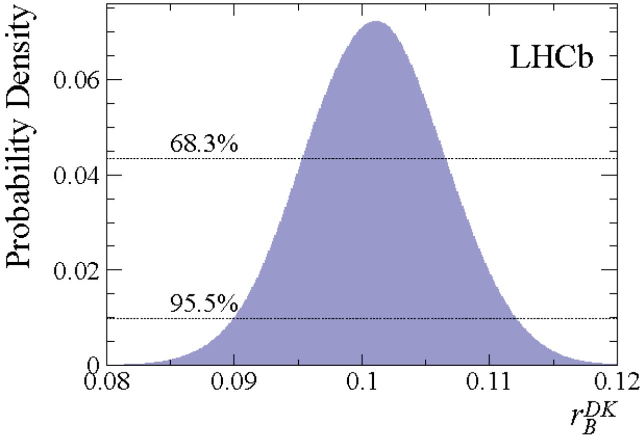


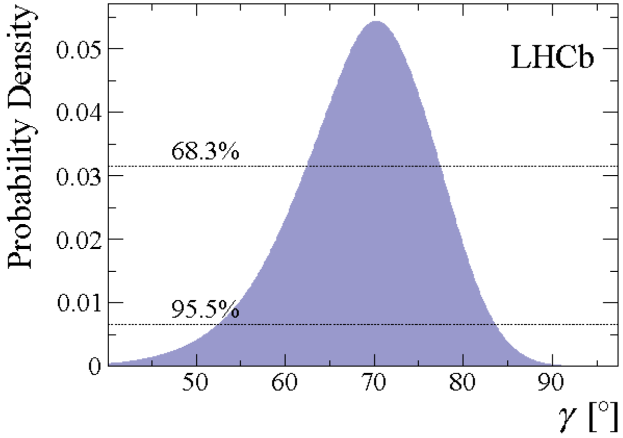




$r_B^{D\pi}$ “small” so no shrinkage

D K combination





Matter antimatter differences in beauty baryon decays

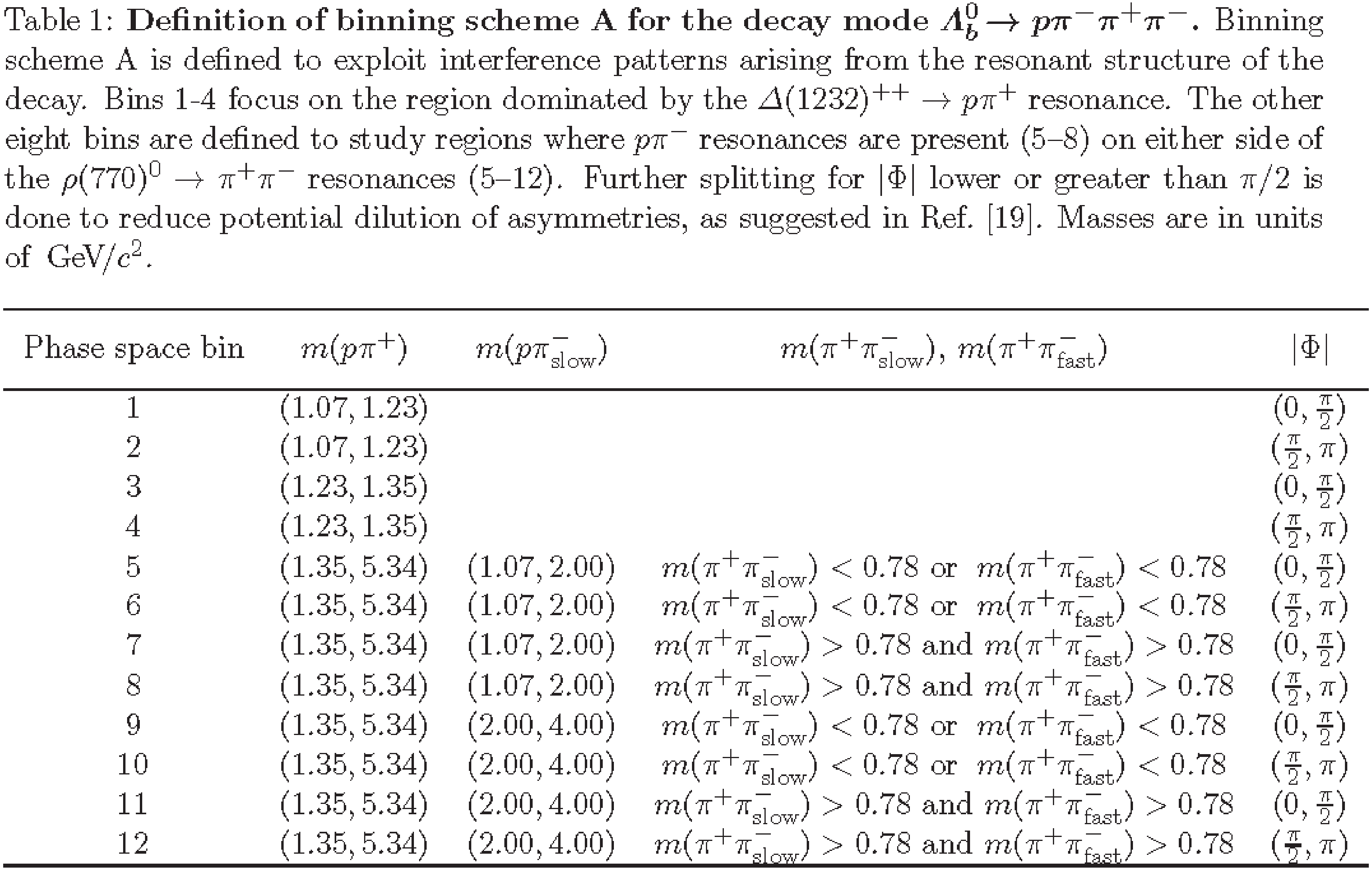
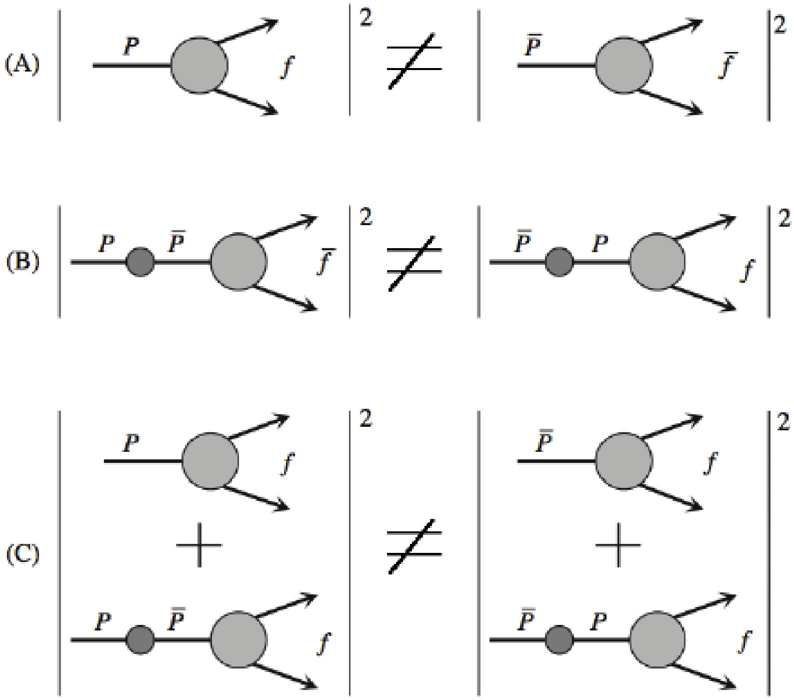


Table 1: **Definition of binning scheme A for the decay mode $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$.** Binning scheme A is defined to exploit interference patterns arising from the resonant structure of the decay. Bins 1-4 focus on the region dominated by the $\Delta(1232)^{++} \to p\pi^+$ resonance. The other eight bins are defined to study regions where $p\pi^-$ resonances are present (5–8) on either side of the $\rho(770)^0 \to \pi^+\pi^-$ resonances (5–12). Further splitting for $\|\Phi\|$ lower or greater than $\pi/2$ is done to reduce potential dilution of asymmetries, as suggested in Ref. [19]. Masses are in units of GeV/c^2.

Phase space bin	$m(p\pi^+)$	$m(p\pi^-_{\mathrm{slow}})$	$m(\pi^+\pi^-_{\mathrm{slow}})$, $m(\pi^+\pi^-_{\mathrm{fast}})$	$\|\Phi\|$
1	$(1.07, 1.23)$			$(0, \frac{\pi}{2})$
2	$(1.07, 1.23)$			$(\frac{\pi}{2}, \pi)$
3	$(1.23, 1.35)$			$(0, \frac{\pi}{2})$
4	$(1.23, 1.35)$			$(\frac{\pi}{2}, \pi)$
5	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\mathrm{slow}}) < 0.78$ or $m(\pi^+\pi^-_{\mathrm{fast}}) < 0.78$	$(0, \frac{\pi}{2})$
6	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\mathrm{slow}}) < 0.78$ or $m(\pi^+\pi^-_{\mathrm{fast}}) < 0.78$	$(\frac{\pi}{2}, \pi)$
7	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\mathrm{slow}}) > 0.78$ and $m(\pi^+\pi^-_{\mathrm{fast}}) > 0.78$	$(0, \frac{\pi}{2})$
8	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\mathrm{slow}}) > 0.78$ and $m(\pi^+\pi^-_{\mathrm{fast}}) > 0.78$	$(\frac{\pi}{2}, \pi)$
9	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\mathrm{slow}}) < 0.78$ or $m(\pi^+\pi^-_{\mathrm{fast}}) < 0.78$	$(0, \frac{\pi}{2})$
10	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\mathrm{slow}}) < 0.78$ or $m(\pi^+\pi^-_{\mathrm{fast}}) < 0.78$	$(\frac{\pi}{2}, \pi)$
11	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\mathrm{slow}}) > 0.78$ and $m(\pi^+\pi^-_{\mathrm{fast}}) > 0.78$	$(0, \frac{\pi}{2})$
12	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\mathrm{slow}}) > 0.78$ and $m(\pi^+\pi^-_{\mathrm{fast}}) > 0.78$	$(\frac{\pi}{2}, \pi)$



CPV in decays (A)

Need **CP invariant** (strong) phase δ and **CPV** (weak) phase ϕ.

$$A(P \to f) = a_1 e^{i\delta_1} e^{i\phi_1} + a_2 e^{i\delta_2} e^{i\phi_2}$$

$$A(\bar{P} \to \bar{f}) = a_1 e^{i\delta_1} e^{-i\phi_1} + a_2 e^{i\delta_2} e^{-i\phi_2}$$

$$\to \boldsymbol{\Delta |A|^2 \propto \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)}$$

e.g: $B^+ \to J/\psi K^+$ vs $B^- \to J/\psi K^-$.

CPV in mixing (B)

Mass eigenstates vs flavour eigenstates:

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

$\to$ CPV if $|q/p| \neq 1$

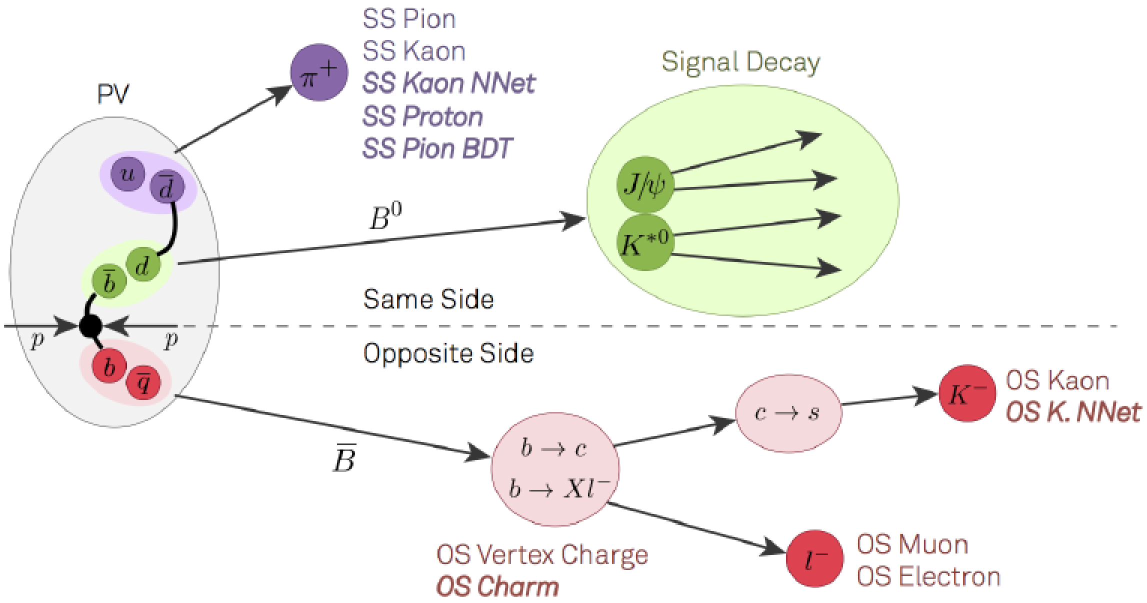
e.g: Lepton charge asymmetry in $B_s^0 \to D_s^\mp \mu^\pm \nu_\mu X$ decays.

CPV in interference between decay and mixing (C)

Neutral meson decaying into *non-flavour specific* states.

$$\frac{A(\bar{P} \to f) - A(P \to f)}{A(\bar{P} \to f) + A(P \to f)} = \frac{C_f \cos(\Delta m t) - S_f \sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

S_f and D_f coefficients: interference between mixing and decay. C_f coefficient: direct CPV.



$B_s \to D_s$ Pi DATA

	$\varepsilon_{\text{tag}}\ [\%]$	$\varepsilon_{\text{eff}}\ [\%]$
OS	37.15 ± 0.17	3.55 ± 0.33
SS(KaonNNet)	63.93 ± 0.17	1.92 ± 0.22

Efficiency and mistag:

$$\epsilon_{\text{tag}} = \frac{N_{\text{tag}}}{N_{\text{tag}} + N_{\text{untag}}}, \quad \omega = \frac{N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}}}$$

Tagging power: $\boldsymbol{\epsilon_{\text{eff}} = \epsilon_{\text{tag}} D^2 = \epsilon_{\text{tag}} \left\langle (1 - 2\omega)^2 \right\rangle}$

Statistical uncertainty: $\boldsymbol{\sigma_{\text{stat}} \propto 1/\sqrt{\epsilon_{\text{eff}} N}}$

Mistag: dilution of time-dependent asymmetries.

Details here: [EPJC (2012) 72:2022], [JINST 10 (2015) P10005], [JINST 11 (2016) P05010], [arXiv:1610:06019].