CP violation measurements in b hadrons at LHCb

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Meeting of the APS Division of Particles and Fields

August 4$^{\text{th}}$, 2017

GOBIERNO DE ESPAÑA

MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Charge-Parity Violation: why the interest?

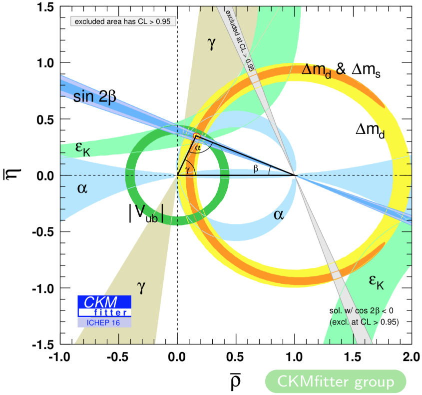
The Standard Model (SM) of particle physics **despite** being **very successful in its predictions** **fails to explain matter anti-matter differences** in our universe.

New sources of these asymmetries (CPV) are therefore **expected** in any satisfactory SM extension!

Flavour transitions in the quark sector are parametrised by the **CKM matrix**

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CKM matrix: unitary, 3×3 matrix describing quark mixing (3 angles, one phase). (A, λ, ρ, η) are not predicted by the SM. They need to be measured!



CKMfitter group

These parameters are over constrained in the SM → great scenario to search for incompatibilities and small deviations due to New Physics (NP) effects

Why b hadrons? related unitary triangles are less squeezed hence expect larger sensitivity to any CP violation effect.

CPV phenomenology

How: measure interfering amplitudes with different CKM phases

Mixing

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

- $|q/p| \neq 1$
- **Neutral meson mixing**: $\mathcal{P}(X \to \overline{X}) \neq \mathcal{P}(\overline{X} \to X)$
- *Ex.:* $a_{sl}^{s,d} = \frac{R(\overline{B}^0 \to \overline{\ell}X) - R(B^0 \to \ell X)}{R(\overline{B}^0 \to \overline{\ell}X) + R(B^0 \to \ell X)}$

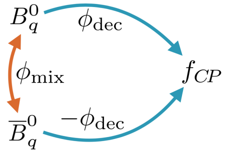
Decay

$\mathcal{A}(X \to f) \neq \mathcal{A}(\overline{X} \to \overline{f})$

- Amplitudes for **CP conjugates differ**
- Possible also for charged hadrons
- Only option for baryons (baryon number conservation)
- *Ex.:* $B^0 \to K^+\pi^-$ vs $\overline{B}^0 \to K^-\pi^+$

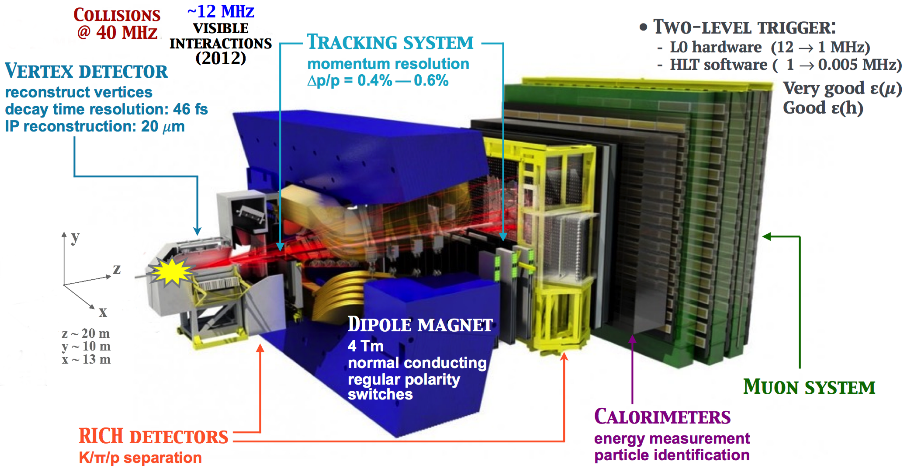
Interference Mixing and Decay

- **Interference of direct decay and decay after mixing**
- Partial decay widths are sensitive to $\phi_q = \phi_{mix} - 2\phi_{dec}$
- Decay-time dependent CP asymmetry:
  $a_{CP} = \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to f)}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to f)} = \frac{C_f \cos(\Delta M t) - S_f \sin(\Delta M t)}{\cosh(\frac{\Delta\Gamma t}{2}) + A_f^{\Delta\Gamma} \sinh(\frac{\Delta\Gamma t}{2})}$
- *Ex.:* $B^0 \to J/\Psi K_s^0$



The LHCb detector

LHCb Detector Performance

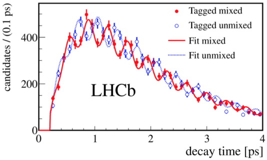


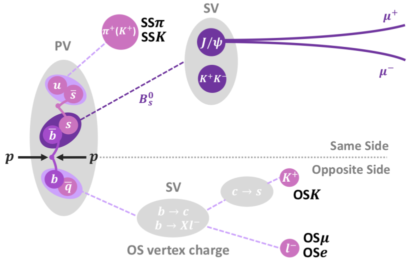
Experimental challenges

To **measure CPV** an experiment **needs**:

- Excellent **vertexing:**
  - to separate primary from secondary vertexes
  - to resolve fast oscillations
- Very good **PID** performance:
  - to distinguish between topologically identical events
  - to tag the initial flavour content
- Very **large sample sizes** to be sensitive to tiny variations
- **Control** over known CP asymmetries/effects

New J. Phys. 15 (2013) 053021



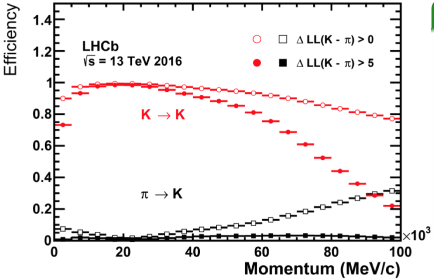


To help with these, the **LHCb:**

- runs at **lower instantaneous luminosity** than ATLAS or CMS
- **levels the luminosity**, making trigger conditions constant throughout the runs
- takes data with **different magnet polarities**

A word on PID and tagging

LHCb RICH Performance

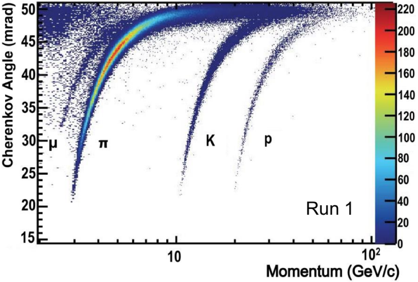


Particle Identification

- π/K separation: $\varepsilon_K \sim 90\%, \pi \to K$ misID $\sim 5\%$
- π/μ separation: $\varepsilon_\mu \sim 97\%, \pi \to \mu$ misID $\sim 1-3\%$
- Calibrated via **data driven** methods
- Good control and understanding of the **PID performance is critical** to our analyses.

Flavour tagging

- Efficiency: $\varepsilon_{tag} = \frac{N_{tag}}{N_{tag}+N_{untag}}$
- Mistag: $\omega = \frac{N_{wrong}}{N_{right}+N_{wrong}}$
- Tagging power: $\varepsilon_{eff} = \varepsilon_{tag}\langle(1-2\omega)^2\rangle$
- Statistical uncertainty: $\sigma_{stat} \propto \frac{1}{\sqrt{\varepsilon_{eff} N}}$



Status of $\beta_{(s)}$ measurements

→Accessible from the **interference between** **mixing and decay**

Standard Model predictions

B_s^0 system: $\phi_s^{c\bar{c}s} \equiv -2arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = 0.0365^{+0.0013}_{-0.0012}$ rad

B^0 system: $\phi_d^{c\bar{c}s} \equiv -2arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) = 0.771^{+0.017}_{-0.041}$ rad

PRD (2015) 073007

→**Golden modes** provide **exact match to the CKM angle**:

$B_s^0 \to J/\psi K^+K^-(\phi_s = -2\beta_s)$ and $B^0 \to J/\psi K_s^0(\phi_d = 2\beta)$

Latest published results:

Decay	Result	Reference
$B_s^0 \to J/\psi\pi^+\pi^-$	$+0.070\pm0.068\pm0.008$	PLB B736 186 (2014)
$B_s^0 \to D_s^+D_s^-$	$+0.02\pm0.17\pm0.02$	PRL113 211801 (2014)
$B_s^0 \to J/\psi K^+K^-$	-0.058$\pm$0.049$\pm$0.006	PRL114 041802 (2015)
$B^0 \to D^+D^-$	$\Delta\phi = -0.16^{+0.19}_{-0.21}$	PRL 117 261801(2016)
$B_s^0 \to \psi(2S)\phi$	$+0.23^{+0.29}_{-0.28} \pm 0.02$	PLB B762, 252-262 (2016)
$\mathbf{B_s^0 \to J/\psi K^+K^-}$ $(m_{K^+K^-} > m_{\phi(1020)})$	$+0.119 \pm0.107\pm0.034$	arXiv:1704.08217 (2017)

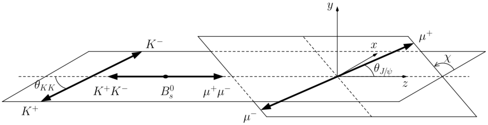
Ongoing new analyses and updates:

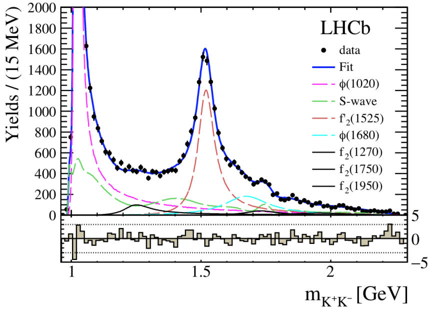
- $B_s^0 \to J/\psi(\to e^+e^-)\phi$ with Run I
- $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ with Run I
- $B_{(s)}^0 \to h^+h^-$ with Run I (update)
- $B_s^0 \to J/\psi K^+K^-$,$B_s^0 \to J/\psi\pi^+\pi^-$ Run II

Measurement of $\phi_s^{c\bar{c}s} = -2\beta_s$ in $B_s^0 \to J/\psi K^+ K^-$

arXiv:1704.08217 (2017)

Flavour-tagged, **time-dependent** **amplitude analysis** with $m_{K^+K^-}$ above the $\phi(1020)$ threshold with full LHCb Run I data sample.





Analysis strategy

- Selection using **multivariate** analysis, **background subtraction** via **sWeights** in $m(J/\psi K^+K^-)$ and **multi-dimensional fit** to the decay time, $m_{K^+K^-}$ and the helicity angles.
- **Reconstruction and selection efficiency** vs decay time are **measured on data** (control channel: $B^0 \to J/\psi K^{*0}(\to K^+\pi^-)$)
- Dominant systematics arise from resonance modelling and background subtraction
- First time that ϕ_s is measured in **final states dominated by a tensor**

Measurement of $\phi_s^{c\bar{c}s} = -2\beta_s$ in $B_s^0 \to J/\psi K^+K^-$

arXiv:1704.08217 (2017)

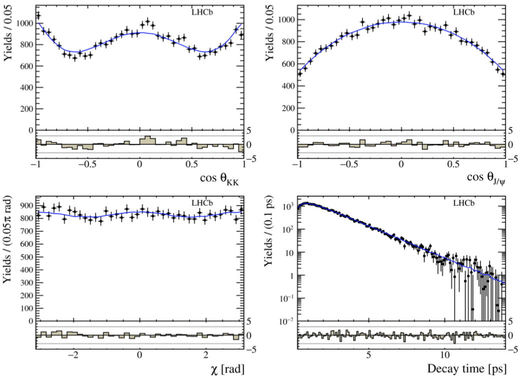
Fit results

$B_s^0 \to J/\psi K^+K^-$	$m_{K^+K^-}$ >1.05GeV
ϕ_s	$119 \pm 107 \pm 34$ mrad
$\lvert\lambda\rvert$	$0.994 \pm 0.018 \pm 0.006$
Γ_s	$0.650 \pm 0.006 \pm 0.004$ ps^{-1}
$\Delta\Gamma_s$	$0.066 \pm 0.018 \pm 0.010$ ps^{-1}

$+ B_s^0 \to J/\psi\phi$	
ϕ_s	$-25 \pm 45 \pm 8$ mrad
$\lvert\lambda\rvert$	$0.978 \pm 0.013 \pm 0.003$
Γ_s	$0.6588 \pm 0.0022 \pm 0.0015$ ps^{-1}
$\Delta\Gamma_s$	$0.0813 \pm 0.0073 \pm 0.0036$ ps^{-1}

PRL 114 (2015) 041801

Fit projections



Combining these also with the previous LHCb measurements using the $B_s^0 \to J/\psi\pi^+\pi^-$ yields **$\phi_s = 1 \pm 37$ mrad**

PLB 736 (2014)

TD CPV in $B^0_{(s)} \to h^+ h^-$

LHCb-CONF-2016-018

Motivation

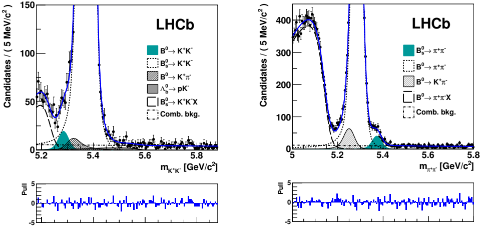
→Two battle fronts:

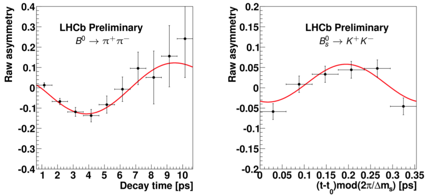
- Extremely rare $\mathbf{B^0 \to K^+ K^-}$ and $\mathbf{B^0_s \to \pi^+ \pi^-}$
- Sizeable sample for their high stats partners!

→Branching ratios are measured for the rare modes

→TD CPV analysis can be done with the high stats. samples

→**Assuming U-spin symmetry**, flavour tagged TD CPV analysis can constrain γ and ϕ_s





Most precise single measurement in $\mathbf{B^0 \to \pi^+\pi^-}$

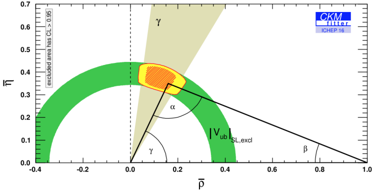
Unique measurement performed of $\mathbf{B^0_s \to K^+K^-}$

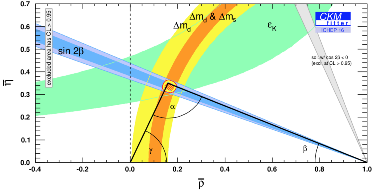
Better precision expected with the **inclusion of the SS taggers!**

$$C_{\pi\pi} = -0.24 \pm 0.07\ (\text{stat}) \pm 0.01\ (\text{syst})$$
$$S_{\pi\pi} = -0.68 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})$$
$$C_{KK} = 0.24 \pm 0.06\ (\text{stat}) \pm 0.02\ (\text{syst})$$
$$S_{KK} = 0.22 \pm 0.06\ (\text{stat}) \pm 0.02\ (\text{syst})$$
$$A^{\Delta\Gamma}_{KK} = -0.75 \pm 0.07\ (\text{stat}) \pm 0.11\ (\text{syst})$$

Status of γ measurements

- **Least well measured** angle of the CKM unitarity triangle
- No top quark coupling in its definition: $\gamma = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ (theoretically clean)
- Single measurements aren't precise enough to challenge the SM $\rightarrow$ big effort in producing a **combination of results from many (GLW+ADS) channels**
- **Direct** determination: $\gamma = (72.1^{+5.4}_{-5.8})^\circ$ vs **Indirect**: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$



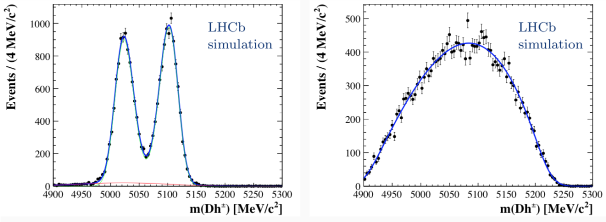


CKMfitter group

Latest addition: $B^{\pm} \to D^{*0}(\to D^0\pi^0 \text{ or } D^0\gamma)K^{\pm}$

LHCb-PAPER-2017-021

- **Theoretically similar** to the very well studied $B^{\pm} \to D^0 h^{\pm}$ PLB 760 (2016)
- **Experimental challenge** of π^0/γ **reconstruction** at LHCb overcame → these particles are ignored in the analysis
- Selection is then identical to that from $B^{\pm} \to D^0 h^{\pm}$
- Final **fit** is performed simultaneously over **12** ($B||\overline{B} \times (K||\pi) \times 3 - D$ daughters) **disjoint samples** and accesses 19 CPV observables
- These are built from different (double) **ratios of partial decay widths** (GLW) and **phase differences** for both the fully reconstructed and the D^{*0} modes
- The Run I results from the **fully reconstructed $\mathbf{B^{\pm} \to D^0 h^{\pm}}$** decays are **updated** with the same fit.



The **shape** of the **$\mathbf{m(D^0h^{\pm})}$** distribution allows to **distinguish the $\boldsymbol{\pi^0}$** and the **γ modes**.

Results from $B^{\pm} \to D^{*0}(\to D^0\pi^0$ or $D^0\gamma)K^{\pm}$ $D^0 \to K\pi$

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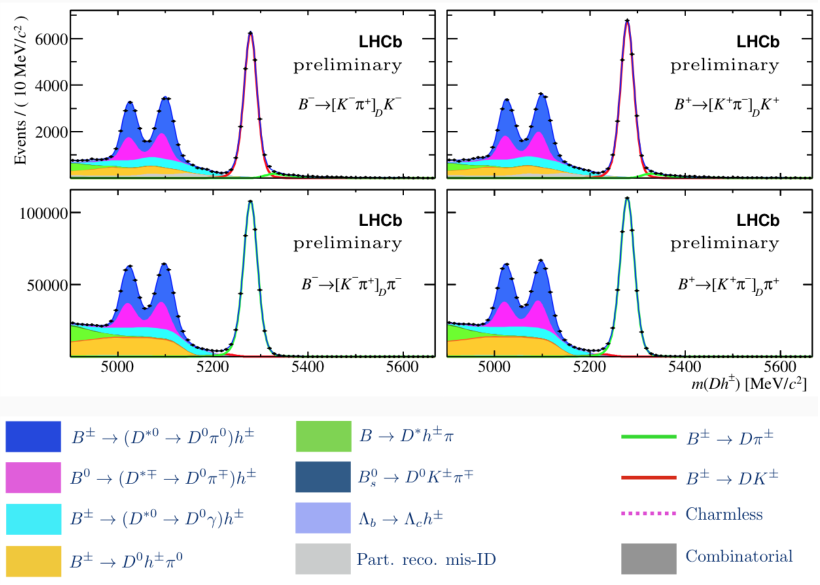


Latest LHCb γ combination

LHCb-CONF-2017-004

→ Obtained from the **combination of several time-integrated** analyses and the **time-dependent** $B_s^0 \to D_s^{\mp} K^{\pm}$

→ Follows the **same strategy** as the previous LHCb combination: $\gamma = (72.2^{+6.8}_{-7.3})^\circ$

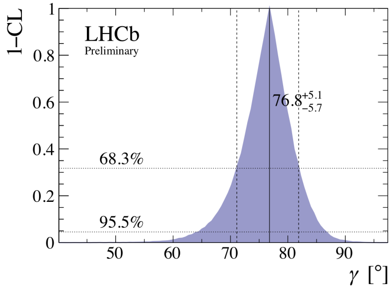
JHEP 12 (2016) 087

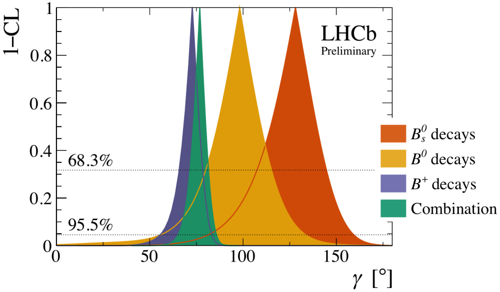
→ New modes added since last publication:

- $B^{\pm} \to D^0 K^{*\pm}$ ADS/GLW **(new)**
- $\mathbf{B^{\pm} \to D^{*0} K^{\pm}}$ GLW **(new)**
- $B_s^0 \to D_s^{\mp} K^{\pm}$ TD (1 fb^{-1} → **3fb^{-1}**)
- $B^{\pm} \to D^0 K^{\pm}$ GLW (3 fb^{-1} → **5fb^{-1}**)

$\gamma = (\mathbf{76.8^{+5.1}_{-5.7}})^\circ$ (preliminary)

most precise measurement to date!



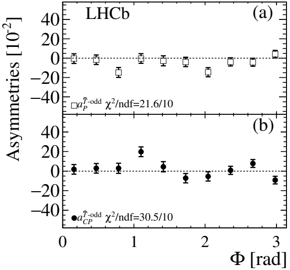


Baryons enter the game too! CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

Nature Physics 13 (2017) 391

Motivation

- **Direct CP violation** (CPV) had **never been observed** in baryon decays
- Large CPV effects are expected in charmless Λ_b decays ($A_{CP} \sim 20\%$) Y. K. Hsiao et al.
- Both tree and penguin diagrams contribute with similar amplitudes
- $a_{CP} \neq 0$ at 3.3σ was seen!



Observables construction

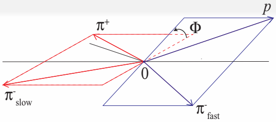
Triple products in the Λ_b rest frame:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+}) \propto \sin\Phi$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h^+} \times \vec{p}_{h^-}) \propto \sin\overline{\Phi}$$

$\hat{\text{T}}$-odd asymmetries:

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}}>0) - N_{\Lambda_b^0}(C_{\hat{T}}<0)}{N_{\Lambda_b^0}(C_{\hat{T}}>0) + N_{\Lambda_b^0}(C_{\hat{T}}<0)}$$

$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}$$



CP-violating observable:

$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$$

P-violating observable:

$$a_{P}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}})$$

NEW

Summary and conclusions

→ **Results found** so far are **compatible with SM** expectations **but CPV knowledge** remains having several **grey areas**

→ Many of them are within the **LHCb physics-case**!

→ With the **statistics** achieved by **LHCb** during the Run I & II, many new analyses have become **feasible** and **high precision measurements are being performed**. Some expectations on the precisions to achieve by the end of Run II would be:

- 4° for γ
- $\sim 0.8^\circ$ in β
- < 20 mrad for ϕ_s

→ **Stay tuned for many interesting new results!**

Thank you for your attention!

...questions

Backup slides

Systematics in the TD CPV analysis of $B^0_{(s)} \to h^+h^-$

LHCb-CONF-2016-018

Parameter	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$
Time acceptance	0.001	0.001	0.003	0.003	0.093
Time resolution calibration	0.000	0.000	0.016	0.017	0.012
Time resolution model	0.000	0.000	0.007	0.008	0.000
Time error distribution	0.002	0.002	0.002	0.002	0.019
Input parameters: $\Gamma_{d,s}$, $\Delta\Gamma_{d,s}$, $\Delta m_{d,s}$	0.001	0.001	0.001	0.003	0.046
Tagging calibration	0.002	0.003	0.002	0.003	0.000
Cross-feed bkg. time model	0.003	0.002	0.001	0.001	0.021
Comb. and 3-body bkg. time model	0.001	0.001	0.000	0.000	0.001
Mass model	0.003	0.003	0.006	0.005	0.010
Total	0.005	0.005	0.019	0.020	0.109

Results from $B^{\pm} \to D^{*0}(\to D^0\pi^0$ or $D^0\gamma)K^{\pm}$ $D^0 \to KK$

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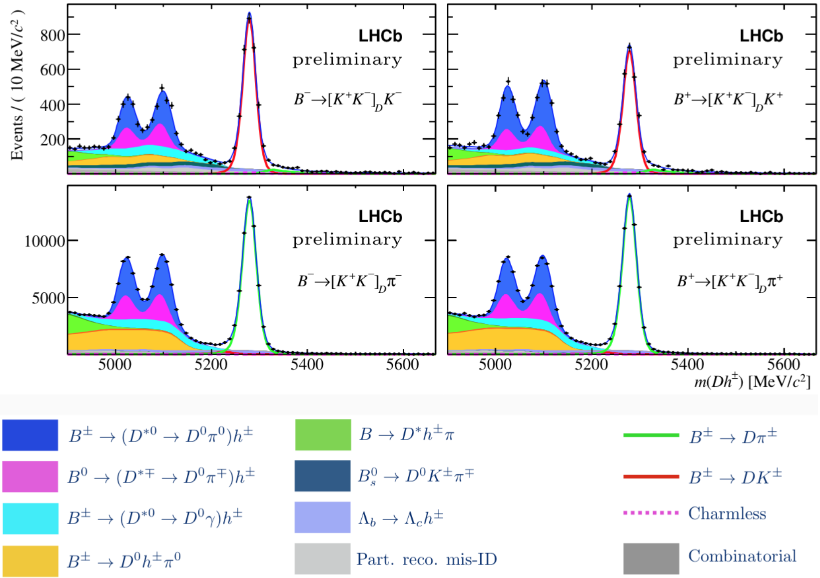

Results from $B^{\pm} \to D^{*0}(\to D^0\pi^0 \text{ or } D^0\gamma)K^{\pm}$ $D^0 \to \pi\pi$

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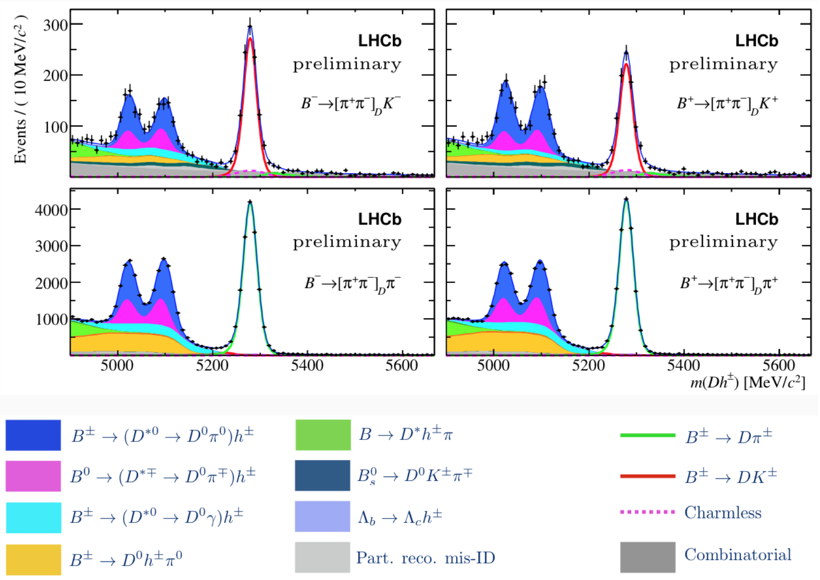

Binning schemes for the $\Lambda_b^0 \to p\pi\pi\pi$ measurements

Nature Physics 13 (2017) 391

Scheme A Region	$m_{p\pi^+}$ (GeV/c^2)	$m_{p\pi^-_{slow}}$ (GeV/c^2)	$m_{\pi^+\pi^-_{slow}}$, $m_{\pi^+\pi^-_{fast}}$ (GeV/c^2, GeV/c^2)	Φ
1	$(1.00, 1.23)$			$(0, \frac{\pi}{2})$
2	$(1.00, 1.23)$			$(\frac{\pi}{2}, \pi)$
3	$(1.23, 1.35)$			$(0, \frac{\pi}{2})$
4	$(1.23, 1.35)$			$(\frac{\pi}{2}, \pi)$
5	$(1.35, 5.40)$	$(0.90, 2.00)$	$(m_{\pi^+\pi^-_{slow}} < 0.78 \| \| m_{\pi^+\pi^-_{fast}} < 0.78)$	$(0, \frac{\pi}{2})$
6	$(1.35, 5.40)$	$(0.90, 2.00)$	$(m_{\pi^+\pi^-_{slow}} < 0.78 \| \| m_{\pi^+\pi^-_{fast}} < 0.78)$	$(\frac{\pi}{2}, \pi)$
7	$(1.35, 5.40)$	$(0.90, 2.00)$	$!(m_{\pi^+\pi^-_{slow}} < 0.78 \| \| m_{\pi^+\pi^-_{fast}} < 0.78)$	$(0, \frac{\pi}{2})$
8	$(1.35, 5.40)$	$(0.90, 2.00)$	$!(m_{\pi^+\pi^-_{slow}} < 0.78 \| \| m_{\pi^+\pi^-_{fast}} < 0.78)$	$(\frac{\pi}{2}, \pi)$
9	$(1.35, 5.40)$	$(2.00, 4.00)$	$(m_{\pi^+\pi^-_{slow}} < 0.78 \| \| m_{\pi^+\pi^-_{fast}} < 0.78)$	$(0, \frac{\pi}{2})$
10	$(1.35, 5.40)$	$(2.00, 4.00)$	$(m_{\pi^+\pi^-_{slow}} < 0.78 \| \| m_{\pi^+\pi^-_{fast}} < 0.78)$	$(\frac{\pi}{2}, \pi)$
11	$(1.35, 5.40)$	$(2.00, 4.00)$	$!(m_{\pi^+\pi^-_{slow}} < 0.78 \| \| m_{\pi^+\pi^-_{fast}} < 0.78)$	$(0, \frac{\pi}{2})$
12	$(1.35, 5.40)$	$(2.00, 4.00)$	$!(m_{\pi^+\pi^-_{slow}} < 0.78 \| \| m_{\pi^+\pi^-_{fast}} < 0.78)$	$(\frac{\pi}{2}, \pi)$
Scheme B Region				
i	$(i = 1, 2, ..., 10)$			$(\frac{i-1}{10}\pi, \frac{i}{10}\pi)$