CP violation in B decays at LHCb

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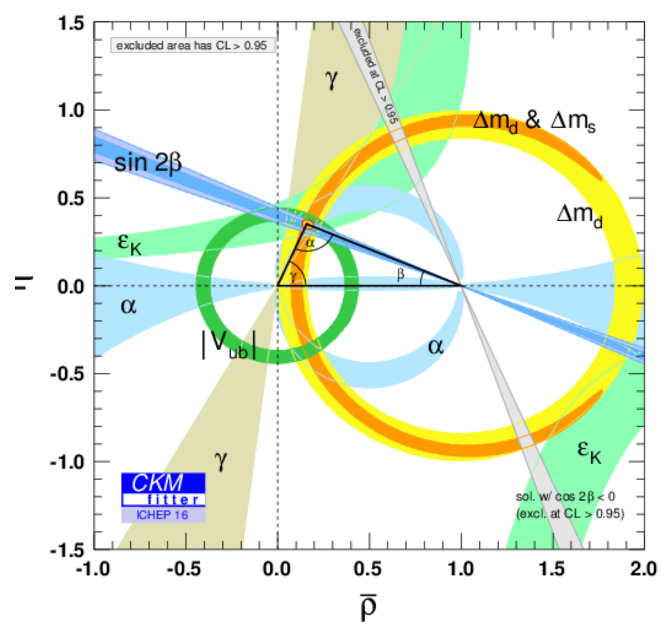
(On behalf of the LHCb Collaboration)



HFCPV-2018, 河南郑州, 2018年10月26-29日

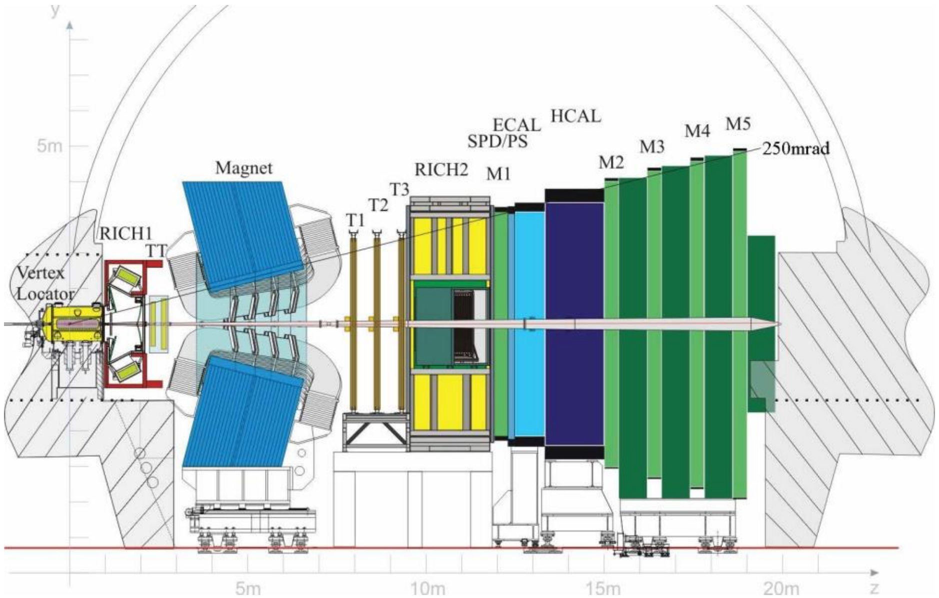
Outline

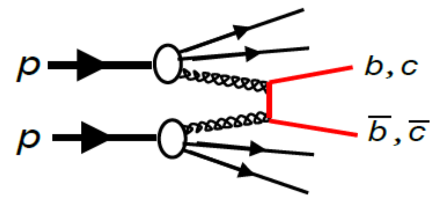
- Introduction to LHCb
- CKM unitarity test
- CPV in neutral B mixing
- Mixing-induced CPV in B_s decays
- Direct CPV in Λ_b decays
- Summary and outlook

Introduction to LHCb

LHCb experiment

Designed to study heavy flavor physics: ~~CP~~ and rare decays



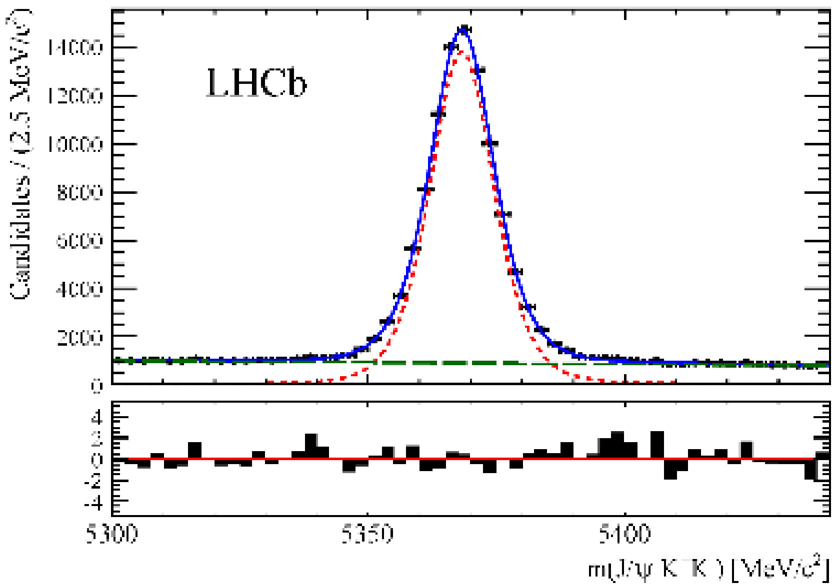


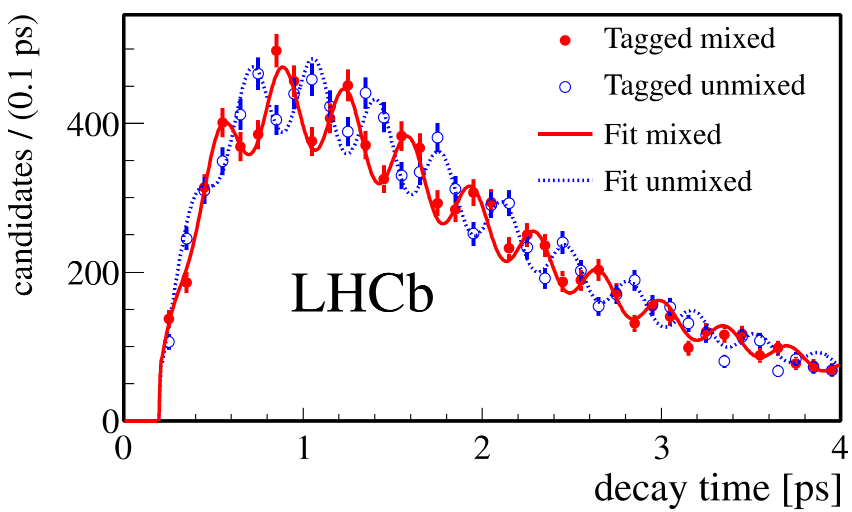
- **Large $b\bar{b}$ cross section**
  $\sigma(b\bar{b}) \sim$ **1% of pp X-section**
- **All b hadrons produced**
  $B^0,\ B_s^0, B^{\pm}, B_c^{+}, \Lambda_b^0, \ldots$

Unique opportunities for CPV study

- **Particularly CPV in B_s and Λ_b decays, γ measurement**

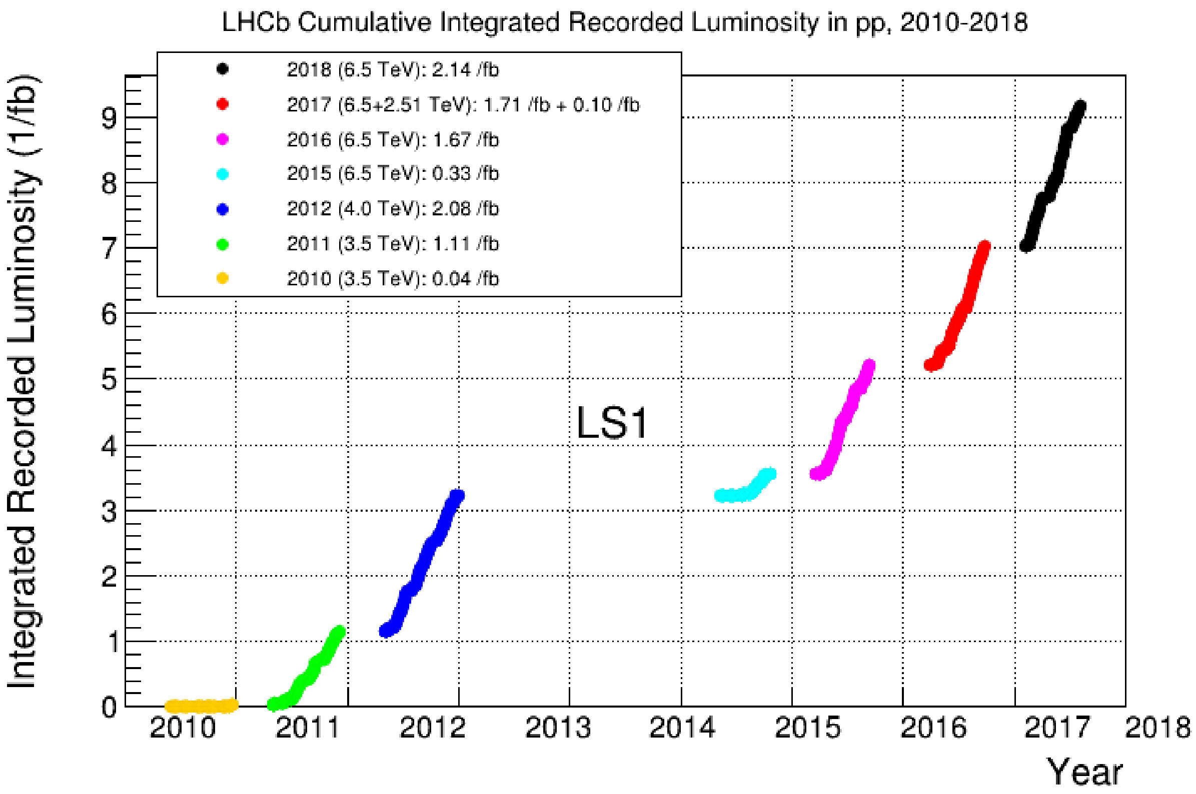
Detector performance





- Excellent mass resolution
- Excellent PID to suppress background
- Decay time resolution:
  $\sigma_t \sim 45$ fs
  for resolving fast B_s oscillation
- Flavour tagging power:
  $\epsilon\omega^2 \sim 3 - 4\%$

LHCb running (pp collisions)



- **9 fb^{-1} have been accumulated**
  - ✓ **Most results are based on 3 fb^{-1} (Run 1), a few on 5 fb^{-1}**
- **Gain factor of 5 wrt run 1, considering σ_{bb} increase**
  - ✓ **Look forward to exciting new results**

CKM unitarity test

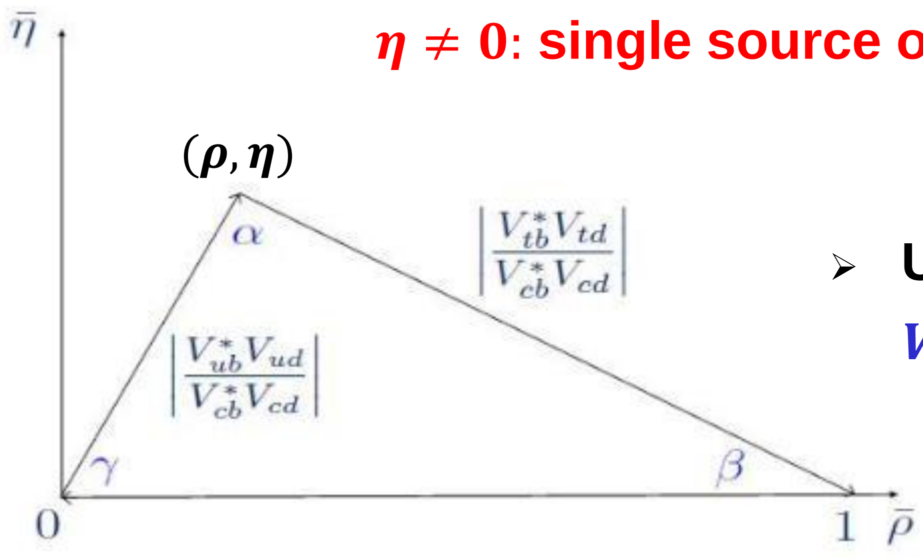
CKM matrix

- **CKM matrix describes change of quark flavor**
- **Each element related to a transition probability, $|V_{ij}|^2$**

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

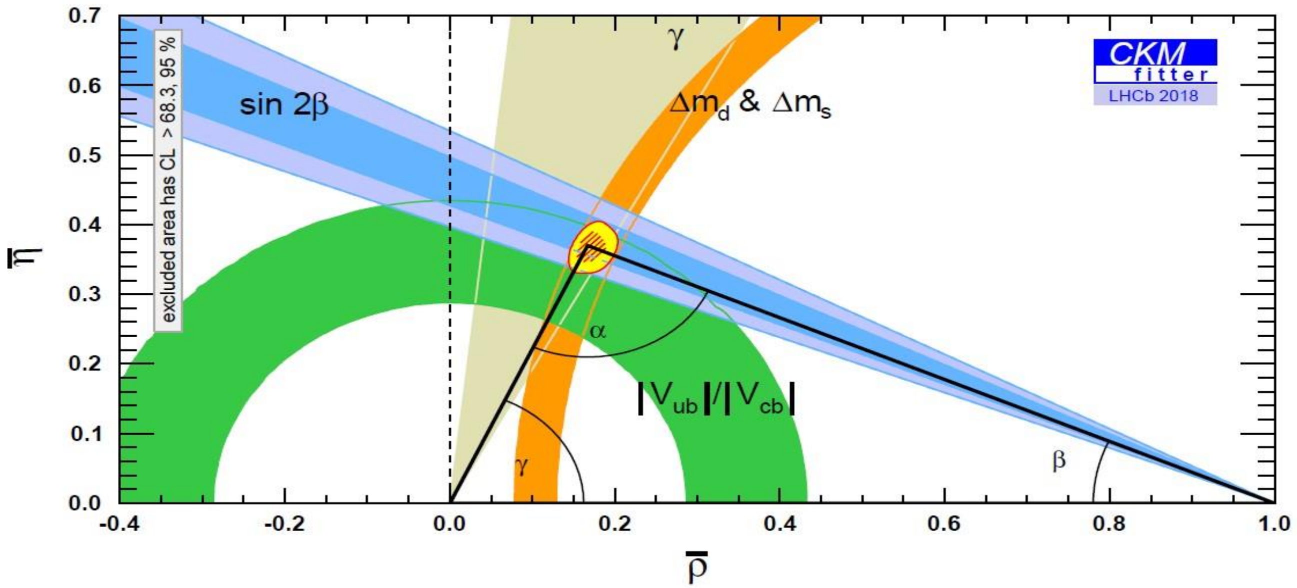
$\eta \neq 0$: single source of CPV in SM



- **Unitarity triangle**

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 1$$

CKM global fit



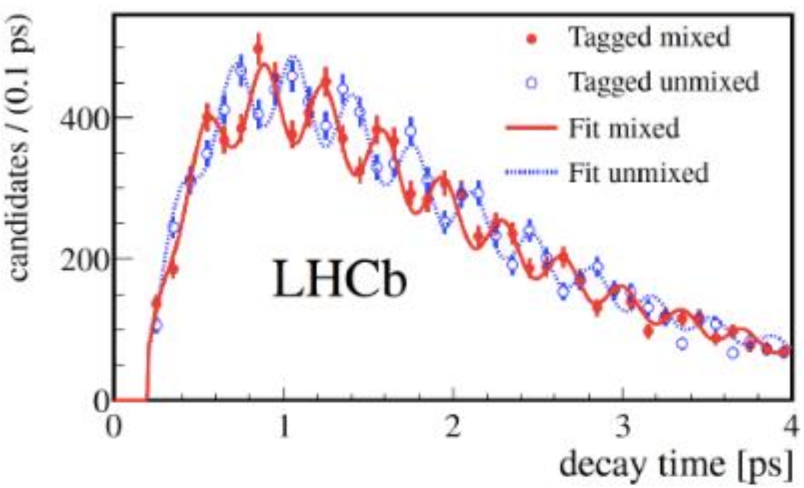
- **Inputs:** **measurements of all sides and angles $(\beta, \gamma, \alpha, |V_{ub}|/|V_{cb}|, \Delta \mathrm{m}_{\mathrm{s/d}})$ in different ways**
- **Outputs:** A, λ, ρ, η
- **Good consistency is seen between inputs**
- **LHCb contributes to all input measurements, and starts to dominate β, γ and $\Delta \mathrm{m}_{\mathrm{s/d}}$**

Δm_d and Δm_s measurments

- Completely dominated by LHCb

$B_s \to D_s^- \pi^+$

New J.Phys. 15 (2015) 053201 Run I, 1 fb^{-1}



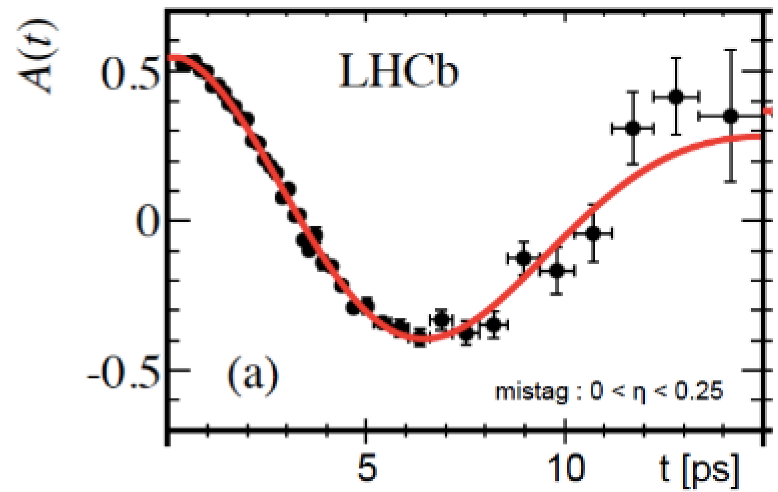
$\Delta m_s = 17.768 \pm 0.023 \pm 0.006$ ps^{-1}

WA: $\Delta m_s = 17.757 \pm 0.021$ ps^{-1}

SM: $\Delta m_s = 16.3 \pm 1.1$ ps^{-1}

$B^0 \to D^{(*)-} \mu^+ \nu$

EPJC 76 (2016) 412 Run 1, 3 fb^{-1}



$\Delta m_d = 0.5050 \pm 0.0021 \pm 0.0010$ ps^{-1}

WA: $\Delta m_d = 0.5065 \pm 0.0019$ ps^{-1}

SM: $\Delta m_d = 0.566^{+0.035}_{-0.043}$ ps^{-1}

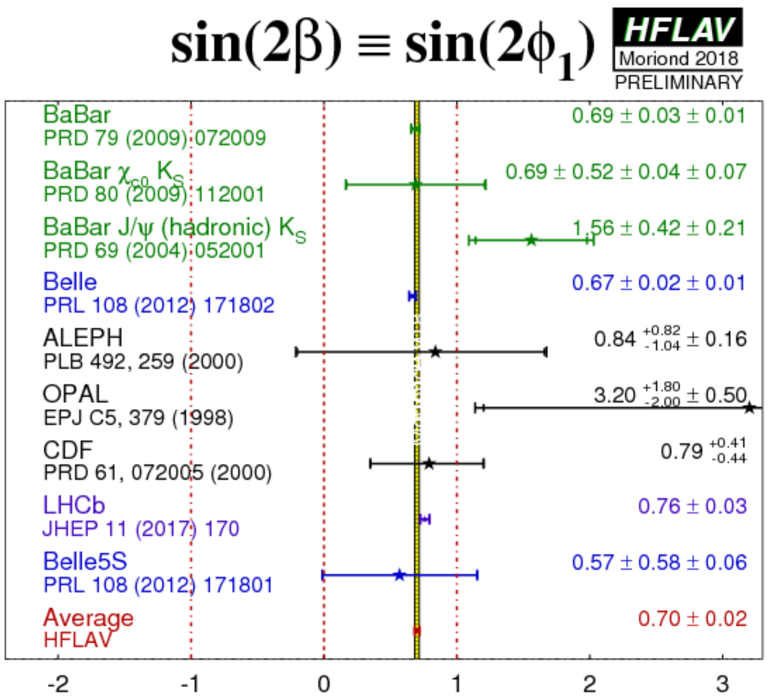
Limited by hadronic uncertainties in SM predictions

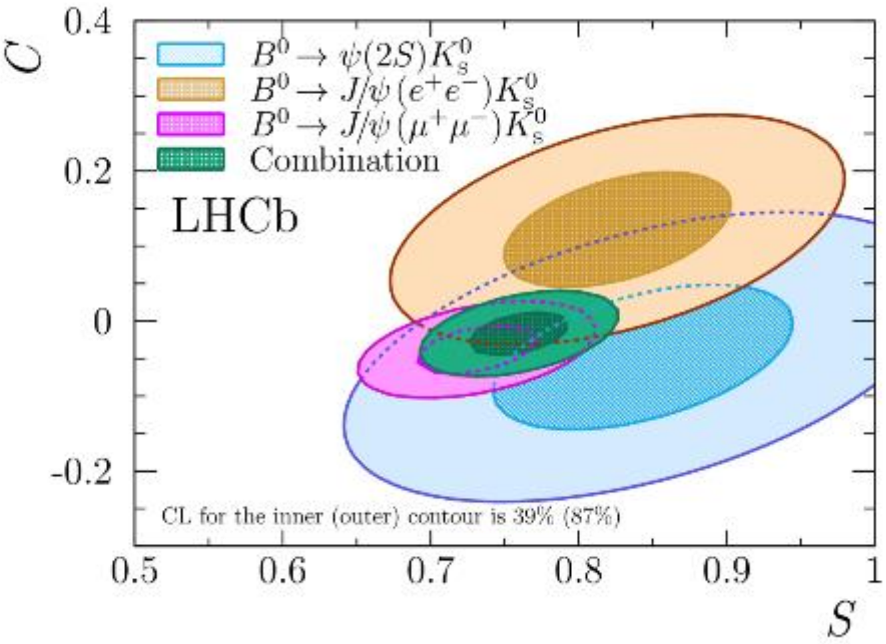
$\sin 2\beta$ measurement

- **LHCb $b \to c\bar{c}s$ channels: $\sin 2\beta = 0.760 \pm 0.034$**

World average: $\sin 2\beta = 0.70 \pm 0.02$

Indirect determination: $\sin 2\beta = 0.740^{+0.020}_{-0.025}$





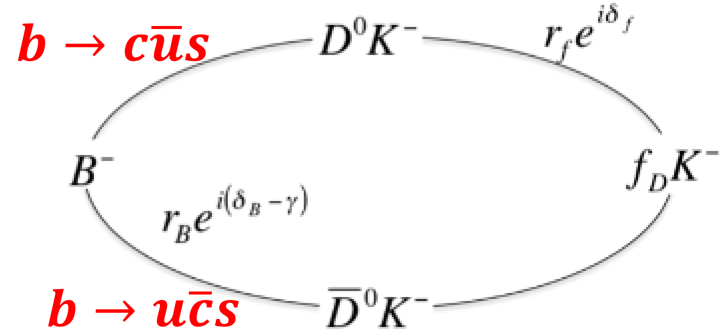
JHEP 11 (2017) 170 Run I, 3 fb^{-1}

Large improvement from run 2 data expected

γ measurement

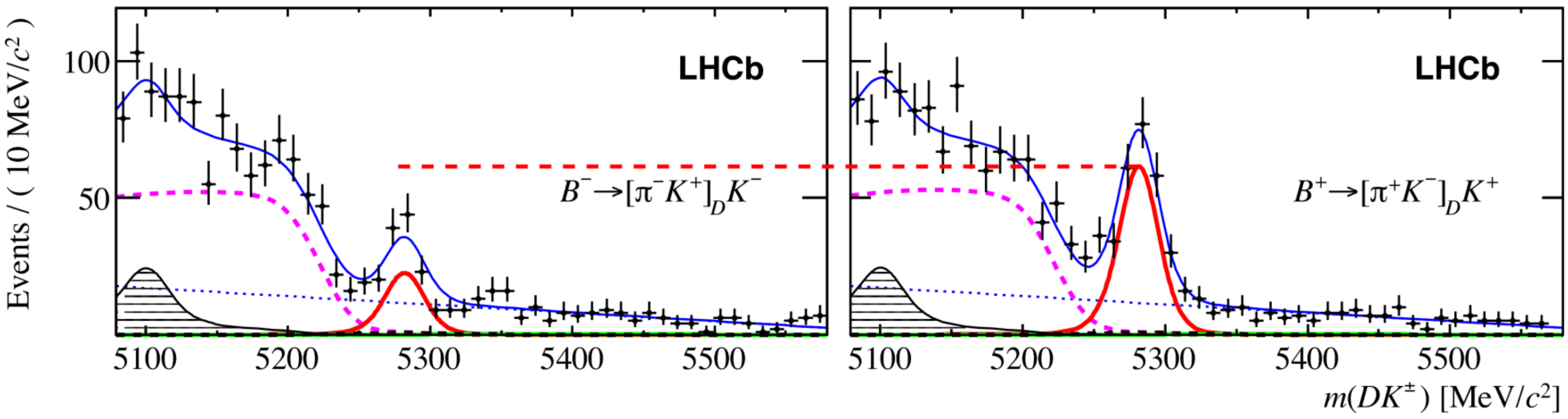
- **Exploit interference of $b \to c\bar{u}s$ and $b \to u\bar{c}s$ amplitudes**

Large CPV if r_f is small
(e.g. with suppressed $D^0 \to K^+\pi^-$)



- **γ can be estimated from CPV**

$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B(2F_+ - 1)\sin(\delta_B)\sin(\gamma)$$

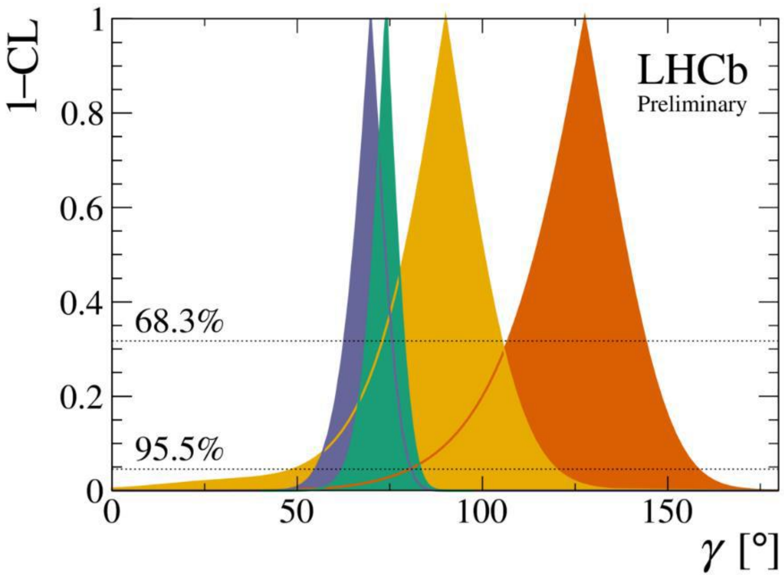


PLB 760 (2016) 117 Run I, 3 fb^{-1}

γ measurements @ LHCb

- **Three measurement methods: GLW/ADS, GGSZ, TD**
- **Combine 16 measurements to obtain average**

LHCb-CONF-2018-002   Run I+II, 3-5 fb^{-1}



$B^{\pm}$ **ALL** B^0 B_s

$B^+ \to DK^+$	$D \to h^+h^-$	GLW	Run 1 & 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	Run 1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	Run 1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	Run 1
$B^+ \to DK^+$	$D \to K_S^0 h^+h^-$	GGSZ	Run 1
$B^+ \to DK^+$	$D \to K_S^0 h^+h^-$	GGSZ	Run 2
$B^+ \to DK^+$	$D \to K_S^0 K^+\pi^-$	GLS	Run 1
$B^+ \to D^* K^+$	$D \to h^+h^-$	GLW	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	Run 1 & 2
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	Run 1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	Run 1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	Run 1
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	GGSZ	Run 1
$B_s^0 \to D_s^{\mp} K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	Run 1
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	Run 1

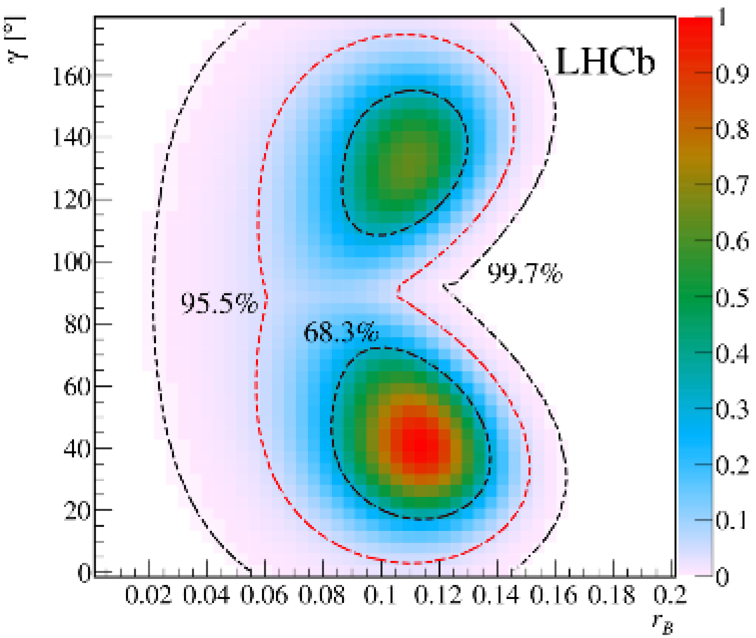
γ: first $B^+ \to DK^{*+}$ (ADS/GLW)

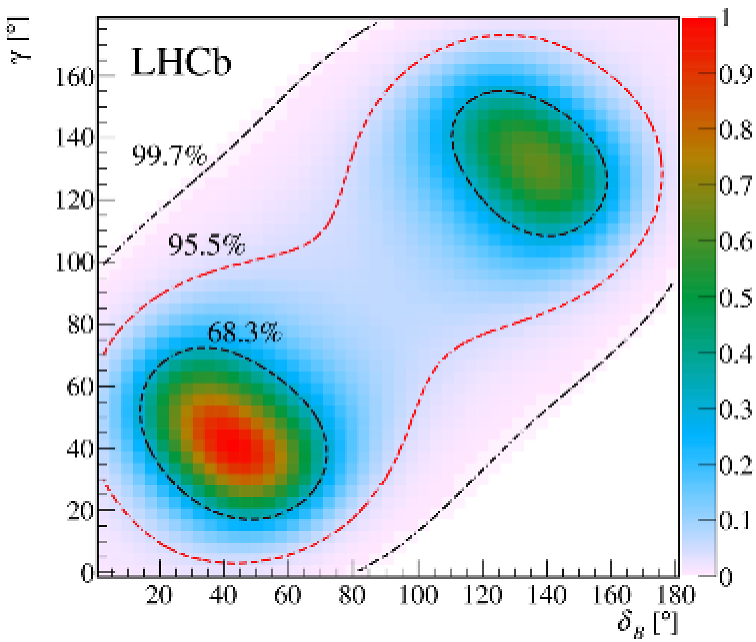
- **Combine D^0 decays to $K\pi, KK, \pi\pi, K3\pi, 4\pi$**
- **Determine γ from CPV of total decay rates**

$$\Gamma(B^- \to DK^-) \propto r_D^2 + r_B^2 + 2\, r_D\, r_B \cos(\delta_B + \delta_D - \gamma)$$

$$\Gamma(B^+ \to DK^+) \propto r_D^2 + r_B^2 + 2\, r_D\, r_B \cos(\delta_B + \delta_D + \gamma)$$

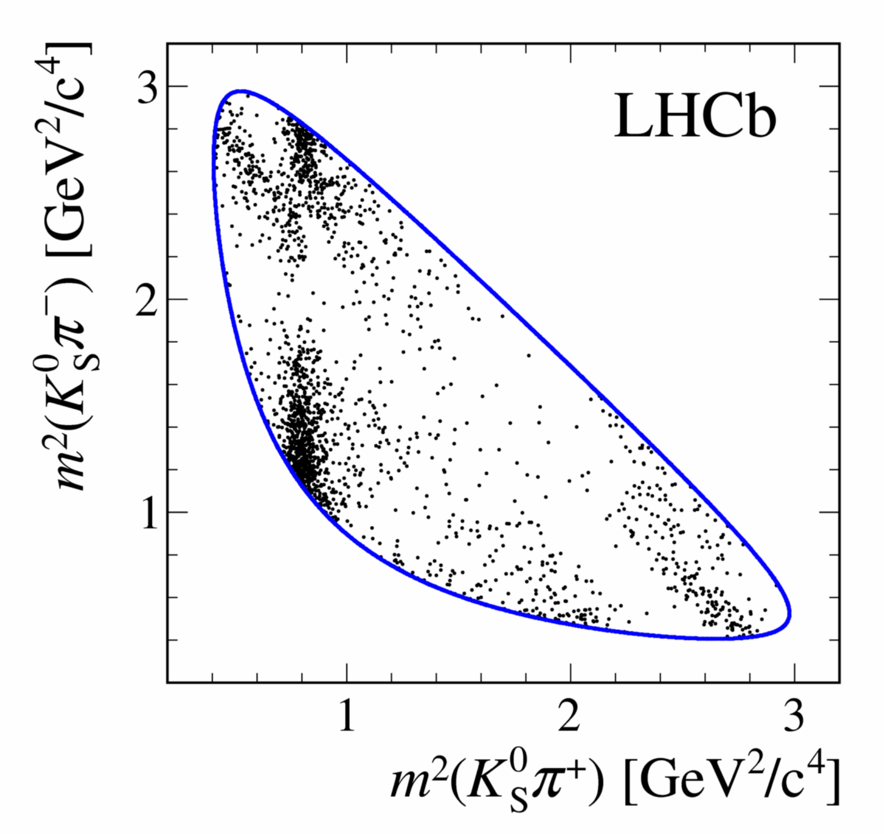
JHEP 11 (2017) 156 Run I+II, 5 fb^{-1}





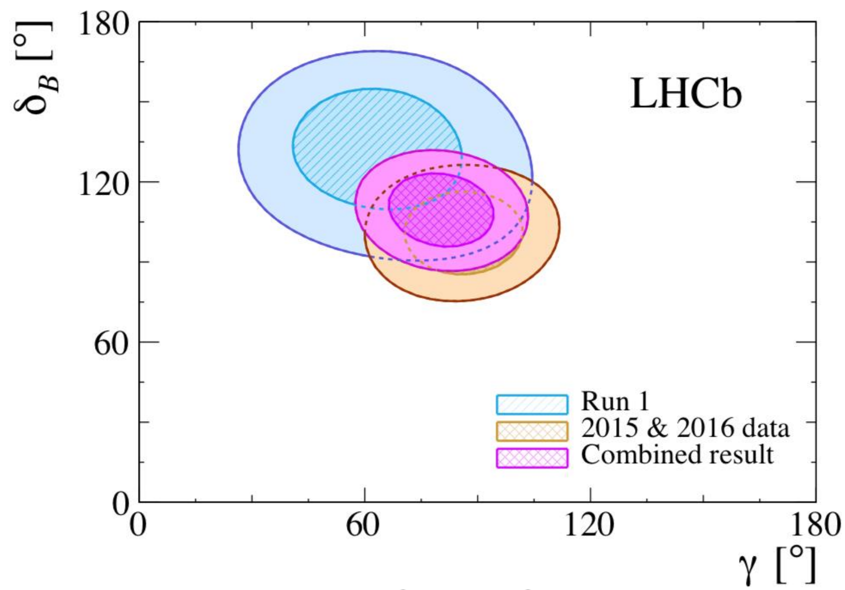
γ: $B^{\pm} \to DK^{\pm}$ (GGSZ)

- Determine γ from local CPV in the Dalitz plot of $D^0 \to K_S\pi^+\pi^-$



$$A_{B^+} \propto \overline{A}_f + r_B e^{i(\delta_B+\gamma)} A_f$$

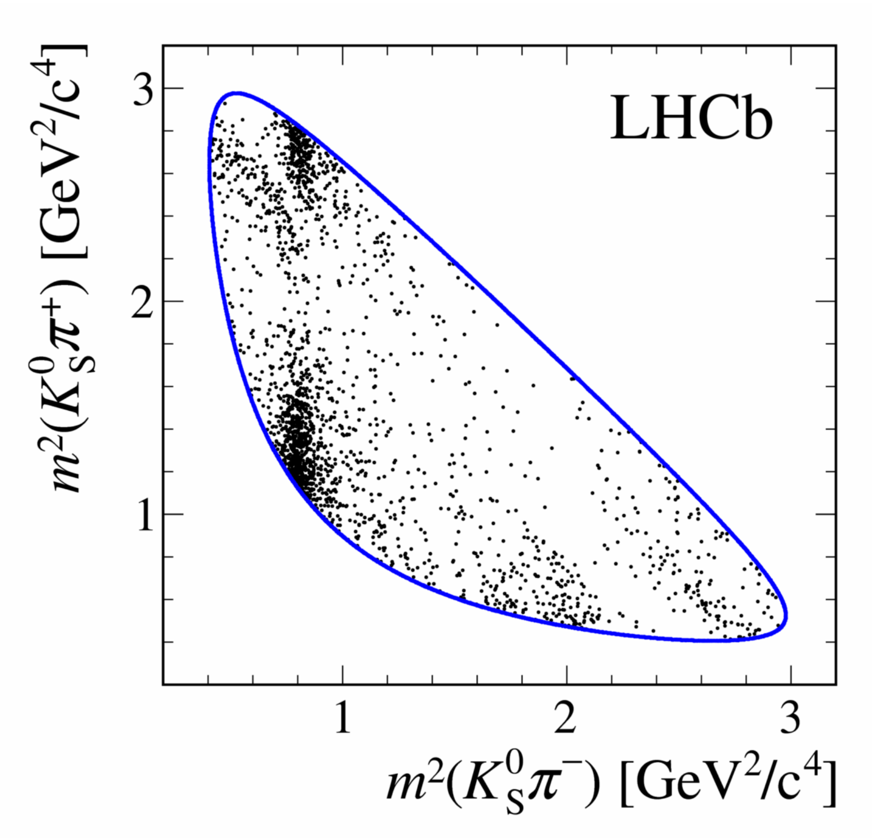
arXiv:1806.01202 Run I+II, 5 fb^{-1}



$$\gamma = 80^\circ\,{}^{+10^\circ}_{-9^\circ}\,\left({}^{+19^\circ}_{-18^\circ}\right),$$
$$r_B = 0.080\,{}^{+0.011}_{-0.011}\,\left({}^{+0.022}_{-0.023}\right),$$
$$\delta_B = 110^\circ\,{}^{+10^\circ}_{-10^\circ}\,\left({}^{+19^\circ}_{-20^\circ}\right).$$

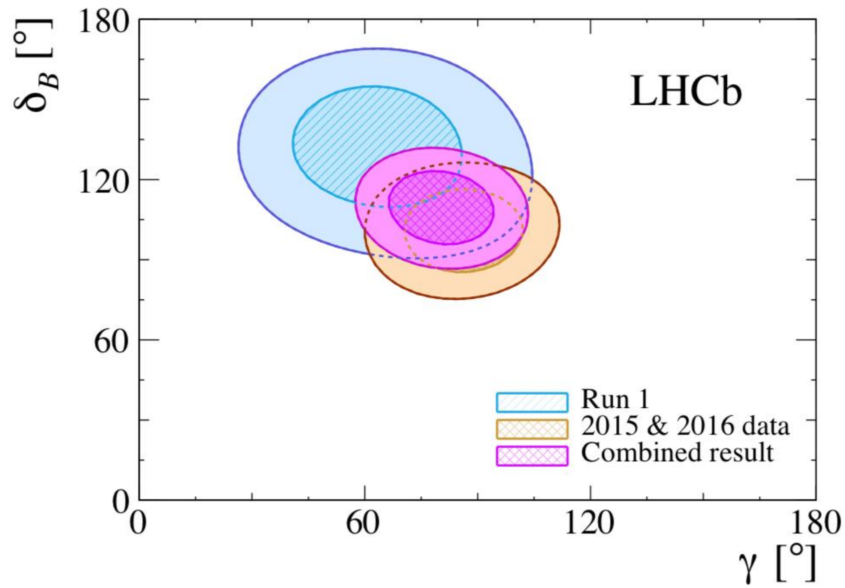
γ: $B^{\pm} \to DK^{\pm}$ (GGSZ)

- **Determine γ from local CPV in the Dalitz plot of $D^0 \to K_S\pi^+\pi^-$**



$$A_{B^-} \propto A_f + r_B e^{i(\delta_B - \gamma)} \overline{A}_f$$

arXiv:1806.01202 Run I+II, 5 fb^{-1}



$$\gamma = 80^\circ\,{}^{+10^\circ}_{-9^\circ}\,\left({}^{+19^\circ}_{-18^\circ}\right),$$
$$r_B = 0.080\,{}^{+0.011}_{-0.011}\,\left({}^{+0.022}_{-0.023}\right),$$
$$\delta_B = 110^\circ\,{}^{+10^\circ}_{-10^\circ}\,\left({}^{+19^\circ}_{-20^\circ}\right).$$

γ: $B^0 \to D^{\mp}\pi^{\pm}$ (time-dependent)

- **Time dependent rates**

$$\Gamma_{B^0\to f}(t) \propto e^{-\Gamma t}[1 + C_f \cos(\Delta m t) - S_f \sin(\Delta m t)]$$

$$\Gamma_{B^0\to \bar{f}}(t) \propto e^{-\Gamma t}[1 + C_{\bar{f}} \cos(\Delta m t) - S_{\bar{f}} \sin(\Delta m t)]$$

$$C_f = -C_{\bar{f}} = \frac{1-r_{D\pi}^2}{1+r_{D\pi}^2}$$

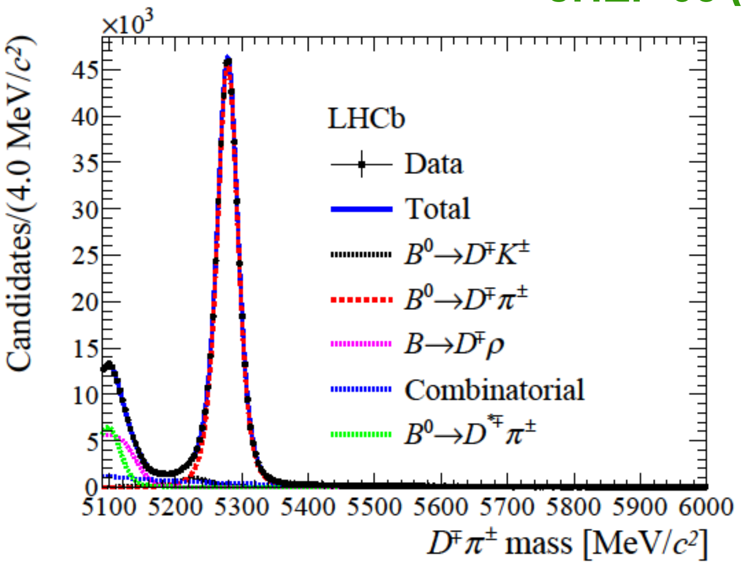
$$S_f = \frac{2r_{D\pi}\sin[\delta - (2\beta+\gamma)]}{1+r_{D\pi}^2}$$

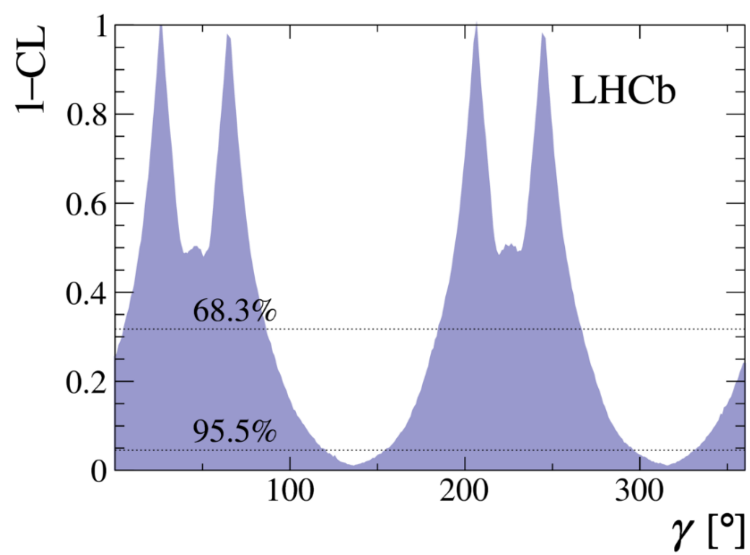
$$S_{\bar{f}} = \frac{2r_{D\pi}\sin[\delta + (2\beta+\gamma)]}{1+r_{D\pi}^2}$$

- **Huge tagged sample (500k)**

$$\gamma \in [5, 86]^{\circ} \cup [185, 266]^{\circ}$$

JHEP 06 (2018) 084 Run I, 3 fb^{-1}





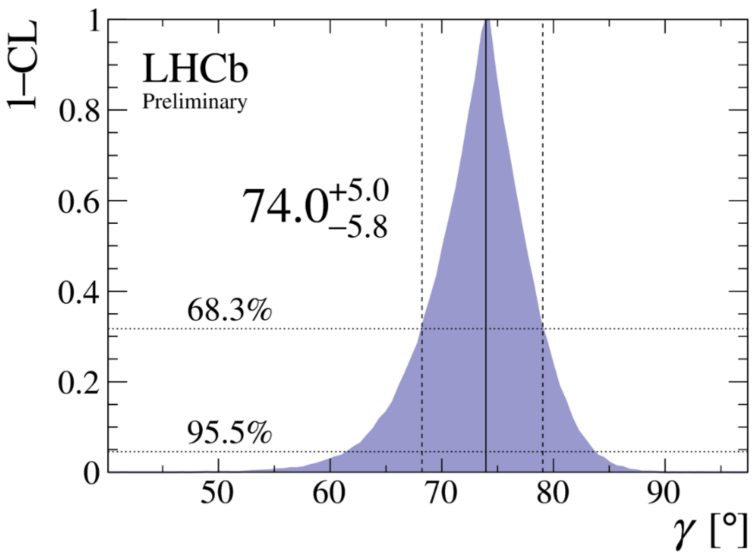
TD measurement helps resolve ambiguities

γ average

- **LHCb combination**

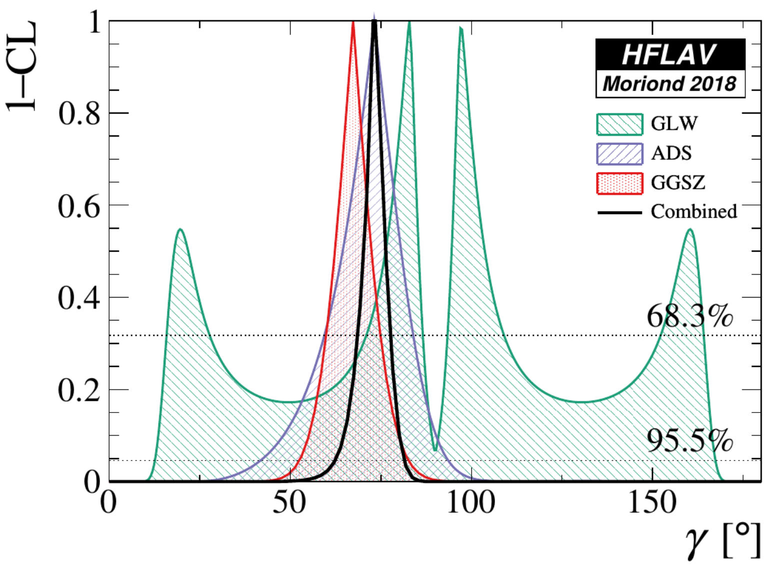
$$\gamma = \left(74.0^{+5.0}_{-5.8}\right)^{\circ}$$

LHCb-CONF-2018-002 Run I+II, 3-5 fb^{-1}



- **World average**

$$\gamma = \left(73.5^{+4.2}_{-5.1}\right)^{\circ}$$



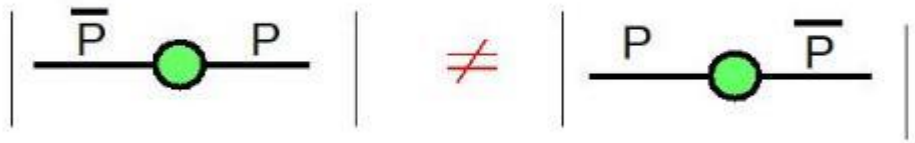
- **Consistent with indirect determination:** $\gamma = \left(65.3^{+1.0}_{-2.5}\right)^{\circ}$

Expect $\sigma_\gamma < 3^{\circ}$ with LHCb run 2 sample

CPV in neutral B mixing

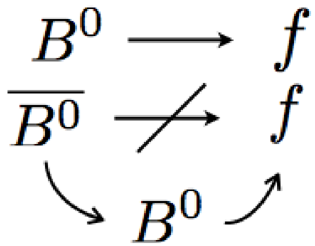
CPV in neutral B mixing

Indirect CPV



- **Flavor-specific decays $B \to f$ provide clean measurements of CPV in B mixing**

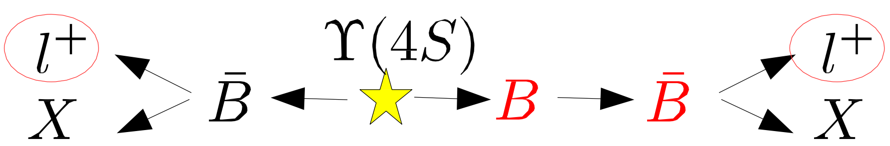
$$a_{\rm sl} = \frac{N(\bar{B}\to B \to f) - N(B\to\bar{B} \to \bar{f})}{N(\bar{B}\to B \to f) + N(B\to\bar{B} \to \bar{f})}$$



- **B-factory: same-sign dilepton asymmetry at $\Upsilon(4S)$**

$$A_{CP} = \frac{\mathcal{P}_{ll}^{++} - \mathcal{P}_{ll}^{--}}{\mathcal{P}_{ll}^{++} + \mathcal{P}_{ll}^{--}}$$

$$ll = \{ee, \mu\mu, e\mu, \mu e\}$$



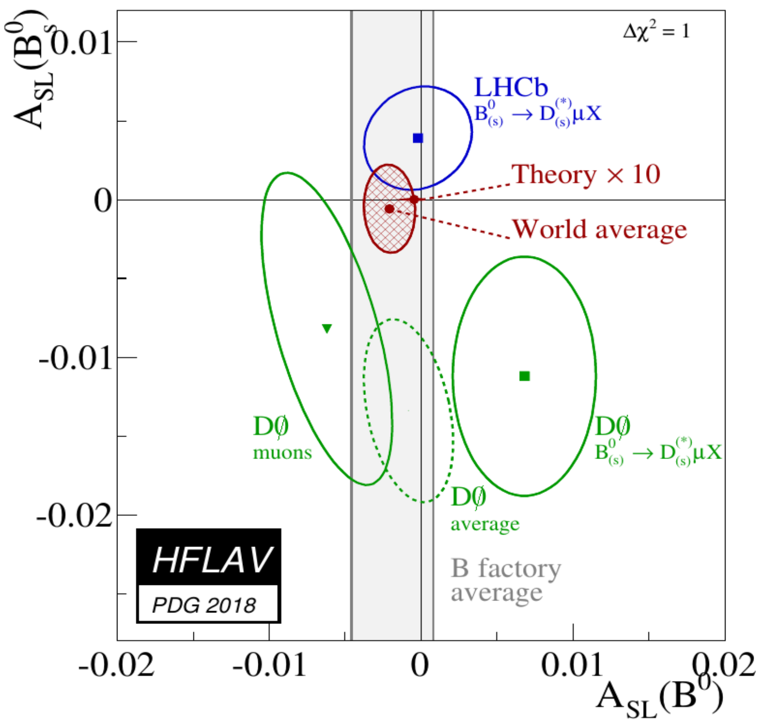
Babar $a_{sl}^{d} = A_{CP} = (-0.39 \pm 0.35 \pm 0.15)\%$ PRL 114 (2015) 081801

HFLAV $a_{sl}^{d} = A_{CP} = (-0.29 \pm 0.27)\%$

LHCb measurements of $a_{sl}^{s/d}$

- **Time integrated semi-leptonic asymmetry**

$$A_{raw} = \frac{N(D_{(s)}^{-}\mu^{+}) - N(D_{(s)}^{+}\mu^{-})}{N(D_{(s)}^{-}\mu^{+}) + N(D_{(s)}^{+}\mu^{-})} = \frac{a_{sl}^{s/d}}{2}$$



$B_s \to D_s^- \mu^+ \bar{\nu}$:

$a_{sl}^{s} = (0.39 \pm 0.26 \pm 0.20)\%$

PRL 117 (2016) 061803

$B_d \to D^{(*)-} \mu^+ \bar{\nu}$:

$a_{sl}^{d} = (-0.02 \pm 0.19 \pm 0.30\,)\%$

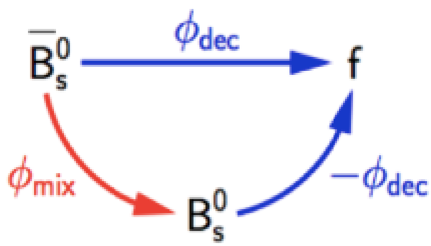
PRL 114 (2014) 041601

No significant CPV in mixing, compatible with SM predictions

Mixing-induced CPV in B_s decays

ϕ_s: LHCb benchmark measurement

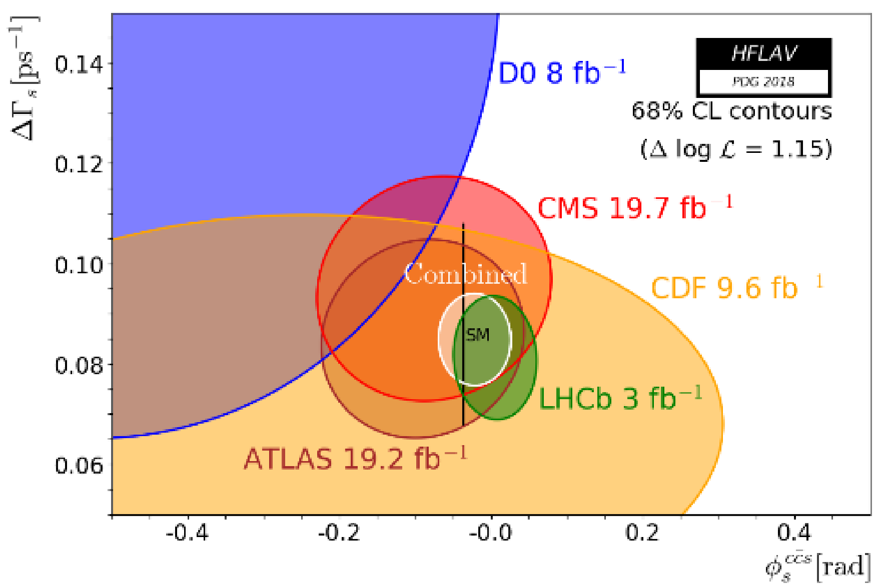
$\phi_s \equiv \phi_{mix} - 2\phi_{dec}$



- LHCb run 1 results in $b \to c\bar{c}s$ decays

  $B_s \to J/\psi\phi$ and $B_s \to J/\psi\pi^+\pi^-$ PRL 114 (2015) 041801

  $B_s \to J/\psi K^+K^-$ above $\phi(1020)$ JHEP 08 (2017) 037



- LHCb combination

  $\phi_s = 0.001 \pm 0.037$ rad

- World average

  $\phi_s = -0.021 \pm 0.031$ rad

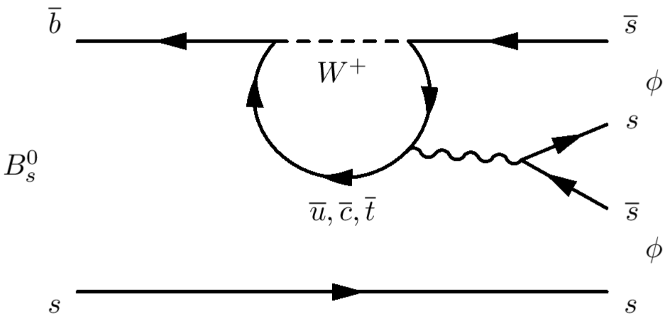
- SM prediction:

  $\phi_s^{SM} = -0.038 \pm 0.001$ rad

- Analysis of 2015+2016 data ongoing

Factor of 2 improvement expected with run 2 sample

CPV in $b \to s$ decays



- **FCNC loop decays sensitive to NP not only in mixing but also in decay**

- $B_s \to \phi\phi$: $b \to s\bar{s}s$ **penguin decay**

  Update with 2015+2016 data **LHCb-CONF-2018-001**

  $\phi_s^{s\bar{s}s} = -0.06 \pm 0.13 \pm 0.03$ rad

  Direct CPV $|\lambda| = 1.02 \pm 0.05 \pm 0.03$

- $B_s \to K^{*0}(K^+\pi^-)\bar{K}^{*0}(K^-\pi^+)$: $b \to s\bar{d}d$ **penguin decay**

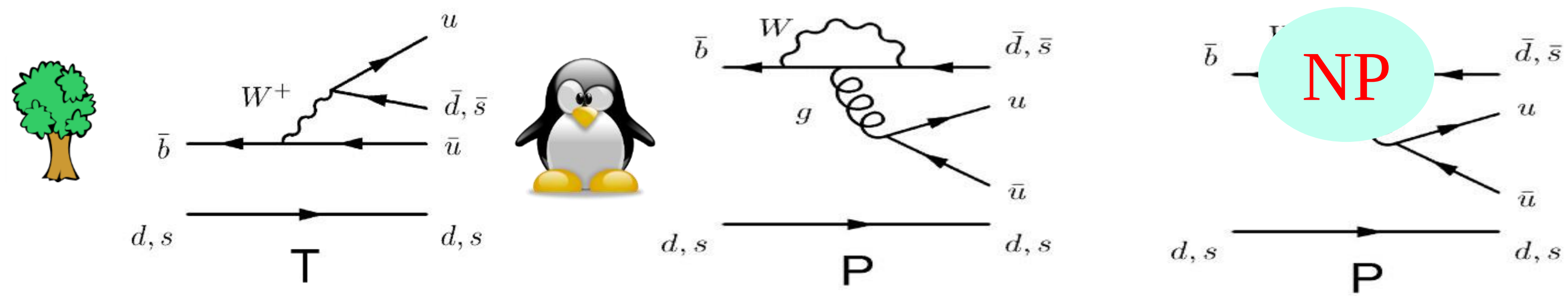
  First measurement with run 1 **JHEP 03 (2018) 140**

  $\phi_s^{s\bar{d}d} = -0.10 \pm 0.13 \pm 0.14$ rad

  Direct CPV $|\lambda| = 1.035 \pm 0.034 \pm 0.089$

Both consistent with no CPV and SM predictions

CPV in $B \to hh'$



- **Presence of penguin diagrams ⇒ sensitivity to New Physics**

arXiv:1805.16759 Update with full run I

$B^0 \to \pi^+\pi^-$

$$C_{\pi^+\pi^-} = -0.34 \pm 0.06,$$
$$S_{\pi^+\pi^-} = -0.63 \pm 0.05,$$

$B_s^0 \to K^+K^-$

$$C_{K^+K^-} = 0.20 \pm 0.06,$$
$$S_{K^+K^-} = 0.18 \pm 0.06,$$
$$A^{\Delta\Gamma}_{K^+K^-} = -0.79 \pm 0.07,$$

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

$$A_{CP}(B^0 \to K^+\pi^-) = -0.084 \pm 0.004,$$

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

$$A_{CP}(B_s^0 \to \pi^+K^-) = 0.213 \pm 0.015,$$

Most precise measurements from a single experiment.

$(C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-})$ deviates **4.0 σ** from $(0, 0, -1)$

$\Longrightarrow$ Strongest evidence for time-dependent CP violation in the B_s^0 sector!

Could be turned into constraints on ϕ_s and γ

Direct CPV in Λ_b decays

Evidence of CPV in $\Lambda_b \to p\pi^-\pi^+\pi^-$

- Measure $a_{P/CP}^{T-odd} = (A_T \pm \overline{A}_T)/2$ using triple product asymmetries

$$\Lambda_b^0 : \; C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \qquad A_{\hat{T}} \equiv \frac{N(C_{\hat{T}} > 0) - N(C_T < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

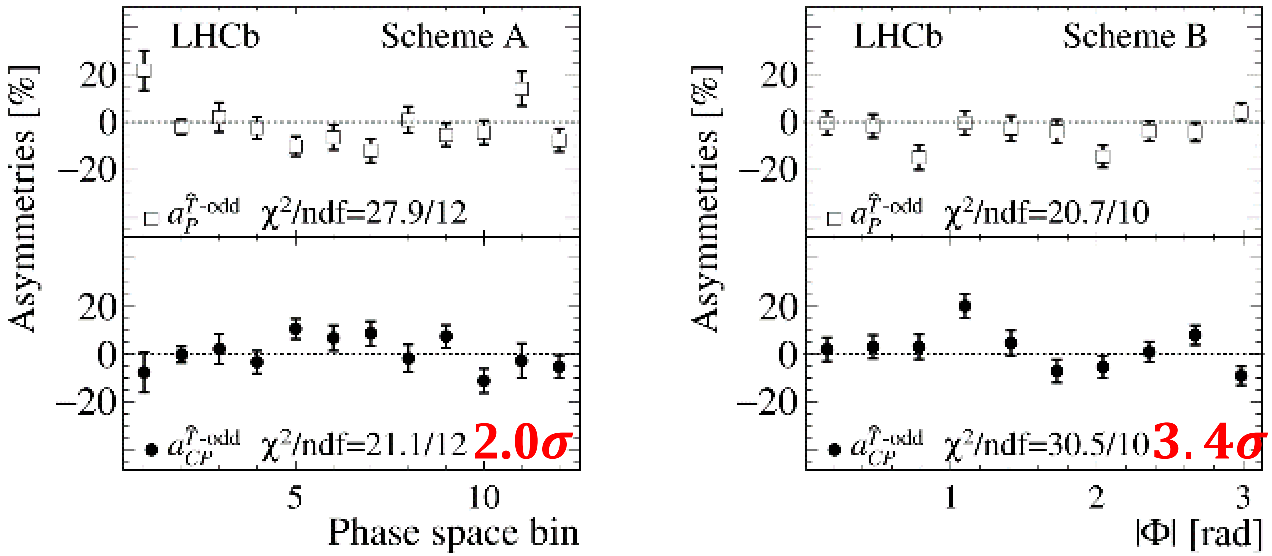
$$\bar{\Lambda}_b^0 : \; \bar{C}_{\hat{T}} \equiv \vec{p}_{\bar{p}} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \qquad \bar{A}_{\hat{T}} \equiv \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_T < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$$

- CPV ($a_{CP}^{T-odd} \neq 0$) at 3.3σ is found in localized asymmetries

Nature Physics 13 (2017) 39 Run I, 3 fb^{-1}

a_P^{T-odd}

a_{CP}^{T-odd}



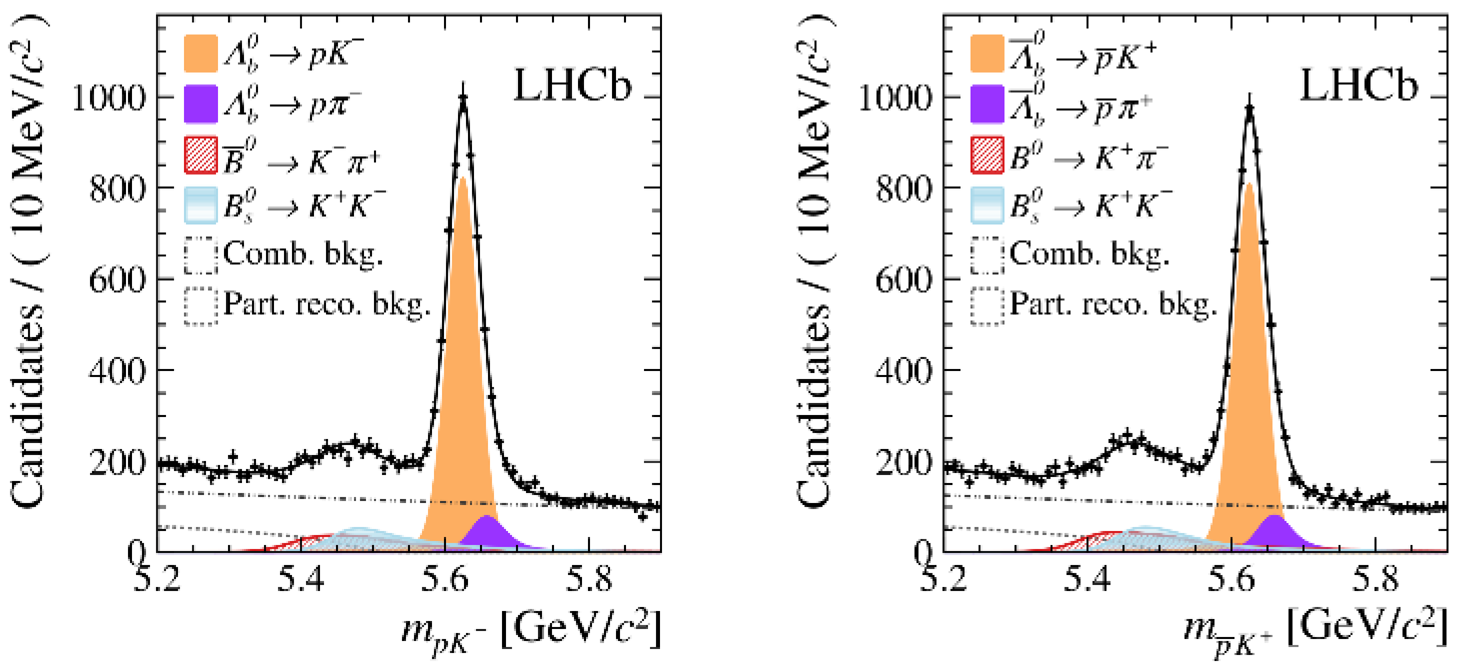
CPV in $\Lambda_b \to ph^-$ decays

- **Theory predicts ~30% asymmetries in $\Lambda_b \to p\pi^-$ and $\Lambda_b \to pK^-$**
- **CDF measurements consistent with no CPV** PRD 80 (2009) 034011

$$A_{CP}^{p\pi^-} = +0.06 \pm 0.07 \pm 0.03, A_{CP}^{pK^-} = -0.10 \pm 0.08 \pm 0.04$$

- **LHCb run1 results compatible with no CPV** arXiv:1807.06544

$$A_{CP}^{p\pi^-} = -0.035 \pm 0.017 \pm 0.020, A_{CP}^{pK^-} = -0.020 \pm 0.013 \pm 0.019$$



Summary and outlook

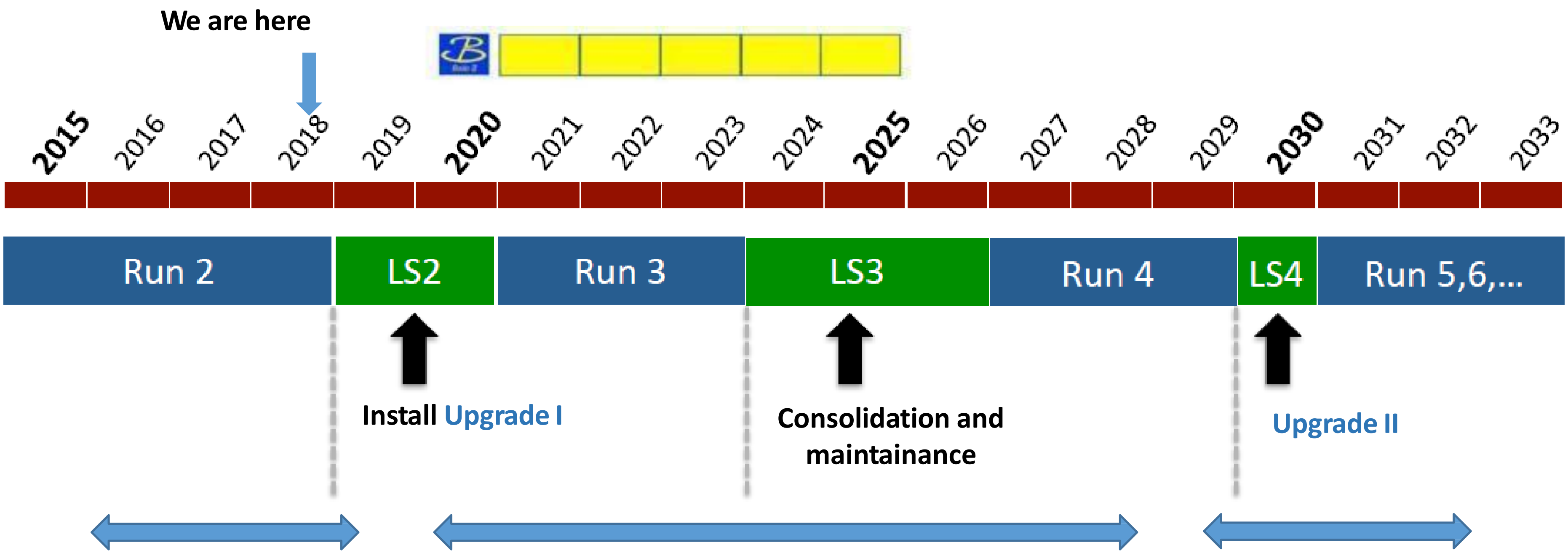
- **Run 1 data (3 fb^{-1}) have been carefully scrutinized**
  - ✓ **Large improvements in many measurements**
  - ✓ **No sign of deviation from SM in CPV sector so far**

- **LHCb run 2 is coming to an end soon, adding 6 fb^{-1}**
  - ✓ **Can reduce most measurement uncertainties by factor of 2 or more**

- **Future upgrades towards 300 fb^{-1}**
  - ✓ **Upgrade 1a: replacing major parts, $2 \times 10^{33} cm^{-2} s^{-1}$**
  - ✓ **Upgrade 1b: consolidation**
  - ✓ **Upgrade 2: new detector, $2 \times 10^{34} cm^{-2} s^{-1}$**

(Talk on LHCb upgrade by Zhengwei Yang on Sunday)

LHCb timeline



$\mathcal{L} = 4 \times 10^{32}\ cm^{-2}s^{-1}$

1.1 visible interactions / crossing

8 fb^{-1} collected

$\mathcal{L} = 2 \times 10^{33}\ cm^{-2}s^{-1}$

5.5 visible interactions / crossing

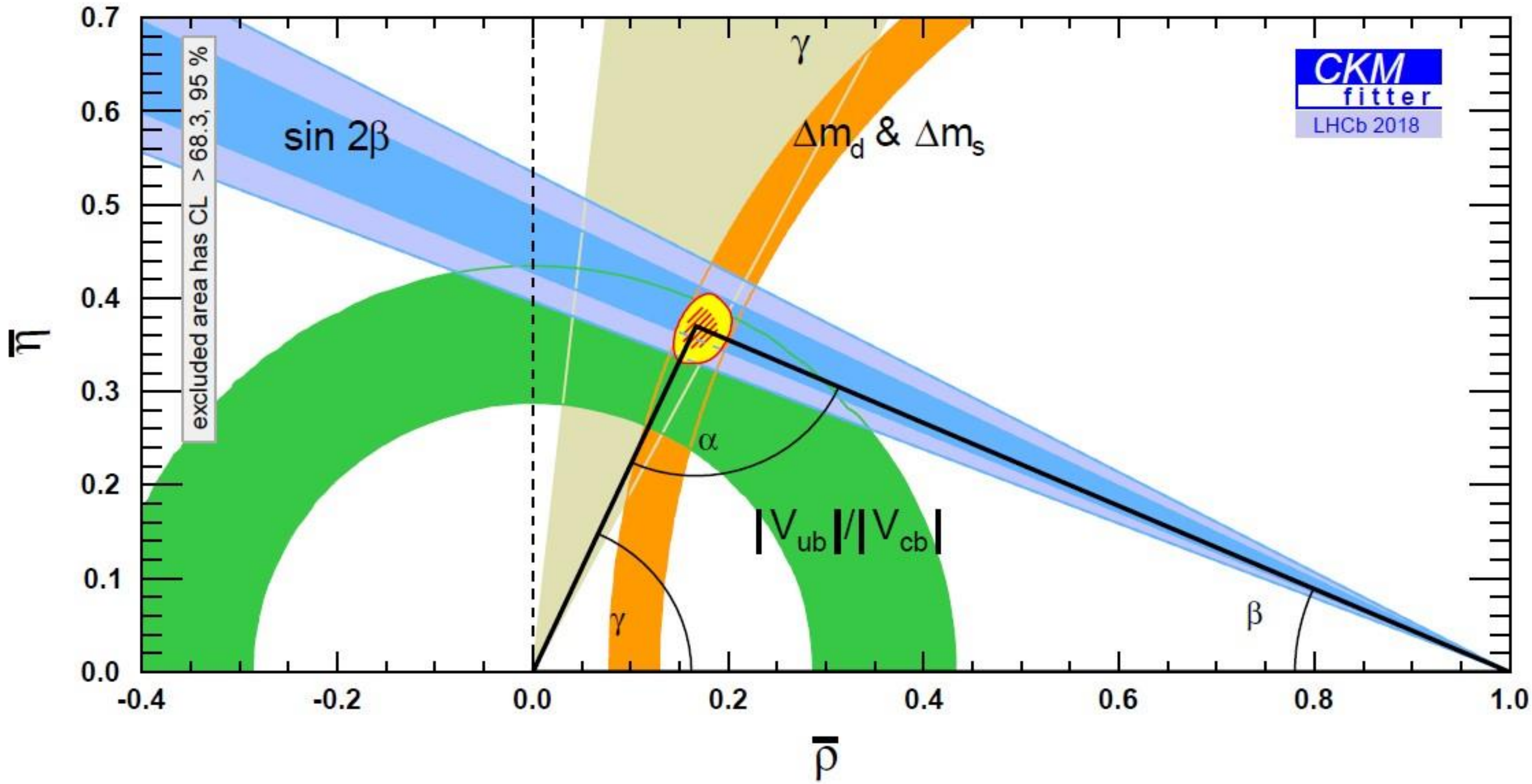
50 fb^{-1} collected

$\mathcal{L} = 2 \times 10^{34}\ cm^{-2}s^{-1}$

55 visible interactions / crossing

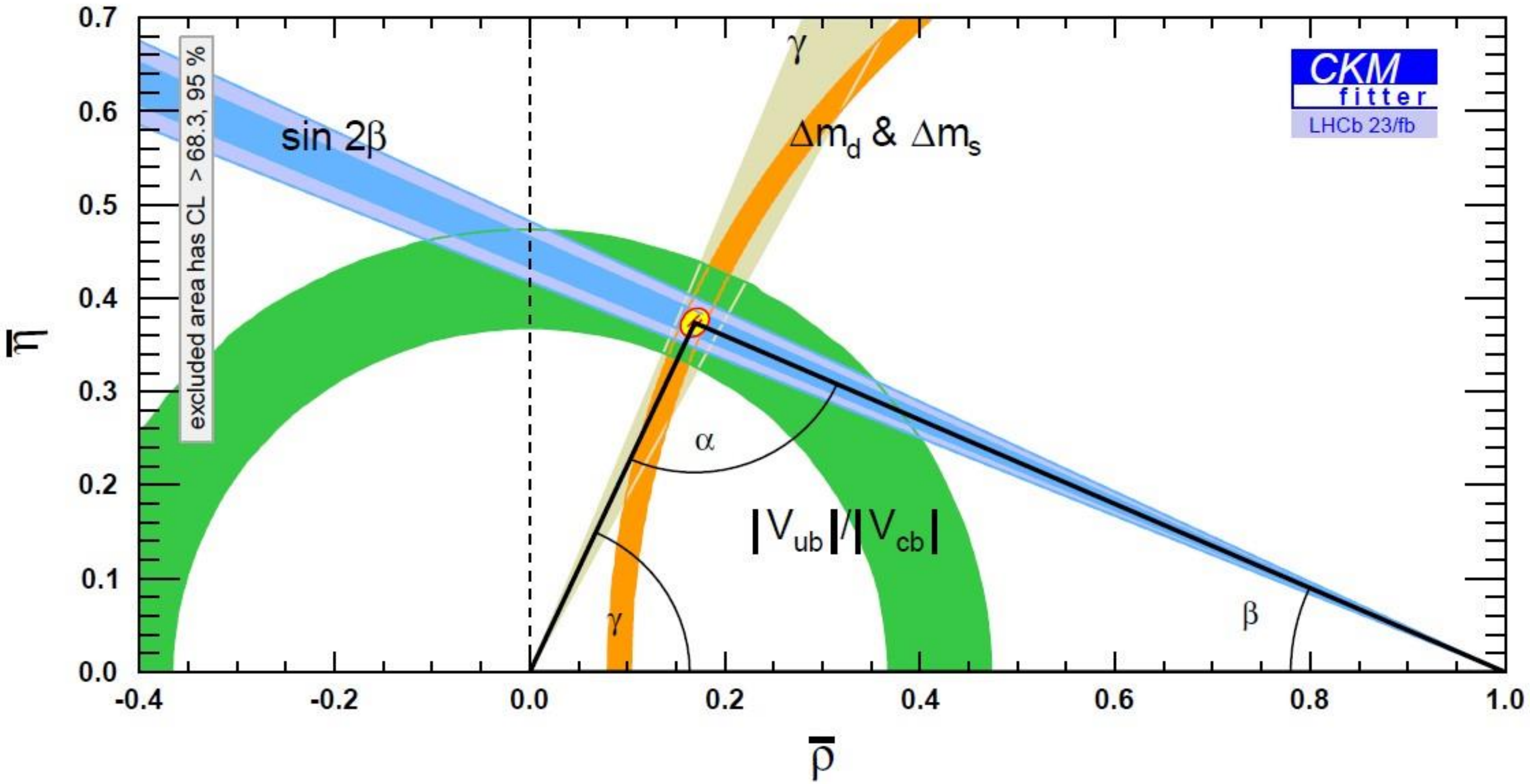
300 fb^{-1} collected

Evolution of the UT: current precision



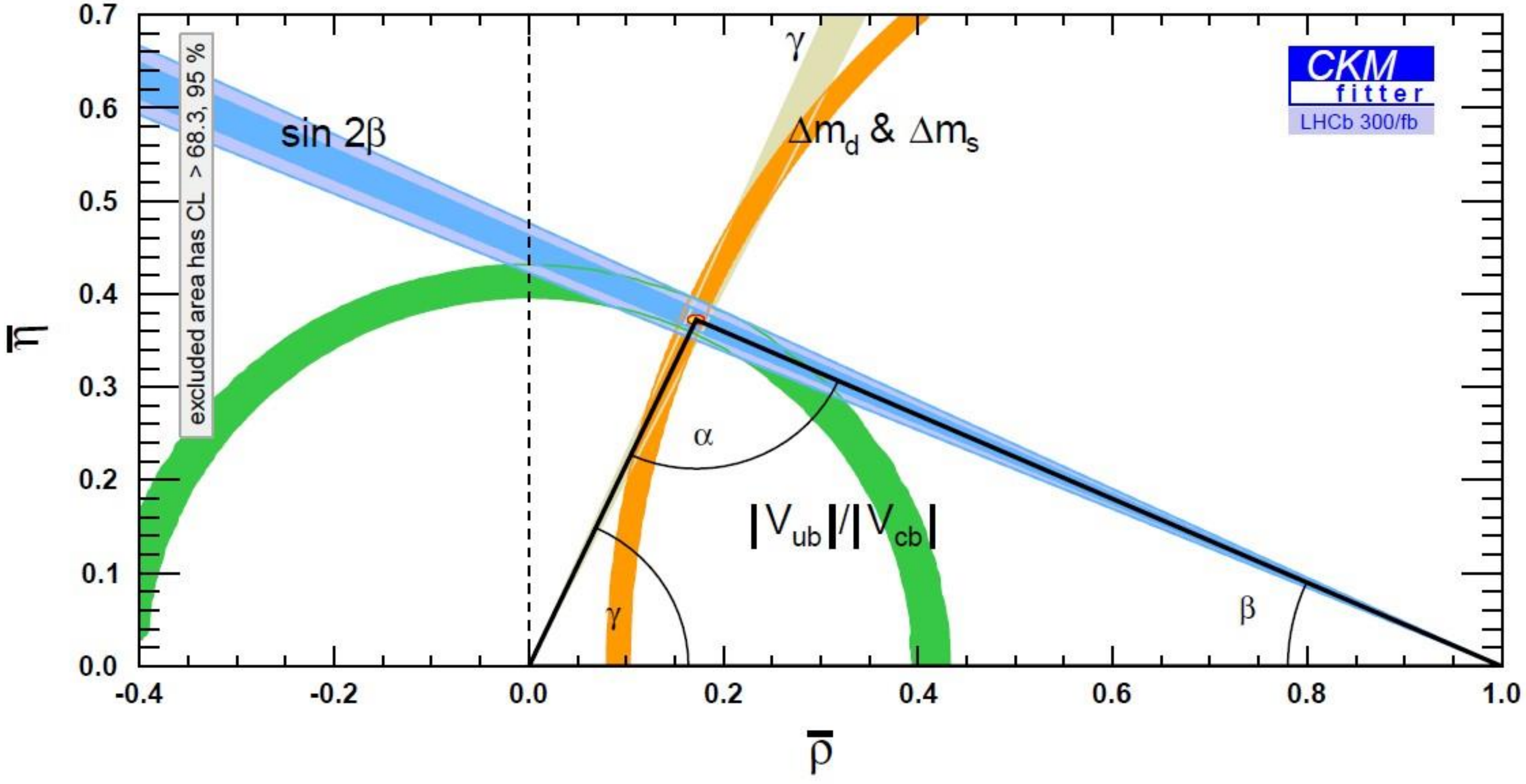
Evolution of the UT: 23 fb^{-1}

(After run 3, ~2025)



Evolution of the UT: 300 fb^{-1}

(End of Upgrade II, ~2040)

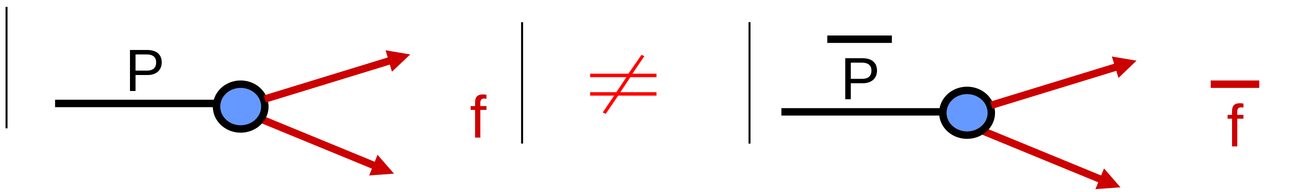


New physics will have no place to hide, if it is not CKM-like…

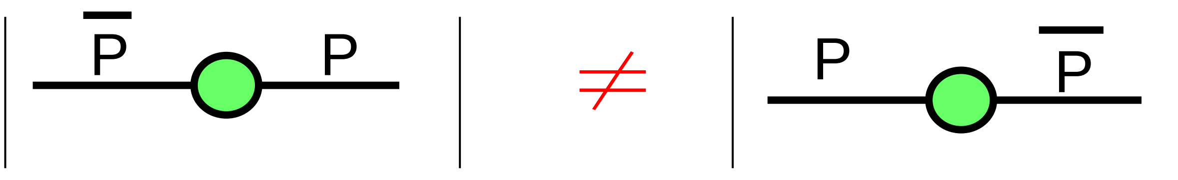
Backup slides

Three types of CPV

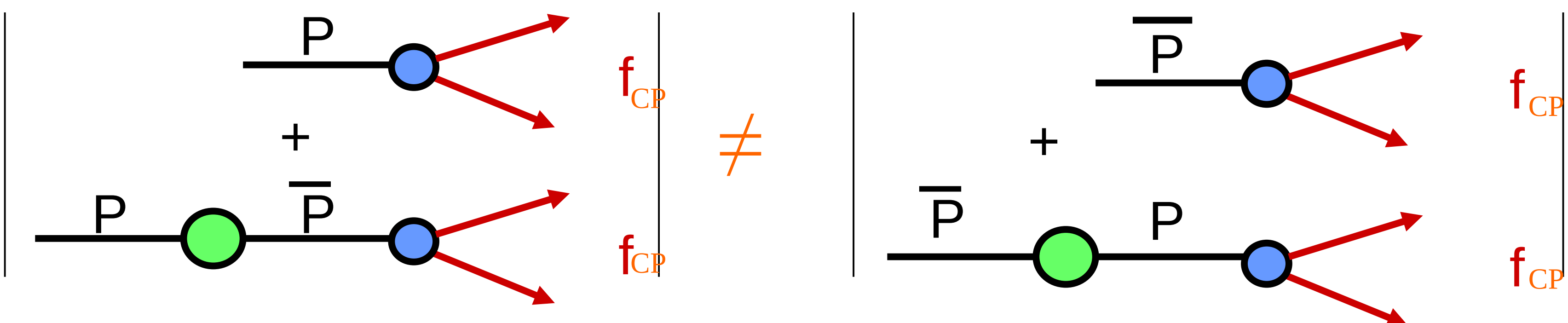
~~CP~~ in decay



~~CP~~ in mixing (“indirect ~~CP~~”)



~~CP~~ in interference between mixing and decay (“Mixing induced ~~CP~~”)

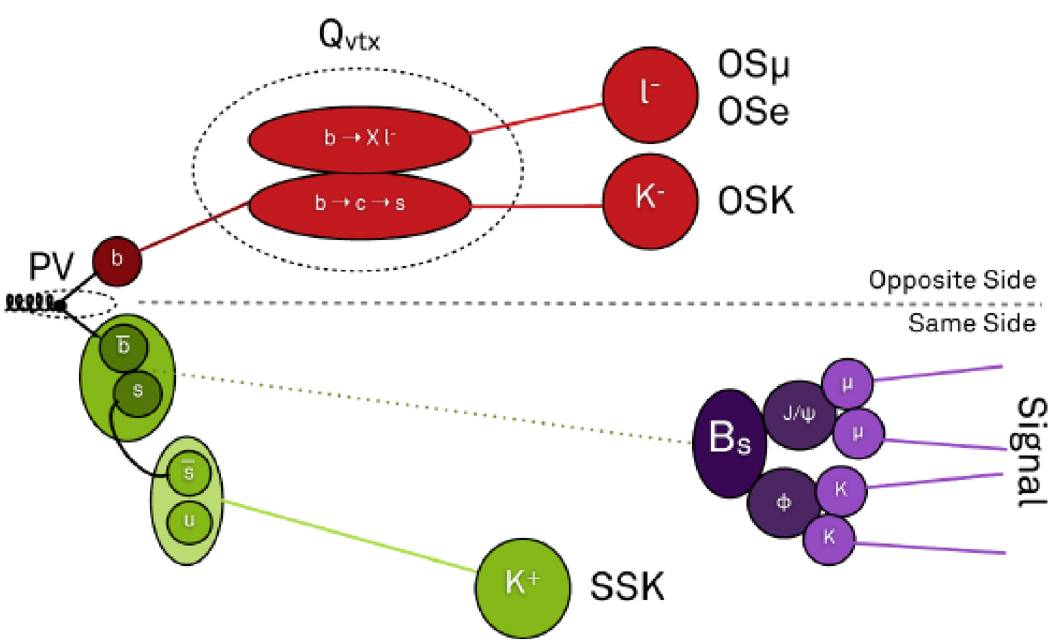


Flavour tagging

Opposite side (OS): using information of the other B decay

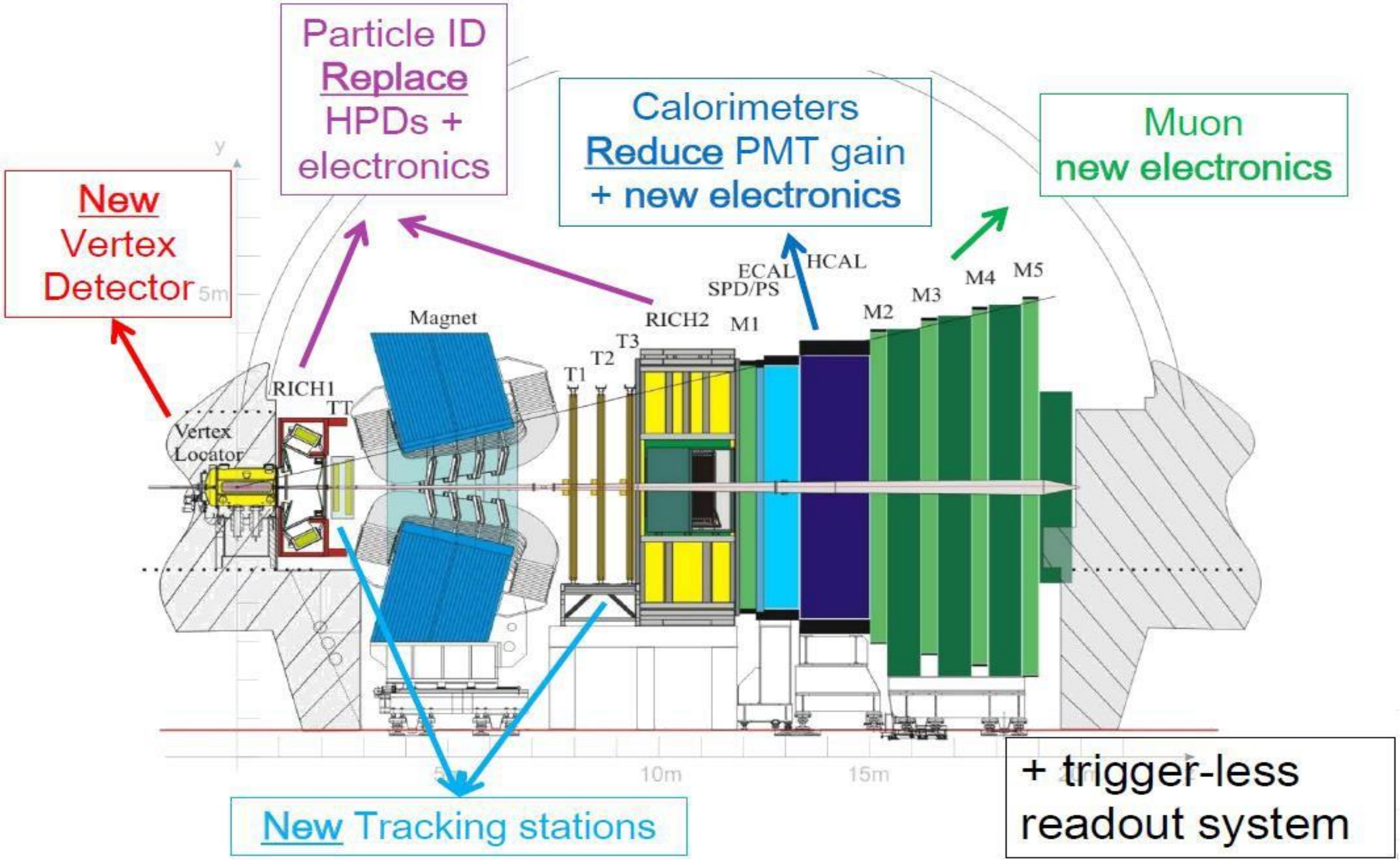
Same side (SS): using information of particles in association production

Category	Effective $\varepsilon(1-2\omega)^2$ (%)
only OS tagged	1.19 ± 0.06
only SS tagged	0.84 ± 0.11
OS&SS tagged	1.7 ± 0.08
Total	3.73 ± 0.15



Upgrade I detector

- **Fully software trigger at 40 MHz readout**
- **Redesign detector to cope with higher luminosity**
  - ✓ **Finer granularity and more radiation hardness**



Upgrade II detector assumptions

Detector enhancements will bring additional physics reach on top of what will come from the increase in integrated luminosity.

- **Improved tracking**

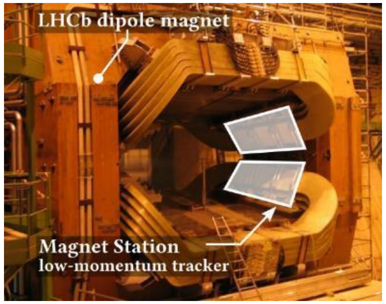
  Increased acceptance

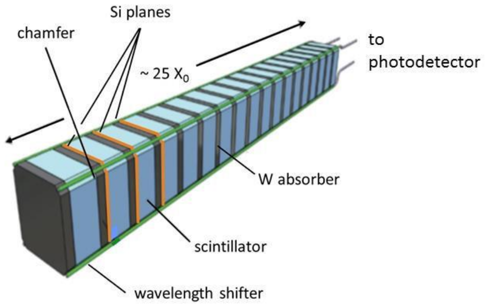
  Added Magnet stations

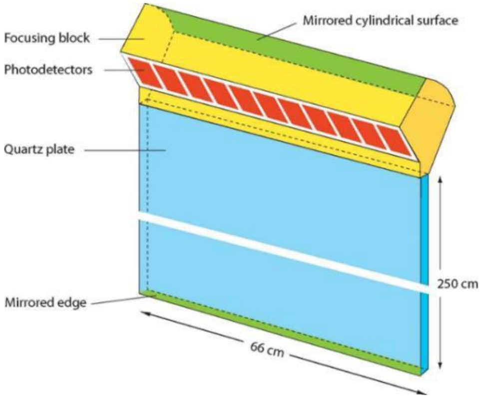
  Approach closer to beam pipe

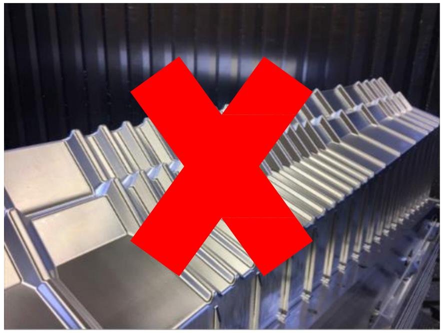
  Removal of VELO RF foil

- **Improved ECAL**
- **Improved low-momentum PID**









Much R&D required to achieve higher granularity, higher radiation resistance, fast timing

Upgrade II physics motivation

- **Greatly improve knowledge of golden and theoretically clean observables**
  - ✓ **E.g.** $\gamma, \beta, \phi_s, \mathrm{B}(B_s \to \mu\mu)/\mathrm{B}(B_d \to \mu\mu)$, **charm CP violation**
- **Widen the set of observables beyond those accessible at Upgrade I**
  - ✓ **E.g. additional measurements involving** $b \to s/d\ l^+l^-, b \to c/u\ l$ **decays**
- **Fully exploit the HL-LHC for topics beyond flavour physics**

Upgrade II sensitivities

Table 10.1: Summary of prospects for future measurements of selected flavour observables. The projected LHCb sensitivities take no account of potent
detector improvements, apart from in the trigger. Unless indicated otherwise the Belle-II sensitivies are taken from Ref. [568].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–
$\|V_{ub}\|/\|V_{cb}\|$	6% [186]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%	21% [573]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [244]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c l^- \bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	9% [199, 202]	3%	2%	1%	–
$R(J/\psi)$	25% [202]	8%	–	2%	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [574]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [222]	4.3×10^{-5}	3.5×10^{-5}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [210]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–