LHCb status and highlights

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Outline

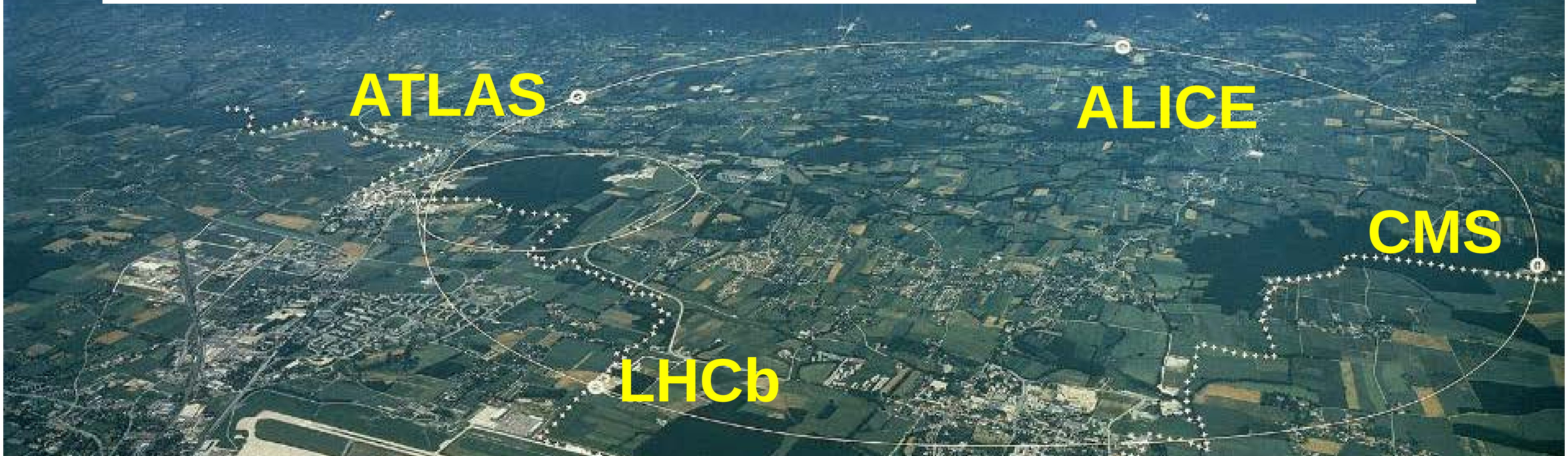
- Introduction to LHCb
- Rare B decays & lepton universality violation
- CKM test
- Charm mixing and CP violation
- Hadron spectroscopy
- Future upgrades of LHCb

Introduction to LHCb

The two frontiers at LHC

Energy frontier: ATLAS, CMS

- **Higgs**
- **Direct search for TeV scale new particles**



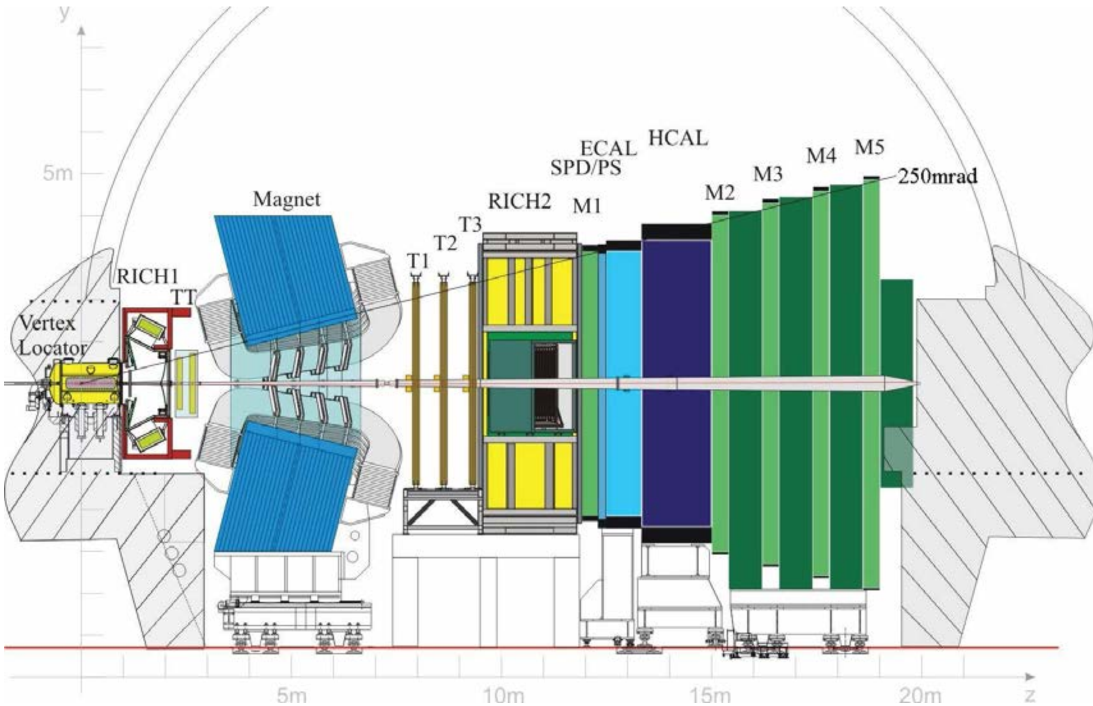
Precision frontier: LHCb

- **Indirect search for new physics up to 100 TeV (rare decays)**
- **Understanding matter/antimatter asymmetry (CP violation)**
- **Understanding strong interaction (hadron spectroscopy)**

LHCb experiment

Designed to study heavy flavor physics.

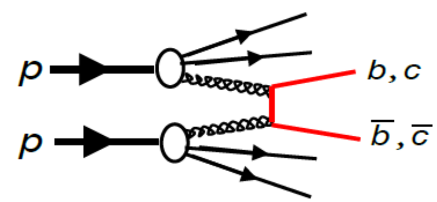
Nowadays a general purpose detector for physics in forward region.



Δp/p=0.4-0.6%
ε(μ→μ)~95%, ε(π→μ)~1%
ε(K→K)~95%, ε(π→K)~5%
$\sigma t \sim 45$ fs

- **Large $b\overline{b}$ cross section**

  $\sigma(b\overline{b}) \sim 600\ \mu b$ **@ 13 TeV,**
  $B^0,\ B_s^0, B^{\pm}, B_c^{+}, \Lambda_b^0, \ldots$



- **Single arm forward geometry**

  ~4% solid angle,
  ~30% b production

- **Excellent tracking, vertexing, particle identification**

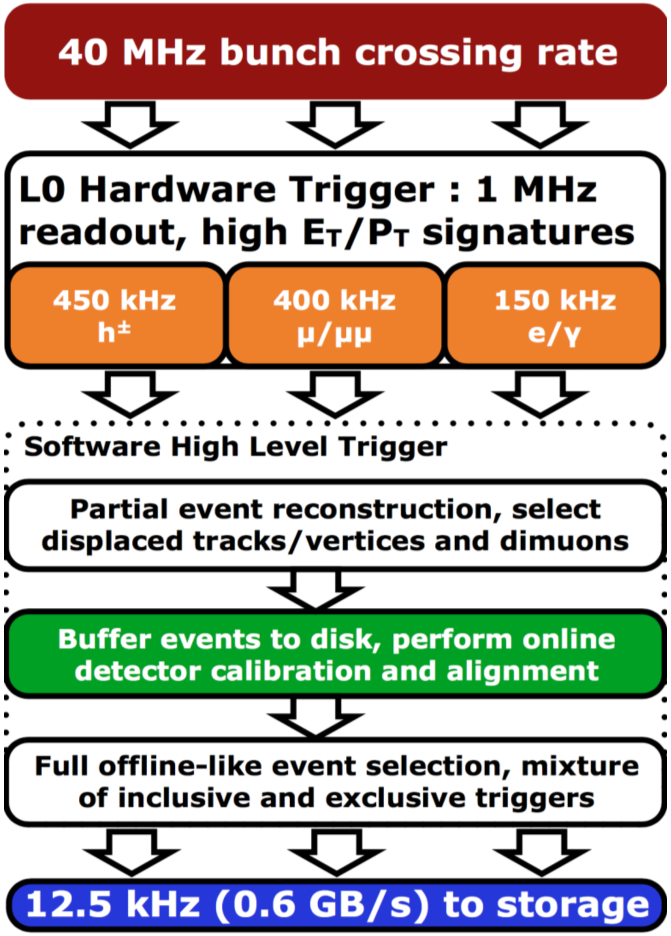
LHCb Collaboration

1263 members, 77 institutes, 17 countries

中国: 清华大学，华中师大，国科大，武汉大学，高能所，华南师大

LHCb Trigger

Trigger is essential for reducing event rate to manageable level



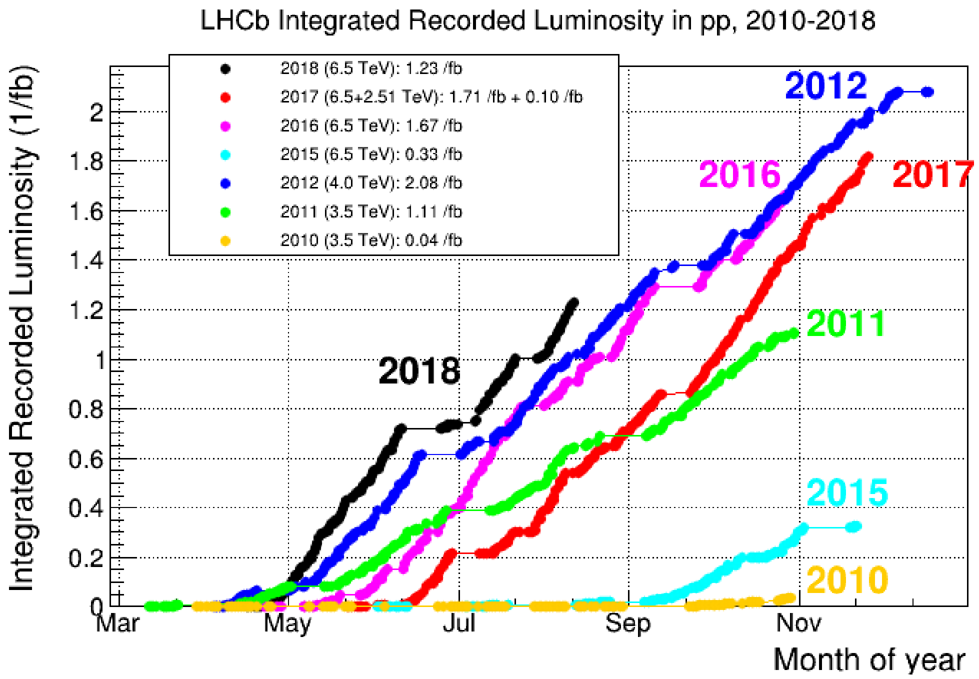
Hardware trigger (L0)

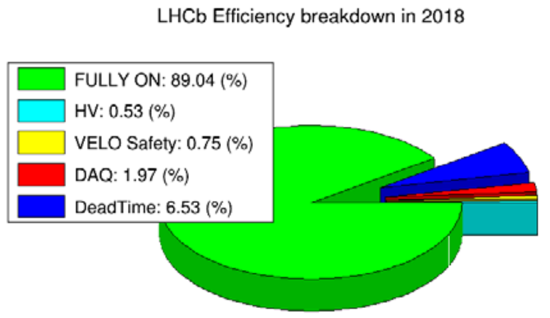
- ✓ FPGA
- ✓ High p_T of decay products
- ✓ 1MHz readout

Software trigger (HLT)

- ✓ CPU farm
- ✓ Displaced tracks/vertices
- ✓ Real time calibration and alignment
- ✓ 12.5 kHz to storage

LHCb running (pp collisions)



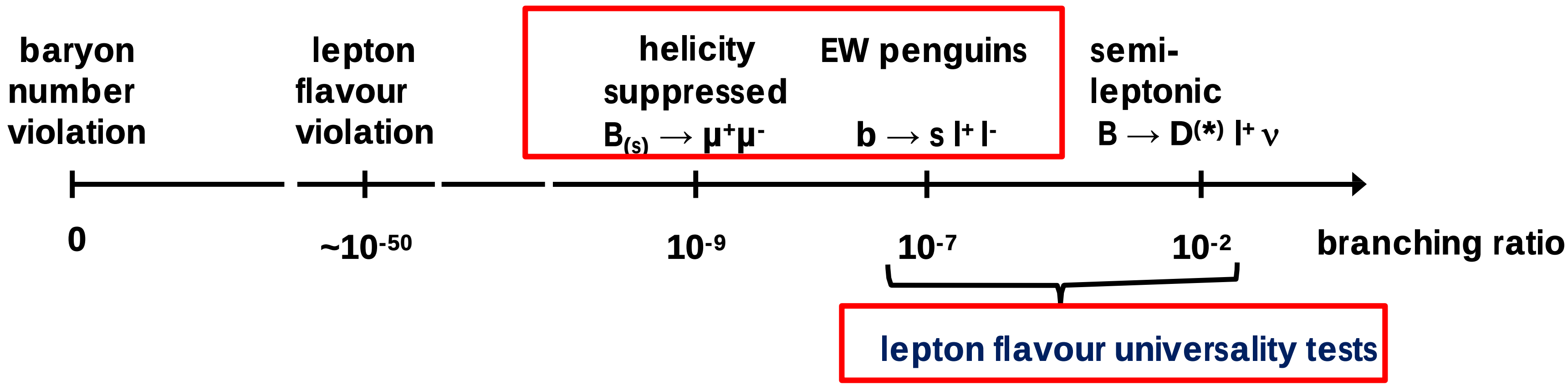


Recording efficiency ~90%

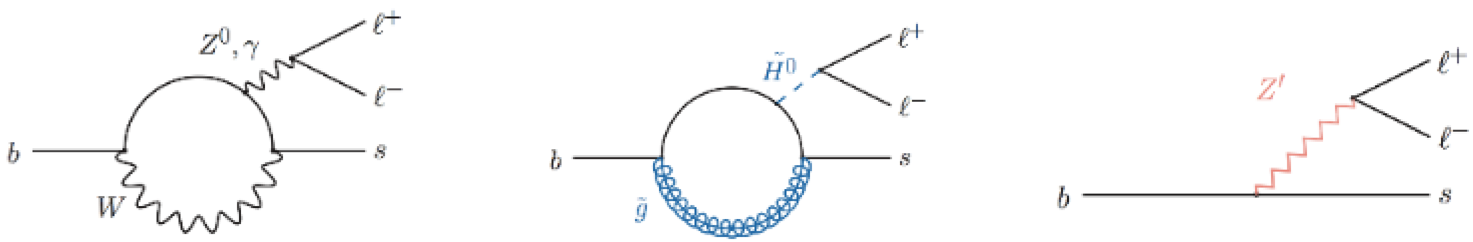
- **8 fb^{-1} have been accumulated, 5 fb^{-1} used in analysis**
  - ✓ **2017 and 2018 data not ready for analysis yet**
- **LHCb will finish phase I running in December**
  - ✓ **First detector upgrade planned for 2019**

Rare B decays and lepton flavur universality violation

Motivation



- $b \to sl^+l^-$ transitions probe mass scale far beyond direct search
  - ✓ With suppressed SM, NP effect could be pronounced



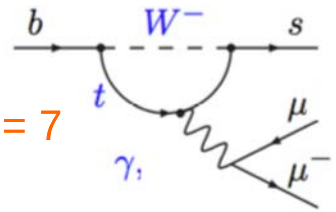
- Null test of SM with Lepton flavour universality
  - ✓ In the SM, ratio like $\Gamma(B^+ \to K^+\mu^+\mu^-)/\Gamma(B^+ \to K^+e^+e^-)$ differs from unity only because of phase space difference

Theoretical description of FCNC

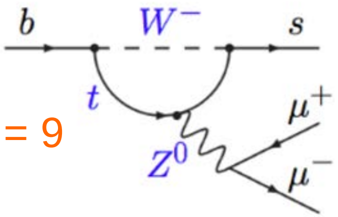
- **Described by an effective Hamiltonian**
  - ✓ **O_i (Operators): long-distance, non-perturbative physics**
  - ✓ **C_i (Wilson coefficients): short distance, high energy physics**
    - **BSM processes may modify these coefficients**

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$

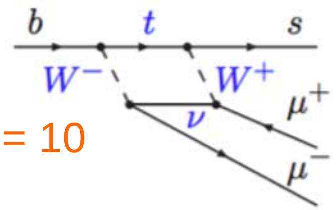
i = 7



i = 9



i = 10



Operators | **Wilson coefficients**

0.2 GeV ... | 4 GeV ... 80 GeV ... 10-100 TeV

Λ_{QCD} (non-perturbative) | Λ_b b mass | Λ_{EW} W mass | Λ_{BSM} BSM scale

Helicity suppressed $B_{s/d} \to \mu^+\mu^-$

- **Very precise predictions available**
  - **Only C_{10} contribute in the SM:** $\mathrm{BR}(B_q \to \mu^+\mu^-) \propto |C_{10}|^2 m_l^2 \sqrt{1 - \frac{4m_l^2}{m_{B_q}^2}}$

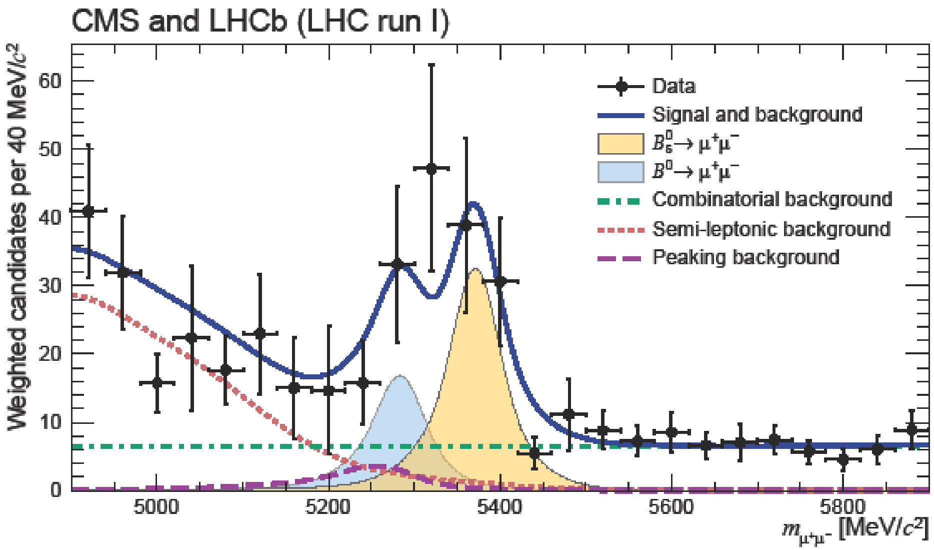
$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.52 \pm 0.15) \times 10^{-9}, \qquad \mathrm{BR}(B^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (1.12 \pm 0.12) \times 10^{-10}$$

  - **BSM scalar and pseudo-scalar operators may contribute**

- **LHCb+CMS run I result**
  - **Observation of $B_s \to \mu^+\mu^-$ (6.2σ)**
  - **evidence for $B_d \to \mu^+\mu^-$ (3.0σ)**

Nature 522 (2015) 68

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.0^{+1.6}_{-1.4}) \times 10^{-10}$$



- **ATLAS run I result** EPJC 76 (2016) 513

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(0.9^{+1.1}_{-0.8}\right) \times 10^{-9}$$ **(significance: 1.4 σ)**

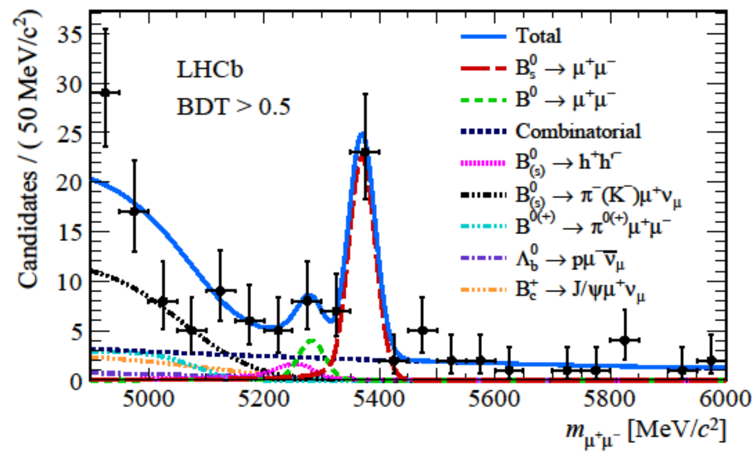
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ (95 \% CL)}$$

Helicity suppressed $B_{s/d} \to \mu^+\mu^-$

- LHCb update with run I+II data, 3+1.4 fb^{-1} PRL118 (2017) 191801
  - first single experiment observation of $B_s \to \mu^+\mu^-$ (7.9σ)

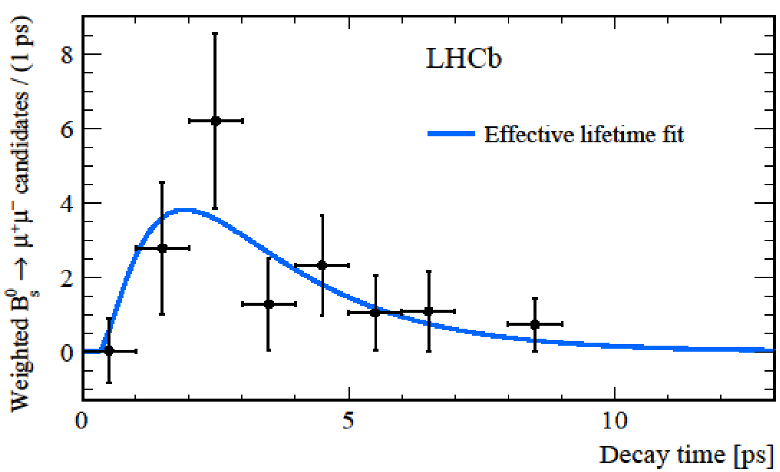
$$\mathrm{B}(B_s \to \mu^+\mu^-) = \left(3.0 \pm 0.6^{+0.3}_{-0.2}\right) \times 10^{-9}$$

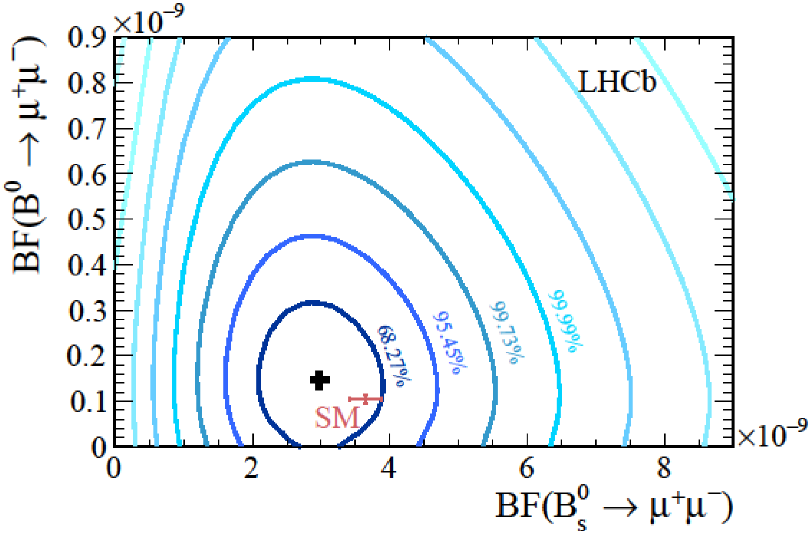
$$\mathrm{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$



- Effective lifetime of $B_s \to \mu^+\mu^-$

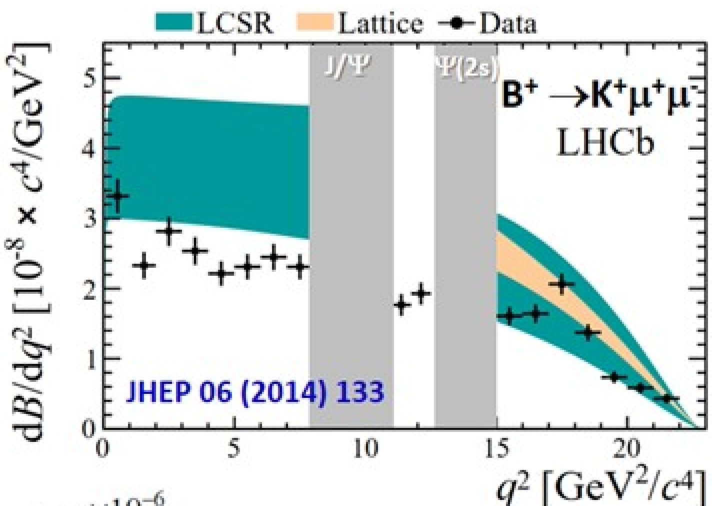
$$\tau(B_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

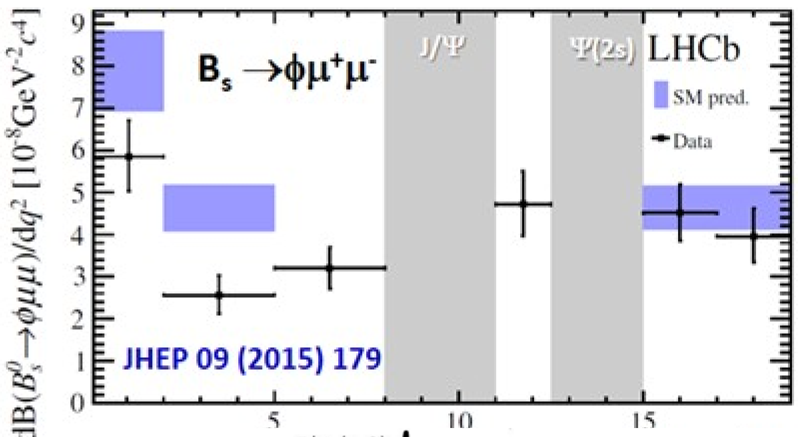


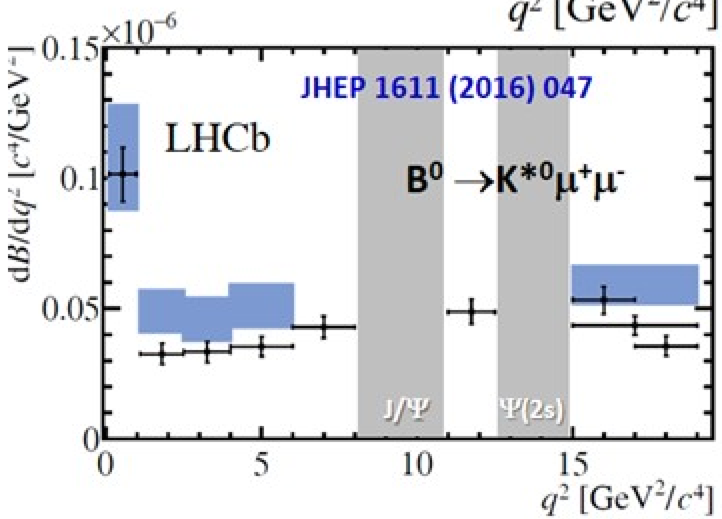


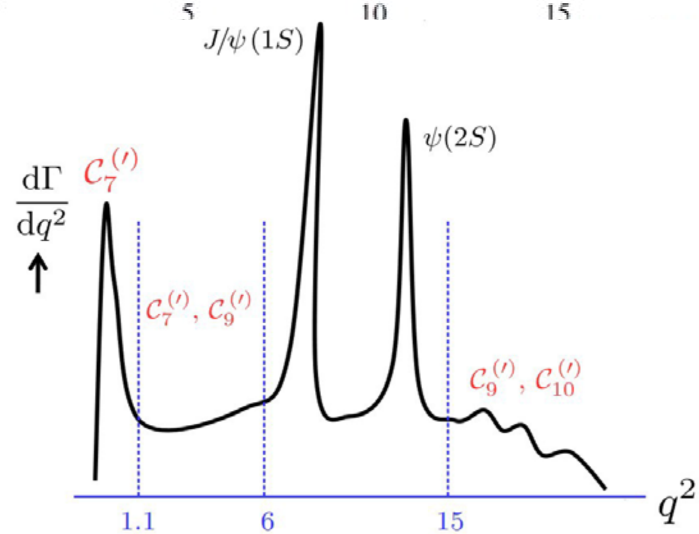
Differential BF: $b \rightarrow s\mu^+\mu^-$

- **Hint of smaller branching fractions than SM predictions around $2 < q^2 < 7$ GeV²**
- **This region is related to $C_9^{(\prime)}$**

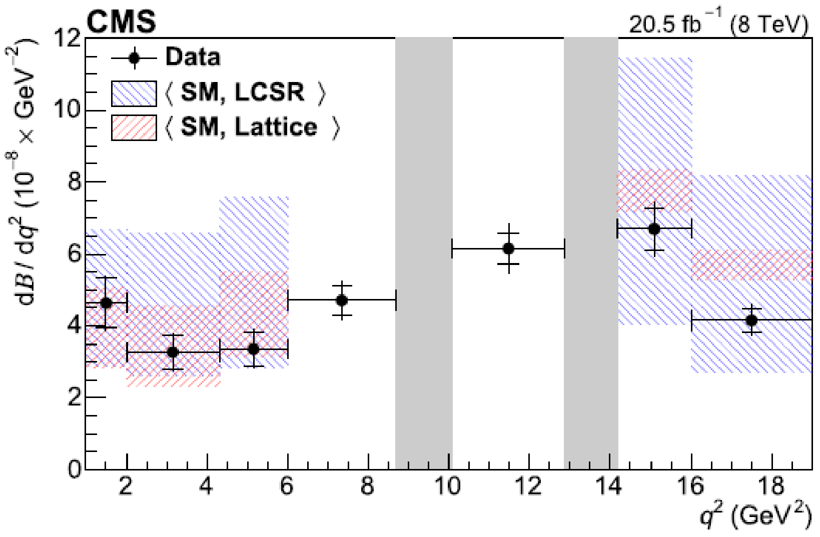


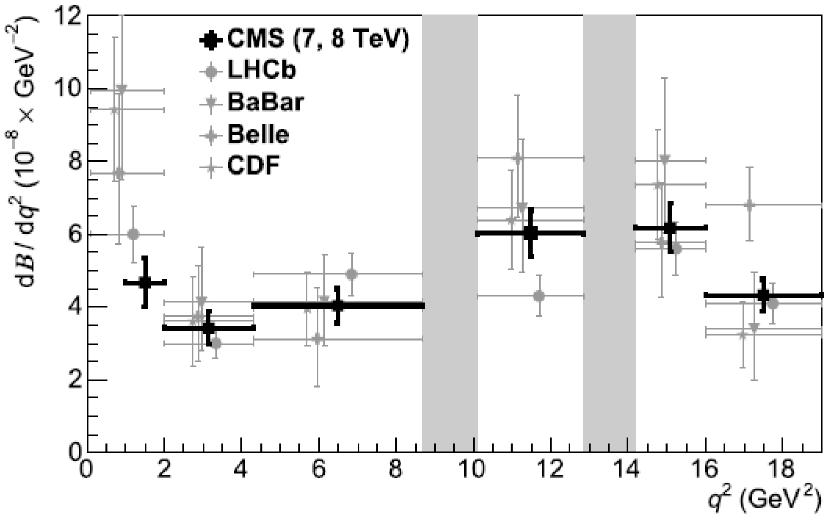






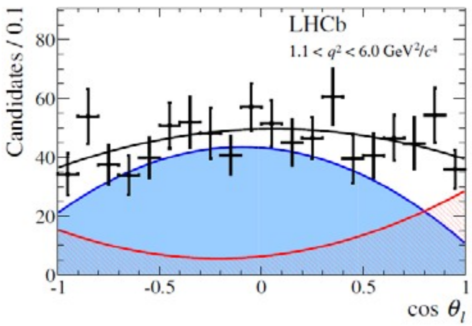
Differential BF: $b \to s\mu^+\mu^-$

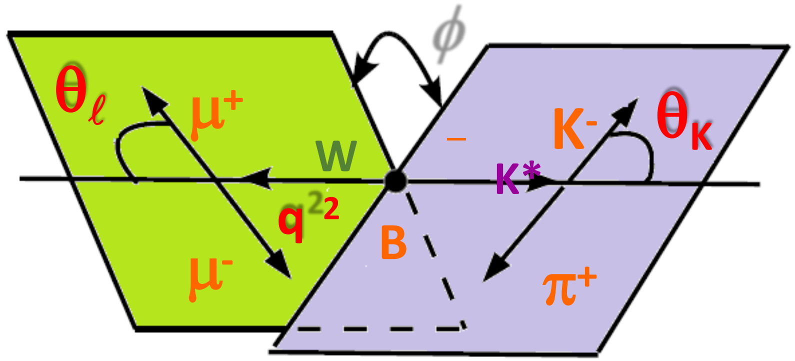


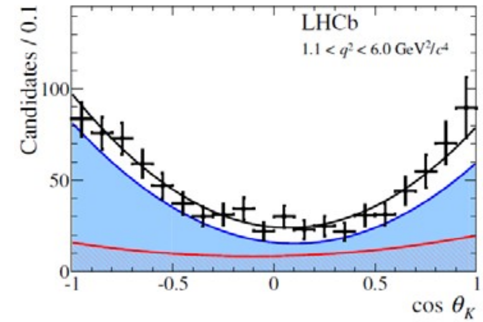


- **Different experiments get compatible results**
- **Too early to draw a clear conclusion**
  - ✓ **Results dominated by statistical uncertainties**
  - ✓ **Difficult to assess hadronic uncertainties in SM predictions**
  - ✓ **Charm resonance contributions to be accounted for**

Angular analysis: $B^0 \to K^{*0}\mu^+\mu^-$







$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Eeight independent observables

- ✓ F_L: fraction of longitudinal polarization
- ✓ $S_6 = 4/3\ A_{FB}$: forward-backward asymmetry of the $\mu^+\mu^-$ system
- ✓ $S_{3,4,5,7,8,9}$: remaining CP-averaged observables

F_L and A_{FB}

LHCb

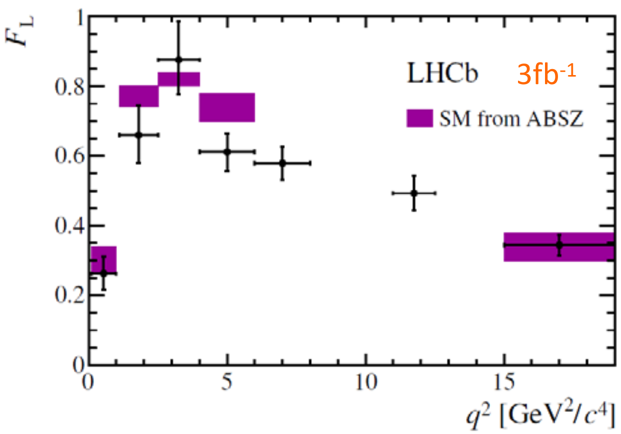
[JHEP02(2016)104]

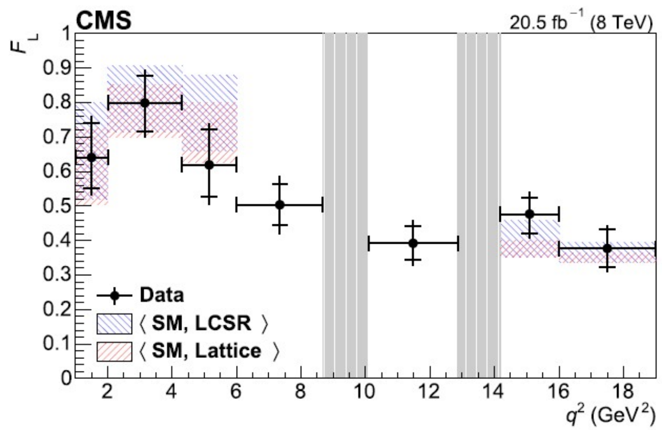
CMS

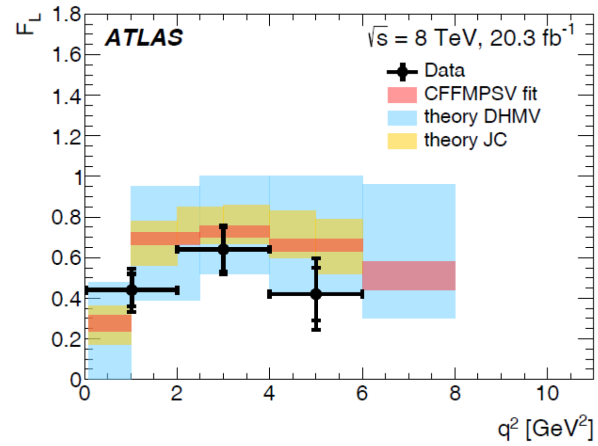
[PLB 753 (2016) 424]

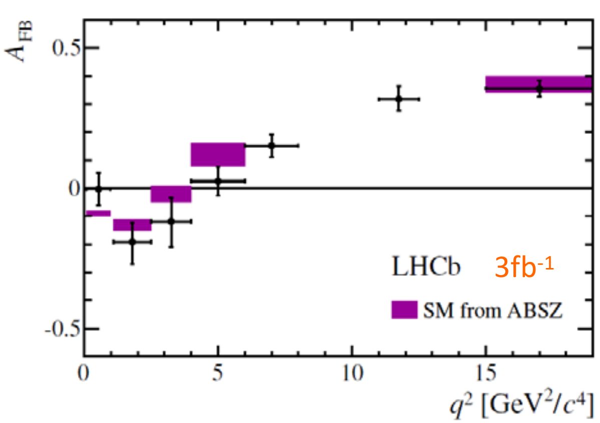
ATLAS

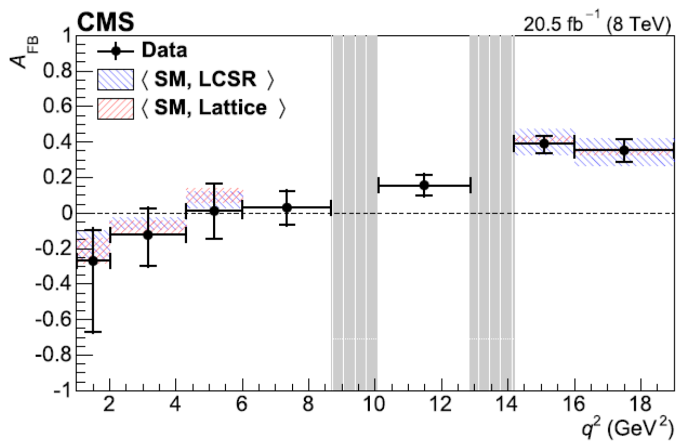
[arXiv:1805.04000]











SM predictions

ABSZ: EPJC 75 (2015) 382

LSCR: JHEP 08 (2016) 98

Lattice: arXiv:1501.00367

Agree well with SM predictions

P'_5 puzlle

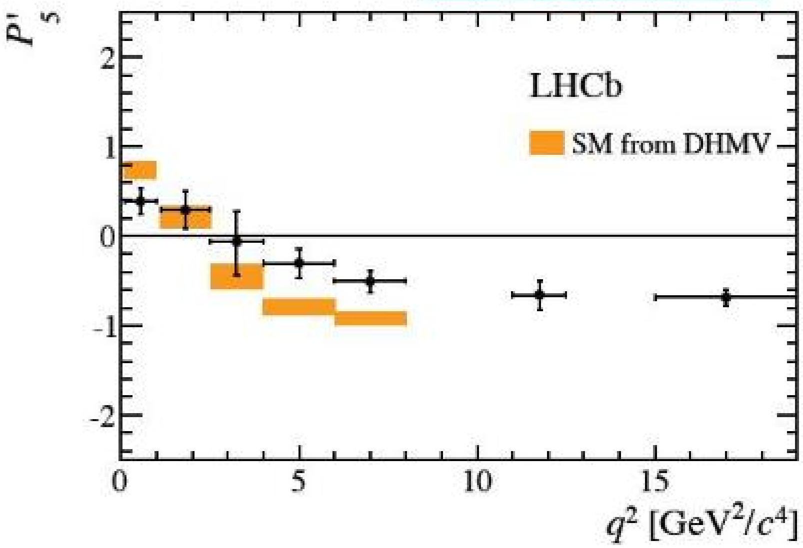
- "optimized observables", with form factor cancellations

[Descotes-Genon et al, JHEP 05 (2013) 137]

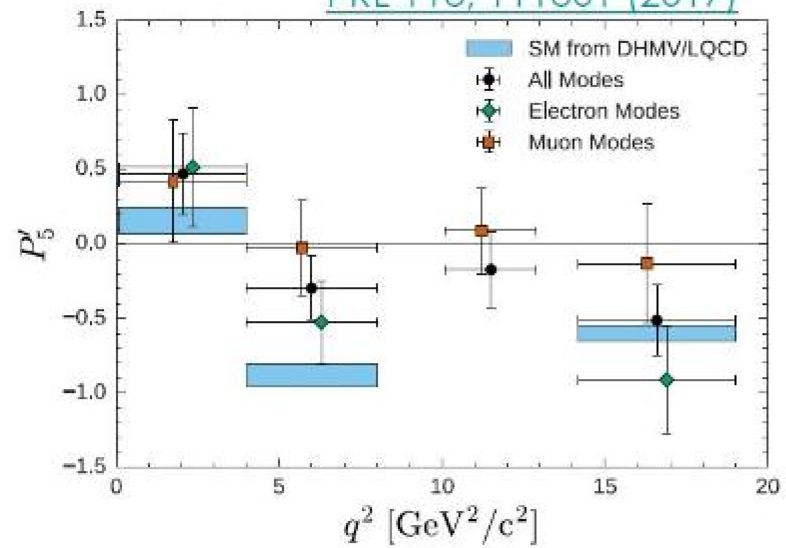
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

- They are functions of $q^2 = m^2_{\mu^+\mu^-}$ and Wilson coefficients C_i

JHEP02 (2016) 104

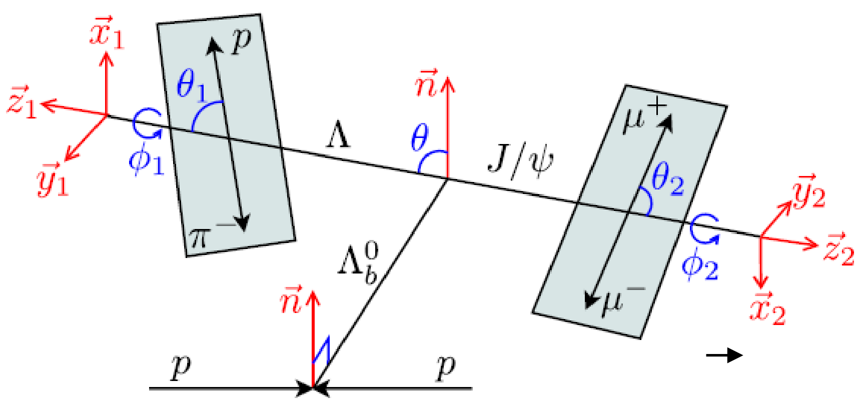


PRL 118, 111801 (2017)



~ 3σ discrepancy seen around 4-8 GeV^2 by both LHCb and Belle

Angular analysis: $\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$



$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2} \sum_i^{34} K_i(q^2) f_i(\vec{\Omega})$$

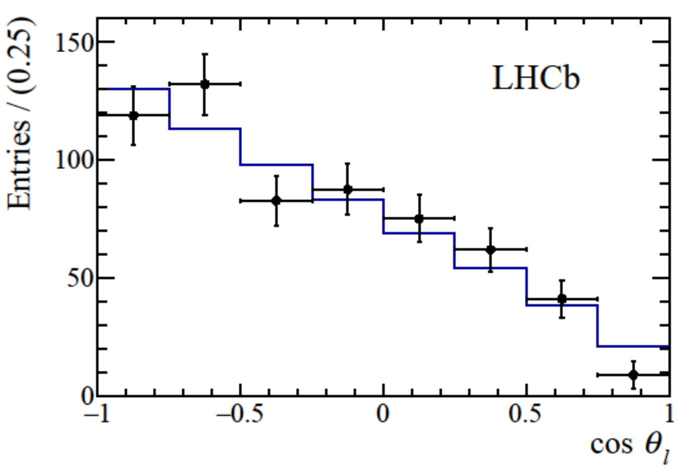
- **5 angles**
- **q^2-dependent observables K_i**
- **Method of moment**
- **Signals only observed in $15 < q^2 < 20$ GeV2**

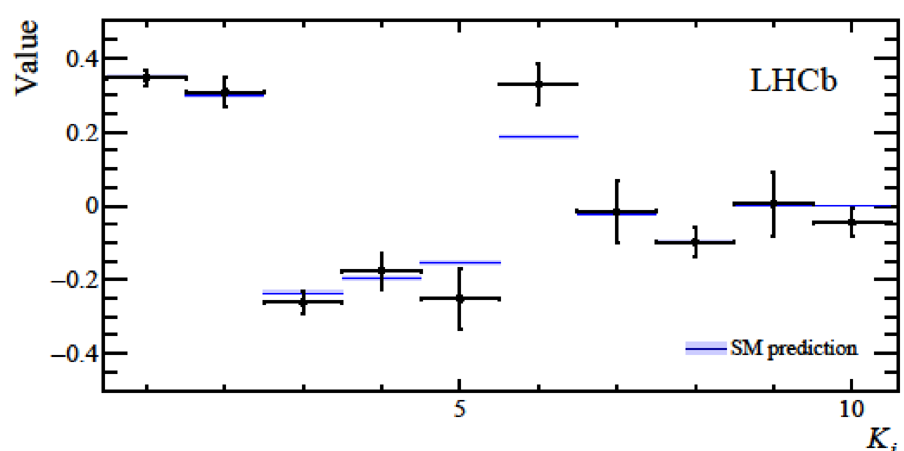
Results compatible with SM predictions

[Boër et al, JHEP 01 (2015) 155]

[Detmold et al. PRD 93 (2016) 074501]

arXiv: 1808.00264 Run 1+II, 5 fb^{-1}

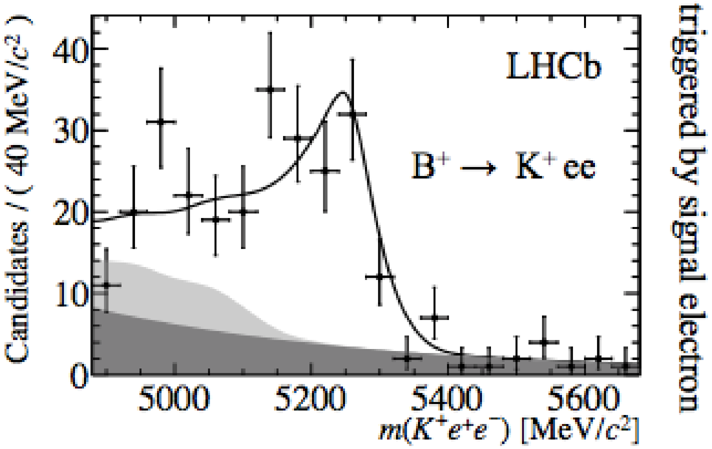


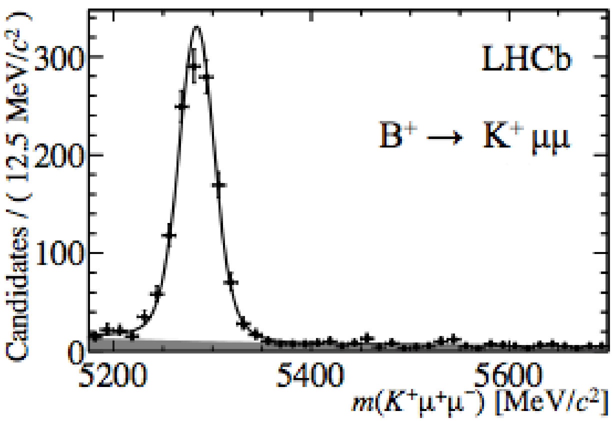


LFU test in $B \to K^{(*)} l^+ l^-$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B^{0/+} \to K^{0/+(*)} \mu^+ \mu^-)}{\mathcal{B}(B^{0/+} \to K^{0/+(*)} e^+ e^-)}$$

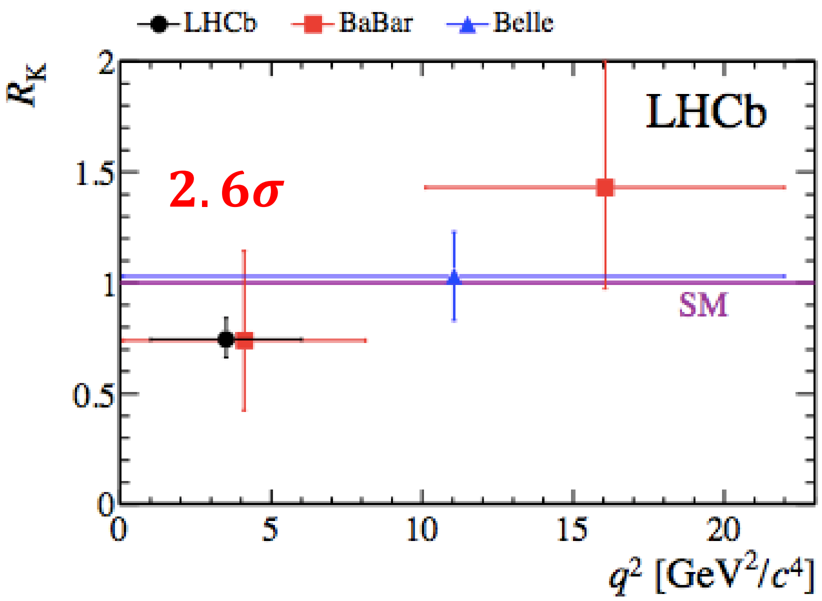
- **$R_{K^{(*)}}$ close to unity within O(10^{-3}) in the SM**
  - **hardly affected by hadronic uncertainty**
- **Experimentally challenging**
  - **bremsstrahlung effect for the electron mode**



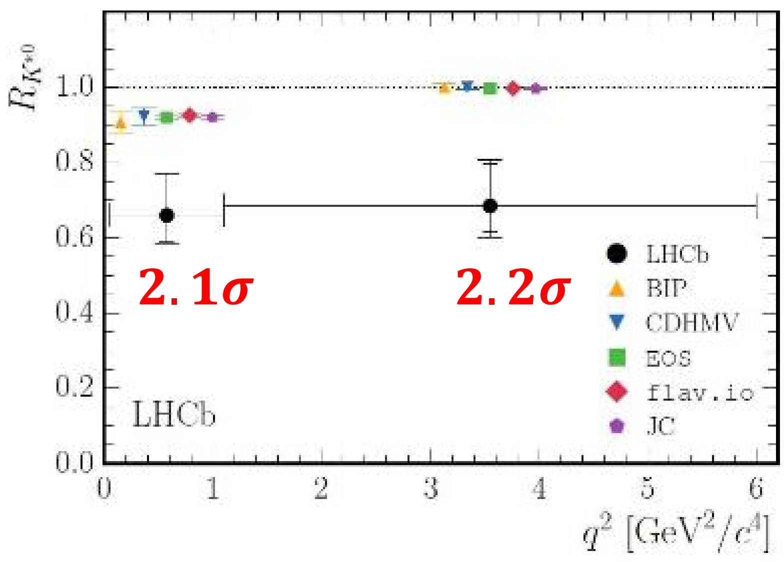


LHCb run I results

$B^+ \to K^+ l^+ l^-$



$B^0 \to K^{*0} l^+ l^-$



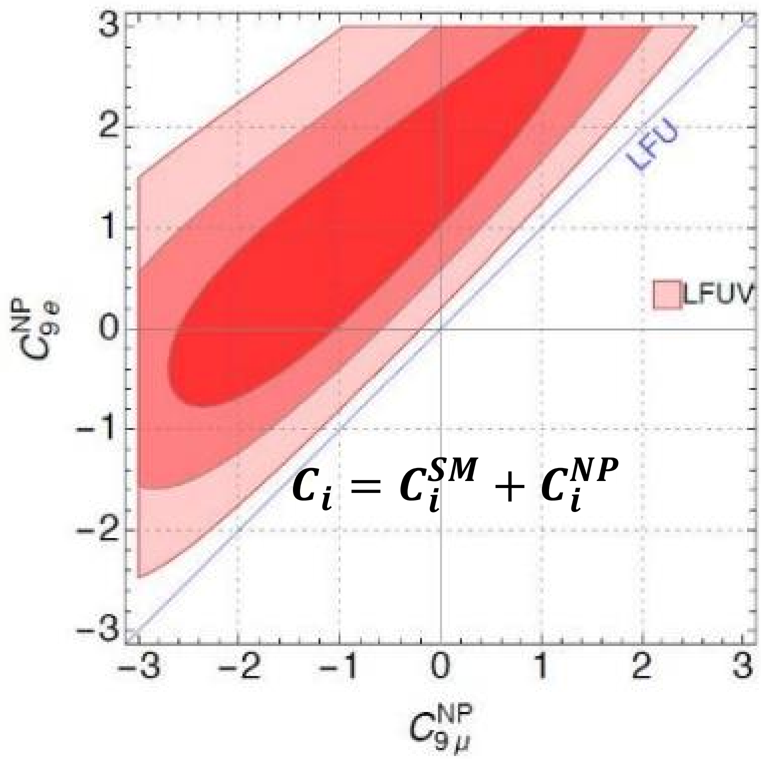
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

PRL 113 (2014) 151601

JHEP 01 (2017) 055

Global fit to $b \to sl^+l^-$ results

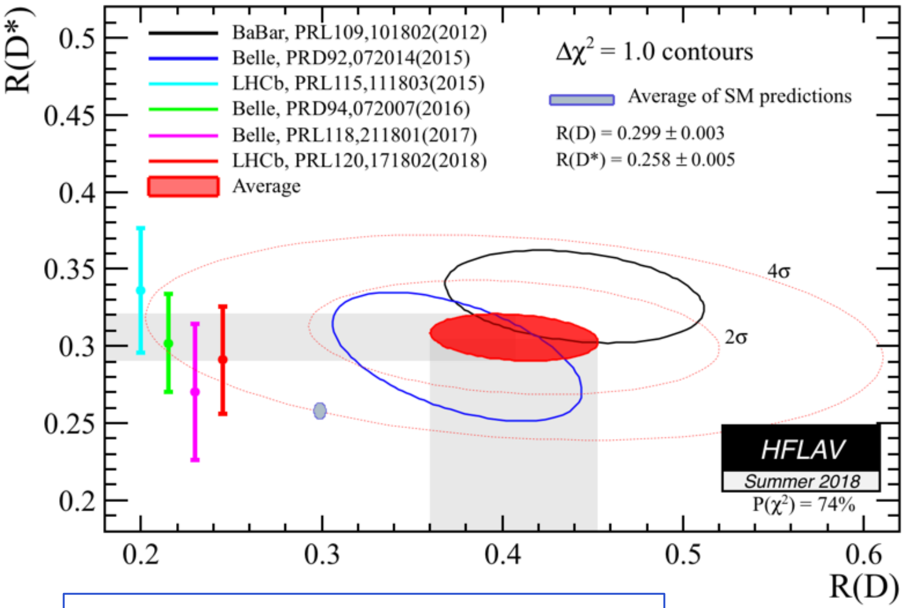
- **Include all angular variables and LFU results in $b \to sl^+l^-$ transitions**
- **Allow for $C_{ie}^{NP} \neq C_{i\mu}^{NP}$**
  - ✓ **Preference for $C_{9\mu}^{NP} \neq 0$**
  - ✓ **Data disagree with SM by more than 3.5σ**



LFU in semi-leoptonic B decays

$$R_{D^{(*)}} = \frac{\mathcal{B}(B^{0/-} \to D^{0/-(*)}\tau^+\nu_\tau)}{\mathcal{B}(B^{0/-} \to D^{0/-(*)}l^+\nu_l)}$$

- R_D by Babar and Belle
- R_{D^*} by Babar, Belle, LHCb
- Tension with SM predictions
  - ✓ 2.3σ in R_D
  - ✓ 3.0σ in R_{D^*}
  - ✓ 3.8σ combined



- Recent LHCb result of $R_{J/\psi}$

$$R_{J/\psi} = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

$$R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$$

PRL 120 (2018) 121801

  - ✓ 2σ from SM prediction: $0.12 - 0.28$

CKM test

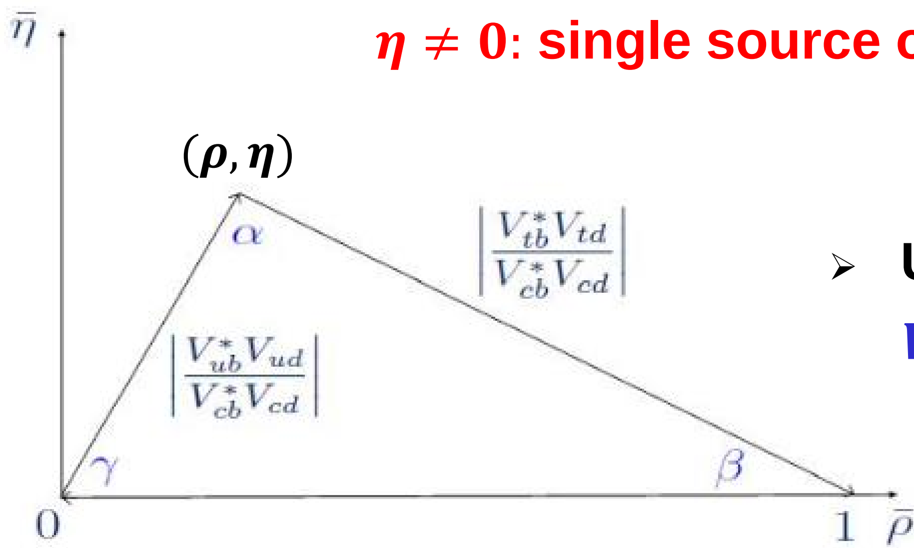
CKM matrix

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

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

$$V_{CKM} \approx \begin{matrix} 1 \quad \frac{\lambda^2}{2} & \lambda & A\lambda^3 \; \rho \quad i\eta \\ \lambda \quad iA^2\lambda^5\eta & 1 \quad \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3 \; 1 \quad \hat{\rho} \quad i\hat{\eta} & A\lambda^2 \quad iA\lambda^4\eta & 1 \end{matrix}$$

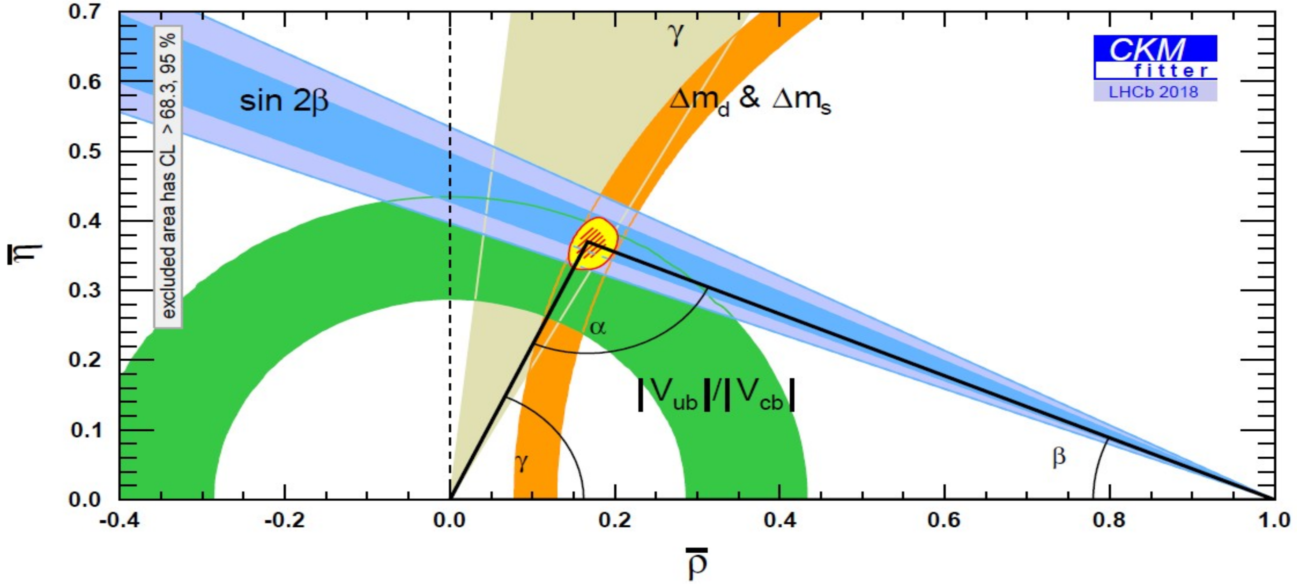
$\eta \neq 0$: single source of CPV in SM



- **Unitarity triangle**

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

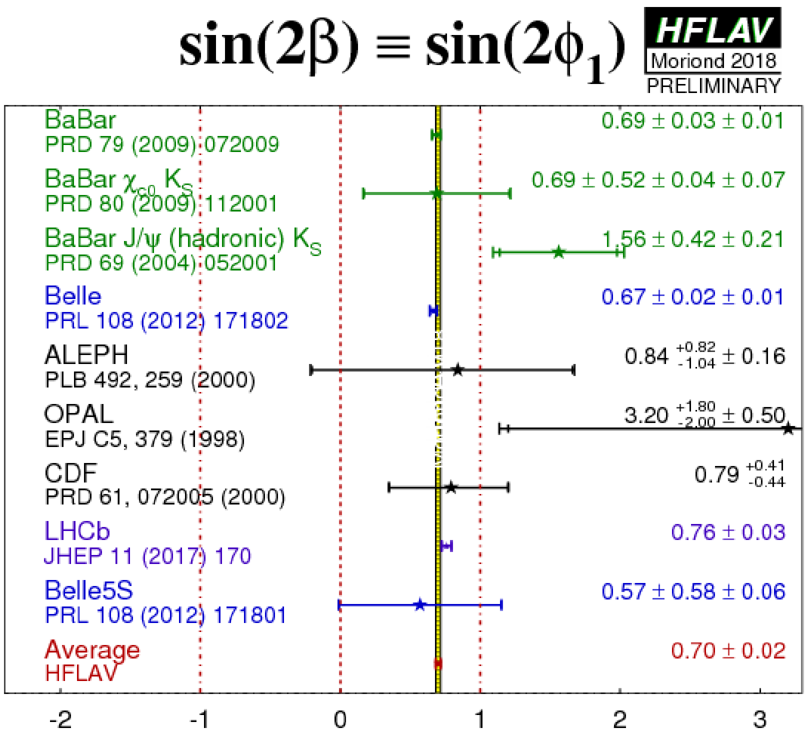
CKM global fit

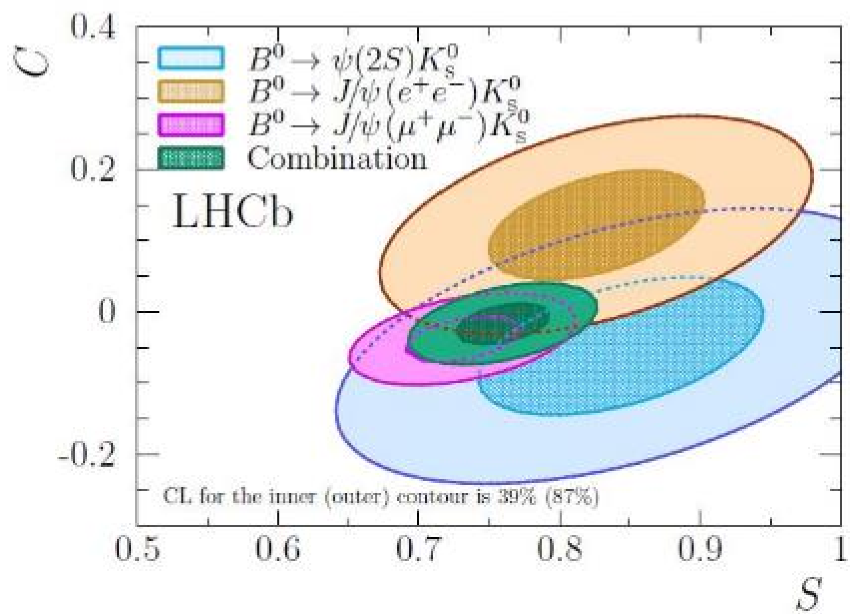


- **Inputs: measurements of all sides and angles** $(\beta, \gamma, \alpha, |V_{ub}|/|V_{cb}|, |V_{td}|/|V_{cb}|)$ **in different ways**
- **Outputs:** A, λ, ρ, η
- **Good consistency is seen between inputs and CKM is successful with current precision**
- γ **is least well measured**

$\sin 2\beta$ measurement

- **LHCb provide the most precise measurement combining several $b \to c\bar{c}s$ 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

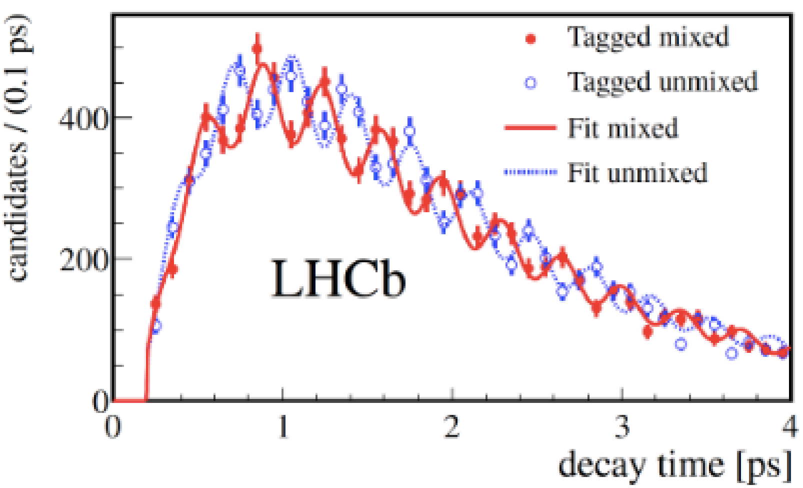
Run I, 3 fb^{-1}

Δm_d and Δm_s measurments

- Completely dominated by LHCb

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

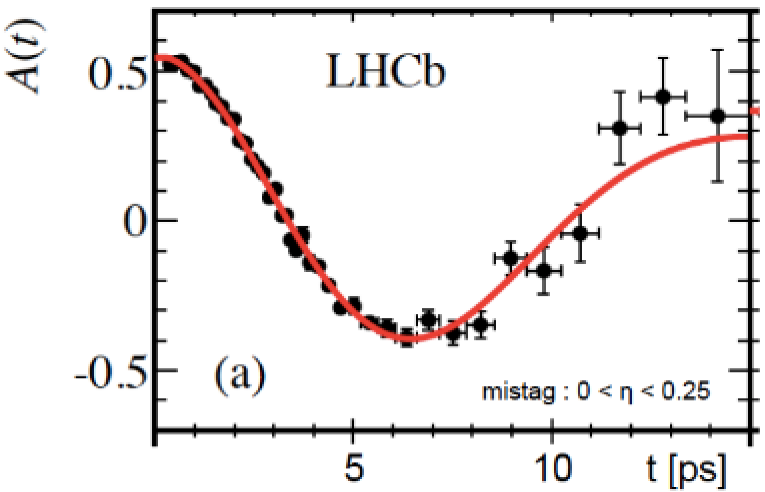
New J.Phys. 15 (2015) 053201 Run I, 1 fb^{-1}



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

$B_s \to D_s^- \mu^+ \nu$

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



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

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

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

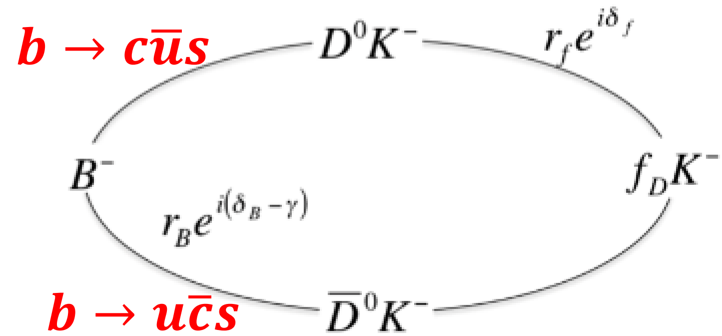
WA: $\Delta m_d = 0.5065 \pm 0.0019$ ps^{-1}

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

Idea to measure γ

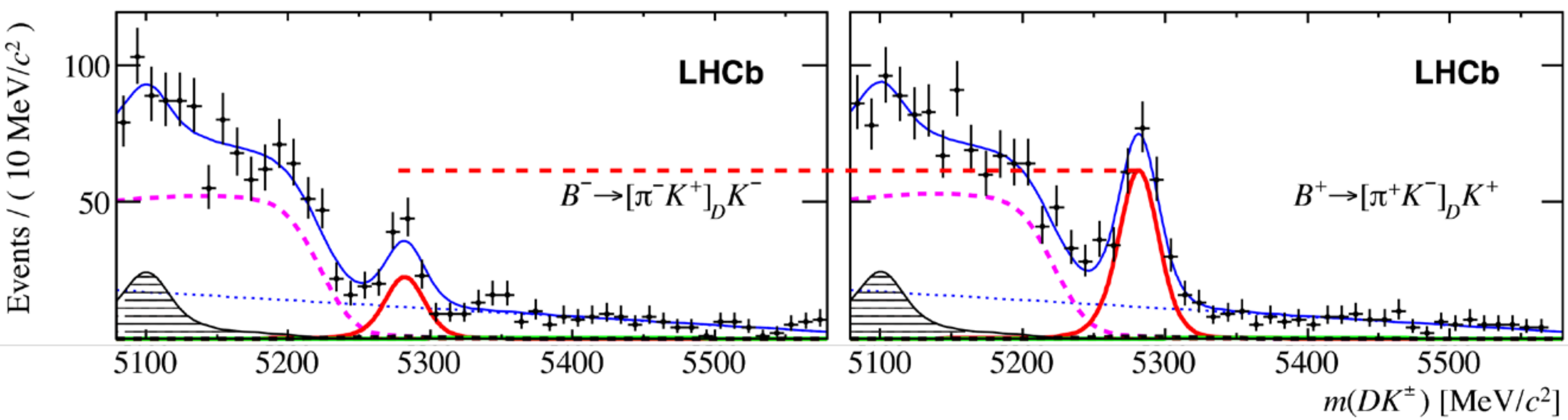
- **Exploit interference of $b \to c\bar{u}s$ and $b \to u\bar{c}s$ amplitudes**

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

γ measurements @ LHCb

B decay	D decay	Method	Ref.	Dataset[†]	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV.

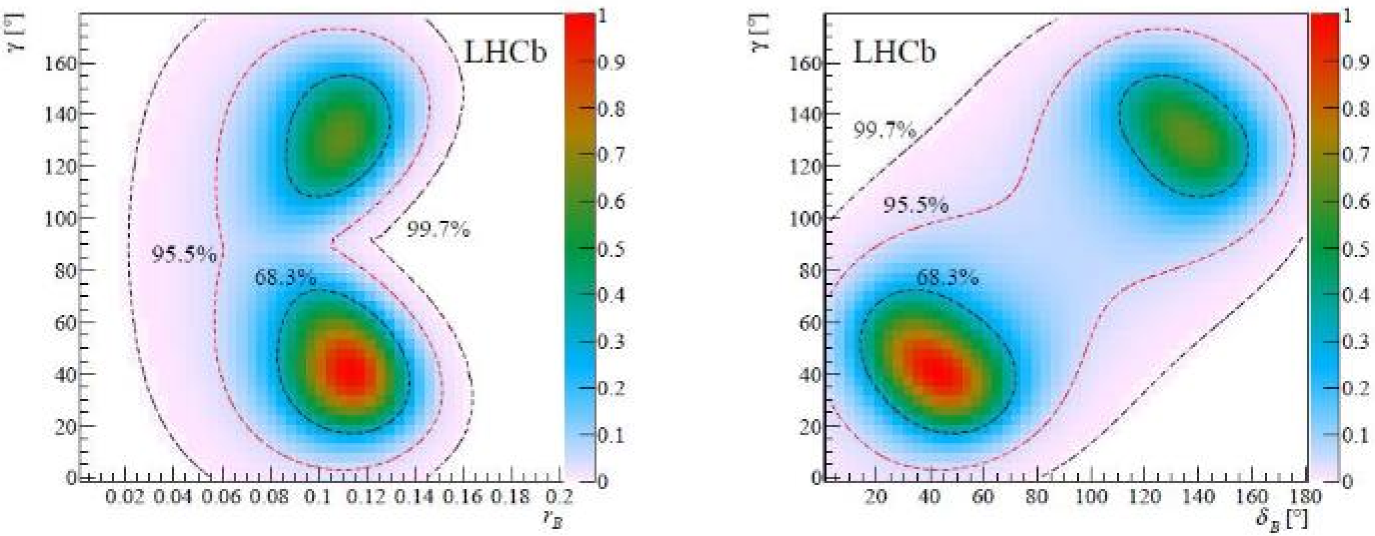
γ: first DK^* ADS/GLW result

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

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

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

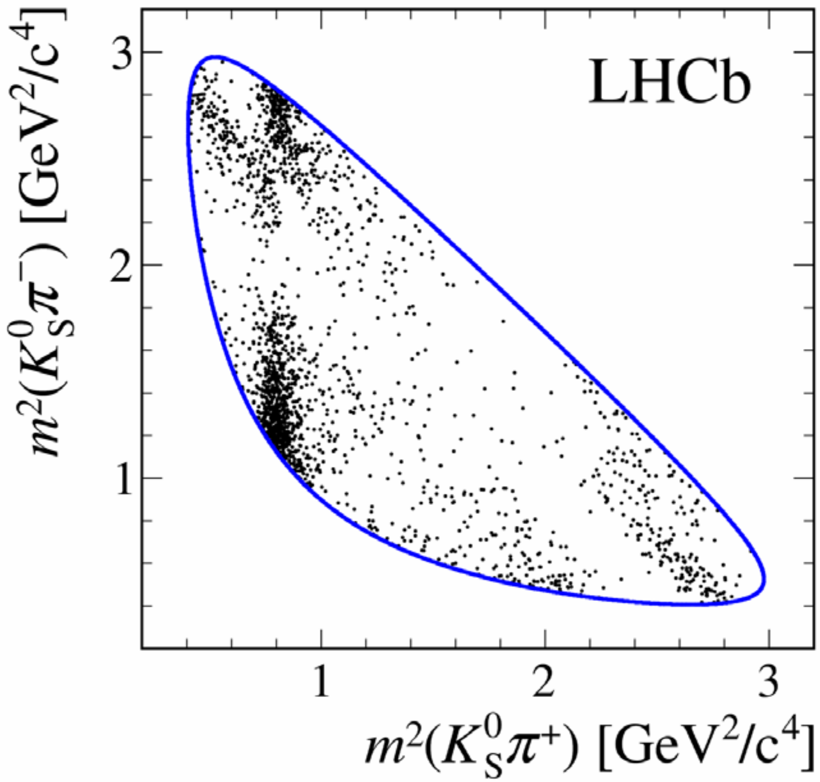
JHEP 11 (2017) 156   Run I+II, 4.8 fb^{-1}



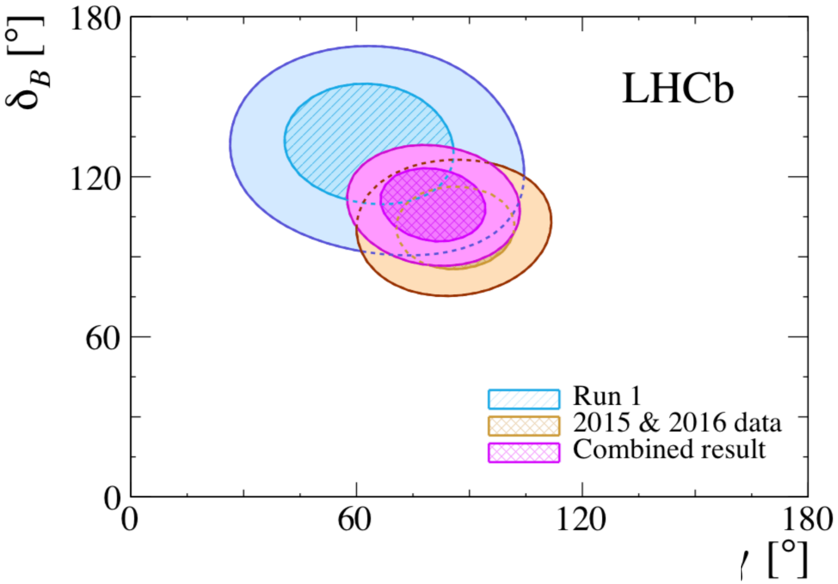
- Will become valuable in constraining γ in the future

γ: GGSZ with $B^{\pm} \to DK^{\pm}$

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



arXiv:1806.01202



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

$$\gamma = 80^\circ\,^{+10^\circ}_{-9^\circ}\;\left(^{+19^\circ}_{-18^\circ}\right),$$

$$r_B = 0.080\,^{+0.011}_{-0.011}\;\left(^{+0.022}_{-0.023}\right),$$

$$\delta_B = 110^\circ\,^{+10^\circ}_{-10^\circ}\;\left(^{+19^\circ}_{-20^\circ}\right).$$

γ: GGSZ with $B^{\pm} \to DK^{\pm}$

- Use self-conjugate $D^0 \to K_S\pi^+\pi^-$
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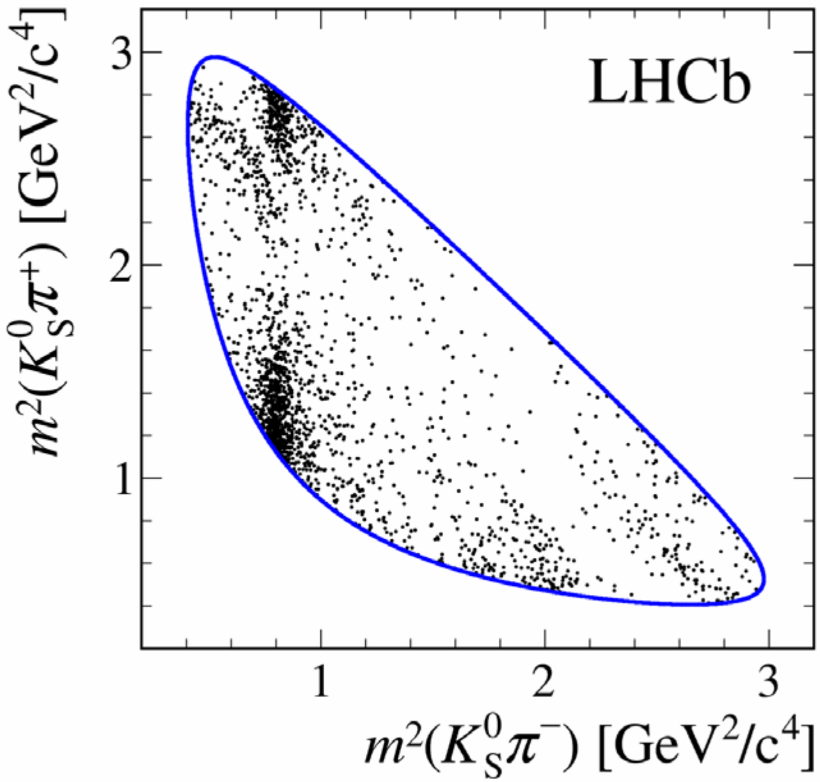
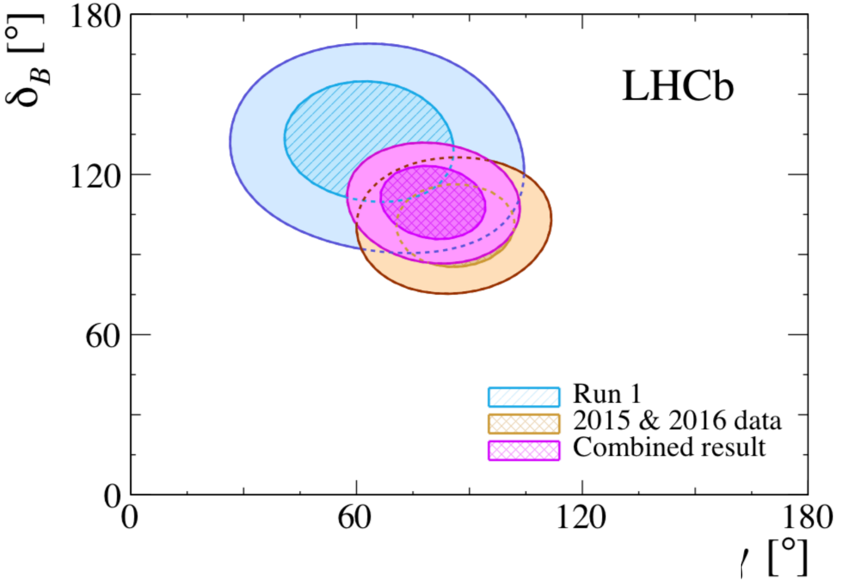


$$A_{B^-} \propto A_f + r_B e^{i(\delta_B-\gamma)}\overline{A}_f$$

arXiv:1806.01202



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

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

- **Flavour tagged TD analysis**

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

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

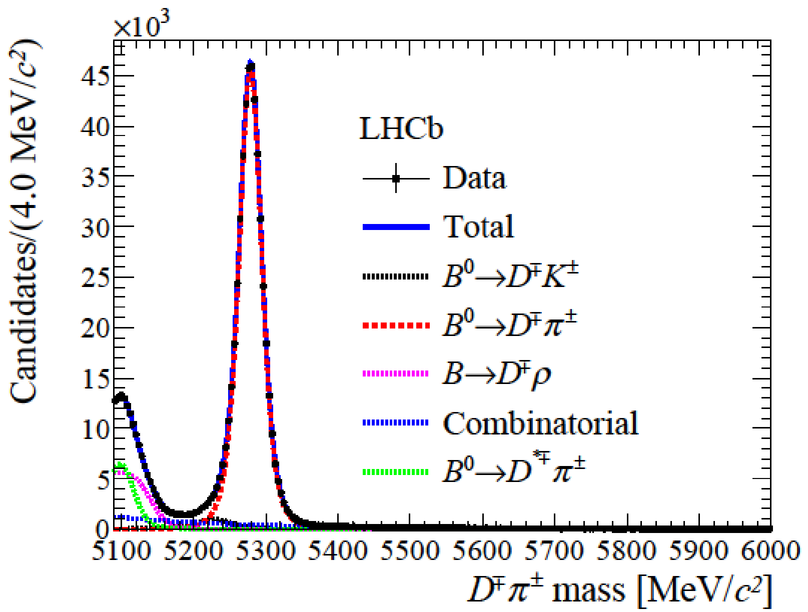
$$\Gamma_{B^0\to \bar{f}}(t) \propto e^{-\Gamma t}[1 + C_{\bar{f}}\cos(\Delta m t) - S_{\bar{f}} \sin(\Delta m t)]$$

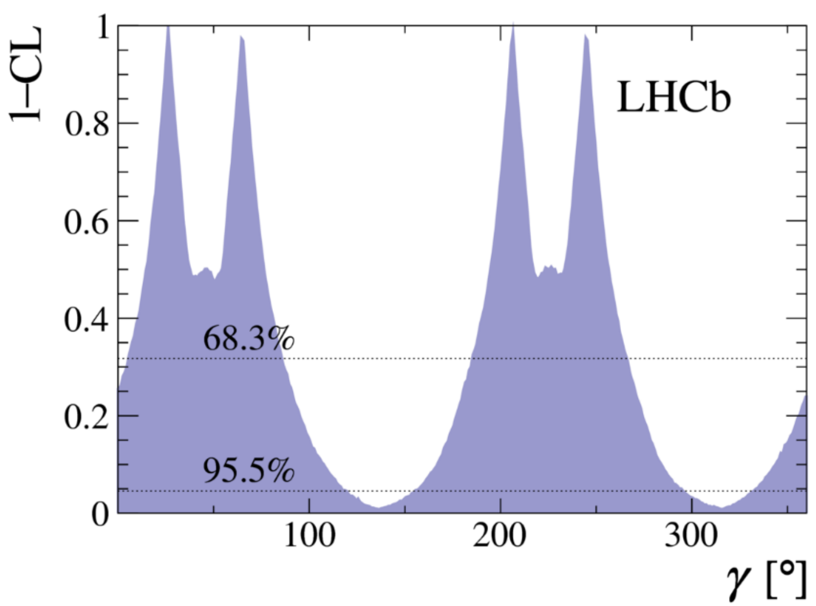
$$S_f = \frac{2r_{D\pi}sin[\delta - (2\beta+\gamma)]}{1+r_{D\pi}^2}$$

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

arXiv:1805.03448 Run I, 3 fb^{-1}

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





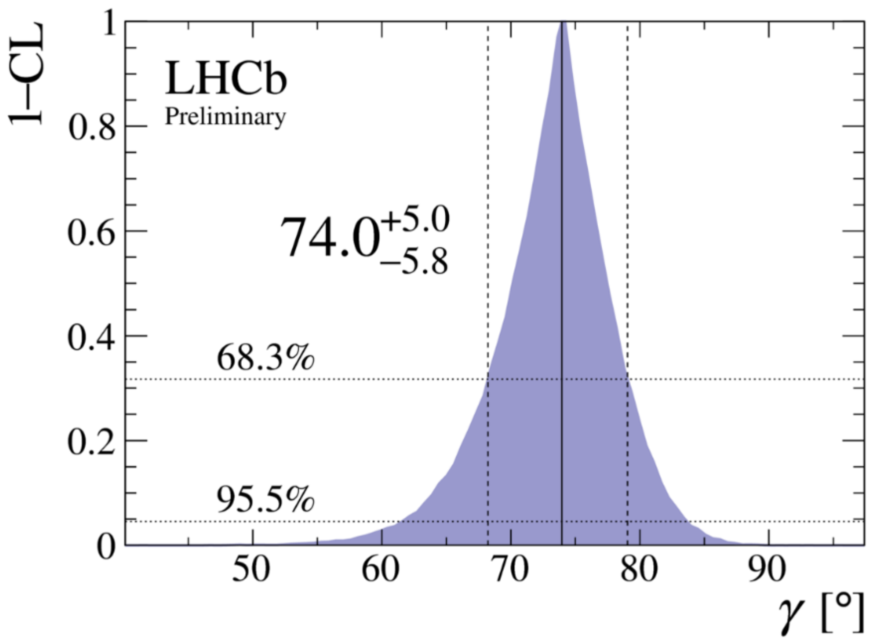
γ combination result

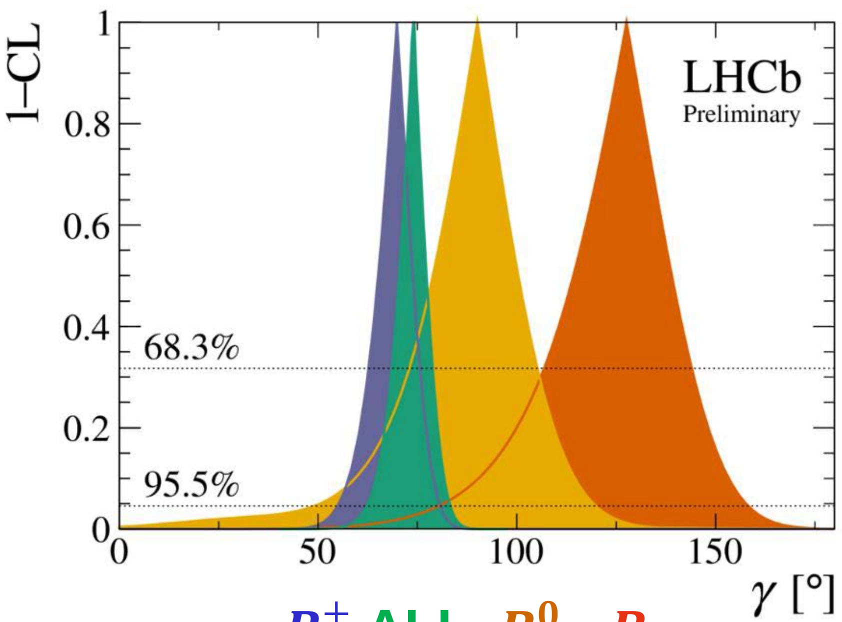
- **Most precise measurement from a single experiment**

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

LHCb-CONF-2018-002

- **WA:** $\gamma = (73.5^{+4.2}_{-5.1})^{\circ}$
- **Indirect:** $\gamma^{indirect} = (65.3^{+1.0}_{-2.5})^{\circ}$





$B^{\pm}$ **ALL** B^{0} B_{s}

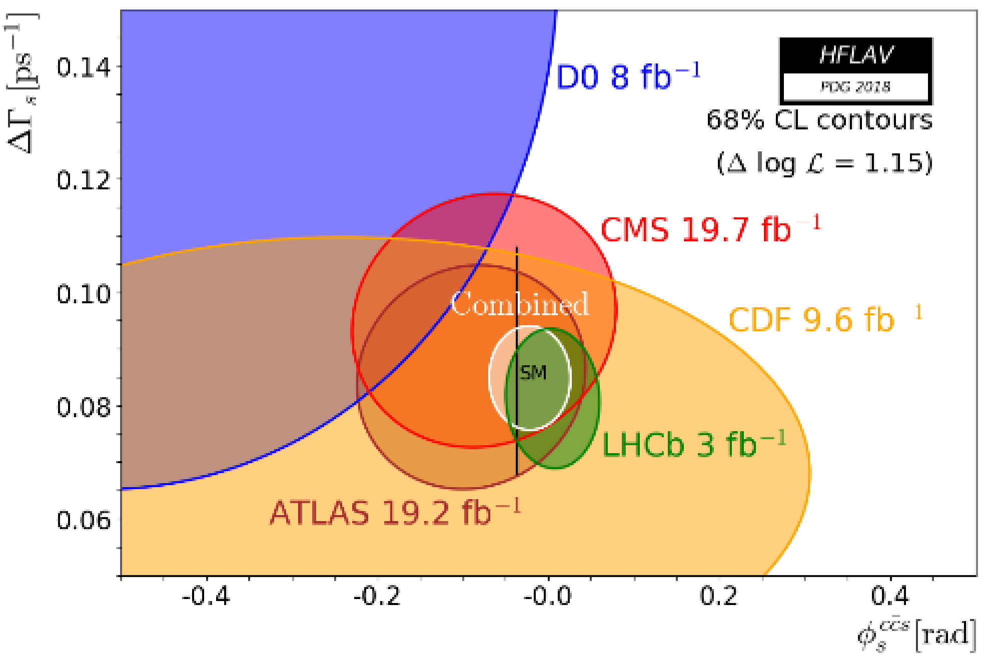
ϕ_s measurements

- **LHCb is dominating**
  - ✓ **Previously $B_s \to J/\psi\phi$ and $B_s \to J/\psi\pi^+\pi^-$** PRL 114 (2015) 041801
  - ✓ **Adding $B_s \to J/\psi K^+K^-$ above $\phi(1020)$** JHEP 08 (2017) 037

$\phi_s = 0.001 \pm 0.037$ rad

Run I, 3 fb^{-1}

- **Analysis of LHCb run II data ongoing**



- **World average**

$\phi_s = -0.021 \pm 0.031$ rad

- **SM prediction:**

$$\phi_s^{SM} = -2arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$
$$= -0.038 \pm 0.001 \text{ rad}$$

Charm mixing and CP violation

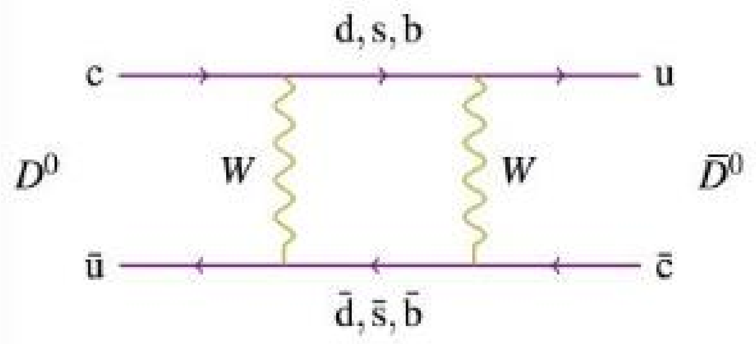
$D^0 - \bar{D}^0$ mixing

- **Mixing due to box diagram**

$|D_{1,2}> = p|D^0> \pm q|\bar{D}^0>$

$x = (m_2 - m_1)/\Gamma,\ y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$

$|x|^2 + |y|^2 \neq 0$ => mixing



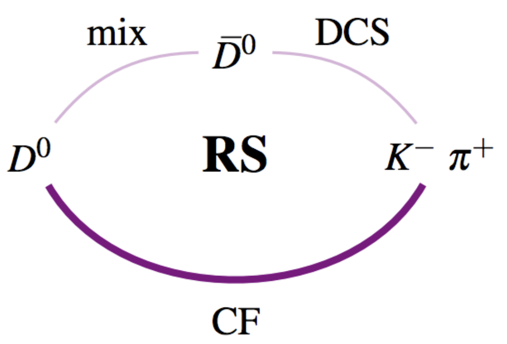
- **Ratio of WS to RS decay rates changes with proper decay time *t***

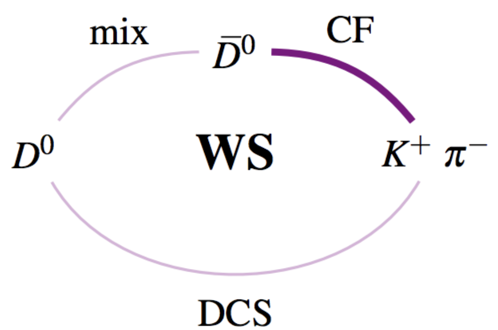
$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

$$x' = x\cos\delta + y\sin\delta$$

$$y' = y\cos\delta - x\sin\delta$$

$$\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} = -\sqrt{R_D}\, e^{-i\delta}$$





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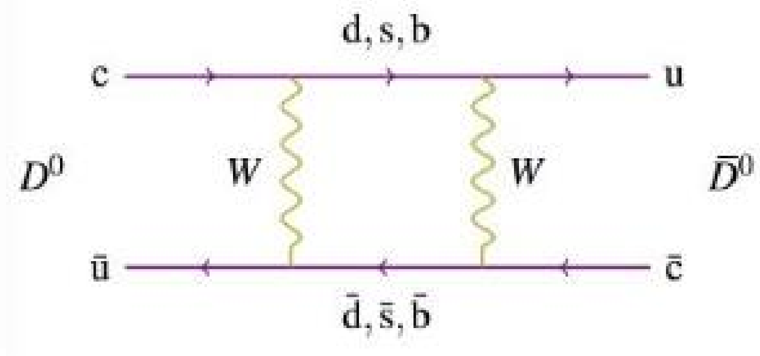

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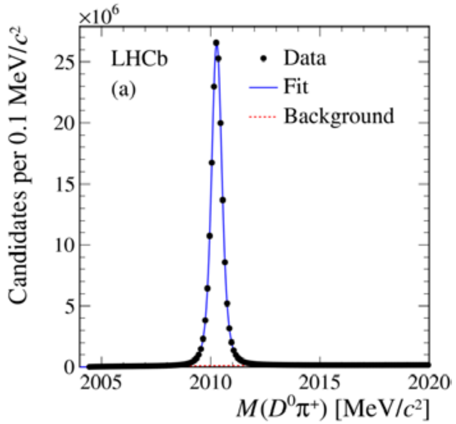
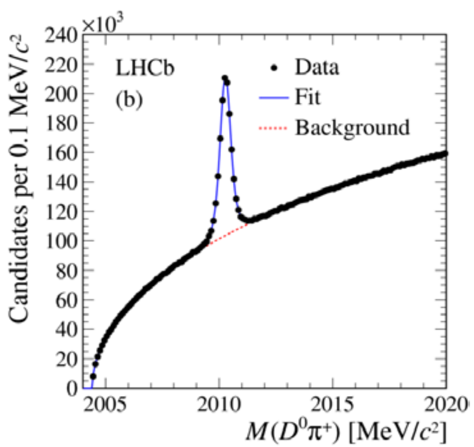
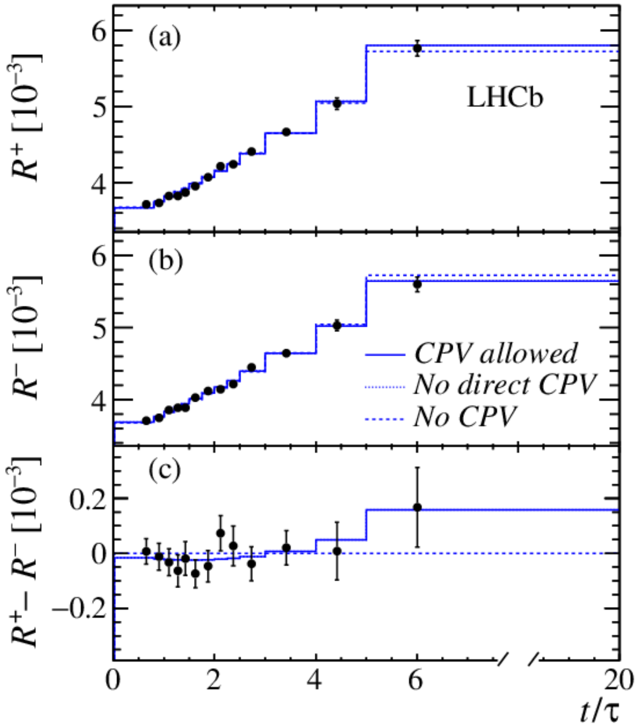
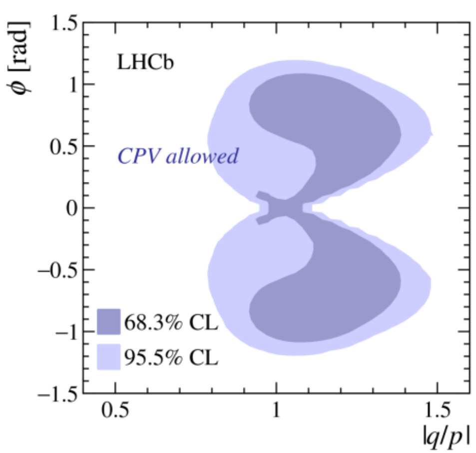




WS/RS fit results





PRD 97 (2018) 031101

Run I, 3 fb^{-1}

Run II, 2 fb^{-1}

- **Assuming CP invariance**

$$x'^2 = (3.9 \pm 2.7) \times 10^{-5}$$

$$y' = (5.28 \pm 0.52) \times 10^{-3}$$

$$R_D = (3.454 \pm 0.031) \times 10^{-3}$$

- **Direct CP asymmetry ~ 0**

$$A_D = \frac{R_D^+ - R_D^+}{R_D^+ + R_D^+} = (-0.1 \pm 9.1) \times 10^{-3}$$

- **Limits on indirect CPV**

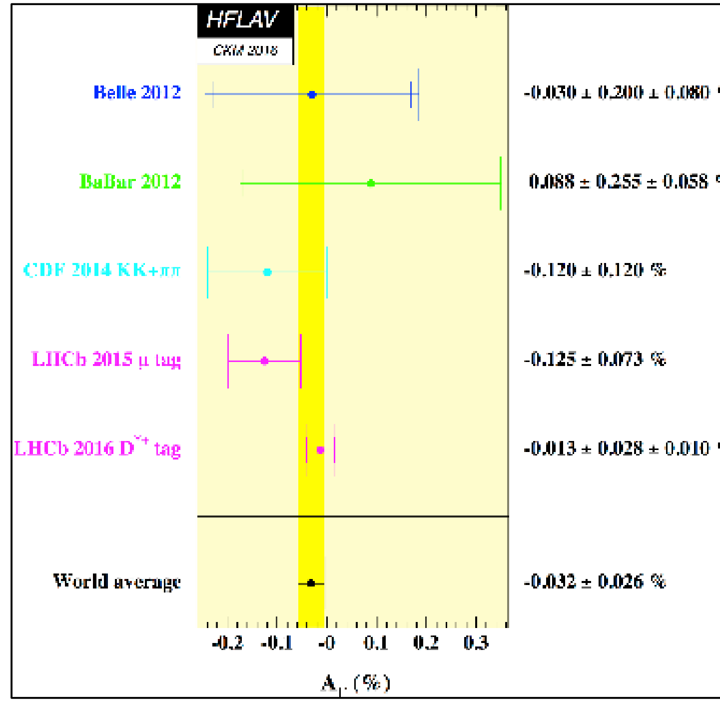
$$0.82 < \left|\frac{q}{p}\right| < 1.45 \text{ @95\% CL}$$

A_Γ: indirect CP violation

- Indirect CPV: $\left|\frac{q}{p}\right| \neq 1$ or $\sin\phi \neq 0$
- Width asymmetry $A_\Gamma \approx -x\sin\phi$

$$A_\Gamma = \frac{\hat{\Gamma}(\mathrm{D}^0 \to h^+h^-) - \hat{\Gamma}(\overline{\mathrm{D}}^0 \to h^+h^-)}{\hat{\Gamma}(\mathrm{D}^0 \to h^+h^-) + \hat{\Gamma}(\overline{\mathrm{D}}^0 \to h^+h^-)},\ \hat{\Gamma} = 1/\tau^{eff}$$

- LHCb results are most precise, compatible with CP conservation



D^* tag

$$A_\Gamma(K^+K^-) = (-0.030 \pm 0.032 \pm 0.010)\%$$
$$A_\Gamma(\pi^+\pi^-) = (+0.046 \pm 0.058 \pm 0.012)\%$$
$$A_\Gamma = (-0.013 \pm 0.028 \pm 0.010)\%$$

PRL 118 (2017) 261803

Run I, 3 fb^{-1}

μ tag

$$A_\Gamma(K^+K^-) = \left(-0.134 \pm 0.077^{+0.026}_{-0.034}\right)\%$$
$$A_\Gamma(\pi^+\pi^-) = \left(-0.092 \pm 0.145^{+0.025}_{-0.033}\right)\%$$
$$A_\Gamma = (-0.125 \pm 0.073)\%$$

JHEP 04 (2015) 043

Run I, 1 fb^{-1}

Direct CP violation

- **Time-integrated CPV in $D^0 \rightarrow K_S K_S$**

$$A_{CP}(K_S K_S) = 0.020 \pm 0.029 \pm 0.010$$

PRD 97 (2018) 031101

Run II, 2 fb^{-1}

- **Time-integrated CPV in $D^0 \rightarrow h^+ h^-$**

$$A_{CP}(K^+ K^-) = (0.04 \pm 0.12 \pm 0.10)\%$$

$$A_{CP}(\pi^+ \pi^-) = (0.07 \pm 0.14 \pm 0.11)\%$$

PLB 767 (2017) 167

Run I, 3 fb^{-1}

- **CPV measured in other decays**

✓ $A_{CP}(\Lambda_c^+ \rightarrow p K^+ K^-) - A_{CP}(\Lambda_c^+ \rightarrow p \pi^+ \pi^-)$ — JHEP 03 (2018) 182

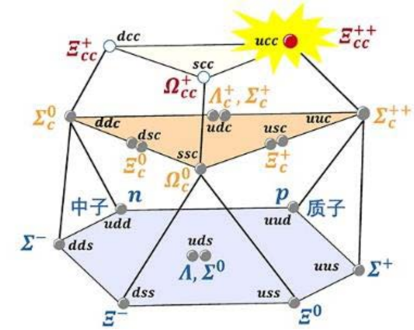
✓ **CPV in phase space of $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$** — PLB 769 (2017) 345

✓ $A_{CP}(\mathrm{h}^+ \mathrm{h}^- \mu^+ \mu^-)$ — arXiv:1806.10793

All results consistent with zero CP violation, though with poor precision

Hadron spectroscopy

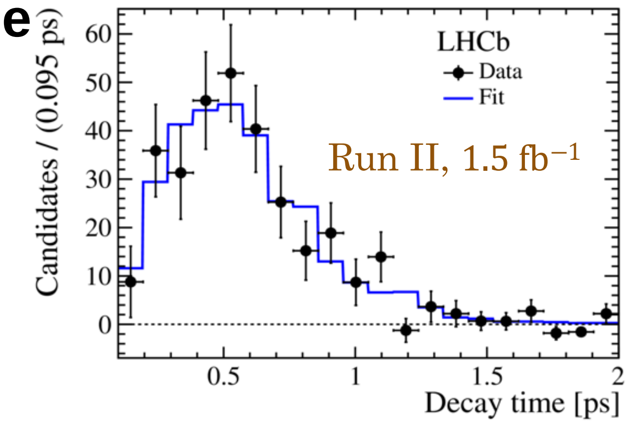
New Ξ_{cc}^{++} results



- $\Xi_{cc}^{++}(ucc)$ first discovered in $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ PRL 119(2017)112001

- Revisit same sample to measure lifetime
  $\tau(\Xi_c^+) = 256^{+24}_{-22} \pm 14$ fs
  - ✓ Theory predictions: [200-1050] fs
  - ✓ Conforming nature of weak decays

PRL 121 (2018) 052002



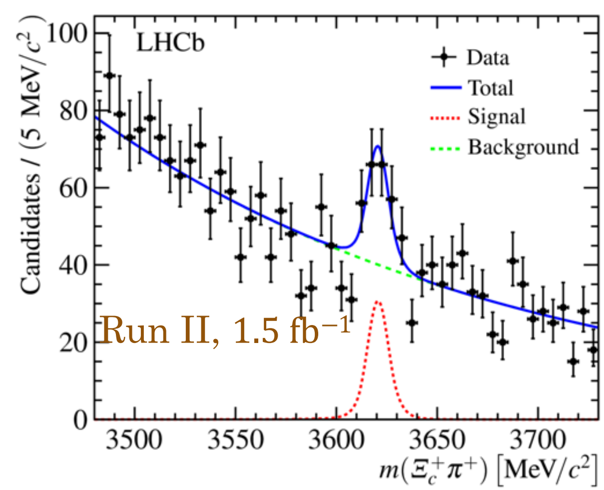
- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ observation (5.9σ)
  $m(\Xi_{cc}^{++}) = 3620.6 \pm 1.5 \pm 0.4 \pm 0.3$ MeV

$$\frac{B(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times B(\Xi_c^+ \to p K^- \pi^+)}{B(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times B(\Lambda_c^+ \to p K^- \pi^+)}$$

$$= 0.035 \pm 0.009 \pm 0.003$$

  - ✓ In agreement with prediction in F.-S. Yu, CPC 42 (2018) 051001

arXiv:1807.01919



Ω_c^0 lifetime

PRL 121 (2018) 072002

Run I, 3 fb^{-1}

- **Most studies predict the hierarchy**

  $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$

- **LHCb measured**

  $$\frac{\tau(\Omega_c^0)}{\tau(D^+)} = 0.258 \pm 0.023 \pm 0.010$$

  $\tau(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2$ fs

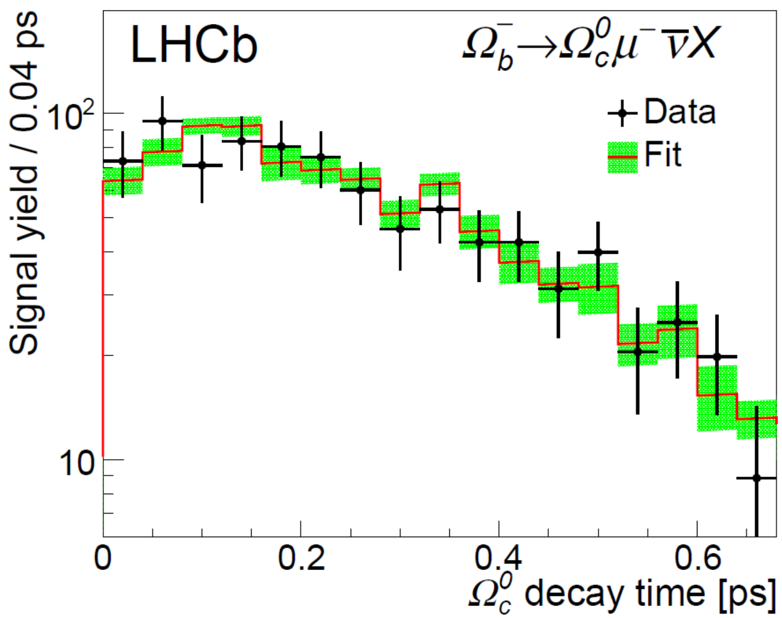
  $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$

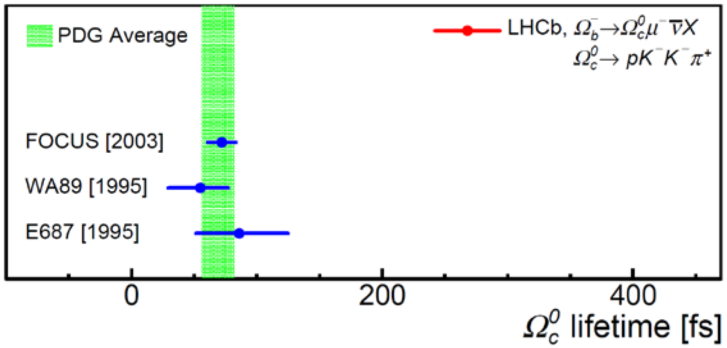
- **Four time larger than PDG value:**

  $\tau(\Omega_c^0) = 69 \pm 12$ fs

- **Consistent with calculation**

  H-Y Cheng, arXiv: 1807.00916





New Ξ_b^- state

arXiv:1805.09418

Run I, 3 fb^{-1}

Run II, 1.5 fb^{-1}

- **Hadronic channel**

  $\Xi_b(6227)^- \to (\Lambda_b^0 \to \Lambda_c^+\pi^-)K^-$

  $m_{\Xi_b(6227)} = 6226.9 \pm 2.0 \pm 0.3 \pm 0.2$ MeV

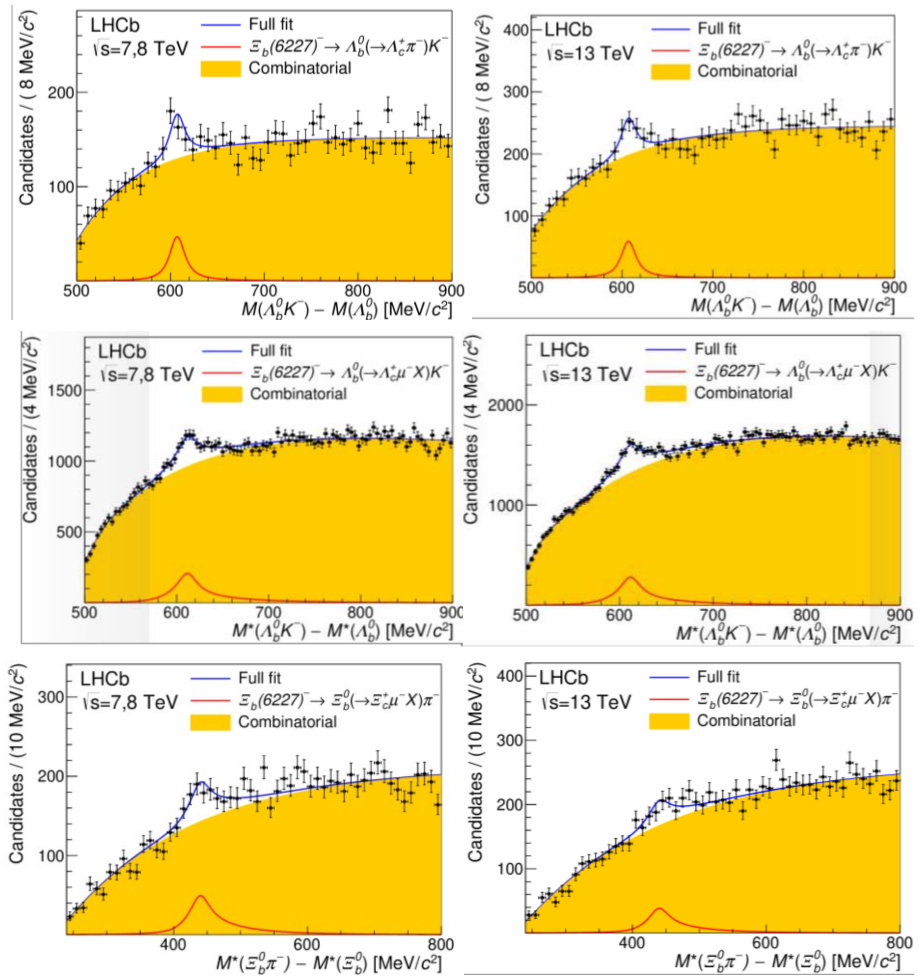
  $\Gamma_{\Xi_b(6227)} = 18.1 \pm 5.4 \pm 1.8$ MeV

- **Semileptonic channel**

  $\Xi_b(6227)^- \to (\Lambda_b^0 \to \Lambda_c^+\mu^- X)K^-$

  $\Xi_b(6227)^- \to (\Xi_b^0 \to \Xi_c^+\mu^- X)\pi^-$

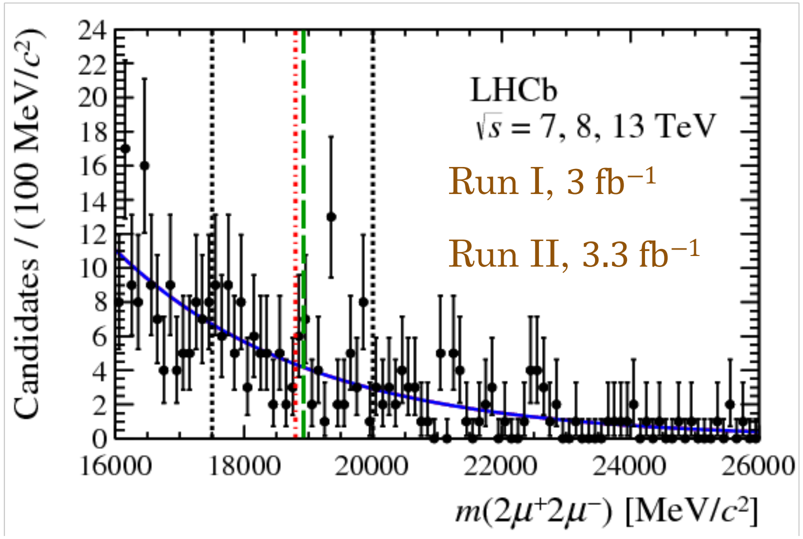
- **Consistent with strong decay of radially excited $\Xi_b(2S)$ or orbitally excited $\Xi_b(1P)$**

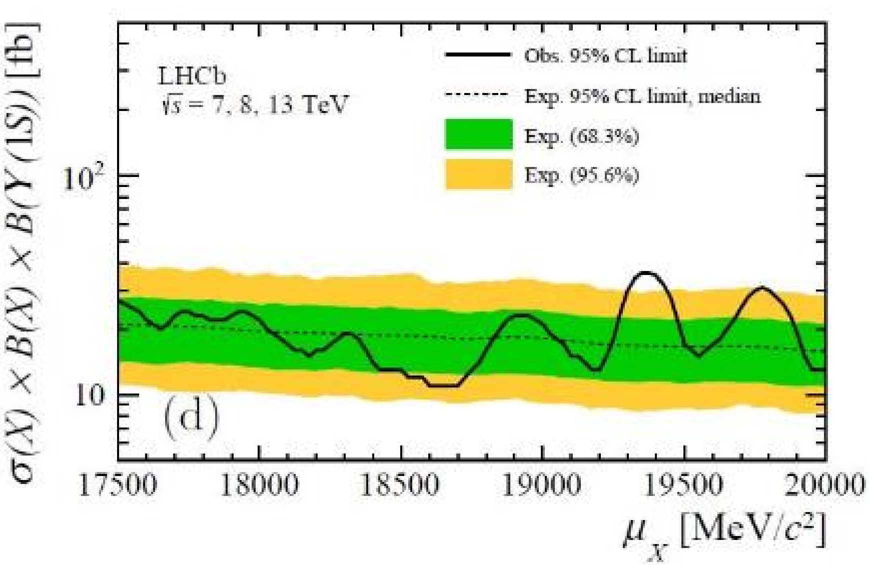


Search for $X_{b\bar{b}b\bar{b}}$

arXiv:1806.09707

- CMS reported a peak at 18 GeV in $\Upsilon(1S)\mu^+\mu^-$ final state in APS April meeting 2018
  - Tetraquark with $b\bar{b}b\bar{b}$ quark concent?
- LHCb searched for $X \to (\Upsilon(1S) \to \mu^+\mu^-)\mu^+\ \mu^-$
- No signal is observed
  - ✓ Set upper limit on production cross-section in forward region (2<η<5) as a function of *X* mass





Five narrow Ω_c^0 states

- Ω_c^0: **ccs quark content**
- **Only Ω_c^0 and $\Omega_c(2770)^0$ observed , assumed to be $1/2^+$and $3/2^+$**
- **LHCb studied mass spectrum of**
  $(\Xi_c^+ \to pK^-\pi^+)K^-$

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		<1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		<2.6 MeV, 95% C.L.
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

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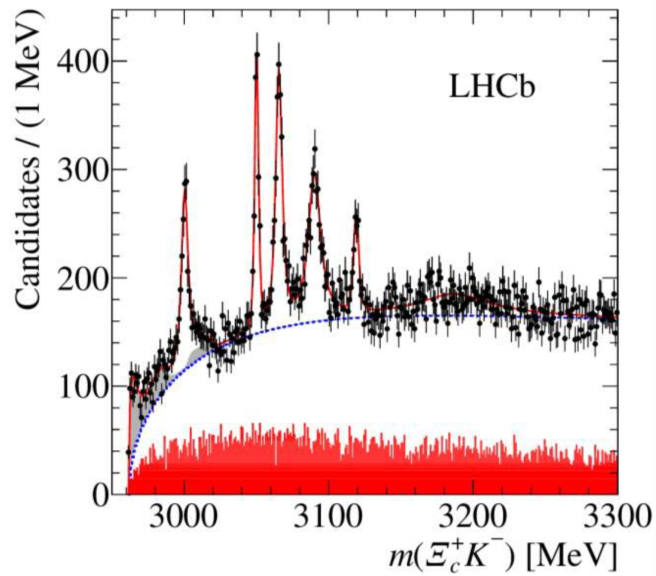
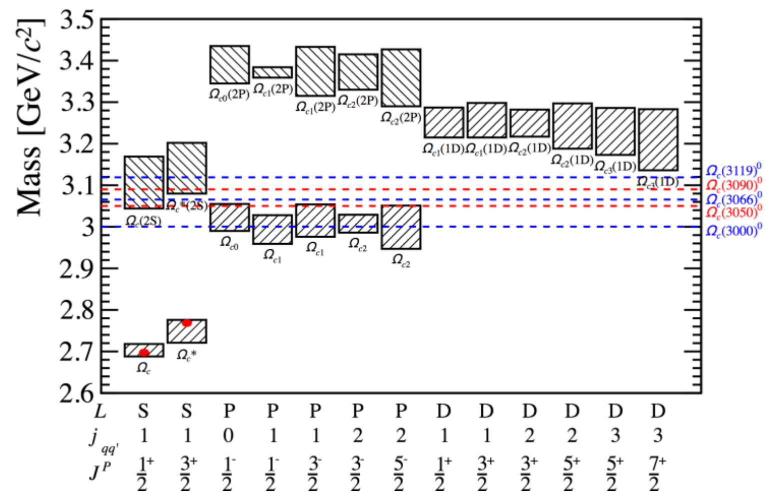
Run I, 3 fb^{-1} + Run II, 0.3 fb^{-1}

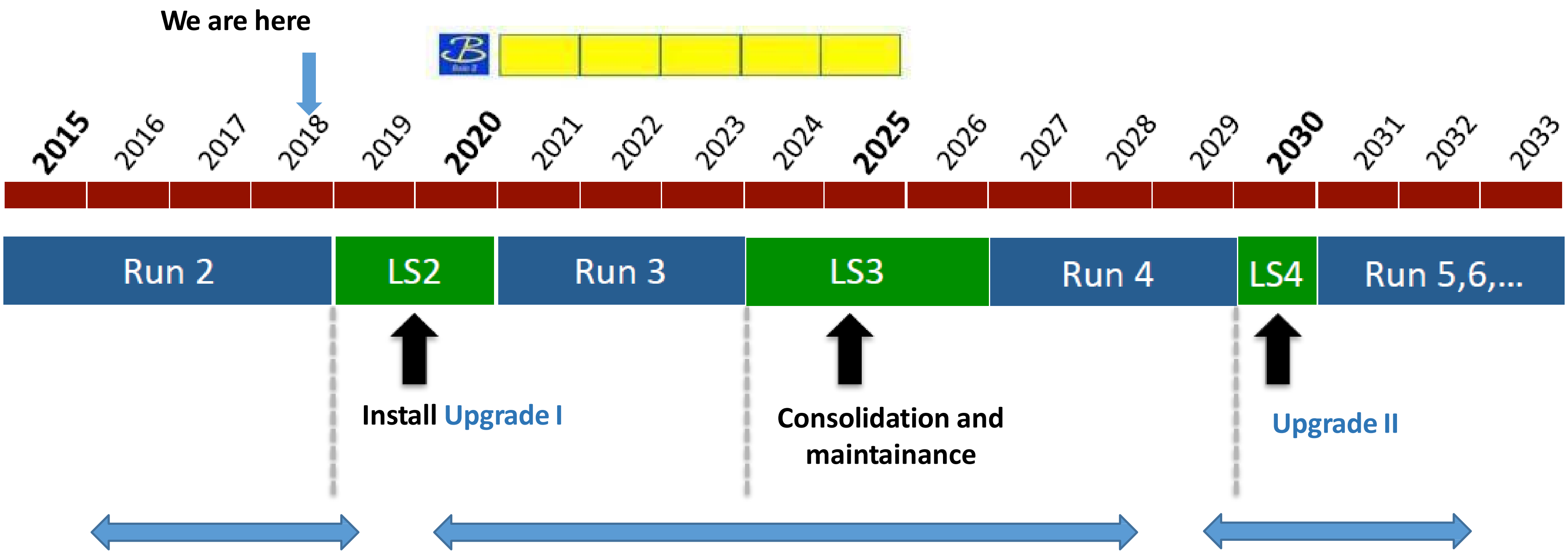




- **Spin-parity info needed for interpretation**

Future upgrades of LHCb

LHCb timeline



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

1.1 visible interactions / crossing

8 fb^{-1} collected

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

5.5 visible interactions / crossing

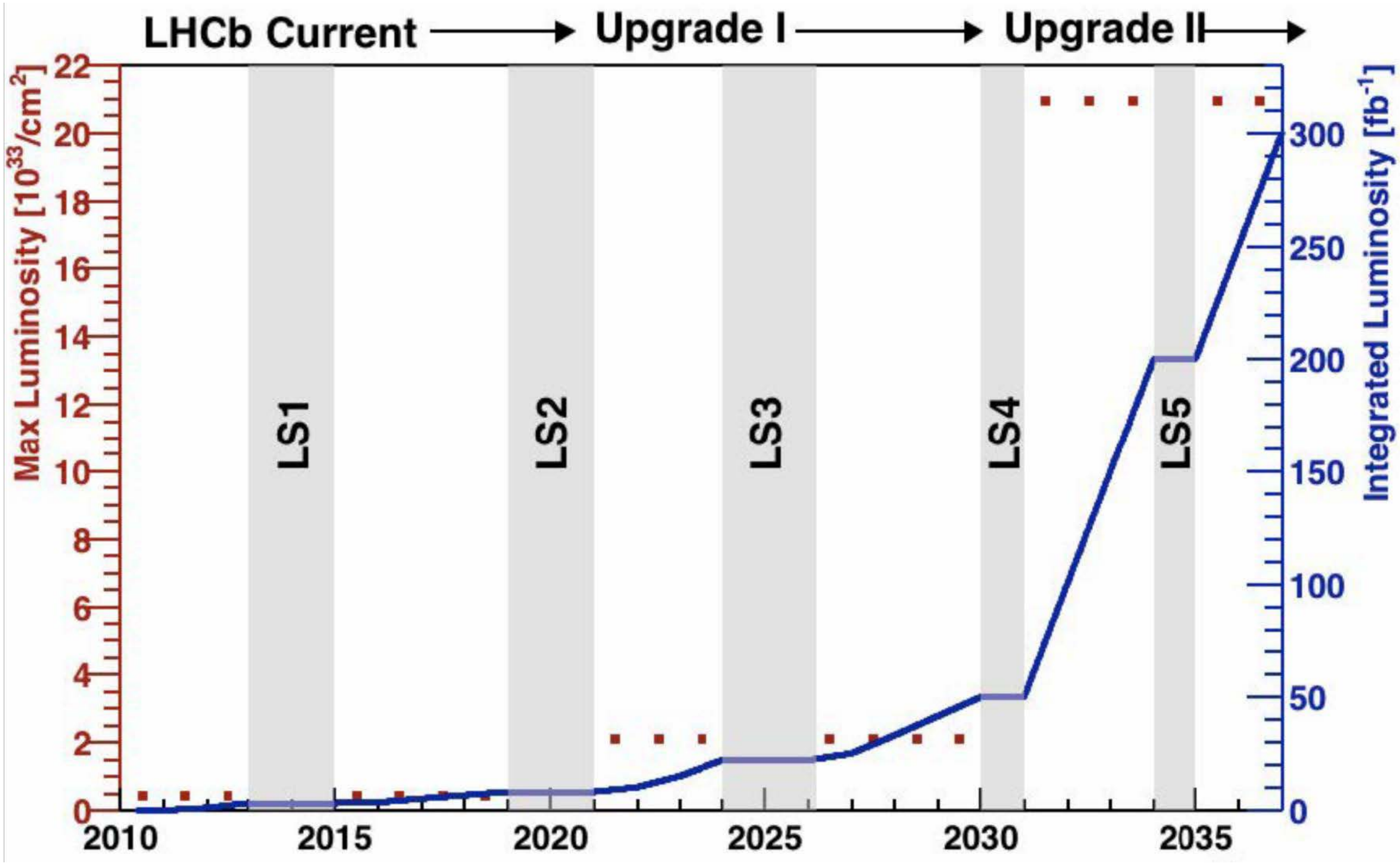
50 fb^{-1} collected

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

55 visible interactions / crossing

300 fb^{-1} collected

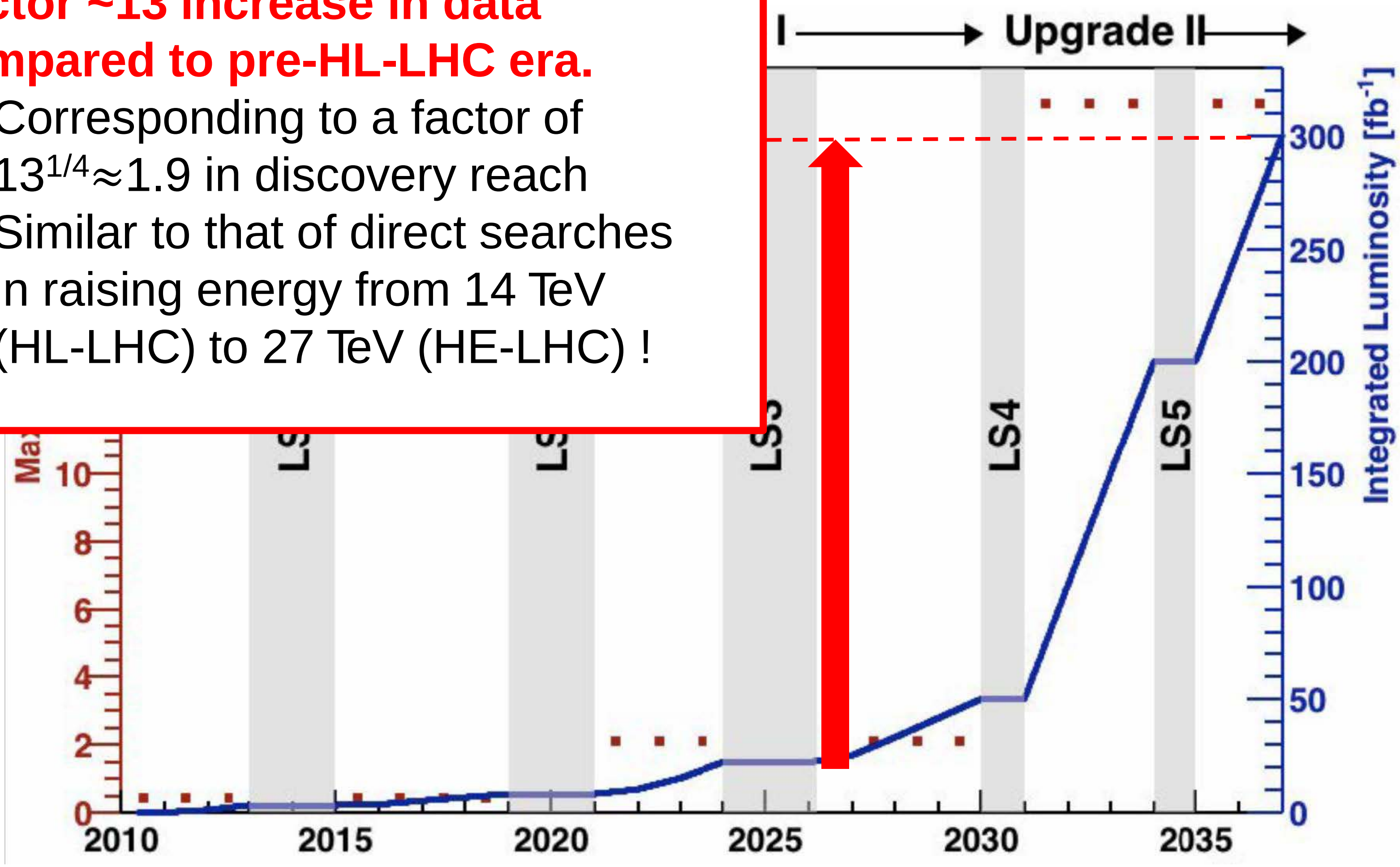
Luminosity vs year



Luminosity vs year

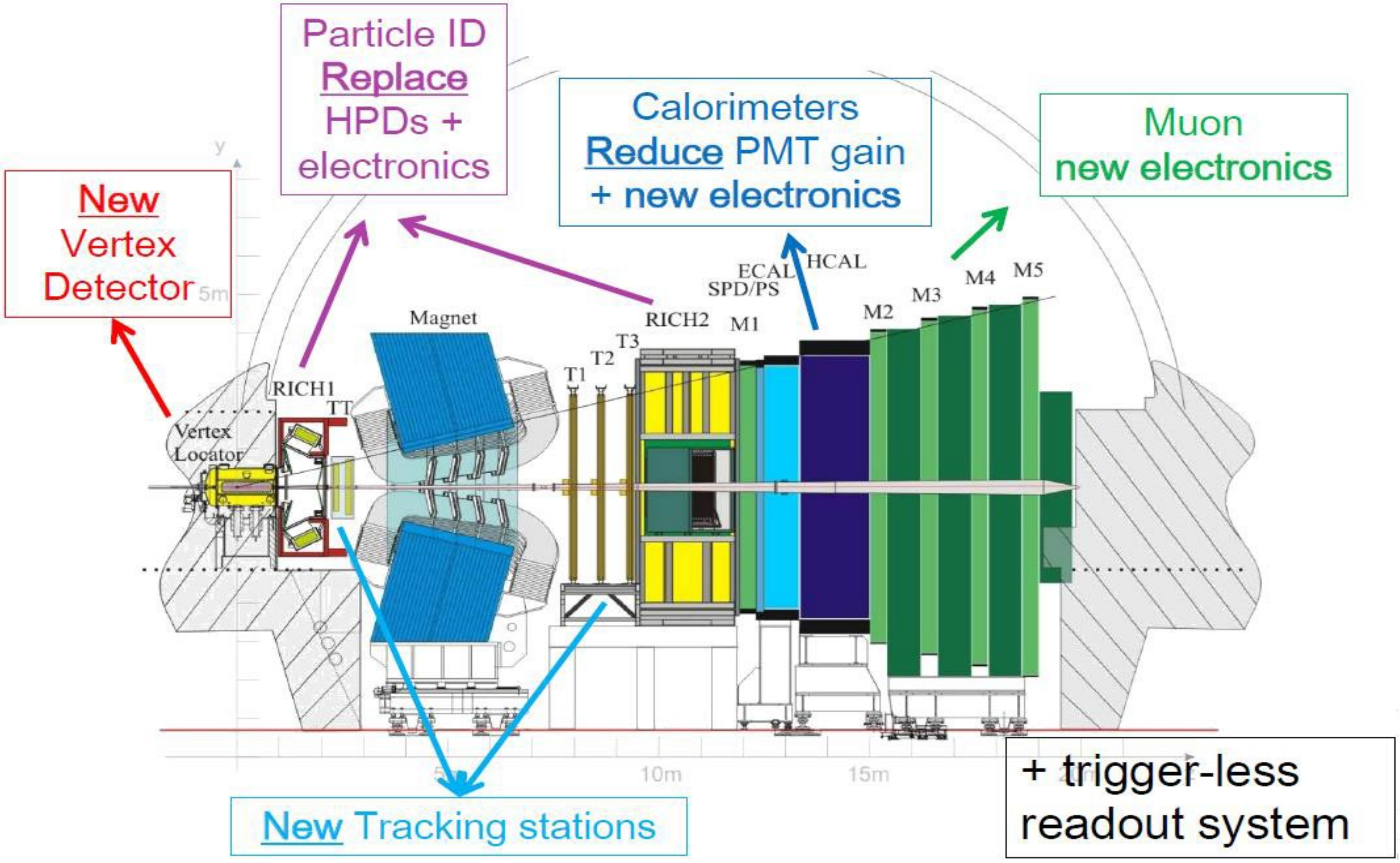
Factor ~13 increase in data compared to pre-HL-LHC era.

- Corresponding to a factor of $13^{1/4} \approx 1.9$ in discovery reach
- Similar to that of direct searches in raising energy from 14 TeV (HL-LHC) to 27 TeV (HE-LHC) !

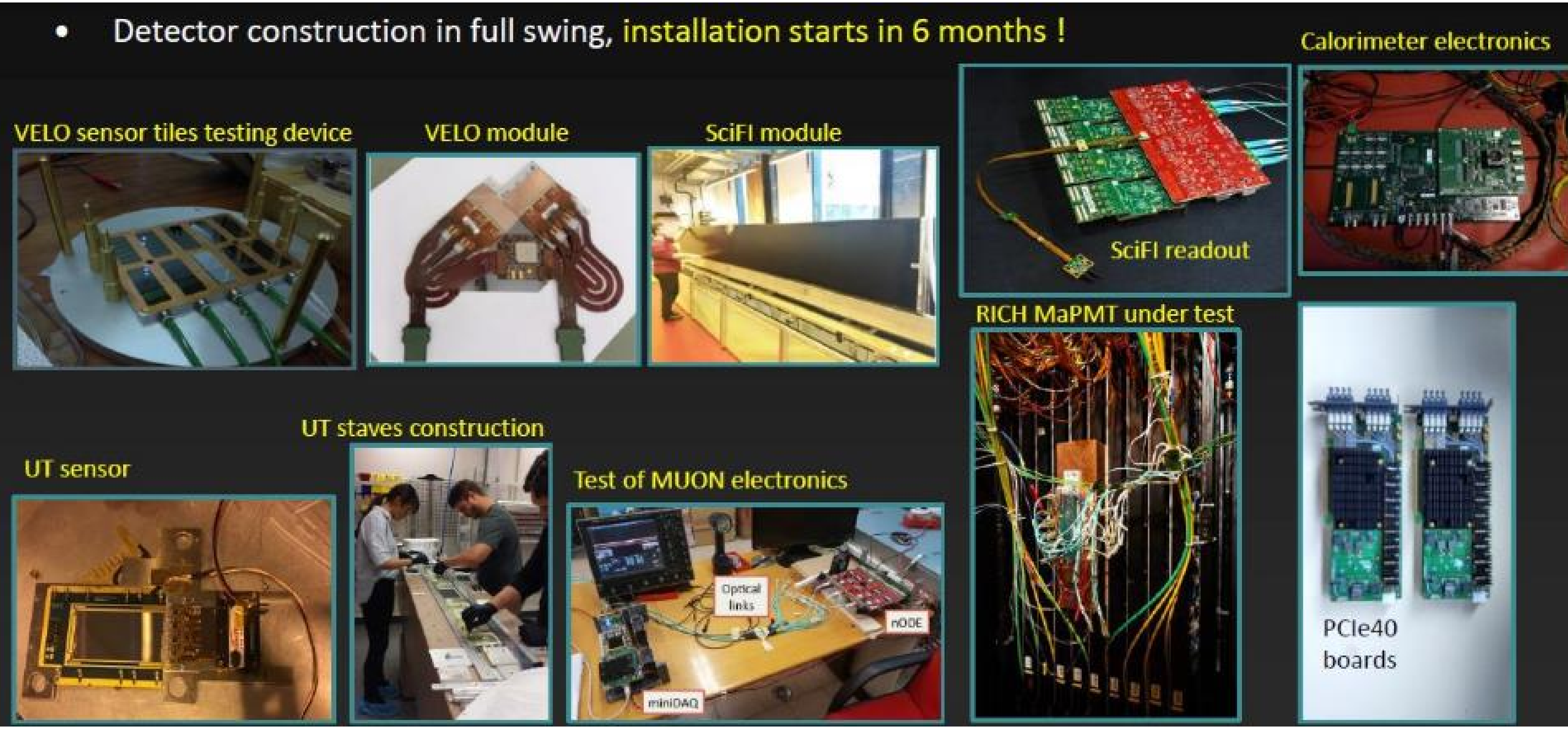


Upgrade I detector

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



Upgrade I: towards installation



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**

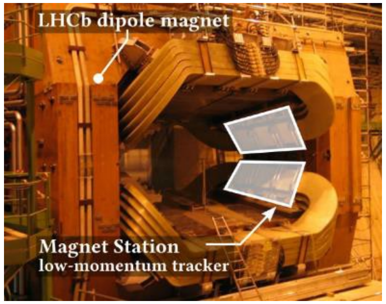
  Increased acceptance

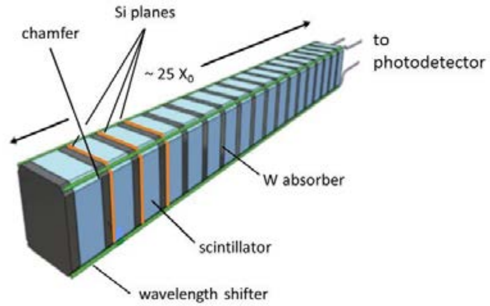
  Added Magnet stations

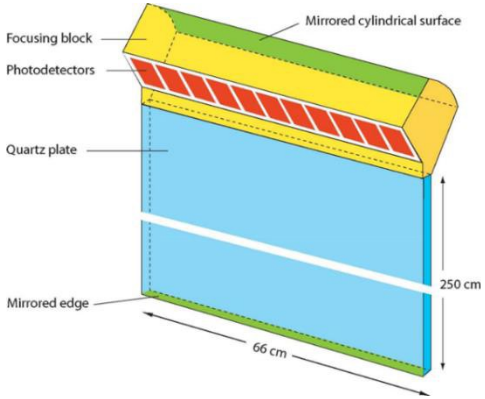
  Approach closer to beam pipe

  Removal of VELO RF foil

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

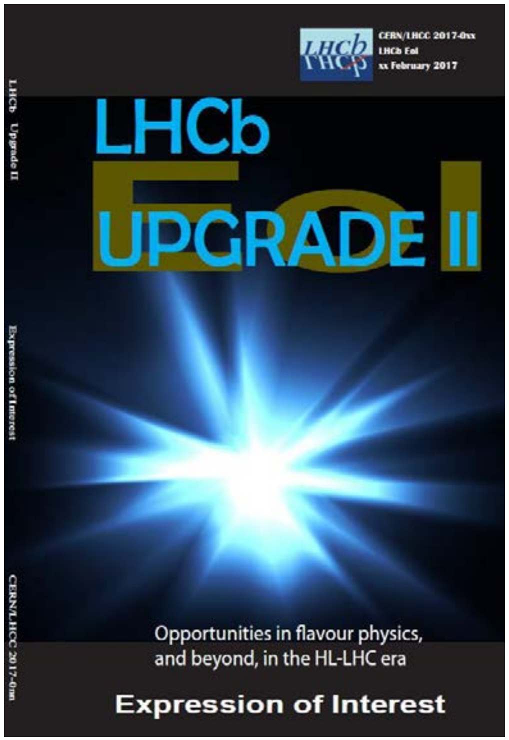






Much R&D required to achieve higher granularity, higher radiation resistance, fast timing

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**

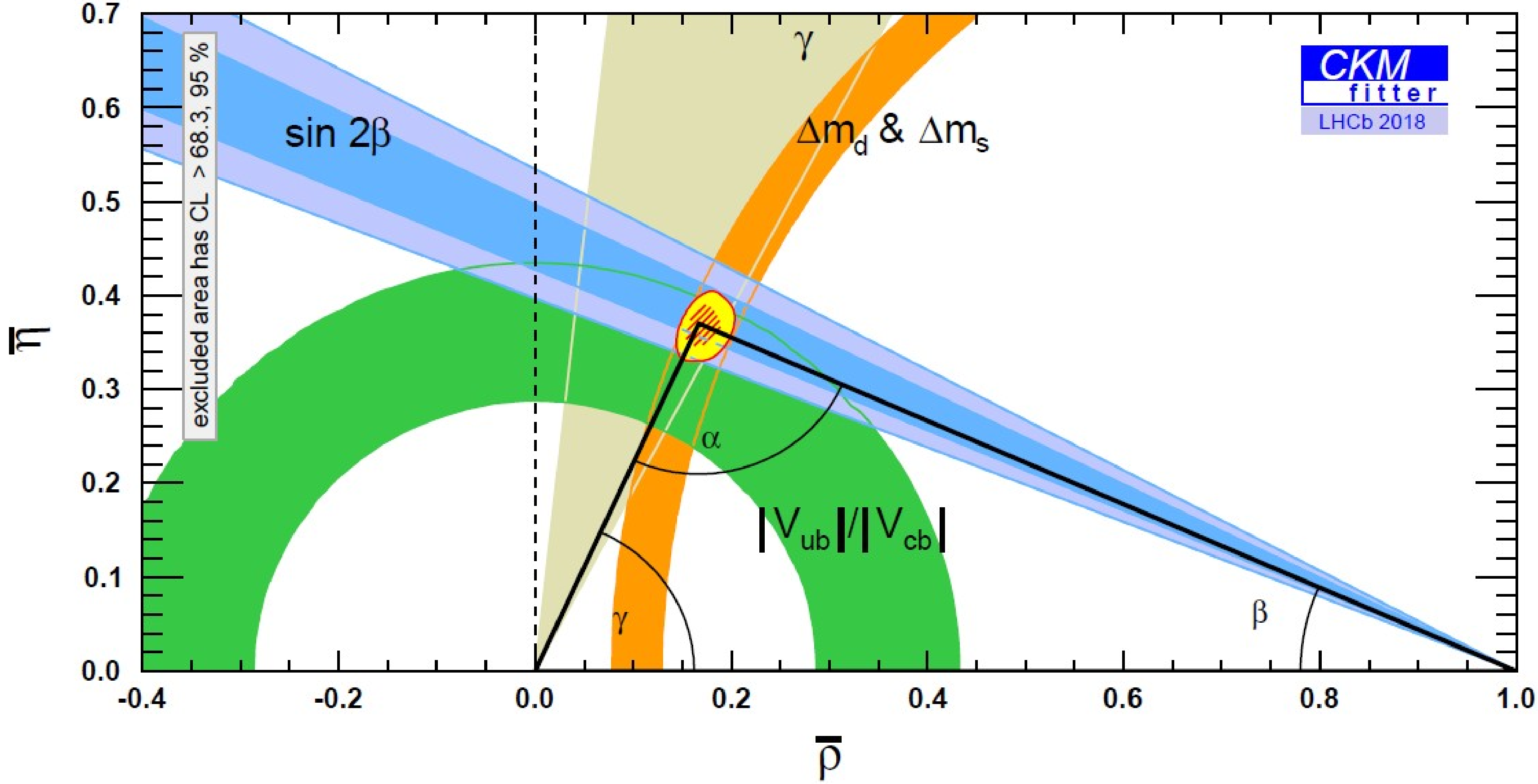
- **Fully exploit the HL-LHC for topics beyond flavour physics**

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].

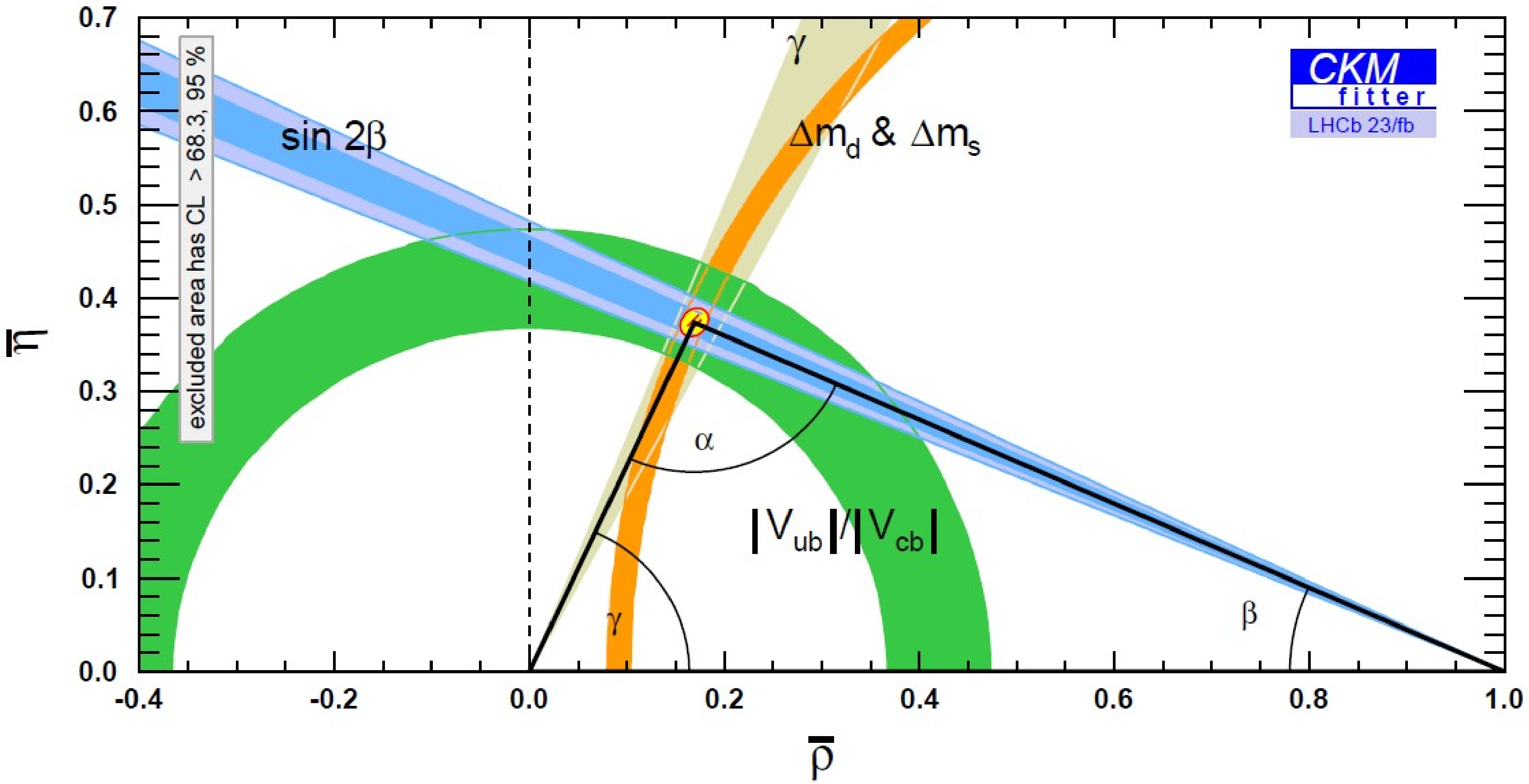
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, 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}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	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}	–

Evolution of the UT: current precision

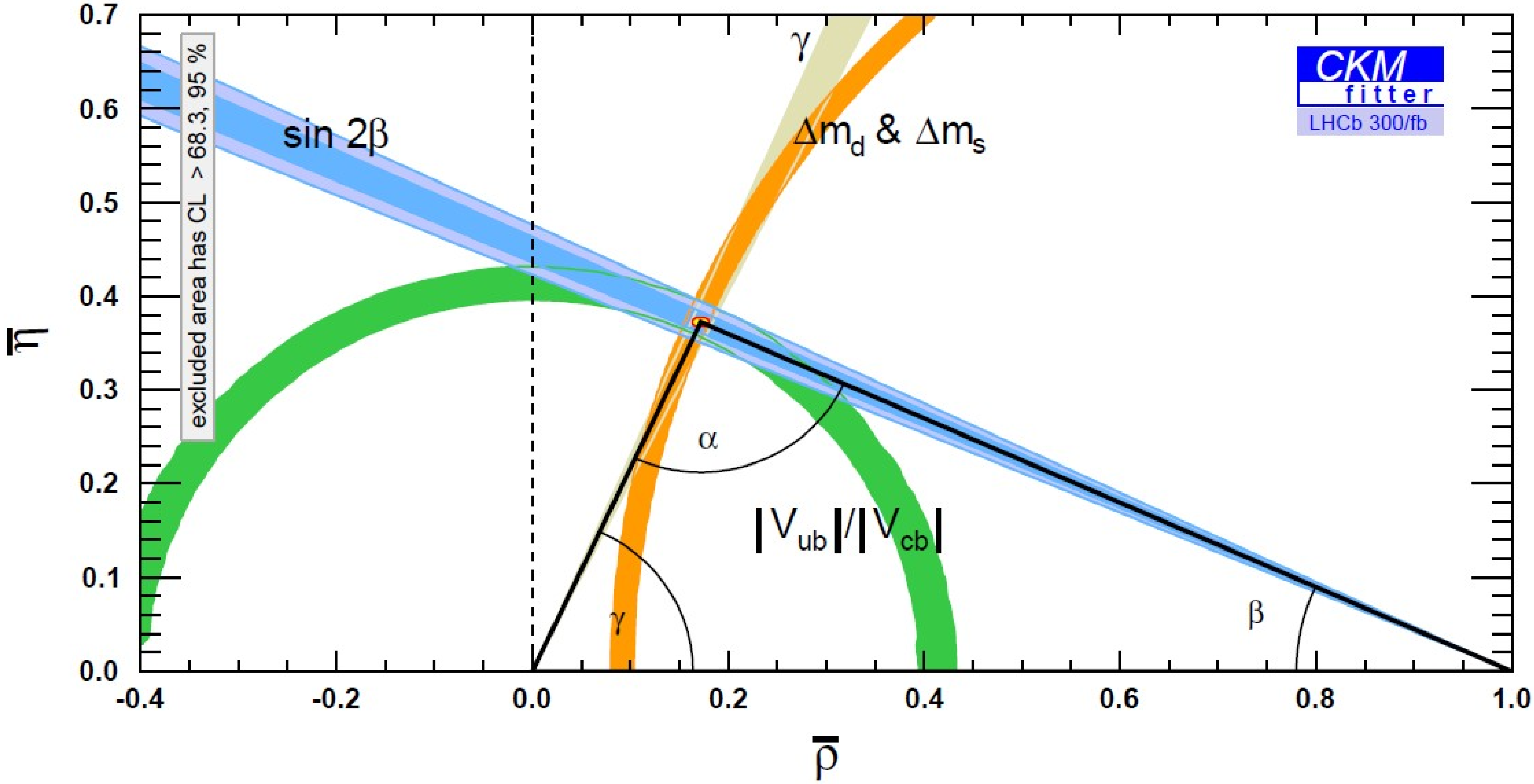


Evolution of the UT: 23 fb^{-1}

(End of Upgrade Ia)



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



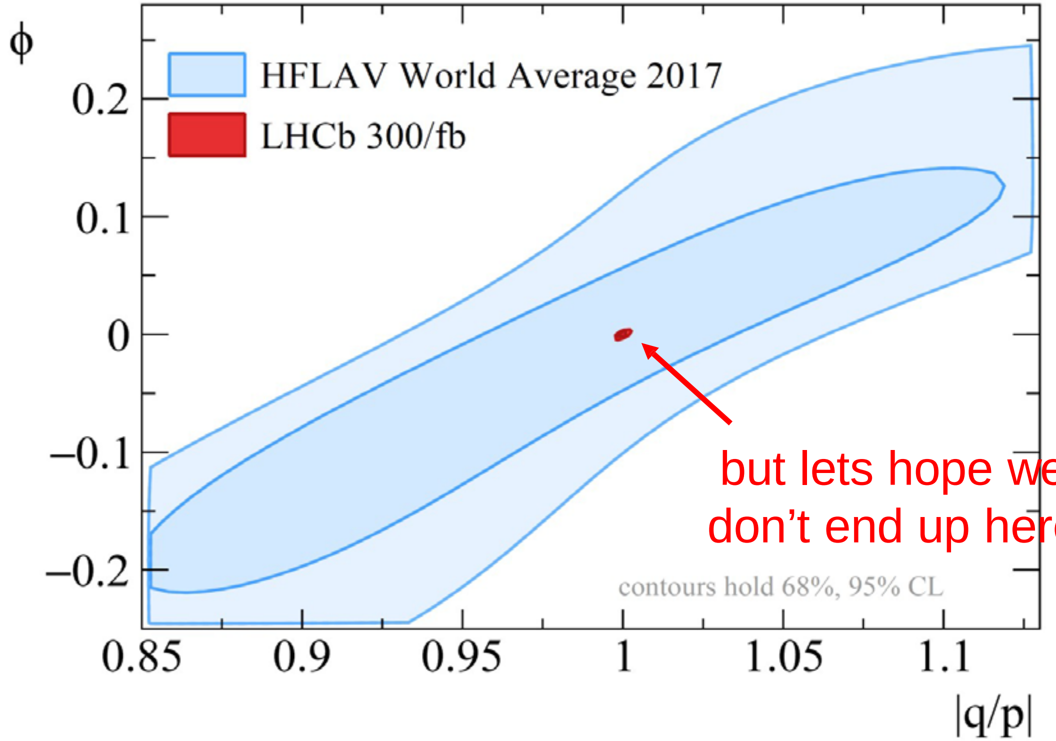
Indirect charm CP violation

- **Predicted to be ~10^{-4} in the Standard Model**
- $\sigma_{A_\Gamma} \sim 10^{-5}$ **with 300 fb^{-1}**

$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to h^+h^-) - \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}$$

- $D^0 - \bar{D}^0$ **mixing parameter:**

$$\sigma_\phi \sim 0.1^\circ, \ \sigma_{\left|\frac{q}{p}\right|} \sim 0.001$$

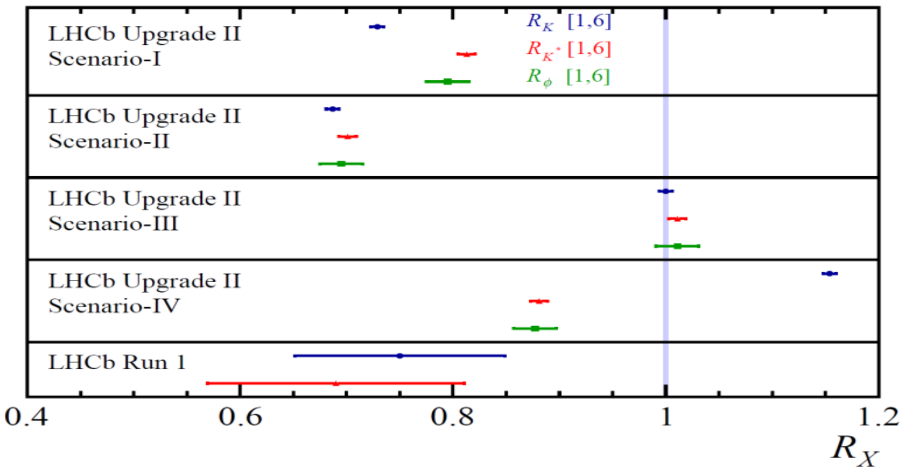


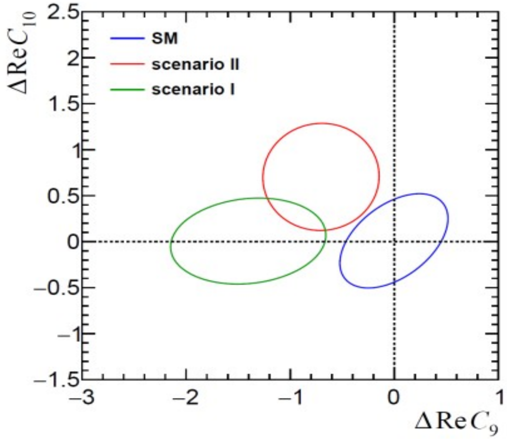
but lets hope we don't end up here

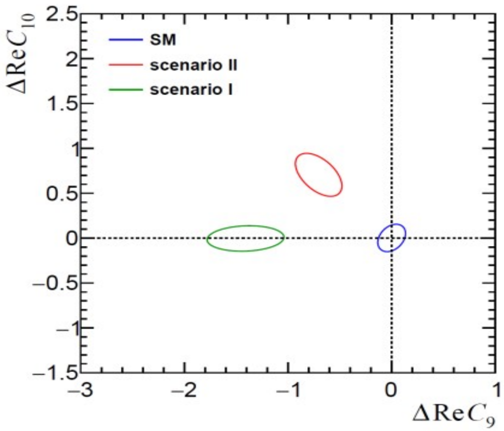
Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

Lepton universality violation

Improved ECAL will allow LUV observables (R_K, R_{K^*}, R_ϕ) to be measured with high precision, which can provide discrimination of NP models (scenarios with different Wilson coefficients for illustration)





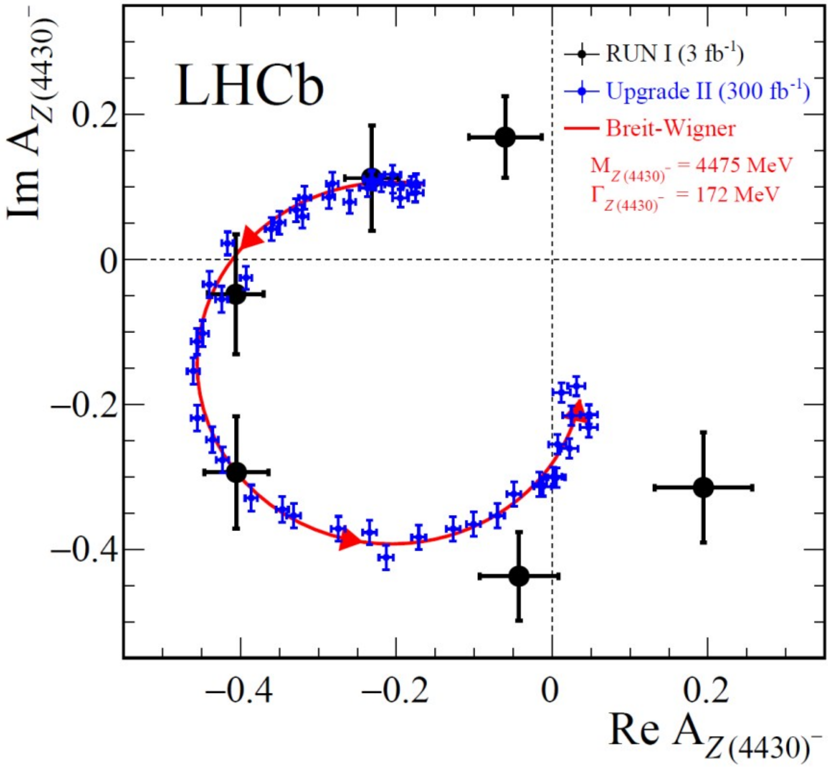


$$\Delta\mathrm{Re}C_{9(10)} = \mathrm{Re}C_9^{\mu} - \mathrm{Re}C_9^{e}$$

Spectroscopy

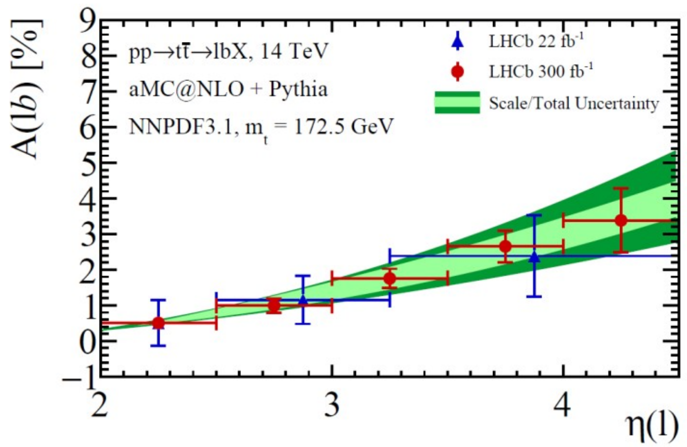
High yields in a wide range of decay modes make precision amplitude studies possible

Decay mode	LHCb 300 fb^{-1}	Belle II 50 ab^{-1}
$B^+ \to X(3872)(\to J/\psi \pi^+\pi^-)K^+$	200k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	4.8M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	100	—
$\Lambda_b^0 \to J/\psi\, pK^-$	5M	—
$\Xi_b^- \to J/\psi\, \Lambda K^-$	62k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+\pi^+$	90k	<6k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	600	—

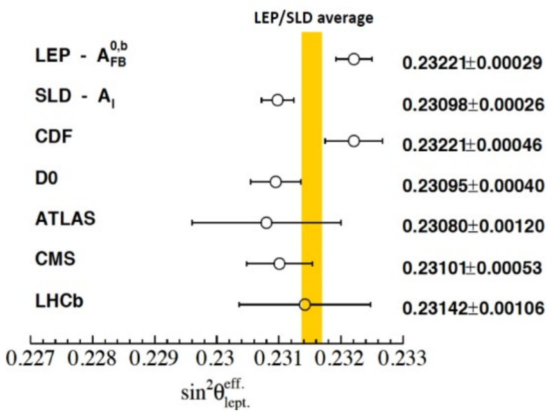


Forward and high p_T physics

Top physics in the forward

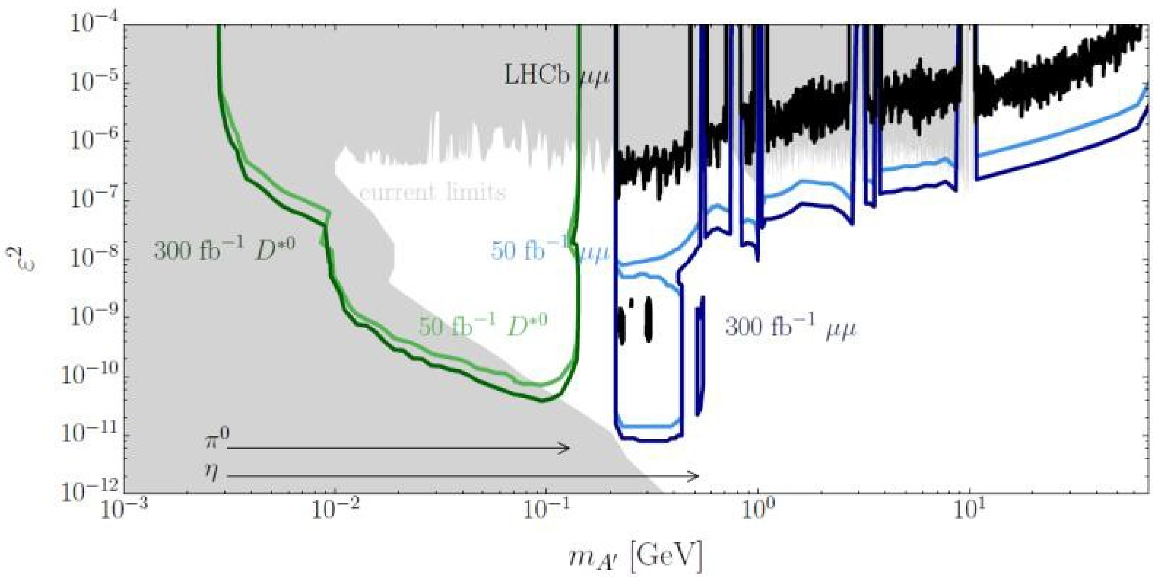


Precision measurement of $\sin^2\theta_W$



LHCb run1 only. Precision improved to 5×10^{-5} with 300 fb^{-1}

Dark photon search



And much more

- ✓ W mass measurement
- ✓ W/Z production
- ✓ Higgs to $c\bar{c}$
- ✓ …

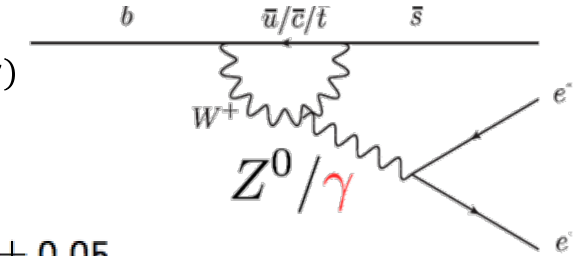
LHCb is and will continue to be a GPD!

Summary

- A consistent pattern of anomalies are seen in $b \to s\, l^+ l^-$
  - ✓ Differential branching fractions, angular observable, LFUV
- New physics explanation emerges
  - ✓ $C_{9\mu}^{NP} \neq 0$ preferred
  - ✓ Plausible scenarios: leptoquark, Z', composite Higgs
- Test of CKM mechanism approaches higher and higher precision
  - ✓ Particularly benefitting from improvement in β and γ
- LHCb is not not just about B. There have been fruitful studies of charm, spectroscopy and more
- With the anticipated upgrades, LHCb will run for two more decades, accumulating 300 fb^{-1}
  - ✓ New physics has no place to hide!

Backup slides

Angular analysis: $B^0 \to K^{*0} e^+ e^-$



- $A_T^{(2)}$ and A_T^{Im} in $q^2 < 1$ GeV region sensitive to $C_7^{(\prime)}$

$$A_T^{(2)}(q^2 \to 0) = \frac{2\,\mathrm{Re}\,(\mathcal{C}_7 \mathcal{C}_7'^{*})}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

$$A_T^{\mathrm{Im}}(q^2 \to 0) = \frac{2\,\mathrm{Im}\,(\mathcal{C}_7 \mathcal{C}_7'^{*})}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

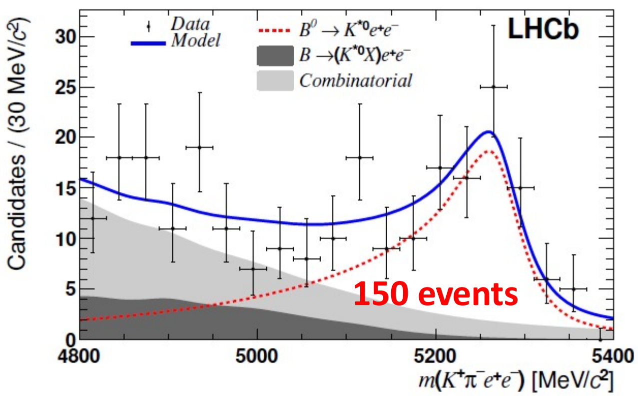
$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$

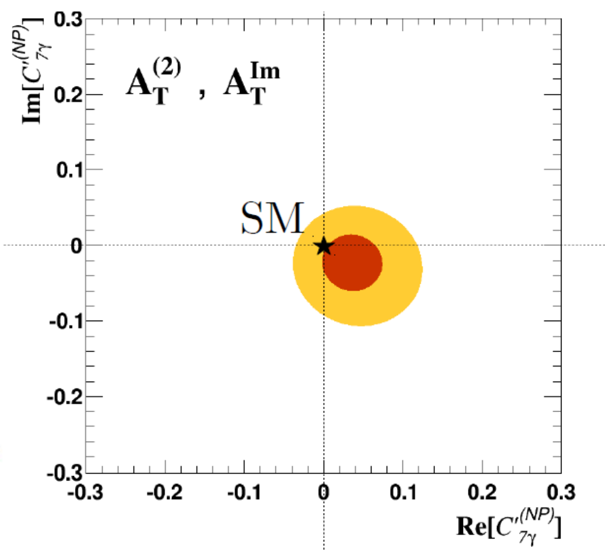
$$A_T^{\mathrm{Im}} = +0.14 \pm 0.22 \pm 0.05$$

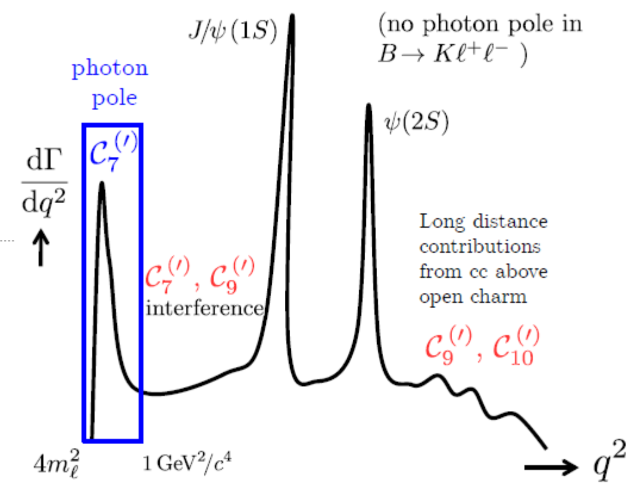
Compatible with SM ($\simeq 0$)

JHEP 04 (2015) 064

Run 1, 3 fb^{-1}







Compatible with the SM predictions

[Adapted from Jäger and Camalich, arXiv:1412.3183]

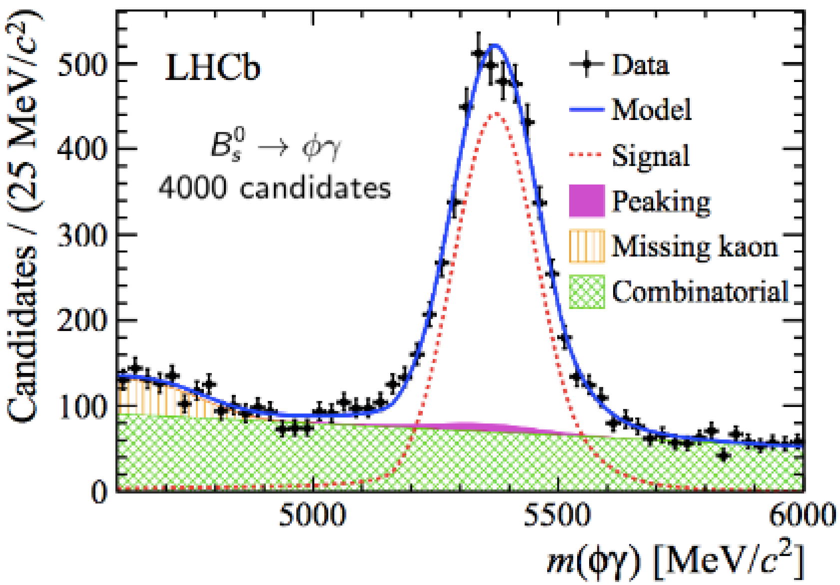
$B_s \to \phi\gamma$

- A_Δ sensitive to right-handed BSM contribution

$$\Gamma_{B_s^0 \to \phi\gamma}(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\Delta\Gamma_s t/2\right) - \mathcal{A}^{\Delta} \sinh\left(\Delta\Gamma_s t/2\right)\right]$$

$$\mathcal{A}^{\Delta} \simeq \frac{2\,\mathrm{Re}\left(e^{-i\phi_s}\,\mathcal{C}_7\,\mathcal{C}_7'\right)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

Muheim, Xie, Zwicky, PLB 664 (2008) 174



- **LHCb run I result**

PRL 118 (2017) 021801

$$A^{\Delta} = -0.98^{+0.46+0.23}_{-0.52-0.20}$$

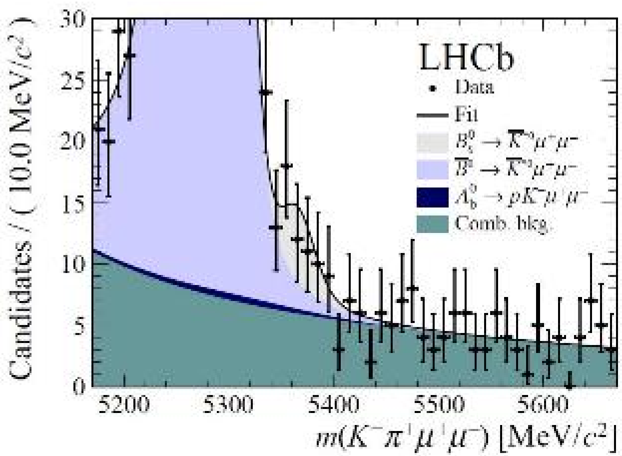
Compatible with SM within 2σ

$$\mathcal{A}^{\Delta}_{\mathrm{SM}} = 0.047^{+0.029}_{-0.025}$$

Search for new rare b decays

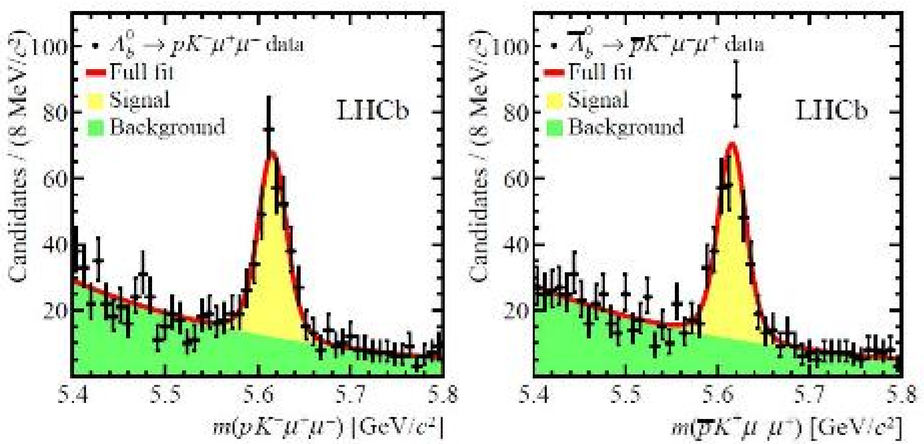
Evidence for $B_s \to K^{*0}\mu^+\mu^-$

JHEP 07 (2018) 020



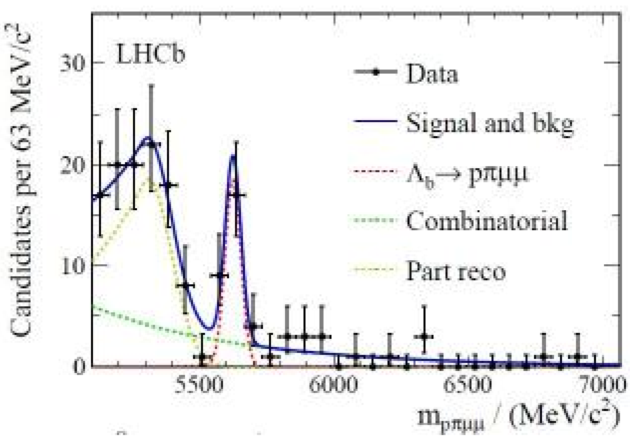
Observation of $\Lambda_b^0 \to pK^-\mu^+\mu^-$

JHEP 06 (2018) 108



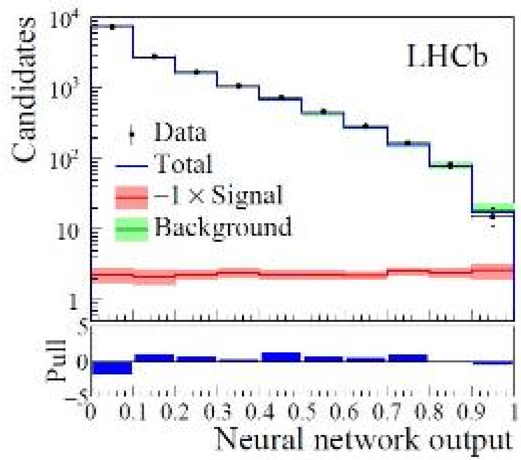
Observation of $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$

JHEP 04 (2017) 029



Search for $B_{s/d} \to \tau^+\tau^-$

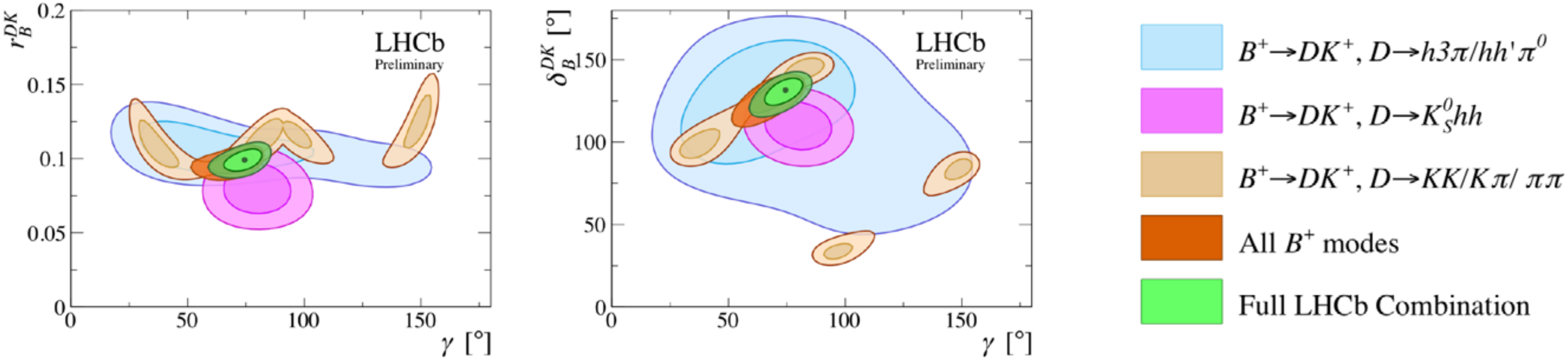
PRL 118 (2017) 251802



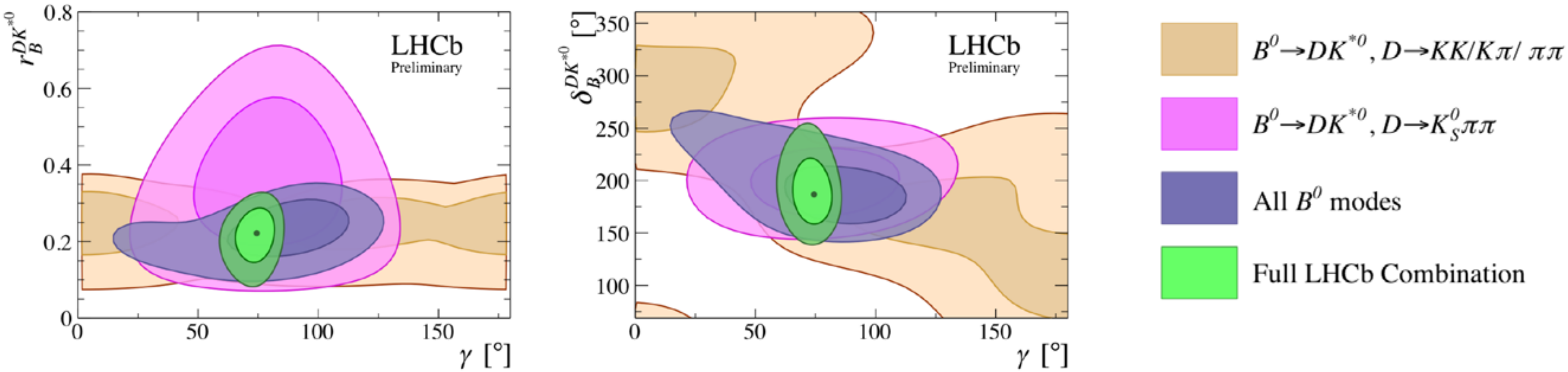
γ combination

$B \to DK^+$ (run 1 + 2015+2016)

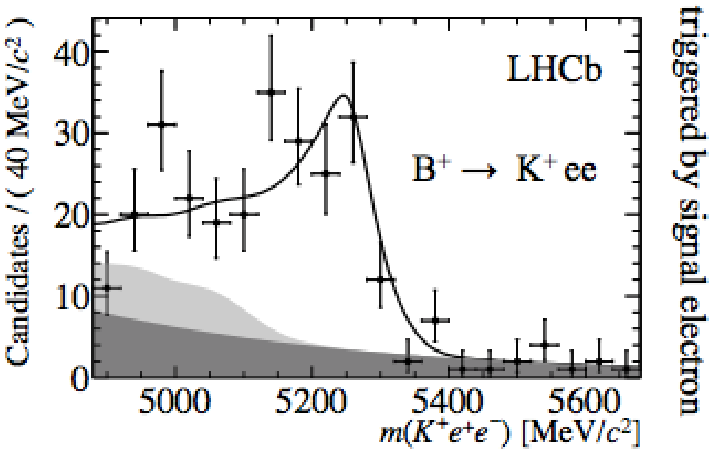
LHCb-CONF-2018-002



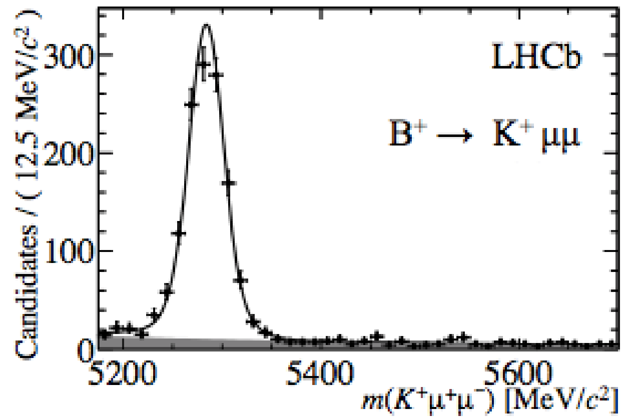
$B^0 \to DK^{*0}$ (run 1)



$B^+ \to K^+ l^+ l^-$

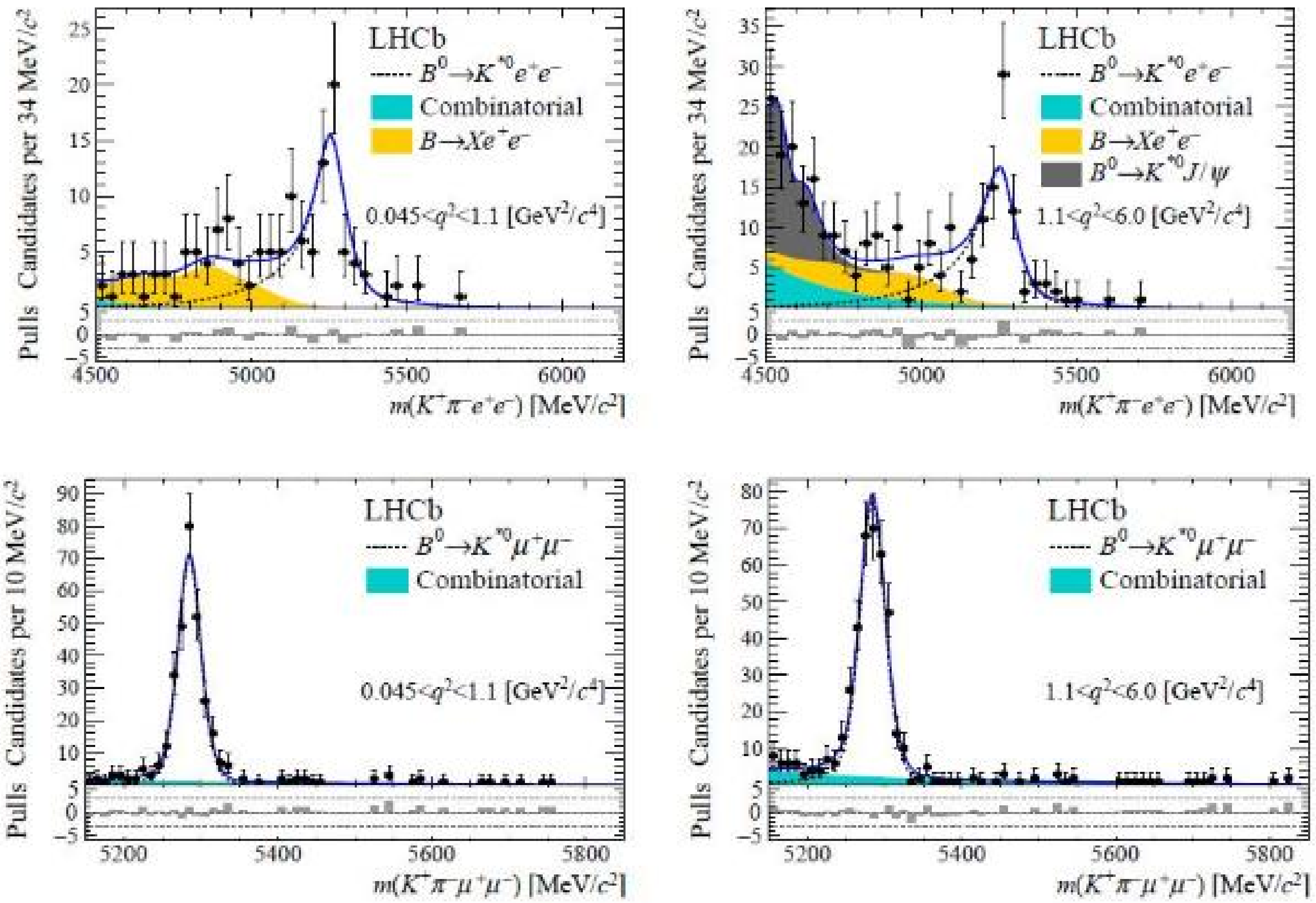


LHCb
B⁺ → K⁺ ee
Candidates / (40 MeV/c²)
m(K⁺e⁺e⁻) [MeV/c²]
triggered by signal electron



LHCb
B⁺ → K⁺ μμ
Candidates / (12.5 MeV/c²)
m(K⁺μ⁺μ⁻) [MeV/c²]

$B^0 \rightarrow K^{*0} l^+ l^-$



$B_c^+ \to J/\psi\tau^+\nu$ vs $B_c^+ \to J/\psi\mu^+\nu$