Recent progress at LHCb

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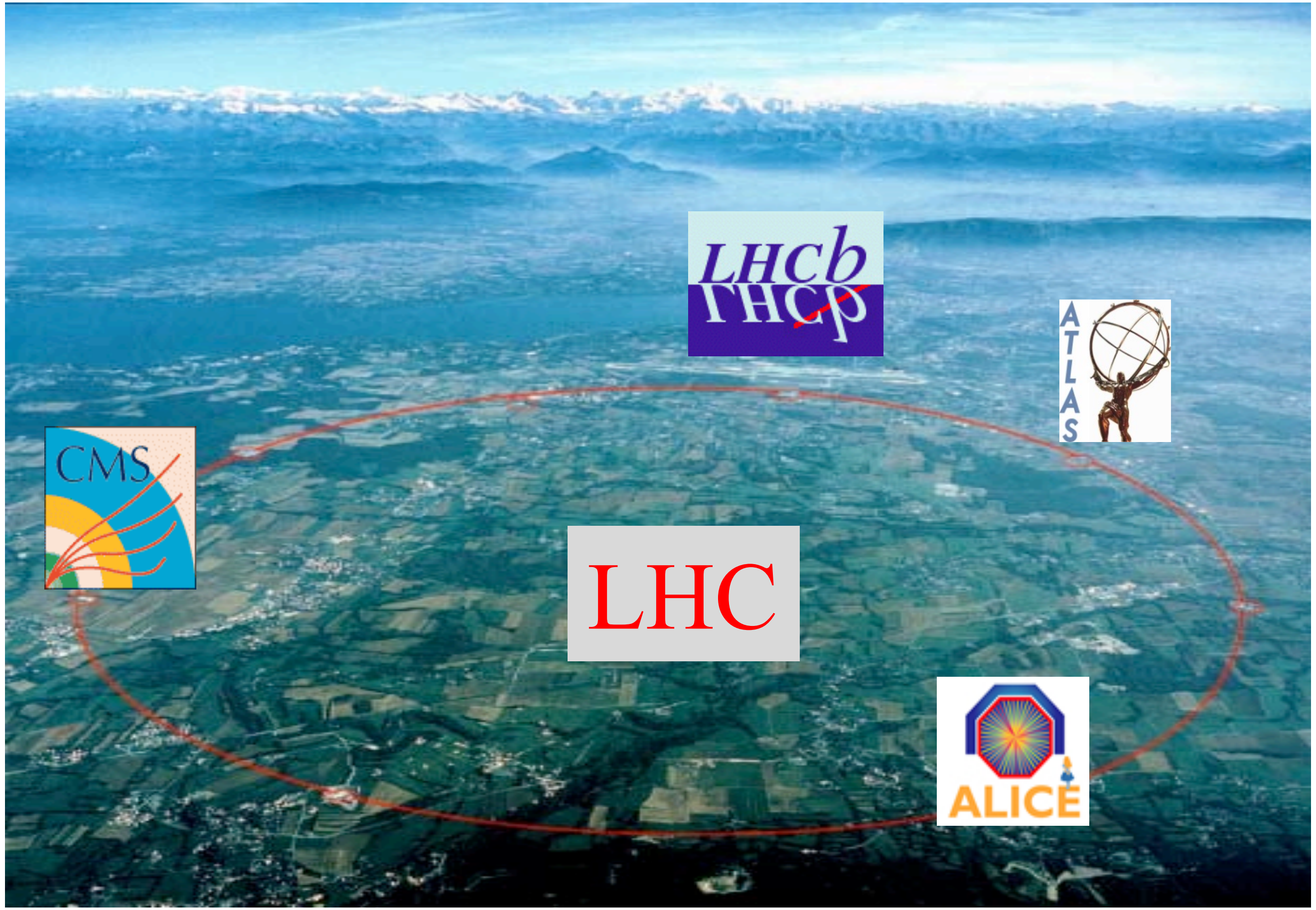
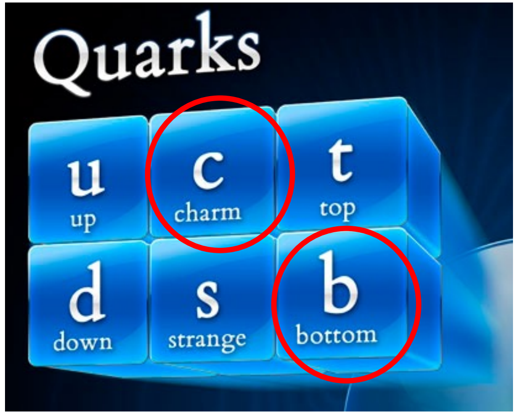
Outline

- **LHCb experiment**
- CP violation and CKM matrix
- Rare decays
- Hadron spectroscopy
- Prospects
- Summary

LHCb experiment

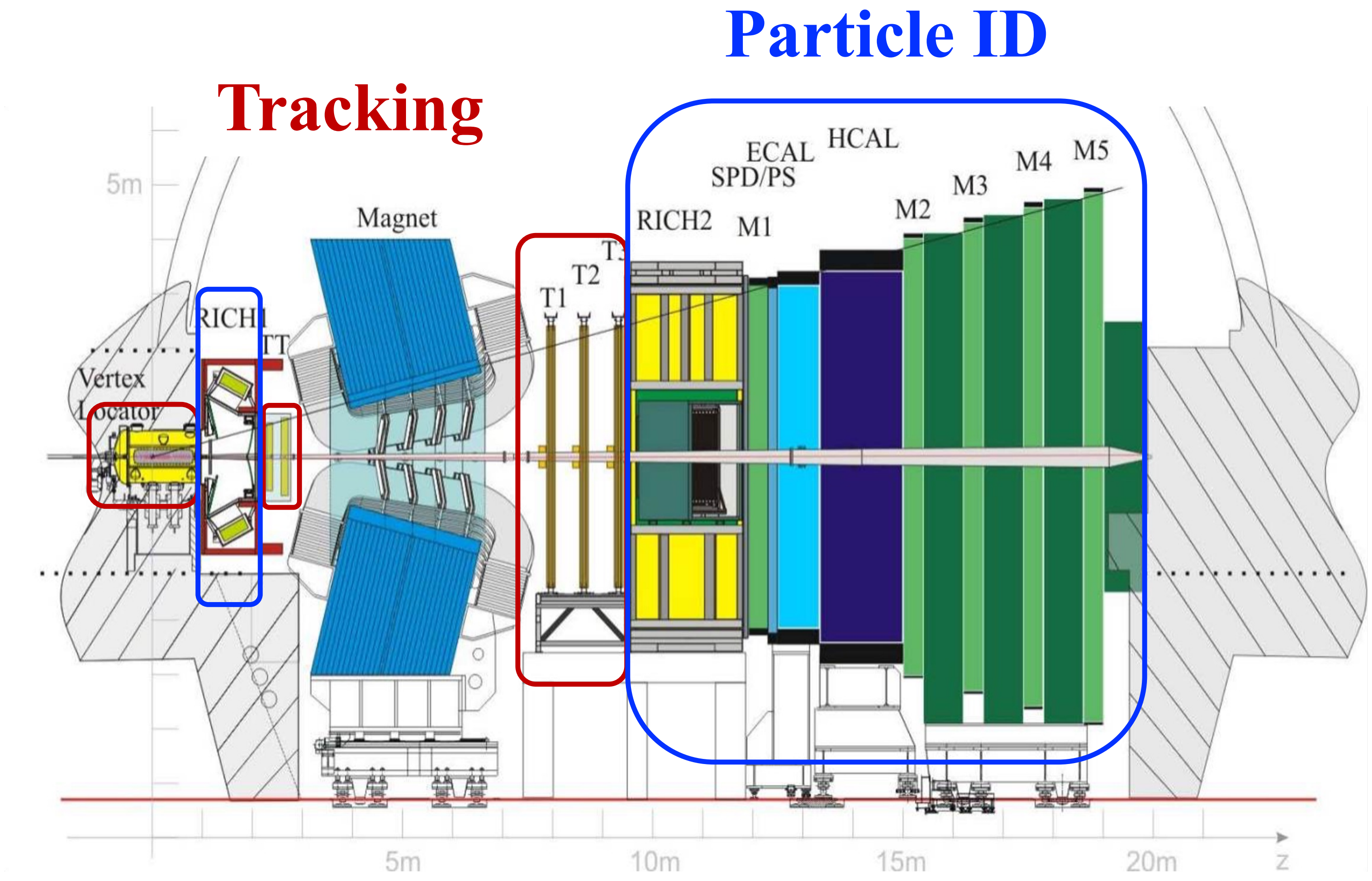
- One of the four large experiments on Large Hadron Collider (LHC) at CERN
- Dedicated to studying heavy flavor (beauty and charm) hadrons





LHCb detector

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



Run 1-2 detector

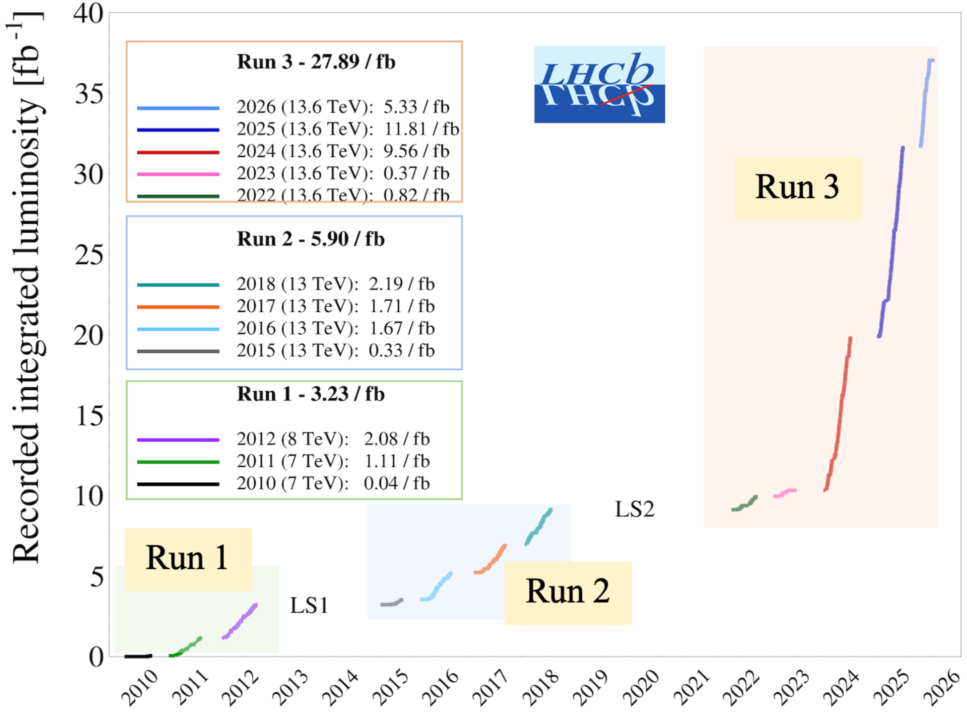
- ✓ Excellent vertexing
  $\sigma_\tau \sim 45$ fs for $B_s^0 \to J/\psi\phi$ decay
- ✓ Precise momentum measurement
  $\Delta p/p = 0.5 - 1\%$ $(5 \sim 200$ GeV$/c)$
  $\delta m_{B\to K\pi}/m_B \sim 0.5\%$
- ✓ Hadron PID
  $\epsilon(K \to K), \epsilon(p \to p) > 90\%$
- ✓ Muon PID
  $\epsilon(\mu \to \mu) \sim 90\%$ for $1-3\%$
  $\pi \to \mu$ misID rate

LHCb data

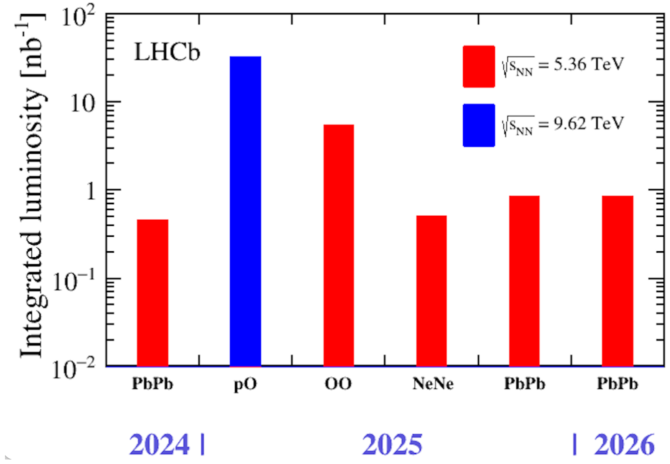
- pp collisions: $\sqrt{s} = 7, 8, 13, 13.6$ TeV, $\int \mathcal{L}dt \approx 37\ \mathrm{fb}^{-1}$

  $\sigma(b\bar{b}, 13\ \mathrm{TeV}) \approx 0.5$ mb, $\sigma(c\bar{c}) \approx 20\times\sigma(b\bar{b})$, all possible species

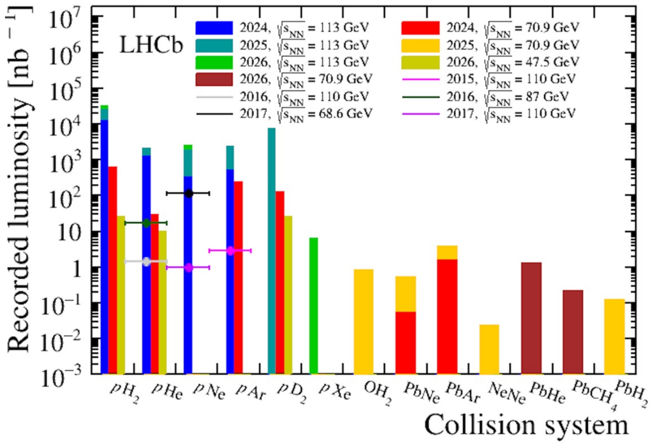
- pp data



- Heavy ion data



Colliding mode



Fixed target mode

LHCb physics

- **CP violation**

  胡晓凡: LHCb实验上CP破坏最新进展

  - Measurements of CKM matrix, new CP violation sources

- **Rare decay and new physics**

  俞洁晟:LHCb实验上稀有衰变的研究

  - Flavor changing neutral currents, forbidden decays, lepton flavor universality…

- **Quantum Chromodynamics**

  何吉波：LHCb上双重味重子实验研究
  任赞: Hardon Spectroscopy at LHCb

  - Heavy flavor production, conventional and exotic hadron spectroscopy

- Electroweak at forward rapidity region
  - W/Z production, mass, weaking mixing angle…

- Heavy ion at forward rapidity region
  - Quark gluon plasma, initial and final state effects…

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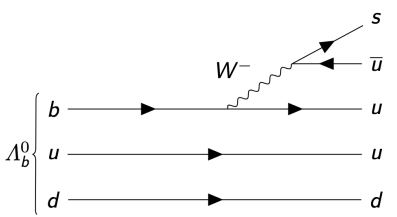
First observation of CP violation in baryons

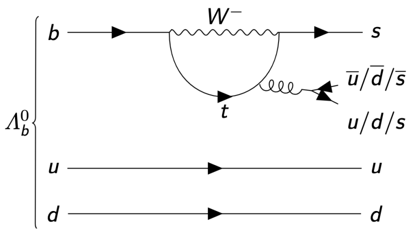
Nature 643 (2025) 1223

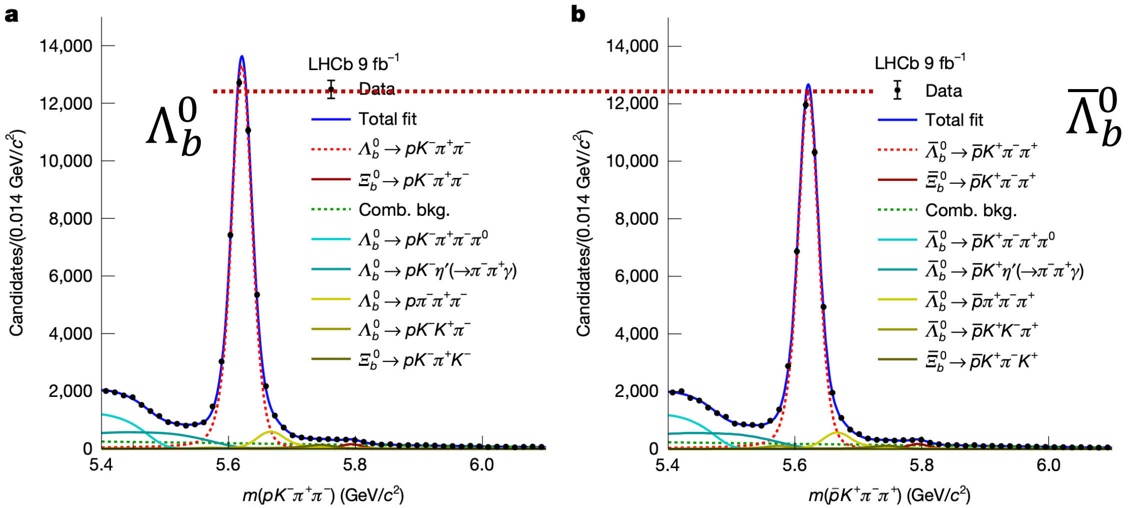
- $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay: CP violation may arises from "tree" and "penguin" interference, could be enhanced by intermediate resonances
- 80K Λ_b^0 and $\overline{\Lambda}_b^0$ measured, almost background free

"Tree"



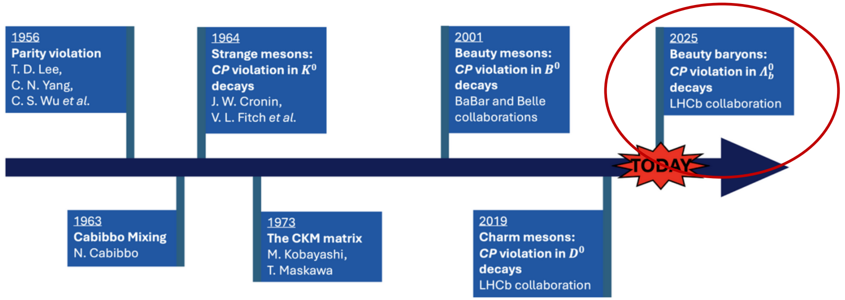
"penguin"





- CP asymmetry determined after accounting for biases from production and detection

$$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%,\ 5.2\sigma \text{ from zero}$$

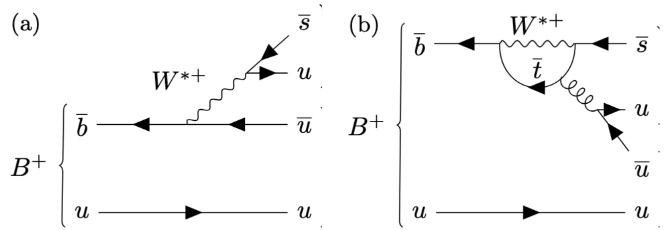


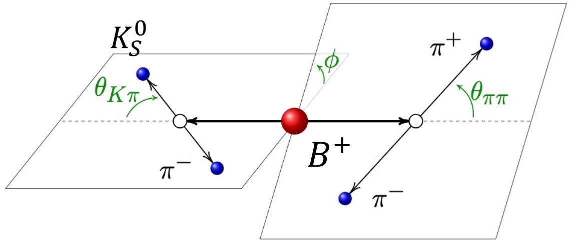
Analysis of $B^+ \to \rho K^{*+}$ decays

PRL 136 (2026) 021803

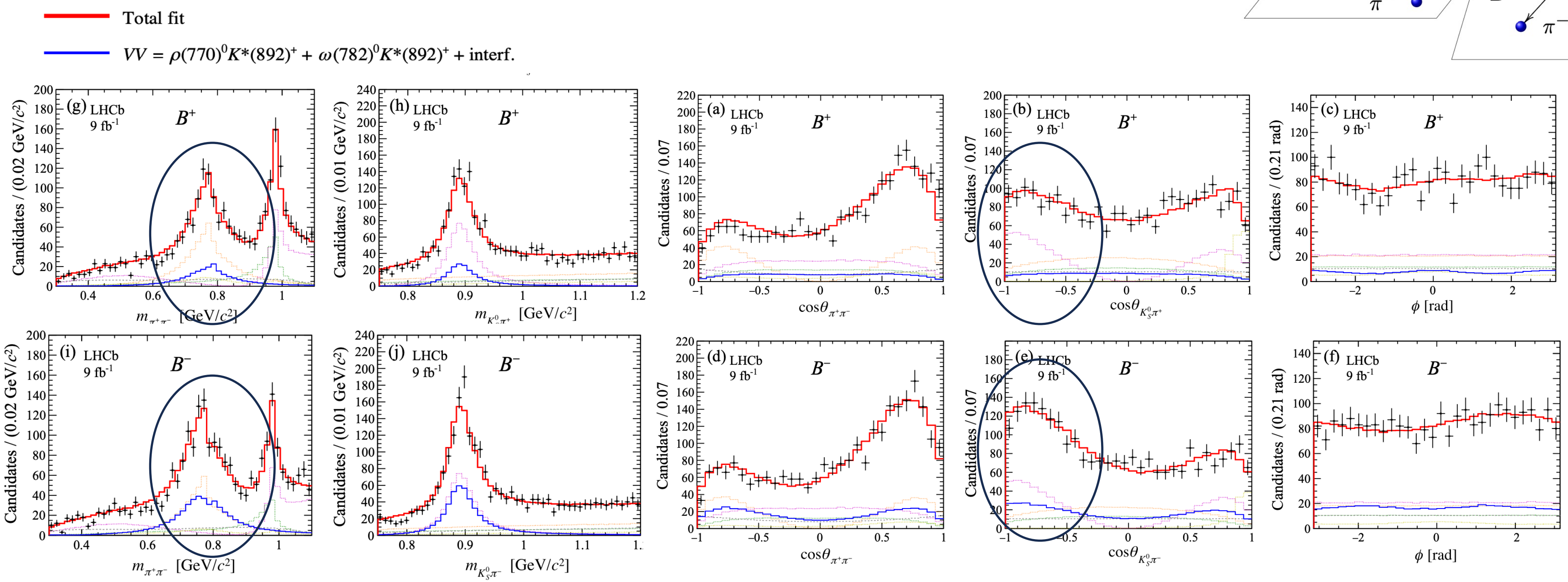
- Charmless $B \to VV$ highly interesting
  - Three polarizations: 0, ⊥ and ∥; relative phases can be extracted
  - Interference between tree and penguin diagrams: CP violation
  - Longstanding polarization puzzle

Nucl. Phys. B774 (2007) 64





- Amplitude analysis of $B^+ \to \rho(\to \pi^+\pi^-)K^{*+}(\to K_S^0\pi^+)$



$B^+ \to \rho K^{*+}$: polarization and CP violation

- CP averaged longitudinal fraction

$$f_L^{\text{avg}} \equiv \frac{|A_0|^2 + |\bar{A}_0|^2}{\sum_\lambda (|A_\lambda|^2 + |\bar{A}_\lambda|^2)} = 0.720 \pm 0.028 \pm 0.009$$

- Direct CP asymmetry

$$\mathcal{A}_{CP}^{\text{dir}} \equiv \frac{\sum_\lambda (|\bar{A}_\lambda|^2 - |A_\lambda|^2)}{\sum_\lambda (|\bar{A}_\lambda|^2 + |A_\lambda|^2)} = 0.507 \pm 0.062 \pm 0.017$$

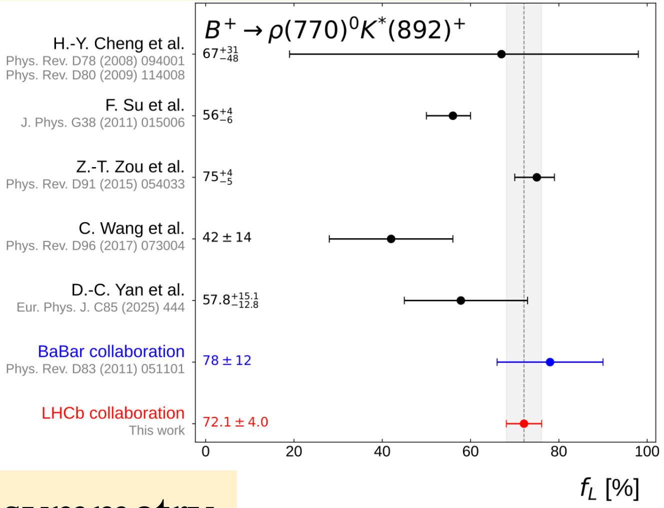
- CP asymmetries for magnitude and phase of longitudinal component

$$\mathcal{A}_{CP}(|A_0|^2) \equiv \frac{|\bar{A}_0|^2 - |A_0|^2}{|\bar{A}_0|^2 + |A_0|^2} = 0.664 \pm 0.083 \pm 0.025$$

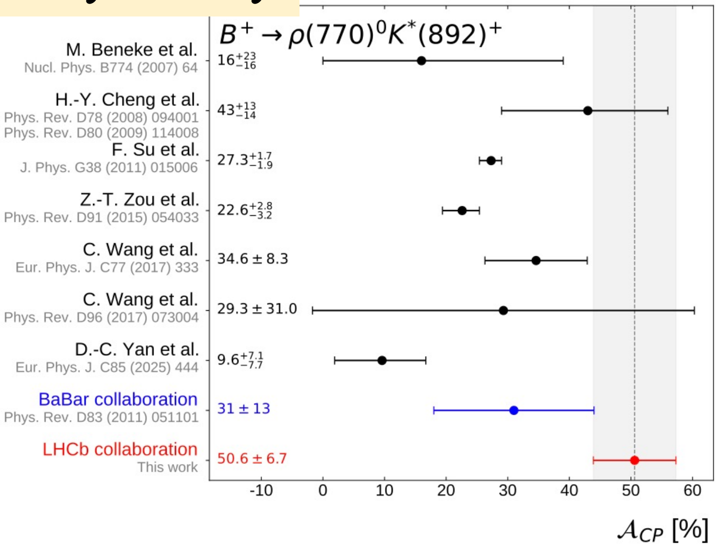
$$\Delta_{CP}(\delta_0) \equiv \bar{\delta}_0 - \delta_0 = 0.720 \pm 0.177 \pm 0.048$$

First observation CP violation in this decay

Longitudinal polarization

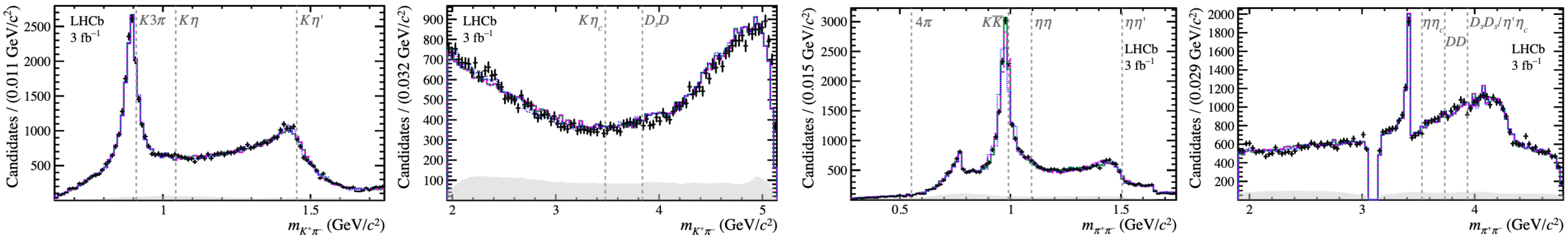


CP asymmetry



Amplitude analysis of $B^+ \to K^+\pi^+\pi^-$

- Improved $K^+\pi^-$ S-wave modelling: Isobar, K-matrix, Quasi-model independent
  - $\mathcal{B}(B^+ \to K_0^*(1430)^0\pi^+)$ agrees with QCD factorisation predictions



- Ten new intermediate states are observed for the first time

Component	HFLAV (10^{-6})	Branching fraction (10^{-6})
$B^+ \to K_2^*(1430)^0\pi^+$	$5.6^{+2.2}_{-1.4}$	$3.90 \pm 0.57 \pm 0.31 \pm 0.13$
$B^+ \to f_2(1270)K^+$	1.07 ± 0.31	$2.21 \pm 0.30 \pm 0.30 \pm 0.09$
$B^+ \to K^*(1410)^0\pi^+$	< 45 (90% CL)	$9.17 \pm 2.39 \pm 2.49 \pm 1.82$
$B^+ \to \rho_3(1690)^0K^+$	–	$1.00 \pm 0.26 \pm 0.37 \pm 0.06$
$B^+ \to K_0^*(1950)^0\pi^+$	–	$1.32 \pm 0.27 \pm 0.08 \pm 0.36$
$B^+ \to f_0(1370)K^+ \dagger$	< 11 (90% CL)	$9.67 \pm 0.70 \pm 0.23$
$B^+ \to f_0(1500)K^+$	–	$4.65 \pm 0.74 \pm 0.32$
$B^+ \to f_0(500)K^+ \dagger$	–	$1.06 \pm 0.22 \pm 0.03$
$B^+ \to f_0(1710)K^+ \dagger$	–	$0.41 \pm 0.34 \pm 0.01$
$B^+ \to (\pi\pi - \pi\pi)K^+ \dagger$	–	$3.09 \pm 1.03 \pm 0.08$

Uncertainties:
- Total uncertainty (Isobar S-wave model)
- S-wave models
- External inputs of BF

†: Product BF of the resonance and its decay to $K^+\pi^-/\pi^+\pi^-$

Observation of resonance CP violation

- CP violation on branching fraction

$\pi^+\pi^-$ resonance

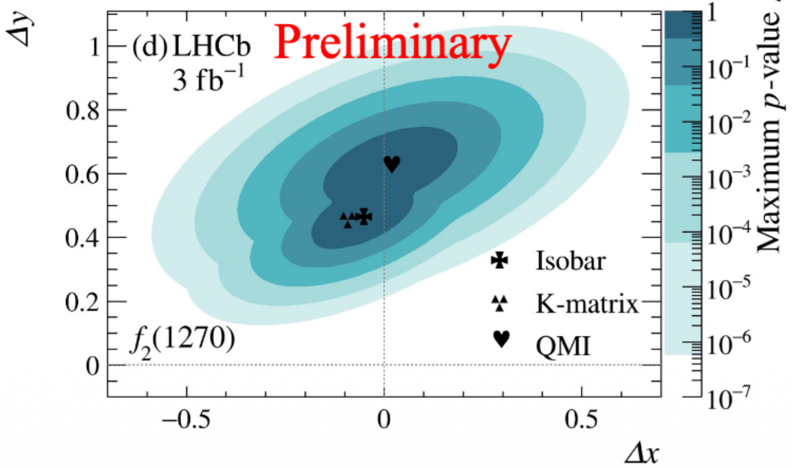
Parameter	Isobar	K-matrix	QMI
$\mathcal{A}_{CP}(\rho(770)^0)$	$+0.280 \pm 0.022 \pm 0.029\ (7.6\sigma)$	$+0.271 \pm 0.022 \pm 0.014\ (10.3\sigma)$	$+0.359 \pm 0.037 \pm 0.048\ (5.9\sigma)$
$\mathcal{A}^{\mathrm{S}}_{CP}(m_{\pi^+\pi^-} < m_{4\pi})$	$+0.657 \pm 0.033 \pm 0.059\ (9.7\sigma)$	$+0.638 \pm 0.008 \pm 0.016\ (35.5\sigma)$	$+0.754 \pm 0.115 \pm 0.113\ (4.7\sigma)$
$\mathcal{A}^{\mathrm{SD}}_{\mathcal{I}}\ (\times 10^{-1})$	$+0.058 \pm 0.007 \pm 0.009\ (4.9\sigma)$	$+0.055 \pm 0.007 \pm 0.007\ (5.3\sigma)$	$+0.071 \pm 0.014 \pm 0.009\ (4.4\sigma)$
$\mathcal{A}^{\mathrm{SP}}_{\mathcal{I}}\ (\times 10^{-1})$	$-0.232 \pm 0.018 \pm 0.037\ (5.7\sigma)$	$-0.242 \pm 0.021 \pm 0.039\ (5.6\sigma)$	$-0.253 \pm 0.025 \pm 0.028\ (6.7\sigma)$
$\mathcal{A}_{CP}(\rho_3(1690)^0)$	$+0.603 \pm 0.090 \pm 0.120\ (4.2\sigma)$	$+0.477 \pm 0.100 \pm 0.096\ (3.4\sigma)$	$+0.698 \pm 0.135 \pm 0.163\ (3.3\sigma)$

Preliminary

- First observation of CPV in $B^+ \to \rho(770)^0 K^+$ through amplitude analysis
- First observation of CPV in interference between $\pi^+\pi^-$ S- and P-waves
- First evidence of CPV in $B^+ \to \rho_3(1690)^0 K^+$, involving a spin-3 resonance

- χ^2 test of amplitude couplings $(\Delta x_j, \Delta y_j)$

$$a_j^{\pm} \equiv (x_j \pm \Delta x_j) + i(y_j \pm \Delta y_j)$$



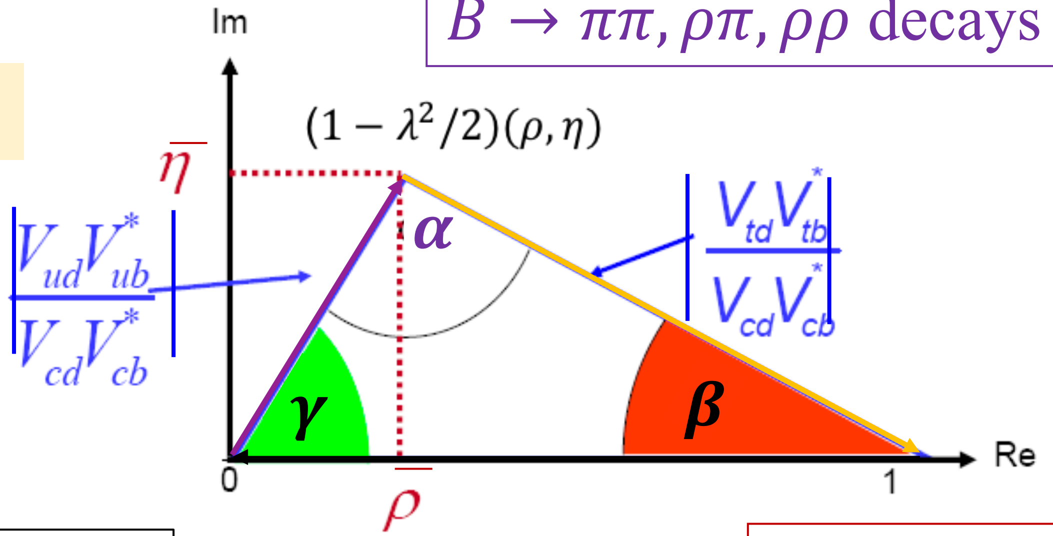
- $(\Delta x_j, \Delta y_j)$ deviates from zero by 8.2σ for all three S-wave models
  - Significance of $A^{CP}(F_j)$ is only 2.1σ (QMI)
- First observation of CPV in $B^+ \to f_2(1270)^0 K^+$

The Unitarity triangle

$$V_{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$ is unitary

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

α: time dependent CPV of $B \to \pi\pi, \rho\pi, \rho\rho$ decays



γ: direct CPV of $B \to DK,\ D\pi$ decays

β: time dependent CPV of $B^0 \to \psi K_{S/L}$ decays

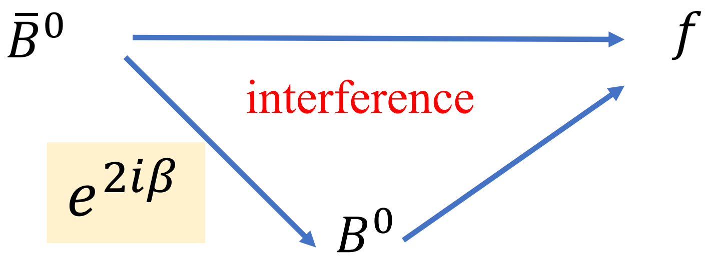
$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \qquad \alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

Angle β

PRL 132 (2024) 021801

- β extracted using interference between $\bar{B}^0$ decay and $\bar{B}^0 - B^0$ mixing

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



$$\mathcal{A}(\bar{B}^0 \to B^0) \propto (V_{td}^*)^2 \propto e^{2i\beta}$$

Time-dependent CP violation

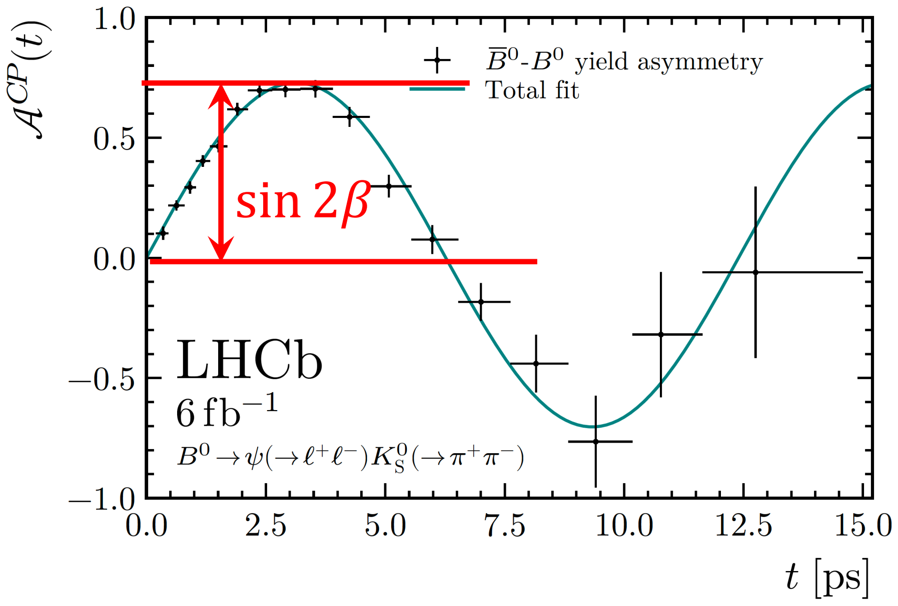
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0 \to f}(t) - \Gamma_{B^0 \to f}(t)}{\Gamma_{\bar{B}^0 \to f}(t) + \Gamma_{B^0 \to f}(t)} = -\eta_f \sin 2\beta \sin(\Delta M_d t)$$

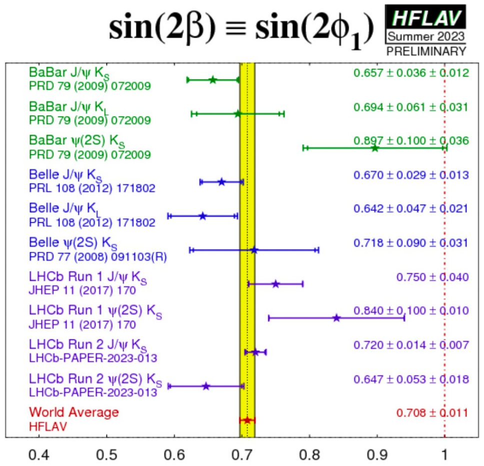
- Golden modes: $B^0 \to \psi K^0_{S,L}$

- Latest result

LHCb: $\sin 2\beta = 0.717 \pm 0.015$

World average: $\beta = (22.5 \pm 0.4)^\circ$

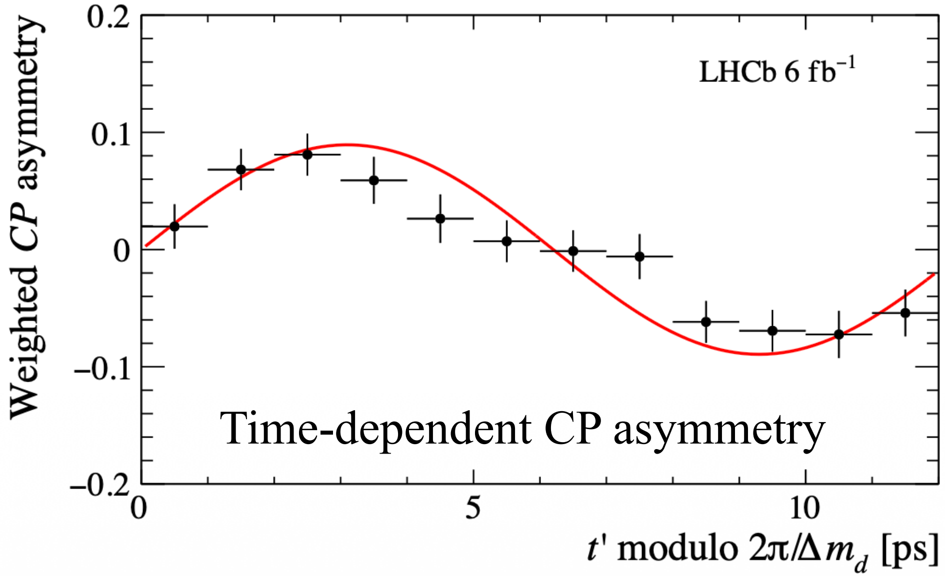


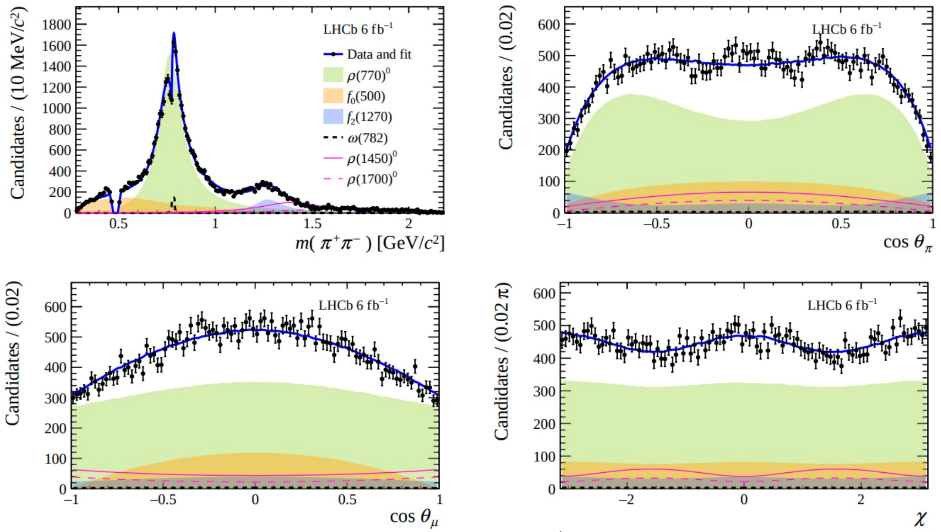


β_{eff} determination with $B^0 \to J/\psi\pi^+\pi^-$

arXiv:2601.15646

- $b \to c\bar{c}d$ decay, more sensitive to charm loop (penguin pollution)
- Dominated by $B^0 \to J/\psi\rho(770)^0$, about 70%
- Time-dependent amplitude analysis to split CP-odd and CP-even final-state components

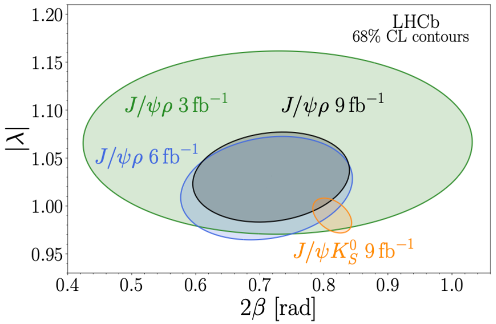


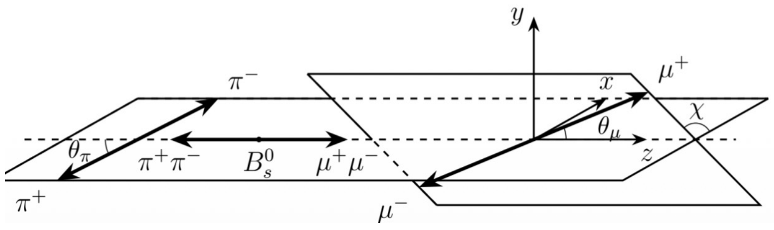


$$2\beta^{\text{eff}}_{c\bar{c}d} = 0.710 \pm 0.084 \pm 0.028 \text{ rad}$$

Penguin pollution on ϕ_s:

$$\Delta\phi_s = 5.0 \pm 4.2 \text{ mrad}$$

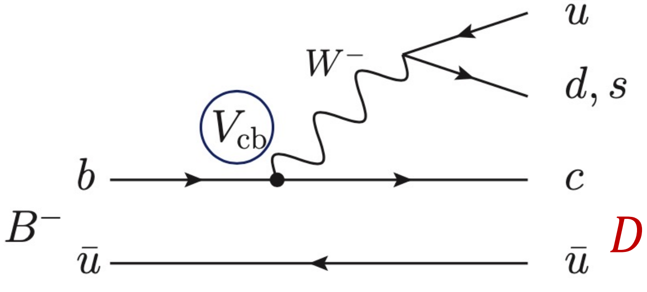




Angle γ

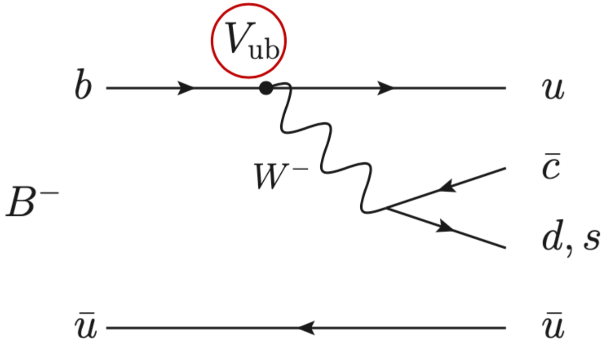
- Measured with interference between $b \to c$ and $b \to u$
  - ➢ Tree-level decays, theoretically clean ($\delta\gamma \sim 10^{-7}$)

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



K/π

$D^{(*)0} \to f$



$\overline{D}^{(*)0} \to f$

K/π

$$\boxed{\Gamma(B^\pm \to Dh^\pm) \propto r_D^2 + r_B^2 + 2 r_D r_B \cos(\delta_B + \delta_D \pm \gamma)}$$

- $\overline{D}$ and D to same final states to interfere

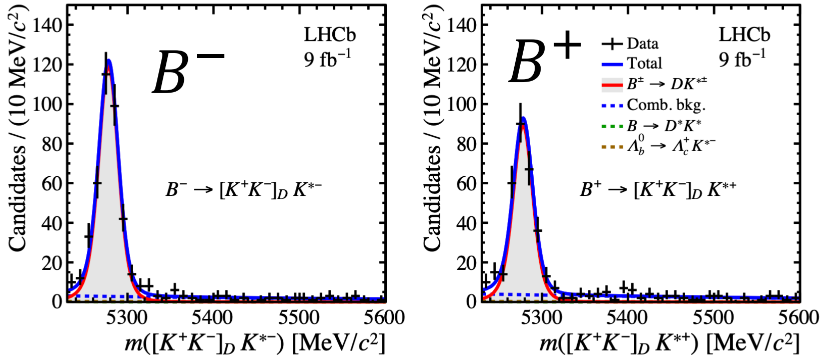
GLW: $f = KK, \pi\pi$ etc, CP eigenstates
PLB 253 (1991) 483, PLB 265 (1991) 172

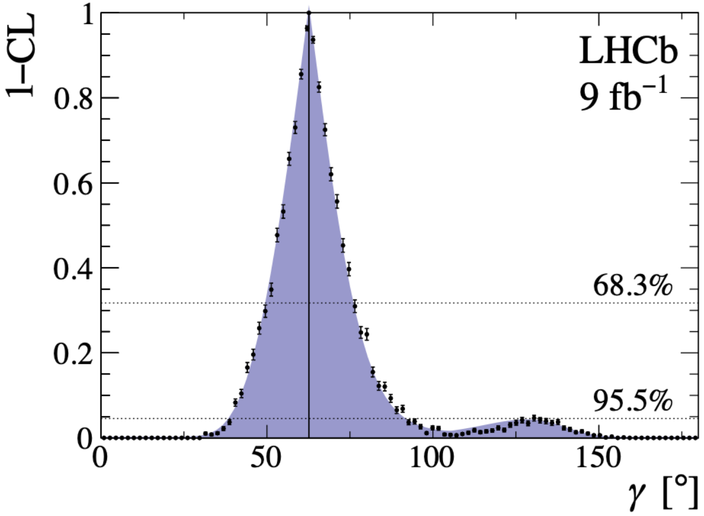
ADS: $f = K\pi, K3\pi$ etc, quasi-flavor-specific sates PRL 78 (1997) 3257

BPGGSZ: $f = K_s\pi\pi$ etc, self-conjugate multi-body
PRD 68 (2003) 054018

New γ measurements

- $B^+ \to DK^{*+}$ with $D \to 2h$ and $D \to 4h$





$\gamma = (63 \pm 13)°$

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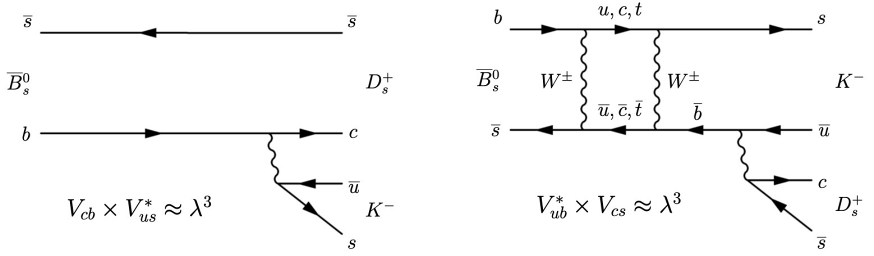
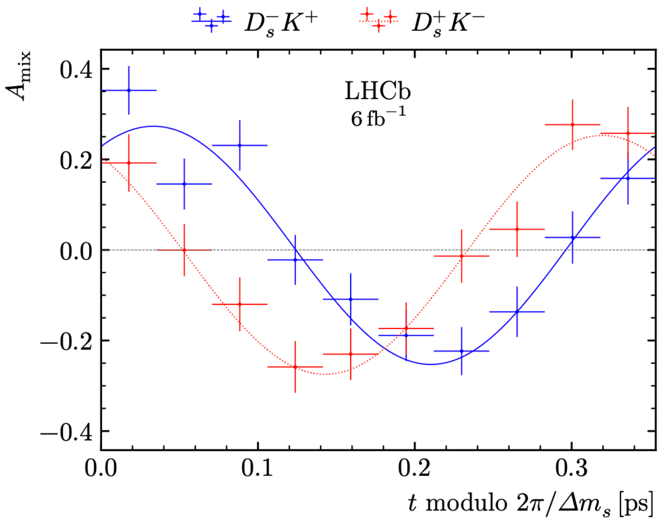
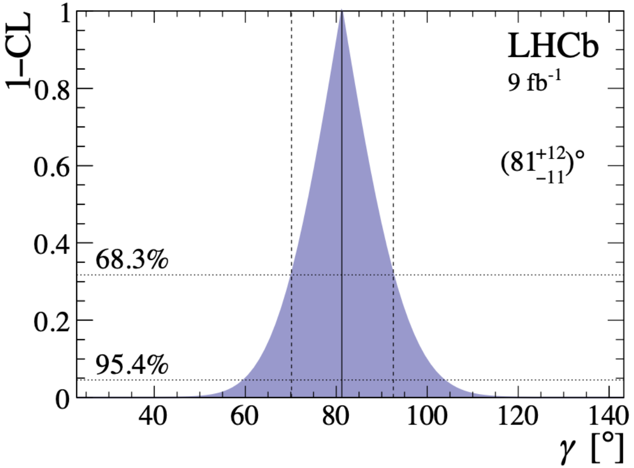
- Time dependent analysis of $B_s^0 \to D_s^{\mp} K^{\pm}$





Mixing asymmetry



$\gamma = (81^{+12}_{-11})°$

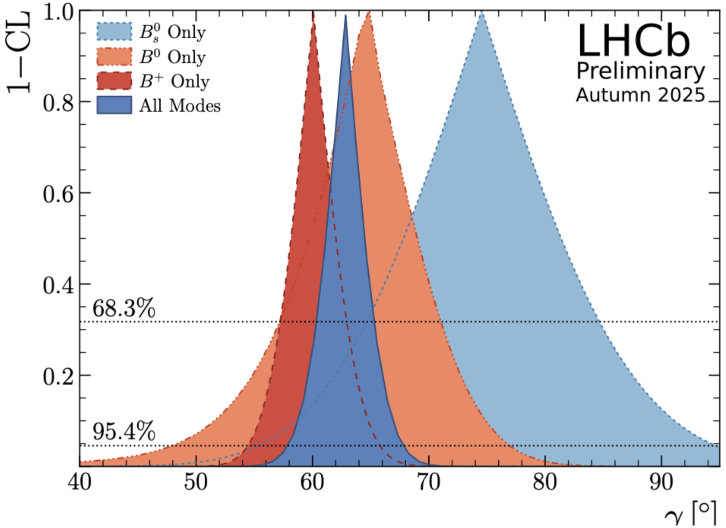
JHEP 03 (2025) 139

γ combination

Combined determination of γ, and charm mixing and CP violation parameters

B decay	D decay
$B^\pm \to Dh^\pm$	$D \to h^\pm h'^\mp$
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^+\pi^-$
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^+\pi^-$
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$
$B^\pm \to Dh^\pm$	$D \to h^\pm h'^\mp\pi^0$
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$
$B^\pm \to D^*h^\pm$	$D \to h^\pm h'^\mp$ (PR)
$B^\pm \to D^*h^\pm$	$D \to K^0_S h^+h^-$ (PR)
$B^\pm \to D^*h^\pm$	$D \to K^0_S h^+h^-$ (FR)
$B^\pm \to DK^{*\pm}$	$D \to h^\pm h'^\mp$
$B^\pm \to DK^{*\pm}$	$D \to h^\pm\pi^\mp\pi^+\pi^-$
$B^\pm \to DK^{*\pm}$	$D \to K^0_S h^+h^-$
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^\pm h'^\mp$
$B^0 \to DK^{*0}$	$D \to h^\pm h'^\mp$
$B^0 \to DK^{*0}$	$D \to h^\pm\pi^\mp\pi^+\pi^-$
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$

D decay	Observable(s)
$D^0 \to h^+h^-$	ΔA_{CP}
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$
$D^0 \to h^+h^-$	ΔY
$D^0 \to K^\pm\pi^\mp$ (double tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$
$D^0 \to K^\pm\pi^\mp$ (single tag)	$R_{K\pi}$, $\overset{(\sim)}{A}_{K\pi}$, $c^{(\prime)}_{K\pi}$, $\Delta \overset{(\sim)}{c}{}^{(\prime)}_{K\pi}$
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	r, $\kappa y'$, $(x^2+y^2)/4$
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$r_i^\pm$, $(\kappa y'^\pm)_i$, $x^{2\pm}+y^{2\pm}$
$D^0 \to K^0_S\pi^+\pi^-$	x, y
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy
$D^0 \to \pi^+\pi^-\pi^0$	$\Delta Y^{\rm eff}$



$$\boldsymbol{\gamma = (62.8 \pm 2.6)^\circ}$$

Indirect extraction:

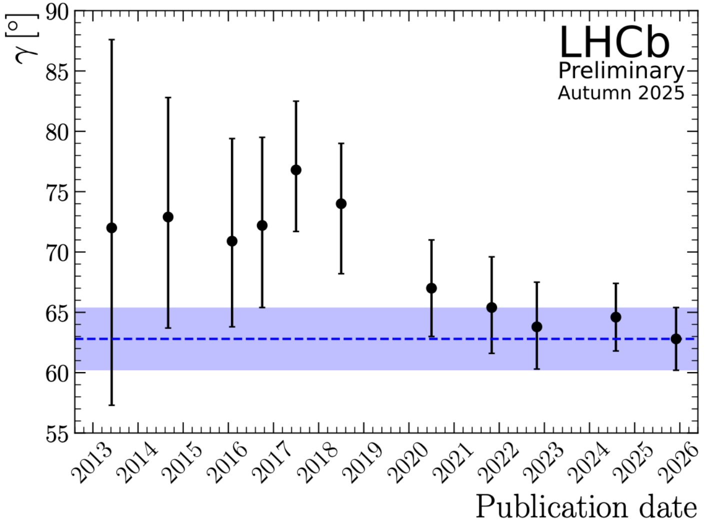
$\gamma = (66.0^{+0.7}_{-1.9})^\circ$, CKMfitter

PRD 91 (2015) 073007

$\gamma = (64.9 \pm 1.4)^\circ$, UTfit

JHEP 10 (2006) 081

$\delta\gamma \approx 15^\circ$
2013

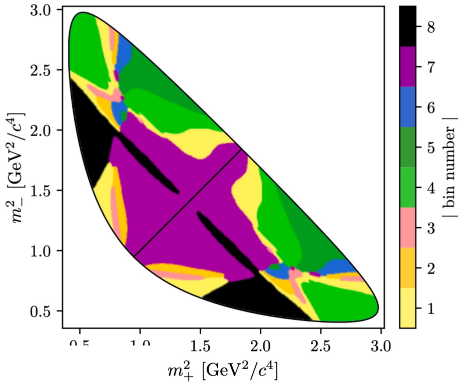


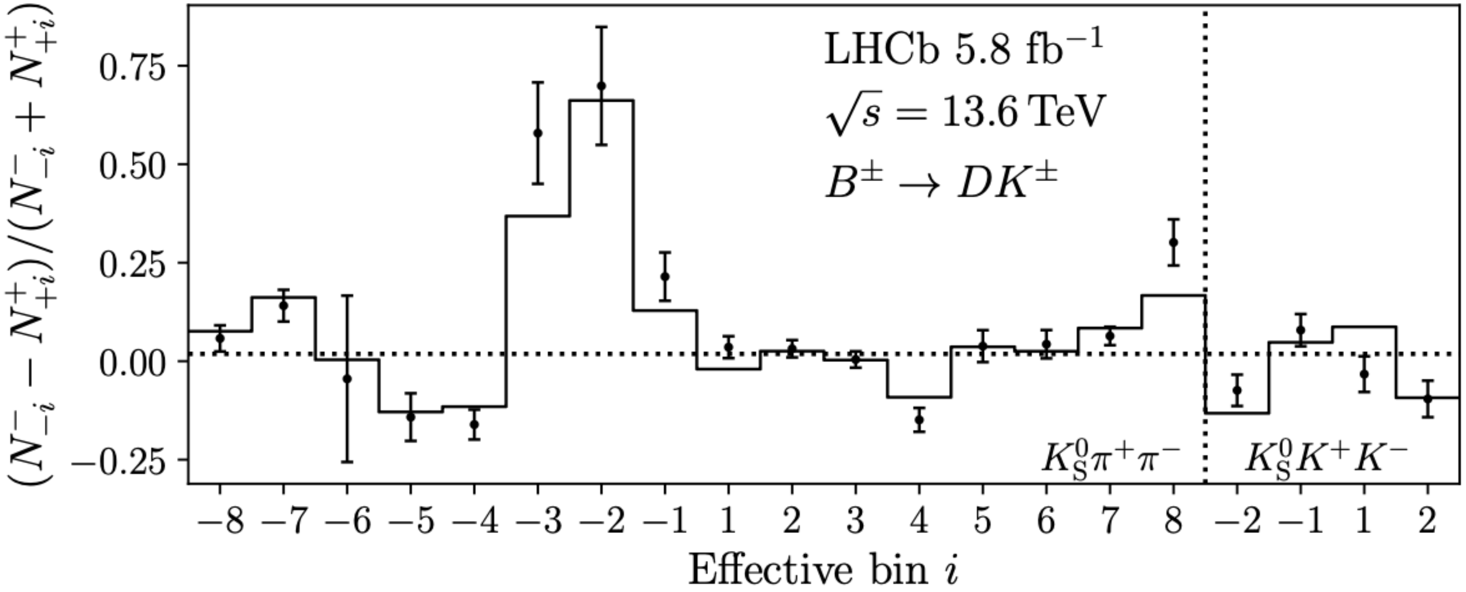
$\delta\gamma = 2.6^\circ$
2025

γ with 2024 data

arXiv:2605.03501

- γ measurement currently limited by statistical precision
- Foreseen improvement by accumulating data
- Analysis of golden channel $B^{\pm} \to D\left(\to K_S^0 h^+ h^-\right)h^+$ with new data ($5.8\mathrm{fb}^{-1}$)





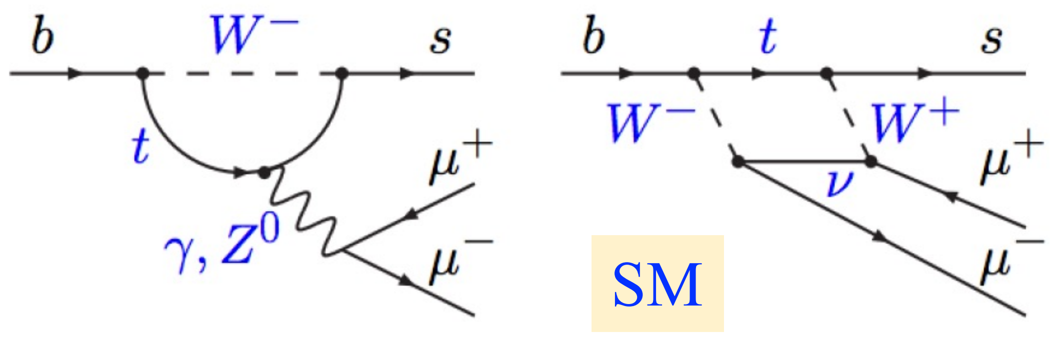
$\gamma = (68.1 \pm 6.7)^{\circ}$, precision close to Run1-2

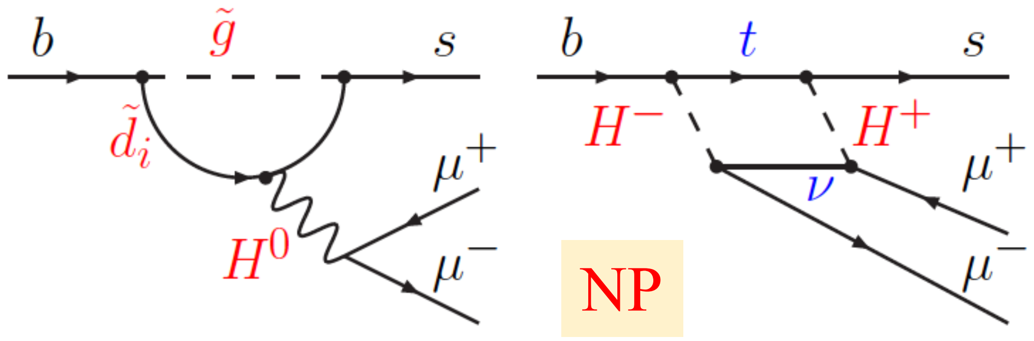
Outline

- LHCb experiment
- CP violation and CKM matrix
- **Rare decays**
- Hadron spectroscopy
- Prospects
- Summary

$b \to s l^+ l^-$ decays

- $b \to s l^+ l^-$ mediated by FCNC loops, SM clean process, sensitive to physics beyond SM

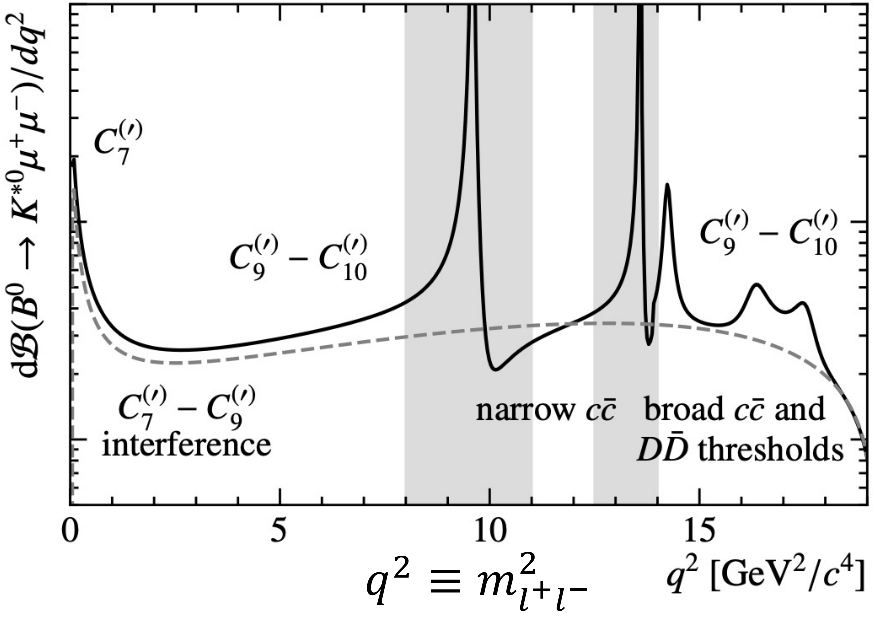




- Effective field theory

$$\mathcal{H}_{\mathrm{WET}} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i \boxed{\mathcal{C}_i^{(\prime)}(\mu)} \mathcal{O}_i^{(\prime)}(\mu)$$

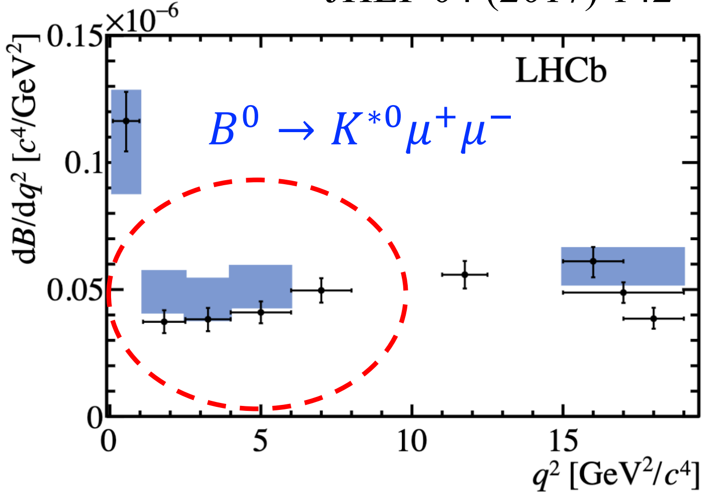
- $b \to s l^+ l^-$ probes Wilson coefficients C_7, C_9, C_{10}
- New physics modifies C_i or introduces new terms



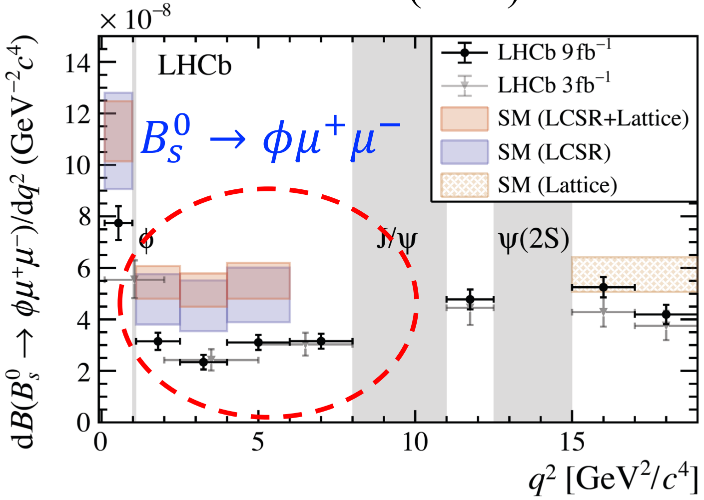
Flavor anomalies in $b \to s l^+ l^-$ decays

- Anomalous tensions with SM in differential rate: new physics or SM uncertainties?

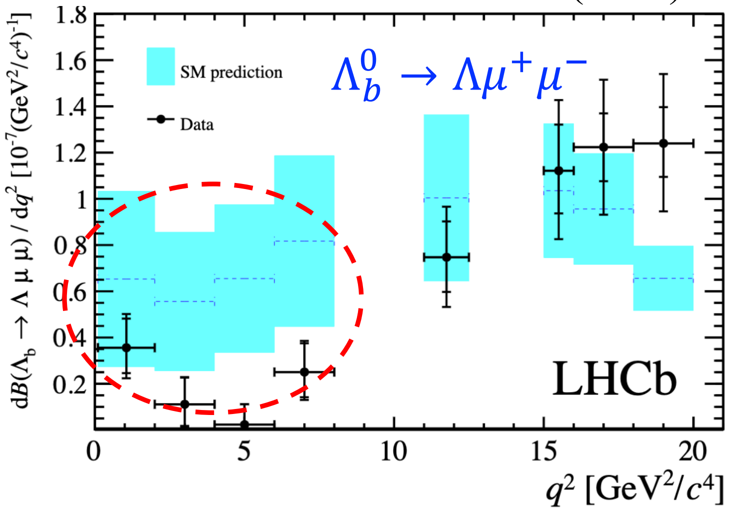
JHEP 04 (2017) 142



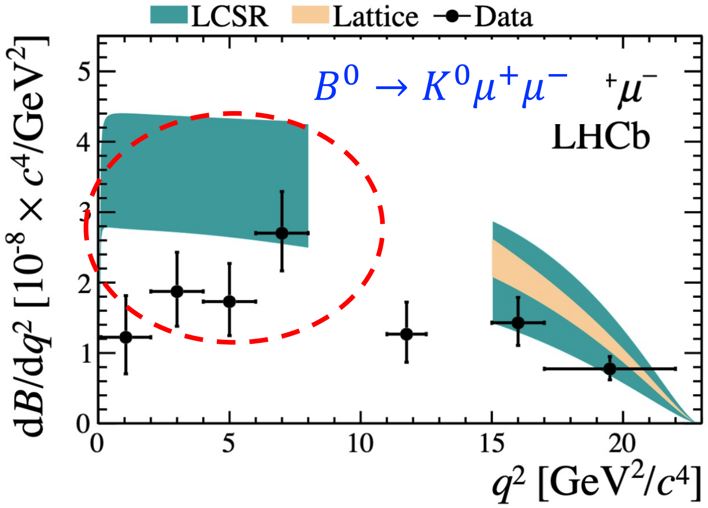
PRL 127 (2021) 151801

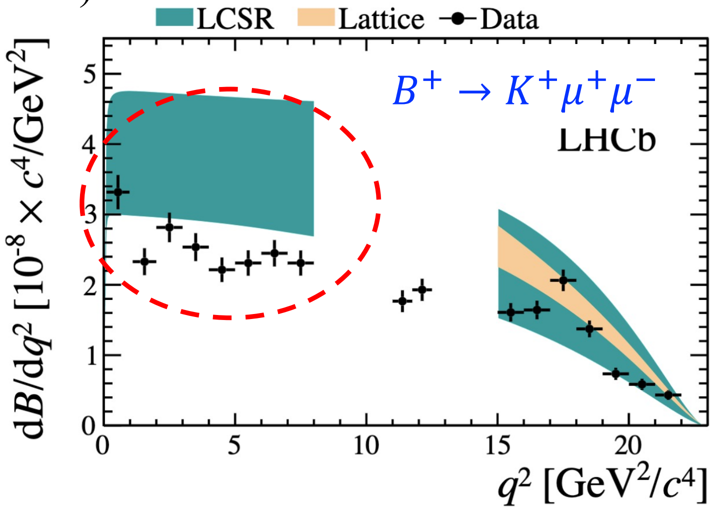


JHEP 06 (2015) 115

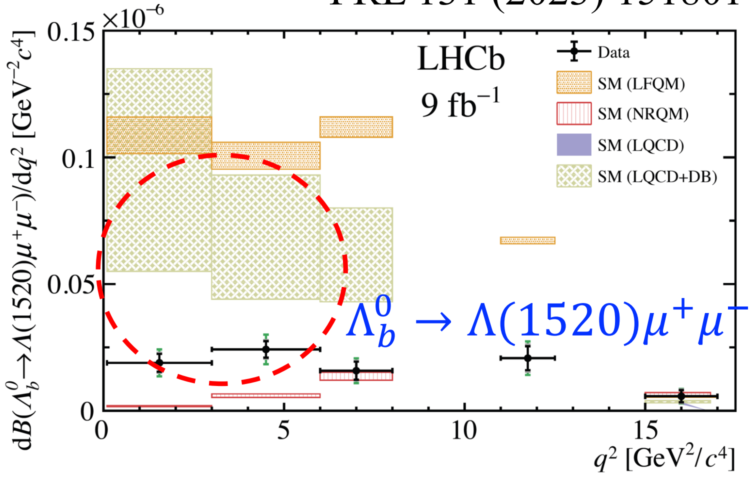


JHEP 06 (2014) 133



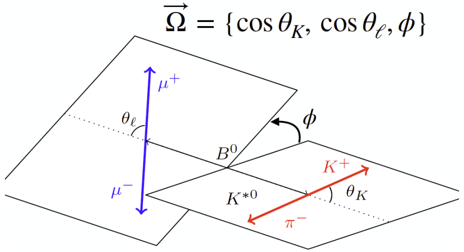


PRL 131 (2023) 151801



Angular analysis in q^2

- Detailed information to test SM calculations



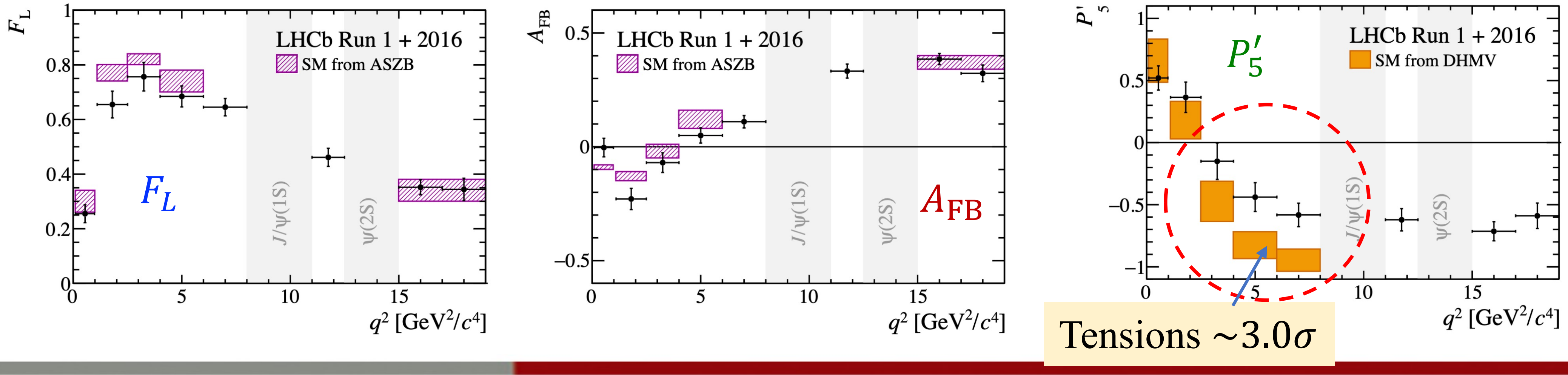
Angular distribution for $B^0 \to K^* l^+ l^-$ decay (CP averaged):

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\vec{\Omega}}\Bigg|_P = \frac{9}{32\pi}\Bigg[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\frac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Bigg]$$

F_L: longitudinal polarization, A_{FB} forward-backward asymmetry

PRL 125 (2020) 011802

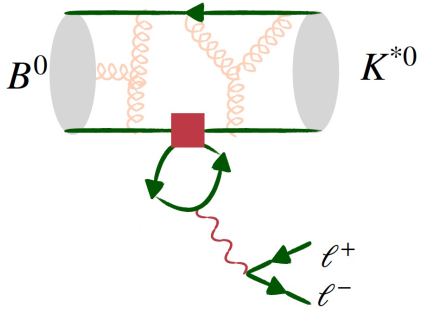
Cleaner observables: $P_i' = S_i\sqrt{F_L(1-F_L)}$



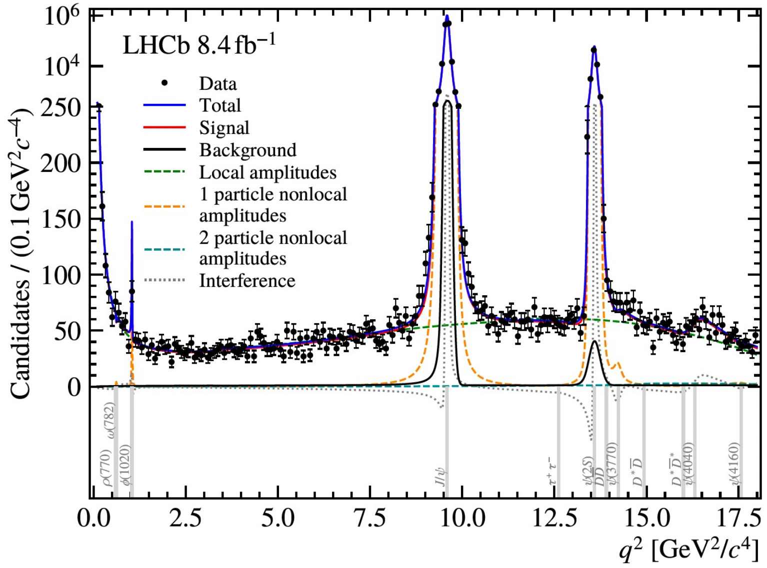
Model dependent analysis of $B^0 \to K^{*0}\mu^+\mu^-$

JHEP 09 (2024) 026

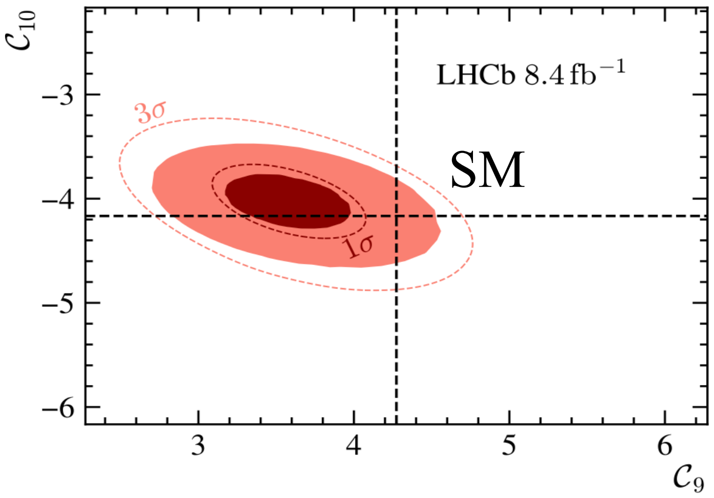
- $b \to sl^+l^-$ decay polluted by nonlocal $(\omega, \rho, \phi, \psi, D\bar{D}\ldots)$ effects
- Amplitude analysis to separate local and nonlocal contributions
  - ➢ Dedicated form factor distribution for each component
  - ➢ Direct measurement of Wilson coefficients C_i



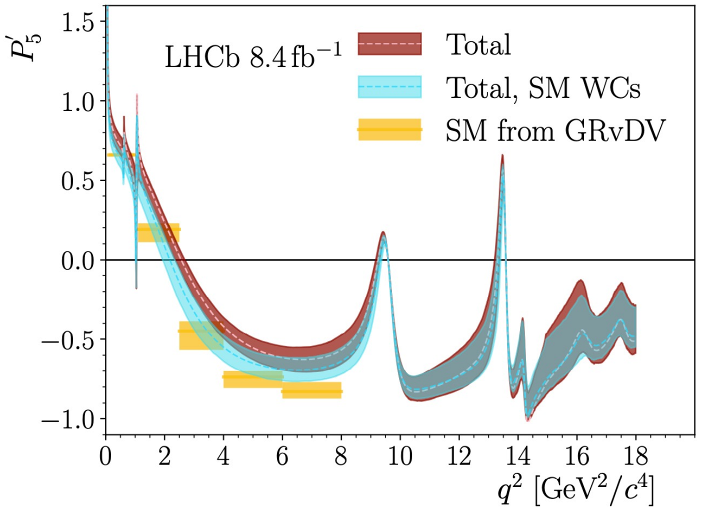
q^2 distribution



$\boldsymbol{C_9}$: 2.1σ tension with SM



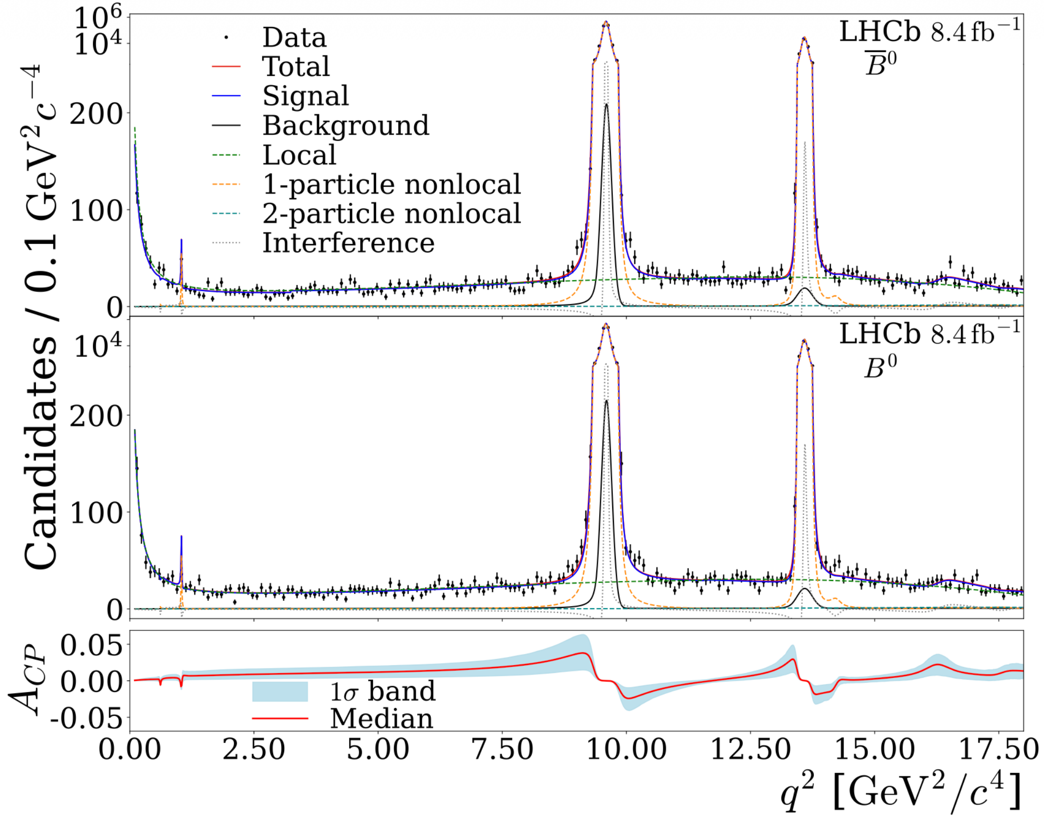
$\boldsymbol{P_5'}$: tension persists but with reduced significance

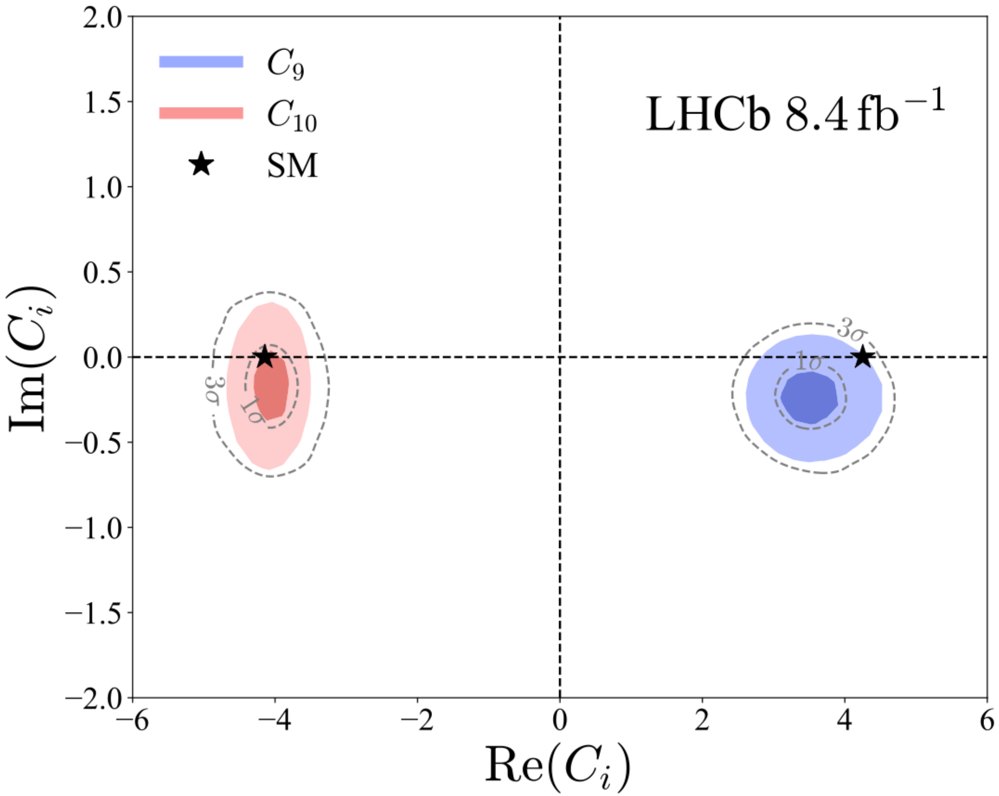


GRvDV: JHEP 09 (2022) 133

CP violation for $B^0 \to K^{*0}\mu^+\mu^-$ decay

- Extract CP violation and complex Wilson-coefficients, $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$ relative to C_7
  - C_i are real in SM





No evident CP violation

C_9 and C_{10} consistent with SM, phase≈ 0

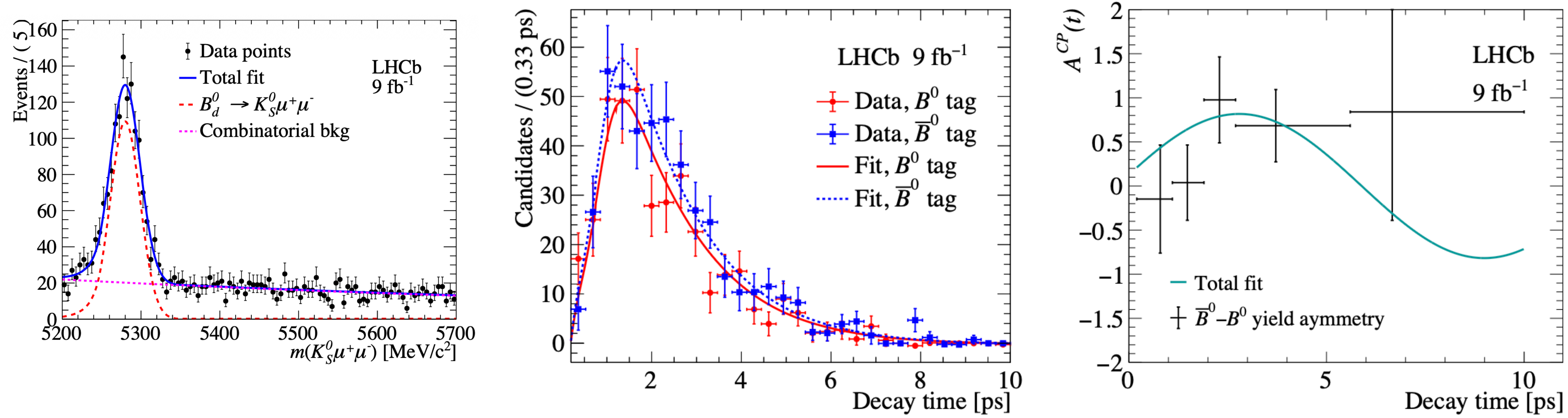
CP violation for $B^0 \to K_S^0 \mu^+ \mu^-$ decay

PRL 136 (2026) 231904

- First study of time-dependent CP violation in $b \to s l^+ l^-$ processes

$$\mathcal{A}^{CP}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to K_S^0\mu^+\mu^-) - \Gamma(B^0(t) \to K_S^0\mu^+\mu^-)}{\Gamma(\overline{B}^0(t) \to K_S^0\mu^+\mu^-) + \Gamma(B^0(t) \to K_S^0\mu^+\mu^-)} \simeq S\sin(\Delta m_d t) - C\cos(\Delta m_d t)$$

Complementary to decay rate measurements



$$C = -0.13 \pm 0.32 \pm 0.04$$

$$S = +0.82 \pm 0.29 \pm 0.05$$

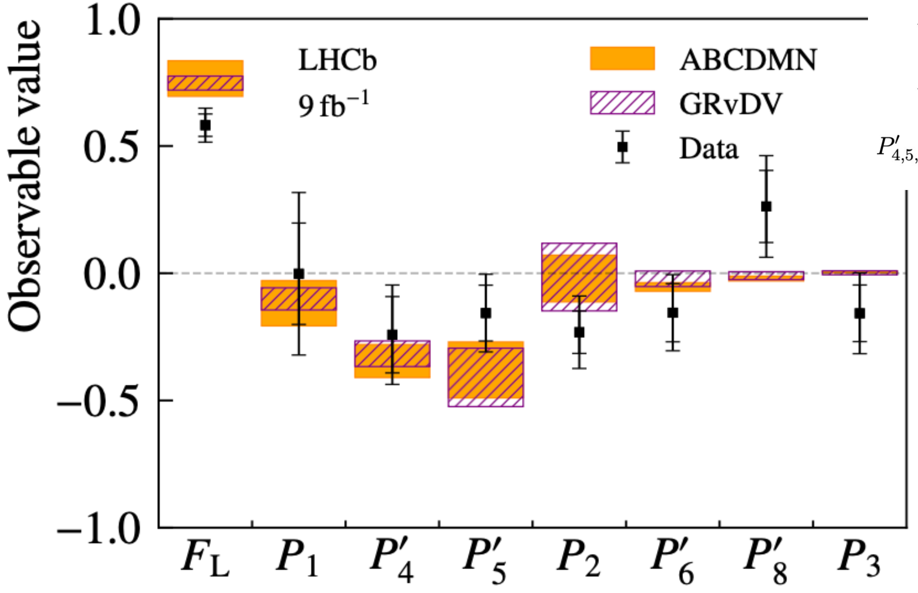
Consistent with SM

Angular analysis of $b \to s e^+ e^-$ decays

JHEP 06 (2025) 140

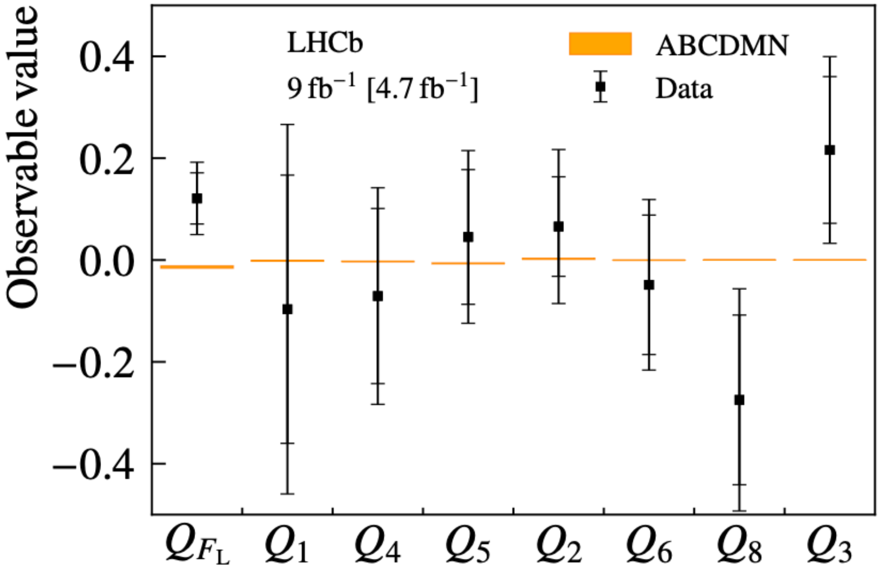
- Test of lepton flavor universality (LFU) against $b \to s\mu^+\mu^-$
- Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decay $\quad q^2 \in [1.1, 6]\ \mathrm{GeV}^2/c^4$

Clean observables



$$P_1 = \frac{2S_3}{(1-F_L)}\,,\quad P_2 = \frac{2}{3}\frac{A_{FB}}{(1-F_L)}\,,\quad P_3 = \frac{-S_9}{(1-F_L)}\,,\quad P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}\,.$$

$$Q_i = P_i^{\mu\mu} - P_i^{ee}$$



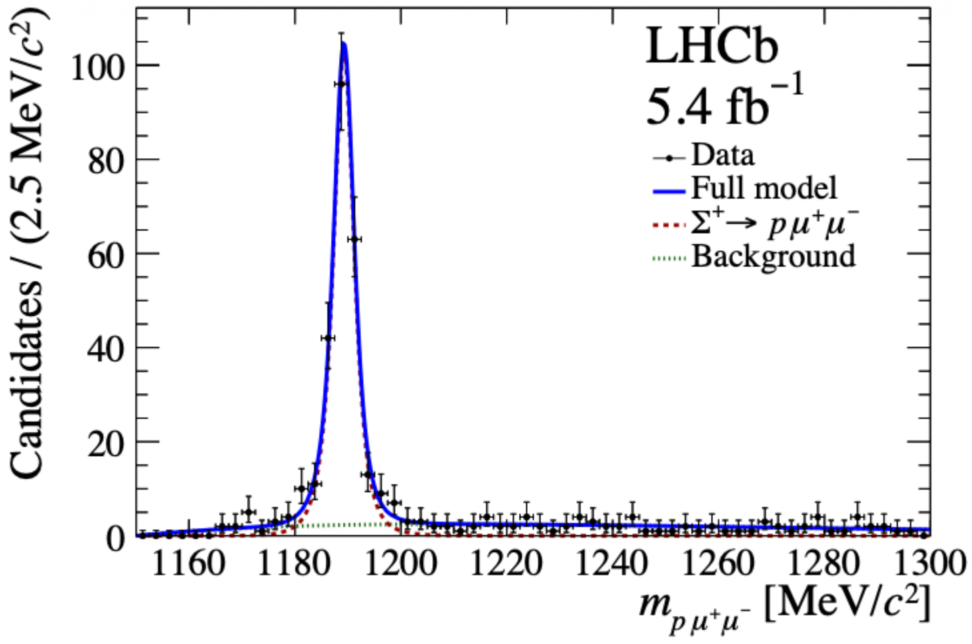
Consistent with SM predictions

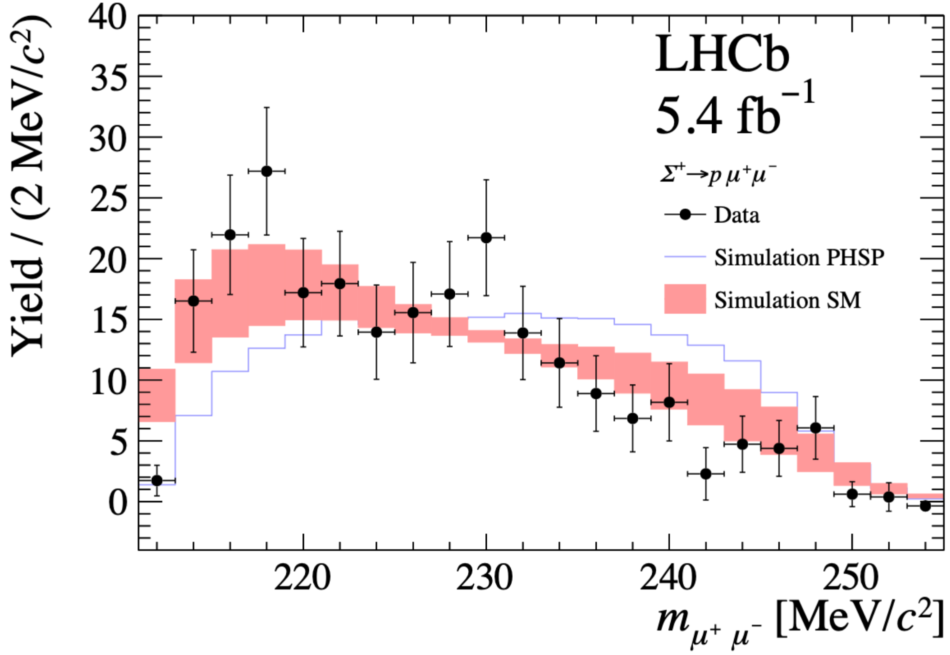
$\mu^+\mu^-$ and e^+e^- modes no sign of LFU violation

Observation of $\Sigma^+ \to p\mu^+\mu^-$ decay

PRL 135 (2025) 051801

- Rare $s \to d$ process, dominated by long distance contributions
- Observation at LHCb with measurement $\mathcal{B} = (1.09 \pm 0.17)\times 10^{-8}$
- $m_{\mu^+\mu^-}$ compatible with SM, no obvious structure hinted by HyperCP



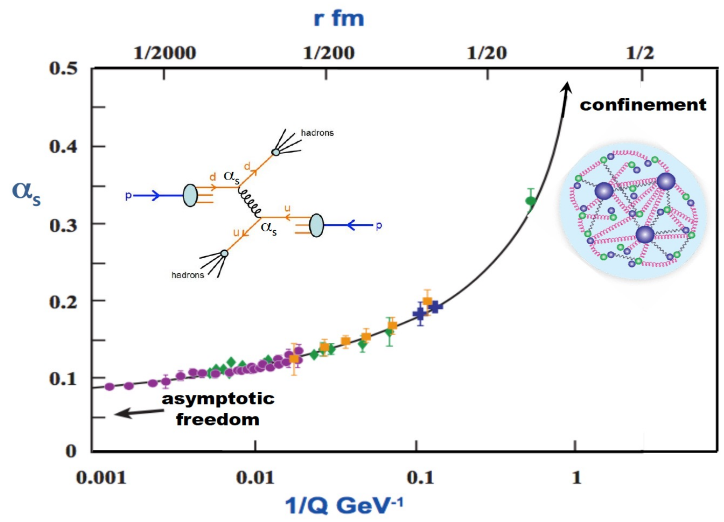


Outline

- LHCb experiment
- CP violation and CKM matrix
- Rare decays
- **Hadron spectroscopy**
- Prospects
- Summary

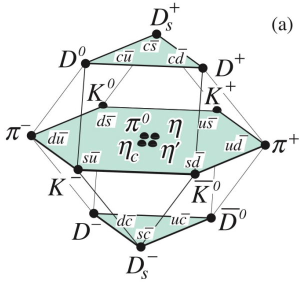
Hadron spectroscopy and low-energy QCD

- Hadron spectroscopy provides ideal opportunities to study QCD in non-perturbative region

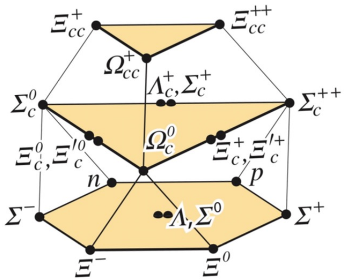


- Hadron classification
  - **Conventional**: mesons and baryons
  - **Exotic** (beyond two or three quarks): multiple color structure, strong experimental evidence in last years

Conventional



Mesons



Baryons

Exotic

Mesonic molecule ?

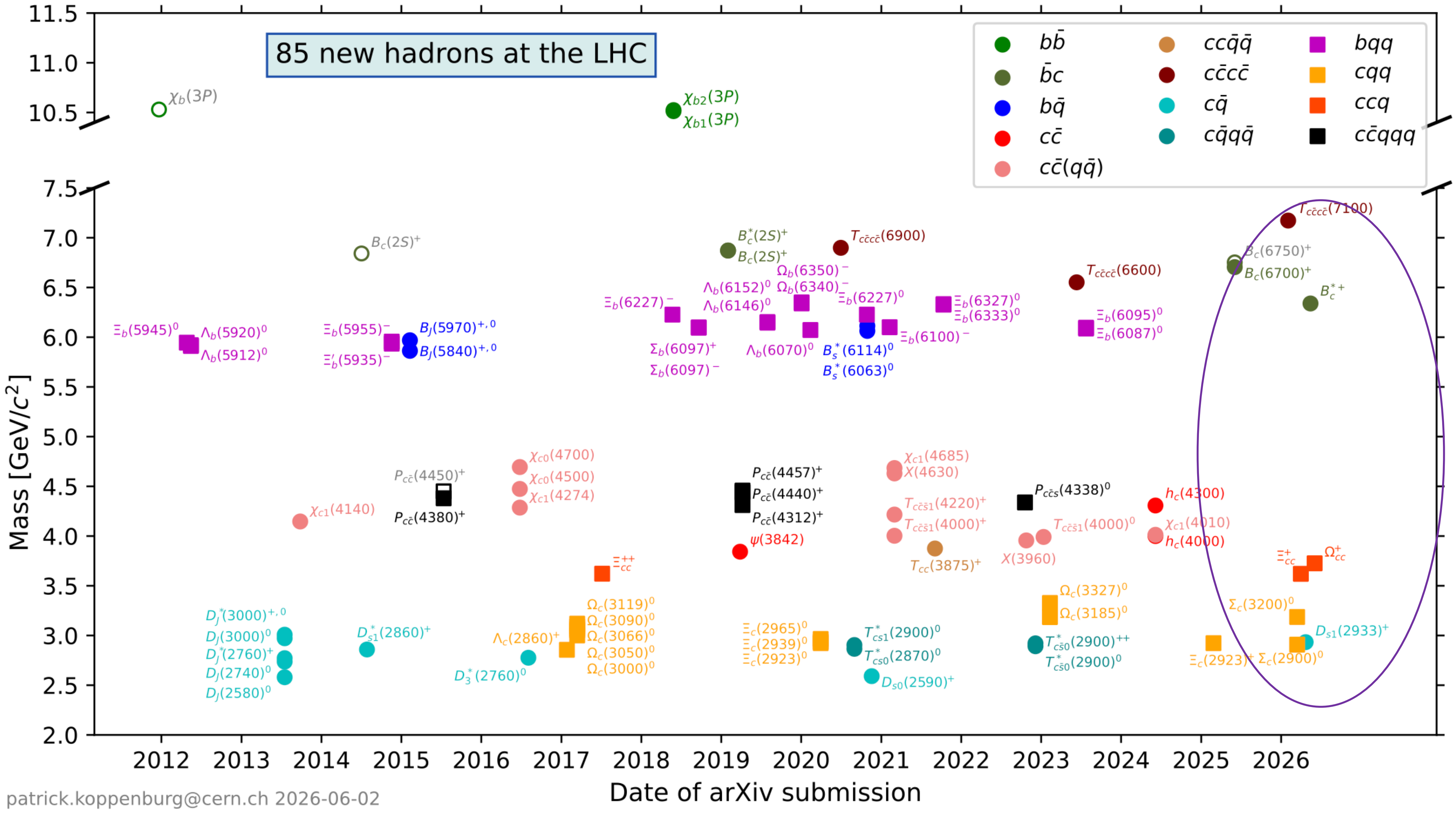
Tetraquark ?

Pentaquark ?

Hybrid ?

…

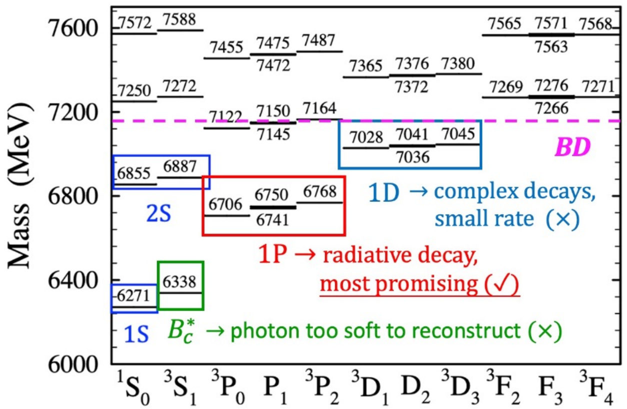
New states observed at LHCb



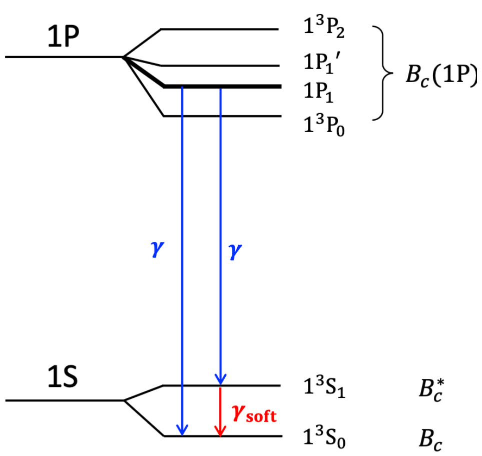
Observation of new B_c^+ states

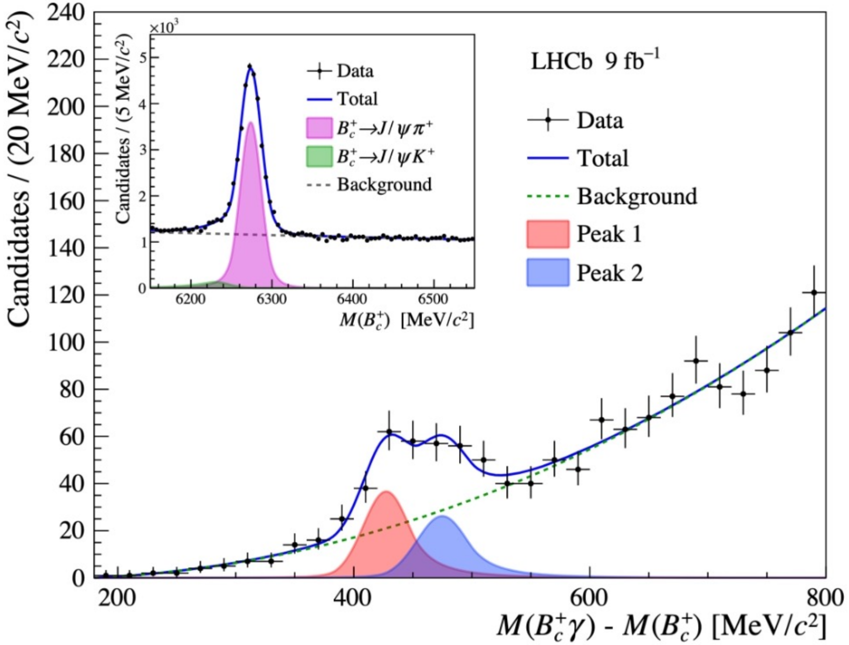
PRL 135 (2025) 231902
PRD 112 (2025) 112003

- $B_c^+[\bar{b}c]$ meson: system of two different heavy quarks
- Only $B_c^+(1S)$, $B_c^+(2S)$, $B_c^{*+}(2S)$ observed before
- Observation of excited B_c^+ states in $B_c^+\gamma$ spectrum
  - ➢ Corresponding to orbitally excited $B_c^+(1P)$ states
  - ➢ Six peaks expected, but not possible to resolve all



$B_c^+(1P) \to B_c^{(*)+}\gamma$





Global significance $> 7\sigma$

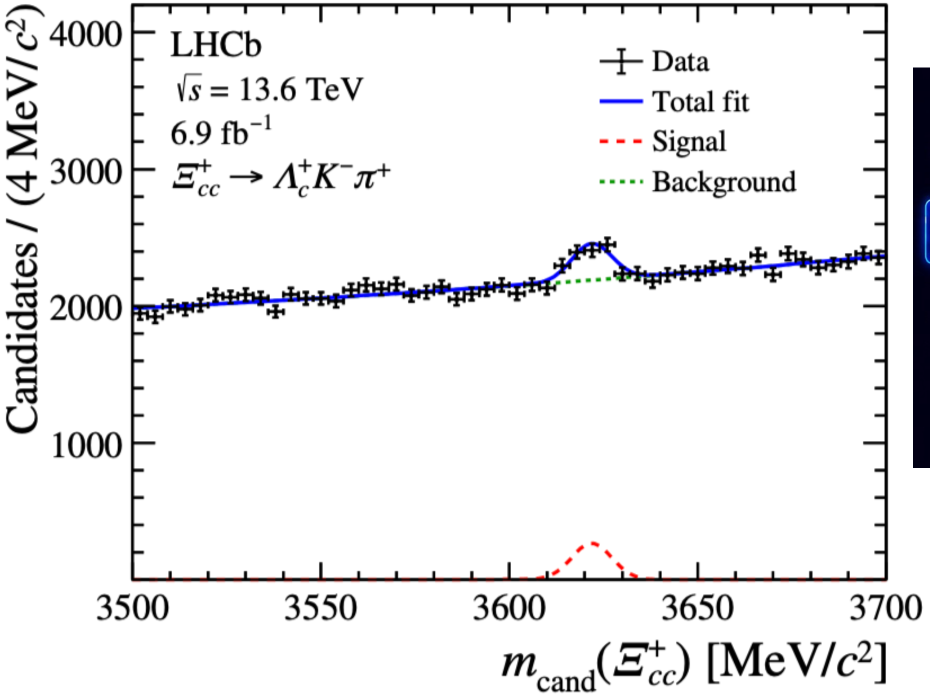
Two-peak hypothesis:

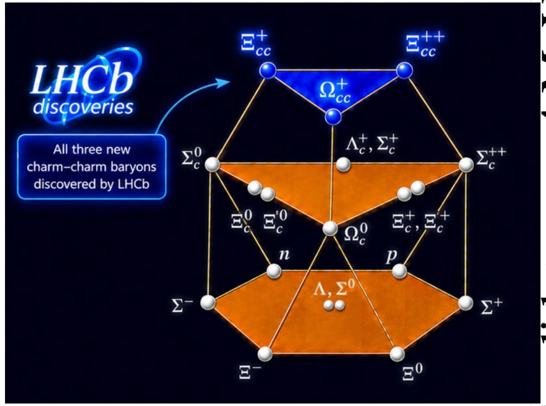
$$M_1 = 6704.8 \pm 5.5 \pm 2.8 \pm 0.3 \ \text{MeV}/c^2$$
$$M_2 = 6752.4 \pm 9.5 \pm 3.1 \pm 0.3 \ \text{MeV}/c^2$$

Doubly charmed baryons

- Unique hadrons, properties allowed to test phenomenological models

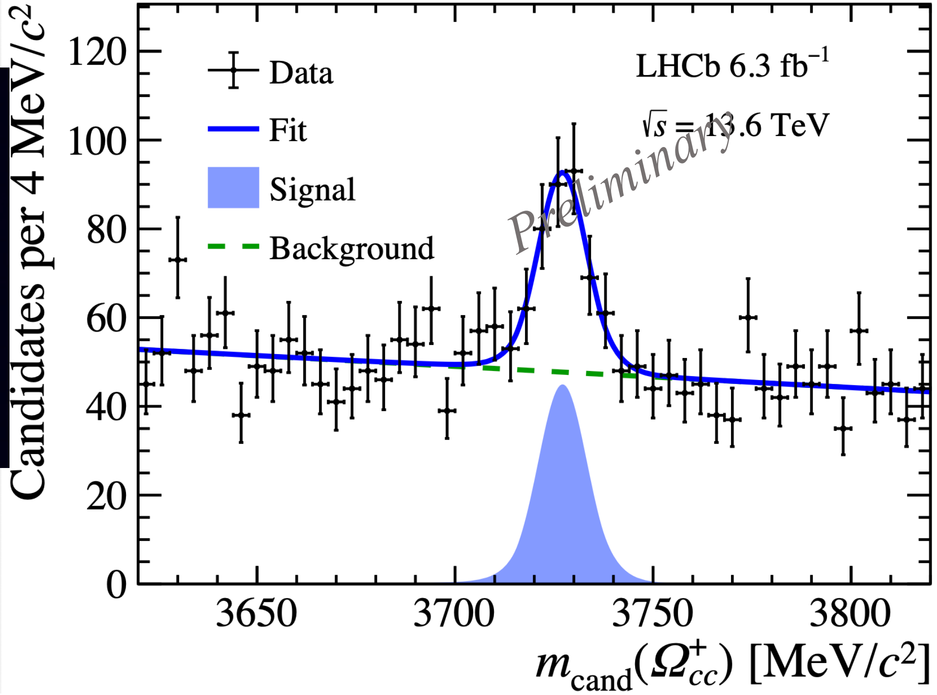
$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$





20-plet $\left(J = \frac{1}{2}\right)$

$\Omega_{cc}^{+} \to \Omega_c^{0} \pi^{+}$



PRL 137 (2026) 021902

LHCb-PAPER-2026-022

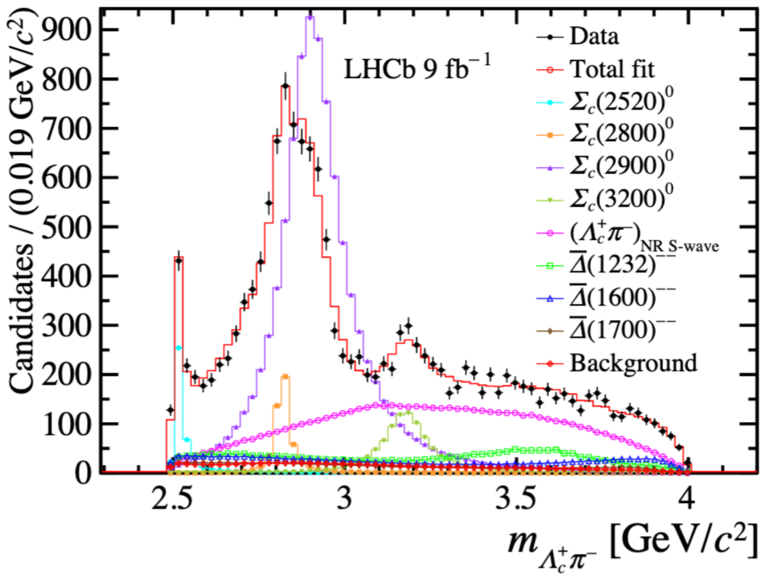
Observation of new excited Σ_c^0 states

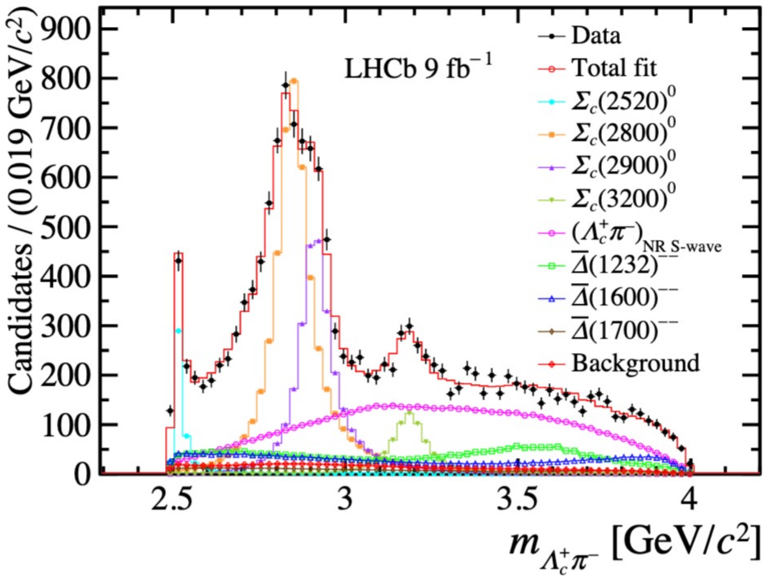
arXiv:2607.10595

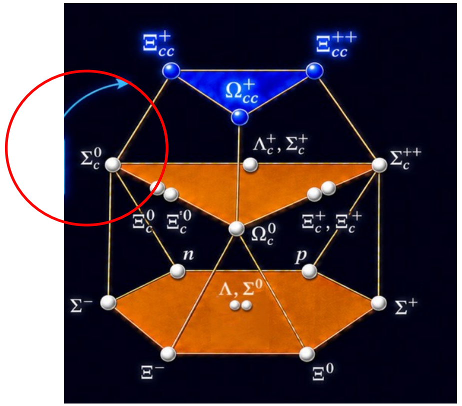
- Amplitude analysis of $B^- \to \Lambda_c^+ \bar{p} \pi^-$ decay, observing two Σ_c^{**0} in $\Lambda_c^+ \pi^-$ spectrum

$\Sigma_c(2900)^0$, $\Sigma_c(3200)^0$

New flavor symmetric 6_F states







Parameter	Group A	Group B	
$m_{\Sigma_c(2800)^0}$ [GeV/c^2]	$2.819 \pm 0.006 \pm 0.002$	$2.848 \pm 0.004 \pm 0.006$	1P or 2S
$\Gamma_{\Sigma_c(2800)^0}$ [GeV]	$0.033 \pm 0.007 \pm 0.008$	$0.099 \pm 0.007 \pm 0.021$	
$m_{\Sigma_c(2900)^0}$ [GeV/c^2]	$2.908 \pm 0.005 \pm 0.009$	$2.914 \pm 0.003 \pm 0.008$	1P or 2S
$\Gamma_{\Sigma_c(2900)^0}$ [GeV]	$0.175 \pm 0.008 \pm 0.023$	$0.092 \pm 0.006 \pm 0.023$	
$m_{\Sigma_c(3200)^0}$ [GeV/c^2]	$3.186 \pm 0.006 \pm 0.014$	$3.190 \pm 0.005 \pm 0.011$	2P or 3S
$\Gamma_{\Sigma_c(3200)^0}$ [GeV]	$0.133 \pm 0.018 \pm 0.027$	$0.100 \pm 0.015 \pm 0.032$	

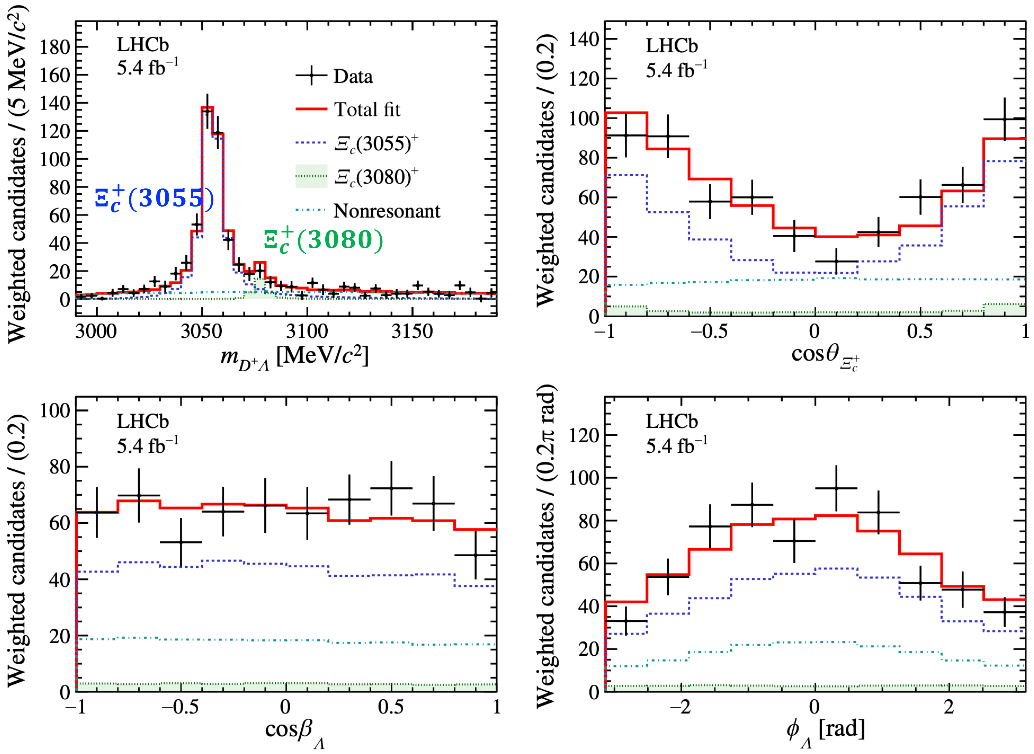
Analysis not sensitive to J^P

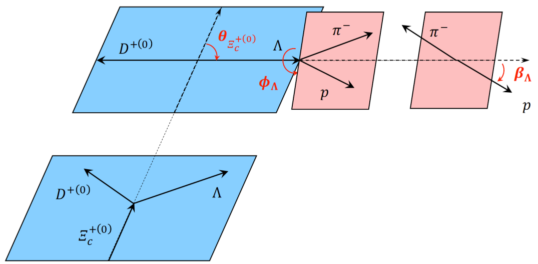
Determination of J^P for $\Xi_c(3055)^{+,0}$

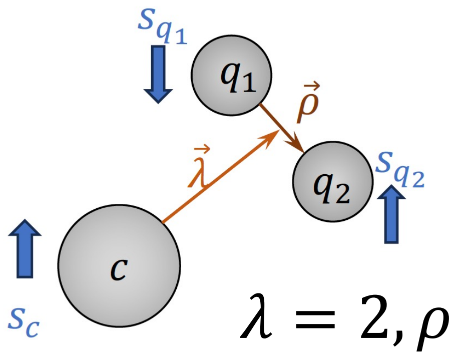
PRL 134 (2025) 081901

- First observation of $\Xi_b^{0,-} \to \Xi_c(3055)^{+,0}(\to D\Lambda)\pi^-$ decays, evidence for $\Xi_c(3080)$
- Measurement of $\Xi_c(3055)^{+,0}$ properties with amplitude analysis

Amplitude analysis of four observables $(m_{D\Lambda}, \theta_{\Xi_c}, \beta_\Lambda, \theta_\Lambda)$







$\lambda = 2, \rho = 0$

- $J^P = 3/2^+$ determined for $\Xi_c(3055)^{+,0}$ with significances of more than 6.5σ (3.5σ)
- Favor $\Xi_c(3055)$ as a 1D λ-mode excitation of flavor antitriplet

Outline

- LHCb experiment
- CP violation and CKM matrix
- Rare decays
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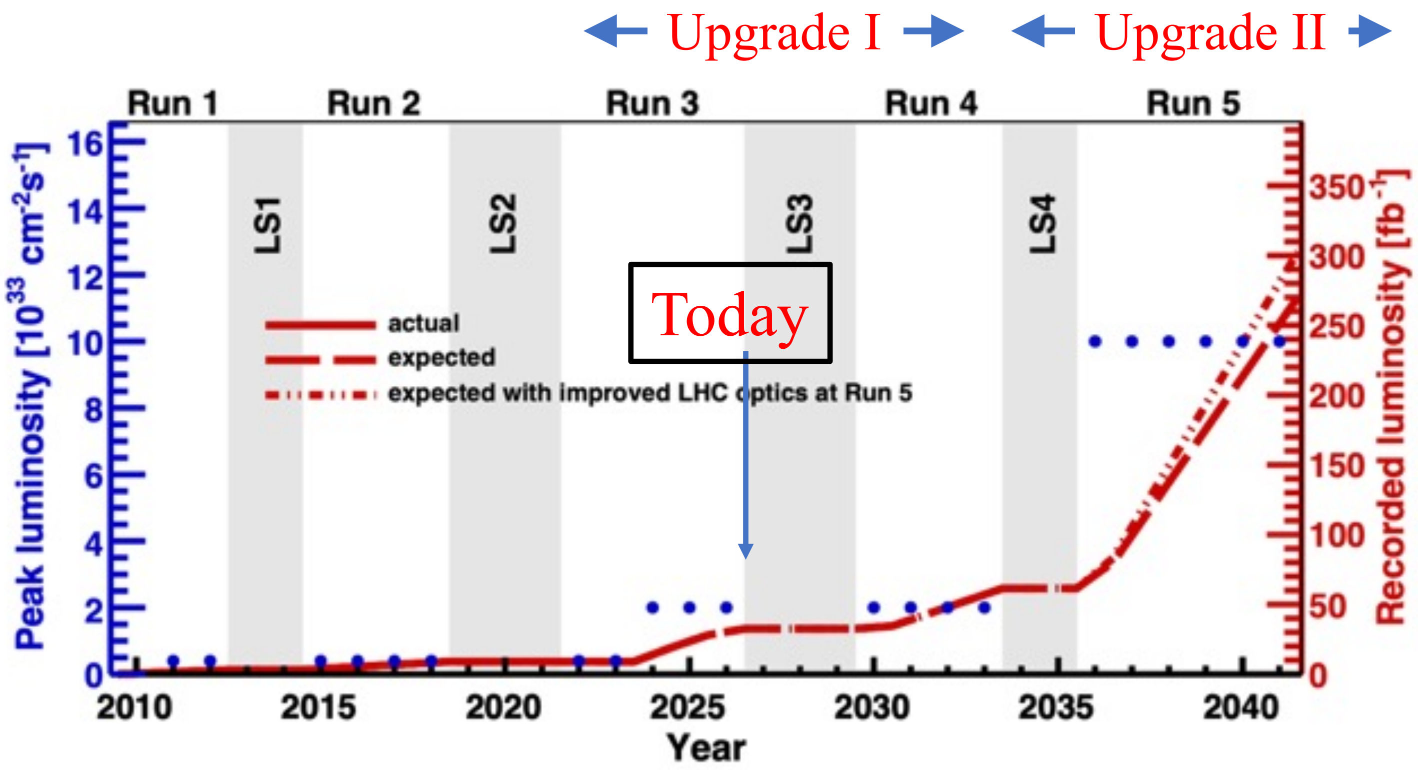
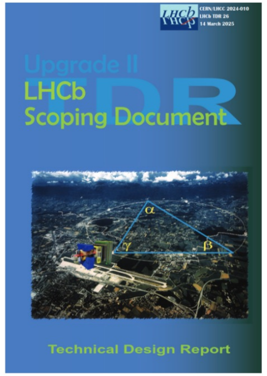
LHCb timeline





CERN-LHCC-2024-010

CERN-LHCC-2021-012

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

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

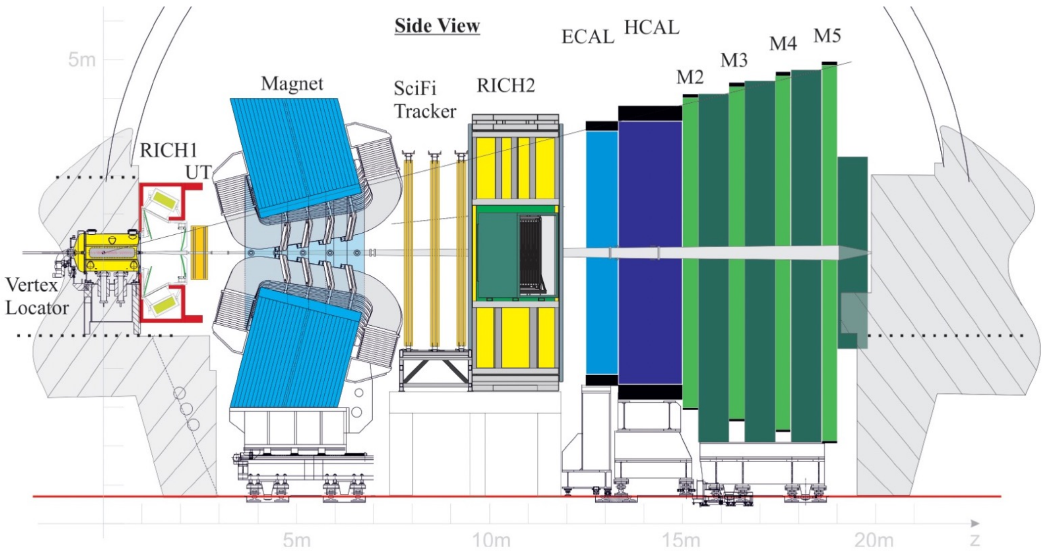
$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

55 visible interactions / crossing

300 fb^{-1} collected

Run 3 operation

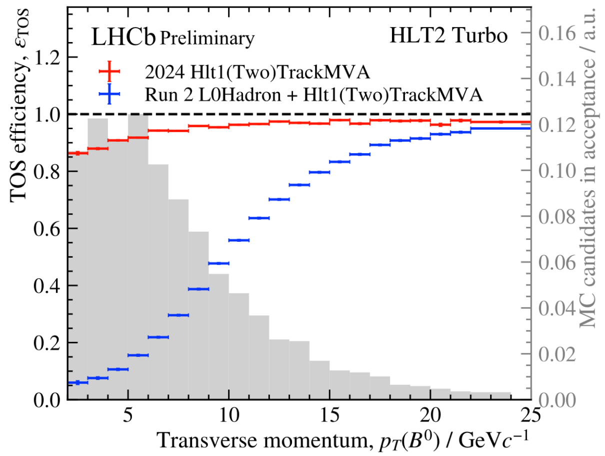
- New tracking system: VELO+UT+SciFi
- About 27 fb^{-1} pp collision data collected
- Full detector readout at 30 MHz



JINST 19 (2024) P05065

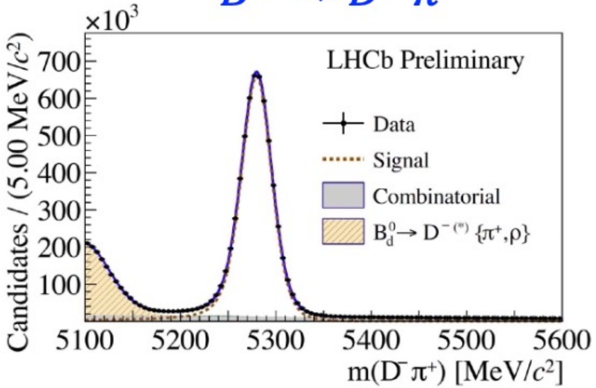
Improved trigger efficiency

LHCb-FIGURE-2024-030



Increased signal yields per unit lumi

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

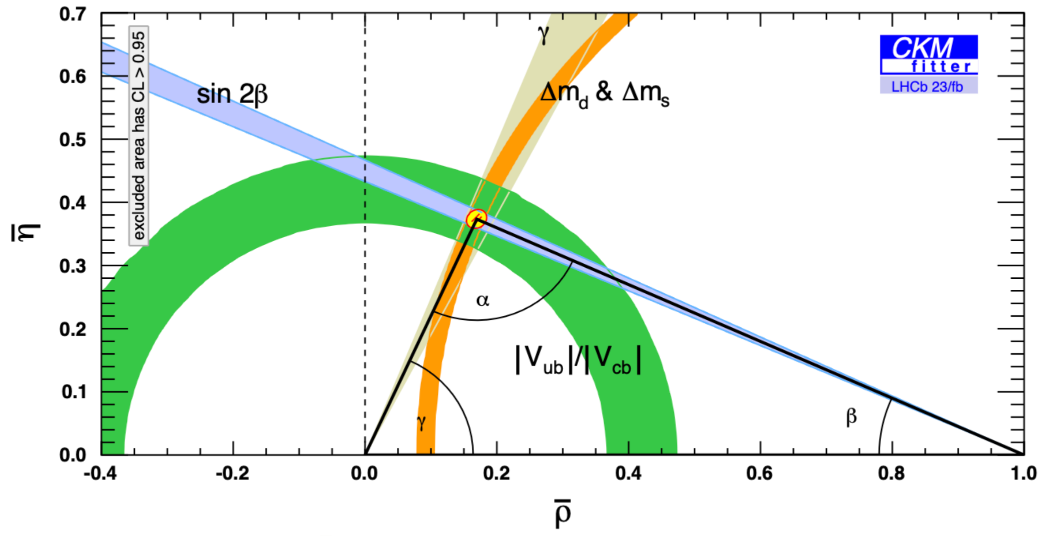


3× Run2

Summary

- LHCb: heavy flavor physics at CERN for studies of SM and new physics
  - ➢ Precision measurements CP violation and CKM matrix
  - ➢ Anomalies and possible new physics in rare decays
  - ➢ Observing new hadrons
- Many more data in run3, results coming out

The Unitarity triangle after Run 3 will likely be:



Many thanks !