LHCb实验最新进展

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天问论坛，湖南长沙， 2023年11月11-12日

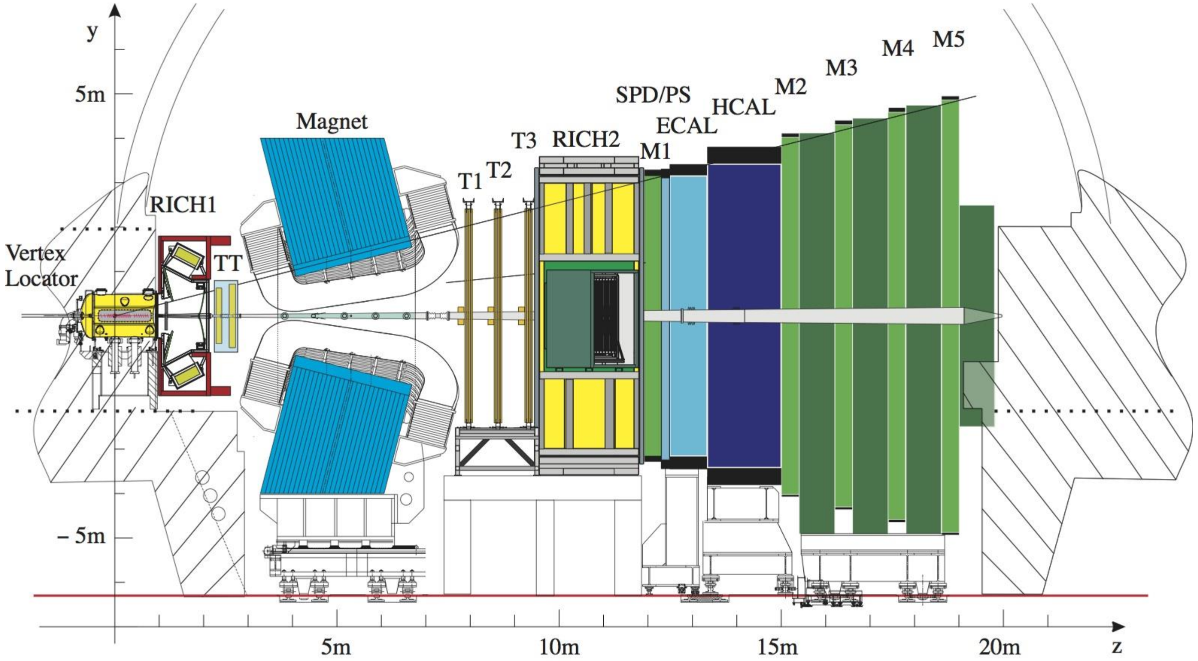
提纲

- LHCb实验介绍
- CP破坏相位角的高精度测量
- 稀有衰变和轻子普适性中的反常结果
- 若干常规与非常规强子的发现
- 展望和总结

大型强子对撞机

27公里环形质子-质子加速器，
每秒4千万次对撞，设计能量14 TeV

LHCb实验



LHCb合作组

21个国家，97家单位，1626名成员

中国单位：

清华大学，华中师范大学，中国科学院大学，武汉大学，高能所, 华南师范大学，湖南大学，北京大学，兰州大学

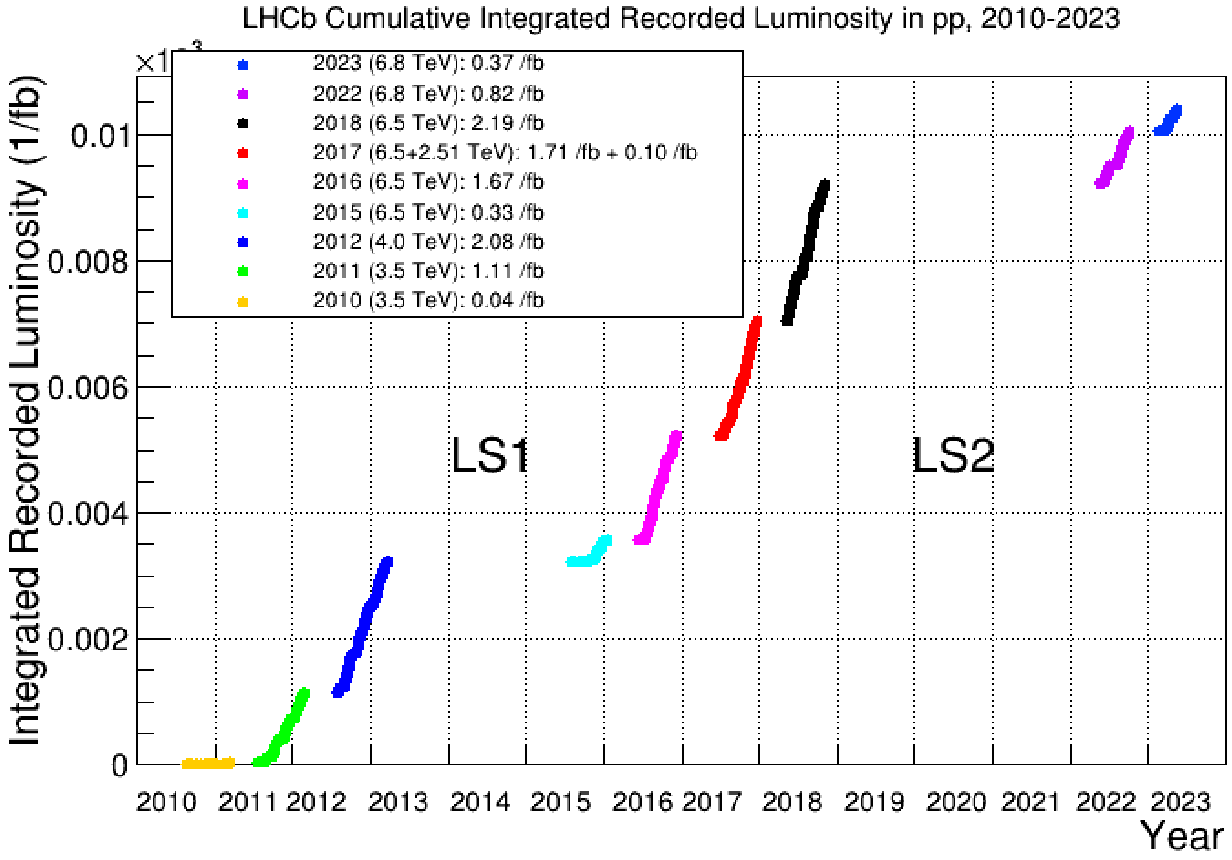
- **理解正反物质不对称** (重味强子衰变中的CP破坏)
- **间接寻找新物理效应** (稀有衰变、轻子普适性检验)
- **理解强相互作用机制** (强子性质、新强子态)
- **前向区域的物理研究** (电弱物理、重离子物理、QCD)

LHCb数据获取（pp 对撞）

第一运行期：Run 1（2011-2012），3 fb^{-1}

第二运行期：Run 2（2015-2018），6 fb^{-1}

第二运行期：Run 3（2022-　　　），~1 fb^{-1}



High-precision measurements of CP-violating phases

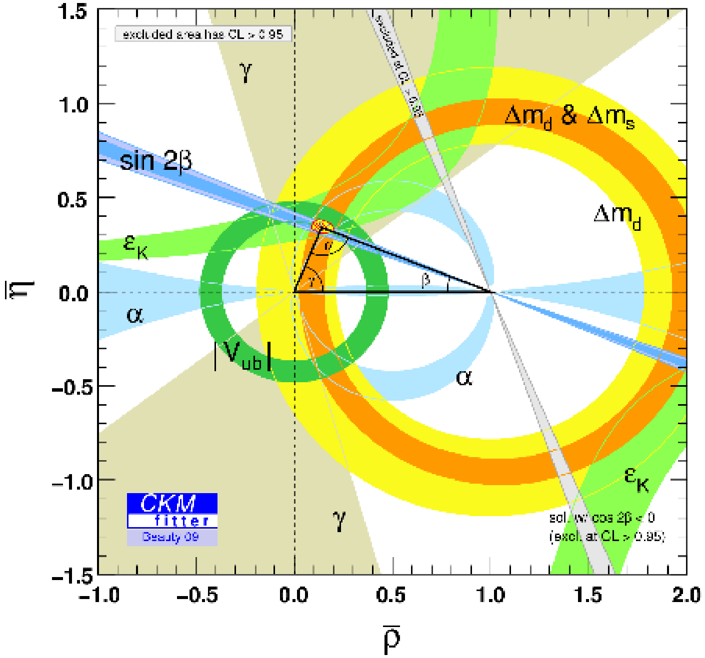
CP violation and CKM matrix

CP violation in the quark sector successfully described by the CKM matrix

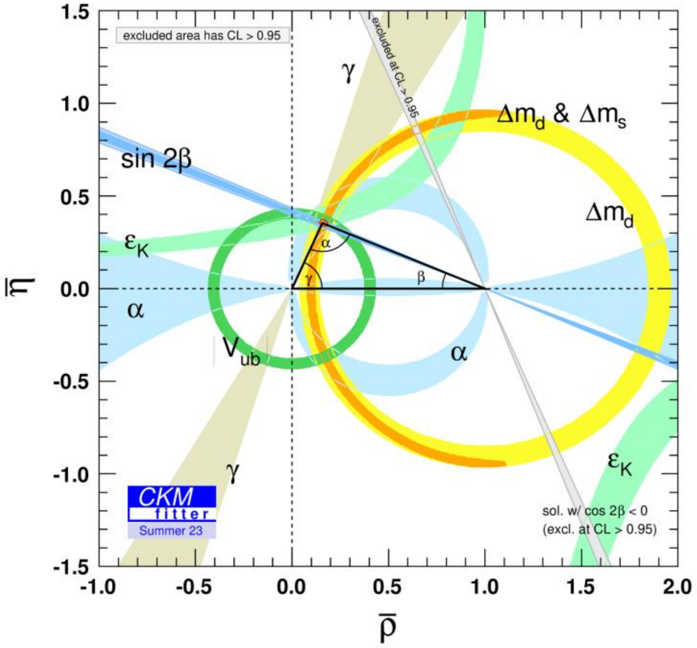
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

When LHC started



Current picture

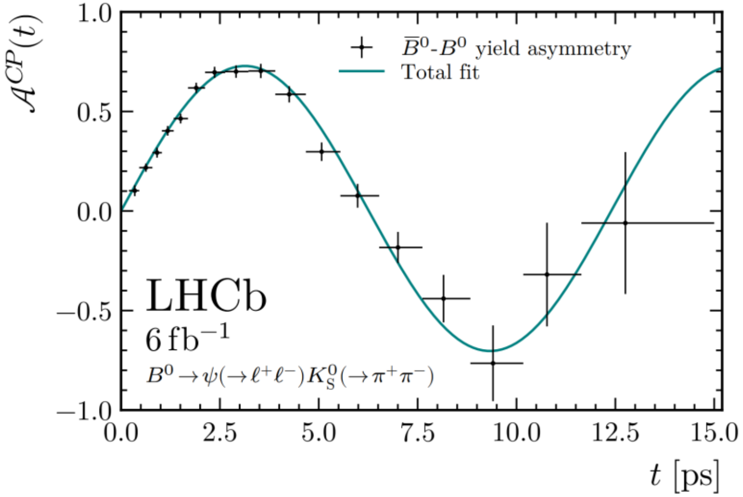


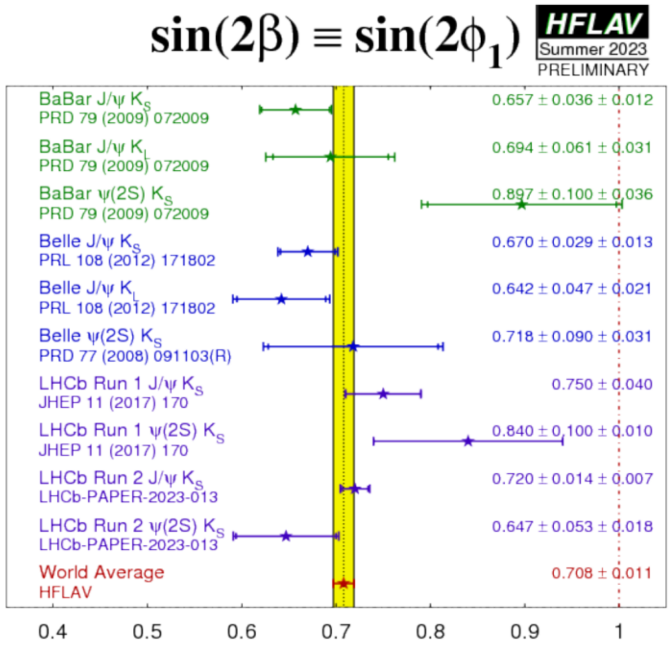
LHCb has achieved the most precise measurements of β, β_s, γ

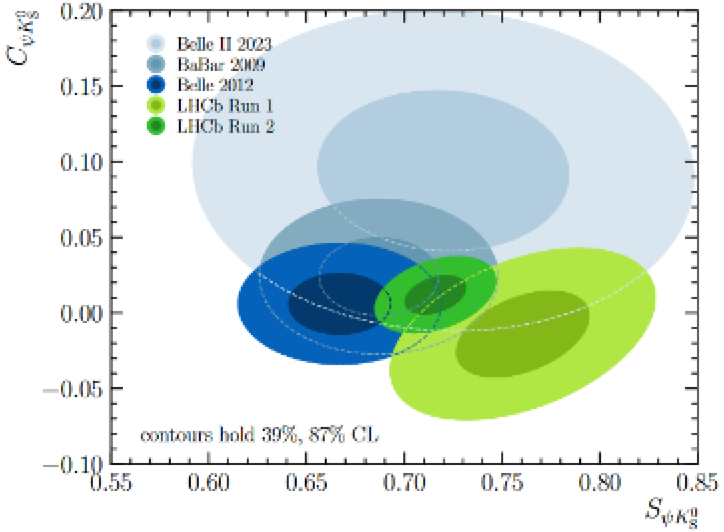
Run 2 legacy measurement of $\sin 2\beta$

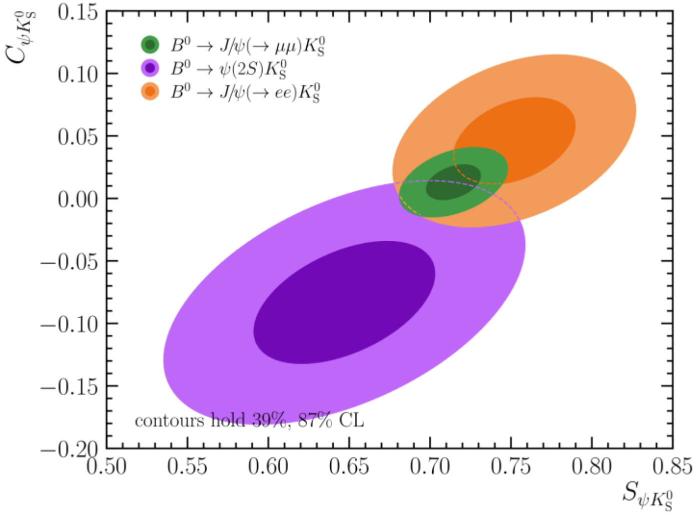
arXiv:2309.09728

$$A_{CP}(t) = \sin 2\beta \, \sin(\Delta m_d t)$$









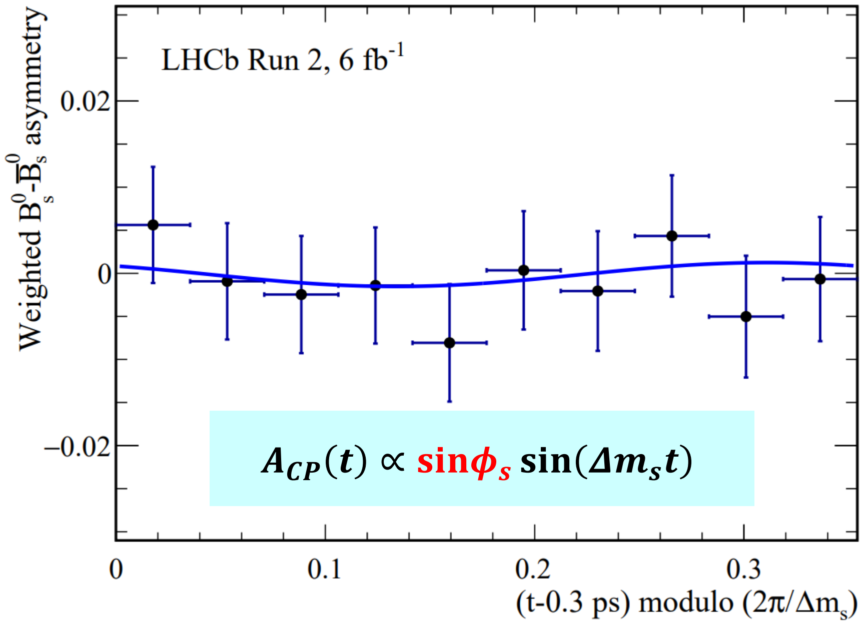
LHCb: $\sin 2\beta = 0.724 \pm 0.014$

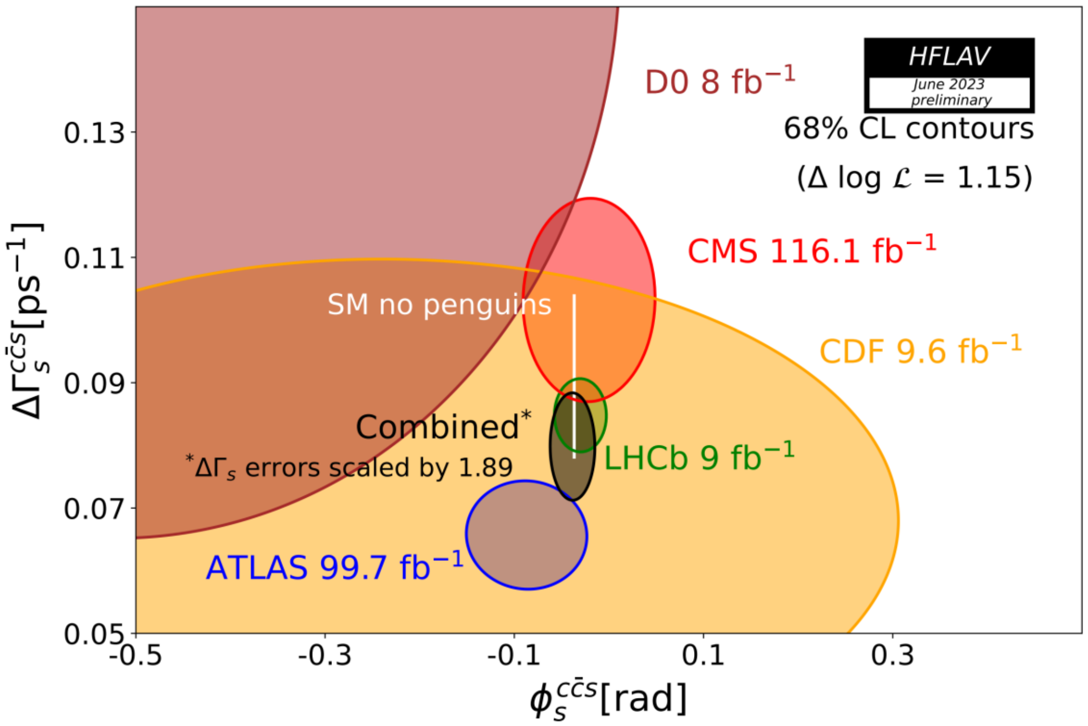
New WA: $\sin 2\beta = 0.708 \pm 0.011$

SM prediction: $\sin 2\beta = 0.731^{+0.029}_{-0.016}$

Most precise measurement of ϕ_s in $B_s^0 \to J/\psi\phi$

arXiv:2308.01468





No sign of CP violation
No significant polarization dependency

LHCb: $\phi_s^{c\bar{c}s} = -0.038 \pm 0.018$ rad

New WA: $\phi_s^{c\bar{c}s} = -0.038 \pm 0.018$ rad

SM prediction: $\phi_s = -2\beta_s = -0.0368^{+0.006}_{-0.009}$ rad

Tension in $\Delta\Gamma_s$ remains

LHCb $\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024$ ps^{-1}

ATLAS $\Delta\Gamma_s = 0.0657 \pm 0.0043 \pm 0.0037$ ps^{-1}

CMS $\Delta\Gamma_s = 0.1032 \pm 0.0095 \pm 0.0048$ ps^{-1}

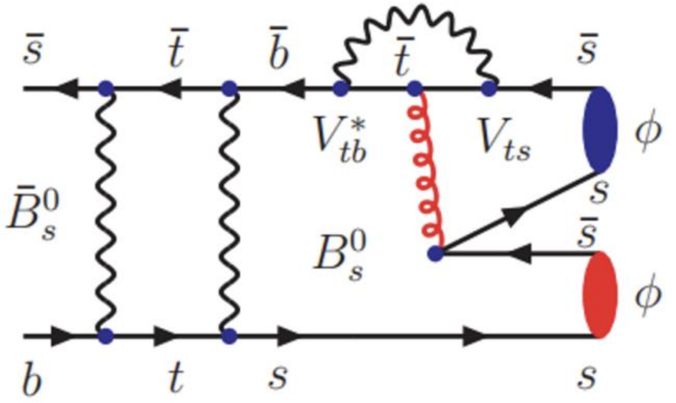
ϕ_s in penguin decay $B_s^0 \to \phi\phi$

PRL 131 (2023) 171802

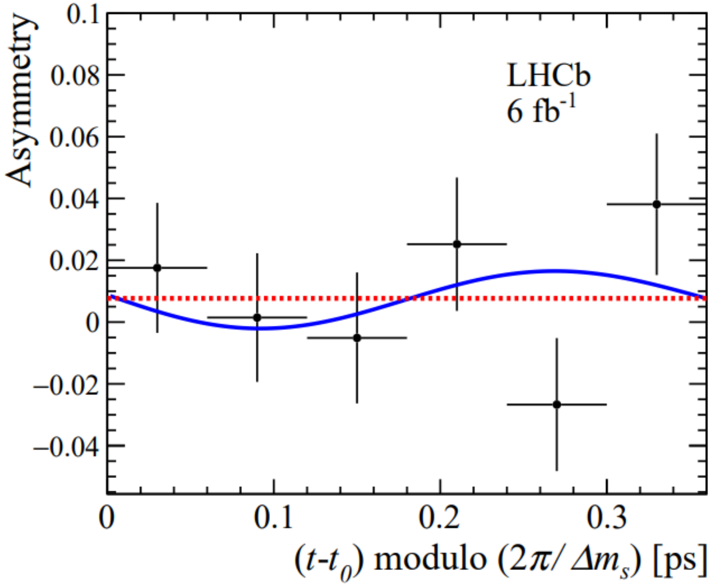
- Penguin-dominated decay sensitive to NP
- Most precise measurement of time-dependent CP violation in penguin decays, consistent with SM

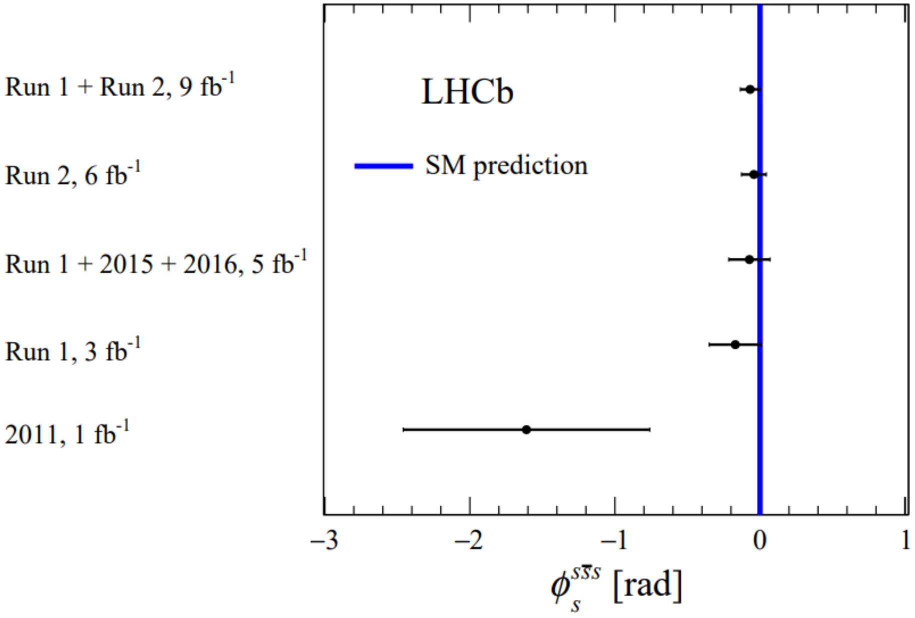
LHCb: $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad

SM prediction: $\phi_s^{\text{SM}} = 0.00 \pm 0.02$ rad



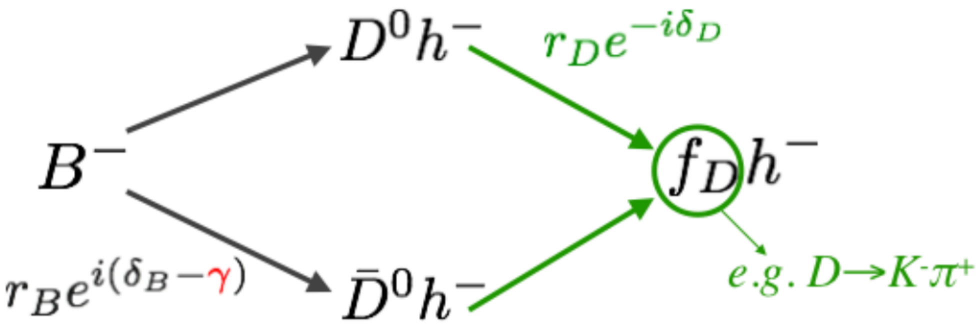
$A_{CP}(t) \propto \sin\phi_s \sin(\Delta m_s t)$





γ from $B \to Dh$ decays

- Access γ from interference of $b \to u$ & $b \to c$ transitions in $B^{\pm} \to Dh^{\pm}$ $(h = K, \pi)$ decays



$$\Gamma(B^{\pm} \to Dh^{\pm}) \propto \left| r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)} \right|^2$$

γ, δ_B, r_B: to be measured

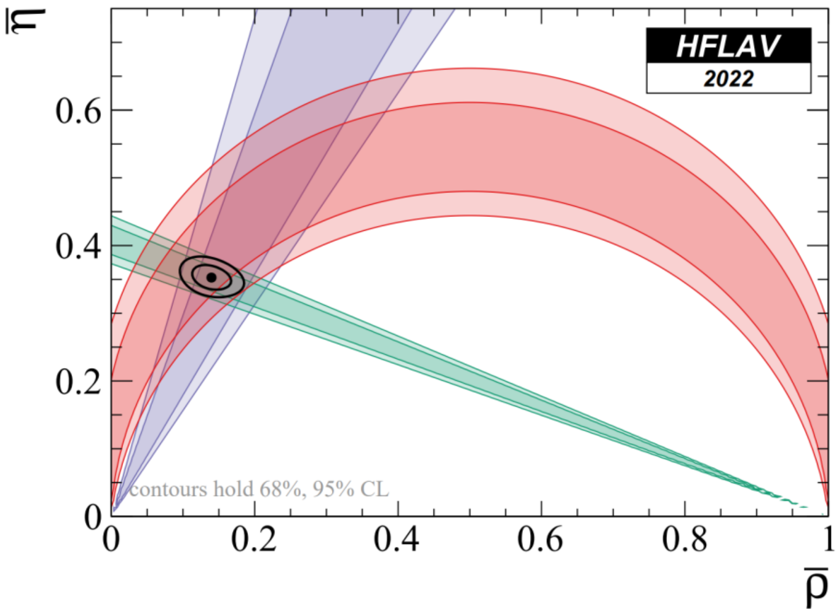
δ_D, r_D: external inputs

- γ remains a limiting factor for test of CKM unitarity

LHCb: $\gamma = (63.8^{+3.5}_{-3.7})°$ LHCB-CONF-2022-002

BaBar: $\gamma = (70 \pm 18)°$ PRD 87 (2015) 052 015

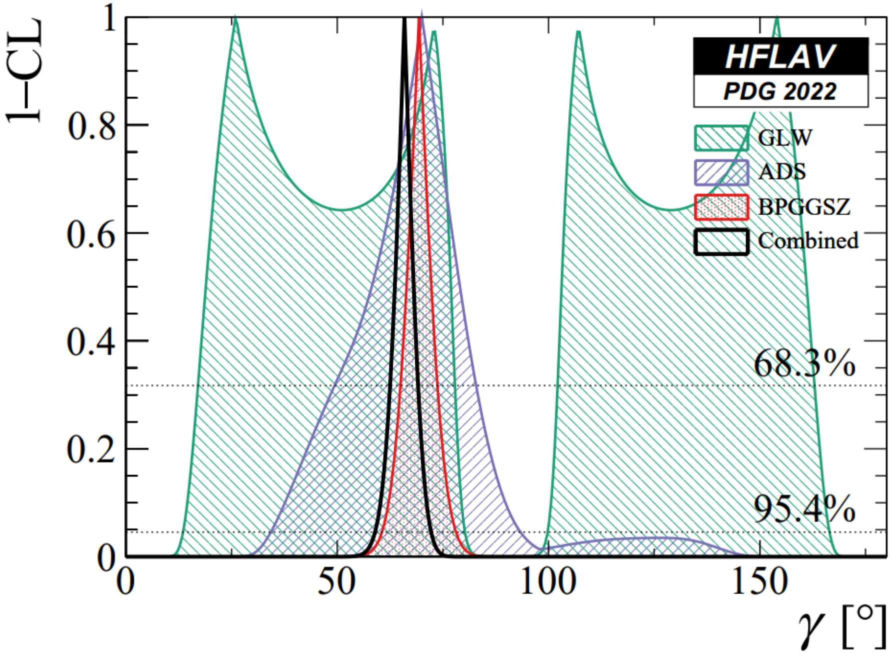
BELLE: $\gamma = (73^{+13}_{-15})°$ arXiv: 1301.2033



γ measurement methods

Categorise decays sensitive to γ depending on the D final state
Optimal sensitivity only when combining them together

- GLW
  - CP eigenstates e.g. $D \to hh$
  - [Phys. Lett. B253 (1991) 483]
  - [Phys. Lett. B265 (1991) 172]
- ADS
  - CF or DCS decays e.g. $D \to K\pi$
  - [Phys. Rev. D63 (2001) 036005]
  - [Phys. Rev. Lett. 78 (1997) 3257]
- BPGGSZ
  - 3-body final states e.g. $D \to K^0_S\pi\pi$
  - [Phys. Rev. D68 (2003) 054018]



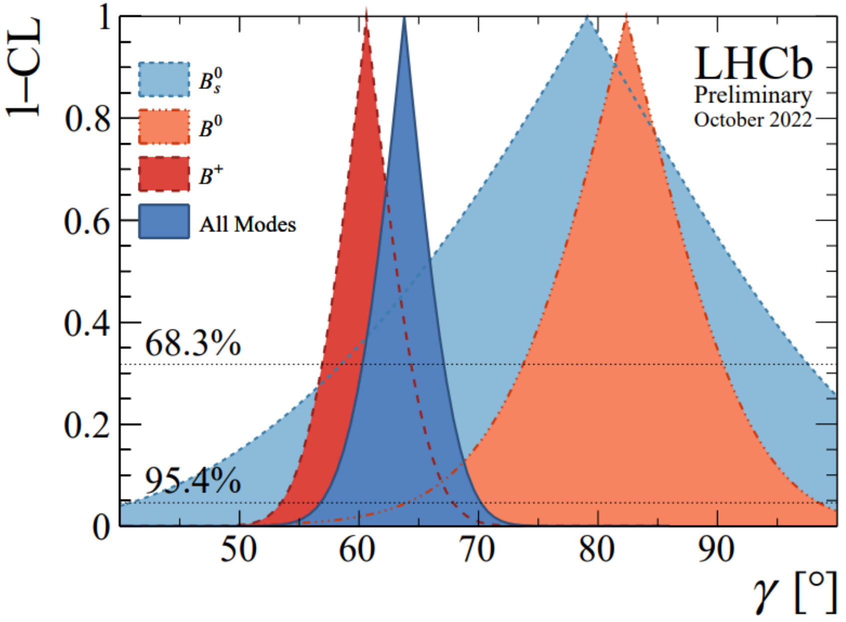
- TD (Time-dependent)
  - Interference between mixing and decay e.g. $B^0_s \to D^-_s K^+$ [phase is $(\gamma - 2\beta_s)$]
  - Penguin free measurement of ϕ_s one day
- Dalitz
  - Multi-body B decays with D^0 or $\overline{D}^0$ in the final state, e.g. $B^0 \to \overline{D}^0 K^+\pi^-$
  - [Phys. Rev. D79 (2009) 051301]

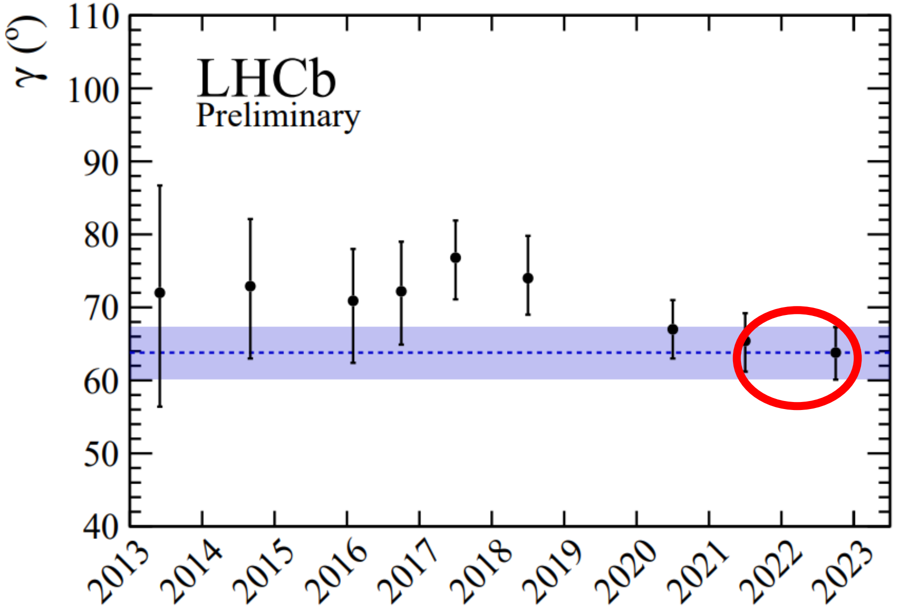
Latest LHCb γ combination

LHCb-CONF-2022-002

Combination of many B and D decay modes

- $B^{\pm} \to DK^{(*)\pm}$
- $B^0 \to DK^{*0}$
- $B^0 \to D^{\mp}\pi^{\pm}$
- $B_s^0 \to D_s^{\mp}K^{\pm}(\pi\pi)$
- $D \to K^+\pi^-$
- $D \to K^+\pi^-$
- $D \to h^+h^-\pi^0$
- $D \to \pi^+\pi^-\pi^+\pi^-$
- $D \to K^+\pi^-\pi^0$
- $D \to K^{\pm}\pi^{\mp}\pi^+\pi^-$
- $D \to K_S^0K^{\pm}\pi^{\mp}$
- $D \to K_S^0K^{\pm}\pi^{\mp}$





LHCb: $\gamma = \left(63.8^{+3.5}_{-3.7}\right)^{\circ}$

Consistent with SM prediction: $\gamma = \left(65.5^{+1.1}_{-2.7}\right)^{\circ}$

New γ results using $D \to K_S^0 h^+ h^-$ decays (BPGGSZ)

arXiv:2310.04277

$B^0 \to D(K_S^0 h^+ h^-) K^{*0}$

Most precise single measurement: $\gamma = (69^{+13}_{-14})^\circ$

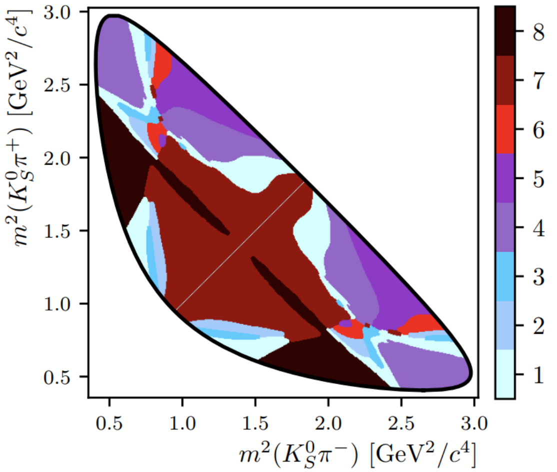
$$N^+_{\pm i} = h_{B^+}\left[F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$

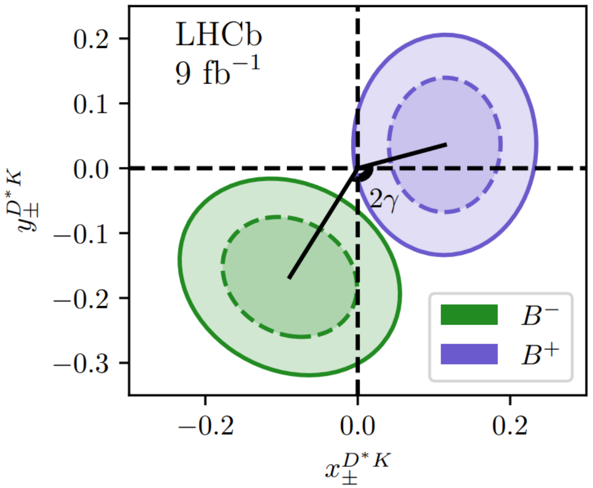
$$N^-_{\pm i} = h_{B^-}\left[F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} - y_- s_{\pm i})\right]$$

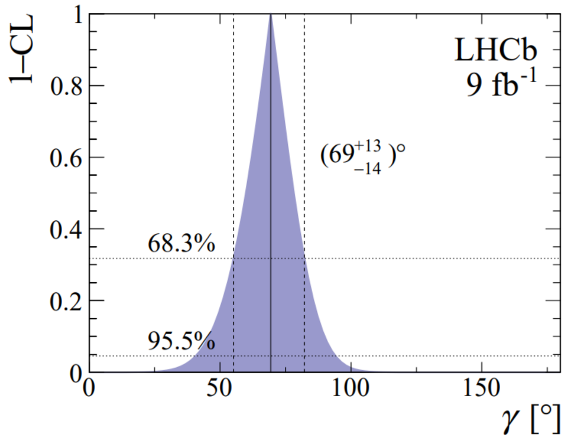
c_i, s_i: from BESIII/CLEO

$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$

$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$







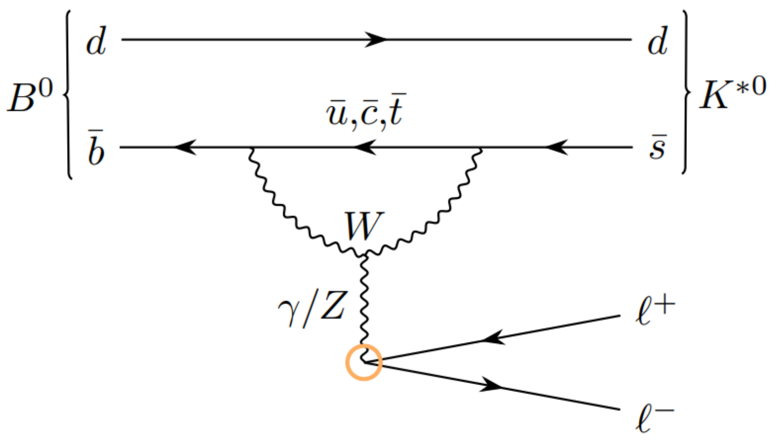
$B^\pm \to D^* h^\pm, D^* \to D(K_S^0 h^+ h^-)\gamma/\pi^0$

$\gamma = (49^{+22}_{-19})^\circ$

arXiv:2309.0551

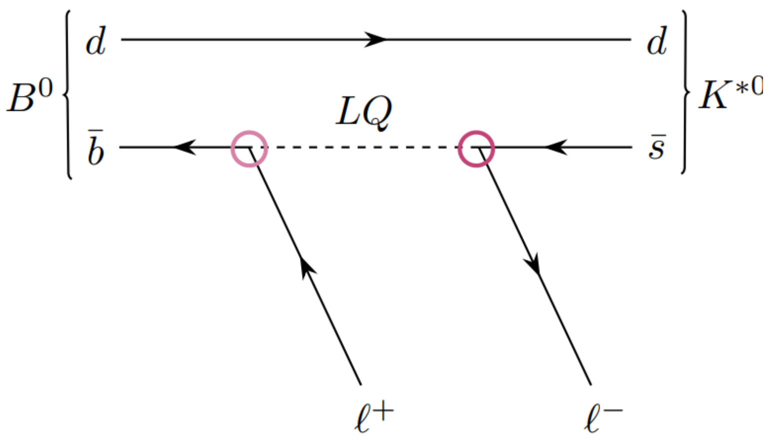
Anomalies in rare decays and lepton flavour universality test

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



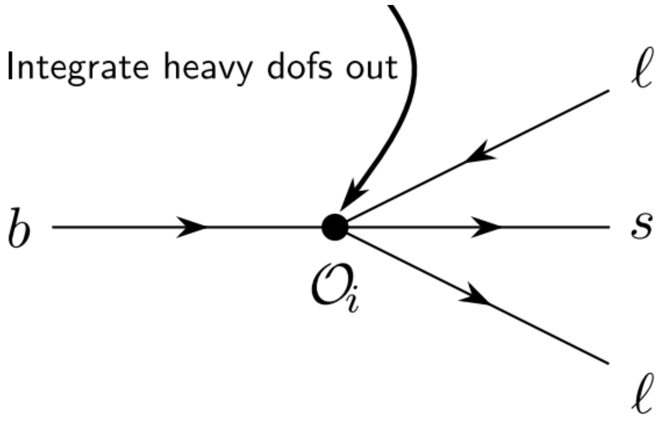
SM

- loop-suppressed (FCNC)
- universal couplings guaranteed



NP

- can enter at tree-level
- universal couplings not guaranteed

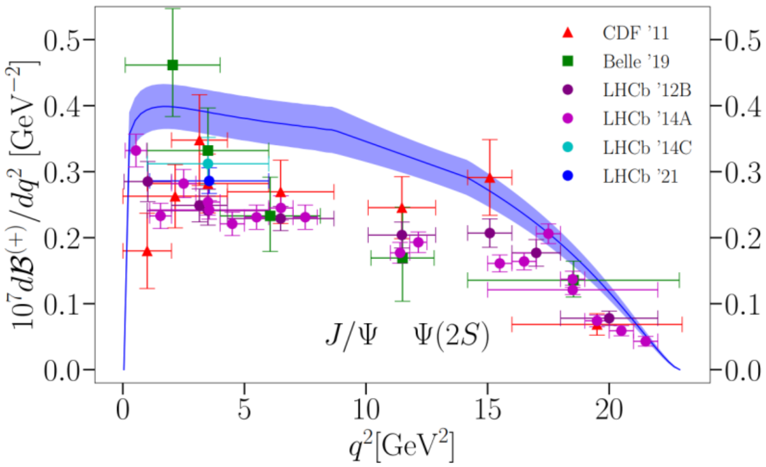


$$\mathcal{H}_{\text{eff}} \propto \Sigma_i C_i \mathcal{O}_i$$

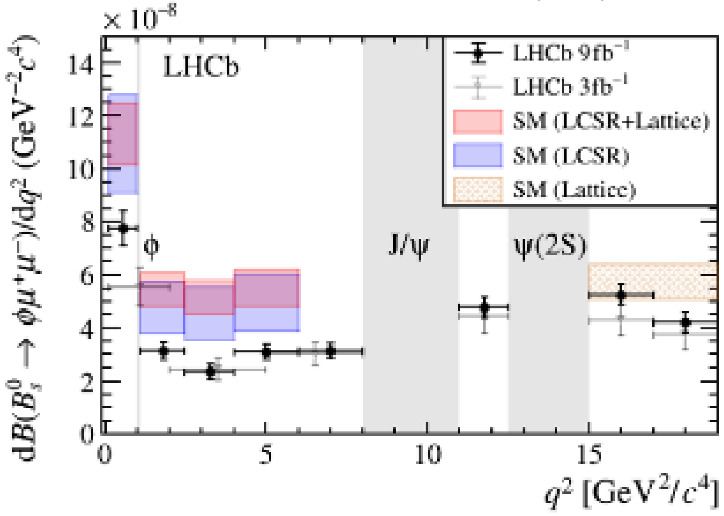
- local operators relevant at different $q^2 \equiv m^2(\ell^+\ell^-)$
- "effective coupling" coefficients may be affected by NP

Tension in differential decay rates

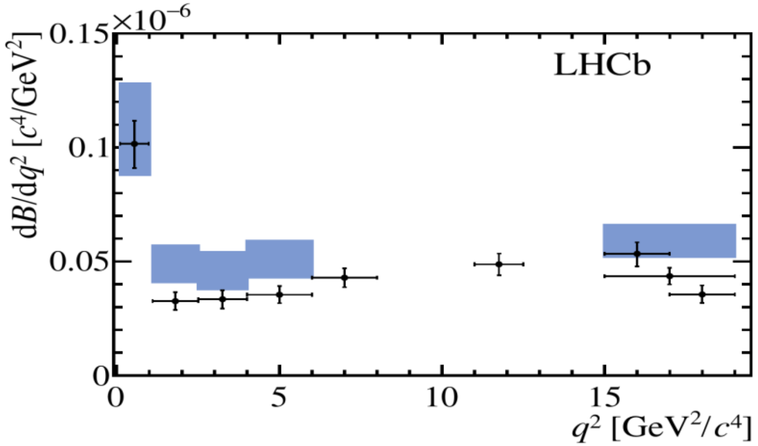
$B^+ \to K^+\mu^+\mu^-$ PRD 107 (2023) 119903



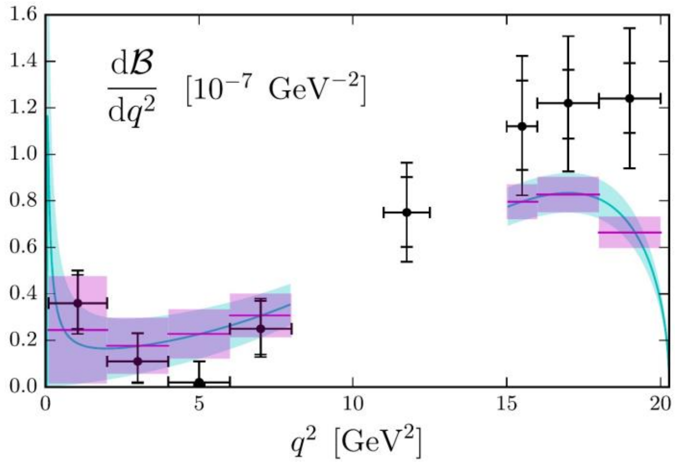
$B_s^0 \to \phi\mu^+\mu^-$ PRL 127 (2021) 151801



$B^0 \to K^{*0}\mu^+\mu^-$ JHEP 04 (2017) 142

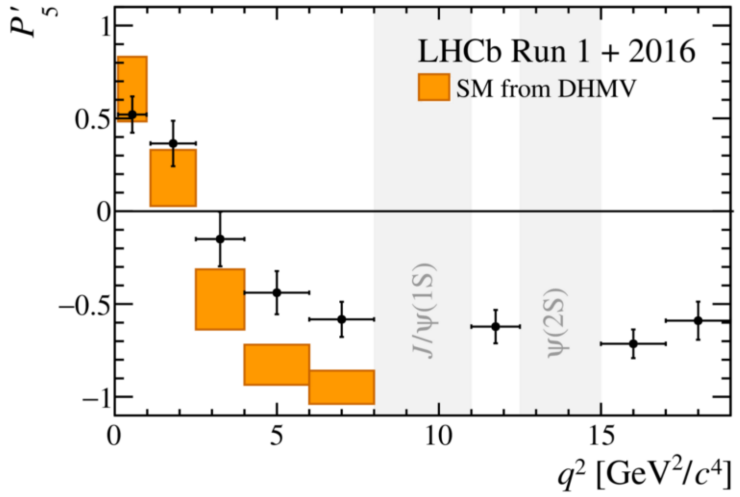


$\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ JHEP 06 (2015) 115

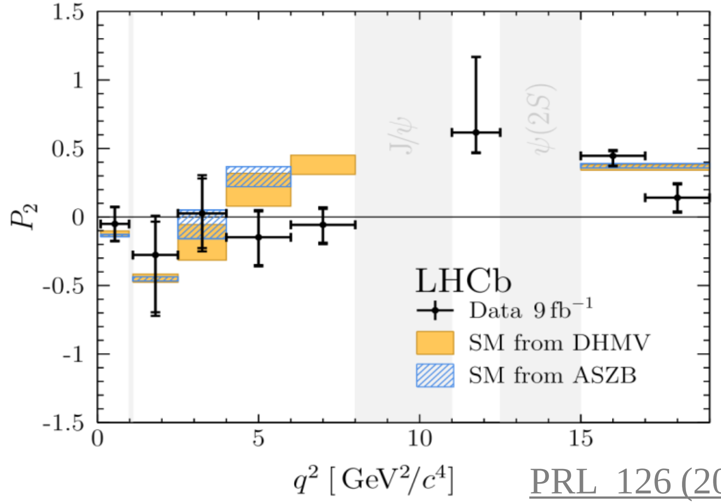


Anomalies in binned angular analysis

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

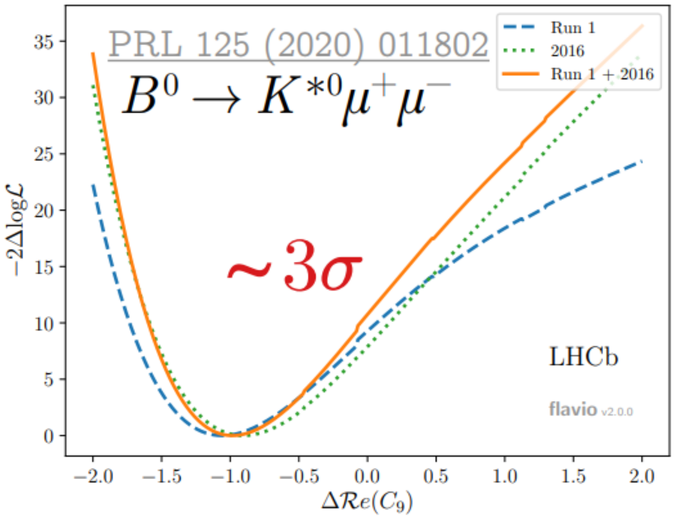


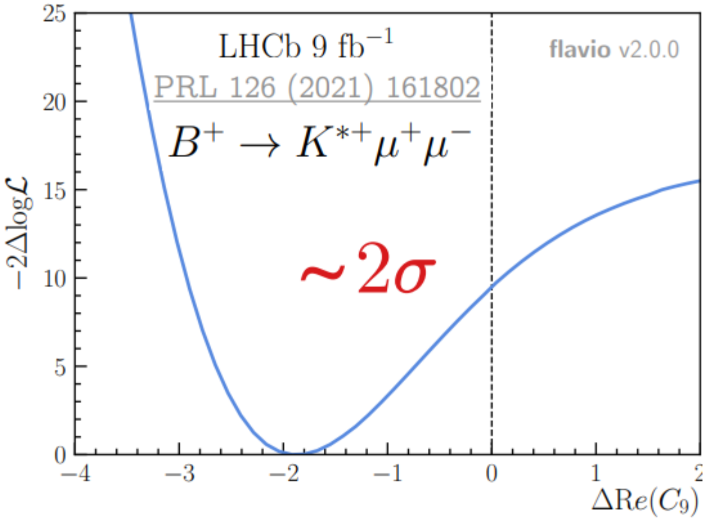
$B^+ \to K^{*+}\mu^+\mu^-$

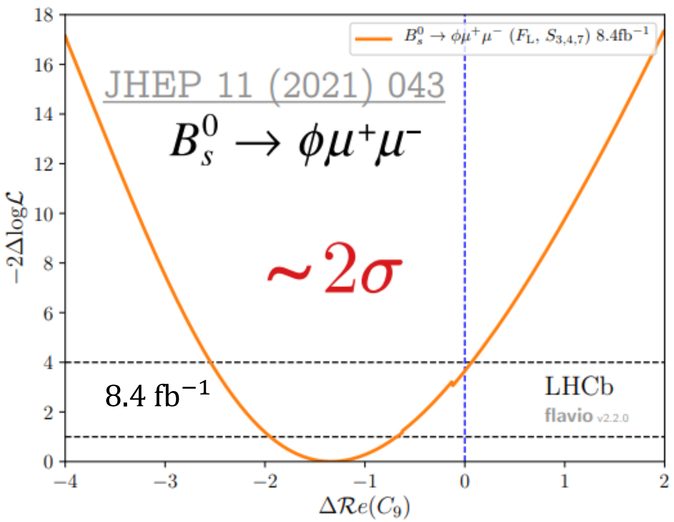


PRL 126 (2021) 161802

Shift of effective coupling C_9 preferred



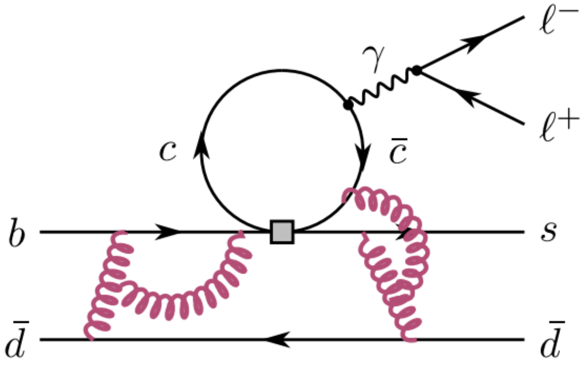


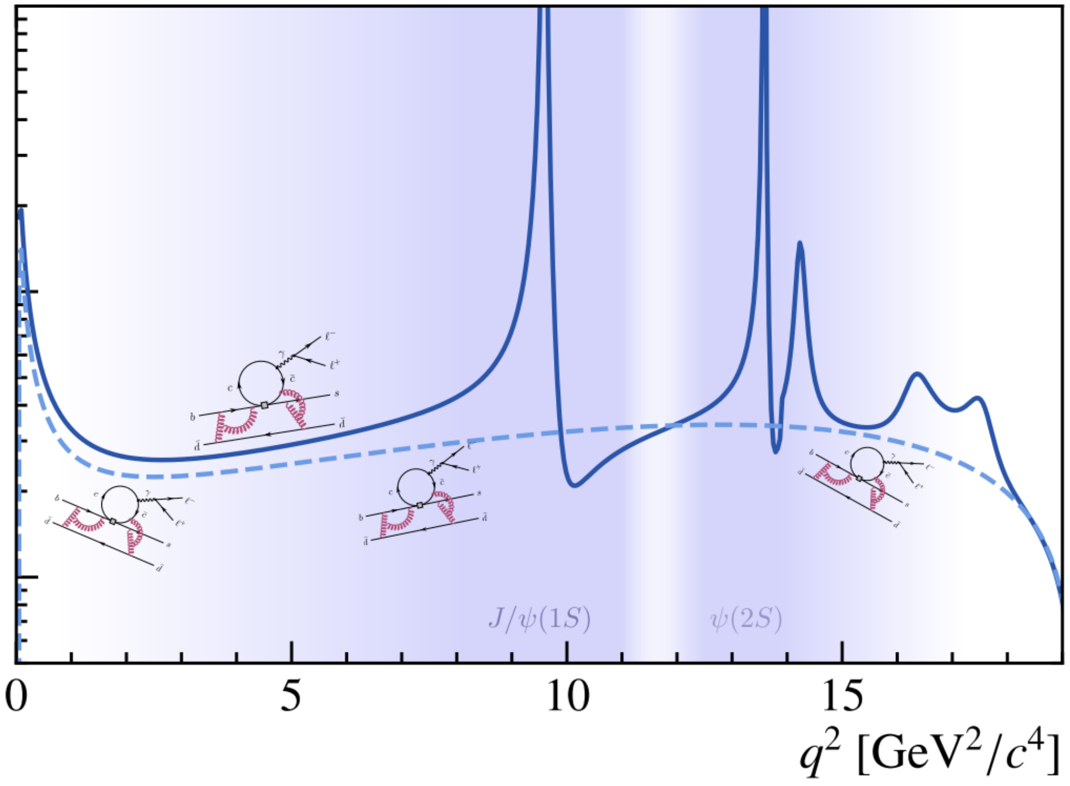


Possible interpretations

- New physics contributions in $b \to s\mu^+\mu^-$ decays?
- Under-estimated form factor uncertainties?
- Effect of SM charm loops? Get it from Run 1+ 2016 data

SM $c\bar{c}$ loop





Unbinned amplitude analysis of $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$

- Perform q^2 unbinned amplitude analysis
  - model *local* vs *non-local* contributions

non-local hadronic matrix elements "charm-loop"

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ \left[(\mathcal{C}_9 \pm \mathcal{C}_9') \mp (\mathcal{C}_{10} \pm \mathcal{C}_{10}') \right] \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[(\mathcal{C}_7 \pm \mathcal{C}_7') \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

$\lambda = \perp, \parallel, 0$

Wilson coeff.

Form Factors

Polynomial expansion

JHEP 09 (2022) 133

Photon penguin	$\mathcal{O}_7$	$=$	$\frac{m_b}{g_e}(\bar{s}\sigma^{\mu\nu}b_R)F_{\mu\nu}$
Vector penguin	$\mathcal{O}_9$	$=$	$(\bar{s}\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$
Axial vector penguin	$\mathcal{O}_{10}$	$=$	$(\bar{s}\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$

$$\mathcal{H}_\lambda(z) = \frac{1 - zz_{J/\psi}^*}{z - z_{J/\psi}} \frac{1 - zz_{\psi(2S)}^*}{z - z_{\psi(2S)}} \times \ldots \times \sum_n \alpha_{\lambda,n} z^n$$

- **Fit 5-D differential decay rate!**

  ↳ $q^2, m_{K\pi}^2, \cos\theta_\ell, \theta_K, \phi$

External inputs

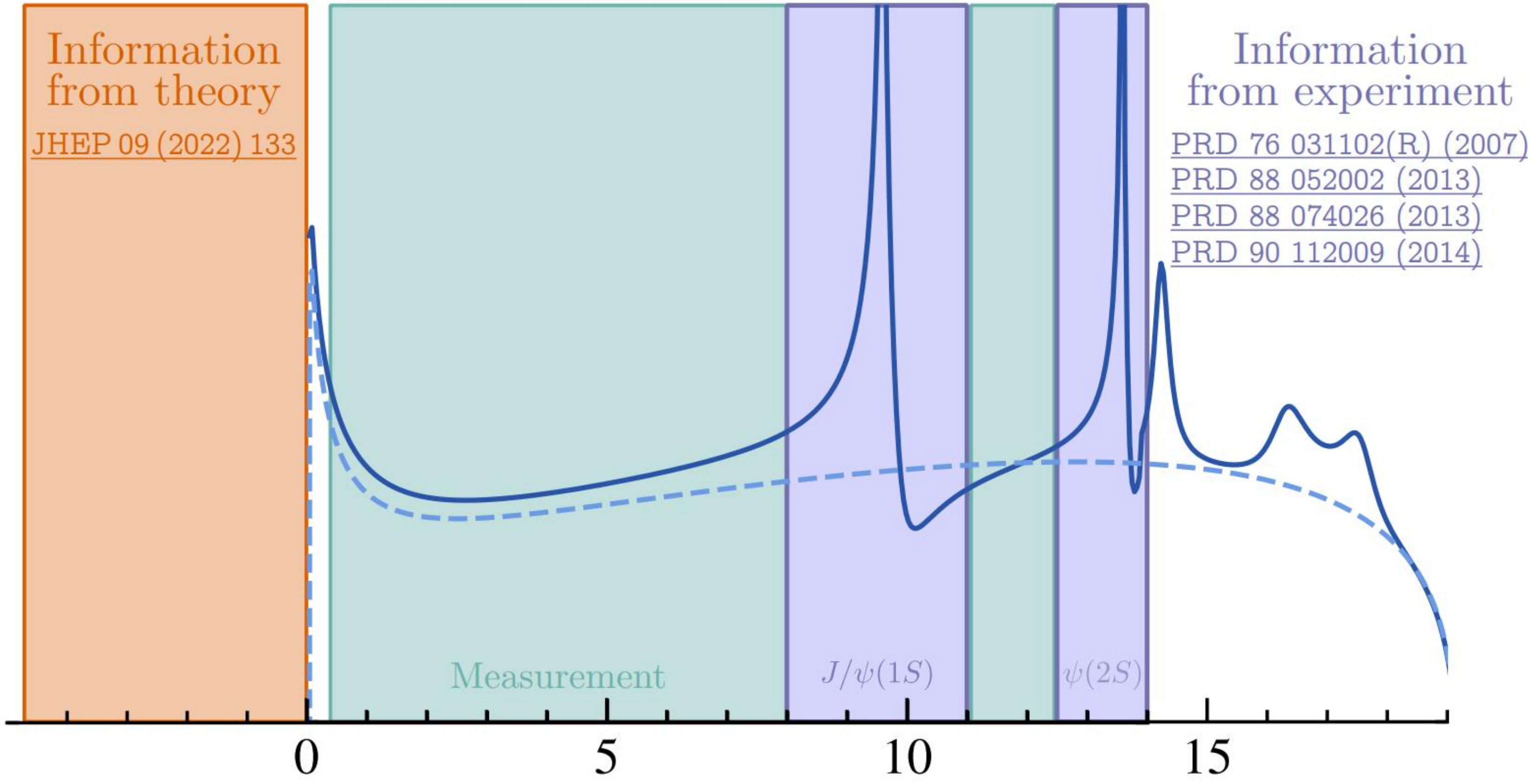
Theory information

Value of charm-loop at $q^2 < 0$

▸ reliable for $q^2 \ll 4m_c^2$

Experimental measurements

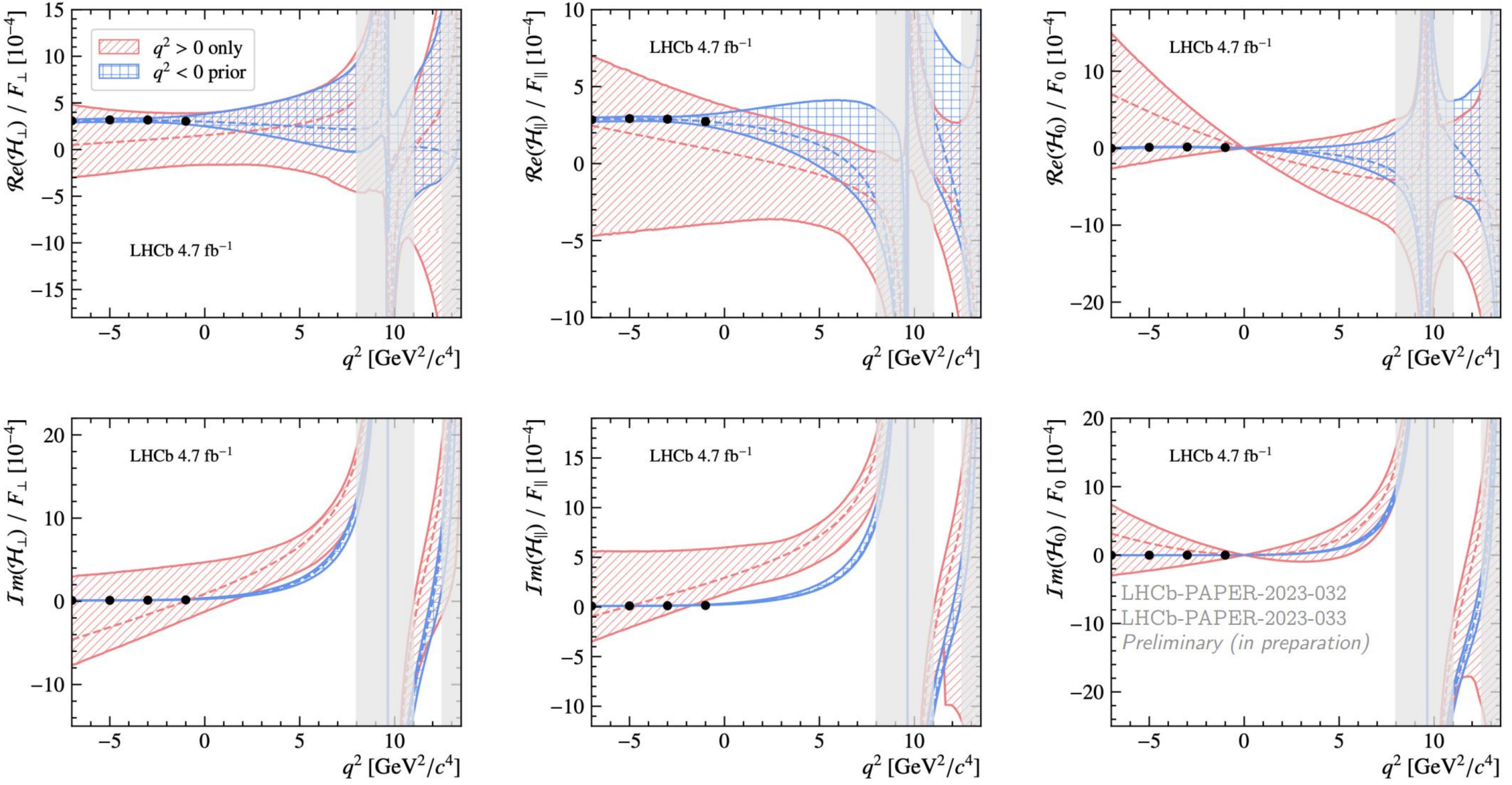
Branching ratio, polarization fraction and phase difference from $B^0 \to \psi_n K^{*0}$



Local form factors constrained to theoretical calculations

Fit results for charm loop matrix elements

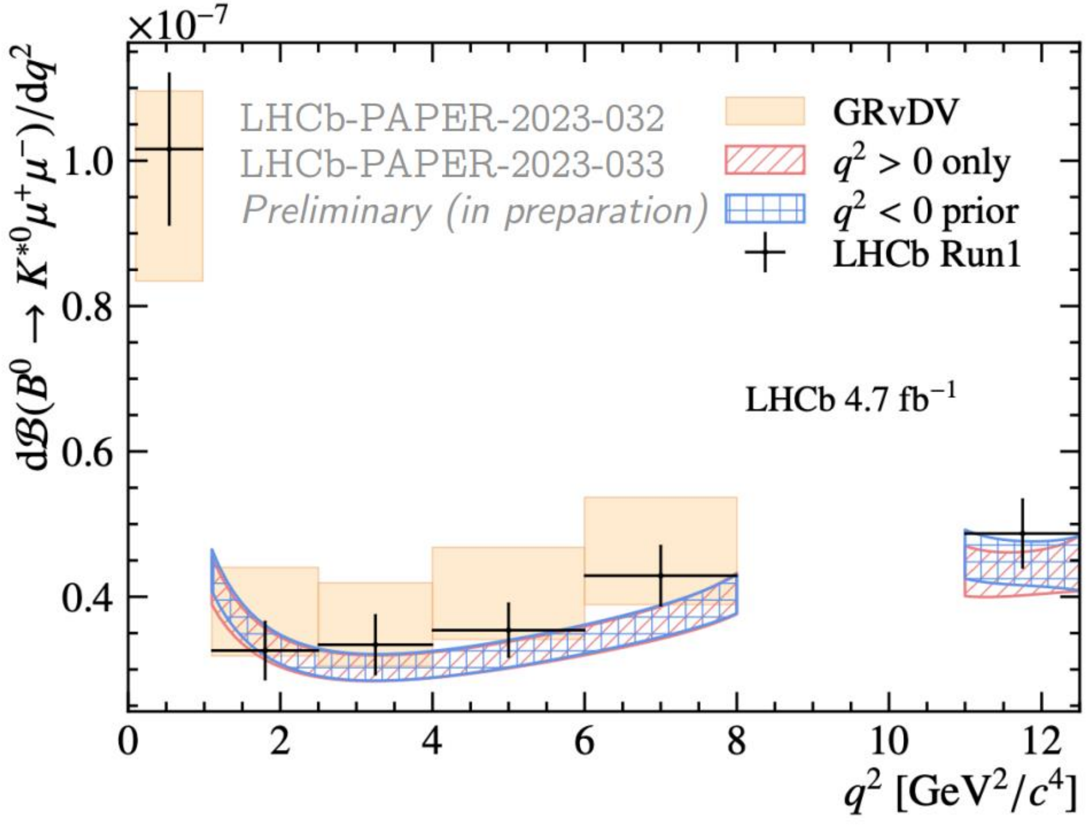
LHCb-paper-2023-032, in prep.

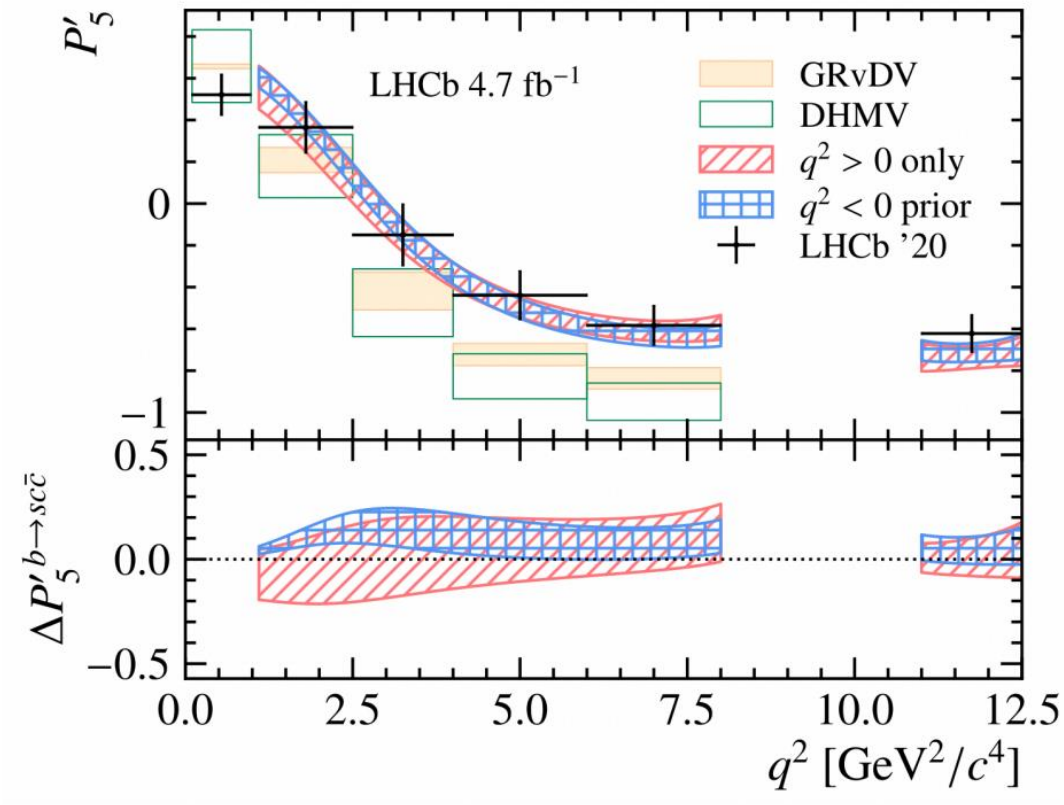


Fit results with and without $q^2 < 0$ theory constraints broadly compatible

Binned $d\mathcal{B}/dq^2$ and P'_5 from unbinned results

LHCb-paper-2023-032, in prep.



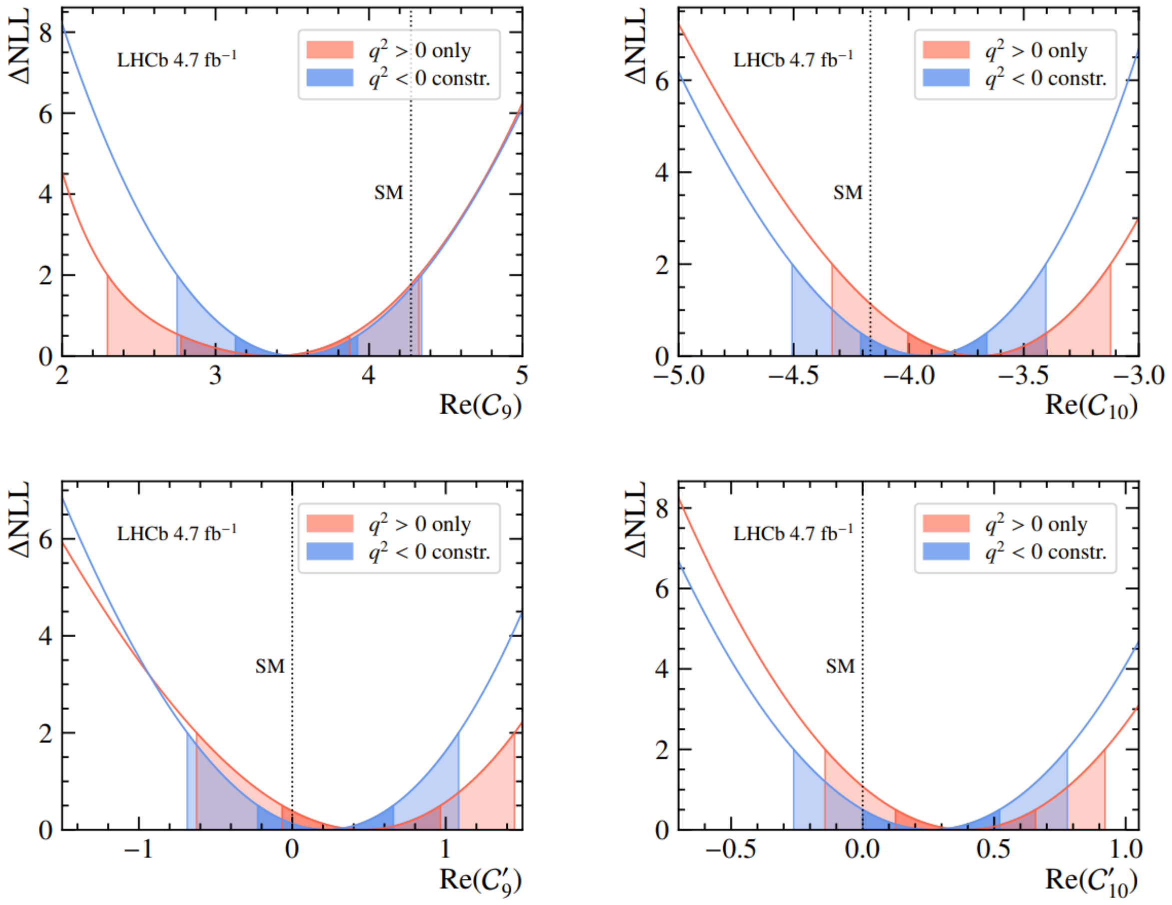


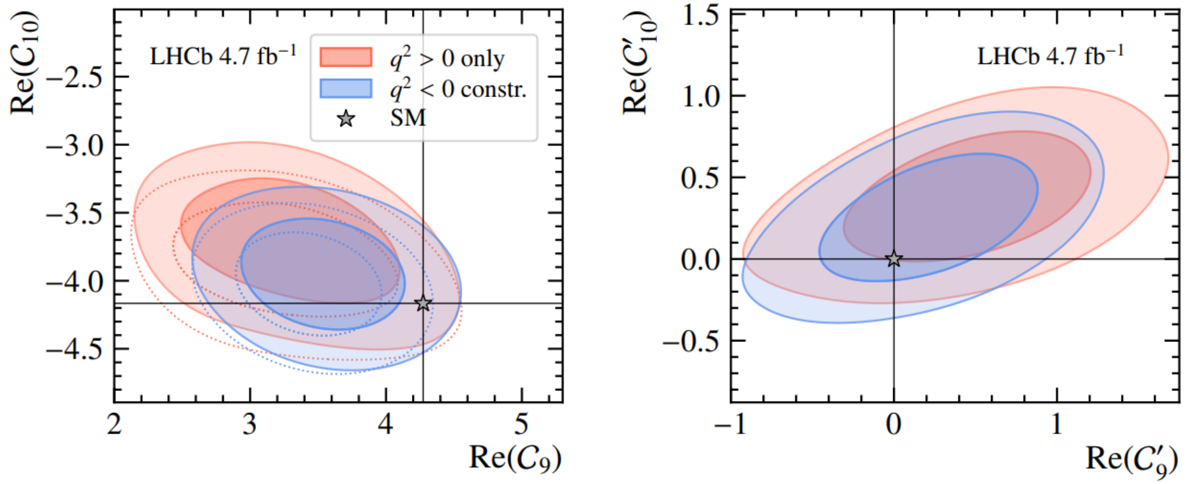
Updated normalisation inputs
⇒ lower BR *cf.* Run 1

Great agreement w/ binned result
Impact of $c\bar{c}$ up to 20%

Constraints on Wilson coefficients

LHCb-paper-2023-032, in prep.



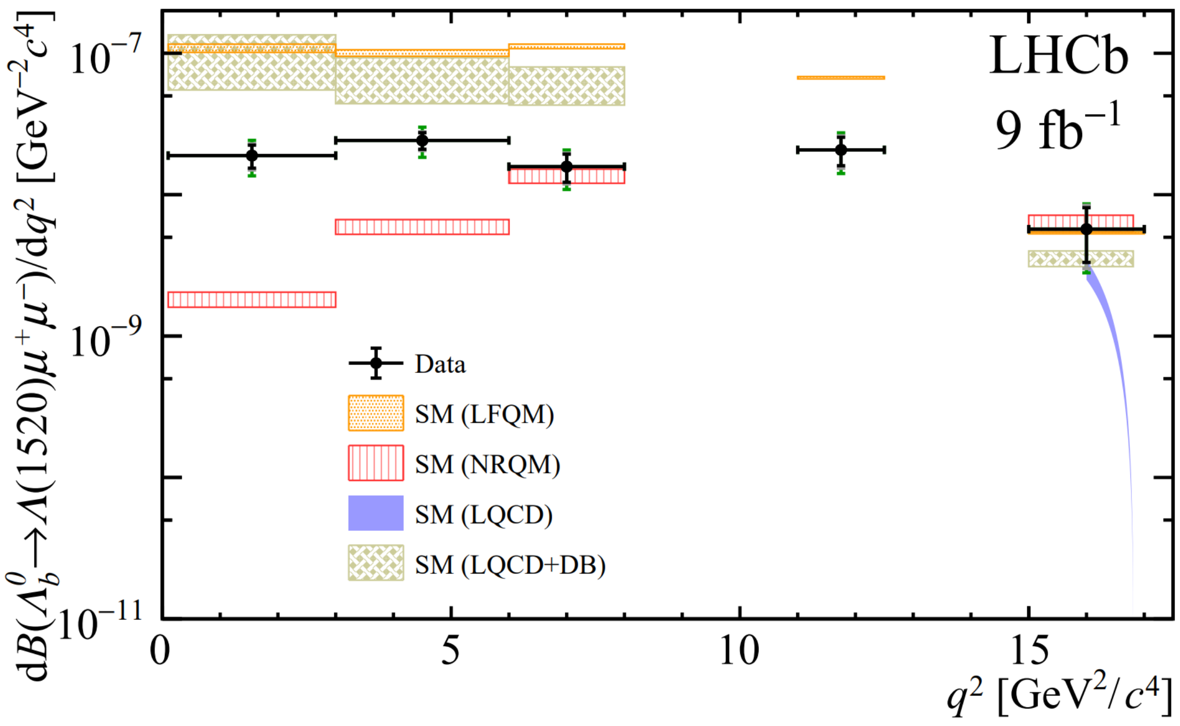


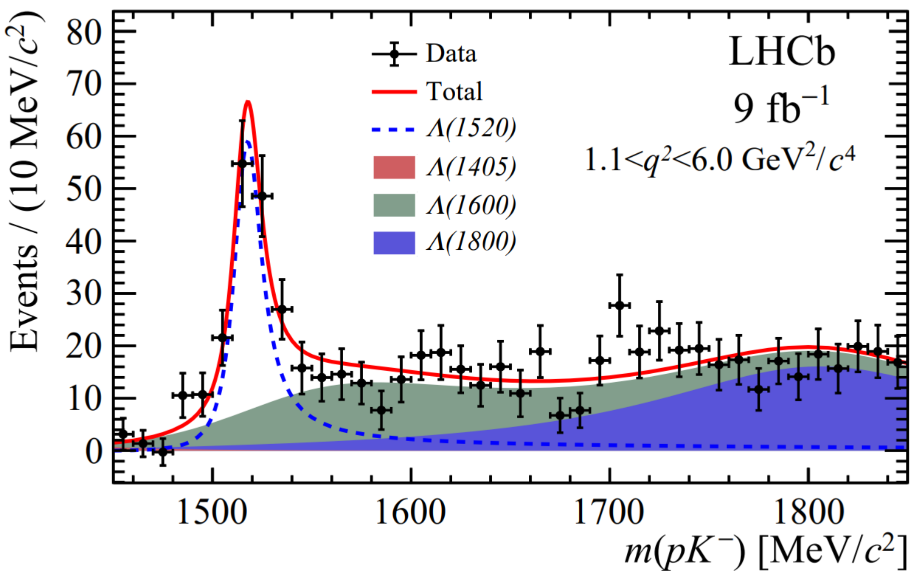
$$\Delta\mathcal{C}_9 = -0.93^{+0.53}_{-0.57} \quad (-0.68^{+0.33}_{-0.46})$$
$$\Delta\mathcal{C}_{10} = 0.48^{+0.29}_{-0.31} \quad (0.24^{+0.27}_{-0.28})$$
$$\Delta\mathcal{C}_9' = 0.48^{+0.49}_{-0.55} \quad (0.26^{+0.40}_{-0.48})$$
$$\Delta\mathcal{C}_{10}' = 0.38^{+0.28}_{-0.25} \quad (0.27^{+0.25}_{-0.27})$$

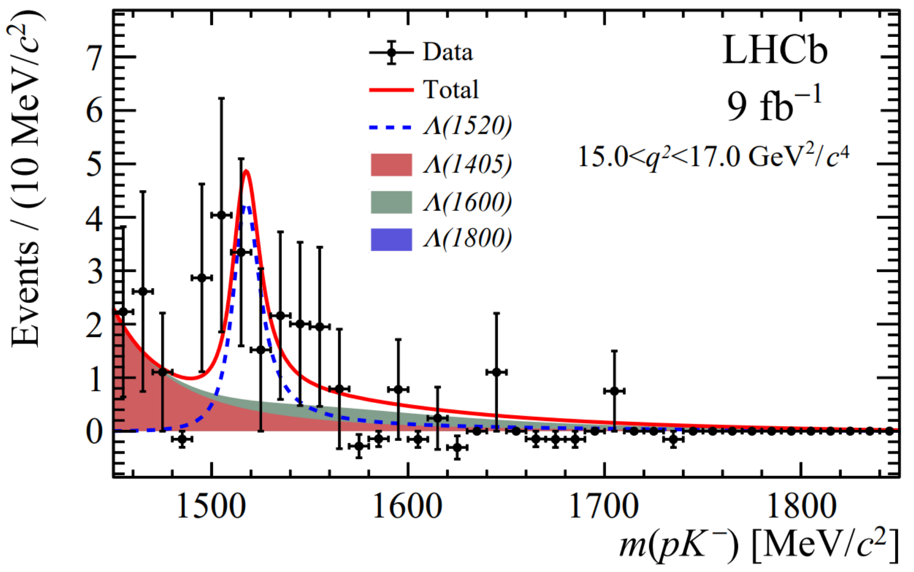
Tension between data and SM ~ 1.9σ in C_9 and up to 1.5σ in C_{10}.
Combined discrepancy ~ 1.4σ

$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$ differential BF

PRL 131 (2023) 151801





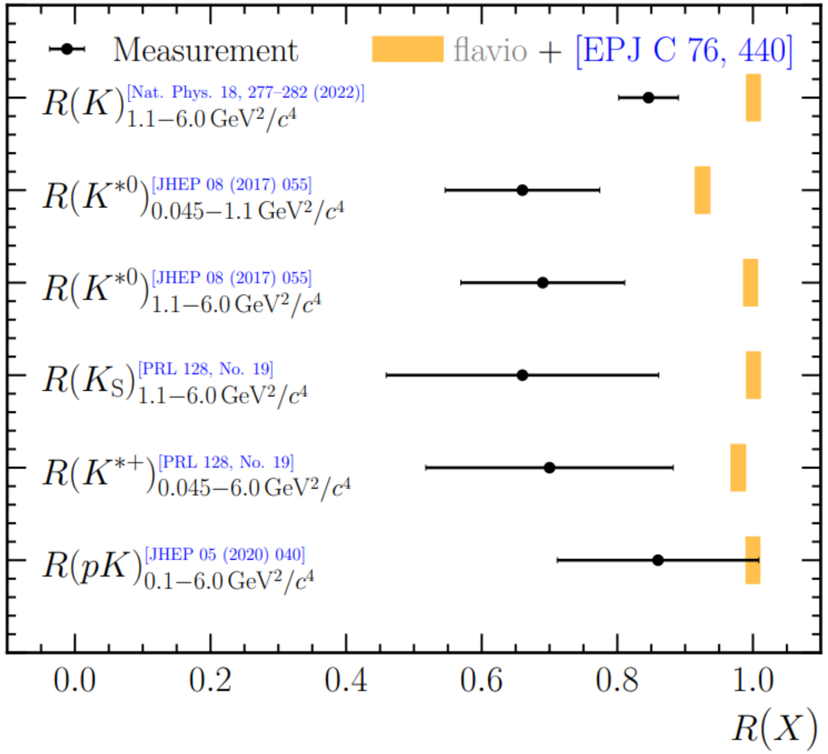


- High q^2: consistent with SM predictions
- Low q^2: significant variation in theoretical predictions

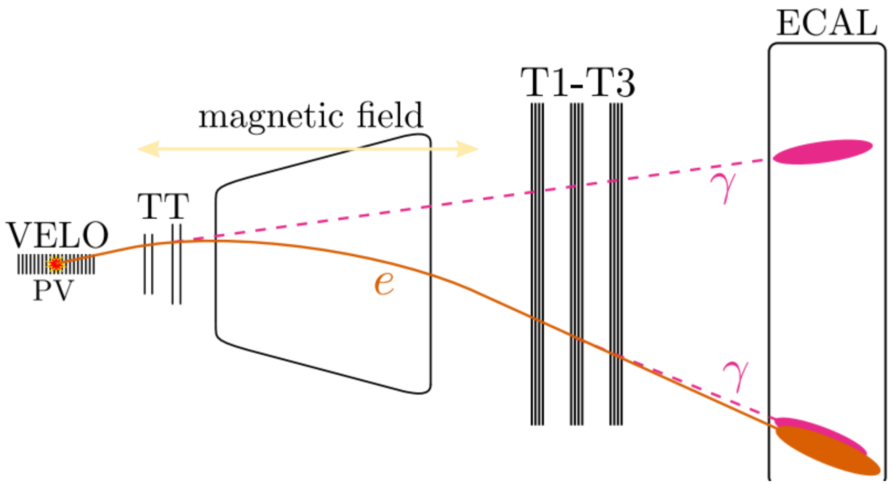
Previous lepton flavour universality tests in $b \to sl^+l^-$

$$R_{H_s} \equiv \frac{\mathcal{B}(B^+ \to H_s\mu^+\mu^-)}{\mathcal{B}(B^+ \to H_s e^+e^-)} \Big/ \frac{\mathcal{B}(B^+ \to H_s J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to H_s J/\psi(\to e^+e^-))}$$

Previous tension with SM



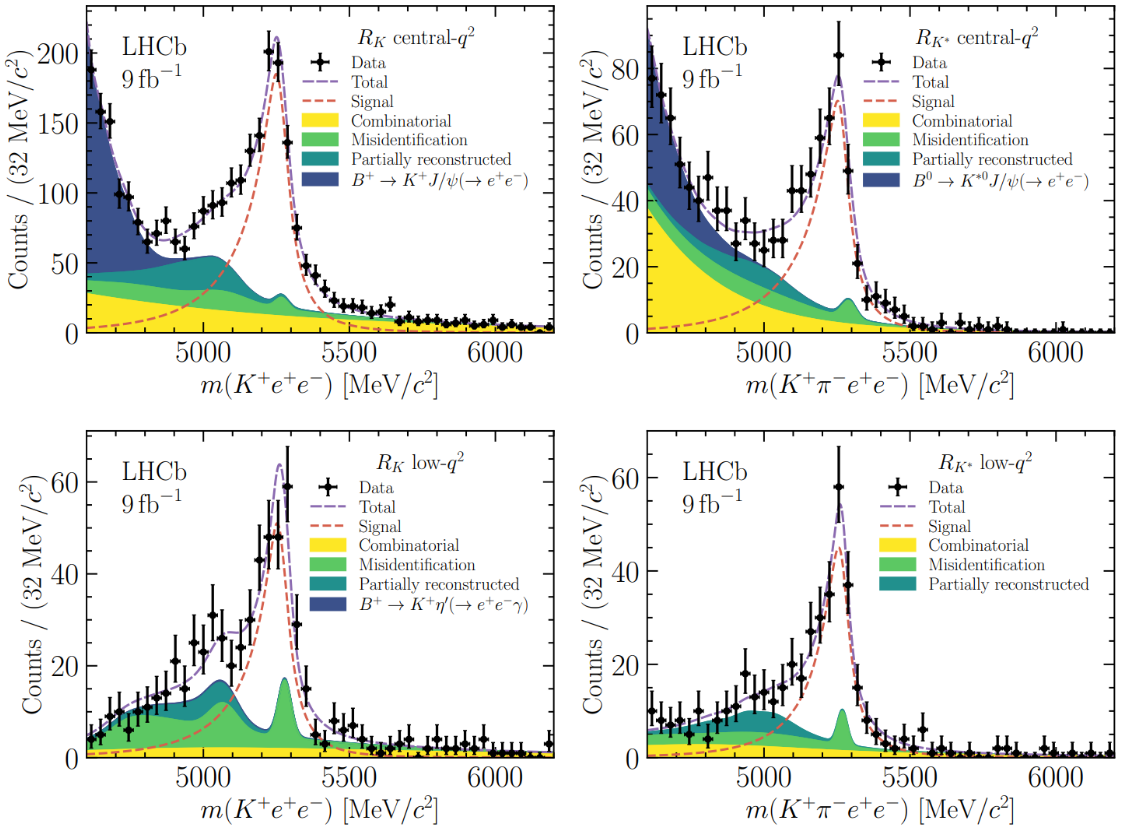
Electron reconstruction challenging



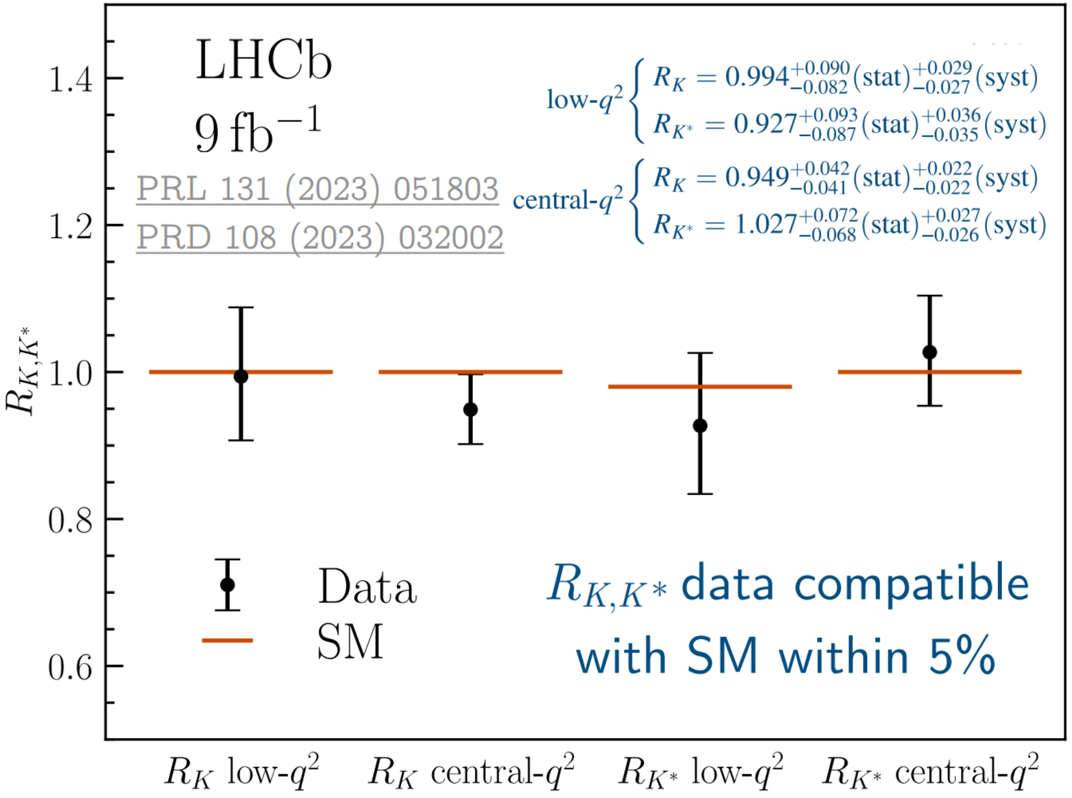
Updated $R_{K^{(*)}}$ measurements

PRL 131 (2023) 051803

Benefitting from tighter PID selection, and novel data-driven background modelling

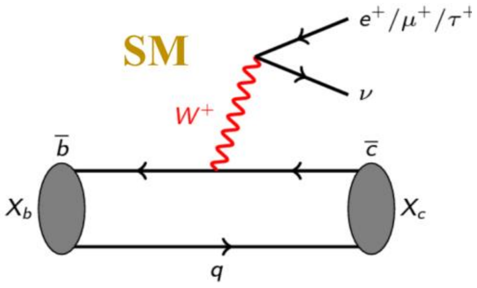


New results consistent with SM, superseding previous results

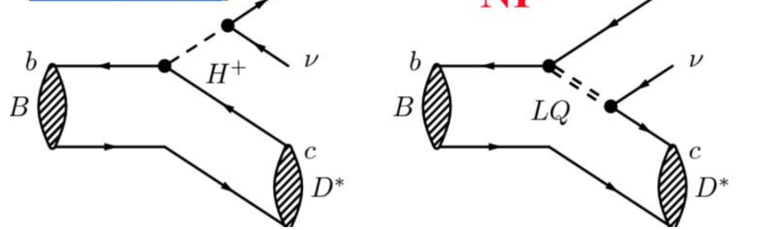


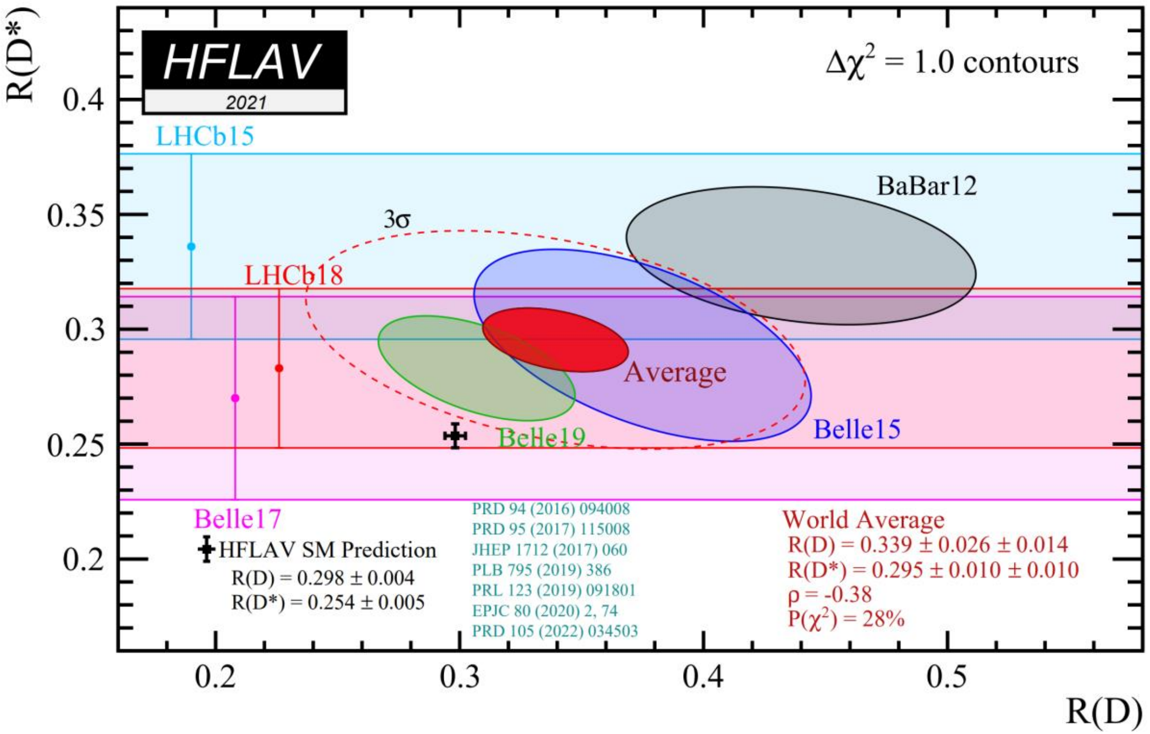
Hint of LFU violation in $b \to cl\nu$

$$R \equiv \frac{BR\left(B \to X_c \tau \nu_\tau\right)}{BR\left(B \to X_c \ell \nu_\ell\right)}$$

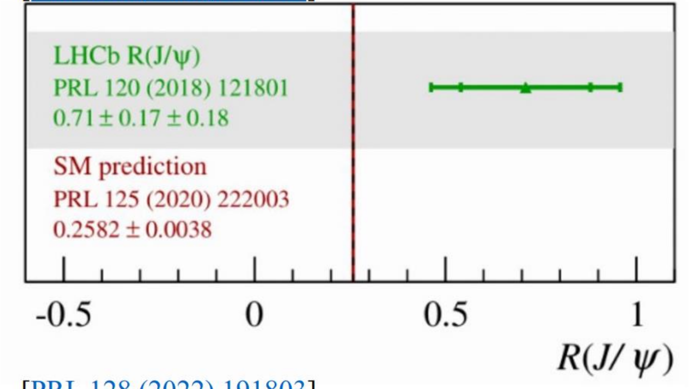


[PRD 85, 094025 (2012), PLB 755, 270 (2016)]

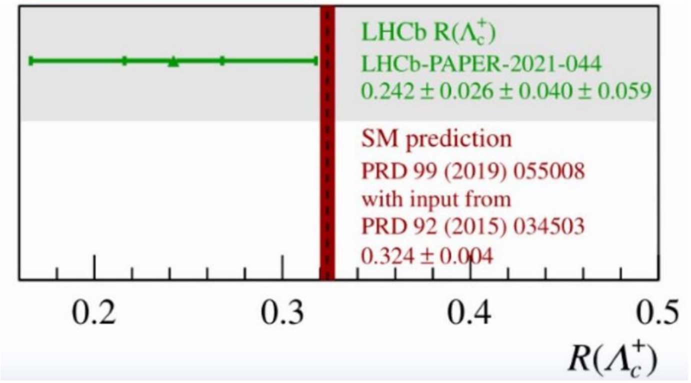




[PRL 120 (2018) 121801]



[PRL 128 (2022) 191803]



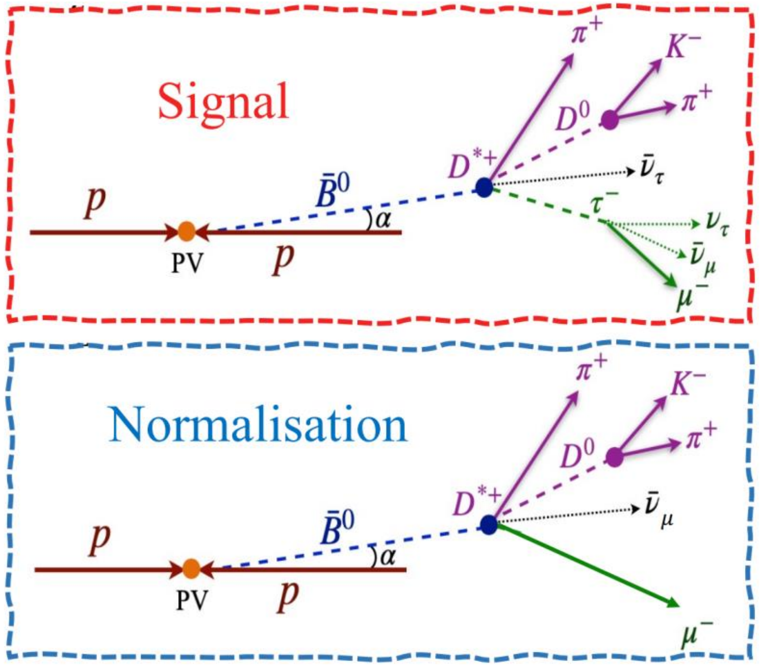
Long standing 3.3σ hint of deviation from LFU

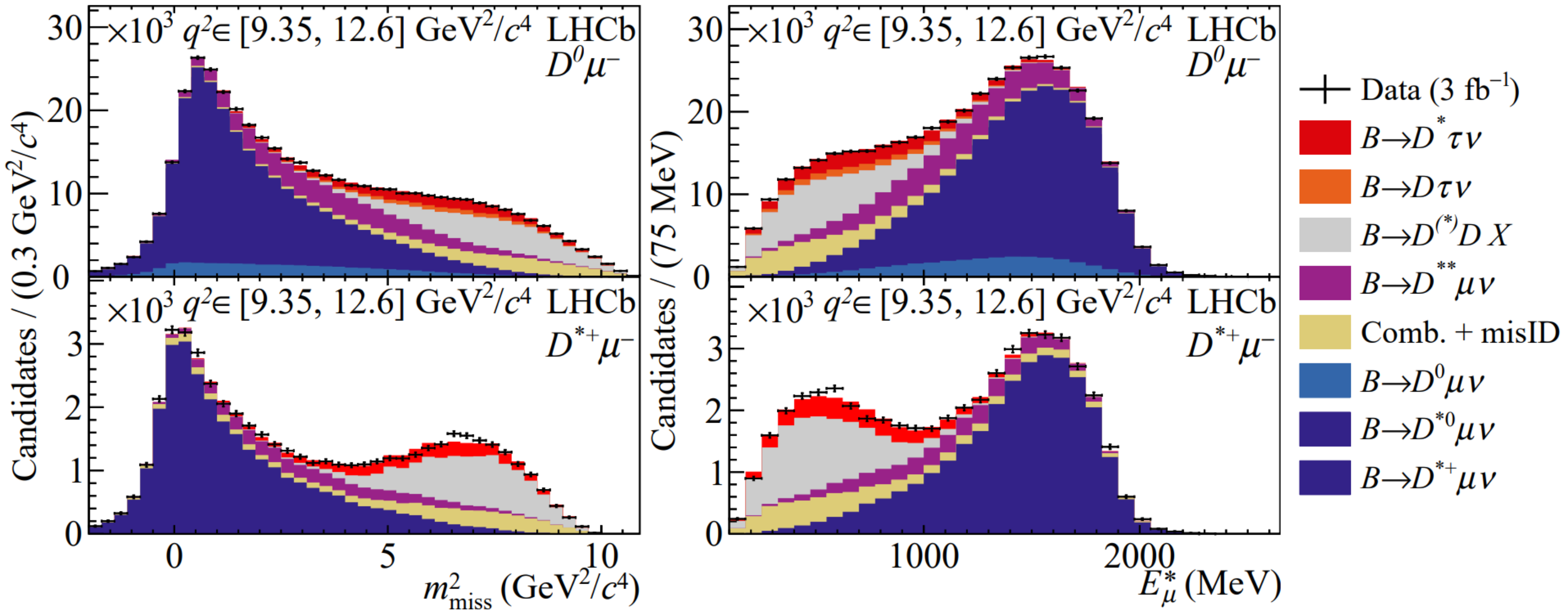
LHCb $R(D^{(*)})$ with $\tau \to \mu\bar{\nu}_\mu\nu_\tau$ decays

PRL 131 (2023) 111802

Measure $R(D^{(*)})$ with Run 1 data, assuming isospin symmetry for $R(D^{*0})$ and $R(D^{*+})$

$D^{*+} \to D^0\pi^+, D^{*0} \to D^0\pi^0$ or $D^0\gamma$



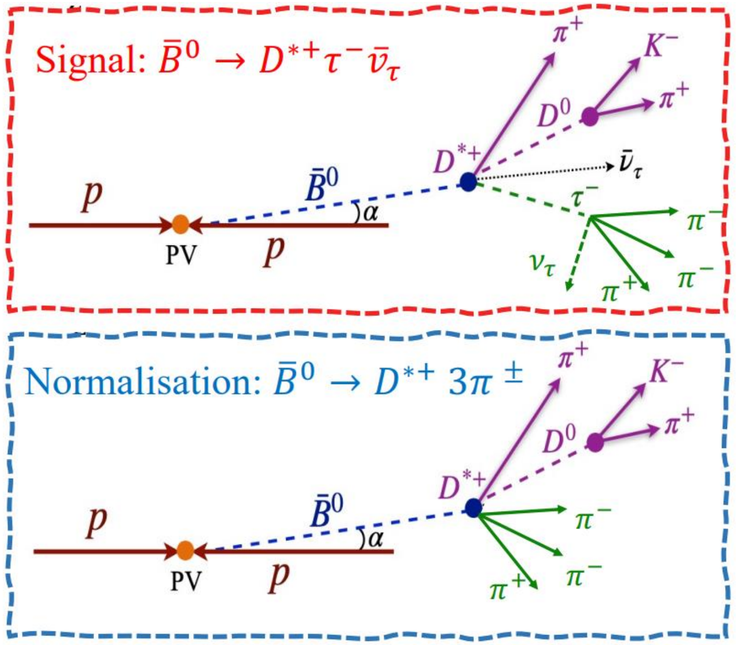


$\bar{B}^0 \to D^{*+}\mu^-\pi^+$ for normalization

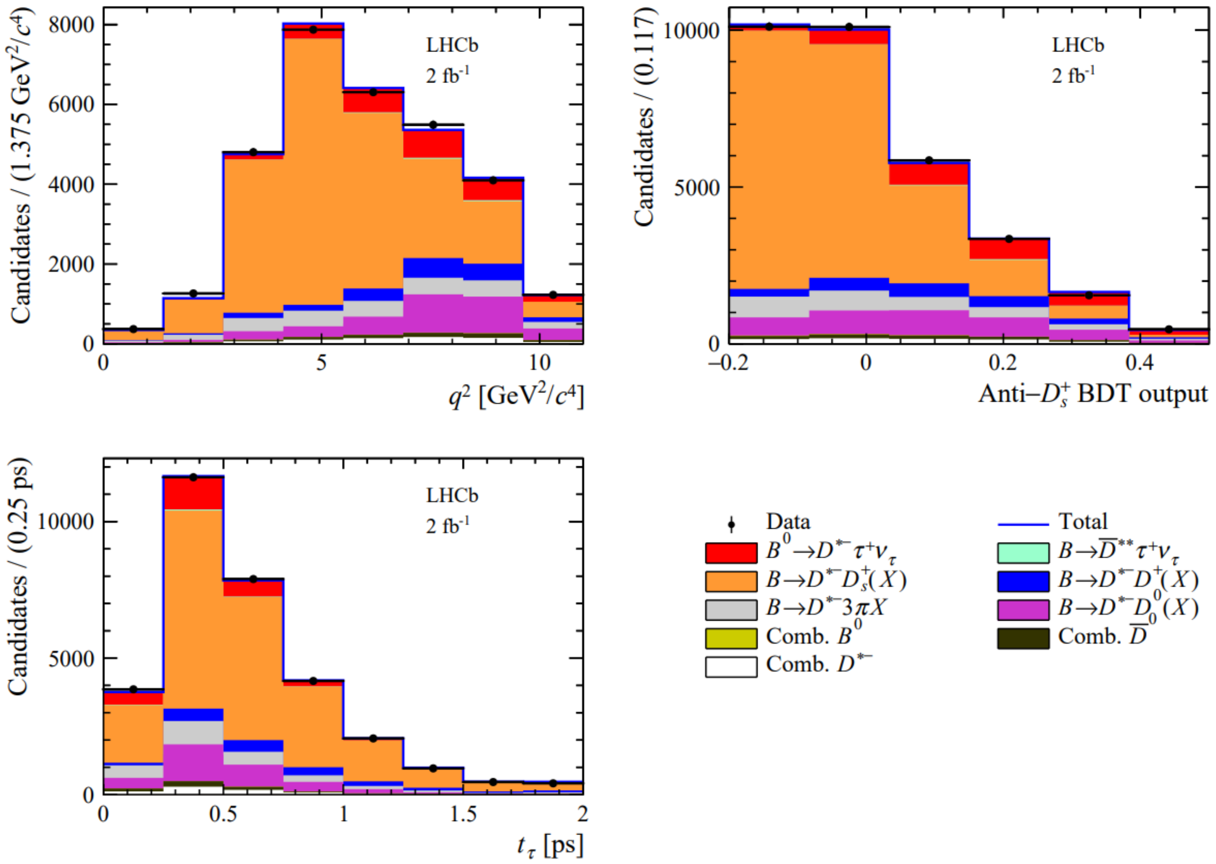
$\boldsymbol{R(D^*) = 0.282 \pm 0.018 \pm 0.024}$
$\boldsymbol{R(D) = 0.441 \pm 0.060 \pm 0.066}$
$\boldsymbol{\rho = -0.43}$

LHCb $R(D^*)$ with hadronic τ decays

PRD 108 (2023) 012018



$\bar{B}^0 \to D^{*+}3\pi^\pm$ for normalization



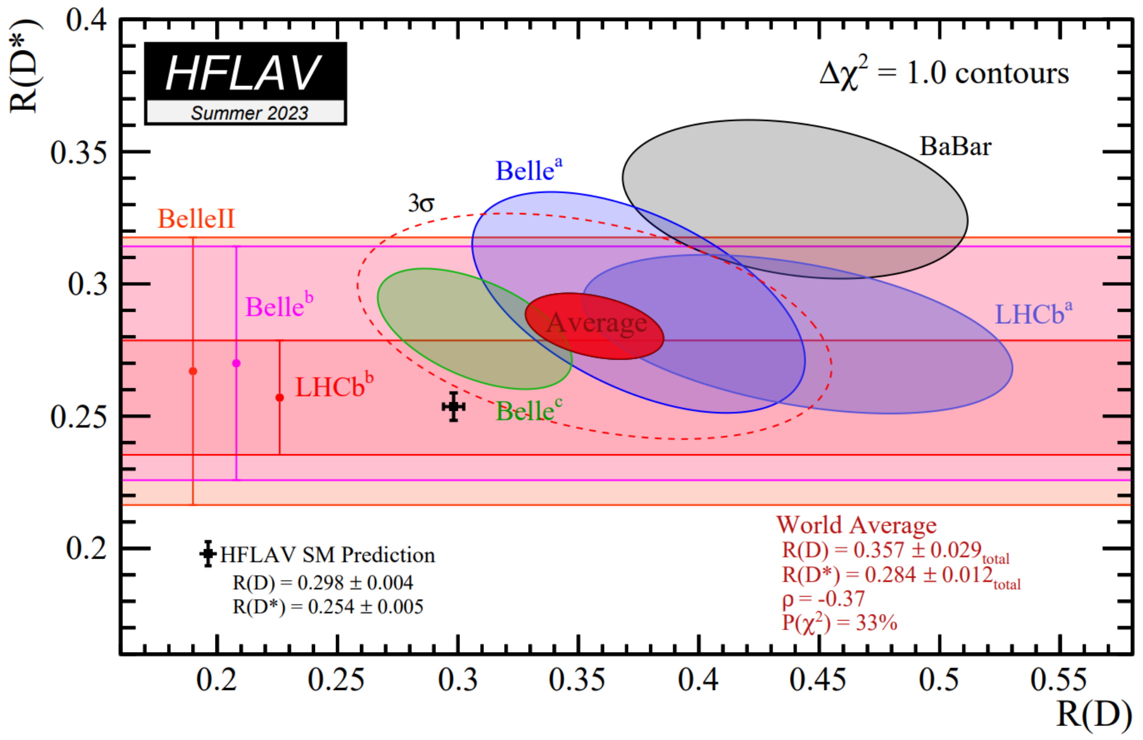
Using 2015+2016 data: $R(D^*) = 0.247 \pm 0.015(\text{stat}) \pm 0.015(\text{syst}) \pm 0.012(\text{ext})$

Combination with Run 1: $R(D^*) = 0.257 \pm 0.012(\text{stat}) \pm 0.014(\text{syst}) \pm 0.012(\text{ext})$

One of the most precise measurements of $R(D^*)$!

World average of $R(D^{(*)})$

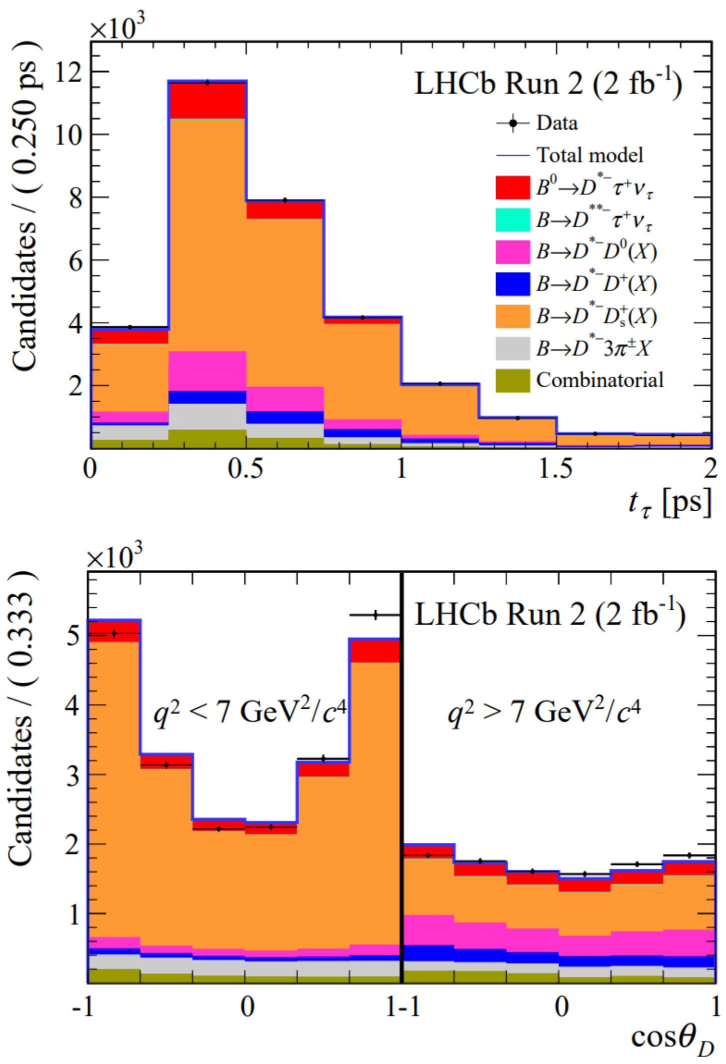
Experiment	R(D*)	R(D)	Rescaled Correlation (stat/syst/total)
BaBar	0.332 ± 0.024 ± 0.018	0.440 ± 0.058 ± 0.042	-0.45/-0.07/-0.27
BELLE[a]	0.293 ± 0.038 ± 0.015	0.375 ± 0.064 ± 0.026	-0.56/-0.11/-0.49
BELLE[b]	$0.270 \pm 0.035\ ^{+0.028}_{-0.025}$	-	-
BELLE[c]	0.283 ± 0.018 ± 0.014	0.307 ± 0.037 ± 0.016	-0.53/-0.51/-0.51
LHCb[a]	0.281 ± 0.018 ± 0.024	0.441 ± 0.060 ± 0.066	-0.49/-0.39/-0.43
LHCb[b]	0.257 ± 0.012 ± 0.018	-	-
Belle II	$0.267\ (^{+0.041}_{-0.039})\ (^{+0.028}_{-0.033})$	-	-
Average .txt	**0.284 ± 0.012**	**0.357 ± 0.029**	**-0.37**



Discrepancy with SM remains at 3.3σ, p-value = 1.04×10^{-4}

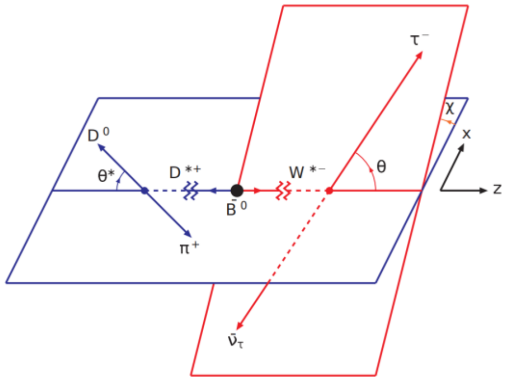
D^* longitudinal polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$

arXiv:2311.05224



$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

$$F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$



LHCb result of $F_L^{D^*}$

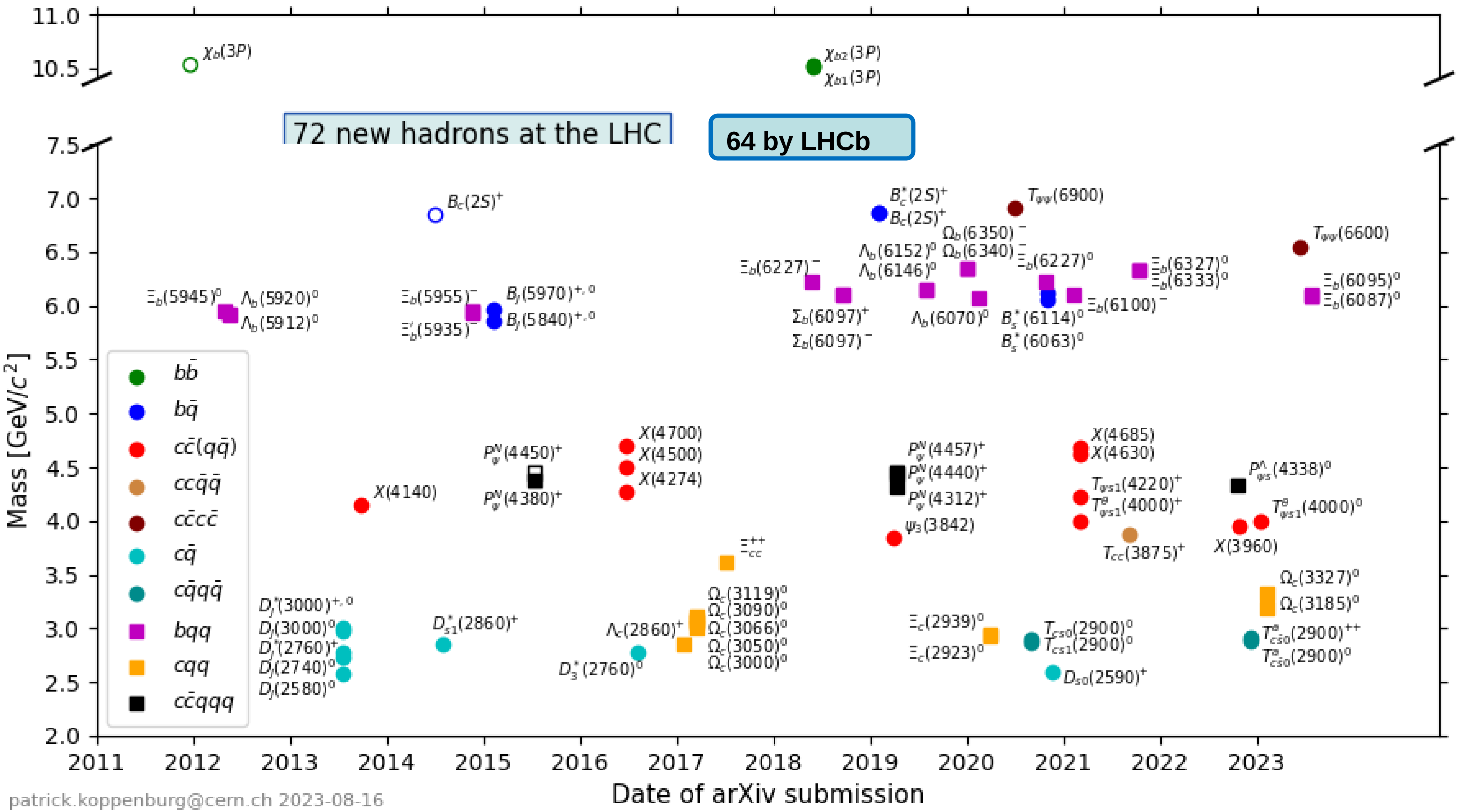
$$q^2 < 7\,\mathrm{GeV}^2/c^4 \;:\; 0.51 \pm 0.07\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}),$$
$$q^2 > 7\,\mathrm{GeV}^2/c^4 \;:\; 0.35 \pm 0.08\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst}),$$
$$q^2 \text{ whole range} : \; 0.43 \pm 0.06\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}).$$

Belle result: $F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$

SM predictions: $F_L^{D^*} \approx 0.44 - 0.47$

Recently observed new hadrons

Hadrons observed at the LHC



New naming scheme

arXiv: 2206.15233

Idea of the proposal:

- T for tetra, P for pentaquark
- Superscript: indication of isospin, parity and G-parity:
  $N: I = \frac{1}{2}$; $\Lambda: I = 0$
- Subscript: heavy quark content:
  c indicates $c\bar{c}$ content,
  s-open strangeness,

- No change in name if not unambiguously declared exotic

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(4140)$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}$, $J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+$, $J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$

P_{cs} is a possible J/ψ resonance

Pentaquark $P_{\psi s}^{\Lambda}(4338)^0$ in $\Lambda_b \to J/\psi \Lambda p$

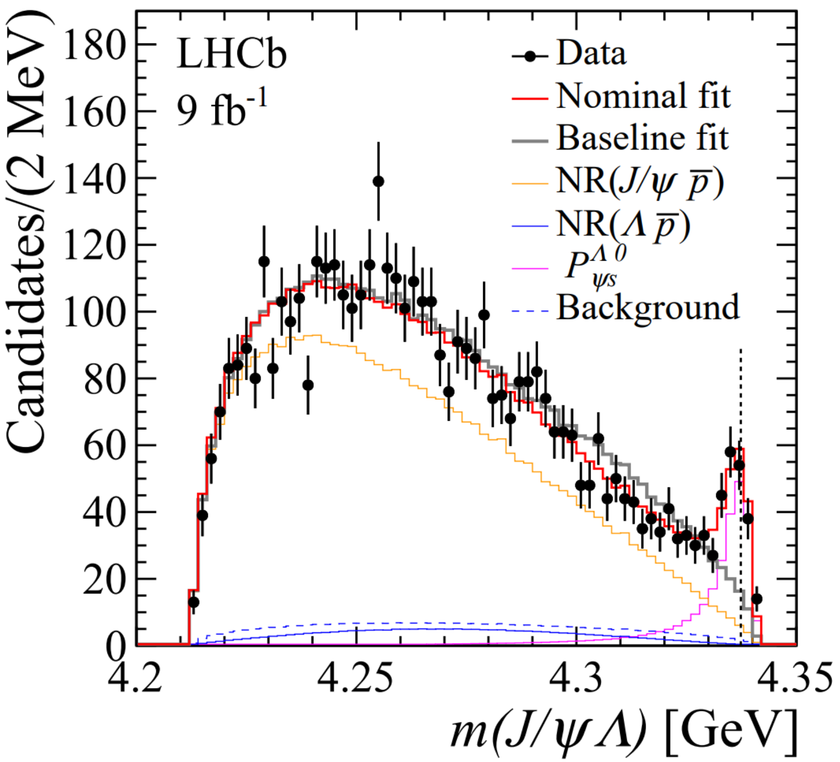
PRL 131 (2023) 031901

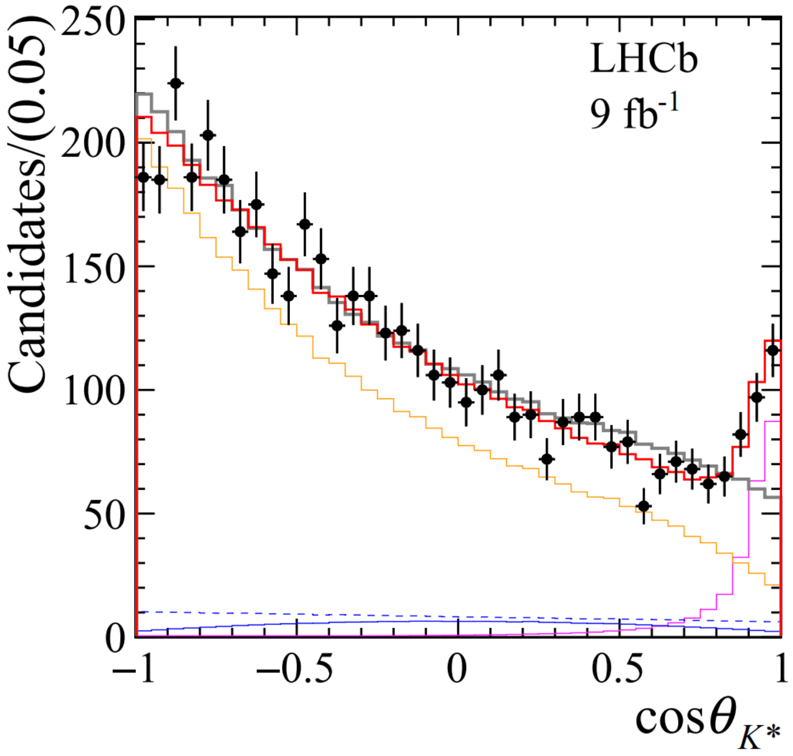
A narrow resonance below $\Xi_c D^0$ threshold observed, $> 10\sigma$

$M\left(P_{\psi s}^{\Lambda}(4338)\right) = 4338.2 \pm 0.7 \pm 0.4$ MeV

$\Gamma\left(P_{\psi s}^{\Lambda}(4338)\right) = 7 \pm 1.3 \pm 1.3$ MeV

$J = 1/2$ determined, $P = -1$ favoured, $P = +1$ rejected at 90% CL





New $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$

PRL 131 (2023) 071901

New resonance below $D_s^+ D_s^-$ threshold, 12.6σ

$M\big(X(3960)\big) = 3956 \pm 5 \pm 10$ MeV

$\Gamma\big(X(3960)\big) = 43 \pm 13 \pm 9$ MeV

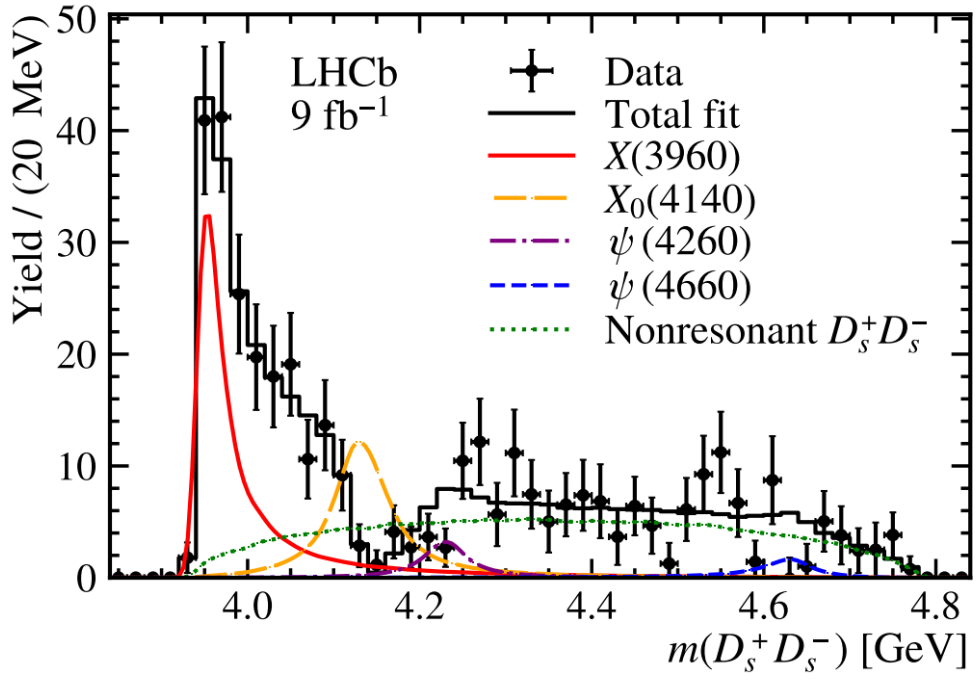
$J^{PC} = 0^{++}$

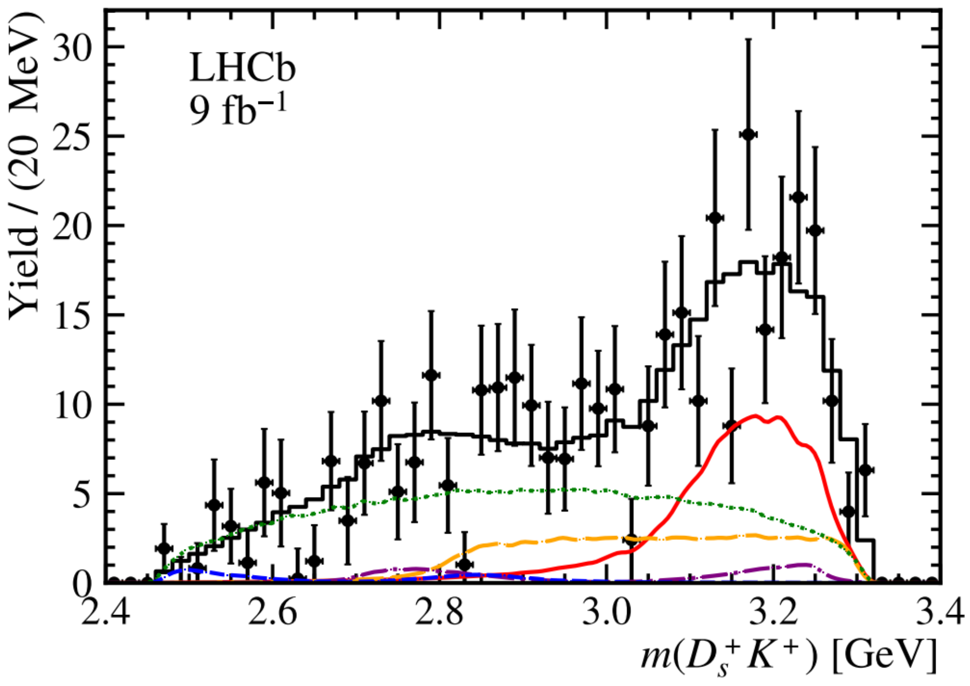
Evidence of another state, 3.8σ

$M\big(X_0(4140)\big) = 4133 \pm 6 \pm 6$ MeV

$\Gamma\big(X_0(4140)\big) = 60 \pm 17 \pm 7$ MeV

$J^{PC} = 0^{++}$

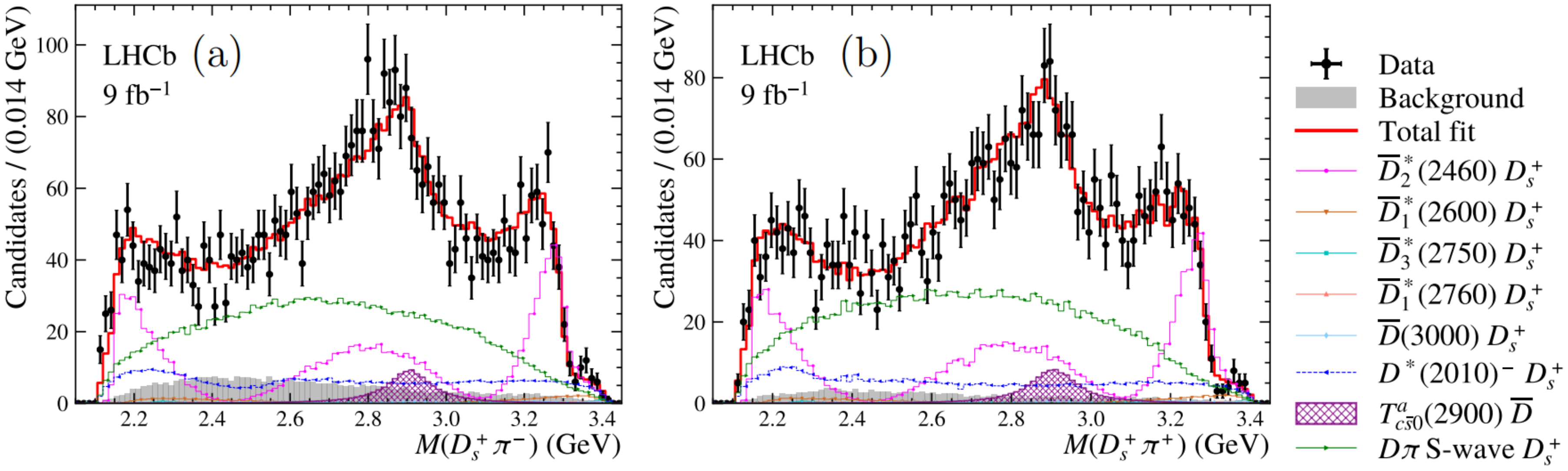




Observation of $T^a_{c\bar{s}0}(2900)^{++/0}$ in $B \to DD_s\pi$

PRL 131 (2023) 041902

$B^0 \to \bar{D}^0 D_s^+ \pi^-$ $\quad$ $B^+ \to D^- D_s^+ \pi^+$



First observation of a doubly-charged tetraquark and its neutral partner

$T^a_{c\bar{s}0}(2900)^{++}$: $M = 2921 \pm 17 \pm 20$ MeV

$\Gamma = 137 \pm 32 \pm 17$ MeV

$T^a_{c\bar{s}0}(2900)^{0}$: $M = 2892 \pm 14 \pm 15$ MeV

$\Gamma = 119 \pm 26 \pm 13$ MeV

Assuming isospin relation

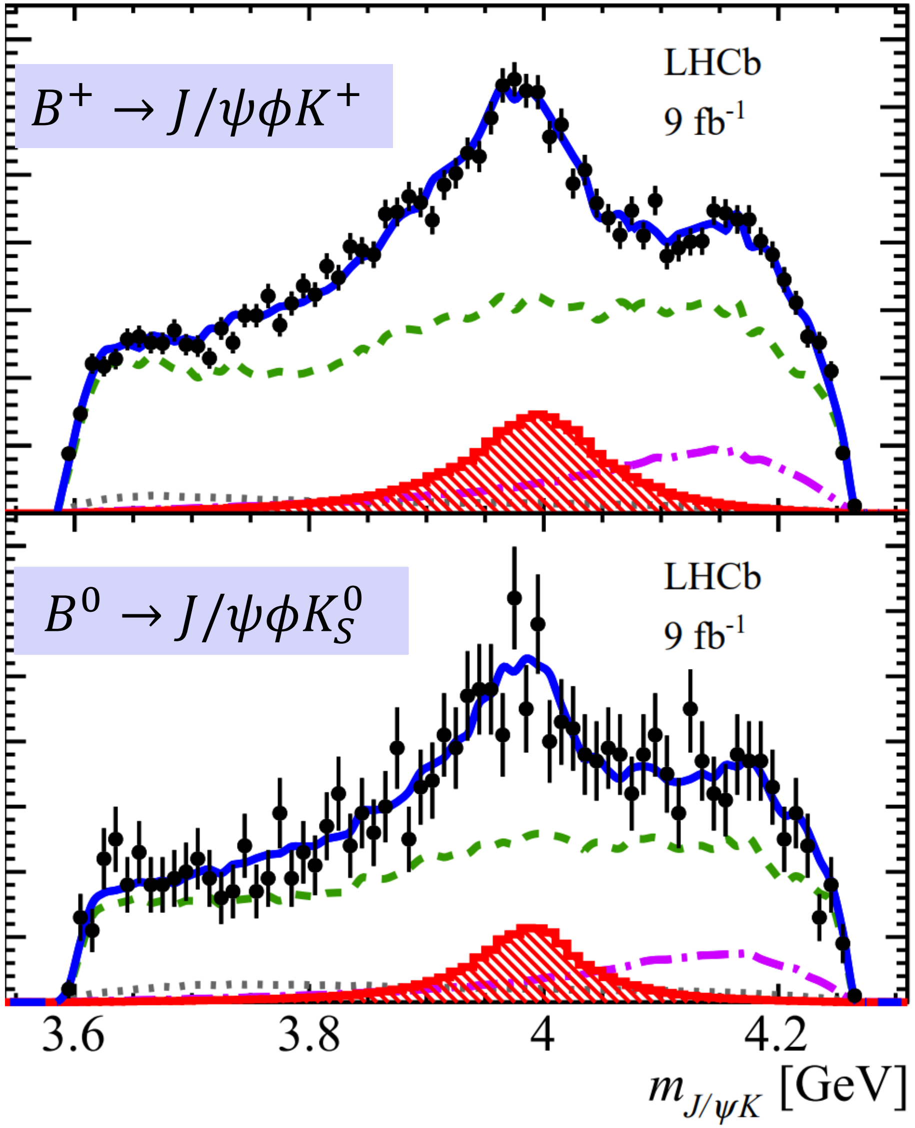
$M = 2908 \pm 11 \pm 20$ MeV

$\Gamma = 136 \pm 23 \pm 13$ MeV

$J^P = 0^+$

Evidence of $T^{\theta}_{\psi s1}(4000)^0$ in $B^0 \to J/\psi\phi K^0_S$

PRL 131 (2023) 131901



LHCb previously observed the 1^+ $Z_{cs}(4000)$ and 1^+or 1^{-1} $Z_{cs}(4220)^+$ decaying to $J/\psi K^+$ (also called $T^{\theta}_{\psi s1}(4000)^+$ and $T^{\theta}_{\psi s1}(4220)^+$)

[PRL 127 (2021) 082001]

$M(T^{\theta}_{\psi s1}(4000)^+) = 4003 \pm 6\,^{+4}_{-14}$ MeV

$\Gamma\left(T^{\theta}_{\psi s1}(4000)^+\right) = 131 \pm 15 \pm 26$ MeV

A possible isospin partner of $T^{\theta}_{\psi s1}(4000)^+$ that decays to $J\psi K^0_S$ is seen with 4.0σ

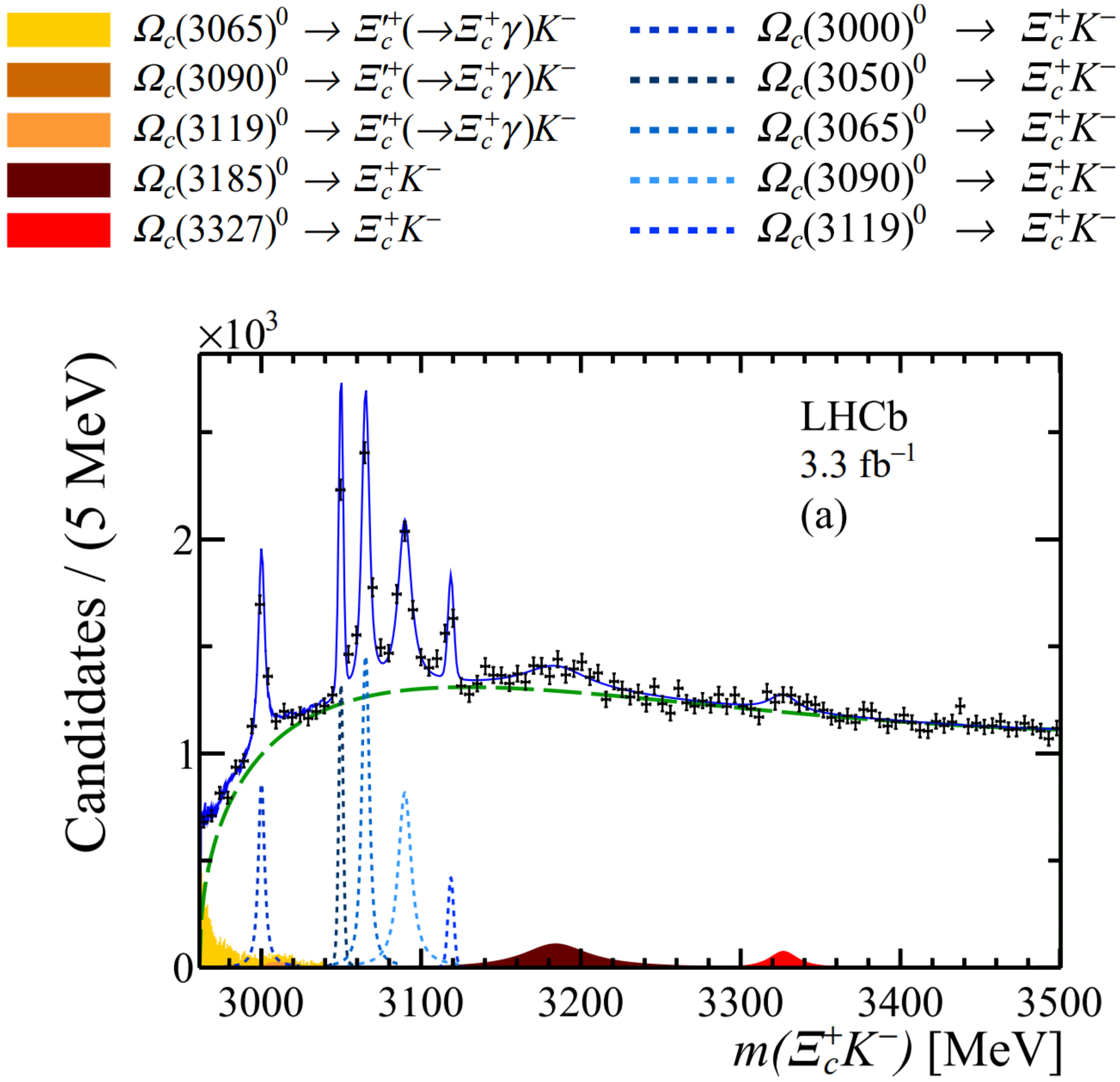
$M(T^{\theta}_{\psi s1}(4000)^0) = 3991\,^{+12}_{-10}\,^{+9}_{-17}$ MeV

$\Gamma(T^{\theta}_{\psi s1}(4000)^0) = 105\,^{+29}_{-25}\,^{+17}_{-23}$ MeV

$\Delta M = -12\,^{+11}_{-10}\,^{+6}_{-4}$ MeV

Observation of $\Omega_c(3185/3327)^0$ states

PRL 131 (2023) 131902



with $\Xi_c^+ \to pK^-\pi^+$

Observation of excited states decaying to $\Xi_c^+K^-$

$M\left(\Omega_c(3185)^0\right) = 3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2$ MeV

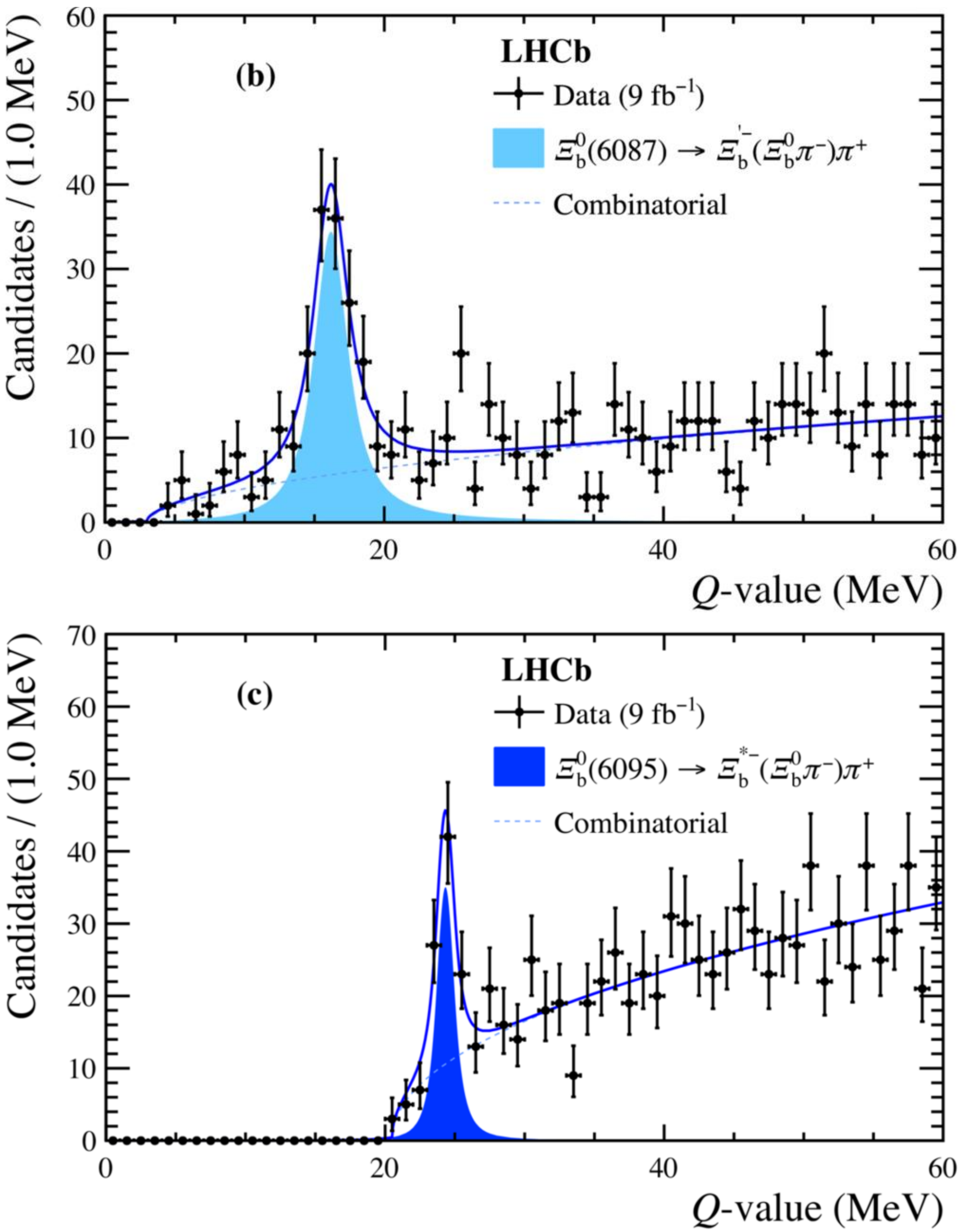
$\Gamma(\Omega_c(3185)^0) = 50 \pm 7\ ^{+10}_{-20}$ MeV

$M\left(\Omega_c(3327)^0\right) = 3327.1 \pm 2.7\ ^{+0.1}_{-1.3} \pm 0.2$ MeV

$\Gamma(\Omega_c(3327)^0) = 20 \pm 5\ ^{+13}_{-1}$ MeV

Observation of excited $\Xi_b^{0/-}$ baryons

PRL 131 (2023) 171901



$$Q = m_{\Xi_b\pi\pi} - m_{\Xi_b} - 2m_\pi$$

Observation of two new baryons with quark content bsu that decay to $\Xi_b^{0/-}\pi^+\pi^-$

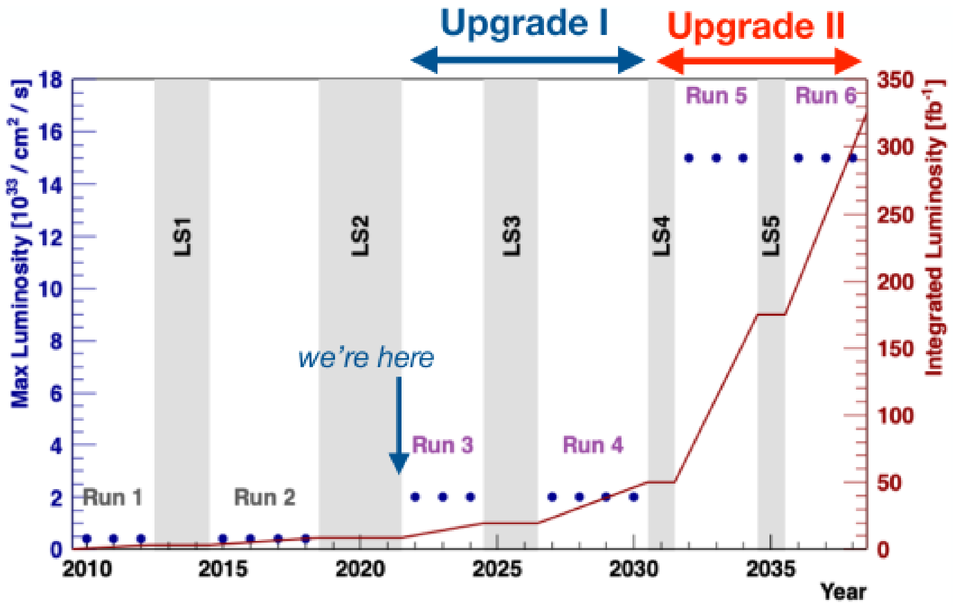
$M\left(\Xi_b(6087)^0\right) = 6087.24 \pm 0.20 \pm 0.06 \pm 0.50$ MeV

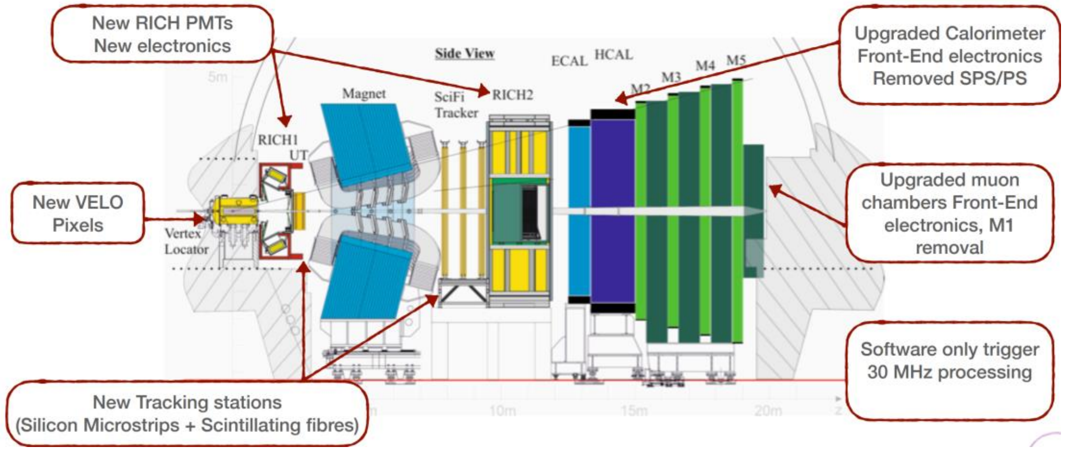
$\Gamma\left(\Xi_b(6087)^0\right) = 2.43 \pm 0.51 \pm 0.10$ MeV

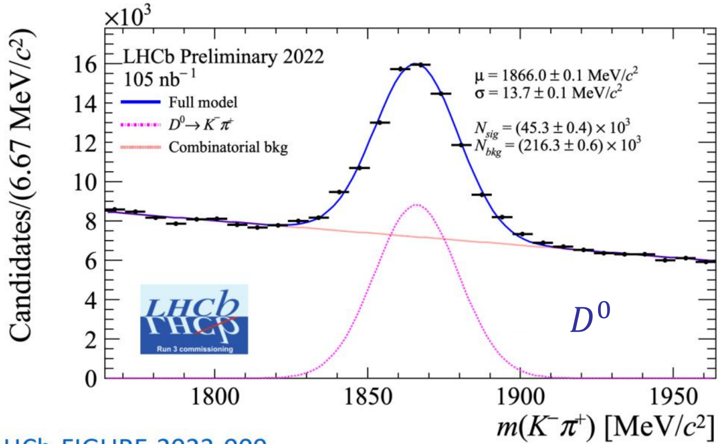
$M\left(\Xi_b(6095)^0\right) = 6095.36 \pm 0.15 \pm 0.03 \pm 0.50$ MeV

$\Gamma(\Xi_b(6095)^0) = 0.50 \pm 0.33 \pm 0.11$ MeV

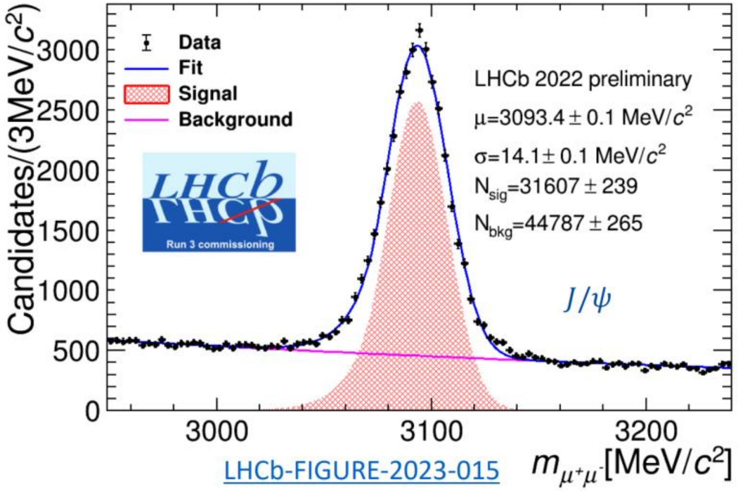
Entering LHCb Run 3



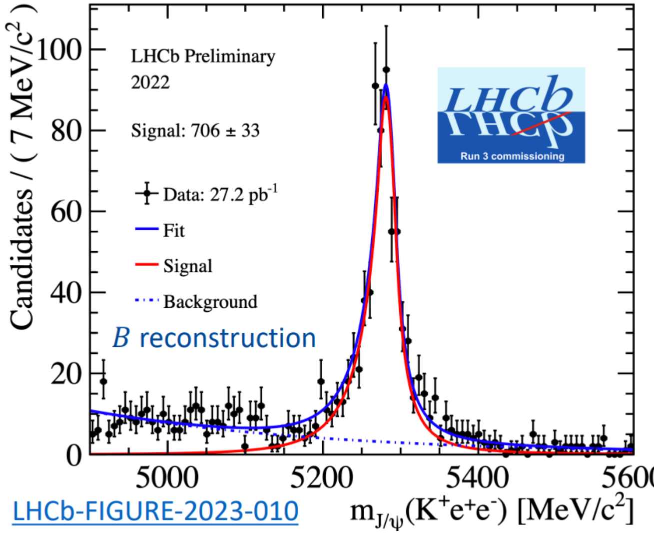




LHCb-FIGURE-2023-009



LHCb-FIGURE-2023-015

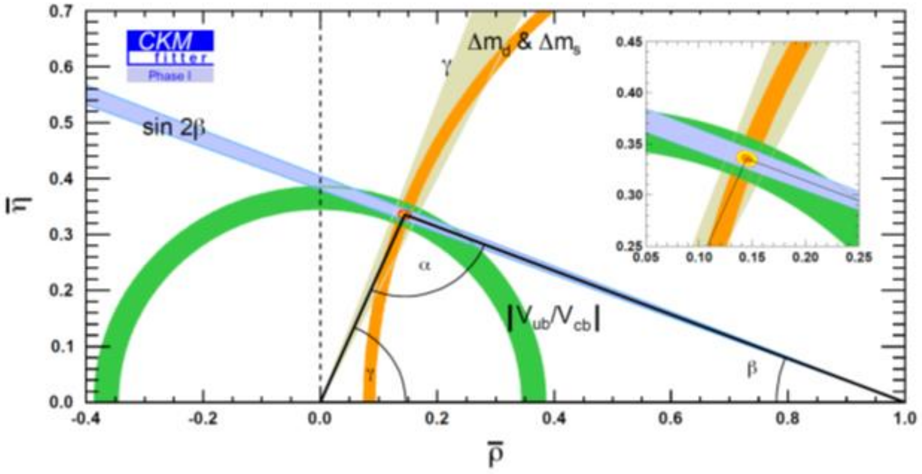


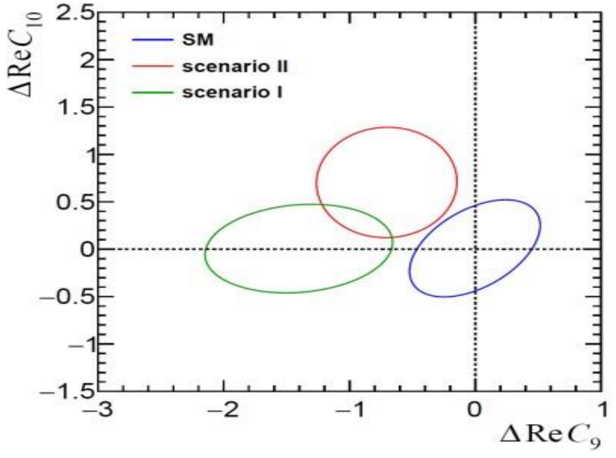
LHCb-FIGURE-2023-010

Vision

Upgrade I

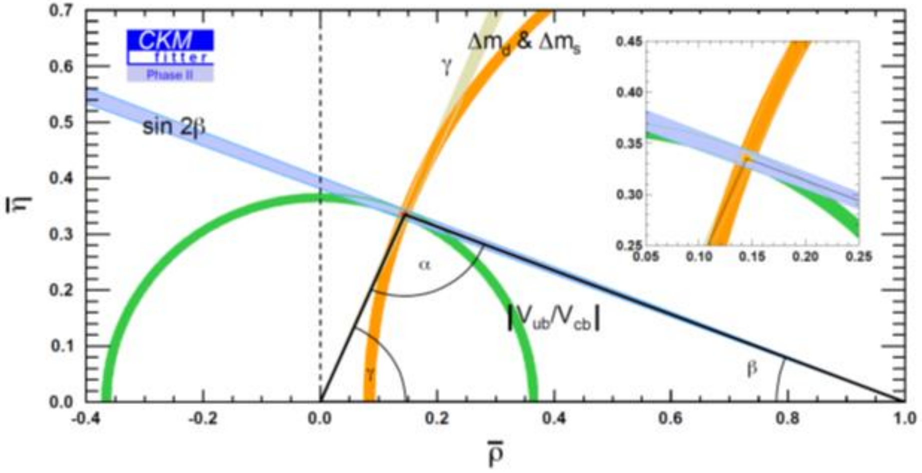
(50 $\mathbf{fb^{-1}}$)

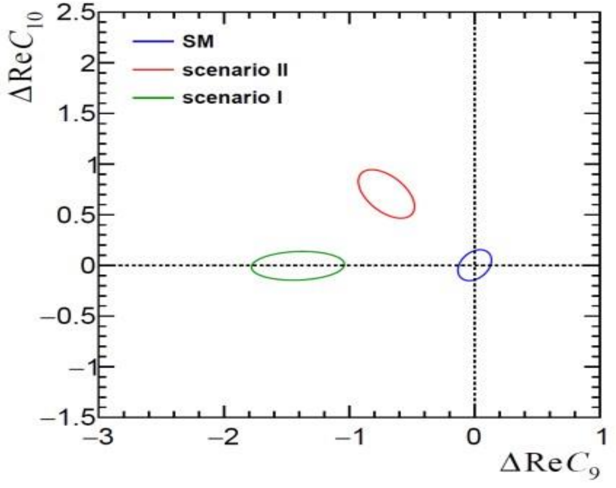




Upgrade II

(300 $\mathbf{fb^{-1}}$)





Summary

- CKM mechanism seems to stand the rigorous tests so far
  - ✓ High-precision measurements of β, β_s, γ at LHCb
- Some puzzles with $b \to s l^+ l^-$ processes remain
  - ✓ $R(K^{(*)})$ anomalies disappeared
  - ✓ $R(D^{(*)})$ tension between experiments and theory persists
  - ✓ Charm loops unable to explain the anomalies in $b \to s\mu^+\mu^-$ rates and angular distributions
- The hadron zoo is quickly expanding
  - ✓ Call for revolutionary development in understanding structure, spectroscopy and interaction of hadrons
- Looking forward to data from LHCb Run 3/4/5/6…