LHCb experimental results

Antonio Romero Vidal
antonio.romero@usc.es

Instituto Galego de Física de Altas Enerxías (IGFAE)
Universidade de Santiago de Compostela (USC), Spain

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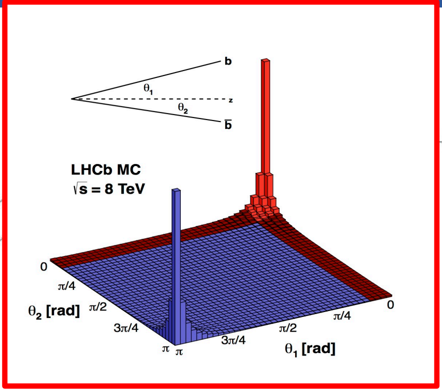
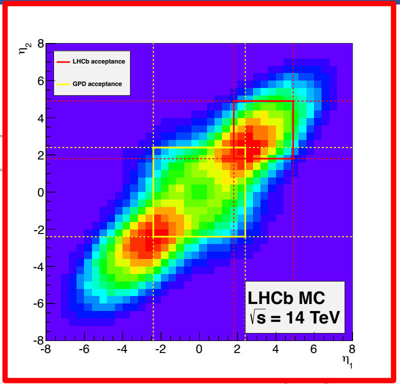
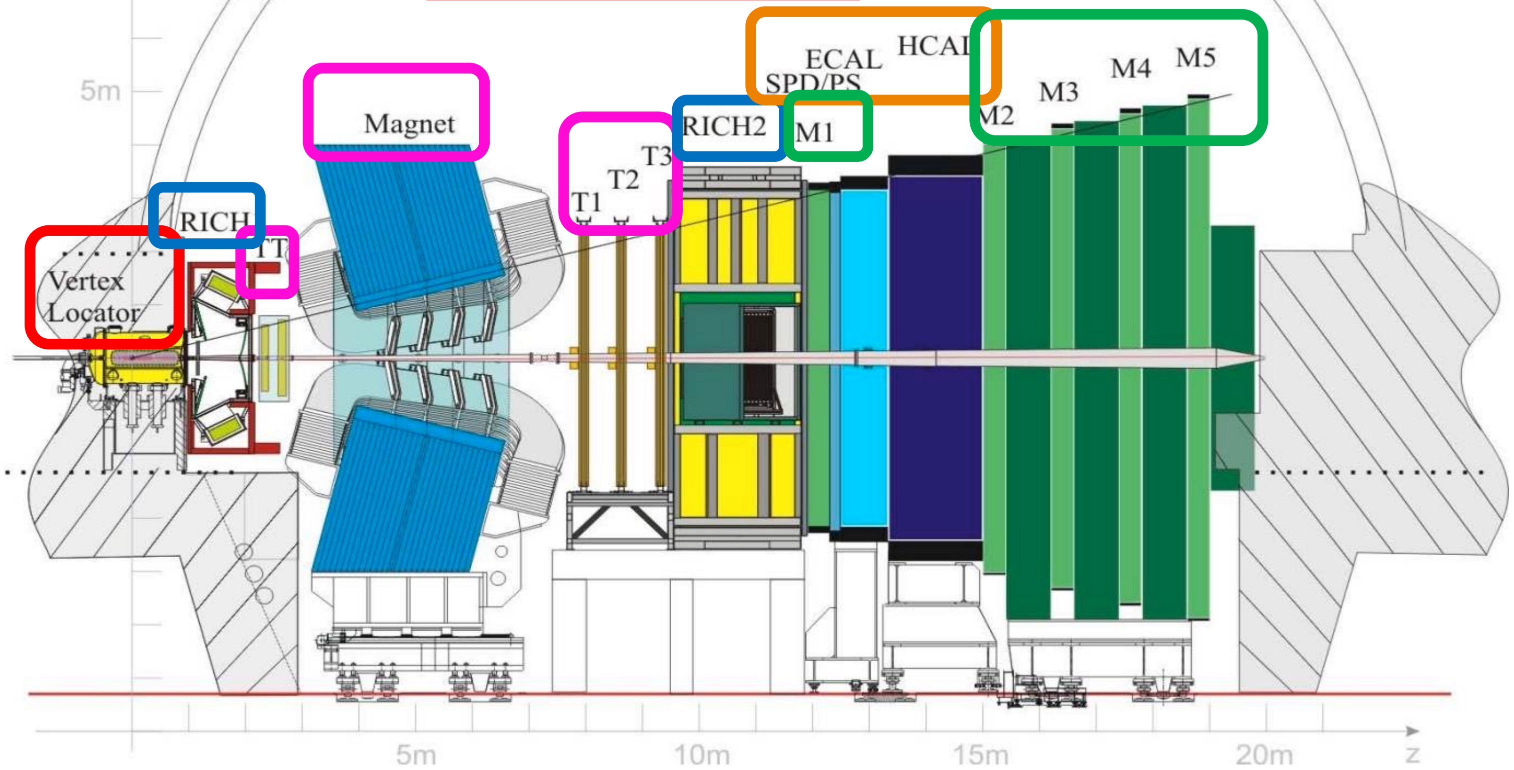
The run1+2 LHCb detector

Run1 (2010-2012)
+
Run2 (2015-2018)

JINST 3 (2008) S08005





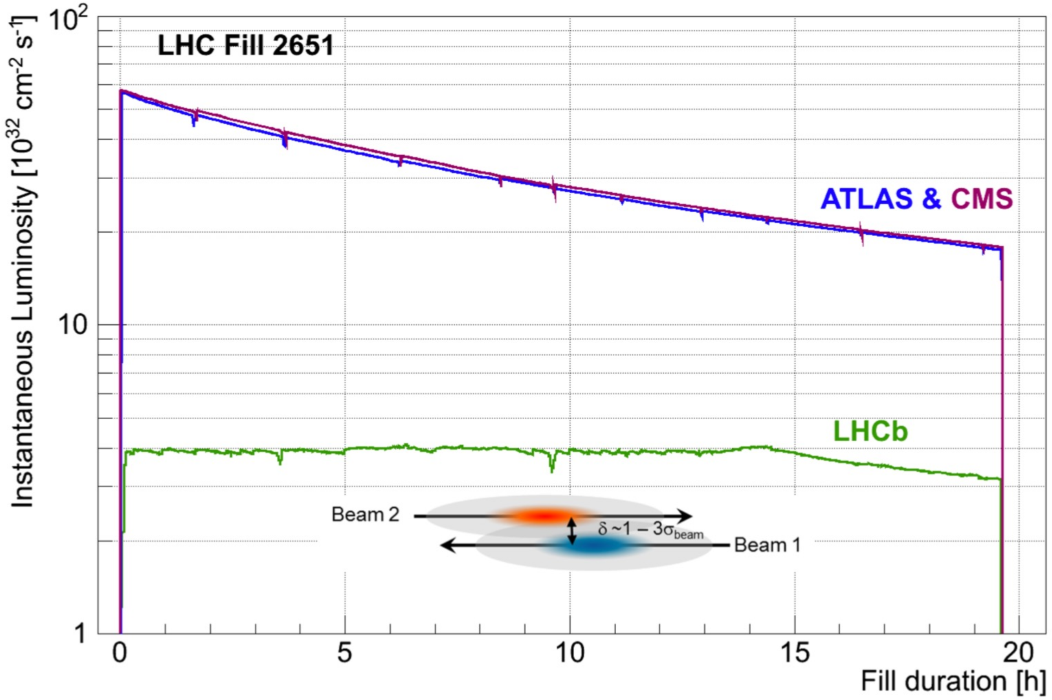


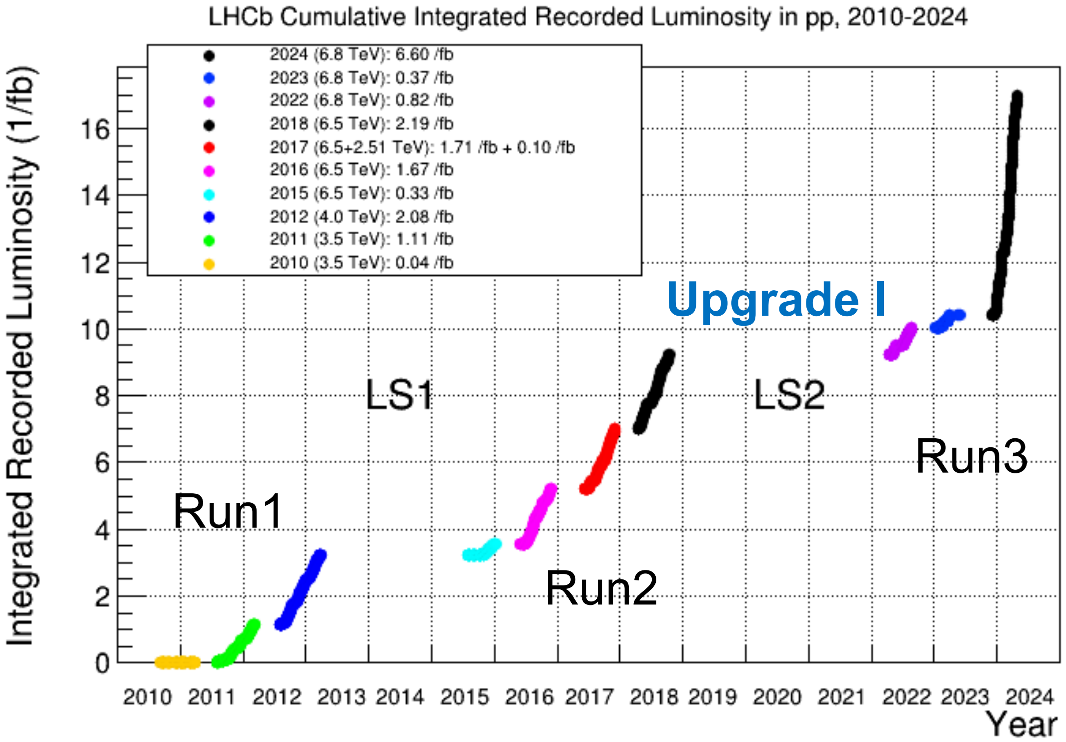
- LHCb originally designed for the study of **CP violation in beauty and charm.**
- In pp collisions **b/$\bar{\textbf{b}}$** pairs produced with very small opening angle → **LHCb** is a **forward** spectrometer (**2<η<5**).
- Vertex detector (VELO):
  - Excellent vertex resolution: **20 μm** resolution on impact parameter.
  - Decay time resolution **~45 ps**.
- Tracking system (plus a 4T magnet):
  - Momentum resolution **$\Delta p/p$~0.4%−0.6%.**
- RICH detectors:
  - Excellent **K/π/p separation**.
- Calorimeter systems:
  - Energy measurement (i.e: π^0, γ).
- Muon system:
  - Very high efficiency for muons.

Detector operation

- LHCb designed to run at **lower instantaneous luminosity** $\mathcal{L}$ than ATLAS and CMS.
- pp **beams displaced** to reduce $\mathcal{L}$ **(Run1+Run2).**
- Mean number of interactions per bunch crossing ~1.

- **3 fb^{-1}** of pp collisions at **7-8 TeV** in **Run 1** (2010-2012).
- **6 fb^{-1}** of pp collisions at **13 TeV** in **Run 2** (2015-2018).
- **8 fb^{-1}** of pp collisions at **14.6 TeV** in **Run 3** (Upgrade I: 2022- …).
- Other configurations: pPb, PbPb, fixed-target mode.



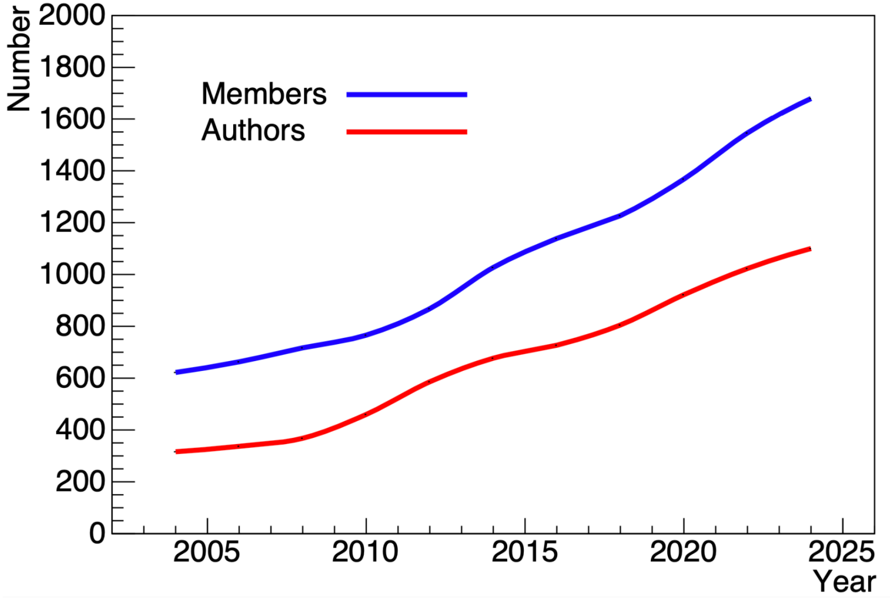


Evolution of LHCb Physics programme

Original design: CP violation, Rare decays, Charm → Strange Spectroscopy → Semileptonics, EW → Heavy Ions → Fixed target

More than 700 papers published

103 institutes and 1766 members



Selected LHCb results

1. Spectroscopy:

- $\chi_{c1}(3872)$
- Pentaquarks

2. Rare decays:

- Angular analysis of $B^0 \to K^{*0}e^+e^-$
- Search for :
  - $B_s^0 \longrightarrow \mu^+\mu^-\gamma$
  - $B_{(s)}^{*0} \longrightarrow \mu^+\mu^-$
  - $B_s^0 \longrightarrow \phi\mu^\pm\tau^\mp$
  - $D^0 \longrightarrow \mu^+\mu^-$
  - $D^{*0} \longrightarrow \mu^+\mu^-$

3. CPV in Charm:

- CPV in $D^0 \to \pi^+\pi^-\pi^0$

4. CKM:

- $\sin(2\beta)$ with $B^0 \longrightarrow \psi K_S^0$
- ϕ_s with $B_s^0 \longrightarrow J/\psi\phi$
- $\phi_s^{s\bar{s}s}$ with $B_s^0 \longrightarrow \phi\phi$
- $\Delta\Gamma_s$ with $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$
- Simultaneous determination of γ

5. Electroweak:

- effective leptonic mixing angle $sin^2\theta_{eff}^{\ell}$

6. Semileptonics:

- LFU in semitauonic B decays: $R(D^+)/R(D^{*+})$

7. Upgrade I

1. Spectroscopy:

- $\chi_{c1}(3872)$
- Pentaquarks

Spectroscopy

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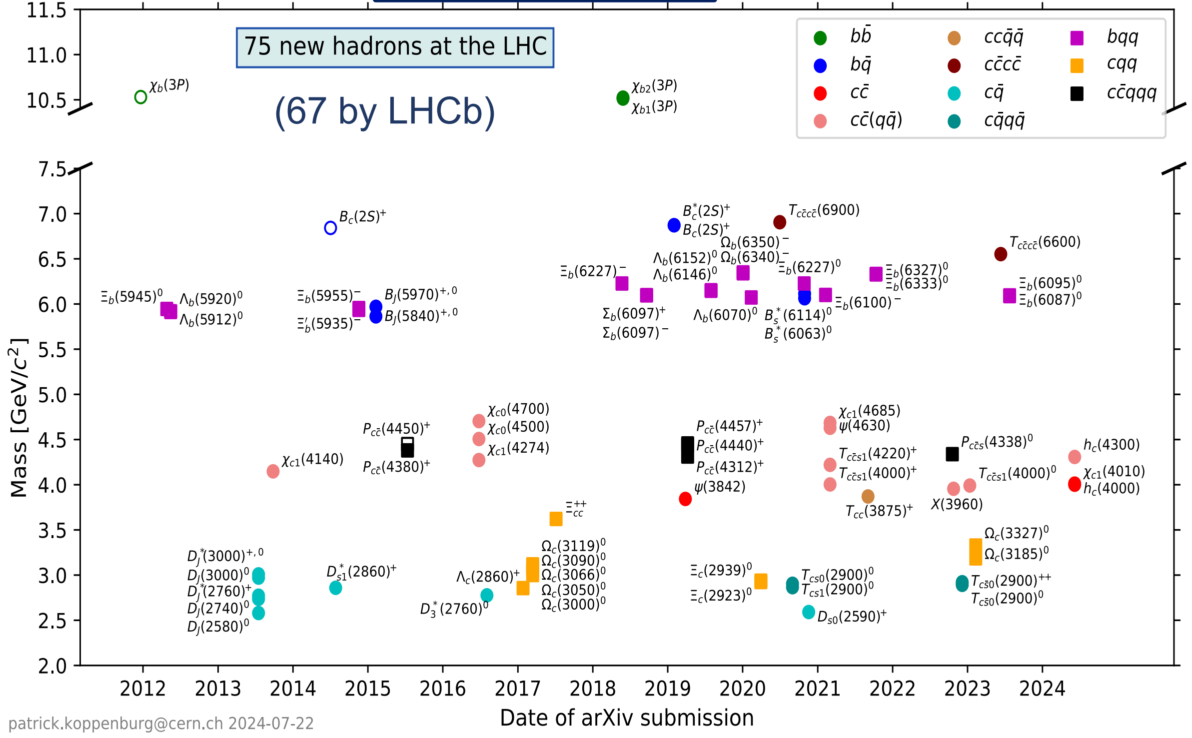
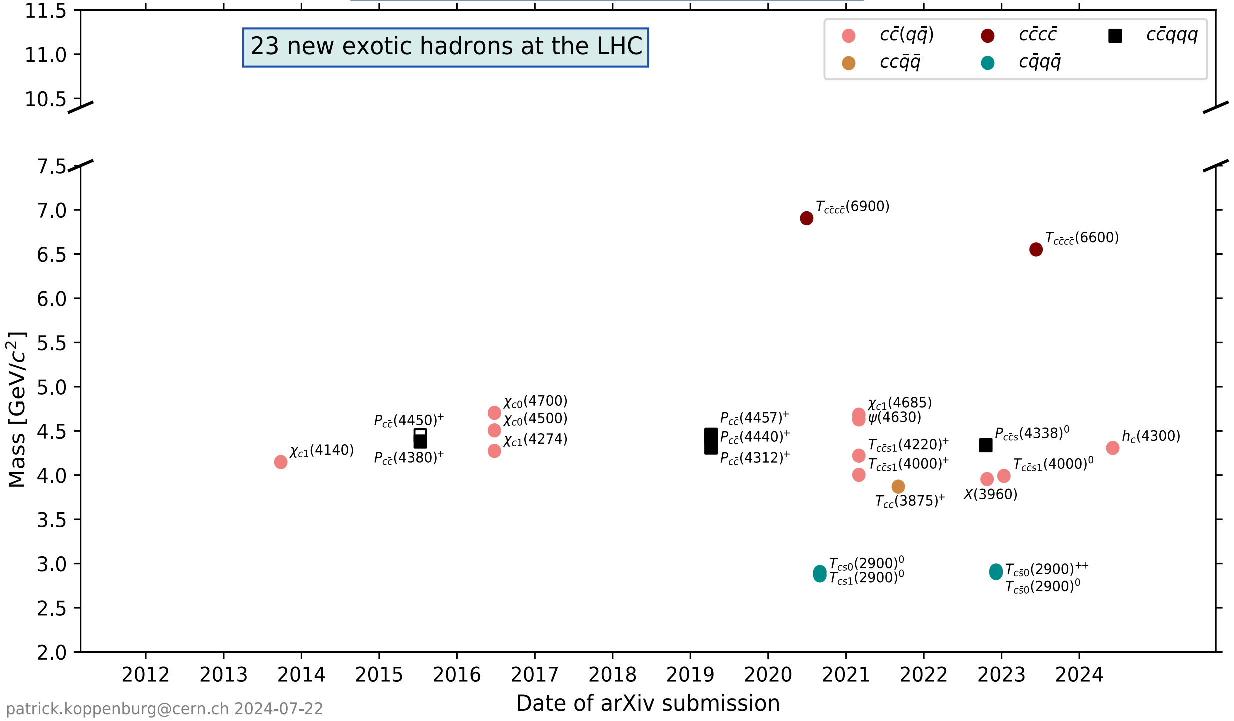
- Only **1 fundamental particle discovered** at the LHC (the Higgs boson, CMS+ATLAS).

- But many **new hadrons discovered**.

New Hadrons



New Exotic Hadrons



$\chi_{c1}(3872)$ in $B^+ \to J/\psi\pi^+\pi^-K^+$ decays

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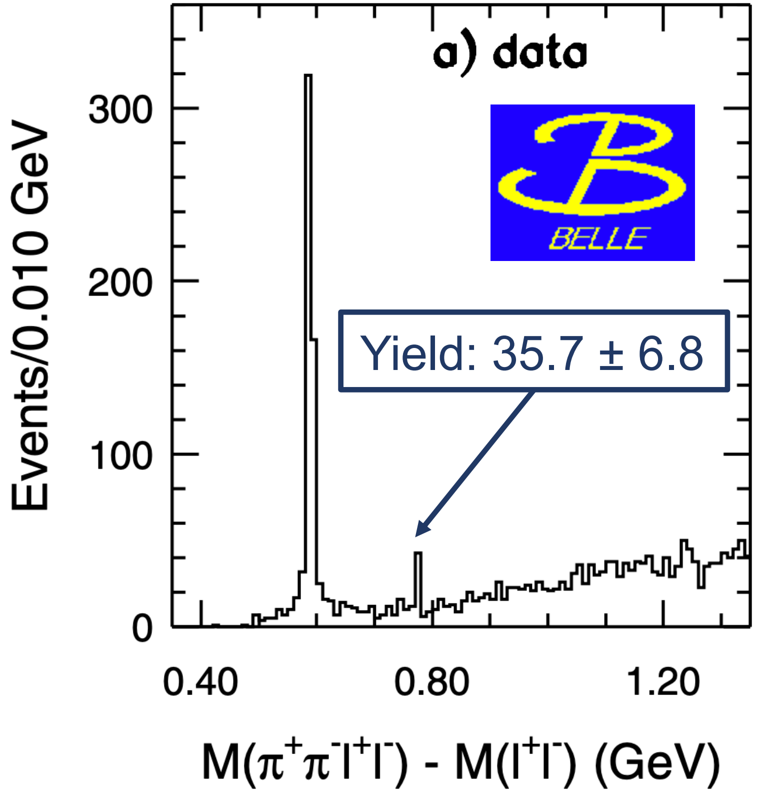
$\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ discovered in **2003** by **Belle** in $B^+ \to J/\psi\pi^+\pi^-K^+$ decays.

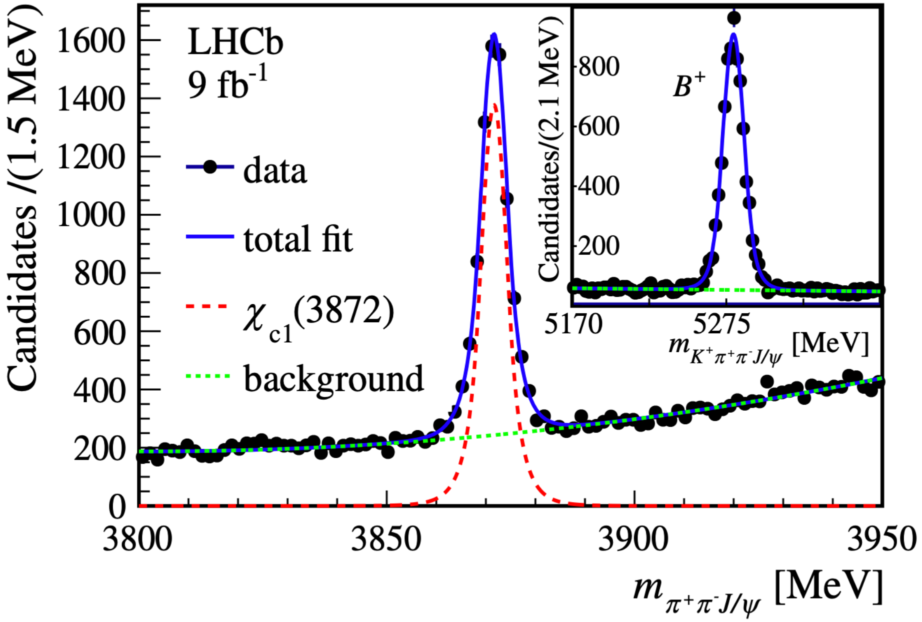
20 years after since discovery
~200 x more data.

Amplitude analysis of $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ decays shows a sizeable $\boldsymbol{\omega}$ contribution.

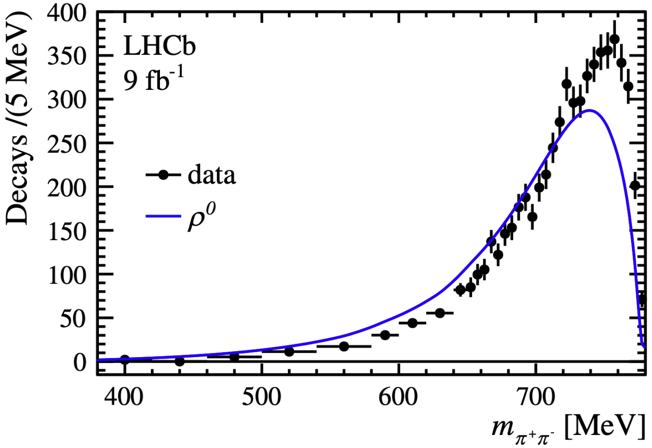


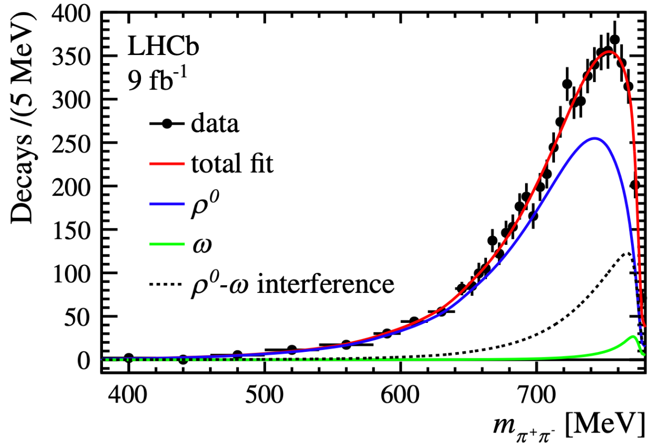
PRL 91 (2003) 262001

Yield: 6788 ± 117



PRD 108 (2023) L011103





χ_{c1}(3872) production in pp collisions

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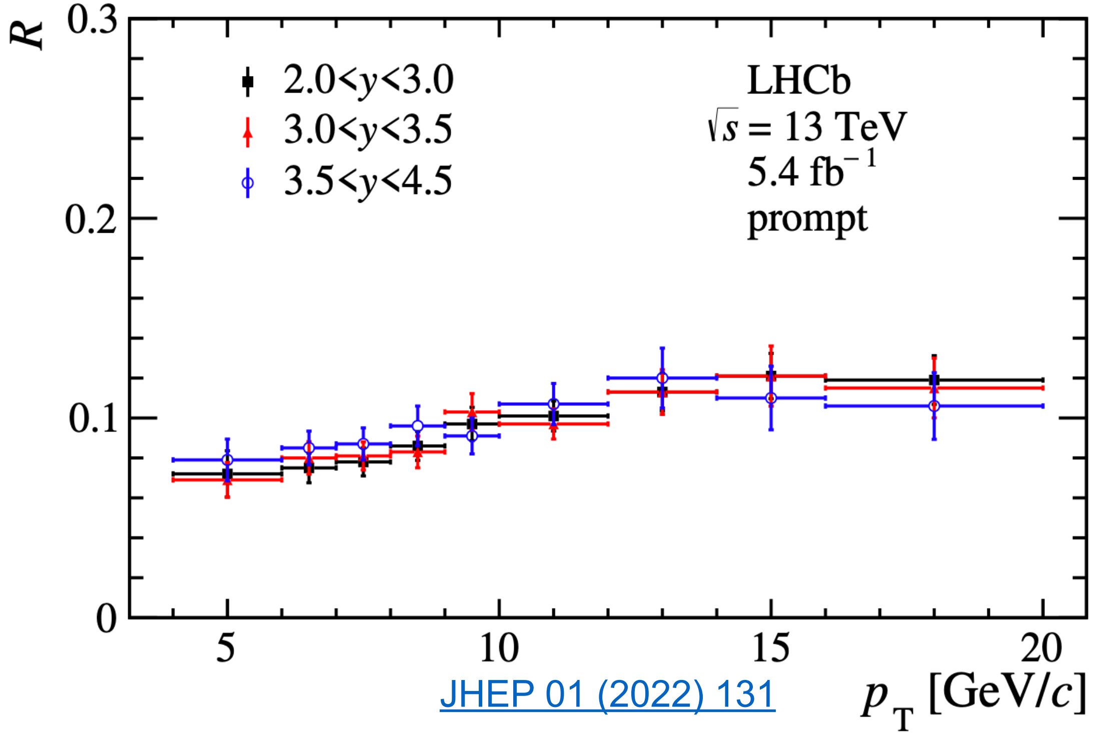
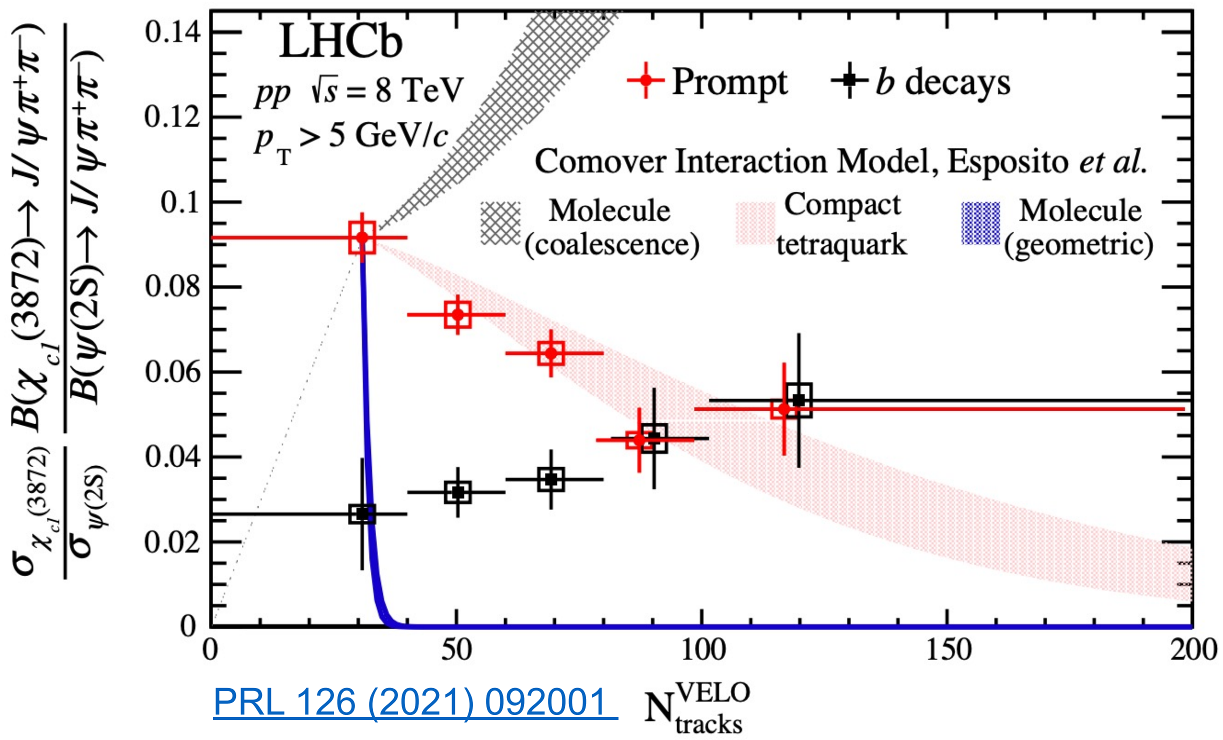
- $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ production studied as a function of $\mathbf{p_T}$ and **event multiplicity** (number of tracks in vertex detector).

- $\psi(2S) \to J/\psi\pi^+\pi^-$ used as normalisation channel:

$$R = \frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \frac{B(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{B(\psi(2S) \to J/\psi\pi^+\pi^-)}$$



JHEP 01 (2022) 131



PRL 126 (2021) 092001

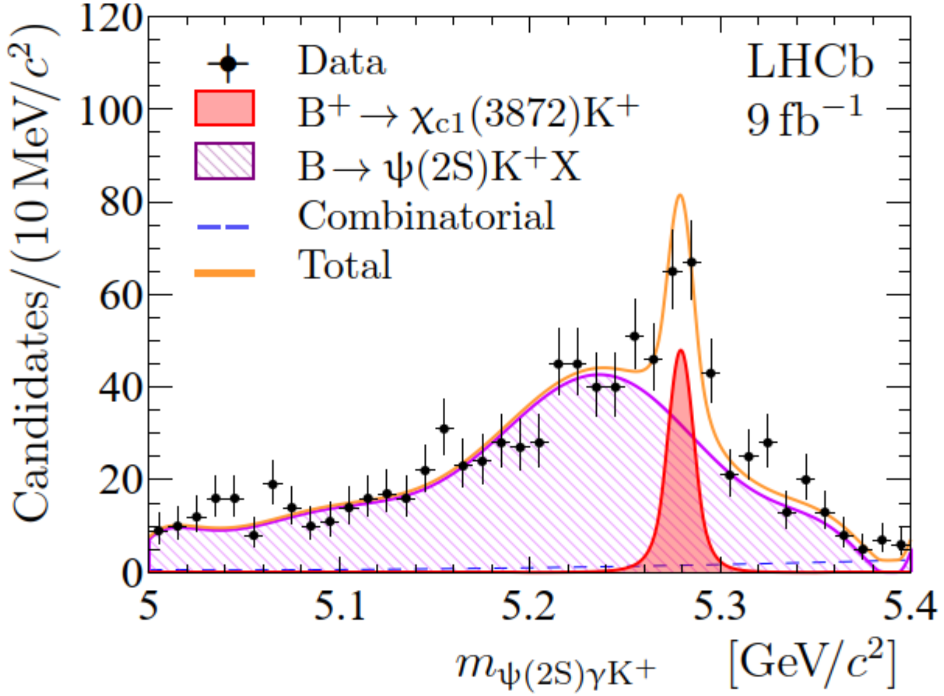
Study of production in other configurations (pPb, etc...) ongoing.

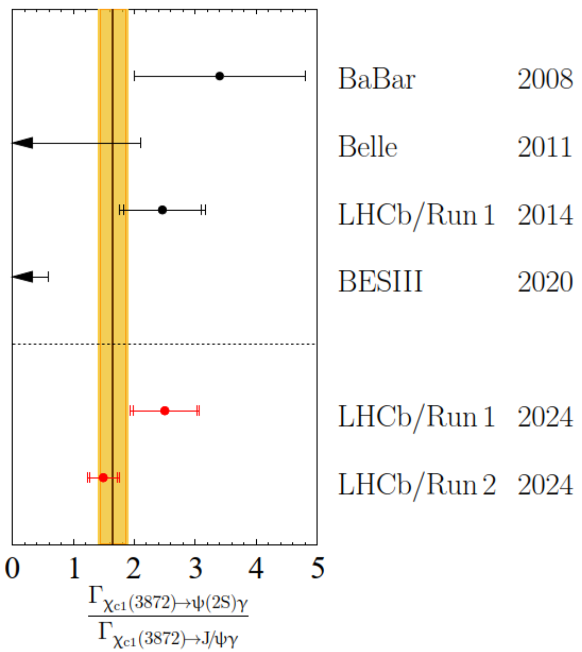
Probing the nature of the $\chi_{c1}(3872)$

- $\chi_{c1}(3872)$ mass just below the sum of the D^0 and D^{*0} masses (D^0D^{*0} molecule?).
- The ratio $R_{\psi\gamma}$ used as a tool to study the nature of the $\chi_{c1}(3872)$.
- $R_{\psi\gamma}$ different from zero indicates some compact component (charmonium or tetraquark).

$$R_{\psi\gamma} = \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

- Generally inconsistent with calculations based on pure D^0 and D^{*0} molecule.
- Agrees with wide range of predictions, including $c\bar{c}$ charmonium, $c\bar{c}q\bar{q}$ tetraquark and molecules mixed with substantial compact component.

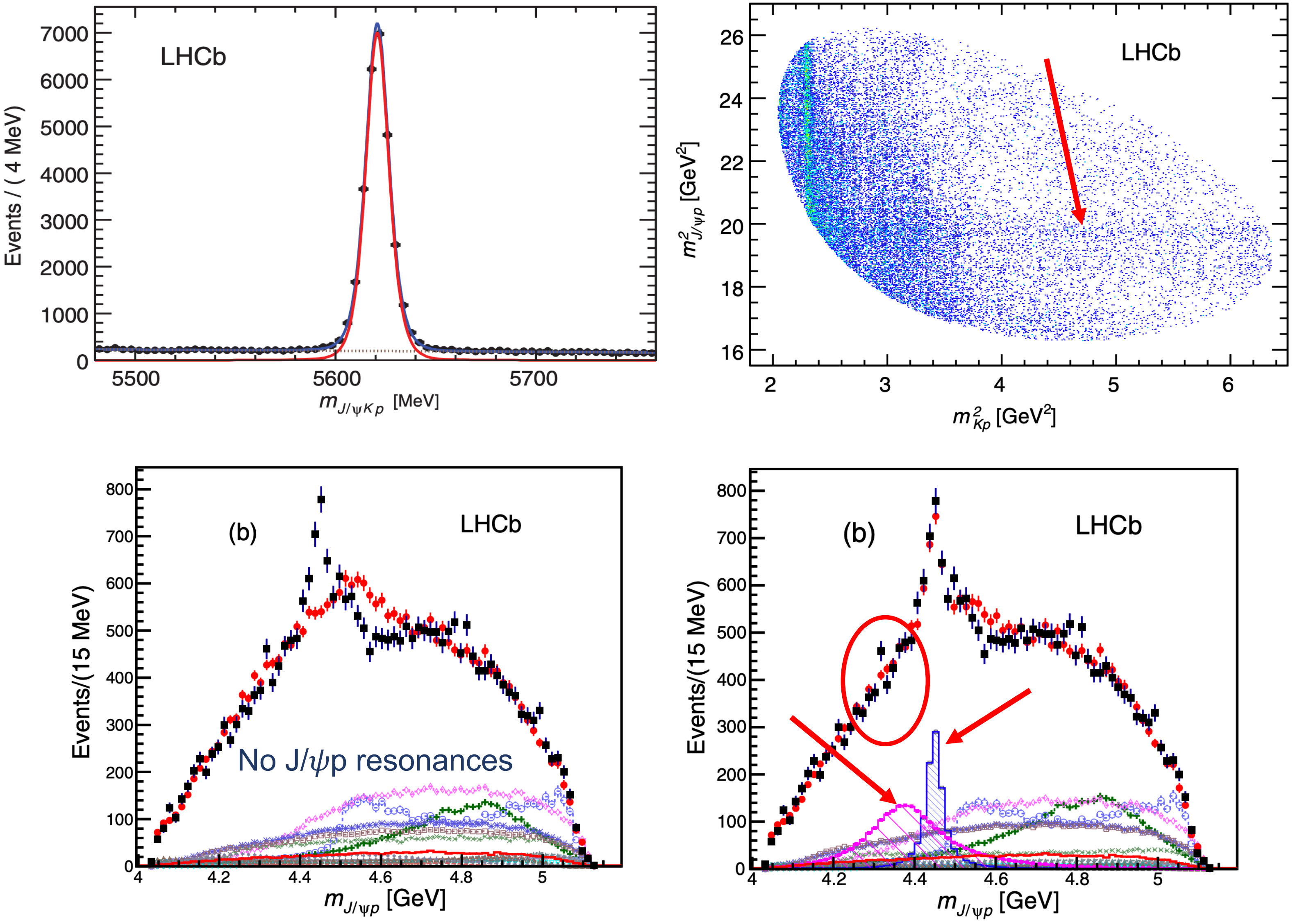




LHCb-PAPER-2024-015
arXiv:2406.17006

Charmonium Pentaquarks discovery

- Observation of $J/\psi p$ resonances consistent with pentaquarks in 2015.
- Clean $\Lambda_b^0 \to J/\psi p K^-$ signal, almost background-free.
- Clear structure in $m(J/\psi p)$, indicating the presence of **exotic contributions**.
- Fit without $J/\psi p$ resonances cannot describe the data.
- Two P_{cc}^+ states needed to get a reasonable fit. But fit is not perfect.



Latest on Charmonium Pentaquarks

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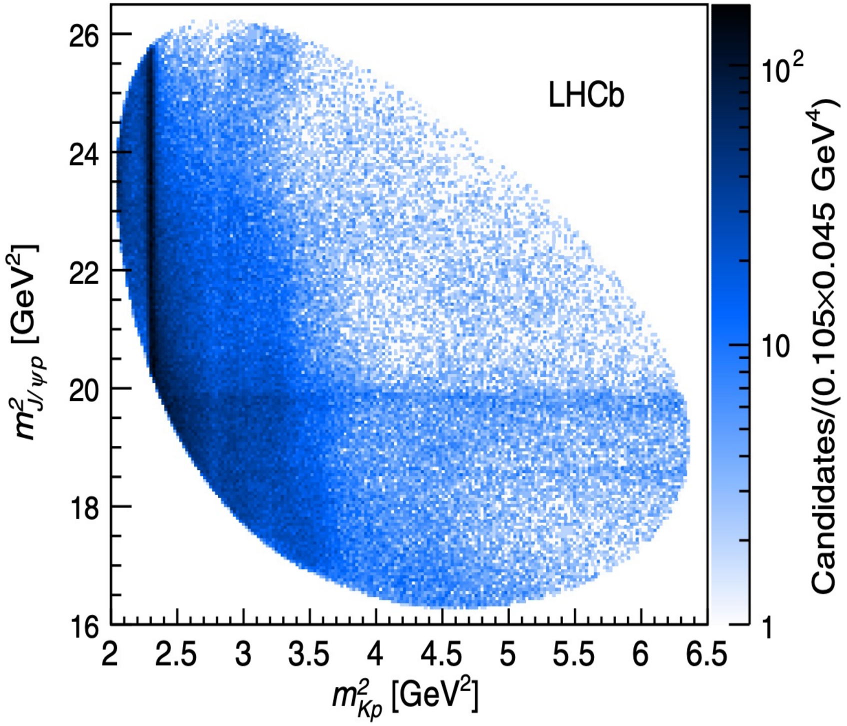
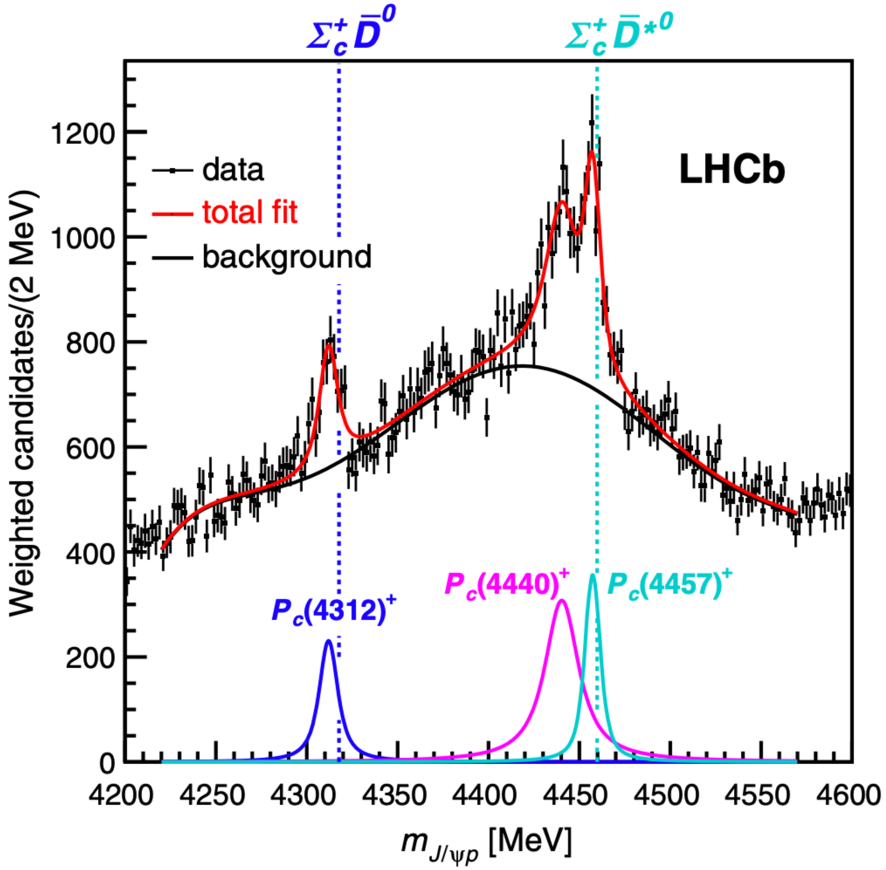
- Four years later (2019) : ~10 x more data.
- Structures in Dalitz plot more evident.

State	M [MeV]	Γ [MeV]	(95% C.L.)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(<49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(<20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$



PRL 122 (2019) 222001

- 3 peaks right below the $\Sigma_c^+D^0$ and $\Sigma_c^+D^{*0}$ thresholds.
- Full angular analysis necessary to determine quantum numbers (work in progress). Coupled-channel analyses of line shapes may be necessary.



Charmonium Pentaquarks to Open Charm ?

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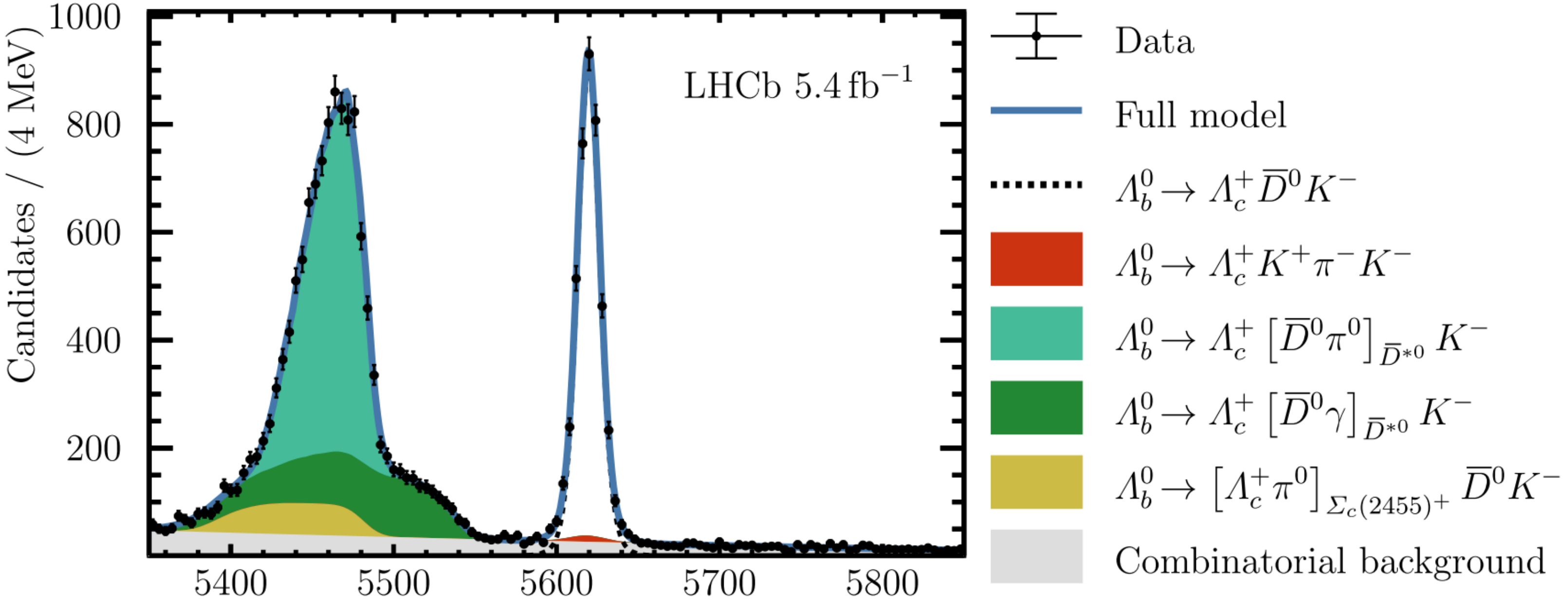
- Observation of $\Lambda_b^0 \longrightarrow \Lambda_c^+ \overline{D}^{(*)0} K^-$ and $\Lambda_b^0 \longrightarrow \Lambda_c^+ D_s^{*-}$ decays.
- Determined ratios of branching fractions:

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi\, p K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-\right)} = 0.152^{+0.032}_{-0.028}$$

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi\, p K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-\right)} = 0.049^{+0.011}_{-0.009}$$



Eur. Phys. J. C (2024) 84:575

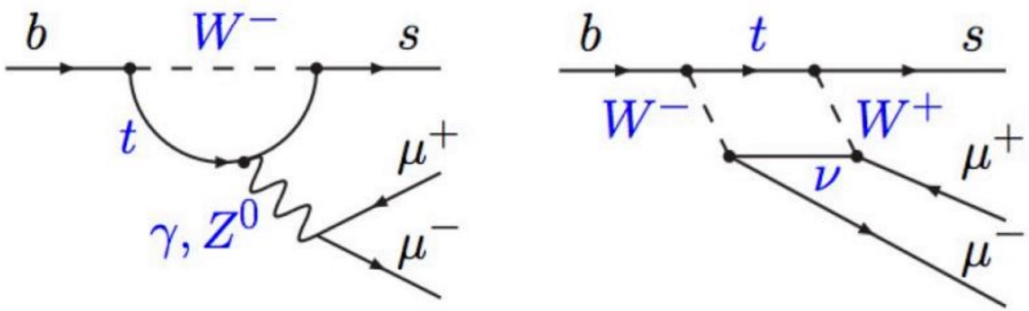
- Possible P_{cc}^+ contributions to these decays? Amplitude analysis needed.

2. Rare decays:

- Angular analysis of $B^0 \to K^{*0}e^+e^-$
- Search for :
  - $B_s^0 \longrightarrow \mu^+\mu^-\gamma$
  - $B_{(s)}^{*0} \longrightarrow \mu^+\mu^-$
  - $B_s^0 \longrightarrow \phi\mu^\pm\tau^\mp$
  - $D^0 \longrightarrow \mu^+\mu^-$
  - $D^{*0} \longrightarrow \mu^+\mu^-$

$b \to s\ell^+\ell^-$ transitions

- Decays mediated by $\boldsymbol{b \to s\ell^+\ell^-}$ quark transitions suppressed in the SM due to the absence of **Flavour Changing Neutral Currents (FCNC)**. → Can only occur at **loop** level.

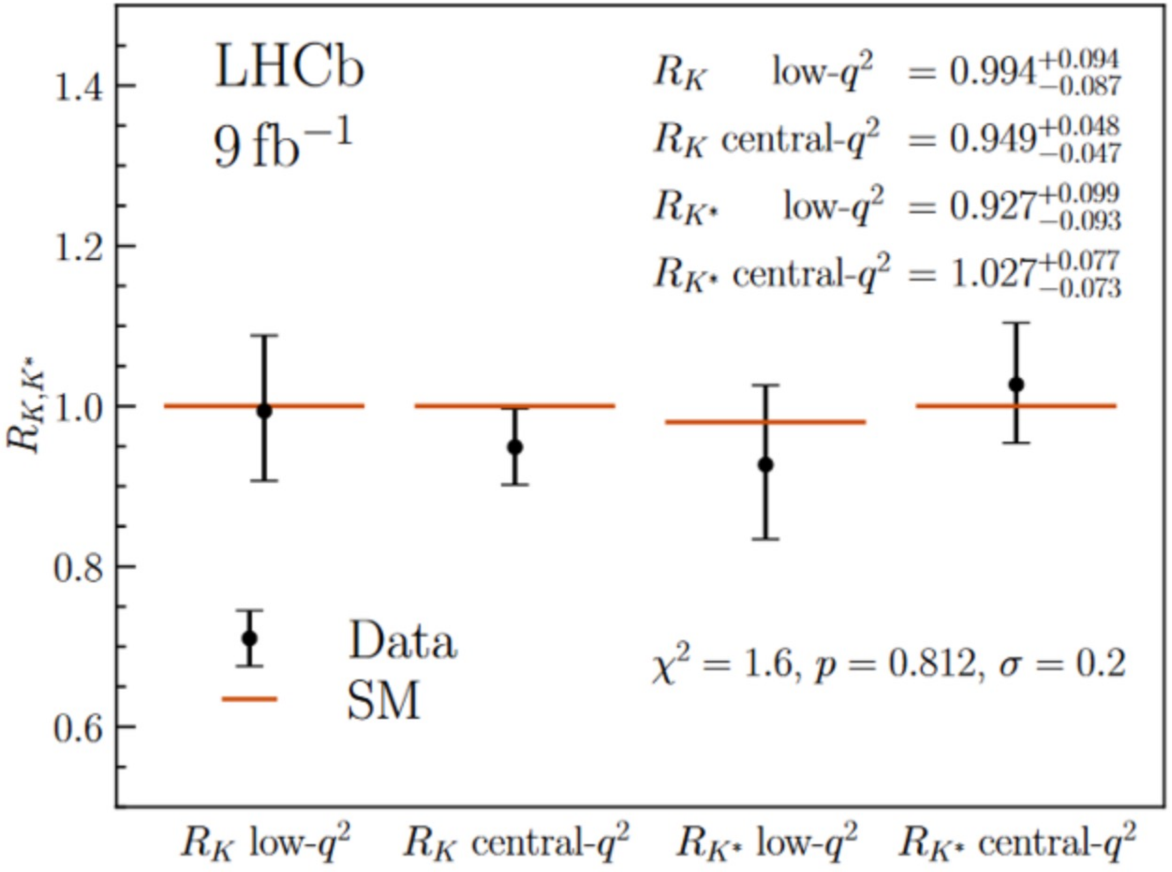


- But this is not necessarily true in a NP scenario.

- Measurements of the properties are sensitive to new particles with masses up to ~100 TeV:

    - Branching fractions.
    - Angular analysis of $B \to K^{(*)}\ell^+\ell^-$ decays.
    - LFU tests: $R_{K^{(*)}} = \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to K^{(*)}e^+e^-)}$.

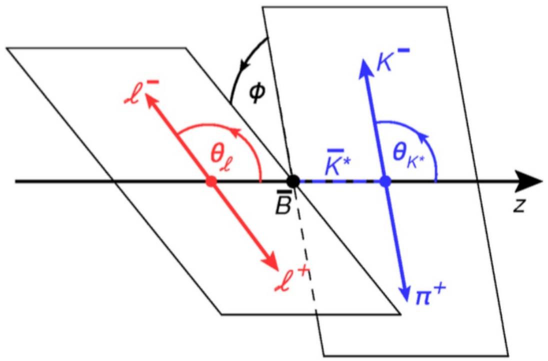
$R_{K^{(*)}}$ results: PRL 131, 051803 (2023)



$q^2 = m^2(\ell^+\ell^-)$

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

- First angular analysis of $B^0 \to K^{*0}e^+e^-$ decays in the central q^2 region ($q^2 = m^2(e^+e^-)$).
- Dataset: Full Run1+Run2 (9 fb^{-1}) statistics.
- 4D unbinned fit to the B mass and angular distributions.



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

Fraction of longitudinal polarisation of the K*

Forward-backward asymmetry of the di-lepton system

S_i: CP-averaged observables.
$P_i^{(\prime)}$: Optimized observables (reduced form-factor uncertainties).

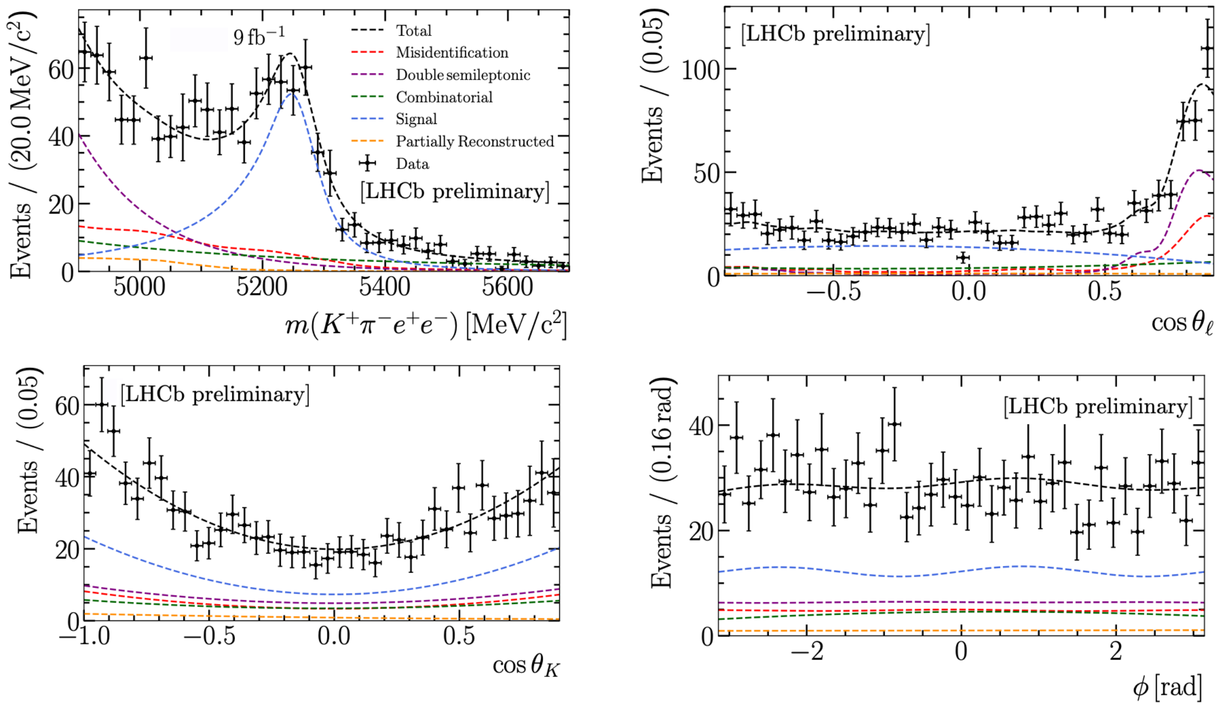
$$P_5' = \frac{S_5}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$$

Q_i: LFU observables. Obtained by comparing results with already published muon analysis.

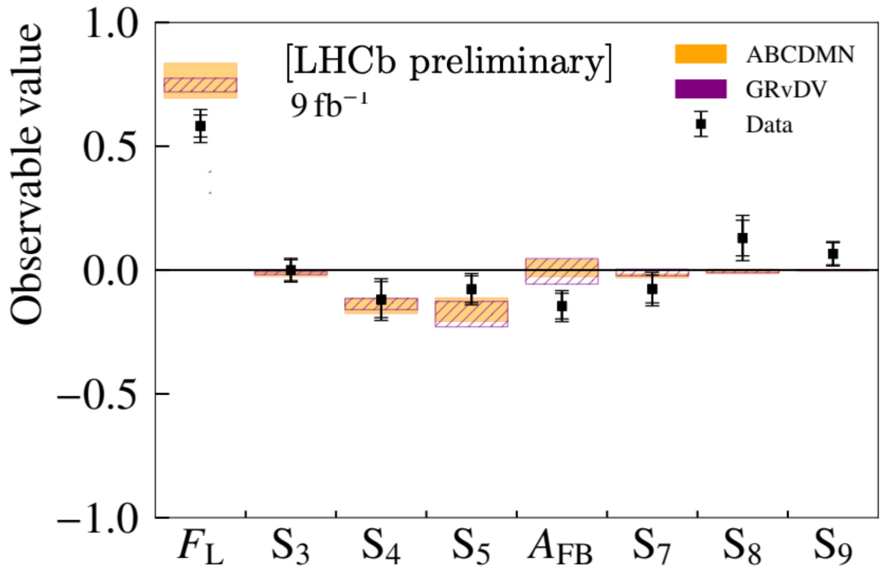
$$Q_i = P_i^{(\mu)} - P_i^{(e)}$$

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

- Projections of the model from a 4D unbinned fit to the B mass and angular distributions.



- Angular observables measured in the q^2 region [1.1,6.0] GeV²/c⁴.

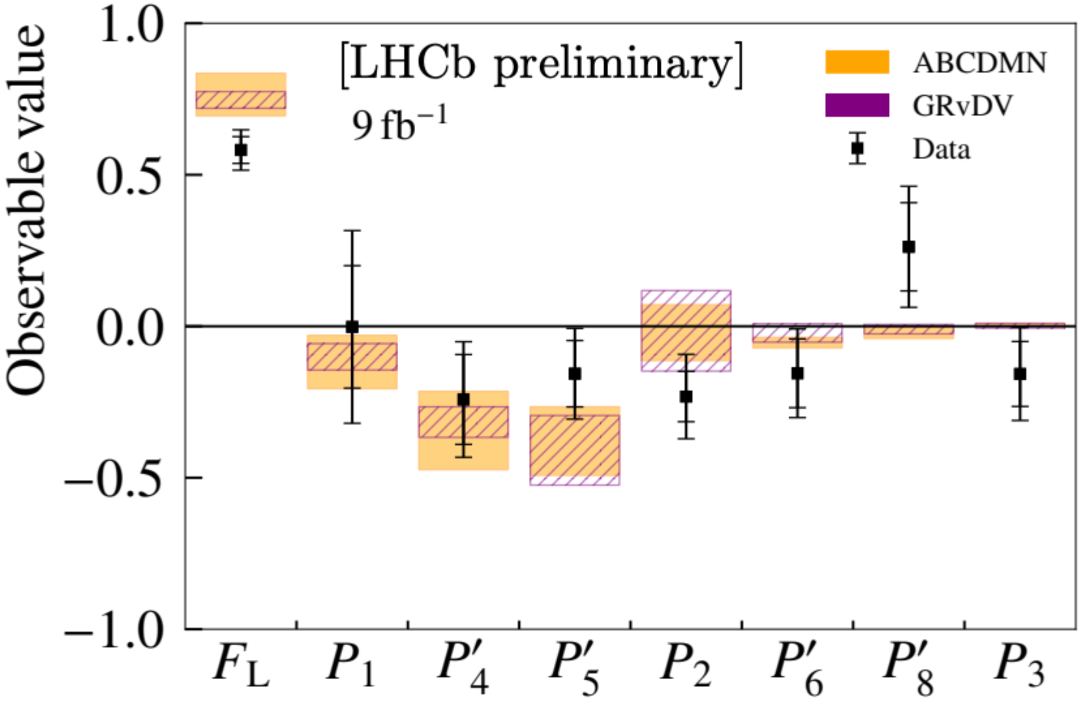


- Good agreement with SM predictions.

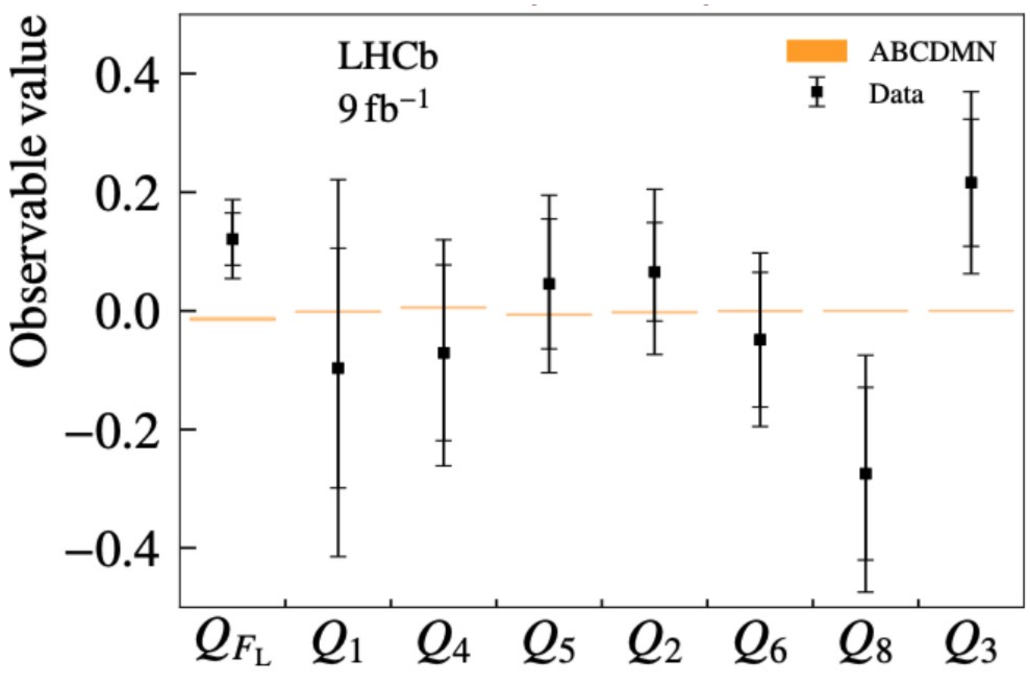
LHCb-PAPER-2024-022 in preparation

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

- $P_i^{(\prime)}$ based on F_L, A_{FB} and S_i → Reduced form-factor uncertainties.



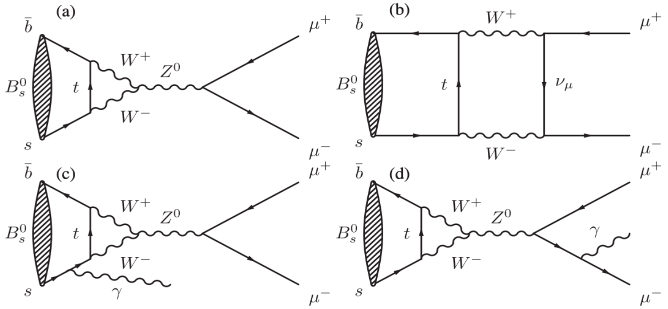
- LFU in angular observables. $Q_i = P_i^{(\mu)} - P_i^{(e)}$
- Obtained by comparing with $B^0 \to K^{*0}\mu^+\mu^-$ analysis (PRL 132 (2024) 131801).



LHCb-PAPER-2024-022 in preparation

Search for the $B_s^0 \longrightarrow \mu^+\mu^-\gamma$ decay

$B_s^0 \longrightarrow \mu^+\mu^-\gamma$ vs $B_s^0 \longrightarrow \mu^+\mu^-$

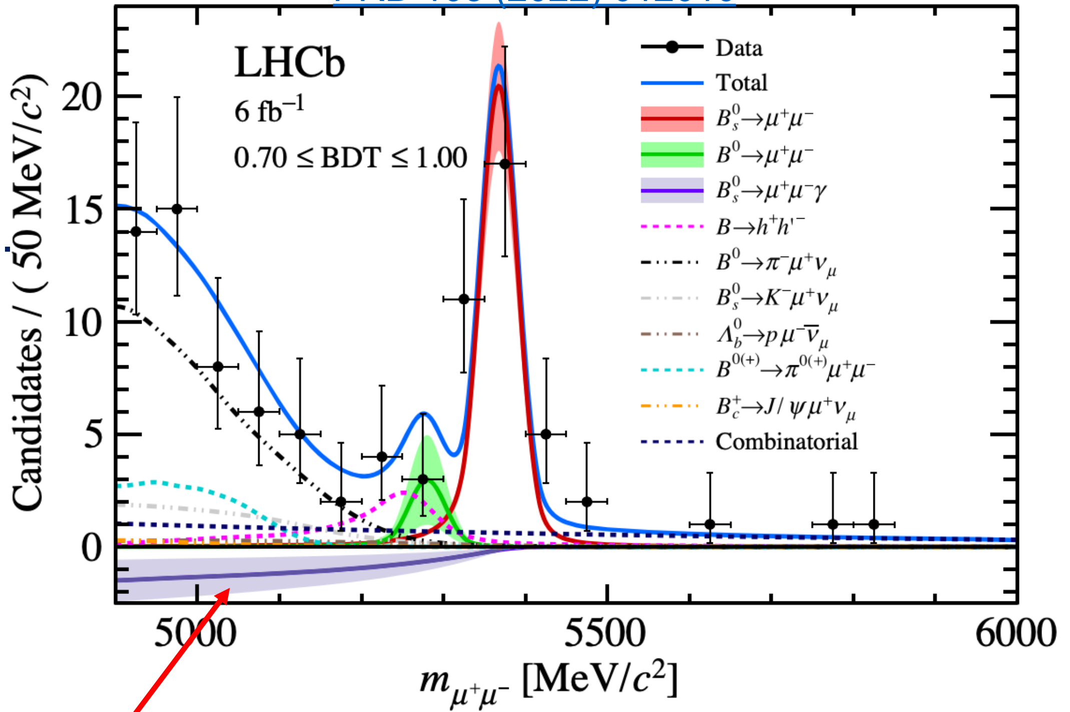


- Sensitive to a larger set of WC ($C^{(\prime)}_{7,9,10}$) than $B_s^0 \longrightarrow \mu^+\mu^-$ ($C^{(\prime)}_{10}$).
- $\mathfrak{B}(B_s^0 \longrightarrow \mu^+\mu^-\gamma) \sim \mathfrak{B}(B_s^0 \longrightarrow \mu^+\mu^-)$, but larger theoretical uncertainties.
- Worse mass resolution due to the photon reconstruction.
- Theoretical prediction (JHEP 11(2017) 184):
  - $\mathfrak{B}(B_s^0 \longrightarrow \mu^+\mu^-\gamma)_{low\ q^2(<8.64\ GeV^2/c^4)} = (8.4 \pm 1.3)\times 10^{-9}$
  - $\mathfrak{B}(B_s^0 \longrightarrow \mu^+\mu^-\gamma)_{high\ q^2(>15.84\ GeV^2/c^4)} = (8.90 \pm 0.98)\times 10^{-10}$

[$q^2 = m^2(\mu^+\mu^-)$]

Indirect search from $B_s^0 \longrightarrow \mu^+\mu^-$ analysis

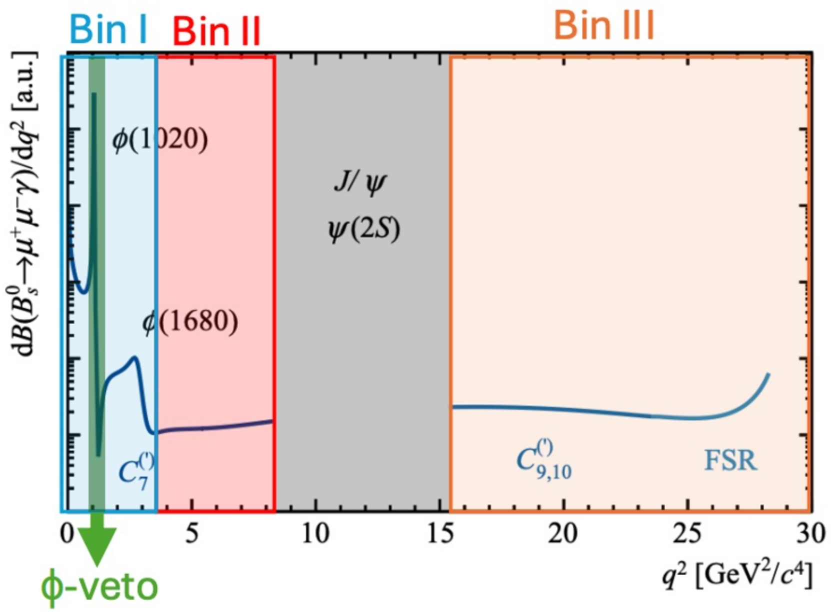
PRD 105 (2022) 012010



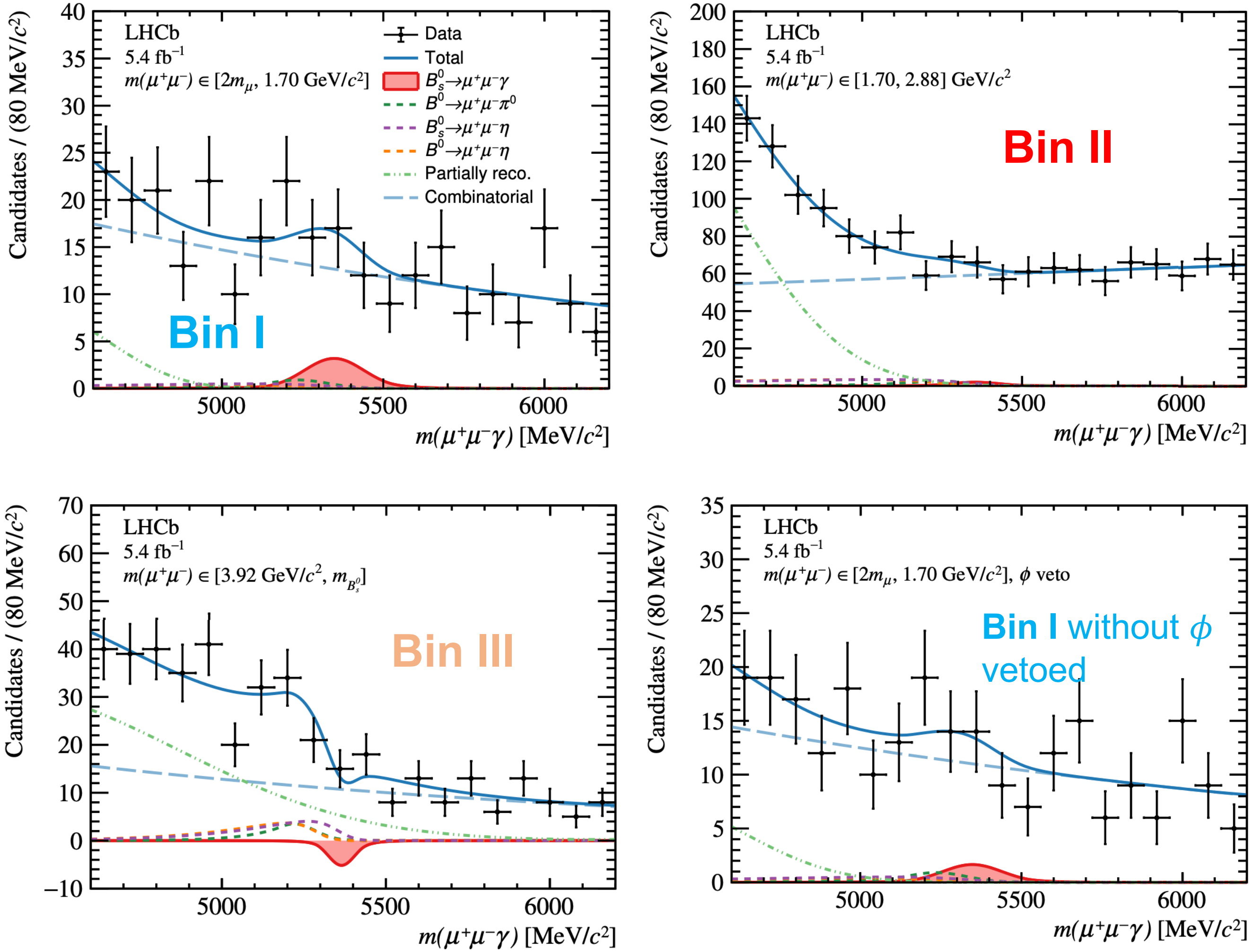
$\mathfrak{B}(B_s^0 \longrightarrow \mu^+\mu^-\gamma) < 1.5(2.0)\times 10^{-9}$ at 90% (95% CL) with $m(\mu^+\mu^-)>4.9$ GeV/c^2.

Search for the $B_s^0 \longrightarrow \mu^+\mu^-\gamma$ decay

- Dataset: 5.4 fb^{-1} of Run2 data (2016-2018).
- Direct search in **3 q^2 bins**.
    - **Bin I** : low q^2 (with ϕ vetoed).
    - **Bin II** : middle q^2.
    - **Bin III** : high q^2.



Mass fit in all q^2 bins



JHEP 07(2024) 101

Search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay

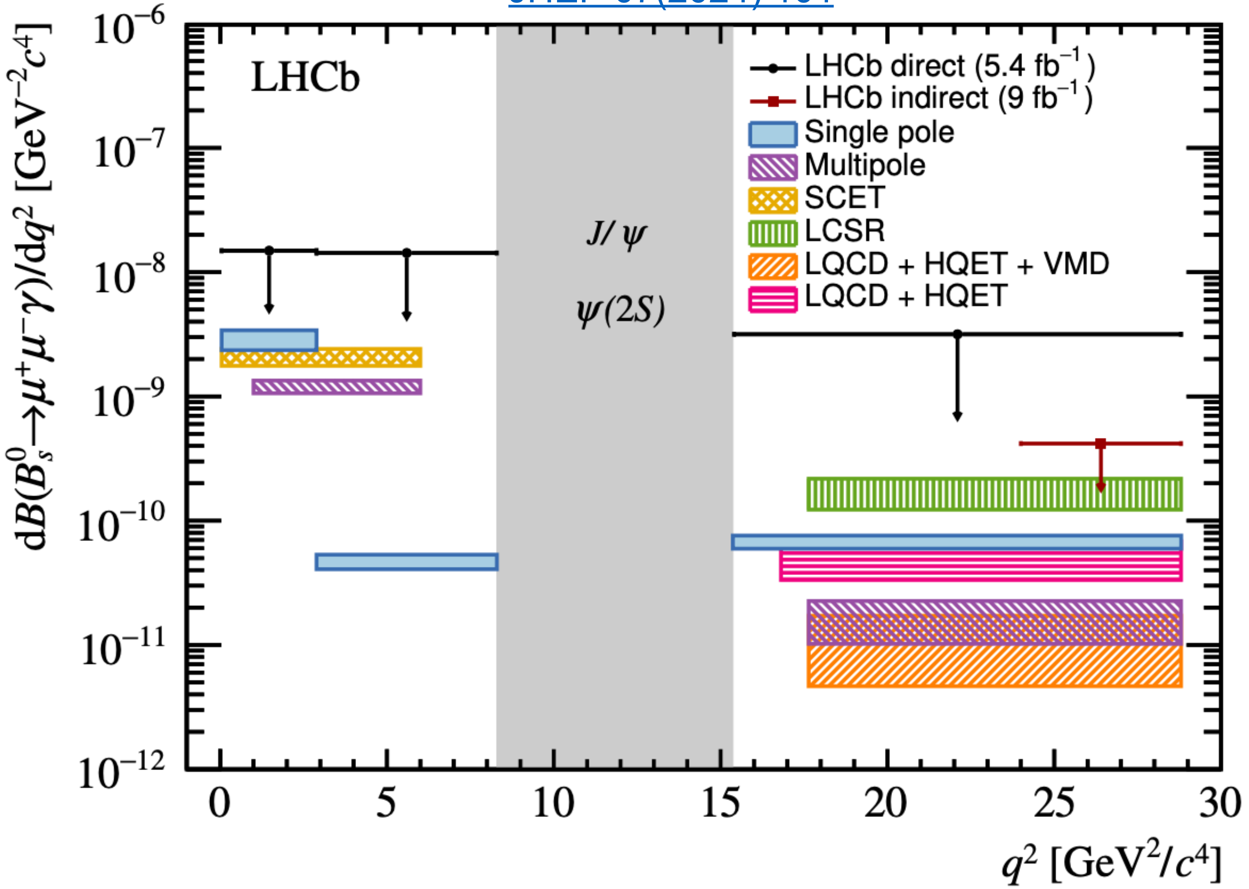
- No significant excess is observed.
- Upper limits on the branching fractions (at 90 %(95%) C.L.):

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{I}} < 3.6\,(4.2) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{II}} < 6.5\,(7.7) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{III}} < 3.4\,(4.2) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{I,\ with\ }\phi\mathrm{\ veto}} < 2.9\,(3.4) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{\mathrm{comb.}} < 2.5\,(2.8) \times 10^{-8},$$

- First direct search of $B_s^0 \to \mu^+\mu^-\gamma$ at low q^2.

Differential branching fraction $B_s^0 \to \mu^+\mu^-\gamma$

JHEP 07(2024) 101



Run3 data is expected to improve sensitivity.

Search for $B^{*0}_{(s)} \to \mu^+\mu^-$ in $B_c^+ \to \pi^+\mu^+\mu^-$ decays

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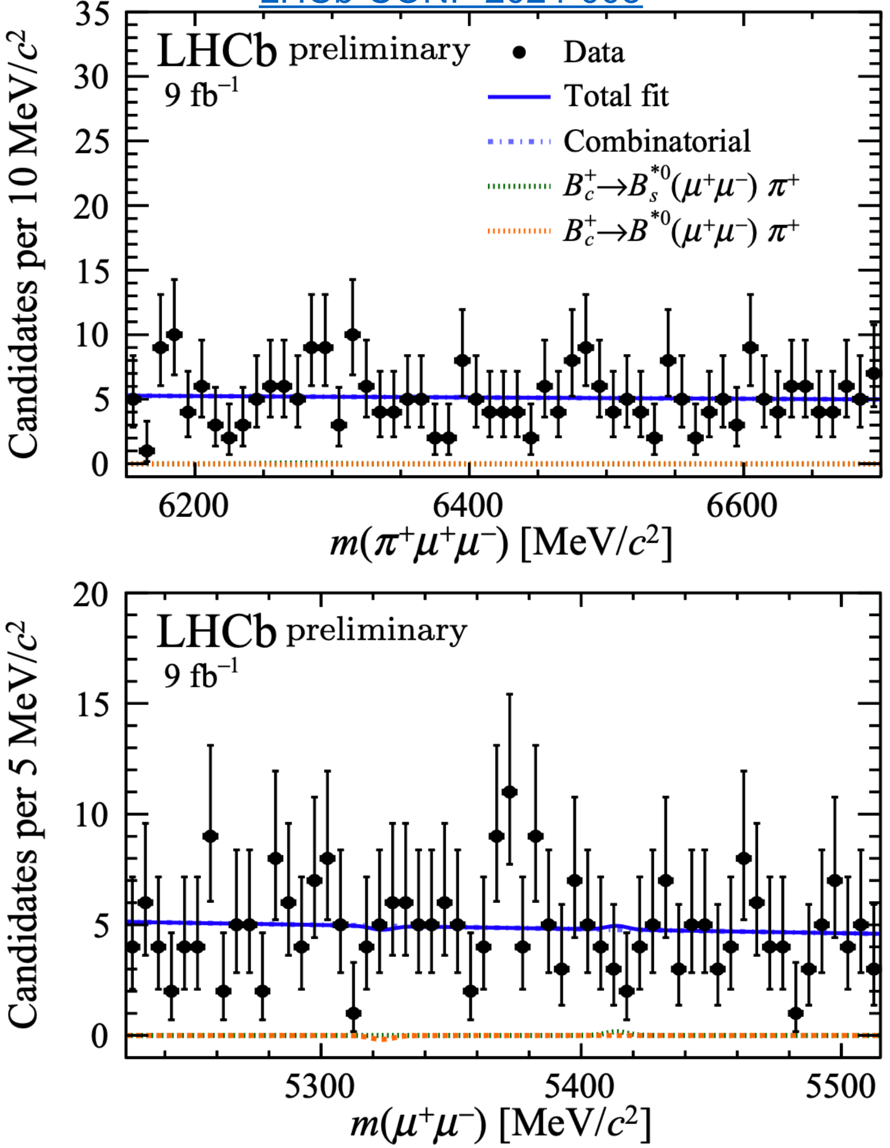
- $B^{*0}_{(s)} \to \mu^+\mu^-$ can provide constraints on WC complementary to $B^0_{(s)} \to \mu^+\mu^-$ decays.
- SM prediction $\mathfrak{B} \sim 10^{-11}$ (PRL 116 (2016) 141801).
- First search for $B^{*0}_{(s)} \to \mu^+\mu^-$ decays.

$$\mathcal{R}_{B^{*0}_{(s)}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} \equiv \frac{\mathcal{B}(B_c^+ \to B^{*0}_{(s)}(\mu^+\mu^-)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

- Full Run1+Run2 dataset (9 fb^{-1}).
- Search within the $B_c^+ \to B^{*0}_{(s)}\pi^+ \to \mu^+\mu^-\pi^+$ decay chain.
- Exploit displaced B_c^+ vertex to suppress background.
- Simultaneous fit to m($\mu^+\mu^-$) and m($\pi^+\mu^+\mu^-$).
- No signal observed:

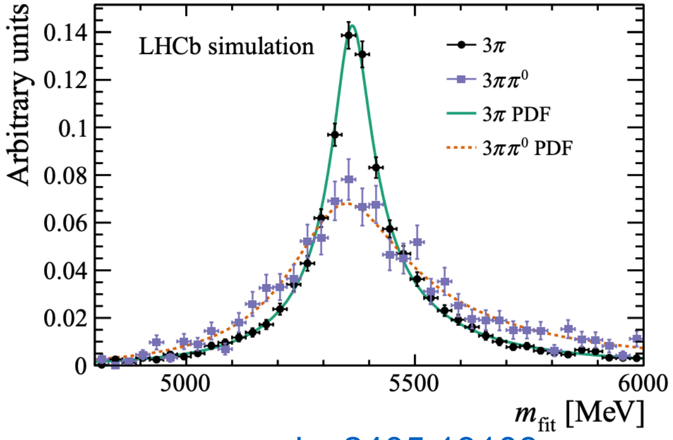
$$\mathcal{R}_{B^{*0}(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 3.8\,(5.2) \times 10^{-5} \text{ at } 90\ (95)\%\,\text{CL},$$
$$\mathcal{R}_{B^{*0}_s(\mu^+\mu^-)\pi^+/J/\psi\pi^+} < 5.0\,(6.3) \times 10^{-5} \text{ at } 90\ (95)\%\,\text{CL}.$$

LHCb-CONF-2024-003



Search for the LFV $B_s^0 \to \phi(\to K^+K^-)\mu^\pm\tau^\mp$

- Possible in SM with neutrino oscillation ($\mathfrak{B}<10^{-50}$).
- In some NP scenarios could be as large as $\mathfrak{B}\sim10^{-11}$.
- First search of the decay $B_s^0 \to \phi\mu^\pm\tau^\mp$.
- Data from full Run1+Run2 sample (9 fb^{-1}).
- Signal reconstruction with $\phi(\to K^+K^-)$ and $\tau\to3\pi\nu$ (including $\tau\to3\pi\pi^0\nu$).
- Missing neutrino: reconstruct B_s^0 mass using kinematic fit (vertices and tau mass constraints).

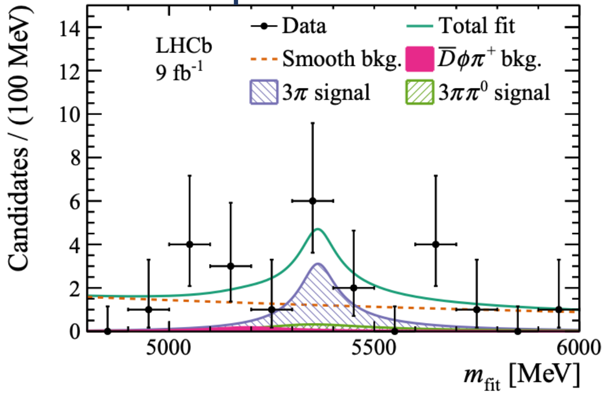


Signal mass distribution from simulation.

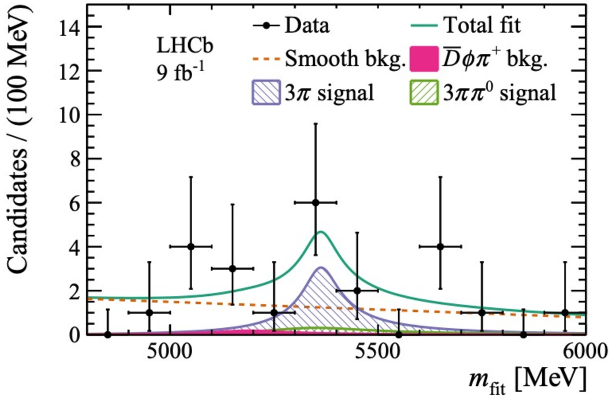
arxiv: 2405.13103

- The model includes four different background shapes.

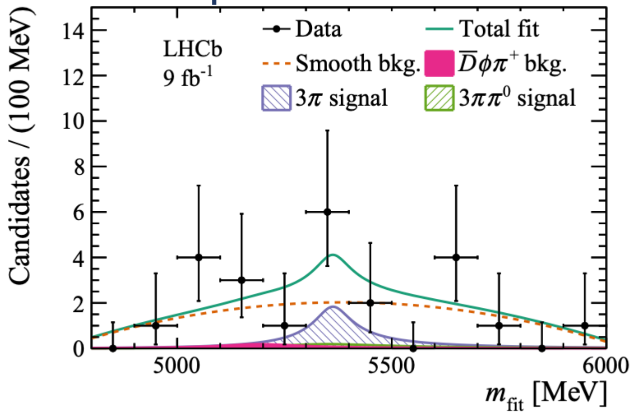
exponential



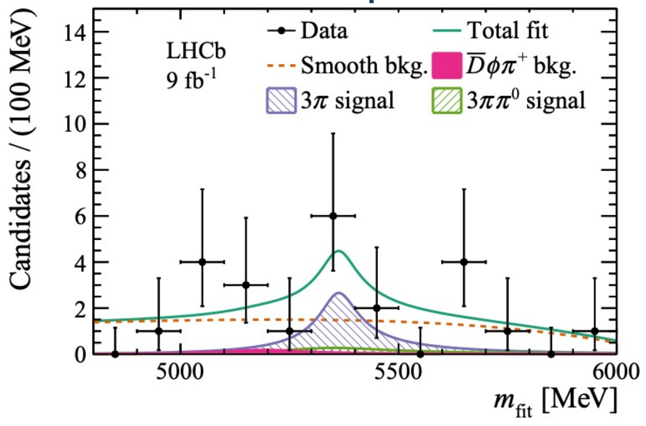
linear



quadratic



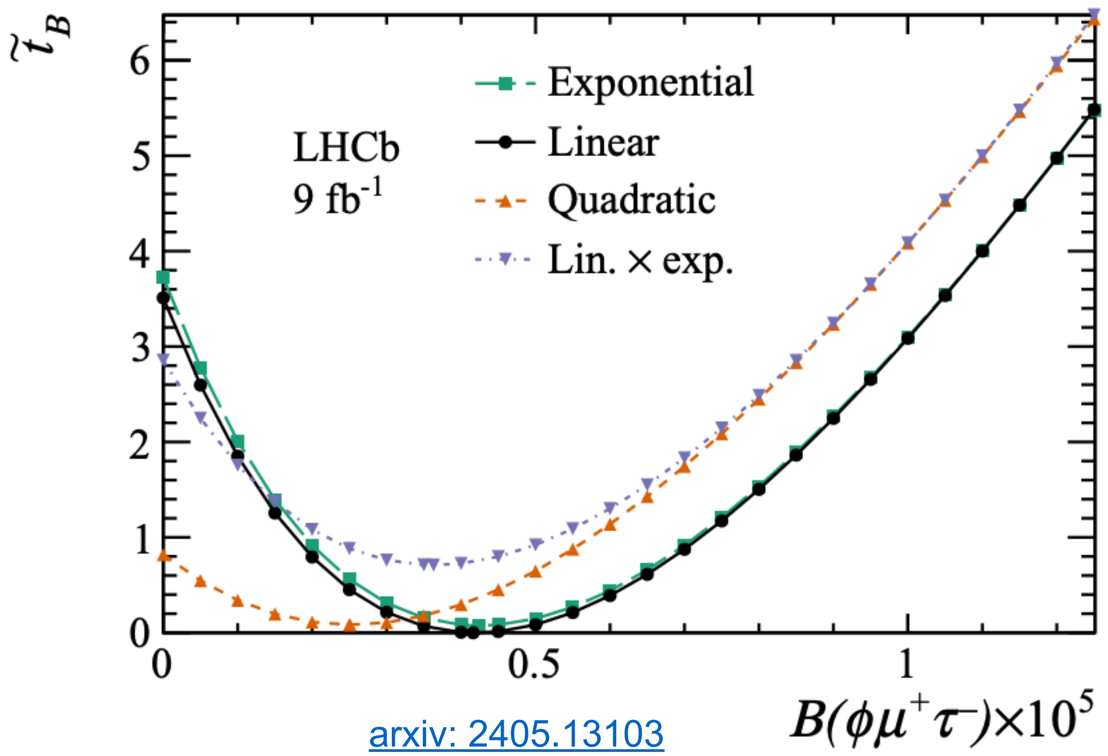
Linear x exponential



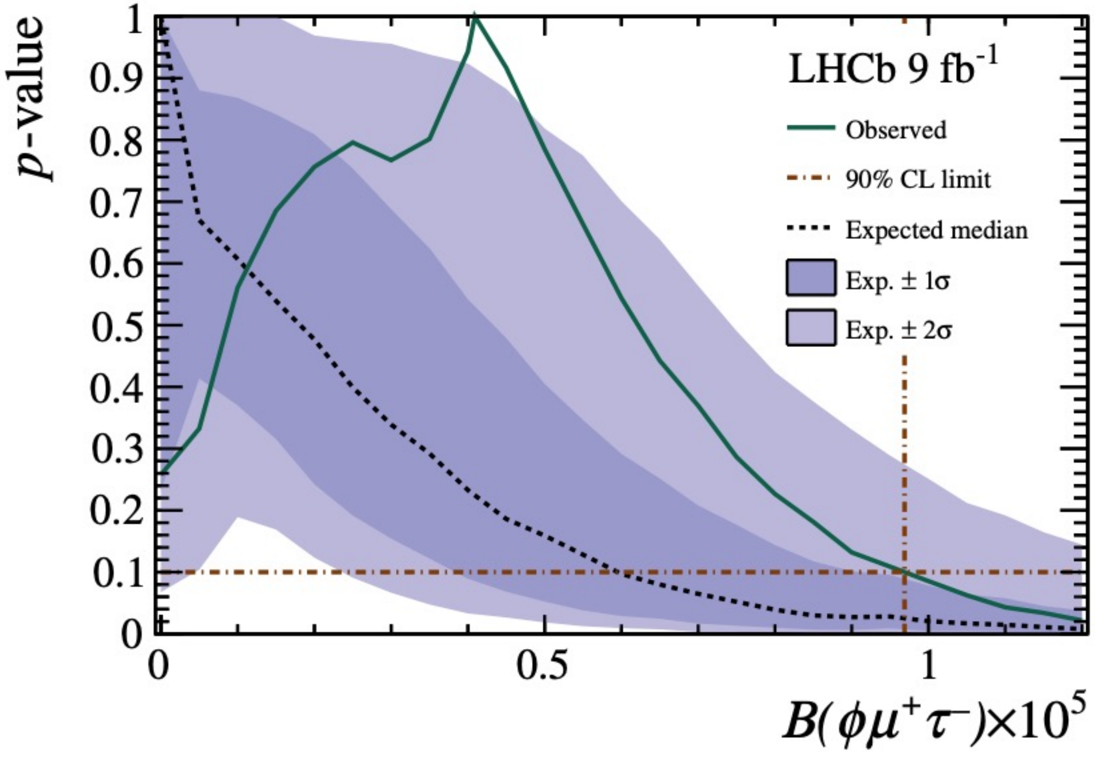
Search for LFV $B_s^0 \longrightarrow \phi(\longrightarrow K^+K^-)\mu^\pm\tau^\mp$

- No excess observed over background-only hypothesis.
- First upper limit on this decay mode.
- Sensitivity comparable with other $b \longrightarrow s\mu\tau$ searches.

$$\mathcal{B}(B_s^0 \to \phi\mu^+\tau^-) < 1.0 \times 10^{-5} \text{ at } 90\% \text{ CL},$$
$$\mathcal{B}(B_s^0 \to \phi\mu^+\tau^-) < 1.1 \times 10^{-5} \text{ at } 95\% \text{ CL}.$$

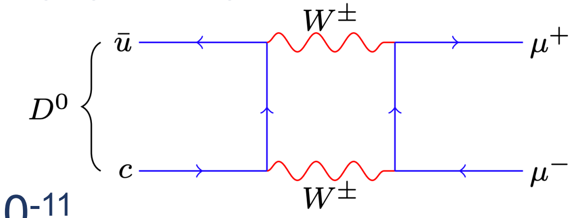


arxiv: 2405.13103



Search for the rare $D^0 \to \mu^+\mu^-$ decay

- Very rare flavour changing neutral current (FCNC) decay:
  - GIM mechanism stronger in charm than in beauty decays.
  - Helicity suppressed.



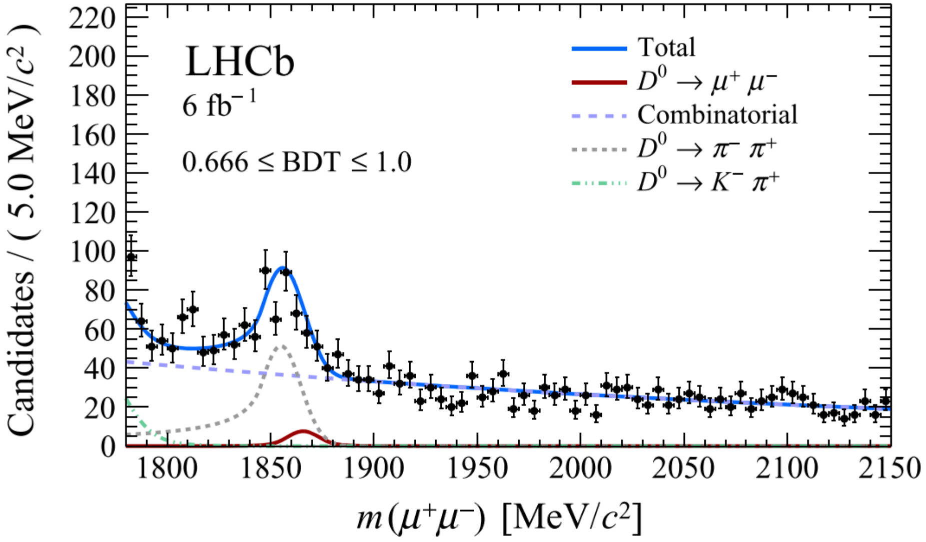
- SM prediction $\mathfrak{B}(D^0 \to \mu^+\mu^-) \sim 10^{-11}$.

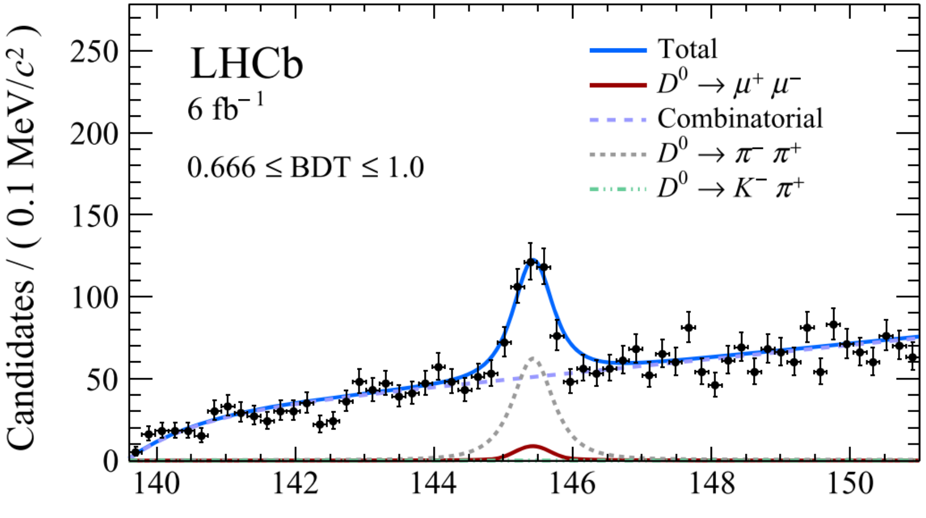
- Sensitivity to NP, e.g. contribution from leptoquarks.

- Search using $D^{*+} \to D^0\pi^+$ decays.
  - Two normalisation channels: $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+\pi^-$ decays.

- World best upper limit:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1(3.5) \times 10^{-9} \text{ at } 90(95)\%\text{C.L.}$$



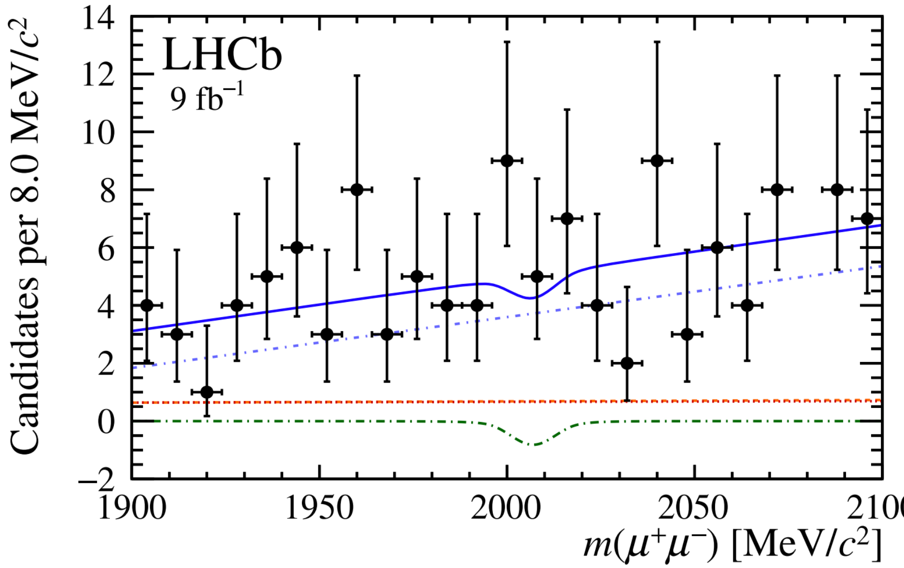


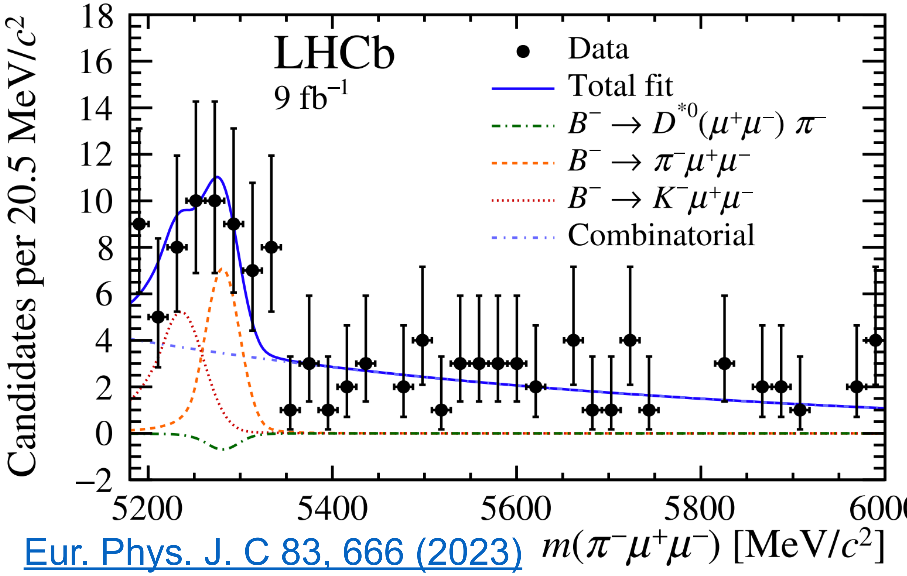
PRL 131 (2023) 041804

Search for the rare $D^{*0} \longrightarrow \mu^+\mu^-$ decay

- Complementary search to $D^0 \longrightarrow \mu^+\mu^-$.
- No helicity suppression (vector meson).
- Search of $D^{*0} \longrightarrow \mu^+\mu^-$ in $B^+ \longrightarrow \pi^+ D^{*0}$ decays ($\mathfrak{B}$=4.9 x 10^{-3}).
- Signature:
  - Reconstruct $B^+ \longrightarrow \pi^+\mu^+\mu^-$ decays.
  - Search for **simultaneous peaks** in $\mu^+\mu^-$ and $\pi^+\mu^+\mu^-$ invariant masses.
- Normalisation channel: $B^+ \longrightarrow K^+ J/\psi(\longrightarrow \mu^+\mu^-)$.
- Main backgrounds: combinatorial background and mis-ID $B^+ \longrightarrow K^+\mu^+\mu^-$.
- First result in this decay mode:

$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8} \text{ at } 90\,(95)\%\text{ CL}.$$





Eur. Phys. J. C 83, 666 (2023)

3. CPV in Charm:

- CPV in $D^0 \to \pi^+\pi^-\pi^0$

CP violation in charm

- In the SM, CP violation in charmed hadrons expected to be very small $(10^{-4} - 10^{-3})$.
- Theoretical predictions difficult to compute due to low-energy strong interaction effects.
- **LHCb'19**: **First observation of CP violation in charm** (PRL 122, 211803 (2024)).
  - Time-integrated CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays.

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}$$

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$

5.3σ deviation from no CPV hypothesis

- **LHCb'22**: **Measurement of $A_{CP}(K^+K^-)$** (PRL 131 091802 (2023)).

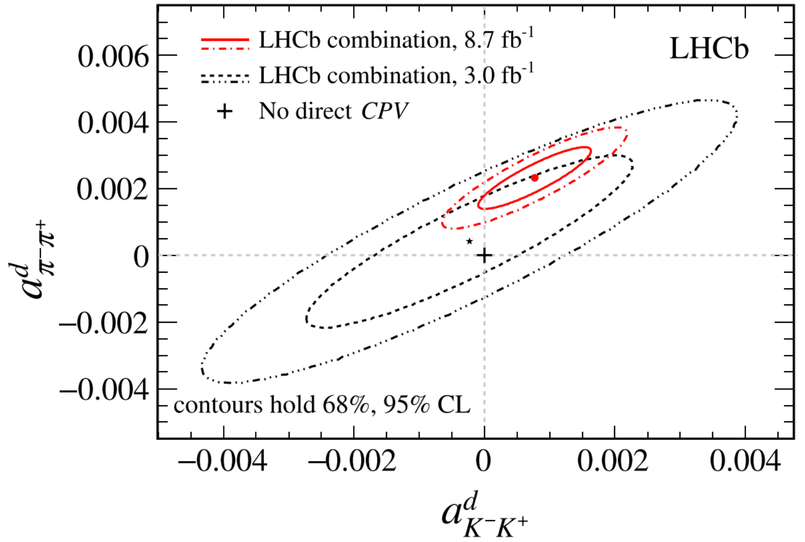
$$\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-4}$$

$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4} \quad (1.4\sigma)$$

$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4} \quad (3.8\sigma)$$

$$(\varrho = 0.88)$$

  - First evidence of direct CPV in a specific decay.
  - U-spin $(d \leftrightarrow s)$ symmetry ($a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = 0$) violated at 2.7σ level: $a^d_{K^-K^+} + a^d_{\pi^-\pi^+} = (30.8 \pm 11.4) \times 10^{-4}$



Time-dependent CPV in $D^0 \to \pi^+\pi^-\pi^0$

- Time-dependent CP asymmetry can be expanded as:

$$A_{CP}(f_{CP},t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)} \approx a^{\rm dir}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}}$$

  - f_{CP}: self-conjugated final state ($\pi^+\pi^-\pi^0$).
  - τ_{D^0}: D^0 lifetime.

- Neglecting direct CPV ($a^{dir}_{f_{CP}}$), the gradient $\Delta Y_{f_{CP}}$ becomes independent of the final state.

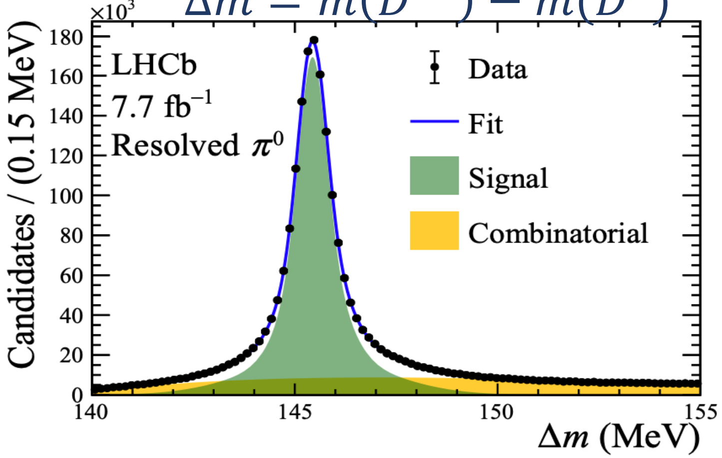
- Dataset: 2012+Run2 (7.7 fb^{-1}).

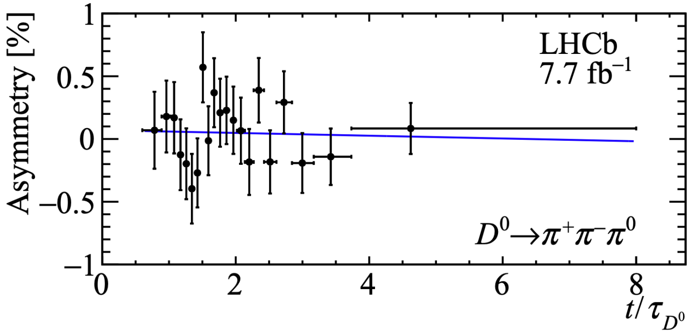
- D^0 reconstructed from $D^{*+} \to D^0\pi^+$ decays.

- Sample divided depending on t, data-taking period, magnet polarity and $\pi^0 \to \gamma\gamma$ category (resolved or merged photons.)

- Fit of A_{Cp} vs time to measure ΔY.

$\Delta m = m(D^{*+}) - m(D^0)$





$$\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$$

- Consistent with no CPV.

- Statistically limited.

- First measurement of time-dependent CPV in a decay with π^0 in final state at hadron collider.

arXiv:2405.06556

4. CKM:

- $\sin(2\beta)$ with $B^0 \longrightarrow \psi K_S^0$
- ϕ_s with $B_s^0 \longrightarrow J/\psi\phi$
- $\phi_s^{s\bar{s}s}$ with $B_s^0 \longrightarrow \phi\phi$
- $\Delta\Gamma_s$ with $B_s^0 \rightarrow J/\psi\eta'$ and $B_s^0 \rightarrow J/\psi\pi^+\pi^-$
- Simultaneous determination of γ

The CKM matrix

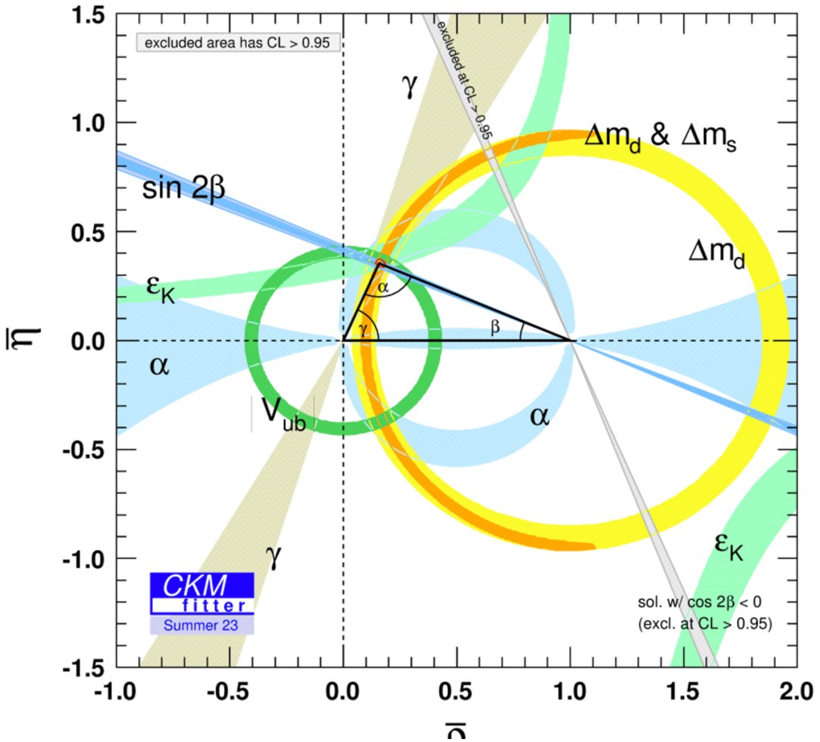
- **Quark flavour mixing** determined by the CMK matrix. It connects weak to mass eigenstates.

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

- Unitarity of CKM matrix leads to the **unitarity relations** that form **triangles** in the complex plane.

$$\sum_k V_{ik} V_{jk}^* = 0$$

- **CP violation** in the SM comes from a **complex phase** in the CKM matrix.



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right).$$

Measurement of sin(2β) with $B^0 \longrightarrow \psi(\longrightarrow \ell^+\ell^-)K_S^0(\longrightarrow \pi^+\pi^-)$

IGFAE Instituto Galego de Física de Altas Enerxías

- Measurement using Run2 data (6 fb^{-1}).

PRL 132, 021801 (2024)

- Three decay modes:
  - $B^0 \longrightarrow J/\psi(\longrightarrow \mu^+\mu^-)K_S^0(\longrightarrow \pi^+\pi^-)$, 306k events.
  - $B^0 \longrightarrow J/\psi(\longrightarrow e^+e^-)K_S^0(\longrightarrow \pi^+\pi^-)$, 42k events.
  - $B^0 \longrightarrow \psi(2S)(\longrightarrow \mu^+\mu^-)K_S^0(\longrightarrow \pi^+\pi^-)$, 23k events.
- Time-dependent analysis.
- Measure CP violating parameters **S** and **C**:

S, C, $\mathcal{A}_{\Delta\Gamma}$: CP violating parameters

Δm_d : $B^0 - \bar{B}^0$ mixing oscillation frequency

$\Delta\Gamma_d$: B^0 mass eigenstate decay width difference. **Compatible with zero**.

$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B}^0 \longrightarrow f) - \Gamma(B^0 \longrightarrow f)}{\Gamma(\bar{B}^0 \longrightarrow f) + \Gamma(B^0 \longrightarrow f)} = \frac{S\,sin(\Delta m_d t) - C\,cos(\Delta m_d t)}{cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\,sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\mathcal{A}_{CP} \approx S\,sin(\Delta m_d t) - C\,cos(\Delta m_d t)$$

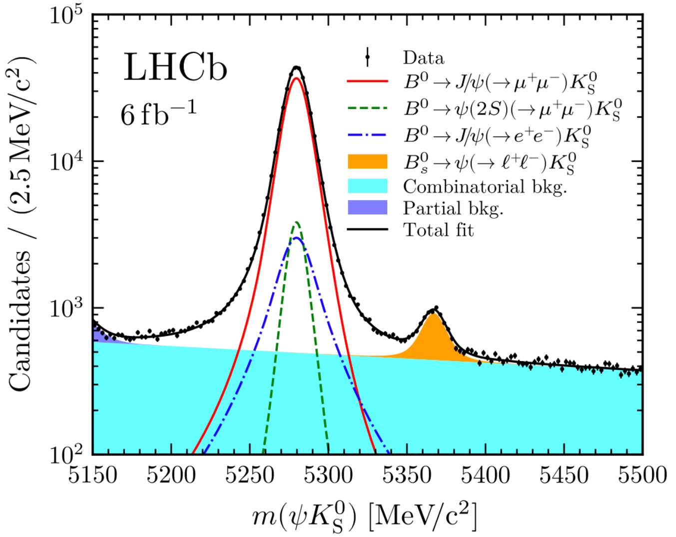
$$S \approx sin(2\beta + \Delta\phi_d + \Delta\phi_{NP})$$

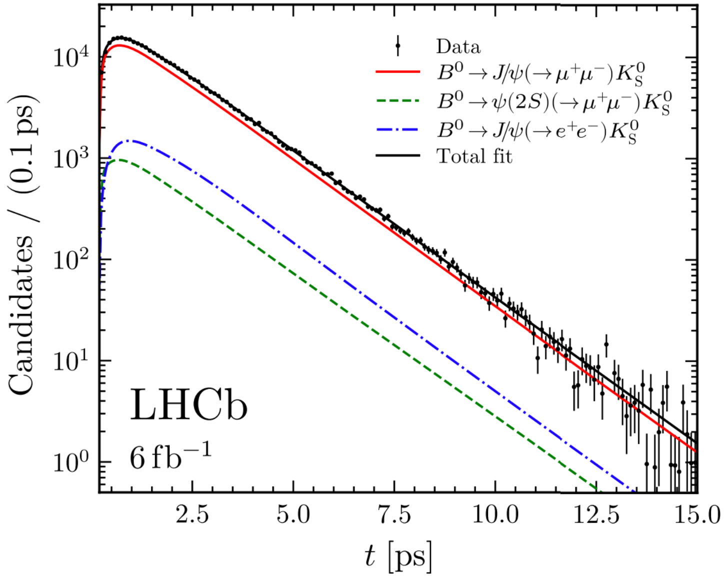
$\Delta\phi_d$: contributions from penguin decays. CKM supressed. Small in SM.

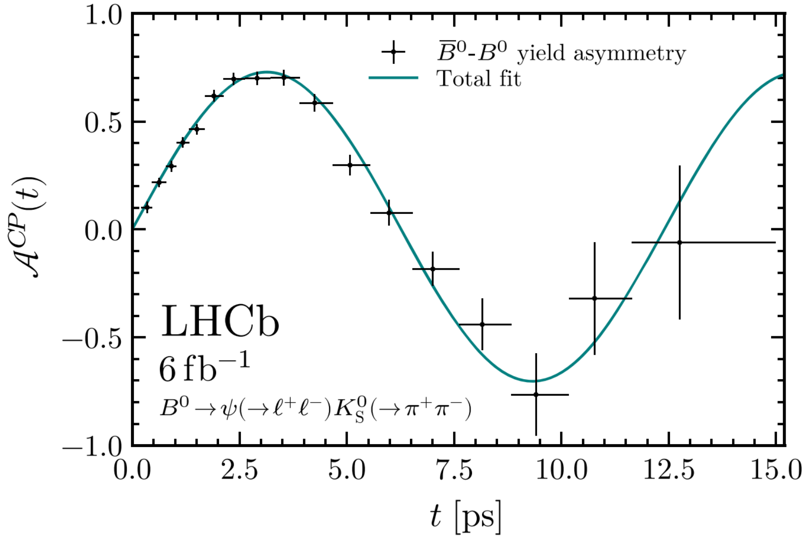
$\Delta\phi_{NP}$: possible contributions from NP.

Measurement of sin(2β) with $B^0 \to \psi(\to \ell^+\ell^-)K_S^0(\to \pi^+\pi^-)$

- Weights to subtract background determined to a fit to *B* mass (sPlot technique).







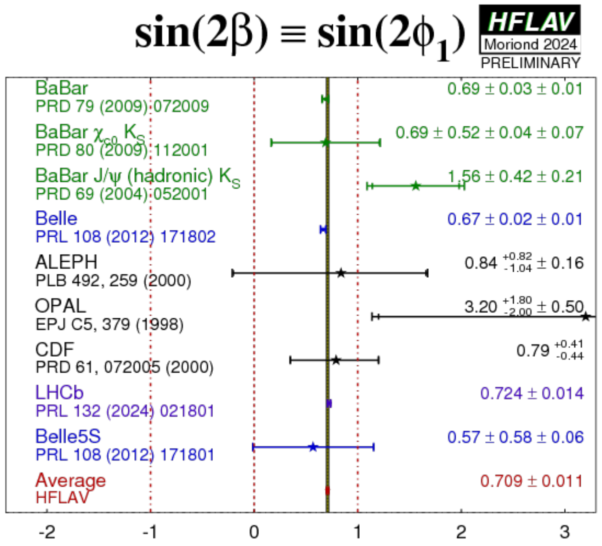
- Fit to decay time distribution to measure S and C.

- Single most precise determination of CKM phase β.

- Statistically dominated.

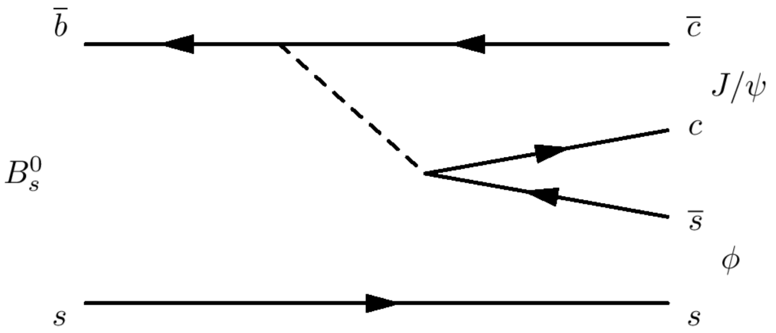
$$S_{\psi K_S^0} = 0.717 \pm 0.013(\text{stat}) \pm 0.008(\text{syst})$$
$$C_{\psi K_S^0} = 0.008 \pm 0.012(\text{stat}) \pm 0.003(\text{syst})$$

PRL 132, 021801 (2024)

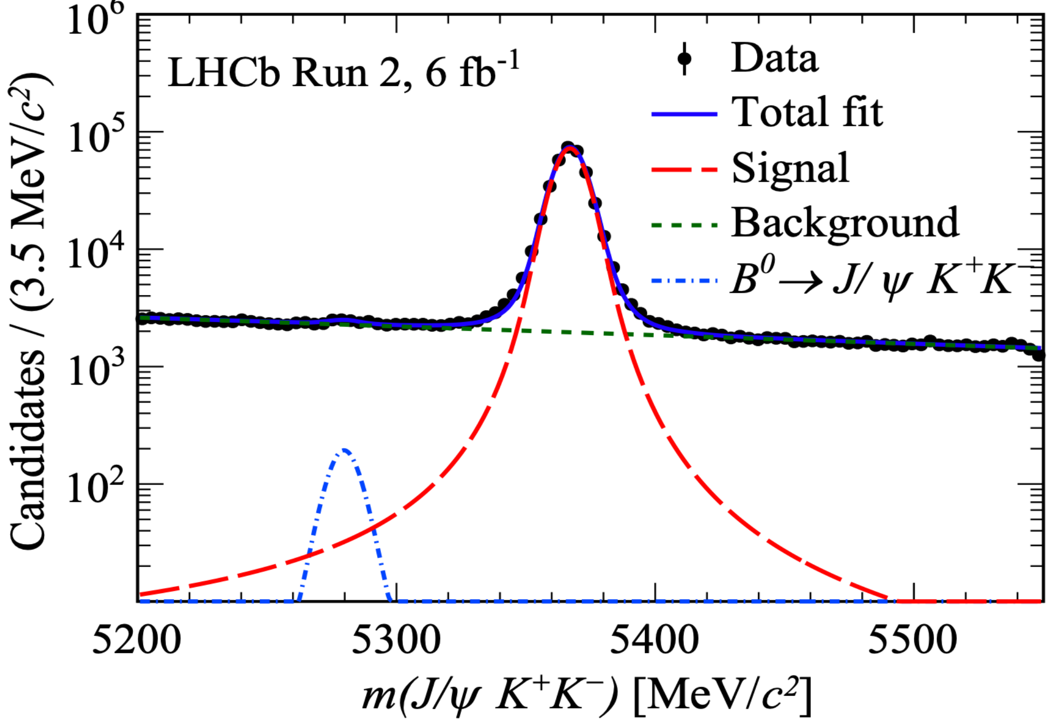


Measurement of ϕ_s with $B_s^0 \to J/\psi\phi$

- A golden mode for the study CP violation.
- Probe of CKM phase β_s.
- Neglecting sub-leading loop contributions:
  - $\phi_s^{c\bar{c}s} = -2\beta_s$
  - $\beta_s = \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$
- SM prediction very precise:
  - $-2\beta_s^{SM} = -0.037 \pm 0.001\, rad$



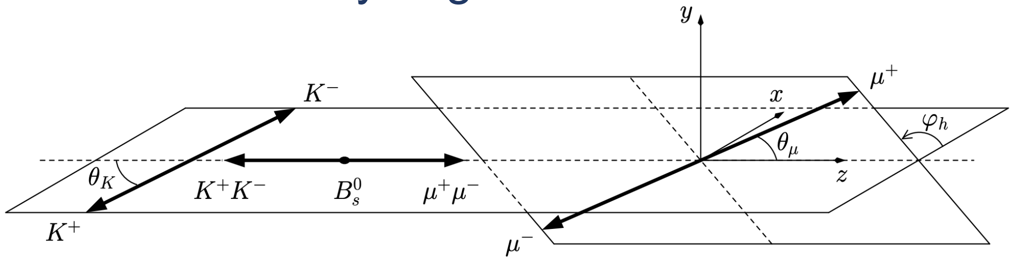
PRL 132, 051802 (2024)



Measurement of ϕ_s with $B_s^0 \longrightarrow J/\psi\phi$

[PRL 132, 051802 (2024)]

- $\phi_s^{c\bar{c}s}$ extracted from 4D fit to decay time and 3 helicity angle distributions.



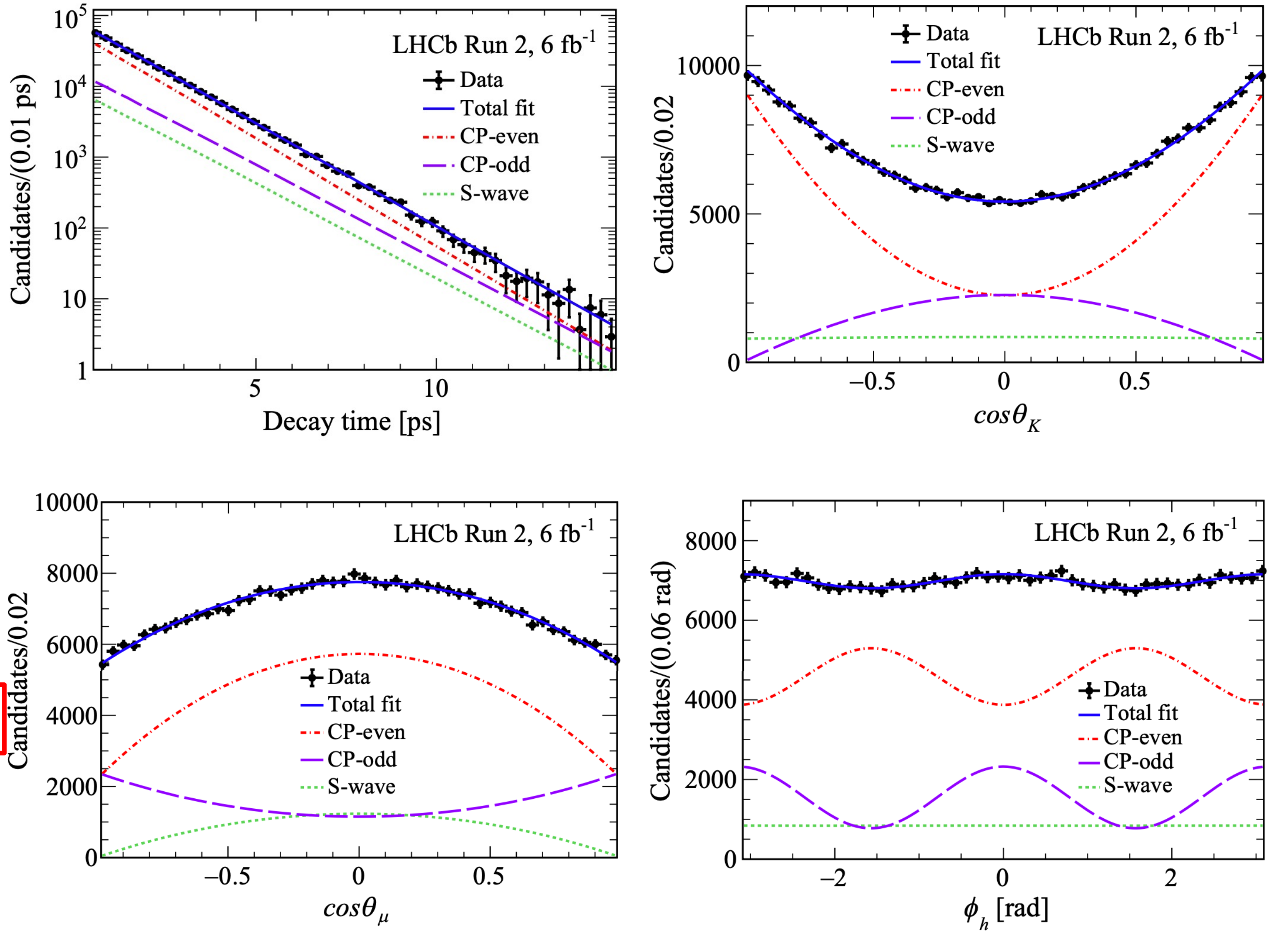
  - Disentangle CP-odd and CP-even components.
  - The model accounts for flavour tagging and acceptance.

- Fit results with full Run2 dataset yields **~350k events**.

$$\phi_s^{c\bar{c}s} = -0.039 \pm 0.022(stat) \pm 0.006(syst)\ rad$$

- Most precise measurement of ϕ_s to date.

- Consistent with SM.



Measurement of $\phi_s^{s\bar{s}s}$ with $B_s^0 \longrightarrow \phi\phi$

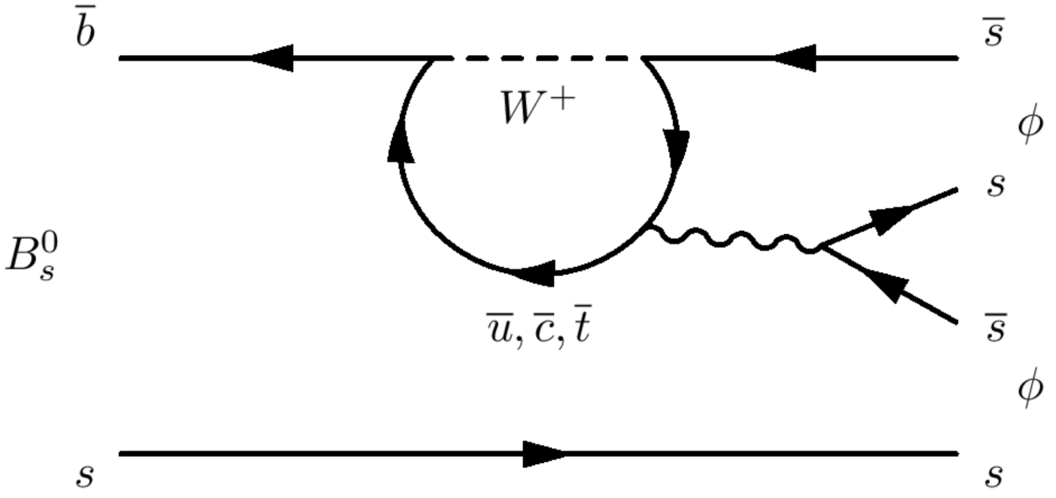
- Another golden channel of LHCb.
- Probe of CP violation in penguin-dominated decays.
- Experimentally very clean.
- CP violation in mixing and decay predicted to cancel in the SM.

$$\phi_s^{s\bar{s}s} = \phi^{mixing} - \phi^{decay} \approx 0$$

(upper limit 0.02 rad, arXiv:0810.0249)

- Significant deviation from zero would be a clear signature of BSM physics.

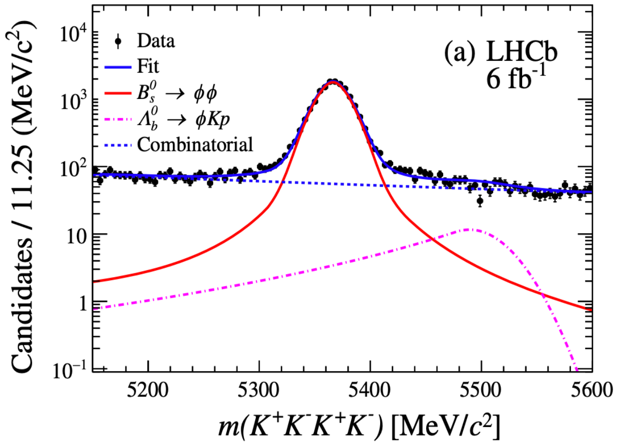
penguin (loop) decay



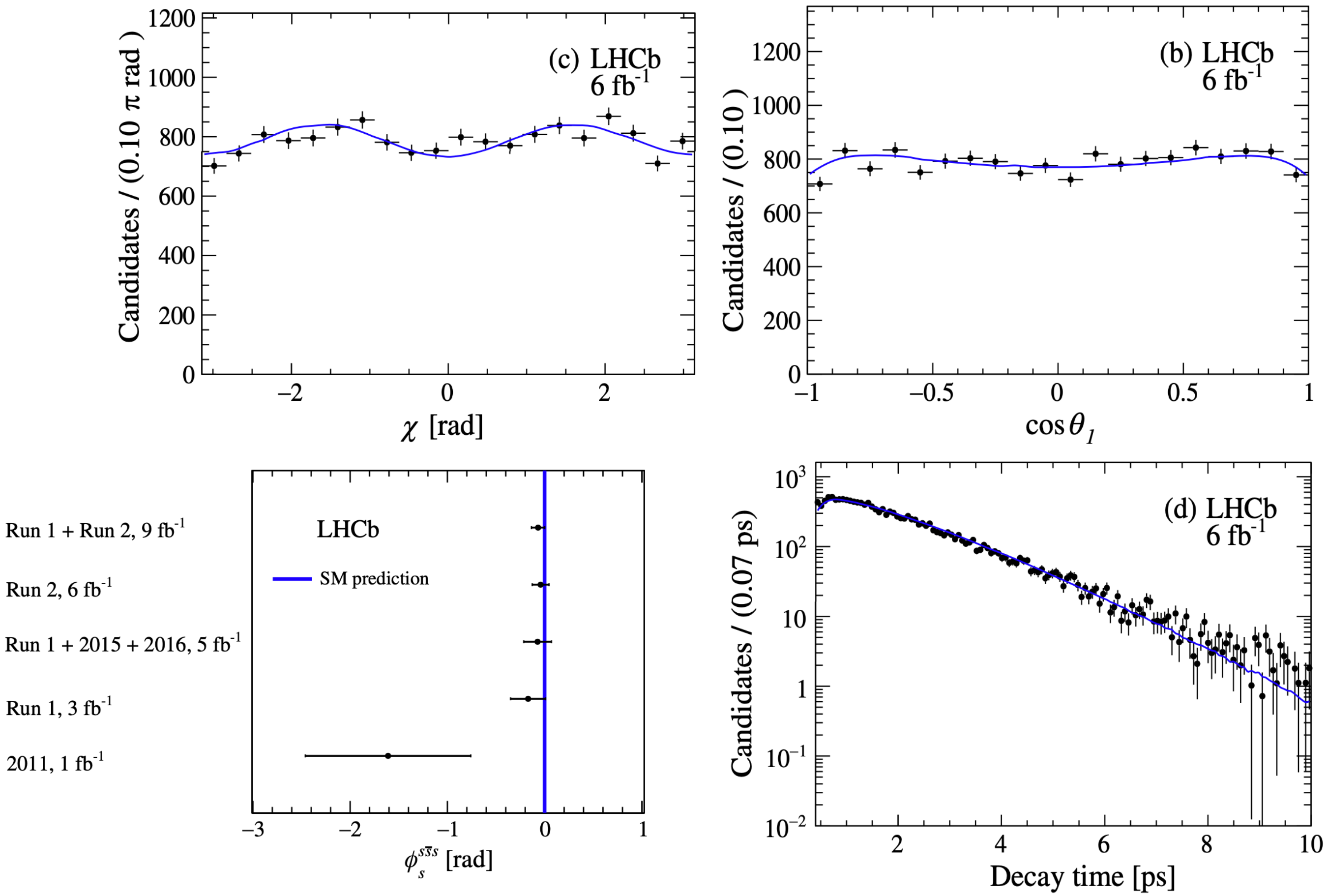
Measurement of $\phi_s^{s\bar{s}s}$ with $B_s^0 \longrightarrow \phi\phi$

- Value of $\phi_s^{s\bar{s}s}$ extracted from a 4D fit to **decay time** and **3 helicity angles**.

- Fit result using full Run2 dataset yields ~16k events.



PRL 131, 171802 (2023)



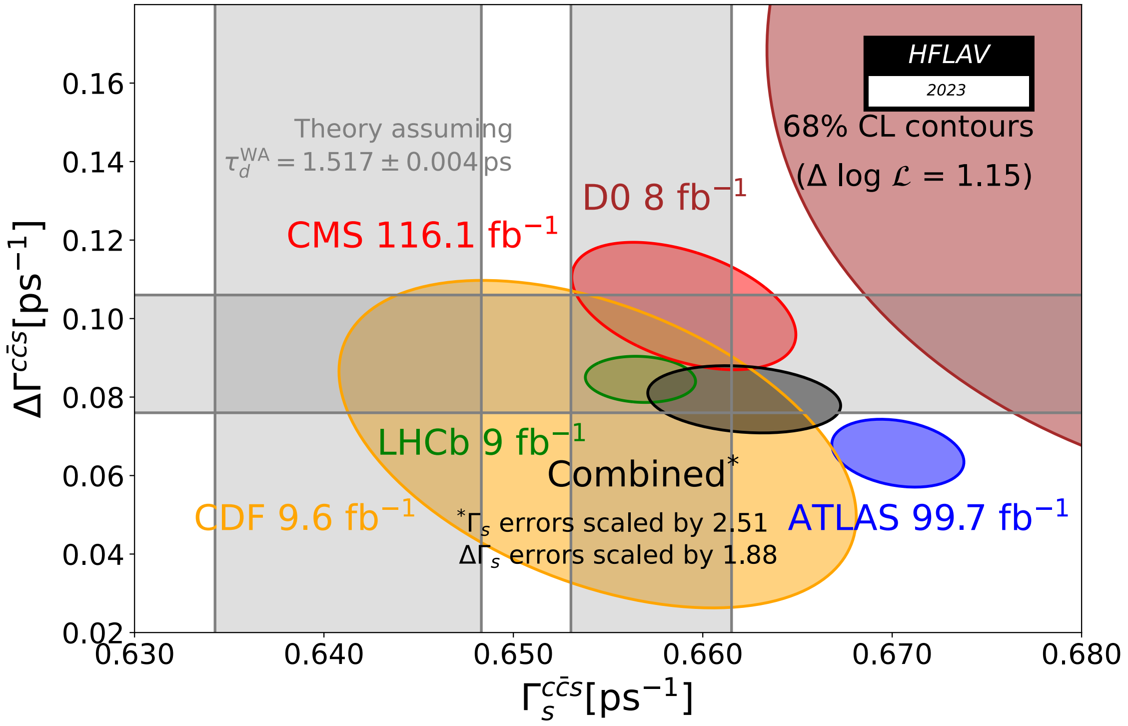
$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075(stat) \pm 0.009(syst)\ rad$$

- Most precise measurement of time-dependent CP asymmetry in penguin-dominated B decays to date.

- Consistent with zero and SM prediction.

Measurement of $\Delta\Gamma_s$ with $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$

- **Tension** between measurements of $\Delta\Gamma_s$ using $\boldsymbol{B_s^0 \to J/\psi\phi}$ decays from. **LHCb, ATLAS** and **CMS**.



- Since ϕ_s is small, to good approximation:
  - CP-even decay measures light lifetime.
  - CP-odd decay measures heavy lifetime.

- $\Delta\Gamma_s$ measured from decay-width difference between:
  - **CP-even** decay: $\boldsymbol{B_s^0 \to J/\psi\eta'}$.
  - **CP-odd decay**: $\boldsymbol{B_s^0 \to J/\psi\pi^+\pi^-}$, which is CP-odd via $\boldsymbol{B_s^0 \to J/\psi f_0(980)(\to \pi^+ \pi^-)}$.

- **Independent cross-check** of the measurement of $\Delta\Gamma_s$.

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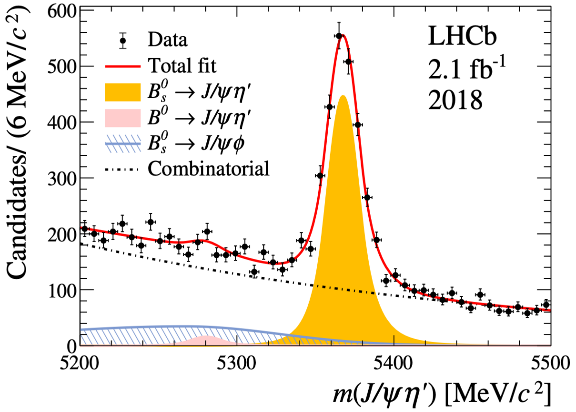
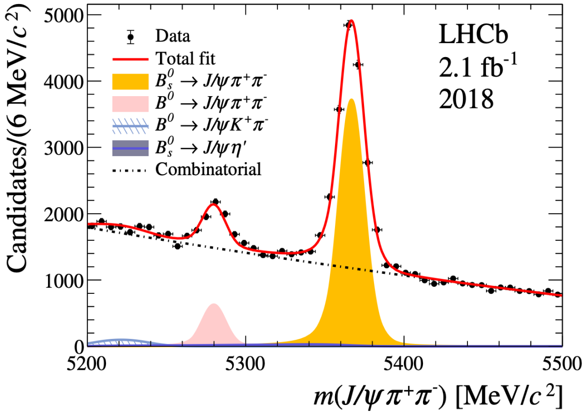
Measurement of $\Delta\Gamma_s$ with $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$

- Analysis uses de full Run1+Run2 (9 fb^{-1}) LHCb dataset.
- Lifetime divided in 8 bins. For each bin, fit to the B mass distribution.





- First time-dependent measurement of $\Delta\Gamma_s$ using $B_s^0 \to J/\psi\eta'$ decays.

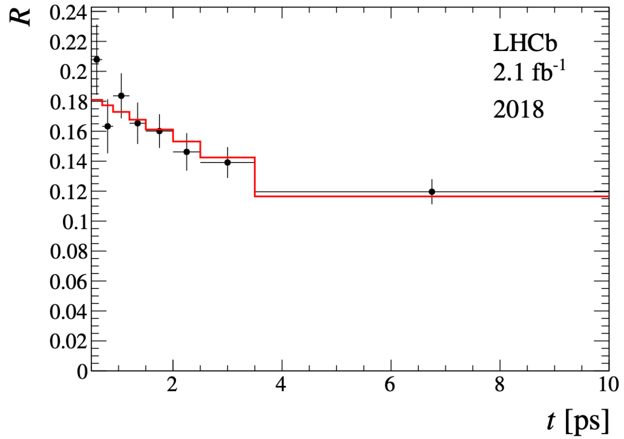
$$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009\,\mathrm{ps}^{-1}$$

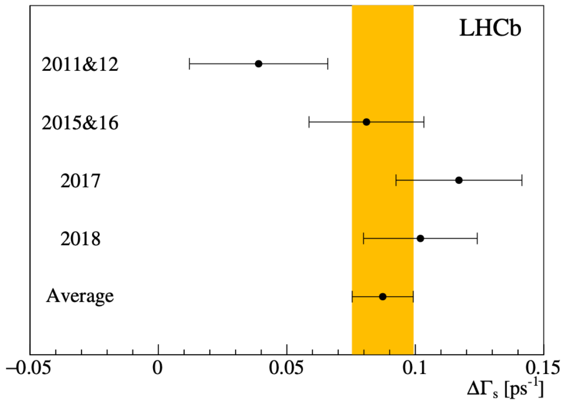
- In agreement with LHCb $B_s^0 \to J/\psi\phi$ result and HFLAV averages.

- $\Delta\Gamma_s$ determined from a χ^2 fit to the ratio:

$$R_i = \frac{N_{\rm L}}{N_{\rm H}} \propto \frac{\left[e^{-\Gamma_s t(1+y)}\right]_{t_1}^{t_2}}{\left[e^{-\Gamma_s t(1-y)}\right]_{t_1}^{t_2}} \cdot \frac{(1-y)}{(1+y)}, \quad y = \Delta\Gamma_s/2\Gamma_s$$

NL: yield of CP-even decays in [t_1,t_2] bin
N_H: yield of CP-odd decays in [t_1,t_2] bin





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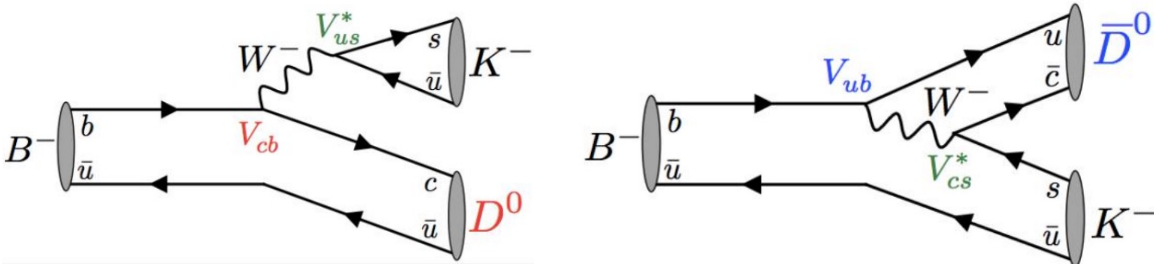
Simultaneous determination of the CMK angle γ

- γ is the only angle that can be measured purely from tree-level decays.

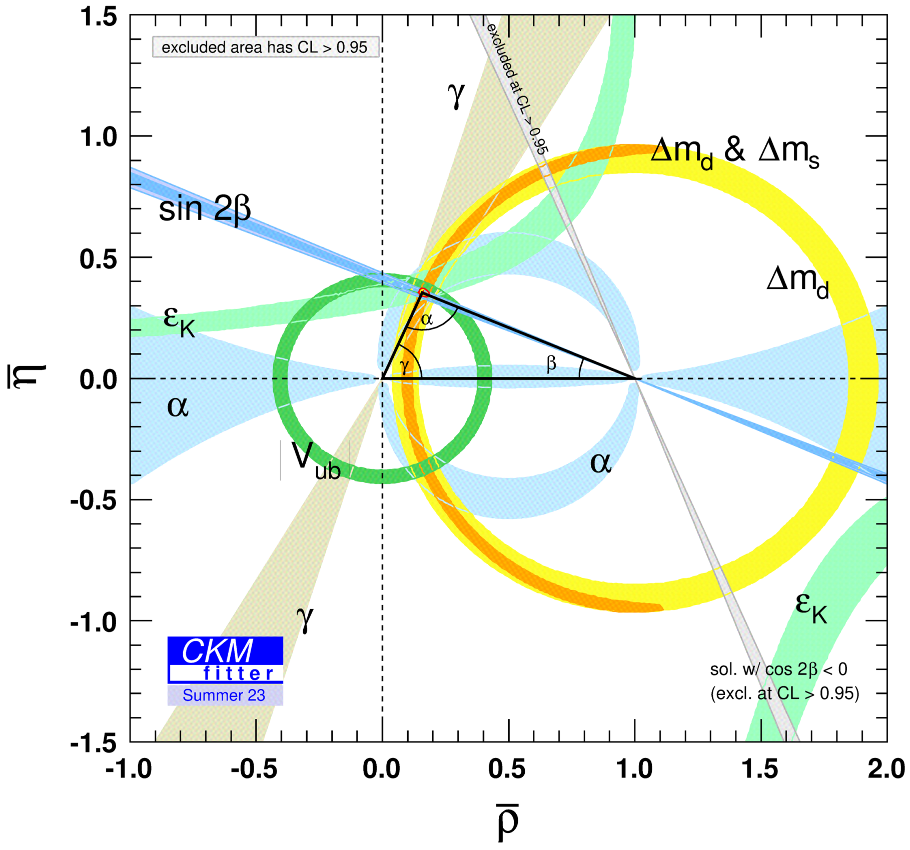
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



- Theoretically clean.

- Can be measured by exploiting interference effects in $B \to DK$ decays (and others).

- Any discrepancy between direct and indirect measurements would be a clear sign of BSM physics.



LHCb-CONF-2024-004

Simultaneous determination of the CMK angle γ

IGFAE
Instituto Galego de Física de Altas Enerxías

- γ determined from a combination of:
  - **11 LHCb *B*** decay measurements (4 new, 3 superseded).
  - **9 LHCb *D*** decay measurements (1 new, 1 superseded).

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^\pm h'^\mp$	[35]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^+\pi^-$	[19]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[36]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to h^\pm h'^\mp\pi^0$	[37]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[38]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[39]	Run 1&2	*As before*
$B^\pm \to D^*h^\pm$	$D \to h^\pm h'^\mp$ (PR)	[35]	Run 1&2	*As before*
$B^\pm \to D^*h^\pm$	$D \to K^0_S h^+h^-$ (PR)	[20]	Run 1&2	**New**
$B^\pm \to D^*h^\pm$	$D \to K^0_S h^+h^-$ (FR)	[21]	Run 1&2	**New**
$B^\pm \to DK^{*\pm}$	$D \to h^\pm h'^\mp$	[22]†	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^\pm\pi^\mp\pi^+\pi^-$	[22]†	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to K^0_S h^+h^-$	[22]†	Run 1&2	**New**
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^\pm h'^\mp$	[40]	Run 1	*As before*
$B^0 \to DK^{*0}$	$D \to h^\pm h'^\mp$	[23]	Run 1&2	**Updated**
$B^0 \to DK^{*0}$	$D \to h^\pm\pi^\mp\pi^+\pi^-$	[23]	Run 1&2	**Updated**
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$	[24]	Run 1&2	**Updated**
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[41]	Run 1	*As before*
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[25, 42]†	Run 1&2	**Updated**
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[43]	Run 1&2	*As before*

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- 27 auxiliary inputs from LHCb, HFLAV, CLEO-c and BESIII (1 new, 2 updated).

- Many Beauty and Charm measurements share parameters and provide complementary information.

- Produces a single LHCb value for 29 physics parameters (+ nuisance parameters).

D decay	Observable(s)	Ref.	Dataset	Status since Ref. [13]
$D^0 \to h^+h^-$	ΔA_{CP}	[41–43]	Run 1&2	*As before*
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[43–45]	Run 2	*As before*
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[46, 47]	Run 1&2	*As before*
$D^0 \to h^+h^-$	ΔY	[48–51]	Run 1&2	*As before*
$D^0 \to K^+\pi^-$ (double tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[52]	Run 1	*As before*
$D^0 \to K^+\pi^-$ (single tag)	$R_{K\pi}$, $A_{K\pi}$, $c^{(\prime)}_{K\pi}$, $\Delta c^{(\prime)}_{K\pi}$	[27, 53]	Run 1&2	**Updated**
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[54]	Run 1	*As before*
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[55]	Run 1	*As before*
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[56]	Run 1	*As before*
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[57, 58]	Run 2	*As before*
$D^0 \to \pi^+\pi^-\pi^0$	$\Delta Y^{\rm eff}$	[26]	Run 2	**New**

Simultaneous determination of the CMK angle γ

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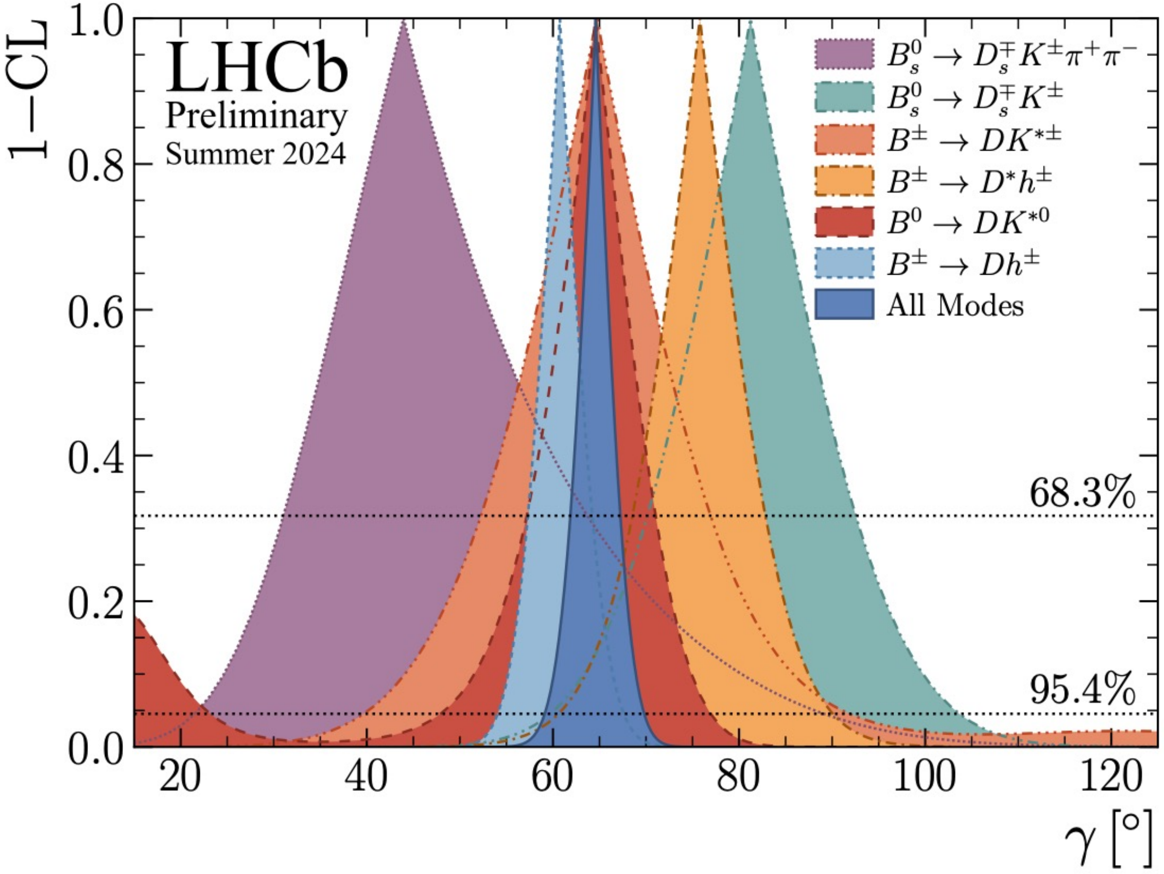
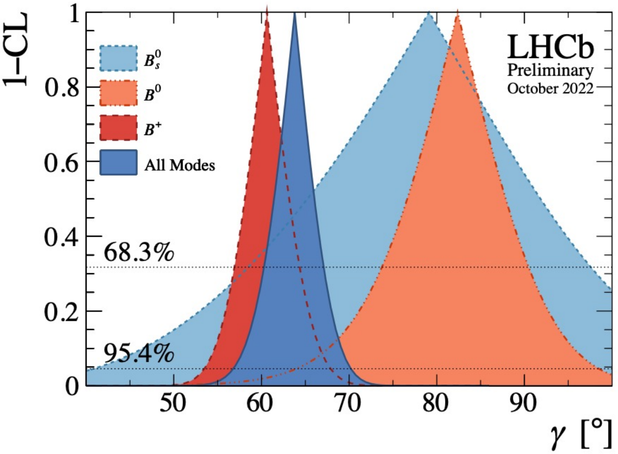
$$\gamma = (64.6 \pm 2.8)^o$$

- 0.7º (20%) improved precision with respect to LHCb 2022 combination.
- Reduced tension between B_s^0 measurements.
- Consistent with global CKM fit predictions.
- Statistically limited. Run3 data will improve the precision.

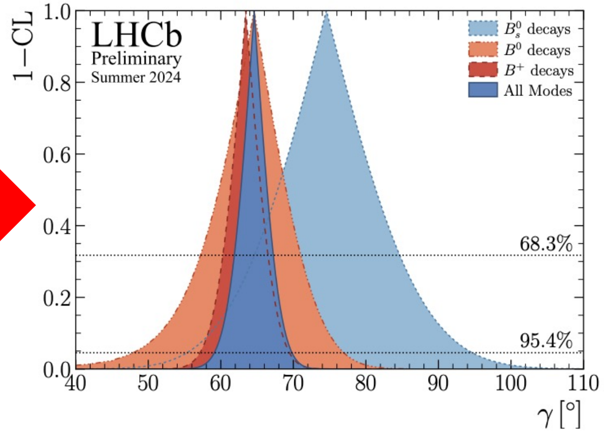
LHCb 2024 γ combination per B decay



2022



2024

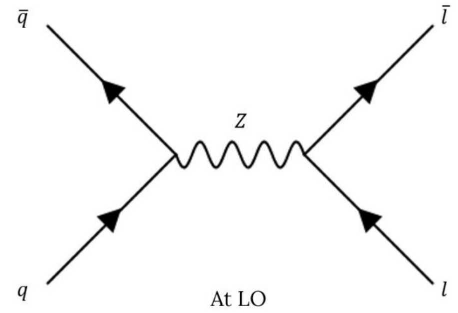


5. Electroweak:

- effective leptonic mixing angle $sin^2\theta_{eff}^{\ell}$

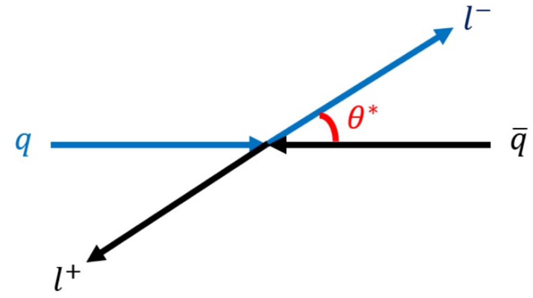
Measurement of the effective leptonic mixing angle $sin^2\theta^{\ell}_{eff}$

- A fermion of **charge Q** and **third weak-isospin component I_3** has both **vector** and **axial vector** couplings to the Z boson that depend on the weak-mixing angle $\boldsymbol{\theta_W}$:
  - Vector coupling: $v = I_3 - 2Q sin^2\theta_W$
  - Axial-vector coupling: $a = I_3$
- Presence of vector and axial vector components introduces a forward-backward asymmetry A_{FB}.
- At **tree level**, $cos\theta_W = \frac{m_W}{m_Z} \Longrightarrow sin^2\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)$
- $sin^2\theta^{\ell}_{eff}$ accounts for **higher-order corrections**.
- Key parameter in the SM.
- Potential sensitivity to BSM processes.



$$\propto 1 + \cos^2\theta^* + A_4 \cos\theta^*$$

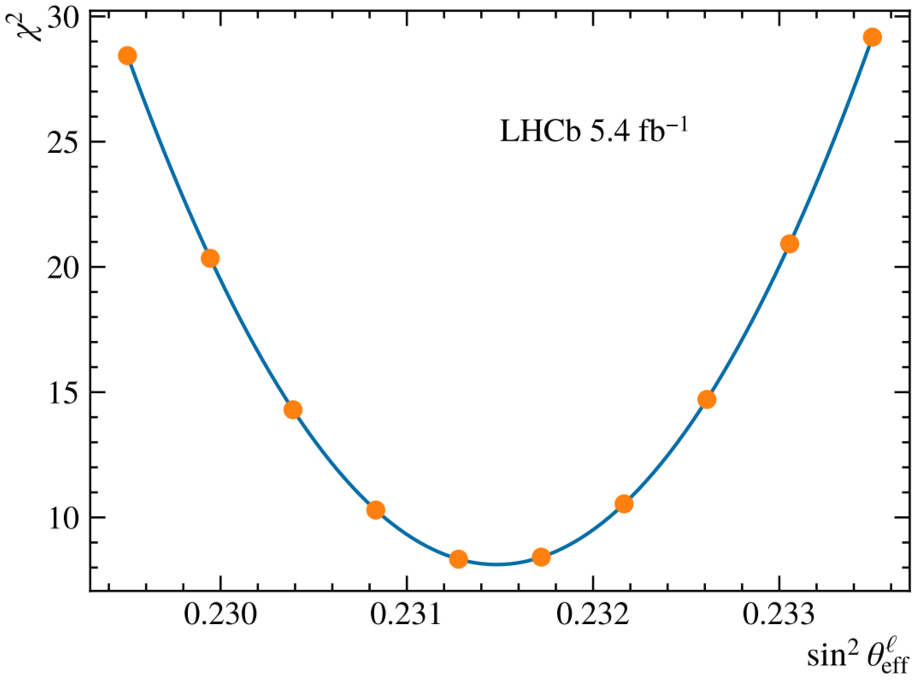
$$A_{FB} = \frac{N(\cos\theta^*>0) - N(\cos\theta^*<0)}{N(\cos\theta^*>0) + N(\cos\theta^*<0)} = \frac{N_F - N_B}{N_F + N_B} = \frac{3}{8}A_4$$



Measurement of the effective leptonic mixing angle $sin^2\theta^{\ell}_{eff}$

- Analysis using Run2 dataset (2016-2018, 5.3 fb^{-1}).
- Main kinematic cuts applied:
  - $2.0 < \eta_{\mu} < 4.5$
  - $p_T^{\mu} > 20\ GeV/c$
  - $66 < M_{\mu\mu} < 116\ GeV/c^2$
- Background (~2 per mil of events) estimated from simulation and subtracted.
- Fit A_{FB} in 10 bins of $\Delta\eta$ ($cos\theta^{*} \sim tan\frac{\Delta\eta}{2}$). $\Delta\eta = \eta^{-} - \eta^{+}$.
- Simulation shows that this binning improves sensitivity to the weak mixing angle by 14%.
- $sin^2\theta^{\ell}_{eff}$ extracted using predictions at NLO in the strong and EW couplings using POWHEG-BOX.

- Compare data with predictions to extract the value of $sin^2\theta^{\ell}_{eff}$ that best corresponds to data. A χ^2 is computed.



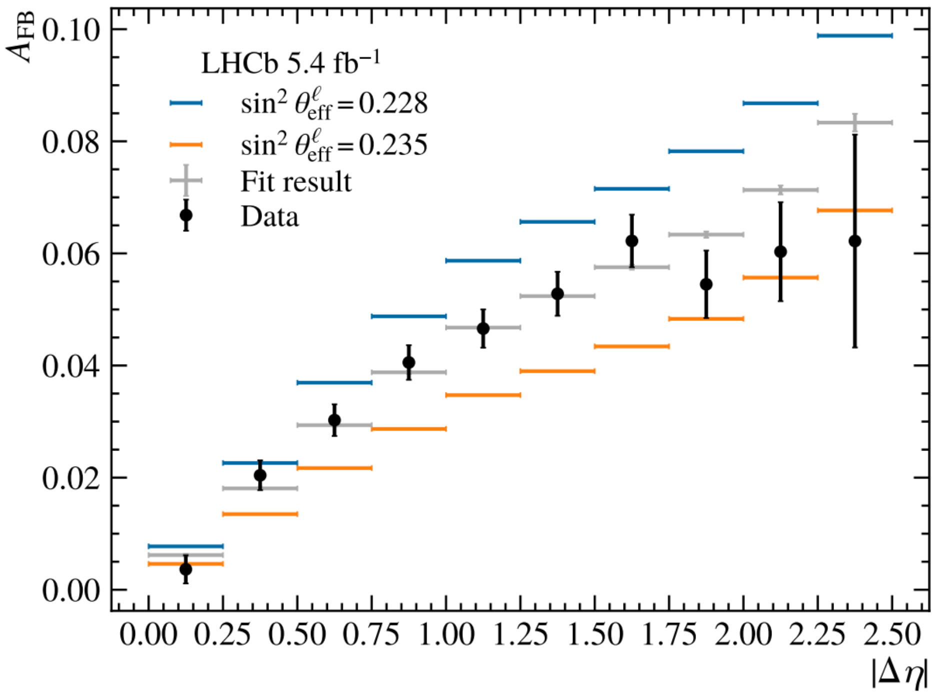
LHCb-PAPER-2024-028 in preparation

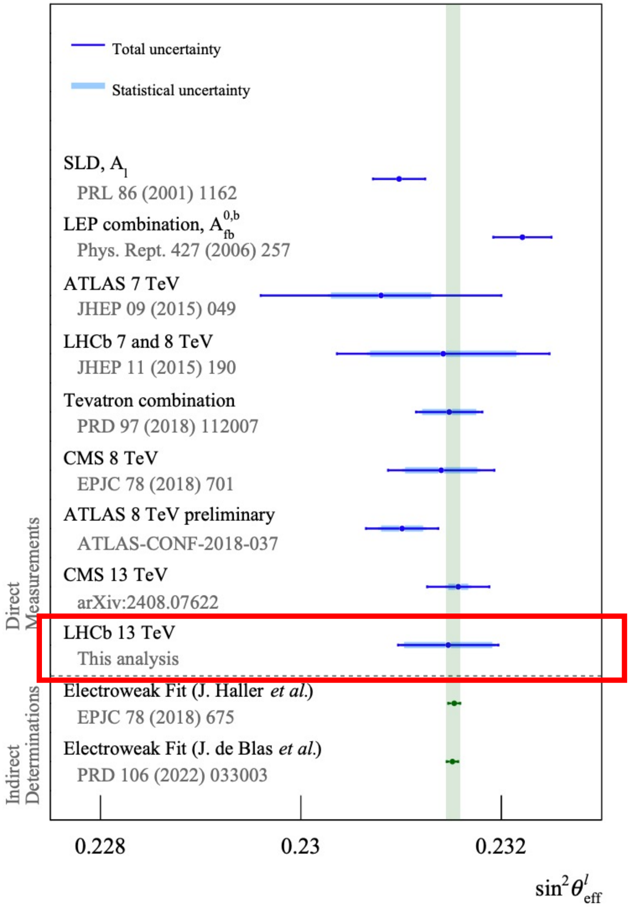
Measurement of the effective leptonic mixing angle $sin^2\theta^{\ell}_{eff}$

- Result:

$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23147 \pm 0.00044 \pm 0.00005 \pm 0.00023$$

- Consistent with previous measurements and indirect determinations from global electroweak fit.
- Precision dominated by statistical uncertainty.
- Aim to improve precision with upgraded LHCb detector (~5x more instantaneous luminosity).





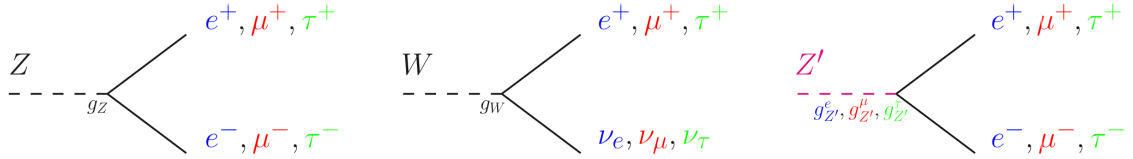
LHCb-PAPER-2024-028 in preparation

6. Semileptonics:

- LFU in semitauonic B decays

LFU in semitauonic B decays

- In the SM, couplings of the gauge boson with charged leptons are independent of flavour → **L**epton **F**lavour **U**niversality (**LFU**).
- Branching fractions involving **e**, $\boldsymbol{\mu}$ and $\boldsymbol{\tau}$ leptons differ only due to their **different masses** (phase space and helicity suppressions).
- Some extensions of the SM predict new particles that can break LFU: W', Z', leptoquarks…



- In some NP scenarios, new particles couple preferentially to the third family → Important to study semitauonic B decays.
- Any significant deviation from LFU is a sign of NP.

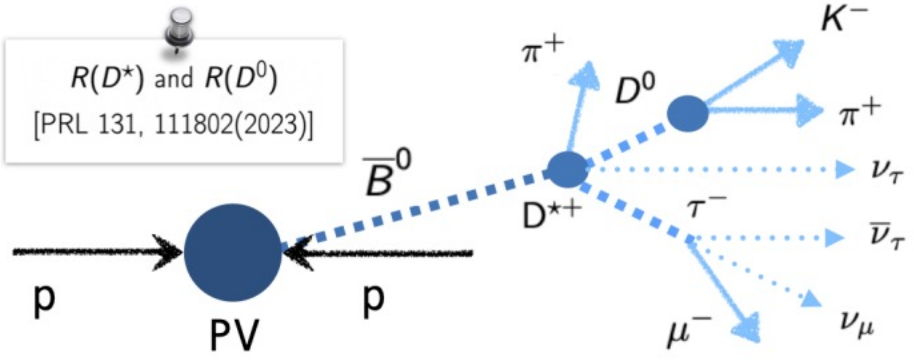
- LFU can be tested by measuring ratios of branching fractions to final states with different lepton flavours ($\ell \in e, \mu$).

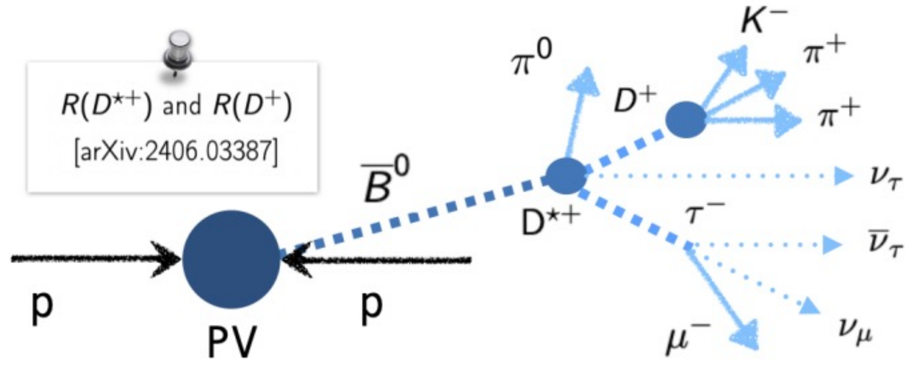
$$R(D^{(*)}) = \frac{Br(B^0 \to D^{(*)}\tau\nu_\tau)}{Br(B^0 \to D^{(*)}\ell\nu_\ell)}$$

- Very clean SM prediction due to partial cancellation of hadronic form-factor uncertainties in the ratio.
- Experimentally, also some systematics cancel.
- LHCb results on $R(D^*)$ based on two τ reconstruction methods:
  - Muonic mode $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$.
    - $R(D^*)$ and $R(D^0)$ (2023) [PRL 131, 111802 (2023)] (supersedes [PRL 115, 111803 (2015)]).
    - $R(D^{*+})$ and $R(D^+)$ (2024) [arXiv: 2406.03387].
  - Hadronic mode $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$:
    - $R(D^{*+})$ [PRD 108, 012018 (2023)] [PRD 109, 119902 (2024) (E)].

LFU in semitauonic B decays

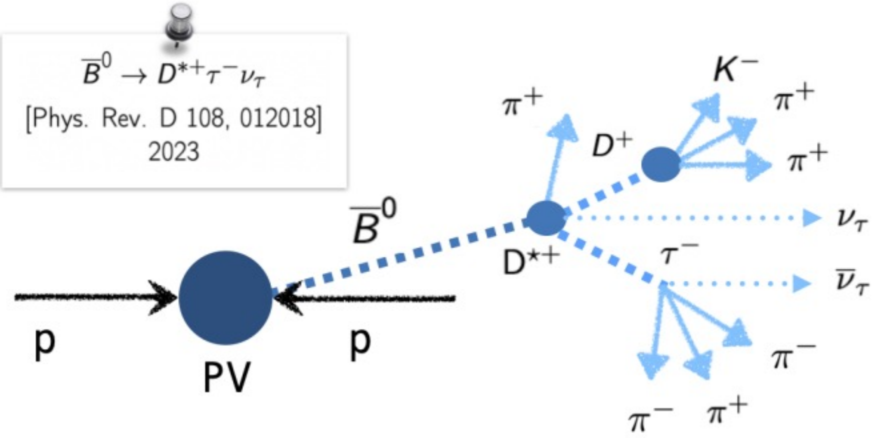
Muonic mode $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$





- Higher statistics.
- 3 missing neutrinos.

Hadronic mode $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$



- Tau decay vertex is reconstructed → Access to tau decay time (signal/background discrimination).
- Higher purity.
- 2 missing neutrinos.
- External inputs needed (branching fractions of normalisation modes).

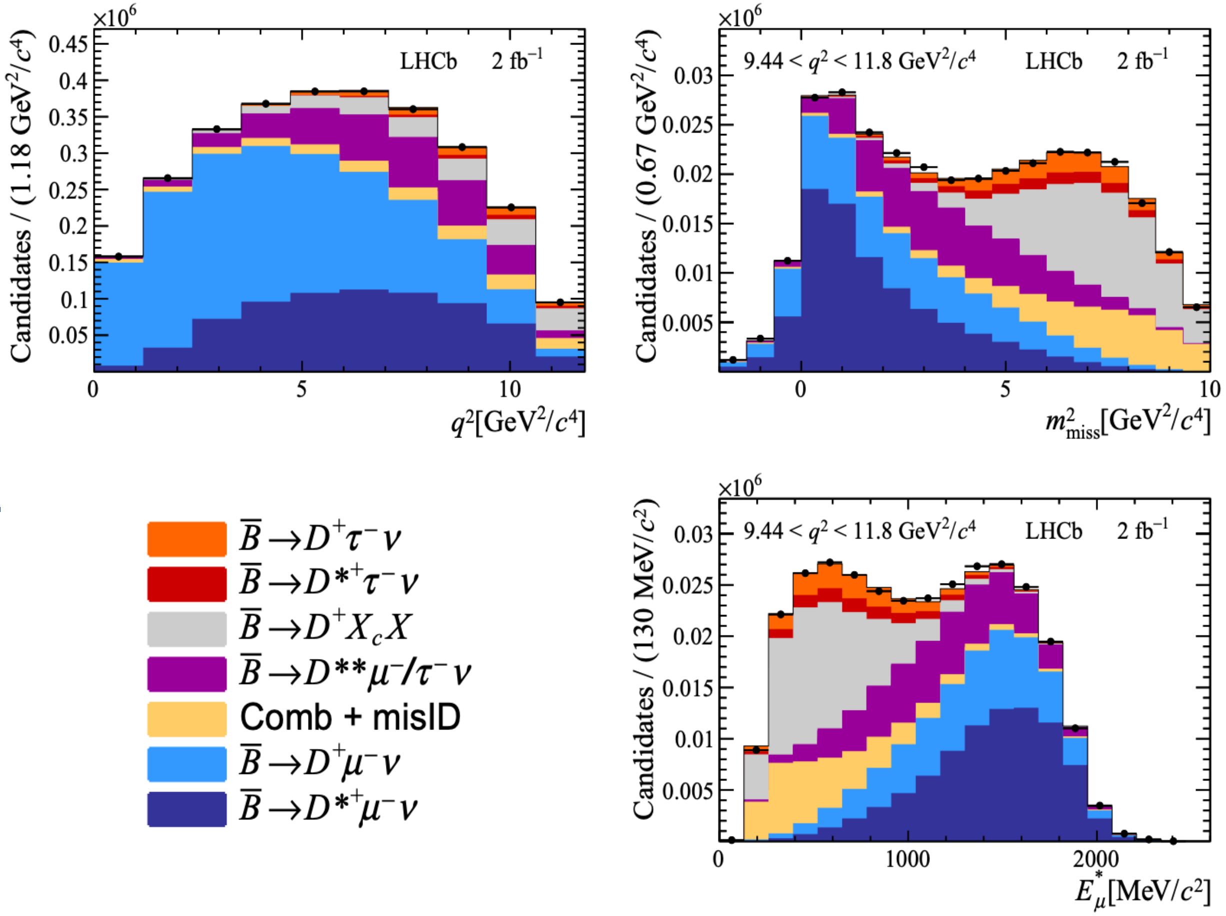
Muonic $R(D^{*+})$ and $R(D^+)$ (2024)

- First LHCb measurement of $R(D)/R(D^*)$ using $D^+ \to K^-\pi^+\pi^+$.
  - Primary goal is to measure $R(D^+)$.
  - Feed-down from $D^{*+} \to D^+\pi^0/\gamma$ with not reconstructed π^0 or γ gives also access to $R(D^{*+})$.
- Data sample: 2 fb^{-1} of 2015-2016 data at 13 TeV.
- 3D template fit to $\boldsymbol{q^2}$, energy of the muon in the B rest frame ($\boldsymbol{E_\mu^*}$) and the squared of the missing mass ($\boldsymbol{m^2_{miss}}$).

$$R(D^+) = R(D) = 0.249 \pm 0.043_{stat} \pm 0.047_{syst}$$
$$R(D^{*+}) = R(D^*) = 0.402 \pm 0.081_{stat} \pm 0.085_{syst}$$
$$\rho = -0.39$$

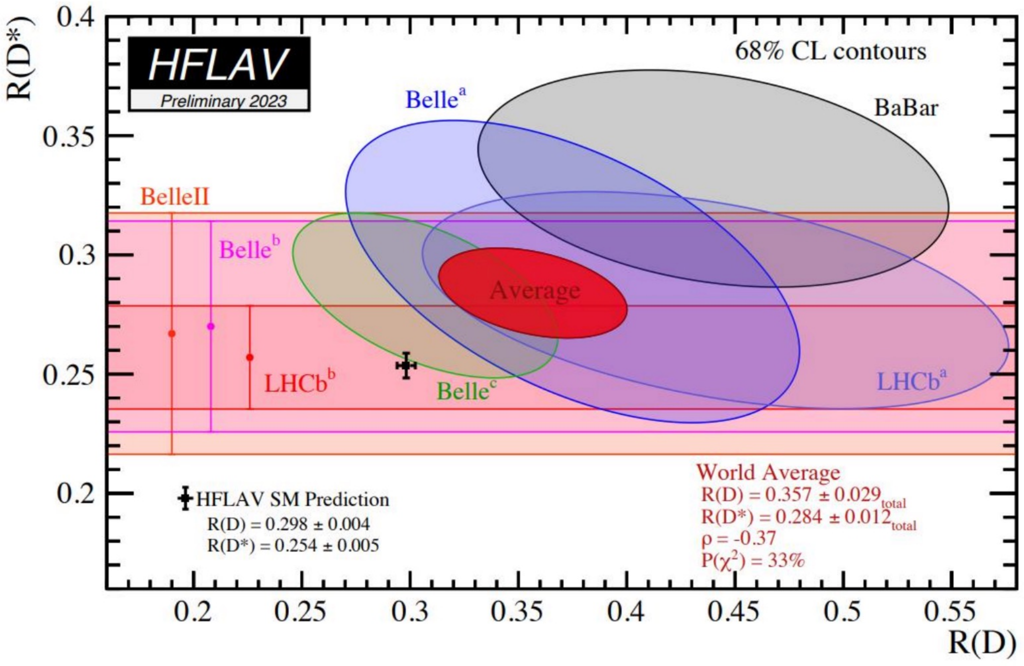
- Compatible with **SM** at $\boldsymbol{0.78\sigma}$ level and wit previous **WA** at $\boldsymbol{1.09\sigma}$.
- Main systematics from form-factors parameterisation and background modelling.

arXiv:2406.03387



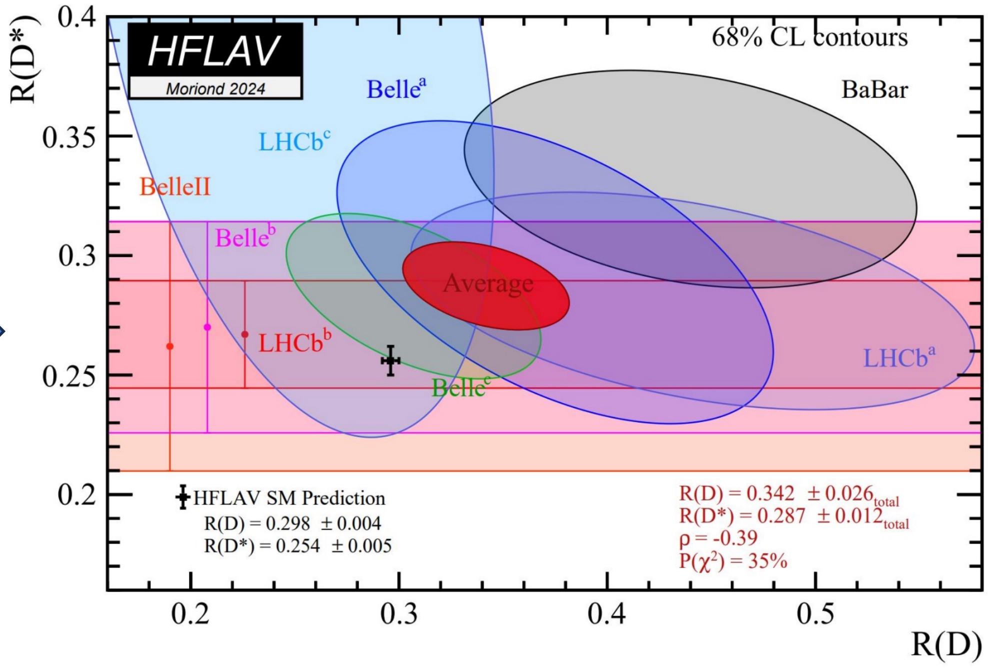
New $R(D)/R(D^*)$ World Average

Tension with SM slightly reduced.



Previous WA

3.34σ tension with SM



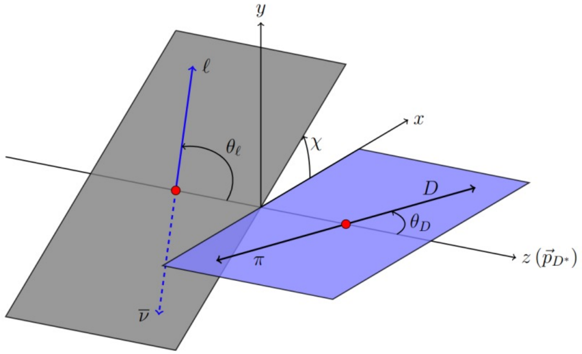
New WA

3.17σ tension with SM

Measurement of $F_L(D^*)$ in $B^0 \to D^{*-}\tau^+\nu_\tau$

- New Physics (NP) can be detected in angular coefficients even if $R(D^*)$ is compatible with the SM.
- Full angular decay rate for $\bar{B} \to D^*(\to D\pi)\ell\nu$ as a function of $cos\theta_\ell$, $cos\theta_D$ and χ:

$$\frac{d^4\Gamma^{(\ell)}}{dq^2 d\cos(\theta_\ell) d\cos(\theta_D) d\chi} = \frac{3}{8\pi}\sum_i J_i^{(\ell)}(q^2) f_i(\cos(\theta_\ell), \cos(\theta_D), \chi)$$

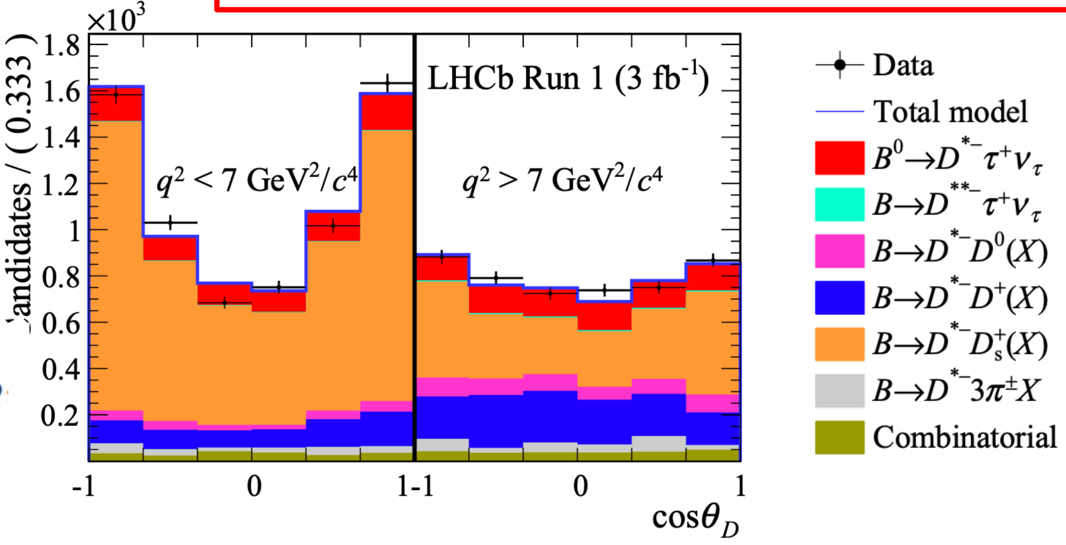


J_i^ℓ: Angular coefficients.
$\boldsymbol{\theta_D}$: D^* helicity angle.
$\boldsymbol{\theta_\ell}$: ℓ helicity angle.
$\boldsymbol{\chi}$: Azimuthal angle.

- D^* longitudinal polarisation: $\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$
- $F_L(D^*)$ can be computed as: $F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$
- a_θ and c_θ are linear combinations of the angular coefficients.

- Analysis dataset: Run1+2015+2016 data (5 fb^{-1}).
- $F_L(D^*)$ determined from a 4D fit to:
  - $cos\theta_D$, tau lifetime, q^2, anti-D_s^+ BDT.
- Results:

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



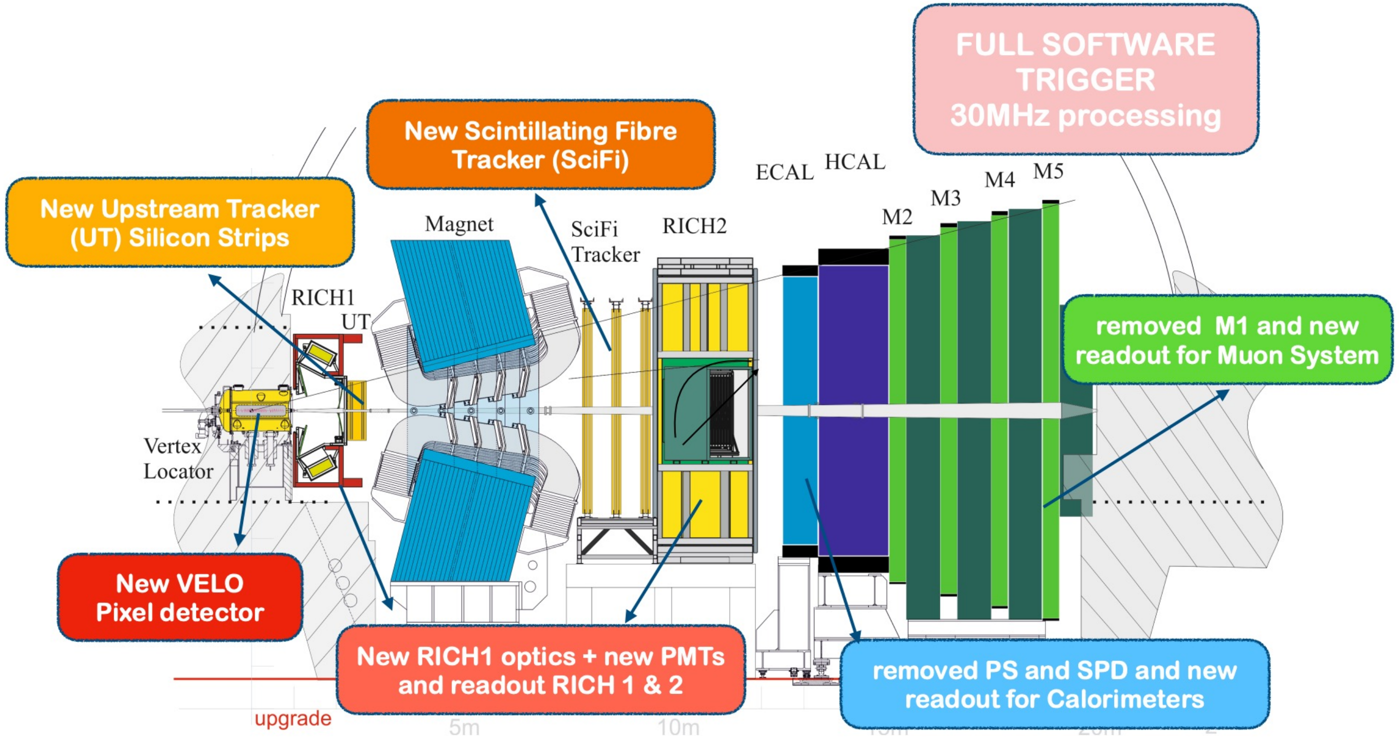
- Compatible with Belle measurement and SM.

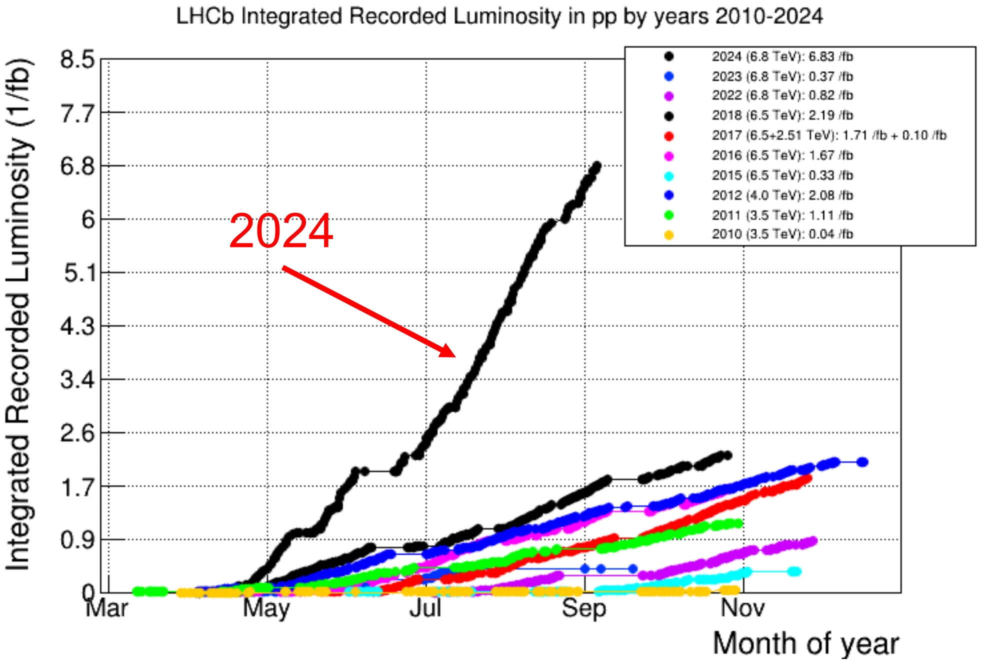
arXiv:2311.05224

7. Upgrade I

The LHCb Run3 detector

- At Run3: 5x higher luminosity than in Run2 → pile-up of ~5.
    - Major upgrade (Upgrade I) of all sub-detectors and readout.
    - Re-designed trigger system.

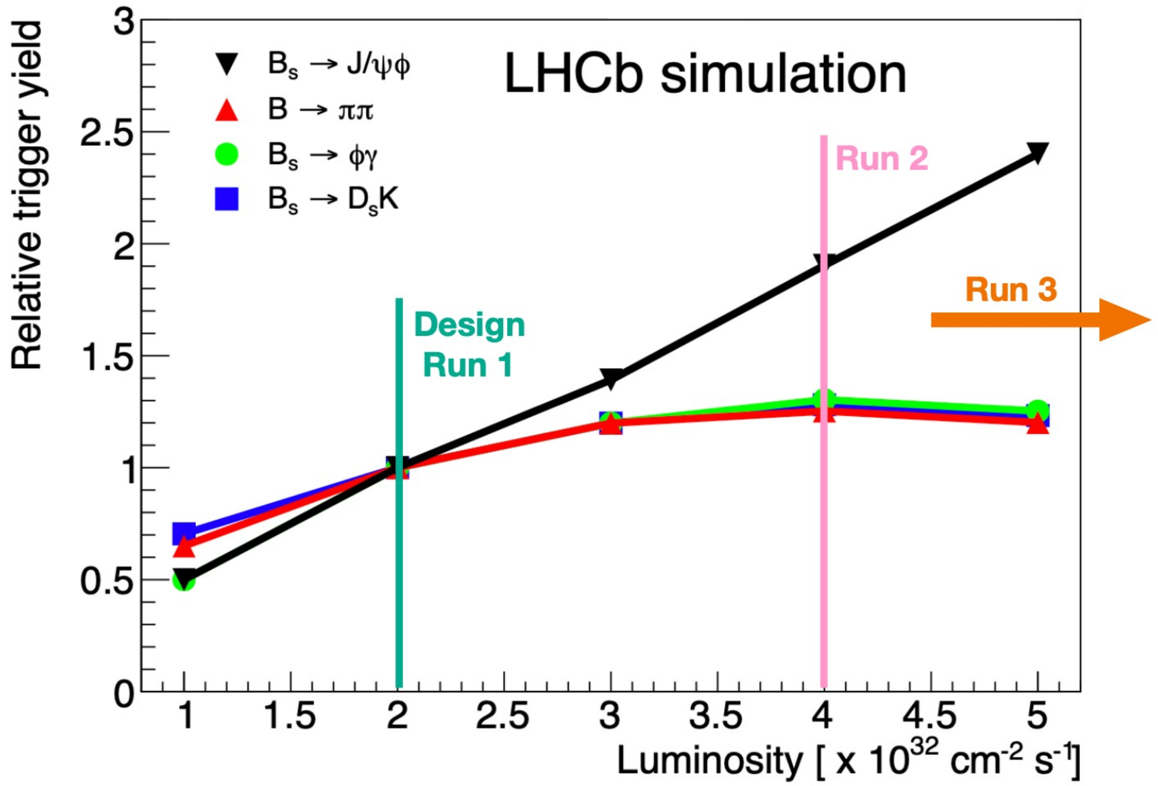




arXiv:2305.10515

Limitations of the Run2 trigger system

- **Run2 trigger system**:
    - Hardware trigger (L0).
    - Two-stage software trigger (Hlt1 + Hlt2).
- Tight p_T/E_t requirements by L0 → Trigger rates saturate with luminosity for fully hadronic decay modes.
- **Run3 trigger system**:
    - Removal of the hardware L0 trigger.
    - Run Hlt1 directly at the collision rate (30MHz).

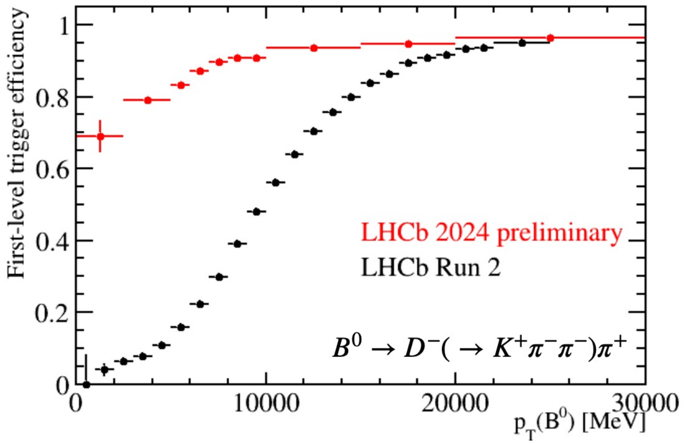


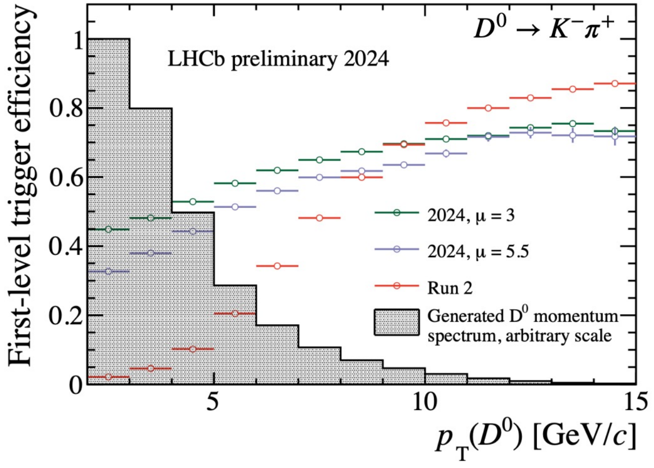
arXiv:2305.10515

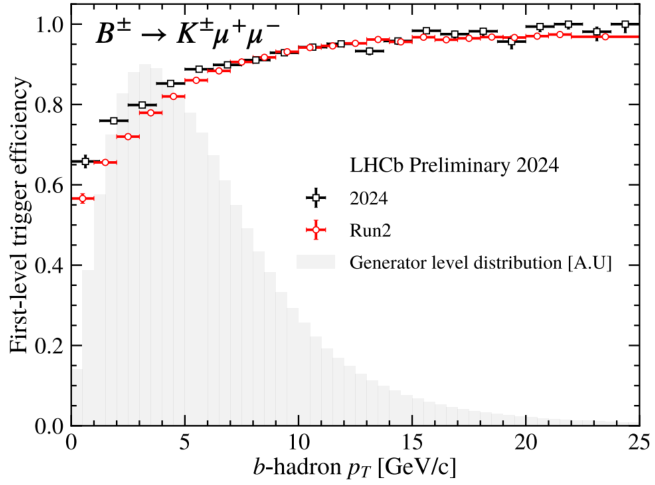
Hlt1

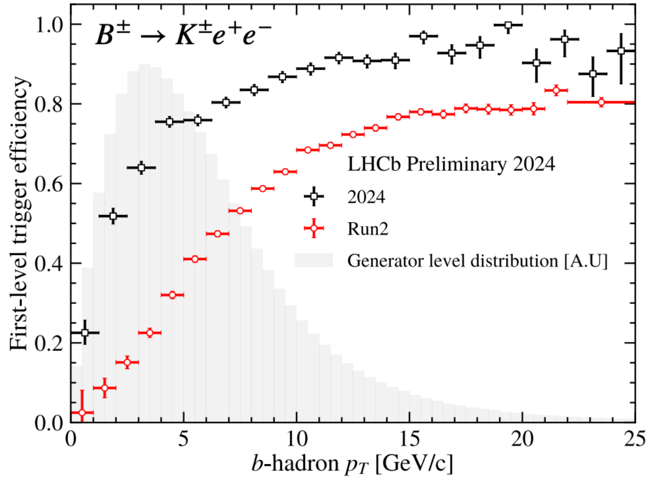
- Based on GPUs.
- Partial event reconstruction at 30 MHz.
  - Track reconstruction (Patter recognition and track fitting).
  - Vertex reconstruction (Primary and secondary decay vertices).
  - Electron clustering and bremsstrahlung recovery.
  - Muon identification.
- Event selection to reduce date rate by a factor ~30.
- Significant improvements in trigger efficiencies at Hlt1 level.
  - Huge gain at low-p_T.
  - Muon channels at similar performance as in Run2.
  - Large impact for electron channels.

LHCB-FIGURE-2024-014 LHCB-FIGURE-2024-006 LHCB-FIGURE-2024-007



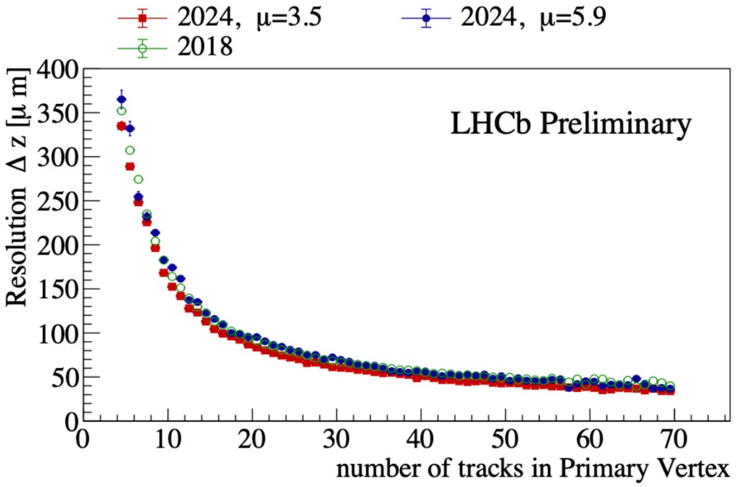


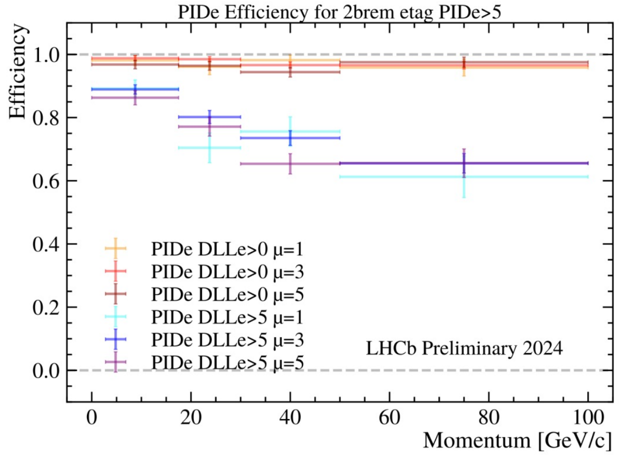


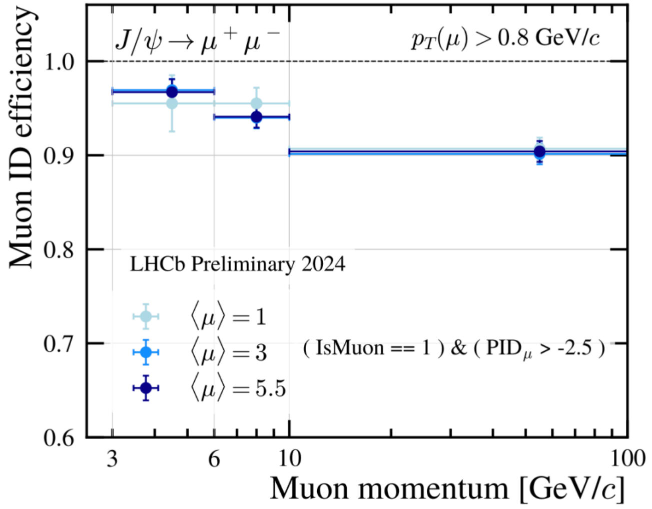


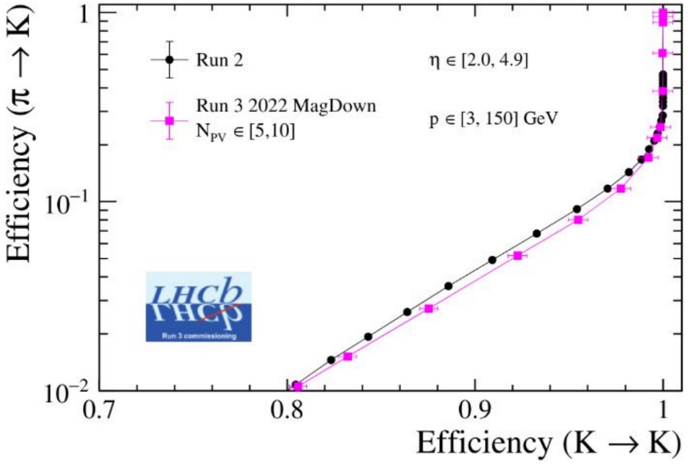
Hlt2

- Based on CPUs.
- Full event reconstruction (including PID) at ~0.5 MHz.
- Dedicated trigger selections representing the broad LHC physics programme.
  - ~2700 selections developed by analysts.
- Excellent vertex resolution.
- **Particle identification (PID)** by combining information from different sub-detectors:
  - Difference in Log-Likelihood between different hypothesis.
  - Stable PID performance for hadrons, muons and electrons.









[LHCB-FIGURE-2024-010](#) [LHCB-FIGURE-2024-011](#)
[LHCB-FIGURE-2023-019](#)

Conclusions

- Presented a selection of LHCb physics results.
- LHCb physics programme in constant evolution.
- Many measurements make use of the full legacy Run1+Run2 dataset.
- In Run3, detector stably operating.
- Expected improvement in trigger efficiencies for hadronic channels.