Lepton Flavor Universality Highlights from LHCb

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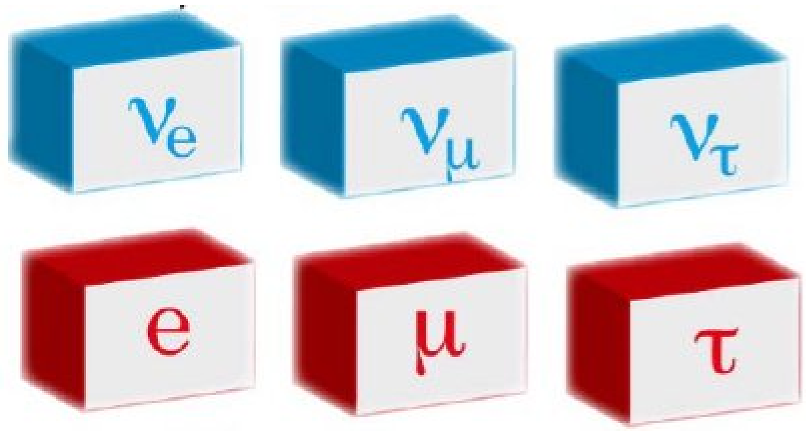
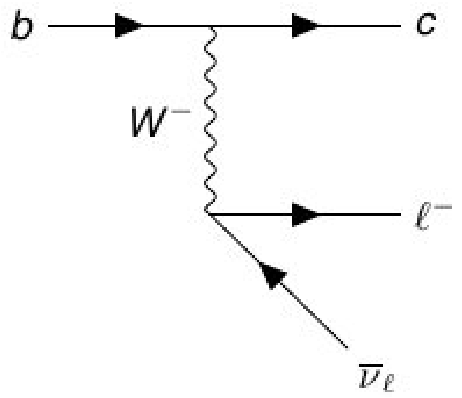
第5届LHCb前沿物理研讨会
2025/04/27

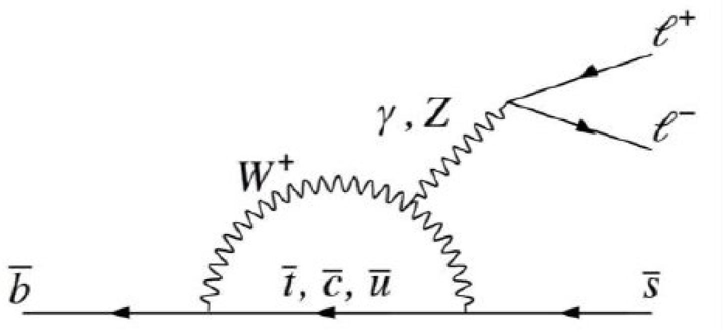
Outline

- LFU tests in semi-leptonic B decays (Charged currents)
  - τ versus μ
  - For τ reco: muonic versus hadronic
- LFU tests in rare B decays (Neutral currents)
  - μ versus e
- Summary



Charged currents versus neutral currents

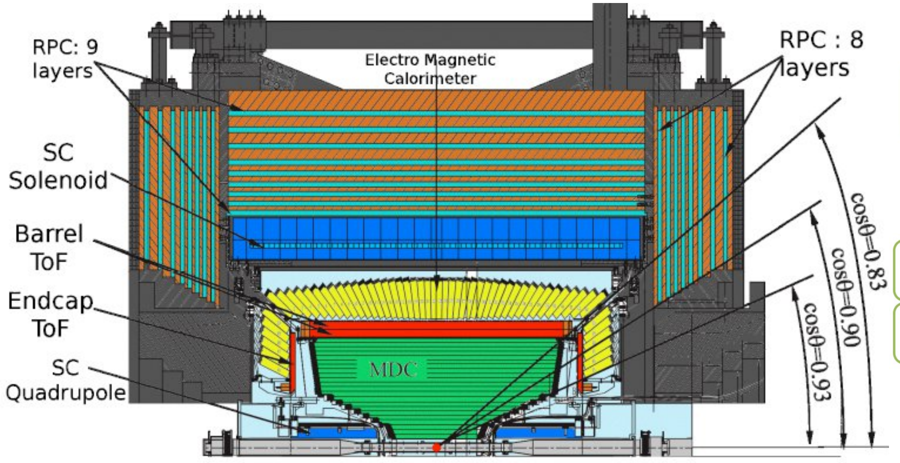




- One charged lepton in the final state
- Tree level
- Theoretically clean
- Abundance of data
- Experimentally challenging due to missing neutrino

- Dilepton final states
- Forbidden at tree level in SM
- Sensitive to NP
- Highly suppressed, statistically limited in experiments
- Mainly on e-μ asymmetry

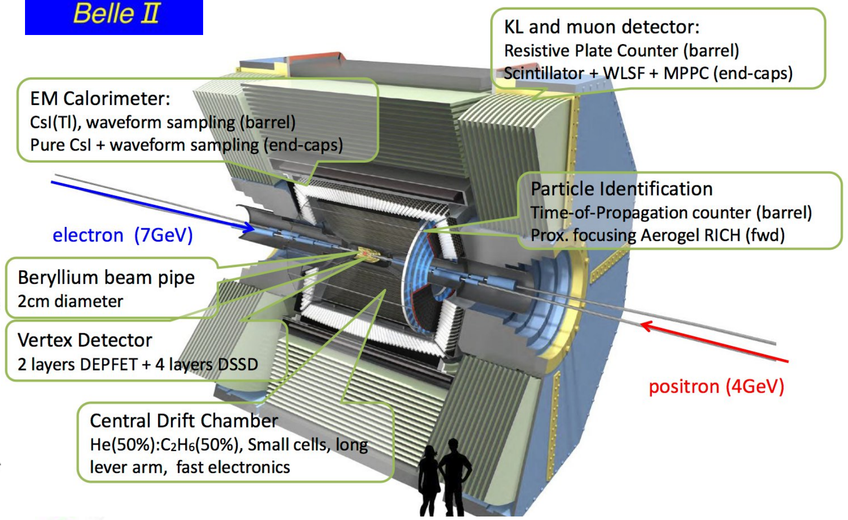
Major experiments for LFU tests



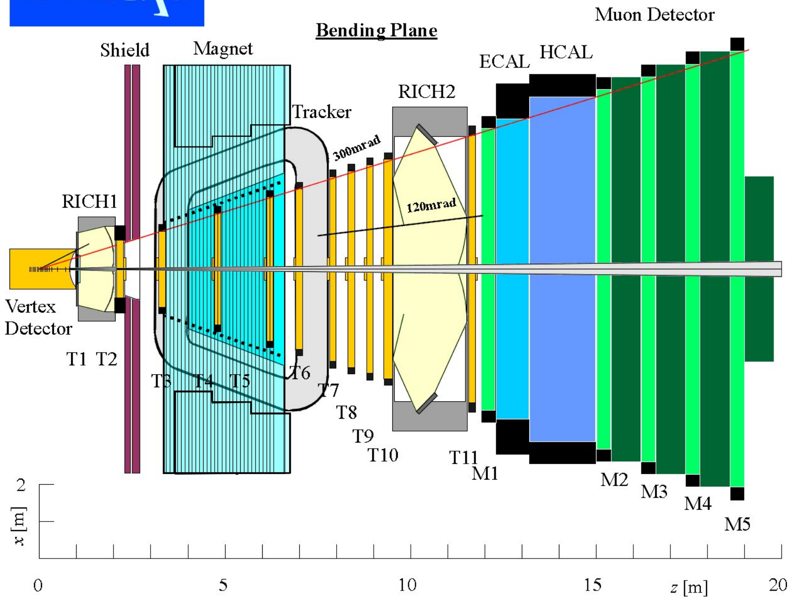
Wire tracker (no Si); TOF + dE/dx for PID; CsI Ecal; RPC muon

- ✓ double-tag method for bkg. suppr. & neutrino reco.
- ✓ extremely clean environment
- ✓ high efficiency detection on electrons/neutrals
- ✓ quantum coherence
- ● no CM boost, no T-dep analyses

Belle II Detector



- ✓ clean event environment
- ✓ high trigger efficiency
- ✓ high-efficiency detection of neutrals
- ✓ many high-statistics control samples
- ✓ time-dependent analysis
- ● smaller cross-section than hadron colliders

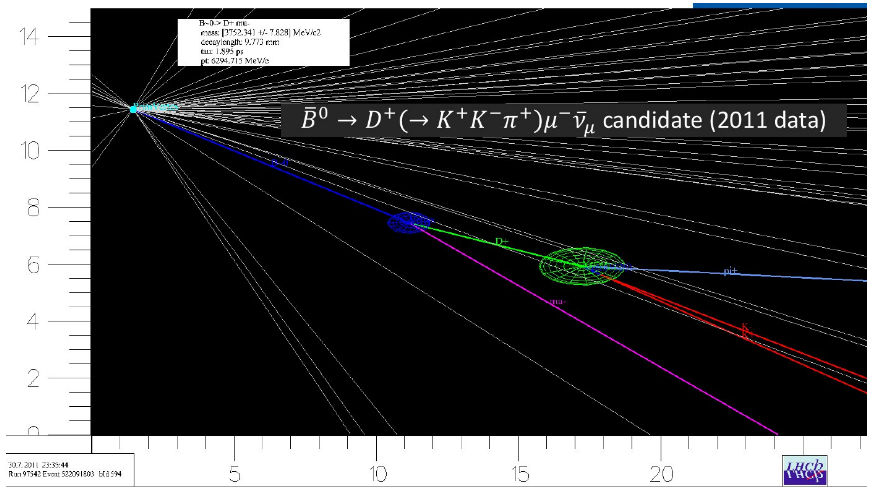


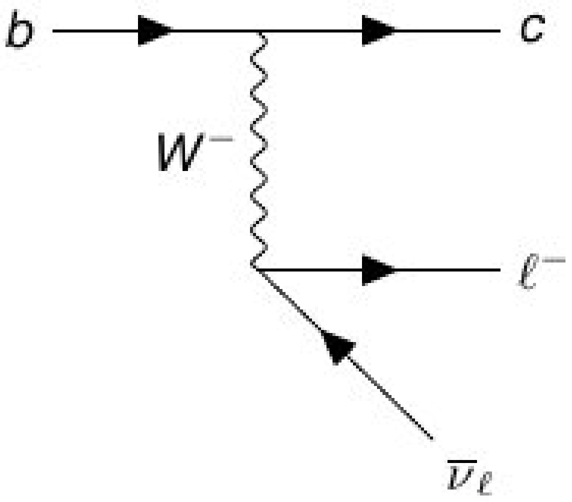
- ✓ large production cross-section
- ✓ large boost: excellent time res
- ● dedicated trigger required
- ● hard to do neutrals and neutrinos

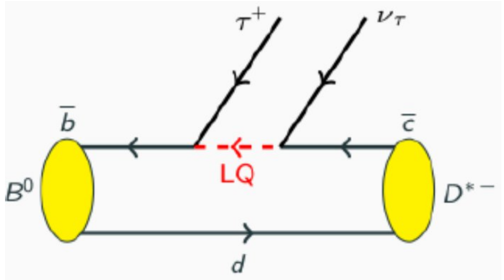
Experimental challenges for LFU tests

- Hadronic part: most of uncertainties cancel in the ratio at 1st order
- Missing neutrinos for (semi-)leptonic processes:
  - e^+e^- machines: inferred using beam condition & mising info
  - Hadron machines: more difficult, using info such as decay vertices, isolation info, kinematics of visible part, etc
- Electron: generally more difficult in experiments such as LHCb
- Muon: difficuties in μ/π separation for low-P tracks @ BESIII
- Tau lepton: short lifetime, decaying into final states with $\geq 1\nu$
  - e^+e^- machines: $\tau \to e\nu\bar{\nu}$, $\tau \to \mu\nu\bar{\nu}$, $\tau \to \pi(\pi^0)\nu$
  - **Hadron machines:** $\tau \to \mu\nu\bar{\nu}$, $\tau \to \pi\pi\pi\nu$

LFU tests in semi-leptonic B decays

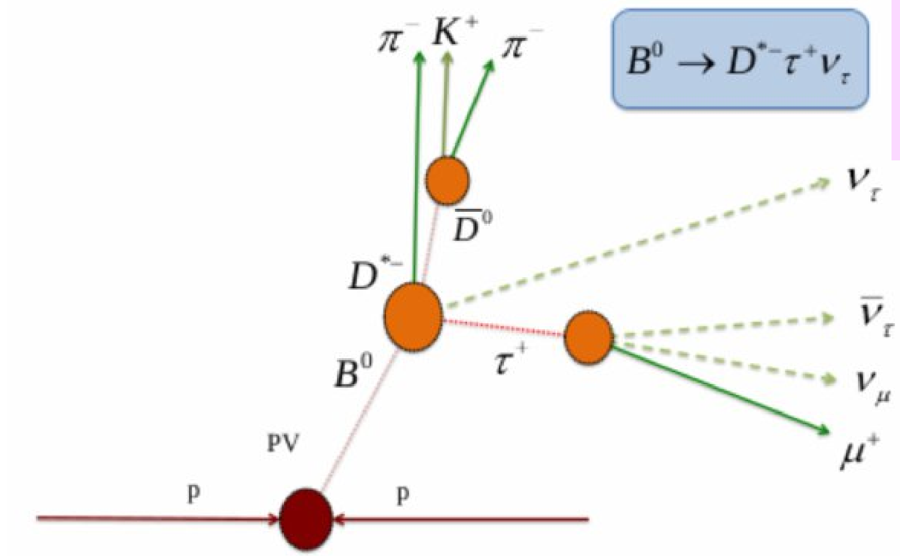




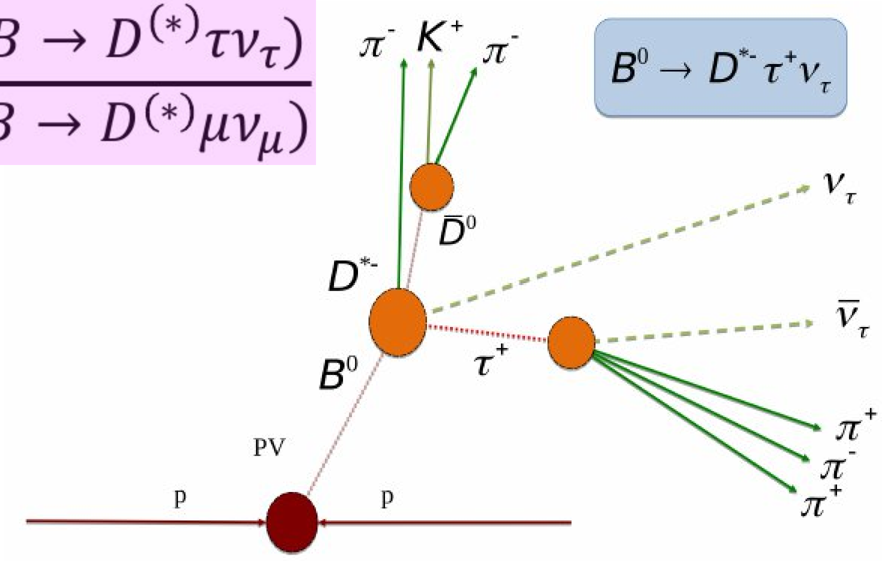


PRL 131, 111802 (2023)
PRD 108, 012018 (2023);
PRD 109, 119902(E) (2024)

$R(D^{(*)})$ measurements @ LHCb



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu\nu_\mu)}$$



Muonic :

- Large statistics
- Study of μ and τ modes in one dataset
- Can measure R(D) and R(D*) simultaneously

Hadronic :

- Relatively high purity
- External BR measurement for normalization
- Decay vertex of well measured to suppress dominant backgrounds
- 3π dynamics important for the separation of B-> D*DX backgrounds

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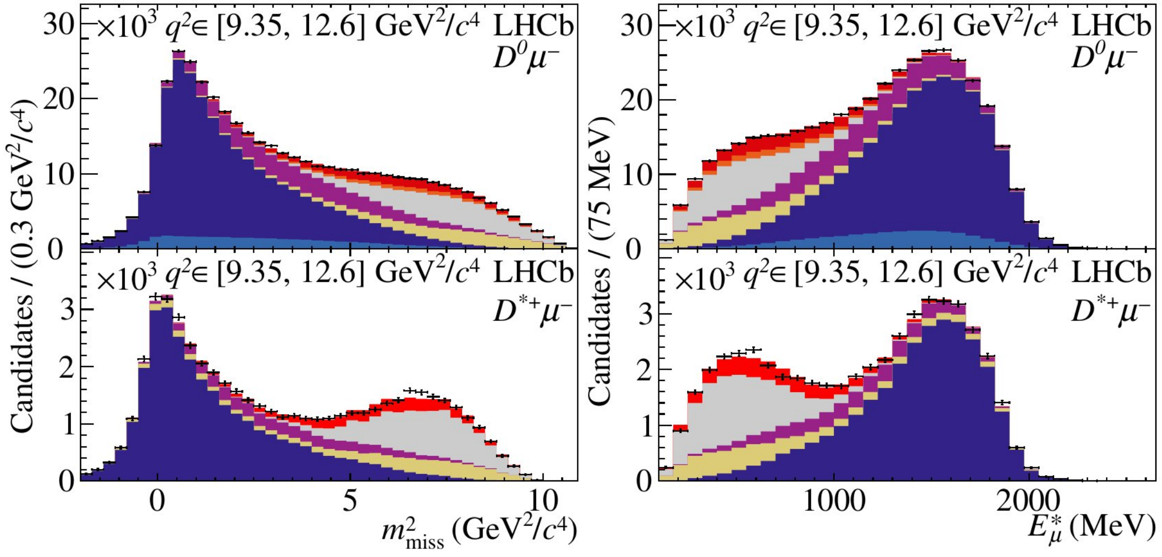
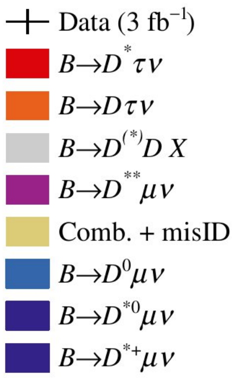
$R(D^{(*)})$ measurements @ LHCb

Muonic





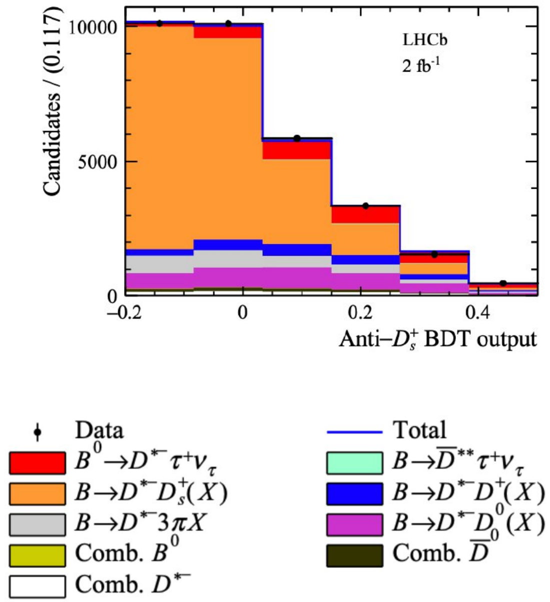
Using Run1 3 fb^{-1} data:

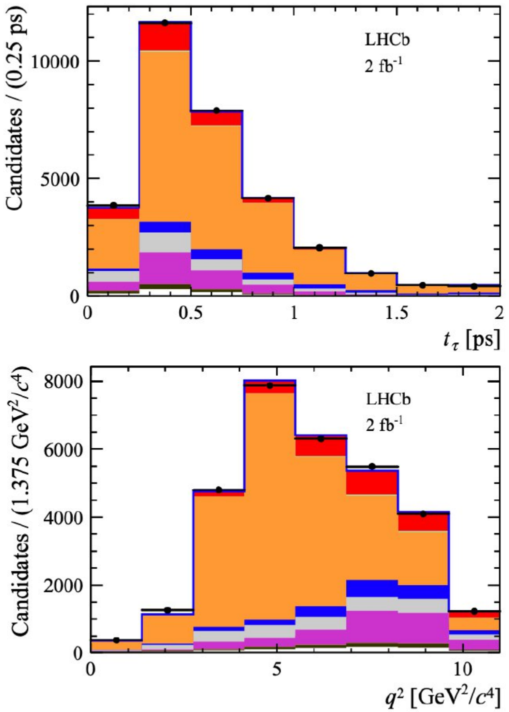
$$R(D^*) = 0.281 \pm 0.018\ (\text{stat.}) \pm 0.024\ (\text{syst.})$$

$$R(D) = 0.441 \pm 0.060\ (\text{stat.}) \pm 0.066\ (\text{syst.})$$

1.9σ deviation from SM

Hadronic





Using Run1+2 5 fb^{-1} data:

Agreement w/ SM <1σ

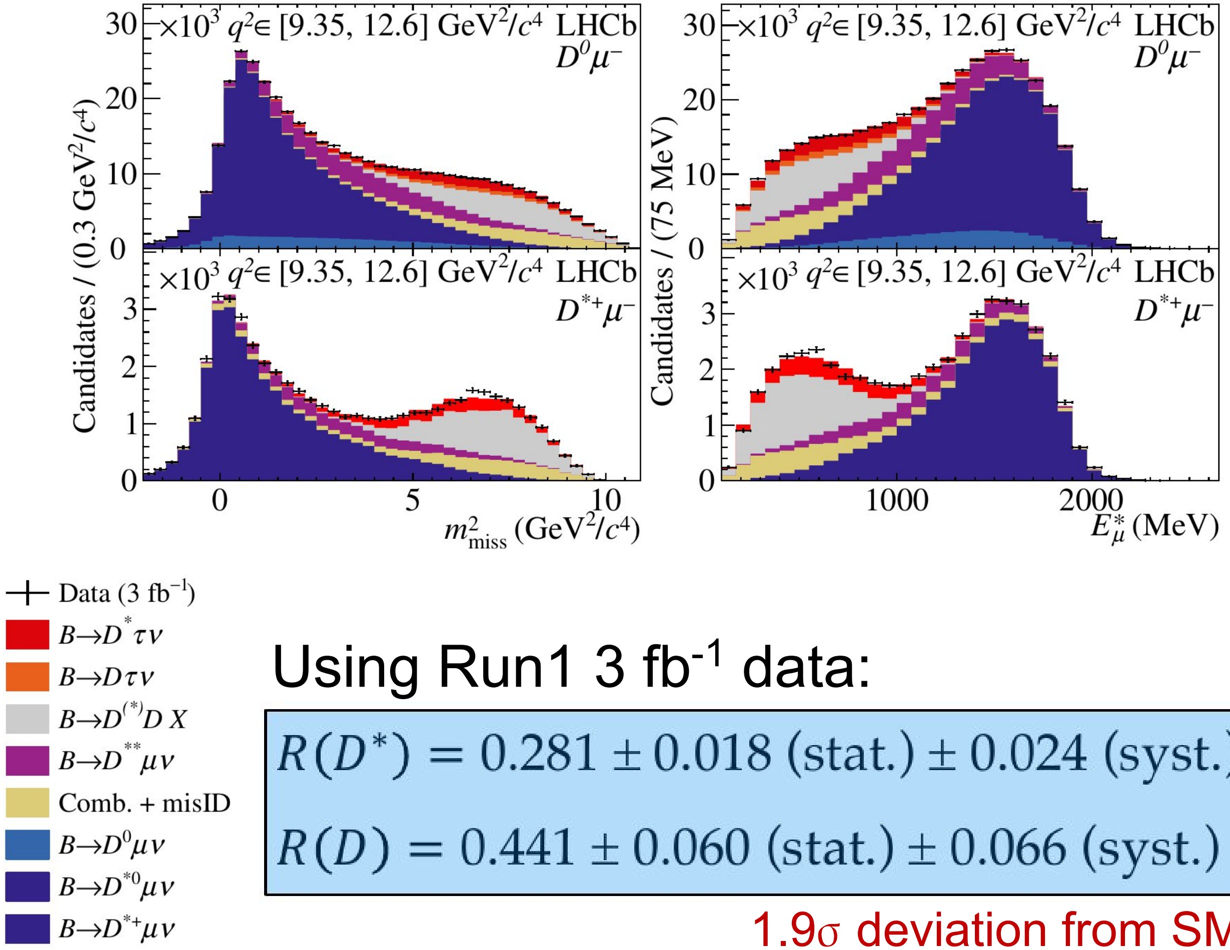
$$R(D^*) = 0.257 \pm 0.012\ (stat) \pm 0.014\ (syst) \pm 0.012\ (ext)$$

Considerable systematic uncertainty due to limited sample sizes

PRL 131, 111802 (2023)
PRD 108, 012018 (2023);
PRD 109, 119902(E) (2024)

R(D$^{(*)}$) measurements @ LHCb

Muonic



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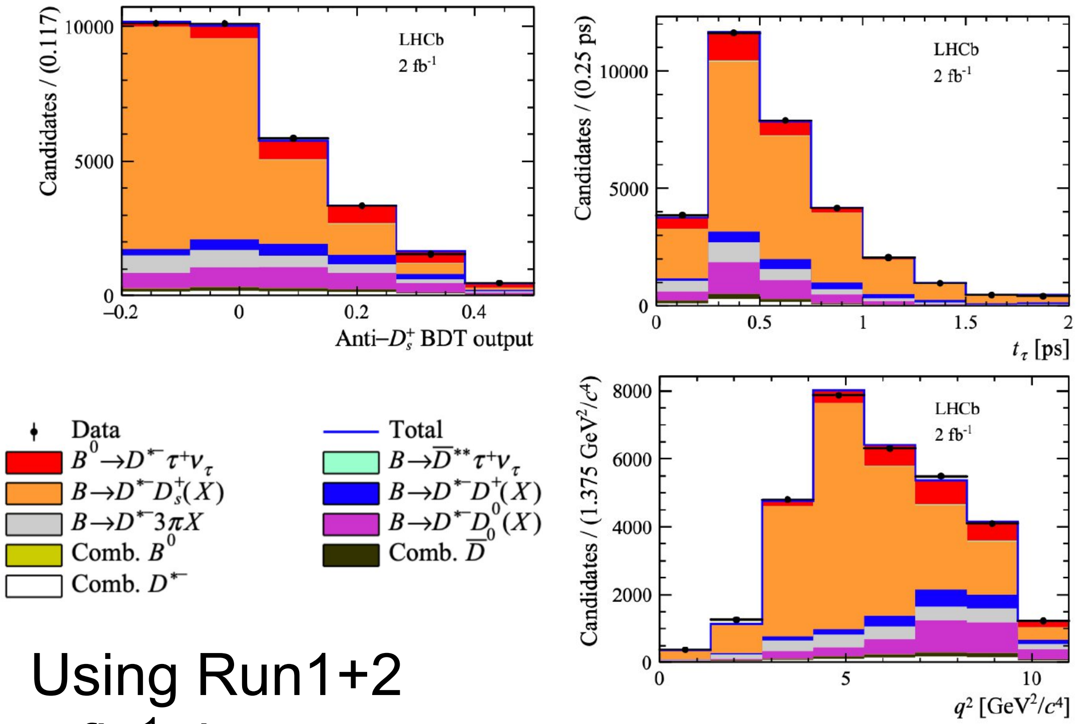
Hadronic



Using Run1+2 5 fb^{-1} data:

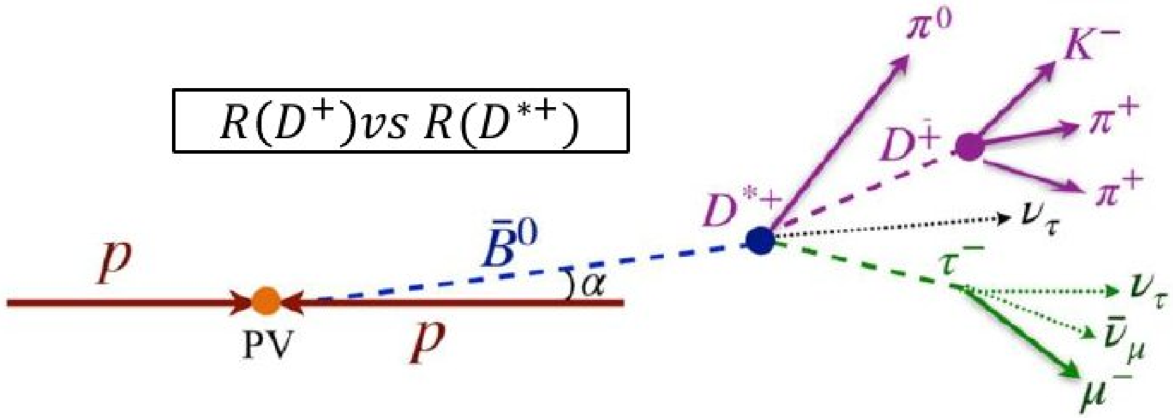
Agreement w/ SM <1σ

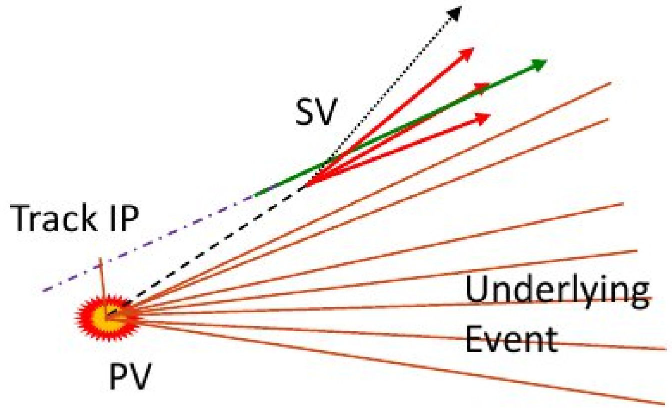
$$R(D^{*-})_{\text{comb}} = 0.267 \pm 0.012(\text{stat}) \pm 0.015(\text{syst}) \pm 0.013(\text{ext})$$

Details can be found in Bo Fang's PhD thesis

PRL 134, 061801 (2025)

R(D$^{(*)+}$) with $\tau \to \mu\nu\bar{\nu}$





- Using 2016 (2 fb^{-1}) data
- First measurement with dedicated $B \to H_c\tau(\to \mu\nu\nu)\nu$ trigger line for Run2
- 3D template fit to single $D^+(\to K\pi\pi)\mu^-$ sample
  - π^0 from $D^{*+} \to D^+\pi^0$ not reconstructed
  - Fast “track-only” simulation to boost statistics for templates
  - BDT-based isolation tools to separate $\bar{B}^0 \to D^+\tau\nu$ & $\bar{B}^0 \to D^{*+}\tau\nu$, and suppress backgrounds

PRL 134, 061801 (2025)

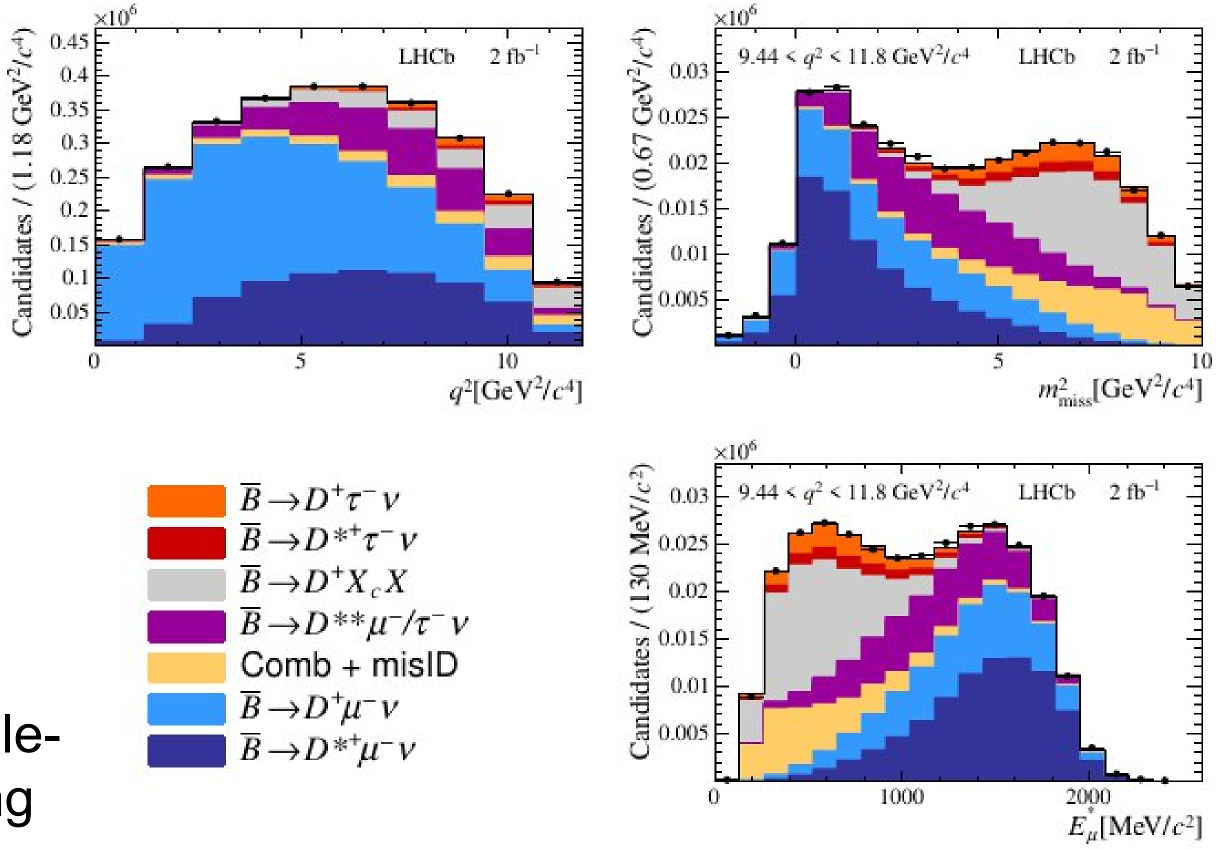
R(D$^{(*)+}$) with $\tau \to \mu\nu\bar{\nu}$

- Using 2016 (2 fb^{-1}) data
- First measurement yields:

$$R(D^{+}) = 0.249 \pm 0.043 \pm 0.047,$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085,$$

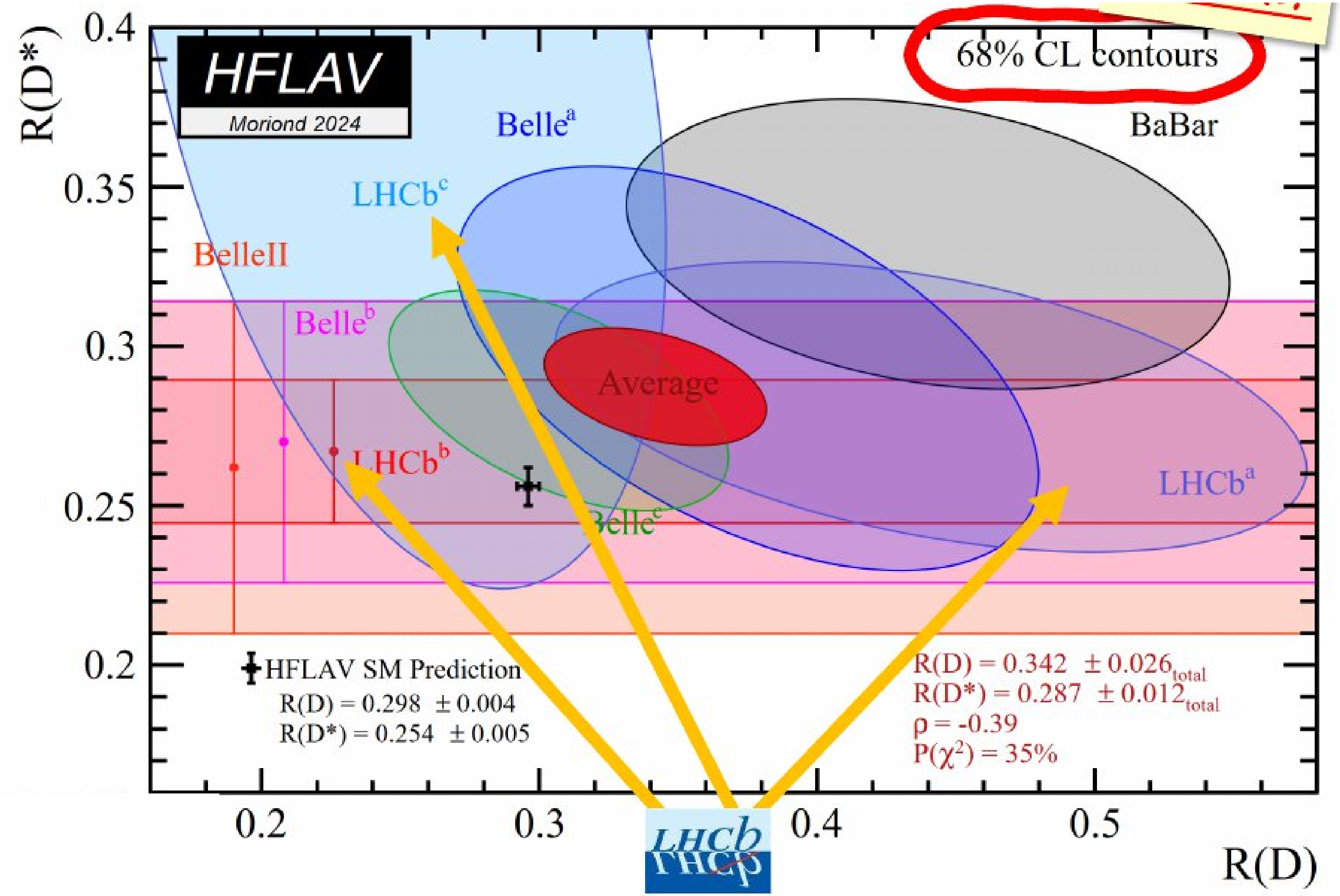
correlation coefficient = −0.39

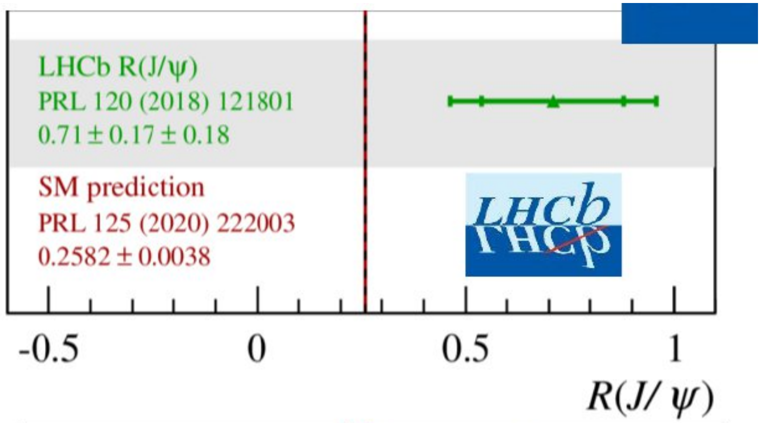
➢ Dominating systematic sources: FFs, double-charm background shape and misID modelling
➢ MC sample size no longer a major limiting factor

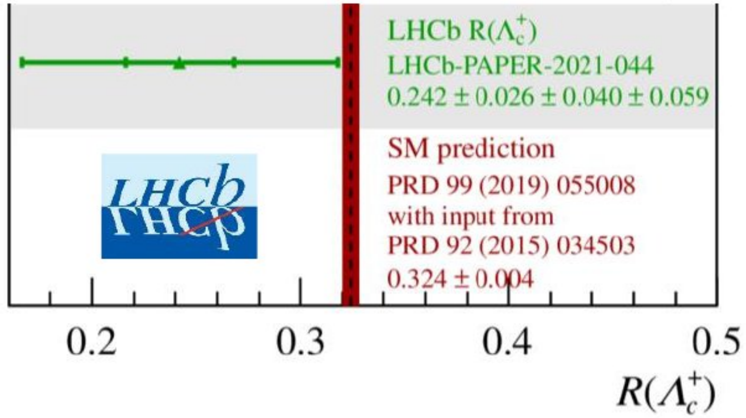


a) PRL 131, 111802 (2023)
b) PRD 108, 012018 (2023); E
c) PRL 134, 061801 (2025)

Current R(X) status





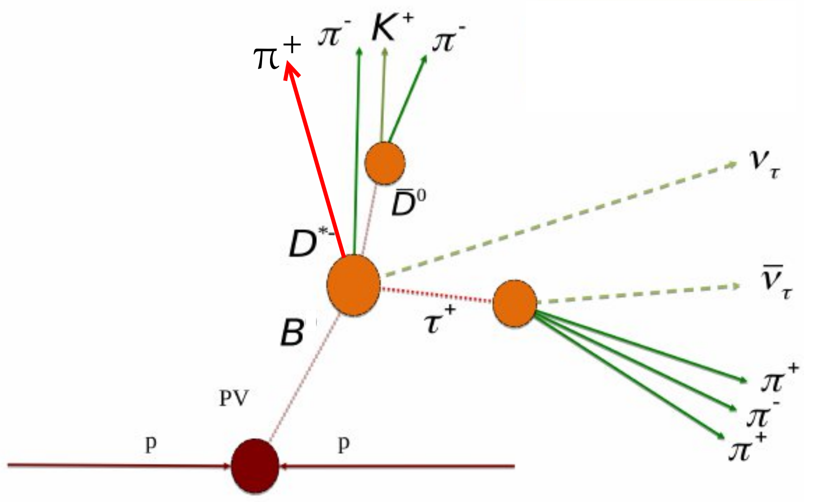


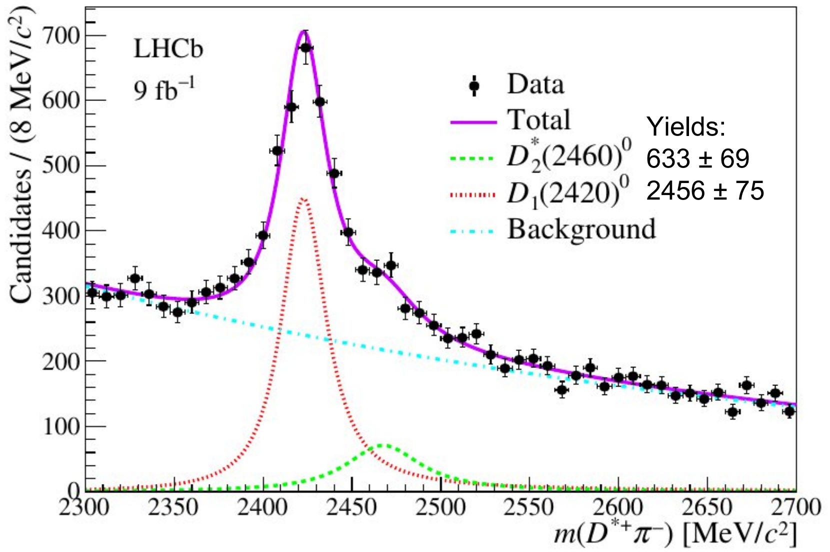
[Deviation from SM for combined R(D) − R(D∗) ~ 3.3σ]

arXiv:2501.14943, submitted to PRL

R(D**) with $\tau \to \pi\pi\pi\nu$

- $B^- \to D^{**0}(\to D^{(*)}\pi(\pi))\tau^-\bar{\nu}_\tau$ as a common feed-down background source for R(D$^{(*)}$) and R(D*)
- D** family: two narrow states $D_1(2420)$ & $D_2(2460)$ and a wide one $D_1'(2400)$
  - Separation of three states via mass and angular distributions
- Same selection as for R(D*) with an extra pion track consistent with being from B vertex





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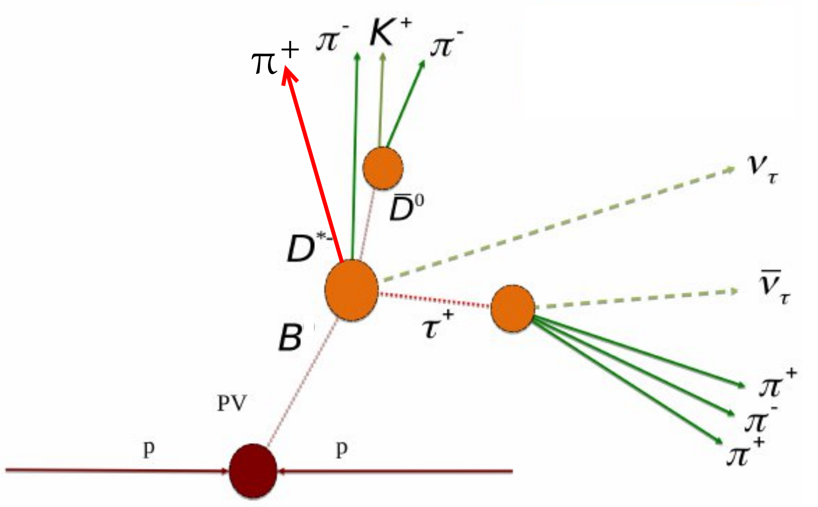
R(D**) with $\tau \rightarrow \pi\pi\pi\nu$

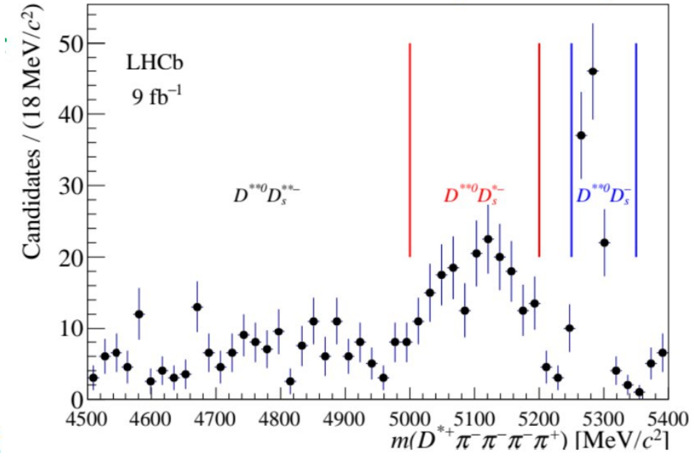
- $B^- \rightarrow D^{**0}(\rightarrow D^{(*)}\pi(\pi))\tau^-\bar{\nu}_\tau$ as a common feed-down background source for R(D(*)) and R(D*)
- D** family: two narrow states D_1(2420) & D_2(2460) and a wide one D_1'(2400)
  - Separation of three states via mass and angular distributions
- Same selection as for R(D*) with an extra pion track consistent with being from B vertex
- Normalization channel: $B^- \rightarrow D_{1,2}^{**0} D_s^{(*)}$ with $D_s^+ \rightarrow \pi^+\pi^+\pi^-$ w/ the same decay topology



Clear separation of D_s, D_s^* and D_s^{**} domains

$B^- \rightarrow D^{**0} D_s^{*-}$

$B^- \rightarrow D^{**0} D_s^-$



Yields

$B^- \rightarrow D^{**0} D_s^-$: 116 ± 11

$B^- \rightarrow D^{**0} D_s^{*-}$: 177 ± 14

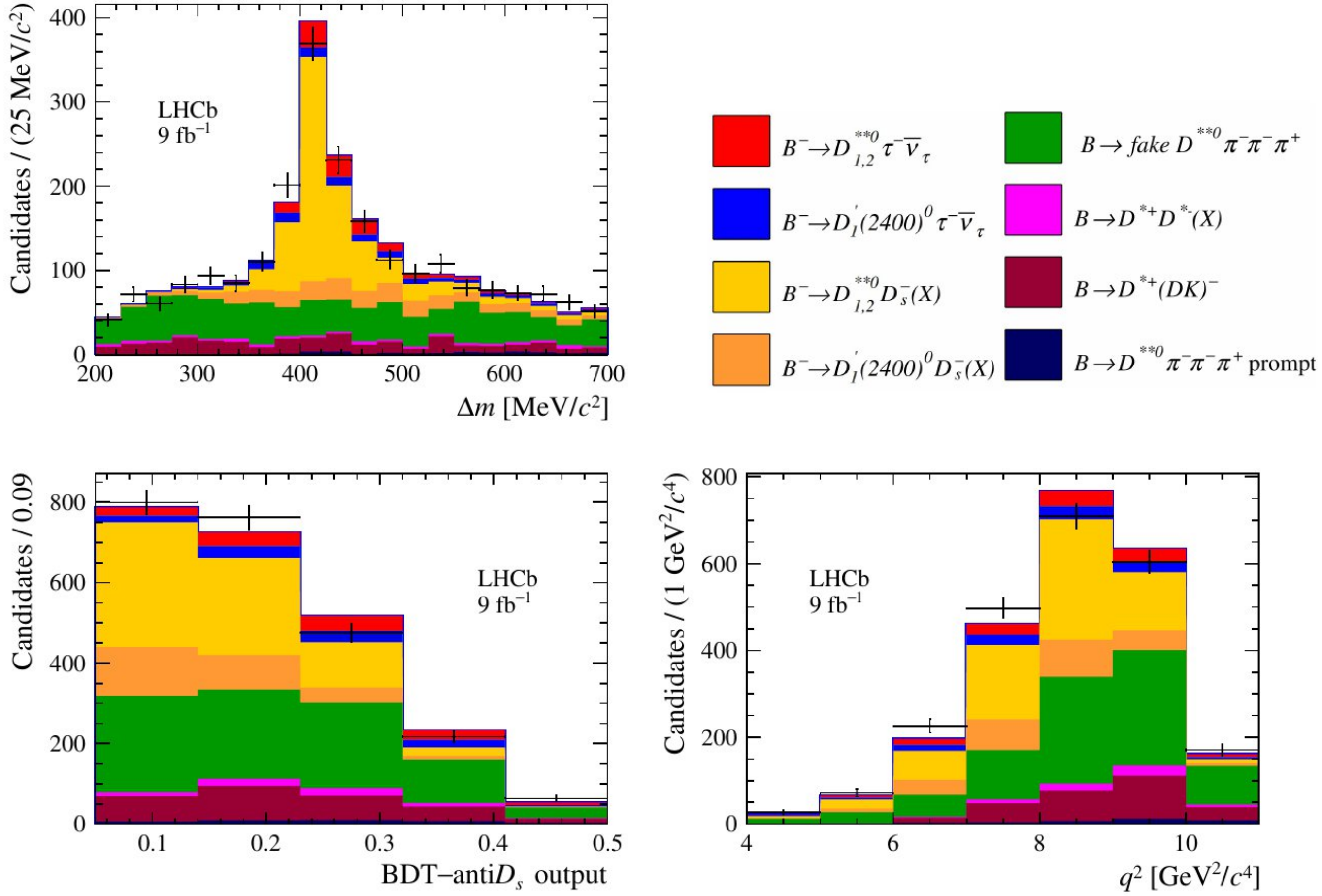
arXiv:2501.14943, submitted to PRL

R(D^{**}) with $\tau \to \pi\pi\pi\nu$: fit to data

The 3 variables are :

- Δm to isolate D_1 and D_2 components
- antiD$_s$_BDT, to isolate 3π from τ decays
- q^2

Fit Parameter	Yield
$(D_1^0(2420) + D_2^{*0}(2460))\tau\nu$	122.6±23.2
$D_1^{\prime 0}(2400)\tau\nu$	96.7±24.9
$D_1^0(2420)D_s^{*+}$	317.1±19.2
$D_1(2420)D_s^+$	235.4±15.9
$D_2^{*0}(2460)D_s^+$	39.0±3.1
$D_2^{*0}(2460)D_s^{*+}$	48.1±12.4
$D^{**}D_s^{**+}$	31.5±30.3
$D_1^{\prime 0}(2400)D_s^{*+}$	140.7±28.1
$D_1^{\prime 0}(2400)D_s^+$	112.5±17.1
D^{**} WrongSign	8793.8±73.7
D^{**} Prompt	34.6±7.0
$D^{*-}D^{*+}$ (X)	51.4±55.3
Extra K	248.3±48.4



First evidence for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ with 3.5σ significance

arXiv:2501.14943, submitted to PRL

R(D**) with $\tau \to \pi\pi\pi\nu$: results

- Using the normalisation channel yield , one finds:

$$\frac{\mathcal{B}(B^- \to D^{**0}_{1,2}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(B^- \to D^{**0}_{1,2}D_s^{(*)-})} = 0.19 \pm 0.04\,(\text{stat}) \pm 0.02\,(\text{syst})$$

This leads to:

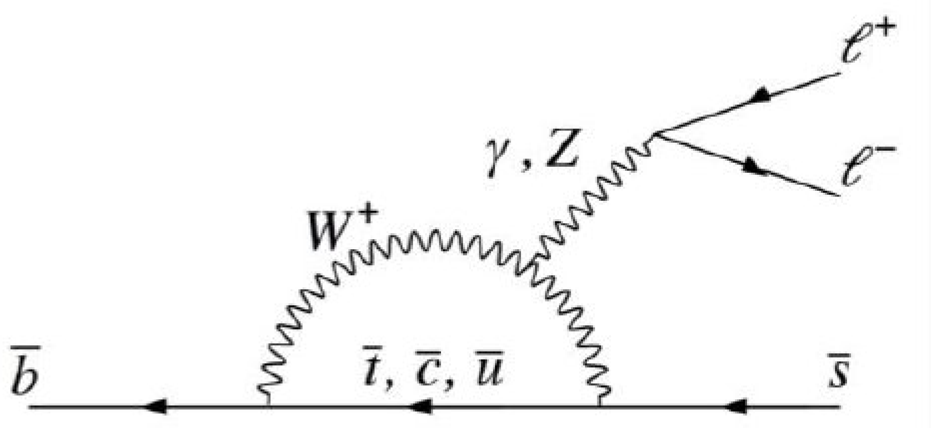
$$\mathcal{B}(B^- \to D^{**0}_{1,2}\tau^-\overline{\nu}_\tau)\times\mathcal{B}(D^{**0}_{1,2} \to D^{*+}\pi^-)$$
$$= (0.051\pm0.013\,(\text{stat})\pm0.006\,(\text{syst})\pm0.009(\text{ext}))\%,$$

and $\mathcal{R}(D^{**0}_{1,2}) = 0.13 \pm 0.03\,(\text{stat}) \pm 0.01\,(\text{syst}) \pm 0.02\,(\text{ext})$

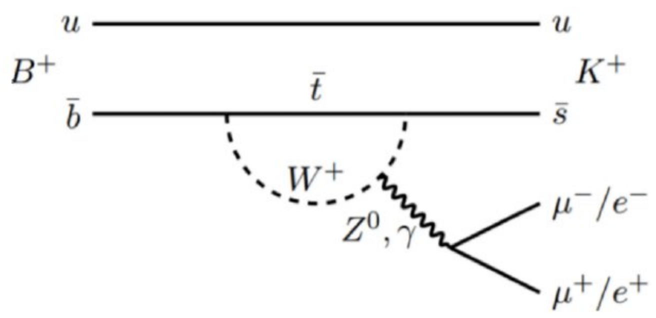
The SM prediction is 0.09±0.02 :This result is compatible with SM within 1 σ

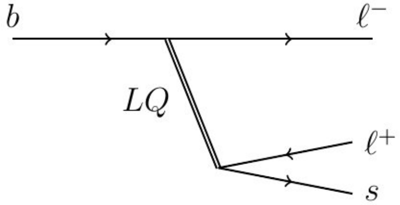
BESIII measurements of $D_s^+ \to 3\pi X$ crucial inputs to control background related systematic uncertainties

LFU tests in rare b-hadron decays



LFU tests in $b \to s l^+ l^-$ decays





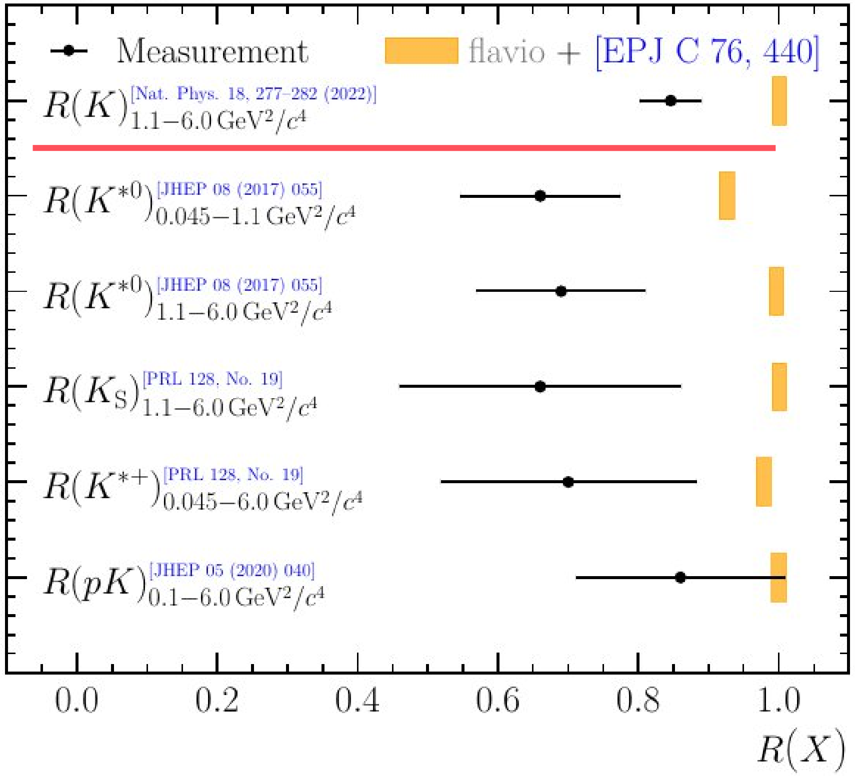
- FCNC processes highly suppressed in SM
- NP may manifest in the loops and cause LFU violation
- LFU tests use

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

$$R_X = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B_q \to X_s \mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B_q \to X_s e^+e^-)}{dq^2} dq^2} = 1 \pm \mathcal{O}(1\,\%)$$

  - Cancellation of hadronic uncertainties in the ratio => precise prediction of R_X

Status Late 2022



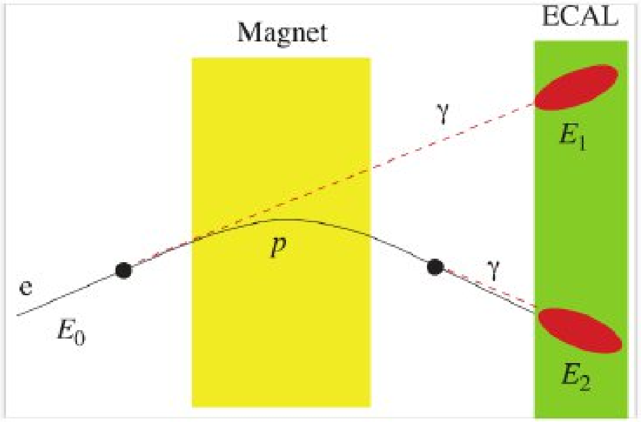
PRL 131 (2023) 051803
PRD 108 (2023) 032002

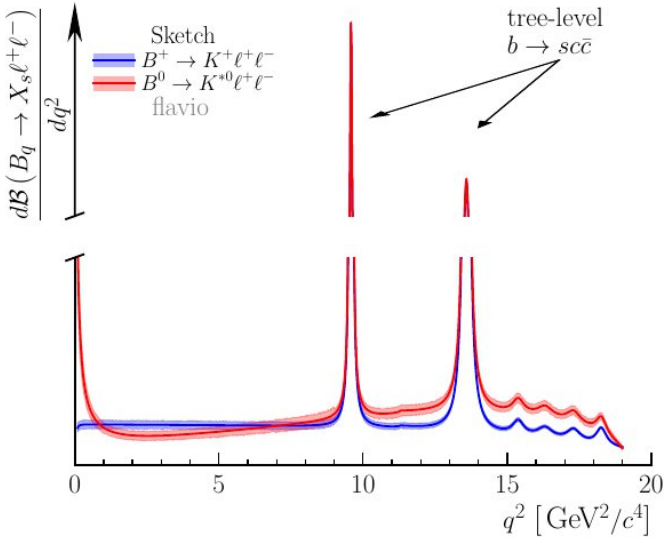
R(K$^{(*)}$) measurements @ LHCb

- Electrons & muons behave quite differently in the LHCb detector
- Lower efficiencies & worse resolution (energy loss) for electrons
- Double-ratio of branching fractions:

$$R_X = \frac{\mathcal{B}(B_q \to X_s \mu^+\mu^-)}{\mathcal{B}(B_q \to X_s J/\psi(\mu^+\mu^-))} \cdot \frac{\mathcal{B}(B_q \to X_s J/\psi(e^+e^-))}{\mathcal{B}(B_q \to X_s e^+e^-)}$$

  - Most of systematic uncertainties cancel to 1st order
  - LFU in $J/\psi \to l^+l^-$ well established at ‰ level [BESIII, PRD 88, 032007 (2013)]
  - Validated in ψ(2S) mode

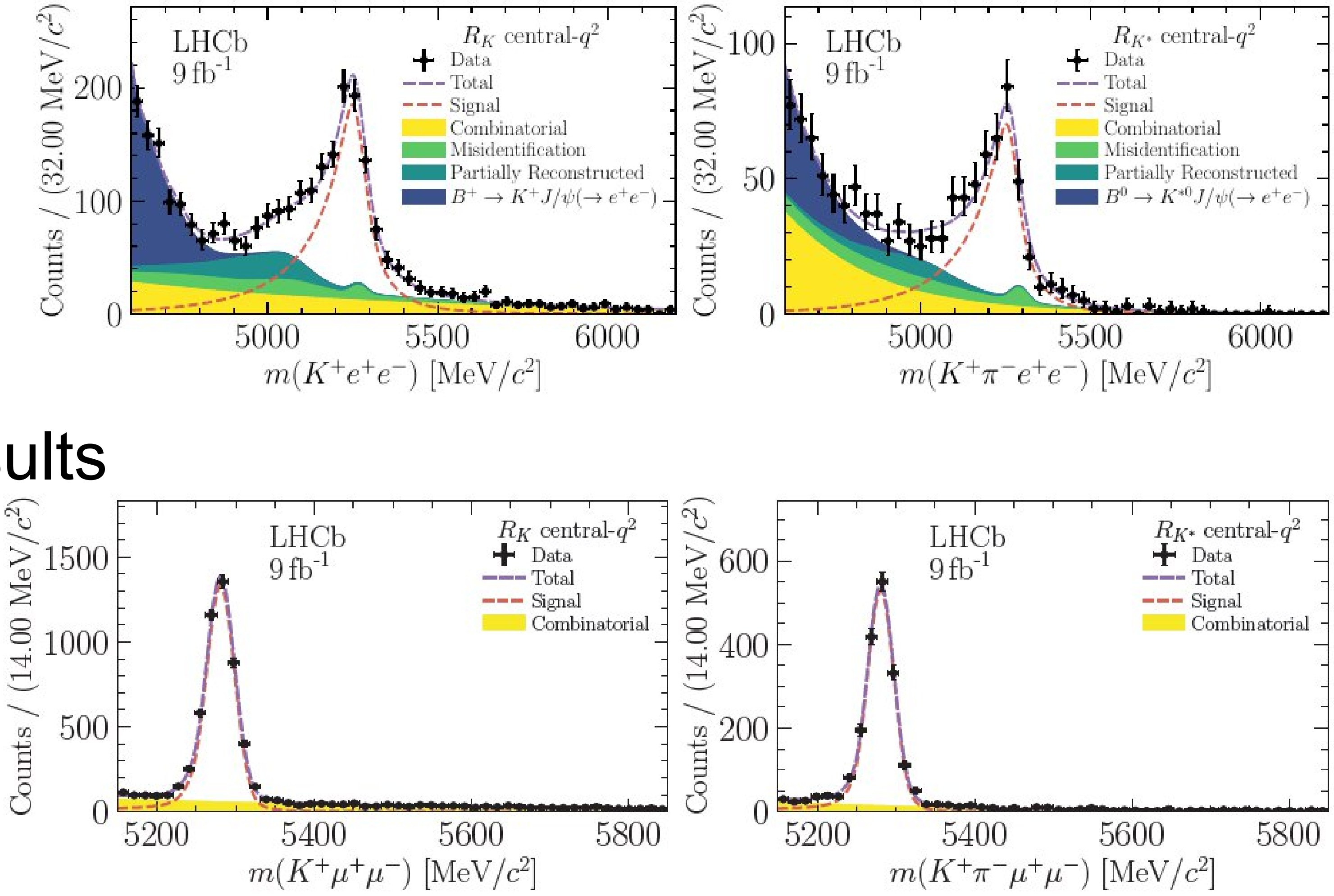




PRL 131 (2023) 051803
PRD 108 (2023) 032002

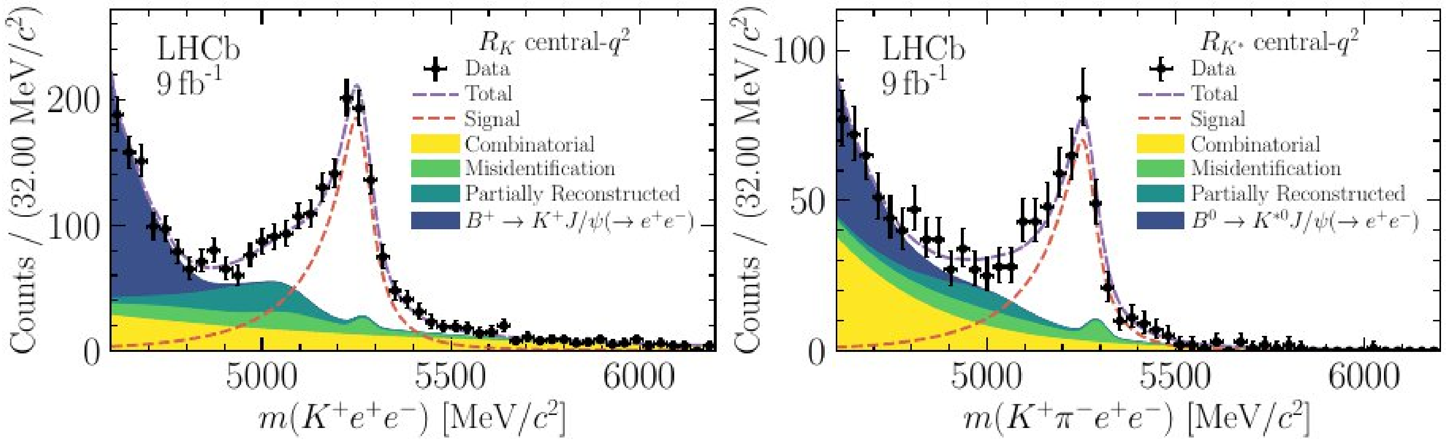
R(K$^{(*)}$) results @ LHCb

- Most precise LFU test in $b \to s l^+ l^-$ decays
- Supersedes previous results

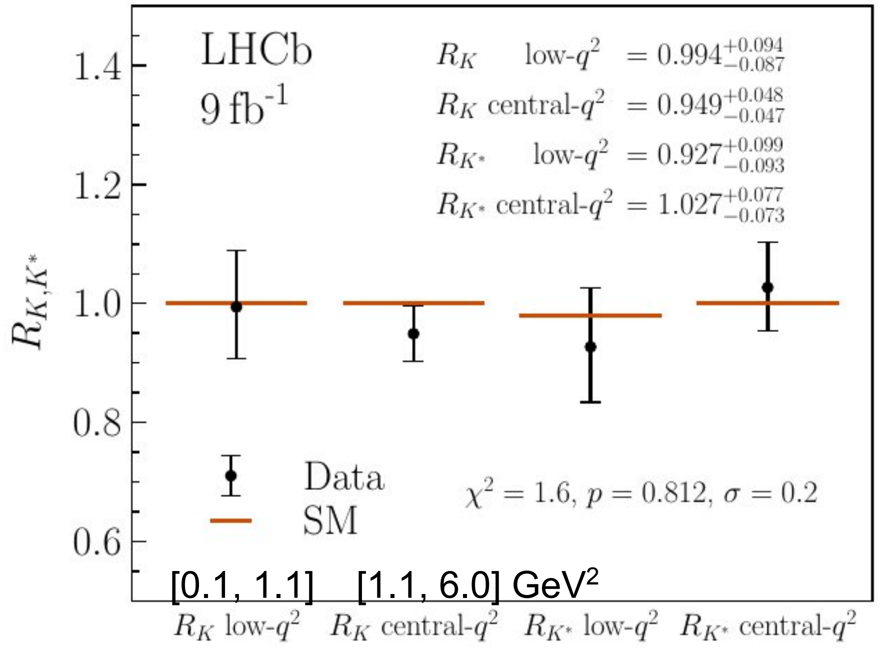


PRL 131 (2023) 051803
PRD 108 (2023) 032002

R(K$^{(*)}$) results @ LHCb

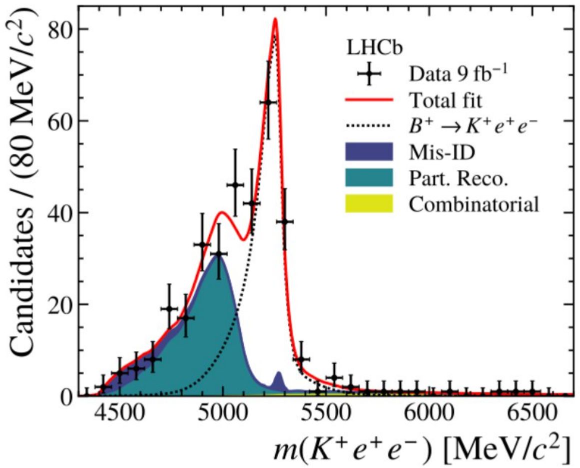


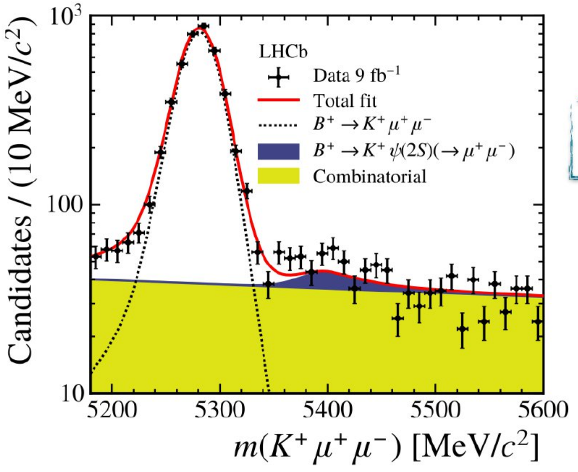
- Most precise LFU test in $b \to s l^+ l^-$ decays
- Supersedes previous results
- Improved systematics of mis-IDed hadronic background in electron mode
- Now compatible with SM predictions at 0.2σ level
- Uncertainties statistically dominated



R(K) result at high q^2

- First LHCb result at high q^2 region above $\psi(2S)$ ($q^2 > 14.3$ GeV^2)
- Full Runs1-2 9 fb^{-1} analysis





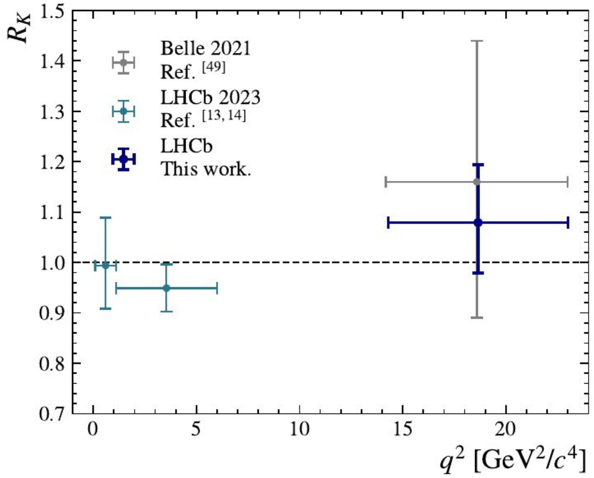
$N(K^+\mu^+\mu^-) = 4008 \pm 71$

$$R_K = \frac{N(K^+\mu^+\mu^-)}{N(K^+e^+e^-)} \cdot \frac{\varepsilon(K^+e^+e^-)}{\varepsilon(K^+\mu^+\mu^-)} \cdot \frac{1}{r_{J/\psi}}$$

Most precise to date:

$$R_K(q^2 > 14.3\ \mathrm{GeV}^2/c^4) = 1.08^{+0.11}_{-0.09}{}^{+0.04}_{-0.04}$$

- Compatible with the SM

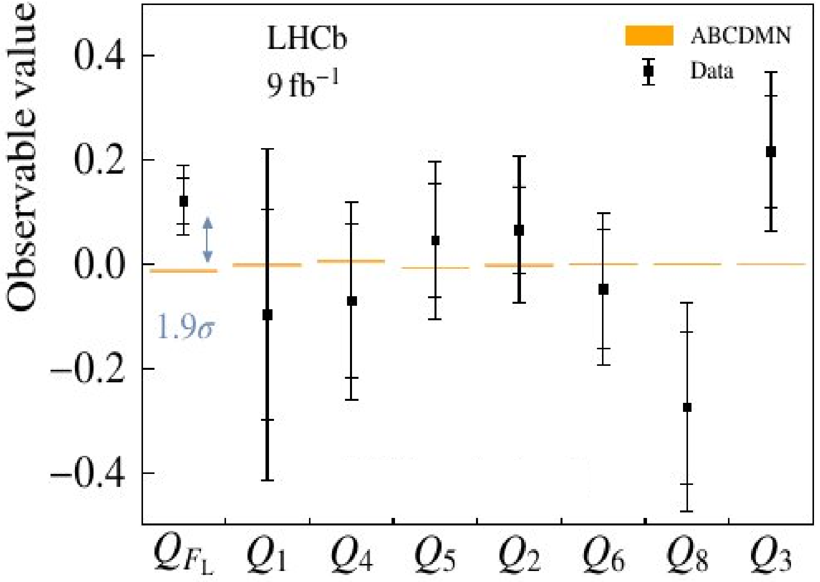


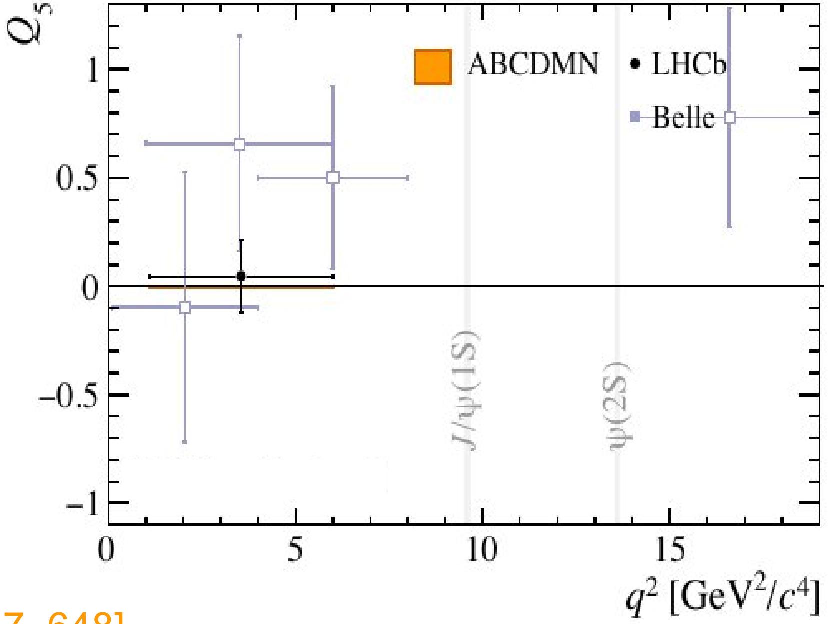
arXiv:2502.10291

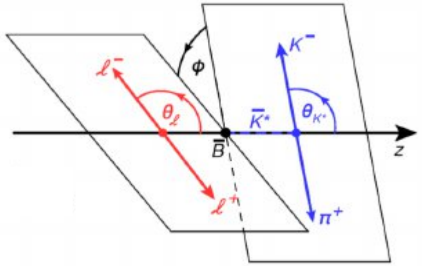
LFU in angular analysis of $\mathrm{B} \to K^{*0}\mathrm{e}^+\mathrm{e}^-$

- First angular analysis at central q^2 region
- Full Runs1-2 9 fb^{-1} analysis with 5D unbinned weighted fit
- LFU quantities derived by comparing $\mathrm{e}^+\mathrm{e}^-$ to $\mu^+\mu^-$ results in [PRL 132 (2024) 131801]

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







Results are all consistent with LFU conservation hypothesis

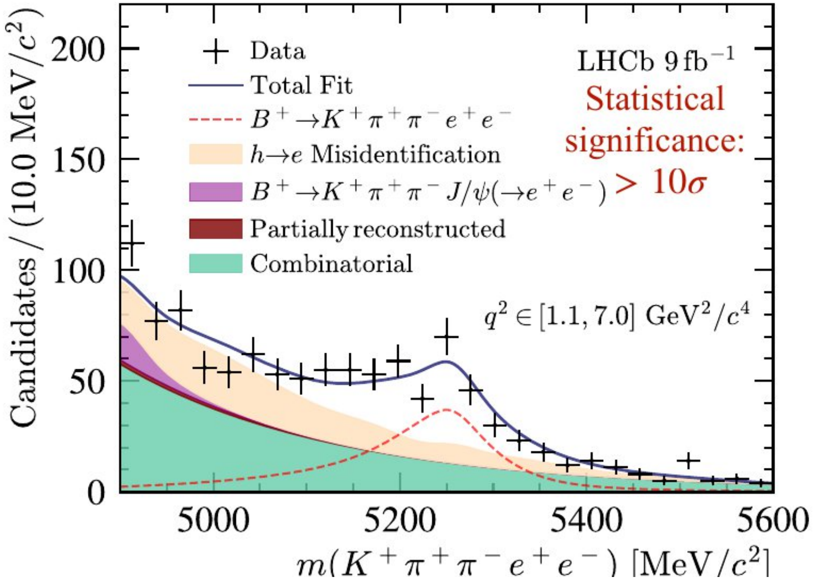
[M. Algueró et al., EPJC 83 (2023) 7, 648]

arXiv:2412.11645

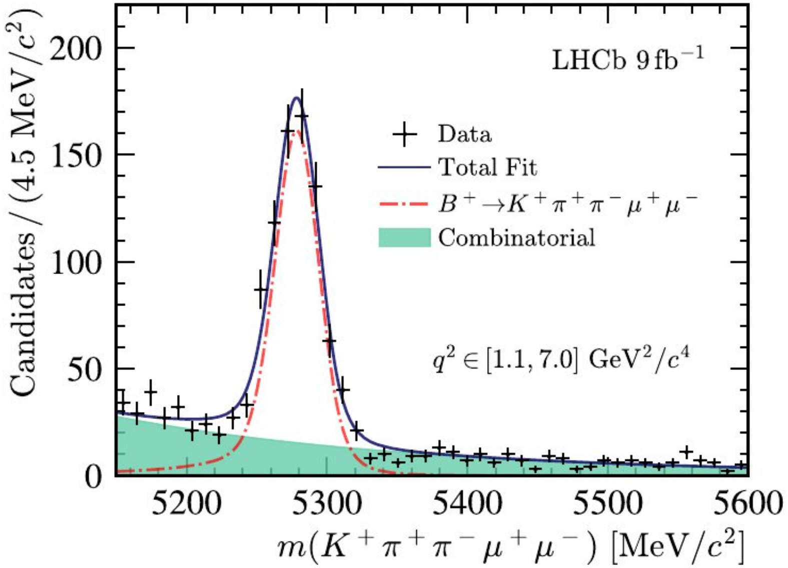
R(Kππ): LFU in $B \to K\pi\pi l^+ l^-$

- First LFU test in this channel, inclusive $K\pi\pi$ system
- In central q² region: $1.0 < q^2 < 7.0$ GeV²
- First observation of $B^+ \to K^+\pi^+\pi^- e^+ e^-$
- Cross-checks: $r_{J/\psi} = 1.033 \pm 0.017, R_{\psi(2S)} = 1.040 \pm 0.030$

$$R^{-1}_{K\pi\pi} \equiv \frac{\frac{\mathcal{N}}{\varepsilon}(B^+ \to K^+\pi^+\pi^- e^+ e^-)}{\frac{\mathcal{N}}{\varepsilon}[B^+ \to K^+\pi^+\pi^- J/\psi\,(\to e^+e^-)]} \Bigg/ \frac{\frac{\mathcal{N}}{\varepsilon}(B^+ \to K^+\pi^+\pi^- \mu^+\mu^-)}{\frac{\mathcal{N}}{\varepsilon}[B^+ \to K^+\pi^+\pi^- J/\psi\,(\to \mu^+\mu^-)]}$$



$\mathcal{N}(B^+ \to K^+\pi^+\pi^- e^+ e^-) = 264 \pm 21$



$\mathcal{N}(B^+ \to K^+\pi^+\pi^- \mu^+ \mu^-) = 731 \pm 31$

$$R^{-1}_{K\pi\pi} = 1.31^{+0.18}_{-0.17}\,(\text{stat})\,^{+0.12}_{-0.09}\,(\text{syst})$$

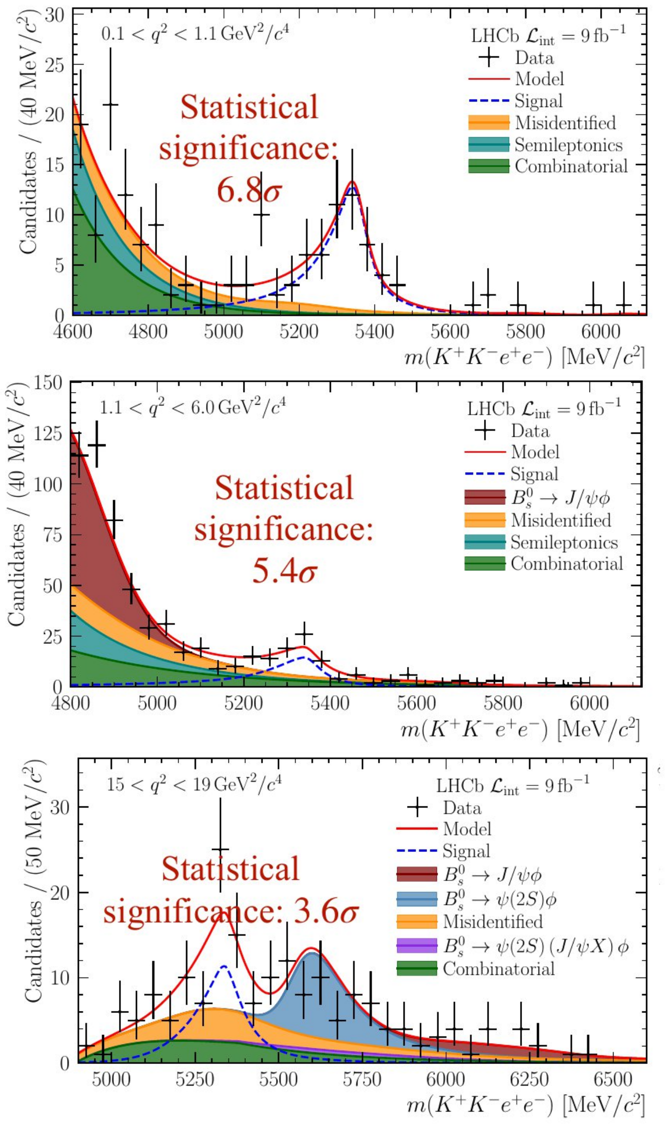
- Compatible with the SM

R(ϕ): LFU in $B_s^0 \to \phi l^+ l^-$

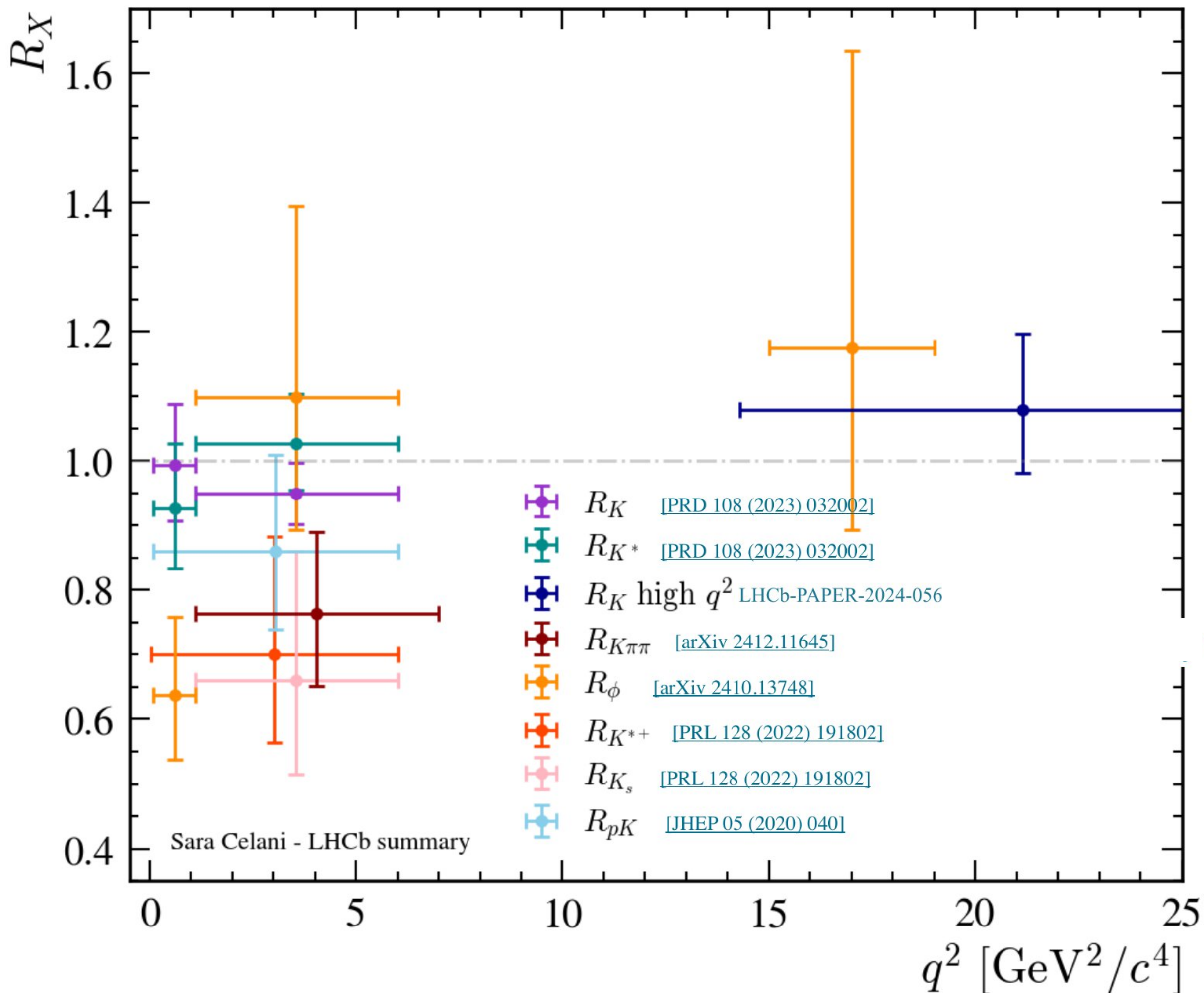
- First LFU test for B_s^0 decays
- In three q^2 regions: [0.1, 1.1], [1.1, 6.0], [15, 19] GeV^2
- Cross-checks: $r_{J/\psi} = 0.997 \pm 0.013$, $R_{\psi(2S)} = 1.010 \pm 0.026$
- Results in agreement with SM:

q^2 [GeV$^2/c^4$]	R_ϕ^{-1}
$0.1 < q^2 < 1.1$	$1.57\,^{+0.28}_{-0.25} \pm 0.05$
$1.1 < q^2 < 6.0$	$0.91\,^{+0.20}_{-0.19} \pm 0.05$
$15.0 < q^2 < 19.0$	$0.85\,^{+0.24}_{-0.23} \pm 0.10$

$$R_\phi = \left(\frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi)}\right) \Big/ \left(\frac{\mathcal{B}(B_s^0 \to \phi e^+e^-)}{\mathcal{B}(B_s^0 \to J/\psi(\to e^+e^-)\phi)}\right)$$



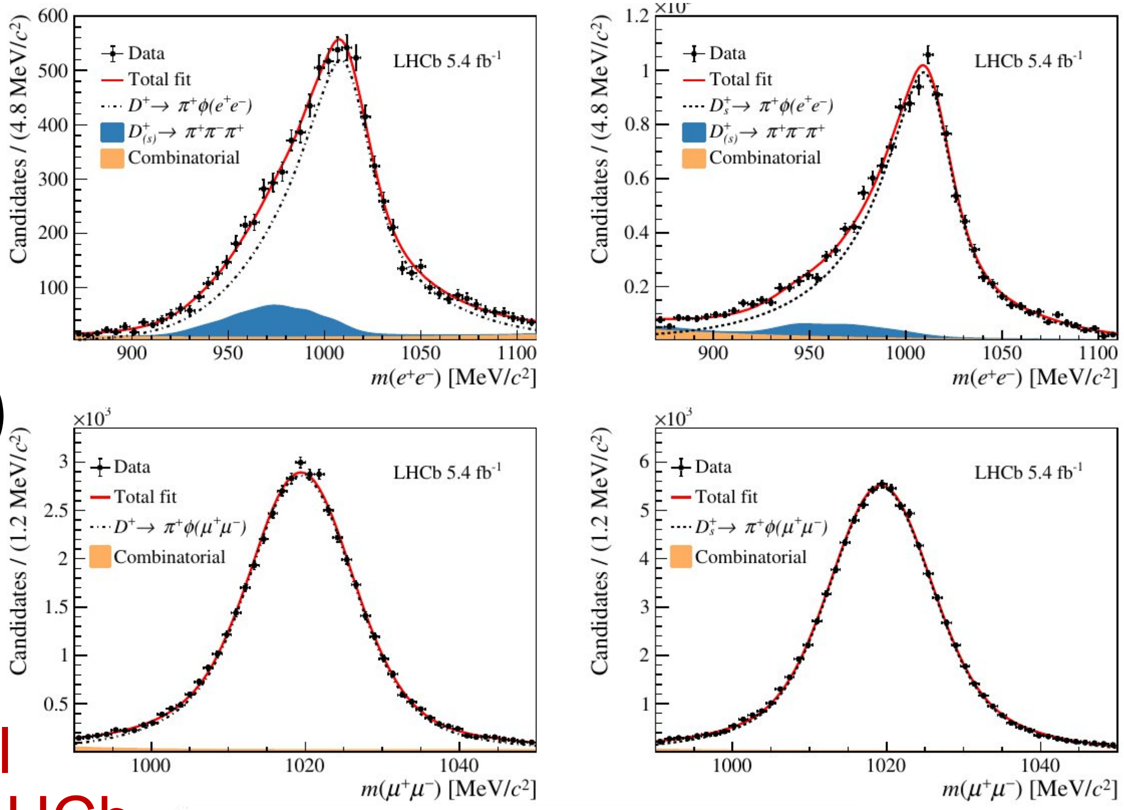
Summary of LHCb results



Moriond QCD 2025 - Flavour changing neutral currents decay at LHCb

LFU in $D_s^+ \to \pi^+\phi(\to l^+l^-)$

- Based on 2016-2018 data (5.4 fb^{-1})
- The BF ratio $R(\phi\pi) \equiv \frac{B(\phi\to\mu\mu)}{B(\phi\to ee)}$ is measured in D_s^+ decays, and normalized wrt $B^+ \to K^+J/\psi(\to l^+l^-)$
  - $R_{\phi\pi} = 1.022 \pm 0.012\,(\text{stat}) \pm 0.048\,(\text{syst})$
  - Consistent with LFU within 1σ
  - Crucial for understanding experimental features of low-mass dileptons in the LHCb environment



Decay mode	Yield
$D^+ \to \pi^+\phi(\to e^+e^-)$	$7\,460 \pm 140$
$D^+ \to \pi^+\phi(\to \mu^+\mu^-)$	$43\,512 \pm 220$
$D_s^+ \to \pi^+\phi(\to e^+e^-)$	$16\,740 \pm 210$
$D_s^+ \to \pi^+\phi(\to \mu^+\mu^-)$	$87\,022 \pm 300$

arXiv:2412.09414

LFU in $\mathrm{D}^0 \to \mathrm{hh}l^+l^-$

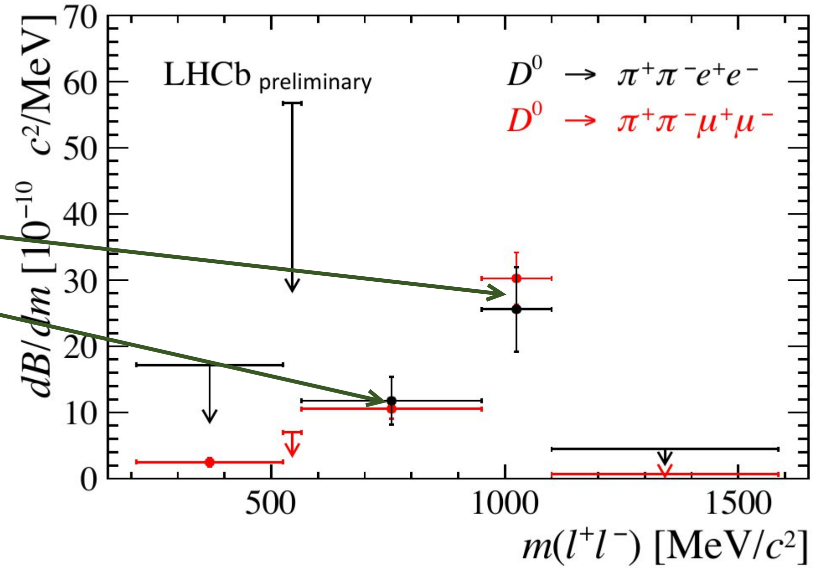
- Based on 2015-2018 data (6 fb^{-1})
- First observation of $\mathrm{D}^0 \to \pi^+\pi^-e^+e^-$

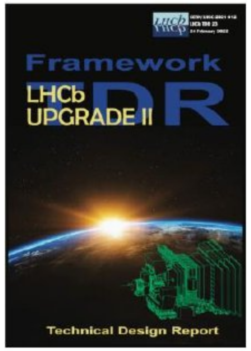
$$\mathcal{B}(D^0 \to \pi^+\pi^-[e^+e^-]_{m(e^+e^-)>2m_\mu}) = (13.3 \pm 1.1 \pm 1.7 \pm 1.8) \times 10^{-7}$$

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$

Phys. Rev. Lett. 119 (2017) 181805

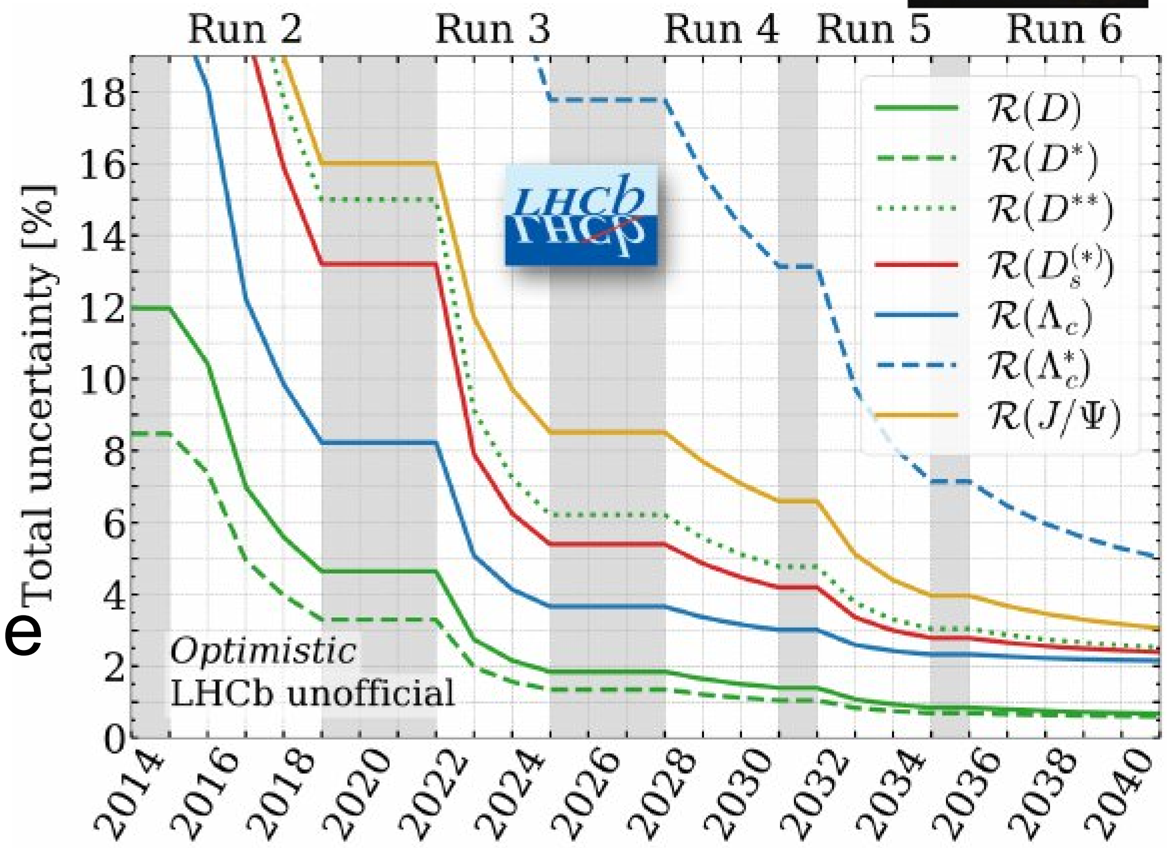
- Integrating over the dielectron mass ranges $D^0 \to \pi^+\pi^-e^+e^-$: compatible within 1.3σ with muon mode
- Similarly in in ρ/ω and φ dilepton mass regions confirming lepton flavour universality at the current level of precision





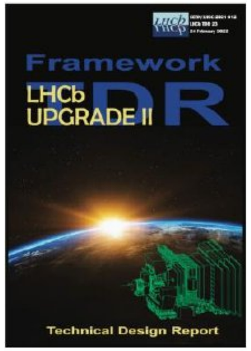
Prospects on LFU @ LHCb

- Broad program of related measurements underway
- With larger data samples, more efforts are need to have better control of systematics
- Fast MC production with small event size is certainly a move in the right direction
- High trigger efficiency essential at high pileup



Rev. Mod. Phys. 94, 015003 (2022)

Prospects on LFU @ LHCb



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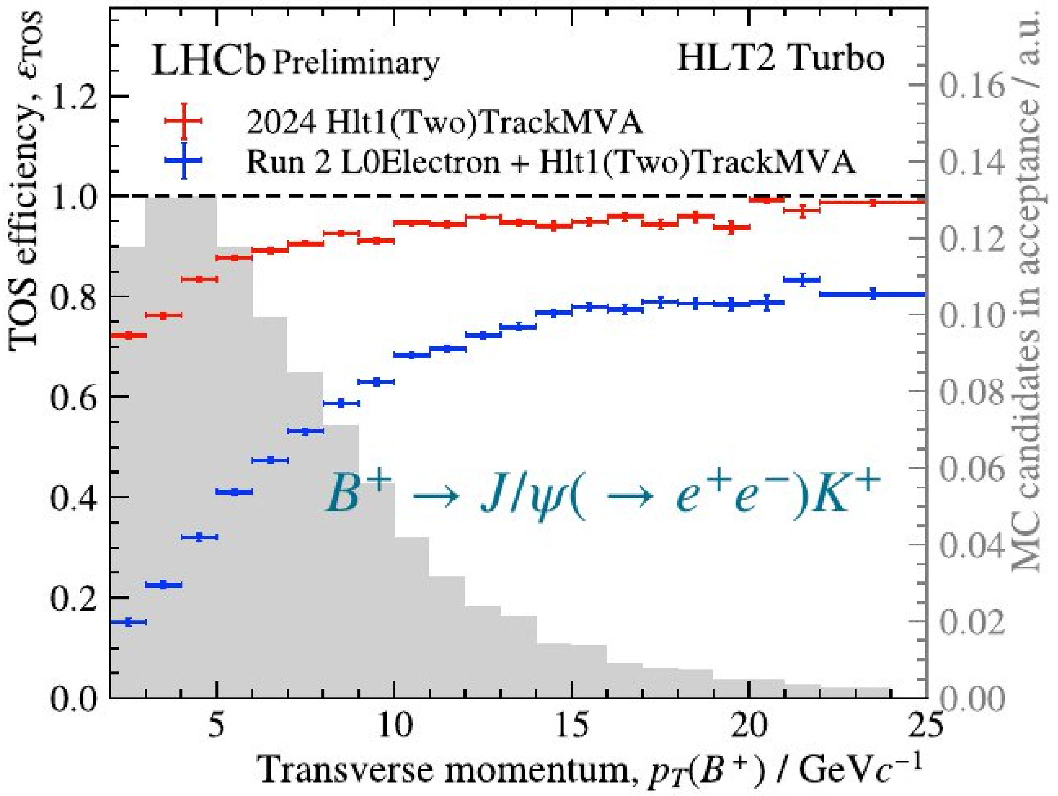
LHCB-FIGURE-2024-030



Summary & outlook

- LFU tests in a large range of decay channels have been performed recently by LHCb, mostly in the beauty sector
- With improved precision or being first measurements, all results show good agreement with LFU
- $R(D^{(*)})$ results still show tension with SM
- Upcoming Run2 results: $R(D^*)$, $R(J/\psi)$, $R(\Lambda_c)$, etc.
- Run3: Doubled int. lumi. already with 2024 data, more efficient trigger system
- Synergy of different experiments important to improve precision
- Cooperation with theorists essential for more stringent LFU tests

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