Lepton Flavor Universality Highlights from LHCb

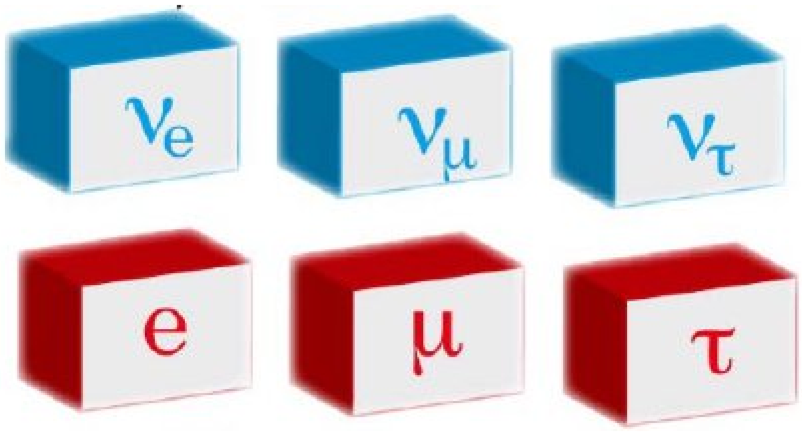
Liang Sun

Wuhan University

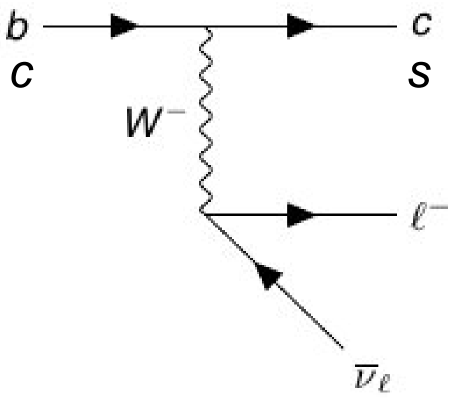
July/29/2024

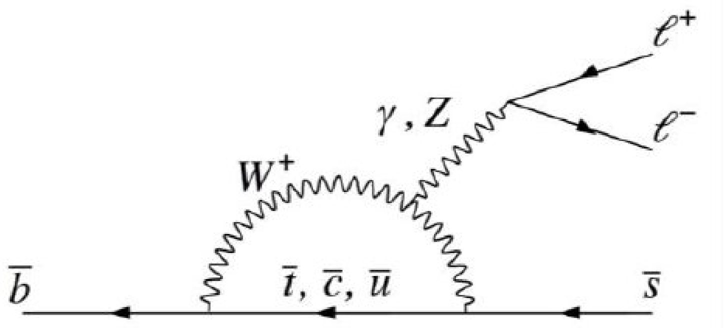
Outline

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



Charged currents versus neutral currents



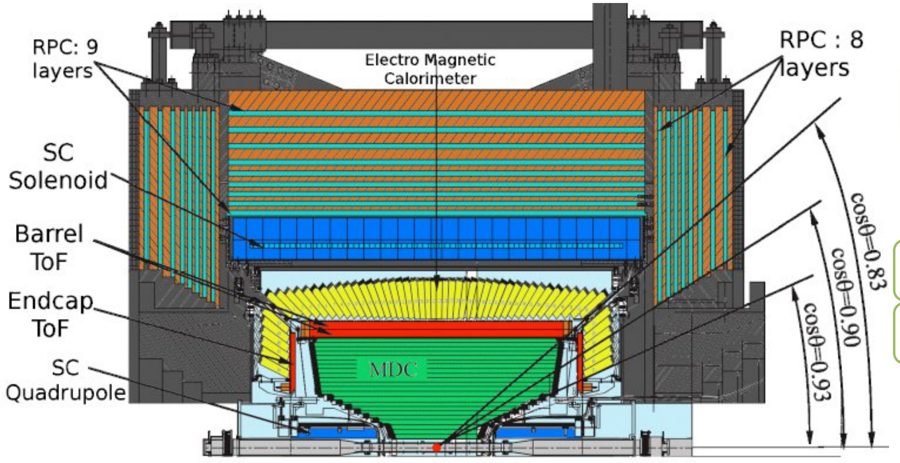


- One charged lepton in the final state
- Tree level
- Theoretically clean
- Abundance of data
- Experimentally challenging due to missing neutrino

- 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

BESIII

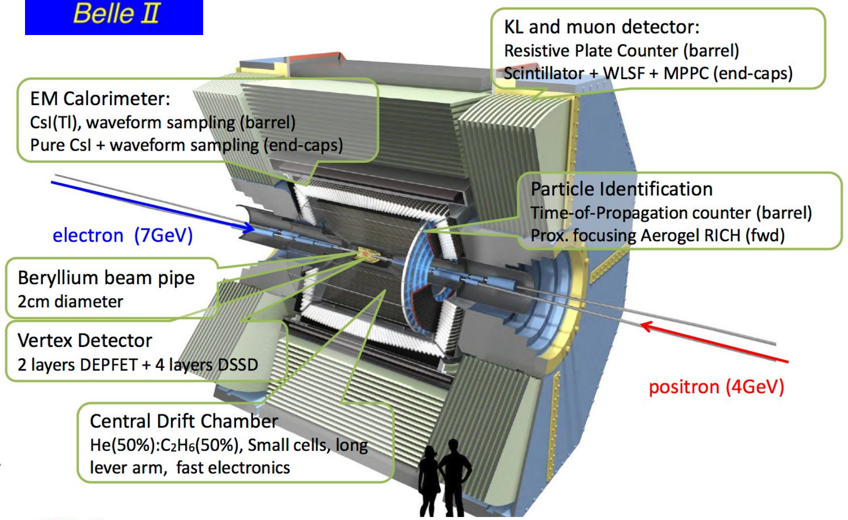


Wire tracker (no Si); TOF + dE/dx for PID; CsI Ecal; RPC muon

- ✓ 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

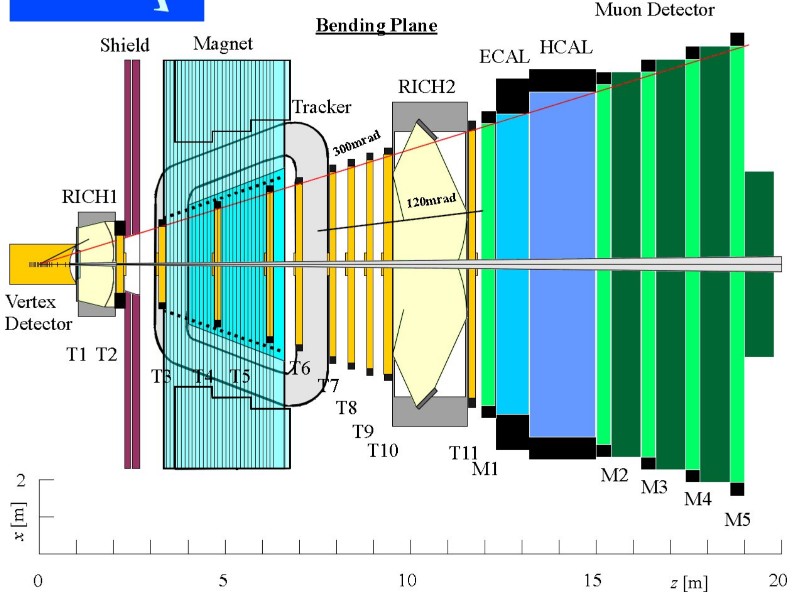
Belle II

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

LHCb

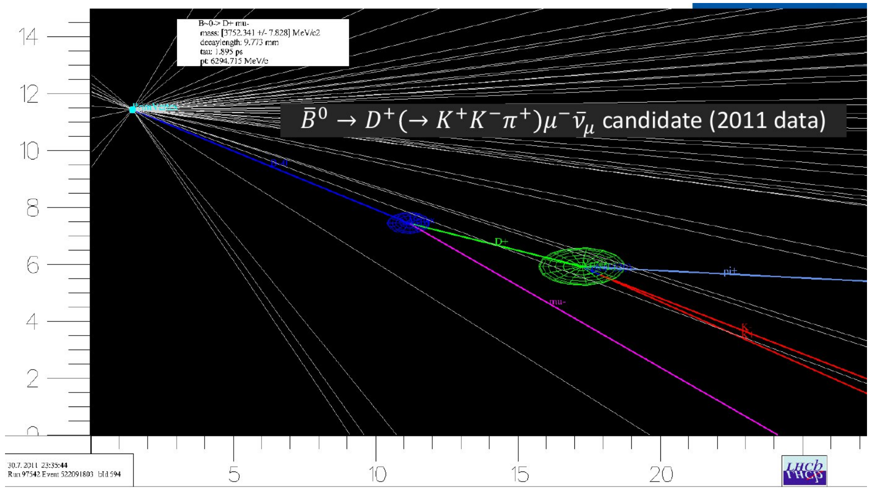


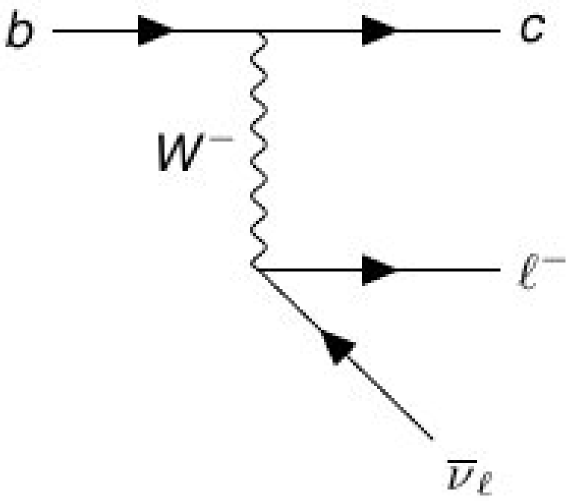
- ✓ large production cross-section
- ✓ large boost: excellent time res
- ● dedicated trigger required
- ● hard to do neutrals and neutrinos

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: $\tau \to e\bar{\nu}\nu, \mu\bar{\nu}\nu, \pi(\pi^0)\nu$
  - **Hadron machines:** $\boldsymbol{\tau \to \mu\bar{\nu}\nu, \pi\pi\pi(\pi^0)\nu}$

LFU tests in semi-leptonic B decays

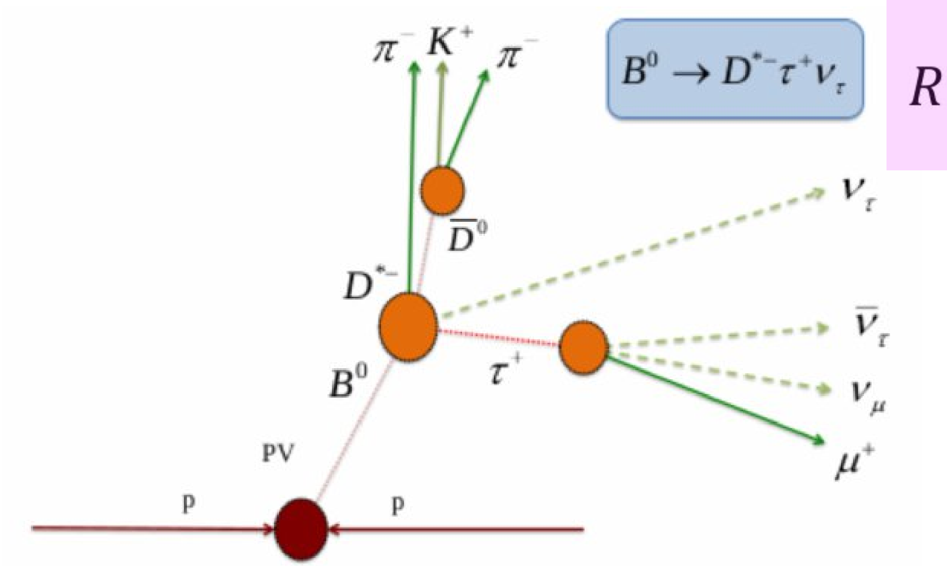


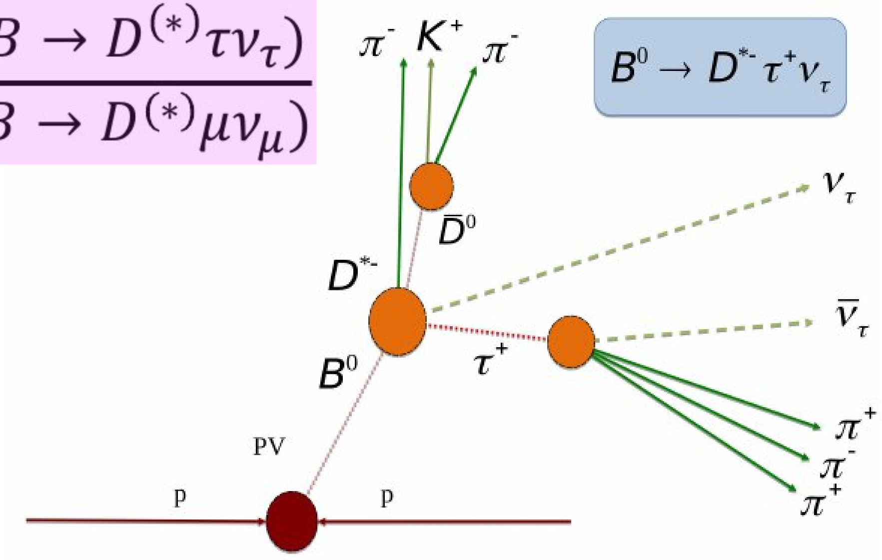


PRL 131, 111802 (2023)
PRD 108, 012018 (2023);
PRD 109, 119902(E) (2024)

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

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





Muonic $\tau \to \mu\bar{\nu}\nu$:

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

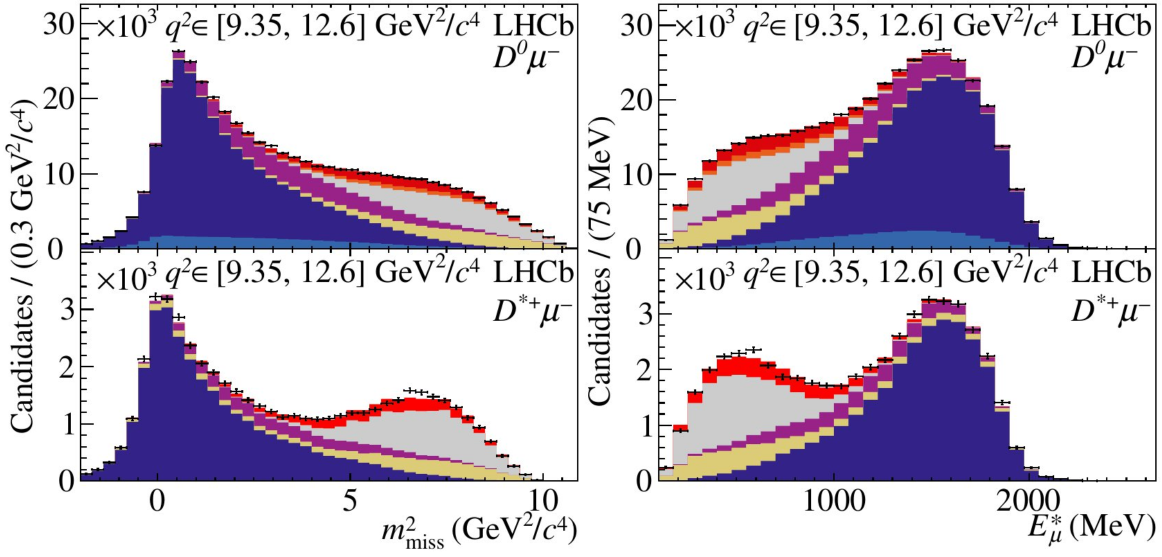
Hadronic $\tau \to \pi\pi\pi(\pi^0)\bar{\nu}$:

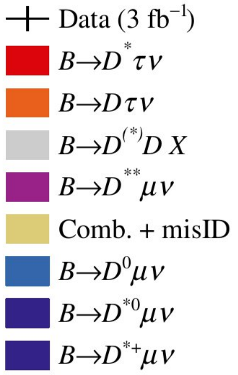
- Relatively high purity
- External BR measurement for normalization
- Decay vertex of τ well measured to suppress dominant backgrounds
- 3π dynamics important for the separation of B-> D*DX backgrounds

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

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

Muonic $\tau \to \mu\bar{\nu}\nu$





Using Run1 3 fb^{-1} data:

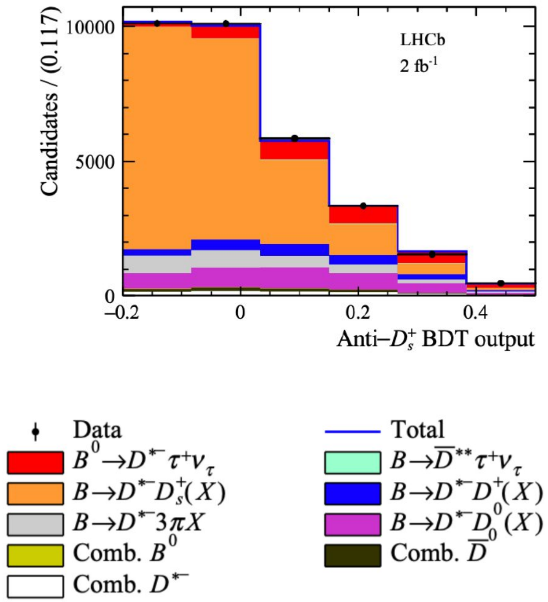
$$R(D^*) = 0.281 \pm 0.018\,(\text{stat.}) \pm 0.024\,(\text{syst.})$$

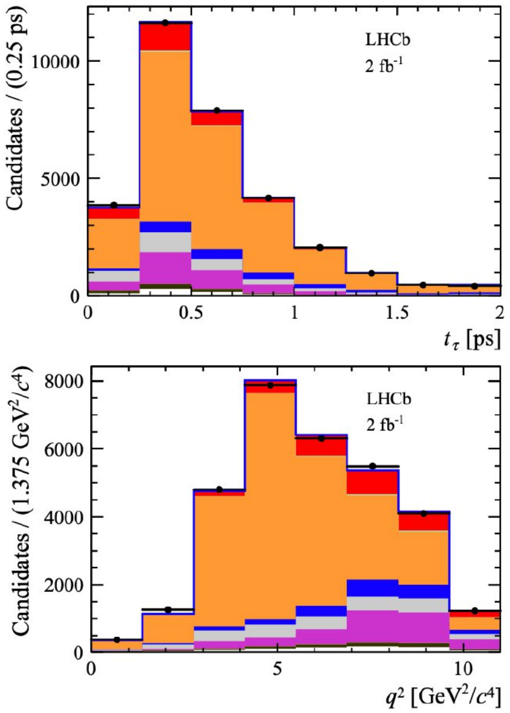
$$R(D) = 0.441 \pm 0.060\,(\text{stat.}) \pm 0.066\,(\text{syst.})$$

$$\rho = -0.43$$

1.9σ deviation from SM

Hadronic $\tau \to \pi\pi\pi(\pi^0)\nu$





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

Agreement w/ SM <1σ

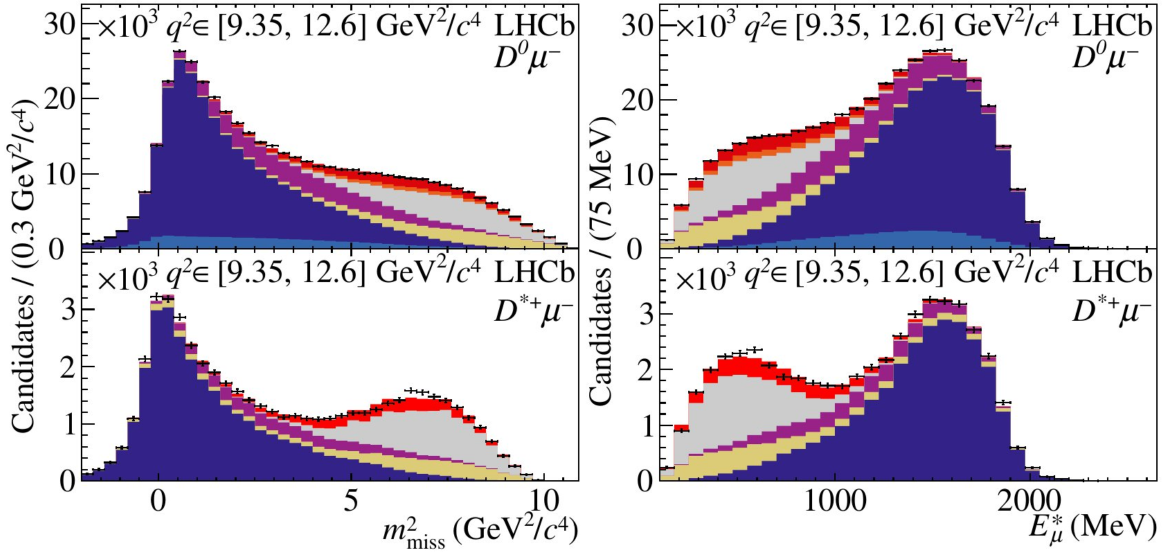
$$R(D^*) = 0.257 \pm 0.012\,(stat) \pm 0.014\,(syst) \pm 0.012\,(ext)$$

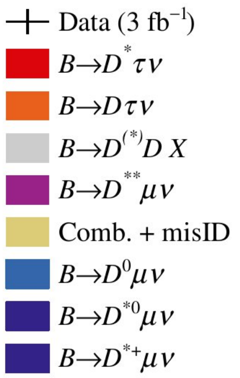
Considerable systematic uncertainty due to limited sample sizes

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

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

Muonic $\tau \to \mu\bar{\nu}\nu$





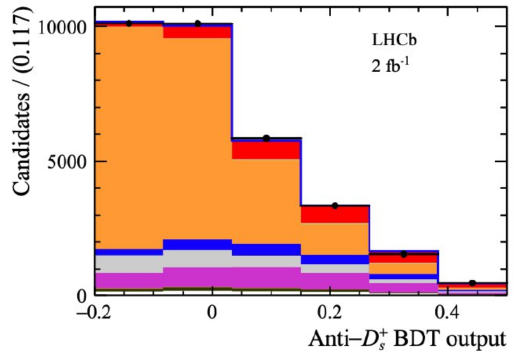
Using Run1 3 fb^{-1} data:

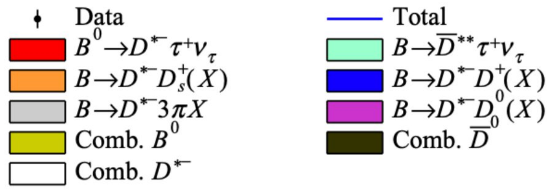
$$R(D^*) = 0.281 \pm 0.018\,(\text{stat.}) \pm 0.024\,(\text{syst.})$$
$$R(D) = 0.441 \pm 0.060\,(\text{stat.}) \pm 0.066\,(\text{syst.})$$

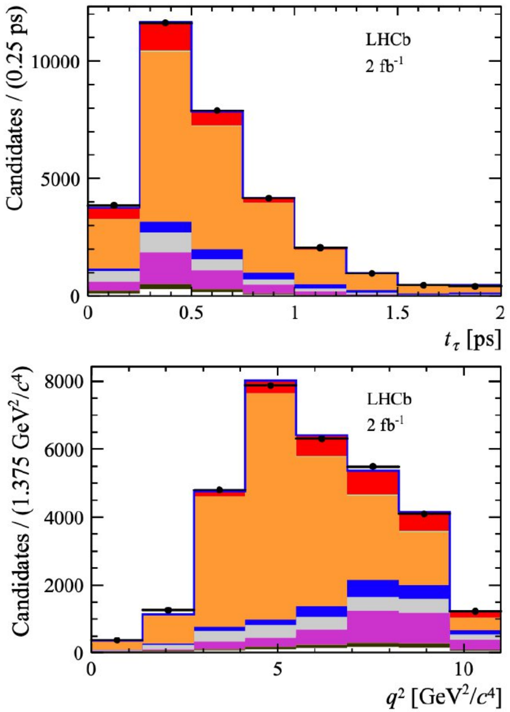
$$\rho = -0.43$$

1.9σ deviation from SM

Hadronic $\tau \to \pi\pi\pi(\pi^0)\nu$







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

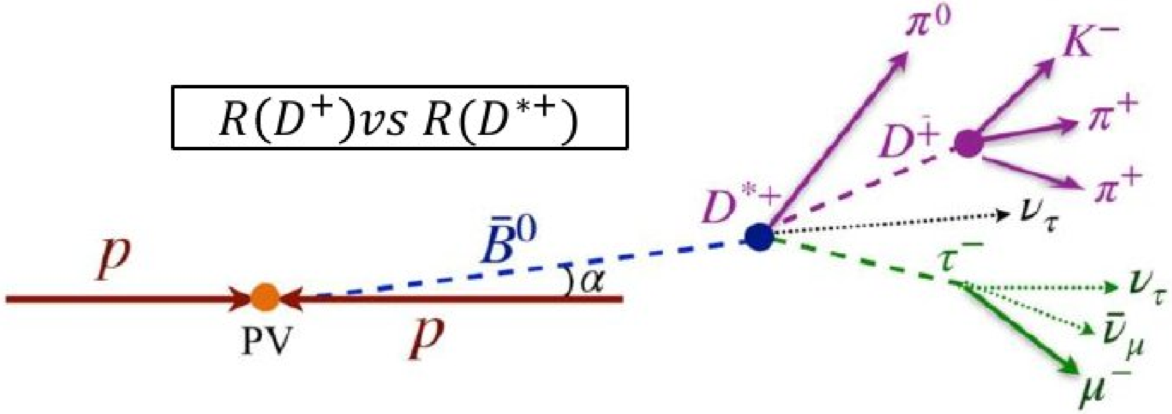
Agreement w/ SM <1σ

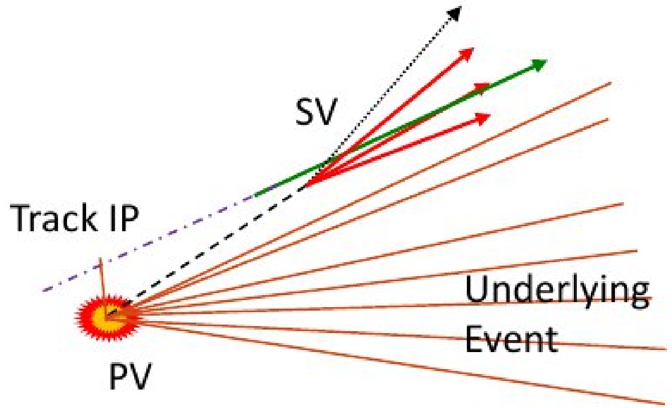
$$R(D^{*-})_{\rm comb} = 0.267 \pm 0.012(\text{stat}) \pm 0.015(\text{syst}) \pm 0.013(\text{ext})$$

Details can be found in Bo Fang’s PhD thesis

arXiv:2406.03387
submitted to PRL

New results: $R(D^{(*)+})$ with $\tau \rightarrow \mu\nu\bar{\nu}$





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

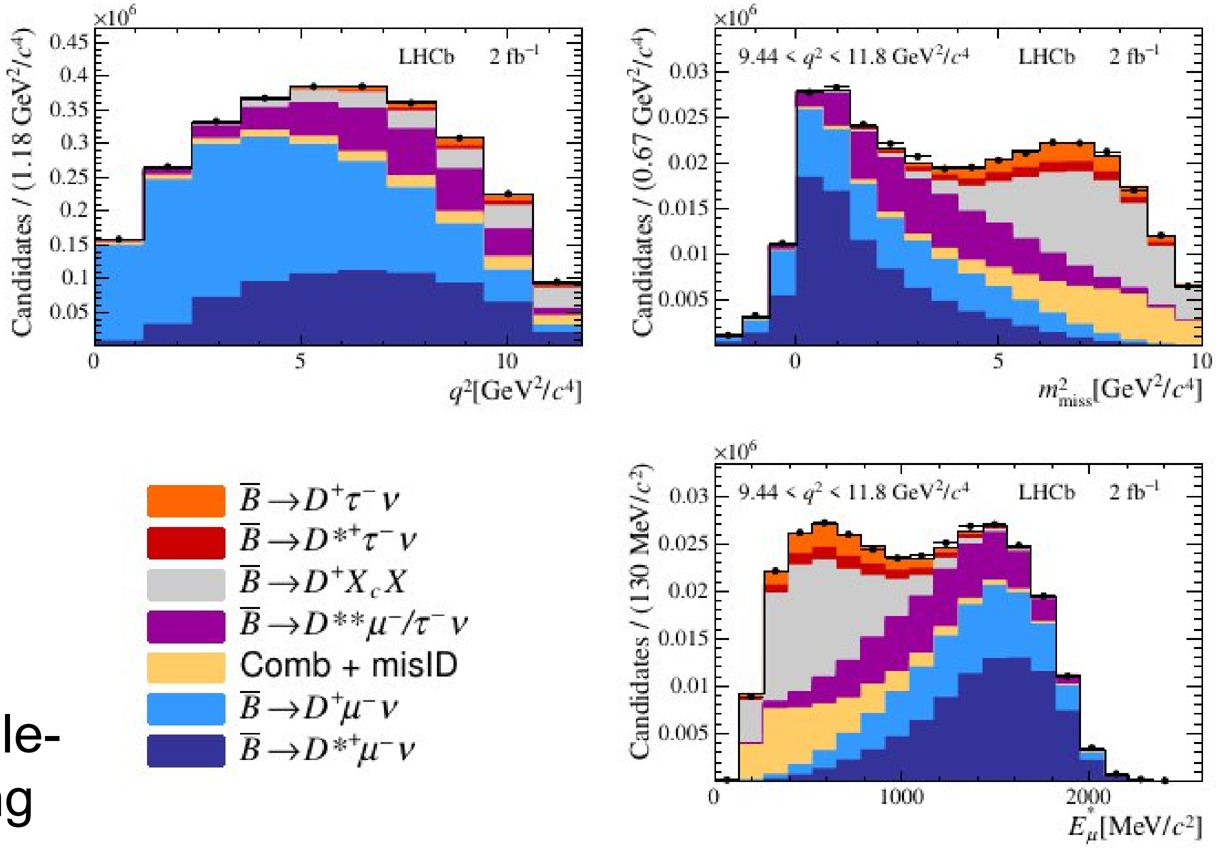
arXiv:2406.03387
submitted to PRL

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

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

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

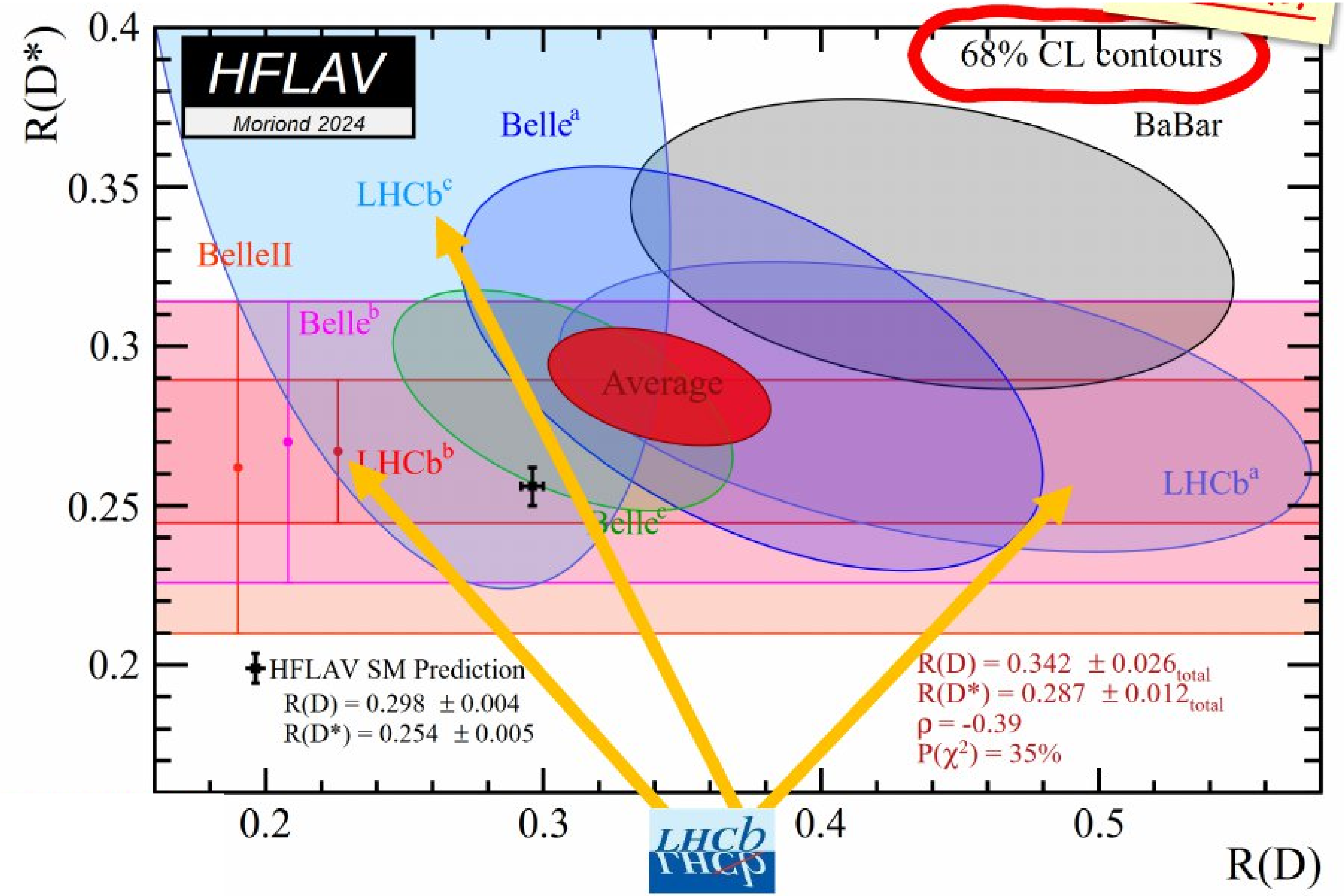
correlation coefficient = −0.39

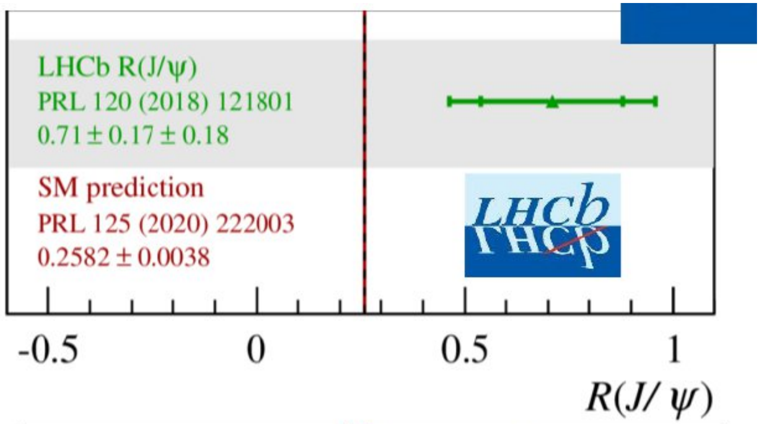


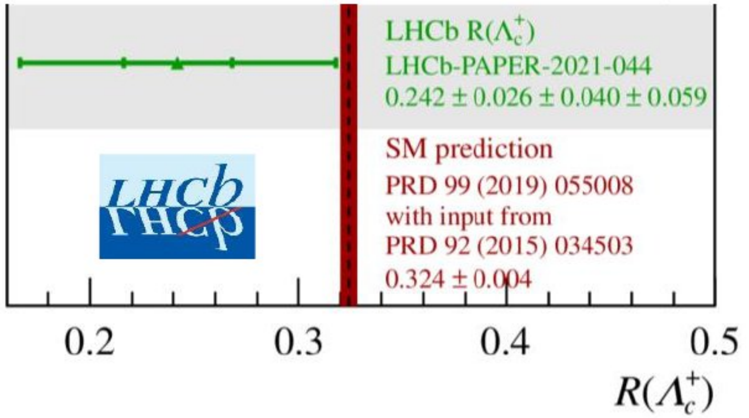
- ➢ Dominating systematic sources: FFs, double-charm background shape and misID modelling
- ➢ MC sample size no longer a major limiting factor

(a) PRL 131, 111802 (2023)
(b) PRD 108, 012018 (2023); E
(c) arXiv:2406.03387

Current R(X) status

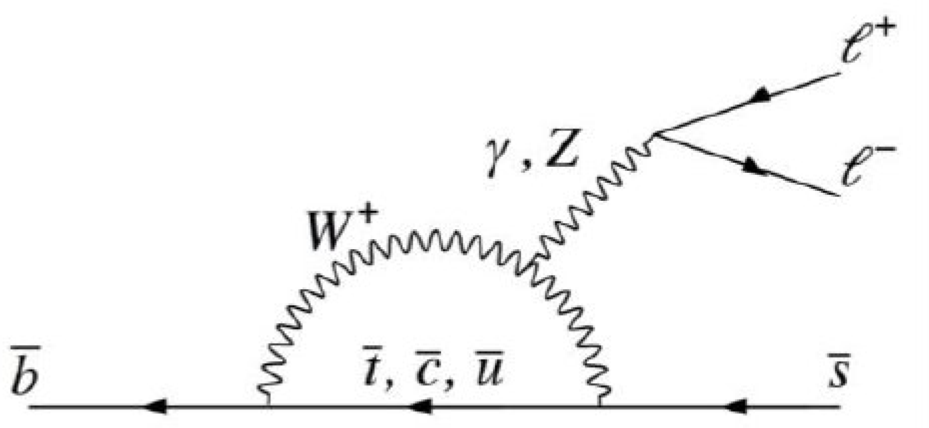




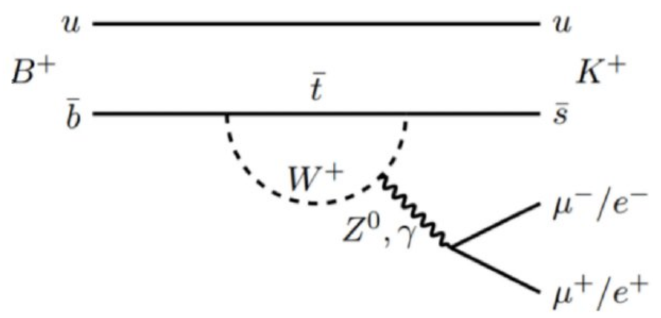


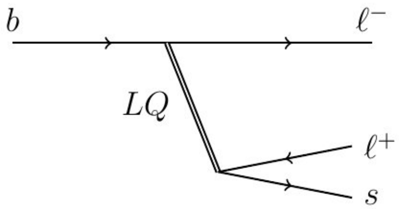
[Deviation from SM for combined R(D) − R(D∗) ~ 3.3σ]

LFU tests in rare b-hadron decays



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



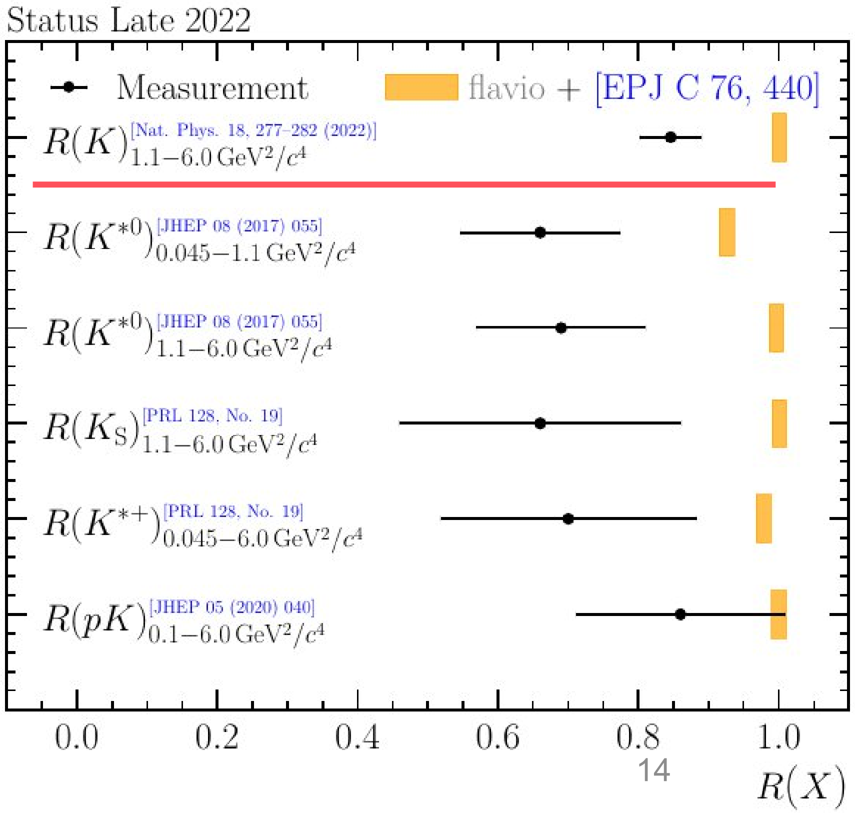


- $b \to s\ell^+\ell^-$ FCNC processes highly suppressed in SM
- NP may manifest in the loops and cause LFU violation
- LFU tests use

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

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

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



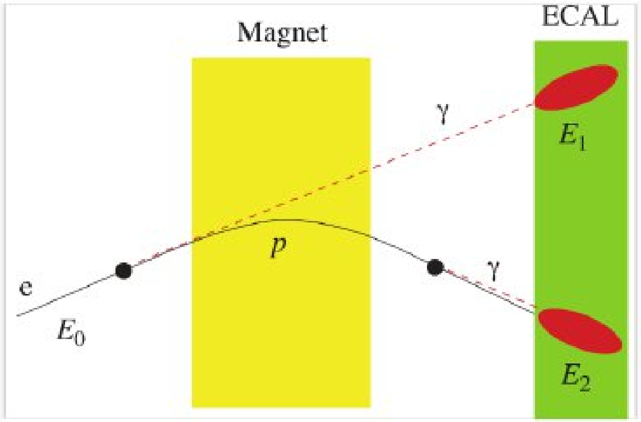
PRL 131 (2023) 051803
PRD 108 (2023) 032002

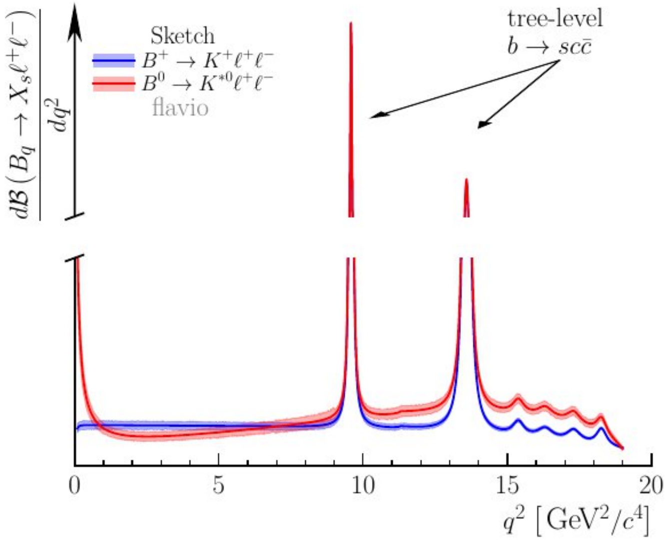
R(K$^{(*)}$) measurements @ LHCb

- 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/ψ $\to \ell^+\ell^-$ well established at ‰ level [BESIII, PRD 88, 032007 (2013)]
  - Validated in ψ(2S) mode

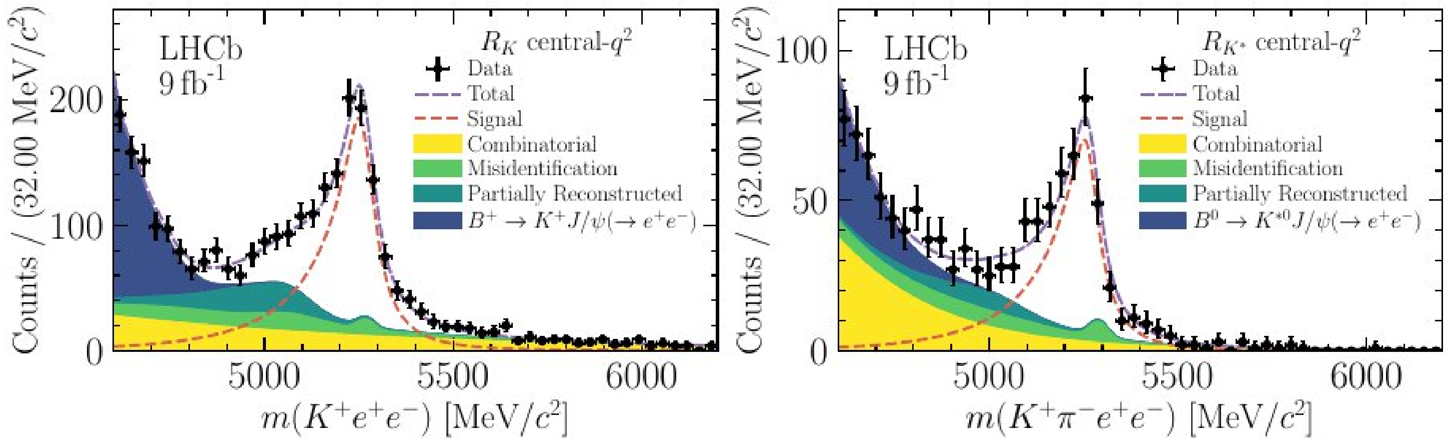


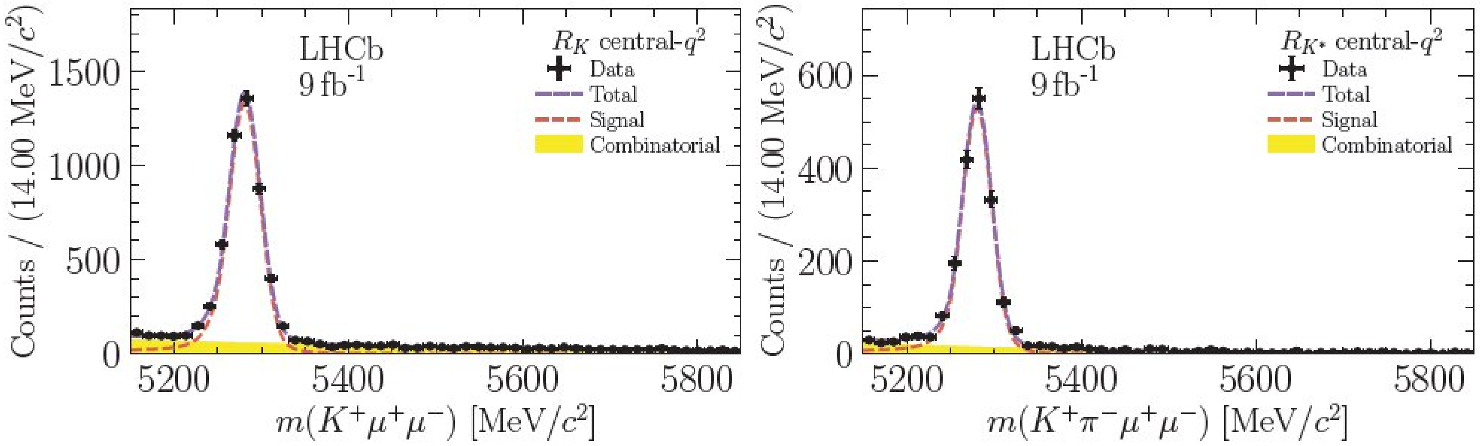


PRL 131 (2023) 051803
PRD 108 (2023) 032002

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

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

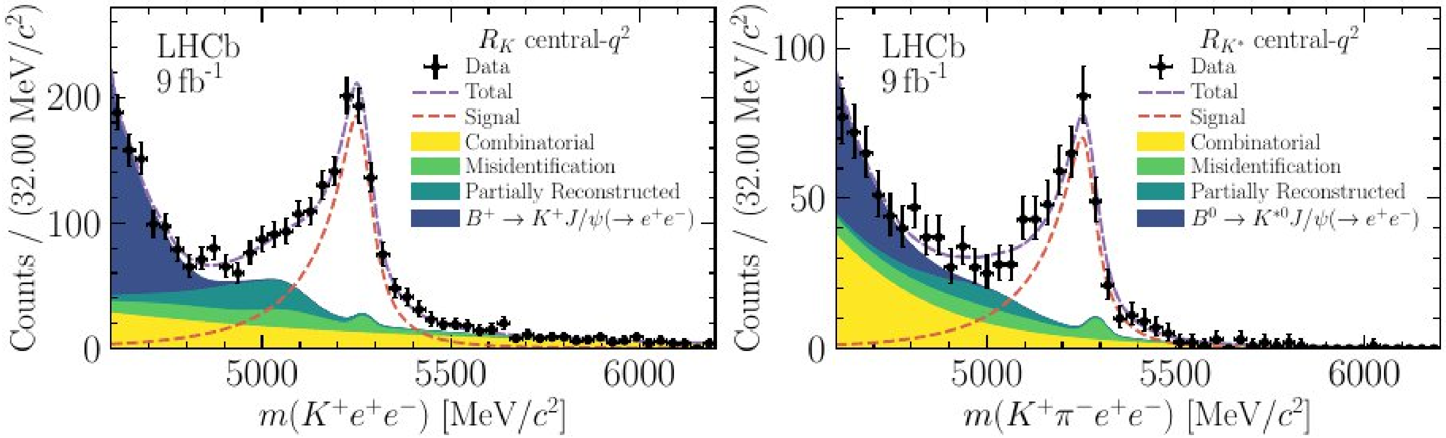


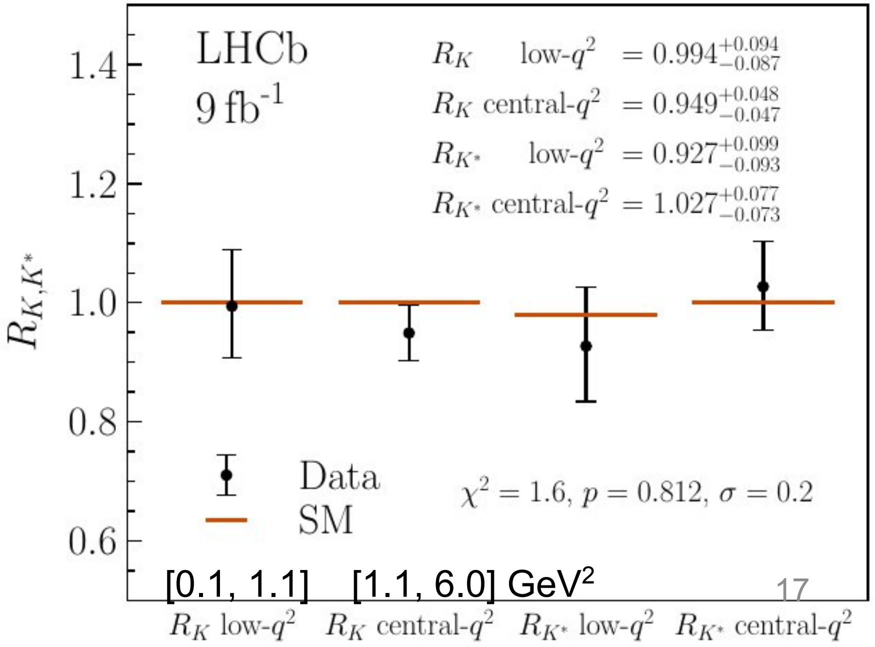


PRL 131 (2023) 051803
PRD 108 (2023) 032002

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

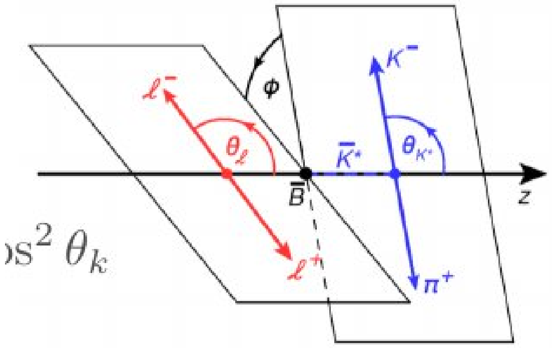
- Most precise LFU test in $b \to s\ell^+\ell^-$ decays
- Supersedes previous results
- Improved systematics of mis-IDed hadronic background in electron mode
- Now compatible with SM predictions at 0.2σ level
- Uncertainties statistically dominated



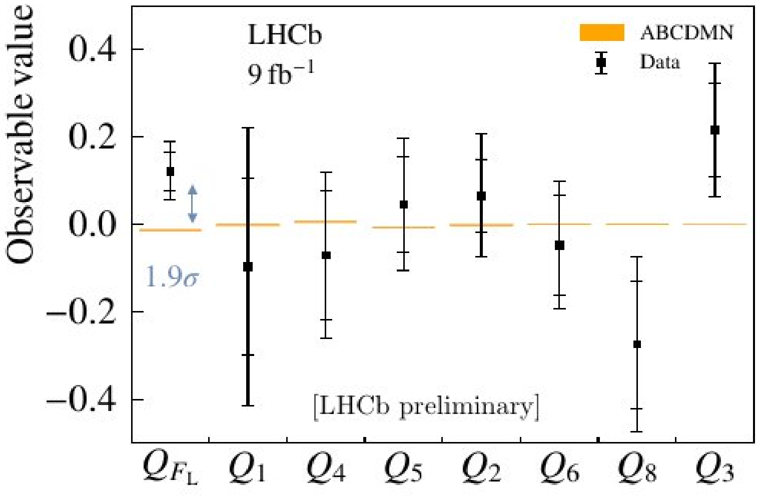


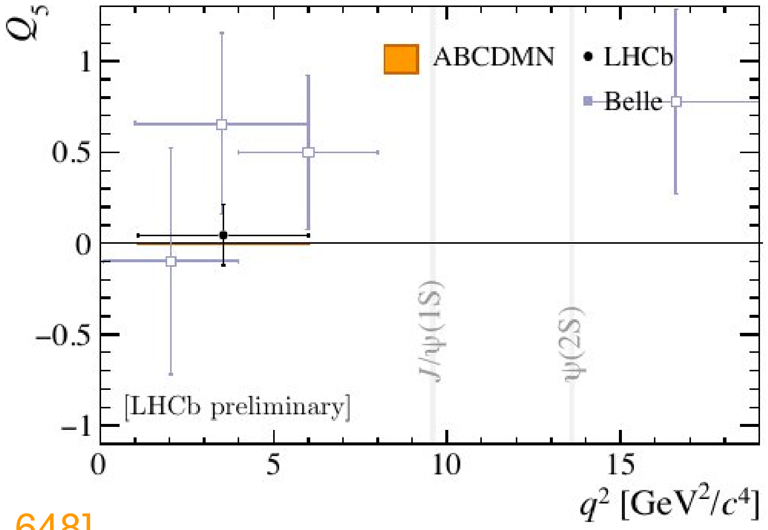
LFU in angular analysis of $B^0 \to K^{*0} l^+ l^-$

- First angular analysis of $B^0 \to K^{*0} e^+ e^-$ at central q² region
- Full Runs1-2 9fb⁻¹ analysis with 5D unbinned weighted fit
- LFU quantities derived by comparing to muon results [PRL 132 (2024) 131801]



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



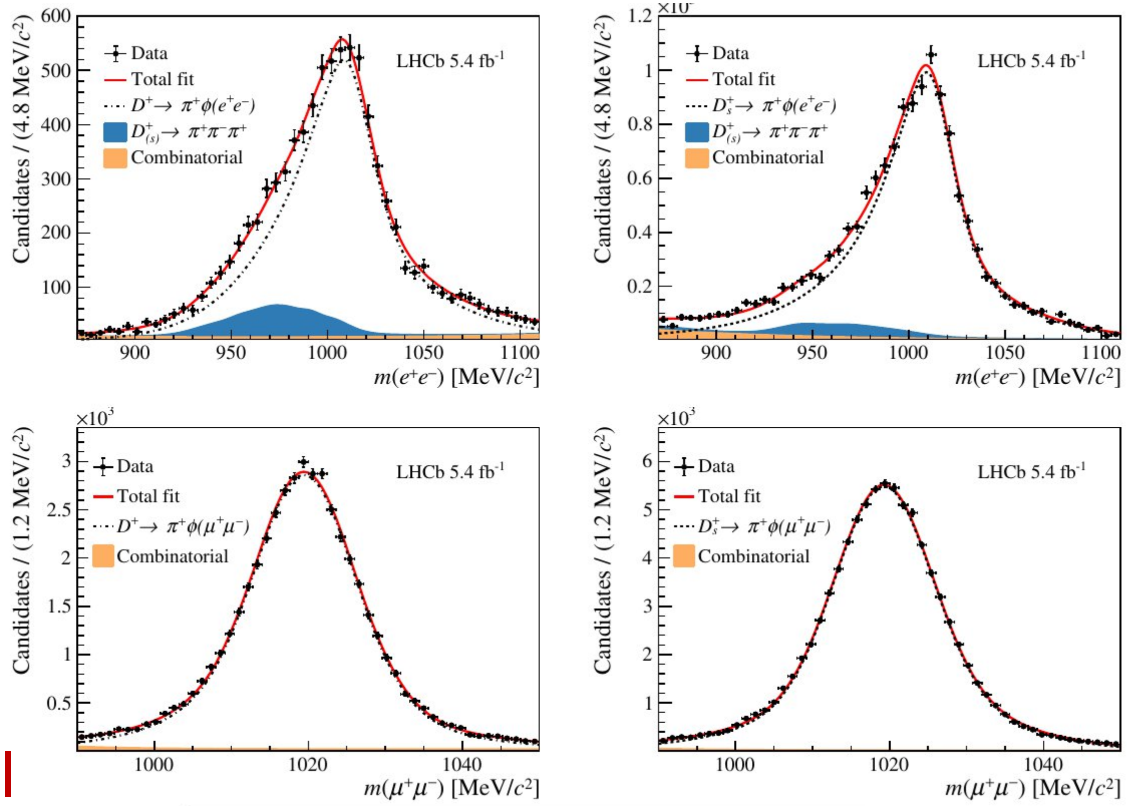


[M. Algueró et al., EPJC 83 (2023) 7, 648]

Results are all consistent with LFU conservation hypothesis

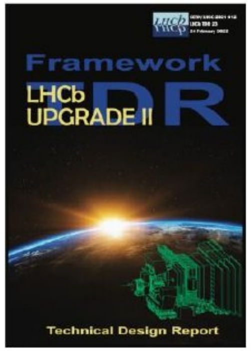
LFU in $D^+_{(s)} \to \pi^+\phi(\to l^+ l^-)$

- Based on 2016-2018 data (5.4 fb^{-1})
- The BF ratio $R_{\phi\pi} = \frac{B(\phi\to\mu^+\mu^-)}{B(\phi\to e^+e^-)}$ 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

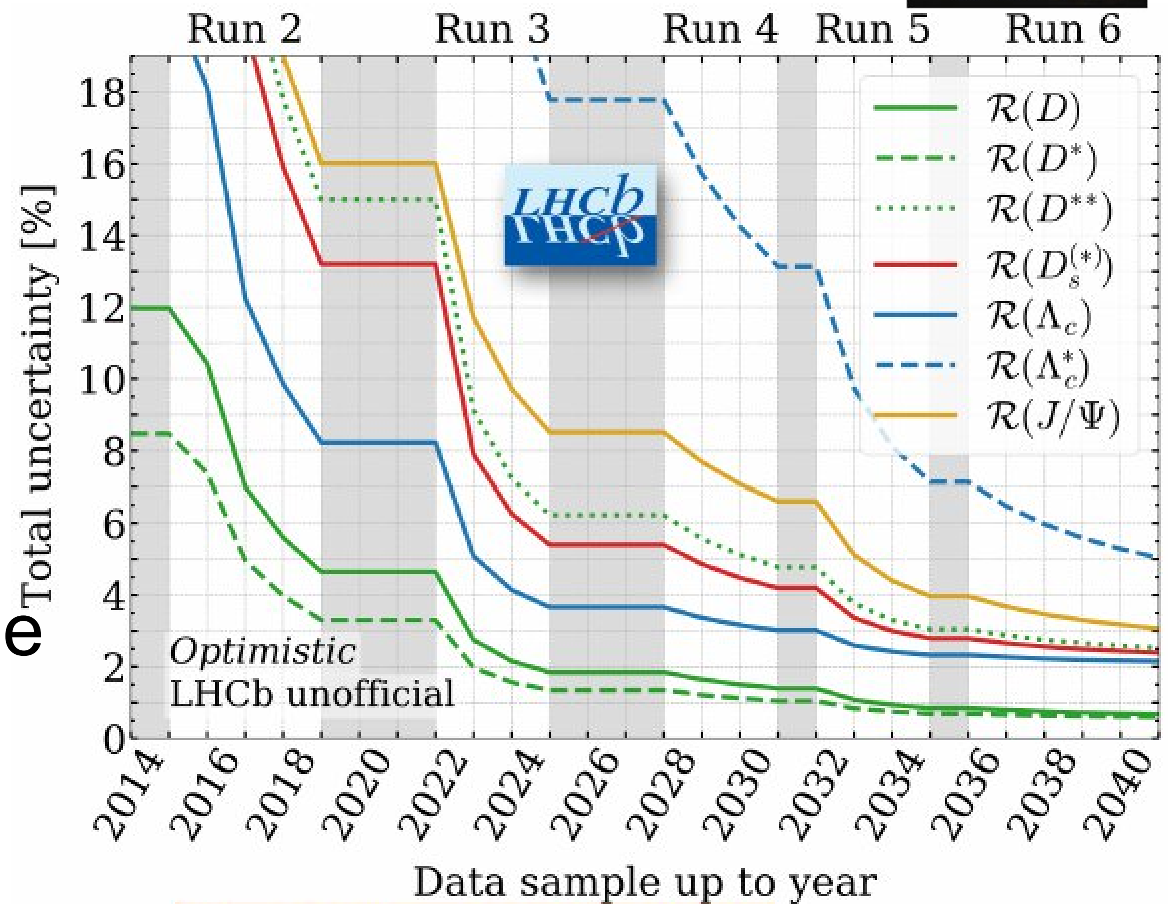


Decay mode	Yield
$D^+ \to \pi^+\phi(\to e^+e^-)$	$7\,460 \pm 140$
$D^+ \to \pi^+\phi(\to \mu^+\mu^-)$	$43\,512 \pm 220$
$D_s^+ \to \pi^+\phi(\to e^+e^-)$	$16\,740 \pm 210$
$D_s^+ \to \pi^+\phi(\to \mu^+\mu^-)$	$87\,022 \pm 300$

Prospects on $b \to cl\nu$ 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)

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
- LHCb is capable of exploring LFU in charm SL decays, although not as competitive as e^+e^- experiments
- Synergy of different experiments important to improve precision
- Cooperation with theorists essential for more stringent LFU tests

Backup Slides