Lepton Universality and cLFV at LHCb

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on behalf of the LHCb Collaboration

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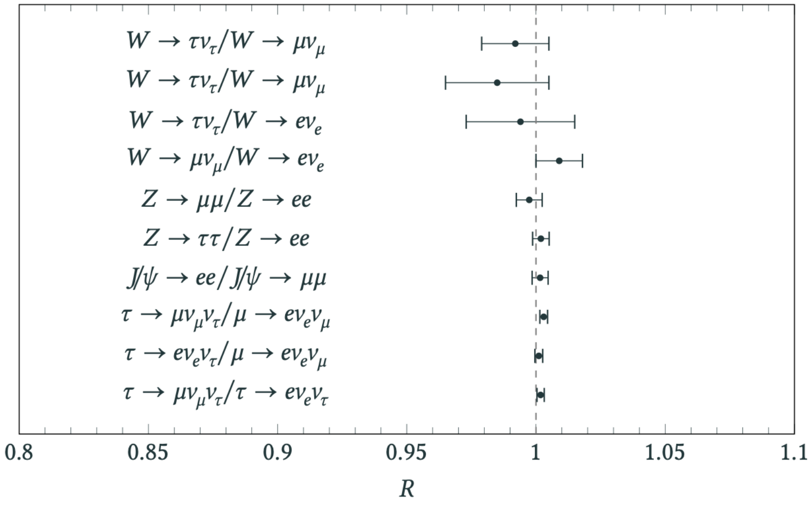
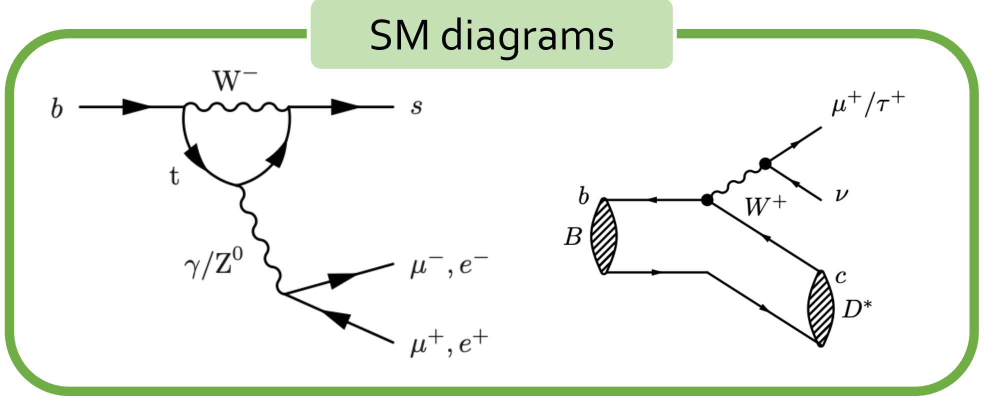
FSP LHCb
Erforschung von
Universum und Materie

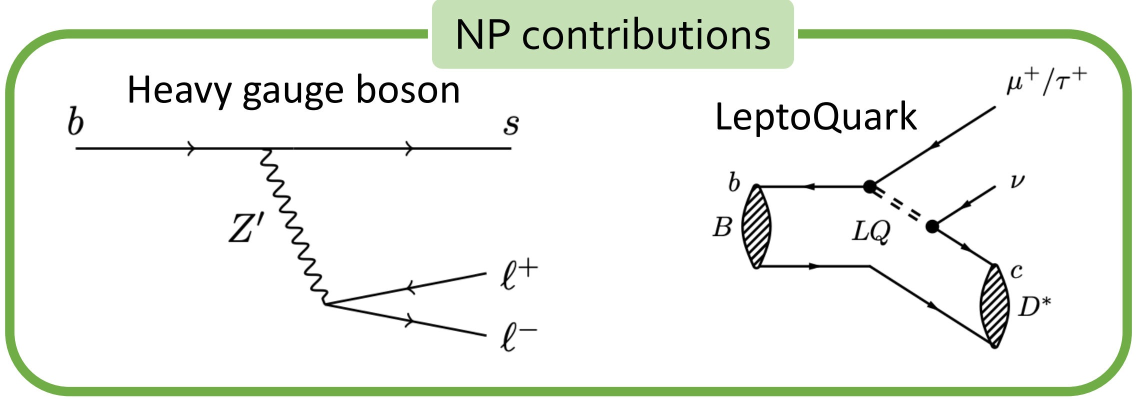
IMPRS
for Precision Tests of
Fundamental Symmetries
INTERNATIONAL MAX PLANCK
RESEARCH SCHOOL

Lepton flavour universality

- Standard Model (SM) predicts same electroweak coupling for all three lepton flavours
  - → **Lepton Flavour Universality** (LFU)
- validated experimentally in W and Z bosons decays, quarkonia, lepton decays
- **Contribution from New Physics** (NP) **can affect**
  - **relative decay rates** ($b \to sll$ and $b \to cl\nu_l$ transitions)
    - very well predicted (deviation from unity → hint of LFU violation)
    - cancellation of uncertainties (form factors, $c\bar{c}$ loop)



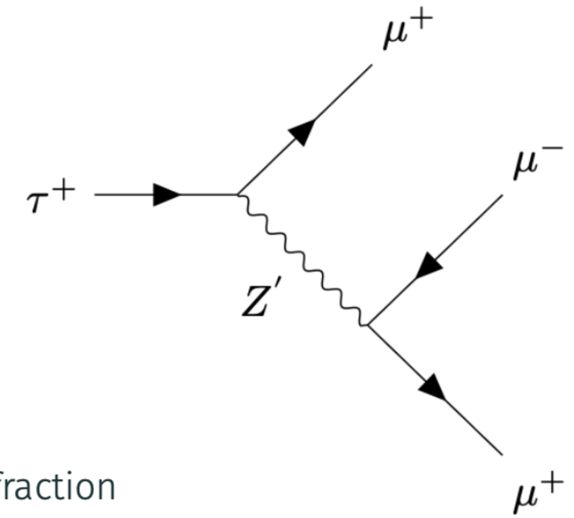


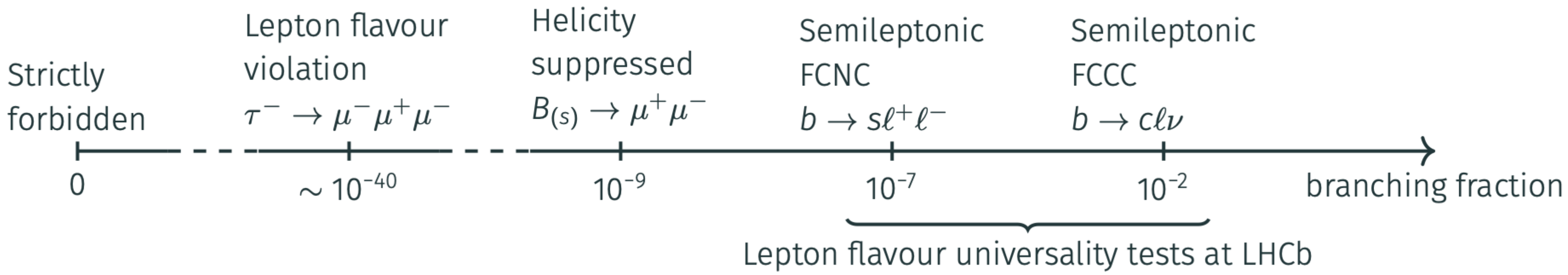


- At LHCb, tension with SM observed in precise analyses of $b \to s\mu\mu$ decays
  - **differential BF measurement** of $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127, 151801]
  - **angular observables** in $B_s^0 \to \phi\mu^+\mu^-$ and $B^{(+)} \to K^{*(+)}\mu^+\mu^-$ [JHEP11(2021)043, PRL 125, 011802, PRL 126, 161802]

Lepton flavour violation

- LFU violation generally implies **Lepton Flavour Violation** (LFV) [PRL 114 (2015) 091801]
- Tensions with SM observed in LFU tests motivate search for cLFV in b-hadron (or purely leptonic) decays
- cLFV strongly suppressed in the SM with neutrino oscillations ($< \mathcal{O}(10^{-40})$)
  - **Observation** of cLFV → sign of **new physics**
  - **Limit** setting **on BF** → **constrain theories of NP** [Phys. Rev. D 92, 054013, Phys. Rev. D 94, 115021]
    - including Z' or leptoquarks, heavy neutrinos…
    - that predict BF~$\mathcal{O}(10^{-10} - 10^{-7})$





[A. Seuthe, Moriond 2023]

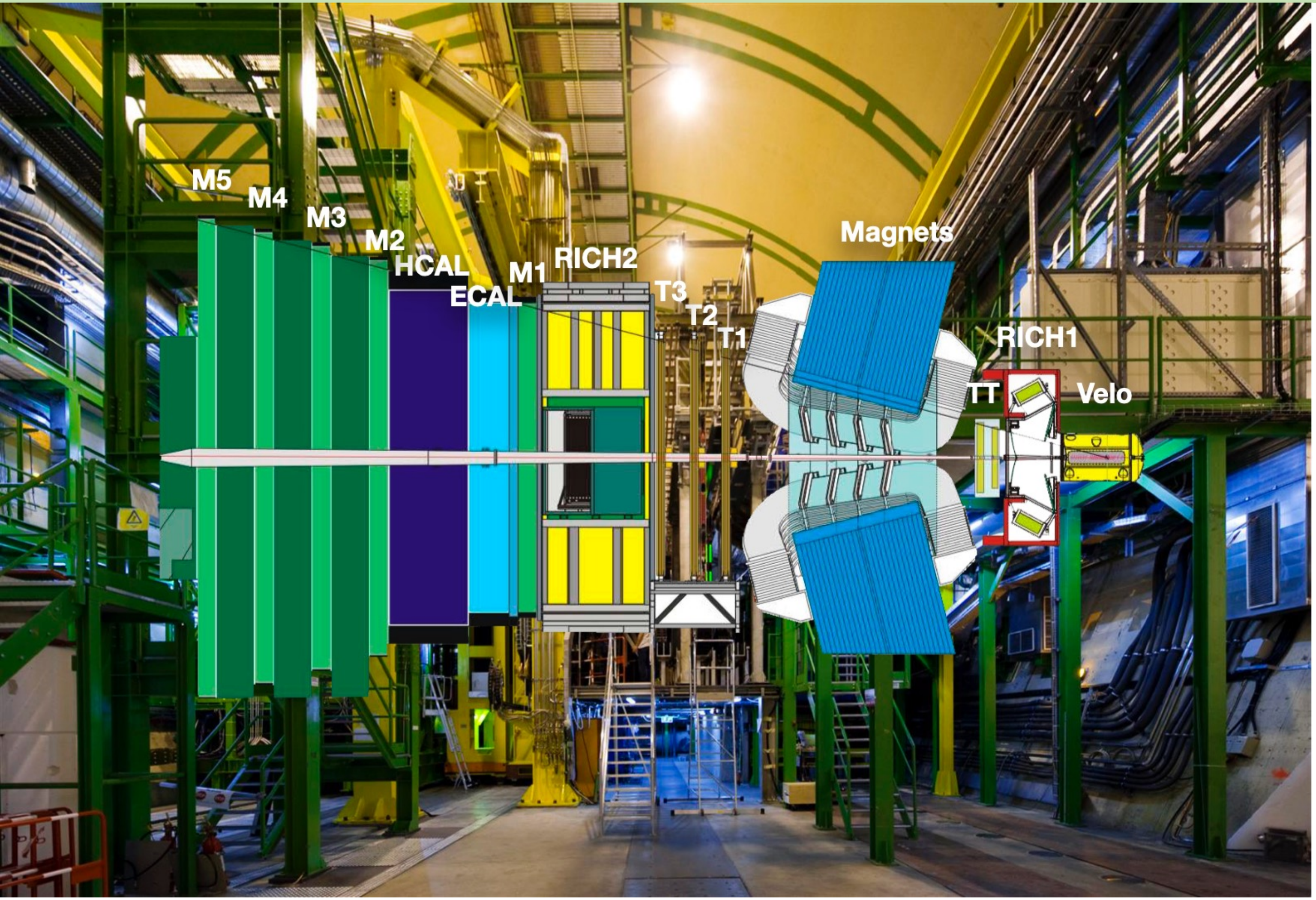
In this talk

Latest results on **LFU** tests and **LFV** searches by LHCb including:

- LFU tests with $b \to s l^+ l^-$ decays (R_K, R_{K^*})
- LFU tests with $b \to c l^+ \nu_l$ decays (R_{D^*}, R_{D^0})

- cLFV semileptonic B decays
  - $B^0 \to K^{*0} \mu^\pm e^\mp$ and $B_s^0 \to \phi \mu^\pm e^\mp$
  - $B^0 \to K^{*0} \tau^\pm \mu^\mp$
- The $\tau^+ \to \mu^+ \mu^- \mu^+$ decay

The LHCb detector in Run 1 and Run 2



- Single arm forward spectrometer ($2 < \eta < 5$) located at the LHC
- Excellent **particle identification (PID)** from RICH(1,2), ECAL and Muon Stations
  - $\epsilon(e \to e) \sim 90\%$ and $\epsilon(e \to h) \sim 5\%$
  - $\epsilon(K \to K) \sim 95-97\%$ and $\epsilon(\pi \to K) \sim 5\%$
  - $\epsilon(\mu \to \mu) \sim 97\%$ and $\epsilon(\pi \to \mu) \sim 1-3\%$
- Good **tracking system**
  - $\Delta p/p = 0.5\%$ at low momentum
  - IP resolution $(15 + 29\ /p_T[\text{GeV}])\mu m$

	Run 1 (2011,2012)		**Run 2 (2015-2018)**
$\sqrt{s}$	7 TeV	8 TeV	13 TeV
$\mathcal{L}_{int}$	1.0 fb^{-1}	2.0 fb^{-1}	~6 fb^{-1}

[2008 JINST 3 S08005], [arXiv:1306.0249]

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

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

- FCNC processes only allowed at loop level (BF$\sim 10^{-6}$)

  → clean probe for NP

- LFU test performed via the measurement of the ratio

$$R_{H_s}(q^2_{min}, q^2_{max}) = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H_s \mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H_s e^+e^-)}{dq^2} dq^2}$$

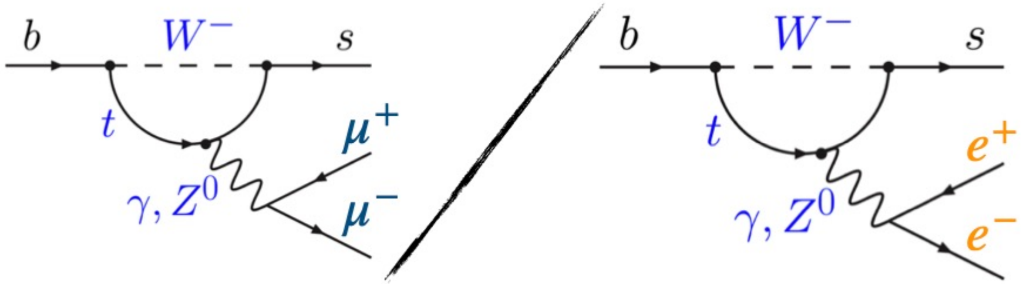
- with $\boldsymbol{H_b = B, \Lambda_b}$ and $\boldsymbol{H_s = K, K^*, K^0_s, \phi, pK}$
- Advantage: cancellation of hadronic uncertainties in theory predictions
- Expected to be unity except for different Yukawa couplings and kinematic effects
- Any **deviation from unity** → clear **sign of NP**
- Effective Hamiltonian

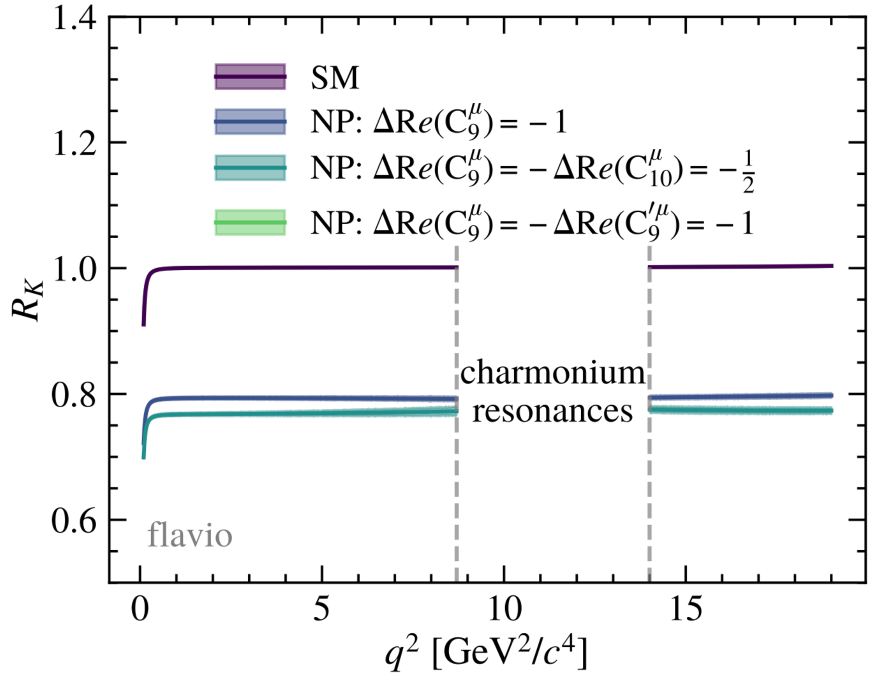
$$\mathcal{H}_{eff} \sim -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts} \Sigma_i (\mathcal{C}_i^{\mathrm{SM}} + \Delta_i^{\mathrm{NP}}) \mathcal{O}_i$$

Local operator

NP contribution

Wilson coefficient operator





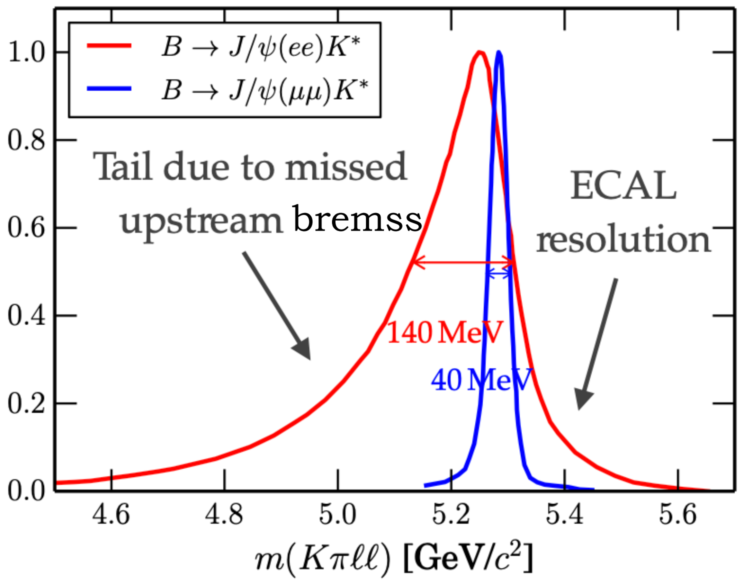
[LHC seminar talk]

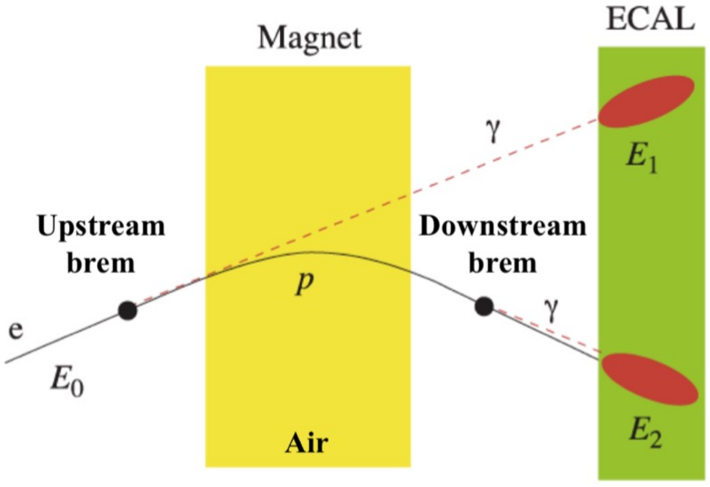
LFU tests with $b \to s l^+ l^-$ decays

- Very **different reconstruction** at LHCb for **electrons and muons**
- Electrons
  - Energy loss due to Bremsstrahlung photon emission
  - High occupancy in ECAL
- Recovery procedure to improve energy resolution
  - look for photon cluster in the ECAL compatible with *e* direction before the magnet
- Higher background contamination and sensitivity to background modelling
- Measurement of **double ratio** to **reduce experimental systematics**

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

  - Simultaneous fit to resonant and non-resonant channels
  - Cross-check with $r_{J/\psi} = \frac{\mathcal{B}(B\to KJ/\psi(\mu^+\mu^-))}{\mathcal{B}(B\to KJ/\psi(e^+e^-))} \equiv 1$ [arXiv:1307.1189]





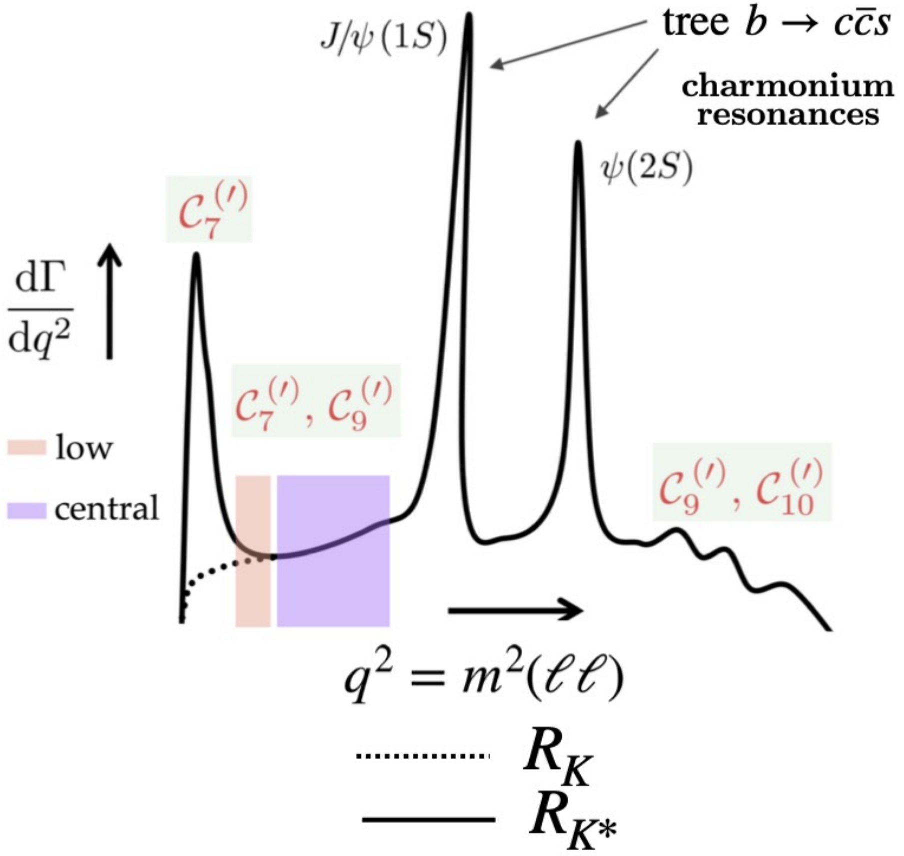
R_K and R_{K^*}

[arXiv:2212.09152, submitted to PRL; arXiv:2212.09153, submitted to PRD]

- **Simultaneous measurement of R_K and R_{K^*}** with Run 1 + Run 2 data in two q^2 regions
  - low-$q^2 \in [0.1,1.1]\ \mathrm{GeV}^2/c^4$
  - central-$q^2 \in [1.1,6.0]\ \mathrm{GeV}^2/c^4$
- K^* reconstructed via its $K^+\pi^-$ decay

- **Background suppression**
  - In both modes, multivariate classifiers trained to suppress combinatorial bkg
  - In electron mode, second multivariate classifier trained against partially reconstructed bkg based on vertex and track quality information
  - Vetoes for specific decays
  - Lepton and hadron PID selection to reduce mis-ID bkg

- Residual background from mis-ID modelled with data-driven approach



R_K and R_{K^*}

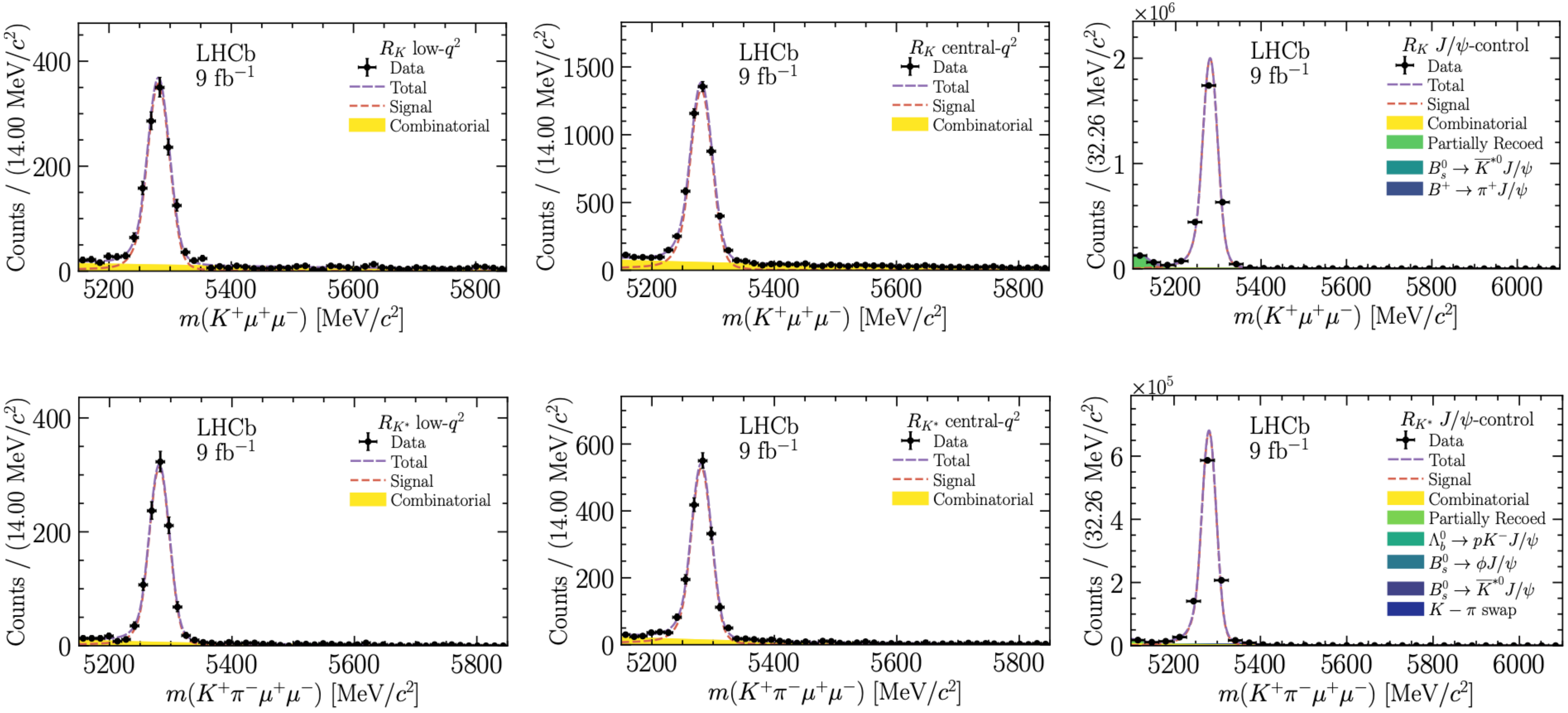
Muon mode

- Very clean
- BF compatible with published results [JHEP 06 (2014) 133, JHEP 11 (2016) 047]

low-q^2 | central-q^2 | J/ψ control region

R_K

R_{K^*}



R_K and R_{K^*}

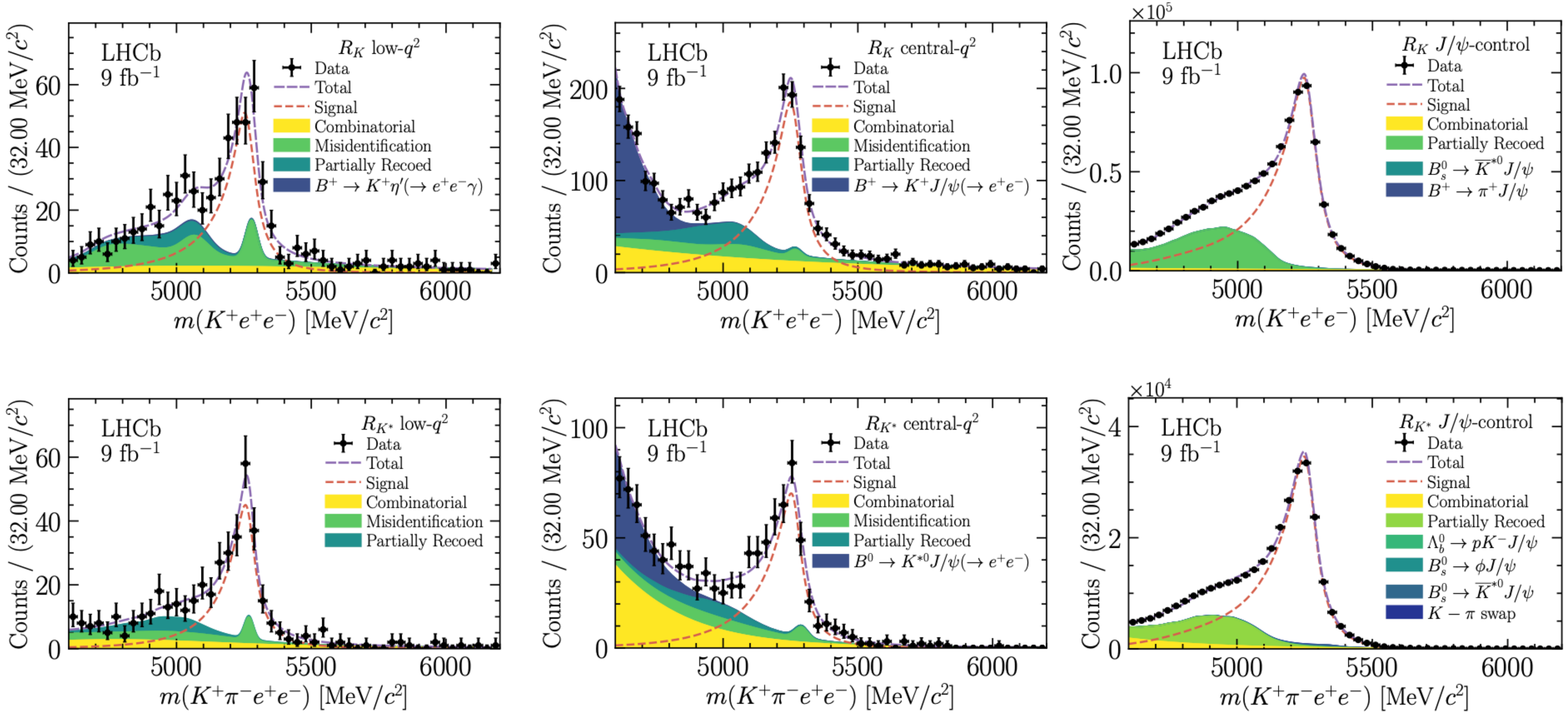
Electron mode

- Brems. tail from J/ψ entering rare mode constrained in simultaneous fit
- Partially reconstructed bkg from $K^{*0}e^+e^-$ constrained in $K^+e^+e^-$

low-q^2 | central-q^2 | J/ψ control region

R_K

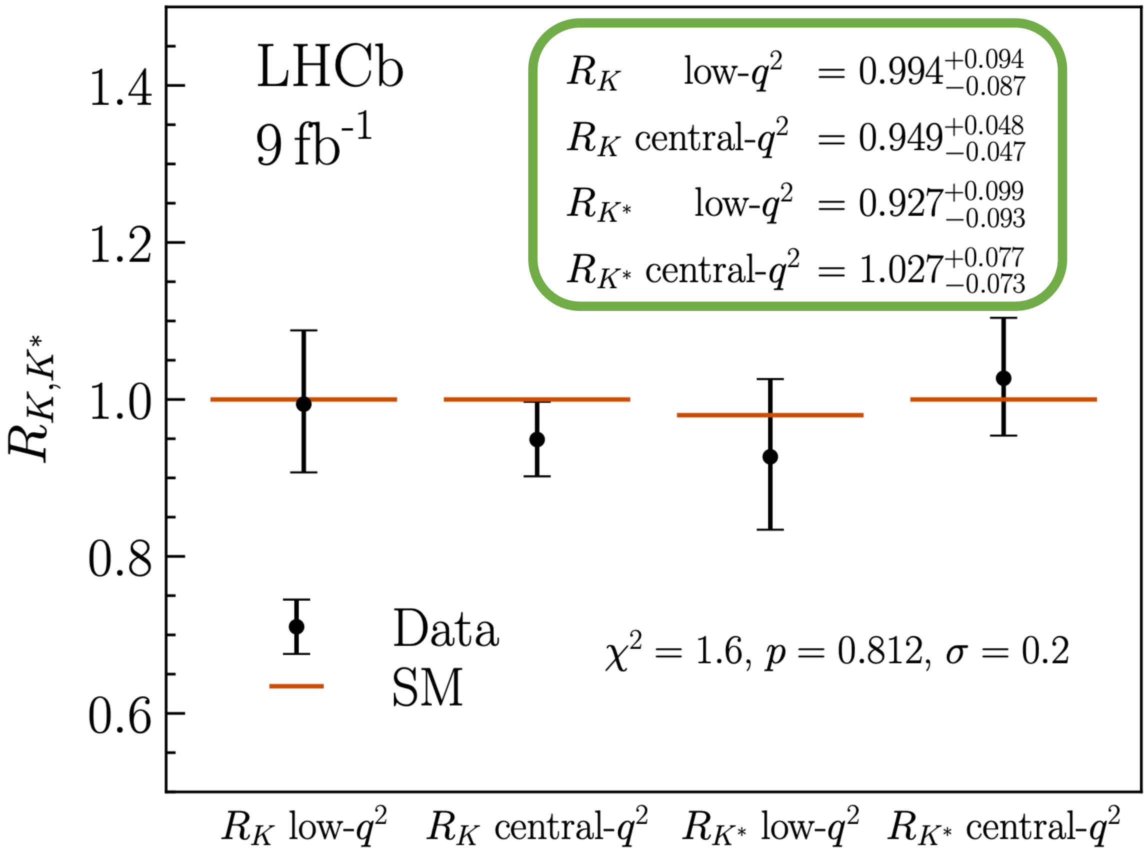
R_{K^*}



R_K and R_{K^*}

[arXiv:2212.09152, submitted to PRL; arXiv:2212.09153, submitted to PRD]

- **Most precise** LFU test with $b \to s l^+ l^-$ decays
- **First measurement of R_K in low q^2** ($\in [0.1,1.1]\ \mathrm{GeV}^2/c^4$)
- Results in **agreement with SM** predictions within 0.2σ
- Dominated by statistical uncertainties
- Leading systematic from mis-ID backgrounds



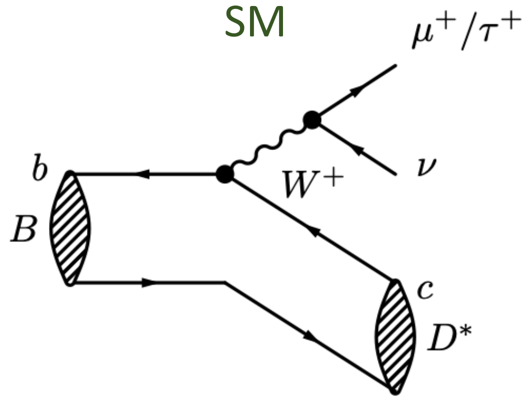
- Shift to higher values in R_K central-q^2 wrt [Nat. Phys. 18, 277–282 (2022)]
  - $+0.064$ due to contamination at looser working point
  - $+0.038$ due to not inclusion of background in mass fit

LFU tests with $b \rightarrow c l^{+} \nu_{l}$ decays

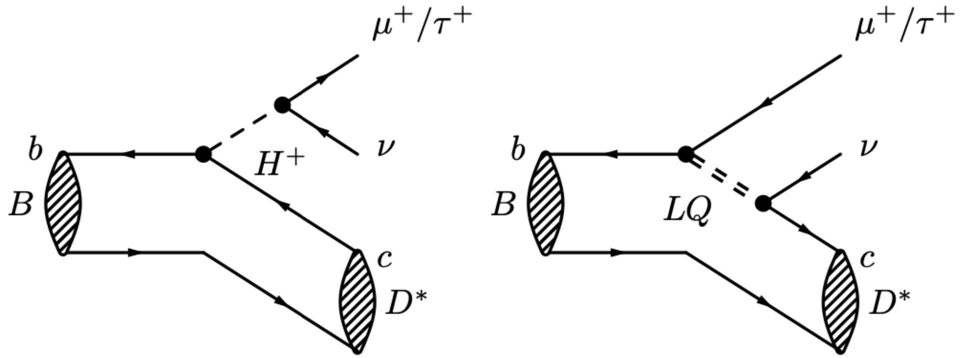
LFU tests with $b \to c l^+ \nu_l$ decays

- FCCC semileptonic tree level processes mediated by a W boson in the SM
- Measurement of the ratio $\boldsymbol{R(X_c)} = \frac{\mathcal{B}(X_b \to X_c \tau \nu_\tau)}{\mathcal{B}(X_b \to X_c l \nu_l)}$
  - with $\boldsymbol{X_b = B^0, B^+_{(c)}, B^0_s, \Lambda_b}$, ... and $\boldsymbol{X_c = D, D^*, D_s, \Lambda_c, J/\psi}$
- Sensitive to NP couplings of third lepton generation (LQ, charged Higgs, W')
- **Advantages**
  - reduction of theoretical and systematic uncertainties
- **Challenges**
  - missing neutrinos: τ reconstructed via its muonic $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ or hadronic $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$ decay
  - Several background sources
  - Relative contributions extracted by means of template fits from control sample or simulations

SM



NP contributions



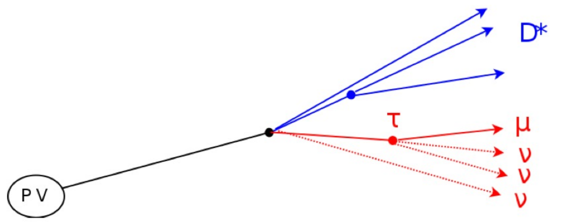
- **Longstanding** $\sim$ **3σ deviation** from SM in $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$ [Eur.Phys.J.C 77 (2017) 12, 895]
- **Before**: measurement of $\mathcal{R}(D^*)$ with Run 1 $D^{*+}\mu^-$ data [PRL 115, 111803]
  - 2.1σ deviation from SM expectation
- **Now**: first joint measurement of $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$ using Run 1 data

First measurement at a hadron collider

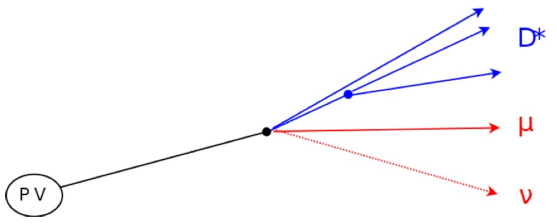
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{(*)}\mu^-\bar{\nu}_\mu)} \text{ with } \tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau \text{ and } D^* \to D^0(\to \pi K)\pi$$

- **Selected using $D^0\mu^-$** sample $\sim$ 5 times bigger than $D^{*+}\mu^-$ sample
  - Higher branching fractions and higher efficiency
- Simultaneous analysis of the two samples
  - constrain common parameters of the fit models applied to data
  - reduce correlation
- **Background sources**: partially reconstructed B decays, combinatorics, mis-ID of charged tracks

$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$



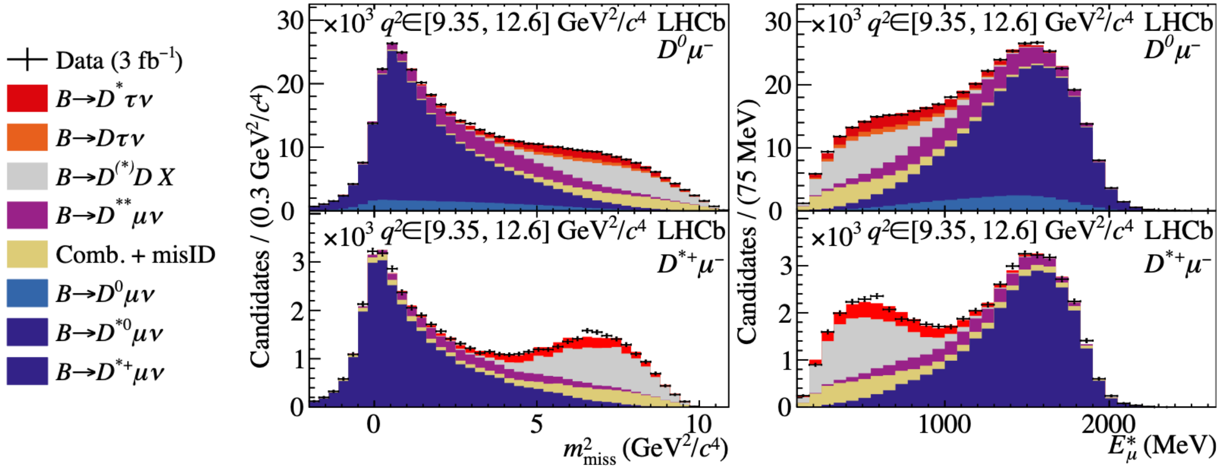
$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$

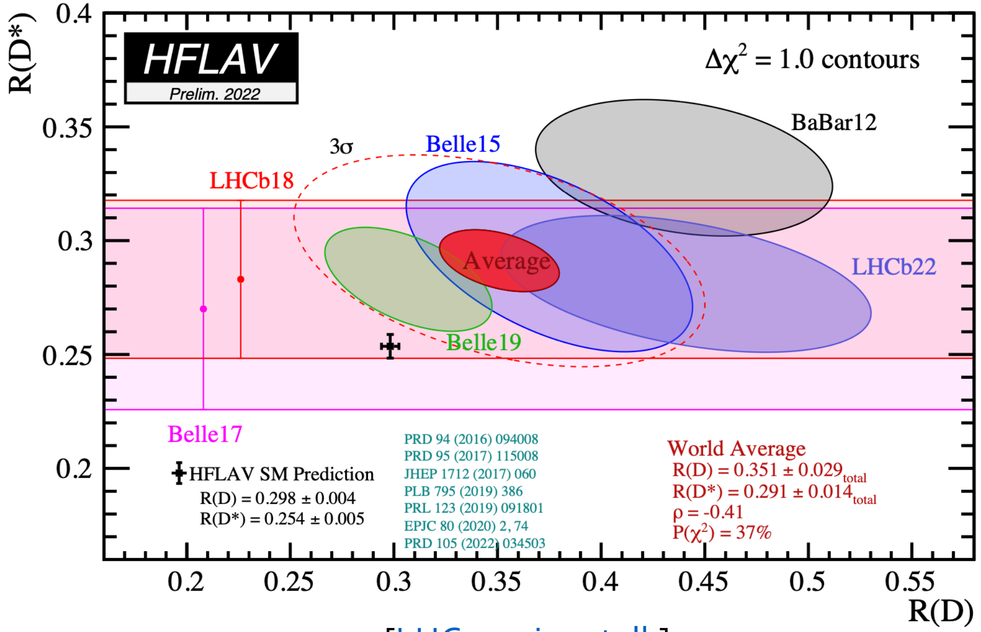


[LHC seminar talk]

Simultaneous measurement of $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$

- **3D template fit**
  - E^*_μ, $m^2_{miss} = (p_B - p_{D^{(*)}} - p_\mu)^2$, $q^2 = (p_B - p_{D^{(*)}})^2$
- **Results**
  - $\mathcal{R}(D^*) = 0.281 \pm 0.018 \pm 0.024$
  - $\mathcal{R}(D^0) = 0.441 \pm 0.060 \pm 0.066$
  - correlation $\rho = -0.43$
  - 1.9σ agreement with SM expectation
- **New preliminary average**
  - slightly lower $\mathcal{R}(D^*)$ and slightly higher $\mathcal{R}(D^0)$
  - Reduced correlation
  - $3.3\sigma \rightarrow 3.5\sigma$ deviation from the SM observed in the combination of $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$





[LHC seminar talk]

- Measurement of $\mathcal{R}(D^*)$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ on Run 2 data (2 fb^{-1})
- Lower statistics wrt muonic decay but more control over background
- $\boldsymbol{B^0 \to D^{*-}\pi^+\pi^-\pi^+}$ as **normalisation channel**

$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}$$

External inputs

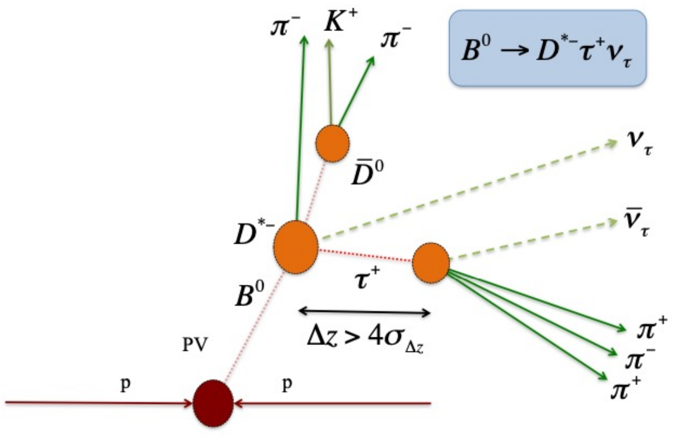
$$\mathcal{R}(D^{*-}) = \mathcal{K}(D^{*-}) \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

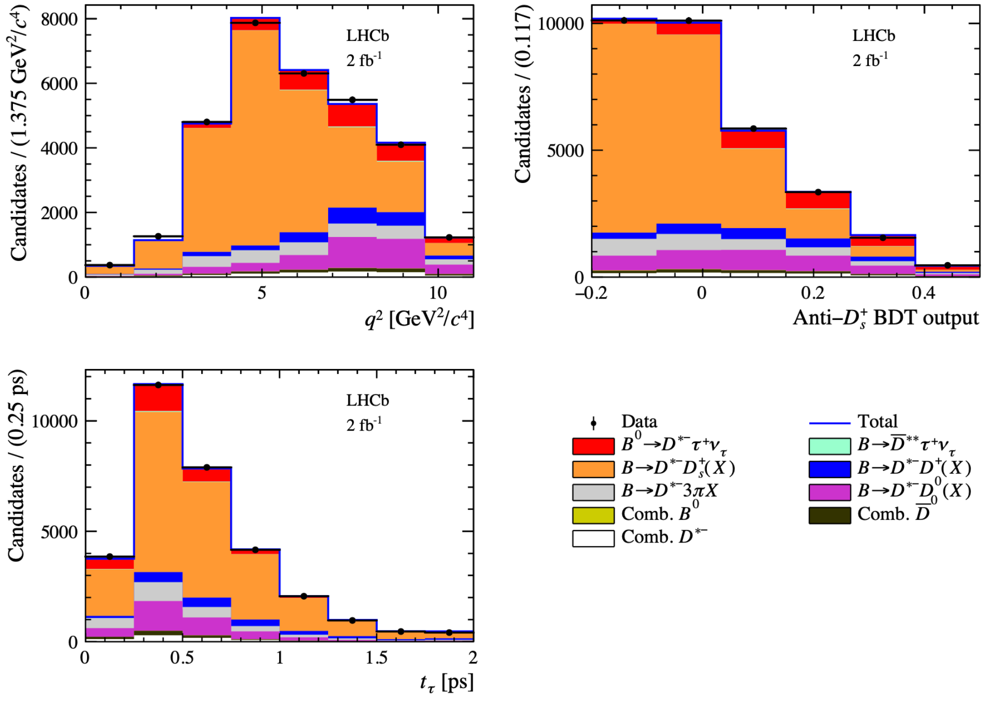
- **3D template fit**: $q^2 \equiv (p_{B^0} - p_{D^*})^2$, τ^+ decay time, τ vs. D_s^+ BDT output
- **Results**

$$\mathcal{K}(D^{*-}) = 1.70 \pm 0.10(\text{stat})^{+0.11}_{-0.10}(\text{syst})$$

$$\mathcal{R}(D^{*-}) = 0.247 \pm 0.015(\text{stat}) \pm 0.015(\text{syst}) \pm 0.012(\text{ext})$$

- Limited by the size of the simulation sample used to extract PDF





$\mathcal{R}(D^*)$ with hadronic τ channels

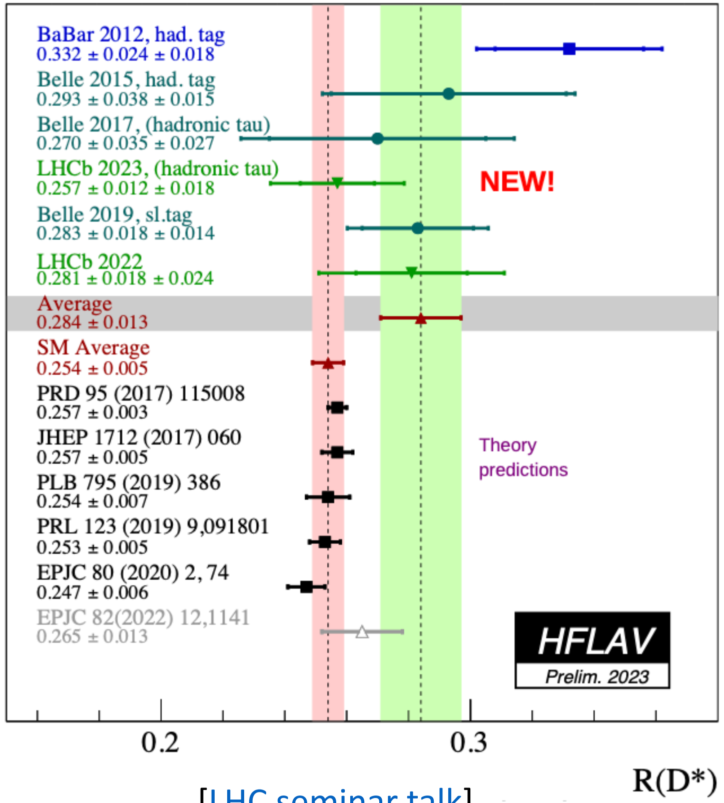
NEW

[arXiv:2305.01463, submitted to PRD]

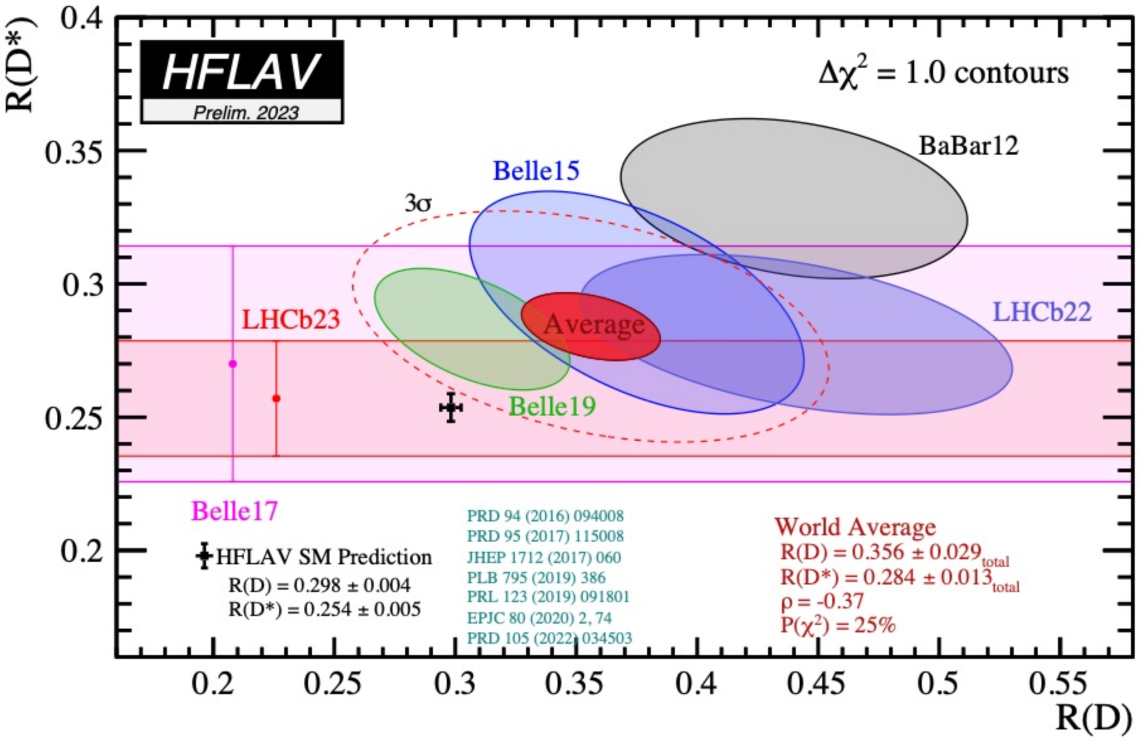
- **Combined results with Run 1 data**

$$\mathcal{R}(D^*)_{\text{comb}} = 0.257 \pm 0.012(\text{stat}) \pm 0.014(\text{syst}) \pm 0.012(\text{ext})$$

- In agreement with the SM within 1σ ($R(D^*)_{SM} = 0.254 \pm 0.005$ [HFLAV])
- One of the most **precise measurements of $\mathcal{R}(D^*)$**



[LHC seminar talk]



- **New preliminary world average**

$$\mathcal{R}(D^*) = 0.284 \pm 0.013 \qquad \mathcal{R}(D) = 0.356 \pm 0.029$$

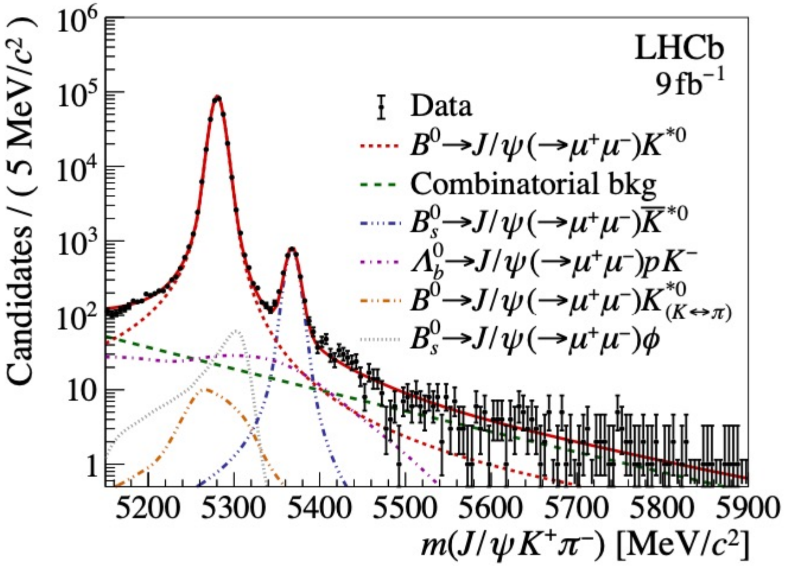
- **3.2σ deviation** from SM expectation for the combination $\mathcal{R}(D^*)$- $\mathcal{R}(D)$
- Recent results: $\mathcal{R}(J/\psi)$ [Phys. Rev. Lett. 120, 121801], $\mathcal{R}(\Lambda_c)$ [PRL 128, 191803]...
- Other ongoing measurements of $\mathcal{R}(D_s)$, $\mathcal{R}(D)$

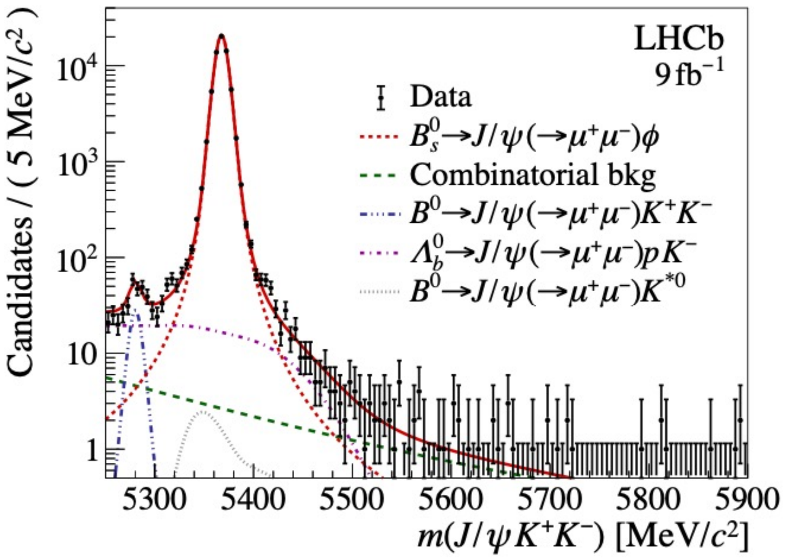
cLFV searches

$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\mp}$

[JHEP 06 (2023) 073]

- **NP predictions** can reach 10^{-7} [Phys. Rev. D 92, 054013]
  - Different NP effects on $b \to s\mu^+e^-$ and $b \to s\mu^-e^+$
  - Separate BF limit evaluation for $B^0 \to K^{*0}\mu^+e^-$ and $B^0 \to K^{*0}\mu^-e^+$ also provided
- Search on **Run 1 + Run 2** data
- $K^{*0}(892)$ and $\phi(1020)$ reconstructed via $K^{*0} \to K^+\pi^-$ and $\phi \to K^+K^-$
- $\boldsymbol{B^0 \to J/\psi(\mu^+\mu^-)K^{*0}}$ and $\boldsymbol{B_s^0 \to J/\psi(\mu^+\mu^-)\phi}$ used as **control and normalisation channels**
- **Background rejection**
  - dedicated vetoes to reject background from mis-ID in b-hadron decays
  - BDT trained against combinatorial background
- **Modelling** of the remaining **background contamination**
  - Precise description of $B \to Dl\nu_l$ decays needed





$B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

[JHEP 06 (2023) 073]

- No significant signal is observed

- **Improved upper limits** at 90%(95%) CL

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7(6.9)\times10^{-9}$$

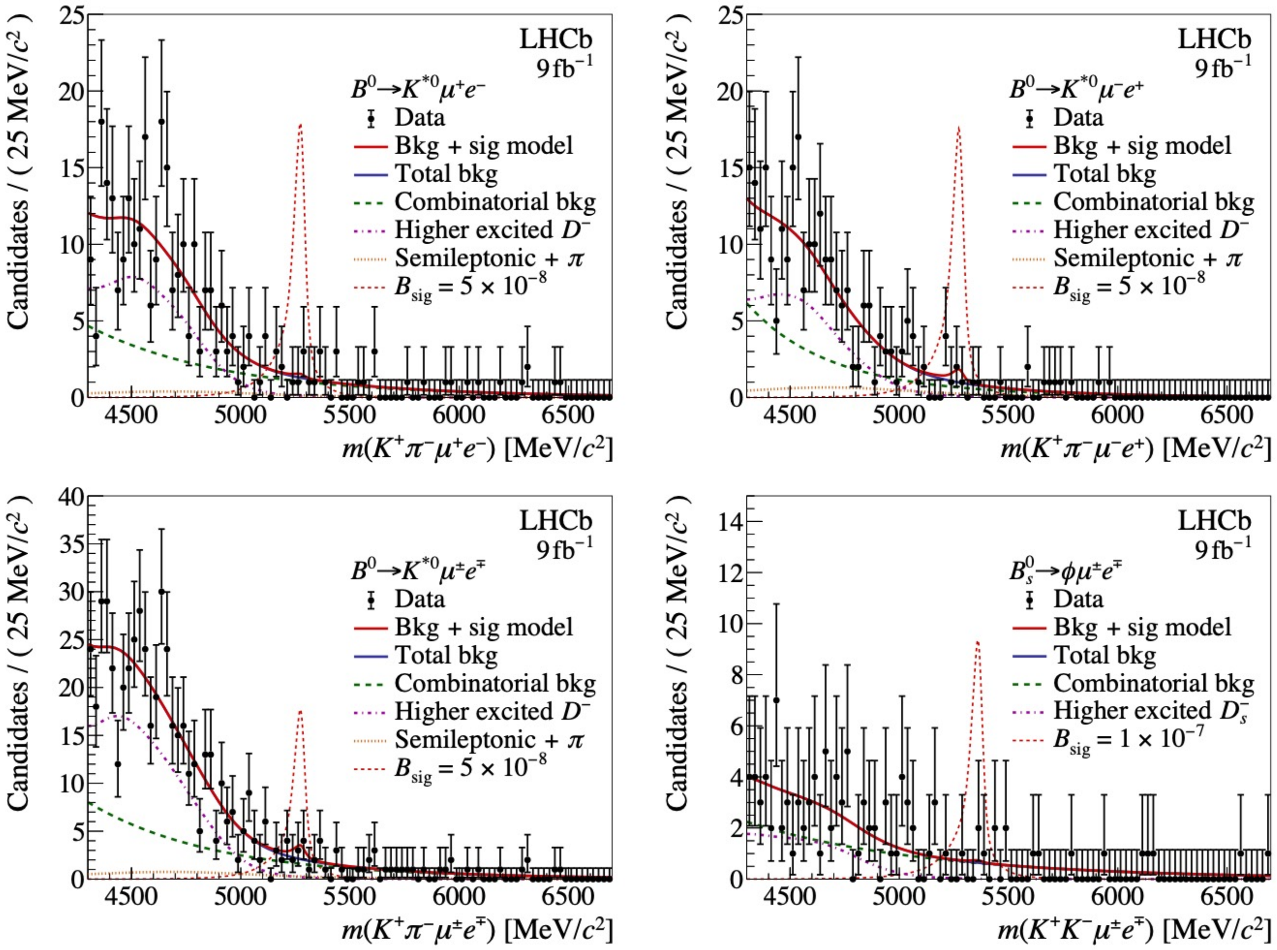
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8(7.9)\times10^{-9}$$

$$\mathcal{B}\left(B^0 \to K^{*0}\mu^\pm e^\mp\right) < 10.1(11.7)\times10^{-9}$$

wrt Belle's result ($\mathcal{O}(10^{-7})$) [PRD 98, 071101(R) (2018)]

- **World's first limit** at 90%(95%) CL

$$\mathcal{B}\left(B_s^0 \to \phi\mu^\pm e^\mp\right) < 16.0(19.8)\times10^{-9}$$



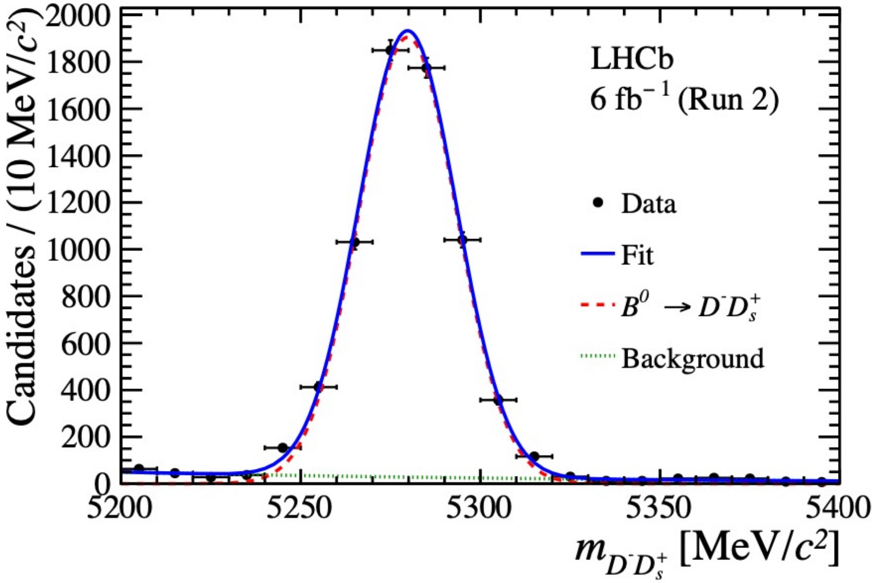
- Limits on BFs assuming uniform phase-space decay model

- (Re-)intepretation in terms of scalar and left-handed LF violating NP models also provided

$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

[arXiv:2209.09846, submitted to JHEP]

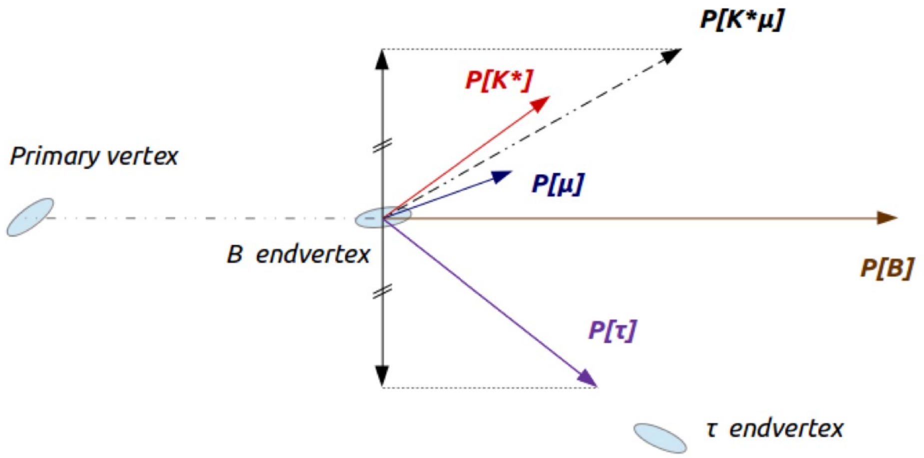
- **First search** for the $\boldsymbol{B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}}$ decay on **Run 1 + Run 2** data
- **Analysis strategy**
  - K^{*0} reconstructed via $K^{*0} \to K^+\pi^-$
  - τ reconstructed via $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
  - Independent analysis on $B^0 \to K^{*0}\tau^+\mu^-$ and $B^0 \to K^{*0}\tau^-\mu^+$
    - Affected by different backgrounds
    - Different theoretical interpretation
  - $\boldsymbol{B^0 \to D^-(K^+\pi^-\pi^-)D_s^+(K^+K^-\pi^+)}$ as **normalisation channel**
  - Multivariate classifiers trained againts combinatorial and mis-ID background + PID cuts

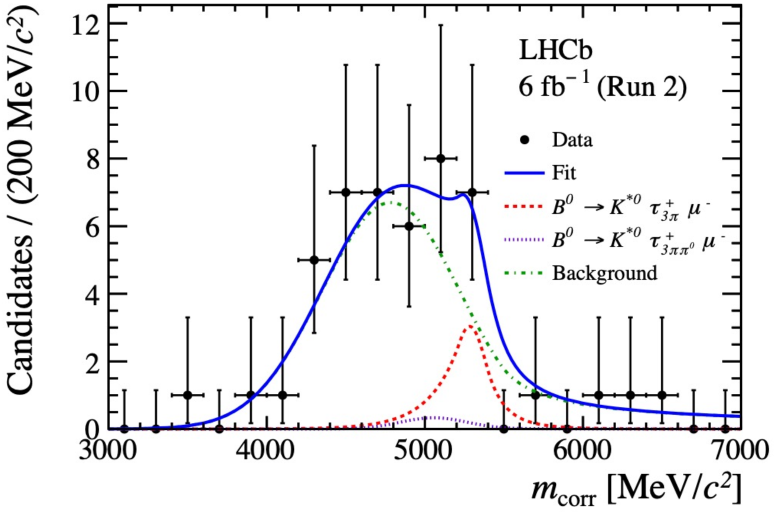


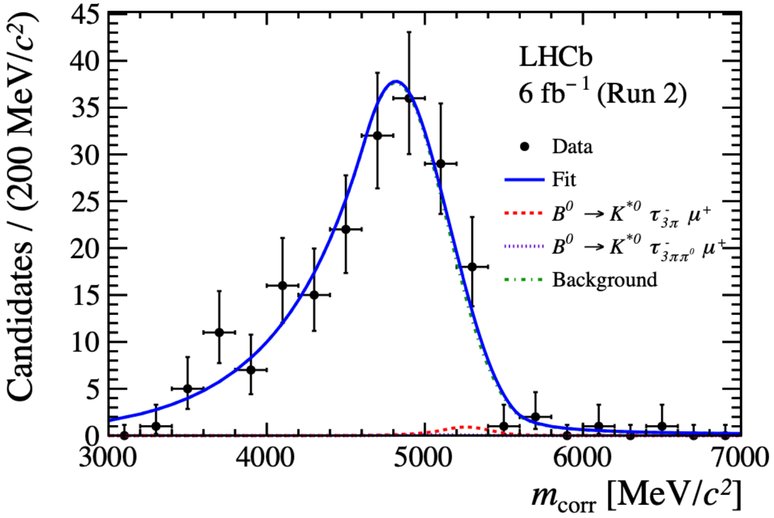
$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

[arXiv:2209.09846, submitted to JHEP]

- Fit to $m_{corr} = \sqrt{p_{\perp}^2 + m_{K^*\tau\mu}^2} + p_{\perp}$
  - $p_{\perp}$ missing momentum perpendicular to B^0 direction







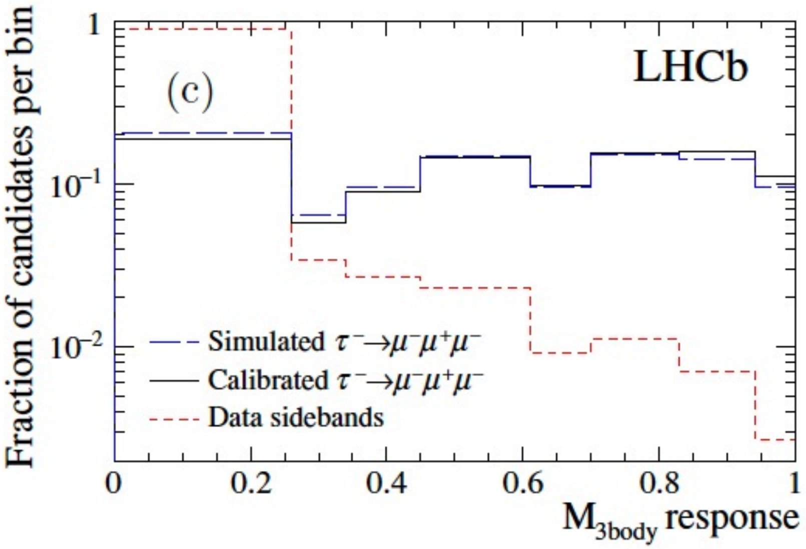
- No significant signal is observed
- **Most stringent limits on $b \to s\tau\mu$ transitions** set at 90%(95%) CL

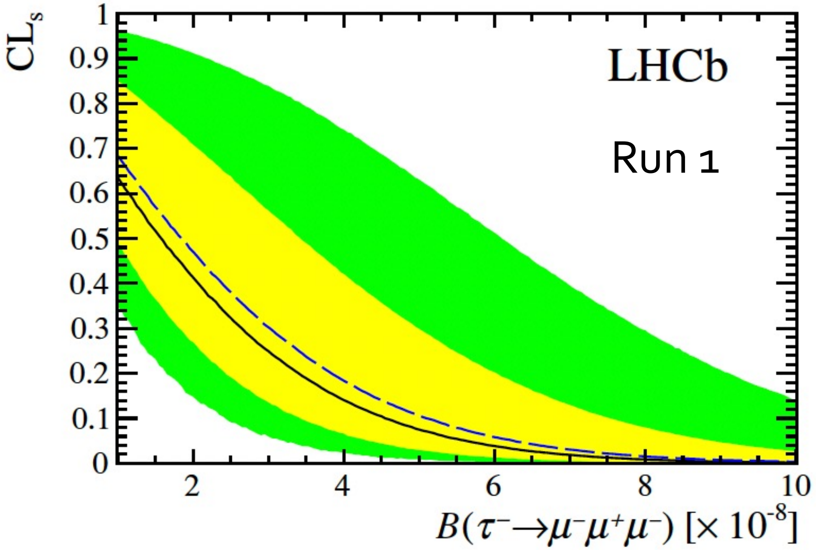
$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2)\times 10^{-5}$$

$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2(9.8)\times 10^{-6}$$

The $\tau^+ \to \mu^+\mu^-\mu^+$ decay

- Current **best experimental limit** from **Belle** [arXiv:1001.3221]
  - $2.1{\times}10^{-8}$ at 90% CL
- **LHCb** analysis on **Run 1** data [JHEP02(2015)121]
  - $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$ used as a normalisation channel
  - Challenges: identify and reject background sources
    - Combinatorial and mis-ID background ($D_{(s)}^+ \to 3\pi$, $D^+ \to K^-\pi^+\pi^+$)
  - Background suppression achieved by means of multivariate classifiers
  - Upper limit: $4.6(5.6){\times}10^{-8}$ at 90%(95%) CL
- **Ongoing analysis with Run 2 data (coming out soon!)**
- **Extrapolated limit** from Run 1 to Run 1 + Run 2 (higher luminosity and cross section)
  - $2.5(3.1){\times}10^{-8}$ at 90%(95%) CL
- Development of a more efficient selection





A lot more...

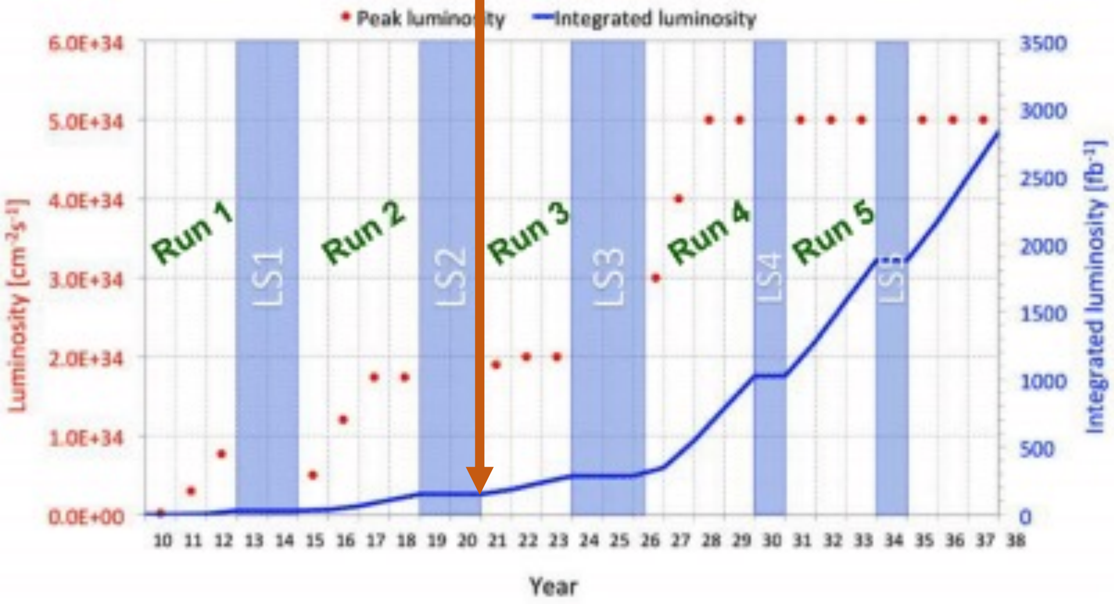
- **LFU tests**: many **analyses** and **updates** are **ongoing**
  - $b \to sll$ decays: R_{ϕ}, R_{Λ}, R_{pK}, $R_{K\pi\pi}$
  - $b \to cl\nu_l$ decays: R_{D_s}, R_{D^+}, R_{D^*} with μ/e, $R_{D^{**}}$

- **Previous cLFV searches**
  - $B^+ \to K^+\mu^{\pm}e^{\mp}$ [arXiv:1909.01010]
  - $B^+ \to K^+\mu^-\tau^+$ using B_{s2}^{*0} decays [JHEP06(2020)129]
  - $B^0_{(s)} \to \tau^{\pm}\mu^{\mp}$ [PRL 123, 211801 (2019)]
  - Charm sector: $D^+_{(s)} \to h^{\pm}l^{\pm}l'^{\mp}$ [JHEP06(2021)044]
- **Ongoing cLFV searches with Run 1 and Run 2 data**
  - $B^0_s \to \phi\, \mu^{\pm}\tau^{\mp}$, $B^0_{(s)} \to e^{\pm}\mu^{\mp}$, $\Lambda_b \to \Lambda e^{\mp}\mu^{\pm}$, $\Lambda_b \to pK\tau^{\mp}\mu^{\pm}$ ...

Summary and conclusions

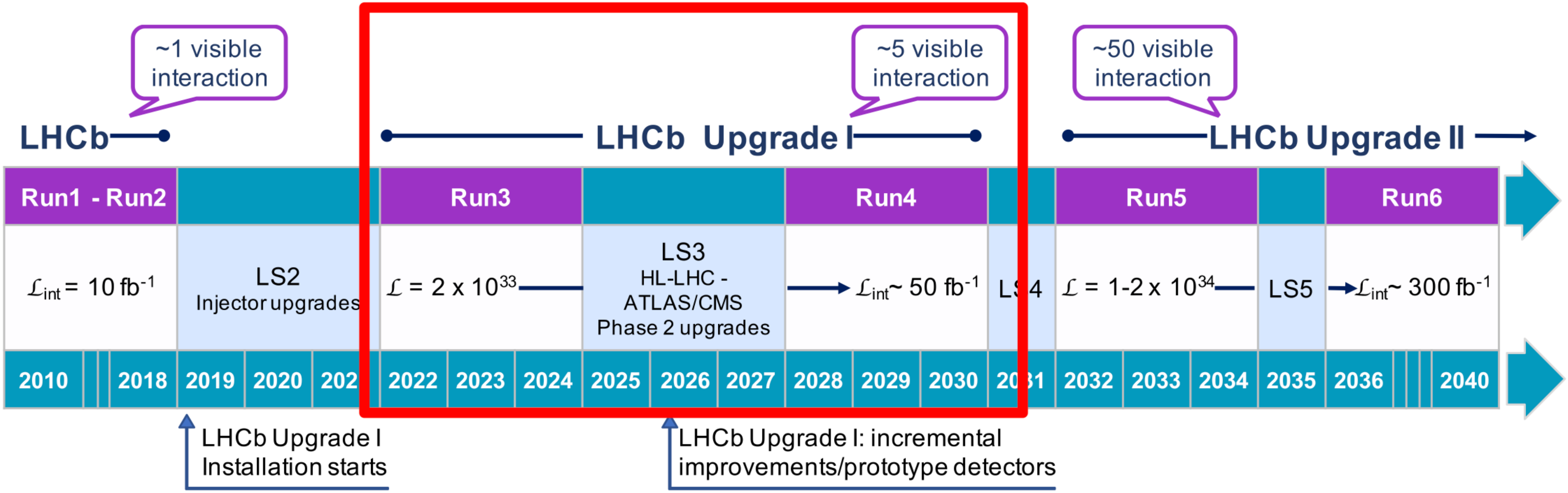
- LHCb has a very rich program in **LFU tests** and **cLFV searches** in b- and c-hadron decays
  - powerful way to **search for NP**
- No cLFV observed so far → More stringent limits on the BFs to constrain BSM theories
- Many other analyses with the whole Run 1 + Run 2 dataset in the pipeline
- **Run 3** has started!
  - upgraded detector and trigger system will enhance signal acceptance
  - 5 times larger instantaneous luminosity than in Run 2 ($50\ \mathrm{fb}^{-1}$)

Little shift due to the pandemic



Backup

LHC timeline



$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\mp}$

[JHEP 06 (2023) 073]