Rare and semileptonic decays & LFNU at LHCb

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Outline

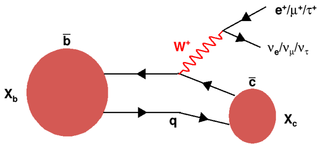
- Introduction
  - Lepton Flavour Universality
  - Rare decays
- Tree-level semileptonic decays at LHCb
  LFU measurements
  - $R(D)$-$R(D^*)$ measurements with muonic τ decays
  - $R(D^*)$ measurement with hadronic τ decays **NEW!**
- Rare decays at LHCb
  - LFU measurements - R_K, R_{K^*}
  - Search for LFV decays
  - Differential decay rates and BF measurements

Lepton Flavour Universality

- Standard Model (SM) is lepton flavour universal
  - Difference between e, μ and τ driven only by mass
- LFU tests with ratios of branching fractions of decays involving different $\ell = e, \mu, \tau$
  - Uncertainties related to form factor normalizations *mostly* cancel
  - Sensitive to possible enhanced coupling to the 3rd generation [PRD 85, 094025 (2012), PLB 755, 270 (2016)]
- In $b \to c\ell\nu_\ell$ transitions: tree-level semileptonic decays

$$R(X_c) = \frac{\mathcal{B}(X_b \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \to X_c \ell \nu_\ell)}$$

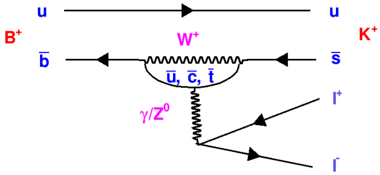
$$X_b = B^0, B^+_{(c)}, B^0_s, \Lambda_b, \ldots \quad X_c = D, D^*, D_s, \Lambda_c, \ldots$$



- In $b \to s\ell\ell$ transitions:

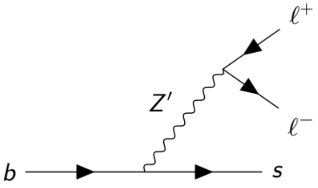
$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$



Also ratios such as R_{pK}, R_ϕ

- What are rare decays?
  - Decays with a small branching fraction ($\leq 10^{-4}$)
  - Penguin or box diagrams in SM
- Decays of the type $\boldsymbol{b \to s\ell^+\ell^-}$ and $\boldsymbol{b \to s}\gamma$, $\ell = e, \mu, \tau$
- Flavour-changing neutral currents
- Rare in SM and sensitive to beyond SM effects
- Examples - $B \to K^{(*)}\ell^+\ell^-$, $\Lambda_b^0 \to \Lambda^{(*)}\ell^+\ell^-$, or Lepton Flavour Violating decays
- With up-type quarks, $\boldsymbol{c \to u\ell^+\ell^-}$



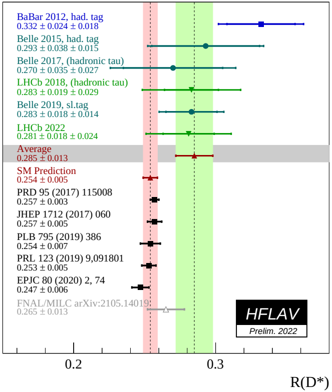
Tree-level semileptonic decays at LHCb

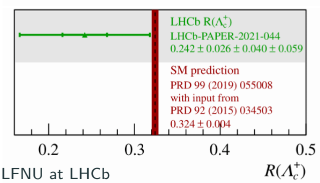
$R(X_c)$ measurements at LHCb

- LFU tests in $b \to c\ell\nu_\ell$ decays
- LHCb Run 1 data : 3 fb^{-1}, 2011-12
- Neutrinos not detected; approximation needed for B reconstruction
- Measurements with muonic τ decays
  - $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
  - $R(D^*)$ and $R(J/\psi)$ measurements

    [PRL **115**, 111803 (2015), PRL **120**, 121801 (2018)]
  - Same visible final state $X_c\mu^+$
- Measurements with hadronic τ decays
  - $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$
  - $R(D^*)$ and $R(\Lambda_c)$ measurements

    [PRL **120**, 171802 (2018), PRD **97**, 072013 (2018), PRL **128**, 191803 (2022)]



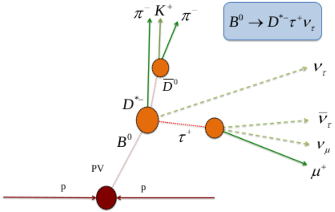


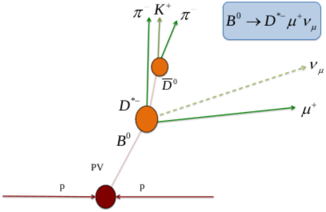
[HFLAV]

$R(D^{(*)})$ with muonic τ decays

- Simultaneous measurement of $R(D)$ and $R(D^*)$ with Run 1 data
  - Muonic $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
  - Supersedes the previous LHCb $R(D^*)$ measurement with muonic τ
- Select $D^0\mu^-$ and $D^{*+}\mu^-$ candidates where
  - $D^0 \to K^-\pi^+$, $D^{*+} \to D^0\pi^+$
  - Reconstructed $D^{*+} \to D^0\pi^+$ is vetoed in $D^0\mu^+$ sample
- Custom muon ID classifier, flatter in kinematic acceptance
  - Reduces misID background, the dominant systematic in the previous $R(D^*)$ measurement
- Trigger on D^0 - preserve acceptance for soft muons
- $D^0\mu^-$ sample **five** times larger than $D^{*+}\mu^-$

[arXiv:2302.02886] (Submitted to PRL)

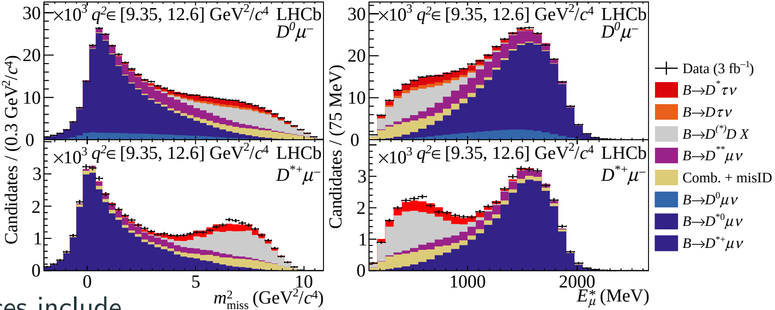




3D Fit to

- $q^2 \equiv (p_B - p_{D^{(*)}})^2$
- $m^2_{\text{miss}} \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$
- E^*_μ energy of μ

[arXiv:2302.02886]



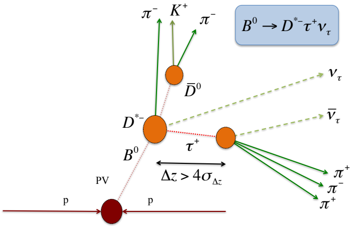
- Main background sources include
  - Partially reconstructed B decays like $B \to D^{**}\mu\nu$, $B \to D^{*(*)}D^{(*)}(\to \mu X)X$
  - Misidentified muons
  - Combinatorial background

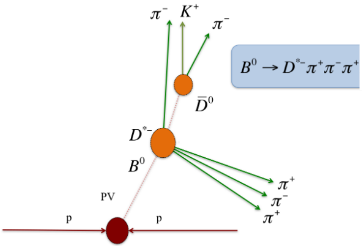
$$R(D) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$$
$$R(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.023(\text{syst})$$

Agreement with SM at 1.9σ

NEW!

[LHCb-PAPER-2022-052] (In preparation)

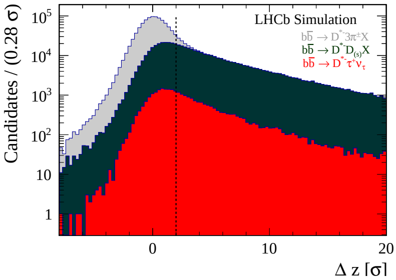


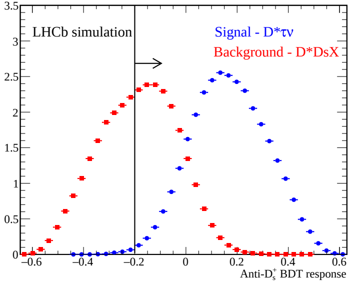


$$R(D^*) = \mathcal{K}(D^*)\frac{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\mu\nu_\mu)}$$

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

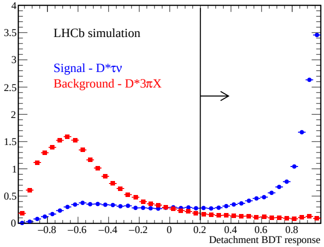
- Hadronic $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$
- LHCb **partial Run 2** data : 2 fb^{-1} at $\sqrt{s}$= 13 TeV, 2015-16 ($\sim 1.5\times$ Run 1 sample)
- Update of the Run 1 analysis from LHCb
- Same visible final state for the normalization mode $B^0 \to D^{*-}3\pi^\pm$
- Main backgrounds : ▶ $B \to D^{*-}3\pi^\pm X$
  ▶ Double charm $(B \to D^{*-}(D_s^+, D^+, D^0)X)$





[LHCb-PAPER-2022-052] (In preparation)

- $B \to D^{*-}3\pi^{\pm}X$ suppressed by requiring the τ vertex to be downstream w.r.t. the B vertex along the beam direction - detachment criteria
- A BDT classifier is used along with the vertex separation variables $\Rightarrow$ >99% bkg rejection



- Another BDT classifier based on kinematics and resonant structure to separate signal from $B \to D^{*-}D_s^+X$
  - This BDT output one of the fit variables

$R(D^*)$ with hadronic τ decays

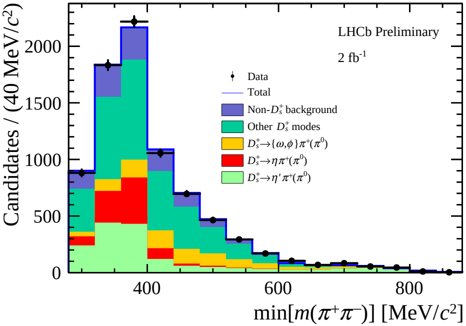
NEW!

- Double charm $B \to D^{*-} D_s^+ (\to 3\pi^\pm X) X$ events mimic signal topology

[LHCb-PAPER-2022-052] (In preparation)

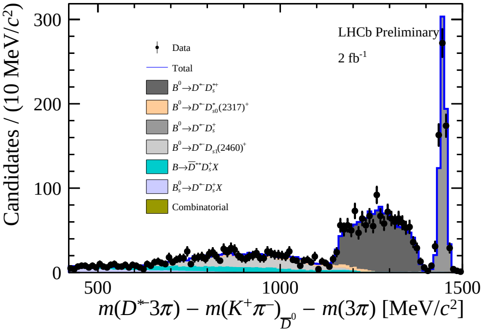
D_s^+ decay

- Data control sample with reverse anti-D_s^+ BDT selection
- $D_s^+ \to 3\pi^\pm X$ BFs determined and corrected in simulation



D_s^+ production

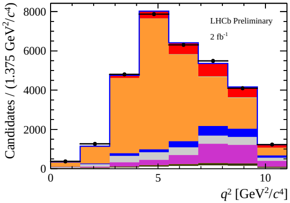
- $B \to D^{*-} D_s^{(*,**)} X$ sample selected with $m(3\pi^\pm)$ around D_s^+ mass
- Fractions constrained in the signal extraction fit

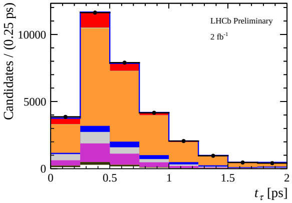


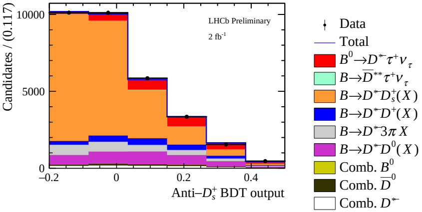
NEW!

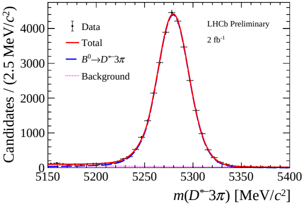
- A 3D binned template fit to extract the signal yield
  - $q^2 \equiv (p_{B^0} - p_{D^*})^2$
  - τ^+ decay time
  - Anti-D_s^+ BDT output

  [LHCb-PAPER-2022-052] (In preparation)
- $\boldsymbol{N(B^0 \to D^{*-}\tau^+\nu_\tau) = 2469 \pm 154}$
  - Run 1 yield $= 1296 \pm 86$
- $B^0 \to D^{*-}3\pi^{\pm}$ normalization yield from a fit to $m(D^{*-}3\pi^{\pm}) \sim 30$k









- Dominant systematic uncertainty from double charm bkg modelling
- Uncertainty from simulation sample size reduced thanks to the use of fast simulation

$R(D^*)$ with hadronic τ decays

NEW!

[LHCb-PAPER-2022-052] (In preparation)

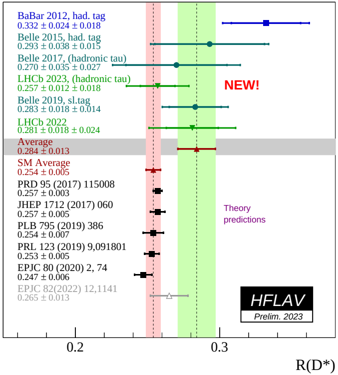
PRELIMINARY

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)} = 1.700 \pm 0.101(\text{stat})^{+0.105}_{-0.100}(\text{syst})$$

The absolute branching fraction of $B^0 \to D^{*-}\tau^+\nu_\tau$ decays, $\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)=$

$$(\mathbf{1.23} \pm \mathbf{0.07}\,(\text{stat}) \pm \mathbf{0.08}\,(\text{syst}) \pm \mathbf{0.05}(\text{ext})) \times 10^{-2}$$

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

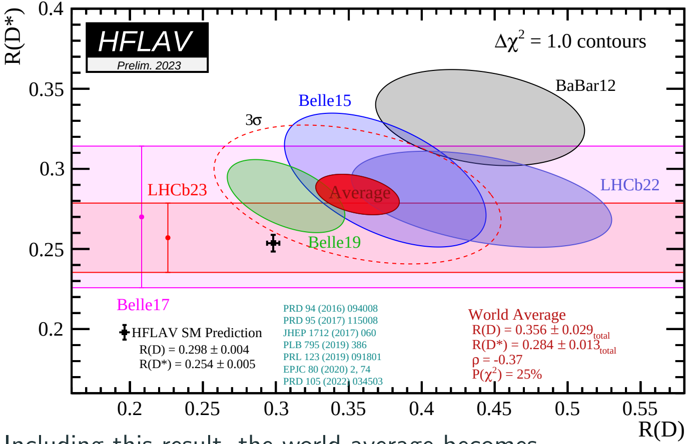


Combining with the Run 1 result

$$\boldsymbol{R(D^*)_{2011-2016} = 0.257 \pm 0.012\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.012\,(\text{ext})}$$

Agreement within 1σ to SM

NEW!



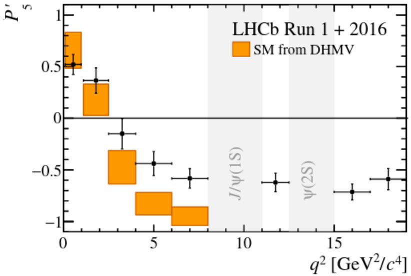
HFLAV PRELIMINARY

[LHCb-PAPER-2022-052]
(In preparation)

- Including this result, the world average becomes
  $R(D^*) = 0.284 \pm 0.013$; $R(D) = 0.356 \pm 0.029$
- The deviation w.r.t. the SM at **3.2σ** for the combination of $R(D)$-$R(D^*)$

Rare decays at LHCb

- Several deviations seen in branching fractions and angular observables
- Hadronic effects largest contributor to the theoretical uncertainties



[PRL **125** 011802 (2020)]

- BF and angular observables potentially suffer from underestimated hadronic effects
- Ratios between decays to different leptons very well predicted

$$R_H = \frac{\mathcal{B}(H_B \to H\mu^+\mu^-)}{\mathcal{B}(H_B \to He^+e^-)} = 1.00 \pm 0.01^{[3]}$$

[JHEP **2016**, 92 (2016), EPJC **76**, 440 (2016)]

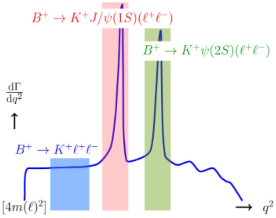
- Deviations would point towards NP!

- At LHCb, we measure the double ratios

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

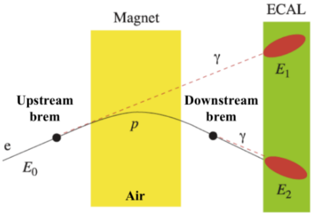
- Better control of efficiency in double ratio with control mode
- Cancellation of most experimental systematics
- Detector efficiencies from simulation are calibrated with control channels in data

- Define three regions
  - Rare region ($1.1 < q^2 < 6.0$ GeV^2)
  - Control region, dominated by J/ψ resonance
  - $\psi(2S)$ region

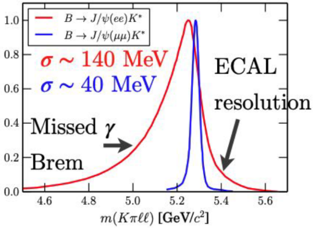


Electrons vs muons at LHCb

- Muons detected from hits in muon stations matched to extrapolated tracks
- Electrons are light, scatter more in detector $\Rightarrow$ Bremsstrahlung emission



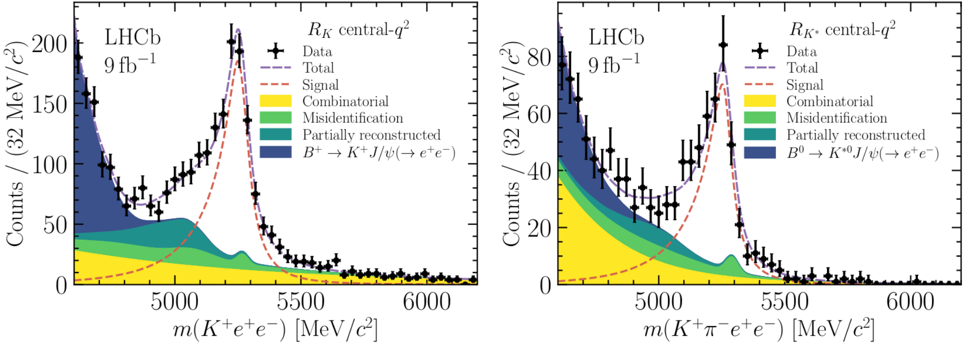
B mass resolution with e and μ in the final state



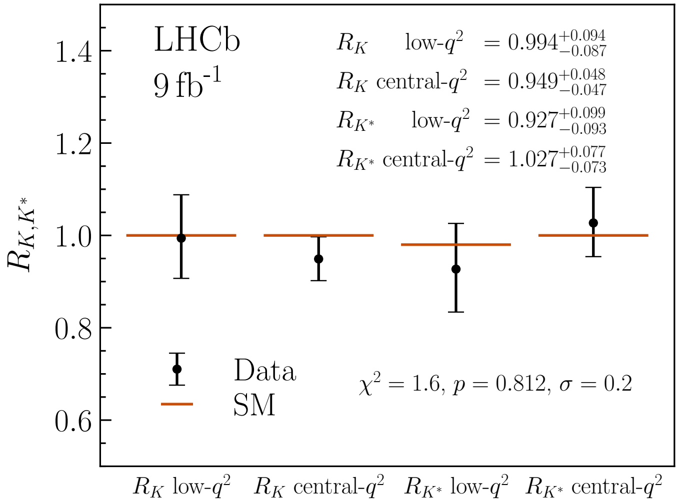
- Recover the energy loss by adding photon cluster energy compatible with electron direction, to the electron momentum

Latest $R_{K^{(*)}}$ measurements from LHCb

- Simultaneous measurement of R_K and R_{K^*} [arXiv:2212.09152, arXiv:2212.09153]
- LHCb Run 1+2 data : 9 fb^{-1} (Submitted to PRL & PRD)
- Ranges of q^2: low [0.1 – 1.1] GeV^2/c^2, central [1.1 – 6.0] GeV^2/c^2
- K^{*0} selected around $m(K^{*0}) \in [792, 992]$ MeV/c^2



Latest $R_{K^{(*)}}$ results



[arXiv:2212.09152, arXiv:2212.09153]

(Submitted to PRL & PRD)

low q^2

$R_K = 0.994^{+0.090}_{-0.082}(\text{stat})^{+0.029}_{-0.027}(\text{syst})$

$R_{K^*} = 0.927^{+0.093}_{-0.087}(\text{stat})^{+0.036}_{-0.035}(\text{syst})$

central q^2

$R_K = 0.949^{+0.042}_{-0.041}(\text{stat})^{+0.022}_{-0.022}(\text{syst})$

$R_{K^*} = 1.027^{+0.072}_{-0.068}(\text{stat})^{+0.027}_{-0.026}(\text{syst})$

R_K central q^2 result supercedes

Nature Physics **18**, 277 (2022)

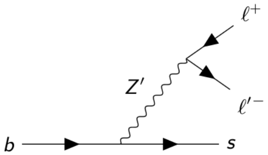
- Tighter e^- identification criteria

Agreement within 1σ to SM

Lepton Flavour Violating decays

- Forbidden within the SM, possible via BSM FCNC processes
- B meson decays are ideal for these searches
- Several recent measurements at LHCb with Run 1+2 dataset [arXiv:2207.04005, arXiv:2209.09846, arXiv:2210.10412]

(Submitted to JHEP, JHEP & PRD)



$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1 \times 10^{-9}$

▶ Most stringent limits!

$\mathcal{B}(B^0_s \to \phi\mu^\pm e^\mp) < 16.0 \times 10^{-9}$

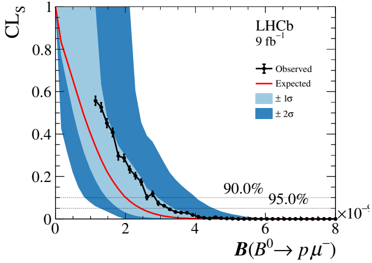
$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5}$

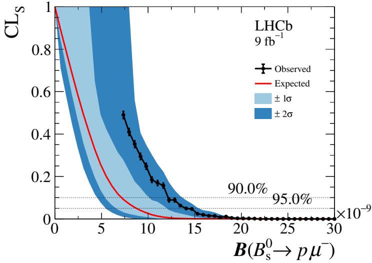
$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2 \times 10^{-6}$

$\mathcal{B}(B^0 \to p\mu^-) < 2.6 \times 10^{-9}$

$\mathcal{B}(B^0_s \to p\mu^-) < 12.1 \times 10^{-9}$

▶ First search for the decays!

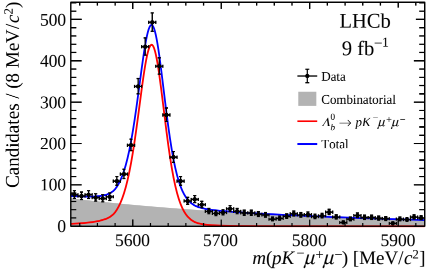


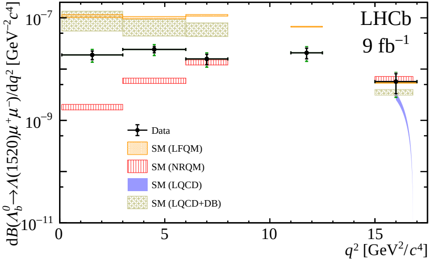


No signal observed for any of the decays

[arXiv:2302.08262]
(Submitted to PRL)

- First measurement of differential branching fraction of $\Lambda_b^0 \to \Lambda^*(pK^-)\mu^+\mu^-$ in intervals of q^2, squared dilepton mass, using LHCb Run 1+2 dataset
- $\Lambda(1520)$ resonance has spin $\frac{3}{2}$ and a narrow width of 16 MeV
  - Complementary info on potential NP effects in $b \to s\ell^+\ell^-$ transitions
- Λ^* selected with $m(pK)$ in the range [1450, 1850] MeV$/c^2$





- Better theory calculations needed at low q^2

FCNC decays with $\mathcal{B} \sim \mathcal{O}(10^{-14}) - \mathcal{O}(10^{-12})$ Key in constraining NP!

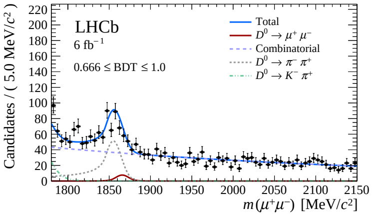
[PRD **66**, 014009 (2002), EPJC **73**, 2678 (2013)]

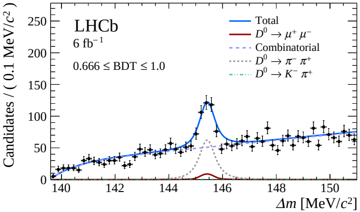
Dominated by $D^0 \to \pi^+\pi^-$ decays

$D^0 \to \mu^+\mu^-$ [arXiv:2212.11203]

(Submited to PRL)

- LHCb Run 1+2 dataset
- $\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.9 \times 10^{-9}$ at 90% CL
- Most stringent limit on FCNC in charm

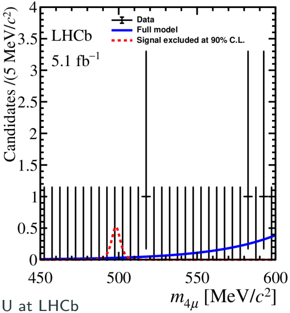




$K^0_{S,L} \to \mu^+\mu^-\mu^+\mu^-$ [arXiv:2212.04977]

(Submited to PRD)

- LHCb Run 2 dataset 5.1 fb^{-1}
- $\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$
- $\mathcal{B}(K^0_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$ at 90% CL
- First reported limits



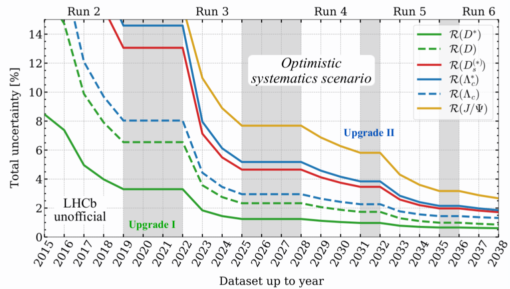
Conclusions

- LFU measurements from our Run 1+2 datasets
- $R(D^*)$ measurement including partial Run 2 dataset using hadronic $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$ decays **PRELIMINARY**

$$R(D^*)_{2011-2016} = \mathbf{0.257} \pm \mathbf{0.012}\,(\text{stat}) \pm \mathbf{0.014}\,(\text{syst}) \pm \mathbf{0.012}\,(\text{ext})$$ **NEW!**

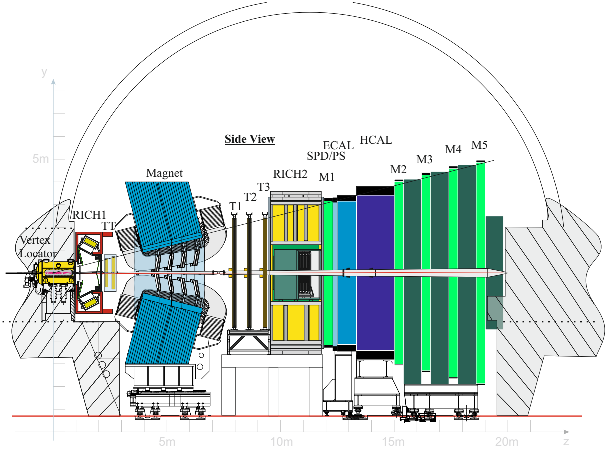
  - Agreement within 1σ to SM
  - Global picture unchanged for $R(D)$-$R(D^*)$ combination with tension with SM at the level of 3σ
- Charm and baryon sectors give promising results
- We have started taking data with first upgrade of LHCb, exciting times ahead!

[arXiv:2101.08326, arXiv:1808.08865]



Back-up slides

LHCb experiment



- Excellent vertex resolution (10 – 40 μm in xy-plane and 50 – 300 μm in z-axis)
- Particle identification efficiencies ∼97% for μ, e and ∼3% pion misidentification, good separation between π, K, p

JINST 3 (2008) S08005, Nucl. Phys. B 871 (2013) 1-20, JHEP 74 (2017)

Latest $R_{K^{(*)}}$ measurements from LHCb : cross-checks

- Fit crosschecks in J/ψ and $\psi(2S)$ regions to validate the precedure, no expected LFU violation effects