Lepton Flavour and Lepton Flavour Universality Violations in B-meson decays at LHCb

Prasanth Krishnan Kodassery

INP Krakow

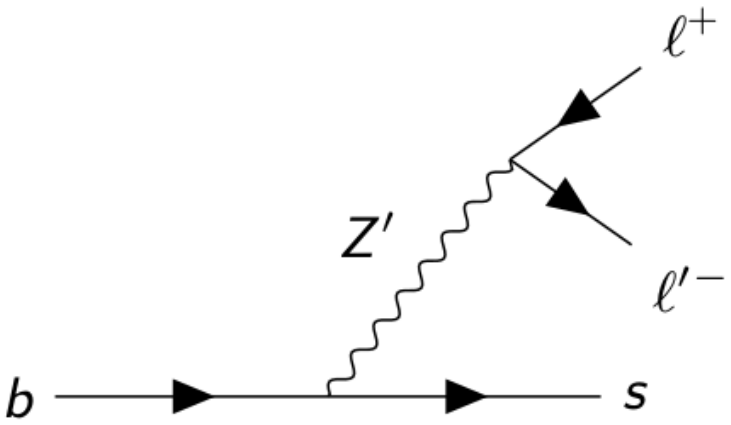
22 October, 2022
Standard Model and Beyond
Katowice

Outline

- Introduction
- Latest results from Lepton Flavour Violation in B meson decays
- Latest results from Lepton Flavour Universality Violation in B meson decays

Lepton-Flavour-Violating decays

- Forbidden within the SM
- Possible beyond the SM, eg: through FCNC process



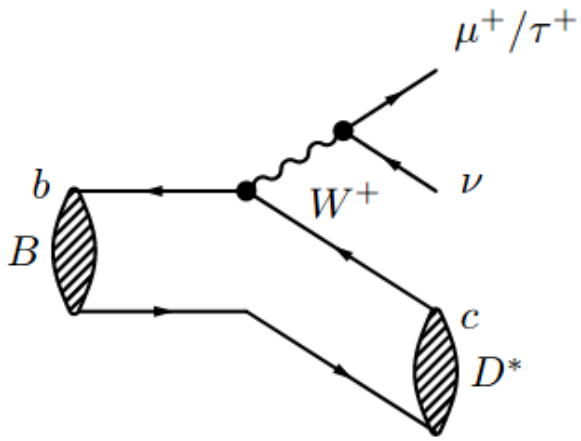
- Beyond Standard Model coupling needed to explain $b \to sll'$ transitions
  arXiv:1411.0565
- Strong motivation to search for $b \to s\mu e$ and $b \to s\tau\mu$ transitions
- B meson decays are ideal for these searches

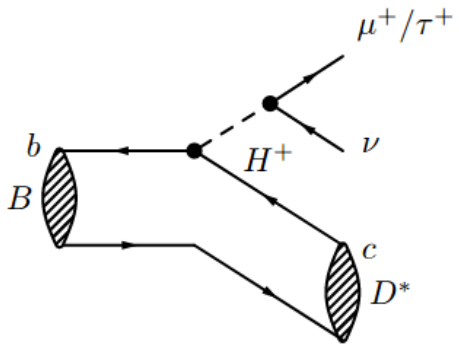
Lepton-Flavour-Universality in B meson decays

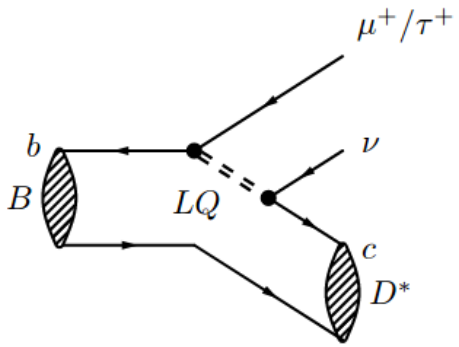
- SM is Lepton-Flavour-Universal
  - Difference between couplings to e, μ, and τ only due to different masses
- **Tree-level process** $B \to D^{(*)} l \nu$ is used
- Observable

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

  - Theoretically clean due to cancellation of most of form factor uncertainty
  - Sensitive to New Physics, *i.e.* extended Higgs, leptoquarks

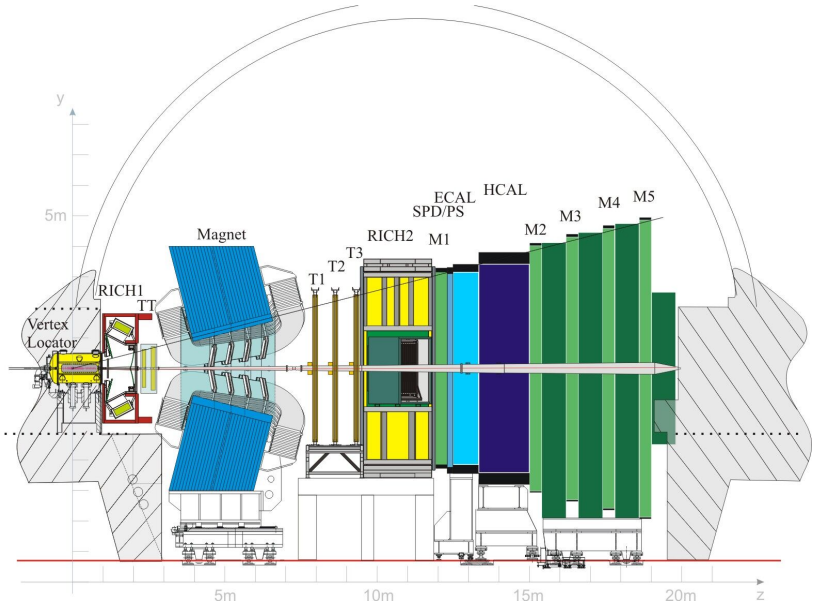






The LHCb Experiment

J. Instrum. **3** (2008) S08005; Nucl.Phys. **B 871** (2013) 1-20; J. High Energ. Phys. **74** (2017)



- Forward-arm spectrometer covering pseudo-rapidity $\eta \in (2, 5)$
- Study mainly beauty and charm hadron decays
- Dataset:
  - Run 1:
    - 2011: 1 fb^{-1} at 7 TeV
    - 2012: 2 fb^{-1} at 8 TeV
  - Run 2:
    - 2015–18: 6 fb^{-1} at 13 TeV

Overview of LHCb results for LFV and LNV decays

Lepton Flavour Violation:

Decay channel	90% (95%) C.L limit	Data	Reference
$B^0 \to e^\pm \mu^\mp$	$< 1.0(1.3) \times 10^{-9}$	3 fb^{-1}	JHEP, **03**, 078 (2018)
$B^0 \to \tau^\pm \mu^\mp$	$< 1.2(1.4) \times 10^{-5}$	3 fb^{-1}	PRL, **123**, 211801 (2019)
$B_s^0 \to e^\pm \mu^\mp$	$< 5.4(6.3) \times 10^{-9}$	3 fb^{-1}	JHEP, **03**, 078 (2018)
$B_s^0 \to \tau^\pm \mu^\mp$	$< 3.4(4.2) \times 10^{-5}$	3 fb^{-1}	PRL, **123**, 211801 (2019)
$B^+ \to K^+ \mu^- \tau^+$	$< 3.9(4.5) \times 10^{-5}$	9 fb^{-1}	JHEP, **06**, 129 (2020)
$B^+ \to K^+ \mu^- e^+$	$< 7.0(9.5) \times 10^{-9}$	3 fb^{-1}	PRL, **123**, 241802 (2019)
$B^+ \to K^+ \mu^+ e^-$	$< 6.4(8.8) \times 10^{-9}$	3 fb^{-1}	PRL, **123**, 241802 (2019)
$D^0 \to e^\pm \mu^\mp$	$< 1.3(1.6) \times 10^{-8}$	3 fb^{-1}	PLB, **754**, 167 (2016)
$D^+ \to K^+ \mu^+ e^-$	$< 1.0(1.1) \times 10^{-7}$	1.6 fb^{-1}	JHEP, **06**, 044 (2021)
$D^+ \to \pi^+ \mu^+ e^-$	$< 2.2(2.2) \times 10^{-7}$	1.6 fb^{-1}	JHEP, **06**, 044 (2021)
$D_s^+ \to K^+ \mu^+ e^-$	$< 5.6(6.4) \times 10^{-7}$	1.6 fb^{-1}	JHEP, **06**, 044 (2021)
$D_s^+ \to \pi^+ \mu^+ e^-$	$< 29.4(11.0) \times 10^{-7}$	1.6 fb^{-1}	JHEP, **06**, 044 (2021)
$\tau^- \to \mu^- \mu^+ \mu^-$	$< 4.6(5.6) \times 10^{-8}$	3 fb^{-1}	JHEP, **02**, 121 (2015)
$\tau^- \to \bar{p} \mu^+ \mu^-$	$< 3.3(4.3) \times 10^{-7}$	1 fb^{-1}	PLB, **724**, 36 (2013)
$\tau^- \to p \mu^- \mu^-$	$< 4.4(5.7) \times 10^{-7}$	1 fb^{-1}	PLB, **724**, 36 (2013)

Lepton Number Violation:

Decay channel	90% (95%) C.L limit	Data	Reference
$B^+ \to K^- \mu^+ \mu^+$	$< 4.1(5.4) \times 10^{-8}$	36 pb^{-1}	PRL, **108**, 101601 (2012)
$B^+ \to \pi^- \mu^+ \mu^+$	$< 4.4(5.8) \times 10^{-8}$	36 pb^{-1}	PRL, **108**, 101601 (2012)

Recent results from LHCb

Lepton Flavour Violation:

1. Search for $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\pm}$ decays
   arXiv:2207.04005, LHCb-PAPER-2022-008 (**submitted in JHEP**)

2. First search for $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ decays
   arXiv:2209.09846 , LHCb-PAPER-2022-021 (**submitted in JHEP**)

Lepton Number Violation & Baryon Number Violation:

1. First search for $B^0 \to p\mu^-$ and $B_s^0 \to p\mu^-$ decays
   arXiv:2210.10412, LHCb-PAPER-2022-022 (**submitted in PRD**)

Branching Fraction measurements at LHCb

- Relative to the well known B meson decay:

$$\mathcal{B}_{sig} = \frac{\mathcal{B}_{norm}}{N_{norm}} \times \underbrace{\frac{\epsilon_{norm}}{\epsilon_{sig}}}_{\textbf{Efficiencies}} \times N_{sig} \equiv \alpha_{sig} N_{sig},$$

  where α_{sig} is single event sensitivity

- Event selection & variable optimisations + fits for Signal $\Rightarrow N_{sig}$
- Event selection & variable optimisations + fits for Normalisation channel $\Rightarrow N_{norm}$
- Selection efficiencies $\Rightarrow \frac{\epsilon_{norm}}{\epsilon_{sig}}$
- Get $\mathcal{B}_{norm}$ and use it to obtain $\mathcal{B}_{sig}$
- All three searches use full LHCb Run 1 + Run 2 dataset $\Rightarrow$ 9 fb^{-1}

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

LFV in $b \to s\mu^{\pm}e^{\mp}$ decays

- **Scalar & Vector Lepto-Quark Model** predicts $\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) \lesssim 10^{-8}$

  PRD, **97**, 015019 (2018); PRD, **97**, 075004 (2018)

- **Models with Z' boson** predicts $\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) \lesssim 10^{-7}$

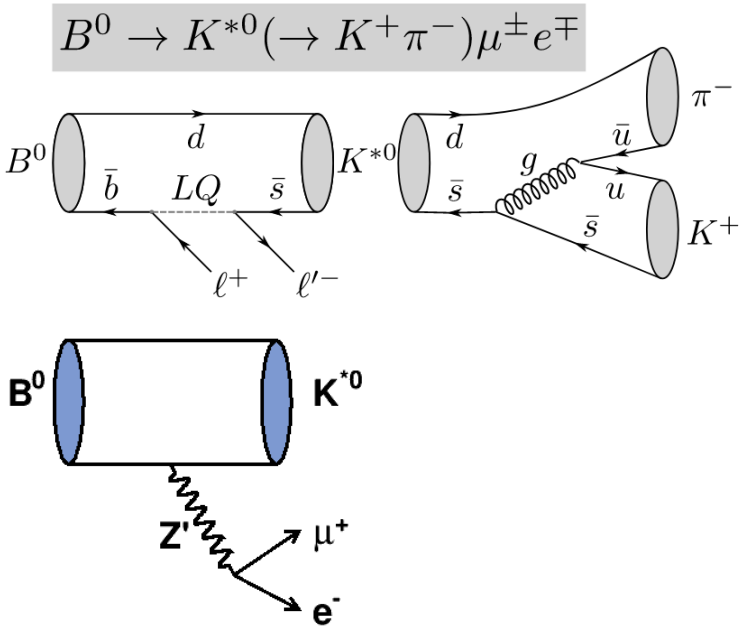
  PRD, **92**, 054013 (2015)

- Current best limit for $\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 1.8 \times 10^{-8}$ at 90% CL by Belle

  PRD, **98**, 071101 (2018)

- No upper limits on $\mathcal{B}(B_s^0 \to \phi\mu^{\pm}e^{\mp})$

- New Physics models can affect $b \to s\mu^+e^-$ and $b \to s\mu^-e^+$ transitions differently

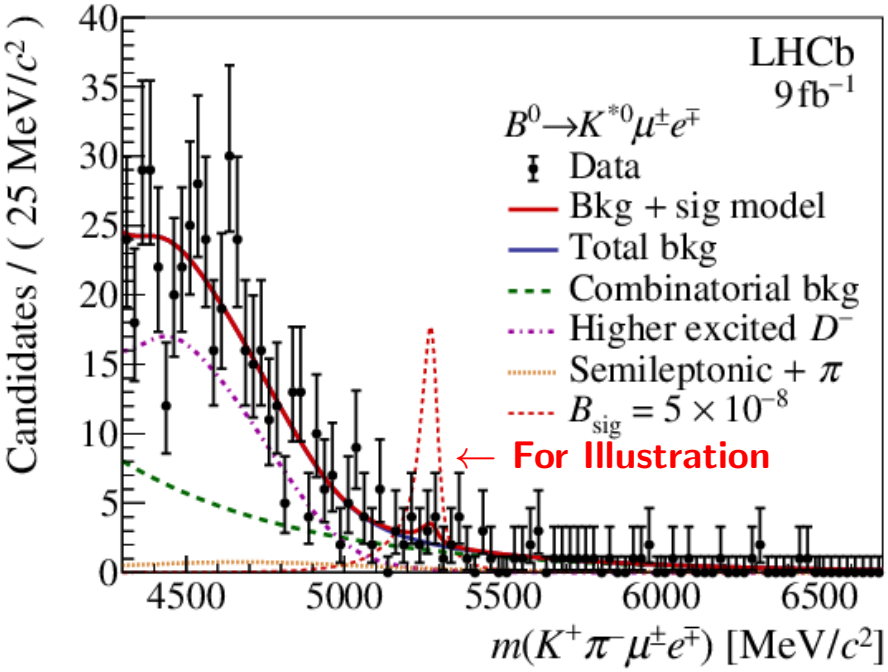


Main backgrounds for $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

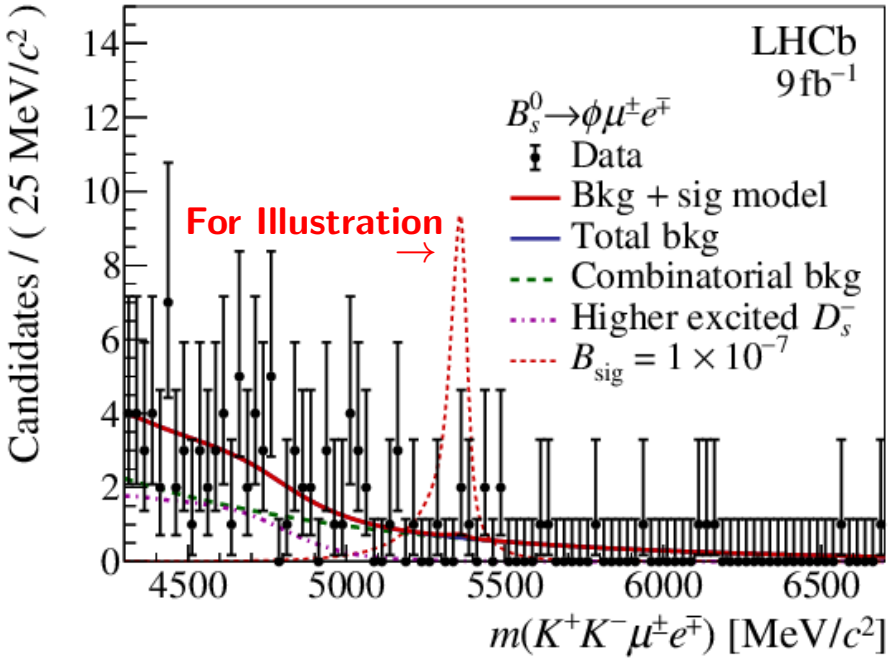
- **Misreconstructed background from $c\bar{c}$ decays:** arXiv:2207.04005
  - One of the leptons l misidentified as other lepton species l' from $B^0 \to J/\psi, \psi(2S)(\to l^+l^-)K^{*0}$ and $B_s^0 \to J/\psi, \psi(2S)(\to l^+l^-)\phi$
  - Lepton misidentified as a hadron or vice-versa ($l \leftrightarrow h$) from above decays
- **Partially reconstructed backgrounds from $B^0 \to D^{(*)-}l^+\nu_l$ and $B_s^0 \to D_s^{(*)-}l^+\nu_l$:**
  - Stringent requirement on invariant mass of $K^+\pi^-l^\pm > 2$ GeV$/c^2$ and $K^+K^-l^\pm > 2$ GeV$/c^2$
- **Partially reconstructed backgrounds from $B^0 \to D_2^{*-}l^+\nu_l$ and $B_s^0 \to D_{s2}^{*-}l^+\nu_l$:**
  - Escape the above mass veto due to higher masses
  - Modelled using simulation and included in the fit to the data
- **Combination of $B^+ \to \bar{D}^0\left(K^+l^-\nu_l\right)l'^+\nu_{l'}$ and a random pion from the event:**
  - Only affect $B^0 \to K^{*0}\mu^\pm e^\mp$ decays
  - Modelled using simulation and included in the fit to the data
- **Combinatorial background:**
  - Combinations of random tracks
  - Reduced with a multivariate classifier

Fit to data arXiv:2207.04005

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



$B_s^0 \to \phi\mu^{\pm}e^{\mp}$



- **Signal**: Sum of two Crystal Ball functions
  - Resolution corrected by $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$
- **Partially reconstructed backgrounds**: Based on simulation
- **Combinatorial background**: Single exponential function
- Simultaneous fit to Run 1 & Run 2 dataset and **set the upper limit**

Systematic uncertainties arXiv:2207.04005

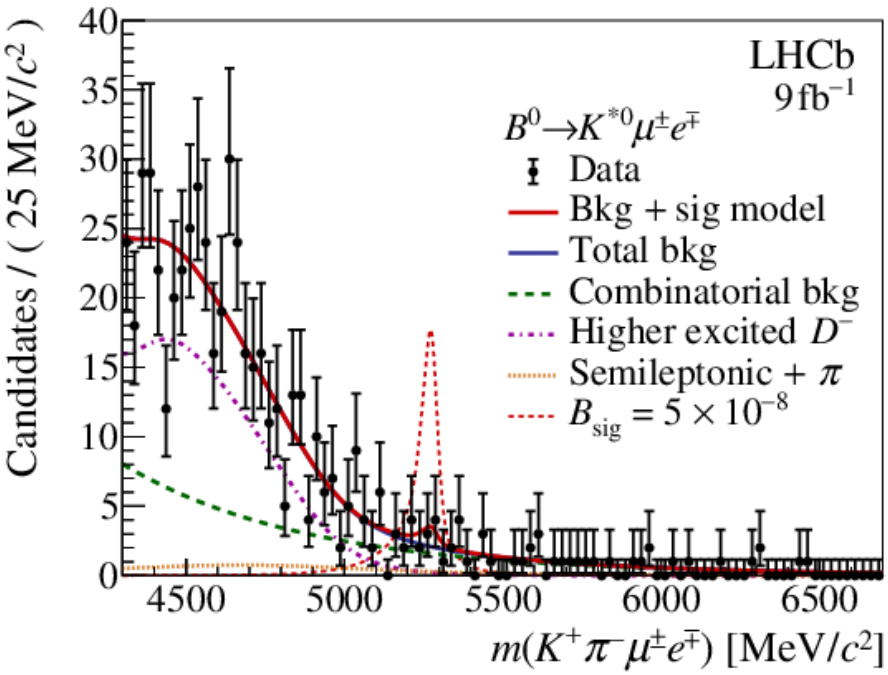
Systematic source	$B^0 \to K^{*0}\mu^\pm e^\mp$	$B_s^0 \to \phi\mu^\pm e^\mp$
Normalisation $\mathcal{B}$	4.0	4.8
$\phi\mu^\pm e^\mp$ decay time distribution	–	3.8–4.5
Limited simulation sample size	0.7–1.5	0.6–1.4
Production kinematics/multiplicity	1.2–2.7	1.6–3.8
Particle identification	0.3–0.8	0.3–0.6
Muon identification	1	1
Tracking efficiency	1	1
L0 trigger calibration	1	1
HLT trigger efficiency	1	1
Residual MC differences	1.7–4.3	1.1–3.7
Sum	5.2–6.7	6.9–8.5

- Dominant systematic uncertainty → **uncertainties on normalisation channels**
  - $\mathbf{B^0 \to J/\psi(\to \mu\mu)K^{*0}}$ for $B^0 \to K^{*0}\mu^\pm e^\mp$
  - $\mathbf{B_s^0 \to J/\psi(\to \mu\mu)\phi}$ for $B_s^0 \to \phi\mu^\pm e^\mp$
- B_s^0 decay width difference affects decay time distribution of $B_s^0 \to \phi\mu^\pm e^\mp$

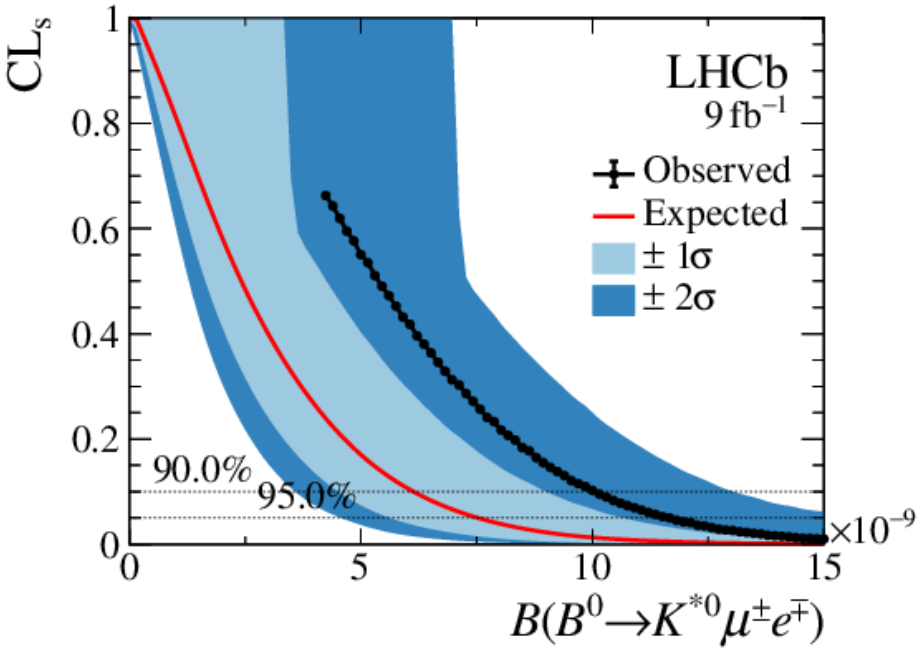
Upper limit for $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$

- Limits are set using **CL_s method**

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

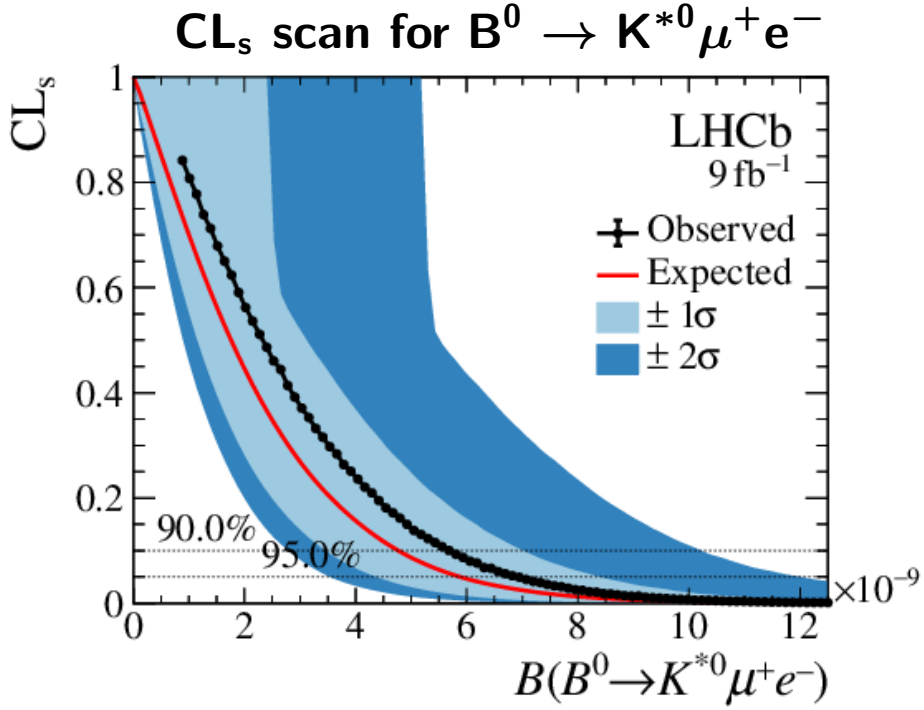


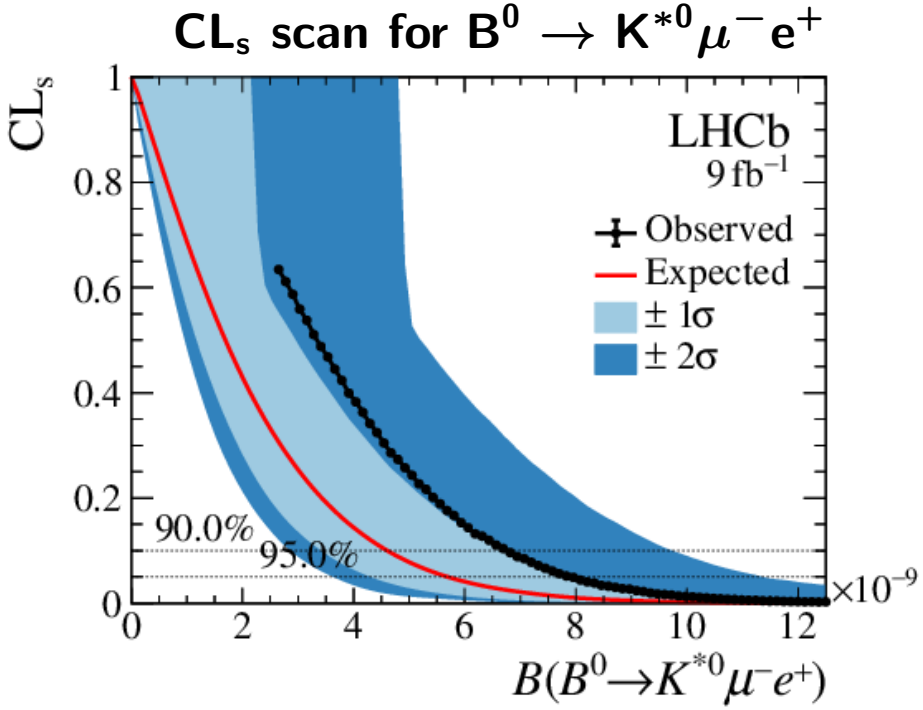
CL_s scan for $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$



- **Expected Limit** (background only hypothesis): arXiv:2207.04005
  - $\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 6.1(7.5) \times 10^{-9}$ at 90% (95%) CL
- **Observed Limit**:
  - $\boldsymbol{\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 10.1(11.7) \times 10^{-9}}$ at 90% (95%) CL

Upper limit for $B^0 \to K^{*0}\mu^+e^-$ and $B^0 \to K^{*0}\mu^-e^+$





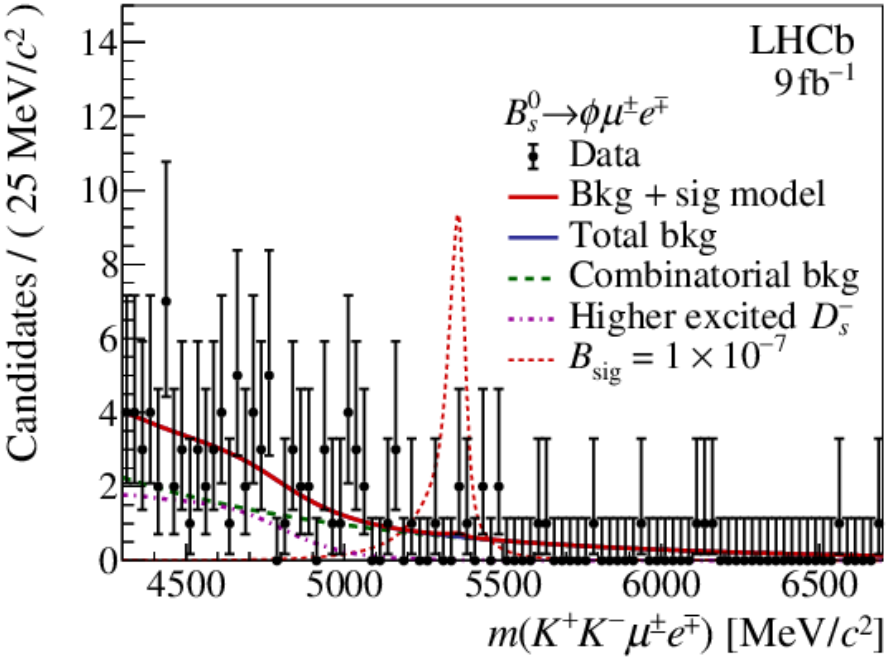
- **Expected Limit** (background only hypothesis):
  arXiv:2207.04005
  $\mathcal{B}(B^0 \to K^{*0}\mu^+e^+) < 4.8(5.9) \times 10^{-9}$ at 90% (95%) CL
- **Observed Limit**:
  $\boldsymbol{\mathcal{B}(B^0 \to K^{*0}\mu^+e^+) < 5.7(6.9) \times 10^{-9}}$ at 90% (95%) CL

- **Expected Limit** (background only hypothesis):
  arXiv:2207.04005
  $\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 4.6(5.7) \times 10^{-9}$ at 90% (95%) CL
- **Observed Limit**:
  $\boldsymbol{\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8(7.9) \times 10^{-9}}$ at 90% (95%) CL

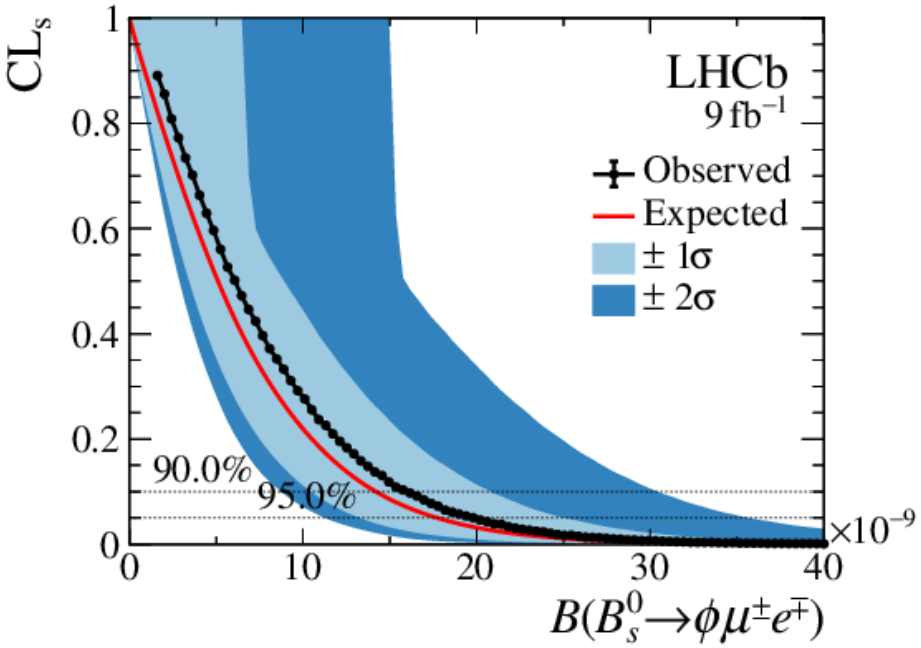
Upper limit for $B_s^0 \to \phi\mu^\pm e^\mp$

- Limits are set using **CL_s method**

$B_s^0 \to \phi\mu^\pm e^\mp$



CL_s scan for $B_s^0 \to \phi\mu^\pm e^\mp$

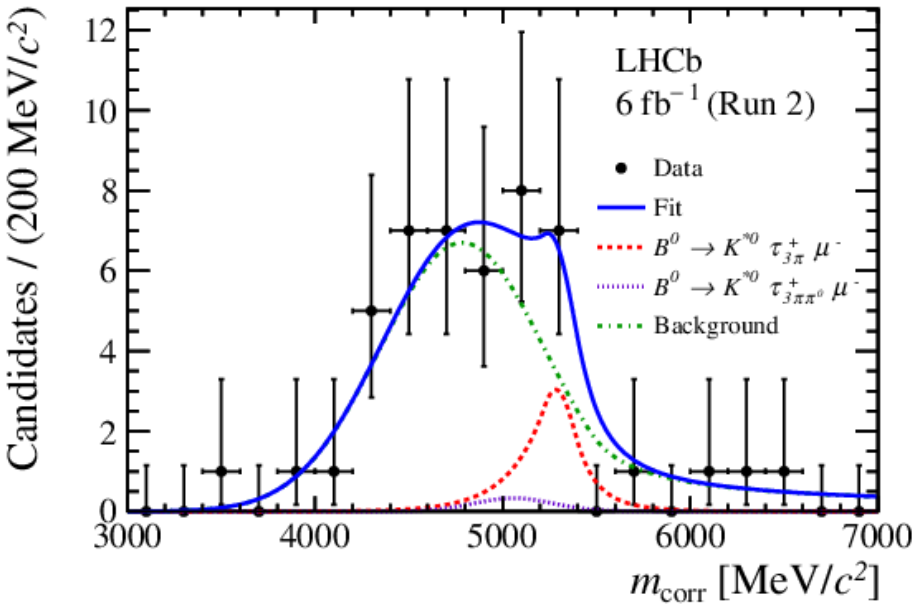


- **Expected Limit** (background only hypothesis): arXiv:2207.04005
  - $\mathcal{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 14.2(17.7) \times 10^{-9}$ at 90% (95%) CL
- **Observed Limit**:
  - $\boldsymbol{\mathcal{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 16.0(19.8) \times 10^{-9}}$ at 90% (95%) CL

First search for $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ decays

τ reconstruction and fit to data arXiv:2209.09846

- Only used $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ decays $\Rightarrow \mathcal{B} \sim$ **14%**
- Corrected Mass $\mathbf{m_{corr}} = \sqrt{\mathbf{p}_\perp^2 + \mathbf{m}^2_{K^*\tau\mu}} + \mathbf{p}_\perp$ used in B reconstruction due to missing momentum
- Signal peaks in m_{corr} with limited resolution

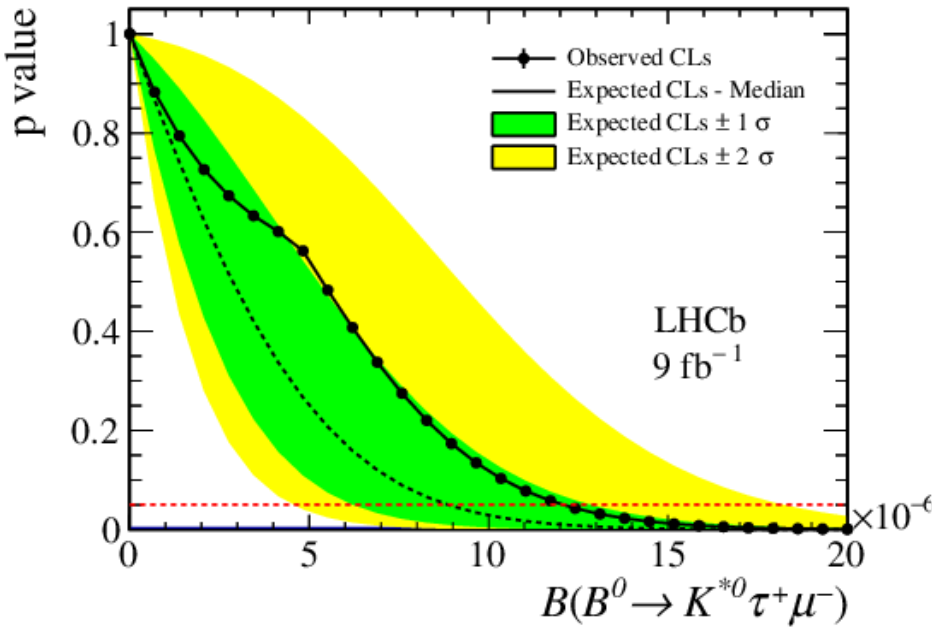


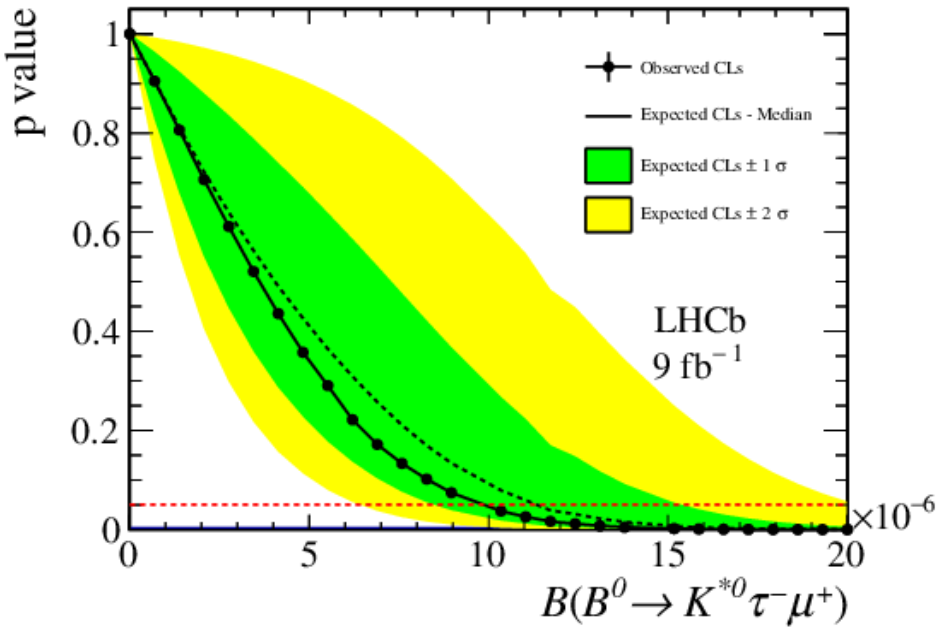
- **Signal:** Double sided Crystal Ball function
- **Background:** Double sided Crystal Ball function
  - Main source for $B^0 \to K^{*0}\tau^-\mu^+$ is $B^0 \to D^{*-}\mu^+\nu_\mu$
  - Main source for $B^0 \to K^{*0}\tau^+\mu^-$ is $B^0 \to D^{*-}\tau^+\nu_\tau$
- Simultaneous fit to Run 1 and Run 2 dataset and **set the upper limit**

Upper limit for $B^0 \to K^{*0}\tau^+\mu^-$ and $B^0 \to K^{*0}\tau^-\mu^+$

- Limits are set using **CL_s method**

arXiv:2209.09846





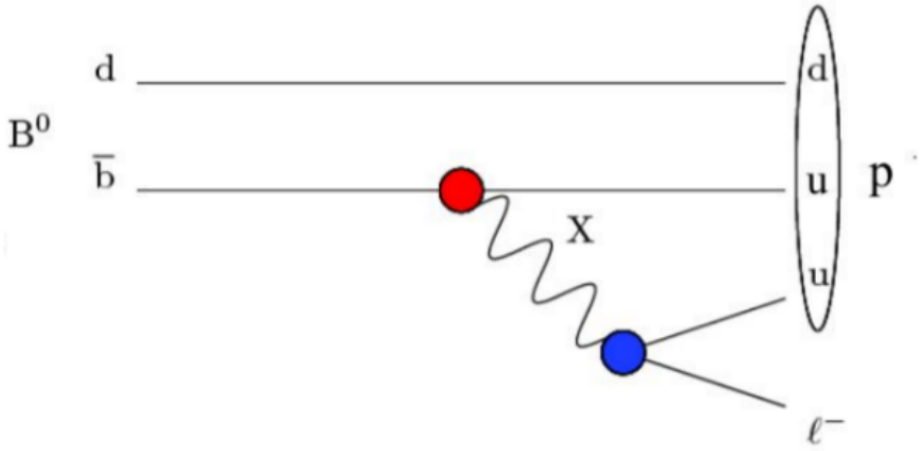
- **Observed Limit:**
  $\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5}$
  at 90%(95%) CL

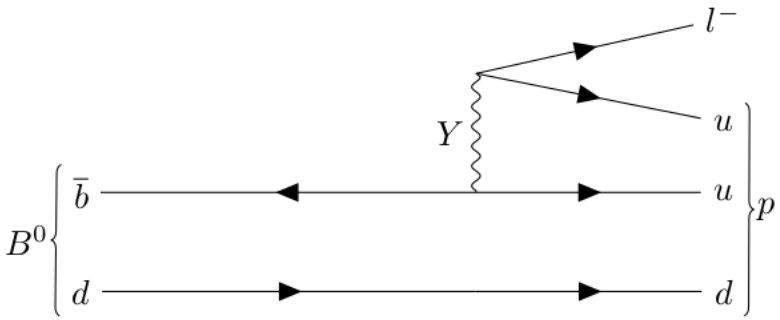
- **Observed Limit:**
  $\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2(9.8) \times 10^{-6}$
  at 90%(95%) CL

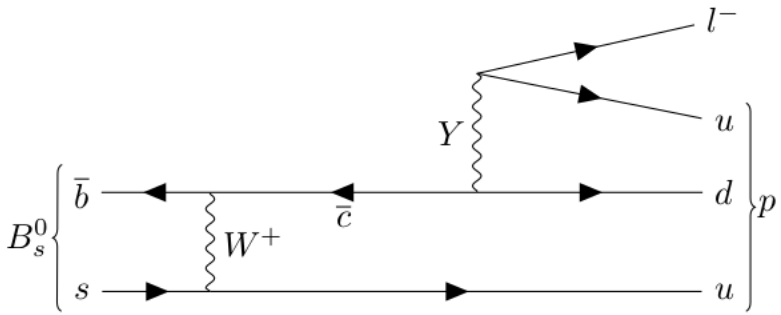
First search for $B^0 \to p\mu^-$ and $B_s^0 \to p\mu^-$ decays

$B^0 \to p\mu^-$ and $B_s^0 \to p\mu^-$ decays

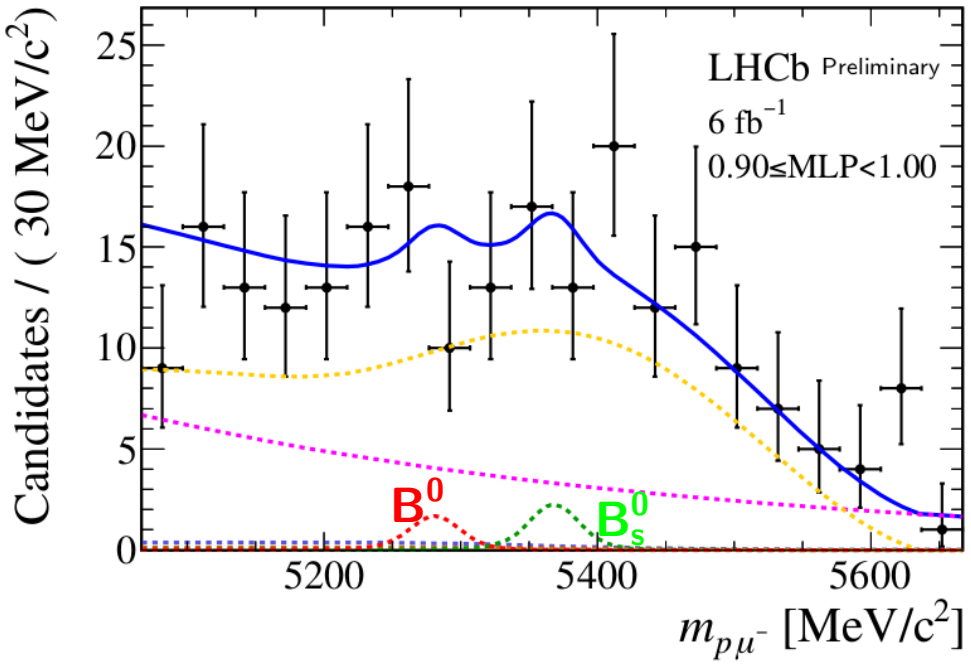
- Lepton-Number-Violating and Baryon-Number-Violating decays
- BNV proton decay could be mediated by massive bosons X & Y which couple to quarks and leptons
- Decays are highly suppressed in the SM
  - $\mathcal{B}(b \to uul^-) < 2.4 \times 10^{-27}$
    PRD, **72**, 095001 (2005)
    - based on the constraint of proton stability







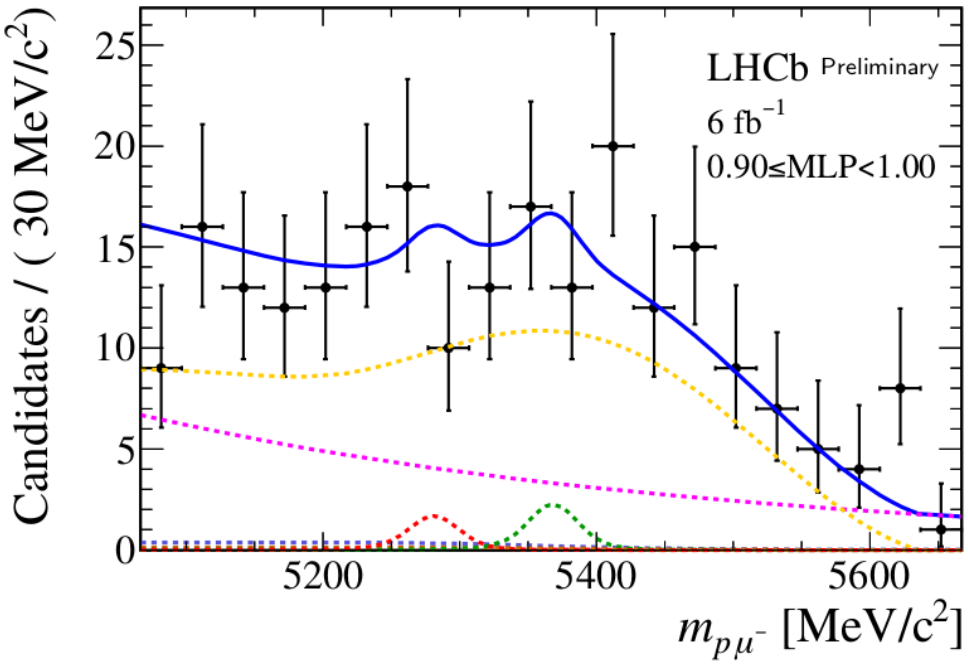
Fit to $B^0_{(s)} \to p\mu^-$ data arXiv:2210.10412

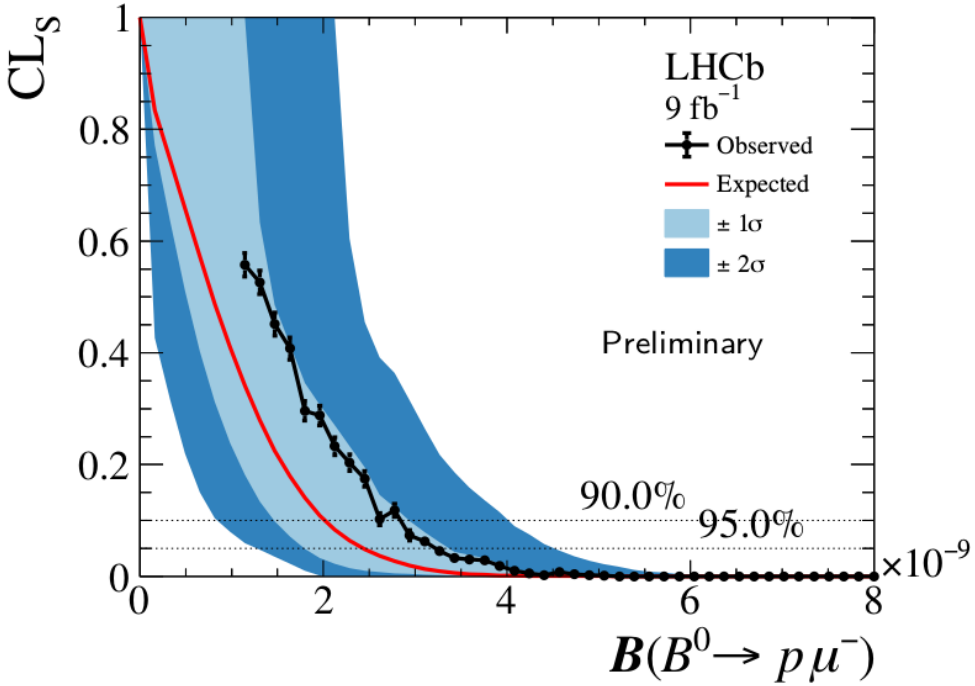


- **Signal**: Double Sided Crystal Ball + Gaussian
- **Physics background**:
  - Mainly $\Lambda_b \to p\mu^-\bar{\nu}_\mu$
- **Combinatorial**: Single Exponential
- Simultaneous fit to Run 1 & Run 2 dataset in 7 bins of multivariate classifier
- No excess of events $\Rightarrow$ Set upper limit

Limit on $B^0 \to p\mu^-$ decays arXiv:2210.10412

- Limits are set using **CL_s method**

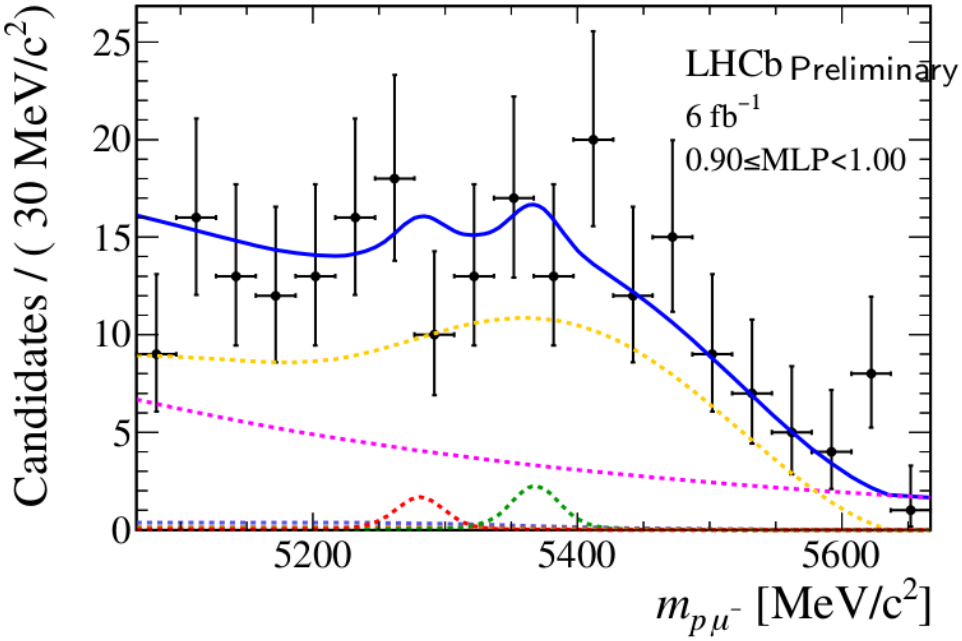


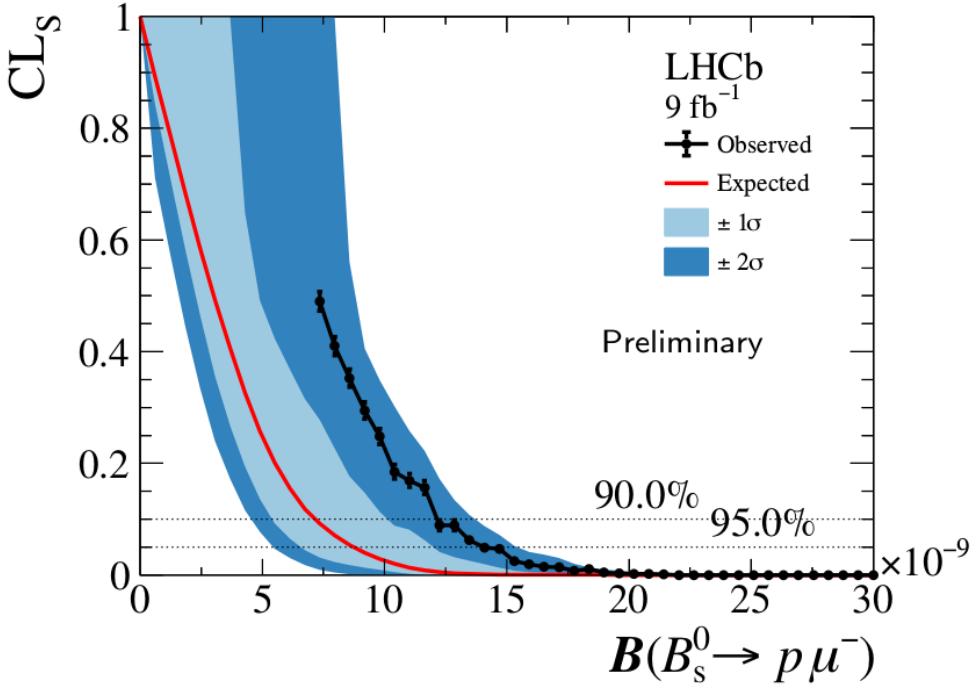


- **Observed Limit**:
  - $\mathcal{B}(\mathrm{B}^0 \to \mathrm{p}\mu^-) < 2.6(3.1) \times 10^{-9}$ at 90%(95%) CL

Limit on $B_s^0 \to p\mu^-$ decays arXiv:2210.10412

- Limits are set using **CL_s method**



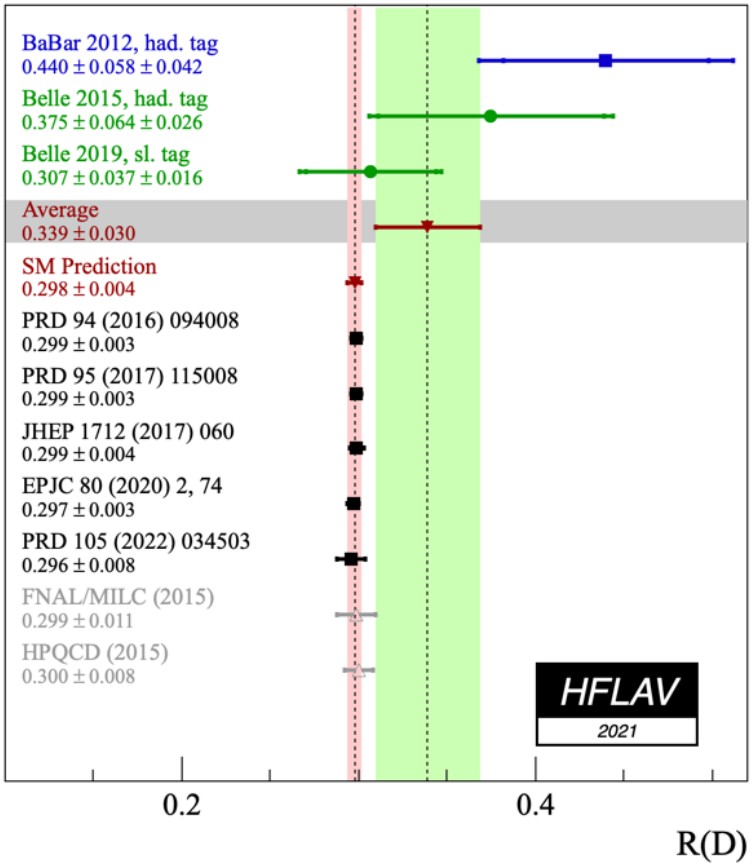


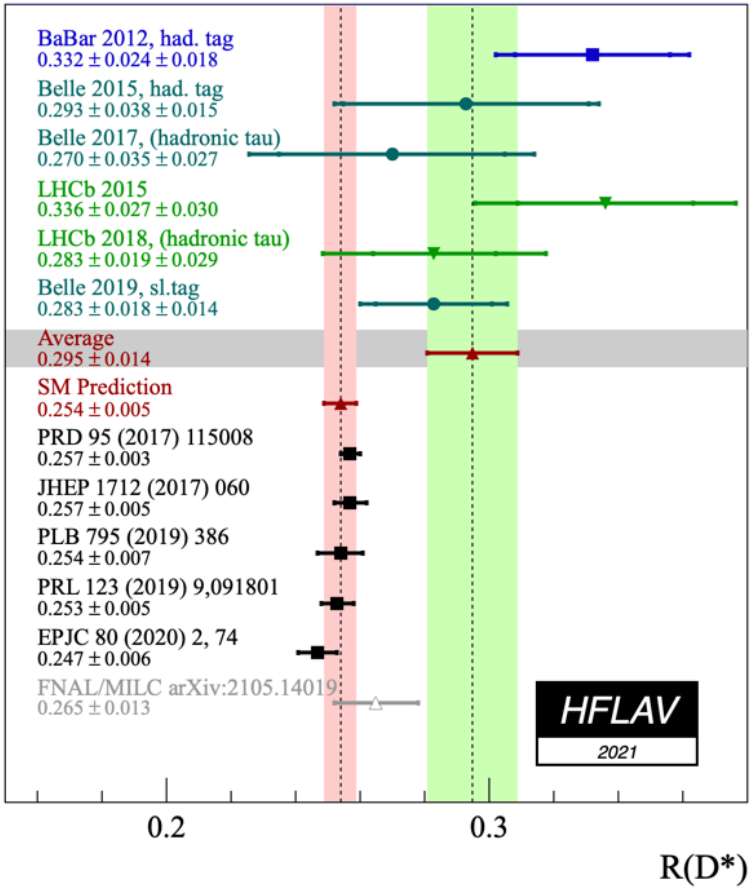
- **Observed Limit**:
  - $\mathcal{B}(B_s^0 \to p\mu^-) < 12.1(14.0) \times 10^{-9}$ at 90%(95%) CL

Testing Lepton-Flavour-Universality with

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

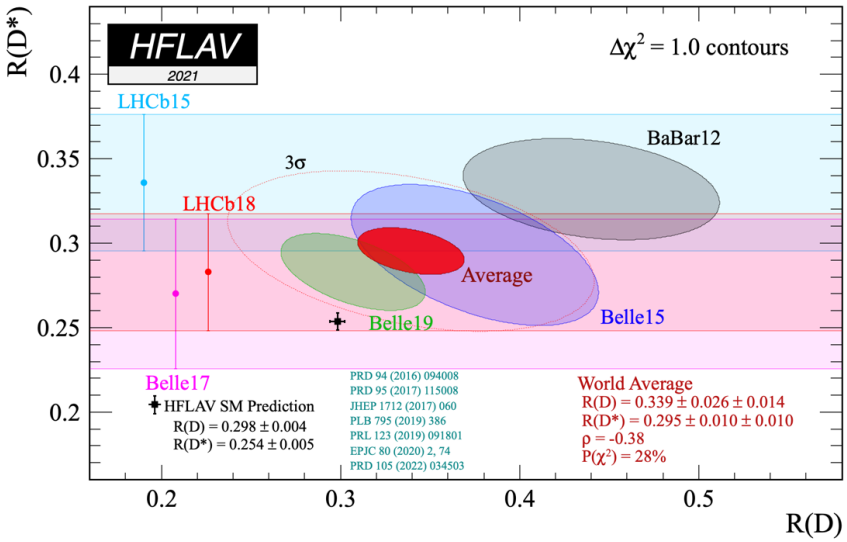
$R(D)$ and $R(D^*)$ measurements so far





- All measurements are with central values above the SM prediction

Simultaneous determination of $R(D)$ and $R(D^*)$



- Earlier: Measure $R(D^*)$ using visible final state $D^*\mu$ for Run 1 data
- Latest result: Simultaneous determination of $R(D)$ and $R(D^*)$ using visible final states $D^*\mu$ and $D^0\mu$ for Run 1 data
- Use $\tau \to \mu\nu\bar{\nu}$

Improvements:

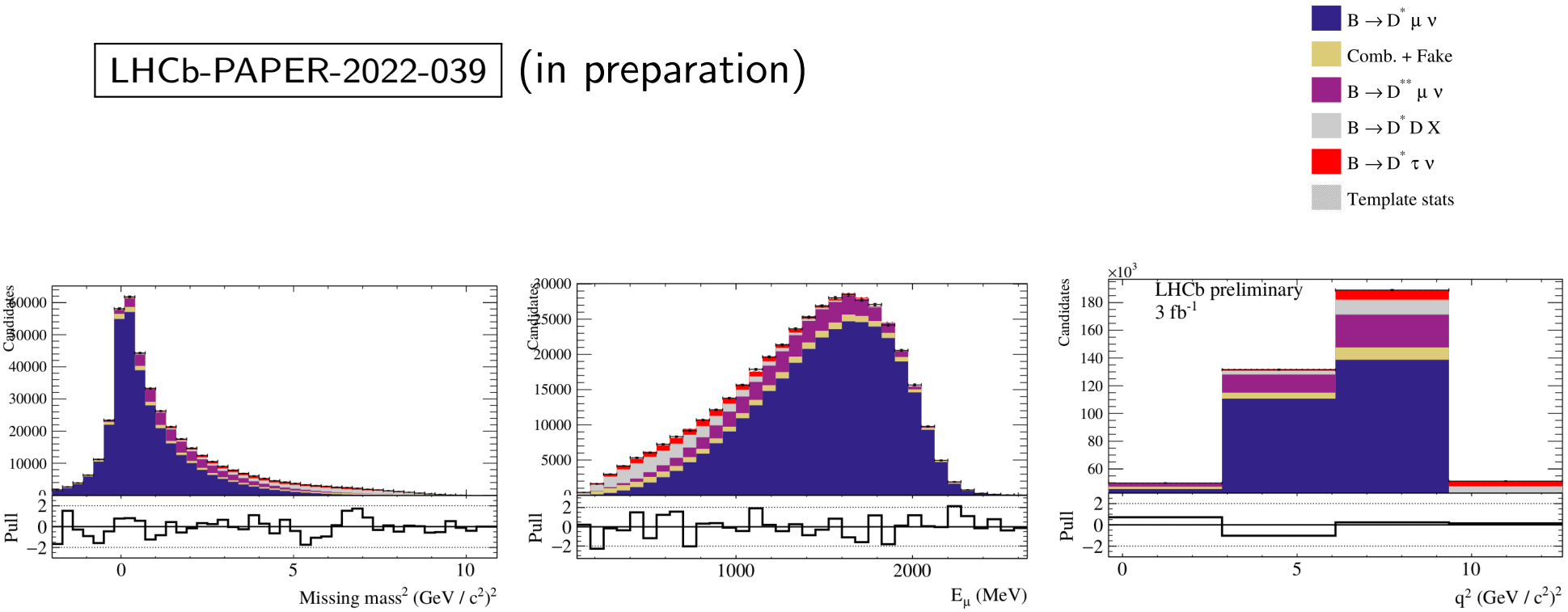
- Data/simulation rigorously checked and calibrated
- μ identification
- Form factor modelling

Experimental Challenges:

- Three neutrinos in the final state $\tau(\to \mu\nu\bar{\nu})\nu$
- Backgrounds: Partially reconstructed B decays, misidentified background and combinatorial

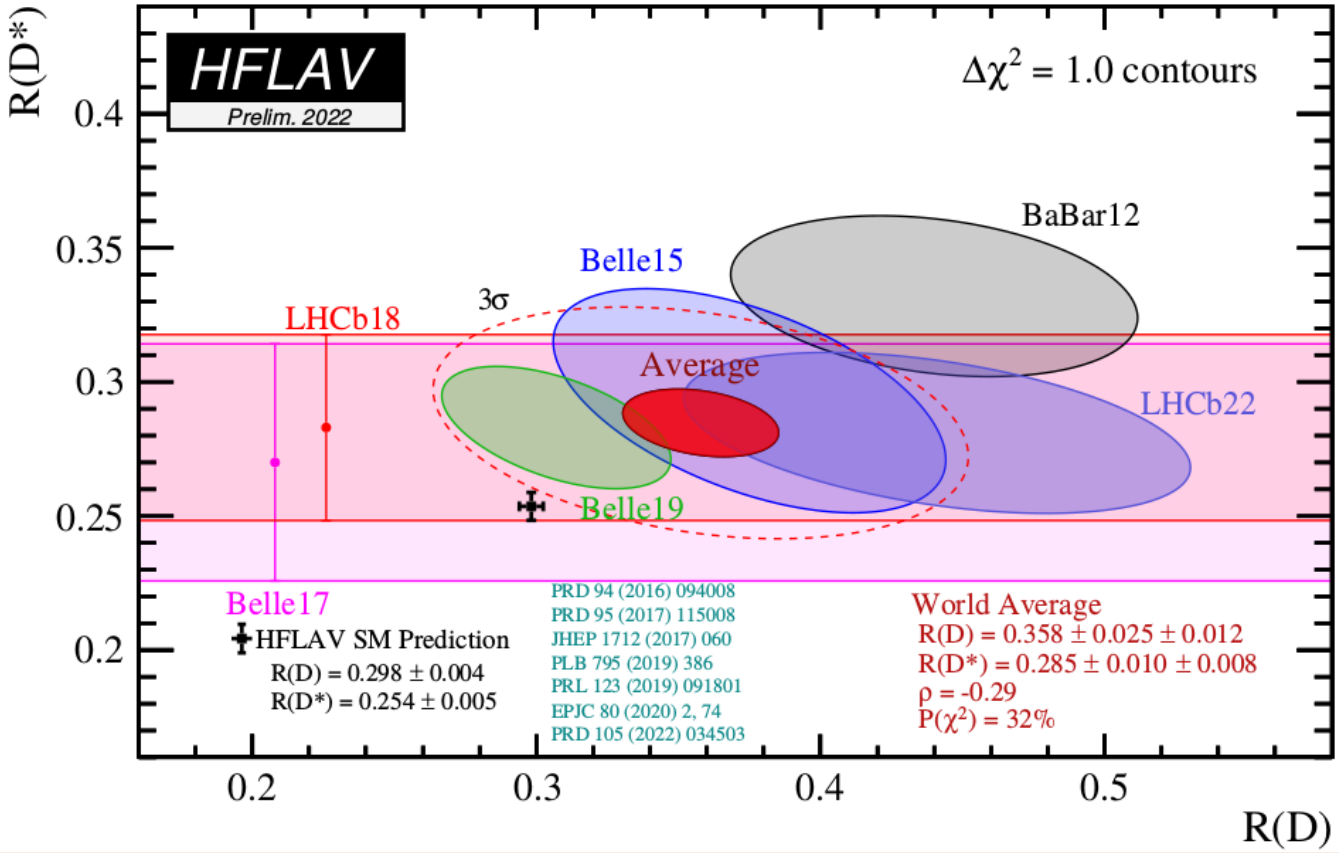
Results

LHCb-PAPER-2022-039 (in preparation)



- Refit the same $D^*\mu$ data as the previous result with improved knowledge
- New $D^*\mu$ sample **R(D*) = 0.293**, 1.6σ agreement from previous result

Results - HFLAV



$$\mathbf{R(D^*) = 0.281 \pm 0.018 \pm 0.024}$$
$$\mathbf{R(D) = 0.441 \pm 0.060 \pm 0.066} \quad \text{with } \boldsymbol{\rho = -0.43}$$

- Slightly lower $R(D^*)$, slightly higher $R(D)$, reduced correlation
- $3.3\sigma \rightarrow 3.2\sigma$ agreement with SM

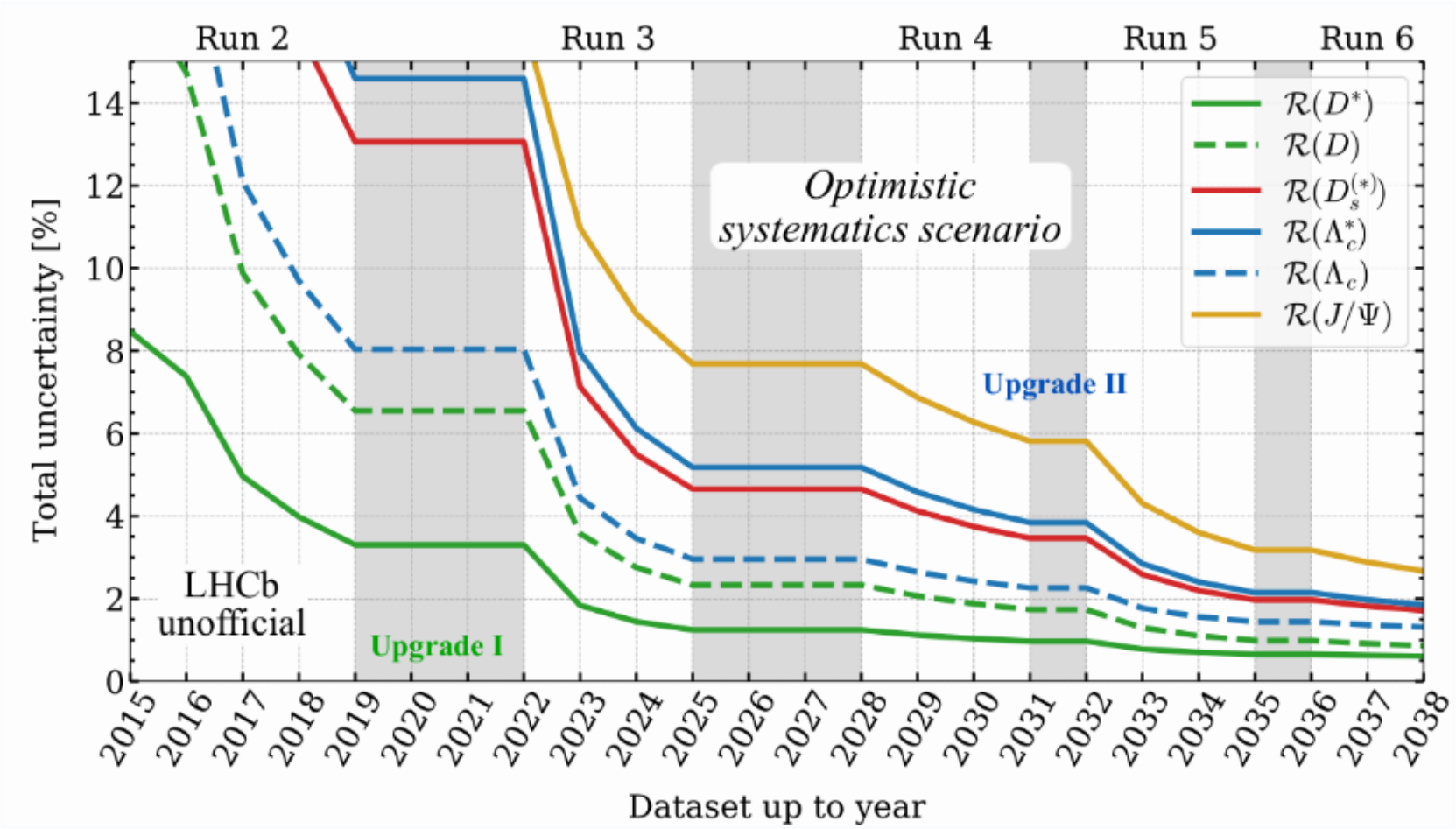
Summary

Lepton Flavour Violation:

- Most stringent limits for $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ decays
- First search for $B_s^0 \to \phi\mu^{\pm}e^{\mp}$ and $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ decays
- First search for Lepton-Number-Violating and Baryon-Number-Violating $B^0 \to p\mu^-$ and $B_s^0 \to p\mu^-$ decays

Lepton Flavour Universality Violation:

- First measurement of $R(D)$ in hadron collider
- Run 2 measurements ongoing

Backup slides

Prospects for $R(X)$ measurements at LHCb