Lepton Flavour Violation at LHCb

WIFAI 2024 - Workshop Italiano sulla Fisica ad Alta intensità - Bologna

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Motivations

- **Lepton Flavour** is an *accidental simmetry* in the SM
- ν *oscillations* lead to Lepton Flavour Violation (LFV) for **neutral leptons**
- No **cLFV** process observed yet, SM+ν mixing: $\mathcal{B}(\tau\to\mu\gamma) \sim\mathcal{O}(10^{-40})$
- Beyond SM new particles can *enhance* such processes up to $\sim\mathcal{O}(10^{-10}\text{-}10^{-7})$
- **Observation** of cLFV: **clear sign** of New Physics
- *Limit setting* on $\mathcal{B}$: *constrain theories* of NP

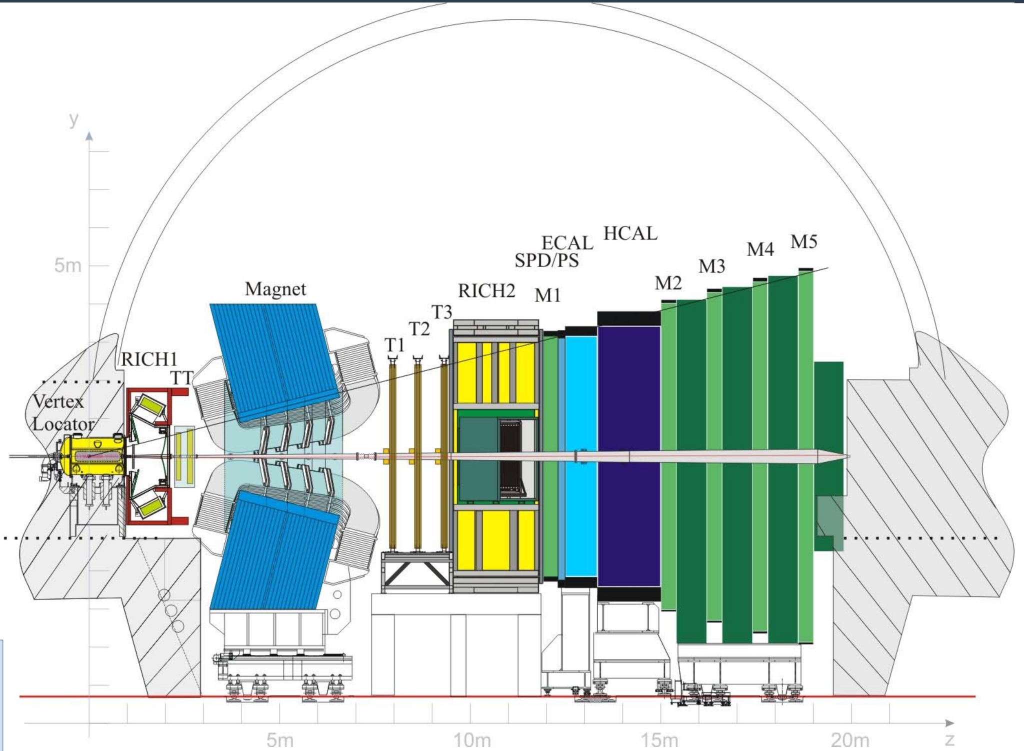
[PhysRevD.110.075004, JHEP09(2024)174, sym16030359]

LHCb

- **Forward spectrometer**: excellent detector for study beauty and charm hadrons
- Most b produced in acceptance
- Excellent vertex resolution, tracking and Particle Identification

$\Delta p/p = 0.5\%$ @ low momentum
IP resolution:
$(15 + 29/p_T\ [GeV])\mu m$

$\epsilon(e)\ \sim 90\%$, misID$(e \to h)\ \sim 5\%$
$\epsilon(K) \sim 96\%$, misID$(\pi \to K) \sim 5\%$
$\epsilon(\mu)\ \sim 97\%$, misID$(\pi \to \mu)\ \sim 2\%$



Run1 & Run2 Detector

Semileptonic B decays: why search cLFV here?

- cLFV is intrinsically connected to Lepton Flavour Universality Violation (coupling strengths are not identical across different lepton flavours) [PhysRevLett.114.091801]

LFU tests with $b \to s\, l^+ l^-$ (R_K,R_{K^*}):
- electron-muon universality compatible with SM [PRD108(2023)032002]

and $b \to c\, l^- \nu_l$ (R_{D^*},R_{D^0}): [PhysRevLett.131.111802]
- $\sim 3\sigma$ deviations with SM

- New particles like Z' or leptoquarks allow for additional tree-level contributions that enhance to experimental level the $\mathcal{B}$ of process like: [PhysRevD.92.054013]

$$B^0 \to K^{*0} e^{\pm} \mu^{\mp} \quad B^0 \to K^{*0} \tau^{\pm} \mu^{\mp}$$
$$B^0_S \to \phi\, e^{\pm} \mu^{\mp} \quad B^0_S \to \phi \tau^{\pm} \mu^{\mp}$$

- Analyses performed on 9 fb^{-1}

Effective Theory

- In the full theory, interactions might involve **heavy particles** with masses well above the *low-energy scale* we're interested in.

[arXiv:1704.05340]

The *weak effective* Hamiltonian relevant to $b \to s\, l^+ l^-$ is:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i + \text{h.c.}\,,$$

Where the Wilson coefficients $\mathcal{C}_i$ quantify the strength of each possible operator

- Recently LHCb performed an angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays: the angular observables are found to be consistent with the SM expectations

[LHCb-PAPER-2024-022]
To be published soon

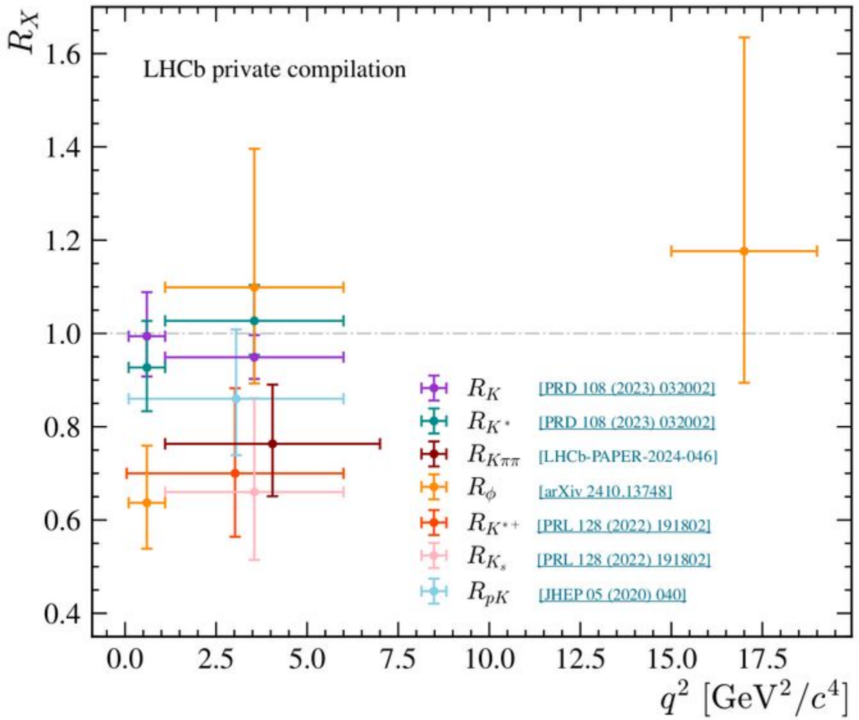
- LFUV in $b \to c\, l^- \nu_l$ are still an interesting source for LFV, especially in tau decays

LFU in $b \to sll$

- $b \to s\,l\,l$ are rare process studied extensively to test LFU of the SM by measuring relative rates

$$R_{(K,K^*)}(q_a^2, q_b^2) = \frac{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{q_a^2}^{q_b^2} \frac{\mathrm{d}\Gamma(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

- $\mathcal{B} \sim 10^{-7}$–10^{-6} (loops or boxes transitions)
- non-LFU new physics mediators can contribute with amplitudes similar to SM one's



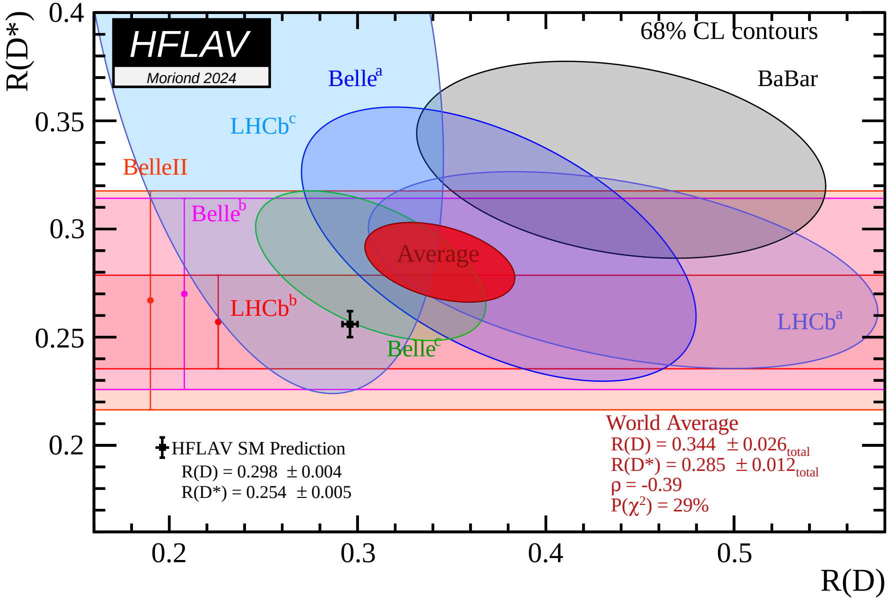
- See also Gabriele's talk for more details

LFU in $b \to c l \nu$

- LFU can be studied using **tree-level semileptonic** transition $b \to c l \bar{\nu}$

- In particular, $b \to c \tau \bar{\nu}_\tau$ decays are *sensitive* to NP contributions, due to the 3rd gen. fermions
- Currently, there is a $\boldsymbol{3.3\sigma}$ tension $R(D^{(*)})$ with SM predictions for *tau-muon universality*

- Very **prolific** research field: different decay channels and angular analysis ongoing
- Many systematics are **driven by data**: with HL Upgrade sample $\rightarrow \sigma_{R(D^{(*)})} < 3\%$



[arXiv:2101.08326]

Branching ratio's Recipe

- The number of expected events for $X \rightarrow$ Y can be expressed as

$$N(X \rightarrow Y) = \mathcal{L} \cdot \sigma(X \rightarrow Y) \cdot \mathcal{B}(X \rightarrow Y) \cdot \epsilon(X \rightarrow Y)$$

- Since at LHCb the number of X produced in the sample of analysed data is not known, branching ratios $\mathcal{B}$ are normalized to a well measured control channel

$$\mathcal{B}_{\text{sig}} = \underbrace{\frac{\mathcal{B}_{\text{norm}}}{N_{\text{norm}}} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}}_{=\alpha} \times N_{\text{sig}},$$

- α is a normalization factor that represent the single event sensitivity

Search for $B^0 \to K^{*0} e^\pm \mu^\mp$ and $B^0_S \to \phi e^\pm \mu^\mp$ [JHEP06(2023)073]

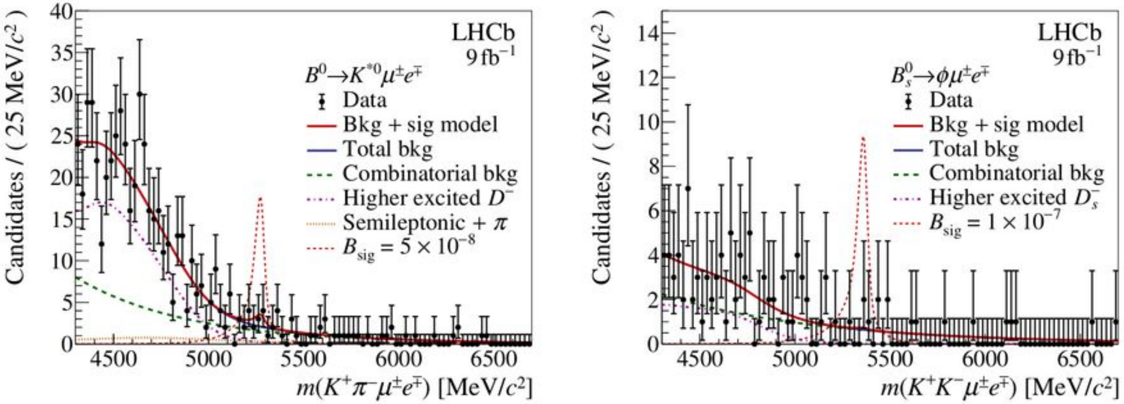
Final states studied *separately* (different BSM effects)

- **Normalization Modes:**

$B^0 \to K^{*0} J/\psi(\mu^+\mu^-)$ and $B^0_s \to \phi J/\psi(\mu^+\mu^-)$

Backgrounds:

- Combinatorial reduced with BDT selection
- Main MisID backgrounds included into the fit



Yields obtained with unbinned **extended fit**

$$\mathcal{B}(B^0 \to K^{*0}\mu^+ e^-) < 5.7 \times 10^{-9}\ (6.9 \times 10^{-9}),$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^- e^+) < 6.8 \times 10^{-9}\ (7.9 \times 10^{-9}),$$

$$\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1 \times 10^{-9}\ (11.7 \times 10^{-9}),$$
$$\mathcal{B}(B^0_s \to \phi\mu^\pm e^\mp) < 16.0 \times 10^{-9}\ (19.8 \times 10^{-9})$$

World's most stringet limits to date @ 90% (95%) of C.L.

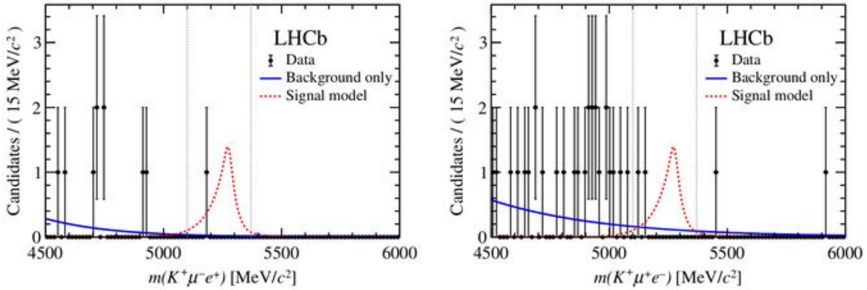
Search for $B^+ \to K^+\mu^\pm e^\mp$ [PhysRevLett.123.241802]

- **Normalization mode**: $B^+ \to K^+ J/\psi(\mu^+\mu^-)$,
- **Control channel**: $B^+ \to K^+ J/\psi(e^+e^-)$

Backgrounds:

- *Combinatorial* reduced with BDT
- *Partially reco'ed* (doubly semileptonics) and decays with *charmonium resonances* removed with mass vetoes and with another BDT
- Lastly, PID cuts to fight *misID*
- Potential contamination from b-hadron decays after selection studied with MC but found negligible

- Invariant mass distributions for 2011 and 2012
- Fit performed *with and without* signal component



$$\mathcal{B}(B^+ \to K^+\mu^+e^-) < 6.4(8.8) \times 10^{-9}$$

$$\mathcal{B}(B^+ \to K^+\mu^-e^+) < 7.0\,(9.5) \times 10^{-9}$$

Limits at 90% (95%) of C.L. improved previous results by one order of magnitude

τ reconstruction strategies

- In $b \rightarrow s\tau\mu$ transitions the tau lepton is reconstructed as $\tau \rightarrow \pi\pi\pi\nu_\tau$ or $\tau \rightarrow \pi\pi\pi\pi^0\nu_\tau$
- Since *neutral particles* are not explicitely reconstructed, different techinques could be implemented to **reconstruct** the signal candidates:

1. The **corrected mass** is used to recover part of the missing energy of the B meson: [inSPIRE]

B rest frame

$$M = \sqrt{M_{vis}^2 + P_t^2 + P_{vis,l}^2} + \sqrt{M_0^2 + P_t^2 + P_{0,l}^2}$$

$\perp$ only

$M_0=0$

$$M_{corr} = \sqrt{M_{vis}^2 + P_t^2} + |P_t|$$

   - M_{vis} (M_0) are the total invariant masses of the set of vertex-associated tracks (set of missed particles), $P_{t(l)}$ is the momentum sum transverse (along) the B flight direction

2. Direction and mass constraints can be applied to perform a **kinematic fit** [NIMA552(2005)566] in a parameterization of the whole decay chain in terms of vertex positions, momenta and decay times

Search for $B^0 \to K^{*0} \tau^\pm \mu^\mp$ [JHEP06(2023)143]

- **Signal Modes:**

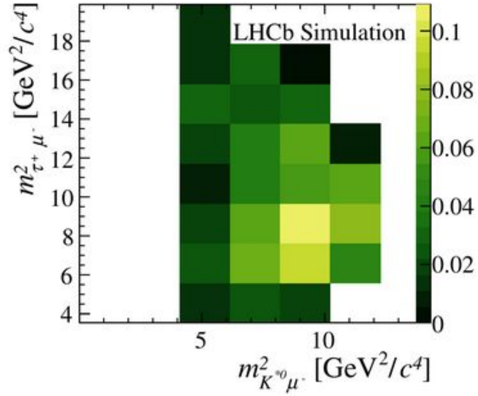
$K^{*0}(K^\pm \pi^\mp), \tau \to (3\pi\nu_\tau \text{ or } 3\pi\pi^0\nu_\tau)$

- **Normalization Mode:**

$B^0 \to D^-(K^+\pi^-\pi^-)D_s^+(K^+K^-\pi^+)$

most stringent limits on $b \to s\tau\mu$
@ 90% (95%) of C.L.

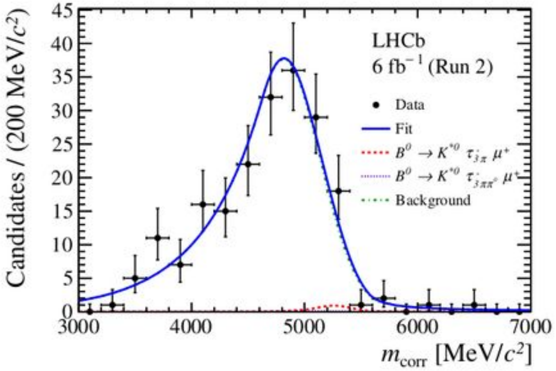
$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 8.2(9.8) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5}$$

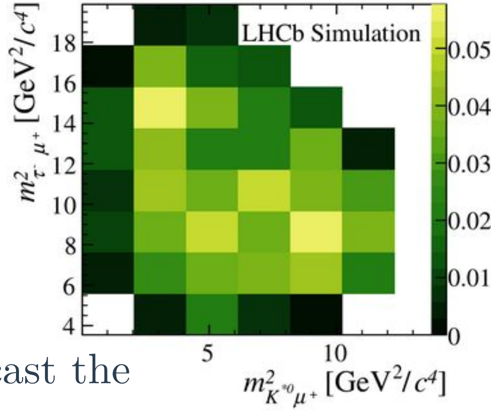


Backgrounds:

- Physics: multi-stage selection with BDTs

1) Combinatorial bkg (exploits topological differences)
2) Rejection of charmed mesons mis-identified as tau





Efficiencies:

- Most of them computed on MC
- PID evaluated using calibration samples

- Efficiency maps used to recast the results for different decay models

Search for $B_s^0 \to \phi\,\mu^{\mp}\tau^{\pm}$ [arXiv:2405.13103]

- **Signal Modes**:

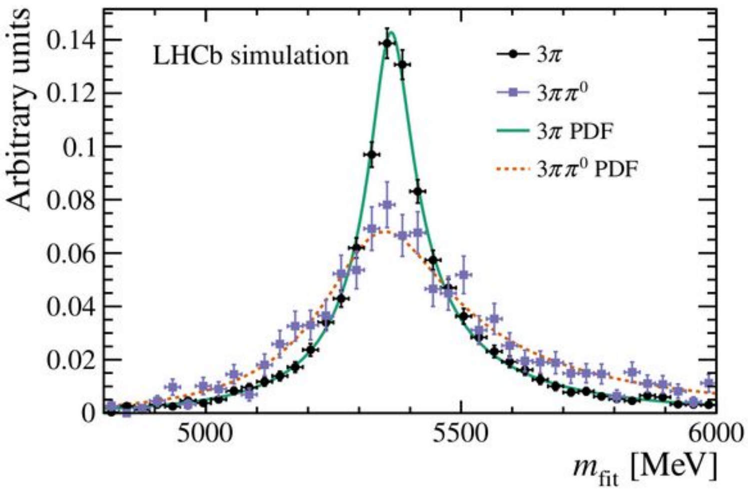
$\phi(K^+K^-)$, $\tau \to (3\pi\nu_\tau$ or $3\pi\pi^0\nu_\tau)$

- **Normalization Mode**:

$B_s^0 \to \phi(K^+K^-)\,\psi(2S)\ (J/\psi\,(\mu^+\mu^-)\pi^+\pi^-)$

Backgrounds:

- BDTs for combinatorial and for partially reco'ed
- misID$_{\pi\to\mu}$ $B \to \overline{D}K^+K^-\pi^+$ similar to signal: contribution estimed with exclusive $\overline{D} \to 3\pi X$ samples



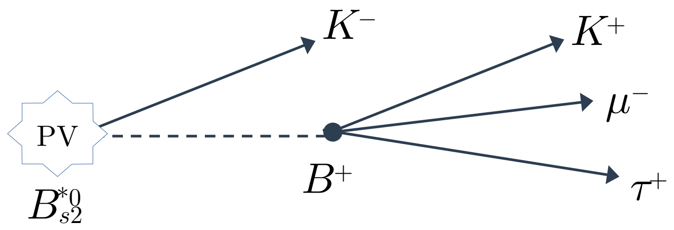
- Distribution of the constrained mass for simulated decays

first limit on this decay – competitive with similar searches

$$\mathcal{B}(B_s^0 \to \phi\,\mu^{\mp}\tau^{\pm}) < 1.0(1.1)\times 10^{-5}\ @\ 90\%\ (95\%)\ of\ C.L.$$

B meson from B* decays

- The **long lifetime** of B/B* mesons allows to have vertices well separated from any PV, reducing the amount of **background**
- By *tagging* the B produced by the excited state, it's **energy** can be determined up to a *quadratic ambiguity* (using decay vertices and mass constraint)
- τ leptons selected inclusively: 1-prong



(mass constraints on the B mesons) + (K^- momentum) $\rightarrow$ m_{miss} peaking at m_τ^2

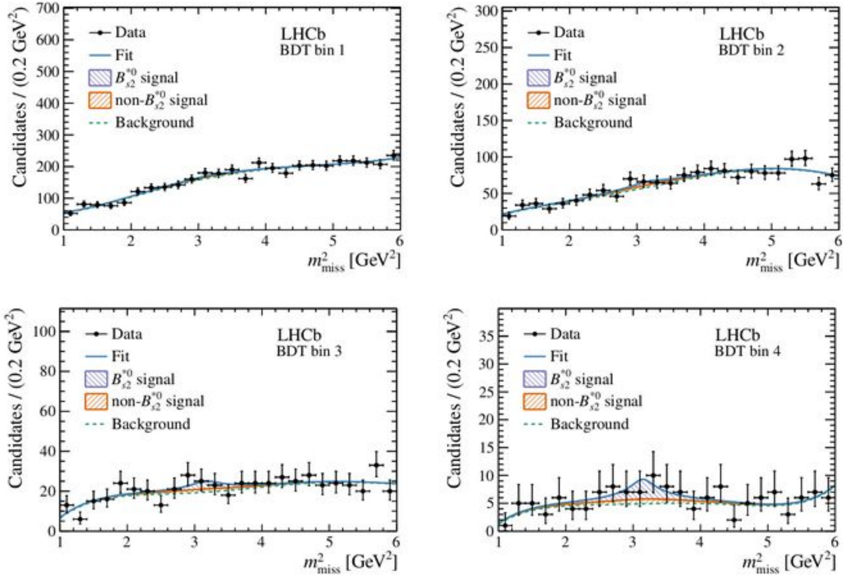
Search for $B^+ \to K^+\mu^-\tau^+$ [JHEP06(2020)129]

- **Signal mode** $\mu^-\tau^+$ preferred (lower background from $B \to \overline{D}X\mu^+\nu_\mu$): $B^{*0}_{s2} \to K^- B^+(K^+\mu^-\tau^+)$
- *full four-momentum* of the τ lepton reconstructed: search for a peak in τ missing-mass m^2_{miss}
- **Normalization mode**: $B^+ \to K^+ J/\psi(\mu^+\mu^-)$
- PID cuts on the third track to define *signal* and *normalization* region and reduce partially reco'ed background (allows also to define a SS sample of candidates not from B^{*0}_{s2})
- **BDT** as last stage of selection to fight *residual background*

$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 3.9 \times 10^{-5} @ 90\% \, C.L.$$

Limit comparable to the world-best limit

- Fits to the missing-mass-squared distribution signal sample in each bin of BDT output



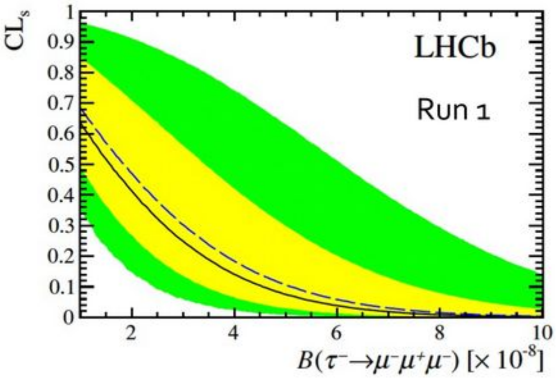
cLFV in tau decays

- τ reconstructed at LHCb originated mainly from *prompt* or *secondary* decays of ***b*- and *c*- hadrons** (e.g. D_s^+, D and B mesons decays), which are abundantly produced at LHCb
- ~80% of them come from D_s^+, while at *b-factories* tau come from $e^+e^- \to \tau^+\tau^-$
- b-factories have studies radiative and decays with all combinations of leptons [Phys.Lett.B 687 (2010) 139-143]
- Among $l \to l'l'l'$ decays the $\tau \to \mu\mu\mu$ offers a *clear final state*, with high reconstruction and identification efficiencies at LHCb

Search for $\tau^\pm \to \mu^\pm \mu^\mp \mu^\pm$

- LHCb analysis on Run1 Data ($3fb^{-1}$) [JHEP02(2015)121]
  - **Normalization** and control mode: $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$
  - **Background**: Combinatorial and misID ($D_{(s)}{}^+ \to 3\pi$,$D^+ \to K^-\pi^+\pi^+$)

$$\mathcal{B}\,(\tau^+ \to \mu^+\mu^-\mu^+) < 4.6(5.6) \times 10^{-8} \,@\, 90\%\,(95\%)\,C.L.$$



- Current best experimental limit from Belle: $2.1 \times 10^{-8} \,@\, 90\%\ C.L.$ [arXiv:1001.3221]

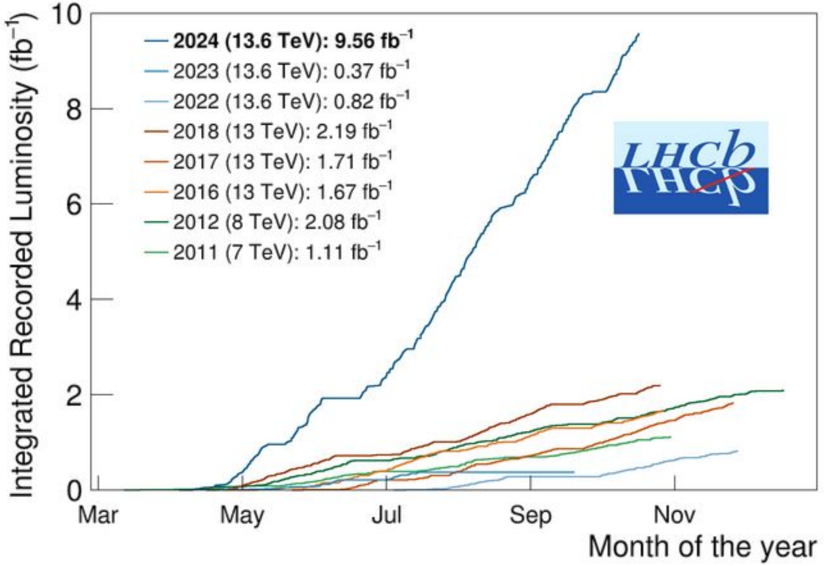
- Ongoing analysis with Run2 Data (coming out very soon!)

  - Extrapolated limit from Run1+Run2: $2.5(3.1) \times 10^{-8}$ @ $90\%\,(95\%)\,C.L.$
  - More efficient selection and detailed analysis, final results should be improved even more

Outlook

- LHCb has a very rich program of cLFV searches in b- and c-hadron decays
  - No signal observed so far, but more constraints on BSM theories set thanks to improved limits on $\mathcal{B}$

- New Data from Run3!
  - Upgraded detector and improved trigger system allow to run at $\times 5\,\mathcal{L}_{\text{inst}}$ $(2{\times}10^{33} cm^{-2} s^{-1})$
  - Already record ~10 fb^{-1} : reduce statistical error and systematics due to data-driven methods



Thank you!