Status of Lepton Flavour Violation searches in B decays at LHCb

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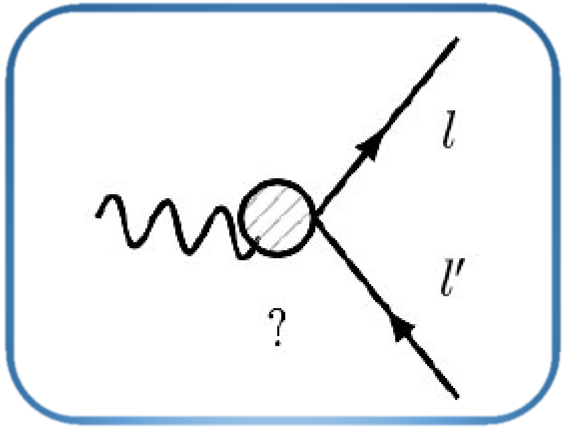
Motivations

- Lepton flavour conservation: accidental symmetry in the Standard Model (SM)
  → general motivation for these searches
- Violated in neutral sector via neutrino oscillations
- LFV for charged leptons expected in SM with massive neutrinos:
  - Small branching ratios ($\sim 10^{-50}$)



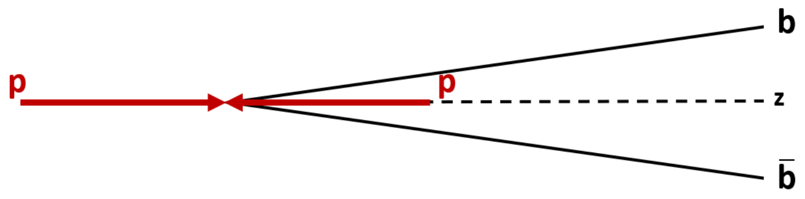
→ observation of charged LFV processes would be a clear sign for New Physics (NP)

→ several extensions of SM predict LFV

LHCb experiment

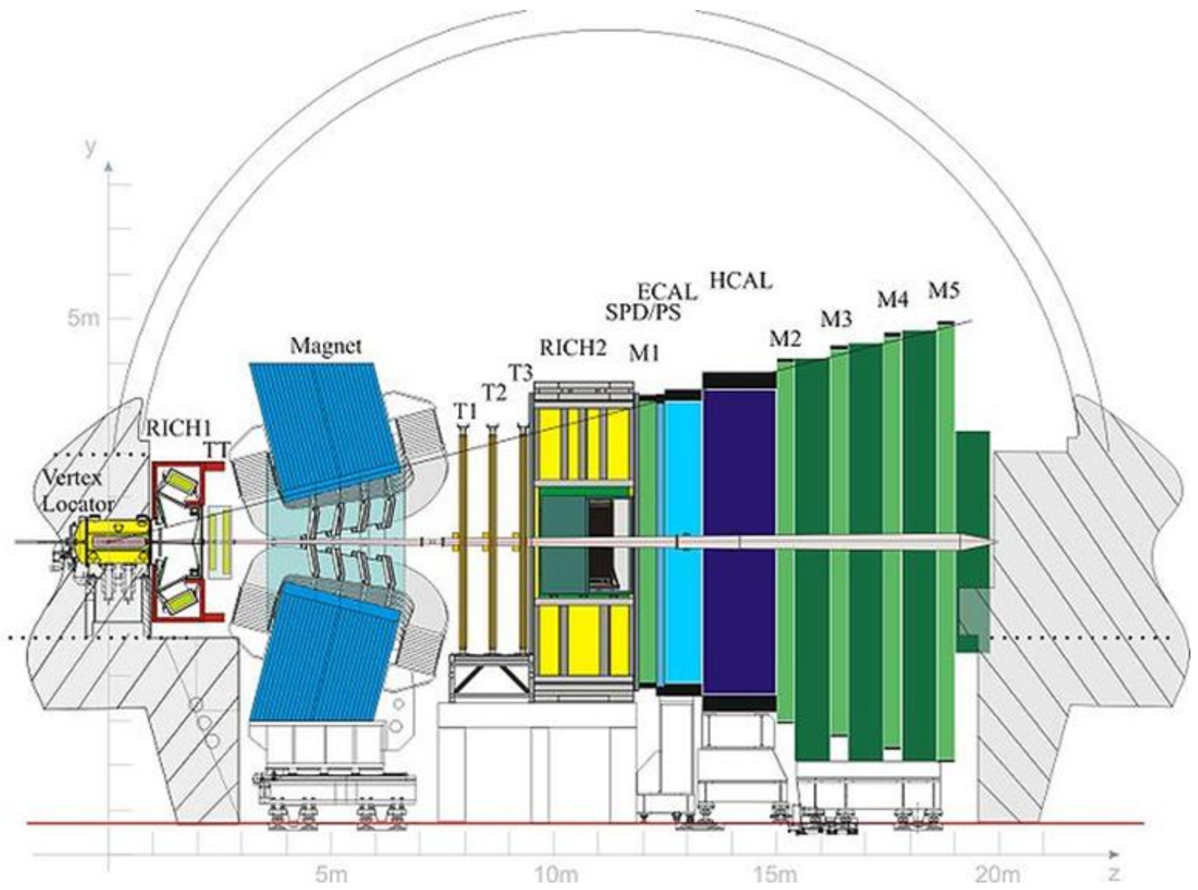
LHCb provides ideal environment for searches of LFV in B meson decays
[Int. J. Mod. Phys. A 30, 1530022 (2015)]

- Forward spectrometer
  → $b\bar{b}$ produced at low angle



- Excellent vertex resolution and tracking

- Good PID



On the menu today

- Search for $B^+ \to K^+\tau^+\mu^-$ [JHEP 06 (2020) 129]
- Search for $B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$ [JHEP 06 (2023) 073]
- Search for $B^0 \to K^{*0}\tau^\pm\mu^\mp$ [JHEP 06 (2023) 143]

Data: full LHCb dataset (Run1 + Run2)

- Run 1: $\int \mathcal{L} = 3\ fb^{-1}$ at $\sqrt{s} = 7-8\ \mathrm{TeV}$
- Run 2: $\int \mathcal{L} = 6\ fb^{-1}$ at $\sqrt{s} = 13\ \mathrm{TeV}$

$= 9\ fb^{-1}$

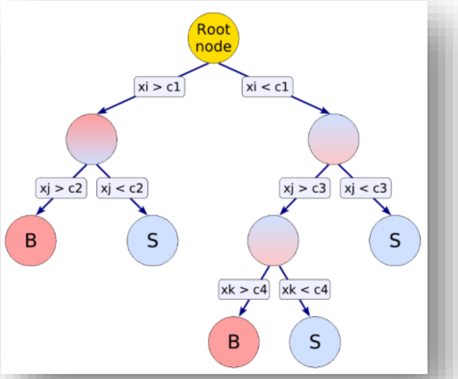
LFV analysis strategy at LHCb

- Signature: event excess in invariant mass spectrum

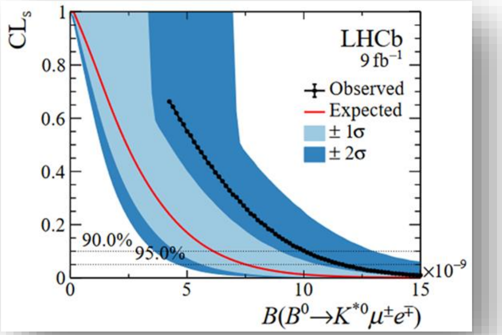
- Measurements normalized to channel with same topology of searched decay

$$N_{signal} = N_{norm} \frac{BR(signal)\ \varepsilon_{signal}}{BR(norm\ process)\ \varepsilon_{norm}}$$

- Multivariate analysis for combinatorial background reduction



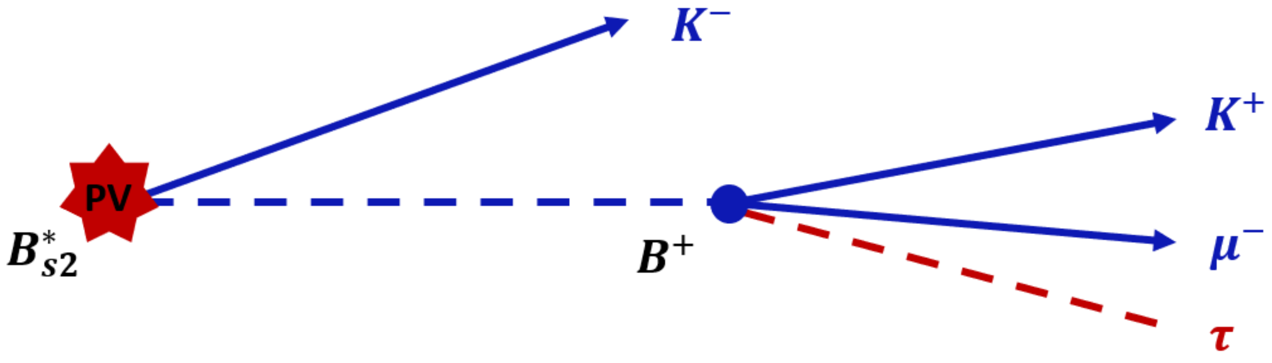
- Upper limit set



[JHEP 06 (2020) 129]

$B^+ \to K^+\tau^+\mu^-$

No SM predictions: $BR \sim 10^{-5} - 10^{-6}$
[JHEP 10 (2018) 148, Phys. Rev. D 96, 115011]



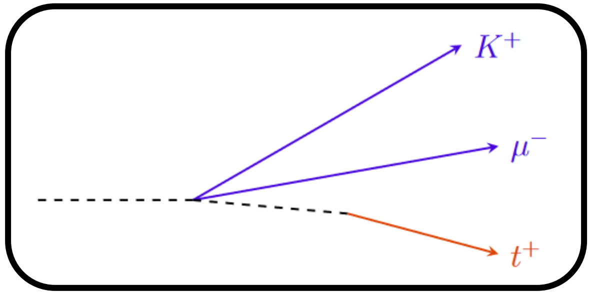
Final state: $K^-K^+\mu^-\tau^+$

Strategy:

- τ reconstruction:
  - 4-momentum indirectly reconstructed using B^+ from $B^{*0}_{s2} \to B^+K^-$ (1% of B^+ production)
  - Mass constrains on B^{*0}_{s2} and B^+
  - Inclusive τ decay

  → search for a peak at m^2_τ in m^2_{miss} distribution

- Background reduction:
  - Additional charged track (t^+) consistent with τ decay
  - BDT to suppress combinatorial background

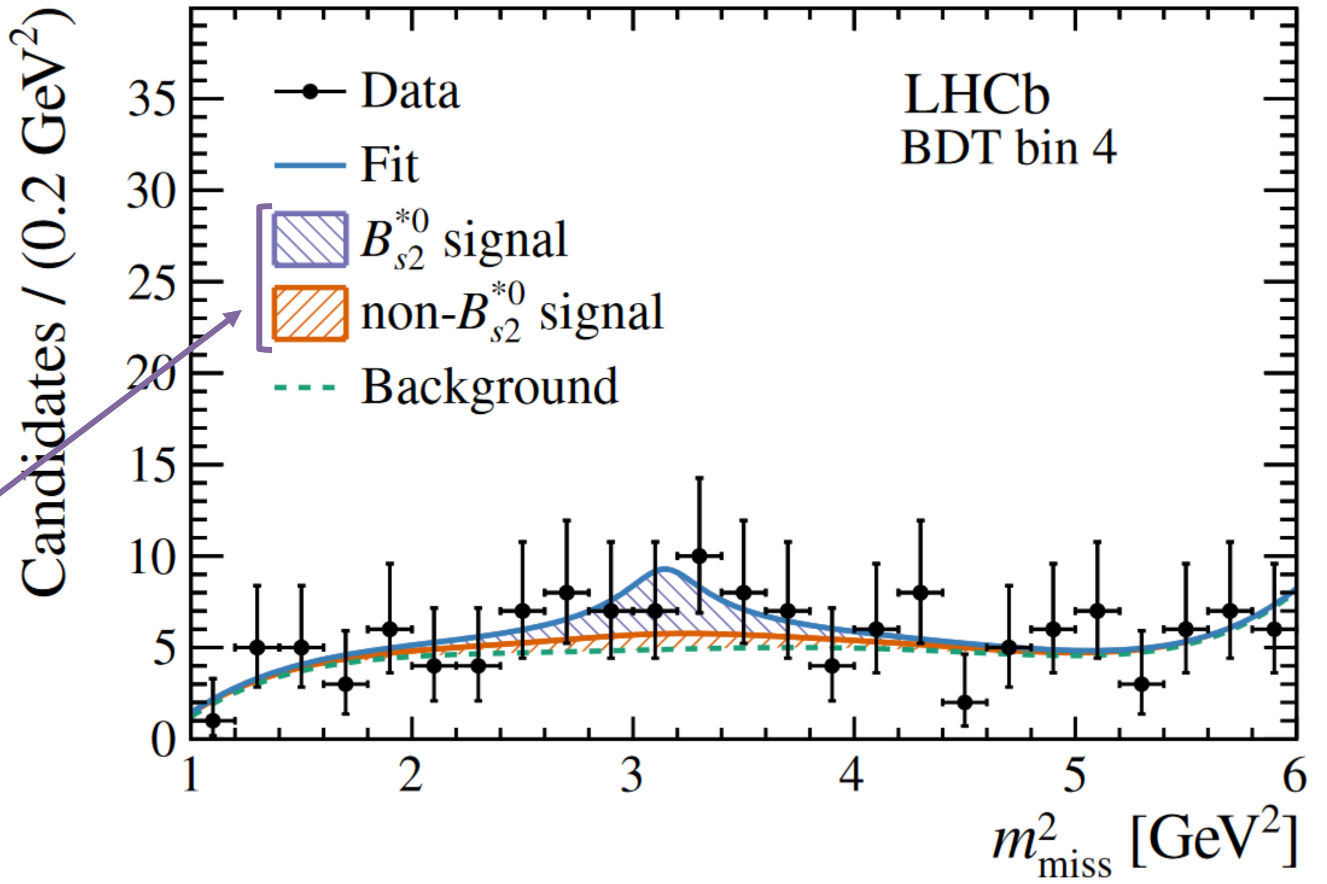


$B^+ \to K^+\tau^+\mu^-$

Missing mass fit:
Simultaneous fit in four bins of BDT output

Background: from same-sign kaons data sample

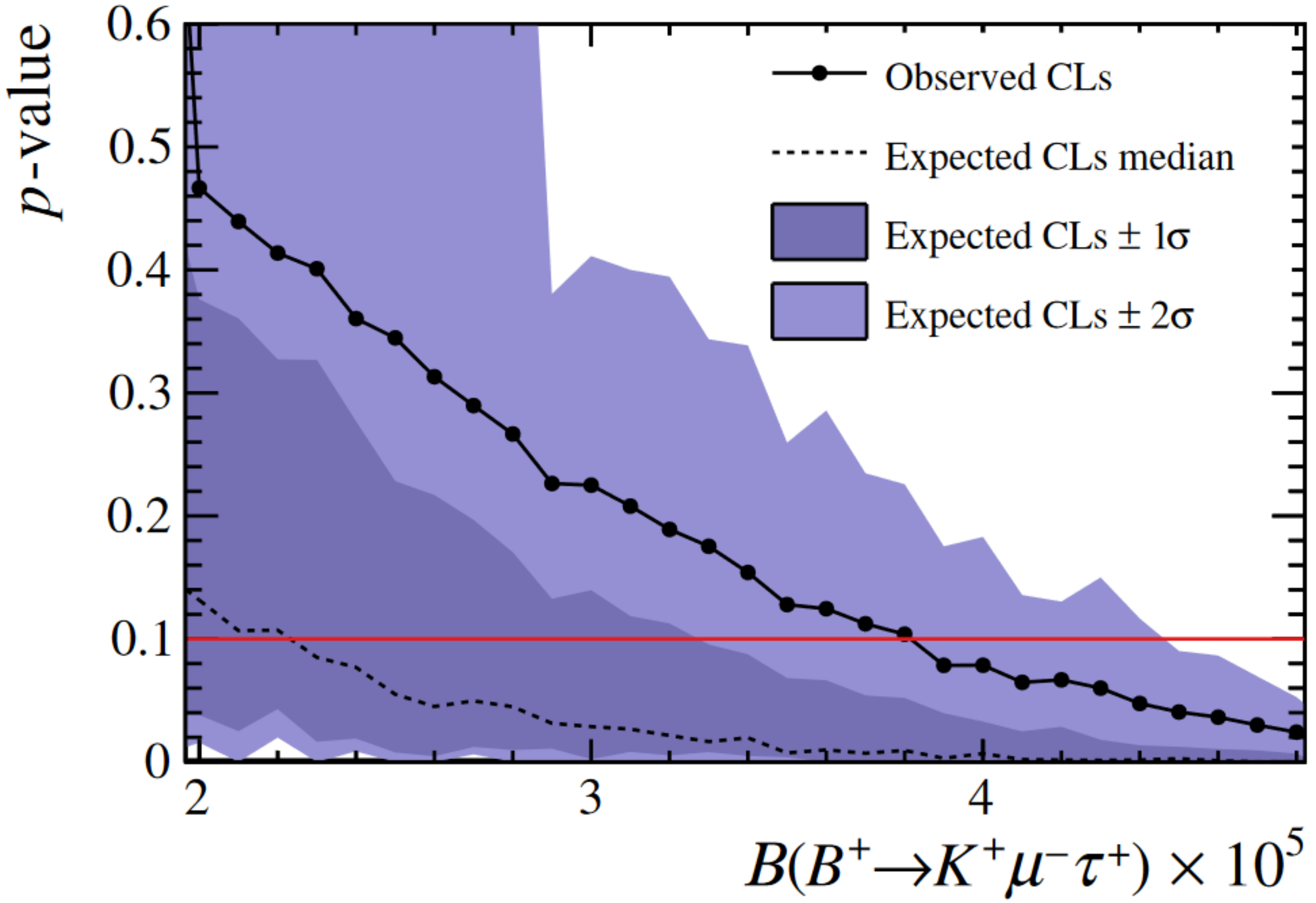
Signal:
- B^+ from B_{s2}^{*0} decay
- B^+ not from B_{s2}^{*0} decay



No significant excess found

[JHEP 06 (2020) 129]

$B^+ \to K^+\tau^+\mu^-$



Limit on branching ratio

$\mathcal{B}(B^+ \to K^+\tau^+\mu^-) < 3.9\ (4.5)\ \cdot 10^{-5}$
at 90(95)% confidence level

- Belle experiment limit:
  $\mathcal{B}(B^+ \to K^+\tau^+\mu^-) < 0.59\ \times 10^{-5}$ (90% CL)
  [PRL 130, 261802 (2023)]

- Also limits on decay via scalar or pseudoscalar operators ($O_S^{(\prime)}$ or $O_P^{(\prime)}$)
  [Eur. Phys. J. C 76, 134 (2016)]

[JHEP 06 (2023) 073]

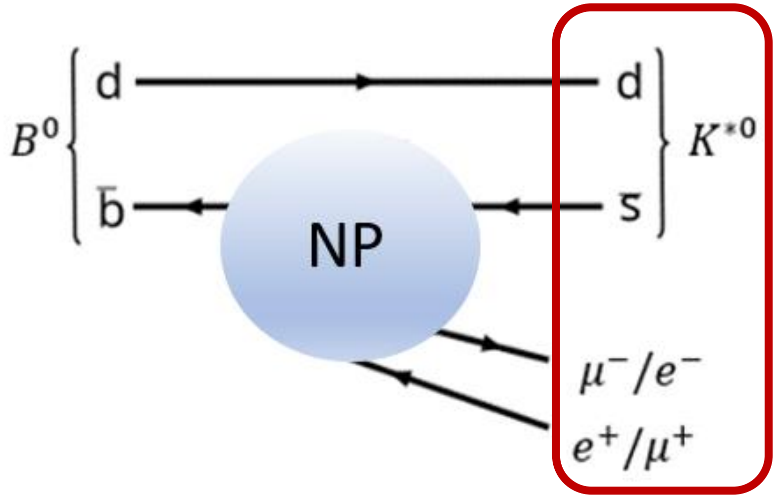
$B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

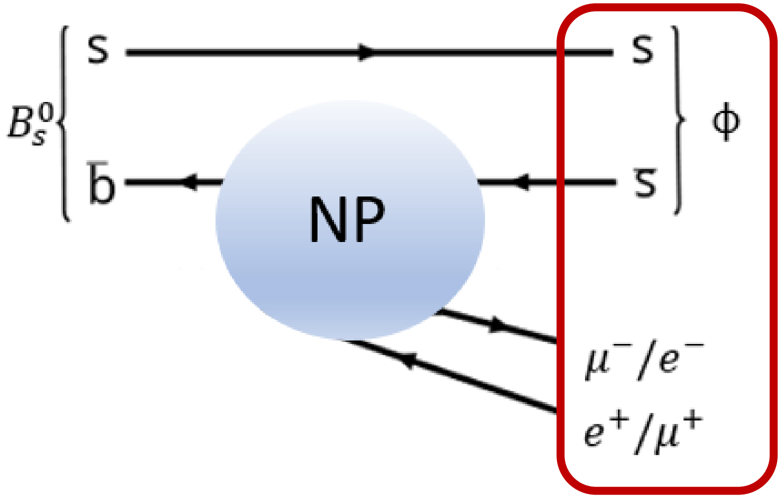
No SM predictions: $BR \sim 10^{-7}$ [Phys. Rev. D 92, 054013]

Final states: $\boldsymbol{K^+\pi^-}\boldsymbol{\mu^\pm e^\mp}$ and $\boldsymbol{K^+K^-}\boldsymbol{\mu^\pm e^\mp}$ ($K^+\pi^- \to K^{*0}$, $K^+K^- \to \phi$)

Strategy:

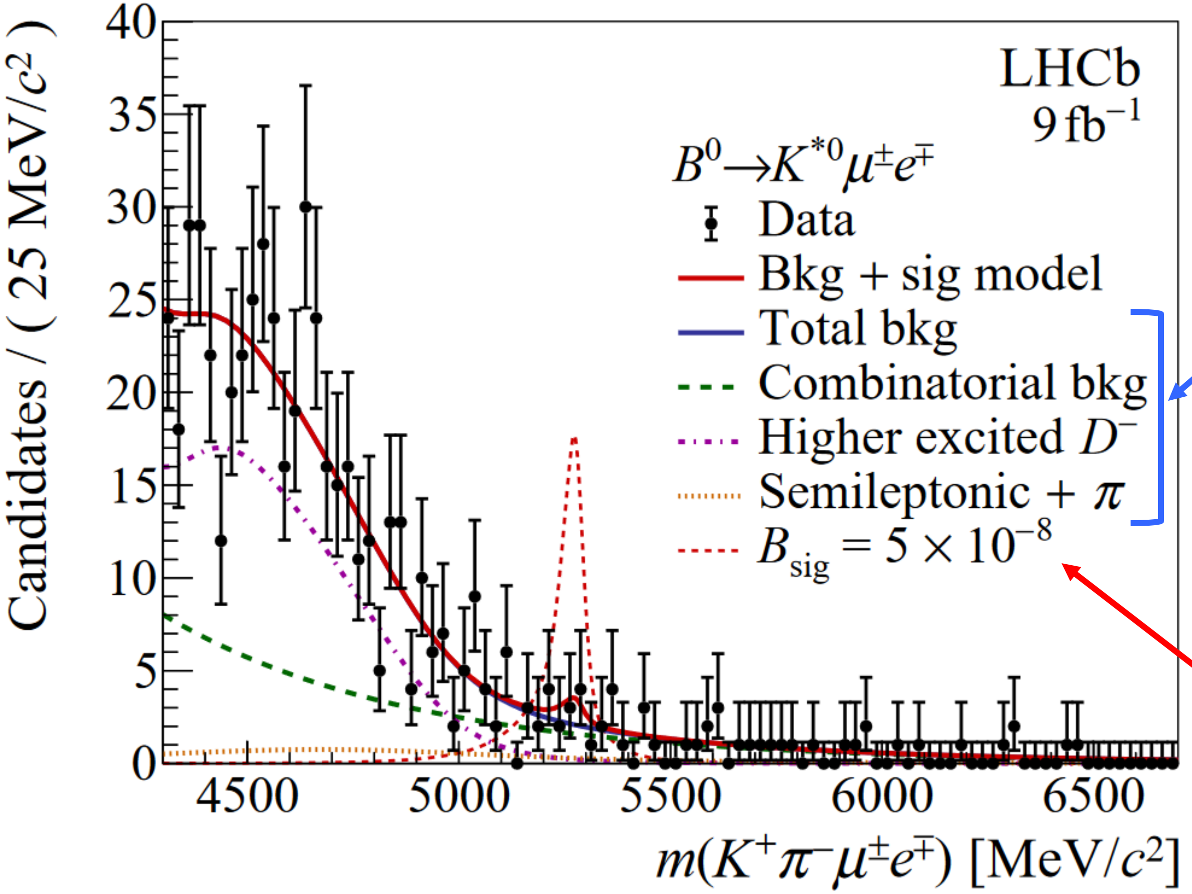
- $B^0 \to K^{*0}\mu^\pm e^\mp$ treated separately depending on charge configuration of $K^+\mu$
  (NP and backgrounds differ between charge configurations)
- $K^+\pi^-(K^+K^-)$ invariant mass required close to nominal $K^{*0}(\phi)$ mass
- Background reduction:
  - vetoes on misidentified B decays and semileptonic cascades involving D mesons
  - BDT to suppress combinatorial background
  - requirements on particle identification to suppress double misidentification $(B^0_{(s)} \to (K^{*0}/\phi)\pi^+\pi^-)$





[JHEP 06 (2023) 073]

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



No significant excess found

Invariant mass fit:

Background:

- some backgrounds can pass vetoes → modelled from simulations
- combinatorial background measured from same-sign leptons data samples

Signal: shape scaled to 5×10^{-8} branching ratio

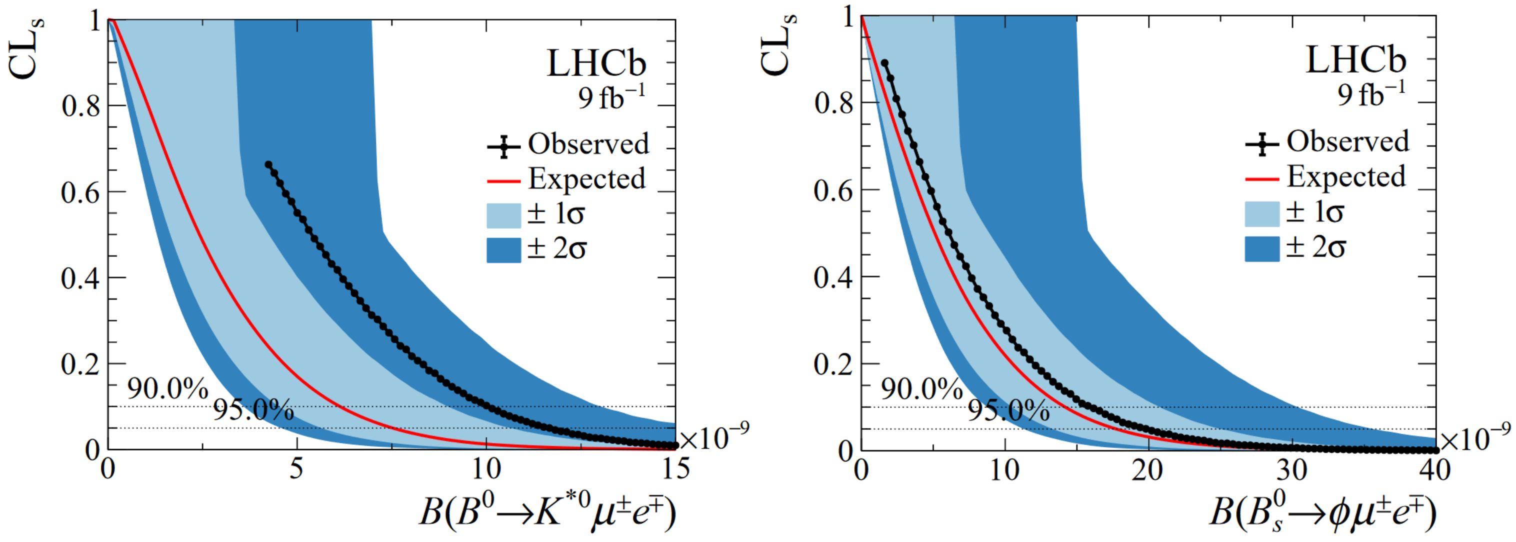
[JHEP 06 (2023) 073]

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

Limits on branching ratios

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7(6.9)\cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) < 6.8(7.9)\cdot 10^{-9}$$
$$\mathcal{B}\left(B^0 \to K^{*0}\mu^\pm e^\mp\right) < 10.1(11.7)\cdot 10^{-9}$$
$$\mathcal{B}\left(B^0 \to \phi\mu^\pm e^\mp\right) < 16.0(19.8)\cdot 10^{-9}$$

at 90(95)% confidence level

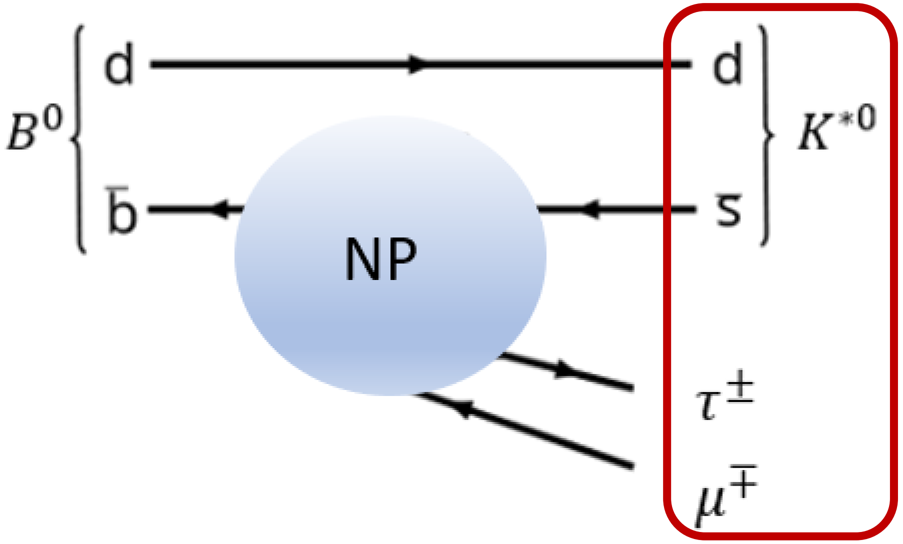


- K^{*0} channel: limit improved wrt previous searches (Belle: $O(10^{-7})$) [PRD 98, 071101(R) (2018)]
- ϕ channel: first limit on semileptonic LFV B_s^0 decay

Also limits on parameters of two NP models: scalar model, left-handed model [EPJC 76 (2016) 134]

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

[JHEP 06 (2023) 143]



No SM predictions: $BR \sim 10^{-6}$ [Phys. Rev. D 92, 054013]

Final state: $\boldsymbol{K^\pm\pi^\mp}$ $\boldsymbol{\pi^+\pi^-\pi^\pm\nu_\tau(\pi^0)}$ $\boldsymbol{\mu^\mp}$

($K^\pm\pi^\mp \to K^{*0}$; $\pi^+\pi^-\pi^\pm\nu_\tau(\pi^0) \to \tau$)

Strategy:

τ reconstruction:

- τ leptons decay undetected → reconstructed from decay products
- ν_τ and π^0 not explicitly reconstructed → missing momentum

→ $m_{K^*\tau\mu}$ does not peak at B^0 mass

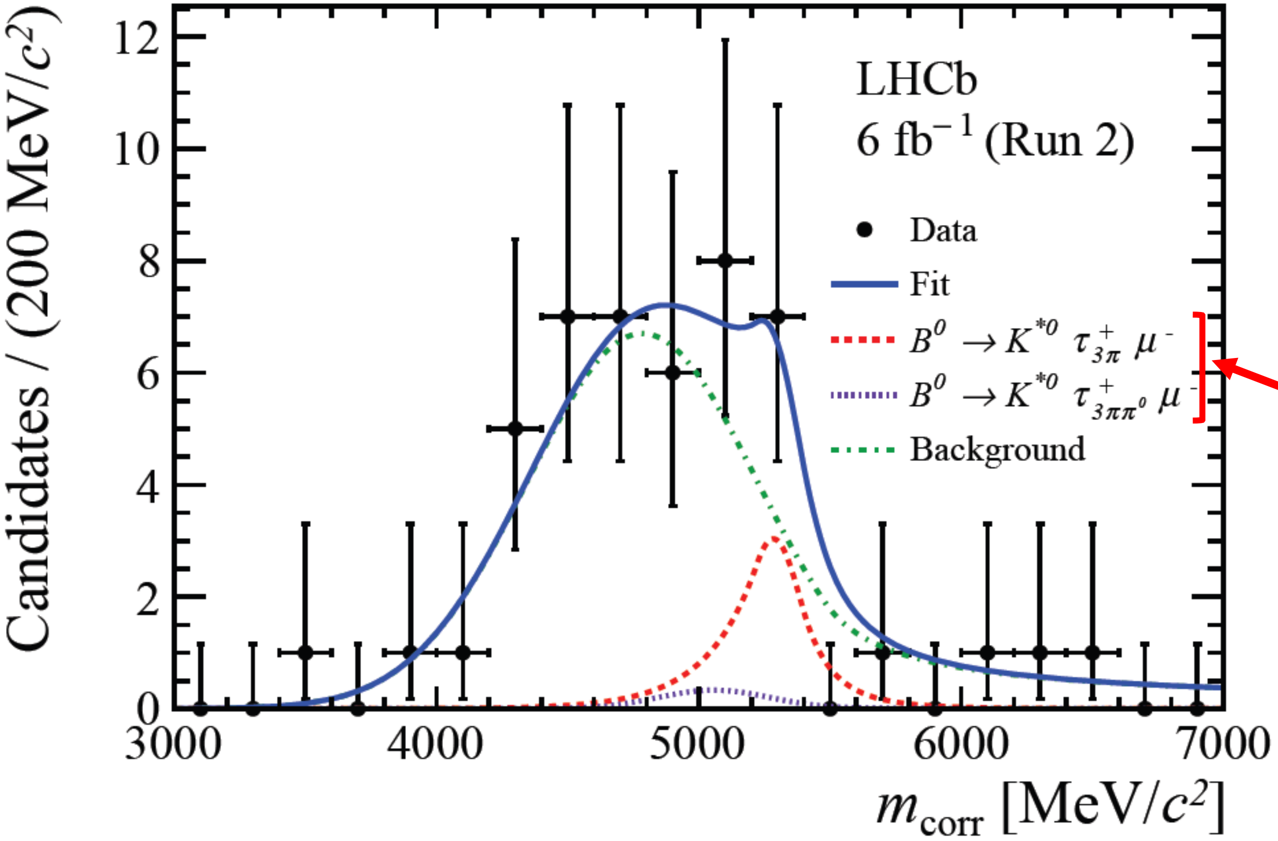
$$m_{corr} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$$

missing momentum perpendicular to B^0 direction

Background reduction:

- Two BDT to suppress: combinatorial background, charmed mesons decays identified as τ
- Requirements on particle identification and intermediate masses, vetoes on physical backgrounds via D mesons

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



No significant excess found

Invariant mass fit:

Background: control sample with loosened combinatorial BDT

Signal:

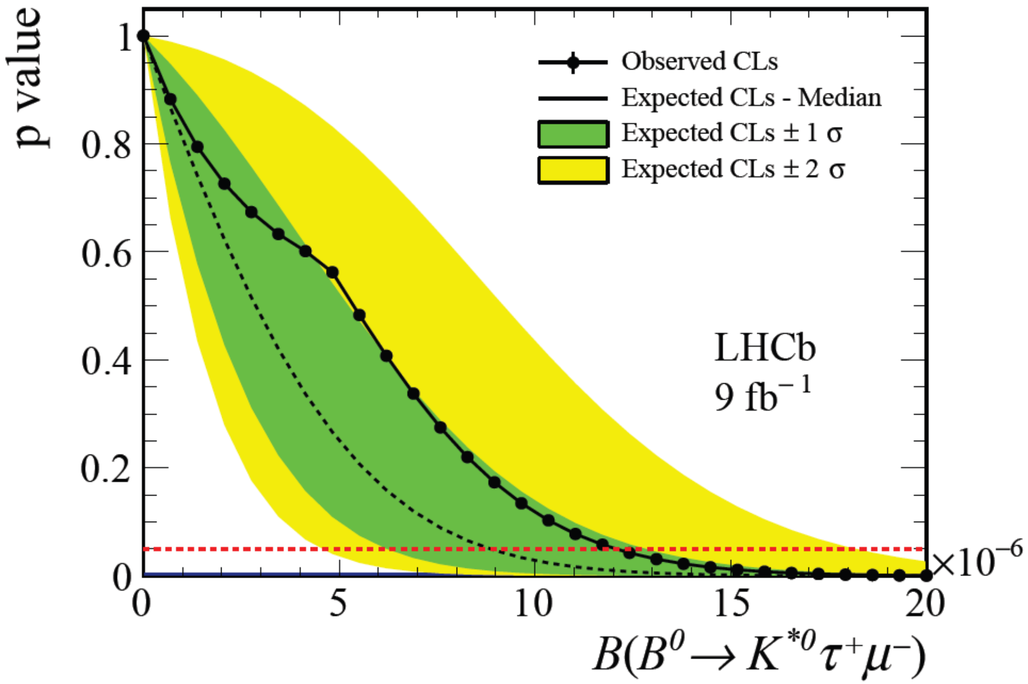
- $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\overset{(-)}{\nu}_\tau$: dominant component
- $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\pi^0\overset{(-)}{\nu}_\tau$: subdominant component

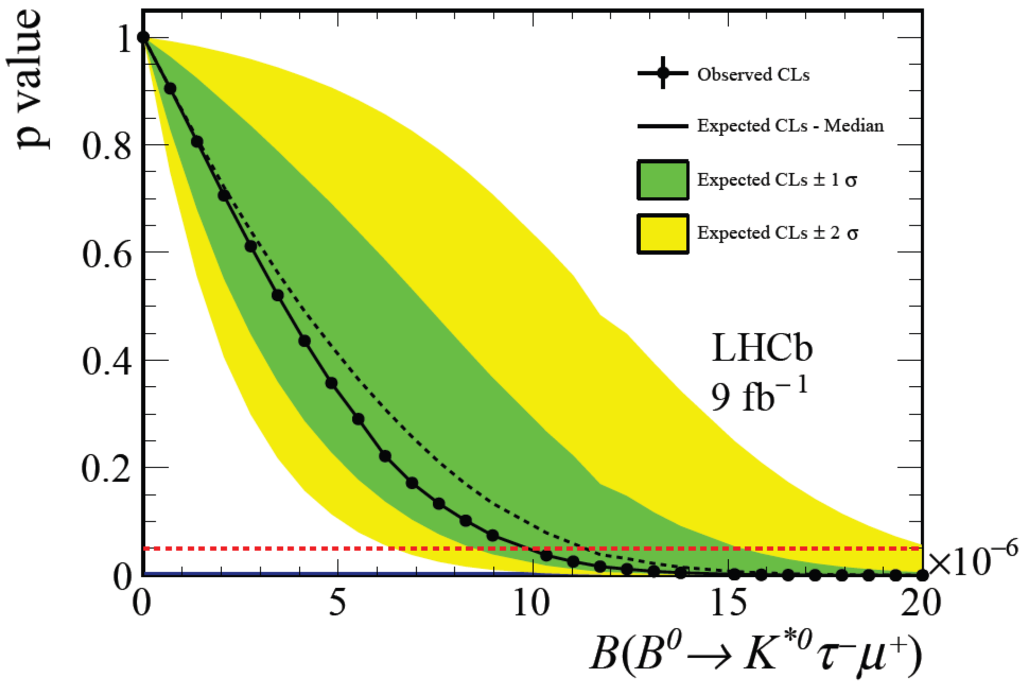
$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

Limits on branching ratios

$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2)\cdot 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2(9.8)\cdot 10^{-6}$
at 90(95)% confidence level

Most stringent limit on $b \to s\tau\mu$ transitions to date





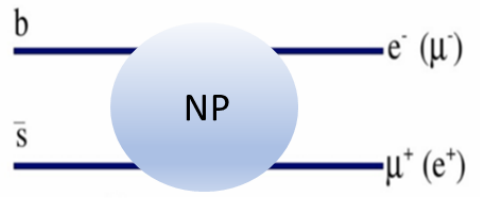
Previous LFV results at LHCb

Process	Upper limit	Data	Reference
$B^+ \to K^+\mu^-e^+$ $B^+ \to K^+\mu^+e^-$	$7.0(9.5) \times 10^{-9}$ *at* 90(95)% *CL* $6.4(8.8) \times 10^{-9}$ *at* 90(95)% *CL*	$3\ fb^{-1}$	Phys. Rev. Lett.123 (2019) 241802
$B^0 \to \mu^\pm\tau^\mp$ $B^0_{(s)} \to \mu^\pm\tau^\mp$	1.4×10^{-5} *at* 95% *CL* 4.2×10^{-5} *at* 95% *CL*	$3\ fb^{-1}$	Phys. Rev. Lett. 123 (2019) 211801
$B^+ \to e^\pm\mu^\mp$	$1.0(1.3) \times 10^{-9}$ *at* 90(95)% *CL*	$3\ fb^{-1}$	JHEP 03 (2018) 078

Future perspectives

Further searches for LFV processes possible at LHCb, new analyses in progress:

- Already searched decays with more statistics:
  - $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ (Run 2 data)

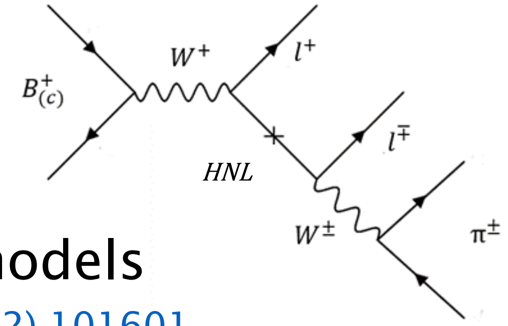


- Decays never searched at LHCb:
  - $B^0_s \to \phi\mu^{\pm}\tau^{\mp}$ (Run 1 + Run 2 data)
  - $B^+ \to \pi^+\mu^{\pm}e^{\mp}$ (Run 1 + Run 2 data)
  - Searches for Heavy Neutral Leptons (HNLs):

    $B^+_{(c)} \to \mu^+ HNL(\to e^{\pm}\pi^{\mp})$

    → massive right-handed neutrinos, predicted by NP theoretical models

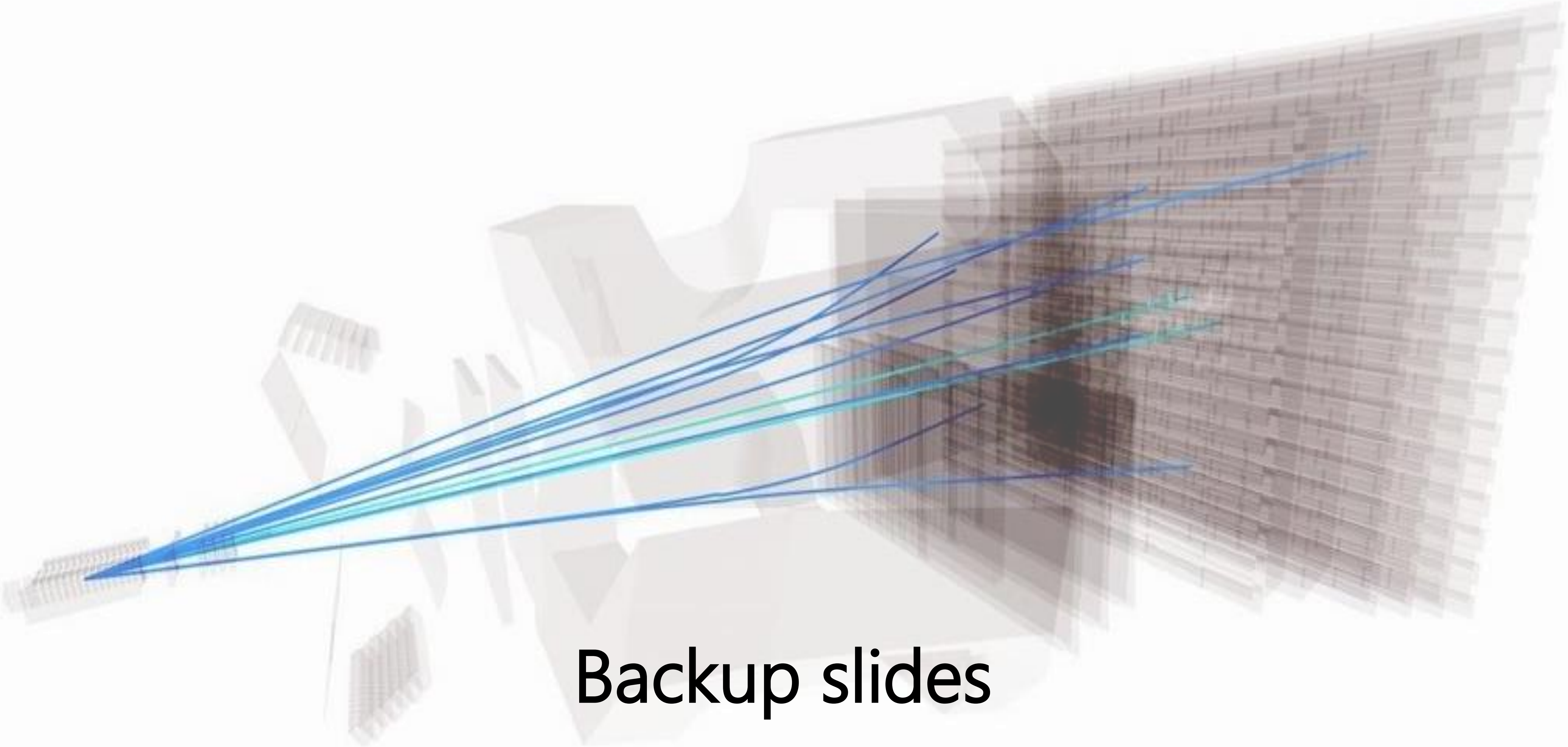
    (previous results on HNL's: Phys. Rev. Lett. 112 (2014) 131802, Phys. Rev. Lett. 108 (2012) 101601, Phys. Rev. D85 (2012) 112004)



Summary

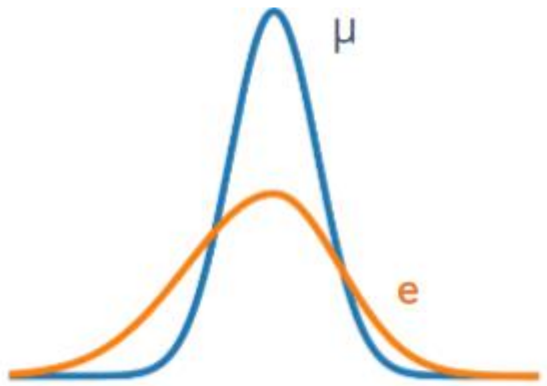
- LFV provides interesting probe for NP
- Active field at LHCb → constraints on many models
- No evidence for LFV yet, but stringent limits set
- Several analyses with current data ongoing
- New possibilities with Run 3 data (more statistics, detector upgrade, new channels)

Thank you for the attention!



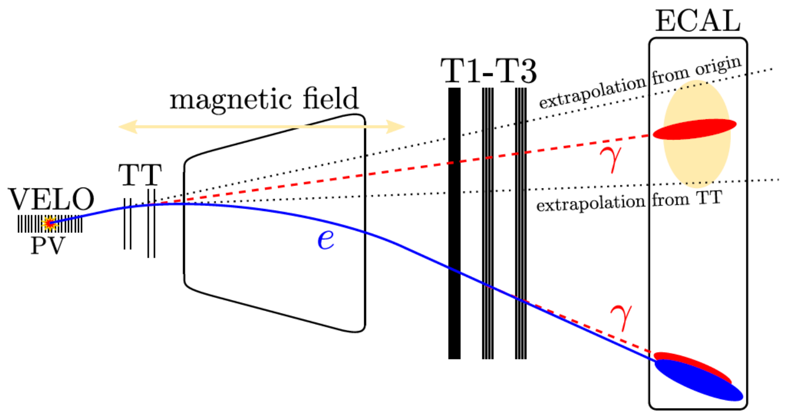
Backup slides

Charged leptons at LHCb



Muons:
- Easy to trigger on (dedicated muon chambers)
- Excellent dimuon mass resolution

Electrons:
- High occupancies in the calorimeter require tighter thresholds wrt muons
- Energy loss due to bremsstrahlung affects → most of electrons emit one energetic photon before magnet (recovery ~50% efficient)



Taus:
- Short lifetime (0.3 ps), indirect detection
- Missing energy from neutrinos

Systematic uncertainties

Dominant sources:

- $B^+ \to K^+\tau^+\mu^-$
  - Choice of background model

- $B^0 \to K^{*0}\mu^\pm e^\mp$ / $B_s^0 \to \phi\mu^\pm e^\mp$
  - BR of normalization channels $B^0 \to J/\psi\,(\to \mu^+\mu^-)K^{*0}$ and $B_s^0 \to J/\psi\,(\to \mu^+\mu^-)\phi$
  - Effective B_s^0 decay time

- $B^0 \to K^{*0}\tau^\pm\mu^\mp$
  - Background control region choice

Statistical uncertainty dominant wrt systematic uncertainty in all these measurements!

$B^+ \to K^+\tau^+$: analysis details

- **Normalization channel**: $B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+$
- $\boldsymbol{B^+}$ **energy** obtained from:

$$E_B = \frac{\Delta^2}{2E_K}\frac{1}{1-(p_K/E_K)^2\cos^2\theta}[1 \pm \sqrt{d}]$$

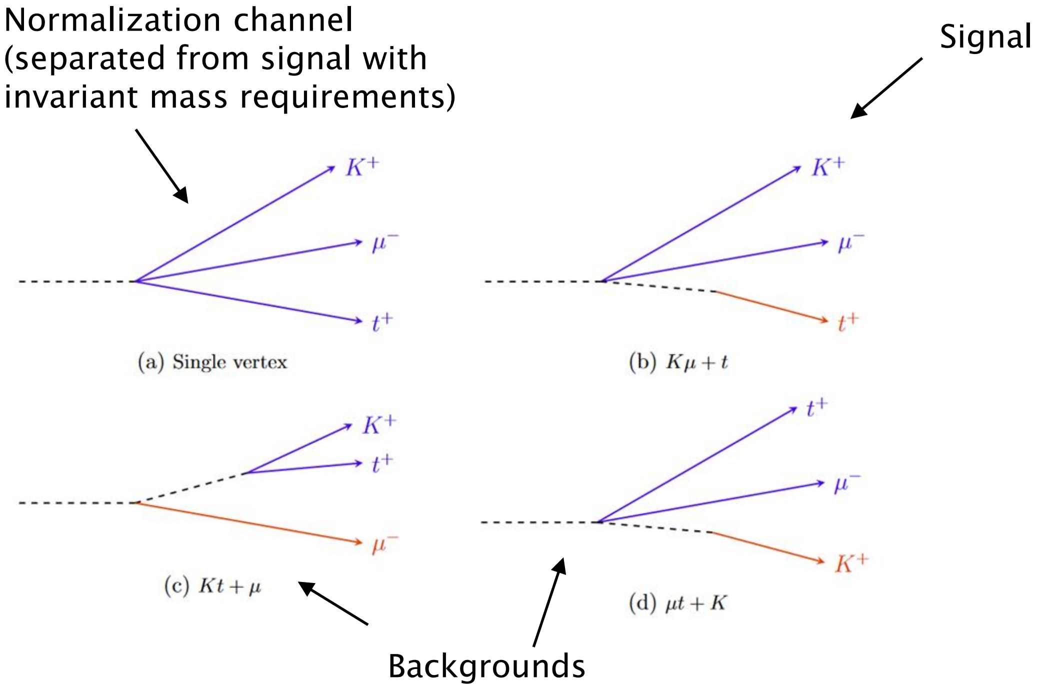
where

$$d = \frac{p_K^2}{E_K^2}\cos^2\theta - \frac{4m_B^2 p_K^2\cos^2\theta}{\Delta^4}\left(1 - \frac{p_K^2}{E_K^2}\cos^2\theta\right)$$

$$\Delta^2 = m_{BK}^2 - m_B^2 - m_K^2$$

lower energy real solution considered

- **Main background:** partially reconstructed B decays (additional charged tracks combined with signal Kμt). Signal: no extra tracks (except 3 prong dacay) -> charged isolation variable for signal-background separation



[JHEP 06 (2020) 129]

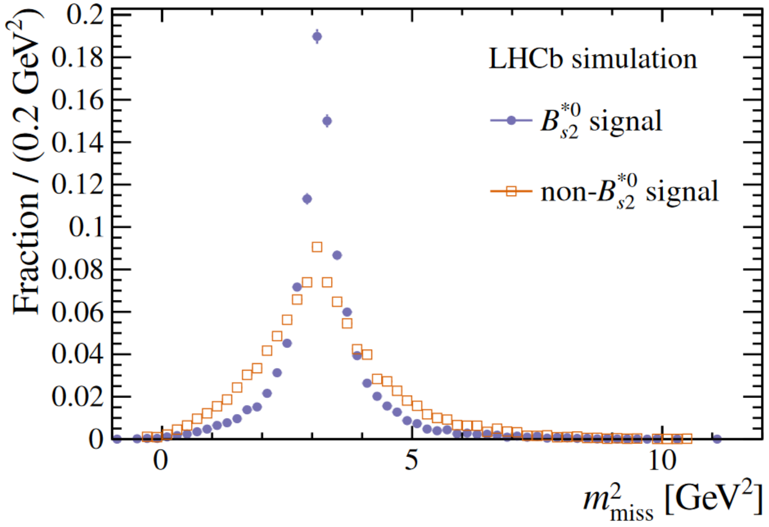
$B^+ \to K^+\tau^+\mu^-$: analysis details

- **BDT trained on:**
  - SS kaons sample in mass range around tau mass (bkg proxy)
  - MC simulations (signal proxy)

- **BDT inputs** chosen to distinguish additional tracks coming from τ decays from various sources of background

- **No peaky backgrounds in the signal region**: extensive studies performed

- **Fit:**
  - Signal: hyperbolic distribution (shape parameters from simulations)
  - Background shape: polynomial fit of SS kaons data sample



[JHEP 06 (2020) 129]

$B^+ \to K^+\tau^+\mu^-$: NP models

- Default limits assume a uniform phase space model (PHSP)

NP models:

- Decay via vector or axial operators ($O_9^{(\prime)}$, $O_{10}^{(\prime)}$) → same limits as PHSP

- Decay via scalar or pseudoscalar operators ($O_S^{(\prime)}$, $O_P^{(\prime)}$) → obtained limits:

$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 4.4 \times 10^{-5} \text{ at } 90\% \text{ CL and } < 5.0 \times 10^{-5} \text{ at } 95\% \text{ CL}$$

[JHEP 06 (2023) 073]

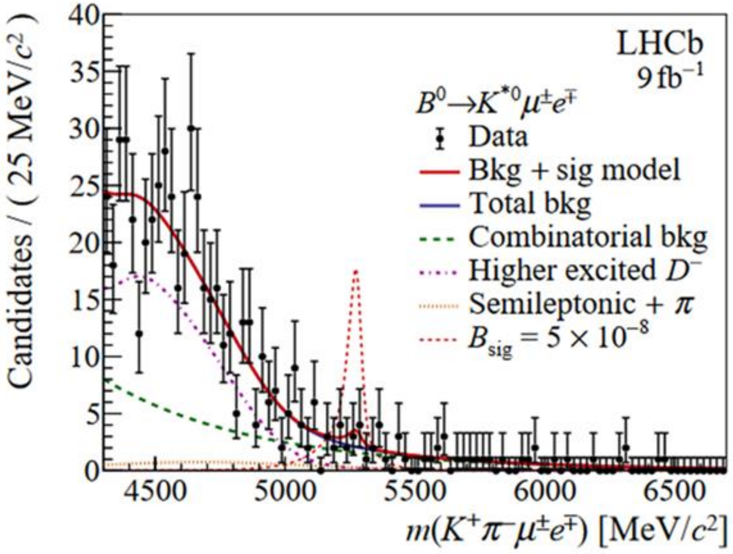
$B^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$: analysis details

Normalization channels: $B^0 \to J/\psi\,(\to \mu^+\mu^-)K^{*0}$ and $B_s^0 \to J/\psi\,(\to \mu^+\mu^-)\phi$

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

Fit functions:

- Signal: sum of two Crystal Balls
- Physical backgrounds passing the selection: model with KDE based on simulation
  $B^0 \to D_2^*(2460)^-(\to \bar{D}^0(\to K^+l^-\bar{\nu}_l)\pi^-)l'^+\nu_{l'}$, $B_s^0 \to D_{2s}^*(2573)^-(\to \bar{D}^0(\to K^+l^-\bar{\nu}_l)K^-)l'^+\nu_{l'}$,
  $B^+ \to \bar{D}^0(\to K^+l^-\bar{\nu}_l)l'^+\nu_{l'}$ + random π^-
- Combinatorial background: single exponential



[JHEP 06 (2023) 073]

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

- Default limits assume a uniform phase space model (PHSP)

NP models:

Left-handed model: leptoquark inspired model, $C_9^{e\mu} = C_{10}^{e\mu} \neq 0$
Contributing LVF operators:

$$O_9^{e\mu} = (e/g)^2\left(\bar{s}\gamma_\mu P_L b\right)(\bar{\mu}\gamma^\mu e)$$
$$O_{10}^{e\mu} = (e/g)^2\left(\bar{s}\gamma_\mu P_L b\right)(\bar{\mu}\gamma^\mu\gamma^5 e)$$

$C_i^{e\mu}$ = lepton flavour violating Wilson coefficients

Scalar model: $C_S^{e\mu} \neq 0$
chosen as a counterpart, underlining the non-negligible impact of the choice of signal model on kinematics and efficiency
Scalar operator:

$$O_S^{e\mu} = (e/g)^2(\bar{s}P_L b)(\bar{\mu}e)$$

NP models can result in very different decay kinematics and differential decay rates → PHSP MC reweighted

Upper limits at 90(95)% CL

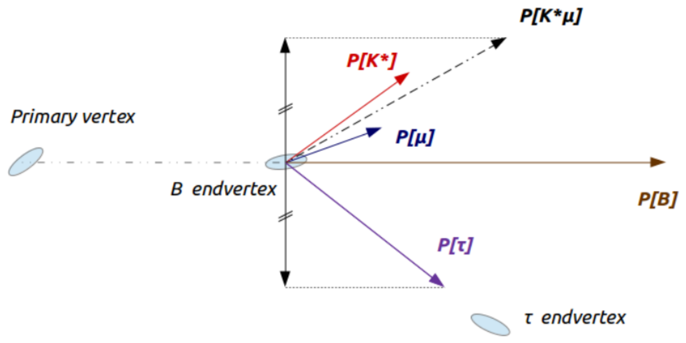
Mode	Left-handed	Scalar
$B^0 \to K^{*0}\mu^+e^-$	6.7 (8.3)	8.4 (10.2)
$B^0 \to K^{*0}\mu^-e^+$	8.0 (9.5)	9.9 (11.5)
$B^0 \to K^{*0}\mu^\pm e^\mp$	12.0 (13.9)	14.7 (17.0)
$B_s^0 \to \phi\mu^\pm e^\mp$	16.5 (20.5)	18.8 (23.1)

$\times 10^{-9}$

→ reduced signal efficiency (increased limits on signal branching fraction)

[JHEP 06 (2023) 143]

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



Possible strategy: Fully Corrected Mass of B

- p(K^{*0}) and B vertexing used to determine p_T(τ) (with respect to B direction)
- τ and neutrino momenta form τ vertexing
- B momentum by fixing one of the lepton masses

But:

- τ decay vertex not well measured for high boost
- Sinus of angle between K^{*0}μ system and τ directions of flight not precisely known

Applied strategy:

$$\boldsymbol{P_B} = P_B \boldsymbol{u_B} = P_\tau \boldsymbol{u_\tau} + P_y \boldsymbol{u_y}$$

$$\Rightarrow P_B \boldsymbol{u_B} = P_y \boldsymbol{u_y} + \frac{P_{\tau\perp}}{\sin(\vartheta_{B\tau})} \boldsymbol{u_\tau}$$

$$= P_y(\boldsymbol{u_y} + \frac{\sin(\vartheta_{yB})}{\sin(\vartheta_{B\tau})} \boldsymbol{u_\tau})$$

$$\Rightarrow P_B = P_y(\boldsymbol{u_y} \cdot \boldsymbol{u_B} + \frac{\sin(\vartheta_{yB})}{\sin(\vartheta_{B\tau})} \boldsymbol{u_\tau} \cdot \boldsymbol{u_B})$$

$$\Rightarrow P_B = P_y(\cos(\vartheta_{yB}) + \frac{\sin(\vartheta_{yB})}{\sin(\vartheta_{B\tau})} \cos(\vartheta_{B\tau}))$$

→ Only angles defined from B (know better)

Ok for 60% of reconstructed events
→ mass correction needed

$$m_{corr} = \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$$ (Minimal Corrected Mass)

$p_\perp$ = momentum sum, transverse to B flight direction, of reconstructed tracks = transverse momentum sum of the missed particles

[JHEP 06 (2023) 143]

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

Normalization channels: $B^0 \to D^-(\to K^+\pi^-\pi^-)D^+(\to K^+K^-\pi^+)$

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

Vetoes on:

$$B^0 \to D^{*-}\mu^+\nu, \text{ with } D^{*-} \to \bar{D}^0\pi \text{ and } \bar{D}^0 \to K^+\pi^-\pi^+\pi^-$$

$$B^0 \to D^{*-}\tau^+\nu, \text{ with } D^{*-} \to \bar{D}^0\pi,\ \bar{D}^0 \to K^+\mu^-\nu \text{ and } \tau^+ \to \pi^+\pi^-\pi^+\nu$$

Fit functions:

$$P_{\rm tot} = Y_{\tau_{3\pi}}P_{\tau_{3\pi}} + Y_{\tau_{3\pi\pi^0}}P_{\tau_{3\pi\pi^0}} + Y_{\rm bkg}P_{\rm bkg}$$

- Signal: double sided Crystal Balls
- Background: double sided Crystal Ball