Searches for Lepton Flavour Violating decays at LHCb

Cédric Méaux[1]
On behalf of the LHCb collaboration

[1] **Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France**

WIN 2019
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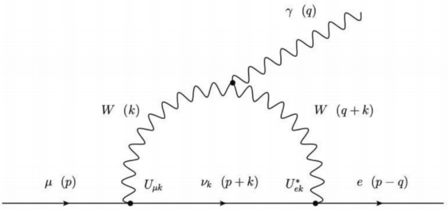
- LFV in **neutral sector**: neutrino oscillation (e.g. $\nu_\mu \to \nu_\tau$)
- **Charged** lepton flavor is conserved in SM
  not supported by strong theoretical reasons
  e.g. underlying symmetry



$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \frac{U_{\mu k} U^*_{ek} m^2_{\nu_k}}{M^2_W} \right|^2$$
$$\simeq 10^{-55} - 10^{-54}$$

- Any observation of charged LFV decay:

$\Rightarrow$ **Indisputable sign of physics Beyond the SM (BSM)**

Lepton Flavor Universality Violation (LFUV)

Interest in LFV decay renewed since:

Set of coherent experimental evidences of LFUV by LHCb/Belle/BaBar

- $b \to c$ charged currents: τ vs light leptons (μ, e) $[R_D, R_{D^*}, R_{J/\Psi}]$
- $b \to s$ neutral currents: μ vs e $[R_K, R_{K^*}, P_5']$
- ▶ See talk of Julian Garcia Pardinas for more details

LFU maybe just a low-energy property:

The different generations may well have a different behavior at higher energies.

What if LFU anomalies are due to BSM physics...?:

Many BSM models explaining LFU deviations predict large effect in LFV modes:

SUSY, Extended Higgs, little Higgs, LQ, Z', etc..

[JHEP09(2017)040, Phys.Rev.D 59, 034019 (1999), Phys.Rev.Lett. 114 (2015) 091801, Phys.Rev.D 92, 054013 (2015), arXiv:1211.5168v3v, Phys.Rev.D86 (2012) 054023,arXiv:1505.05164, Phys.Rev.Lett. 118 (2017), 011801, JHEP11(2017)044, Phys.Rev.D 98, 115002 (2018), JHEP10(2018)148, arXiv:1903.11517 etc...]

LFUV $\Rightarrow$ **LFV**:

$$\frac{\mathcal{B}(B_s^0 \to \tau(e,\mu))}{\mathcal{B}(B_s^0 \to \mu\mu)_{SM}} \sim 4 \left(\frac{1-R_K}{0.23}\right)^2, \qquad \frac{\mathcal{B}(B_s^0 \to \mu^+ e^-)}{\mathcal{B}(B_s^0 \to \mu\mu)_{SM}} \sim 0.01 \left(\frac{1-R_K}{0.23}\right)^2,$$

$$\mathcal{B}(B \to K\tau(e,\mu)) \sim 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2, \text{[Hiller, Loose and Schonwald, JHEP12(2016)027]}$$

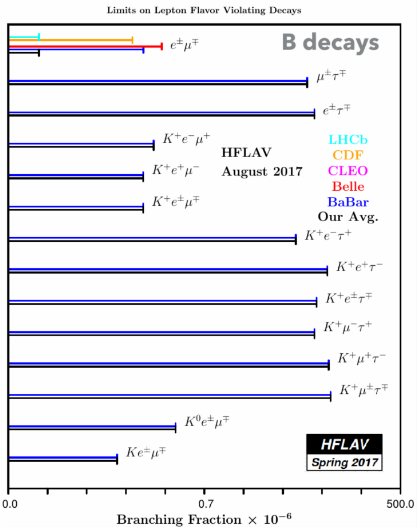
EXCITING TIMES!!!

Historic of LFV searches at LHCb and other experiments

Decays	Experimental upper limit at 90% C.L.	LHCb -PAPER -Number
$B^+ \to K^+\mu^-e^+$	7.0×10^{-9}	2019-022*
$B^+ \to K^+\mu^+e^-$	7.1×10^{-9}	2019-022*
$B^0_s \to \tau\mu$	3.4×10^{-5}	2019-016
$B^0 \to \tau\mu$	1.2×10^{-5}	2019-016
$B^0_s \to e\mu$	5.4×10^{-9}	2017-031
$B^0 \to e\mu$	1.0×10^{-9}	2017-031
H-like $\to \mu\tau$	< 22 pb**	2018-030
$D^0 \to e\mu$	1.3×10^{-8}	2015-048
$\tau \to 3\mu$	4.6×10^{-8}	2015-052
...		

* in preparation: preliminary

** Limit given on $\sigma_H \times \mathcal{B}$ at 95%C.L., ranges from 22 pb for a Higgs-like boson mass at 45 GeV/c^2, to 4 pb for 195 GeV/c^2.



$B^0_{(s)} \to \tau\mu$

Many BSM model explaining the anomalies predict large $\mathcal{B}$ for $B^0_{(s)} \to \tau\mu$:

- Z': 10^{-8} [1] to 10^{-5} [2]
- LQs: 10^{-9} [3] to 10^{-4} [4], 10^{-5} [5]
- PS^3: 10^{-4} [6]

[1] Becirevic et al. [EPJ C76(2016)134]
[2] Crivellin et al. [PRD 92 (2015) 050413]
[3] Becirevic et al. [JHEP 11(2016)035]
[4] Bhattacharya et al. [JHEP 01(2017)15]
[5] Smirnov [MPLA 33(2018)1550019]
[6] Bordone et al. [JHEP10(2018)148]

Experimental status before May 2019:

$\mathcal{B}(B^0 \to \tau\mu) < 2.2 \times 10^{-5}$ [BaBar, Phys.Rev.D77,091104(2008)]

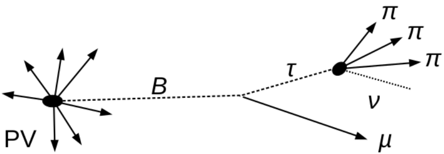
$\mathcal{B}(B^0_s \to \tau\mu)$: no limit yet

Analysis strategy

- Run1 data ($3\,\mathrm{fb}^{-1}$)
- Challenging reconstruction based on 3-prong τ decays: $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ ($\mathcal{B} \sim 9\%$)
  $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ taken into account, $\mathcal{B} \sim 5\%$
  $\Rightarrow$ B mass reconstruction possible up to a 2-fold ambiguity
- Signal region blinded for data
- Background rejection:
  - ▶ BDT classifiers
  - ▶ Isolation variables
  - ▶ Background modeled from Same-Sign (SS) data ($\tau^\pm\mu^\pm$)
  and MC simulation for qualitative studies.
- Signal yield extraction:
  Simultaneous fit to the mass distributions in bins of a final BDT
- Determine $\mathcal{B}$ normalized to $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$

B Mass reconstruction

Only 1 missing ν, only 4 tracks, μ points to the B decay vertex
$\Rightarrow$ enough constraints to compute the ν momentum

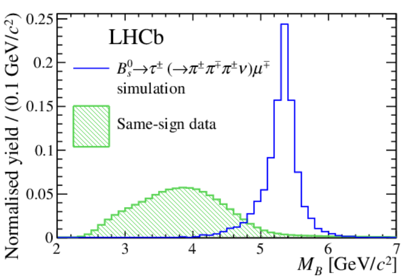


$$\begin{cases} m_\tau{}^2 = (E_{3\pi} + |\vec{p}_\nu|)^2 - (\vec{p}_{3\pi} + \vec{p}_\nu)^2 \\ \vec{x}_B \in (\mathrm{d}_\mu) \\ (\vec{p}_{3\pi} + \vec{p}_\nu) \parallel (\vec{x}_\tau - \vec{x}_B) \\ (\vec{p}_{3\pi} + \vec{p}_\mu + \vec{p}_\nu) \parallel (\vec{x}_B - \vec{x}_{\mathrm{PV}}) \end{cases}$$

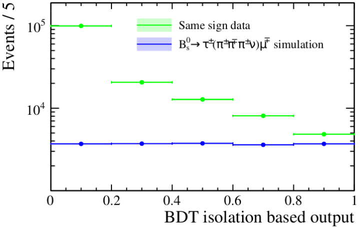
$$M_B = \sqrt{(E_{3\pi} + E_\mu + |\vec{p}_\nu|)^2 - (\vec{p}_{3\pi} + \vec{p}_\mu + \vec{p}_\nu)^2}$$

B mass reconstructed with a 2-fold ambiguity:
Use solution with largest signal-vs-bkg separation

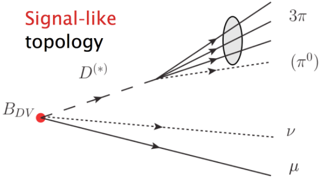
Data blinded for $4.9 < M_B < 5.8$ GeV/c^2



Cut on an isolation based BDT classifier
Uses charged, neutral, and vertex isolation variables
40% of signal efficiency, $>$ 90% bkg rejection

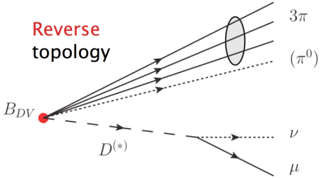


Signal-like topology

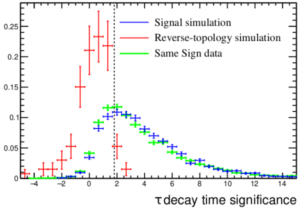


Cut on a second BDT
$\to$ Suppress Signal-like topology
Trained on SS data and MC
Use vertex related variables and opening angles

Reverse topology



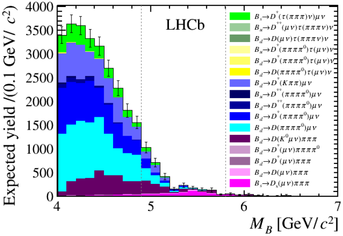
Cut on τ lifetime significance
$\to$ Suppress reverse topology
(peaking in the signal region)



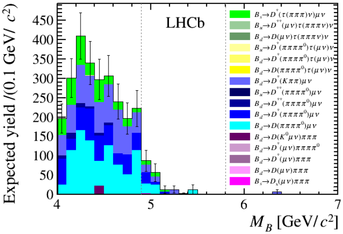
$B^0_{(s)} \to \tau\mu$ at LHCb [arXiv:1905.06614] (May 2019)

Set of 16 exclusive backgrounds (signal-like and reverse topology)

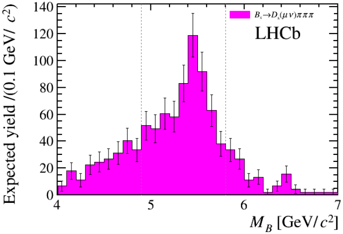
Before the full selection

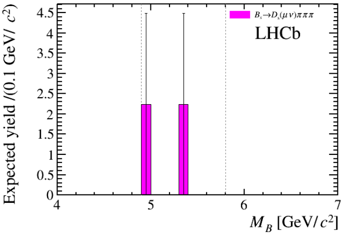


After the full selection



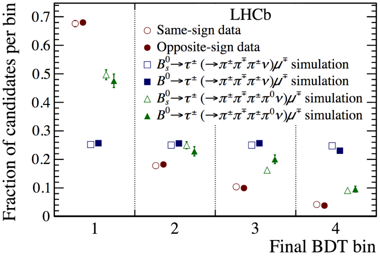
Zoom on the reverse-topology background $B^0_s \to D_s(\mu\nu)\pi\pi\pi$



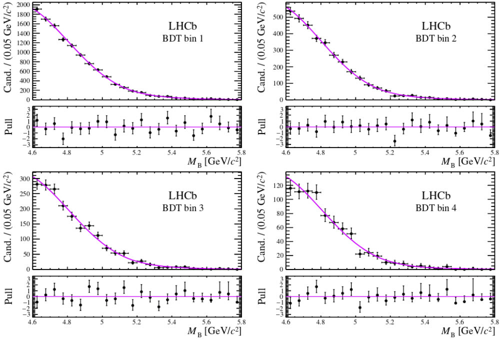


Final BDT

Trained on same sign data and MC signal
Uses output of first BDTs, vertex related variables and $2/3\pi$-masses.



Simultaneous fit to the mass distributions in bins of the final BDT



Separation between B_s^0 and B^0 limited
$\Rightarrow$ fitting B_s^0 neglecting B^0 and vice versa

No signal found:

$N_{B_s^0} = -16 \pm 38$
$N_B^0 = -65 \pm 58$

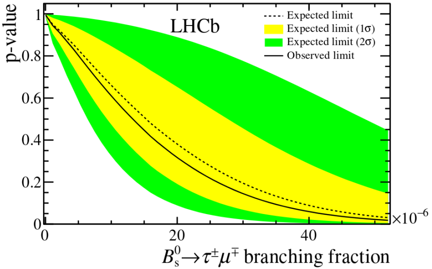
Determine $\mathcal{B}$ normalized to $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$

$$\mathcal{B}(B^0_{(s)} \to \tau\mu) = \frac{f^0_B}{f_{B^0_{(s)}}} \cdot \frac{\mathcal{B}(B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+)}{\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^+\nu_\tau)} \cdot \frac{\epsilon_{B^0\to D\pi}}{\epsilon_{B^0_{(s)}\to\tau\mu}} \cdot \frac{N^{sig}_{(s)}}{N^{Norm}} = \alpha_{(s)} \cdot N^{sig}_{(s)}$$

$$\alpha_s = (4.32 \pm 0.61) \times 10^{-7}$$
$$\alpha_d = (1.25 \pm 0.16) \times 10^{-7}$$

Systematics dominated by:

- Bkg shape (∼35%)
- Trigger (∼ 11%)
- External inputs (∼ 8%)
- Data-vs-MC corr. (∼ 2%)



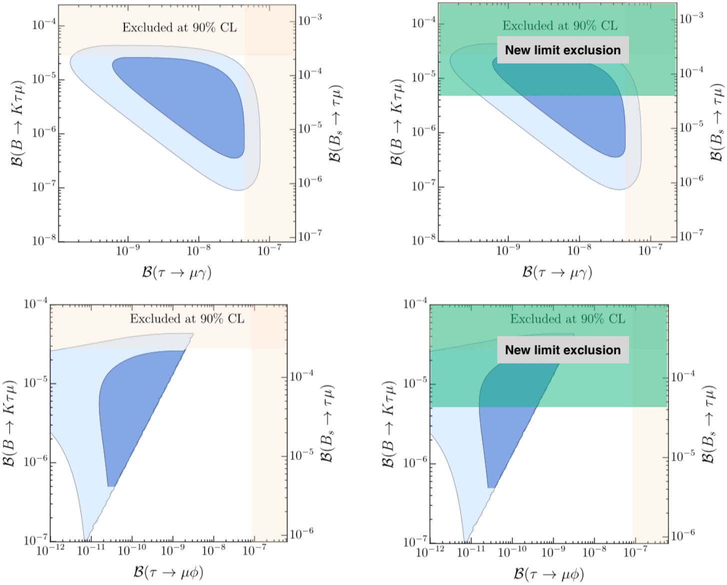
Mode	Limit	90% CL	95% CL
$B^0_s \to \tau^\pm\mu^\mp$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \to \tau^\pm\mu^\mp$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

First measurement for B^0_s
Best world limit for B^0, improvement by a factor ∼ 2!

$B^0_{(s)} \to \tau\mu$ limit impact

Preferred 2D fit regions for vector LQ (U1):

[Cornella, Fuentes-Martin and Isidori, arXiv:1903.11517]



$B^+ \to K^+ e^\pm \mu^\mp$ (Preliminary, LHCb-Paper-2019-022 in preparation)

Many BSM models predict large $\mathcal{B}$

- LQs: $\mathcal{B}(B \to K\mu e) \sim 3 \cdot 10^{-8}(\frac{1-R_K}{0.23})^2 \sim 10^{-8}$ [1], [2]
- Z': $\mathcal{B} \sim 10^{-8}$ [3]
- CPV in ν oscillations: $\mathcal{B} \sim 10^{-10}$ [4]

[1] Medeiros Vaezilas and Hiller, JHEP06 (2015) 072
[2] Hiller ar al., JHEP12 (2016) 027
[3] Crivellin et al. PRD92 (2015) 054013
[4] Boucenna et al. PLB (2015) 09 040

Previous experimental status:

$\mathcal{B}(B^+ \to K^+ e^+ \mu^-) < 9.1 \times 10^{-8}$ [BaBar, PRD73 (2006) 092001]
$\mathcal{B}(B^+ \to K^+ e^- \mu^+) < 13 \times 10^{-8}$

$B^+ \to K^+ e^\pm \mu^\mp$ (Preliminary, LHCb-Paper-2019-022 in preparation)

Analysis strategy

- Run1 data (3 fb^{-1})

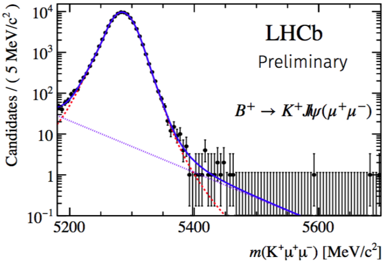
- Search designed for two charge configurations:
$B^+ \to K^+ e^+ \mu^-$
$B^+ \to K^+ e^- \mu^+$

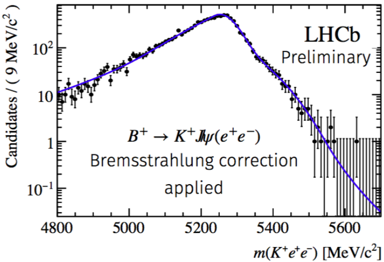
- Normalized with $B^+ \to K^+ J/\Psi(\mu^- \mu^+)$

- MC corrected using data:
$B^+ \to K^+ J/\Psi(\mu^- \mu^+)$
$B^+ \to K^+ J/\Psi(e^- e^+)$

- Background rejection:
Double semileptonic decays
Charmonium decays
Suppressed by vetoes and double-stage BDT

- Developed blind in the region
$m(Ke\mu) \in [4985, 5385]$ GeV/c^2





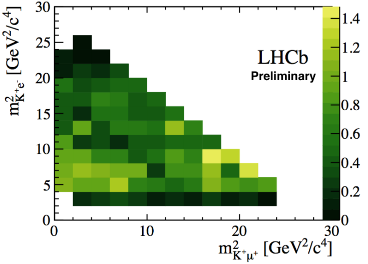
$B^+ \to K^+ e^\pm \mu^\mp$ (Preliminary, LHCb-Paper-2019-022 in preparation)

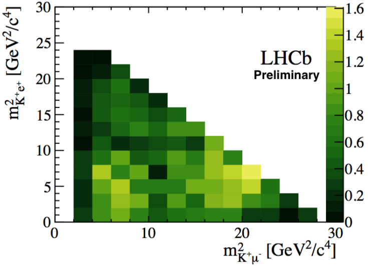
Preselection

- Most significant backgrounds from $B^+ \to \bar{D}^0 X \ell^+ \nu_\ell$, with $\bar{D}^0 \to K^+ Y \ell^- \bar{\nu}_\ell$
  - ▶ $m(K^+\ell^-) < 1885\ \mathrm{MeV/c^2}$
- Charmonium decays $B^+ \to K^+ J\Psi$, $\Lambda_b^0 \to pK^- J/\Psi$, ...
  - ▶ Vetoes on charmonium regions
- Strong requirements on particle identification criteria

BDT selection

- BDT to remove random tracks combinations trained on upper mass sideband B kinematics, topological variables, isolation
- BDT to remove partially reconstructed b-hadron decays trained on lower mass sideband same set of discriminant variables used





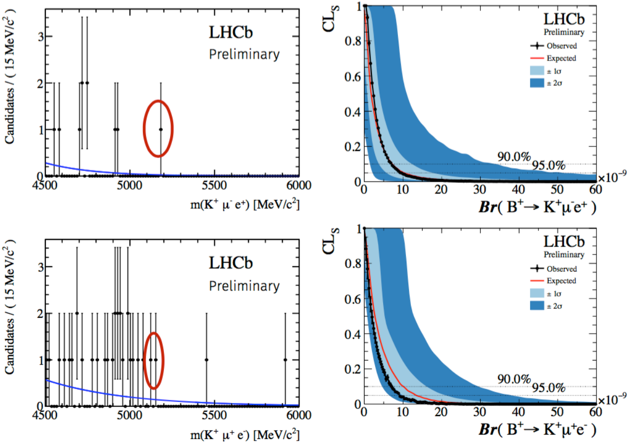
Determine $\mathcal{B}$ normalized to $B^+ \to K^+ J/\Psi(\mu\mu)$

$\alpha_{B^+ \to K^+ e^+ \mu^-} = (1.97 \pm 0.14) \times 10^{-9}$

$\alpha_{B^+ \to K^+ e^- \mu^+} = (2.21 \pm 0.14) \times 10^{-9}$

Systematics dominated by:

- Knowledge of $\mathcal{B}(B^+ \to K^+ J/\Psi(\mu\mu))$
- Background modeling
- Particle Identification

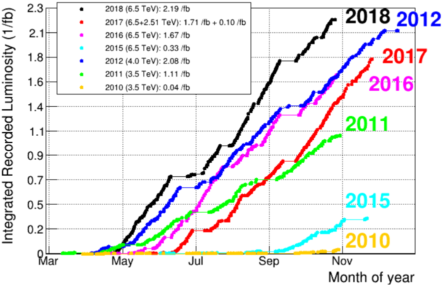


Mode	Limit at 90 % C.L.
$B^+ \to K^+ \mu^- e^+$	7.0×10^{-9}
$B^+ \to K^+ \mu^+ e^-$	7.1×10^{-9}

Reduce current world best limit by more than 10!

- A whole family to be searched for:

  $B^0_{(s)} \to e\mu$ released, Run2 to be added
  $B^0_{(s)} \to \tau\mu$ just released! Run2 to be added
  $B^0_{(s)} \to K\tau\mu$
  $B^0_{(s)} \to K^*\tau\mu$ (on-going)
  $B^+ \to K^+ e\mu$ soon released!
  $\Lambda_b \to \Lambda^0 e\mu$
  $\tau \to 3\mu$
  $\tau \to p\mu\mu$
  ...



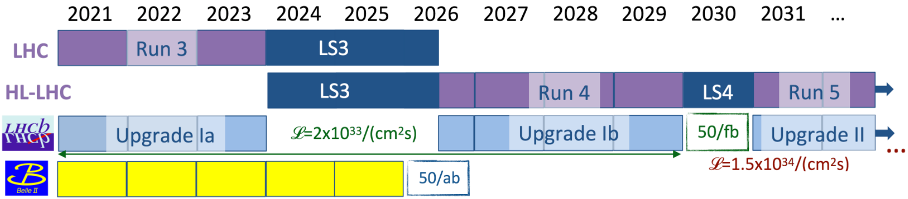
Only Run1 dataset exploited so far: 3 fb^{-1} of pp collisions at 7/8 TeV.

Run2 dataset: 6 fb^{-1} of pp collisions at 13 TeV ($\sigma_{b\bar{b}} \times 2$)
$\Rightarrow\sim$ 4 more data to analyze!!
Significant improvements expected by adding Run2 dataset!

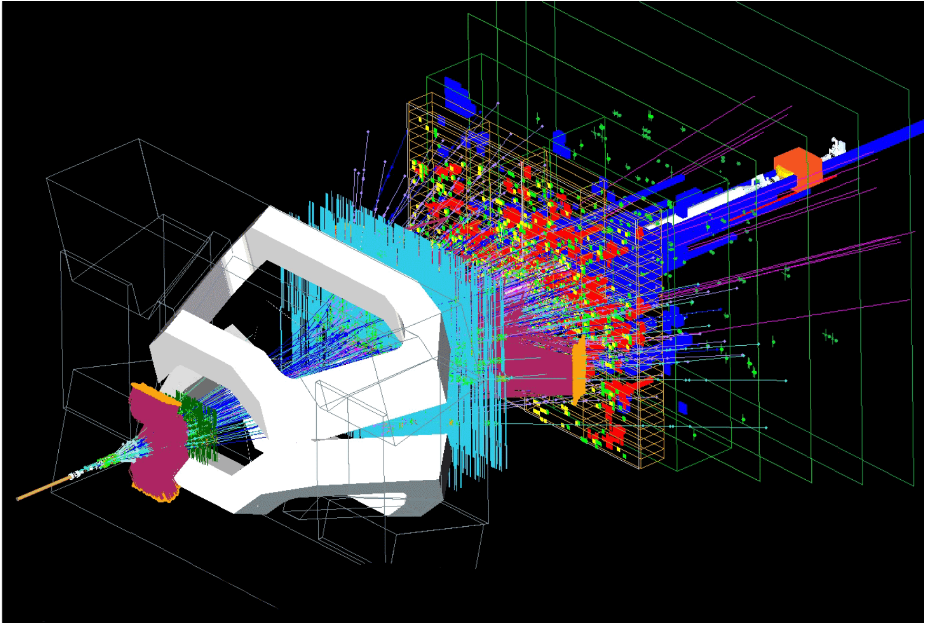
Conclusions

- A lot of work have been done by LHCb on LFV decay
- First and world-best limits recently set on $B^0_{(s)} \to \tau\mu$ and $B^+ \to K^+\mu^\pm e^\mp$
- Very challenging at LHCb
  Missing energy
  Electron ID
  High level and variety of backgrounds
- Most of analysis are handmade by small group of people!
- New experiments coming (Belle II, CMS, ...)
  Great for double-checking, interplay among experiments.

Need analysis improvement and upgrades to get to more interesting regimes:

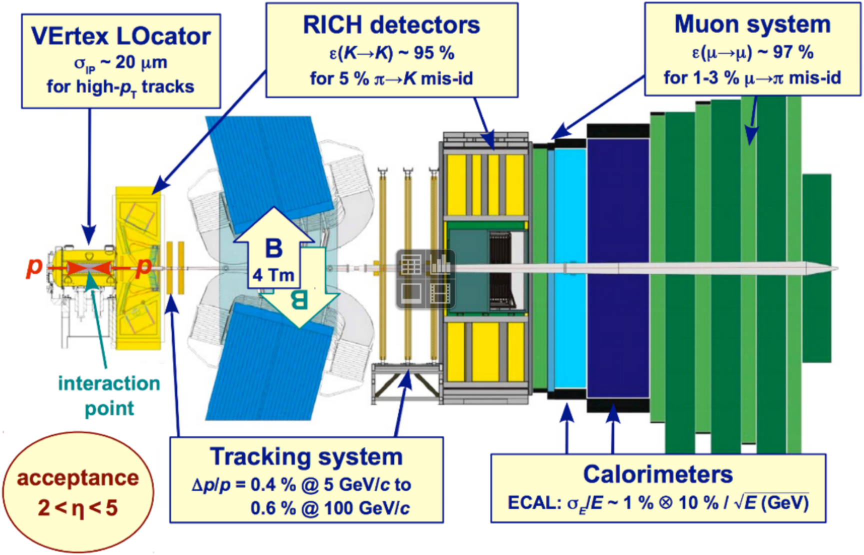


BACK-UP



LHCb detector

[LHCb performance, Int.J.Mod.Phys. A30 (2015) no.07, 1530022]
[The LHCb Detector at the LHC, JINST 3 (2008) S08005]



Other LFV measurements

μ^- DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^- \nu_e \overline{\nu}_\mu$	LF	[f] < 1.2 %	90%	53
$e^- \gamma$	LF	$< 4.2 \times 10^{-13}$	90%	53
$e^- e^+ e^-$	LF	$< 1.0 \times 10^{-12}$	90%	53
$e^- 2\gamma$	LF	$< 7.2 \times 10^{-11}$	90%	53

$\mathcal{B}(Z^0 \to e^\pm \mu^\mp) < 7.5 \times 10^{-7}$ (@95%CL)

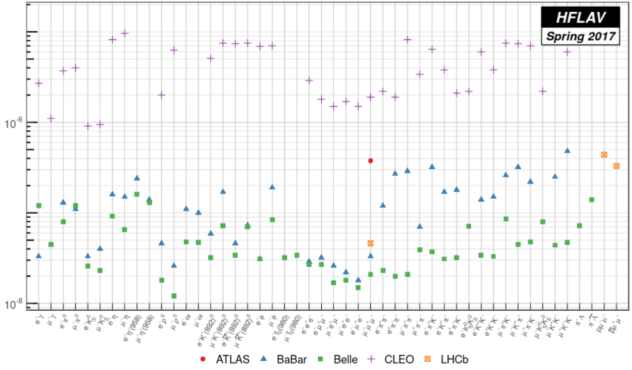
$\mathcal{B}(Z^0 \to e^\pm \tau^\mp) < 9.8 \times 10^{-6}$ (@95%CL)

$\mathcal{B}(Z^0 \to \mu^\pm \tau^\mp) < 1.2 \times 10^{-5}$ (@95%CL)

$\mathcal{B}(H^0 \to \mu\tau) < 0.25\%$ (@95%CL)

$\mathcal{B}(H^0 \to e\tau) < 0.61\%$ (@95%CL)

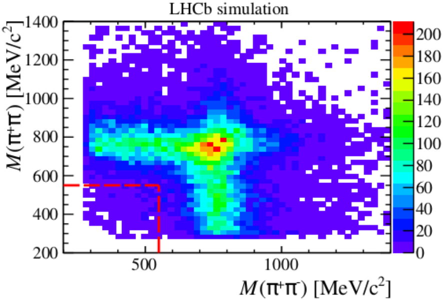
90% CL upper limits on τ LFV decays

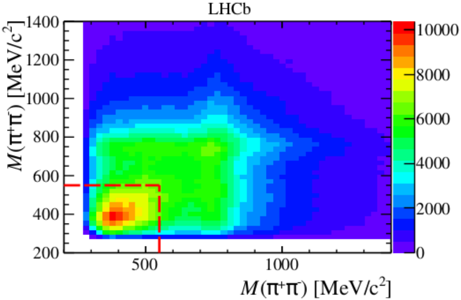


More about the preselection:

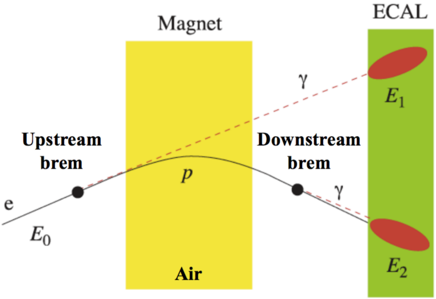
$M_B < 4$ GeV/c^2 discarded

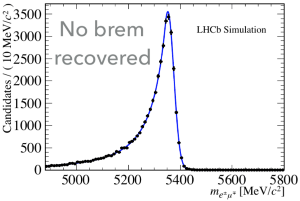
$$\tau^- \to a1(1260)^- \nu_\tau$$
$$\hookrightarrow \pi_1^- \rho(770)^0$$
$$\hookrightarrow \pi_2^+ \pi_3 -$$

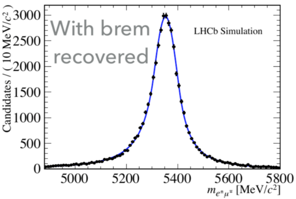




Electron energy resolution degraded by energy loss from bremsstrahlung effect



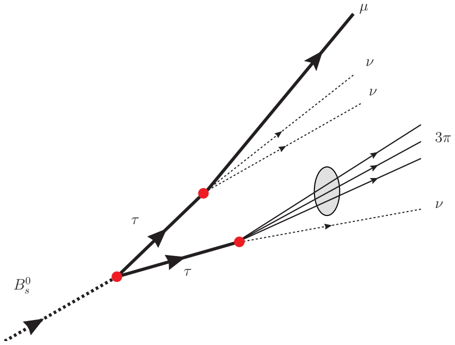




Examples taken from
$B_s^0 \to e\mu$
[JHEP 1803 (2018) 078]

Isolation variables

- Neutral isolation variables
  Count neutral objects in a cone around the B candidate
- Vertex isolation variables
  Combine tracks making a τ candidate with other tracks in the events, refit vertex, and check for improvement
- Track isolation variables
  BDT-based, identify tracks coming from other vertex



Observables entering in the χ^2 fit:

Observable	Experiment	Corr.	SM
R_D	$0.334(31)$ [5]	-0.37	$0.299(3)$ [63–65]
R_{D^*}	$0.297(15)$		$0.258(5)$ [64–66]
$\mathcal{B}(B \to \tau\nu)$	$1.09(24) \cdot 10^{-4}$ [67]	–	$0.812(54) \cdot 10^{-4}$ [68]
$\Delta\mathcal{C}_9^{\mu\mu} = -\Delta\mathcal{C}_{10}^{\mu\mu}$	-0.40 ± 0.12 [41, 42]	-0.5	–
$\Delta\mathcal{C}_9^U$	-0.50 ± 0.38		–
$\mathcal{B}(B_s \to \tau^+\tau^-)$	$0.0(3.4) \cdot 10^{-3}$ [69]	–	$7.73(49) \cdot 10^{-7}$ [70]
$\mathcal{B}(B^+ \to K^+\tau^+\tau^-)$	$1.36(0.71) \cdot 10^{-3}$ [71]	–	$1.5(0.2) \cdot 10^{-7}$
$\mathcal{B}(\tau \to \mu\gamma)$	$0.0(3.0) \cdot 10^{-8}$ [53]	–	–
$\mathcal{B}(B^+ \to K^+\tau^+\mu^-)$	$0.0(1.7) \cdot 10^{-5}$ [72]	–	–
$\mathcal{B}(\tau \to \mu\phi)$	$0.0(5.1) \cdot 10^{-8}$ [73]	–	–
$(g_\tau/g_\mu)_{\ell,\pi,K}$	1.0000 ± 0.0014 [53]	–	1.

Effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = -\frac{2C_U}{v^2}\Big[-2\,(\beta_L^{i\alpha})^*\beta_R^{l\beta}(\bar{\ell}_L^\alpha e_R^\beta)(\bar{d}_R^l q_L^i) + \text{h.c.} + \beta_R^{i\alpha}(\beta_R^{l\beta})^*(\bar{e}_R^\beta\gamma_\mu e_R^\alpha)(\bar{d}_R^i\gamma^\mu d_R^l) \\ +\frac{1}{2}\beta_L^{i\alpha}(\beta_L^{l\beta})^*(\bar{\ell}_L^\beta\gamma_\mu\ell_L^\alpha)(\bar{q}_L^i\gamma^\mu q_L^l) + \frac{1}{2}\beta_L^{i\alpha}(\beta_L^{l\beta})^*(\bar{\ell}_L^\beta\sigma^a\gamma_\mu\ell_L^\alpha)(\bar{q}_L^i\sigma^a\gamma^\mu q_L^l)\Big], \tag{2.5}$$

where $C_U \equiv g_U^2 v^2/(4M_U^2)$ and $v = (\sqrt{2}\,G_F)^{-1/2} \approx 246$ GeV is the SM Higgs vacuum expectation value (vev).

Fit results:

$$C_U \in [0.3, 1.0] \cdot 10^{-2}, \quad \beta_L^{s\tau} \in [0.08, 0.25], \quad \beta_L^{d\tau} \in [-0.17, -0.01],$$
$$\beta_L^{b\mu} \in [-0.42, -0.07], \quad \beta_L^{s\mu} \in [0.01, 0.08].$$