



Searches for Lepton Flavour Violating decays at LHCb

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Searches for Lepton Flavour Violating decays at LHCb

Cédric Méaux¹

On behalf of the LHCb collaboration

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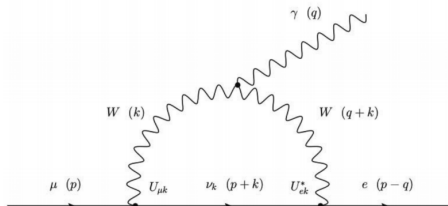
WIN 2019

2019 5th June



Lepton Flavour Violation (LFV) in Standard Model (SM)

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



$$\mathcal{B}(\mu \rightarrow e \gamma) \simeq \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \frac{U_{\mu k} U_{ek}^* m_{\nu_k}^2}{M_W^2} \right|^2$$
$$\simeq 10^{-55} - 10^{-54}$$

- 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

- $b \rightarrow c$ charged currents: τ vs light leptons (μ, e) [$R_D, R_{D^*}, R_{J/\psi}$]
- $b \rightarrow s$ 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:

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

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

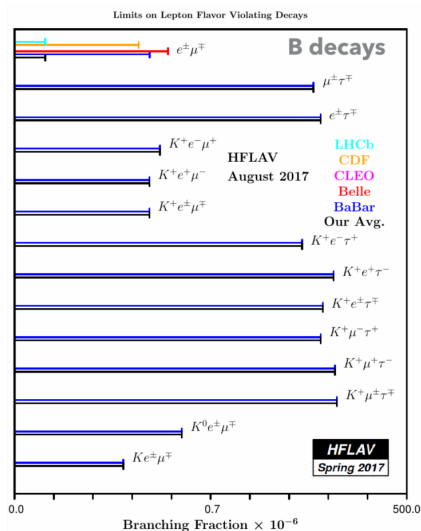
EXCITING TIMES!!!

Historic of LFV searches at LHCb and other experiments

Decays	Experimental upper limit at 90% C.L.	LHCb -PAPER -Number
$B^+ \rightarrow K^+ \mu^- e^+$	7.0×10^{-9}	2019-022*
$B^+ \rightarrow K^+ \mu^+ e^-$	7.1×10^{-9}	2019-022*
$B_s^0 \rightarrow \tau \mu$	3.4×10^{-5}	2019-016
$B^0 \rightarrow \tau \mu$	1.2×10^{-5}	2019-016
$B_s^0 \rightarrow e \mu$	5.4×10^{-9}	2017-031
$B^0 \rightarrow e \mu$	1.0×10^{-9}	2017-031
H-like $\rightarrow \mu \tau$	$< 22 \text{ pb}^{**}$	2018-030
$D^0 \rightarrow e \mu$	1.3×10^{-8}	2015-048
$\tau \rightarrow 3 \mu$	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/c², to 4 pb for 195 GeV/c².



$$B_{(s)}^0 \rightarrow \tau\mu$$

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

- 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:

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

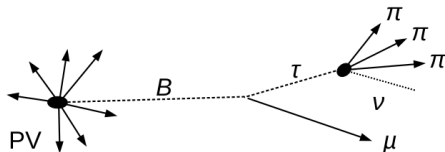
$\mathcal{B}(B_s^0 \rightarrow \tau\mu)$: no limit yet

Analysis strategy

- Run1 data (3 fb^{-1})
- Challenging reconstruction based on 3-prong τ decays: $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ ($\mathcal{B} \sim 9\%$)
 $\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ 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 $B^0 \rightarrow D^-(\rightarrow K^+ \pi^- \pi^-) \pi^+$

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

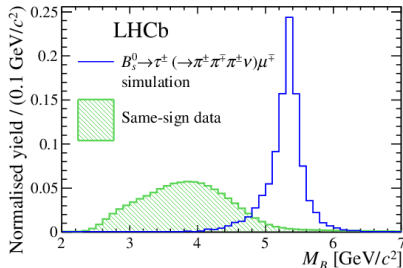


$$\left\{ \begin{array}{l} m_\tau^2 = (E_{3\pi} + |\vec{p}_\nu|)^2 - (\vec{p}_{3\pi} + \vec{p}_\nu)^2 \\ \vec{x}_B \in (d_\mu) \\ (\vec{p}_{3\pi} + \vec{p}_\nu) \parallel (\vec{x}_\tau - \vec{x}_B) \\ (\vec{p}_{3\pi} + \vec{p}_\mu + \vec{p}_\nu) \parallel (\vec{x}_B - \vec{x}_{PV}) \end{array} \right.$$

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

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

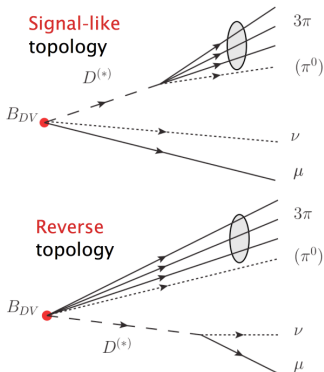
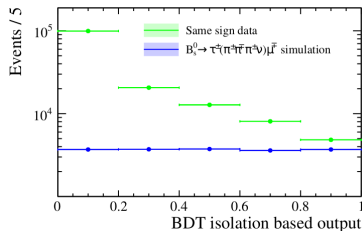
Data blinded for $4.9 < M_B < 5.8 \text{ GeV}/c^2$



Cut on an isolation based BDT classifier

Uses charged, neutral, and vertex isolation variables

40% of signal efficiency, > 90% bkg rejection



Cut on a second BDT

→ Suppress Signal-like topology

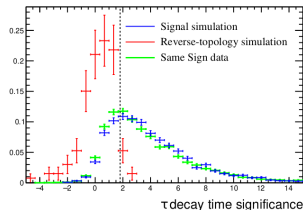
Trained on SS data and MC

Use vertex related variables and opening angles

Cut on τ lifetime significance

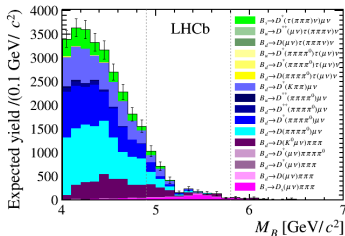
→ Suppress reverse topology

topology
(peaking in the signal region)

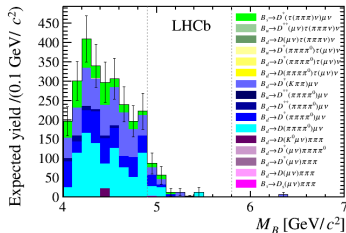


Set of 16 exclusive backgrounds (signal-like and reverse topology)

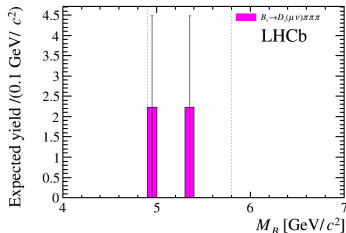
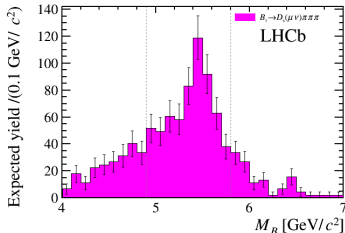
Before the full selection



After the full selection



Zoom on the reverse-topology background $B_s^0 \rightarrow D_s(\mu\nu)\pi\pi\pi$

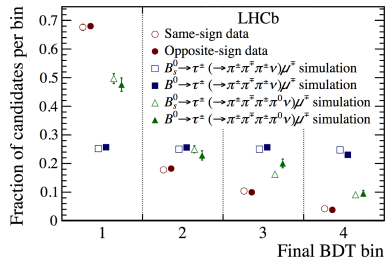
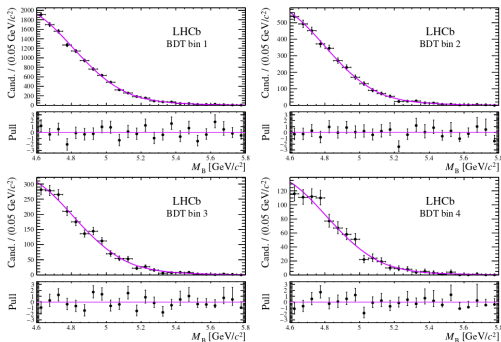


Final BDT

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

$$\mathcal{B}(B_{(s)}^0 \rightarrow \tau\mu) = \frac{f_B^0}{f_{B_{(s)}^0}} \cdot \frac{\mathcal{B}(B^0 \rightarrow D^-(\rightarrow K^+\pi^-\pi^-)\pi^+)}{\mathcal{B}(\tau^- \rightarrow \pi^-\pi^+\pi^+\nu_\tau)} \cdot \frac{\epsilon_{B^0 \rightarrow D\pi}}{\epsilon_{B_{(s)}^0 \rightarrow \tau\mu}} \cdot \frac{N_{(s)}^{sig}}{N^{Norm}} = \alpha_{(s)} \cdot N_{(s)}^{sig}$$

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

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

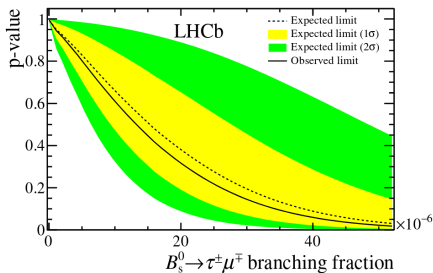
Systematics dominated by:

Bkg shape ($\sim 35\%$)

Trigger ($\sim 11\%$)

External inputs ($\sim 8\%$)

Data-vs-MC corr. ($\sim 2\%$)



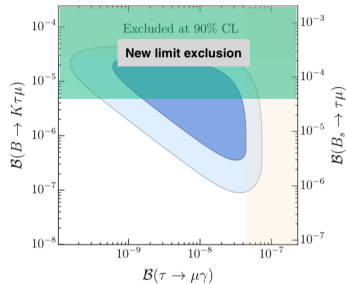
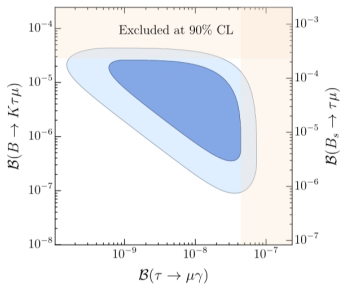
Mode	Limit	90% CL	95% CL
$B_s^0 \rightarrow \tau^\pm \mu^\mp$	Observed	3.4×10^{-5}	4.2×10^{-5}
	Expected	3.9×10^{-5}	4.7×10^{-5}
$B^0 \rightarrow \tau^\pm \mu^\mp$	Observed	1.2×10^{-5}	1.4×10^{-5}
	Expected	1.6×10^{-5}	1.9×10^{-5}

First measurement for B_s^0

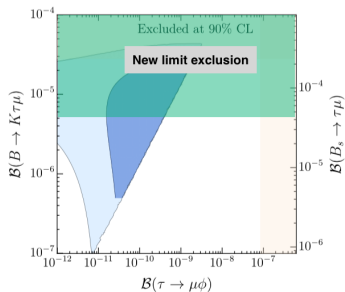
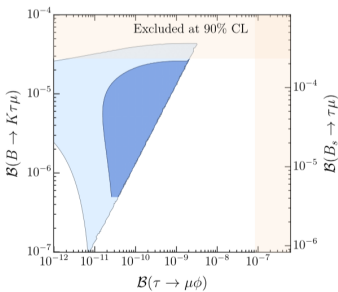
Best world limit for B^0 , improvement by a factor $\sim 2!$

$B_{(s)}^0 \rightarrow \tau\mu$ limit impact

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



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



Many BSM models predict large \mathcal{B}

- LQs: $\mathcal{B}(B \rightarrow K \mu e) \sim 3 \cdot 10^{-8} (\frac{1-R_K}{0.23})^2 \sim 10^{-8}$ [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 et al., JHEP12 (2016) 027

[3] Crivellin et al. PRD92 (2015) 054013

[4] Boucenna et al. PLB (2015) 09 040

Previous experimental status:

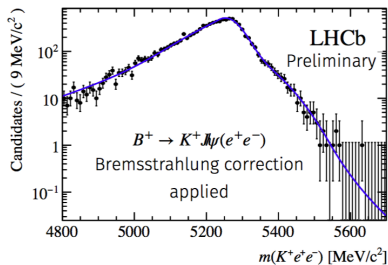
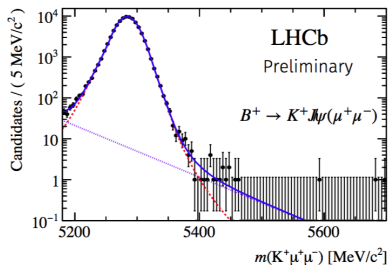
$$\mathcal{B}(B^+ \rightarrow K^+ e^+ \mu^-) < 9.1 \times 10^{-8} \text{ [BaBar, PRD73 (2006) 092001]}$$

$$\mathcal{B}(B^+ \rightarrow K^+ e^- \mu^+) < 13 \times 10^{-8}$$

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

Analysis strategy

- Run1 data (3 fb⁻¹)
- Search designed for two charge configurations:
 $B^+ \rightarrow K^+ e^+ \mu^-$
 $B^+ \rightarrow K^+ e^- \mu^+$
- Normalized with $B^+ \rightarrow K^+ J/\psi(\mu^- \mu^+)$
- MC corrected using data:
 $B^+ \rightarrow K^+ J/\psi(\mu^- \mu^+)$
 $B^+ \rightarrow K^+ J/\psi(e^- e^+)$
- Background rejection:
Double semileptonic decays
Charmonium decays
Suppressed by vetoes and double-stage BDT
- Developed blind in the region
 $m(K e \mu) \in [4985, 5385] \text{ GeV}/c^2$

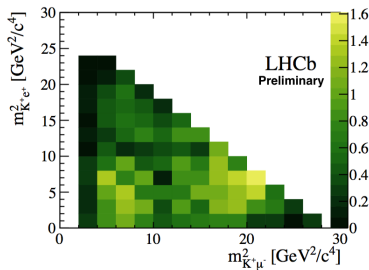
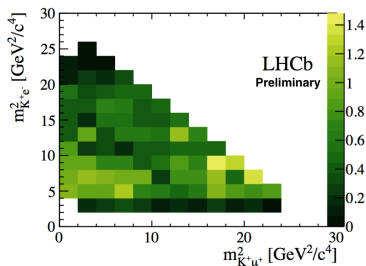


Preselection

- Most significant backgrounds from $B^+ \rightarrow \bar{D}^0 X \ell^+ \nu_\ell$, with $\bar{D}^0 \rightarrow K^+ Y \ell^- \bar{\nu}_\ell$
 - ▶ $m(K^+ \ell^-) < 1885 \text{ MeV}/c^2$
- Charmonium decays $B^+ \rightarrow K^+ J\psi$, $\Lambda_b^0 \rightarrow p K^- J/\psi$, ...
 - ▶ 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



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

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

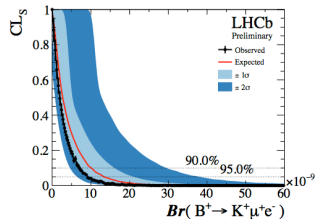
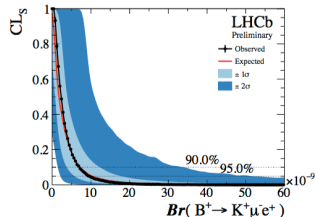
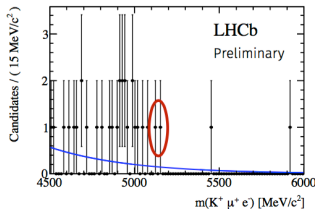
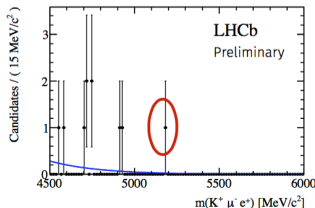
$$\alpha_{B^+ \rightarrow K^+ e^- \mu^-} = (1.97 \pm 0.14) \times 10^{-9}$$

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

Systematics

dominated by:

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



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

Reduce current world best limit by more than 10!

- A whole family to be searched for:

$B_{(s)}^0 \rightarrow e\mu$ released, Run2 to be added

$B_{(s)}^0 \rightarrow \tau\mu$ just released! Run2 to be added

$B_{(s)}^0 \rightarrow K\tau\mu$

$B_{(s)}^0 \rightarrow K^*\tau\mu$ (on-going)

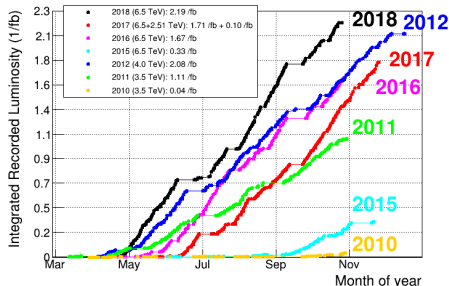
$B^+ \rightarrow K^+e\mu$ soon released!

$\Lambda_b \rightarrow \Lambda^0 e\mu$

$\tau \rightarrow 3\mu$

$\tau \rightarrow \rho\mu\mu$

...



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 ($\sigma_{b\bar{b}} \times 2$)

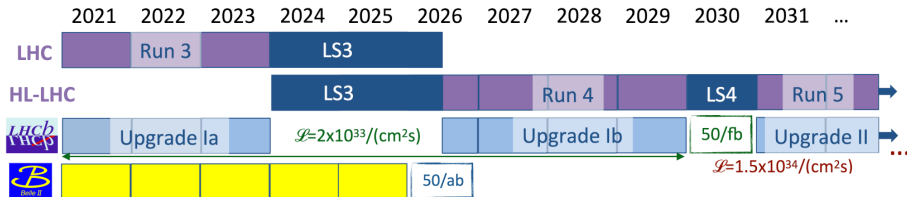
⇒ ~ 4 more data to analyze!!

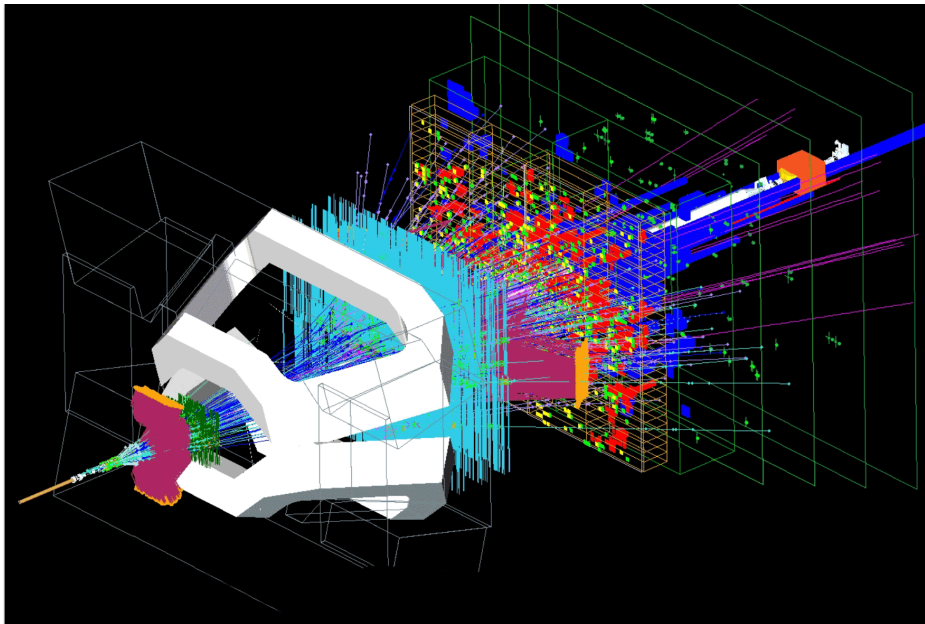
Significant improvements expected by adding Run2 dataset!

Conclusions

- A lot of work have been done by LHCb on LFV decay
- First and world-best limits recently set on $B_{(s)}^0 \rightarrow \tau \mu$ and $B^+ \rightarrow K^+ \mu^\pm e^\mp$
- 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:

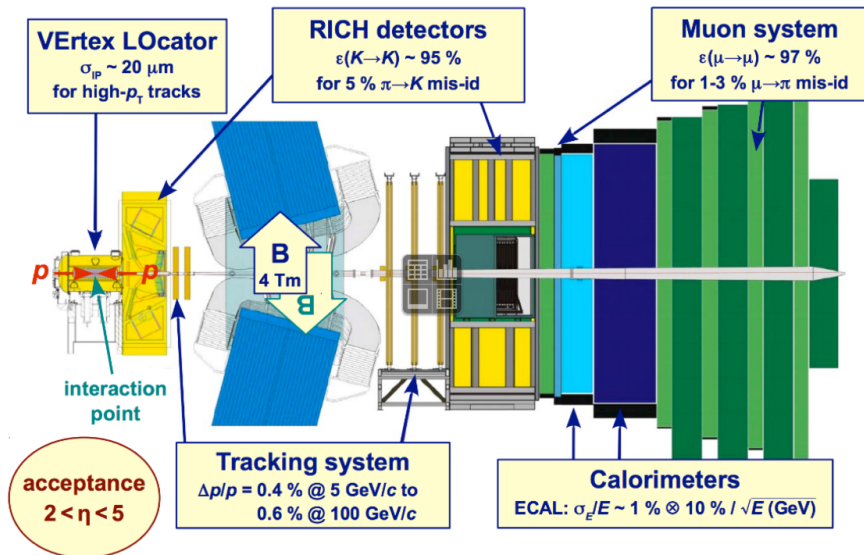




LHCb detector

[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)
$e^- \nu_e \bar{\nu}_\mu$	LF	$[f] < 1.2$	%	90%
$e^- \gamma$	LF	< 4.2	$\times 10^{-13}$	90%
$e^- e^+ e^-$	LF	< 1.0	$\times 10^{-12}$	90%
$e^- 2\gamma$	LF	< 7.2	$\times 10^{-11}$	90%

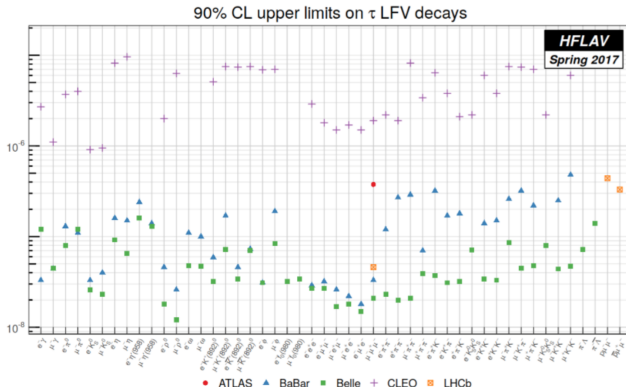
$$\mathcal{B}(Z^0 \rightarrow e^\pm \mu^\mp) < 7.5 \times 10^{-7} \text{ (@95\%CL)}$$

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

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

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

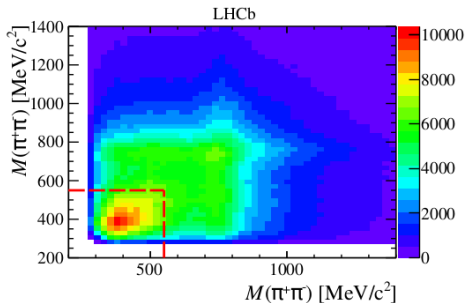
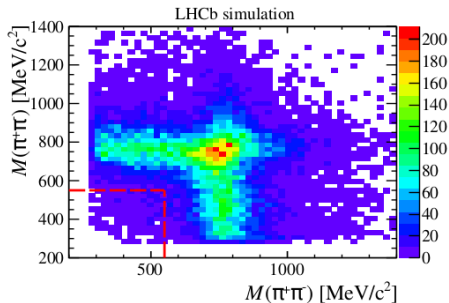
$$\mathcal{B}(H^0 \rightarrow e\tau) < 0.61\% \text{ (@95\%CL)}$$



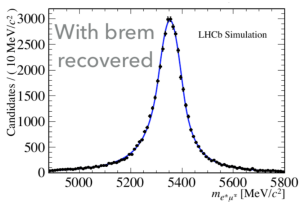
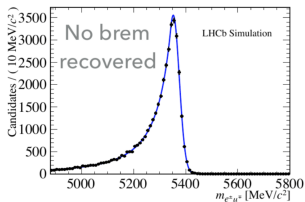
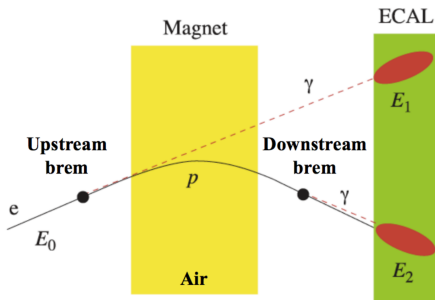
More about the preselection:

$M_B < 4 \text{ GeV}/c^2$ discarded

$$\begin{aligned}\tau^- &\rightarrow a1(1260)^- \nu_\tau \\ &\hookrightarrow \pi_1^- \rho(770)^0 \\ &\hookrightarrow \pi_2^+ \pi_3^-\end{aligned}$$



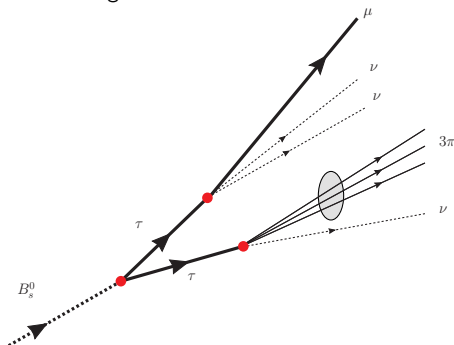
Electron energy resolution degraded by energy loss from bremsstrahlung effect



Examples taken from
 $B_s^0 \rightarrow e\mu$
 [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) [5]	-	0.258(5) [64-66]
$\mathcal{B}(B \rightarrow \tau \nu)$	$1.09(24) \cdot 10^{-4}$ [67]	-	$0.812(54) \cdot 10^{-4}$ [68]
$\Delta C_9^{\mu\mu} = -\Delta C_{10}^{\mu\mu}$	-0.40 ± 0.12 [41, 42]	-0.5	-
ΔC_9^U	-0.50 ± 0.38 [41, 42]	-	-
$\mathcal{B}(B_s \rightarrow \tau^+ \tau^-)$	$0.0(3.4) \cdot 10^{-3}$ [69]	-	$7.73(49) \cdot 10^{-7}$ [70]
$\mathcal{B}(B^+ \rightarrow K^+ \tau^+ \tau^-)$	$1.36(0.71) \cdot 10^{-3}$ [71]	-	$1.5(0.2) \cdot 10^{-7}$
$\mathcal{B}(\tau \rightarrow \mu \gamma)$	$0.0(3.0) \cdot 10^{-8}$ [53]	-	-
$\mathcal{B}(B^+ \rightarrow K^+ \tau^+ \mu^-)$	$0.0(1.7) \cdot 10^{-5}$ [72]	-	-
$\mathcal{B}(\tau \rightarrow \mu \phi)$	$0.0(5.1) \cdot 10^{-8}$ [73]	-	-
$(g_\tau/g_\mu)_{\ell, \pi, K}$	1.0000 ± 0.0014 [53]	-	1.

Effective Lagrangian:

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

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:

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