LVF and other very rare decay searches at LHCb

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on behalf of the LHCb collaboration

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Outline

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   - $\Sigma^+ \to p\mu^+\mu^-$
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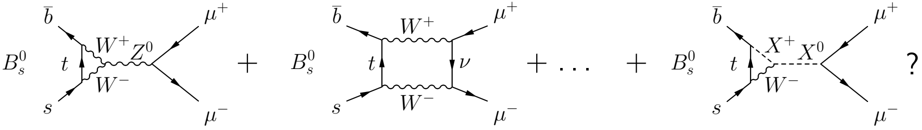
4. Conclusion

Introduction

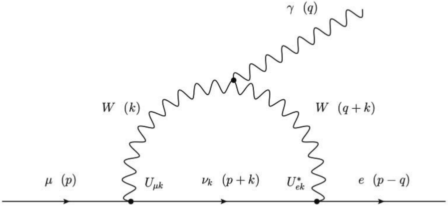
- Rare heavy flavour decays are a good place to look for New Physics
- When Standard Model is suppressed New Physics contributions could become apparent
- Sensitive also to new mediators with masses inaccessible by direct production
- Interesting in particular:
  - Flavour changing neutral currents (FCNC), in the Standard Model proceeds only via loop diagrams, possible new particles in the loops
  - Lepton flavour violating (LFV) decays, practically forbidden in the Standard Model, an observation is a clear sign of New Physics



Lepton Flavour violating decays

Lepton Flavour violating decays

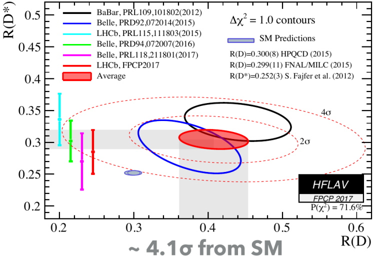
- Lepton flavour essentially conserved in the Standard Model
- BUT not supported by strong theoretical reasons (e.g. underlying symmetry)
- AND neutrino oscillation implies LFV in loops ($\mathcal{B} < 10^{-40}$)

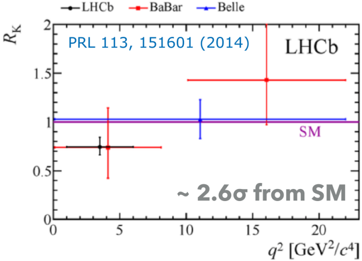


$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \frac{U_{\mu k} U^*_{ek} m^2_{\nu_k}}{M^2_W} \right|^2 \simeq 10^{-55} - 10^{-54}$$

LFUV → LFV ?

Recently several hints of LFUV (See talks of Vitalii Lisovskyi and Adam Morris)



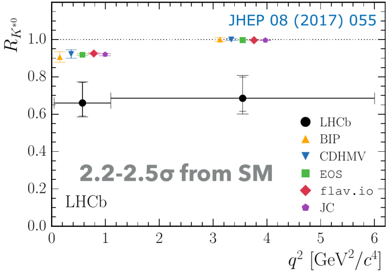


A natural consequence of several LFUV models is LFV in B decays, for example

[Hiller, Loose, Schönwald (2016)]

$$\mathcal{B}(B \to K\mu^{\pm}e^{\mp}) \sim 3 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2, \; \mathcal{B}(B \to K(e^{\pm},\mu^{\pm})\tau^{\mp}) \sim 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)$$

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



LFV experimental status

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

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

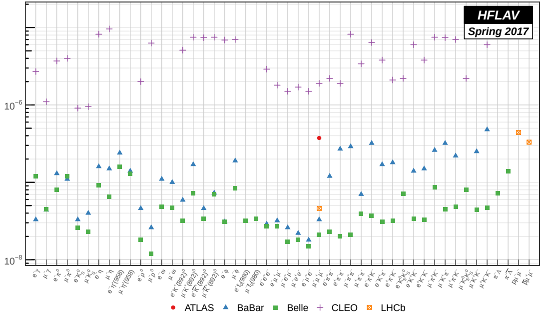
$$\mathcal{B}(Z^0 \to e^\pm \tau^\mp) < 9.8 \times 10^{-6} \quad (@95\%CL)$$

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

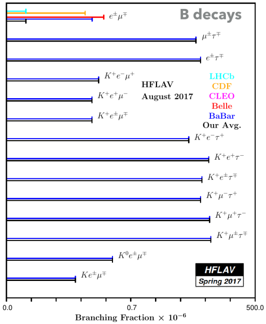
$$\mathcal{B}(H^0 \to \mu\tau) < 0.25\% \quad (@95\%CL)$$

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

90% CL upper limits on τ LFV decays



Limits on Lepton Flavor Violating Decays



In summary no LFV observed to date, only upper limits set

But several BSM models allow LFV just below current limits

LFV searches @ LHCb

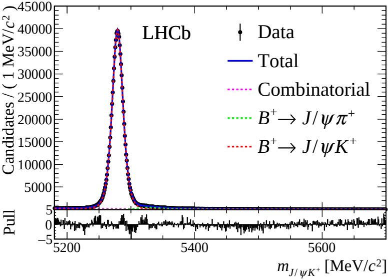
$\tau^- \to p\mu^-\mu^-$	$\mathcal{B} < 4.4 \times 10^{-7}$ @ 90% CL	[Physics Letters B 724 (2013)]
$\tau^- \to \bar{p}\mu^+\mu^-$	$\mathcal{B} < 3.3 \times 10^{-7}$ @ 90% CL	[Physics Letters B 724 (2013)]
$\tau \to \mu\mu\mu$	$\mathcal{B} < 4.7 \times 10^{-8}$ @ 90% CL	[JHEP 02 (2015) 121]
$D^0 \to e^\pm\mu^\mp$	$\mathcal{B} < 1.3 \times 10^{-8}$ @ 90% CL	[Phys. Lett. B754 (2016) 167]
$B^0 \to e^\pm\mu^\mp$	$\mathcal{B} < 1.0 \times 10^{-9}$ @ 90% CL	[JHEP 1803 (2018) 078]
$B_s^0 \to e^\pm\mu^\mp$	$\mathcal{B} < 5.4 \times 10^{-9}$ @ 90% CL	[JHEP 1803 (2018) 078]
$H^0 \to \mu^\pm\tau^\mp$	$\mathcal{B} < 26\%$ @ 95% CL	[arXiv:1808.07135]

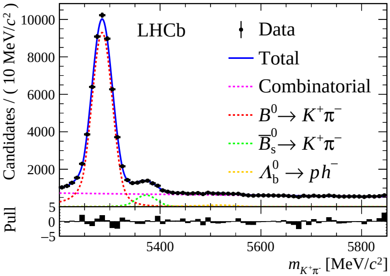
And several others in the pipeline involving all 3 leptons

$$B^0_{(s)} \to e^{\pm}\mu^{\mp}$$

[JHEP 1803 (2018) 078]

- LFV decay forbidden in the Standard Model but can be up to $\mathcal{O}(10^{-11})$ in lepton non-universality scenarios
- Search uses full Run I sample (follows [Phys.Rev.Lett. 111 (2013) 141801] performed with 1 fb^{-1})
- Uses two normalisation channels
  - $B^+ \to J/\psi K^+$ (clean final state)
  - $B^0 \to K^+\pi^-$(same topology as the signal)





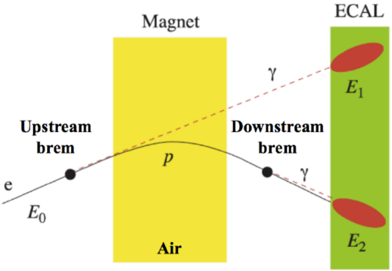
$B^0_{(s)} \to e^\pm \mu^\mp$ [JHEP 1803 (2018) 078]

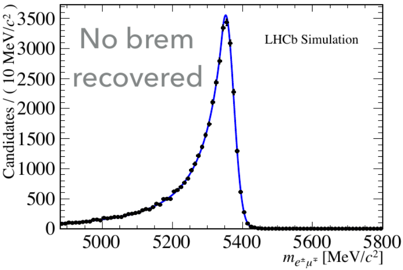
Muon reconstruction

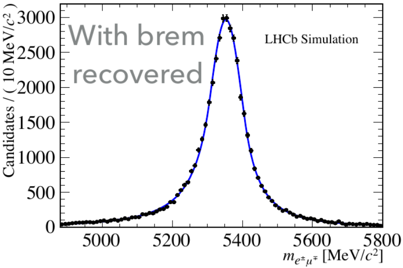
- Extremely performant in LHCb
  - dedicated muon chambers
  - very efficient tracking system
  - clean trigger signature

Electron reconstruction

- Resolution degraded by energy loss from bremsstrahlung

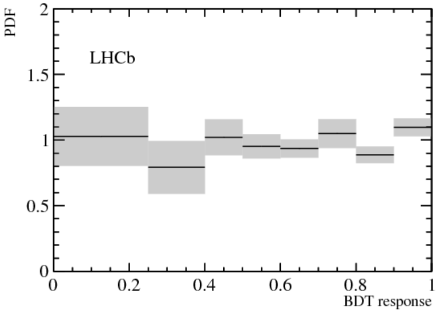




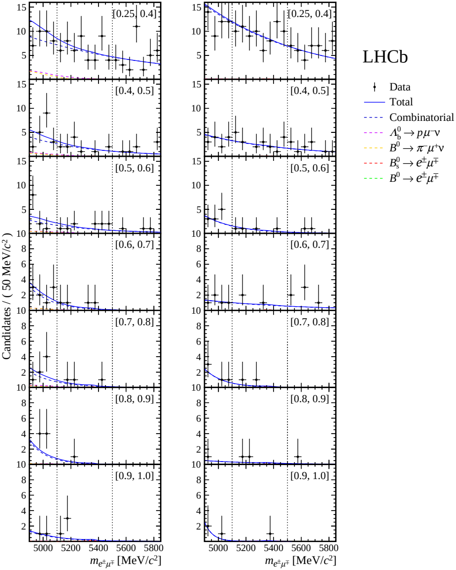


$B^0_{(s)} \to e^\pm \mu^\mp$ [JHEP 1803 (2018) 078]

- Candidates selected with improved BDT (trained with signal MC and same sign $e^\pm \mu^\pm$ background)
- BDT calibrated on $B^0 \to K^+ \pi^-$ to flatten response on signal
  - Smaller systematic for efficiency estimation
- Main background from $B^0_{(s)} \to h^+ h'^-$ with both hadrons misidentified suppressed with PID



$B^0_{(s)} \to e^{\pm}\mu^{\mp}$ [JHEP 1803 (2018) 078]



- Candidates split by number of Bremsstrahlung photons (0 left; $\geqslant 1$ right)
- Simultaneous fit to 7 bins of BDT classifier
- Best World's limits set

$$\mathcal{B}(B_s^0 \to e^{\pm}\mu^{\mp}) < 5.4(6.3) \times 10^{-9} \quad @90\%(95\%)\ \text{C.L.}$$

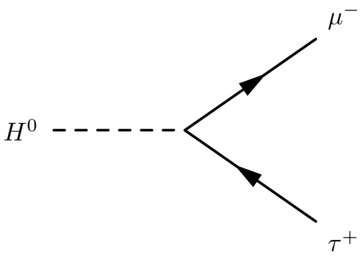
$$\mathcal{B}(B^0 \to e^{\pm}\mu^{\mp}) < 1.0(1.3) \times 10^{-9} \quad @90\%(95\%)\ \text{C.L.}$$

B_s^0 limit assumes only heavy mass eigenstate to contribute

$$H^0 \to \mu^{\pm}\tau^{\mp}$$

[arXiv:1808.07135 submitted to Eur Phys J. C]

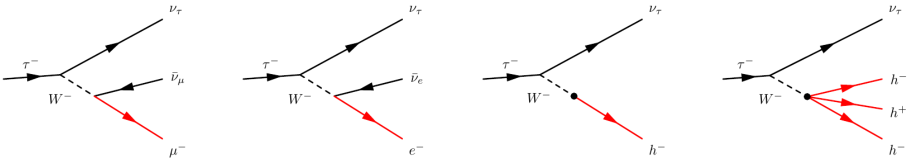
- Aim: Search for LFV decay $H^0 \to \mu^\pm\tau^\mp$ of Higgs-like particle using 2 fb^{-1} at $\sqrt{s} = 8$ TeV
- Built on the experience of the $Z^0 \to \tau^+\tau^-$ analysis [arXiv:1806.05008 submitted to JHEP]
- Higgs mass ranging from 45 to 195 GeV (steps of 10 GeV)



- Final state: hard prompt muon + displaced tau
- Model independent search
- Limits set also by CMS and ATLAS but only for 125 GeV SM Higgs

ATLAS: $\mathcal{B}(H^0 \to \mu^\pm\tau^\mp) < 1.85\%$ @95% CL [JHEP11(2015)211]
CMS: $\mathcal{B}(H^0 \to \mu^\pm\tau^\mp) < 0.25\%$ @95% CL [JHEP 06 (2018) 001]

- τ reconstructed in 4 different final states (for τ_{h1} and τ_{h3} allow also an extra π^0)

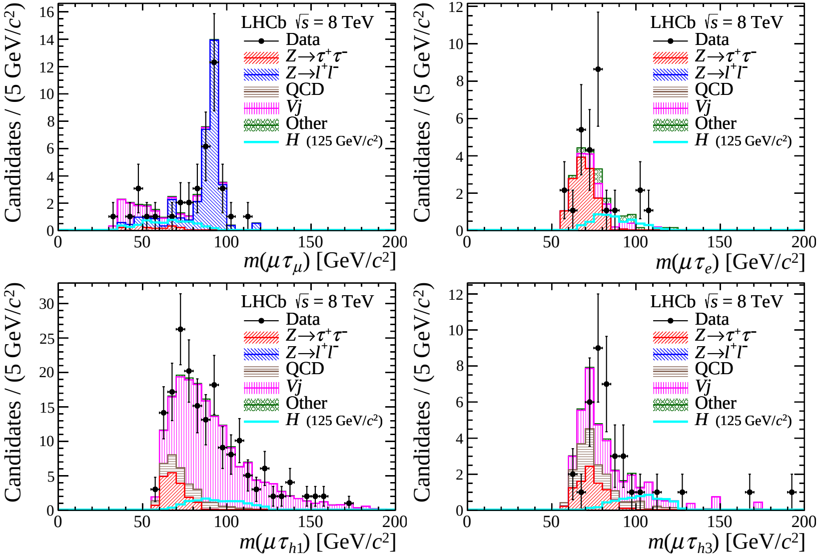


(a) τ_μ, 17.4% **(b)** τ_e, 17.8% **(c)** τ_{h1}, 50.1% **(d)** τ_{h3}, 14.6%

- Correct the mass of τ_{h3} as $m_{corr} = \sqrt{m^2 + p^2 \sin^2\theta} + p\sin\theta$
- Require the τ to be displaced (reconstruct decay vertex for τ_{h3} while rely on IP for the others)
- Exploit isolation variables against QCD
- $A_{p_\mathrm{T}} = |p_{\mathrm{T}\mu} - p_{\mathrm{T}\tau}|/(p_{\mathrm{T}\mu} + p_{\mathrm{T}\tau})$ used against Vj background in $\mu\tau_{h1}$ ($A_{p_\mathrm{T}}(sgn) < A_{p_\mathrm{T}}(Vj)$) and against $Z \to \mu^+\mu^-$ in $\mu\tau_\mu$ ($A_{p_\mathrm{T}}(sgn) > A_{p_\mathrm{T}}(Z \to \mu^+\mu^-)$)

- Three different selections optimised for different $m_{\mu\tau}$ regions: central, higher and lower
  - lower: lower p_{T} cut, more stringent isolation
  - higher: higher p_{T} cut on the muon
- For each mass point evaluate the best selection to use maximising the FOM $\varepsilon_{sel}/(1+\sqrt{N_{obs}})$
  - Three regions obtained (central selection $75-85$ GeV, below the lower one and above the higher one)
- Signal yield obtained from simultaneous extended maximum likelihood fit
  - Signal shape from MC
  - Shapes and normalisations of main backgrounds estimated with data driven methods

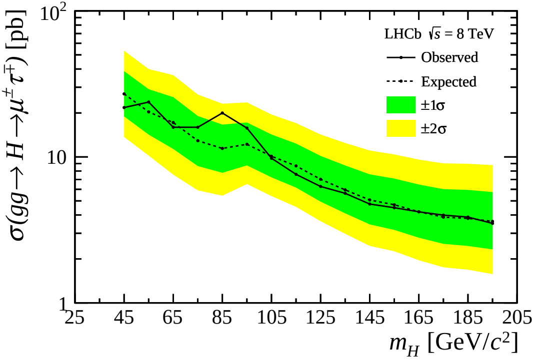
Higher region



$H^0 \to \mu^{\pm}\tau^{\mp}$ [arXiv:1808.07135 submitted to Eur Phys J. C]

Use CLs to set upper limit on product of production cross section and branching fraction

95% CL limit on $\sigma(gg \to H^0 \to \mu^{\pm}\tau^{\mp})$ goes from 22 pb ($m_H = 45$ GeV) to 4 pb ($m_H = 195$ GeV)

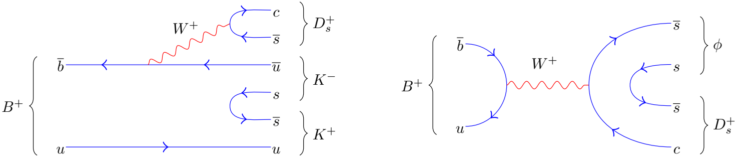


Additionally for SM Higgs at 125 GeV: $\mathcal{B}(H^0 \to \mu^{\pm}\tau^{\mp}) < 26\%$

Other very rare decays

$B^+ \to D_s^+ \phi$ [JHEP 01 (2018) 131]

- Search for pure annihilation decay (large branching fraction possible in New Physics scenarios)
- Update with Run I + Run II dataset ($4.8\ \text{fb}^{-1}$) of previous measurement [JHEP 02(2013) 043] done with $1\ \text{fb}^{-1}$
- Search at the same time for $B^+ \to D_s^+ K^+ K^-$ and $B^+ \to D_s^+ \phi$
- Normalise with $B^+ \to D_s^+ (D^0 \to K^+ K^-)$



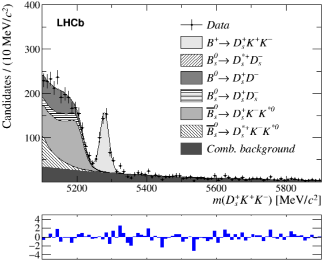
$B^+ \to D_s^+ \phi$ [JHEP 01 (2018) 131]

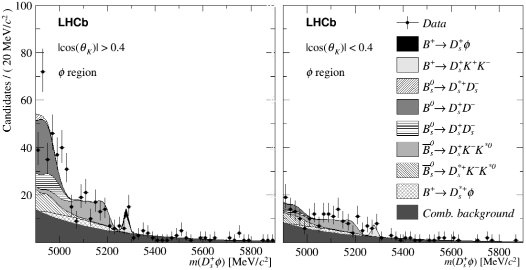
- For $B^+ \to D_s^+ K^+ K^-$ fit phase-space-efficiency-corrected yields

$$\mathcal{B}(B^+ \to D_s^+ K^+ K^-) = (7.1 \pm 0.5\,(\text{stat.}) \pm 0.6\,(\text{syst.}) \pm 0.7\,(\text{norm.})) \times 10^{-6}$$

- Majority of $B^+ \to D_s^+ \phi$ candidates expected in narrow range around ϕ mass and with $|\cos(\theta_K)| > 0.4$
  - simultaneous fit in four regions with different ϕ mass and $\cos(\theta_K)$
- No signal observed and upper limit set

$$\mathcal{B}(B^+ \to D_s^+ \phi) < 4.9 \times 10^{-7}\ @95\%\ \text{C.L.}$$





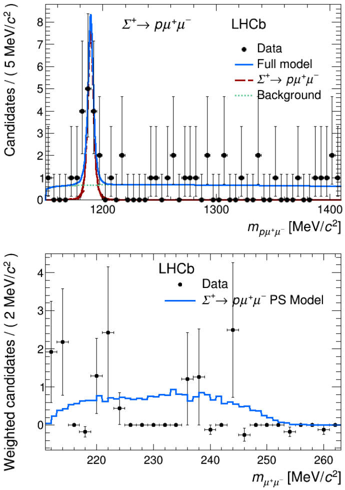
$\Sigma^+ \to p\mu^+\mu^-$ [Phys. Rev. Lett. 120, 221803 (2018)]

- FCNC $s \to dll$ transition
- $1.6 \times 10^{-8} < \mathcal{B}_{SM} < 9.0 \times 10^{-8}$ [He, Tandean, Valencia, PRD '05] dominated by long distance contributions
- Evidence from HyperCP [Phys.Rev.Lett.94:021801,2005]: three candidates with approximately same $\mu^+\mu^-$ mass close to lower kinematic limit (214.3 ± 0.5 MeV)
  - New intermediate particle?

Search on Run I data (3 fb^{-1})

$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$ (4.1σ)

No significant structure observed in $\mu^+\mu^-$ invariant mass distribution



$\Lambda_c^+ \to p\mu^+\mu^-$ [Phys. Rev. D 97, 091101 (2018)]

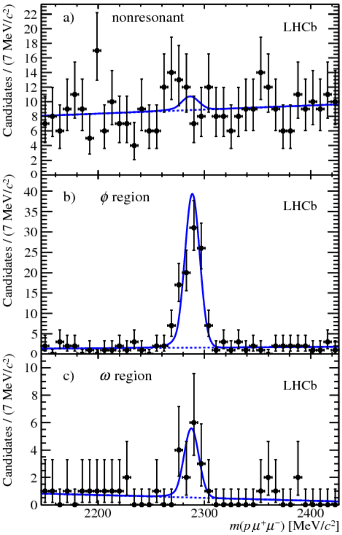
- FCNC $c \to ull$ transition less explored than $b \to sll$
- Short-distance
  $\mathcal{B}_{SM}(\Lambda_c^+ \to p\mu^+\mu^-) \sim 10^{-9}$
- Long-distance
  $\mathcal{B}_{SM}(\Lambda_c^+ \to p(V \to \mu^+\mu^-)$ up to 10^{-6}
- Could be enhanced also by New Physics

Search on Run I data (3 fb^{-1})

- 3 q^2 regions: a) nonresonant, b) ϕ, c) ω
- First observation in the ω region at 5σ

$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.4 \pm 3.2\,(\text{stat.}) \pm 1.0\,(\text{syst.}) \pm 2.0\,(\text{ext.})) \times 10^{-4}$$

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7 \times 10^{-8} \text{ @ } 90\% \text{ C.L.}$$



Conclusion

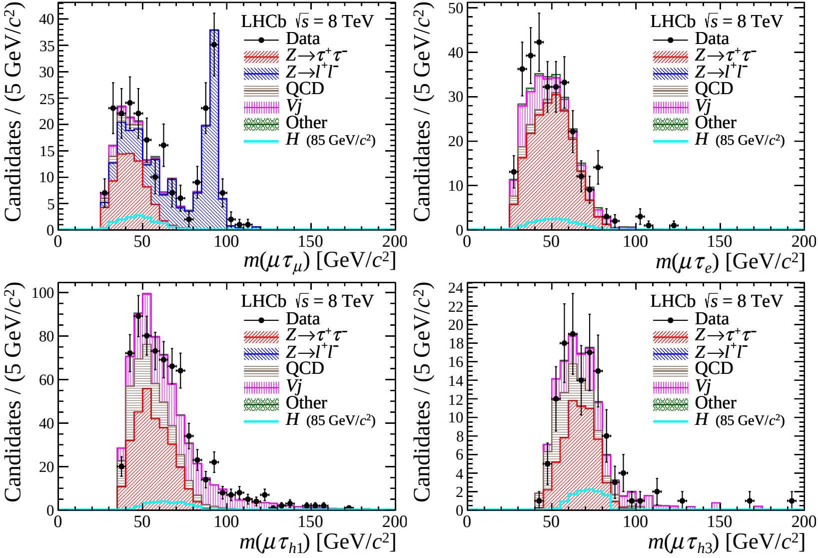
- LFV good place to look for new physics expecially now
- LHCb active player of the field with analyses involving all three leptons and more results to come in the future
  - World's best upper limit on $B^0_{(s)} \to e^\pm \mu^\mp$
  - Search for decay $H^0 \to \mu^\pm \tau^\mp$ of Higgs-like particle in mass range $45 - 195$ GeV
- LHCb active also in search of other very rare decays that also have the potential to uncover new physics
  - Updated limit on pure annihilation decay $B^+ \to D_s^+ \phi$
  - Evidence for $\Sigma^+ \to p\mu^+\mu^-$ but no evidence for intermediate state decaying to $\mu^+\mu^-$
  - First observation of $\Lambda_c^+ \to p\mu^+\mu^-$ in the ω region

BACKUP

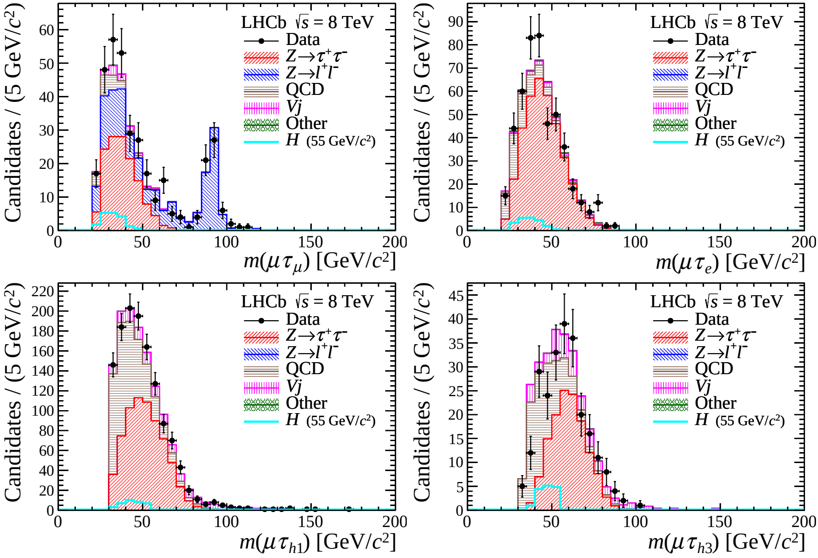
$H^0 \rightarrow \mu^{\pm}\tau^{\mp}$

[arXiv:1808.07135 submitted to Eur Phys J. C]

Central region



Lower region



Selection

Selection set	Variable	$\mu\tau_e$	$\mu\tau_{h\mu\tau_\mu}$ mumu		
All	p_{T} (τ) [GeV/c]	> 5	> 10	> 12	> 5
	$p_{\mathrm{T}}(\tau_{h3}^{\mathrm{prong1}})$ [GeV/c]	—	—	> 1	—
	$p_{\mathrm{T}}(\tau_{h3}^{\mathrm{prong2}})$ [GeV/c]	—	—	> 1	—
	$p_{\mathrm{T}}(\tau_{h3}^{\mathrm{prong3}})$ [GeV/c]	—	—	> 6	—
	$p_{\mathrm{T}}(\mu) - p_{\mathrm{T}}(\tau)$ [GeV/c]	> 0	—	—	—
	m $(\tau_{h\,\mathrm{GeV}/c^2}$]	—	—	0.7–1.5	—
	m_{corr} $(\tau_{h\,\mathrm{GeV}/c^2}$]	—	—	> 3	—
	Time-of-flight $(\tau_{h\,\mathrm{fs}}$]	—	—	> 30	—
	IP(τ) [µm]	> 10	> 10	—	> 50
	IP(μ) [µm]	< 50	< 50	< 50	< 50
	$\Delta\phi$ [rad]	> 2.7	> 2.7	> 2.7	> 2.7
	$\hat{I}_{p_{\mathrm{T}}}$ (τ)	> 0.9	> 0.9	> 0.9	> 0.9
	$\hat{I}_{p_{\mathrm{T}}}$ (μ)	> 0.9	> 0.9	> 0.9	> 0.9
L-selection	p_{T} (μ) [GeV/c]	> 20	> 20	> 20	> 20
	$A_{p_{\mathrm{T}}}$	< 0.6	< 0.4	—	> 0.3
	$I_{p_{\mathrm{T}}}$ (τ) [GeV/c]	< 2	< 2	< 2	< 2
	$I_{p_{\mathrm{T}}}$ (μ) [GeV/c]	< 2	< 2	< 2	< 2
C-selection	p_{T} (μ) [GeV/c]	> 30	> 30	> 30	> 30
	$A_{p_{\mathrm{T}}}$	—	< 0.5	—	> 0.3
H-selection	p_{T} (τ) [GeV/c]	> 20	> 20	> 20	—
	p_{T} (μ) [GeV/c]	> 40	> 40	> 40	> 50
	$A_{p_{\mathrm{T}}}$	—	—	—	> 0.4

Systematics

	$\mu\tau_e$	$\mu\tau_{h\mu\tau_\mu}$ mumu		
Luminosity	1.16	1.16	1.16	1.16
Tau branching fraction	0.22	0.18	0.48	0.23
PDF	2.6–7.1	3.5–7.2	2.6–7.3	3.0–7.9
Scales	0.9–1.9	0.8–1.7	0.9–1.7	0.9–1.9
Reconstruction efficiency	1.8–3.6	1.9–5.4	3.3–7.1	1.5–3.3
Selection efficiency	2.5–6.0	1.9–4.1	4.0–9.3	3.8–8.5

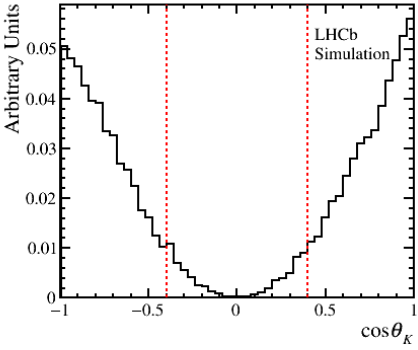
Backgrounds

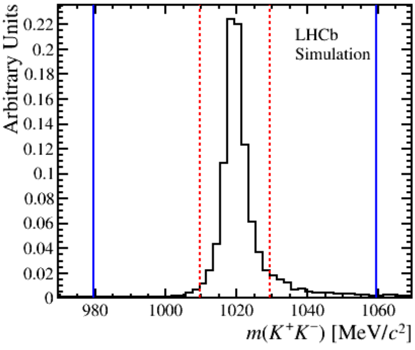
Table 1: DD = using data-driven method, MC = from simulation

Process	Normalization	Note
$Z \to \tau\tau$	DD + MC	Use $N = \sigma\mathcal{L}\varepsilon$.
$Z \to ll$	DD	Use prompt dimuon peak [80,100] GeV/c^2 as control. Use data-validated mis-ID rate.
QCD	DD	Use same-sign candidates as control.
Vj	DD	Use same-sign candidates as control.
$t\bar{t}$,VV, $Z \to b\bar{b}$	MC	Small, use $N = \sigma\mathcal{L}\varepsilon$

$B^+ \to D_s^+ \phi$

[JHEP 01 (2018) 131]





$\lvert m(K^+K^-) - m_\phi \rvert$ (MeV/c^2)	Helicity Category	
	$\lvert\cos\theta_K\rvert > 0.4$	$\lvert\cos\theta_K\rvert < 0.4$
< 10	82%	6%
(10, 40)	11%	1%

$B^+ \to D_s^+ \phi$

[JHEP 01 (2018) 131]