LFV in Tau Decays: Results and Prospects at the LHC

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On behalf of the ATLAS, CMS & LHCb Collaborations

Tau 2016

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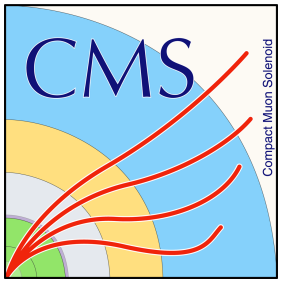
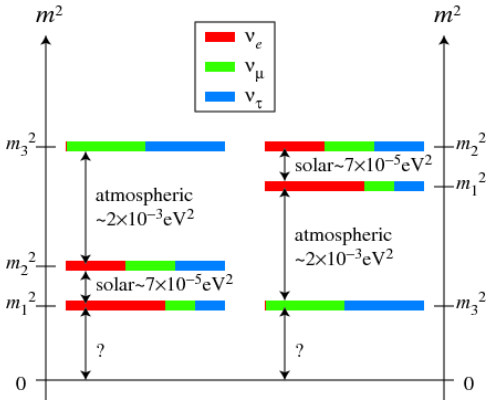


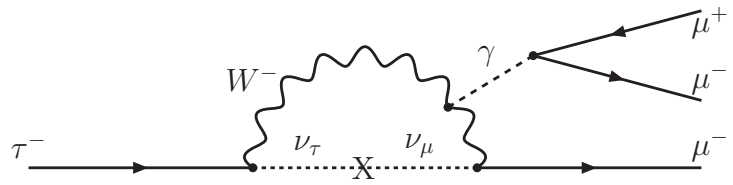
Charged Lepton Flavour Violation

Neutrino Oscillation

Neutrino Masses



Lepton Flavour Violation

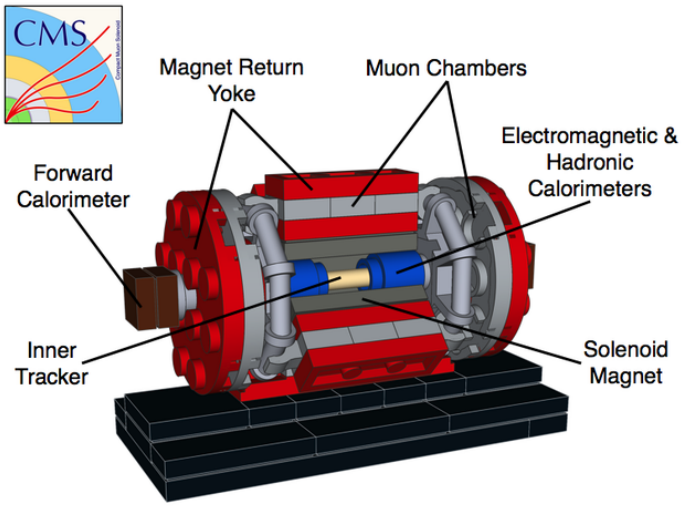


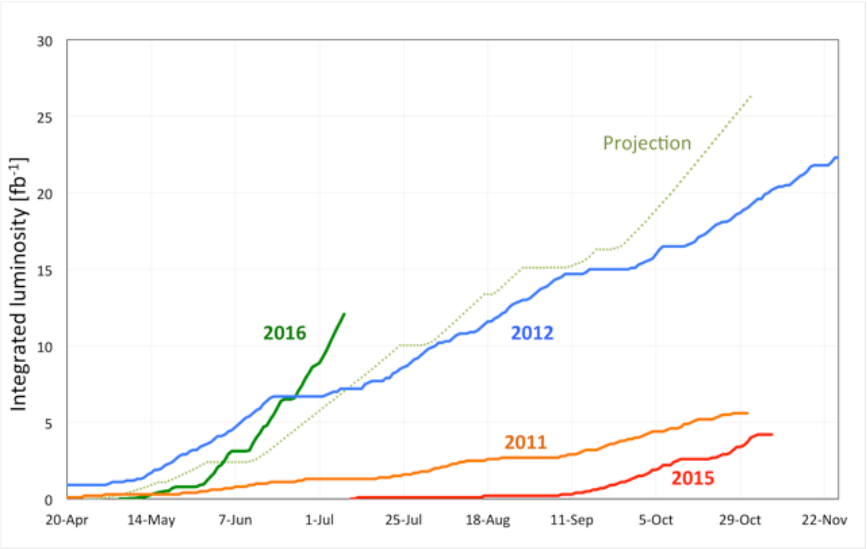
- Loop suppressed
- $\mathcal{B} \propto (m_\nu / m_W)^4 \to \mathcal{O}(10^{-40})$

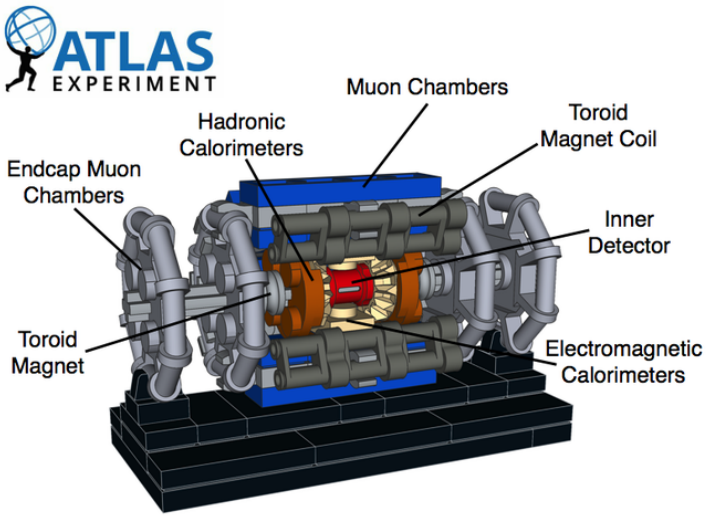
- Ideal playground to search for Beyond the SM physics
- Many BSM models with TeV scale new physics predict rates within reach of current experiments.

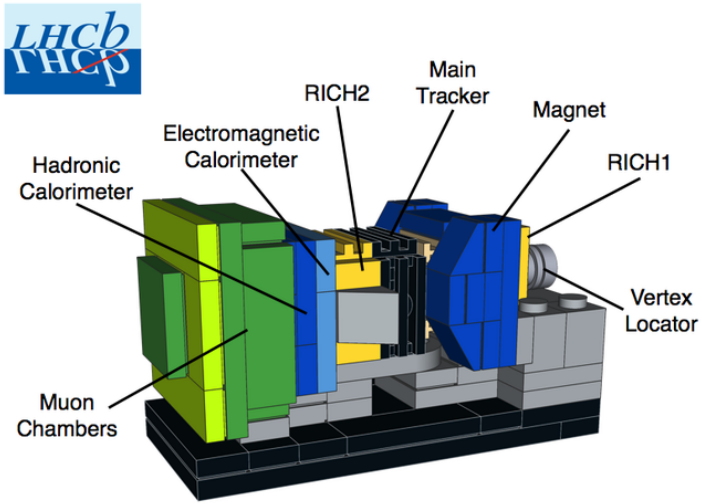
$\to$ Is there a counterpart in the charged lepton sector?

LHC Experiments









Overview

This Talk

1. $\tau^- \to \mu^-\mu^+\mu^-$
2. $Z^0 \to \tau^\pm\mu^\mp$
3. $D^0 \to e^\pm\mu^\mp$

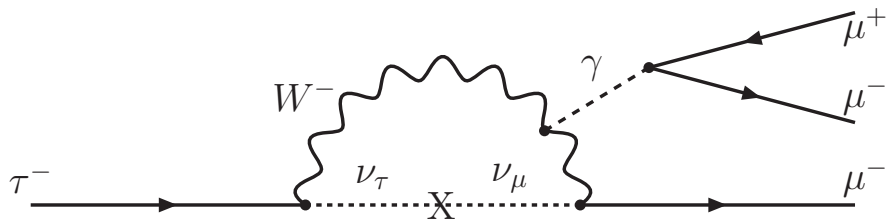
Other LHC Results

- $H \to \tau^\pm\mu^\mp$ — See preceding ATLAS & CMS Talks
- $H \to \tau^\pm e^\mp$ — See preceding ATLAS & CMS Talks
- $Z \to e^\pm\mu^\mp$ — ATLAS, PRD 90 (2014) 072010, arxiv:1408.5774
- $\tau^- \to p\mu^-\mu^-$ — LHCb, PLB 724 (2013), arxiv:1304.4518
- $B^0_{(s)} \to e^\pm\mu^\mp$ — LHCb, PRL 111 (2013) 141801, arxiv:1307.4889

$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$ @ ATLAS & LHCb

Neutrino-less τ Decay

- Strongly suppressed in the Standard Model



- Can be enhanced by new physics at tree level (Z', . . .) or loops (SUSY, . . .)
- Current best limit:

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \times 10^{-8} \quad @\,90\%\ \text{C.L.}$$

Belle, PLB 687 (2010) 139, arxiv:1001.3221

Experimental Signature

→ No missing energy in τ decay

- Three muons with invariant mass $m_{3\mu} \approx m_\tau$
- Displaced vertex

ATLAS: Strategy

ATLAS, EPJC 76 (2016) 232, arxiv:1601.03567

- Analysis based on 20.3 fb^{-1} of data, collected at 8 TeV in 2012

Experimental Setup

- Uses $W^- \to \tau^-\bar{\nu}_\tau$ decays (highest efficiency for trigger & reconstruction)

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \frac{N_{\text{sig}}}{\epsilon_{\text{sig}} \times \sigma_{W^- \to \tau^-\bar{\nu}_\tau} \times \mathcal{L}}$$

- N_{sig} = signal yield, ϵ_{sig} = selection efficiency, σ = cross section, $\mathcal{L}$ = luminosity
- Relies on the $W^- \to \ell^-\bar{\nu}$ cross-section measurement

ATLAS, PRD 85 (2012) 072004, arxiv:1109.5141

- Estimate about $(2.41 \pm 0.08) \times 10^8$ τ's produced
- Contamination from other sources ($Z^0 \to \tau^+\tau^-$, heavy flavour) is less than 3%

ATLAS: Strategy

ATLAS, EPJC 76 (2016) 232, arxiv:1601.03567

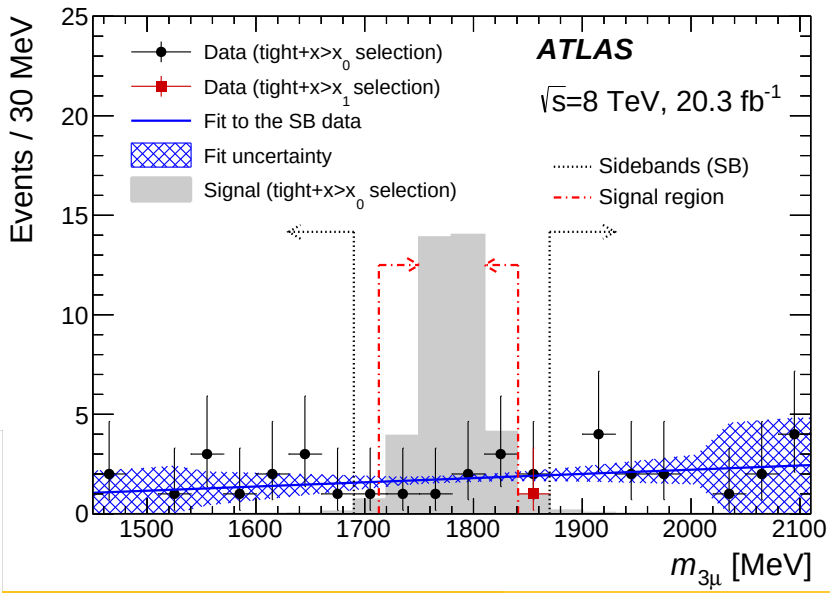
Selection

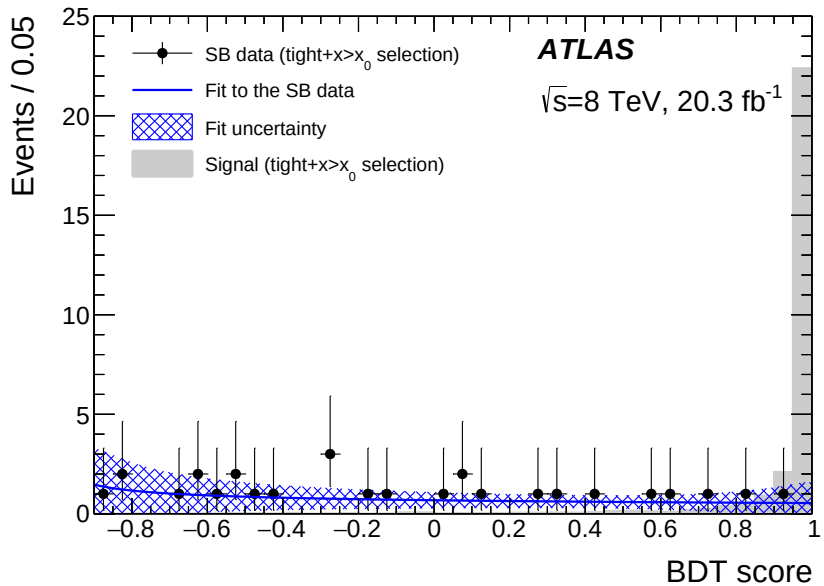
1. Cut-based *loose* selection
2. Train Boosted Decision Tree and apply loose cut x_0 on BDT output x
3. Cut-based *tight* selection
4. Apply tight cut x_1 on BDT output, optimising for the expected $\mathcal{B}$ limit

Fit Strategy

- Blinded analysis: ignore signal region: $m_{3\mu} \in [1713, 1841]\,\mathrm{MeV}/c^2$

1. Estimate background yield from mass sidebands using "tight + $x > x_0$"
2. Fit BDT output in region $x > x_0$
3. Extrapolate background yield for "tight + $x > x_1$"





ATLAS: Results

ATLAS, EPJC 76 (2016) 232, arxiv:1601.03567

Unblinding

- No events found in signal region
- Expected background $N_{\text{bkg}} = 0.193 \pm 0.037\,(\text{stat}) \pm 0.131\,(\text{syst})$
  (dominant uncertainty = extrapolation procedure)
- Efficiency $\epsilon_{\text{sig}} = 0.0231 \pm 0.0005\,(\text{Jet}) \pm 0.0009\,(\text{MC}) \pm 0.0025\,(\text{trig}) \pm 0.0030\,(\text{reco})$
- Limit:

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.76 \times 10^{-7} \quad @\,90\%\ \text{C.L.}$$

Outlook

- Not competitive with results from B-factories or LHCb
- Demonstrates ATLAS' potential for LFV searches
- Helped improve muon trigger and reconstruction of "low-p_T" muons (4 – 18 GeV/c)

LHCb: Strategy

LHCb, JHEP 02 (2015) 121, arxiv:1409.8548

- Analysis based on $3\,\text{fb}^{-1}$ of data (full Run 1)

Experimental Setup

- τ originate from b and c-hadron decays
- Normalisation mode: $D_s^- \to \phi(\to \mu^+\mu^-)\pi^-$

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \frac{\mathcal{B}(D_s^- \to \phi(\to \mu^+\mu^-)\pi^-)}{\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)} \times f_\tau^{D_s} \times \frac{\epsilon_{\text{cal}}}{\epsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{cal}}} = \alpha \times N_{\text{sig}}$$

- N_{sig} = signal yield, N_{cal} = yield of calibration mode, ϵ = selection efficiency
- $f_\tau^{D_s} = 0.80 \pm 0.03$ is the fraction of τ that originates from D_s mesons

→ Input: $b\bar{b}$, $c\bar{c}$ cross-sections LHCb, NPB 871 (2013), arxiv:1302.2864

→ Input: inclusive $b \to D_s$, $c \to D_s$, $b \to \tau$ and $c \to \tau$ branching fractions

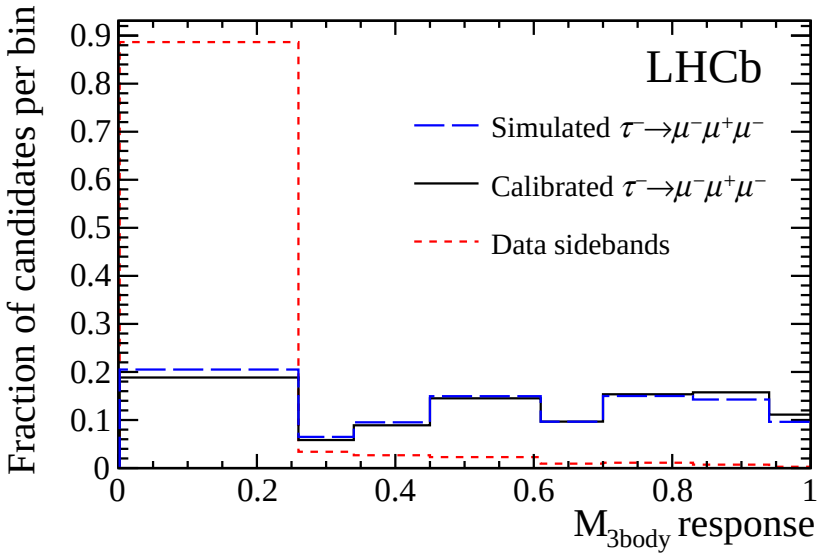
- Normalisation factor:
  $\alpha(7\text{ TeV}) = (7.20 \pm 0.98) \times 10^{-9}$ $\alpha(8\text{ TeV}) = (3.37 \pm 0.50) \times 10^{-9}$
  Different trigger: $p_T(\mu) > 1.48$ GeV/c (2011) vs $p_T(\mu) > 1.76$ GeV/c (2012)
- Corresponds to about 8.5 to 9×10^{10} τ's produced

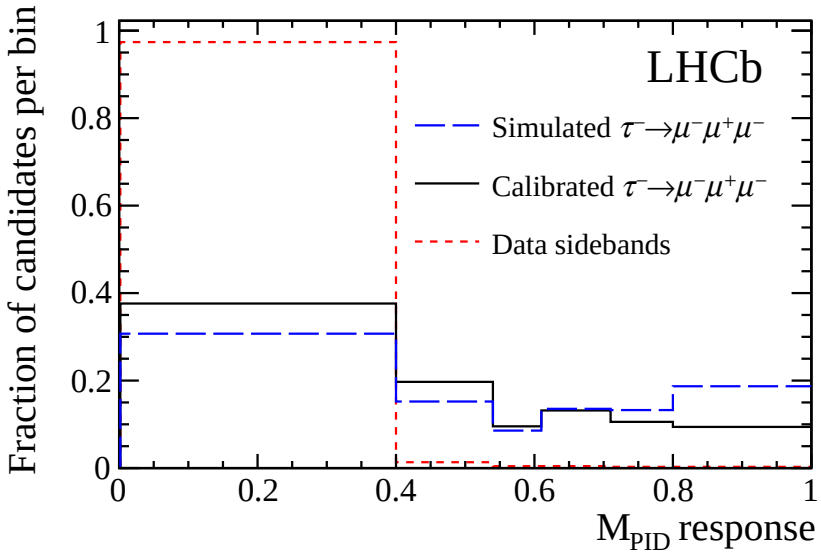
LHCb: Strategy

LHCb, JHEP 02 (2015) 121, arxiv:1409.8548

Selection

- Cut-based loose selection
- Three likelihoods to distinguish signal from background
  1. MVA exploiting the geometrical properties $\mathcal{M}_{\text{3body}}$
  2. Neural Network for muon particle identification $\mathcal{M}_{\text{PID}}$
  3. Invariant mass $m_{3\mu}$ of three muons



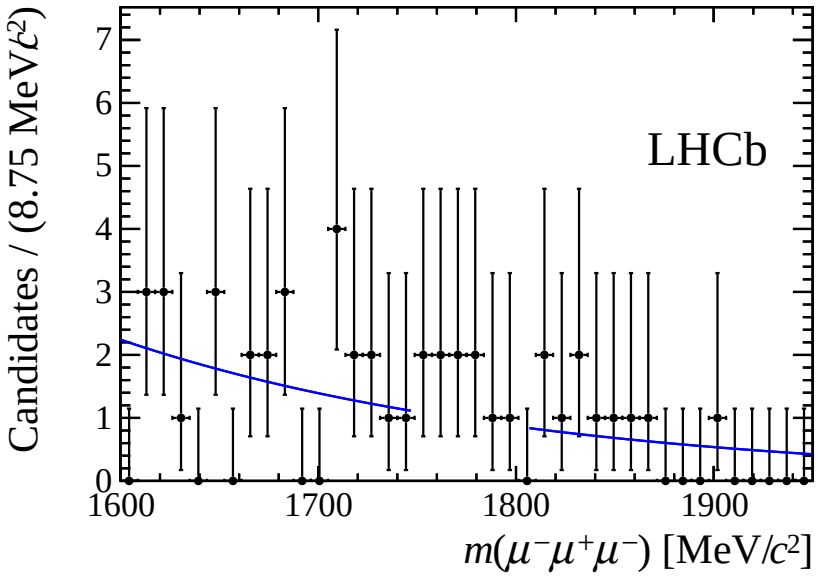


Fit Strategy

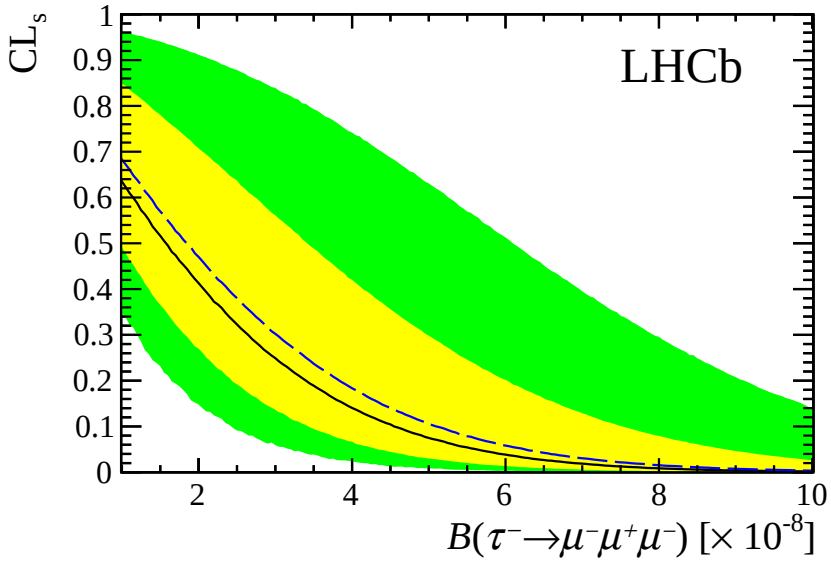
- Fit invariant mass in each bin of $\mathcal{M}_{\text{3body}} \times \mathcal{M}_{\text{PID}}$
- Blinded analysis: ignore signal region: $(m_\tau \pm 30)\,\text{MeV}/c^2$

LHCb: Results

LHCb, JHEP 02 (2015) 121, arxiv:1409.8548



dashed: expected – solid: observed



- All bins consistent with background-only hypothesis
- Limit:

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

Outlook

- Still factor 2.5 worse than Belle
- Run 2: Might overtake Belle ...
- ... and be overtaken again by Belle II

$Z^0 \to \tau^\pm\mu^\mp$ @ ATLAS

ATLAS: Strategy

ATLAS, arxiv:1604.07730

- Analysis based on 20.3 fb^{-1} of data, collected at 8 TeV in 2012

Experimental Setup

- Reconstructed in $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ mode

- Background decomposition
  - $W+$ jets (using dedicated control region)
  - $Z^0 \to \tau^+\tau^-$ (modelled using $Z^0 \to \mu^+\mu^-$)
  - Combinatorial bkg (taken from same-sign data)

$\to$ Adopt data-driven techniques to control them

- Analysis strategy similar to $H \to \mu^\pm\tau^\mp_{\text{had}}$ ATLAS, JHEP 1511 (2015) 211, arxiv:1508.03372
- But larger contribution from $W+$ jets

$\to$ More detailed study of this component

ATLAS: Strategy

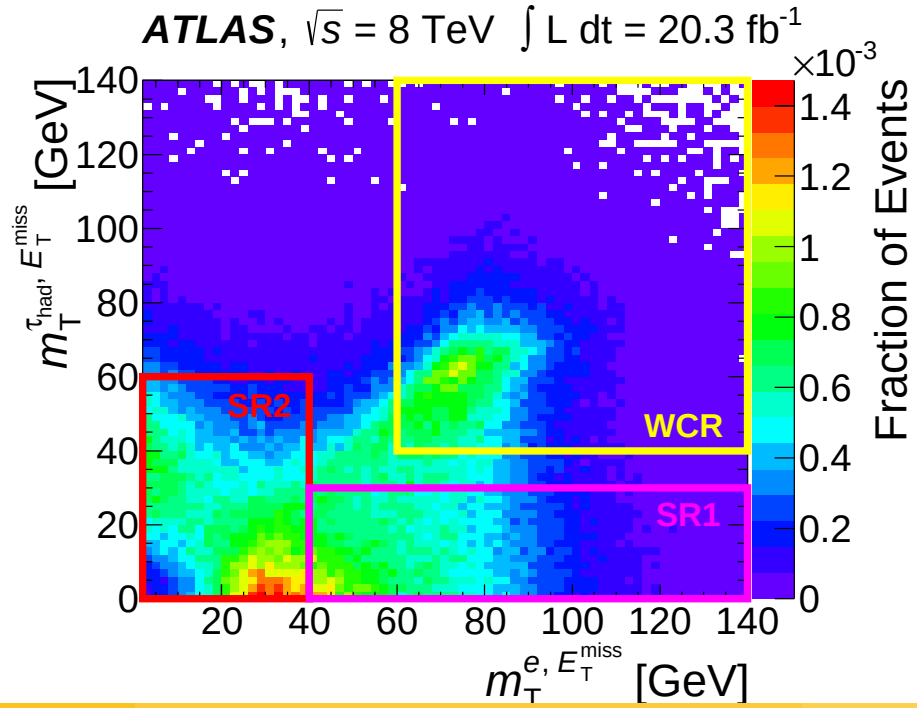
ATLAS, arxiv:1604.07730

Fit Strategy:

- Combined analysis of signal region + control regions
  - Two signal search windows: SR1 & SR2
  - Control region for the modelling of $W+$ jets (WCR) background
  - Control region for $t\bar{t}$ events (normalisation)
- Regions defined in terms of the *transverse mass*

$$m_{\mathrm{T}}^{\ell,E_{\mathrm{T}}^{\mathrm{miss}}} \equiv \sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\Delta\phi)}$$

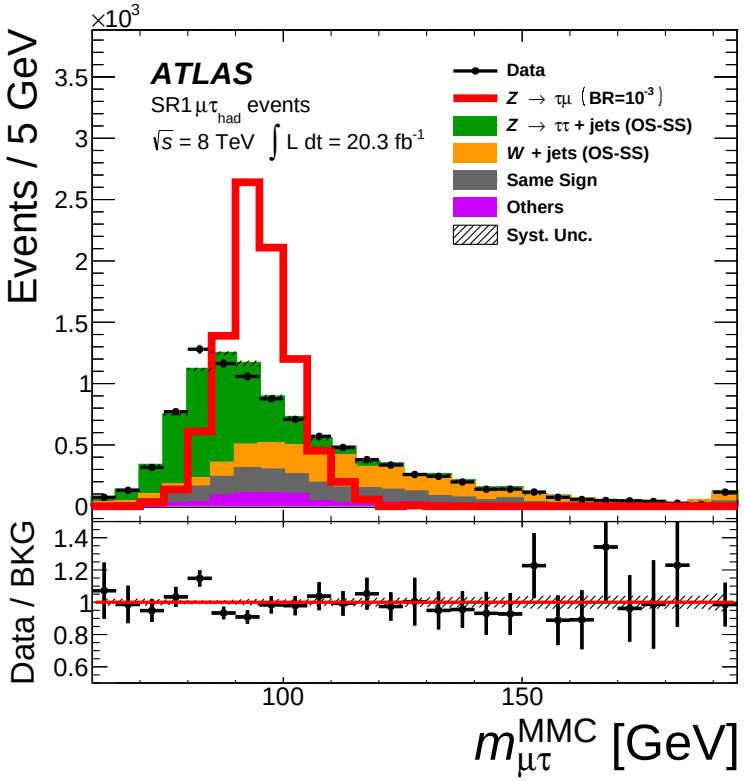
with $\Delta\phi$ angle between ℓ and the direction of $E_{\mathrm{T}}^{\mathrm{miss}}$



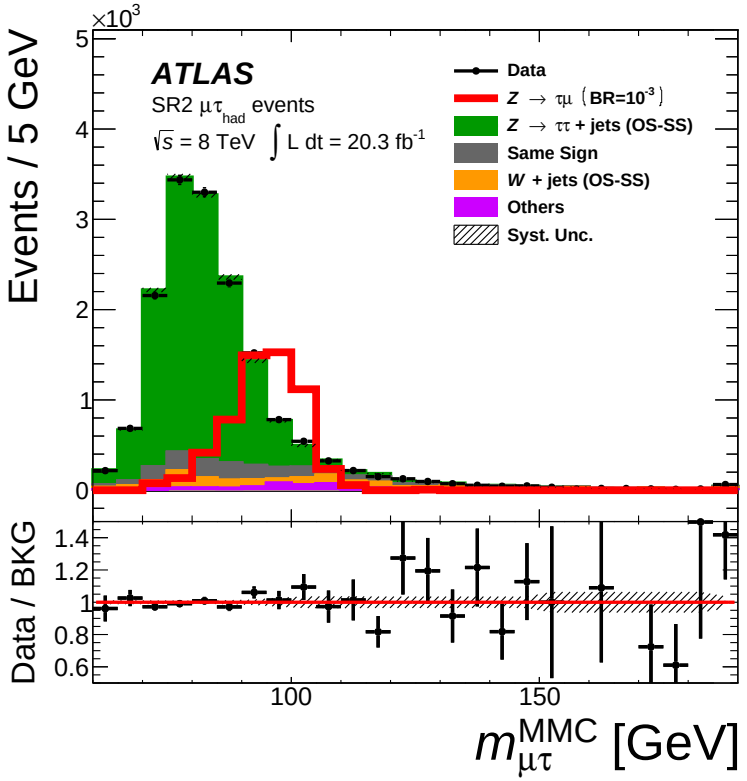
ATLAS: Results

ATLAS, arxiv:1604.07730

Signal Region 1



Signal Region 2



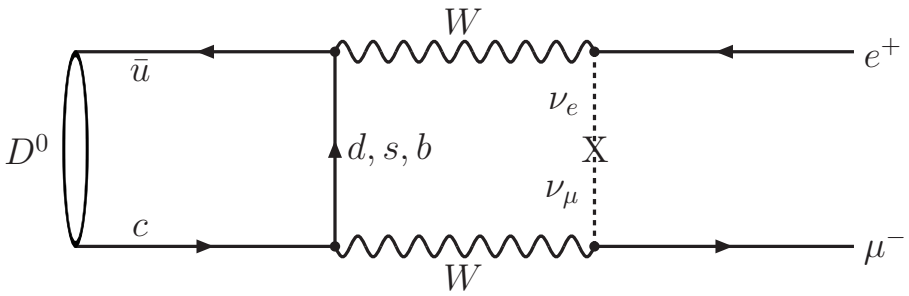
- Small deficit compared to background expectation
- Limit:

$$\mathcal{B}(Z \to \tau^\pm \mu^\mp) < 1.69 \times 10^{-5} \quad @\ 95\%\ \text{C.L.}$$

$D^0 \to e^\pm\mu^\mp$ @ LHCb

Forbidden Decay

- Strongly suppressed in the Standard Model



- Enhanced in many beyond the SM theories:
  - SUSY with R-parity violation: $\mathcal{O}(10^{-6})$
  - Leptoquarks: $\approx 4 \times 10^{-8}$
  - Multiple Higgs doublets: $\approx 7 \times 10^{-10}$
- Previous best limit:

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 2.6 \times 10^{-7} \quad @\ 90\%\ \text{C.L.}$$

Belle, PRD 81 (2010) 091102, arxiv:1003.2345

LHCb: Strategy

LHCb, PLB 754 (2016) 167, arxiv:1512.00322

- Analysis based on $3\,\text{fb}^{-1}$ of data (full Run 1)

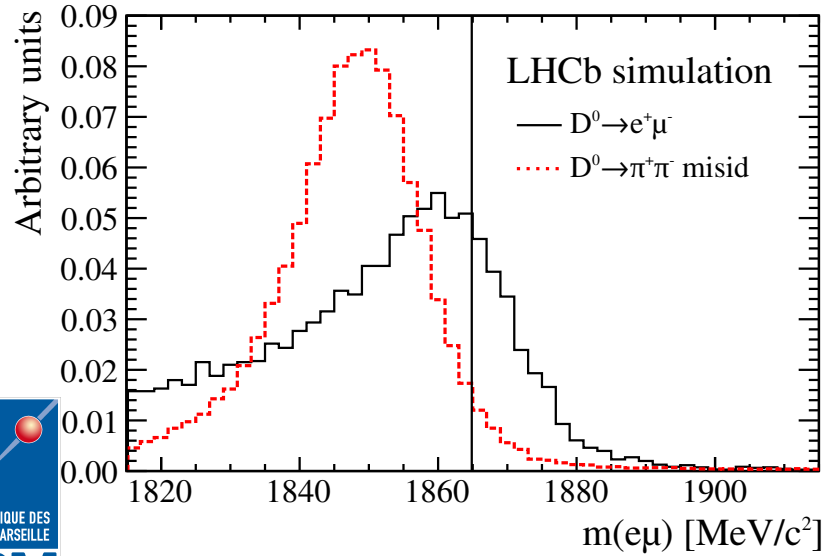
Experimental Setup

- Candidates selected from $D^{*+} \to D^0\pi^+$ decays
- Normalisation mode: $D^0 \to K^-\pi^+$

$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) = \mathcal{B}(D^0 \to K^-\pi^+) \times \frac{\epsilon_{\text{cal}}}{\epsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{cal}}}$$

- N_{sig} = signal yield, N_{cal} = yield of calibration mode, ϵ = selection efficiency
- Efficiencies: $\epsilon_{\text{sig}} = (4.4 \pm 0.3) \times 10^{-4}$ $\epsilon_{\text{cal}} = (2.5 \pm 0.1) \times 10^{-6}$

→ Difference: keep only 1% of triggered $D^0 \to K^-\pi^+$ events



Backgrounds

- Main background: misID-ed $D^0 \to \pi^+\pi^-$

→ Probability $[\pi\pi \to e\mu] = (1.8 \pm 0.4) \times 10^{-8}$

- $\mathcal{B}(D^0 \to \pi^+\pi^-) = (1.421 \pm 0.025) \times 10^{-3}$
- Electron momentum corrected for bremsstrahlung losses (→ Tails)

LHCb: Strategy

LHCb, PLB 754 (2016) 167, arxiv:1512.00322

Fit Strategy

- Cut-based + BDT selection $\to$ divide data in 3 bins
- Simultaneous fit to m_{D^0} and $\Delta m = m_{D^{*+}} - m_{D^0}$
- Legend: $D^0 \to e^\pm\mu^\mp$ $D^0 \to \pi^+\pi^-$ Dashed: Combinatorial Bkg

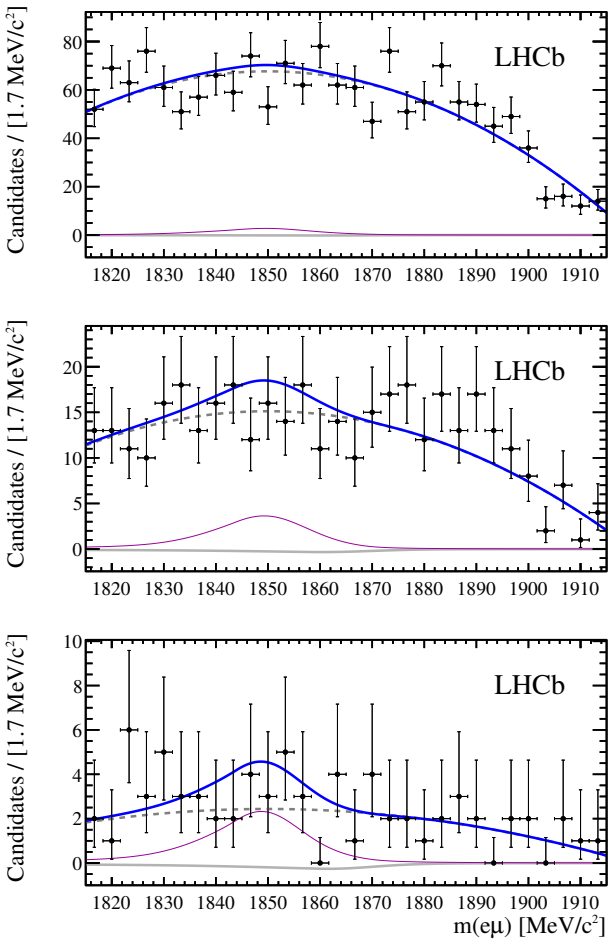
Most Bkg-like

$\uparrow$

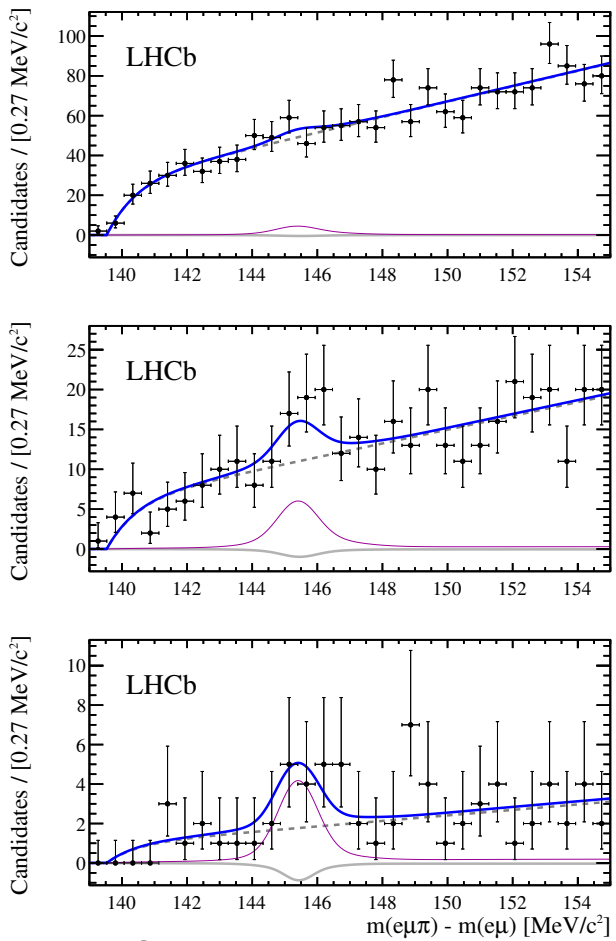
Intermediate

$\downarrow$

Most Sig-like



m_{D^0}

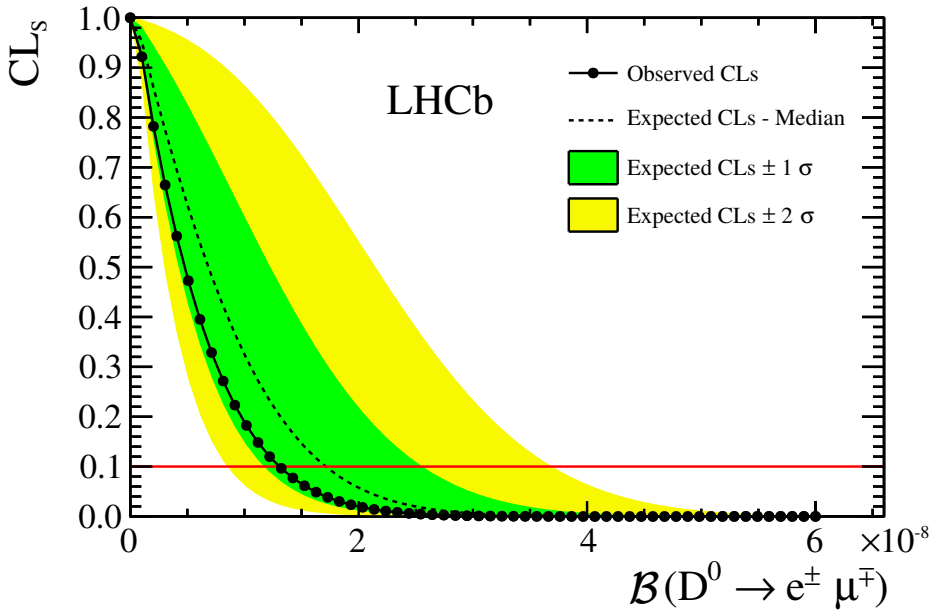


$\Delta m = m_{D^{*+}} - m_{D^0}$

LHCb: Results

LHCb, PLB 754 (2016) 167, arxiv:1512.00322

- Simultaneous fit to the 3 BDT bins gives: $N_{\text{sig}} = -7 \pm 15$



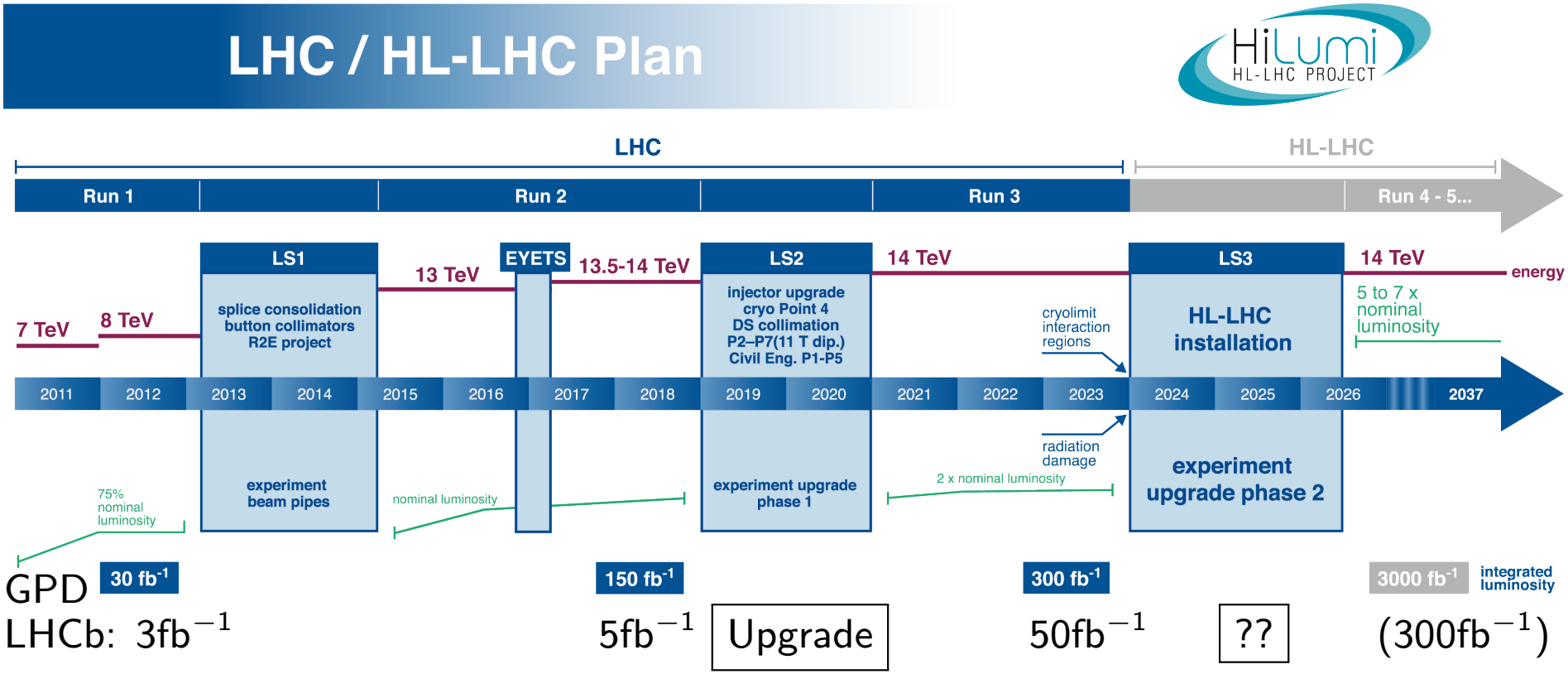
- Limit:

$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3 \times 10^{-8} \quad @\ 90\%\ \text{C.L.}$$

- Factor 20 improvement over Belle

Prospects for LHC Run 2 and Beyond

LHC Run 2 and Beyond



GPD LHCb: 3fb^{-1} | 5fb^{-1} Upgrade | 50fb^{-1} ?? | (300fb^{-1})

Prospects for LHC Run 2 and Beyond

Ambitious Plans:

- Sensitivities strongly depend on trigger settings
- These depend on pile-up, available bandwidth, ...
- Difficult to predict $\Rightarrow$ no official numbers!

ATLAS:
- Added *insertable B layer* in 2014, for improved tracking
- Improved trigger and reconstruction for "low-p_T" muons
- Aim for result on $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$ with Run 2 data that is competitive with LHCb and/or Belle II

CMS:
- Will replace the inner tracker during EYETS 2016/17 (extra layer)
- Beneficial for B-physics programme
- Plans to study $\tau^- \to \mu^-\mu^+\mu^-$ with the future upgrade

LHCb:
- Aim for a limit on $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$ of $\mathcal{O}(10^{-9})$ – $\mathcal{O}(10^{-10})$ with Run 2 data, may be competitive with Belle II

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Conclusion

- ATLAS limit on the $\tau^- \to \mu^-\mu^+\mu^-$ branching ratio

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.76 \times 10^{-7} \quad @\,90\%\ \text{C.L.}$$

- LHCb limit on the $\tau^- \to \mu^-\mu^+\mu^-$ branching ratio

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

- ATLAS limit on the $Z^0 \to \tau^\pm\mu^\mp$ branching ratio

$$\mathcal{B}(Z \to \tau^\pm\mu^\mp) < 1.69 \times 10^{-5} \quad @\,95\%\ \text{C.L.}$$

- LHCb limit on the $D^0 \to e^\pm\mu^\mp$ branching ratio

$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3 \times 10^{-8} \quad @\,90\%\ \text{C.L.}$$

- Decays involving τ's play an important role in searches for charged lepton flavour violation

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