Lepton flavour and lepton universality violation at LHCb

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on behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects
CERN , 3-5th November 2015

Lepton flavour and lepton universality violation at LHCb

- An increasing number of experimental 'anomalies' hint at the possibility for New Physics (NP)
- Measurements of lepton flavour violation (LFV) and lepton universality violation (LUV) are closely related in many NP models
- LHCb's capabilities allow us to constrain a number of the final states of interest
  $\rightarrow$ worthwhile to explore all the options
- Will present today a selection of current and upcoming results

Search for the lepton-flavour violating decay $D^0 \to e^\pm \mu^\mp$

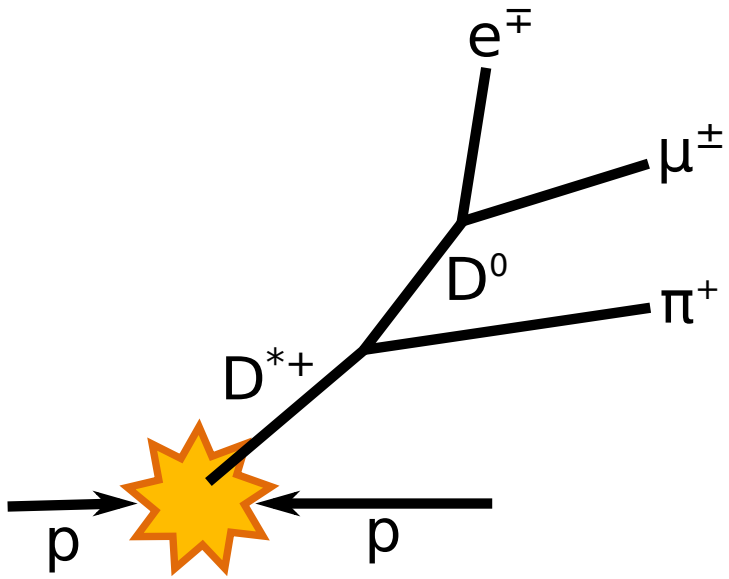
- LFV decay $D^0 \to e^\pm \mu^\mp$ is forbidden in the SM with contributions from neutrino oscillations well below the reach of any currently feasible experiment
- Predicted in a range of NP models, such as MSSM with $\mathcal{R}$-parity violation, multiple Higgs doublets, SM with extra fermions
- Predictions vary by 8 orders of magnitude depending on the model
- Limits on $D_s^+ \to K^+ e^\pm \mu^\mp$ and $D^+ \to \pi^+ e^\pm \mu^\mp$ suggest[1,2] $\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 10^{-7} - 10^{-8}$
- Previous world's best limit from Belle of 2.6×10^{-7} at 90% CL[3]
- Improving the limit would help constrain RPV SUSY models

[1] F. Tahir, A. Mir and S. Mahmood, Chin. Phys. C38 (2014) 123101
[2] R. M. Wang *et al.*, Int. J. Mod. Phys. A29 (2014) 1450169
[3] M. Petric *et al.*, Phys. Rev. D81 (2010) 091102

$D^0 \to e^\pm \mu^\mp$: Strategy

LHCb-PAPER-2015-048

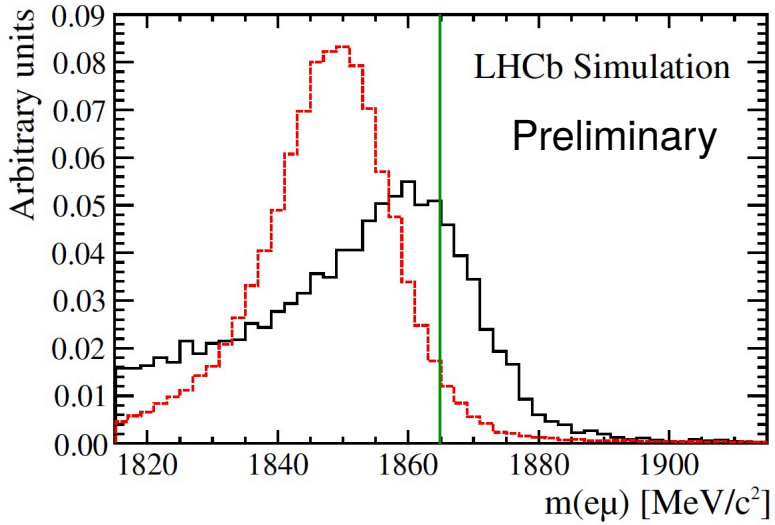
- Select $D^{*+} \to D^0\pi^+$ decays from 3.0 fb^{-1} data collected at 7 and 8 TeV
- Analysis is normalised to $D^0 \to K^-\pi^+$ and performed blind



- Separate signal and background via geometric and isolation based BDT trained on data sidebands and simulated signal
- Split data into 3 bins of BDT output and perform a simultaneous fit to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$
- Efficiencies from simulation and control samples of $J/\psi \to l^+l^-$ and $D^{*+} \to D^0(K^-\pi^+)\pi^+$

$D^0 \to e^\pm \mu^\mp$: Backgrounds and systematics

- $D^0 \to \pi^+\pi^-$ dominant background at the 10^{-8} level
- Also account for combinatorial background including $D^0 \to \pi^+ e^- \overline{\nu}_e$ and $D^0 \to \pi^+ \mu^- \overline{\nu}_\mu$
- $D^0 \to K^-\pi^+$ contribution is found to be negligible



$D^0 \to \pi^+\pi^-$ and $D^0 \to e^+\mu^-$ reconstructed as $e^+\mu^-$

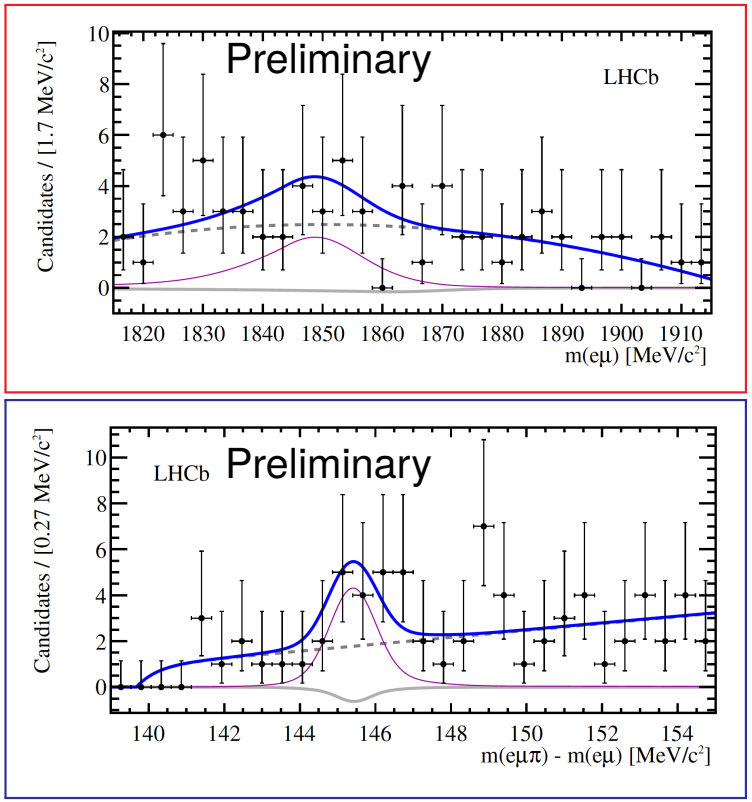
- Systematics from selection efficiencies, particle identification, bin migration, normalisation and PDF shape uncertainties
- Fit model tested with $B^+ \to J/\psi(e^+e^-)K^+$ events in data and MC
- Bin migration tested with $D^0 \to e^\pm\mu^\mp$, simulated $D^0 \to \pi^+\pi^-$ and $D^0 \to \pi^+\pi^-$ in data

$D^0 \to e^\pm \mu^\mp$: Fit model

➜ Signal PDF reweighted in three bins of track multiplicity to account for differences in bremsstrahlung, with a simultaneous fit to the full decay chain to improve mass resolution

1) Signal $m(D^0)$: Double Crystal Ball, second order polynomial for combinatorial background
2) Signal Δm: Triple Gaussian plus combinatorial background function
3) Norm $m(D^0)$: Double Gaussian
4) Norm Δm: Triple Gaussian plus combinatorial background function

➜ $D^0 \to \pi^+\pi^-$ background PDF from data with the same model



Most signal-like bins

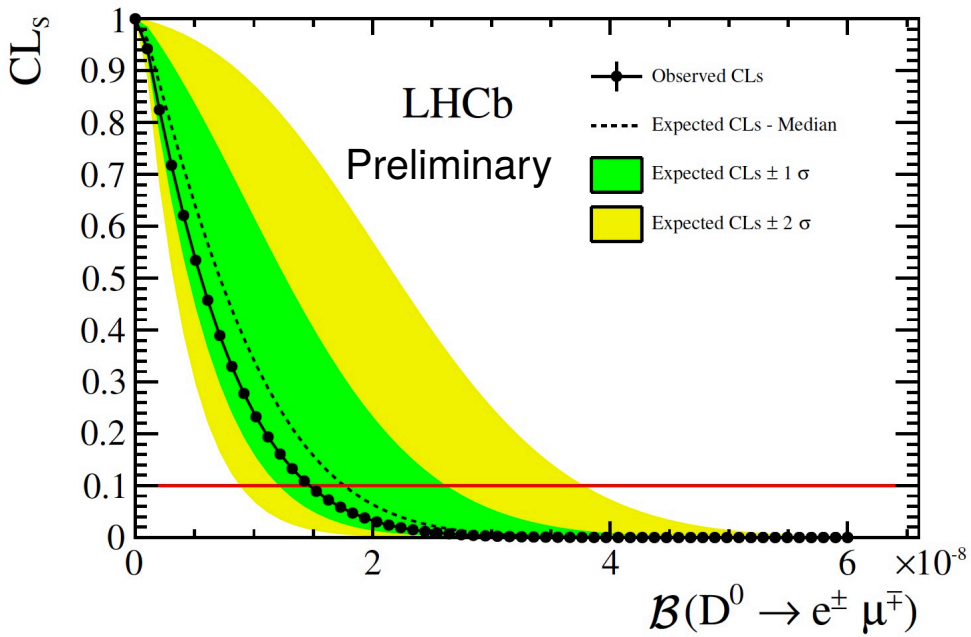
Thick: Signal, Dashed: Combinatorial

$D^0 \to e^\pm \mu^\mp$: Results

- No evidence for any signal
- Upper limit from the CL_s method via:

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

- Good agreement between expected and observed CL_s values
- Set a world's best limit of $\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.5 \times 10^{-8}$
- Result further constrains products of couplings in RPV SUSY[1]



To theorists: Are these limits of interest to NP with leptoquarks?

[1] G. Burdman, E. Golowich, J. L. Hewett and S. Pakvasa, Phys. Rev. D66 (2002) 014009

Search for $D^+_{(s)} \to hll'$ decays

In preparation

- Search for decays of the type $D^+_{(s)} \to hll$ where $h = \pi, K$ and $l = \mu, e$ using Run 2 data

- 28 channels total
- $D^+_{(s)} \to h^+ l^+ l^-$ (with same flavour leptons) decays are either FCNC or weak annihilation and are suppressed in the SM
- Other decays are LNV/LFV
- Can constrain FCNC, LFV, LNV and LUV

- Previous LHCb limits of
  $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3 \times 10^{-8}$
  $\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1 \times 10^{-7}$
  $\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2 \times 10^{-8}$
  $\mathcal{B}(D_s^+ \to \pi^-\mu^+\mu^+) < 1.2 \times 10^{-7}$ using $1.0\,\text{fb}^{-1}$ (LHCb-PAPER-2012-051)
- Limits on electron modes are $10^{-5} - 10^{-6}$
  $\to$ expect to improve by at least an order of magnitude

To theorists: Are any other channels of interest?

Test of lepton universality using $B^+ \to K^+ l^+ l^-$ decays

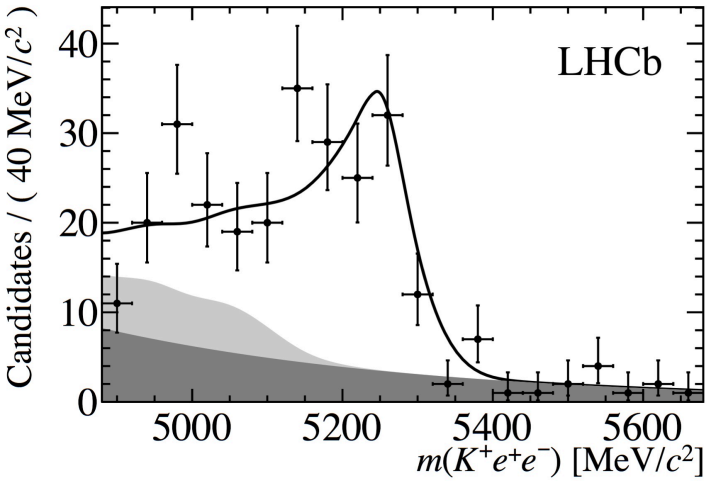
LHCb-PAPER-2014-024

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

expected to be $R_K^{SM} = 1 + O(\frac{m_\mu^2}{m_b^2})$ in the SM with low theoretical uncertainty

➜ Use double ratio to reduce systematics

$$R_K = (\frac{N_{K^+\mu^+\mu^-}}{N_{K^+e^+e^-}})(\frac{N_{J/\psi(e^+e^-)K^+}}{N_{J/\psi(\mu^+\mu^-)K^+}})(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}})(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}})$$



e triggered

0, 1 and 2 photons combined

➜ Challenging measurement in $B^+ \to K^+ e^+ e^-$ channel

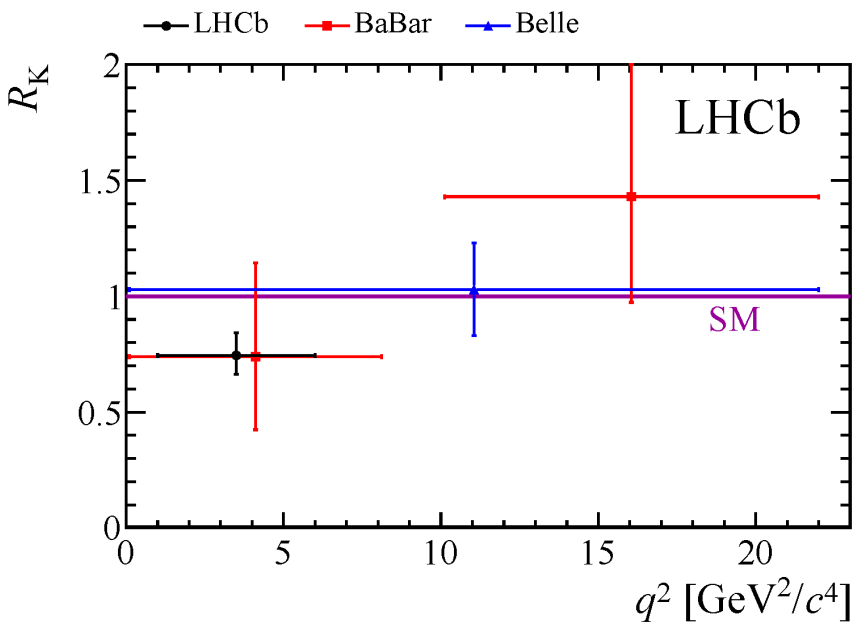
→ proof of principle for future electron analyses

➜ Separate PDF according to:

1) Particle firing the hardware trigger
2) Number of bremsstrahlung photons

R_K: Results

- $R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$ in the range $1 < q^2 < 6\ \text{GeV}^2$, using $3.0\,\text{fb}^{-1}$
- Compatible with SM expectation at 2.6σ



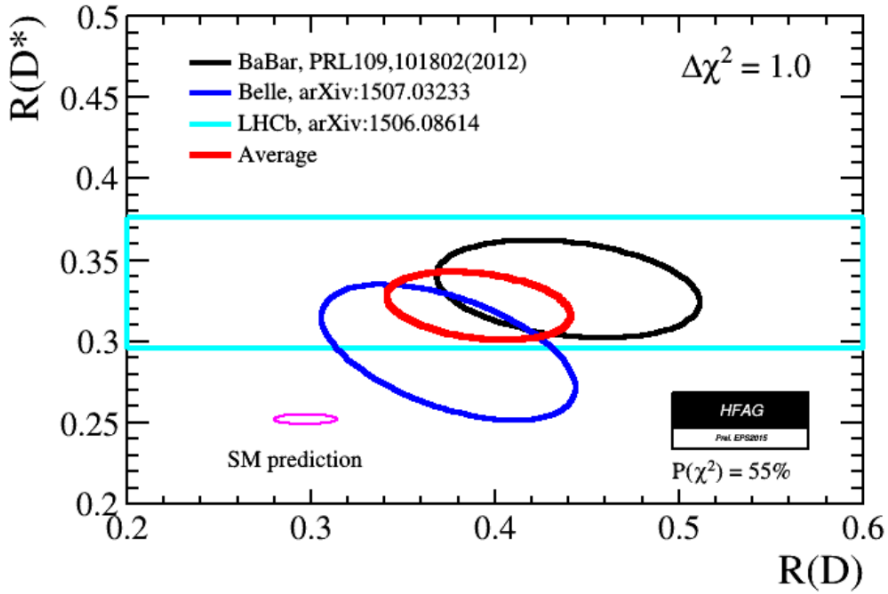
- Could point to additional Higgs bosons or Z'
- Try to improve analysis technique and add R_{K^*}, $R_{(K\pi)^*}$, R_{Λ^*}, R_ϕ and more...
- Can extend analysis to other q^2 bins with addition of Run 2 data

Measurement of $\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$

LHCb-PAPER-2015-025

- $R(D^*) = \mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu) =$ $0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$, using $3.0\,\text{fb}^{-1}$
- First measurement at a hadron collider, compatible with SM at 2.1σ
- Sensitive to charged Higgs and non-MFV couplings

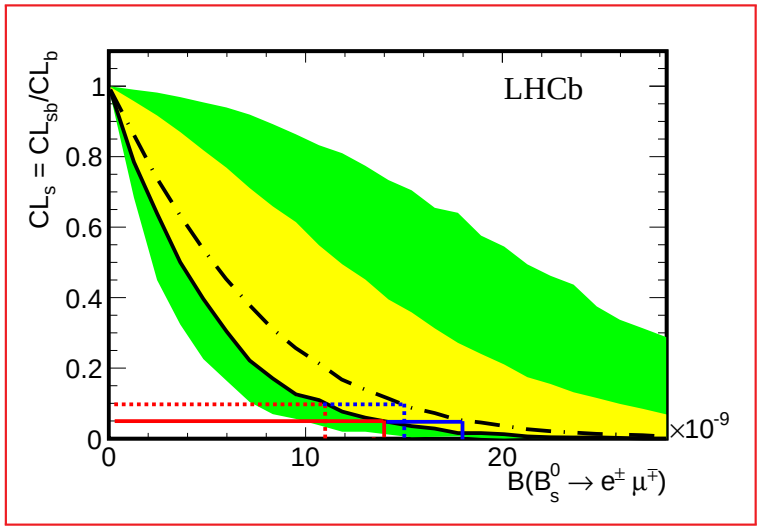
- Confirms BaBar results and compatible with recent Belle result (hadronic tag)
- Systematics from limited size of control samples will decrease with more data
- See Basem's talk (16.15, 04/11) for more information

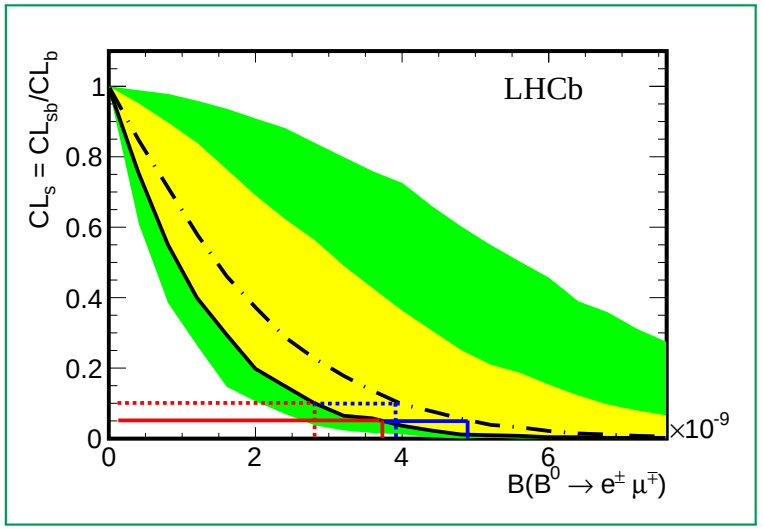


Search for the lepton-flavour violating decays $B^0_{(s)} \to e^\pm \mu^\mp$

LHCb-PAPER-2013-030

- $B^0_{(s)} \to e^\pm \mu^\mp$ decays are allowed in the Pati-Salam model
- Order of magnitude improvement over previous limits from CDF
- Set world's best limits on leptoquark masses of $M_{LQ}(B^0 \to e\mu) > 126\,\text{TeV/c}^2$ and $M_{LQ}(B^0_s \to e\mu) > 101\,\text{TeV/c}^2$ at 95% CL
- Update to $3.0\,\text{fb}^{-1}$ underway



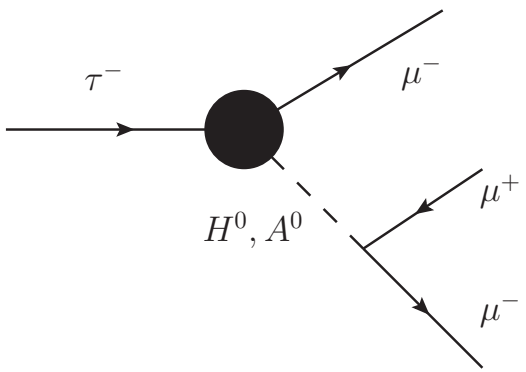


Channel	Observed (90% CL)	Observed (95% CL)
$B^0_s \to e^\pm \mu^\mp$	1.1×10^{-8}	1.4×10^{-8}
$B^0 \to e^\pm \mu^\mp$	2.8×10^{-9}	3.7×10^{-9}

τ lepton flavour and baryon number violation

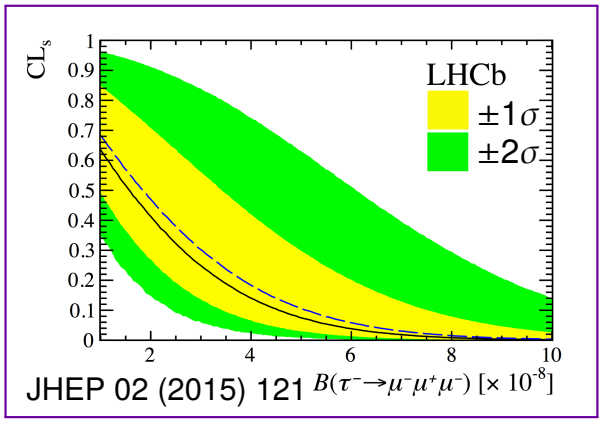
LHCb-PAPER-2014-052, LHCb-PAPER-2013-014

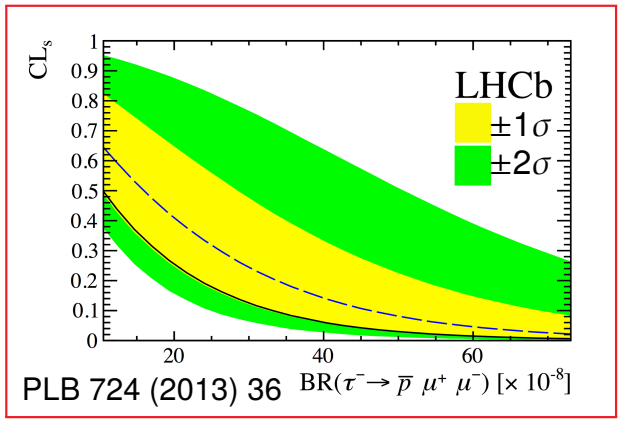
- Lepton flavour violating (LFV) decay $\tau^- \to \mu^-\mu^+\mu^-$ forbidden in SM
- Suppressed in SM + neutrino oscillations to $\mathcal{B} \sim 10^{-54}$
- Enhanced by new physics $\to$ can be as large as 10^{-8}
- Current experimental upper limit of 2.1×10^{-8} from Belle

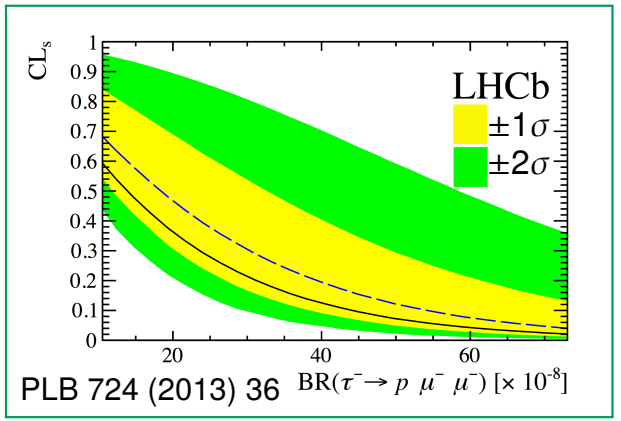


- Search for baryon number violation (BNV) processes so far unsuccessful
- $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ are both $\Delta(B-L) = 0$ as required in the SM and most of its extensions
- Limits on $\tau \to \Lambda h$ and $B \to \Lambda l$ in the range $10^{-7} - 10^{-8}$ from BaBar and Belle
- $\tau^- \to \mu^-\mu^+\mu^-$ and $\tau \to p\mu\mu$ analyses follow a similar strategy

τ LFV and BNV results



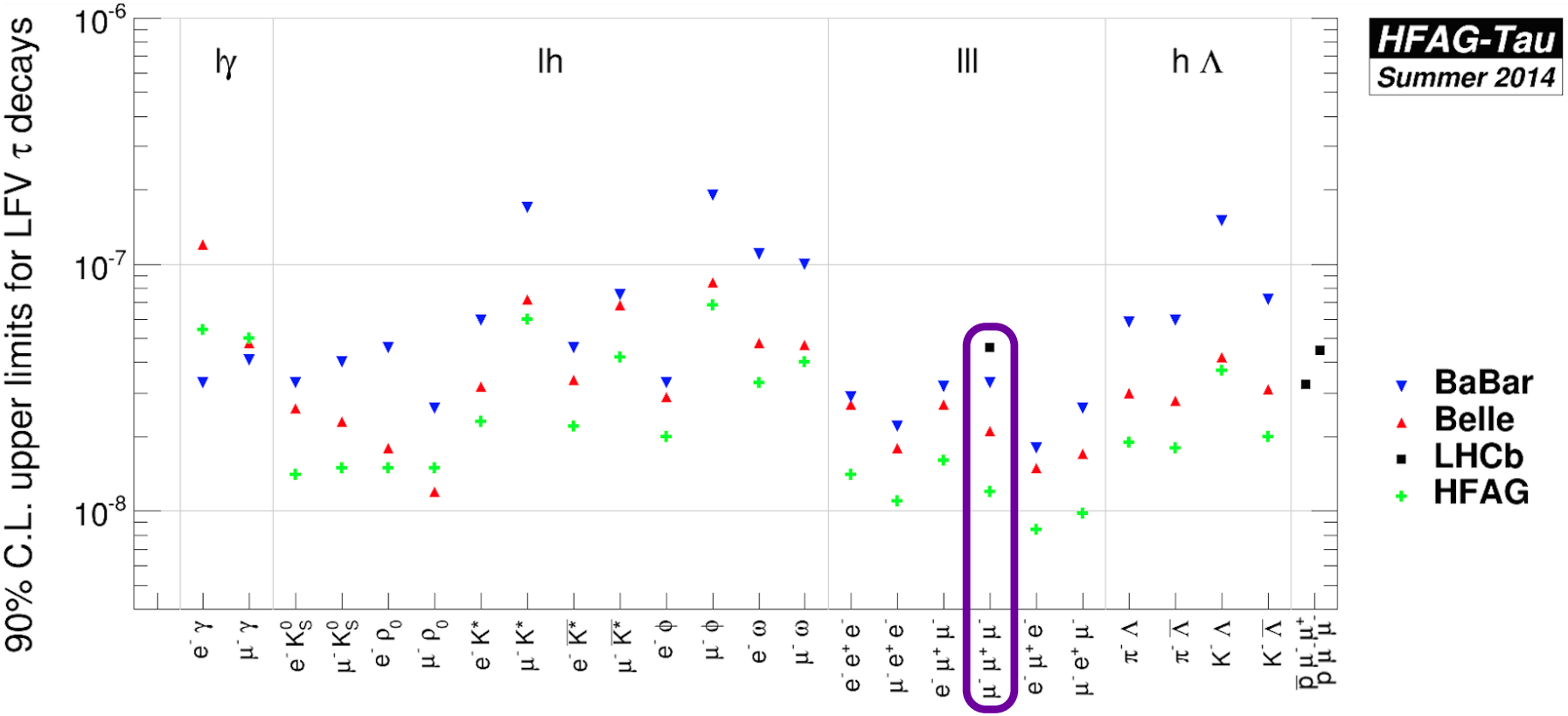




- First τ LFV results at a hadron collider
- $\tau^- \to \mu^-\mu^+\mu^-$ results updated to use full Run I data sample
- First ever constraints on $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$

Channel	Expected (90% CL)	Observed (90% CL)
$\tau^- \to \mu^-\mu^+\mu^-$	5.0×10^{-8}	4.6×10^{-8}
$\tau^- \to \bar{p}\mu^+\mu^-$	4.6×10^{-7}	3.3×10^{-7}
$\tau^- \to p\mu^-\mu^-$	5.4×10^{-7}	4.4×10^{-7}

Combination of τ LFV results



➜ LHCb and *B*-factory results on τ LFV combined by HFAG using CLs method[1]

→ Combined limit on $\tau^- \to \mu^-\mu^+\mu^-$ of 1.2×10^{-8}

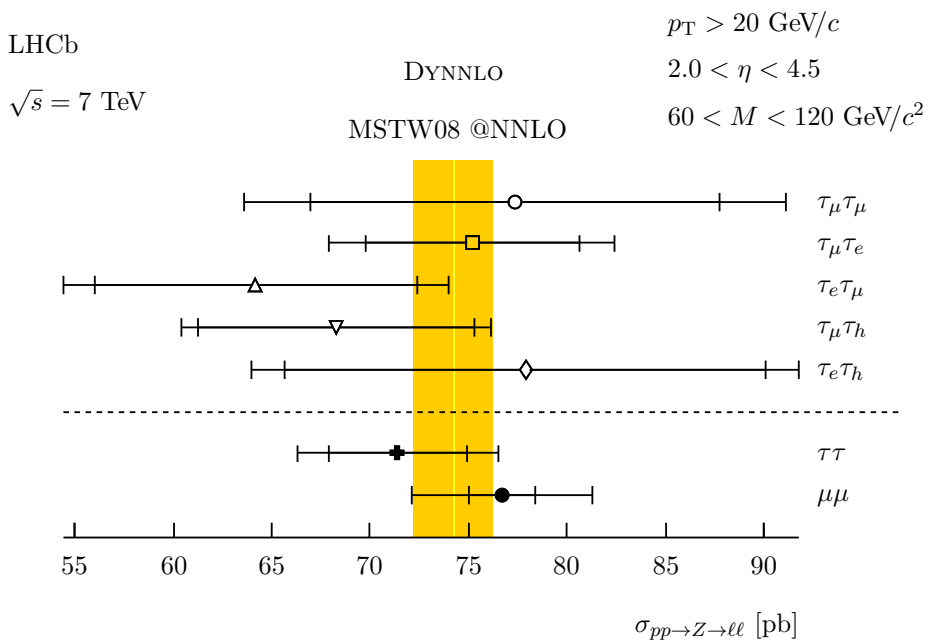
[1] Heavy Flavour Averaging Group, arXiv: 1412.7515

Other channels studied at LHCb

- Ratio of cross-sections, $\frac{\sigma_{pp\to Z\to\tau\tau}}{\sigma_{pp\to Z\to\mu\mu}} = 0.93 \pm 0.09$
  $\longrightarrow$ Consistent with lepton universality (also for $Z \to ee$)

Channel	$\mathcal{B}_{UL}$ 95% CL
$B^+ \to K^- \mu^+ \mu^+$	5.4×10^{-8}
$B^+ \to D^- \mu^+ \mu^+$	6.9×10^{-7}
$B^+ \to D^{*-} \mu^+ \mu^+$	2.4×10^{-6}
$B^+ \to \pi^- \mu^+ \mu^+$	4.0×10^{-9}
$B^+ \to D_s^- \mu^+ \mu^+$	5.8×10^{-7}
$B^+ \to D^0 \pi^- \mu^+ \mu^+$	1.5×10^{-6}

LHCb-PAPER-2013-064
LHCb-PAPER-2011-038
LHCb-PAPER-2011-009



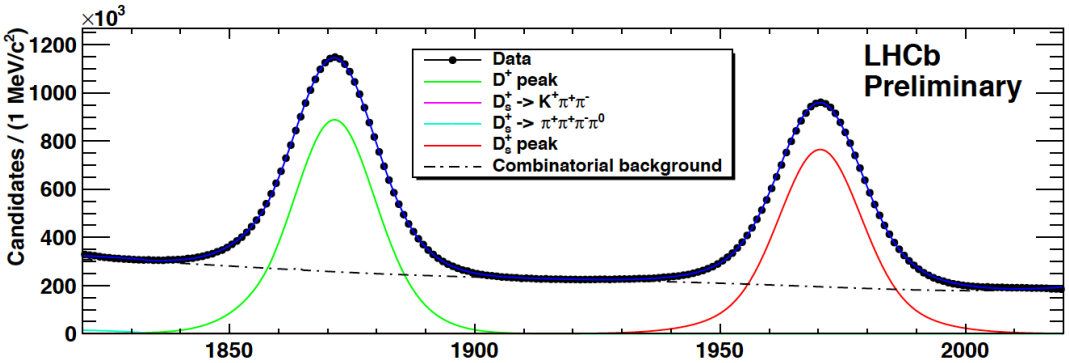
LHCb-PAPER-2012-029

- World's best limits on a number of $B^+ \to h^- \mu^+ \mu^+$ channels
- Upcoming results in $B \to \tau\mu$, $B^+ \to he\mu$, $B^+ \to h\tau\mu$, $B \to hhe\mu$ and $B_s \to \phi e\mu$

Search for the strong CP-violating decays $\eta^{(\prime)} \to \pi^+\pi^-$

In preparation

- The QCD lagrangian has a natural 'θ term' which violates CP, but no CP violation is observed in strong processes
- World's best limits[1,2] (90% CL):
  $\mathcal{B}(\eta \to \pi^+\pi^-) < 1.3 \times 10^{-5}$, $\mathcal{B}(\eta' \to \pi^+\pi^-) < 5.5 \times 10^{-5}$



MVA selected $\pi^+\pi^+\pi^-$ candidates in 3.0 fb^{-1}

- Search for η and η' contributions as narrow peaks in the inclusive $\pi^+\pi^-$ mass spectra from $D^+_{(s)} \to \eta^{(\prime)}\pi^+$ decays
- Extrapolate background in η and η' signal regions from $\pi^+\pi^-$ sidebands
- Expect competitive results, analysis currently in review

[1] KLOE collaboration, Phys. Lett. B606 (2005) 276
[2] BESIII collaboration, Phys. Rev. D84 (2011) 032006

Summary

- LHCb has performed a number of searches for LFV and LUV
- World's best limit on $D^0 \to e^{\pm}\mu^{\mp}$
- High accuracy measurement of R_K in the low q^2 region (2.6σ wrt SM)
- $R(D^*)$ result compatible with B factories (2.1σ wrt SM)
- Closing in on the world's best single-experiment limit for $\tau^- \to \mu^-\mu^+\mu^-$ and contributing to the world average
- First ever constraints on $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$
- Upcoming results in $D^+_{(s)} \to hll'$, $B \to \tau\mu$, $B^+ \to he\mu$, $B^+ \to h\tau\mu$, $B \to hhe\mu$, and $B_s \to \phi e\mu$ and more
- See also Mitesh's talk (12.35, 04/11) for searches for hidden-sector bosons in $B^0 \to K^*\chi$ decays

LHCb is making significant contributions to LFV and LUV searches
$\to$ more to come throughout Run 2

Backup

Prospects for rare charm decays

- Interest[1] in measuring $R_\pi^{ll} = \frac{\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-)_{q^2 \in [1.25^2, 1.73^2]\text{GeV}^2}}{\mathcal{B}(D^+ \to \pi^+ e^+ e^-)_{q^2 \in [1.25^2, 1.73^2]\text{GeV}^2}}$
- Assuming no NP in $D^+ \to \pi^+ e^+ e^-$
- Depending on constraints on Wilson coefficients, $1/R^{ll} \sim 0.1$–0.2
- Extrapolate Run I yields to Upgrade ($50\,\text{fb}^{-1}$) and allow for improvements in electron efficiency (x1, x2, x3 Run I)

Channel	BF or 90% UL ($\times 10^{-8}$)	90% UL on R_π^{ll}
$D^+ \to \pi^+ \mu^+ \mu^-$	2.6 ± 0.1	
$D^+ \to \pi^+ e^+ e^-$ (x1)	$< 2.6 \times 10^{-8}$	1
$D^+ \to \pi^+ e^+ e^-$ (x2)	$< 1.3 \times 10^{-8}$	0.5
$D^+ \to \pi^+ e^+ e^-$ (x3)	$< 0.9 \times 10^{-8}$	0.3

- Observation of large LUV in charm decays possible in upgrade with improvement in e^+e^- efficiency
- May be able to measure asymmetries at level of 1% (5%) with $D^+ \to \pi^+ \mu^+ \mu^- (D^0 \to \pi^+ \pi^- \mu^+ \mu^-)$

[1] S. Fajfer, N. Kosnik, arXiv: 1510.00965