Lepton flavour violation searches and test of lepton flavour universality at LHCb

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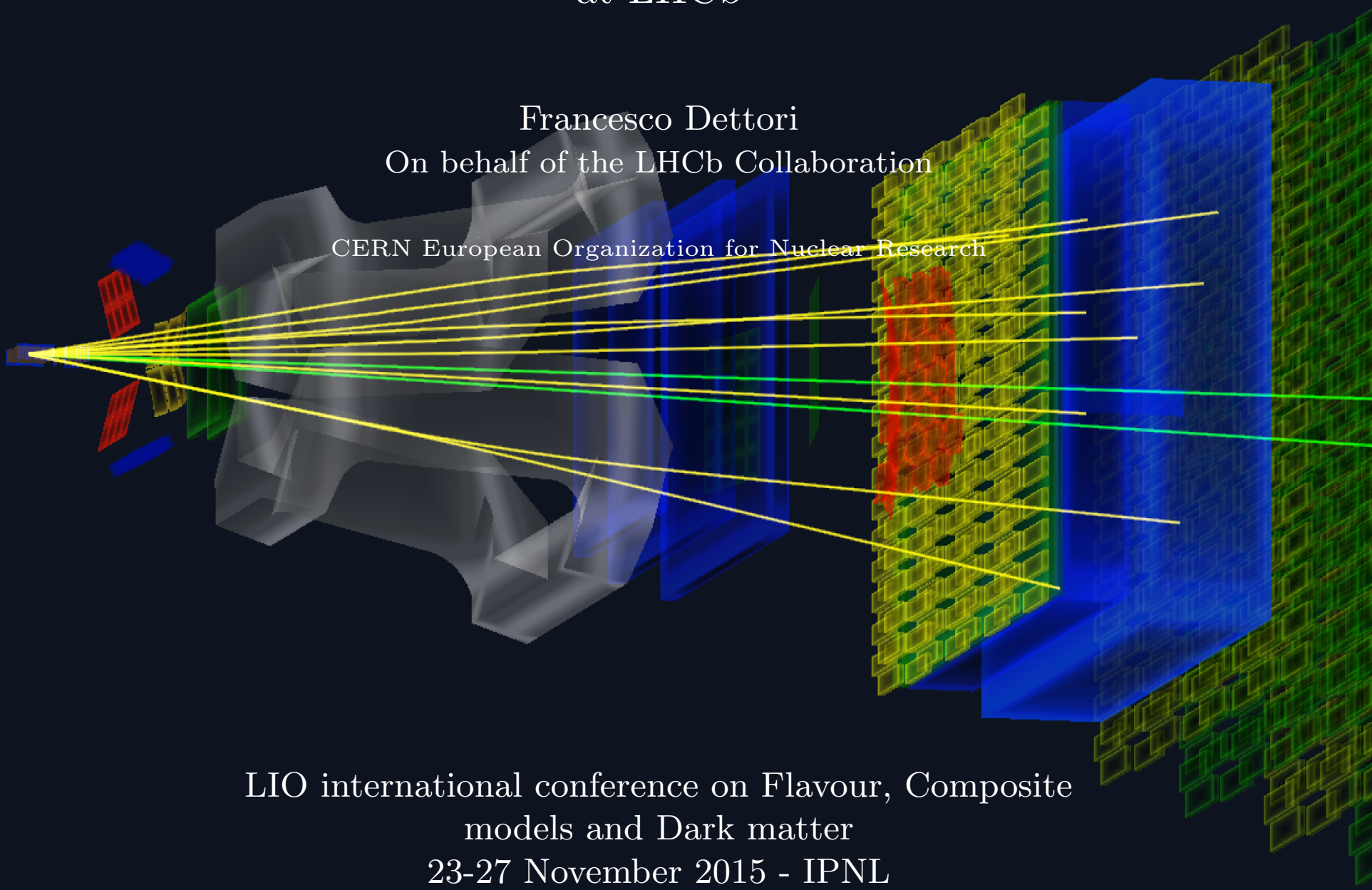
On behalf of the LHCb Collaboration

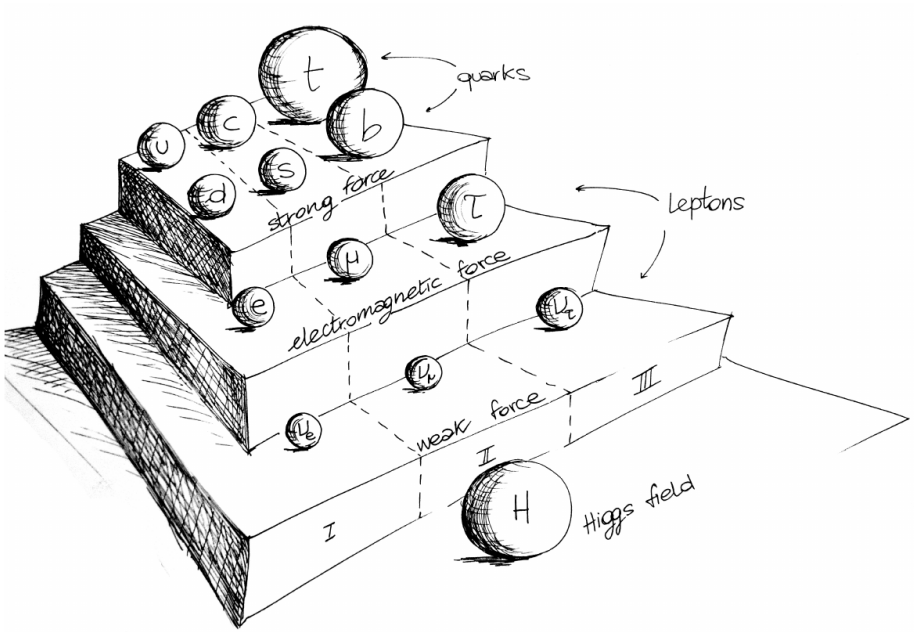
CERN European Organization for Nuclear Research



LIO international conference on Flavour, Composite models and Dark matter
23-27 November 2015 - IPNL

Introduction

- Lepton flavour universality and conservation are accidents of the SM
- Any evidence of LFV will point directly to new physics
- Despite countless searches in many experiments no evidence of LFV (apart from neutrinos...)
- LHCb starts to play its role in this field



Outline

- Searches for Majorana neutrinos
- Search for LFV in $B^0_{(s)} \to e^\pm \mu^\mp$ and $D^0 \to e^\pm \mu^\mp$ decays
- Search for LFV in τ decays
- Tests of lepton flavour universality

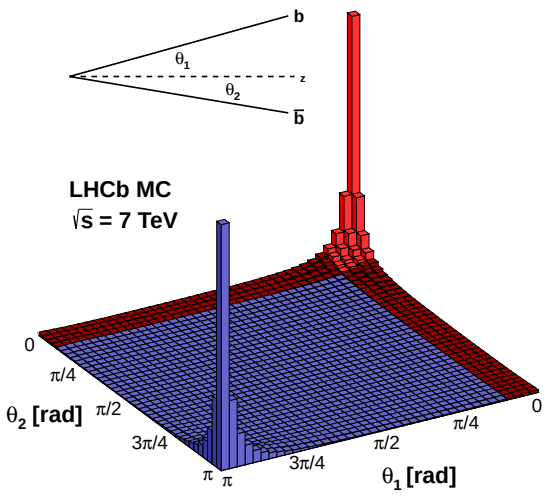
The LHCb experiment

Large Hadron Collider
as flavour factory

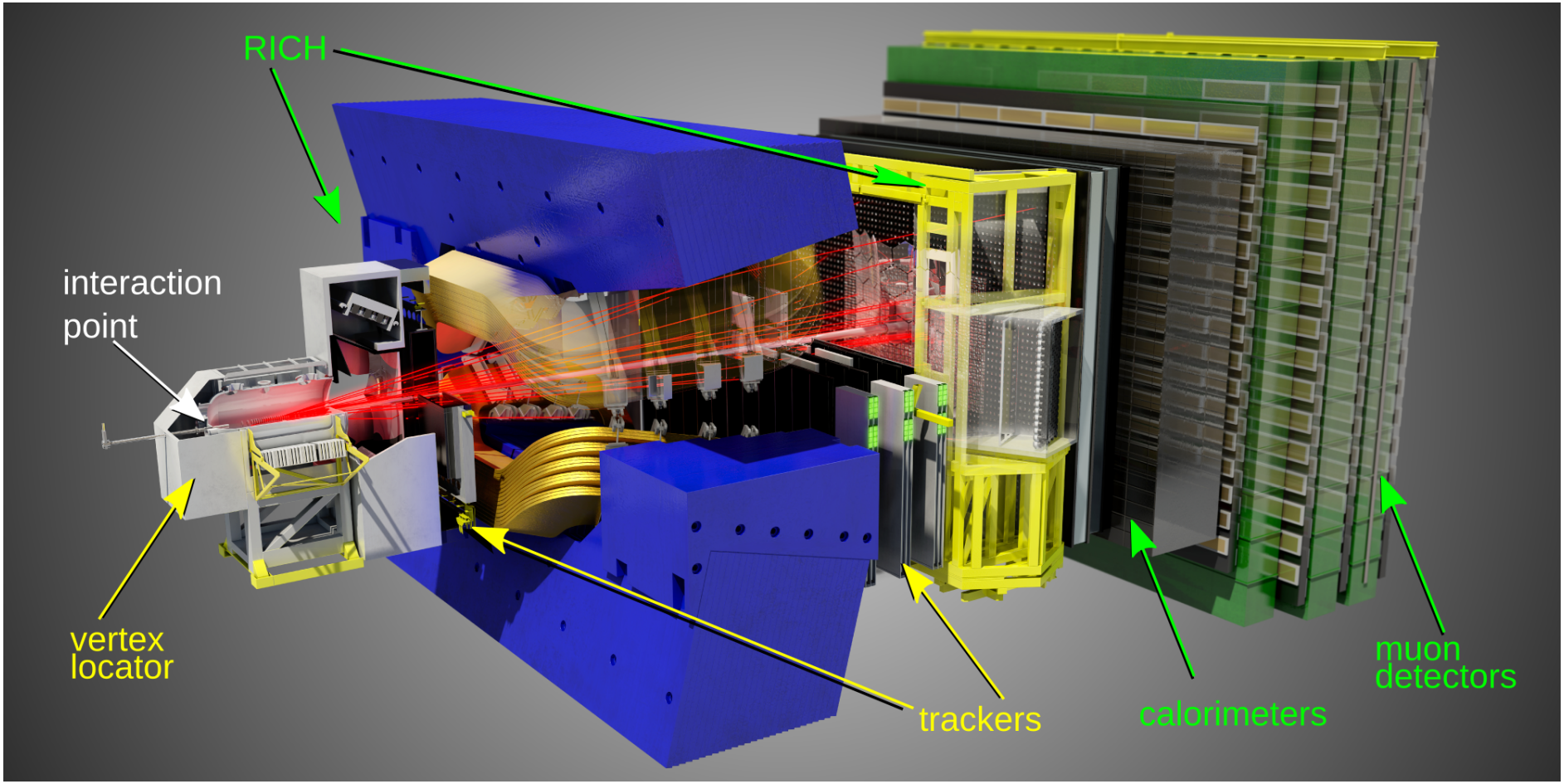
- pp collisions at 7-8-13 TeV
- Large b-quark production in the forward region
- Full b-hadrons spectrum
- $\mathcal{L} = 3 - 4 \cdot 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\int \mathcal{L} = 3.0 \mathrm{fb}^{-1}$ in Run I
  $\Rightarrow \mathcal{O}(10^{12})$ $b\bar{b}$ pairs
  and $\mathcal{O}(10^{13})$ $c\bar{c}$ pairs

LHCb:

- Specialized B-physics experiment
- Forward single arm spectrometer
- Acceptance: $2 < \eta < 5$



The LHCb detector



Excellent vertex and IP resolution

- $\sigma(IP) \simeq 24\mu$m at $p_{\mathrm{T}} = 2$ GeV/c
- $\sigma_{\mathrm{BV}} \simeq 16\mu$m in x, y

Very good momentum resolution

- $\sigma(p)/p = 0.5\% - 0.8\%$ for $p \in (0, 100)$ GeV/c
- $\sigma(m_B) \sim 25$ MeV/c^2 for two body decays

Muon identification

- $\varepsilon_\mu = 98\%$, $\varepsilon_{\pi\to\mu} = 0.6\%$, $\varepsilon_{K\to\mu} = 0.3\%$, $\varepsilon_{p\to\mu} = 0.3\%$

Trigger

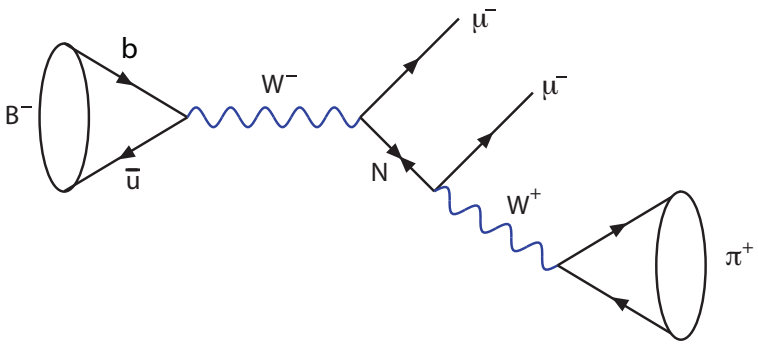
- $\varepsilon_\mu = 90\%$

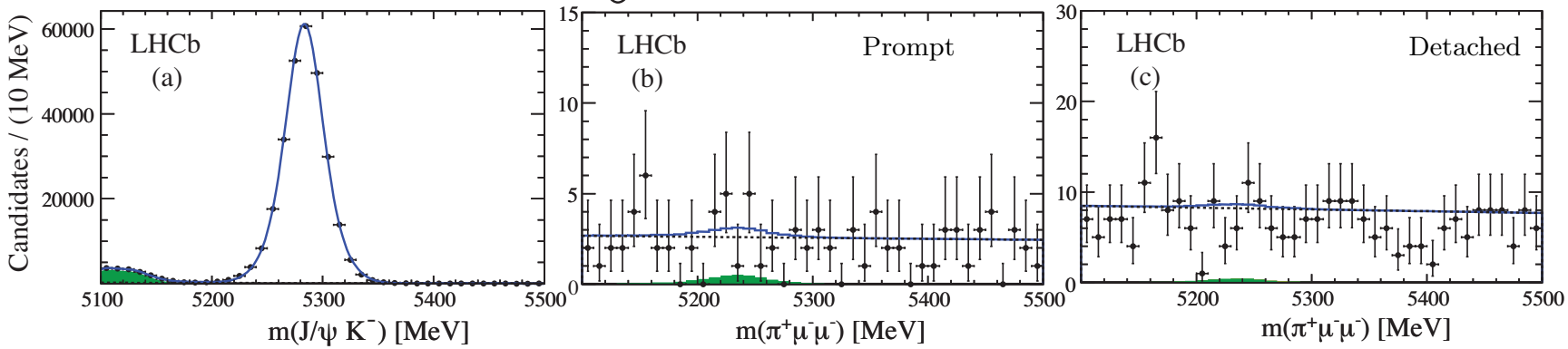
Int. J. Mod. Phys. A 30 (2015) 1530022

Search for Majorana neutrinos at LHCb: $B^- \to \pi^+\mu^-\mu^-$

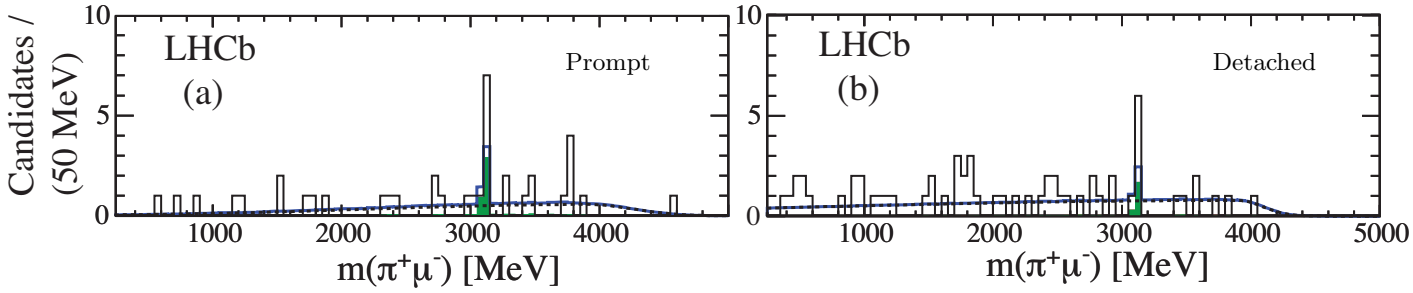
PRL 112, 131802 (2014)

- Search for Majorana neutrinos $B^- \to \mu^- N(\to \mu\pi)$
- Prompt (no detachment) and detached topologies (up to lifetimes of 1000 ps)
- No excess in the B mass: $\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 4.0 \cdot 10^{-9}$ (95%CL)

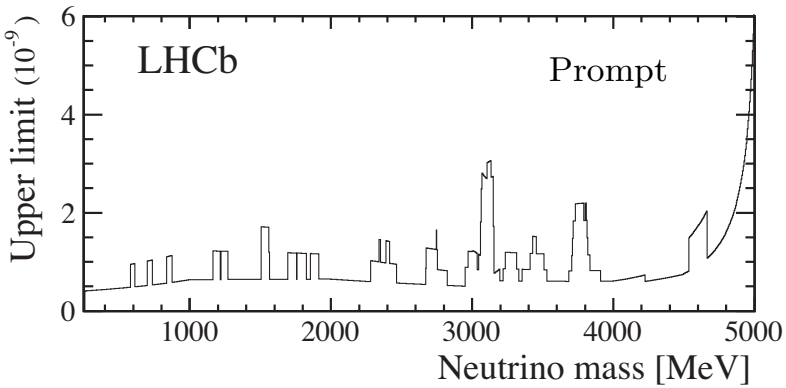


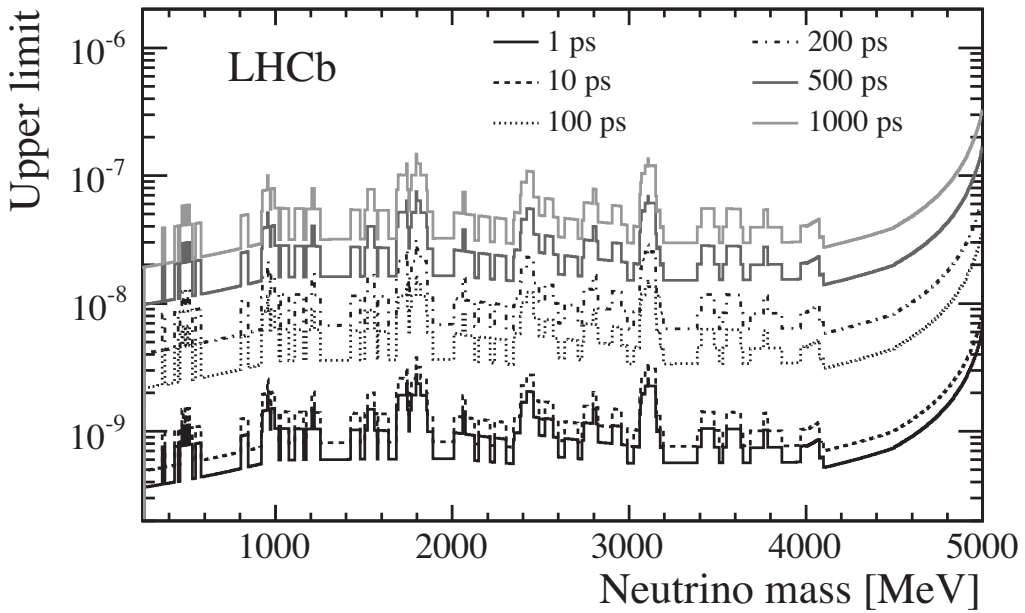


Search for Majorana neutrinos at LHCb: $B^- \to \pi^+ \mu^- \mu^-$



- Upper limit with CLs method
- Efficiency varies depending on τ_N
- Different upper limits as a function of τ_N



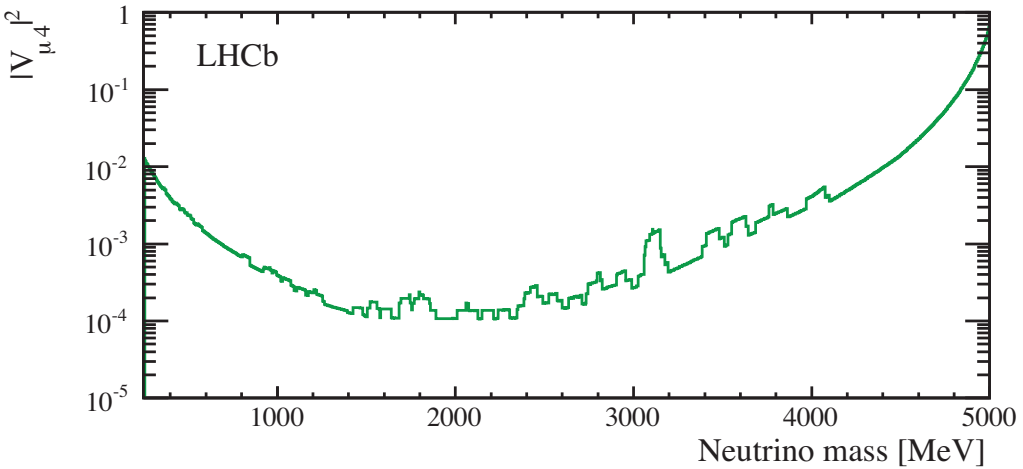


PRL 112, 131802 (2014)

Search for Majorana neutrinos at LHCb: $B^- \to \pi^+ \mu^- \mu^-$

PRL 112, 131802 (2014)

- Upper limits on a fourth generation neutrino coupling $|V_{\mu 4}|$
- Model dependent limit versus m_N



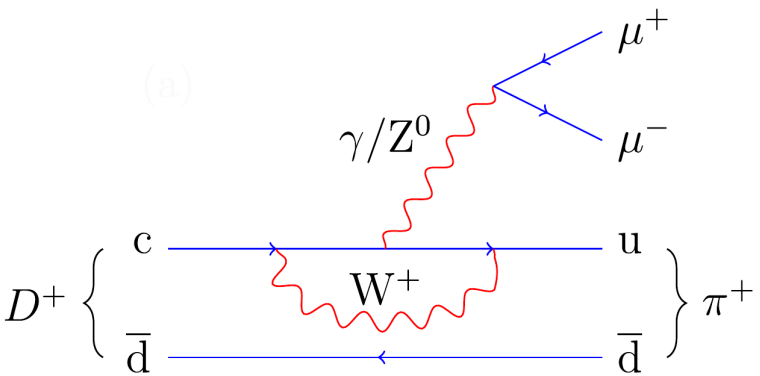
$$\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-) = \frac{G_F^4 f_B^2 f_\pi^2 m_B^5}{128\pi^2\hbar} |V_{ub}V_{ud}|^2 \tau_B (1 - \frac{m_N^2}{m_B^2}) \frac{m_N}{\Gamma_N} |V_{\mu 4}|^4$$

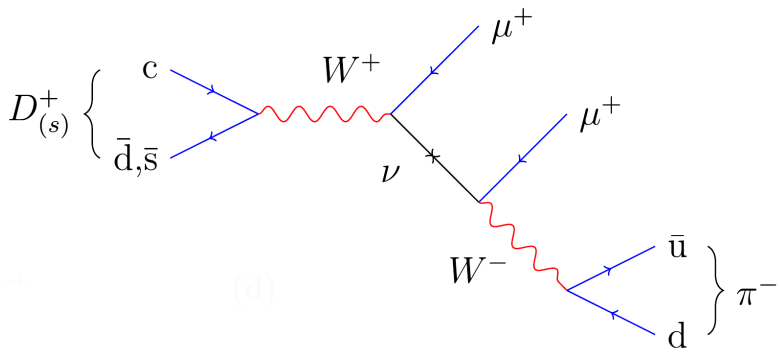
Total width parametrised as:
$\Gamma_N = f(m_N) \times |V_{\mu 4}|^2$

Search for Majorana neutrinos at LHCb: $D^+_{(s)} \to \pi^- \mu^+ \mu^+$

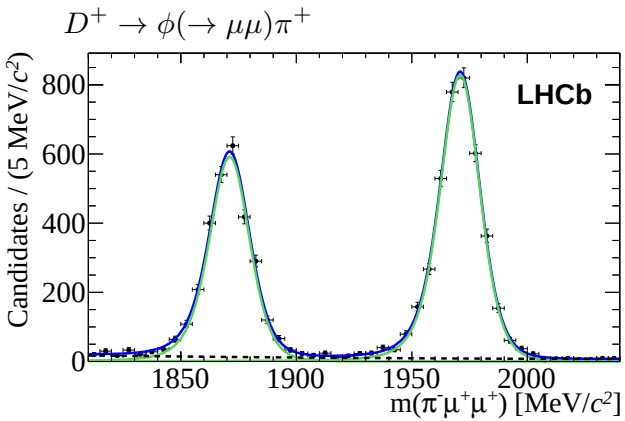
Phys. Lett. B 724 (2013) 203-212

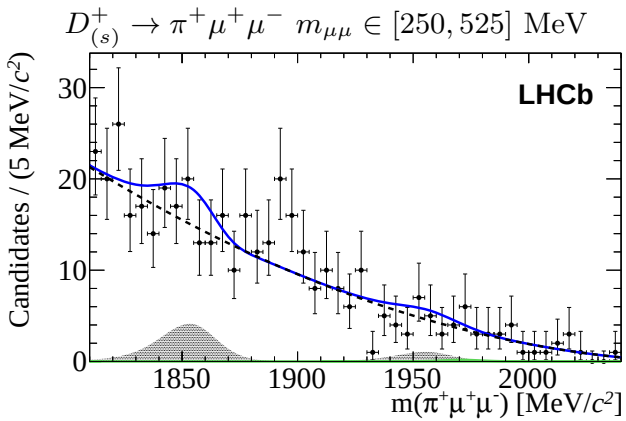
- Search for non-resonant $D^+_{(s)} \to \pi^+ \mu^+ \mu^-$ (FCNC)
- and LFV $D^+_{(s)} \to \pi^- \mu^+ \mu^+$ decays (Majorana neutrinos?)
- $\mathcal{L} = 1\text{fb}^{-1}$ at $\sqrt{s} = 7$ TeV
- Normalise to $D^+_{(s)} \to \phi(\to \mu\mu)\pi^+$
- No displacement allowed in this case

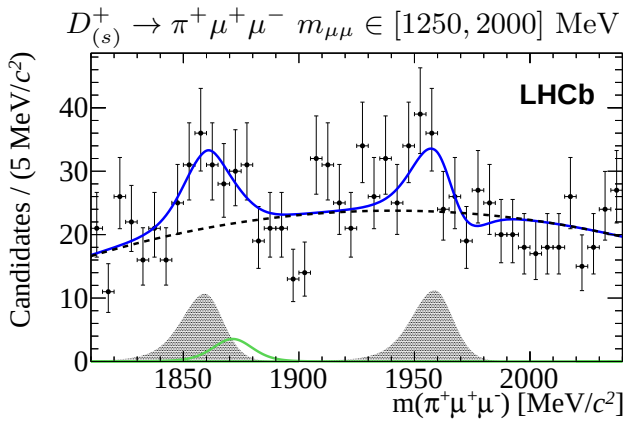




Search for Majorana neutrinos at LHCb: $D^+_{(s)} \to \pi^-\mu^+\mu^+$







Phys. Lett. B 724 (2013) 203-212

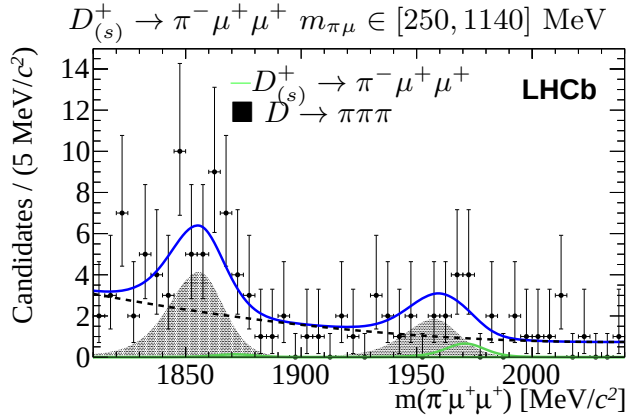
No signal observed, limit at 90%CL:
for FCNC:

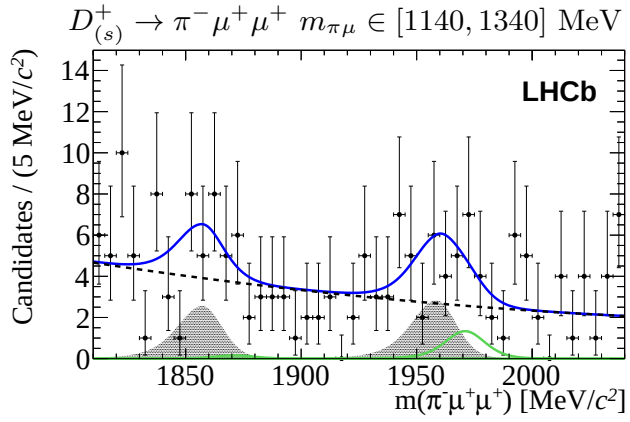
$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3 \cdot 10^{-8}$$
$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1 \cdot 10^{-7}$$

for LFV:

$$\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2 \cdot 10^{-8}$$
$$\mathcal{B}(D_s^+ \to \pi^-\mu^+\mu^+) < 1.1 \cdot 10^{-8}$$

Limits for different $m_{\pi\mu}$ also set





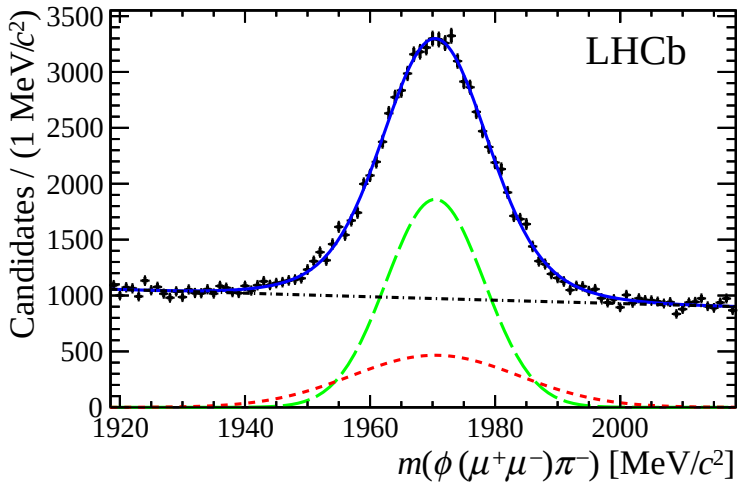
Lepton violation in τ decays: search for $\tau^- \to \mu^-\mu^+\mu^-$

JHEP 1502 (2015) 121

- Large inclusive τ production ($\sigma \sim 80\mu b$) at LHCb
- Clear signature of three muons in the final state

Normalisation

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



Background discrimination

Three likelihoods

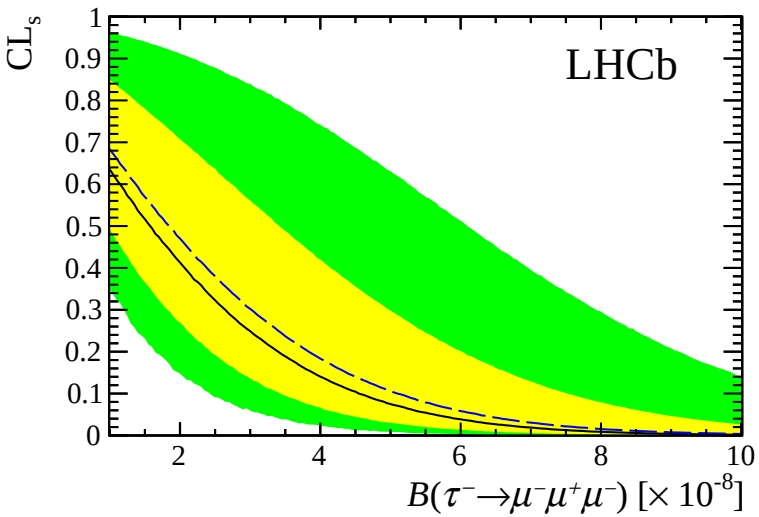
- $\mathcal{M}_{\rm 3body}$: multivariate topological variable to reject multi-body decays and combinatorial
- $\mathcal{M}_{\rm PID}$: identification likelihood to reject mis-ID
- Invariant mass

Lepton flavour violation in τ decays

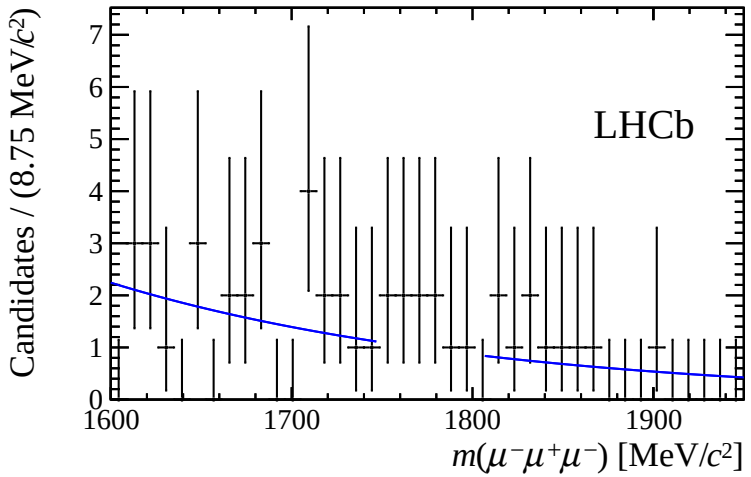
- No signal observed
- Upper limit with CLs method at the 90% CL

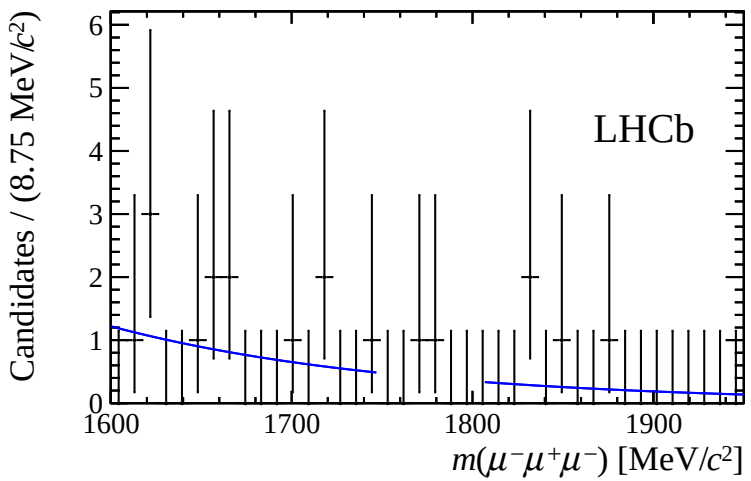
$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) \quad < \quad 4.6 \times 10^{-8}$$

- Phase space models used but efficiencies vary of 10 - 20% over the $\mu\mu$



Two most sensitive bins:



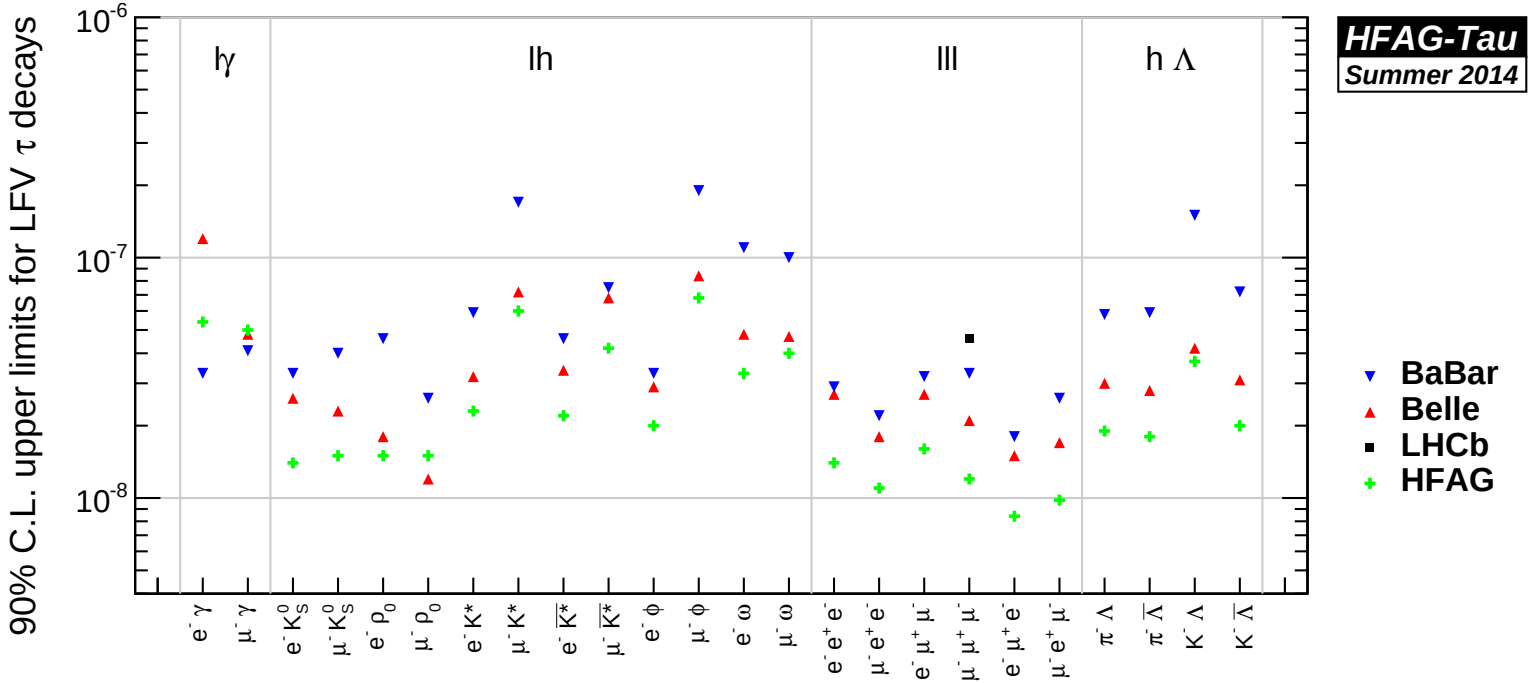


JHEP 1502 (2015) 121

Lepton flavour violation in τ decays

JHEP 1502 (2015) 121

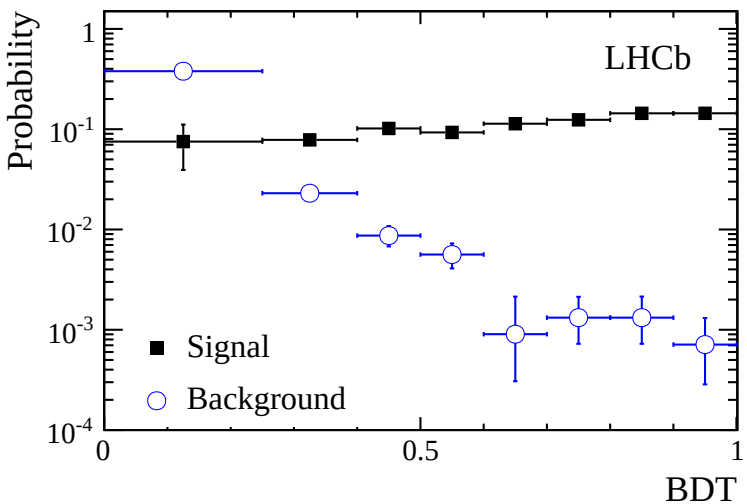
- LHCb limit still not competitive with B-factories
- Combined limit improves

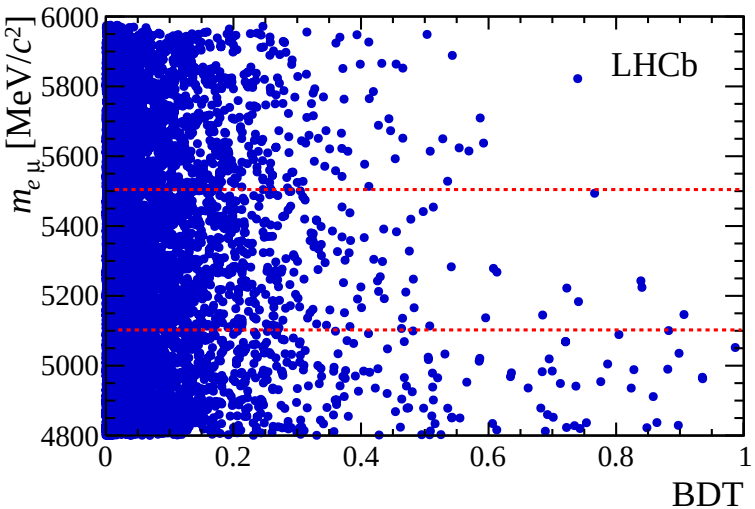


Search for the LFV decays $B^0_{s,d} \to e^{\pm}\mu^{\mp}$

Phys. Rev. Lett. 108, 231801 (2012)

- 1 fb^{-1} of pp collisions at 7 TeV
- Strategy
  - ⋆ Search in invariant mass distribution in bins of BDT
  - ⋆ Combined search for B^0_s and B^0
  - ⋆ Normalization to $B \to K\pi$ decays
  - ⋆ Calibration using $J/\psi \to \ell\ell$ decays

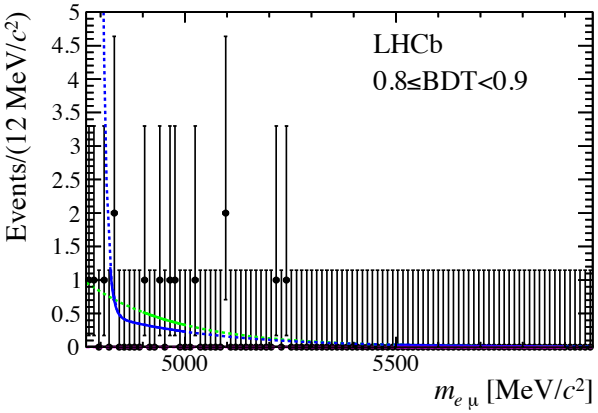


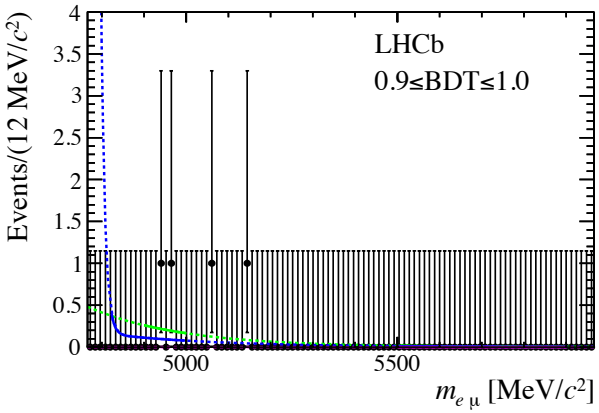


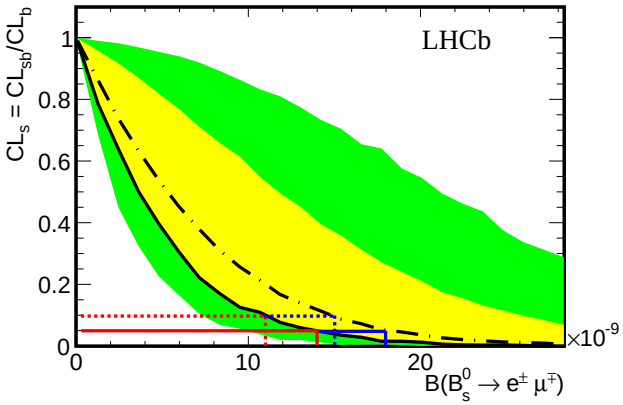
Search for the LFV decays $B^0_{s,d} \to e^{\pm}\mu^{\mp}$

Phys. Rev. Lett. 108, 231801 (2012)

- No signal excess over background is observed







- Limit with CLs method

Upper limits on the branching fractions at 90% CL:

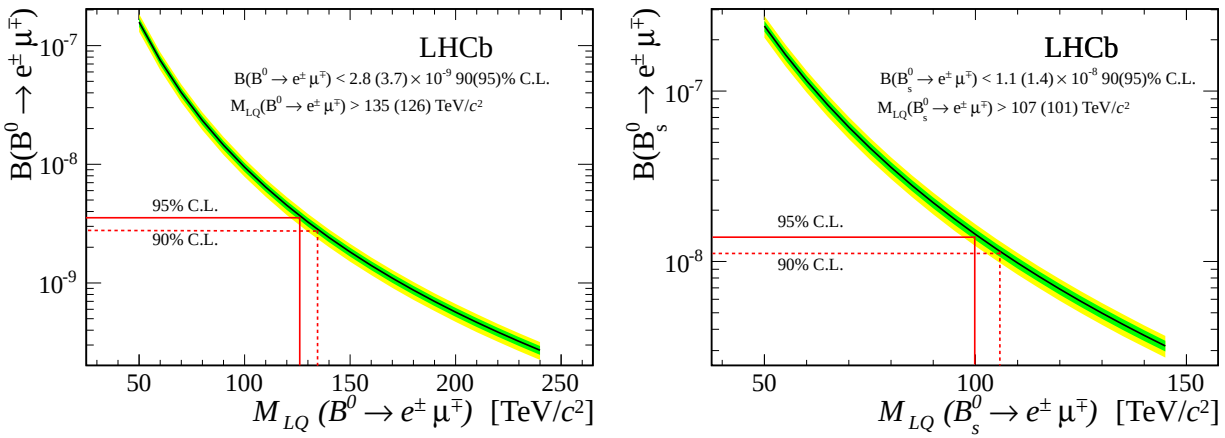
$$\mathcal{B}(B^0 \to e^{\pm}\mu^{\mp}) < 2.8 \times 10^{-9}$$
$$\mathcal{B}(B^0_s \to e^{\pm}\mu^{\mp}) < 1.1 \times 10^{-9}$$

An improvement of a factor 20 over previous experiments

Search for the LFV decays $B^0_{s,d} \to e^{\pm}\mu^{\mp}$

- Limits interpreted within the Pati-Salam model:

$$\mathcal{B}(B^0_{(s)} \to e^{\pm}\mu^{\mp}) = \pi \frac{\alpha_S^2(M_{LQ})}{M_{LQ}^4} F^2_{B_{(s)}} m^3_{B_{(s)}} R^2 \frac{\tau_{B_{(s)}}}{\hbar}$$



Limits on different generation-connecting Lepto-quarks

$$M_{LQ|B^0_s \to e^{\pm}\mu^{\mp}} > 107 \text{ TeV/c}^2$$

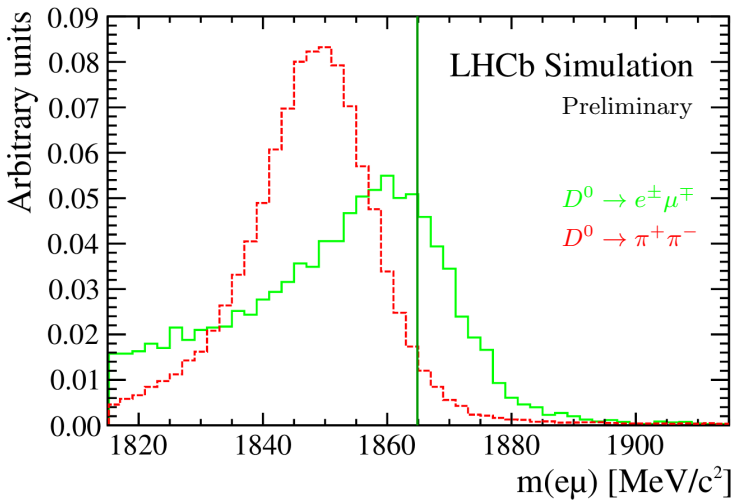
$$M_{LQ|B^0 \to e^{\pm}\mu^{\mp}} > 135 \text{ TeV/c}^2$$

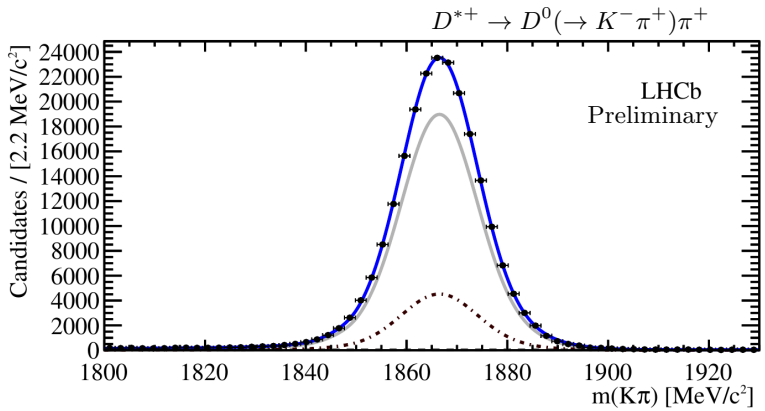
Full Run I (3fb^{-1}) analysis on the pipeline...

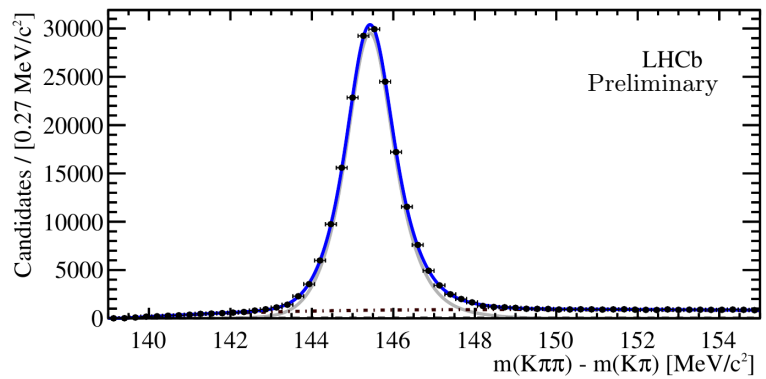
Phys. Rev. Lett. 108, 231801 (2012)

Search for LFV $D^0 \to e^{\pm}\mu^{\mp}$ decays

- Search for tagged $D^{*+} \to D^0(\to e^{\pm}\mu^{\mp})\pi^+$ decays
- Full Run I statistics of 3fb^{-1}
- Normalized to $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays
- Most dangerous background misID $D^0 \to \pi^+\pi^-$



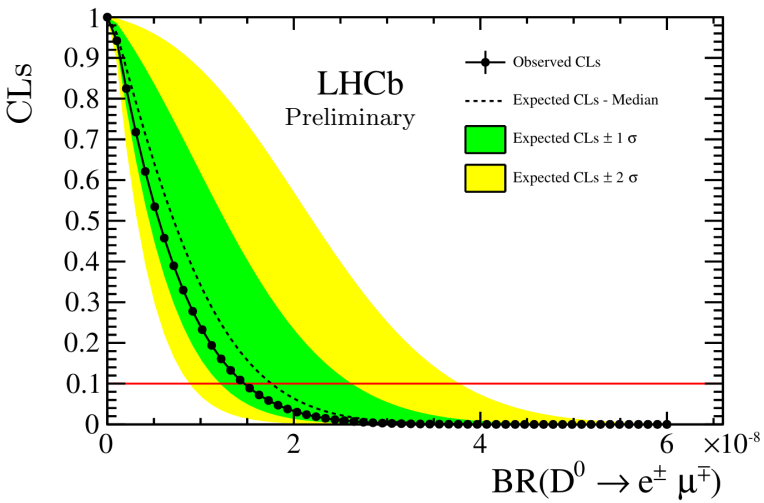


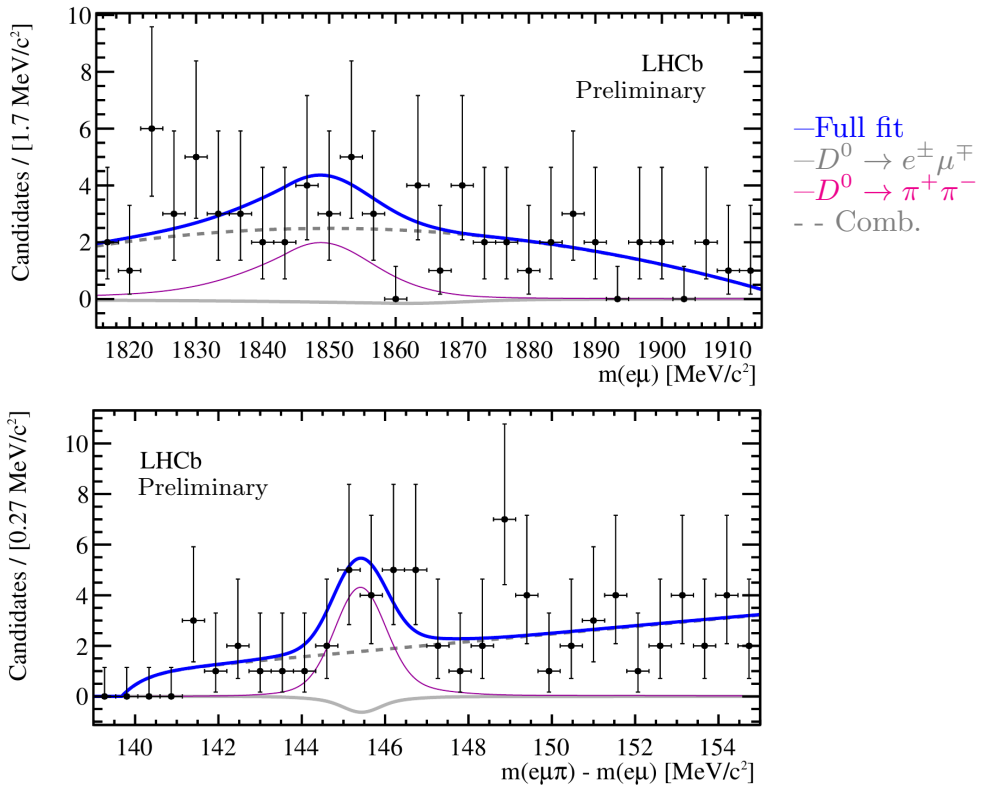


LHCB-PAPER-2015-048 - Preliminary

Search for LFV $D^0 \to e^\pm \mu^\mp$ decays

- Final search in 3 bins of MVA operator
- 2D fit to M and ΔM
- $D^0 \to \pi^+\pi^-$ constrained in the fit





No signal observed, set world best limit of:

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.5 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

improving by an order of magnitude on previous limits.

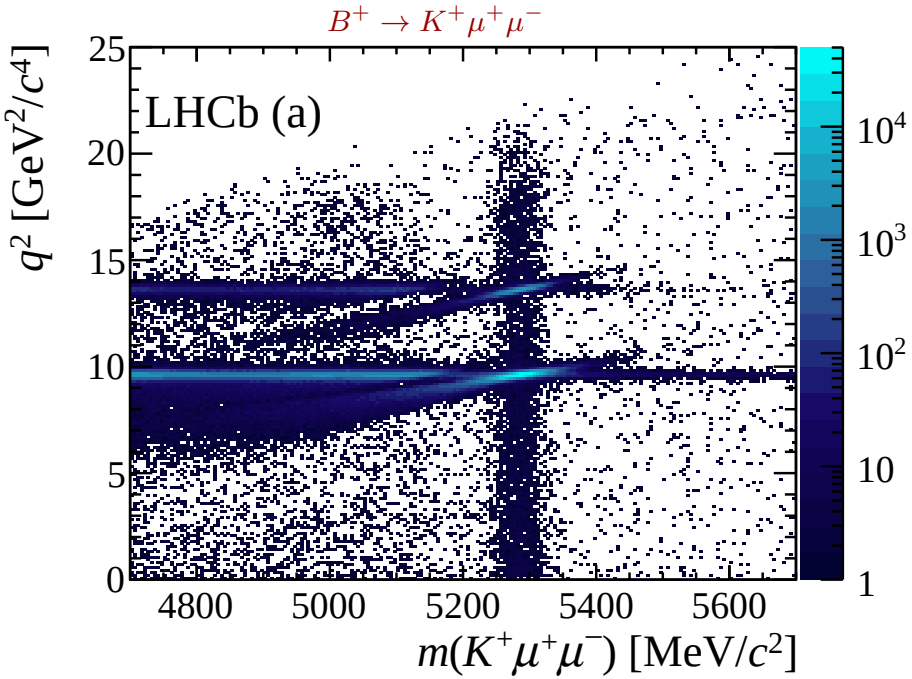
LHCB-PAPER-2015-048 - Preliminary

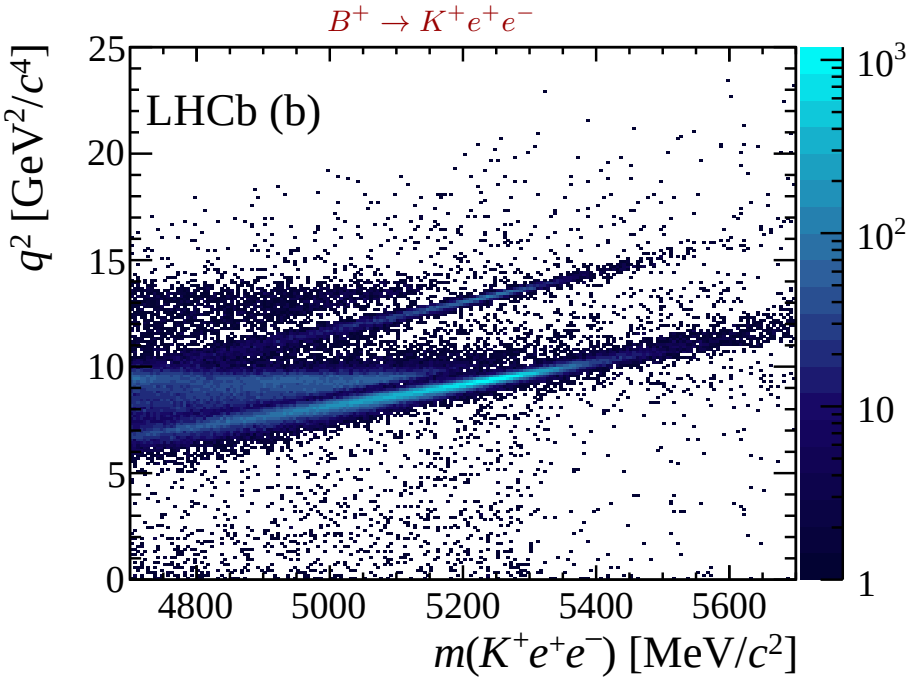
Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays

- Ratio of branching fractions of $B^+ \to K^+e^+e^-$ and $B^+ \to K^+\mu^+\mu^-$ sensitive to lepton universality

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[\mathcal{B}(B^+\to K^+\mu^+\mu^-)]}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[\mathcal{B}(B^+\to K^+e^+e^-)]}{dq^2} dq^2} = \left(\frac{N_{K\mu\mu}}{N_{Kee}}\right)\left(\frac{N_{J/\psi(ee)K}}{N_{J/\psi(\mu\mu)K}}\right)\left(\frac{\varepsilon_{Kee}}{\varepsilon_{K\mu\mu}}\right)\left(\frac{\varepsilon_{J/\psi(ee)K}}{\varepsilon_{J/\psi(\mu\mu)K}}\right)$$

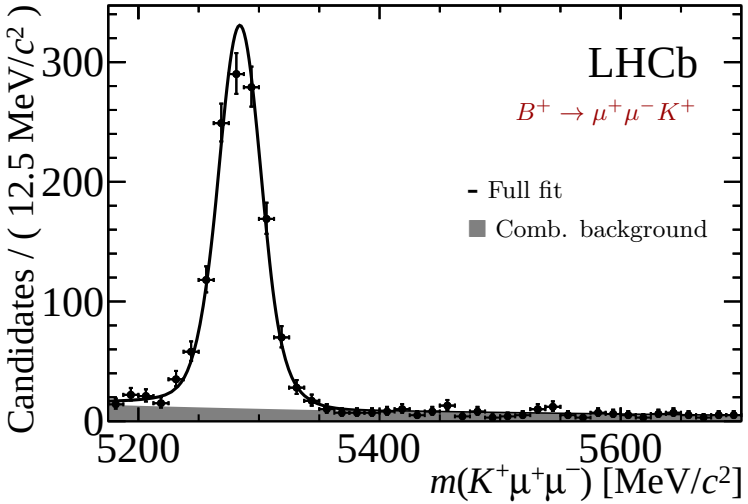
- SM prediction is $R_K = 1$ with an uncertainty of $\mathcal{O}(10^{-3})$
- Measurement relative to resonant $B^+ \to J/\psi K^+$ modes

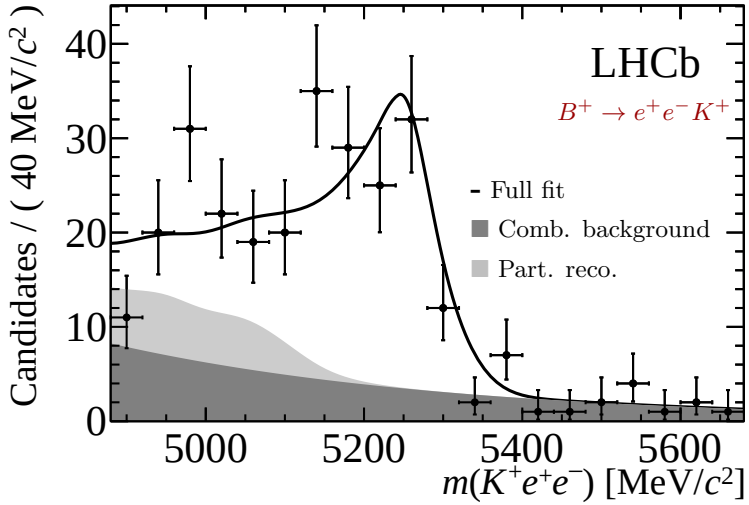




Phys. Rev. Lett. 113, 151601 (2014)

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





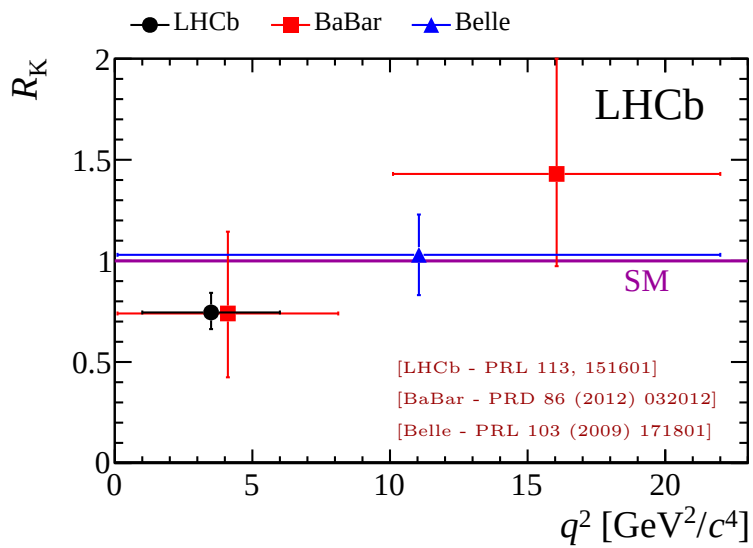
$q^2 \in [1, 6]\text{GeV}^2/\text{c}^4$

Electron Trigger

The combination of the various trigger channels gives:

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

Most precise measurement to date, compatible with SM at 2.6σ level



The branching fraction of $B^+ \to e^+e^-K^+$ is measured as

$\mathcal{B}(B^+ \to e^+e^-K^+) = 1.56^{+0.19}_{-0.15}(\text{stat})^{+0.06}_{-0.05}(\text{syst}) \times 10^{-7}$

well compatible with SM predictions

Phys. Rev. Lett. 113, 151601 (2014)

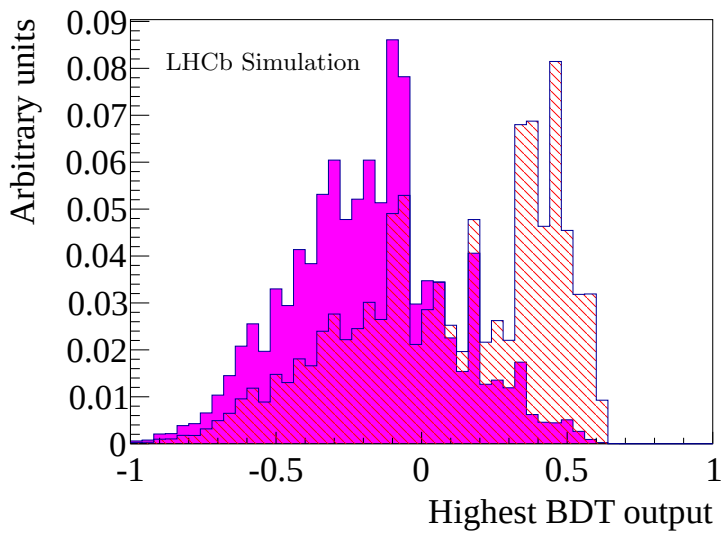
Measurement of the Ratio of Branching Fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

Phys. Rev. Lett. 115, 111803 (2015)

- $\mathcal{R}(D^*)$ is sensitive to NP coupling asymmetrically to lepton generations: e.g. a charged Higgs
- BaBar have reported discrepancies on $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$ of 2.7σ and 2.0σ respectively
- SM prediction is very precise 0.252 ± 0.003
- First measurement of these decays at a hadron collider

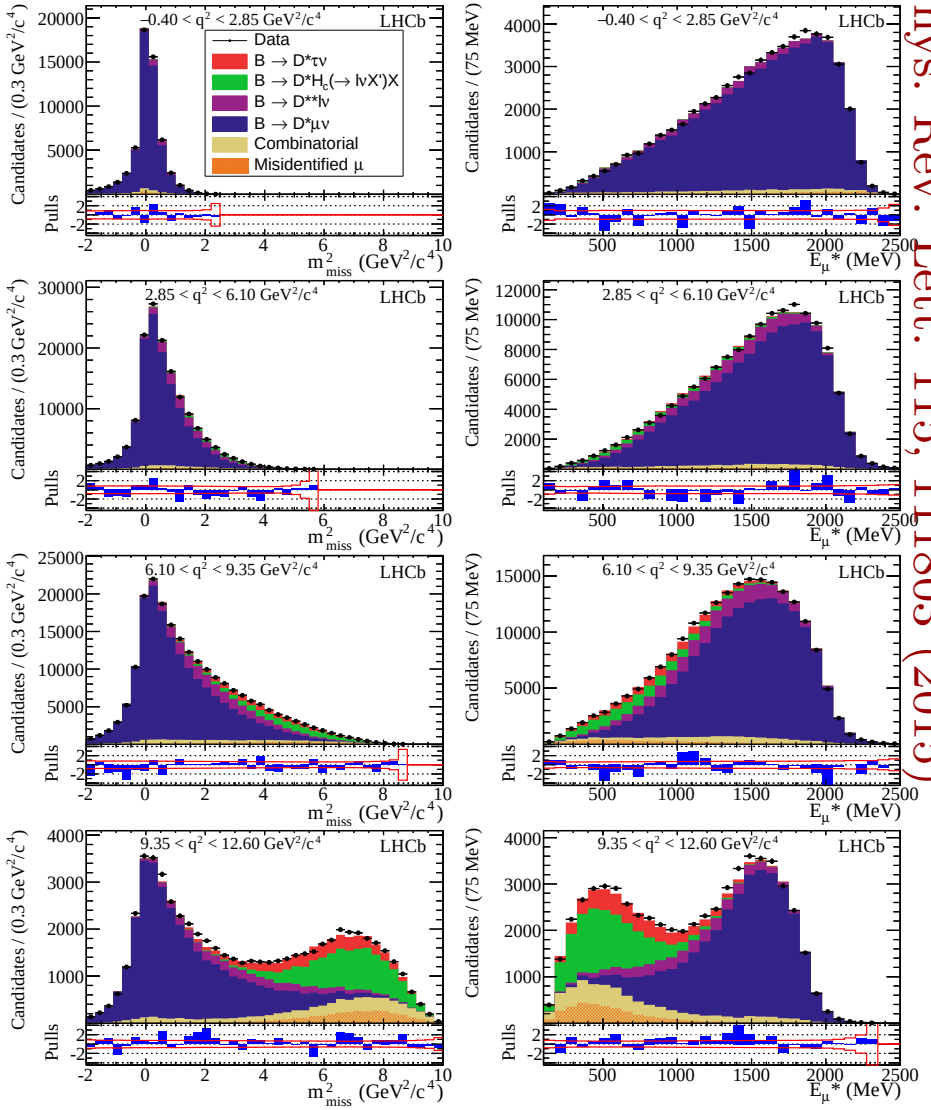
Strategy:

- $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ combined with muons
- Trigger unbiased w.r.t. muons
- Multivariate method to separate from other tracks (to suppress $B \to D^*(\mathrm{n}\pi)\ell$ decays)



Measurement of the Ratio of Branching Fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

- Simultaneous templated fits in 3 variables in the B rest-frame
  - $q^2 = |p_B - p_D|^2$,
  - $m^2_{\text{miss}} = |p_B - p_D - p_\mu|^2$
  - E^*_μ
- Fit also to background-enriched components to understand some of the components
- Large statistics:
  $N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu) = 363000$
  $\frac{N(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} = (4.54 \pm 0.46) \times 10^{-2}$
- Form factor uncertainties folded into the fit
- Additional sources of systematics are sub-dominant



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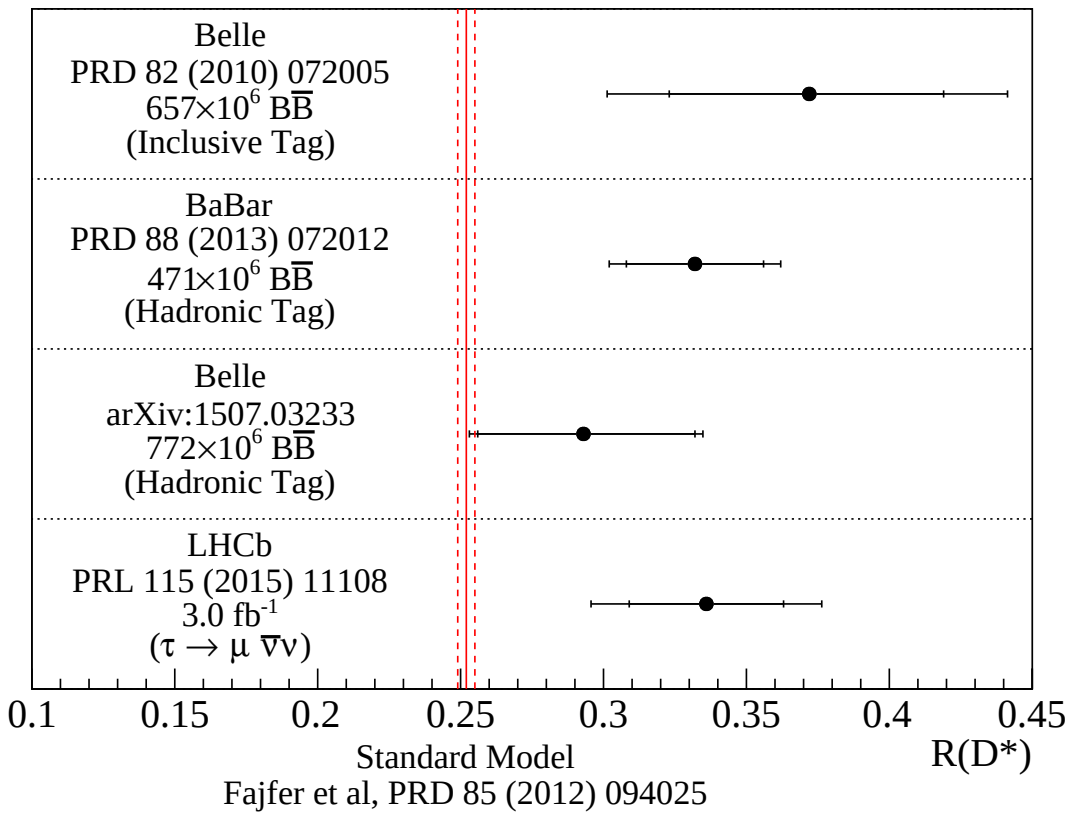
Measurement of the Ratio of Branching Fractions

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

After efficiencies correction:

$$\mathcal{R}(D^*) = 0.336 \pm 0.034$$

in agreement with previous measurements and 2.1σ away from SM prediction of 0.252 ± 0.003



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Outlook: what can LHCb still say with Run I data

- Only a selection of the LHCb analyses presented here
- Some of the presented measurements were performed on 1/3 of the statistics and are being updated with full Run I data.
- Re-optimized analysis will increase sensitivity beyond luminosity scaling
- Many additional "typical" channels are being probed on which world best limits are expected
  - $B \to he\mu$ and $B \to hh'e\mu$
- Some more challenging possibilities are also being developed
  - Inclusive searches for Majorana neutrinos
  - $B \to h\mu\tau$ and $B \to hh'\mu\tau$
- Lepton Universality:
  - R_{K^*} and R_ϕ in the pipeline

Conclusions

- Lepton flavour conservation and universality are accidents of the SM
- Much smaller and more controlled theoretical uncertainties
- Any evidence of LFV or LFNU would point directly to new physics
- LHCb is putting tight constraints on LFV observables
- Two about 2σ indications of LFNU are seen in $B \to K\ell\ell$ and $B \to D^*\ell\nu$ decays
- These can be confirmed already with other channels in Run I
- Run II already has 0.3 fb^{-1} on tape... the best is yet to come

Additional material