Tests of Lepton Flavour Universality with semileptonic decays at LHCb

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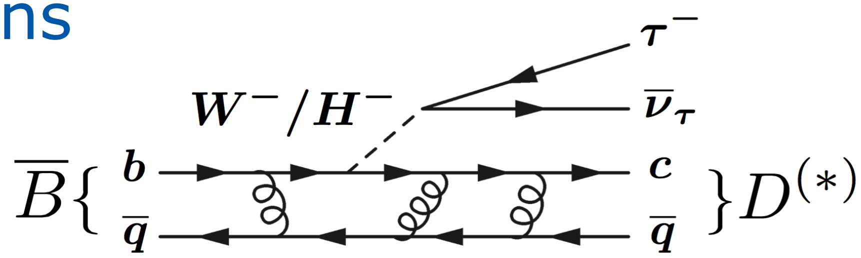
LFU in B decays

- In the SM Lagrangian the **couplings** between gauge bosons and the different lepton families are expected to be the same

→**Branching Ratios** of semileptonic B decays in e, μ and τ differ only for phase space and helicity-suppressed contributions

- Many **New Physics** models envisage favoured interactions with third leptonic family
- **LFU Violation** would be a clear signal of New Physics

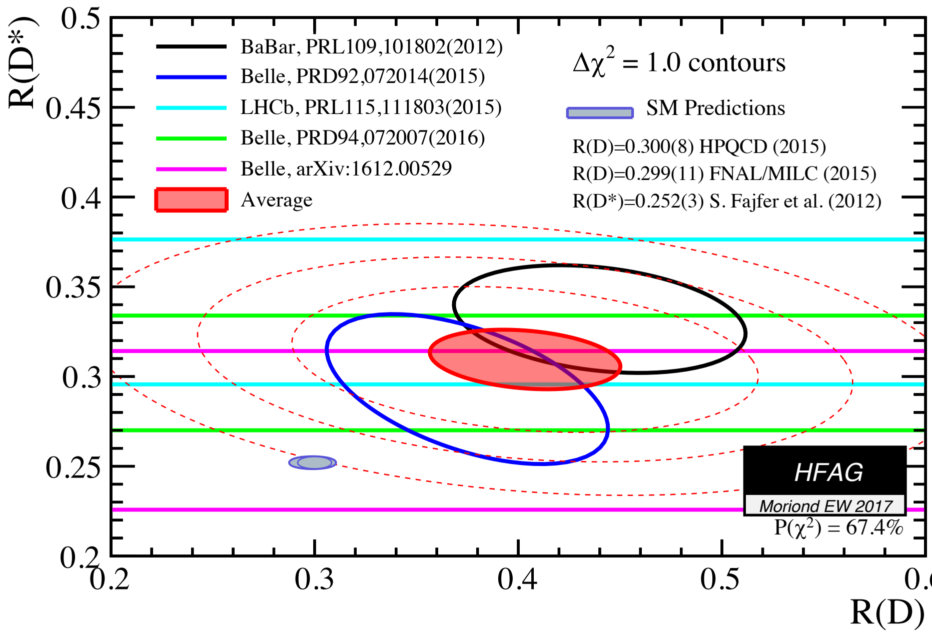


$\mathcal{R}(D^{(*)})$

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

- 5 measurements by **BaBar**, **Belle** and **LHCb**
- $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ combination exceeds SM by $\mathbf{3.9\sigma}$
- LHCb measurement: τ reconstructed in the **muonic** mode $\tau \to \mu\nu\nu$

http://www.slac.stanford.edu/xorg/hfag/semi/index.html



This discrepancy must be **confirmed or disproved**!

$\mathcal{R}(D^*)$ at LHCb (muonic channel)

[PRL **115**, 111803 (2015)]

- **Signal**: $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$, with
  $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$
- **Normalization**:
  $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$
- Main **backgrounds**:
  $B \to D^{**}\mu\nu$,
  $B \to D^* H_c X$ with $H_c \to \mu\nu_\mu X$
- **Isolation**: use MVA to suppress events with additional tracks from the same B

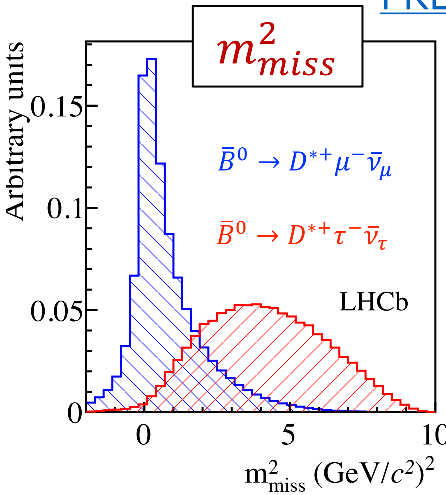
Approximation:

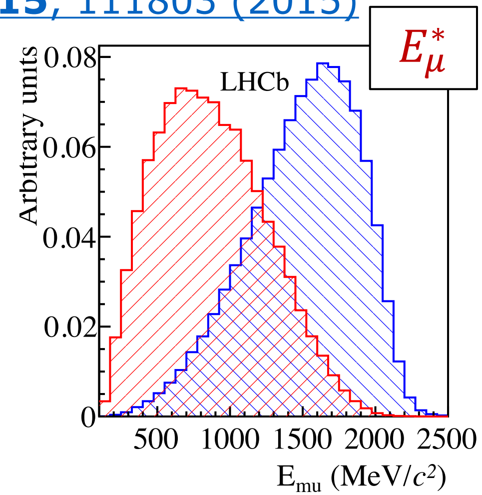
$$\Rightarrow (p_B)_z = m_B/m_{\text{reco}} \cdot (p_{\text{reco}})_z$$

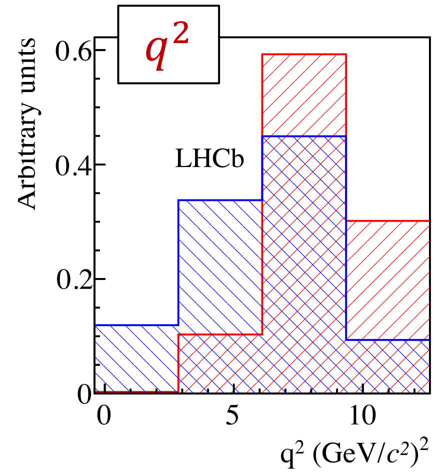
used to compute:

➔ **18%** resolution on p_B

- $q^2 = B - D^*$ transferred 4-momentum
- E^*_μ = muon energy in c.o.m. frame
- m^2_{miss} = squared missing mass

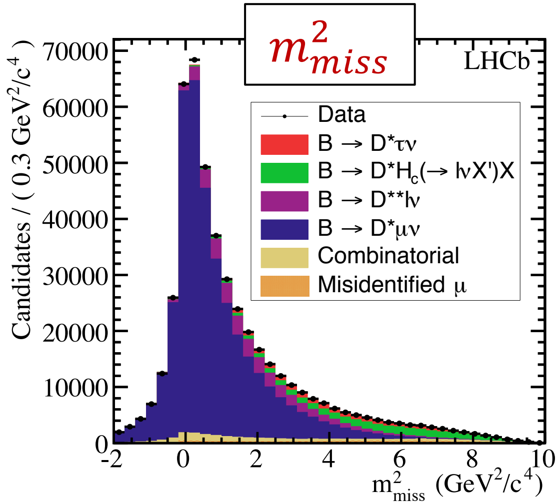


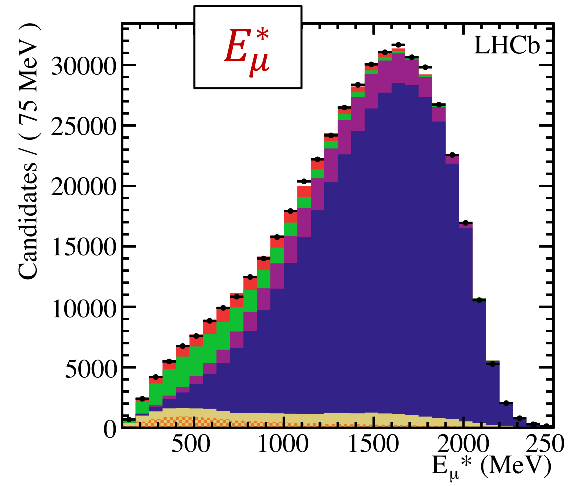




$\mathcal{R}(D^*)$ at LHCb (muonic channel)

- 3D **template** fit on q^2, E^*_μ, m^2_{miss} distributions
- Templates extracted from simulations validated against data
- **Form Factors** floating in the fit





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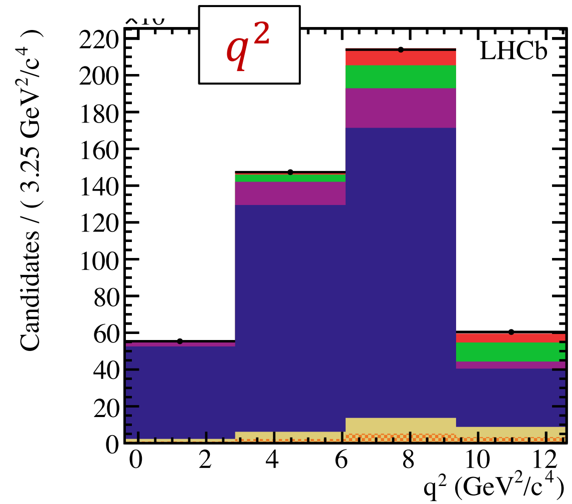


$$\boxed{\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})}$$

2.1σ larger than the SM expectation

$\mathcal{R}(D^*)$ with hadronic τ decays

Select $\boldsymbol{\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau}$ decay channel

Experimentally convenient to measure:

$$\mathcal{R}_{had}(D^*) = \frac{\mathcal{B}\left(B^0 \to D^{*-}\tau^+\nu_\tau\right)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}$$

Signal

Normalization

Same final state

Most of **systematic** uncertainties cancel

$$\mathcal{R}(D^*) = \mathcal{R}_{had}(D^*) \times \boxed{\frac{\mathcal{B}\left(B^0 \to D^{*-}\pi^+\pi^-\pi^+\right)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}}$$

External input

- Pro: good $\boldsymbol{\tau}$ **vertex** reconstruction
- Cons: large hadronic **background**

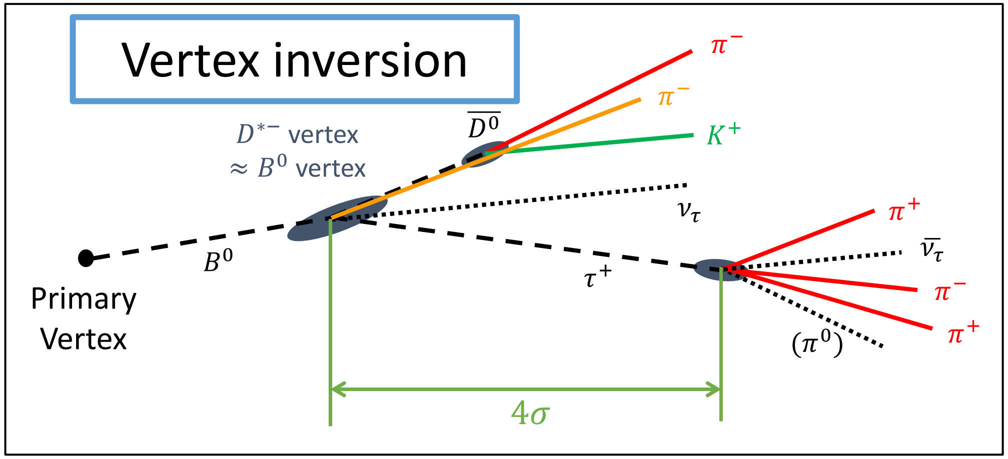
The vertex inversion

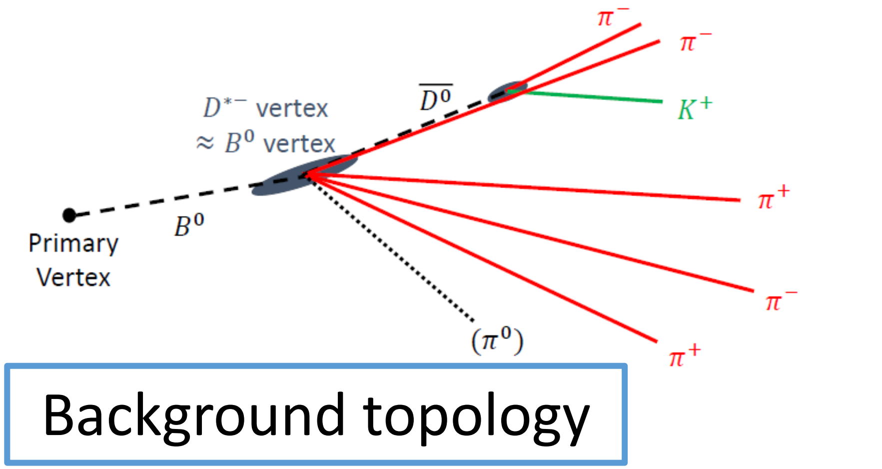
- Most dominant background: $\boldsymbol{H_b \to D^* 3\pi X}$ ($BF \sim 100$ times larger than signal)

➔ Suppressed by requiring the τ vertex to be **downstream** wrt B vertex along beam direction with a 4σ significance

➔ this background is reduced by 3 orders of magnitude

- This can be done thanks to good $\boldsymbol{\tau}$ **vertex** resolution





Double-charmed background

- Background surviving the first selection is dominated by $\boldsymbol{H_b \to D^* H_c X}$, with $H_c \to 3\pi Y$

→ e.g. $\mathcal{B}\left(B^0 \to D^* D_s(\to 3\pi N)\right) \sim 4$ times larger than signal

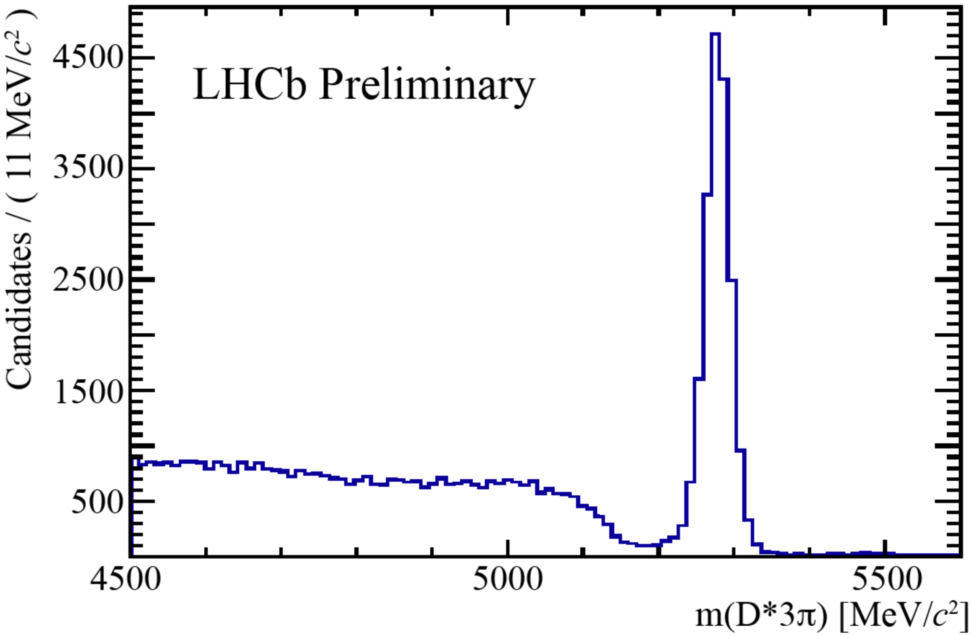
- **Discriminate** this background from signal by training a **BDT** which uses:
    - Variables computed with two **partial reconstruction** techniques (signal and background hypotheses)
    - **Isolation** criteria against charged tracks and neutral energy deposits
    - $\boldsymbol{3\pi}$ system dynamics
- **High BDT** region ($BDT > -0.075$) → used to extract signal yield

Fit strategy

- Partial reconstruction used to compute $\boldsymbol{q^2}$ and $\boldsymbol{\tau}$ **decay time**
- **3-dimensional** shapes of q^2, τ decay time and BDT output are extracted from simulated and data-driven control samples which represent the various contributions in data
- A 3-dimensional extended maximum likelihood **template fit** is performed on data in order to extract signal yield
- 5 categories:
  - Signal $\tau \to 3\pi\nu$ and $\tau \to 3\pi\pi^0\nu$
  - $B^0 \to D^{**}\tau\nu$
  - Double-charmed components
  - $B^0 \to D^* 3\pi X$
  - combinatorial

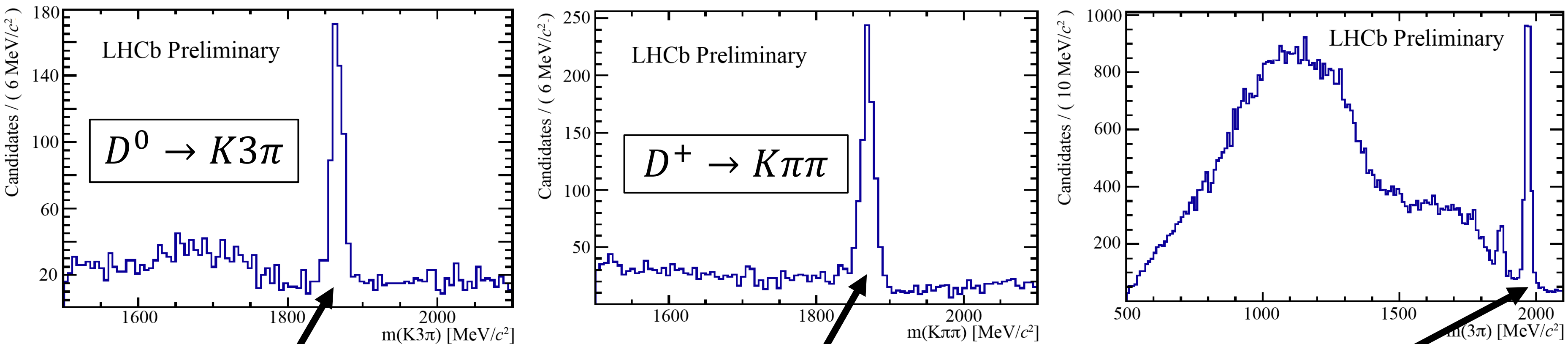
Normalization channel

- **Normalization** obtained requiring the τ vertex to be **upstream** wrt D^0 vertex
- Very similar to signal → **systematics** linked to trigger, particle ID and selection cancel out
- Small **residual** effects on efficiency ratio due to different kinematics of D^* and soft π



Fit $\boldsymbol{B^0 \rightarrow D^* 3\pi}$ mass peak to extract normalization yield

Control channels



Anti-isolation cut

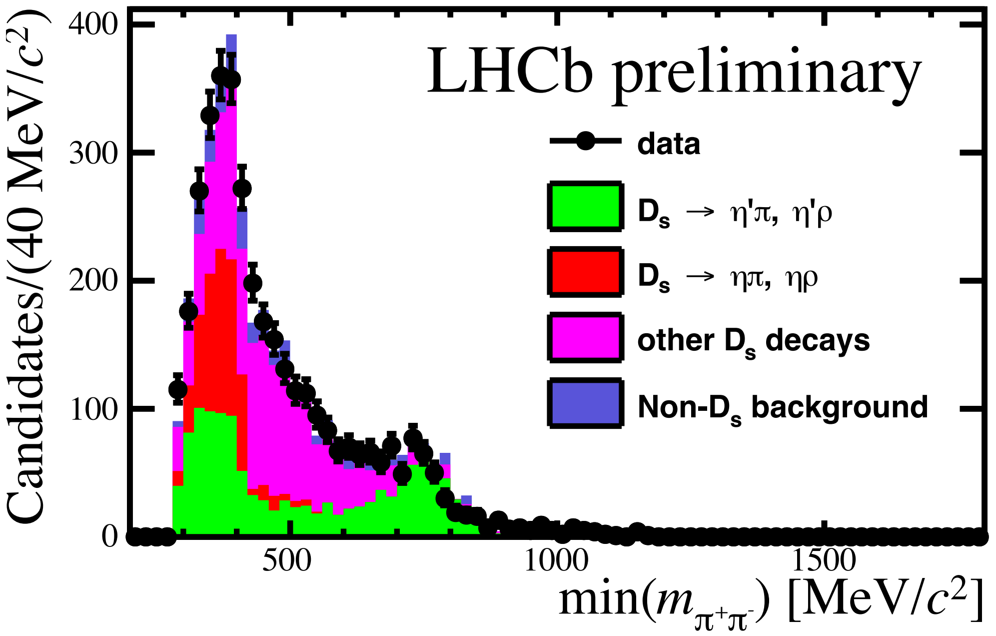
Anti-PID cut

Pure D_s **peak** at early stage of selection

Used to check data and MC **agreement**

D_s decay model

- Relative fractions of various $\boldsymbol{D_s \to 3\pi X}$ decays are not well known ➔ we can determine them on data in **low BDT** region (enriched in such decays)
- Fit $\min[m(\pi^+\pi^-)]$, $\max[m(\pi^+\pi^-)]$, $m(\pi^+\pi^+)$, $m(3\pi)$ distribution
- Get a **constraint** to the D_s decay model to be used at high BDT



Main systematics sources

- Dominated by limited **MC statistics**

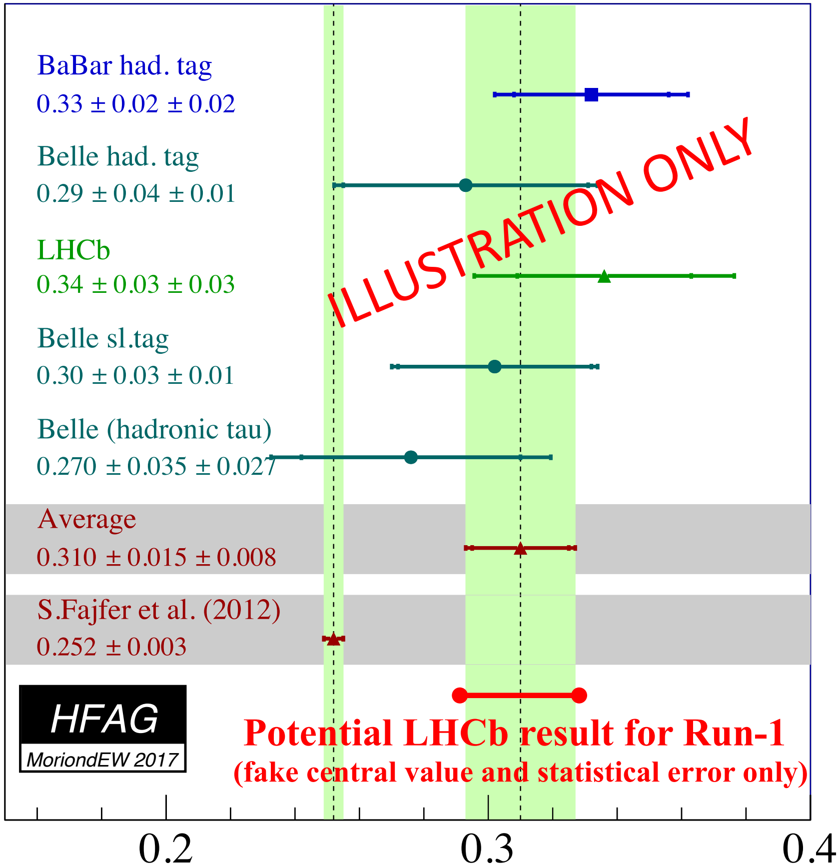
➔ Will be improved with more MC

- Decay models of **double-charmed** backgrounds
- External: $\mathcal{B}(B^0 \to D^* 3\pi)$ → 4.3% contribution, recently measured by BaBar [Phys. Rev. D 94, 091101 (2016)]
- External: $\mathcal{B}(B^0 \to D^* \mu\nu)$ → 2% contribution

➔ Knowledge of **external BRs** can be reduced with the help of other experiments

Conclusions

- **Semileptonic** decays in LHCb provide a good test for LFU
- Important measurement of $\mathcal{R}(D^*)$ with **muonic** τ decay channel
- **Hadronic** $\mathcal{R}(D^*)$:
  - No results yet → please stay tuned!
  - Statistical precision with **Run 1**: **~7%** → **competitive** with the muonic LHCb measurement and with the world average
- Many **other analysis** ongoing → $\mathcal{R}(D)$, $\mathcal{R}(J/\psi)$, $\mathcal{R}(D_s)$, $\mathcal{R}(\Lambda_c)$



Adapted from:

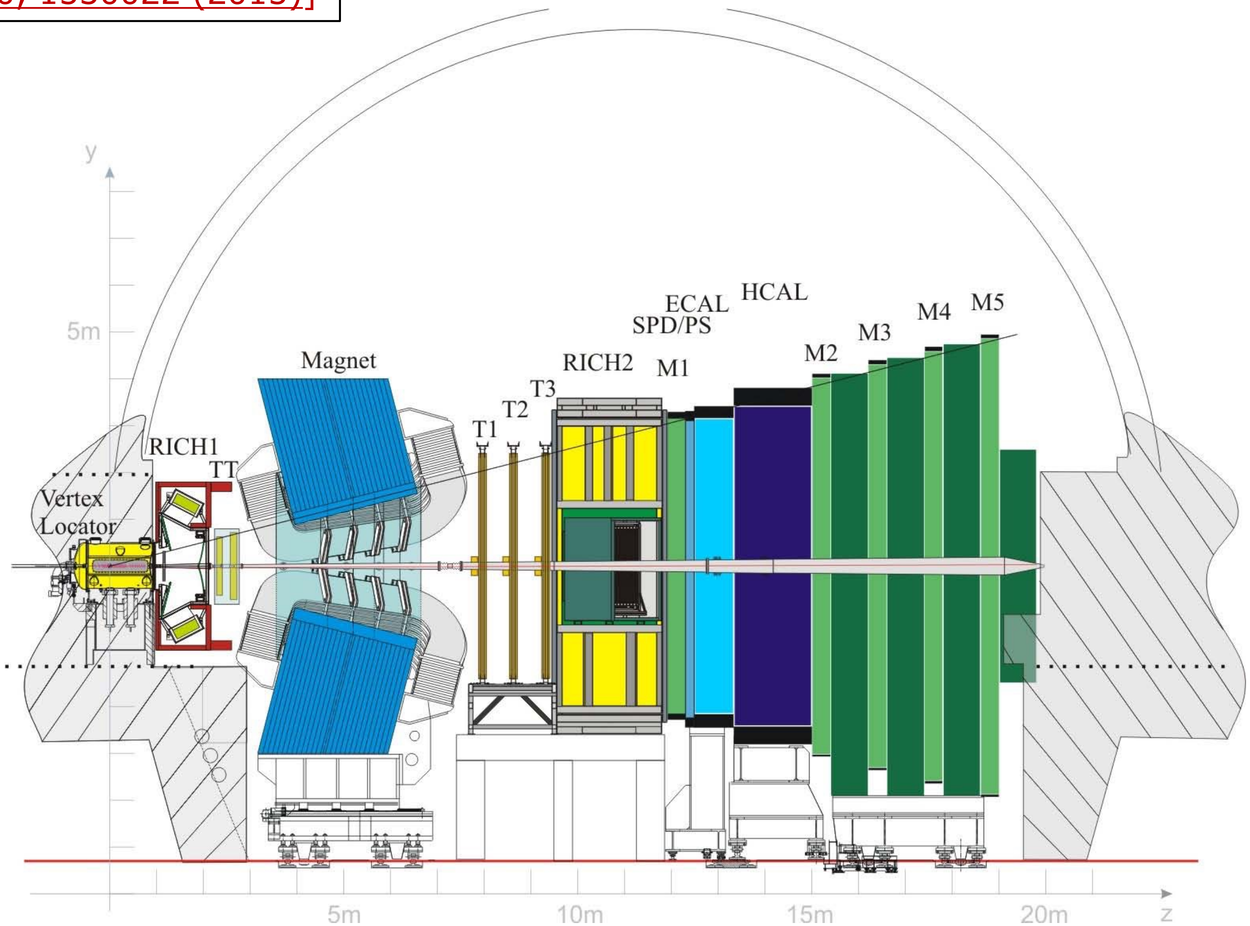
http://www.slac.stanford.edu/xorg/hfag/semi/index.html

Backup slides

The LHCb detector

[Int. J. Mod. Phys. A 30, 1530022 (2015)]

- Single arm spectrometer in $2 < \eta < 5$ range
- Excellent **vertex** resolution ($13\ \mu\mathrm{m}$ in transverse plane for primary vertex)
- Excellent **IP** resolution ($\sim 13\ \mu\mathrm{m}$ on the transverse plane)
- Very good **momentum** resolution ($\delta p/p \sim 0.5\% - 0.8\%$)
- Excellent **PID** capabilities
- Very good **trigger** efficiency ($\sim 90\%$)



Prospects for other final states

Other ongoing analyses in LHCb:

- $\bar{B}^0 \rightarrow D^+\tau^-\bar{\nu}_\tau$
- $\Lambda_b^0 \rightarrow \Lambda_c^{*+}\tau^-\bar{\nu}_\tau$
- $B_c^- \rightarrow J/\psi\tau^-\bar{\nu}_\tau$
- $\bar{B}_s^0 \rightarrow D_s^+\tau^-\bar{\nu}_\tau$
- $\Lambda_b^0 \rightarrow \Lambda_c^+\tau^-\bar{\nu}_\tau$

Muonic τ channel

Hadronic τ channel