Test of Lepton Flavour Universality with semitauonic decays of b-hadrons at LHCb

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Lepton Universality

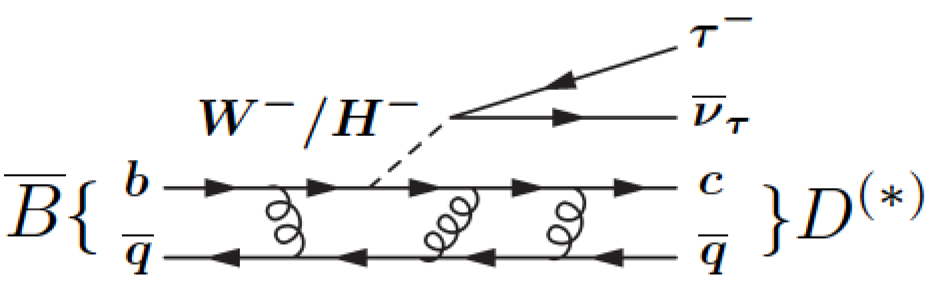
- In the Standard Model, the couplings of the gauge bosons to leptons are independent of the lepton flavour
  - Charged Lepton Universality implies that the branching fractions of e, μ and τ differ only by phase space and helicity-suppressed contributions
- The Lepton Flavour Universality (LFU) is enforced in the SM by costruction
  - Any violation of lepton universality would be a clear sign of physics beyond the SM.
- Over the years, LFU violation has been searched in several system
  - $Z \to ll$, $W \to l\nu$, $J/\psi \to ll$, $\psi(2S) \to ll$, $\Upsilon \to ll$, $\tau \to l\nu\bar{\nu}$, $\pi \to l\nu$, $K \to (\pi) l\nu$
  - These measurements provide very strong limit in the non-universality in the SM EW sector
  - More significant tests involve the 1° and 2° quarks and leptons families

Lepton Universality

- Hints of LFU violation in $B^+ \rightarrow K^+ l^+ l^-$ ($l=e,\mu$) (PRL 113(2014) 151601)
    - New measurements necessary in semileptonic decays

- A large class of SM extensions contain new interactions that involve third generation of quarks and leptons
    - Higgs-like charged scalar: $H^{\pm}$, new vectors coupled to SM Higgs doublet, leptoquarks, 2 Higgs doublets model (2HDM type II or III)…

- A quantity sensitive to contribution beyond the SM is the branching fraction of $\overline{B}^0 \rightarrow D^* \tau^- \overline{\nu}$



$B^0 \rightarrow D^* \tau \nu$

- $BR(B^0 \rightarrow D^* \tau\nu) = (1.84 \pm 0.22)\ \%$ → no rare decay
- $$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\mathrm{p}| q^2}{96\pi^3 m_B^2}\left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[\left(|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2\right)\left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3}{2}\frac{m_\tau^2}{q^2}|H_{0t}|^2\right]$$
    - $H_{00,++,--}$: elicity amplitudes common to e,μ,τ
    - H_{0t}: relevant only for tauonic decays.

- The ratio R(D*) is defined:

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

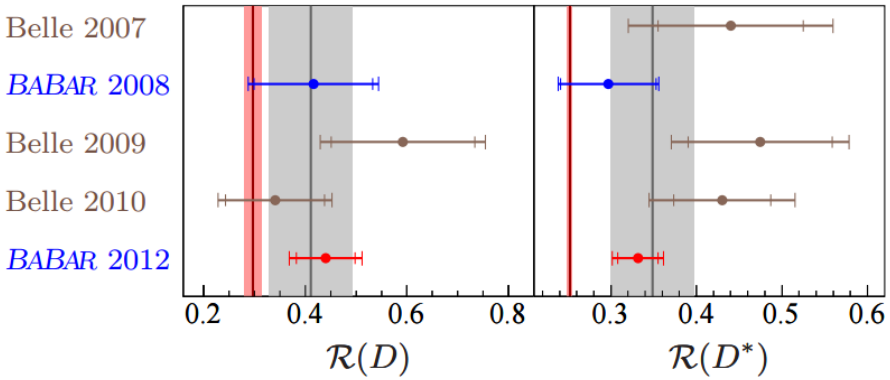
- It is theoretically clean due to cancellation of $|V_{cb}|$ and form factors uncertainties
    - R(D*) = 0.252 ± 0.003 (PRD 85094025 (2012))
- It is experimentally clean with muonic tau decays

$$B(\tau^- \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau) = (17.41 \pm 0.04)\%$$

- Several uncertainties cancel in ratio:
    - D* recostruction, Particles identification and tracking efficiencies

R(D*)

- R(D*) measurements until 2015 (PRD 88, 072012(2013))



- R(D*): 2.7σ from SM prediction
- Combination of R(D*) and R(D): 3.4σ from SM prediction

- New result from Belle (see Christoph SCHWANDA's talk)

- B factory measurements are based on recostructing missing mass using opposite side recostruction

- Not possible to LHCb:
  - Unconstrained kinematics due to unkown parton-parton collision energy and neutrinos in the final state

R(D*)@LHCb: experimental challenge

(PRL115,111803(2015))

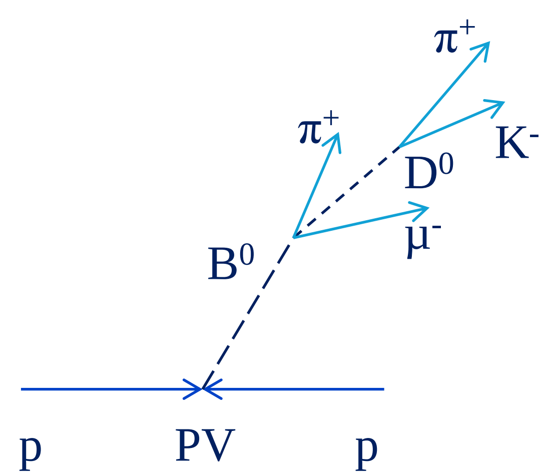
- *Additional tracks*: underlying event, MPI and Jets

- *Large background*: partially reconstructed B decays

- *Unconstrained kinematics* due to unknown parton-parton collision energy and neutrino in the final state
  - B^0 direction well determined by unit vector from PV to B vertex decay
  - Assuming that the velocity of visibile part of semileptonic decay along the beam axis is equal to the b hadron velocity →

$$(p_B)_z = \frac{m_B}{m_{D^*\mu}}(p_{D^*\mu})_z$$

$$|p_B| = \frac{m_B}{m_{D^*\mu}}(p_{D^*\mu})_z\sqrt{1+\tan^2\alpha}$$

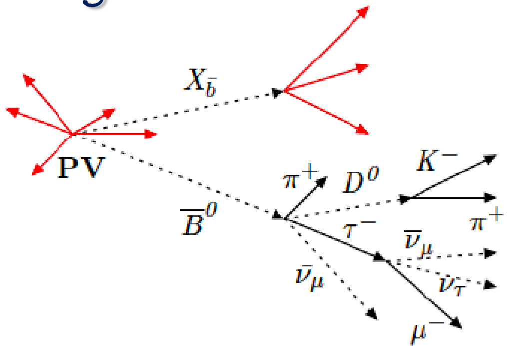


- 18% resolution on p_B

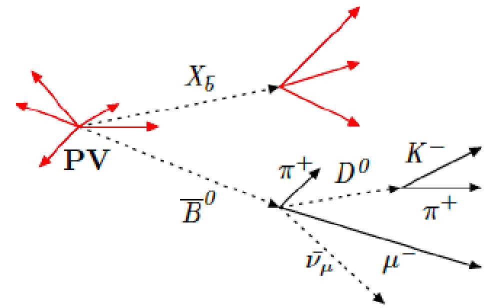
R(D*) @LHCb

- Data sample: 3 fb^{-1} collected @LHCb during 2011 and 2012, $\sqrt{s}$ = 7,8 TeV

Signal $B^0 \rightarrow D^{*}\tau\nu$



Normalization $B^0 \rightarrow D^{*}\mu\nu$



- Trigger
  - charm trigger: selection on $D^0 \rightarrow K\pi$ with high p_T and displaced vertex
  - no trigger on p_T muon to not bias the signal kinematics distruibutions

- **$\varepsilon_\tau / \varepsilon_\mu$ = (77.6 ± 1.4) %**
  - signal losses due to lower p_T and worst vertex in tau decay

- Distinguish between signal and normalization channel
  - Identical particles in the final states for signal and normalization channel

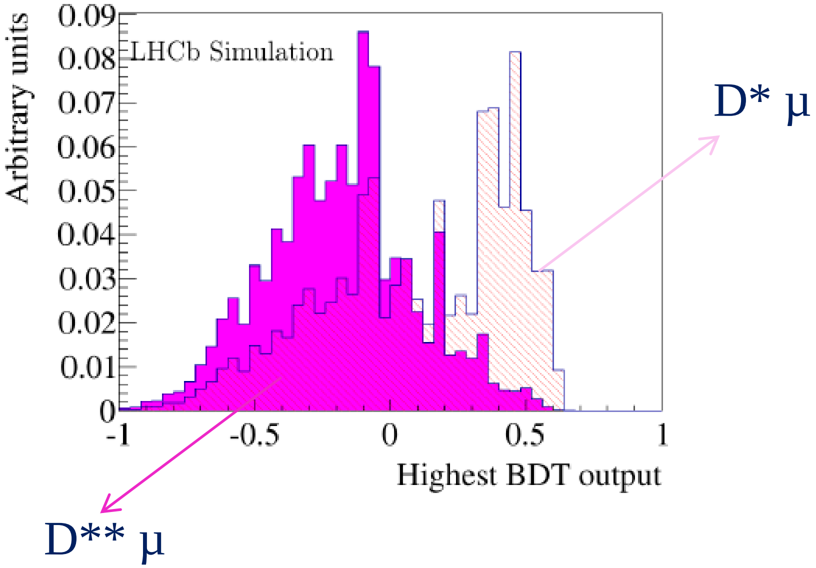
- Large background: $B \rightarrow D^{**}\mu\nu_\mu$ and $B \rightarrow D^{*}\mu\nu_\mu$
- Most dangerous backgrounds:
  - $B \rightarrow D^{**}\mu\nu_\mu$, $B \rightarrow D^{*} n\pi\mu\nu_\mu$, $B \rightarrow D^{*} H_c X$ (any possible $H_c \rightarrow Y\mu\nu_\mu$)

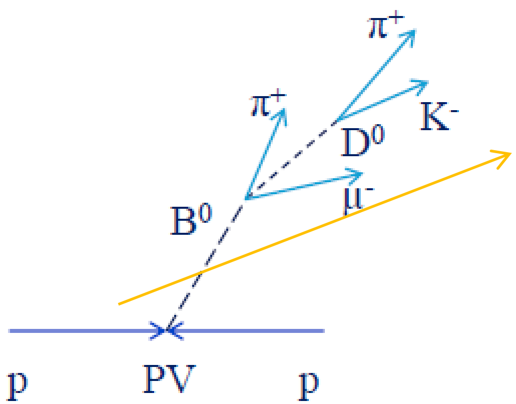
Isolation MVA

(PRL115,111803(2015))

- Multivariate approach to reject the backgrounds $B \to D^{**}\mu\nu_\mu$ with additional charged track around the B vertex with respect to signal.

  - Data sample enriched in $B \to D^{*}\mu\nu_\mu$ and $B \to D^{*}\tau\nu_\tau$





- Alternative requirement allow to select three data control samples used in the backgrounds analysis:

  - $B \to D^{*}\mu X\, \boldsymbol{\pi}$
  - $B \to D^{*}\mu X\, \boldsymbol{\pi\, \pi}$
  - $B \to D^{*}\mu X \mathbf{K}$

$B^0 \to D^* \tau \nu$ and $B^0 \to D^* \mu \nu$

(PRL115,111803(2015))

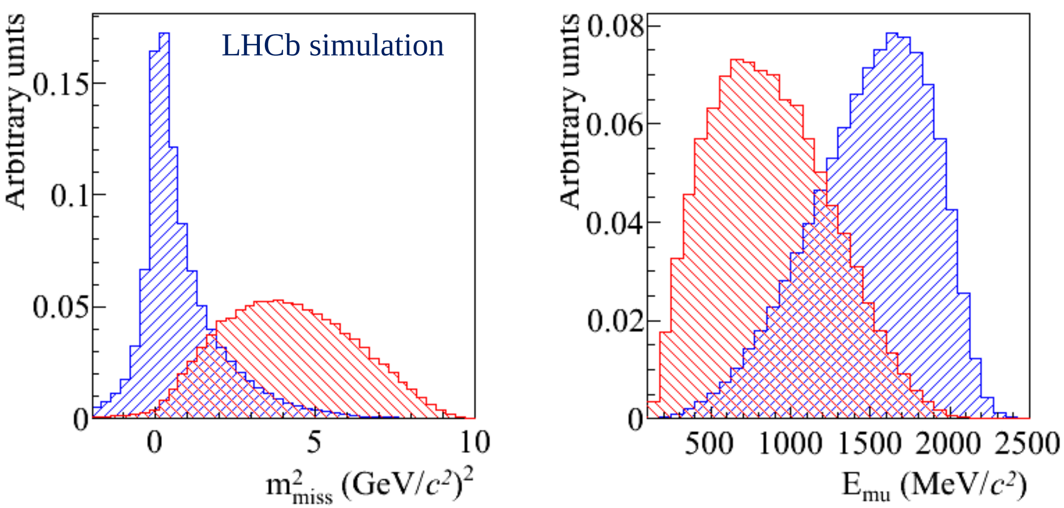
- In the B rest frame, three kinematics variables allow to distinguish $B^0 \to D^* \tau \nu$ and $B^0 \to D^* \mu \nu$

- $m^2_{miss} = (p_B - p_{D^*\mu})^2$

- $q^2 = (p_B - p_{D^*})^2$

- E^*_l: energy of lepton

$B^0 \to D^* \tau \nu$	$B^0 \to D^* \mu \nu$
$m^2_{miss} > 0$	$m^2_{miss} = 0$
E^*_l spectrum is soft	E^*_l spectrum is hard
$m_\tau^2 \leq q^2 \leq 10.6\ GeV^2$	$0 \leq q^2 \leq 10.6\ GeV^2$



- $B^0 \to D^* \tau \nu$, $B^0 \to D^* \mu \nu$ MCs

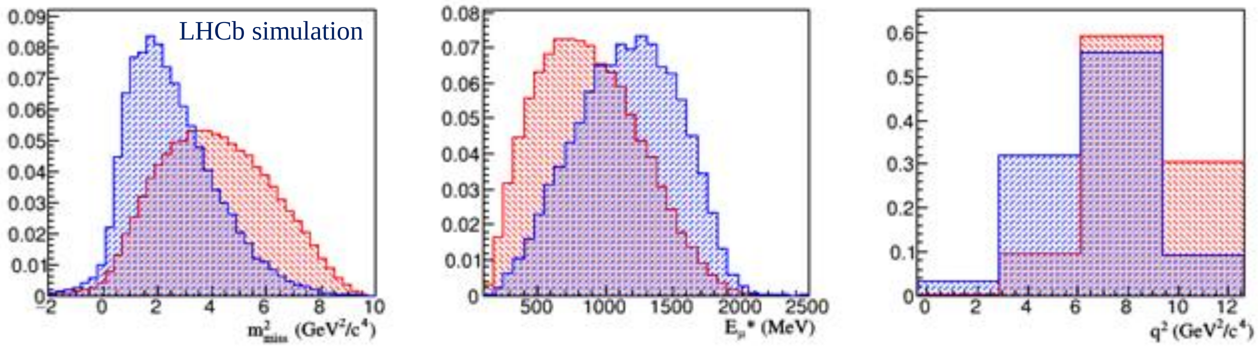
Fit strategy

(PRL115,111803(2015))

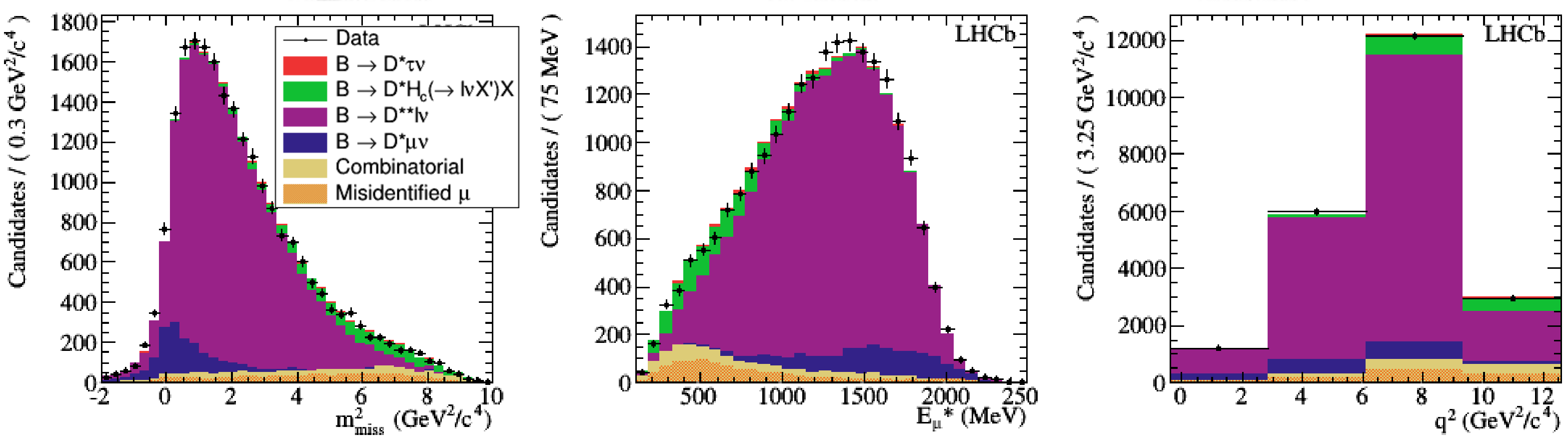
- Maximum Likelihood Fit to binned m^2_{miss}, E^*_l and q^2 distributions with 3D templates representing $B^0 \to D^* \tau \nu$, $B^0 \to D^* \mu \nu$ and background sources
  - Simulated and data templates are validated on separate fits on data control samples
- All uncertainties on the template shapes are incorporated in the fit:
  - uncertainties due to finite number of simulated events → incorporated in the L using Beeston Barlow "lite" procedure
  - uncertainties with bin to bin correlation → incorportated via interpolation between nominal and alternative histograms (e.g factor form)

$B \to D^{**}\mu\nu_\mu$

- $B \to D^{**}\mu\nu_\mu$ refers to any higher charm resonances or not resonant hadronic mode
- Known resonances: $D_1(2420)$, $D_2^*(2420)$, $D_1'(2430)$
  - Separate templates for $D_1(2420)$, $D_2^*(2420)$, $D_1'(2430)$
  - Use LLSW model (Phys.Rev.D.(1997) 57 307) with Isgur Wise function slope floated
  - Parameters constraints and validation of model performing a fit on $B \to D^*\mu\pi$



•$B^0 \to D^*\tau\nu$
•$B^0 \to D_1(2420)\mu\nu$



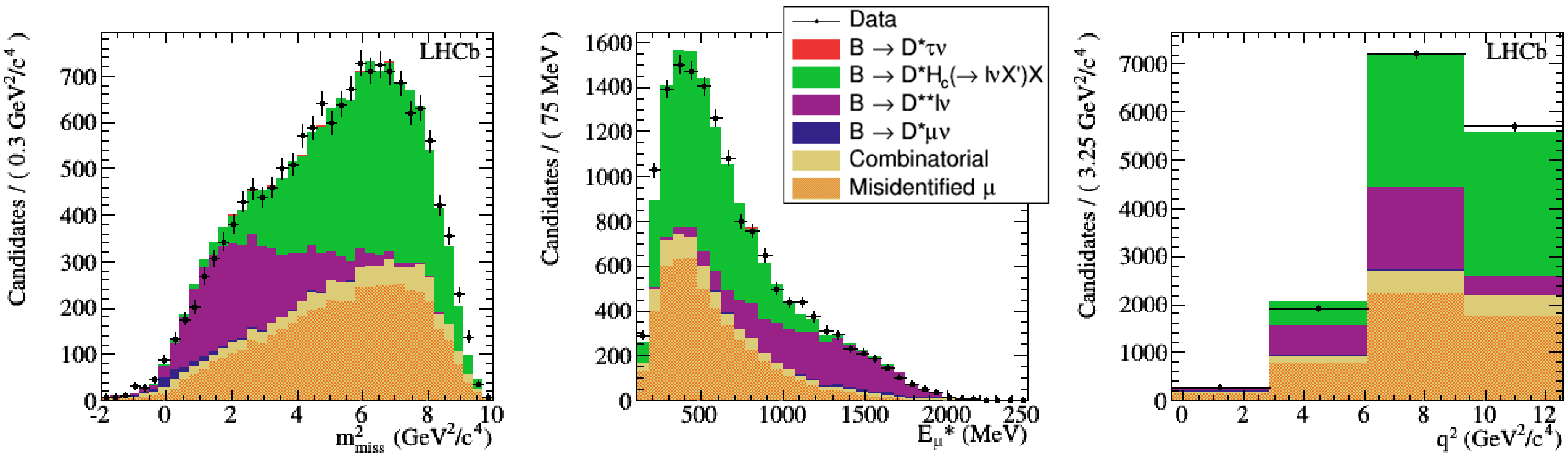
(PRL115,111803(2015))

$B \to D^{**}\mu\nu_\mu$

(PRL115,111803(2015))

- Semipletonic decay to heavier charmed hadrons decaying as $D^{**} \to D^*\pi\pi$

Since the resonances which contribute to final states and their form factors are not known → a fit on the $B \to D^*\mu X \pi \pi$ control sample is performed to tuned the q^2 distribution



- The contribution of $B \to D^{**}\mu\nu_\mu$ to semimuonic decay mode is ~12%

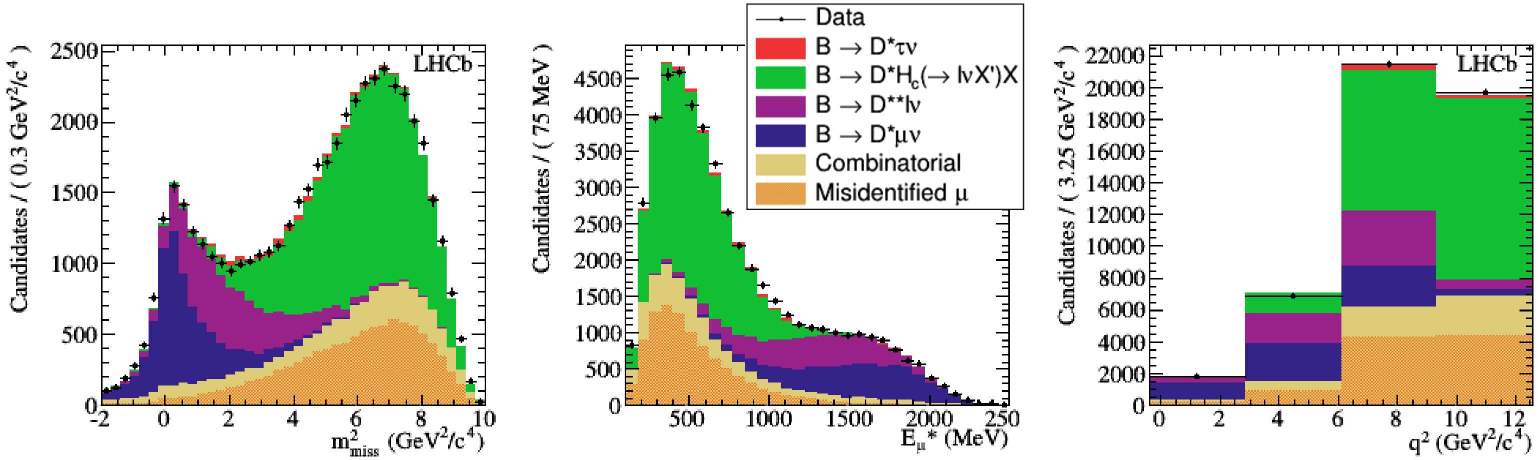
- Similar parametrization are used to semitauonic D** decay mode

$B \rightarrow D^{*}H_c(\rightarrow \mu\nu_\mu X)X$

- These processes occur the 6-8% of normalization mode (PRL115,111803(2015))

- The templates are generated using a cocktail of simulated B^0 and B^+ decays in appropriate final states

- Isolation MVA selects track with loose Kaon ID → select a sample enriched in $B \rightarrow D^{*}\mu K$
- Use to constrain, correct and justify the $B \rightarrow D^{*}H_c(\rightarrow \mu\nu_\mu X)X$ shapes



- Similar simulated sample for tertiary muon decays $B \rightarrow D^{*}D_s$ with $D_s \rightarrow \mu\nu_\mu$

Other backgrounds

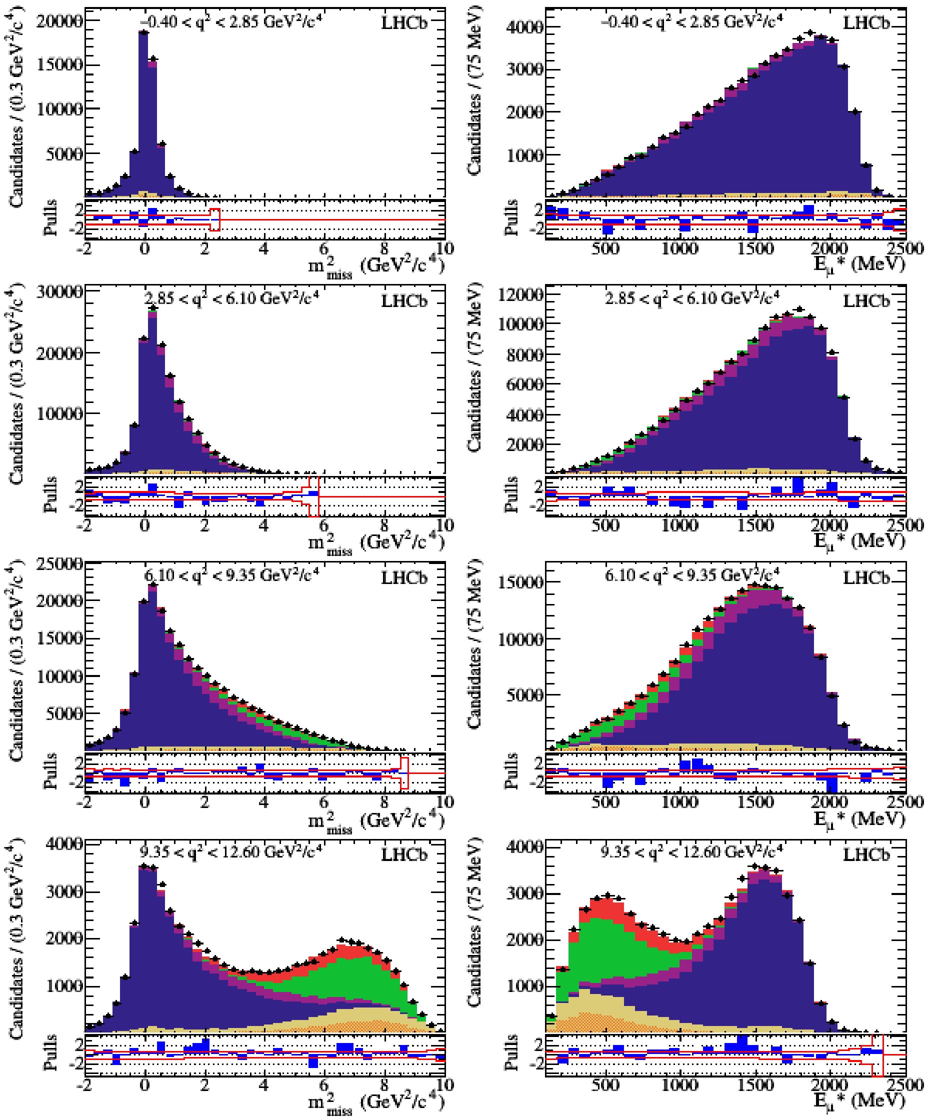
(PRL115,111803(2015))

- Hadrons misidentified as muons:
  - The kinematic distributions are derived from D*h sample
  - Sample of D* and Λ events are used to obtain the misidentification probabilities of p, K, π in data

- Combinatorial background:
  - Wrong sign $D^0\mu^-\pi^-$ events to determine the D^{*+} misreconstructed
  - Wrong sign $D^{*+}\mu^+$ sample to indentify the μ^+ from unrelated b hadron decays

Fit Result

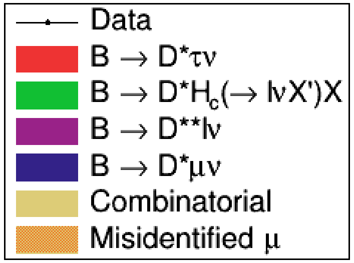
(PRL115,111803(2015))



- Fit determines the yields fraction of the two decays:

$$\frac{N(B^0 \to D^{*-}\tau^+\nu_\tau)}{N(B^0 \to D^{*-}\mu^+\nu_\tau)} = (4.54 \pm 0.46)\%$$

- To convert to R(D*)
  - account for $\varepsilon_\tau/\varepsilon$
  - $B(\tau \to \mu\nu\nu)$



q² bins

Systematics

(PRL115,111803(2015))

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$B^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

- Largest systematics from simulation statistics → reducible
- The uncertainties of the μ shape is determined by comparing results of two different method to extract the shape
- Depends on the control sample size → scale down with more data → run2

- The total systematic uncertaintiy is 3%

R(D*) measurement result

- LHCb measured (PRL115,111803(2015)):

$$R(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$$

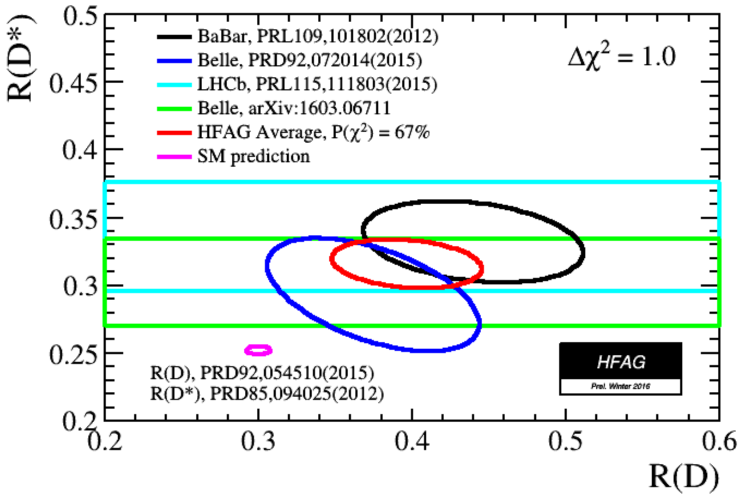
- SM calculations excpects (PRD 85094025 (2012)):

$$R(D^*) = 0.252 \pm 0.003$$

  - LHCb measurement is 2.1 σ from SM prevision

HFAG average of R(D) and R(D*) :
Combination average, including correlations, is 4σ from SM prevision

Recent R(D*) measurements		
BaBar	0.332±0.024±0.018	Phys.Rev.D 88, 072012 (2013)
Belle	0.293±0.038±0.015	Phys.Rev.D 92, 072014 (2015)
Belle	0.302±0.030±0.011	Preliminary at Moriond EW 2016
LHCb	**0.336 ±0.027±0.030**	**Phys.Rev.Lett.115,111803 (2015)**



Ongoing and future LHCb measurements

- R(D*) measurement with $\tau \to \pi\pi\pi(\pi^0)\nu$
  - external imput (Br($B \to D^*\pi\pi\pi$)) from B factories to reduce the systematics
- R(D) measurement
  - feed-down background from D^* and D^{**}
- R(D_s) measurement
  - separation of D_s ground state from $D^*_{s(1,2,J)}$ ($\to D_s$ + neutral)
- R(Λ_c) and R(Λ_c*) measurements
  - only LHCb measurement can explore Λ_b

Conclusions

- Recent hints of Lepton Flavour Universality Violation and the longstanding tesion between $|V_{ub}|$ and $|V_{cb}|$ from exclusive and inclusive B decay measurements push to new measurements in semileptonic decays
- A large class of SM extensions contain new interactions that involve third generation of quarks and leptons

  $\rightarrow$ semitauonic decays are under investigation

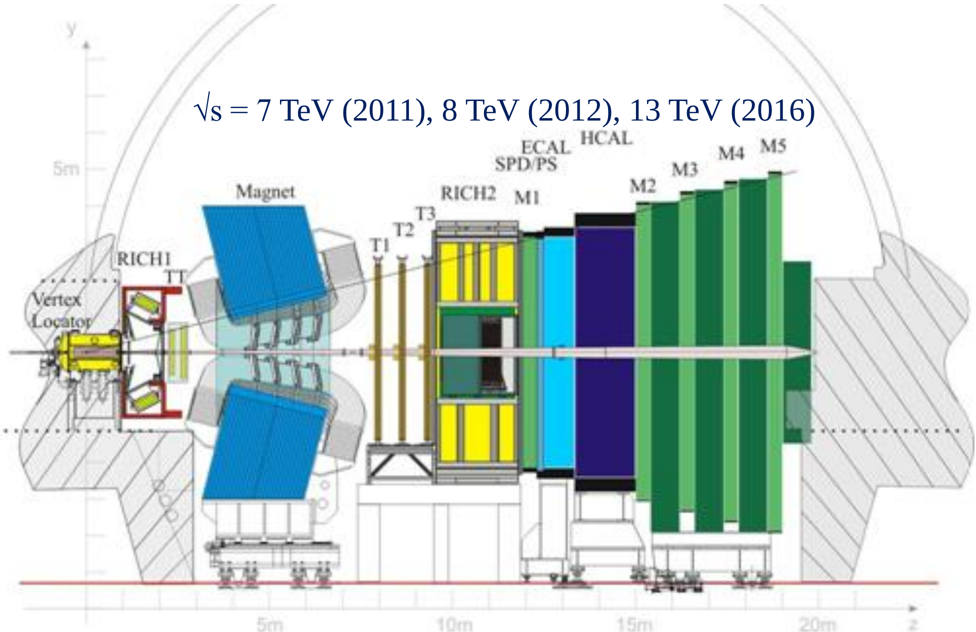
- LHCb performed the first measurement of $B \rightarrow X\tau\nu_\tau$ at a hadron collider: R(D*)
  - The precision result similar to B factories measurements
  - The dominant systematic is the MC statistic $\rightarrow$ fast simulation will allow to improve this
  - Most other systematic scale with data or control samples $\rightarrow$ improvements with LHC run2

- The LHCb R(D*) measurement results in agreement at 2.1 with respect to SM
- The R(D*) and R(D) averages combination of the measurements from LHCb and B factories is 4σ discrepant with respect to SM prevision

Thank you for your attention

The LHCb @ LHC

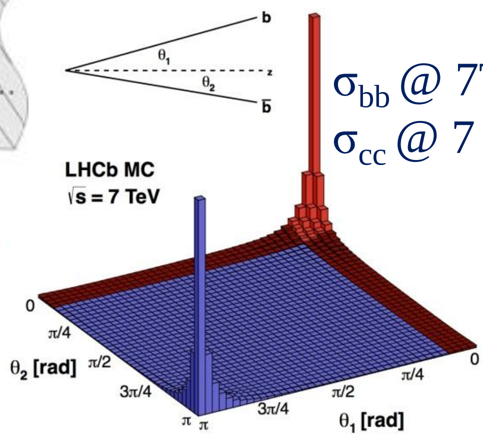
- Single arm spectrometer optimized for beauty and charm physics



➢ Dominant production mechanism

gluon fusion

➢ Partons CM frame highly boosted



σ_{bb} @ 7TeV ~ 280μb
σ_{cc} @ 7 TeV ~ 6mb

- *Precise vertex resolution:*
  - impact parameter resolution: 20 μm for high-pT tracks
  - σ_{τ} ~ 45 fs for $B_s \rightarrow J/\psi\phi$
- *High momentum resolution:*
  - σ_p / p ~ 0.4 - 0.6 % for momenta up to 200GeV/c
- *Particles identification:*
  - ~ 97 % for 1-3 % $\pi\rightarrow\mu$ mis-id probability
- *High trigger efficiencies:*
  - ~ 90 % for dimuon channels, ~ 30 % for multi-body hadronic final states