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

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On behalf of the LHCb Collaboration

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EPS

Wien 24 July 2015

Motivations

- CKM mechanism is well tested, but there is still room for NP if mostly coupled to third generation
  - Obvious example: two Higgs doublets (2HDM type II or type III)

- Lepton flavour universality enforced in SM by construction
  - Any violation of LFU would be a clear sign of NP

- Existing hints of non universality in $B^+ \to K^+ l^+ l^-$ (l=e,μ) and tensions among V_{ub}(V_{cb}) parameters measured with inclusive/exclusive semileptonic decays
  - New measurements in the lepton sector are required.

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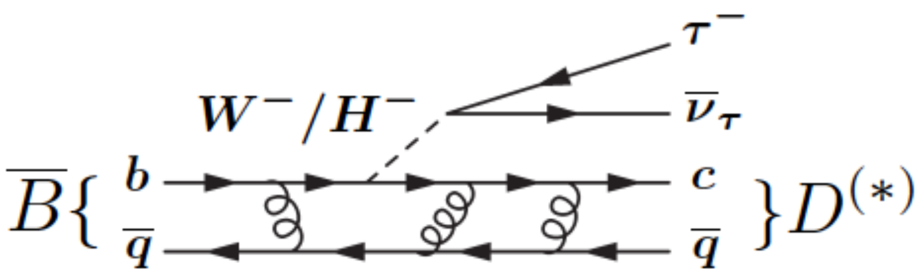
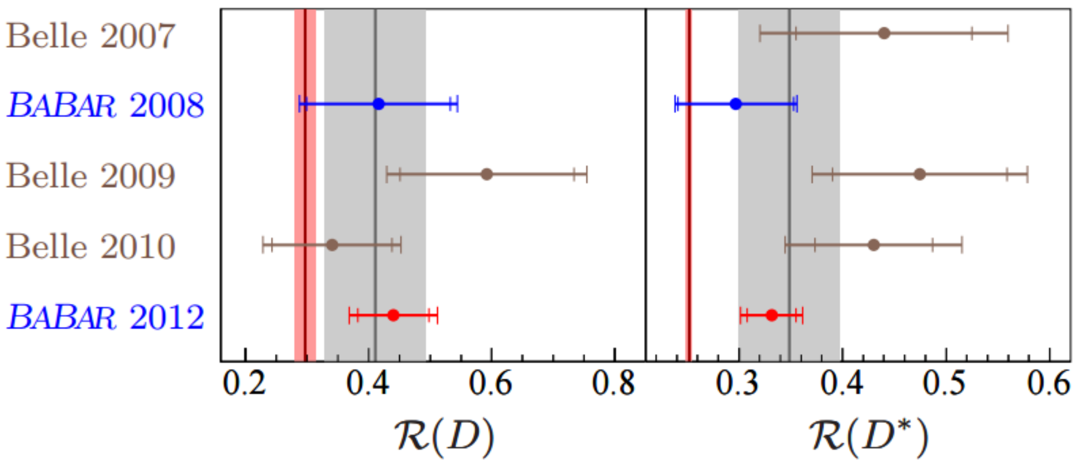
$B^0 \to D^{(*)} \tau \nu_\tau$

- B semileptonic decays well described in the SM
  - Charged lepton universality implies branching fractions to e,μ,τ differ only for phase space and helicity-suppressed contributions

- $B^0 \to D^{(*)}\tau\nu$ sensitive to NP



- Babar and Belle measurements hint to deviation from SM



PRD 88, 072012(2013)

R(D*)

- Precise measurement of $B \rightarrow X\tau\nu_\tau$ decay considered unfeasible at hadronic colliders so far
  - no kinematic constraint (as in B Factories) and large backgrounds
- Take ratio of branching fractions, with $\tau \rightarrow \mu\nu_\mu\nu_\tau$ decay
  - The two modes have same visible final state particles

$$R(D^*) \equiv \frac{\mathrm{B}\left(\overline{B}^0 \rightarrow D^{*+}\tau^-(\mu^-\overline{\nu}_\mu\nu_\tau)\overline{\nu}_\tau\right)}{B\left(\overline{B}^0 \rightarrow D^{*+}\mu^-\overline{\nu}_\mu\right)}$$

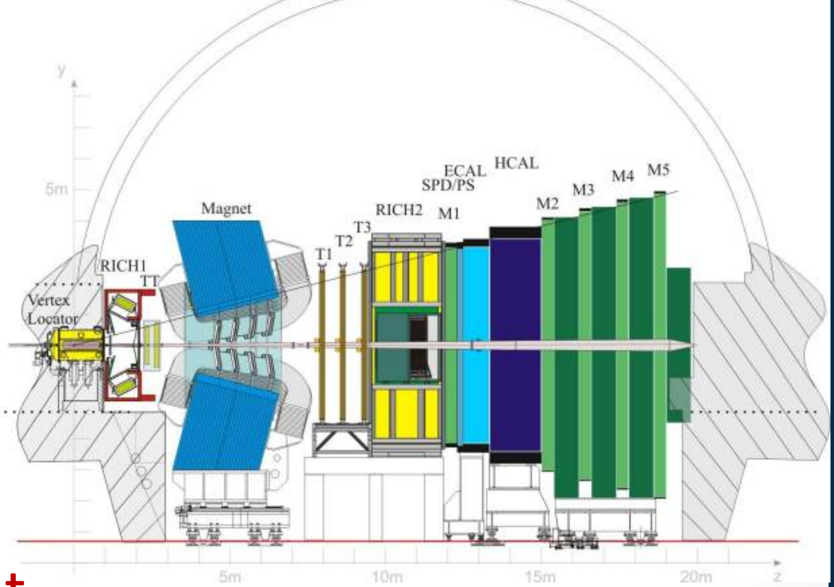
- Theoretically clean, cancellation of form factor uncertainties

  $R(D^*)^{SM} = 0.252 \pm 0.003$ PRD **85**094025 (2012)

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

R(D*) at LHCb

- $3fb^{-1}$ collected in Run I at √s =7, 8 TeV

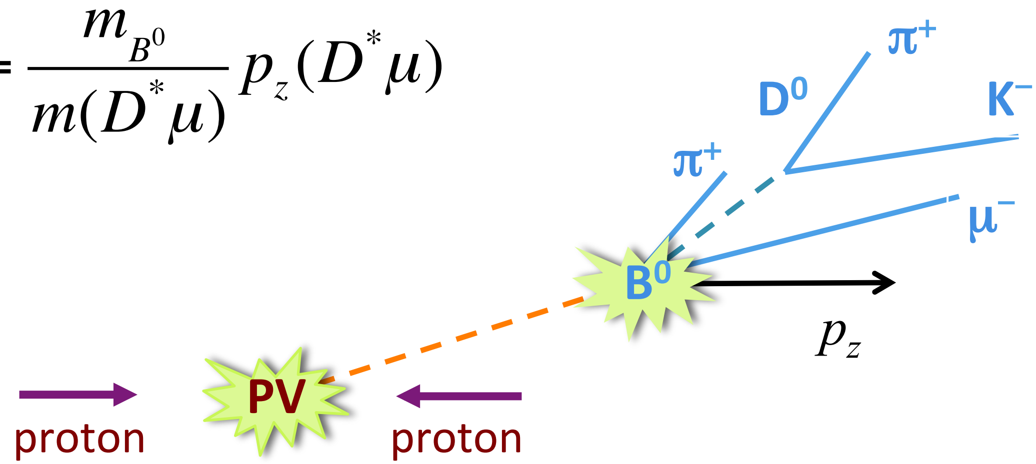


- Trigger on the charm component
  - no hardware-trigger requirement on muon p_T
  - software trigger selects $D^0 \rightarrow K\pi$ with high p_T and displaced vertex
- Selection exploiting excellent LHCb performances
  - 20 μm IP resolution
  - μ identification eff.~97% for 1%-3% $\pi \rightarrow \mu$ mis-identification
- Full selection efficiency ratio: $\varepsilon_\tau / \varepsilon_\mu$ = (77.6±1.4) %
  - signal losses due to lower p_T and worst vertex in the tau decay

B^0 rest frame determination

- B^0 momentum unknown in production from pp collisions (mainly gg→ $b\bar{b}$) at LHC
- B^0 direction well determined by vector from PV to B vertex
- B^0 boost along beam direction approximated with boost of the visible system

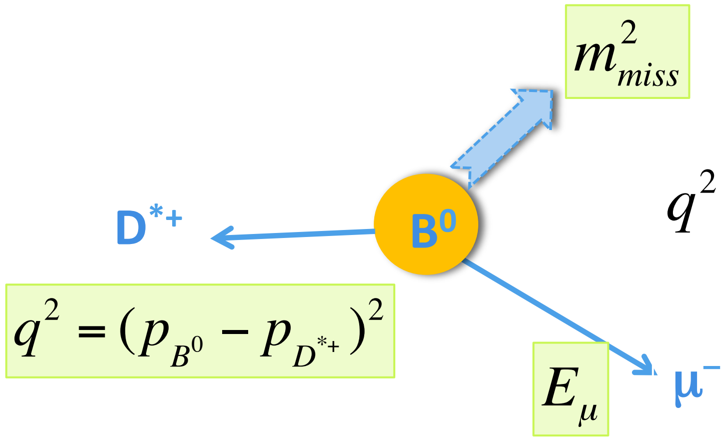
$$p_z(B^0) = \frac{m_{B^0}}{m(D^*\mu)} p_z(D^*\mu)$$



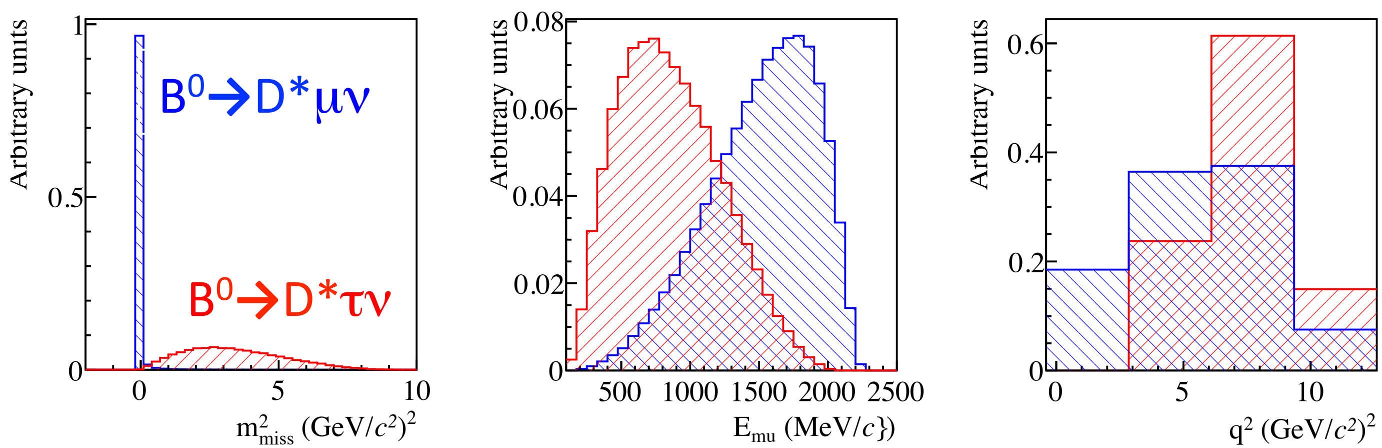
- 15-20% resolution on variables calculated in the B rest frame

Separating $B^0 \to D^*\tau\nu$ from $B^0 \to D^*\mu\nu$

- 3 key kinematic variables computed in the B rest frame



$$q^2 = (p_\ell + p_\nu)^2$$

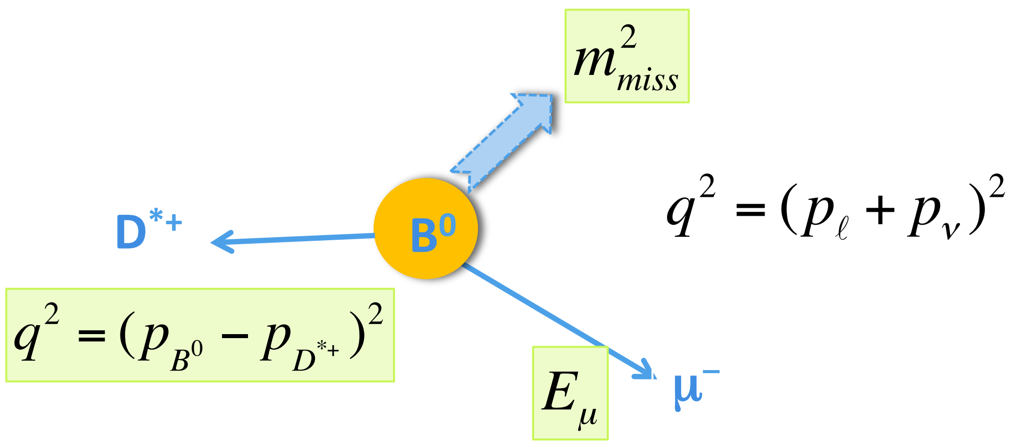


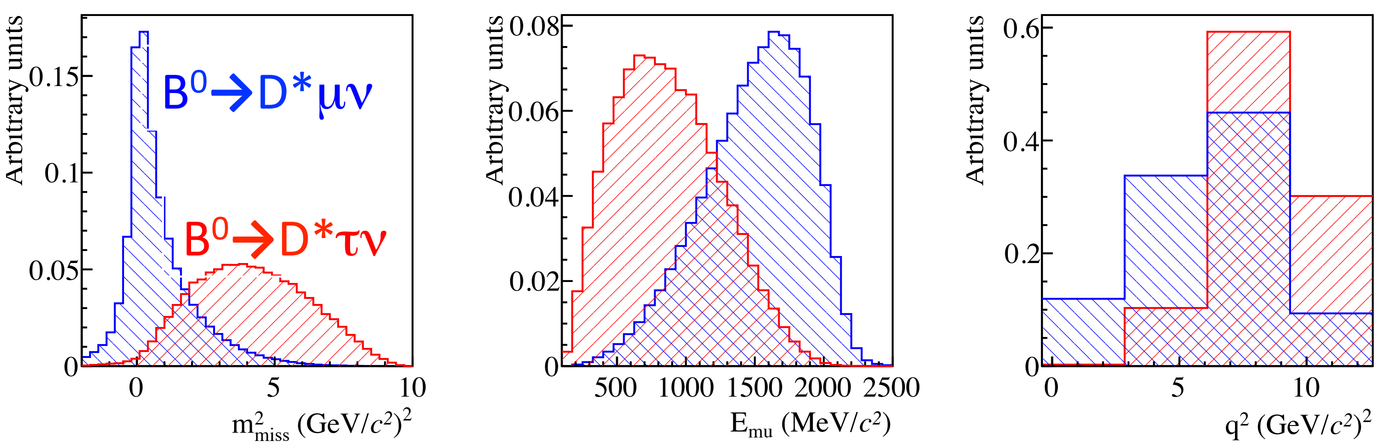
LHCb simulation

MC truth

Separating $B^0 \to D^*\tau\nu$ from $B^0 \to D^*\mu\nu$

- 3 key kinematic variables computed in the B rest frame



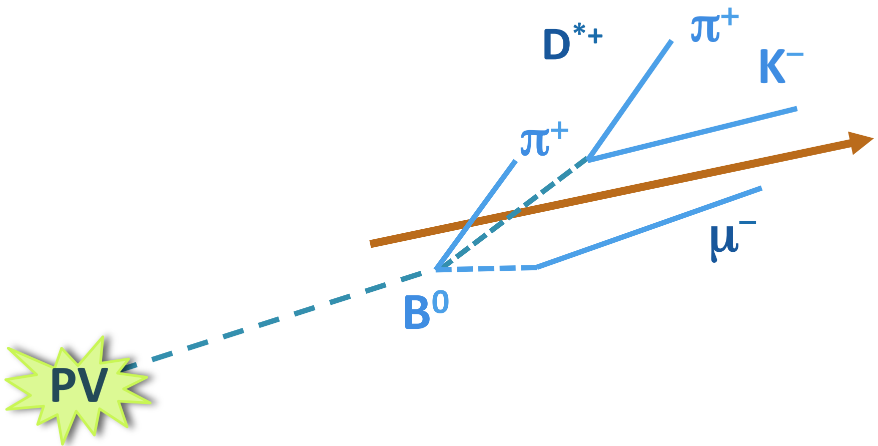


LHCb simulation

approximate B rest frame

Separating signal from backgrounds

- Backgrounds from partially reconstructed B decays.
- MVA used to determine track compatibility with B vertex.
  - Data sample enriched in $B^0 \rightarrow D^* \tau \nu$ and $B^0 \rightarrow D^* \mu \nu$ requiring zero additional track at the B^0 vertex



- Alternative requirements select three control samples
  - 1 track at B vertex: "$D^{*+}\mu^-\pi^-$" sample
  - 2 tracks at B vertex: "$D^{*+}\mu^-\pi^-\pi^+$" sample
  - >= 1 track with kaon ID at B vertex: "$D^{*+}\mu^- K^{\pm}$" sample

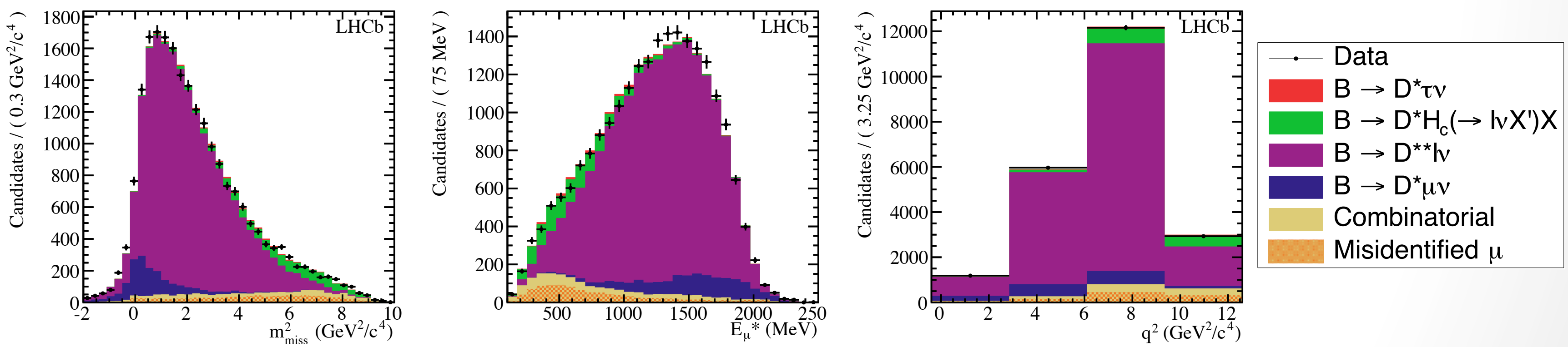
Data Fit

- ML fit to m^2_{miss}, E_μ, q^2 distributions with 3D templates representing $B^0 \to D^*\tau\nu$, $B^0 \to D^*\mu\nu$ and background sources.
  - Templates derived from simulation and data, validated with separate fits on data control samples.

- In simulation:
  - $B^0 \to D^*\tau\nu$, $B^0 \to D^*\mu\nu$ form factors from HQET, parameters floated in the fit with constraints from world average values.
- Template uncertainties included in the fit
  - uncertainties due to finite number of simulated events incorporated in the likelihood using Beeston-Barlow light procedure
  - shape uncertainties included via interpolation between nominal and alternative histograms.

Background: B→D**$\mu^-\nu$ (I)

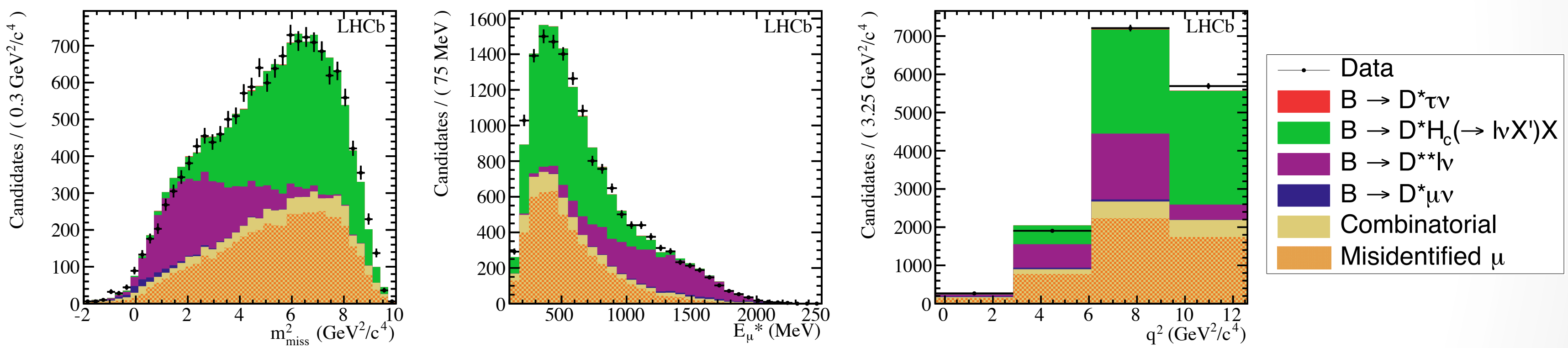
- Large contribution to semileptonic decays of excited charm states "D** "
  - Separate templates for established narrow resonances $D_1(2420)$, $D_2^*(2460)$, $D_1'(2430)$
  - Form factors from LLSW with slope of Isgur Wise function floating.
  - Model choice validated, and parameter constrained, from a separate fit to the "$D^{*+}\mu^-\pi^-$" control sample



- Similar parametrization used for smaller $B_s \to D_s^{**}\mu^-\nu$ background

Background: $B \rightarrow D^{**}\mu^- \nu$ (II)

- Higher charm states less well measured, single fit component.
  - Modelled using ISGW2 parametrization
  - q^2 distribution tuned on data with "$D^{*+}\mu^-\pi^+\pi^-$" control sample



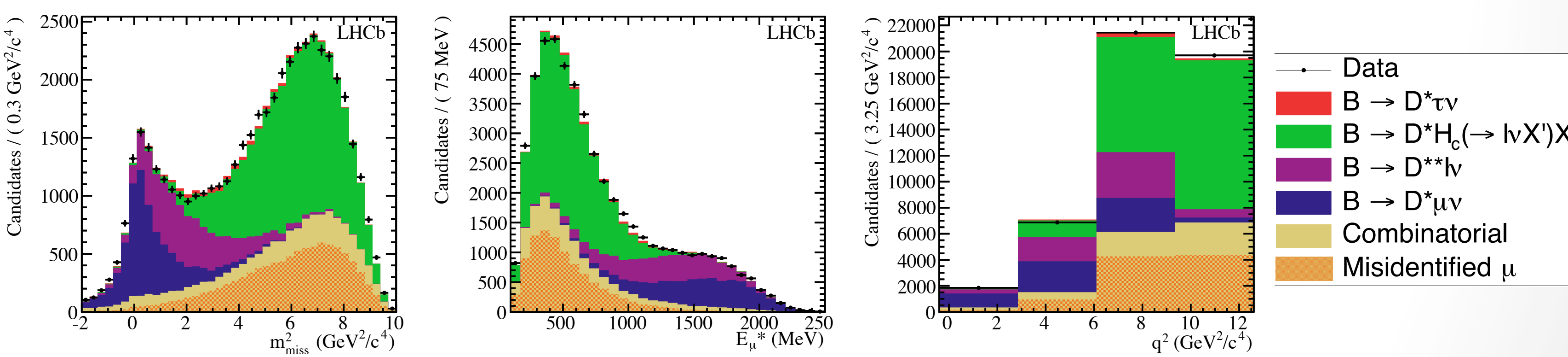
- Similar parametrization used for semitauonic decays $B \rightarrow D^{**}\tau^- \nu$

- Total contribution of semileptonic background is ~12% of the normalization mode

Background: $B \to D^{*+} H_c X$; $H_c \to \mu^- \nu X'$

- Semileptonic decays of a second charmed hadron contribute ~6-8% of the normalization mode

  - Simulated event sample of B^0,B^+ with approximate mixture of final states
  - Empirical corrections to templates from fits to "$D^{*+} \mu^- K^{\pm}$" control sample



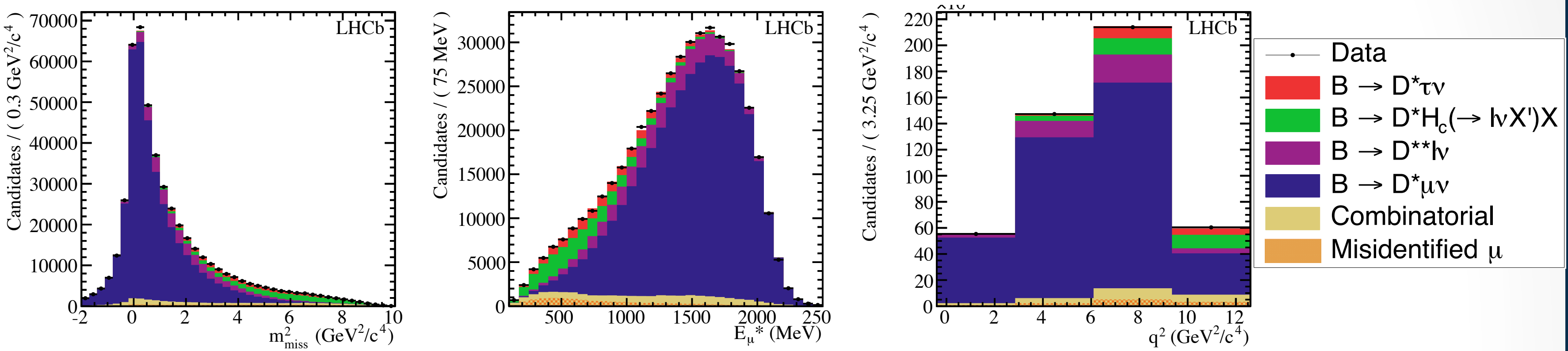
- Similar simulated sample for tertiary muon decays $B \to D^* D_s X$ with $D_s \to \tau^- \nu$

Other backgrounds

- Hadrons misidentified as muons.
  - Distributions for derived from “D^{*+} $h^{\pm}$” sample
  - Samples of D^* and Λ^0 events used to derive misidentification probabilities of p,K,π in data

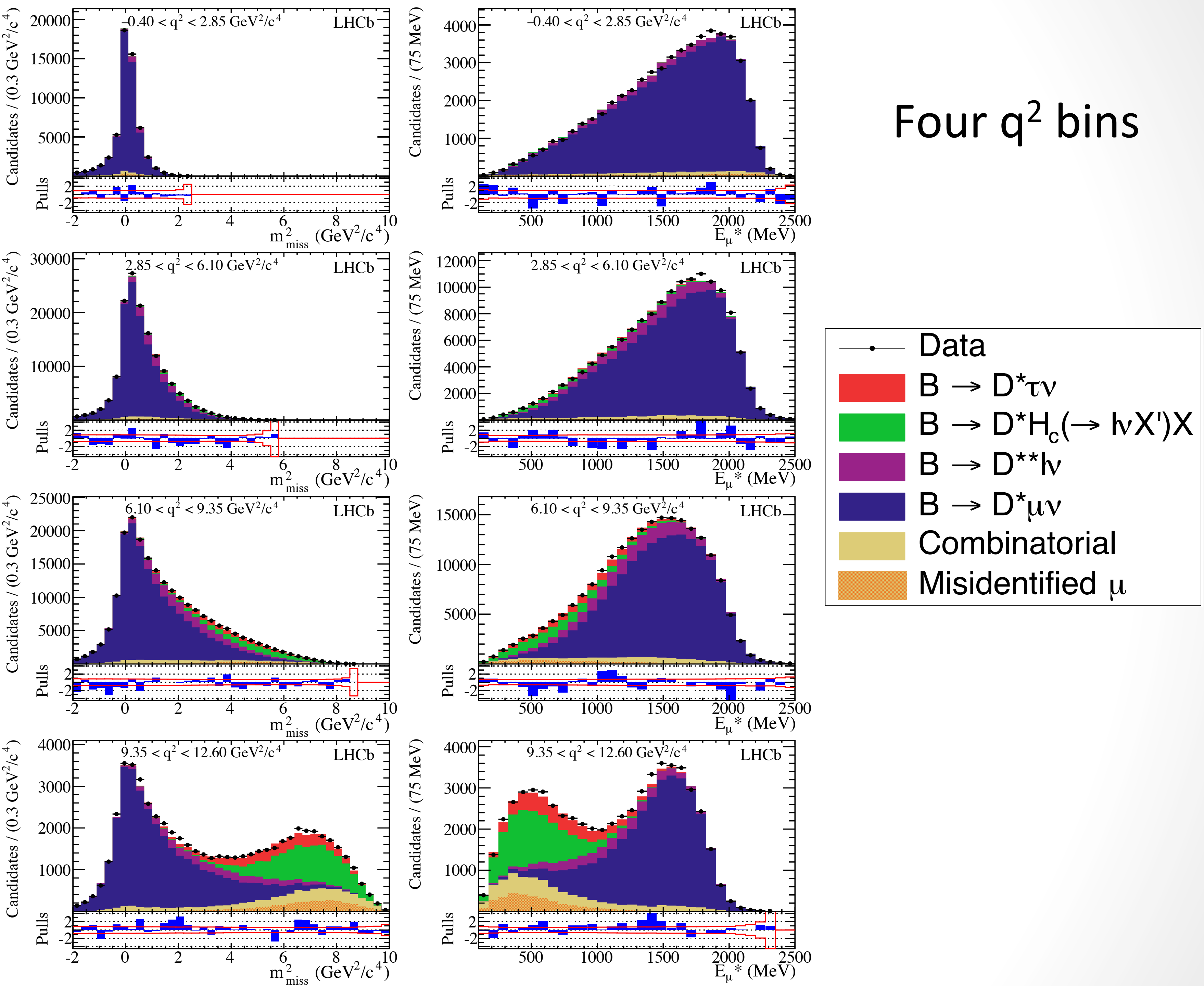
- Combinatorial background
  - Random combination of muon and D^{*+} modelled from with wrong-charge combination $D^{*+}\mu^+$
  - Fake D^{*-} modelled from with wrong-charge combination $D^0\pi^-\mu^-$

Signal Fit Result



- Fit determines the fraction of signal and normalization channel.
  - Model fits well. 363000±1600 events in the $B^0 \rightarrow D^*\mu\nu$ sample.
- $N(D^*\tau\nu)/N(D^*\mu\nu) = (4.54 \pm 0.46)\%$
  - Small signal fraction as expected from small $\mathcal{B}(\tau \rightarrow \mu\nu\nu)$ and phase space suppression

Four q^2 bins



-0.40 < q2 < 2.85 GeV2/c4
2.85 < q2 < 6.10 GeV2/c4
6.10 < q2 < 9.35 GeV2/c4
9.35 < q2 < 12.60 GeV2/c4
LHCb
Candidates / (0.3 GeV2/c4)
Candidates / (75 MeV)
Pulls
m2miss (GeV2/c4)
Eμ* (MeV)
Data
B → D*τν
B → D*Hc(→ lνX')X
B → D**lν
B → D*μν
Combinatorial
Misidentified μ

Systematic uncertainties

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ 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**

Background modelling; depends on control sample size

Result

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

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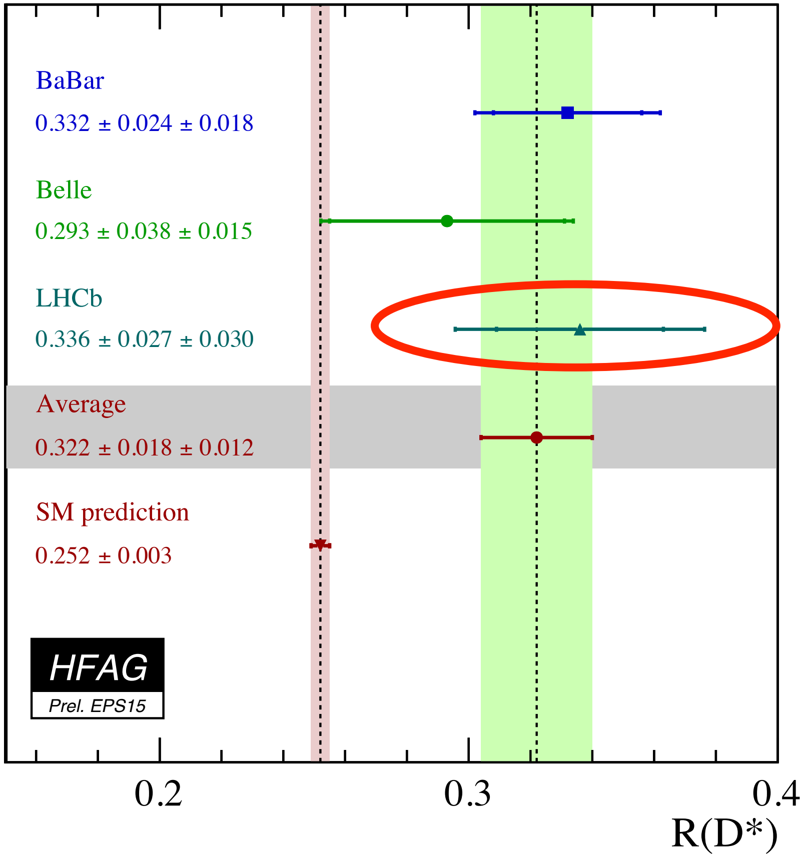
arXiv:1506.08614

- In agreement with previous measurements.

- 2.1 σ higher than SM
  $R(D^*)^{SM} = 0.252 \pm 0.003$

New HFAG average

http://www.slac.stanford.edu/xorg/hfag/semi/eps15/eps15_dtaunu.html



New HFAG average of R(D) and R(D*)

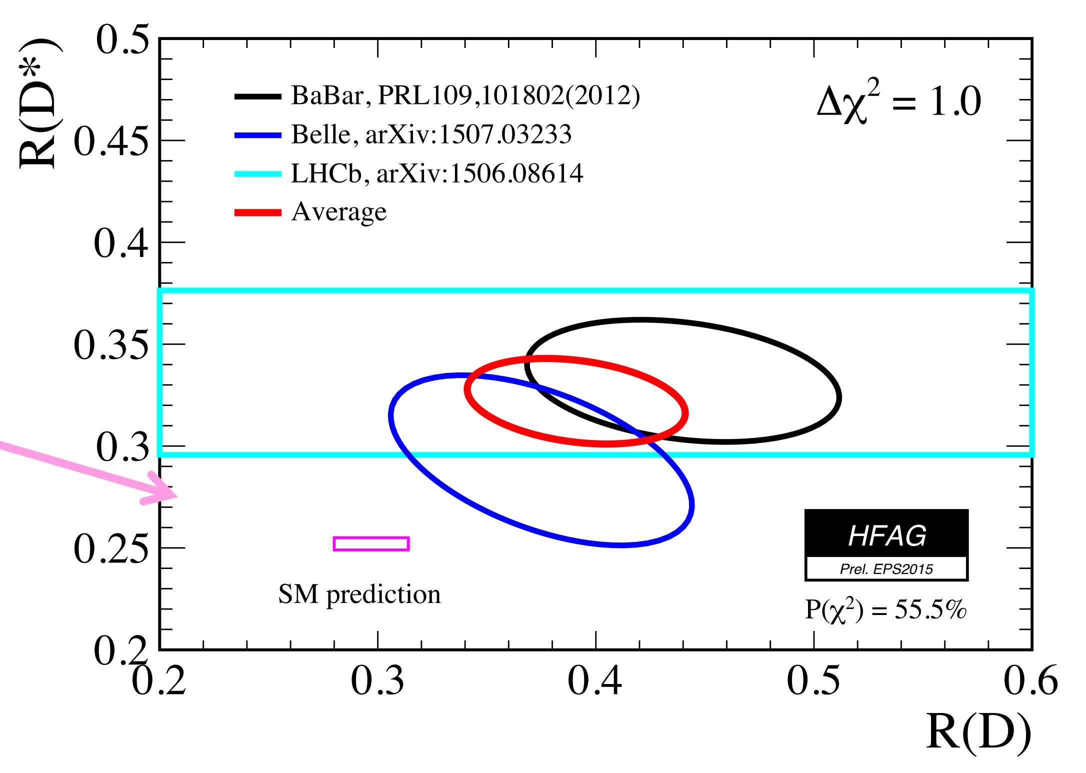
SM predictions

R(D*)=0.252 ±0.003

*PRD **85** (2012) 094025*

R(D) =0.297 ±0.017

*PRD **78** (2008) 014003*



HFAG average

$R(D^*) = 0.322 \pm 0.018 \pm 0.012$

$R(D) = 0.391 \pm 0.041 \pm 0.028$

Corr (D,D*)= − 0.29

- Difference with the SM predictions at 3.9 σ level.

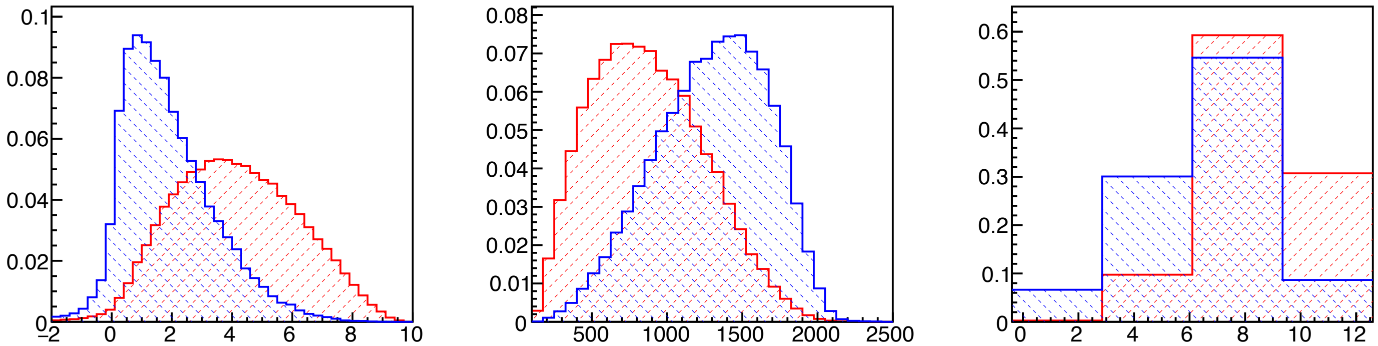
Conclusion

- First measurement of $B \rightarrow X\tau\nu_\tau$ decay at a hadron collider performed by LHCb
  - Similar precision of previous B Factories measurements
  - Demonstrate LHCb capabilities for high precision measurements in semileptonic decays
  - Similar studies with hadronic tau decays ongoing

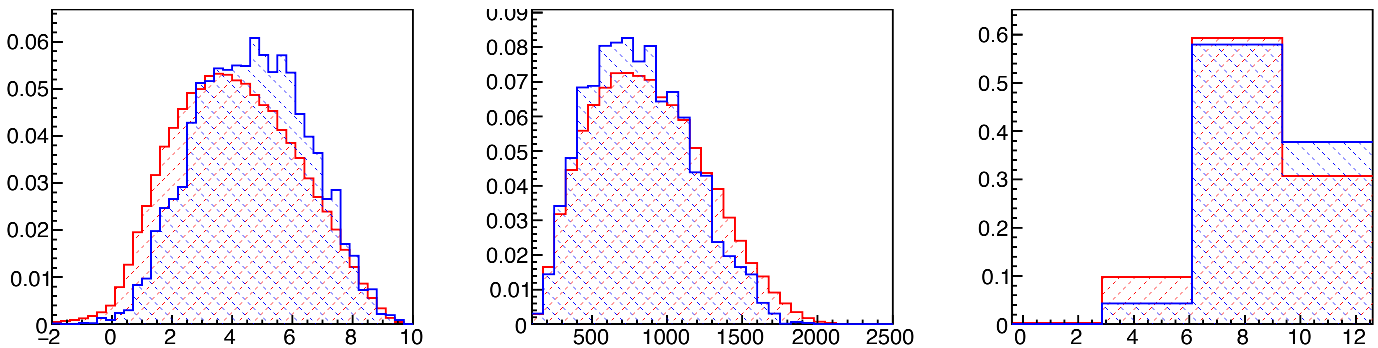
- $\mathcal{B}(D^*\tau\nu)/\mathcal{B}(D^*\mu\nu) = 0.336 \pm 0.027 \pm 0.030$
  - In agreement with SM at 2.1 σ level
  - Similar deviation is observed in all current $R(D^{(*)})$ results, the combined average is 3.9 σ over the SM.

backup

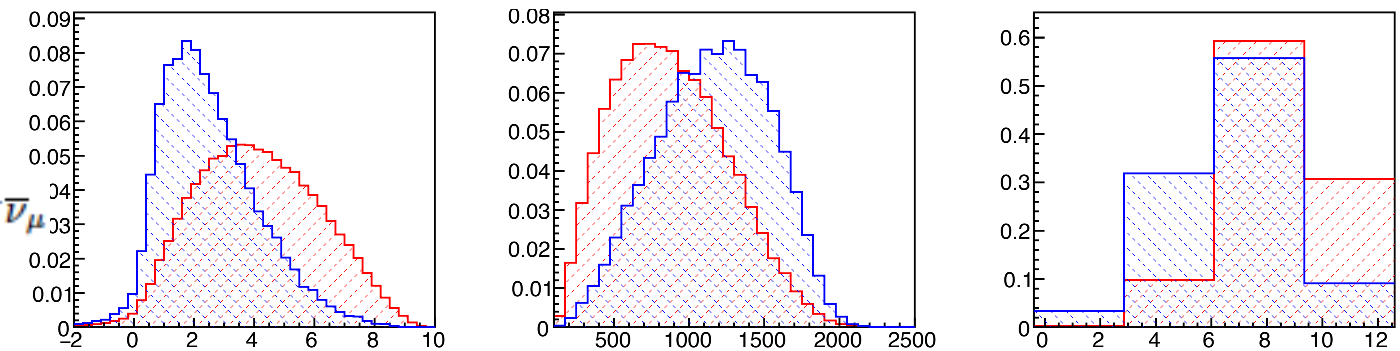
$D_1^+(2420)\mu^-\overline{\nu}_\mu$



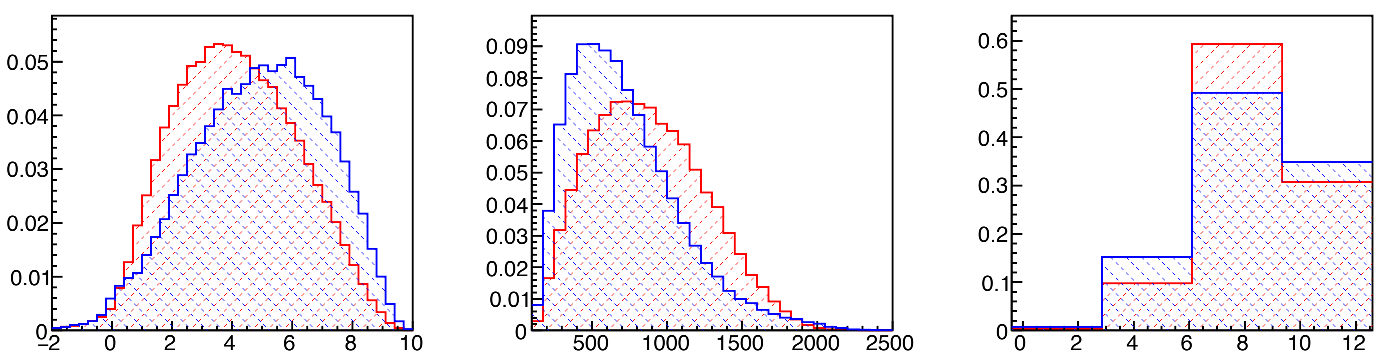
$D_2^{*+}(2460)\tau^-\overline{\nu}_\tau$

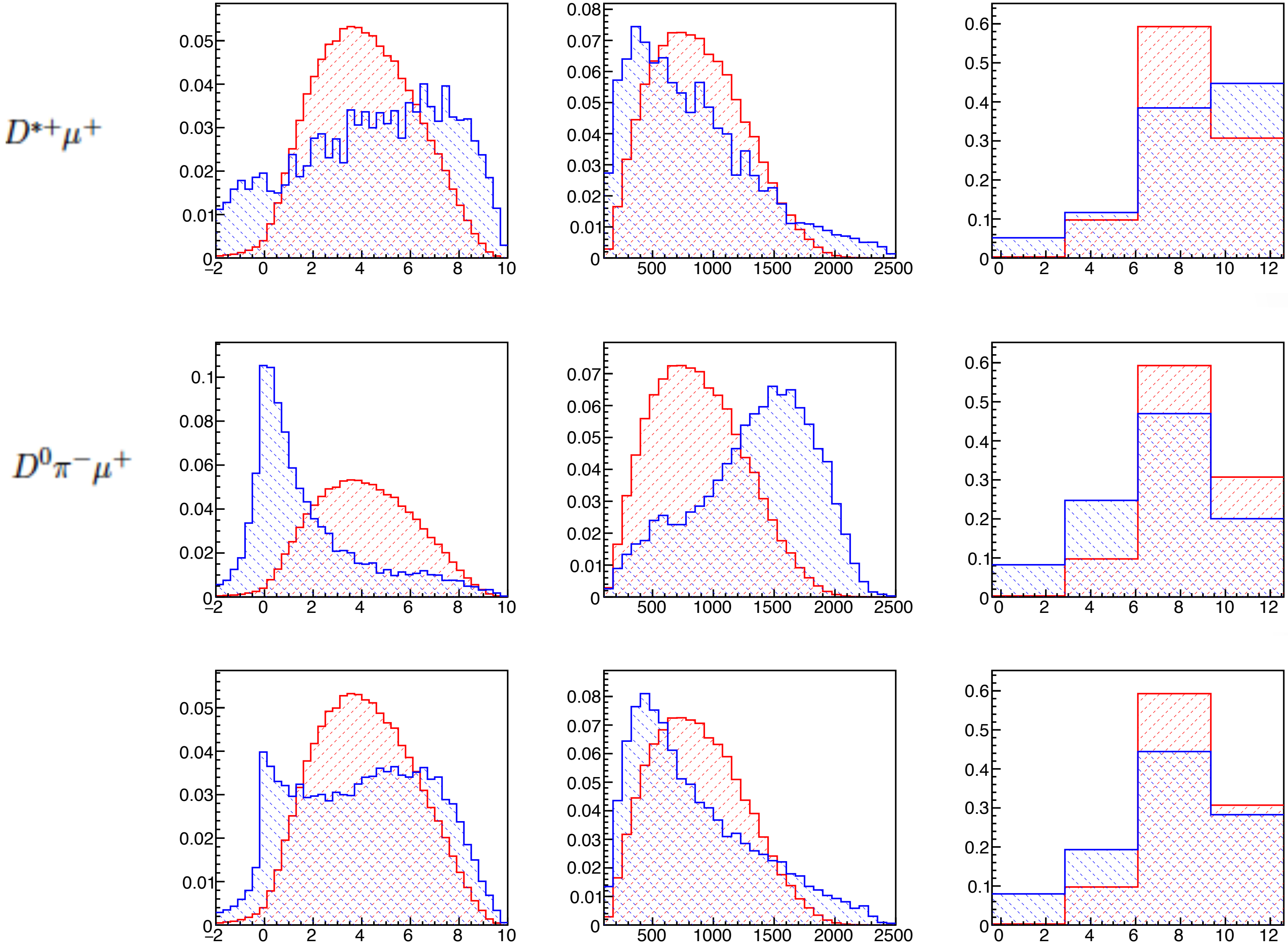


$D^{**}(\to D^{*+}\pi\pi)\mu^-\overline{\nu}_\mu$



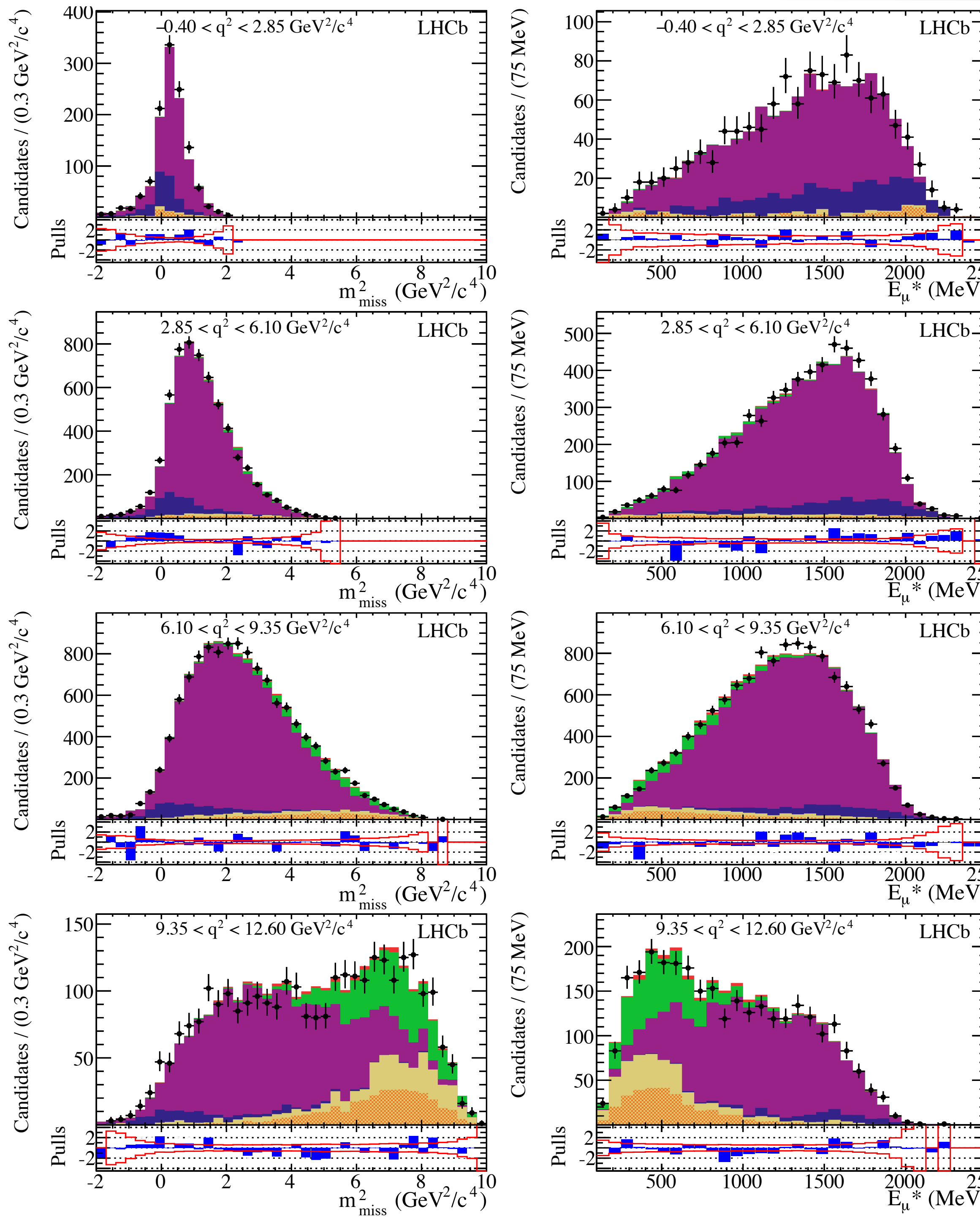
$D^{*+}H_c(\to \mu\nu X')X$



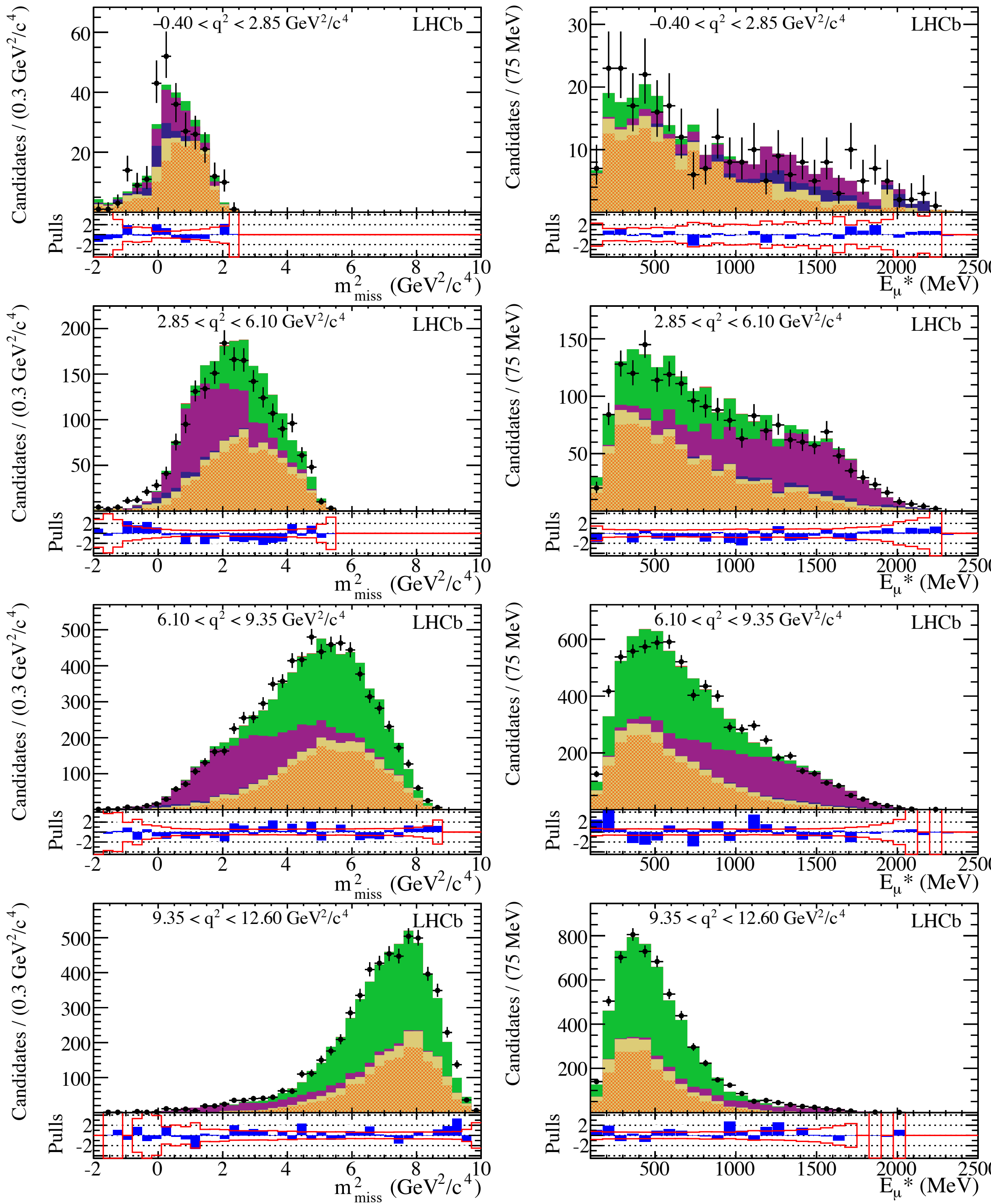


hadrons misidentified as muons

$D^{*+}\mu^{-}\pi^{-}$ control sample



$D^{*+}\mu^{-}\pi^{+}\pi^{-}$ control sample



$D^{*+}\mu^{-}K^{\pm}$ control sample