Overview of LHCb's semileptonic measurements

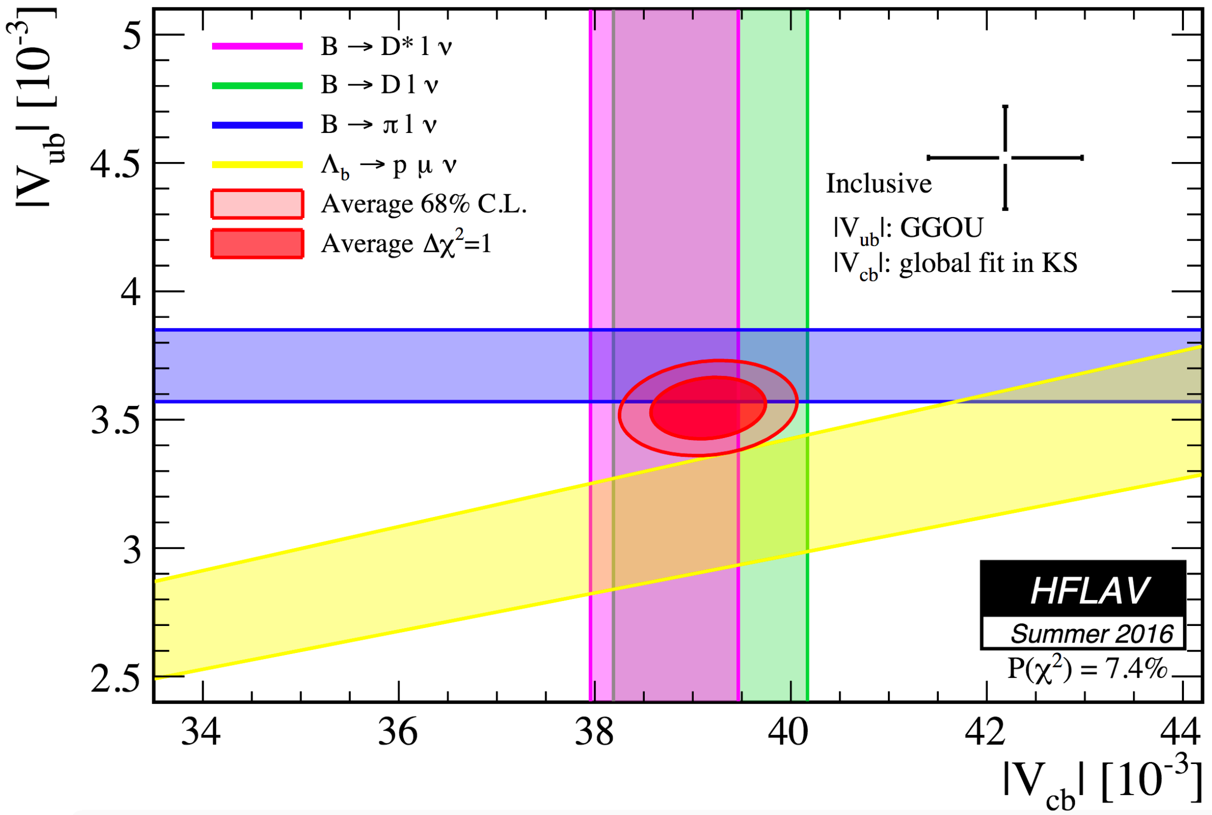
Suzanne Klaver, on behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects

CERN, 10 October 2018

Introduction

- Diverse physics program:
  - measuring the CKM matrix elements: $|V_{\rm ub}|$ and $|V_{\rm cb}|$
  - form factors
  - lepton flavour universality in $B \to D\ell\nu$ decays
  - production properties: fractions, cross-sections, asymmetries
  - CPV and mixing



Introduction

Advantages:

- Large data samples
- Theoretically clean: only 1 hadronic current which allows for measuring form factors
- Can trigger on muons

Challenges:

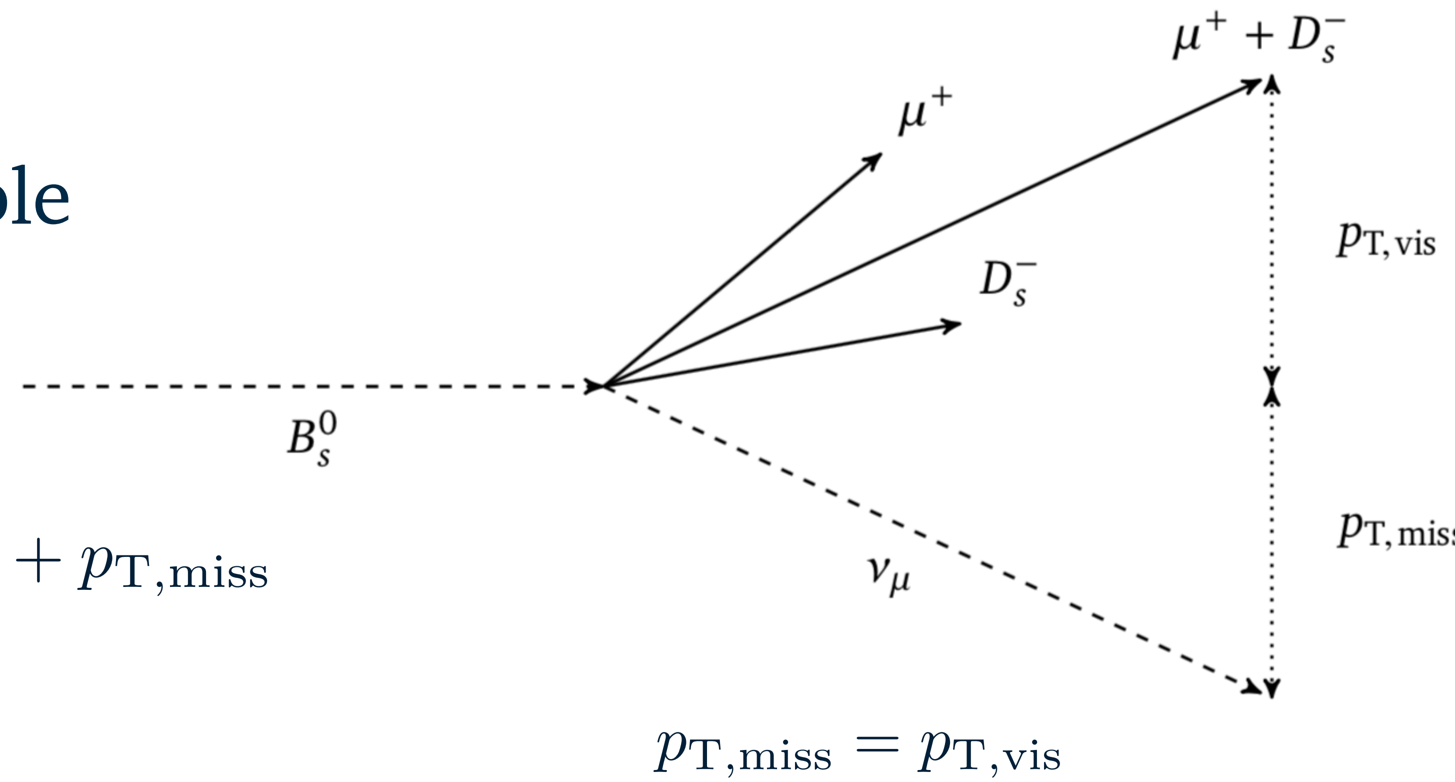
- All decays are partially reconstructed due to the neutrino
- Large amounts of background
- Large samples of simulation are needed

Common methods

Corrected mass:

- use flight direction of visible particles to reconstruct missing mass

$$m_{\mathrm{corr}} = \sqrt{(m_{\mathrm{vis}})^2 + (p_{\mathrm{T,miss}})^2} + p_{\mathrm{T,miss}}$$



- quadratic ambiguity improved using MVA

JHEP 02 (2017) 21

Other variables:

- isolation tool to suppress charged and neutral particles
- other mass variables, *e.g.* missing mass

Overview

Results that we know and love:

- $\mathcal{R}(D^*)$ hadronic and muonic
- $\mathcal{R}(J/\Psi)$ muonic
- $\mathit{\Lambda}_b^0 \to \mathit{\Lambda}_c^+ \mu^- \overline{\nu}_\mu$ form factors

New since the last implications workshop:

- Relative $B^- \to D^0/D^{*0}/D^{**0}\mu^-\overline{\nu}_\mu$ branching fractions using $\overline{B}{}_{s2}^{*0}$ decays
- Search for $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$

Outlook and conclusion

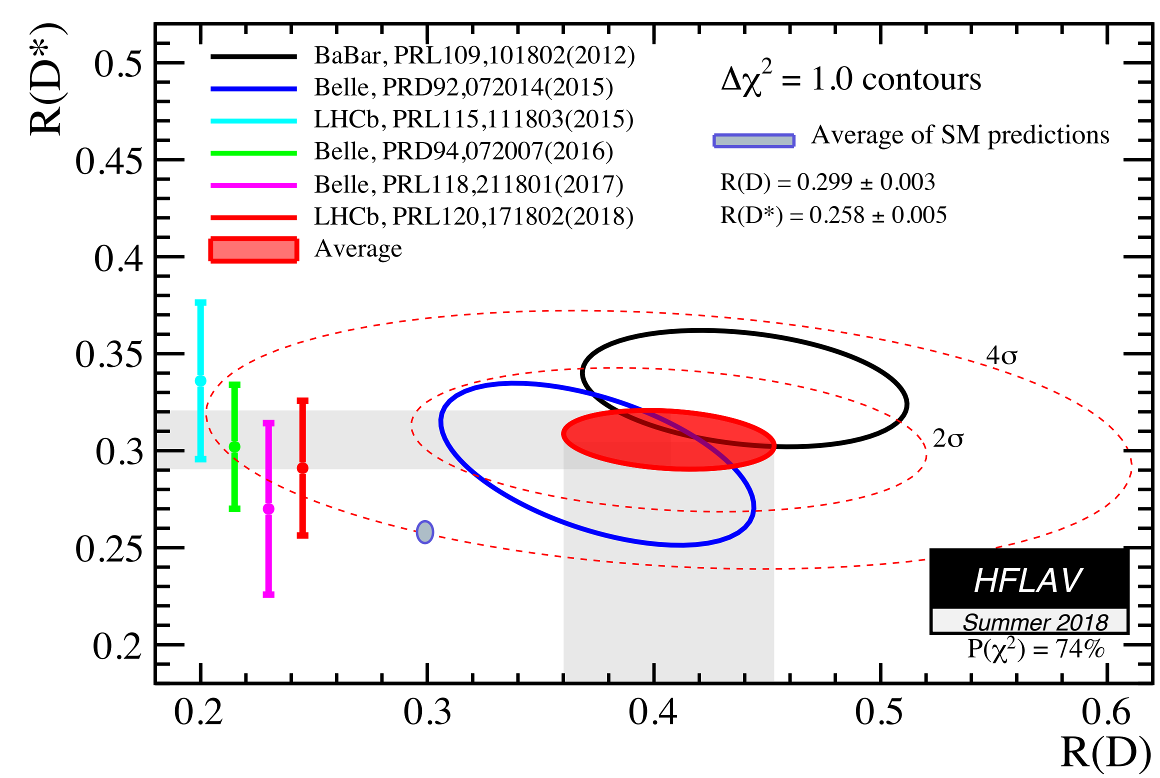
Overview *R(D)* and friends

- Measurements of lepton flavour universality
- Tree-level processes are sensitive to new physics: charged Higgs, leptoquarks etc.
- Currently 4σ tension with the SM for *R(D)-R(D*)*
- Predictions are theoretically clean, or at least that's what we thought…

16:20 **From $R(D^*)$ to $R(D\pi)$: the role of longitudinal corrections (15+5)**
Speaker: Genaro Toledo (UNAM)

16:40 **Comments on D^* measurements in B decays (15+5)**
Speaker: patrick roudeau (Laboratoire de l'Accélérateur Linéaire (LAL))

17:00 **Soft photon correction for $R(D^{(*)})$ (15+5)**
Speaker: Stefan de Boer



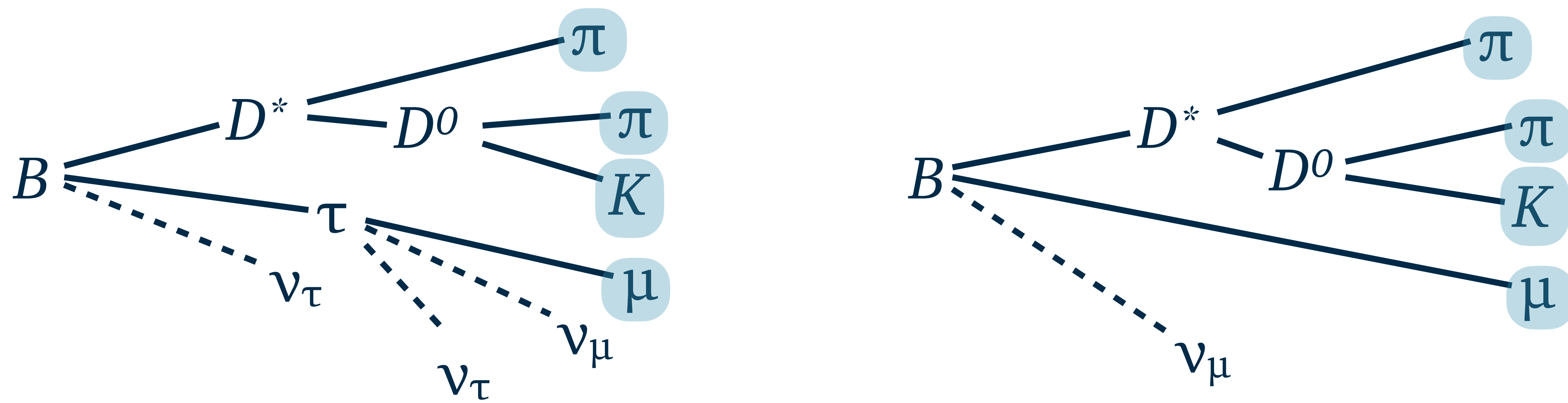
Overview *R*(*D*) and friends

Reconstructing τ in LHCb

- Muonic decays:
  $\tau \to \mu\, \nu_\mu\, \nu_\tau$
- Hadronic decays:
  $\tau \to \pi\, \pi\, \pi\, (\pi^0)\, \nu_\tau$

Strategy:

- Signal and normalisation channels have same visible final state



- Make the fit templates from most discriminating variables: kinematic
- Need for large MC samples, many checks to ensure good detector description etc.

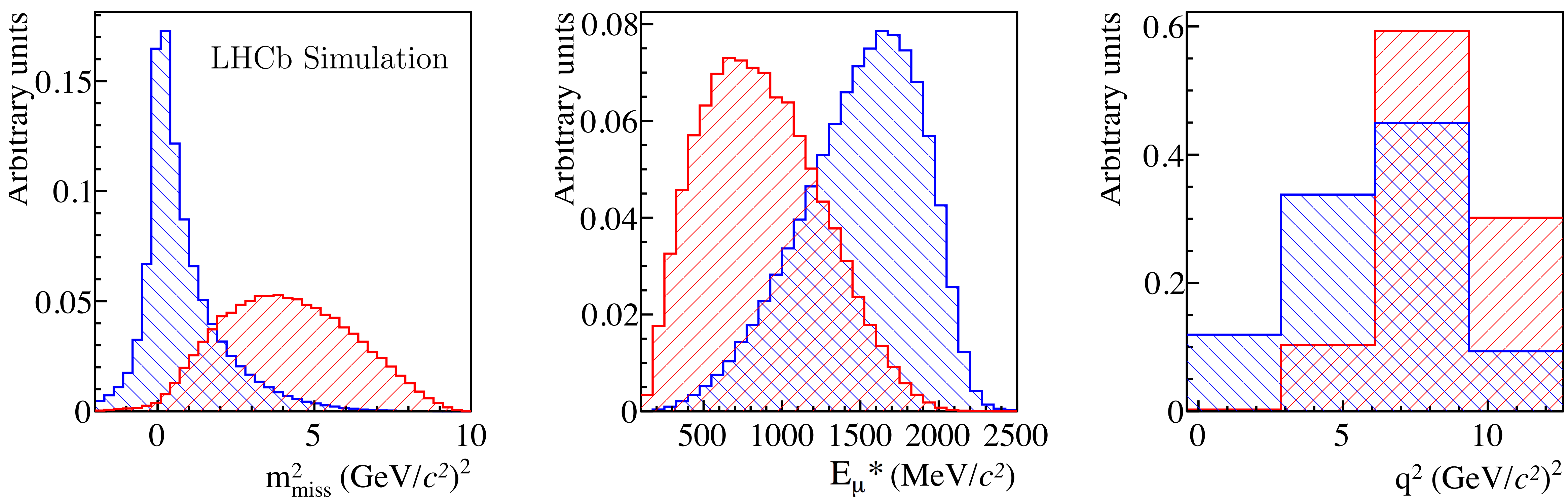
Discriminating variables for *R(D)*

As an example, the muonic *R(D*)* analysis: PRL 115 (2015) 111803

- signal channel: $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$
- normalisation channel: $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$

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

$q^2 = (p_\ell + p_\nu)^{=}(p_B - p_{D^*})^2$



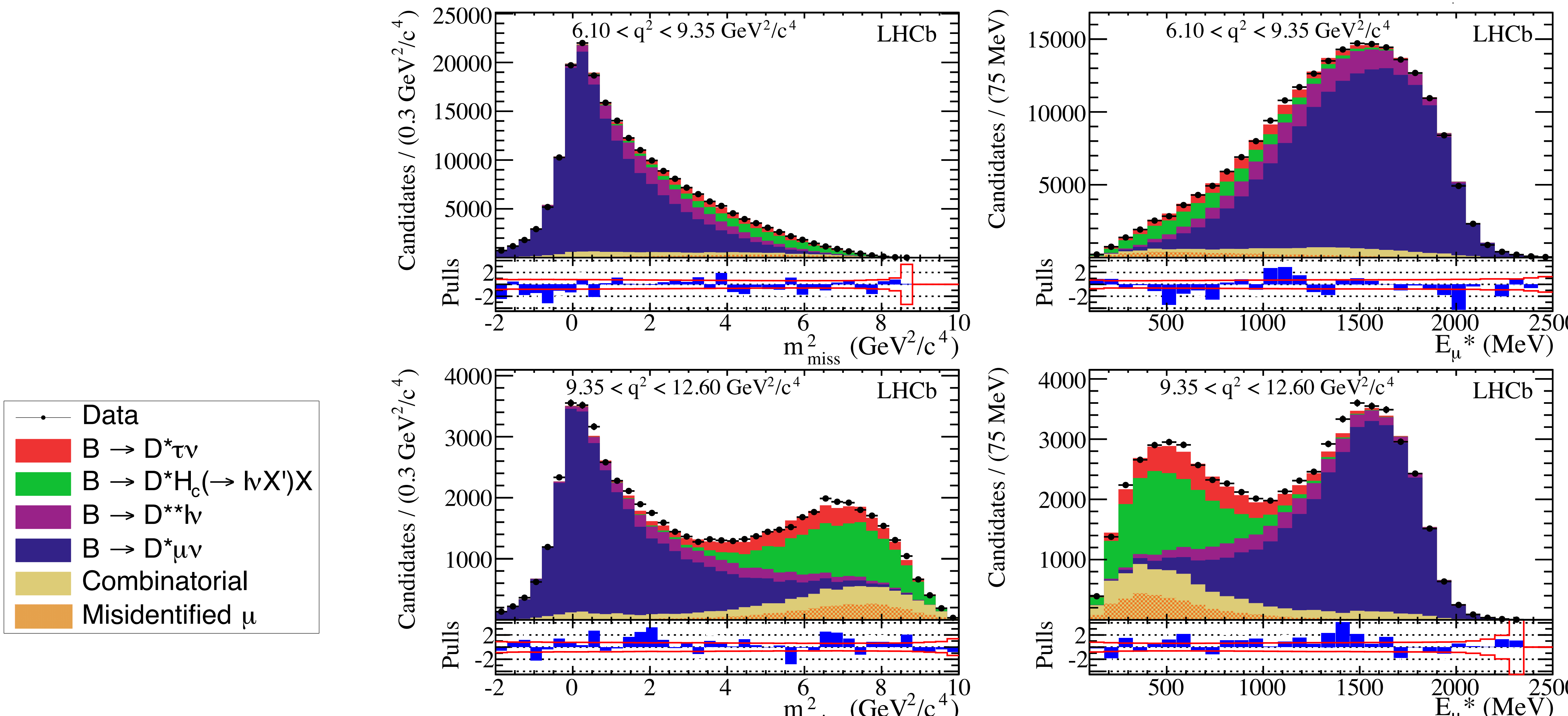
- In other analyses, we also use MVA and decay time

$R(D^*)$ leptonic

PRL 115 (2015) 111803

$$\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst}) \qquad \mathcal{R}(D^*) = \frac{\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau}{\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu}$$

- Compatible with SM within 2.1σ



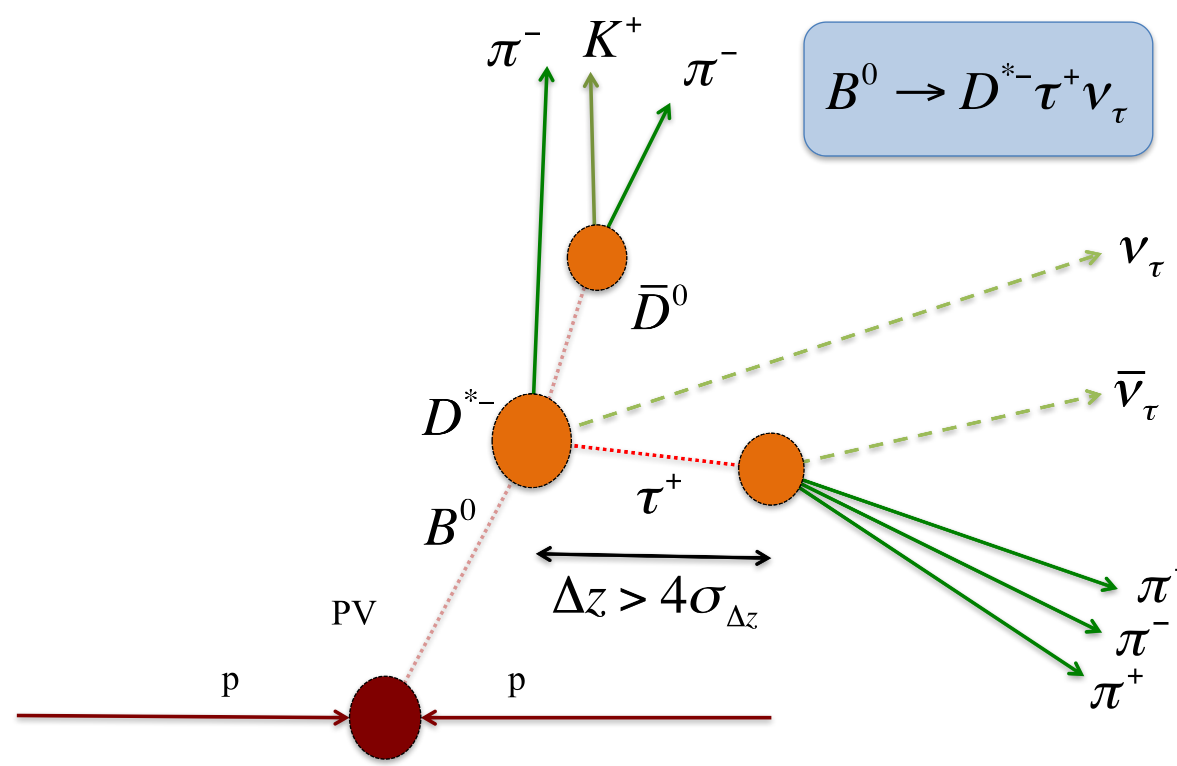
$R(D^*)$ hadronic

PRL 120, 171802 (2018)

PRD 97, 072013 (2018)

$$\mathcal{R}(D^*) = \underbrace{\left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}\right)_{\text{meas}}}_{\mathcal{K}(D^*)} \times \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}\right)_{\text{external}}$$

- Signal and normalisation channels have the same final state, such that many systematics cancel in the ratio.
- Use topology of the decay to suppress backgrounds

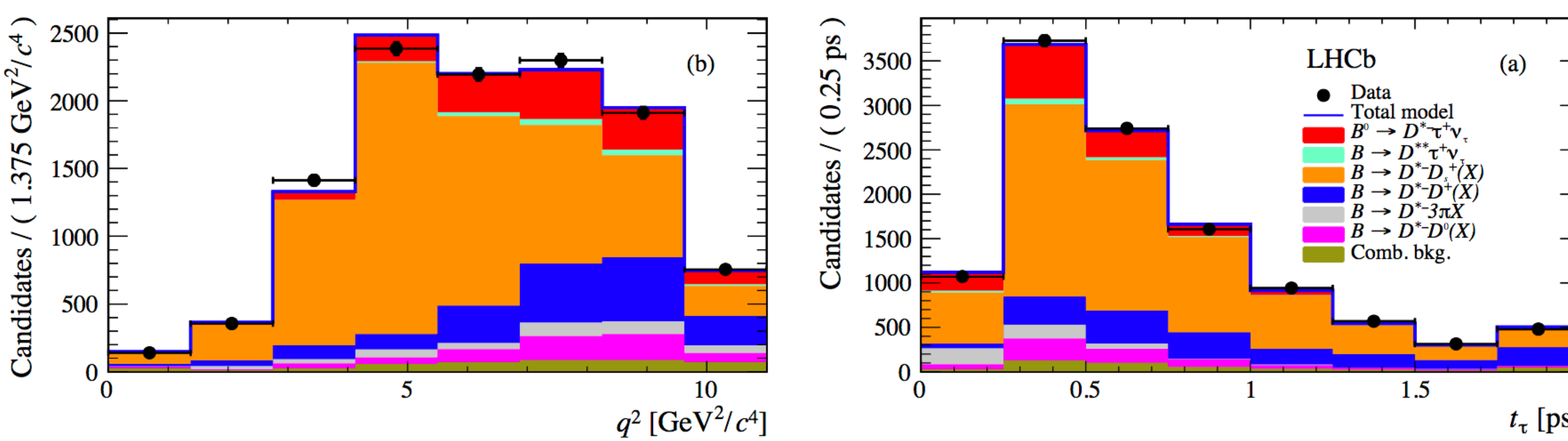


[PRL 120, 171802 (2018)](https://doi.org/10.1103/PhysRevLett.120.171802)
[PRD 97, 072013 (2018)](https://doi.org/10.1103/PhysRevD.97.072013)

$R(D^*)$ hadronic

$$\mathcal{R}(D^*) = \underbrace{\left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}\right)_{\text{meas}}}_{\mathcal{K}(D^*)} \times \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}\right)_{\text{external}}$$

- $\mathcal{K}(D^*) = 1.93 \pm 0.12(\text{stat}) \pm 0.17(\text{syst})$
- $\mathcal{R}(D^*) = 0.291 \pm 0.019(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{BR})$
- Compatible with SM within 1σ

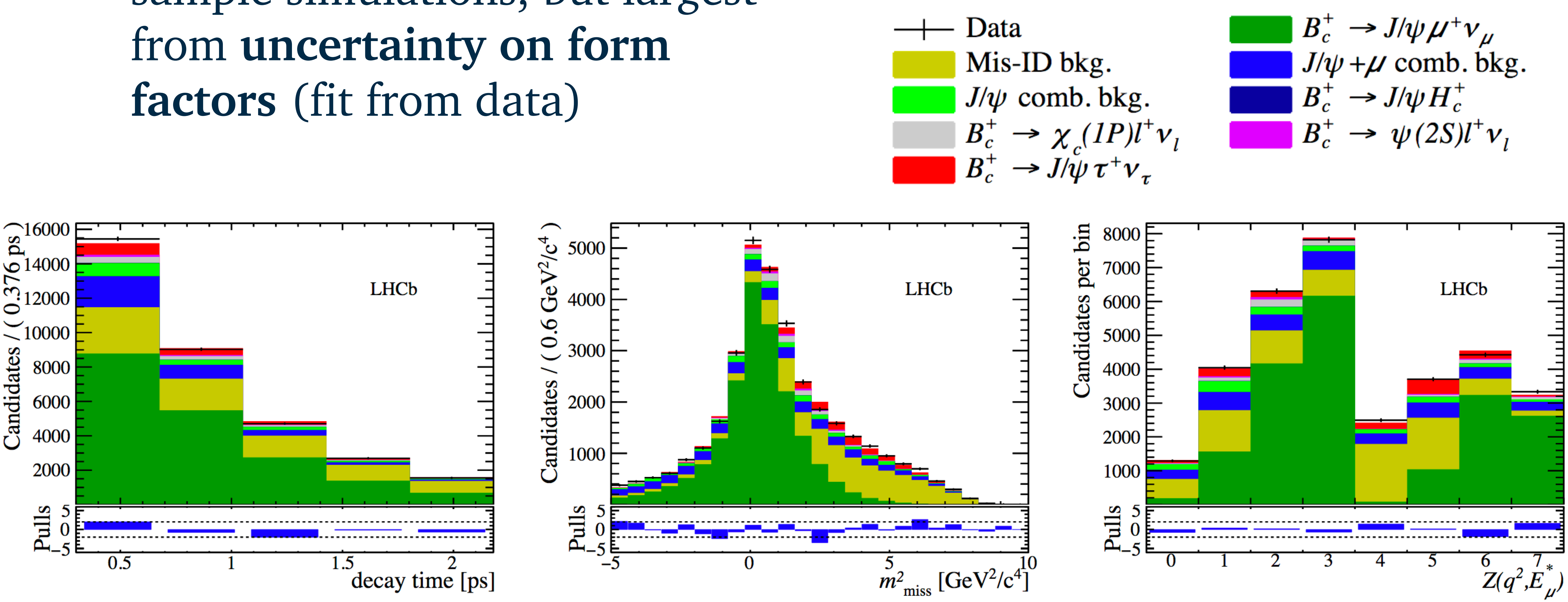


PRL 120, 121801 (2018)

$R(J/\Psi)$ muonic

- $\mathcal{R}(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$
- Compatible with SM within 2σ
- Systematics come from limited sample simulations, but largest from **uncertainty on form factors** (fit from data)

$$\mathcal{R}(J/\psi) = \frac{B_c^+ \to J/\psi \tau^+ \nu_\tau}{B_c^+ \to J/\psi \mu^+ \nu_\mu}$$



Shape of $\Lambda_b \to \Lambda_c \mu \nu$ decay rate

- Differential distributions are crucial for comparisons with HQET and lattice QCD; also a first step towards measuring $|V_{cb}|$
- The decay $\Lambda_b \to \Lambda_c \mu \nu$ is described by 6 form factors, reducing to a single function in heavy quark limit: the Isgur-Wise function $\xi_B(w)$:

$$\frac{d\Gamma}{dw} = GK(w)\xi_B^2(w) \qquad w = v_{\Lambda_b} \cdot v_{\Lambda_c} = \frac{m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2}{2m_{\Lambda_b} m_{\Lambda_c}}$$

- This function cannot be determined from first principle in HQET, but can be predicted using various approaches which can be tested
- Expanding $\xi_B(w)$ around w=1 yields:

$$\xi_B(w) = 1 - \rho^2(w-1) + \frac{1}{2}\sigma(w-1)^2 + \ldots$$

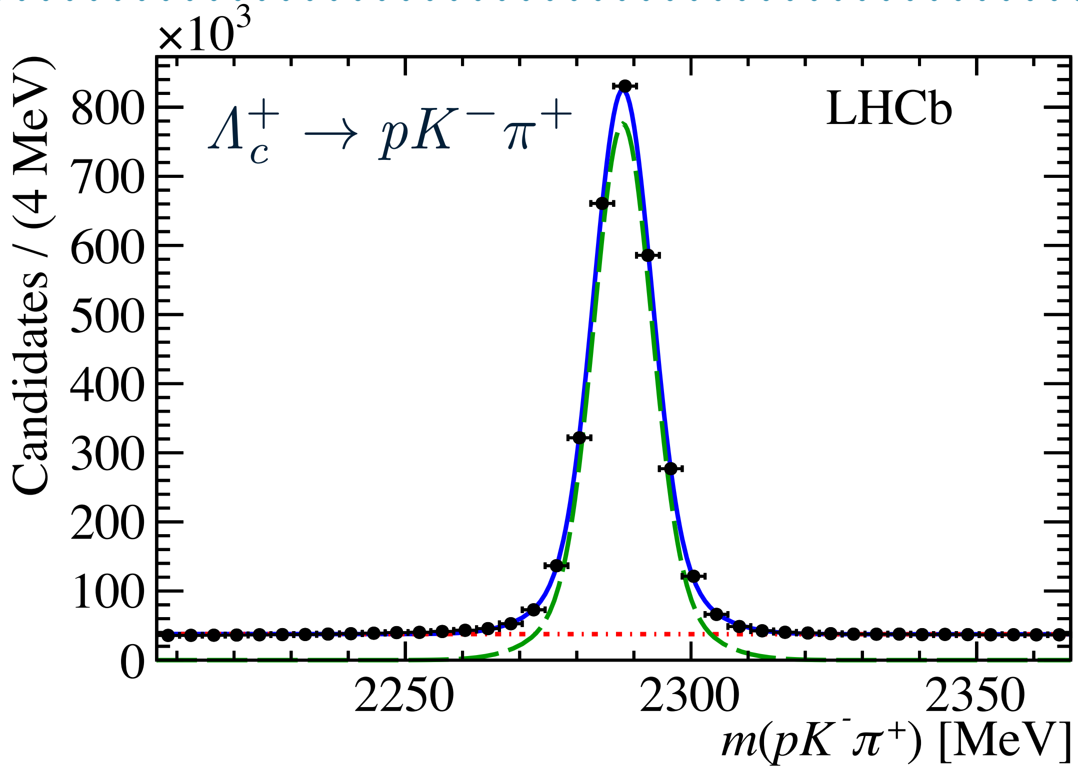
used for fitting the decay rate

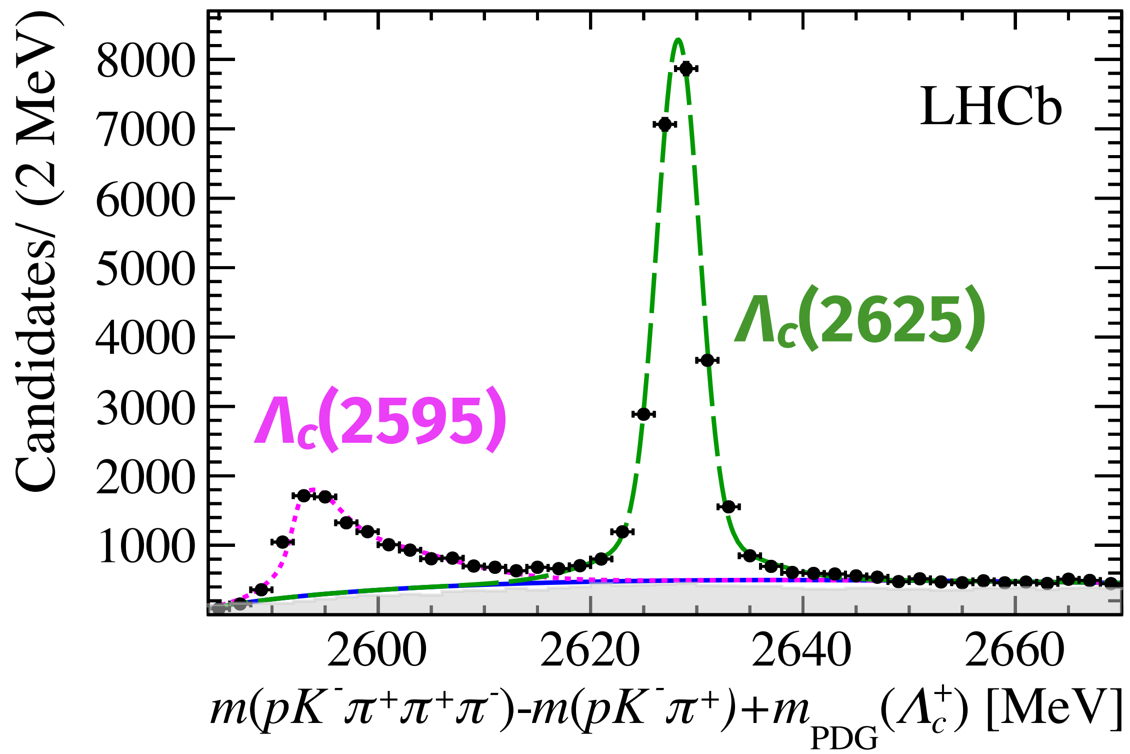
PRD 96, 112005 (2017)

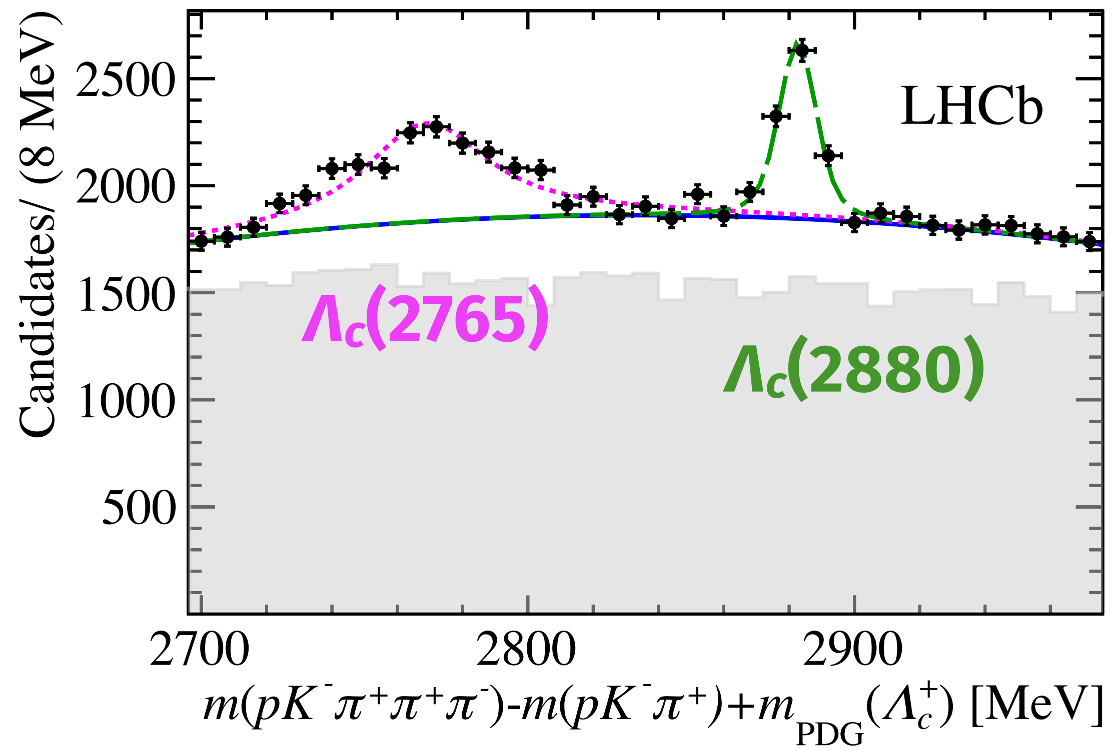
Shape of $\Lambda_b \to \Lambda_c \mu\nu$ decay rate

- Large and clean samples of $\Lambda_b \to \Lambda_c \mu\nu$ decays: 2.7 M in analyses Run I sample.

- Subtract feed-down from higher resonances:



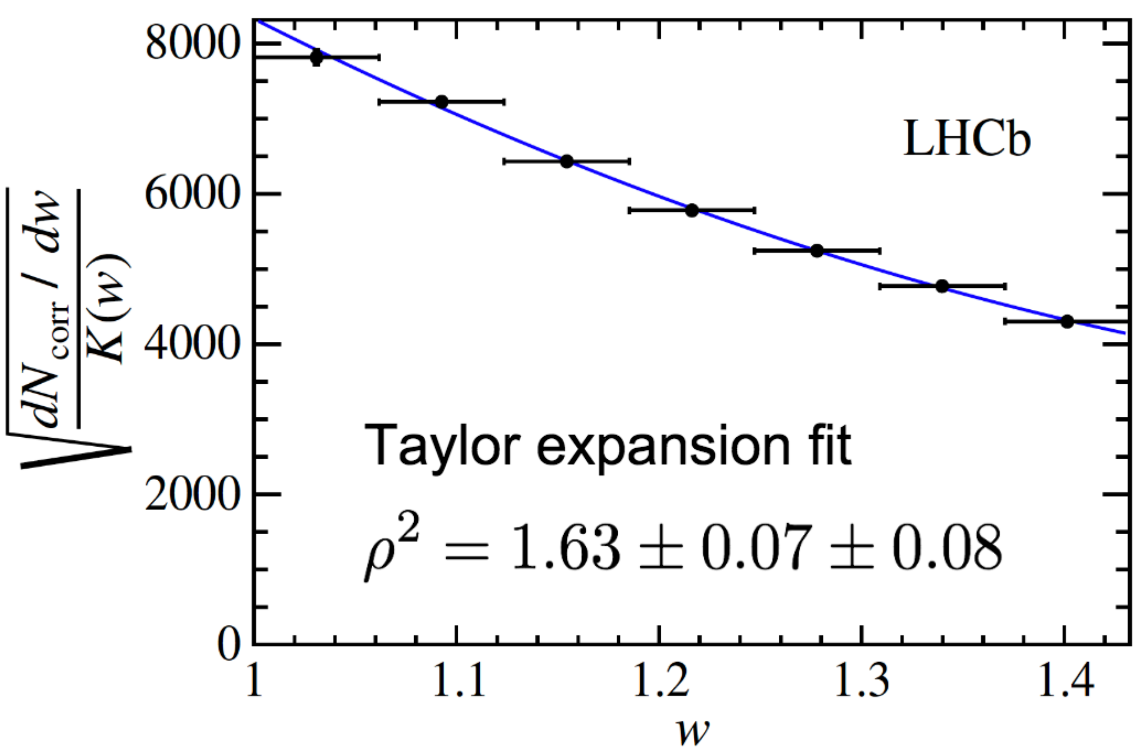


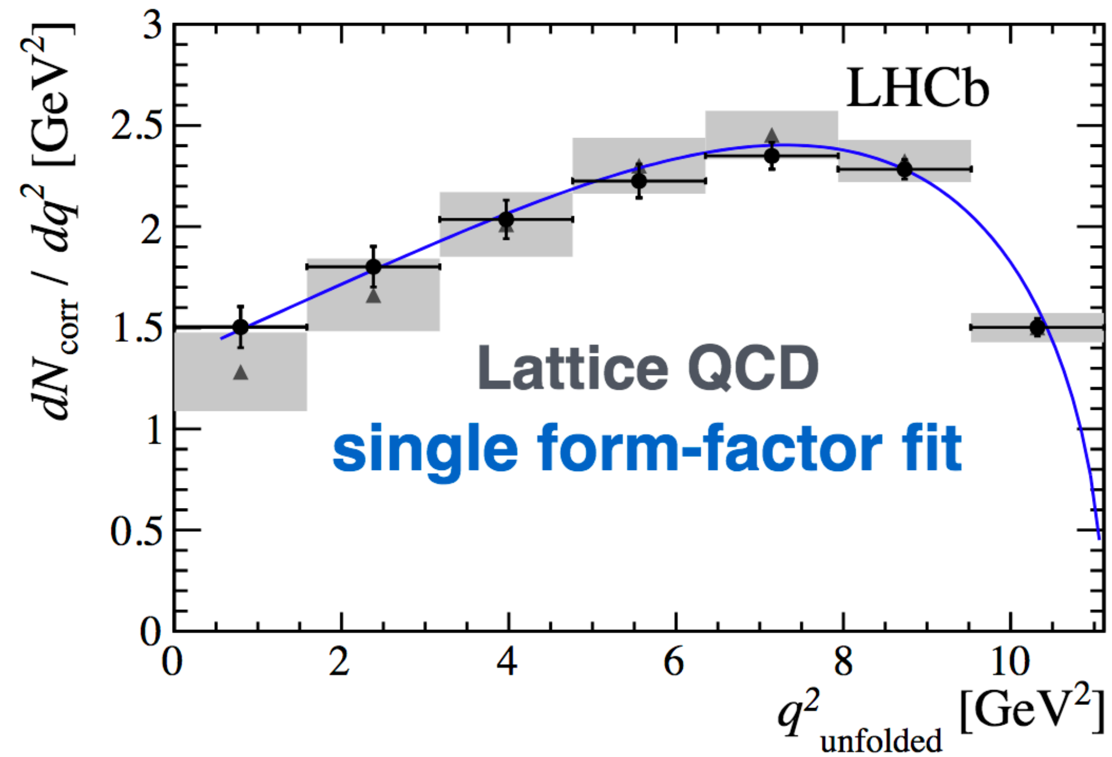


PRD 96, 112005 (2017)

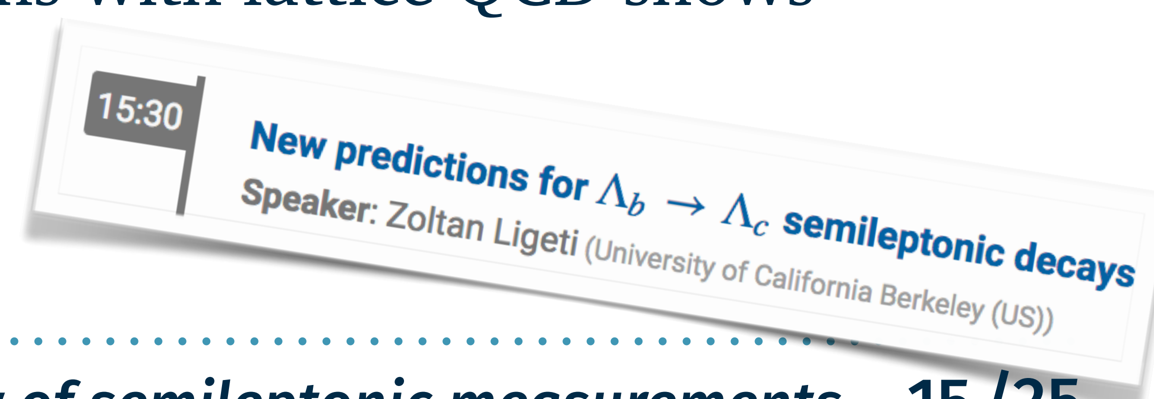
Shape of $\Lambda_b \rightarrow \Lambda_c \mu \nu$ decay rate

- w distributions are unfolded and corrected for efficiencies
- Then they are fit using 3 approaches, here is example from Taylor expansion. They are in good agreement with HQET predictions





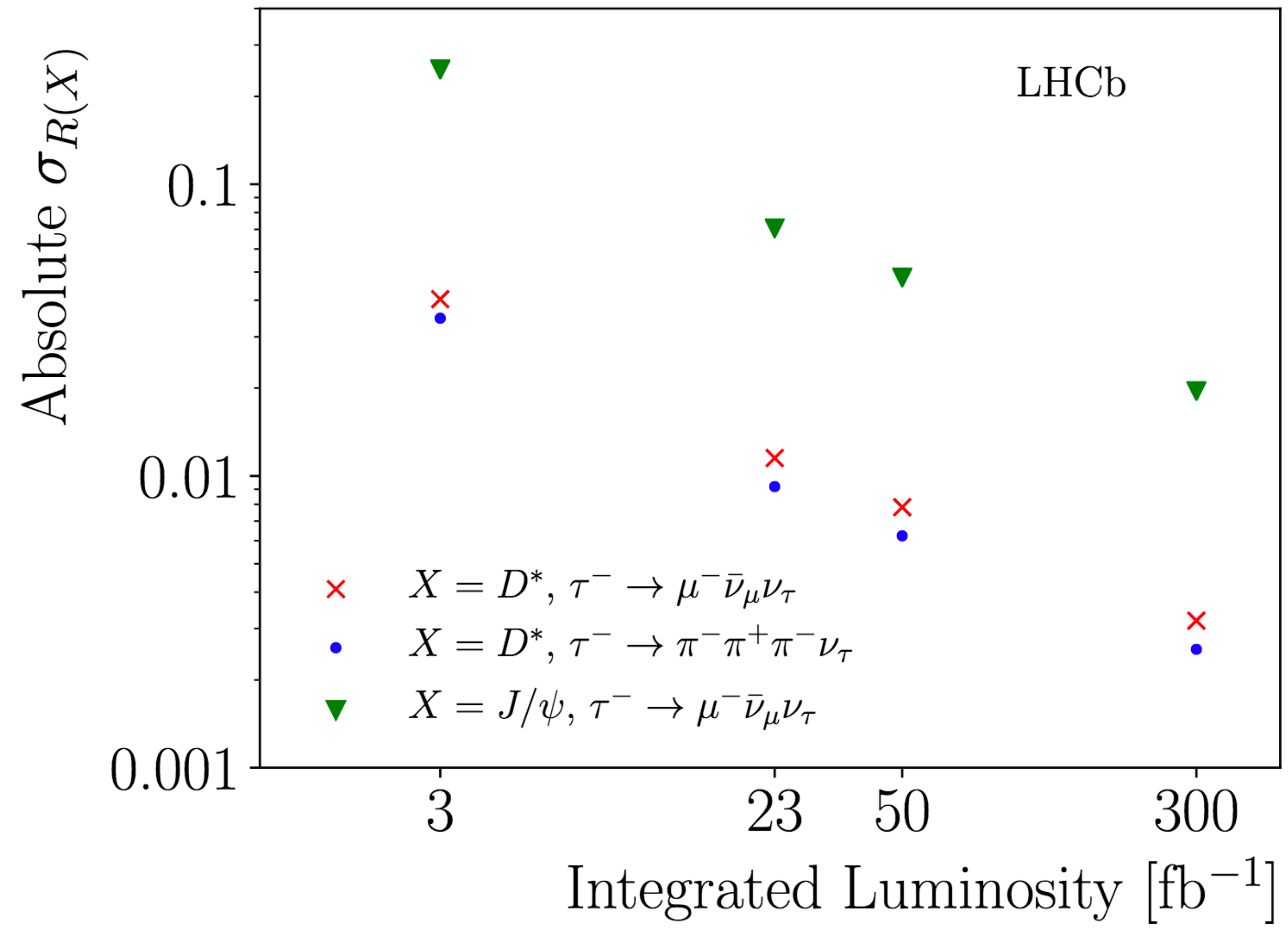
- Also comparison with $d\Gamma/dq^2$ distributions with lattice QCD shows excellent agreement. PRD 92 (2015) 034503
- More theory predictions coming soon!



Outlook

- Expected precision improves with integrated luminosity
- Measurement of *R(D)-R(D*)* is on its way
- Also other channels:
  - $R(\Lambda_c)$, $R(D^+)$, $R(pp)$, $R(D_s^{(*)})$, $R(\Lambda_c)$ (muonic and hadronic)
- Other form factor measurements are also on the way:
  - $\Lambda_b \to \Lambda_c^* \mu\nu$
  - $B_s \to D_s^{(*)} \mu\nu$

LHCb-PUB-2018-009

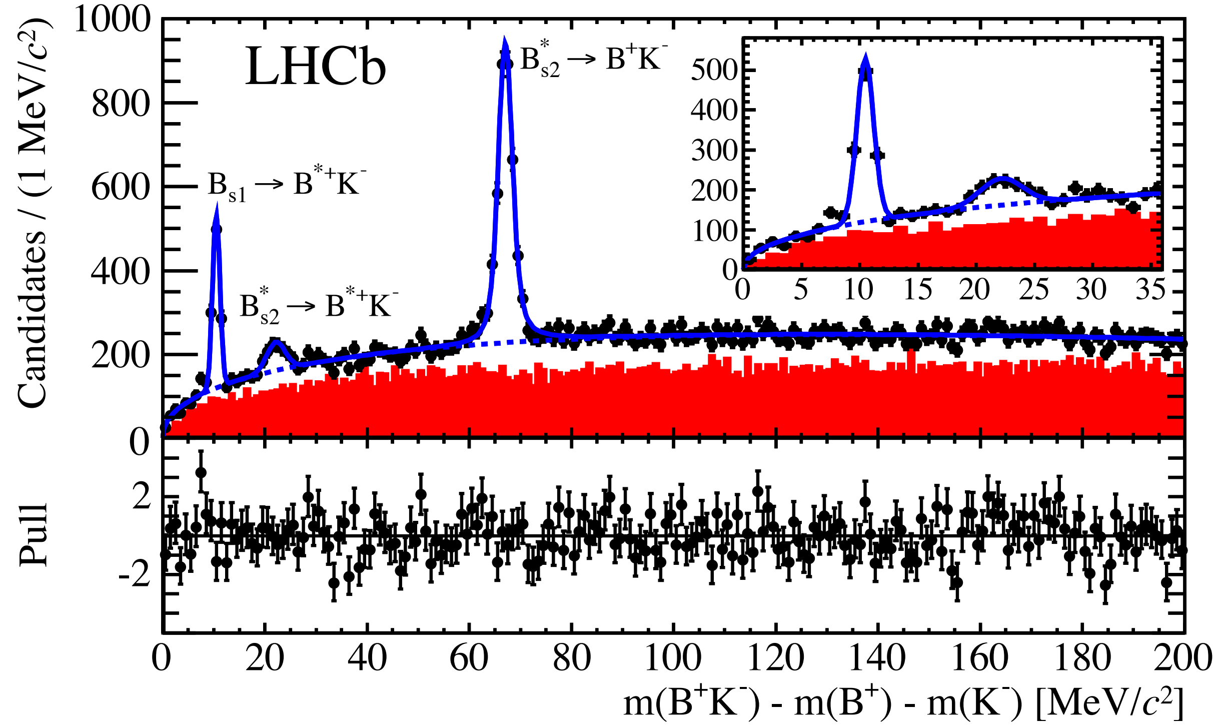


Relative branching fractions

$B^- \to D^0/D^{*0}/D^{**0}\mu^-\overline{\nu}_\mu$

- Gap between the inclusive and exclusive branching fractions of semileptonic $B \to D\ell\nu$ decays.
- Measure semi-inclusive decays: $B^- \to D^{0(*/**)}X\mu^-\overline{\nu}_\mu$
- Excited states also background for $B \to D\ell\nu$ decays.
- Study the excited states if B momentum is known, so missing mass can be calculated.

PRL 110 151803 (2013)



- Use B from $\overline{B}_{s2}^{*0}$ decays to tag the B and determine its momentum
- $\sim$1% of B^- originate from $\overline{B}_{s2}^{*0}$

Relative branching fractions

$B^- \to D^0/D^{*0}/D^{**0}\mu^-\overline{\nu}_\mu$

arXiv: 1807.10722

- Use B from $\overline{B}^{*0}_{s2}$ decays to tag the B and determine its momentum:

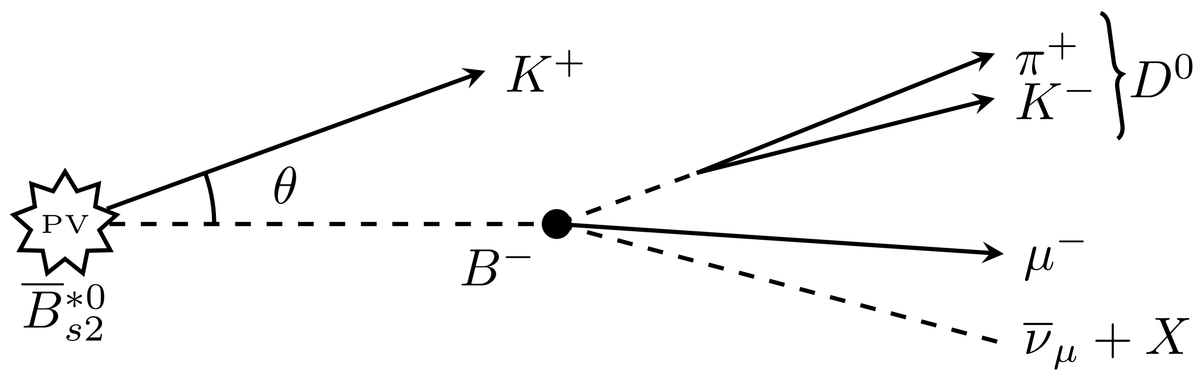
  Adv. HEP (2014) 931257

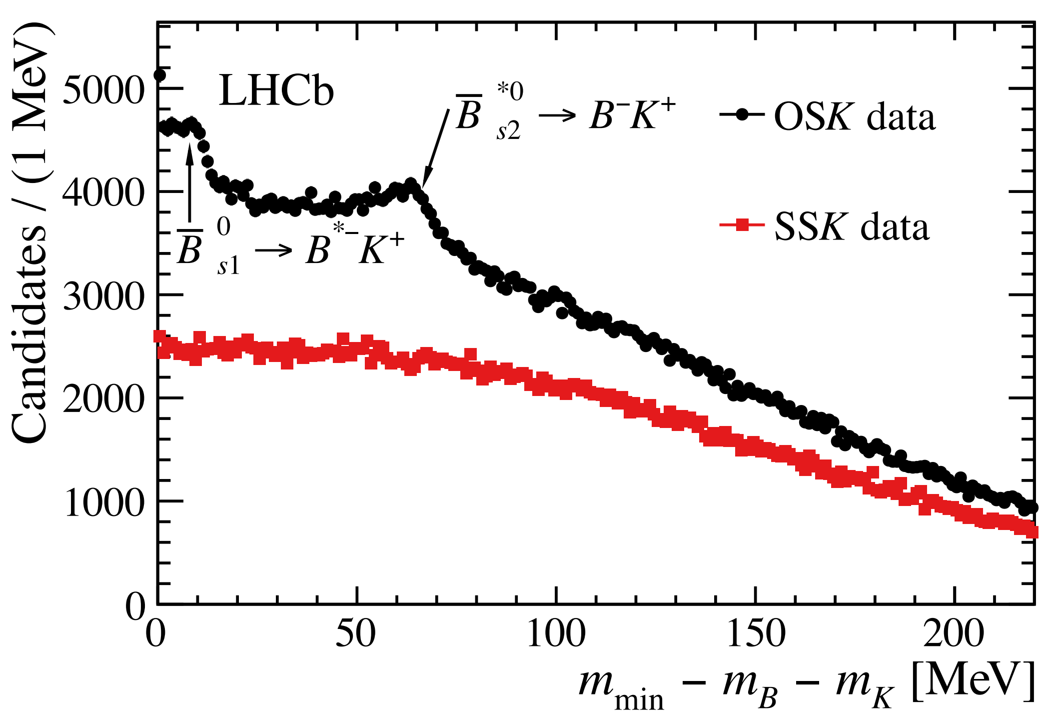
  - impose mass constraints on B^-
  - quadratic equation for E_B, depending on m_{BK}
  - minimum mass of BK pair:

$$m_{\min} = \sqrt{m_B^2 + m_K^2 + 2m_B\sqrt{p_K^2\sin^2\theta + m_K^2}}$$

  - calculate E_B, assuming that $m_{BK} = m_{Bs2}$ and calculate missing mass:

$$m^2_{\text{miss}} = (p_B - p_{\text{vis}})^2$$



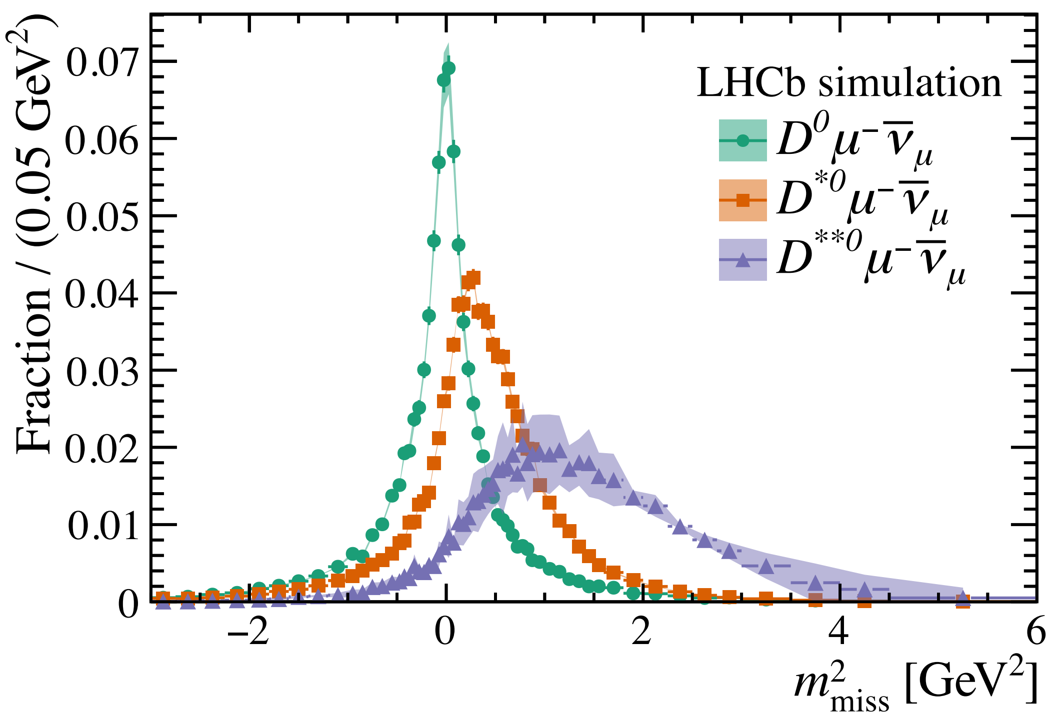


Relative branching fractions

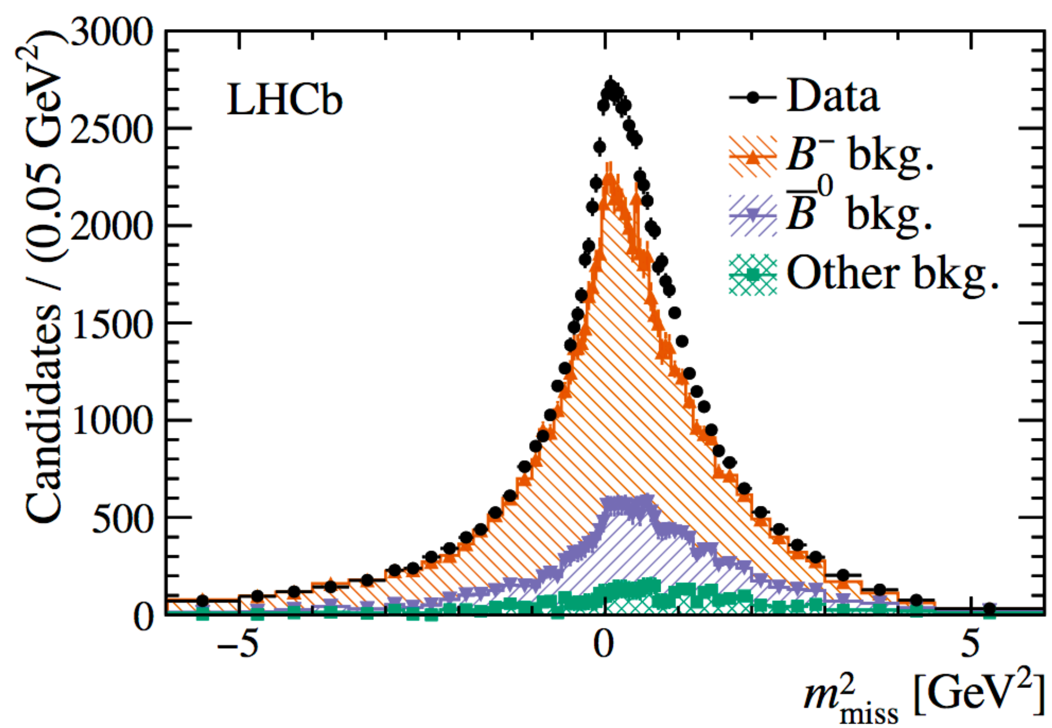
$B^- \to D^0/D^{*0}/D^{**0}\mu^-\overline{\nu}_\mu$

arXiv: 1807.10722

- Keeping only physical solutions for E_B, with lowest energy in case of two physical solutions, correctly solves 85-90%.



- Biggest challenge of the analysis: determine large amount of background
- Main background are semileptonic B^- and B^0 decays not coming from $\overline{B}^{*0}_{s2}$, which is 83% of selected candidates → determined from OS (B^-K^-)
- Other: non-semileptonic (8%) and τ decays



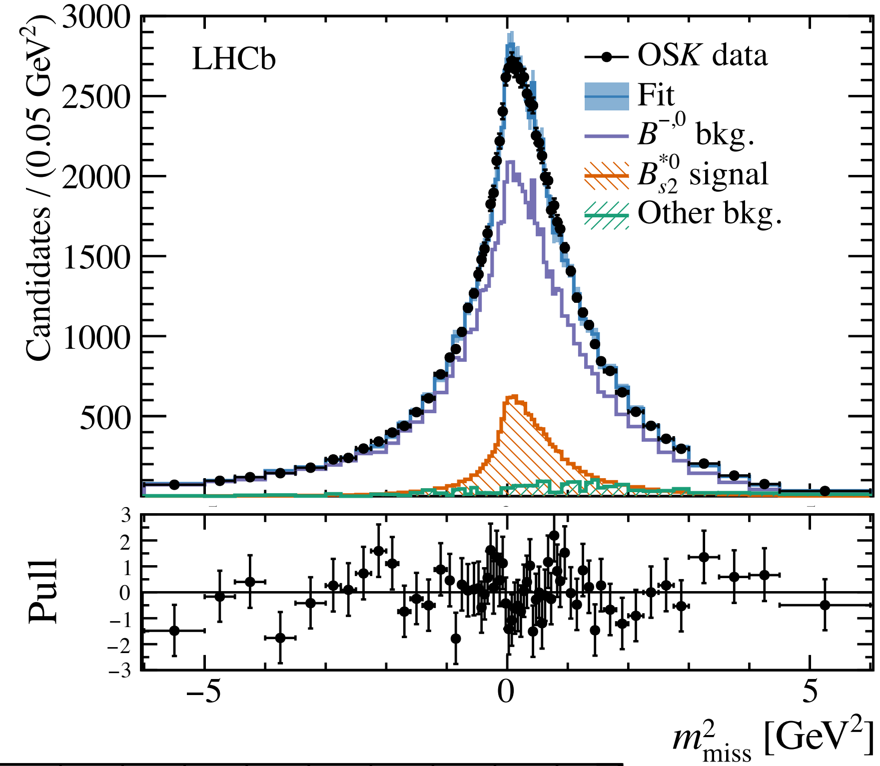
Relative branching fractions

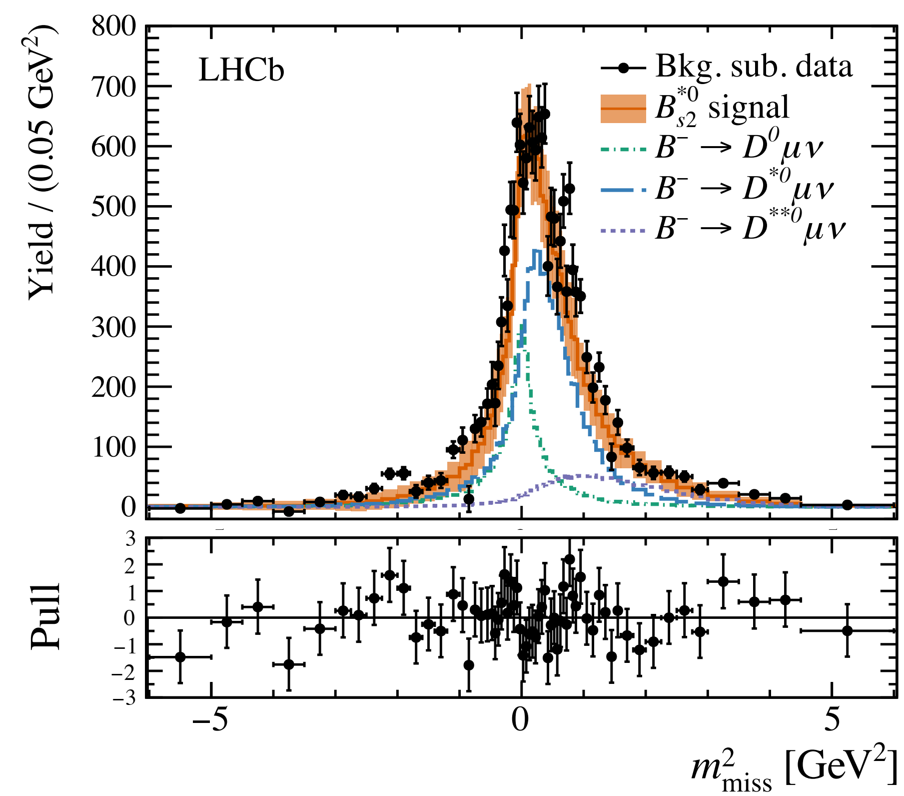
arXiv: 1807.10722

$B^- \to D^0/D^{*0}/D^{**0}\mu^-\overline{\nu}_\mu$

- Relative branching fractions are extracted in template fit with 8 contributions: 3 for signal and 5 for backgrounds

$$\begin{aligned} f_{D^0} &= 0.25 \pm 0.06 \\ f_{D^{**0}} &= 0.21 \pm 0.07 \\ 1 - f_{D^0} - f_{D^{**0}} &= 0.54 \pm 0.07 \end{aligned}$$

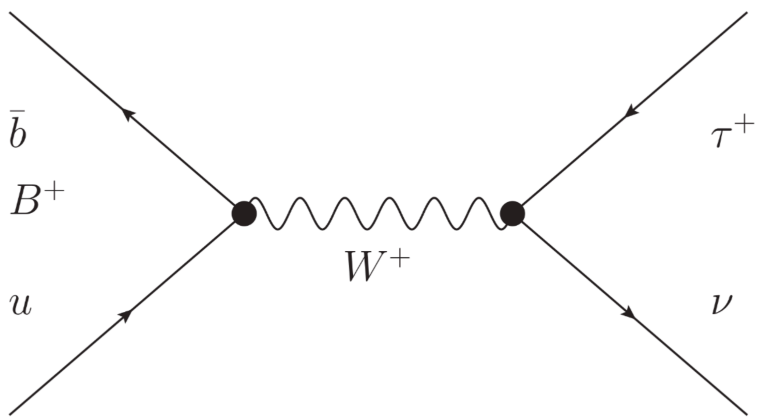




- Results are compatible with expectations and previous results from BaBar PRD 76, 051101 (2007)
- Promising method, working on improving understanding of backgrounds with simulations and more statistics to explain inclusive-exclusive gap

Search for B→3μν decays

- Leptonic B^+ decays have branching fraction proportional to $|V_{ub}|^2$ and are helicity suppressed



- Precise SM predictions and sensitive to new physics
- Measurements from BaBar and Belle in agreement with SM

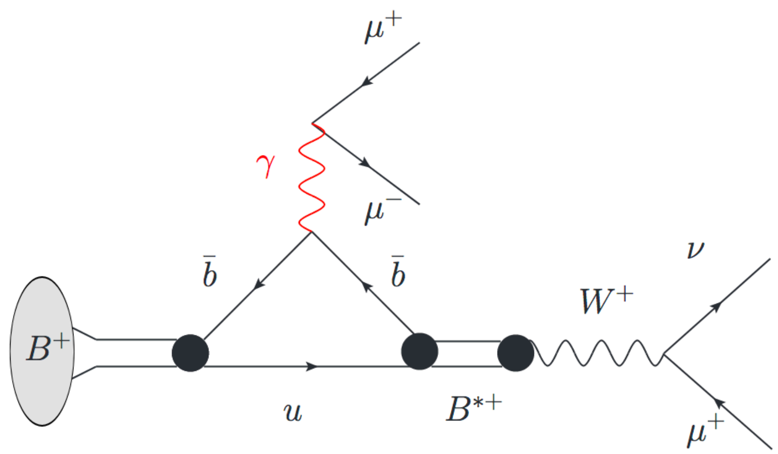
- In LHCb, difficult to measure $B\to\ell\nu$ decays, because there's only 1 track
- Adding photon to the decay: $B^+\to\gamma\mu\nu$, lifts helicity suppression, still very hard to measure in LHCb
- Photon decaying to 2μ, such that $B^+\to 3\mu\nu$, makes it feasible to reconstruct in LHCb!
- Recent prediction: $\mathscr{B}(B^+\to 3\mu\nu) = 1.3\times10^{-7}$

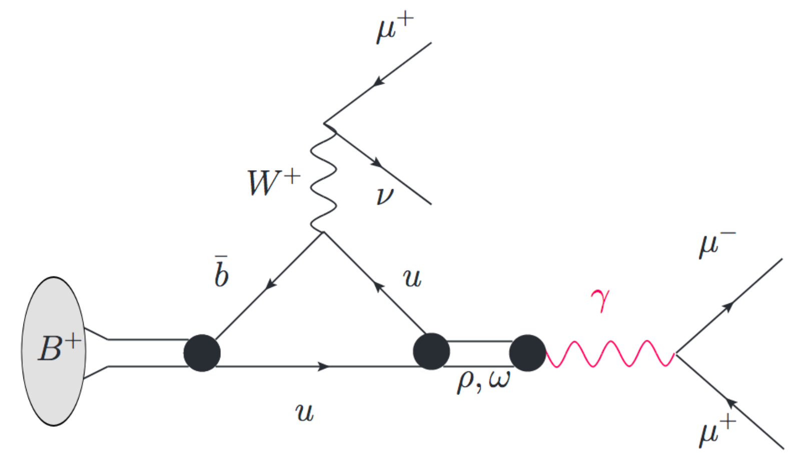
Phys. Atom. Nucl. 81 (2018) 34

Search for B→3μν decays

LHCb-PAPER-2018-037
in preparation

- With 3 muons in the final state gives a well-defined B vertex:





- Decay is normalised to $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ decays:

$$\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) = \mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)$$

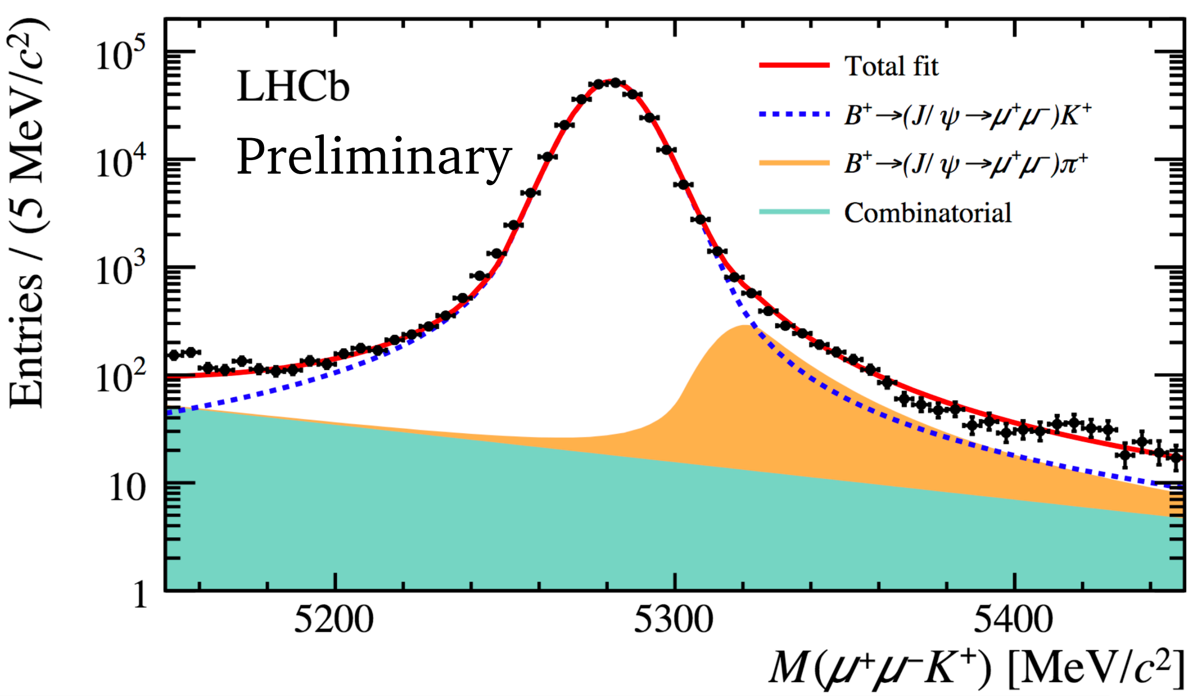
from PDG

$$\times \frac{\varepsilon(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\varepsilon(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)}$$

0.37±0.003

$$\times \frac{N(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)}{N(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}$$

blinded fit



Search for B→3μν decays

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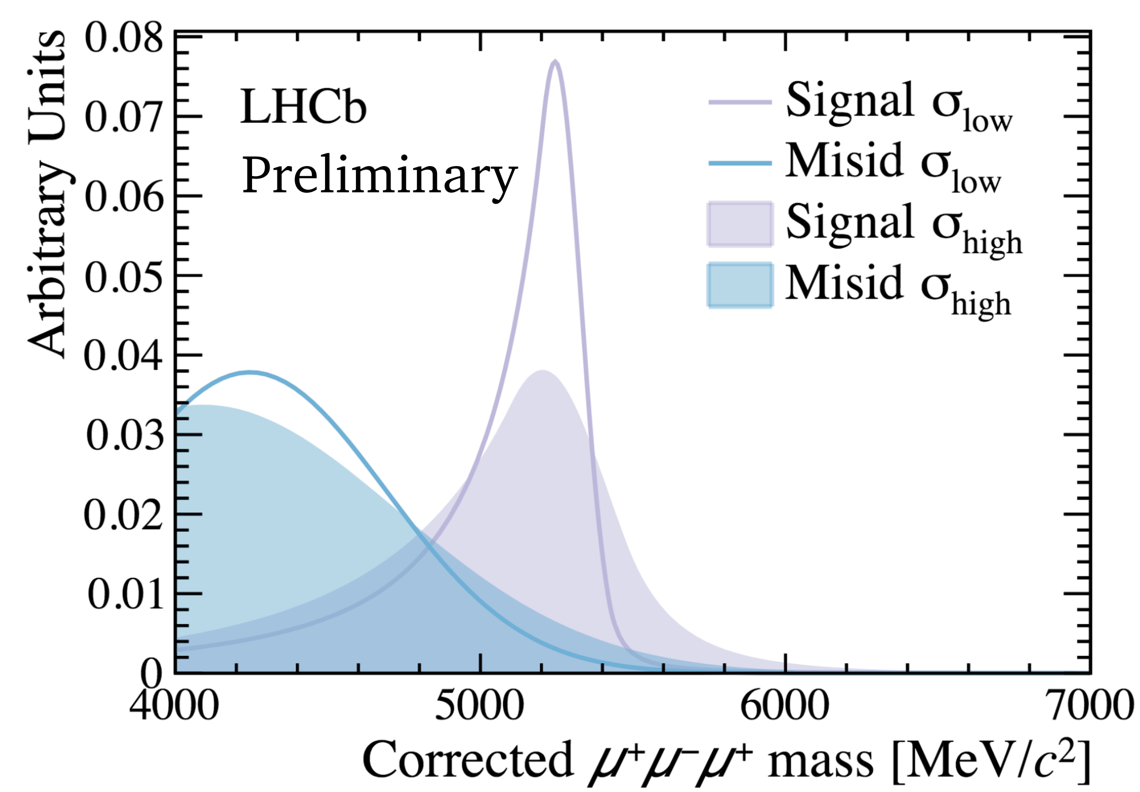
in preparation

- Backgrounds from J/ψ and ψ(2S) are removed with vetoes
- m(μμ)<980 MeV to reduce combinatorial background
- Remaining backgrounds are reduced using BDT and modelled through simulation

- To improve sensitivity: uncertainty on primary and secondary vertices are propagated to corrected mass and the sample is split into two: high and low uncertainties on m_{corr}:



Search for B→3μν decays

LHCb-PAPER-2018-037
in preparation

- Analysis was performed using 4.7 fb^{-1} (2011+2012+2016)
- No significant signal is found
- Limit is set 1.4×10^{-8} at 95% using the CLs method (preliminary!)
- Plot also shows prediction based on vector meson dominance model, which shows tension with the measurement

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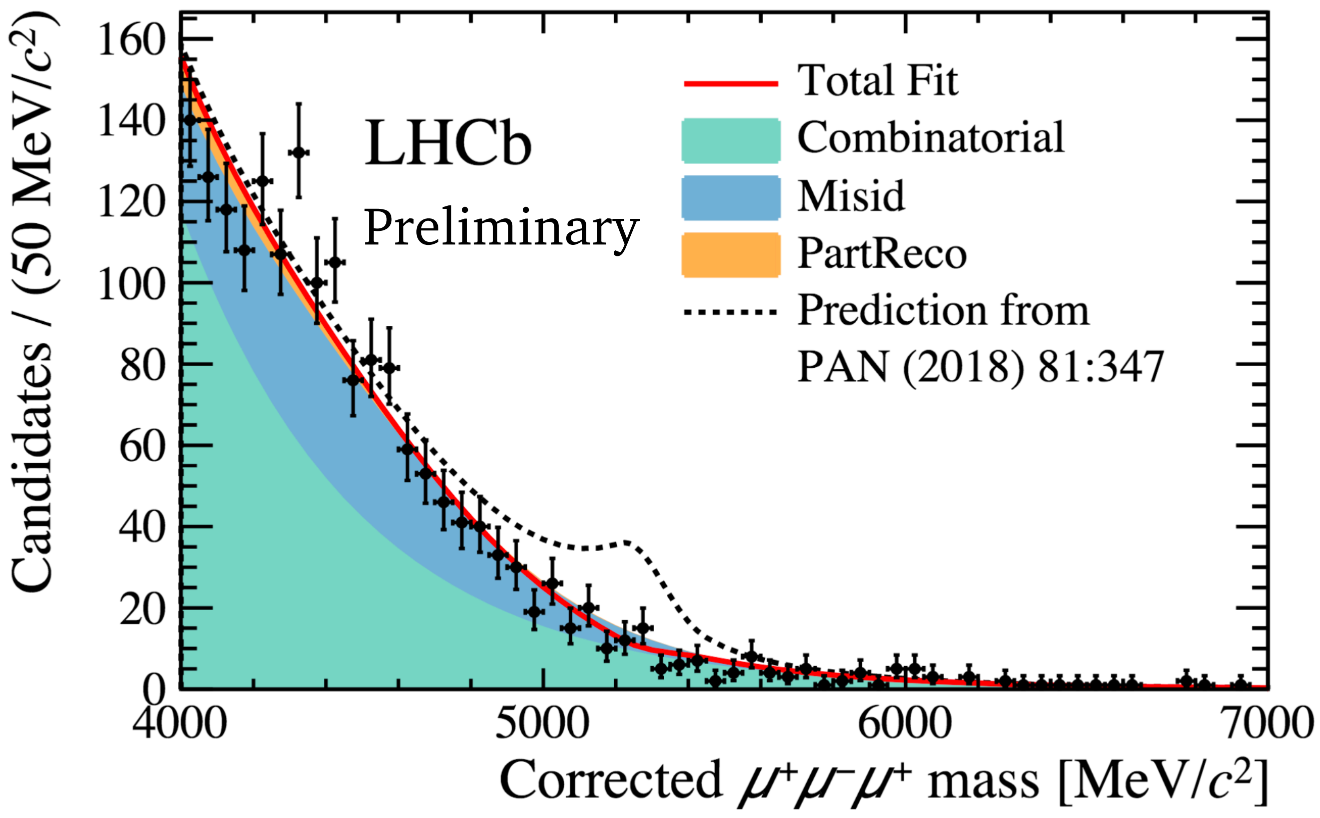

Conclusion

- Measured relative $B^- \to D^0/D^{*0}/D^{**0}\mu^-\overline{\nu}_\mu$ branching fractions using $\overline{B}^{*0}_{s2}$ decays
- Limit $\mathcal{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) < 1.4 \times 10^{-8}$
- Many more interesting analyses are on their way!
    - More tests of LFU
    - Form factors
    - $|V_{\text{ub}}|/|V_{\text{cb}}|$
- Looking forward to discussion withs the theory community in the coming talks!