# $b-$baryon and $B_c$ Fragmentation functions

## Why, how and future prospects

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# Motivation

- At the LHC we can study heavier b-flavored hadrons such as $\Lambda_b^0, \Xi^{0,\pm}, \Omega_b \ldots$ and mesons such $B_s^0$ and $B_c^+$. Precise determination of absolute branching fractions relies on the well-measured exclusive decays at $e^+e^- b$-factories
- Study of fragmentation functions of b-baryons allow us to probe interesting facets of QCD and effective theories, such as HQET, in particular the quark-diquark model of baryons
- Inclusive methods to access b-fractions (such as inclusive semileptonic decays) allow to probe charmed baryon states and discover new resonances (especially with the high-statistics available at the LHC (and HL-LHC).

# b-baryon fragmentation functions - some theory

https://arxiv.org/abs/2510.04656

- Hadronization mechanism in QCD and what they tell us:
  - Model of hadronization based on “string junctions,” fundamental structures that can be produced and liberated in nuclear collisions; under appropriate conditions the string junctions can migrate over a considerable rapidity space.
  - Heavy quarks produced in the initial hard scattering and Parton shower (hence assumptions that b-hadron production fractions universal).
  - However heavy quarks, produced in the early part of the collisions, thus they traverse the dense QCD medium created in the nuclear collisions, thereby carrying the **signature of the medium**
  - Why is it important?
    - Of great interest to the heavy ion community
    - Of great interest to whoever needs to do extensive reweighting to match the data kinematics with the MC kinematics.

As we strive for high-precision results we should not forget the MC generators

# b-hadron fragmentation functions from inclusive semileptonic decays

## LHCb Run I, LHCb Run II

- B-hadron fragmentation functions derived from charm-$\mu$ final states:
  - $D^0\mu$ and $D^+\mu$ are produced mostly in $B^0$ and $B^+$ decays
  - $D_s^0\mu$ is produced mostly in $B_s^0$ decays
  - $\Lambda_c^+\mu$ is produced mostly in $\Lambda_b^0$ decays
- Cross-feeds are accounted for studying the specific decay channels:
  - $D^0K\mu\nu\ (B^0,\ B^+,\ B_s^0)$
  - $D_sK\mu\nu\ (B^0,\ B^+,\ B_s^0)$
  - $D^0p\mu\nu\ (B^0,\ B^+,\ \Lambda_b^0)$

Charge-conjugate cross-feeds are inferred from known branching fractions and isospin symmetry

# $\Lambda_b^0$ fragmentation function

## LHCb Measurements, RUN I RUN II

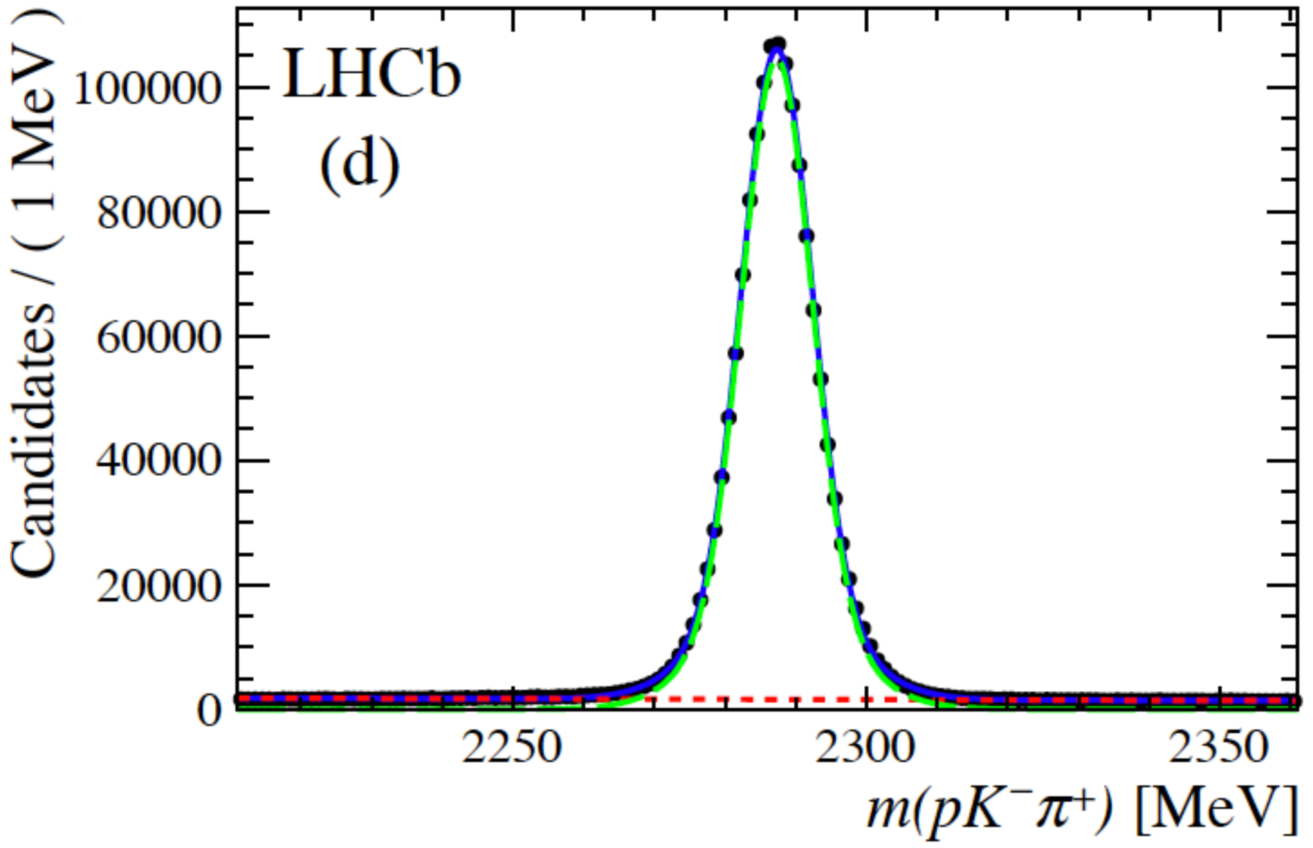
- Formalism:

$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = \frac{n_{\mathrm{corr}}(\Lambda_b^0 \to D\mu)}{n_{\mathrm{corr}}(B \to D^0\mu) + n_{\mathrm{corr}}(B \to D^+\mu)} \frac{\tau_{B^-} + \tau_{\bar{B}^0}}{2\tau_{\Lambda_b^0}} (1 - \xi_{\Lambda_b})$$

- The corrected yields $n_{\mathrm{corr}}$ are the yields corrected for charm branching fractions, efficiencies, and cross-feed decays
- Relies on the equality of semileptonic widths (HQE) - correction $\xi_{\Lambda_b^0} = (4.1 \pm 1.6)\ \%$ , [ Bordone, Gambino 2022]
- Note:
  - the final states are very similar in the numerator and denominator (only the $D^0\mu$ final state has 3 rather than 4 tracks
  - By combining $B_u$ and $B_d$ in the final state, we do not need a precise account of the $D^{\star\star}$ decay modes and the "semileptonic gap"

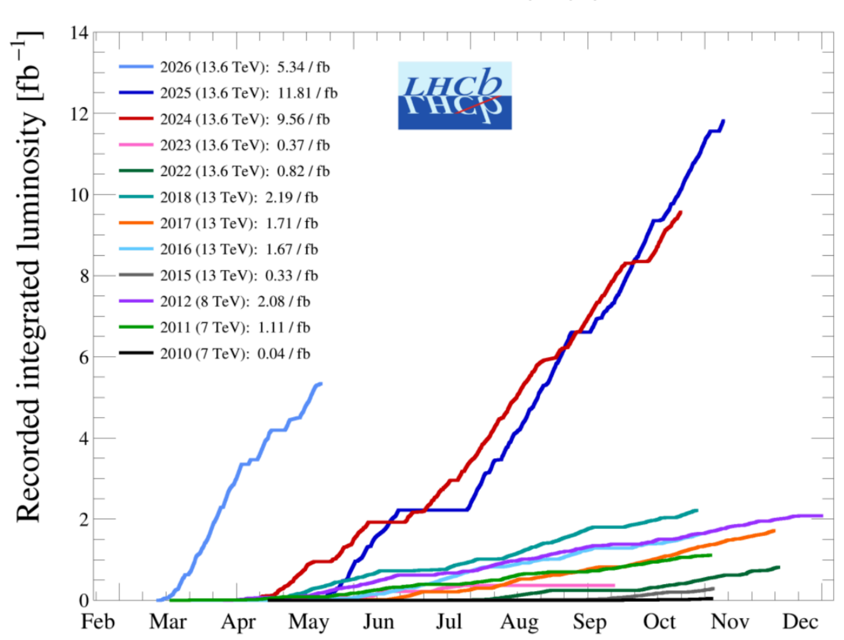
# Determining the signal yields

- Signal determined from fits to the charm hadron invariant mass



| | | |
|---|---|---|
| $\Lambda_c^+\mu X$ | 1753550± 1417 | in 1.67 fb$^{-1}$ |

Now:

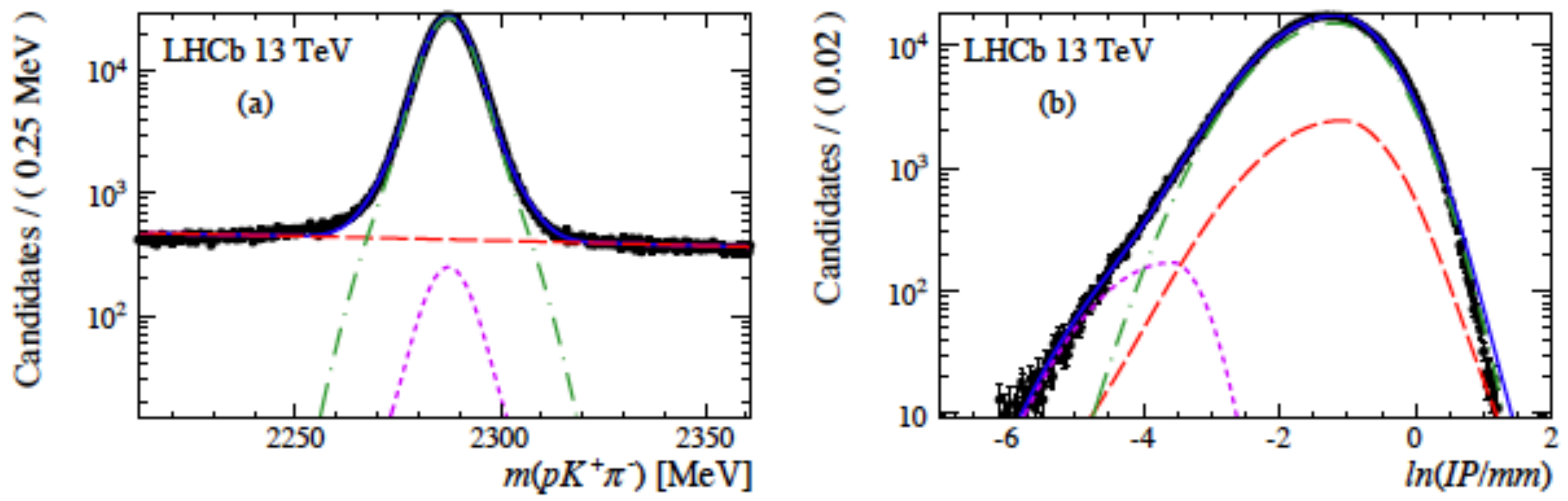


Final sample for 2026: 5.34 invfb!

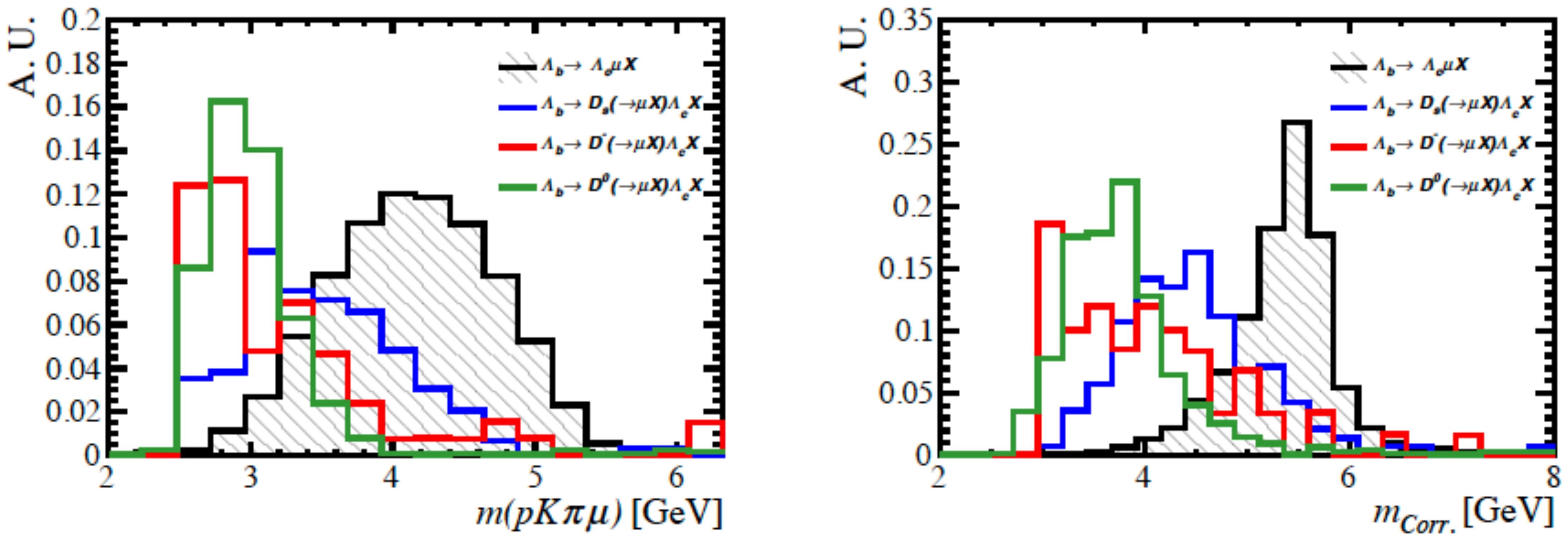
RUN3

# Peaking backgrounds

- Prompt charm: suppressed by cutting in ln(IP/mm)



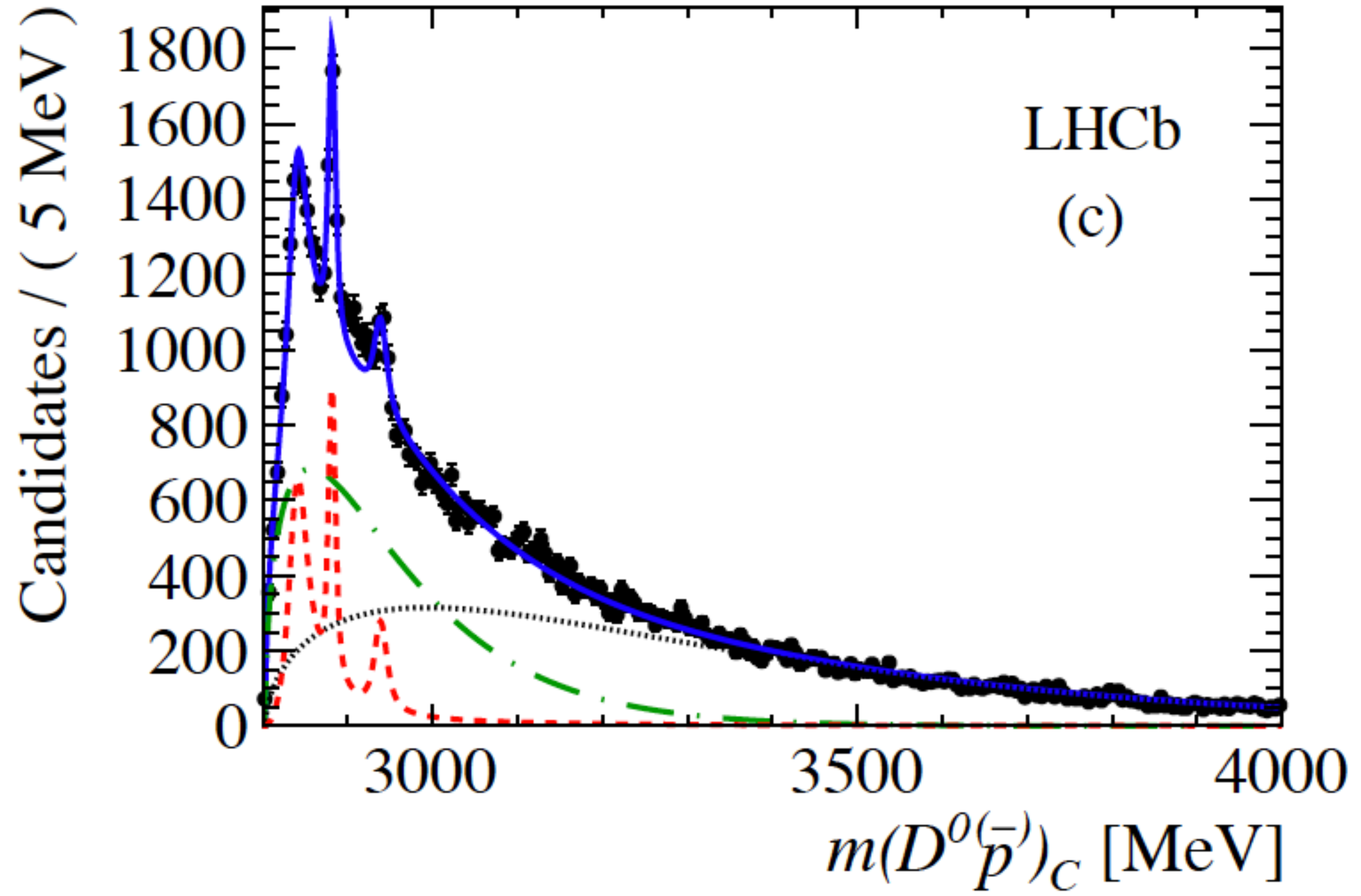
- $b \to c\bar{c}X$ background

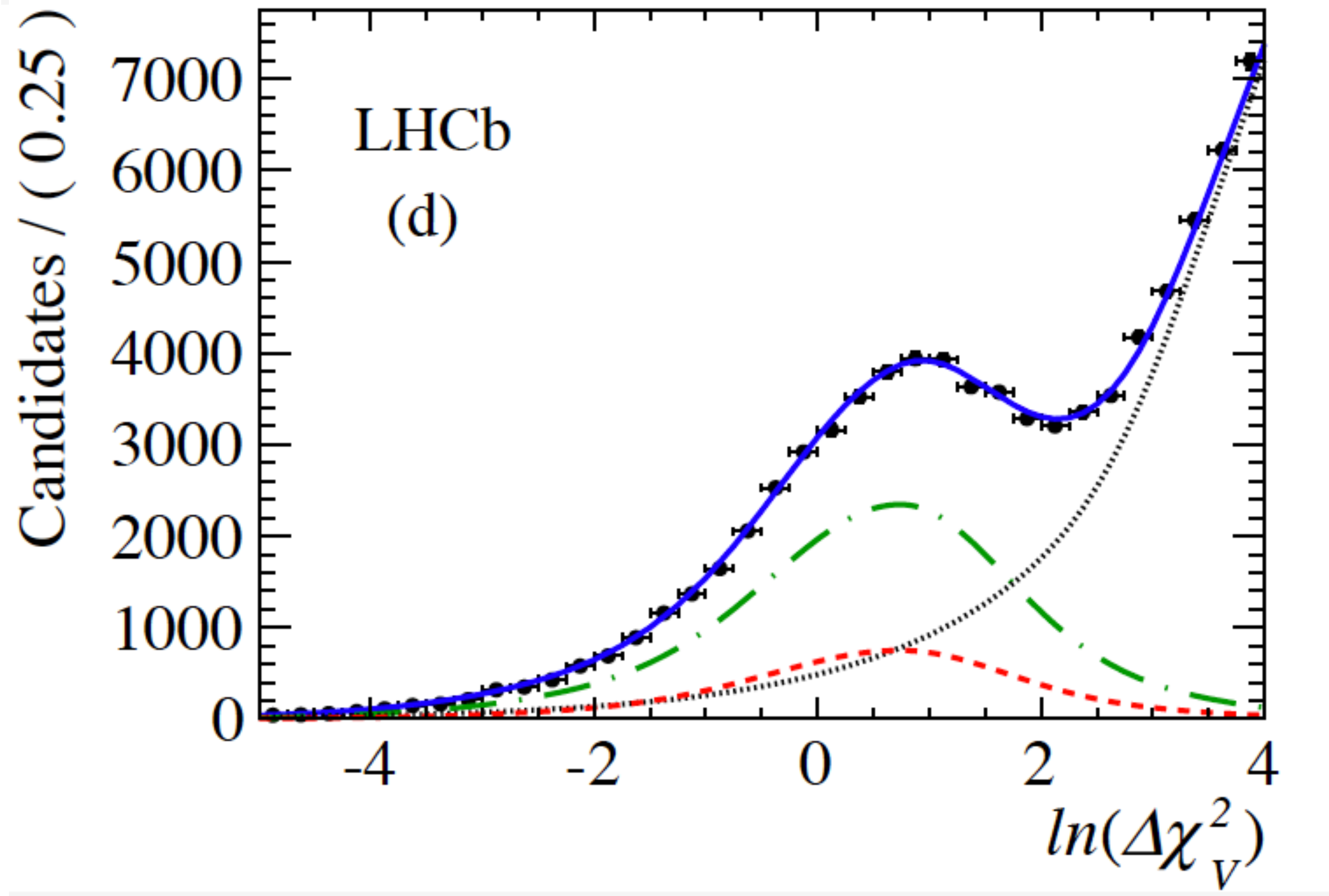


- Fake muons and $\mu - \Lambda_c$ combinations from different b-hadrons studied with WS samples

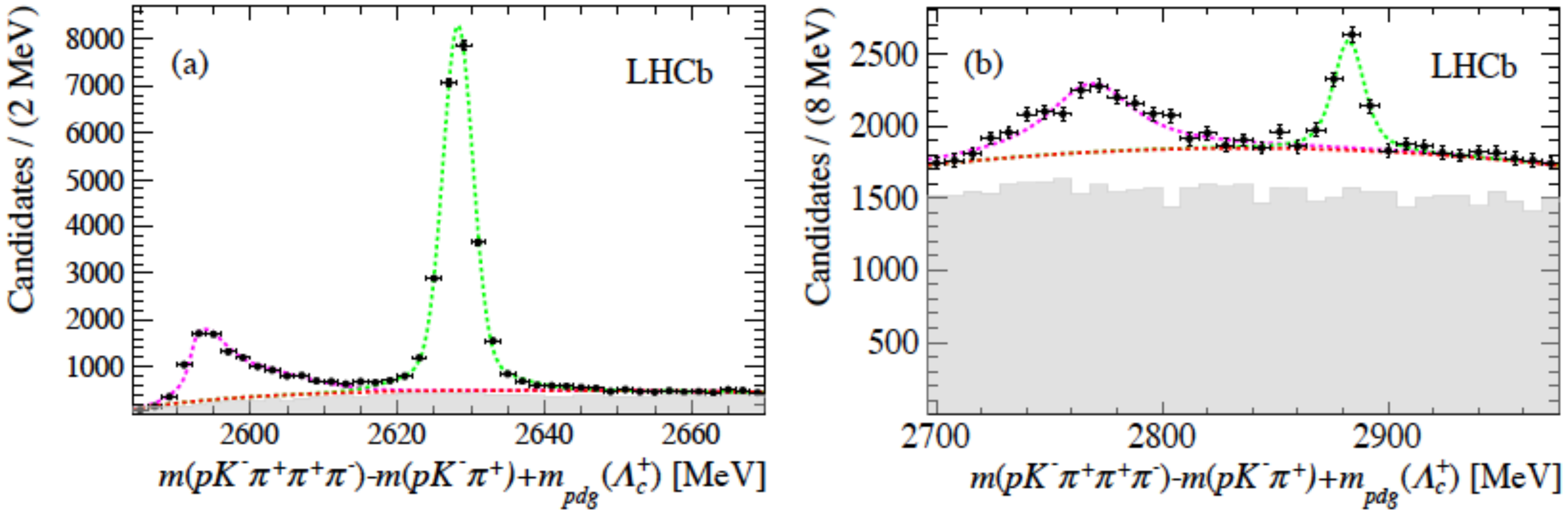
# Cross-feeds LHCb Run II

- In order to determine the $D^0\mu$ yields coming from the $\Lambda_b^0$ we study the final state $D^0 p\mu$. We remove the assumption that the $\Lambda_c^\star$ decaying into this final state comprise only resonant components. You can see from these fits that the NR $\Lambda_b^0 \to D^0 p\mu\bar{\nu}$ is significant
- NR is distinguished from combinatoric background via vertex topology (p consistent with coming from the $D^0\mu$ vertex), this is a tool that can be exploited more generally to study NR component of inclusive b-baryon semileptonic width
- These studies help also in **elucidating hadron composition in b-hadron semileptonic decays**





# Implications for inclusive semileptonic decays

- The vertex criteria can be applied to other semi-inclusive decays, for example $\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \mu^- X$
- 

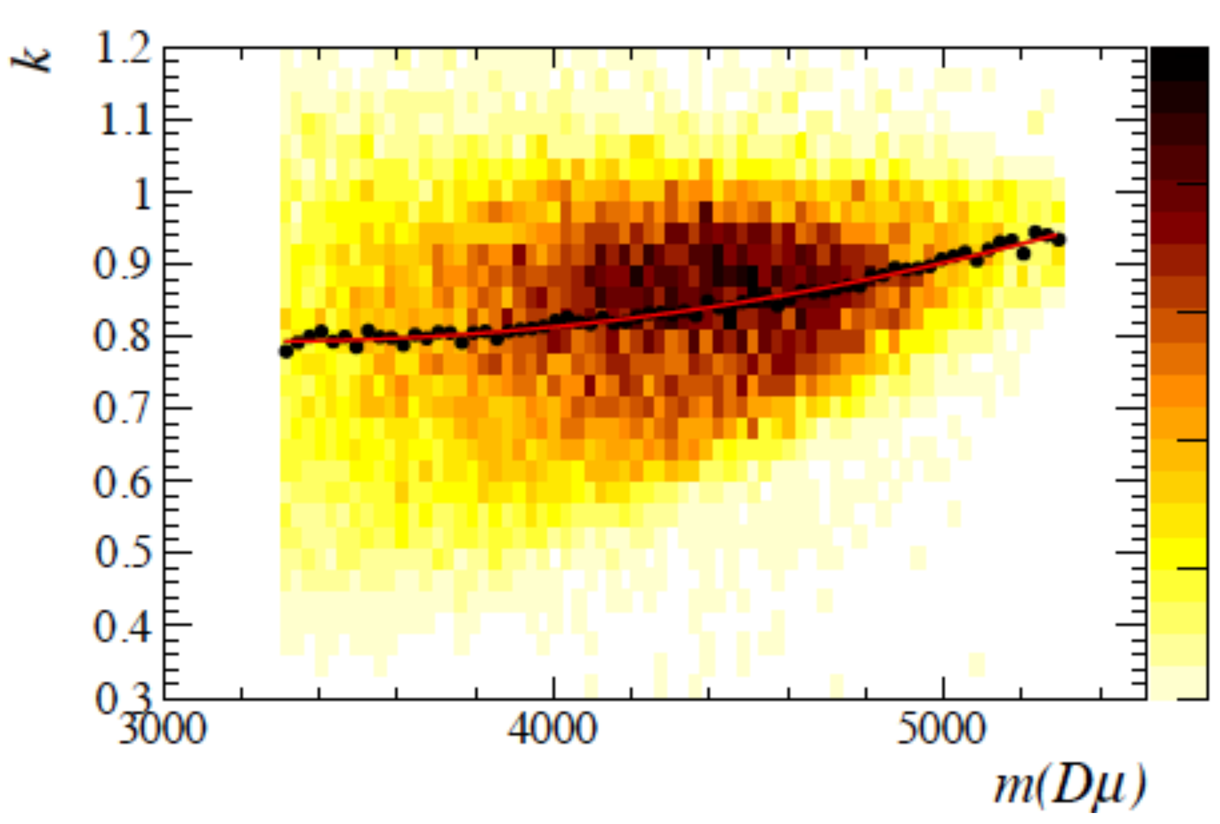
https://arxiv.org/abs/1709.01920

Shape in 1d fit cannot distinguish NR from background, 2d fit remedies this [in preparation]

# Results

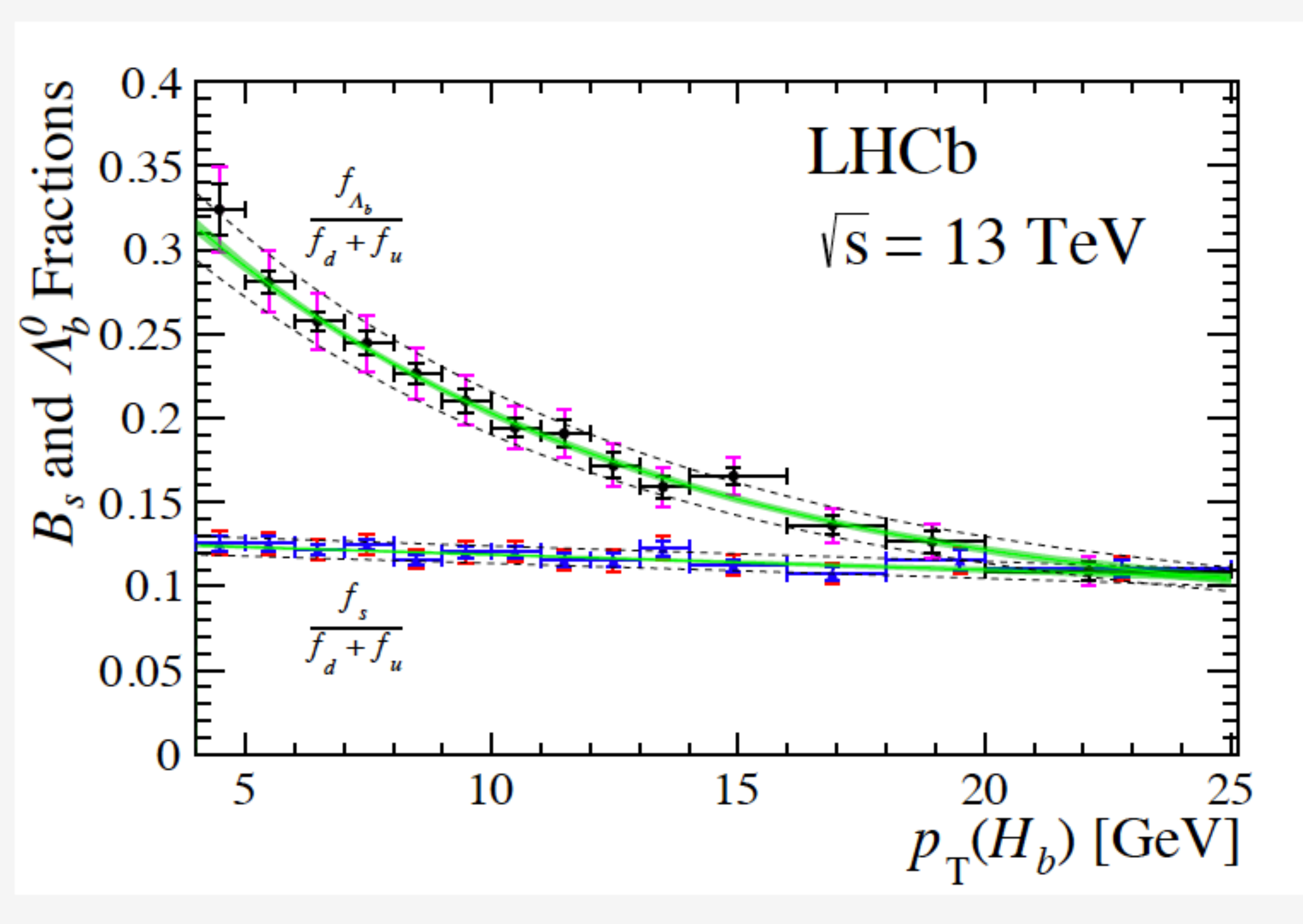
- In order to study the b-baryon $p_T$, it is necessary to correct for the non-reconstructed $\bar{\nu}_\mu$
- Using an average correction factor:

$$k = \frac{p_T^{reco}}{p_T^{true}}$$



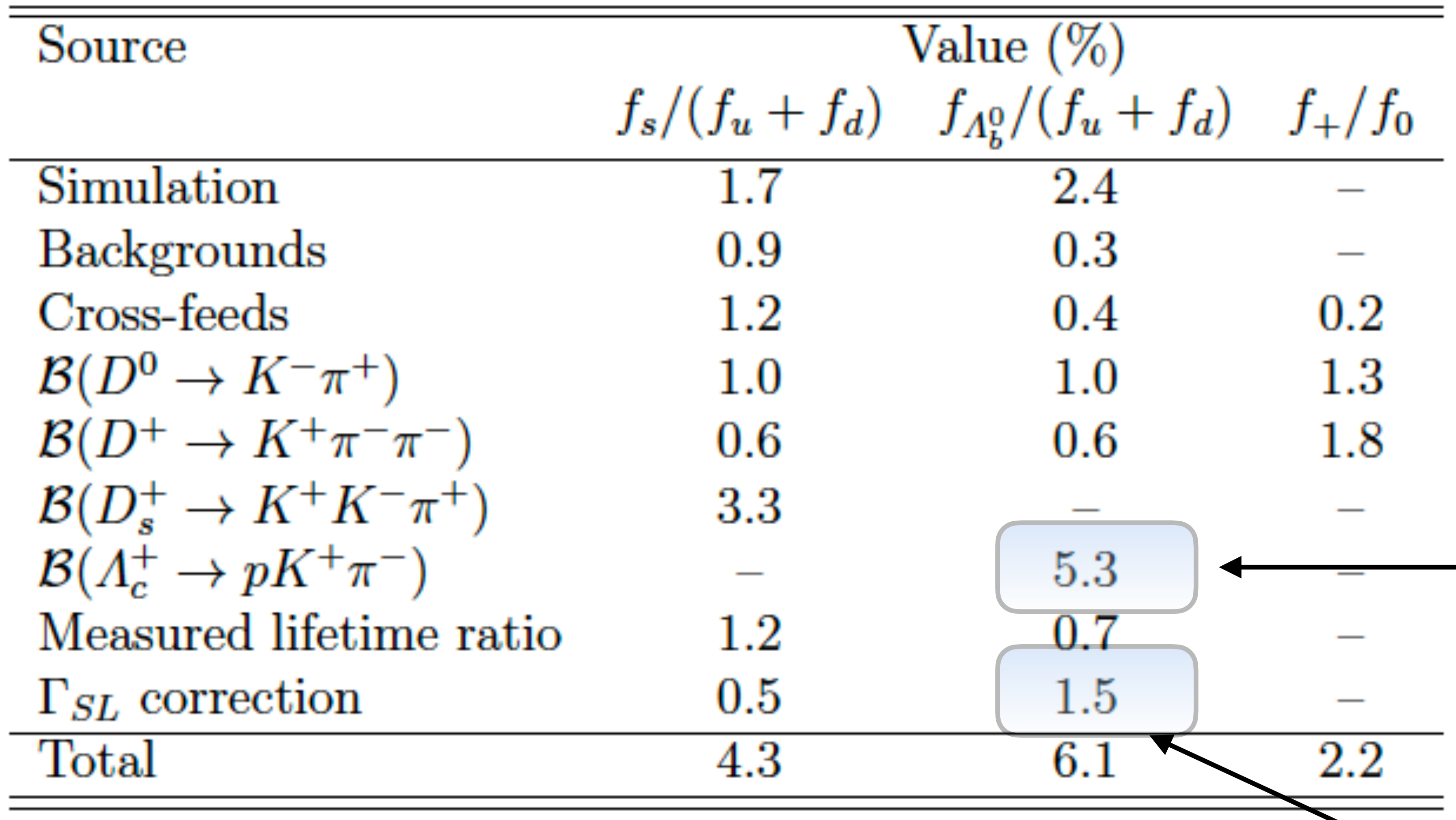
$$\frac{f_{\Lambda_b^0}}{f_u + f_d}(p_T) = A\left[p_1 + \exp\left(p_2 + p_3 \times p_T\right)\right],$$

$$A = 1\pm0.061,\ p_1 = (7.93\pm1.41)\cdot10^{-2},\ p_2 = -1.022\pm0.047$$



# What drives the uncertainty?

- External inputs: charm branching fractions



| Source | Value (%) | | |
|---|---|---|---|
| | $f_s/(f_u+f_d)$ | $f_{\Lambda_b^0}/(f_u+f_d)$ | $f_+/f_0$ |
| Simulation | 1.7 | 2.4 | – |
| Backgrounds | 0.9 | 0.3 | – |
| Cross-feeds | 1.2 | 0.4 | 0.2 |
| $\mathcal{B}(D^0\to K^-\pi^+)$ | 1.0 | 1.0 | 1.3 |
| $\mathcal{B}(D^+\to K^+\pi^-\pi^-)$ | 0.6 | 0.6 | 1.8 |
| $\mathcal{B}(D_s^+\to K^+K^-\pi^+)$ | 3.3 | – | – |
| $\mathcal{B}(\Lambda_c^+\to pK^+\pi^-)$ | – | 5.3 | – |
| Measured lifetime ratio | 1.2 | 0.7 | – |
| $\Gamma_{SL}$ correction | 0.5 | 1.5 | – |
| Total | 4.3 | 6.1 | 2.2 |

Now, thanks to new BES 3 measurement ±3.9 %

New calculation https://arxiv.org/abs/2203.13107

Uncertainty similar to the original estimates with more precise calculation

# Other results

- Averaging over the LHCb phase space:

$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = 0.259 \pm 0.018$$

Note: published result uses the old $\mathscr{B}(\Lambda_c \to pK^-\pi^+)$

Total uncertainty, dominated by systematic uncertainty

- If we assume that $1 = f_u + f_d + f_{B_s} + f_{\Lambda_b}(1 + \delta)$
  - $f_u = f_d = 0.346 \pm 0.008$
  - $f_s = 0.084 \pm 0.011$
  - $f_{\Lambda_b} = 0.179 \pm 0.013$

Correction for $\Xi_b$ and $\Omega_b$ production $\delta = 0.25 \pm 0.10$ from https://arxiv.org/abs/1612.05140

Other b-baryons $0.045 \pm 0.018$

https://arxiv.org/abs/1405.6842

# Determining the shape of $f_{\Lambda_b^0}/f_d$

- Use the final states $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\bar{B}^0 \to D^+\pi^-$

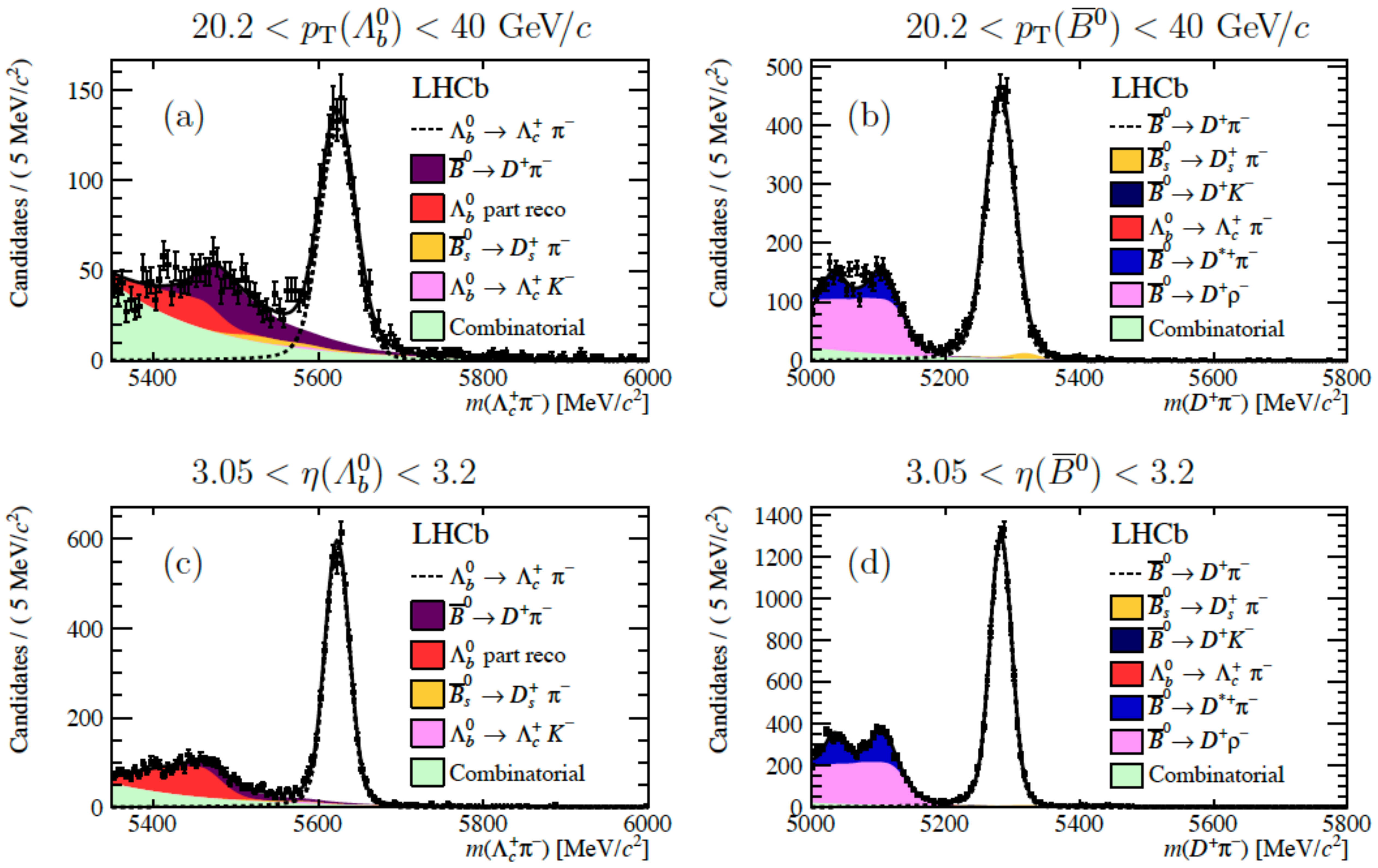
measured

- $$\mathcal{R}(x) \equiv \boxed{\frac{N_{\Lambda_b^0\to\Lambda_c^+\pi^-}(x)}{N_{\overline{B}^0\to D^+\pi^-}(x)}} \times \frac{\varepsilon_{\overline{B}^0\to D^+\pi^-}(x)}{\varepsilon_{\Lambda_b^0\to\Lambda_c^+\pi^-}(x)},$$

- $$\frac{f_{\Lambda_b^0}}{f_d}(x) = \frac{\mathcal{B}(\overline{B}^0\to D^+\pi^-)}{\underbrace{\boxed{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\pi^-)}}_{\text{Determined with this analysis}}} \times \frac{\mathcal{B}(D^+\to K^-\pi^+\pi^+)}{\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)} \times \mathcal{R}(x)$$

$x = p_{\mathrm{T}}, \eta$

- Note $\mathscr{R}(x)$ gives shape, but normalization needs to incorporate result from semileptonic $f_{\Lambda_b^0}/f_d$

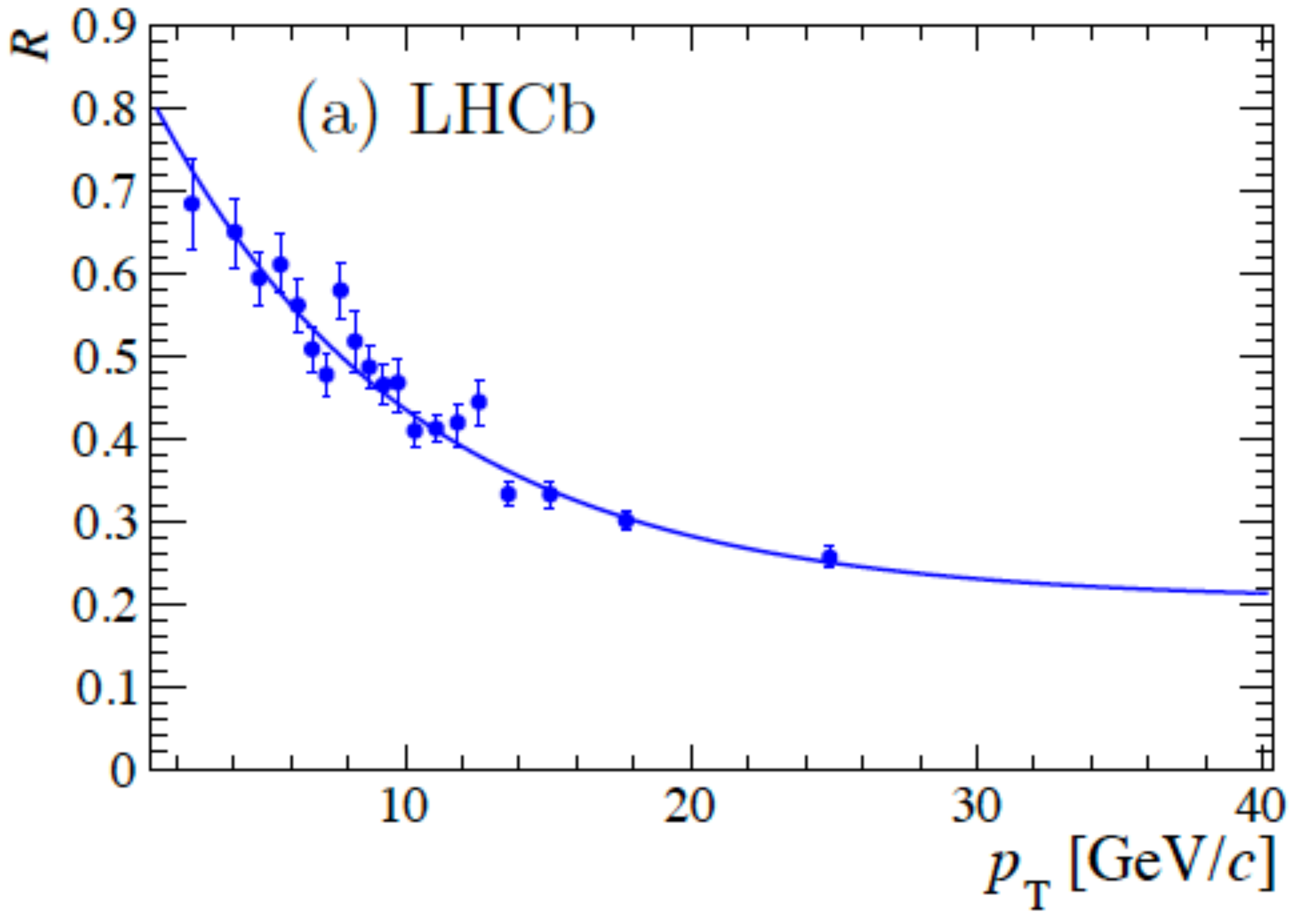


https://arxiv.org/abs/1405.6842

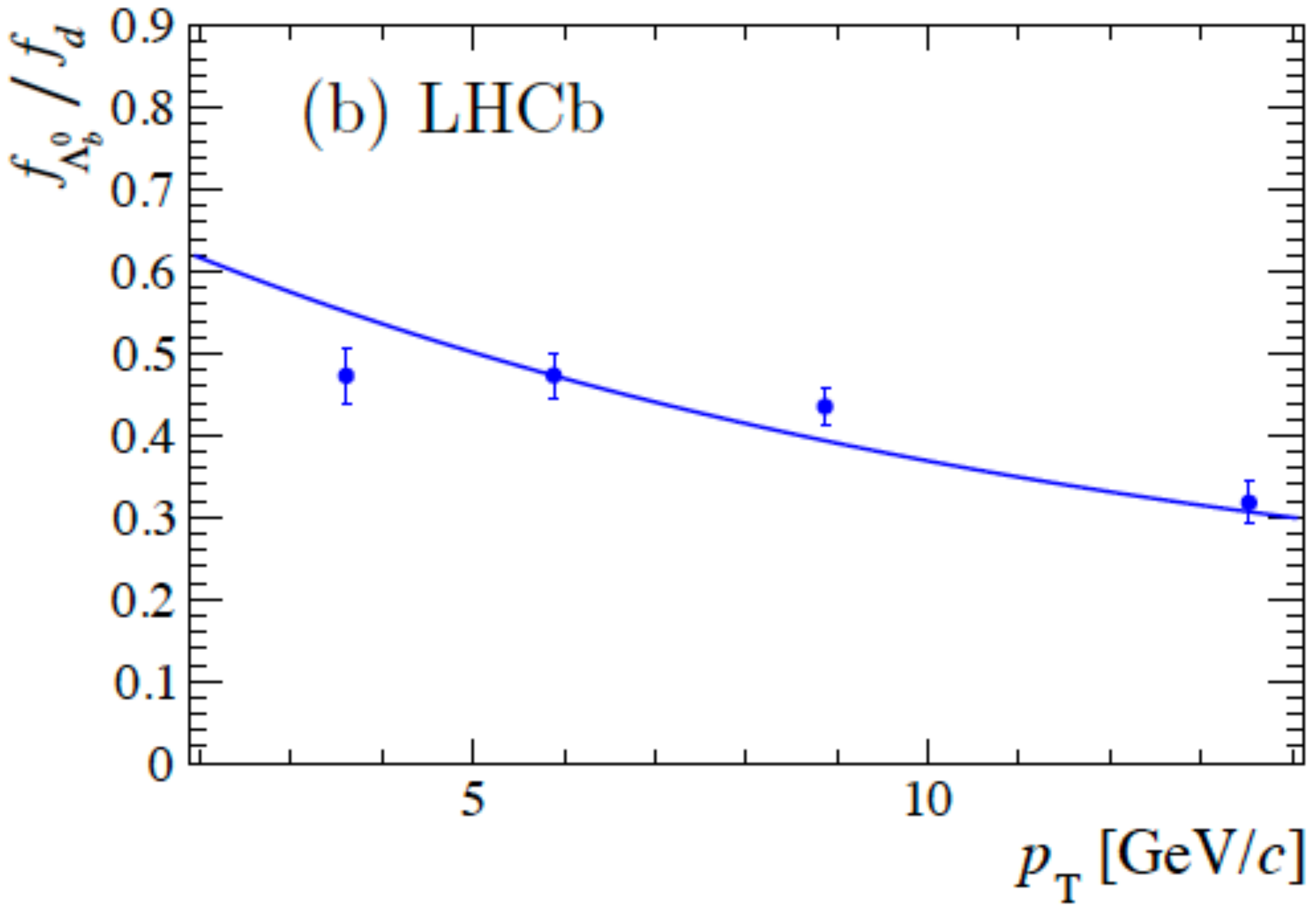
# Determining the shape of $f_{\Lambda_b^0}/f_d$

Run I: SL based on 3pb$^{-1}$

https://arxiv.org/pdf/1612.05140



Shape: fit to ratio of corrected yields



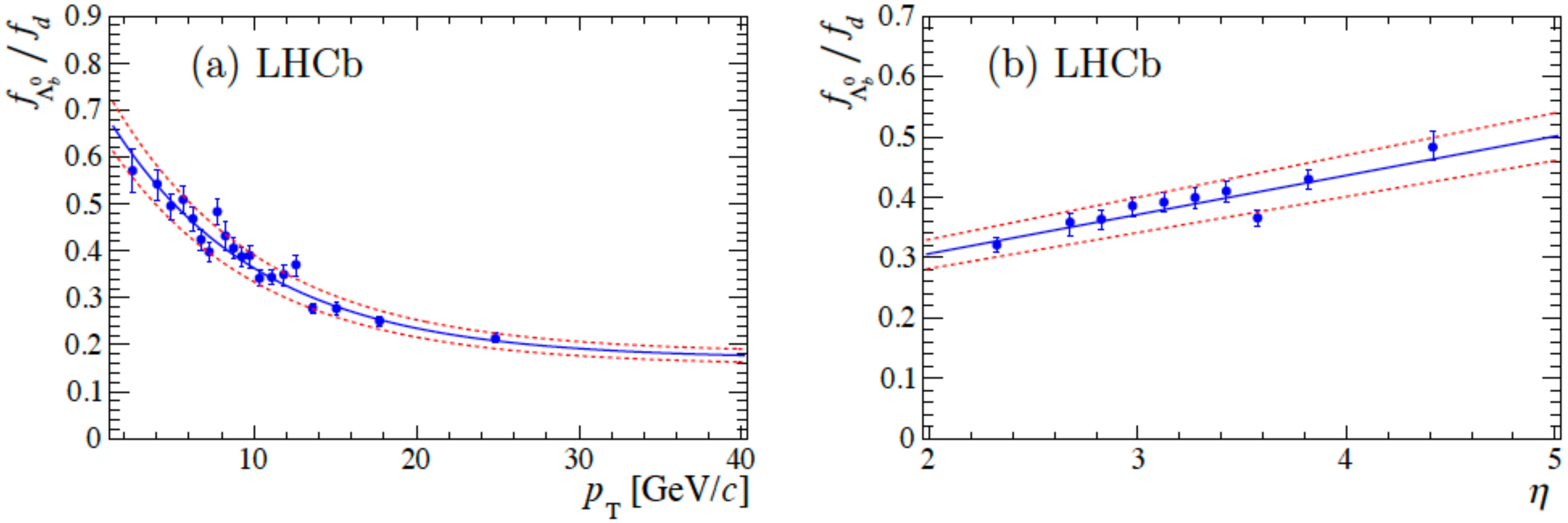
Absolute scale: fit $f_{\Lambda_b^0}/f_d$ from inclusive semileptonic

## Overall results:

$$f_{\Lambda_b^0}/f_d(p_T) = a' + \exp(b' + c' \times p_T[\text{GeV}/c]),$$

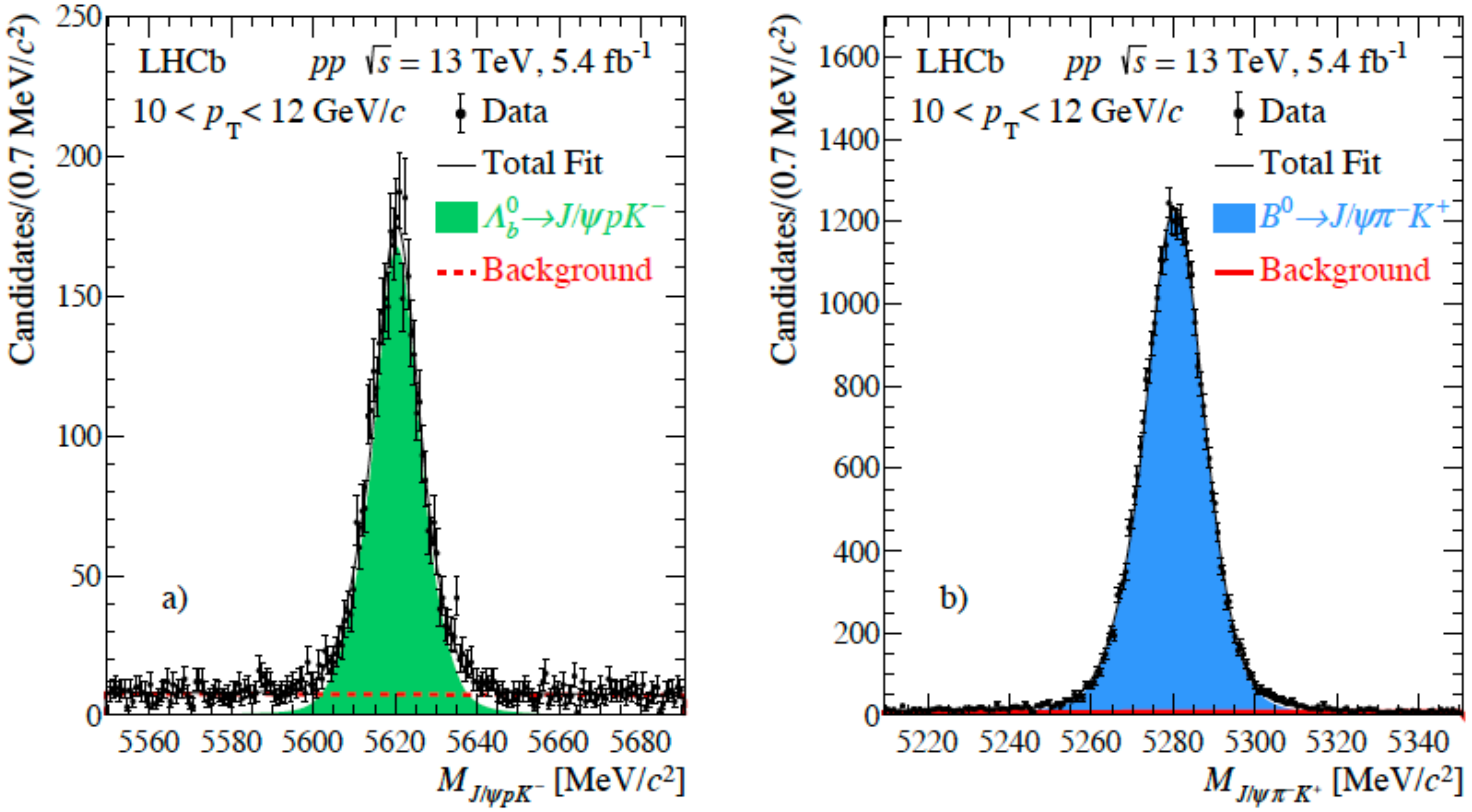
with

$$\begin{aligned} a' &= +0.151 \pm 0.016\,^{+0.024}_{-0.025}, \\ b' &= -0.573 \pm 0.040\,^{+0.101}_{-0.097}, \\ c' &= -0.095 \pm 0.007 \pm 0.014\ \ [\text{GeV}/c]^{-1}, \end{aligned}$$



# Other kinematic dependencies?

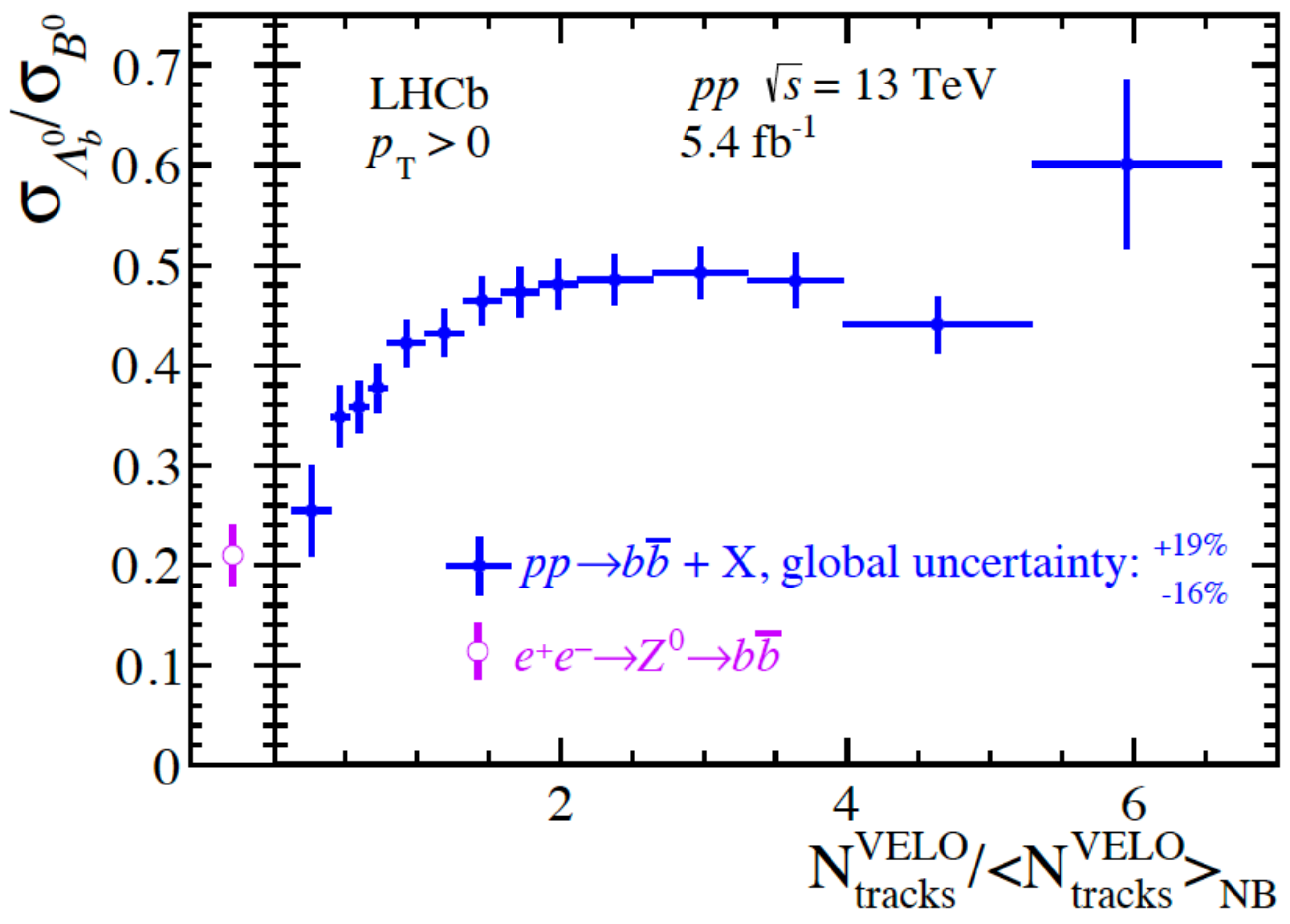
**<u>arXiV:2310.12278</u> RUN 2**



- Baryon-to-hadron ratio

  measured as a function of $p_T$ and multiplicity (normalized number of tracks in the vertex detector)

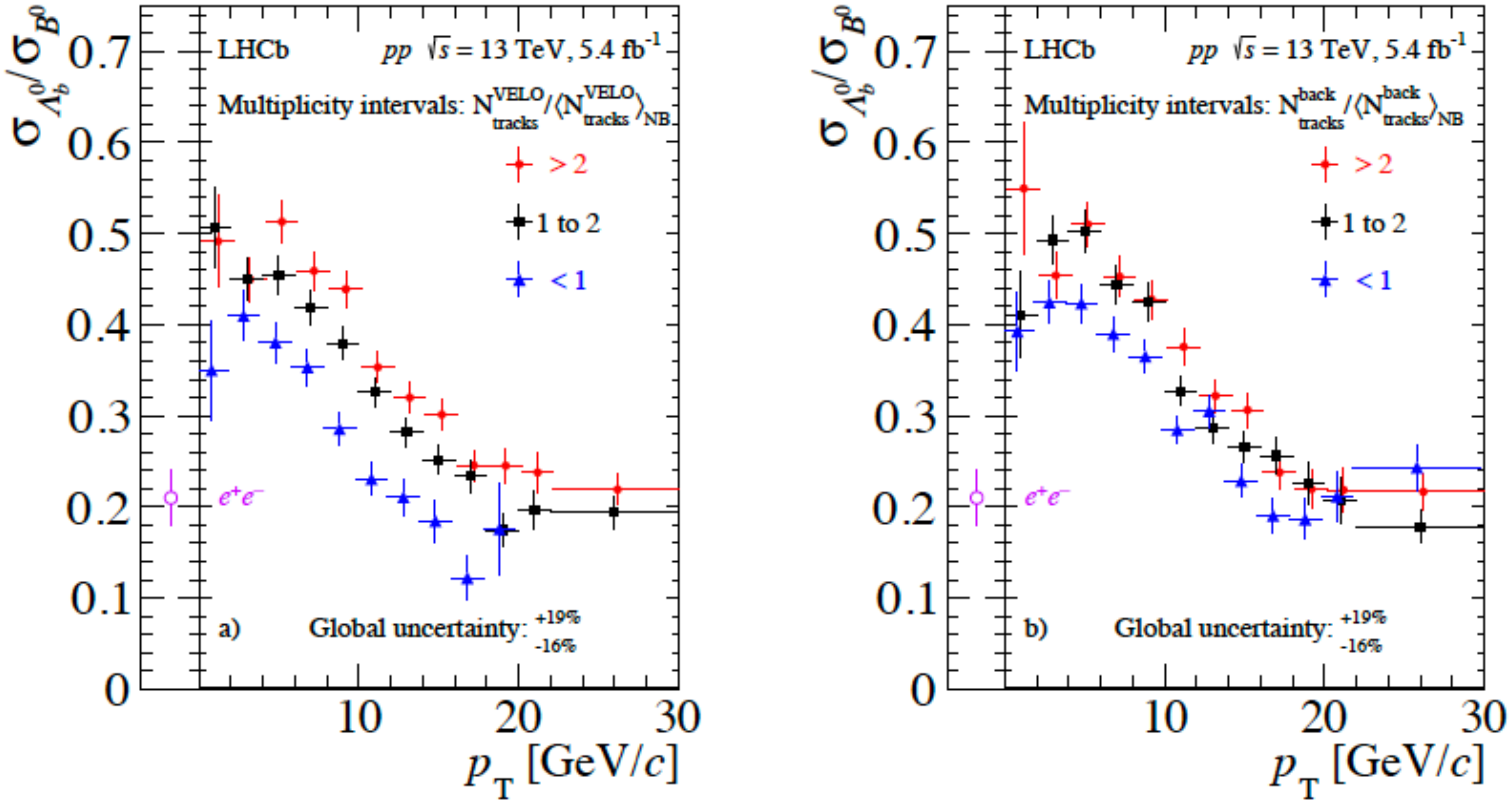
- Multiplicity dependence



# Other kinematic dependencies?

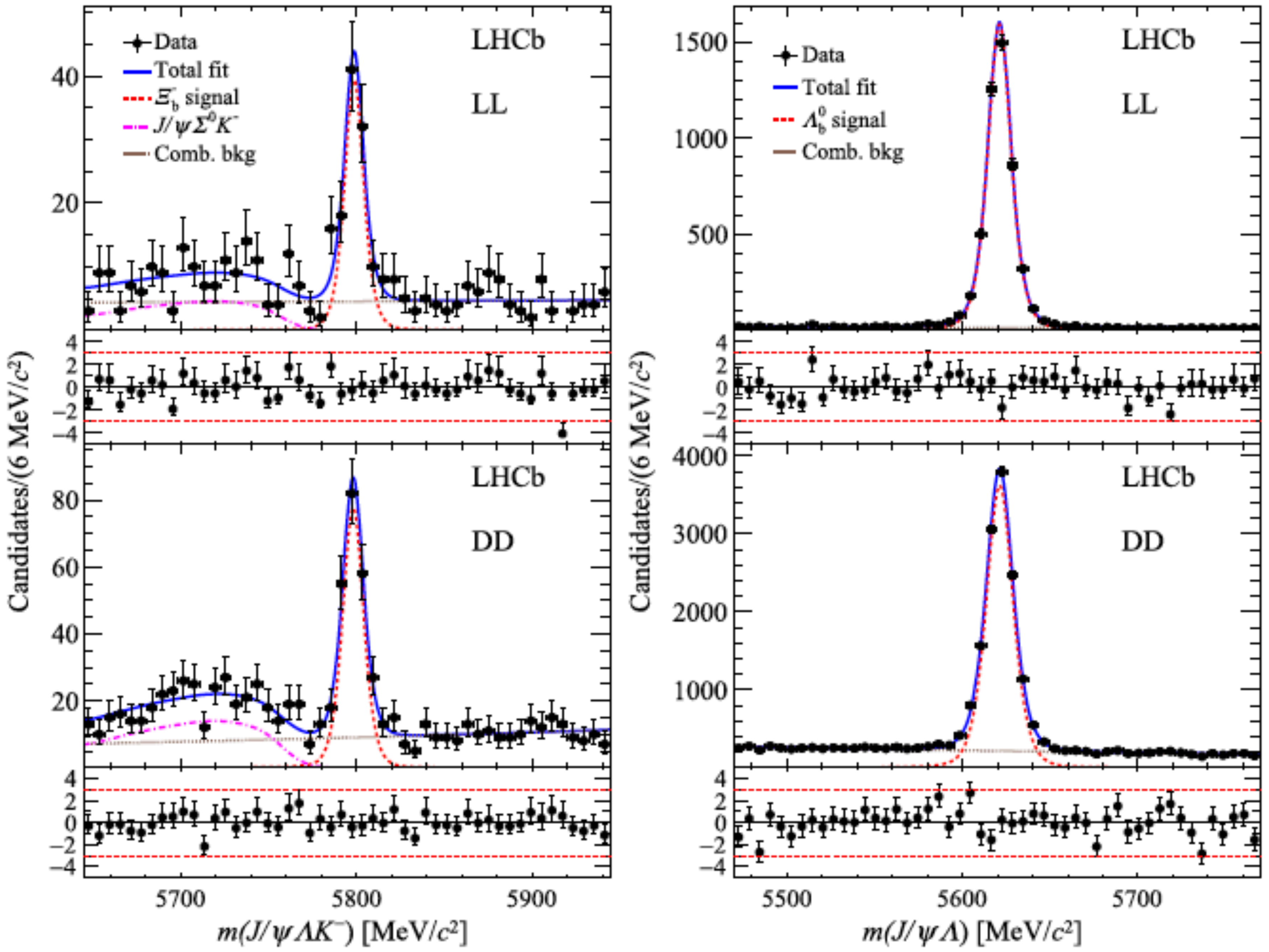
**arXiV:2310.12278**

- Non-universality of b-baryon fractions in terms of b-hadron $p_T$ influenced by hadronic environment in which the production takes place (measured by multiplicity)
- collective effects in QCD
- Effect not modeled in current MC



# What about other b-baryons

◆ Spectroscopy and lifetimes studied, branching fractions typically given modulo b-baryon fragmentation ratios



Most recent measurement:

https://arxiv.org/pdf/1701.05274

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}}\frac{\mathcal{B}(\Xi_b^- \to J/\psi\,\Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = (4.19 \pm 0.29\,(\text{stat}) \pm 0.15\,(\text{syst})) \times 10^{-2},$$

# $B_c$ production fraction

arXiv:1910.13404v4

- The approach is similar to the b-hadron fractions measurements from inclusive semileptonic decays, but here the normalization utilizes the measured inclusive semileptonic branching fraction $< \mathscr{B}_{\rm sl}(B_u, B_d) >$ and theoretical predictions for $\mathscr{B}(B_c \to j\psi)\mu\nu$

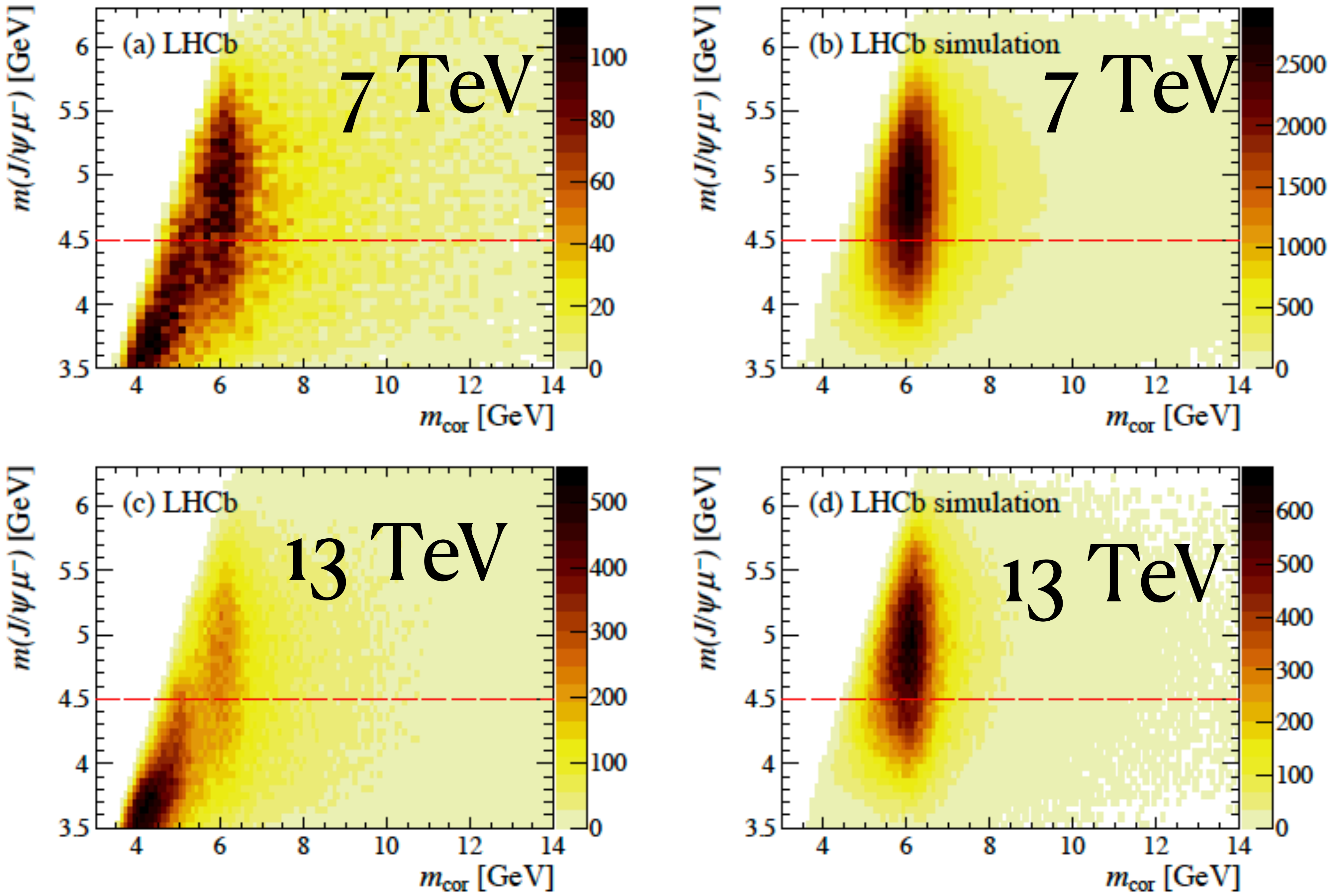
two heavy quarks in the initial state ⇒ different strategy needed

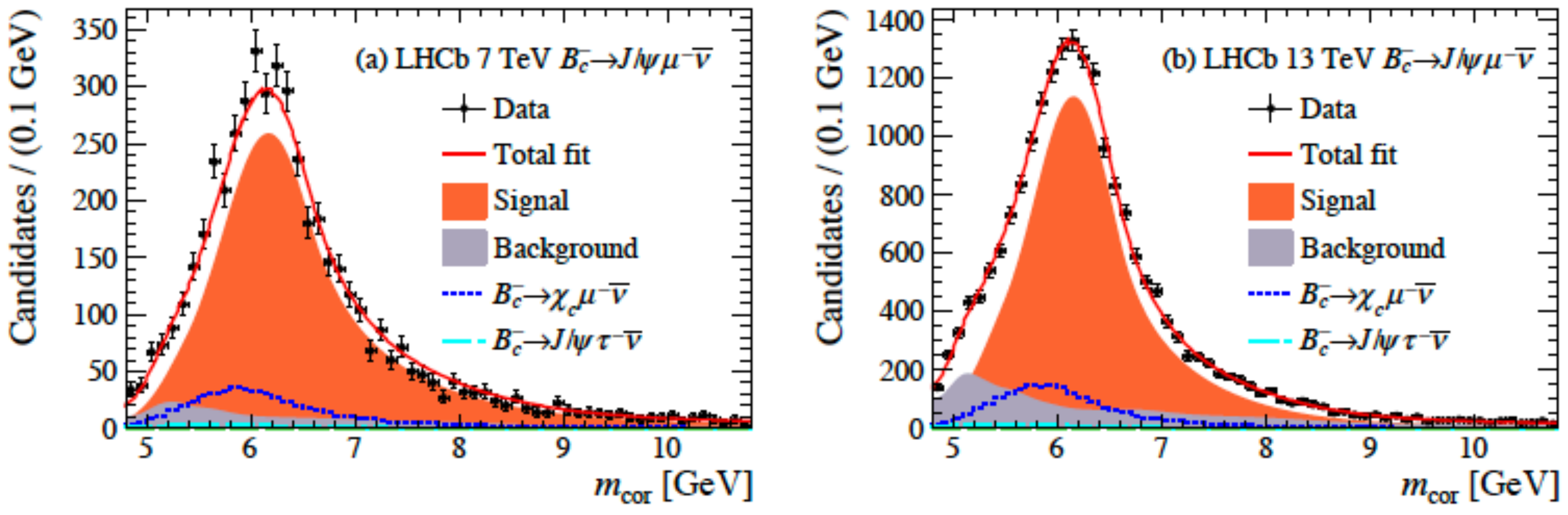
$$R_c = \frac{f_c}{f_u + f_d} \equiv \frac{n_{\rm cor}(B_c^- \to J/\psi\, \mu^-\overline{\nu})}{n_{\rm cor}(B \to D^0 X \mu^-\overline{\nu}) + n_{\rm cor}(B \to D^+ X \mu^-\overline{\nu})} \cdot \frac{\langle \mathcal{B}_{\rm sl} \rangle}{\mathcal{B}(B_c^- \to J/\psi\, \mu^-\overline{\nu})}$$

https://arxiv.org/pdf/1910.13404

# $B_c^-$ production fraction - experimental strategy

- This time the $B_c^-$ decay mode that measures the production fraction is an exclusive decay, so the exclusive needs to be accounted for, excluding contributions to $B_c^- \to J/\psi\mu^-\bar{\nu}_\mu X$ from higher mass resonances ⇒ the corrected mass $M_{corr} \equiv \sqrt{M(J/\psi\mu)^2 + p_{\mathrm{T}}^2} + p_{\mathrm{T}}$ is used



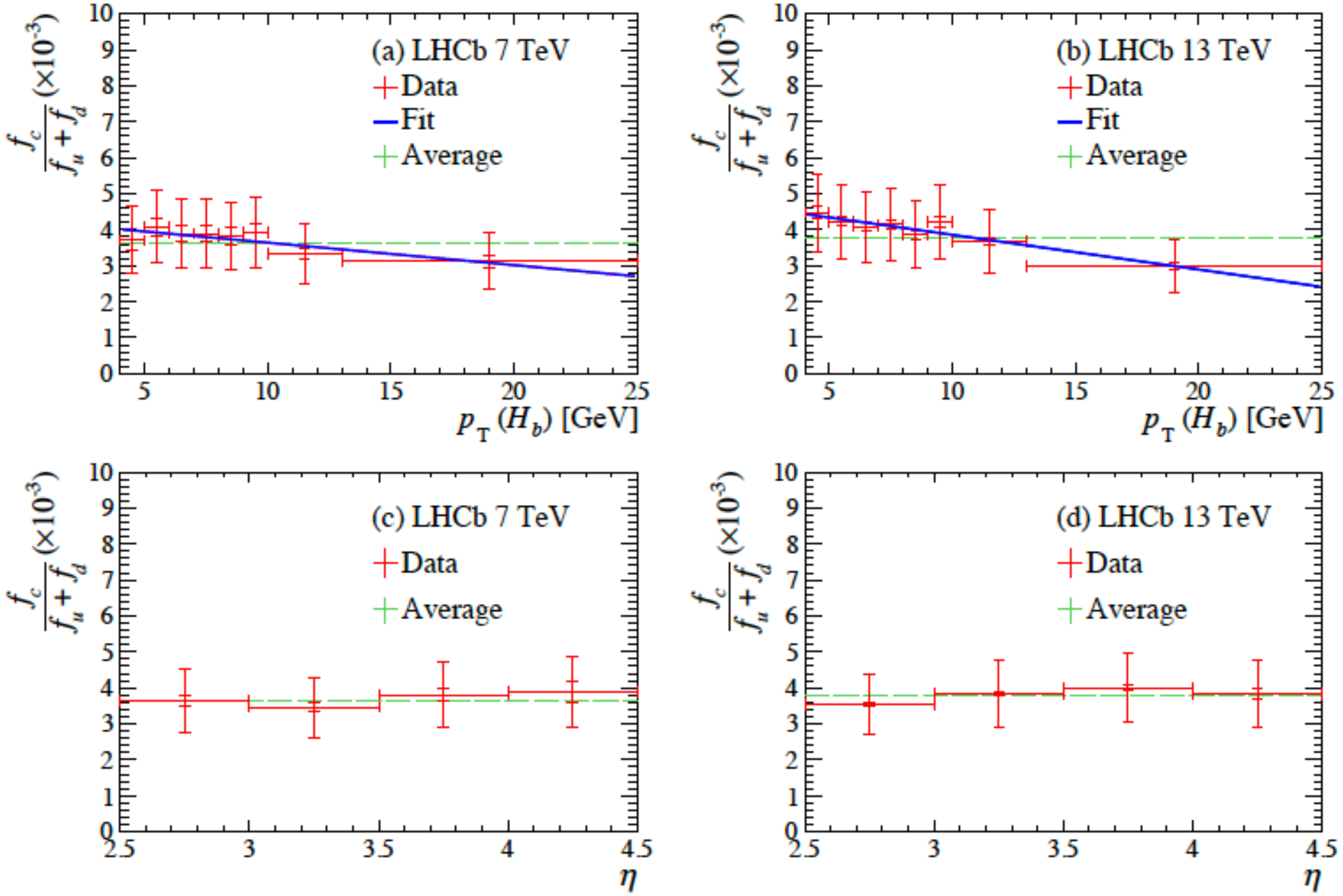


# Results

- $\frac{f_c}{f_u+f_d}(p_T) = A[p_1 + p_2\,(p_T(H_b) - \langle p_T \rangle\,)$
- Using $f_u + f_d$ shown before:

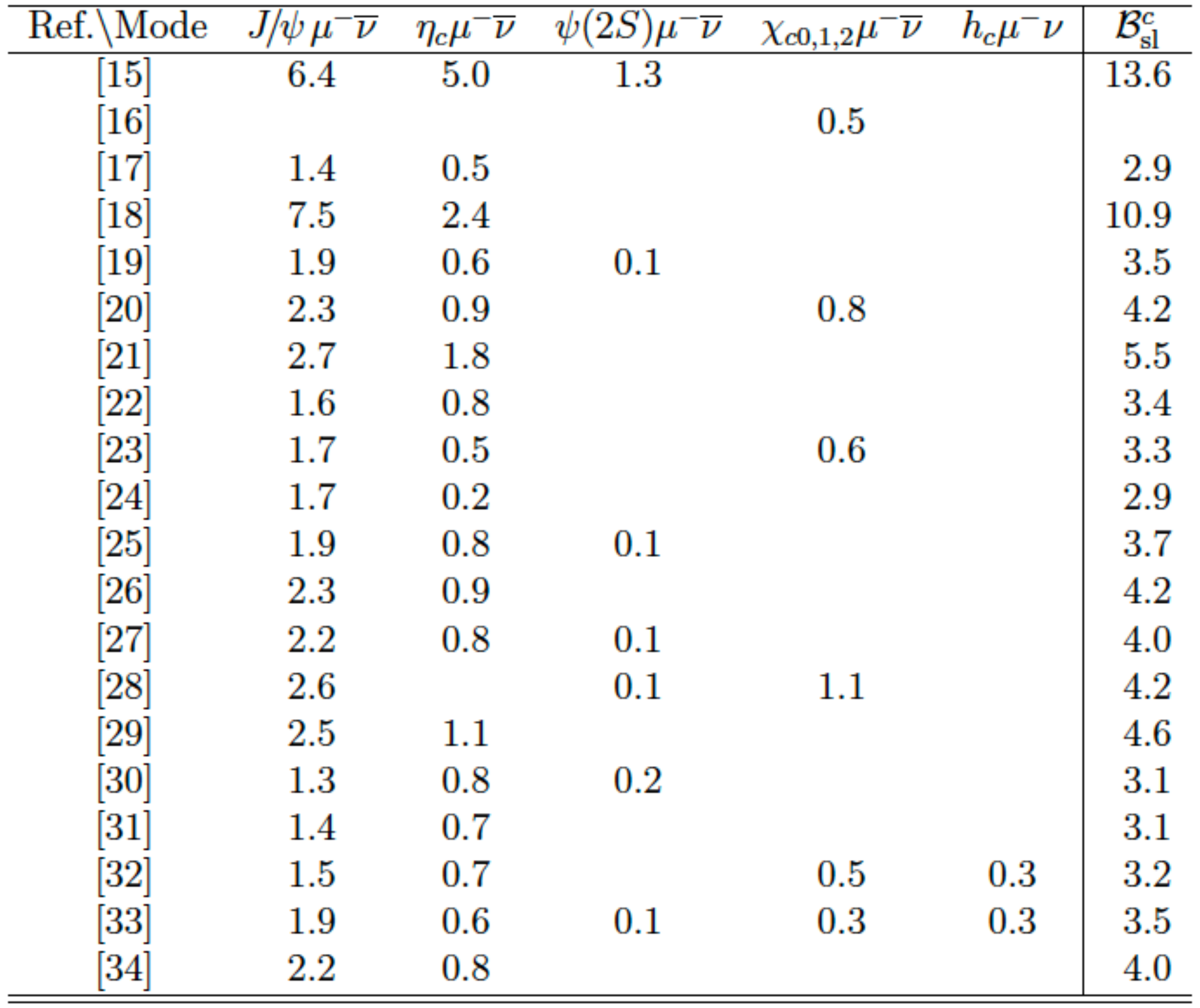
$$f_c \cdot \mathcal{B}(B_c^- \to J/\psi\,\mu^-\overline{\nu}) = \begin{cases} (5.04 \pm 0.11 \pm 0.17 \pm 0.18)\cdot 10^{-5} & (7\,\text{TeV}) \\ (5.09 \pm 0.06 \pm 0.21 \pm 0.11)\cdot 10^{-5} & (13\,\text{TeV}) \end{cases},$$

$$f_c = \begin{cases} (2.58 \pm 0.05 \pm 0.62 \pm 0.09)\cdot 10^{-3} & (7\,\text{TeV}) \\ (2.61 \pm 0.03 \pm 0.62 \pm 0.06)\cdot 10^{-3} & (13\,\text{TeV}) \end{cases},$$



With the new lattice results: $f_c = (3.26 \pm 0.04 \pm 0.17 \pm 0.07)$

- Compendium of the branching fractions used in https://arxiv.org/pdf/1910.13404



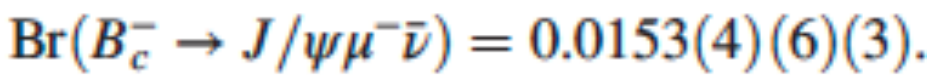
| Ref.\Mode | $J/\psi\,\mu^-\overline{\nu}$ | $\eta_c\mu^-\overline{\nu}$ | $\psi(2S)\mu^-\overline{\nu}$ | $\chi_{c0,1,2}\mu^-\overline{\nu}$ | $h_c\mu^-\nu$ | $\mathcal{B}^c_{\rm sl}$ |
|---|---|---|---|---|---|---|
| [15] | 6.4 | 5.0 | 1.3 | | | 13.6 |
| [16] | | | | 0.5 | | |
| [17] | 1.4 | 0.5 | | | | 2.9 |
| [18] | 7.5 | 2.4 | | | | 10.9 |
| [19] | 1.9 | 0.6 | 0.1 | | | 3.5 |
| [20] | 2.3 | 0.9 | | 0.8 | | 4.2 |
| [21] | 2.7 | 1.8 | | | | 5.5 |
| [22] | 1.6 | 0.8 | | | | 3.4 |
| [23] | 1.7 | 0.5 | | 0.6 | | 3.3 |
| [24] | 1.7 | 0.2 | | | | 2.9 |
| [25] | 1.9 | 0.8 | 0.1 | | | 3.7 |
| [26] | 2.3 | 0.9 | | | | 4.2 |
| [27] | 2.2 | 0.8 | 0.1 | | | 4.0 |
| [28] | 2.6 | | 0.1 | 1.1 | | 4.2 |
| [29] | 2.5 | 1.1 | | | | 4.6 |
| [30] | 1.3 | 0.8 | 0.2 | | | 3.1 |
| [31] | 1.4 | 0.7 | | | | 3.1 |
| [32] | 1.5 | 0.7 | | 0.5 | 0.3 | 3.2 |
| [33] | 1.9 | 0.6 | 0.1 | 0.3 | 0.3 | 3.5 |
| [34] | 2.2 | 0.8 | | | | 4.0 |

Average with some external constraints gives

$\mathscr{B}(B_c \to J/\psi\mu\nu) = (1.95 \pm 0.46)\,\%$

New lattice result:

https://journals.aps.org/prd/pdf/10.1103/wll6-z4cb



$$\mathrm{Br}(B_c^- \to J/\psi\mu^-\bar{\nu}) = 0.0153(4)(6)(3).$$

5% accuracy

# Conclusions

- Studying the b-hadron production at LHCb has many important physics goals:
  - Establish absolute scales for exclusive branching fractions for all the b-flavored hadrons
  - Develop a deeper understanding of the hadronization process
  - Complete the understanding of b-hadron spectroscopy
  - Contribute to the understanding of non-resonant components in b-hadron semileptonic decays

Many precision measurements are on the horizon

# The end

Support information follows

# B-fractions from semileptonic decays - formalism