Recent results on Λ_b and B_s production at 13TeV pp collisions

Siim Tolk (CERN)
on behalf of the LHCb collaboration

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Victoria BC

b-hadron production

Production cross section measurements allow us to study (in that order)

- perturbative QCD models (**proton-proton** collisions)
- (cold) nuclear matter interaction effects (**proton-lead** collisions)
- Quark Gluon Plasma formation (heavy **ion-ion** collisions)

Heavy hadron production: an instrumental benchmark process in understanding pQCD models:

- *quark mass (m_q) defines the scale at which the strong-interaction coupling constant (α_s) is evaluated. High heavy quark mass ($m_b \gg \Lambda_{QCD}$) allows the production properties to be estimated within the perturbation theory.*

Fragmentation functions

The b hadron production cross section can be expressed as a convolution of the b quark production cross section ($\sigma^{pp\to bb}$) and the b hadron fragmentation function ($D_{b\to B}$) :

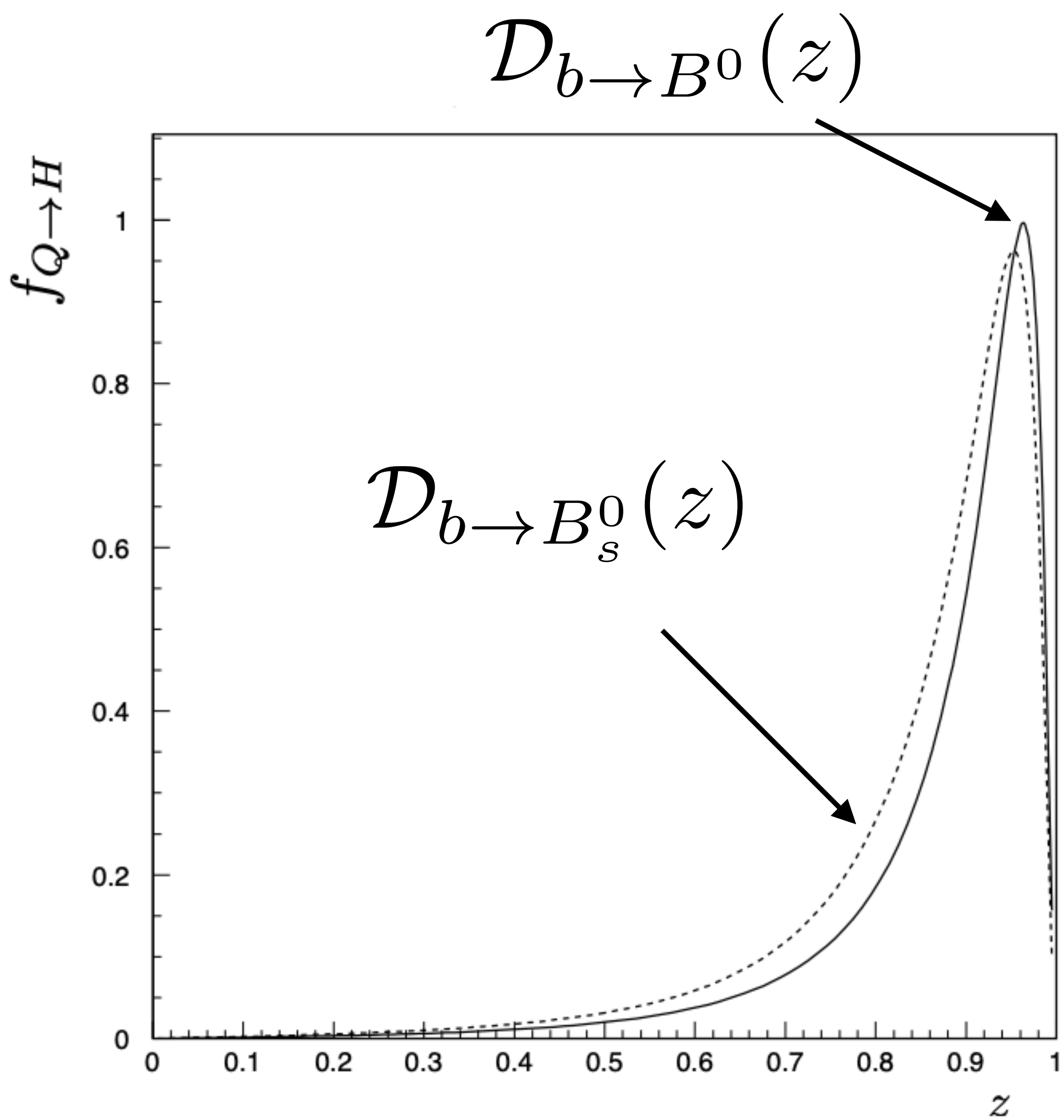
$$\frac{d\sigma^B}{dp_T^B} = \int dp_T^b \; dx \; \frac{d\sigma^{pp\to b\bar{b}}}{dp_T^b} \; \mathcal{D}_{b\to B}(x) \; \delta(p_T - xp_T^b)$$

perturbative

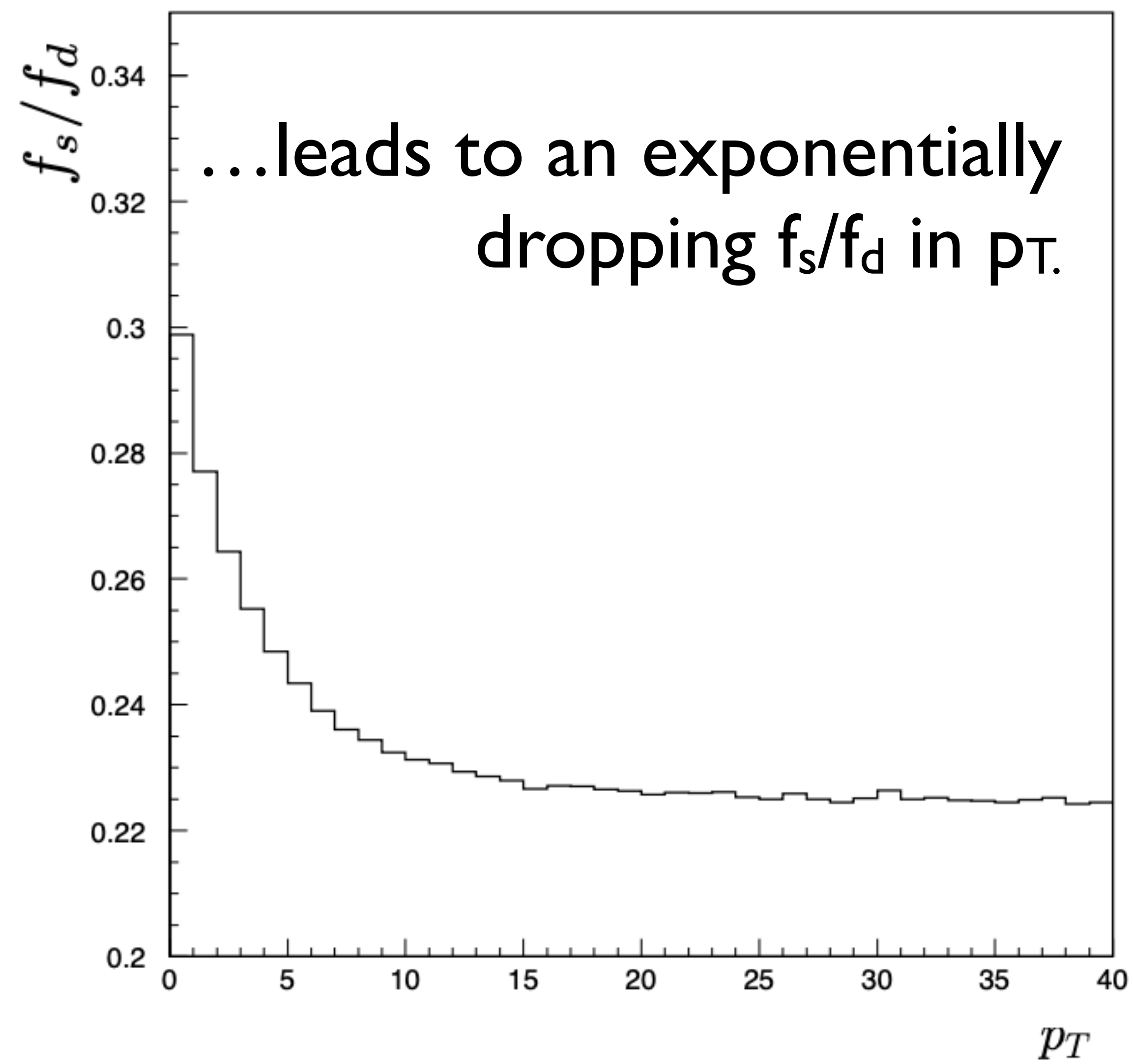
non-perturbative
(not known from the first-principles)

The relative b hadron production measurements in bins of B meson kinematic variables allow us to experimentally probe the shape of the (non-perturbative) b quark fragmentation functions (depend on m_q).

An example of how the differences between fragmentation functions for B_s and B^0 can experimentally be seen:



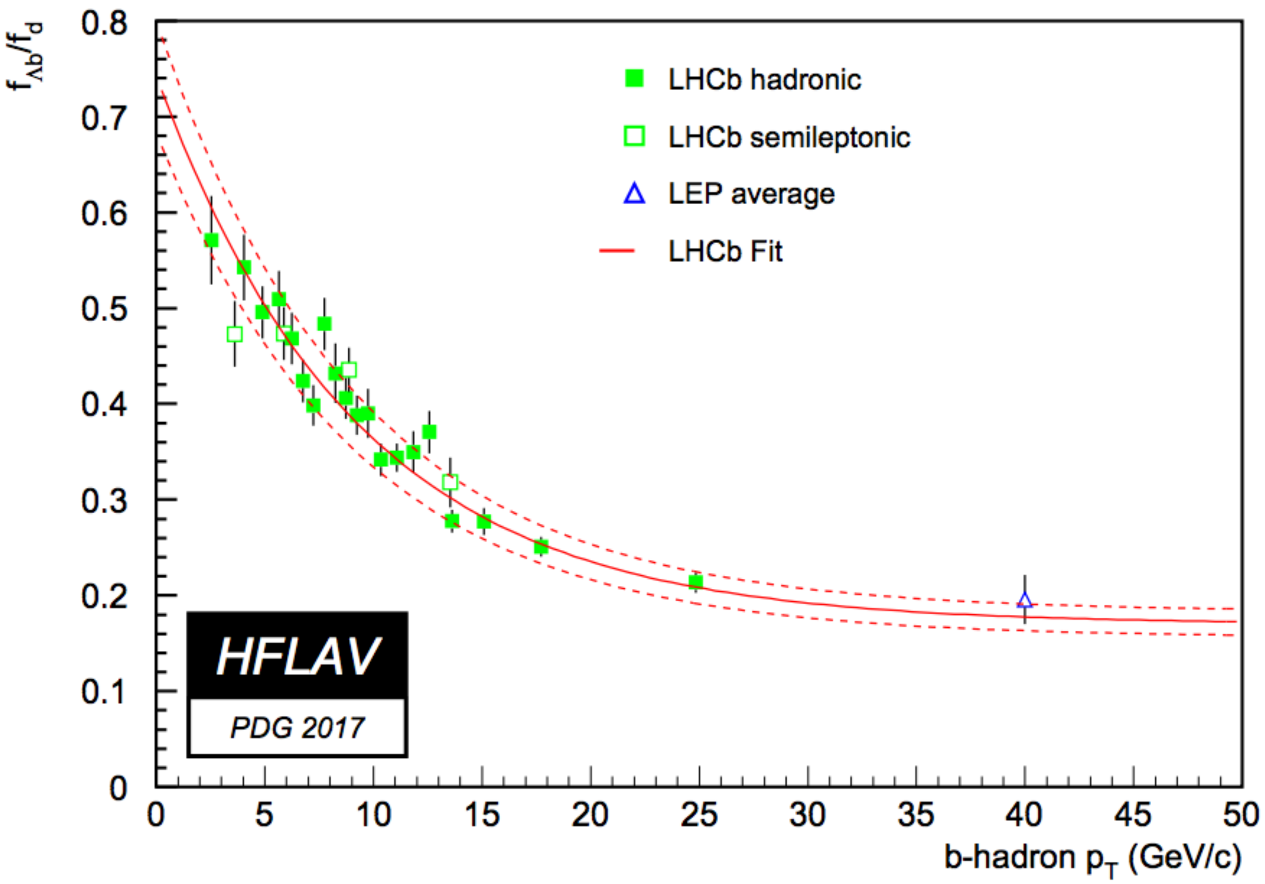
[arXiv:1309.1979]



* differences also lead to noticeable effects in like-sign asymmetry [PRD 84 (2011) 014035] and if accounted for, have been shown to alleviate the 3-fold tensions in B production [PRL 89 (2002) 122003]

Kinematic dependence of Λ_b production is clear and very likely for B_s (though experimentally less clear):

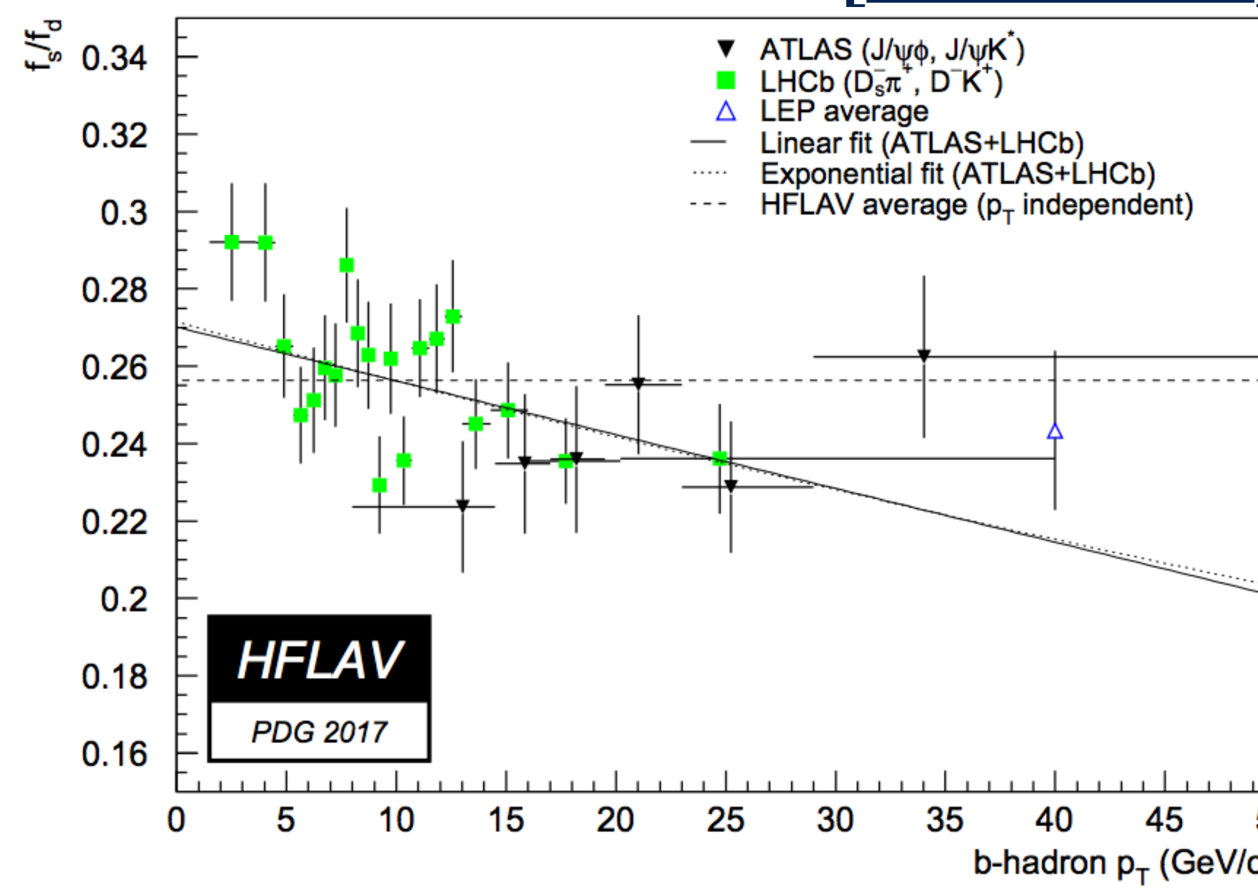
[HFLAV 2016]



a) Relative Λ_b and $B^{0(+)}$ production ($f_{\Lambda b}/f_d$) varies strongly with the hadron transverse momentum

[JHEP 08(2014)143]

[HFLAV 2016]



b) Experimental hints for the relative B_s and B^0 production (f_s/f_d) dependence on meson transverse momentum

[JHEP 1304 (2013) 001]

[LHCb-PAPER-2018-050]
Submitted to PRL

Relative B_s and Λ_b production at 13TeV pp collisions

- Measure $\mathbf{f_s / (f_u+f_d)}$ and $\mathbf{f_{\Lambda b} / (f_u+f_d)}$ with semileptonic decays
- Analysis performed in (2D) bins of b-hadron transverse momentum (p_T) and pseudorapidity (η)
- Update to the previous LHCb measurement at 7TeV [PRD 85 (2012) 032008]
- Restrict the measurement to

$4 < p_T < 25$ GeV (was $0 < p_T < 14$ GeV)

$2 < \eta < 5$

B^0, B^+, B_s and Λ_b yields

[LHCb-PAPER-2018-050]
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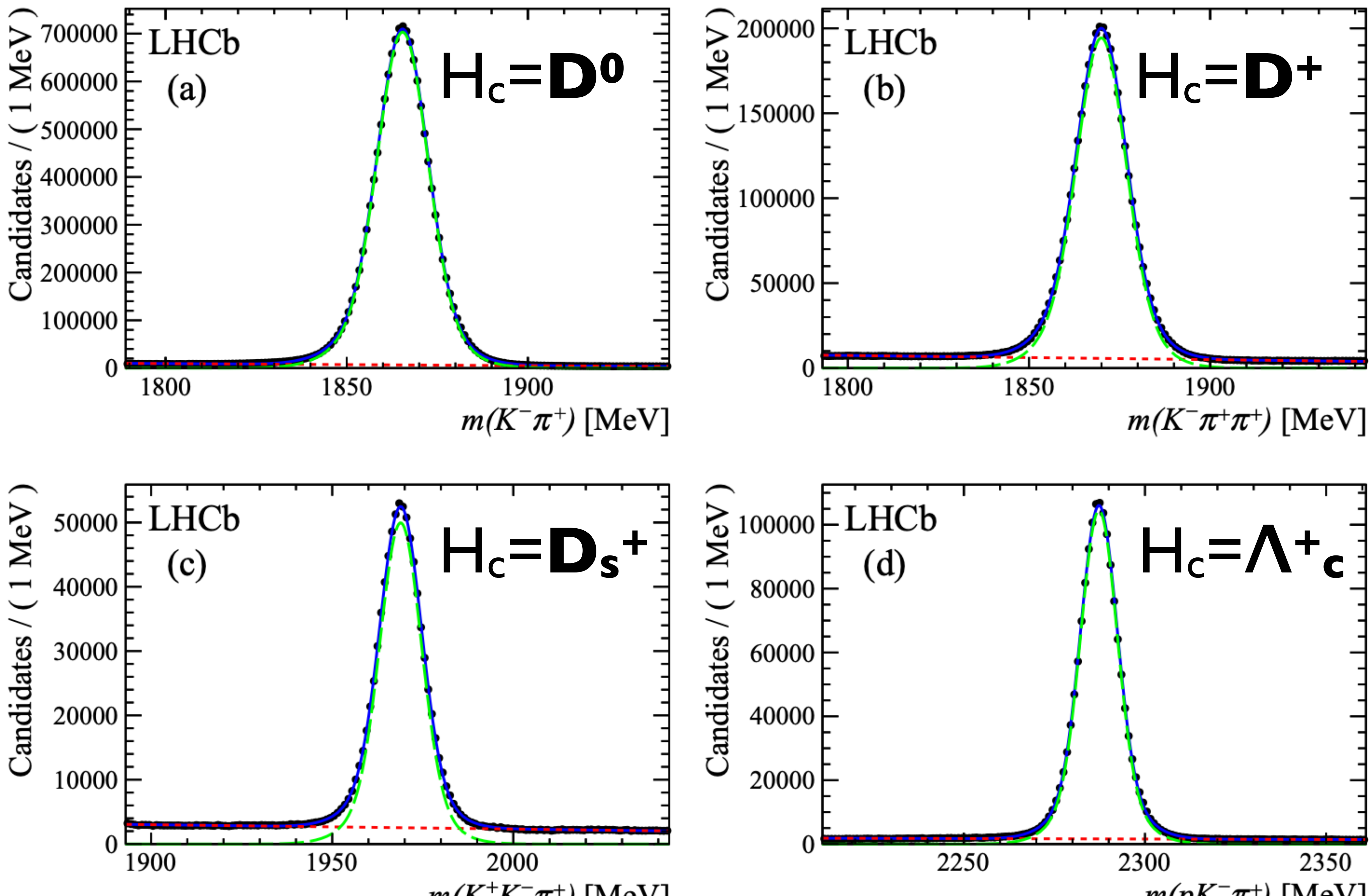
The yields are measured from abundant semileptonic decays to: $\mathbf{H_c \, \mu \, \nu_\mu \, X}$, where H_c is:



[LHCb-PAPER-2018-050]
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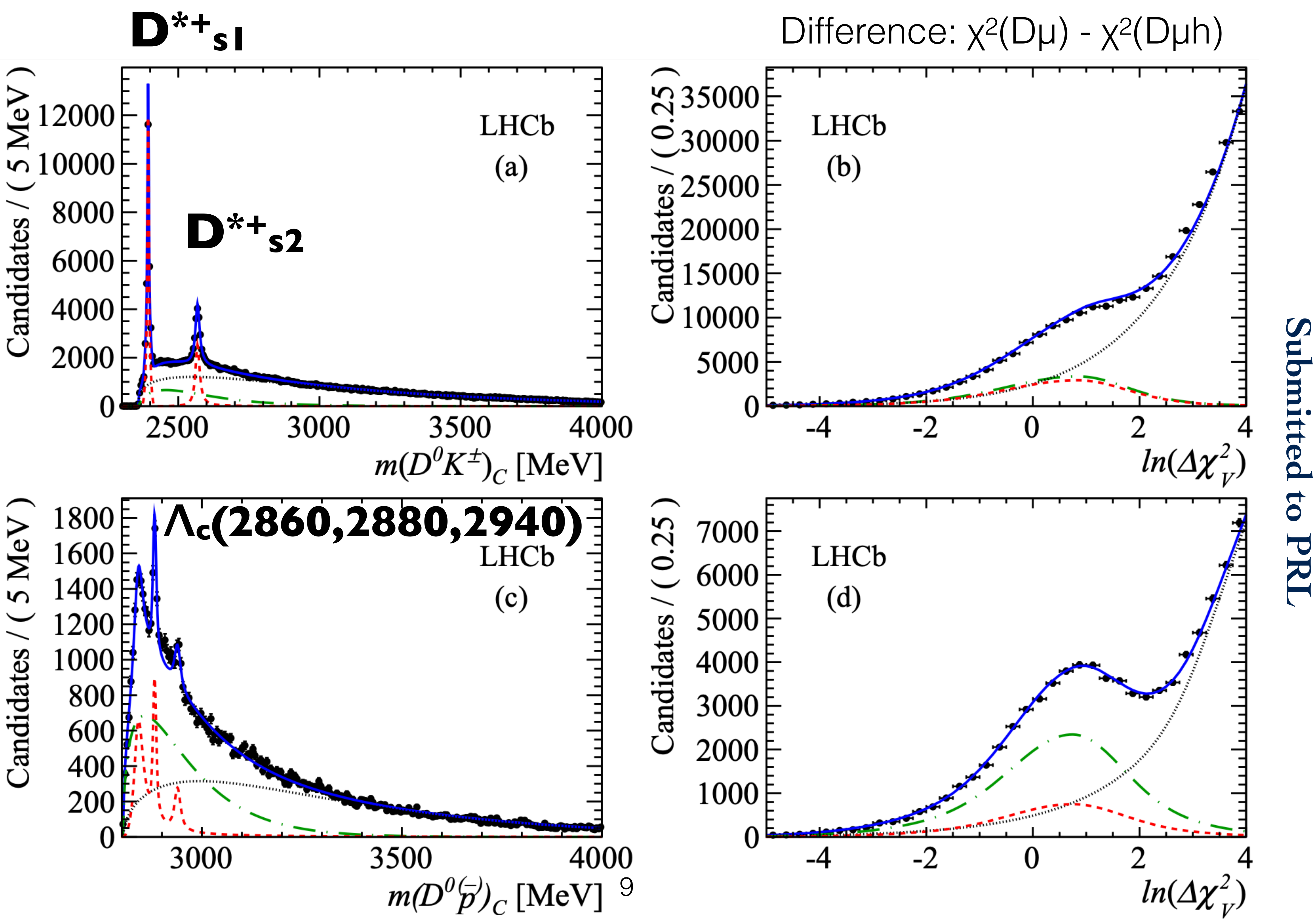
- **B^0** yield is estimated from the **$D^0\ \mu\nu_\mu X$** final state:

$$n_{\rm corr}(B \to D^0\mu^-) = \frac{1}{\mathcal{B}(D^0 \to K^-\pi^+)\epsilon(B \to D^0)} \times \left[n(D^0\mu^-) - n(D^0K^+\mu^-)\frac{\epsilon(\overline{B}{}^0_s \to D^0)}{\epsilon(\overline{B}{}^0_s \to D^0K^+)} - n(D^0p\mu^-)\frac{\epsilon(\Lambda_b^0 \to D^0)}{\epsilon(\Lambda_b^0 \to D^0p)} \right]$$

after correcting for the (non)resonant contributions from B_s and Λ_b.

The (non)resonant $B_s \to (D^0K^+)\ \mu\nu$ and $\Lambda_b \to (D^0p^+)\ \mu\nu$ yields determined from simultaneous fits to the corresponding mass distributions and vertex likelihood difference:



[LHCb-PAPER-2018-050]
Submitted to PRL

- **B^+** yield is estimated from the total **$D^+ \mu \nu_\mu X$** final state:

$$n_{\rm corr}(B \to D^+\mu^-) = \frac{1}{\epsilon(B \to D^+)}\left[\frac{n(D^+\mu^-)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} - \frac{n(D^0K^+\mu^-)}{\mathcal{B}(D^0 \to K^-\pi^+)}\frac{\epsilon(\overline{B}{}^0_s \to D^+)}{\epsilon(\overline{B}{}^0_s \to D^0K^+)} - \frac{n(D^0p\mu^-)}{\mathcal{B}(D^0 \to K^-\pi^+)}\frac{\epsilon(\Lambda_b^0 \to D^+)}{\epsilon(\Lambda_b^0 \to D^0p)}\right].$$

Rely on isospin sym:

$B_s \to D^+K^0 \mu\nu$ from $B_s \to D^0K^+ \mu\nu$

$\Lambda_b \to D^+n \mu\nu$ from $\Lambda_b \to D^0p \mu\nu$

- **B_s yield** is estimated from the total **$D_s^+ \mu\nu_\mu X$** final state:

$$n_{\rm corr}(\overline{B}{}^0_s \to D_s^+\mu^-) = \frac{n(D_s^+\mu^-)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)\epsilon(\overline{B}{}^0_s \to D_s^+\mu^-)} - N(\overline{B}{}^0 + B^-)\mathcal{B}(B \to D_s^+\overline{K}{}^0)\frac{\epsilon(\overline{B} \to D_s^+\overline{K}{}^0\mu^-)}{\epsilon(\overline{B}{}^0_s \to D_s^+\mu^-)}.$$

plus the estimated decays to $D^+K^0\mu\nu_\mu X$ final state:

$$n_{\rm corr}(\overline{B}{}^0_s \to DK\mu^-) = \kappa\frac{n(D^0K^+\mu^-)}{\mathcal{B}(D^0 \to K^-\pi^+)\epsilon(\overline{B}{}^0_s \to D^0K^+\mu^-)},$$

- **Λ_b yield** is estimated from the total **$H_c\, \mu\nu_\mu X$** final state:

$$n_{\rm corr}(\Lambda_b^0 \to H_c\mu^-) = \frac{n(\Lambda_c^+\mu^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)\epsilon(\Lambda_b^0 \to \Lambda_c^+)} + 2\frac{n(D^0p\mu^-)}{\mathcal{B}(D^0 \to K^-\pi^+)\epsilon(\Lambda_b^0 \to D^0p)}$$

Express f_s / (f_u+f_d) and $f_{\Lambda b}$ / (f_u+f_d) assuming equality of the semileptonic widths:

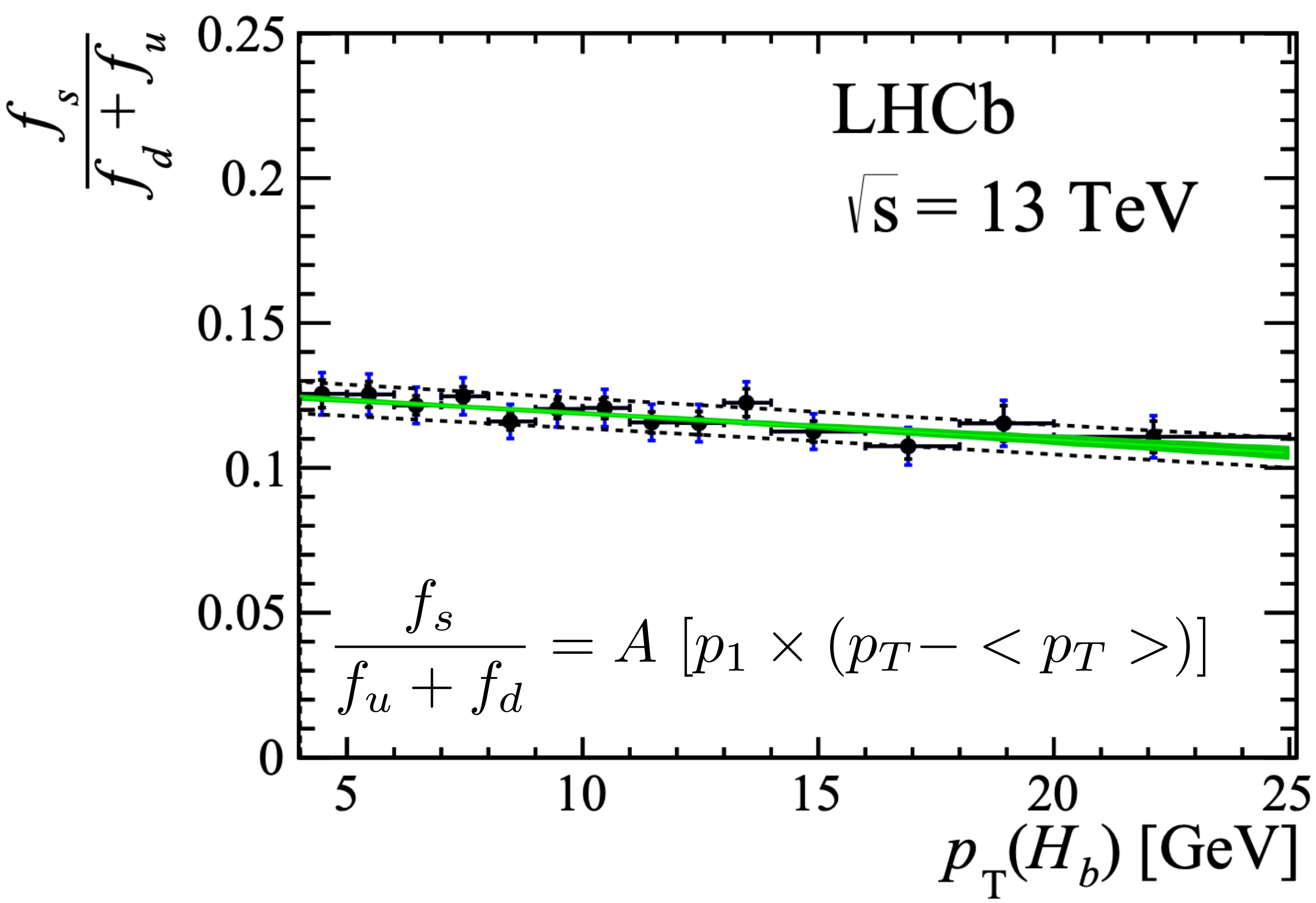
$$\frac{f_s}{f_u + f_d} = \frac{n_{\rm corr}(\overline{B}{}^0_s \to D\mu^-)}{n_{\rm corr}(B \to D^0\mu^-) + n_{\rm corr}(B \to D^+\mu^-)} \frac{\tau_{B^-} + \tau_{\overline{B}{}^0}}{2\tau_{\overline{B}{}^0_s}}(1 - \xi_s)$$

$$\frac{f_{\Lambda^0_b}}{f_u + f_d} = \frac{n_{\rm corr}(\Lambda^0_b \to H_c\mu^-)}{n_{\rm corr}(B \to D^0\mu^-) + n_{\rm corr}(B \to D^+\mu^-)} \frac{\tau_{B^-} + \tau_{\overline{B}{}^0}}{2\tau_{\Lambda^0_b}}(1 - \xi_{\Lambda^0_b})$$

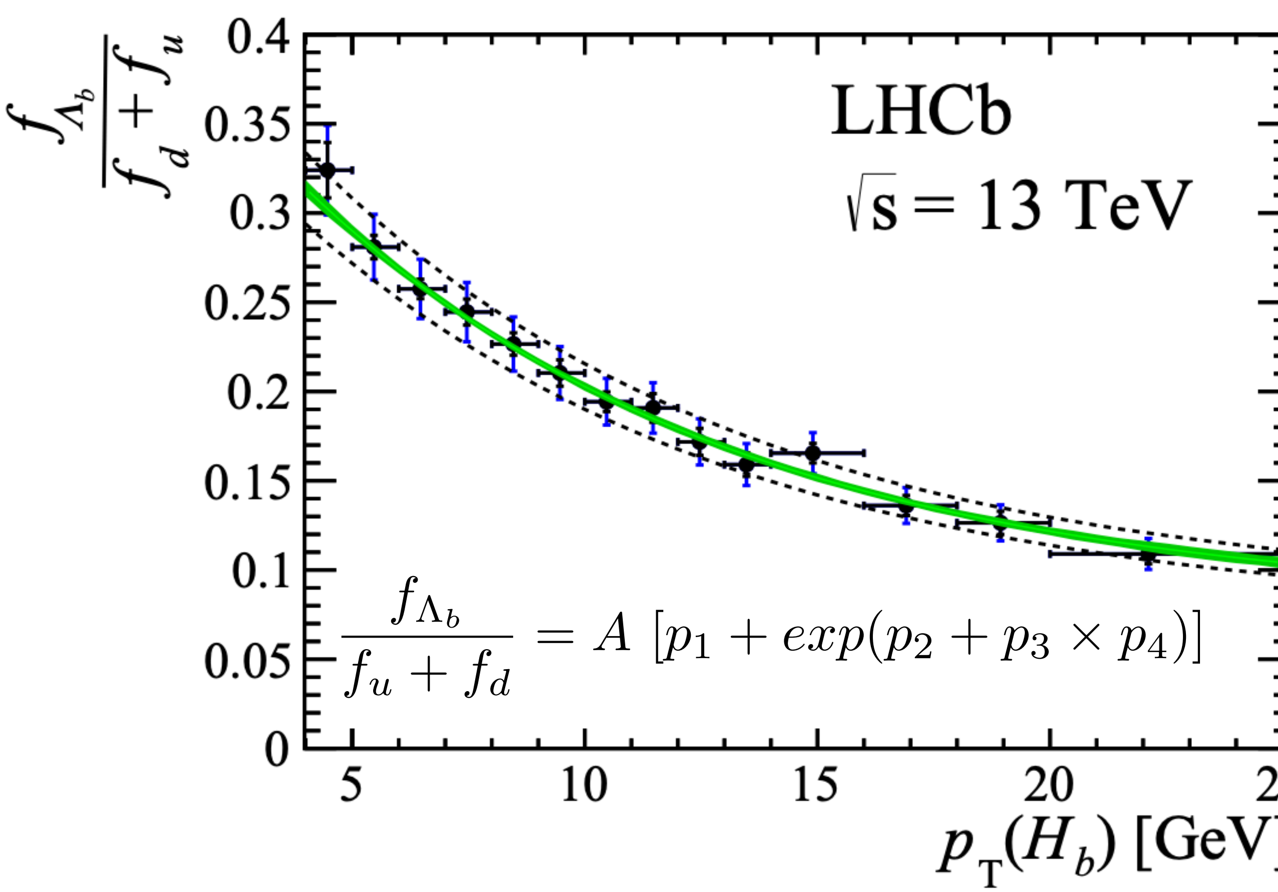
Correct for the known differences:

ξ_s = -1.0 (0.5) %
$\xi_{\Lambda b}$ = 3.0 (1.5) % (for different chromomagnetic effects in mesons/baryons)

13TeV results: f_s / (f_u+f_d) and $f_{\Lambda b}$ / (f_u+f_d) are both observed to depend on transverse momentum

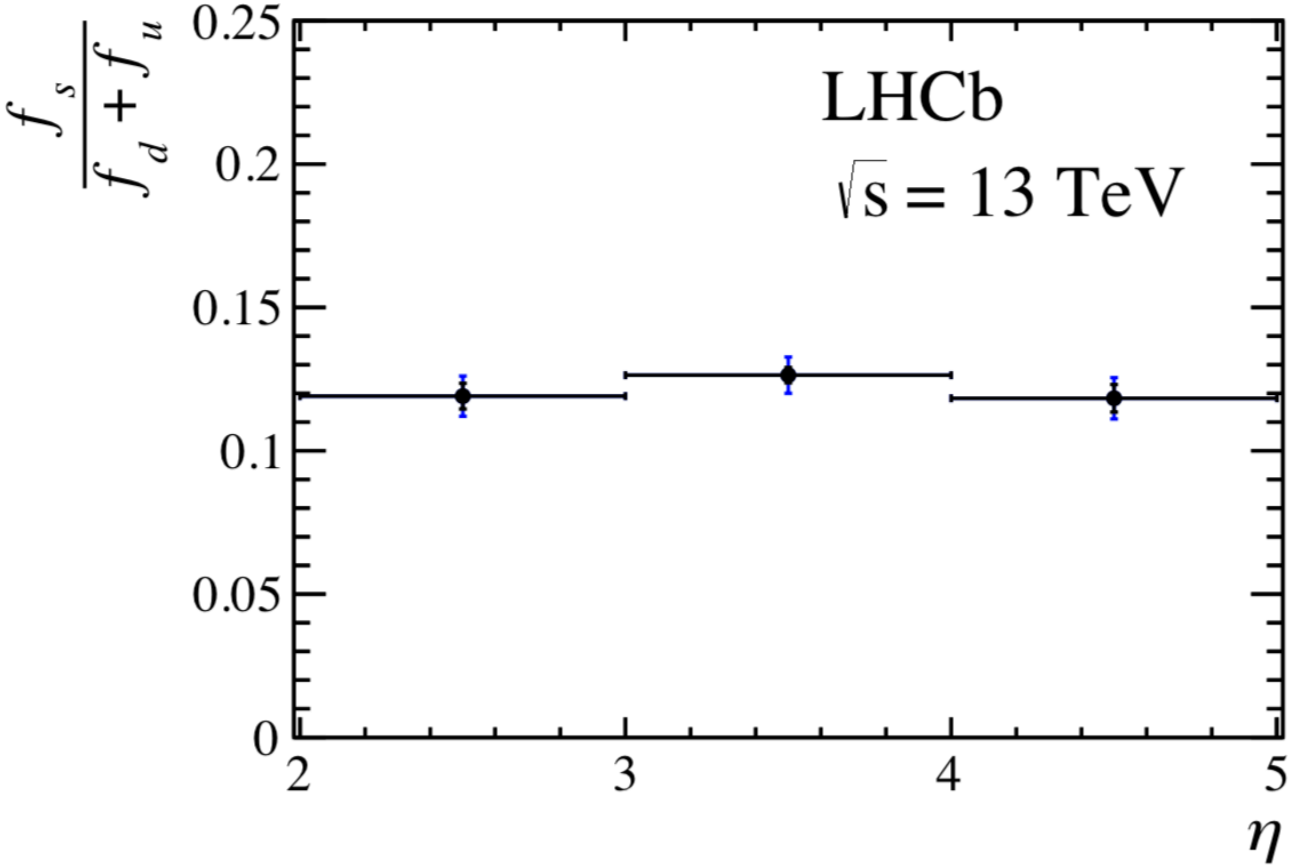


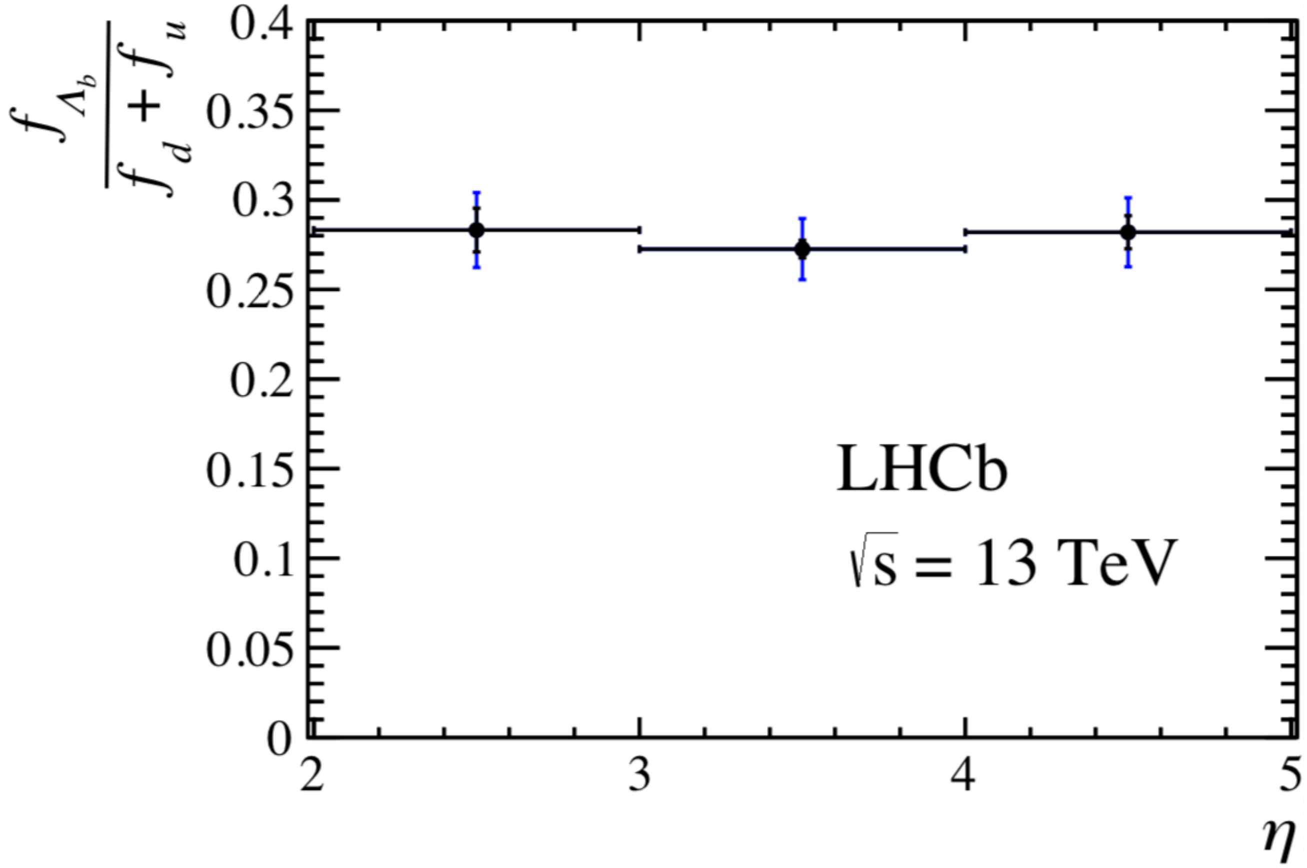
Fit results:
- A = 1 ± 0.043
- p_1 = 0.119 ± 0.001
- p_2 = (−0.91 ± 0.25) · 10^{-3} GeV^{-1}
- $\langle p_T \rangle$ = 10.1 GeV



Fit results:
- A = 1±0.061 (syst. unc)
- p_1 = (7.93±1.41) ·10^{-2}
- p_2 = −1.022±0.047
- p_3 = −0.107 ± 0.002 GeV^{-1}

The relative b-hadron production in pseudo-rapidity is stable (as expected from pQCD)**:**





Integrated results

[LHCb-PAPER-2018-050]
Submitted to PRL

Efficiency corrected yields are summed over p_T and η bins

$$\frac{f_{\Lambda_b^0}}{f_u + f_d} = 0.259(18) \qquad \frac{f_s}{f_u + f_d} = 0.122(6)$$

NB! These results should not be compared directly to 7 TeV results, because of the different p_T ranges: $4 < p_T < 25$ GeV (was $0 < p_T < 14$ GeV).

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	–
Γ_{sl} correction	0.5	1.5	–
Total	4.3	6.1	2.2

- Uncertainty dominated by H_c branching fractions
- Improvement over the LHCb 7TeV f_s/f_d average precision (5.8%)

[LHCb-CONF-2013-011]

Relative B_s and $B^\pm$ production at 7,8 and 13TeV

New!

Measure the relative $B^\pm \to J/\psi K^\pm$ and $B_s \to J/\psi \Phi$ yields at 7, 8 and 13 TeV pp collision data to study f_s/f_u...

- **energy dependence** using f_s/f_u 8 / 7TeV and 13 / 7 TeV ratios
- **kinematic dependencies** (p_T, p_L, p, η, y)

Strengths:

- trigger on $J/\psi \to \mu^+\mu^-$ (greatly reduces trigger efficiency uncertainty)
- near identical selection (bar the additional kaon from Φ)
- no hadron PID requirements necessary

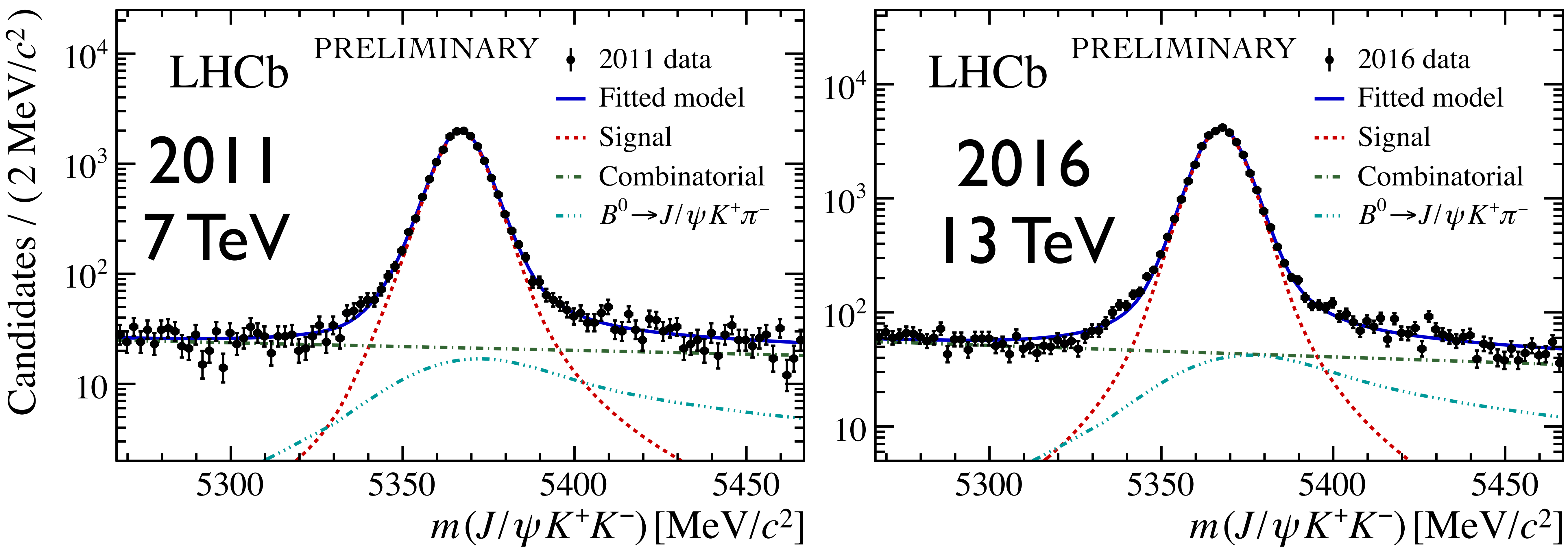
Weakness:

- precise f_s/f_u value measurement not possible due to the uncertain branching fraction (after the excluding the measurements normalised to the $B^\pm \to J/\psi K^\pm$). Will scale to match the LHCb 7TeV f_s/f_d result.

[LHCb-PAPER-2019-020]
In preparation

New!

$B_s \to J/\psi \Phi$ mass fits

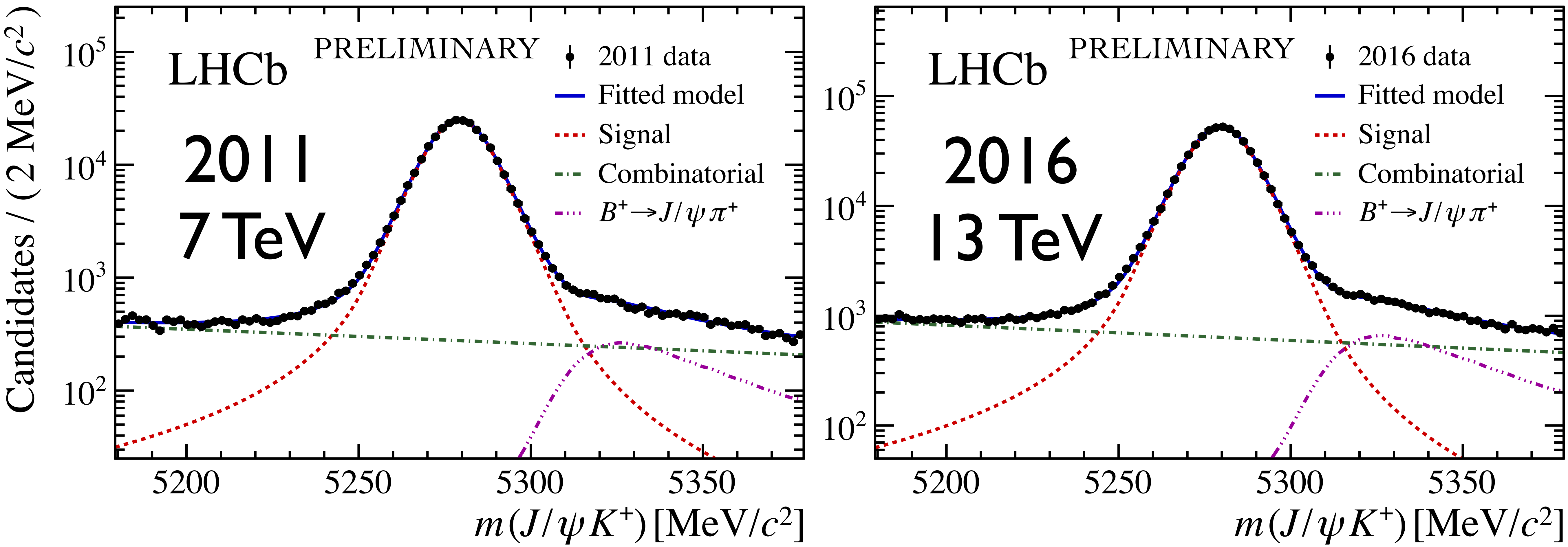


- Signal clearly separated despite no hadron PID is applied
- Important to correctly model the mis-identified contributions (across the kinematic bins)

[LHCb-PAPER-2019-020]
In preparation

New!

$B^{\pm} \to J/\psi K^{+}$ mass fits



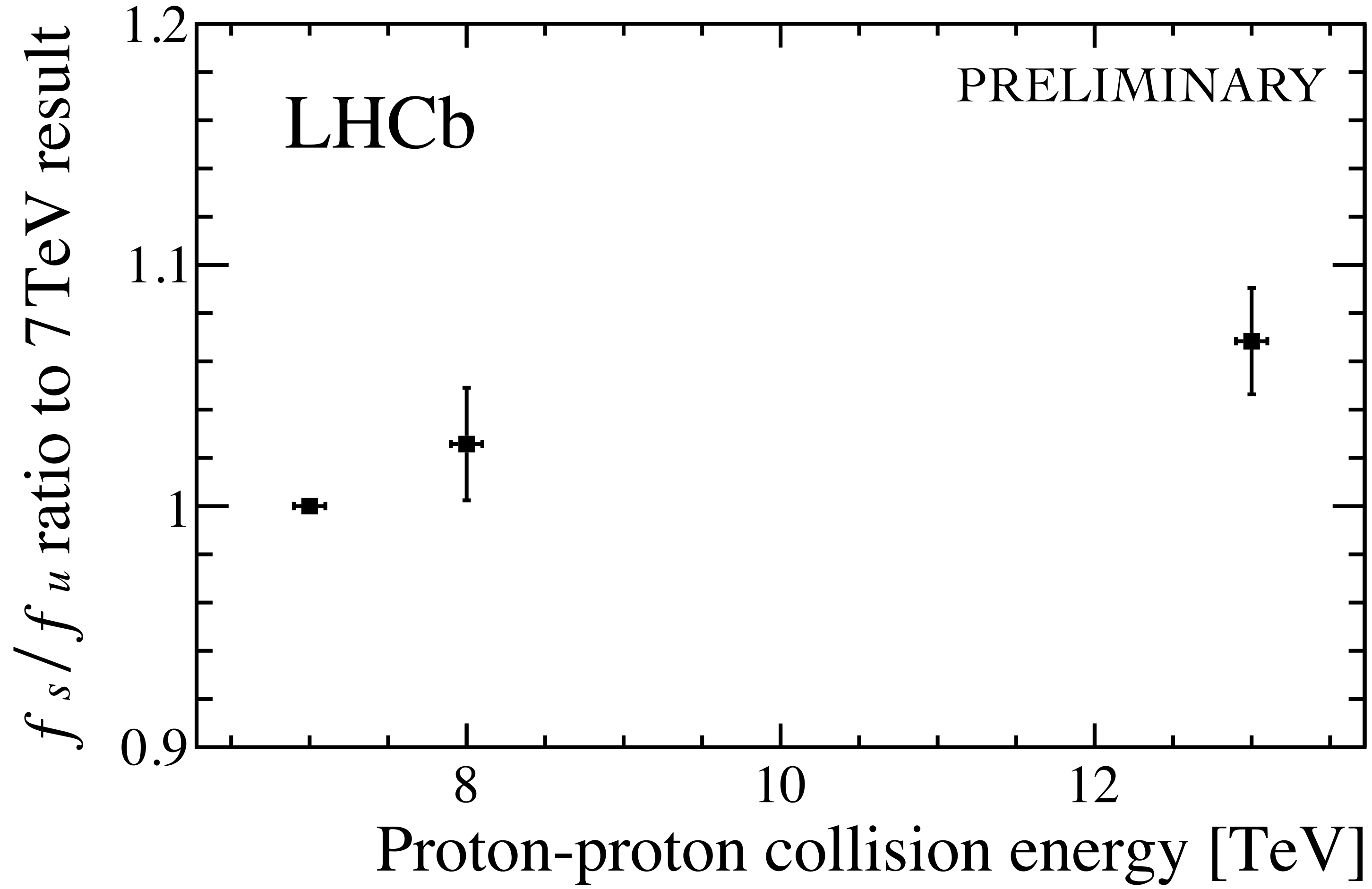
- Signal clearly separated despite no hadron PID is applied
- Important to correctly model the mis-identified contributions (across the kinematic bins)

B_s production at different pp collision energies

[LHCb-PAPER-2019-020]
In preparation

New!

- 2011 (7TeV) 2012 (8TeV) 2015,2016 (13TeV) treated separately
- Normalised to 2011, 2015, 2016 combined
- Bins correlated, consistent with no energy dependence



Double ratios:

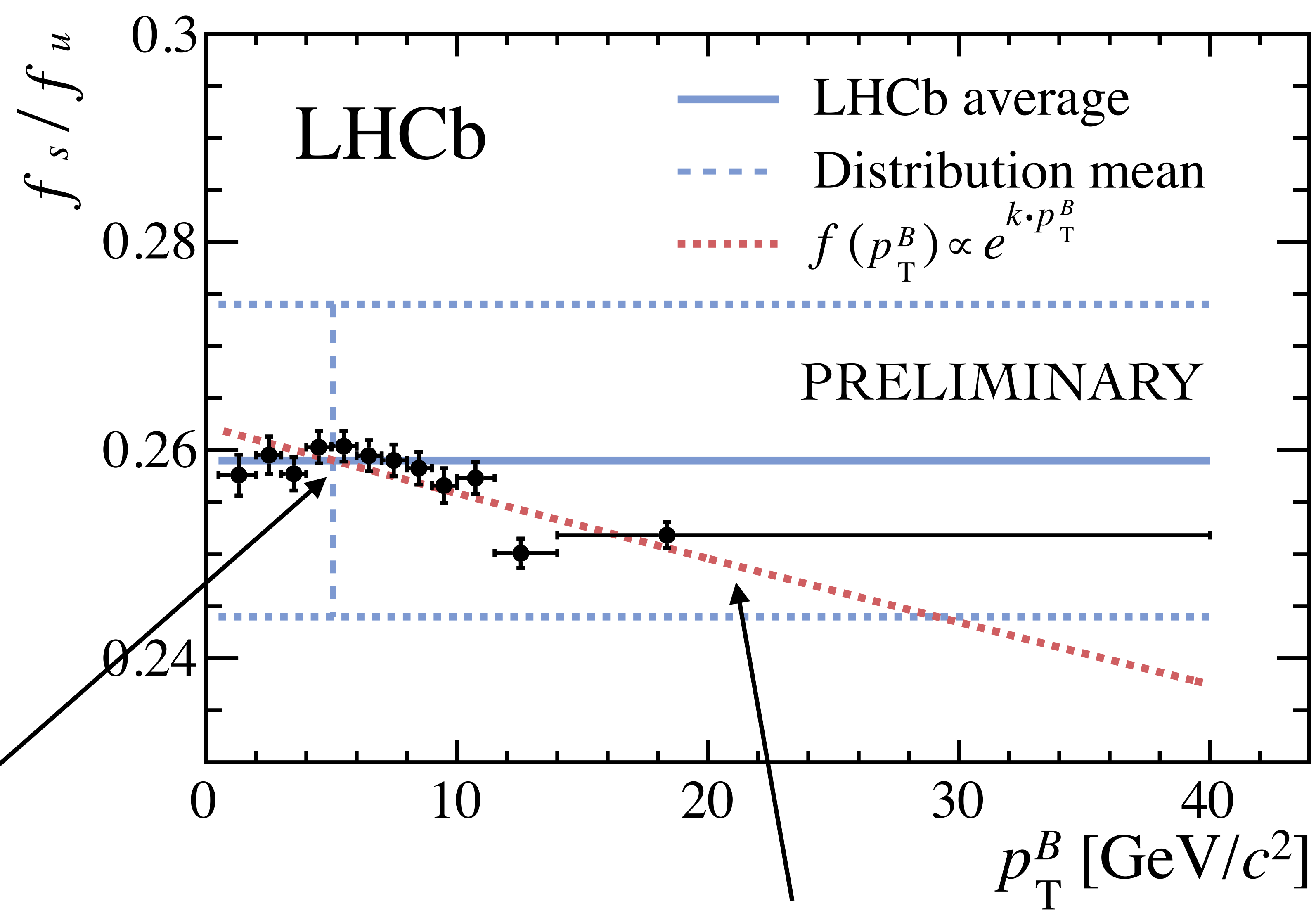
$$\mathcal{R}_{8\,\text{TeV}}/\mathcal{R}_{7\,\text{TeV}} = 1.026 \pm 0.017(MC) \pm 0.009(syst) \pm 0.011(stat)$$
$$= 1.026 \pm 0.023,$$
$$\mathcal{R}_{13\,\text{TeV}}/\mathcal{R}_{7\,\text{TeV}} = 1.068 \pm 0.017(MC) \pm 0.009(syst) \pm 0.011(stat)$$
$$= 1.068 \pm 0.022.$$

In transverse momentum bins:

[LHCb-PAPER-2019-020]
In preparation

New!

- efficiencies for years estimated separately
- results combined and scaled to the LHCb 7TeV f_s/f_d
- a clear p_T variation observed, compatible with: [LHCb-PAPER-2018-050]



Scaled to match the LHCb 7TeV f_s/f_d average (only for illustrative purposes)
[LHCb-CONF-2013-011]

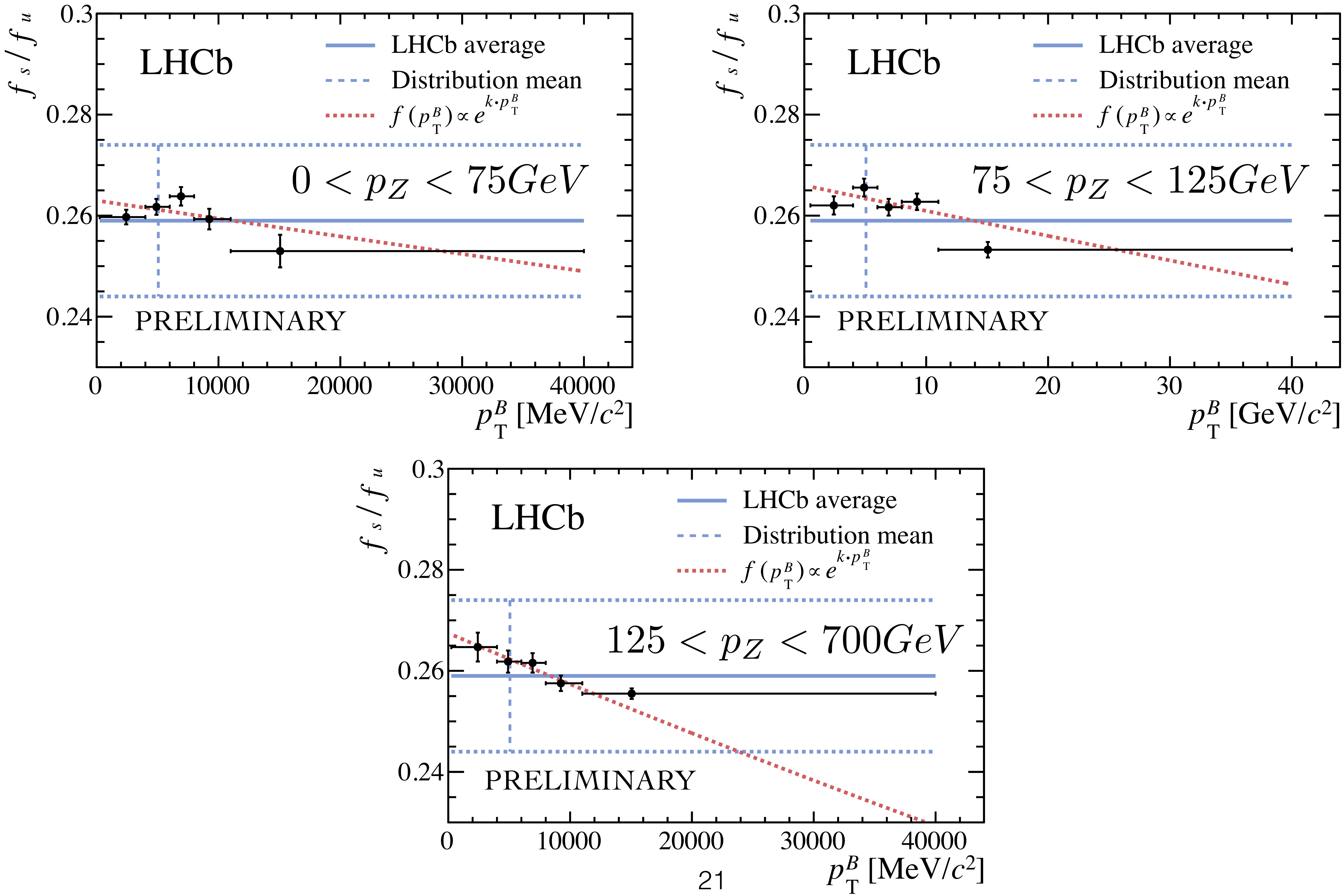
Fit an exponential to estimate the significance of the variation (6σ):

$$k = -(2.50 \pm 0.55) \times 10^{-7} (GeV/c)^{-1}$$

A clear transverse momentum dependence across the longitudinal momentum range:

[LHCb-PAPER-2019-020]
In preparation

New!

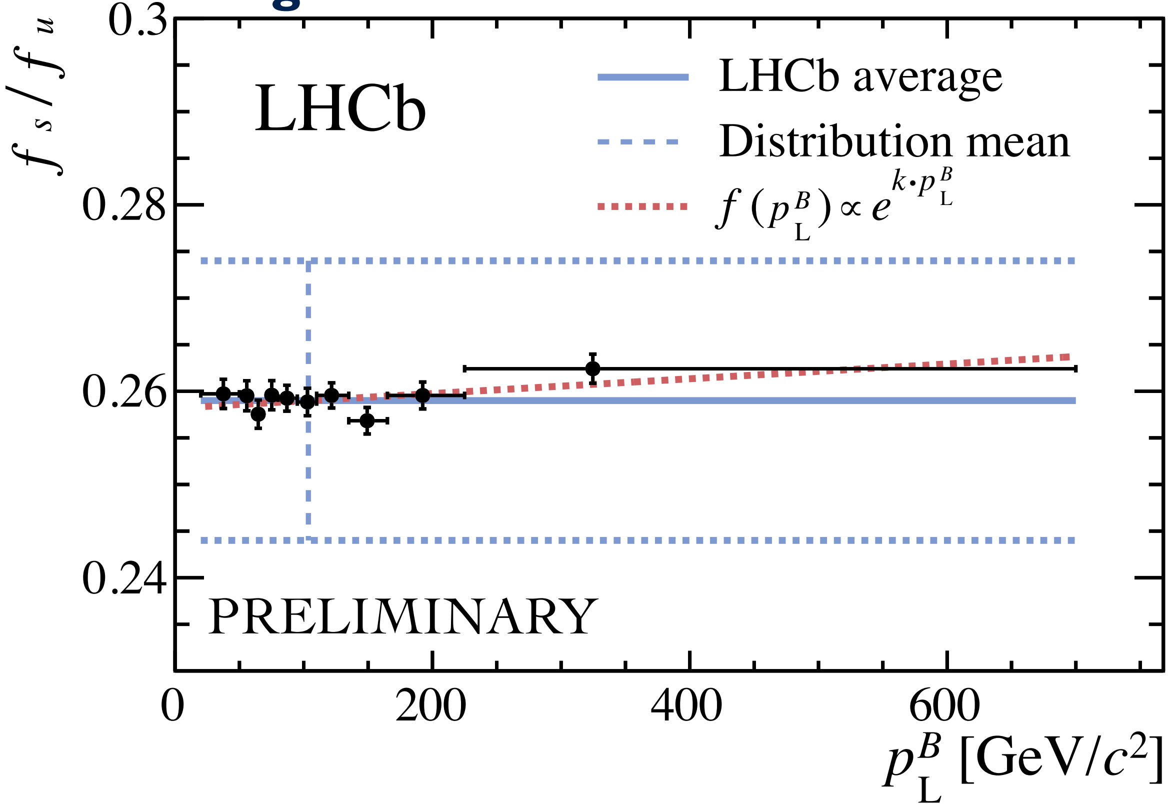


No evidence is seen for f_s/f_u variation in other considered kinematic variables:

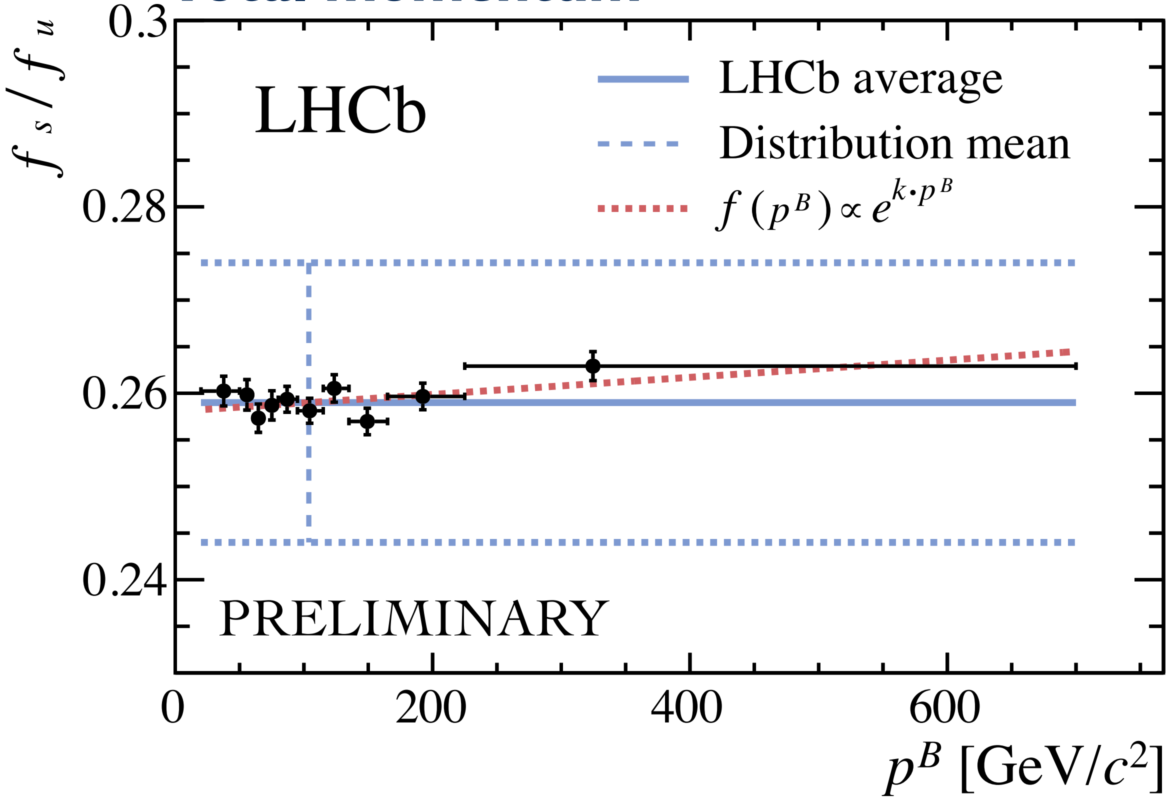
[LHCb-PAPER-2019-020]
In preparation

New!

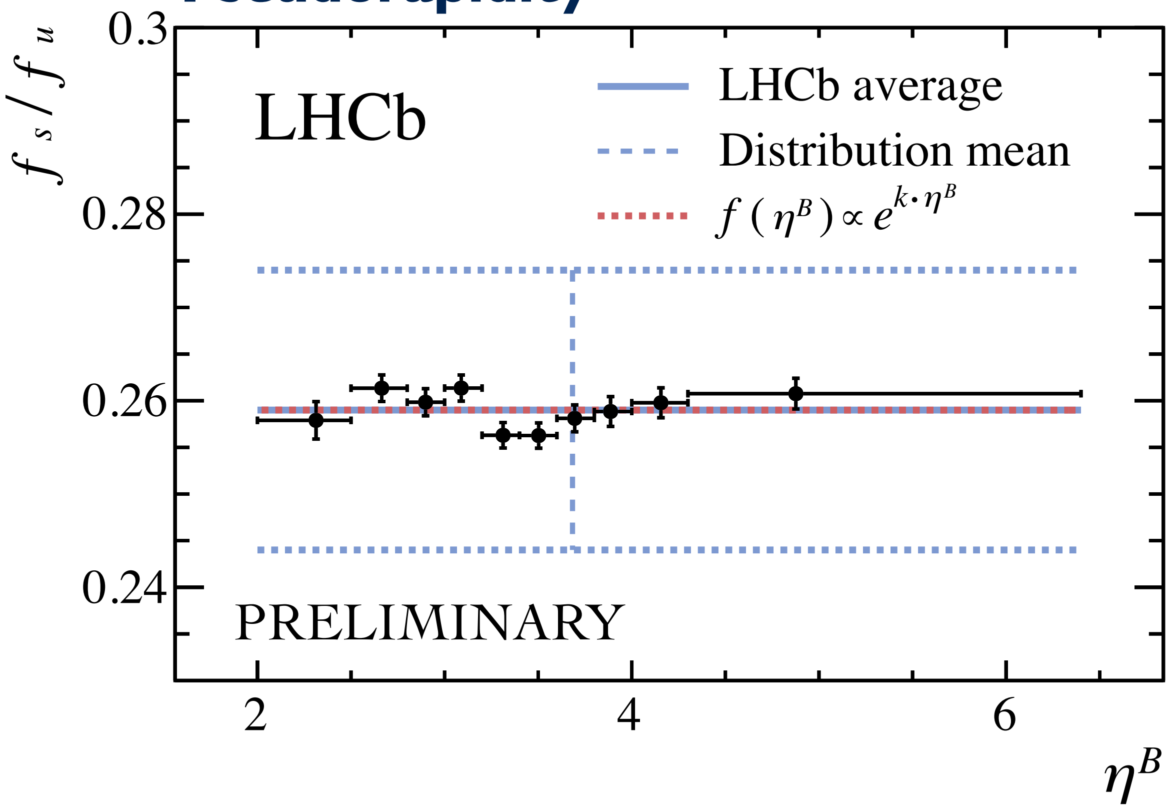
Longitudinal momentum



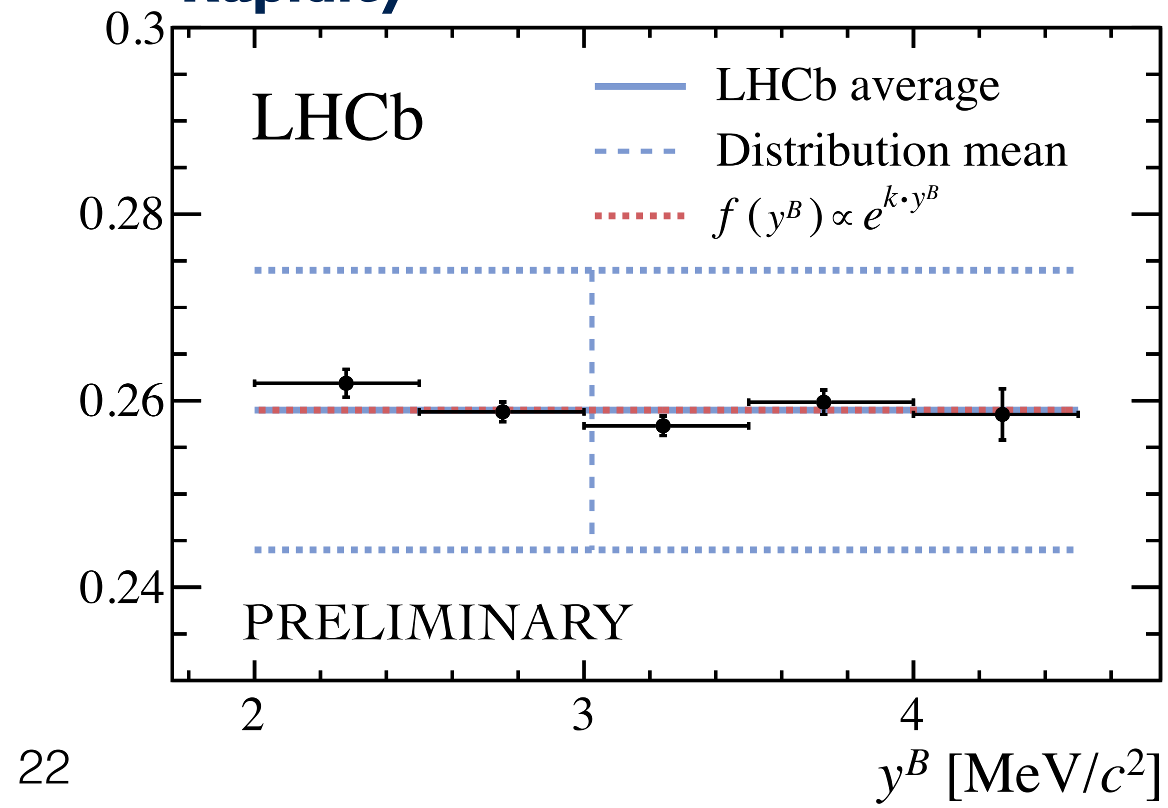
Total momentum



Pseudorapidity



Rapidity



Summary

Two recent results on b-hadron production from LHCb:

[a] Λ_b / (f_u+f_d) and f_s / (f_u+f_d) measurement at 13TeV pp data with semileptonic decays [LHCb-PAPER-2018-050]
submitted to PRL

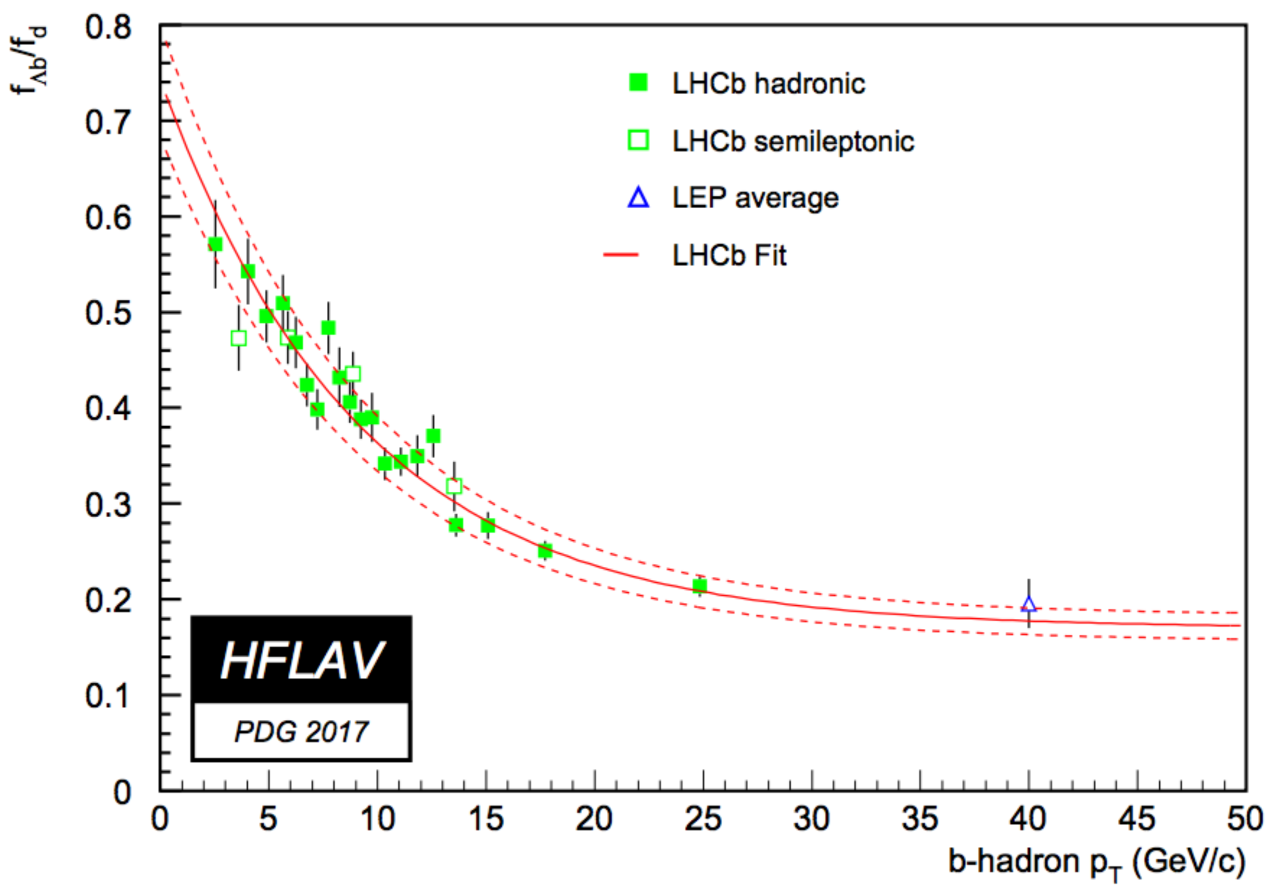
New!

[b] dedicated f_s/f_u collision energy and kinematic variation analysis using $B \to J/\Psi X$ decays at 7, 8 and 13 TeV pp data [LHCb-PAPER-2019-020]
in preparation

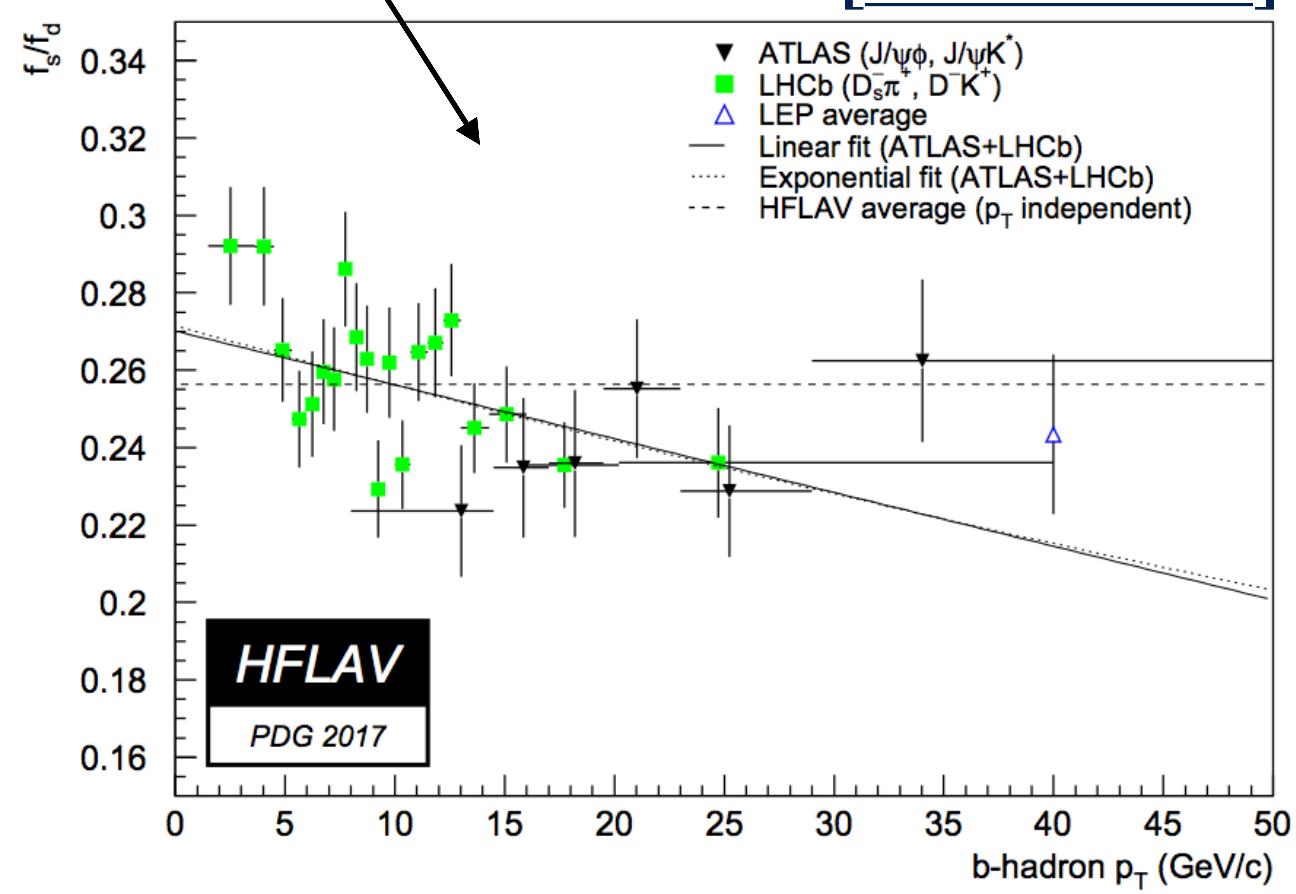
- first absolute $f_{\Lambda b}$ / (f_u+f_d) and f_s / (f_u+f_d) measurement at 13TeV **[a]**
- no evidence seen for variation in collision energy **[b]**
- both ratios depend on transverse momentum **[a,b]**
- no evidence for variation in other kinematic variables **[a,b]**

Results will be included in the HFLAV combination plots: $f_s/f_{d(u)}$ p_T dependence now clearly observed by LHCb:

[HFLAV 2016]



[HFLAV 2016]



Backup slides

Perturbative QCD can predict both the shape and normalisation of fragmentation functions for *doubly heavy* mesons. For instance, the fragmentation function for the formation of B_c^+ mesons has the form [arXiv:1309.1979]

$$f_{\bar{b}\to B_c}(z) = \frac{2\alpha_s^2|R_S(0)|^2}{27\pi m_c^3}\frac{rz(1-z)^2}{(1-(1-r)z)^6}\Big(2-2(3-2r)z+3(3-2r+4r^2)z^2 - 2(1-r)(4-r+2r^2)z^3+(1-r)^2(3-2r+2r^2)z^4\Big)\,, \quad (9.3)$$

where $R_S(0)$ is the value of the non-relativistic B_c^+ wave function at the origin, and $r = \frac{m_c}{m_c+m_b}$. This fragmentation function can also be applied to the formation of *heavy-light* mesons, in which case the quantity r is a phenomenological parameter to be obtained from data. In this case, the normalisation cannot be determined from perturbative QCD.

B-fragmentation functions have been previously shown to play a crucial role in understanding large (3x) discrepancies between the measured b hadron production cross sections (CDS,HERA,LEP) and the NLO QCD predictions. Especially important due to the limited experimental acceptance.

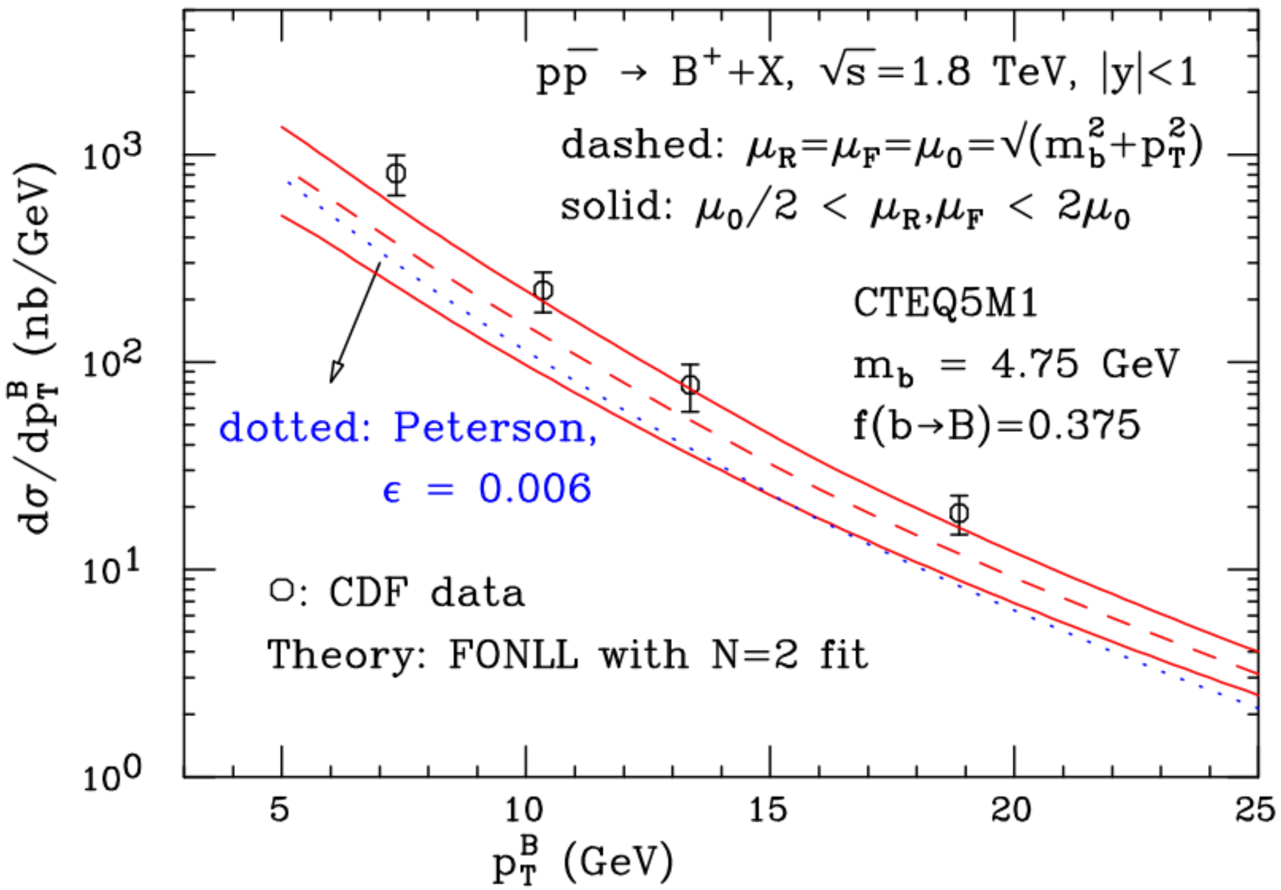


FIG. 2. Prediction for the B cross section, obtained using the calculation of Ref. [22] supplemented with the $N = 2$ fit of the non-perturbative fragmentation function, compared to the CDF data of Ref. [10]. For comparison, the result obtained using a Peterson form with $\epsilon = 0.006$ is also shown.

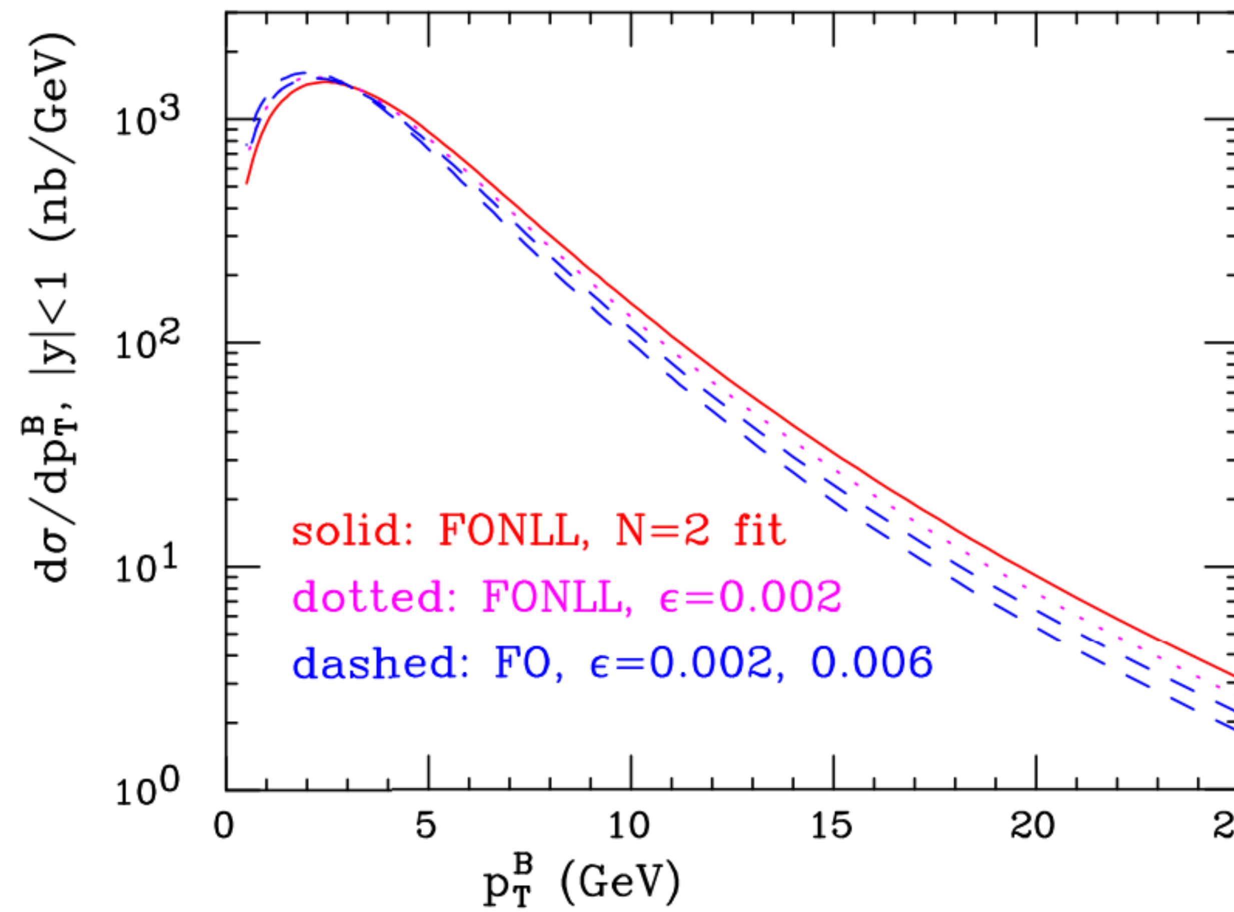


FIG. 4. The effect of the different ingredients in the calculation presented in this work, relative to a fixed order calculation with Peterson fragmentation and $\epsilon = 0.006$.

[LHCb-PAPER-2019-020]
In preparation

Binning in B meson kinematics is chosen to:

New!

- align with the binning used in the LHCb B^+ production analysis [JHEP 12 (2017) 026]
- contain sufficient statistics (limited by the Generator level MC)
- maximise the overlap with ATLAS/CMS ($2<\eta(B)<2.5$)

$p_T(B)$ = [0.5, 2., 3., 4., 5., 6., 7., 8., 9., 10., 11.5, 14., 40.] GeV/c

$\eta(B)$ = [2.0, 2.5, 2.8, 3.0, 3.2, 3.4, 3.6, 3.8, 4.0, 4.3, 6.4]

$p_Z(B)$ = [20., 50., 60., 70., 80., 95., 110., 135., 165., 225., 700.] GeV/c

$p(B)$ = [20., 50, 60, 70., 80., 95., 110., 135., 165., 225., 700.] GeV/c

$y(B)$ = [2.0, 2.5, 3.0, 3.5, 4.0, 4.5]

Detection efficiency

The total detection efficiency is given w.r.t the number of B's produced in a given bin in an MC sample (unfolds the fragmentation function assumed by Pythia):

$$N_{Bq}^{LHCb} \propto \int^{LHCb} \frac{\delta}{\delta x}\sigma(pp \to b\bar{b}) \times \frac{\delta}{\delta x} f_q(b \to B_q) dx$$

(cross section * b-fragmentation function assumed in Pythia)

The efficiency is factorised into generator level, reconstruction and selection, and trigger efficiencies:

$$N_{B\to X}^{Bin} \to N_{B\to X}^{Bin|XInAcc} \to N_{B\to X}^{Bin|XInAcc|RecSel} \to N_{B\to X}^{Bin|XInAcc|RecSel|TOS\mu\mu}$$