CMS results on the production fractions ratios

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Motivation : Production Fractions (ratios) - I

- The pp collisions @ LHC **produce** copious pairs of ***b* and $\bar{b}$ quarks**
  … which immediately *hadronize into* the **full spectrum of beauty hadrons.**
  The knowledge of their production rates is crucial for measuring their branching fractions (BFs).

  - The **Production (a.k.a. Fragmentation) Fractions (PFs)** f_u , f_d , f_s , f_{baryon} are defined as **probabilities for a *b* quark to hadronize** into a B^+, B^0, B_s^0 **meson** or a ***b* baryon**

  - Many of the B^+ and B^0 BFs are well known whereas that is not the case for several of the B_s^0 BFs. The B_s^0 BFs generally rely on ratios to B^+ and B^0 decay modes, thus requiring the knowledge of $\frac{f_s}{f_u}$, $\frac{f_s}{f_d}$.

    $B_s^0 \to J/\psi\,\phi$ is the most studied B_s^0-meson decay but the precision on its BF is still limited [LHCb, PRD 87 (2013) 072004] (*) :

    $$\mathcal{B}(B^0 \to J/\psi\,\phi) = (1.050 \pm 0013 \pm 0.064 \pm 0.082) \cdot 10^{-3}$$

(*) recently uncertainty was halved [PRD 104 (2021) 032005] adding part of 13TeV data: $(1.018 \pm 0032 \pm 0.037) \cdot 10^{-3}$

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Measuring the **relative production of b hadrons** is not only important for the studies of the underlying QCD but f_s/f_u is also an **essential input** & a **dominant source** of systematic uncertainty in B_s^0 BFs measurements performed in hadron colliders **(**relevant example is $B_s^0 \to \mu^+\mu^-$ where the f_s/f_u **uncertainty is a limiting factor)**. Precise knowledge of PFs is also important for CP asymmetries (in the determination of the systematics due to production asymmetries).

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- **Isospin symmetry** implies that f_u = f_d , thus $\frac{f_s}{f_u} = \frac{f_s}{f_d}$

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Motivation : Production Fractions ratios - II

The b-hadron FFs were initially measured: **- in e^+e^- collisions at the Z resonance @ LEP** (till 2003)

- in $p\bar{p}$ coll. @ c.o.m. energy $\sqrt{s} = 1.8\text{TeV}$ by CDF (2008) $|\eta| < 1$

- in pp coll. @ c.o.m. energy $\sqrt{s} = 7\text{TeV}$ by ATLAS (2015) $|\eta| < 2.5$

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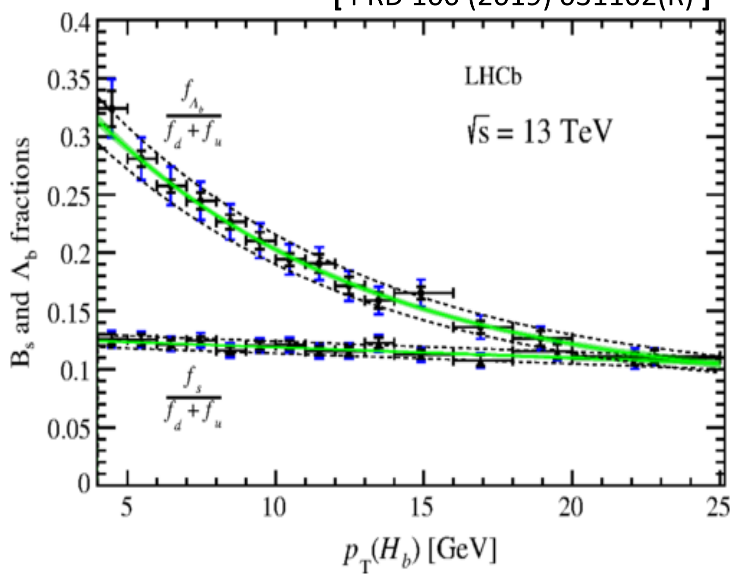

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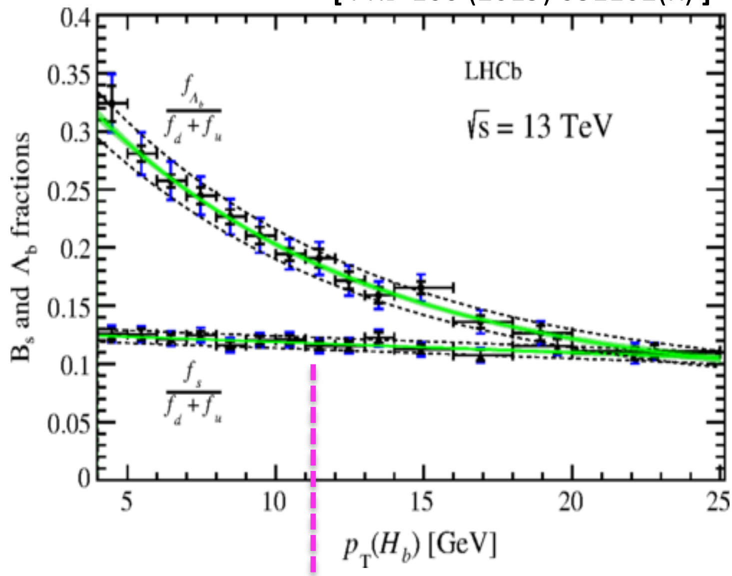

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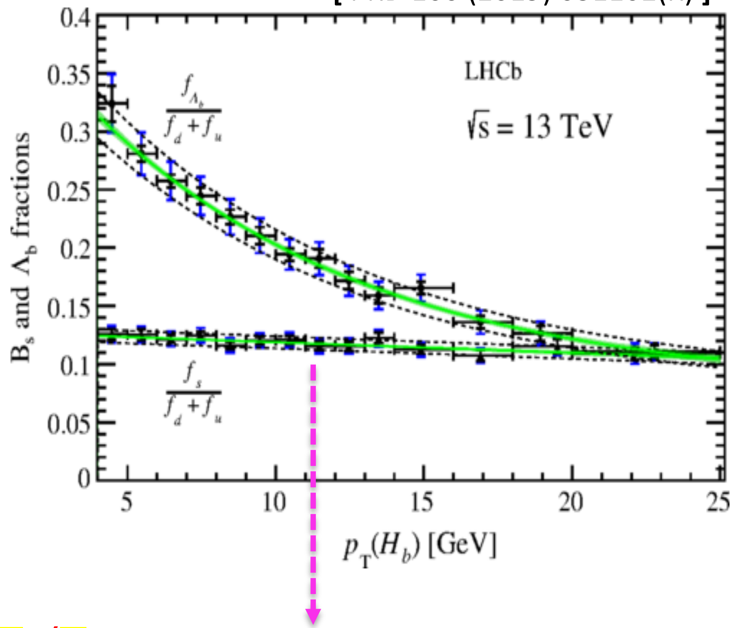

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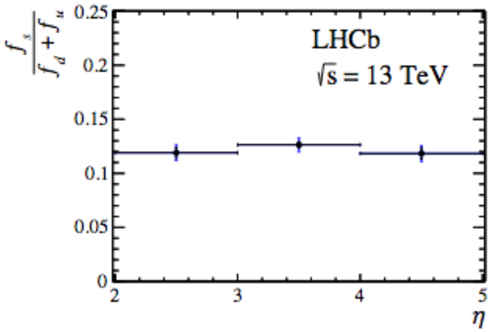
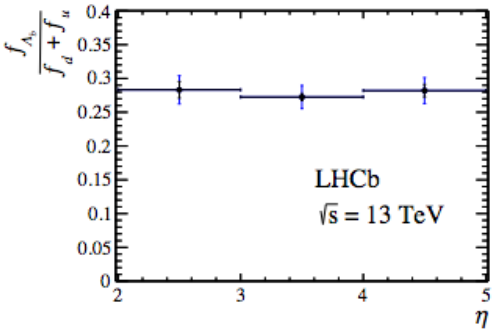
On the other hand**, no η-dependence** is visible:





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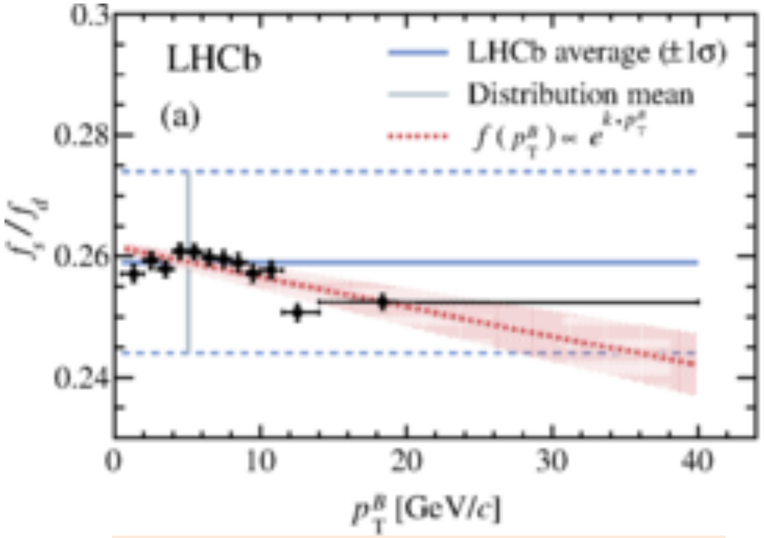
Motivation : Production Fractions ratios - III

- The f_s/f_u p_T**-dependence** has been investigated in detail by LHCb in a more recent analysis of $\sqrt{s} = 7, 8, 13\text{TeV}$ datasets (in the full forward region $2 < |\eta| < 6.4$) [PRL 124 (2020) 122002]

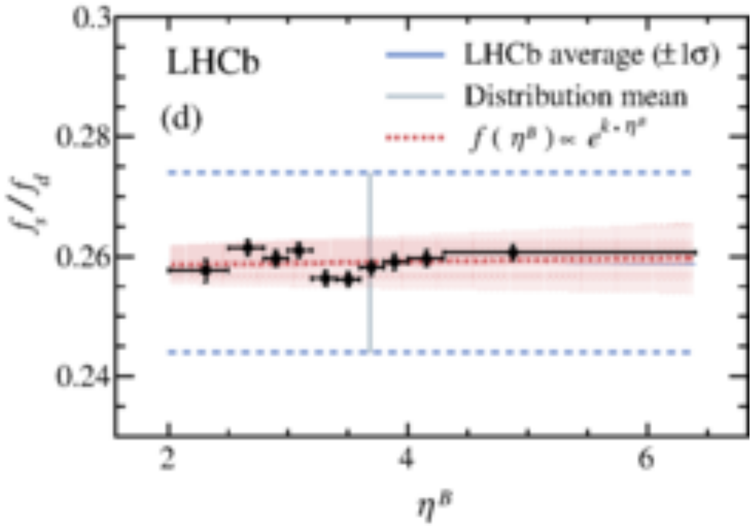
- **f_s/f_u observed to depend on p_T^B with a significance of 6.0σ**

  This dependency is driven by the 13TeV sample (8.7σ), while the results for the other collision energies are not significant when considered separately.

- **No evidence of f_s/f_u variation is seen in η^B**



Exponetial fits used to estimate the statistical significances of the variations ($k = 0$ vs k free)



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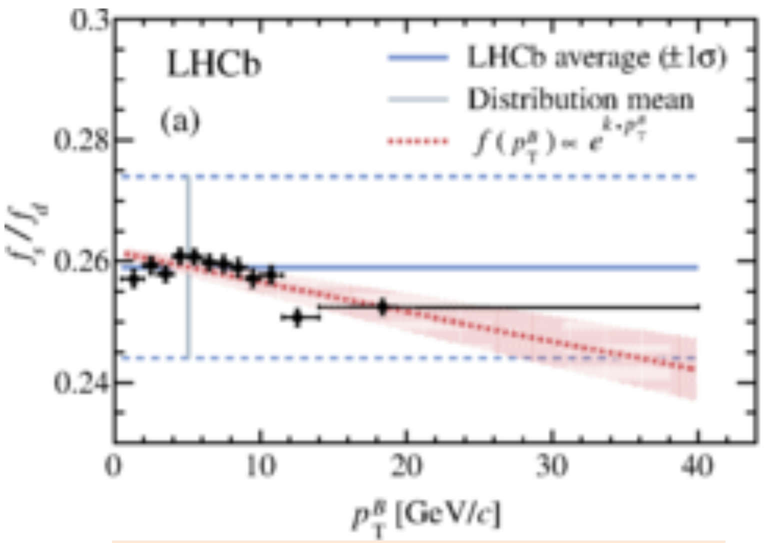

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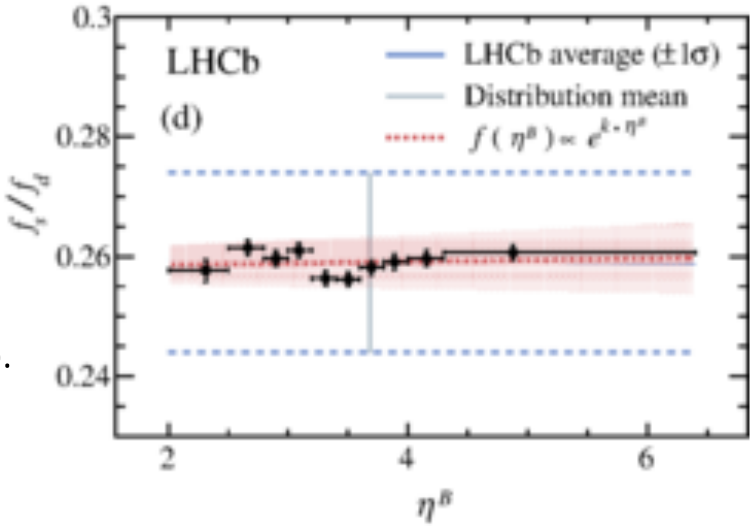


LHCb effectively measures the ratio $\mathcal{R}$ of efficiency corrected yields of $B_s^0 \to J/\psi\,\phi$ & $B^+ \to J/\psi\,K^+$ reconstructed signals : no attempt is made to measure the absolute f_s/f_u value (because of the large uncertainty on the $B_s^0 \to J/\psi\,\phi$ BF). For illustrative purpose only, the **averaged** signal-yield ratios are ***scaled*** - assuming $f_u = f_d$ - to match the average f_s/f_d value measured at $\sqrt{s} = 7\text{TeV}$ [JHEP 04 (2013) 001] at the corresponding **variable distribution means** (grey vertical lines).

Behavior confirmed in the LHCb re-analysis of PRD 104 (2021) 032005

Motivation : Production Fractions ratios - IV

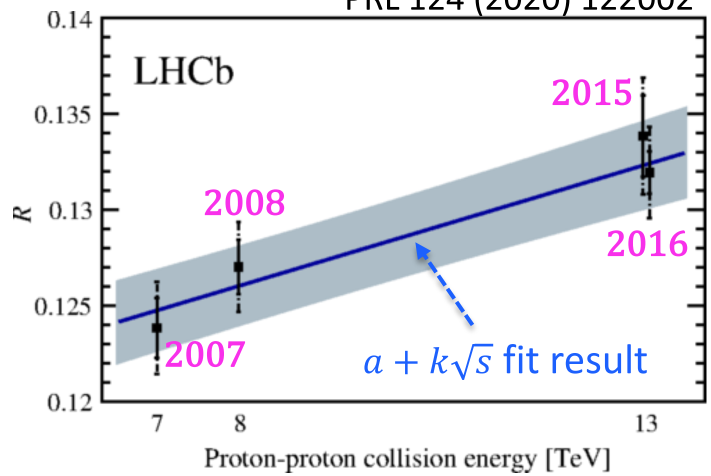
- **Evidence for an increase of f_s/f_u as a function of collision energy :**

  - the 2-sided significance of the 2-param fit (model $a + k\sqrt{s}$) is $\mathbf{4.8\sigma}$ w.r.t. no energy depedence

  - measured double ratios for different collision energies:

$$\frac{\mathcal{R}_{8TeV}}{\mathcal{R}_{7TeV}} = 1.026 \pm 0.017 \qquad \frac{\mathcal{R}_{13TeV}}{\mathcal{R}_{7TeV}} = 1.068 \pm 0.016$$

PRL 124 (2020) 122002



  - Behavior confirmed in the re-analysis of PRD 104 (2021) 032005 :

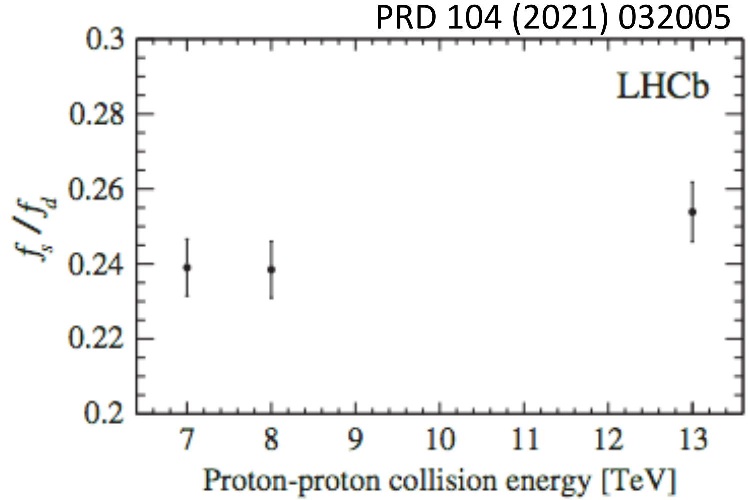
$$\frac{f_s/f_d\,(13TeV)}{f_s/f_d\,(7TeV)} = 1.064 \pm 0.008$$

$$\frac{f_s/f_d\,(13TeV)}{f_s/f_d\,(8TeV)} = 1.065 \pm 0.007$$

$$\frac{f_s/f_d\,(8TeV)}{f_s/f_d\,(7TeV)} = 0.998 \pm 0.008$$

$$\frac{f_s/f_d\,(Run2)}{f_s/f_d\,(Run1)} = 1.064 \pm 0.007$$

PRD 104 (2021) 032005



Coordinates of CMS measurement

- CMS **has recently submitted for publication the paper draft** that can be found on **arXiv** (please refer also to the **CMS** dedicated **public page** **(*)** **)** :

Measurement of the dependence of the hadron production fraction ratio f_s/f_u on B meson kinematic variables in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration

Abstract

The dependence of the ratio between the B_s^0 and B^+ hadron production fractions, f_s/f_u, on the transverse momentum (p_T) and rapidity of the B mesons is studied using the decay channels $B_s^0 \to J/\psi\,\phi$ and $B^+ \to J/\psi\,K^+$. The analysis uses a data sample of proton-proton collisions at a center-of-mass energy of 13 TeV, collected by the CMS experiment in 2018 and corresponding to an integrated luminosity of $61.6\,\mathrm{fb}^{-1}$. The f_s/f_u ratio is observed to depend on the B p_T and to be consistent with becoming asymptotically constant at large p_T. No rapidity dependence is observed. The ratio of the B^0 to B^+ hadron production fractions, f_d/f_u, measured using the $B^0 \to J/\psi\,K^{*0}$ decay channel, is found to be consistent with unity and independent of p_T and rapidity.

$\sqrt{s} = 13 TeV$

(Run-2 / 2018)

$\mathcal{L} = 61.6\ fb^{-1}$

- **(*)** Pointers to all CMS Heavy Flavour results can be found here:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

What we measure? $\mathcal{R}_s \propto f_s/f_u$

- By reconstructing the decay channels $B^+ \to J/\psi\, K^+$ & $B_s^0 \to J/\psi\, \phi$

  ... we measure the **Ratio of efficiency-corrected measured meson yields:** $\mathcal{R}_s = \frac{\mathrm{N}_{B_S^0}}{\mathrm{N}_{B^+}} \cdot \frac{\epsilon_{B^+}}{\epsilon_{B_S^0}}$

This ratio is directly proportional to f_s/f_u :

$$\mathcal{R}_s = \frac{f_s}{f_u} \cdot \frac{\mathcal{B}(B_s^0 \to J/\psi\, \phi)\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(B^+ \to J/\psi\, K^+)} \cdot \cancel{\frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)}}$$

- Given that .... the available measurements of f_s & $\mathcal{B}(B_s^0 \to J/\psi\, \phi)$ are ***correlated*** **...**

  ... we report $\mathcal{R}_s$ rather than $\frac{f_s}{f_u}$

  To be clearer, the motivation of this choice is that the world-average value of the BF $\mathcal{B}(B_s^0 \to J/\psi\, \phi)$ is dominated by the LHCb result (with which we want to compare our result), that uses $B^+ \to J/\psi\, K^+$ as normalization channel and therefore depends - in turn - on the f_s/f_u ratio.

  We want to avoid this circularity.

What we measure? f_d/f_u

Similarly, by reconstructing the decay channels $B^+ \to J/\psi\, K^+$ & $B^0 \to J/\psi\, K^{*0}$

... we measure the **Ratio of efficiency-corrected meson yields :** $\mathcal{R}_d = \frac{N_{B^0}}{N_{B^+}} \cdot \frac{\epsilon_{B^+}}{\epsilon_{B^0}}$

This ratio is directly proportional to f_d/f_u : $\mathcal{R}_d = \frac{f_d}{f_u} \cdot \frac{\mathcal{B}(B^0 \to J/\psi\, K^{*0})\mathcal{B}(K^{*0} \to K^+\pi^-)}{\mathcal{B}(B^+ \to J/\psi\, K^+)} \cdot \cancel{\frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)}}$

Given that:

- the involved branching fractions are independently obtained from high-precision (B-factories based) measurements (under assumption of isospin invariance)

... $\boxed{\text{we report the more relevant } \frac{f_d}{f_u}}$ rather than $\mathcal{R}_d$

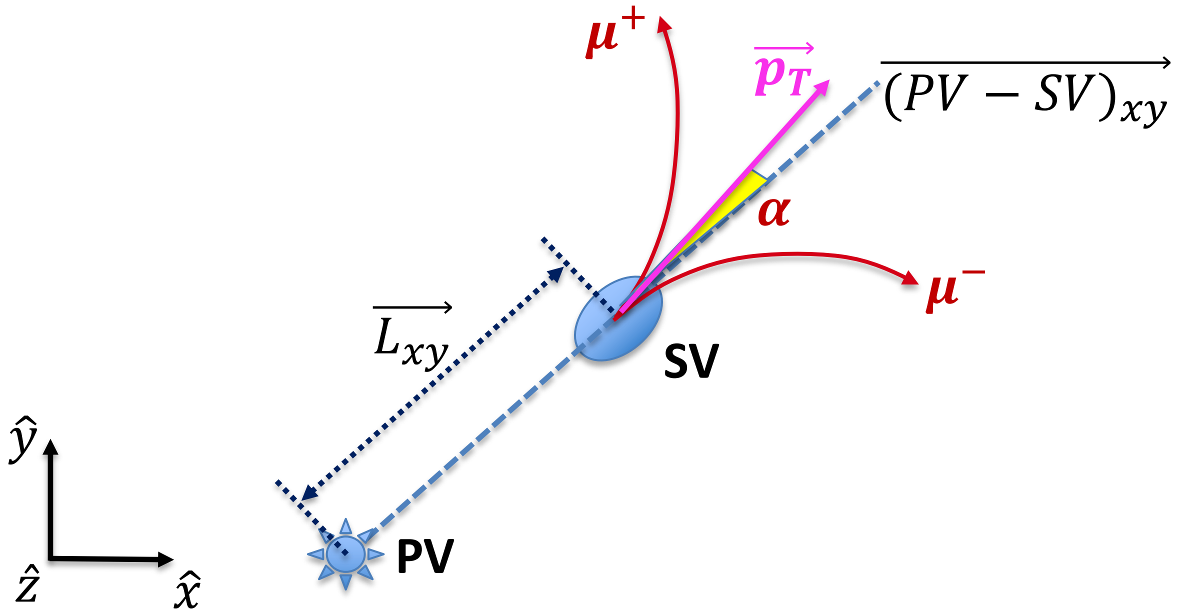
Given that f_d/f_u is expected to be =1 from isospin symmetry, ...

... by exploring $\mathcal{R}_d$ (and thus f_d/f_u) we have a "calibration/control" mode for the $\mathcal{R}_s$ measurement : a flat distribution outcome for $\mathcal{R}_d$ would corroborate the correctness of the $\mathcal{R}_s$ analysis procedure.

Signals' extraction - I

- **Events selected by triggering on a *displaced* dimuon+track High Level Trigger**

  - the two oppositely charged muons must have: $p_T > 4.0GeV$, $|\eta| < 2.5$, $2.9 < m(\mu\mu) < 3.3GeV$
  - dimuon $\overrightarrow{p_T}$ & transverse displacement vector $\overrightarrow{L_{xy}}$ must be aligned (i.e., very small "pointing angle") α
  - dimuon **transverse displacement** : $L_{xy}/\sigma_{L_{xy}} > 3$
  - the track, compatible with being produced at dimuon vertex, must have $p_T > 1.2GeV$, $d_{xy}/\sigma_{d_{xy}} > 2$
  - di-muon vertex & dimuon+track **vertex fits** quality: $P_{\chi^2}^{fit} > 10\%$



Signals' extraction ($B^+ \to J/\psi\, K^+, B_s^0 \to J/\psi\, \phi\,, B^0 \to J/\psi\, K^{*0}$) - I

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Selection criteria (*offline* requirements) for **muons** and **tracks :**

- muons fulfill ***"soft" identification*** requirements; all charged tracks must pass ***"high-purity"*** criteria
- muons & one of the charged tracks must ***match*** the ***trigger objects***
- all charged tracks must have $p_T > 1.2GeV, \; |\eta| < 2.4$, ***at least*** 5(1) silicon strip (pixel) hits

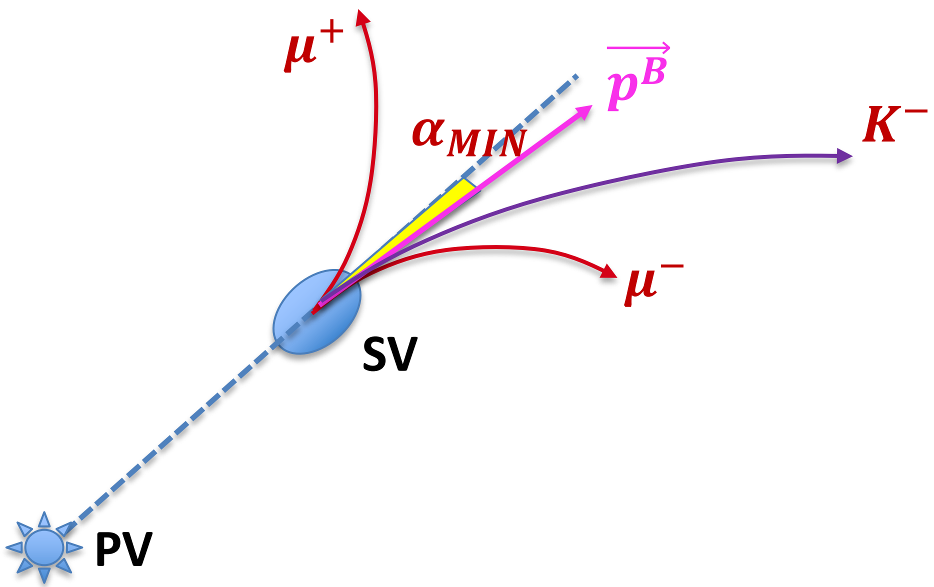
B meson candidates obtained by … vertex-fitting together 1 or 2 tracks
& constraining the dimuon invariant mass to the PDG J/ψ mass

Selection criteria for B meson candidates :

- invariant masses are calculated **assigning π or K mass** to each track as suitable (CMS has no hadronic PID)
- invariant masses for pairs of tracks: $\left|M(KK) - m_{\phi}^{PDG}\right| < 10 MeV$ or $\left|M(\pi K) - m_{K^{*0}}^{PDG}\right| < 50 MeV$
- in the K^{*0} case **two combinations** are possible ($\pi^+ K^-, K^+ \pi^-$): if both match the window requirement only the one closer to $m_{K^{*0}}^{PDG}$ is kept

this implies a contribution due to *swapped* $J/\psi\, K^{*0}$ candidates (which is the 12% of unswapped ones)

- the Primary Vertex (PV) is the one **minimizing the pointing angle of the B meson**; the **PV is refitted** without the tracks of the B candidate **before** computing the B decay length L_{3D}^B (PV-SV)



Signals' extraction ($B^+ \to J/\psi\, K^+, B_s^0 \to J/\psi\, \phi\, , B^0 \to J/\psi\, K^{*0}$) - II

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- arbitration of multiple candidates (only in 1% of the events) : keep the one with the highest $P_{\chi^2}^{B-fit}$

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The two **efficiency ratios** are evaluated using **simulated event samples,** reflecting …
1) the **trigger step** and **2) reconstruction step** as well as **3) the detector acceptance.**

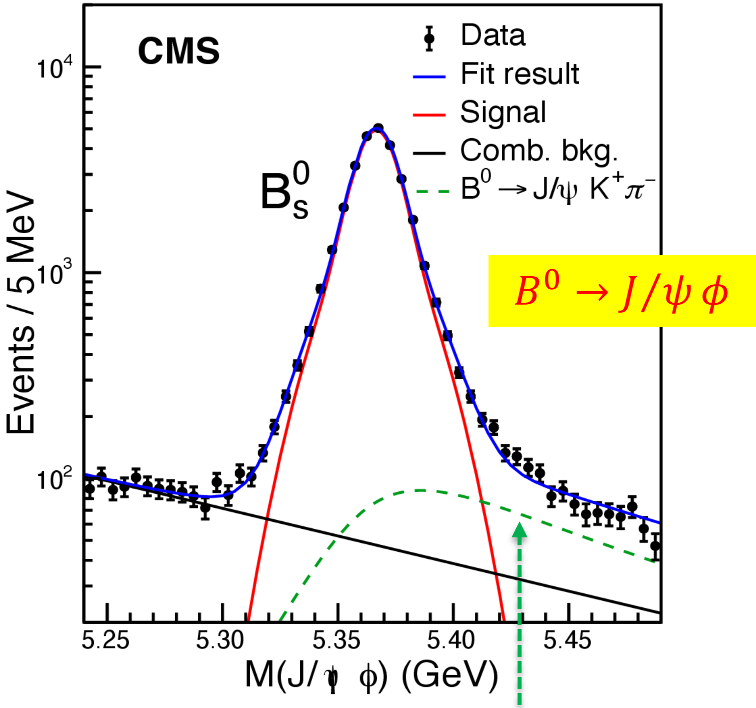
Both ratios, $\frac{\epsilon_{B^+}}{\epsilon_{B_S^0}}$ & $\frac{\epsilon_{B^0}}{\epsilon_{B_S^0}}$, increase by around a factor 3.5 between the lowest & highest p_T^B-bins,

while the variation with *rapidity* is only at the ~10% level.

Fits for yields' measurement

The B_s^0, B^+, and B^0 meson yields are extracted by (UML) fitting the $J/\psi\,\phi$, $J/\psi\,K^+$ and $J/\psi\,K^{*0}$ invariant mass distributions, for 12 different p_T^B-bins (integrated over $|y^B|$) or 7 $|y^B|$-bins (integrated over p_T^B).

Example for the $20–23GeV$ p_T^B-bin: - **Signal : double Gaussian with common mean**
- **Combinatorial Bkg.: Exponential**



B^0 **signal reflection** (from π/K mis-ID)
[Johnson function; gauss-constrained normalization to the signal yield & properly scaled]

Fits for yields' measurement

- The B_s^0, B^+, and B^0 meson yields are extracted by (UML) fitting the $J/\psi\,\phi$, $J/\psi\,K^+$ and $J/\psi\,K^{*0}$ invariant mass distributions, for 12 different p_T^B-bins (integrated over $|y^B|$) or 7 $|y^B|$-bins (integrated over p_T^B).

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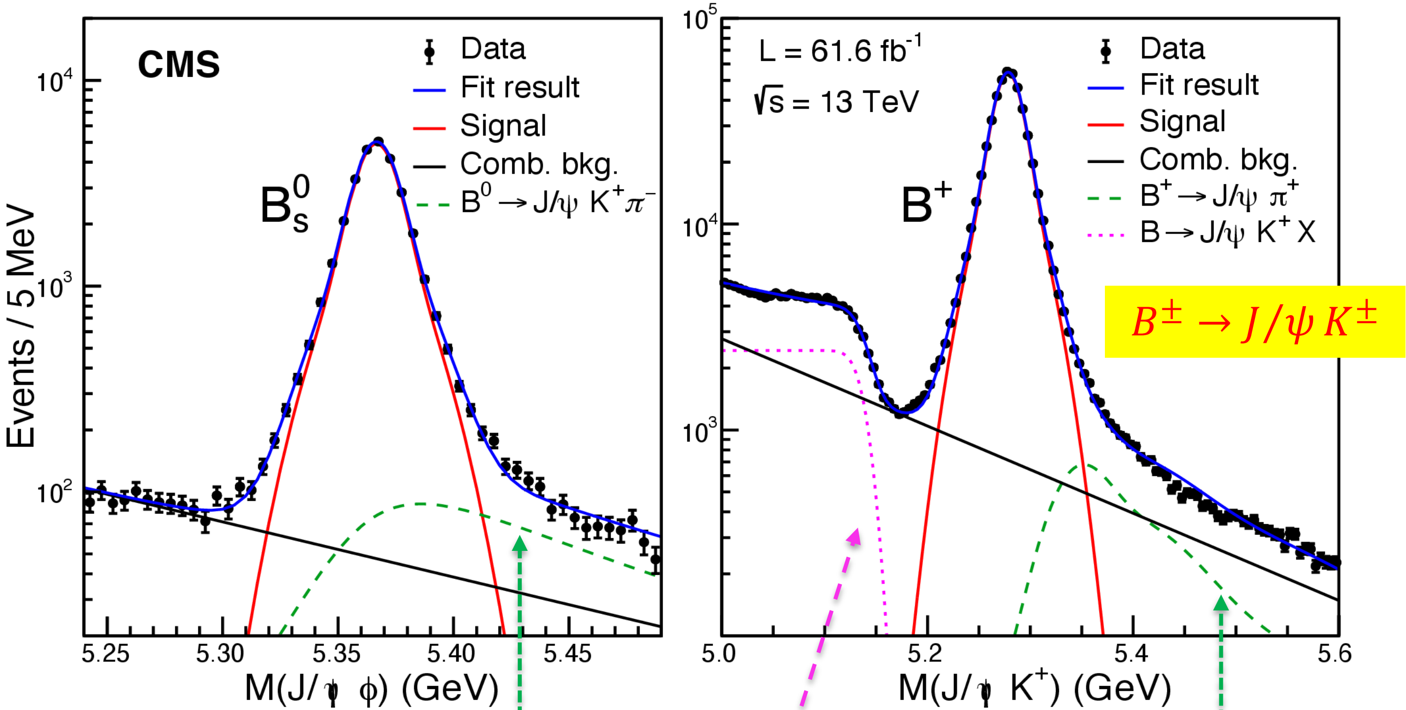

Partially reconstructed multi-body decay (X undetected/unassociated)
[Error function with 2 free shape params]

B^0 signal reflection (from π/K mis-ID)
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Cabibbo suppressed decay ($+\,\pi/K$ mis-ID ; shape from MC) [normalized to signal yield & scaled by BFs' ratio]

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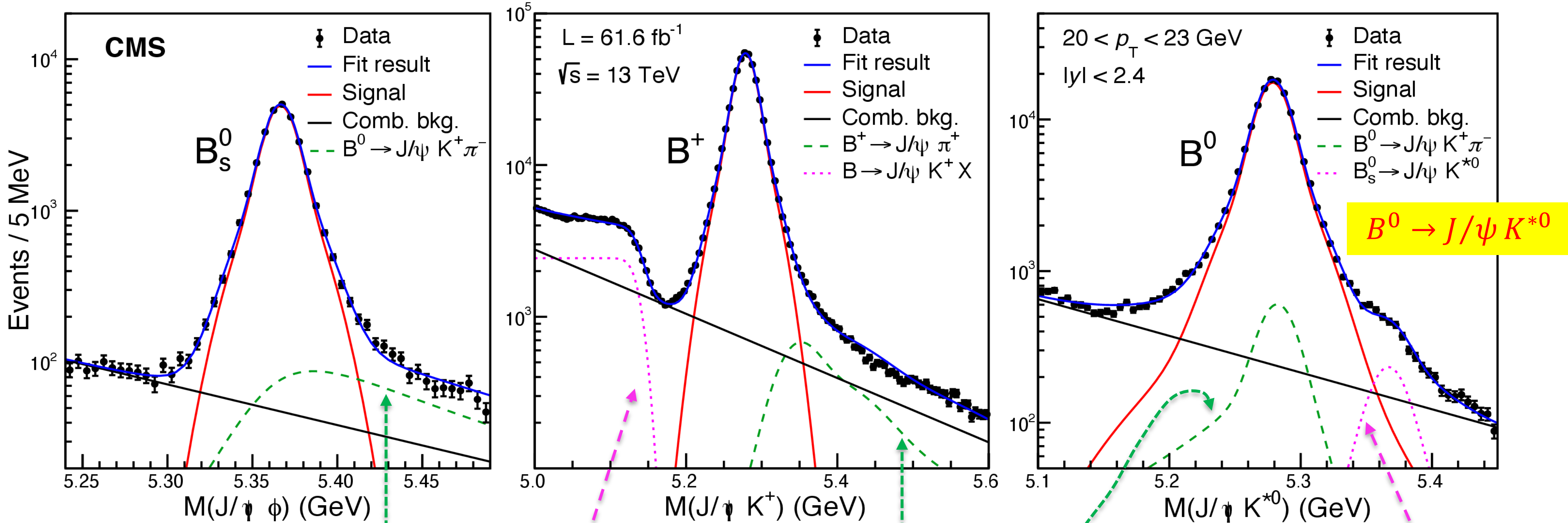
- **Example for the $20\text{–}23 GeV$ p_T^B-bin:** **- Signal : double Gaussian with common mean [+ contribution for *swapped* $J/\psi\,K^{*0}$ candidates] (shape & norm. from MC (12% of unswapped)]**
  - Combinatorial Bkg.: Exponential



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B_s^0 Cabibbo suppressed decay
(shifted & broadened B^0 signal shape)
[free normalization]

Peaking bkg. [double-sided CB + Gaussian; gaussian-constrained normalization to signal yield & properly scaled]

Systematic uncertainties

- **Systematic uncertainties can be divided in *bin-by-bin* and *global* (i.e., equal for every bin) ones.**
  We report here the former and in next slides the latter.
  The bin-by-bin uncertainties are affected by systematic uncertainties associated to …

1) determination of the fitted signal yields

2) determination of the efficiency ratios

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- the fits are repeated in alternative (independent) conditions … obtained by changing … signal model, combinatorial model, normalization of *swapped* $J/\psi\, K^{*0}$ contribution

- the fit procedure itself is checked to provide unbiased results (both for central values & uncertainties) through a ***pseudo-experiment study*** carried out for each of the bins

⇒ **systematic uncertainties are in the ranges** 1.6-2.6% **($\mathcal{R}_s$) &** 2.0-2.5% **($\mathcal{R}_d$)**

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2) determination of the efficiency ratios

- a ≈1% uncertainty, for each of the bins, reflects the size of the used simulated samples

- several potential sources of uncertainty considered & found to have negligible effect on ratios; example: efficiencies' recomputing with varied $p_T^{B_s}$ distributions & decay angular distributions reweighed to match the data

- **MC events were reweighed with weights dependent on p_T^B , y^B, and p_T^K to match distributions with measured ones**

systematic uncertainties are in the ranges 1-2% **($\mathcal{R}_s$) &** 2-5% **($\mathcal{R}_d$)**

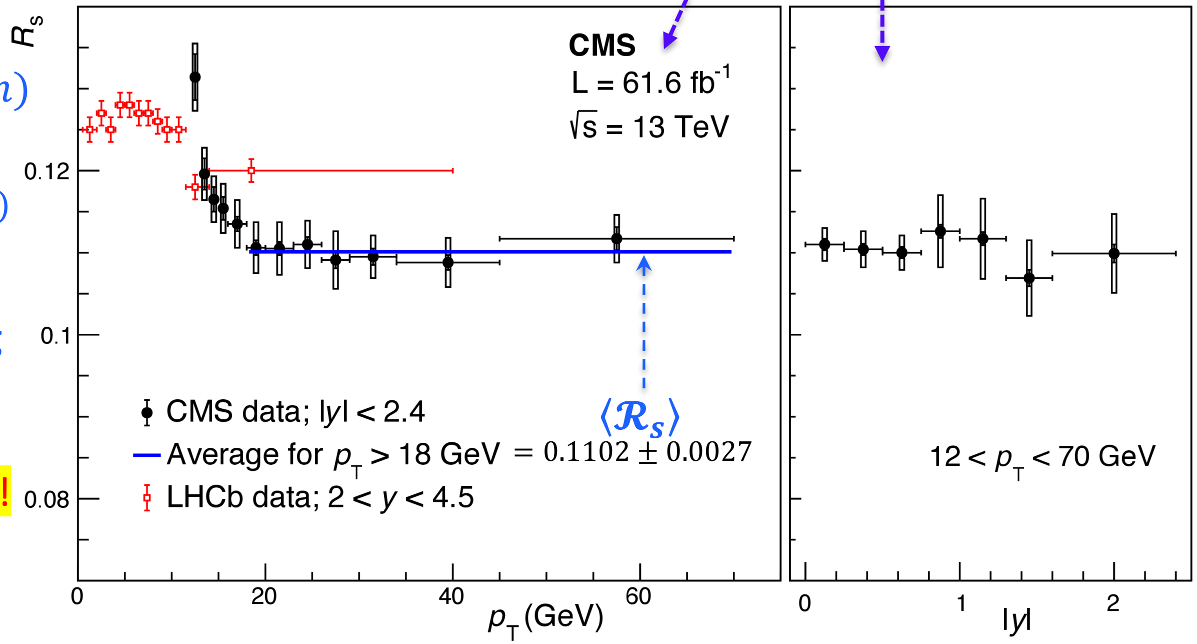
Results : $\mathcal{R}_s \propto f_s/f_u$

The **efficiency-corrected yields' ratio** $\mathcal{R}_s$ are provided as a function of (in bins of) p_T^B and $|y^B|$:

$\forall$ bin: vert. *bar* ⇔ stat. error $\approx$ **1%** ($\sim$2% *in* 1st *bin*)

vert. *box* ⇔ syst. error $\begin{cases} (\sim 2.3 - 3.2\% \text{ for } p_T^B) \\ (\sim 1.8 - 4.4\% \text{ for } |y^B|) \end{cases}$

Global systematic uncertainty ~2.3% **due to tracking** (associated to additional track in signal mode: it corresponds to single-track reco efficiency uncertainty): common to every bin & not graphically represented !



We observe: **a clear p_T^B-dependence at low p_T^B values, followed by a flat high$-p_T^B$ trend**

[blue line represents the average $\langle \mathcal{R}_s \rangle$ for $p_T^B > 18 GeV$]

For comparison the LHCb measurement **[PRL 124 (2020) 122002]** is also shown: it appears compatible with CMS data, thus reinforcing the observed p_T^B-dependence

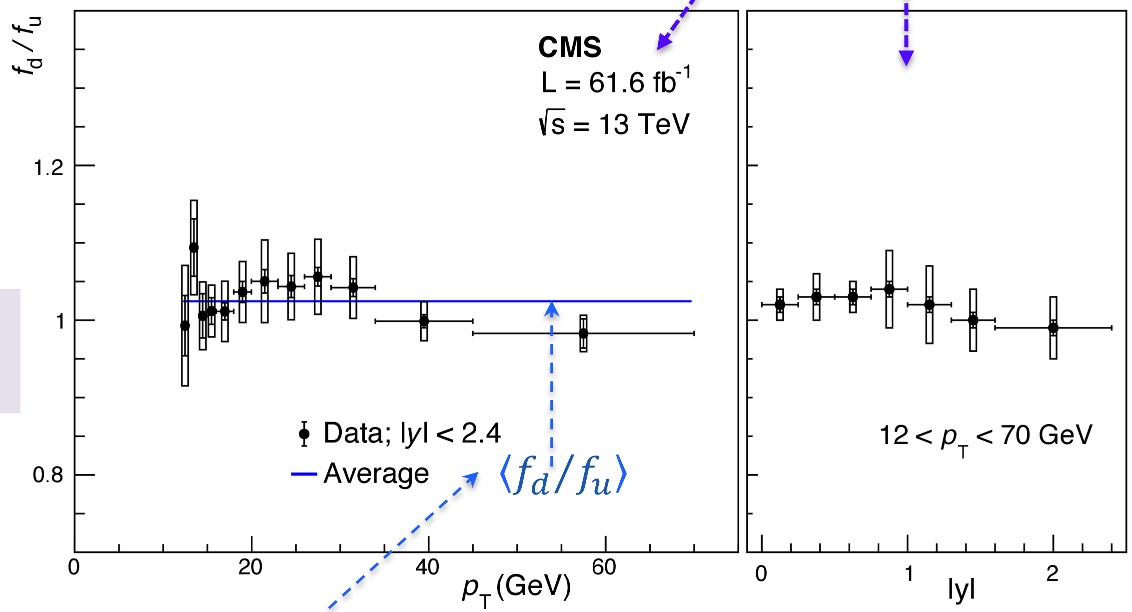
We do not observe any dependence on the B meson rapidity

Results : f_d / f_u

The **efficiency-corrected yields' ratio** $\mathcal{R}_d$ and thus f_d/f_u are provided as a function of p_T^B and $|y^B|$:

$\forall$ bin: vert. *bar* $\Leftrightarrow$ stat. error $\approx$ **1%**

vert. *box* $\Leftrightarrow$ syst. error $\begin{cases} (\sim 2.4 - 7.8\% \text{ for } p_T^B) \\ (\sim 2.3 - 4.9\% \text{ for } |y^B|) \end{cases}$



The larger $\mathcal{R}_d$ systematic uncertainties arise from the more complex background composition of the B^0 decay

Global (common to every bin) systematic uncertainty **~4.9%** not graphically represented !
It comes from the ~2.3% tracking uncertainty added in quadrature to the extra global ~4.3% uncertainty which reflects the BFs' uncertainties used to pass from $\mathcal{R}_d$ to f_d/f_u.

NO dependence on p_T^B or $|y^B|$ is observed

the average over all the p_T^B bins $= 1.015 \pm 0.051$ (stat.+full syst.) **consistent with unity**

Note: ***assuming isospin invariance***, the ratio $\frac{f_d}{f_u}$ is predicted to be: - independent of kinematic variables
- identical to 1

Conclusions

- **At LHC the Ratios of Production Fractions are probed in different rapidity regions (and c.o.m. energies) as reported by LHCb [**PRL 124 (2020) 122002; $2 < |\eta| < 6.4$**] & ATLAS [**PRL 115 (2020) 122002; $|\eta| < 2.5$] so far.

  With just this experimental info, it's not clear how the f_s/f_u (& f_s/f_d) ratios really behave. Possibilities are:

  1) Ratios are independent of p_T^B, as found by ATLAS (in 8-50GeV range, with large statistical uncertainties);
  2) Ratios continue to decrease as a function of p_T^B , as found by LHCb (in the 4-20GeV range);
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- **The CMS result shows** ($|y^B| < 2.4$, p_T^B in 12-70GeV) **that the 3rd statement is the correct one :**

  the ratio $\mathcal{R}_s \propto f_s/f_u$ decreases as p_T^B increases, up to $p_T^B \sim 18 GeV$, & then flattens out, @ higher p_T^B (with the "asymptotic value" which also agrees with the LEP value at high p_T^B).

  - This observation is only possible because of …
    - the much better statistical accuracy, compared to the ATLAS result, and …
    - the larger acceptance in p_T^B, compared to the LHCb result.

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This observation is only possible because of …
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- the larger acceptance in p_T^B, compared to the LHCb result.

The measured f_d/f_u is found to be compatible with unity and independent of p_T^B & rapidity …
… as predicted by strong isospin symmetry.
It can be considered as a "control ratio" to validate the analysis procedure.