# FRAGMENTATION FRACTIONS AND $b \rightarrow s\ell\ell$ TRANSITIONS

*Greg Landsberg - Flavour Physics*

*Qui Nhon, Vietnam, August 16, 2022*

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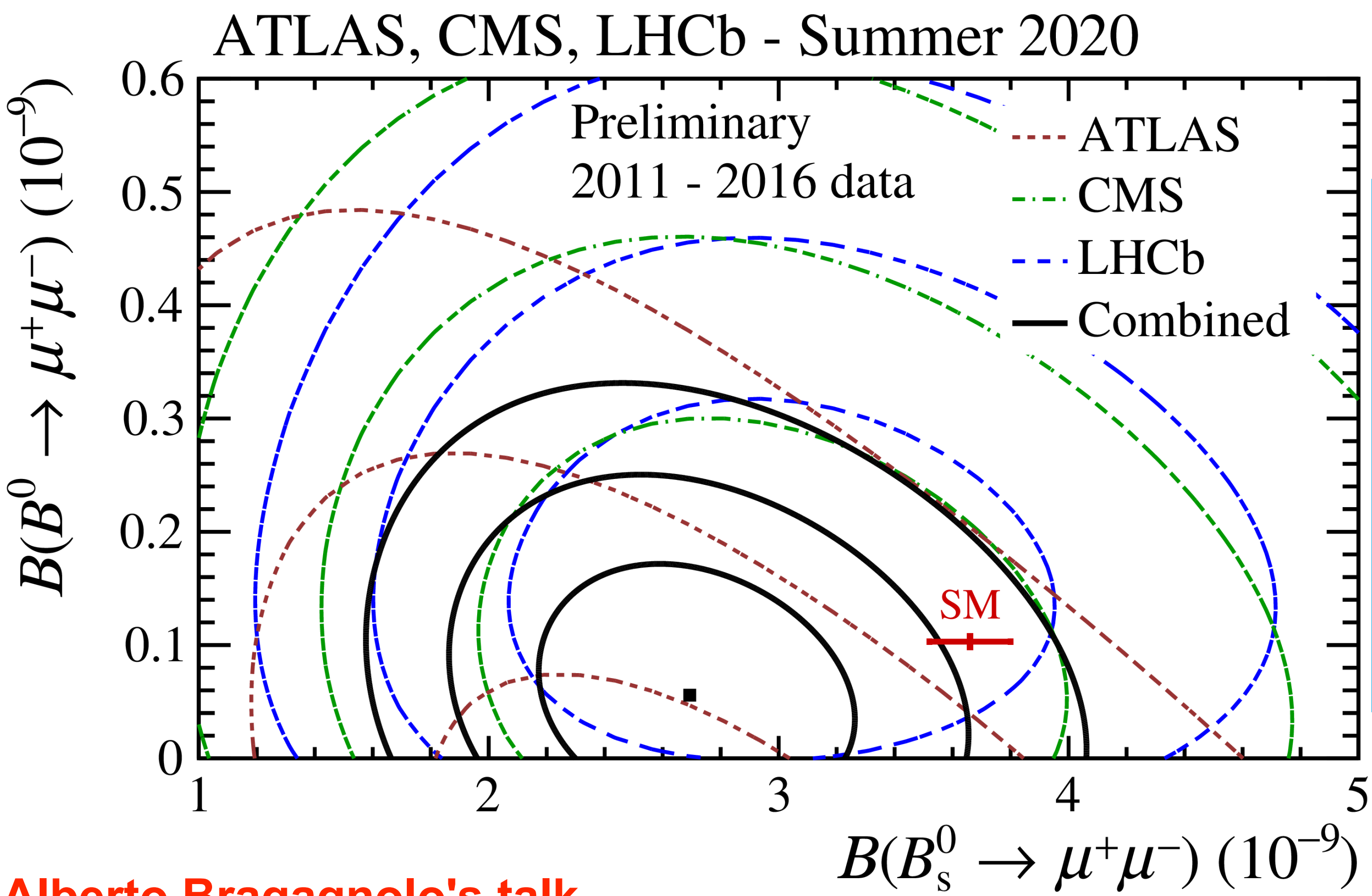
# Introduction

- In this talk I'll draw a connection between tests of flavour anomalies in b → s$\ell\ell$ transitions and the determination of fragmentation fraction ratios (FFRs), ***which are relative probabilities of b quark fragmentation into $B^0$, $B^+$, and $B_s$ mesons***
- Experimental situation with the FFR determination is somewhat messy and there are a number of fine points that are often missed or ignored
- I'll talk about these caveats and the best ways to cleaning up the situation using the existing LHC and future Belle II data
- Some of these observations are explicitly targeting the CMS B physics program, particularly the new capabilities made possible by the large set of 2018 b-parked data
- The rest goes beyond CMS and targets more general issues related to both the LHC and the B factories

# $B_s(\mu\mu)$ Status

- ATLAS, CMS, LHCb combination: ~2σ tension w.r.t. the SM prediction - similar to other $b \to s\mu\mu$ decays
- New LHCb result based on full 9/fb data set reduces the tension to ~1σ
- Very recent CMS result based on 140/fb Run 2 data erased the discrepancy completely




CMS PAS BPH-20-003

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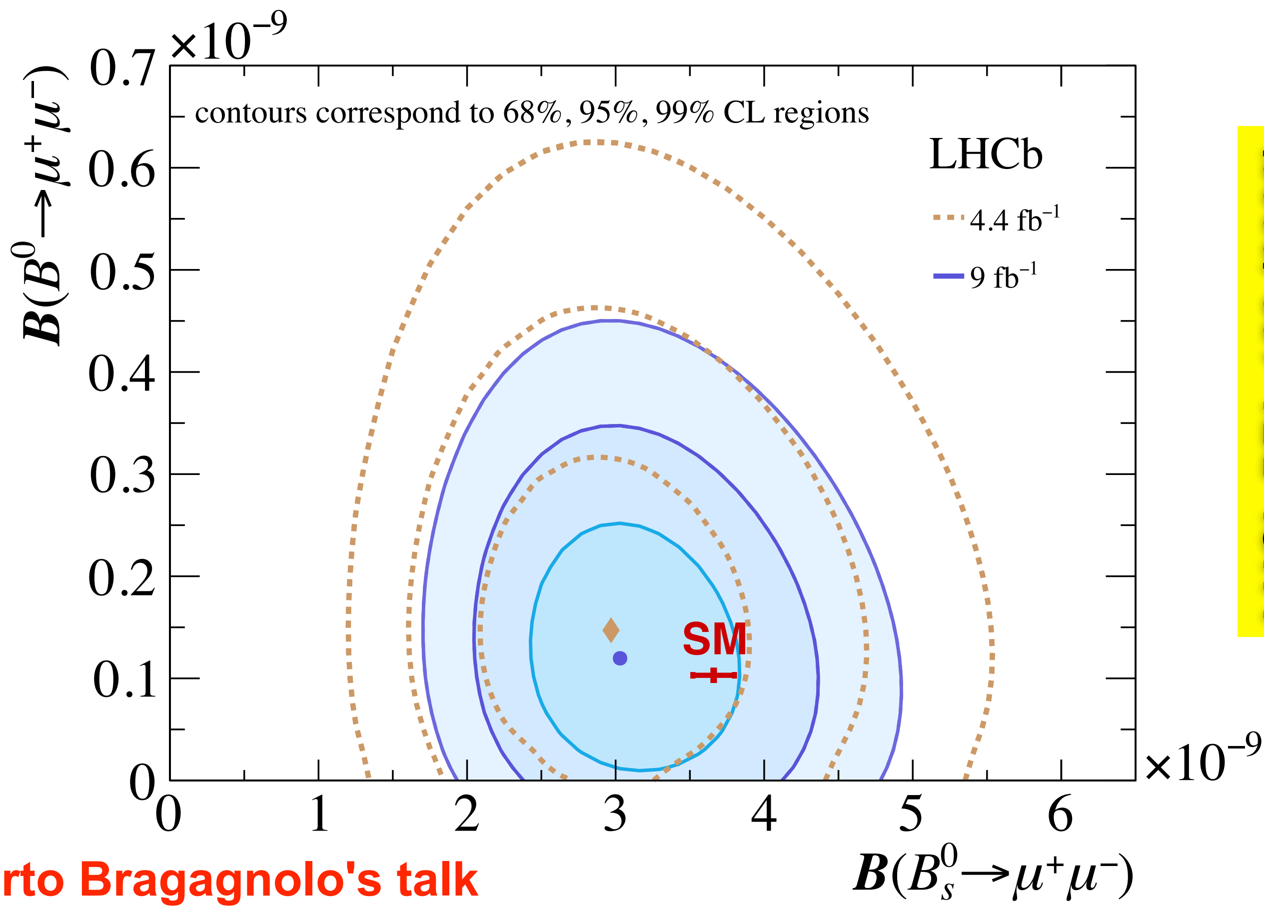


LHCb PRL 128 (2022)

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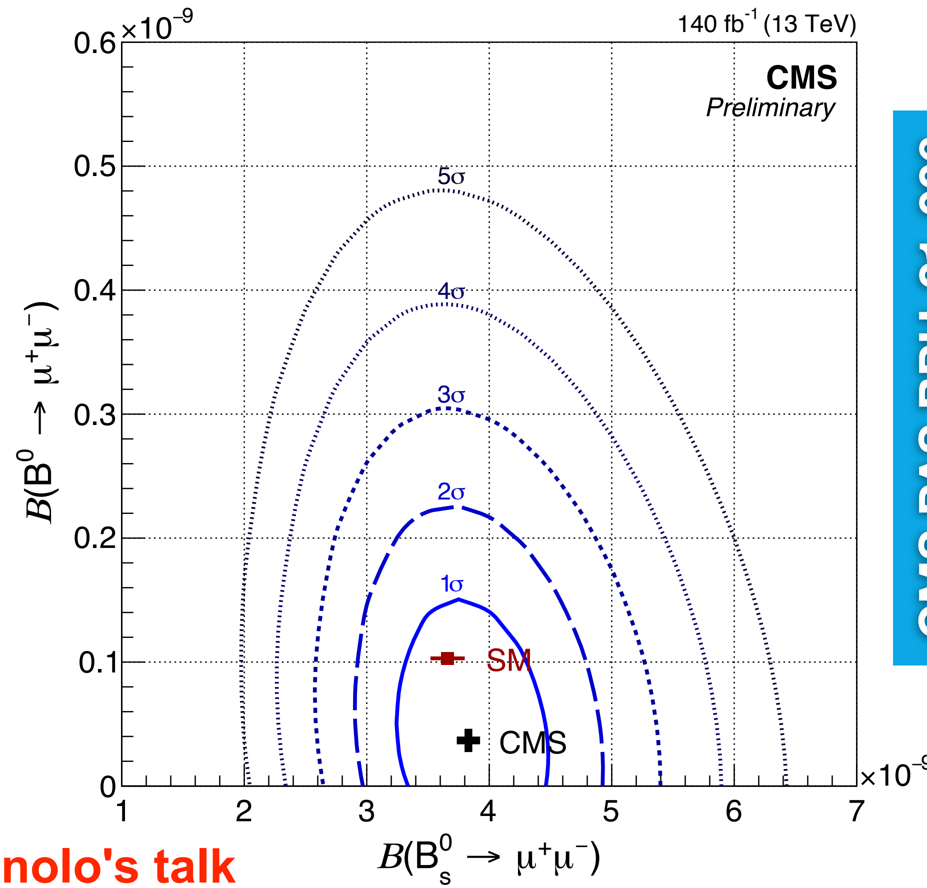


CMS PAS BPH-21-006

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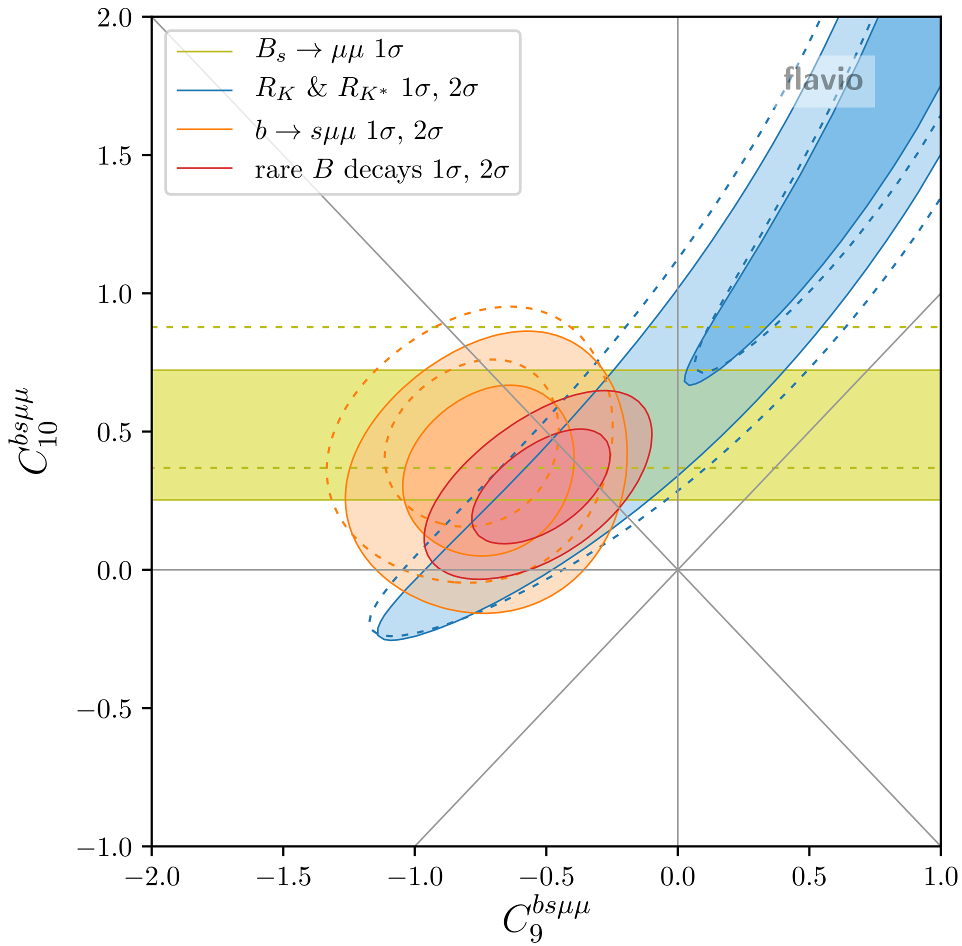
# $B_s(\mu\mu)$ and Flavour Anomalies

- Connection to flavor anomalies: it's unlikely that the $b \to sll$ anomalies can be explained by the $O_{10}$ operator




Altmannshofer, Stangl, EPJC 81 (2021) 952

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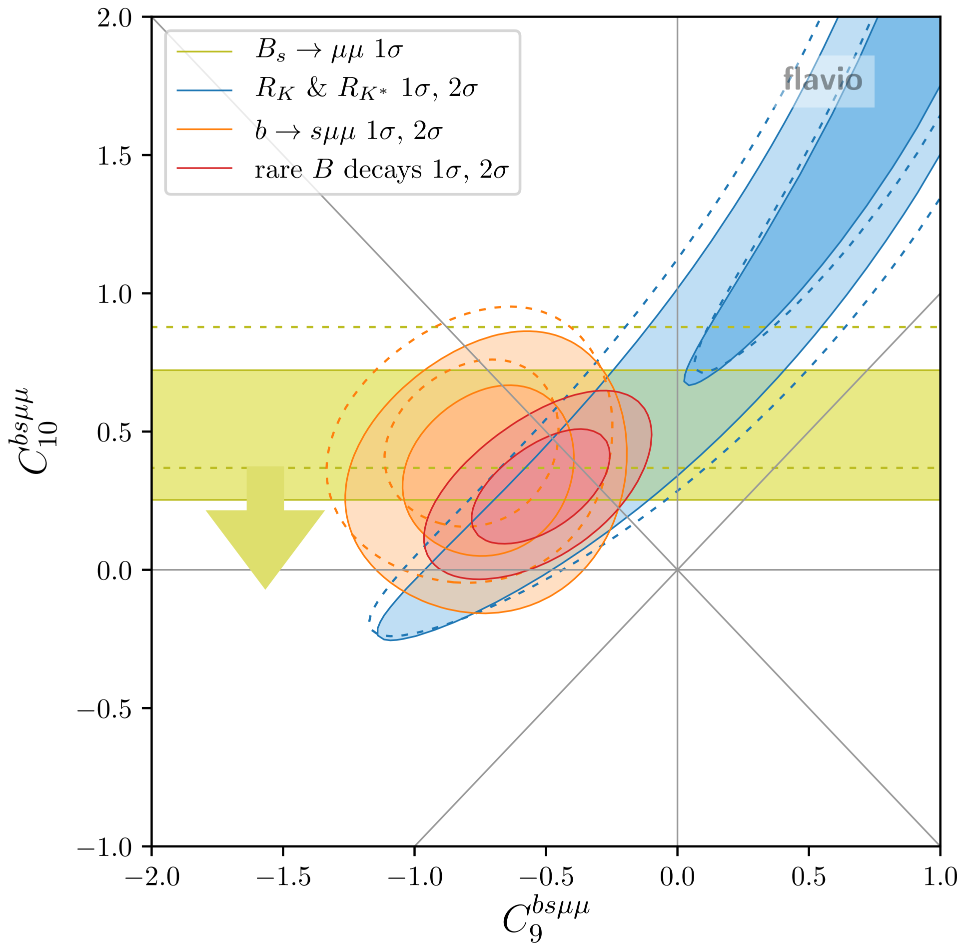
- ✦ Connection to flavor anomalies: it's unlikely that the $b \to sll$ anomalies can be explained by the $O_{10}$ operator

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# On the Normalization

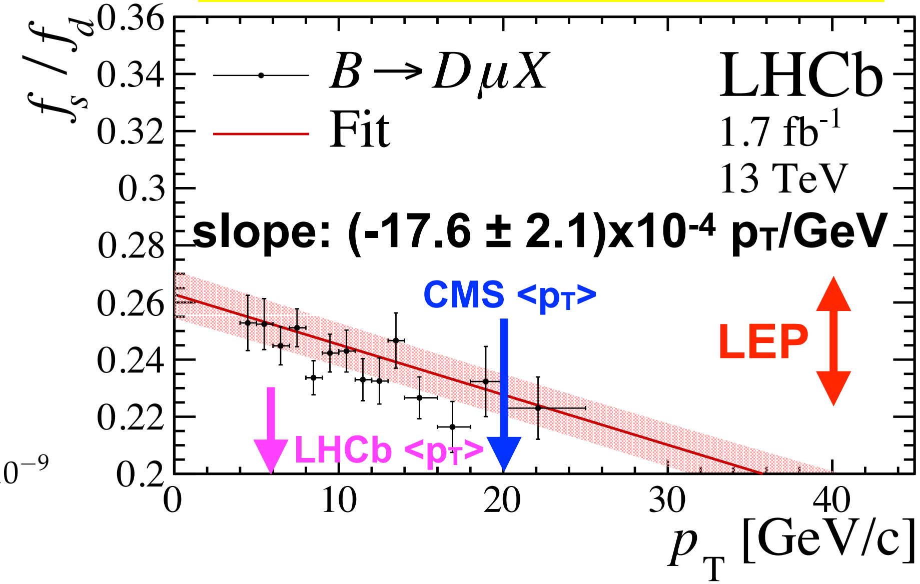
- At the moment, all three LHC collaborations use $B^+ \to J/\psi K^+$ as the normalization channel [LHCb also uses $B^0 \to K^+\pi^-$, assuming $f_u = f_d$, but the uncertainty is dominated by the former]
  - This brings the $f_s/f_u$ fragmentation function ratio (FFR) as the necessary input to the branching fraction measurement
  - The current LHCb best value is 0.254 ± 0.008 [assuming $f_u = f_d$]
  - In the CMS case, we correct this value for the $p_T$ variation [the latter is reported at ~8σ by the LHCb at 13 TeV, but not seen by ATLAS or internally in CMS]:
    - $f_s/f_u = 0.231 \pm 0.008$ (3σ lower)
  - This 3.5% uncertainty is the dominant systematic uncertainty in the overall result:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9}$$

so it's important to reduce it!

- N.B. 0.008 is aggressive if the linear $p_T$ dependence is not confirmed!

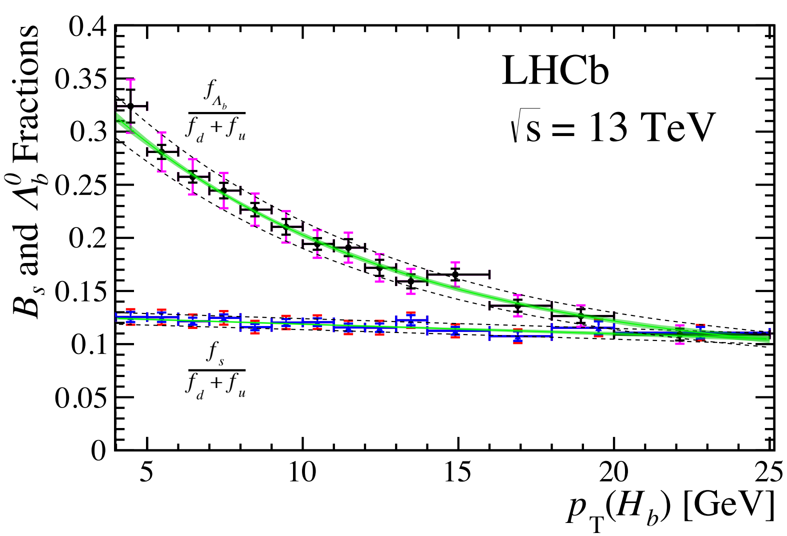
**LHCb PRD 104 (2021) 032005**



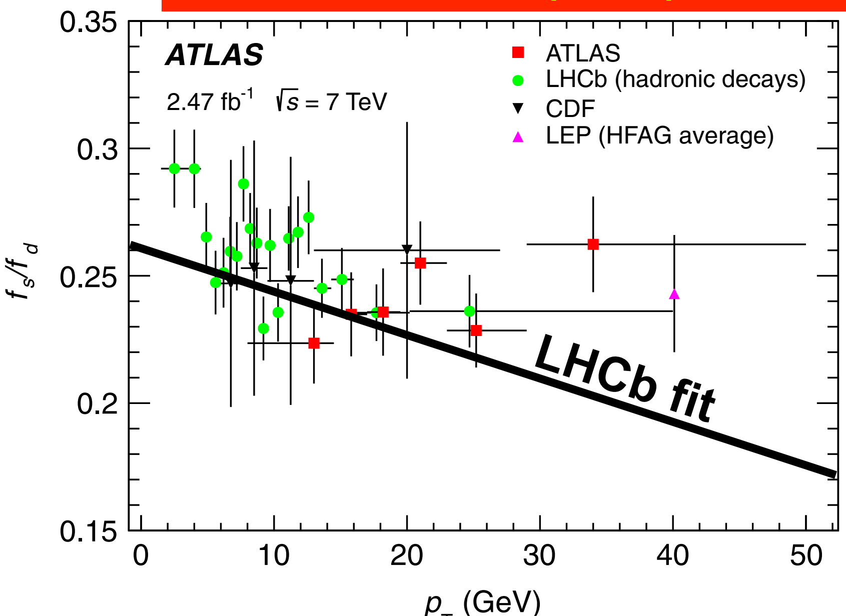
# The $p_T$ Dependence?

- The jury is still out whether the linear slope suggested by LHCb holds
- There is undoubtedly a strong $p_T$ dependence for the $\Lambda_b$ fragmentation fraction, but:
  - Different production mechanism from meson production
  - Possible proton remnant effects
  - Significant feed-down from heavier beauty baryons
- CDF and ATLAS see no strong $p_T$ dependence for $f_s/f_d$ and agree with the asymptotic LEP value

**LHCb PRD 100 (2019) 031102**




**ATLAS PRL 115 (2015) 262001**



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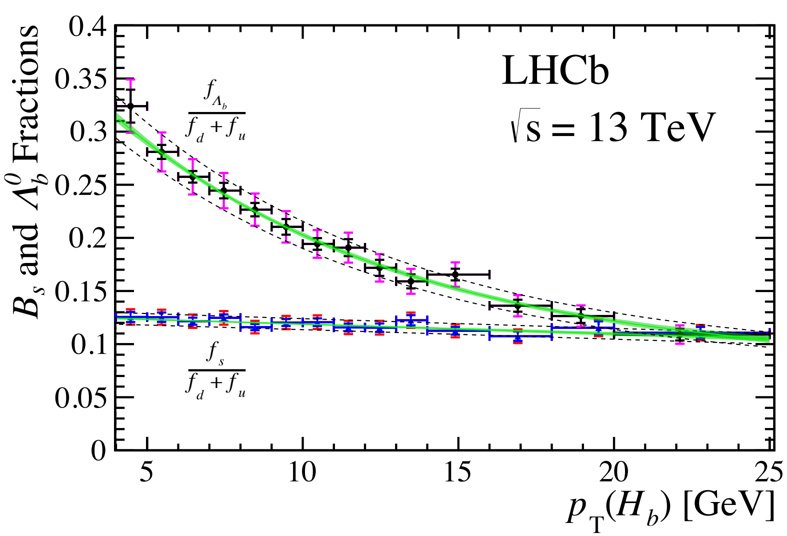


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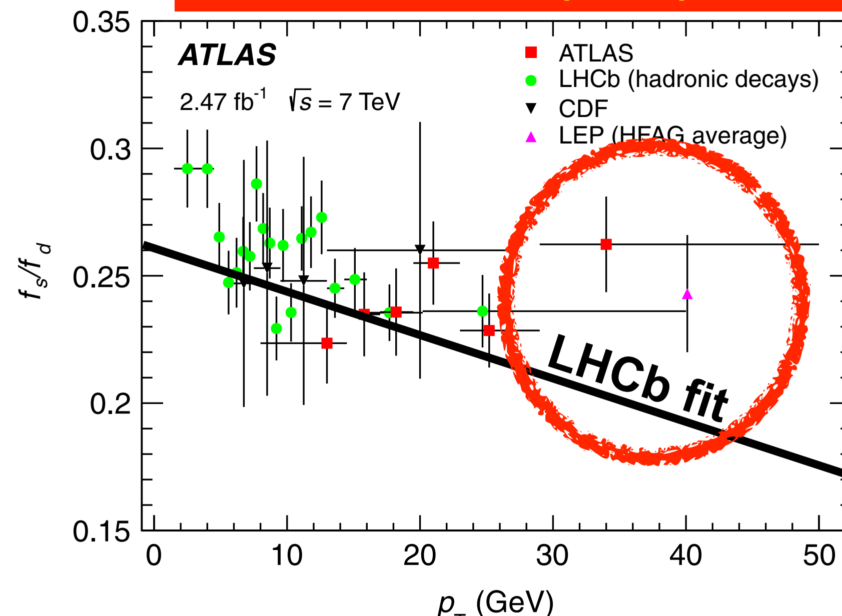


# World Average $f_s/f_d$

- Given the tension between different measurements of FFR and the claimed $p_T$ dependence by LHCb, world average FFRs are no longer being updated:
  - From HFLAV arXiv:2206.07501

With the ever increasing precision in heavy flavour measurements, the $b$-hadron fraction averages provided by HFLAV for high-energy hadron collisions are no longer of interest, since they are not directly transferable from one experiment to the other. We have therefore decided to no longer maintain these averages. The interested reader should refer to Sec. 4.1.3 of our previous publication [1].

[1] HFLAV collaboration, Y. S. Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018*, Eur. Phys. J. **C81** (2021) 226, arXiv:1909.12524.

- PDG still provides the world average values:

**Table 75.1:** $\overline{\chi}$ and $b$-hadron fractions (see text).

| | $Z$ decays [96] | Tevatron [96] | LHC ($\sqrt{s}$) [97, 98] |
|---|---|---|---|
| $\overline{\chi}$ | $0.1259 \pm 0.0042$ | $0.147 \pm 0.011$ | |
| $f_u = f_d$ | $0.408 \pm 0.007$ | $0.344 \pm 0.021$ | |
| $f_s$ | $0.100 \pm 0.008$ | $0.115 \pm 0.013$ | |
| $f_{\rm baryon}$ | $0.084 \pm 0.011$ | $0.198 \pm 0.046$ | |
| $f_s/f_d$ | $0.246 \pm 0.023$ | $0.333 \pm 0.040$ | $0.239 \pm 0.007$ (7 TeV) |
| | | | $0.239 \pm 0.008$ (8 TeV) |
| | | | $0.254 \pm 0.008$ (13 TeV) |

Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

# Normalization (cont'd)

- Alternative would be to use the $B_s \to J/\psi\phi$ decay for the $B_s \to \mu\mu$ normalization, which should eliminate the need for the $f_s/f_u$ ratio
- Currently, the world average [PDG] is based on three results:
  - CDF, 1.96 TeV: $B(B_s \to J/\psi\phi) = (1.5 \pm 0.5 \pm 0.1)\times10^{-3}$
  - Belle, $\Upsilon(5S) \to B_sB_s$, $B(B_s \to J/\psi\phi) = (1.25 \pm 0.24)\times10^{-3}$
  - LHCb, 7,8,13 TeV: $B(B_s \to J/\psi\phi) = (1.037 \pm 0.032 \pm 0.022)\times10^{-3}$
    - However, the dominant LHCb result uses $B^+$ and $B^0$ decays as the normalization channel, so this measurement is ~100% correlated with their $f_s/f_u$ or $f_s/f_d$ measurement - not an independent normalization channel!
- Can we use some other $B_s$ decay mode to normalize?
  - Not really as none of them have been measured to a precision better than 10%, and most are affected by the same normalization channel issue
- Really need Belle II $\Upsilon(5S)$ measurements to make a breakthrough in precision
  - Why don't you guys run on the $\Upsilon(5S)$ first??? 😃

# FFR Measurements - I

- Three main methods are used at the LHC
  - Semileptonic decays with charm ($B_{(s)} \rightarrow D_{(s)}X\mu\nu$)
    - Based on a theoretical calculation in the HQ expansion scheme predicting semileptonic widths for all species to be ≈equal, within a ~1% precision [Bigi et al, arXiv:1105.4574]
    - The experimental precision (~4%) is dominated by the systematic uncertainty, which mainly comes from excited charm states modeling, lifetime measurements, and cross-feeds from all-hadronic decays
      - No theoretical uncertainty is considered, while theoretical calculations may not be that clean
    - Experimental difficulties include the contamination from D*, D**, etc. decays, which are poorly known

# FFR Measurements - II

- Hadronic decays with charm ($B_{(s)} \to D_{(s)}K$; $D_{(s)}\pi$)
  - Claimed to be the most clean theoretically
  - Calculations are done in the factorization scheme [Fleischer et al., arXiv:1004.3982]
  - Dominant systematic uncertainty is in determination of the form-factor $B_{(s)} \to D_{(s)}$ ratio, $N_F$ (discussed later)
  - Experimental advantage: fully reconstructible decays largely remove contamination from excited states
- Hadronic decays with charmonium ($B_{(s)} \to J/\psi K^*(\phi)$)
  - The ATLAS method is based on a single available theoretical calculation of the ratio:

$$\frac{\mathcal{B}(B_s^0 \to J/\psi\phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})} = 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c),$$

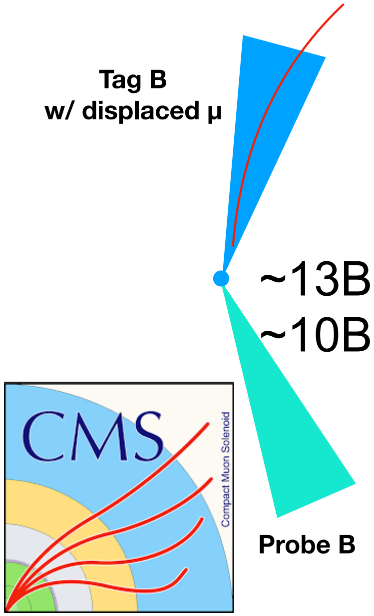
FF shape par. Decay const. Charm mass

  - Unfortunately, this prediction [Liu et al., arXiv:1309.0313] is based on pQCD predictions, which are notoriously unreliable
  - Thus, the claimed precision $f_s/f_d = 0.240 \pm 0.004$ (stat) $\pm 0.010$ (syst) $\pm 0.017$ (th), which is completely dominated by the theoretical uncertainty, is likely to be overstated
  - This channel, while very clean experimentally, is only useful for shape measurements (e.g., $p_T$ dependence), but not for the absolute $f_s/f_d$ determination

BROWN

# B Meson Spectrometer

As the luminosity drops, turn on various single-muon |η|-restricted seeds, which allow to keep L1 rate constant and increase HLT rate toward the end of each fill

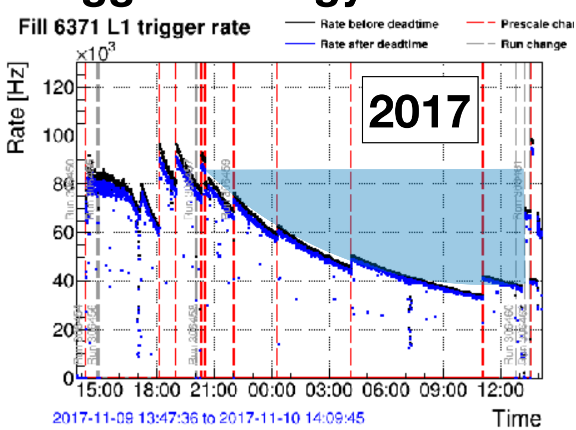



~13B events =
~10B b hadrons

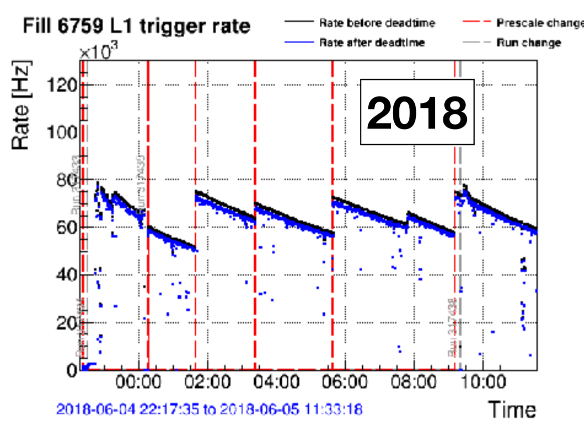
| Lumi (E34) | L1 seed | HLT | rate | purity |
|---|---|---|---|---|
| 1.7 | Mu12er1p5 | Mu12_IP6 | 1585 | 0.92 |
| 1.5 | Mu10er1p5 | Mu9_IP5 | 3656 | 0.80 |
| 1.3 | Mu8er1p5 | Mu9_IP5 | 3350 | 0.80 |
| 1.1 | Mu8er1p5 | Mu7_IP4 | 6153 | 0.59 |
| 0.9 | Mu7er1p5 | Mu7_IP4 | 5524 | 0.59 |

**~50/fb of data recorded**

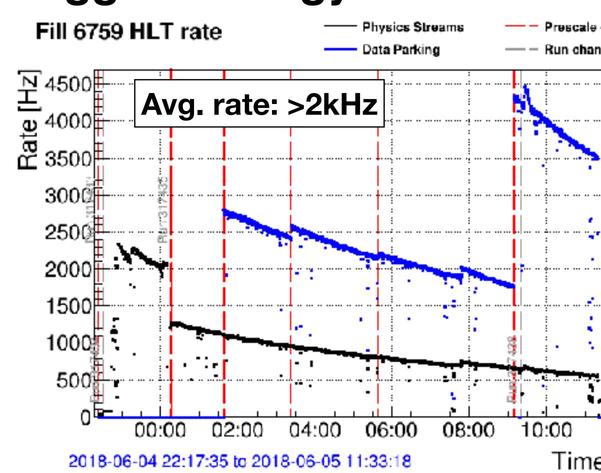
## Trigger strategy — L1




**<PU> = 20**




## Trigger strategy — HLT



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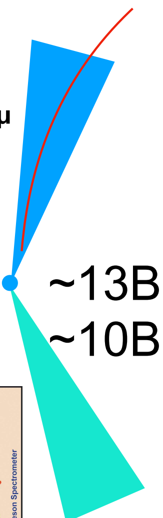
**Tag B w/ displaced μ**



~13B events = ~10B b hadrons

BMS

**Probe B**

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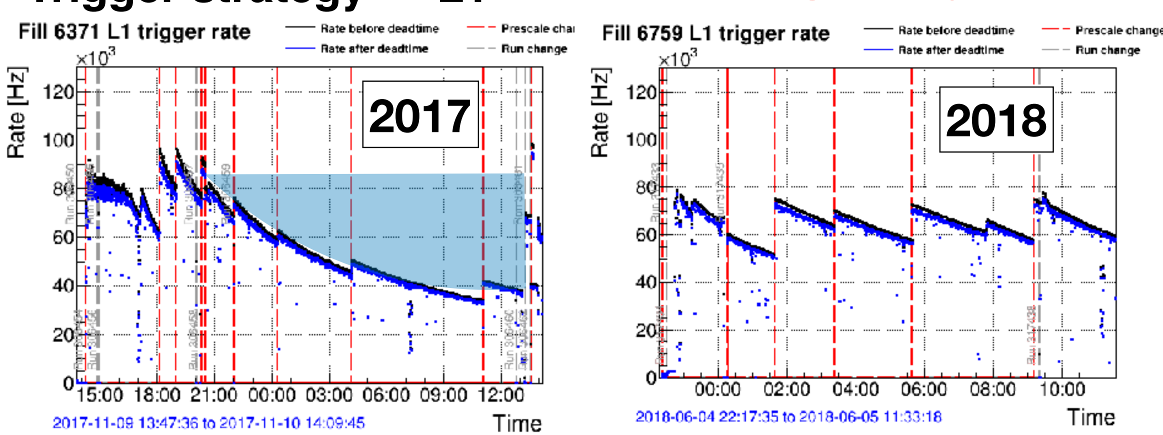
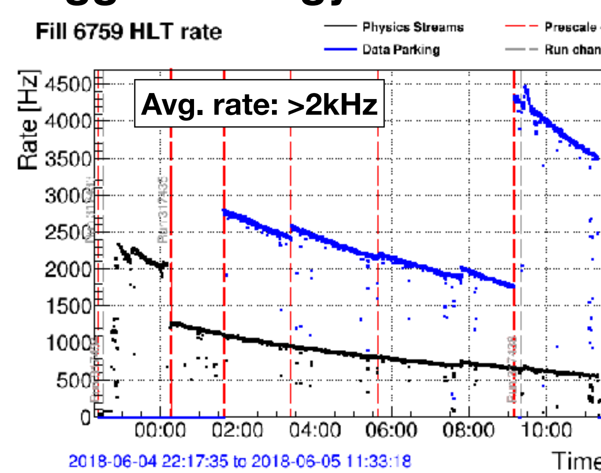



## Trigger strategy — HLT



# FFR in CMS

- Several analyses are ongoing, with the results expected this year:
  - FFR with charmonium $B_s \to J/\psi\phi$, $B^0 \to J/\psi K^*$ (non-parked data; shape measurement - testing claimed $p_T$ dependence)
  - FFR with fully hadronic charm decays $B_s \to D_s^-\pi^+/K^+$, $B^0 \to D^-K^+$ via $D^-\pi^+$ (parked data - never thought it would be possible - Charm Meson Spectrometer!)
  - FFR with charmonium $B_s \to J/\psi\phi$, $B^0 \to J/\psi K^*$ (parked data)
- However, one has to use theoretical input to calculate the FFR in hadronic charm decays (the present measurement of $B(B_s \to D_s^-\pi^+)$ is dominated by LHCb and uses $f_s/f_d$ as an input): $B(B_s \to D_s^-\pi^+) = (3.20 \pm 0.10 \pm 0.16)\times10^{-3}$
- Belle measurement has a 20% uncertainty: $B(B_s \to D_s^-\pi^+) = (3.6 \pm 0.5 \pm 0.5)\times10^{-3}$ - need Υ(5S) data!

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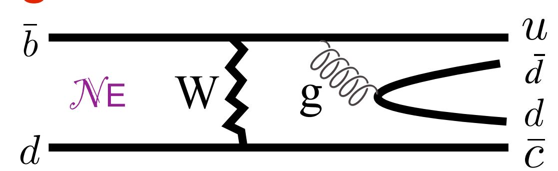
# Theoretical Calculations



- The LHCb extraction is based on the QCD factorization framework [Fleischer, Serra, Tuning PRD **83** (2011) 014017]:
  - Cabibbo-suppressed $D^-K^+$ channel is cleaner than the $D^-\pi^+$ channel, due to the lack of an extra non-factorizable diagram




$$\frac{f_s}{f_d} = \frac{\mathcal{B}(B^0 \to D^- K^+)}{\mathcal{B}(B_s^0 \to D_s^- \pi^+)} \frac{\epsilon_{DK}}{\epsilon_{D_s\pi}} \frac{N_{D_s\pi}}{N_{DK}}$$

$$= \Phi_{\rm PS} \left| \frac{V_{us}}{V_{ud}} \right|^2 \left( \frac{f_K}{f_\pi} \right)^2 \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{1}{\mathcal{N}_a \mathcal{N}_F} \frac{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^- \to K^+K^-\pi^-)} \frac{\epsilon_{DK}}{\epsilon_{D_s\pi}} \frac{N_{D_s\pi}}{N_{DK}}$$

| Input | Value | Reference |
|---|---|---|
| $\mathcal{B}(\overline{D}^0 \to K^+\pi^-)$ | $(3.999 \pm 0.045)\%$ | [6] |
| $\mathcal{B}(D^- \to K^+\pi^-\pi^-)$ | $(9.38 \pm 0.16)\%$ | [7] |
| $\mathcal{B}(D_s^- \to K^-K^+\pi^-)$ | $(5.47 \pm 0.10)\%$ | [6, 39] |
| $\tau_{B_s^0}/\tau_{B^0}$ | $1.006 \pm 0.004$ | [6] |
| $(\tau_{B^+} + \tau_{B^0})/2\tau_{B_s^0}$ | $1.032 \pm 0.005$ | [6] |
| $(1 - \xi_s)$ | $1.010 \pm 0.005$ | [34] |
| $\mathcal{N}_a$ Non-fact. corr. | $1.000 \pm 0.020$ | [36] |
| $\mathcal{N}_F$ Form factors | $1.000 \pm 0.042$ | [19, 40] |
| $\mathcal{N}_E$ For Dπ decay | $0.966 \pm 0.062$ | [7, 36] |
| $\|V_{us}\|f_K/\|V_{ud}\|f_\pi$ | $0.2767$ | [9] |

← Bordone et al., EPJC **80** (2020) 347 and 951

On the other hand, what was a tendency to overestimate the individual branching fractions in the past, is now a clear discrepancy: naively we observe a $4\sigma$ difference between prediction and measurement in $\bar{B}_s^0 \to D_s^+\pi^-$, over $5\sigma$ difference in $\bar{B}^0 \to D^+K^-$, about $2\sigma$ in $\bar{B}_s^0 \to D_s^{*+}\pi^-$ and $3\sigma$ in $\bar{B}^0 \to D^{*+}K^-$. A fit to the same data as above, but

# Non-Cabibbo-Suppressed Channel



- In CMS, due to the lack of particle ID, using the Cabibbo-suppressed channel is difficult
  - Use non-Cabibbo-suppressed $B^0 \to D^-\pi^+$ instead and normalize to the theoretically clean channel via the ratio of the branching fractions: $B(B^0 \to D^-K^+)/B(B^0 \to D^-\pi^+)$
  - This ratio is known to a rather fine 3.3% precision [PDG]: $(8.22 \pm 0.11 \pm 0.25)\%$
  - This is twice better than the precision on the non-factorizable diagram contribution $N_E = 0.966 \pm 0.062$
- Using parked data we can also measure $B(B_s \to J/\psi\phi)/B(B_s \to D_s\pi)$ (benefiting from the same trigger!) and normalize the charmonium channel to the same (clean!) theoretical hadronic charm value!

# "Two B or not Two B - that's the ?"

- In all of the FFR measurements it is assumed that there is an isospin symmetry: $f_u = f_d$
- In fact, this assumption is implicitly or explicitly used in most of the $B^+$ and $B^0$ branching fraction measurements at the B factories!
  - The isospin symmetry enters the branching fractions through the assumption: $R^{\pm 0} \equiv \dfrac{\mathscr{B}(\Upsilon(4S) \to B^+B^-)}{\mathscr{B}(\Upsilon(4S) \to B^0\overline{B}^0)} = 1$
- Is this really a good assumption?
  - Actually, not quite, as the isospin violation at Y(4S) from the final-state Coulomb interactions near threshold could be as large as ~20%, which would imply significant corrections to the measured $B^+/B^0$ branching fractions

# The $R^{\pm 0}$ Review

- Atwood, Marciano: PRD **41** (1990) 1736: $R^{\pm 0} \approx 1.18$
- Lepage: PRD **42** (1990) 3251: $R^{\pm 0} \approx 1.14$
- Byers, Eichten: PRD **42** (1990) 3885: $R^{\pm 0} \approx 1.18$
- Kaiser, Manohar, Mehen: PRL **90** (2003) 142001: $R^{\pm 0} \approx 1.09$-$1.25$
- Voloshin: Phys. Atom. Nucl. **68** (2005) 771: connection to the $\psi(3770) \to DD$ and $\phi \to KK$ decays; large variation of $R^{\pm 0}$ across the resonance
- Experimentally, however, the ratio appears to be significantly smaller:
  - HFLAV arXiv:2206.07501 (CLEO, Belle, BaBar): $R^{\pm 0} = 1.059 \pm 0.027$ ($2.2\sigma$ from unity)
- BaBar [PRL **95** (2005) 042001] used a clever technique of a double-tag vs. single tag to measure inclusive $B^+$ and $B^0$ semileptonic branching fractions without any isospin assumptions, resulting in $R^{\pm 0} = 1.048 \pm 0.042 \pm 0.044$
- Work in progress: Bernlocher, Jung, GL, Ligeti:
  - Difficult problem, as one has to disentangle isospin violation in production and decay
  - Pursuing a novel idea on how to do it properly with the existing and future data
  - Proposal for an experimental program for Belle II and the LHC experiments to resolve the $R^{\pm 0}$ puzzle to ~1% precision [paper in preparation]

# Conclusions

- Proper measurement of the fragmentation fraction ratios $f_s/f_d$ and $f_s/f_u$ is an important input to the precision determination of the $B_s \to \mu\mu$ branching fraction
- This, in turn, has an impact on the interpretation of flavor anomalies seen in the $b \to sl^+l^-$ transitions
- Proper determination of FFRs would require more theoretical and experimental work
- In particular, future Belle II Υ(5S) data will be invaluable for more precise FFR measurements
- In the meantime, it's important to understand the claimed $p_T$ dependence of the $f_s/f_d$ using host of LHC data
- Serious experimental program is required to avoid an ad hoc $f_u = f_d$ assumption, which may change the entire PDG table of $B^0$ and $B^+$ branching fractions (dominated by B factories)

# Thank You!