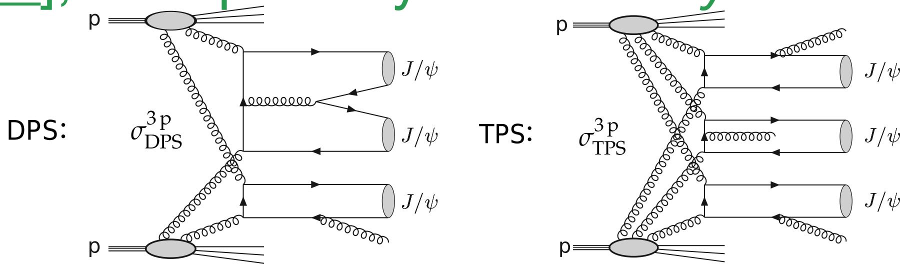
RECENT RESULTS AND PROSPECTS IN FLAVOUR PHYSICS AT CMS

Greg Landsberg - 8th Workshop on Theory, Phenomenology and Experiments in Flavour Physics

Anacapri, Italy, June 11, 2022

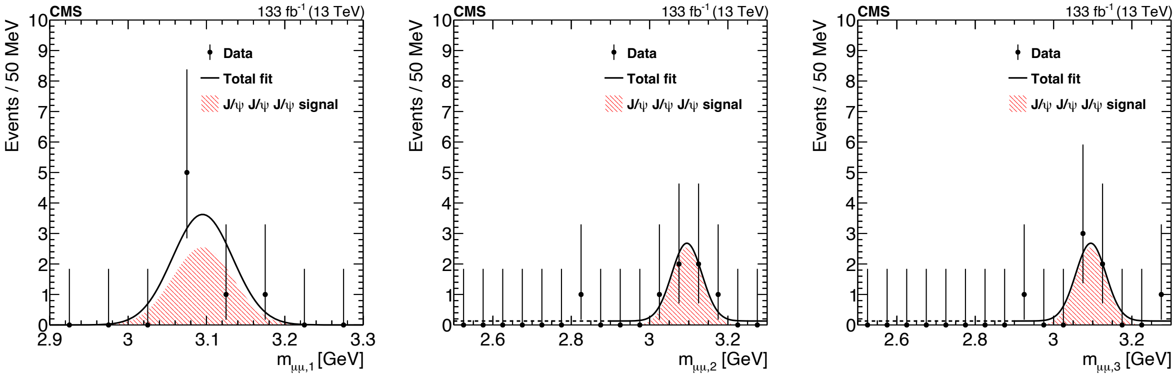
Observation of Triple J/ψ Production

- Recent result [arXiv:2111.05370], accepted by *Nature Phys.*
- Dominated by DPS (~80%) and TPS (~20%); SPS contribution is small
  - First time TPS is directly accessed experimentally



- Observed 6 events in the J/ψ(μμ) mode, with the background of $1.0^{+1.4}_{-0.8}$ events
  - Shape analysis results is a 6.8σ observation
  - Measured cross section:

$$\sigma_{\mathrm{fid}}(pp \to J/\psi J/\psi J/\psi + X) = 272^{+141}_{-104}\ (\mathrm{stat}) \ \pm 17\ (\mathrm{syst})\ \mathrm{fb}$$



Fiducial phase space:

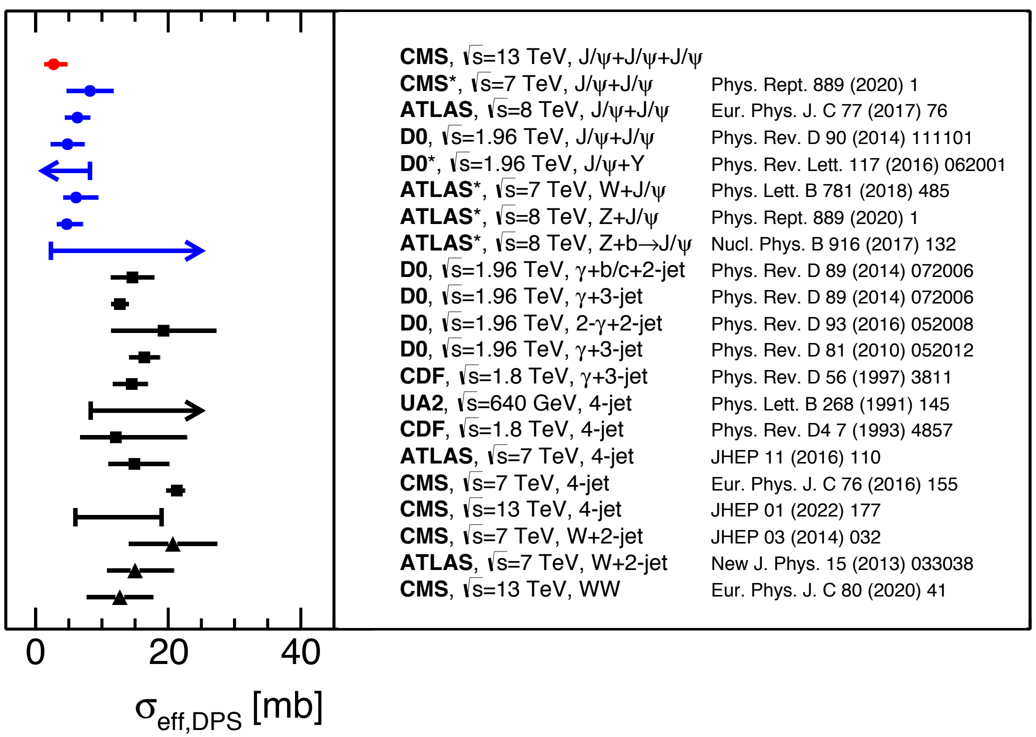
For all muons	$p_T > 3.5$ GeV for $\lvert\eta\rvert < 1.2$ $p_T > 2.5$ GeV for $1.2 < \lvert\eta\rvert < 2.4$
For all J/ψ mesons	$p_T > 6$ GeV and $\lvert y\rvert < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3$ GeV

Effective DPS Cross Section

- Definition of effective nPS cross section is given by:

$$\sigma_{\rm DPS}^{pp\to\psi_1\,\psi_2+X} = \binom{\mathfrak{m}}{2}\frac{\sigma_{\rm SPS}^{pp\to\psi_1+X}\,\sigma_{\rm SPS}^{pp\to\psi_2+X}}{\sigma_{\rm eff,DPS}} \qquad \sigma_{\rm TPS}^{pp\to\psi_1\,\psi_2\,\psi_3+X} = \binom{\mathfrak{m}}{3!}\frac{\sigma_{\rm SPS}^{pp\to\psi_1+X}\,\sigma_{\rm SPS}^{pp\to\psi_2+X}\,\sigma_{\rm SPS}^{pp\to\psi_3+X}}{\sigma_{\rm eff,TPS}^2},$$

- Using fiducial cross section and $\sigma_{\rm eff,TPS} = (0.82 \pm 0.11)\,\sigma_{\rm eff,DPS}$ as calculated in [arXiv:1612.05582] yields $\sigma_{\rm eff,DPS} = 2.7^{+1.4}_{-1.0}\,(\rm exp)^{+1.5}_{-1.0}\,(\rm theo)\,mb$, in line with double-quarkonium measurements



Observation of Rare $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_S$ decays

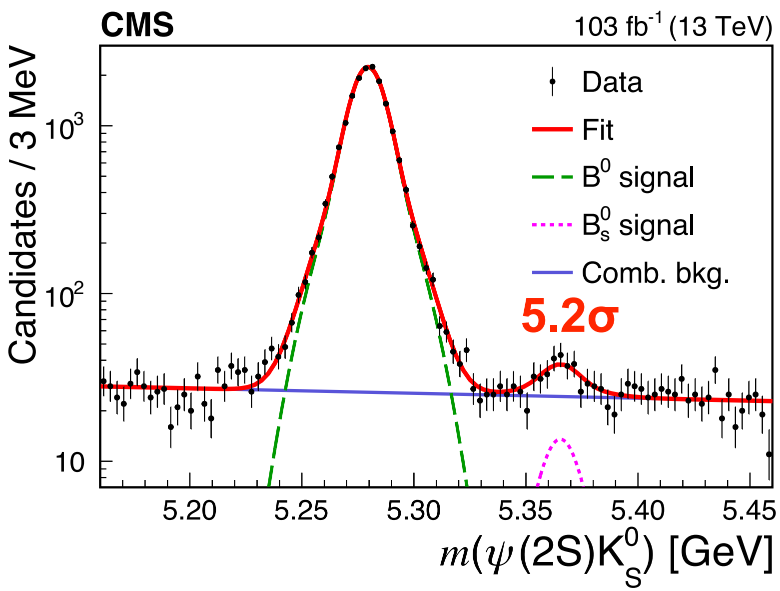
- New CMS analysis based on 2017-2018 data, using the $K^0_S \to \pi^+\pi^-$ decay mode with a large displacement of the $\pi^+\pi^-$ vertex, inspired by searches for exotic states in B meson decays [arXiv:2201.09131, EPJC **82** (2022) 499]

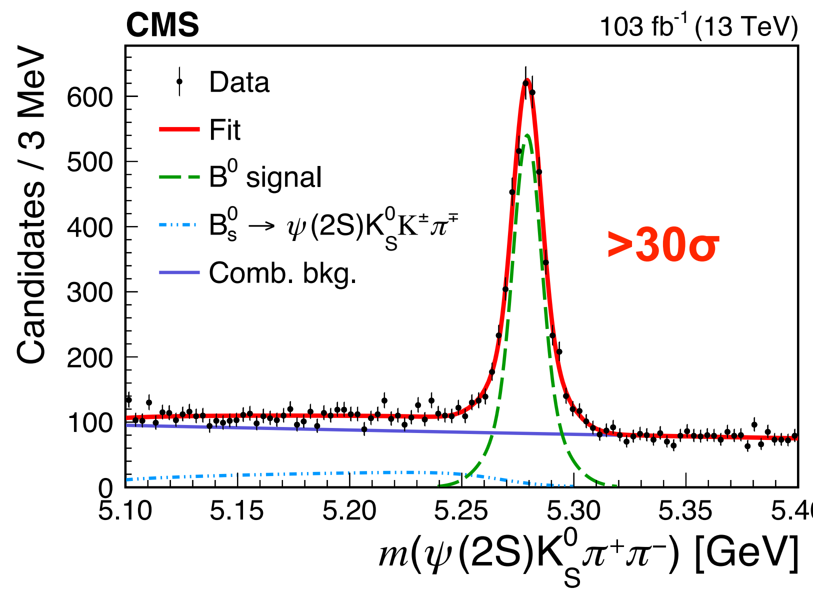
$$R_s = \frac{\mathcal{B}(B^0_s \to \psi(2S)K^0_S)}{\mathcal{B}(B^0 \to \psi(2S)K^0_S)} = (3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2}$$

$$R_{\pi^+\pi^-} = \frac{\mathcal{B}(B^0 \to \psi(2S)K^0_S\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K^0_S)} = 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst})$$

$$\mathcal{B}(B^0_s \to \psi(2S)K^0_S) = (0.97 \pm 0.20\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.22\,(f_s/f_d) \pm 0.08\,(\mathcal{B})) \times 10^{-5},$$
$$\mathcal{B}(B^0 \to \psi(2S)K^0_S\pi^+\pi^-) = (13.9 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst}) \pm 1.2\,(\mathcal{B})) \times 10^{-5},$$

- No peaking structures in the 2- and 3-body $\psi(2S)h_1(h_2)$ spectra observed





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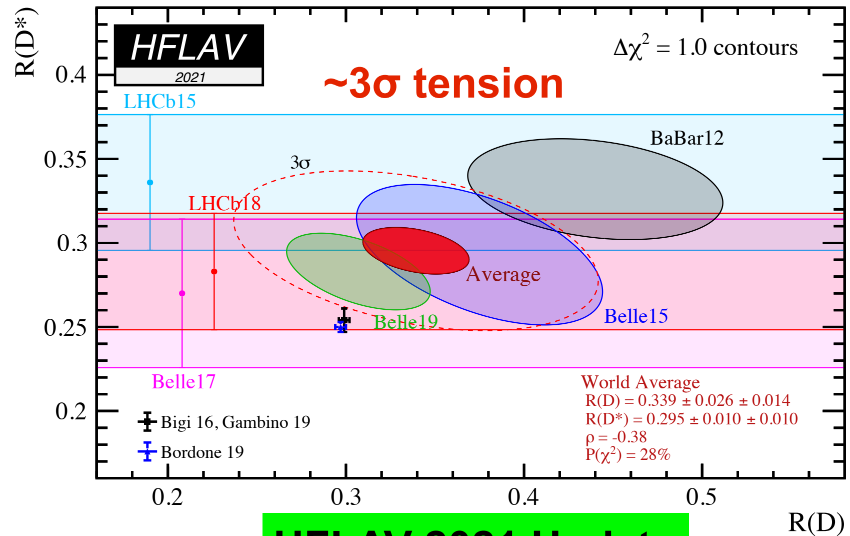
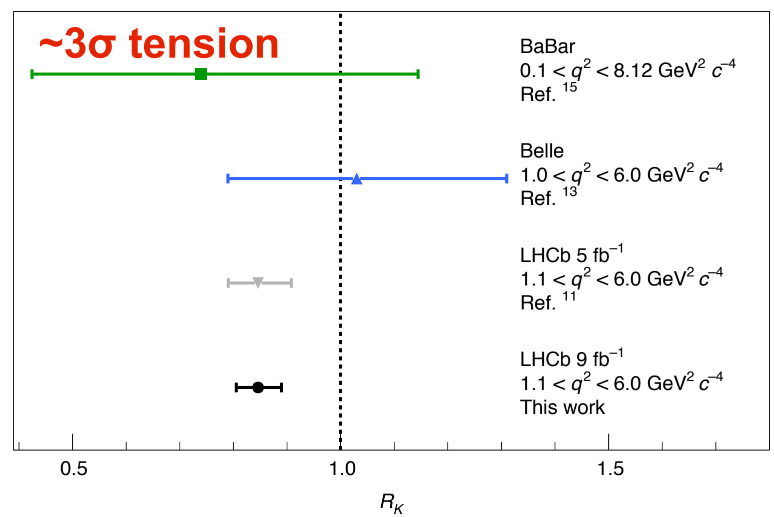
Lepton Flavor Anomalies

- Recently, a number of lepton flavor anomalies have been observed in various semileptonic channels, largely driven by the LHCb experiment:
  - ~3σ tension in R(D/D*), the ratio of $\mathscr{B}(b \to c\tau\nu)/\mathscr{B}(b \to cl\nu)$ [tree-level process]
  - ~2σ tension in R(J/ψ), the ratio of $\mathscr{B}(b \to c\tau\nu)/\mathscr{B}(b \to cl\nu)$ [tree-level process]
  - ~2σ deficit in various $b \to s\mu^+\mu^-$ transitions, compared to theory predictions, both in inclusive and differential measurements [loop-level process]
  - ~3σ tension in R(K), R(K*), the ratio of $\mathscr{B}(b \to s\mu^+\mu^-)/\mathscr{B}(b \to se^+e^-)$ [loop-level process]
- Arguably the strongest hints of new physics to date that survived a dozen of years of the LHC program



HFLAV 2021 Update



LHCb Nature Phys. 18 (2022) 277

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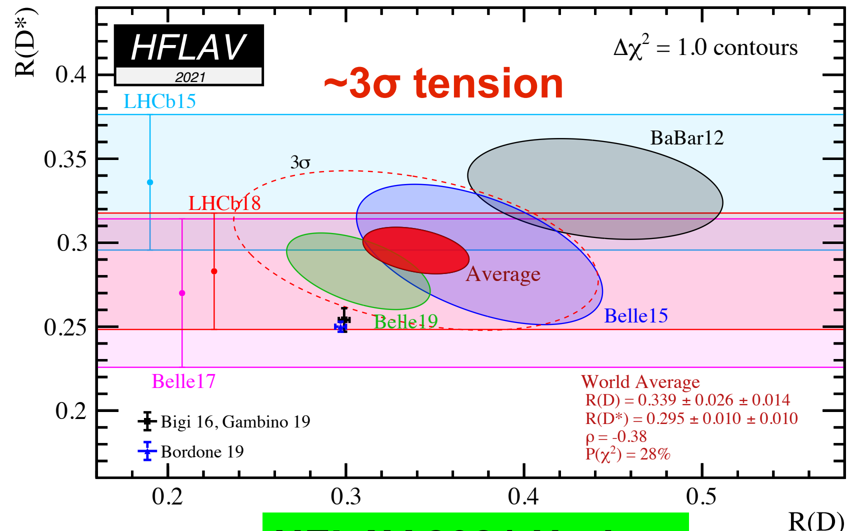

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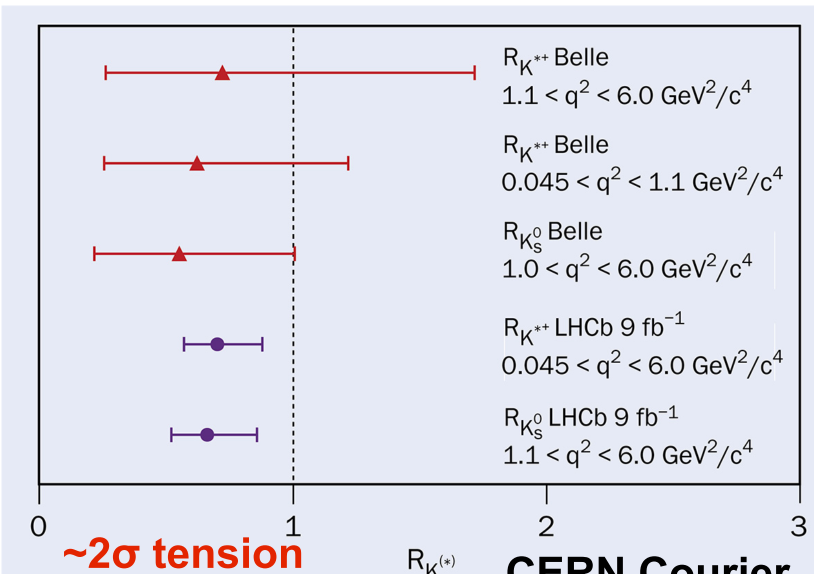


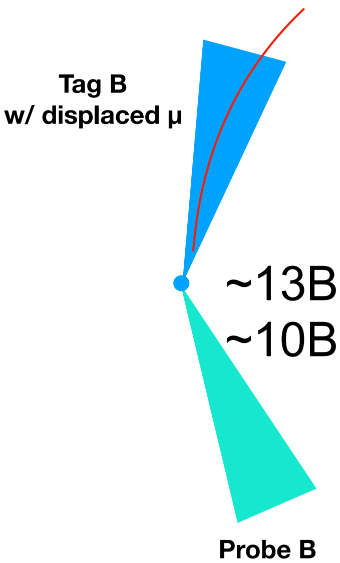
CERN Courier

CMS and Flavor Anomalies

- In CMS, a number of analyses probing these anomalies are ongoing
  - While no new results are available as of yet, expect the first new results to become public this summer and the coming fall
- These analyses use both the 2018 parked data (10^{10} unbiased b hadron decays on tape) and standard dimuon triggers:
  - R(K) - parked data
  - R(D*) - parked data (leptonic τ decays)
  - R(J/ψ) = $\mathscr{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathscr{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$ - non-parked data (both the muonic and hadronic τ decays)
  - $B/B_s(\mu\mu)$ - non-parked data, full Run 2 analysis
  - P_5' and differential branching fractions in $B^0 \to \mu^+\mu^-K^{0*}$ decays - non-parked data, full Run 2 analysis
  - Also have $B^\pm \to \mu^+\mu^-K^\pm$ and $B_s^0 \to \mu^+\mu^-\phi$ angular analyses in progress using non-parked data, full Run 2 analyses

CMS 2018 B Parking

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

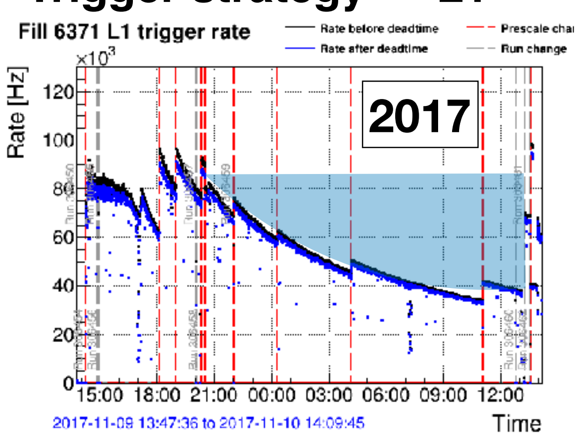


~13B events = ~10B b hadrons

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



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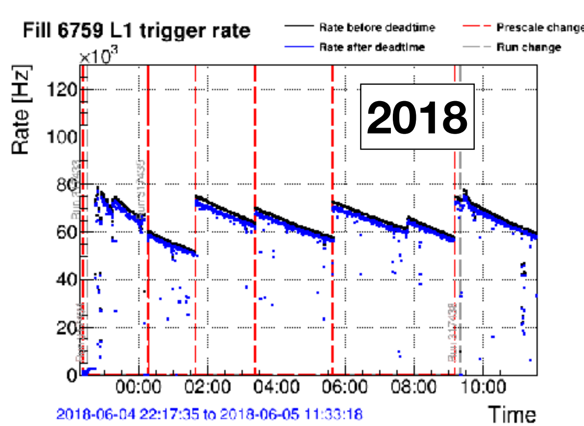
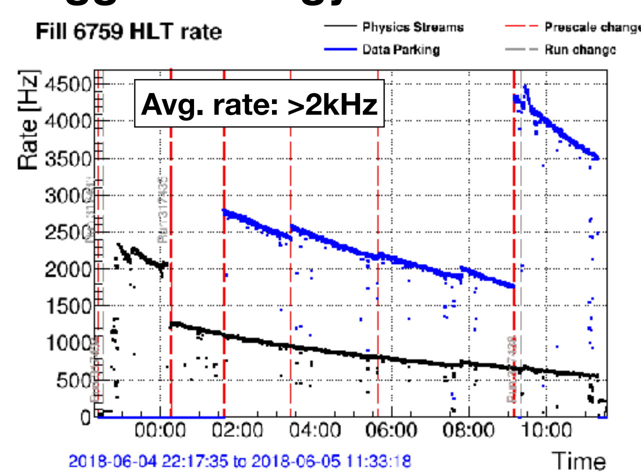


Trigger strategy — HLT

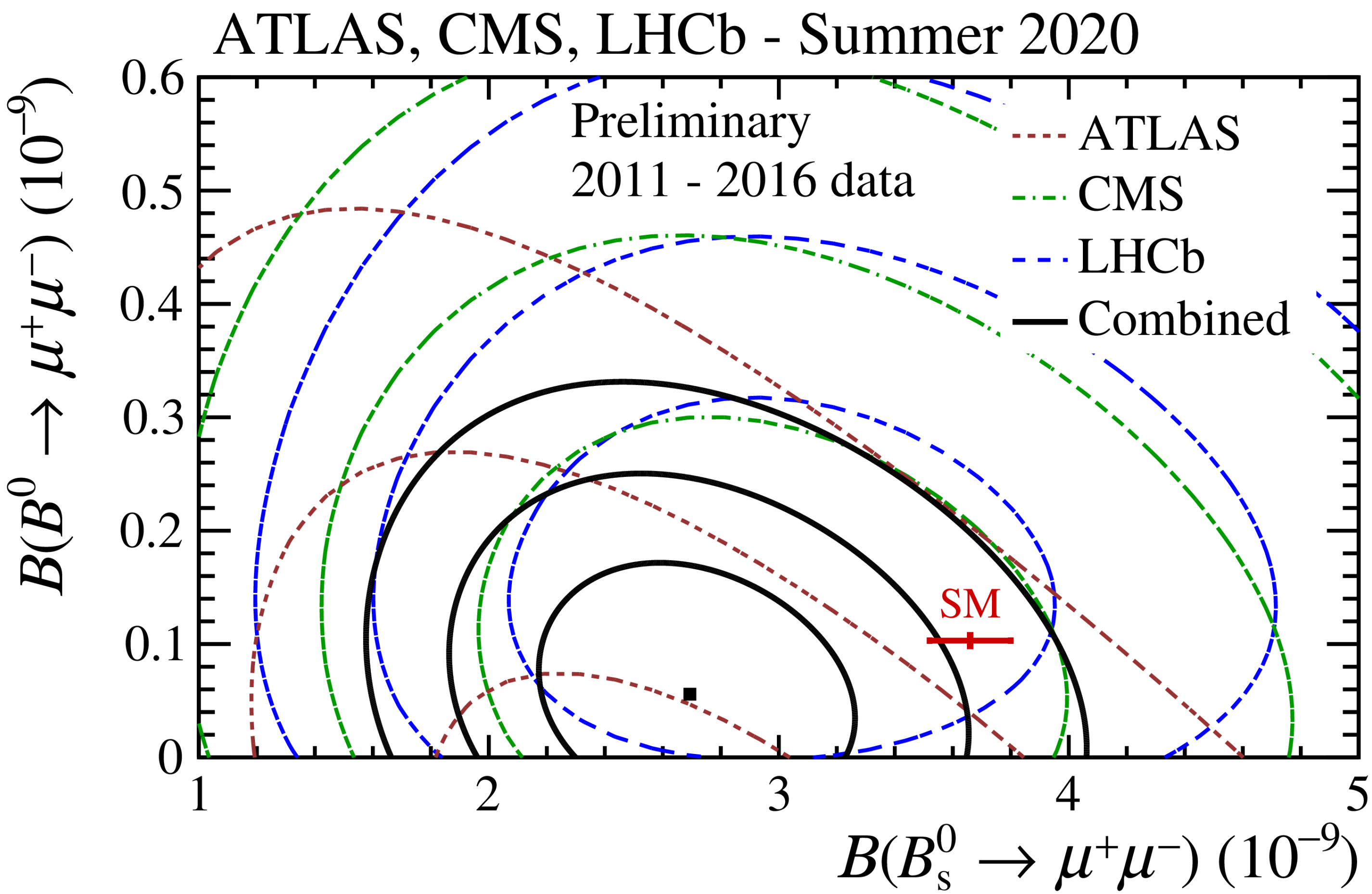


R(K) General Strategy

- Low-p_T electrons are very hard (spent three years optimizing the reconstruction and selection - a lot more challenging than we originally thought) - do not expect competitive precision in R(K) with the 2018 parked data
  - Rethinking trigger strategy for Run 3
  - Focusing on high precision in the muon channel, which may shed light on whether muons are suppressed compared to the SM predictions, which LHCb data seem to indicate

$B_s(\mu\mu)$ 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



CMS PAS BPH-20-003

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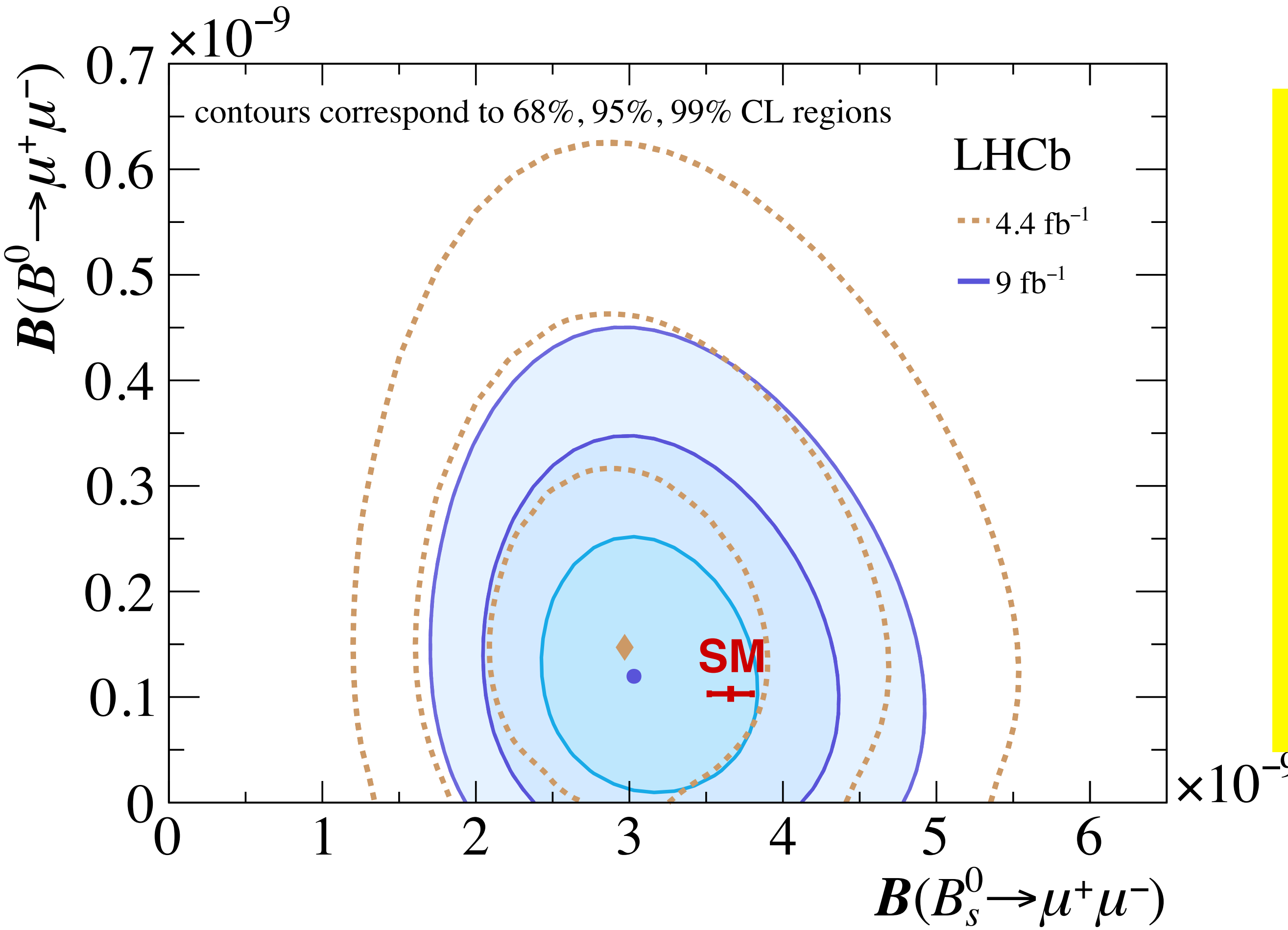
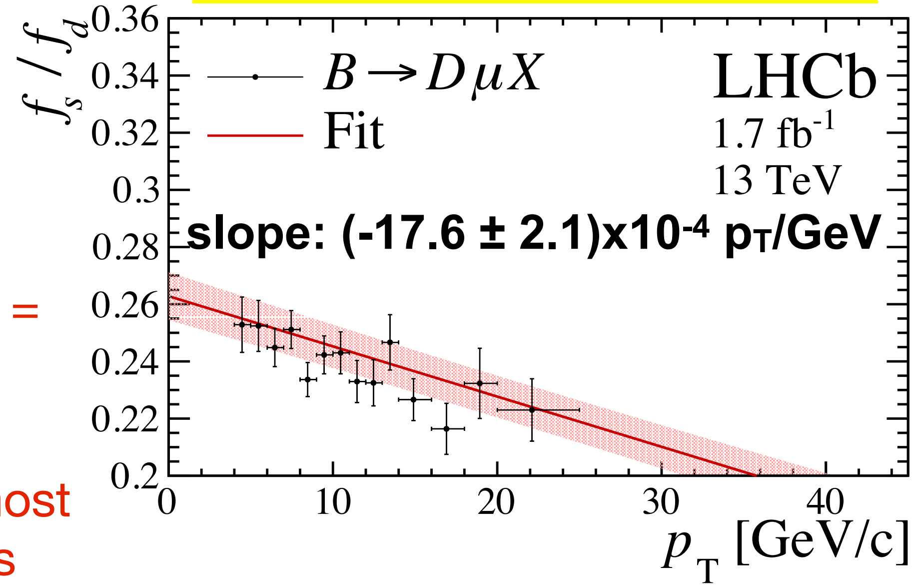


LHCb PRL 128 (2022) 041801

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 statistical weight in the combination is dominated by the former]
  - This brings the f_s/f_u fragmentation function ratio 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 increase the uncertainty to cover possible 8 TeV/13 TeV and p_T variations [the latter is reported at ~8σ by the LHCb at 13 TeV, but not seen by ATLAS or internally in CMS]
  - As a result, in CMS we add a $0.015 = 0.008 \oplus 0.013$ uncertainty and use:
    - $f_s/f_u = 0.252 \pm 0.019$
  - This 6% uncertainty is one of the most dominant in the overall result, so it's important to reduce it

LHCb PRD 104 (2021) 032005



World Average f_s/f_d

- Given the tension between different measurements of FFR and the claimed p_T dependence by LHCb, world average FFR are no longer being updated:
  - From HFLAV arXiv:1909.12524

[3] The LHC production fractions results are still incomplete, lacking measurements of the production of weakly-decaying baryons heavier than Λ_b^0. In Ref [1], we provided also a third set of averages including measurements performed at LEP, Tevatron and LHC, but this was mostly for comparison with previous averages. We have decided to discontinue these "world averages", because they mix environments with different fractions.

- PDG still provides the world average values:

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

	in Z decays [8]	at Tevatron [8]	at LHC [89–91]
$\overline{\chi}$	0.1259 ± 0.0042	0.147 ± 0.011	
$f_u = f_d$	0.408 ± 0.007	0.344 ± 0.021	
f_s	0.100 ± 0.008	0.115 ± 0.013	
$f_{\rm baryon}$	0.084 ± 0.011	0.198 ± 0.046	
f_s/f_d	0.246 ± 0.023	0.333 ± 0.040	0.247 ± 0.009

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

Normalization (cont'd)

- One possibility is to use the $B_s \to J/\psi\phi$ decay, for normalization, which should eliminate the need for the f_s/f_u ratio
- Currently, the world average [PDG] is based on two results:
  - Belle, Υ(5S) → B_sB_s, $B(B_s \to J/\psi\phi) = 1.25 \pm 0.24$
  - LHCb, 7 TeV: $B(B_s \to J/\psi\phi) = 1.050 \pm 0.105$
    - Unfortunately, the LHCb result uses $B^+ \to$ J/psi K^+ as the normalization channel, so this measurement is ~100% correlated with their f_s/f_u measurement - not an independent result
    - N.B. ATLAS uses a theory prediction on $B(B_s \to J/\psi\phi)/B(B \to J/\psi K^*) = 0.83$ +- 0.03 [Liu, Wang, Xie, PRD **89** (2014) 024010] for their f_s/f_d ratio - but it's not reliable
- Can CMS 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 a Belle II Υ(5S) measurement to make a breakthrough in precision
  - Why don't they run on the Υ(5S) first??? 😃

FFR in CMS

- Several analyses are ongoing, with the results expected this summer:
  - 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)
  - 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): $B(B_s \to D_s^-\pi^+) = (2.99 \pm 0.24)\times10^{-3}$
- Belle measurement has a 20% uncertainty: $B(B_s \to D_s^-\pi^+) = (3.6 \pm 0.5 \pm 0.5)\times10^{-3}$

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

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

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

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 ± 0.004	[6]
$(\tau_{B^+} + \tau_{B^0})/2\tau_{B_s^0}$	1.032 ± 0.005	[6]
$(1 - \xi_s)$	1.010 ± 0.005	[34]
$\mathcal{N}_a$	1.000 ± 0.020	[36]
$\mathcal{N}_F$	1.000 ± 0.042	[19, 40]
$\mathcal{N}_E$	0.966 ± 0.062	[7, 36]
$\lvert V_{us}\rvert f_K/\lvert V_{ud}\rvert f_\pi$	0.2767	[9]

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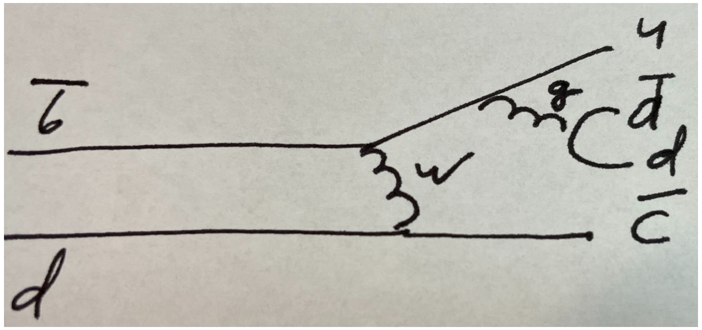
← Bordone et al., EPJC **80** (2020) 347 and 951

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 4σ difference between prediction and measurement in $\bar{B}_s^0 \to D_s^+\pi^-$, over 5σ difference in $\bar{B}^0 \to D^+K^-$, about 2σ in $\bar{B}_s^0 \to D_s^{*+}\pi^-$ and 3σ in $\bar{B}^0 \to D^{*+}K^-$. A fit to the same data as above, but

Using non-Cabibbo-Suppressed Channel

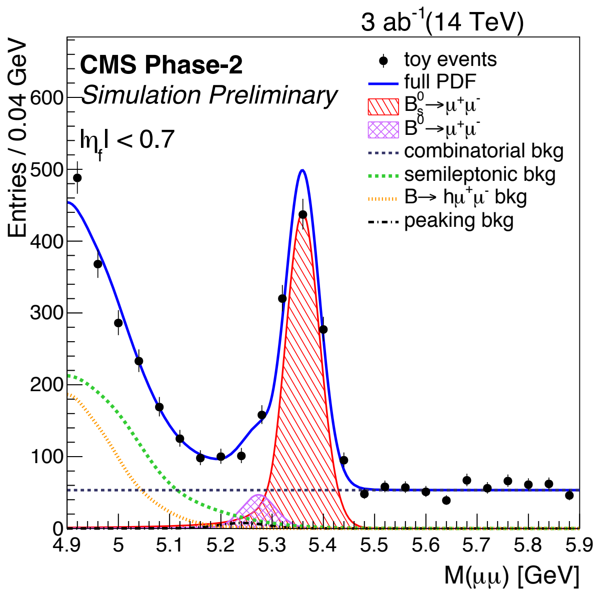
- In CMS, due to the lack of particle ID, Cabibbo-suppressed channel is difficult
  - Use non-Cabibbo-suppressed $B^0 \to D^-\pi^+$ instead and normalize to the theoretically clean channel via the ratio of the branching fractions: $\mathcal{B}(B^0 \to D^-K^+)/\mathcal{B}(B^0 \to D^-\pi^+)$
  - This ratio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

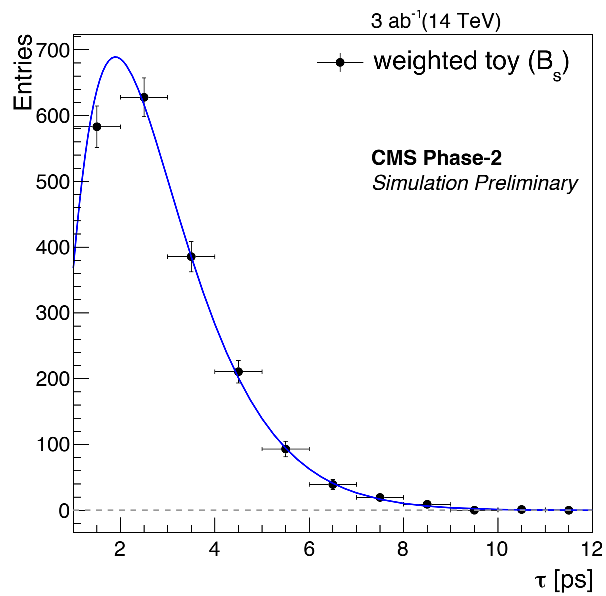


$B_s(\mu\mu)$ Prospective

- 3x more Run 2 data is yet to be analyzed - expect a significant improvement! - coming very soon!
- For the $B(\mu\mu)$ discovery, need HL-LHC; will also be able to probe the lifetime with sufficient enough precision to resolve the two B_s states

CMS PAS FTR-18-013



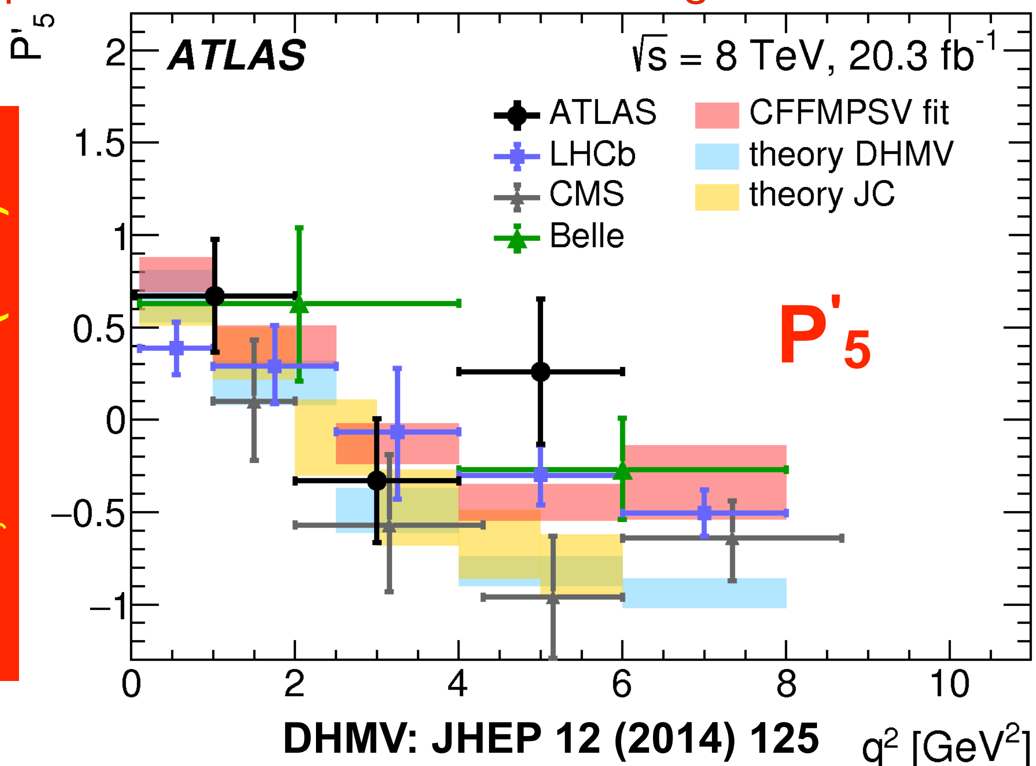


$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps

P'$_5$: Experimental Situation

- Experimental situation: all over the place
  - The results are consistent among the experiments; inconsistency with the theory is an open question (both experimentally and theoretically!)
- In CMS, working on the 13 TeV analysis with significantly higher statistics
  - Will attempt to have finer bins and including the ones between J/ψ and ψ(2S)

ATLAS, JHEP 10 (2018) 047

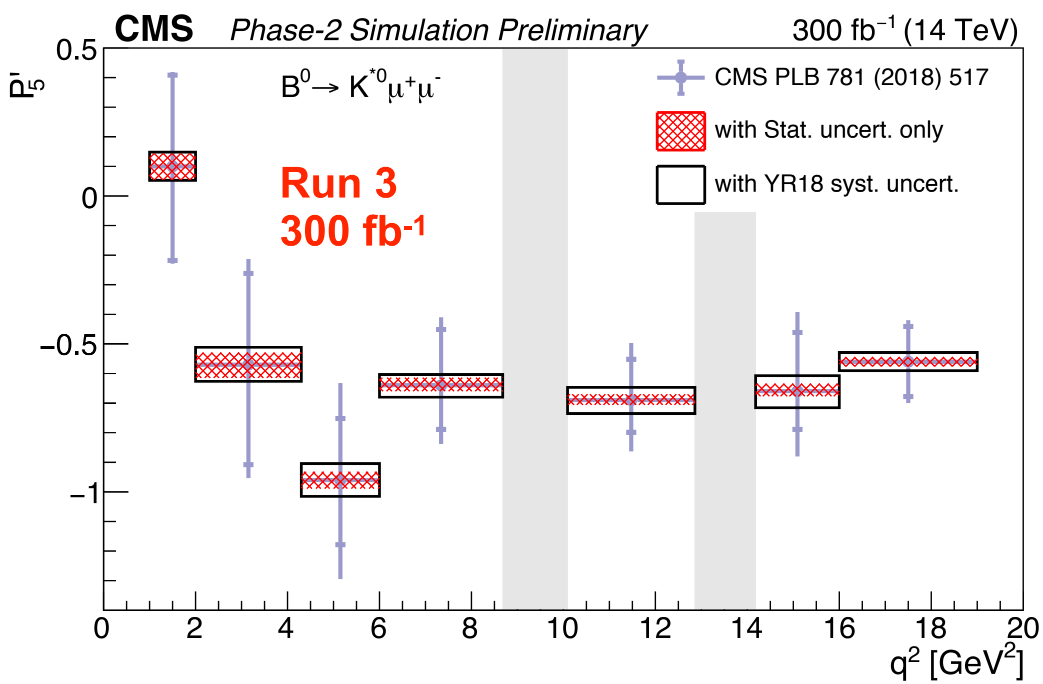


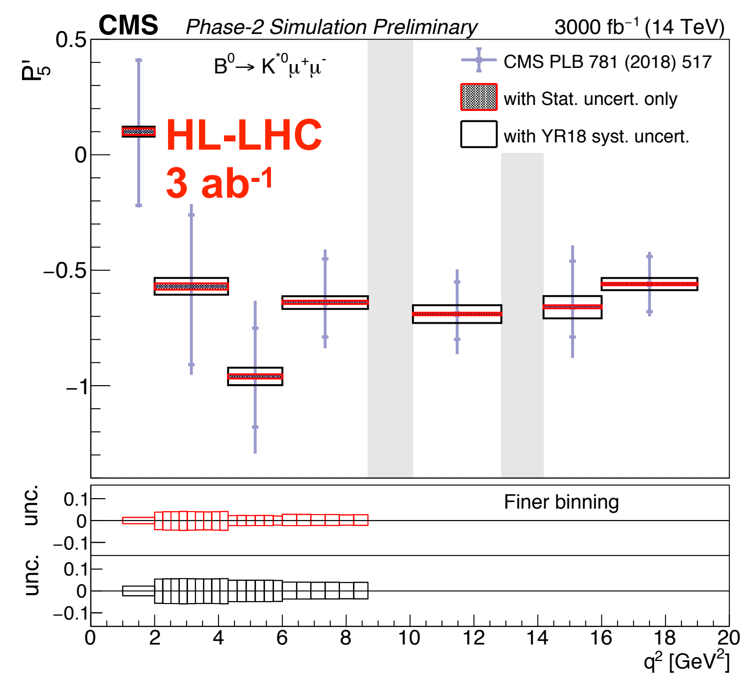
DHMV: JHEP 12 (2014) 125
JC: JHEP 05 (2013) 043, PRD 93 (2016) 014028
CFFMPSV: JHEP 06 (2016) 116

P'$_5$: HL-LHC Projections

- Run 3 and HL-LHC projections
  - Up to x15 improvement w/ 3 ab^{-1} compared to the 8 TeV CMS result [PLB 781 (2018) 517]
  - Should be possible to resolve the situation experimentally already in Run 3

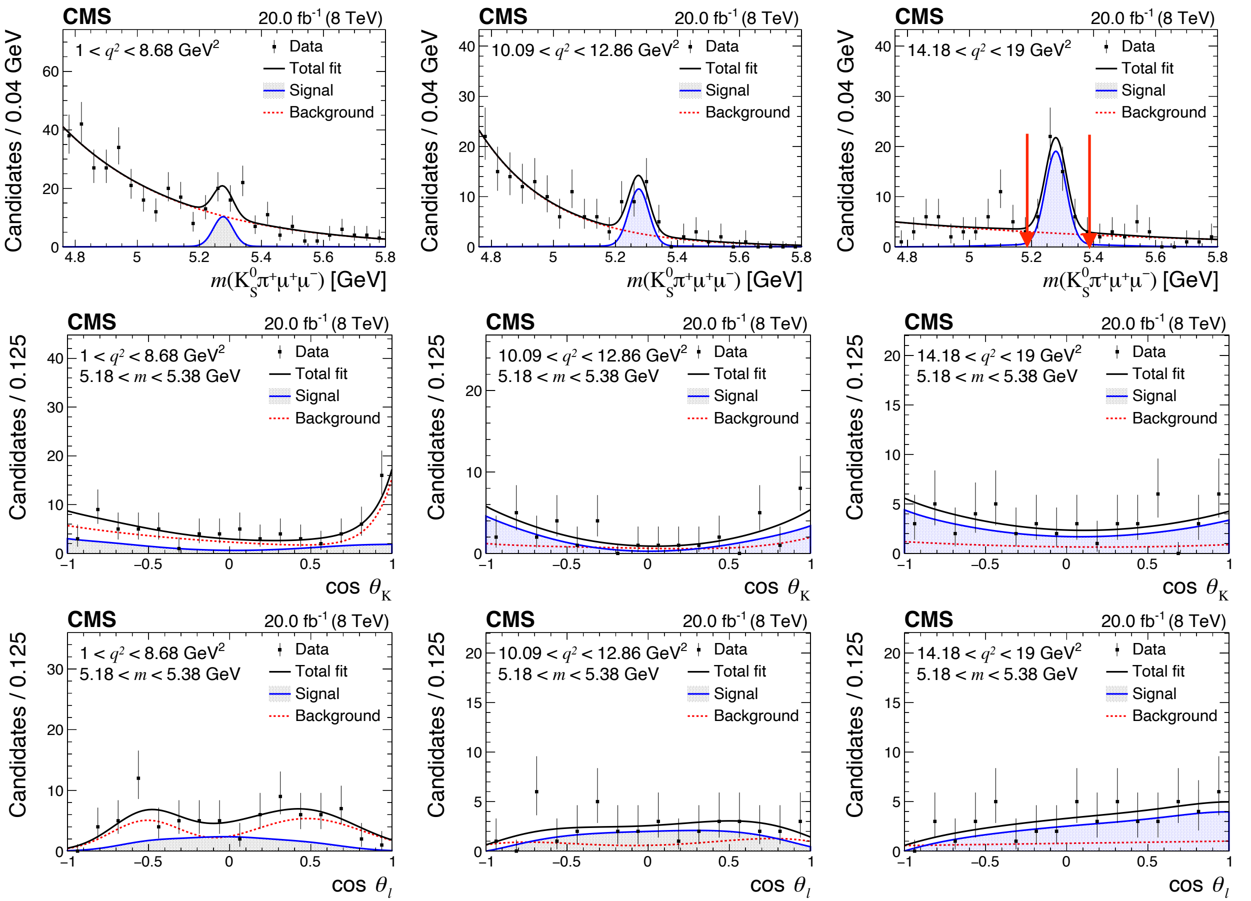
CMS PAS FTR-18-033

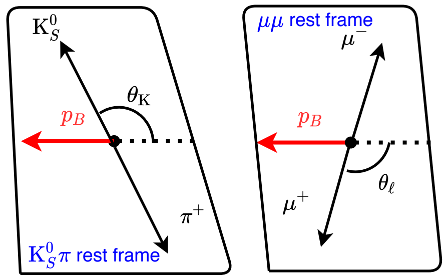


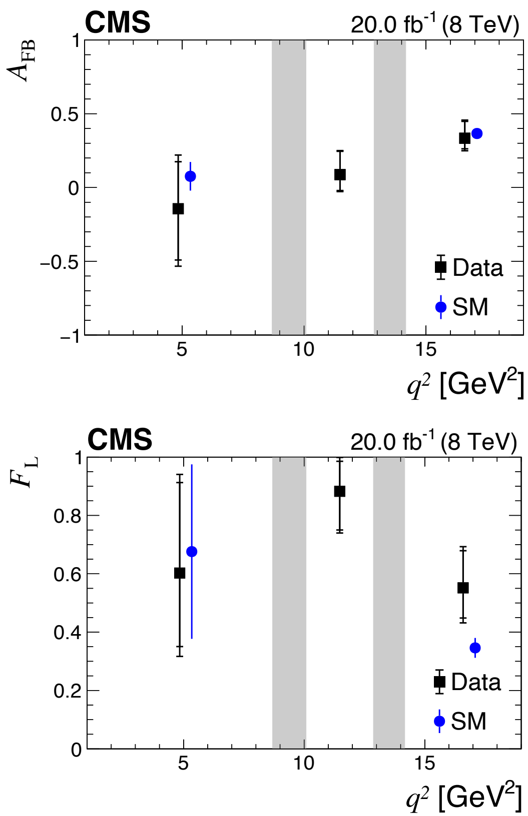


$B^+ \to K^{+*}\mu\mu$ Angular Analysis

- Recent result on a challenging charged B angular analysis, with the K^{+*} reconstruction via the $K^0_S\pi^+$ decay w/ 8 TeV 2012 data
  - Good agreement with the SM predictions in muon A_{FB} and K^* F_L







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SM: QCDF + lattice

Search for Dimuon Asymmetry

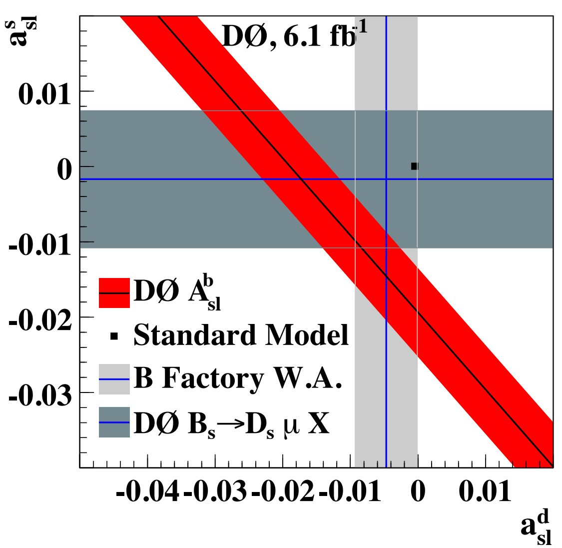
- Uncontested D0 result [PRD 82 (2010) 032001]
- Probes charge asymmetry in semileptonic B meson decays:

$$A^b_{\text{sl}} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

- The measured value is 3.2σ from zero:

$$A^b_{\text{sl}} = +0.0094 \pm 0.0112\ (\text{stat}) \pm 0.0214\ (\text{syst})$$

- This is a very hard measurement to make; D0 has used the fact that both the solenoid and the toroid polarities were periodically switched
  - While CMS always has the opposite solenoid and toroid fields, they have never been switched to an opposite polarity (this can be potentially done but would require some investment in the solenoid control circuit)
  - On the other hand, the systematics due to the Lorentz angle in the CMS silicon tracker is much smaller than for the D0 drift chamber



Can CMS Test This?

- Not with the standard triggers, as most of the low-mass dimuon triggers required opposite-sign muons
- Could potentially do this with the parked data sample, using the trigger side, which guarantees at least one muon per event
- Systematics may be hard to control, but given the enormous size of the data set, many sources could be studied in situ
- Hard, but not impossible measurement!

Conclusions

- CMS has succeeded in a bold and aggressive program of putting ~10^{10} b hadron decays on tape in 2018
  - Unprecedented data set, with very huge potential
- Allows to do a number of B physics measurements, thought not to be possible before in CMS:
  - R(K)
  - R(D*)
  - FFR
  - ...
- New CMS results on flavor anomalies, including the first results on B parking dataset, will come this summer and fall
- Rethinking trigger strategy for Run 3 in order to get more data for R(K/K*/ϕ) analyses