RECENT B PHYSICS RESULTS FROM CMS (AND BEYOND)

Greg Landsberg - MITP Workshop

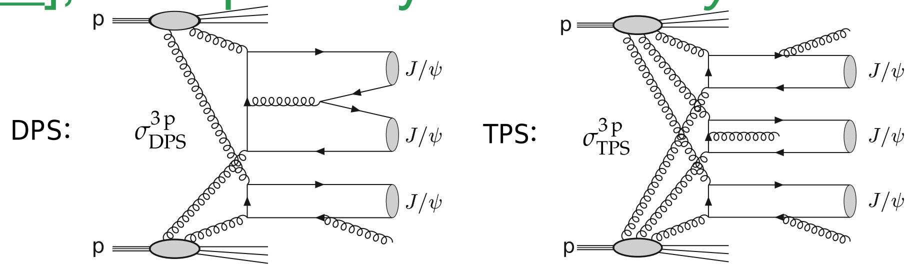
Flavour of BSM in the LHC Era - October 19, 2022

Outline

- Recent B Physics Results From CMS
  - Observation of Triple J/ψ Production
  - Exotic States
  - Rare B^0/B_s Decays
  - $B_s \to \mu\mu$
- Connection to Flavour Anomalies
- Fragmentation Fraction Story
- Isospin Invariance Tests
- Premium: Run 2 LHC high-p_T Excesses

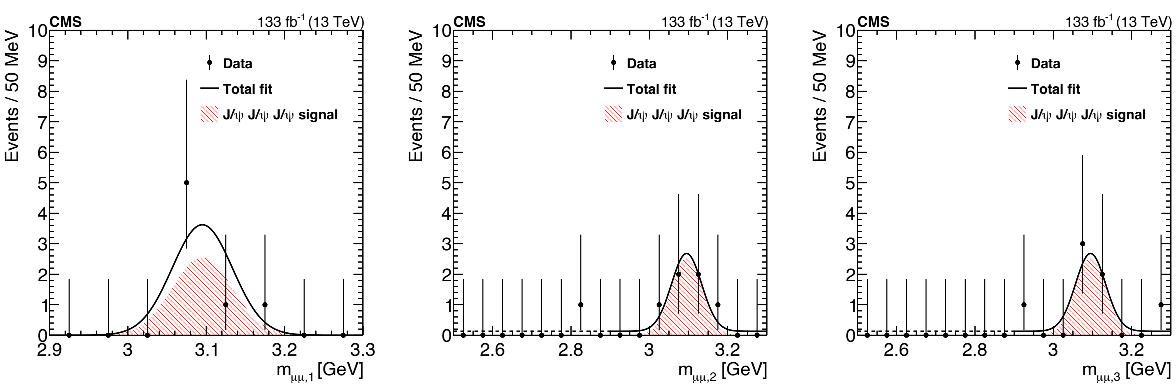
Observation of Triple J/ψ Production

- 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:

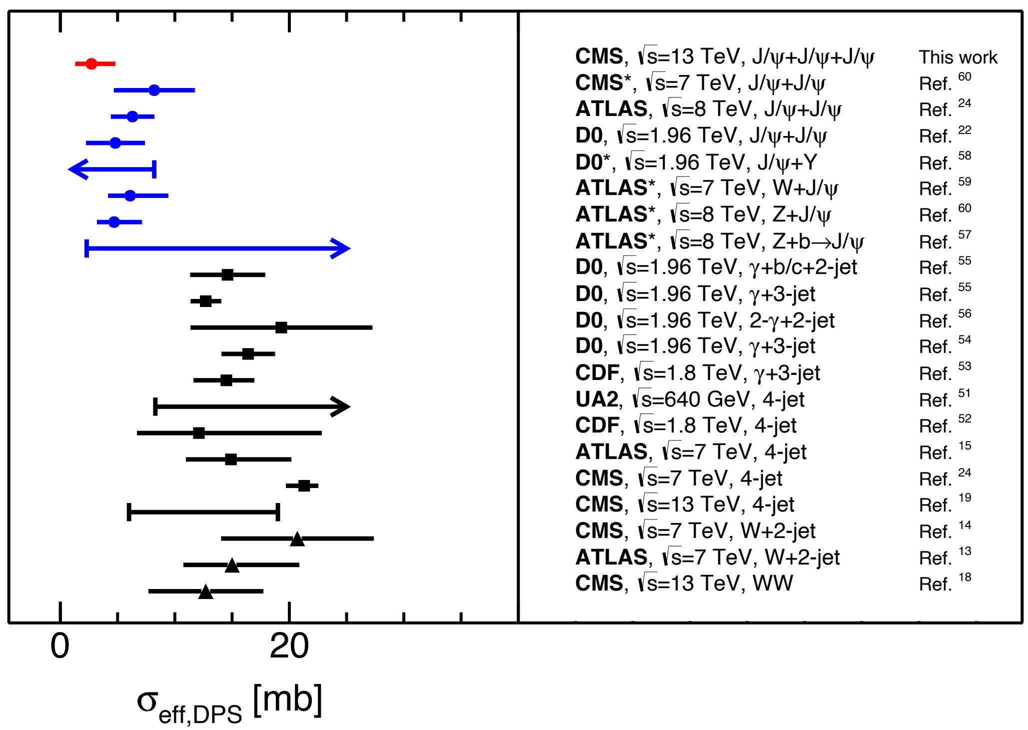
For all muons	$p_{\mathrm{T}} > 3.5\,\mathrm{GeV}$ for $\lvert\eta\rvert < 1.2$ $p_{\mathrm{T}} > 2.5\,\mathrm{GeV}$ for $1.2 < \lvert\eta\rvert < 2.4$
For all J/ψ mesons	$p_{\mathrm{T}} > 6\,\mathrm{GeV}$ and $\lvert y\rvert < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3\,\mathrm{GeV}$

Effective DPS Cross Section

- Definition of effective nPS cross section is given by:

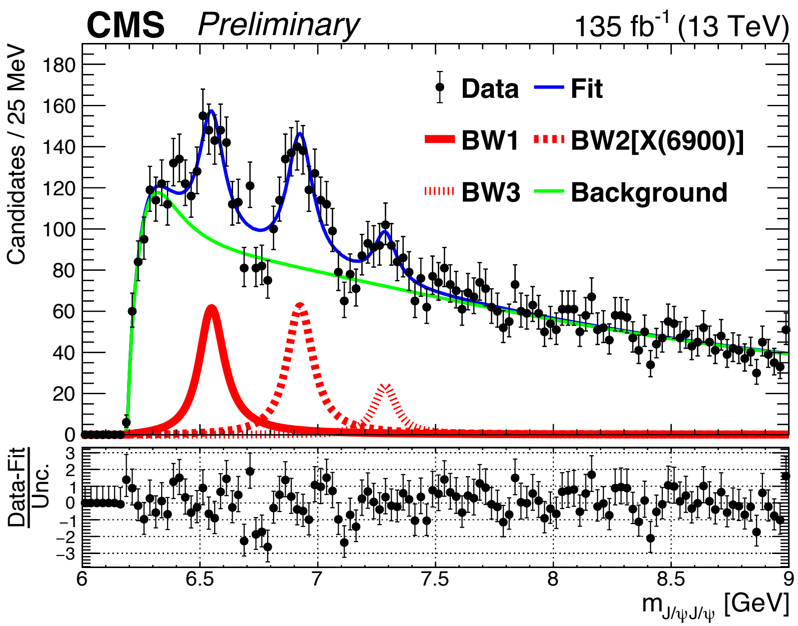
$$\sigma_{\mathrm{DPS}}^{\mathrm{pp}\to\psi_1\,\psi_2+\mathrm{X}} = \left(\frac{\mathfrak{m}}{2}\right) \frac{\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_1+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_2+\mathrm{X}}}{\sigma_{\mathrm{eff,DPS}}} \qquad \sigma_{\mathrm{TPS}}^{\mathrm{pp}\to\psi_1\,\psi_2\,\psi_3+\mathrm{X}} = \left(\frac{\mathfrak{m}}{3!}\right) \frac{\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_1+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_2+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_3+\mathrm{X}}}{\sigma_{\mathrm{eff,TPS}}^2},$$

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



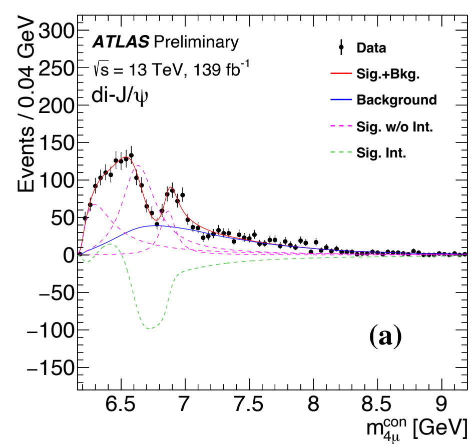
Double J/ψ Puzzles

- Recent preliminary CMS result confirmed a near-threshold structure in the J/ψJ/ψ mass spectrum near 6.9 GeV observed earlier by LHCb [Sci. Bull. **65** (2020) 1983], but also observed a 6.55 GeV structure and an evidence for a 7.3 GeV structure
  - Some of these structures could be a result of an interference with the backgrounds - fits with the LHCb interference models are not very good, but we are working on a more detailed interference study for the publication
  - ATLAS also reported two excesses consistent with the two lower mass CMS structures
- The X(6900) is a good candidate for a charm tetraquark; the nature of other peaks remains a puzzle; they may be radial excitations ($1\,^3P_1$, $2\,^3P_1$, $3\,^3P_1$) of the charm tetraquark



CMS PAS BPH-21-003

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56



ATLAS-CONF-2022-040

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

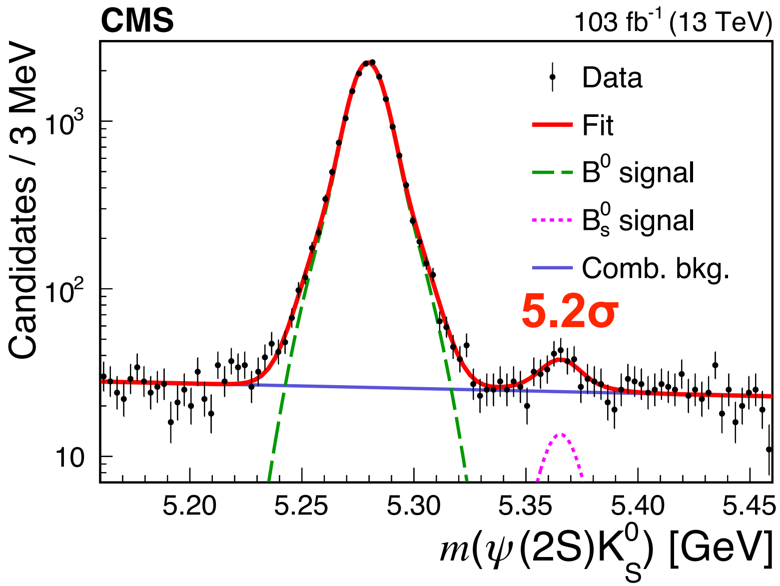
- New CMS analysis based on 2017-2018 data, using the $K^0_S \to \pi^+\pi^-$ decay mode with a large displacement of the $\pi^+\pi^-$ vertex, inspired by searches for exotic states in B meson decays [arXiv:2201.09131, EPJC **82** (2022) 499]

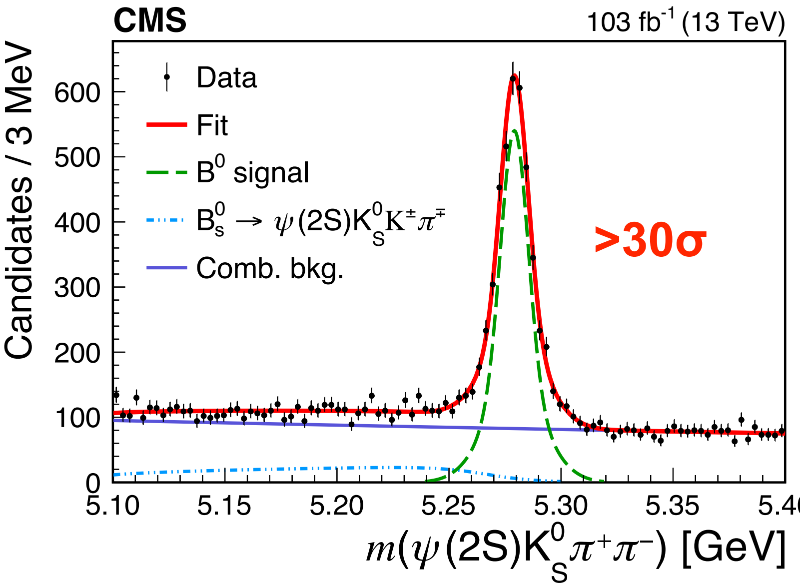
$$R_s = \frac{\mathcal{B}(B^0_s \to \psi(2S)K^0_S)}{\mathcal{B}(B^0 \to \psi(2S)K^0_S)} = (3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2}$$

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

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

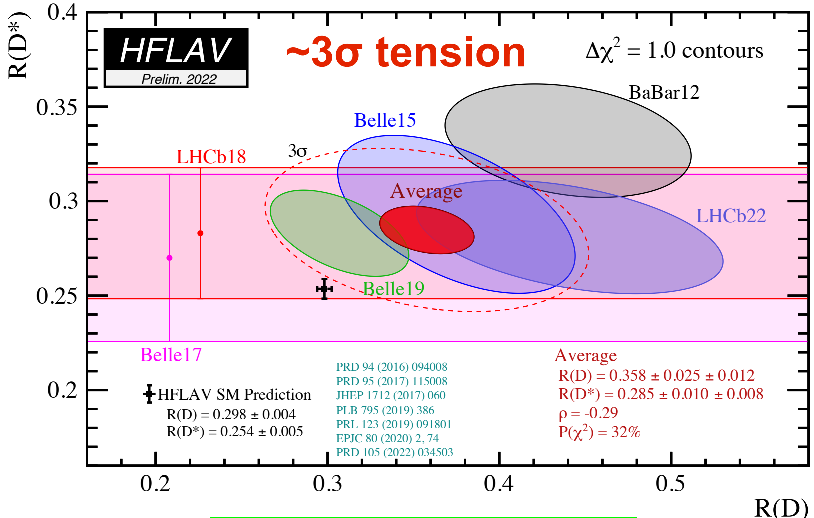
- No peaking structures in the 2- and 3-body $\psi(2S)h_1(h_2)$ spectra observed



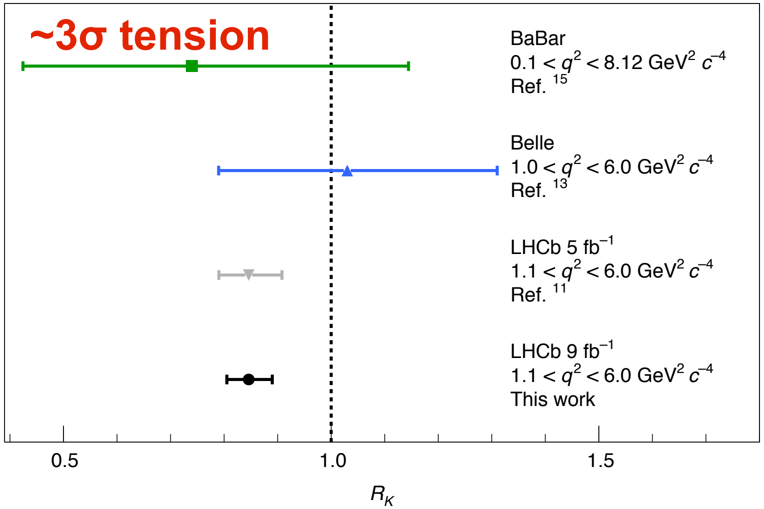


Lepton Flavor Anomalies

- 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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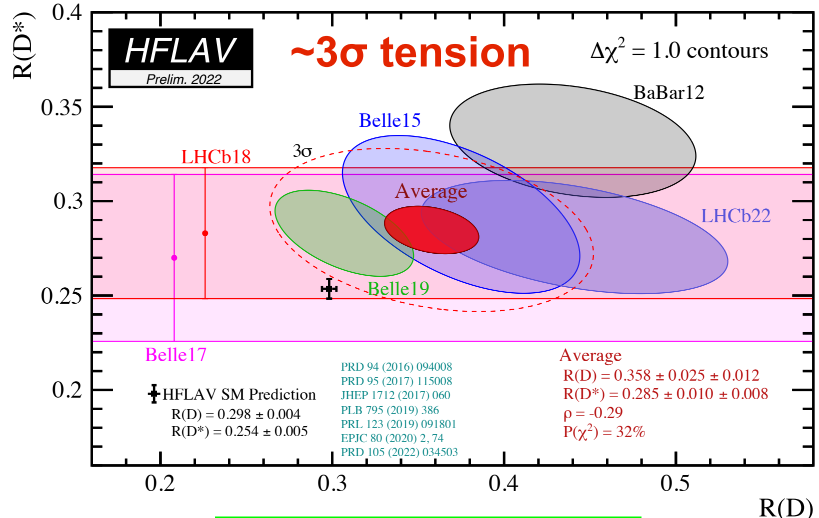

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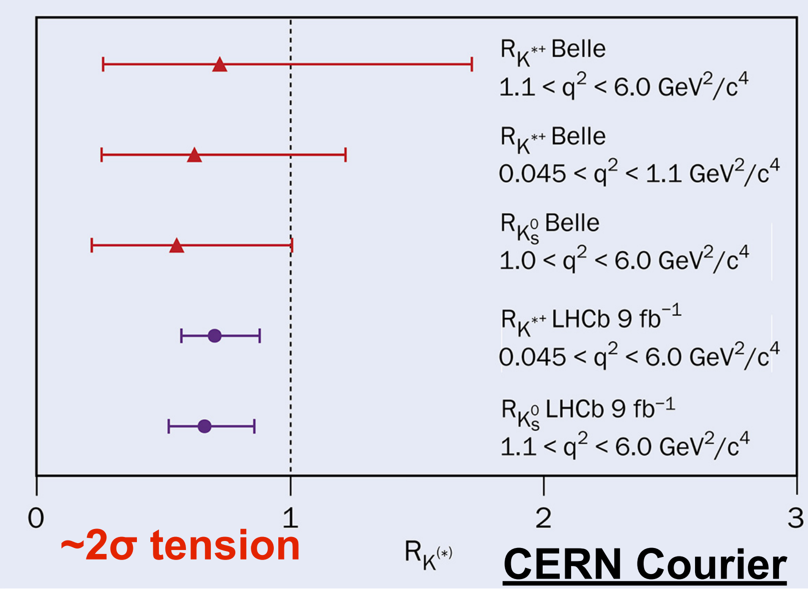

CMS and Flavor Anomalies

- 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 later this year
- 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

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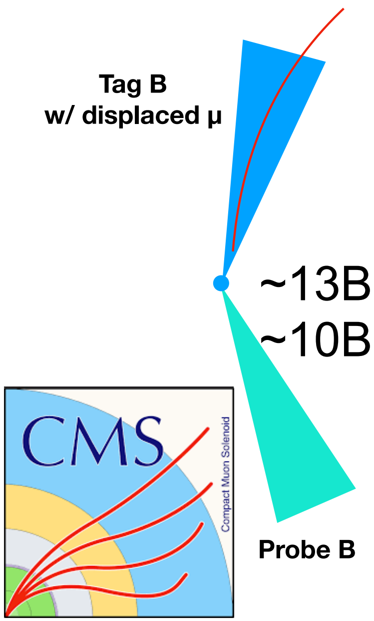
B Meson Spectrometer

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

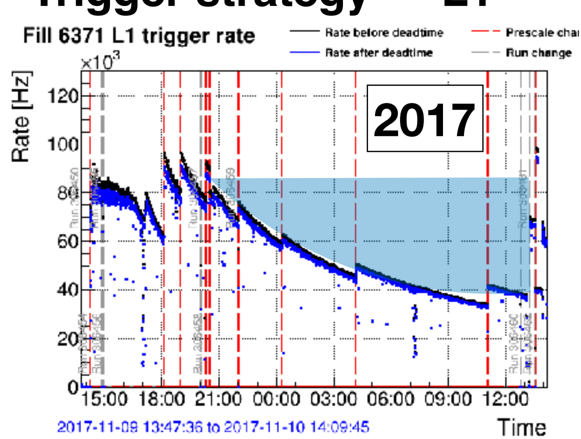


~13B events = ~10B b hadrons

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



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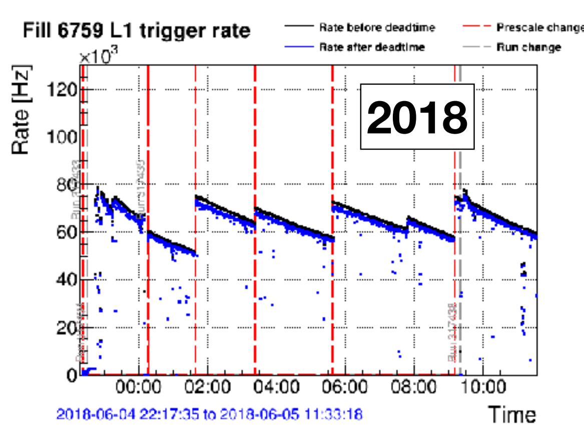

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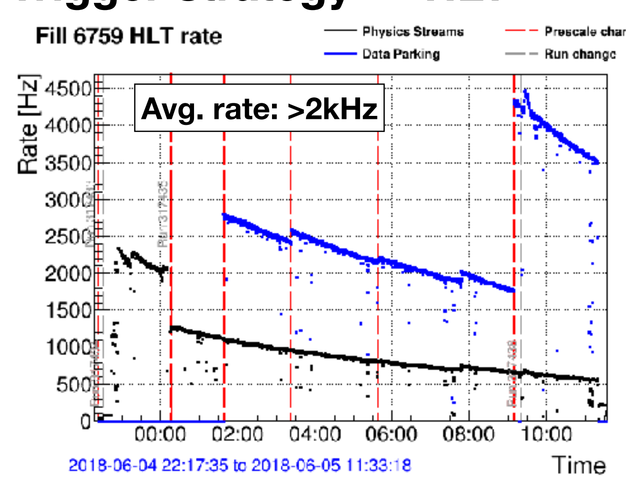

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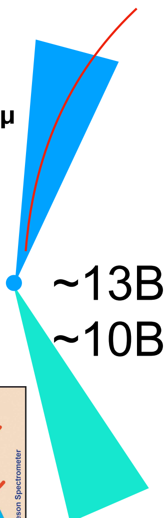
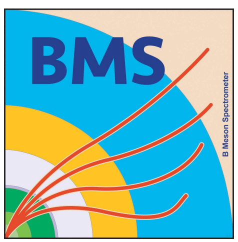
Tag B w/ displaced μ



Probe B

~13B events = ~10B b hadrons



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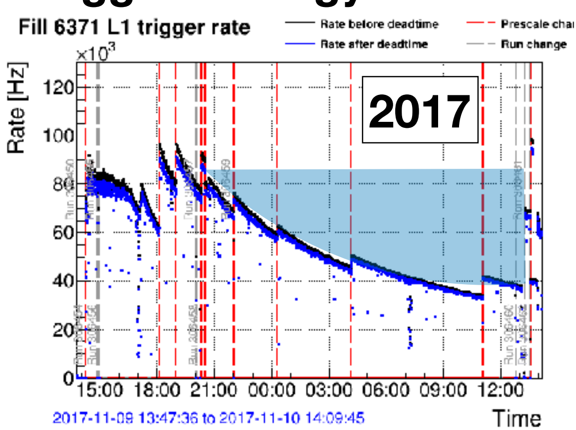

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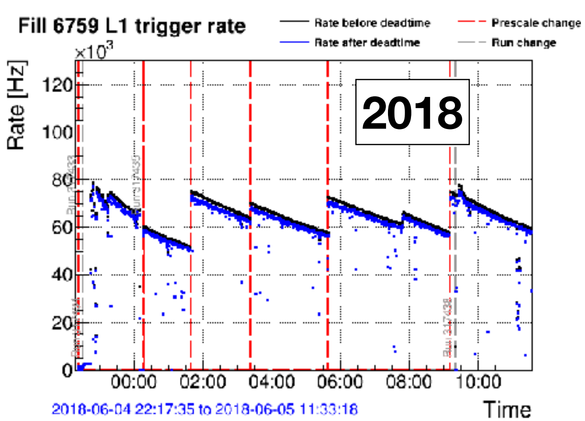
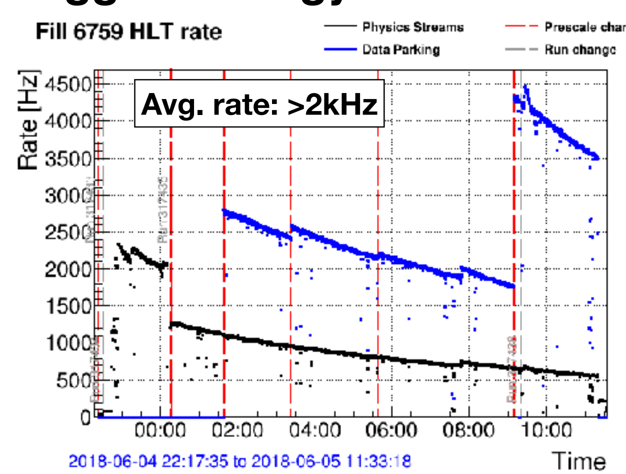


Trigger strategy — HLT



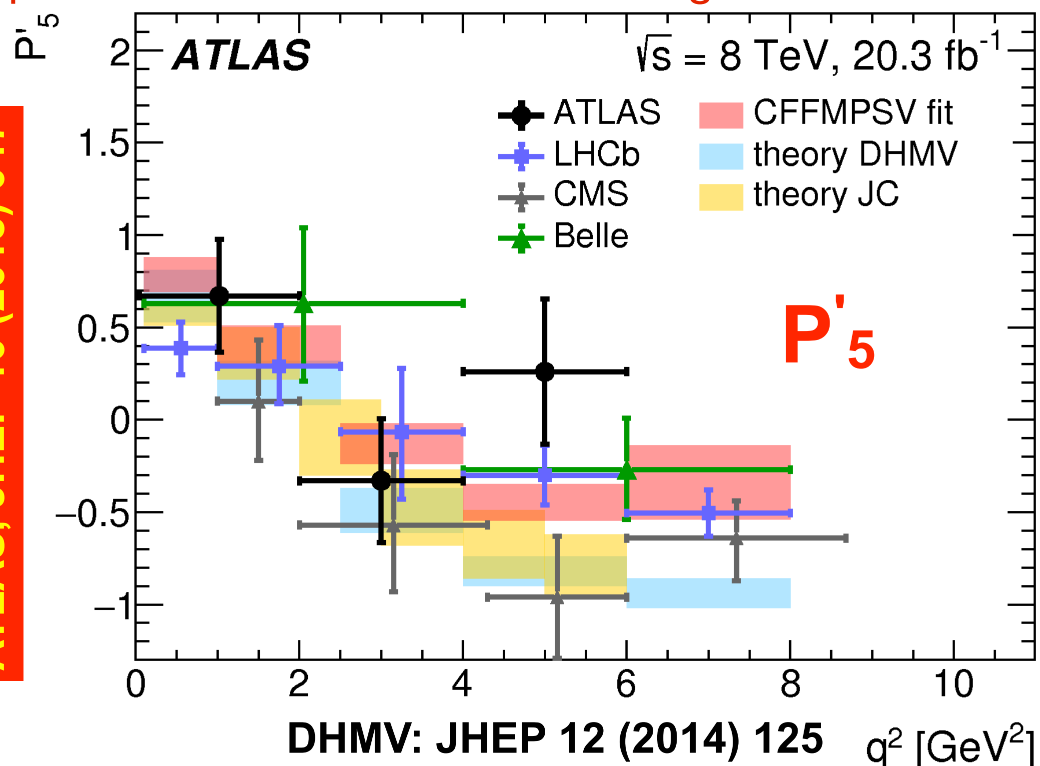
R(K) General Strategy

- 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
  - Rethought 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

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

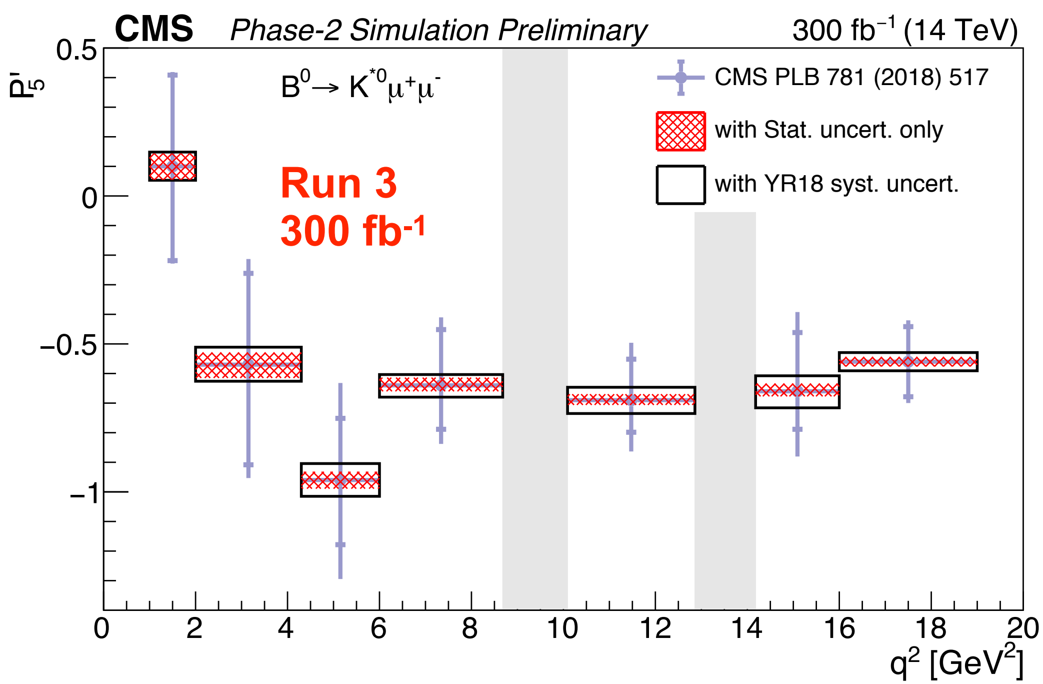


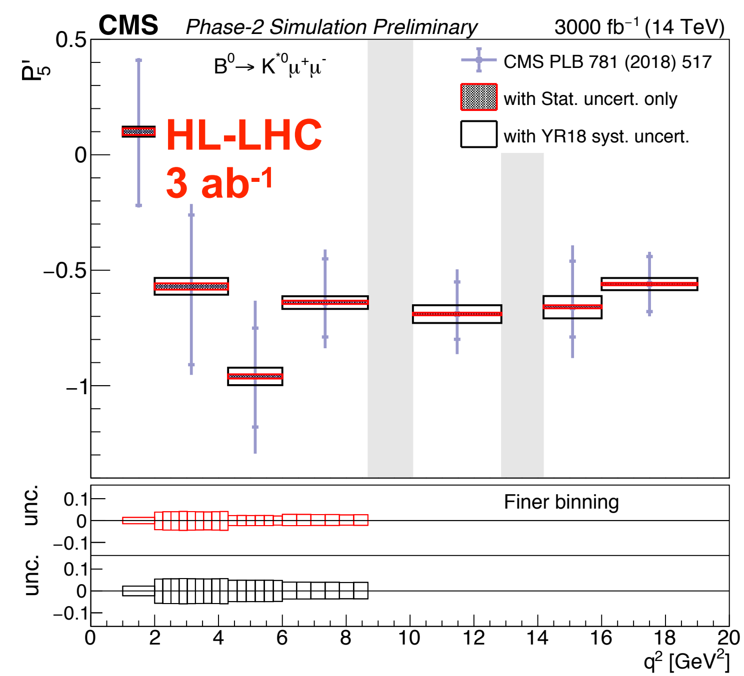
DHMV: JHEP 12 (2014) 125
JC: JHEP 05 (2013) 043, PRD 93 (2016) 014028
CFFMPSV: JHEP 06 (2016) 116

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

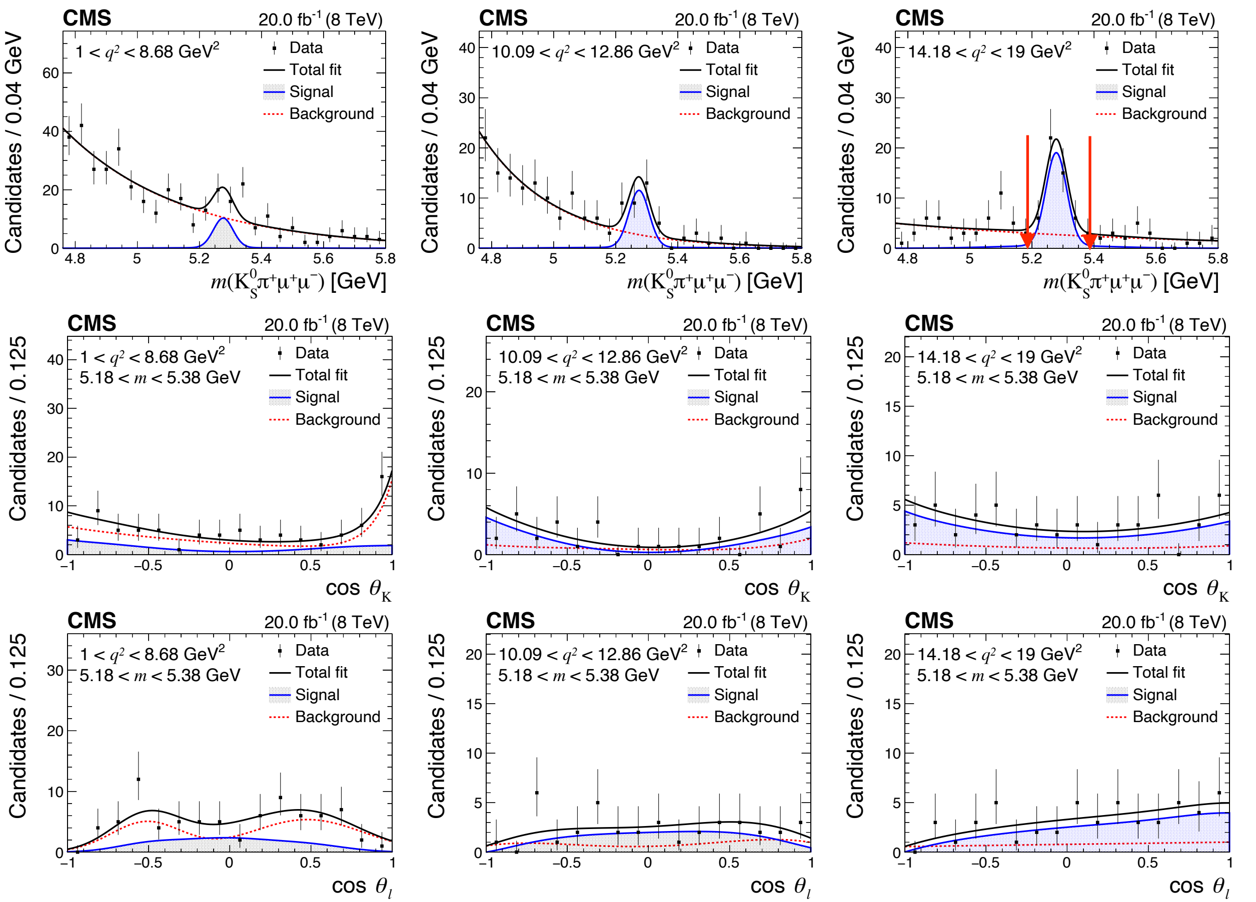
CMS PAS FTR-18-033

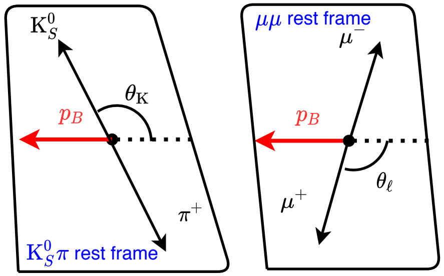


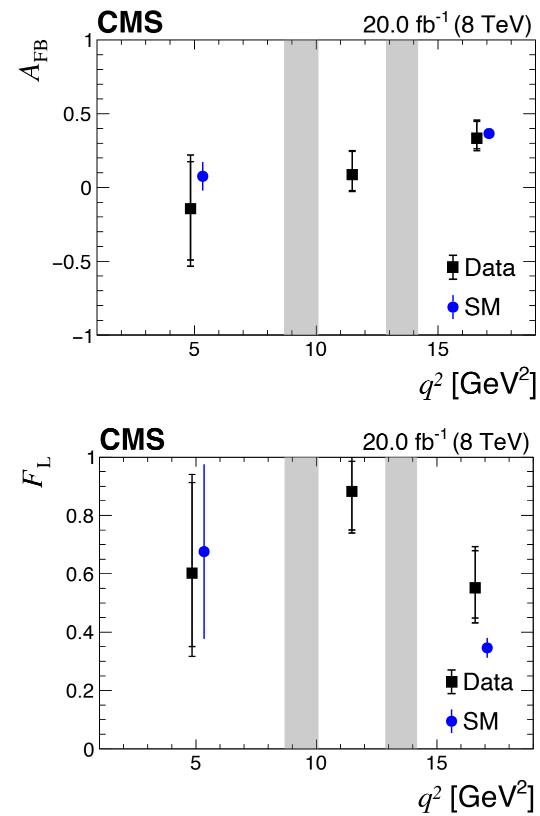


$B^+ \to K^{+*}\mu\mu$ Angular Analysis

- 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





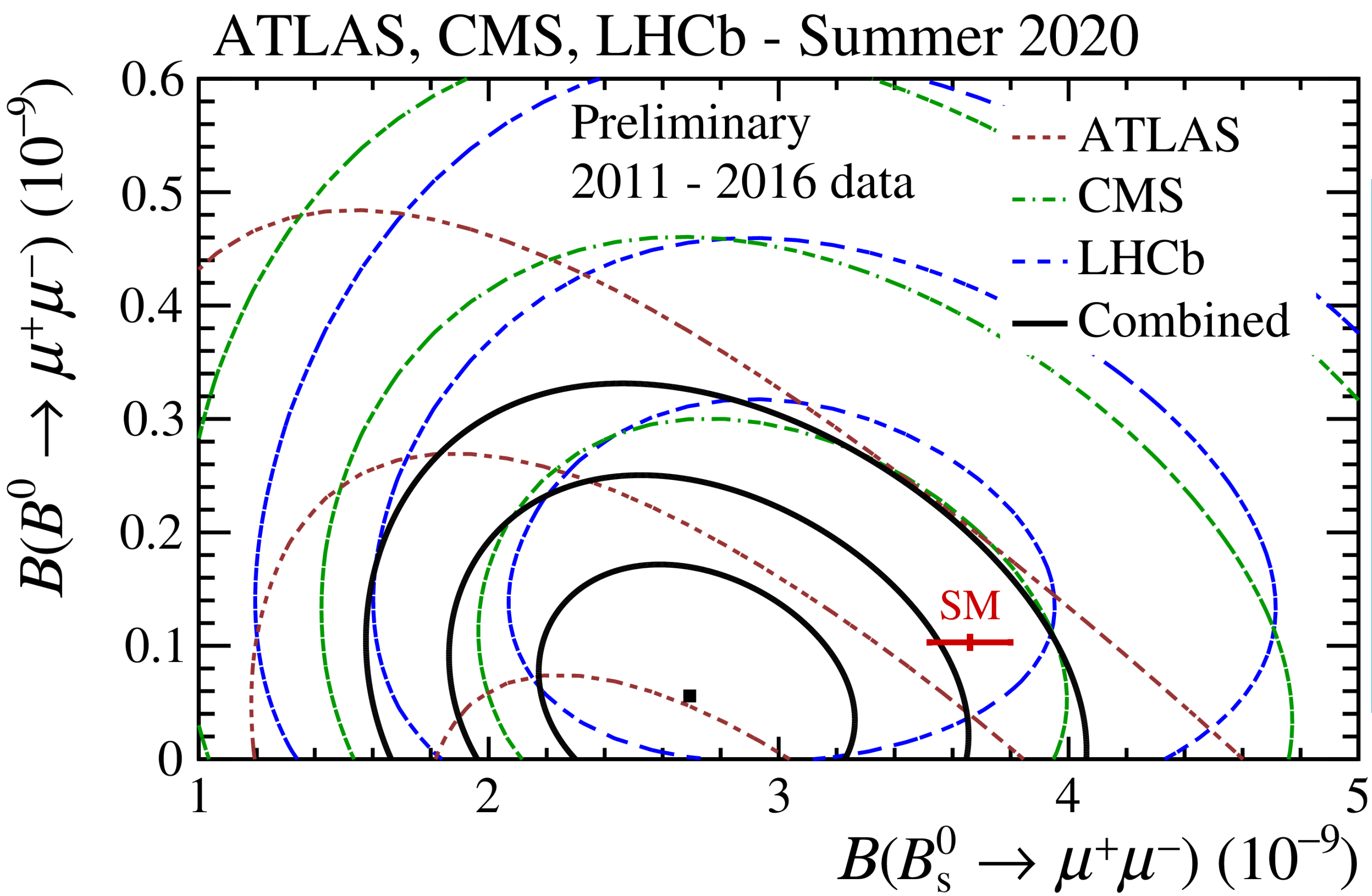


SM: QCDF + lattice

CMS JHEP 04 (2021) 124

$B_s(\mu\mu)$ Status

- ATLAS, CMS, LHCb combination: ~2σ tension w.r.t. the SM prediction - similar to other b → sμμ 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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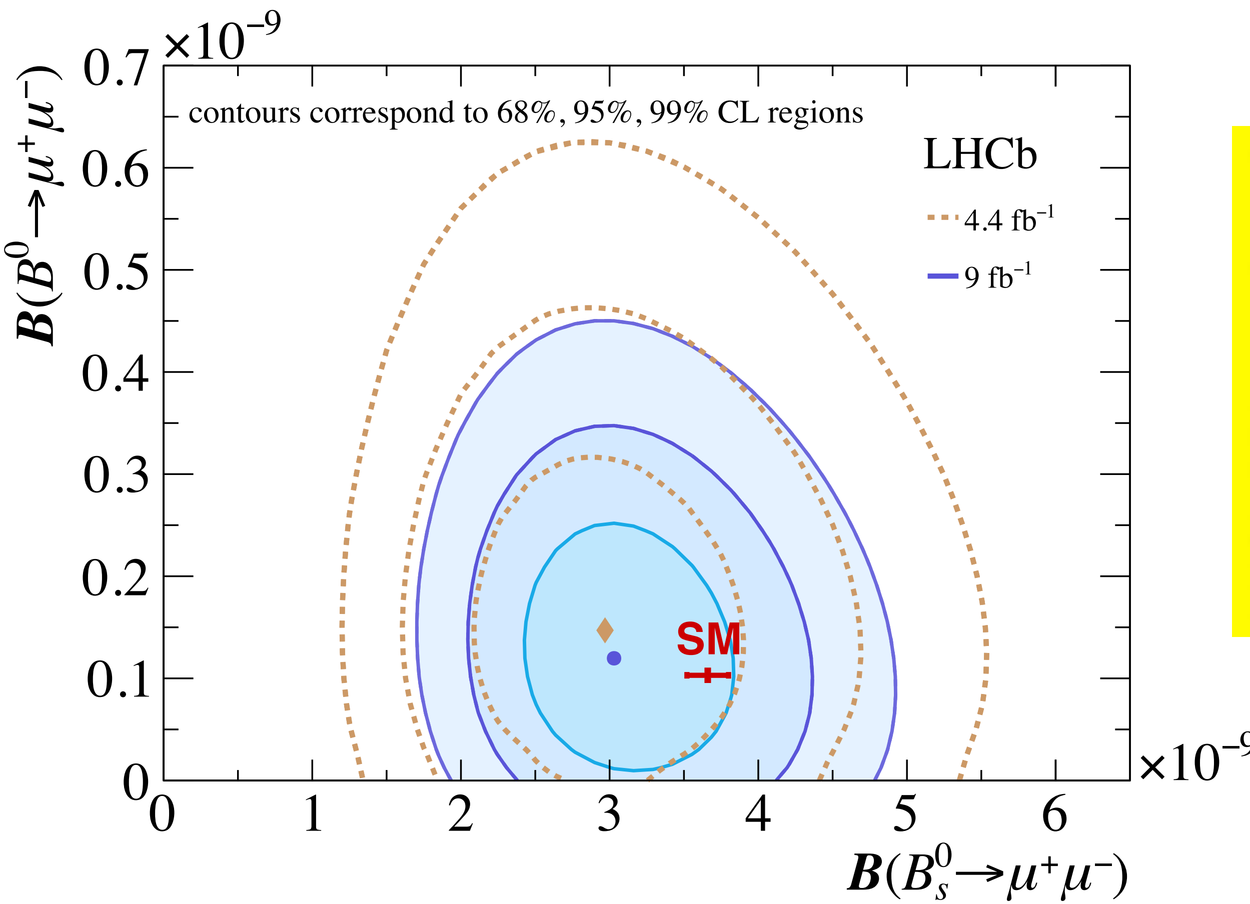

LHCb PRL 128 (2022)

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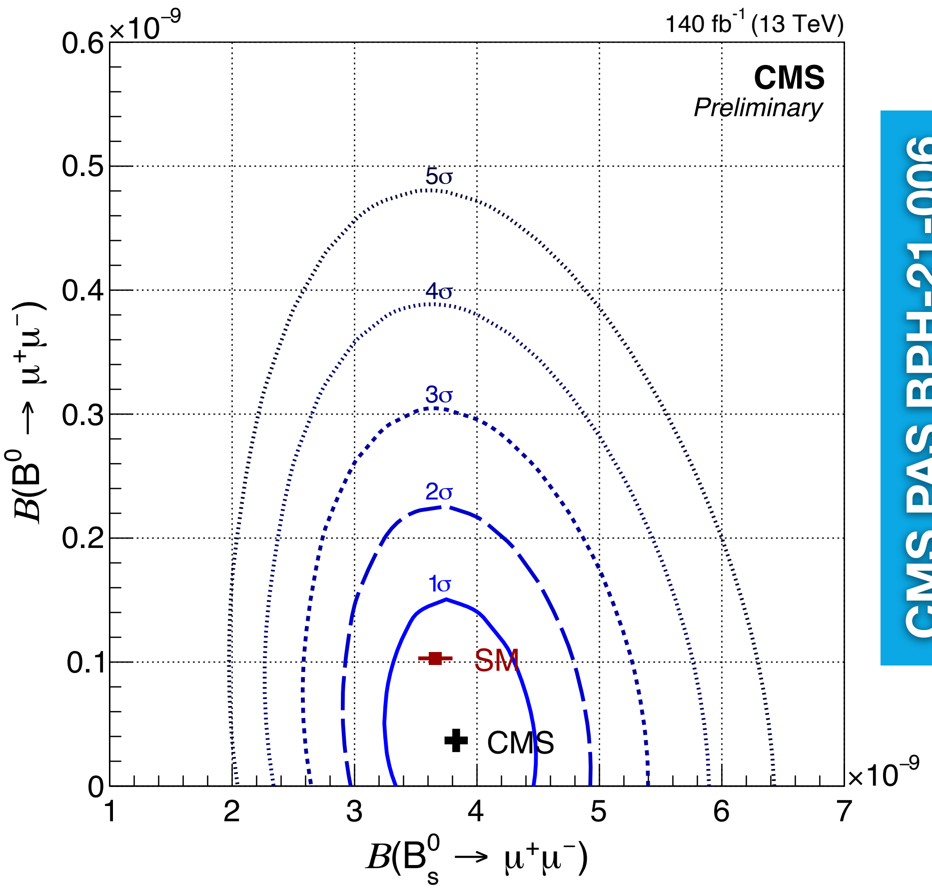
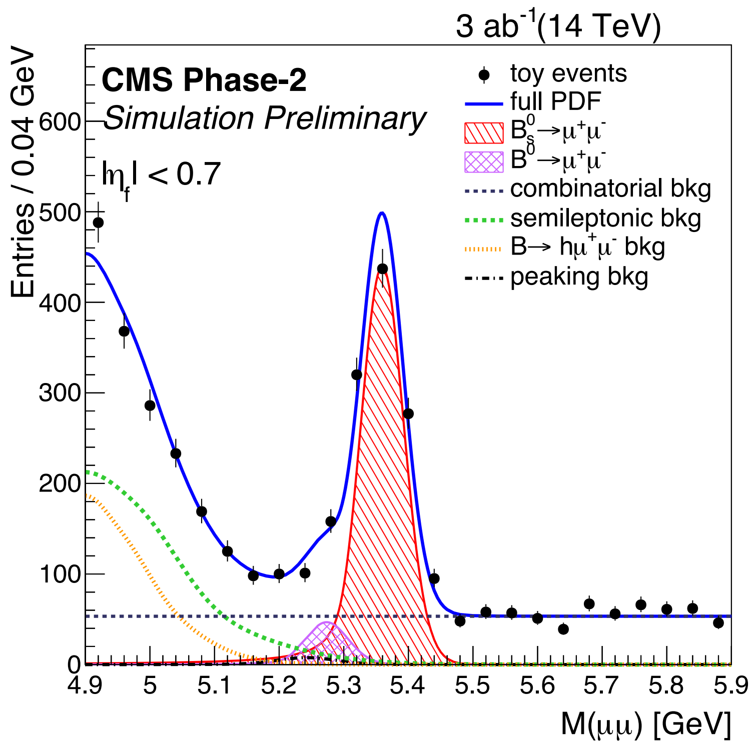


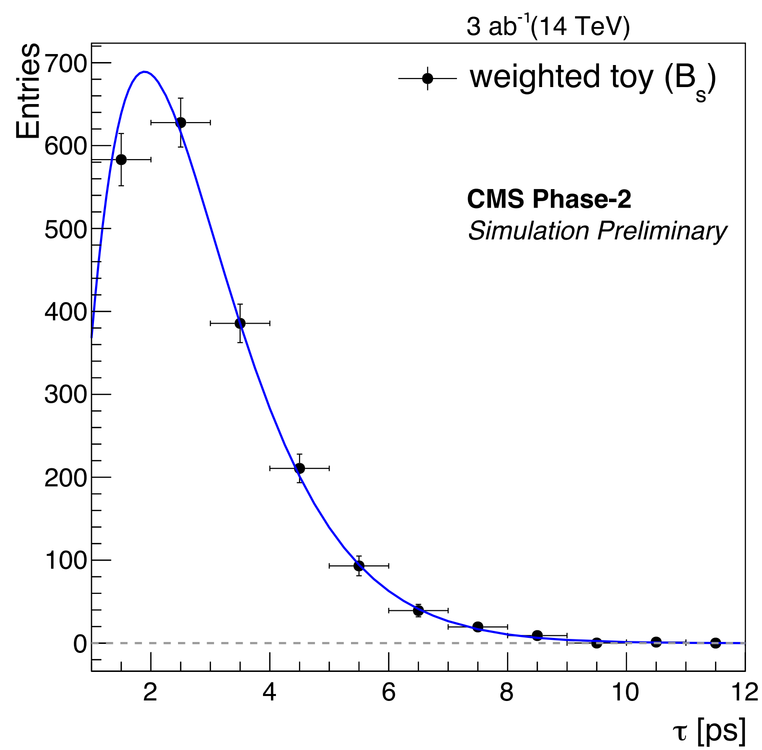
CMS PAS BPH-21-006

$B_s(\mu\mu)$ Prospective

- For the B(μμ) 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

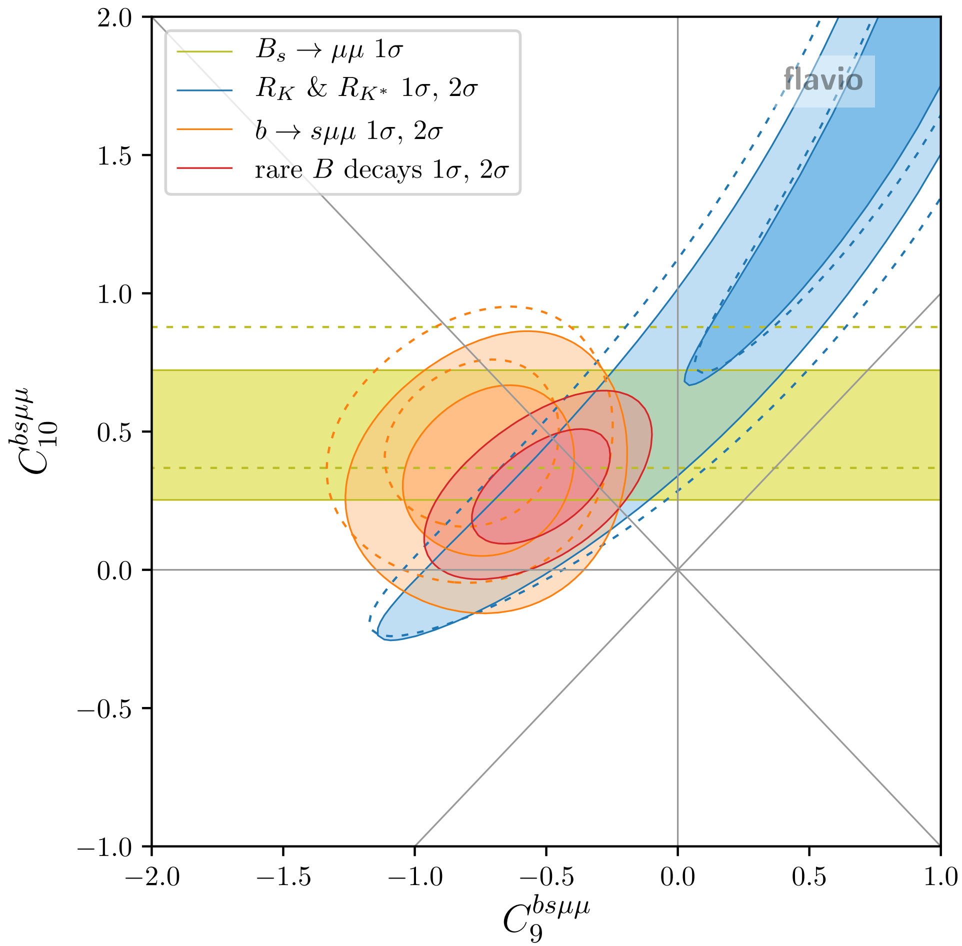




$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps

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

✦ Connection to flavour anomalies



Altmannshofer, Stangl, EPJC 81 (2021) 952

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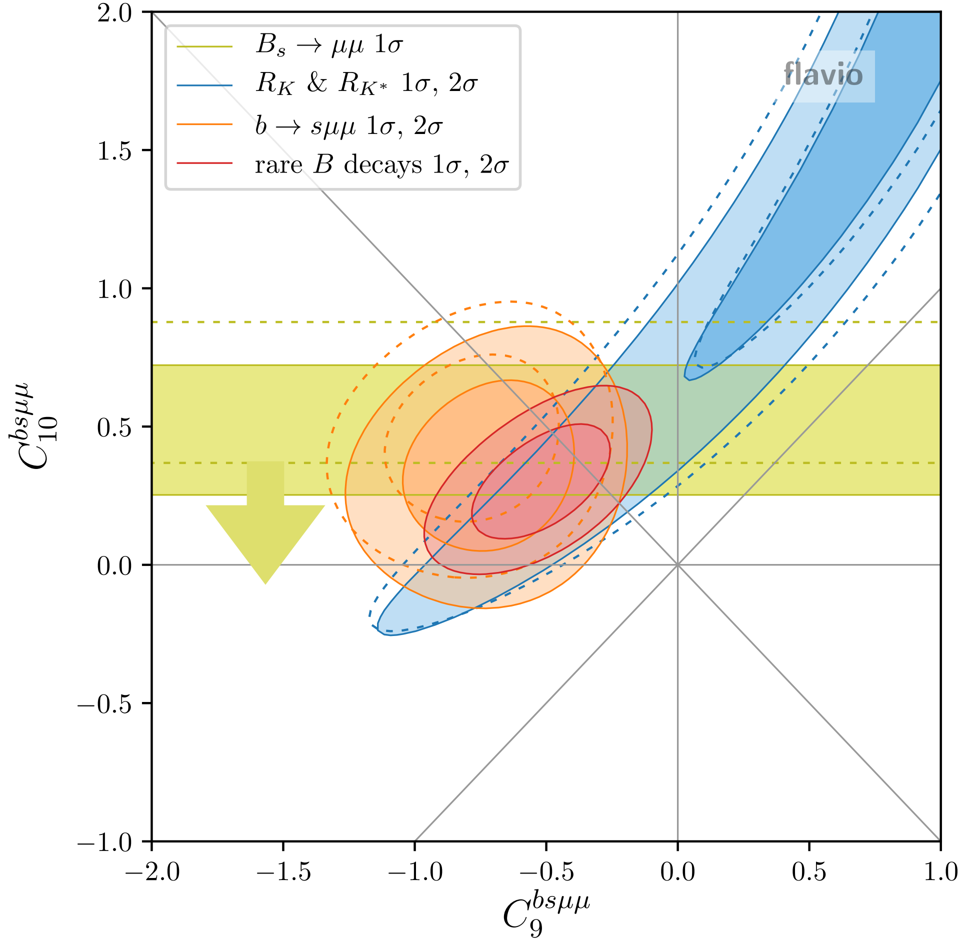


Altmannshofer, Stangl, EPJC 81 (2021) 952

FFR Woes

- There is a connection between tests of flavour anomalies in $b \to s\ell\ell$ 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

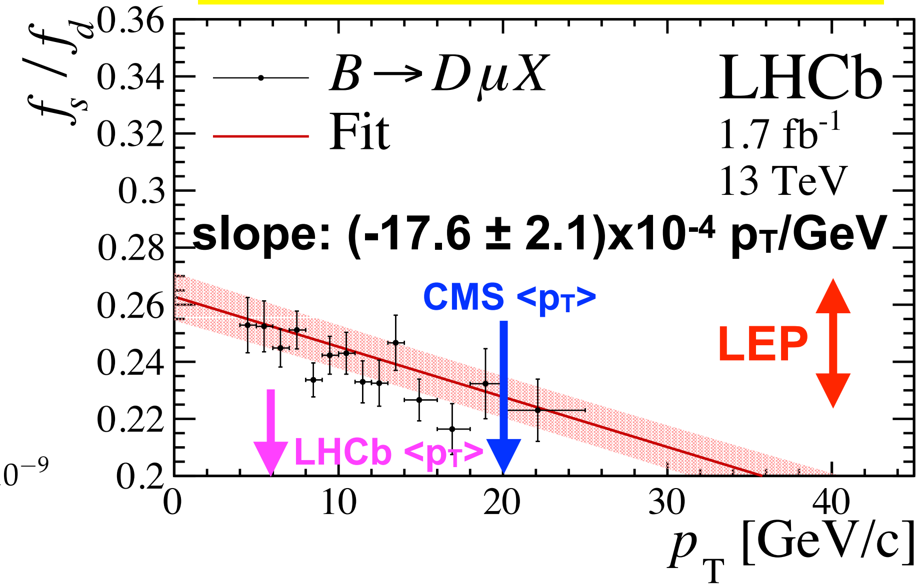
On the Normalization

- 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:

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

so it's important to reduce it!
    - N.B. 0.008 is aggressive if the linear p_T dependence is not confirmed!

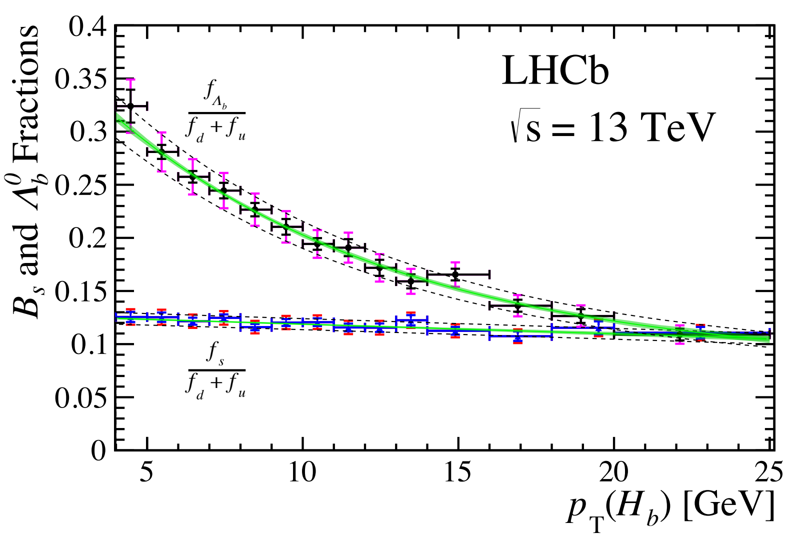
LHCb PRD 104 (2021) 032005



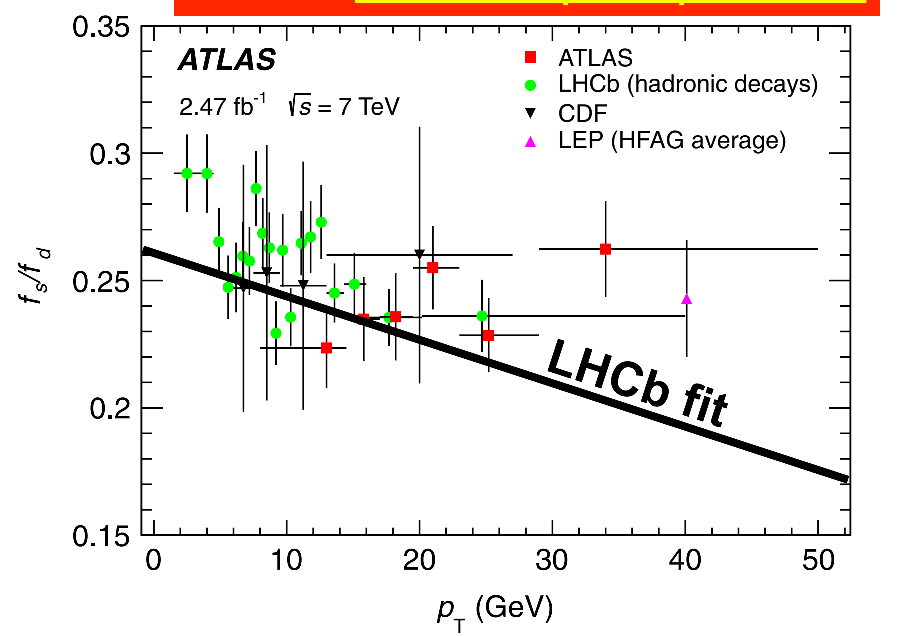
The p_T Dependence?

- The jury is still out whether the linear slope suggested by LHCb holds
- There is undoubtedly a strong p_T dependence for the Λ_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



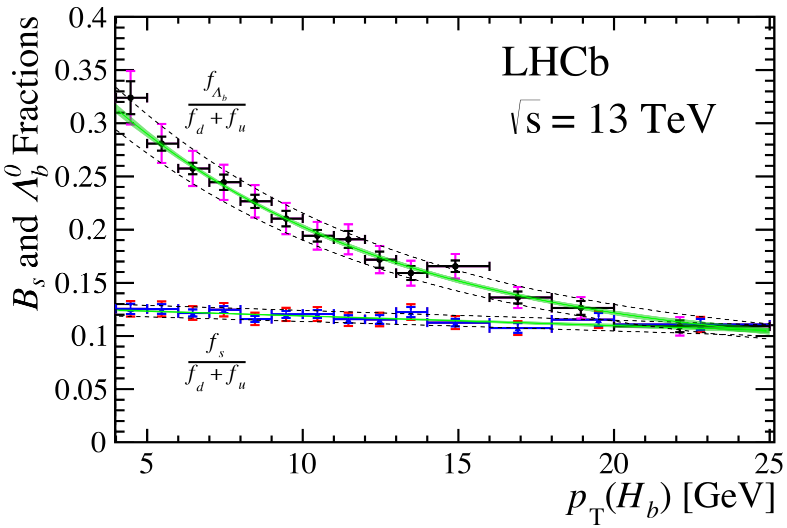
ATLAS PRL 115 (2015) 262001



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 Λ_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



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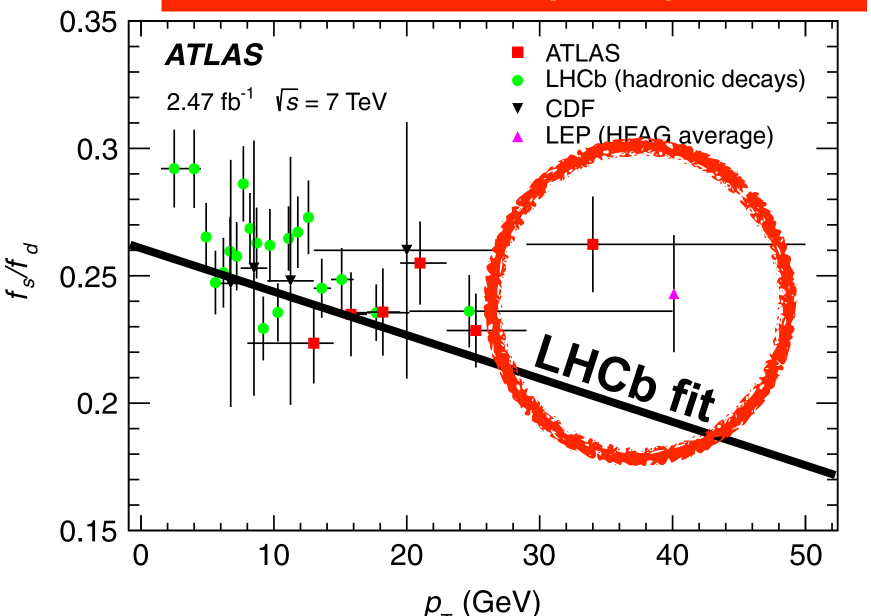

World Average f_s/f_d

- 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 ± 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	0.239 ± 0.007 (7 TeV)
			0.239 ± 0.008 (8 TeV)
			0.254 ± 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 Υ(5S) measurements to make a breakthrough in precision
  - Why don't they run on the Υ(5S) first??? 😃

FFR Measurements - I

- Three main methods are used at the LHC
  - Semileptonic decays with charm ($B_{(s)} \to D_{(s)}X\mu\nu$)
    - 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 ($B_{(s)} \rightarrow D_{(s)}K$; $D_{(s)}\pi$)
  - 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 $B_{(s)} \rightarrow D_{(s)}$ ratio, N_F (discussed later)
  - Experimental advantage: fully reconstructible decays largely remove contamination from excited states
- Hadronic decays with charmonium ($B_{(s)} \rightarrow J/\psi K^*(\phi)$)
  - 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) ± 0.010 (syst) ± 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

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 $\mathcal{B}(B_s \to D_s^-\pi^+)$ is dominated by LHCb and uses f_s/f_d as an input): $\mathcal{B}(B_s \to D_s^-\pi^+) = (3.20 \pm 0.10 \pm 0.16)\times10^{-3}$
- Belle measurement has a 20% uncertainty: $\mathcal{B}(B_s \to D_s^-\pi^+) = (3.6 \pm 0.5 \pm 0.5)\times10^{-3}$ - 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 ± 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]
$\mathcal{N}_a$ Non-fact. corr.	1.000 ± 0.020	[36]
$\mathcal{N}_F$ Form factors	1.000 ± 0.042	[19, 40]
$\mathcal{N}_E$ For Dπ decay	0.966 ± 0.062	[7, 36]
$\lvert V_{us}\rvert f_K/\lvert V_{ud}\rvert f_\pi$	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 4σ 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 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

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: $\mathcal{B}(B^0 \to D^-K^+)/\mathcal{B}(B^0 \to D^-\pi^+)$
  - This ratio is known to a rather fine 3.3% precision [PDG]: $(8.22 \pm 0.11 \pm 0.25)\%$
  - This is 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 $\mathcal{B}(B_s \to J/\psi\phi)/\mathcal{B}(B_s \to D_s\pi)$ (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: $R^{\pm 0} \equiv \dfrac{\mathcal{B}(\Upsilon(4S) \to B^+B^-)}{\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)} = 1$
- 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 $\psi(3770) \rightarrow DD$ and $\phi \rightarrow KK$ 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): $R^{\pm 0} = 1.059 \pm 0.027$ (2.2σ 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]

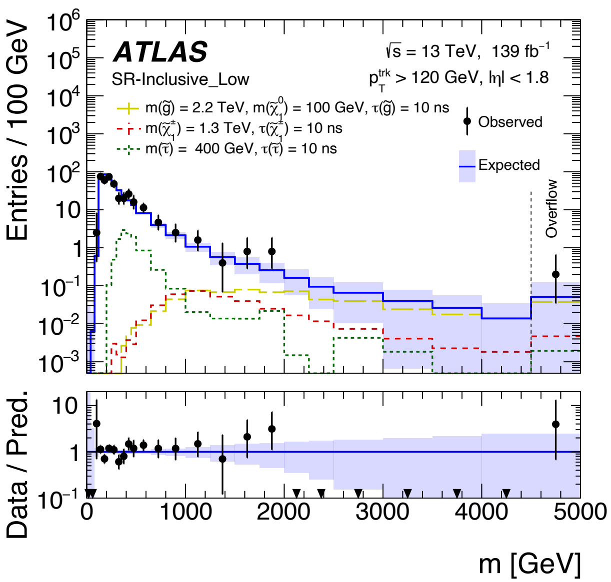
Thank You!

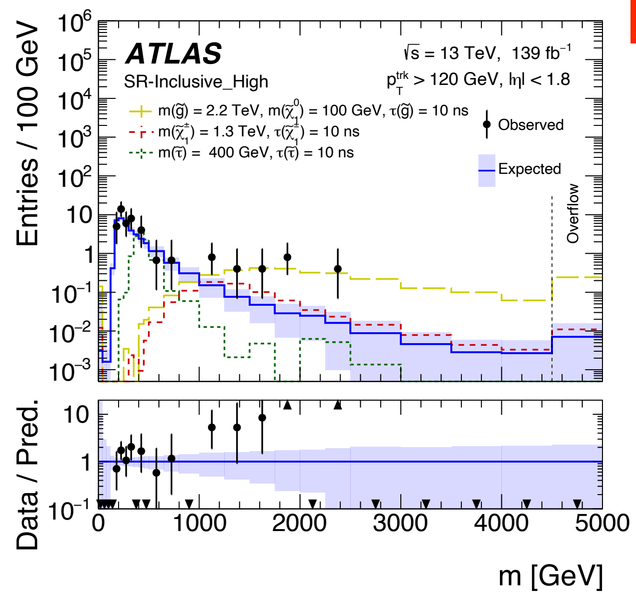
High-p_T Run 2 Excesses

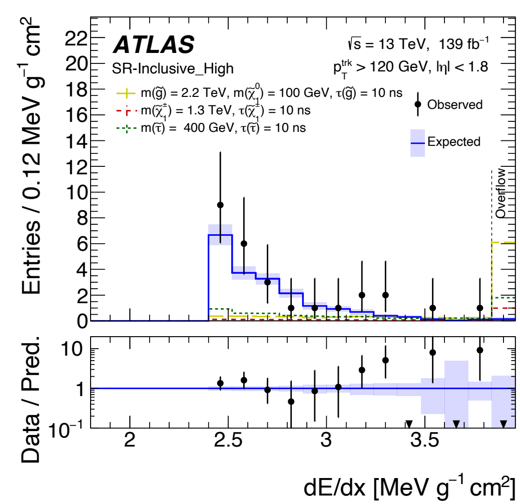
ATLAS LLP dE/dx Excess

- Search based on high-p_T and high-dE/dx tracks in the ATLAS pixel detector
  - ★ Dedicated time-dependent calibration accounting for the pixel detector aging
  - ★ dE/dx to βγ calibration based on dedicated low-pileup run
- Several signal regions, as well as a number of control and validation regions for background estimation
- An excess of high-dE/dx events in the 1.1-2.8 TeV mass window is seen, with the local (global) significance of 3.6 (3.3)σ
- Excess events very scanned for pixel detector pathologies, and none were found
- However, the time-of-flight information for these events is consistent with β = 1 (which is not inconsistent with the dE/dx results for |q| > e)

ATLAS, arXiv:2205.06013



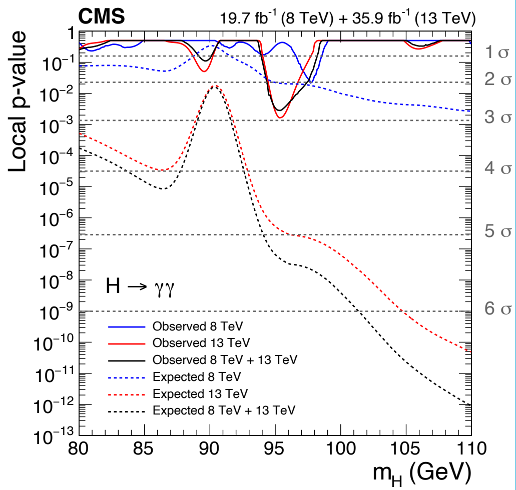




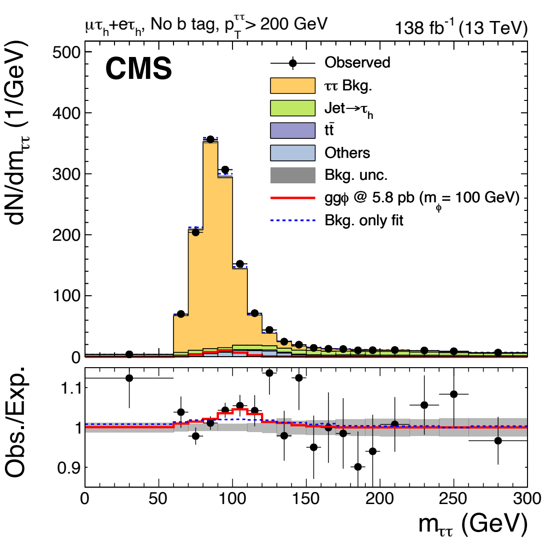
No competitive CMS results yet

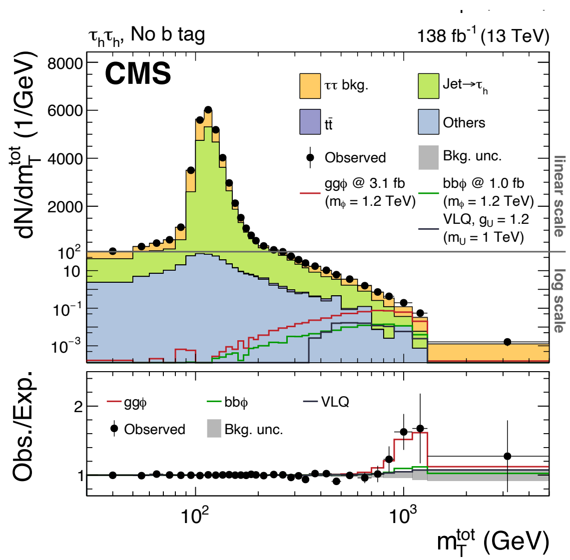
CMS ~0.1 and ~1.2 TeV ττ Excesses

- Search for MSSM Higgs bosons decaying into the ττ final state also reinterpreted as a search for VLQs
  - ★ Sophisticated background prediction using the "τ-embedding" method
- Two ~3σ excesses are seen in the ditau mass distributions (or its proxy) around 0.1 and 1.2 TeV
  - ★ Excesses are reasonably distributed between various ττ decay channels
  - ★ The ~100 GeV excess appears to be well aligned with the low-mass diphoton excess seen in an earlier analysis of Run 1 + 2016 data

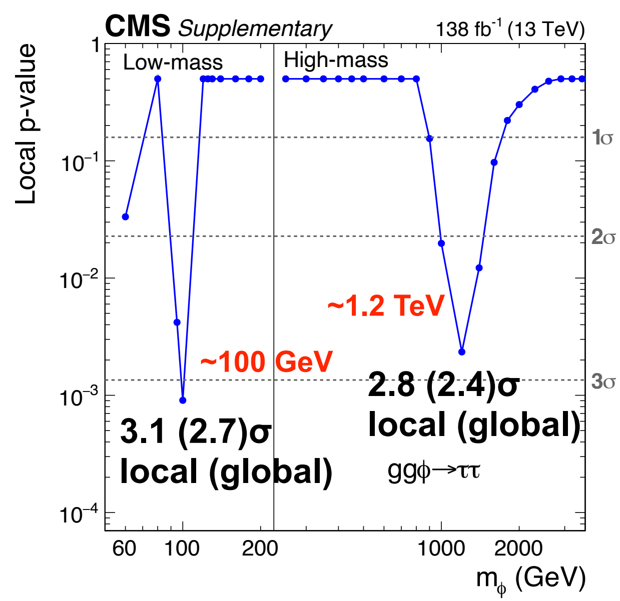


CMS, PLB 793 (2019) 320



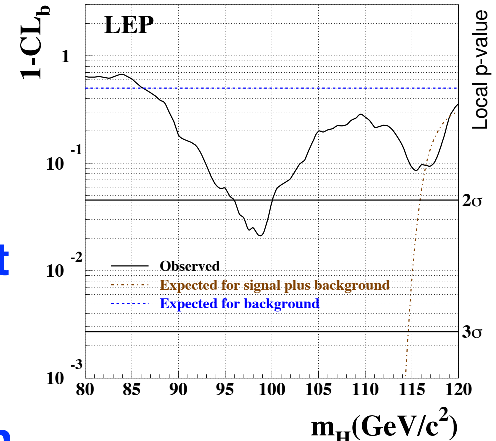


CMS, arXiv:2208.02717

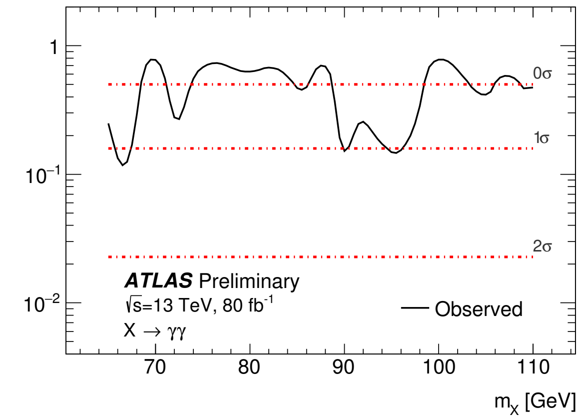


What Does ATLAS See?

- No full Run 2 result in low-mass diphoton channel yet
  - ★ The 2016 ATLAS result is not inconsistent with the CMS one
- The full Run 2 MSSM H(ττ) result contradicts the 1.2 TeV excess seen in CMS
- The 95-96 GeV light Higgs boson has long been a subject of theoretical interest since an old LEP hint in the H(bb) channel

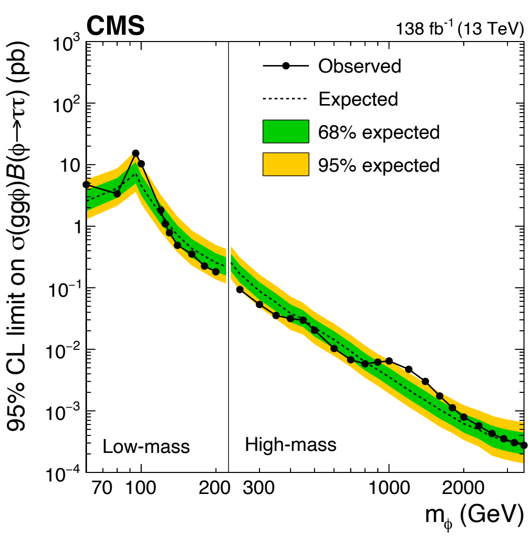


ADLO, hep-ex/0306033

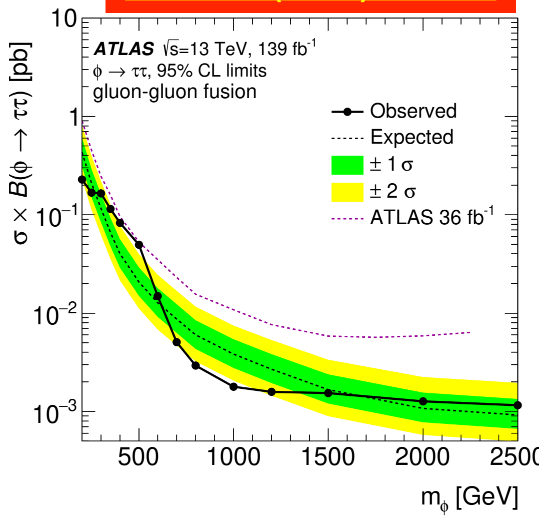


ATLAS-CONF-2018-025

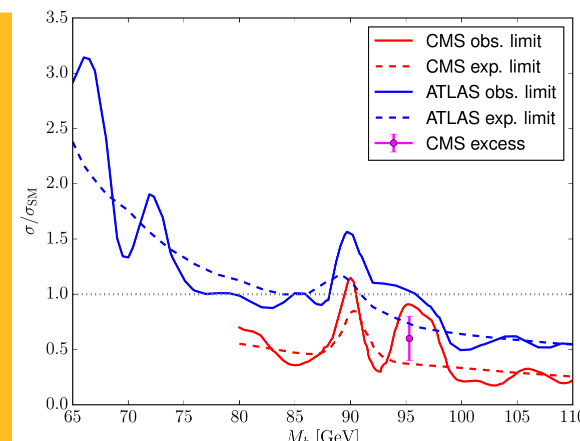
CMS, arXiv:2208.02717



ATLAS
PRL 125 (2020) 051801



Heinemeyer, Stefaniak
arXiv:1812.05864

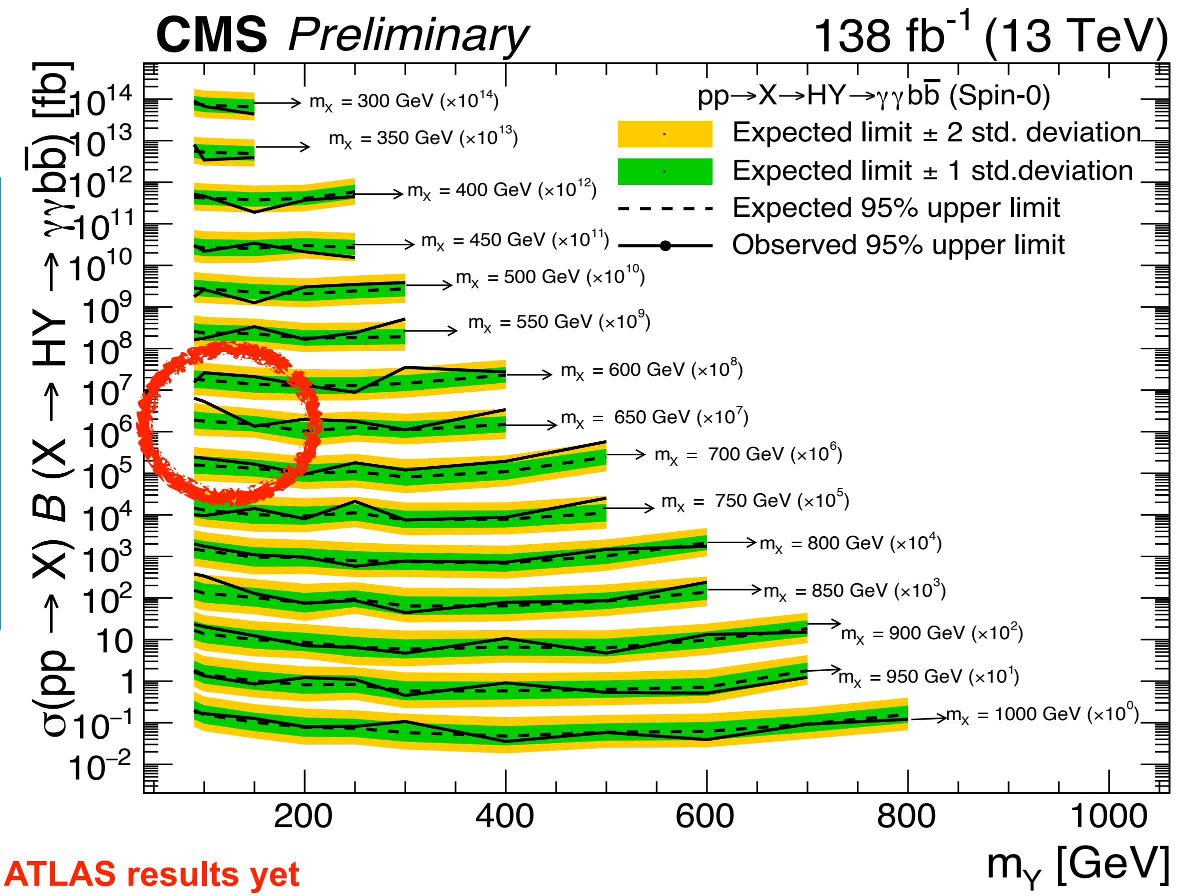


Looking forward to ATLAS 139 fb^{-1} updates in the γγ channel!

CMS Y(bb)H(γγ) Excess

- Recent preliminary result from CMS on resonant search in the $X \to Y(bb)H(\gamma\gamma)$ channel
  - ★ See ~3.5σ (2.8σ globally) excess at M(bb) ~100 GeV, M(X) = 650 GeV

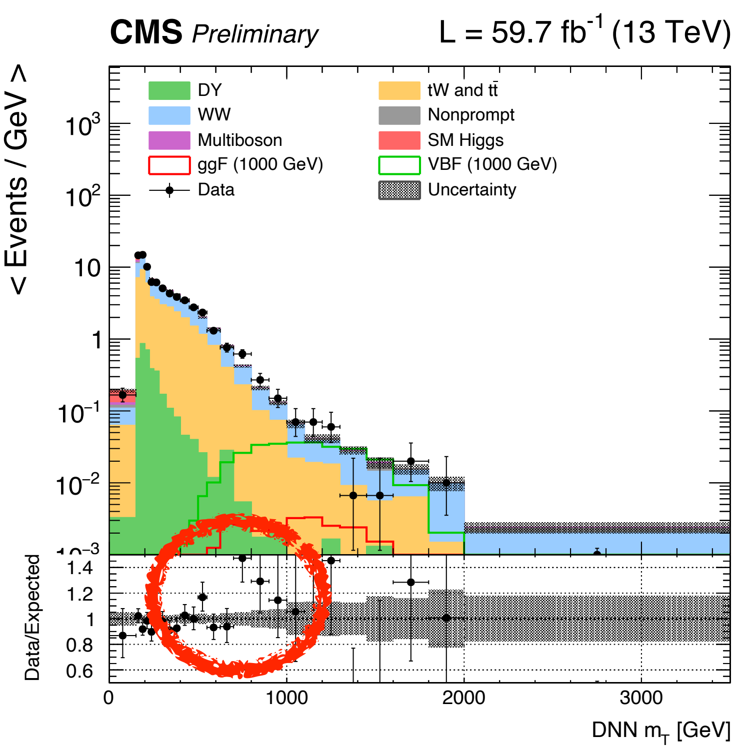
CMS-PAS-HIG-21-011



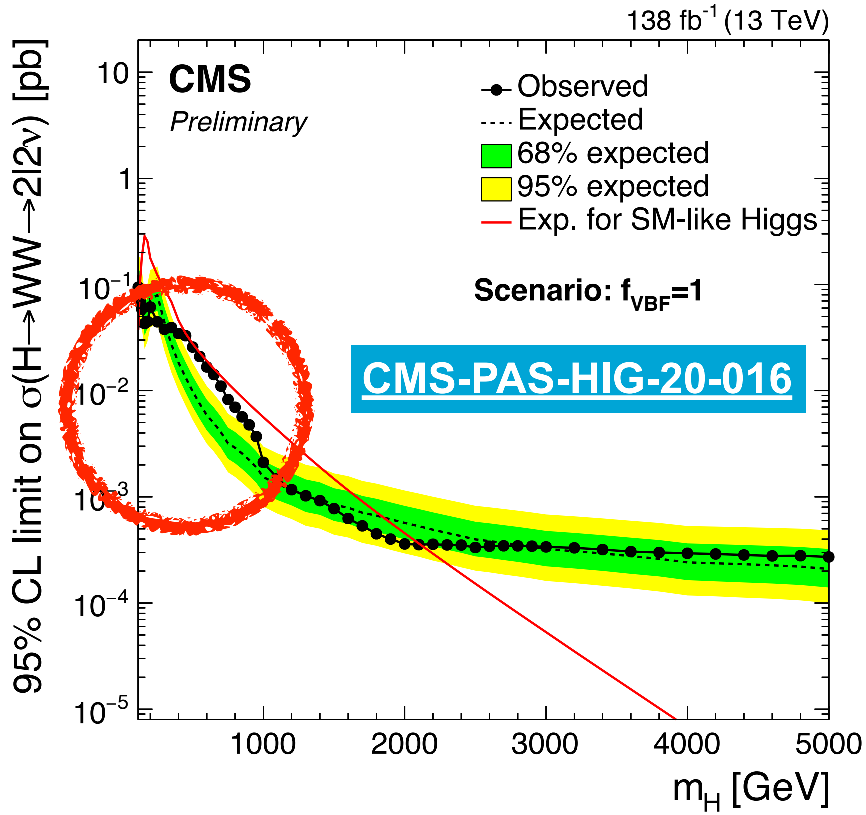
No competitive ATLAS results yet

Excess in H(WW) Search?

- **Curiously, a 650 GeV bump is also observed in the recent CMS high-mass H(WW) search in dilepton channel (low resolution), but only in the VBF category with a 3.8σ (2.8σ global) significance**
  - ★ **ATLAS 2016 leptonic H(WW) doesn't have an excess, but the sensitivity is not sufficient to rule out the CMS excess; neither does the full Run 2 Z'(WW) semileptonic analysis**
  - ★ **However, there is a small VBF H(ZZ → 4l + 2l2ν) excess at 620 GeV (2.4σ; 0.9σ global) in the ATLAS data**



CMS-PAS-HIG-20-016



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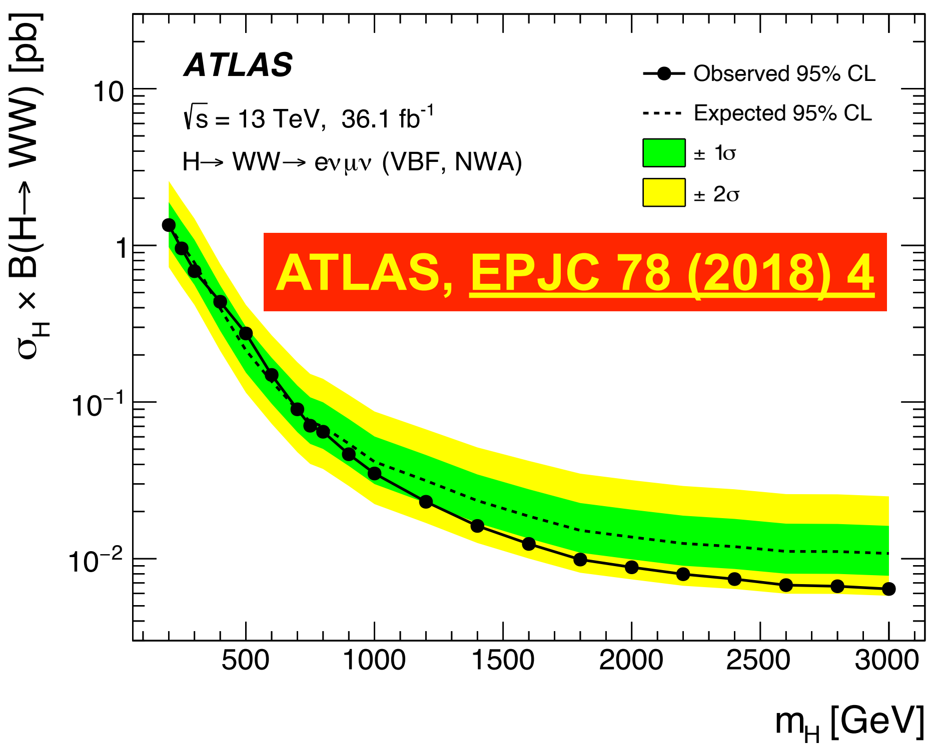

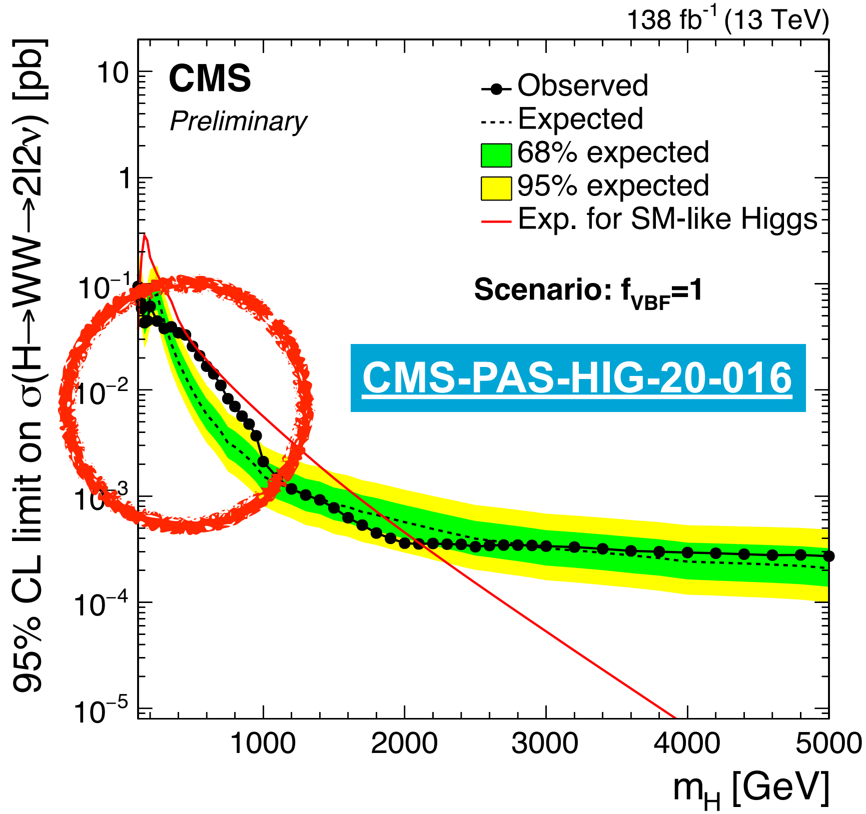

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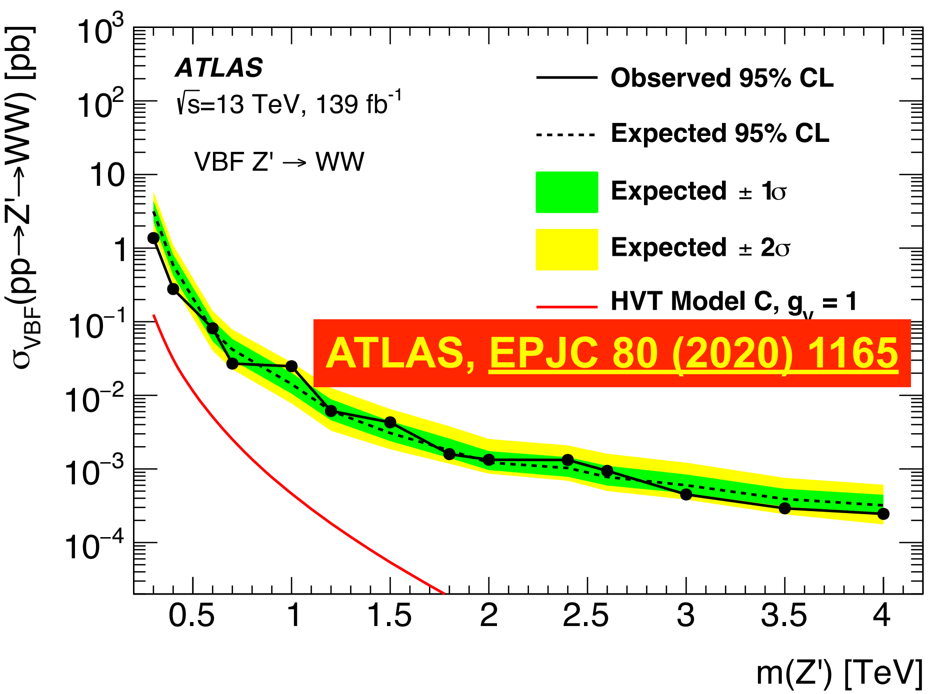
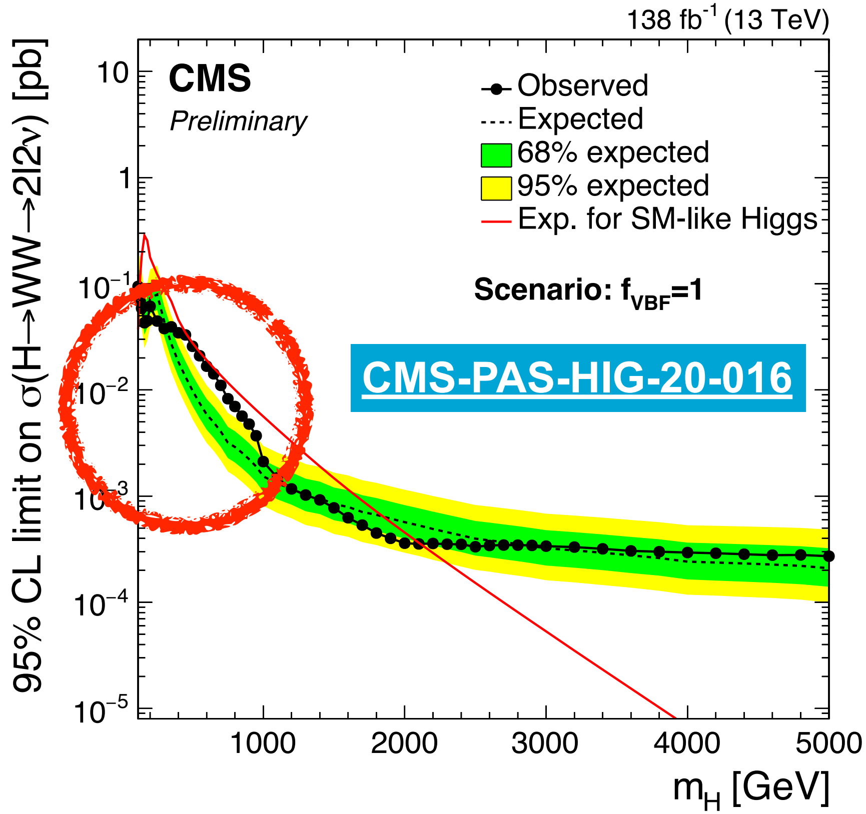


ATLAS, EPJC 80 (2020) 1165



CMS-PAS-HIG-20-016

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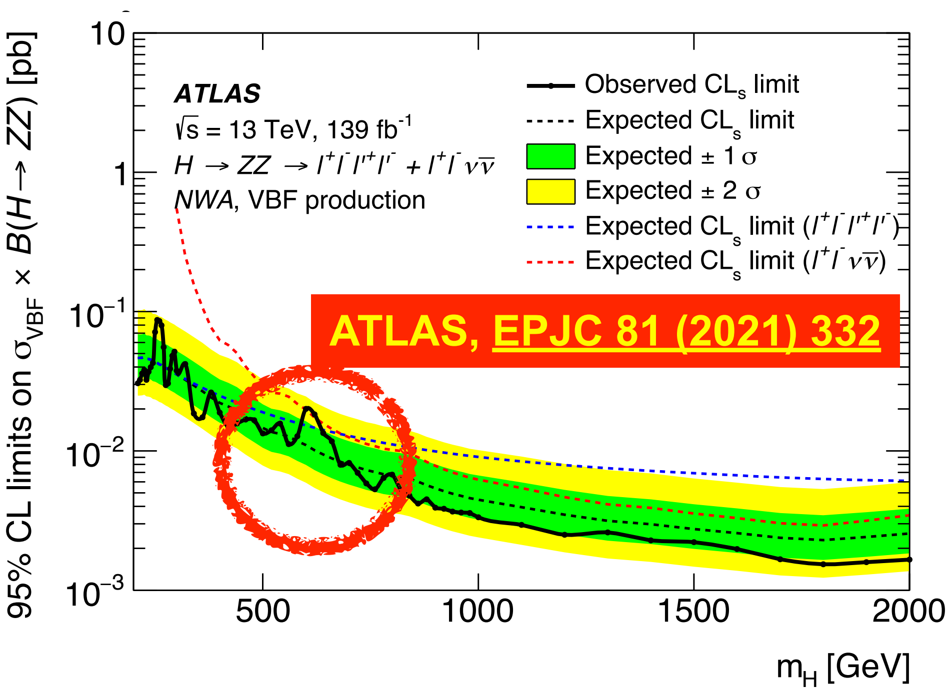
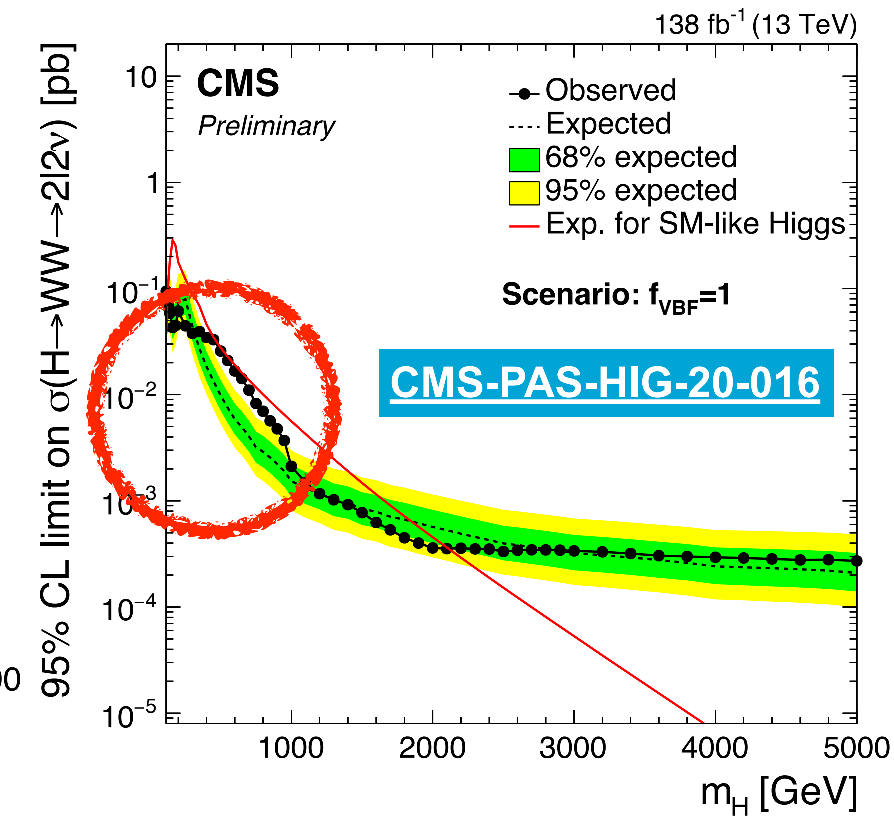
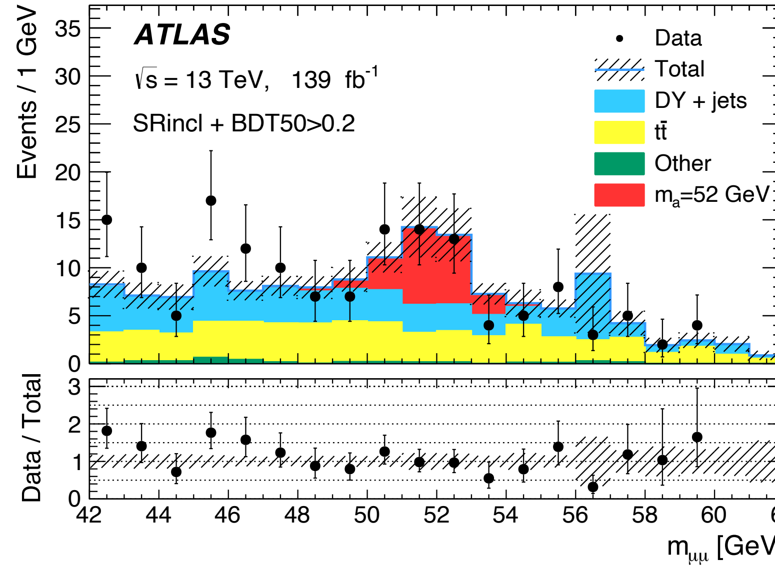
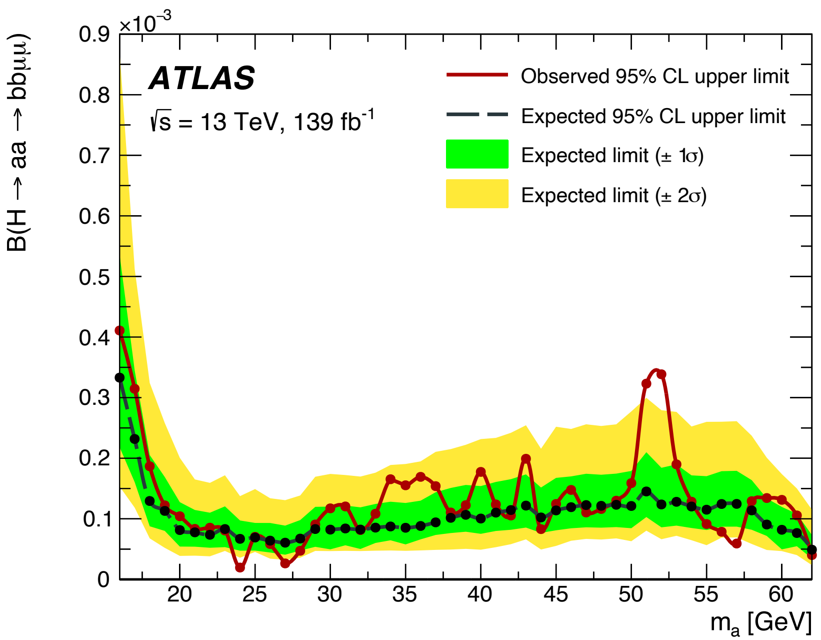




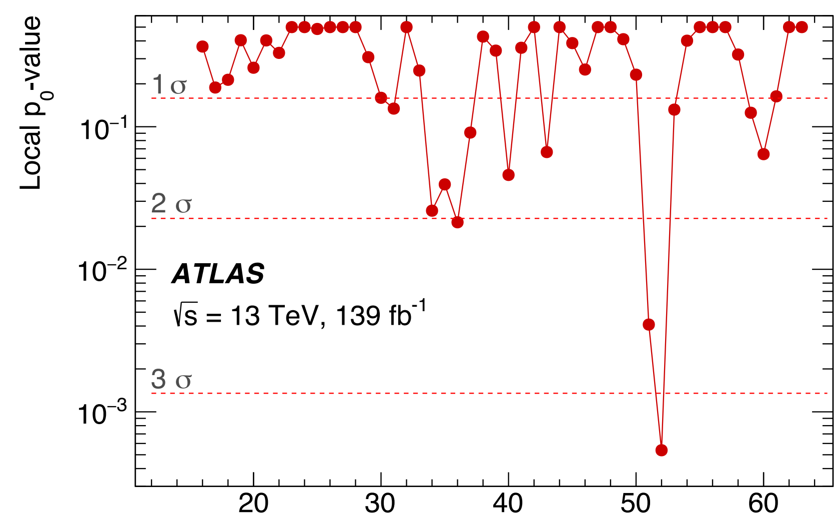
ATLAS H → a(bb)a(μμ) Excess

- An excess observed in a Run 2 search looking for H → a(bb)a(μμ) in high-resolution dimuon mass distribution
  - ★ Local (global) significance of 3.3 (1.7)σ at M(a) = 52 GeV





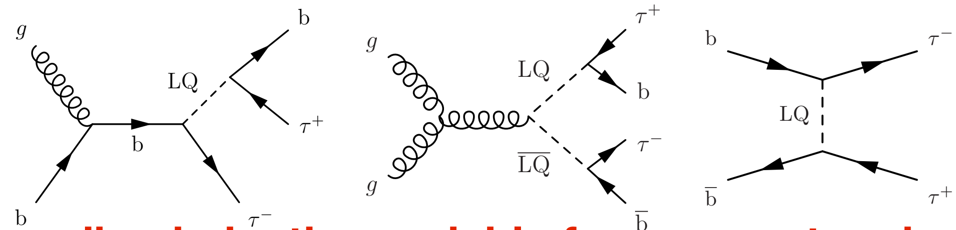
ATLAS, PRD 105 (2022) 012006



No competitive CMS results yet

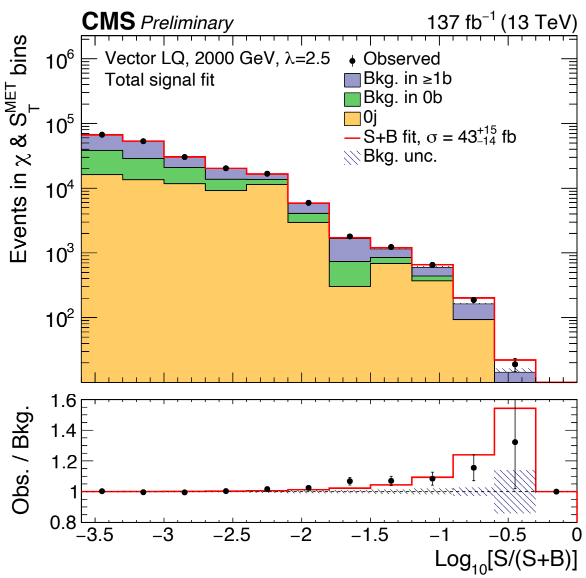
CMS Excess in LQ3 Search

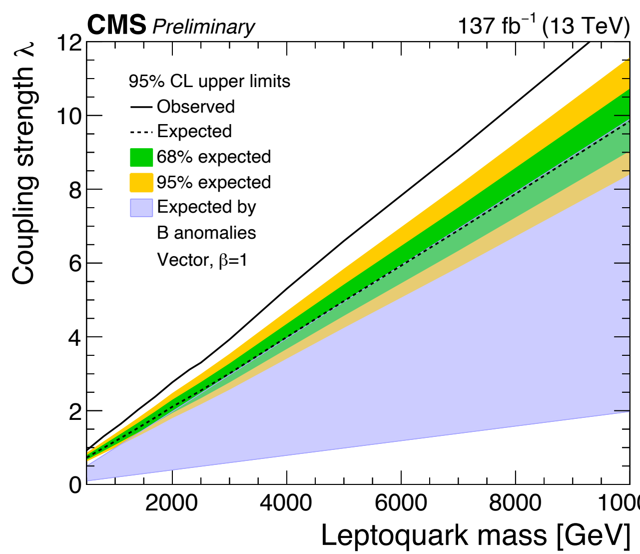
- Another preliminary result from CMS, inspired by the flavor anomalies
- Looks for single, pair, and t-channel production of LQ3 in the ττ+X final states



  - ★ Uses $S_T = \Sigma p_T(\tau) + p_T(j_1) + ME_T$ as a discriminating variable for resonant and $\chi = e^{-2y^*}$, where $y^* = |y_1 - y_2|/2$ the rapidity separation between two leading (tau) jets
- Global fit to multiple search regions for different LQ3 mass and couplings
  - ★ See ~3.5σ excess peaking in non-resonant production at large VLQ masses and couplings; no excess is seen for resonant production; global σ is hard to quantify

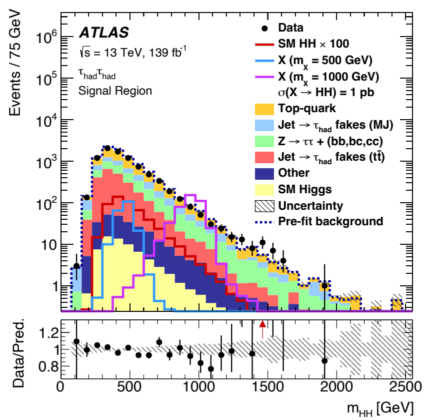
CMS-PAS-EXO-19-016

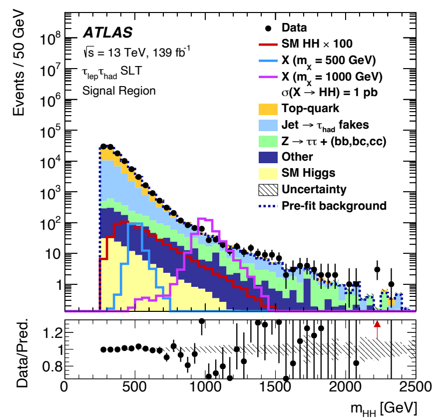


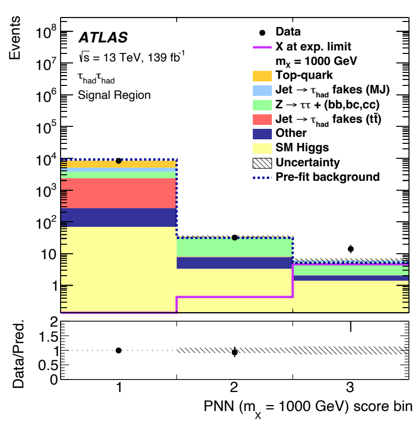


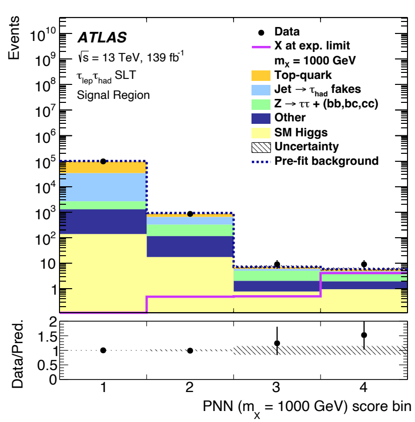
ATLAS H(ττ)H(bb) Search

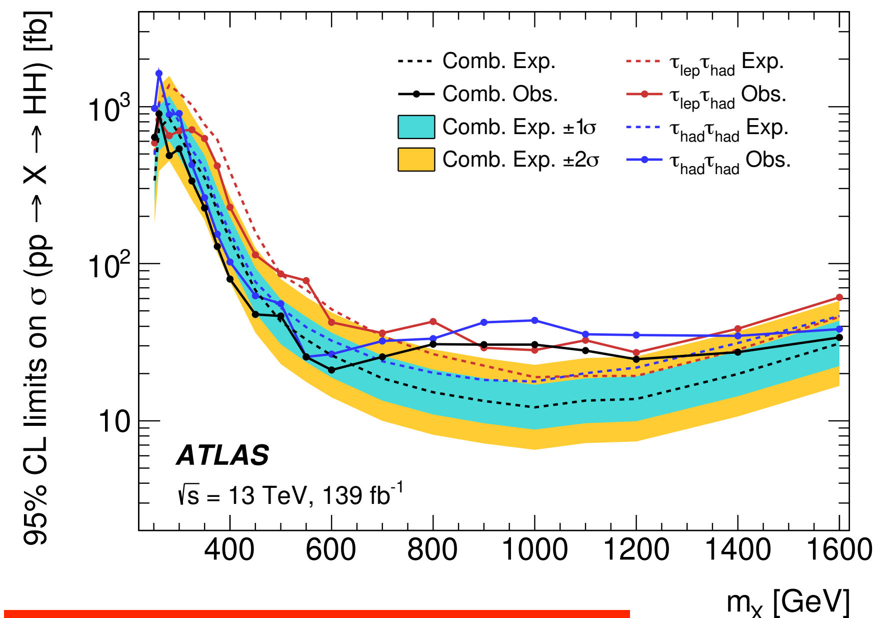
- **ATLAS reported a 3.1 (2.0)σ excess at about 1 TeV in an X → H(ττ)H(bb) resonant search**
  - ★ **An excess can be clearly seen only in the NN discriminant distribution; the mass spectrum before the NN application doesn't show a sizable excess**
  - ★ **Consistent excess in semileptonic and hadronic final states**
- **Not directly comparable with the CMS LQ3 excess but could be related**









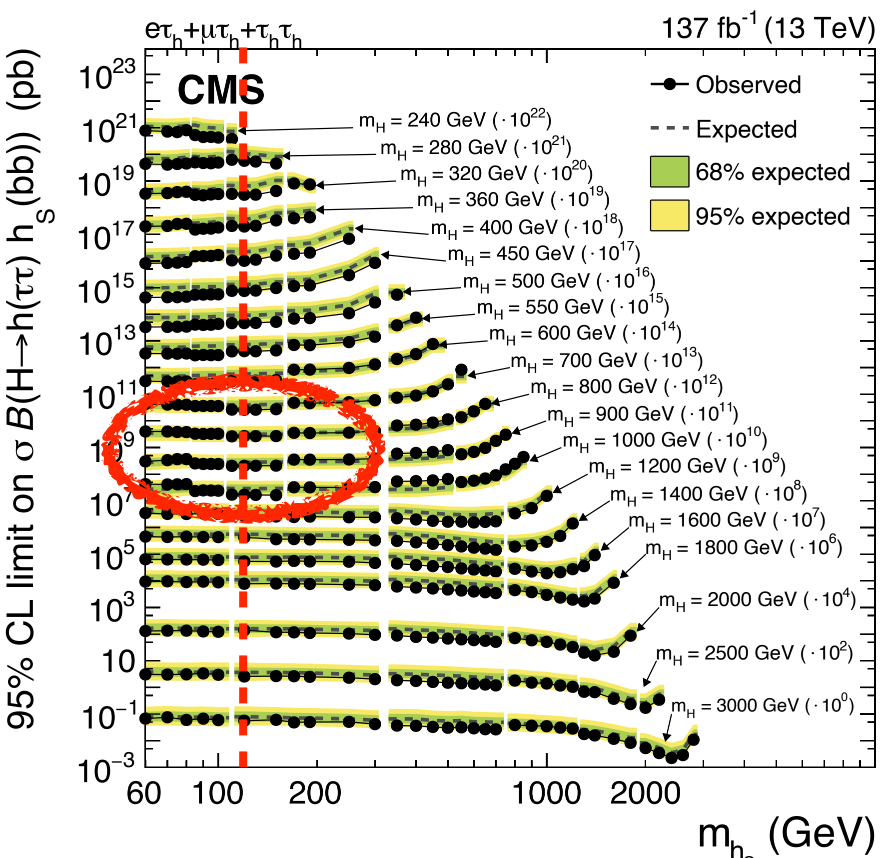


ATLAS, arXiv:2209.10910

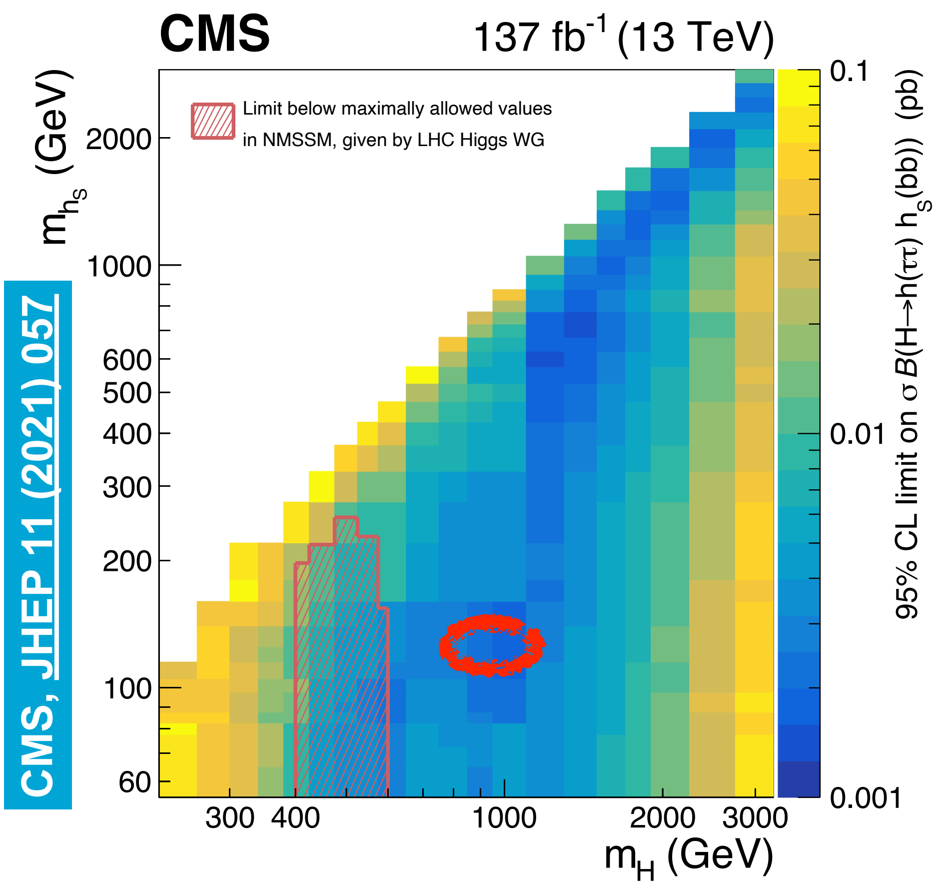
Greg Landsberg - LHC Run 2 Excesses

What About CMS?

- No resonant X → H(ττ)H(bb) results with full Run 2 data yet
- However, a search was done for H → H_{125}(ττ)h_s(bb), with h_s being a scalar in a broad mass range for H and h_s
  - ★ No excesses seen for m(h_s) = 125 GeV, with the cross section times branching fraction (7.3%) limit set ~2 fb, which is very similar to the ATLAS observed limit

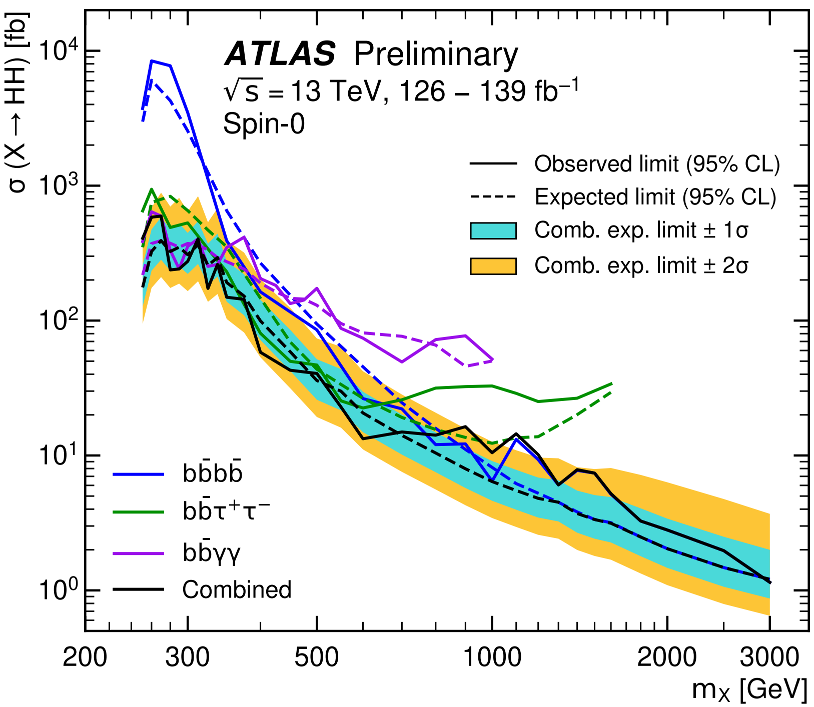


CMS, JHEP 11 (2021) 057

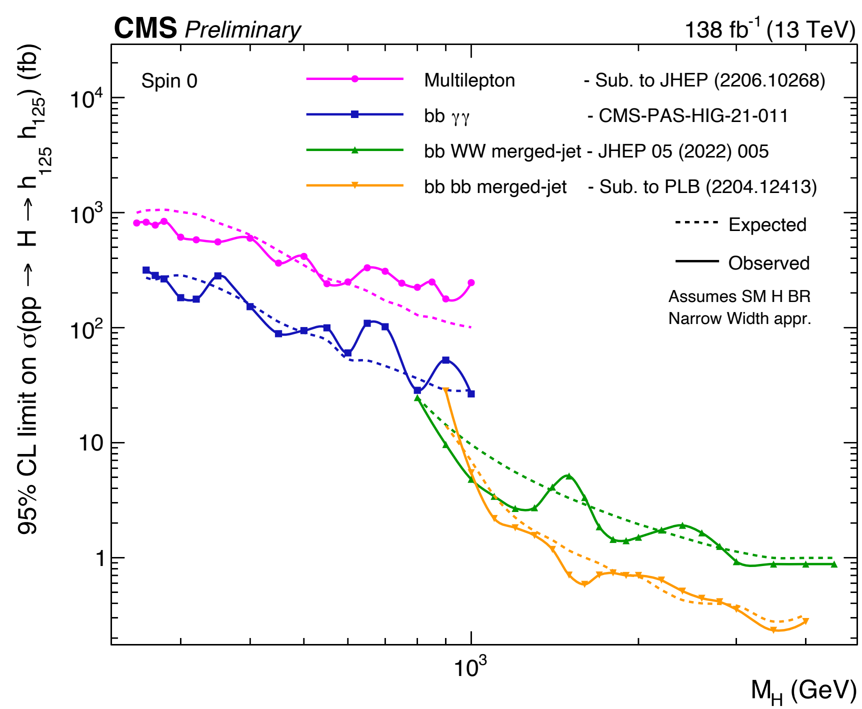


Other X → HH Searches

- Assuming that the H(bb)H(ττ) channel corresponds to the SM Higgs boson decays, the 1 TeV excess in ATLAS is still present at 3.2σ (2.1σ global) level
- However, CMS rules it out by X→HH searches in more sensitive channels
- This technically doesn't hold in the case when there is another boson with the mass ~125 GeV decaying into either bb or ττ with branching fraction different from the SM ones



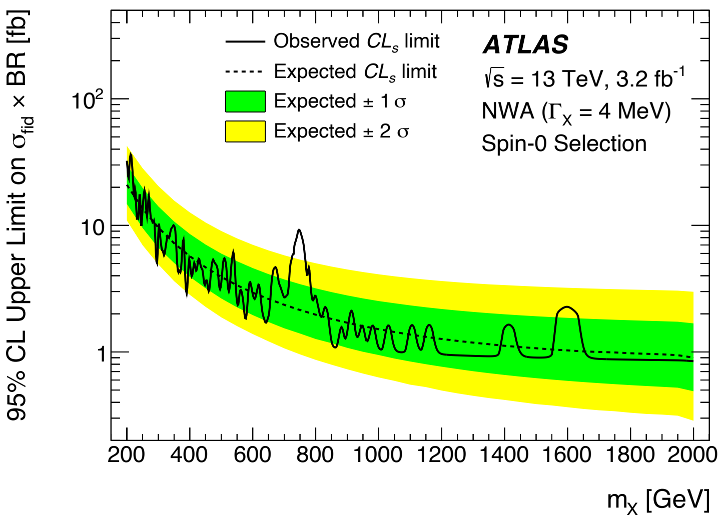
ATLAS-CONF-2021-052



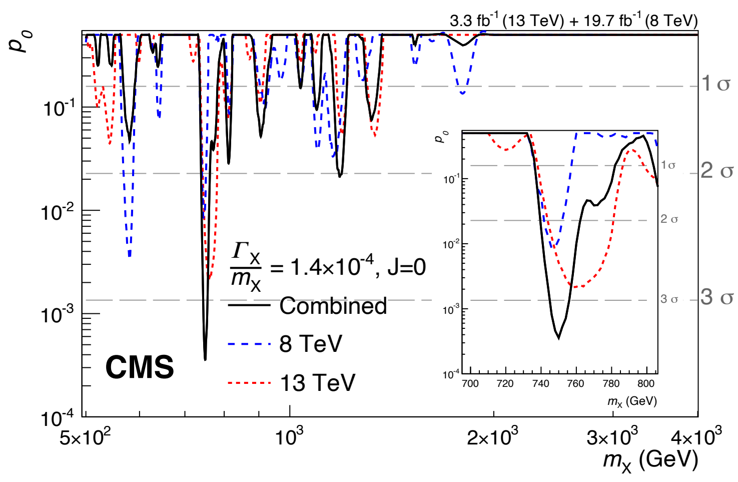
CMS, Summary HH Plot

Excited? - Memento 750!

ATLAS, JHEP 09 (2016) 001

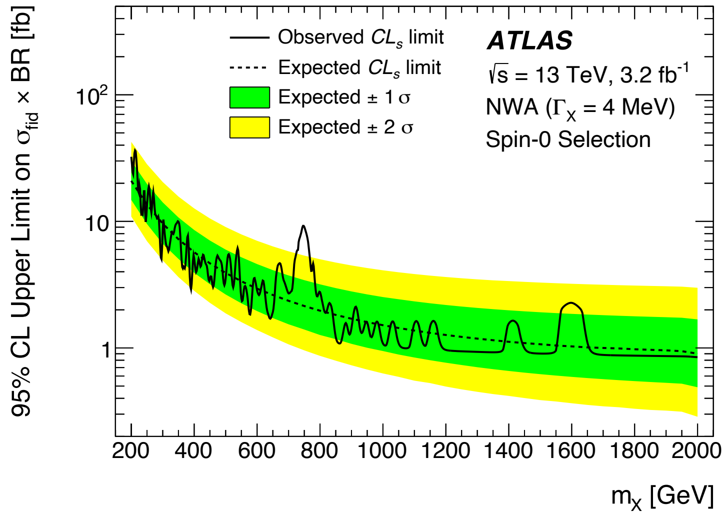


CMS, PRL 117 (2016) 051802

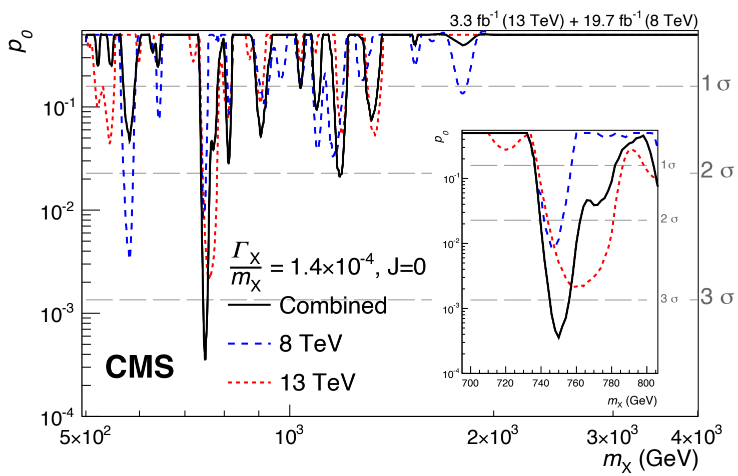


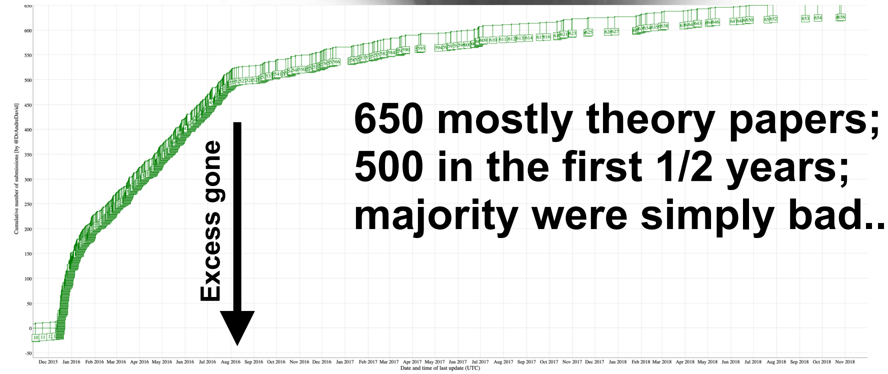
Excited? - Memento 750!

ATLAS, JHEP 09 (2016) 001



CMS, PRL 117 (2016) 051802





650 mostly theory papers;
500 in the first 1/2 years;
majority were simply bad...