Heavy Flavors at ATLAS and CMS

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28 Mar 2023

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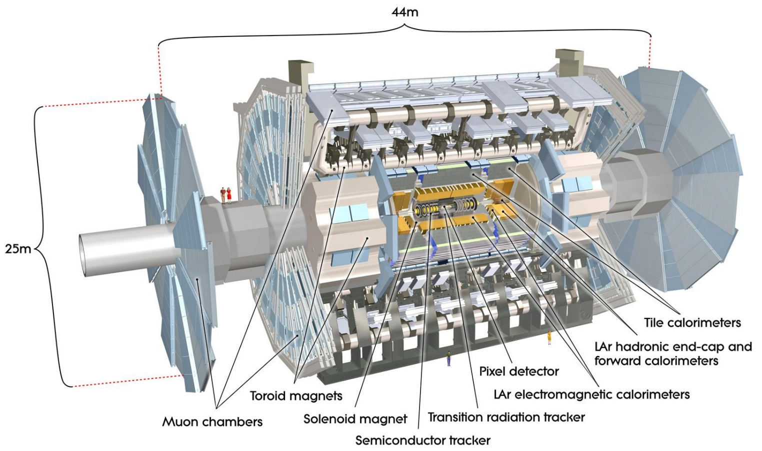
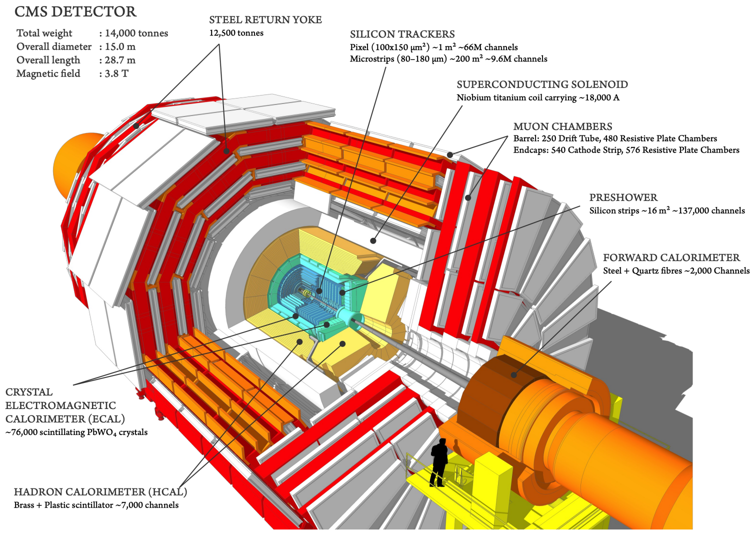
What do we look for?

- Searches for new physics:
  - precision measurement of weak hadron decays
  - rare/forbidden decay searches (including decays of leptons)
- Studies of emergent properties:
  - searches for new bound states in QCD, precision spectroscopy
- Tests of calculational abilities
  - Production cross sections, exclusive hadronic decays, ...

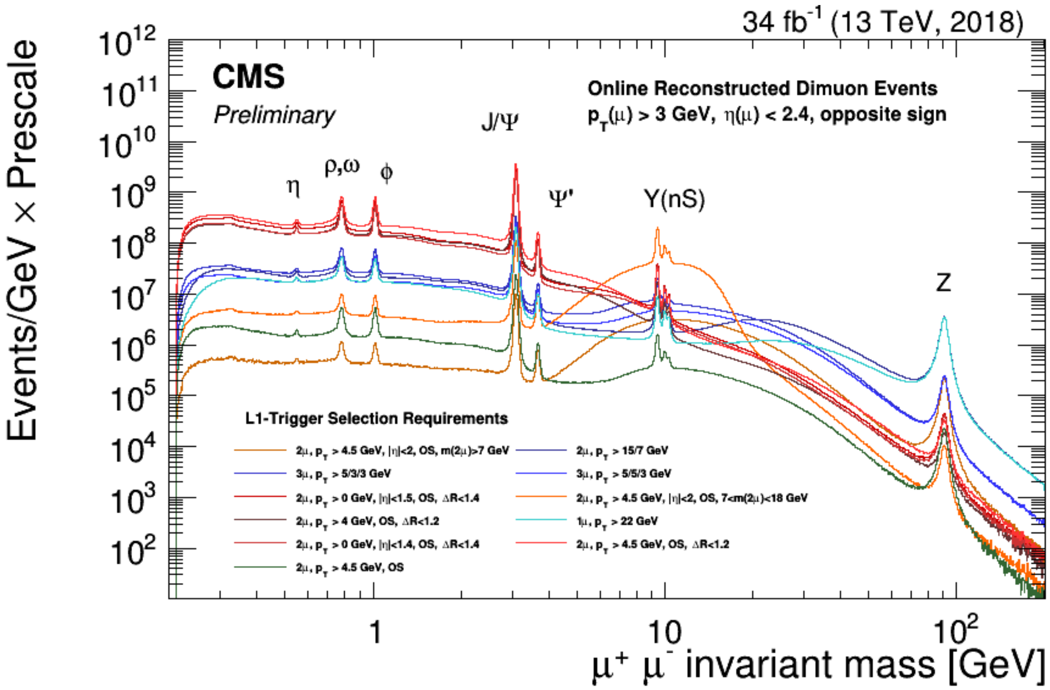
Features & Techniques

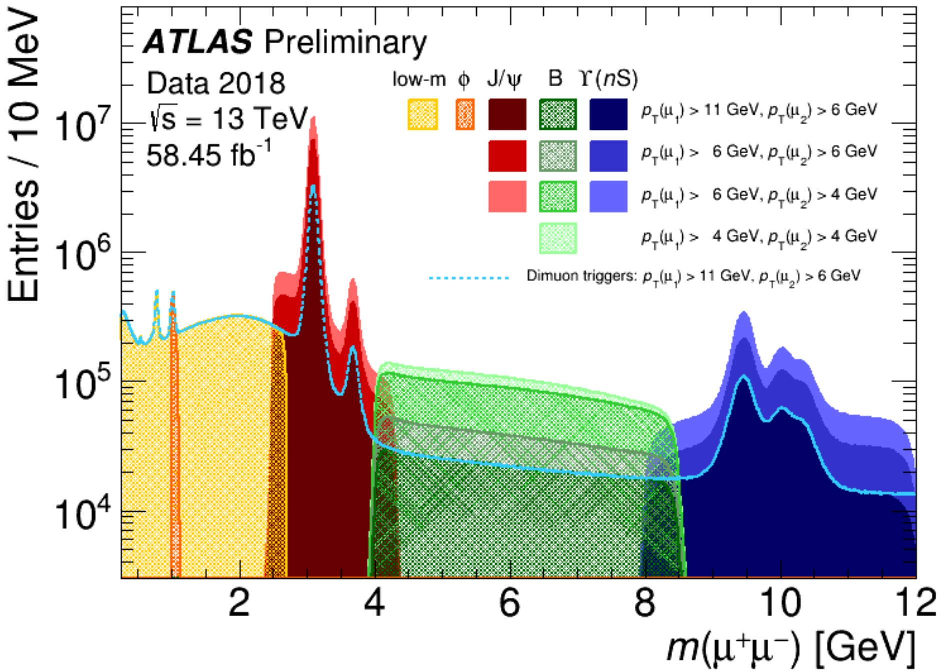
- Compared to Belle, BaBar:
  - Copious production of B_s, B_c, Λ_b, etc.
  - Can directly produce non-vector resonances
- Compared to LHCb:
  - CMS and ATLAS have central acceptance for tracks ($|\eta| \lesssim 2.5$)
  - Operated at full LHC pileup rate (up to ~ 60 collisions / bunch crossing) – higher lumi but much messier environment
  - Weak-to-nonexistent hadron particle ID
  - Kinematic acceptance effectively puts p_T cut on parent hadrons
  - Strong reliance on multi-muon triggers for physics program
- Often use specialized trigger techniques
  - ATLAS: "topological" triggers make selections using information from muon hardware trigger primitives; precision tracking, decay topology selections in software triggers
  - CMS: topological triggers; "data scouting" – using trigger-reconstructed objects for analysis, throwing away raw data





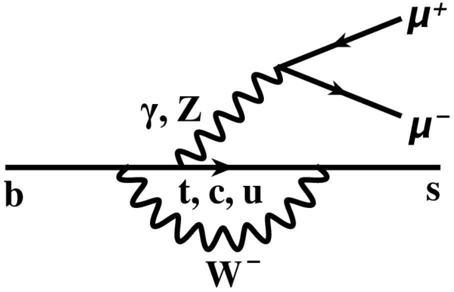
Dimuon Trigger Performance

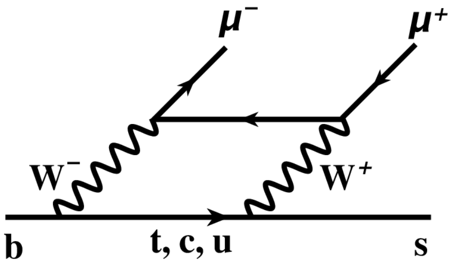




Weak Decays: bsℓℓ

- Interesting vertex with many suggestions of anomalies
- Main probes are for bsμμ: $B_s \to \mu\mu$ and $B_d \to K^{(*)}\mu\mu$
  - different decays look at different EFT operator structures, e.g. $B_s \to \mu\mu$ probes operators with spin-0 currents
  - $B_d \to K^*\mu\mu$ offers a rich set of angular observables for probes
- Both experiments are interested in also measuring the bsee vertex
  - lepton flavor universality test
  - triggering is a major problem – either try to collect a generic B hadron sample (CMS) or use very unusual trigger paths for soft electrons (ATLAS)





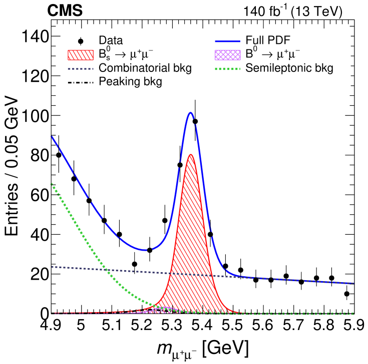
Wilson coefficients	largest effect in
C_7, C_7'	S_1^s, S_1^c, S_2^s, S_2^c, S_3, S_4, S_5, S_6^s, A_7, A_8, A_9, $\mathrm{BR}(B \to X_s\gamma)$, $\mathrm{BR}(B \to X_s\mu^+\mu^-)$
C_9, C_9', C_{10}, C_{10}'	S_1^s, S_1^c, S_2^s, S_2^c, S_3, S_4, S_5, S_6^s, A_7, A_8, A_9, $\mathrm{BR}(B \to X_s\mu^+\mu^-)$
$C_S - C_S'$	S_6^c, $\mathrm{BR}(B_s \to \mu^+\mu^-)$
$C_P - C_P'$	$S_1^c + S_2^c$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$

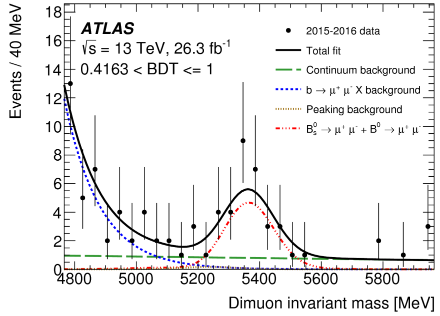
Observable	mostly affected by	
S_1^s, S_1^c, S_2^s, S_2^c	C_7, C_7', C_9, C_9', C_{10}, C_{10}'	
S_3	C_7', C_9', C_{10}'	
S_4	C_7, C_7', C_{10}, C_{10}'	
S_5	C_7, C_7', C_9, C_{10}'	← P_5'
S_6^s	C_7, C_9	
A_7	C_7, C_7', C_{10}, C_{10}'	
A_8	C_7, C_7', C_9, C_9', C_{10}'	
A_9	C_7', C_9', C_{10}'	
S_6^c	$C_S - C_S'$	

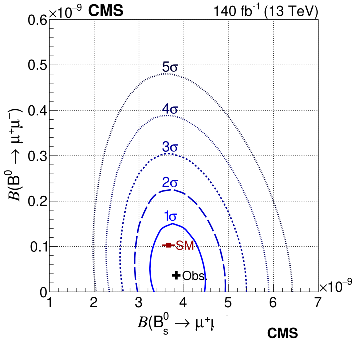
from Altmannshofer et al., JHEP 01(2009) 019

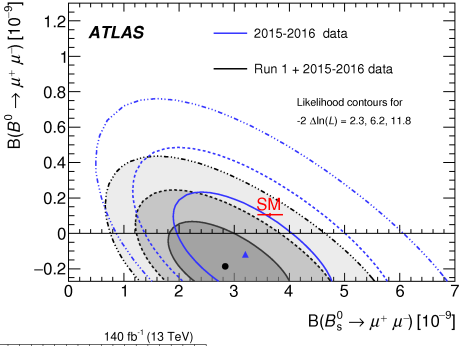
$B_s \rightarrow \mu\mu$

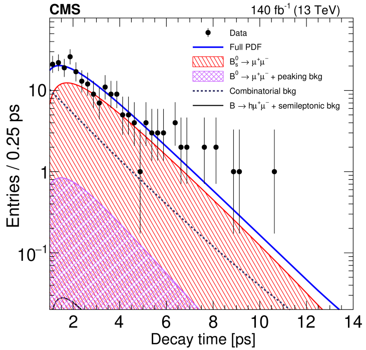
- Rare (but not zero) in SM
  - effective lifetime of decay also carries information
- Search for a dimuon mass peak
  - relatively easy for triggers to target
- Mass resolution is important for S/B and to separate B_d and B_s
  - CMS has edge here, ATLAS separation of B_d and B_s is poor
- Results more or less consistent with SM (ATLAS and LHCb a bit low)







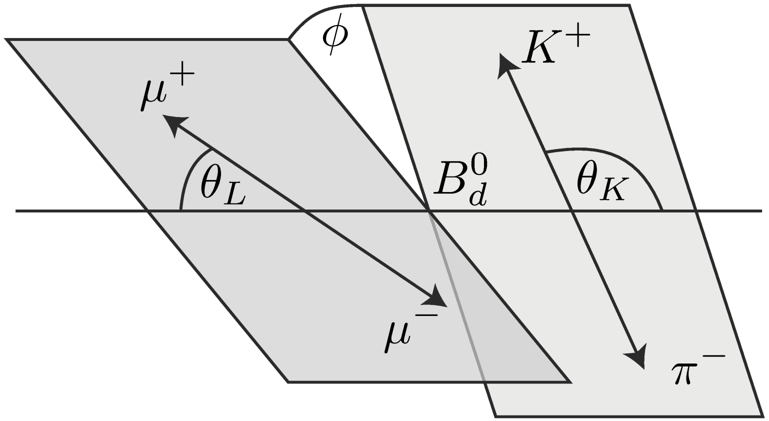




CMS: *arXiv:2212.10311 (sub to PLB, 140 fb^{-1})*
ATLAS: *JHEP 04 (2019) 098 (26 fb^{-1})*

$B \longrightarrow K^*\mu\mu$

- A large number of potentially accessible decay angular parameters available
- Higher statistics available for $K^{*0} \rightarrow K^+\pi^-$ over $K^{*+} \rightarrow K_S\pi^+$
  - More complete angular analyses done by both experiments for $K^{*0}\mu\mu$
  - CMS has done simplified analysis for $K^{*+}\mu\mu$



$$\frac{9}{32\pi}\Bigg[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Bigg]$$

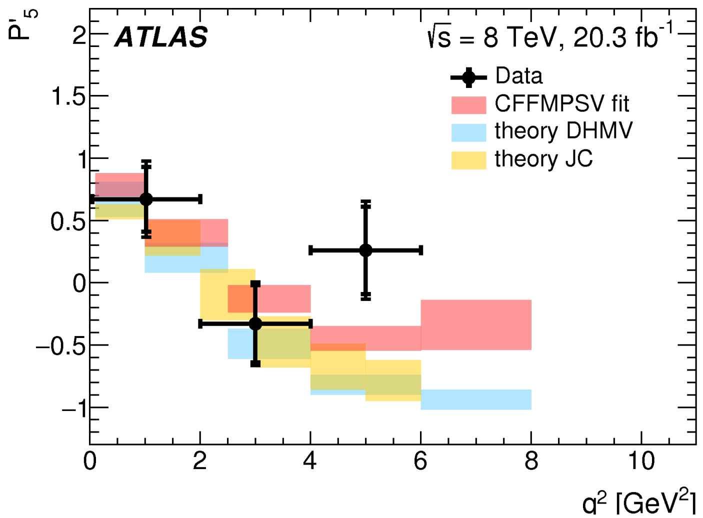
$$P'_{j=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

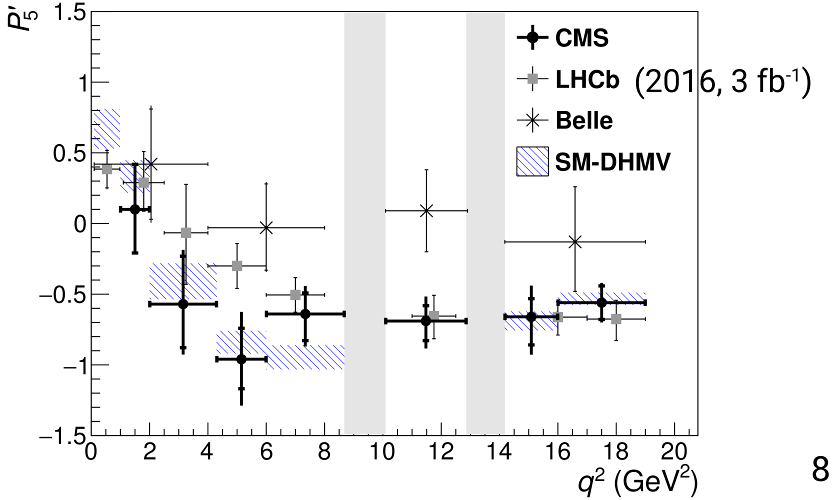
(ignoring potential S-wave Kπ)

$B_d \to K^{*0}\mu\mu$

- One particular angular effect has had hints of an anomaly: "P_5'" for $q^2(\mu\mu)$ above 4 GeV^2
- ATLAS a bit high compared to SM, CMS close to SM expectation
  - latest LHCb result (not on plot) continues to be high compared to SM
- Results for different angular observables constrain different EFT operators

***ATLAS**: JHEP 10 (2018) 047*
***CMS**: PLB 781 (2018) 517*

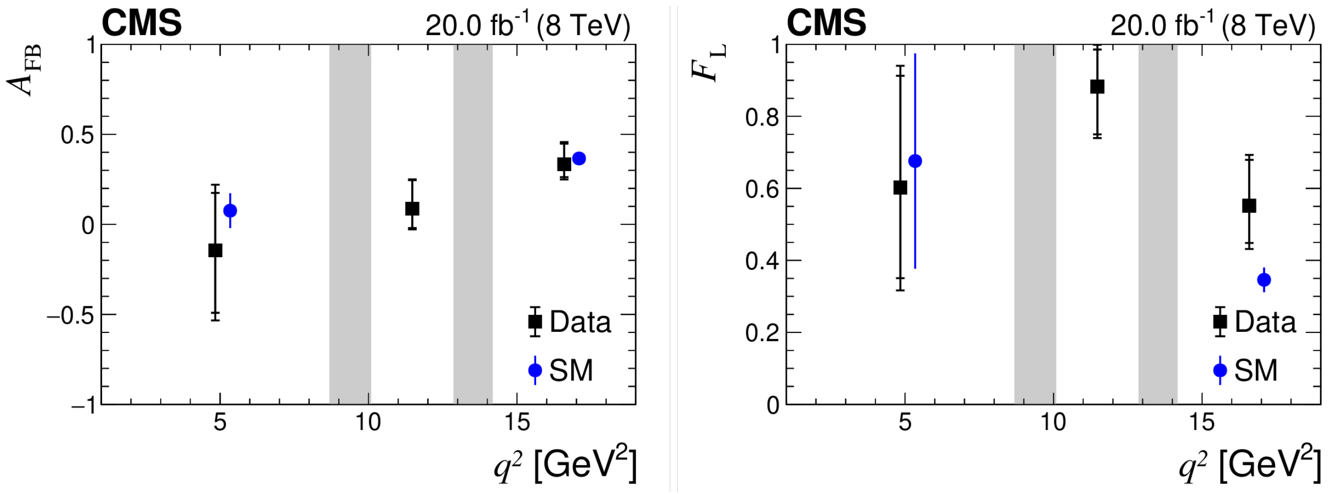




$B^+ \to K^{*+} \mu\mu$, $K^+ \mu\mu$

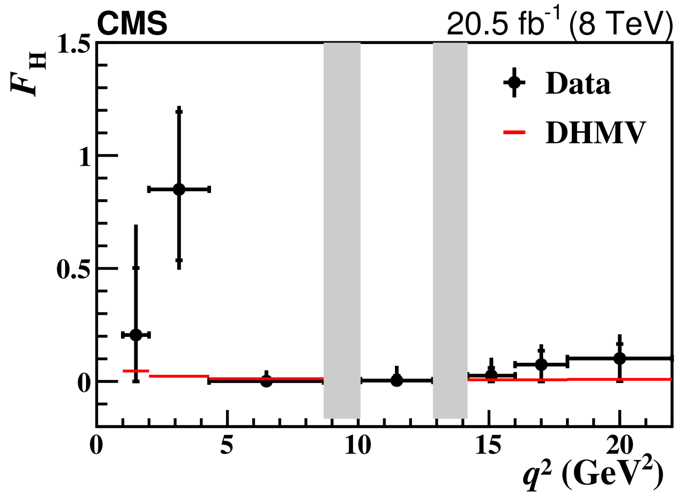
- K^{*+} ($\to K_S\pi^+$) $\mu\mu$ has smaller statistics than K^{*0}, so fewer parameters are studied
- High statistics but less angular information available for $K^+ \mu\mu$
- Agreement with SM expectations

$K^{*+} \mu\mu$



CMS: JHEP 04 (2021) 124

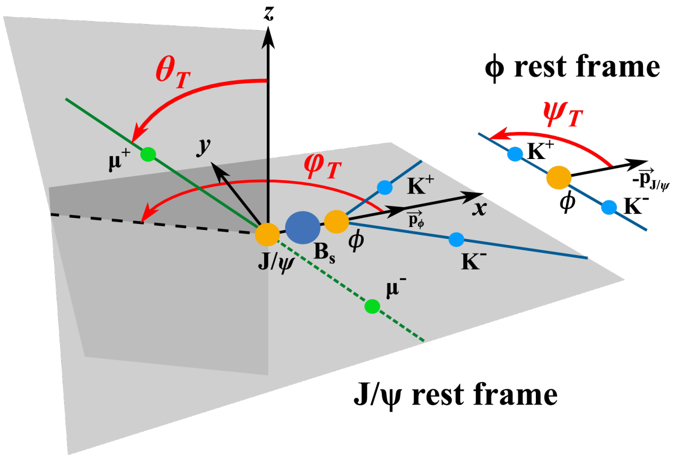
$K^+ \mu\mu$: non-vector fraction



CMS: PRD 98 (2018) 112011

$B_s \rightarrow J/\psi\ \varphi\ (\rightarrow K^+K^-)$

- Classic CP violation test
  - interference between direct decays and decays via mixing
  - weak phase is predicted well from CKM elements: $\phi_s \simeq -2\beta_s = -2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
  - main parameters of interest are φ_s and the lifetime difference of mass eigenstates $\Delta\Gamma_s$; need to determine various strong phases along the way
- Time-dependent angular analysis measures the evolution of the interference with flight distance
  - need to tag production flavor of B_s (signaled by "opposite" B hadron)
  - potentially confounded by scalar KK amplitude



$$O_i(ct,\alpha) = N_i e^{-\Gamma_s t}\left[a_i\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + b_i\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + c_i\cos(\Delta m_s t) + d_i\sin(\Delta m_s t)\right]$$

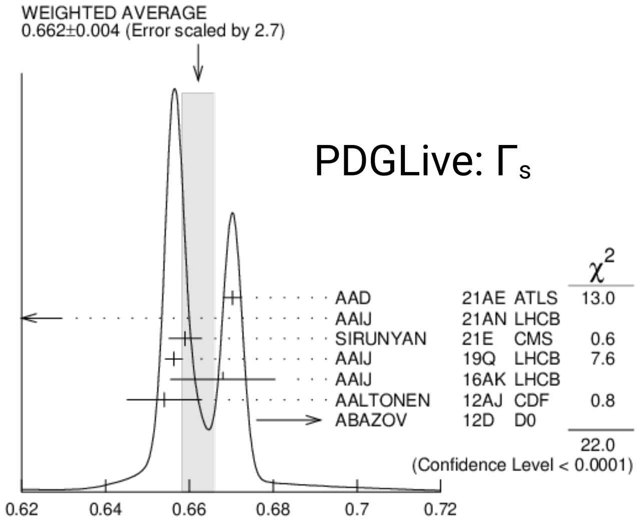
i	$g_i(\theta_T,\psi_T,\varphi_T)$	N_i	a_i	b_i	c_i	d_i
1	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert\lvert A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \quad S = -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \quad D = -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}.$$

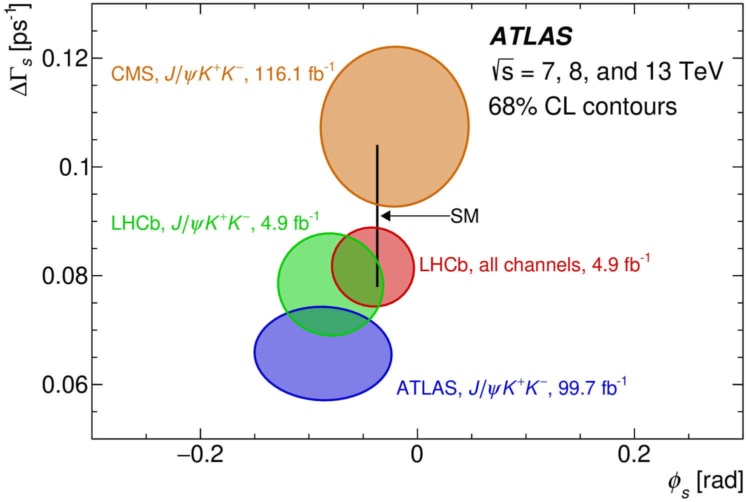
$B_s \to J/\psi\ \varphi$

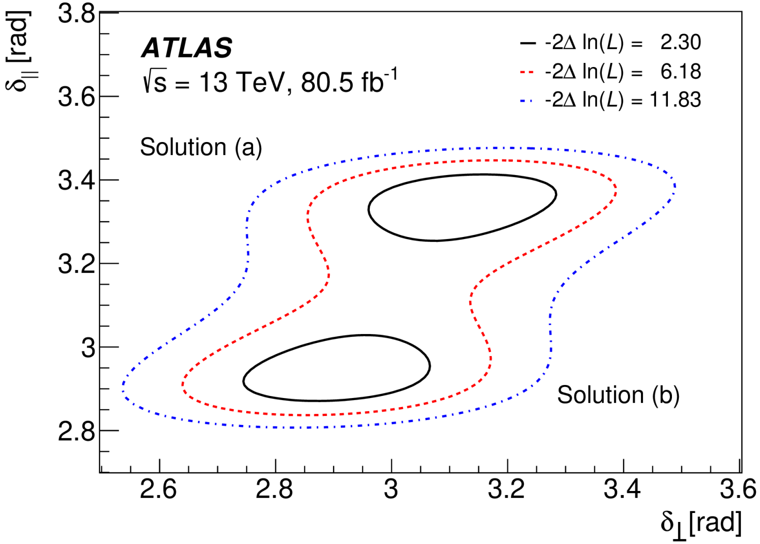
- Experiments individually in good agreement with SM
- Some tension in fit parameters between experiments
  - hope to resolve with full Run 2 dataset & very close attention to systematics

***CMS**: PLB 816 (2021) 136188*
***ATLAS**: EPJ C 81 (2021) 342*



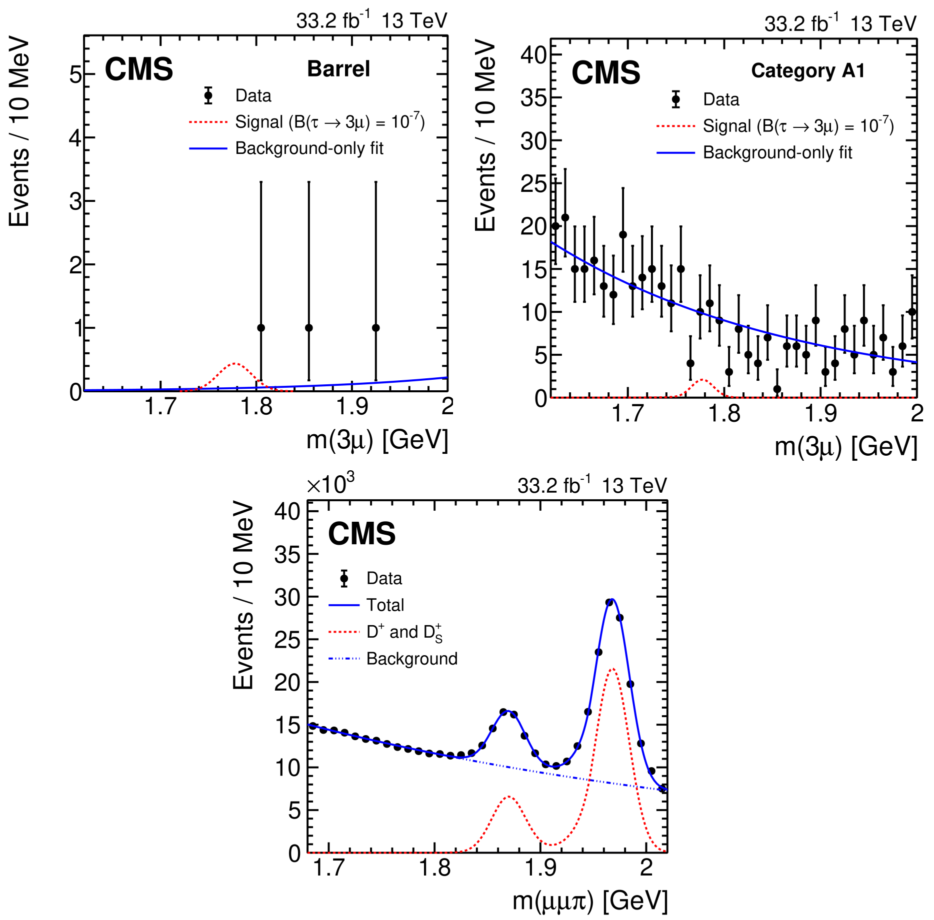
PDGLive: Γ_s





Search for τ → 3μ

- Search for lepton flavor violation in charged leptons
- Copious production of τ in both electroweak (W → τν) and heavy-flavor (B/D → τνX) channels
  - electroweak has lower σ, but easier to suppress backgrounds with MET & isolated high-p_T signal candidate; two channels have similar sensitivity
- Take three-muon combinations and look for a mass peak
  - background suppression with BDT
- For branching fraction determination, need an estimate of total τ production
  - W production is under control
  - Heavy flavor production estimated with a ratio to observed $D_s \to \varphi\pi \to \mu\mu\pi$
- $B(\tau \to 3\mu) < 8.0 \times 10^{-8}$ @ 90% CL



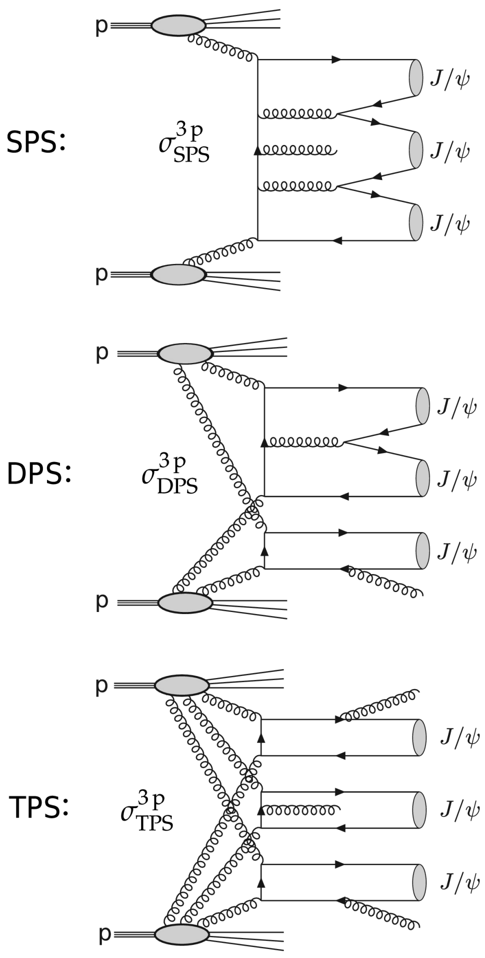
CMS: *JHEP 01 (2021) 163*

Multi-parton Scattering: Triple J/ψ

- Calculations of pp collisions typically assume we can factorize processes:
  - single hard scatter between one pair of partons, kinematics described by a PDF
  - soft "underlying event"
- Entirely possible to have more complex topologies: multiple hard scatters
  - boundary between single parton scattering + underlying event and multi-parton scattering is a bit arbitrary
  - usual assumption: hard multiple parton scatters are independent of each other with a geometric-like overlap factor
- First observation of triple-J/ψ production from CMS: probe of triple parton scattering
  - single parton scattering rate expected ~ negligible

***CMS**: Nature Phys 19, 338 (2023)*

Pure prompt production:



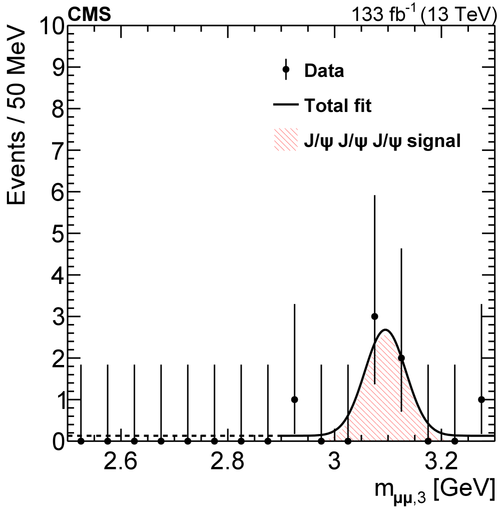
Multi-parton Scattering: Triple J/ψ

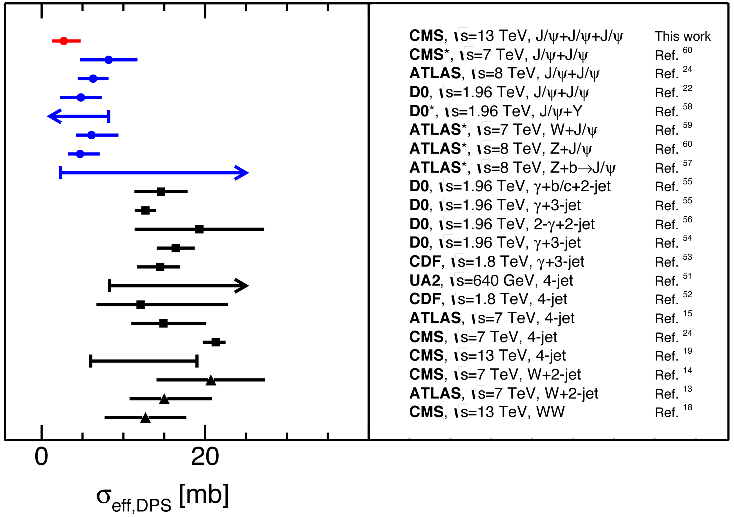
- Observed $5.0^{+2.6}_{-1.9}$ triple-J/ψ events in Run 2 data, on a background of $1.0^{+1.4}_{-0.8}$
  - significance > 5σ
  - includes both direct and b-decay J/ψ
- Standard ansatz of independent multi-parton interactions assumes an effective geometric overlap parameter σ_{eff}

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

$$\sigma_{eff,TPS} = (0.82 \pm 0.11)\,\sigma_{eff,DPS}$$

- Mounting evidence that σ_{eff} is not universal for different processes
  - different initial states? Bjorken x-dependence? badly-handled SPS?

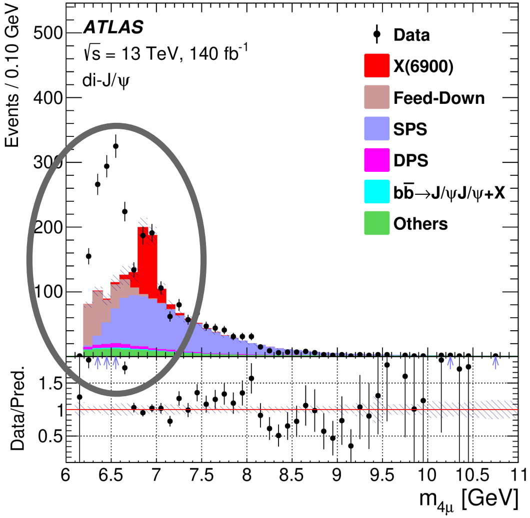


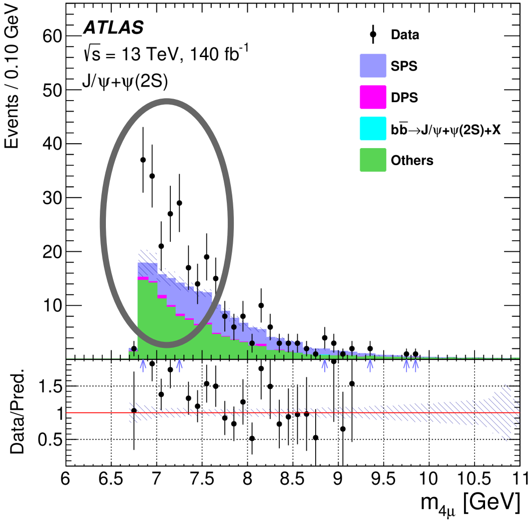


New Structures

- Slowly uncovering a rich spectroscopy of multi-quark structures outside the $q\bar{q}$, qqq paradigm
  - tetraquarks, pentaquarks? molecules? dynamic effects?
- Structures observed in di-J/ψ, J/ψ+ψ(2S) mass spectra by LHCb, ATLAS, CMS
- Feed-down from J/ψ+ψ(2S) to di-J/ψ is non-trivial
  - systems need to be understood in a coherent manner

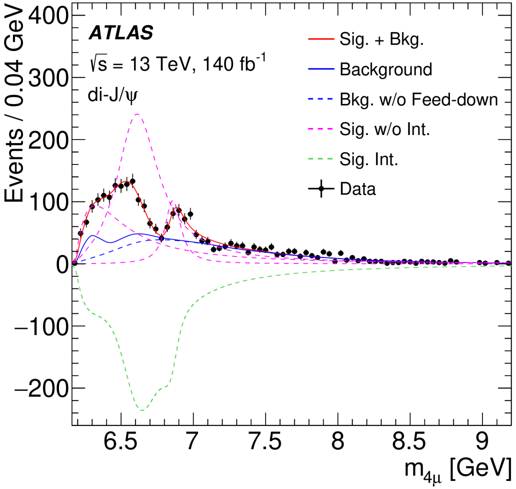
***ATLAS**: BPHY-2022-01*
***CMS**: CMS-PAS-BPH-21-003*

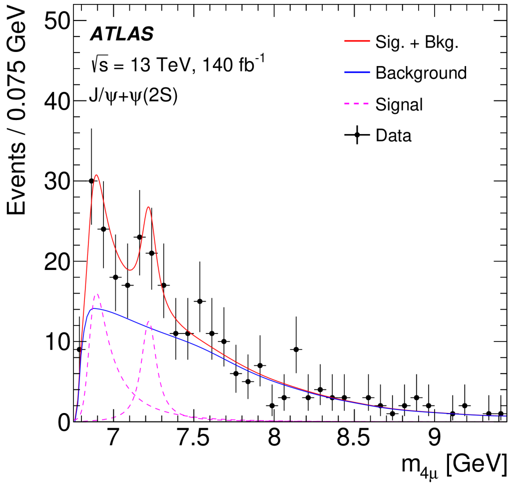


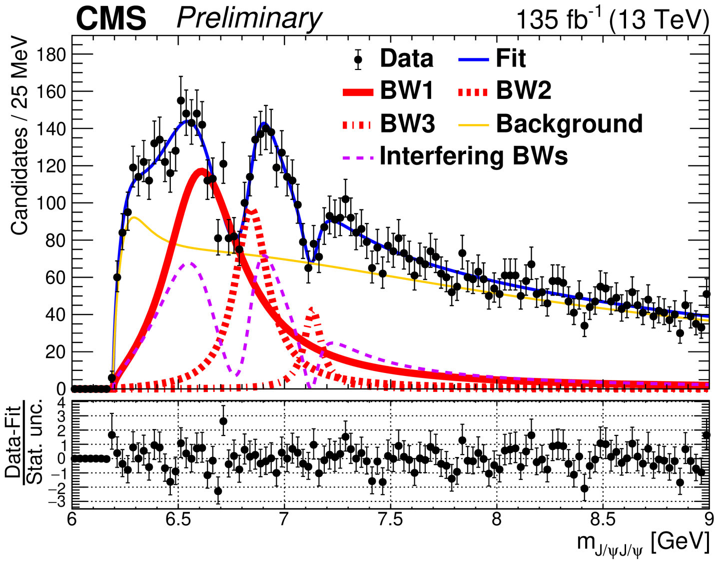


Di-charmonium Structures

- Excesses over background expectations observed at many σ
- Background models are quite different
- Experiments have different preferred fits
  - interference is seemingly important
  - all experiments agree on an X(6900)
  - CMS sees evidence for an X(7300) in di-J/ψ; ATLAS sees a weak hint for this in J/ψ+ψ(2S)
  - nature of threshold enhancement unclear
- Further progress will rely heavily on angular analysis for spin-parity

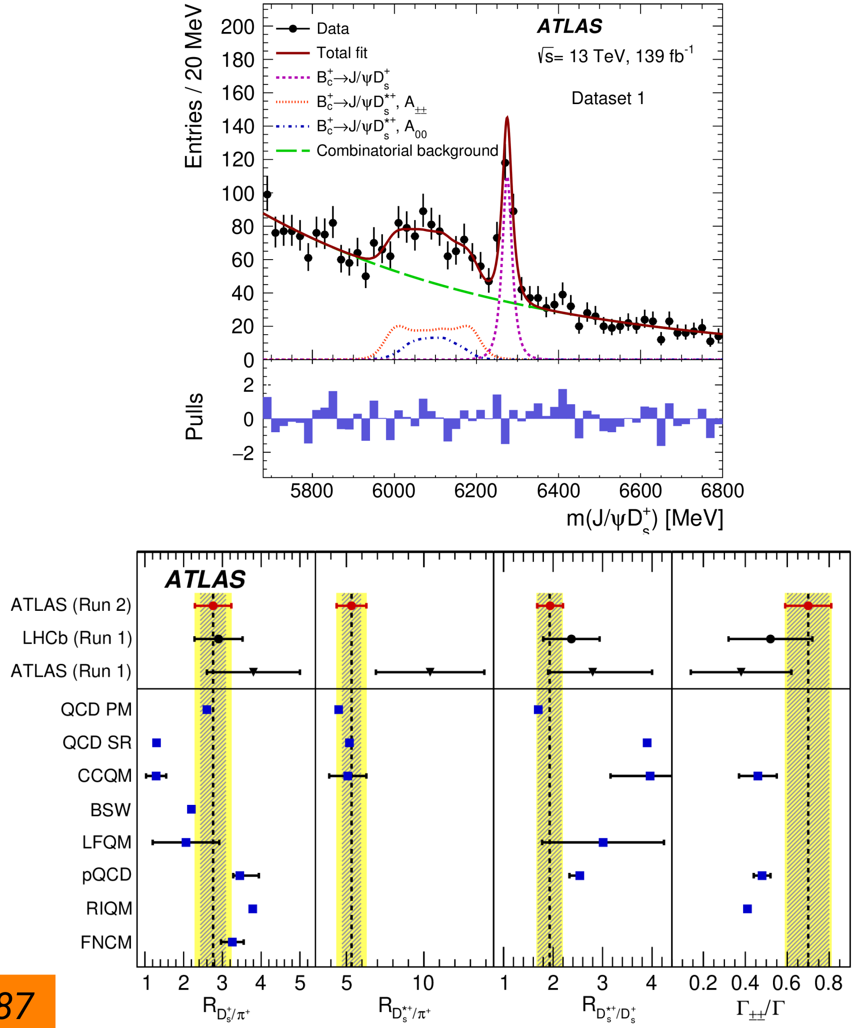


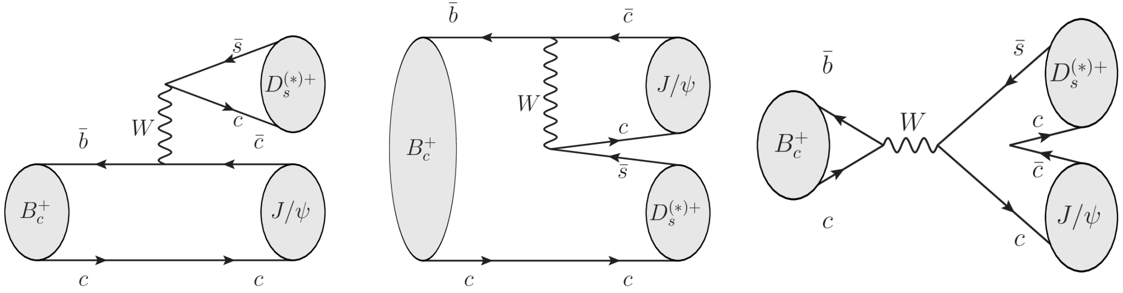




Exclusive Hadronic Decays: $B_c \rightarrow J/\psi\ D_s^{(*)}$

- Can we work out the properties of specific hadronic final states in weak decays?
- Look at $B_c \rightarrow J/\psi\ D_s^{(*)}$: same quark content but different spins, can measure polarization states
- Certain calculations much more consistent with data than others

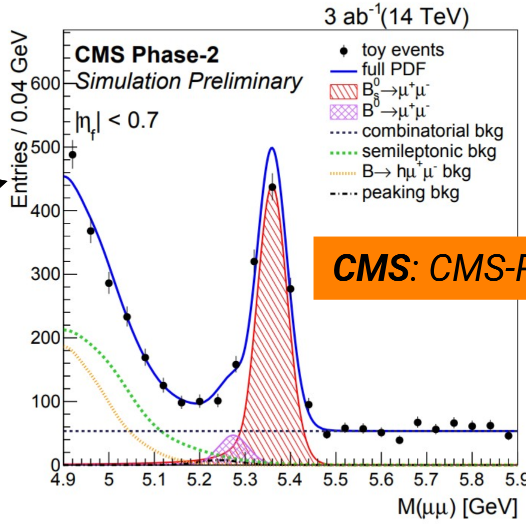




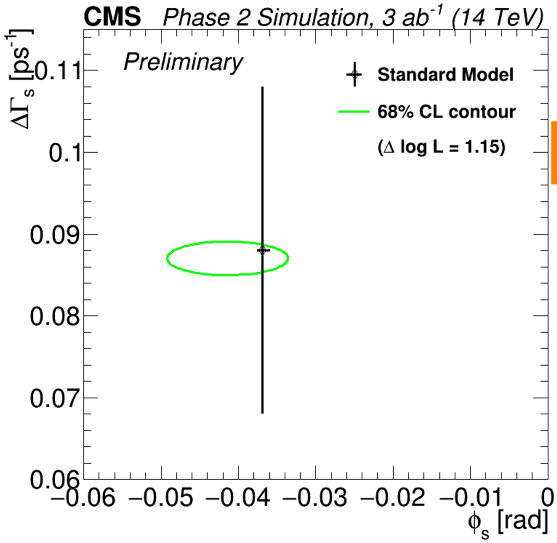
ATLAS: *JHEP 08 (2022) 087*

Projections

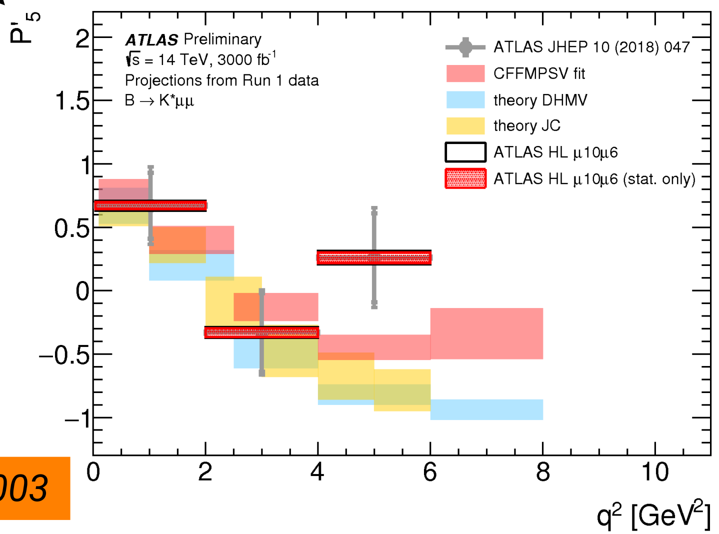
- Experiments expect to continue their B physics programs into the HL-LHC era
- Potential highlights:
  - 5σ observation of $B_d \to \mu\mu$
  - enormous improvement in P_5' uncertainties
  - improve φ_s uncertainty by a factor of 5



CMS: *CMS-PAS-FTR-18-013*



CMS: *CMS-PAS-FTR-18-041*



ATLAS: *ATL-PHYS-PUB-2019-003*

Summary

- Active program in heavy flavor in ATLAS and CMS
- “Classic” measurements: CP violation in $B_s \to J/\psi\ \varphi$, search for rate modifications in $B_s \to \mu\mu$
- Following up potential interesting physics in the $bs\ell\ell$ vertex
- Additional searches for rare/forbidden decays
- More bread-and-butter work on spectroscopy, QCD factorization, calculational methods …

Extra

Triple J/ψ Cross Sections

Process:	3 prompt	2 prompt+1 nonprompt	1 prompt+2 nonprompt	3 nonprompt	Total
$\sigma^{3J/\psi}_{SPS}$ (fb)	<0.005	5.7	0.014	12	18
$N^{3J/\psi}_{SPS}$	0.0	0.10	0.0	0.22	0.32
$\sigma^{3J/\psi}_{DPS}$ (fb)	8.4	8.9	90	95	202
$N^{3J/\psi}_{DPS}$	0.15	0.16	1.65	1.75	3.7
$\sigma^{3J/\psi}_{TPS}$ (fb)	6.1	19.4	20.4	7.2	53
$N^{3J/\psi}_{TPS}$	0.11	0.36	0.38	0.13	1.0
$\sigma^{3J/\psi}_{tot}$ (fb)	15	34	110	114	272
$N^{3J/\psi}_{tot}$	0.3	0.6	2.0	2.1	5.0

Di-J/ψ States

- ATLAS models:
  - A = interference of three resonances + noninterfering nonresonant background
  - B = interference of two resonances + nonresonant background

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—
J/ψ+$\psi(2S)$	model α	model β
m_3 or m	$7.22 \pm 0.03^{+0.01}_{-0.03}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3 or Γ	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$

- CMS: threshold enhancement + three resonances, with or without interference

No interference

	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

		BW1	BW2	BW3
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ [MeV]	$444^{+226+109}_{-199-235}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

Di-J/ψ : LHCb

- Comparable statistics

No X(6900) interference

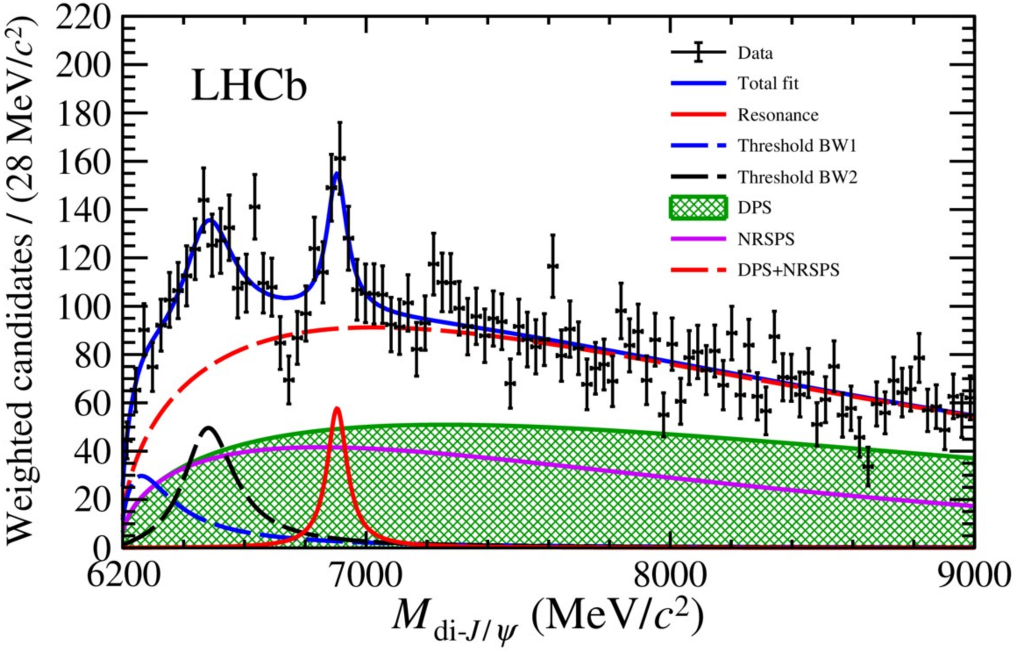
$$m[X(6900)] = 6905 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$

$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV},$$

X(6900) interference

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\mathrm{MeV}/c^2$$

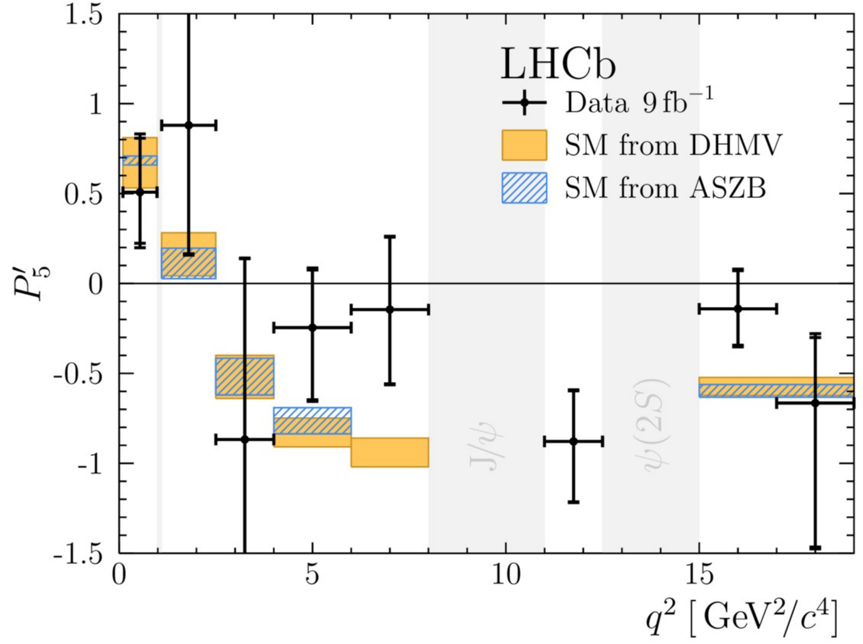
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\mathrm{MeV}.$$



***LHCb**: Science Bulletin 65 (2020) 1983*

P_5': LHCb

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



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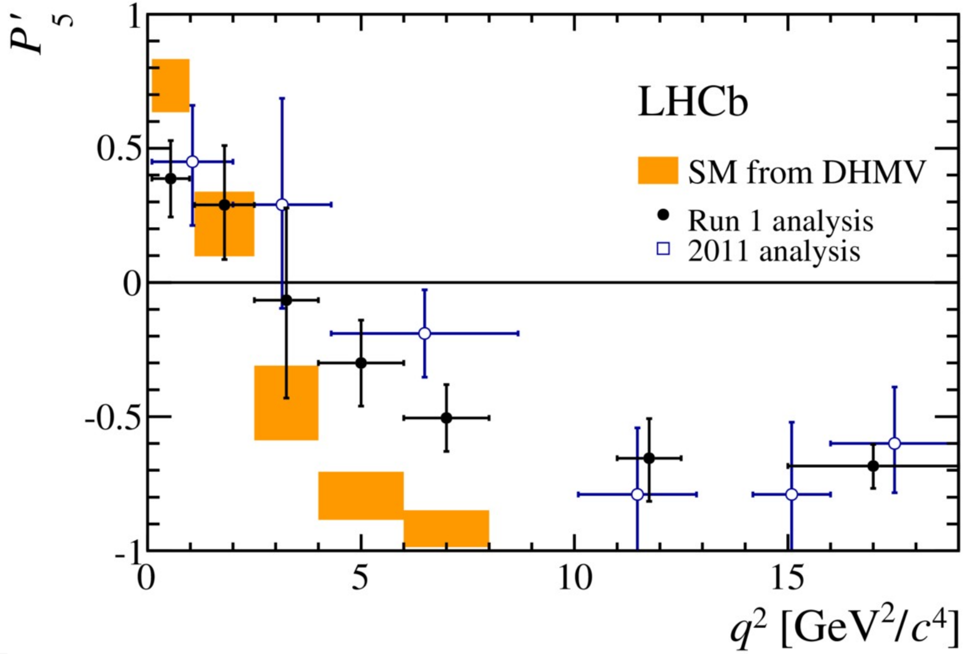
$B^0 \to K^{*0} \mu\mu$



LHCb: *JHEP 02 (2016) 104*