Hadron spectroscopy and decays at ATLAS and CMS

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on behalf of ATLAS and CMS Collaborations

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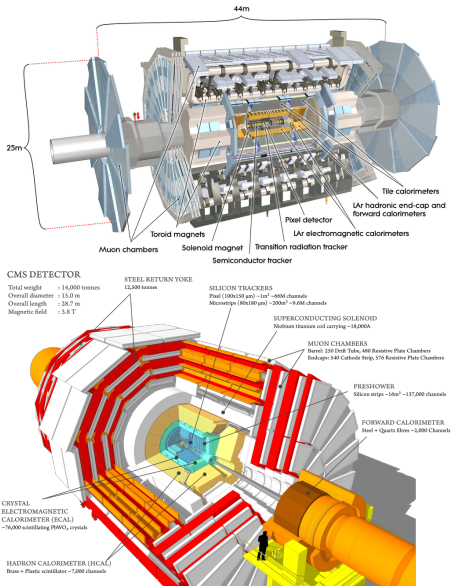
ATLAS and CMS detectors

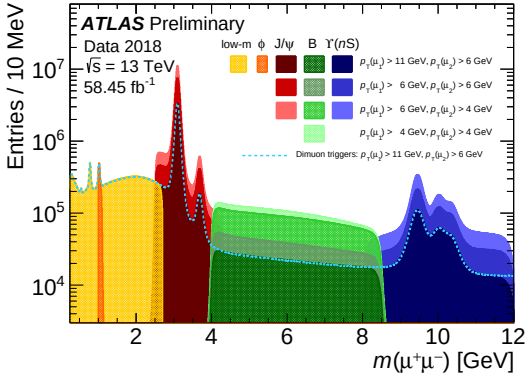
- Compared to B-factory experiments
  - Abundant production of B_s^0, B_c^+, b baryons, including excited states
  - Challenging reconstruction and triggering in pp environment
- Compared to LHCb
  - Central acceptance for tracks and muons ($|\eta| \lesssim 2.5$) – complementary production measurements
  - Higher integrated luminosity ($140\,\text{fb}^{-1}$ vs $6\,\text{fb}^{-1}$ in Run-2) and pile-up – beneficial in certain studies but higher background
  - Practically no particle identification
  - Lower acceptance in p_T due to trigger limitations
- Most of the B-physics program is based on di-muon triggers

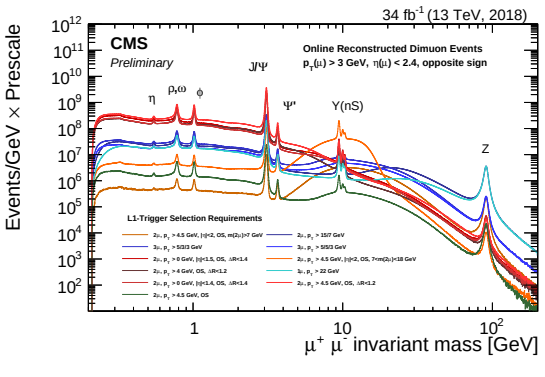


Di-muon triggers

Dedicated trigger options to overcome the rate limitations for low-p_T dimuons

- ATLAS uses *topological selection* using muon trigger hardware information (cuts on $m(\mu^+\mu^-)$, $\Delta R(\mu^+\mu^-)$), software selection based on *full reconstruction of certain decays* with precision tracking (e.g. $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$)
- *Data scouting* in CMS – doing certain analyses using only trigger-level information to save bandwidth throwing away raw data



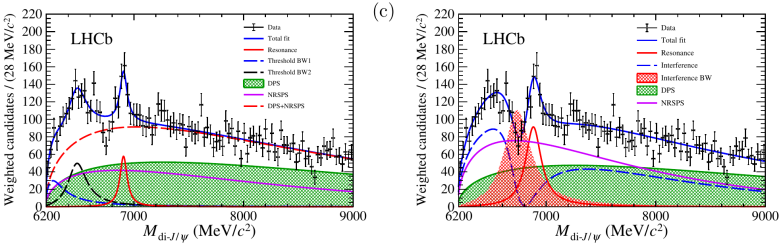


Outline

- New tetraquark-like structures in di-charmonium final states
  - ATLAS – arXiv:2304.08962
  - CMS – CMS-PAS-BPH-21-003
- Measurement of $B_s^0 \to \mu^+\mu^-$ decay properties
  - CMS with full Run-2 dataset – arXiv:2212.10311
  - ATLAS+CMS+LHCb combination with 2011–2016 data – ATLAS-CONF-2020-049
- First observation of $\eta \to 4\mu$ rare decay by CMS – arXiv:2305.04904
- Measurement of CPV parameters in $B_s^0 \to J/\psi\phi$
  - ATLAS – EPJC 81 (2021) 342
  - CMS – PLB 816 (2021) 136188
- Observation of $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_S^0$ by CMS – EPJC 82 (2022) 499
- Precision measurement of $B_c^+ \to J/\psi D_s^{(*)+}$ decays by ATLAS – JHEP 08 (2022) 087
- ⋆**NEW**⋆ Observation of $\Lambda_b^0 \to J/\psi\Xi^-K^+$ decay by CMS – CMS-PAS-BPH-22-002

Structures in di-charmonium spectrum

- LHCb claimed (arXiv:2006.16957) observation of a new *X(6900)* structure in $pp \to J/\psi J/\psi \to 4\mu$ mass spectrum
  - consistent with predictions for $T_{cc\bar{c}\bar{c}}$ tetraquarks
    - e.g. in diquark+antidiquark model (EPJC 80 (2020) 1004, PLB 811 (2020) 135952)
  - non-tetraquark interpretations also possible
    - e.g. in Pomeron exchanges in near-threshold $J/\psi - J/\psi$ scattering (PLB 824 (2022) 136794)
  - broad lower-mass structure can be e.g. a mixture of multiple $cc\bar{c}\bar{c}$ states or feed-down from their decays via heavier charmonia
- In 2022 confirmed by both CMS (CMS-PAS-BPH-21-003) and ATLAS (arXiv:2304.08962)



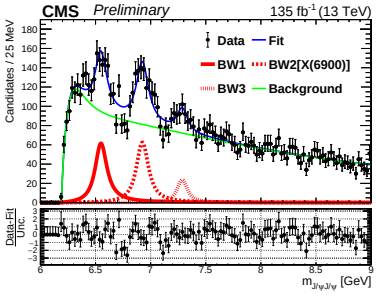
Assuming no interference:

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV},$$

With NRSPS interference:

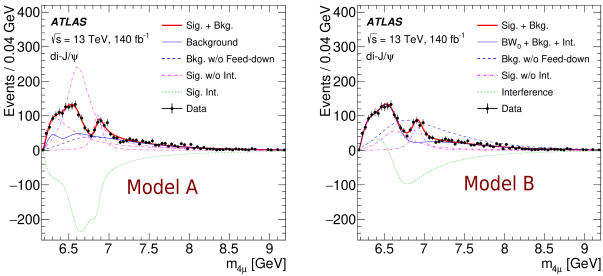
$$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}.$$

Di-J/ψ channel (1)



- Nominal model with 3 BW resonances
- Good description, except the dips between the BWs
- LHCb fit models yield consistent parameters for $X(6900)$ (but worse fit overall)

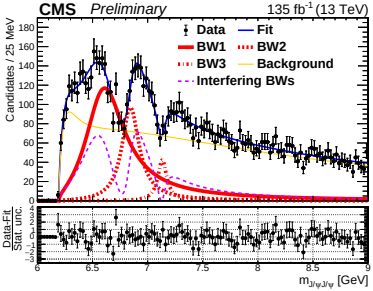
	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56
	6.5σ	**9.4σ**	**4.1σ**



- Model A: 3 *interfering* BW resonances
- Model B: 1 BW interfering with SPS background, 1 BW standalone

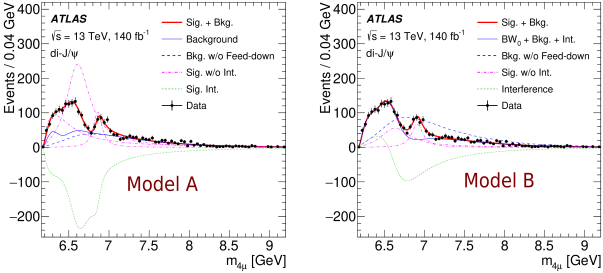
di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

Di-J/ψ channel (2)



- Another model with 3 *interfering* resonances
- Dip near 6.75 GeV described better
- Still consistent for $X(6900)$
  - demonstrated importance of interference?

		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}



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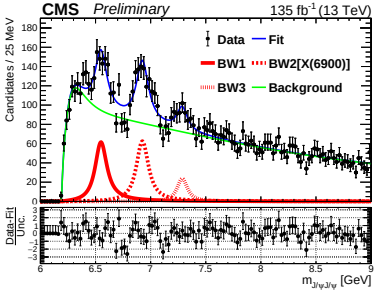
$J/\psi + \psi(2S)$ channel in ATLAS



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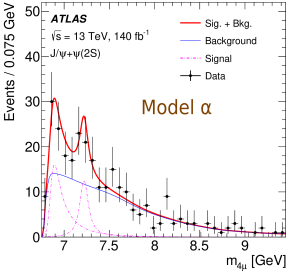
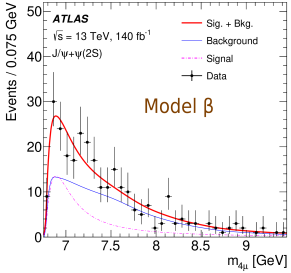




- Model α: same 3 resonances decaying to $J/\psi + \psi(2S)$ and a 4th standalone BW resonance – 4.7σ
  - parameters fixed from di-J/ψ fit
- Model β: a single BW resonance – 4.3σ
- 3σ significance of the 7.2 GeV resonance in model α

J/ψ+ψ(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	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$

4-muon structures summary

- $X(6900)$ state is reliably confirmed by both ATLAS and CMS with consistent parameters and significance well above 5σ
- Another resonance also hinted in LHCb results near 7.2–7.3 GeV is seen by CMS in di-J/ψ ($X(7300)$) and by ATLAS in $J/\psi + \psi(2S)$ at level of 3–4σ
- The lowest-mass structure nature is less certain
  - CMS observes a single BW $X(6600)$ structure
    - 3 masses measured by CMS agrees with expectations for 3 radial excitations of P-wave 1^{-+} states in diquark-antidiquark model (EPJC 81 (2021) 324)
  - ATLAS provides fits with either 1 or 2 BW resonances
  - Could also result from other effects, e.g. a more complicated mixture of states or feed-down from higher di-charmonium resonances

⋆ *Welcome to follow a more detailed talk on this afternoon by Zhen Hu on these analyses!*

$B_s^0 \to \mu^+\mu^-$ branching fraction in CMS

CMS-PAS-BPH-21-003

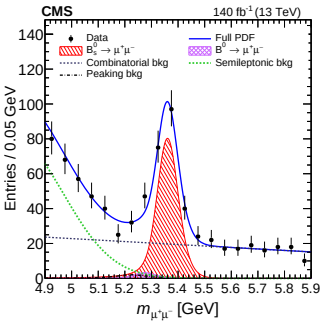
- Perfect test for anomalies in $b \to s\ell\ell$ transition
  - Precise theory predictions and clean experimental signature
- Main backgrounds are combinatorial and from double hadron-muon mis-id
  - Use MVA to suppress both
- Measure the BF w.r.t. $B^+ \to J/\psi(\mu^+\mu^-)K^+$ reference:

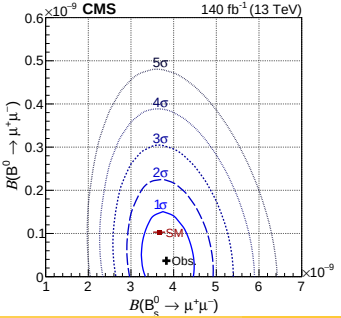
$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\mathrm{stat})\,^{+0.19}_{-0.16}\,(\mathrm{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9},$$

$$\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\,(\mathrm{stat})\,^{+0.08}_{-0.09}\,(\mathrm{syst})\right] \times 10^{-10}.$$

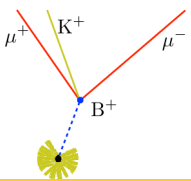
- or w.r.t. $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$ (different external systematics):

$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \left[3.95^{+0.39}_{-0.37}\,(\mathrm{stat})\,^{+0.27}_{-0.22}\,(\mathrm{syst})\,^{+0.21}_{-0.19}\,(\mathrm{BF})\right] \times 10^{-9}.$$

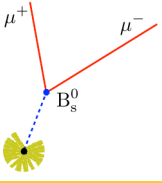




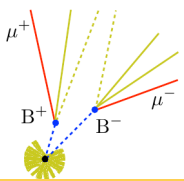
3-body and partial decays



Signal $B_s \to \mu\mu$

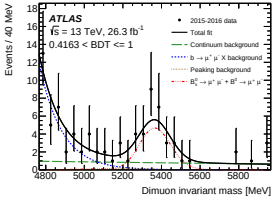


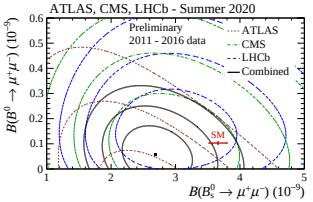
Combinatorial Background



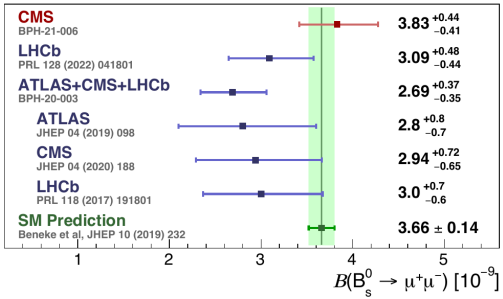
$B^0_{(s)} \to \mu^+\mu^-$ branching fraction status

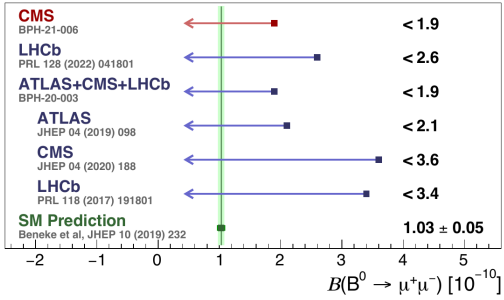
- ATLAS full Run-2 measurement is on-going, only 2011–2016 result available so far (JHEP 04 (2019) 098)
- Combination of ATLAS+CMS+LHCb results for that period was also made (ATLAS-CONF-2020-049)





- Some tension between CMS and the previous combined result for $B^0_s \to \mu^+\mu^-$
  - back to good agreement with the SM
- $B^0 \to \mu^+\mu^-$ still beyond the experimental reach





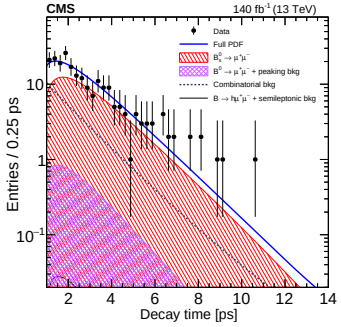
plots by D. Kovalskiy, CERN seminar 27 Jul 2022

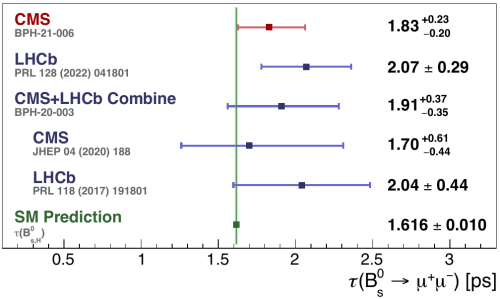
$B_s^0 \to \mu^+\mu^-$ lifetime in CMS

CMS-PAS-BPH-21-003

- In absence of CP violation only the heavy, CP odd, $B^0_{s,H}$ state decays to $\mu^+\mu^-$
  - deviation of effective lifetime from SM predictions for $B^0_{s,H}$ would indicate BSM contribution
- Measured from unbinned ML fit:
  $\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})$ ps.
- Agrees with SM, best precision so far
- ATLAS measurement on-going...

No significant deviations from SM in $B^0_{(s)} \to \mu^+\mu^-$ measurements





First observation of $\eta \to 4\mu$ decay by CMS

arXiv:2305.04904

- Double-Dalitz decay serving a precision SM test, sensitive to certain new physics scenarios
  - light-by-light hadronic component of the muon anomalous magnetic moment
- Data collected by dedicated high-rate low-p_T dimuon triggers saving only HLT information
- Measure the $\mathcal{B}$ w.r.t. $\eta \to \mu^+\mu^-$ decay

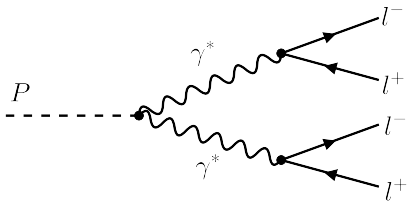
$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.86 \pm 0.14\,(\text{stat}) \pm 0.12\,(\text{syst})) \times 10^{-3}$$

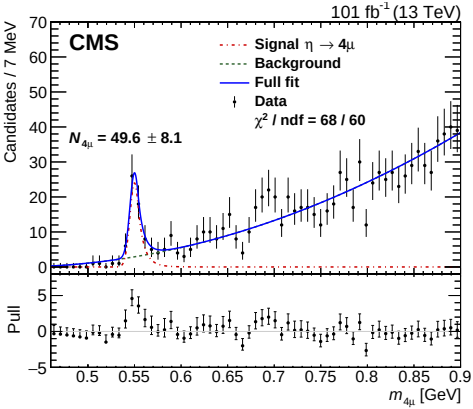
$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B}_{2\mu})) \times 10^{-9}$$

  - agrees with the prediction of $(3.95 \pm 0.15) \times 10^{-9}$

A unique measurement made possible by special trigger strategy

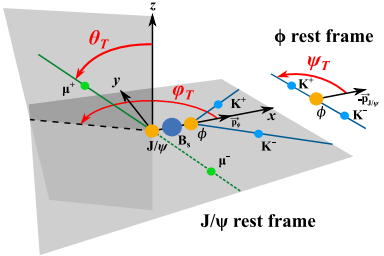
⋆ More details in a parallel talk by Alessandra Fanfani 6 Jun afternoon

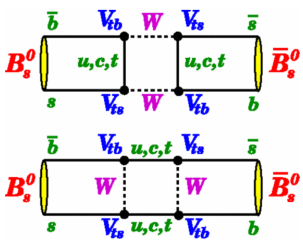


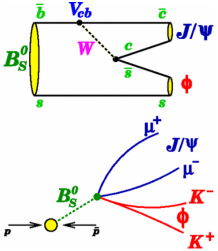


CP violation in $B_s^0 \to J/\psi\phi$

- $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ known as a *golden channel* for CPV studies at LHC
- CPV due to interference between direct B_s^0 decay and decay from $B_s^0 - \bar{B}_s^0$ mixing
  - can be enhanced by NP couplings in the mixing amplitude
- Most interesting parameter *CP violating phase* ϕ_s: weak phase difference between the $B_s^0 - \bar{B}_s^0$ mixing and $b \to c\bar{c}s$ transition amplitude
  - $\phi_s^{b\to c\bar{c}s} \approx -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.0370 \pm 0.0006$
- Unbinned ML fit to mass, lifetime and decay angles to disentangle the CP states
- Tag signal B flavour using the opposite b hadron charge

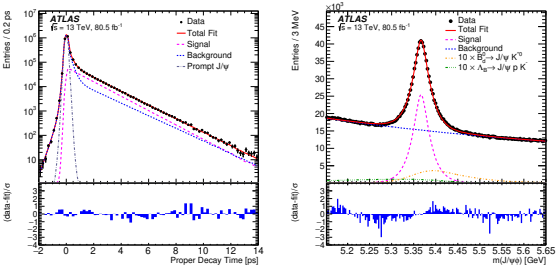




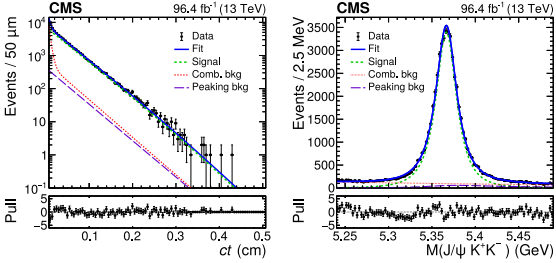


$B_s^0 \to J/\psi\phi$ measurement results

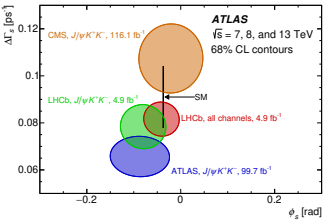
- ATLAS (EPJC 81 (2021) 342) uses full lifetime range to constrain the backgrounds

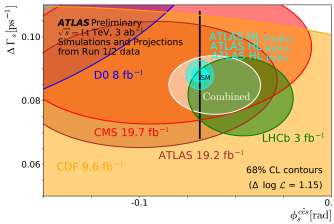


- CMS (PLB 816 (2021) 136188) cuts on $c\tau > 70\,\mu$m to reduce it



- Tension between in $\Delta\Gamma_s$ between CMS and ATLAS/LHCb
- *All results consistent with SM overall*
- To be further tested with Run-3 and HL-LHC
  - Projected sensitivity – order of magnitude improvement

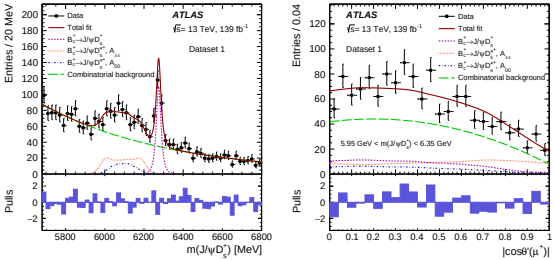


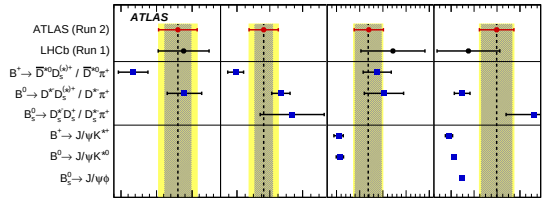


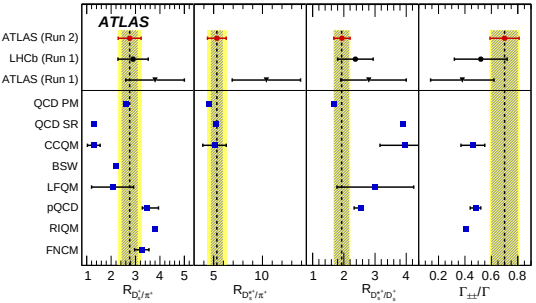
Study of $B_c^+ \to J/\psi D_s^{(*)+}$ decays in ATLAS

JHEP 08 (2022) 087

- Studied earlier by LHCb and ATLAS in Run-1
- Measure relative $\mathcal{B}$ w.r.t. $B_c^+ \to J/\psi\pi^+$
  - and polarization in $B_c^+ \to J/\psi D_s^{*+}$
- *Most precise measurement to date*
  - thanks to 2D fit with J/ψ helicity angle and BDT for the signal selection
- Challenges some of the models
  - $\Gamma_{\pm\pm}/\Gamma$ agrees with naive 2/3 expectation







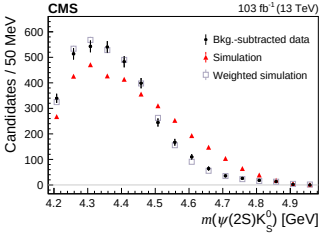
$B_s^0 \to \psi(2S)K_S^0$ and $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decays at CMS EPJC 82 (2022) 499

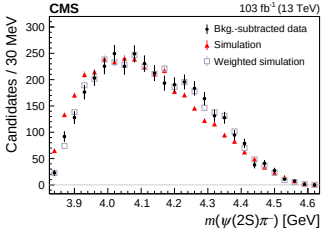
- Two new decays observed with significance above 5σ
- Branching fractions measured w.r.t. $B^0 \to \psi(2S)K_S^0$ to reduce systematics

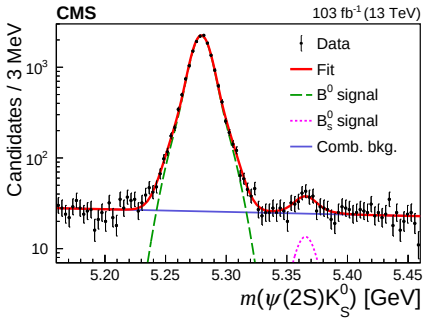
$$R_s = \frac{\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} = (3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2},$$

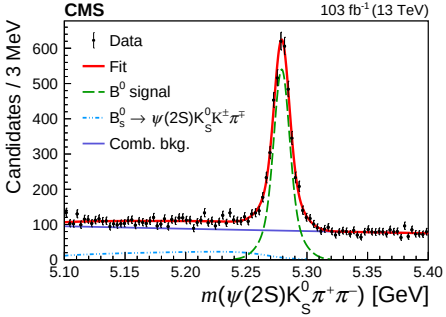
$$R_{\pi^+\pi^-} = \frac{\mathcal{B}(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} = 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst}).$$

- $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ can be used for searches for studying exotic resonances
  - mass distributions differ from phase-space, but no indications of narrow exotic states







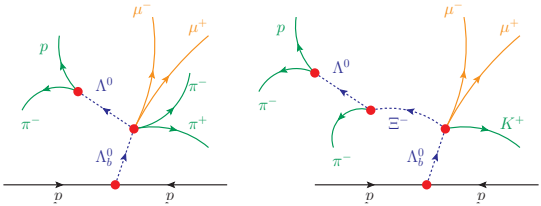


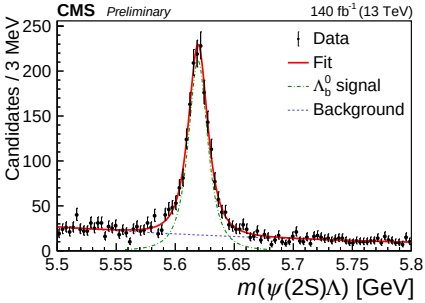
Observatin of $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay in CMS

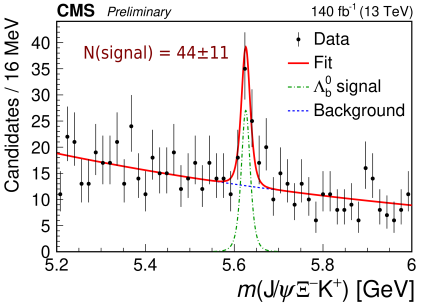
CMS-PAS-BPH-22-002

- Study motivated by recent discoveries of pentaquark structures in $J/\psi p$ and $J/\psi \Lambda^0$ systems
  - Studying $J/\psi \Xi$ and $J/\psi \Omega^-$ can lead to doubly-/triply-strange pentaquarks
- Challenging reconstruction of 3-vertex cascade decay
- Observation significance above 5σ
- Measure $\mathcal{B}$ w.r.t. reference $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay
  - different cascade, still high systematics cancellation

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = [2.5 \pm 0.8\,(\text{stat}) \pm 0.9\,(\text{syst})]\%,$$

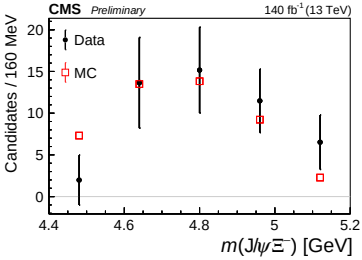


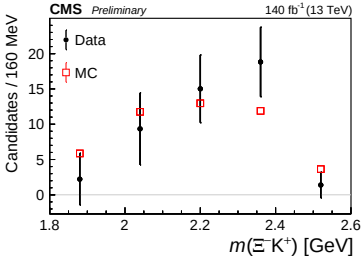


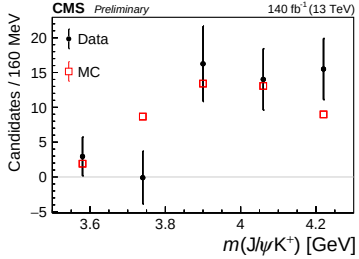


$\Lambda_b^0 \to J/\psi \Xi^- K^+$ – intermediate system masses

- First observation of a multi-body decay with $J/\psi\Xi^-$ system
  - Nice demonstration of the potential in studying complicated multi-body final states
- Limited statistics does not yet allow to study intermediate resonances







⋆ More details in a parallel talk by Adriano Di Florio 7 Jun afternoon

Summary

- ATLAS and CMS have active B-physics programmes in Run-2 and taking data for future Run-3 studies
- Focus on those where we are competitive benefiting from high statistics and good muon performance
- Studies of exotic resonances and precision SM tests were presented
  - Exotics results challenging various QCD models
  - No violations of SM found with the available precision –
- Room for many more studies even with Run-2, and the new Run-3 dataset being collected

You are welcome to follow these parallel talks for more results and details:

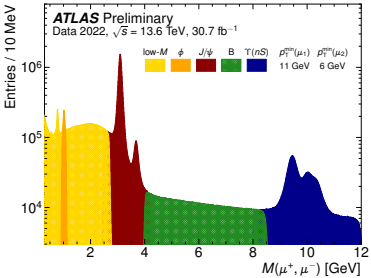
- *Conventional heavy baryons* (Adriano Di Florio), f_u/f_s *ratio* (Alexis Pompilli), *4-charm resonances* (Zhen Hu), B_c *results* (Vincenzo Mastrapasqua), $\eta \to 4\mu$ (Alessandra Fanfani)

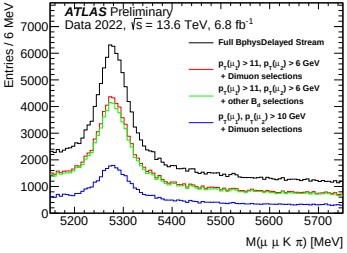
B-physics public result pages:

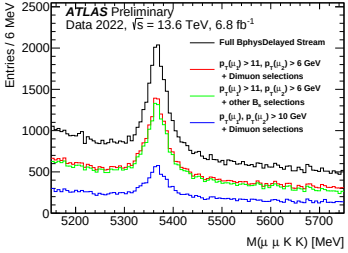
- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
- CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

Backup slides

ATLAS B-physics trigger in Run-3







Search for $bb\bar{b}\bar{b}$ states in CMS

PLB 808 (2020) 135578

- Tetraquark states can be searched in $bb\bar{b}\bar{b}$ as well
  - numerous predictions, e.g. within non-relativistic QFT with OGE potential EPJC (2018) 647
- First search done by LHCb (JHEP 10 (2018) 086
- CMS search covers a complementary kinematic region
  - (by-product of di-Υ production measurement)
  - *still no signal seen, upper limits set*
- ATLAS analysis on-going