Double-charm spectroscopy at ATLAS and CMS

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on behalf of ATLAS and CMS Collaborations

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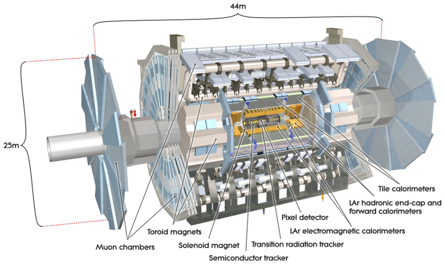
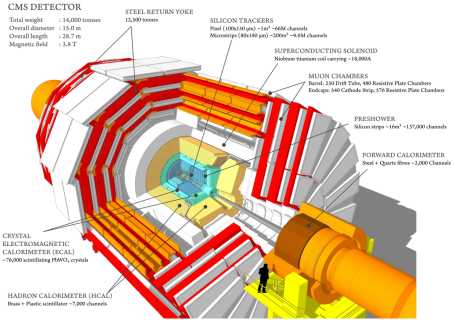
ATLAS and CMS detectors

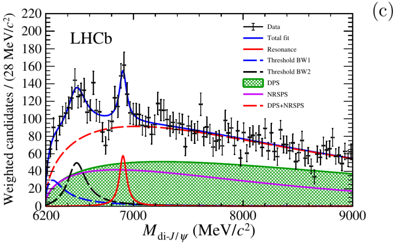
- Compared to B-factory experiments
  - Abundant production of B_s^0, B_c^+, b baryons, including excited states
  - Challenging reconstruction and triggering in pp environment
- Compared to LHCb
  - Central acceptance for tracks and muons ($|\eta| \lesssim 2.5$) – complementary production measurements
  - 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 (multi-)muon triggers

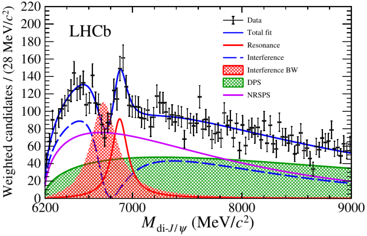




Structures in di-charmonium spectrum

- 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 (arXiv:2306.07164) and ATLAS (PRL 131 (2023) 151902)





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:

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

Strategy and event selection

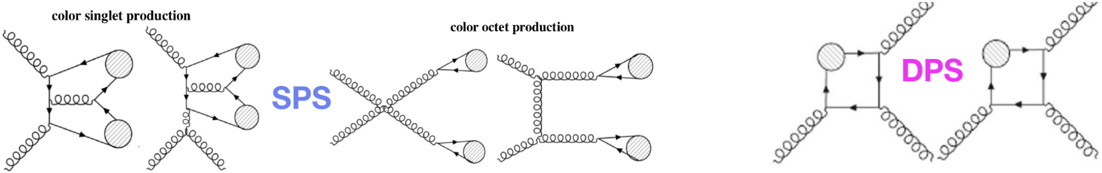
- Investigate di-J/ψ mass spectrum with 4-muon final state
  - ATLAS also looks at $J/\psi + \psi(2S)$ in the same final state
- **Triggers:** tri-muon (CMS), tri-muon + di-muon (ATLAS)
- Signal region $m_{4\mu} < 7.5(7.8)$ GeV was **blinded** in ATLAS (CMS)
- ATLAS event selection:

<table>
<tr><th>Signal region</th><th>Control region</th><th>Non-prompt region</th></tr>
<tr><td colspan="3">Di-muon or tri-muon triggers, oppositely charged muons from each charmonium,
loose muons, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $|\eta_{1,2,3,4}| < 2.5$ for the four muons,
$m_{J/\psi} \in [2.94, 3.25]$ GeV, or $m_{\psi(2S)} \in [3.56, 3.80]$ GeV,
Loose vertex requirements $\chi^2_{4\mu}/N < 40$ ($N = 5$) and $\chi^2_{\text{di-}\mu}/N < 100$ ($N = 2$),</td></tr>
<tr><td colspan="2">Vertex $\chi^2_{4\mu}/N < 3$, $L^{4\mu}_{xy} < 0.2$ mm, $|L^{\text{di-}\mu}_{xy}| < 0.3$ mm, $m_{4\mu} < 11$ GeV,</td><td rowspan="2">Vertex $\chi^2_{4\mu}/N > 6$,
or $|L^{\text{di-}\mu}_{xy}| > 0.4$ mm</td></tr>
<tr><td>$\Delta R < 0.25$ between charmonia</td><td>$\Delta R \geq 0.25$ between charmonia</td></tr>
</table>

- Very similar in CMS, except no ΔR cut

Background processes

- **Prompt** production of charmonium pairs – *dominant source*
  - Single Parton Scattering (SPS)
  - Double Parton Scattering (DPS)
- Production of two **non-prompt** J/ψ's, i.e. $b\bar{b} \to J/\psi J/\psi X$
- Events with at least one **fake** J/ψ
  - either from real muons or hadronic fakes
- **Feed-down** from tetraquark decays via heavier charmonia



SPS and DPS backgrounds

- SPS and DPS are modelled by MC, kinematics corrected in CRs with $\Delta R \geq 0.25$
  - *SPS*: $m_{4\mu} \in [7.5, 12.0]$ GeV
  - *DPS*: $m_{4\mu} \in [14.0, 25.0]$ GeV
- Normalization constrained using the common CR in the fit

Signal region	Control region	Non-prompt region
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *loose* muons, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, or $m_{\psi(2S)} \in [3.56, 3.80]$ GeV, Loose vertex requirements $\chi^2_{4\mu}/N < 40$ ($N = 5$) and $\chi^2_{\text{di-}\mu}/N < 100$ ($N = 2$),		
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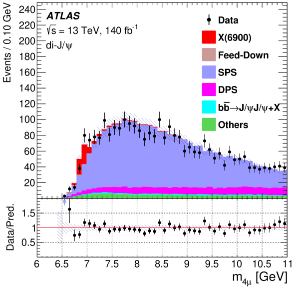
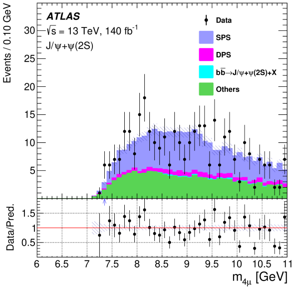
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	or $\lvert L^{\text{di-}\mu}_{xy}\rvert > 0.4$ mm

Control region





Non-prompt and other backgrounds

- Non-prompt background modelled with MC
  - validated and normalized using *inverted $\chi^2_{4\mu}/N$ and L_{xy} region*
- Other backgrounds: non-resonant di-muons, muon fakes – data-driven estimate
  - estimated requiring one ψ to contain a non-muon track
  - normalized using charmonium mass sideband events
- Feed-down background
  - shape from MC
  - normalization from $J/\psi + \psi(2S)$ fitted signal with an efficiency and $\mathcal{B}$ corrections

Signal region	Control region	Non-prompt region
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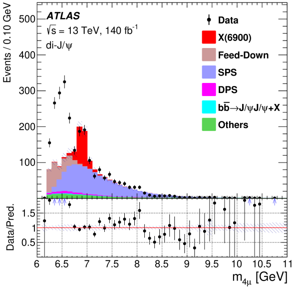
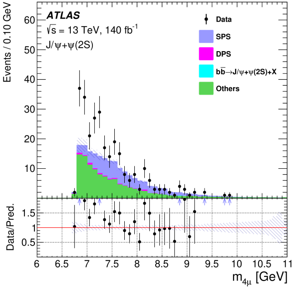
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	

Signal region





Di-J/ψ fit models

CMS

- Backgrounds:
  - SPS and DPS: parametrization of simulated distributions, one exponential slope free in the fit
  - Additional component to model the near-threshold enhancement – *BW_0*
    - good *ad-hoc* description of the feature
- Signal *no-interference model*
  - BW resonances added as long as their above 3σ significant
  - end up with 3 peaks
- Signal *interference model*
  - Same 3 BW structures allowed to interfere to each other

ATLAS

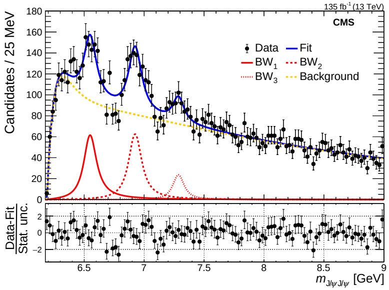
- Backgrounds:
  - As described above, SPS and DPS also constrained by the fit with CR
- Signal *Model A*
  - 3 interfering BW resonances

$$f_s(x) = \left|\sum_{i=0}^{2} \frac{z_i}{m_i^2 - x^2 - i m_i \Gamma_i(x)}\right|^2 \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\theta),$$

  - analog of *LHCb model I* $(+$ interference)
- Signal *Model B*
  - 1 BW resonance interfering with SPS di-J/ψ production, another standalone

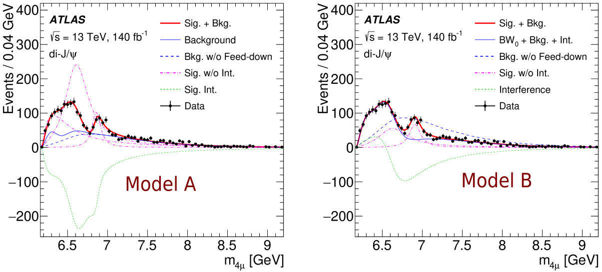
$$f(x) = \left(\left|\frac{z_0}{m_0^2 - x^2 - i m_0 \Gamma_0(x)} + A e^{i\phi}\right|^2 + \left|\frac{z_2}{m_2^2 - x^2 - i m_2 \Gamma_2(x)}\right|^2\right) \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\theta),$$

  - analog of *LHCb model II*



- *No-interference* with 3 BW resonances
- Good description, except the dips between the BWs

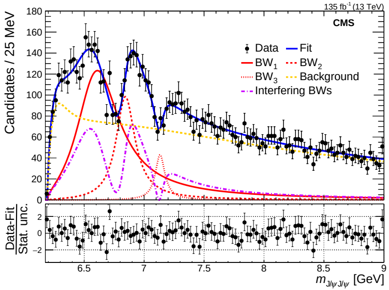
	BW_1	BW_2	BW_3
m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
	6.5σ	**9.4σ**	**4.1σ**



- Both models describe data well
- Model A w/o interference excluded at 95%CL
- Significance of all BWs or of X(6900) well above 5σ

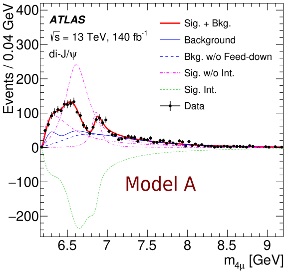
di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11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

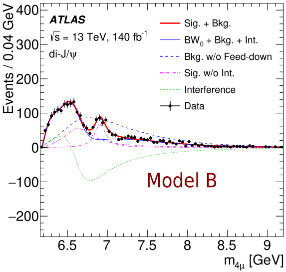
Di-J/ψ channel fits (2)



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

	BW_1	BW_2	BW_3
m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}





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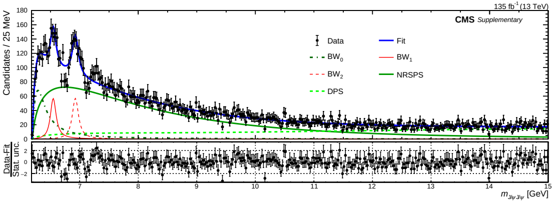
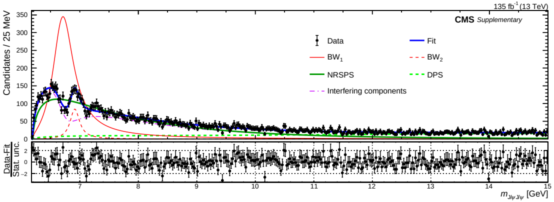
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

CMS compatibility with LHCb

- *LHCb model I*: just 2 signal BW resonances (and background BW_0)
- Poorer quality w.r.t. no-interference model with 3 signals
  - χ^2 probability of 0.9% w.r.t. 9% in signal region
  - note very similar di-J/ψ yield to LHCb



- *LHCb model II*: 2 signal BW resonances (and background BW_0), BW_1 interfering with SPS
- Dip at 6.75 GeV modelled better, but overall quality still poor
  - χ^2 probability 0.8% – even worse



Nevertheless, the mass and width of $X(6900)$ are still fairly consistent

Exp.	Fit	M_{BW_1}	Γ_{BW_1}	$M_{X(6900)}$	$\Gamma_{X(6900)}$
LHCb [14]	Model I	—	—	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [14]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

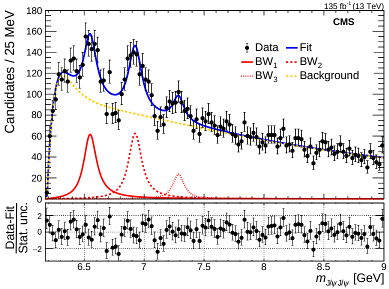
ATLAS $J/\psi + \psi(2S)$ channel fit

- Alternative way to probe the new structures
- Two alternative models tested:
- *Model α*:
  - same three resonances from di-J/ψ Model A assumed to decay to $J/\psi + \psi(2S)$
    - parameters fixed from di-J/ψ fit
  - additional stand-alone resonance

$$f_s(x) = \left(\left| \sum_{i=0}^{2} \frac{z_i}{m_i^2 - x^2 - i m_i \Gamma_i(x)} \right|^2 + \left| \frac{z_3}{m_3^2 - x^2 - i m_3 \Gamma_3(x)} \right|^2 \right) \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x} \right)^2} \otimes R(\theta),$$

- *Model β*:
  - just a single resonance (i.e. $z_{0,1,2} = 0$ in eq. above)

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



- *No-interference* with 3 BW resonances
- Good description, except the dips between the BWs

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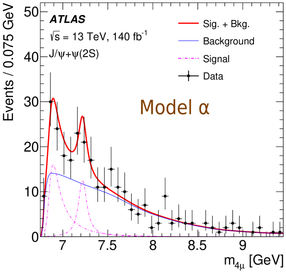
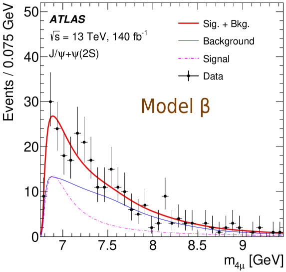




- Model α: significance 4.7σ
  - significance of the resonance at 7.2 GeV: 3σ
- Model β: significance 4.3σ

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

Systematics

CMS

Fit	Dominant sources	M_{BW_1}	M_{BW_2}	M_{BW_3}	Γ_{BW_1}	Γ_{BW_2}	Γ_{BW_3}
No-interference	Signal shape	3	3	3	10	5	5
	NRSPS shape	3	1	1	18	15	17
	Feed-down	11	1	1	25	8	6
	Total uncertainty	12	4	5	33	18	19
Interference	Signal shape	7	12	7	56	8	7
	DPS shape	1	3	2	18	6	2
	NRSPS shape	9	14	13	85	9	20
	Mass resolution	8	4	1	24	7	13
	Combinatorial bkg.	7	2	<1	5	3	2
	Feed-down	$^{+0}_{-27}$	$^{+44}_{-0}$	$^{+38}_{-0}$	$^{+0}_{-210}$	$^{+19}_{-0}$	$^{+12}_{-0}$
	Total uncertainty	$^{+16}_{-31}$	$^{+48}_{-20}$	$^{+41}_{-15}$	$^{+110}_{-240}$	$^{+25}_{-17}$	$^{+29}_{-26}$

ATLAS

Systematic Uncertainties (MeV)	di-J/ψ m_2	di-J/ψ Γ_2	J/ψ+$\psi(2S)$ m_3	J/ψ+$\psi(2S)$ Γ_3
Muon calibration	± 6	± 7	<1	± 1
SPS model parameter	± 7	± 7	<1	
SPS di-charmonium p_T	± 7	± 8	<1	
Background MC sample size	± 7	± 8	± 1	<1
Mass resolution	± 4	-3	-1	$^{+2}_{-4}$
Fit bias	-13	$+10$	$^{+9}_{-10}$	$^{+50}_{-16}$
Shape inconsistency	<1		± 4	± 6
Transfer factor	—		± 5	± 23
Presence of 4th resonance	<1		—	
Feed-down	$^{+4}_{-1}$	$^{+6}_{-2}$	—	
Interference of 4th resonance	—		-32	-11
P and D-wave BW	$+9$	$+19$	<1	± 1
ΔR and muon p_T requirements	$^{+3}_{-2}$	$^{+6}_{-4}$	$^{+1}_{-2}$	-2
Lower resonance shape	—		$^{+3}_{-7}$	$^{+31}_{-34}$

Summary

- $X(6900)$ state is reliably confirmed by both ATLAS and CMS with consistent parameters and significance well above 5σ
- CMS and ATLAS employs different paradigms in the results interpretation
  - CMS claims the *sequence of 3 non-interfering BW resonances* as the main result (not assuming identical J^{PC} or production coherence)
    - adding interference, though improving the fits, is too arbitrary procedure
    - 3 masses agree with expectations for 3 radial excitations of P-wave 1^{-+} states in diquark-antidiquark model (EPJC 81 (2021) 324)
  - ATLAS proposes two equally good descriptions similar to the models tested by LHCb *with interference*
- Nature of the lowest-mass structure nature is thus rather uncertain
  - Could also result from other effects, e.g. a more complicated mixture of states or feed-down from higher di-charmonium resonances
- 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

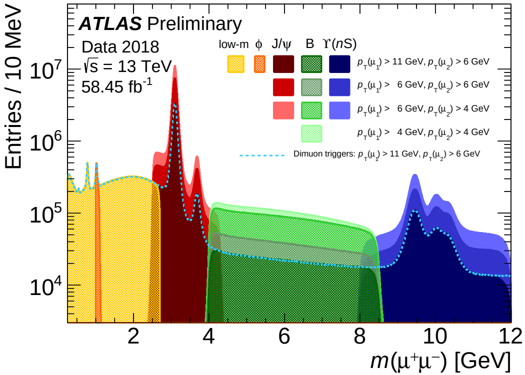
- **Further possibilities:**
  - Investigate $J/\psi + \psi(2S)$ channel with $4\mu + 2\pi$ final state
  - Run full amplitude analysis to reveal the nature of the new structures

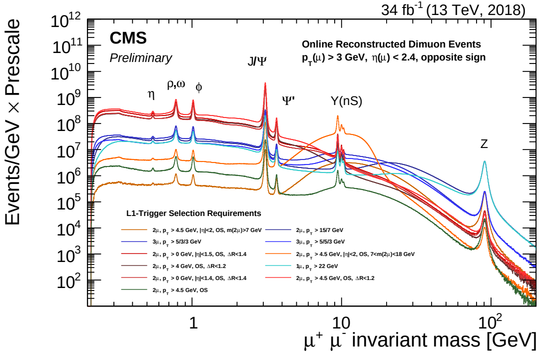
Backup slides

Di-muon triggers

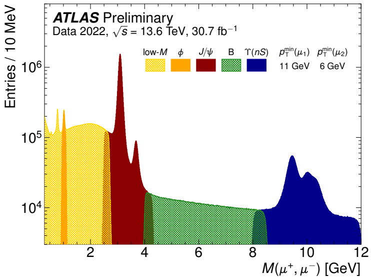
Dedicated trigger options to overcome the rate limitations for low-p_T dimuons

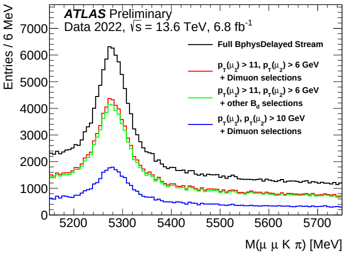
- ATLAS uses *topological selection* using muon trigger hardware information (cuts on $m(\mu^+\mu^-)$, $\Delta R(\mu^+\mu^-)$), software selection based on *full reconstruction of certain decays* with precision tracking (e.g. $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$)
- *Data scouting* in CMS – doing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

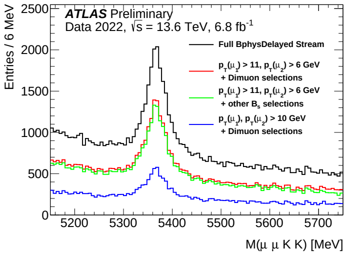


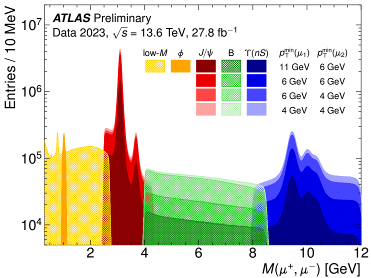


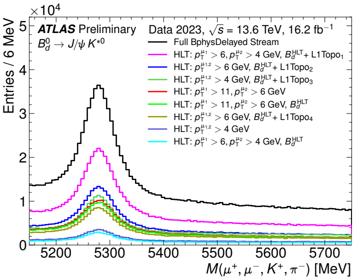
ATLAS B-physics trigger in Run-3

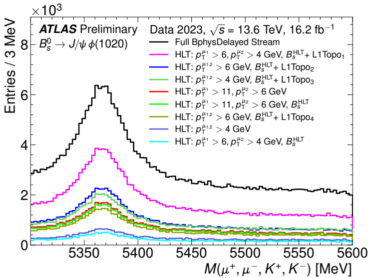




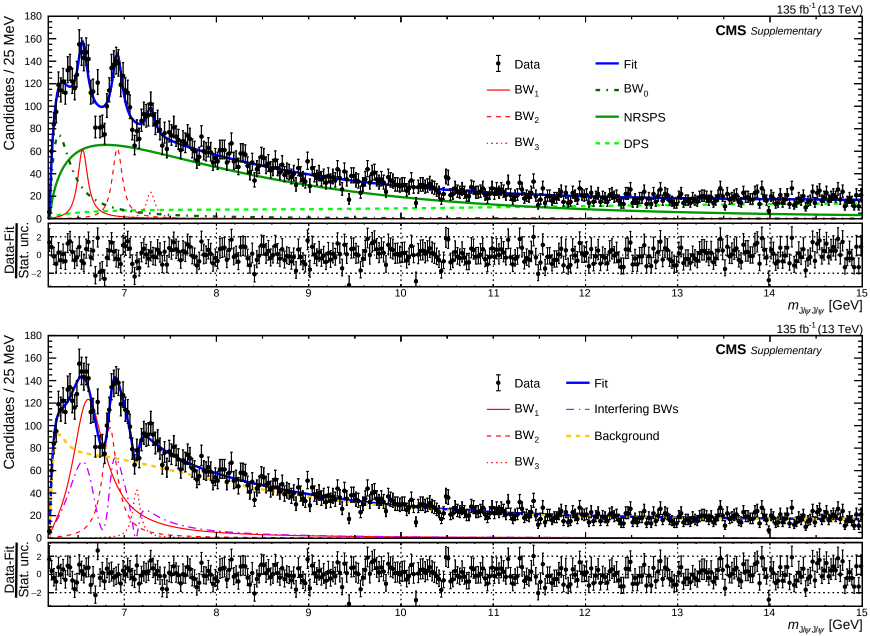




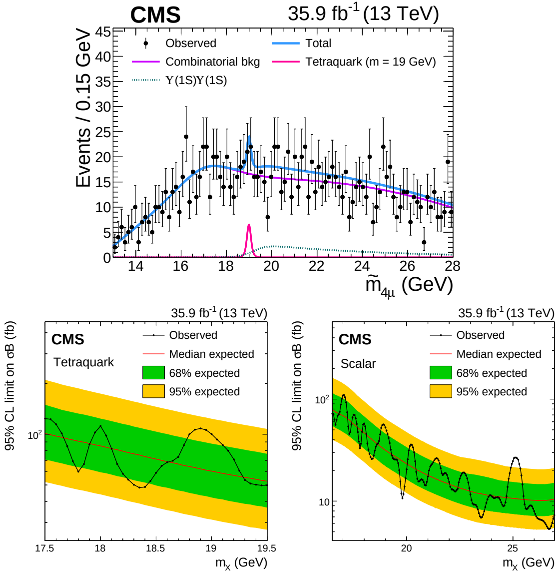




CMS mass fits in the whole range



- 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)
  - *no signal seen, upper limits set*



Search for $\Upsilon + 2\mu$ resonances in ATLAS

- ATLAS sees a structure at $m_{4\mu} = 18$ GeV in 2012 data
  - global significance 1.9–5.4σ depending on selection choice
- Much less significant structure in 2015–17 data and no signal in 2018 (with tighter trigger)
  - MC and data-driven studies confirm reduction of sensitivity in Run-2 data
  - 13 TeV result is in tension with 8 TeV at 2.7σ level