ATLAS results on exotic hadrons

Xin Chen
Tsinghua University

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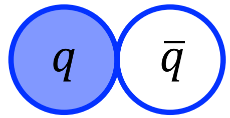
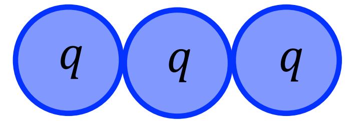
Introduction – exotic hadrons

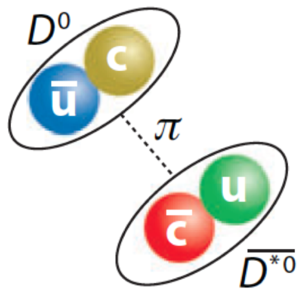
Traditional quark models:



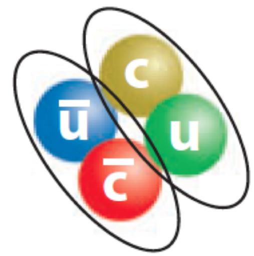
Meson



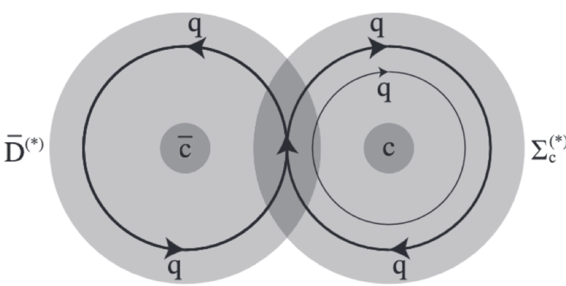
Baryon



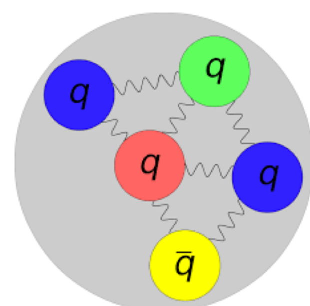
D^0–$\overline{D^{*0}}$ "molecule"



Diquark–diantiquark



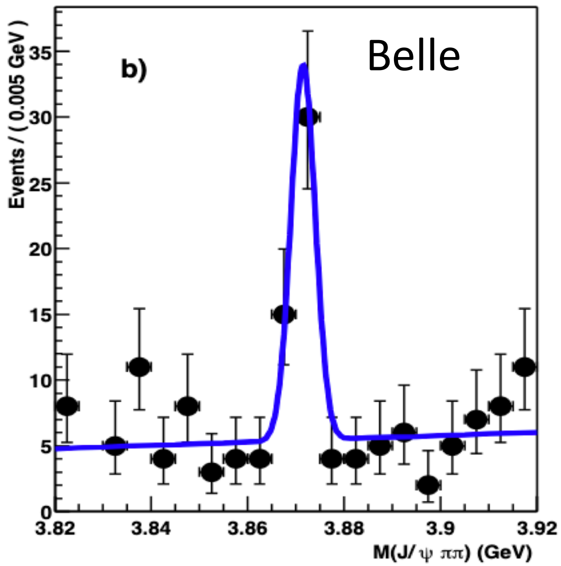
Meson + baryon "molecule"



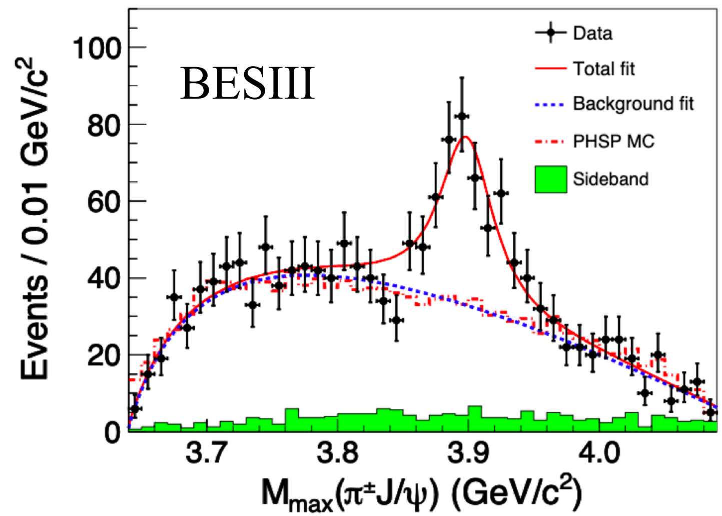
Pentaquark

Hidden charm tetraquark

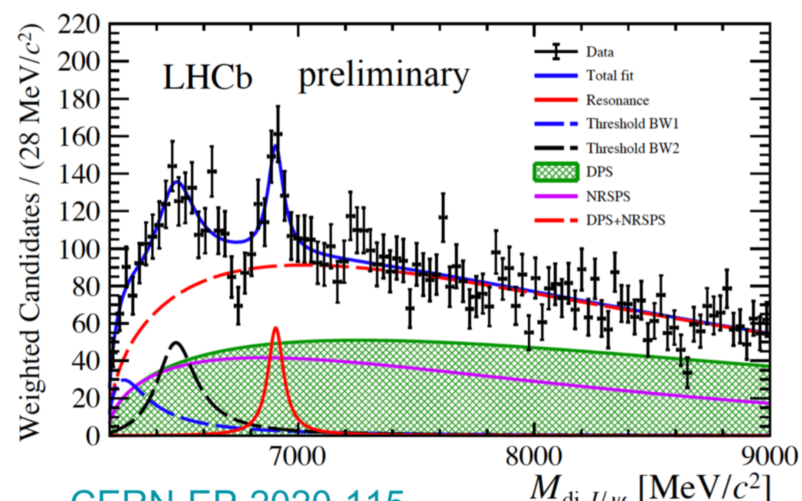
[Phys. Rev. Lett 91 (2003) 262001]



[Phys.Rev.Lett. 110 (2013) 252001]

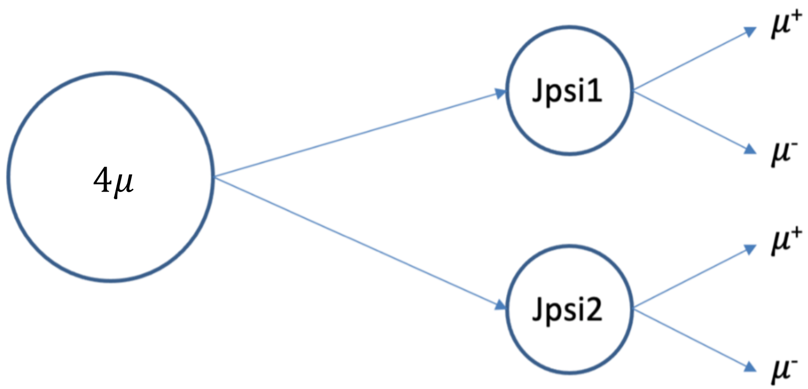


- X(3872) at Belle, Y(4260) at BABAR, $Z_c^+(3900)$ at BESIII, and later a number of XYZ states …
- Charmed Tetraquark (TQ) state is often proposed for these LS
- Potential 4-charm TQ from LHCb

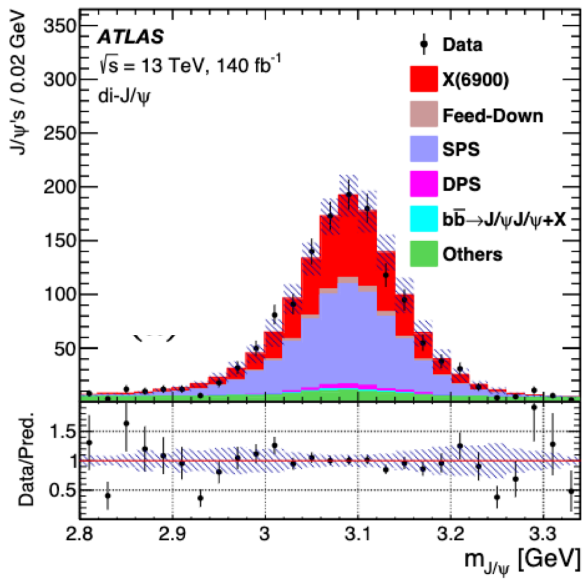


CERN-EP-2020-115

Reconstruction of 4μ vertex at ATLAS



[Phys. Rev. Lett. 131 (2023) 151902]



- We first find vertices of J/ψ candidates and geometrically fit the 4 tracks of a J/ψ pair to a common vertex. We revertex two J/ψ tracks with a mass constraint, improving the 4μ mass resolution from ~95 MeV to ~20 MeV
- Use sum of χ^2/N of two charmonia and 4μ vertices to select the best 4μ candidate per event

Signal and Backgrounds

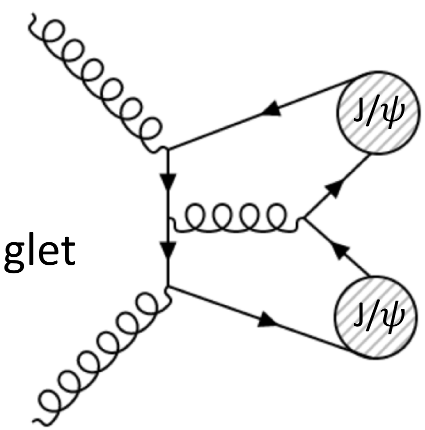
- Signal process
  - Signal samples for process: pp → X → di-$J/\psi \rightarrow 4\mu$
    - TQ mass = 6.9 GeV, width = 0.1 GeV, spin = 0 with JHU
- Background processes:
  - Prompt di-J/ψ background: Single Parton Scattering (SPS), Double Parton Scattering (DPS) with Pythia8
  - Non prompt di-J/ψ background: $b\bar{b} \rightarrow J/\psi\ J/\psi$ with Pythia8
  - Single J/ψ background
    - Prompt or nonprompt J/ψ, plus fake muons from the primary vertex
  - Non-peaking background containing no real J/ψ candidates

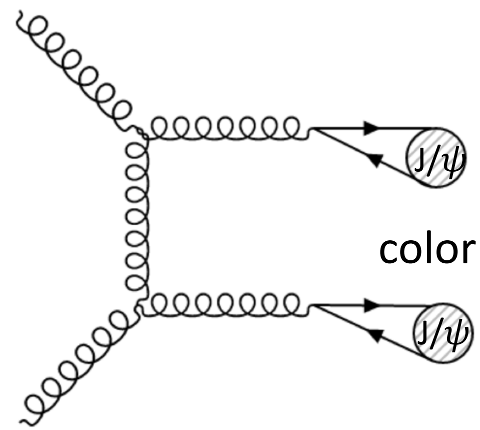
Single J/ψ background and non-peaking background are collectively called "others", and are estimated from data by reversing one muon's ID

SPS and DPS backgrounds

- Both color singlet and color octet processes are included for di-charmonium SPS, dominated by gluon–gluon interactions. As a result, the two J/ψ's from SPS are highly correlated

color singlet



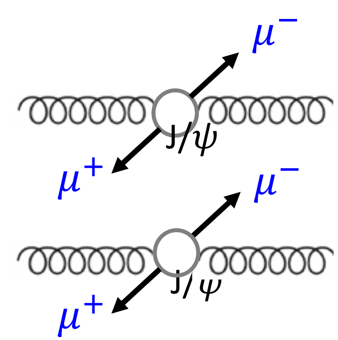


color octet

- DPS populates the reatively low-p_T region, and becomes more important with larger collider energy, as the parton density increases at small x
- If neglecting correlations between partons (effective cross section approximation):

$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{J/\psi,J/\psi}_{\text{DPS}}}$$

DPS:

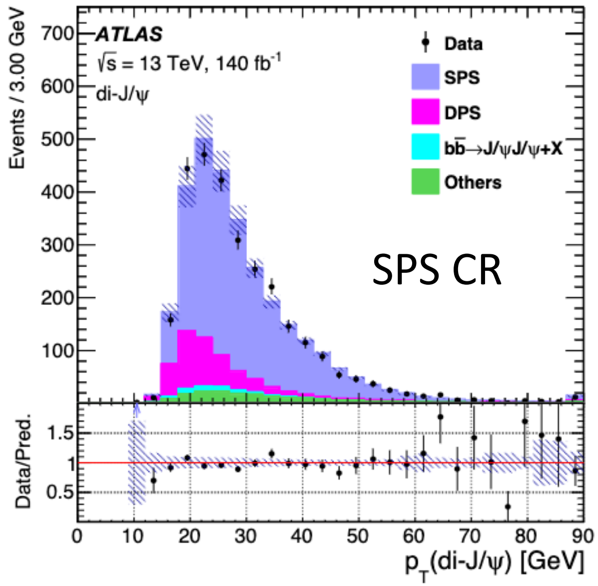


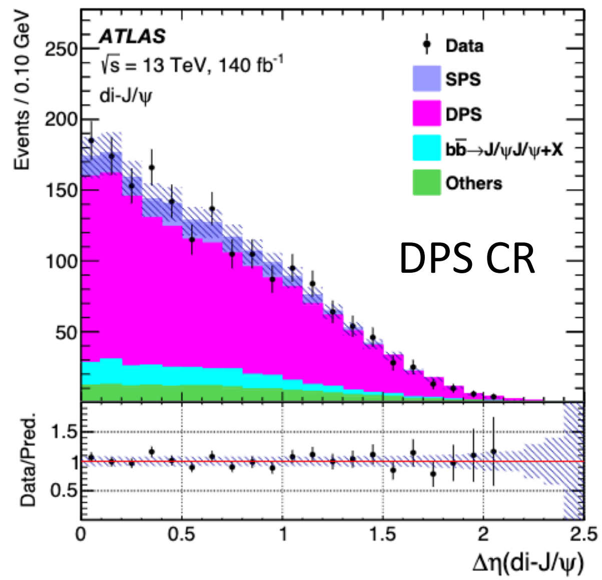
Event selection

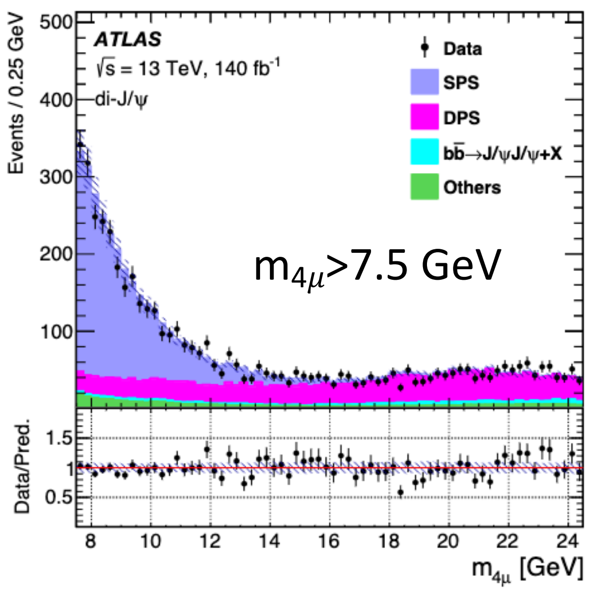
Signal region	Control region	Non-prompt region
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *loose* muons, $p_{\mathrm{T}}^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, or $m_{\psi(2S)} \in [3.56,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

- Signal region cuts:
  - di-μ or tri-μ triggers per year for maximum efficiency
  - 4 muons with minimum p_T of 3 GeV within accepance
  - Vertex χ^2/N cut, J/ψ mass window cuts
  - L_{xy} (distance between J/ψ and PV vertices) cut
  - $\Delta R < 0.25$ of two J/ψ's
- SPS and DPS are estimated by MC, and are kinematically corrected by SPS and DPS enriched 4μ mass sidebands (SPS and DPS CRs)
- Non-prompt J/ψ background is estimated with data by reversing the L_{xy} or χ^2/N cut

SPS and DPS CRs in di-J/ψ channel

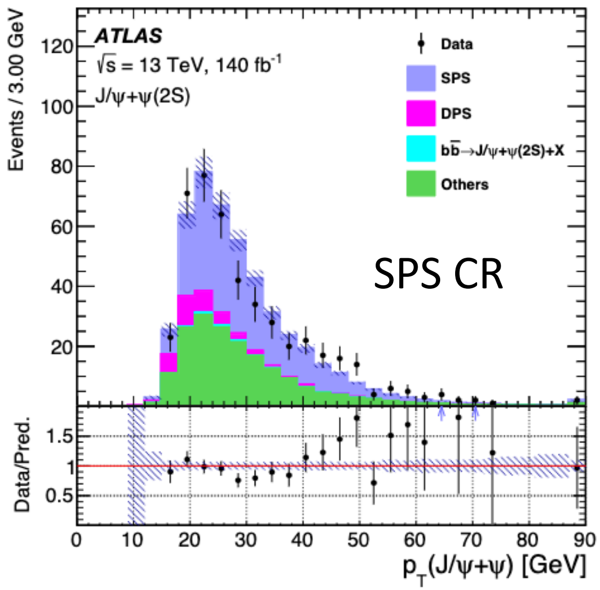


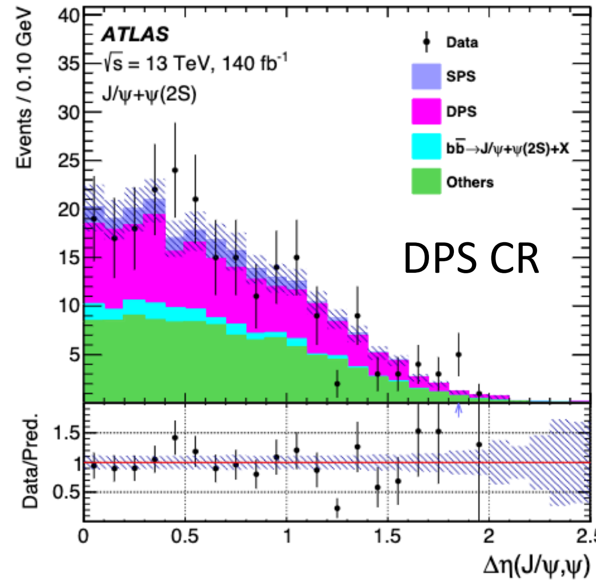


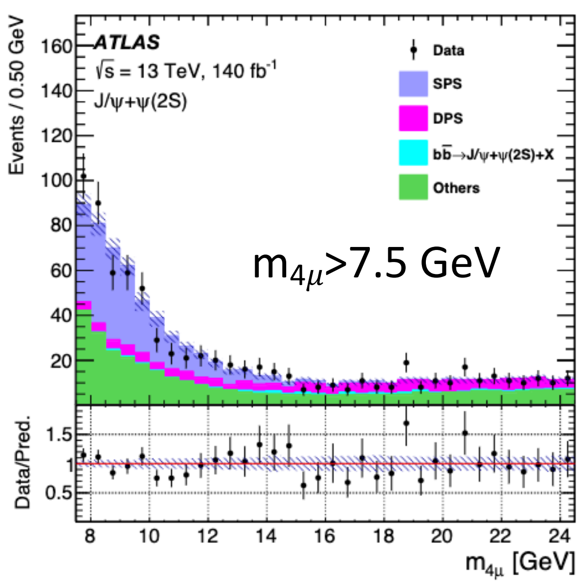


- Discrepancies in some kinematics distributions are resolved by event reweighting in the SPS and DPS CRs without ΔR cut
  - ✓ SPS CR: 7.5 GeV < $m_{4\mu}$ < 12.0 GeV
  - ✓ DPS CR: 14.0 GeV < $m_{4\mu}$ < 24.5 GeV
- After reweighting, other kinematic distributions are also improved

SPS and DPS CRs in J/ψ+ψ(2S) channel

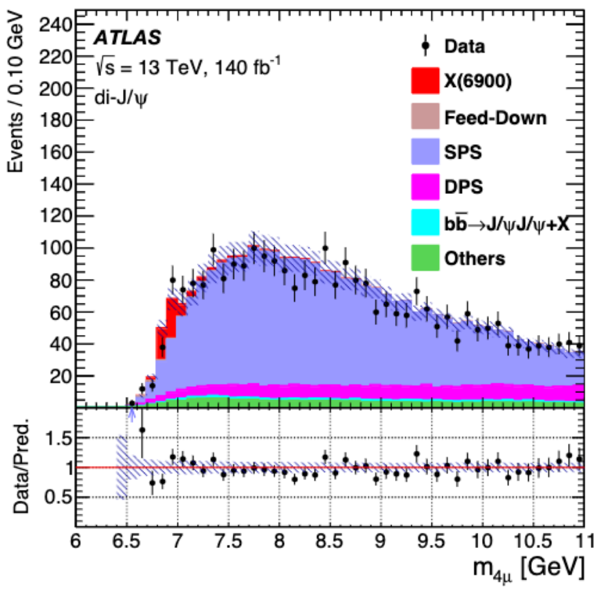


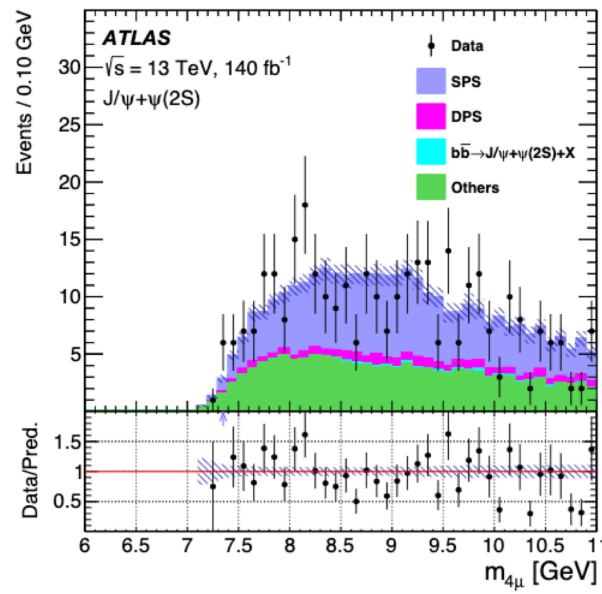




- Larger “others” background due to smaller signal/background ratio for ψ(2S)
- SPS and DPS are also corrected through reweighting method (after “others” corrections in its dedicated CR – J/ψ mass sidebands)

Control region ($\Delta R > 0.25$)





- The control region has the same cuts as the signal region, but with $\Delta R > 0.25$ between two J/ψ's. It serves two purposes
  - ✓ Correct and validate the SPS 4μ mass shape. Pythia8 ***pT0timesMPI*** parameter is first tuned to data in SPS CR in $m_{4\mu}$ > 7.5 GeV, and validated in the control region with $m_{4\mu}$ < 7.5 GeV
  - ✓ The total background yields in the CR are used in the fit to constrain the background yields in the signal region

Fit models in di-J/ψ channel

- In the di-J/ψ channel, two models are considered
  - Model A with three interfering S-wave resonances

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

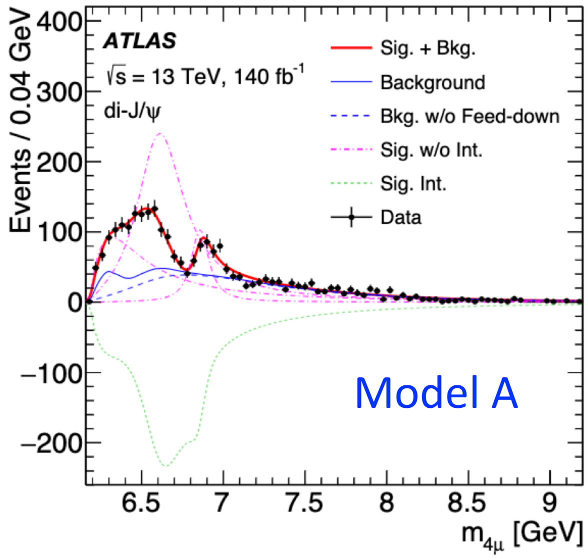
where z_1 is fixed to unity with zero phase, and R is the mass resolution function that the BWs convolute with

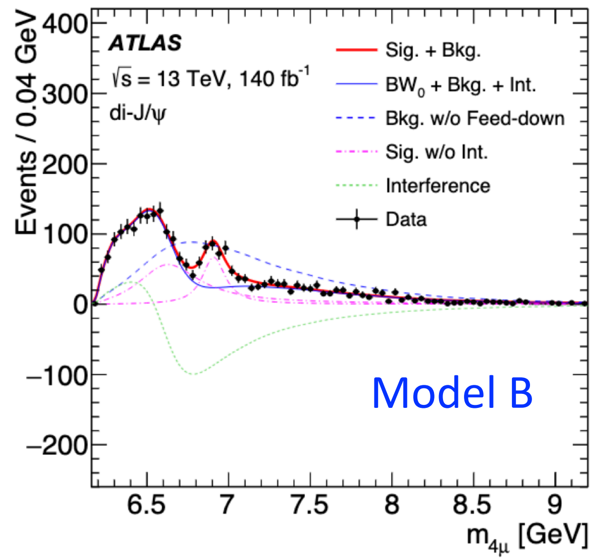
  - Model B with two S-wave resonances. The first interferes with SPS, while the second is standalone

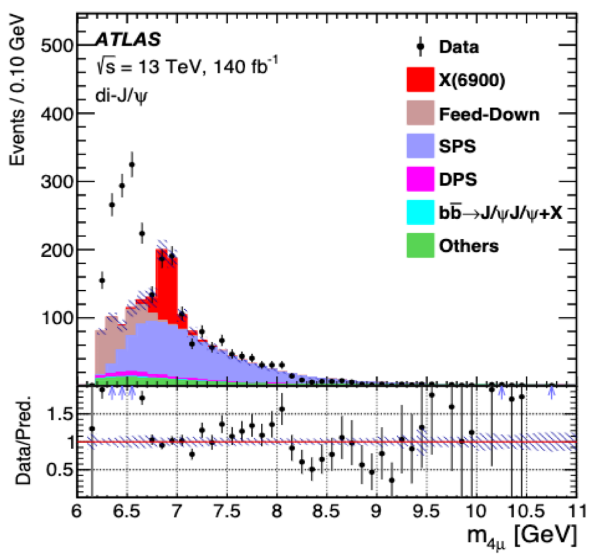
$$f(x) = \left(\left| \frac{z_0}{m_0^2 - x^2 - i m_0 \Gamma_0(x)} + A(x) e^{i\phi} \right|^2 + \left| \frac{z_2}{m_2^2 - x^2 - i m_2 \Gamma_2(x)} \right|^2 \right) \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\theta)$$

where $|A(x)|^2$ reproduces the non-interfering SPS background from the MC prediction

Fit result in di-J/ψ channel







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	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

Fit models in J/ψ+ψ(2S) channel

- In the J/ψ+ψ(2S) channel, two models are also considered
  - Model α with two resonances. The first is the same as Model A in di-J/ψ channel (parameters fixed), and second is standalone

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

  - Model β with a single resonance

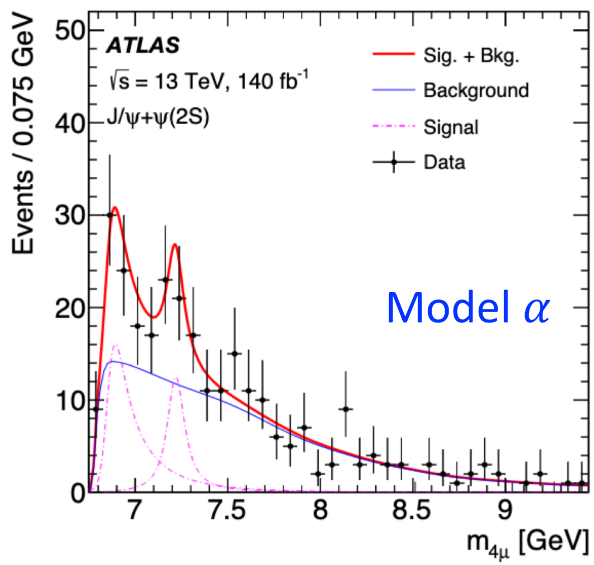
- The feed-down background normalization is obtained as

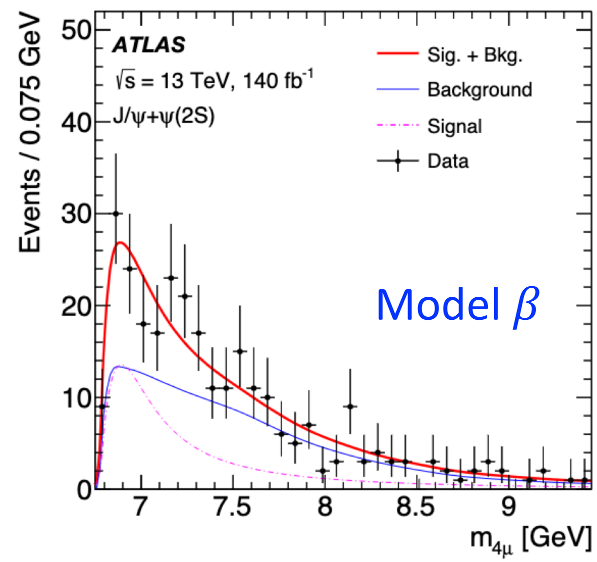
$$N_{\mathrm{fd}} = \frac{\mathcal{B}' \epsilon'}{\mathcal{B}\left(\psi(2S) \to \mu\mu\right) \epsilon} N$$

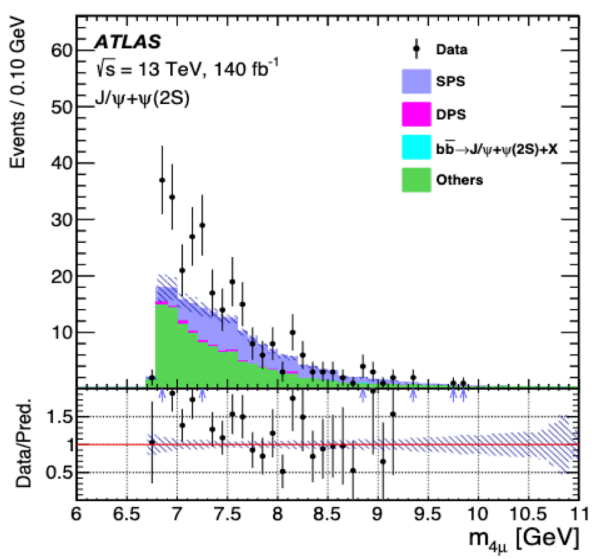
where $\mathcal{B}' = \left[\mathcal{B}\left(\psi(2\mathrm{S}) \to J/\psi + X\right) + \mathcal{B}\left(\psi(2\mathrm{S}) \to \gamma\chi_{cJ}\right) \mathcal{B}(\chi_{cJ} \to \gamma J/\psi)\right] \mathcal{B}(J/\psi \to \mu\mu)$

Reconstruction systematics largely cancel each others in the ratio. The only significant systematics comes from the fitted error on signal yields N in the J/ψ+ψ(2S) channel

Fit result in J/ψ+ψ(2S) channel







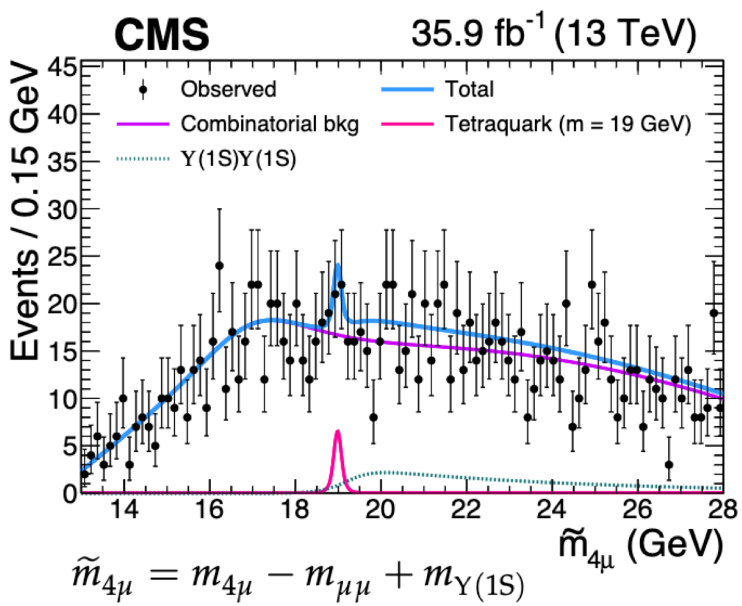
$J/\psi+\psi(2S)$	model α	model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

Total signal significance is 4.7σ (4.3σ) for Model α (β). In model α, the significance of the second resonance alone is 3.0σ

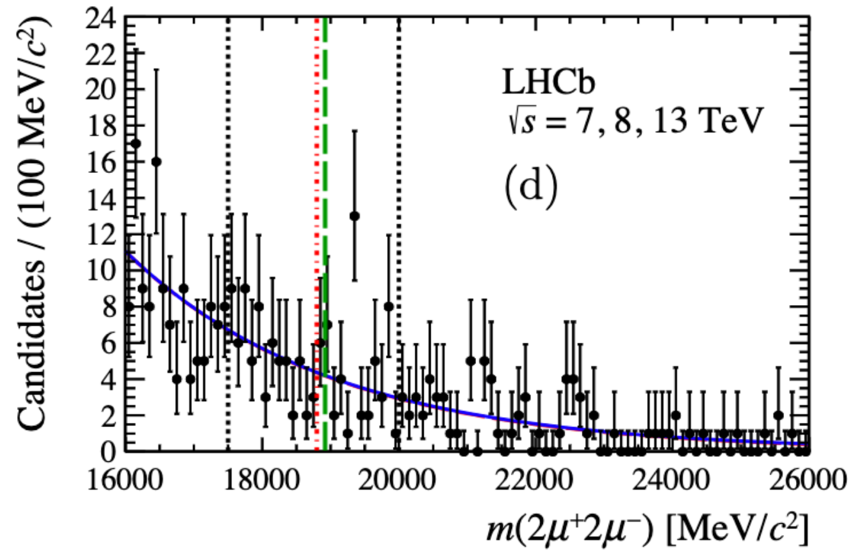
Full-beauty tetraquark?

- A tightly bound $b\bar{b}b\bar{b}$ tetraquark state can have a mass below the threshold of $\eta_b\eta_b$, and decays to $\Upsilon(1S) + \mu^+\mu^- \to 4\mu$. This possible full-beauty tetraquark has been searched by ATLAS and other experiments (while other theoretical interpretations, e.g. a BSM Higgs, is also feasible)
- A potential resonance in the $\Upsilon(1S) + \mu^+\mu^-$ channel have not been established by CMS and LHCb. It deserves a further check at ATLAS

[Phys. Lett. B 808 (2020) 135578]



[JHEP 10 (2018) 086]



Baseline cuts

[ATLAS-CONF-2023-041]

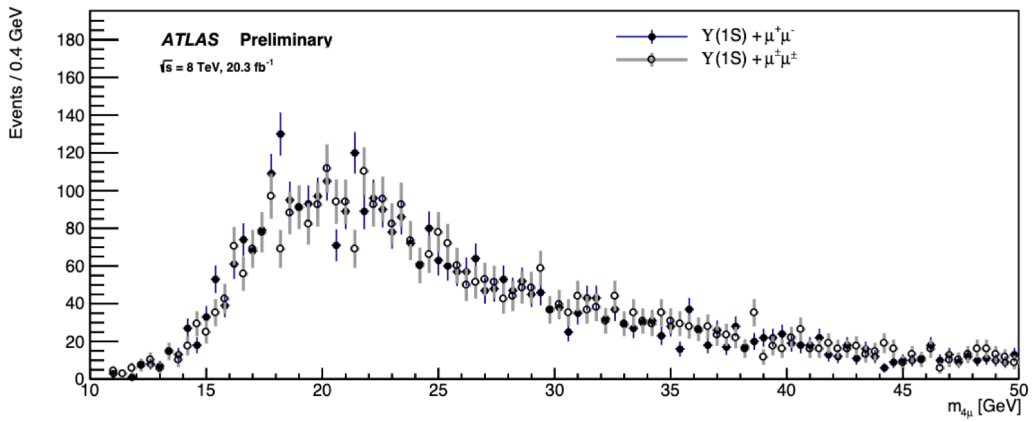
- Baseline event selections for the $\Upsilon(1S) + \mu^+\mu^-$ search at ATLAS:

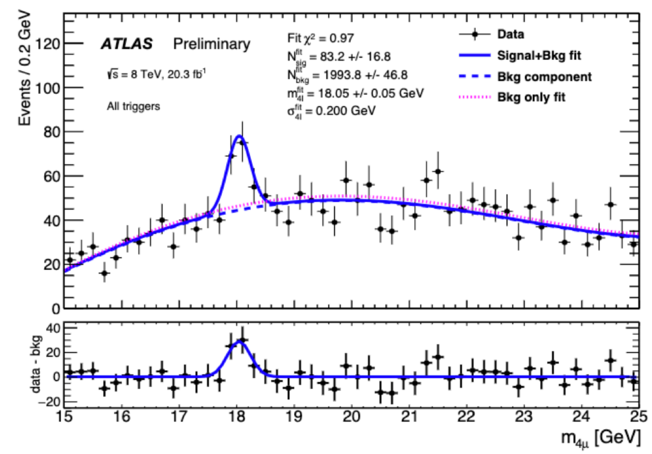
Candidate object	Requirements
Muons	$p_T(\mu) > 3$ GeV and $\|\eta\| < 2.5$, $\|z_0 \sin\theta\| < 1$ mm and $\|d_0/\sigma_{d_0}\| < 6$
Muon quadruplet	≥ 3 muons passing LowPt selection criteria, $\sum q_\mu = 0$, four-muon vertex fit $\chi^2/N_{\text{d.o.f}} \leq 10$, $10\ \text{GeV} \leq m_{4\mu} \leq 50\ \text{GeV}$
Muon doublet	di-muon vertex fit $\chi^2 < 3$
$\Upsilon(1S)$ candidate	OS muon doublet with $p_T(\mu_{1,2}) > 4$ GeV, $9.2\ \text{GeV} \leq m_{\mu^+\mu^-} \leq 9.7\ \text{GeV}$
$\Upsilon(1S) + \mu^+\mu^-$ candidate events	$\Upsilon(1S)$ candidate plus OS muon doublet with $m_{\mu^+\mu^-} > 1$ GeV, both muon doublets point to a common PV

- The background is modelled by a 4th-order Chebyshev polynomial and the signal by a Gaussian with its width fixed to the detector resolution (~0.2 GeV).
- Since the run-1 data did not follow a blind/unblind procedure, various modified selections w.r.t. the baseline cuts are applied to check the stability of the peak around 18 GeV (backup)

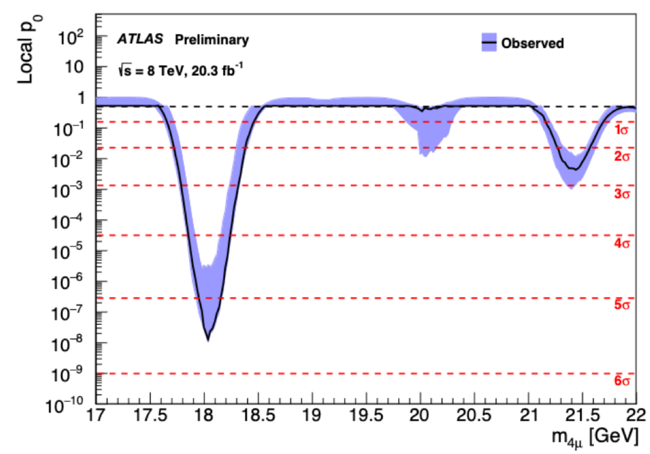
$\Upsilon + \mu\mu$ search with 8 TeV run-1data

- In 8 TeV run-1 data, three potential peaks are found at about 18.05 GeV, 21.4 GeV, and 31.7 GeV with local significances of 5.5, 2.4, and 2.6 σ



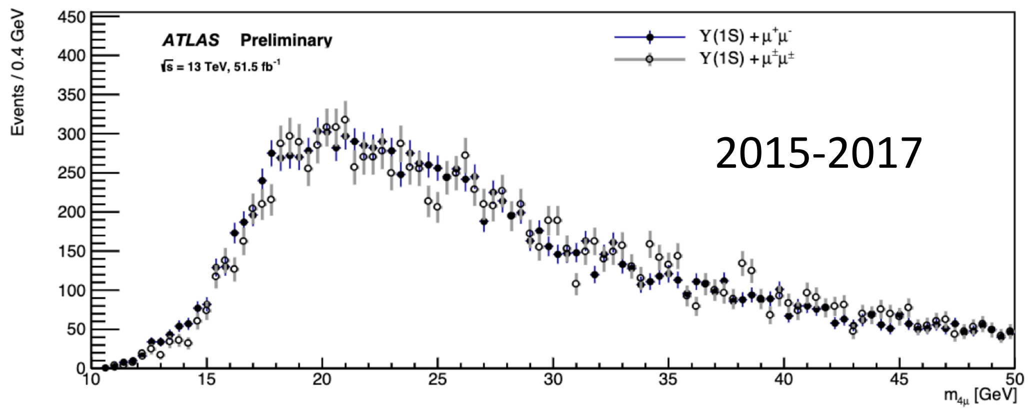


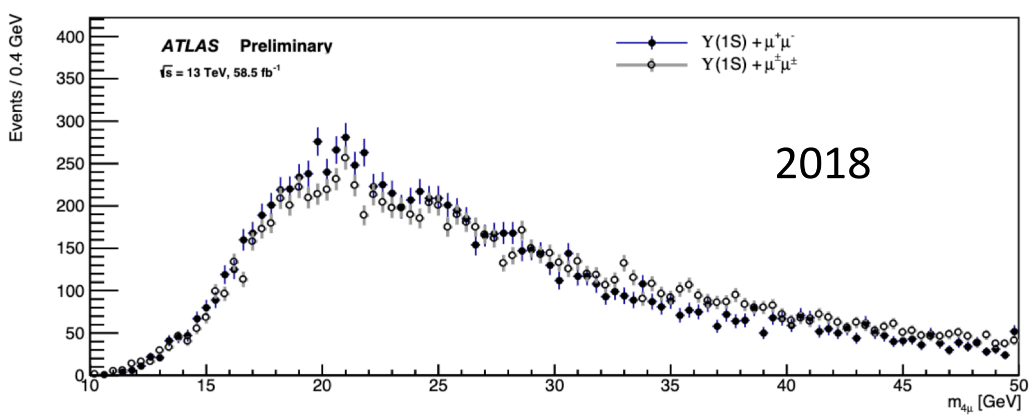
- To check if the peaks are artificial due to selection cuts, SS muons sample, $m_{\mu\mu}$ mass sideband control samples, Υ+di-track and single-muon + 3tracks data, event-mixed data, are investigated. No artificial structures are found in these checks



$\Upsilon + \mu\mu$ search with 13 TeV run-2 data

- Selection cuts for 13 TeV run-2 data were restricted to those used for the 8 TeV data. It serves as an independent check of the observed peaks in run-1



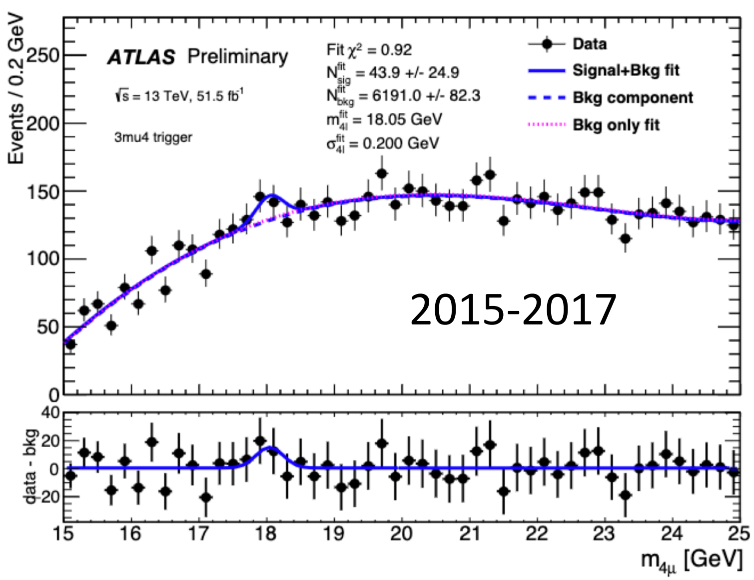


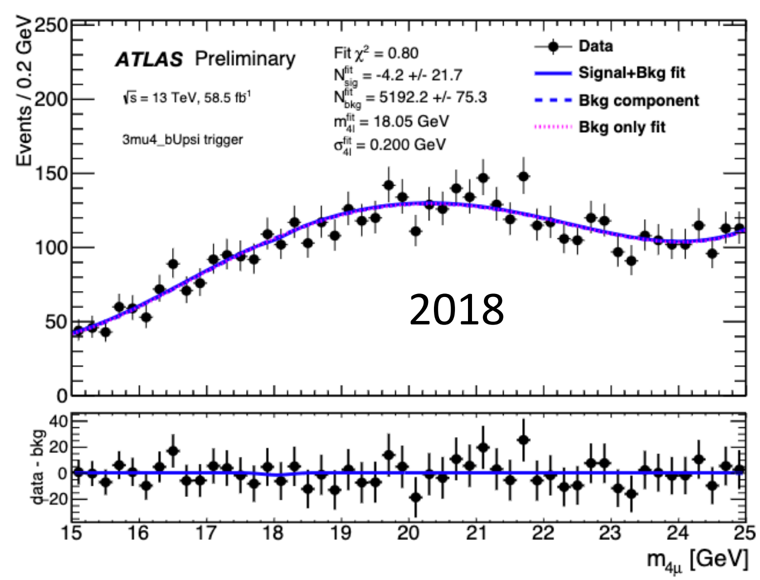
- In run-1, both di-muon and tri-muon triggers are used. No charge or mass requirements are imposed in the latter
- In run-2 data in years 2015-2017, similar trigger as run-1. But in run-2 2018, charge and mass cuts were required, which cause a shape difference in the OS vs SS $m_{4\mu}$ distribution

$\Upsilon + \mu\mu$ search with 13 TeV run-2 data

- Signal yields around 18 GeV are much smaller than in run-1, so the Gaussian width is fixed to 0.2 GeV, and the mass in 2015-2017 (2018) is floated (fixed to 18.05 GeV)

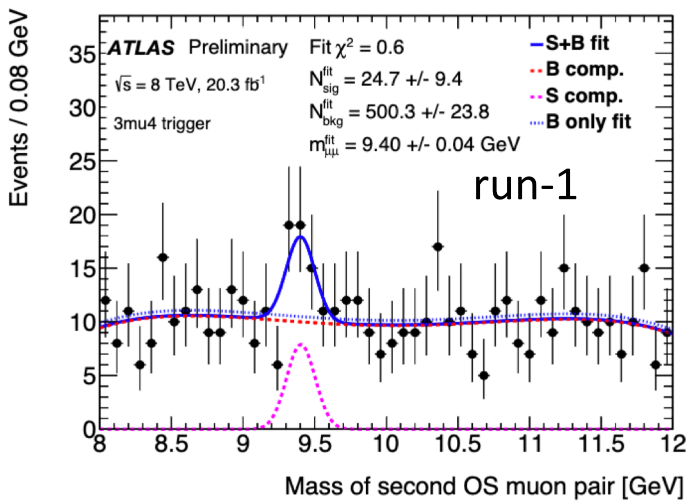
- Fitted signal yields are 48 ± 25 and −4 ± 22 in the two periods, while the backgrounds are ~2.5 times larger per unit integrated luminosity in run-2 than in run-1

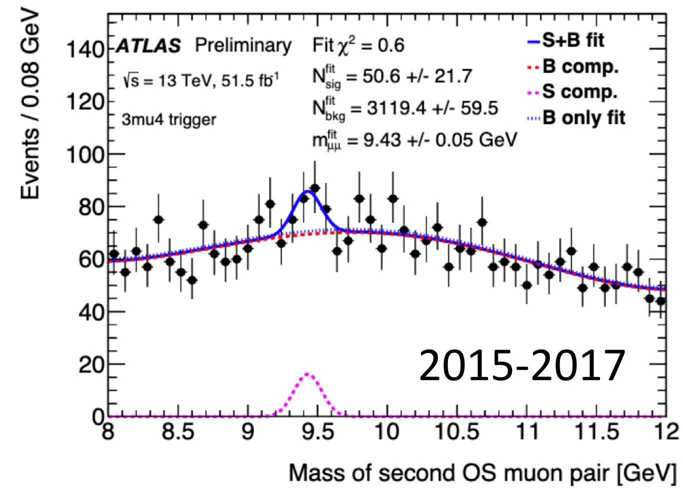


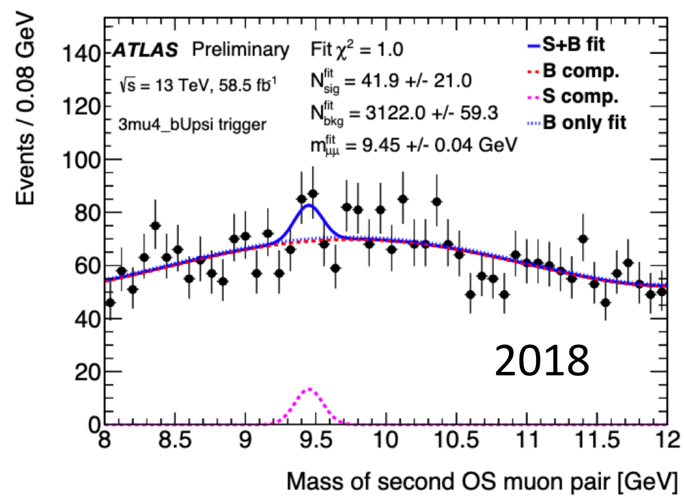


$\Upsilon + \mu\mu$ search with 13 TeV run-2 data

- With other things equal and assuming $\frac{\sigma_{13\mathrm{TeV}}}{\sigma_{8\mathrm{TeV}}} = 1.4$, the expected signal yield in 2015-2017 (2018) data is 89 (101), whereas the fitted signal yield is 51 ± 22 (42 ± 21)

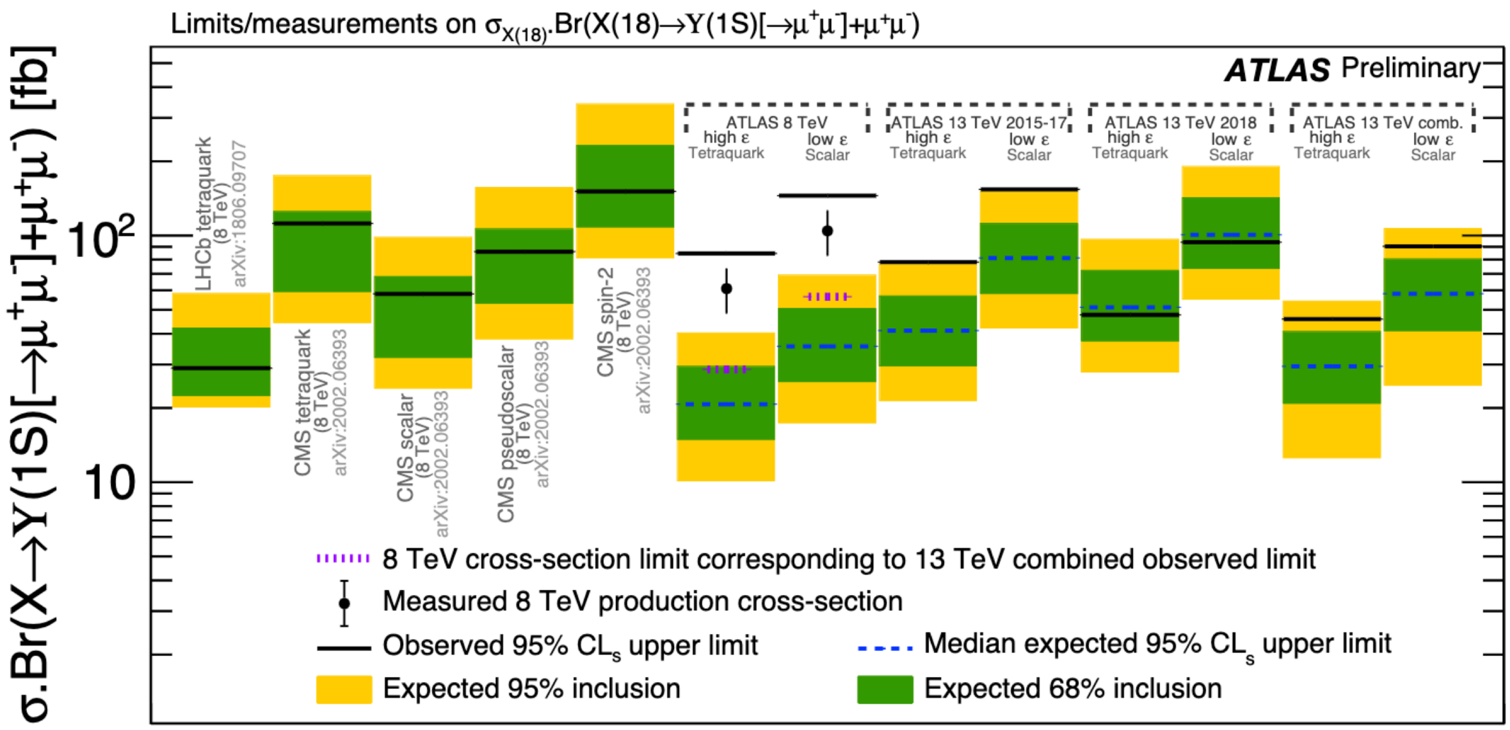






- Similar trend is observed in the di-Υ data. The observed yield in run-2 is ~60% of what would be expected if extrapolating from run-1 8 TeV data

$\Upsilon + \mu\mu$ search limits



- CL_S limits on $\sigma \times \mathrm{BR}$ of the 18 GeV peak are calculated with different signal models: 'Low ε' and 'high ε' refer to the limits derived from signal models with lowest (Higgs-like scalar) and highest (pseudoscalar tetraquark) predicted selection plus reconstruction efficiencies, respectively
- Further study with increased statistics from Run-3 data is needed

Summary

- ATLAS is not only a discovery machine for high energy physics, but can also make low energy hadron measurements owing to its excellent tracking

- Hadron colliders are important for new hadron searches and for understanding QCD. New states should better be checked in different experiments. For example, the potential 18 GeV peak in $\Upsilon + \mu\mu$ has not been established by ATLAS (and not by LHCb and CMS either)

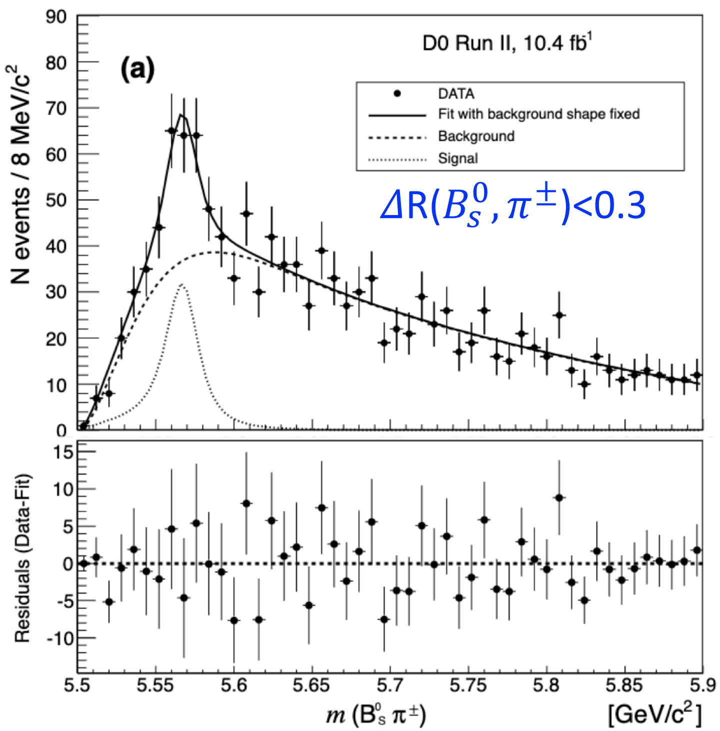
- ATLAS searched for potential $cc\bar{c}\bar{c}$ tetraquarks decaying into a pair of J/ψ's, or into J/ψ+ψ(2S), in the 4μ final state
  - ✓ Two models are used to fit the significant excess in the di-J/ψ channel, one of which is consistent with X(6900) by LHCb and CMS
  - ✓ Two models are used to fit the excess in the J/ψ+ψ(2S) channel. More data is needed to measure its parameters

- We look forward to new results combing Run-3 of LHC

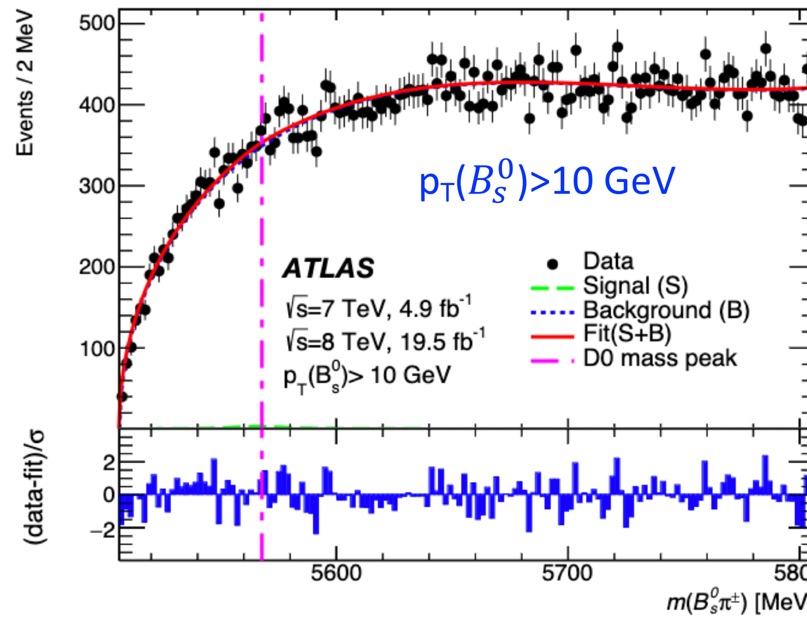
Backup Slides

$X^{\pm}(5568)$ from D0 and ATLAS

[Phys. Rev. Lett. 117 (2016) 22003]



[Phys. Rev. Lett. 120 (2018) 202007]



- In 2016, D0 claimed a potential resonance at about 5568 MeV in $B_s^0 + \pi^{\pm}$ (5.1σ), which is ~200 MeV below $B_d^0 + K^{\pm}$ and favors a tetraquark than a molecular interpretation
- However, $X^{\pm}(5568)$ is not confirmed by ATLAS (neither by CMS or LHCb). Two main backgrounds are modelled separately – fake B_s^0 (modelled by B_s^0 sidebands) and random pions (modelled by MC with B_s^0 p_T tuned to data)

$\Upsilon + \mu\mu$ search with 8 TeV run-1data

- Since the run-1 data did not follow a blind/unblind procedure, various modified selections are applied to check the stability of the peak around 18 GeV

Selection criteria	N_B	Mass (GeV)	N_S	Significance (σ)
Baseline	1994 ± 47	18.05 ± 0.05	83 ± 17	5.5
Selection variations from the baseline				
≥ 2 LowPt muons	3124 ± 59	18.09 ± 0.06	94 ± 20	5.0
$= 4$ LowPt muons	689 ± 28	18.03 ± 0.07	37 ± 10	4.1
$m_{\mu^+\mu^-}^{\text{non-res}} > 0$ GeV	2515 ± 53	18.00 ± 0.06	81 ± 19	4.7
$m_{\mu^+\mu^-}^{\text{non-res}} > 0.5$ GeV	2306 ± 51	18.00 ± 0.05	87 ± 18	5.3
$m_{\mu^+\mu^-}^{\text{non-res}} > 2$ GeV	1696 ± 43	18.05 ± 0.07	58 ± 15	4.3
Vertex fit $\chi^2/N_{\text{d.o.f}} \leq 4$	1705 ± 43	18.03 ± 0.05	69 ± 15	5.0
Vertex fit $\chi^2/N_{\text{d.o.f}} \leq 20$	2077 ± 48	18.04 ± 0.05	81 ± 17	5.0
$m_{\Upsilon(1S)} \pm 2\sigma_m$ window	3705 ± 64	18.09 ± 0.06	90 ± 22	4.5
$\Upsilon(1S)$ mass correction	1998 ± 47	18.02 ± 0.08	64 ± 17	4.1
$m_{\mu^+\mu^-}^{\text{non-res}} < m_{\Upsilon(1S)}$	1418 ± 40	18.06 ± 0.05	94 ± 17	6.3
$p_T > 2.5$ GeV non-res. muons	2741 ± 55	18.05 ± 0.05	70 ± 19	4.1
$p_T > 4$ GeV non-res. muons	982 ± 33	18.06 ± 0.08	35 ± 11	3.6
Tight IP cuts	1469 ± 40	18.01 ± 0.05	71 ± 15	5.5
Lifetime $\lvert\tau/\sigma_\tau\rvert < 3$	1873 ± 45	18.04 ± 0.05	86 ± 17	5.6
MBS < 3	1749 ± 44	18.05 ± 0.04	83 ± 16	5.8

Full heavy tetraquark

$(cc)_{\underline{3}^*} - (\overline{cc})_{\underline{3}}$

L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.55
	1	$0^{-+}, 1^{-+}, 2^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}$	
2	0	2^{++}	6.78
	1	$1^{+-}, 2^{+-}, 3^{+-}$	
	2	$0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}$	
3	0	3^{--}	6.98
	1	$2^{-+}, 3^{-+}, 4^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

$(cc)_{\underline{6}} - (\overline{cc})_{\underline{6}^*}$

L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.82
2	0	2^{++}	7.15
3	0	3^{--}	7.41

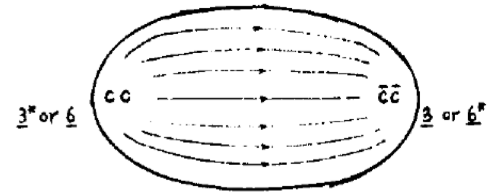


Fig.2

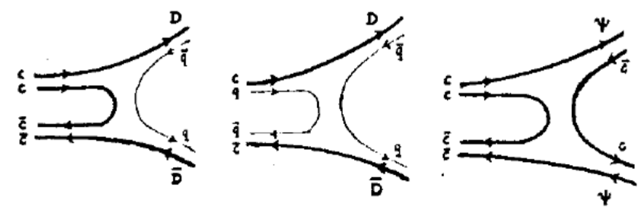


Fig.3(a) Fig.3(b) Fig.3(c)

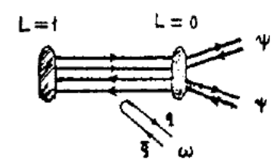


Fig.4

- First mention of the 4c state (6.2 GeV, 1975): Prog. of Theo. Phys. Vol. 54, No. 2
- First calculation of the 4c mass (diquark+antidiquark): Z. Phys. C 7 (1981) 317

Full heavy tetraquark is different from heavy+light quark composition

Maximum Likelihood

- Unbinned maximum likelihood fits are made to extract the signal information from data in the 4μ mass spectra
- The likelihood reads:

$$\mathcal{L} = \mathcal{L}_{SR}\left(\vec{\alpha}, \vec{\beta}\right) \cdot \mathcal{L}_{CR}\left(\vec{\alpha}\right) \cdot \prod_{j=1}^{K} G\left(\alpha_j'; \alpha_j, \sigma_j\right),$$

$$\mathcal{L}_{SR} = \frac{(s+b)^N}{N!} e^{-(s+b)} \prod_{i=1}^{N} \left[\frac{s}{s+b} f_s(x_i; \vec{\alpha}, \vec{\beta}) + \frac{b}{s+b} f_b(x_i; \vec{\alpha})\right], \quad \mathcal{L}_{CR} = \frac{b_{CR}^{N_{CR}}}{N_{CR}!} e^{-b_{CR}}, \ \text{with } b_{CR} = b \cdot t(\alpha_t),$$

β are the parameters of interest, α are the nuisance parameters (NP) accounting for systematics shared between the two regions

- Each NP has a Gaussian constraint with a subsidiary measurement α_j', a mean α_j and a width σ_j
- In the di-J/ψ channel, feed-down from J/ψ+ψ(2S) is included as an additional background

Fit models

- The signal probability density function (PDF) consists of several interfering S-wave Breit-Wigner (BW) peaks convoluted with a mass resolution function

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

- In general, the BW function for orbital angular momentum L is (F_L is the Blatt-Weisskopf form factor, R = 3 GeV^{-1})

$$BW(x; m_0, \Gamma_0) = \frac{\left(\frac{q}{q_0}\right)^L \frac{F_L(Rq)}{F_L(Rq_0)}}{m_0^2 - x^2 - i m_0 \Gamma(x)}, \qquad \Gamma(x) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{m_0}{x} \frac{F_L^2(Rq)}{F_L^2(Rq_0)}.$$

- For S-wave, this is simplified to

$$BW(x; m_0, \Gamma_0) = \frac{1}{m_0^2 - x^2 - i m_0 \Gamma(x)} = \frac{1}{m_0^2 - x^2 - i m_0 \boxed{\Gamma_0 \frac{m_0}{x} \sqrt{\frac{x^2 - 4m_{J/\psi}^2}{m_0^2 - 4m_{J/\psi}^2}}}}.$$

Systematics

Since normalizations are freely floating, only systematics affecting the signal and background shapes are considered:

- muon momentum
- J/ψ mass resolution
- MC simulation statistics
- SPS theory and di-charmonium p_T
- background transfer factor
- "others" non-closure
- P and D-wave BW
- Feed-down

Systematic	di-J/ψ		J/ψ+ψ(2S)	
Uncertainties (MeV)	m_2	Γ_2	m_3	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	—		$^{+3}_{-7}$	$^{+31}_{-34}$