# Spectroscopy results from ATLAS

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ATLAS EXPERIMENT

QwG Workshop, IISER Mohali, February 2024

# Motivation and Contents

- **LHC data contains the potential for observation of new rare low-mass states predicted (or not) by QCD and/or BSM theories ($\chi_b$(3P) is an early example –** PRL108(2012)152001**)**
- **Requires large amounts of high-quality reconstructed final states with low-pT tracks**

## This talk covers:

- **Observation of an excess of di-charmonium events in the four-muon final state with the ATLAS detector**

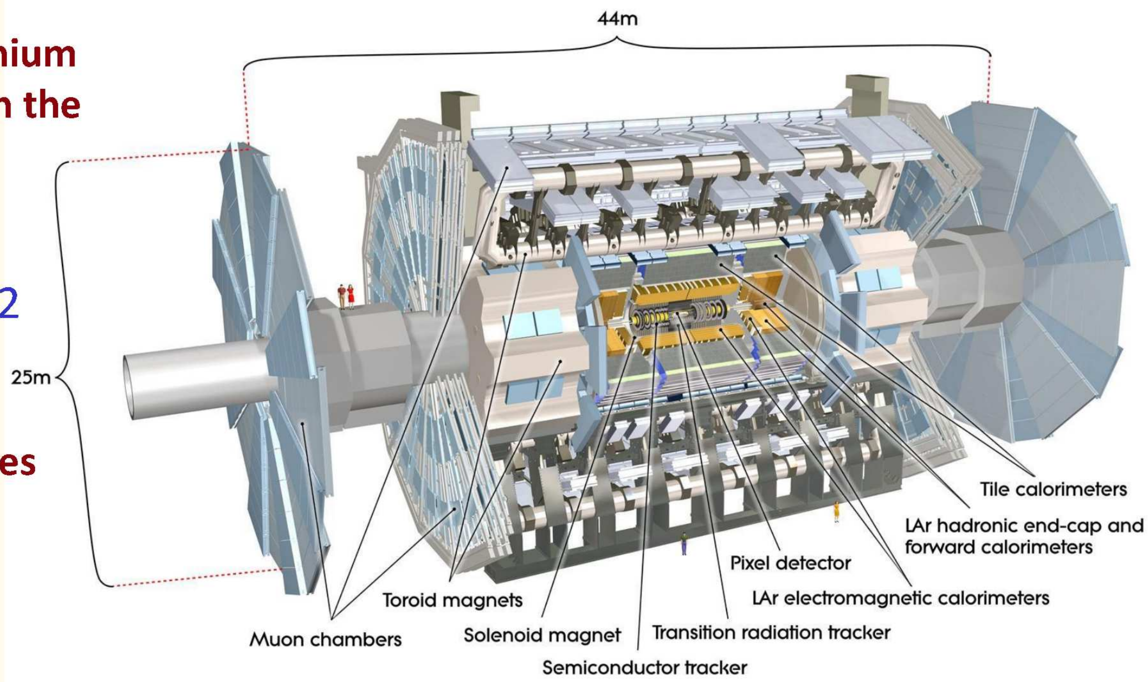
  $X \to J/\psi + J/\psi/[\psi(2S)] \to 4\mu$

  *Phys.Rev.Lett.* 131 (2023) 15, 151902

- **Search for narrow low-mass resonances in the four-muon final state with the ATLAS detector at the LHC**

  $X \to \mu\mu + \Upsilon(1S) \to 4\mu$

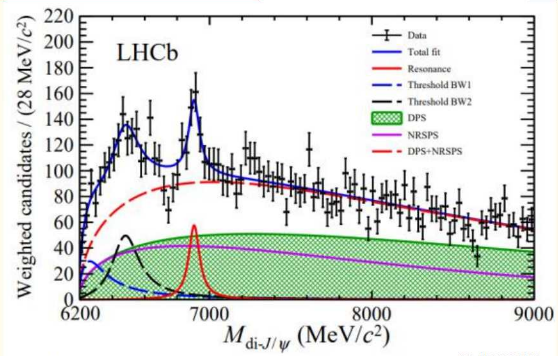
  ATLAS-CONF-2023-041

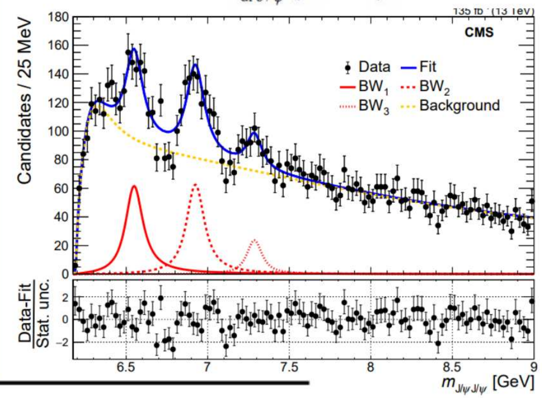


# Searches in X→J/ψ+J/ψ/[ψ(2S)]→4μ

## Motivation

- Di-J/ψ final states is a well-motivated search channel for low-mass resonances.
- LHCb observed narrow structure at 6.9 GeV: can be interpreted as four-charm tetraquark. LHCb arXiv:2006.16957, Sci.Bull.65,1983(2020)
- CMS is seeing a similar picture CMS arXiv:2306.07164



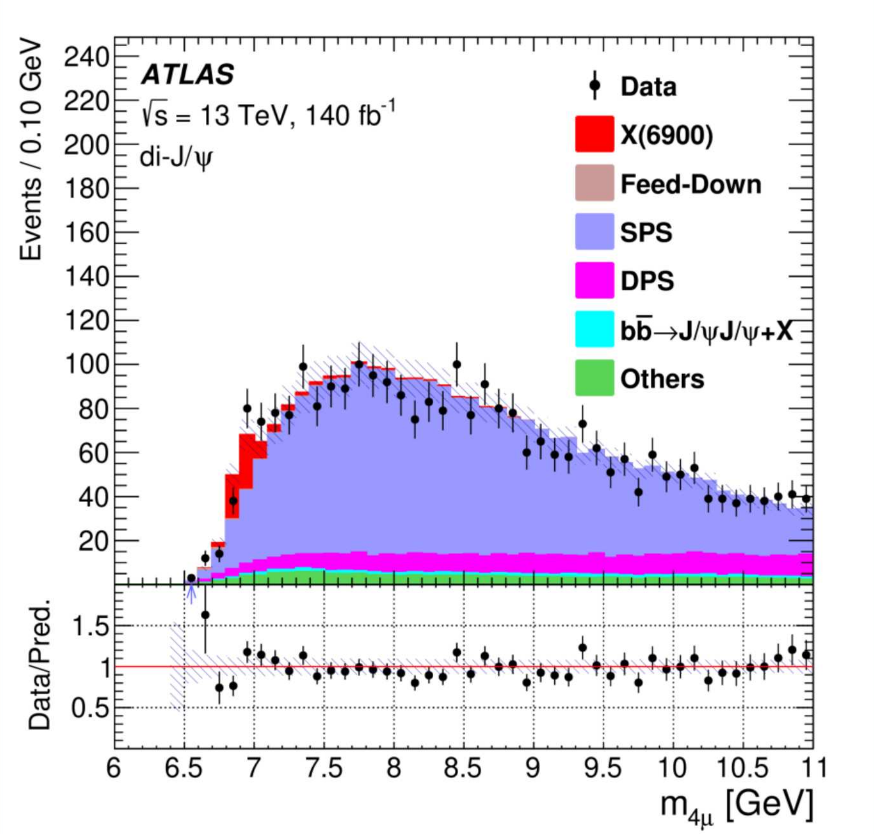



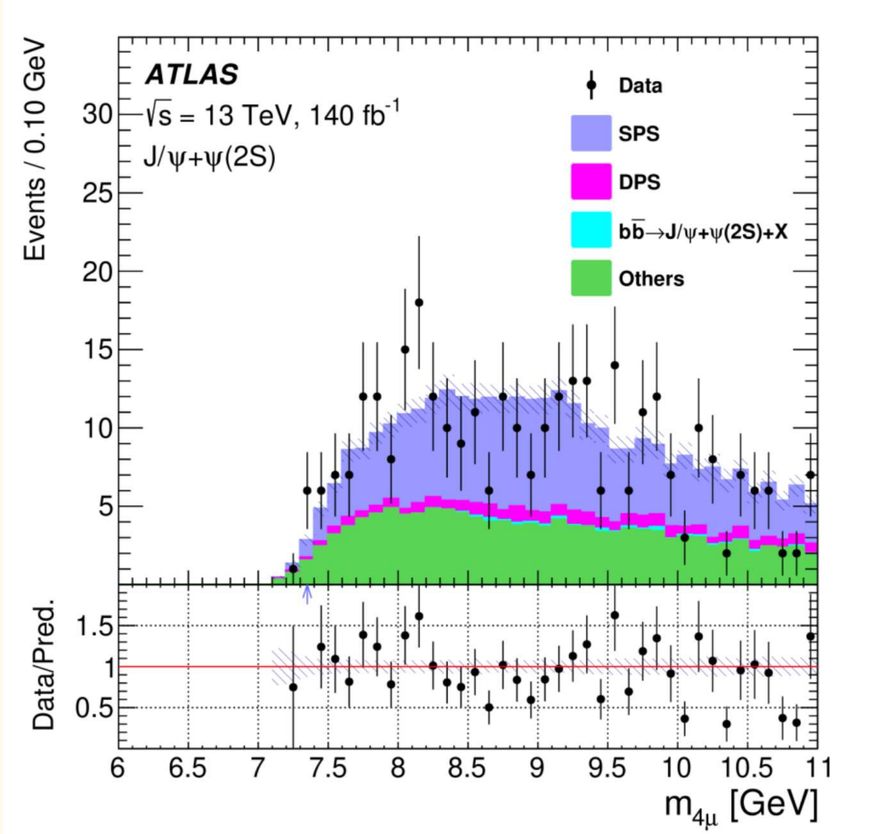

## ATLAS: Datasets and selections

- Datasets: 140/fb of 13 TeV Run II data.
- Lowest pT two-muon and three-muon trigger signatures

| 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 $\chi^2_{4\mu}/N < 3$, $L_{xy}^{4\mu} < 0.2$ mm, $\lvert L_{xy}^{\text{di-}\mu}\rvert < 0.3$ 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 $\lvert L_{xy}^{\text{di-}\mu}\rvert > 0.4$ mm |

# Background studies: control region



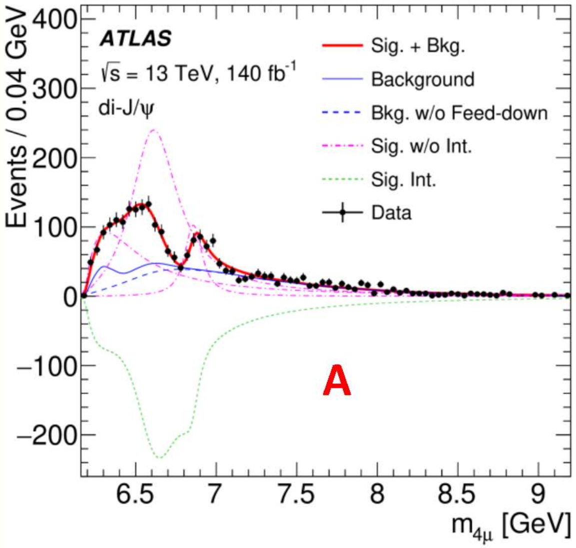

## ANALYSIS STRATEGY

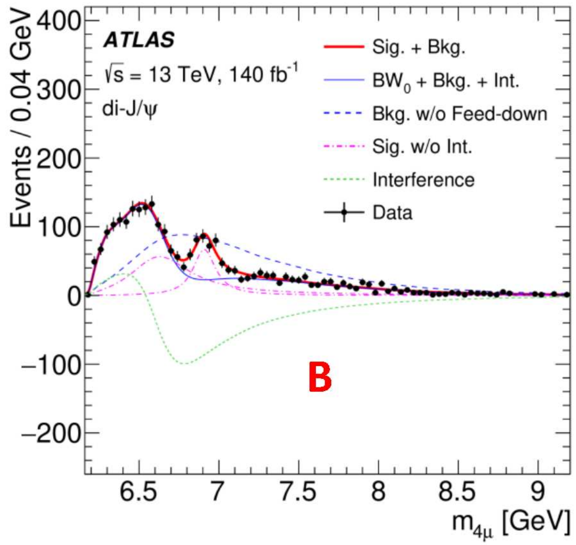
- MC simulation and data control regions used to model/constrain backgrounds.
- Search for excesses in four-muon invariant mass in the signal region

# Fit modelling

**For J/ψ + J/ψ:**
- **Model A:** three interfering S-wave BW resonances
- **Model B:** two resonances, first interfering with background

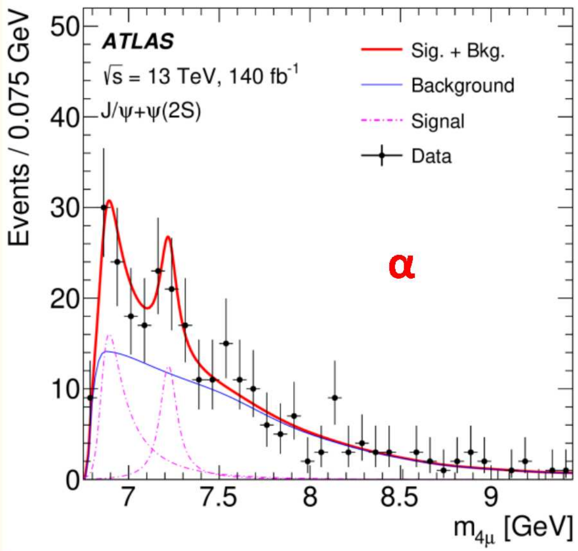
>5σ excess at 6.9 GeV,
broad structure at lower mass (feeddown?)

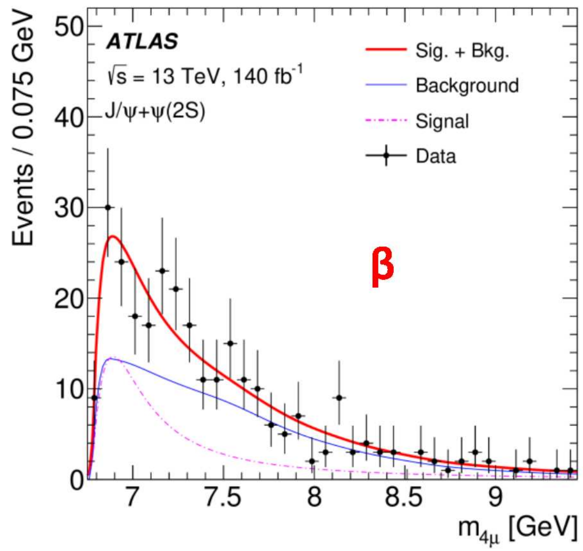



**For J/ψ+ψ(2S):**
- **Model α:** 3 fixed + 1 new BW at 4.7σ
- **Model β :** one standalone BW at 4.3σ

Data supports new resonance at 7.2 GeV [3σ local significance].



# Results for X→J/ψ+J/ψ/[ψ(2S)]→4μ

## Signal characterisation

Observation of up to four resonances.
Mass of third resonance consistent with that observed at LHCb.

Three-resonance model with interference contributions
or
model with broad low mass structure interfering with background
best describes the data.

Data supports new resonance at 7.2 GeV [3σ local significance].

| di-$J/\psi$ | model A | model B |
|---|---|---|
| $m_0$ | $6.41 \pm 0.08^{+0.08}_{-0.03}$ | $6.65 \pm 0.02^{+0.03}_{-0.02}$ |
| $\Gamma_0$ | $0.59 \pm 0.35^{+0.12}_{-0.20}$ | $0.44 \pm 0.05^{+0.06}_{-0.05}$ |
| $m_1$ | $6.63 \pm 0.05^{+0.08}_{-0.01}$ | — |
| $\Gamma_1$ | $0.35 \pm 0.11^{+0.11}_{-0.04}$ | |
| $m_2$ | $6.86 \pm 0.03^{+0.01}_{-0.02}$ | $6.91 \pm 0.01 \pm 0.01$ |
| $\Gamma_2$ | $0.11 \pm 0.05^{+0.02}_{-0.01}$ | $0.15 \pm 0.03 \pm 0.01$ |
| $\Delta s/s$ | $\pm 5.1\%^{+8.1\%}_{-8.9\%}$ | — |
| $J/\psi$+$\psi(2S)$ | model $\alpha$ | model $\beta$ |
| $m_3$ | $7.22 \pm 0.03^{+0.01}_{-0.04}$ | $6.96 \pm 0.05 \pm 0.03$ |
| $\Gamma_3$ | $0.09 \pm 0.06^{+0.06}_{-0.05}$ | $0.51 \pm 0.17^{+0.11}_{-0.10}$ |
| $\Delta s/s$ | $\pm 21\%^{+25\%}_{-15\%}$ | $\pm 20\% \pm 12\%$ |

# Searches in X→μμ+Υ(1S)→4μ channel

ATLAS-CONF-2023-041

**Motivation:**

**Four-lepton final states with on- or offshell vector mesons such as Υ(1S) give wide coverage for searches for fundamental scalars at low mass, or doubly-hidden beauty tetraquarks.**

**Datasets:**

Events (events per /fb)

| Dataset | 8 TeV | | 13 TeV | |
|---|---|---|---|---|
| Luminosity ($\mathrm{fb}^{-1}$) | 20.3 | | 51.5 | 58.5 |
| Trigger | All triggers | $3\mu$ only | $3\mu$ only | $3\mu$_bUpsi only |
| Four muons, $\geq 3$ LowPt, $p_{\mathrm{T}} > (4, 4, 3, 3)$ GeV | 261,893 | 170,467 | 1,152,307 | 231,318 |
| | **2012** | | **2015-17** | **2018** |
| One $\Upsilon(1\mathrm{S})$ and $10 < m_{4\mu} < 50$ GeV | 6,467 | 3,641 (179) | 20,887 (406) | 19,125 (327) |
| $\Upsilon(1\mathrm{S}) + \mu^+\mu^-$ | 3,849 | 2,218 (109) | 13,657 (265) | 10,862 (186) |
| $\Upsilon(1\mathrm{S}) + \mu^\pm\mu^\pm$ | 2,618 | 1,423 ( 70) | 7,230 (140) | 8,263 (141) |

# Analysis strategy and event selection

## Analysis strategy:

- Select Υ(1S) candidate, pair it with another low-pT opposite-sign (OS) di-muon pair.
- Search for narrow structures in four-muon invariant mass.
- **8 TeV analysis non-blind, 13 TeV analyses fixed to chosen 8 TeV baseline selection.**

## Baseline Selection

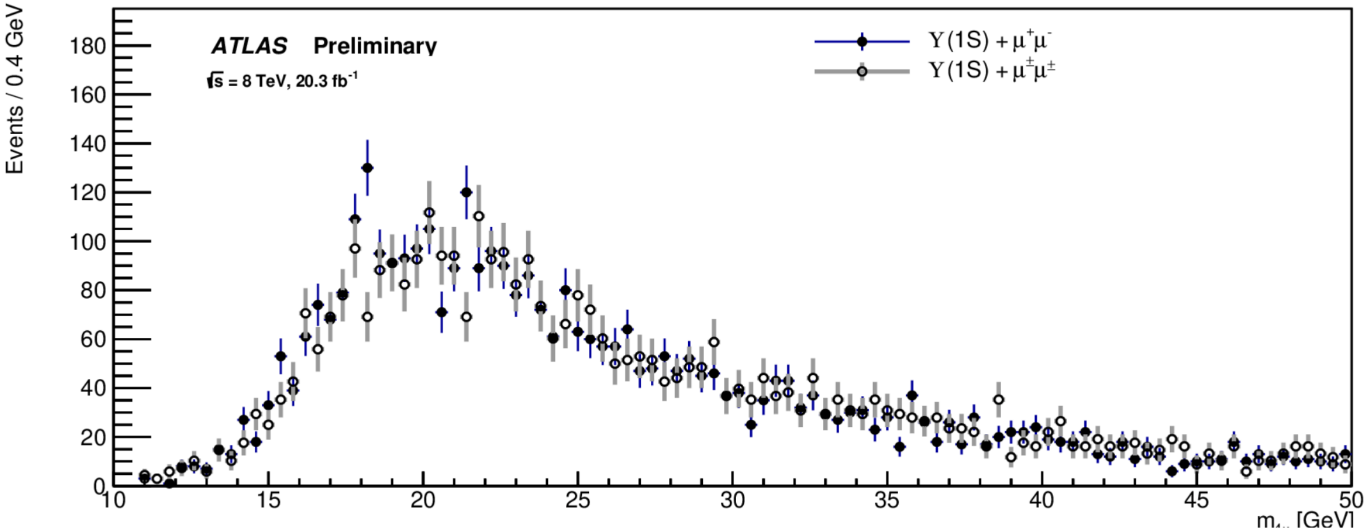
| Candidate object | Requirements |
|---|---|
| Muons | $p_T(\mu) > 3$ GeV and $\lvert\eta\rvert < 2.5$,<br>$\lvert z_0 \sin\theta\rvert < 1$ mm and $\lvert d_0/\sigma_{d_0}\rvert < 6$ |
| Muon quadruplet | $\geq$ 3 muons passing LowPt selection criteria,<br>$\sum q_\mu = 0$, four-muon vertex fit $\chi^2/N_{\mathrm{d.o.f}}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

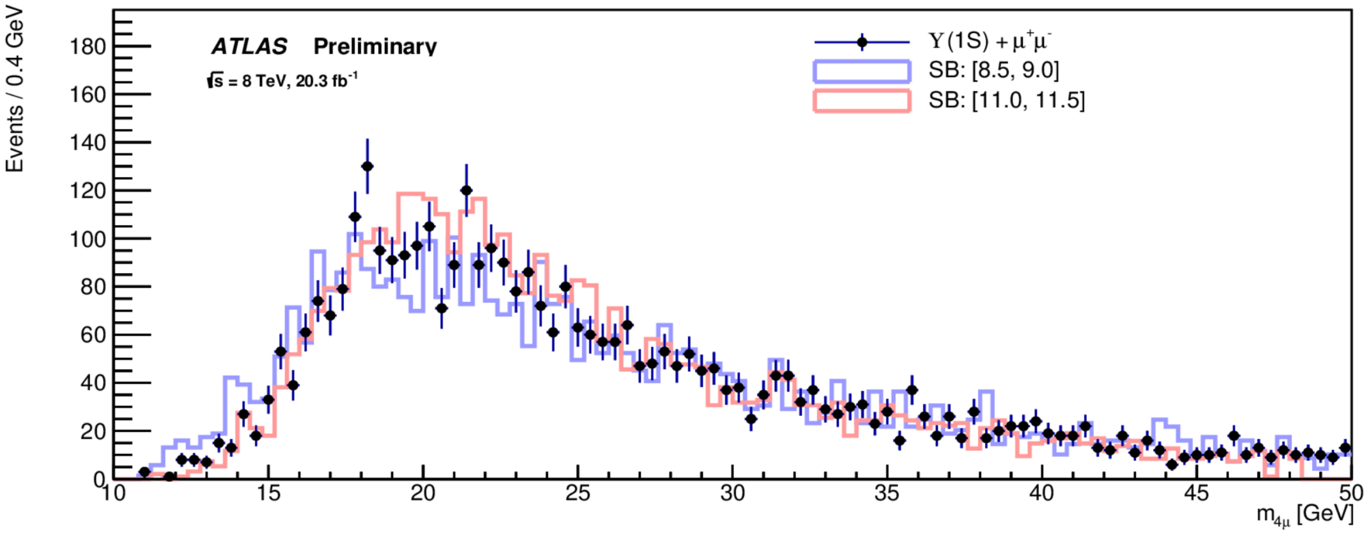
# Mass spectra: 8 TeV sample

**Background shapes compared to**

- **Υ+SS dimuons**
- **Υ sidebands with OS dimuons**

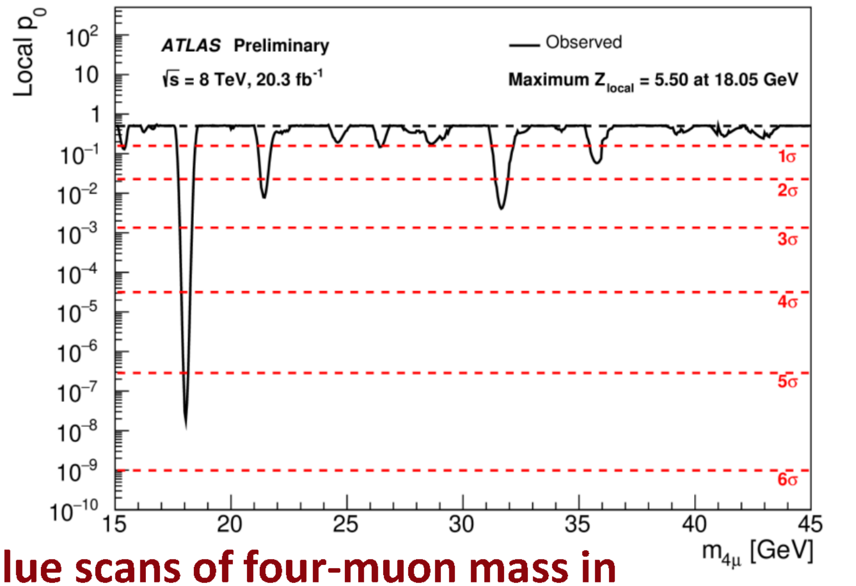
**Indications of an excess of events in narrow region around 18 GeV in Υ(1S) + opposite-sign muon data.**

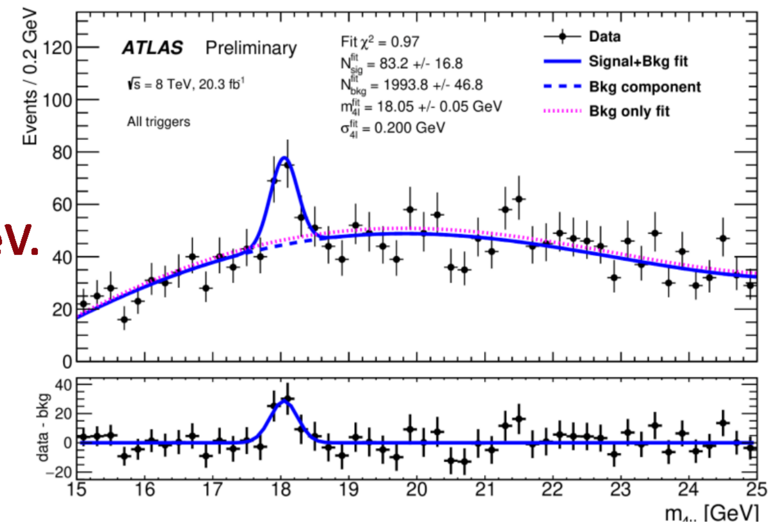


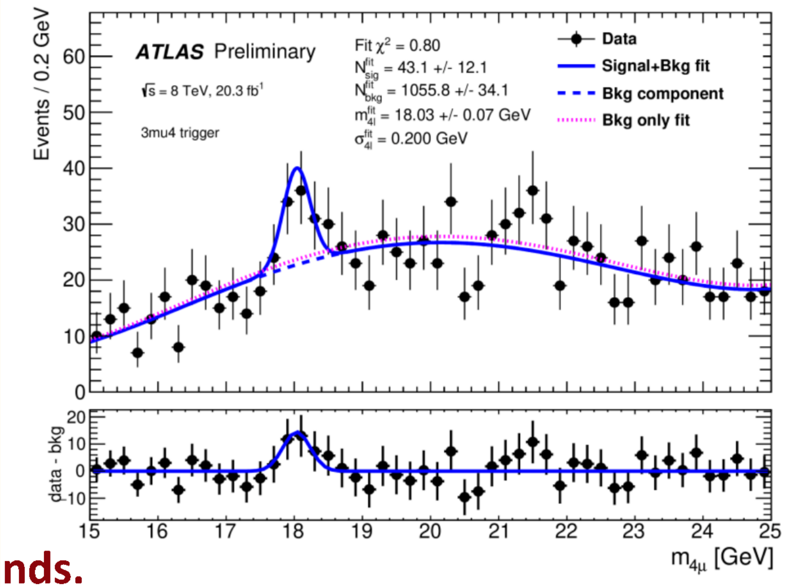



# 8 TeV sample: closer look

- Structure observed in both di-muon and tri-muon triggered data.
- Width fixed to expected det. resolution of 200 MeV
- Background-only fit and p-value scan for chosen baseline selection yields significant excess at ~18 GeV.




**p-value scans of four-muon mass in**

- Υ(1S)+same-sign muon pair
- Left/right Υ(1S) mass sidebands

**find no significant structures.**

**No indications of artificially created structures from triggers/selections in simulated SPS and DPS backgrounds.**

# Cross-checks and variations

**Since analysis not blind, robustness of 18 GeV excess studied with alternative selections:**

| Selection criteria | $N_B$ | Mass (GeV) | $N_S$ | Significance ($\sigma$) |
|---|---|---|---|---|
| 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 |

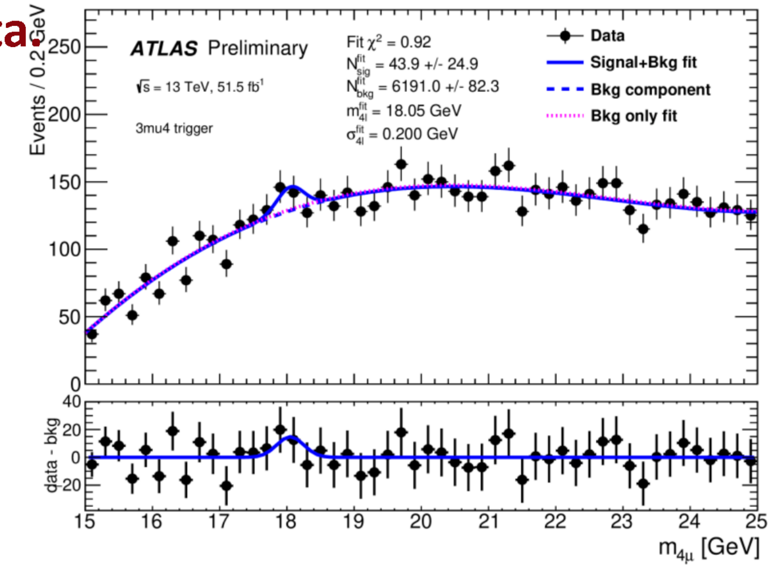
**Global significance over mass range 15-50 GeV varies between 1.9 – 5.4 σ.**

# 13 TeV samples: closer look

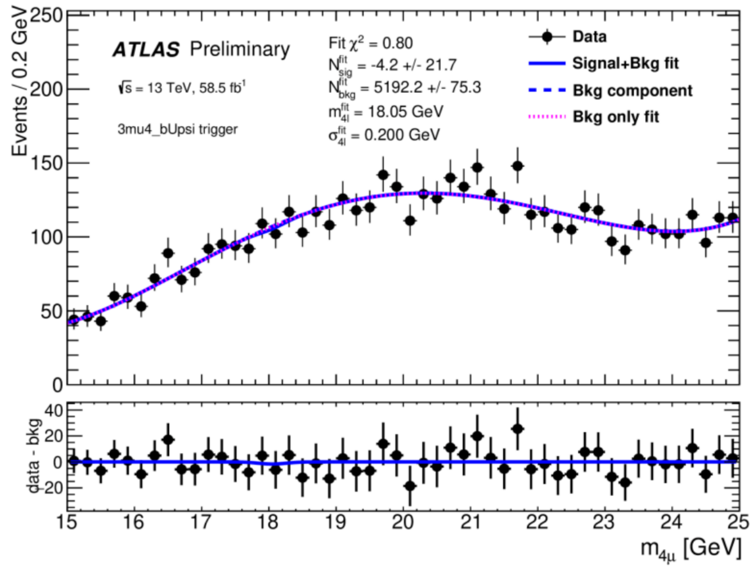
**Unbiased statistical test of the excess in 13 TeV data.**

**At 13 TeV background rate three or more times 8 TeV levels, different trigger menu:**

- No more 2mu4, only 3mu4 in 2015-17
- 3mu4 also gone in 2018
- A new “3mu4bUpsi” available for 2018




**EARLY 13 TEV DATA (2015 -17, 51.5 /fb)**
13 TeV data collected with similar tri-muon triggers finds 1.9σ excess for signal fit fixed to 18.05 GeV.

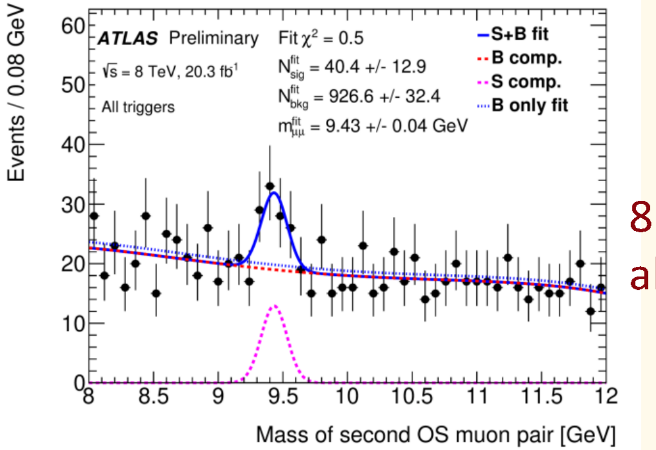



**LATE 13 TEV DATA (2018, 58.5 /fb)**
No evidence for a signal in 2018 data (new trigger).

# Cross check between datasets: Di-Υ(1S)

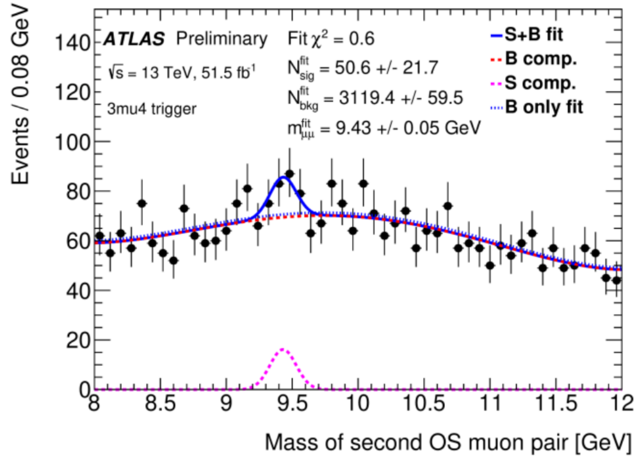
**HOW COMPATIBLE ARE THESE OBSERVATIONS WITH A REAL SIGNAL – a second Υ(1S)?**

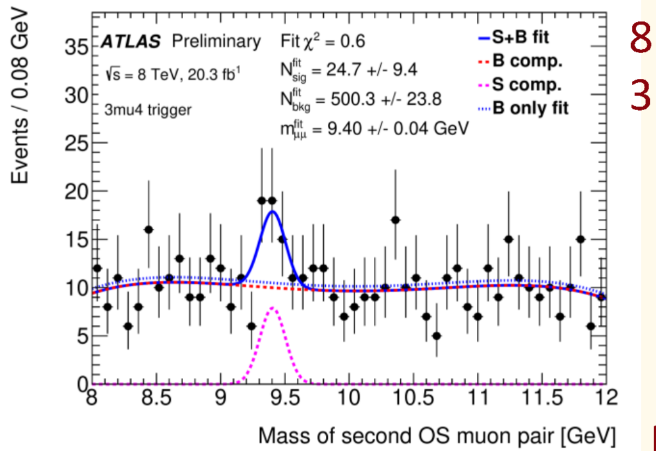
**Second Υ(1S) seen? Depends on relative sensitivity of datasets: luminosity, cross-section enhancement, trigger and reconstruction efficiencies.**




8 TeV
all triggers

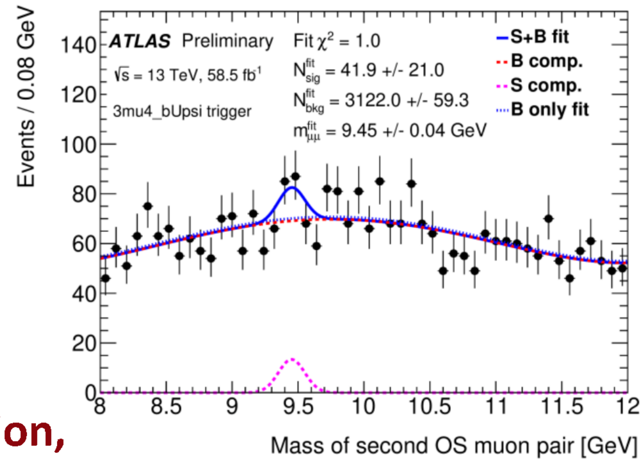
13 TeV
3mu4




8 TeV
3mu4

13 TeV
3mu4 with
OS+Y mass

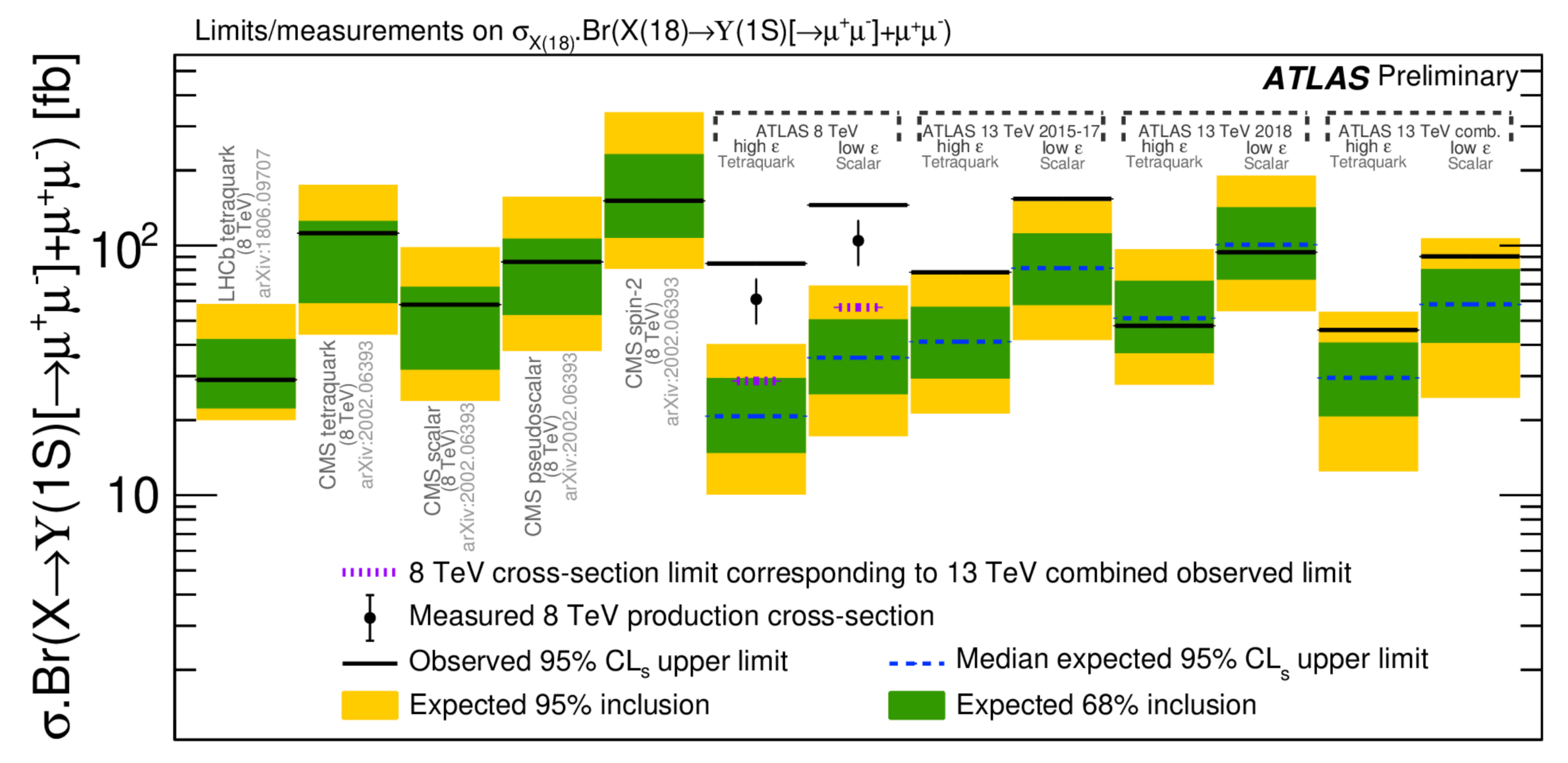



**Evidence for di-Υ(1S) production, large statistical uncertainties**

# Expected/observed cross-section limits

**Limits depend on physics model used in calculations, other factors (<u>very</u> preliminary)**

**Two models considered: tetraquark (higher efficiency) or scalar (lower efficiency)**
**8 TeV results compatible with tetraquark (scalar) with 60 fb (100 fb) cross section.**
**13 TeV results exclude the observed excess at 8 TeV at more than 95% CL for both models.**



# Summary

**Large datasets and breadth of programme at ATLAS allows many opportunities to search for new, rare, low-mass exotic resonances, including some possible surprises.**

## Searches in $X \rightarrow J/\psi + J/\psi/[\psi(2S)] \rightarrow 4\mu$

*Phys.Rev.Lett.* 131 (2023) 15, 151902

**Significant (>5σ) broad low mass excess and resonance at 6.9 GeV observed in di-J/ψ. J/ψ+ψ(2S) data supports additional resonance at 7.2 GeV. Full characterisation of excesses requires further study.**

## Searches in $X \rightarrow \mu\mu + \Upsilon(1S) \rightarrow 4\mu$

ATLAS-CONF-2023-041

**Excess at ~18 GeV in the 8 TeV dataset seen in data-driven analysis.**
**Unbiased test using 13 TeV data did not confirm the excess.**

# THANK YOU!