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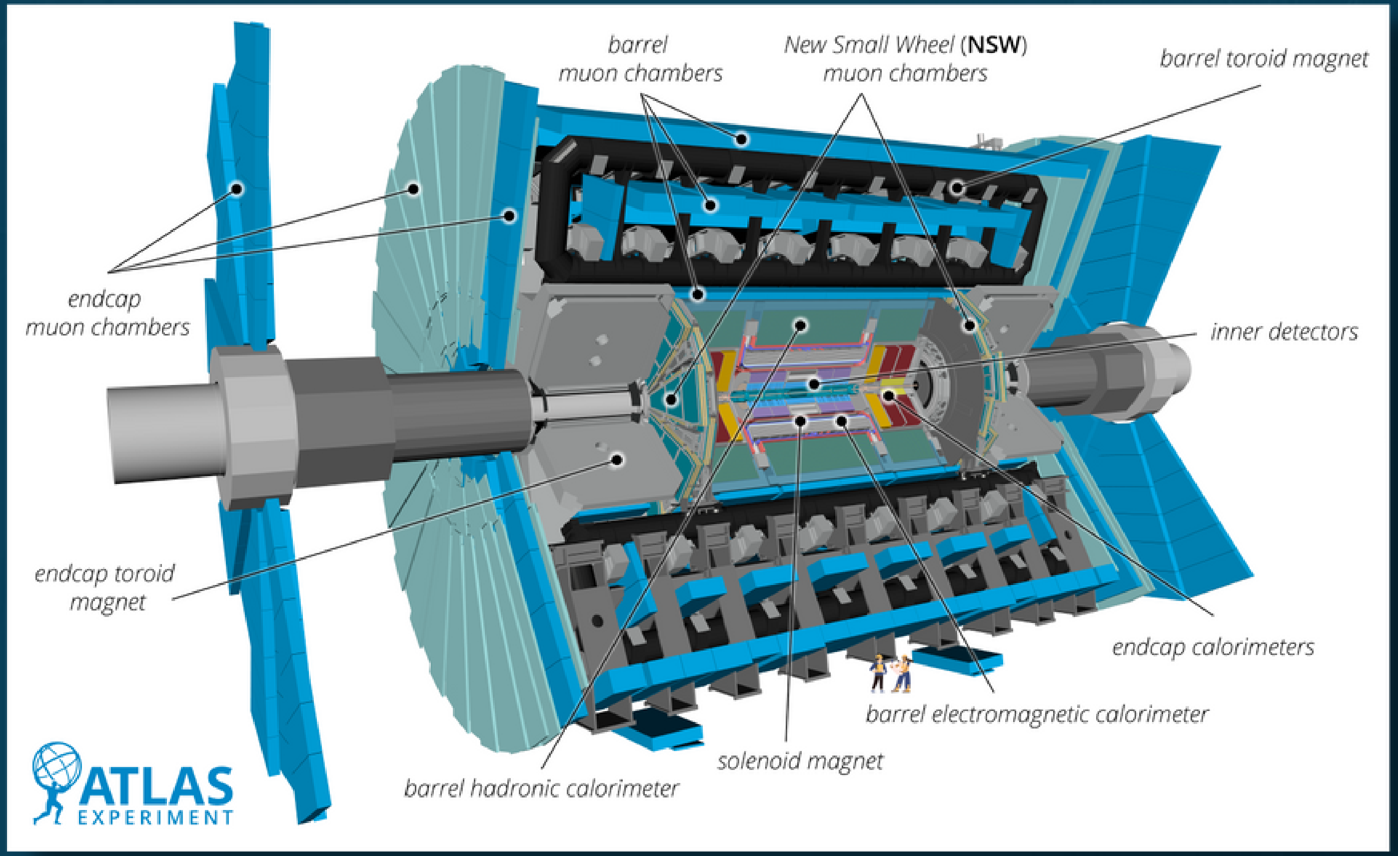
ATLAS EXPERIMENT

ATLAS RESULTS ON EXOTIC HADRONIC RESONANCES

31ST INTERNATIONAL SYMPOSIUM ON LEPTON PHOTON INTERACTIONS AT HIGH ENERGIES, MELBOURNE
JULY 18TH 2023

Darren Price (University of Manchester)
on behalf of the ATLAS Collaboration

Motivation



New low-mass resonances?

- Potential for observation new, rare, low-mass states predicted by QCD and BSM theories.
- Requires large data volumes of high-quality low-p_T reconstructed final states at ATLAS.

Results in this talk

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

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

arXiv:2304.08962

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

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

ATLAS-CONF-2023-041

arXiv:2304.0896

Searches in X→J/ψ+J/ψ/[ψ(2S)]→4μ

Datasets and selections

140 fb^{-1} of 13 TeV data.

Two 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, $p_T^{1,2,3,4} > 4, 4, 3, 3$ 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 $\chi^2_{\text{di-}\mu}/N < 100$ ($N = 2$),		
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,		Vertex $\chi^2_{4\mu}/N > 6$,
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	or $\|L^{\text{di-}\mu}_{xy}\| > 0.4$ mm

MOTIVATION

Di-J/ψ final states well-motivated search channel for low-mass resonances.

LHCb recently observed narrow structure at 6.9 GeV: can be interpreted as four-charm tetraquark.

ANALYSIS STRATEGY

Search for excesses in four-muon invariant mass.

MC simulation and data control regions used to model/constrain backgrounds.

arXiv:2304.08962

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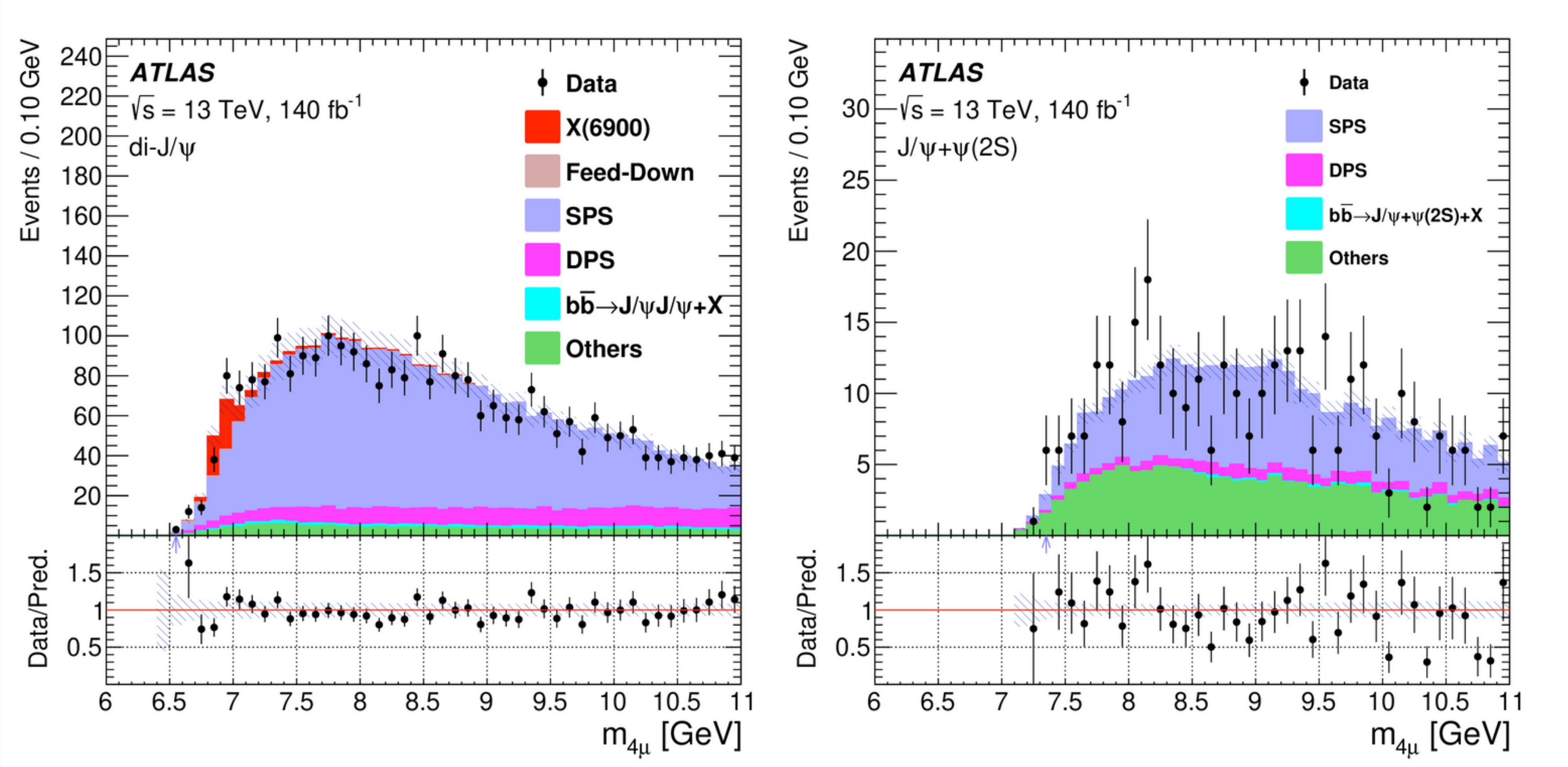


ANALYSIS STRATEGY

Search for excesses in four-muon invariant mass.

MC simulation and data control regions used to model/constrain backgrounds.

Results

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

EXCESSES OBSERVED IN BOTH CHANNELS

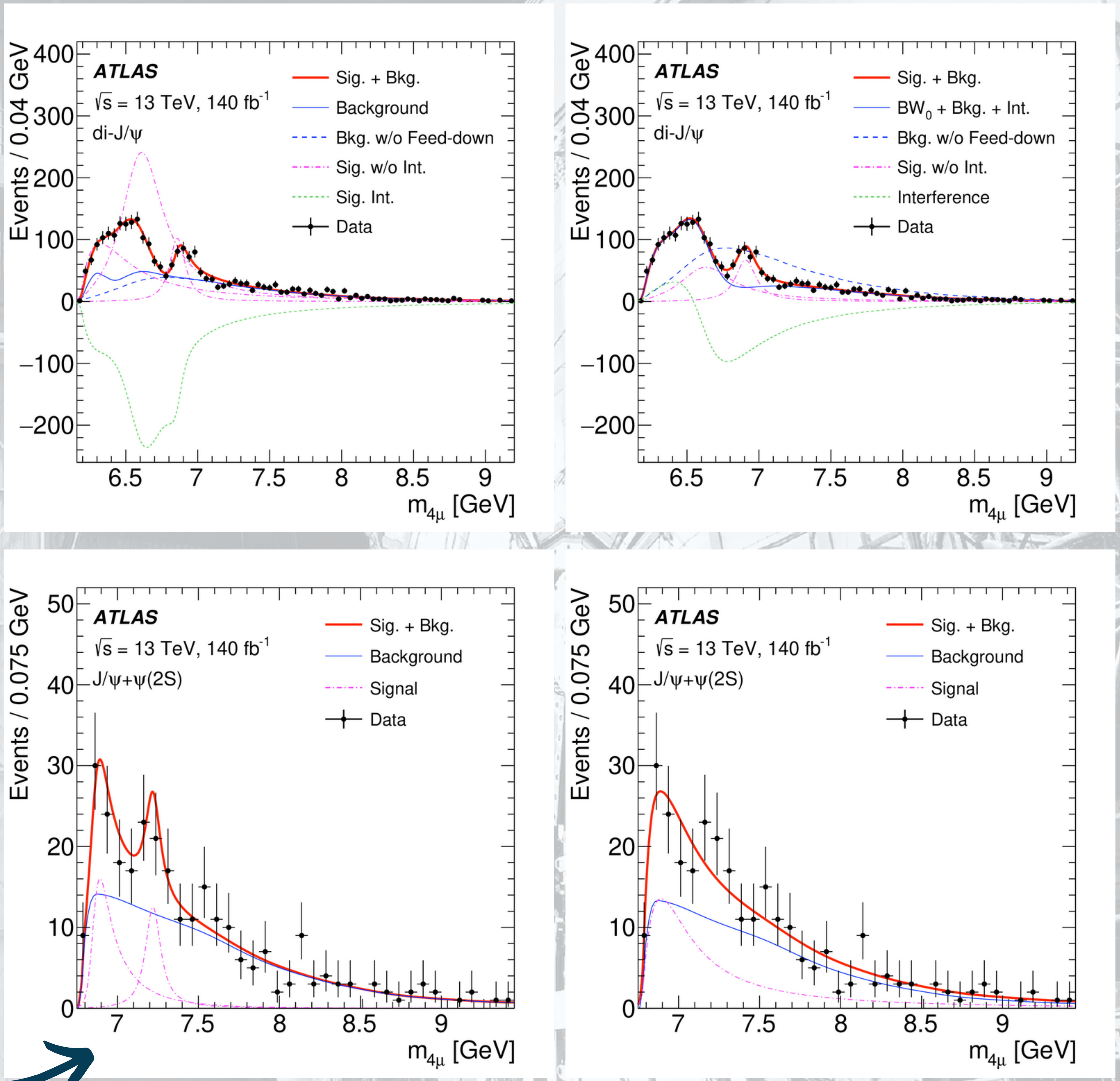
≫5σ excess in di-J/ψ selection.

4.7σ in J/ψ+ψ(2S) when considering model with two resonances.

FIT MODELLING

For J/ψ+J/ψ, consider **three S-wave resonance** model, with signal interference not accounted for in LHCb analysis, and **two-resonance model**. Other model combinations excluded at 95% CL.

For J/ψ+ψ(2S) consider **four- and one-resonance models**: data supports new resonance at 7,2 GeV [3σ local significance].



Searches in X→J/ψ+J/ψ/[ψ(2S)]→4μ

arXiv:2304.08962

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

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.

ATLAS-CONF-2023-041

Searches in X→μμ+Υ(1S)→4μ

Datasets and selections

20.3 fb^{-1} of 8 TeV data.

50.1 + 58.5 fb^{-1} of 13 TeV data

Two and three-muon trigger signatures.

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 $\chi^2/N_{d.o.f} \leq 10$, 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, 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, both muon doublets point to a common PV

MOTIVATION

Four lepton final states with on- or off-shell vector mesons [here Υ(1S)] give wide coverage for searches for fundamental scalars at low mass, or doubly-hidden beauty tetraquarks.

ANALYSIS STRATEGY

Select Υ(1S) candidate, pair with low p_T OS di-muon pair.

8 TeV analysis non-blind, 13 TeV analysis fixed to chosen 8 TeV baseline selection.

Search for narrow structures in four-muon invariant mass.

Mass spectra: 8 TeV

X→μμ+Υ(1S)→4μ

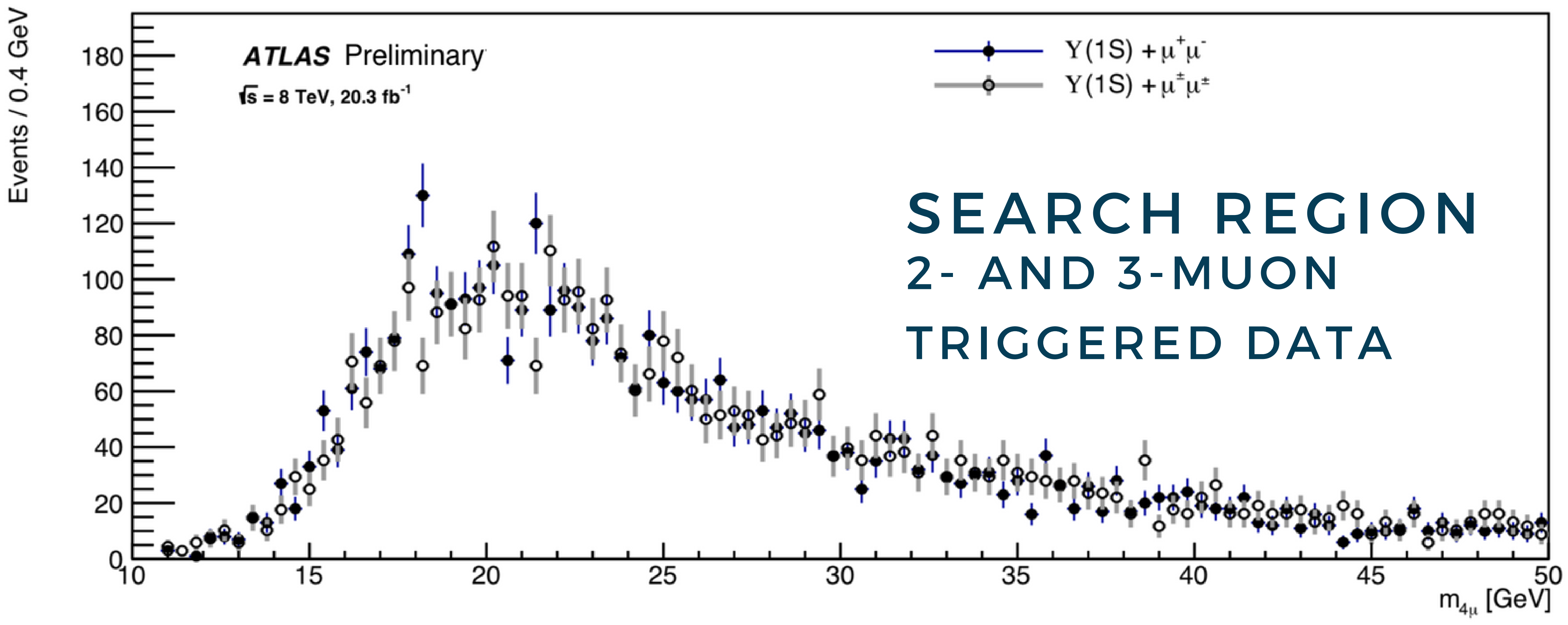
EXCESS OBSERVED

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

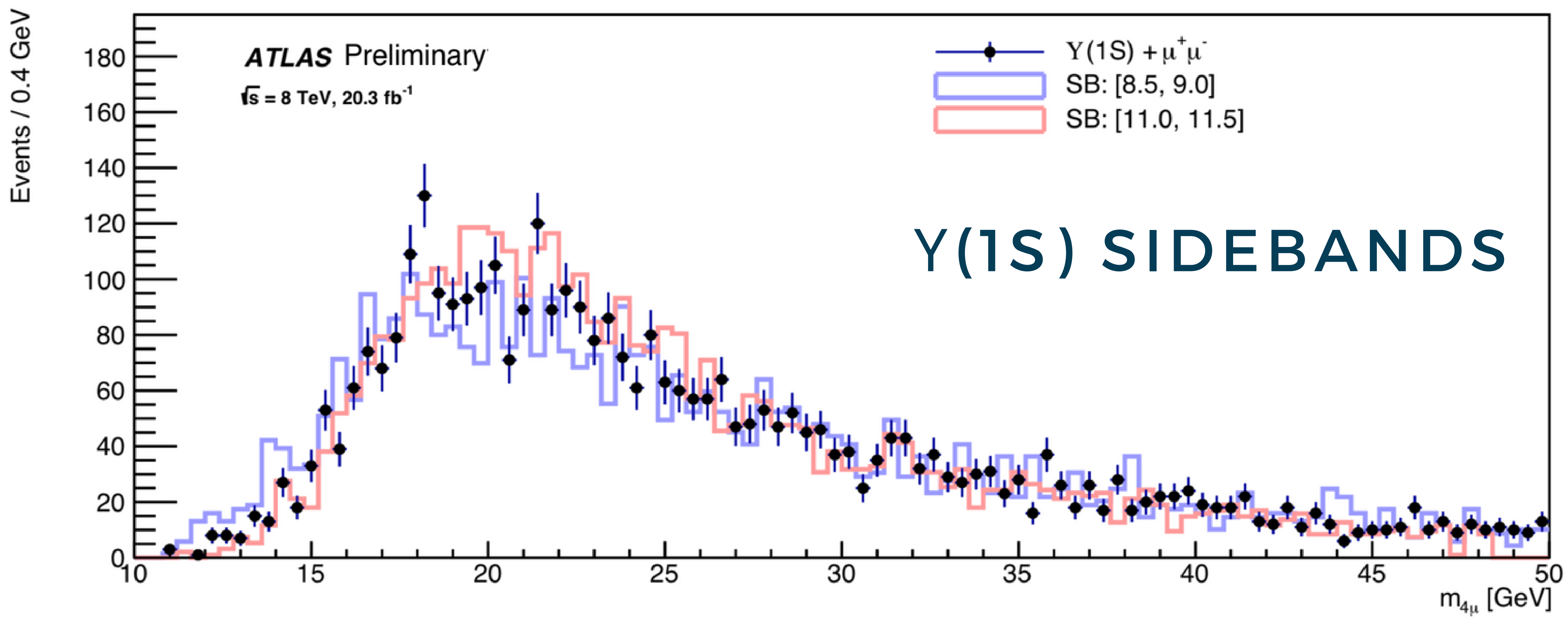
VALIDATION REGIONS

Corresponding same-sign data does not have such a structure.

Mass spectra associated with di-muon sidebands to left/right of Υ(1S) are largely smooth.



SEARCH REGION
2- AND 3-MUON TRIGGERED DATA



Υ(1S) SIDEBANDS

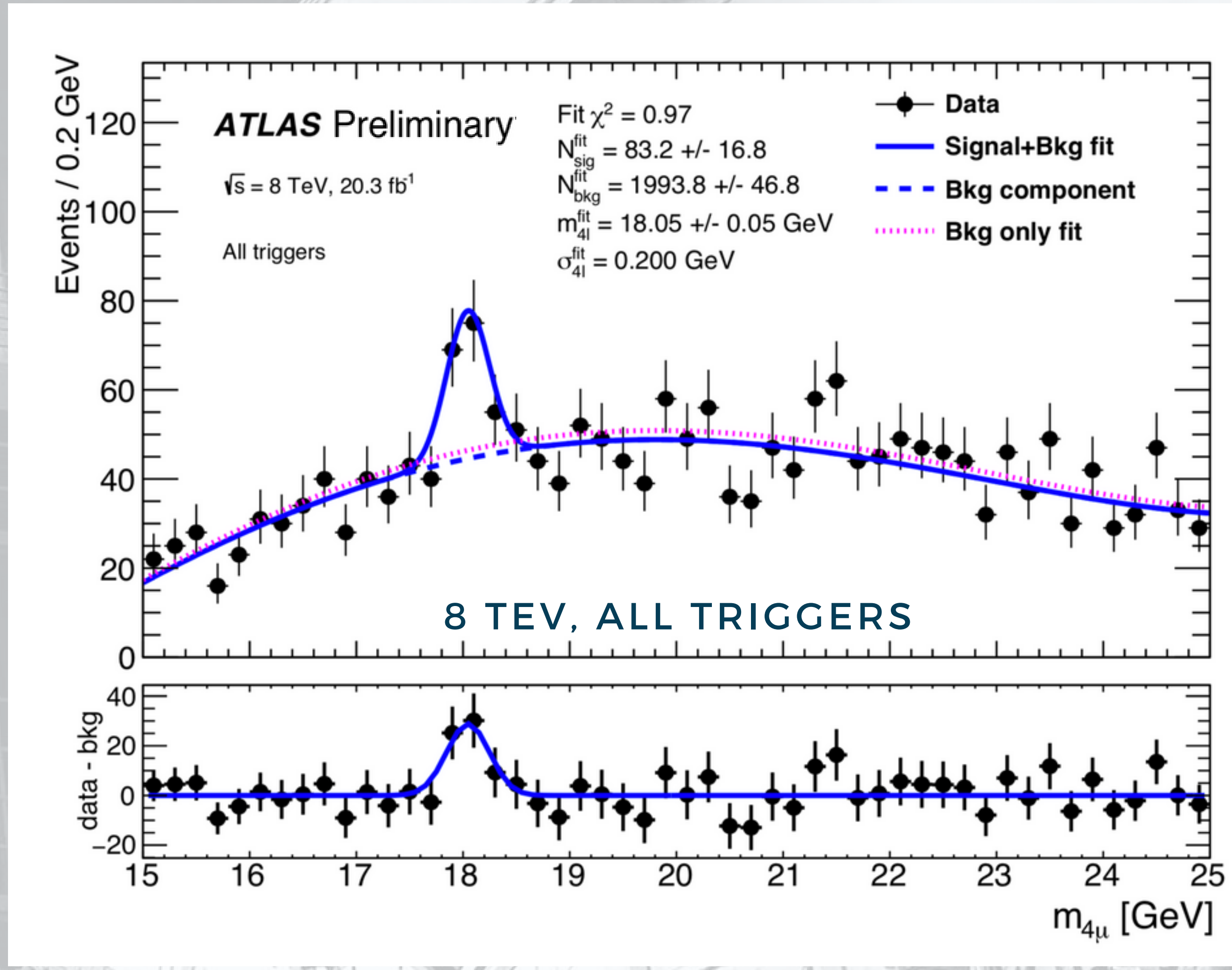
A closer look: 8 TeV

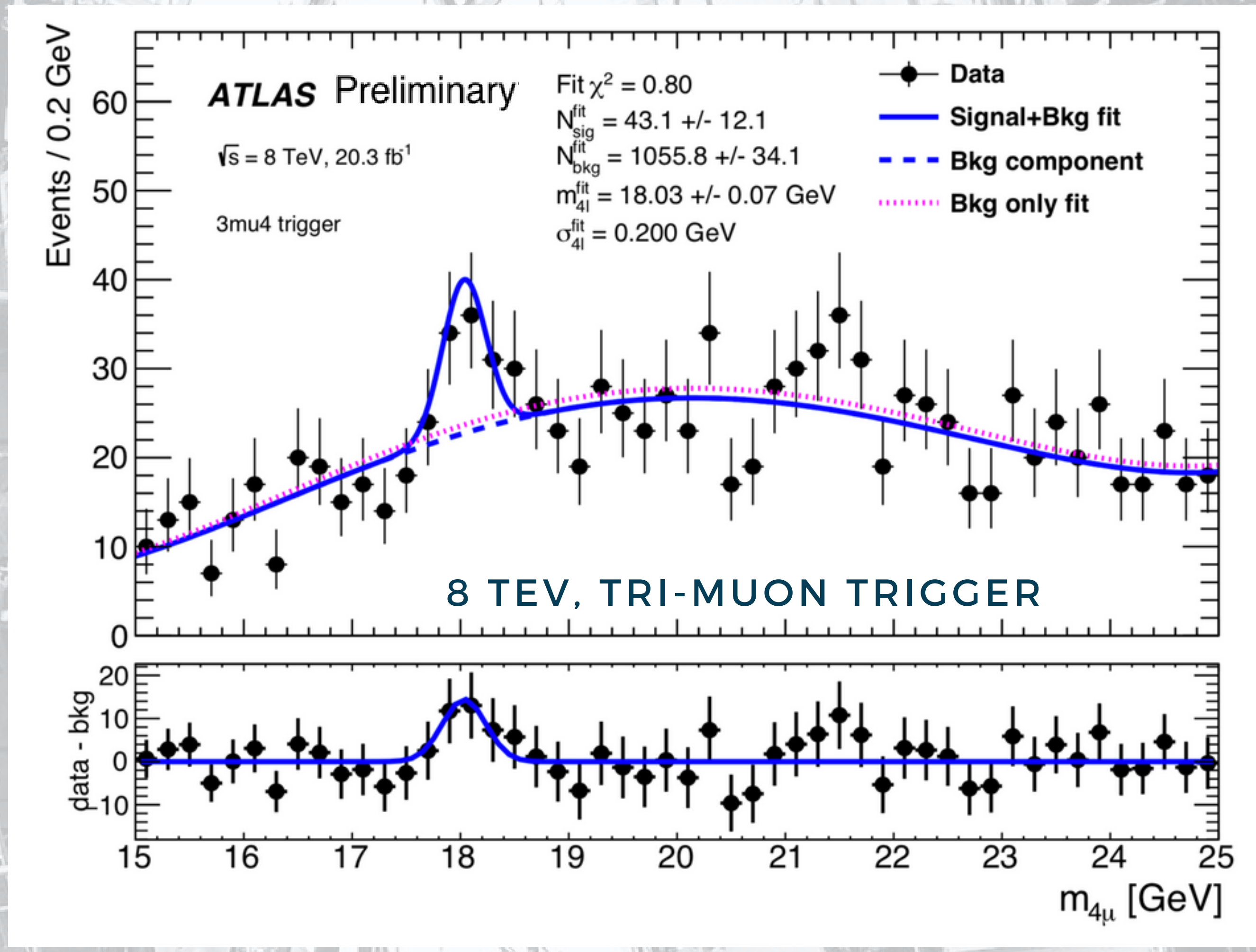
$X \rightarrow \mu\mu + \Upsilon(1S) \rightarrow 4\mu$

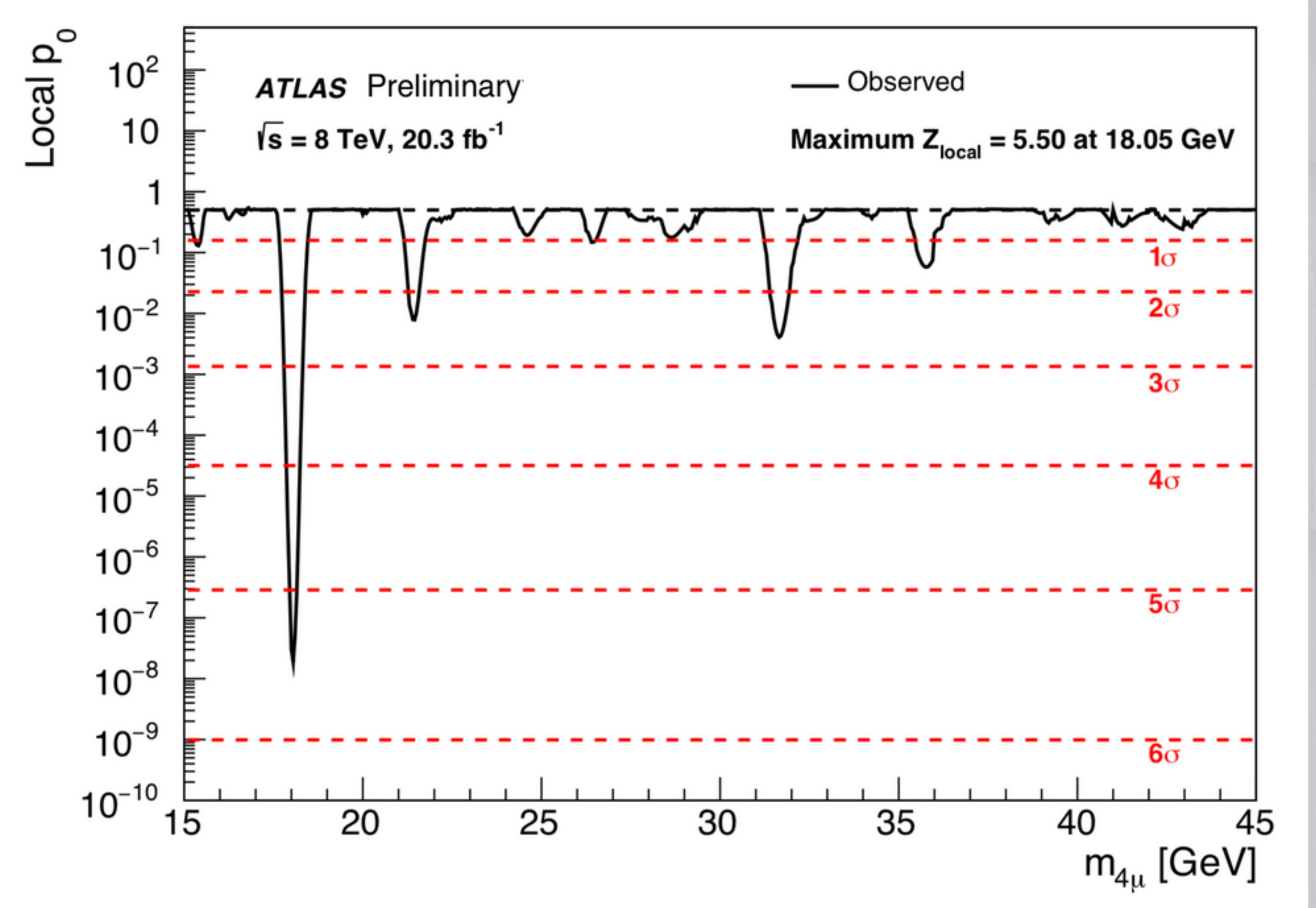
Background-only fit and p-value scan for chosen baseline selection yields significant excess at ~18 GeV.

Structure observed in both di-muon and tri-muon triggered data.

Width fixed to expected detector resolution of 200 MeV.







Cross-checks

X→μμ+Υ(1S)→4μ

SAME-SIGN AND MASS SIDEBANDS

p-value scans of four-muon mass

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

find no significant structures.

MC BACKGROUND SIMULATION

Studies of SPS and DPS backgrounds reveal no indications of artificially created structures from triggers/selections.

ANALYSIS VARIATIONS

As analysis not blind, robustness and characterisation of 18 GeV excess studied with alternative selections.

Global significance: 1.9–5.4σ [MASS RANGE 10–50 GEV]

LOCAL SIGNIFICANCES

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

A closer look: 13 TeV

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

Unbiased statistical test of 8 TeV excess in 13 TeV data.

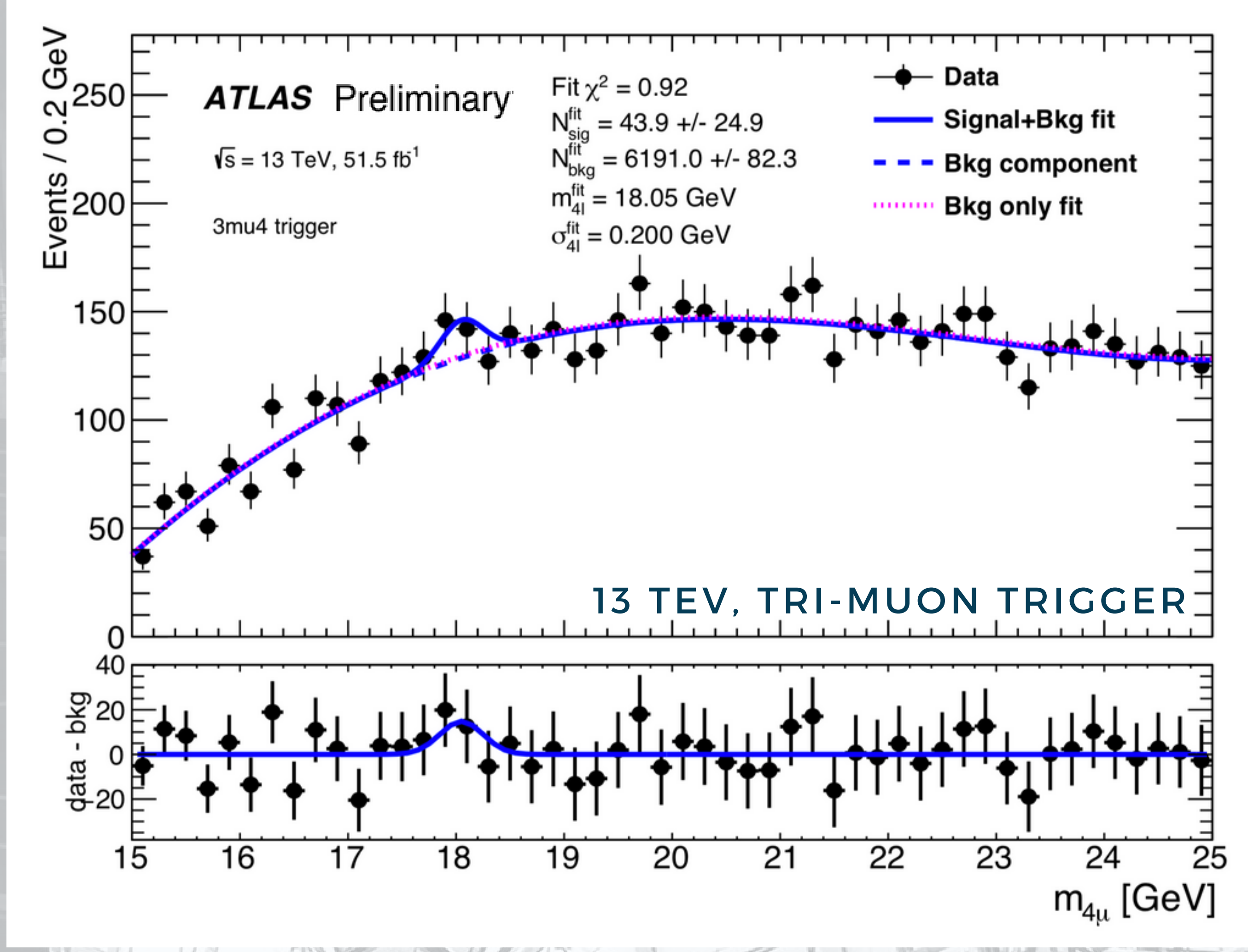
Background rate at 13 TeV three times 8 TeV levels.

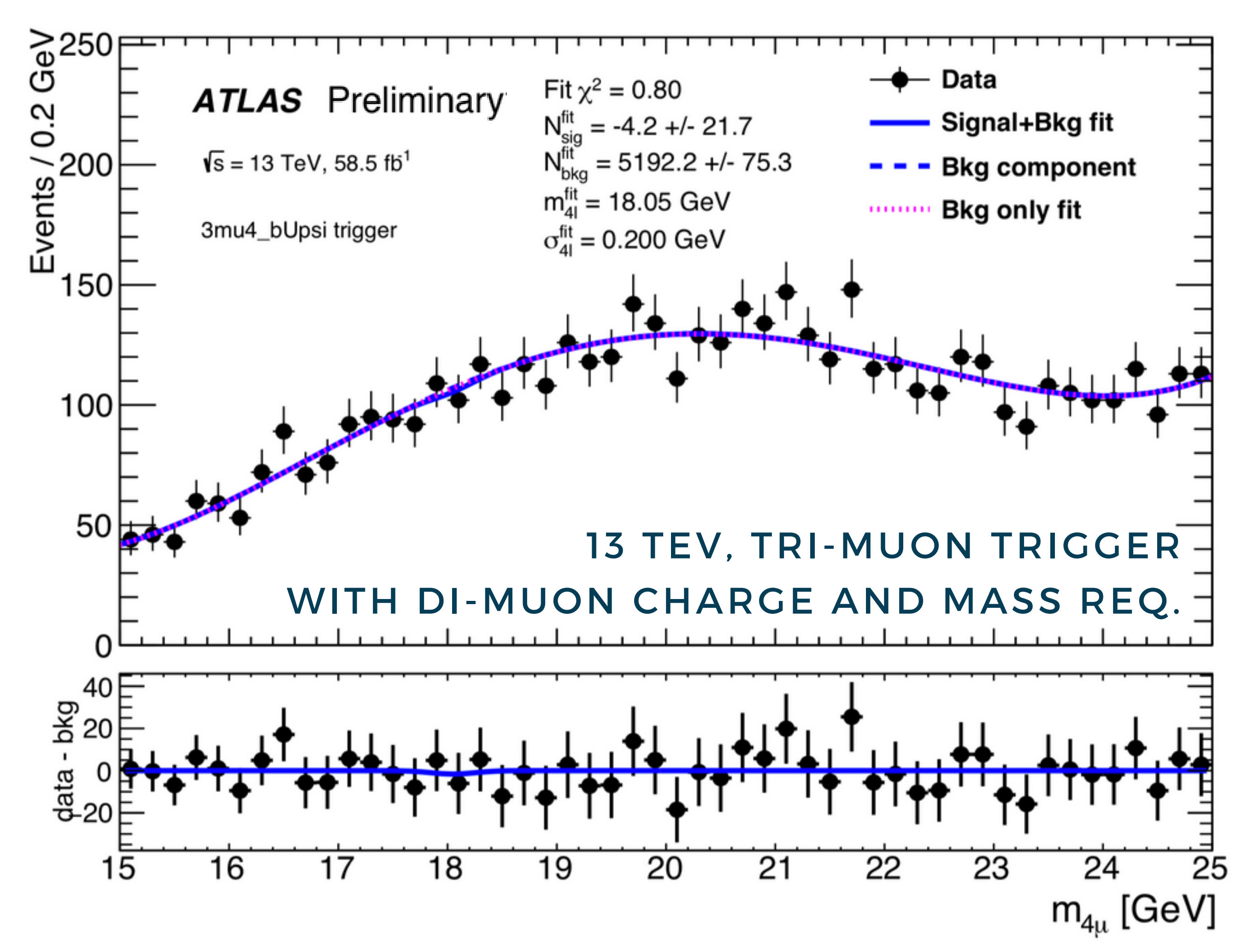
EARLY 13 TEV DATA (2015-17)

13 TeV data collected with same tri-muon triggers finds 1.9σ excess for signal fit fixed to 18.05 GeV.

LATE 13 TEV DATA (2018)

No evidence for a signal in 2018 data (new trigger).





Di-Υ(1S) cross-check among datasets

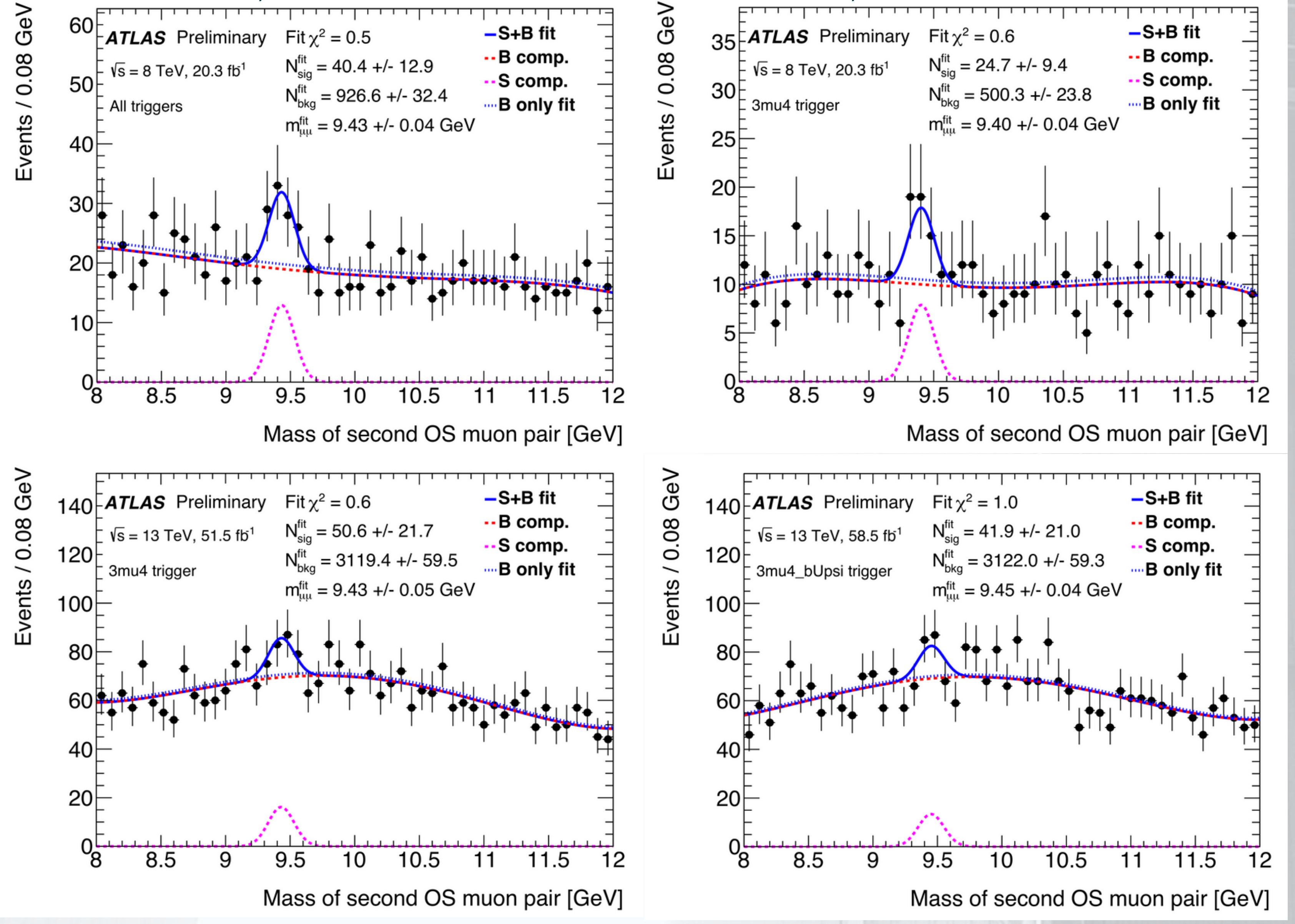
X→μμ+Υ(1S)→4μ

HOW COMPATIBLE ARE THESE OBSERVATIONS WITH A REAL SIGNAL?

Depends on relative sensitivity of datasets: luminosity, cross-section enhancement, trigger and reconstruction efficiencies.

8 TEV; ALL TRIGGERS

8 TEV; TRI-MUON TRIGGER



13 TEV; TRI-MUON TRIGGER

13 TEV; TRI-MUON TRIGGER
+ OS CHARGE/MASS REQ.

Evidence for di-Υ(1S) production.

Large statistical uncertainties.

Searches in X→μμ+Υ(1S)→4μ

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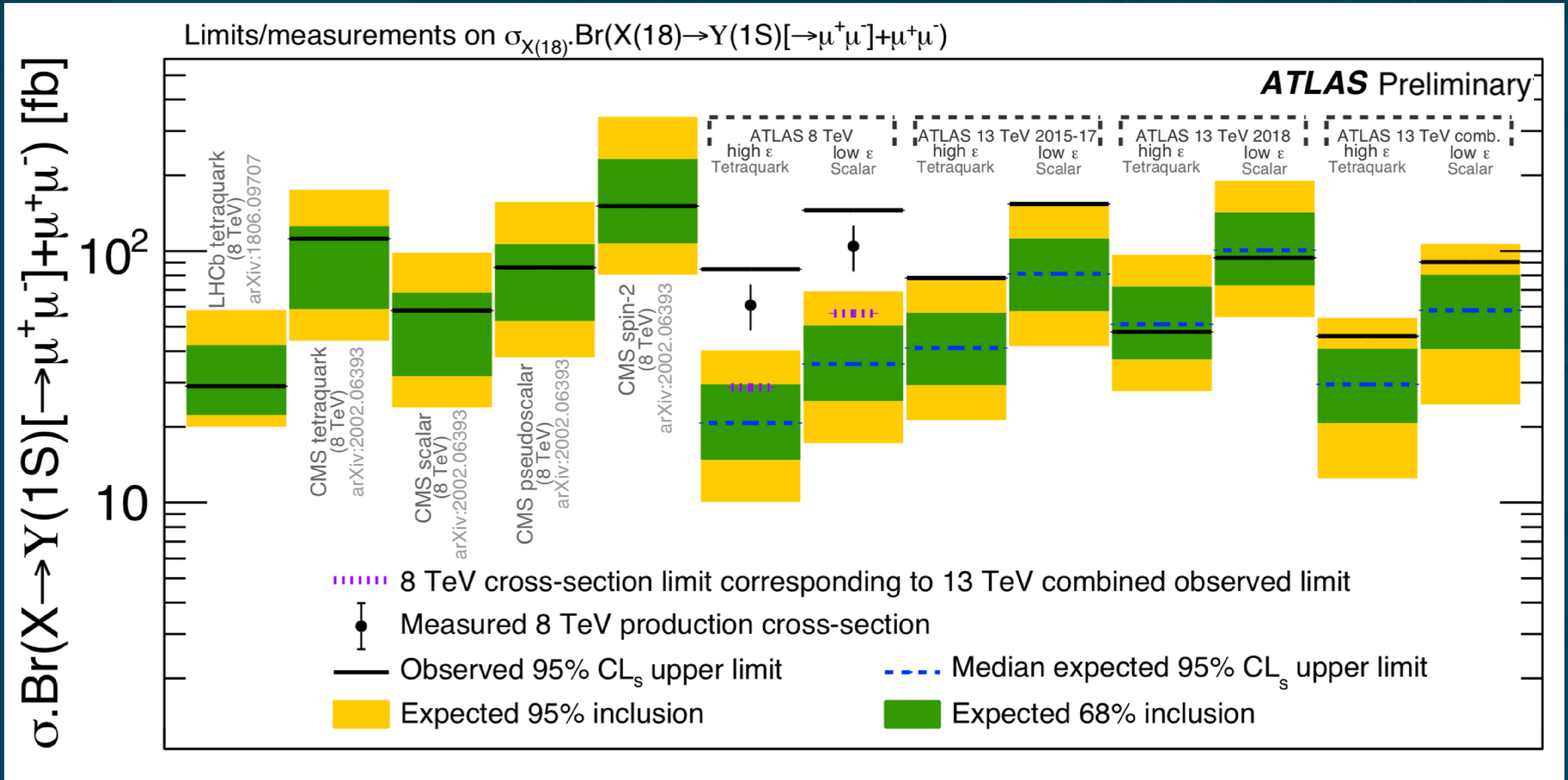
Set expected/observed cross-section limits.

8 TeV results compatible with tetraquark / scalar with 60 / 100 fb cross section.

13 TeV results exclude the observed excess at 8 TeV at more than 95% CL for the above signals



Summary

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

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

Significant (>5σ) broad low mass excess and resonance at 6.9 GeV observed in di-J/ψ.

$J/\psi + \psi(2S)$ data supports additional resonance at 7.2 GeV.

Full characterisation of excesses requires further study.

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

Excess at ~18 GeV in the 8 TeV dataset seen in data-driven analysis.

Unbiased test using 13 TeV data does not confirm excess.