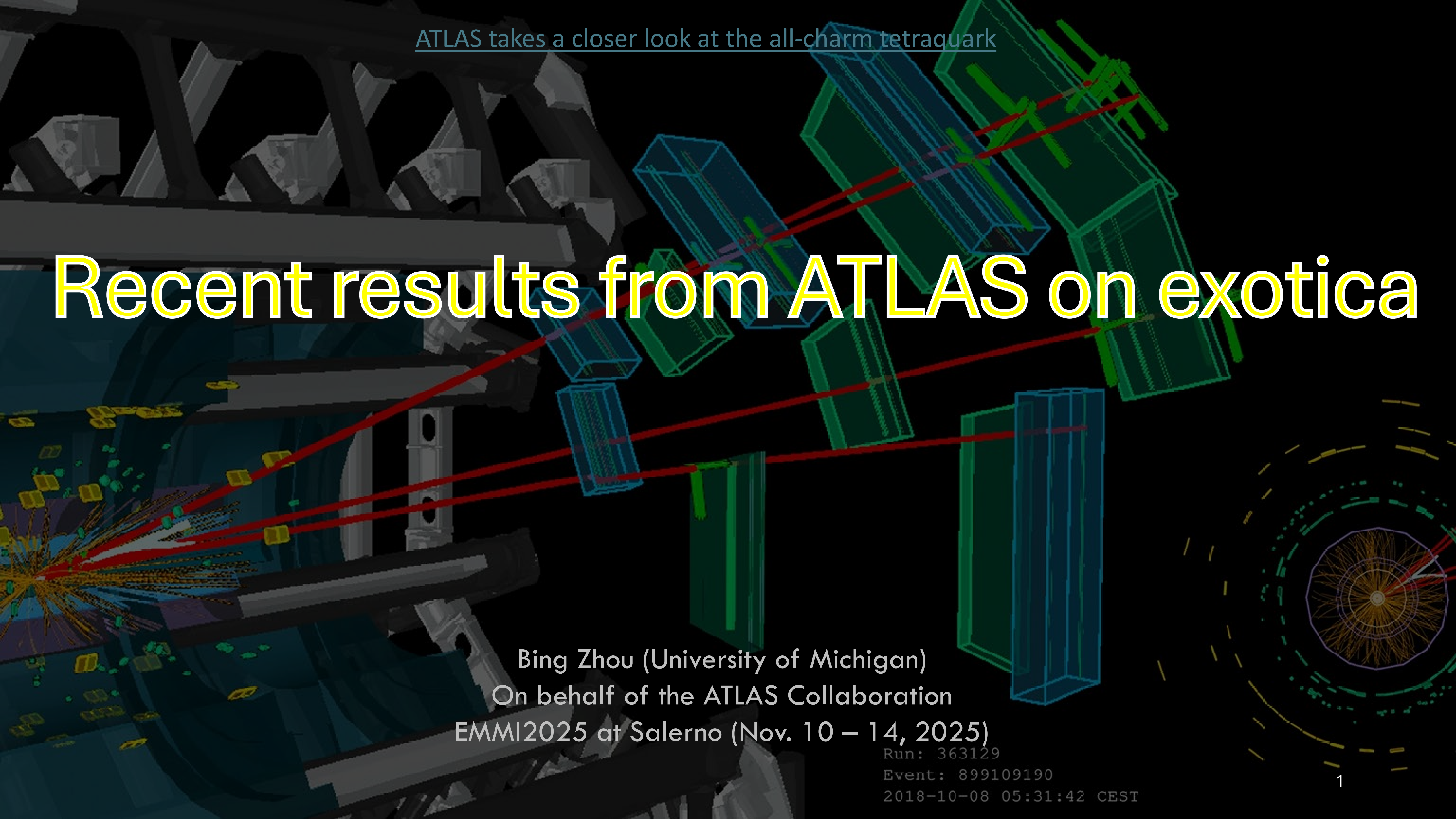
ATLAS takes a closer look at the all-charm tetraquark

Recent results from ATLAS on exotica



Bing Zhou (University of Michigan)
On behalf of the ATLAS Collaboration
EMMI2025 at Salerno (Nov. 10 – 14, 2025)

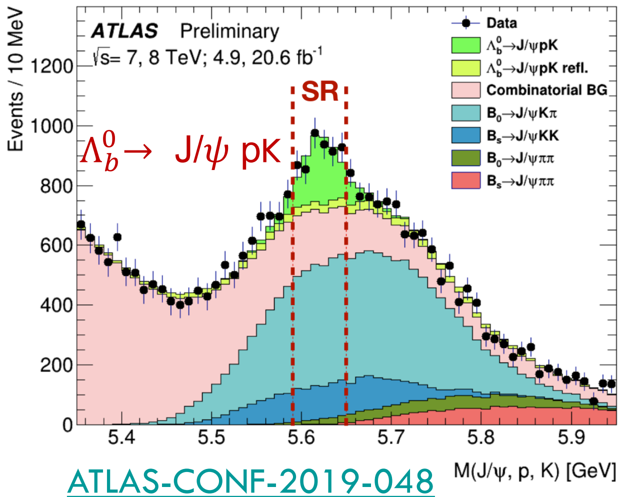
Introduction

Recent ATLAS results on exotic hadron searches

- Standard hadrons observed are mesons ($q\bar{q}$) and baryons (qqq). Exotic hadron made of quarks and possibly gluon, but do not have the same quark content as ordinary hadrons, such as tetraquarks ($qq\bar{q}\bar{q}$), pentaquarks ($qqqq\bar{q}$),…
- Understanding the nature of these exotic states requires a close interplay among experimental observations, phenomenological models, and lattice QCD studies to probe the mechanisms of the strong interaction and color confinement, and to elucidate the spectroscopy of exotic hadrons.
- A series of states consistent with containing four quarks have been discovered, while the existence and interpretation of pentaquark states remain under active investigation.

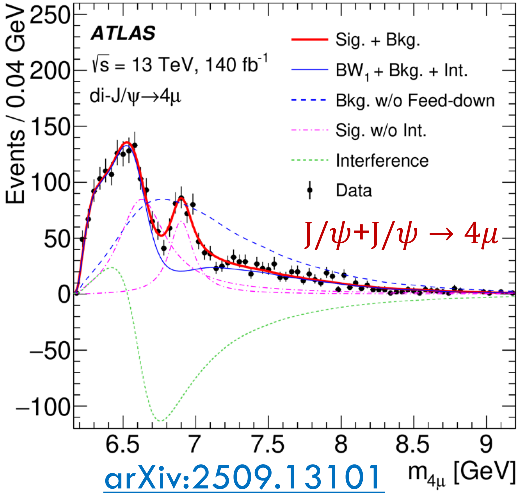
Report:

Search for pentaquark



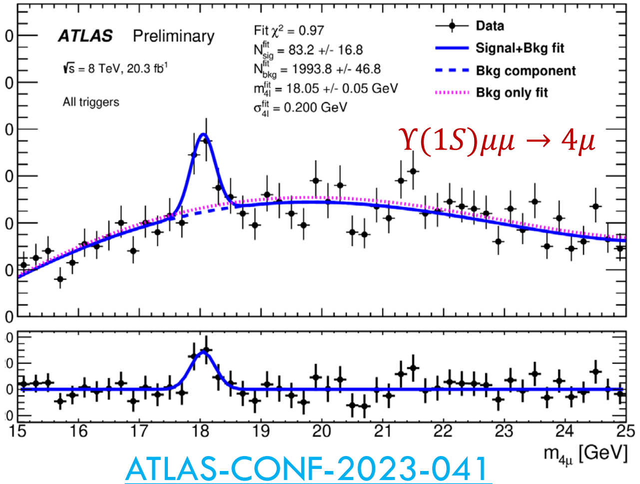
ATLAS-CONF-2019-048

Observation of all-charm tetraquark



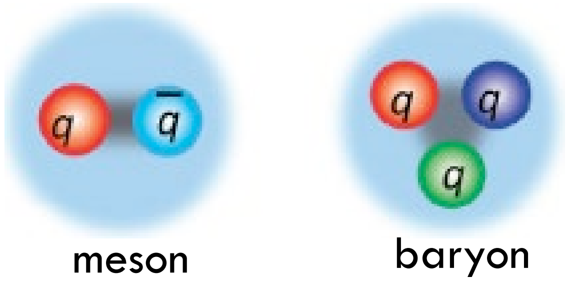
arXiv:2509.13101

Search for tetraquark containing Υ

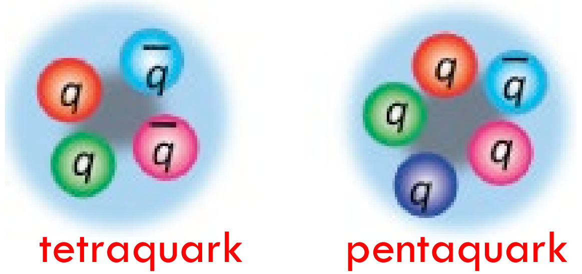


ATLAS-CONF-2023-041

Standard hadrons



Exotic hadrons



Mechanisms to form exotic hadrons ?

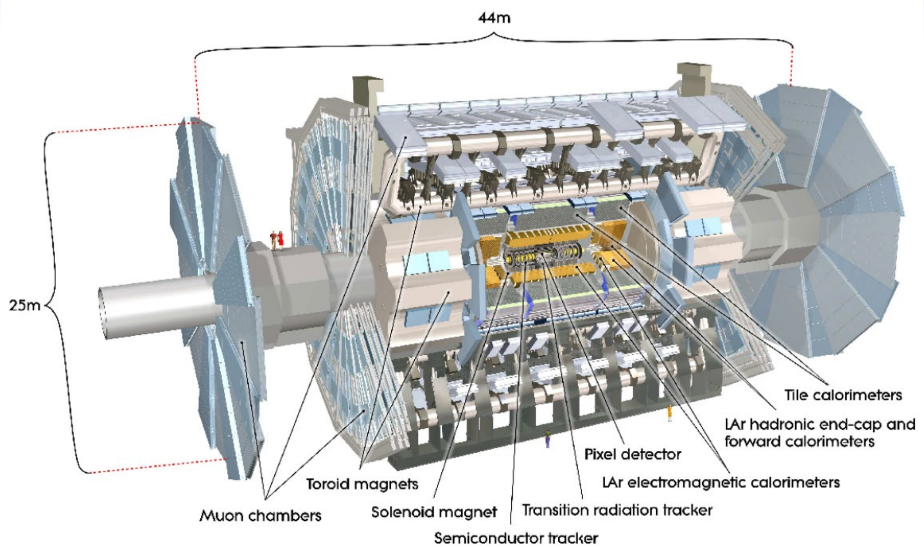
A multiquark "bag"?

A "meson-meson molecule" ?

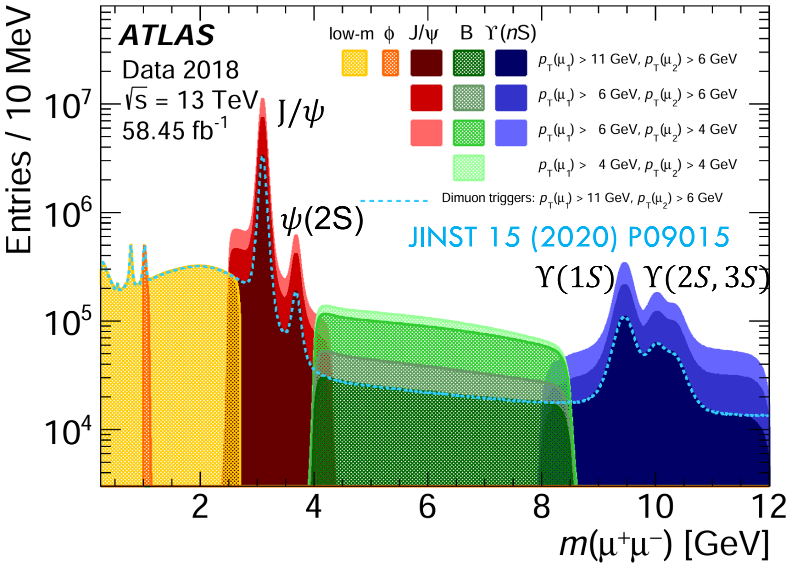
A "meson-baryon molecule"?

The ATLAS Experiment

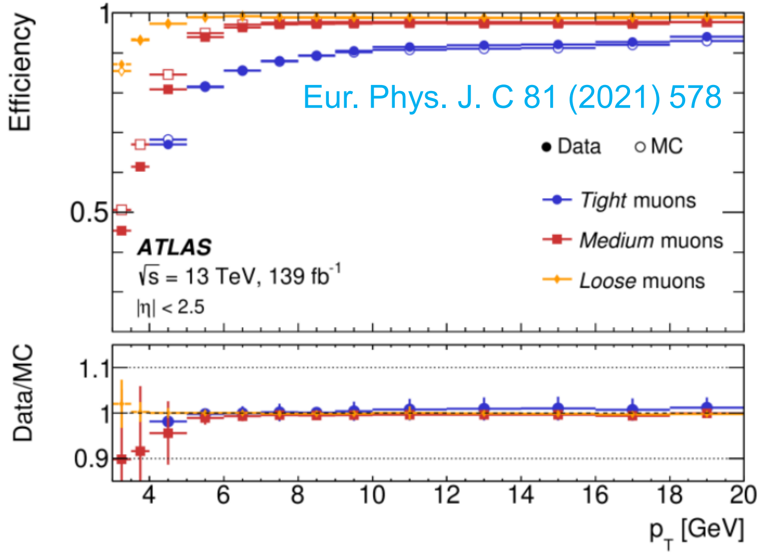
- ATLAS is one of the two general-purpose detectors at the LHC with excellent lepton, photon, and jet measurements
- Ability to trigger and identify muons with low pT:
  - Around 2-3 GeV (threshold due to MIP energy loss in calorimeter)
  - Optimized for rejecting non-prompt muons from light flavor hadron decays
- Study of exotic hadron resonances using $J/\psi \to \mu\mu$ & $\Upsilon \to \mu\mu$, combined with associated produced particles, μ, π, p, K, final states

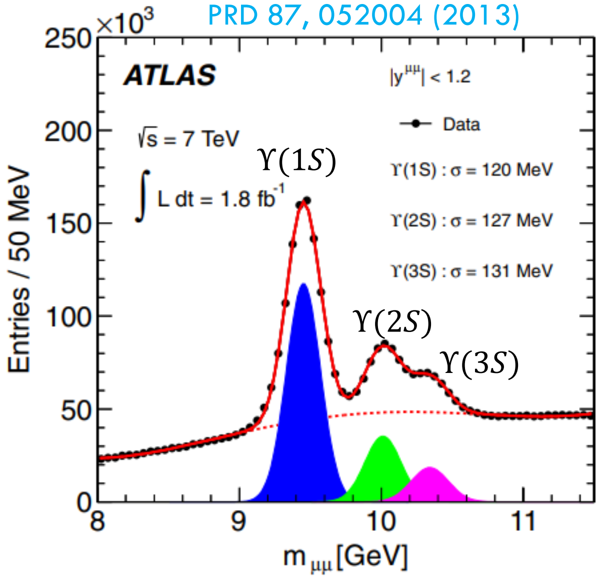


Low pT dimuon trigger



Muon identification efficiency





(ATLAS-CONF-2019-048)

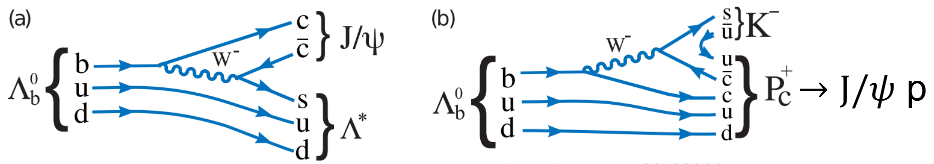
Study of J/ψ p resonances in the Λ_b^0 decays

- In 2015 the **LHCb** first reported the observation of J/ψ p resonance structures in the $\Lambda_b^0 \to$ J/ψ pK decays (PRL 115, 072001), interpreted as ($c\bar{c}$uud) **pentaquark** states; Later observed in $\Lambda_b^0 \to$ J/ψ pπ final state (PRL 117, 082003).
- ATLAS searched for pentaquark states using Run 1 datasets at 7 (4.9 fb^{-1}) and 8 TeV (20.6 fb^{-1}), reconstructed $\Lambda_b^0 \to$ J/ψ pK
- Due to the absence of PID, the $\boldsymbol{\Lambda_b^0}$ decays are reconstructed together with the decays $B^0 \to$ J/$\psi K^+\pi^-$ ($\pi^+\pi^-$), and $B_s^0 \to$ J/ψK^+K^- ($\pi^+\pi^-$). These decays to J/ψ and two additional hadrons (labled as $h_1 h_2$) are reconstructed.
- The B^0 (B_s^0) decay channels are used as the control regions for $\boldsymbol{\Lambda_b^0}$ decays detection. Systematic effects are considered for potential contribution from $B^0 \to Z_c(4200)^- K^+ \to J/\psi\,\pi^- K^+$
- **Event selection:**

  $J/\psi \to \mu\mu,\ p_T^{\mu} > 4\text{GeV},\ |\eta^{\mu}| < 2.3,\ 2807 < m_{\mu\mu}\ 3387\ \text{MeV};$
  $B\ hadrons\text{:}\quad p_T > 12\ \text{GeV},\ |\eta^B| < 2.1, \chi^2/N < 2, L_{xy} > 7\ mm;$
  Angular requirements on $\cos\theta_{P_c,\Lambda_b,\Lambda^*}$;
  $\text{mass}\ (K\pi) > 1.55\ \text{GeV and mass}\ (pK) > 2.0\ \text{GeV}.$

- Fits to the J/ψ $h_1 h_2$ mass is performed after subtracting the same-sign background contribution (both hadron tracks with same charge). Multi-dimensional (different hadron mass assignments) binned maximum likelihood fits

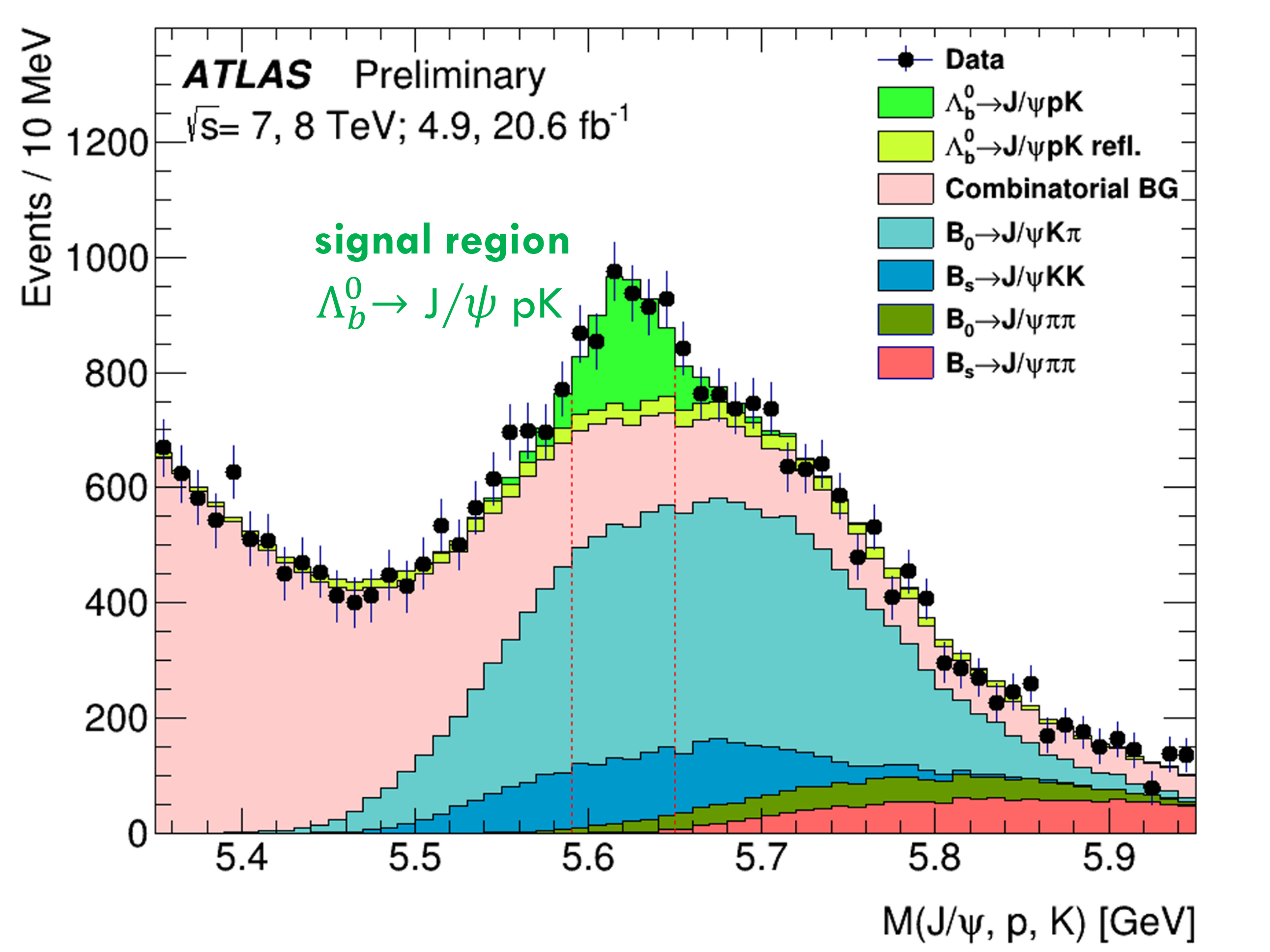
Signal and background processes generated with Pythia 8.1 ("phase space" model)



Phys. Rev. Lett. 122, 222001

	Mass window
Λ_b SR	$5.59 < m(J/\psi, h_1 = p, h_2 = K) < 5.65$ GeV
B^0 CR	$5.25 < m(J/\psi, h_1 = K(\pi), h_2 = \pi(K)) < 5.31$ GeV
B_s^0 CR	$5.337 < m(J/\psi, h_1 = K, h_2 = K) < 5.397$ GeV

J/ψpK Mass Spectrum



The invariant mass distribution M(J/ψpK) for all selected Λ_b^0 candidates. The results of the iterative fit procedure are shown. Red dashed lines label the **signal region: 5.59 GeV < M(J/ψpK) <5.65 GeV**.

- $N(\Lambda_b^0 \to J/\psi p K^-) = 2270 \pm 300$
- $N(B^0 \to J/\psi K^+\pi^-) = 10770$
- $N(B_s^0 \to J/\psi K^+K^-) = 2290$
- $N(B^0 \to J/\psi \pi^+\pi^-) = 1070$
- $N(B_s^0 \to J/\psi \pi^+\pi^-) = 1390$
- In **SR**, $N(\Lambda_b^0 \to J/\psi p K^-)$ ~ 1200

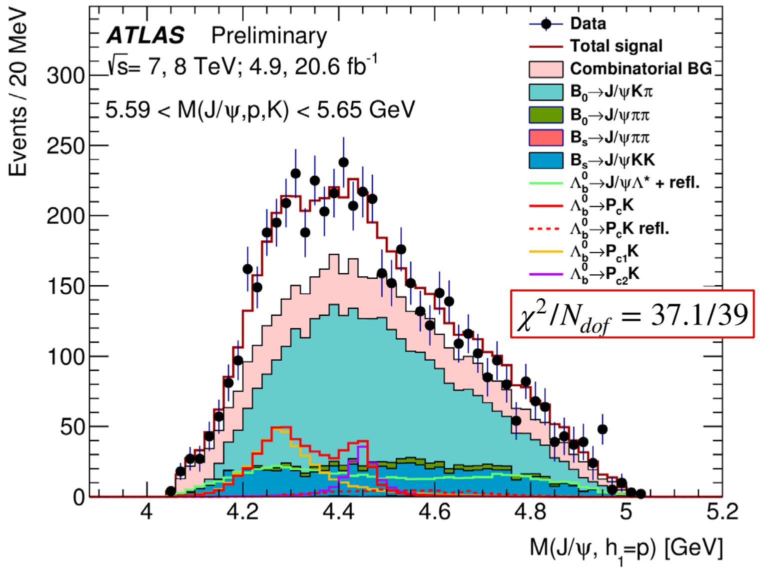
Systematic uncertainties for extracted yields

uncertainty Source	$N(P_{c1})$	$N(P_{c2})$	$N(P_{c1}+P_{c2})$	$\Delta\phi$
Number of $\Lambda_b^0 \to J/\psi p K^-$ decays	$^{+1.8}_{-0.6}\%$	$^{+6.6}_{-9.2}\%$	$^{+1.6}_{-0.8}\%$	$^{+0.3}_{-0.0}\%$
Pentaquark modelling	$^{+21}_{-0}\%$	$^{+1}_{-22}\%$	$^{+8.7}_{-4.4}\%$	$^{+1.6}_{-0.0}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling	$^{+14}_{-2}\%$	$^{+5}_{-44}\%$	$^{+9.2}_{-9.1}\%$	$^{+3.6}_{-1.6}\%$
Combinatorial background	$^{+0.7}_{-4.0}\%$	$^{+18}_{-5}\%$	$^{+4.2}_{-4.8}\%$	$^{+3.2}_{-0.0}\%$
B meson decays modelling	$^{+13}_{-25}\%$	$^{+28}_{-35}\%$	$^{+1.6}_{-9.3}\%$	$^{+0.5}_{-2.1}\%$
Total systematic uncertainty	$^{+28}_{-25}\%$	$^{+35}_{-61}\%$	$^{+14}_{-15}\%$	$^{+5.1}_{-2.7}\%$

Fit data with different pentaquark hypotheses

signal region: 5.59 GeV < M(J/ψpK) <5.65 GeV

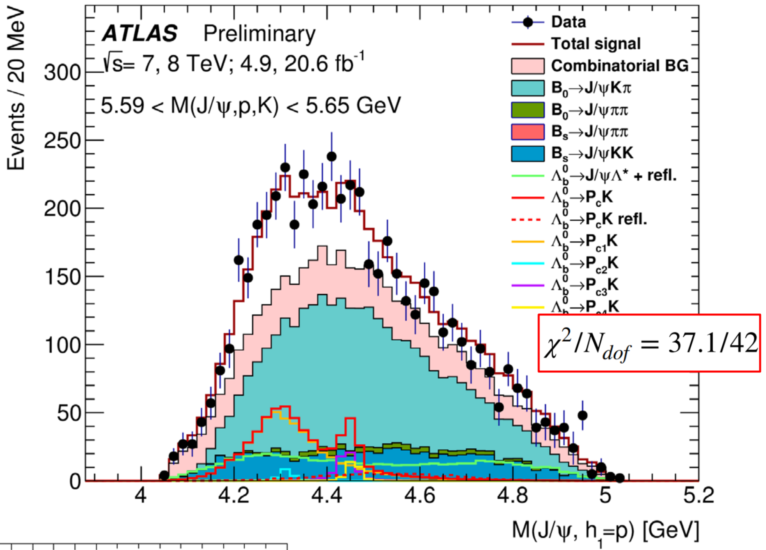
Two pentaquarks Model



The pentaquark masses and widths are consistent with the LHCb results.

Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	$140^{+77}_{-50}(\text{stat})^{+41}_{-33}(\text{syst})$ MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	$4449^{+20}_{-29}(\text{stat})^{+18}_{-10}(\text{syst})$ MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	$51^{+59}_{-48}(\text{stat})^{+14}_{-46}(\text{syst})$ MeV	$39 \pm 5 \pm 19$ MeV

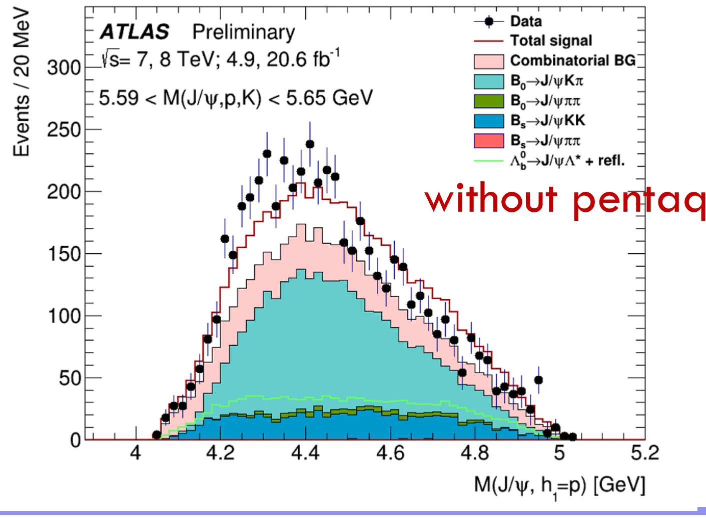
Four pentaquarks Model



Testing the hypothesis without pentaquarks

The fit quality is worse than the models with pentaquarks

χ^2/N_{dof}= 69.2/37, corresponding to a p-value of 1.0×10^{-3}



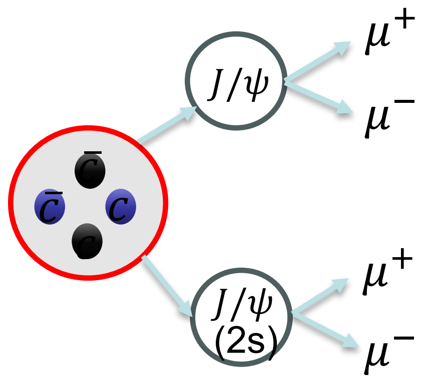
Data is in favor of models with two or more pentaquarks, but the hypothesis without pentaquarks is not excluded.

Ovservation of di-charmonium resonances

The study of tetraquark states can further our understanding of QCD in the non-perturbative regime. The topic of all-charm tetraquarks has gained significant interest recently.

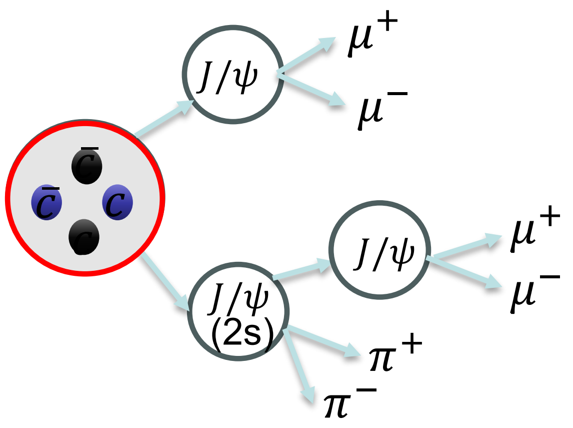
- The **LHCb** Collaboration reported the first observation of a narrow resonance near 6.9 GeV ($X(6900)$) in the di-J/ψ mass spectrum in 2020 (Science Bulletin 65 (2020) 1983)
- The ATLAS and CMS experiments later confirmed the observation of $X(6900)$, as well as another broad structure around 6.6 GeV (ATLAS- Phys. Rev. Lett. 131 (2023) 151902, CMS-Phys. Rev. Lett. 132 (2024) 111901)
- New paper in 2025, "Observation of structures in the $J/\psi + \psi(2S)$ mass spectrum with the ATLAS detector" (Submitted to PRL, arXiv:2509.13101)

- **140 fb^{-1} data recorded by ATLAS Run 2 at 13 TeV**
- Muon trigger combinations with various prescaling to increase Low pT muon acceptance
- 2- or 3-muon triggers with dimuon in mass range in 2.5-4.3 GeV
- X(6900) trigger efficiency is 72% relative to offline selection
- Final states: at least 4 muons (two opposite charge pairs) and fitted to common vertex; two pairs refitted with J/ψ or ψ(2s) mass; final resonance mass $m_{4\mu}$



$X \rightarrow J/\psi + J/\psi \rightarrow 4\mu$

$X \rightarrow J/\psi + \psi(2S) \rightarrow 4\mu$



$X \rightarrow J/\psi + \psi(2S) \rightarrow 4\mu + 2\pi$

Di-charmonium event selection

Signal:
- Four charm bund state → di- J/ψ or J/ψ + ψ 2S → 4μ (+2π)
- 4μ are fitted to a common-vertex by using the ID tracks
- Re-vertex each pair with J/ψ or ψ(2S) mass constraint

Background (estimated using MC, scaling using data CRs)

SPS: containing two prompt J/ψ's (CR: $8 < m_{4\mu} < 12$ GeV)

DPS: containing two prompt J/ψ's. (CR: $14 < m_{4\mu} < 24.5$ GeV)

Non-prompt J/ψ's from $b\bar{b}$ (CR: $\chi^2_{4\mu}/N_{dof} > 6$ or $L^{2\mu}_{xy} > 0.4$ mm)

Other backgrounds estimated by data driven methods

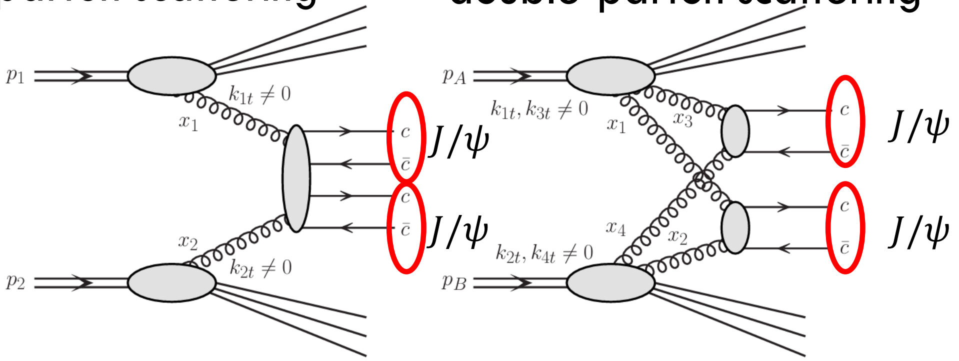
-Single ψ background containing only one real ψ candidate
-Continuum background containing no real ψ candidate

Taking events from **fake region** or **sideband**

Fake region: one J/ψ or ψ(2S) candidate contains a track that does not pass the muon identification WP

Side band: $2.60 < m(J/\psi) < 2.88$ GeV
or $3.30 < m(J/\psi) < 3.50$ GeV
or $3.35 < m(\psi(2S)) < 3.48$ GeV
or $3.88 < m(\psi(2S)) < 4.10$ GeV

single-parton scattering   double-parton scattering



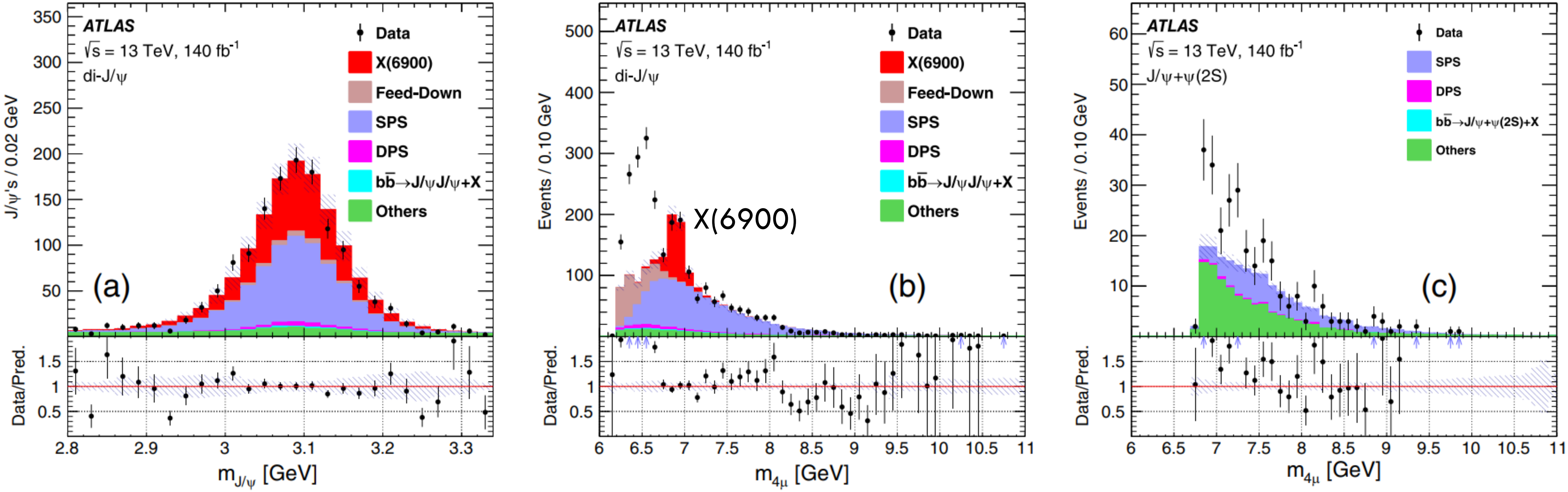
The SPS process includes both resonant production via intermediate states, which could be tetraquarks, and nonresonant production. Pythia 8.244 is used to generate SPS, DPS and non-prompt di-charmonium events

event selection

4μ channel		$4\mu + 2\pi$ channel	
SR	CR	SR	CR
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *Loose* muons, $p_{T1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, $m_{\psi(2S)} \in [3.56, 3.80]$ GeV			
—		Two *loose* OS ID tracks with $p_T > 0.5$ GeV for pions, BDT requirement	
$\chi^2_{4\mu}/N < 3$, $\lvert L^{4\mu}_{xy}\rvert < 0.2$ mm, $\lvert L^{\text{charm}}_{xy}\rvert < 0.3$ mm, $m_{4\mu} < 11$ GeV		$\chi^2_{4\mu+2\pi}/N < 3$, $\lvert L^{4\mu+2\pi}_{xy}\rvert < 0.2$ mm, $\lvert L^{\text{charm}}_{xy}\rvert < 0.3$ mm, $m_{4\mu+2\pi} < 11$ GeV	
$\Delta R(J/\psi, \psi(2S)) < 0.25$	$\Delta R(J/\psi, \psi(2S)) \geq 0.25$	$\Delta R(J/\psi, \psi(2S)) < 0.25$	$\Delta R(J/\psi, \psi(2S)) \geq 0.25$

Mass spectra of selected 4μ events

Selected events in signal region: 6.7 GeV < $m_{4\mu}$ < 7.1 GeV



(a) The J/ψ mass spectrum; (b) the 4μ mass spectrum in the signal region in the di- J/ψ channel; (c) the similar mass spectrum in the $J/\psi + \psi(2S)$ channel. The signal from the X(6900) is scaled to match data around 6.9 GeV. The bars and shaded areas represent uncertainties of data and predictions in each bin, respectively.

Phys. Rev. Lett. 131 (2023) 151902

4μ event kinematic distributions in CRs

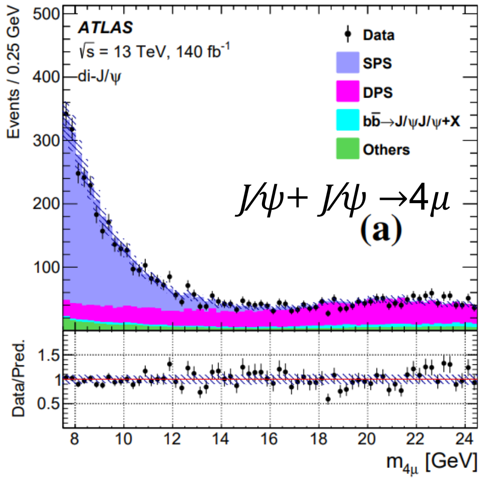
Background estimation with CRs:

Low & high 4μ mass sidebands for SPS & DPS studies, ΔR>0.25 to study SPS mass spectrum

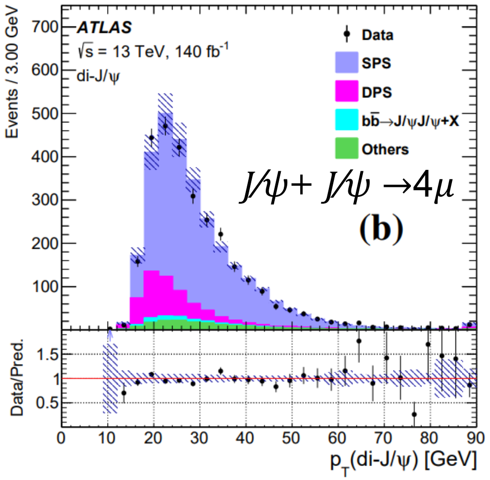
Poor 4μ vertex or very long proper lifetime to select non-prompt control region

Reweighting between data and MC in di-J/ψ pT, Δϕ, Δη between charmonia and lower-pT muons

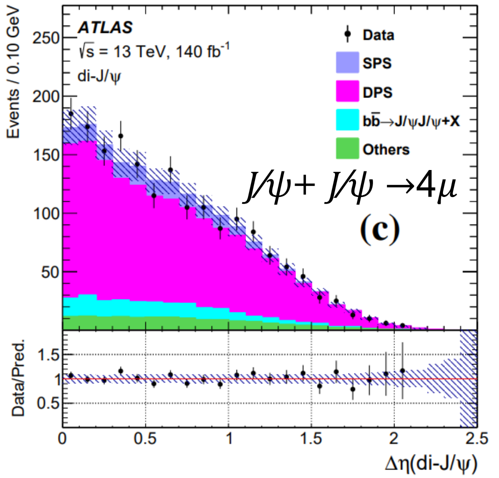
without the ΔR requirement



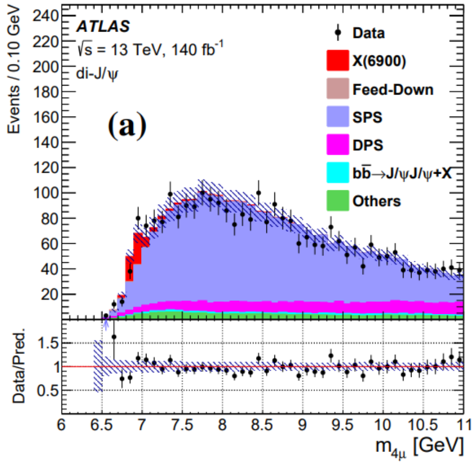
SPS CR ($7.5 < m_{4\mu} < 12.0$ GeV)

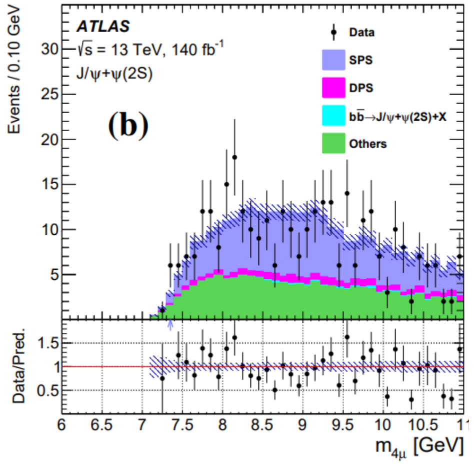


DPS CR ($14 < m_{4\mu} < 24.5$ GeV)

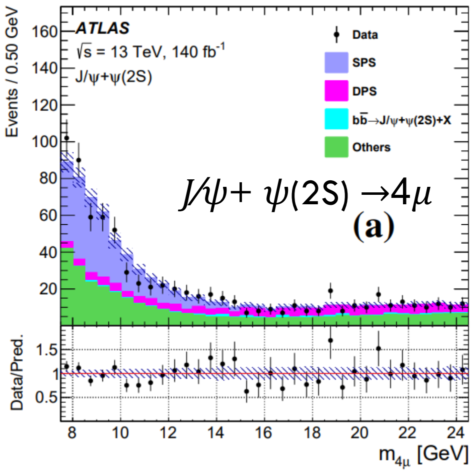


Control region - $\Delta R \geq 0.25$

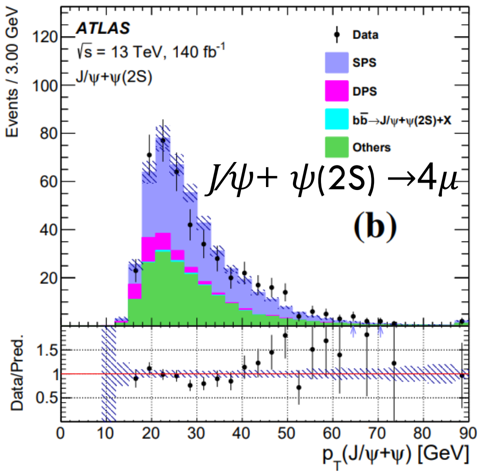




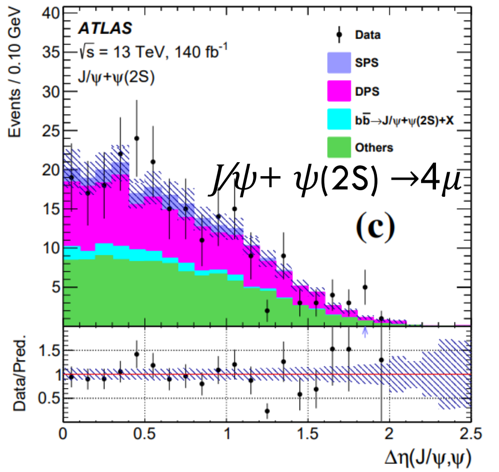
without the ΔR requirement



SPS CR ($7.5 < m_{4\mu} < 12.0$ GeV)



DPS CR ($14 < m_{4\mu} < 24.5$ GeV)



Phys. Rev. Lett. 131 (2023) 151902

Systematic uncertainties

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	—		$^{+3}_{-7}$	$^{+31}_{-34}$

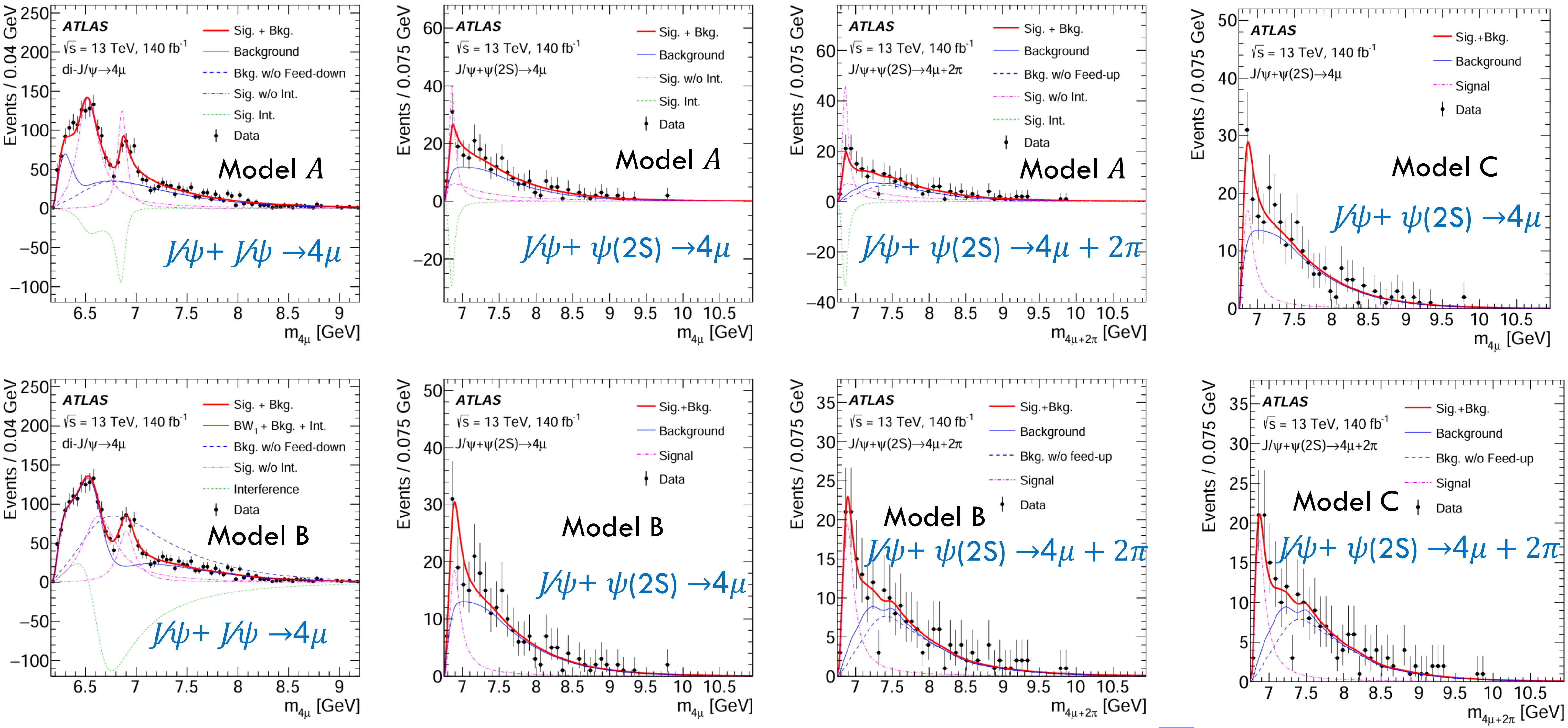
Major systematics affecting the mass spectrum shape

- SPS: PYTHIA uncertainty on suppression of the soft double charmonia production (tuned on data)
- Bkg: shape uncertainty for di-charmonium pT mismodelling
- Fit biases in the resonance parameters.
- The P&D-wave BW functions for systematic on orbital angular momentum assumptions
- Systematic shape variations in the X(6900) and in the second resonance in J/ψ+ψ(2S)
- The 4th resonance around 7.2 GeV (LHCb hint)
- The feed-down background normalizations varied
- J/ψ+ψ(2S): uncertainties on transfer factor between signal and control regions, and on "Others" shape from the non-prompt region
- J/ψ+ψ(2S): interference between the 4th resonance and the others

arXiv:2509.13101

Observation of structures in di-charmonium mass spectrum

Models: *A*(two interfering resonances), B(one interfering with SPS and the other standalone), C (a standalone J/ψ+$\psi(2S)$ resonance)



Confirmation of di-charmonium resonance

The fitted resonance masses and natural widths

	model A	model B	model C
m / GeV	$6.860 \pm 0.023 \pm 0.010$	$6.902 \pm 0.008 \pm 0.010$	$6.884 \pm 0.017^{+0.058}_{-0.005}$
Γ / GeV	$0.082 \pm 0.032 \pm 0.015$	$0.183 \pm 0.025 \pm 0.007$	$0.178 \pm 0.054^{+0.176}_{-0.024}$
R	$1.08 \pm 0.20^{+0.40}_{-0.09}$	$0.93 \pm 0.17 \pm 0.11$	—

The ratio of partial widths, $R = \frac{\Gamma_{X(6900)\to J/\psi\psi(2S)}}{\Gamma_{(6900)\to di-J/\psi}}$, is also given for model A and B.

The fitted resonance mass in all three models is consistently around 6.9 GeV. The existence of $X(7200)$ in the J/ψ+ψ(2S) channels is tested in each model. The ratio of signal yields for $X(7200)$ to $X(6900)$ is found to be 0.12 ± 0.11, with an upper limit of 0.41 at 95% CL.

Summary

- **An excess near 6.9 GeV is observed in both channels with a combined significance of 8.9σ.**
- No significant signal is observed near 7.2 GeV.
- Assume that the resonance $X(6900)$ decays into both the di-J/ψ and J/ψ+ψ(2S), the ratio of partial decay widths between the $J/\psi + \psi$(2S) and di-J/ψ, $R = \frac{\Gamma_{X(6900)\to J/\psi\psi(2S)}}{\Gamma_{(6900)\to di-J/\psi}} = 1.08 \pm 0.20^{+0.40}_{-0.17}$ is obtained with model A being nominal and B as a systematic uncertainty.

Search for resonance in $\Upsilon(1S)\mu\mu \rightarrow 4\mu$

Motivation

Search for tetraquarks containing b-quarks, and BSM scalar/pseudoscalar Higgs-like particles in a previous uncovered low mass region [10, 50] GeV.

Datasets

The data correspond to an integrated luminosity of 20.3 fb^{-1} at a center-of-mass energy ($\sqrt{s}$) of 8 TeV collected in 2012, and 51.5 fb^{-1} and 58.5 fb^{-1} collected at $\sqrt{s}$=13 TeV in 2015--2017 and 2018, respectively.

Signal

Resonance 4μ mass spectrum: $X \rightarrow \Upsilon(1S)\mu^{+}\mu^{-} \rightarrow \mu^{+}\mu^{-}\mu^{+}\mu^{-}$

Trigger

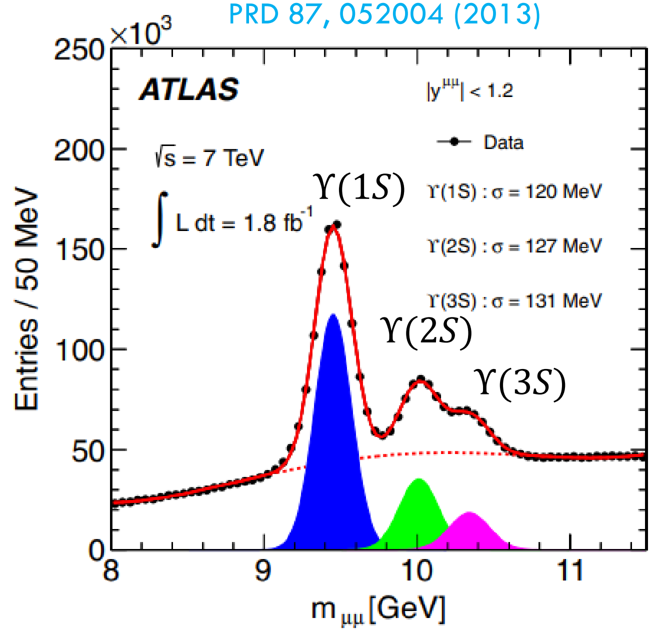
More than 2 or 3 muons with pT > 4 GeV, muon pair opposite charge and mass range for $m_{\mu\mu}$, but with different configurations:

- 8 Tev (2012) combination of un-prescaled 2μ and 3μ, with L=20.3 fb^{-1}
- 13 TeV (2015-2017) pre-scaled 3μ, with L=51.5 fb^{-1}
- 13 TeV(2018) restricted 3μ, pair opposite charge and $m_{\mu\mu}$ in [8-12] GeV with L=58.5 fb^{-1}

Baseline event selection in the $X \to \Upsilon(1S)\mu\mu$ search

Candidate object	Requirements
Muons	$p_T(\mu) > 3$ GeV and $\lvert\eta\rvert < 2.5$, $\lvert z_0 \sin\theta\rvert < 1$ mm and $\lvert d_0/\sigma_{d_0}\rvert < 6$
Muon quadruplet	≥ 3 muons passing LowPt selection criteria, $\sum q_\mu = 0$, four-muon vertex fit $\chi^2/N_{\mathrm{d.o.f}} \leq 10$, 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

PRD 87, 052004 (2013)



Selected numbers of events in data

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

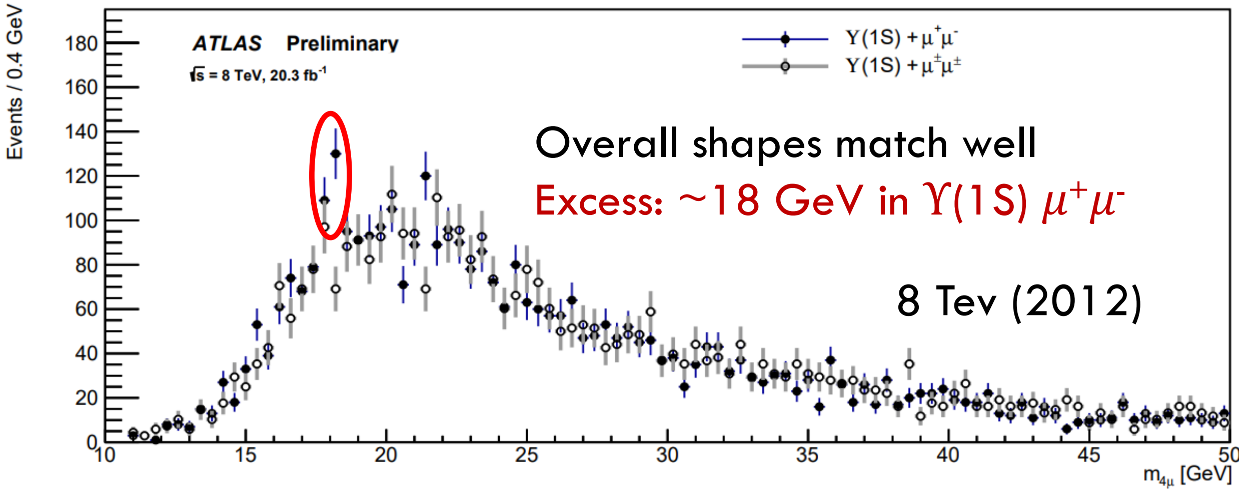
The numbers in parentheses are numbers of events per fb^{-1}

Same-sign di-muon CR

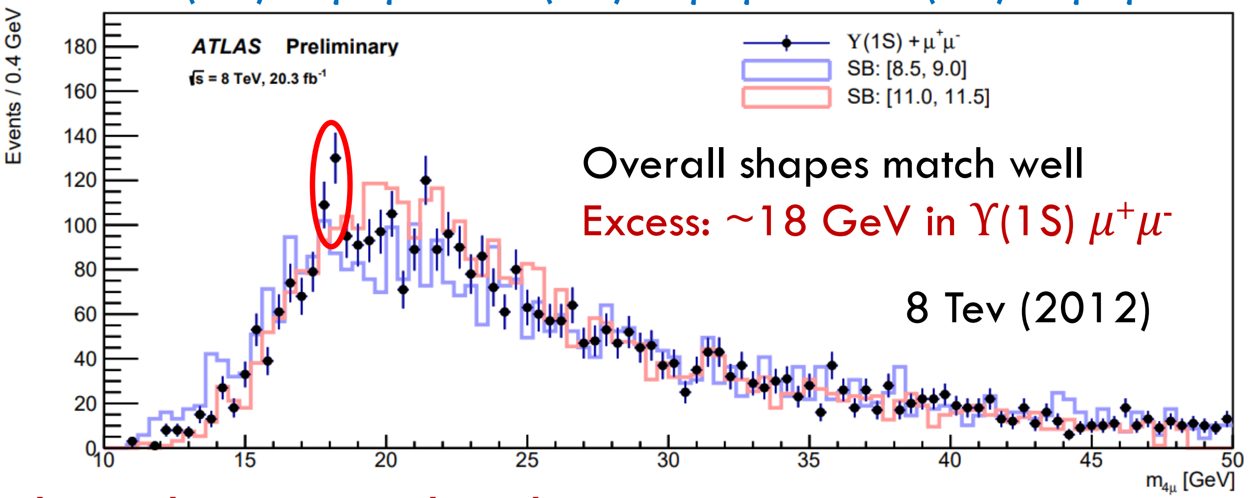
ATLAS-CONF-2023-041

Mass spectra of in $\Upsilon(1S)\mu\mu \rightarrow 4\mu$ events

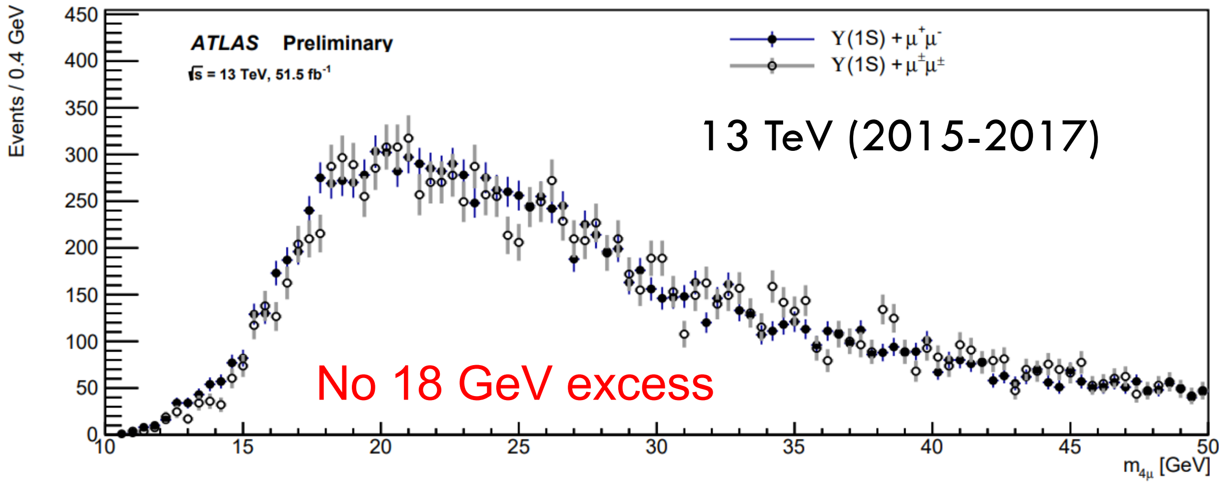
$\Upsilon(1S) + \mu^+\mu^-$ vs. same-sign, $\Upsilon(1S) + \mu^\pm\mu^\pm$

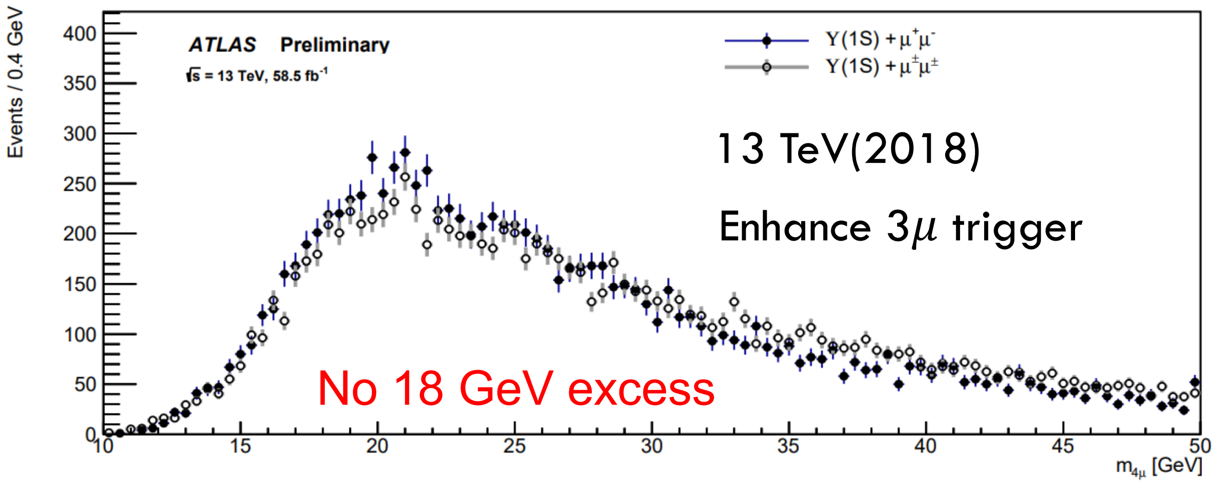


$\Upsilon(1S) + \mu^+\mu^-$ vs. $\Upsilon(2S) + \mu^+\mu^-$ and $\Upsilon(3S) + \mu^+\mu^-$



No evidence for manufactured peaks in $m_{4\mu}$-distribution





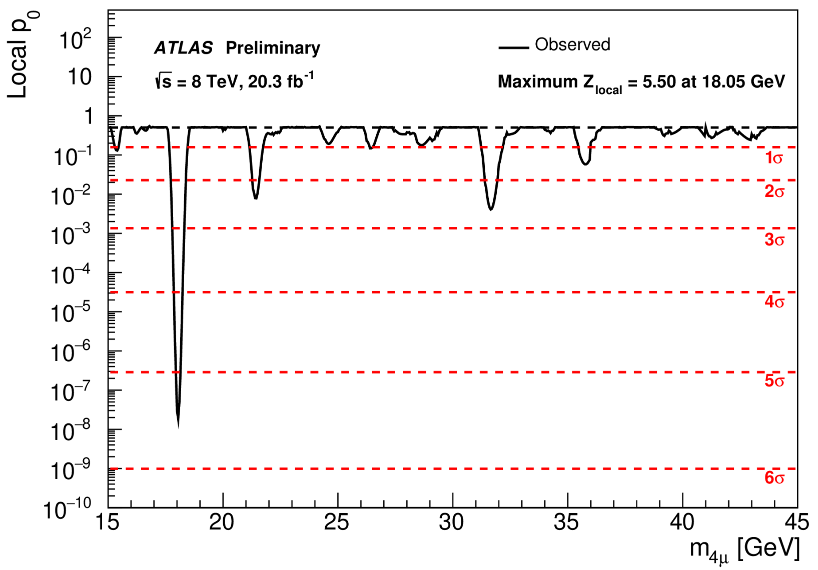
Data excess significance at 8 TeV

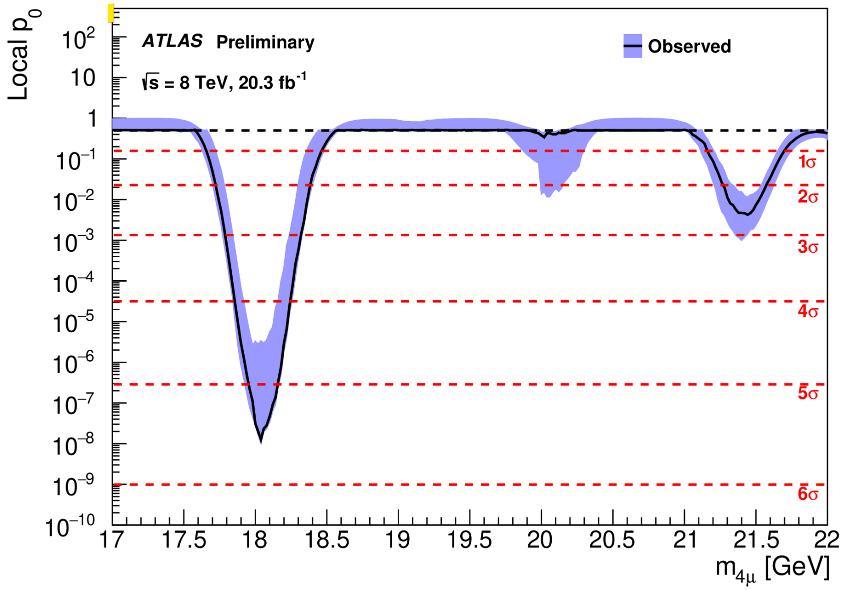
- The likelihood for the signal-plus-background fit of the observed $m_{4\mu}$ distribution is constructed as

$$L(N_S, m_X, \sigma_X, \vec{\theta}) = \prod_{n \text{ events}} \left[N_B \cdot f_B(m_{4\mu}; \vec{\theta}_\mathrm{B}) + N_S \cdot f_S(m_{4\mu}; m_X, \sigma_X, \vec{\theta}_\mathrm{S}) \right] \cdot \frac{e^{-(N_B+N_S)}(N_B+N_S)^n}{n!}$$

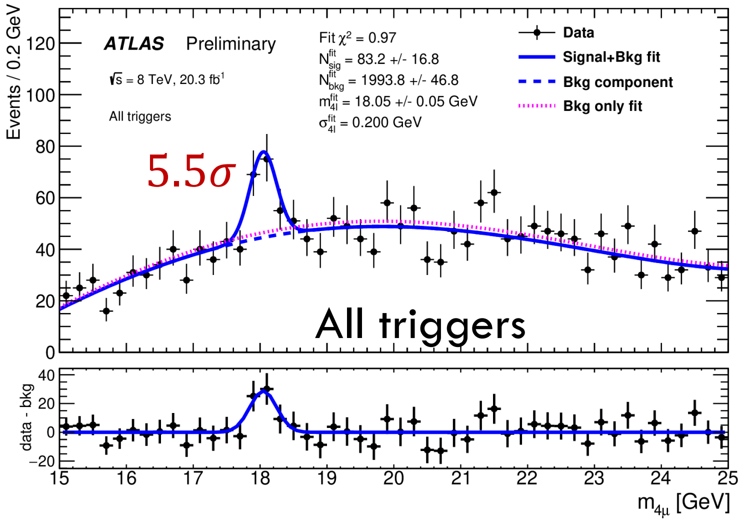
- The local p-value for the compatibility with the background-only hypothesis when testing a hypothesized resonance at m_X is based on the profile likelihood ratio test statistic:

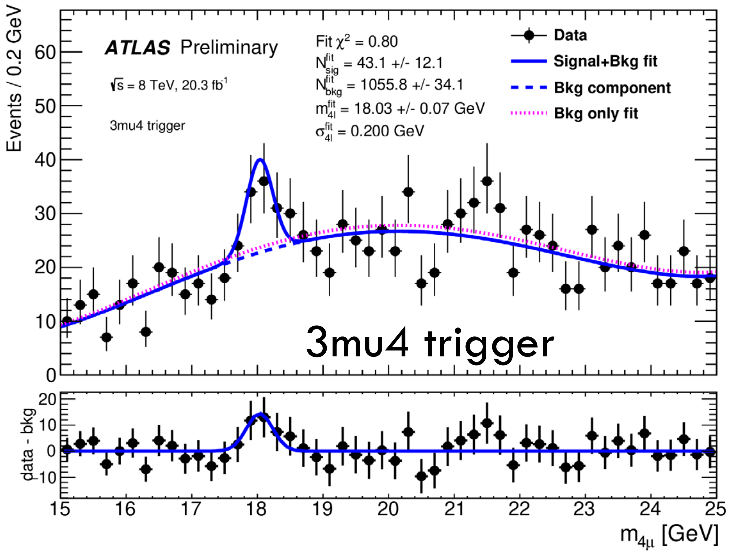
$$q_0(m_X, \sigma_X) = -2\ln\left(\frac{L(0, m_X, \sigma_X, \hat{\hat{\vec{\theta}}})}{L(\hat{N}_S, m_X, \sigma_X, \hat{\vec{\theta}})}\right)$$





Access significances at 18 GeV (8 TeV data)





Alternative event selection and access significances at 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 $\|\tau/\sigma_\tau\| < 3$	1873 ± 45	18.04 ± 0.05	86 ± 17	5.6
MBS < 3	1749 ± 44	18.05 ± 0.04	83 ± 16	5.8

A global significance of between 1.9 σ and 5.4 σ �

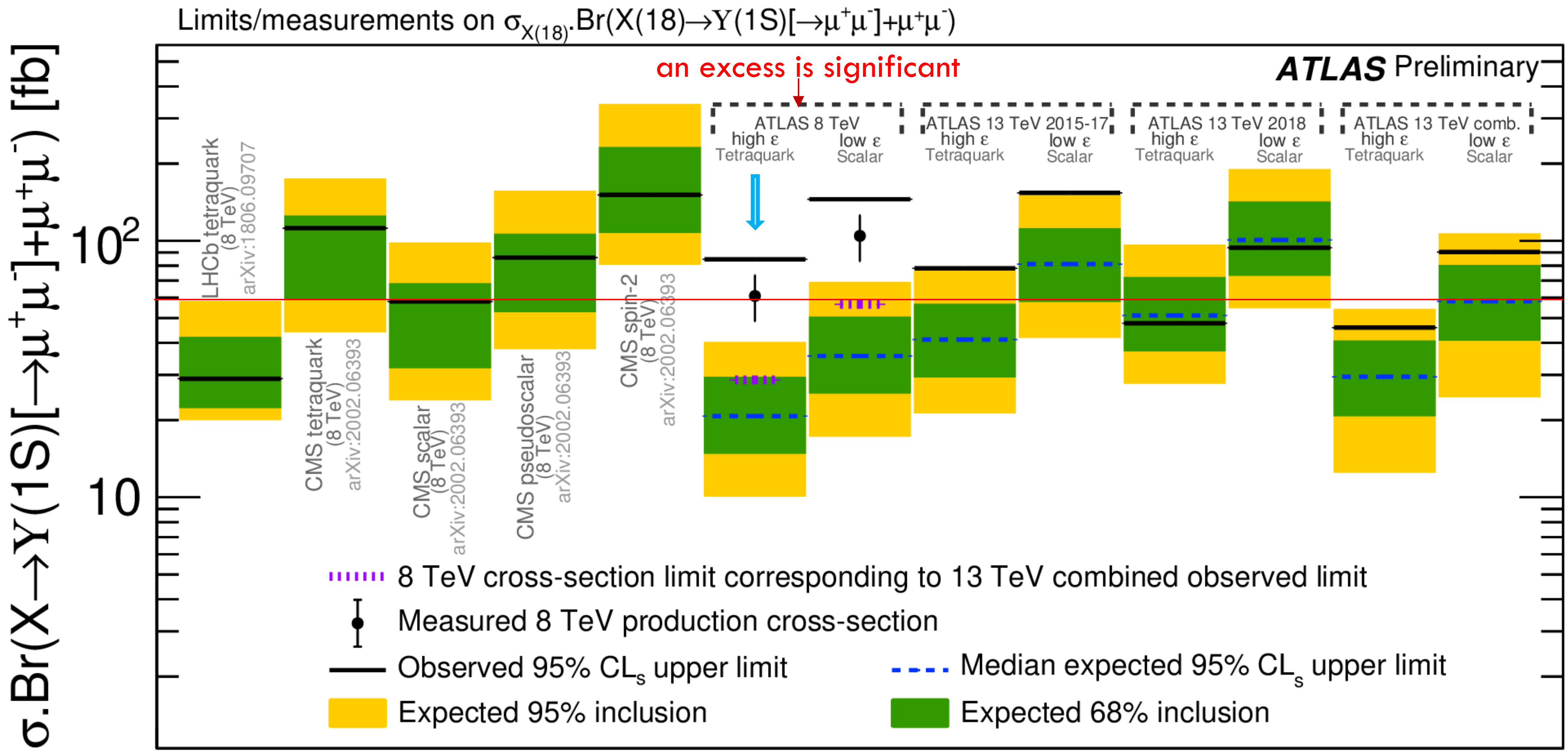
Limits on new particle $X \to \Upsilon(1S)\mu\mu \to 4\mu$

- Expected & observed upper limits on the $\sigma_{\text{production}} \times Br$ for a particle X with an invariant mass of 18 GeV decaying to a $\Upsilon(1S) + \mu^+\mu^- \to \mu^+\mu^-\,\mu^+\mu^-$ final state in the three distinct data-taking periods at ATLAS
- '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.

		Dataset			
		8 TeV	13 TeV 2015–17	13 TeV 2018	13 TeV comb.
Low ε (fb)	Expected	36	81	101	58
	Observed	145	154	94	90
High ε (fb)	Expected	21	41	51	30
	Observed	85	78	48	46

Due to the significant excess in 8 TeV data, the observed limits are necessarily much weaker than the median expected limits. In this case we additionally derive a total production cross-section estimate for the excess, interpreted as the production of a new state decaying to four muons, equal to between 61 $\pm$ 12 fb and 105 $\pm$ 20 fb, dependent on the model considered

The interpretation of data excess at 18 GeV



Summary

- ATLAS searched for exotic hadrons, such as tetraquarks ($qq\bar{q}\bar{q}$), pentaquarks ($qqqq\bar{q}$), with J/$\psi \to \mu^+\mu^-$, or $\psi(2S) \to \mu^+\mu^-$, or $\Upsilon(1S) \to \mu^+\mu^-$ decays associating with other charged hadrons and muons using data collected at 8 and 13 TeV

- ATLAS has confirmed the presence of the all-charm tetraquark candidate X(6900) with a combined significance of 8.9σ — a key step forward in understanding exotic bound states of quarks.

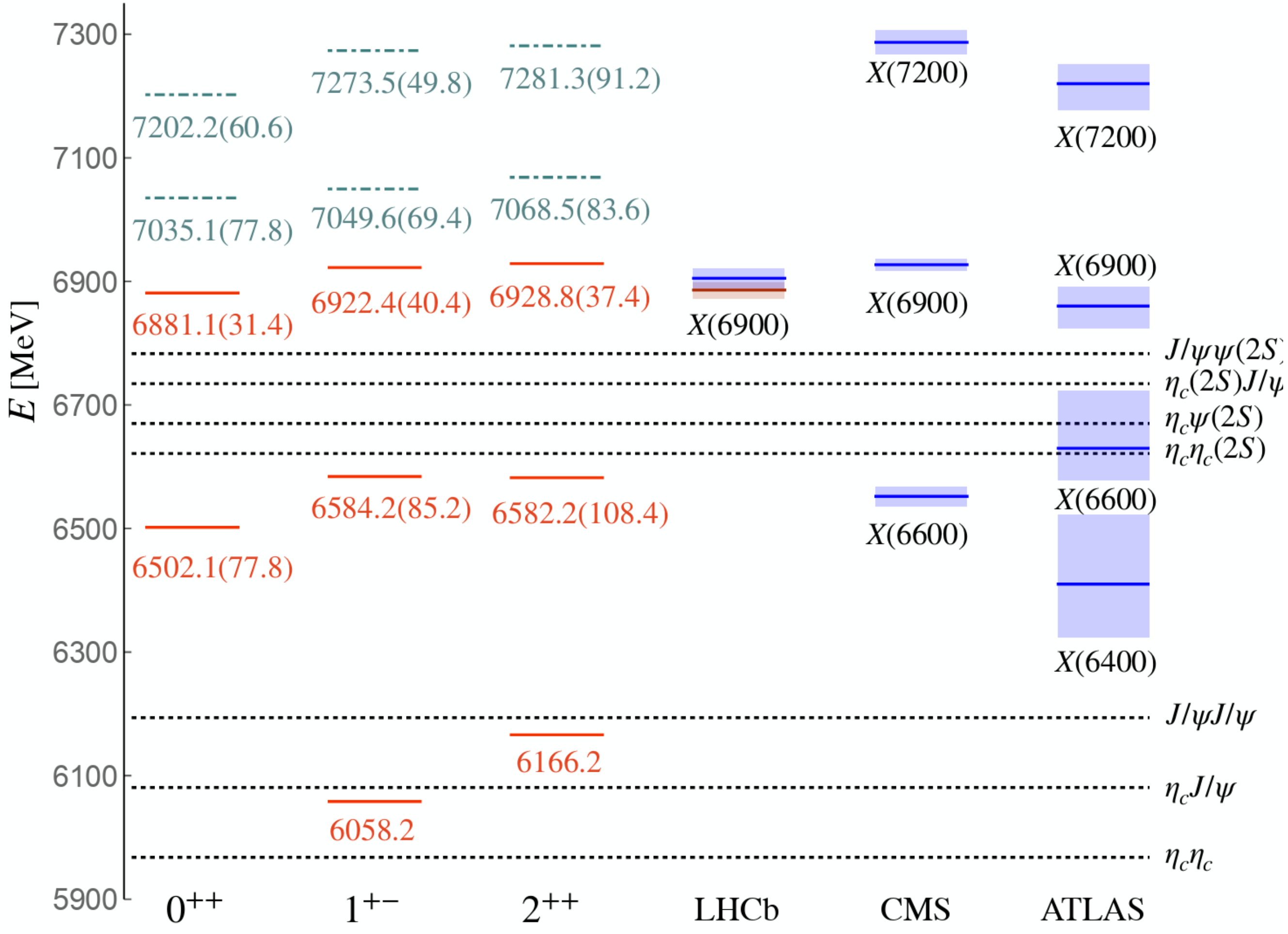
- A search of J/ψ p resonance structures in the $\Lambda_b^0 \to$ J/ψ pK decays is carried out. Data is in favor of models with two or more pentaquarks, but the hypothesis without pentaquarks is not excluded.

- A search for resonances with $\Upsilon(1S)\mu\mu \to 4\mu$ events is performed using 8 and 13 TeV data. We observed an excess consistent with a narrow-width particle is observed at 18 GeV in the four-muon invariant-mass distribution of Υ(1S) + $\mu^+\mu^- \to \mu^+\mu^-\mu^+\mu^-$ events in the 8 TeV dataset with significance vary between 3.6σ and 6.3σ. No significant excess is observed in 13 TeV data. The interpretations of data excess at 18 GeV with different theoretical models are derived by setting the new particle production cross-section times the decay branching fraction.

Backup slides

Theoretical prediction vs. observation

[arxiv :2307.04310]



A new color basis system and confinement mechanism for multi-quark systems are proposed according to the string-type picture of QCD.

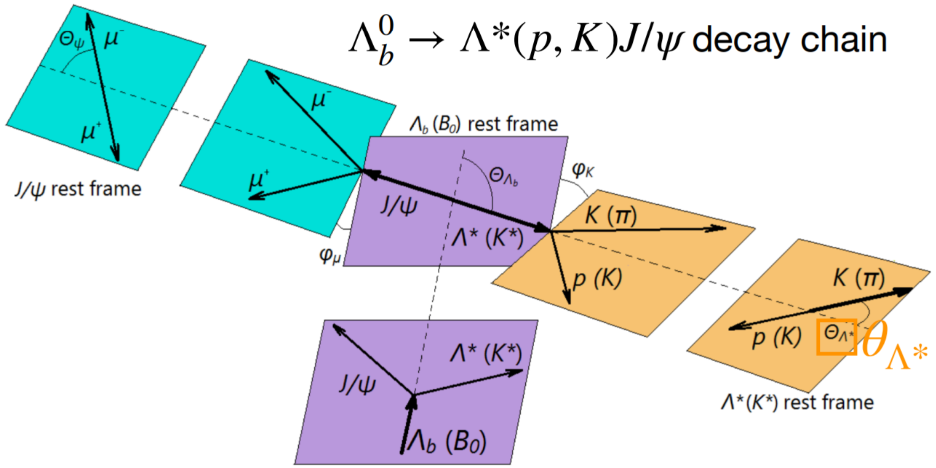
FIG. 2. Comparison of the $cc\bar{c}\bar{c}$ tetraquark spectrum using the novel string-type confinement mechanism with κ = 0.10 GeV (red solid line), the conventional confinement potential (green solid-dot line) [32], and the experimental data reported by LHCb[29], CMS[26] (non-interference results), ATLAS (A and α fitting model) [30], respectively. The theoretical results are presented by the mass E and the decay width Γ as E(Γ) in units of MeV.

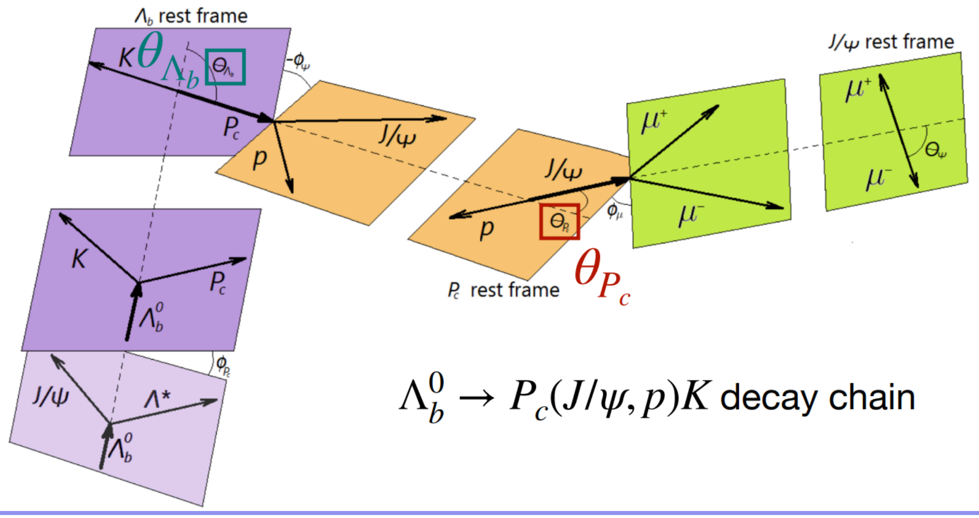
Study of J/ψ p resonances in the Λ_b^0 decays

Angular requirements on $\cos\theta_{P_c,\Lambda_b,\Lambda^*}$

- B-hadron ($H_b = \Lambda_b$, B^0 or B_s) selection:
  - $\cos\theta_{P_c} < 0.5$: θ_{P_c} is the angle between J/ψ momentum in the P_c rest frame and P_c momentum in the Λ_b rest frame
  - $\cos\theta_{\Lambda_b} < 0.8$: θ_{Λ_b} is the angle between Λ_b momentum and P_c momentum in laboratory frame
  - $|\cos\theta_{\Lambda^*}| < 0.85$: θ_{Λ^*} is the angle between kaon momentum in the $\Lambda^* \to pK$ rest frame and Λ^* momentum in the Λ_b rest frame

$\Lambda_b^0 \to \Lambda^*(p,K)J/\psi$ decay chain





$\Lambda_b^0 \to P_c(J/\psi,p)K$ decay chain

Study of J/ψ p resonances in the Λ_b^0 decays

Iterative fit procedure

- The fit procedure is iterative with four steps in each iteration. Parameters obtained in previous step are used in the current step.

  - Step 1: fit $m(J/\psi hh)$, $m(J/\psi h)$, $m(hh)$ spectra to obtain parameters of B_0 and B_s backgrounds.

  - Step 2: fit $m(J/\psi, h_1 = p, h_2 = K)$ spectrum to retrieve total number of Λ_b decays, number of combined B^0 and B_s^0 decays.

  - Step 3: fit $m(J/\psi h)$, $m(hh)$ spectra in SR to get decay constants of Λ_b decays.

  - Step 4: fit $m(J/\psi, h_1 = p)$ spectrum in SR to obtain pentaquark masses, widths, amplitudes and relative phase between pentaquark amplitudes ($\Delta\phi$)

Di-muon mass distribution

Dimuon invariant mass distributions of the second muon pair in $\Upsilon(1S) + \mu^+\mu^-$ events, indicating the presence of di- $\Upsilon(1S)$ production