The potential tetraquark in the 4-muon final state from ATLAS

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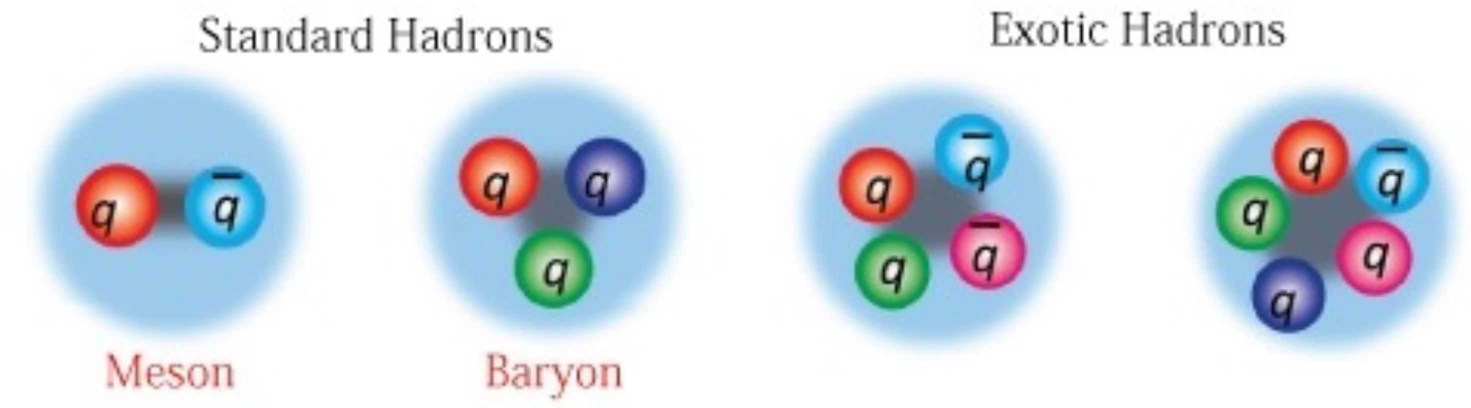
- Event reconstruction and selection
- Background estimation
- Fit models and systematics

Introduction

- Gell-Mann and Zweig proposed the quark model sixty years ago
- Quantum chromodynamics (QCD) is the fundamental theory describing the interaction of quarks and gluons

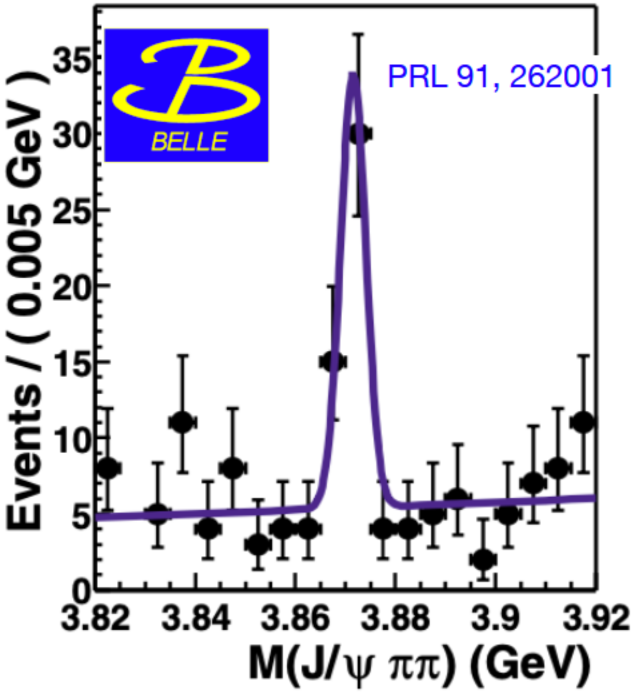


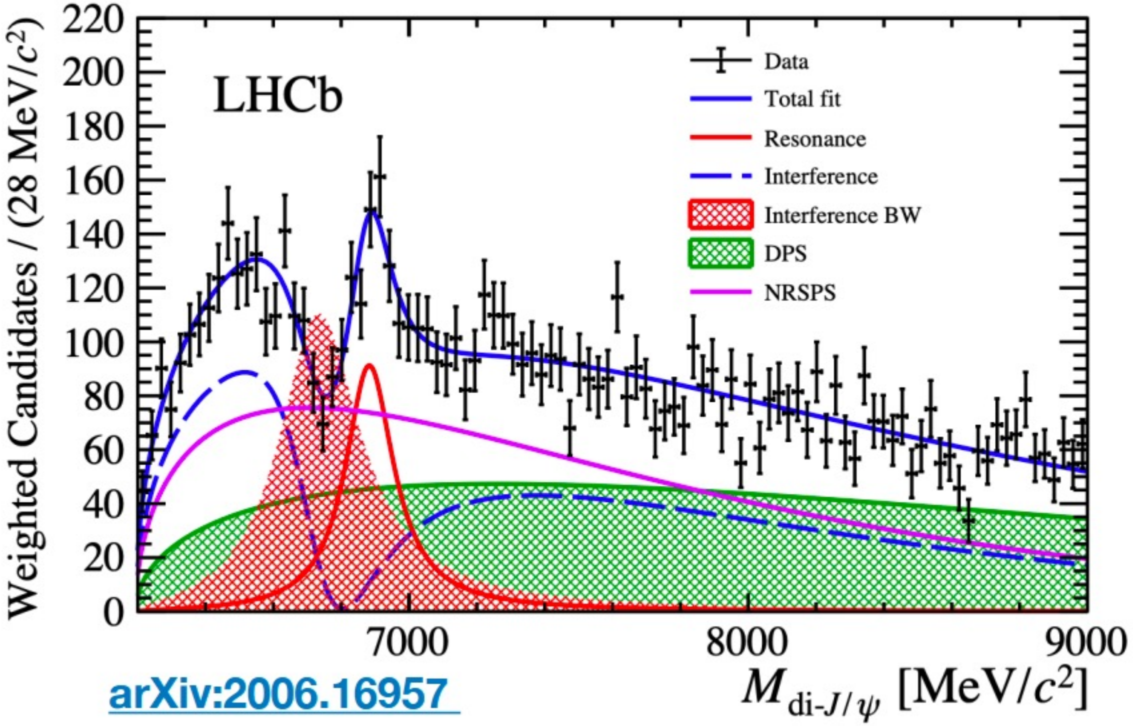
"white" collections

- Beyond the standard hadrons, the exotic hadrons composed of four quarks (tetraquark) can also satisfy the QCD colour confinement requirement
- Four-charm states were first mention by Yoichi Iwasaki[1] in 1975 and first calculation by K.-T. Chao[2] in 1981

1. *DOI: 10.1143/PTP.54.492*
2. *DOI: 10.1007/BF01431564*

Introduction

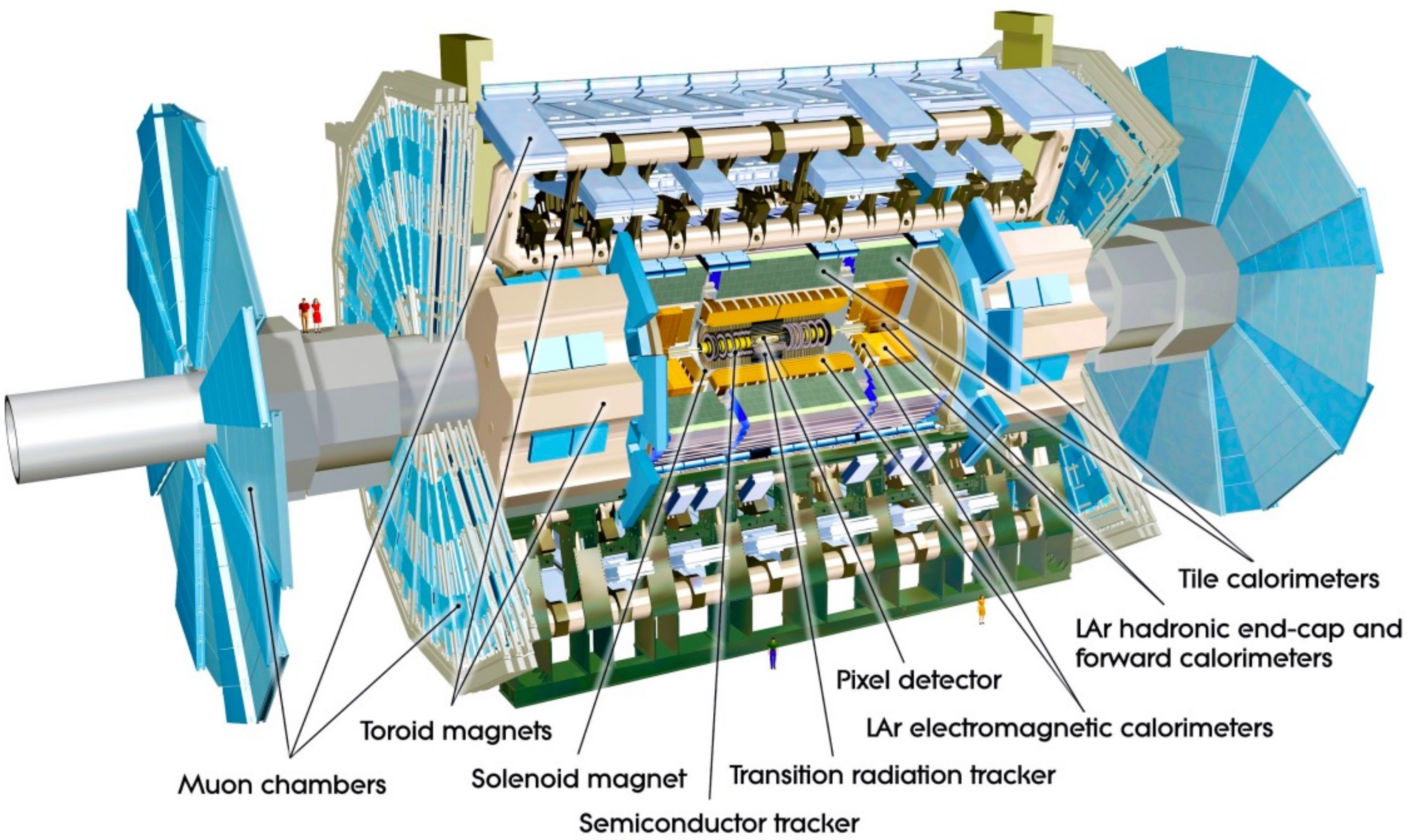




arXiv:2006.16957

- The first narrow Charmonium-like State (X3872) was discovered in 2003 by Belle experiment in the decay products of B mesons. This state decays into $J/\psi + \pi^+\pi^-$
- LHCb claimed an evidence for a narrow resonance at 6.9 GeV in June 2020, which could be the full-charm tetraquark candidate

Introduction



ATLAS detector

- It is the largest volume detector ever constructed for a particle collider
- It consists of an inner tracking detector, calorimeters and a muon spectrometer, which provides precision combined muon identification and measurement at $|\eta| < 2.5$
- Good muon identification ensures clean signal in the 4-muon final states

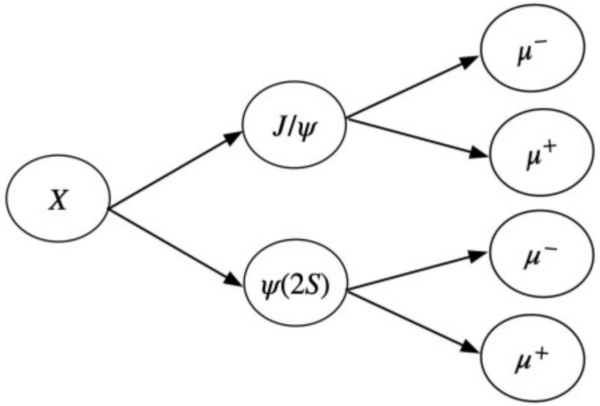
25 m diameter, 44 m long, 7000 tons weight ~ 

https://atlas.cern

Event reconstruction and selection

ATLAS EXPERIMENT

Data: LHC full Run-2 between 2015-2018, corresponding to 140 fb^{-1} at $\sqrt{S} = 13$ TeV



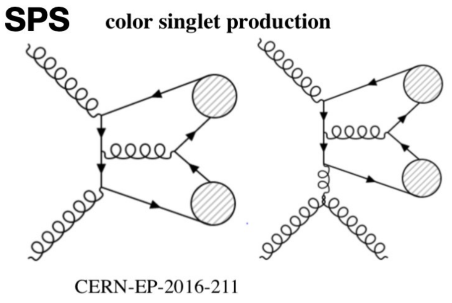
- Signal: tetraquark(TQ) → di- J/ψ or $J/\psi + \psi(2S) \rightarrow 4\mu$
- Four muons with two opposite-charge pairs are fitted to a common vertex by using the inner detector tracks
- Re-vertex each pair with J/ψ or $\psi(2S)$ mass constraint

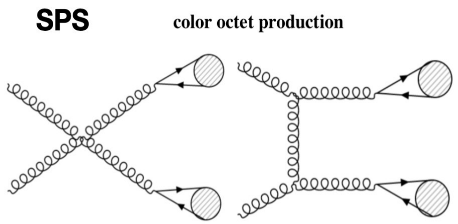
Signal region	SPS/DPS control region	non-prompt region
selection Di-muon or tri-muon triggers, Opposite charged muons from the same J/ψ or $\psi(2S)$ vertex, Loose muon ID, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons $m_{J/\psi} \in \{2.94, 3.25\}$ GeV, or $m_{\psi(2S)} \in \{3.56, 3.80\}$ GeV, Loose vertex cuts $\chi^2_{4\mu}/N < 40$ and $\chi^2_{\text{di-}\mu}/N < 100$,		
Vertex $\chi^2_{4\mu}/N < 3$, $L_{xy}^{4\mu} < 0.2$ mm, $\lvert L_{xy}^{\text{di-}\mu}\rvert < 0.3$ mm,		Vertex $\chi^2_{4\mu}/N > 6$, $\lvert L_{xy}^{\text{di-}\mu}\rvert > 0.4$ mm
$m_{4\mu} < 7.5$ GeV, $\Delta R < 0.25$ between charmonia	7.5 GeV$< m_{4\mu} < 12.0$ GeV (SPS) 14.0 GeV$< m_{4\mu} < 25.0$ GeV (DPS)	

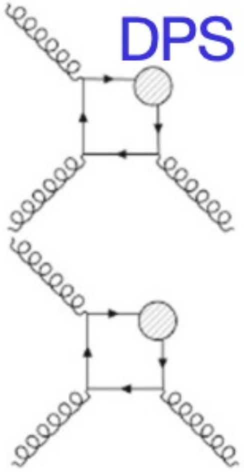
Background

Backgrounds components:

- ➢ The following can be estimated from data + MC：
- ● SPS (Single parton scattering) containing two prompt ψ's.
  - • SPS CR: 8.0 GeV < $m_{4\mu}^{con}$< 12.0 GeV
- ● DPS (Double parton scattering) containing two prompt ψ's.
  - • DPS CR: 14.0 GeV < $m_{4\mu}^{con}$< 24.5 GeV
- ● Non-prompt ψ's from $b\bar{b} \rightarrow J/\psi + \psi + X$
  - • non-prompt CR: $\chi^2_{4\mu}/N_{4\mu}$> 6 or $|L_{xy}^{di-\mu}|$> 0.4 mm





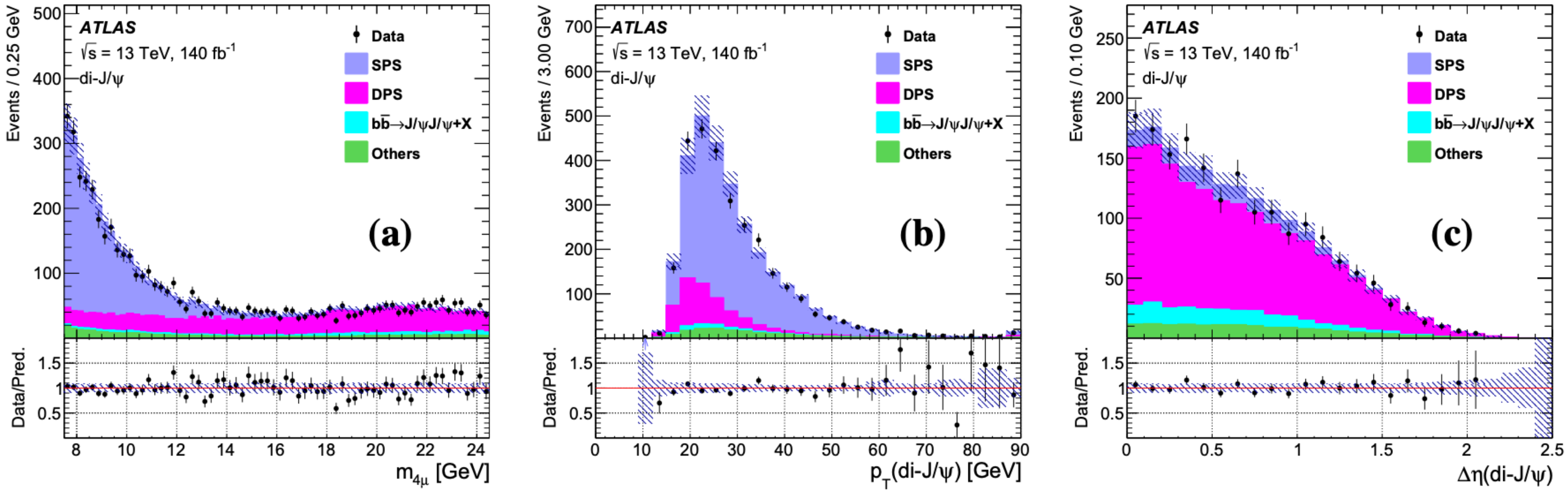


- ➢ The following can be estimated by data driven from fake region and sideband
- ● Single ψ background containing only one real ψ candidate
- ● Non-peaking background containing no real ψ candidate

} Others

Fake region: one J/ψ or ψ(2S) candidate contains a track that does not pass our muon identification WP
Side band: 2.60 GeV < $m(J/\psi)$ < 2.88 GeV or 3.30 GeV < $m(J/\psi)$ < 3.50 GeV
3.35 GeV < $m(\psi(2S))$ < 3.48 GeV or 3.88 GeV < $m(\psi(2S))$ < 4.10 GeV

Background estimation



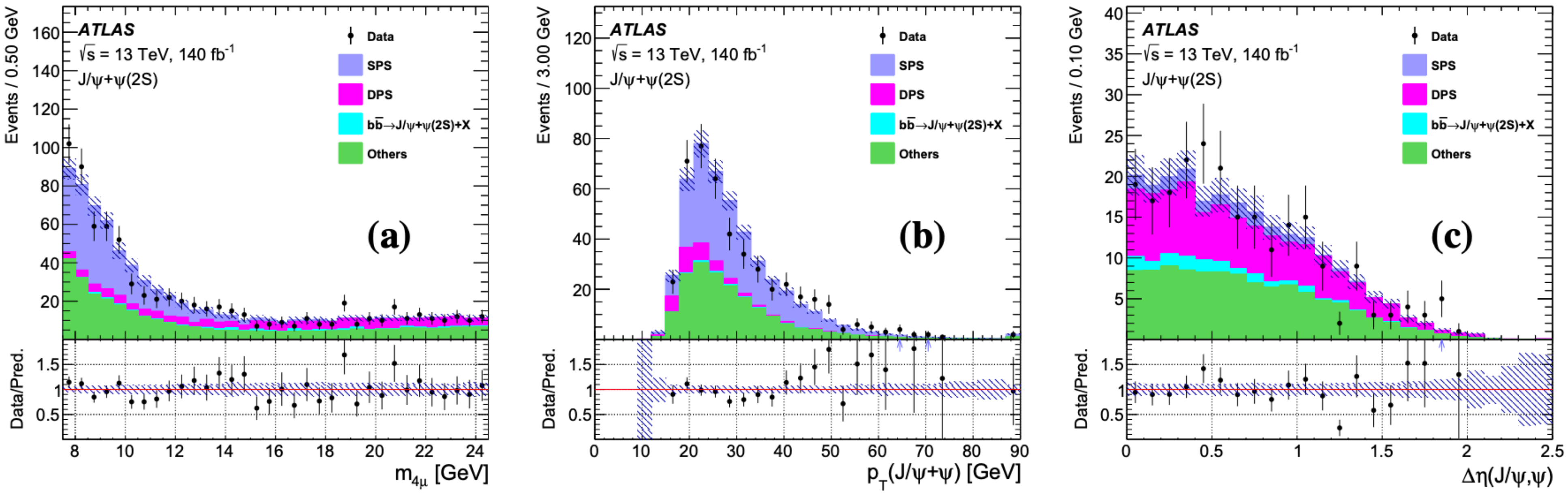
In the di-J/ψ channel:

(a) The 4μ mass spectrum within [7.5, 24.5] GeV and without the ΔR requirement

(b) pT of the di-charmonium in the SPS control region with 7.5 GeV < $m_{4\mu}$ < 12.0 GeV

(c) $\Delta\eta$ between the charmonia in the DPS control region with 14.0 GeV < $m_{4\mu}$ < 24.5 GeV

Background estimation



In the J/ψ+ψ(2S) channel:

(a) The 4μ mass spectrum within [7.5, 24.5] GeV and without the ΔR requirement

(b) pT of the di-charmonium in the SPS control region with 7.5 GeV < $m_{4\mu}$ < 12.0 GeV

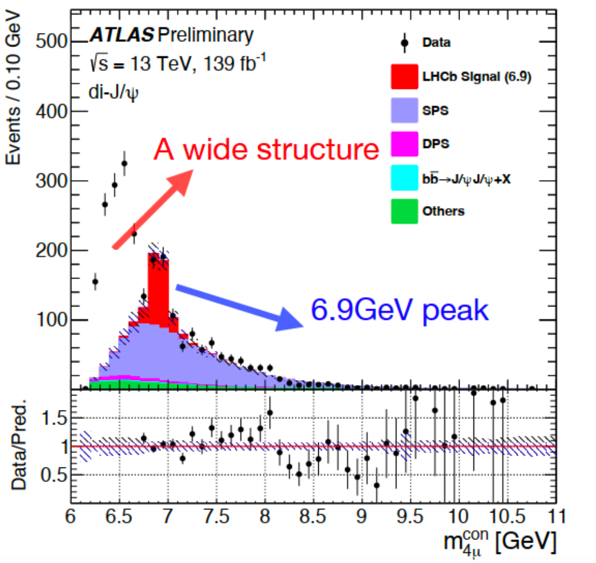
(c) $\Delta\eta$ between the charmonia in the DPS control region with 14.0 GeV < $m_{4\mu}$ < 24.5 GeV

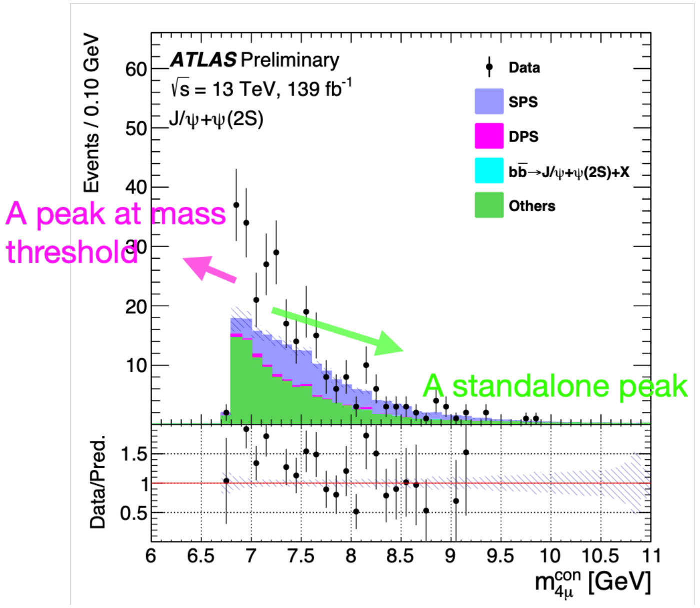
Fit model

- Unbinned maximum likelihood fits are made to extract the signal information

In di-J/ψ channel, the signal PDF consists of several interfering S-wave Breit-Wigner peaks convoluted with a mass resolution function.

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





In J/ψ+ψ(2S) channel, two models are considered due to the low statistic:
Model A: the same peaks with interference observed in the di- J/ψ channel plus a standalone peak
Model B: only one single peak

$$f_s(x) = \left(\left| \sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i} \right|^2 + \left| \frac{z_3}{x^2 - m_3^2 + i m_3 \Gamma_3} \right|^2 \right) \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(x, \vec{\alpha})$$

Fit results in di- J/ψ channel

Phys. Rev. Lett. 131 (2023) 151902

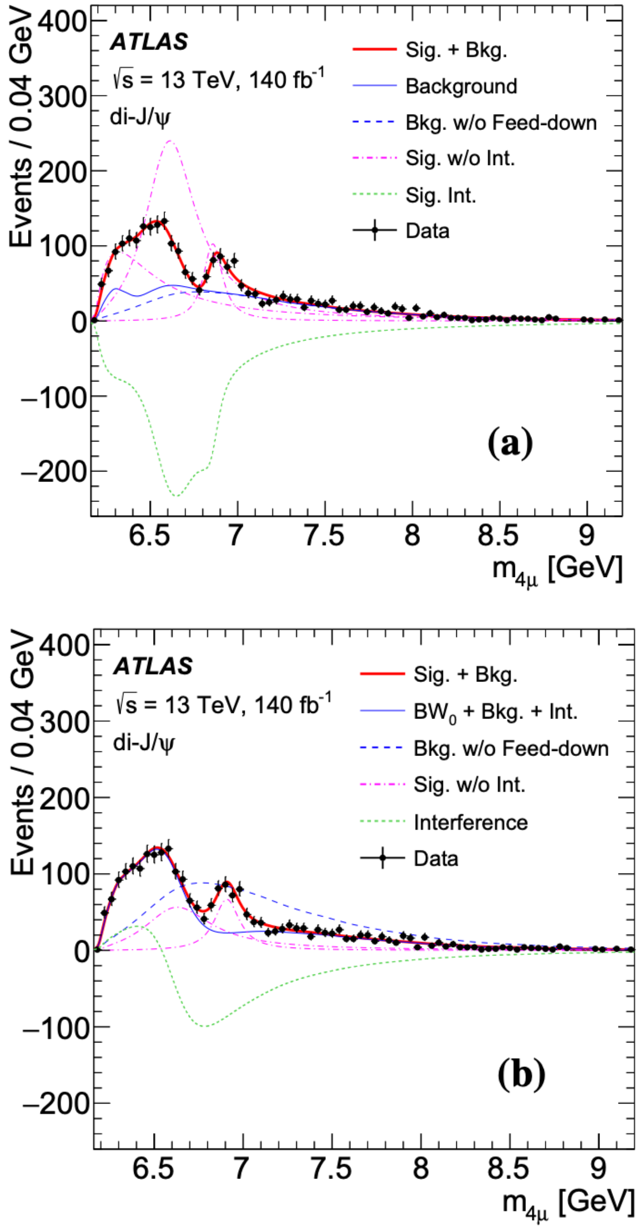
ATLAS EXPERIMENT

- The 3rd peak mass is consistent with the LHCb result X(6900), with the significance of 10.9σ

- The three interfering peaks fit model is favorite by comparing the fit quality (χ^2/N and toy MC)

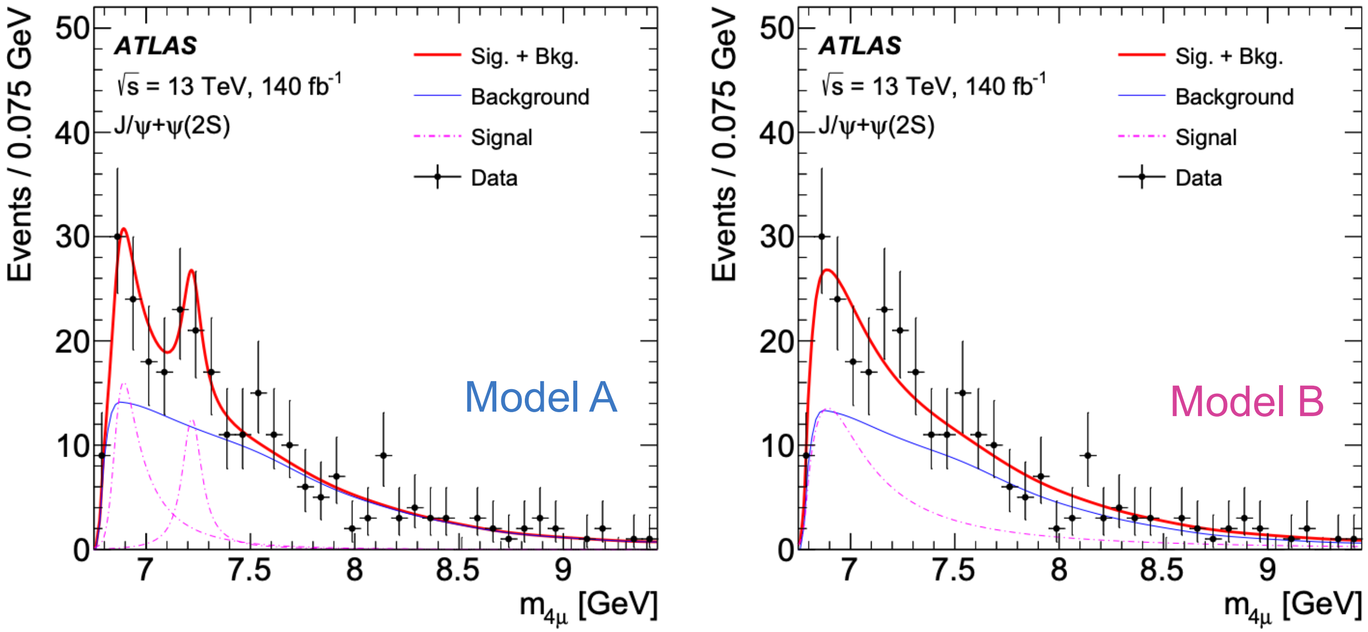
- The fit model is just a possible interpretation of the mass structure. the broad structure at the lower mass could from other physical effects.

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

- Combined significance reach 4.7σ (4.3σ) for Model A (B)
- In model A fit, the first peak could be related to X(6900) in the di-J/ψ channel.
- The significance of the 2nd peak is found to be 3.0σ



The significance of the signal is estimated by fixing its shape parameters to their best fit values, and using the asymptotic formula

$$Z = \sqrt{2\ln\frac{L(\hat{s},\hat{\theta})}{L(0,\hat{\hat{\theta}})}},$$

$J/\psi+\psi(2S)$	model A	model B
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	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	±21% ± 14%	±20% ± 12%

Systematics

Systematic uncertainties on the masses and natural widths (in MeV) of the interfering peaks from different sources

Systematic Uncertainties (MeV)	di-J/ψ						J/ψ+$\psi(2S)$	
	m_0	Γ_0	m_1	Γ_1	m_2	Γ_2	m_3	Γ_3
SPS model parameter	±14	±64	±5	±27	±7	±7	<1	
SPS di-charmonium p_T	±13	±50	±3	±19	±7	±8	<1	
Background MC statistics	±14	±46	<1	±20	±7	±8	±1	<1
Mass resolution	−5	$+82/-60$	$+3/-8$	$+12/-17$	±4	−3	−1	$+2/-4$
Fit bias	+8	+63	$+26/-4$	$+103/-22$	−13	+10	$+9/-10$	$+50/-16$
Non-closure	<1						±4	±6
Transfer factor	—						±5	±23
Presence of 4th resonance	+15	−24	+15	−27	+12	+15	—	
Feed-down	$+39/-22$	$+25/-67$	$+10/-3$	−5	$+4/-1$	$+6/-2$	—	
Interference of 4th resonance	—						−32	−11
P and D-wave BW	$+70/-3$	−166	+69	$+8/-3$	+9	+19	<1	±1

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

Searches in X→μμ+Υ(1S)→4μ

https://cds.cern.ch/record/2869238/files/ATLAS-CONF-2023-041.pdf

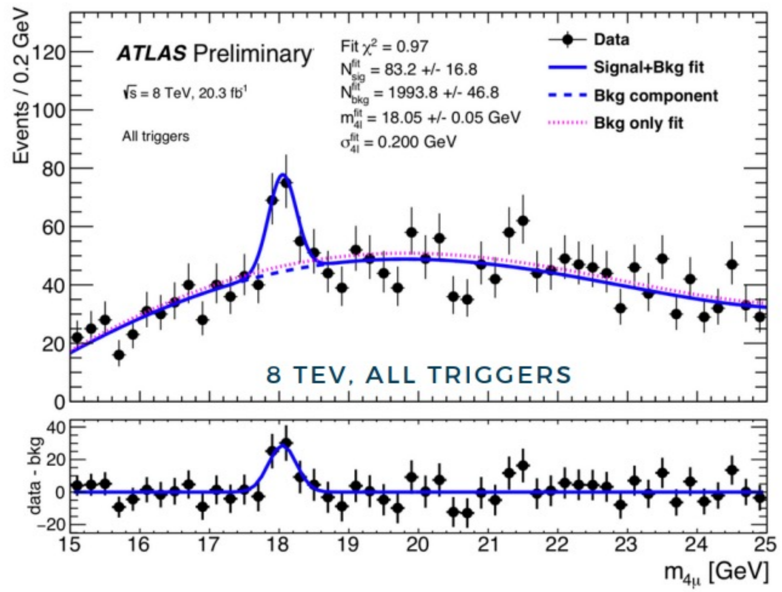
Datasets and selections：

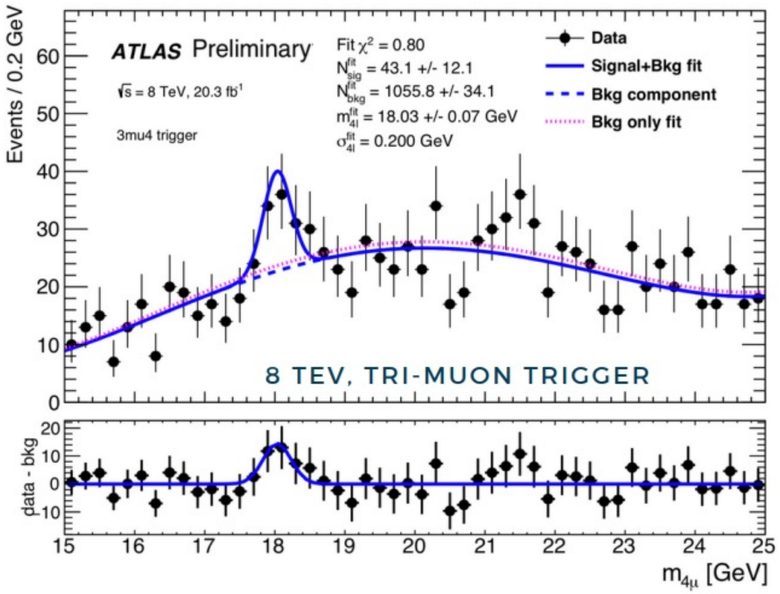
20.3 fb of 8 TeV data； 50.1 + 58.5 fb of 13 TeV data (2015-17 + 2018)

Two and three-muon trigger signatures.

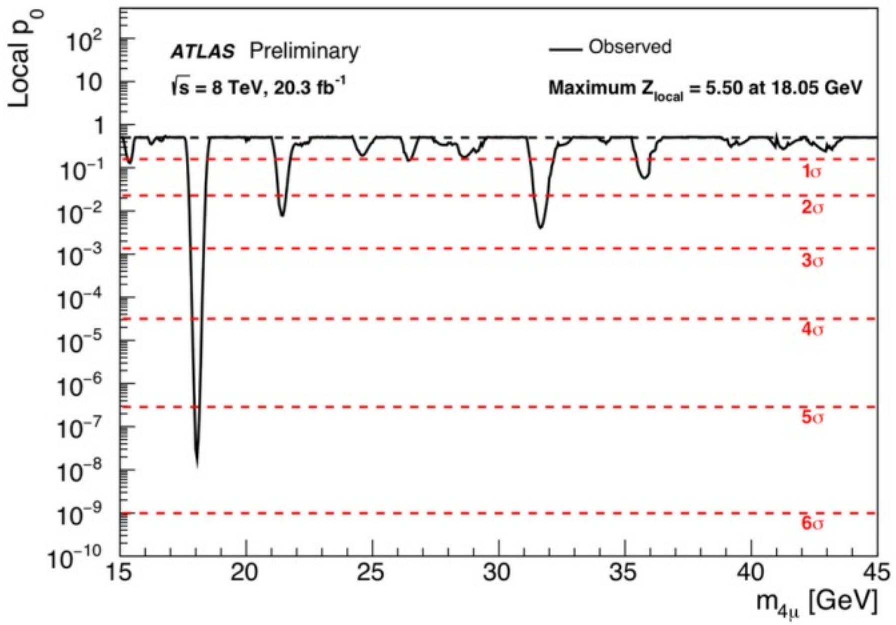
Candidate object	Requirements
Muons	$p_{\mathrm{T}}(\mu) > 3$ GeV and $\lvert\eta\rvert < 2.5$, $\lvert z_0 \sin\theta\rvert < 1$ mm and $\lvert d_0/\sigma_{d_0}\rvert < 6$
Muon quadruplet	≥ 3 muons passing LowPt selection criteria, $\sum q_\mu = 0$, four-muon vertex fit $\chi^2/N_{\mathrm{d.o.f}} \leq 10$, 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 $p_{\mathrm{T}}(\mu_{1,2}) > 4$ 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

Searches in X→μμ+Υ(1S)→4μ

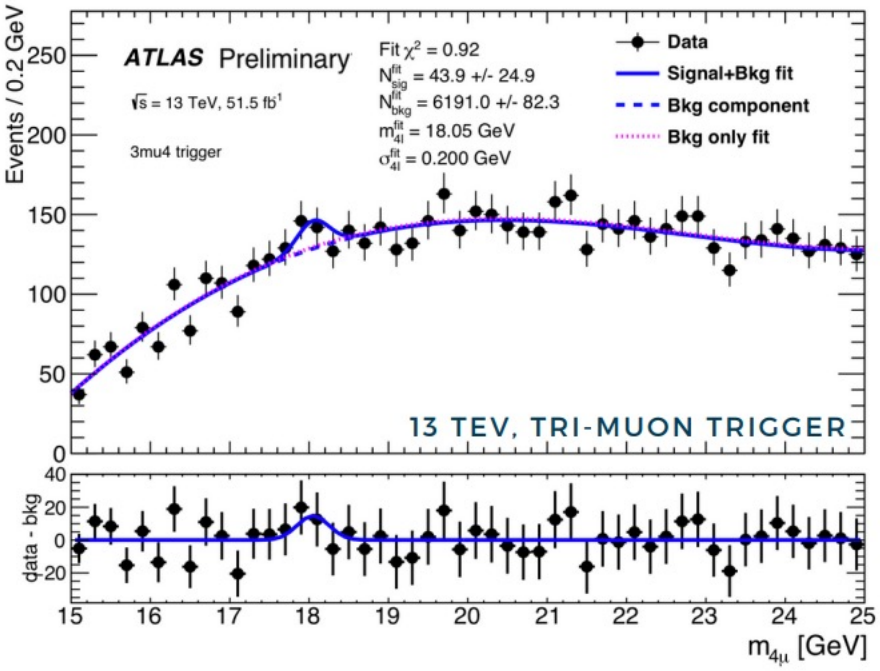


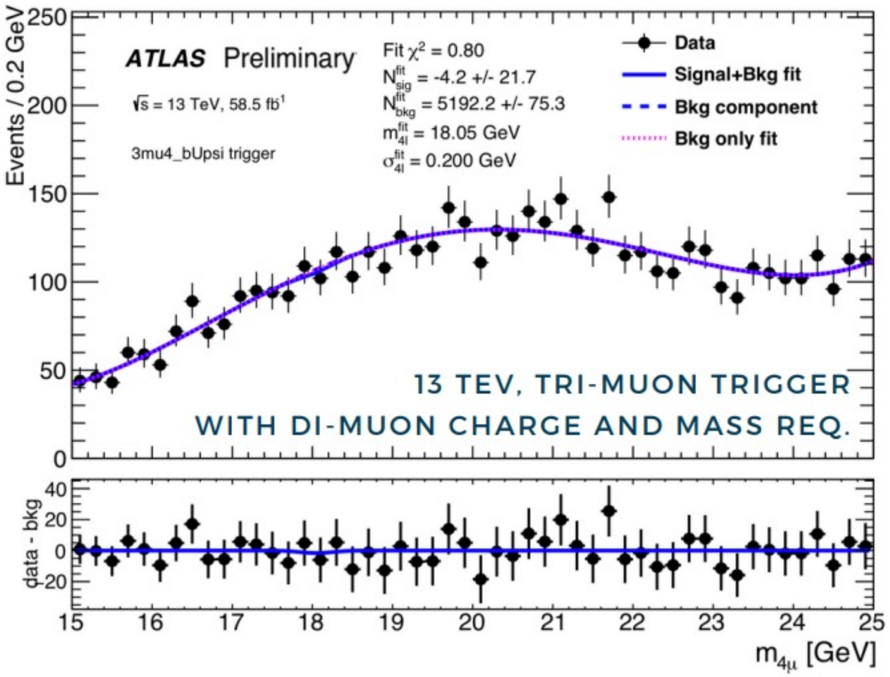


Structure observed in both di-muon and tri-muon triggered 8 TeV data at 18 GeV



Searches in X→μμ+Υ(1S)→4μ





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 (2015-2017)

- 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).

Summary

Searches in X→J/ψ+J/ψ/[ψ(2S)]→4μ *Phys. Rev. Lett. 131 (2023) 151902*

- A broad structure at lower mass region and a resonance around 6.9 GeV with local significance of 10.9σ are observed in the di-J/ψ channel.
- A 4.7σ significant excess is observed in the J/ψ+ψ(2S) channel with model that an enhancement at about 6.9 GeV plus a standalone peak, significance of the standalone peak is found to be 3.0σ.
- More data is need to understand the nature of resonances and threshold structures. Looking forward to the Run 3 data!

Searches in X→μμ+Υ(1S)→4μ

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

https://cds.cern.ch/record/2869238/files/ATLAS-CONF-2023-041.pdf

☺

Thank you!