Tetraquark search at ATLAS

Xin Chen

Tsinghua University

中国物理学会高能物理分会第十二届全国会员代表大会暨学术,

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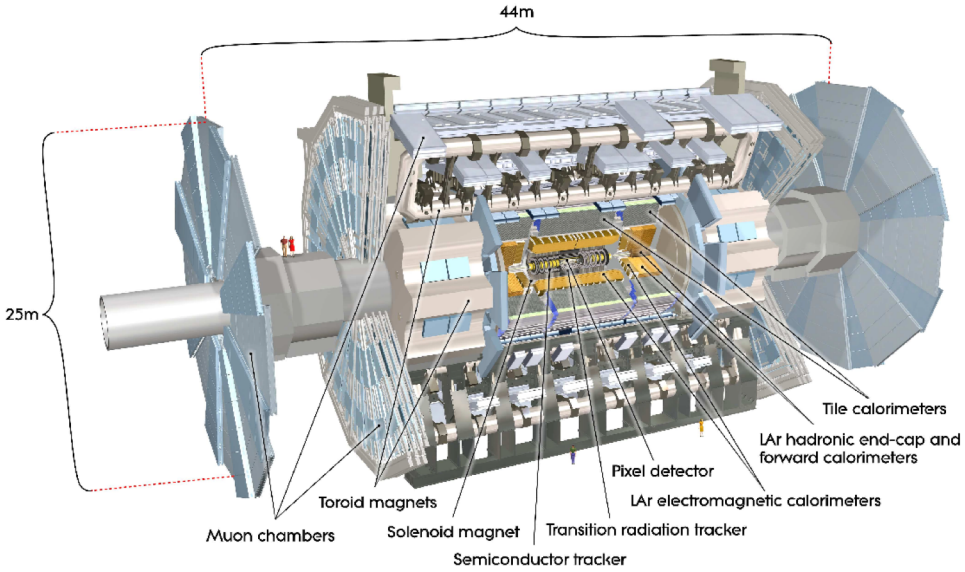
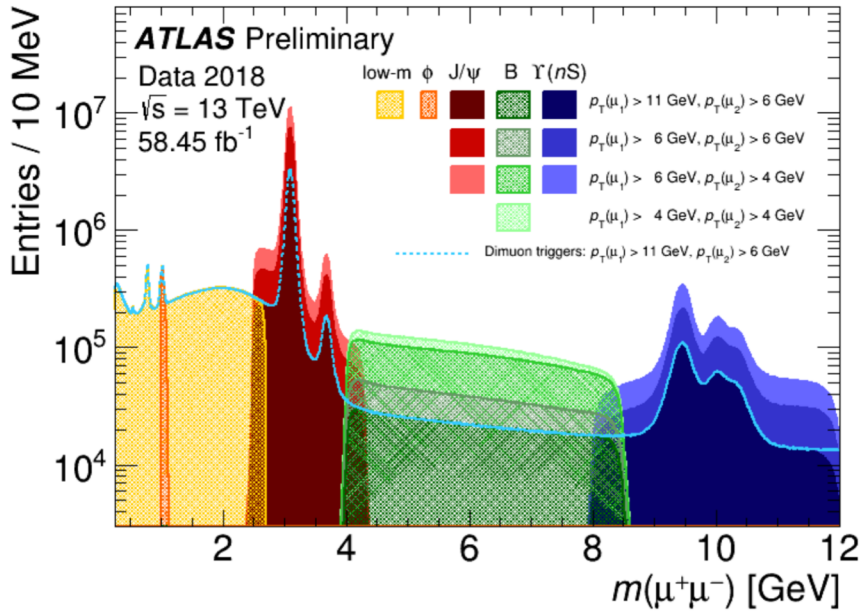
ATLAS B physics

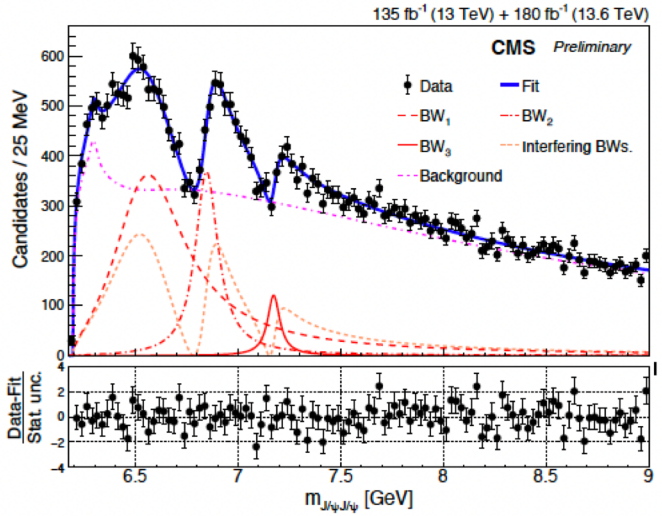
- ATLAS has collected a large set of data:
  - Run 2 (2015-2018): 140 fb^{-1} at 13 TeV
  - Run 3 (2022-2026): ~320 fb^{-1} at 13.6 TeV
- B-physics analyses focus mostly on final states with muons
  - Dedicated B-physics triggers
  - Excellent track and muon identification with the goodness of the inner detector and muon spectrometer
- In this talk:
  - $J/\psi + \psi$ resonance search combining 4μ and $4\mu+2\pi$ final states with ATLAS Run 2 data (Phys. Rev. D 113 (2026) 112015)

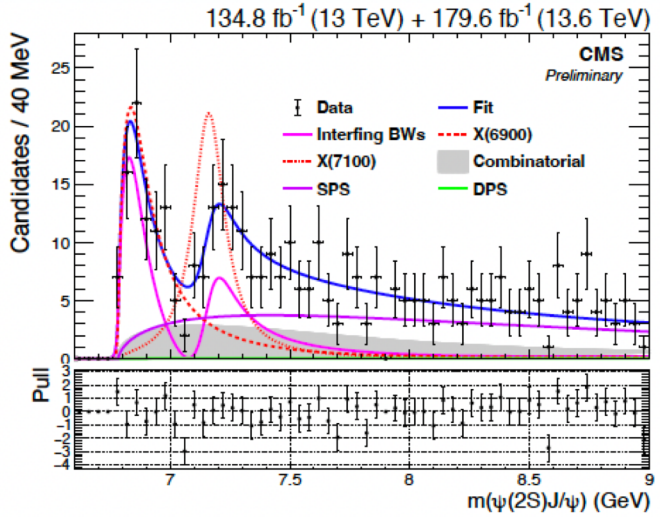


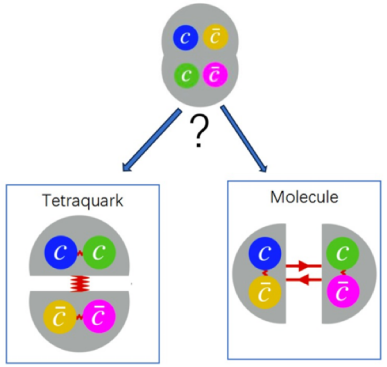


All-charm tetraquark search at LHC

- In 2022, X(6900), a potential all-charm tetraquark ($cc\bar{c}\bar{c}$), was observed in the channel J/ψ+J/$\psi\rightarrow 4\mu$ by LHCb, confirmed by ATLAS [Phys. Rev. Lett.131.151902] and CMS [Phys. Rev. Lett.132.111901]
- In 2025, with Run 2+partial Run 3 data, CMS observed X(7100) in the di-J/ψ channel with more than 5σ. Later, CMS also confirmed excess in the J/ψ+ψ(2S)$\rightarrow 4\mu$ channel, with X(7100) significance estimated to be 4.0σ

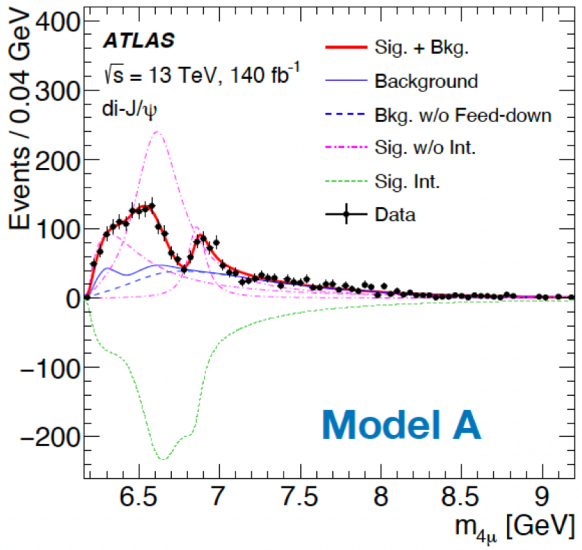


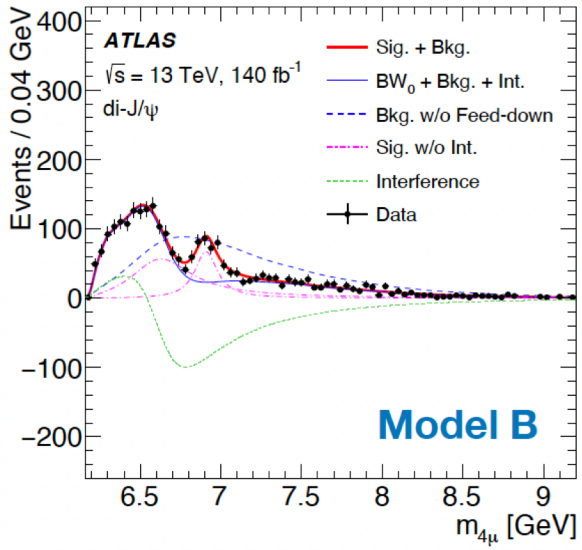




- To understand the structures in J/ψ+ψ(2S) mass spectrum and study the relative partial decay widths of di-J/ψ and J/ψ+ψ(2S) channels, we include the decay J/ψ+ψ(2S)$\rightarrow 4\mu$+2π

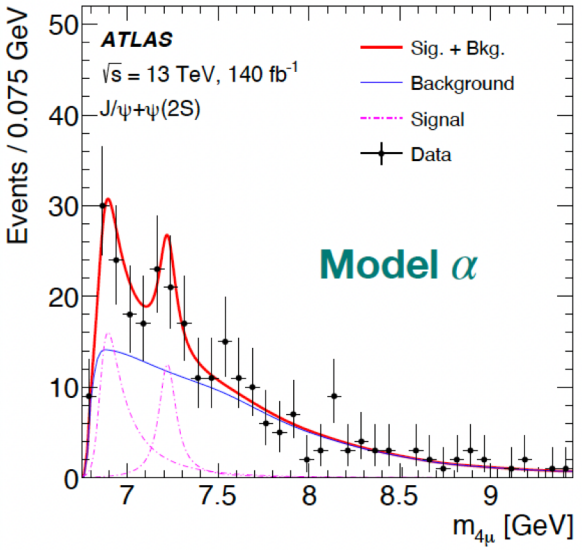
Previous ATLAS study in 4μ channel

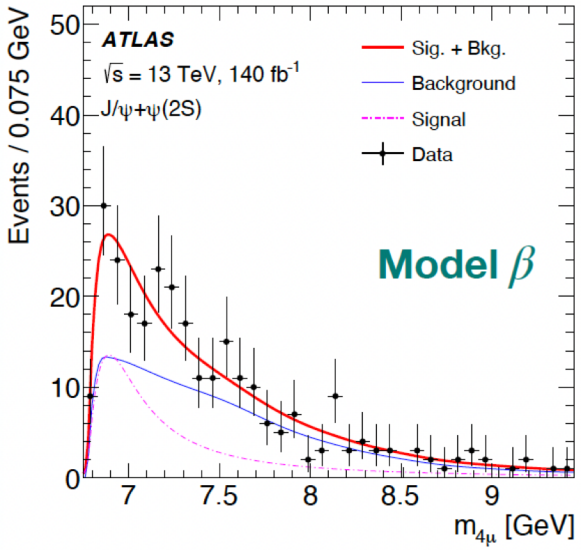




di-J/ψ

- Two signal models are tested:
  - Model A: three interfering signal peaks
  - Model B: two signal peaks
- The peak around 6.9 GeV is consistent with the LHCb observed X(6900), with significance far above 5σ





J/ψ+ψ(2S)

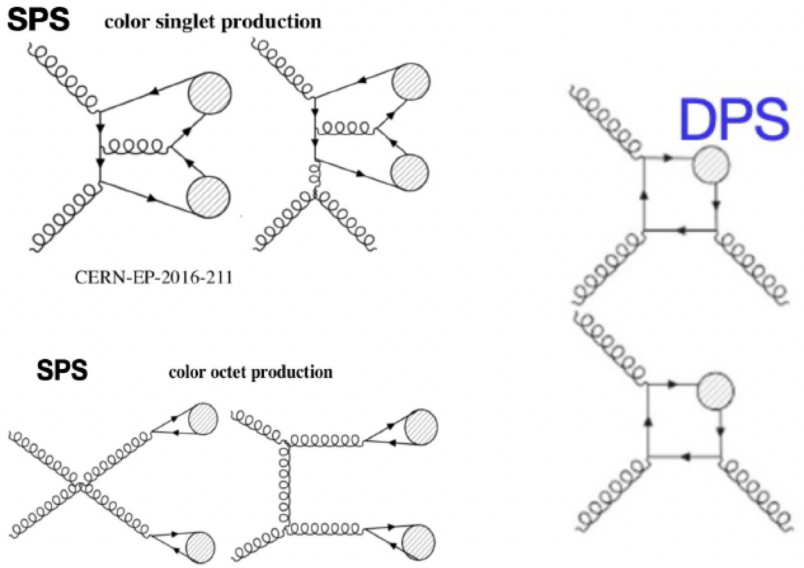
- Two signal models are tested:
  - Model α: the same peaks observed in the di-J/ψ channel also decaying into J/ψ+ψ(2S) plus a standalone peak
  - Model β: only one signal peak
- The signal significance is 4.7σ (4.3σ) for model α (β)

Event selection and analysis regions

- Prompt backgrounds

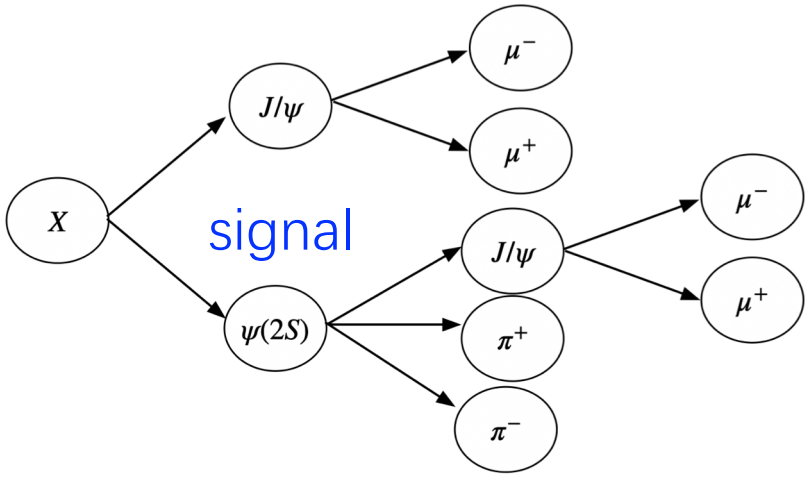
  Single parton scattering (SPS): a pair of mesons can be produced in a single interaction

  Double parton scattering (DPS): a pair of mesons can be produced in two separate interactions of gluons or quarks



- Non-prompt： $b\bar{b} \rightarrow J/\psi + \psi(2S) + X$

- Feed-up background in the 4μ+2π channel: di-J/ψ signal + 2 random pions



Event selection and analysis regions

- Di-muon and tri-muon triggers with ψ mass requirement
- Baseline selection：
  - Four muons with p_T>4, 4, 3, 3 GeV and $|\eta|$<2.5; two opposite-sign (OS) charged tracks with p_T>0.5 GeV
  - J/ψ and ψ(2S) mass requirement
  - Vertex fit quality (χ^2/N) and L_{xy} requirements

<table>
<tr><td>Signal region (SR)</td><td rowspan="4">Vertex cuts:
$|L_{xy}^{charmoinum}| < 0.3$ mm
$L_{xy}^{4\mu(+2\pi)} < 0.2$ mm
$\chi^2_{4\mu(+2\pi)}/N < 3$</td><td rowspan="2">$m_{4\mu(+2\pi)}$ <11GeV
BDT score > -0.3 ($4\mu + 2\pi$)</td><td>$\Delta R < 0.25$</td></tr>
<tr><td>Control region (CR)</td><td>$\Delta R > 0.25$</td></tr>
<tr><td>SPS region</td><td colspan="2">8 GeV $< m_{4\mu(+2\pi)} <$ 12 GeV</td></tr>
<tr><td>DPS region</td><td colspan="2">14 GeV $< m_{4\mu(+2\pi)} <$ 25 GeV</td></tr>
<tr><td>Non-prompt region</td><td colspan="3">Reverse vertex cuts</td></tr>
<tr><td>Fake region</td><td colspan="3">One J/ψ or ψ(2S) candidate contains a track that fails the muon identification</td></tr>
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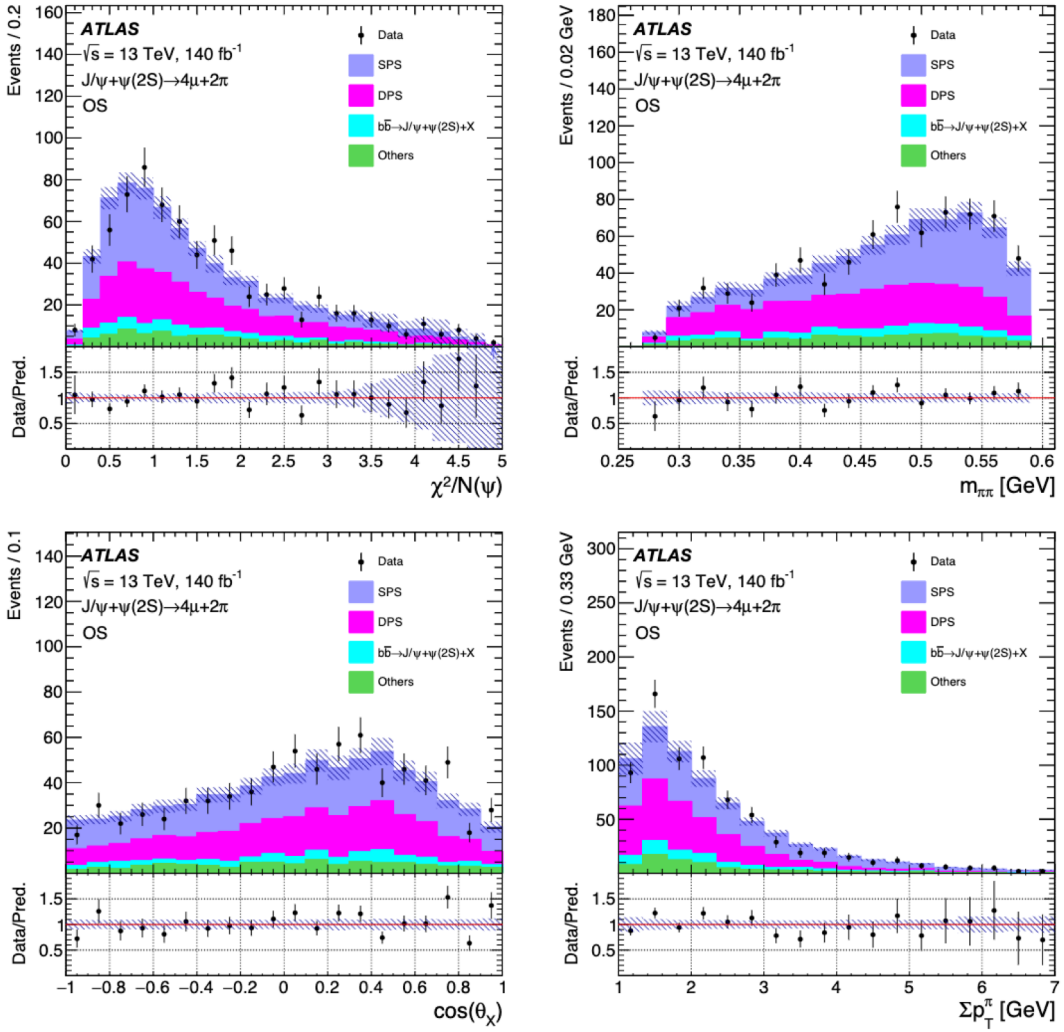
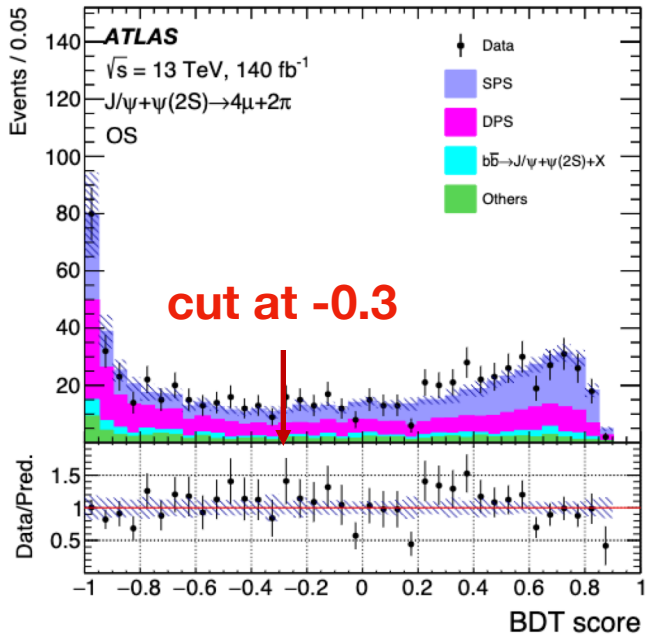
Feed-up background

- A BDT is trained to separate signal and feed-up background. Input variables



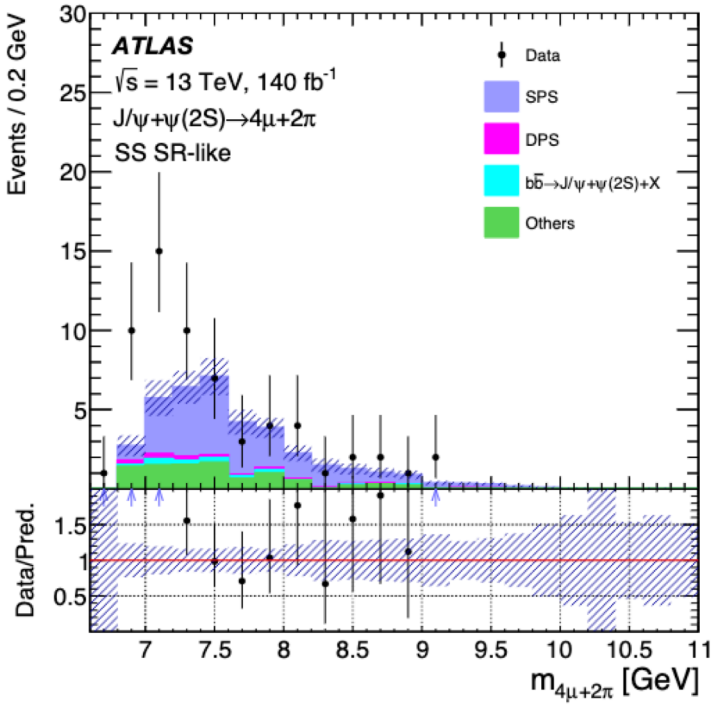
- $\cos\theta_X$: cosine of the angle between J/ψ in $\psi(2S)$ rest frame and $\psi(2S)$ in lab frame
- χ^2/N of $\psi(2S)$ vertex
- Invariant mass of two pions
- Scalar sum of transverse momentum of the 2 pions



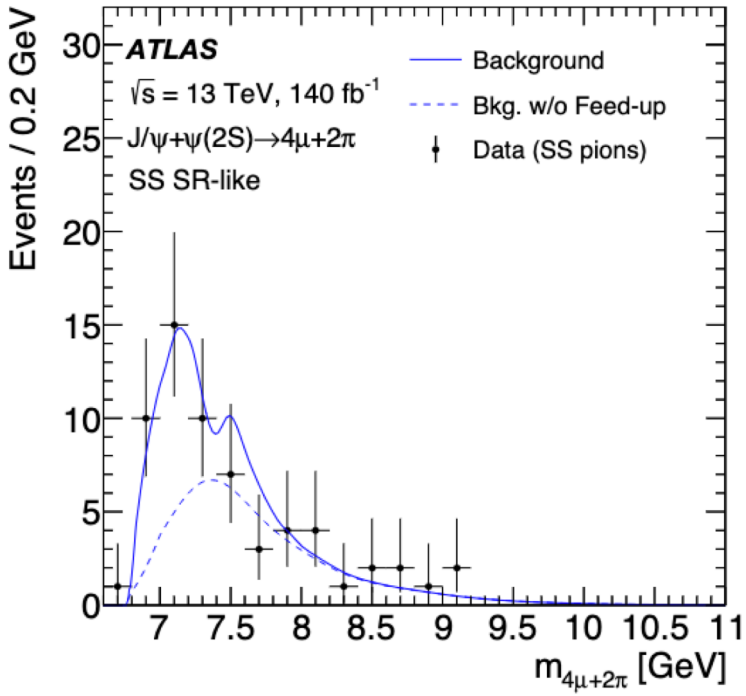
Feed-up background

- The shape is estimated with MC events and used in both OS and SS regions. The normalization is directly obtained from the simultaneous fit
  - OS region: two pions are required to have opposite-sign (OS) charges
  - SS region: two pions are required to have same-sign (SS) charges

Excess in SS data is the feed-up background

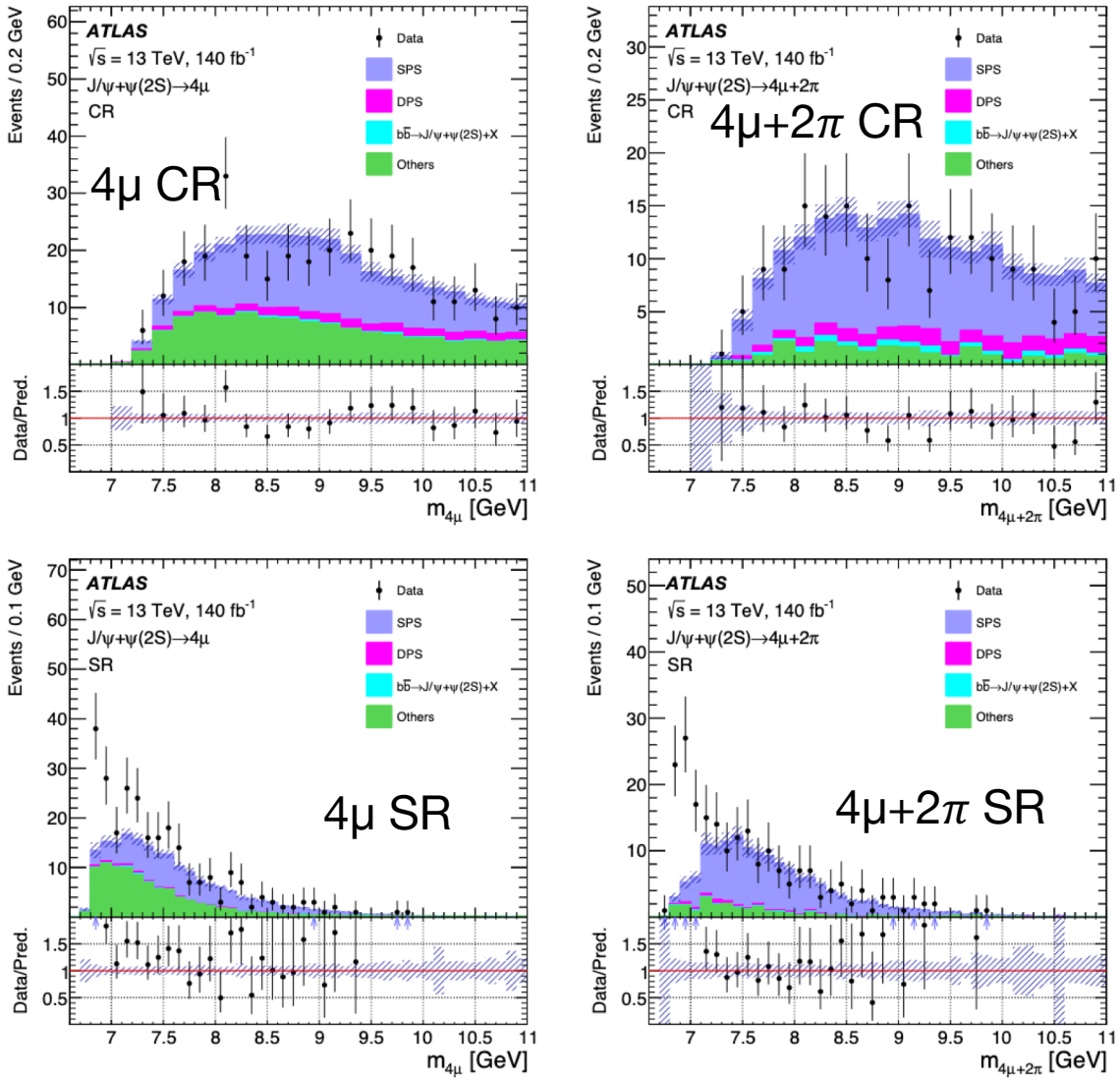


fit



Feed-up background shape is based on MC

Background estimation in analysis CRs and SRs



- 6 analysis regions are fitted simultaneously:
  - 4μ SR and CR
  - $4\mu + 2\pi$ SR and CR
  - SS SR-like ($\Delta R < 0.25$) and CR-like ($\Delta R > 0.25$) regions
- Fractions of different backgrounds in the SRs:

Channel	"others"	non-prompt	DPS	SPS
4μ	47%	0.8%	2.5%	49%
$4\mu + 2\pi$	14%	1.4%	3.6%	82%

The fit models

- The signal resonances can be either standalone or interfering. They can interfere with each other or interfere with the SPS background. Three signal models are used.

Model A: two interfering BWs that decays to both di-J/ψ and J/ψ+ψ(2S)

$$f^{A}_{s,\text{di-}J/\psi}(x) = \left|\sum_{i=1}^{2} \frac{z_i}{m_i^2 - x^2 - im_i\Gamma_i(x)}\right|^2 \sqrt{1 - \frac{4M^2_{J/\psi}}{x^2}} \otimes R(\boldsymbol{\theta}),$$

$$f^{A}_{s,J/\psi+\psi(2S)}(x) = \left|\sum_{i=1}^{2} \frac{z_i}{m_i^2 - x^2 - im_i\Gamma_i(x)}\right|^2 \sqrt{1 - \left(\frac{M_{J/\psi} + M_{\psi(2S)}}{x}\right)^2} \otimes R(\boldsymbol{\theta}),$$

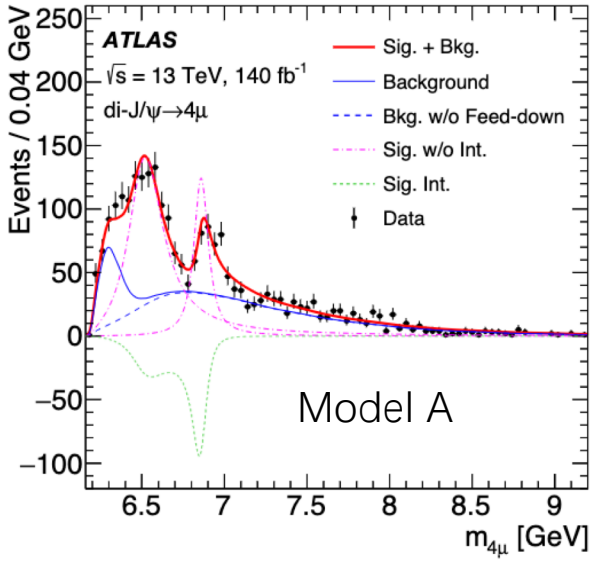
Model B: X(6900) is standalone and the other interferes with SPS. X(6900) decays to both di-J/ψ and J/ψ+ψ(2S)

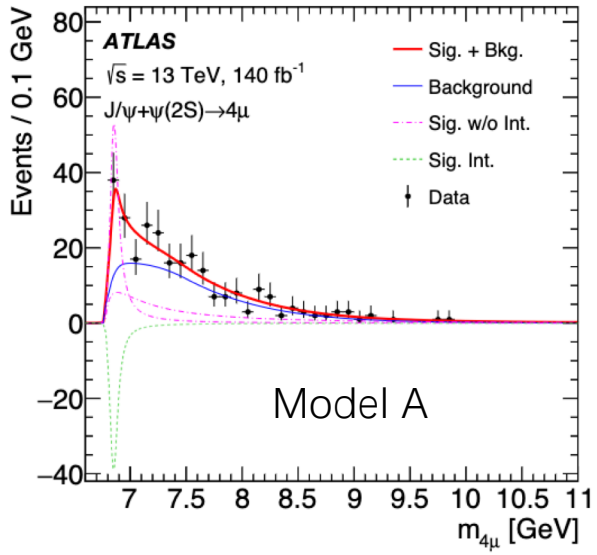
$$f^{B}_{s+\text{SPS},\text{di-}J/\psi}(x) = \left(\left|\frac{z_1}{m_1^2 - x^2 - im_1\Gamma_1(x)} + A(x)e^{i\phi_{\text{SPS}}}\right|^2 + \left|\frac{1}{m_2^2 - x^2 - im_2\Gamma_2(x)}\right|^2\right) \sqrt{1 - \frac{4M^2_{J/\psi}}{x^2}} \otimes R(\boldsymbol{\theta}),$$

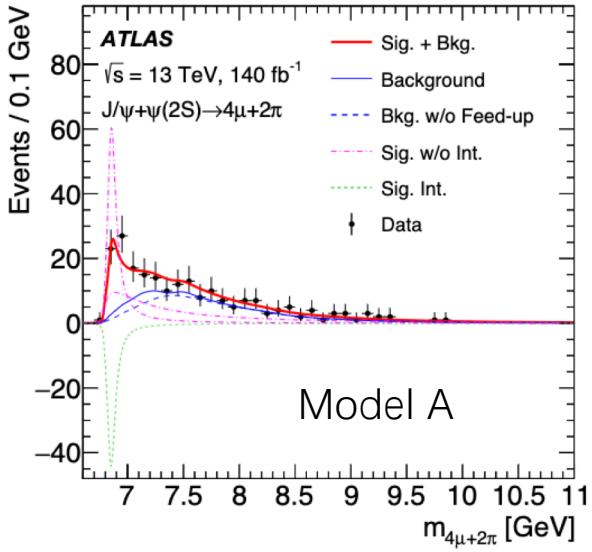
Model C: a single BW in the J/ψ+ψ(2S) channel

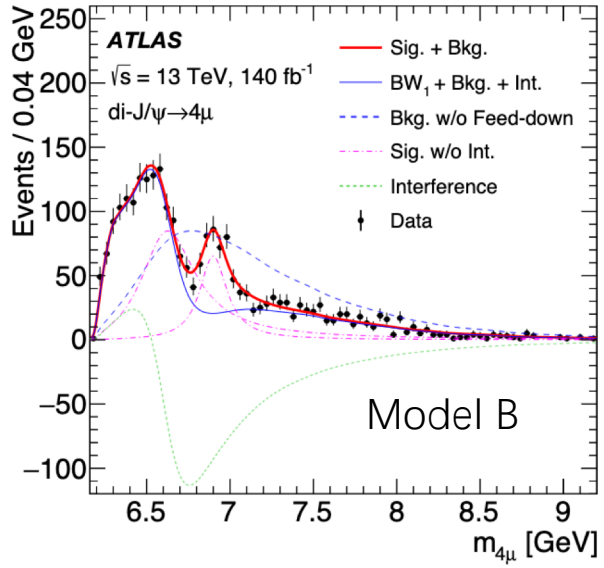
$$f^{C}_{s,J/\psi+\psi(2S)}(x) = \left|\frac{1}{m_2^2 - x^2 - im_2\Gamma_2(x)}\right|^2 \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x}\right)^2} \otimes R(\boldsymbol{\theta}).$$

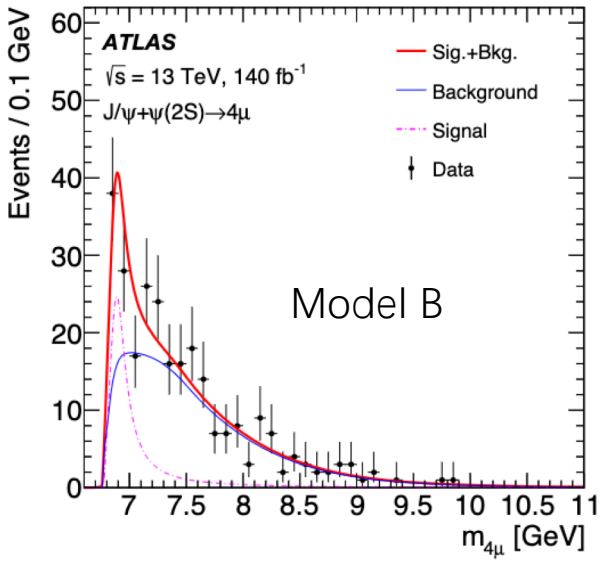
Fit results (1)

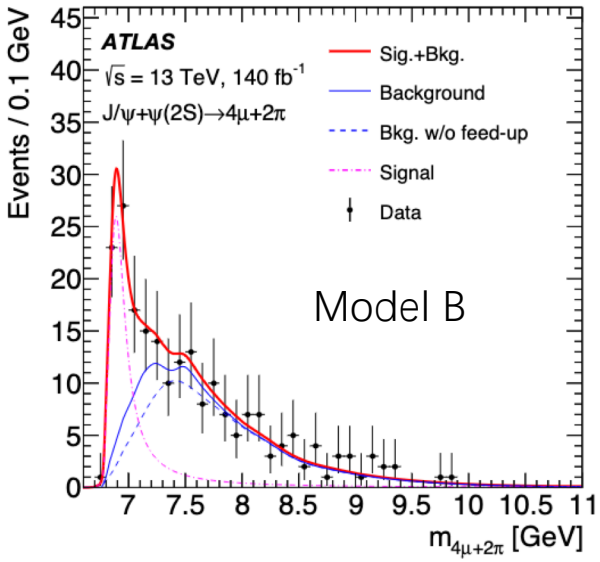












- The signal X(6900) yields in $J/\psi+\psi(2S)\rightarrow 4\mu$ and di-$J/\psi\rightarrow 4\mu$ are related by (R is ratio of its partial decay widths)

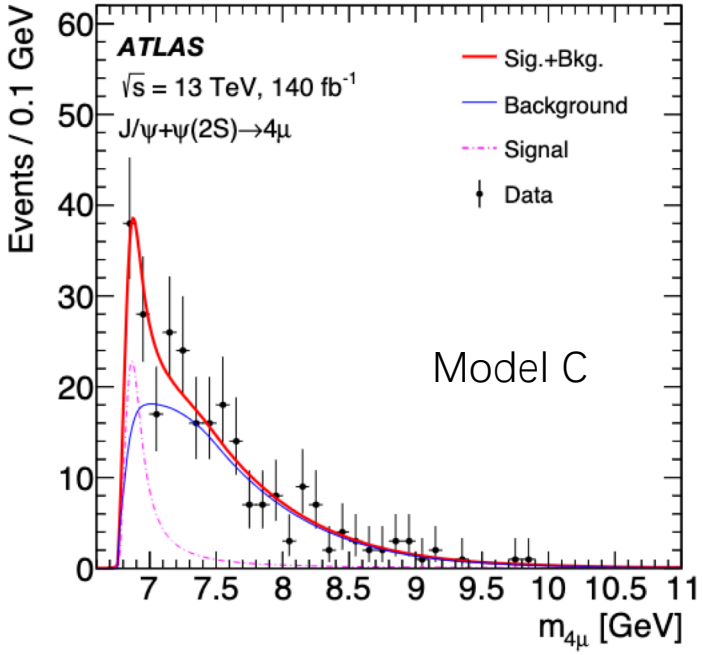
$$\frac{N_{4\mu}}{N_{\text{di-}J/\psi}} = R \cdot \frac{\mathcal{B}(\psi(2S)\rightarrow\mu\mu)\cdot\varepsilon_{4\mu}}{\mathcal{B}(J/\psi\rightarrow\mu\mu)\cdot\varepsilon_{\text{di-}J/\psi}},$$

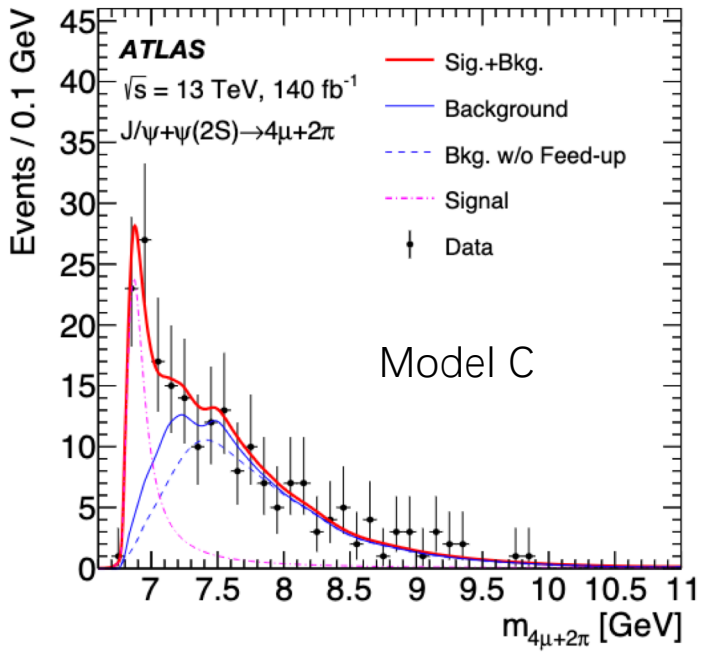
$N_{4\mu}/N_{\text{di-}J/\psi}(R=1) = 0.145\pm0.016$

- Similarly, the X(6900) yields in $J/\psi+\psi(2S)\rightarrow 4\mu$ and $J/\psi+\psi(2S)\rightarrow 4\mu+2\pi$ are related by

$N_{4\mu}/N_{4\mu+2\pi} = 0.880\pm0.072$

Fit results (2)





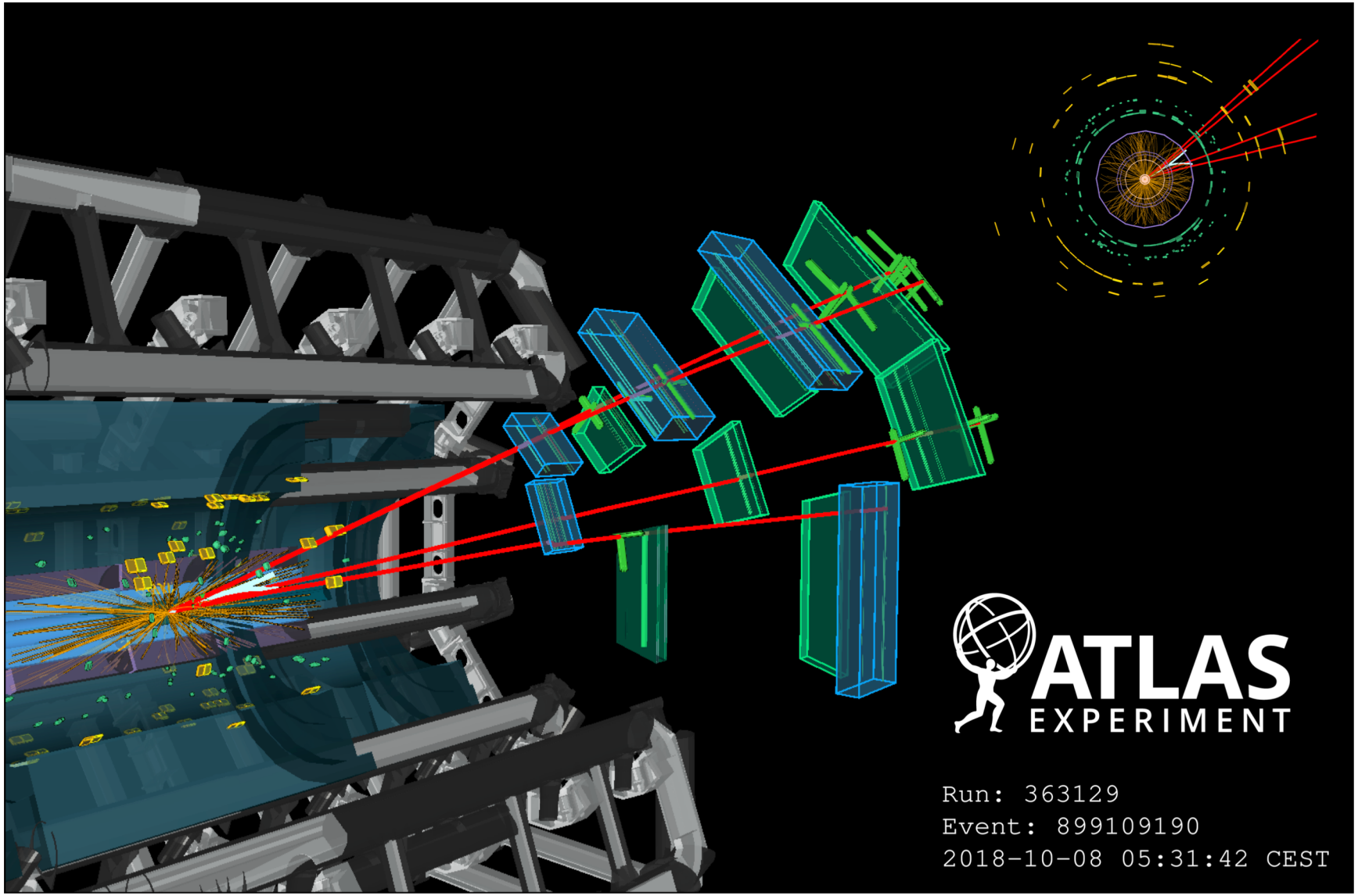
X(6900)	model A	model B	model C
m_2 / GeV	$6.860 \pm 0.023 \pm 0.010$	$6.902 \pm 0.008 \pm 0.010$	$6.884 \pm 0.017^{+0.058}_{-0.005}$
Γ_2 / GeV	$0.082 \pm 0.032 \pm 0.015$	$0.183 \pm 0.025 \pm 0.007$	$0.178 \pm 0.054^{+0.176}_{-0.024}$
R	$1.08 \pm 0.20^{+0.40}_{-0.09}$	$0.93 \pm 0.17 \pm 0.11$	—

$$R = \Gamma_{X(6900)\to J/\psi+\psi(2S)}/\Gamma_{X(6900)\to \text{di-}J/\psi}$$

- In model C, excesses observed in both $\psi(2S)$ decays. A 8.9σ significance in the $J/\psi+\psi(2S)$ channel
- Ratio of partial decay widths is close to 1 – unexpected due to phase space consideration
- The existence of X(7200) in the $J/\psi+\psi(2S)$ channels is tested in each fit model

  The yield of X(7200) relative to X(6900) is 0.12 ± 0.11, with an upper limit of 0.41 at 95% CL
- The dominant systematics: mass resolution, background modeling, BW functions

A candidate of X(6900)$\rightarrow J/\psi+\psi(2S)\rightarrow 4\mu+2\pi$



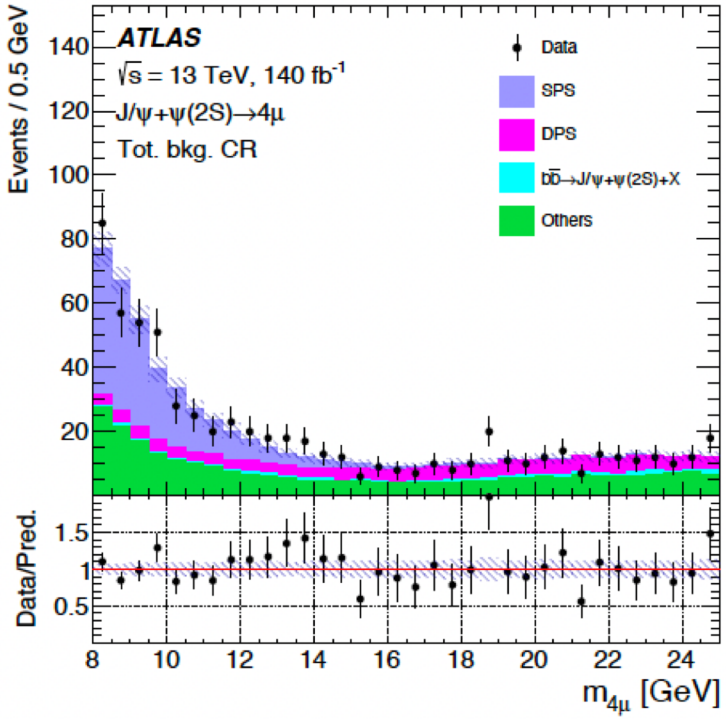
Summary

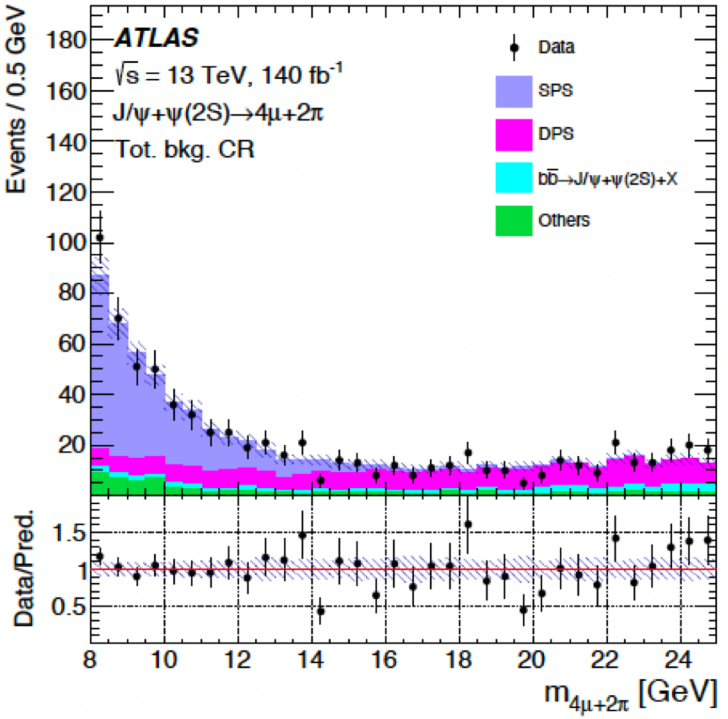
- All-charm tetraquarks are searched in the J/ψ+ψ(2S) channel considering both 4μ and 4μ+2π final states
- A resonance with mass around 6.9 GeV is observed in the J/ψ+ψ(2S) channel with a signal significance of 8.9σ
- The ratio of partial decay widths of X(6900)$\rightarrow J/\psi$+ψ(2S) and X(6900)$\rightarrow$di-J/ψ has been measured to be around 1
- The presence of structures in the J/ψ+ψ(2S) channels is confirmed and data favors a single-resonance hypothesis near 6.9 GeV
- The existence of a potential resonance near 7.2 GeV is not supported by the current data. An upper limit of the relative yield is set at 95% CL

Backup Slides

Background corrections

Mass distributions in the "global" background CRs of the two decay channels:





Since the DPS and SPS backgrounds are based on MC, several kinematic variables are corrected to match background with data in the CRs

"others"	non-prompt	DPS	SPS
4^{th} muon p_{T}, charmonium p_{T}, $m_{4\mu(+2\pi)}$	4^{th} muon p_{T}	di-charmonium p_{T}, $\Delta\eta$ between charmonia, 4^{th} muon p_{T}, 2^{nd} pion p_{T}	di-charmonium p_{T}, $m_{4\mu(+2\pi)}$, $\Delta\eta$ and $\Delta\phi$ between charmonia, 4^{th} muon p_{T}, 2^{nd} pion p_{T}