



# Low-mass resonances in $4\text{-}\mu\text{on}$ channel



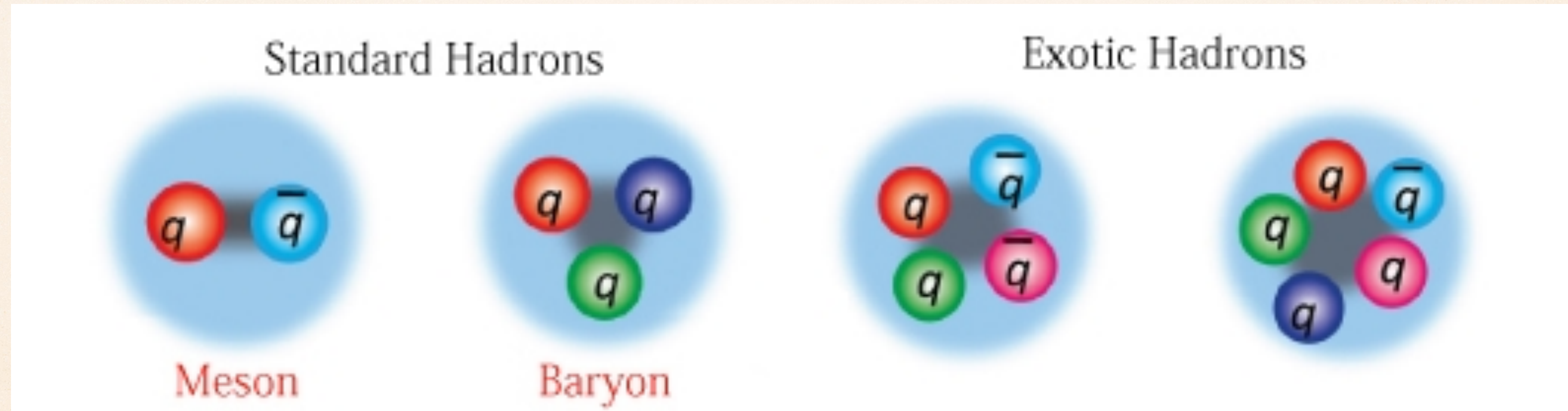
**Hao Pang**  
**for the ATLAS collaboration**

26th to 30th September 2022  
The 15th International workshop  
on Heavy Quarkonium



# Introduction

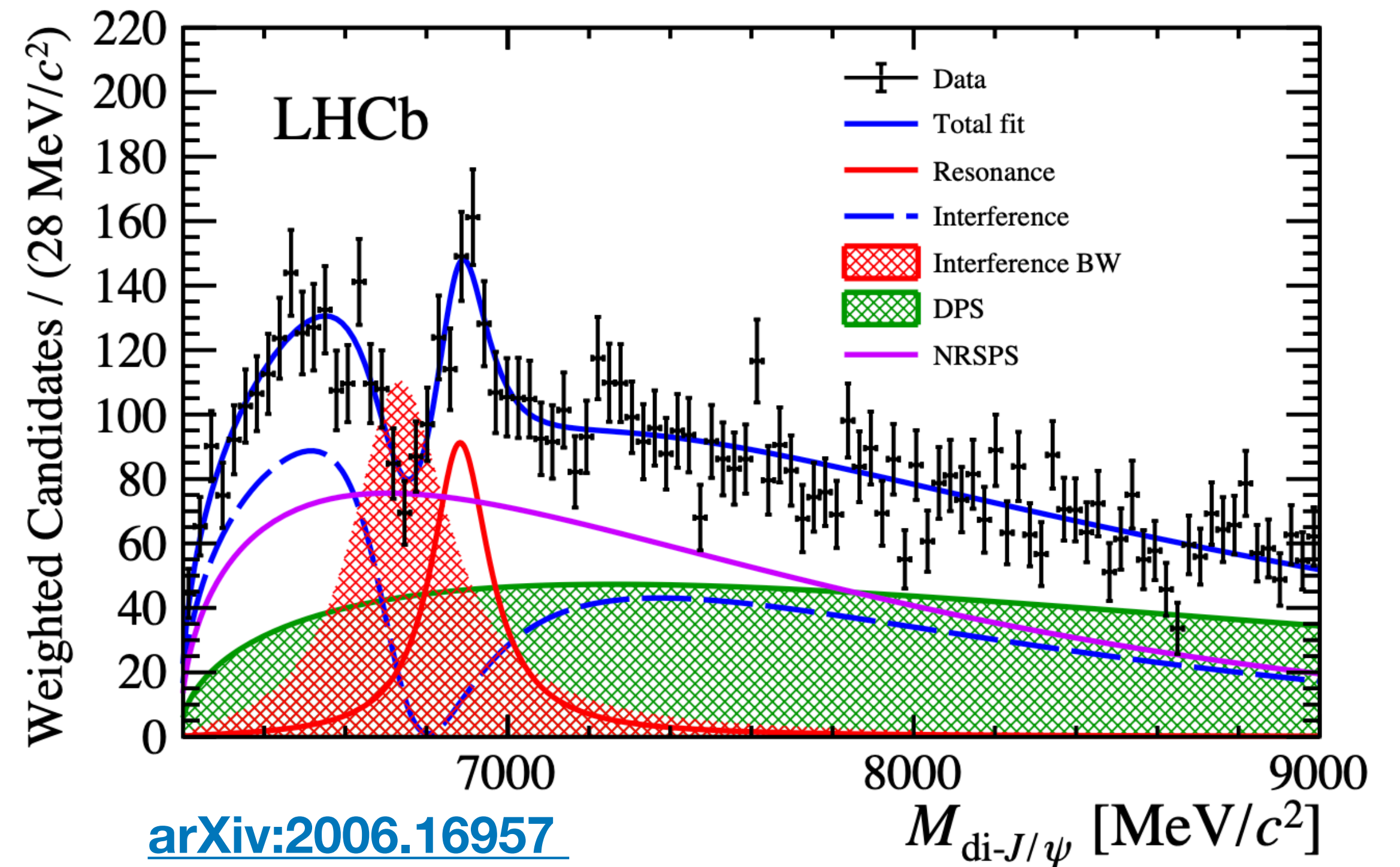
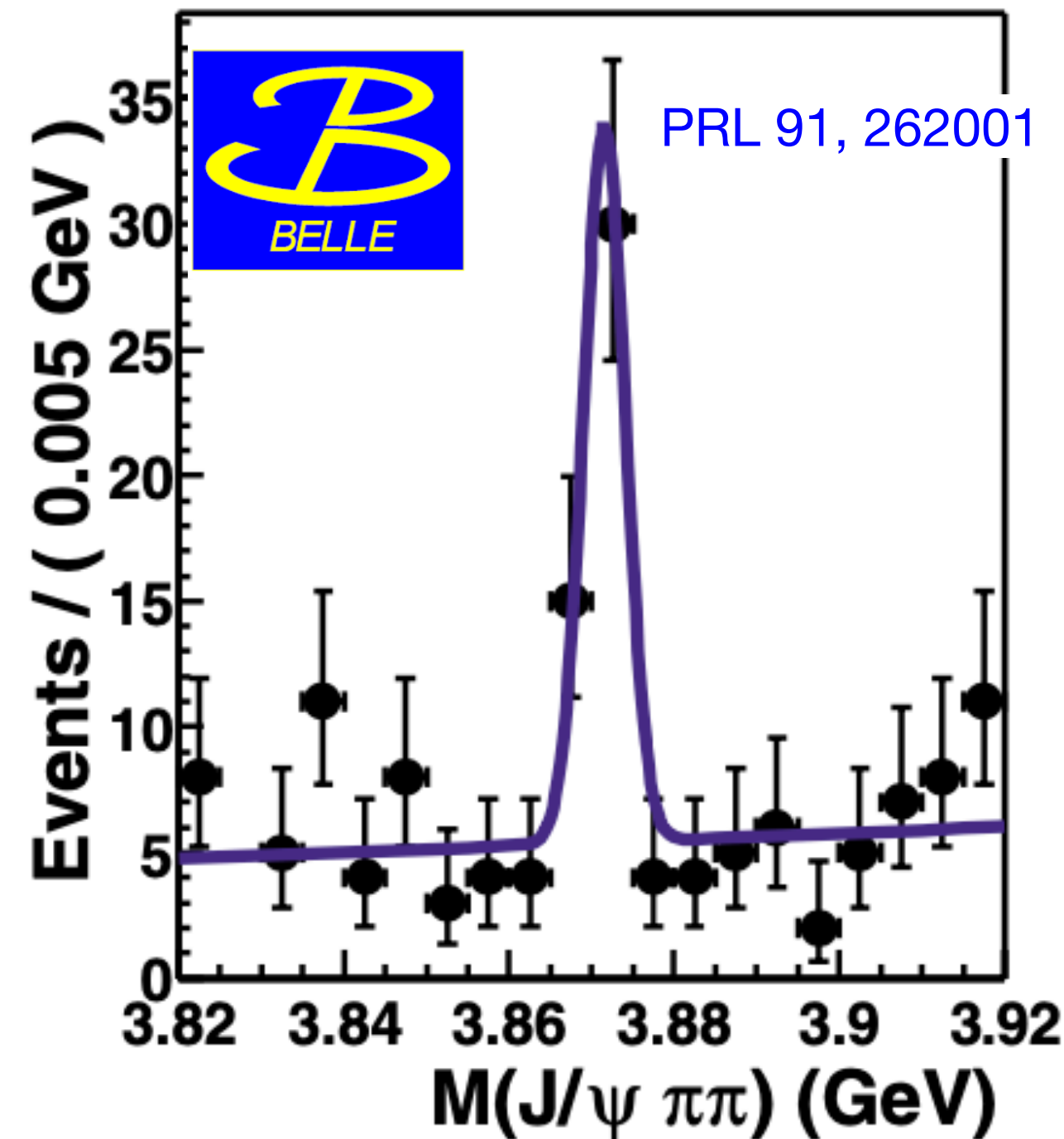
The quark model was proposed by Gell-Mann and Zweig sixty years ago



Beyond the standard hadrons, the exotic hadrons composed of four or five quarks are also allowed under color confinement.



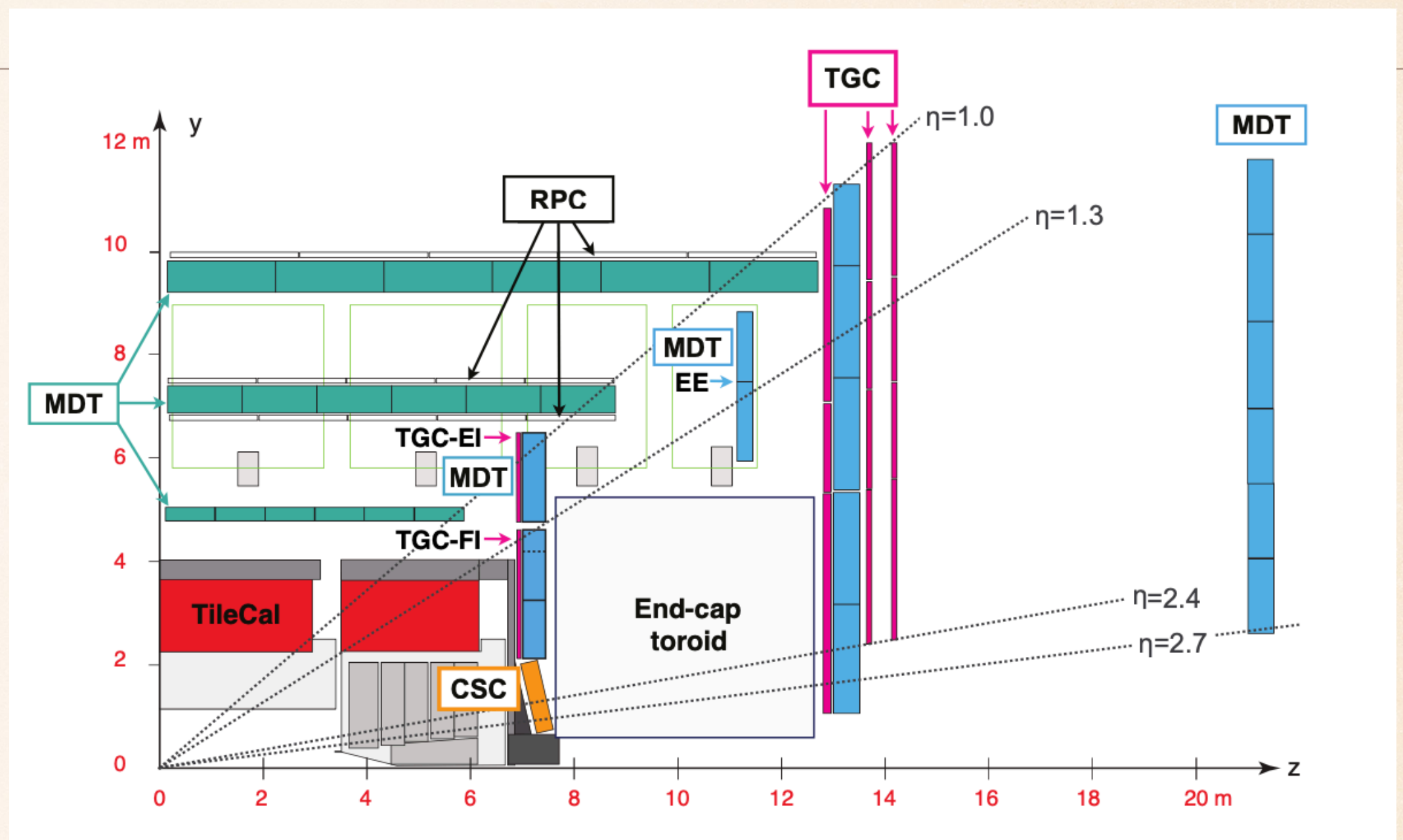
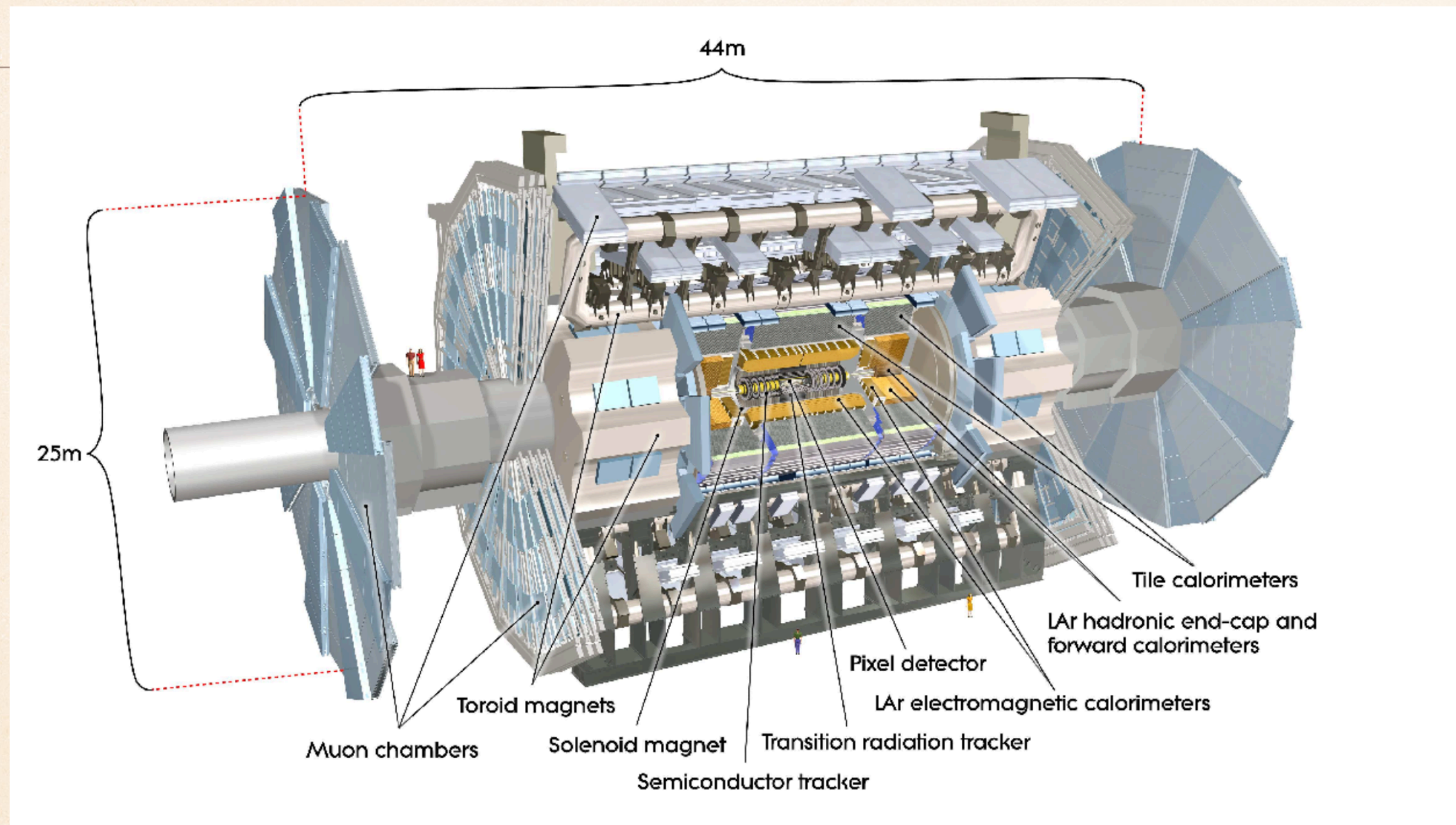
# Exotic Hadrons



- The first narrow Charmoniumlike State (X3872) was discovered by Belle experiment in the decay products of B mesons
- In June 2020, LHCb claimed an evidence for a narrow resonance at 6.9 GeV, which could be the full-charm tetraquark candidate



# The ATLAS detector



- The ATLAS detector 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

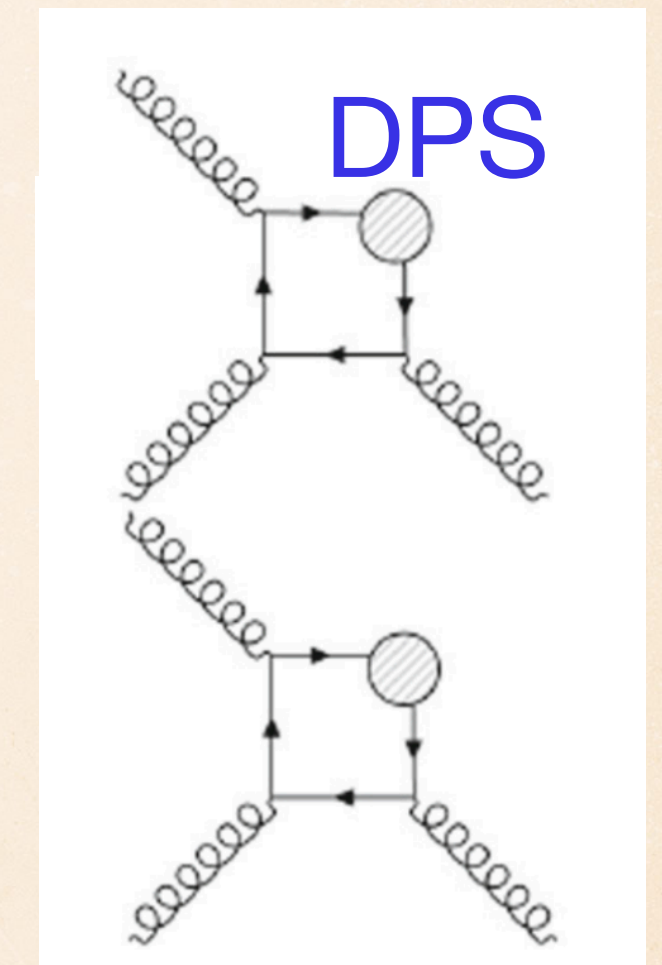
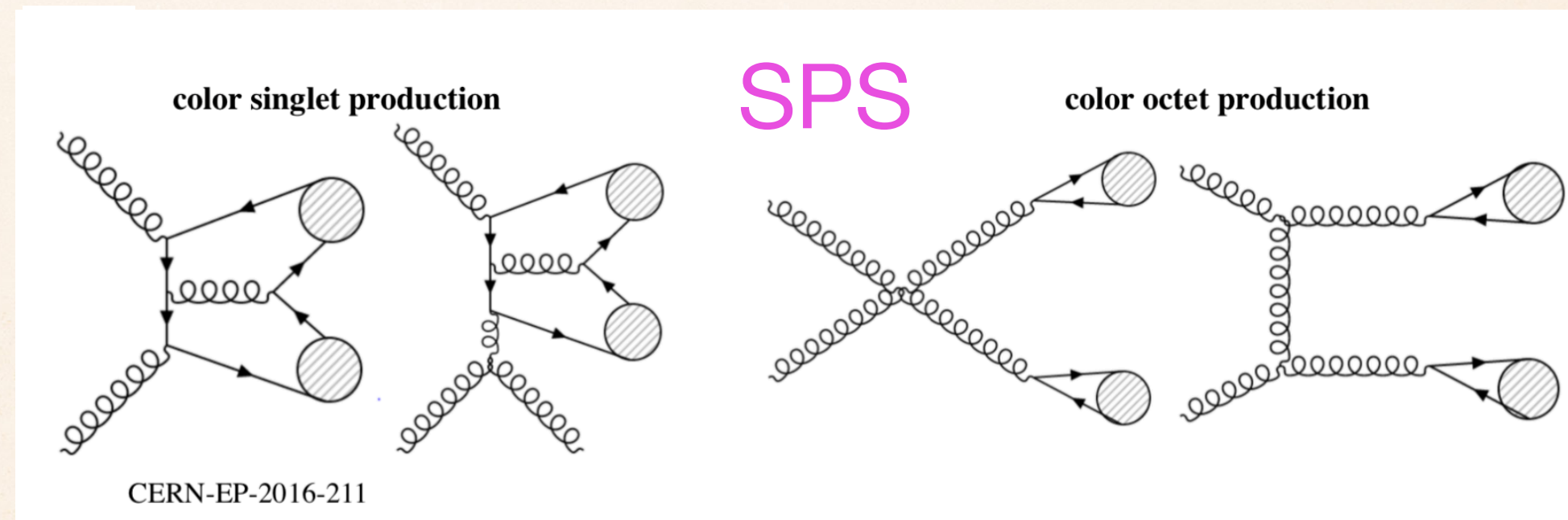


# Data, Signal and Backgrounds

- Data: LHC full Run-2 between 2015-2018, corresponding to  $139 \text{ fb}^{-1}$  at  $\sqrt{s}=13\text{TeV}$
- Signal: tetraquark(TQ)  $\rightarrow$  di- $J/\psi$  or  $J/\psi + \psi(2S) \rightarrow 4\mu$ .  
where TQ Mass = 6.9GeV and width = 0.1GeV, consistent with LHCb prior result

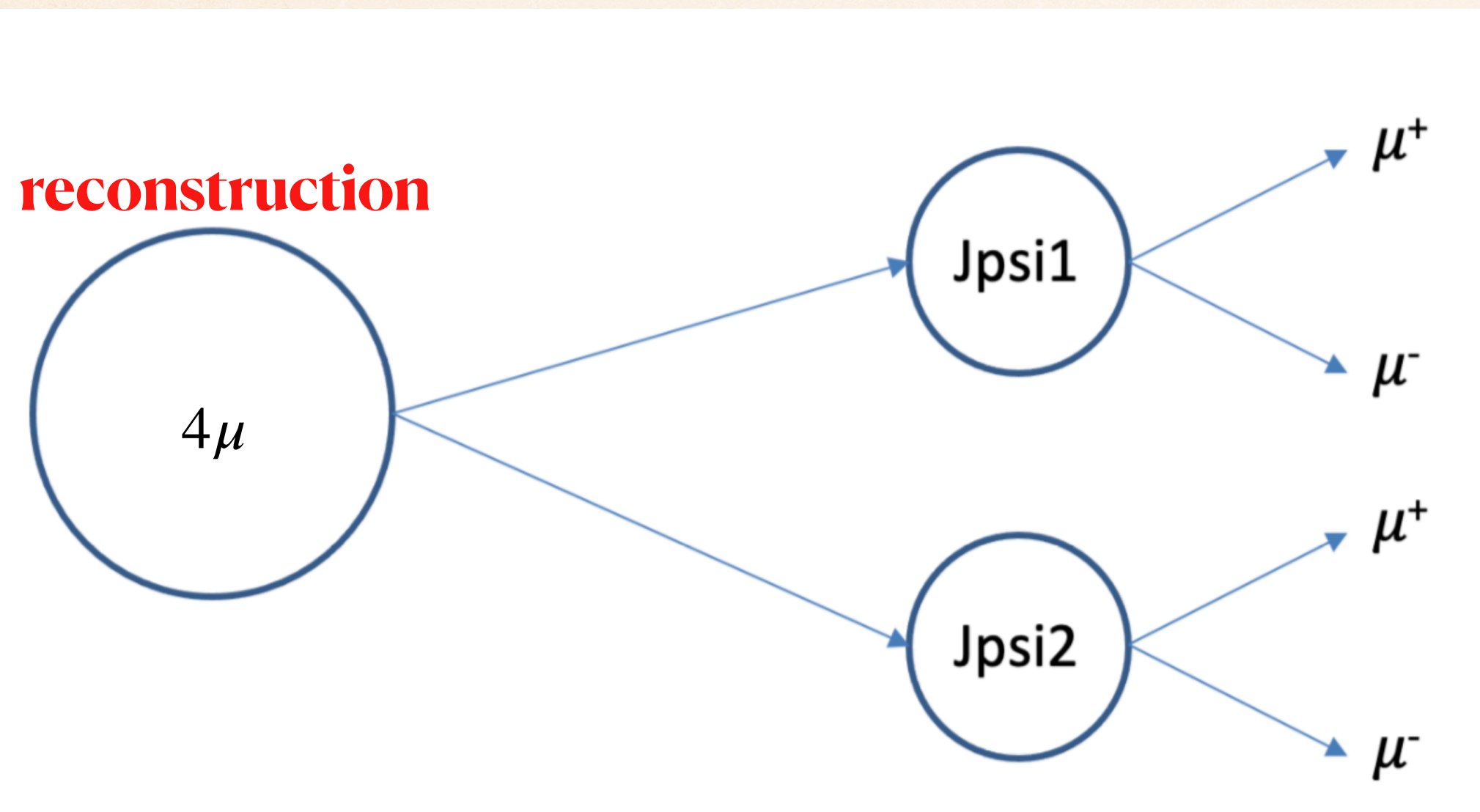
- Background:

- Single parton scattering (SPS)
- Double parton scattering (DPS)
- Non-prompt from b quark decay
- Single  $J/\psi$  background and non-peaking background containing a single or no real  $J/\psi$  (others)





# Event reconstruction and selection



- Four muons with two opposite-charge pairs are fitted to a common vertex by using the inner detector tracks
- Each pair is revertexed with a  $J/\psi$  or  $\psi(2S)$  mass constraint

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

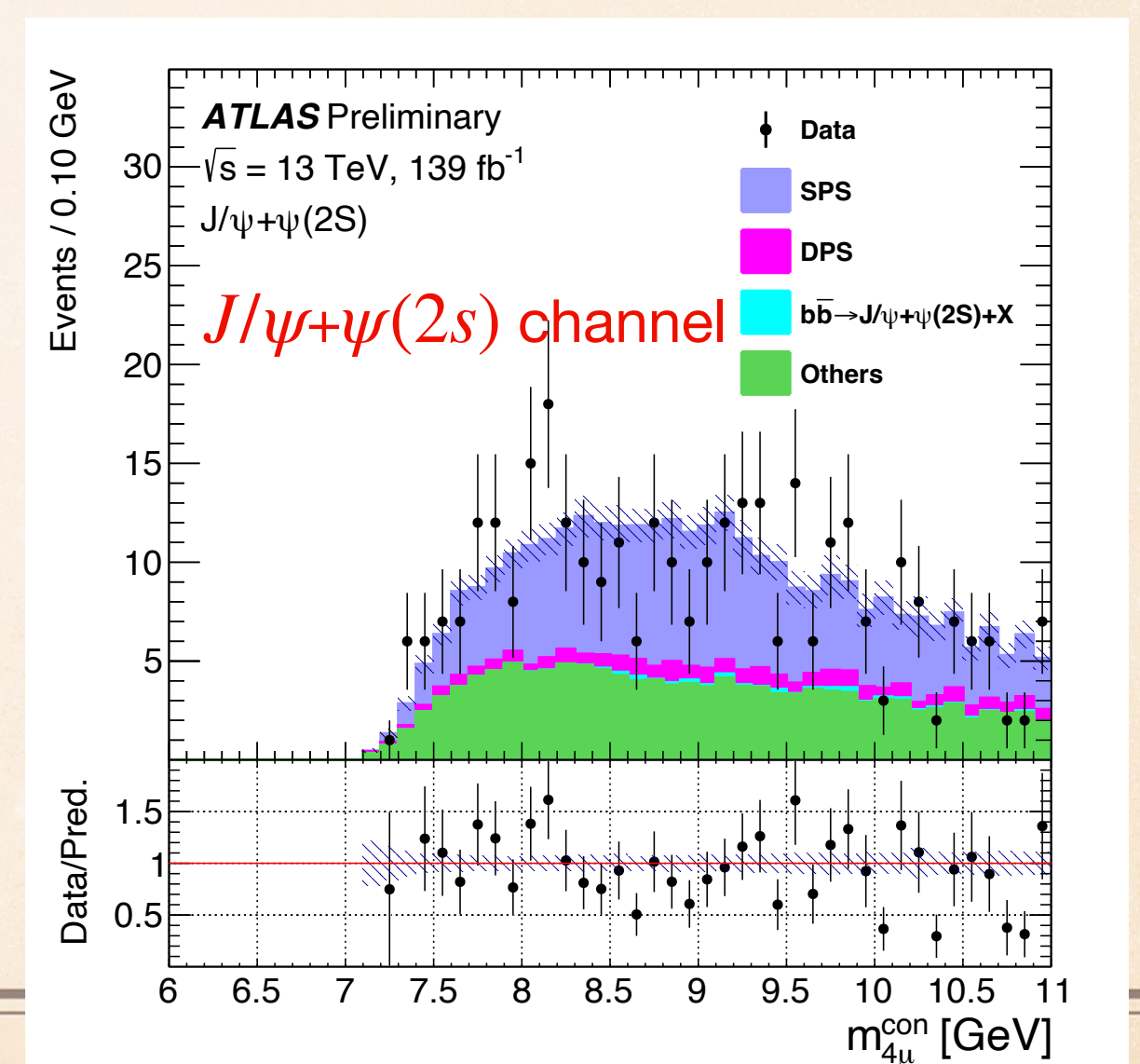
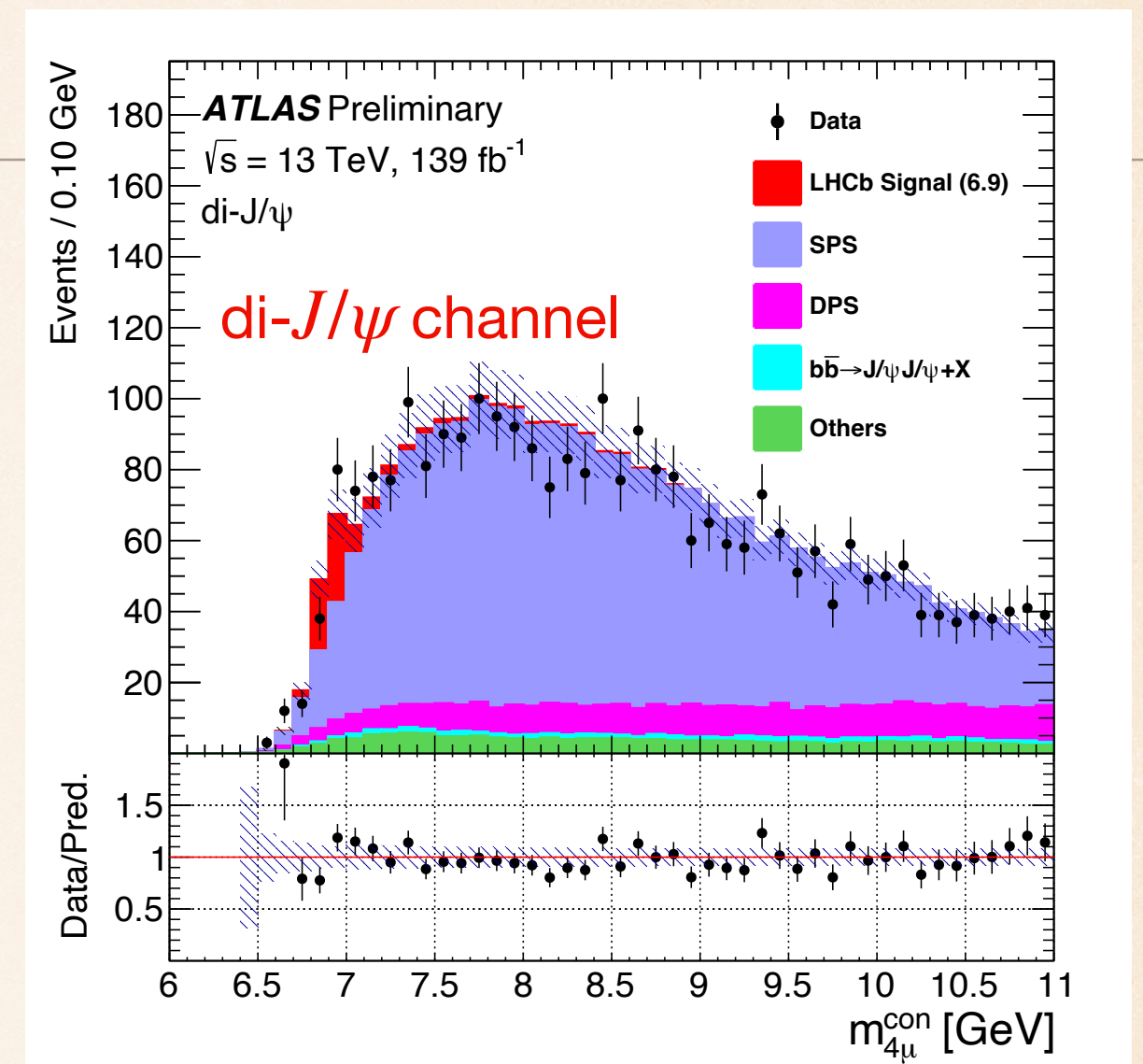
- The cuts in the table are applied to the signal region, SPS/DPS CR or nonprompt region:
- (others) background: **fake region** and **sideband**:
  - one  $J/\psi$  or  $\psi(2S)$  candidate containing a track (not in the “Muons” container)
  - the mass sideband region of  $J/\psi$  or  $\psi(2S)$



# background estimation

- MC simulation is used for modelling **SPS** and **DPS**. Their CRs are used for the normalization factors and kinematic variable corrections
- **Non-prompt** backgrounds are estimated with MC and validated with non-prompt regions
- **Others** backgrounds are estimated by the data-driven method, which uses fake muon events to model it and sideband events for its correction and normalization

Good agreement between data and prediction in the VR!



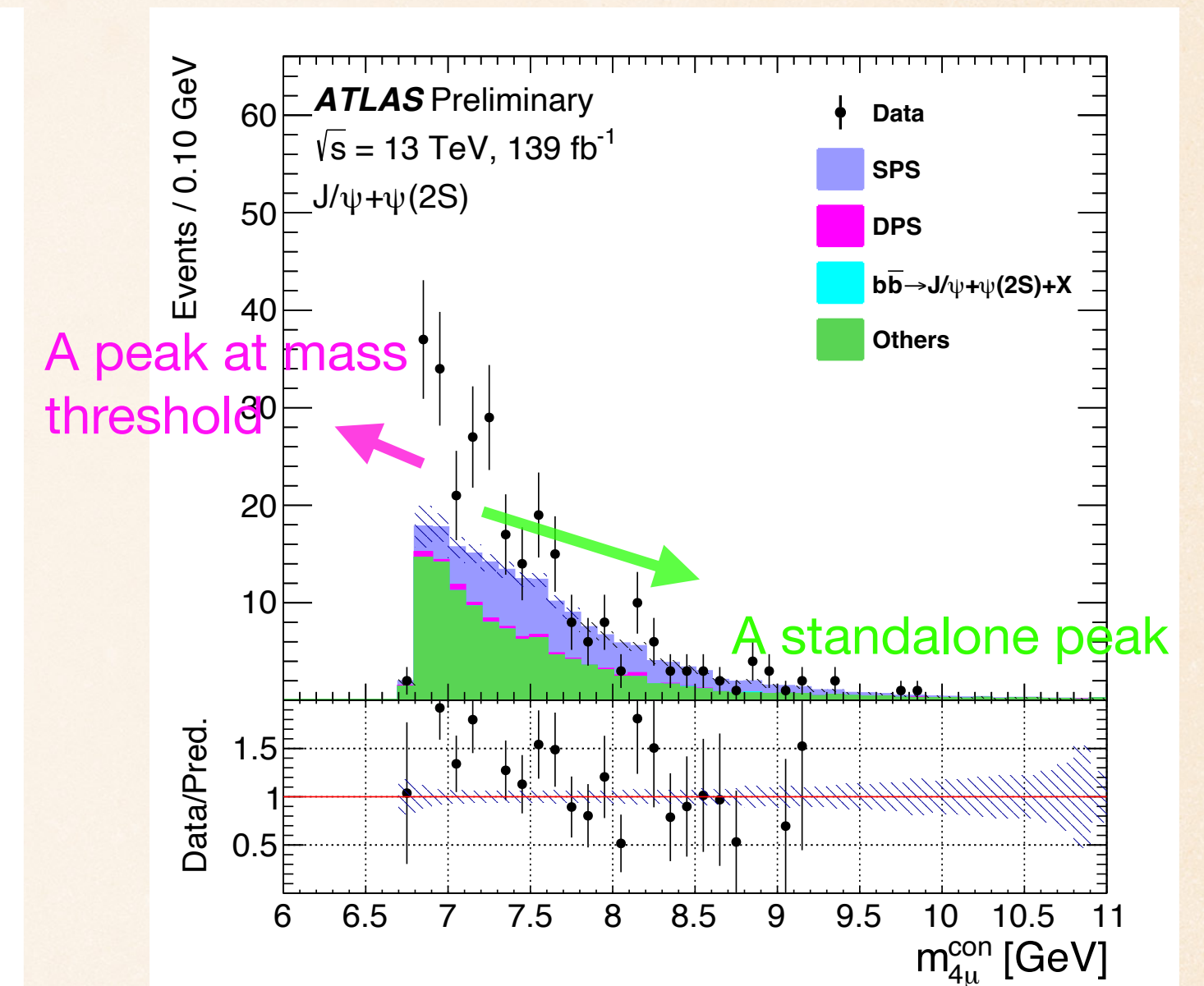
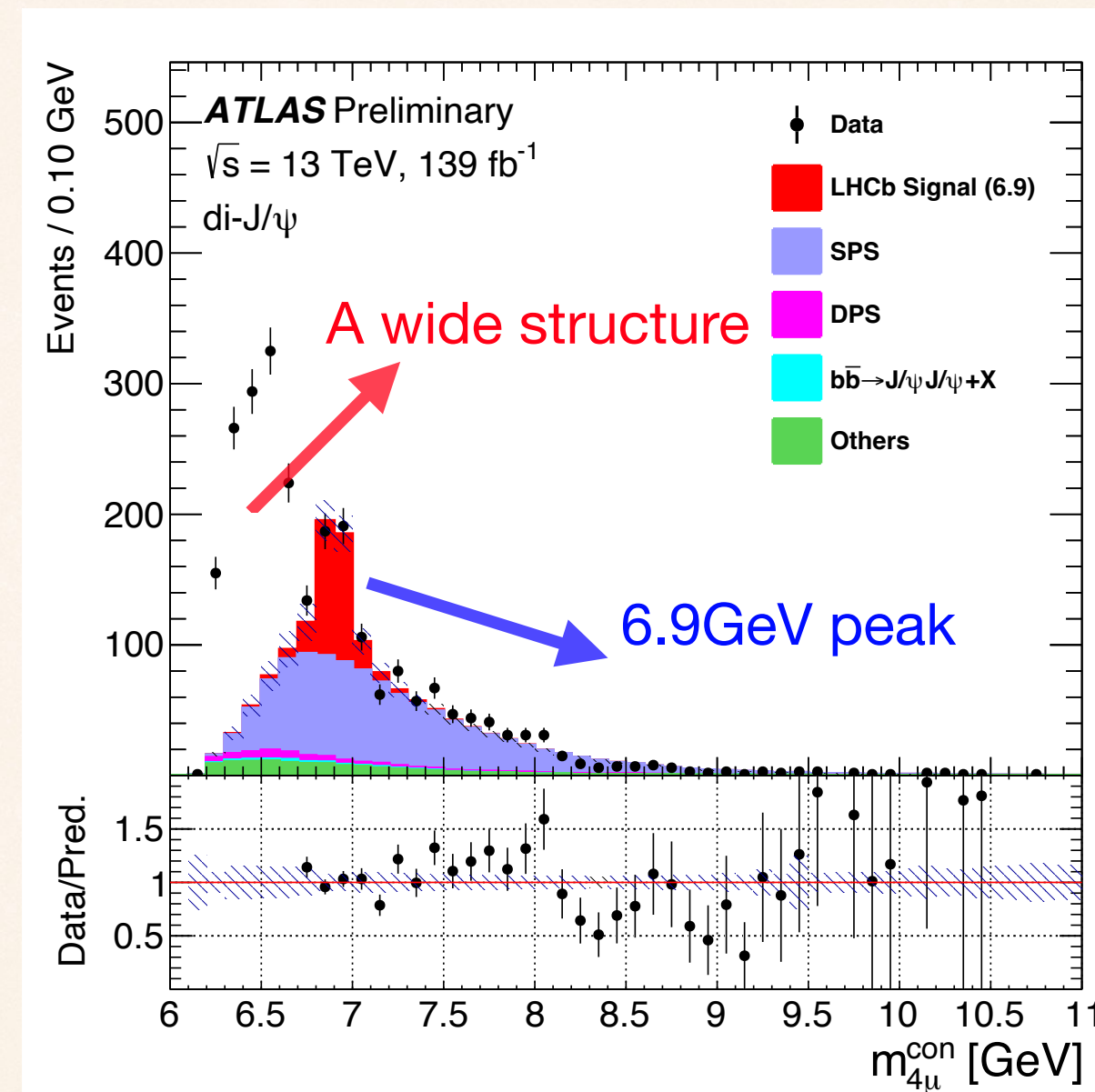


# Fit model

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

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

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



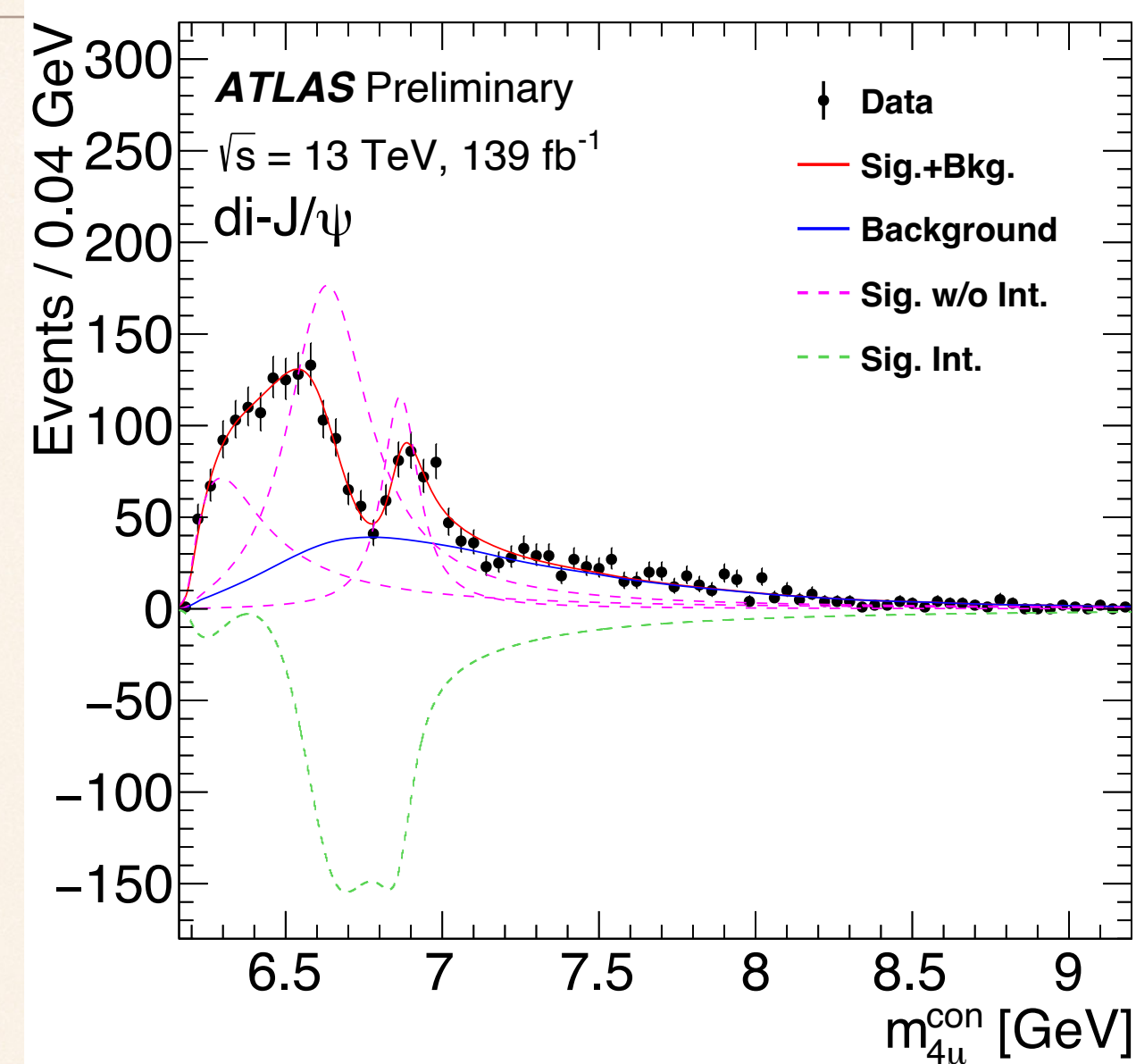
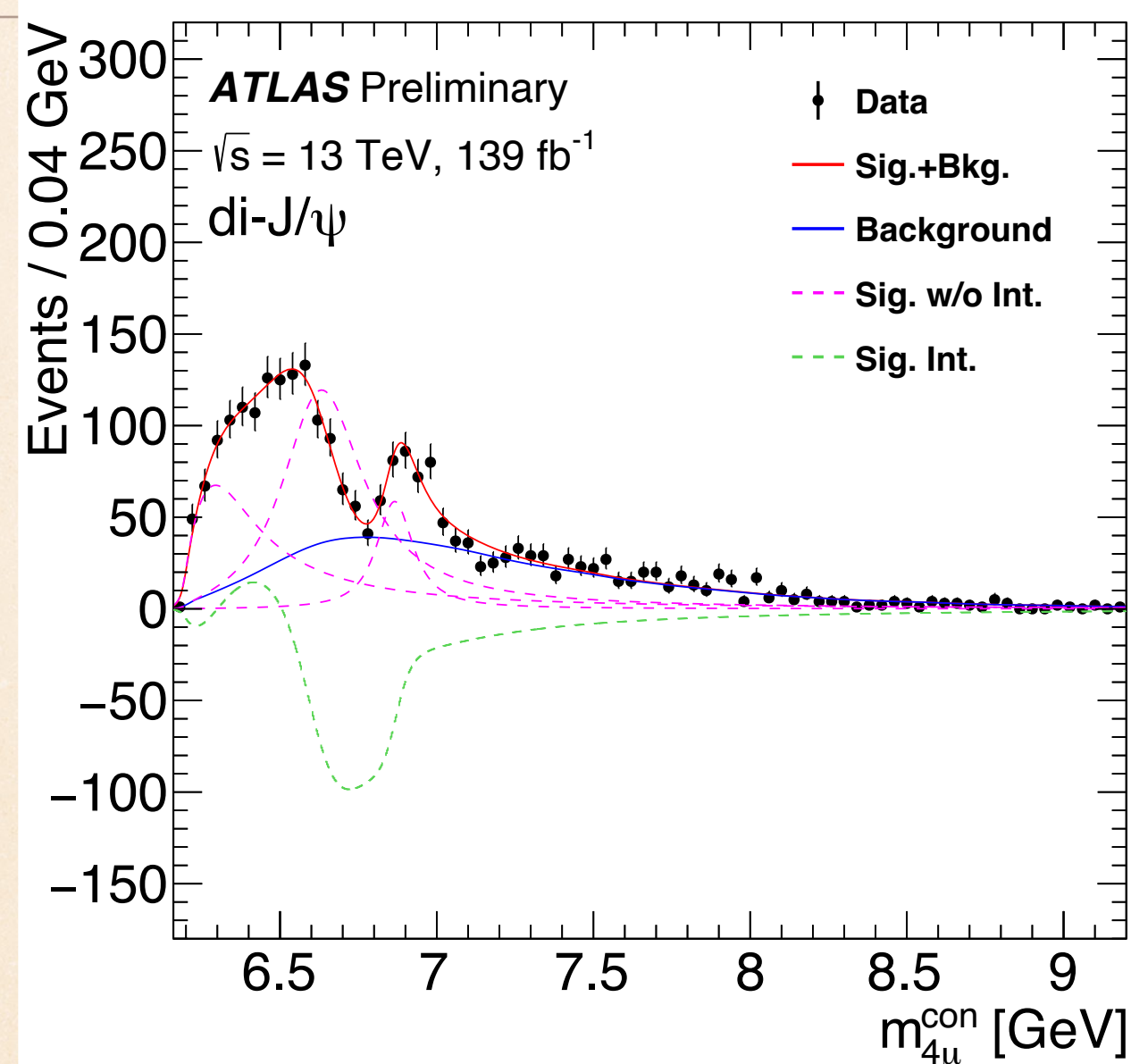
In  $J/\psi + \psi(2S)$  channel, two models are considered due to the low statistic:

- Model A: the same peaks with interference observed in the di- $J/\psi$  channel plus a standalone peak
- Model B: only one single peak

$$f_s(x) = \left( \left| \sum_{i=0}^2 \frac{z_i}{x^2 - m_i^2 + im_i\Gamma_i} \right|^2 + \left| \frac{z_3}{x^2 - m_3^2 + im_3\Gamma_3} \right|^2 \right) \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(x, \vec{\alpha})$$



# Fit results in di- $J/\psi$ channel

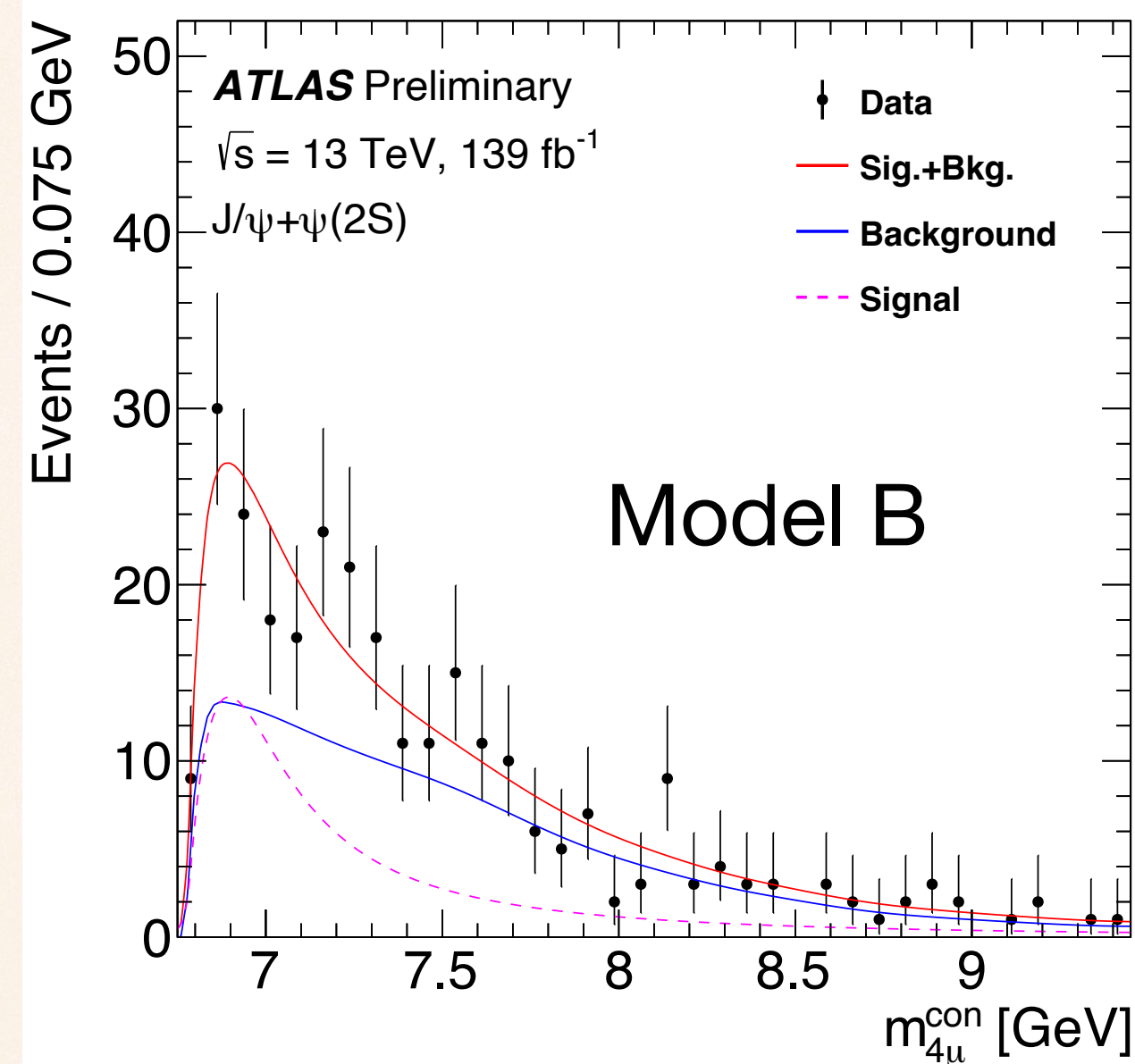
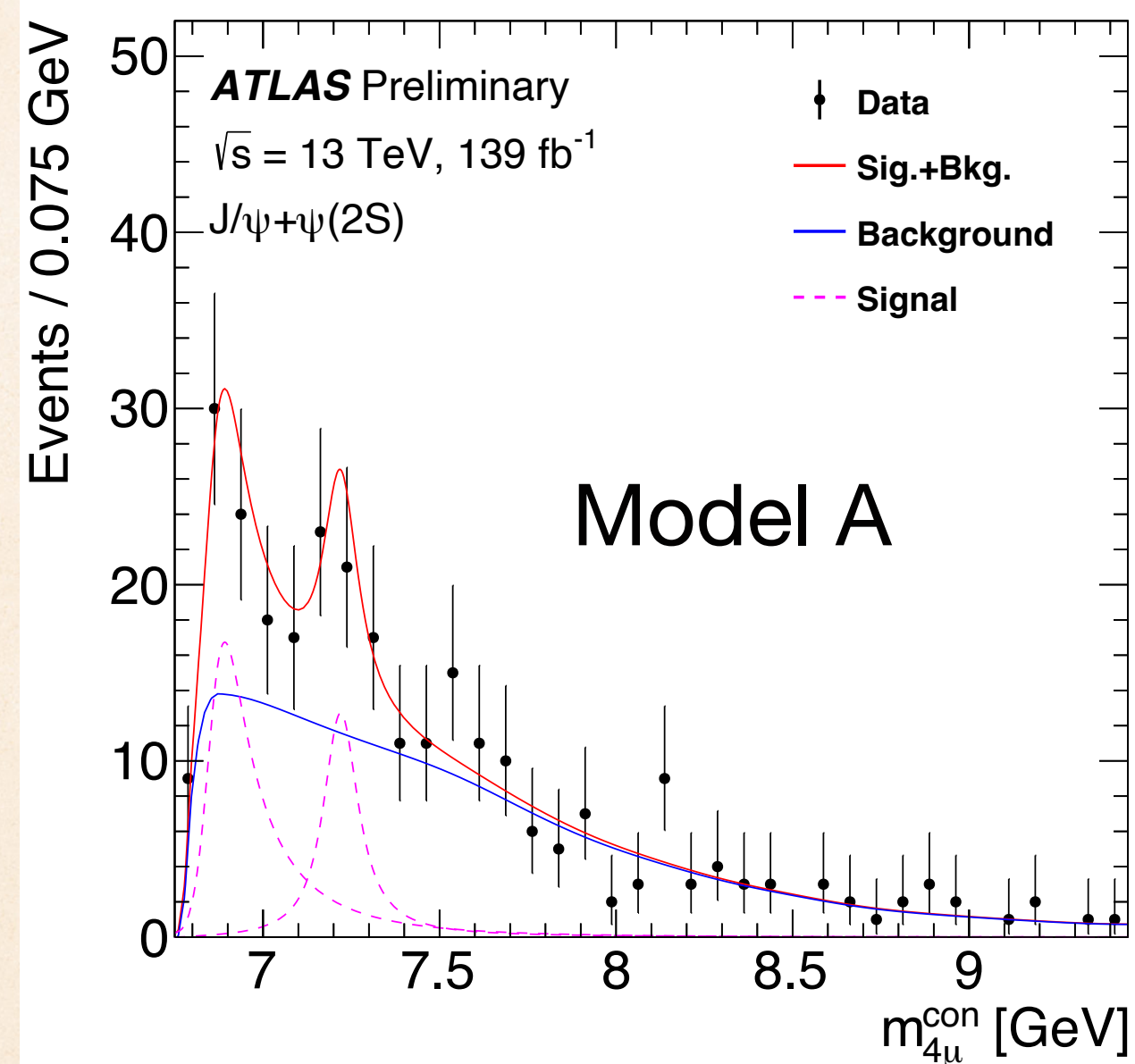


- The 3rd peak mass is consistent with the LHCb result  $X(6900)$ , with the significance of  $10\sigma$
- The three interfering peaks fit model is favorite by comparing the fit  $\chi^2$
- The fit model is just a possible interpretation of the mass structure. the broad structure at the lower mass could from other physical effects, (e.g. feed down from higher states, reflection effects)

(GeV)	$m_0$	$\Gamma_0$	$m_1$	$\Gamma_1$
di- $J/\psi$	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	$m_2$	$\Gamma_2$	—	—
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	—



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



- Significance reach  $4.6\sigma$  ( $4.3\sigma$ ) for Model A (B)
- In model A, the 1st peak could be related to  $X(6900)$  in the di- $J/\psi$  channel. The significance of **2nd peak** (7.2 GeV) reaches  $3.2\sigma$ , also hinted by LHCb and CMS in the di- $J/\psi$  spectrum

(GeV)		$m_3$	$\Gamma_3$	
$J/\psi+\psi(2S)$	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$	—
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$	—

- More data are needed!



# Systematic

Systematic Uncertainties (MeV)	di- $J/\psi$						$J/\psi+\psi(2S)$	
	$m_0$	$\Gamma_0$	$m_1$	$\Gamma_1$	$m_2$	$\Gamma_2$	$m_3$	$\Gamma_3$
SPS theory	7	15	4	20	5	6	<1	
SPS di-charmonium $p_T$	<1	8	4	14	5	7	<1	
Background MC statistics	<1	8	4	14	5	7	<1	
Mass resolution	19	34	3	21	4	9	<1	4
Fit bias	43	58	10	56	11	16	13	41
Nonclosure			<1				<1	
Transfer factor			—				<1	16
Presence of fourth resonance	29	49	11	108	60	18	—	
Interference of fourth resonance			—				29	11
Data statistics	50	119	34	88	30	39	28	130

Systematic and statistical uncertainties on the masses and natural widths (in MeV) of the interfering resonances from different sources in the di- $J/\psi$  and  $J/\psi+\psi(2S)$  channels. In the case of an asymmetric uncertainty, only the larger direction is shown.



# Summary

- A broad structure at lower mass region and a resonance around 6.9 GeV are observed in the di- $J/\psi$  channel.
- A  $4.6\sigma$  significant excess is observed in the  $J/\psi + \psi(2S)$  channel with model that an enhancement at about 6.9 GeV plus a standalone peak.
- More data is needed to understand the nature of resonances and threshold structures. Looking forward to the Run 3 data!

*Thanks!*