Low-mass resonances in 4-muon channel

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for the ATLAS collaboration

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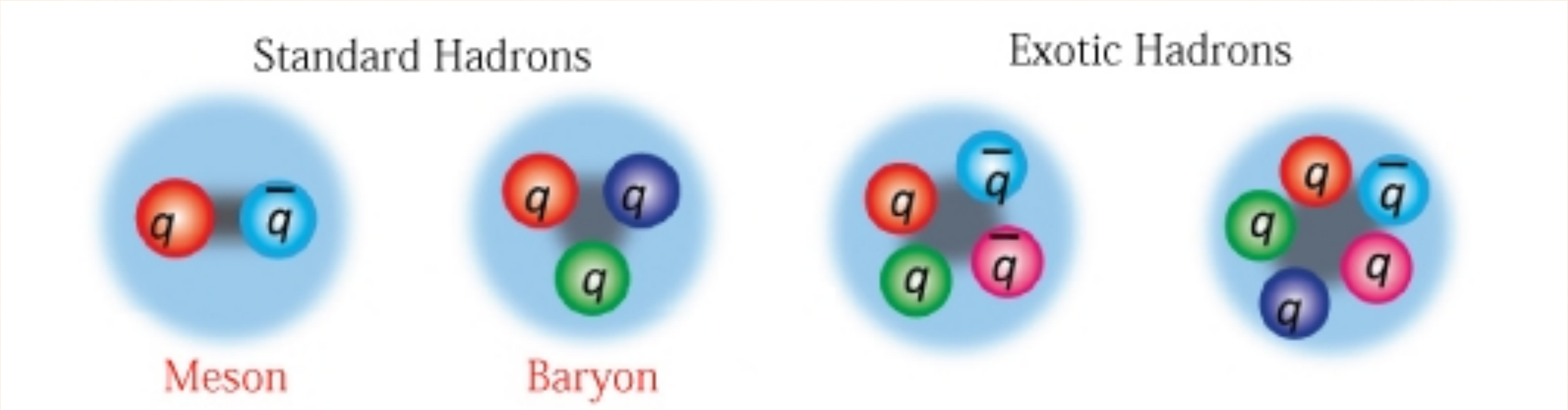
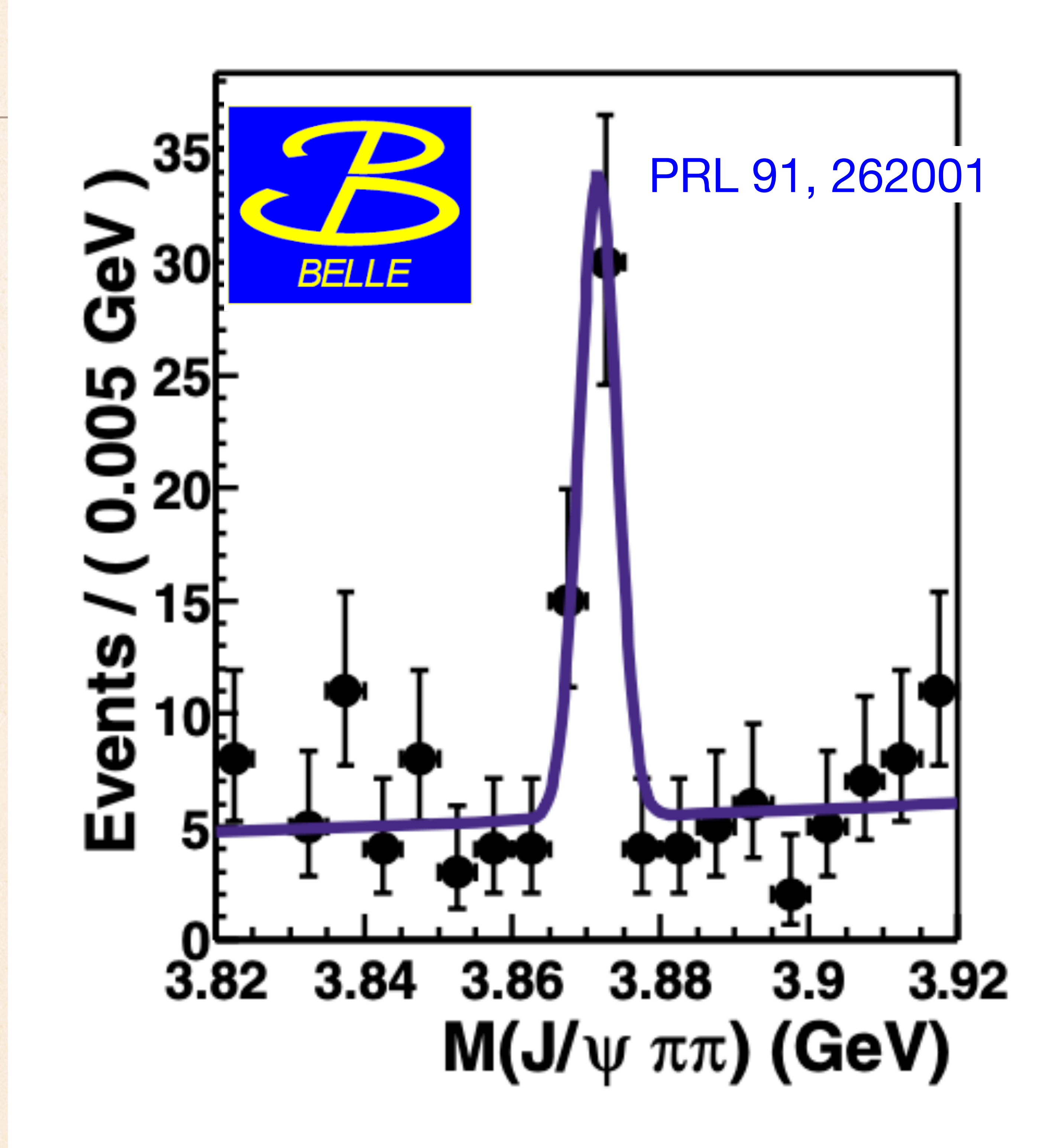
Introduction

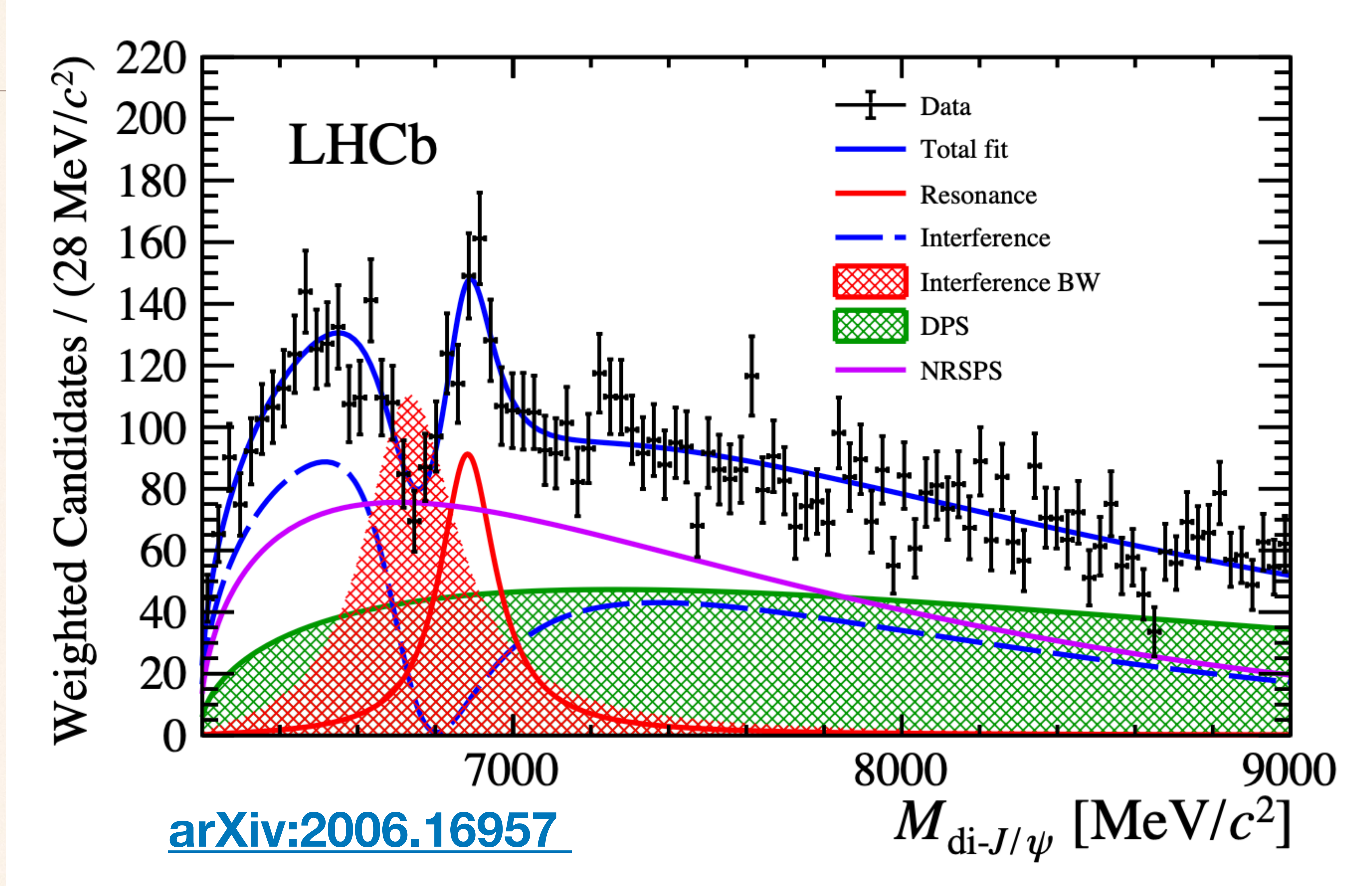
The quark model was proposed by Gell-Mann and Zweig sixty years ago



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

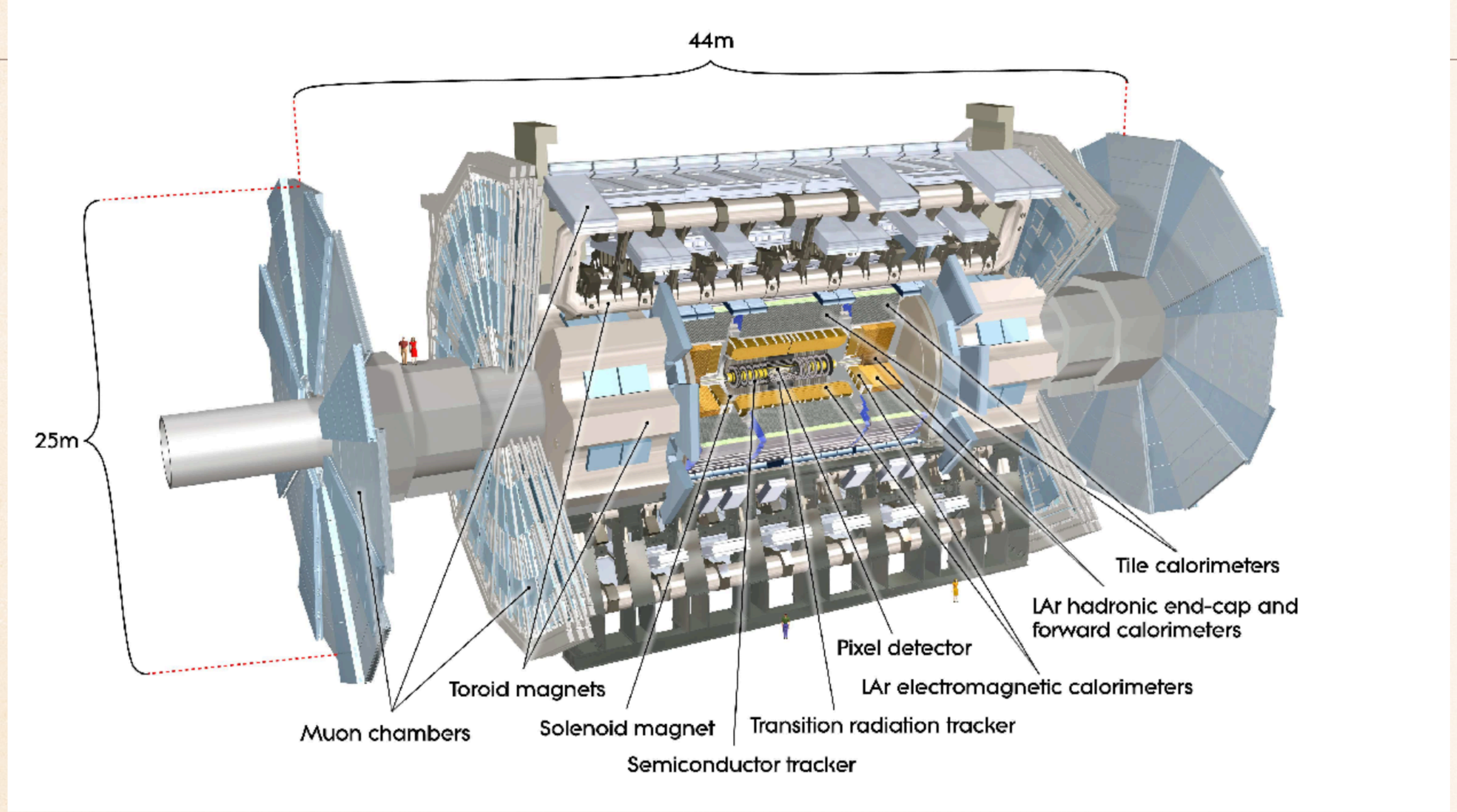
Exotic Hadrons

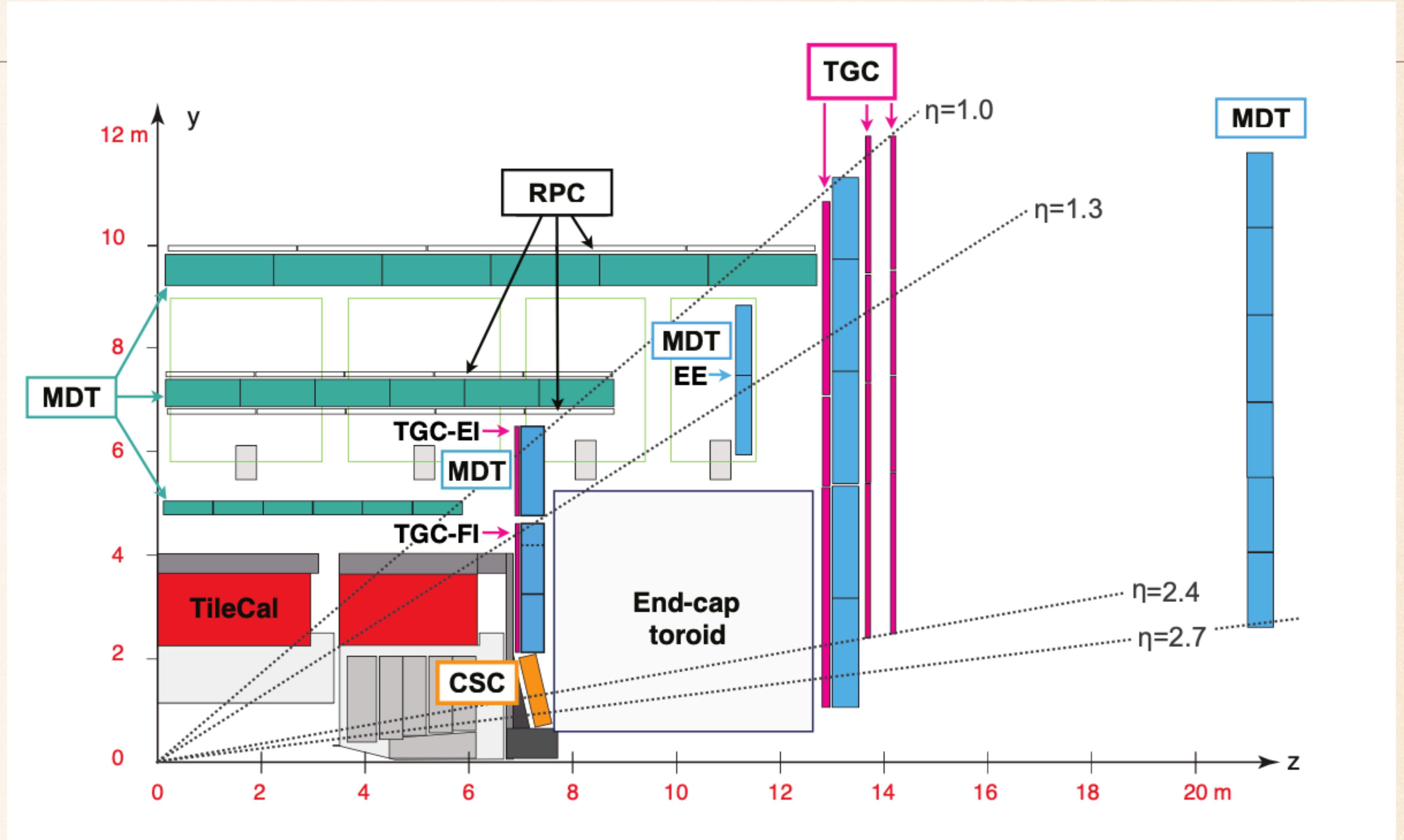




- The first narrow Charmoniumlike State (X3872) was discovered by Belle experiment in the decay products of B mesons
- In June 2020, LHCb claimed an evidence for a narrow resonance at 6.9GeV, which could be the full-charm tetraquark candidate

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

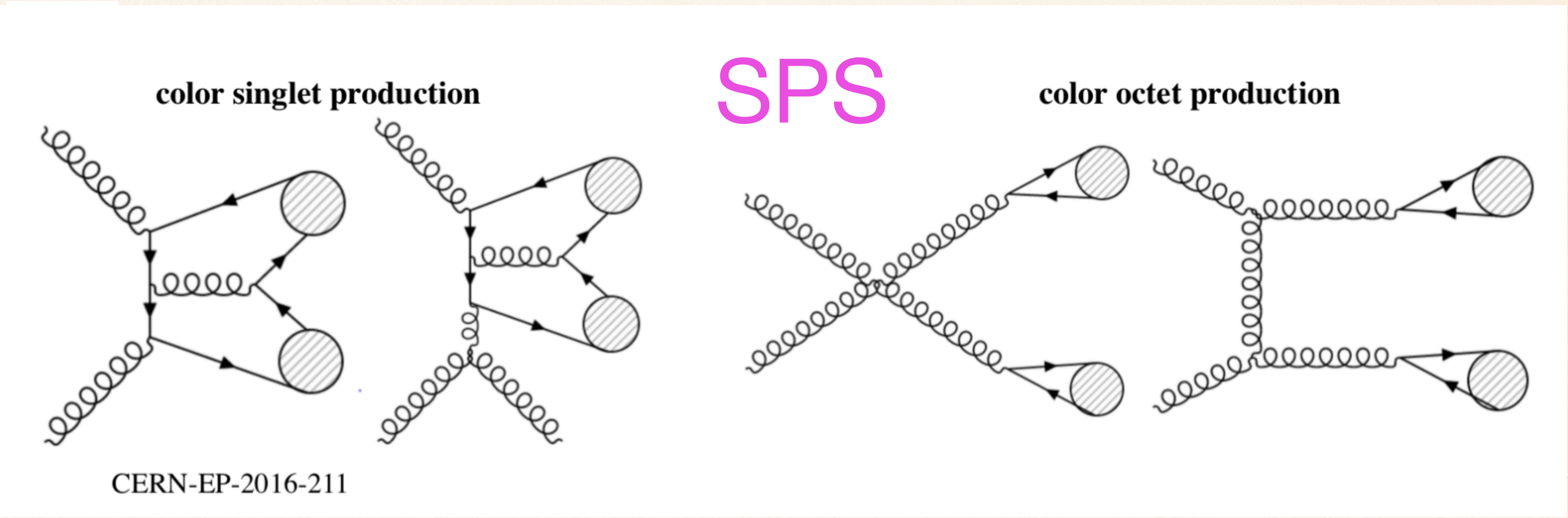
Data, Signal and Backgrounds

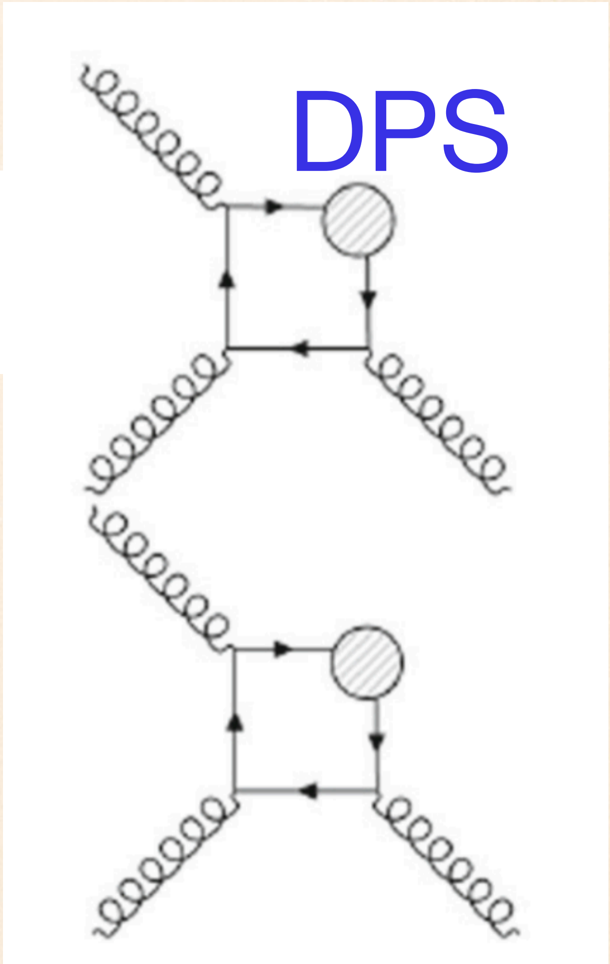
- Data: LHC full Run-2 between 2015-2018, corresponding to 139 fb^{-1} at $\sqrt{s}$=13TeV

- Signal: tetraquark(TQ) → di-J/ψ or $J/\psi + \psi(2S)$ → 4μ.

  where TQ Mass = 6.9GeV and width = 0.1GeV, consistent with LHCb prior result

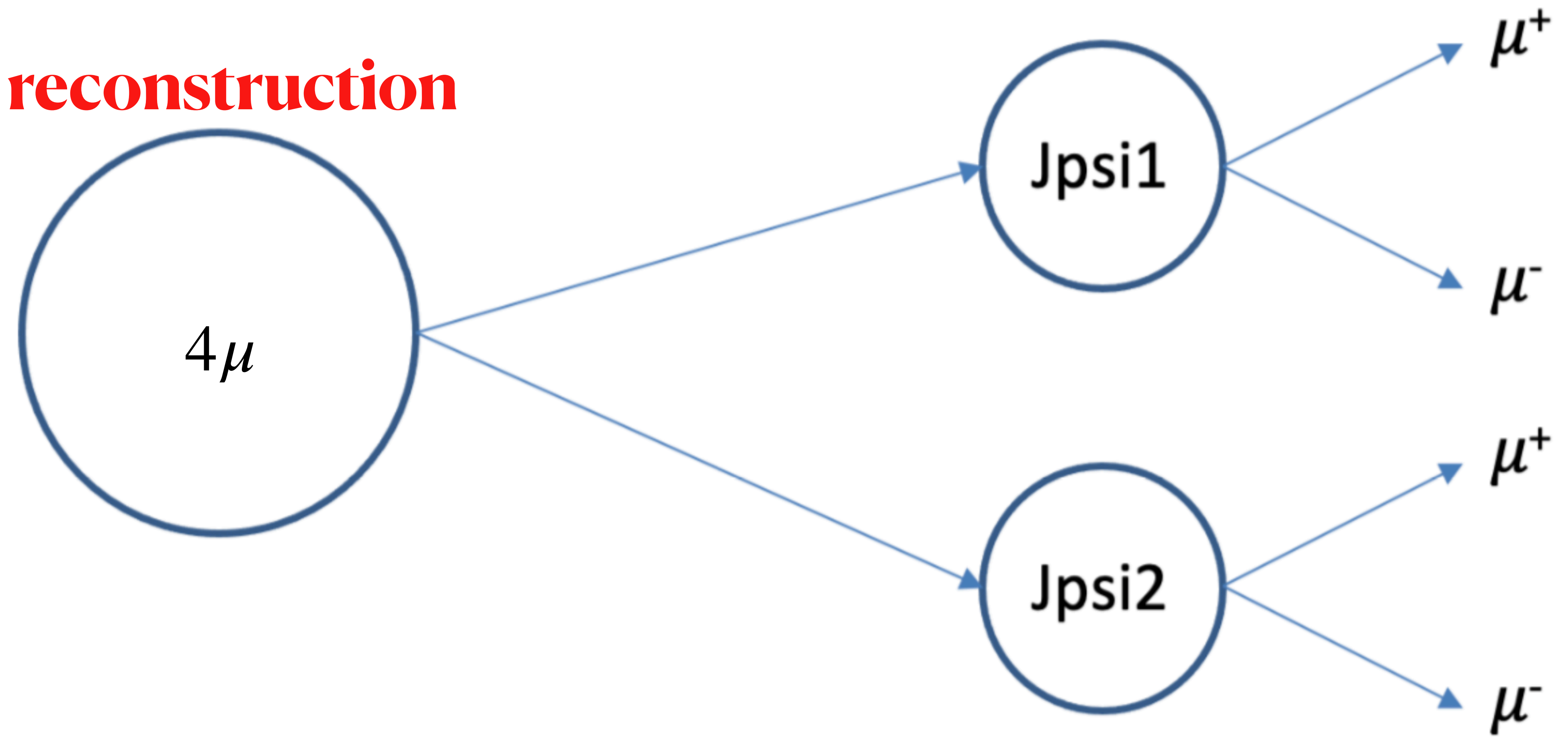
- Background:
  - Single parton scattering (SPS)
  - Double parton scattering (DPS)
  - Non-prompt from b quark decay
  - Single J/ψ background and non-peaking background containing a single or no real J/ψ (others)





Event reconstruction and selection

reconstruction



selection

Signal region	SPS/DPS control region	non-prompt region
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 $\vert\eta_{1,2,3,4}\vert < 2.5$ 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, $\vert L_{xy}^{\text{di-}\mu}\vert < 0.3$ mm,		Vertex $\chi^2_{4\mu}/N > 6$, $\vert L_{xy}^{\text{di-}\mu}\vert > 0.4$ 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)	

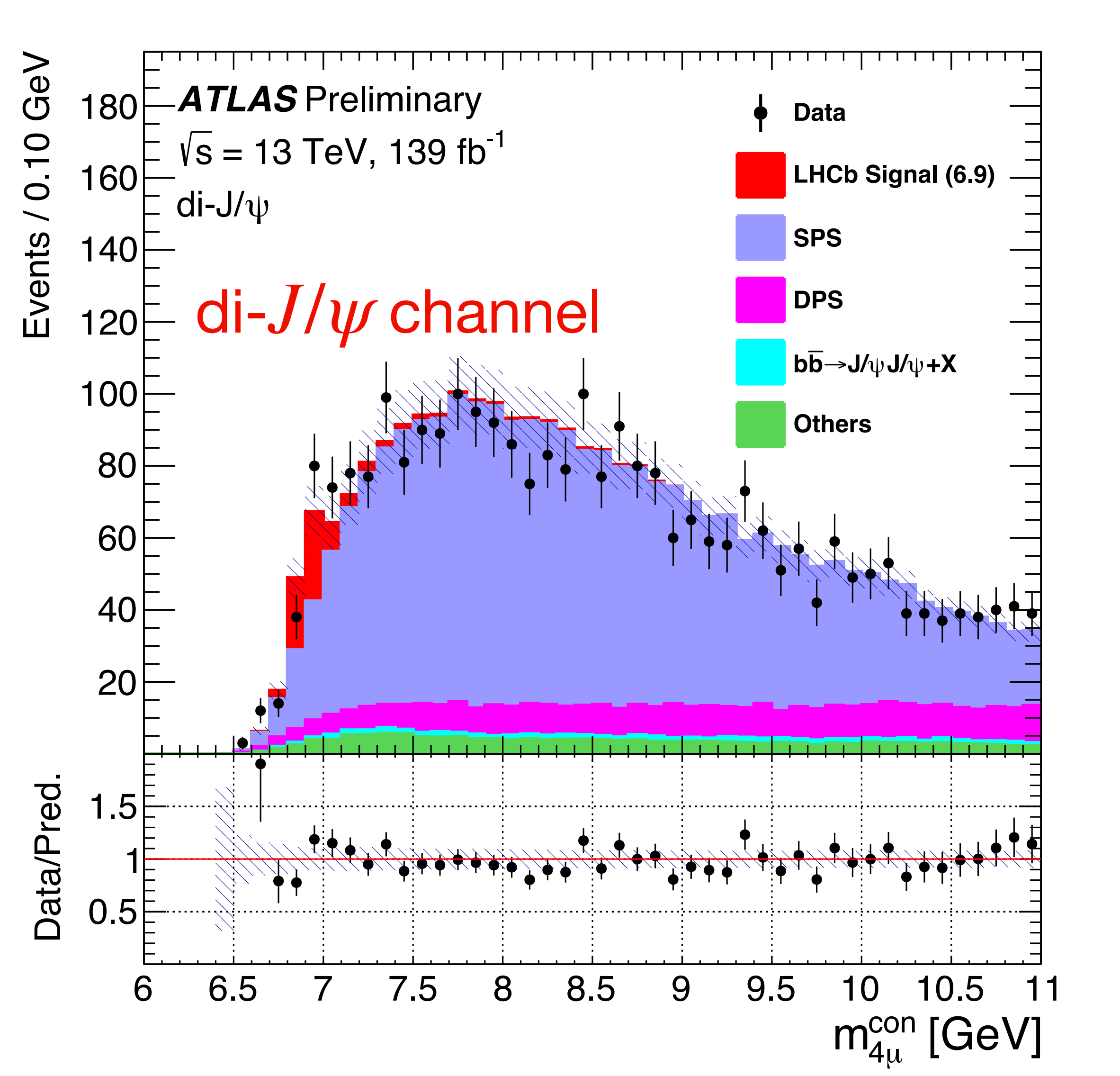
- Four muons with two opposite-charge pairs are fitted to a common vertex by using the inner detector tracks
- Each pair is revertexed with a J/ψ or $\psi(2S)$ mass constraint

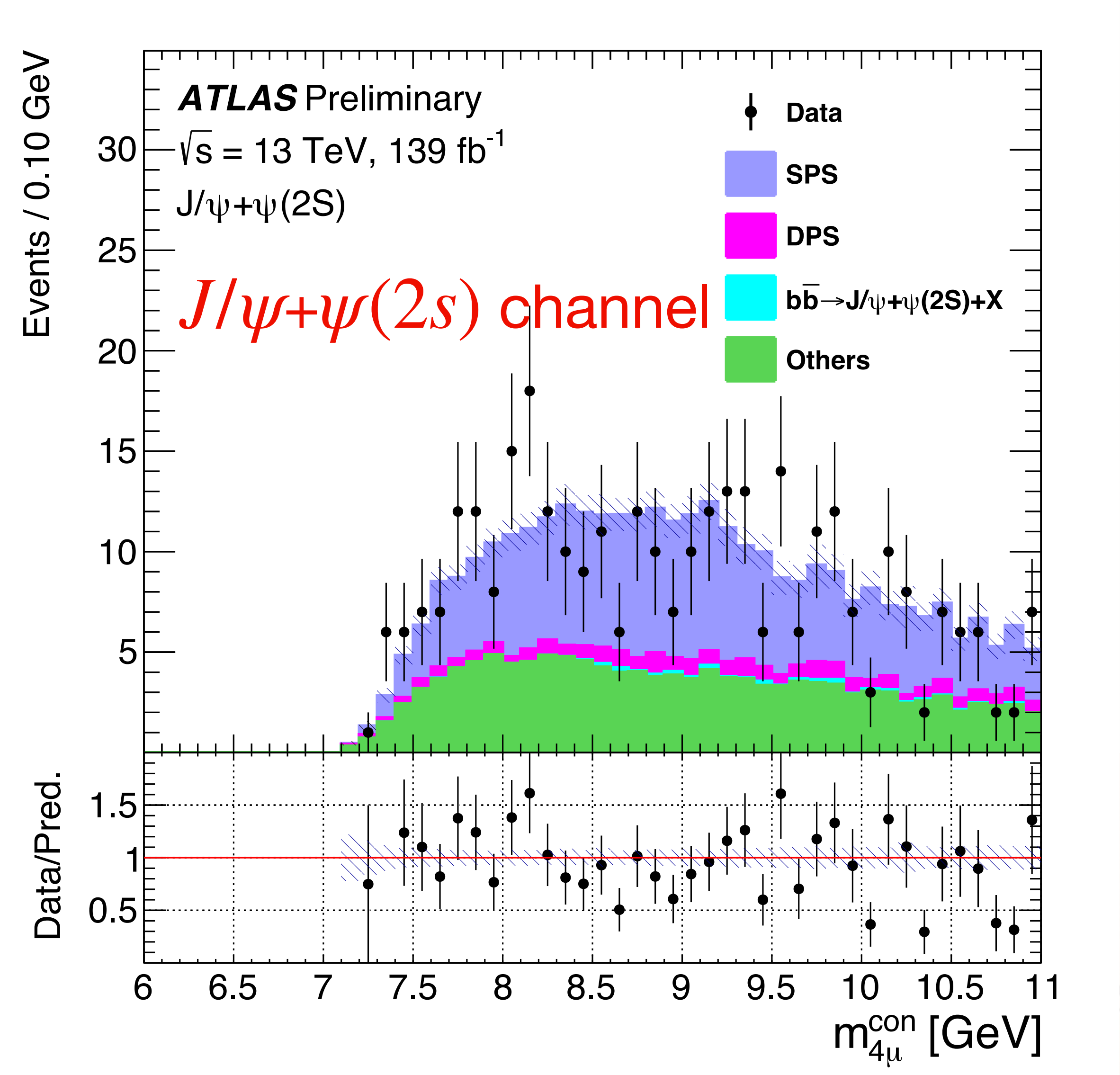
- The cuts in the table are applied to the signal region, SPS/DPS CR or nonprompt region:
- (others) background: fake region and sideband:
  - one J/ψ or $\psi(2S)$ candidate containing a track (not in the “Muons” container)
  - the mass sideband region of J/ψ or $\psi(2S)$

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!



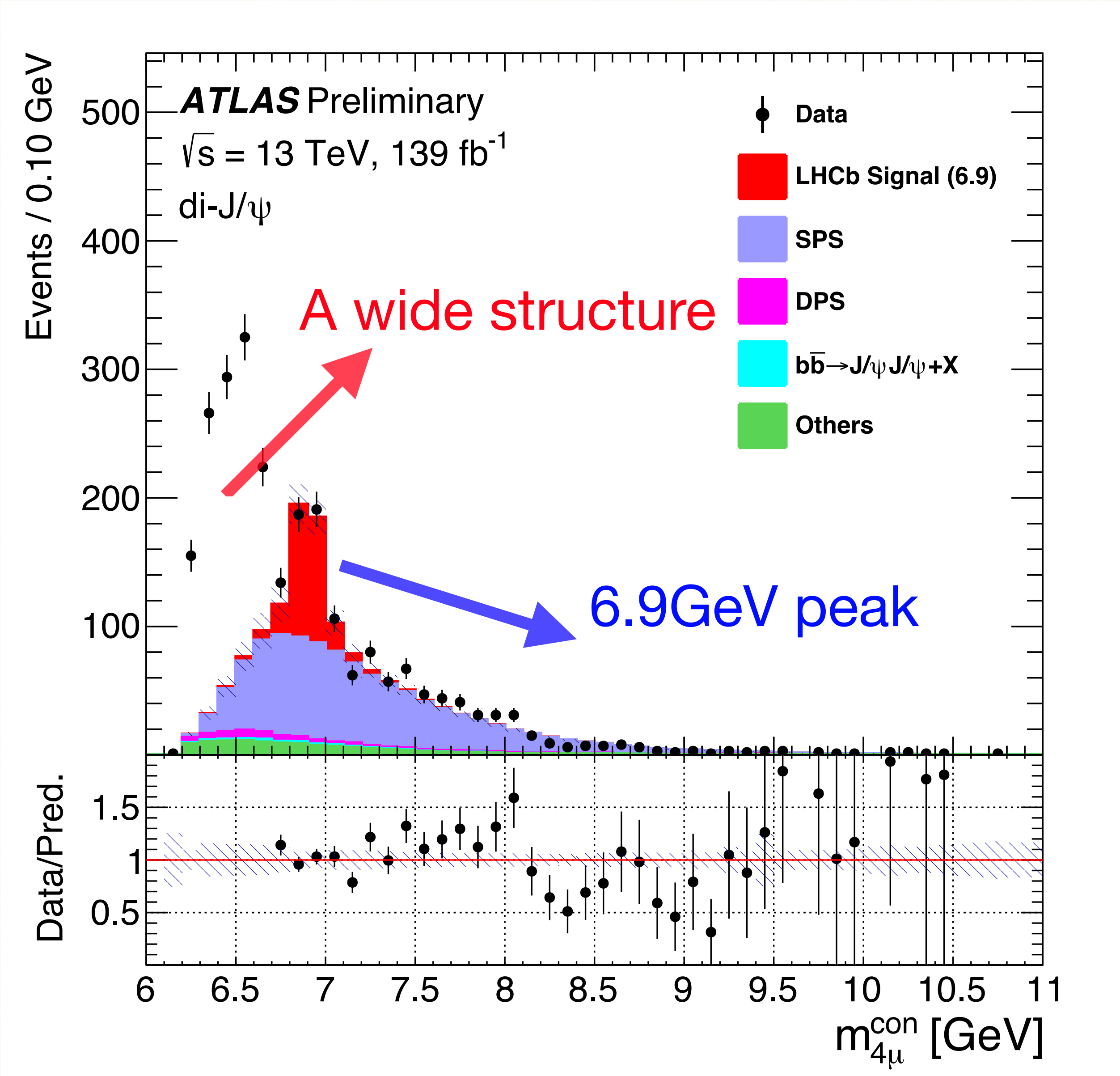


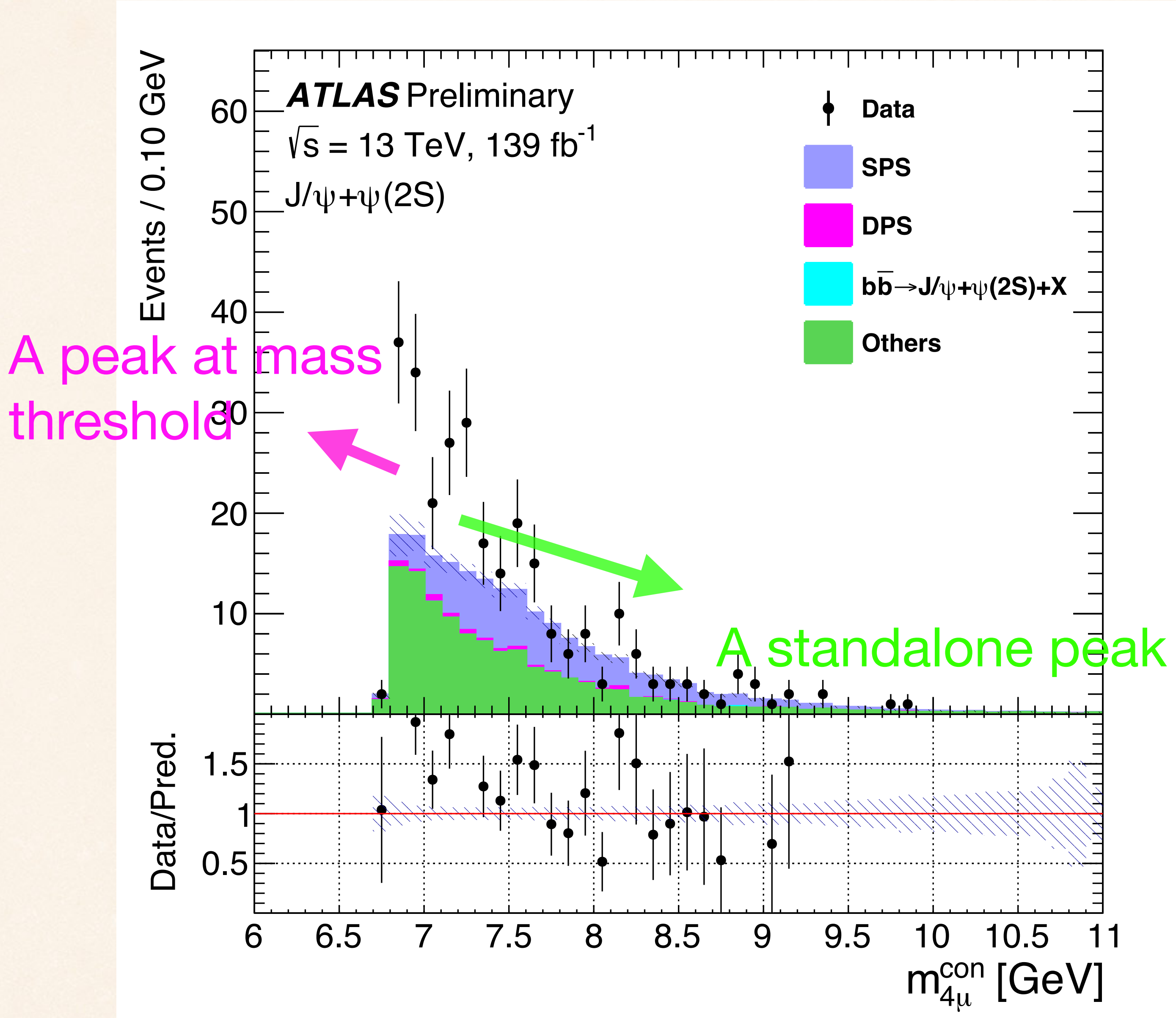
Fit model

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

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

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



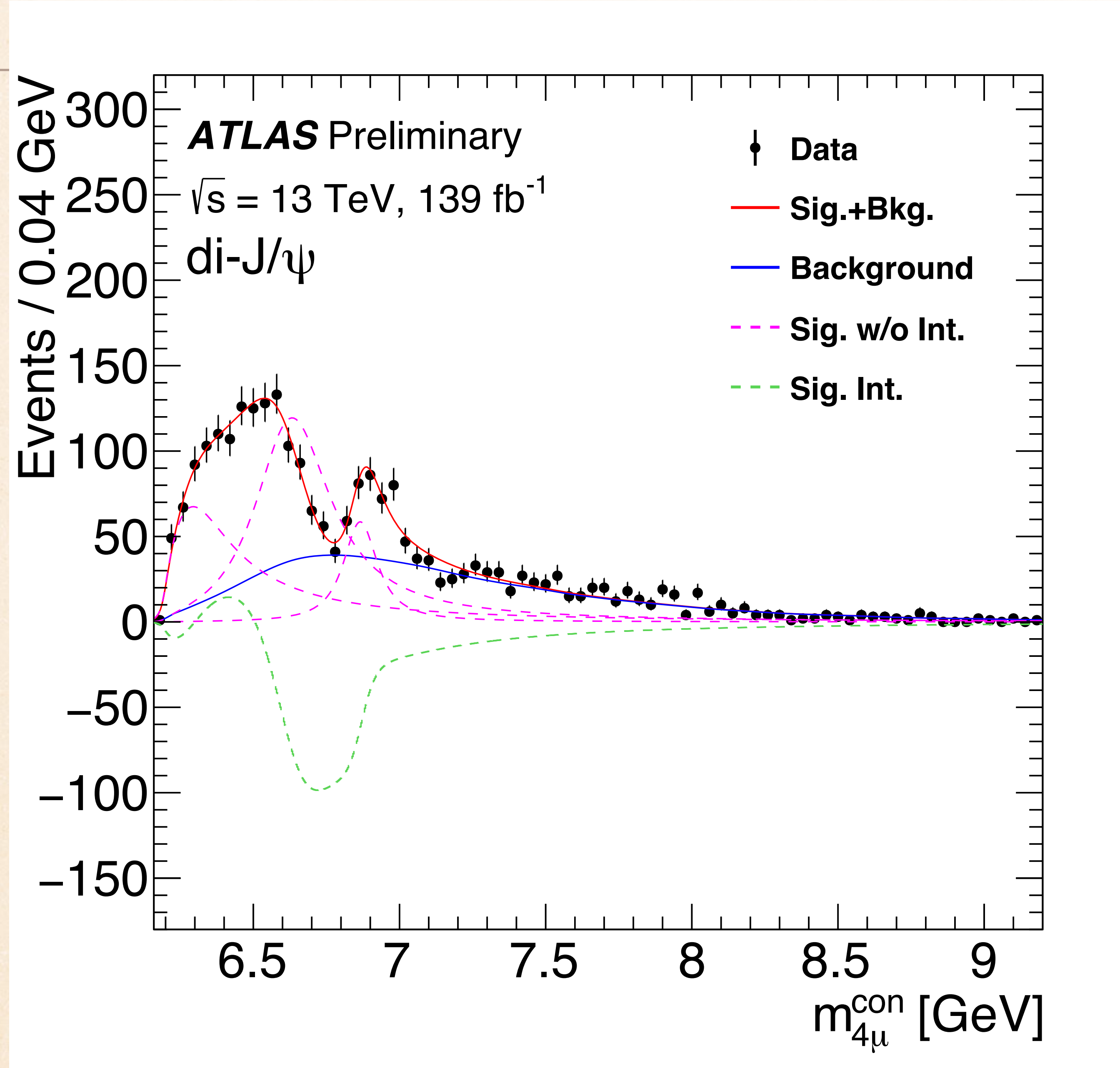


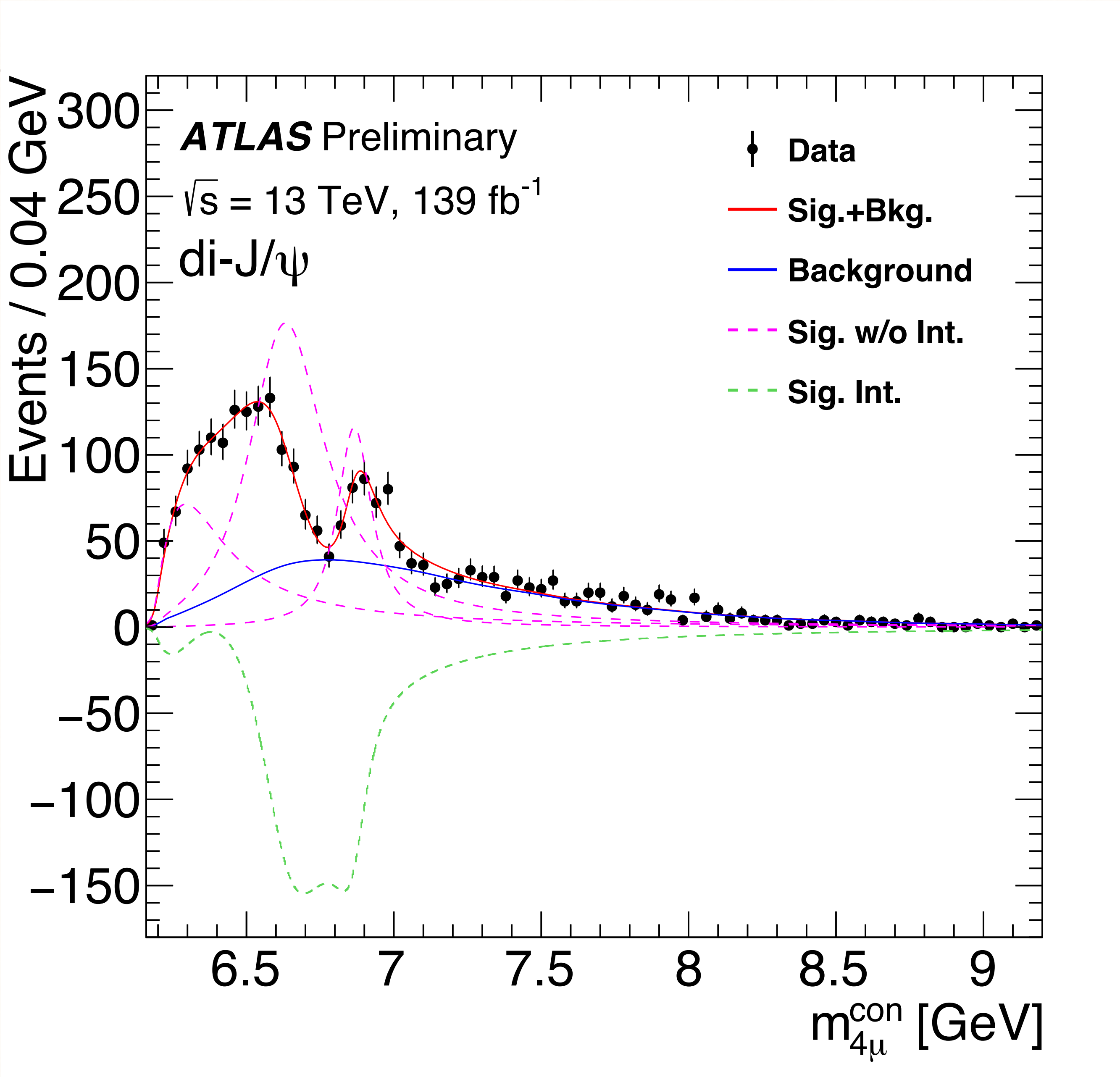
In J/ψ+$\psi(2S)$ channel, two models are considered due to the low statistic:

- 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

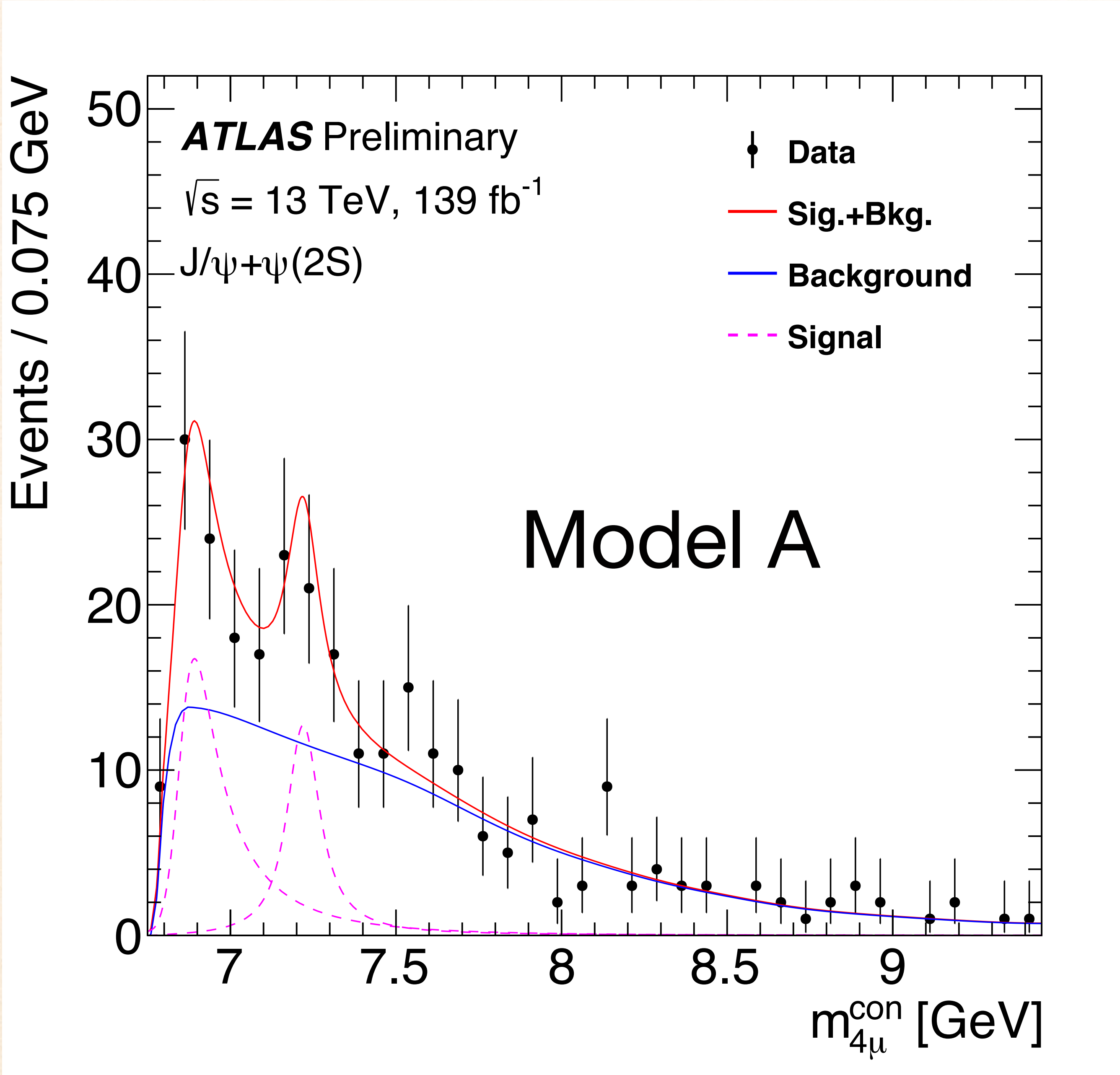


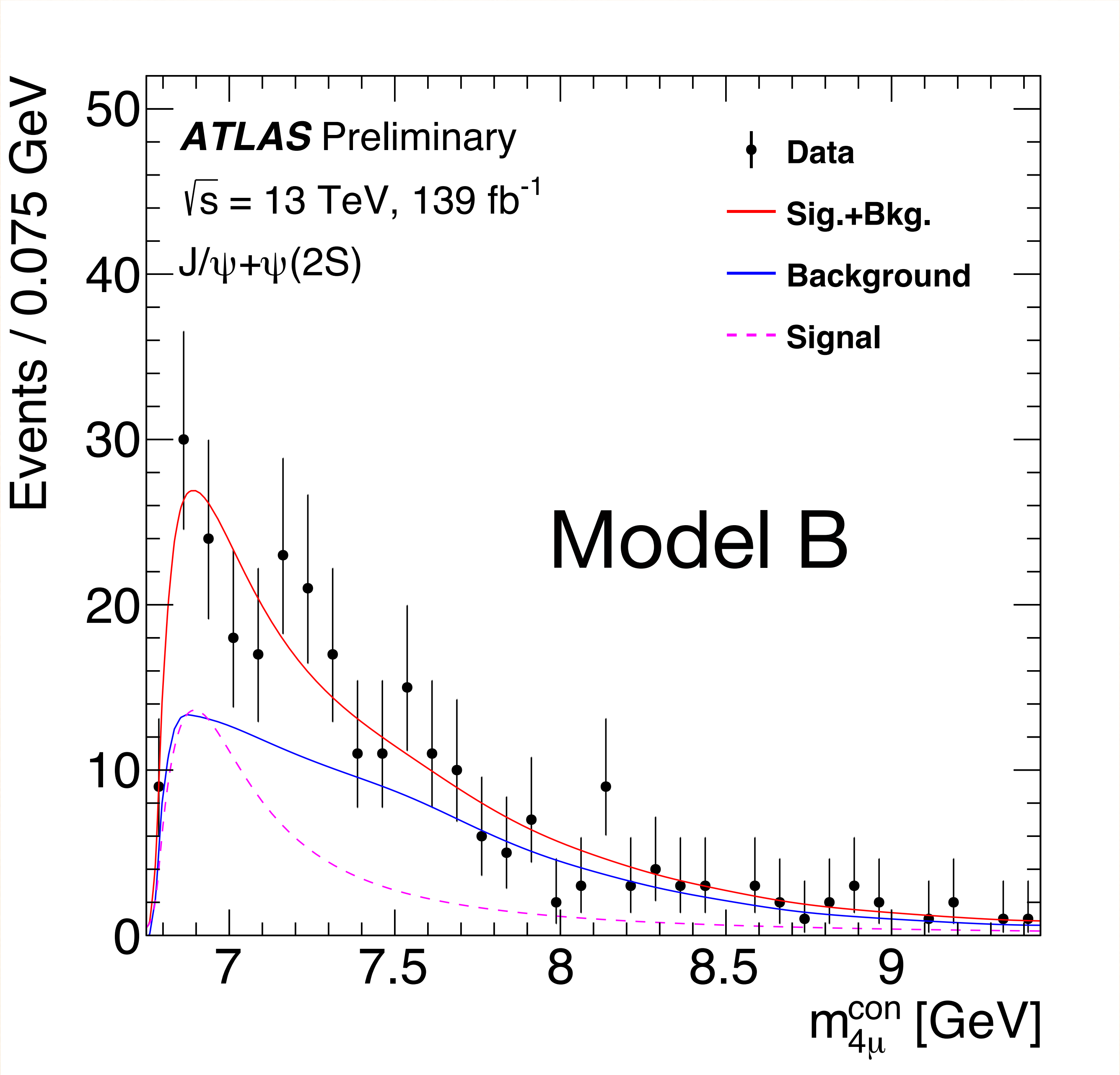


(GeV)	m_0	Γ_0	m_1	Γ_1
di-J/ψ	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2	—	
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	

- The 3rd peak mass is consistent with the LHCb result X(6900), with the significance of 10σ
- The three interfering peaks fit model is favorite by comparing the fit χ^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)

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





(GeV)		m_3	Γ_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	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$	—

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

Systematic

Systematic Uncertainties (MeV)	di-J/ψ m_0	Γ_0	m_1	Γ_1	m_2	Γ_2	J/ψ+ψ(2S) m_3	Γ_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/ψ and J/ψ+$\psi(2S)$ 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 6.9GeV are observed in the di-J/ψ channel.

- A 4.6σ significant excess is observed in the J/ψ+$\psi(2S)$ channel with model that an enhancement at about 6.9 GeV plus a standalone peak.

- More data is need to understand the nature of resonances and threshold structures. Looking forward to the Run 3 data!

Thanks!

Back up

Feed down and Amplitude study

BR[$J/\psi \to \mu\mu$] = 5.96% BR[$\psi(2S) \to \mu\mu$] = 0.8% BR[$\psi(2S) \to J/\psi$+X] = 61.4%

BR[$\psi(2S) \to \mu\mu$+X] = **4.6**BR[$\psi(2S) \to \mu\mu$]

We estimate the yields of Feed Down process from Psi(2S)+Jpsi channel (M6900 and M7200 Psi(2S)->Jpsi+pipi MC)
The fraction of the Feed Down parts is about 30% (very rough)
Refit: only the width of the first peak changes a lot after subtracting the Feed Down yields.

We also study the J^{PC} of the three signal peaks by investigating the final angular distribution, no results so far.