Observation of an excess of di-charmonium events in the four-muon final state with the ATLAS detector

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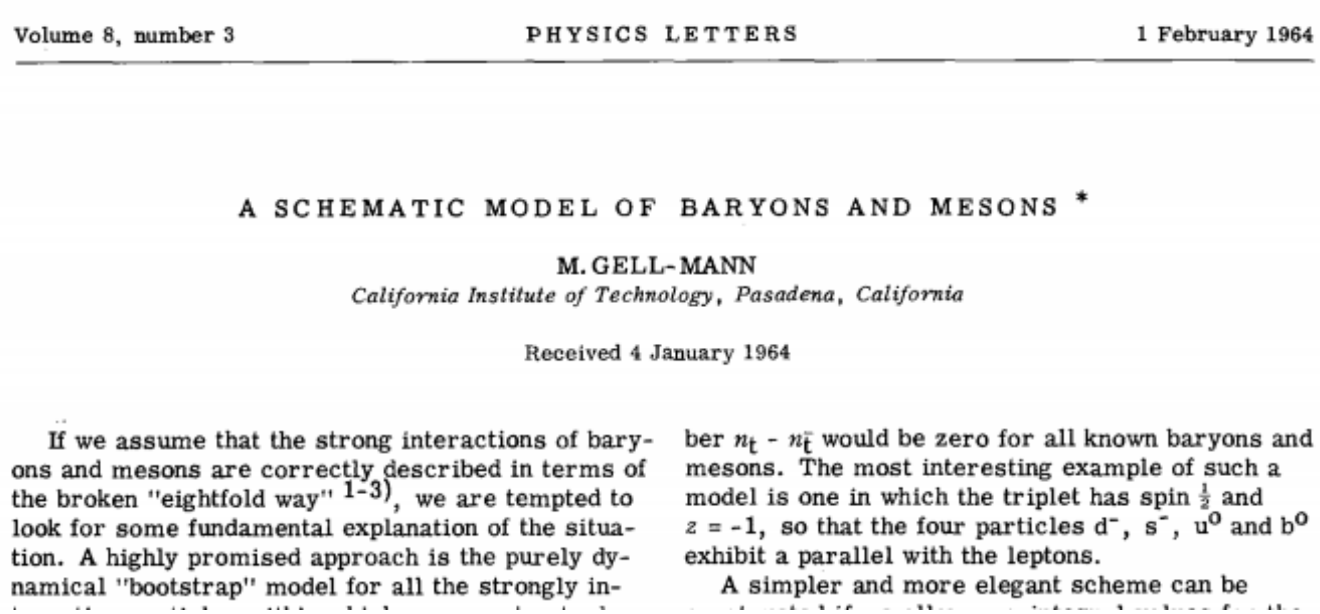
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-040/

Introduction

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



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

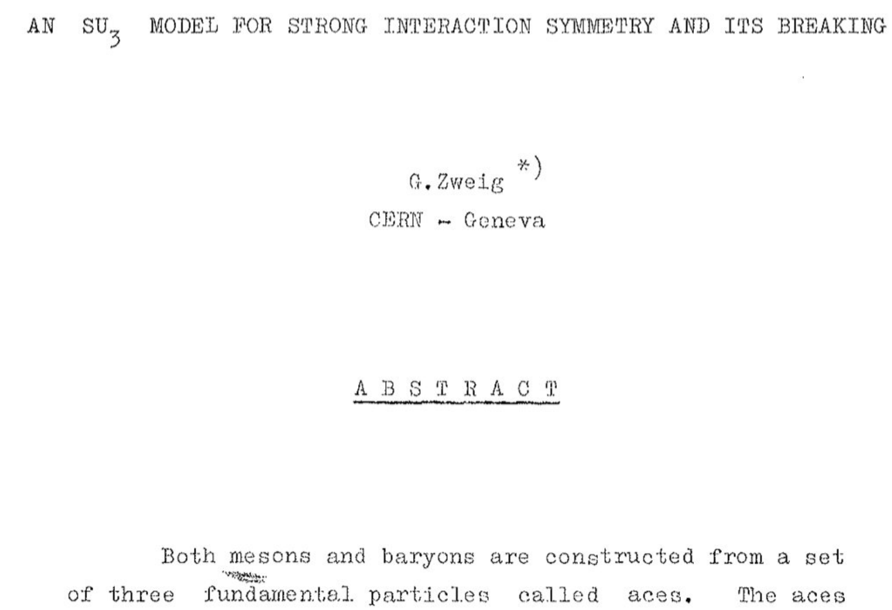
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly in-

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be



AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

ABSTRACT

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces

- Exotic hadrons were predicted at the same time as conventional $q\bar{q}$ mesons and qqq baryons.

Glueball

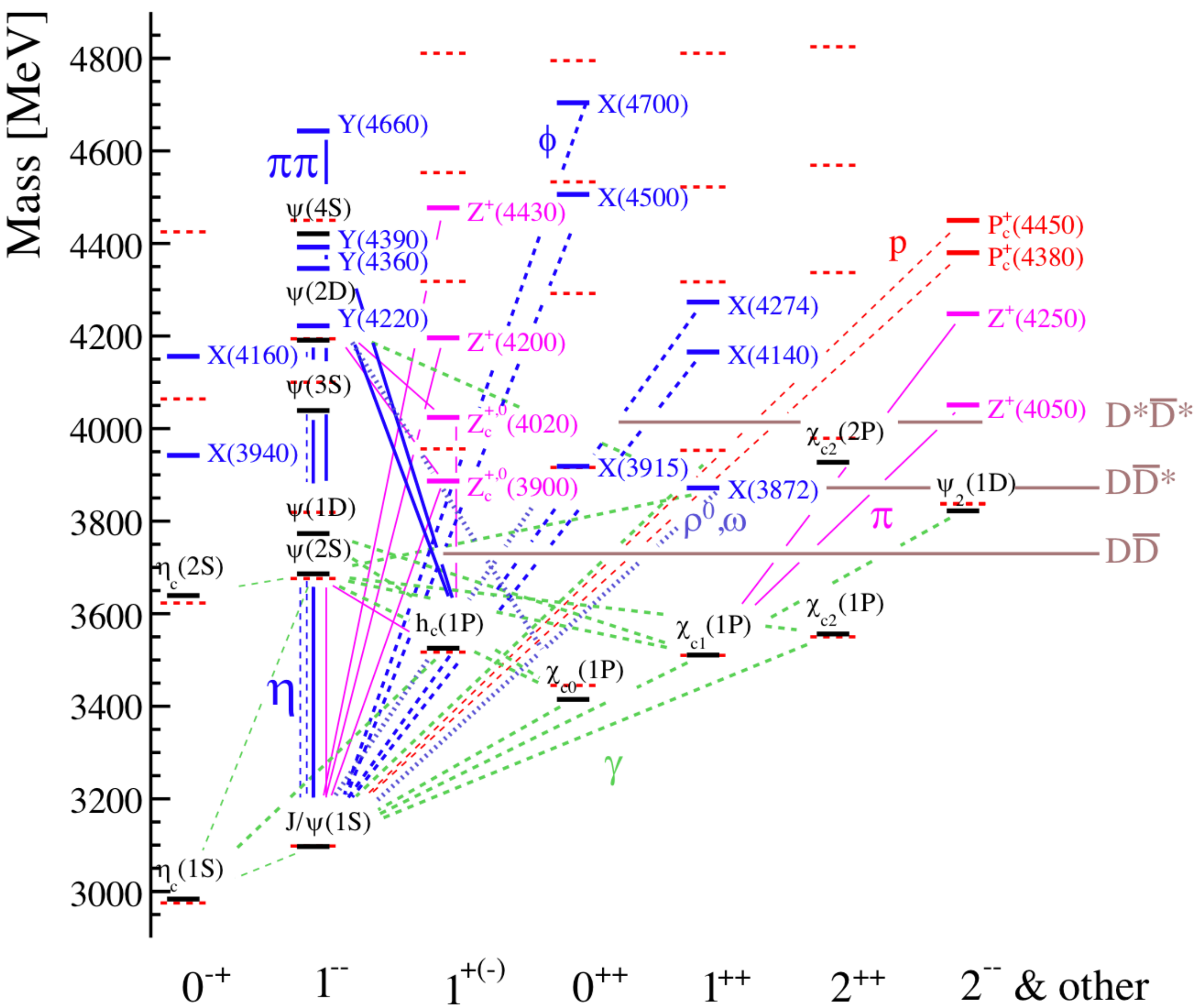
Hybrid meson

Tetraquark

Pentaquark

Exotic hadrons

Charmonium ($c\bar{c}$) -like exotic hadrons



Rev. Mod. Phys. 90, 15003 (2018)

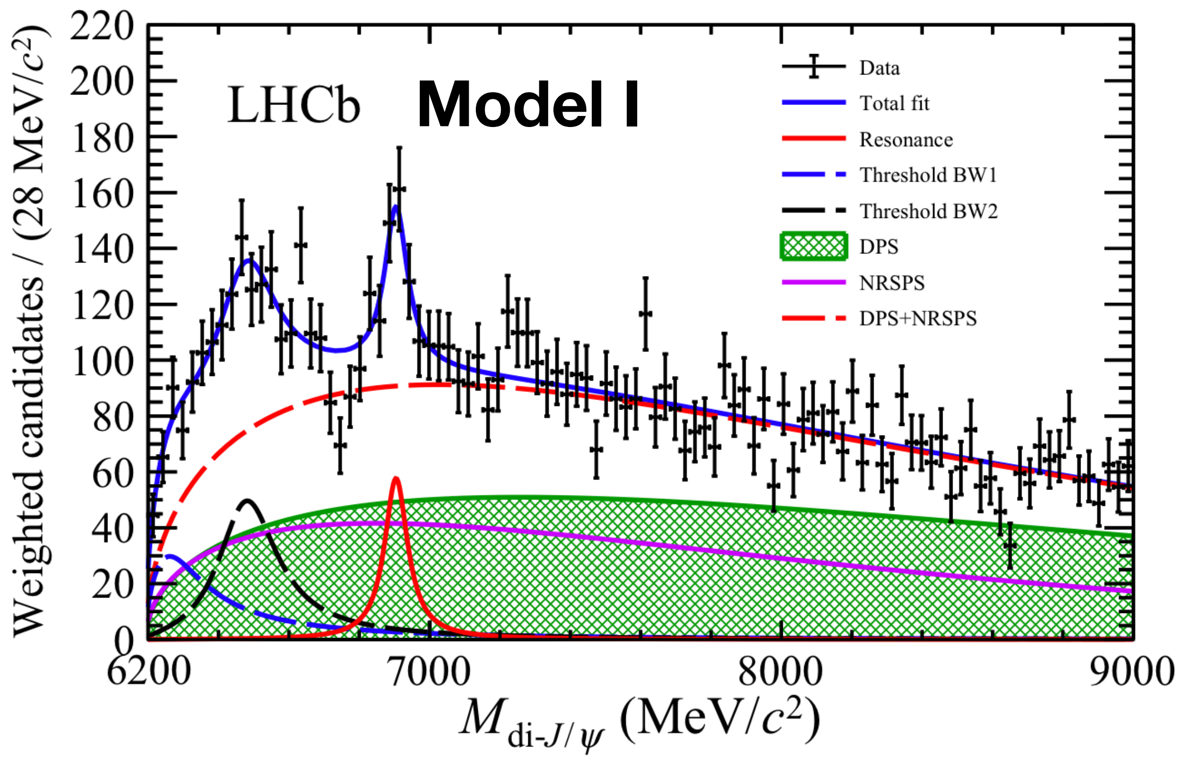
- The X(3872) discovered by Belle in 2003 is the first candidate for an exotic tetraquark state, followed by a series of XYZ states observed by other experiments.
- Lack observations of full-heavy tetraquarks.
- The advantage of fully-heavy tetraquarks is the non-relativistic treatments which largely simplify the calculations, and make theory-experiment comparison easier. Such calculations include lattice QCD, QCD sum rules and potential models.

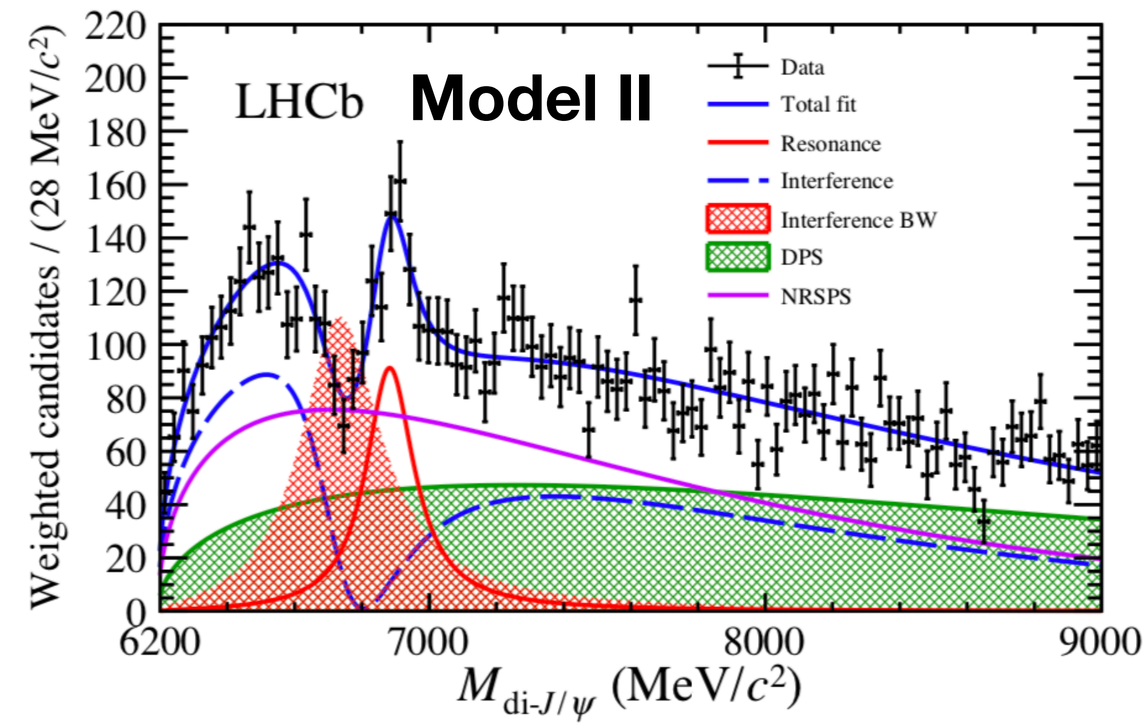
XYZ states:

- X: neutral particle with $J^{PC} \neq 1^{--}$
- Y: neutral particle with $J^{PC} = 1^{--}$
- Z: charged particle

X(6900) from LHCb

- At June 2020, LHCb claimed evidence for a narrow resonance in the di-J/Psi to 4 muons spectrum at **6.9 GeV**, presumably coming from 4-charm quark state.



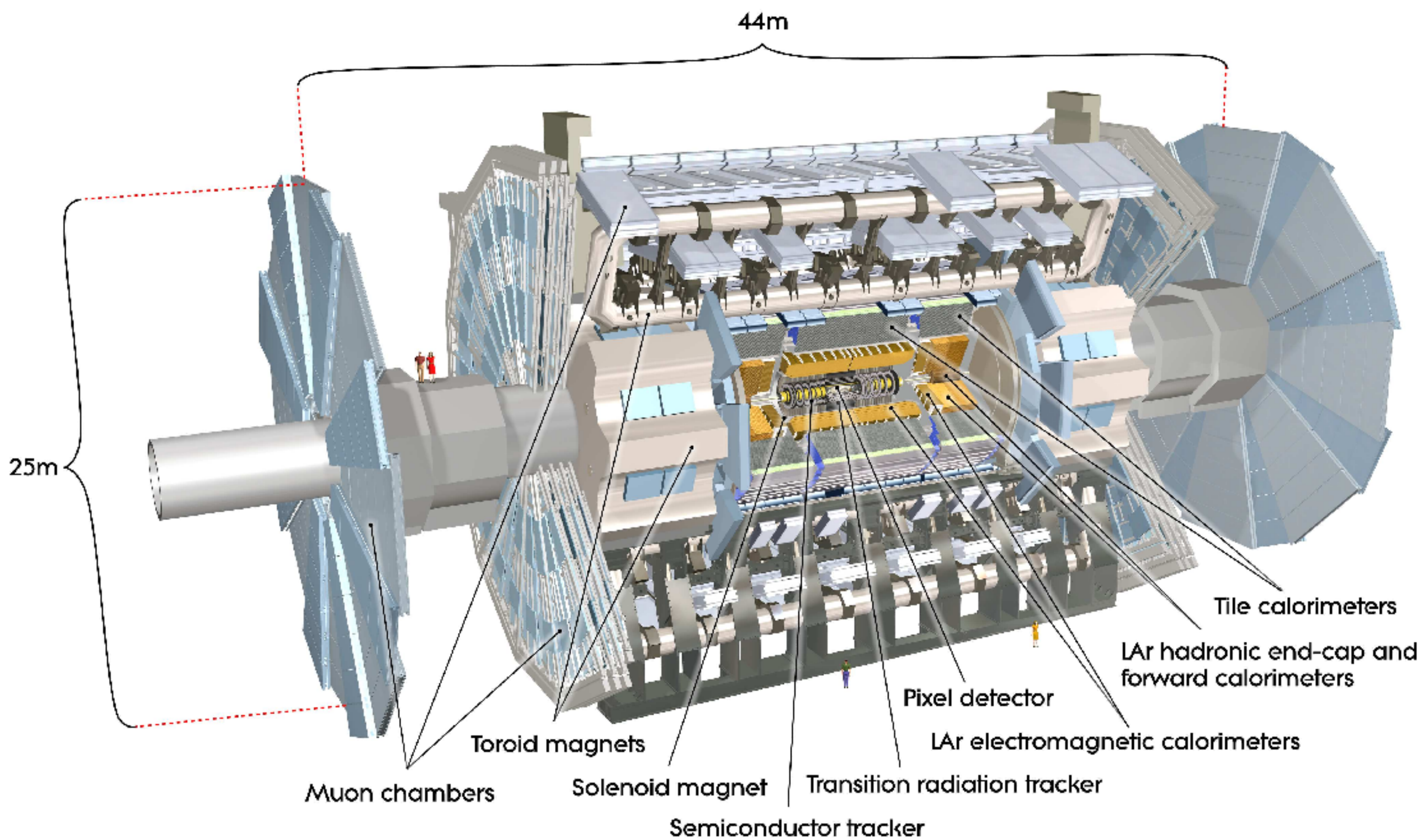


arXiv:2006.16957

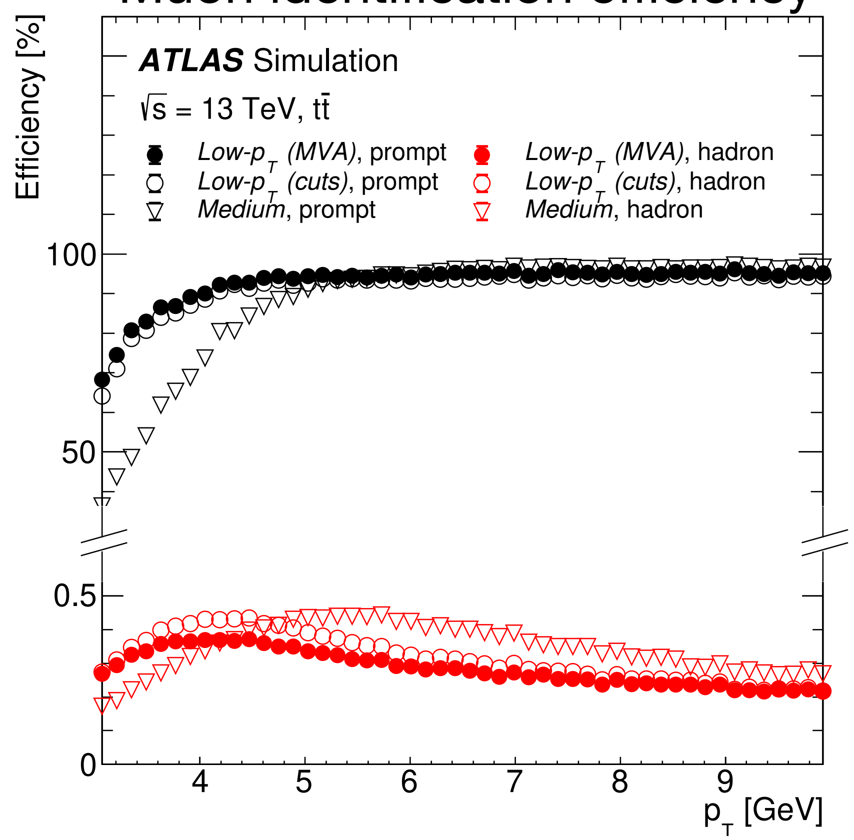
LHCb model I: no interference	$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$ $\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV}$
LHCb model II: interference	$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$ $\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}$

The ATLAS detector and data

- ATLAS (A Toroidal LHC ApparatuS) is one of the two general-purpose detectors at the Large Hadron Collider (LHC)
    - Coverage: $|\eta| < 2.5$
    - Magnetic field: 2T
- Excellent track and muon identification with the goodness of the inner detector and muon spectrometer.
- Data set: Integrated luminosity of $139\ \mathrm{fb}^{-1}$ @ 13 TeV in Run 2 (2015-2018).



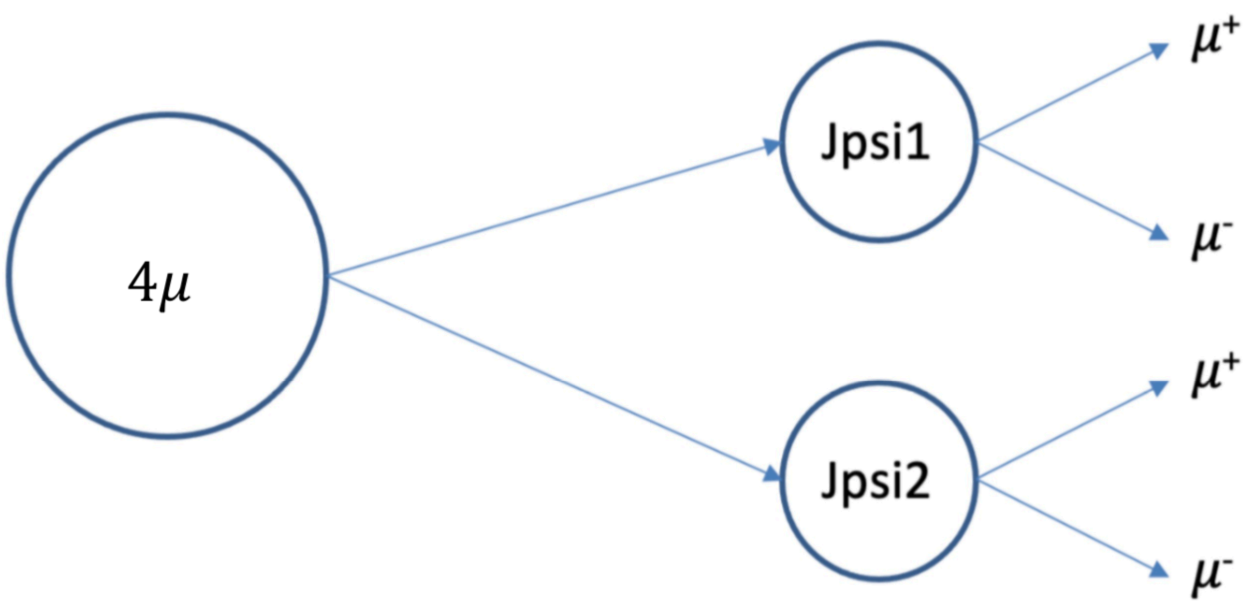
Muon identification efficiency



Eur. Phys. J. C 81 (2021) 578

Signal processes

- Signal process: tetraquark (TQ) $\rightarrow J/\psi + J/\psi$ or $J/\psi + \psi(2S) \rightarrow 4\mu$
- J/ψ or $\psi(2S)$ candidates are reconstructed with $J/\psi/\psi(2S) \rightarrow \mu^+\mu^-$ decay.
- At least four muons with two opposite-charge pairs are fitted to a common vertex.
- Each muon pair is revertex with a J/ψ or $\psi(2S)$ mass constraint, reaching **23 MeV** signal resolution.
- Best 4μ candidate in each event is selected using sum of χ^2/N of two charmonia and 4μ vertices



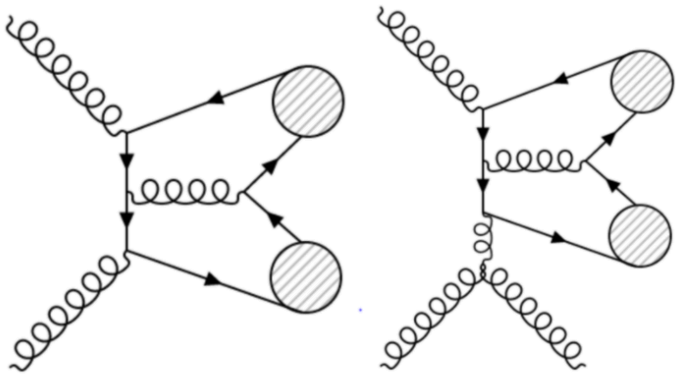
Backgrounds

- **Single parton scattering (SPS)**: a pair of J/ψ mesons can be produced in a single interaction.

- **Double parton scattering (DPS)**: a pair of J/ψ mesons can be produced in two separate interactions of gluons or quarks.

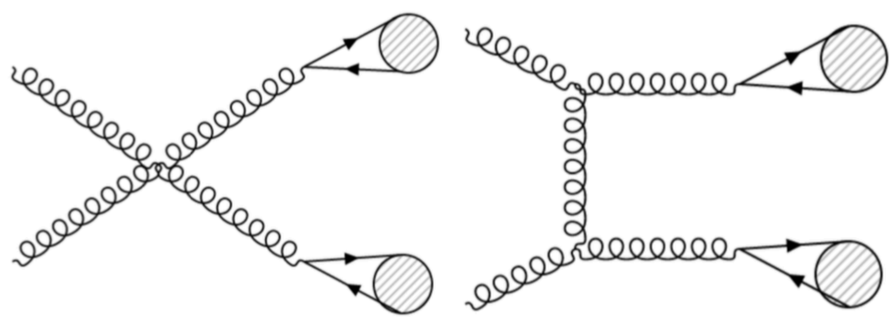
- SPS and DPS are estimated with SPS and DPS control regions which correct normalisations and kinematic variables:

SPS color singlet production

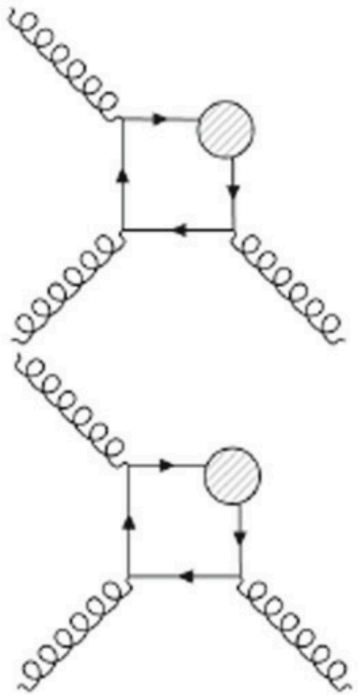


CERN-EP-2016-211

SPS color octet production



DPS



Backgrounds

- **Non-prompt backgrounds** ($b\bar{b} \rightarrow J/\psi + J/\psi/\psi(2S) + X \rightarrow 4\mu$) are modelled with MC and validated with non-prompt region.

- **Other backgrounds** are estimated with data-driven method:

  - Single J/ψ background

  - Non-peaking background containing no real J/ψ candidate

Event selection

✦ Di-muon or tri-muon triggers

✦ Baseline selections:

➡ Two positive charged muons and two negative charged muons:

- $p_T(\mu_1) > 4,\ p_T(\mu_2) > 4,\ p_T(\mu_3) > 3,\ p_T(\mu_4) > 3$ GeV
- $|\eta_{\mu_1,\ \mu_2,\ \mu_3,\ \mu_4}|$ < 2.5

➡ J/ψ mass window: 2.94 GeV< $m_{J/\psi}$ < 3.25 GeV ; $\psi(2S)$ mass window: $3.56 < m_{\psi} < 3.80$ GeV

➡ Loose vertex cuts:

- Vertex fit quality of 4μ candidate: $\chi^2_{4\mu}/N < 40$
- Vertex fit quality of J/ψ and $\psi(2S)$: $\chi^2_{di-\mu}/N < 100$

Analysis regions

- Signal region (SR) is used to extract signal parameters (e.g. mass, width).
- SPS and DPS control regions (CR) are used to estimate SPS and DPS backgrounds.
- Non-prompt region is used to validate non-prompt background estimation.

<table>
<tr><td>SR</td><td rowspan="3">Tight vertex cuts:
$|L_{xy}^{di-\mu}| < 0.3$ mm
$L_{xy}^{4\mu} < 0.2$ mm
$\chi^2_{4\mu}/N < 3$</td><td>$m_{4\mu} < 7.5$ GeV,
$\Delta R < 0.25$ between charmonia</td></tr>
<tr><td>SPS CR</td><td>7.5 GeV $< m_{4\mu} < 12.0$ GeV</td></tr>
<tr><td>DPS CR</td><td>14.0 GeV $< m_{4\mu} < 25.0$ GeV</td></tr>
<tr><td>Non-prompt region</td><td colspan="2">Reverse vertex cuts: $\chi^2_{4\mu}/N > 6$ and $|L_{xy}^{di-\mu}| > 0.4$ mm</td></tr>
</table>

Fit models

- Unbinned maximum likelihood fits are performed to extract the signal parameters (e.g. mass m, width Γ)

$$\mathcal{L} = \mathcal{L}_{SR}\left(\vec{\alpha}, \vec{\beta}\right) \cdot \mathcal{L}_{CR}\left(\vec{\alpha}\right) \cdot \prod_{j=1}^{K} G\left(\alpha_j'; \alpha_j, \sigma_j\right)$$

- Fit regions:
  - Fit SR: $m_{4\mu}^{\text{con}} < 11$ GeV and $\Delta R < 0.25$
  - Fit CR: $m_{4\mu}^{\text{con}} < 11$ GeV and $\Delta R \geq 0.25$

- In di-J/ψ channel, **3-peak model** with interference among signals is considered. 2-peak model is also tested but with worse fit quality.

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

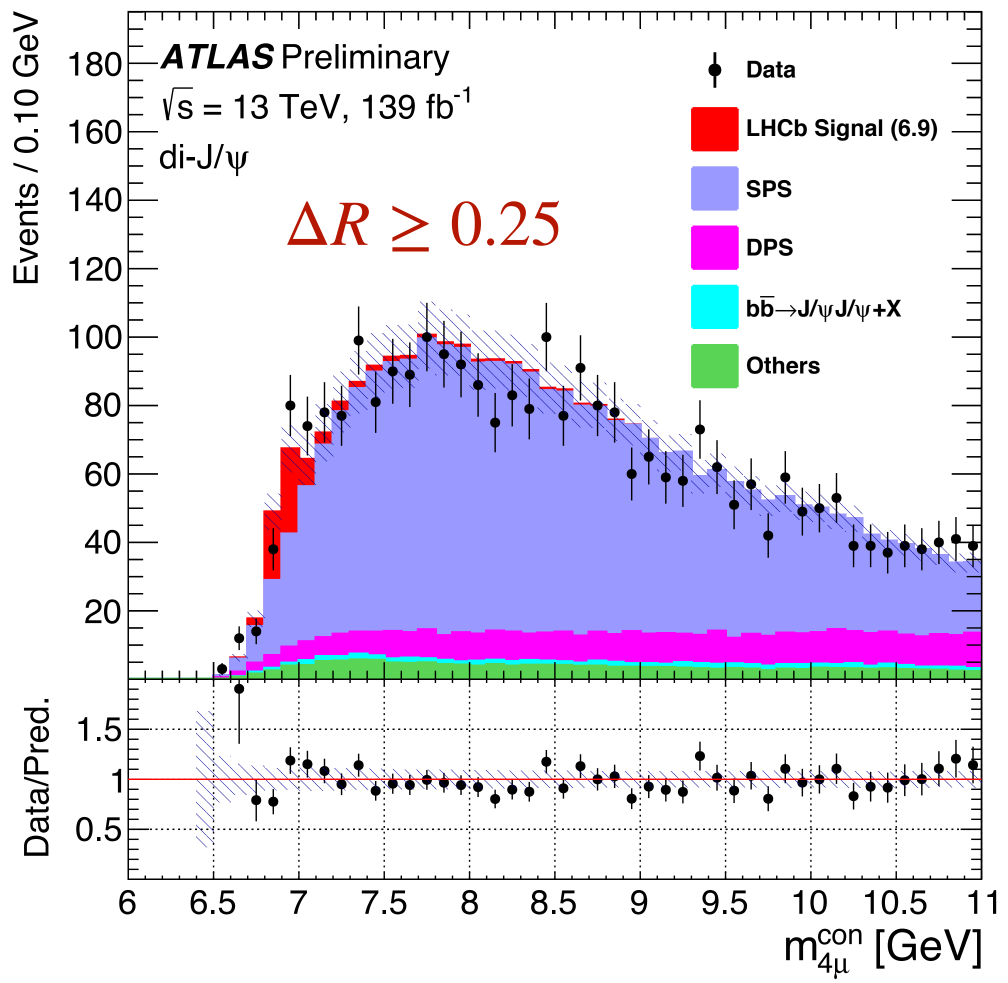
Fit models

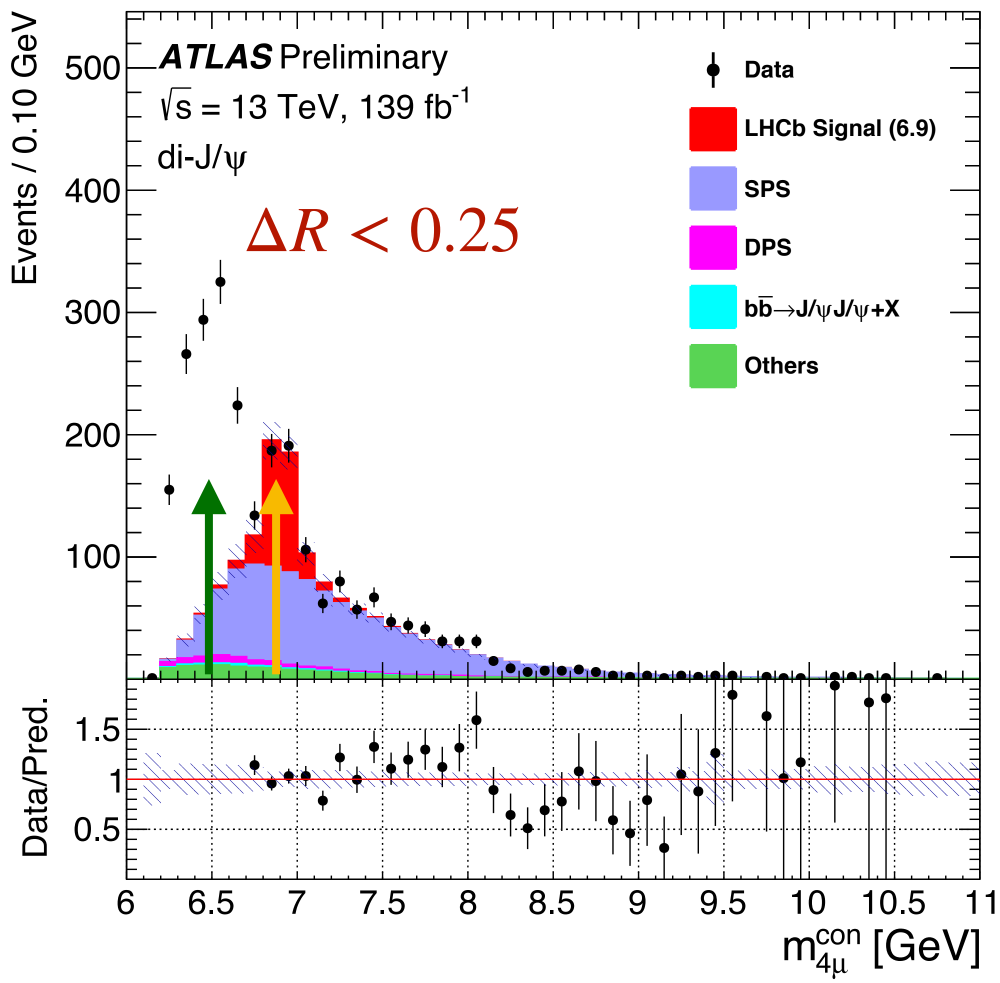
- In $J/\psi + \psi(2S)$ channel, due to lower statistics, two models are considered.
    - Model A: the same peaks with interference observed in the di-J/ψ channel also decaying into $J/\psi + \psi(2S)$ plus a standalone peak.

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

    - Model B: only one single peak

Fit regions in di-J/ψ channel

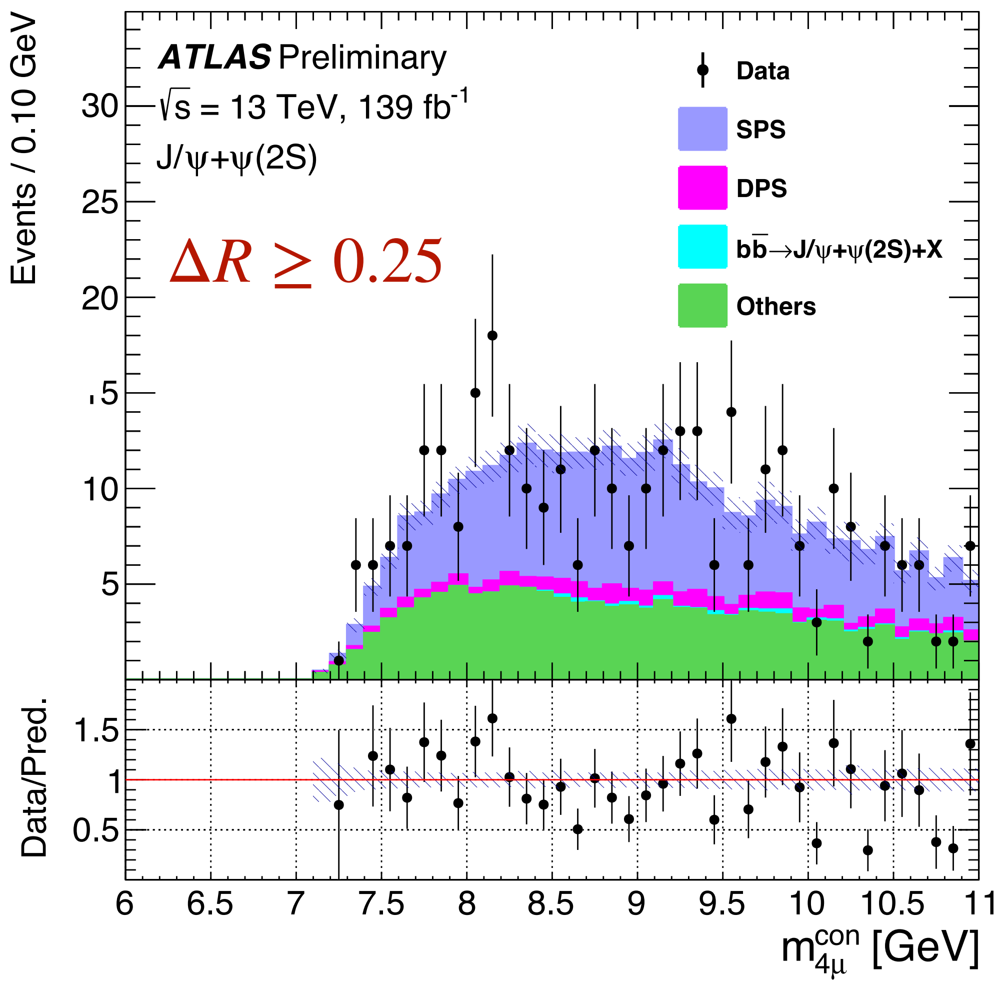


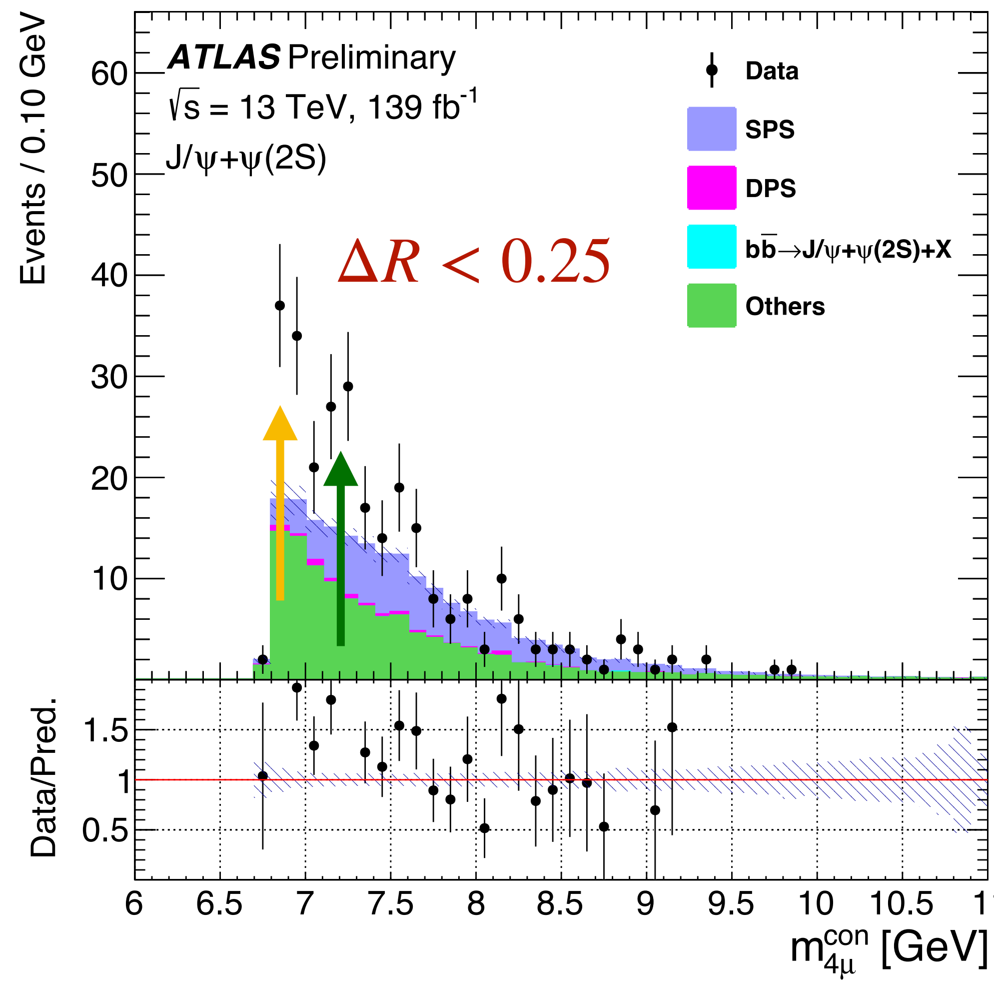


- SPS mass shape is modelled well in signal region.

- A broad structure near threshold from **6.2 to 6.8 GeV**
- A narrow structure around **6.9 GeV**

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





- SPS mass shape is modelled well in signal region.

- A narrow structure around **6.9 GeV**
- Hint for another narrow structure around **7.2 GeV**

Fit results in di-J/ψ channel

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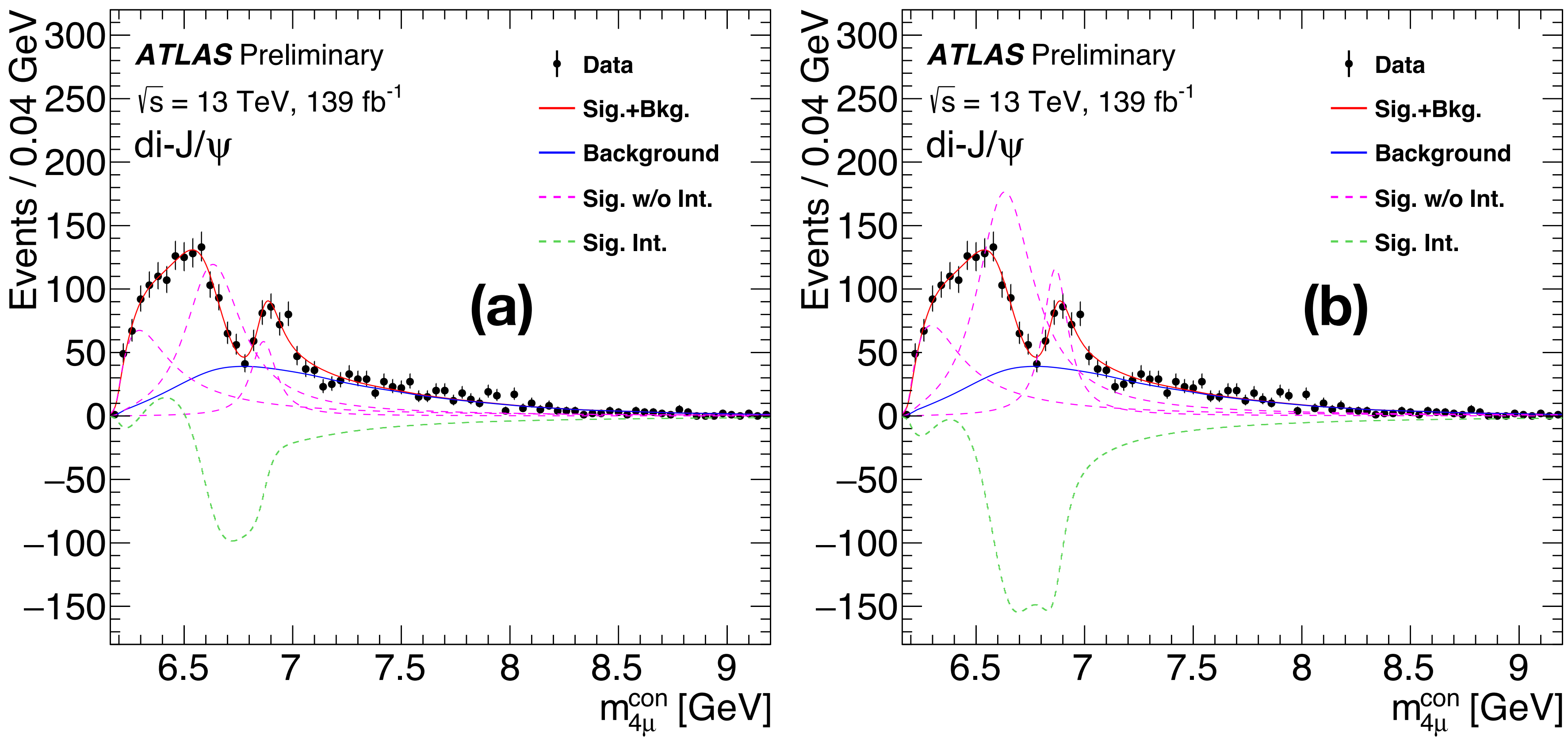

- The **3rd peak** mass is consistent with the LHCb observed X(6900), with significance of **10σ**
- The broad structure at the lower mass could from other physical effects, e.g. feed-down from higher di-charmonium resonances

Extracted masses and widths (GeV)

(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	—	
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	

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

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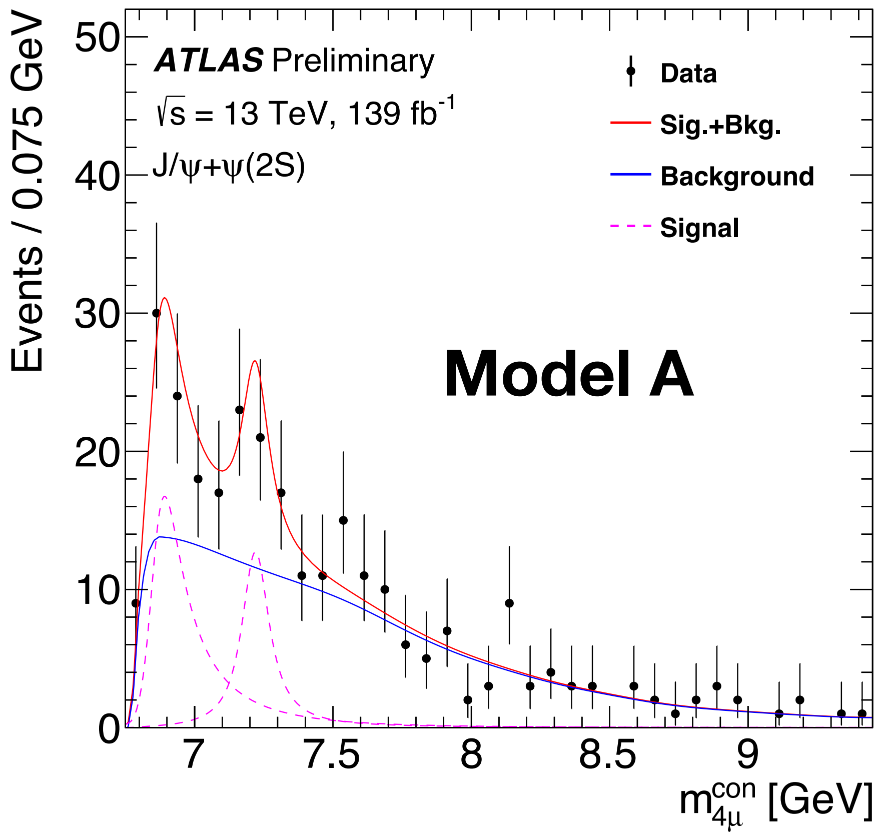

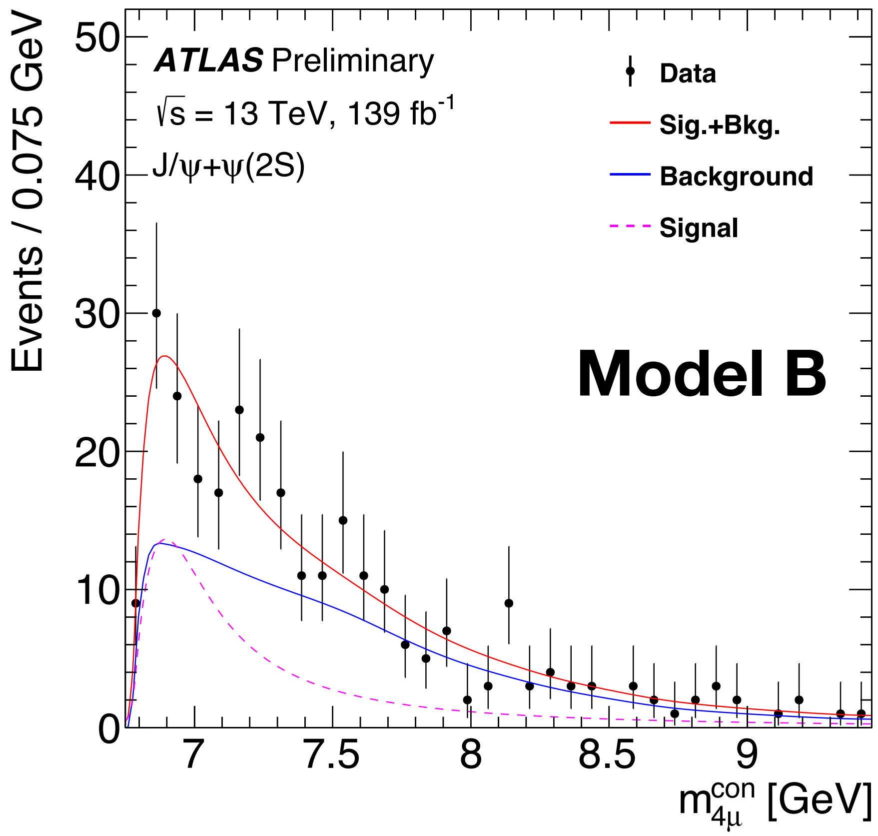

Extracted masses and widths (GeV)

(GeV)		m_3	Γ_3
J/ψ+ψ(2S)	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$

- 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 in the di-J/ψ spectrum

Systematics

Systematics (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 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 peak	29	49	11	108	60	18	—	
Interference of fourth peak	—						29	11
Data statistics	50	119	34	88	30	39	28	130

- Data statistics and systematics of fourth peak have the largest impact in both two channels.

Summary

- A broad structure at lower mass and a resonance around 6.9 GeV are observed in the di-J/ψ channel.

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

- Details of the lower mass structures cannot be well resolved now.

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

Thanks!

BACKUP

X(6900) from LHCb

Minimal quark content	Current name	$I^{(G)},\ J^{P(C)}$
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+,\ J^{PC} = 1^{++}$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+,\ J^P = 1^+$
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G = 1^-$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+,\ J^P = 1^+$
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+, J^{PC} = 1^{++}$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2},\ J^P = 1^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2},\ J^P = 1^?$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+,\ J^{PC} = ?^{?+}$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$

arXiv:2206.15233

Mass calculation with QCD sum rule method

J^{PC}	Currents	$m_{cc\bar{c}\bar{c}}$ (GeV)
0^{++}	$J_1^{0^{++}}$	6.44 ± 0.15
	$J_2^{0^{++}}$	6.46 ± 0.16
1^{+-}	$J_{3\alpha}^{1^{+-}}$	6.51 ± 0.15
2^{++}	$J_{4\alpha\beta}^{2^{++}}$	6.51 ± 0.15
0^{-+}	$J_5^{0^{-+}}$	6.84 ± 0.18
	$J_6^{0^{-+}}$	6.85 ± 0.18
0^{--}	$J_7^{0^{--}}$	6.84 ± 0.18
1^{-+}	$J_{8\alpha}^{1^{-+}}$	6.84 ± 0.18
	$J_{9\alpha}^{1^{-+}}$	6.88 ± 0.18
1^{--}	$J_{10\alpha}^{1^{--}}$	6.84 ± 0.18
	$J_{11\alpha}^{1^{--}}$	6.83 ± 0.18

arXiv:2204.02649

From theory side, it may be interpreted as a P-wave $cc\bar{c}\bar{c}$ tetraquark.

From experiment side:

- Observation needed to be confirmed
- Properties needed to be studied

Event selection

<table>
<tr><th>Signal region</th><th>SPS/DPS control region</th><th>non-prompt region</th></tr>
<tr><td colspan="3">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 $|\eta_{1,2,3,4}| < 2.5$ 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 $\chi^2_{\text{di-}\mu}/N < 100$,</td></tr>
<tr><td colspan="2">Vertex $\chi^2_{4\mu}/N < 3$,
$L^{4\mu}_{xy} < 0.2$ mm, $|L^{\text{di-}\mu}_{xy}| < 0.3$ mm,</td><td rowspan="2">Vertex $\chi^2_{4\mu}/N > 6$,
$|L^{\text{di-}\mu}_{xy}| > 0.4$ mm</td></tr>
<tr><td>$m_{4\mu} < 7.5$ GeV,
$\Delta R < 0.25$ between charmonia</td><td>7.5 GeV$< m_{4\mu} < 12.0$ GeV (SPS)
14.0 GeV$< m_{4\mu} < 25.0$ GeV (DPS)</td></tr>
</table>

Checks

- In the di-J/ψ channel, a two-resonance fit is also attempted, but its fit quality χ^2/N is about 70% worse than the three-resonance model.

- The fit is repeated with the mass and width of the third resonance fixed to the values obtained by LHCb model I. It is found that χ^2/N increases by about 2% in our model, and changes in the values of the fitted parameters of the other two resonances are within statistical uncertainties.

- LHCb model II is checked, but we observed a bit worse fit quality.

- The model with three interfering resonances best describes the data, the broad structure at the lower mass could result from other physical effects. One of the possibilities is feed-down from higher di-charmonium resonances.