Observation of new structures in the J/ψJ/ψ mass spectrum in pp collisions at $\sqrt{s}$=13TeV in CMS

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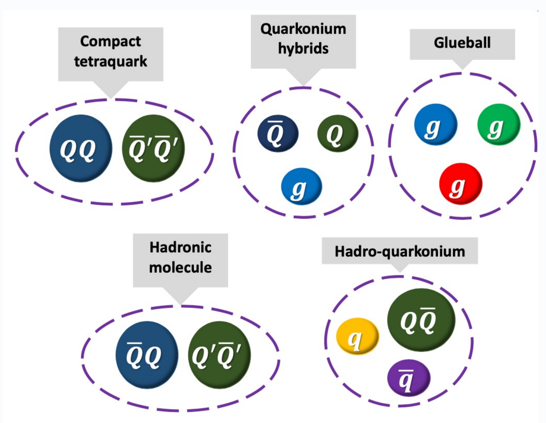
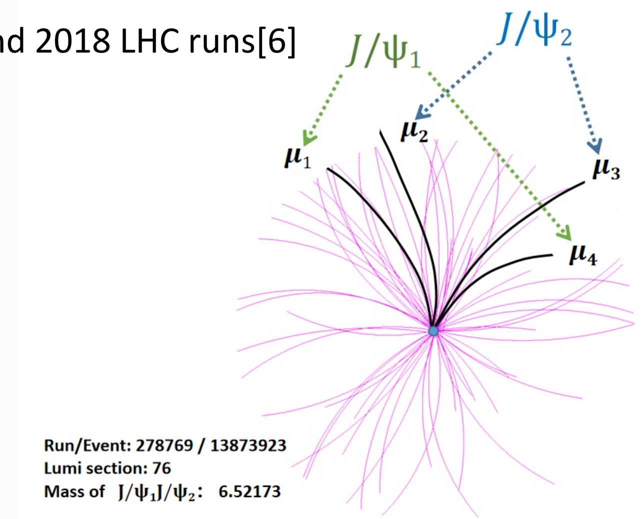
Introduction

- In 1975, charm tetra-quarks were mentioned for the first time[1], and the first calculation happened in 1981[2].
- **Standard model QCD** allows the existence of **more complex structures other than mesons and baryons**, such as **four- or five-quarks hadrons** (tetraquarks or pentaquarks) states and states with **active gluonic degrees of freedom** (hybrids) and even **gluon-only states** (glueballs) [3].
- **supersymmetric light front holographic QCD framework is** available [4, 5].



Data samples & Event selections

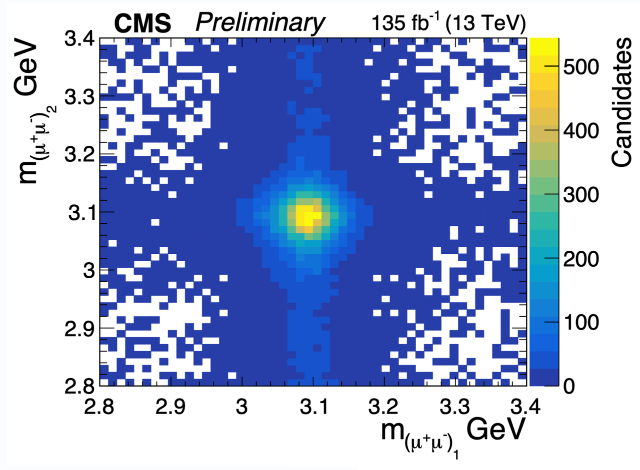
- **135 fb^{-1}** 13 TeV CMS data taken in 2016, 2017 and 2018 LHC runs[6]

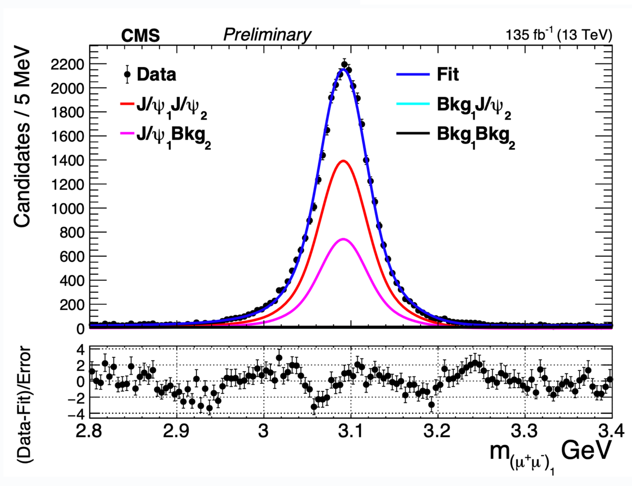


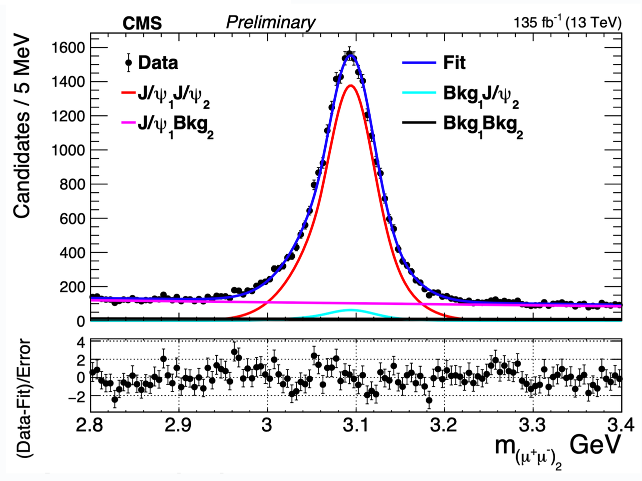
- Trigger:
  3μ with a J/ψ mass window
  μ p$_T$ from J/ψ > 3.5 GeV for 2017 & 2018 data
- Main selections:
  Fire corresponding trigger in each year
  p$_T$(μ)>=2.0 GeV; |η(μ)|<=2.4;
  p$_T$(μ) (J/ψ) >=3.5 GeV (2017&2018); soft muon ID
  p$_T$($\mu^+\mu^-$)>=3.5 GeV; m($\mu^+\mu^-$) in [2.95,3.25] GeV; then constrain m($\mu^+\mu^-$) to J/ψ mass
  4μ vertex probability > 0.005
- Multiple candidates treatment:
  Select best combination of same 4μ (~0.2%) with

$$\chi^2_m = \left(\frac{m_1(\mu^+\mu^-)-M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-)-M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

  Keep all candidates arising from >= 4μ (~0.2%)
- Signal and background samples are produced by Pythia8, JHUGen, HELAC-Onia…

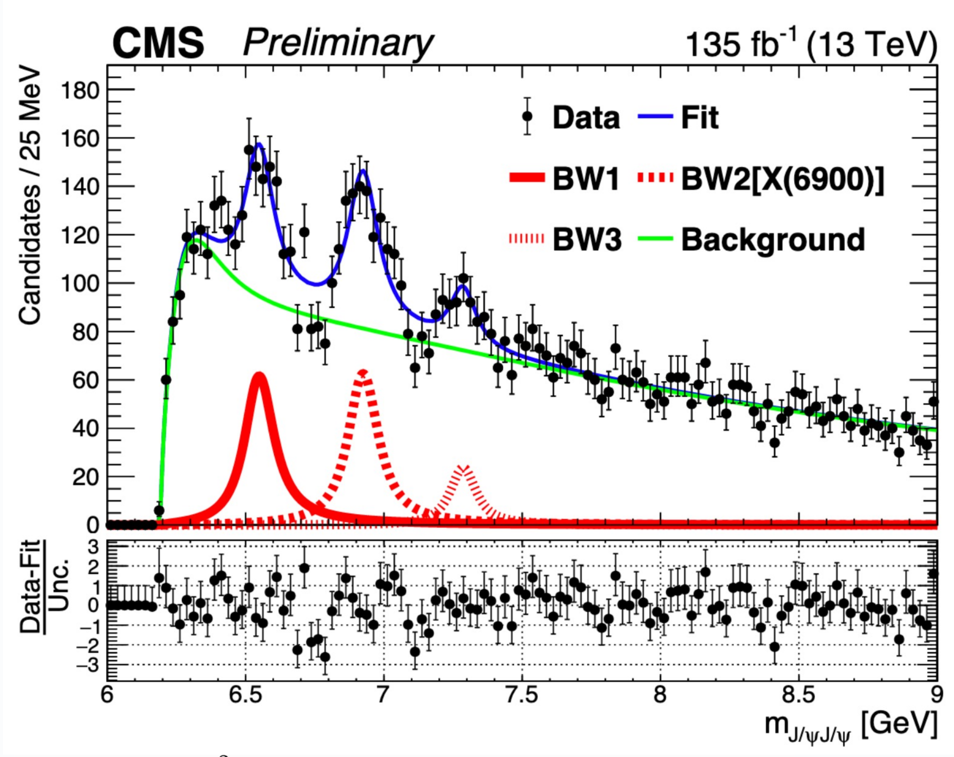


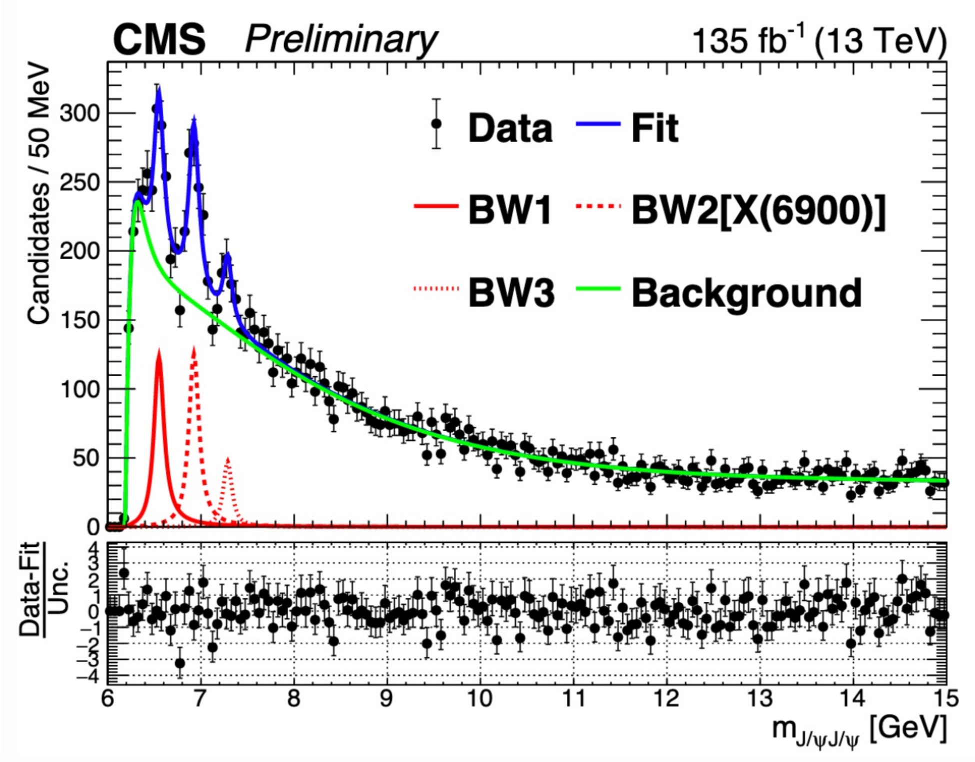




Fit strategy

- The J/ψJ/ψ mass spectrum with the fit **without** interference:





$$Pdf(m) = \sum_{i=0}^{3} N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \bigotimes R(M_i)$$
$$+ N_{NRSPS} \cdot f_{NRSPS}(m) + N_{NRDPS} \cdot f_{NRDPS}(m)$$

Signal shapes:
relativistic **Breit-Wigner** functions convolved with **Gaussian resolution functions** (BW):

- **BW0** → threshold enhancement
- **BW1** → structure at ≃ 6600 MeV
- **BW2** → structure at ≃ 6900 MeV
- **BW3** → structure at ≃ 7200 MeV

Background shapes based on MC simulations:
Nonresonant single-parton scattering (NRSPS)

$$f_{NRSPS}(x, x_0, \alpha, p_1, p_2, p_3) = (x-x_0)^{\alpha} \cdot \left(1 - \left(\frac{1}{(15-x_0)^2} - \frac{p_1}{10}\right) \cdot (15-x)^2\right) \cdot \exp\left(-\frac{(x-x_0)^{p_3}}{2 \cdot p_2^{p_3}}\right),$$
$$x_0 = 2m_{J/\psi},$$

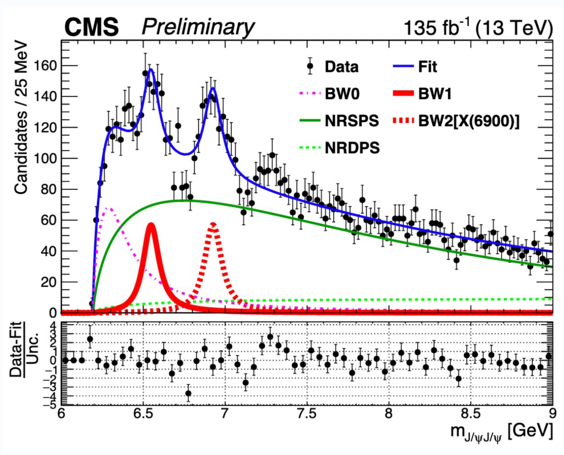
Nonresonant double-parton scattering (NRDPS)

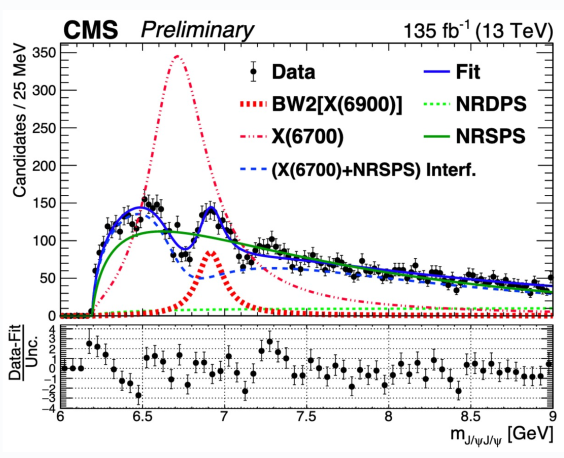
$$f_{NRDPS}(x) = \sqrt{x_t} \cdot \exp(-a \cdot x_t) \cdot (p_0 + p_1 \cdot x_t + p_2 \cdot x_t^2),$$
$$x_t = x - x_0, \quad x_0 = 2m_{J/\psi}.$$

Fit model building:

- Perform a sequence of fits adding new features until a reasonable description of data is obtained
- Starting from NRSPS+NRDPS+BW0 model
- New features are added one at the time if their local significance exceeds 3 standard deviations
- Repeat until no additional structures above 3 standard deviations are found

CMS data with LHCb fit models





Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [7]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [7]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

Model I (LHCb's non-interference Model):

- Background modeled using NRSPS + NRDPS shapes
- Signal modeled using 3 Breit-Wigner functions:
  - BW2 to model X(6900) resonance
  - Two structures around 6300 (BW0) and 6500 MeV (BW1) account for the threshold enhancement.

Results:

- The X(6900) mass and width with this model are consistent with LHCb
- Fit probability $\chi^2 = 1.2 \times 10^{-4}$ for the mass region below 7.5 GeV: the model fails to describe the dip at 6750 MeV and the structure at 7200 MeV.

Model II (LHCb's interference Model):

- BW2 + NRDPS + Interference(BW1, NRSPS)
  - BW2 to model X(6900) resonance
  - Destructive interference between a hypothetical particle BW1 around 6700 MeV and background NRSPS to better account for the dips.

Results:

- Better description of the dip at 6750 MeV and fit results compatible with LHCb
- Fit probability $\chi^2 = 0.84 \times 10^{-4}$ for the mass region below 7.5 GeV: the region around 6550 MeV is poorly described.
- The discrepancies around peak/dip structure at 7200 MeV also contribute to a poor fit result.

Summary
BW parameters are similar to LHCb's published values when applying LHCb's models to CMS data, with the exception of the amplitude and width of the structure around 6700 MeV; but the fit probabilities are poor.

Summary

CMS found 3 significant structures using 135 fb^{-1} 13 TeV data.
The local statistical significances of these peaks are, for increasing mass, 6.5, 9.4, and 4.1 standard deviations.

- BW2 is consistent with **X(6900)** observed by LHCb[7]
- CMS found two new structures, provisionally named as **X(6600), X(7200)**
- **A family of structures which are candidates for all-charm tetra-quarks**

- Dips in the data show possible interference effects. Models incorporating interference are an important class to explore
- Including more resonances in the fit to account for the dips in non-interference models is also foreseen
- More data/knowledge is needed to understand the nature of near-threshold region
- All-heavy quark exotic structures offer a system easier to understand
- A new window to understand strong interaction

Tab. 1: Summary of the fit results for the CMS J/ψJ/ψ distribution: the mass m and natural width Γ, are in MeV, and the signal yields N are given for the three signal structures.

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

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