Observation of new structures in the $J/\psi J/\psi$ mass spectrum at CMS

张敬庆
南京师范大学

第四届重味物理与量子色动力学研讨会
湖南 长沙 2022.07.27-2022.07.30

Outline

- Introduction
- CMS detector and trigger
- Dataset and MC samples
- CMS result
- Application of LHCb fit models
- Summary

Introduction

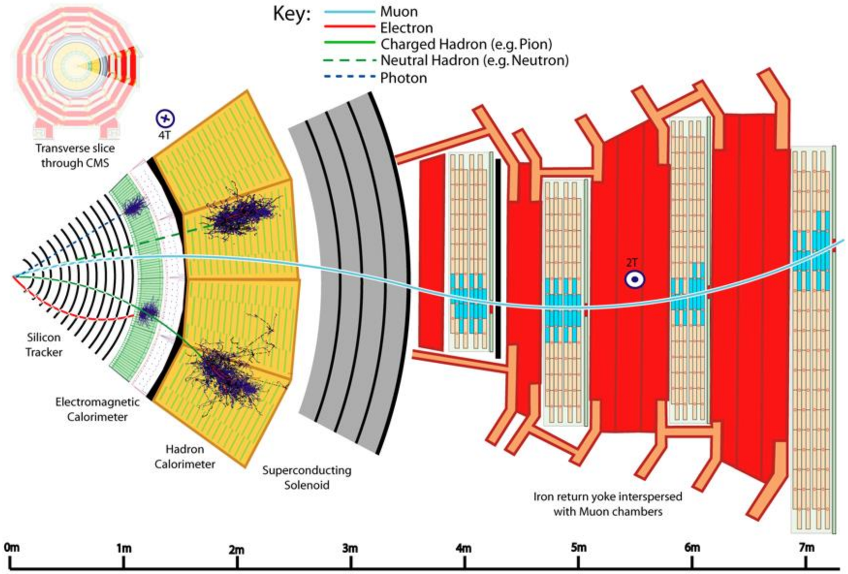
- Exotic hadrons (other than $q\bar{q}$ or qqq) has been explored in theory since quark model proposed by Gell-Mann and Zweig.

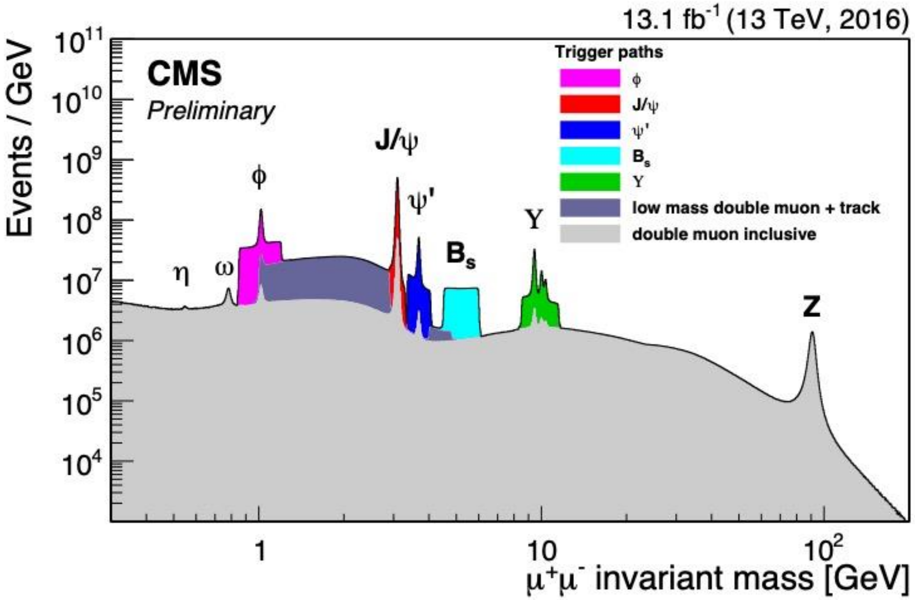
- $X(3872)$ – famous exotic hadron, first observed by Belle, makes searching for exotics in experiment attracting

- Exotics consisting of only (c, b) quarks may offer analogous insights
  - Many theoretical studies just after J/ψ discovery
  - LHCb observed X(6900) in di-J/ψ mass spectrum, Sci. Bull. 65 (2020) 23

- CMS has large dataset for the study of di-J/ψ mass spectrum

CMS detector and trigger





Excellent detectors for (exotic) quarkonium:

- Muon system: High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ
- Silicon Tracking detector: B = 3.8 T, $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution
- Special triggers for different analyses: $\mu\ p_T$, $(\mu\mu)\ p_T$/mass/vertex, and additional μ

Dataset and MC samples

- Signal: $J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$
- Data: 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs
- Signal MC samples:
  - $J^P = 0^+$ resonance

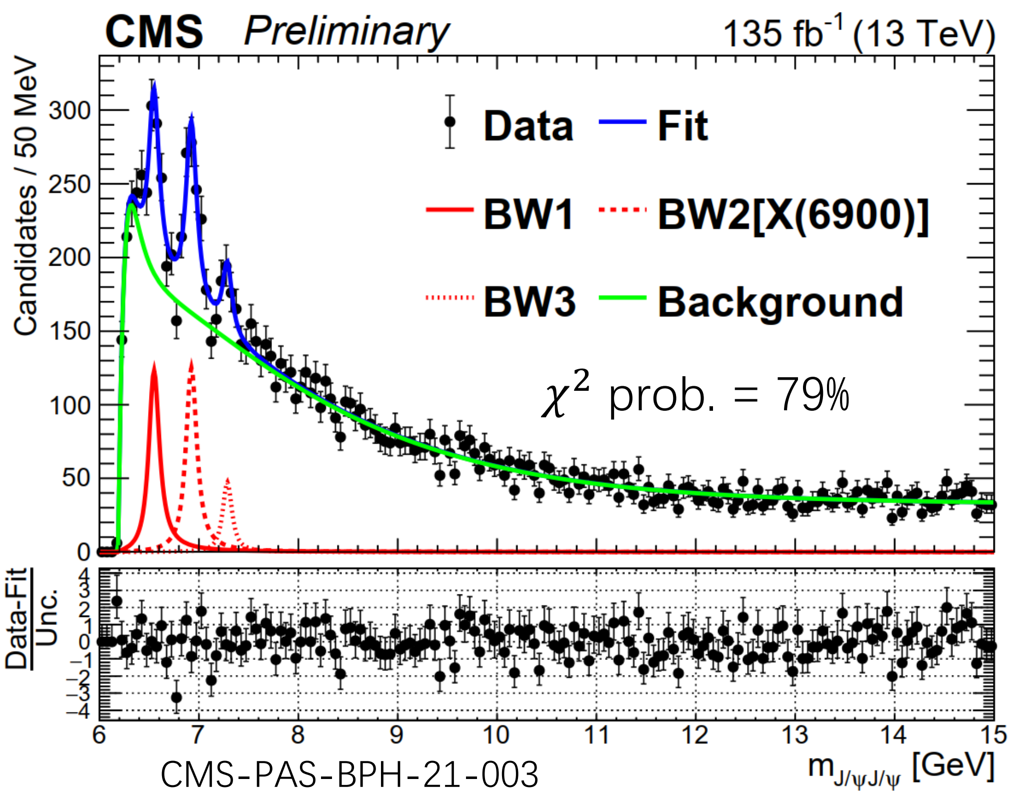
    -- Generator: Pythia8, JHUGen
- Background MC samples:
  - Nonresonant single-parton scattering (NRSPS)

    -- Generator: Pythia8, HelacOnia (next-to-next-to-leading order), Cascade (next-to-leading order)
  - Nonresonant double-parton scattering (NRDPS)

    -- Generator: Pythia8

CMS result

- Signal: S-wave Breit-Wigner convolved with resolution function
- Background: NRSPS, NRDPS, and BW0
- Fit range: always fit in [6, 15] GeV; also shown in zoomed projection



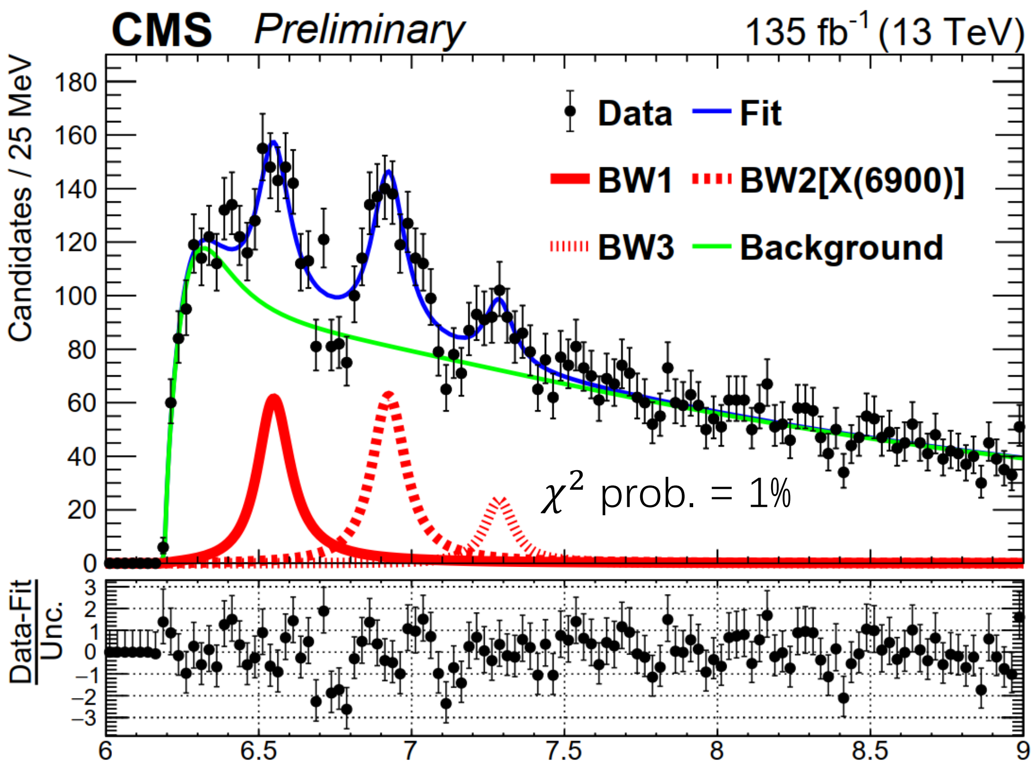
CMS-PAS-BPH-21-003

BW0 near threshold:

- Significantly needed in the fit
- Various possibilities: resonance, coupled-channel interactions, pomeron exchange processes, inadequacy of our NRSPS model…
- Mass and width vary in a wide range under different situations.
- A region populated by feeddown from possible higher mass states.

➢ Regard BW0 as background

CMS result



CMS-PAS-BPH-21-003

Measured m, Γ (in MeV) of BWs

	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

Statistical significance (likelihood ratio test):

- Confirmation of BW2[X(6900)], $\mathbf{9.4\sigma}$
- Observation of BW1, $\mathbf{6.5\sigma}$
- Evidence of BW3, $\mathbf{4.1\sigma}$

- More BW2[X(6900)], CMS vs. LHCb: 492 ± 75 vs. 252 ± 63 (model I)

Systematic uncertainties

- Systematic uncertainties on mass and width

Table 2: Systematic uncertainties on masses and widths, in MeV.

Source	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta\Gamma_{BW1}$	$\Delta\Gamma_{BW2}$	$\Delta\Gamma_{BW3}$
signal shape	3	4	3	14	7	7
NRDPS	1	<1	<1	3	3	4
NRSPS	3	1	1	18	15	17
momentum scaling	1	3	4	-	-	-
mass resolution	<1	<1	<1	<1	<1	1
combinatorial background	<1	<1	<1	2	3	3
efficiency	<1	<1	<1	1	<1	1
feeddown shape	11	1	1	25	8	6
total	12	5	5	34	19	20

- Local significance with syst. uncertainties by a profiling procedure: A discrete set of individual alternative signal and background hypotheses tested in minimization
  - BW1 significance: changed from 6.5σ to 5.7σ
  - BW2 and BW3 significance: no relative change

M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV

BW2 consistent with X(6900)

X(6900) in LHCb:

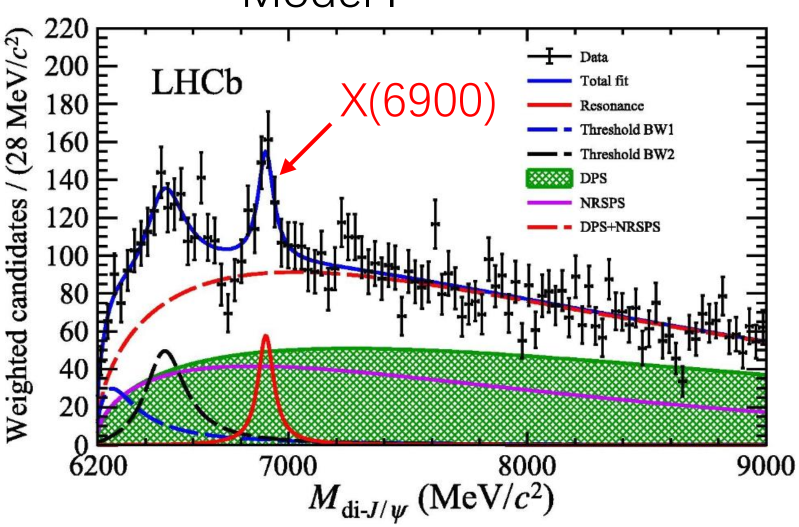
$\mathbf{M} = 6905 \pm 11 \pm 7$ MeV

$\Gamma = 80 \pm 19 \pm 33$ MeV

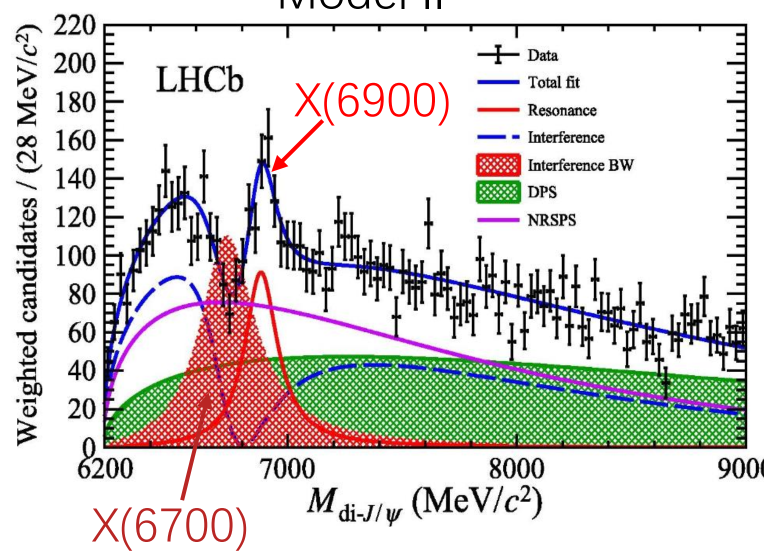
X(6900) reported by LHCb

- In 2020, LHCb reported X(6900) in $J/\psi J/\psi$ final state, Sci. Bull. 65 (2020) 23
- Two different fit models:
  - Model I: background (NRSPS + NRDPS) + 2 auxiliary BWs + X(6900)
  - Model II: a ‘invisible’ X(6700) interfere with NRSPS, + NRDPS + X(6900)
- LHCb agnostic on which one is to be preferred
- What happens if apply LHCb models to CMS data

Model I

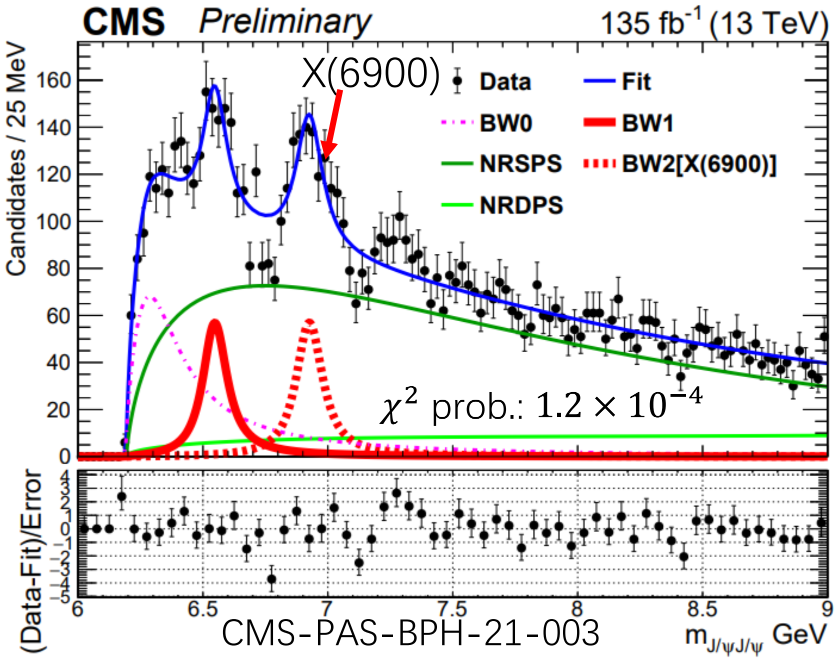


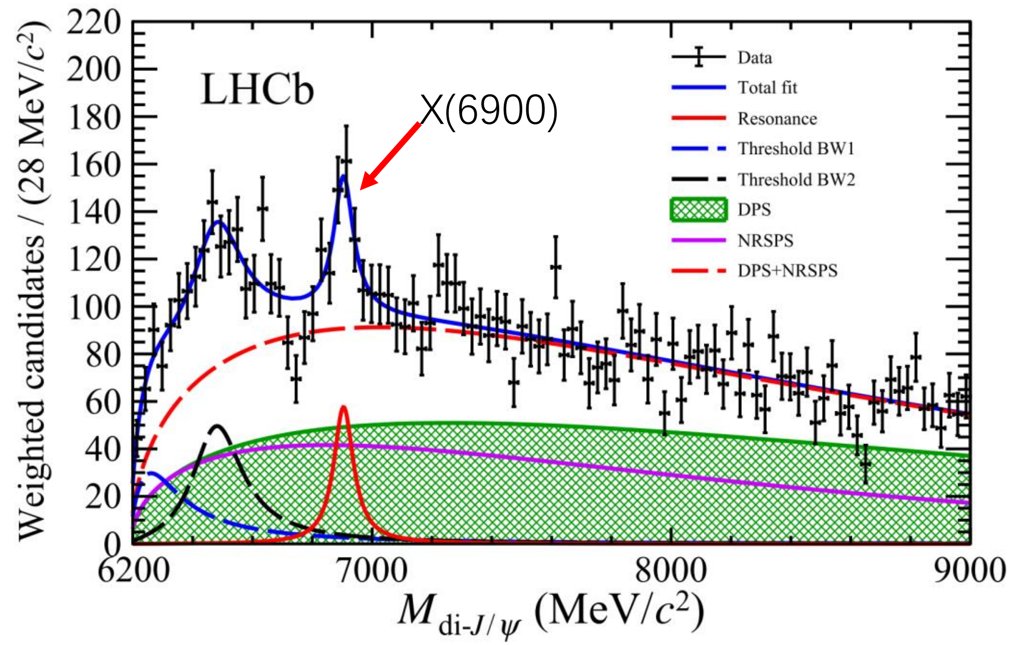
Model II



Fit with LHCb Model I

- NRSPS + NRDPS + 2 auxiliary BWs + X(6900)





- Similar number of final states; CMS has higher muon pT (> 3.5, 2.0 GeV vs. > 0.6 GeV)

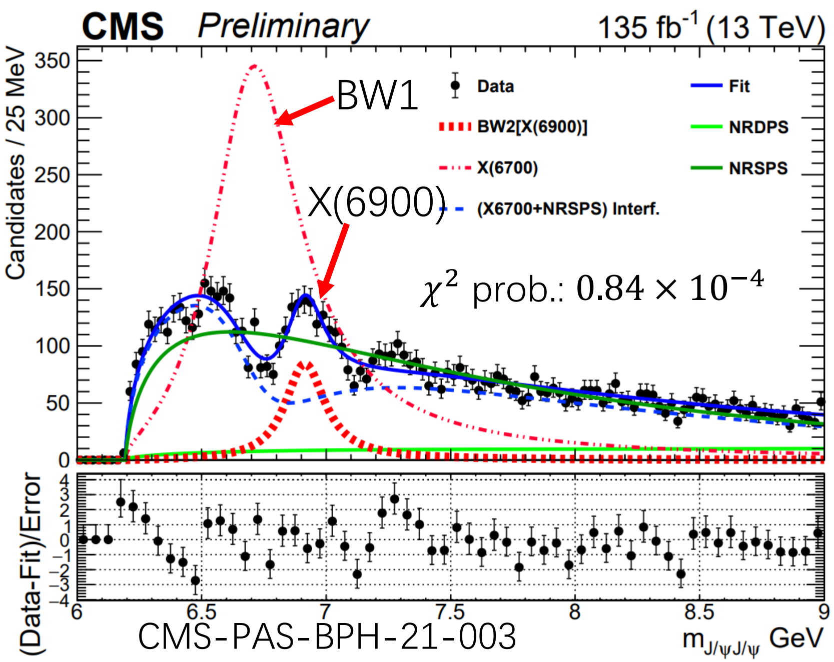
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

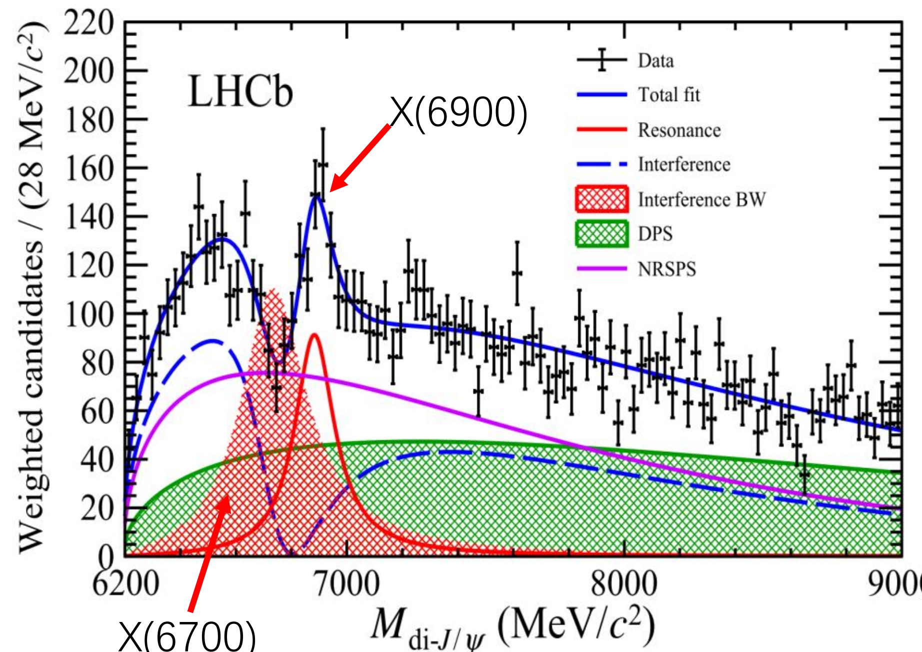
Consistent X(6900) mass and width

- CMS data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct
- Does NOT describe well dips

Fit with LHCb model II

- Incoherent sum of X(6900) and NRDPS + coherent sum of X(6700) and NRSPS





		Interfering BW		Non-interfering BW	
Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	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 [15]	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

Consistent X(6900) mass and width

- CMS obtained larger amplitude and natural width for BW1
- CMS X(6600) is 'eaten' – does not describe X(6600) and below
- Does not describe X(7300) region

Summary

- CMS found 3 significant structures using 135 fb^{-1} 13 TeV data
  https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-003/index.html

M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV	5.7**σ**
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV	9.4**σ**
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV	4.1**σ**

- BW2 consistent with X(6900) reported by LHCb
- Two new structures, provisionally named as X(6600) [BW1], X(7300) [BW3]
- A family of structures which are candidates for all-charm tetra-quarks!

- Dips in data show possible interference effects – under study
- More data/knowledge needed to understand nature of near threshold region

- ***All-heavy quark exotic structures offer system easier to understand***
- ***A new window to understand strong interaction***

Thanks!

Backup

Significance with systematics

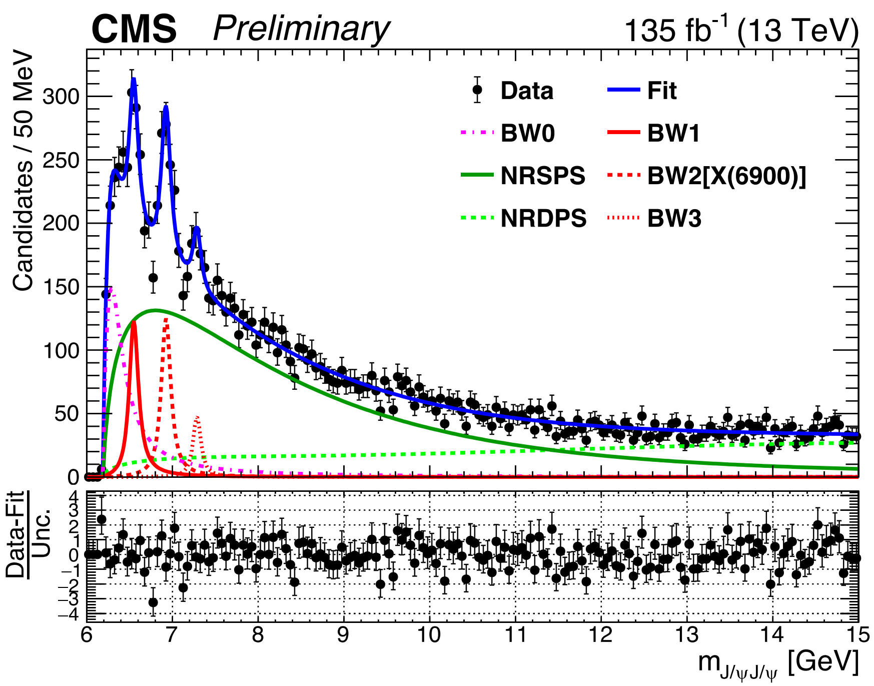
- To include systematics, alternative resonance/background shapes applied in the fit.
- Calculate signal- and null-hypothesis NLL_syst including systematic using:

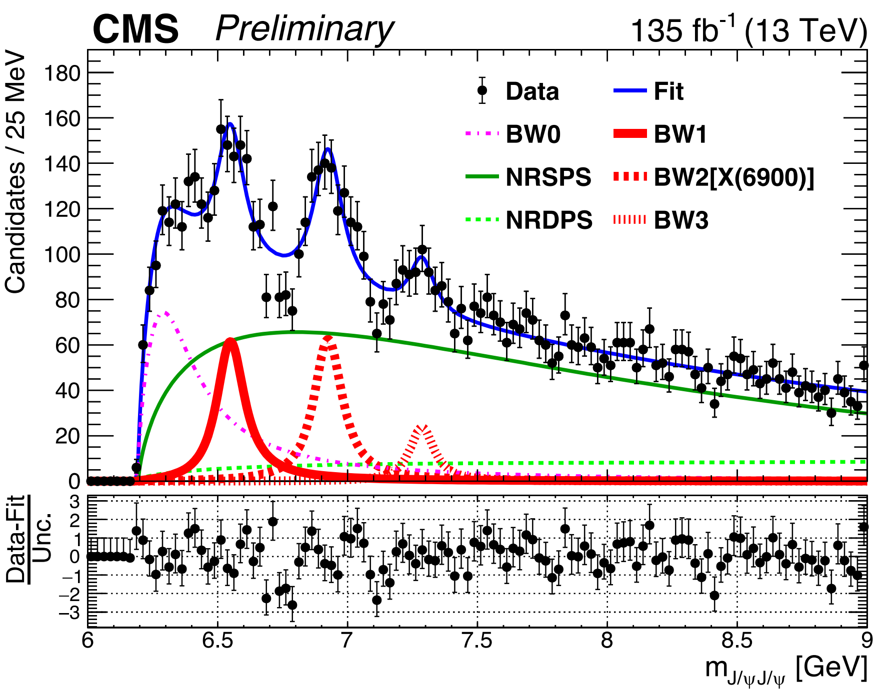
$NLL\_(syst-sig)$ = Min{$NLL\_(nom-sig)$, $NLL\_(alt-i-sig)$+0.5+0.5$\cdot\Delta dof$}

  - $NLL\_(nom-sig)$: the NLL of nominal 'signal hypothesis'fit.
  - $NLL\_(alt-i-sig)$: the NLL of i-th alternative fit of 'signal hypothesis'
  - Δdof: the additional free parameters comparing to the nominal 'signal hypothesis' fit.
- $NLL\_(syst-null)$ = Min{$NLL\_(nom-null)$, $NLL\_(alt-j-null)$+0.5+0.5$\cdot\Delta dof$}
- Significance including systematics as usual from $NLL\_(syst-null)-NLL\_(syst-sig)$

	Significance with syst.
BW1	5.7σ
BW2	*no sensible changes*
BW3	*no sensible changes*

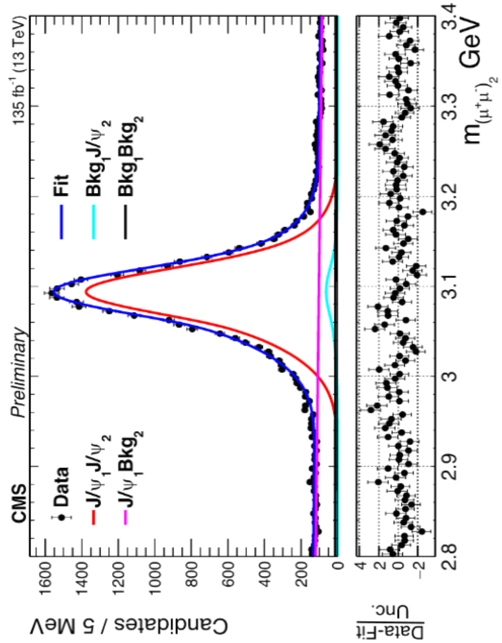
CMS result with BW0 explicitly shown

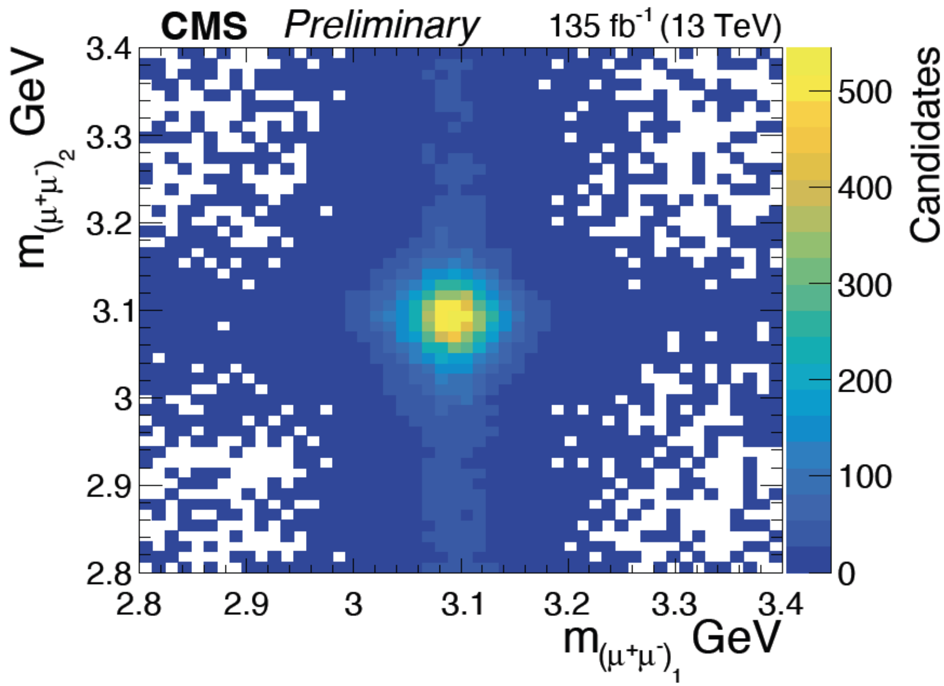


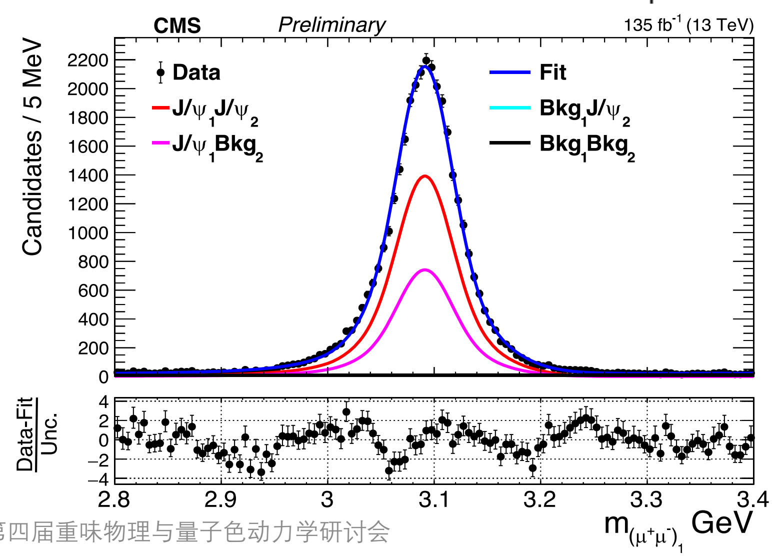


CMS-PAS-BPH-21-003

J/ψ candidates







- J/ψ mass and vertex related cuts removed
- Clean J/ψ signals are seen

CMS-PAS-BPH-21-003

Line shape

- S-wave relativistic Breit-Wigner (used in default fit):

$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)}, \text{where } \Gamma(m) = \Gamma_0 \frac{qm_0}{q_0 m},$$

q is the momentum of a daughter in the mother particle rest frame; q_0 means the value at peak position ($m = m_0$).

- NRSPS and NRDPS:

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

$$f_{NRDPS}(x, a, p_0, p_1, p_2) = \sqrt{x_t} \cdot \exp(-a \cdot x_t) \cdot \left(p_0 + p_1 \cdot x_t + p_2 \cdot x_t^2\right),$$

where $x_0 = 2m_{J/\psi}, x_t = x - x_0$