Observation of new structures in the J/ψJ/ψ mass spectrum at CMS

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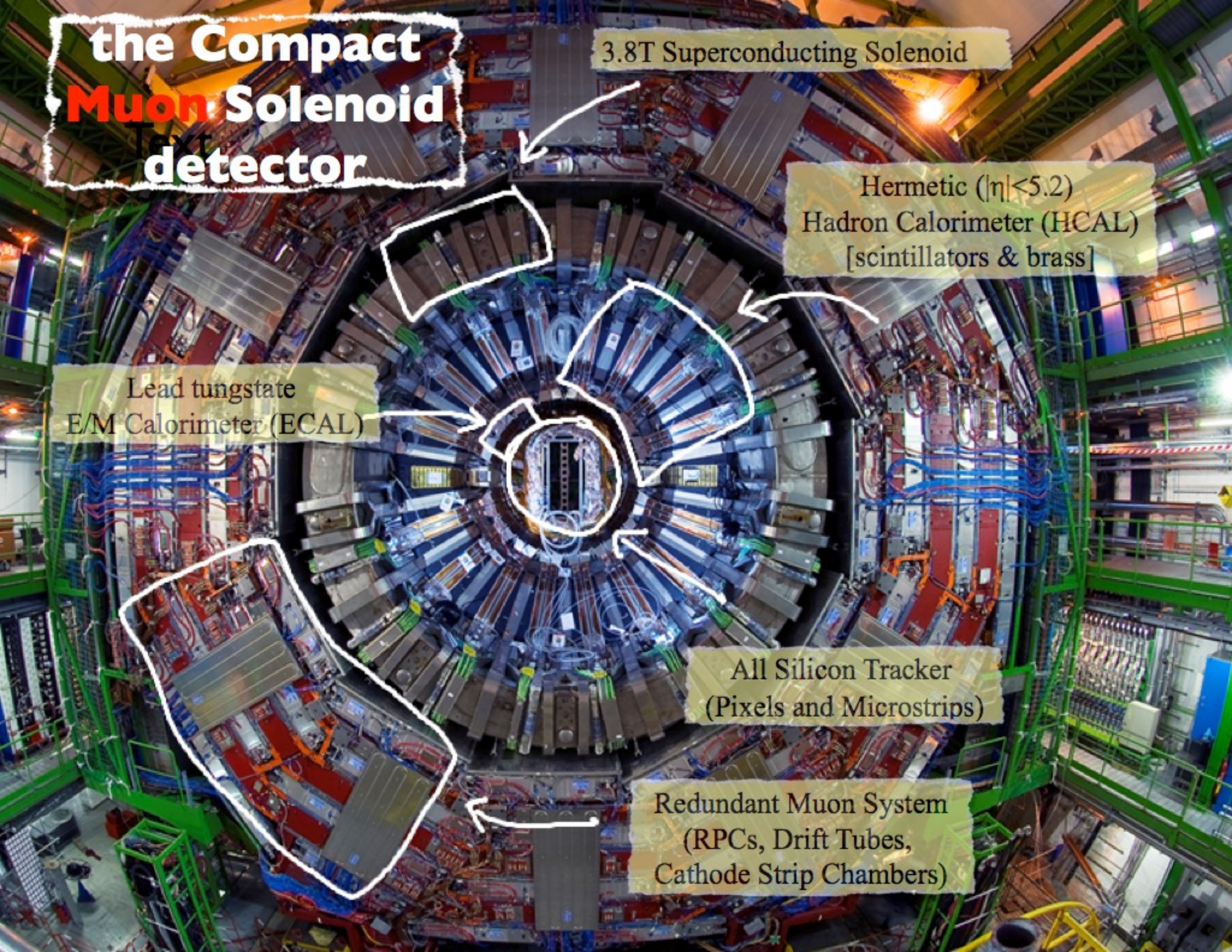
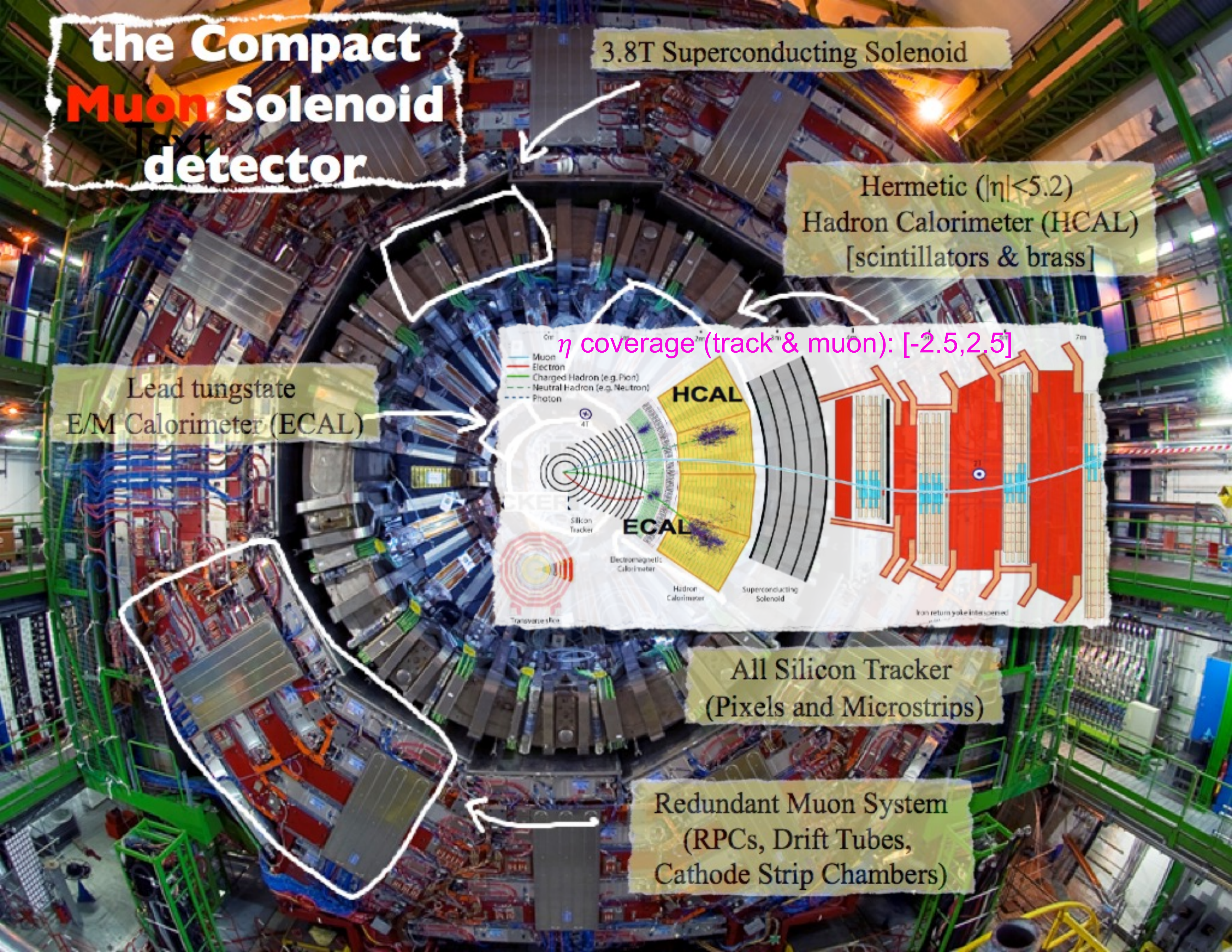

the Compact Muon Solenoid detector
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
Lead tungstate
E/M Calorimeter (ECAL)
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

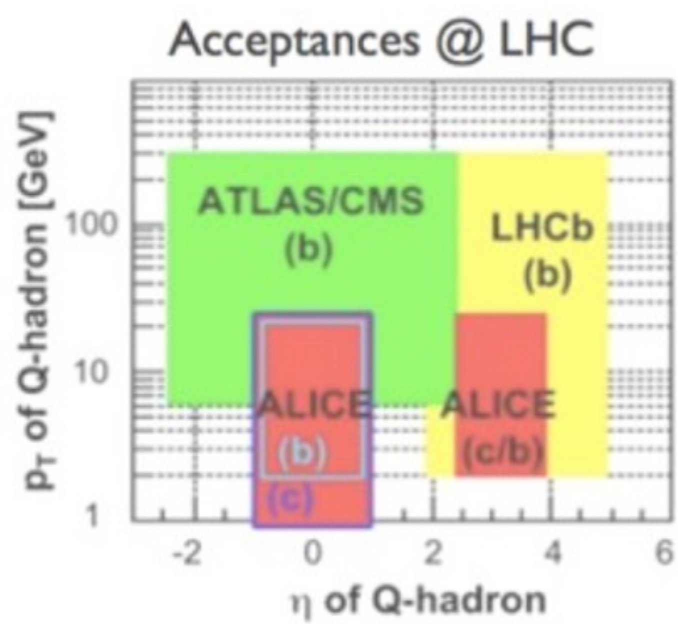


the Compact Muon Solenoid detector
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
η coverage (track & muon): [-2.5,2.5]
Lead tungstate
E/M Calorimeter (ECAL)
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
HCAL
ECAL
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Transverse slice
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

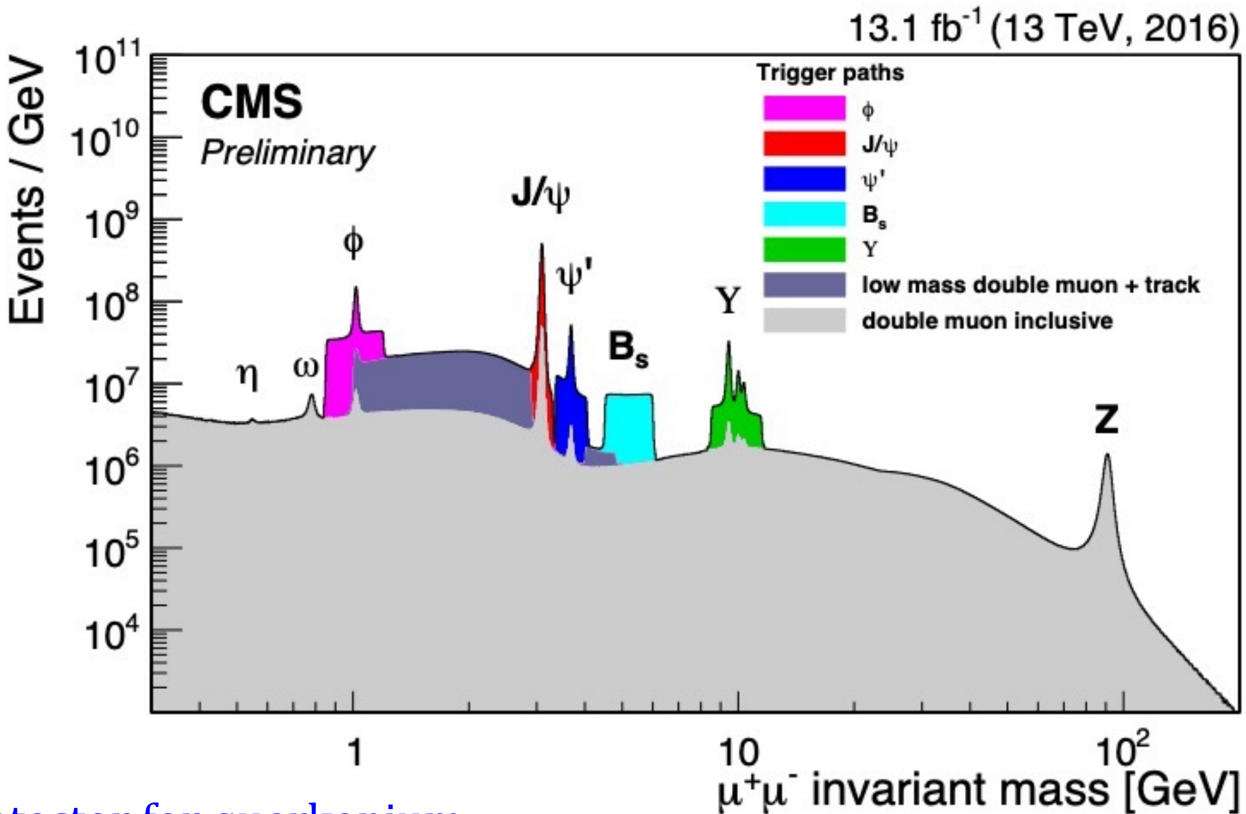
B physics at CMS

(μ dominated final states for B physics)

- vs RHIC
  - better resolution
    - CMS' 1st Υ(1S,2S,3S) measurements in HI
  - additional detector capability
    - CMS' 1st secondary vertex meas. in HI (eg $b \rightarrow J/\psi$)
- vs ALICE
  - complementary acceptance (ALICE access low-pt)
  - CMS better resolution
- vs Tevatron experiments
  - extend kinematic (p_T,y) acceptance
- vs ATLAS
  - more flexible trigger, lower p_T threshold
- vs LHCb
  - complementary acceptance, LHCb great particle ID
  - higher luminosity



Dimuon at CMS & trigger



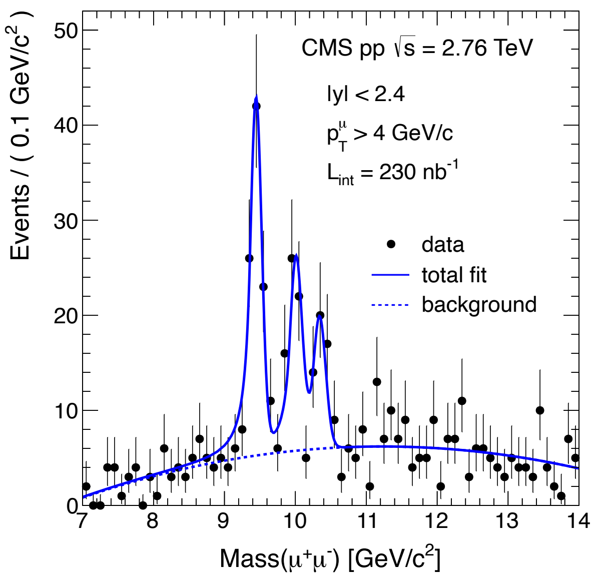
Excellent detector for quarkonium

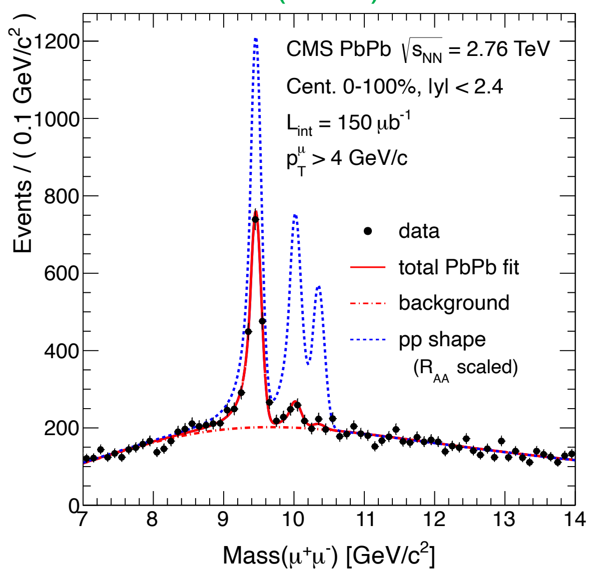
- Muon system
  - High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ
- Silicon Tracking detector, B=3.8T
  - $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution
- Special triggers for different analyses at increasing Inst. Lumi.
  - μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and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

Selected historical CMS contributions with low p_T dimuons

Υ suppression in PbPb collisions

PRL 109 (2012) 222301





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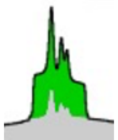

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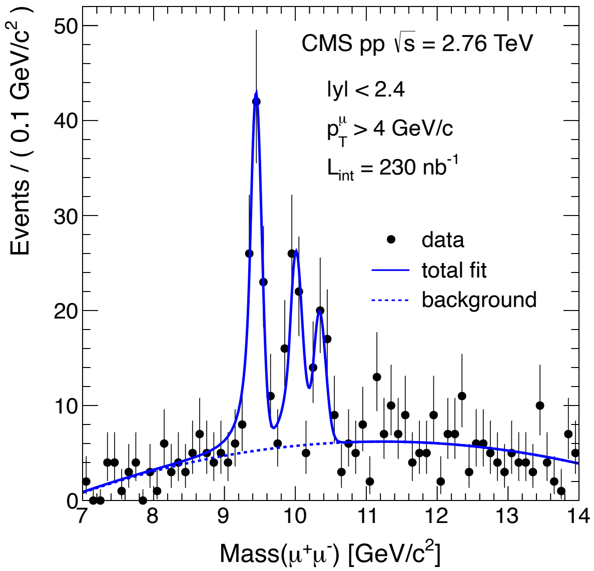
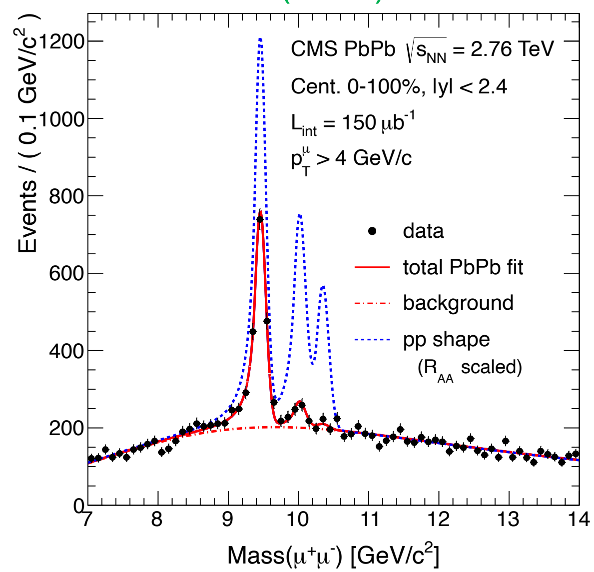
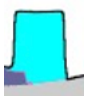
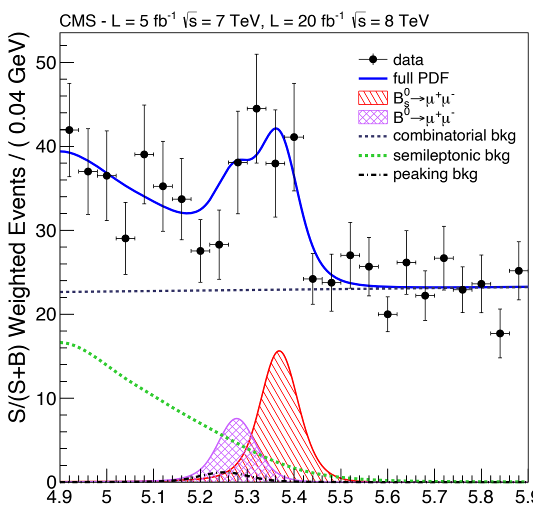


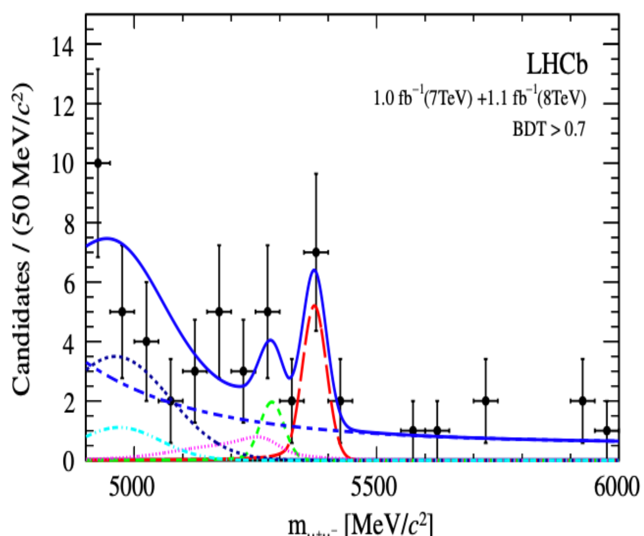




$B_S^0 \rightarrow \mu^+\mu^-$ rare decays



PRL 111 (2013) 101804 $m_{\mu\mu}$ (GeV)

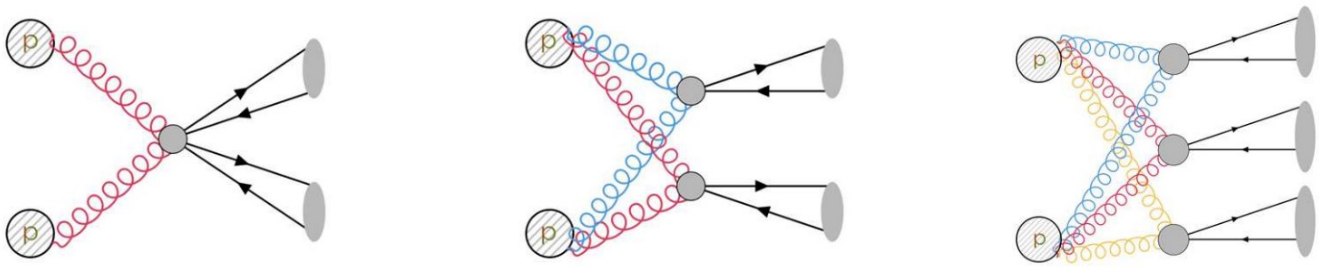


Associated quarkonium production

- Study interplay of soft QCD with (semi)hard QCD and EW physics

- Sensitivity to perturbative heavy flavor generation and nonperturbative initial and final state effects

  - Initial state: e.g. sensitivity to the concepts of single (SPS), double (DPS) and triple (TPS) parton scattering



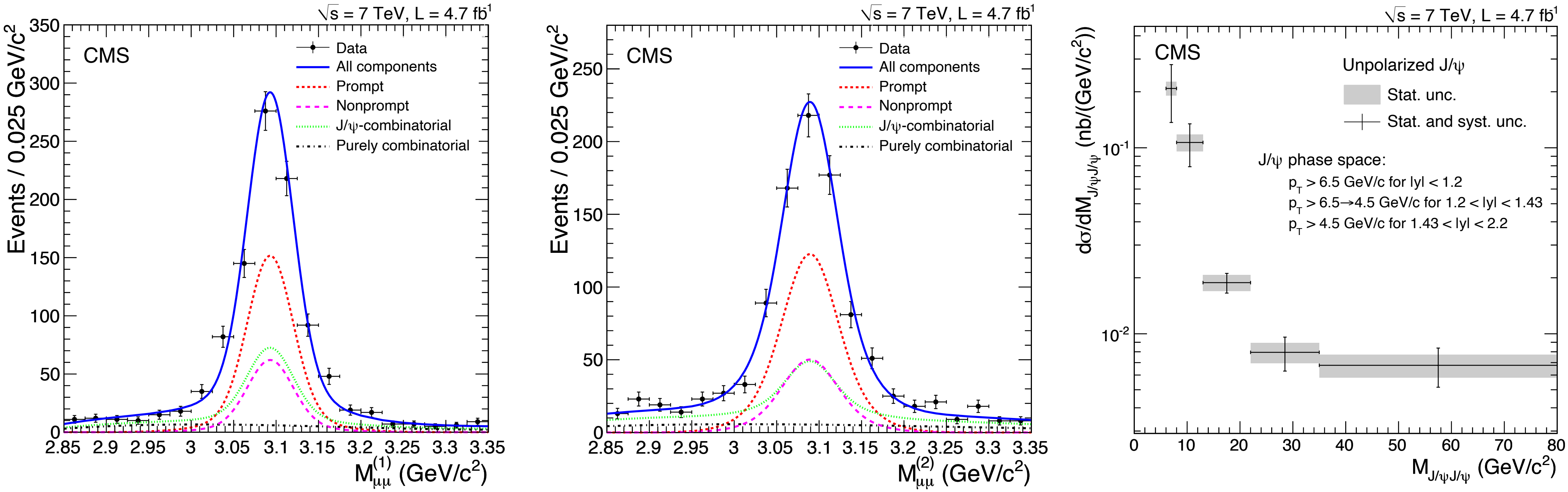
parameterized by σ_{eff}

$$\sigma^{AB}_{\mathrm{DPS}} = \frac{1}{1+\delta_{AB}} \frac{\sigma^A \sigma^B}{\boxed{\sigma_{\mathrm{eff}}}}$$

  - Final state: e.g. sensitivity to heavy flavour hadron formation (colour singlet vs. colour octet), sensitivity to resonant multi-heavy-flavor states

J/ψJ/ψ cross section at 7 TeV

J. High Energy Phys. 09 (2014) 094



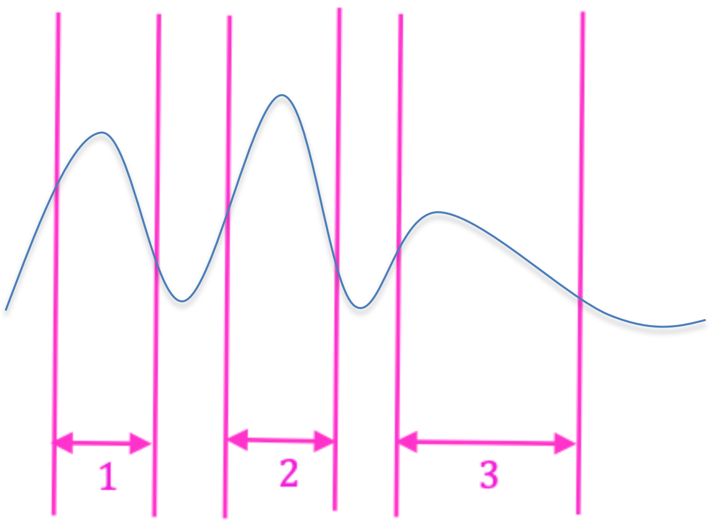
Total cross section, assuming unpolarized prompt J/ψJ/ψ pair production
1.49 ± 0.07 (stat.) ± 0.13 (syst.) nb

Different assumptions about the J/ψJ/ψ polarization imply modifications to the cross section ranging from -31% to +27%.

Blind mass window for 13 TeV

We saw hints at Run I data (7 TeV & 8 TeV)
Proposed three signal regions for Run II data

Signal: $X \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$



Blinded mass windows for Run II:

1. [6.3,6.6] GeV
2. [6.8,7.1] GeV
3. [7.2,7.8] GeV
   (for potential wide structure)

These mass windows will be windows for LEE for potential structures

Run I data will be ignored for significance calculation

CMS eventually decide to blind the whole region: [6.2, 7.8] GeV after LHCb released their result (13 TeV, 2020)

13 TeV dataset and MC samples

- Signal: $\mathrm{X} \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$
- 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

Event selections

Muon selection

- $p_T(\mu^{\pm}) > 2.0$ GeV/c
- $|\eta(\mu^{\pm})| < 2.4$
- All muons are soft
- For 2017-18 years: $p_T(\mu^{\pm}) > 3.5$ GeV/c for at least one $\mu^+\mu^-$ pair, which has $vtxprob(\mu^+\mu^-) > 0.5\%$ and $2.95 < m_{\mu^+\mu^-} < 3.25$ GeV

J/ψ selection

- $2.95 < m_{J/\psi} < 3.25$ GeV
- $p_T(J/\psi) > 3.5$ GeV/c
- $vtxprob(J/\psi) > 0.5\%$
- Constrained $vtxprob(J/\psi) > 0.1\%$

J/ψJ/ψ selection

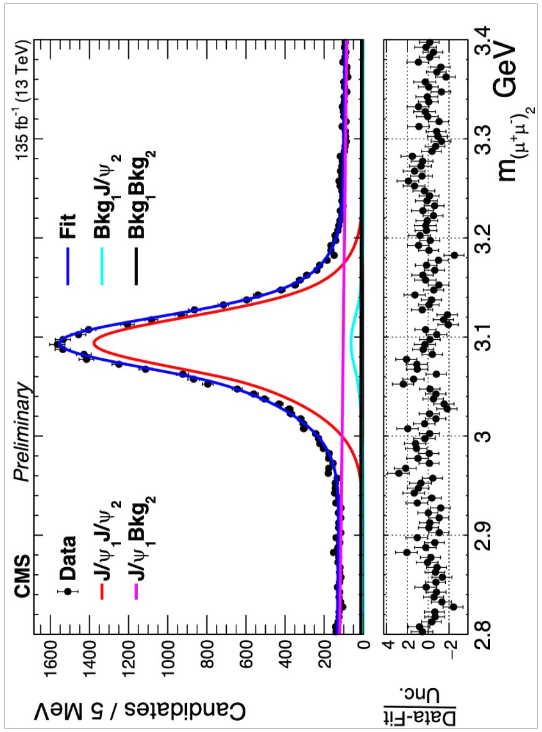
- $vtxprob(4\mu) > 0.5\%$
- $vtxprob(J/\psi J/\psi) > 0.1\%$
- Proper HLT is fired in event

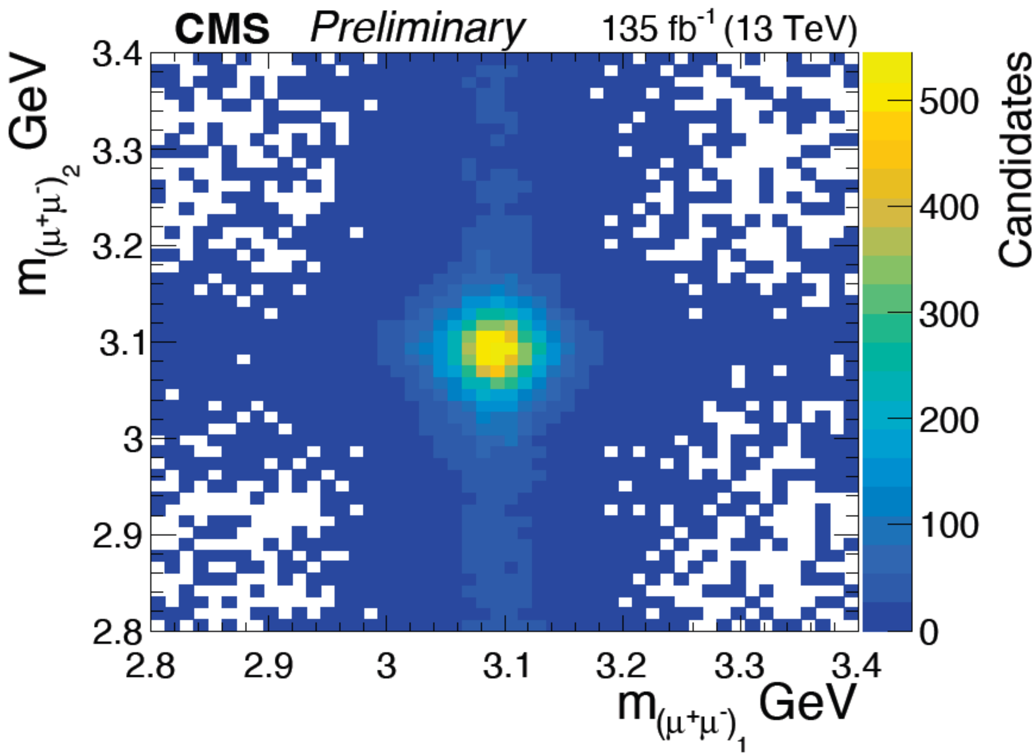
Multiple candidates

- Choose the best candidate with minimum $\left(\frac{M(J/\psi_1)-M(J/\psi_{PDG})}{\sigma(M(J/\psi_1))}\right)^2+\left(\frac{M(J/\psi_2)-M(J/\psi_{PDG})}{\sigma(M(J/\psi_2))}\right)^2$ value if there are 4 muons in event, but more than one candidate (~0.2%)
- Keep all candidates if there are more then 4 muons in event (~0.2%)

Baseline mass variable – invariant mass of two constrained J/ψ candidates

J/ψ candidates at 13 TeV





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

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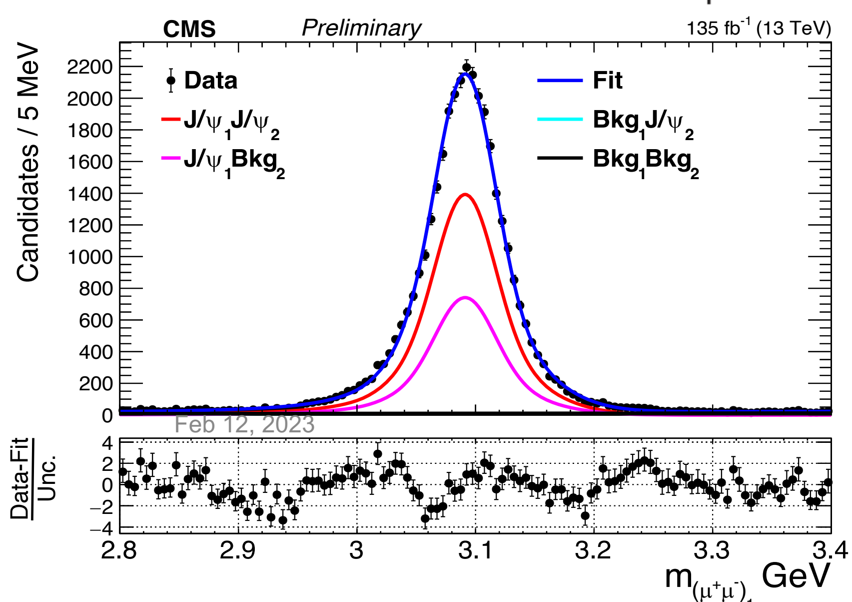

CMS background (SPS + DPS + BW0)

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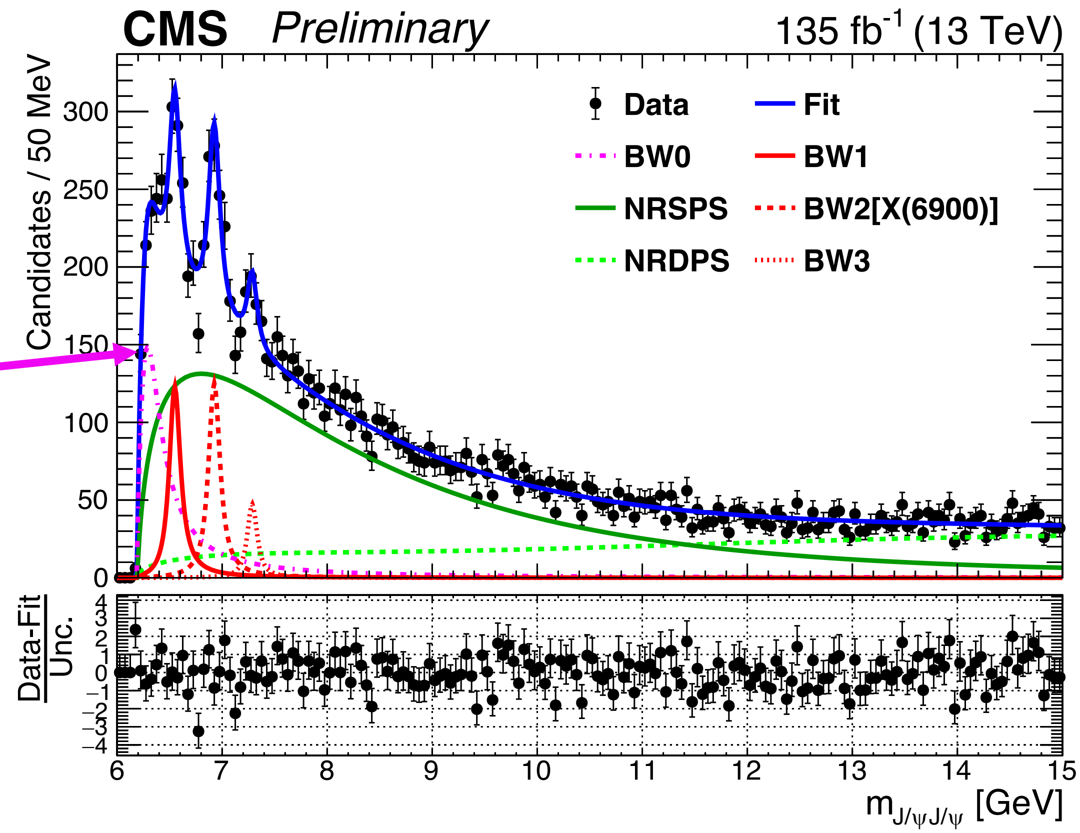
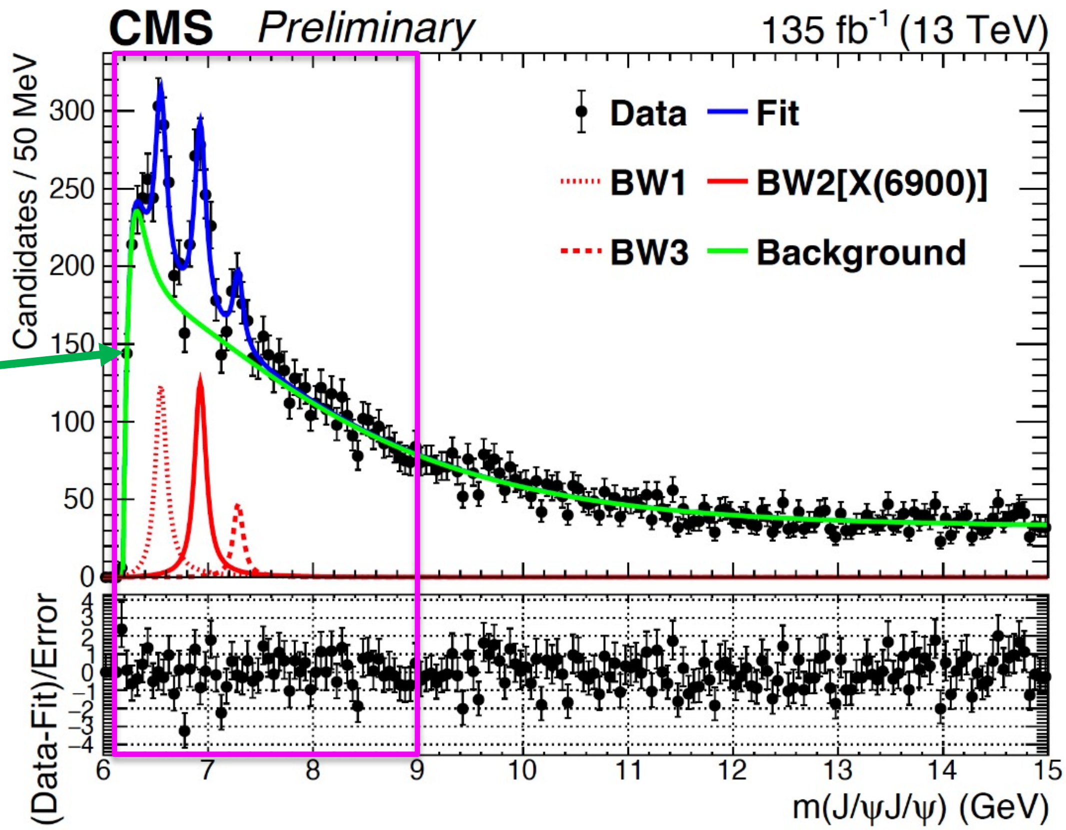


$\chi^2\ prob = 79\%$

[6.2,15] GeV

- Most significant structure is a BW at threshold, BW0--what is its meaning?
- Treat BW0 as part of background due to:
  - BW0 parameters very sensitive to SPS and DPS model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…

CMS background (SPS + DPS + BW0)



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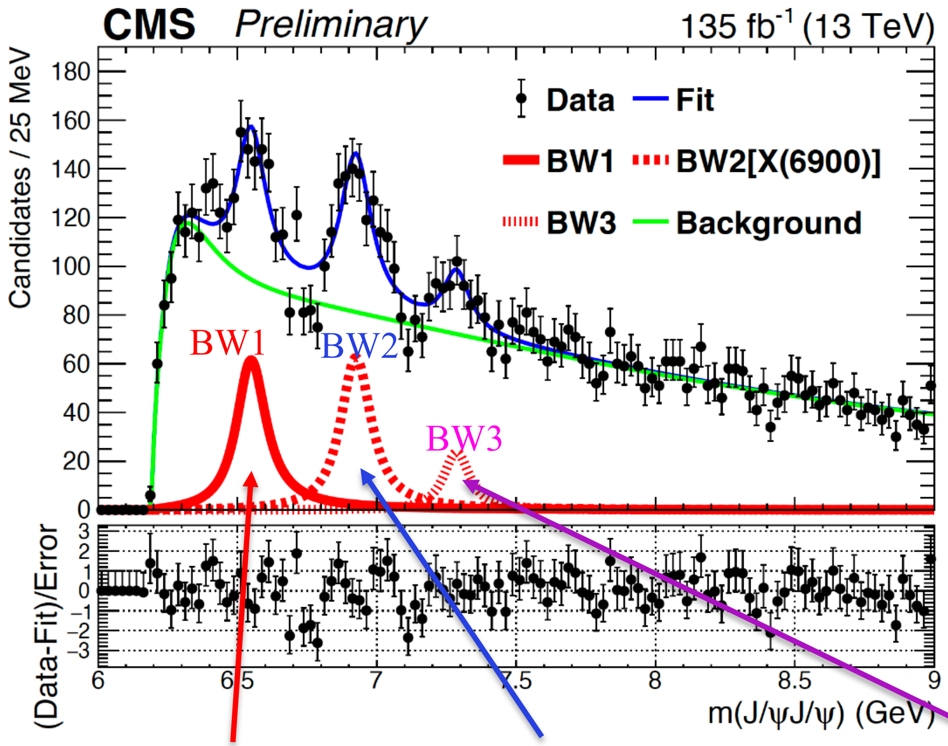
  - BW0 parameters very sensitive to SPS and DPS model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…
- SPS+DPS+BW0 as our background

CMS model: 3 BWs + Background

χ^2 Prob. = 1%

[6.2,7.8] GeV



Statistical significance based on:

$$2\ \ln(L_0/L_{max})$$

	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	6552 ± 10	6927 ± 9	7287 ± 19
Γ	124 ± 29	122 ± 22	95 ± 46
N	474 ± 113	492 ± 75	156 ± 56
σ(stat.)	6.5	9.4	4.1
σ(stat. + syst.)	5.7	9.4	4.1
	Observation	Confirmation of X(6900) from LHCb	Evidence

Significance with systematics

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

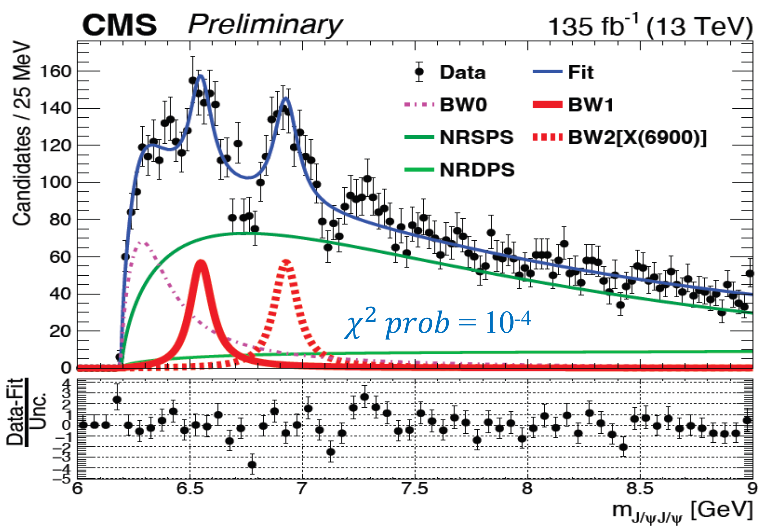
Source	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta\Gamma_{BW1}$	$\Delta\Gamma_{BW2}$	$\Delta\Gamma_{BW3}$
signal shape	3	4	3	14	7	7
NRDPS	1	< 1	< 1	3	3	4
NRSPS	3	1	1	18	15	17
feeddown shape	11	1	1	25	8	6
momentum scaling	1	3	4	-	-	-
resolution	< 1	< 1	< 1	< 1	< 1	1
efficiency	< 1	< 1	< 1	1	< 1	1
combinatorial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

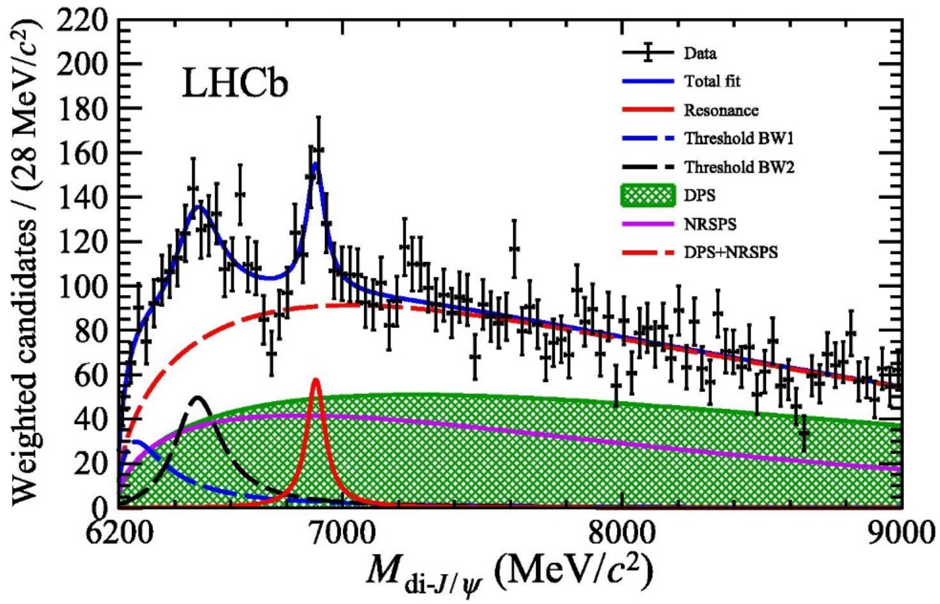
- Investigated effects of systematics on local significance by a profiling procedure
- A discrete set of individual alternative signal and background hypotheses tested in minimization
  - Significant change: BW1 significance changed from 6.5**σ** to >5.7**σ**
  - No relative significance changes for BW2 and BW3

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**

CMS and LHCb Comparison - 1

Fit CMS data with LHCb model I： 2 auxiliary BWs + X(6900) + bkg





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

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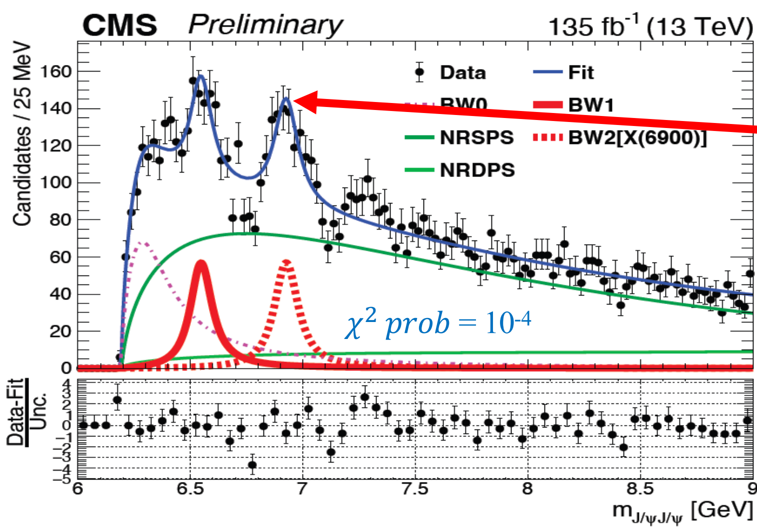
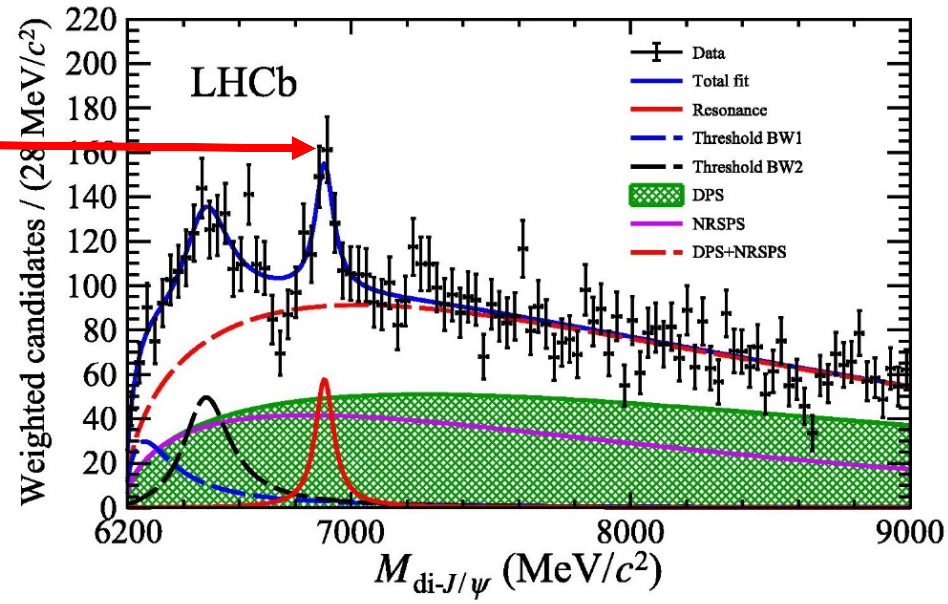


X(6900)
BW2



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BW2 are in good agreement with LHCb X(6900)

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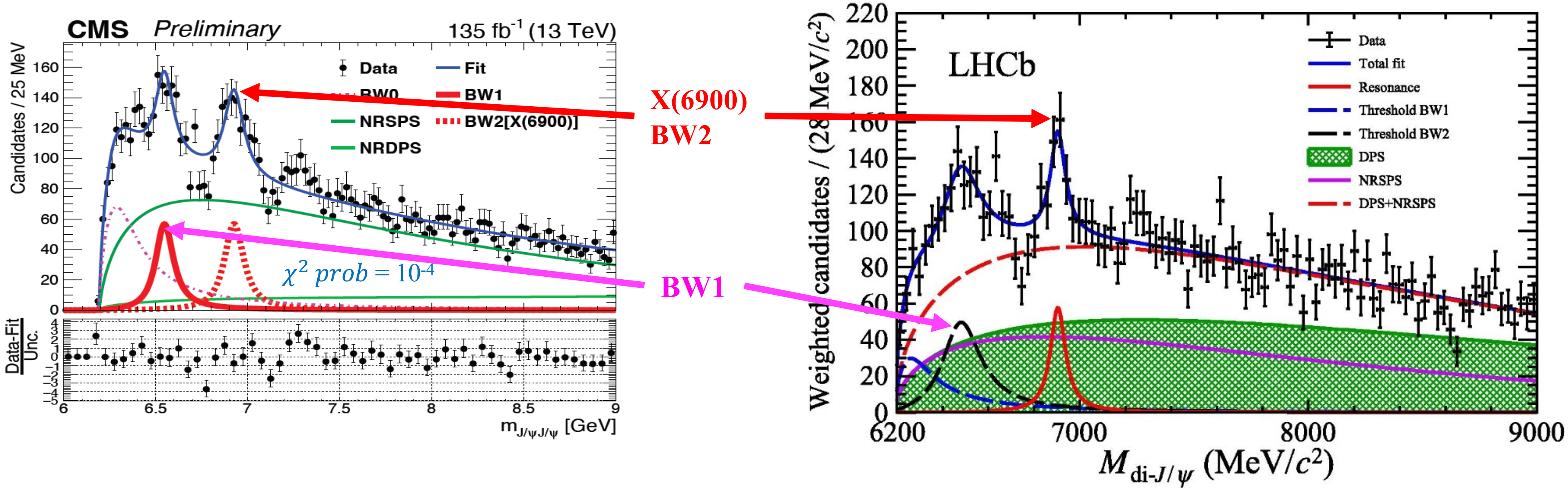

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BW2 are in good agreement with LHCb X(6900)

- LHCb did not give parameters for BW1
  - CMS has a shoulder before BW1
  - helps make BW1 distinct

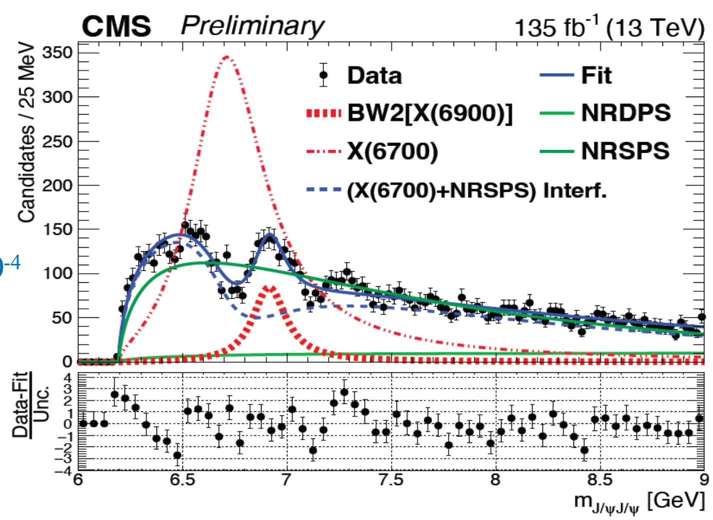
- ***Does not describe 2 dips well***

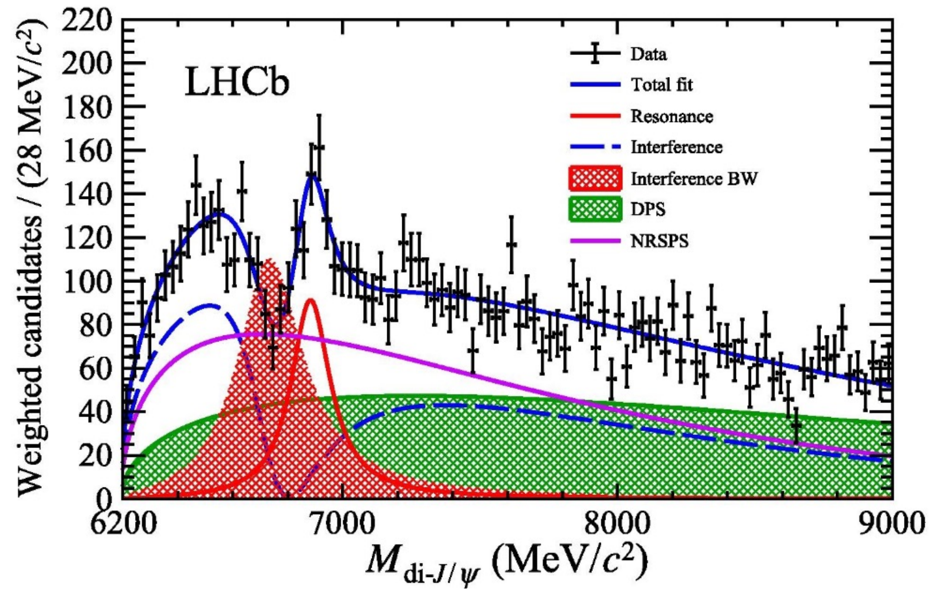
CMS and LHCb Comparison - 2

Fit CMS data with LHCb model II :

"X(6700)" interferes with NRSPS
+ X(6900) + Bkg

χ^2 *prob* = 10^{-4}





Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
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

CMS and LHCb Comparison - 2

Fit CMS data with LHCb model II :

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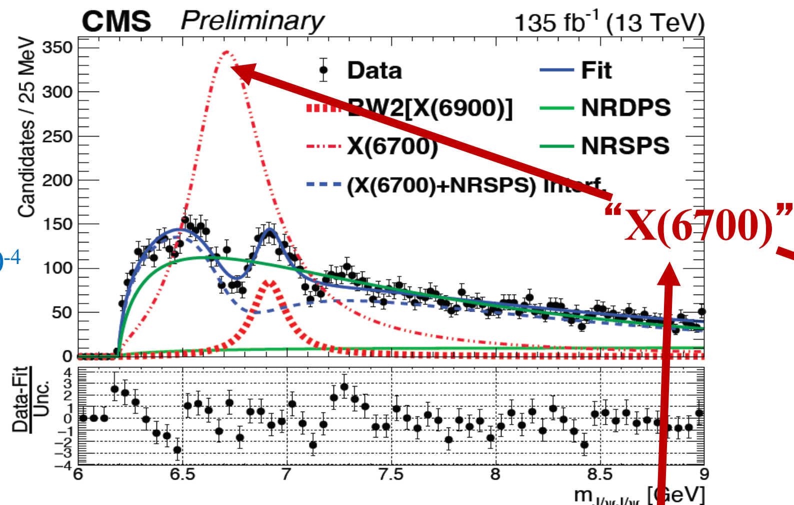

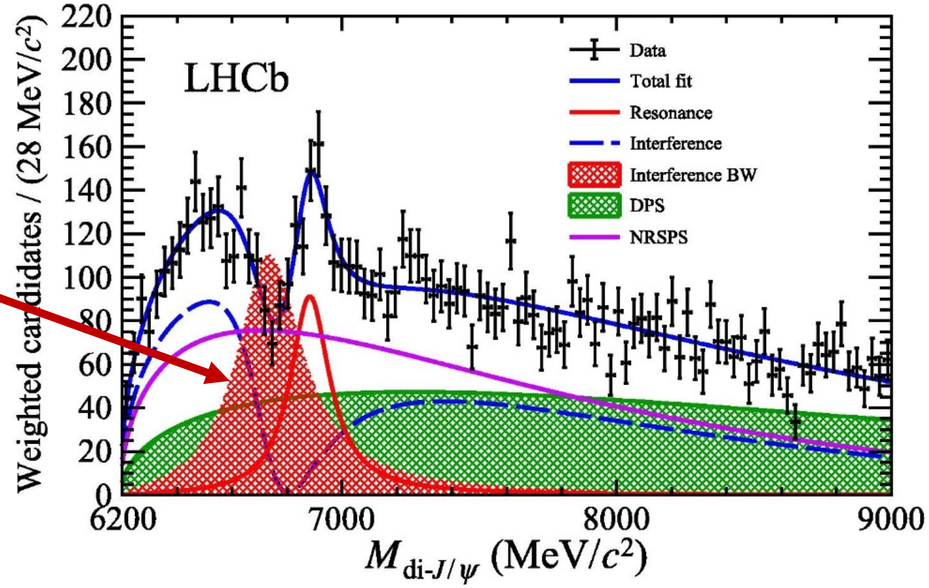

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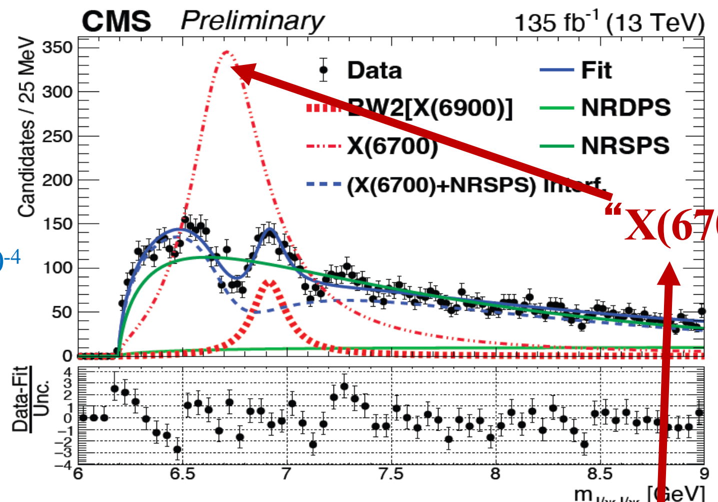
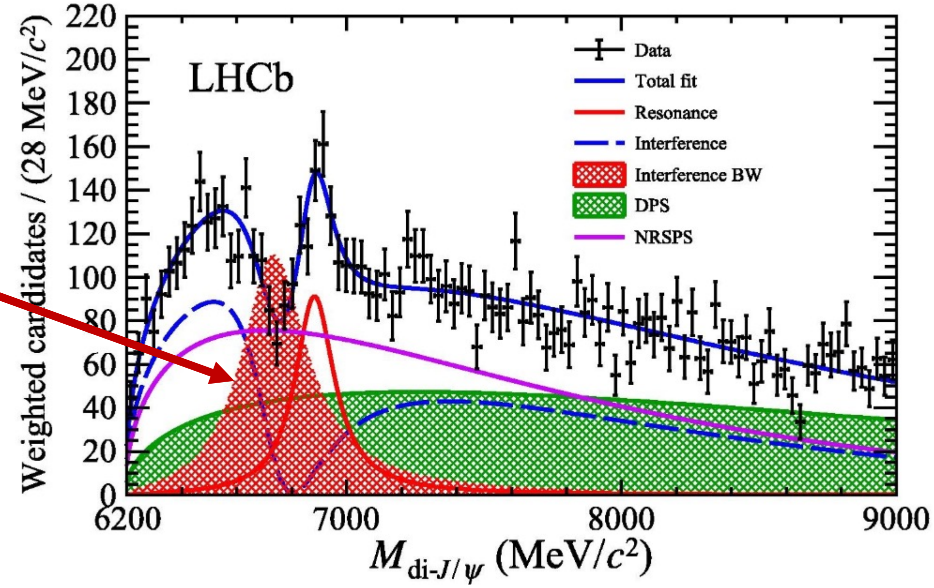


"X(6700)"



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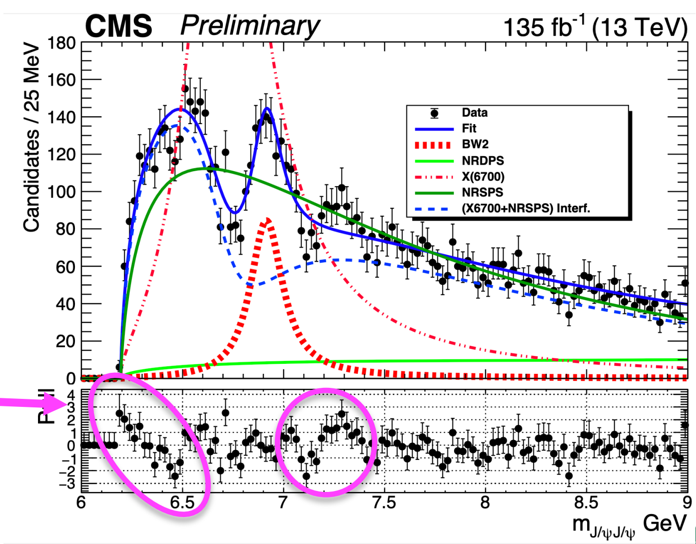
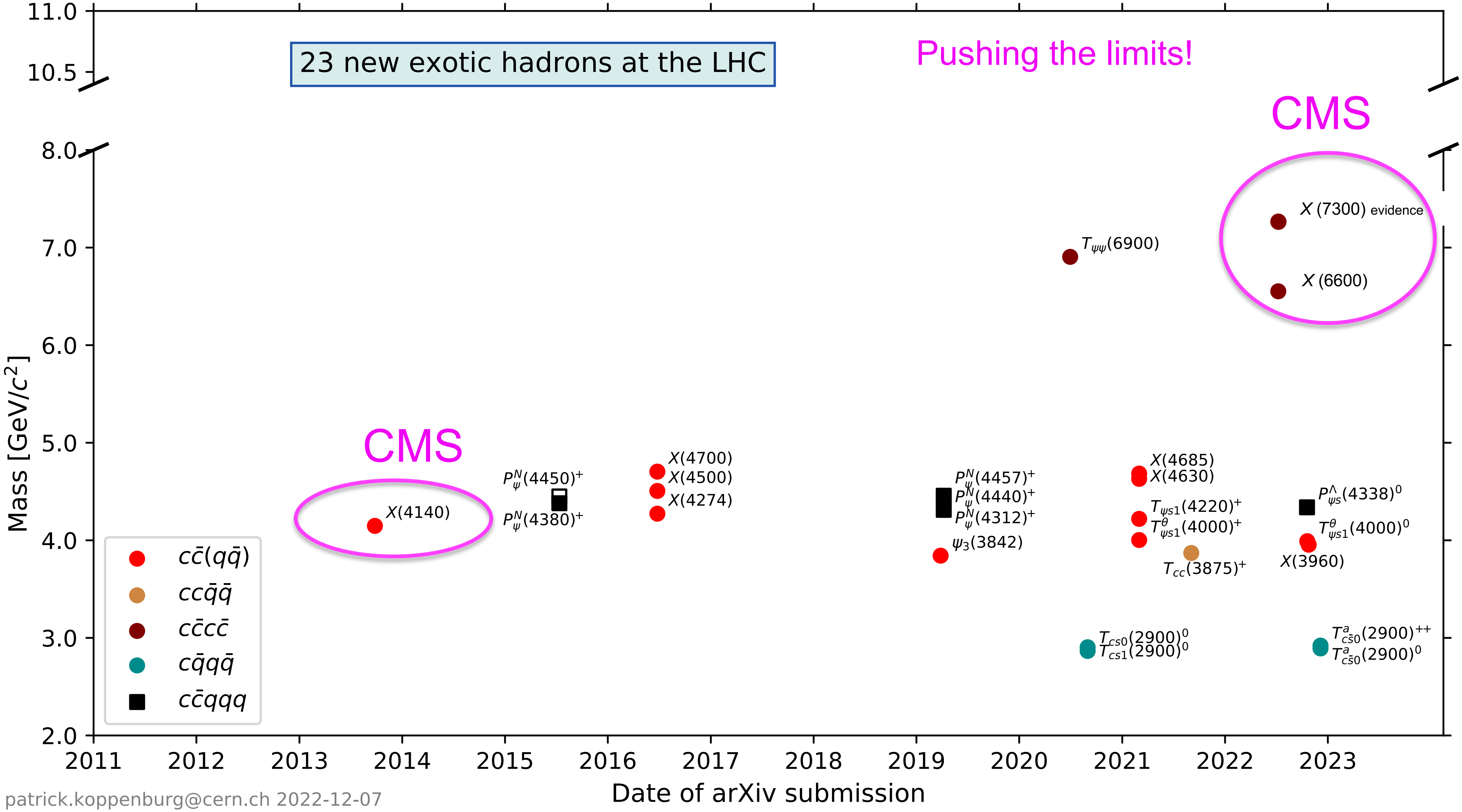


- CMS obtained larger amplitude and natural width for X(6700)
- Does not describe X(6600) and below
- Does not describe X(7200) region

All existing fits presented are not very good:
...other interference scenarios are under study in CMS

New exotic hadrons at LHC



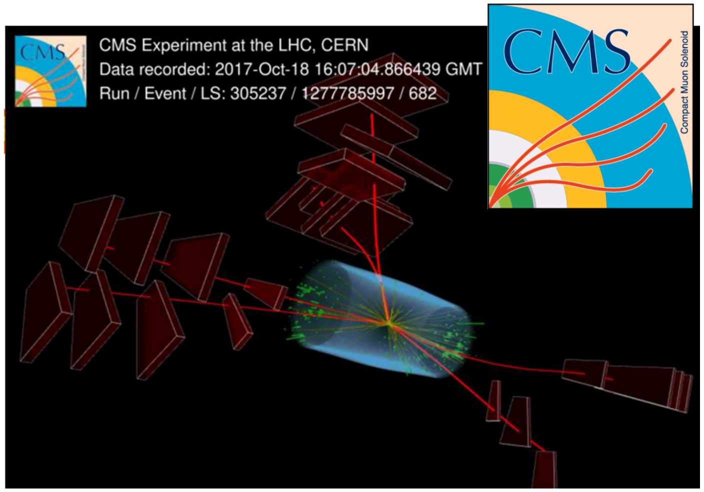
First observation of triple J/ψ production

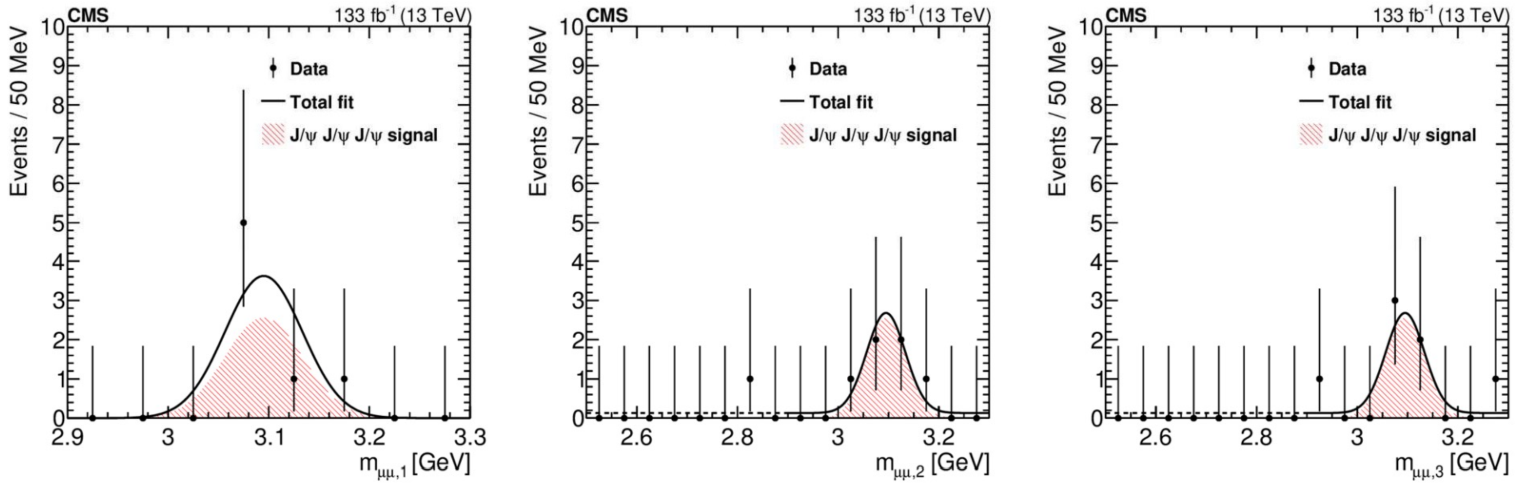
Signal yield: $5^{+2.6}_{-1.9}$events

Significance > 5σ

σ(pp→J/ψJ/ψJ/ψX)
= 272 +141−104 (stat) ± 17 (syst) fb

Nature Physics 2023





"6c" search in future?

Summary

- Successful achievement of quarkonium measurements in the past ~10 years @ CMS

- Recently, CMS found 3 significant structures in double J/ψ mass spectrum
  - X(6900) consistent with LHCb
  - Two new structures f, provisionally named as X(6600), X(7300)
  - **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 a system easier to understand
  - A new window to understand strong interaction

- Triple J/ψ production has also been observed for the first time by CMS

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·Δdof}

  - $NLL\_(nom-sig)$: 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·Δdof}
- 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*

Line shape

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

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

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:

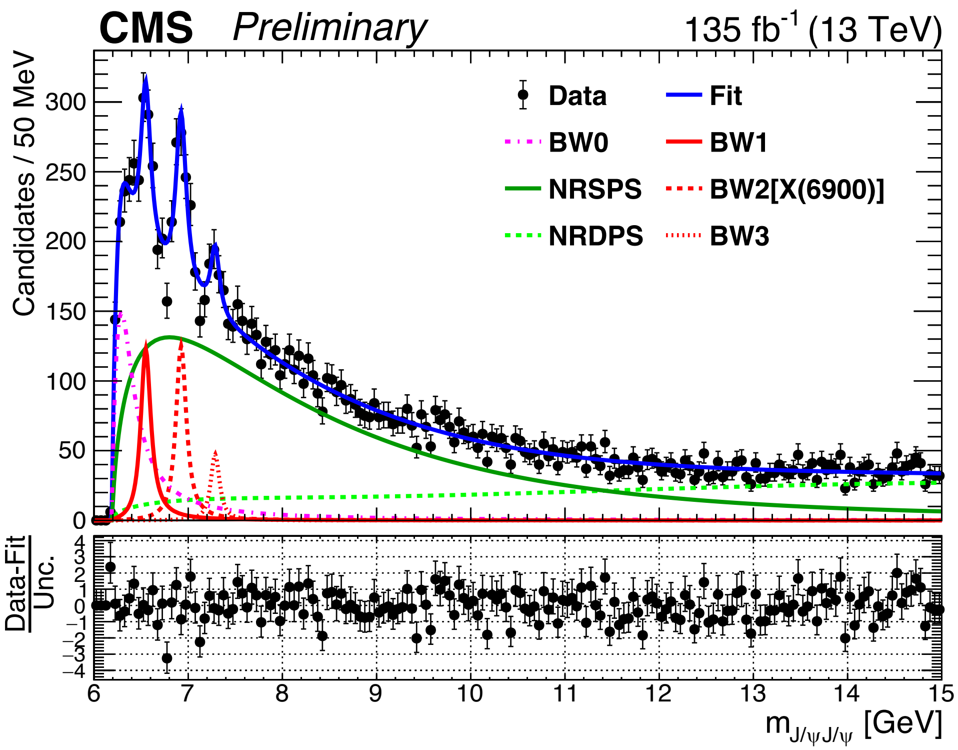
$$f_{NRSPS}(x, x_0, \alpha, p_1, p_2, p_3)$$

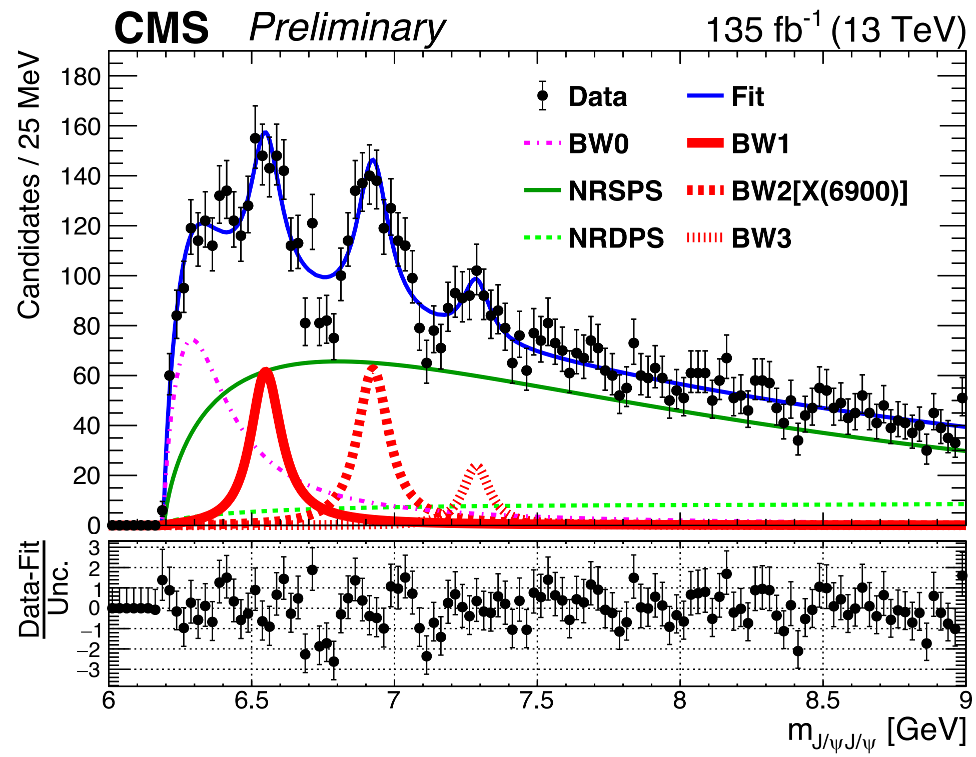
$$= (x - x_0)^{\alpha} \cdot \left(1 - \left(\frac{1}{(15 - x_0)^2} - \frac{p_1}{10}\right) \cdot (15 - x)^2\right) \cdot \exp\left(-\frac{(x - x_0)^{p_3}}{2 \cdot p_2^{p_3}}\right),$$

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

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

CMS result with BW0 explicitly shown





Significance with systematics

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
feeddown shape	11	1	1	25	8	6
momentum scaling	1	3	4	-	-	-
resolution	< 1	< 1	< 1	< 1	< 1	1
efficiency	< 1	< 1	< 1	1	< 1	1
combinatorial background	< 1	< 1	< 1	2	3	3
total	12	5	5	34	19	20

- Investigated effects of systematics on local significance by a profiling procedure
  a discrete set of individual alternative signal and background hypotheses tested in minimization
  - Significant change: BW1 significance changed from 6.5σ to >5.7σ
  - No relative significance changes for BW2 and BW3

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

Significance with systematics

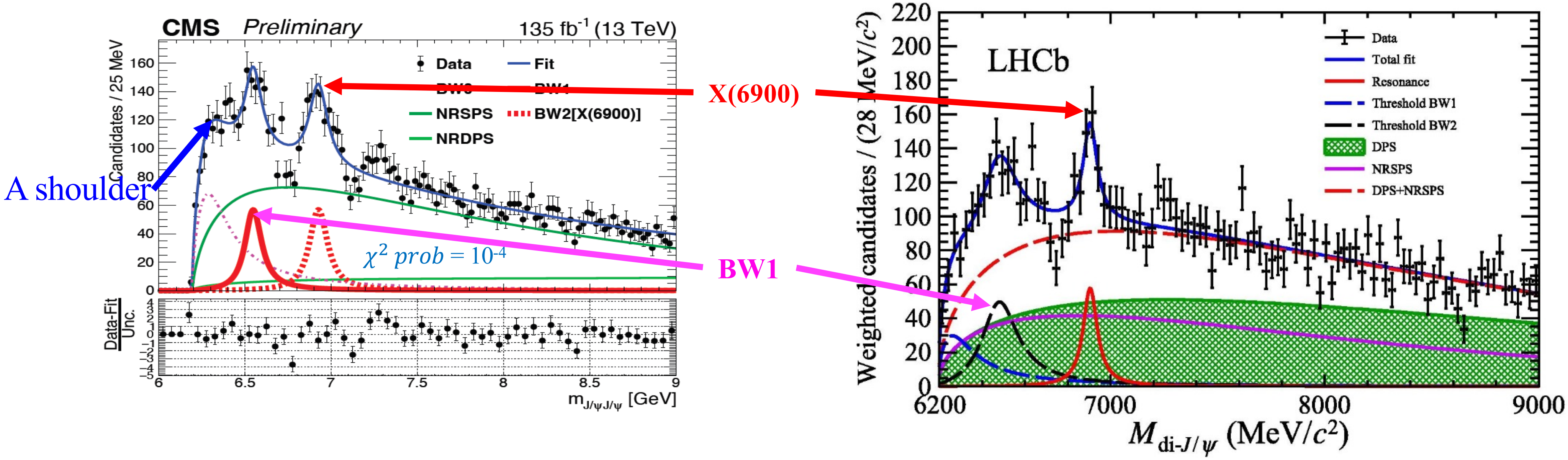
consistent →

X(6900) [LHCb]
(somewhat different fit model)

M[BW2]=6905±11±7 MeV
Γ[BW2] =80±19±33 MeV

CMS and LHCb Comparison - 1

Fit CMS data with LHCb model I： 2 auxiliary BWs + X(6900) + bkg



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

→ X(6900) parameters are in good agreement with LHCb

- LHCb did not give parameters for BW1
  - CMS has a shoulder before BW1
  - helps make BW1 distinct
- ***Does not describe 2 dips well***

CMS vs LHCb comparisons

- CMS has more data
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4 \approx$ 8X (muon acceptance due to pseudo-rapidity range)
- Similar number of final events, but CMS has less DPS bkgd
  - CMS has higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
  - DPS background suppressed by higher p_T

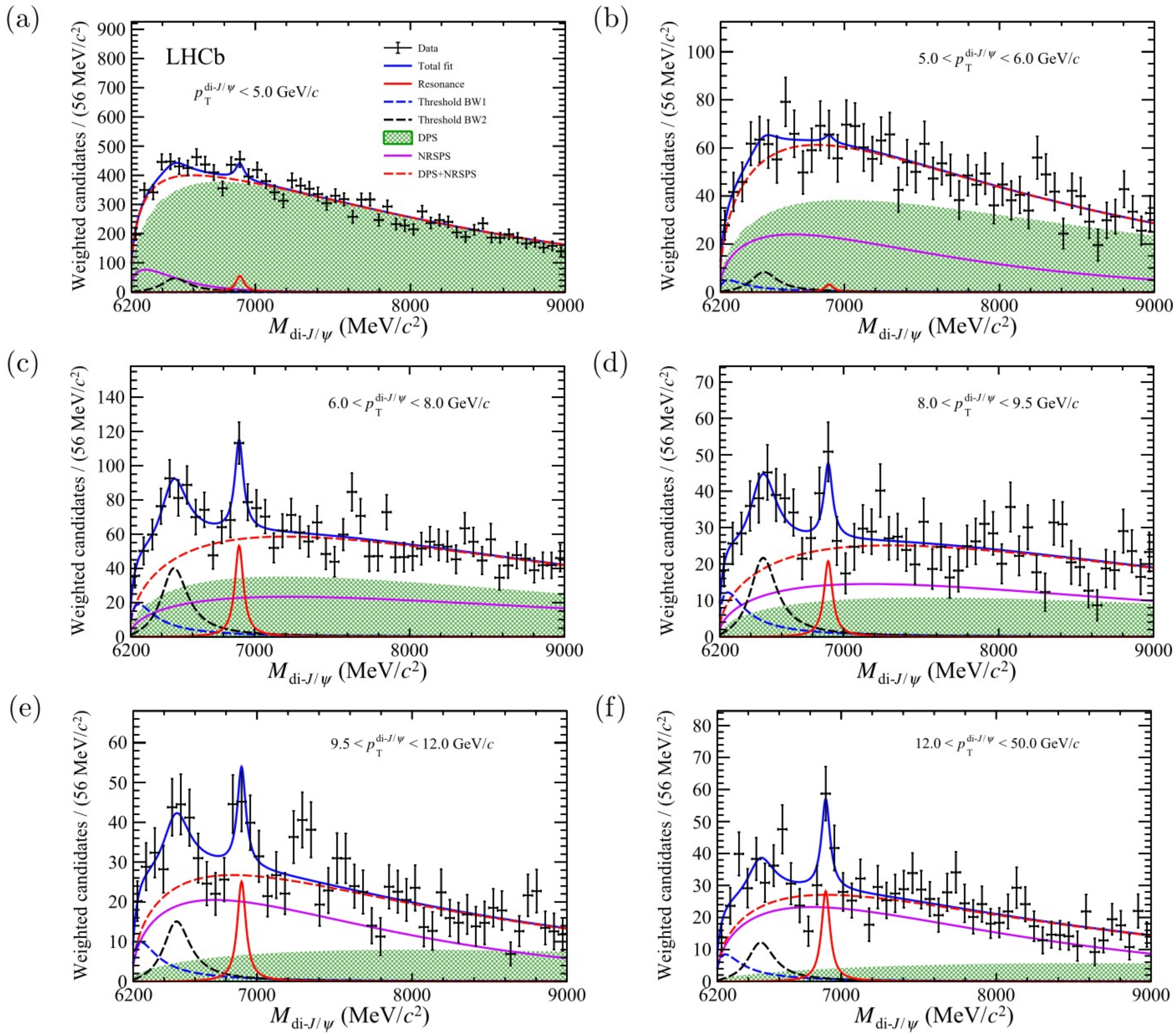


Fig. 4. Invariant mass spectra of weighted di-J/ψ candidates in bins of $p_T^{di-J/\psi}$ and overlaid projections of the $p_T^{di-J/\psi}$-binned fit with model I.