

# CMS results on exotic and conventional spectroscopy

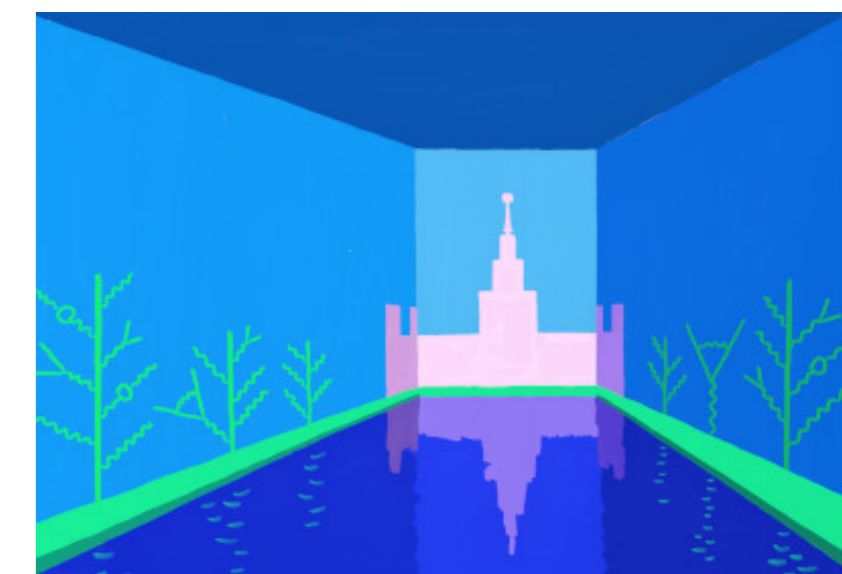
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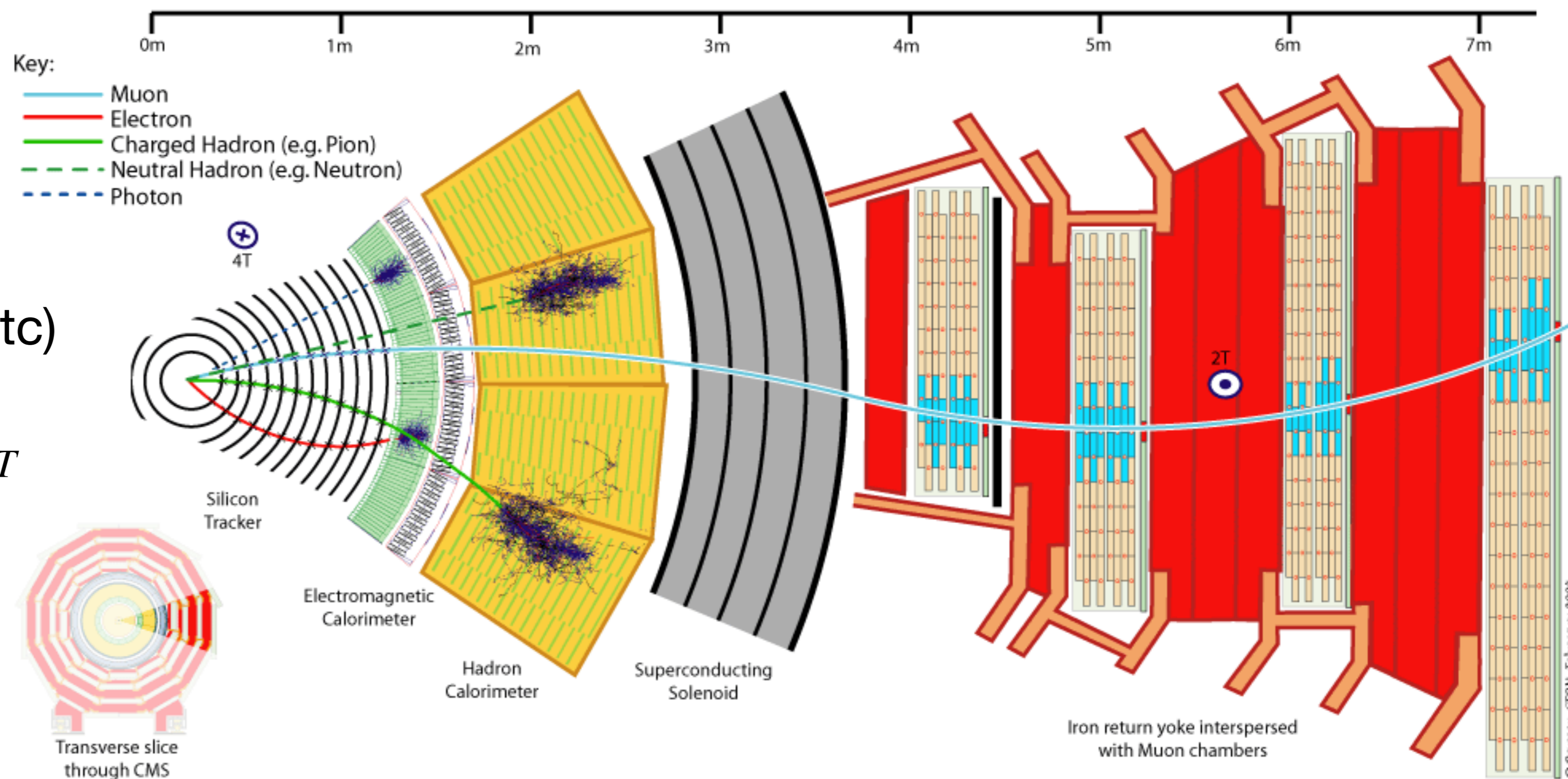
Author acknowledges support by RSF  
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30<sup>th</sup> June 2025,  
QFTHEP-270



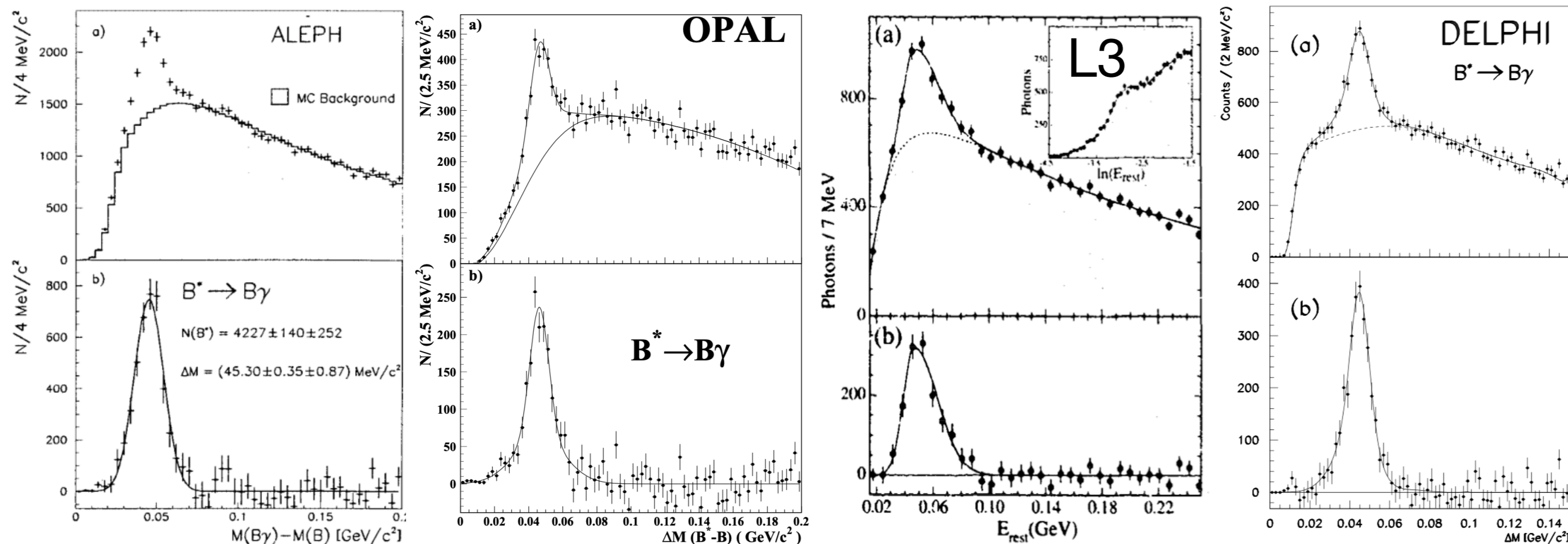
- ◆ CMS experiment
- ◆ Conventional spectroscopy
  - Excited B mesons mass measurement
- ◆ Exotic spectroscopy
  - $J/\psi J/\psi$  mass spectrum, Run2 data
  - $J/\psi J/\psi$  angular analysis
  - $J/\psi J/\psi$  mass spectrum, Run2 + Run3 data
  - $J/\psi \psi(2S)$  mass spectrum, Run2 + Run3 data
- ◆ Summary

- The CMS Experiment at the LHC was designed mainly for high- $p_T$  physics (Higgs, top-quark, SM precision measurement, New Physics searches etc)
- However, robust muon system, good  $p_T$  resolution and perfect vertex reconstruction provide promising opportunities for heavy flavour and quarkonia-related analyses



**First fully exclusive reconstruction of radiative decays of the  $B^{*+}$ ,  $B^{*0}$  and  $B_s^{*0}$  mesons and measurement of their masses in proton-proton collisions at  $\sqrt{s} = 13$  TeV**

- LEP experiments measured only **flavour averaged**  $m(B^*) - m(B)$  mass difference from b-jet and photon conversion



- B-factories CLEO and Belle measured  $B_s^{*0}$  mass from

$$\Upsilon(5S) \rightarrow B_s^0 \bar{B}_s^0$$

$$\Upsilon(5S) \rightarrow B_s^{*0} \bar{B}_s^0$$

$$\Upsilon(5S) \rightarrow B_s^0 \bar{B}_s^{*0}$$

$$\Upsilon(5S) \rightarrow B_s^{*0} \bar{B}_s^{*0}$$

(in tension with each other!)

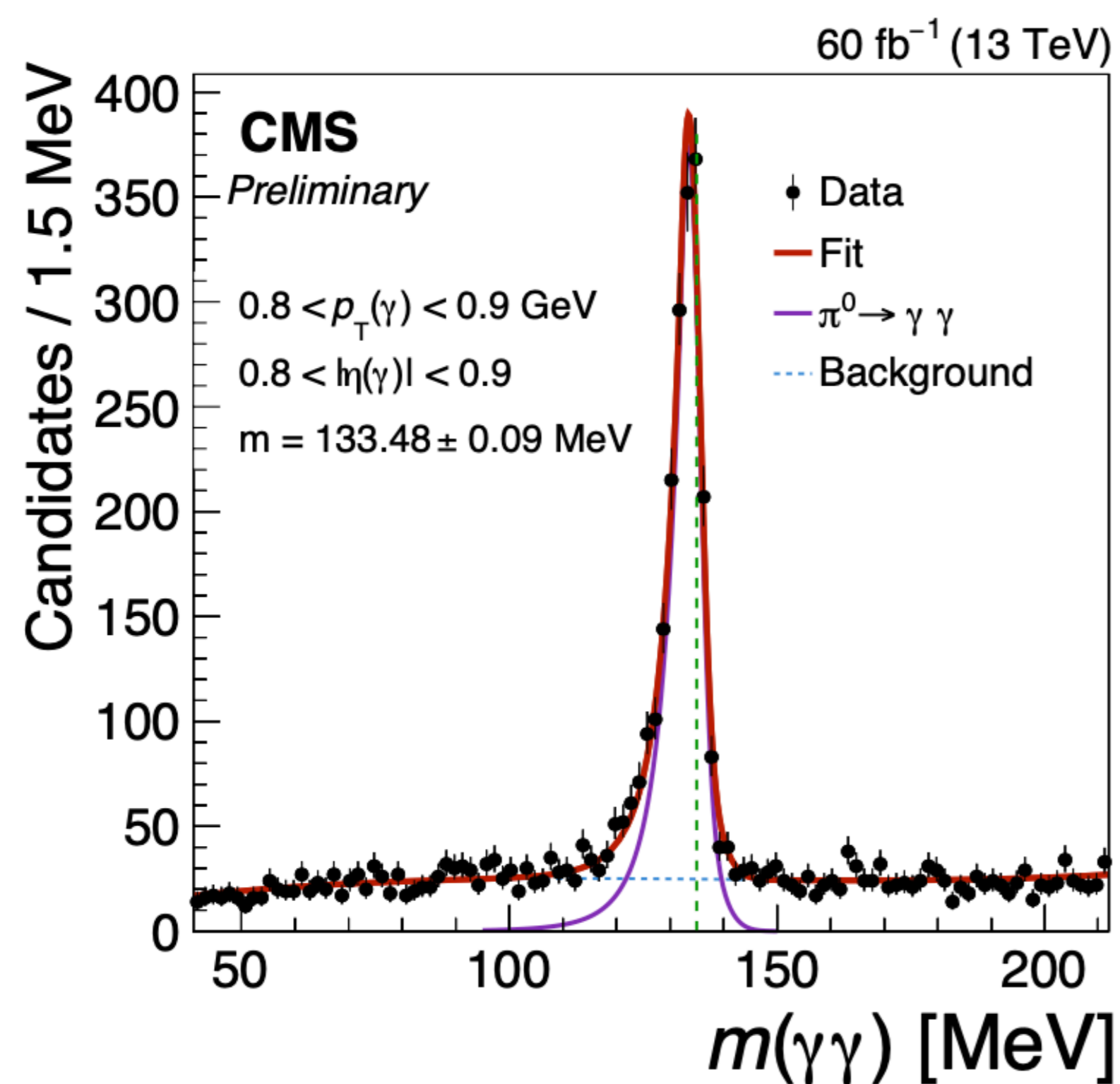
- LHCb and CMS measured mass difference from decays of **P-wave**  $B_s$  states

◆ LHCb measured  $m(B^{*+}) - m(B^+)$  from  $B_{s2}^{*+}(5849) \rightarrow B^{*+} K^-$  and  $B_{s2}^{*+}(5849) \rightarrow B^+ K^-$  peak positions

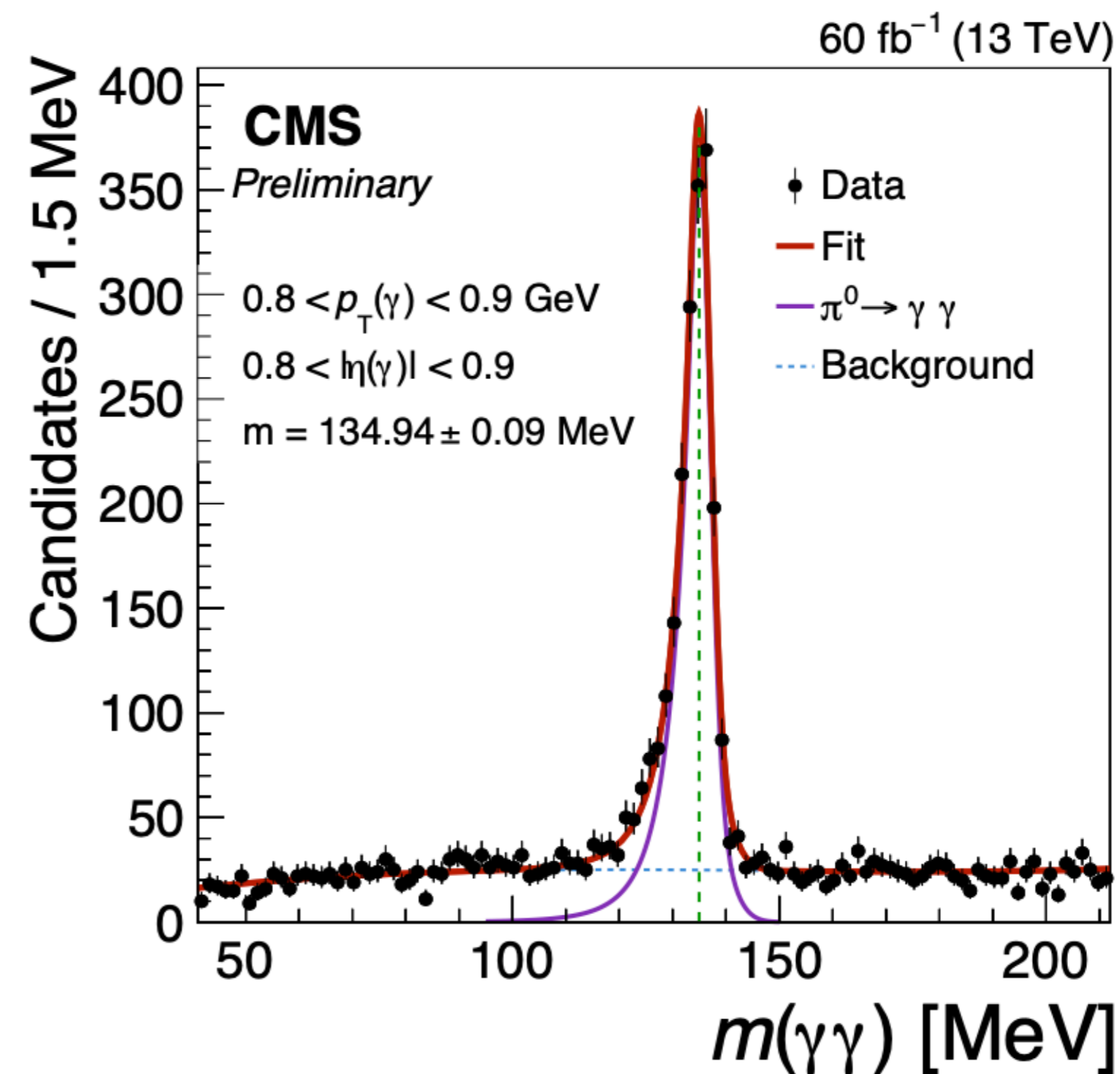
◆ CMS measured  $m(B^{*+}) - m(B^{*0})$  from  $B_{s1}(5830)^0 \rightarrow B^{*0} K_s^0$  and  $B_{s1}(5830)^0 \rightarrow B^{*+} K^-$  peak positions

Measurements of the properties of excited B mesons provide an important input to the **HQET** and our **understanding of QCD**.

- The energy of a converted photon in the data is usually lower than its true energy

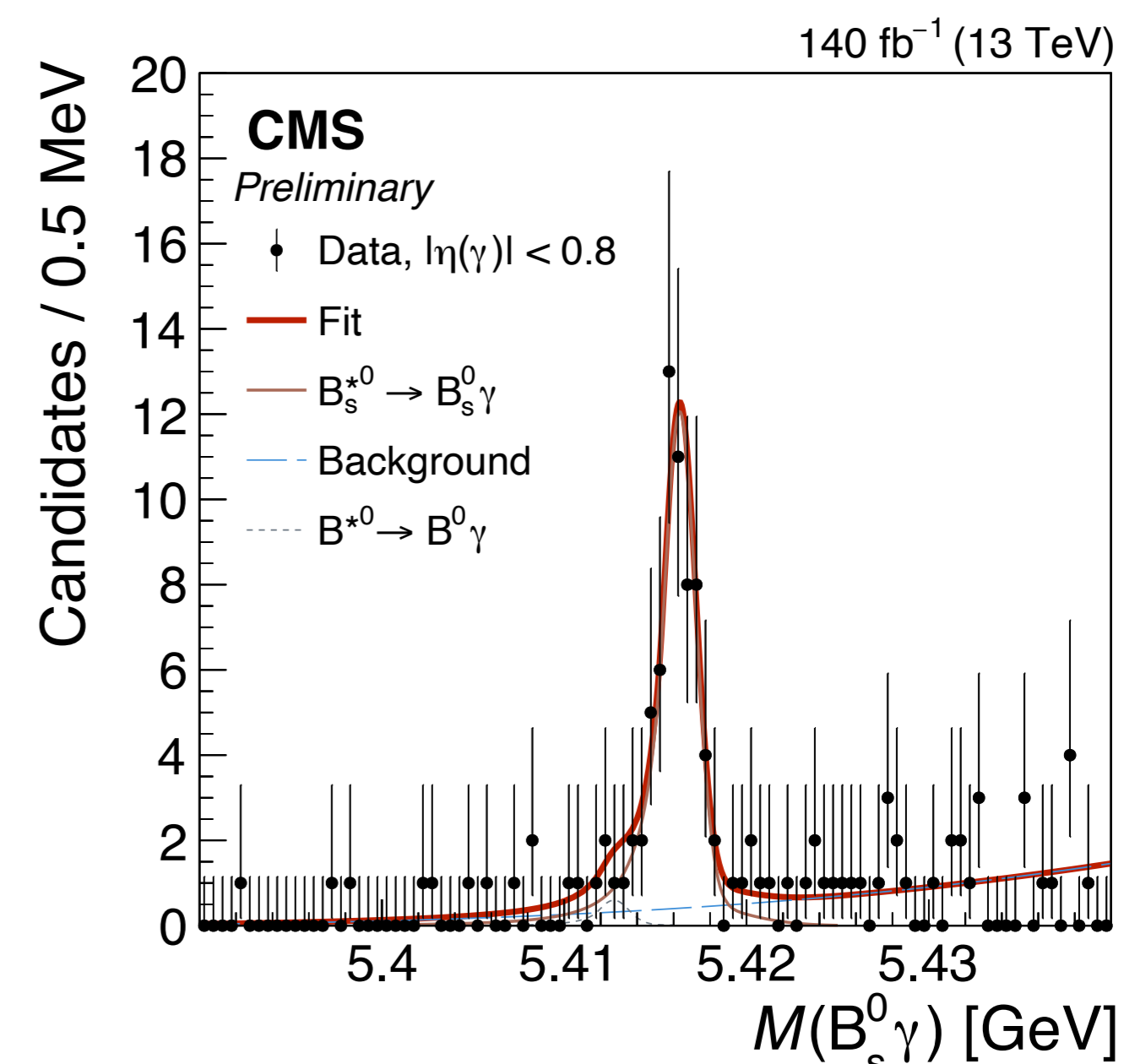
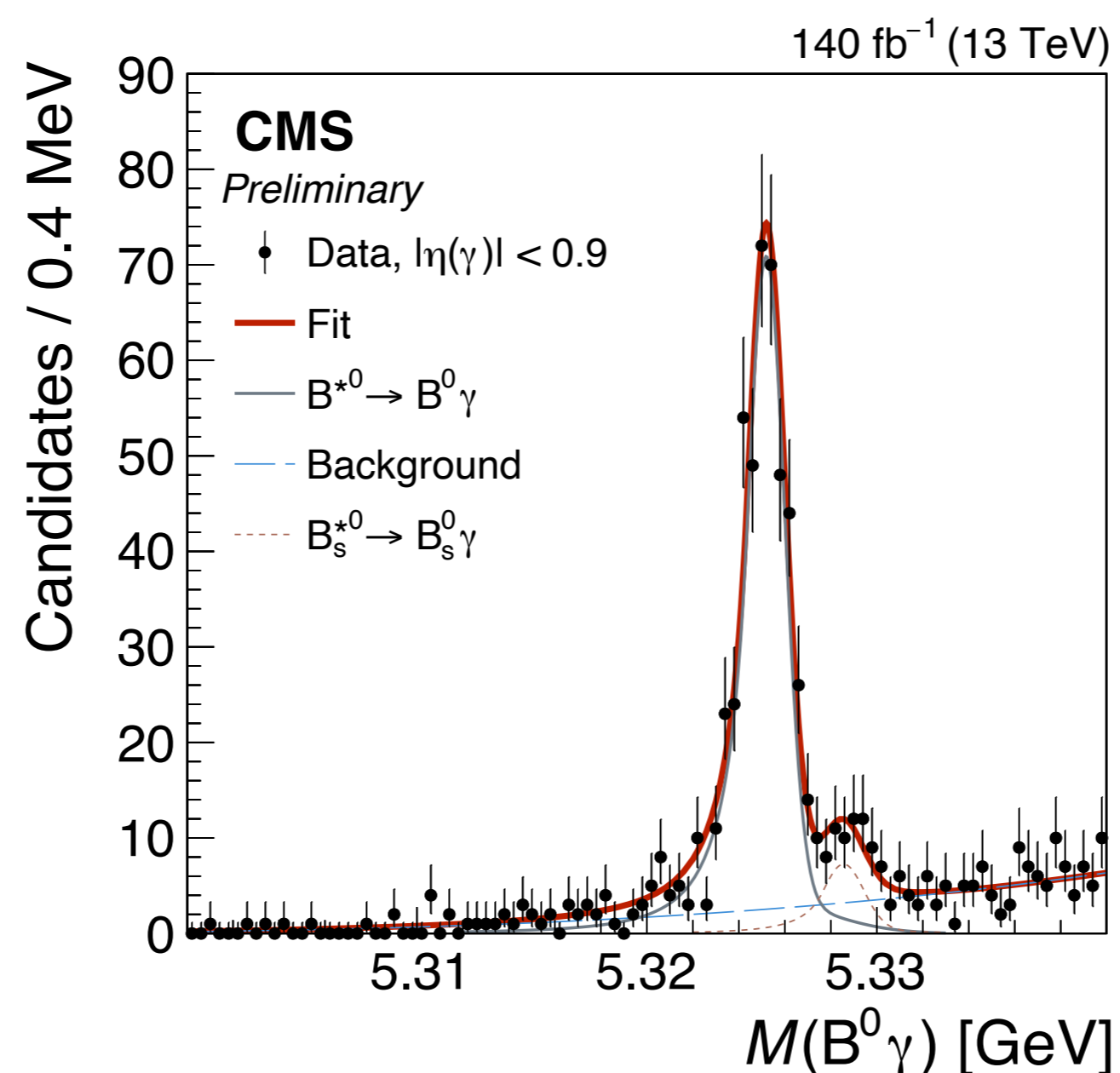
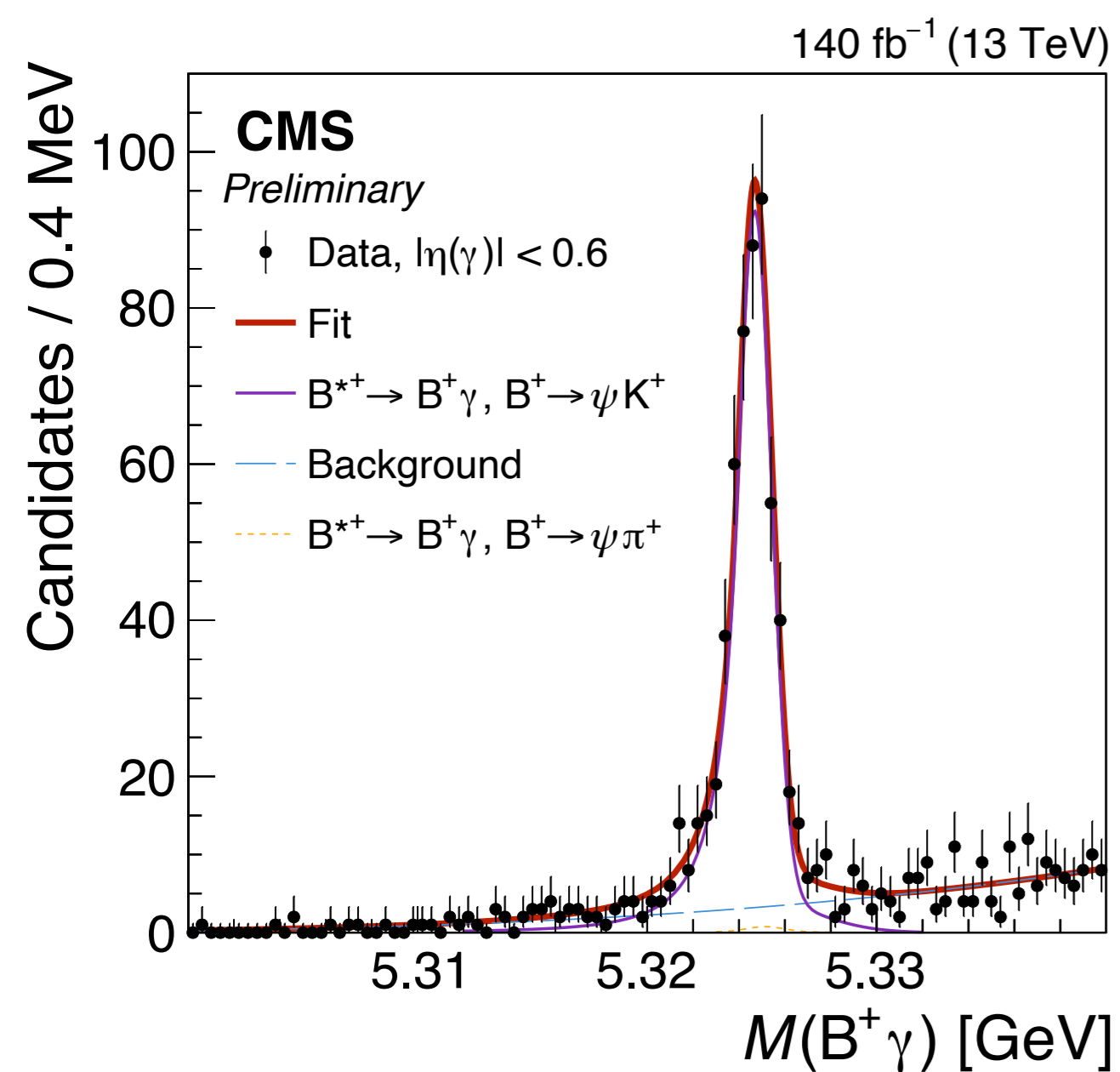


→  
PES  
Correction



- Photons from  $\pi^0 \rightarrow \gamma\gamma$  are used for PES correction

- $B^+ \rightarrow \psi K^+$ ,  $B^0 \rightarrow \psi K^{*0}$  and  $B_s^0 \rightarrow \psi \phi$  decays are reconstructed
- $\psi \rightarrow \mu^+ \mu^-$ :  $J/\psi \rightarrow \mu^+ \mu^-$  or  $\psi(2S) \rightarrow \mu^+ \mu^-$
- **Simultaneous** fit is performed in **7 categories**
- Signals are described by DCB shapes fixed to MCs
- $B^+ \rightarrow J/\psi \pi^+$  shape and fraction fixed from MC
- $B^{*0} \leftrightarrow B_s^{*0}$  cross-feed shape fixed from MC and for  $B^{*0}$  fraction also fixed
- Bkg:  $(m - m^0)^\beta$  with common  $\beta$



	Parameter	Value
1	$\Delta m(\mathbf{B}^{*+}) \equiv m(\mathbf{B}^{*+}) - m(\mathbf{B}^+)$	$45.277 \pm 0.039 \pm 0.021 \text{ MeV}$
2	$\Delta m(\mathbf{B}^{*0}) \equiv m(\mathbf{B}^{*0}) - m(\mathbf{B}^0)$	$45.471 \pm 0.056 \pm 0.024 \text{ MeV}$
3	$\Delta m(\mathbf{B}_s^{*0}) \equiv m(\mathbf{B}_s^{*0}) - m(\mathbf{B}_s^0)$	$49.407 \pm 0.132 \pm 0.034 \text{ MeV}$
4	$m(\mathbf{B}^{*+})$	$5324.69 \pm 0.04 \pm 0.02 \pm 0.07 \text{ MeV}$
5	$m(\mathbf{B}^{*0})$	$5325.19 \pm 0.06 \pm 0.02 \pm 0.08 \text{ MeV}$
6	$m(\mathbf{B}_s^{*0})$	$5416.34 \pm 0.13 \pm 0.03 \pm 0.10 \text{ MeV}$
7	$m(\mathbf{B}^{*0}) - m(\mathbf{B}^{*+})$	$0.50 \pm 0.07 \pm 0.01 \pm 0.05 \text{ MeV}$
8	$m(\mathbf{B}_s^{*0}) - m(\mathbf{B}^{*+})$	$91.66 \pm 0.14 \pm 0.03 \pm 0.12 \text{ MeV}$
9	$m(\mathbf{B}_s^{*0}) - m(\mathbf{B}^{*0})$	$91.15 \pm 0.14 \pm 0.03 \pm 0.12 \text{ MeV}$
10	$m(\mathbf{B}_s^{*0}) - \frac{m(\mathbf{B}^{*0}) + m(\mathbf{B}^{*+})}{2}$	$91.40 \pm 0.13 \pm 0.03 \pm 0.12 \text{ MeV}$
11	$\Delta m(\mathbf{B}^{*0}) - \Delta m(\mathbf{B}^{*+})$	$0.19 \pm 0.07 \pm 0.01 \text{ MeV}$
12	$\Delta m(\mathbf{B}_s^{*0}) - \Delta m(\mathbf{B}^{*+})$	$4.13 \pm 0.14 \pm 0.03 \text{ MeV}$
13	$\Delta m(\mathbf{B}_s^{*0}) - \Delta m(\mathbf{B}^{*0})$	$3.94 \pm 0.14 \pm 0.03 \text{ MeV}$
14	$\Delta m(\mathbf{B}_s^{*0}) - \frac{\Delta m(\mathbf{B}^{*0}) + \Delta m(\mathbf{B}^{*+})}{2}$	$4.03 \pm 0.13 \pm 0.03 \text{ MeV}$
15	$\Delta m(\mathbf{B}^{*0}) / \Delta m(\mathbf{B}^{*+})$	$1.0043 \pm 0.0015 \pm 0.0002$
16	$\Delta m(\mathbf{B}_s^{*0}) / \Delta m(\mathbf{B}^{*+})$	$1.0912 \pm 0.0031 \pm 0.0007$
17	$\Delta m(\mathbf{B}_s^{*0}) / \Delta m(\mathbf{B}^{*0})$	$1.0866 \pm 0.0031 \pm 0.0007$
18	$\frac{2 \cdot \Delta m(\mathbf{B}_s^{*0})}{\Delta m(\mathbf{B}^{*+}) + \Delta m(\mathbf{B}^{*0})}$	$1.0889 \pm 0.0030 \pm 0.0007$

- **order of magnitude more precise** than, the current world-average values

- **In agreement and 3 times more precise** than previous CMS measurement
- **First** measurements of differences between vector states

- **First** measurement of **difference** between hyperfine splittings

- **First** measurement of **ratios** between hyperfine splittings

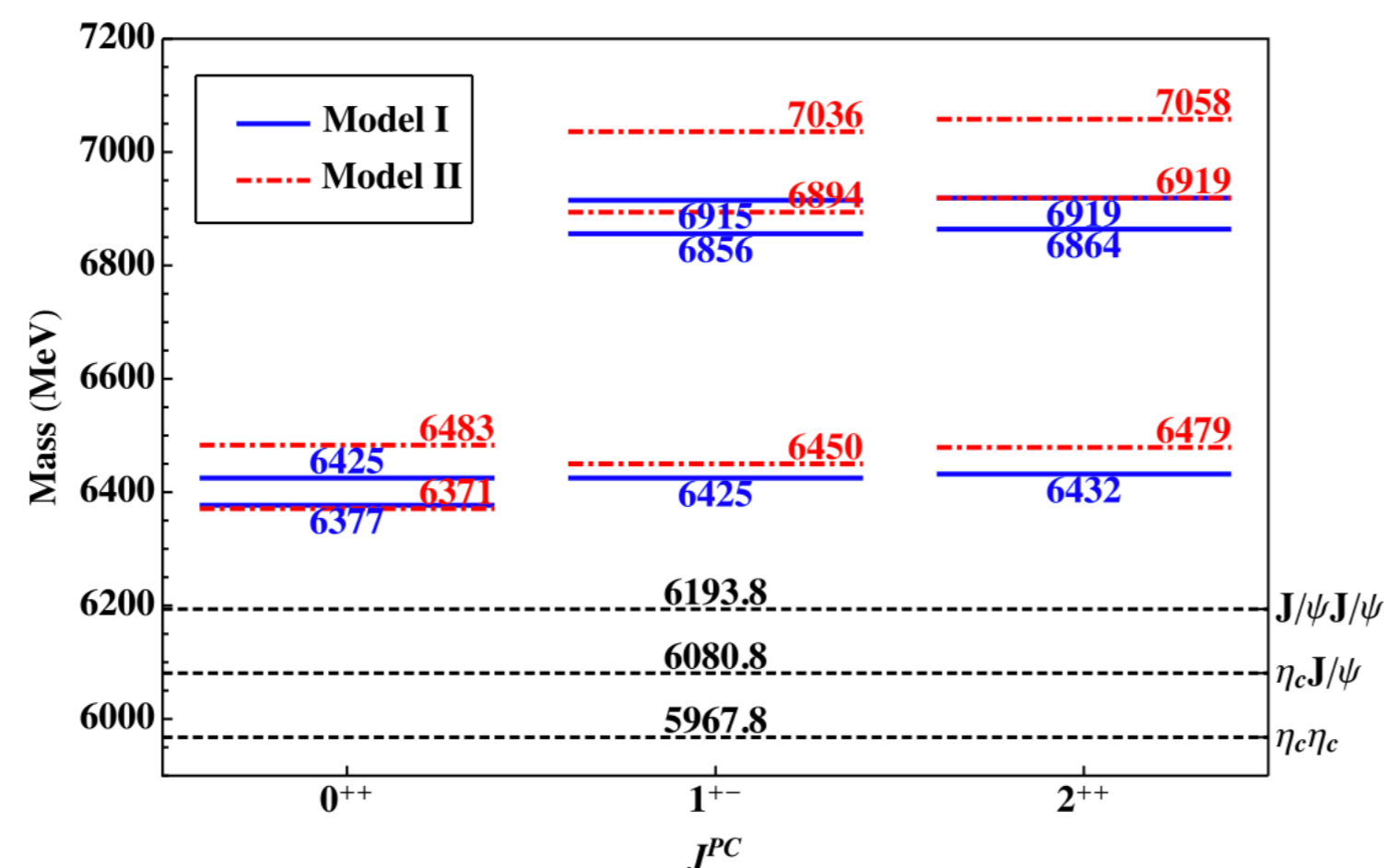
**Observation of new structure in the  $J/\psi J/\psi$  mass spectrum in proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$**

- Theoretical studies of  $J/\psi J/\psi$  structures **started in 1975**, After  $J/\psi$  observation.

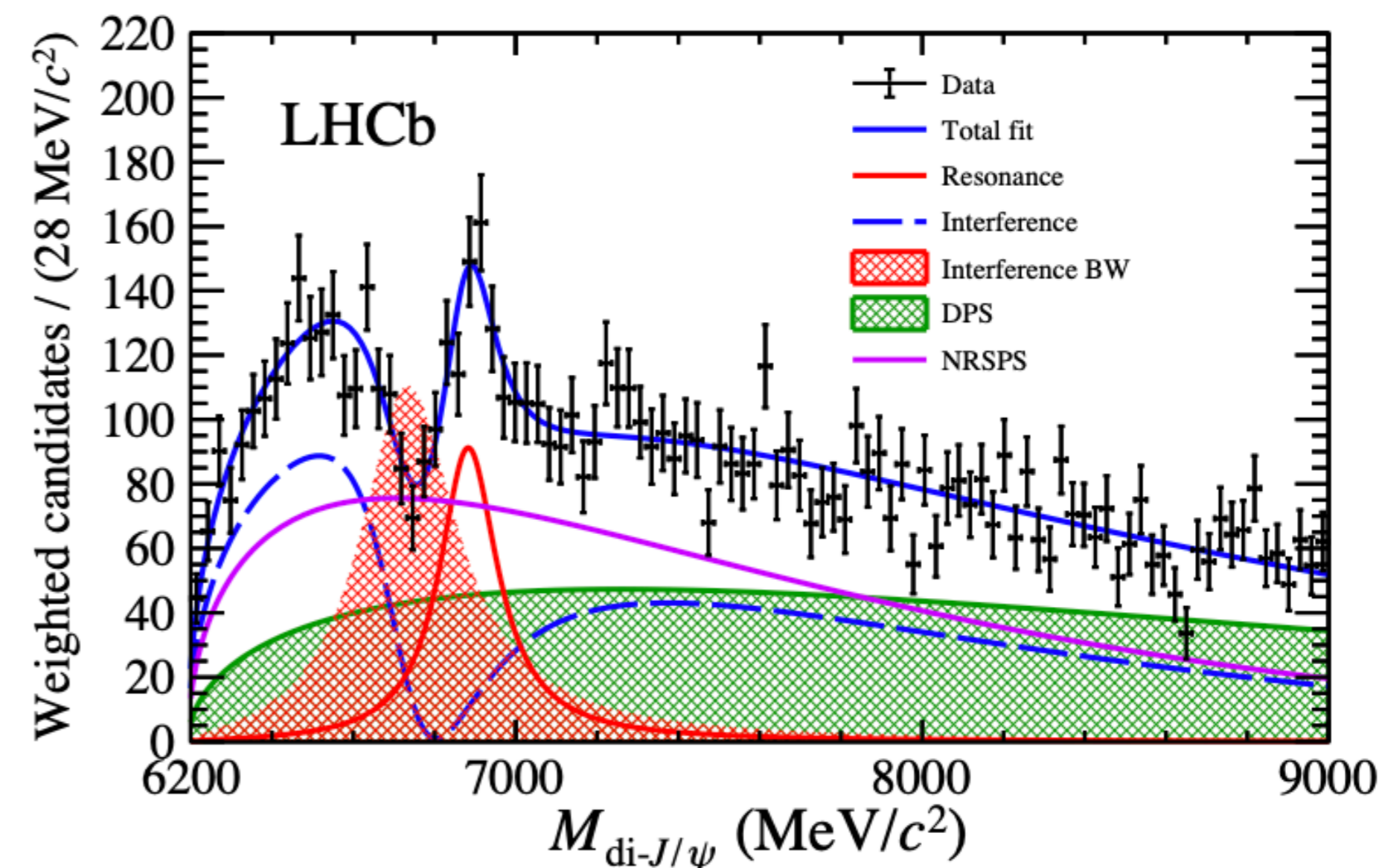
Z. Phys. C 7, 317 (1981)

$L$	$S$	$J^{PC}$	Mass (GeV)
1	0	$1^{--}$	6.55
	1	$0^{-+}, 1^{-+}, 2^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}$	
2	0	$2^{++}$	6.78
	1	$1^{+-}, 2^{+-}, 3^{+-}$	
	2	$0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}$	
3	0	$3^{--}$	6.98
	1	$2^{-+}, 3^{-+}, 4^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

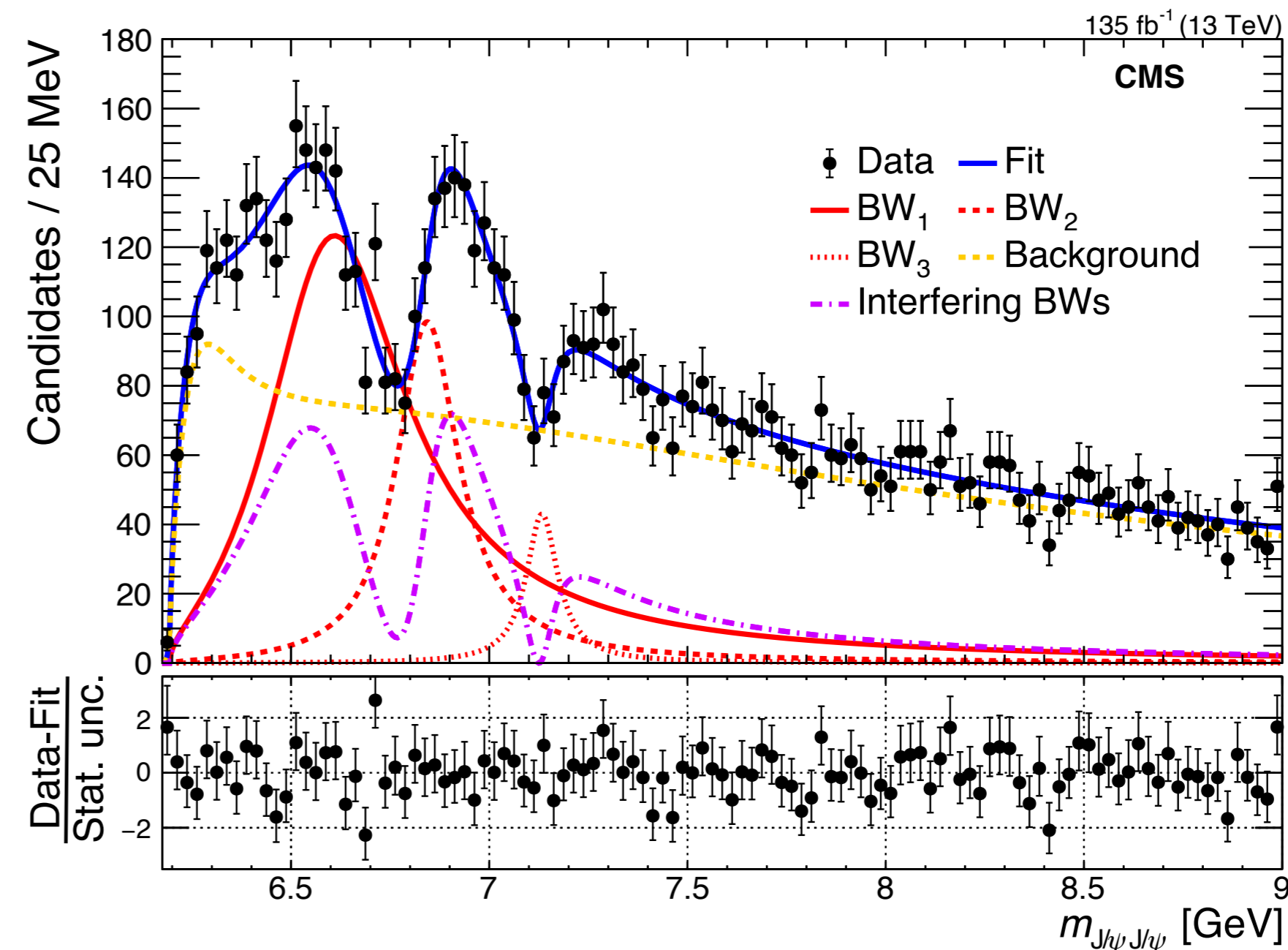
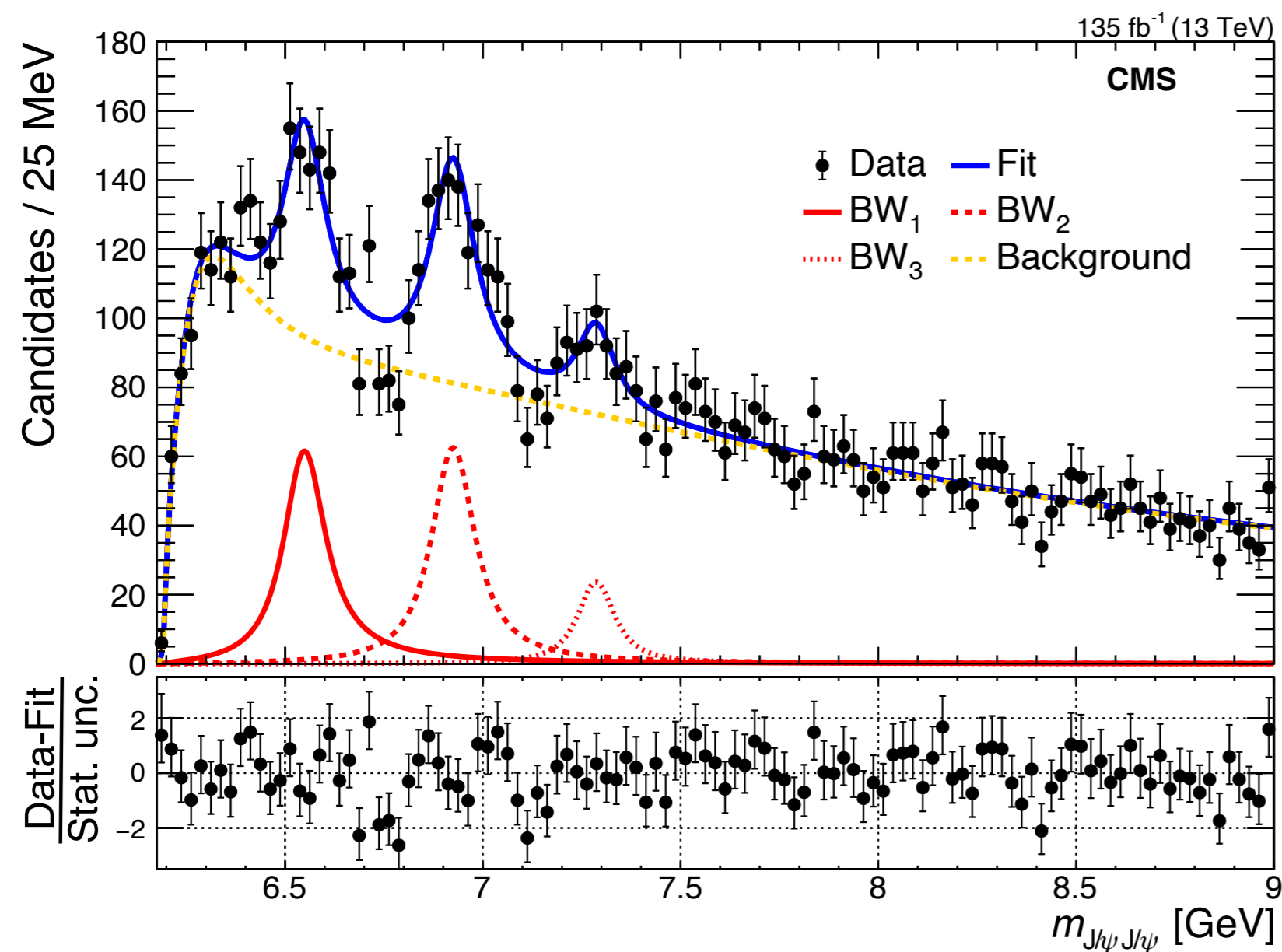
PHYSICAL REVIEW D 100, 096013 (2019)



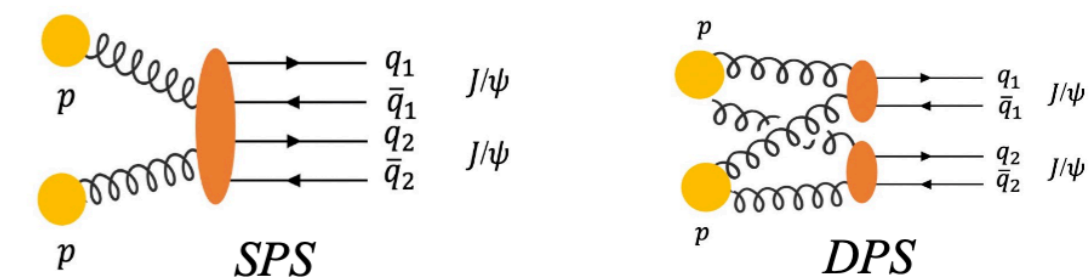
- LHCb observed **X(6900)** structure in  $J/\psi J/\psi$  spectrum in 2020



- CMS  $J/\psi J/\psi$  object has higher  $p_T$ , which means higher sensitivity though we have less events



- Background component: SPS + DPS + Combinatorial bkg +  $BW_0$
- Signal component:  $BW_1 + BW_2 + BW_3$
- Interference model (three-way interference):  $|r_1 \exp(i\phi_1) BW_1 + BW_2 + r_3 \exp(i\phi_3) BW_3|^2$



- For model without interference the full  $\chi^2$  fit probability is 98%. However, the dips in the data around 6750 and 7150 MeV are poorly described: the signal-region probability  $\chi^2$  is **9%**
- **Three-way interference** model, shows a signal-region  $\chi^2$  probability of **65%**
- Significance of obtained resonances: BW1 (**6.5  $\sigma$** ), BW2 (**9.4  $\sigma$** ), BW3 (**4.1  $\sigma$** )

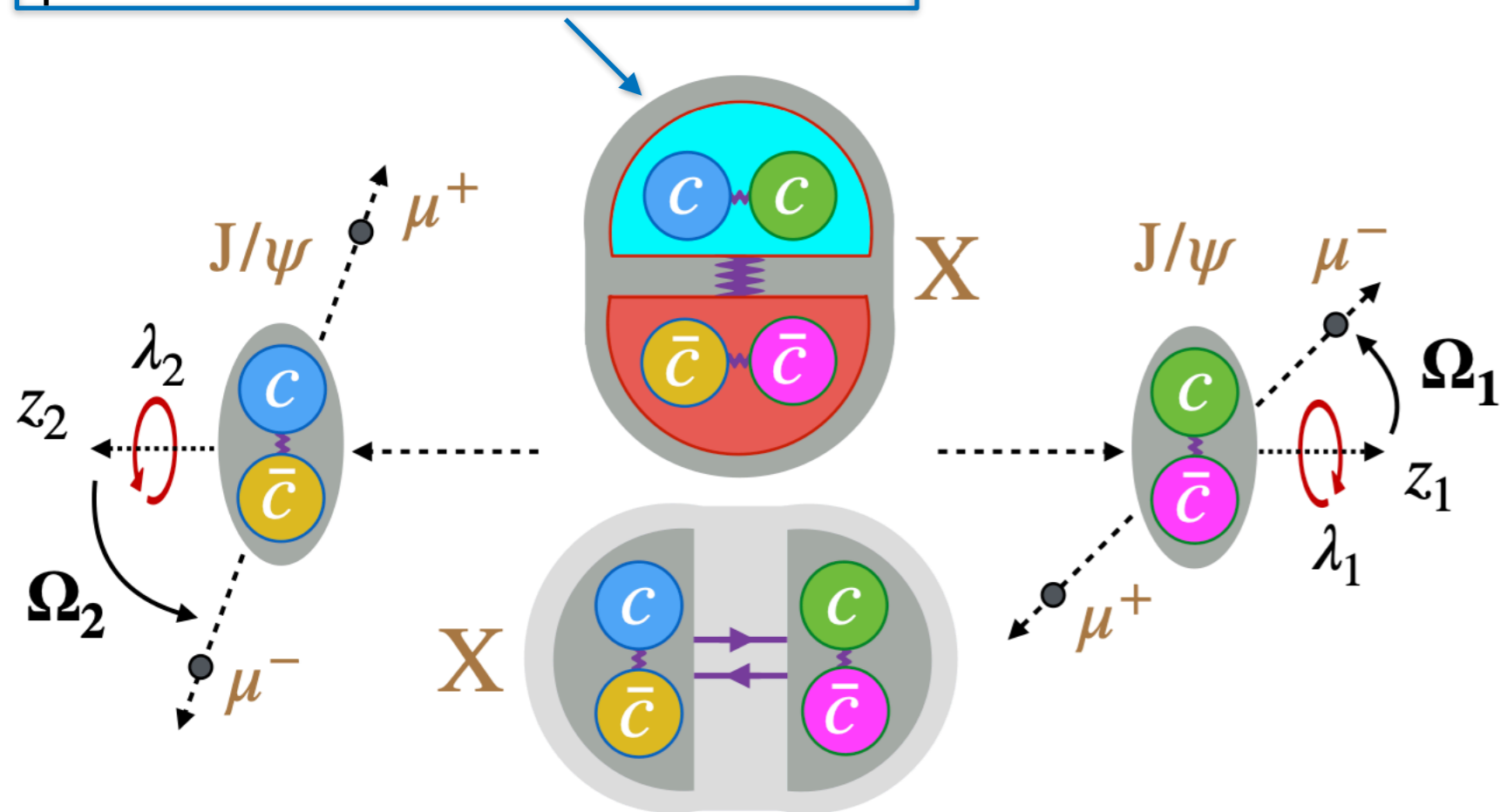
		BW <sub>1</sub>	BW <sub>2</sub>	BW <sub>3</sub>
No interference	$m$ (MeV)	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	$\Gamma$ (MeV)	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
	$N$	$470^{+120}_{-110}$	$492^{+78}_{-73}$	$156^{+64}_{-51}$
Interference	$m$ (MeV)	$6638^{+43+16}_{-38-31}$	$6847^{+44+48}_{-28-20}$	$7134^{+48+41}_{-25-15}$
	$\Gamma$ (MeV)	$440^{+230+110}_{-200-240}$	$191^{+66+25}_{-49-17}$	$97^{+40+29}_{-29-26}$

Two **new** structures!  
X(6600) and X(7100)

# Spin and symmetry properties of all-charm tetraquarks

- Linear  $m^2$  pattern - consistent with  $n = 1, 2, 3 \dots$  (Regge trajectory)
- **Interference** - clear sign that all three tetra quarks might have same  $J^{PC}$

“True” tetra-quark connects two colored objects through direct strong interactions like quarks in a proton or neutron



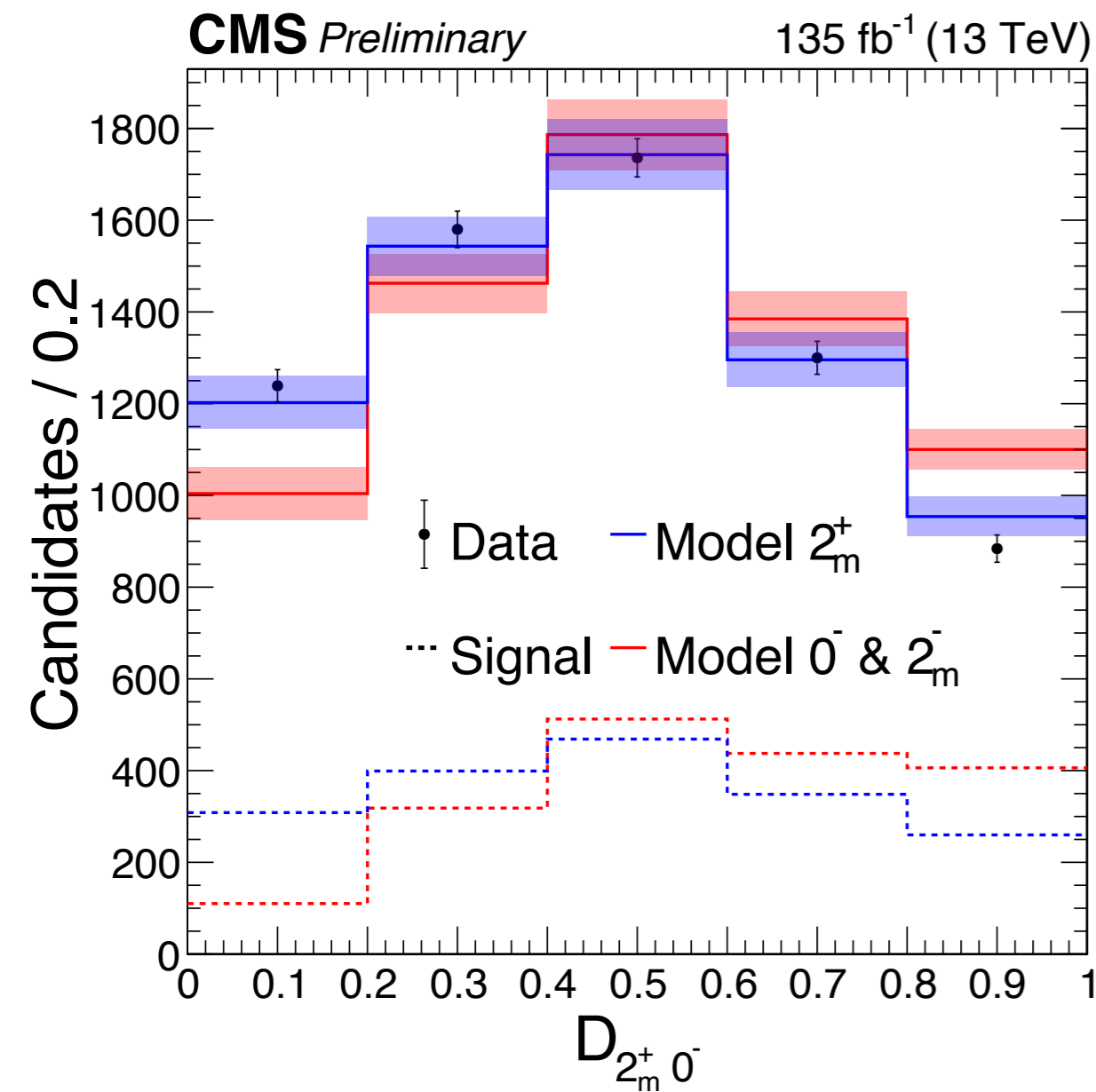
“Molecule” a bound state of two neutral mesons connected by a strong nuclear force, like proton and neutron in a nucleus

$J^{PC}$	Models $J_i^P$	Contributing amplitudes
$0^{-+}$	$0^-$	$A_{++} = -A_{--}$
$0^{++}$	$0_m^+$ and $0_h^+$	$A_{++} = A_{--}$ and $A_{00}$
$1^{-+}$	$1^-$	$A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$
$1^{++}$	$1^+$	$A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$
$2^{-+}$	$2_m^-$ and $2_h^-$	$A_{++} = -A_{--}$ and $A_{+0} = A_{0+} = -A_{-0} = -A_{0-}$
$2^{++}$	$2_m^+$	$A_{++} = A_{--}, A_{00}, A_{+0} = A_{0+} = A_{-0} = A_{0-},$ and $A_{+-} = A_{-+}$

- For 8 listed models there is predicted probability distribution  $P_i(\theta_1, \theta_2, \Phi, m_{4\mu})$
- The aim is to identify the model that best matches the experimental data

There are also other less popular models.

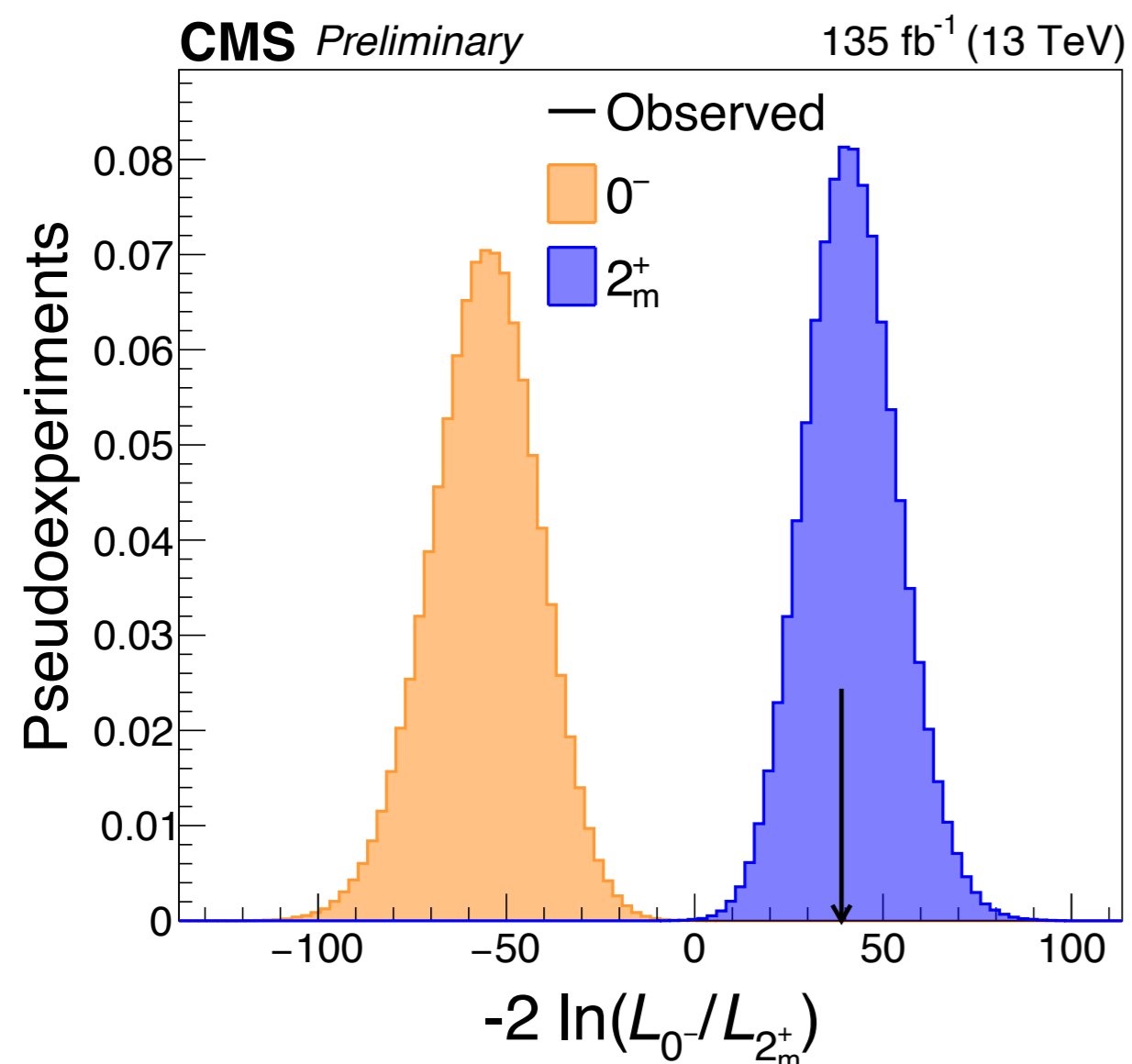
# Angular analysis

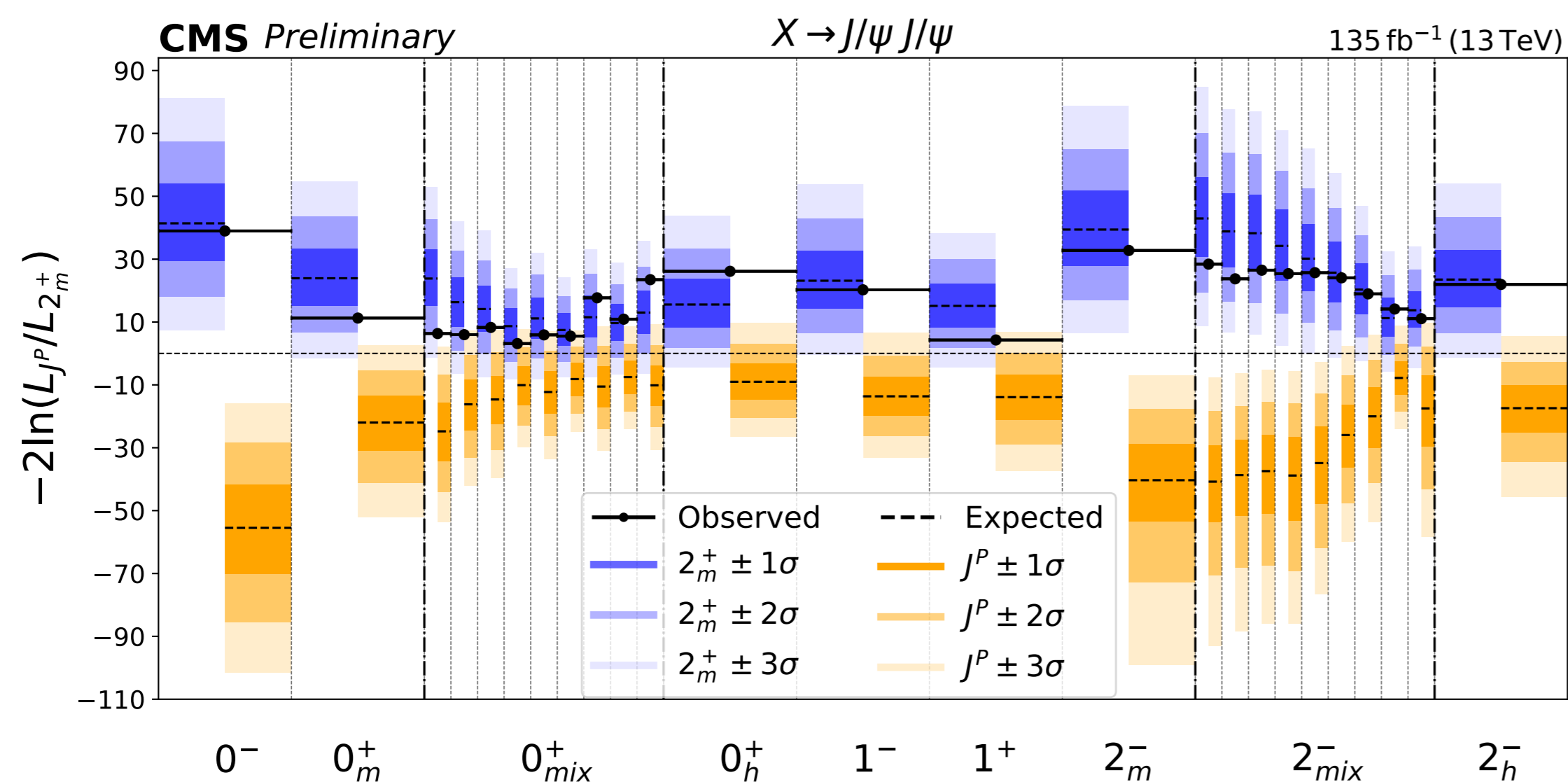


- The angular **analysis techniques** developed for the discovery and characterization of the **Higgs boson** is used
- Pairwise comparisons is conducted between different models characterized by distinct  $J^{PC}$  quantum numbers
- Matrix element approach is used to use only one observable instead of three angles

$$\mathcal{D}_{ij}(m_{4\mu}, \vec{\Omega}) = \frac{\mathcal{P}_i(m_{4\mu}, \vec{\Omega})}{\mathcal{P}_i(m_{4\mu}, \vec{\Omega}) + \mathcal{P}_j(m_{4\mu}, \vec{\Omega})}$$

- Statistical analysis uses only **two-dimensional** distributions  $\mathcal{P}_{i,j}(m_{4\mu}, D_{ij})$





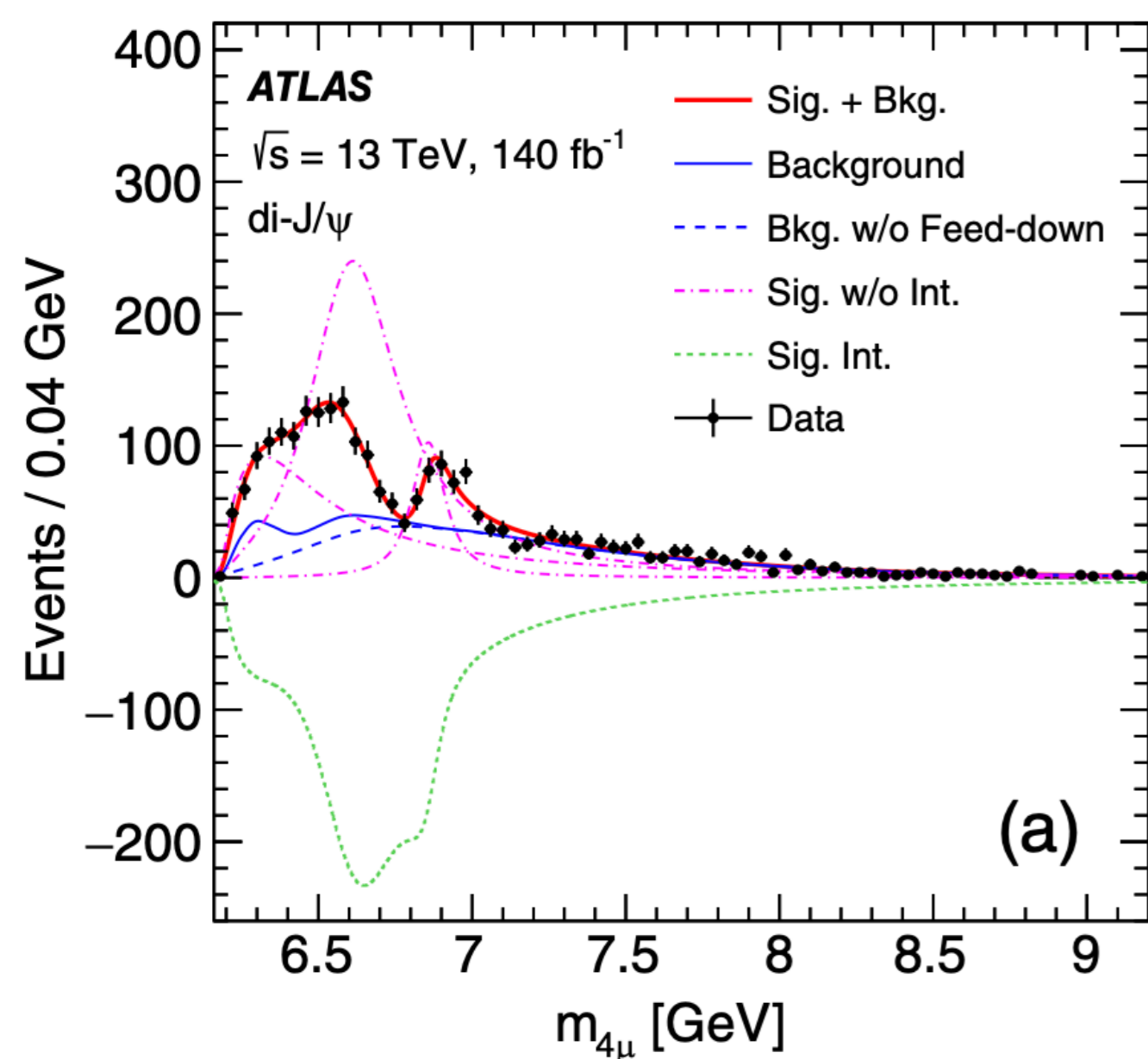
- Comparison of  $2_m^+$  model with others

$J_X^P$	p-value	Z-score reject $J_X^P$
$0^-$	$2.7 \times 10^{-13}$	7.2
$0_m^+$	$4.3 \times 10^{-5}$	3.9
$0_{mix}^+$	$1.4 \times 10^{-2}$	2.2
$0_h^+$	$3.1 \times 10^{-9}$	5.8
$1^-$	$8.0 \times 10^{-8}$	5.2
$1^+$	$4.7 \times 10^{-3}$	2.6
$2_m^-$	$4.1 \times 10^{-12}$	6.8
$2_{mix}^-$	$6.5 \times 10^{-4}$	3.2
$2_h^-$	$2.2 \times 10^{-8}$	5.5

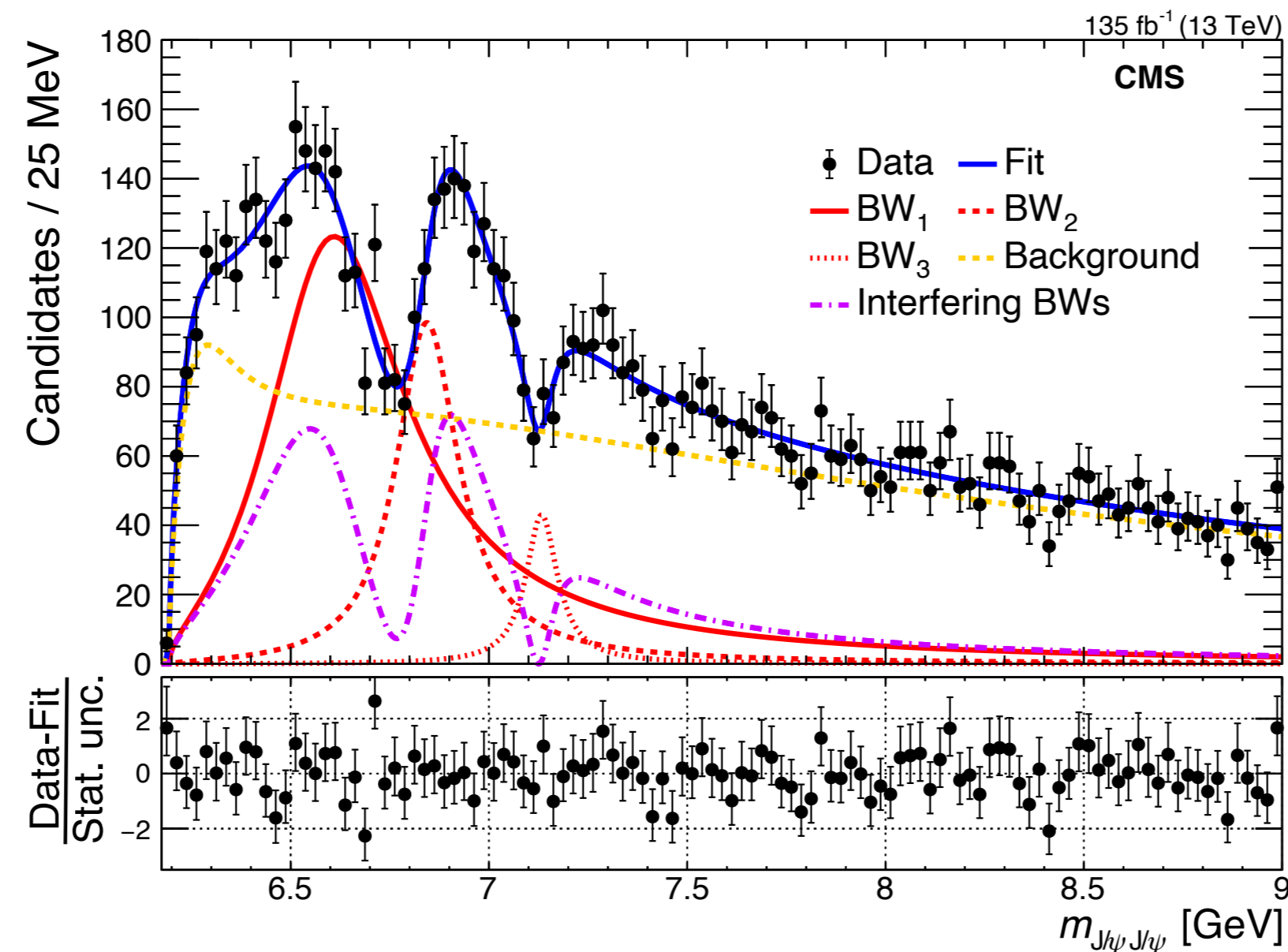
- all models are compared in pairs
- $2_m^+$  model is preferred over all other models
- $2_m^+$  is also better than different models mixtures
- Therefore  $J^{PC} = 2^{++}$  is favoured
- $J > 3$  is still possible, but  $J = 2$  is more likely

# **Observation of a family of all-charm tetraquark candidates at the LHC**

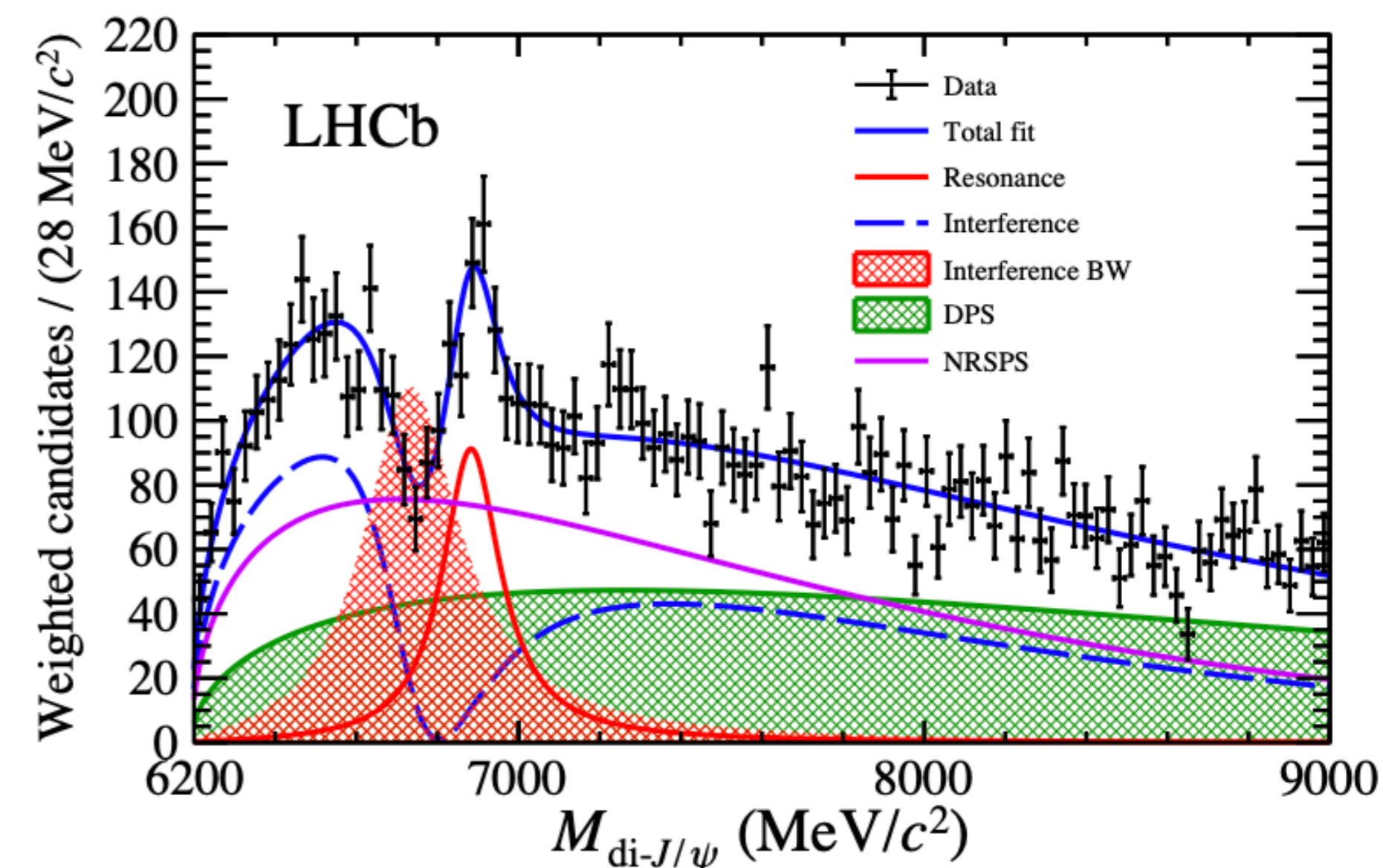
## ATLAS



## CMS

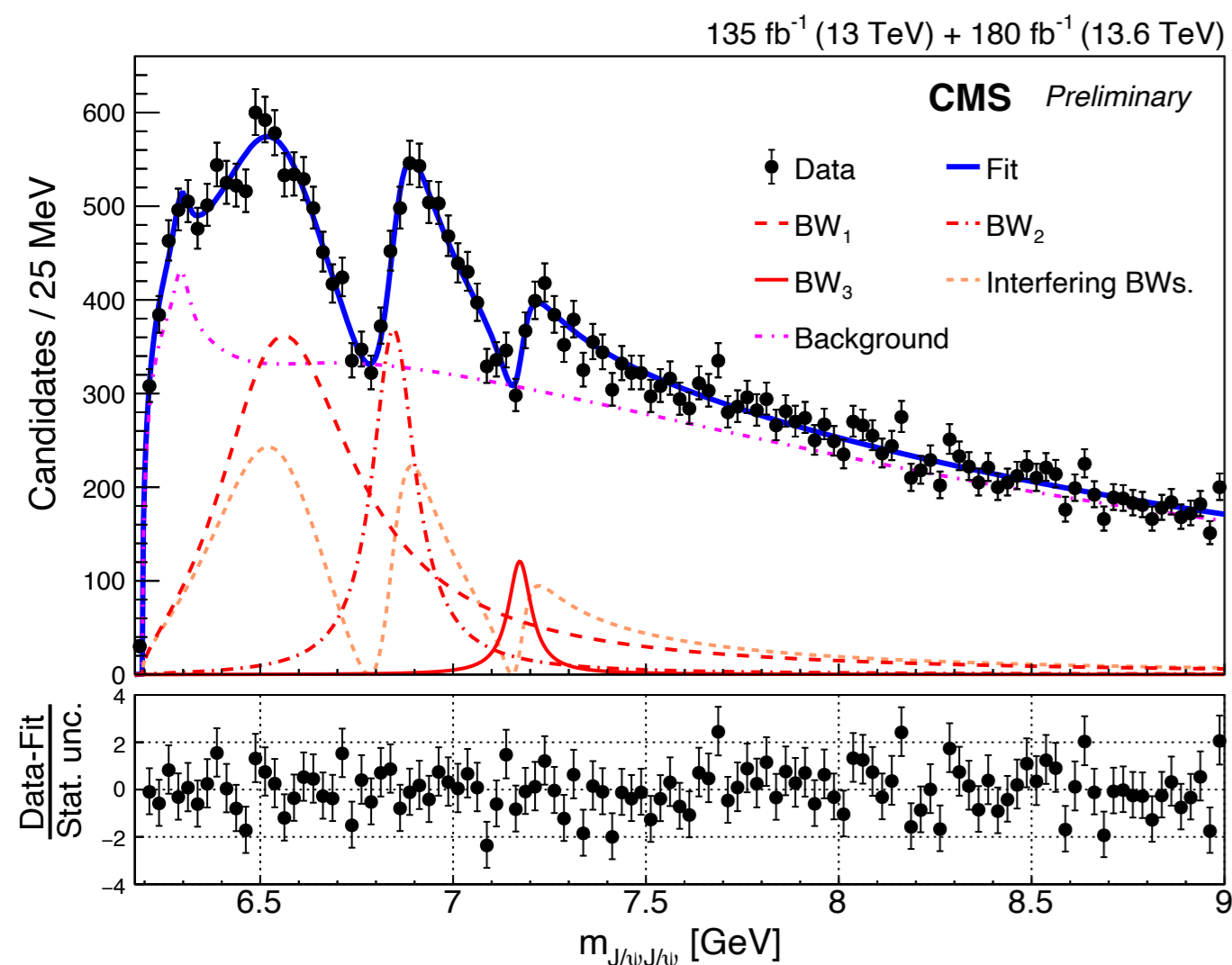


## LHCb

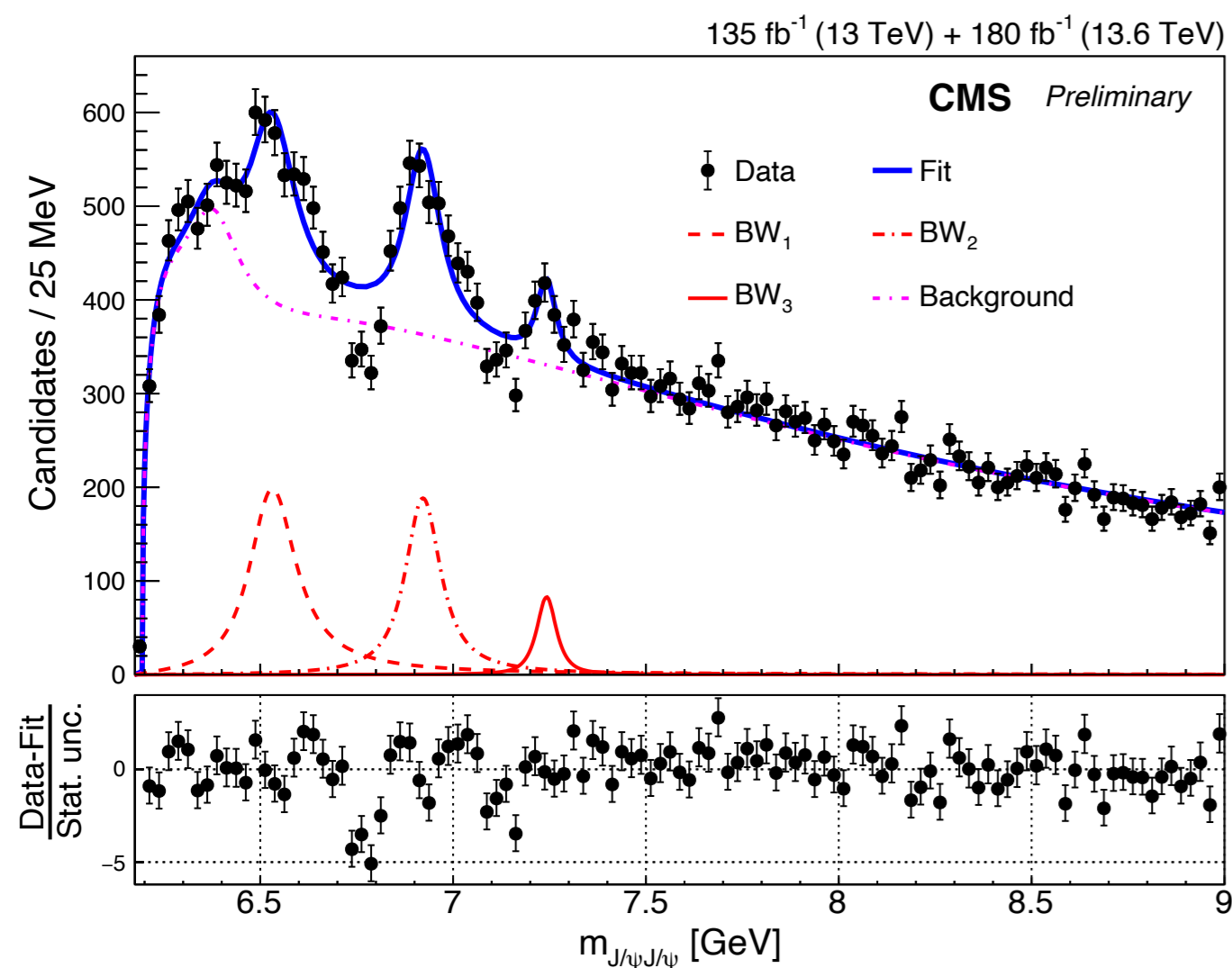
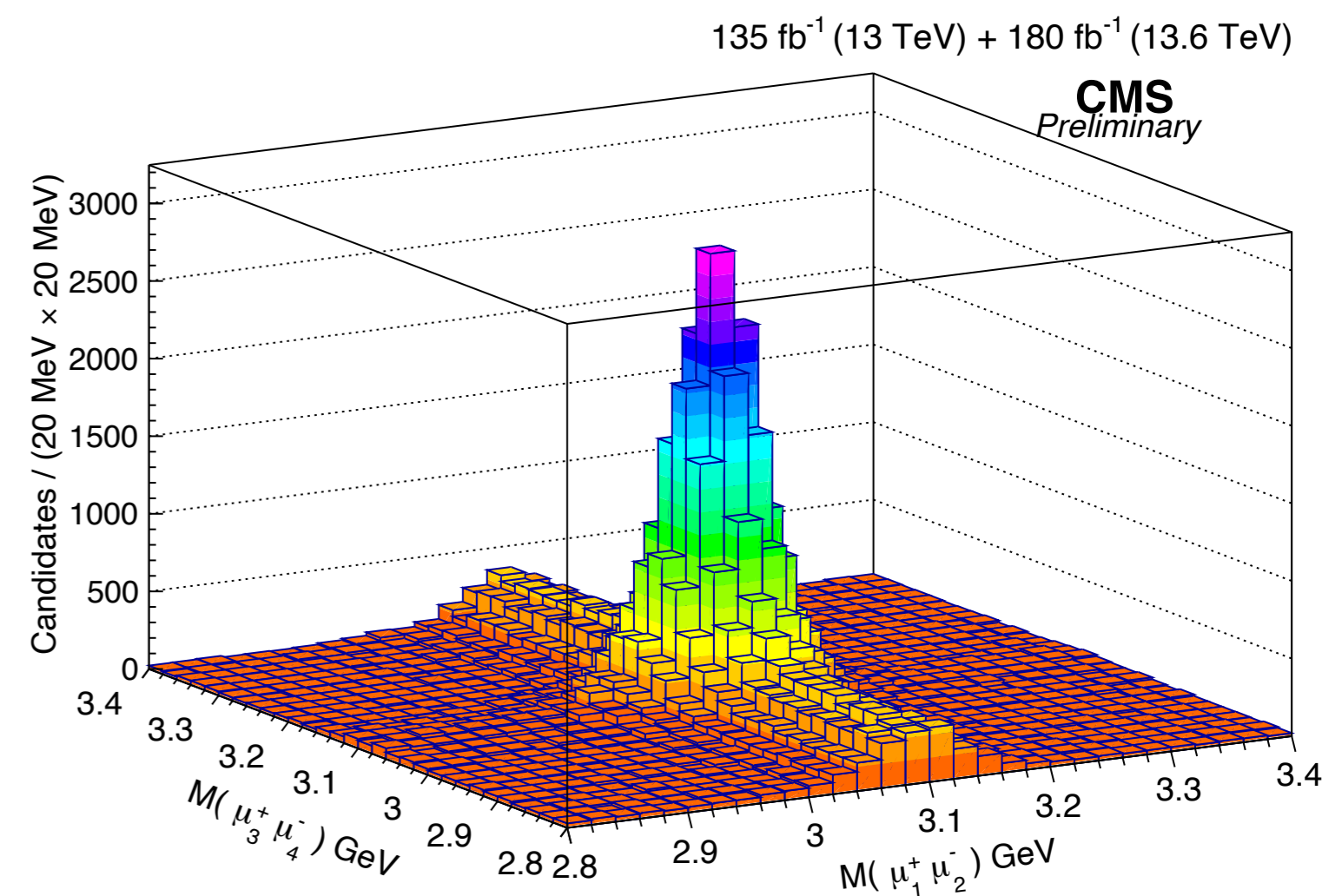


- All experiments **observe X(6900)** and additional structures
- All experiments use interference but in **different ways** and use different model for “hump” below X(6900)
- All experiments see near threshold excess, which is **not explained**

Adding Run 3 data can help to find the answers to these questions! (314 fb<sup>-1</sup> total luminosity)



- Run2 + Run3:  $J/\psi J/\psi$  yield is 3.6x of Run2
- Run2 + Run3: luminosity is 2.1x of Run2
- $12622 \pm 165$  candidates for Run2
- $31802 \pm 476$  candidates for Run3



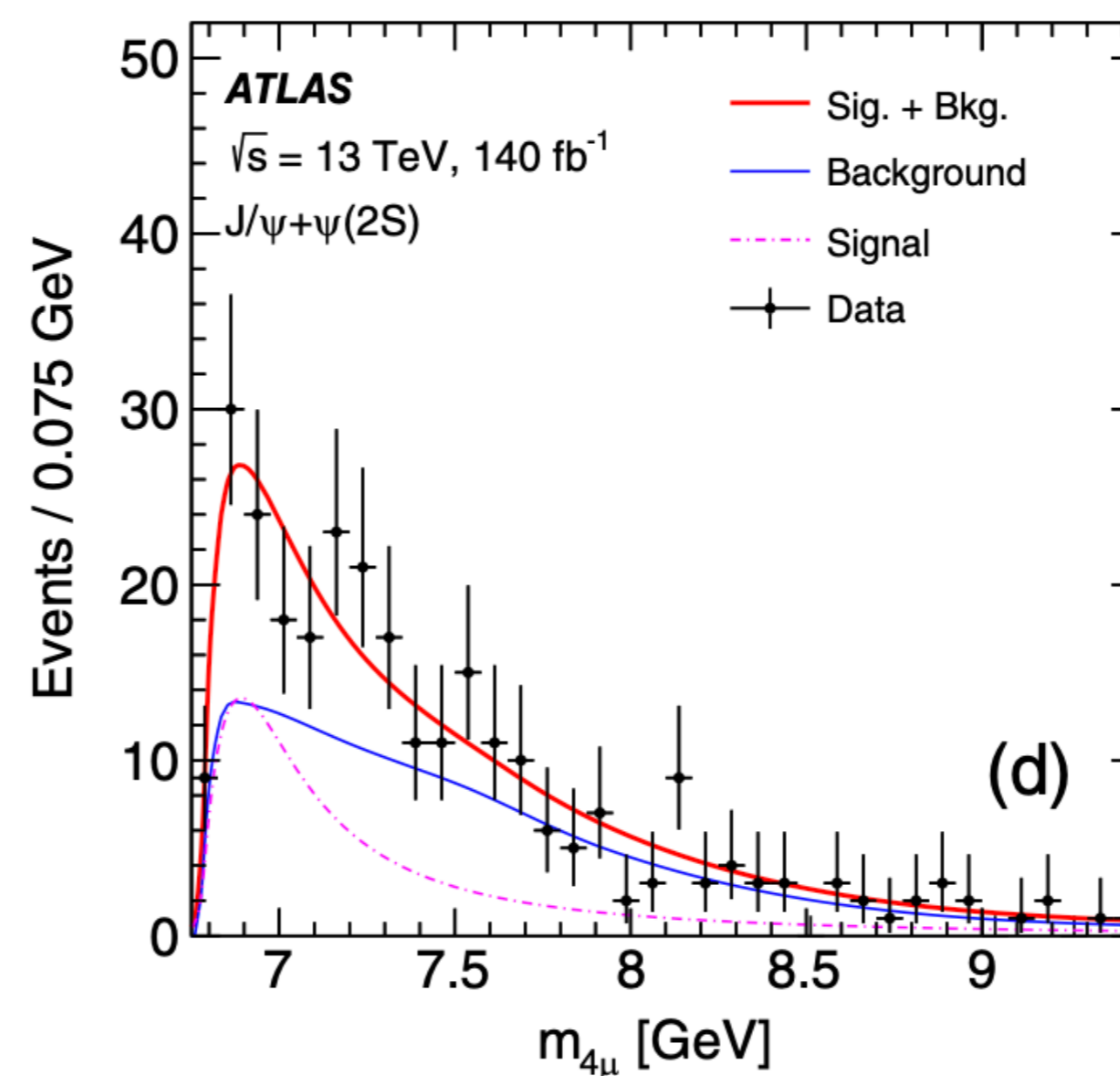
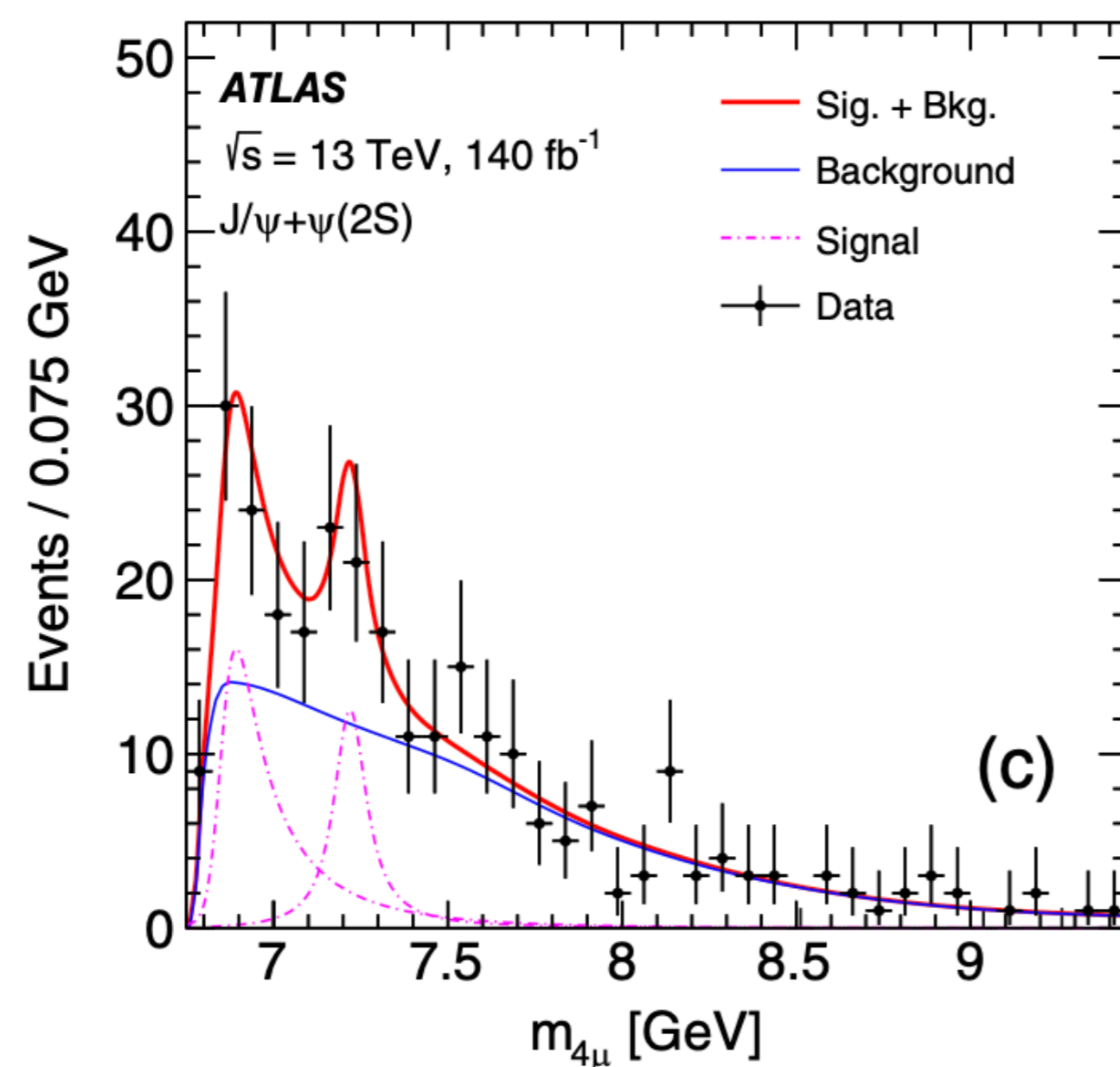
- Background component: NRSPS + DPS + BW<sub>0</sub> + Combinatorial bkg + **Feed down** (was only systematic in Run2 analysis)
- Signal component: BW<sub>1</sub> + BW<sub>2</sub> + BW<sub>3</sub>
- Interference model (three-way interference):  $|r_1 \exp(i\phi_1) BW_1 + BW_2 + r_3 \exp(i\phi_3) BW_3|^2$

		BW <sub>1</sub>	BW <sub>2</sub>	BW <sub>3</sub>
Interference	$m$ (MeV)	$6593^{+15}_{-14} \pm 25$	$6847^{+10}_{-10} \pm 15$	$7173^{+9}_{-10} \pm 13$
(Run 2+Run 3)	$\Gamma$ (MeV)	$446^{+66}_{-54} \pm 87$	$135^{+16}_{-14} \pm 14$	$73^{+18}_{-15} \pm 10$
Interference	$m$ (MeV)	$6638^{+43+16}_{-38-31}$	$6847^{+44+48}_{-28-20}$	$7134^{+48+41}_{-25-15}$
(Run 2 [12])	$\Gamma$ (MeV)	$440^{+230+110}_{-200-240}$	$191^{+66+25}_{-49-17}$	$97^{+40+29}_{-29-26}$

- Precision improved by factor of 3
- Significance of obtained resonances: X(6600) (**15.2**  $\sigma$ ), X(6900) (**16.7**  $\sigma$ ), X(7100) (**7.7**  $\sigma$ )
- Significance of first interference dip is **9.7**  $\sigma$  and significance of second dip is **6.5**  $\sigma$

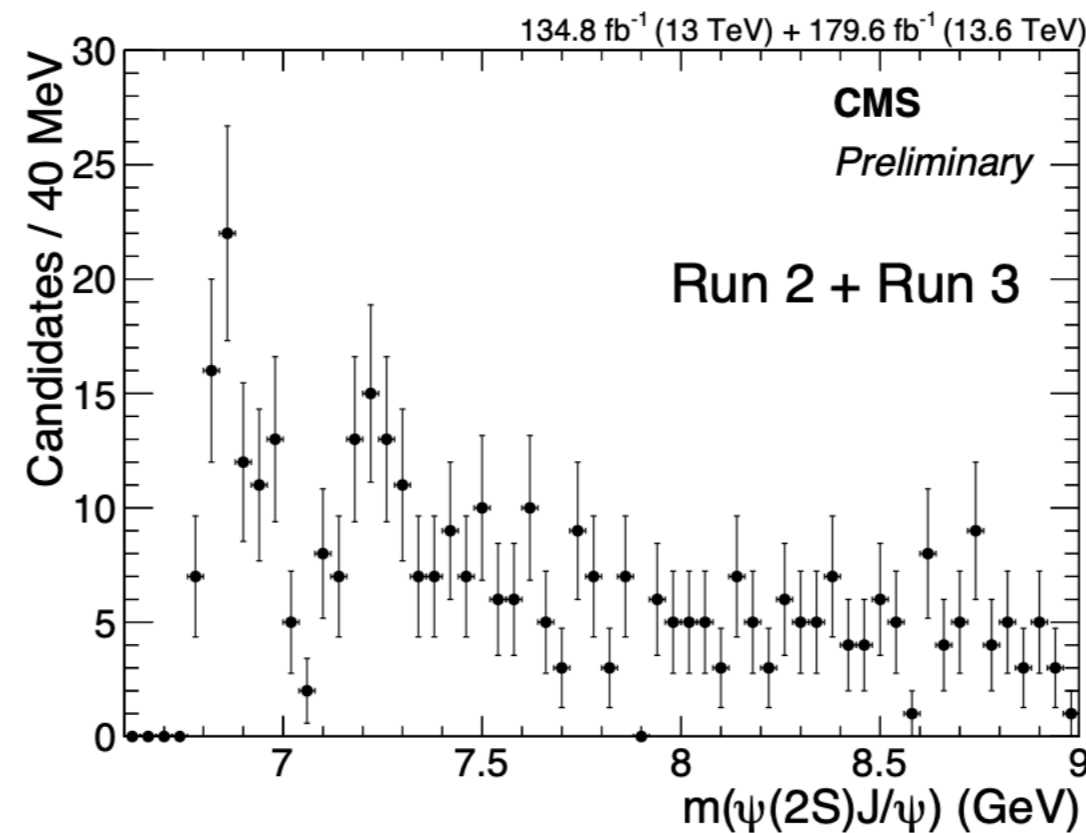
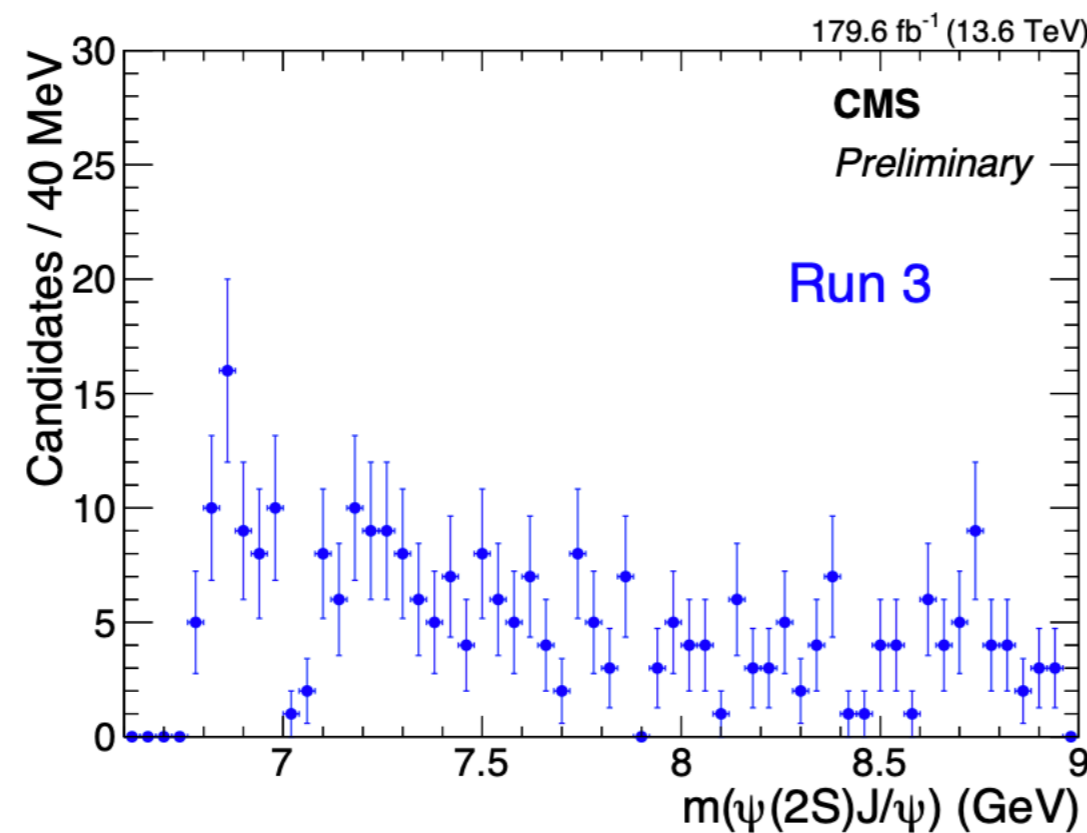
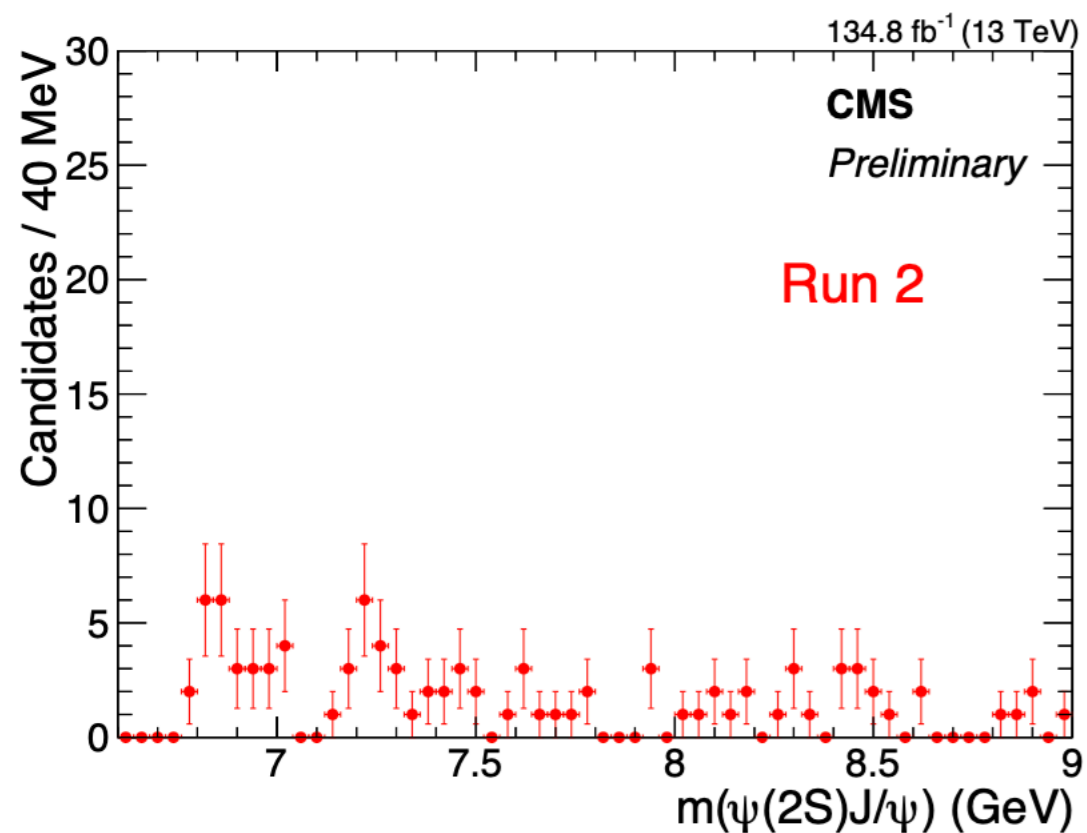
**Observation of X(6900) and evidence for X(7100)  
in the  $J/\psi\psi(2S) \rightarrow \mu^+\mu^-\mu^+\mu^-$  mass spectrum in  
314 fb<sup>-1</sup> of pp collisions at CMS**

- ATLAS reported a **significant near-threshold** excess in this channel in 2023 ( $4.7 \sigma$  from model with both resonances)
- X(6900) is just above threshold



Phys. Rev. Lett. 131, 151902

- It is important to validate ATLAS result. This work extends CMS study of all-charm exotic tetraquark candidates

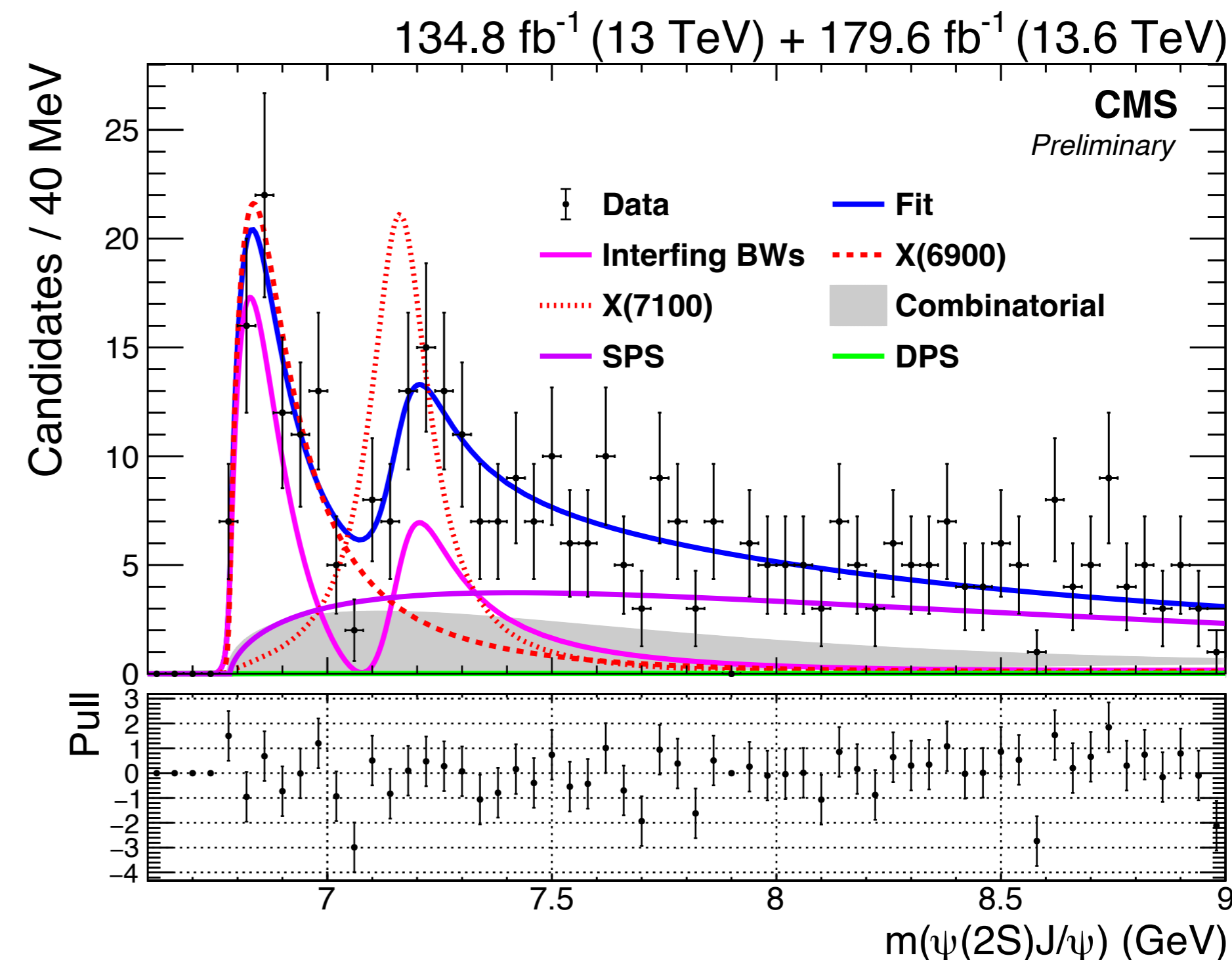


- From the 2D fit there are  **$386 \pm 26$**  signal pairs
- X(6900) and X(7100) are visible
- Signal dominated by Run3 data

- Background component: SPS + DPS + Combinatorial bkg
- Signal component: X(6900) + X(7100)
- Interference model:  $|r_1 \exp(i\phi_1) BW_1 + r_2 \exp(i\phi_2) BW_2|^2$

Significance: X(6900) ( **$7.9 \sigma$** ), X(7100) ( **$4.0 \sigma$** )

Fit	Sample	Interf.		X(6600)	X(6900)	X(7100)
$f_{i23}$	J/ψψ(2S)	BW <sub>2</sub> , BW <sub>3</sub>	$m$ :	—	$6876^{+46+110}_{-29-110}$	$7169^{+26+74}_{-52-70}$
			$\Gamma$ :	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
$f_{JJ}$ [1]	J/ψJ/ψ	BW <sub>1</sub> , BW <sub>2</sub> , BW <sub>3</sub>	$m$ :	$6638^{+43+16}_{-38-31}$	$6847^{+44+48}_{-28-20}$	$7134^{+48+41}_{-25-15}$
			$\Gamma$ :	$440^{+230+110}_{-200-240}$	$191^{+66+25}_{-49-17}$	$97^{+40+29}_{-29-26}$



# Summary

- ❖ Three vector mesons were fully reconstructed for the first time in exclusive final states, with their masses measured precisely relative to ground states. The results align with—but are significantly more precise than—previous world averages. A new photon energy calibration technique is used and a number of difference and ratio measurements are provided for the first time
- ❖ Analysis of the  $J/\psi J/\psi$  invariant mass distribution using Run2 data revealed three resonant structures: two new states, X(6600) and X(7100), and confirmation of the previously observed X(6900). The first determination of quantum numbers for all-charm tetraquarks strongly favours  $J^{PC} = 2^{++}$
- ❖ By combining Run2 and Run3 datasets, CMS obtained a 3.6-fold increase in  $J/\psi J/\psi$  pairs, establishing all structures with over  $5\sigma$  significance. Additionally, a near-threshold state consistent with X(6900) was found in  $J/\psi\psi(2S)$  with evidence for X(7100).