CMS results on flavour spectroscopy

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(on behalf of the CMS Collaboration)

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Outline: selected recent results in exotic and conventional spectroscopy

- Observation of structures in the di-charmonium mass spectrum

  [PRL 132 (2024) 111901] ($X \rightarrow J/\psi\, J/\psi$)

  Confirmation + 1st observation + 1st evidence

- Observation of the transition $\Lambda_b^0 \rightarrow J/\psi\, \Xi^- K^+$

  [arXiv:2401.16303, accepted by EPJC]

  1st observation

- All results are based on the LHC Run-2 dataset collected by CMS in the years 2016-2018 (pp collisions @ $\sqrt{s} = 13 TeV; \mathcal{L}_{int} \approx 135 - 140 fb^{-1}$)

1. Peaking structures in $J/\psi\, J/\psi$ mass spectrum

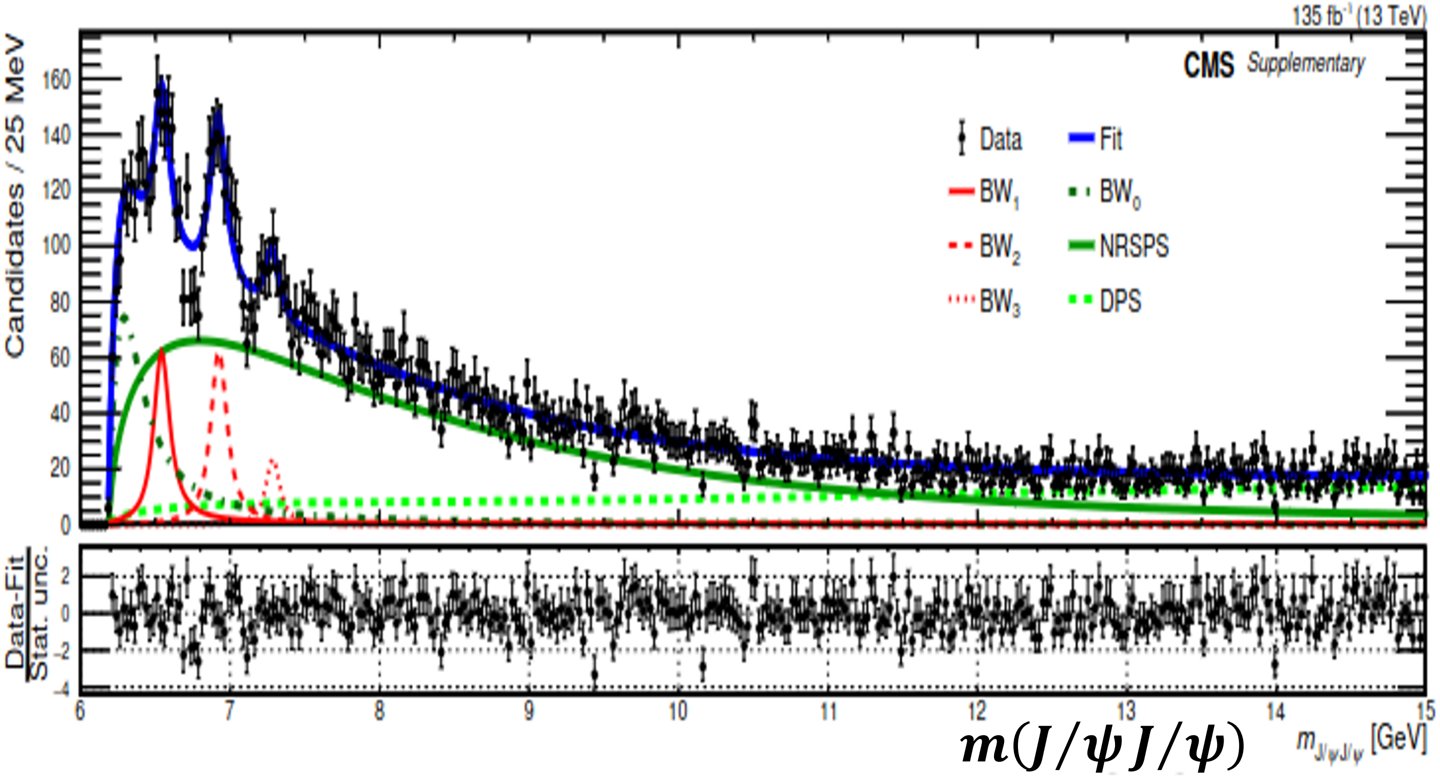
Baseline fit modelling for reconstructed $J/\psi\, J/\psi$ mass spectrum

- In 2020 LHCb observed a peak in the $J/\psi\, J/\psi$ **mass spectrum, the $X(6900)$,** which was considered with great interest as a **possible *all-charm tetraquark*** **(**alternative interpretations have also been advocated**).** [see backup]

- After **event selection** ($\mu^+\mu^-\mu^+\mu^+$ final state; *refer to the paper*)
… a **baseline model** to fit the **di-J/ψ** spectrum is built with a …
… minimal number of potential structures **added to the null-hypothesis (background-only)**
by adding - @ each subsequent step - the *most prominent* structure
& keeping it in the baseline… IF local statistical significance $> 3\sigma$ (by standard likelihood ratio method)
This is repeated until no more structures can be added.

Procedure

- **Spectrum visualization**

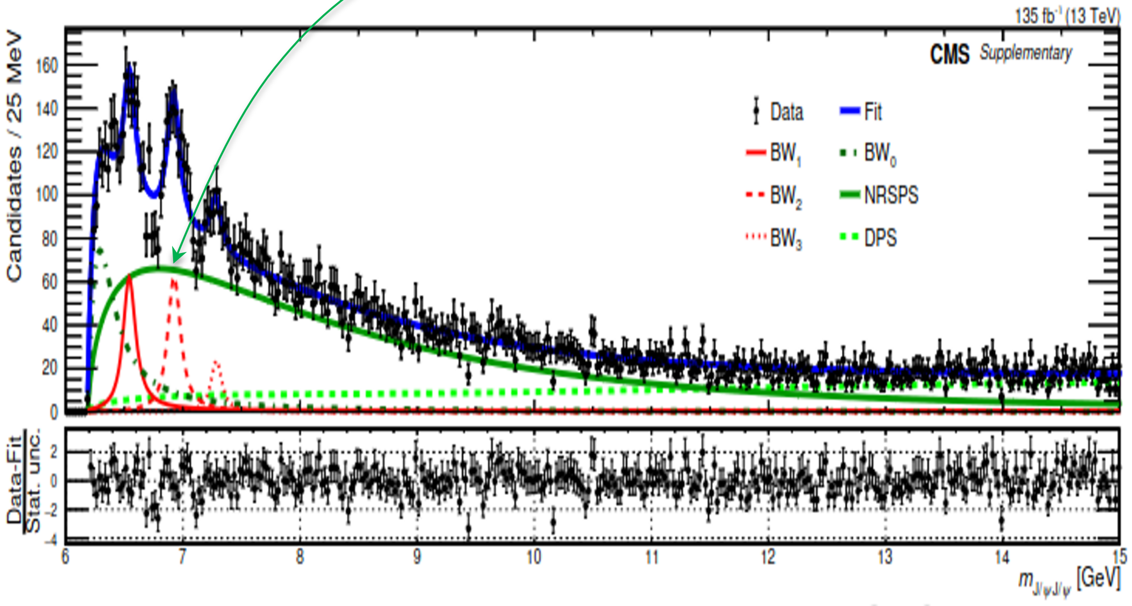


$m(J/\psi\, J/\psi)$

$J/\psi\, J/\psi$ mass spectrum : background description

- **Main physical background sources:**
  - 2 genuine J/ψs combined randomly arising from: non-resonant **single** parton scattering (**NRSPS**)

→ dominant near threshold region ($p_T < 10GeV$)



$J/\psi\, J/\psi$ mass spectrum : background description

Main physical background sources:

- 2 genuine J/ψs combined randomly arising from:
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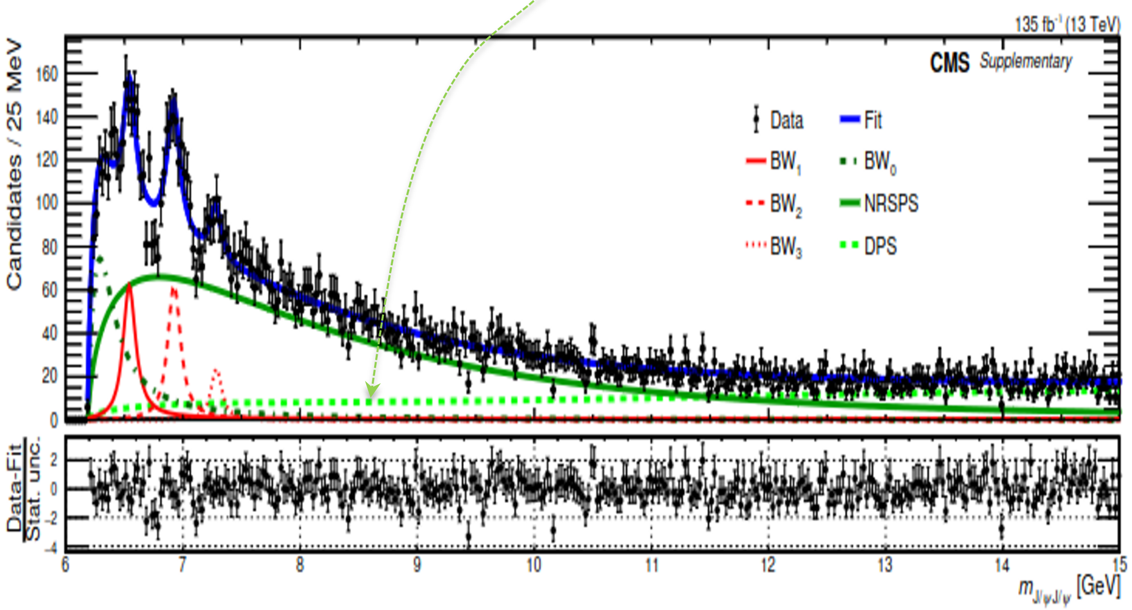
→ dominant from $p_T > 12GeV$



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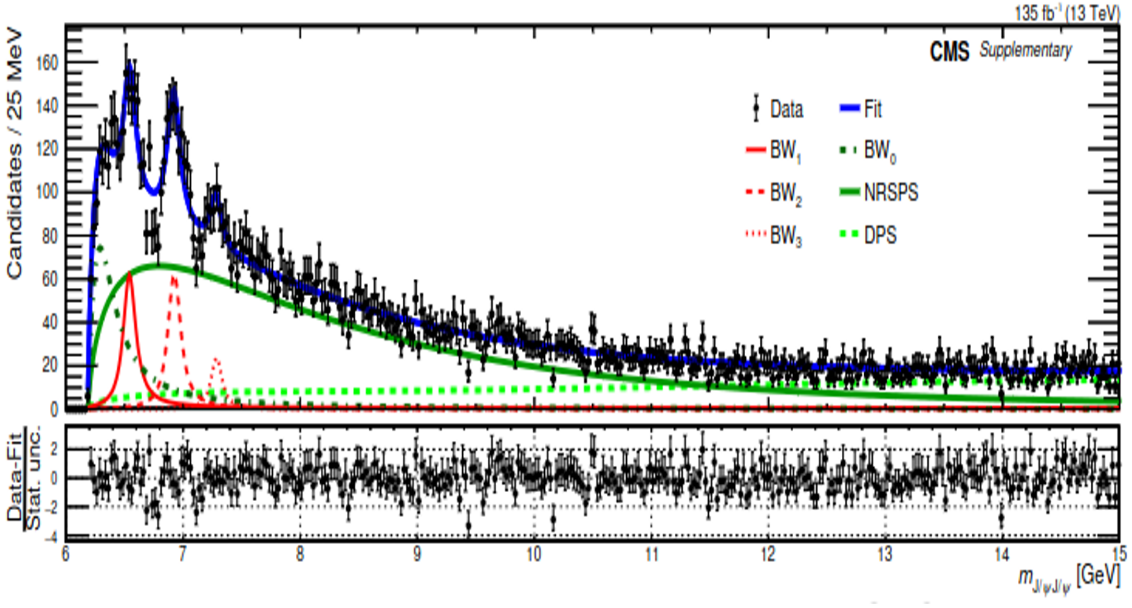
  - **Shapes from simulation** that includes: **direct** production + **feed-down** processes (J/ψ as decay product)

    Additional **feed-down** processes from double-charmonium resonances: generated separately



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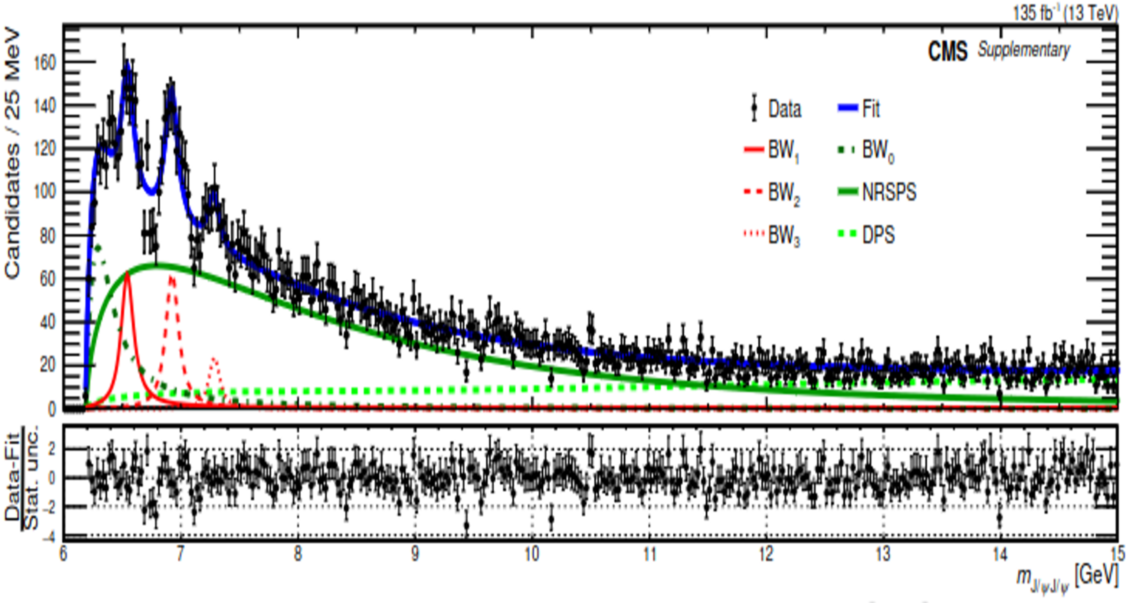
- **Residual combinatorial background sources** (effects are accounted for as systematics) **:**
  - At least one non-genuine J/ψ arising from:
    - $\geq$ **1** genuine μ candidate(s) not from a J/ψ decay
    - $\geq$ **1** hadron(s) misidentified/misreconstructed as μs



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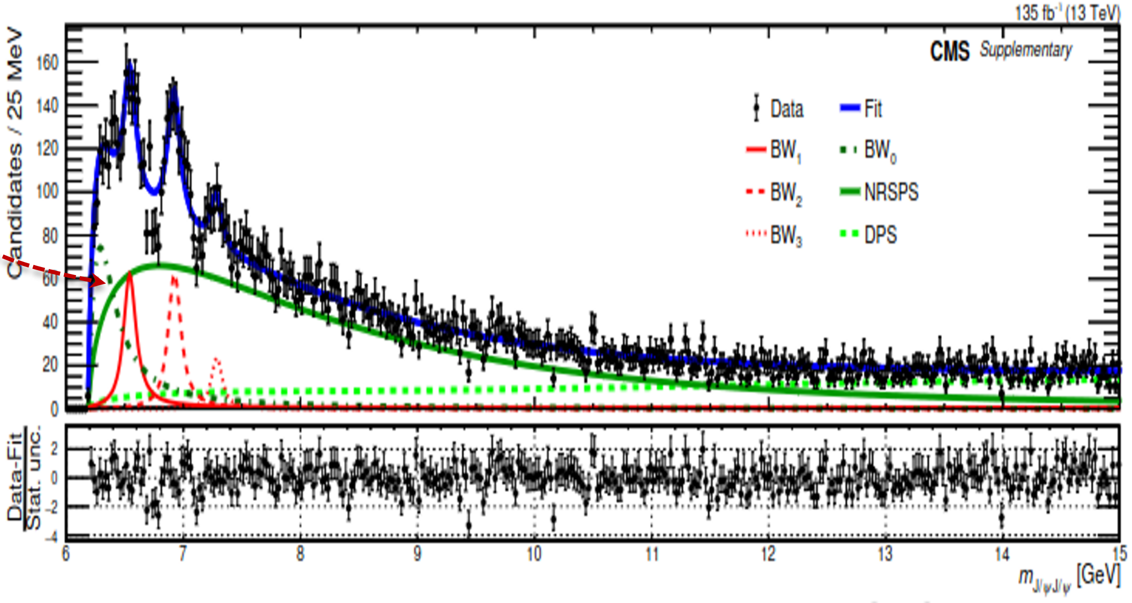
- **Inadequacy** of **NRSPS** near threshold (a resonance? a near-threshold enhancement? feed-down effects?)

  + additional *ad hoc* background

  [modelled empirically by a B.-W. (**BW$_0$**) with free m & Γ]



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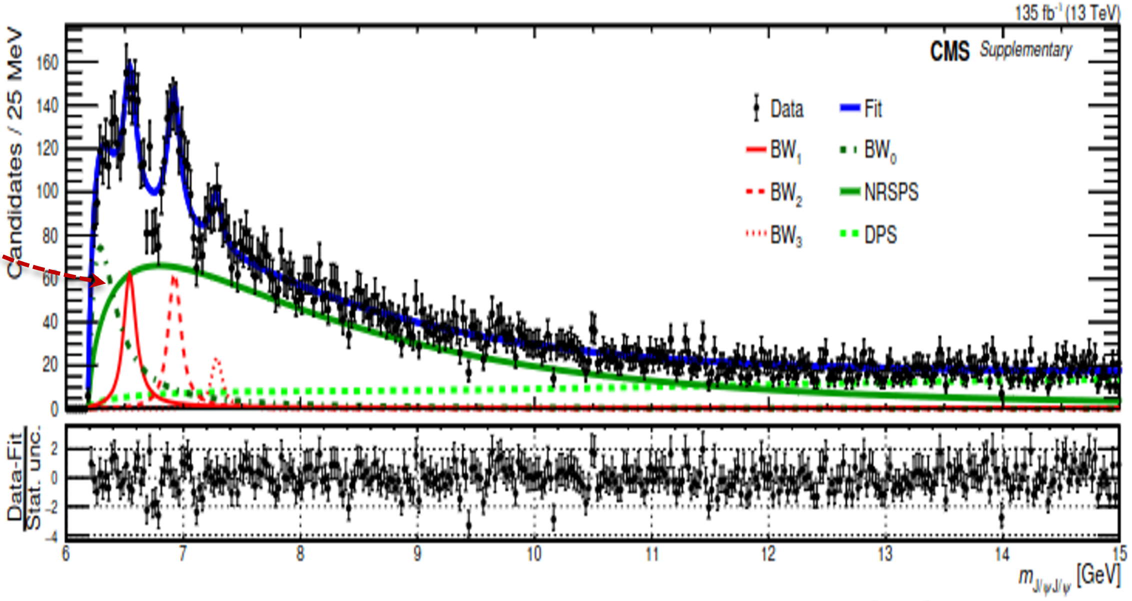


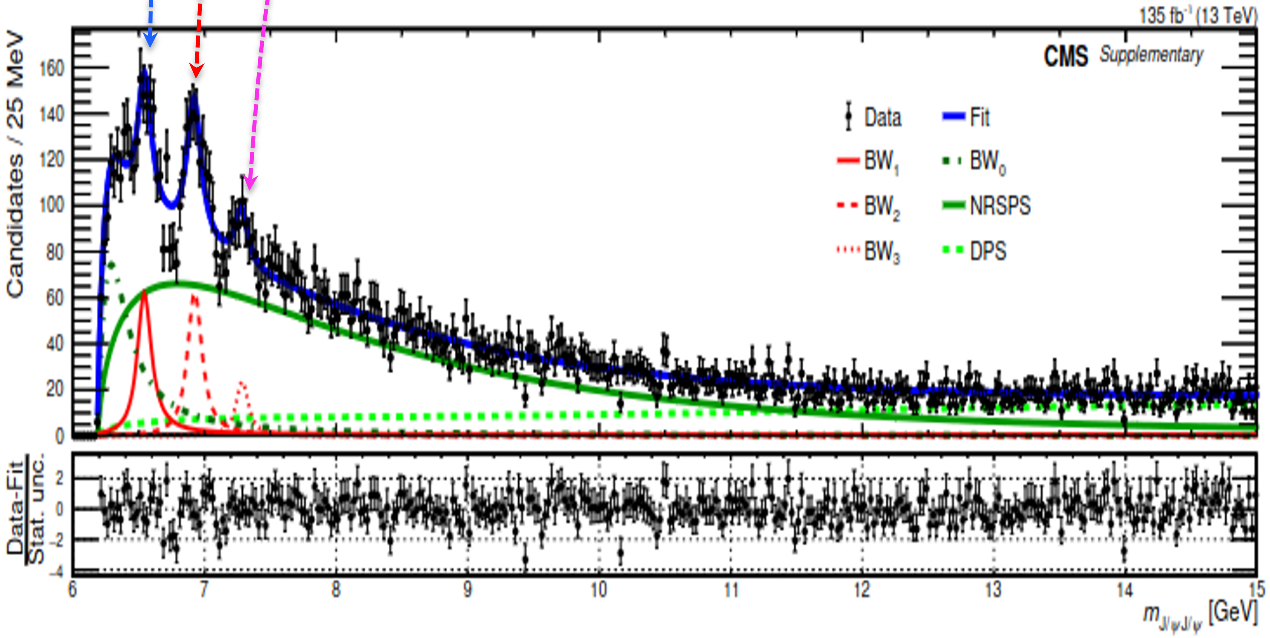
Null-hypothesis ("bkg-only") model:

NRSPS+DPS + BW_0

$J/\psi\, J/\psi$ mass spectrum : fit with 3 non-interfering resonances

Signal model: **3 resonant structures - labelled as BW_1, BW_2, BW_3 -**

Each *scalar* relativistic B.-W. is convoluted
with a Gaussian resolution function `[Pythia`
(ranging from 10MeV @6.5GeV `or JHUGen]`
… to 18MeV @7.3GeV)



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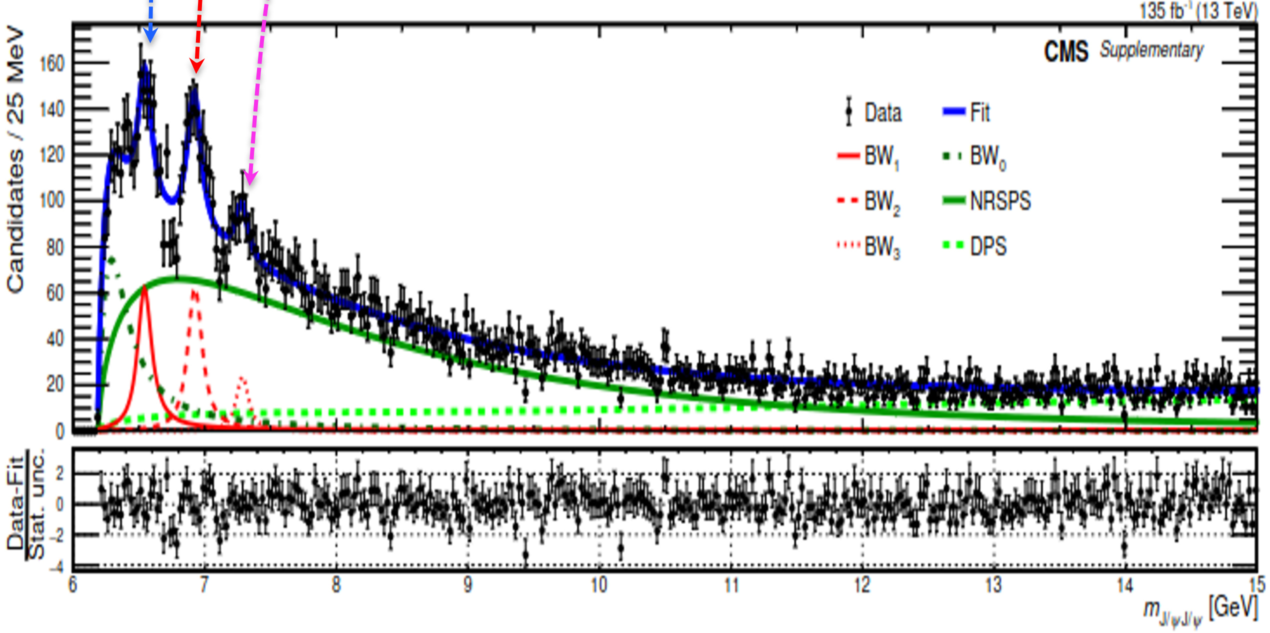
- **UML fit** model: BKG (**NRSPS+DPS+BW_0**)
+ SIGNAL (**BW_2+ BW_1 + BW_3**)

All 3 widths are much larger than the detector mass resolution

- Fit on **full spectrum** up to 15GeV to verify the **adequacy of the background model**: $P(\chi^2) = 98\%$

Fit fractions: **58% NRSPS,**
25% DPS,
9% BW_0
8% BW_1 +BW_2 +BW_2



$J/\psi\, J/\psi$ mass spectrum : fit with 3 non-interfering resonances

- Signal model: **3 resonant structures - labelled as BW_1, BW_2, BW_3 - found to be statistically significant**

Each *scalar* relativistic B.-W. is convoluted with a Gaussian resolution function [Pythia or JHUGen]
(ranging from 10MeV @6.5GeV
… to 18MeV @7.3GeV)

Local significance of the peaks (LR method: *with vs without*):

BW_2: 9.4σ

BW_1: 6.5σ

BW_3: 4.1σ

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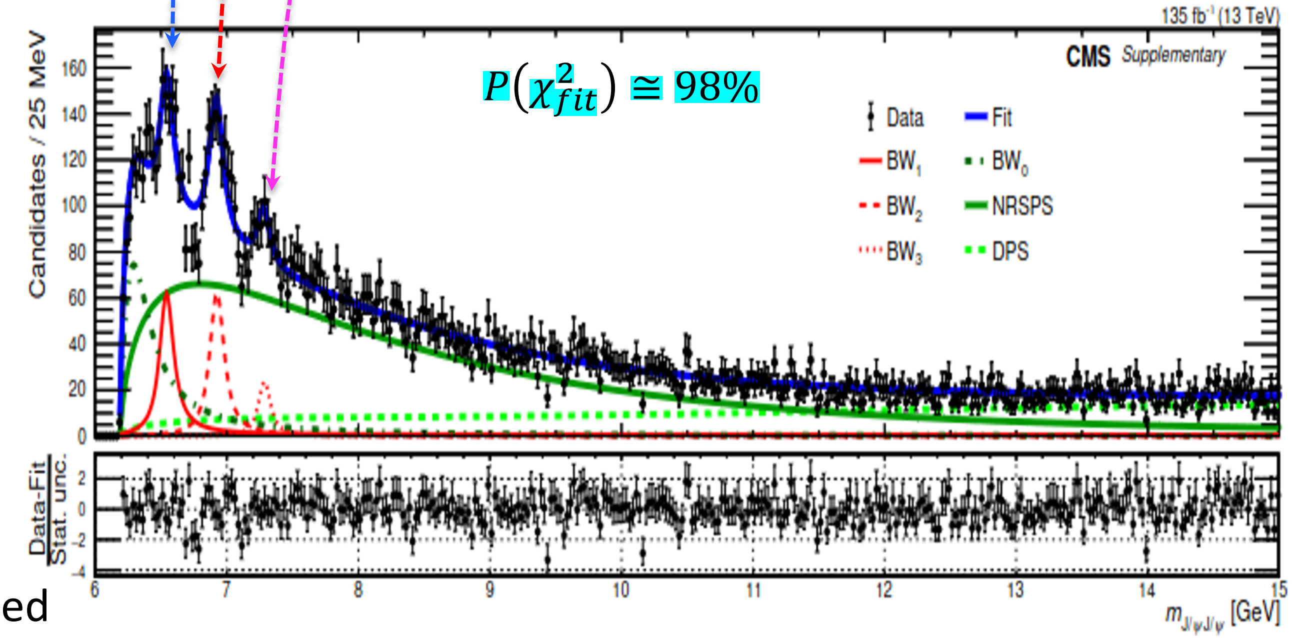


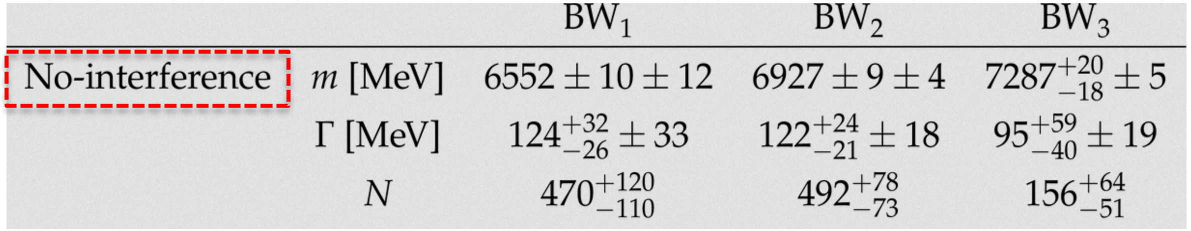
$P(\chi^2_{fit}) \cong 98\%$

Signal region small ⇒impact of deviations diluted

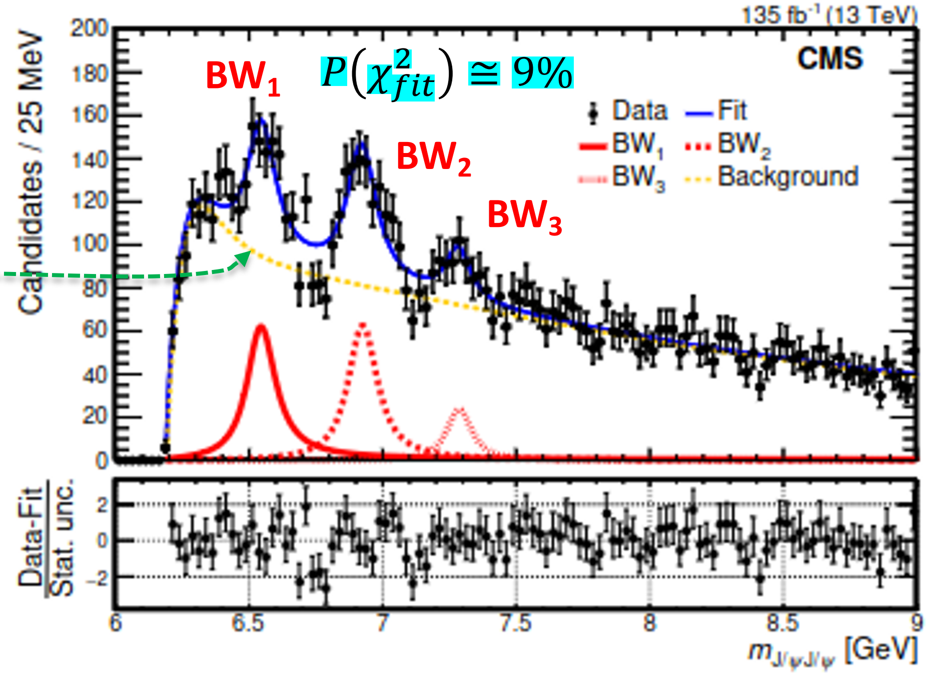
$J/\psi\, J/\psi$ mass spectrum : fit result with no-interference model

- Spectrum and fit up to 9 GeV (“signal region”):

Total background: **NRSPS + DPS + BW$_0$**



		BW$_1$	BW$_2$	BW$_3$
No-interference	m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ [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}



Note: BW$_0$ parameters very sensitive to the additional part of the model

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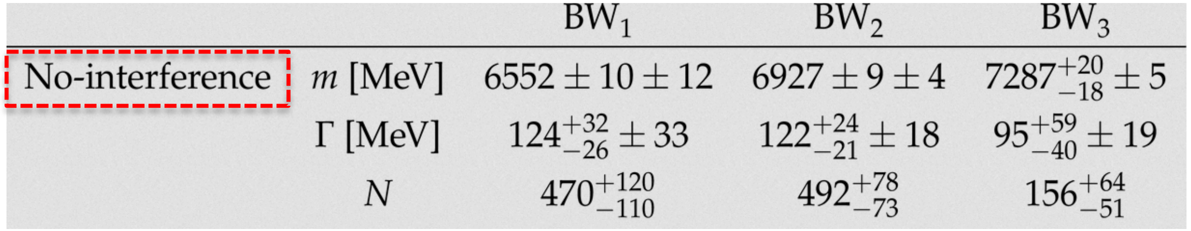

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[first error is statistic, second is systematic]

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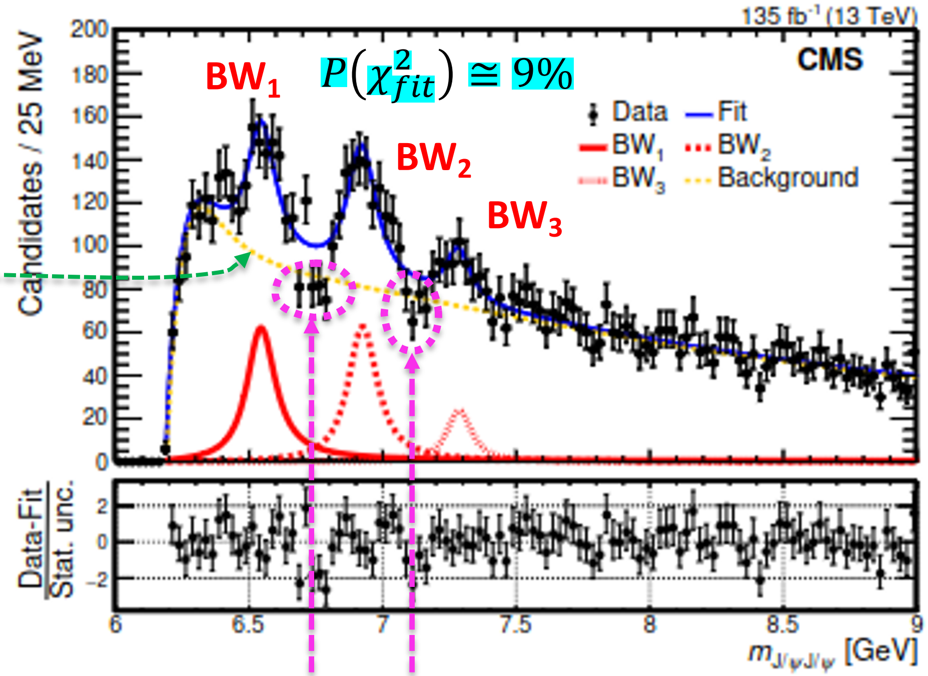

In the signal region P(χ^2) = 9% only:
2 **dips** are poorly described

Next step is to … introduce **interference** with the aim to increase the agreement

(see next slide)

$J/\psi\, J/\psi$ mass spectrum : fit result with no-interference model

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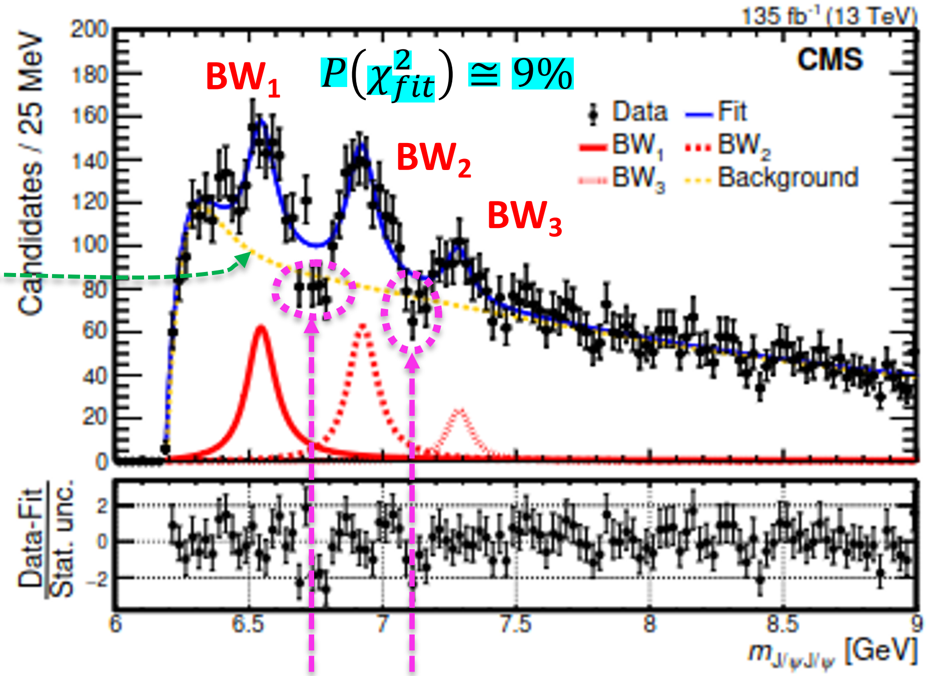

Under the assumption of no interference between signal components and between signal(s) & background

- **CONFIRMATION** of $X(6900)$ **(BW$_2$)** **Values consistent with**
- **OBSERVATION** of $X(6600)$ **(BW$_1$)**
- **EVIDENCE** for $X(7100)$ **(BW$_3$)**

(model I)

$m(6900)$	$\Gamma(6900)$
$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$

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$J/\psi\, J/\psi$ mass spectrum : fit result with interference models - I

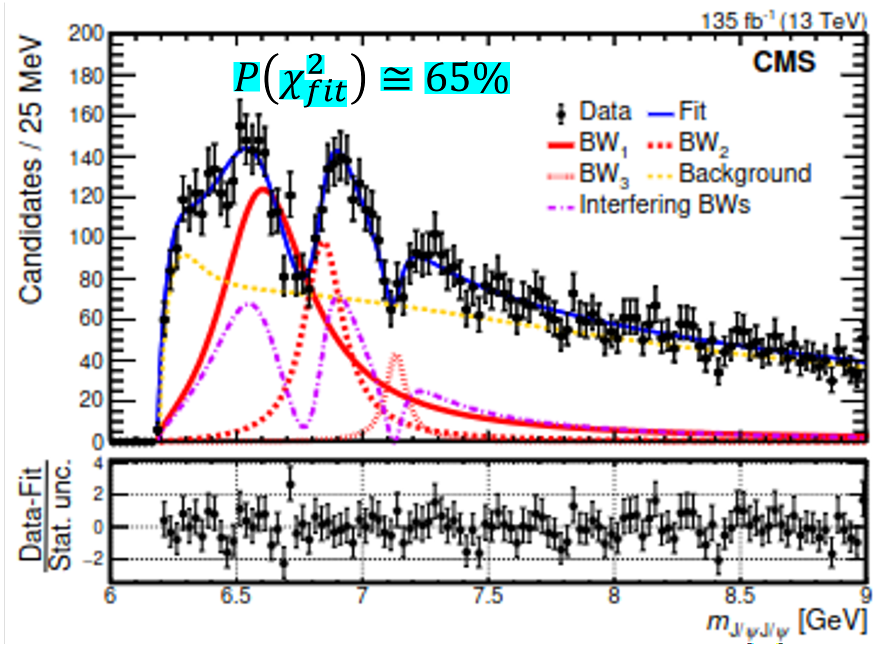
- Interference models based on the 3 found structures:
  - 3-way interference … implemented with a term proportional to:

    [three $J^P = 0^+$ resonances] $|r_1 exp(i\phi_1)BW_1 + r_2 BW_2 + r_3 exp(i\phi_3)BW_3|^2$

    reference

  - improved fit : P(χ²) = 65% (due to improved dips' description)

  - Local statistical significance improved for each signal (BW_3 @4.7σ);
    Global significance for BW_3 with MC pseudo-experiments: 3.4σ.



$P(\chi^2_{fit}) \cong 65\%$

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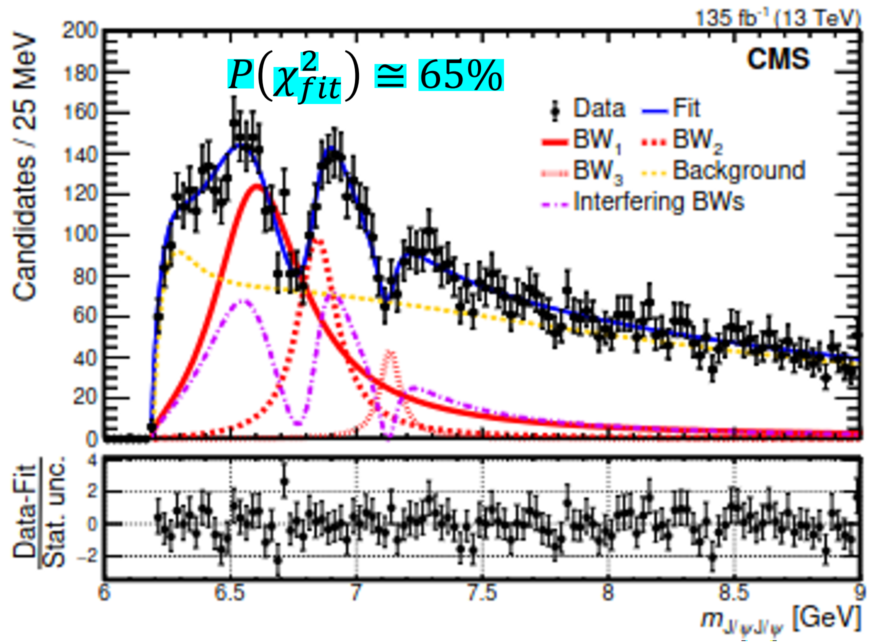

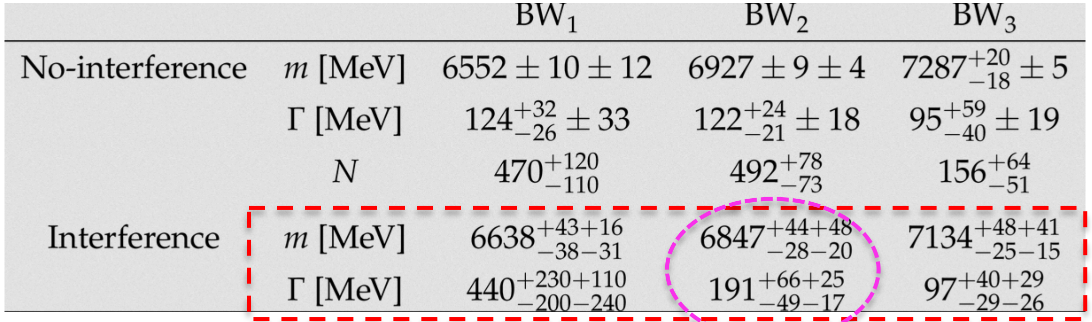

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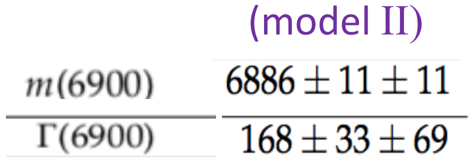
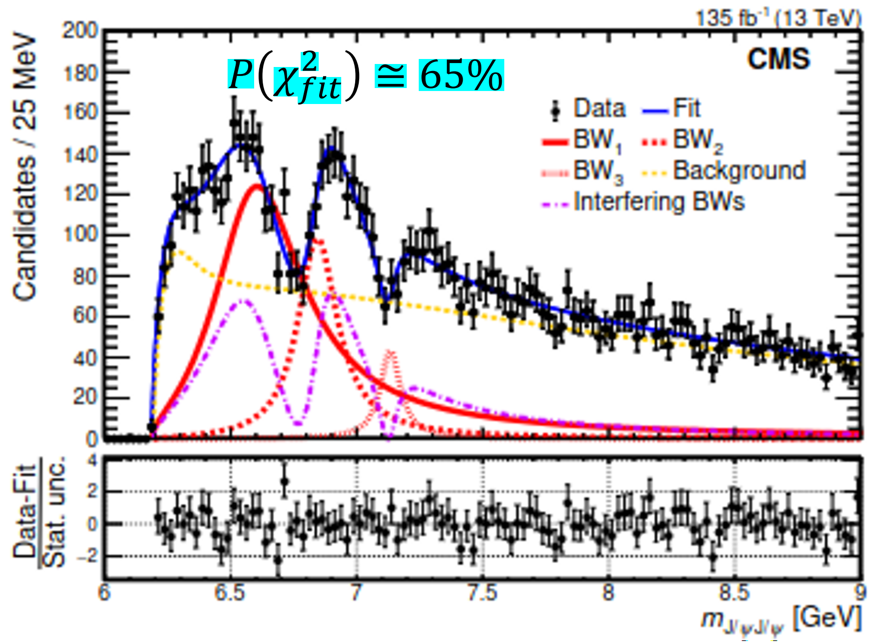
X(6900) is compatible with the LHCb observation



	(model II)
$m(6900)$	$6886 \pm 11 \pm 11$
$\Gamma(6900)$	$168 \pm 33 \pm 69$

$J/\psi\, J/\psi$ mass spectrum : fit result with interference models - I



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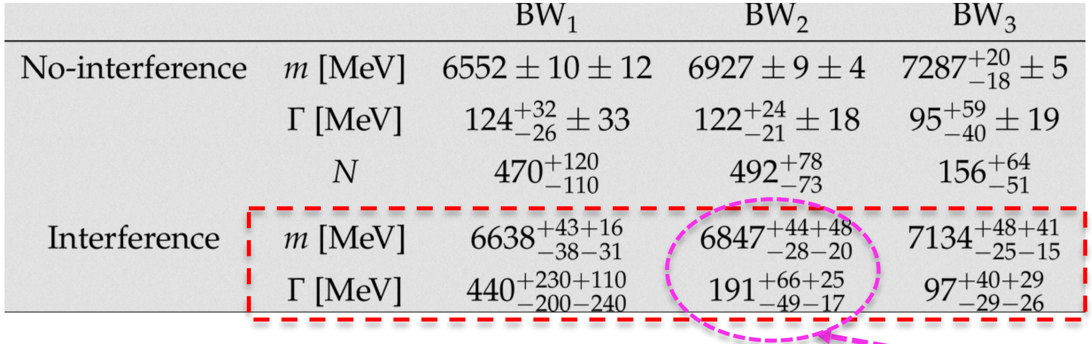

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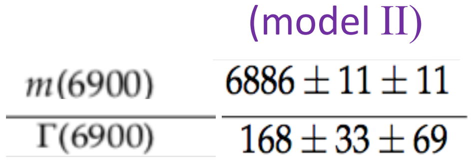

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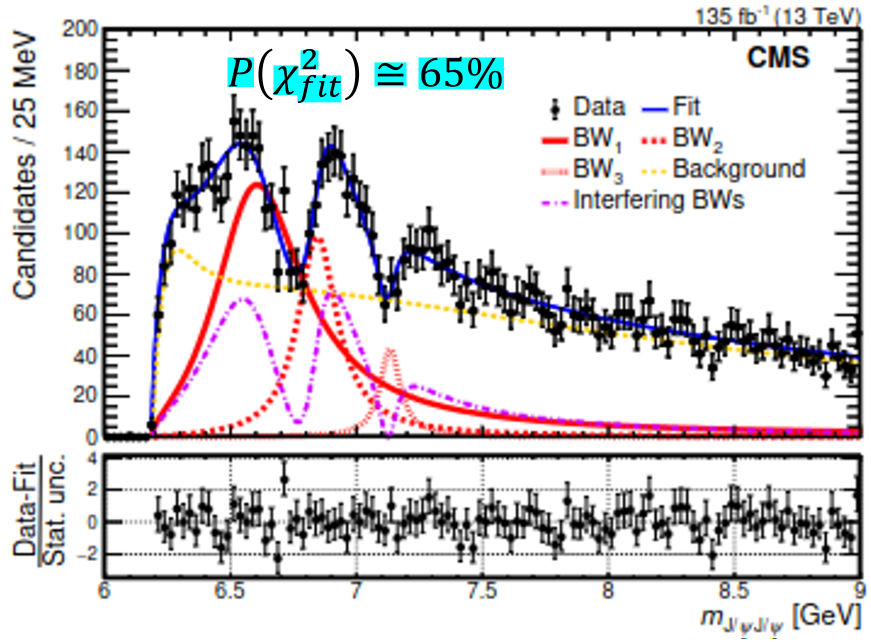
- 2-way interferences
  - less preferred fits : P(χ²) < 30%

$J/\psi\, J/\psi$ mass spectrum : fit result with interference models - II

- **Interference between different resonances** is motivated by the idea that …
  the states could have the same quantum numbers
  and be coherently produced

- NRSPS interfering with BWs (LHCb model II) is considered

  less probable as it may be mixture of different J^P states



- LHCb model II investigated [on CMS data with CMS background shape] → no good fit [see backup]

- Also: 3-way interference + interference between the 3 signal BW and NRSPS bkg → no improvement

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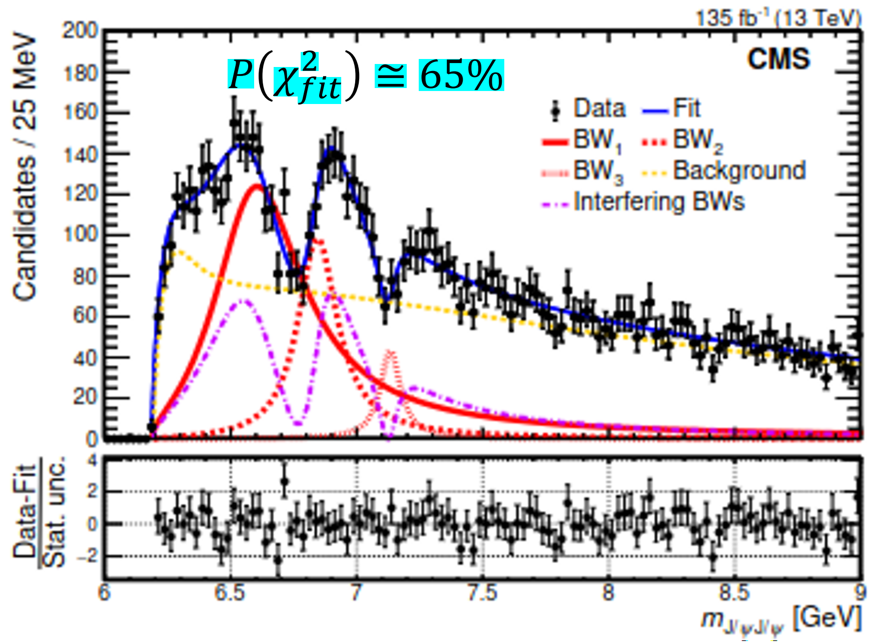

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- Also: 3-way interference **+** interference between the 3 signal BW and NRSPS bkg → no improvement

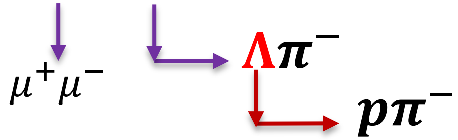
- Interference between resonances is one possible mechanism: other models may be able to reproduce the dips as well

- ATLAS **[** PRL 131 (2023) 151902 **]** also confirmed the $\mathrm{X}(6900)$ structure & a near-threshold excess [see backup]

2. First observation of the decay $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$

Study of the decay $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$

- First observation of the $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$ transition through the decay chain :

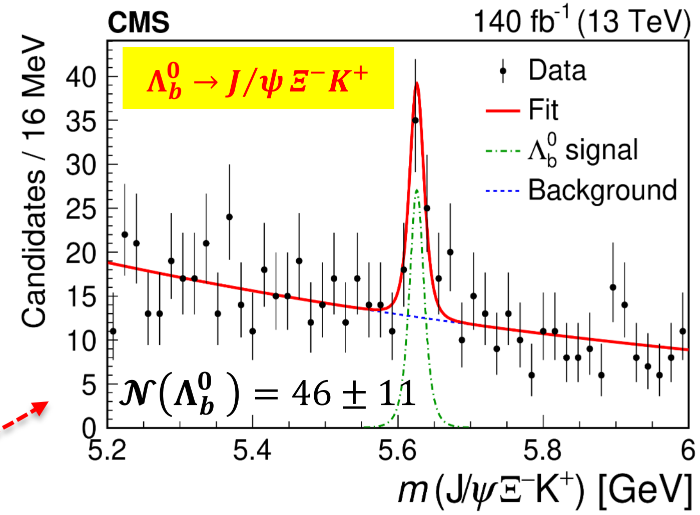


$\mu^+\mu^-$

$\Lambda\pi^-$

$p\pi^-$

LOCAL STATISTICAL
SIGNIFICANCE ~ 5.8σ



- Signal yields extracted by means of UML fits with models:
  - signal: t-Student (μ, σ free; n fixed from MC)
  - background: Exponential

Study of the decay $\Lambda_b^0 \rightarrow J/\psi\, \Xi^- K^+$

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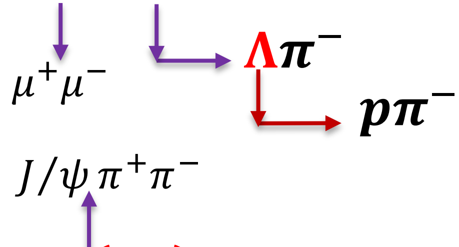
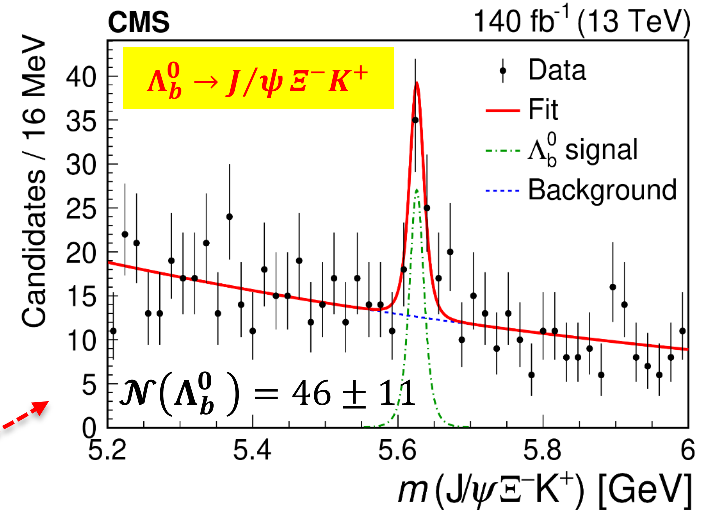
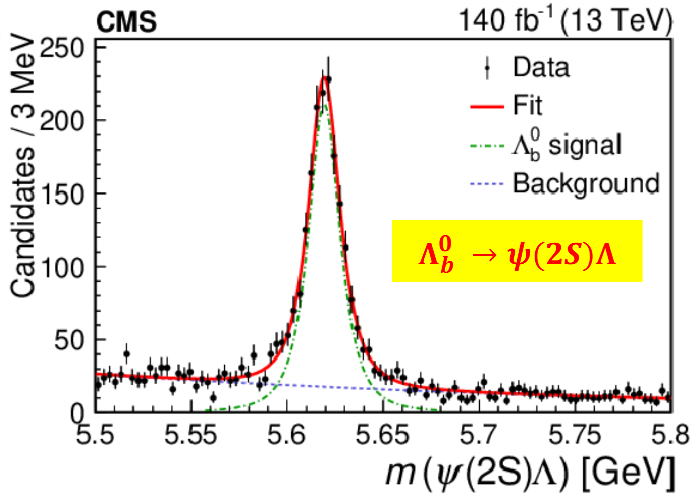
LOCAL STATISTICAL SIGNIFICANCE $\sim 5.8\sigma$



Normalization channel : $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$

(more copious, similar topology and kinematics) → reduced systematics





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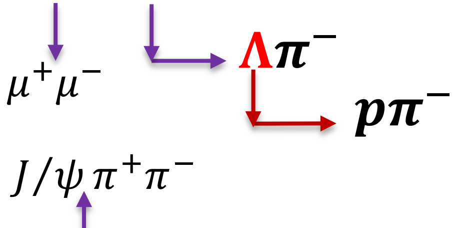

Normalization channel : $\Lambda_b^0 \to \psi(2S)\Lambda$

(more copious, similar topology and kinematics) → reduced systematics

- Signal yields extracted by means of UML fits with models:
  - signal: t-Student (μ, σ free; n fixed from MC)
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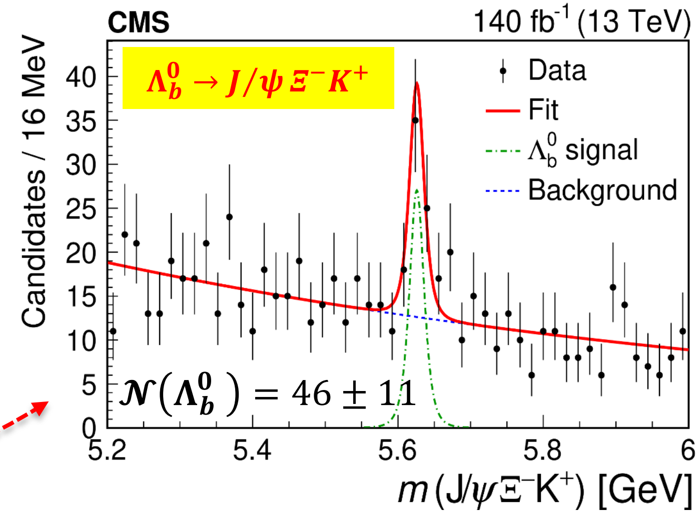
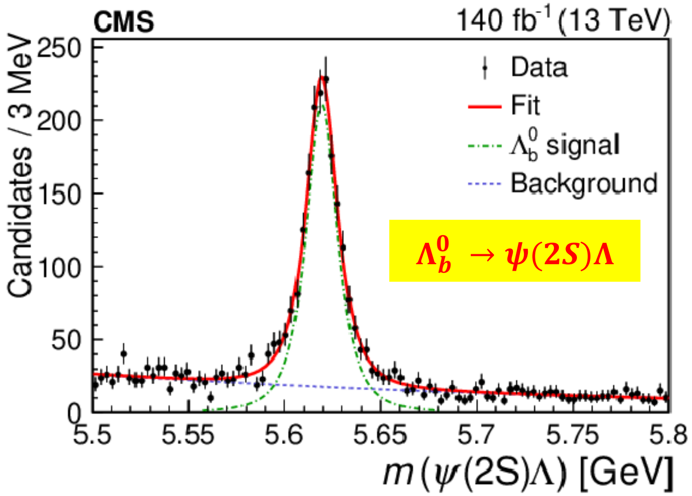




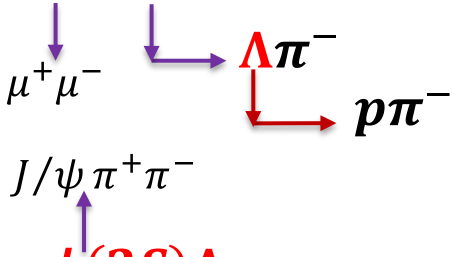
- Branching fraction ratio measurement (with slightly tighter selection):

$$R = \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\, \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} =$$

Study of the decay $\Lambda_b^0 \to J/\psi\,\Xi^- K^+$

- First observation of the $\Lambda_b^0 \to J/\psi\,\Xi^- K^+$ transition through the decay chain :

LOCAL STATISTICAL SIGNIFICANCE ~ 5.8σ



$\mu^+\mu^-$

$\Lambda\pi^-$

$p\pi^-$

$J/\psi\,\pi^+\pi^-$

Normalization channel : $\Lambda_b^0 \to \psi(2S)\Lambda$

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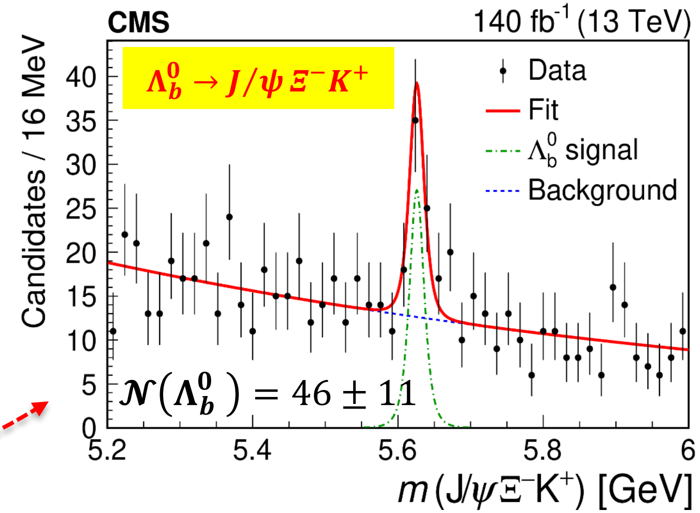

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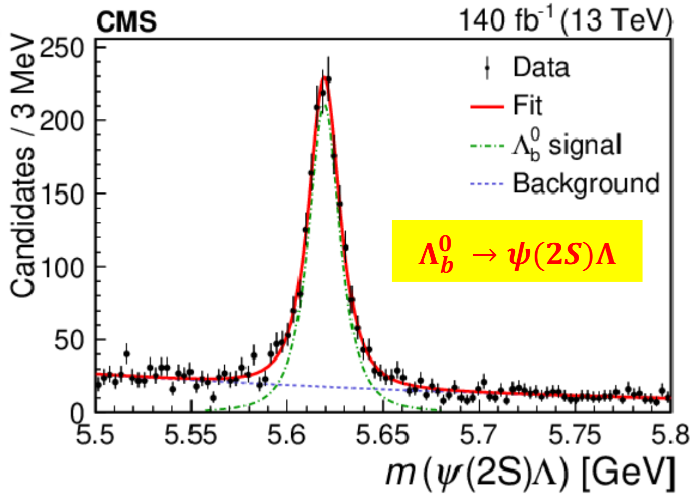

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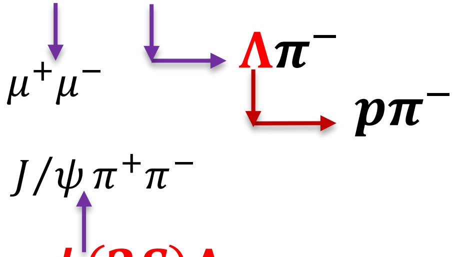

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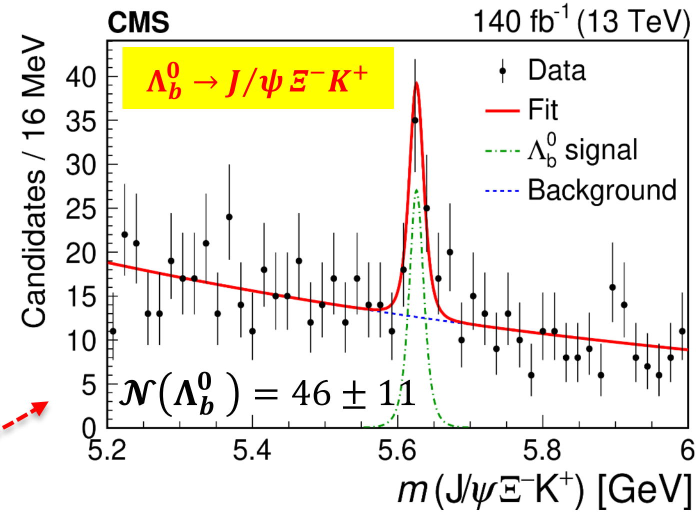

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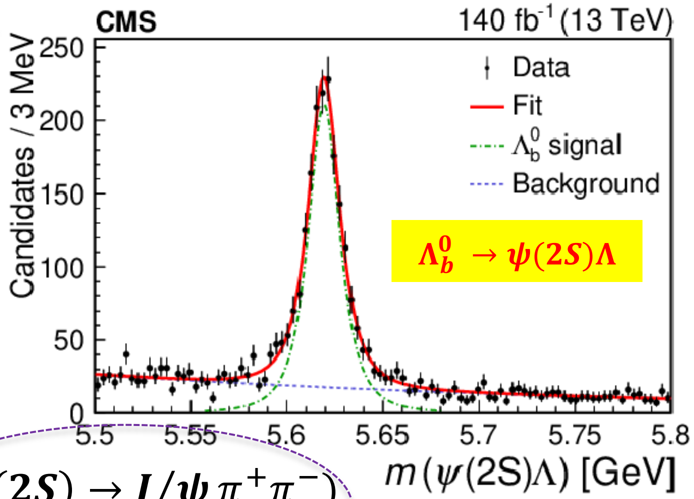

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from PDG

$$= [3.38 \pm 1.02(stat) \pm 0.61(syst) \pm 0.03(\mathcal{B})]\%$$

Large statistical uncertaities due to small signal yield

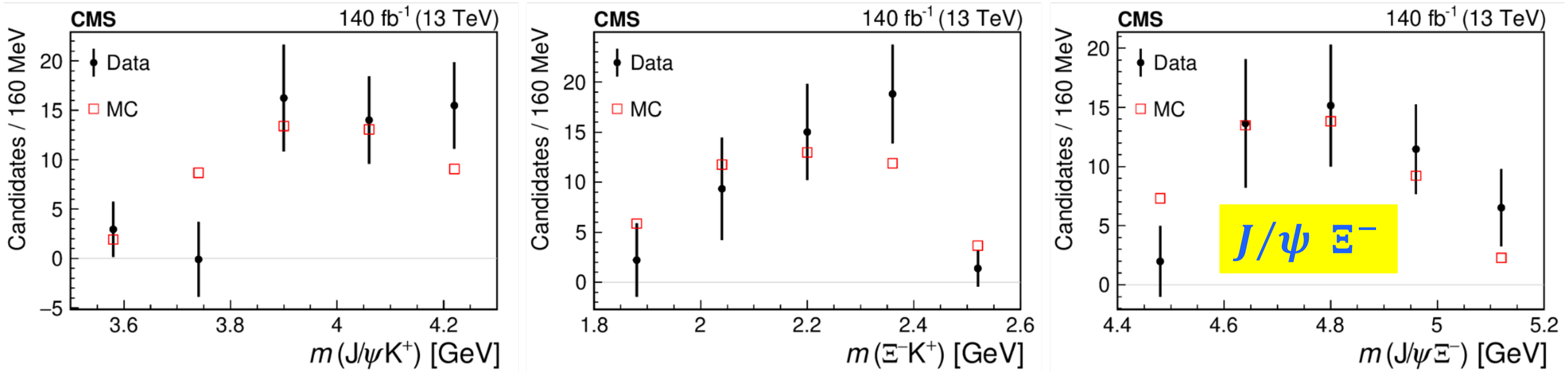
Exploring two-body invariant masses

- **Hidden-charm exotic states** reported by LHCb in $J/\psi\, p$ and $J/\psi\, \Lambda$ **systems**

  (e.g. *pentaquarks* ***candidates*** in $\Lambda_b \to J/\psi\, p\, K^-$ and $\Xi_b^- \to J/\psi\, \Lambda\, K^-$)

- In principle this new decay represents the first 3-body decay allowing to access the $J/\psi\ \Xi^-$ sub-system

- Background-subtracted mass distributions (`sPlot`), to be used to search for intermediate resonances, are compared with the phase-space model (from simulation):



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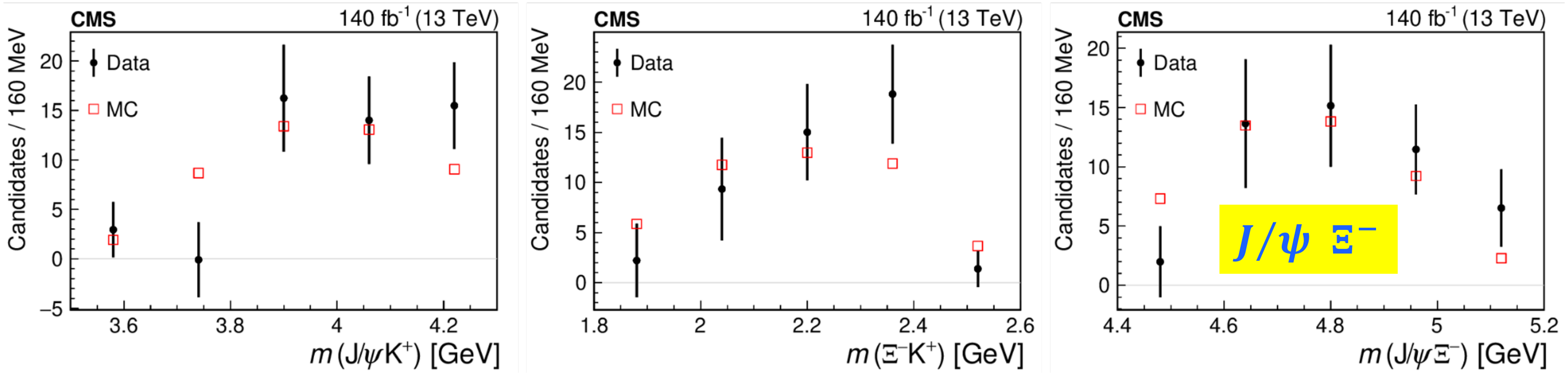

These distributions do not show any relatively narrow peak and agree, within uncertainties, with the predictions from the phase space simulation

- The **sensitivity** of this analysis to potential pentaquark signals in the $J/\psi\ \Xi^-$ intermediate invariant mass distributions is **limited by the low signal yield** for the time being.

Conclusions & Outlook

- Explored $J/\psi\, J/\psi$ mass spectrum finding a likely 3-way structures pattern, confirming the $\mathbf{X(6900)}$ observed by LHCb, observing the $\mathbf{X(6600)}$ and having an evidence for $\mathbf{X(7100)}$, possibly hinting at a new spectroscopy of all-charmed tetraquarks.

  - The measurement of the production Xsections (in a fiducial region) is in our plans as well.

  - In general CMS has good sensitivity to all-muon final states (see also the **triple-J/ψ** result [NATURE Physics 304 (2023) 1], and the $J/\psi \rightarrow 4\mu$ decay).

    (see S.Leontsinis's talk) [Q&LV 19.07 @ 15.45]

    Thus, it is worthy to explore $J/\psi\, \psi(2S)$ and **di-**$\psi(2S)$ spectra.
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  we presented here the **first observation of the decay $\boldsymbol{\Lambda_b^0 \to J/\psi\, \Xi^- K^+}$**.
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[Strong Int. 19.07, 08.45]
[PRD 110 (2024) 012002]

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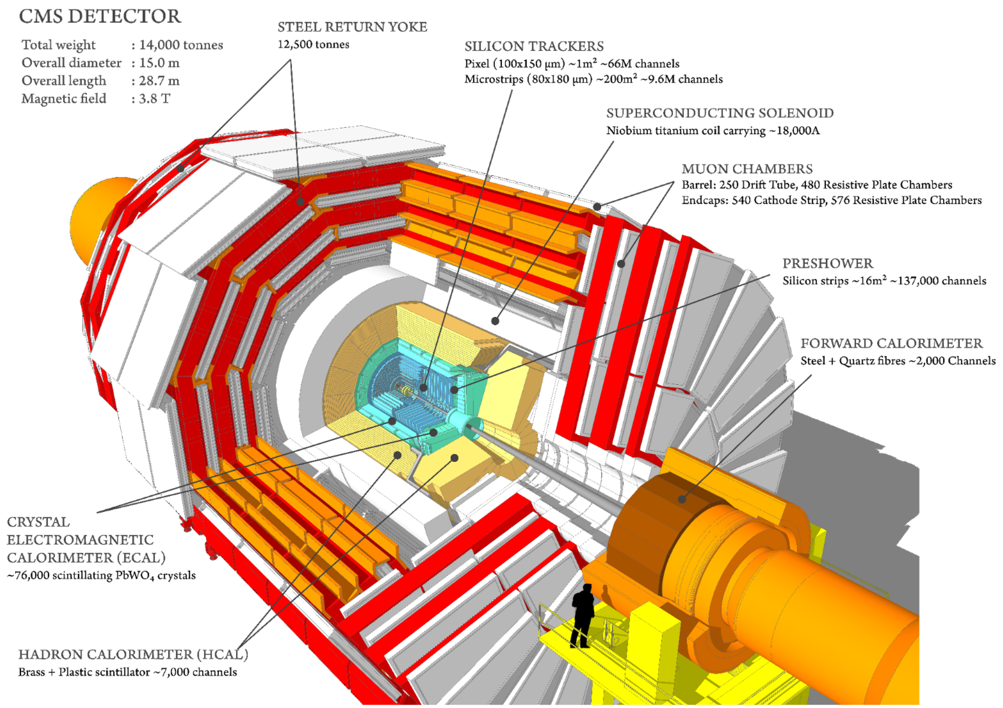
- The Run-3 data being collected will help to achieve very interesting new/updated results, in Heavy Flavour Spectroscopy & Production, integrating and/or complementing LHCb (& ATLAS) results (mainly pp collisions) and ALICE (HI collisions), in spite of huge backgrounds, trigger constraints, particle identification limitations. However, Run-2 data have not yet been fully explored as well.

Backup material

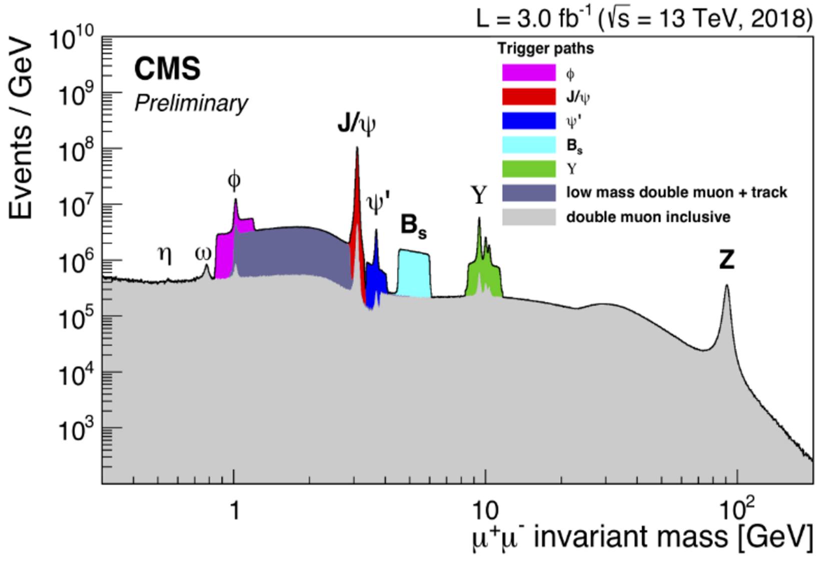
Backup: The CMS detector @LHC

- **General purpose detector** with **cylindrical symmetry** and (almost) **full coverage of the solid angle**



Strengths (for the discussed analyses):

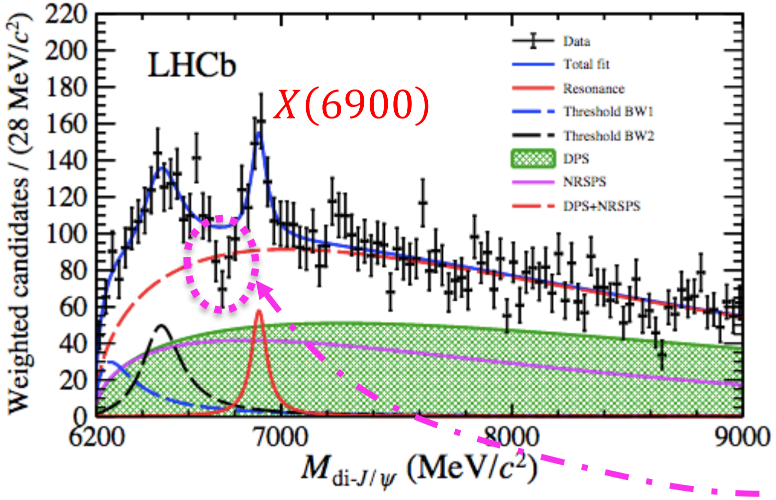
- muon reconstruction and identification
- large muons' acceptance
- high-performance tracking & vertexing



LHCb models fitting the $J/\psi\, J/\psi$ mass spectrum [Sci. Bull. 65 (2020) 23]

- In 2020 LHCb observed a peak in the $J/\psi\, J/\psi$ **mass spectrum, the $X(6900)$**, which was considered with great interest as a **possible *all-charm tetraquark*** **(**even if also alternative interpretations have been advocated**)**. LHCb **reported two alternative fit models:**

Model-I :

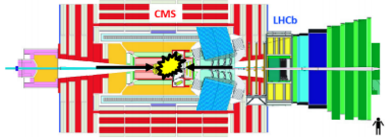


3 B.-W.s: - 1 for the signal peak $X(6900)$

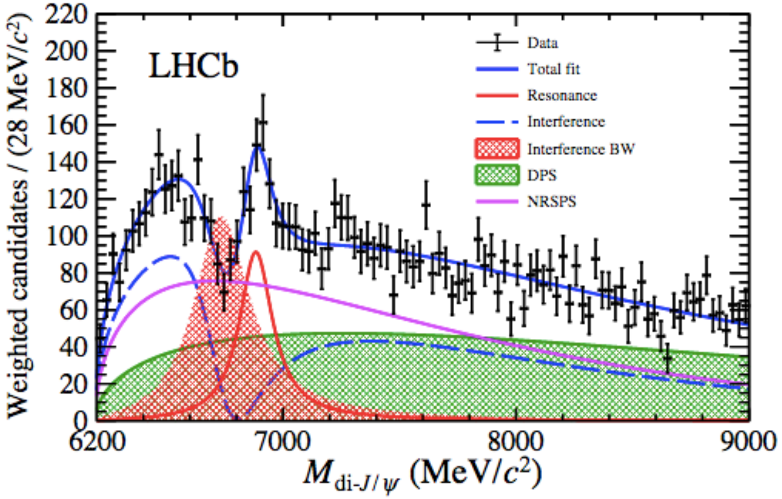
- other 2 auxiliary "threshold" B.-W.s for the initial raise and first "bump"

NRSPS+DPS shapes for the background

Different acceptance →
Different BKG-shape in CMS :



Model-II



It poorly describes the dip, suggesting to try a destructive interference of a "virtual" B.-W. with the NRSPS bkg. component, while getting rid of the "threshold B.-W.s".

X(6900), renamed $T_{\psi\psi}$(6900)

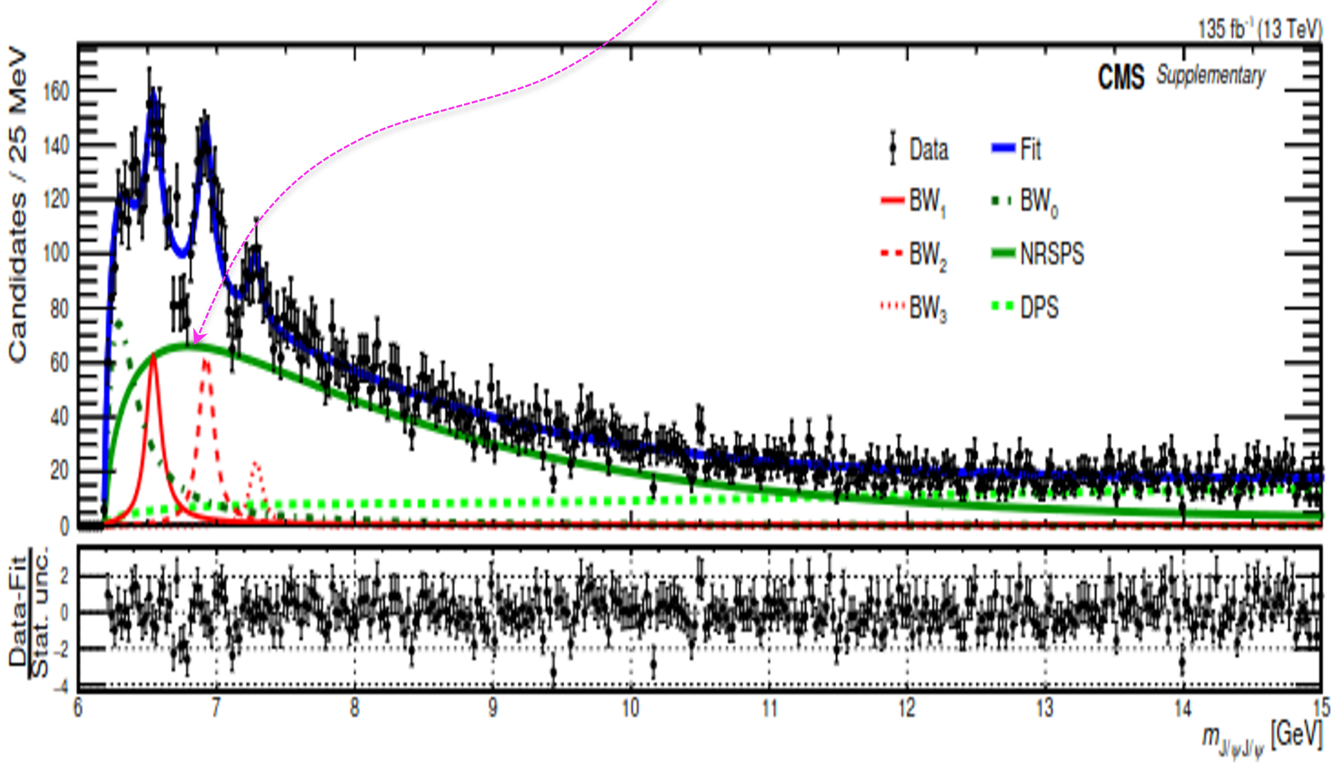
Masses & **natural widths** for the $X(6900)$ result to be compatible in the two models. LHCb is agnostic on which one is to prefer.

$J/\psi\, J/\psi$ mass spectrum : background description - I

- **Major physical background sources:**
  - 2 genuine J/ψs combined randomly, i.e. not from a resonant decay, arising from:

- single parton-parton collision:
  non-resonant **single** parton scattering (**NRSPS**)
  `[Pythia8, CASCADE (NLO), HELAC-ONIA (NNLO)]`

→ dominant near threshold region $(p_T < 10 GeV)$



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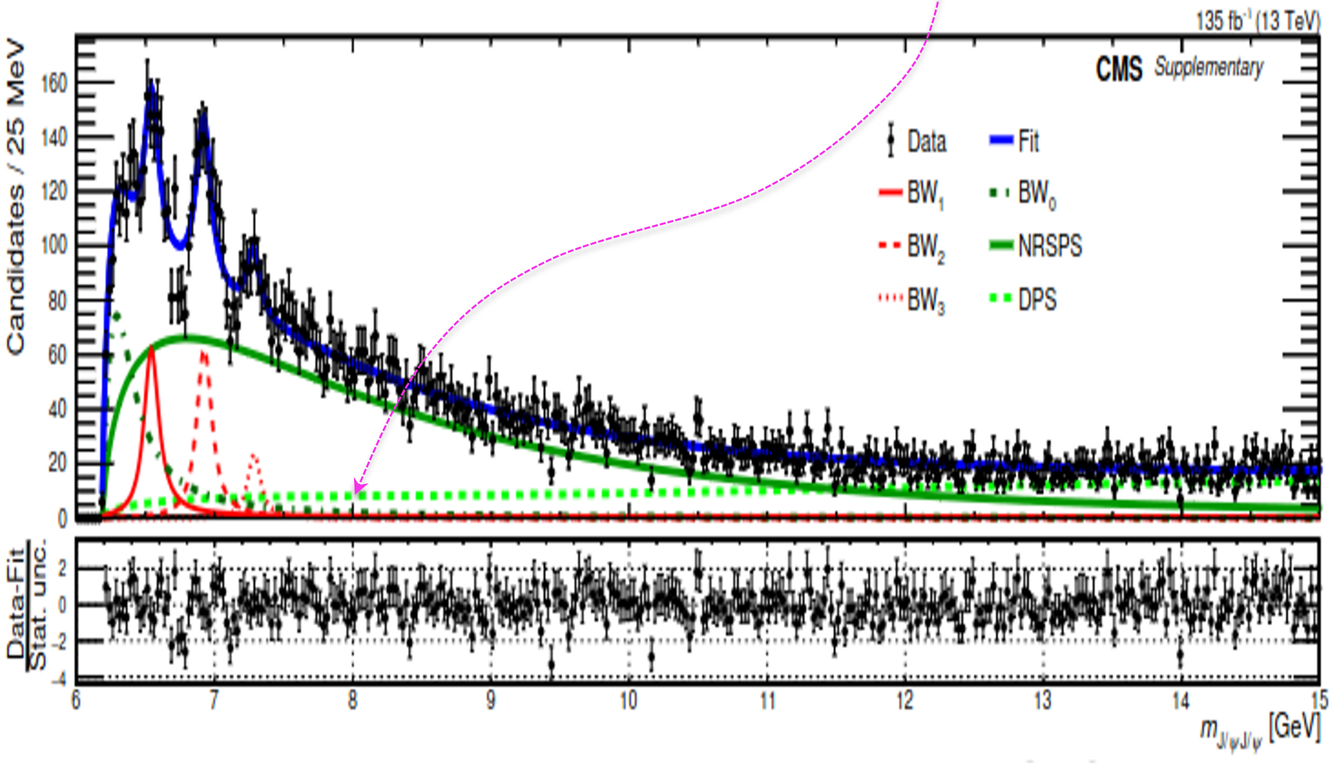
- a pair of parton-parton interactions in a single pp collision:
  double parton scattering (**DPS**) *`[see above]`*
  → dominant from $p_T > 12GeV$



$J/\psi\, J/\psi$ mass spectrum : background description - II

- **Major physical background sources:**
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  - Simulation includes: **direct** production + **feed-down** processes (J/ψ as decay product)

    Additional **feed-down** processes from double-charmonium resonances: generated separately `[Pythia8]`

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    Additional **feed-down** processes from double-charmonium resonances: generated separately `[Pythia8]`

- **Residual combinatorial background sources:** (these residual effects are accounted for as systematics)
  - At least one non-genuine J/ψ arising from:
    - one or more genuine μ candidate(s) not from a J/ψ decay
    - one (or more) hadron(s) misidentified as μ candidate(s) or misreconstructed

$J/\psi\, J/\psi$ mass spectrum : background description - III

- **Null-hypothesis model**: NRSPS+DPS

Shapes from `Pythia8` distributions, parametrized by :

- **SPS**: threshold func. * poly2 * exp. (1 floating param.)
- **DPS**: sqrt * poly2 * exp.

$J/\psi\, J/\psi$ mass spectrum : background description - III

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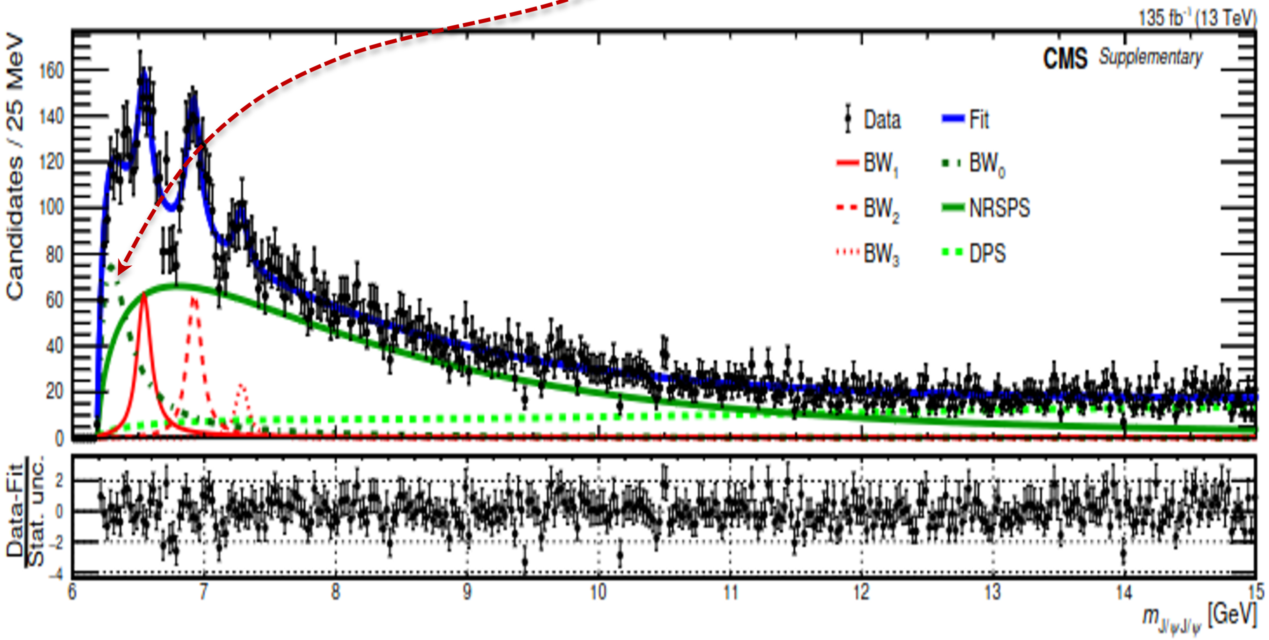
modelled empirically by a B.-W. (**BW$_0$**) with free m & Γ

Spectrum visualization



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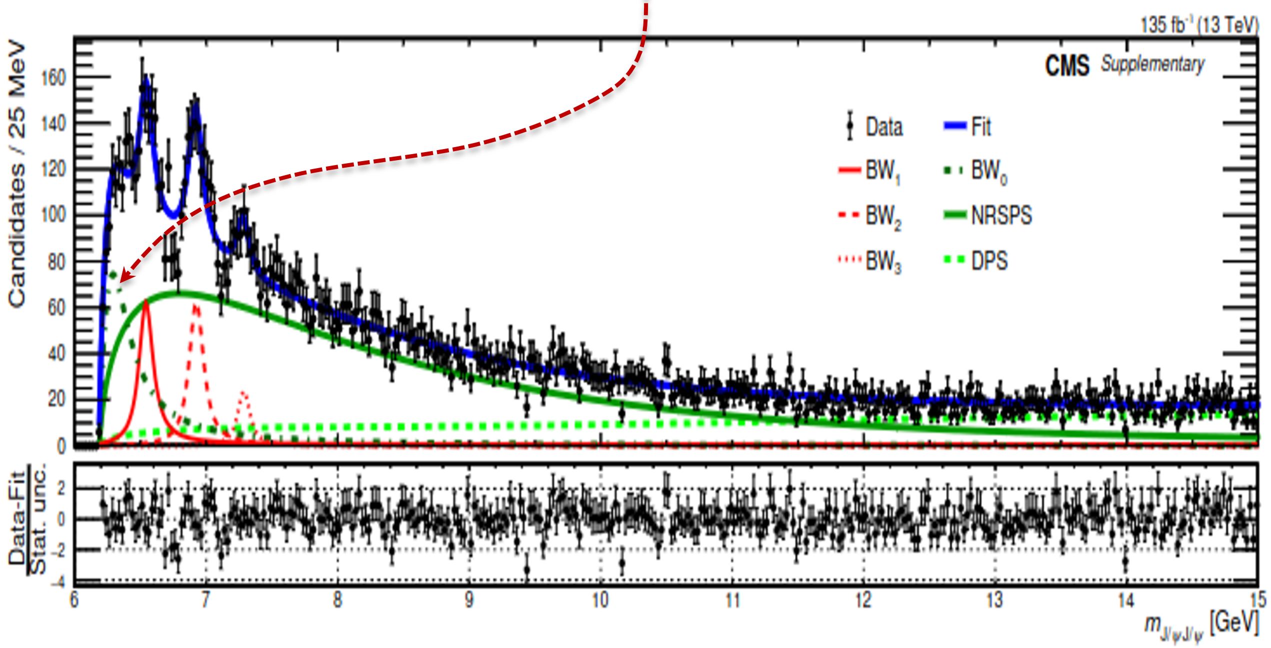
Takes into account the inadequacy of NRSPS near threshold. This excess may be due to:
- a genuine resonance
- feed-down of partially reconstructed higher mass states ($J/\psi\ \psi(2S)$, …) [checked from MC]
- near threshold enhancements as those in mass spectra of VV final states ($\phi\phi, \phi\omega, J/\psi\ \phi, J/\psi\ \omega$)
- coupled-channel interactions, final state rescattering (triangle singularities), pomeron-exchange processes, …

Spectrum visualization



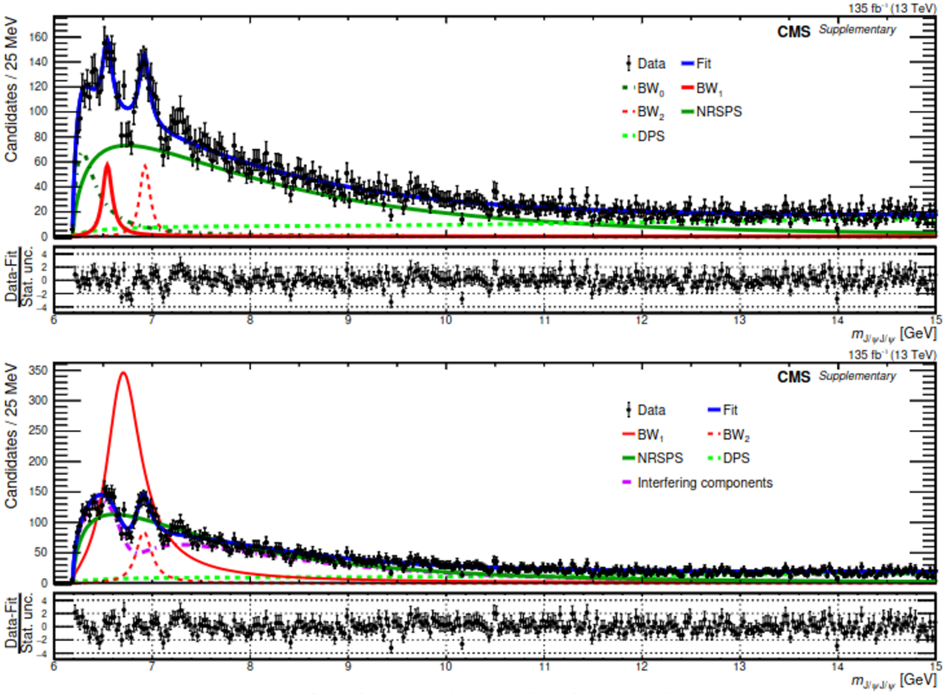
$J/\psi\, J/\psi$ mass spectrum : fit with LHCb models

The LHCb signal models are also tested: similar results, but no improvement on the fit quality

LHCb signal models + CMS background

- **Model I (top):**
  [NRSPS + DPS + X(6900) + 2BW below 6900]
  - X(6900) parameters in agreement
  - but dip at 6.7 not well described

- **Model II (bottom):**
  [NRSPS + DPS + X(6900) + 1BW below 6900 interfering with NRSPS]
  - Larger X(6700) amplitude
  - X(7300) region not well described



Backup: Di-charmonum spectrum @ ATLAS [PRL 131 (2023) 151902]

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 140 fb^{-1} of pp collisions at √s = 13 TeV

Prompt (SPS, DPS) and non-prompt ($b\bar{b} \rightarrow J/\psi J/\psi + X$) background contributions are considered

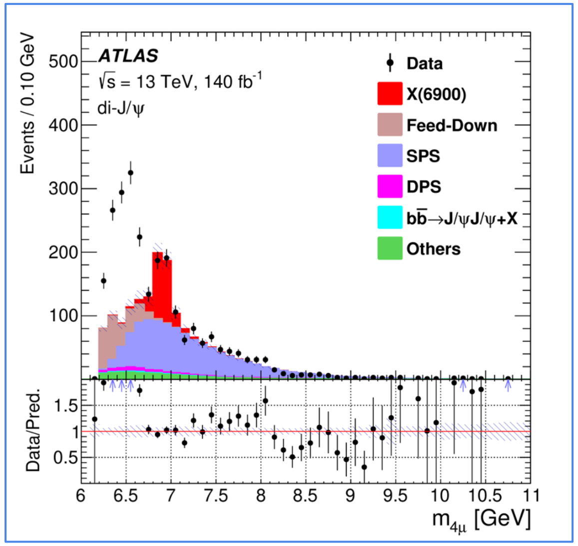
Feed-down included only for di-J/ψ channel

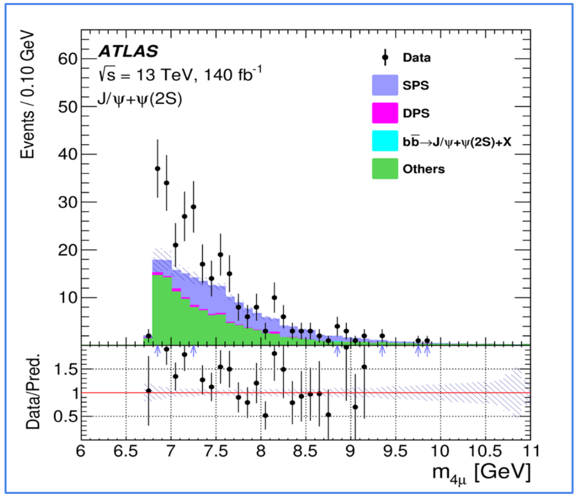
4μ mass data vs background predictions before fit for J/ψ+J/ψ and J/ψ+ψ(2S)

Signal model: interfering BWs ⊗ Gaussian resolution (introduced gradually to improve the fit)

- **di-J/ψ signal**:
  - A) 3 interfering scalar BWs
  - B) 2 interfering scalar BWs, the first interferes also with SPS

- **J/ψ+ψ(2S) signal**:
  - A') 3 interfering BWs from A (fixed) + stand-alone 4th resonance
  - B') single resonance





Statistically significant excesses with respect to SPS-dominated backgrounds are seen in the di-*J*/*ψ* channel consistent with a narrow resonance at 6.9 GeV and a broader structure at lower mass.
A statistically significant excess is also seen in the *J*/*ψ*+*ψ*(2S) channel.

Backup: Di-charmonum spectrum @ ATLAS [PRL 131 (2023) 151902]

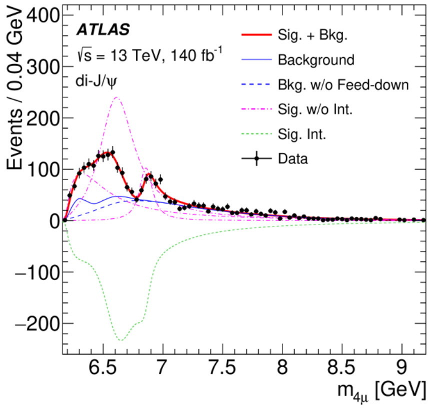
In detail:

- **di-J/ψ:** models A and B describe the spectrum better than models with fewer/no interference.

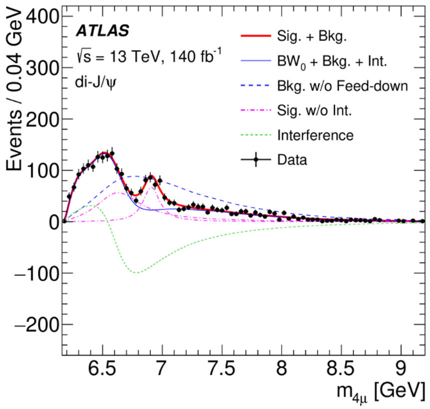
  Significance for all resonances and for X(6900) alone greater than 5σ

  The broad structure at low mass could result from other physical effects (e.g. feed-down from higher di-charmonium resonances)

model-A:



model-B:

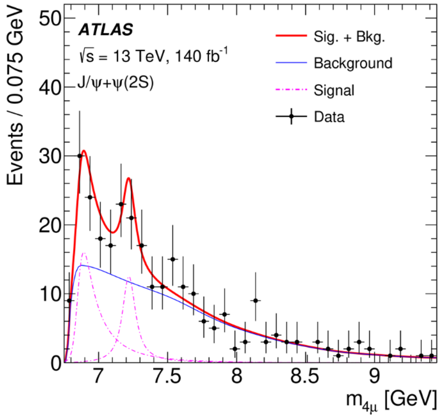


- **J/ψ+ψ(2S)**: significance for all resonances with model A’ (B’) is 4.7σ (4.3σ)

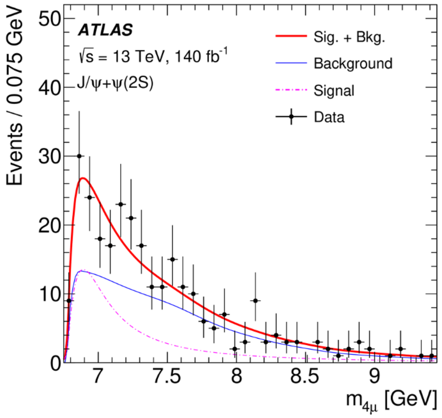
  Structure at 7.2 GeV alone in model A’: 3.0σ

  More statistics will help to better understand the structures in both channels

model-A’:

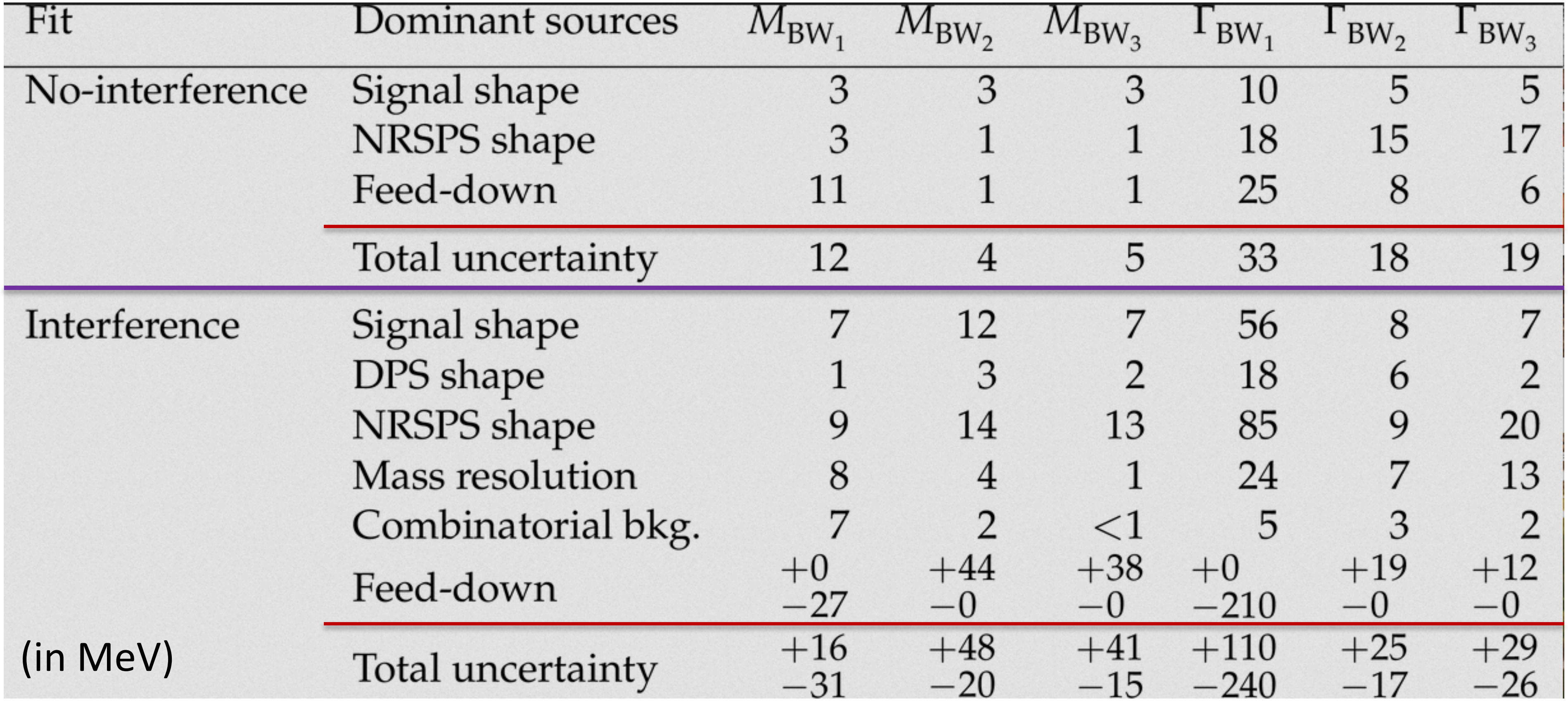


model-B’:



Systematic uncertainties

- Systematic uncertainties for masses & widths of the 3 peaking structures in the $J/\psi\, J/\psi$ spectrum



Fit	Dominant sources	M_{BW_1}	M_{BW_2}	M_{BW_3}	Γ_{BW_1}	Γ_{BW_2}	Γ_{BW_3}
No-interference	Signal shape	3	3	3	10	5	5
	NRSPS shape	3	1	1	18	15	17
	Feed-down	11	1	1	25	8	6
	Total uncertainty	12	4	5	33	18	19
Interference	Signal shape	7	12	7	56	8	7
	DPS shape	1	3	2	18	6	2
	NRSPS shape	9	14	13	85	9	20
	Mass resolution	8	4	1	24	7	13
	Combinatorial bkg.	7	2	<1	5	3	2
	Feed-down	$^{+0}_{-27}$	$^{+44}_{-0}$	$^{+38}_{-0}$	$^{+0}_{-210}$	$^{+19}_{-0}$	$^{+12}_{-0}$
(in MeV)	Total uncertainty	$^{+16}_{-31}$	$^{+48}_{-20}$	$^{+41}_{-15}$	$^{+110}_{-240}$	$^{+25}_{-17}$	$^{+29}_{-26}$

Note: acceptance & trigger/selection efficiencies varying very slowly in the search region: **considered as systematics**