Observation of T_{cccc} in $J/\psi J/\psi$ mass spectrum at LHCb

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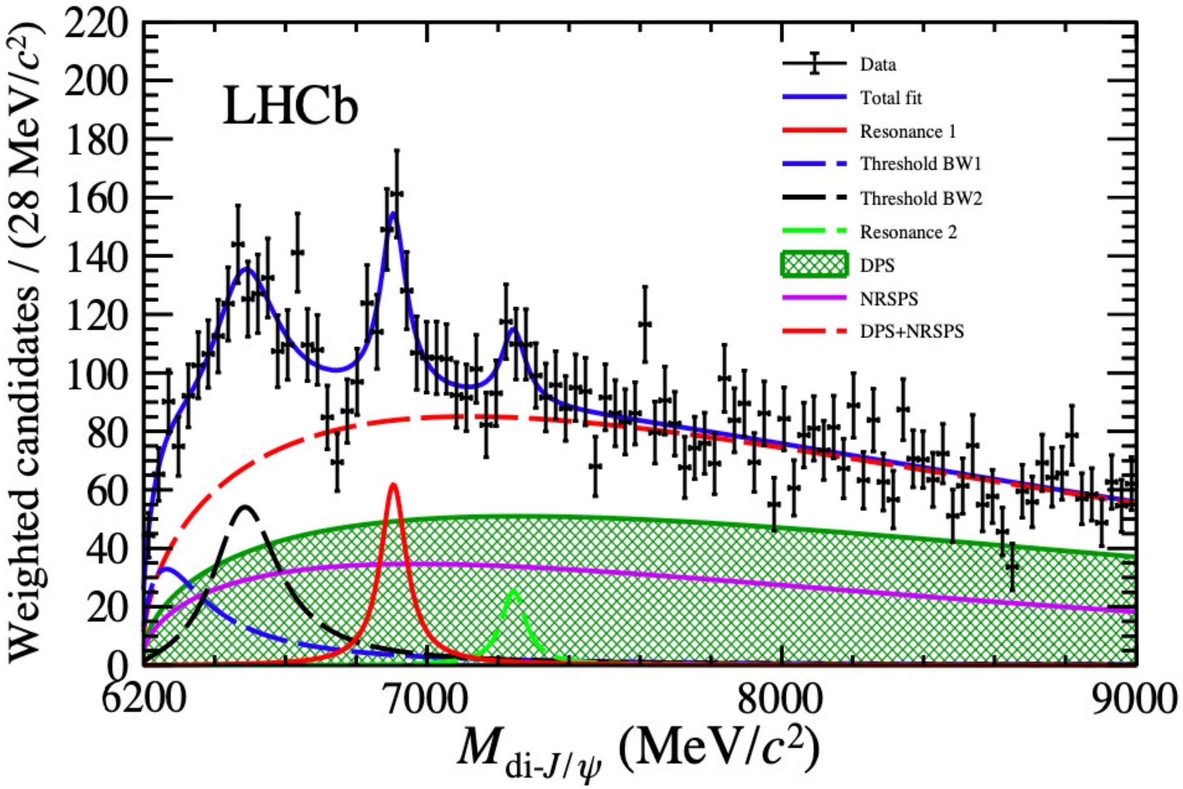
Detailed info: https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/LHCb-PAPER-2020-011.html

Observation of di-J/ψ state in 2020

- LHCb reported structure in di-J/ψ mass spectrum
  - ➢ With $cc\bar{c}\bar{c}$ quark content, first fully heavy tetraquark candidate



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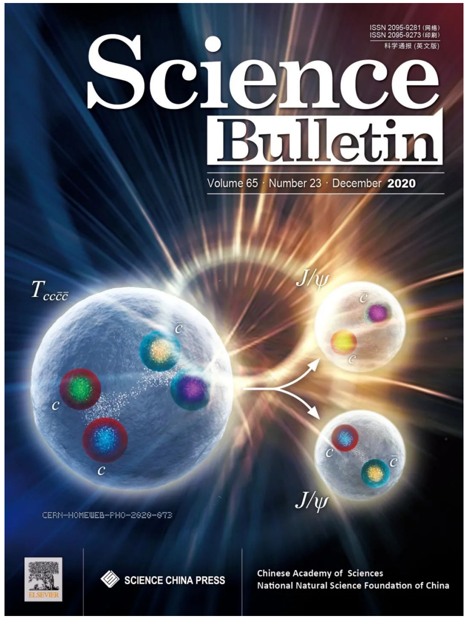


- ✓ Broad structure close to di-J/ψ mass threshold
- ✓ Narrow structure around 6900 MeV
- ✓ Hint at 7200 MeV, but not significant

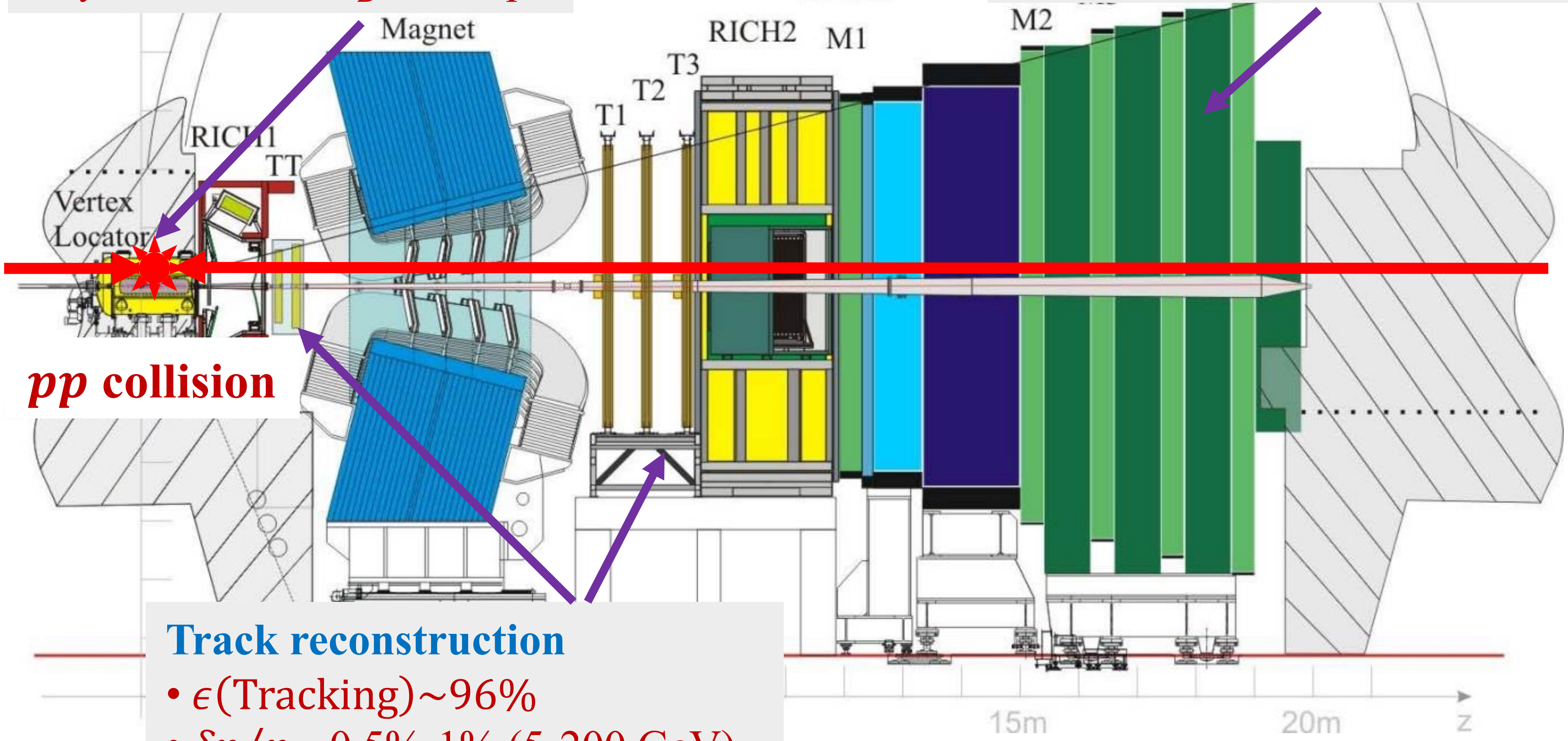
LHCb

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- Heavy flavor experiment covering $2 < \eta < 5$, forward rapidity

Vertex reconstruction
- σ_{IP}~20 μm
- σ_{τ}~45 fs w.r.t. $\tau_B \approx 1.5$ ps

Particle identification
- $\epsilon(\mu \to \mu)$~97%
- MisID rate $(\pi \to \mu)$~$1-3\%$



***pp* collision**

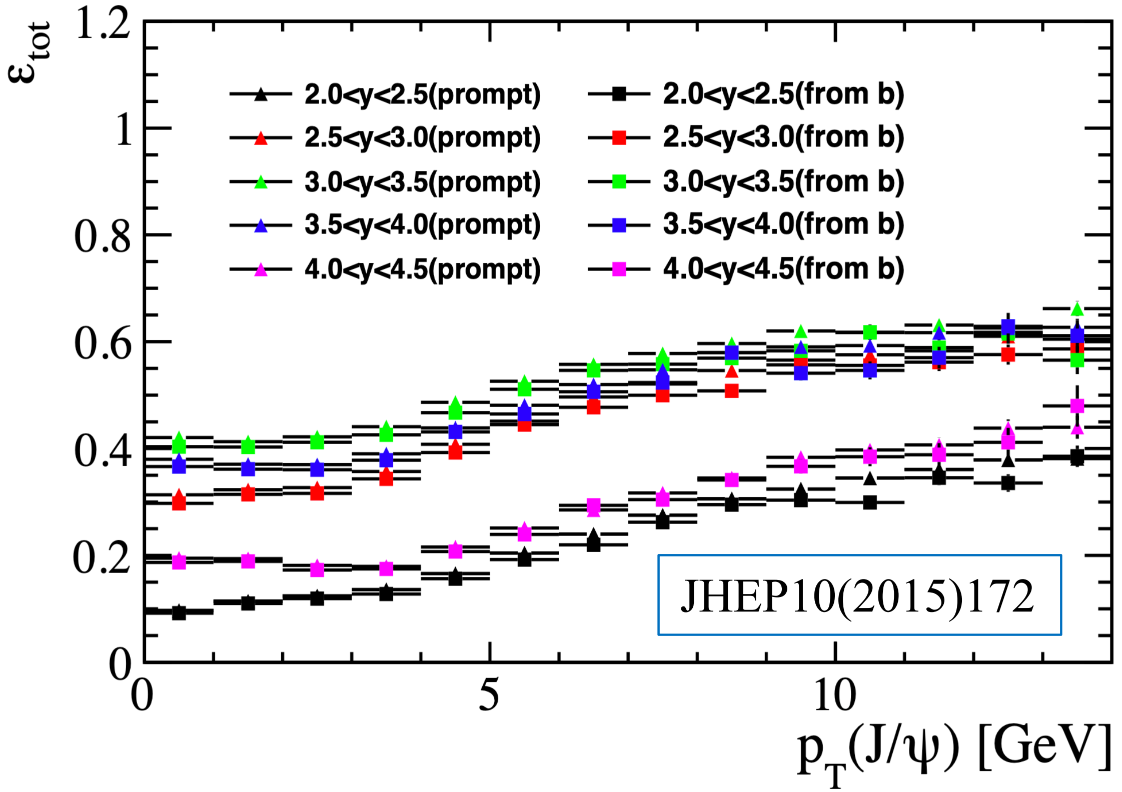
Track reconstruction
- ϵ(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\epsilon(m_{J/\psi}) \approx 15$ MeV

LHCb

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- Heavy flavor experiment covering $2 < \eta < 5$, forward rapidity

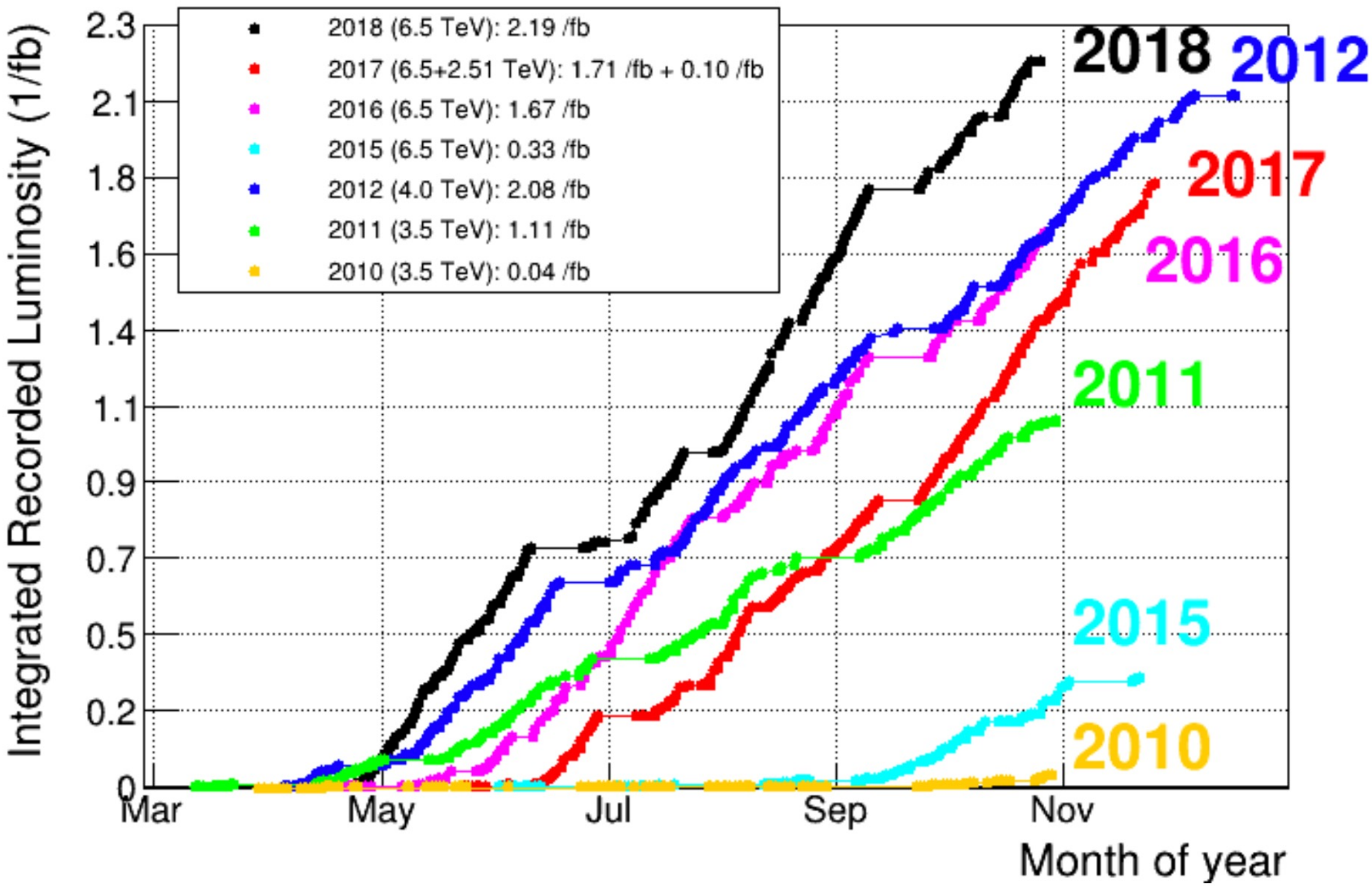
Efficient to detect $J/\psi \to \mu^+\mu^-$ down to zero-p_T



Total J/ψ efficiency: trigger, reconstruction, particle ID etc.

LHCb luminosity

- **3 fb^{-1}** at $\sqrt{s} = 7, 8$ TeV and **6 fb^{-1}** at $\sqrt{s} = 13$ TeV



Di-J/ψ sample at LHCb

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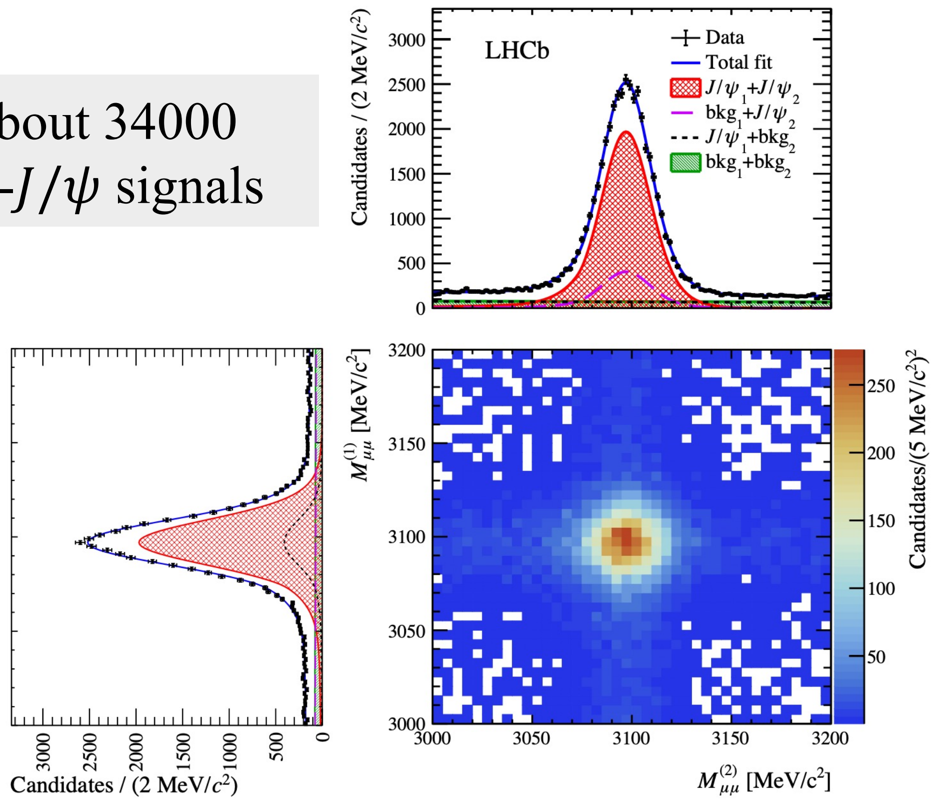
LHCb-PAPER-2020-011: https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/LHCb-PAPER-2020-011.html

- Full LHCb data ~9 fb^{-1}

Background:

- ➢ Fake J/ψ: studied using J/ψ mass distribution
- ➢ J/ψ-from-b and pileup: suppressed using vertexing information

About 34000 di-J/ψ signals

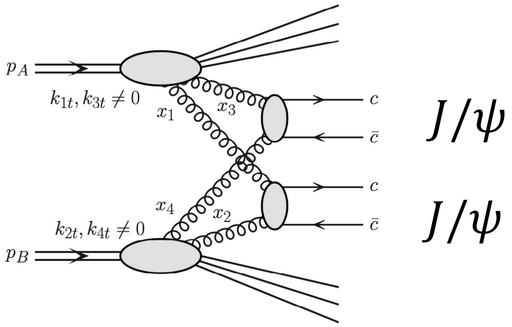


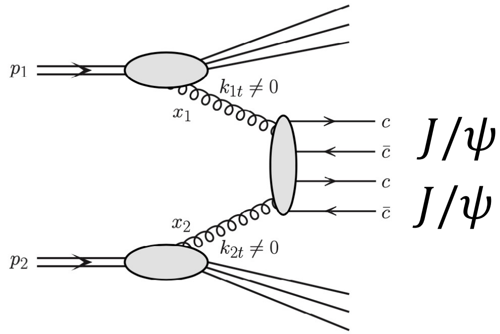
Di-J/ψ mass spectrum

T_{cccc} signal optimization

- Di-J/ψ production mechanism

Fig from arXiv:2204.02649





DPS: two J/ψ uncorrelated, no T_{cccc} expected

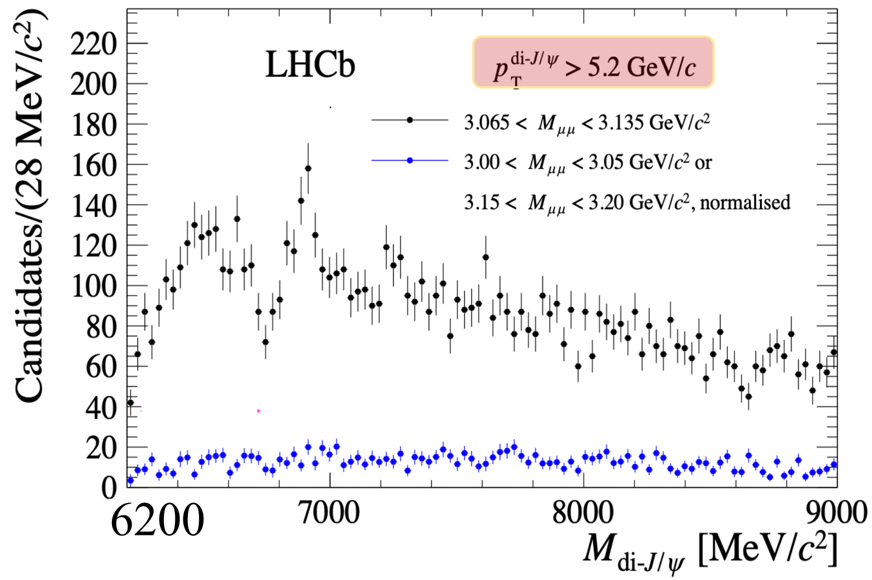
Di-J/ψ mass: Smooth continuum

SPS: two J/ψ correlated, may produce T_{cccc}, averagely high p_T PLB751 (2015) 479

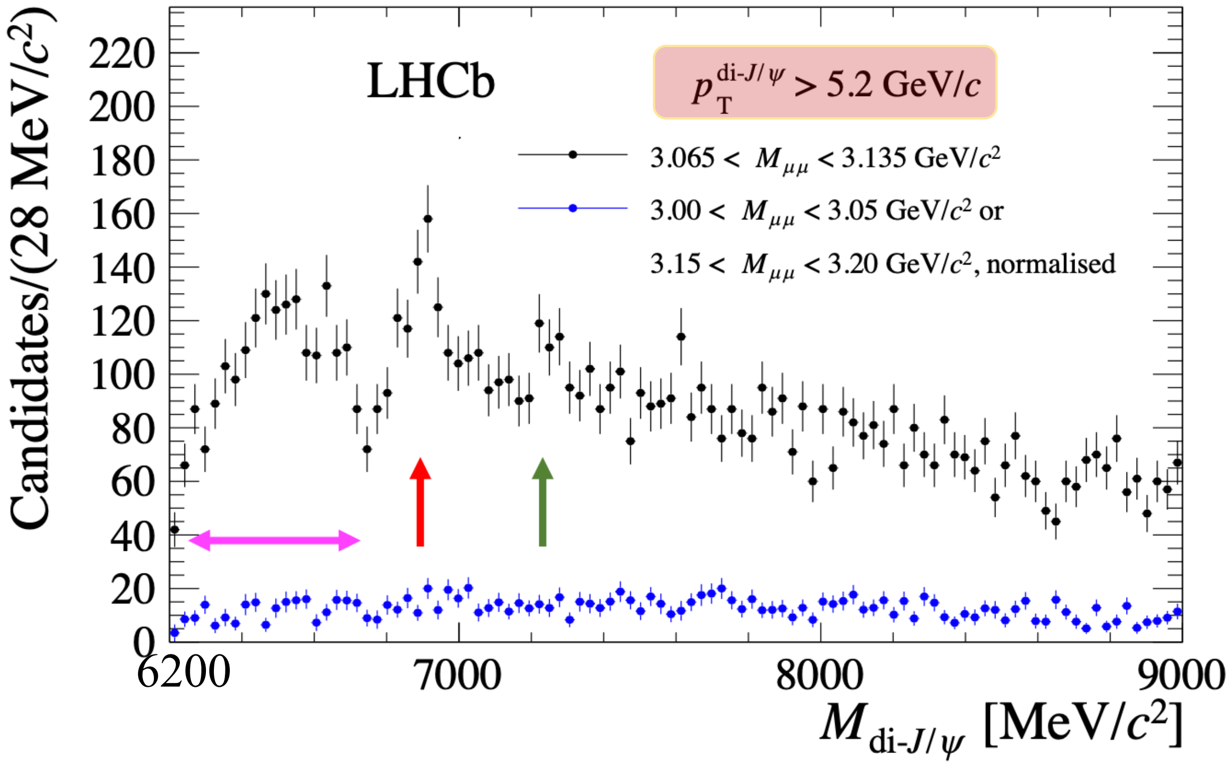
Di-J/ψ mass: Smooth continuum + resonance(s), possible interference between them

- To enhance T_{cccc} signal: optimize di-J/ψ p_T cut or study in bins of p_T

Best cut: $p_T(di - J/\psi) > 5.2$ GeV



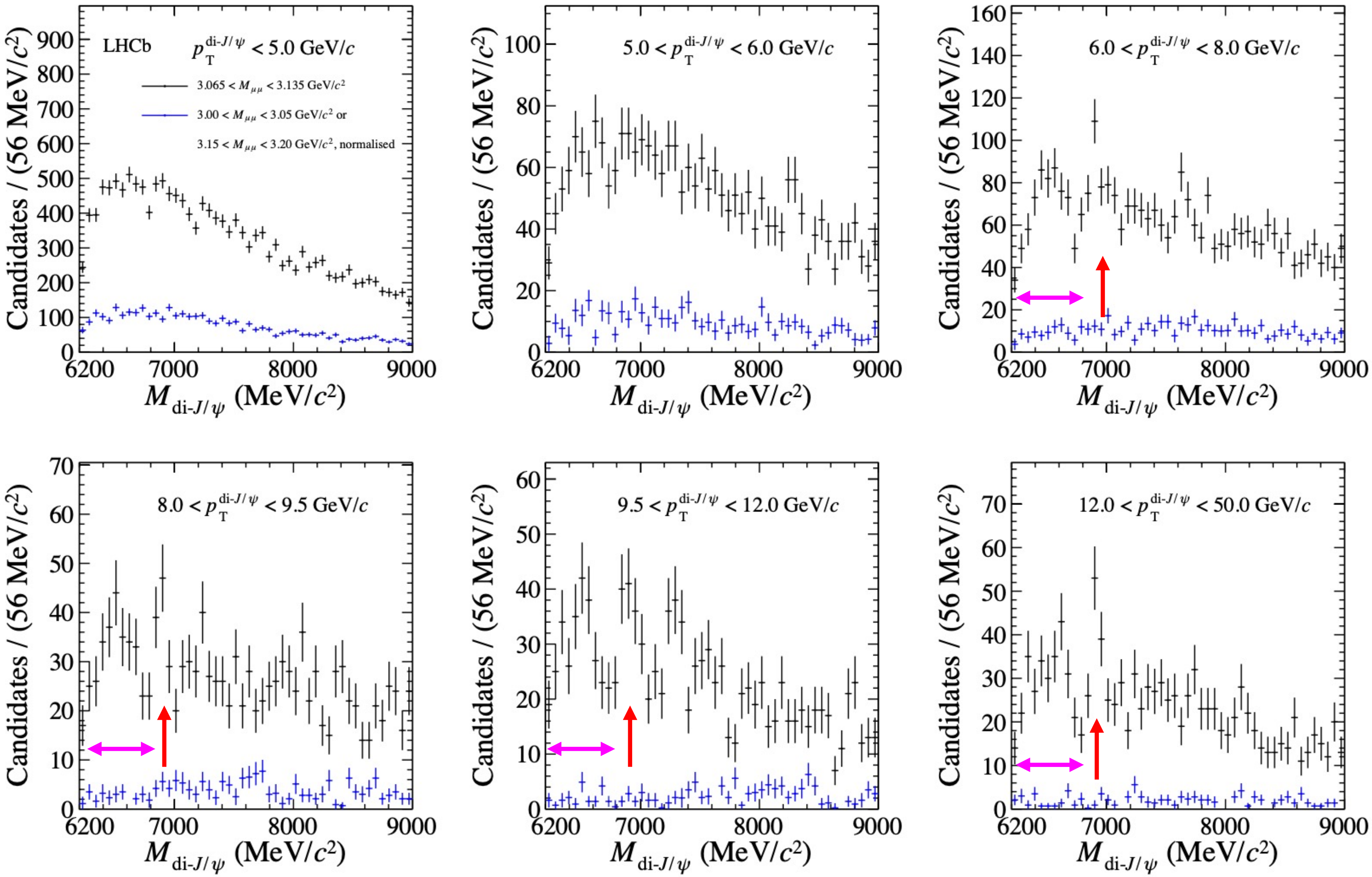
Di-J/ψ invariant mass (I)



- Broad structure at $6.2 - 6.8$ GeV close to di-J/ψ mass threshold
- Narrow peak at 6.9 GeV
- Hint of another structure at 7.2 GeV
- Structure not present in J/ψ background sample

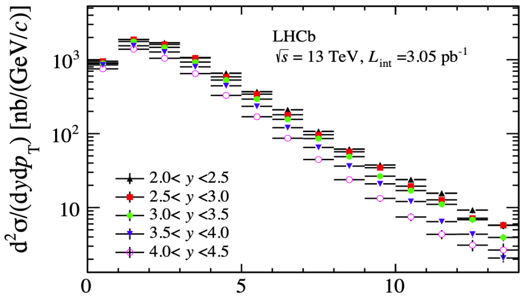
Di-J/ψ invariant mass (II)

- Same structures in all high di-J/ψ p_T bins, evidence increasing with p_T



Modelling Di-J/ψ mass spectrum

- Components and distributions
  - **DPS continuum**: built from differential cross-section of single J/ψ production
    Yield constrained by high di-J/ψ mass region



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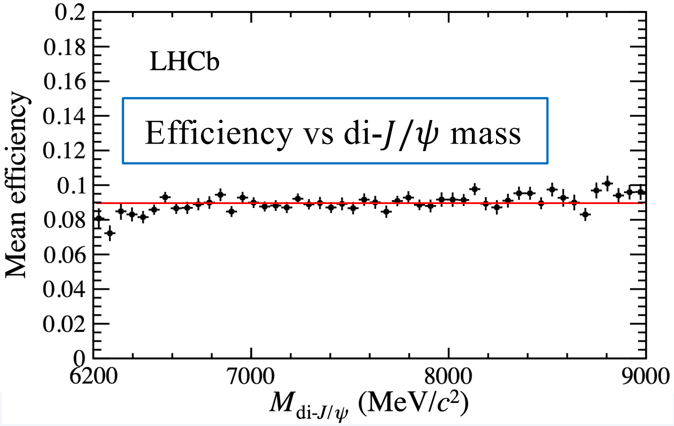
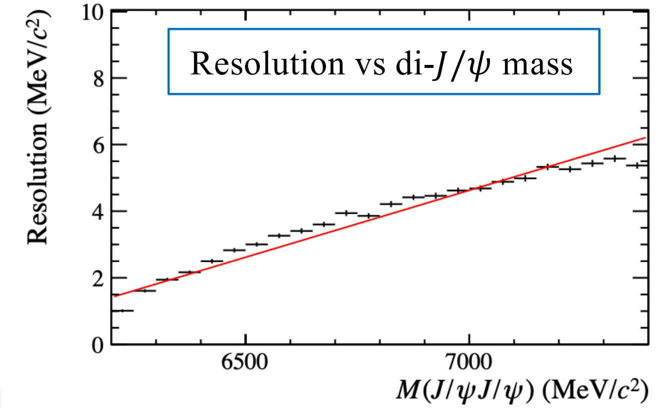
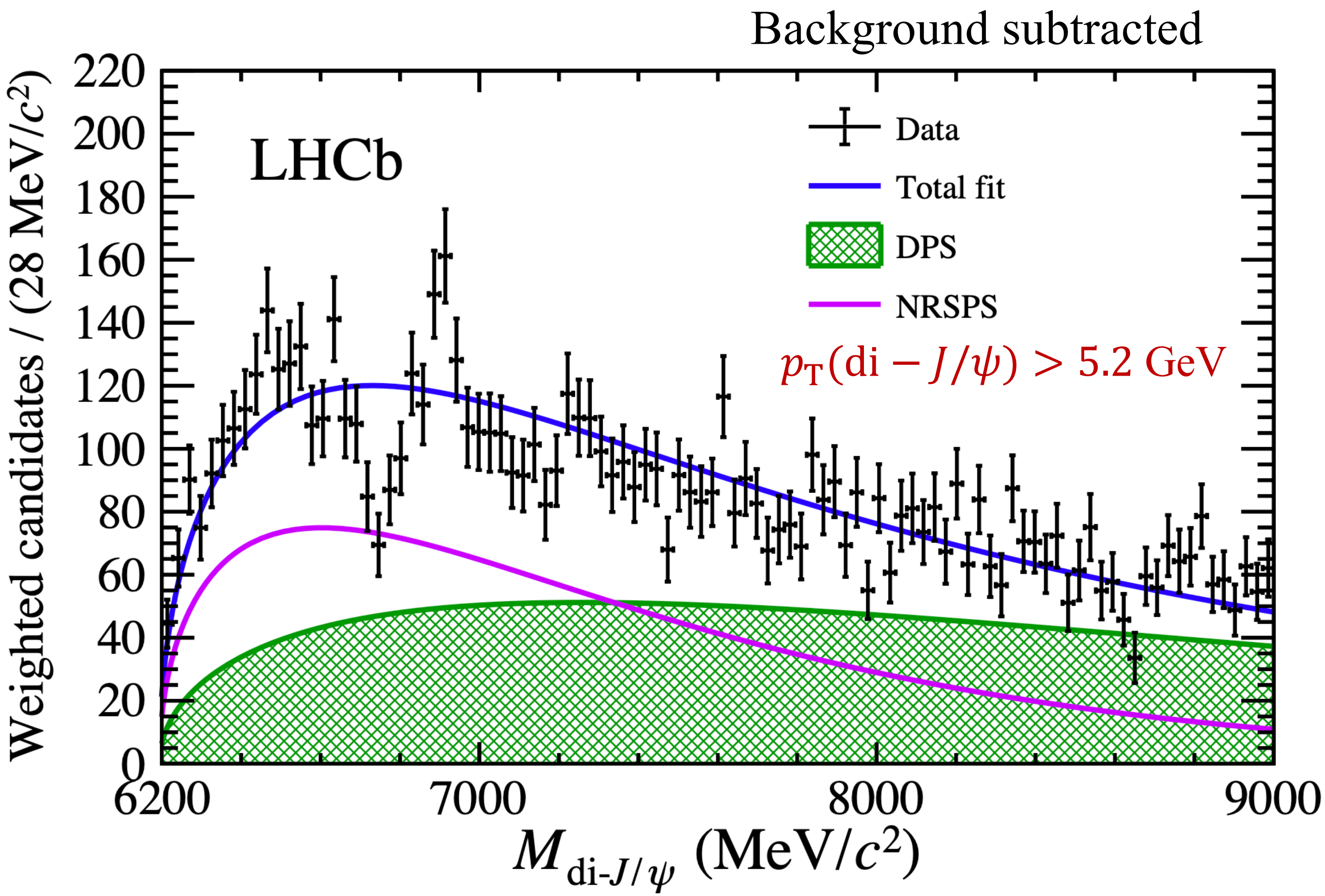
  - **SPS continuum**: two body phasespace modified by exponential, $\Phi_2(m)\times e^{c\cdot m}$
  - **Structures**: relativistic Breit-Wigner (BW)
- Efficiency and resolution neglected





Fit without resonant structure

- Low mass region not described



Fit without resonant structure

- Small di-J/ψ p_{T}: low mass described by SPS+DPS
- High di-J/ψ p_{T}: low mass not described by SPS+DPS
- Fraction of SPS increased with di-J/ψ p_{T}

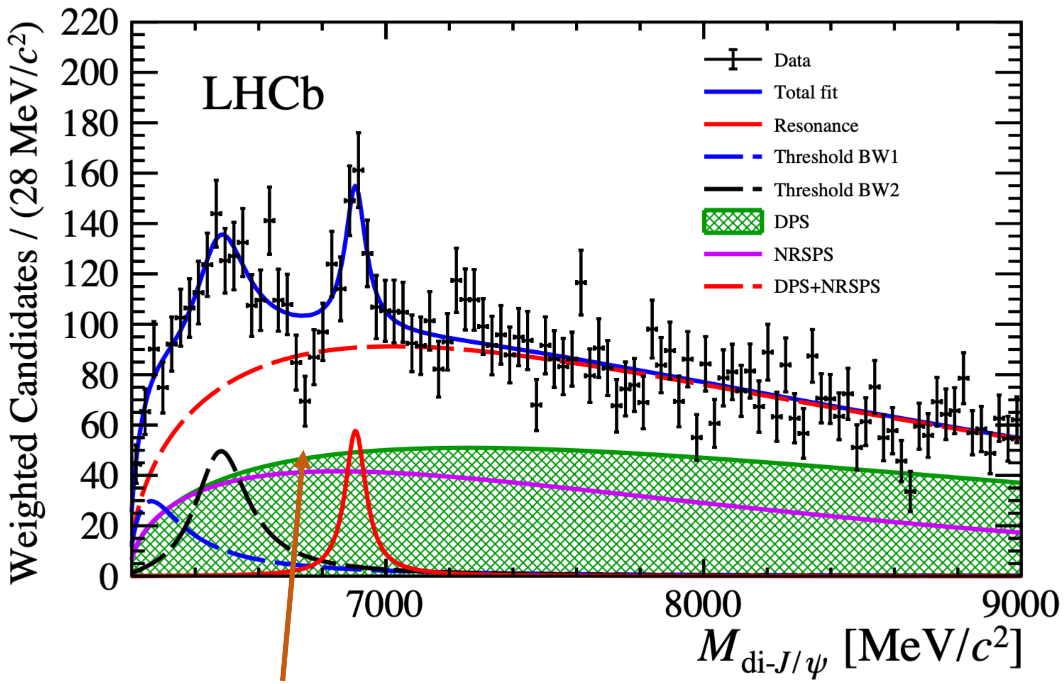
Fits in bins of di-J/ψ p_{T}

Fit with resonant structure: modeling I

- Breit-Wigner (BW) for peaking structures, **no interferences**
  - ➢ The threshold structure $(6.2 - 6.8$ GeV): two BWs, significance $> 6\,\sigma$
  - ➢ Structure at 6.9 GeV: single BW, significance $> 5\,\sigma$

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV}$$

$$N[X(6900)] = 252 \pm 63$$



	m/MeV	Γ/MeV
Res1	~6250	~300
Res2	~6650	~200

Difficulty to model the dip at 6.8 GeV !

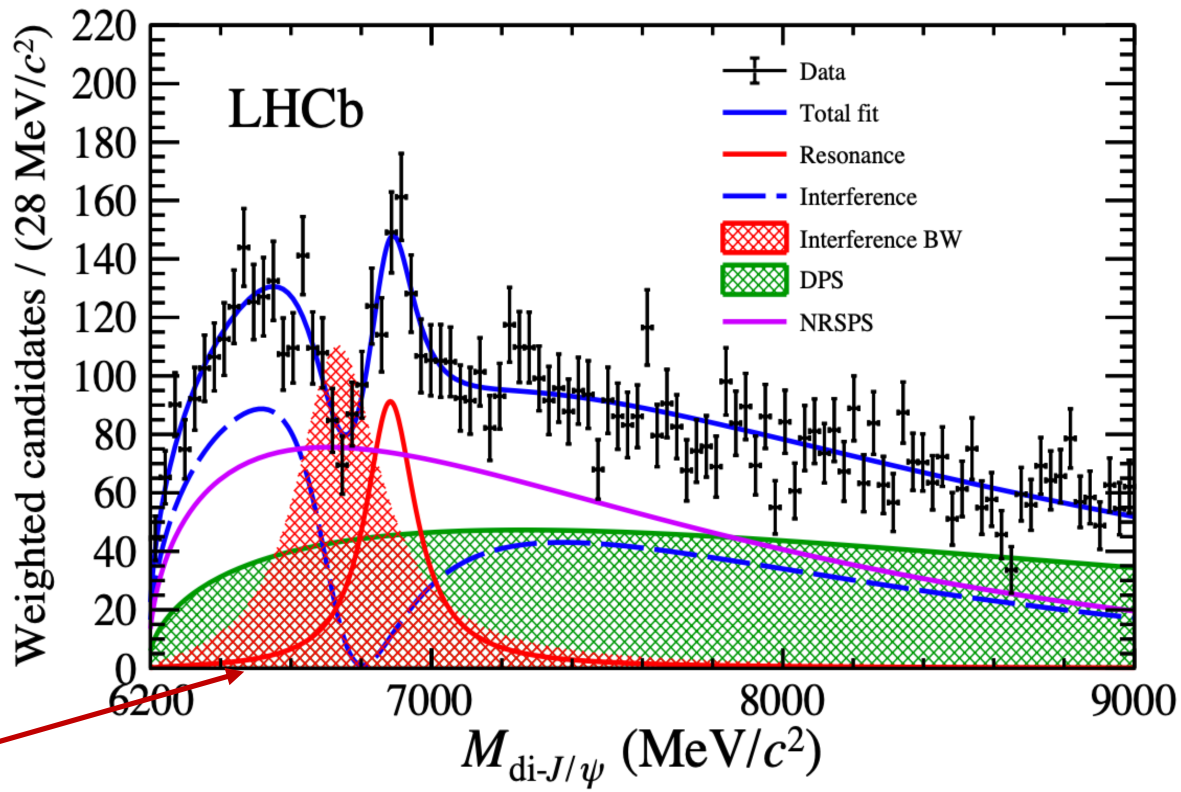
Fit with resonant structure: modeling II

- A wide BW interfering with SPS, a second BW for 6.9 GeV peak
  - Fit quality improve from $P(\chi^2) = 4.6\%$ to 15.5%
  - Caveat: too simple, SPS assumed to have J^P of the wide BW

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\mathrm{MeV}/c^2$$

$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\mathrm{MeV}$$

$$N[X(6900)] = 784 \pm 148$$



Wide BW

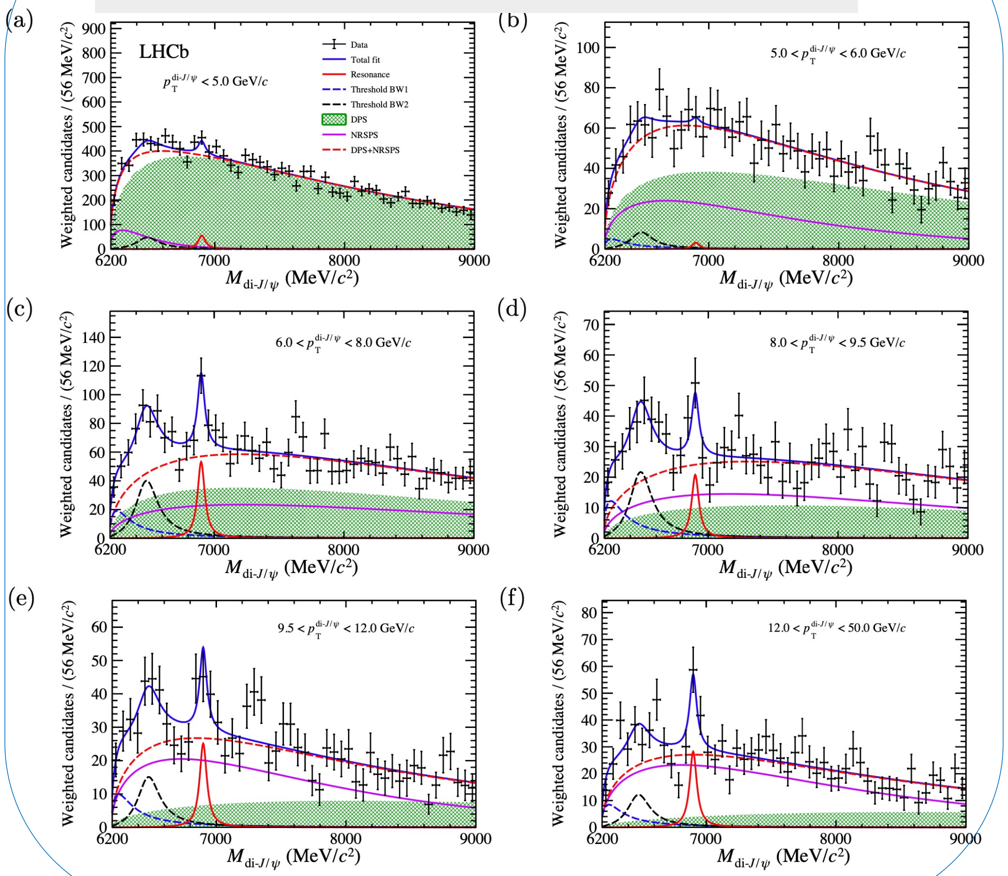
$m \sim 6750$ MeV

$\Gamma \sim 300$ MeV

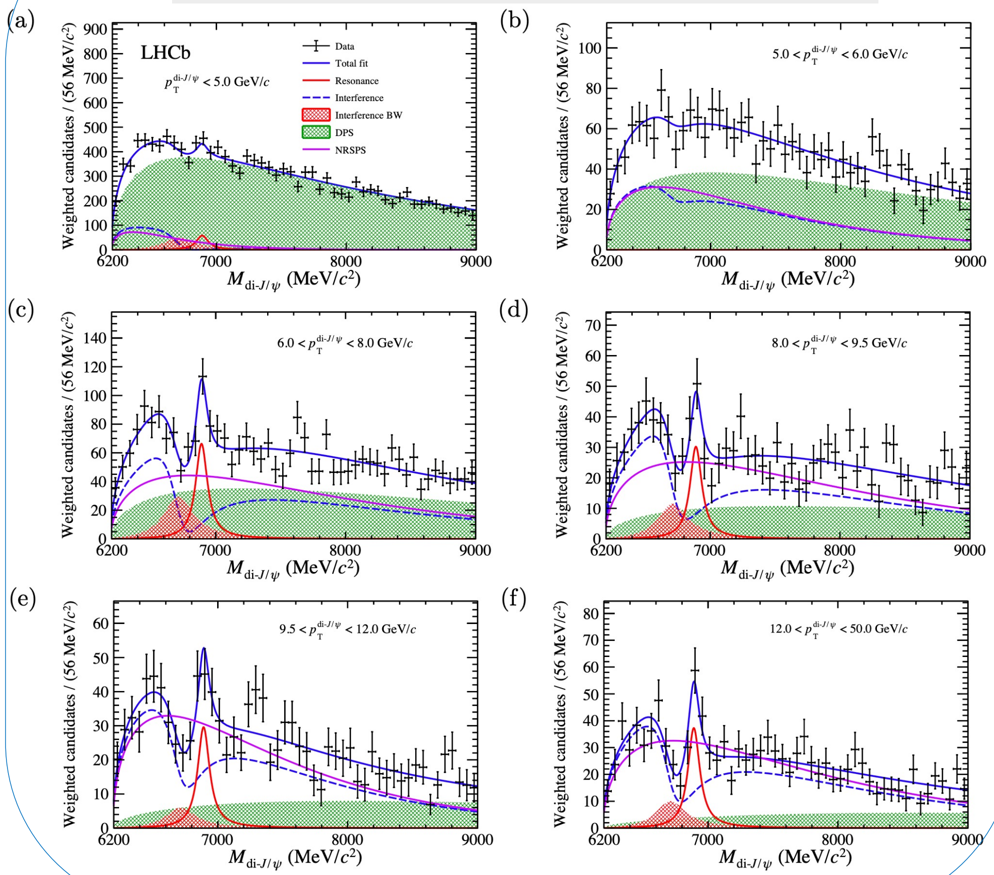
Fits in di-J/ψ p_{T} bins

- Parameters of BW functions shared by all bins
- Mass spectrum well described simultaneously

Model I: Without interference



Model II: With interference



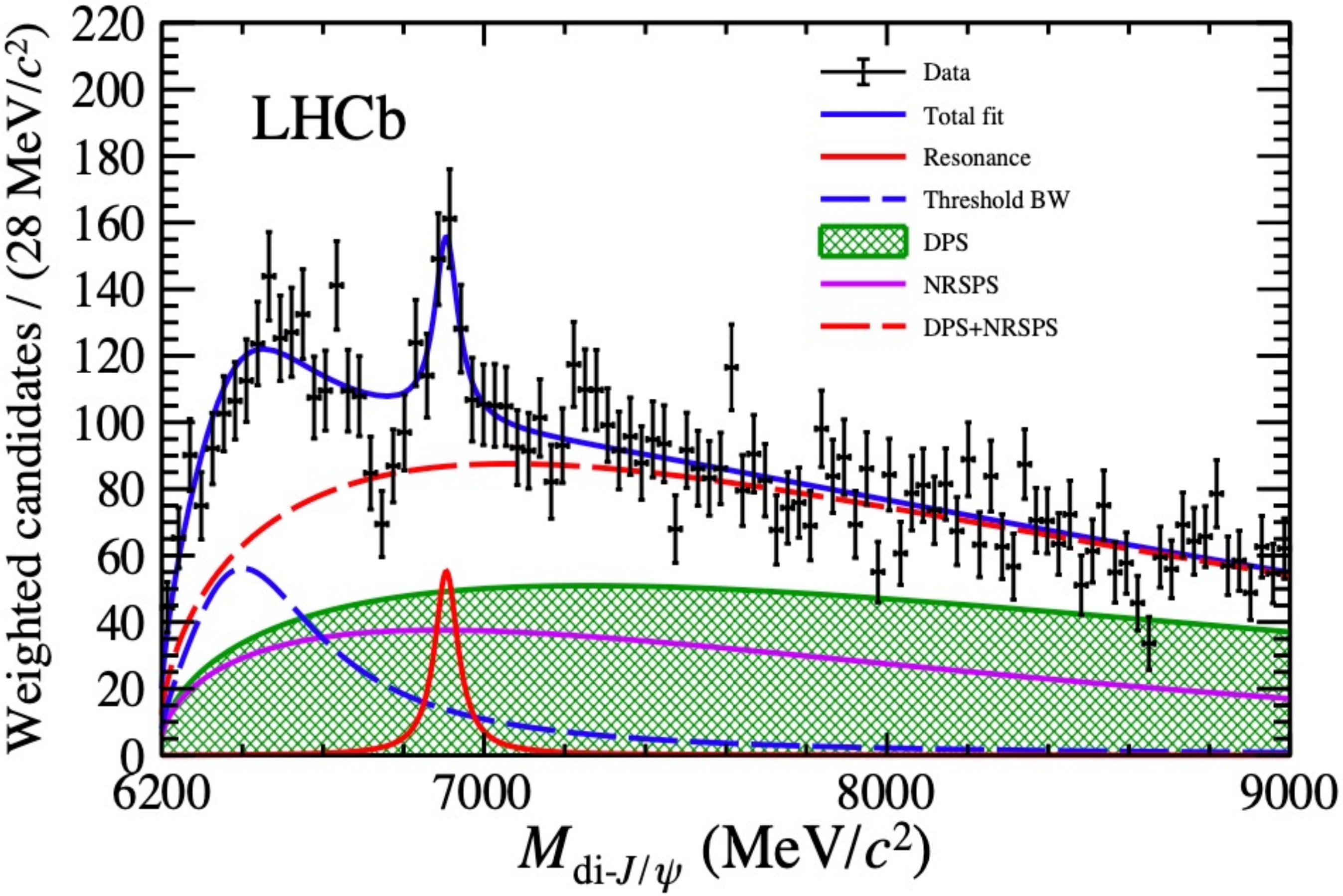
Systematic uncertainties on mass and width

Table 1: Global significance evaluated under the various assumptions described in the text.

	Without interference		With interference	
Component	m [MeV/c^2]	Γ [MeV]	m [MeV/c^2]	Γ [MeV]
sPlot weights	0.8	10.3	4.4	36.9
Experimental resolution	0.0	1.4	0.0	0.6
NRSPS+DPS modelling	0.8	16.1	3.5	9.3
$X(6900)$ shape	0.0	0.3	0.4	0.2
Dependence on $p_{\mathrm{T}}^{\text{di-}J/\psi}$	4.6	13.5	6.2	56.7
b-hadron feed-down	0.0	0.2	0.0	5.3
Structure at $7.2\,\mathrm{GeV}/c^2$	1.3	9.2	6.7	5.2
Threshold structure shape	5.2	20.5	–	–
NRSPS phase	–	–	0.3	1.3
Total	7	33	11	69

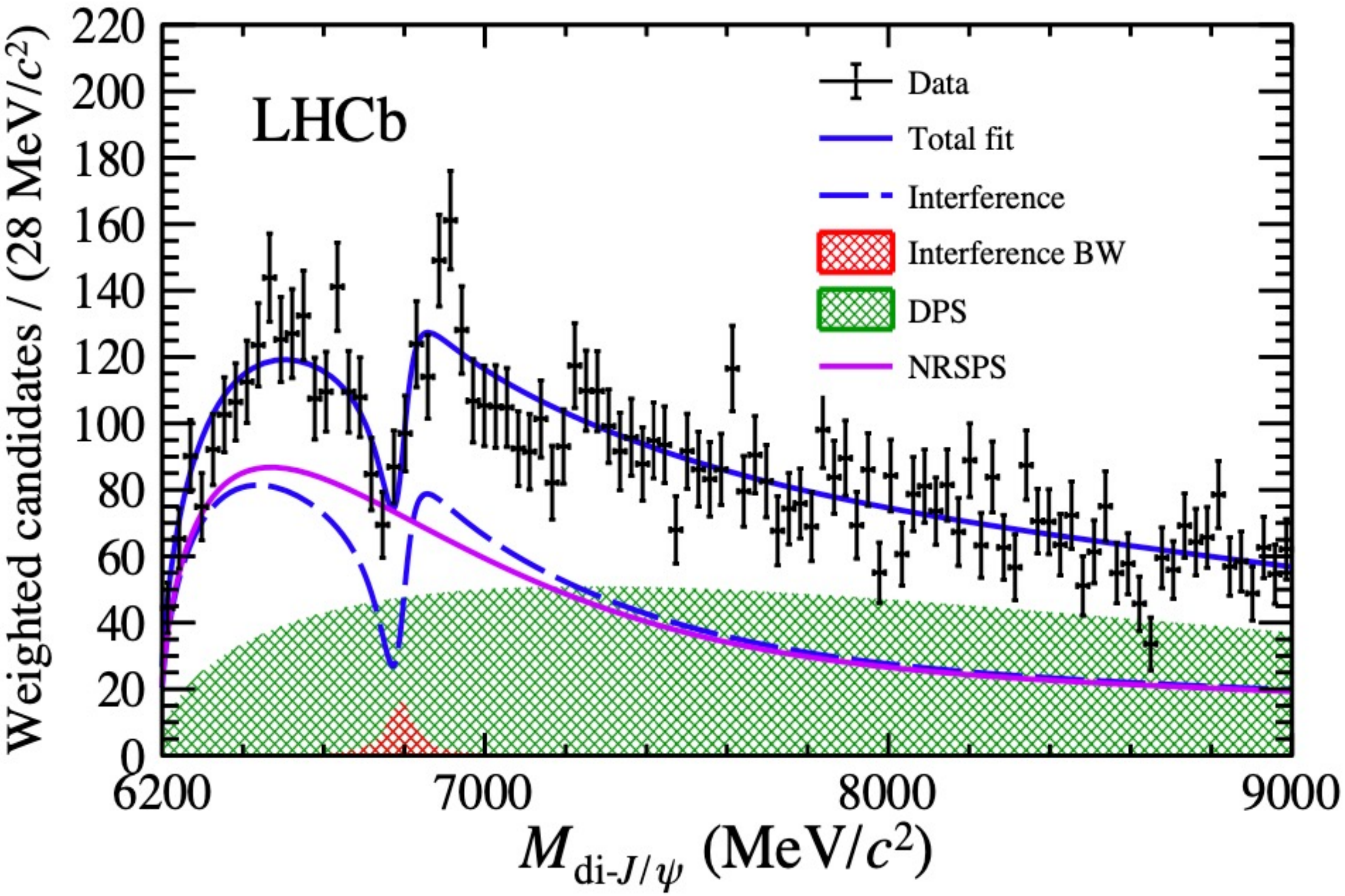
Other models (1)

One BW for threshold structure + X(6900), $P(\chi^2) = 1.2\%$



Other models (2)

Only one BW, interfering with SPS, $P(\chi^2) = 2.8\%$



Other models (3)

Threshold bump due to feed-down decays of excited charmonia

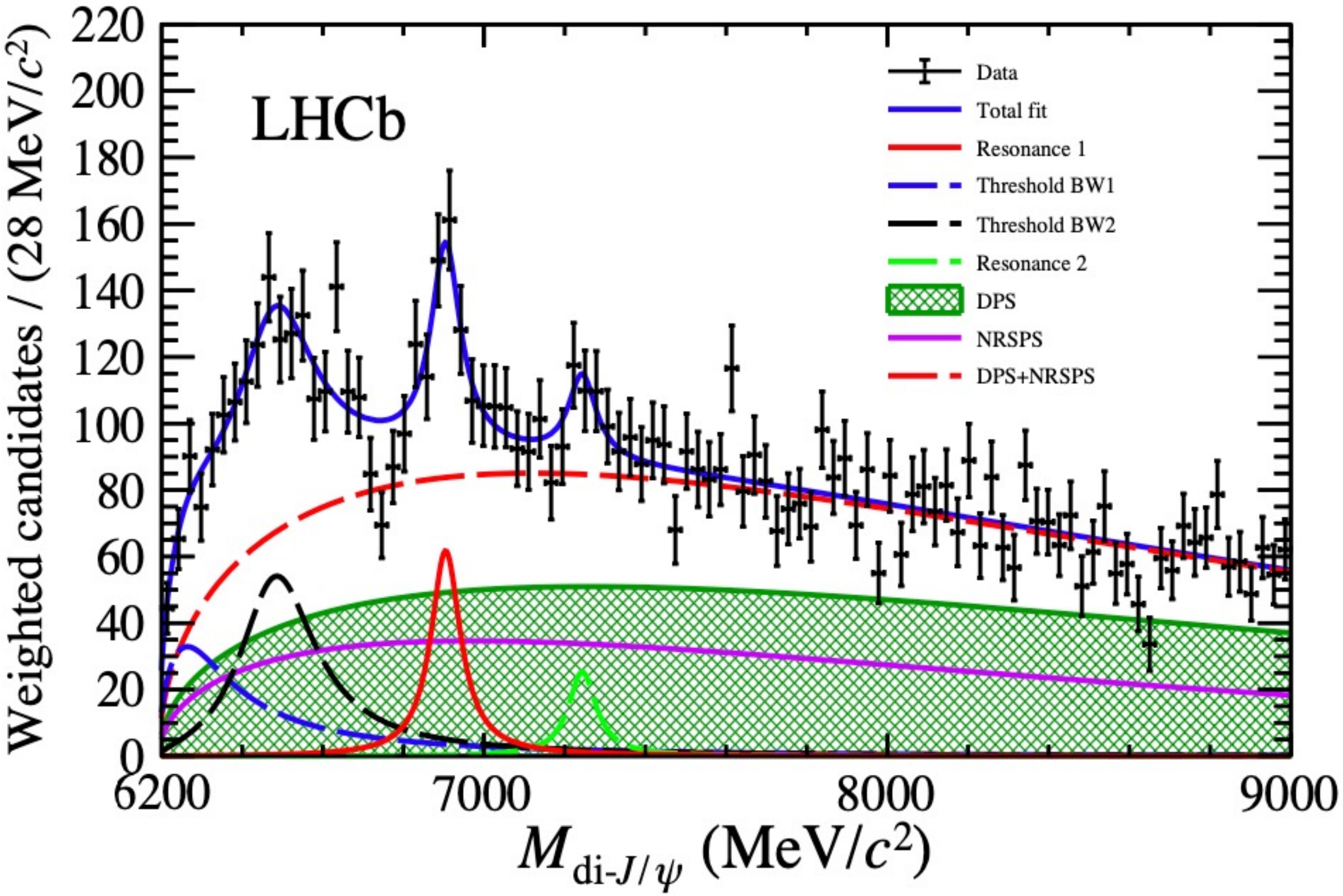
e.g. $X \to J/\psi\ \chi_c$

$\hookrightarrow J/\psi\ \cancel{\gamma}$

Other models (4)

Including structure at 7.2 GeV: significance < 3 σ

$$m \sim 7250 \text{ MeV}, \ \Gamma \sim 100 \text{ MeV}$$



Distribution of $X(6900)$ p_{T}

SPS continuum and $X(6900)$ have similar p_{T} distribution

Production of $X(6900)$

$$R \equiv \frac{\sigma_{X(6900)} \times \mathcal{B}[X(6900) \to J/\psi J/\psi]}{\sigma_{J/\psi J/\psi}} = [1.1 \pm 0.4 \pm 0.3]\%$$

or $[2.6 \pm 0.6 \pm 0.8]\%$ for $p_{\mathrm{T}} > 5.2$ GeV

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Using $\sigma_{J/\psi J/\psi}(\text{LHCb}) = 15.2 \pm 1.0 \pm 0.9$ nb at $\sqrt{s} = 13$ TeV,

$$\sigma_{X(6900)} \times \mathcal{B}[X(6900) \to J/\psi J/\psi](\text{LHCb}) = 167 \pm 77 \text{ pb in } pp \text{ at } 13 \text{ TeV}$$

Summary

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- First observation of fully heavy tetraquark candidate $X(6900)$

  New name: $T_{\psi\psi}(6900)$, Exotic hadron naming convention, arXiv:2206.15233

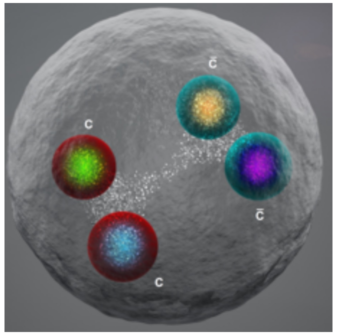
Assuming interference:

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV}$$

Assuming no interference:

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\mathrm{MeV}/c^2$$
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\mathrm{MeV}$$

$\sigma_{X(6900)} \times \mathcal{B}[X(6900) \to J/\psi J/\psi] = 167 \pm 77$ pb within LHCb



- Threshold structure: a few possible interpretations
  - One BW, combination of two BWs, feed-down

Prospects

- Analysis with Run1+2 data

  $J/\psi + \Upsilon, J/\psi + \psi(2S), J^P$ determination (?)…
- Combined analysis with ATLAS, CMS?
- Run3 in operation, statistics increased by $\times 4$

Run 3

Slides by Mike Lamont in ICHEP2022

Proton-proton

- 6.8 TeV
- Levelled to a maximum luminosity 2.05×10^{34} cm^{-2}s^{-1} in ATLAS and CMS
- Levelled to a target of ~1.4×10^{31} cm^{-2}s^{-1} and 2×10^{33} cm^{-2}s^{-1} in ALICE and LHCb respectively
- **~1.8×10^{11} protons/bunch in 2023 – 2025 - long levelling times!**

Mode	ATLAS/CMS	LHCb	ALICE
proton-proton	250 - 270 fb^{-1}	25 – 30 fb^{-1}	200 pb^{-1}
lead-lead	7 nb^{-1}	1 nb^{-1}	7 nb^{-1}
proton-lead	0.5 pb^{-1}	0.1 pb^{-1}	0.25 pb^{-1}
oxygen-oxygen	0.5 nb^{-1}	0.5 nb^{-1}	0.5 nb^{-1}
proton-oxygen	LHCf 1.5 nb^{-1}	2.0 nb^{-1}	

Special run type	Experiment
VdM scans, etc.	all
Low-PU (<0.02) pp	LHCf
High β*(90m) pp	TOTEM
High β*(3/6km) pp	TOTEM, ATLAS
p-He(SMOG) @ 450 GeV	LHCb

Backup slides

Signal stability

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- Combinatorial backgrounds show smooth J/ψ-pair mass distribution
- Structures are stable with respect to different data-taking periods
- Residual backgrounds with multiple use of muon track produce no such structure
- Residual contamination from b-hadron decays has a smooth distribution
- Variation of detection efficiency with respect to mass is marginal
- Contribution from partially reconstructed $\Upsilon \to J/\psi X$ decays is expected to be negligibly small