HADRON 2023

20th International Conference on
Hadron Spectroscopy and Structure
5-9 Jun. 2023

Studies of four-charm-quark states at LHCb

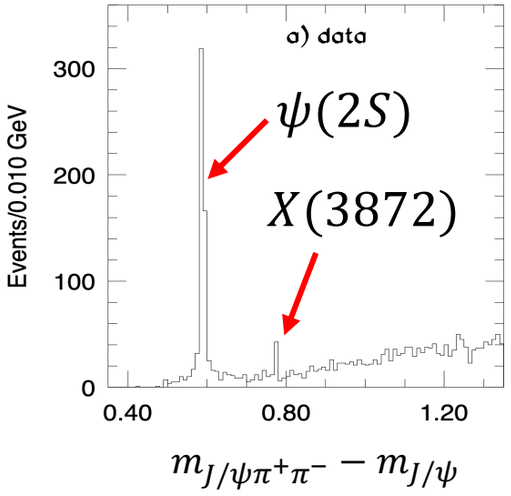
Yanxi ZHANG
on behalf of LHCb
Peking University, Beijing, China

7/Jun/2023

From one to a zoo

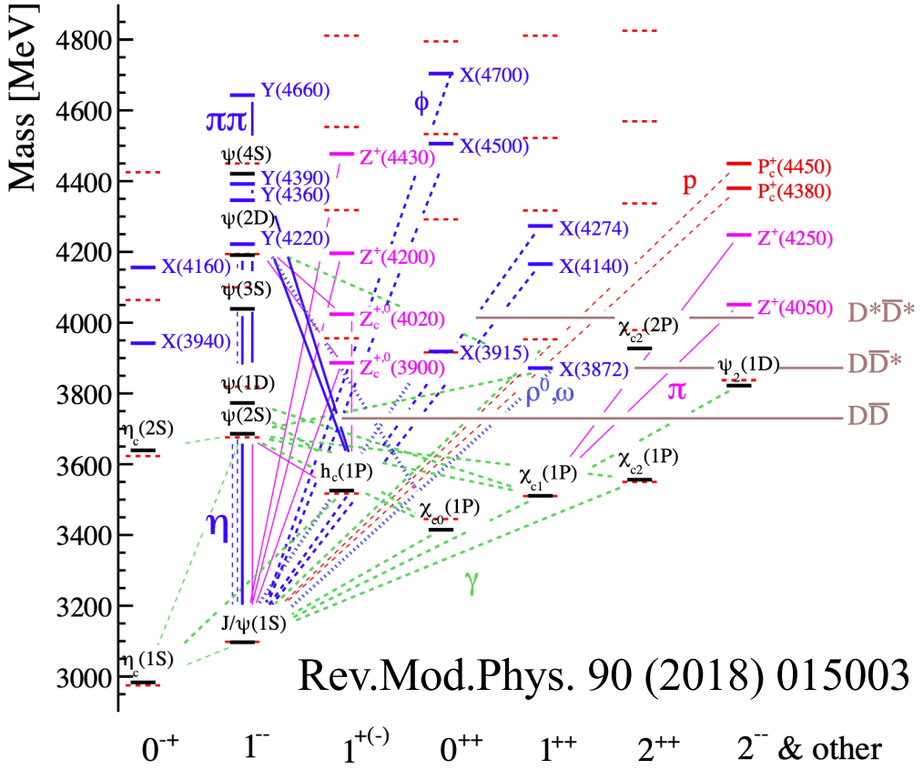
$X(3872)$ discovered in 2003

Narrow width, close to $D^{*0}D^{0}$ threshold, isospin breaking decay …



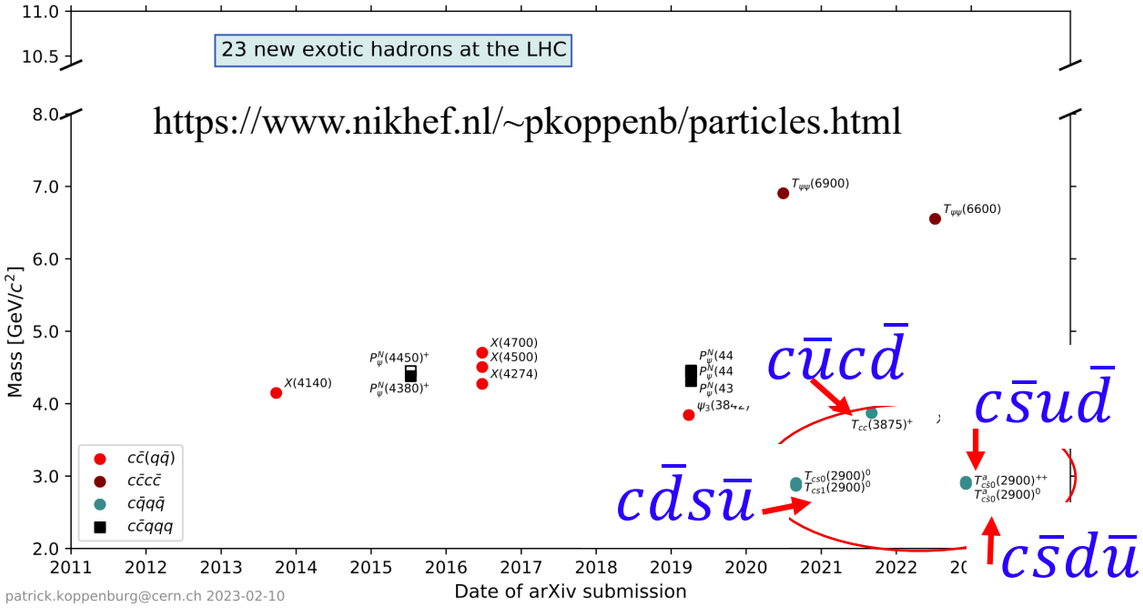
Belle
PRL91(2003)262001

Many more appeared containing $Q\bar{Q}$



Rev.Mod.Phys. 90 (2018) 015003

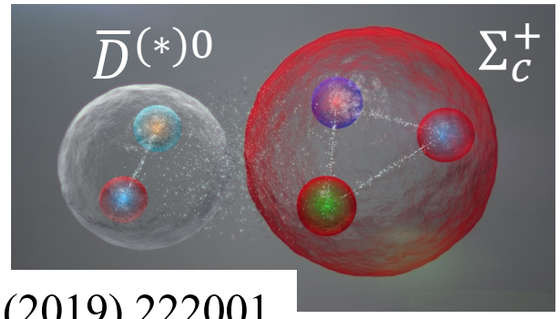
and with open charm



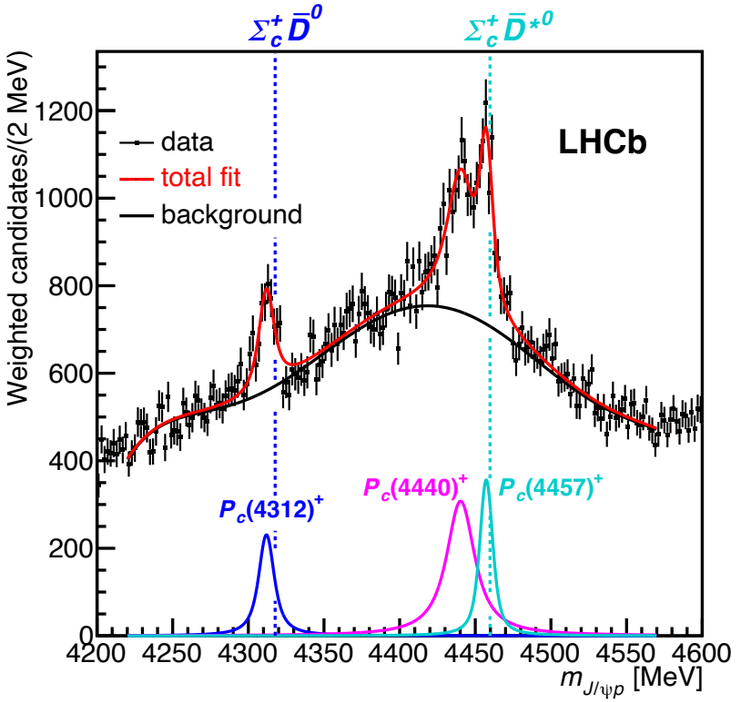
Ongoing studies/debates on internal structures

Hadron molecules: bound by nuclear force

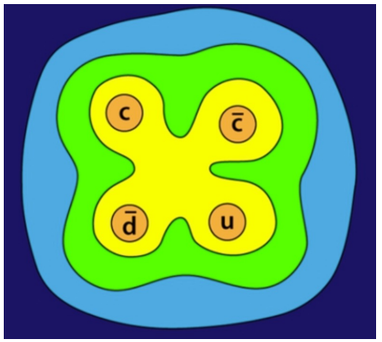
Mass close to di-hadron threshold in S-wave



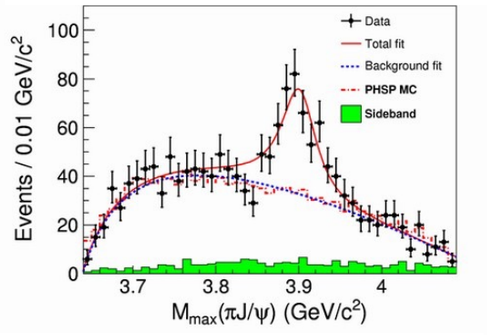
PRL 122 (2019) 222001



Compact tetraquarks: bound by color interaction

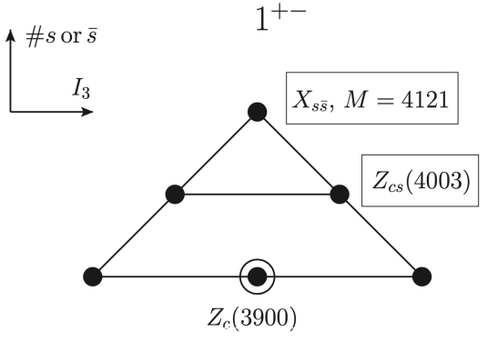


PRL 110 (2013) 252001

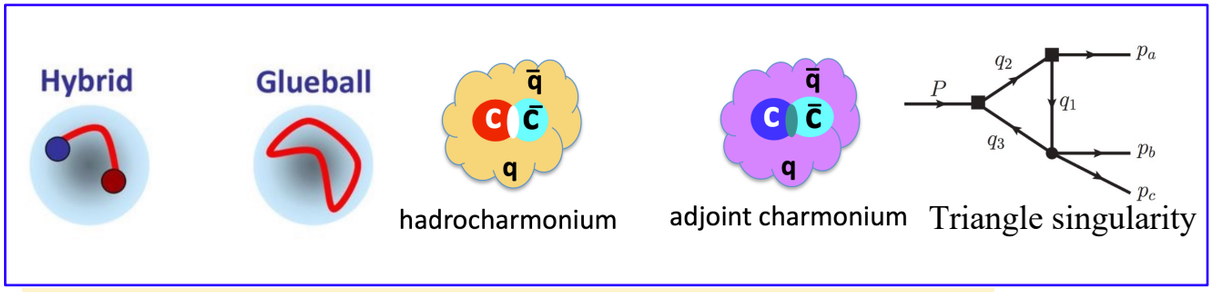


1^{+-}

Sci.Bull.66(2021)1616

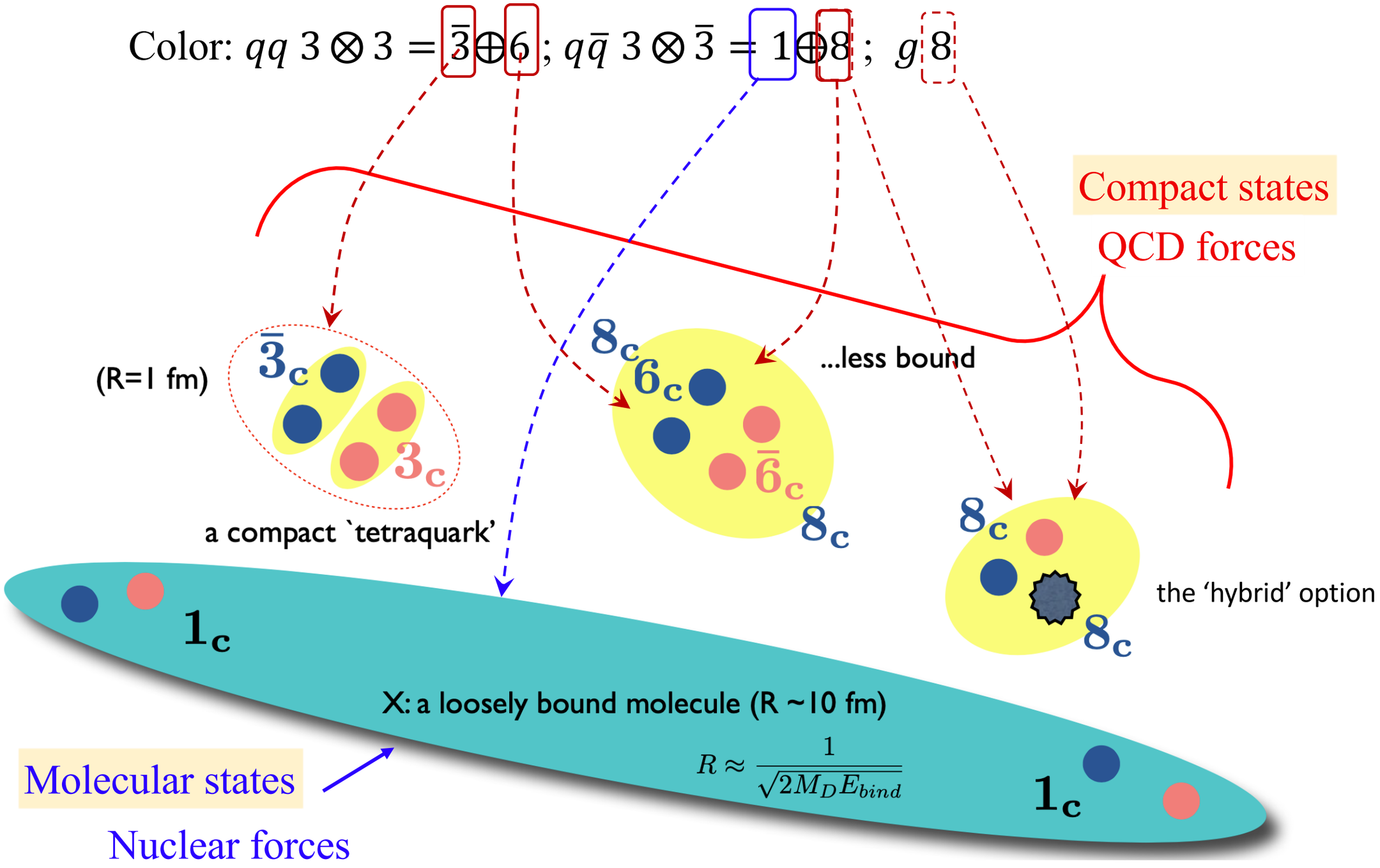


Other variants:



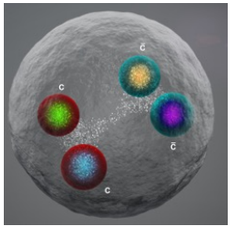
Reviews:
Rev.Mod.Phys.90 (2018)015003
Rev.Mod.Phys.90(2018)015004
Prog.Part.Nucl.Phys.107(2019)237

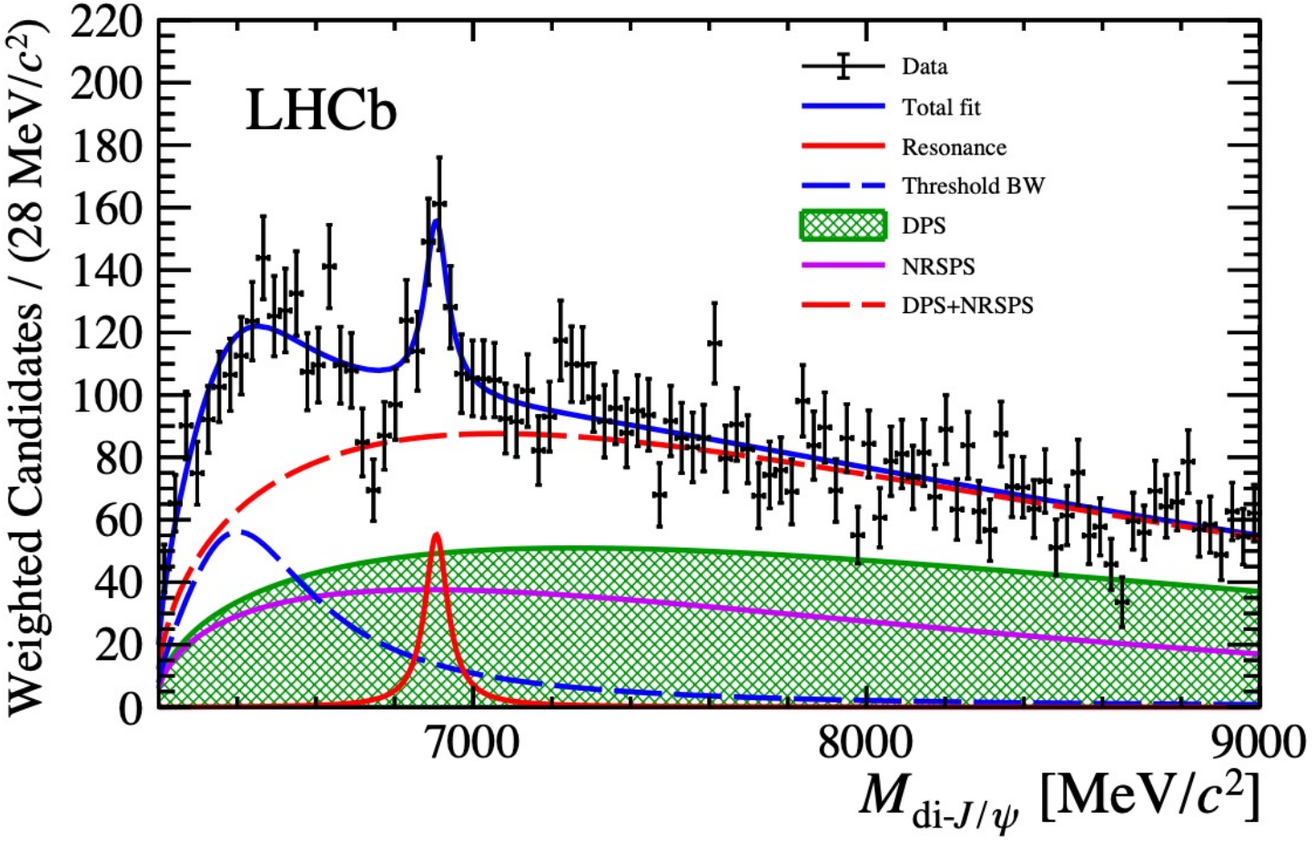
Color structure



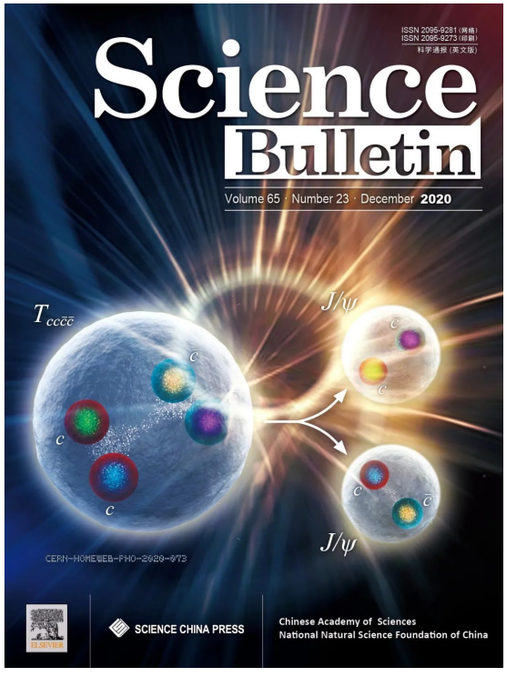
Observation of four-charm tetraquark state

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





Science Bulletin 65 (2020) 1983



- ✓ Broad structure close to di-J/ψ mass threshold
- ✓ Narrow structure around 6900 MeV

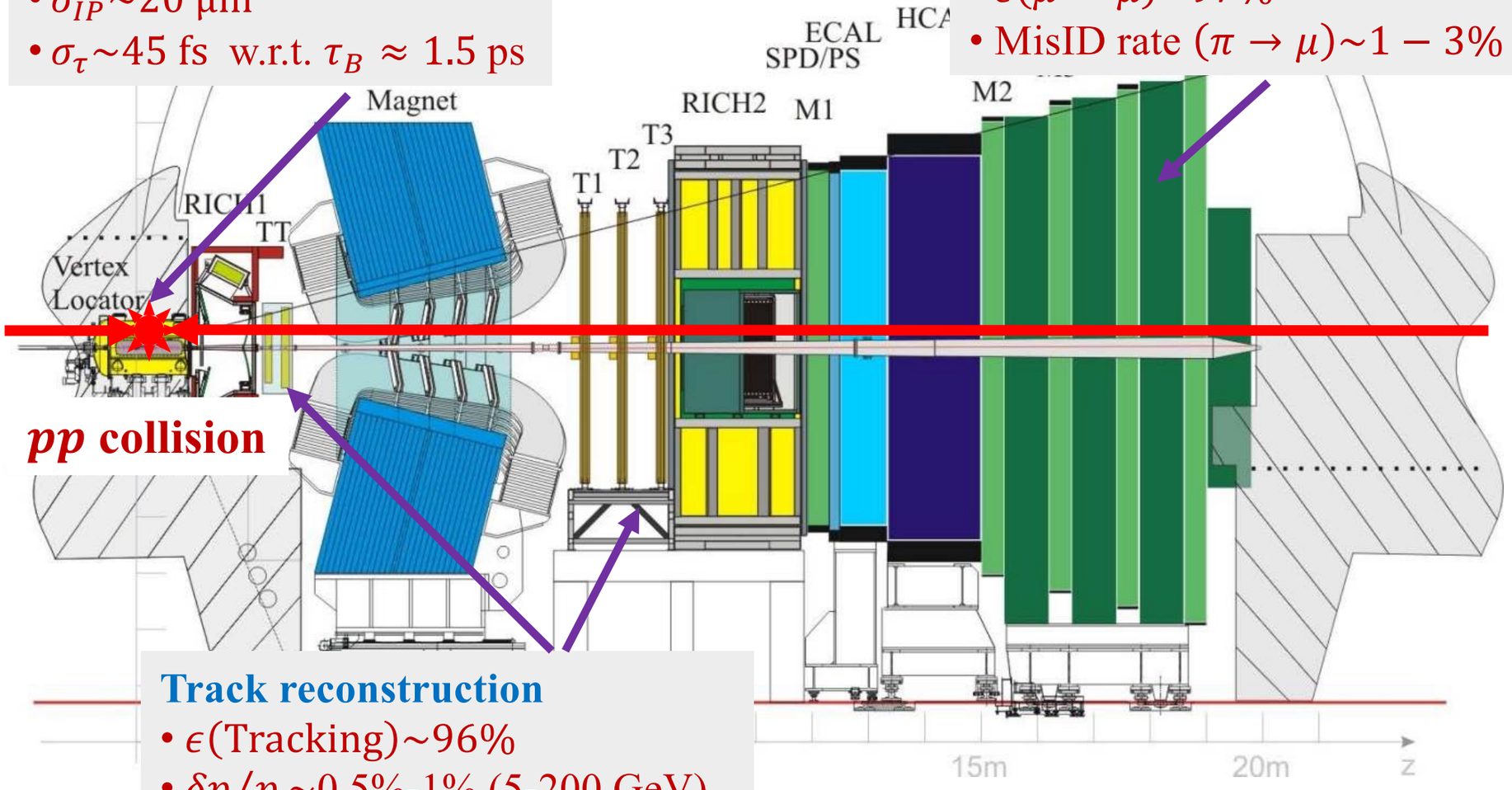
LHCb

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

- Heavy flavor experiment covering $2 < \eta < 5$

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**

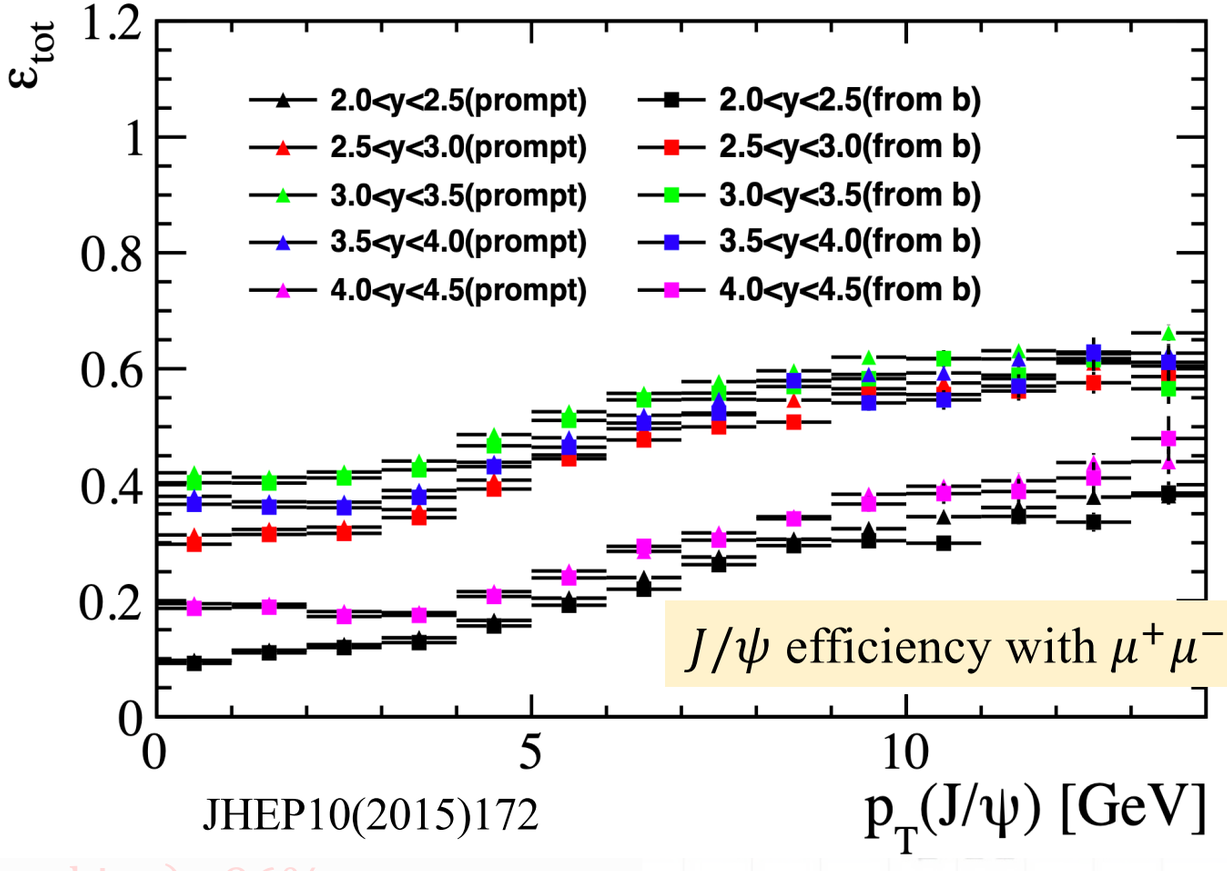
Track reconstruction
- ϵ(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\epsilon(m_{J/\psi}) \approx 15$ MeV

LHCb

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

- Heavy flavor experiment covering $2 < \eta < 5$

Efficient to detect J/ψ down to zero-p_T



JHEP10(2015)172

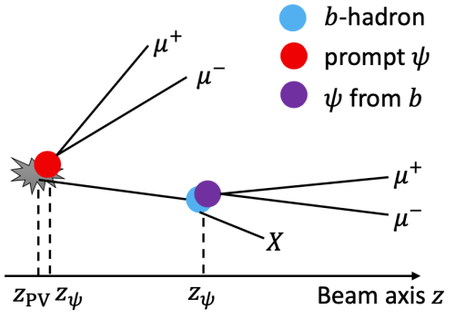
J/ψ efficiency with $\mu^+\mu^-$ decay

Di-J/ψ sample at LHCb

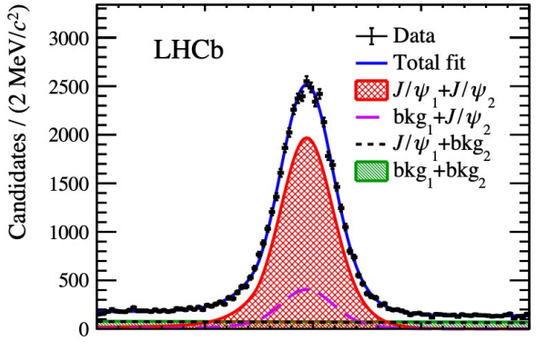
Science Bulletin 65 (2020) 1983

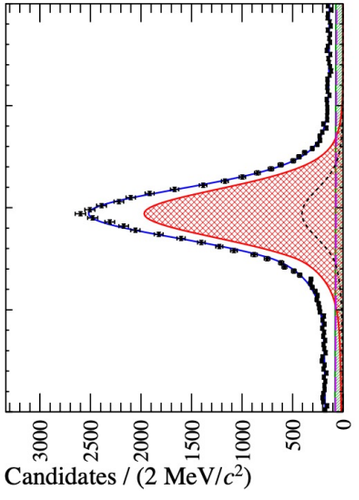
- Full LHCb Run1 ($\sqrt{s} = 7, 8$ TeV, 3 fb^{-1}) and Run2 data ($\sqrt{s} = 13$ TeV, 6 fb^{-1})

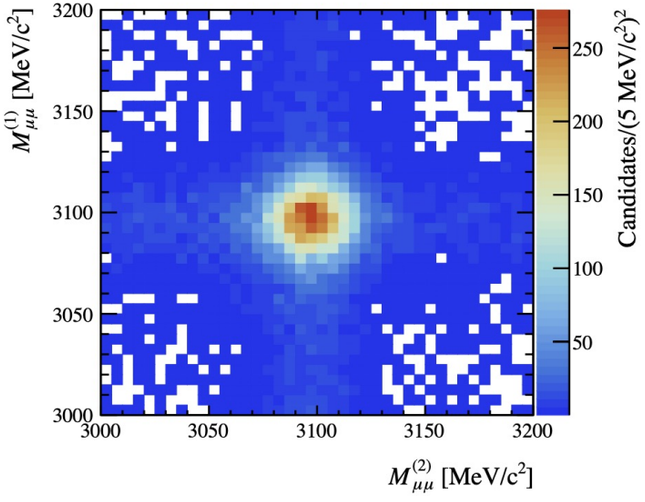
J/ψ-from-b background suppressed using vertexing information



About 34K di-J/ψ signals



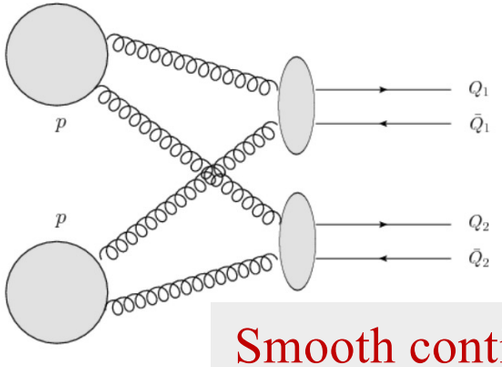




Two production processes

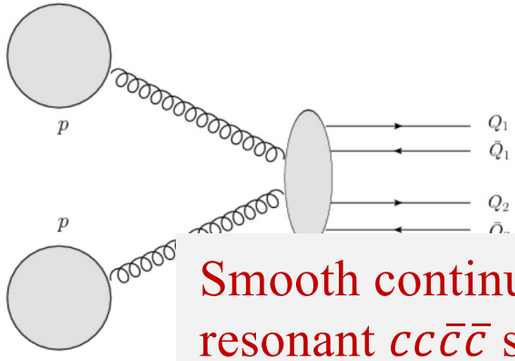
JHEP 06 (2017) 047

Double Parton Scattering (DPS)



Smooth continuum

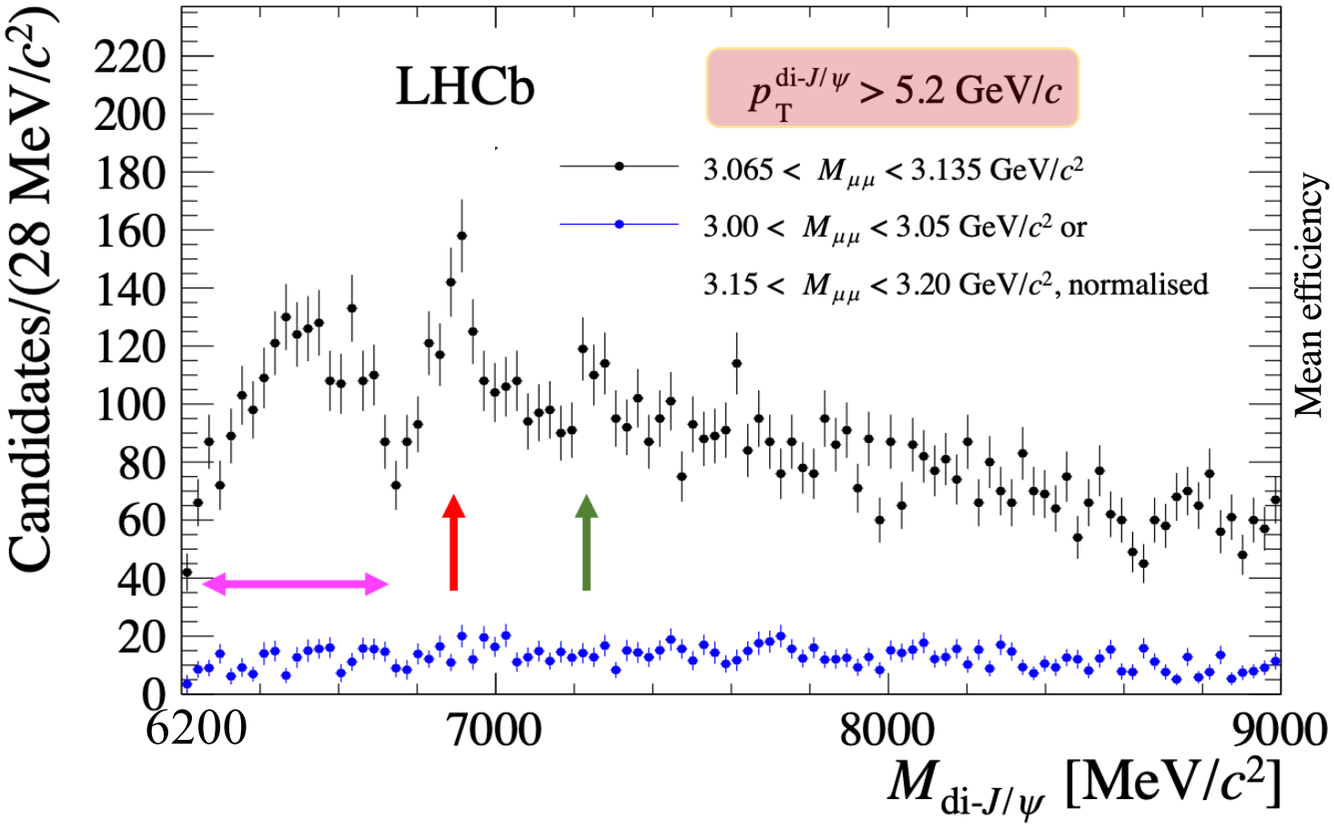
Single Parton Scattering (SPS)

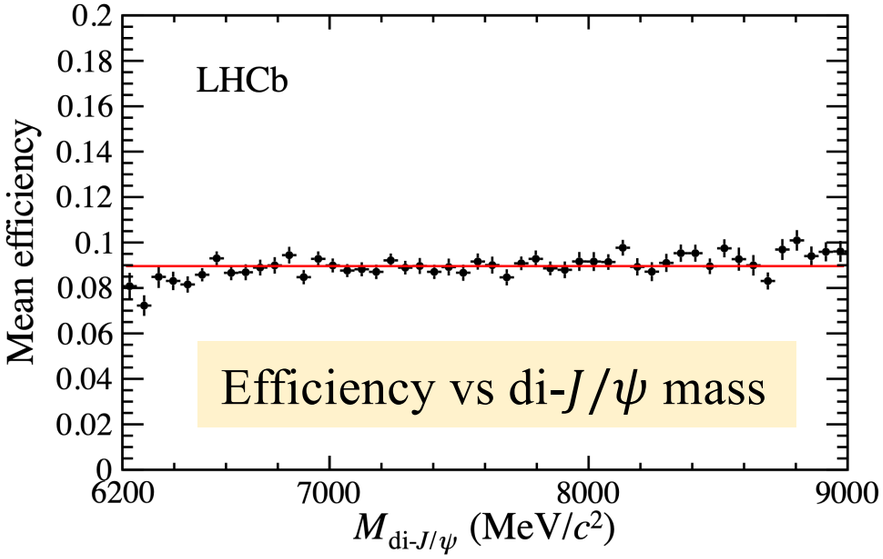


Smooth continuum and resonant $cc\bar{c}\bar{c}$ structures. Averagely large p_T

Di-J/ψ invariant mass (I)

Science Bulletin 65 (2020) 1983





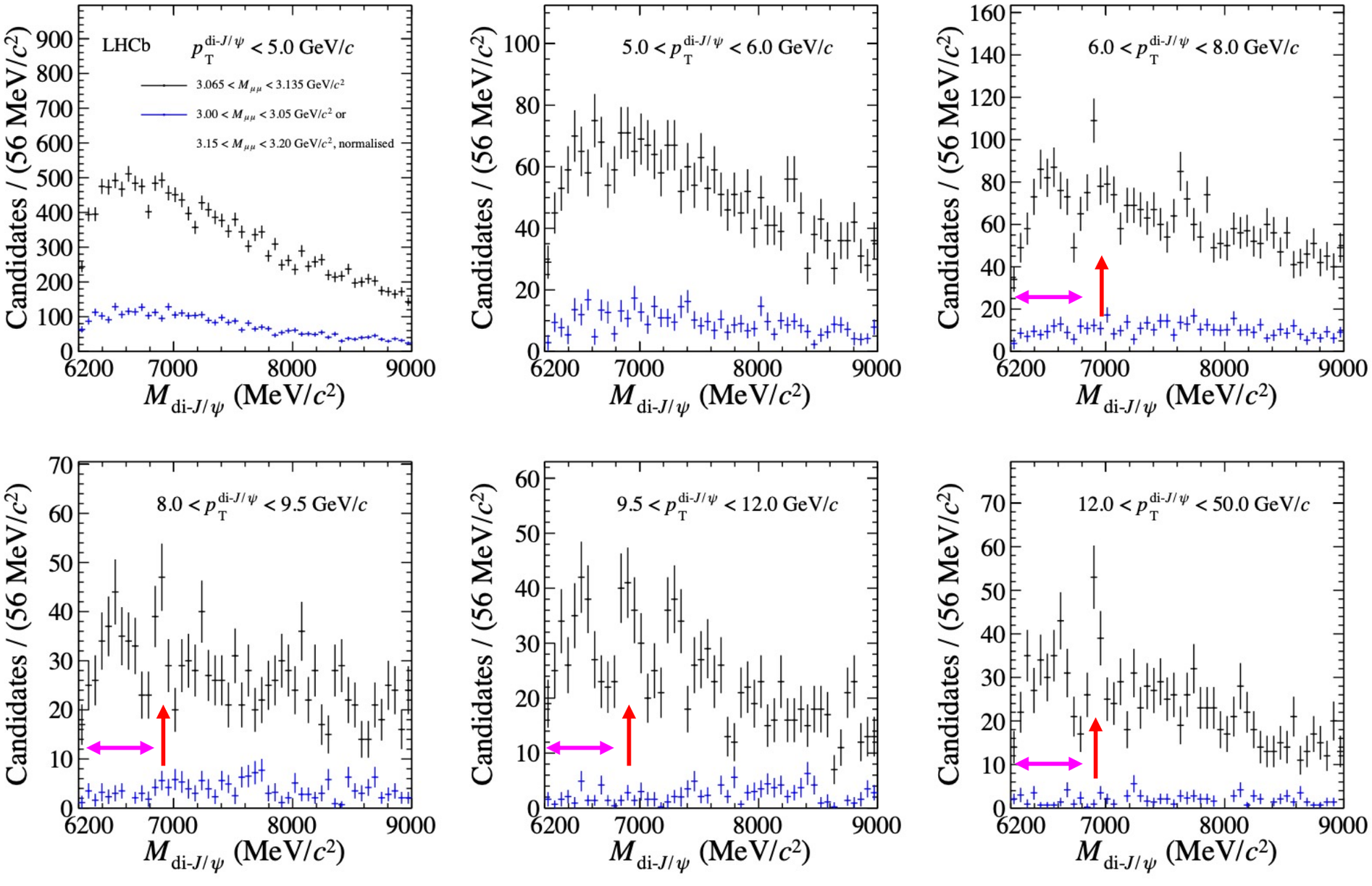
- Broad structure at $6.2 - 6.8$ GeV close to di-J/ψ mass threshold
- Narrow peak at 6.9 GeV
- Hint of another structure at 7.2 GeV
- Structure not present in J/ψ background sample

Only marginal variation of efficiency in mass spectrum

Di-J/ψ invariant mass (II)

Science Bulletin 65 (2020) 1983

- Same structures in all high di-J/ψ p_{T} bins, evidence increasing with p_{T}



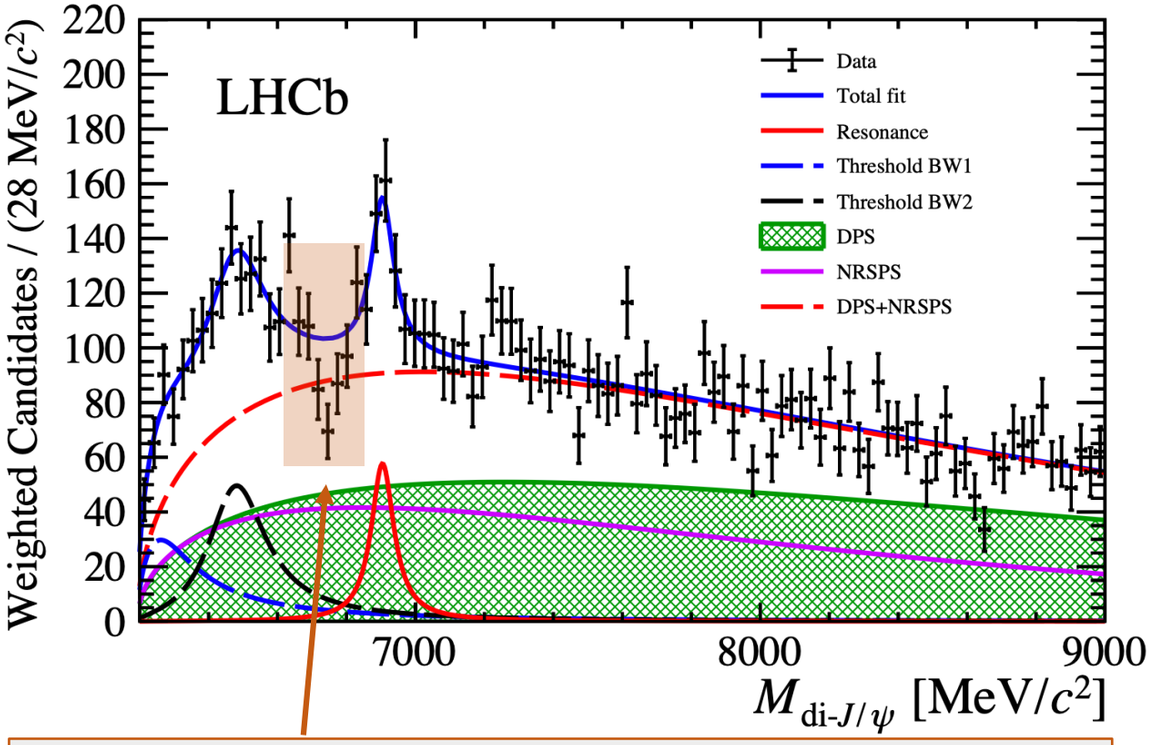
Di-J/ψ mass modeling: without interference

- Model components

Science Bulletin 65 (2020) 1983

  - DPS: constructed using single-J/ψ kinematics
  - SPS continuum: two-body phase space times smooth exponential
  - Threshold structure: two Breit-Wigner (BW) functions, significance > 6 σ
  - Structure at 6.9 GeV: a single BW, significance > 5 σ

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



χ^2 fit quality
$P(\chi^2) = 4.6\%$

Difficulty to model the dip at 6.8 GeV !

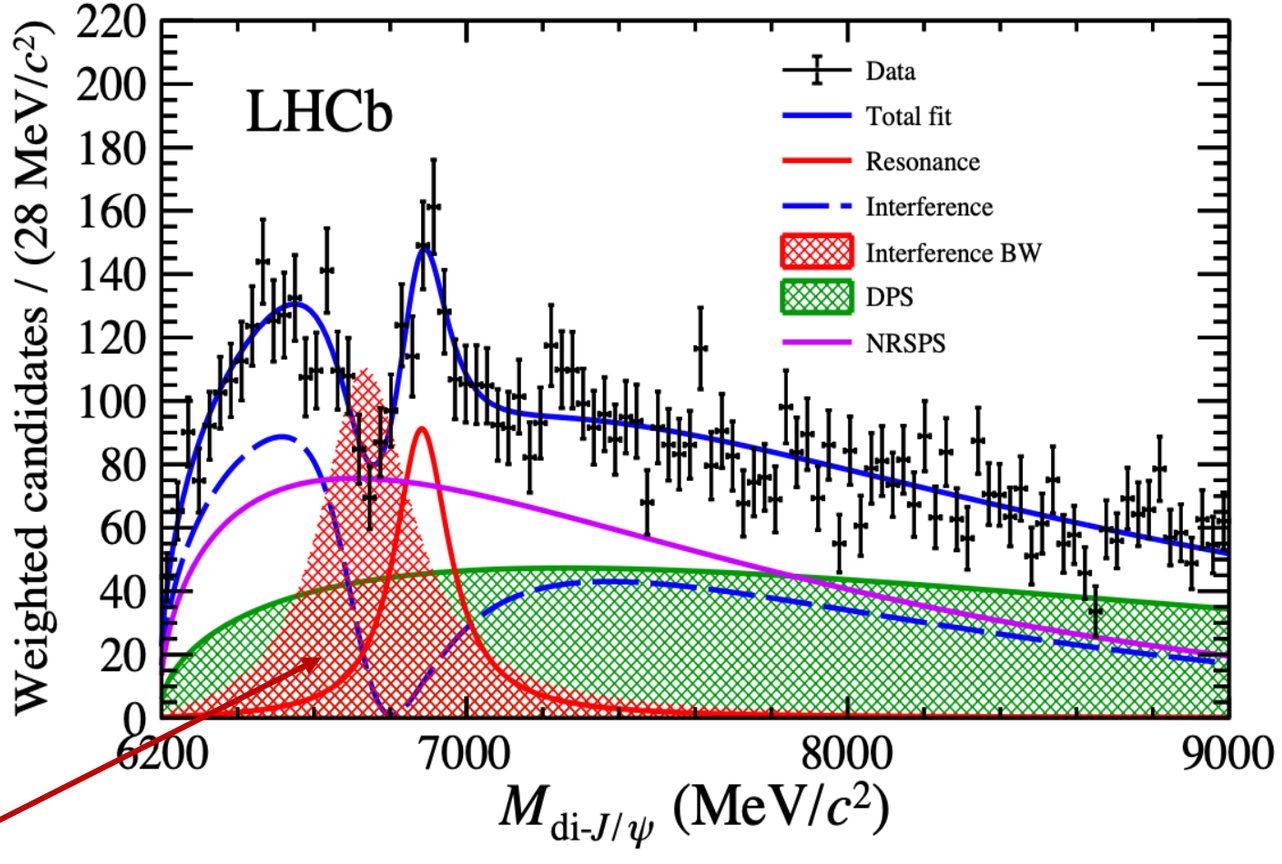
Di-J/ψ mass modeling: with interference

- A wide BW interfering with SPS, a second BW for 6.9 GeV peak

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

  - Overall good fit with dip well described, $P(\chi^2)$ increases to 15.5%
  - Caveat: too simple, SPS assumed to have J^P of the wide BW

Science Bulletin 65 (2020) 1983



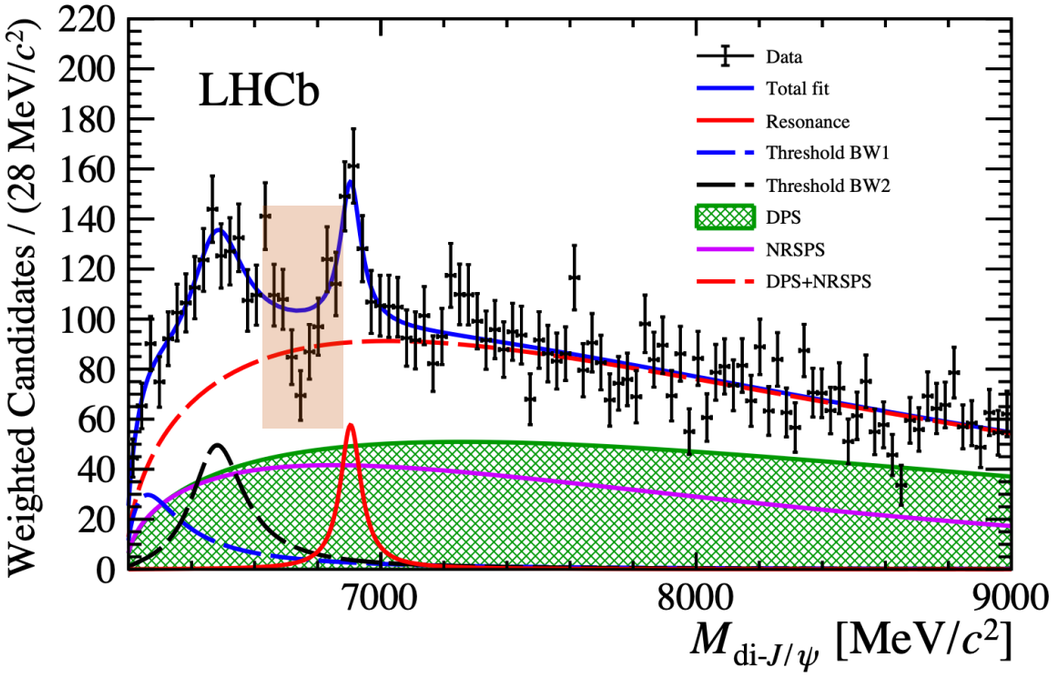
Wide BW

$m = 6741\ \mathrm{MeV}/c^2$
$\Gamma = 288\ \mathrm{MeV}$

Model comparison

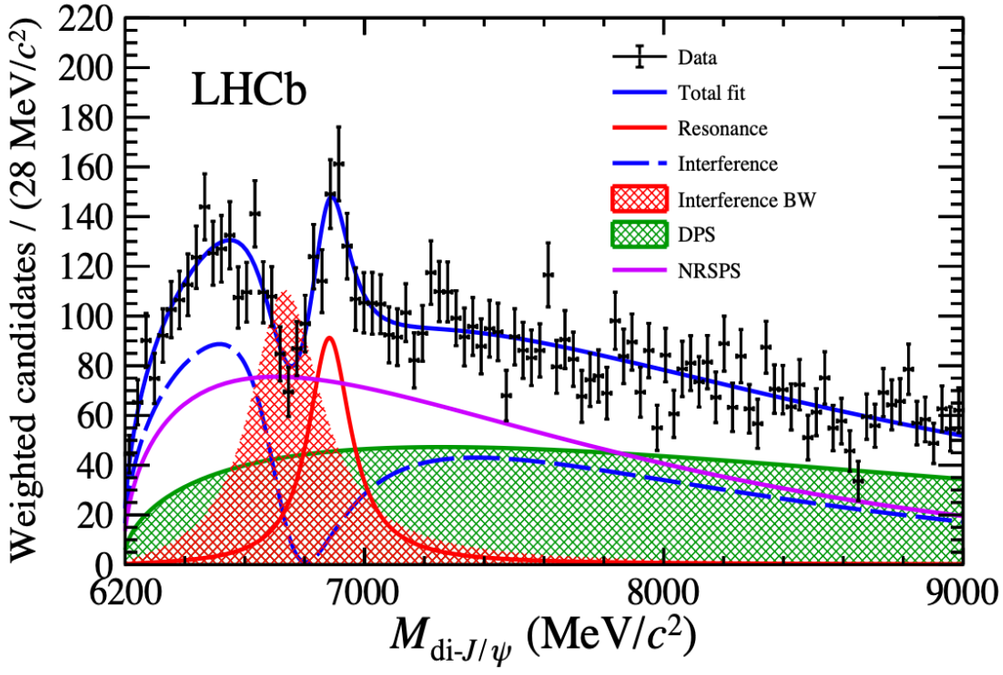
Science Bulletin 65 (2020) 1983

SPS+DPS+2BW(threshold)+BW(6900)



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

|SPS+BW(threshold)|+DPS+BW(6900)



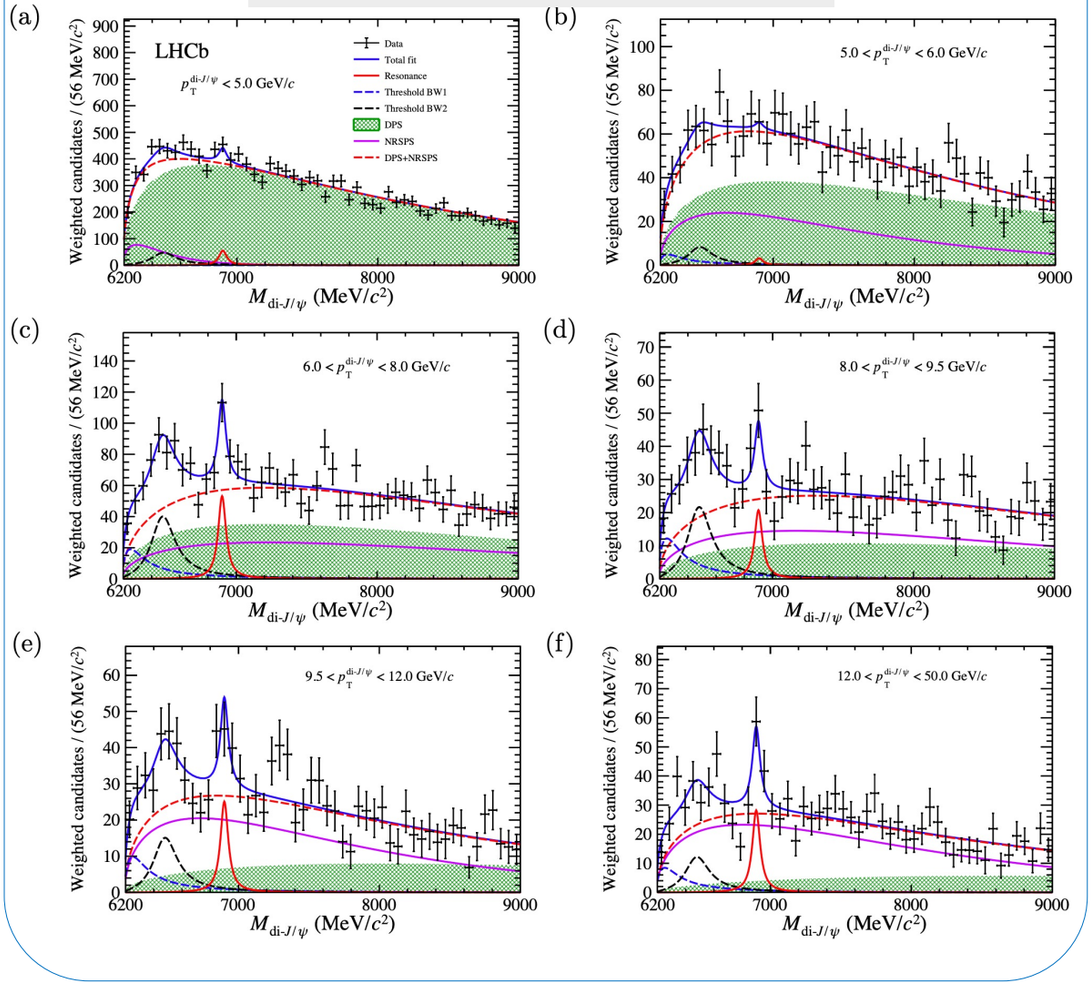
$$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}$$

Fits in di-J/ψ p_{T} bins

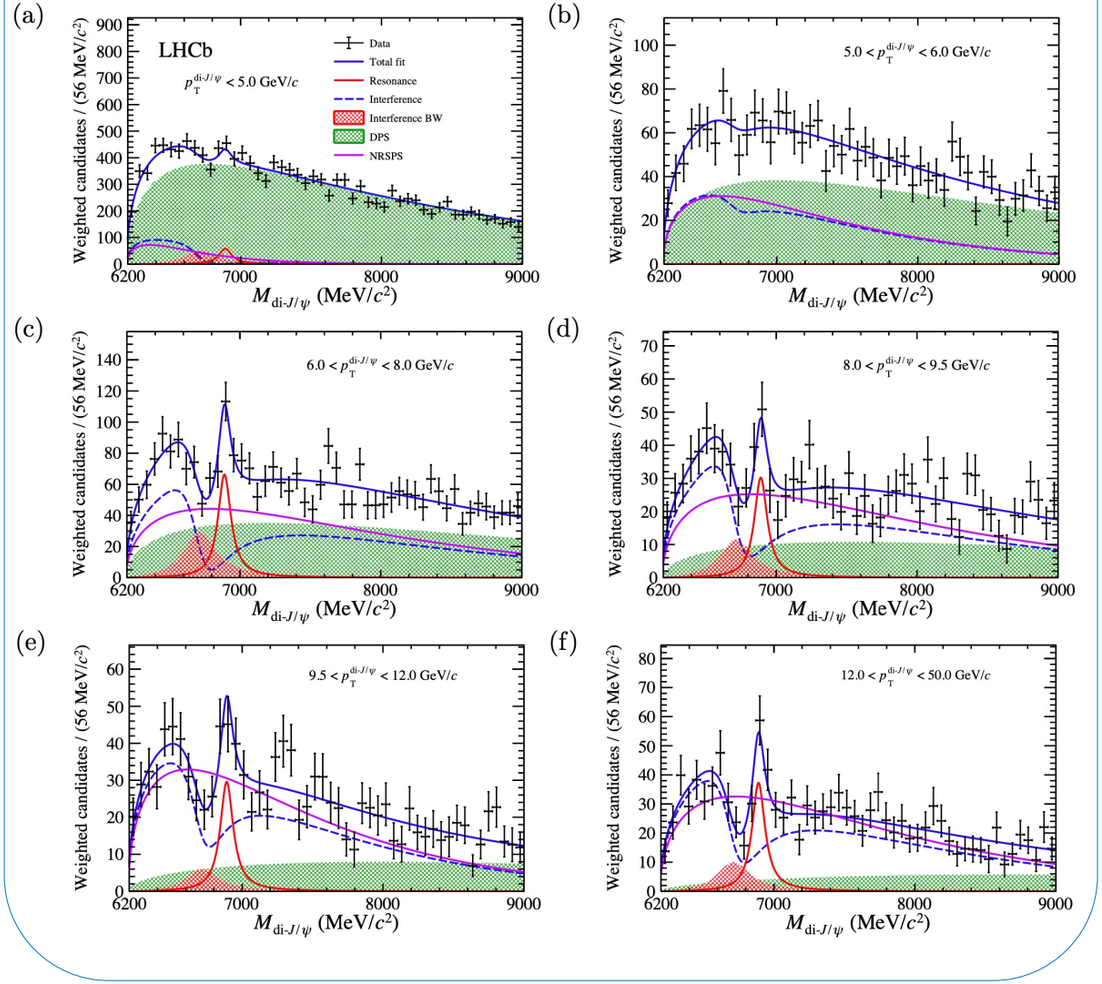
Science Bulletin 65 (2020) 1983

- Parameters of BW functions shared by all bins
- Mass spectrum in different p_{T} bins well described simultaneously

Without interference



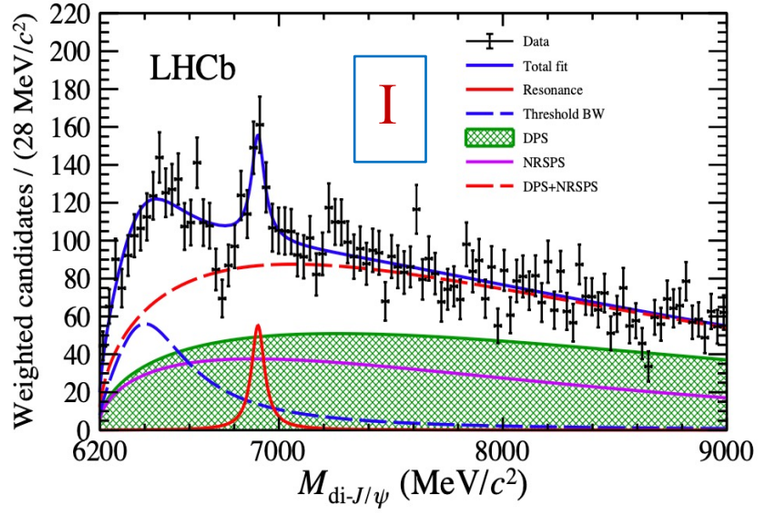
With interference of wide BW and SPS

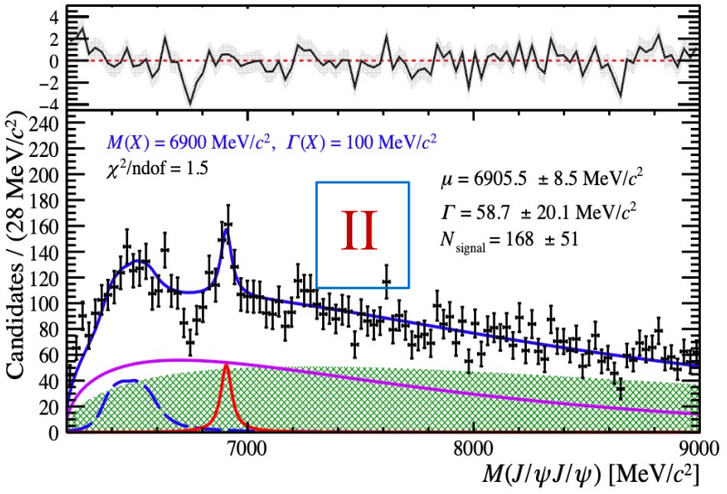


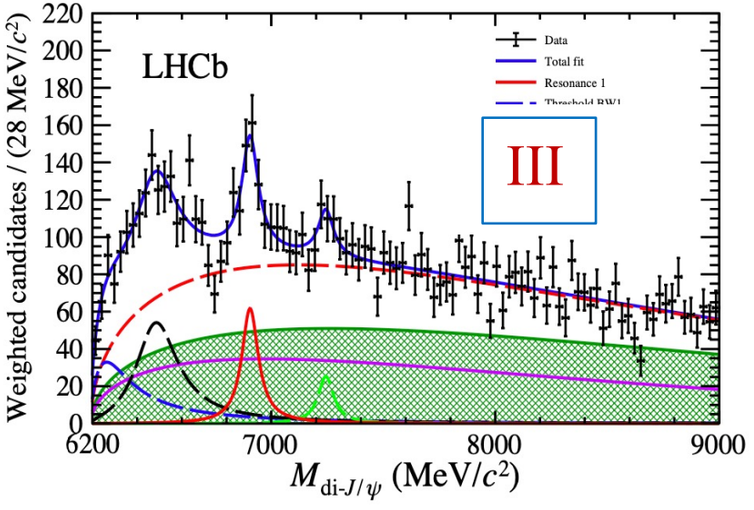
Other models

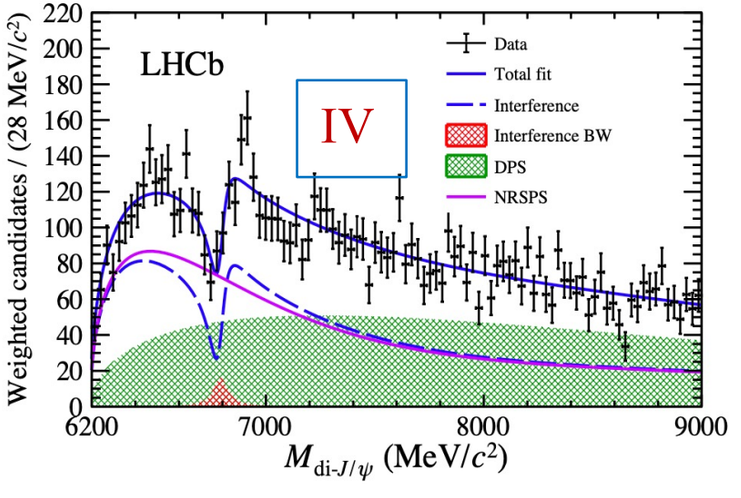
Science Bulletin 65 (2020) 1983

I. Only one BW for threshold structure, $P(\chi^2) = 1.2\%$
II. Threshold structure due to feed-down decays of excited charmonia (e.g. $\chi_c J/\psi$)
III. Including a component for 7.2 GeV peak (significance $< 1\sigma$)
IV. Only one BW, interfering with SPS, $P(\chi^2) = 2.8\%$









Fits summary

Science Bulletin 65 (2020) 1983

- Nontrivial structures in the spectrum
- Structure at threshold: one BW, two BWs or distribution due to feed-down from excited states
- Structure at 6.9 GeV, $X(6900)$: consistent with a BW, shape parameters affected by models for threshold structure
- Evidence of interference between a BW and SPS

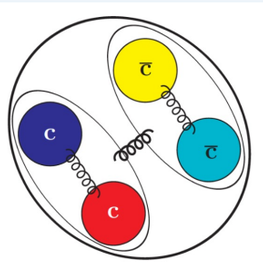
- $X(6900)$ production

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

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

Results under non-interference hypothesis
Measured cross-section approximately scales with relative yields

Interpreted as compact tetraquarks



- $cc\bar{c}\bar{c}$ tetraquarks predicted after charm quark discovery

Y. Iwasaki, *Is a state* $c\bar{c}c\bar{c}$ *found at 6.0 GeV?*, Phys. Rev. Lett. **36** (1976) 1266.

K.-T. Chao, *The* (cc) - $(\bar{c}\bar{c})$ *(diquark-antidiquark) states in* e^+e^- *annihilation*, Z. Phys. C **7** (1981) 317.

- Supported by known properties of the strong interaction

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News & Views

J/ψ-pair resonances by LHCb: a new revolution?

Luciano Maiani [a,b,*]

[a] Dipartimento di Fisica and INFN, Sapienza Università di Roma, Piazzale Aldo Moro 2, I-00185 Roma, Italy
[b] T. D. Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China

That the 6.9 GeV resonance is a hadron molecule or a threshold cusp seems to me rather unlikely possibilities. There are no known color singlet, light particles that may be exchanged between two charmonia to produce binding or final state interactions. What can we say assuming that the resonance(s) seen in Fig. 1 are fully charm tetraquarks?

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News & Views

The possible tetraquark states $cc\bar{c}\bar{c}$ observed by the LHCb experiment

Kuang-Ta Chao [a,b,*], Shi-Lin Zhu [a,b,*]

[a] School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
[b] Center of High Energy Physics, Peking University, Beijing 100871, China

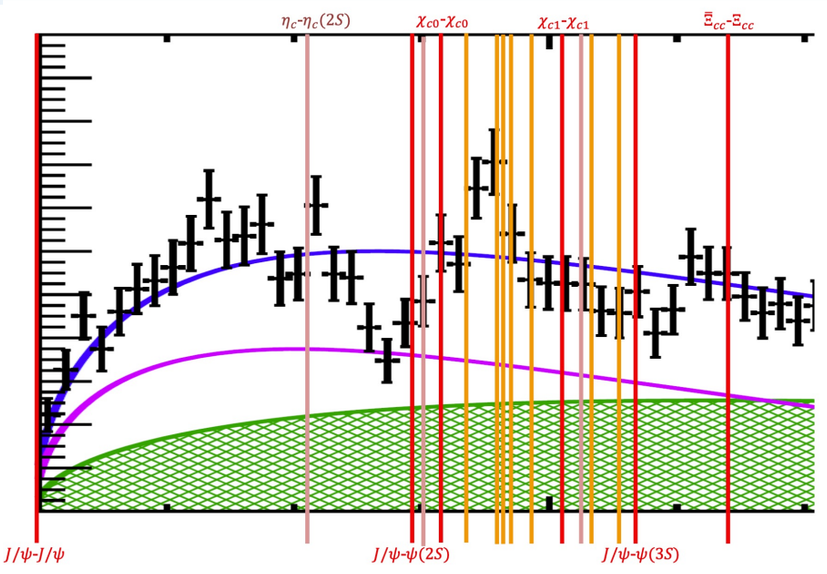
exchanges with small binding energies. Namely, the T_{4c} structures do not suffer any complications from the channel coupling and chiral dynamics. These signals may be good candidates of the "genuine" compact tetraquark states arising from the quark-gluon interaction in QCD [15–20].

- Dedicated analyses: $X(6900)$ as first radial excitation, 1P or 2S $T_{cc\bar{c}\bar{c}}$ state

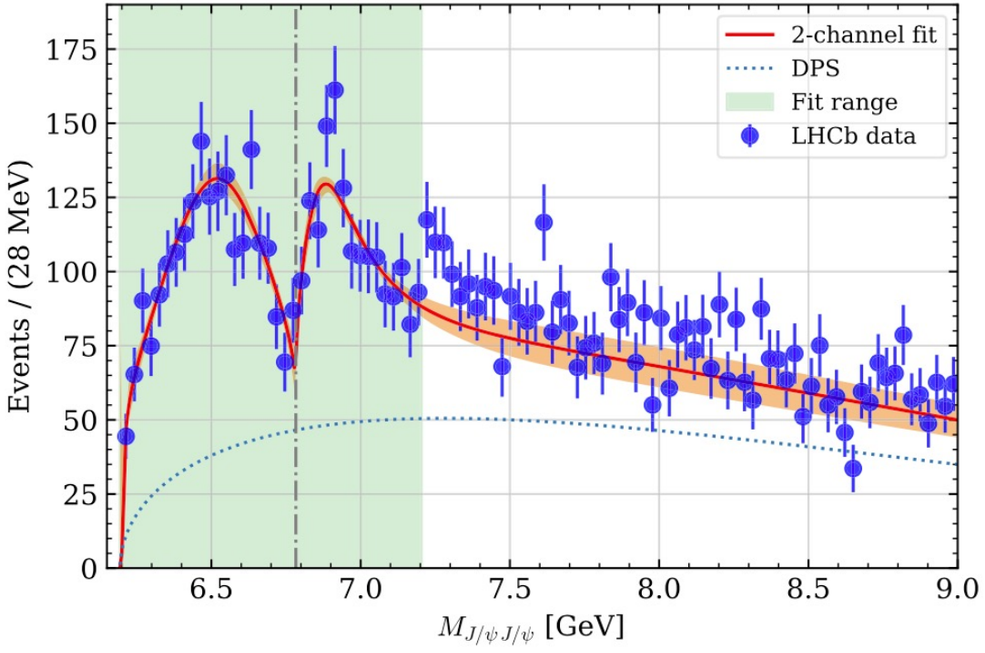
[PRL102 (2009) 114039, PRD102 (2020) 114030, PRD102 (2020) 074003, EPJC80 (2020) 871, PRD102 (2020) 114039, arXiv:2006.13756, arXiv:2009.08376, PRL 126 (2021) 132001, PRD 103 (2021) 014001, PRD 104 (2021) 014018, PRD 103 (2021) 05163, EPJC 80 (2020) 871…]

Coupled channel rescattering

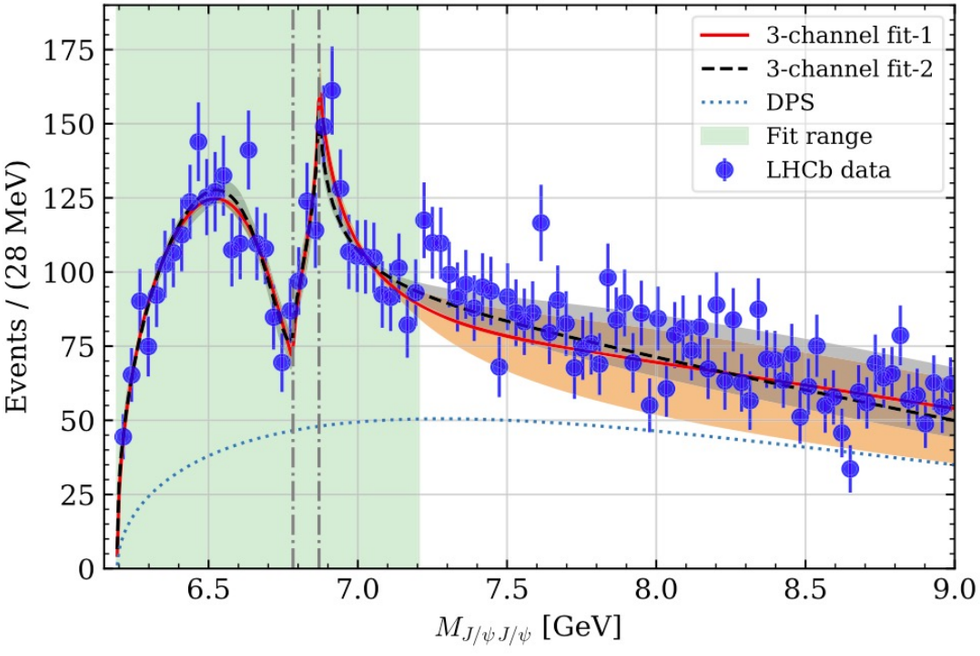
- A few thresholds around $X(6900)$
- LHCb data fitted with di-charmonium rescattering
  - ➢ Existence of $X(6200)$, bound/virtual state
  - ➢ Dip due to $J/\psi\psi(2S)$ threshold
  - ➢ $X(6900)$ due to $J/\psi\psi(3770)$ threshold



Two channels: $J/\psi J/\psi + J/\psi\psi(2S)$



Three channels: $J/\psi J/\psi + J/\psi\psi(2S) + J/\psi\psi(3770)$



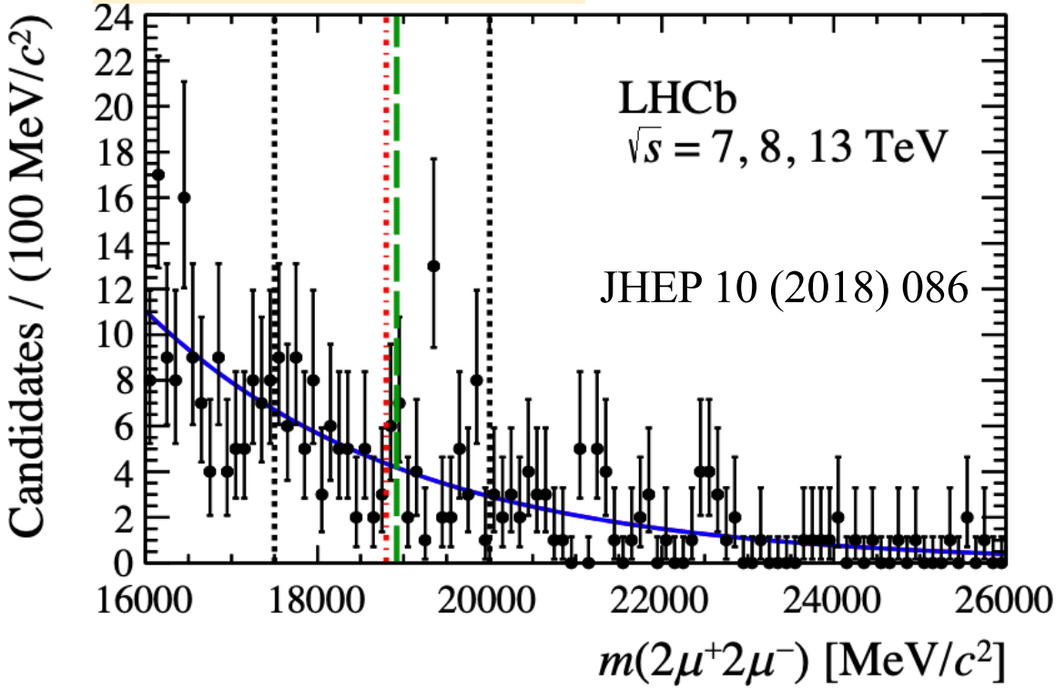
[PRL126(2021)132001, PRL127(2021)119901, PRD104(2021)034034]

Search for $T_{bb\bar{b}\bar{b}}$ state

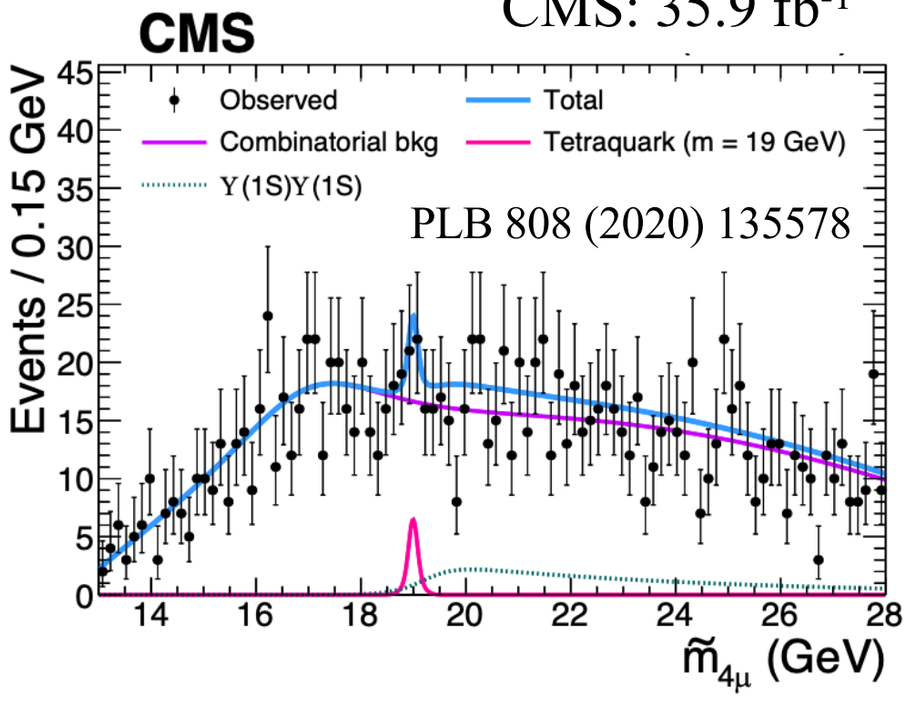
- Studied in $\Upsilon\mu^+\mu^-$ final state by LHCb and CMS

Di-$b\bar{b}$ thresholds

LHCb: 6.3 fb^{-1}



CMS: 35.9 fb^{-1}

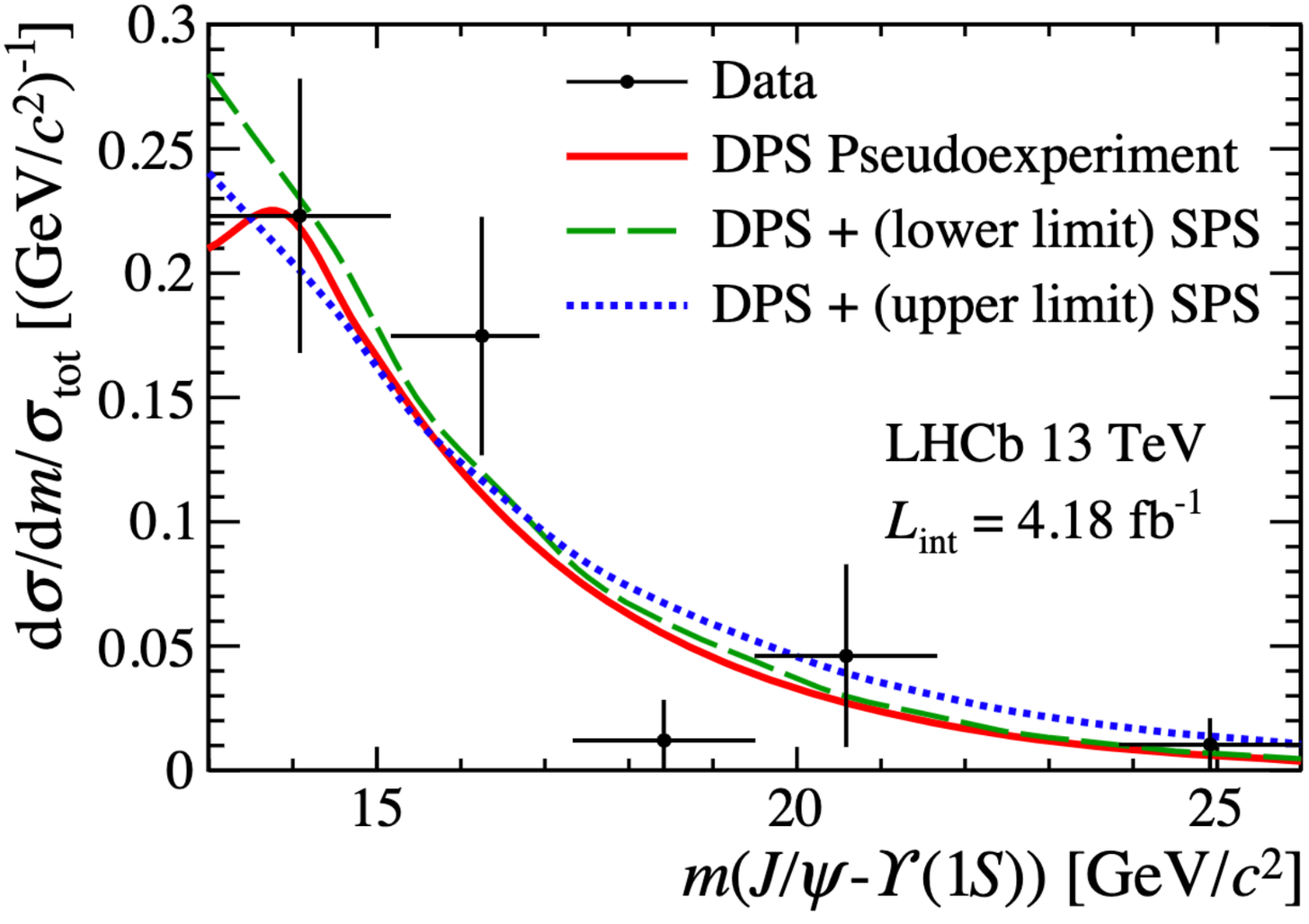


No obvious signals, eager to see full data analysis at CMS/ATLAS

Search for $T_{bc\bar{b}\bar{c}}$ state

LHCb-PAPER-2022-047
arXiv:2305.15580

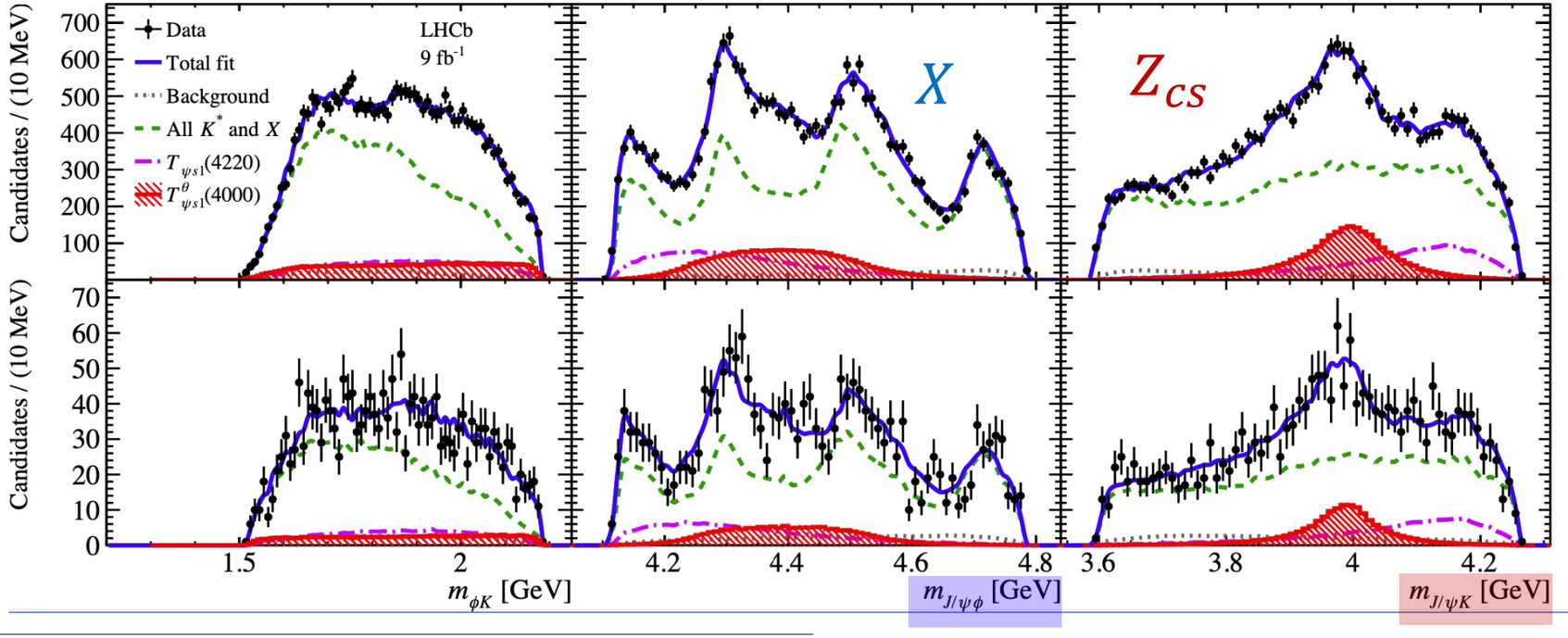
- Statistics too low to seen any structure in $J/\psi - \Upsilon$ mass spectrum
- Data consistent with DPS dominating production



$T_{sc\bar{s}\bar{c}}$ -states?

PRL127(2021)082001
and arXiv:2301.04899

- Six $X \to J/\psi\phi$ and two $Z_{cs} \to J/\psi K^+$ states observed in $B^+ \to J/\psi\phi K^+$
- Similarity with $T_{cc\bar{c}\bar{c}}$: allowed J^{PC} of $X \to VV$. More states in di-J/ψ spectrum?



X

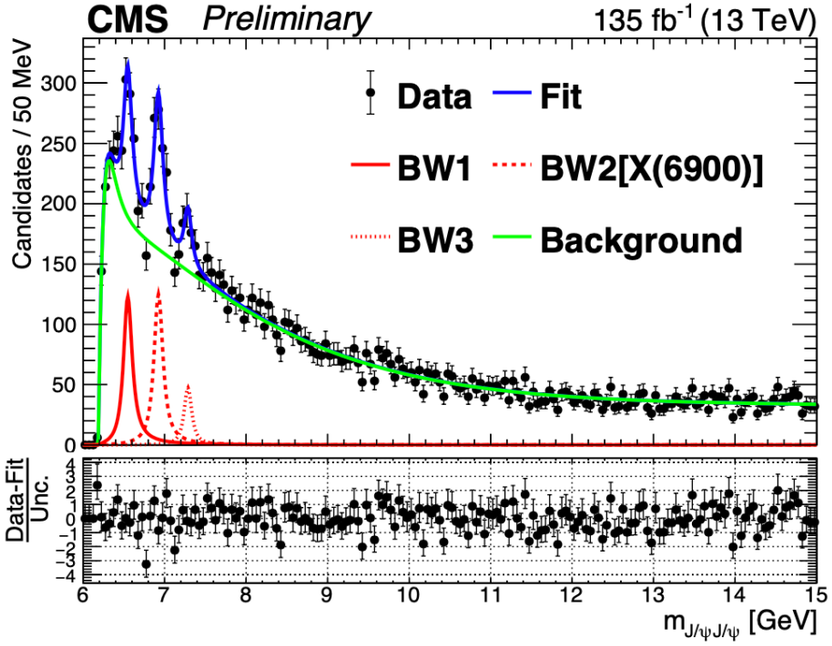
Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$

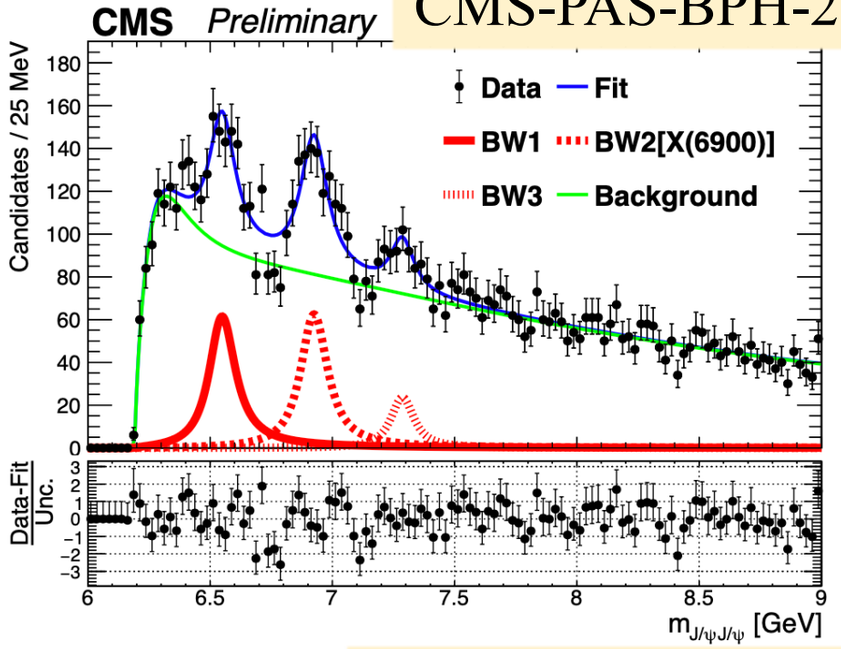
Z_{cs}

Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

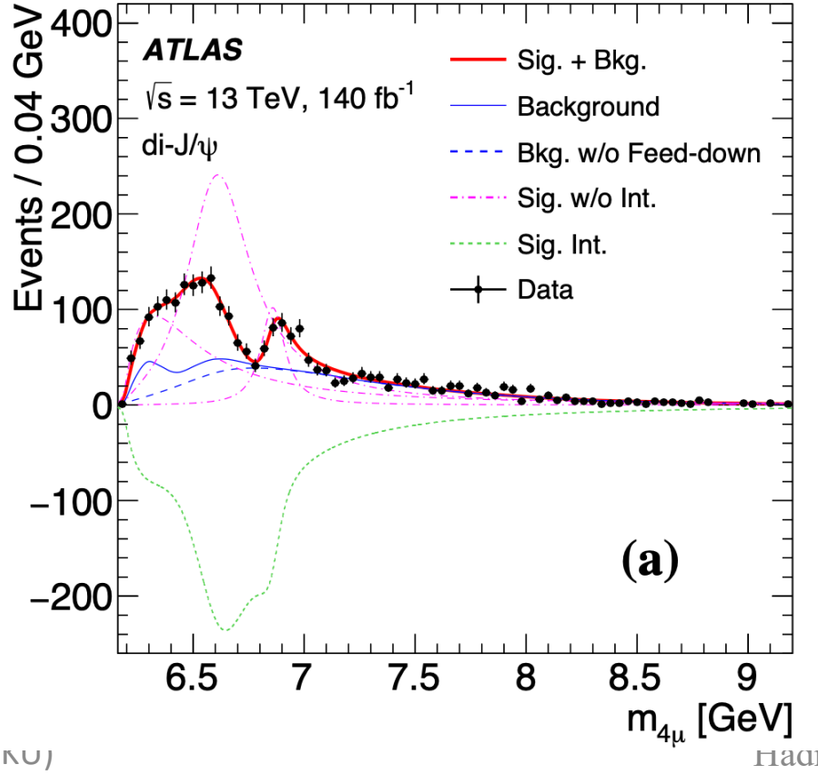
ATLAS and CMS reproduction

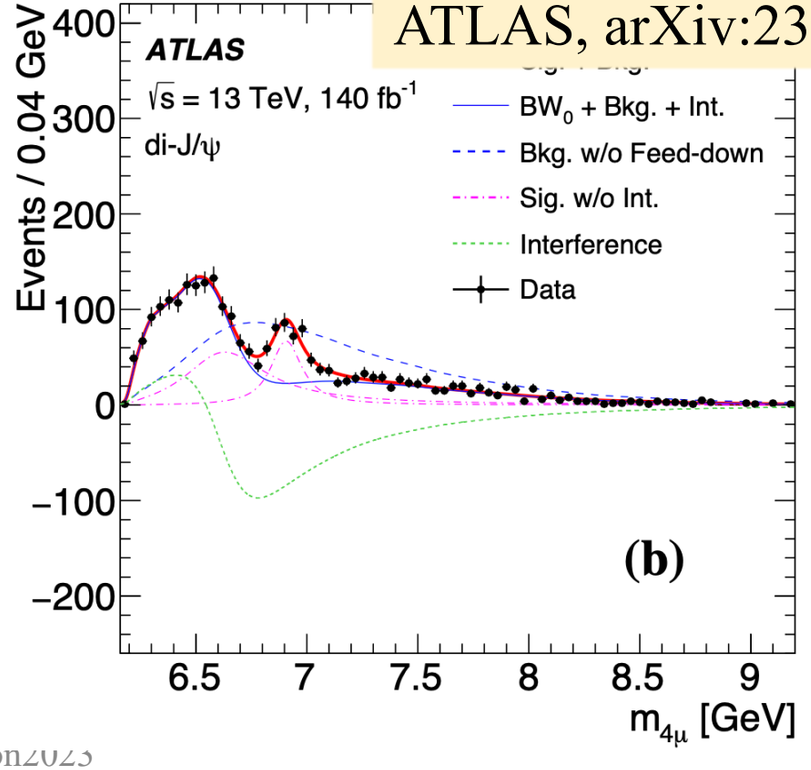
CMS-PAS-BPH-21-003





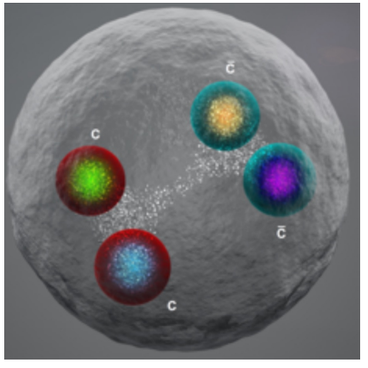
ATLAS, arXiv:2304.08962





Summary

- Observed structure $X(6900)$ in di-J/ψ mass spectrum, consistent with fully charmed tetraquark $T_{cc\bar{c}\bar{c}}$
- Threshold structure: a few possible interpretations
  - ➢ One BW, combination of two BWs, feed-down
- $X(6900)$ Breit-Wigner properties:



Fit without interference:

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV}$$
$$R = [1.1 \pm 0.4 \pm 0.3]\%$$

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Fit with interference:

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

- Looking forward to Run3 data and synergies with CMS/ATLAS analyses

Thank you for your attention

Backup slides

Signal stability

Science Bulletin 65 (2020) 1983

- 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

Systematic uncertainties

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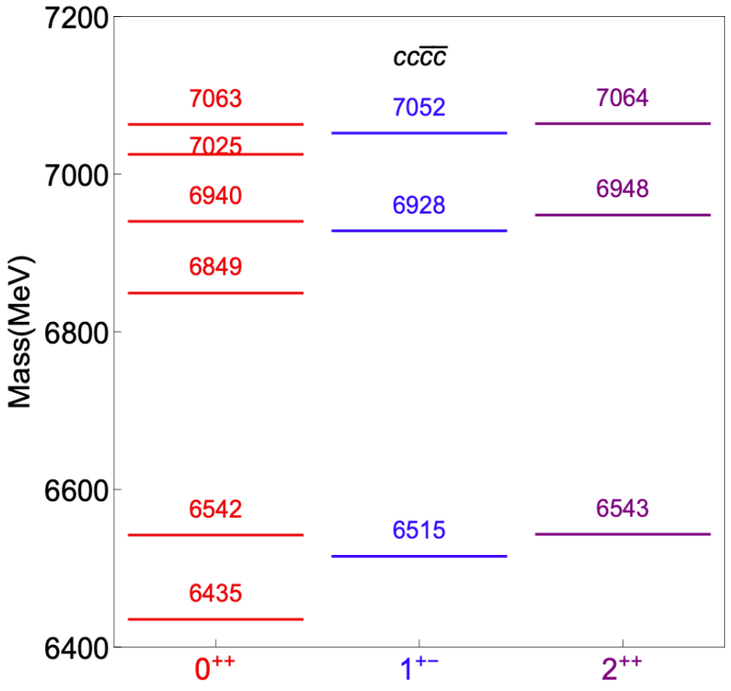
Table 1: Global significance evaluated under the various assumptions described in the text.

Component	Without interference		With interference	
	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 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

Matching to predicted spectrum

Model dependent interpretations

Eur.Phys.J.C 80 (2020) 871



Threshold structure

One or more ground states

X(6900)

First radial excitation

Rept.Prog.Phys.86(2023)026201