Coupled-channel interpretation of the LHCb double-J/psi spectrum

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Based on
X.-K. Dong, V. Baru, F.-K. Guo, C. Hanhart, A.N.
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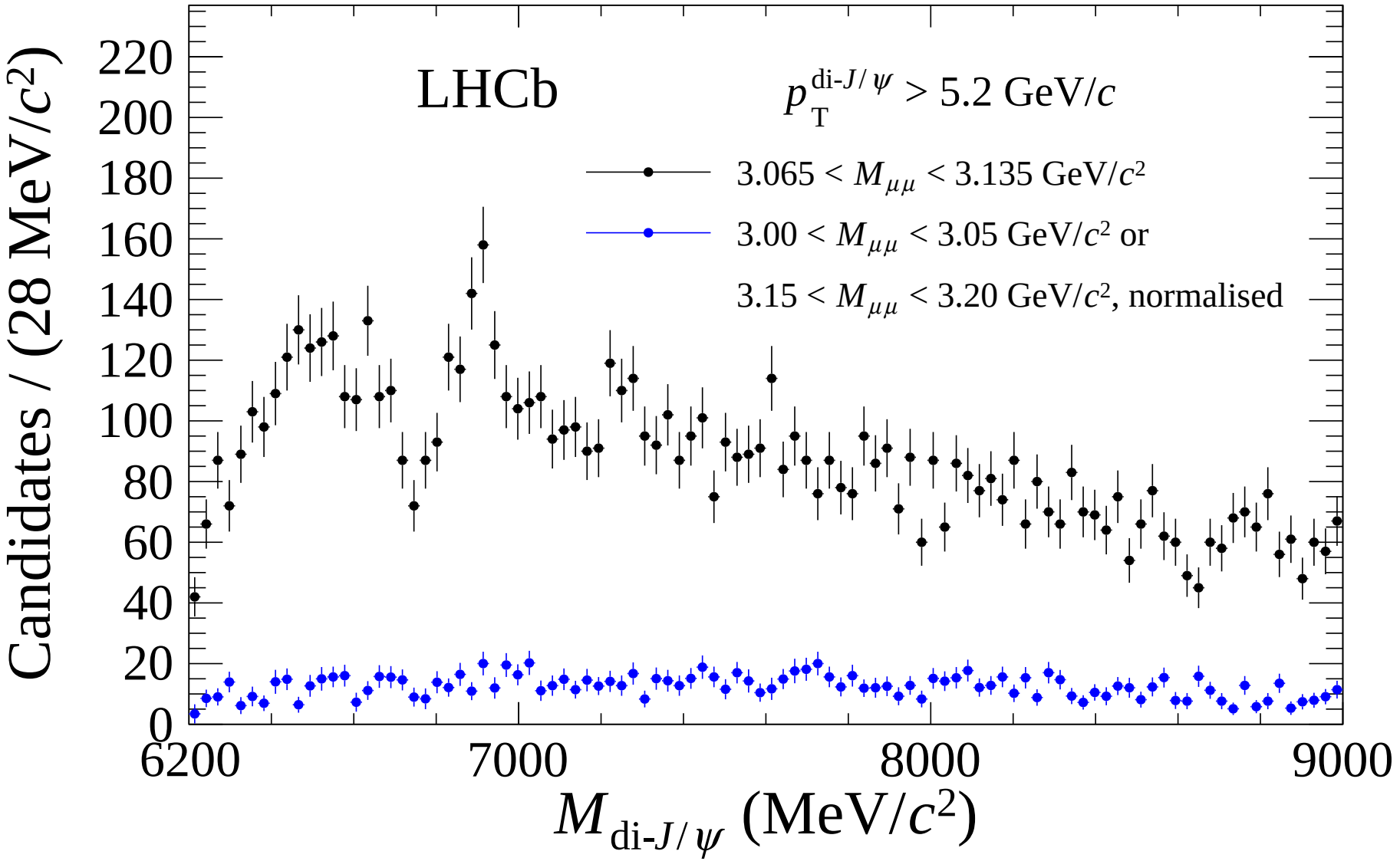
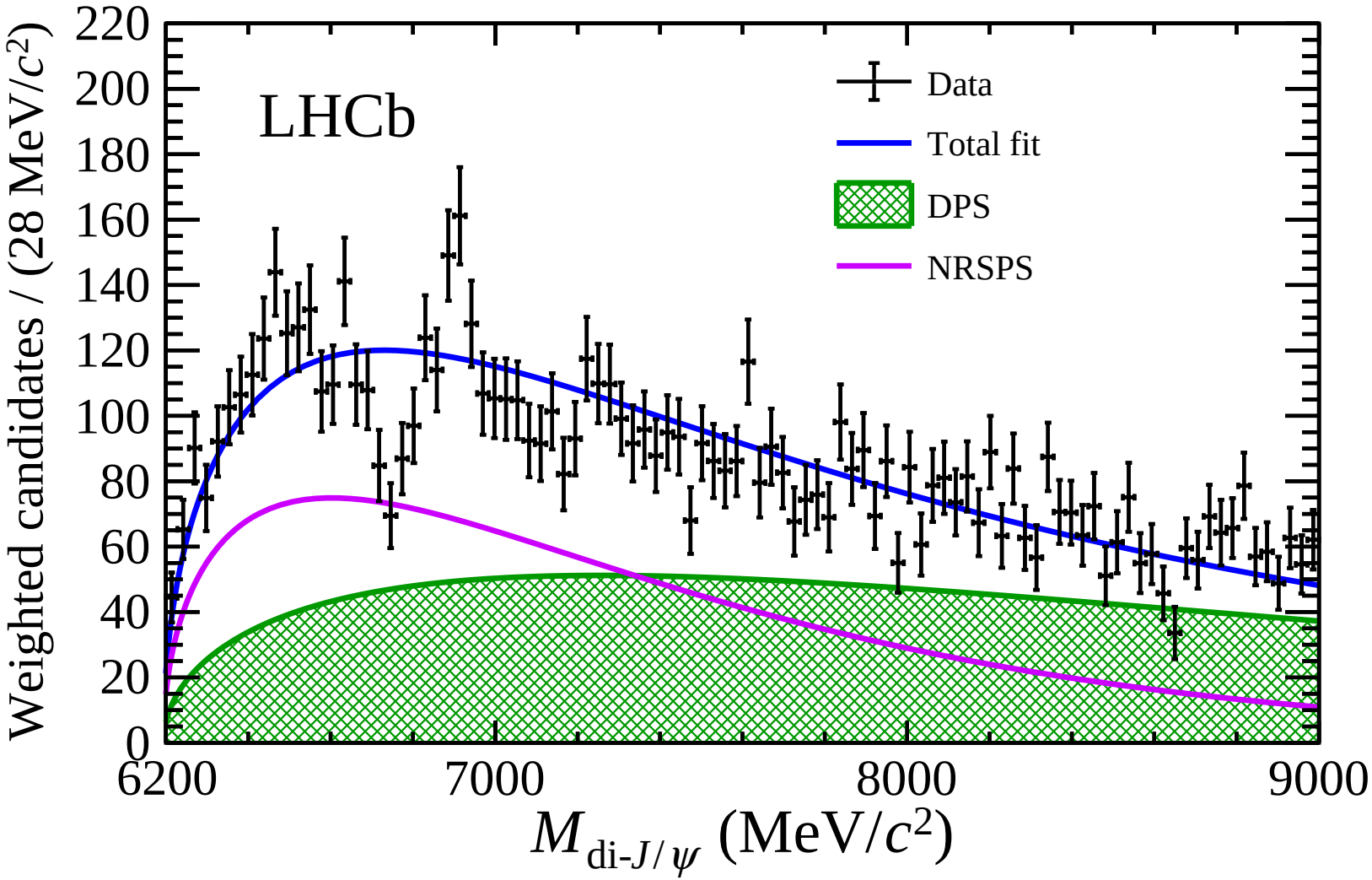
LHCb data (Sc.Bull. 65 (2020) 1983)



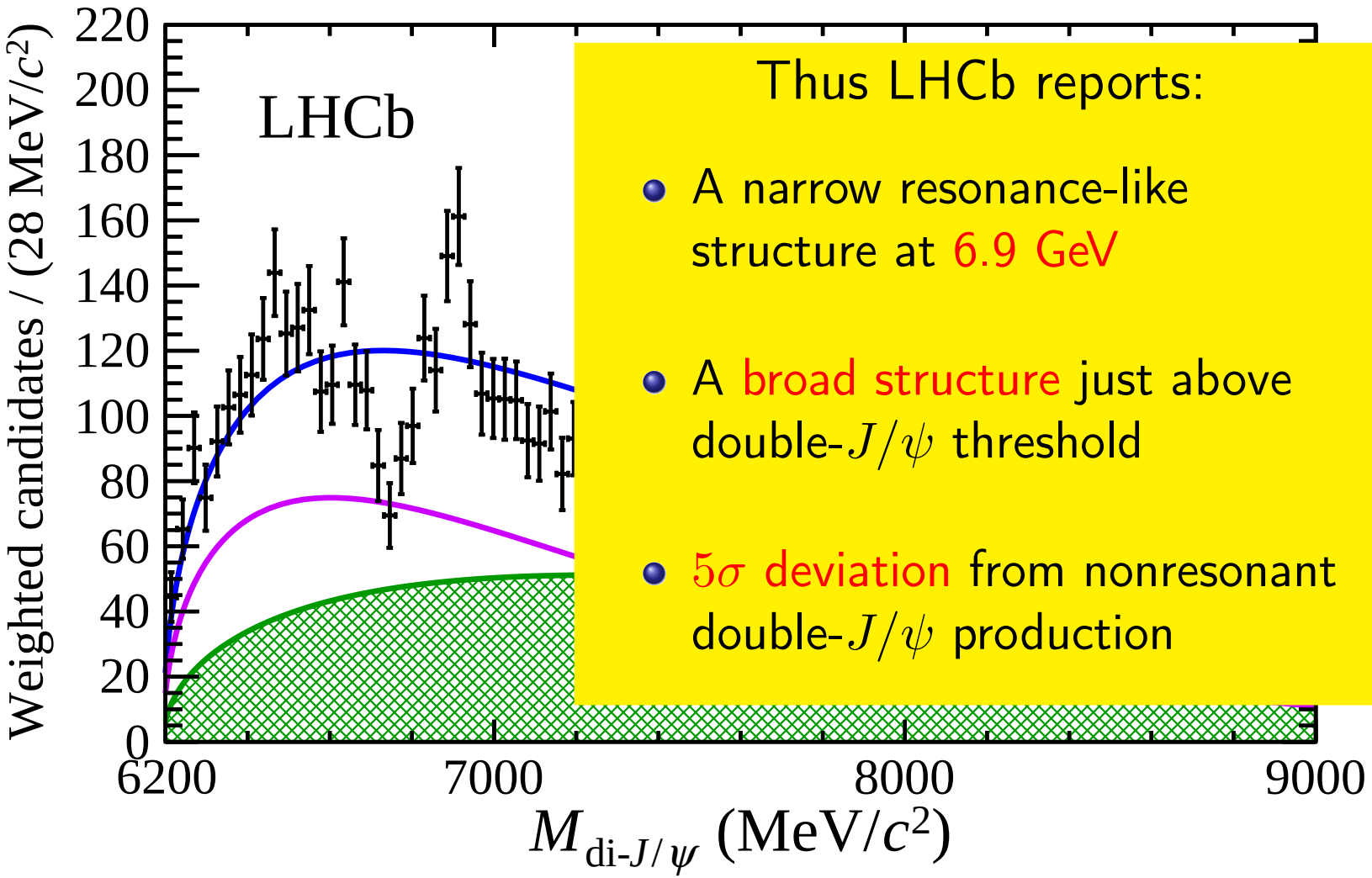
LHCb: nonresonant production



NRSPS=NonResonant Single Parton Scattering

DPS=Double Parton Scattering

LHCb: conclusions from analysis



Thus LHCb reports:

- A narrow resonance-like structure at 6.9 GeV
- A broad structure just above double-J/ψ threshold
- 5σ deviation from nonresonant double-J/ψ production

Response from the community

Immediate and massive:

- LHCb announcement:
  CERN seminar (16 June 2020)
  arXiv submission (30 June 2020)
- First citations:
  3 Nov 2019 (1911.00960)
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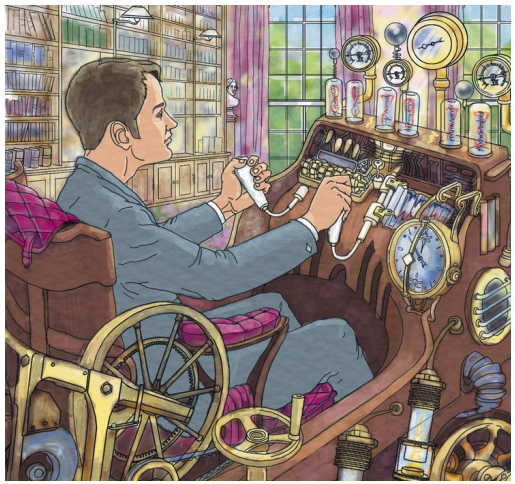

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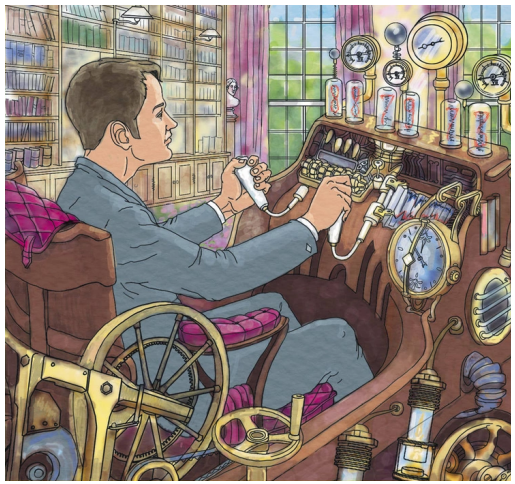

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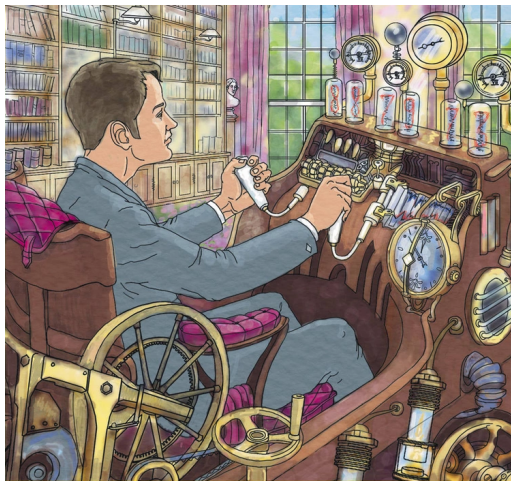

The usual suspects:

- Fully charm tetraquark (most popular model)
- Molecule (several hundred MeV above threshold $\Longrightarrow$ unlikely)
- Threshold effects (to be quantified)

General remarks

- Naive models and parametrisations have to be disregarded

  $\Longrightarrow$ Breit-Wigner fits mislead rather than educate

  $\Longrightarrow$ Breit-Wigner parameters (M and Γ) hide nature of states

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  Minimal models compatible with data are considered

  $\Longrightarrow$ Only most relevant channels included (see next slide)

  $\Longrightarrow$ Minimal necessary order in EFT expansion

  $\Longrightarrow$ Interpret only results robust w.r.t. model modification

  $\Longrightarrow$ Highlight predictions to distinguish between models

Choosing relevant channels

- $J/\psi J/\psi \Leftrightarrow \psi(2S)J/\psi, \psi(3770)J/\psi$

  HQSS-allowed, mediated by soft gluons (two pions)

- $J/\psi J/\psi \Leftrightarrow \psi(2S)\psi(2S), \psi(2S)\psi(3770), \psi(3770)\psi(3770), \ldots$

  Thresholds above the investigated mass range

- $J/\psi J/\psi \Leftrightarrow \eta_c\eta_c, h_c h_c$

  Heavy quark spin flip needed $\Longrightarrow$ HQSS-suppressed

- $J/\psi J/\psi \Leftrightarrow \chi_{cJ}\chi_{cJ'}$ $(J = 0, 1, 2)$

  Lowest exchange particle (ω) is (relatively) heavy $\Longrightarrow$ suppression

The models

Two-channel model (7 parameters)
$J/\psi J/\psi$ & $\psi(2S)J/\psi$

$$V_{2\mathrm{ch}}(E) = \begin{pmatrix} a_1 + b_1 k_1^2 & c \\ c & a_2 + b_2 k_2^2 \end{pmatrix}$$

Three-channel model (8 parameters)
$J/\psi J/\psi$, $\psi(2S)J/\psi$ & $\psi(3770)J/\psi$

$$V_{3\mathrm{ch}}(E) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{pmatrix}$$

Lippmann-Schwinger equation

$$T(E) = V(E) \cdot [1 - G(E)V(E)]^{-1}$$

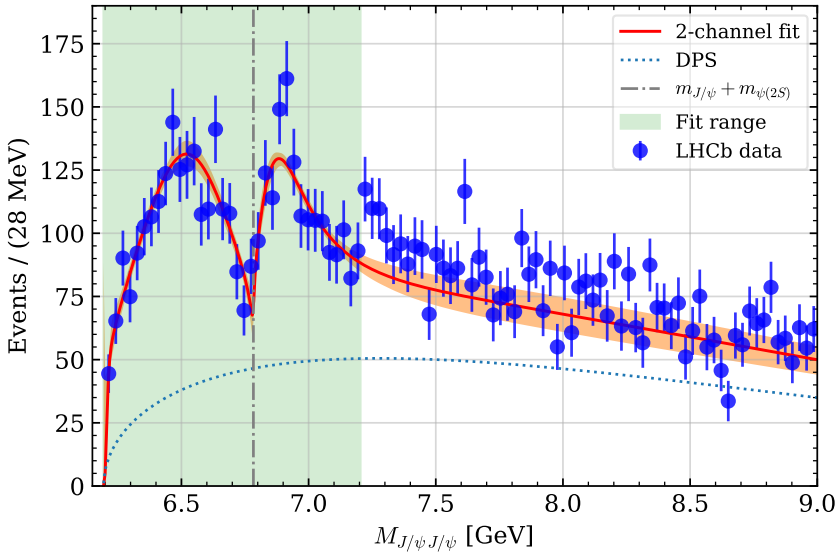
Production amplitude in $J/\psi J/\psi$ channel (channel 1):

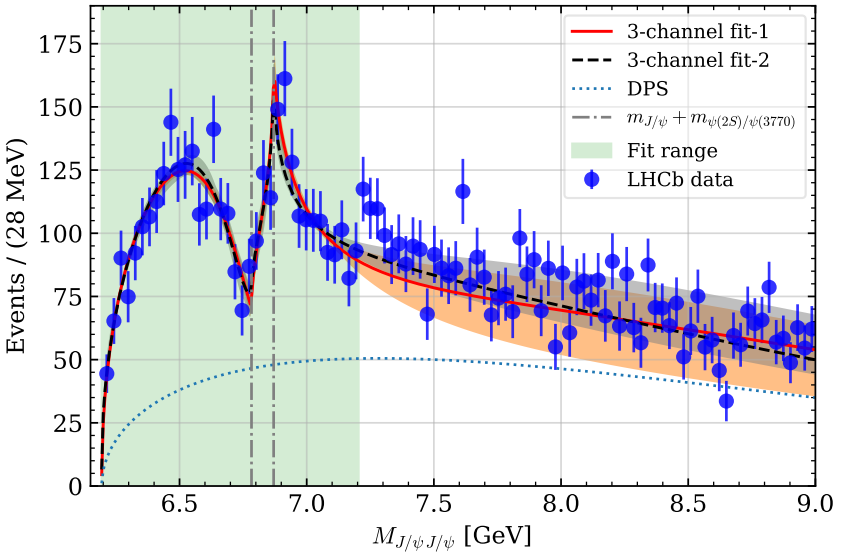
$$\mathcal{M}_1 = \alpha e^{-\beta E^2} \Big[b + G_1(E)T_{11}(E) + G_2(E)T_{21}(E) + r_3 G_3(E)T_{31}(E) \Big]$$

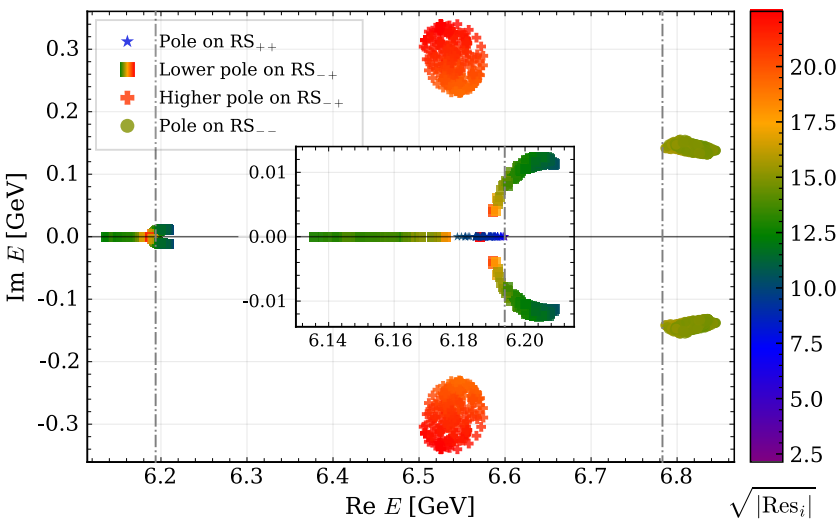
Slope β fixed to double-parton scattering (DPS): $\beta = 0.0123$ GeV^{-2}

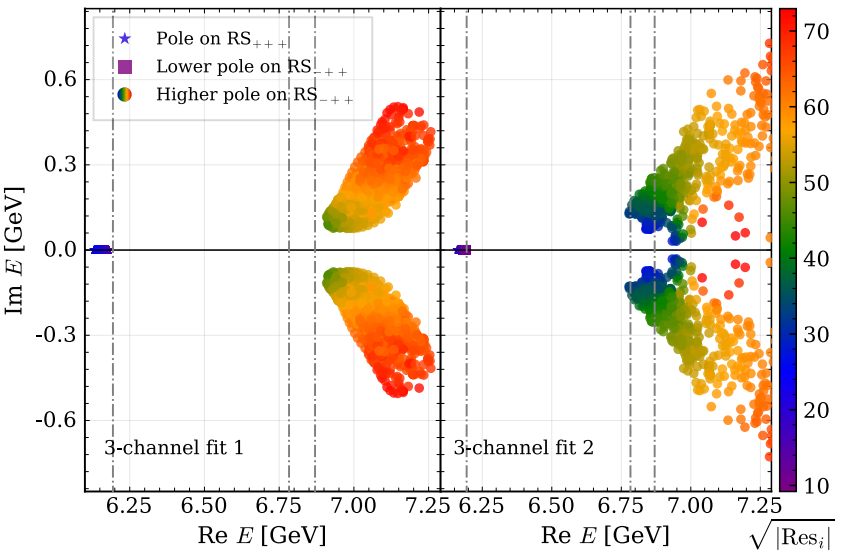
$$r_3 = \begin{cases} 0 & \text{2ch model} \\ 1 & \text{3ch model} \end{cases}$$

Fits & poles


2-channel fit
DPS
$m_{J/\psi}+m_{\psi(2S)}$
Fit range
LHCb data
Events / (28 MeV)
$M_{J/\psi J/\psi}$ [GeV]


3-channel fit-1
3-channel fit-2
DPS
$m_{J/\psi}+m_{\psi(2S)/\psi(3770)}$
Fit range
LHCb data
Events / (28 MeV)
$M_{J/\psi J/\psi}$ [GeV]


Pole on RS$_{++}$
Lower pole on RS$_{-+}$
Higher pole on RS$_{-+}$
Pole on RS$_{--}$
Im E [GeV]
Re E [GeV]
$\sqrt{|\mathrm{Res}_i|}$


Pole on RS$_{+++}$
Lower pole on RS$_{-++}$
Higher pole on RS$_{-++}$
3-channel fit 1
3-channel fit 2
Im E [GeV]
Re E [GeV]
$\sqrt{|\mathrm{Res}_i|}$

$X(6200)$ vs $X(6900)$

- Poles above the double-J/ψ threshold ($X(6900)$) are badly determined
- Pole near the double-J/ψ threshold ($X(6200)$) is robust

$$E_0^{2\text{ch}} = 6203^{+\ 6}_{-27} - i\,12^{+\ 1}_{-12}\ (\text{RS}_{-+}) \text{ or } [6179, 6194]\ (\text{RS}_{++})$$
$$E_0^{3\text{ch}}[\text{Fit 1}] = 6163^{+18}_{-32}\ (\text{RS}_{+++})$$
$$E_0^{3\text{ch}}[\text{Fit 2}] = 6189^{+\ 5}_{-10}\ (\text{RS}_{-++}) \text{ or } [6159, 6194]\ (\text{RS}_{+++})$$

- Compositeness of $X(6200)$ is large $\Longrightarrow$ hint for a molecule

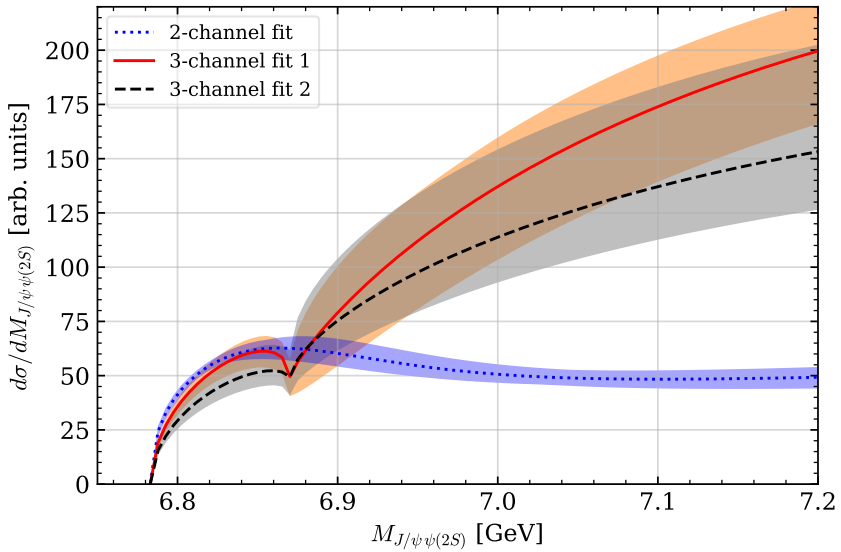
$$T(k) \approx -8\pi\sqrt{s}\left[\frac{1}{a_0} + \frac{1}{2}r_0 k^2 - ik\right]^{-1}$$

$$\bar{X}_A = (1 + 2|r_0/a_0|)^{-1/2} \sim 1$$

Matuschek.et al. Eur.Phys.J. **A57** (2021) 101

Further tests

- Data in the $\psi(2S)J/\psi$ channel $\Longrightarrow$ distingush between the models



- Data in the double-η_c channel $\Longrightarrow$ verify predictive power of the models
- Models for J/ψ-J/ψ binding $\Longrightarrow$ (dis)prove $X(6200)$ nature
- Data on double-Υ production $\Longrightarrow$ check in complementary sector
- Lattice simulation of double-J/ψ (η_c) scattering $\Longrightarrow$ independent test

Conclusions

- LHCb data on the double-J/ψ spectrum are consistent with a coupled-channel description
- Even minimalistic models provide a good description of the data ($\chi^2/\mathrm{dof} \simeq 1$)
- Position of the poles above the double-J/ψ threshold is vaguely fixed by the present data
- All models employed support the existence of the $X(6200)$ state with $J^{PC} = 0^{++}$ or 2^{++} near the double-J/ψ threshold
- Molecular model for $X(6200)$ is plausible and compatible with the data
- Experimental tests are outlined to verify the existence of $X(6200)$ and shed light on its nature
- More data on double charmonium and bottomonium production are desperately awaited!

Backup

Values of the parameters found in the fits

Parameters of the two-channel model ($[\bar{a}_i]$=GeV^{-2}, $[\bar{b}_j]$=GeV^{-4}, $[\bar{c}]$=GeV^{-2})

$\bar{a}_1$	$\bar{a}_2$	$\bar{c}$	$\bar{b}_1$	$\bar{b}_2$	α	b
$0.2^{+0.6}_{-0.5}$	-4.2 ± 0.7	$2.94^{+0.36}_{-0.29}$	$-1.8^{+0.4}_{-0.5}$	-7.1 ± 0.4	70^{+8}_{-7}	3.3 ± 0.4

Parameters of the three-channel model ($[\bar{a}_{ij}]$=GeV^{-2})

$\bar{a}_{11}$	$\bar{a}_{12}$	$\bar{a}_{13}$	$\bar{a}_{22}$	$\bar{a}_{23}$	$\bar{a}_{33}$	α	b
$6.0^{+2.2}_{-1.6}$	$10.3^{+3.4}_{-2.8}$	$-0.2^{+1.9}_{-1.3}$	13^{+5}_{-4}	$-2.6^{+2.4}_{-1.3}$	$-2.3^{+1.5}_{-1.1}$	250^{+70}_{-60}	$-0.12^{+0.21}_{-0.22}$
$7.8^{+3.4}_{-2.0}$	16 ± 4	$0.9^{+2.3}_{-2.5}$	26^{+12}_{-6}	-3^{+4}_{-5}	$-2.5^{+2.1}_{-1.0}$	144^{+67}_{-27}	$-0.7^{+0.5}_{-0.4}$

Each parameter with bar needs to be multiplied by $\prod_{i=1}^{4} \sqrt{2m_i}$, where m_i's are the involved charmonium masses

$$m_{J/\psi} = 3.0969 \text{ GeV} \quad m_{\psi(2S)} = 3.6861 \text{ GeV}$$

Compositeness of $X(6200)$

$$T(k) = -8\pi\sqrt{s}\left[\frac{1}{a_0} + \frac{1}{2}r_0 k^2 - i\,k + \mathcal{O}(k^4)\right]^{-1}$$

$$\bar{X}_A = (1 + 2|r_0/a_0|)^{-1/2}$$

	2-ch. fit	3-ch. fit 1	3-ch. fit 2
$a_0(\mathrm{fm})$	≤ -0.49 or ≥ 0.48	$-0.61^{+0.29}_{-0.32}$	≤ -0.60 or ≥ 0.99
$r_0(\mathrm{fm})$	$-2.18^{+0.66}_{-0.81}$	$-0.06^{+0.03}_{-0.04}$	$-0.09^{+0.08}_{-0.05}$
$\bar{X}_A$	$0.39^{+0.58}_{-0.12}$	$0.91^{+0.04}_{-0.07}$	$0.95^{+0.04}_{-0.06}$