Double-J/ψ system in the spotlight of recent LHCb data

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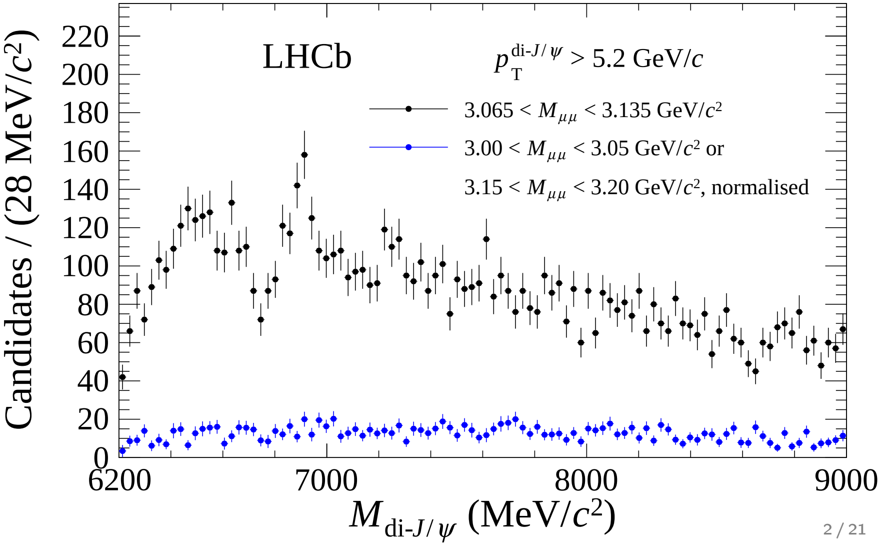
Based on
X.-K. Dong, V. Baru, F.-K. Guo, C. Hanhart, A.N.

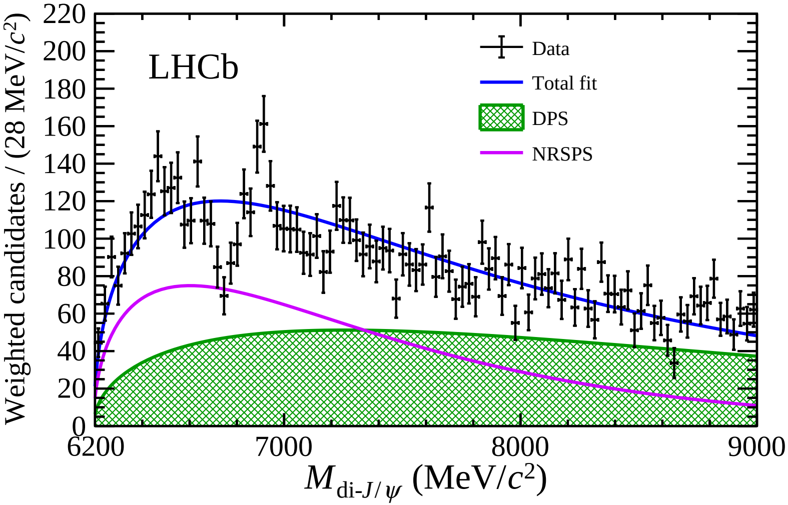
Phys. Rev. Lett. **126** (2021), 132001

Sci.Bull. **66** (2021), 2462-2470

LHCb data on di-J/ψ production (Sci.Bull. 65 (2020) 1983)



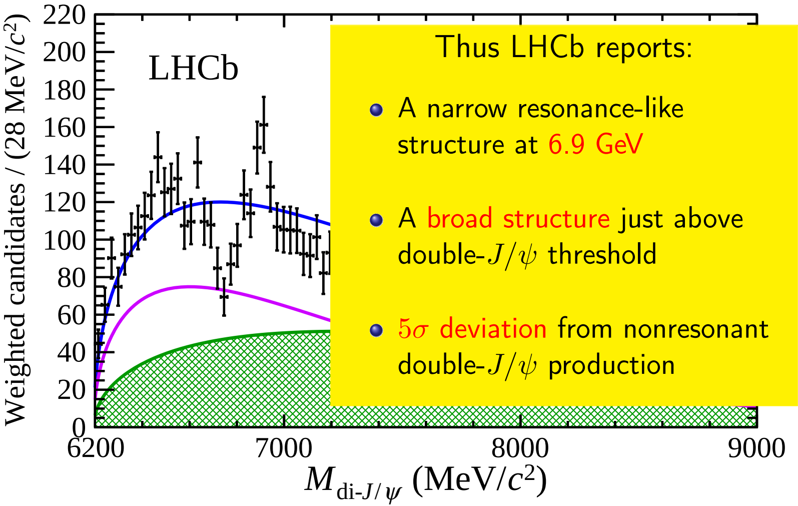
LHCb: nonresonant production



NRSPS=NonResonant Single Parton Scattering

DPS=Double Parton Scattering

LHCb: conclusions from experimental 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

Theoretical analysis of LHCb data

- 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

$\Longrightarrow$ Minimal necessary order in EFT expansion

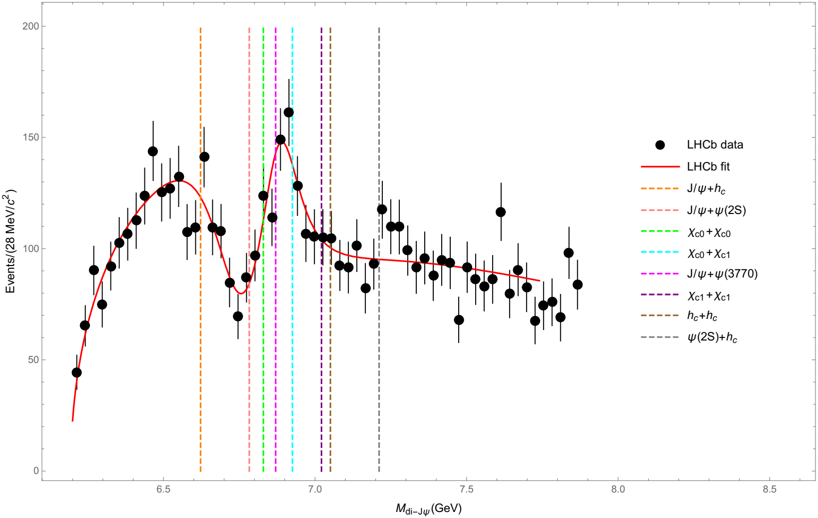
$\Longrightarrow$ Interpret only results robust w.r.t. model modification

$\Longrightarrow$ Highlight predictions to distinguish between models

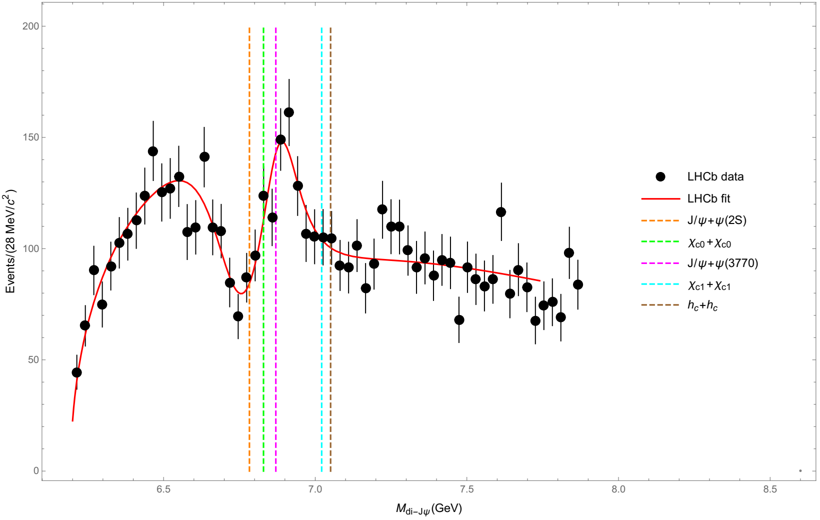
Choosing relevant channels

- Restrict ourselves to thresholds in the range 6.2-7.2 GeV
- Consider only S-wave channels
- Compatible with light exchanges
  - $J/\psi J/\psi \;\Leftrightarrow\; \chi_{cJ}\chi_{cJ}\ (J=0,1)$
    Lowest exchange particle (ω) is (relatively) heavy $\Longrightarrow$ suppression
  - $J/\psi J/\psi \;\Leftrightarrow\; \psi(2S)J/\psi, \psi(3770)J/\psi, \ldots$
    Mediated by soft gluons (two pions) $\Longrightarrow$ no suppression
- Retain only HQSS-allowed channels
  - $J/\psi J/\psi \;\Leftrightarrow\; h_c h_c$
    Heavy quark spin flip needed $\Longrightarrow$ suppressed by $\Lambda_{\text{QCD}}/m_c \ll 1$ (HQSS)
  - $J/\psi J/\psi \;\Leftrightarrow\; \psi(2S)J/\psi, \psi(3770)J/\psi$
    No c-quark spin flip needed $\Longrightarrow$ HQSS-allowed

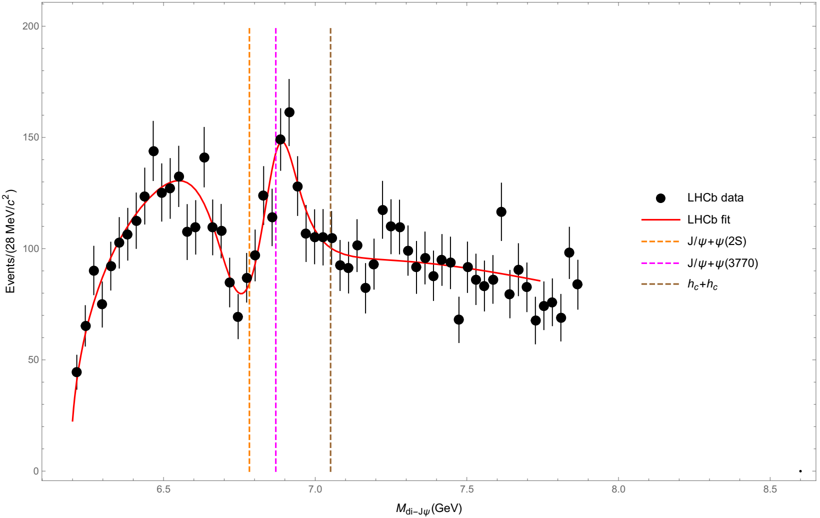
All channels



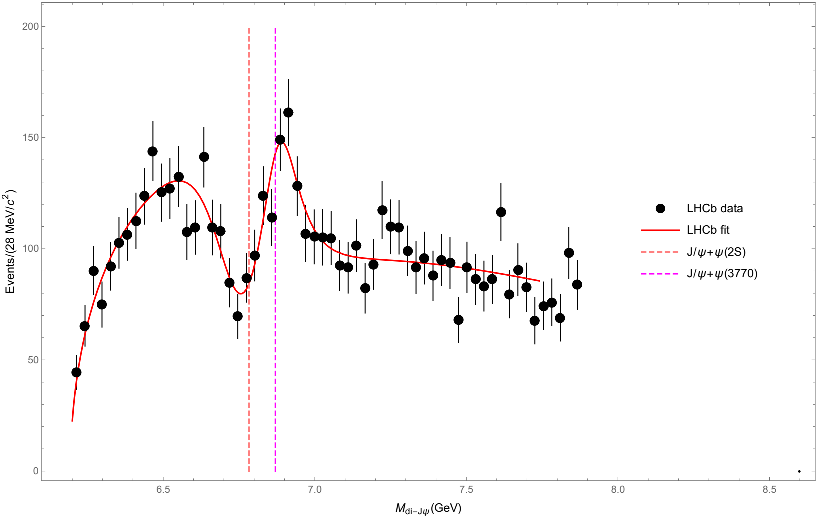
Only S-wave channels



No heavy exchanges



Only HQSS-allowed channels



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

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

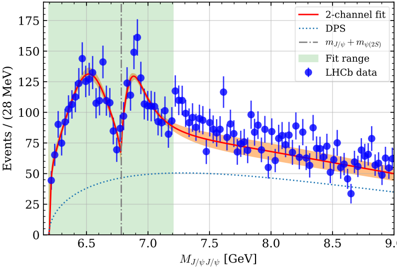
Production amplitude in $J/\psi J/\psi$ channel (channel 1):

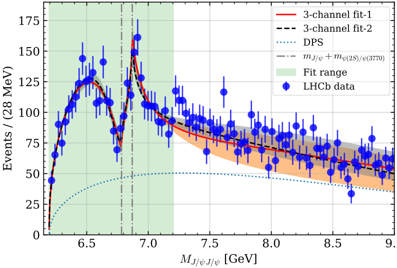
$$\mathcal{M}_1 = \alpha e^{-\beta E^2}\left[b + G_1(E)T_{11}(E) + G_2(E)T_{21}(E) + r_3 G_3(E)T_{31}(E)\right]$$

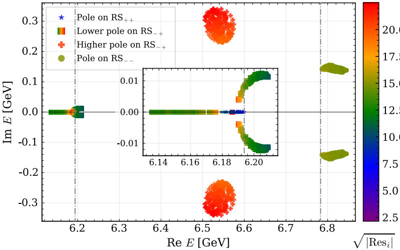
Slope β fixed to double-parton scattering (DPS): $\beta = 0.0123$ GeV^{-2}

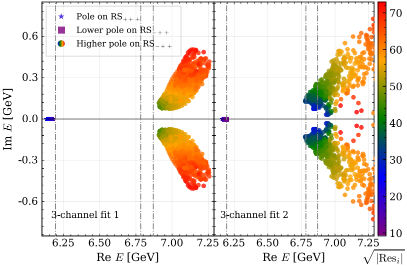
$$r_3 = \begin{cases} 0 & \text{2ch model} \\ 1 & \text{3ch model} \end{cases}$$

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
  - More (accurate) data are needed
  - Parameters of $X(6900)$ are highly uncertain
- Pole near the double-J/ψ threshold ($X(6200)$) is robust

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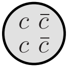
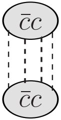
- Pole near the double-J/ψ threshold ($X(6200)$) is robust
- $X(6200)$=tetraquark (2 quarks + 2 antiquarks) $\Longrightarrow$ Different clusterings:
  - Compact Tetraquark



  - Hadronic Molecule

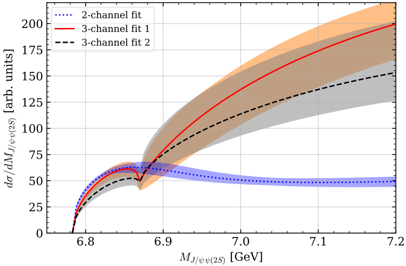


- Compositeness of $X(6200)$ is large $\Longrightarrow$ hint for a molecule

Molecule = large probability to find the studied resonance in the observation hadron-hadron channel ($J/\psi J/\psi$)

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 from data analysis

- 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 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!

Double-J/ψ molecule

Question: Can interaction between two J/ψ's produce a near-threshold pole?

We know: Soft-gluon exchanges hadronise as light-meson ($\pi\pi$,$K\bar{K}$) exchanges

Approach: Multipole expansion for $r_{\bar{Q}Q} \ll \Lambda_{\rm QCD}^{-1}$:

(Gottfried'1977,Voloshin'1978,Peskin'1979,...Voloshin&Sibirtsev'2005)

$$H_{\rm int} \approx -\frac{1}{2}\xi_a \vec{r}\cdot\vec{E}^a \quad\Longrightarrow\quad \mathcal{M}(A\to B\pi\pi) = \alpha_{AB}\langle\pi\pi|\vec{E}^a\cdot\vec{E}^a|0\rangle$$

Problem: How to find $\alpha_{J/\psi J/\psi}$?

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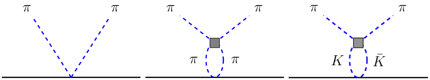
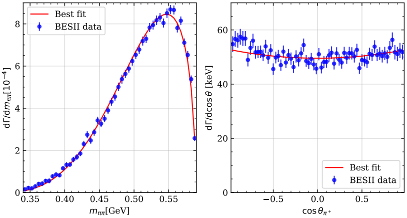
Idea: Extract $\alpha_{\psi(2S)J/\psi}$ from $\psi(2S)\to J/\psi\pi\pi$ and estimate $\alpha_{J/\psi J/\psi}$ from it



$|\alpha_{\psi(2S)J/\psi}| \approx 1.81$ GeV^{-3}



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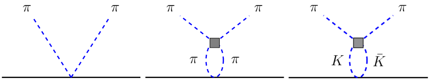

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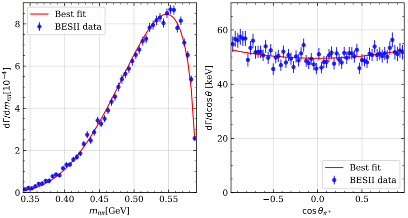
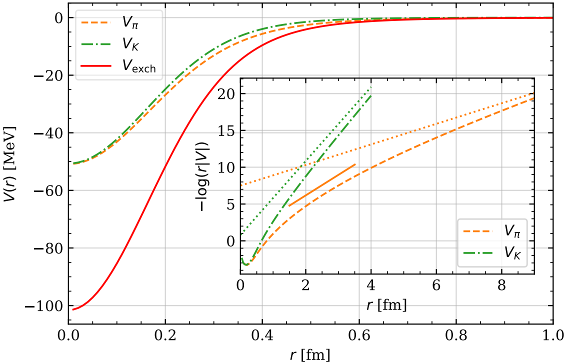


Result: $\alpha_{J/\psi J/\psi} = \xi\alpha_{\psi(2S)J/\psi}$ with $\xi > 1$ (we consider $1 \lesssim \xi \lesssim 3$)

Double-J/ψ molecule



$$V_{\text{tot}}(r,\Lambda) = V_\pi(r,\Lambda) + V_K(r,\Lambda) = V_{\text{CT}}(r,\Lambda) + V_{\text{exch}}(r,\Lambda)$$

$$V_{\text{CT}}(q,\Lambda) = \text{Const} \times F(q^2/\Lambda^2)$$

$$V_{\text{exch}}(r,\Lambda) = -\frac{1}{4\pi M_{J/\psi}^2} \int \frac{d^3q}{(2\pi)^3} e^{i\vec{q}\cdot\vec{r}} \int_{4m_\pi^2}^{\infty} d\mu^2 \, \frac{\text{Im}\mathcal{M}_{J/\psi J/\psi}(\mu^2)}{\mu^2+q^2} F\left(\frac{q^2+\mu^2}{\Lambda^2}\right)$$

Double-J/ψ molecule

Assume: There is a bound (solid line) or virtual (dashed line) state with E_B

$$T\left(E_B;k',k\right) = \xi V^S_{\text{tot}}\left(k',k,\Lambda\right) + \xi \int \frac{\mathrm{d}^3 l}{(2\pi)^3} \frac{V^S_{\text{tot}}\left(k',l,\Lambda\right) T(E_B;l,k)}{E_B - l^2/M_{J/\psi} + i\epsilon}$$

$$V^S_{\text{tot}}\left(k',k,\Lambda\right) = \langle V_{\text{tot}}(\vec{k}-\vec{k}',\Lambda)\rangle_{\vec{n}'} = V^S_{\text{CT}}\left(k',k,\Lambda\right) + V^S_{\text{exch}}\left(k',k,\Lambda\right)$$

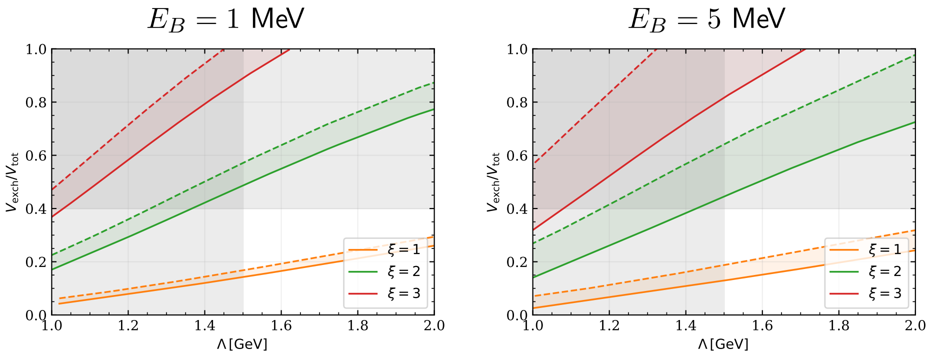
Notice: There are no sources for V_{CT} larger than from pion/kaon exchanges:

- exchange of (soft gluons)/(light mesons) is OZI suppressed
- exchange of charmonia is suppressed as $\Lambda^2_{\text{QCD}}/m_c^2$

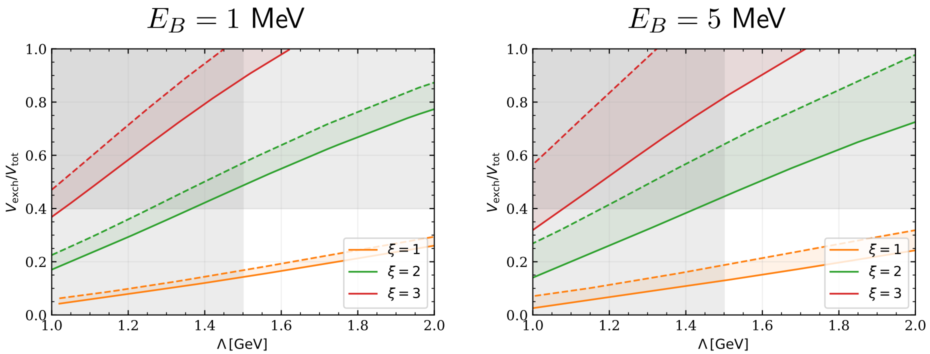
Conclude: It is natural to expect that

$$R \equiv \frac{V^S_{\text{exch}}(k'=0,k=0,\Lambda)}{V^S_{\text{tot}}(k'=0,k=0,\Lambda)} \gtrsim 1/2$$

Double-J/ψ molecule



Double-J/ψ molecule



Conclusion: Existence of a molecular pole near the double-J/ψ threshold is consistent with our knowledge on hadron-hadron interactions

Prediction

- S-wave scattering amplitude at threshold

$$\mathcal{M}_0[J/\psi\pi \to J/\psi\pi] = 8\pi(M_{J/\psi} + m_\pi)a_0$$

was used to fix a_0

- P-wave scattering amplitude at threshold

$$\mathcal{M}_1[J/\psi\pi \to J/\psi\pi] = 8\pi(M_{J/\psi} + m_\pi)k^2 a_1$$

provides prediction for a_1

$$a_1 \simeq -(0.2 \sim 0.6)\ \text{GeV}^{-3}$$

Conclusions

- Discovery of $X(3872)$ started new era in hadronic physics of heavy quarks
- Recent discoveries by LHCb opened new chapter in this book
- Data collected are analysed
  - using (minimal but realistic) coupled-channel scheme
  - preserving unitarity
  - respecting (approximate but accurate) heavy quark spin symmetry
- Existence of a state at $J/\psi J/\psi$ threshold is predicted from data analysis
- Conjecture of molecular nature of $X(6200)$ proved consistent with our knowledge of hadron-hadron interactions
- Tests outlined to verify/falsify approach and conclusions
- To be continued as soon as new data arrive...