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Possible Bound States of J/ψJ/ψ from Two Pion Exchange

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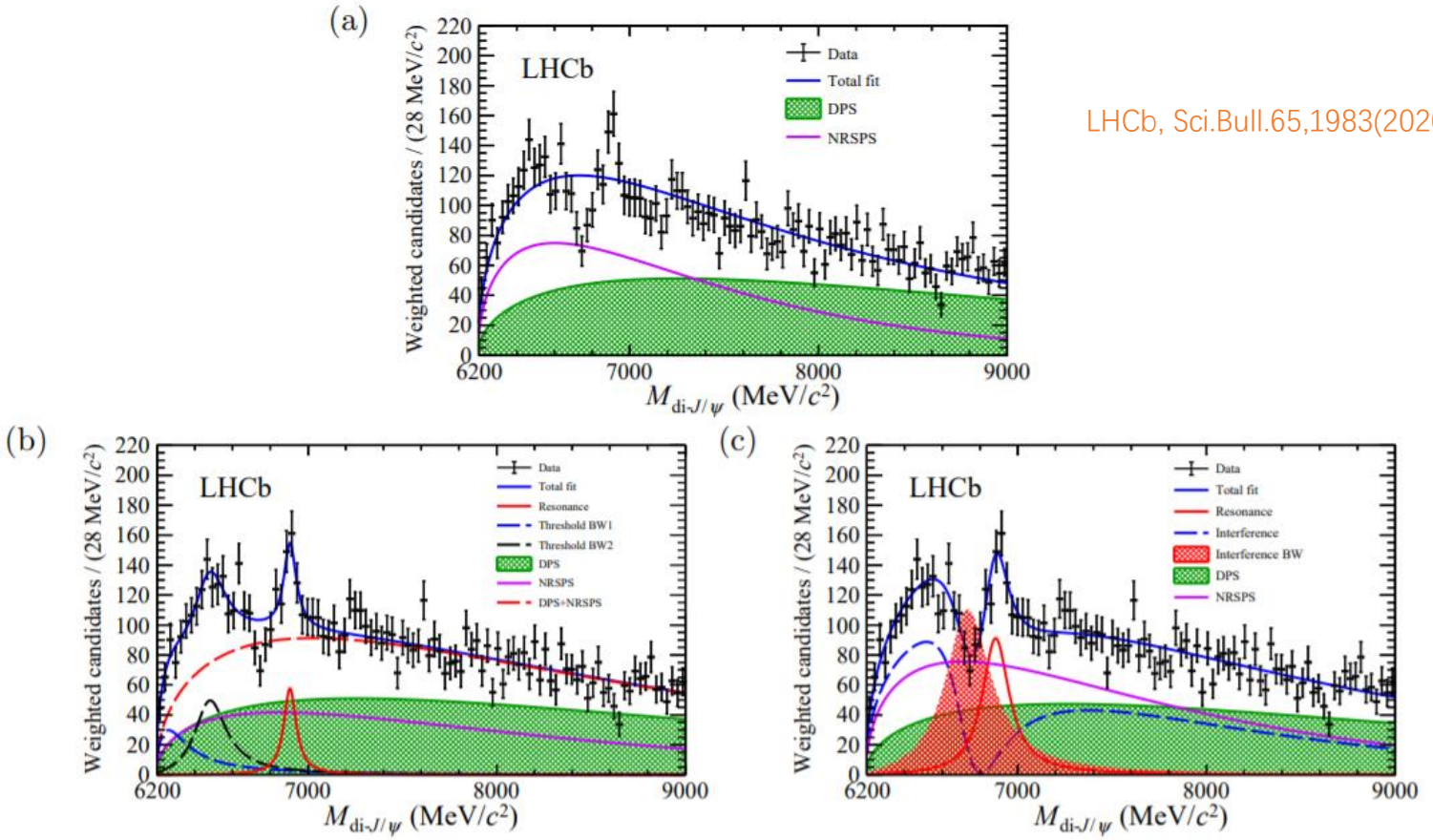
- Is the existence of a J/ψJ/ψ bound state plausible?
  X.-K. Dong, V. Baru, F.-K. Guo, C. Hanhart, A. Nefediev and B.-S. Zou, arxiv:2107.03946

Outline

- Background: Experimental signals of $cc\bar{c}\bar{c}$ states
- Interactions between J/ψJ/ψ: soft gluon exchange → two pion exchange + …
- Possible bound states of J/ψJ/ψ

Background — X(6900) in LHCb measurement



LHCb, Sci.Bull.65,1983(2020)

Figure 3: Invariant mass spectra of weighted di-J/ψ candidates with $p_{\mathrm{T}}^{\text{di-}J/\psi} > 5.2\,\mathrm{GeV}/c$ and overlaid projections of the $p_{\mathrm{T}}^{\text{di-}J/\psi}$-threshold fit using (a) the NRSPS plus DPS model, (b) model I, and (c) model II.

Background — Fully heavy tetraquarks

➢ Compact tetraquarks?

Predictions dated back to 1970s

R.L. Jaffe, PRD15, 267(1977),

K.-T. Chao, Z.Phys.C7, 317(1981),

A. M. Badalian etal, PRD25,2370(1982), …

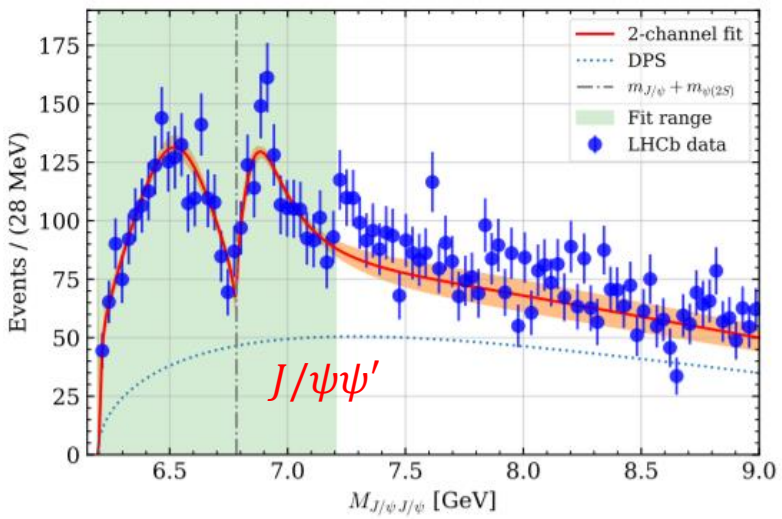
Many theoretical investigations

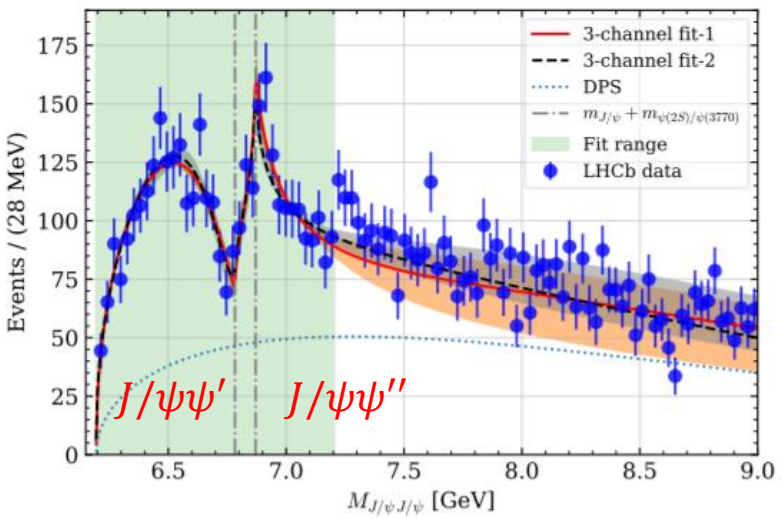
➢ Molecular configurations?

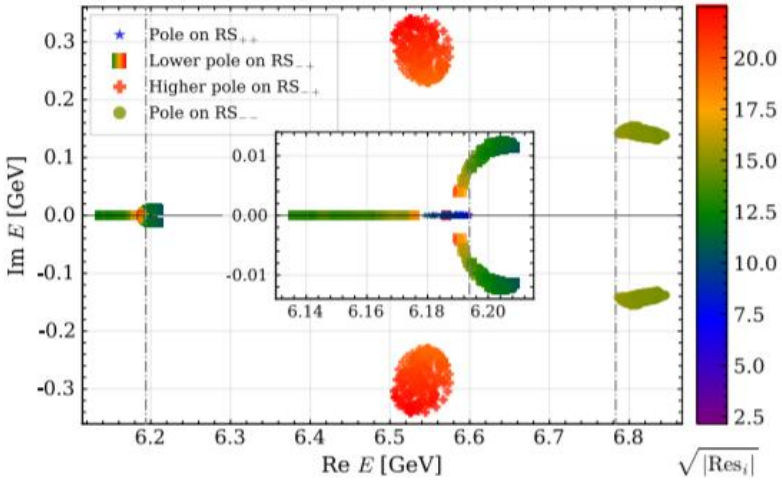
Hints of X(6200) in LHCb data, X.-K. Dong et al, PRL126,132001(2021), Z.-R. Liang et al, arXiv:2104.08589

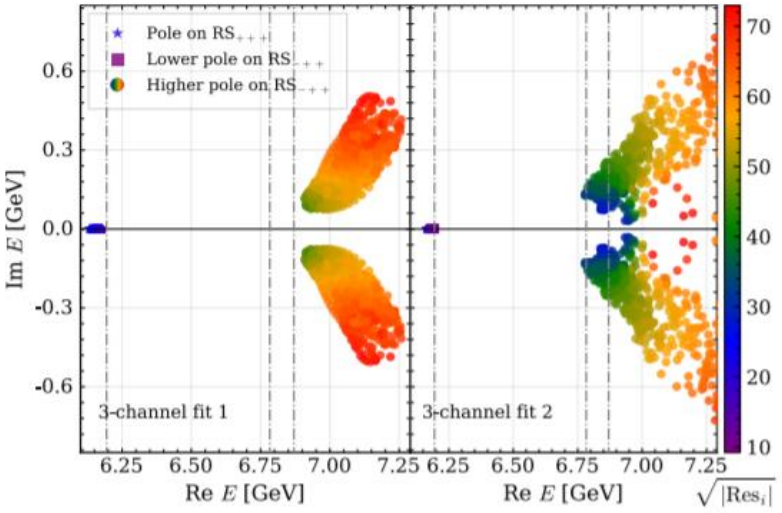
What's the binding mechanism???

Background — Hints of a J/ψ J/ψ molecule









X.-K. Dong et al, PRL126,132001(2021)

Background — Hints of a J/ψ J/ψ molecule

	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
$r_0(\mathrm{fm})$	$-2.18^{+0.66}_{-0.81}$	$-0.06^{+0.03}_{-0.04}$	$-0.09^{+0.08}_{-0.05}$
$\bar{X}_A$	$0.39^{+0.58}_{-0.12}$	$0.91^{+0.04}_{-0.07}$	$0.95^{+0.04}_{-0.06}$

X.-K. Dong et al, PRL126,132001(2021),

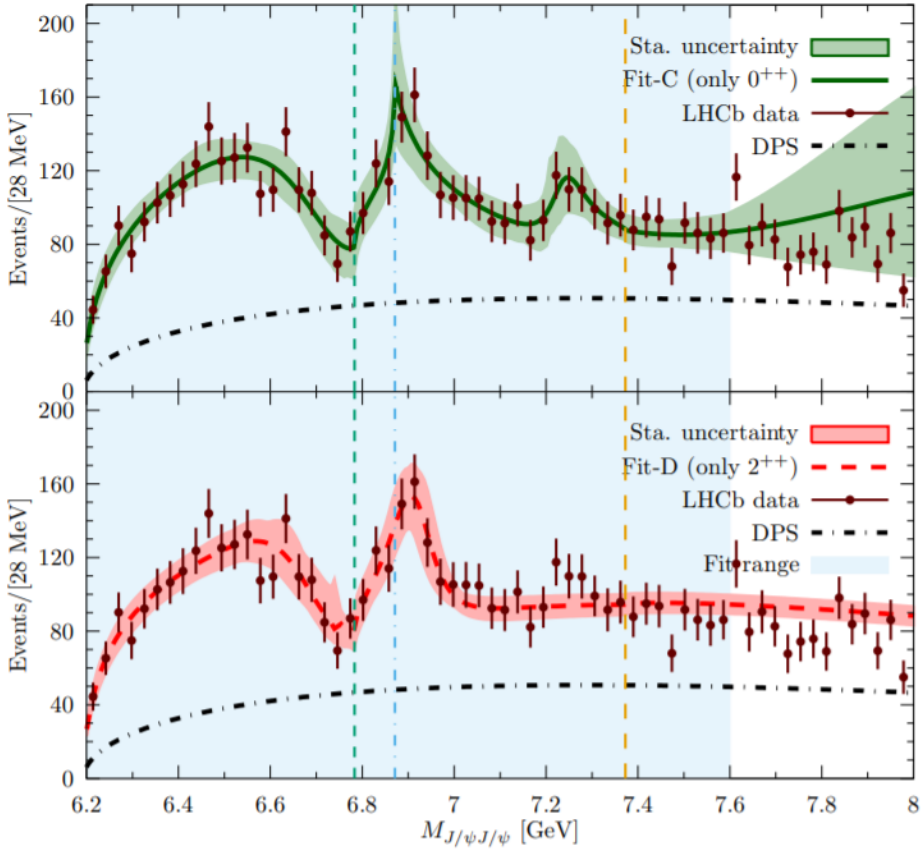
- Compositeness of $X(6200)$

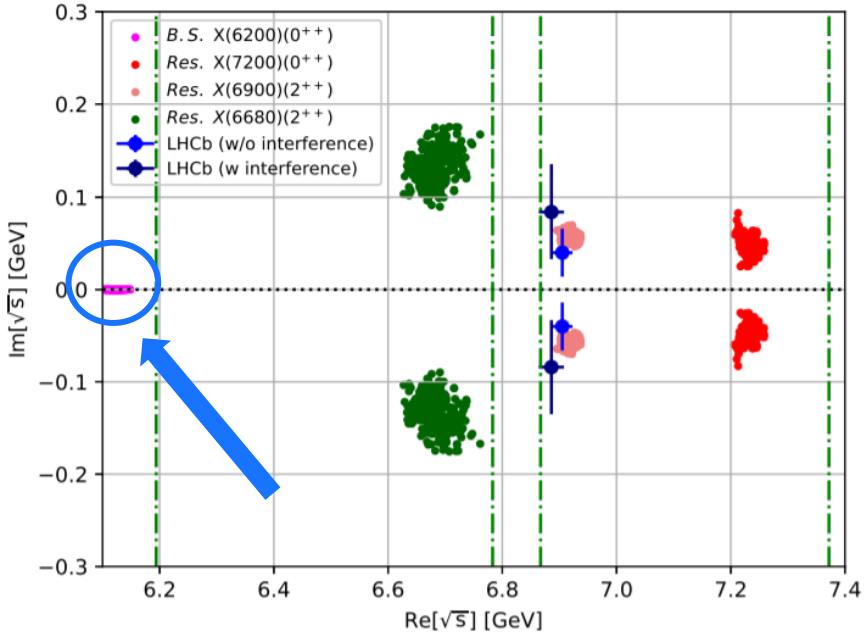
$$\bar{X}_A = (1 + 2|r_0/a_0|)^{-1/2}$$ I. Matusche et al, EPJA57(2021)3,101

$\bar{X}_A = 1$ for molecules and 0 for compact state .

- Large molecular component in $X(6200)$ in 3-channel fit.

Background — Hints of a J/ψ J/ψ molecule



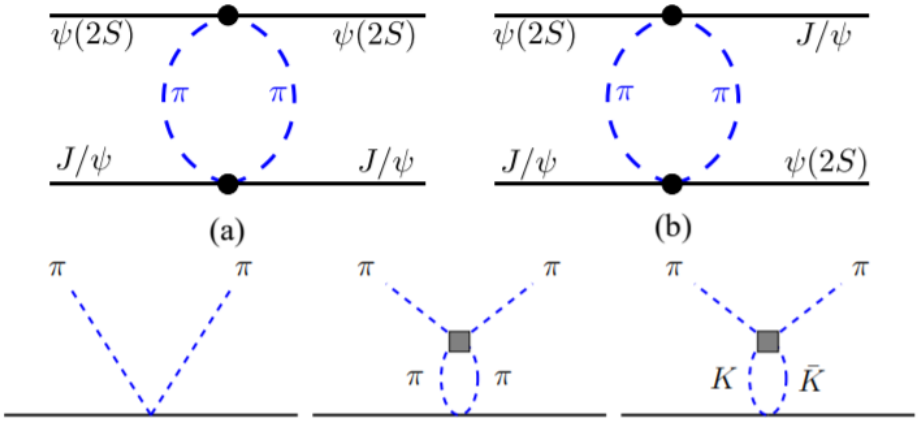


Z.-R. Liang et al, arXiv:2104.08589

- Existence of $X(6200)$ confirmed

Interactions between J/ψ J/ψ

Two pion exchange



- $\psi\psi\pi\pi$ coupling related to the chromopolarisabilities, α_{AB}, satisfying

$$\alpha_{J/\psi J/\psi}\alpha_{\psi(2S)\psi(2S)} \geq \alpha^2_{\psi(2S)J/\psi}.$$ A. Sibirtsev et al, PRD71, 076005(2005)

- Difference between $\psi(2S)$ and J/ψ estimated: $\xi \equiv \frac{\alpha_{J/\psi J/\psi}}{\alpha_{\psi(2S)J/\psi}} \approx 1 \sim 3$

  quark model wavefunction & $J/\psi\pi$ scattering length

- $\psi(2S)J/\psi\pi\pi$ coupling from BESII data on $\psi(2S) \to J/\psi\pi\pi$ decay.

  [BES Collaboration], PLB645, 19 (2007)

- Non-perturbative interaction of scalar-isoscalar $\pi\pi$ and $K\bar{K}$ channel considered.
- Potentials via dispersive relation.

$\psi\psi\pi\pi$ coupling

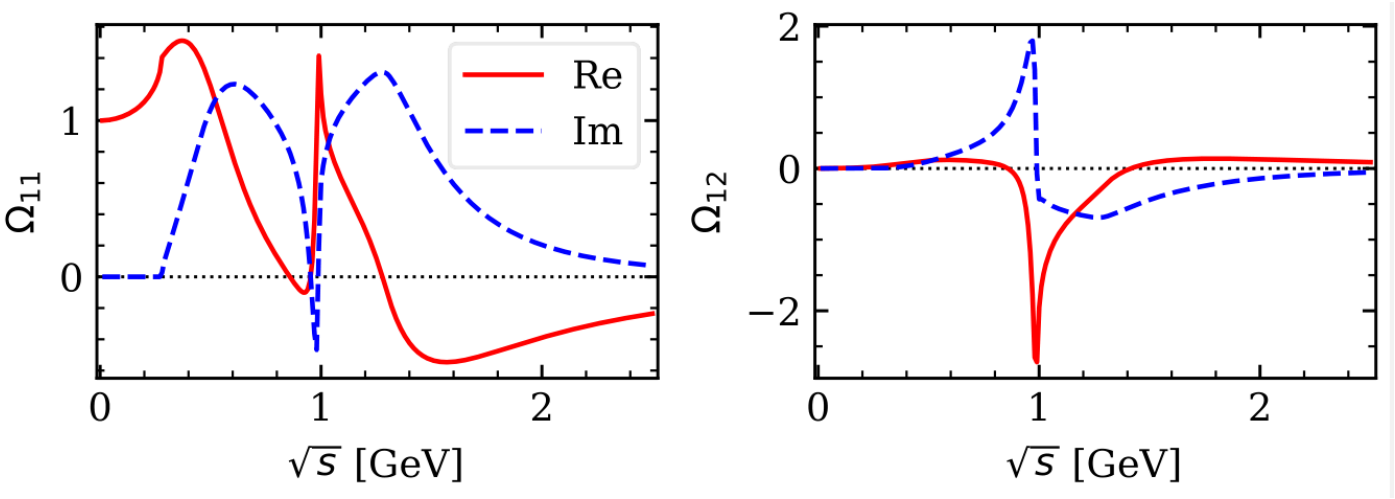
- Lagrangian from HQSS

$$\mathcal{L}_{\psi_\alpha\psi_\beta\Phi\Phi} = \frac{c_1^{(\alpha\beta)}}{2}\left\langle J_\beta^\dagger J_\alpha\right\rangle \mathrm{Tr}[u_\mu u^\mu] + \frac{c_2^{(\alpha\beta)}}{2}\left\langle J_\beta^\dagger J_\alpha\right\rangle \mathrm{Tr}[u_\mu u_\nu]v^\mu v^\nu + \mathrm{H.c.}$$

- Amplitude of $\psi(2S) \to J/\psi\pi\pi$ reads

$$\mathcal{M}_1(s) = \Omega_{11}^S(s)\mathcal{M}^S(s;m_\pi) + \Omega_{12}^S(s)\frac{2}{\sqrt{3}}\mathcal{M}^S(s;m_K)$$

$$\mathcal{M}_{\pi\pi}(s,\theta) = \sqrt{\frac{2}{3}}\left[\mathcal{M}_1(s) + \Omega^D(s)P_2(\cos\theta)\mathcal{M}^D(s;m_\pi)\right]$$



Omnes data from S. Ropertz et al, EPJC78, 1000(2018)

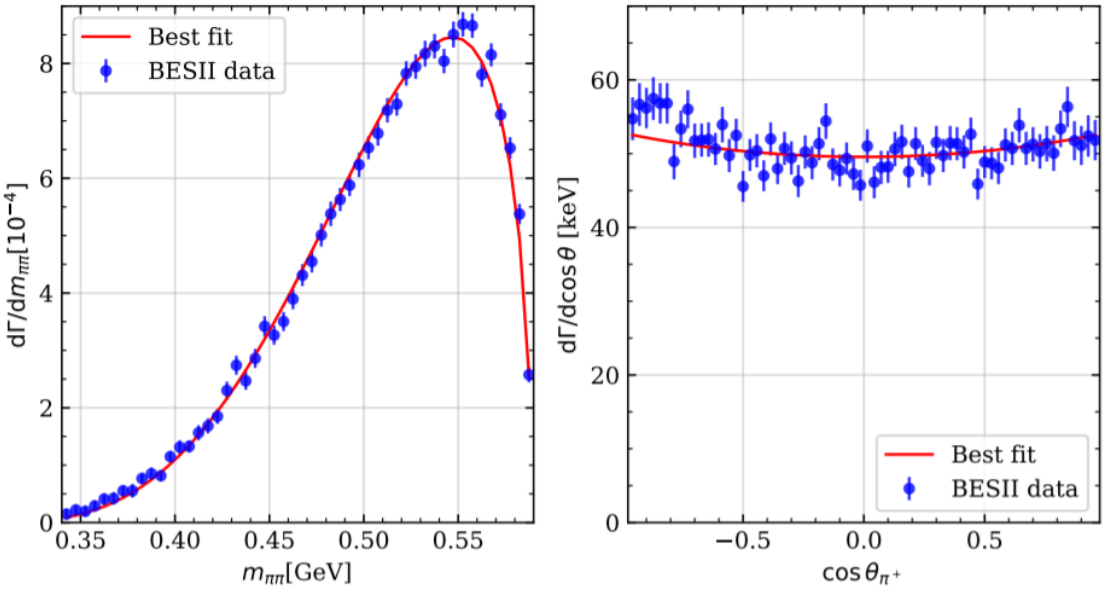
Fitting BESII data

- Formula $$\frac{\mathrm{d}\Gamma[\psi(2S)\to J/\psi\pi^+\pi^-]}{\mathrm{d}m_{\pi\pi}\mathrm{d}\cos\theta}=\frac{\sqrt{s}\sigma_\pi(s)|\vec{k}|}{128\pi^3 M^2_{\psi(2S)}}|\mathcal{M}_{\pi\pi}(s,\theta)|^2$$
- Result $$c_1^{(21)}=0.229\pm0.002,\quad c_2^{(21)}=-0.061\pm0.003$$

$$|\alpha_{\psi(2S)J/\psi}|=(1.81\pm0.01\pm0.11)\ \mathrm{GeV}^{-3}$$

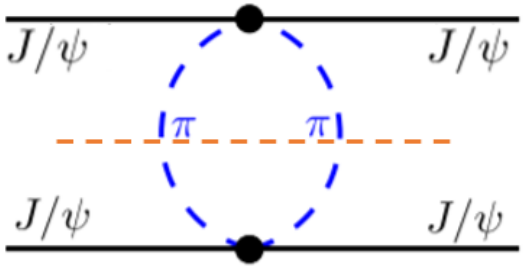
uncertainty from data

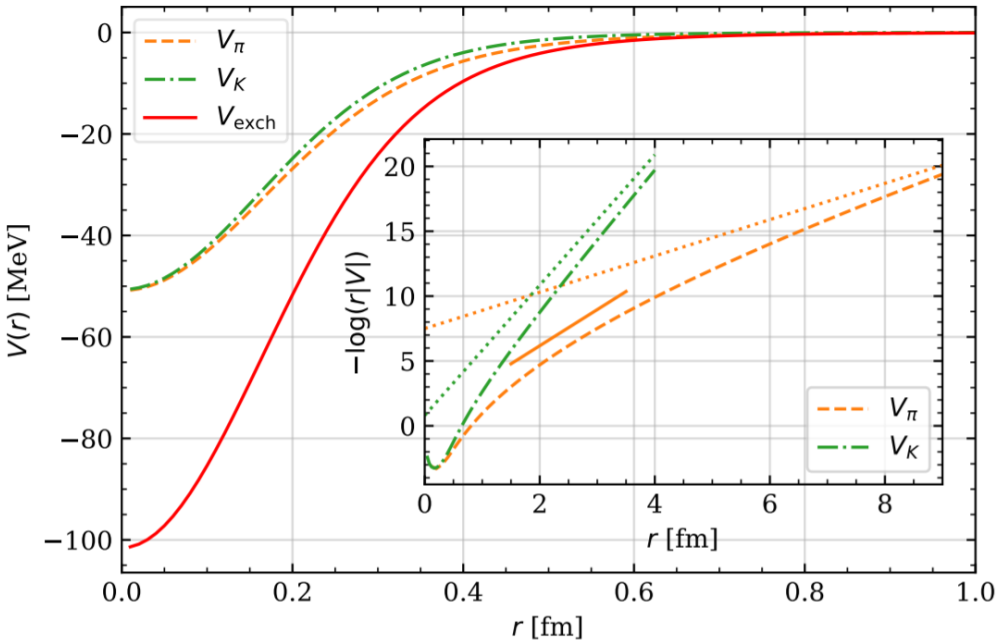
uncertainty from Omnès



Potential

$\mathcal{M}_\pi(s) =$





- two pion (kaon) exchange potential $\mathcal{M}_{J/\psi J/\psi}(s) = \mathcal{M}_\pi(s) + \mathcal{M}_K(s)$

$$V_{\rm exch}(q,\Lambda) = \frac{-1}{4\pi M_{J/\psi}^2}\int_{4m_\pi^2}^{\infty} {\rm d}\mu^2 \frac{{\rm Im}\mathcal{M}_{J/\psi J/\psi}(\mu^2)}{\mu^2+q^2} e^{-\frac{q^2+\mu^2}{\Lambda^2}}$$

- Contact term

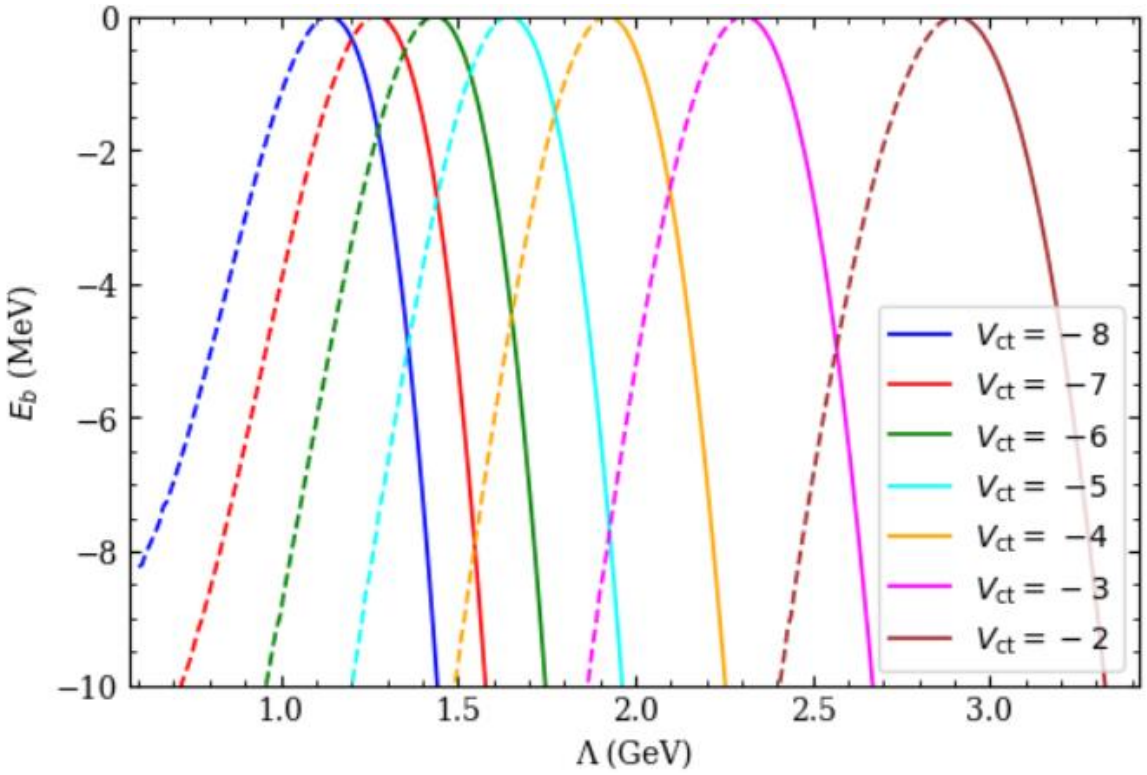
$$V_{\rm CT}(q,\Lambda) = C\ e^{-\frac{q^2}{\Lambda^2}} \qquad V_{\rm tot}(q,\Lambda) = V_{\rm CT}(q,\Lambda) + V_{\rm exch}(q,\Lambda)$$

$J/\psi J/\psi$ molecular states

Solving Lippmann-Schwinger equation

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

- Parameters: $\Lambda(1\sim3\ \mathrm{GeV}),\ \xi(1\sim3)$ and V_{ct} in GeV^{-2}
- Poles for $\xi=1$. Solid for bound states and dashed for virtual states

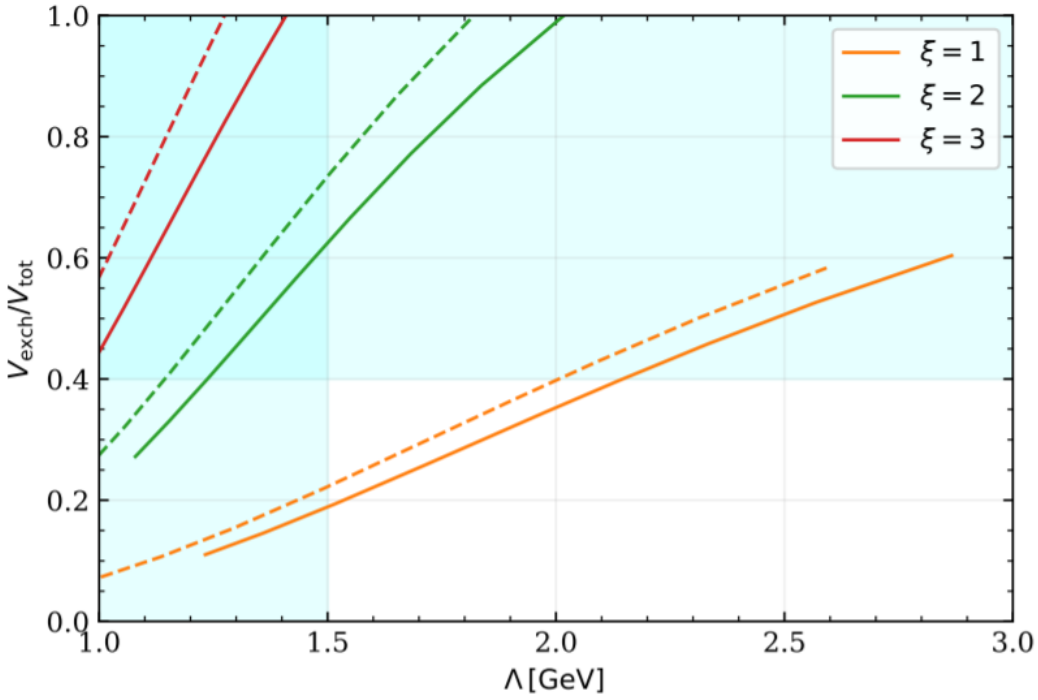


Plausible?

- Contact term + two pion (kaon) exchange leads to a molecule of $J/\psi J/\psi$
- We take it plausible if two pion (kaon) exchange has sizeable contributions to the binding of $J/\psi J/\psi$, characterized by the ratio

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

- The pole position is fixed to be 1 MeV below the threshold.
- Solid for bound states, dashed for virtual states.



Summary

- Experimental hints of a states near $J/\psi J/\psi$ threshold, with possible molecular nature
- Soft gluon exchange between $J/\psi J/\psi$ described by two pion and kaon exchange.
- Coupling constants of $\psi\psi\pi\pi$ coupling extracted from BESII data on $\psi(2S) \to J/\psi\pi\pi$ decay
- $J/\psi J/\psi\pi\pi$ coupling is argued to be $1 \sim 3$ times of $\psi(2S)J/\psi\pi\pi$ coupling
- With reasonable cutoff Λ, two pion and kaon exchange provide sizeable contribution to the $J/\psi J/\psi$ attraction.
- The binding of $J/\psi J/\psi$ system is plausible, given our current understanding of hadron-hadron interaction.
- Take a look at $J/\psi e^+e^-$ or $J/\psi\mu^+\mu^-$ channels.

Thank you!