J/ψ interaction from the two-pion decays of $\psi(2S)$

An attempt to get insight into $J/\psi - N$ interaction from $\psi(2S)$ decay

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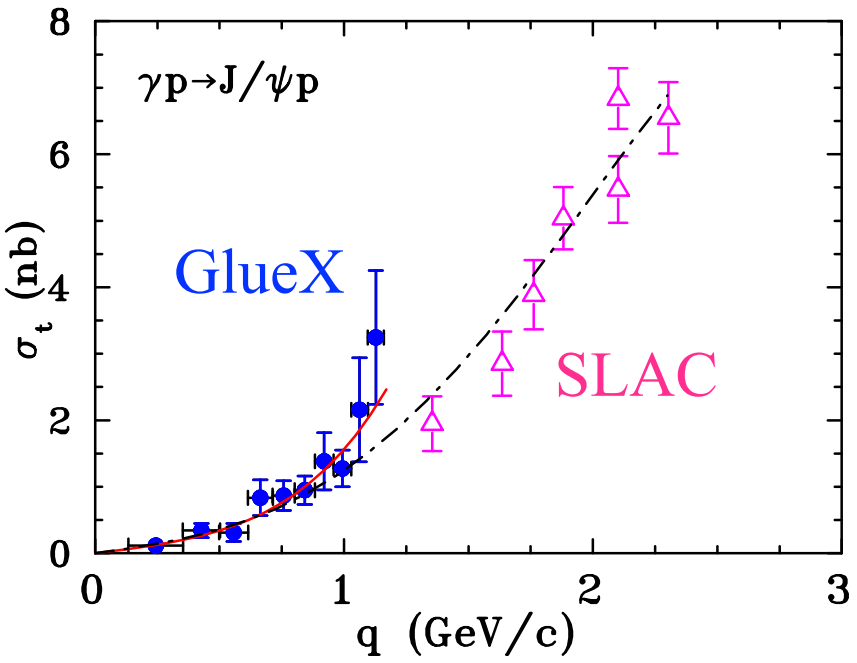
In collaboration with Kazuki Yoshida (RCNP)

1. Motivation
2. Experimental facts
3. J/ψ-N interaction from $\psi(2S)$ decay
4. 4. Summary and to-do

1. Motivations

Controversies in $J/\psi - N$ interaction

- Photoproduction exp: Strakovsky, Epifanov, Pentchev, PRC 101, 042201 (2020)



Glue X: A. Ali *et al.*,
Phys. Rev. Lett. **123**, 072001 (2019).
SLAC: U. Camerini *et al.*,
Phys. Rev. Lett. **35**, 483 (1975).

$$|\alpha_{J/\psi p}| = \frac{g_{J/\psi\gamma}}{2\pi}\sqrt{\frac{ka_1}{\alpha}} = (3.08 \pm 0.55)\,\text{mfm}$$

Very small interaction strength

• Lattice QCD: Lyu, Doi, Hatsuda and Sugiura, PLB860 (2025) 139178

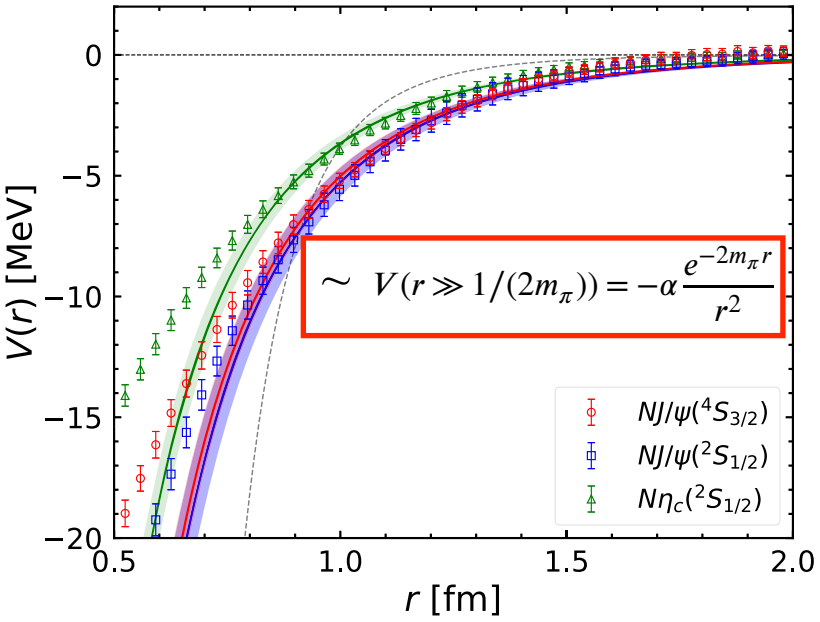
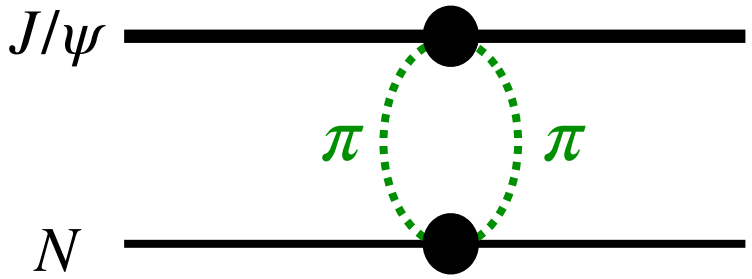


Table 3

The N-$c\bar{c}$ scattering length a_0 and effective range $r_{\rm eff}$ with statistical error (1st parentheses) and systematic error (2nd parentheses).

channel	a_0 [fm]	$r_{\rm eff}$ [fm]
N-$J/\psi(^4S_{3/2})$	$0.30(2)\binom{+0}{-2}$	$3.25(12)\binom{+6}{-9}$
N-$J/\psi(^2S_{1/2})$	$0.38(4)\binom{+0}{-3}$	$2.66(21)\binom{+0}{-10}$
$N\eta_c(^2S_{1/2})$	$0.21(2)\binom{+0}{-1}$	$3.65(19)\binom{+0}{-6}$

Significant amount of attraction
via 2π exchange at intermediate range



cf: Suenaga's talk, 9/24 11:30-

Question:

- How strong is the interaction ?
- How charm (heavy) quarks couple to π (OZI suppressed process)

Our attempt:

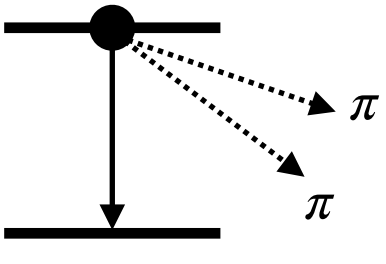
Find the interaction from the decays

2. Experimental facts

Radially excited states emit $\pi\pi$

Already in Abrams et al., PRL34, 1181 (1975)

May 1975 only half year after the november revolution



From PDG	Γ_{tot}	$\Gamma_{\pi^+\pi^-}$	$\Gamma_{\pi^0\pi^0}$	
$\psi(2S \to 1S)$	286	89	52	in keV

Features:

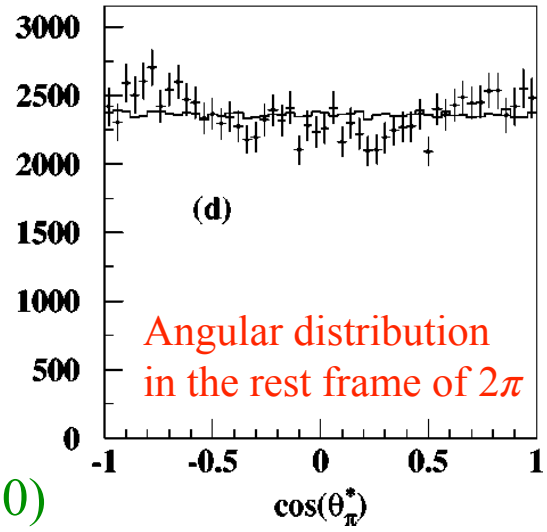
- Dominant branch in

$$\psi(2S) \to \psi(1S) + \text{any hadrons}$$

53% / 62%

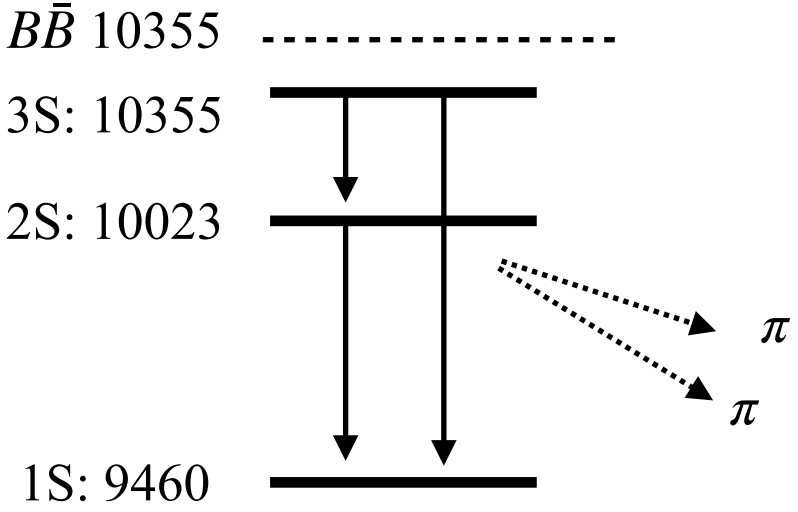
- The ratio of charged/neutral implies isoscalar
- Flat angle distribution implies scalar

⇨ 2π are σ ($f_0(500)$) like



BES: PRD 62, 032002 (2000)

More in Υ



	Γ_{tot}	$\Gamma_{\pi^+\pi^-}$	$\Gamma_{\pi^0\pi^0}$	in keV
$\Upsilon(2S \to 1S)$	32	5.7	2.8	
$\Upsilon(3S \to 1S)$	20	0.9	0.4	
$\Upsilon(3S \to 2S)$	20	0.6	0.4	

3. $J/\psi - N$ from $\psi(2S)$ decay

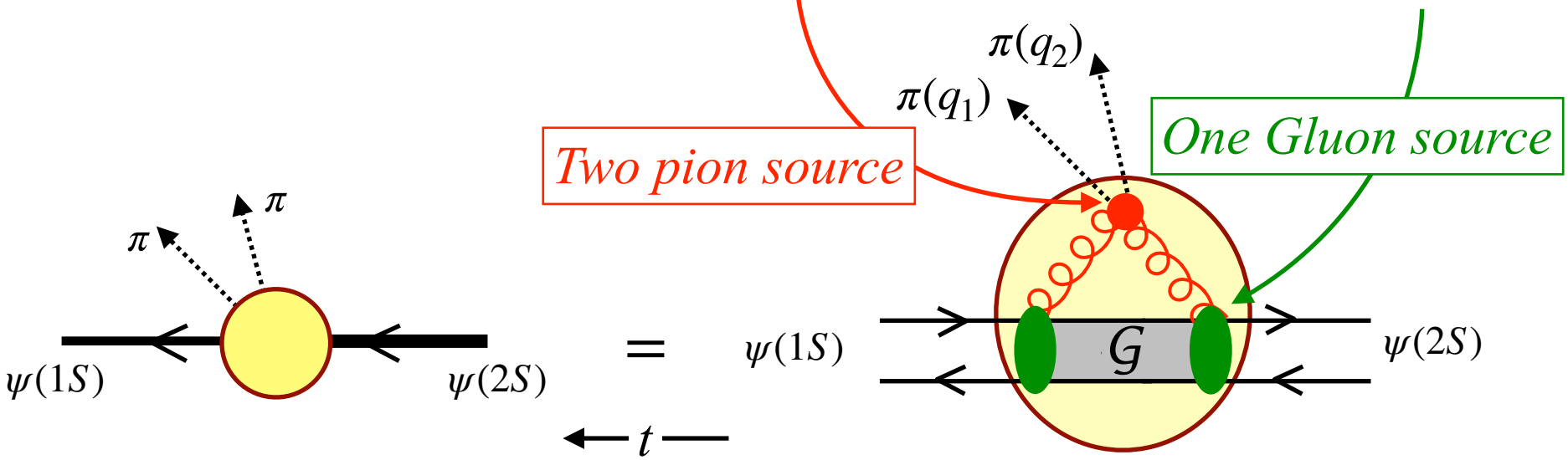
Many references for the decays (~ 2000): eg. Voloshin, PRD74, 054022 (2006)
Pions are emitted from the soft gluon source

$$H_{E1} = -\tfrac{1}{2}\xi^a \vec{r}\cdot\vec{E}^a(0)$$

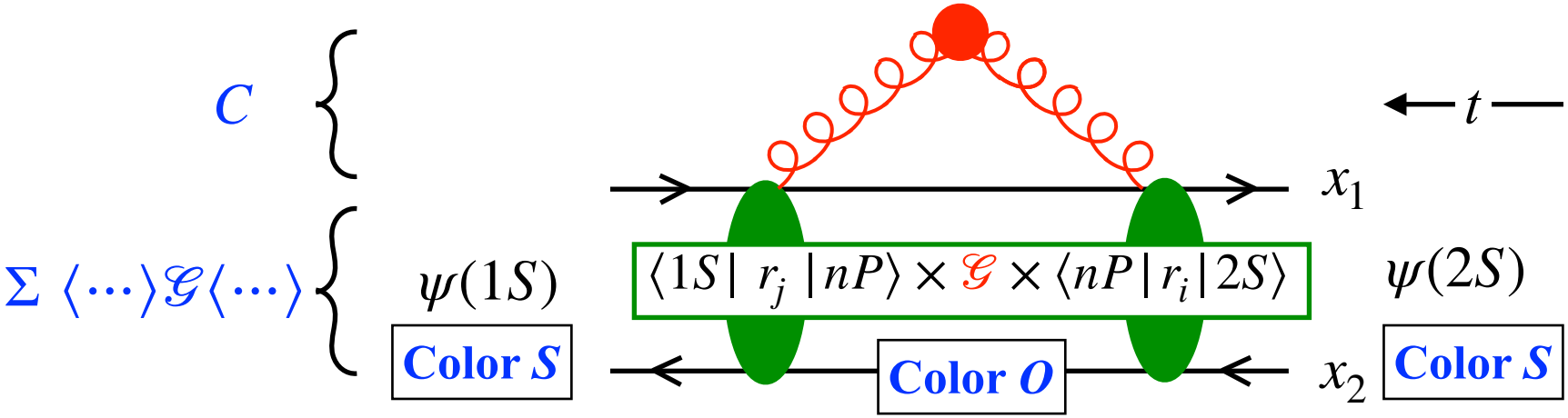
⇩ 2nd order

Considering quarkonium as a compact nonrelativistic object, one can apply the multipole expansion for the quarkonium interaction with a soft gluonic field [4,16].

$$A(\psi_2 \to \pi^+\pi^-\psi_1) = \tfrac{1}{2}\langle\pi^+\pi^-|E_i^a E_j^a|0\rangle \times \tfrac{1}{16}\langle\psi_1|\xi^a r_i \mathcal{G} r_j \xi^a|\psi_2\rangle$$



Gluon source



$$A(\psi_2 \to \psi_1\pi\pi) \sim \text{Pion source} \times \text{Gluon source}$$

$$A(\psi_2 \to \psi_1\pi\pi) \sim C \times \Sigma_n \langle 1S|\ r_j\ |nP\rangle \mathcal{G} \langle nP|\, r_i\, |2S\rangle$$

$$A(\psi_1 \to \psi_1\pi\pi) \sim C \times \Sigma_n \langle 1S|\ r_j\ |nP\rangle \mathcal{G} \langle nP|\, r_i\, |1S\rangle$$

$$A(\psi_{1S} \to \psi_{1S}\pi\pi) \sim \frac{\Sigma_n \langle 1S|\ r_j\ |nP\rangle \mathcal{G} \langle nP|\, r_i\, |1S\rangle}{\Sigma_n \langle 1S|\ r_j\ |nP\rangle \mathcal{G} \langle nP|\, r_i\, |2S\rangle} \times A(\psi_{2S} \to \psi_{1S}\pi\pi)$$

Computable

Decay exp

Computation of $\dfrac{\Sigma_n \langle 1S|\ r_j\ |nP\rangle \mathcal{G} \langle nP|\ r_i\ |1S\rangle}{\Sigma_n \langle 1S|\ r_j\ |nP\rangle \mathcal{G} \langle nP|\ r_i\ |2S\rangle} \equiv \dfrac{N}{D}$

$$N = \sum_n \langle 1S|\ r_j\ |nP\rangle \mathcal{G} \langle nP|\ r_i\ |1S\rangle = \int \frac{d^3p}{(2\pi)^3} \frac{\langle \psi_{1S}|\, r\, |l=1;p\rangle \langle l=1;p|\, r\, |\psi_{1S}\rangle}{E_B - p^2/\mu}$$

$$D = \sum_n \langle 1S|\ r_j\ |nP\rangle \mathcal{G} \langle nP|\ r_i\ |2S\rangle = \int \frac{d^3p}{(2\pi)^3} \frac{\langle \psi_{1S}|\, r\, |l=1;p\rangle \langle l=1;p|\, r\, |\psi_{2S}\rangle}{E_B - p^2/\mu}$$

Brambilla et al, NPB,566, 275 (2000);
PRD.93.054002(2016)

pNRQCD$^{(*)}$ implies the use of

ψ_{1S}, ψ_{2S}: Bound states in a color *singlet potential* $V_S(r)$

$l = 1; p$: Scattering states in a color *octet potential* $V_O(r)$

$$V_S(r) = -\frac{4}{3}\frac{\alpha_S}{r} + br, \quad V_O(r) = \frac{1}{6}\frac{\alpha_S}{r}, \quad \alpha_S \sim 0.5$$

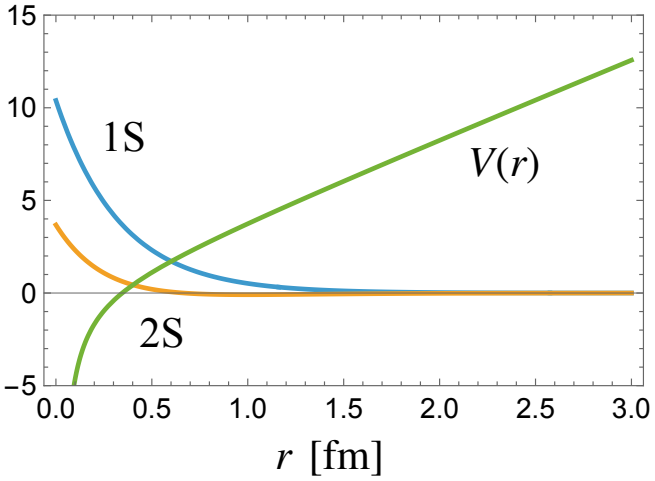
(*) Hierarchies in scales: $1 \gg v \sim \alpha_S \gg \alpha_S^2 \gg \Lambda_{QCD}/m$

Wave functions

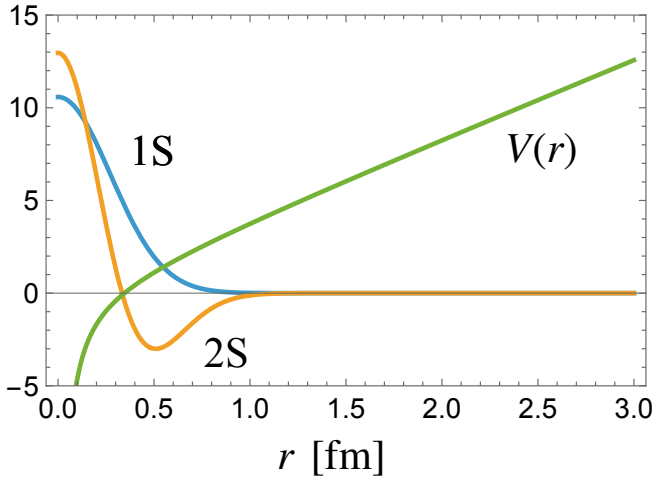
Bound states

In literatures, Coulomb WS are often employed, BUT...

Coulomb



Harmonic Oscillator



Need to use the WS with $V_s(r) = -\frac{4}{3}\frac{\alpha_S}{r} + br$

Work on the way

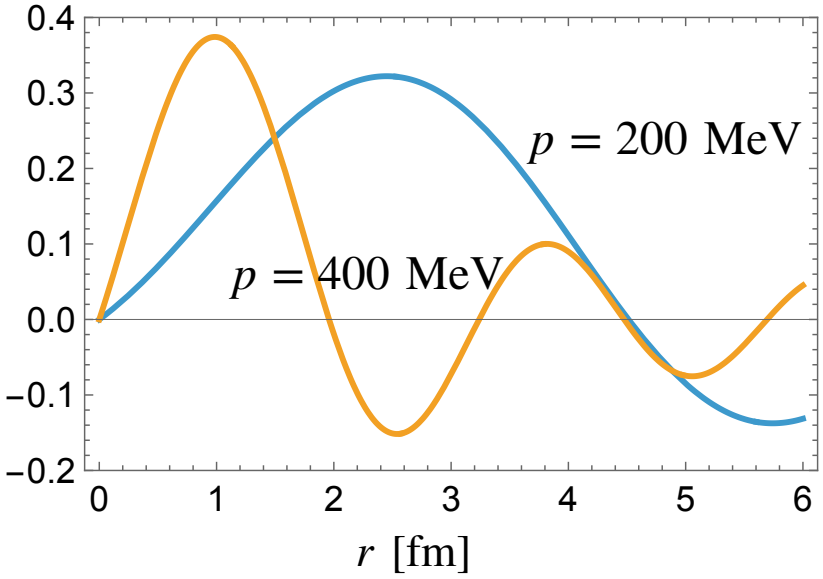
Wave functions

Scattering states

Under the repulsive potential $V_o(r) = \frac{1}{6}\frac{\alpha_S}{r}$

Confluent hypergeometric function ${}_1F_1$

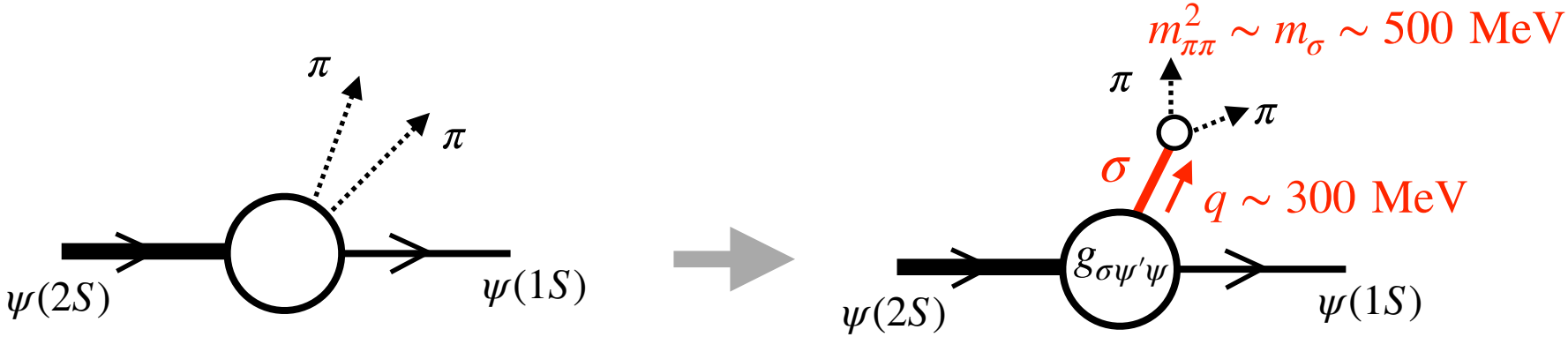
For the region of $c\bar{c} \sim 0.5$ fm, scattering state would be OK



We show tentative results of Coulomb and HO.

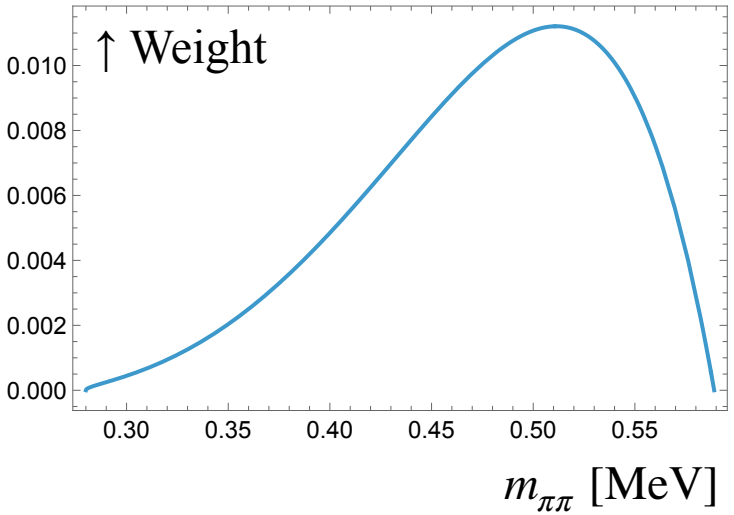
Further simplification

Identify the coupling of 2π to the coupling of σ



- 2π is replaced by a σ meson
- The mass of σ meson is determined by the 2π mass distribution (Averaged with weight)

$$|\boldsymbol{q}|^2 =$$
$$(M_2^4 + M_1^4 + m_{\pi\pi}^4 - 2M_2^2M_1^2 - 2M_2^2m_{\pi\pi}^2 - 2M_1^2m_{\pi\pi}^2)/4M_2^2$$

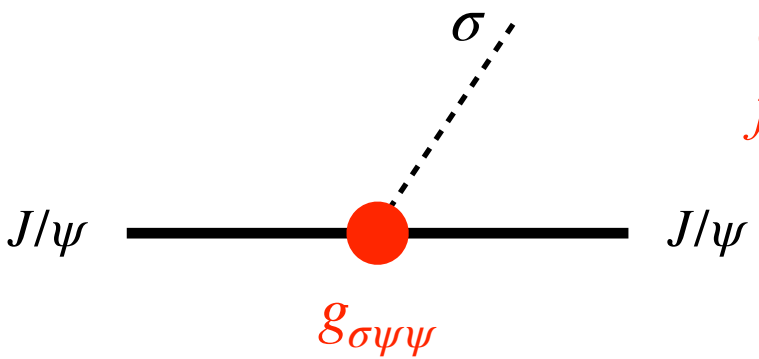


Details

$$L_{\sigma\psi'\psi} = f_{\sigma\psi'\psi}\psi^{\dagger}_{1S}\psi'_{2S} + h.c. \qquad \textit{Lagrangian}$$

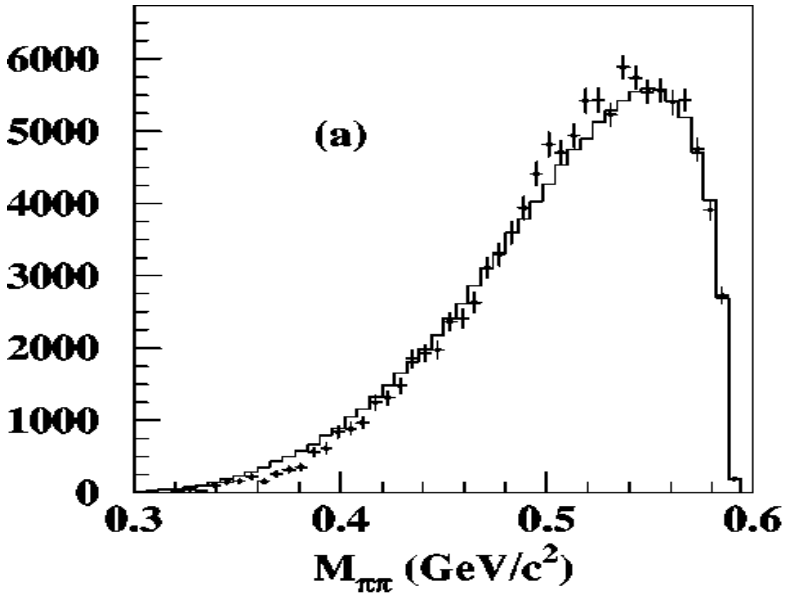
$$\Gamma = \frac{1}{4\pi}\frac{q\ f^2_{\sigma\psi'\psi}}{2M^2_{\psi'}} \rightarrow f_{\sigma\psi'\psi} \sim 416\ \text{MeV} \qquad \textit{Coupling (dimensionfull)}$$

$$\rightarrow f_{\sigma\psi\psi} = R f_{\sigma\psi\psi'} \rightarrow g_{\sigma\psi\psi} = \frac{f_{\sigma\psi\psi}}{2M_{1S}}$$

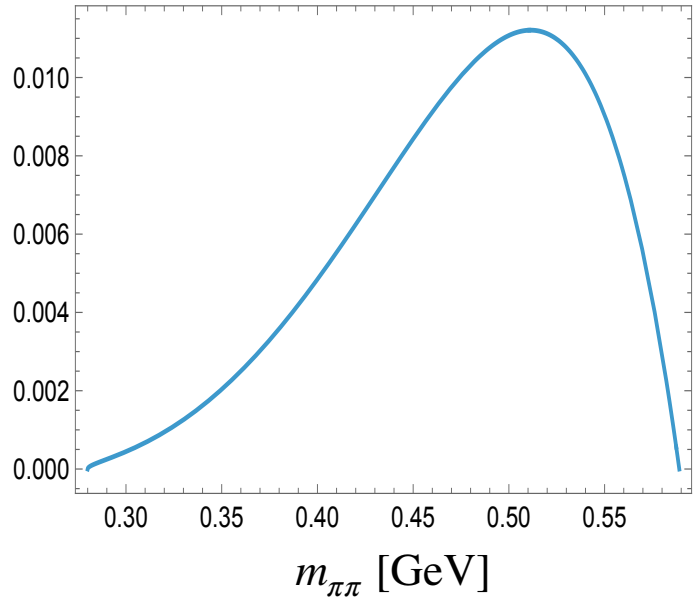


Coupling (dimensionless) for potential couplings

2π mass distribution peaks at around 500 MeV



BES: PRD 62, 032002 (2000)



Simple chiral estimate

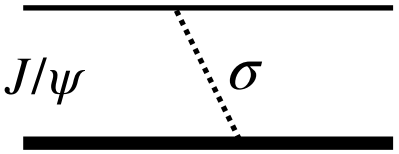
cf: Brown, Cahn, PRL35, 1 (1975)

$$|\boldsymbol{q}|^2 = (M_2^4 + M_1^4 + m_{\pi\pi}^4 - 2M_2^2M_1^2 - 2M_2^2m_{\pi\pi}^2 - 2M_1^2m_{\pi\pi}^2)/4M_2^2$$

$J/\psi - N$ potential

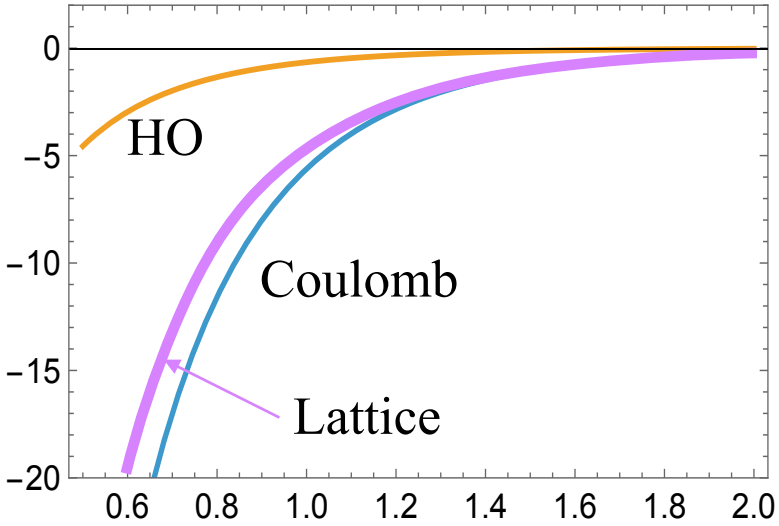
$$H_{\sigma\psi\psi} = g_{\sigma\psi\psi}\psi^\dagger\psi\sigma$$
$$H_{\sigma NN} = g_{\sigma NN}N^\dagger N\sigma$$

$$\Rightarrow \quad V_\sigma(r) = -\frac{g_{\sigma\psi\psi}g_{\sigma NN}}{4\pi}\frac{e^{-m_\sigma r}}{r}$$

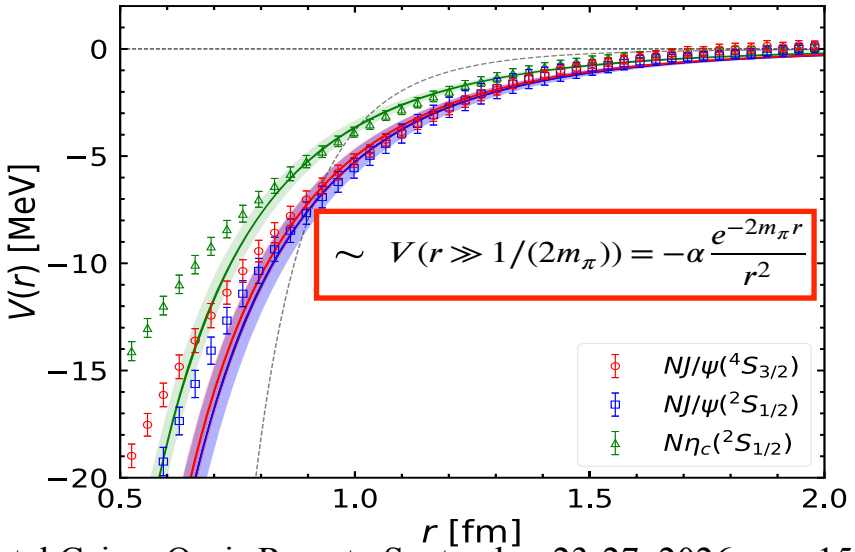


$g_{\sigma\psi\psi}$(Coulomb)	$g_{\sigma\psi\psi}$(HO)	$g_{\sigma NN}$	m_σ
0.43	0.05	10	500 MeV

Present estimate



Lyu, Doi, Hatsuda and Sugiura
PLB860 (2025) 139178

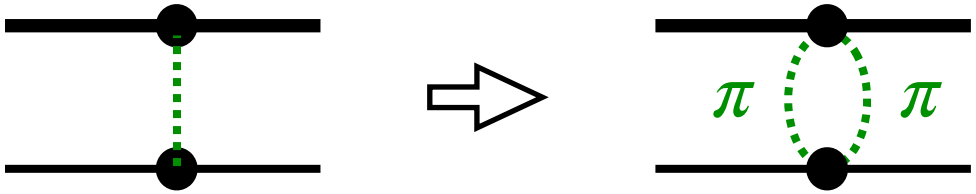


4. Summary and to-do

- 2π ($\sim \sigma$) exchange J/ψ-N force is estimated from $\psi(2S)$ decay.
- Transition via $(E1)^2$ type is computed/estimated.
- There is some strength in J/ψ-N potential
- Photoproduction with vector meson dominance is subject to form factors.

To-do list:

- Bound state wave functions with Coulomb + linear.
- Simplifications by σ exchange to be improved by 2π.



- Extend to the bottom (Υ) and strange sectors ($\phi - N$).
- More thoughts on OZI suppressed and gluon-dominate dynamics.
- And more...