East Asian Workshop on Exotic Hadrons 2024
— 东亚奇特强子态研讨会 —

Deciphering the mechanism of $J/\psi N$ scattering

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Based on arXiv: 2410.19526

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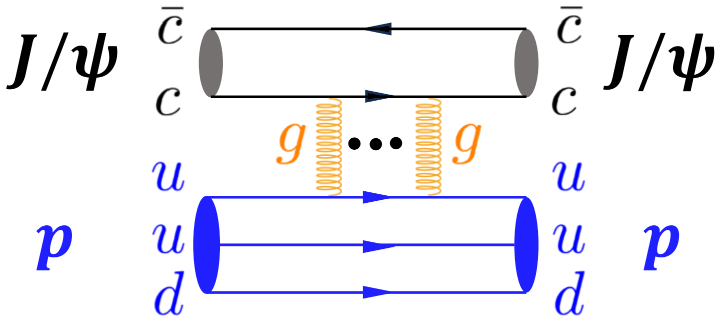
East Asian Workshop on Exotic Hadrons 2024

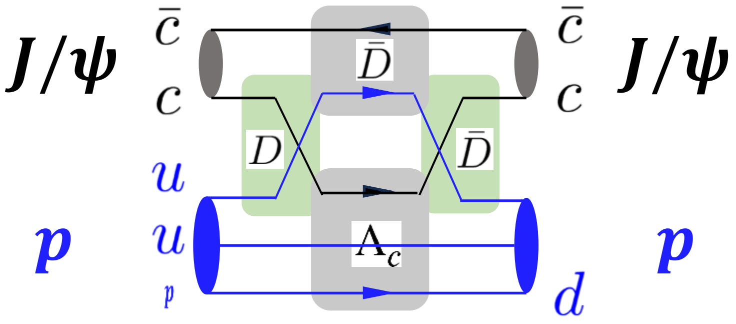
Outline

1 Background

- **The mechanism of the J/ψ and nucleon scattering**
  - Typical OZI suppression process
  - Interaction through meson exchange is suppressed $(1/N_c)$ G. 't Hooft, Nucl. Phys. B 72 (1974) 461
  - Interaction mechanism



Gluon exchanges



Coupled-channel

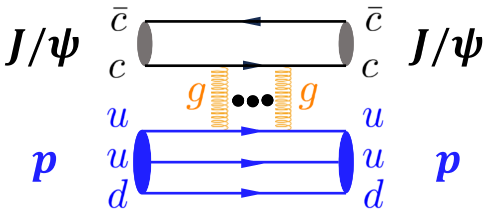
$\langle J/\psi|GG|J/\psi\rangle$ Chromopolarizability
A. Sibirtsev et al., PRD 71 (2005) 076005
Y.-H. Chen et al., PRD 93 (2016) 034030

$\langle N|GG|N\rangle$ gluon trace anomaly contribution to the nucleon mass
Y. Hatta et al., JHEP 12 (2018) 008
Y.-B. Yang et al., PRD 104 (2021) 074507

$$J/\psi N\text{-}\Lambda_c\bar{D}^{(*)}/\Sigma_c^{(*)}\bar{D}^{(*)}\text{-}J/\psi N$$

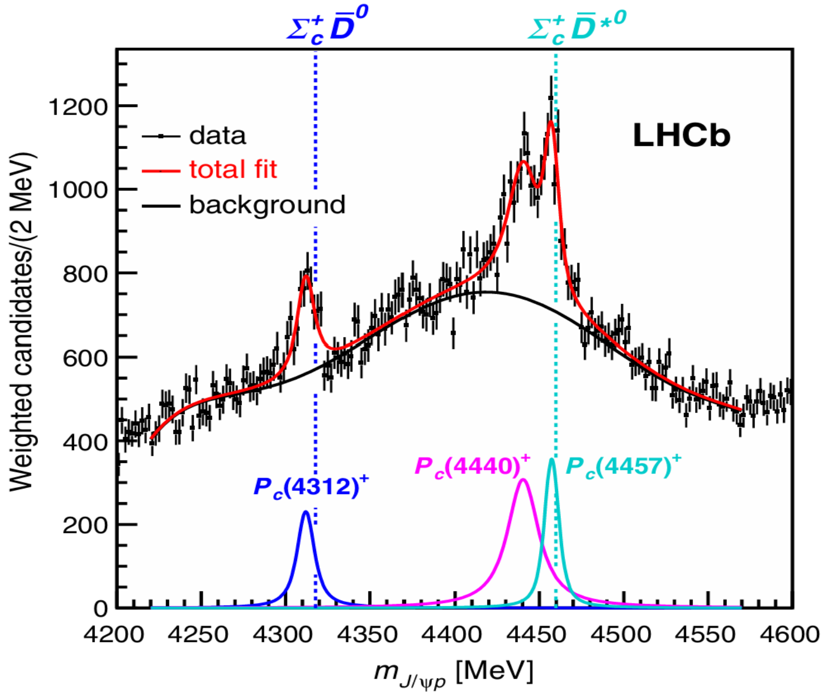
coupled-channel mechanism (hadronic loops) evade the OZI suppression
H. Lipkin, B.-S. Zou, PRD 53 (1996) 6693

- **The low-energy $J/\psi N$ scattering is important for various reasons**
  - It can offer vital insights into the role of gluons in the hadron structures and interactions among hadrons



  - It is crucial in describing the photo- and hadro-production of charmonia on the nuclear targets especially after the discovery of pentaquark P_c states

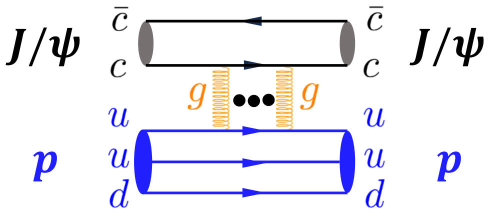
LHCb Collaboration, PRL 115 (2015) 072001
LHCb Collaboration, PRL 122 (2019) 222001



For the introduction of P_c, see Jia-Jun Wu's report in the morning

- The trace anomaly contribution to the nucleon mass

D. Kharzeev, Proc. Int. Sch. Phys. Fermi 130 (1996) 105
D. Kharzeev et al., EPJC 9 (1999) 459



$\langle N|GG|N\rangle$ gluon trace anomaly contribution to the nucleon mass

- Probing the mass of the proton has been listed as one of the main scientific goals of the Electron-Ion Collider. (One suggestion: near-threshold J/ψ photoproduction, where $J/\psi N$ scattering enters through final-state interactions)

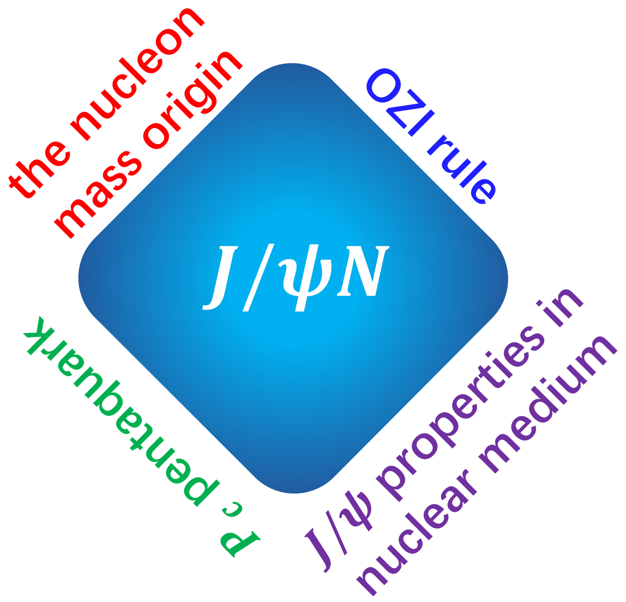
V. Burkert et al., Prog. Part. Nucl. Phys. 131 (2023) 104032
A. Accardi et al., EPJA 60 (2024) 173
D. P. Anderle et al., Front. Phys. (Beijing) 16 (2021) 64701

- It is relevant to the properties of J/ψ in nuclear medium

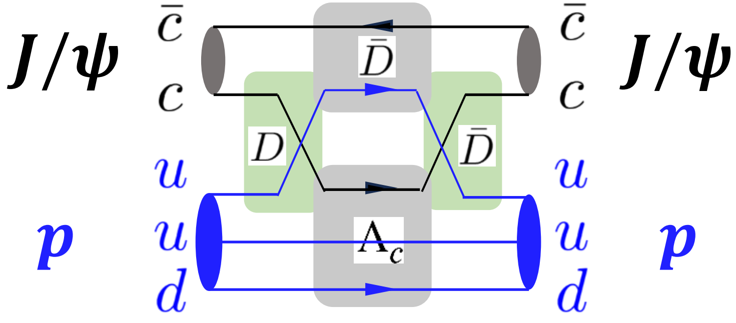
A. Sibirtsev et al., PRD 71 (2005) 076005

- Identifying signals of the quark-gluon plasma

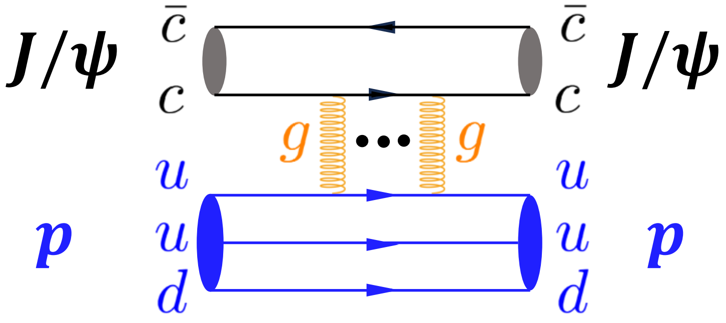
T. Barnes, EPJA 18 (2003) 531



● $J/\psi N$ scattering length



Coupled-channel



Gluon exchanges

☐ Coupled-channel mechanism

- $\Lambda_c \bar{D}^{(*)}$ contribution: 0.2 ... 3 am
  M.-L. Du et al., EPJC 80 (2020) 1053
- $\Sigma_c^{(*)} \bar{D}^{(*)}$ contribution: 0.1 ... 10 am
  M.-L. Du et al., JHEP 08 (2021) 157

☐ How about gluon exchange?

↓ If this mechanism dominate

study the origin of nucleon mass with the J/ψ as a probe is possible

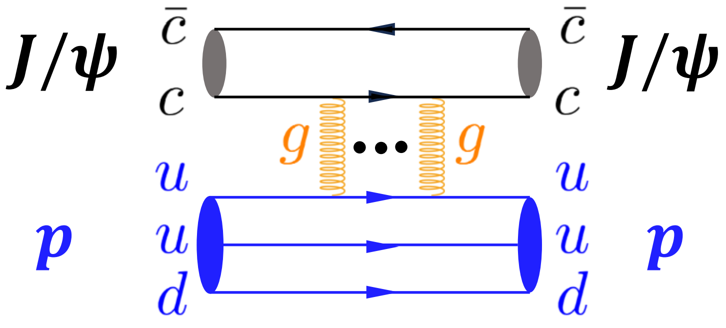
Motivation: Calculate the scattering length of $J/\psi N$ under gluon exchange, and then comparing the contributions of gluon exchange and coupled-channel processes.

decipher the mechanism of the $J/\psi N$ scattering at low energies

2 Formalism

2.1 The definition of scattering length

$J/\psi\, N$ scattering length: $\boxed{a_0^{J/\psi N} = -\dfrac{T_{J/\psi N\to J/\psi N,0}(s_{th})}{8\pi\sqrt{s_{th}}}}$ $\quad s_{th} = (m_{J/\psi} + m_N)^2$



Gluon exchanges

where: $\mathrm{Im}[T_{J/\psi N\to J/\psi N,0}(s)] = |T_{J/\psi N\to J/\psi N,0}(s)|^2\, \rho_{J/\psi N}(s)\theta(\sqrt{s} - m_{J/\psi} - m_N)$

$$\rho_{J/\psi N}(s) = \frac{1}{16\pi}\sqrt{\frac{(s-(m_{J/\psi}+m_N)^2)(s-(m_{J/\psi}-m_N)^2)}{s^2}}$$

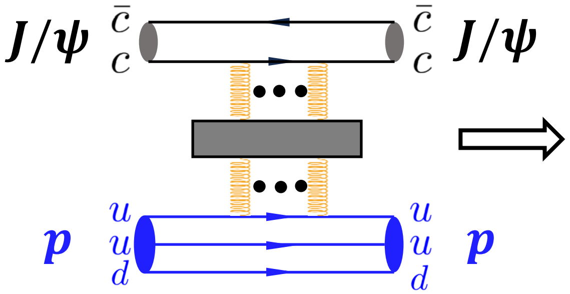
BS equation: $T_l(s) = V_l(s) + V_l(s)G(s)T_l(s) = [1 - V_l(s)G(s)]^{-1}V_l(s)$

Kernel 1: The S-wave $J/\psi N$ interaction potential V_0 through gluon exchange

2.2 The S-wave $J/\psi N$ interaction potential

- At long distances, the exchanged soft gluons hadronize into exchanging $\boldsymbol{\pi}$ and heavier mesons

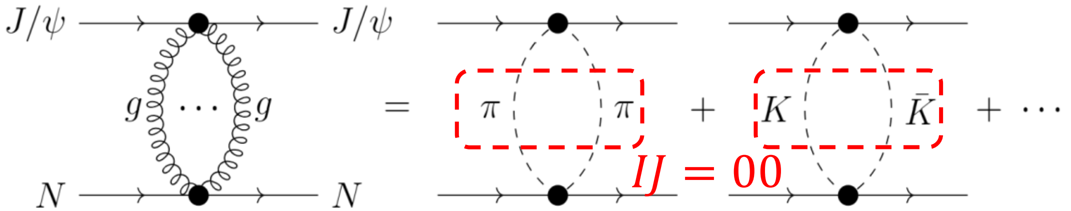
N. Brambilla et al., PRD 93 (2016) 054002
Dong, Baru, Guo, Hanhart, Nefediev, and Zou, Sci. Bull. 66 (2021) 2462

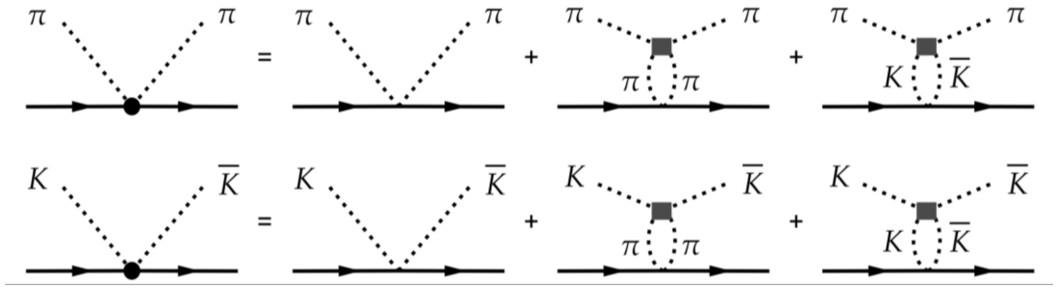


All possible color-singlet states that can couple to gluons: $\pi\pi$, $K\bar{K}$, ...

The longest-distance (lightest exchange particles) contribution

the strong $\pi\pi$-$K\bar{K}$ coupling

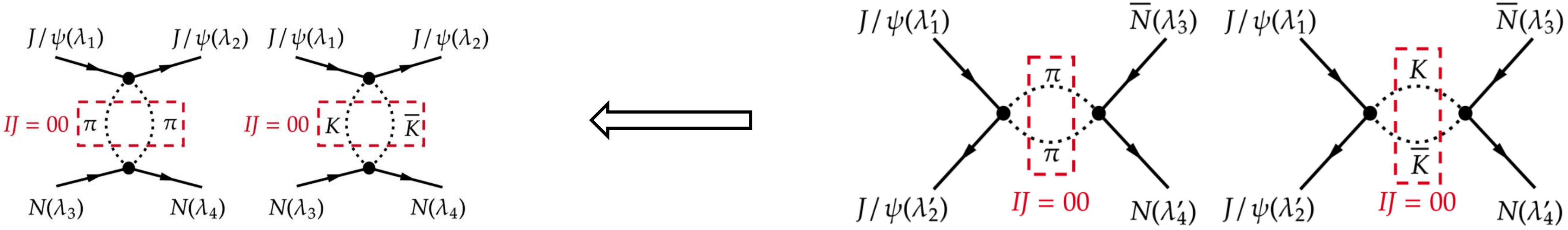




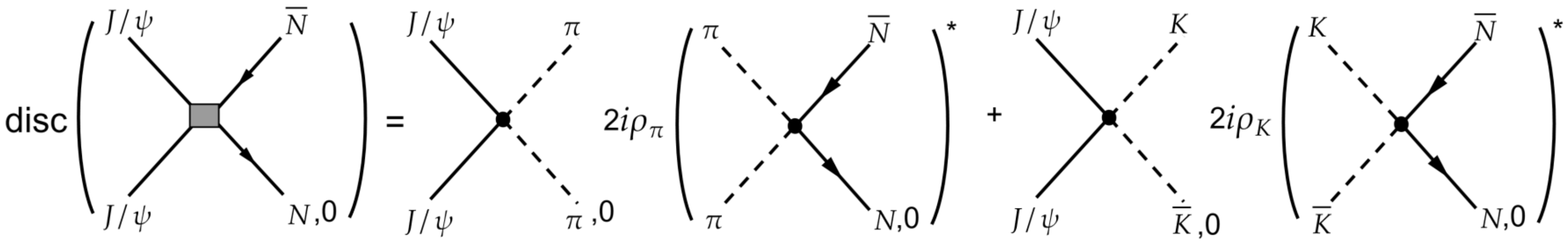
Kernel 2: The S-wave $J/\psi N$ interaction potential through correlated $\pi\pi$-$K\bar{K}$ exchange

- **Crossing relation** A. D. Martin, T. D. Spearman, Elementary particle theory

$$T^{(s)}_{cd;ab}(s,t) = \sum d^{s_a}_{a'a}(\chi_a) d^{s_b}_{b'b}(\chi_b) d^{s_c}_{c'c}(\chi_c) d^{s_d}_{d'd}(\chi_d) T^{(t)}_{c'a';d'b'}(s,t)$$



- **Unitary and dispersion relation**



$$\rho_\pi(s) = \frac{1}{16\pi}\sqrt{\frac{s-4M_\pi^2}{s}}\theta(\sqrt{s}-2M_\pi)$$

$$\rho_K(s) = \frac{1}{16\pi}\sqrt{\frac{s-4M_K^2}{s}}\theta(\sqrt{s}-2M_K)$$

factor arising from kinematic singularities

$$T_{J/\psi J/\psi\to\bar{N}(\lambda_3)N(\lambda_4),0}(s,\Lambda) = \frac{(\lambda_3+\lambda_4)\boxed{\sqrt{s-4m_N^2}}}{2\pi i}\int_{4M_\pi^2}^{+\infty}\mathrm{d}z\frac{\mathrm{disc}\left[T_{\pi\pi,0}(z)+T_{K\bar{K},0}(z)\right]}{z-s}\boxed{e^{-\frac{z-s}{\Lambda^2}}}$$

Gaussian form factor to normalizes the integral of linear divergence

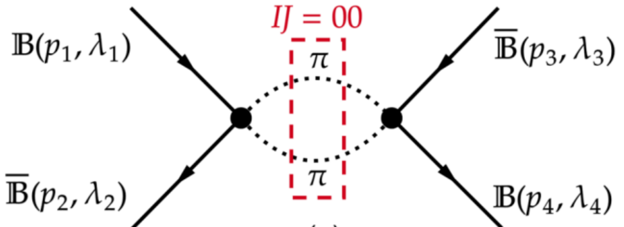
A. D. Martin, T. D. Spearman, Elementary particle theory
B. Wu et al., PRD 109 (2024) 034026

Dong, Baru, Guo, Hanhart, Nefediev, and Zou, Sci. Bull. 66 (2021) 2462

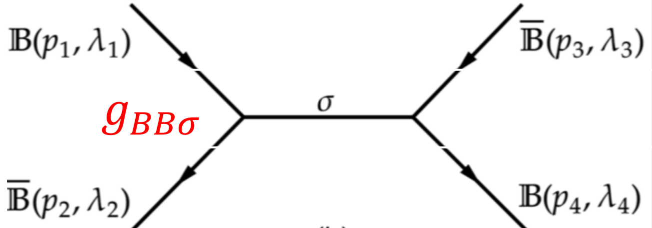
Kernel 3: The S-wave amplitude of $J/\psi\, J/\psi \to \pi\pi/K\bar{K}$ and $\bar{N}N \to \pi\pi/\bar{K}K$, incorporating $\pi\pi$-$K\bar{K}$ FSI

Muskhelishvili-Omnes representation (with LHC)

Single-channel: B. Wu et al., PRD 109 (2024) 034026



(a)



(b)

$$T_{\mathbb{B}\bar{\mathbb{B}}\to\pi\pi,0}(s) = L_{\mathbb{B},0}(s) + \Omega_0(s)\left(\boxed{P_{n-1}(s)} + \frac{s^n}{\pi}\int_{4m_\pi^2}^{+\infty} \mathrm{d}z \frac{\boxed{L_{\mathbb{B},0}(z)}\sin\delta_0(z)}{(z-s)z^n|\Omega_0(z)|}\right)$$

$$\boxed{\Omega_L(s) \equiv \exp\left[\frac{s}{\pi}\int_{s_{\rm th}}^{\infty} dz \frac{\delta_L(z)}{z(z-s)}\right]}$$

be determined by matching to the tree-level chiral amplitudes

	LHC	RHC	Total	[33]	[18]	[34]	[37]	[36]	[24]	[23]	m_σ
$g_{\Sigma\Sigma\sigma}$	$1.8^{+0.5}_{-0.5}$	$3.5^{+2.0+0.8}_{-1.8-0.9}$	$3.5^{+1.8+0.4}_{-1.3-0.4}$	···	···	10.85(8.92)	4.65	···	···	···	519^{+50}_{-48}
$g_{\Xi\Xi\sigma}$	$0.2^{+0.1}_{-0.1}$	$2.6^{+1.5+0.5}_{-1.4-0.6}$	$2.5^{+1.5+0.5}_{-1.3-0.6}$	···	···	···	···	···	3.4	···	614^{+56}_{-81}
$g_{\Lambda\Lambda\sigma}$	$1.2^{+0.4}_{-0.3}$	$6.7^{+1.0+1.4}_{-1.1-1.7}$	$6.8^{+1.0+1.1}_{-1.0-1.4}$	···	···	8.18(6.54)	4.37	···	···	6.59	596^{+41}_{-51}
$g_{NN\sigma}$	$2.9^{+0.9}_{-0.8}$	$8.8^{+1.4+1.9}_{-1.4-2.3}$	$8.7^{+1.3+1.1}_{-1.3-1.4}$	12.78	8.46	8.46	8.58	13.85	10.2	9.86	558^{+33}_{-42}
$g_{NN\sigma}^{\rm SU(2)}$	$2.7^{+0.8}_{-0.8}$	$12.5^{+0.2+2.6}_{-0.2-3.2}$	$12.2^{+0.2+1.9}_{-0.2-2.3}$								586^{+38}_{-48}

☐ Coupled-channel:

For $N\bar{N} \to \pi\pi / K\bar{K}$:

$$\vec{T}_0(s) = \vec{L}_0(s) + \Omega_0(s)\left[\vec{P}_{n-1}(s) - \frac{s^n}{\pi}\int_{4M_\pi^2}^{+\infty} \mathrm{d}z \frac{\mathrm{Im}\left[\Omega_0^{-1}(z)\right]\vec{L}_0(z)}{(z-s)z^n}\right]$$

where

$$\vec{T}_0(s) = \begin{pmatrix} T_{N\bar{N}\to\pi\pi,0}(s) \\ T_{N\bar{N}\to K\bar{K},0}(s) \end{pmatrix} \quad \boxed{\vec{L}_0(s) = \begin{pmatrix} L_{N\bar{N}\to\pi\pi,0}(s) \\ L_{N\bar{N}\to K\bar{K},0}(s) \end{pmatrix}} \quad \boxed{\vec{P}_{n-1}(s) = \begin{pmatrix} P_{n-1}^{N\bar{N}\to\pi\pi}(s) \\ P_{n-1}^{N\bar{N}\to K\bar{K}}(s) \end{pmatrix}} \quad \Omega_0(s) = \begin{pmatrix} \Omega_{0,11}(s) & \Omega_{0,12}(s) \\ \Omega_{0,21}(s) & \Omega_{0,22}(s) \end{pmatrix}$$

matching to the tree-level chiral amplitudes

LO Chiral Lagrangian

A. Krause, Helv. Phys. Acta 63 (1990) 3

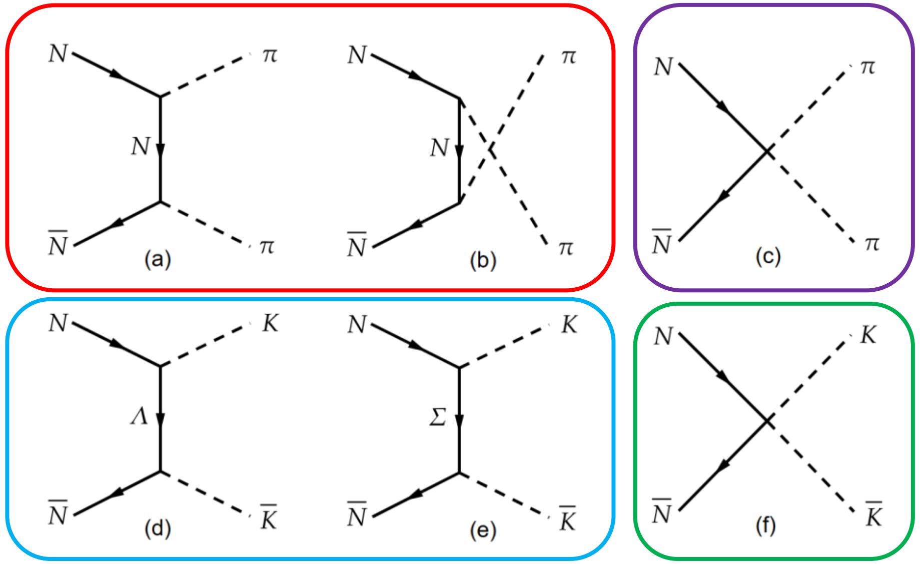
NLO Chiral Lagrangian

M. Frink and U.-G. Meißner, JHEP 07 (2004) 028 J. A. Oller et al., JHEP 09, 079

LECs taken from X.-L. Ren et al., JHEP 12 (2012) 073

$$L_{N\bar{N}\to\pi\pi,0}(s) \sim \hat{A}_{N\bar{N}\to\pi\pi,0}(s)$$

$$L_{N\bar{N}\to K\bar{K},0}(s) \sim \hat{A}_{N\bar{N}\to K\bar{K},0}(s)$$



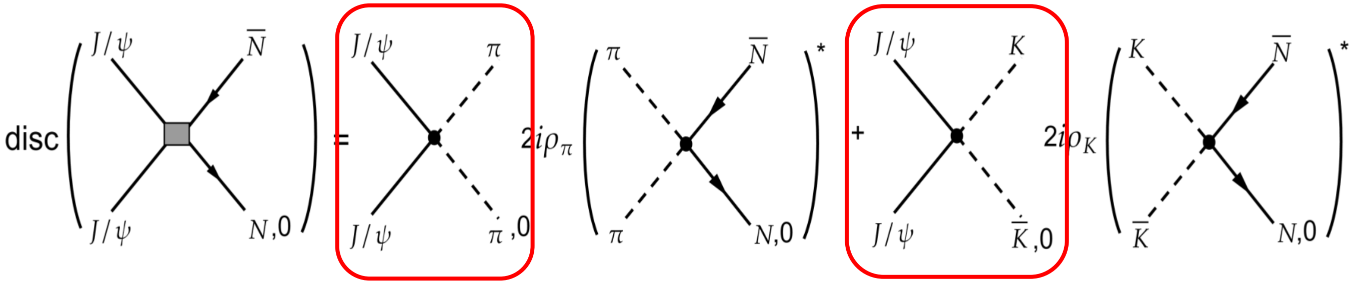
$$P_{n-1}^{N\bar{N}\to\pi\pi}(s) \sim A_{N\bar{N}\to\pi\pi,0}(s)$$

$$P_{n-1}^{N\bar{N}\to K\bar{K}}(s) \sim A_{N\bar{N}\to K\bar{K},0}(s)$$

FIG. 2. The tree-level Feynman diagrams for the process of $N\bar{N} \to \pi\pi$ and $N\bar{N} \to K\bar{K}$.

For $J/\psi J/\psi \to \pi\pi/K\bar{K}$:

Dong, Baru, Guo, Hanhart, Nefediev, and Zou, Sci. Bull. 66 (2021) 2462



$1 \to J/\psi$

$2 \to \psi(2S)$

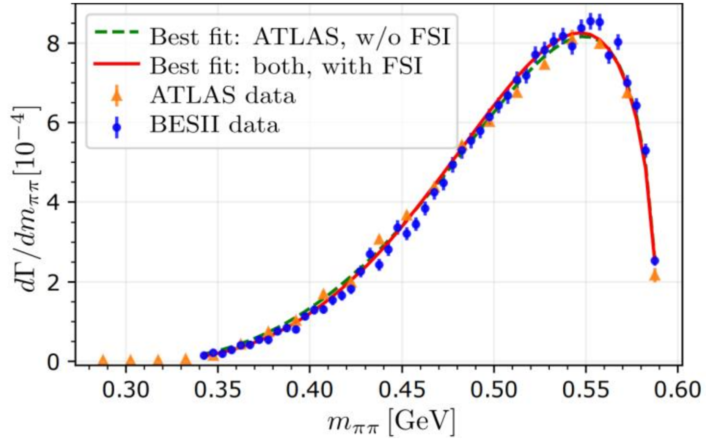
$c_i^{(12)}$

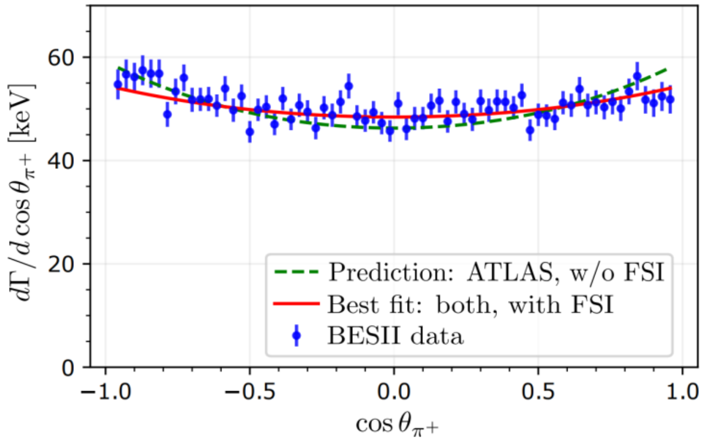
$$T_{J/\psi J/\psi \to |i\rangle,0}(s) = \Omega_{0,i1}(s)\mathcal{M}(s, M_\pi) + \Omega_{0,i2}(s)\frac{2}{\sqrt{3}}\mathcal{M}(s, M_K)$$

$$\mathcal{M}(s, M_p) = -\frac{2}{F_\pi^2}\sqrt{\frac{3}{2}}\left\{\boxed{c_1^{(21)}}(s-2m_p^2) + \frac{\boxed{c_2^{(21)}}}{2}\left[s + \frac{s(s-4M_{J/\psi}^2)}{4M_{J/\psi}^2}\left(1-\frac{s-4M_p^2}{3s}\right)\right]\right\}$$

$$\to -\frac{2I_{\mathcal{P}}}{F_\pi^2}\left\{\boxed{c_1^{(11)}}(s-2M_{\mathcal{P}}^2) + 2\boxed{c_m^{(11)}}M_{\mathcal{P}}^2 + \frac{\boxed{c_2^{(11)}}}{12M_{J/\psi}^2}\left[s^2 + 2s(M_{\mathcal{P}}^2 + M_{J/\psi}^2) - 8M_{\mathcal{P}}^2 M_{J/\psi}^2\right]\right\}$$

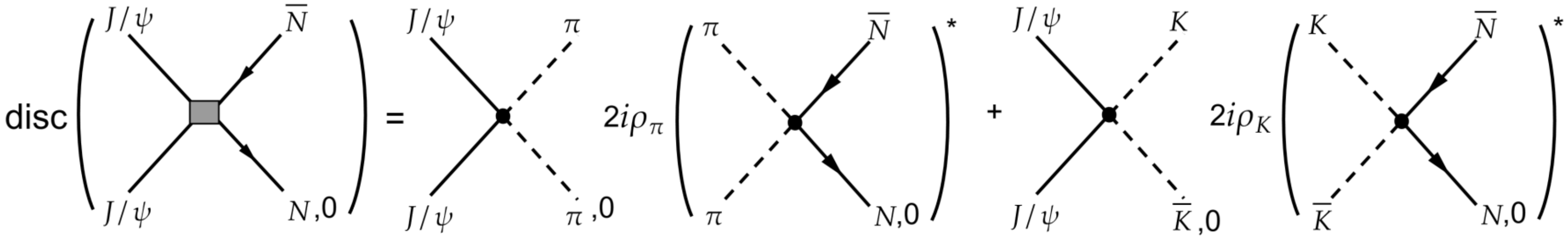
determine the low-energy constants(LECs) by fitting the BESII data on the $\psi(2S) \to J/\psi\pi\pi$



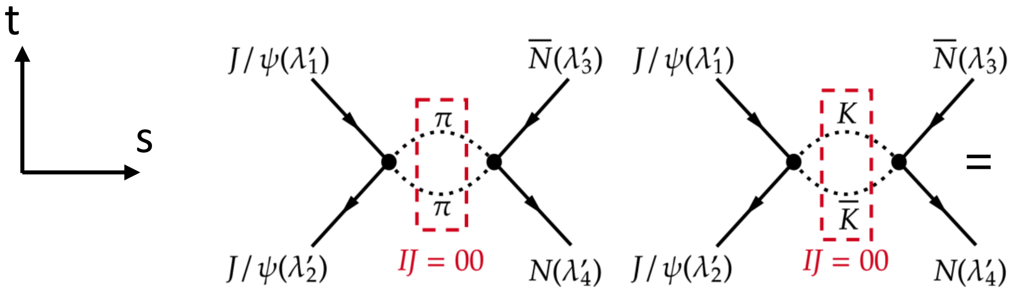


the updated values:

$$c_1^{(21)} = 0.178 \pm 0.002,\ c_2^{(21)} = -0.122 \pm 0.002,\ c_m^{(21)} = 0.222 \pm 0.002$$

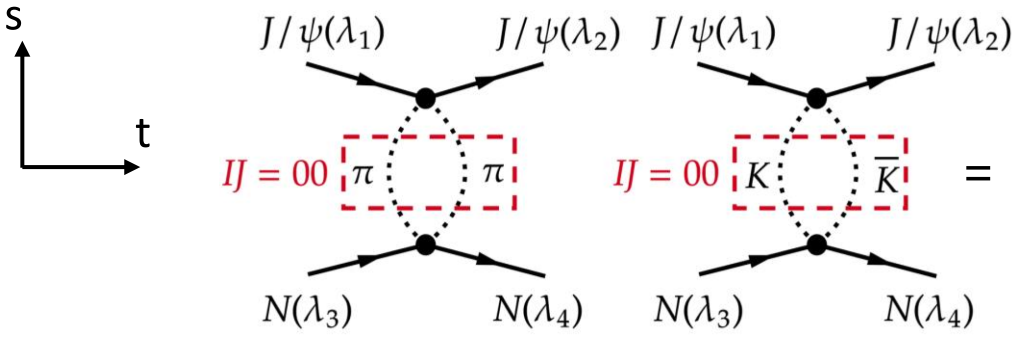


dispersion relation



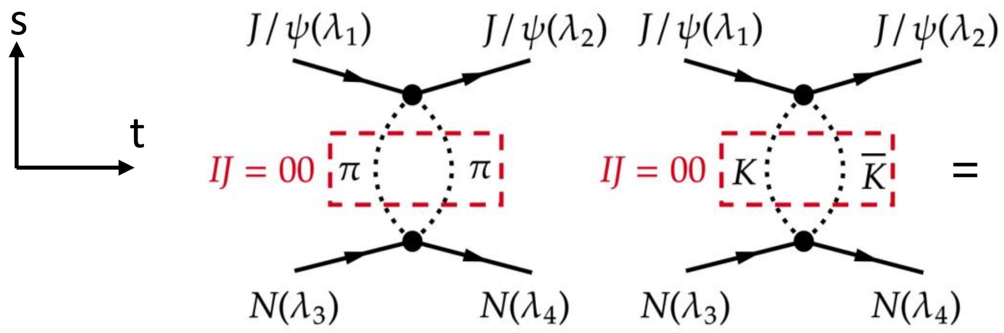
$$= T_{J/\psi J/\psi\to\bar{N}(\lambda_3)N(\lambda_4),0}(s,\Lambda)=\frac{(\lambda_3+\lambda_4)\sqrt{s-4m_N^2}}{2\pi i}\int_{4M_\pi^2}^{+\infty}\mathrm{d}z\frac{\mathrm{disc}\left[T_{\pi\pi,0}(z)+T_{K\bar{K},0}(z)\right]}{z-s}e^{-\frac{z-s}{\Lambda^2}}$$

crossing relation



$$= T_{J/\psi(\lambda_1)N(\lambda_3)\to J/\psi(\lambda_2)N(\lambda_4),0}(s,t,\Lambda)$$
$$=\epsilon(\lambda_1,0,0)\cdot\epsilon^*(\lambda_2,\theta,0)e^{-i\pi\lambda_4}(-1)^{\lambda_3+\lambda_4}\sum_{\lambda_3'\lambda_4'}d^{\frac{1}{2}}_{\lambda_3\lambda_3'}(\omega)d^{\frac{1}{2}}_{\lambda_4\lambda_4'}(\omega+\pi)T_{J/\psi J/\psi\to\bar{N}(\lambda_3')N(\lambda_4'),0}(s,\Lambda)$$

helicity amplitude



$$= T_{J/\psi(\lambda_1)N(\lambda_3)\to J/\psi(\lambda_2)N(\lambda_4),0}(s,t,\Lambda)$$

$$= \epsilon(\lambda_1,0,0)\cdot\epsilon^*(\lambda_2,\theta,0)e^{-i\pi\lambda_4}(-1)^{\lambda_3+\lambda_4}\sum_{\lambda_3'\lambda_4'} d^{\frac{1}{2}}_{\lambda_3\lambda_3'}(\omega)d^{\frac{1}{2}}_{\lambda_4\lambda_4'}(\omega+\pi)T_{J/\psi J/\psi\to\bar{N}(\lambda_3')N(\lambda_4'),0}(s,\Lambda)$$

the relation between the helicity state and LS-coupling state

$$|JM;LS\rangle = \sum_{\mu_1\mu_2}\sqrt{\frac{2L+1}{2J+1}}C^{S(\mu_1-\mu_2)}_{s_1\mu_1;s_2(-\mu_2)}C^{J(\mu_1-\mu_2)}_{L0;S(\mu_1-\mu_2)}|JM;\mu_1\mu_2\rangle$$

$$V^{|^{2S+1}0_S\rangle}_{J/\psi N}(t,\Lambda) = \sum_{\mu_1\mu_2}\sum_{\mu_1'\mu_2'}\frac{1}{2S+1}C^{S(\mu_1'-\mu_2')}_{1\mu';\frac{1}{2}(-\mu_2')}C^{S(\mu_1-\mu_2)}_{1\mu_1;\frac{1}{2}(-\mu_2)}\int\frac{\mathrm{d}\Omega}{4\pi}d^S_{\mu,\mu'}(\theta)T_{J/\psi(\mu_1)N(\mu_2)\to J/\psi(\mu_1')N(\mu_2'),0}(s,t,\Lambda)$$

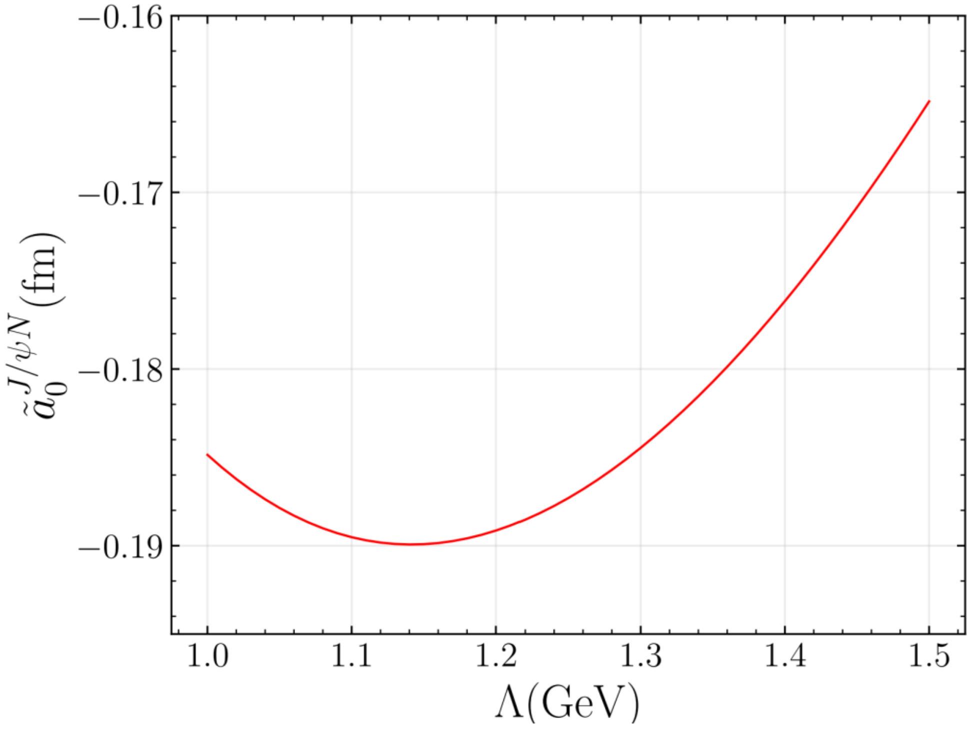
$$a_0 = -\frac{T_{ii,0}(s_{th})}{8\pi\sqrt{s_{th}}}$$

$$T_{J/\psi N\to J/\psi N,0}(s) = \frac{V_{J/\psi N\to J/\psi N,0}(s)}{1-V_{J/\psi N\to J/\psi N,0}(s)G(s)}$$

$$V^{|^{2S+1}0_S\rangle}_{J/\psi N}(t_{\mathrm{th}},\Lambda) = -iT_{J/\psi J/\psi\to\bar{N}(\frac{1}{2})N(\frac{1}{2}),0}(s=0,\Lambda)$$

$$a_0^{J/\psi N} \approx -\frac{V^{|^{2S+1}0_S\rangle}_{J/\psi N}(t=t_{\mathrm{th}},\Lambda)}{8\pi\left(m_{J/\psi}+m_N\right)}$$

3 Numerical Result



S-wave $J/\psi N$ scattering length through soft gluon exchange:

$$\tilde{a}_0^{J/\psi N} = -0.16\ldots-0.19 \text{ fm}$$

- The interaction between J/ψ and N is attractive
- The strength is comparable to the S-wave isospin-0 $\pi\pi$ interaction

$$a_{00}^{\pi\pi} = -0.2210 \pm 0.0047 \pm 0.0015 \text{ fm}$$

J.R. Batley et al., PLB 633 (2006) 173
B. Bloch-Devaux, PoS KAON09 (2009) 033

- This result is obtained with LECs arising from the data on $\psi(2S) \to J/\psi\pi\pi$

$\Downarrow$

need to make a correction

- Inequality of Scattering Lengths

A. Sibirtsev et al., PRD 71 (2005) 076005

- The chromopolarisability

$$\mathcal{M}(A \to B\pi\pi) = \underbrace{\boxed{\alpha_{AB}}}_{\text{chromopolarisability}} \langle \pi\pi | \vec{E}^a \cdot \underbrace{\boxed{\vec{E}^a}}_{\text{chromoelectric field}} | 0 \rangle$$

- The previous numerical result is based on $\alpha_{\psi(2S)J/\psi}$ $\quad \underbrace{\boxed{\tilde{a}_0^{J/\psi N}}}_{\alpha_{\psi(2S)J/\psi}} = -0.16 \ldots -0.19 \text{ fm}$

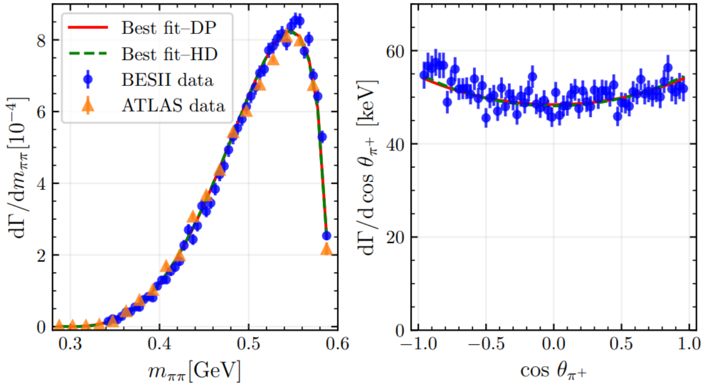


FIG. 3. Fit to the BESII data [70] and ATLAS data [71] for the $\psi(2S) \to J/\psi\pi^+\pi^-$ transition: dipion invariant mass distribution (left) and the helicity angular distribution (right). The "Best fit–DP" and "Best fit–HD" represent the fitting results obtained using the Omnès matrix from Ref. [61] and Ref. [58], respectively.

Dong, Baru, Guo, Hanhart, Nefediev, and Zou, Sci. Bull. 66 (2021) 2462

- The absolute value of $\alpha_{J/\psi J/\psi}$ should be larger than the off-diagonal $\alpha_{\psi(2S)J/\psi}$ $\quad \underbrace{\boxed{a_{J/\psi N}}}_{\alpha_{J/\psi J/\psi}} \lesssim -0.16 \text{ fm}$

- Keep the previous calculation unchanged and replace $m_{J/\psi}$ with $m_{\psi(2S)}$ $\quad \underbrace{\boxed{\tilde{a}_0^{\psi(2S)N}}}_{\alpha_{\psi(2S)J/\psi}} = -0.14 \ldots -0.17 \text{ fm}$

- $\alpha_{\psi(2S)\psi(2S)}\alpha_{J/\psi J/\psi} \geq |\alpha_{\psi(2S)J/\psi}|^2$

- Scattering length inequality $\quad a_0^{J/\psi N} a_0^{\psi(2S)N} \geq \tilde{a}_0^{J/\psi N} \tilde{a}_0^{\psi(2S)N} \approx (-0.15 \text{ fm})^2$

- Compared with the results from Coupled-channel mechanism

$\Lambda_c \bar{D}^{(*)}$ contribution: $0.2 \ldots 3$ am

M.-L. Du et al., EPJC 80 (2020) 11, 1053

M.-L. Du et al., JHEP 08 (2021) 157

$\Sigma_c^{(*)} \bar{D}^{(*)}$ contribution: $0.1 \ldots 10$ am

At least one order of magnitude smaller than the result from the soft gluon exchange!

4 Summary

- We estimate the S-wave scattering length of $J/\psi N$ through soft gluon exchange (correlated $\pi\pi$-$K\bar{K}$)

$$\tilde{a}_0^{J/\psi N} = -0.16 \ldots -0.19 \text{ fm}$$

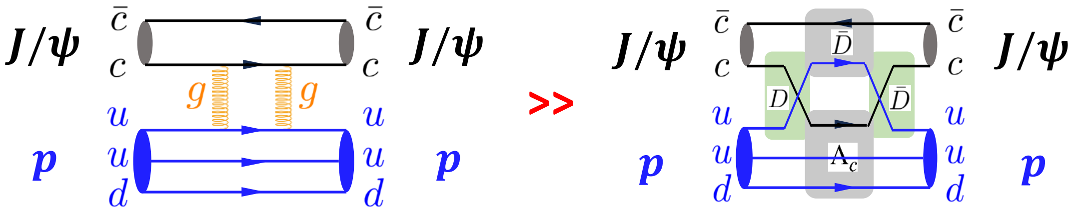
The same process to estimate the scattering length for $\psi(2S)N$ through soft gluon exchange:

$$\tilde{a}_0^{\psi(2S)N} = -0.14 \ldots -0.17 \text{ fm}$$

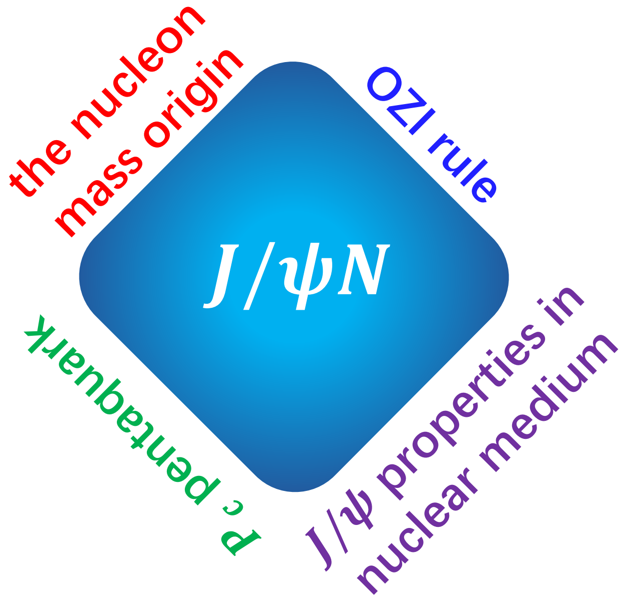
After chromopolarisability correction：

$$a_0^{J/\psi N} a_0^{\psi(2S)N} \geq \tilde{a}_0^{J/\psi N} \tilde{a}_0^{\psi(2S)N} \approx (-0.15 \text{ fm})^2$$

Our result is consistent with Yan Lyu's report on Lattice QCD ($-0.42 \sim -0.28$ fm)

- 

$\lesssim -0.16$ fm $[-10, -0.1] \times 10^{-3}$ fm



In the low-energy interaction of $J/\psi N$, the contribution from soft gluon exchange is dominant

study the origin of nucleon mass with the J/ψ as a probe is possible

Thank you very much for your attention!