Strong QCD 2024

Strong QCD from Hadron Structure Experiments - VI

Reactions models and exotic hadrons:

Mechanisms of ψ/X photoproduction and $J/\psi N$ scattering

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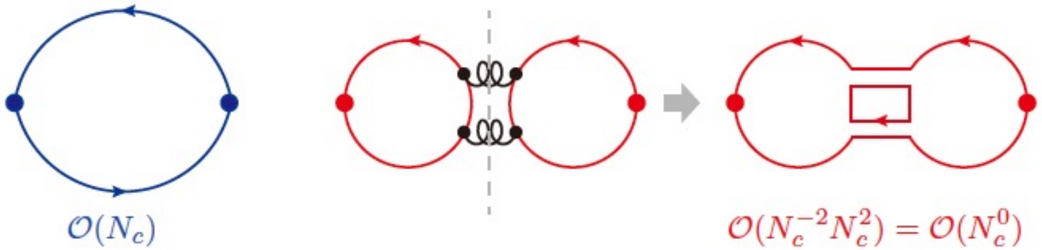
Meng-Lin Du, V. Baru, FKG, C. Hanhart, U.-G. Meißner, A. Nefediev, I. Strakovsky, *Deciphering the mechanism of near-threshold J/ψ photoproduction*, Eur. Phys. J. C 80 (2020) 1053.

Xiong-Hui Cao, Meng-Lin Du, FKG, *Photoproduction of the X(3872) beyond vector meson dominance: the open-charm coupled-channel mechanism*, arXiv:2401.16112

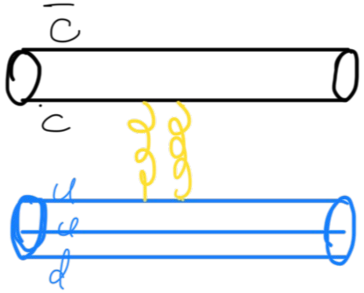
Bing Wu, Xiang-Kun Dong, Meng-Lin Du, FKG, Bing-Song Zou, arXiv:2405.xxxxx

J/ψ-nucleon scattering and photoproduction

- OZI suppressed scattering
  - ☐ Relatively suppressed by $O(1/N_c)$
  - ☐ General mechanisms (take $J/\psi - N$ as an example)



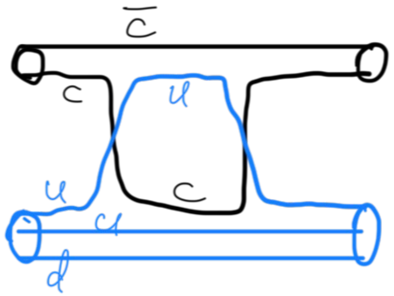
➢ Gluon exchanges



Gluonic matrix elements

- ☐ $\langle J/\psi|GG|J/\psi\rangle$: chromopolarizabilities
- ☐ $\langle N|GG|N\rangle$: trace anomaly contribution to the nucleon mass

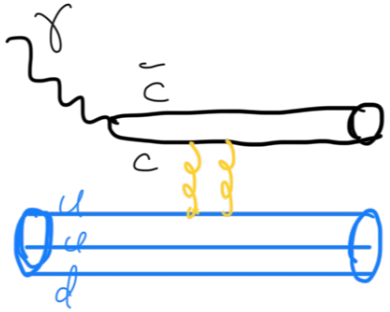
➢ Coupled-channel: $J/\psi N - \Lambda_c \bar{D}^{(*)}/\Sigma_c^{(*)}\bar{D}^{(*)} - J/\psi N$



Importance of coupled-channel mechanism in evading OZI suppression in mesonic sector: H. Lipkin, B.-S. Zou, PRD 53 (1996) 6693

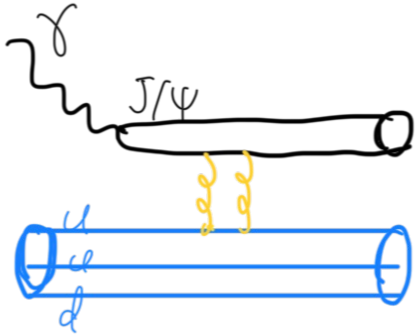
J/ψ-nucleon scattering and photoproduction

- The J/ψ photoproduction probes the gluonic contribution to the nucleon mass
  - □ if the mechanism of gluon exchanges is dominant



  - □ if the J/ψ photoproduction can be modeled by vector-meson dominance

D. Kharzeev, H. Satz, A. Syamtomov, G. Zinovjev, EPJC 9 (1999) 459



$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0) = \frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \times \frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

➢ Scattering length from VMD and photoproduction: $3-25$ am — L. Pentchev, I. Strakovsky, EPJA 57 (2021) 56

21.3 ± 8.2 am — GlueX, PRC 108 (2023) 025201

J/ψ in the VMD model would be highly off-shell, but the scattering length and cross section are defined for real J/ψ

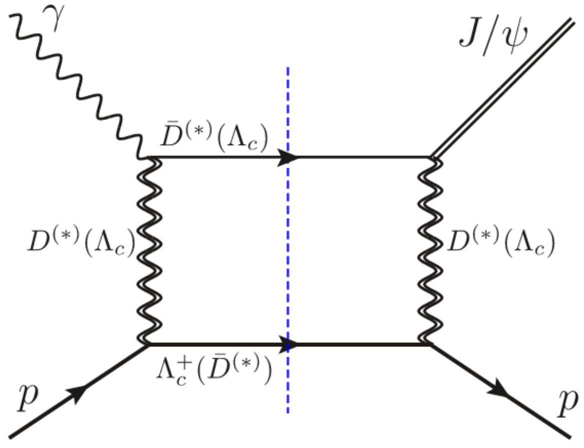
VMD model for photoproduction questioned in M.-L. Du et al., EPJC 80 (2020) 1053; Y.-Z. Xu et al., Eur. Phys. J. C 81 (2021) 895

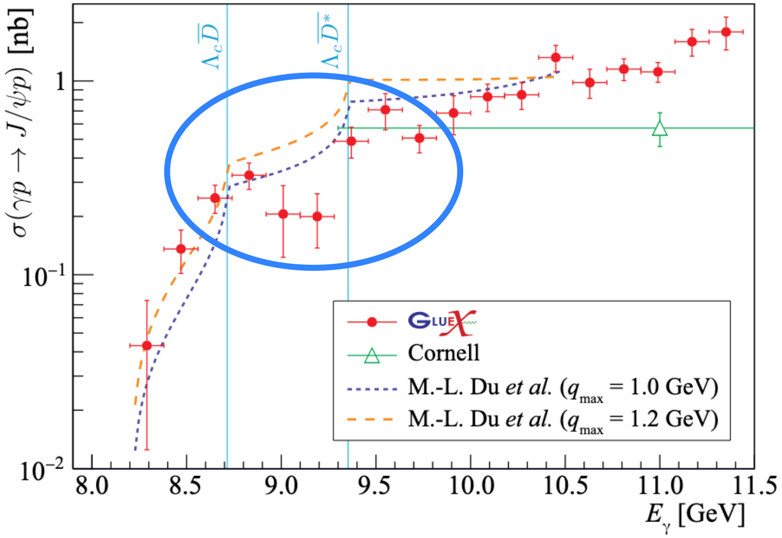
J/ψ-nucleon scattering and photoproduction

- For the near-threshold photoproduction, possible importance of the coupled-channel mechanism
  - Unique feature: threshold cusps M.-L. Du et al., EPJC 80 (2020) 1053

Unitarity: $J/\psi p \to J/\psi p$ enters w/o VMD, but cannot be singled out

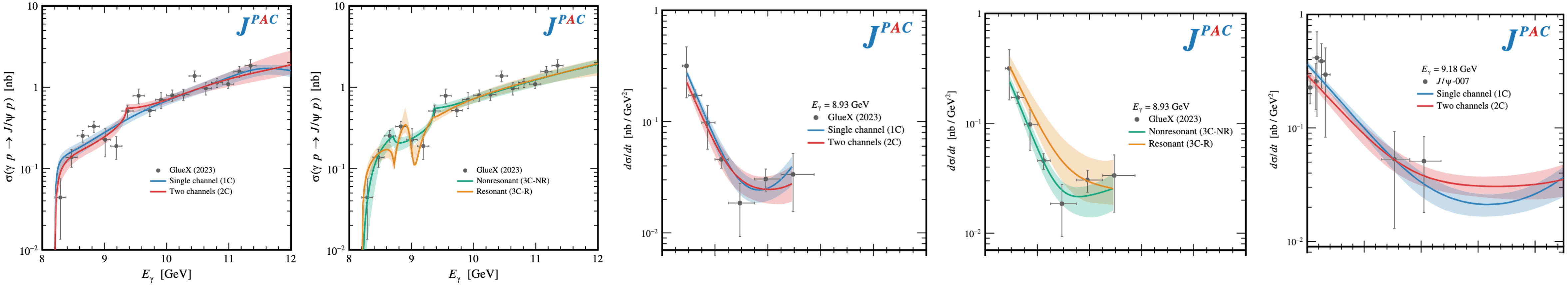
$\Lambda_c^+ + D^-$: 2286 + 1865 = 4151 MeV
$J/\psi + p$: 3097 + 938 = 4035 MeV





GlueX, PRC 108 (2023) 025201

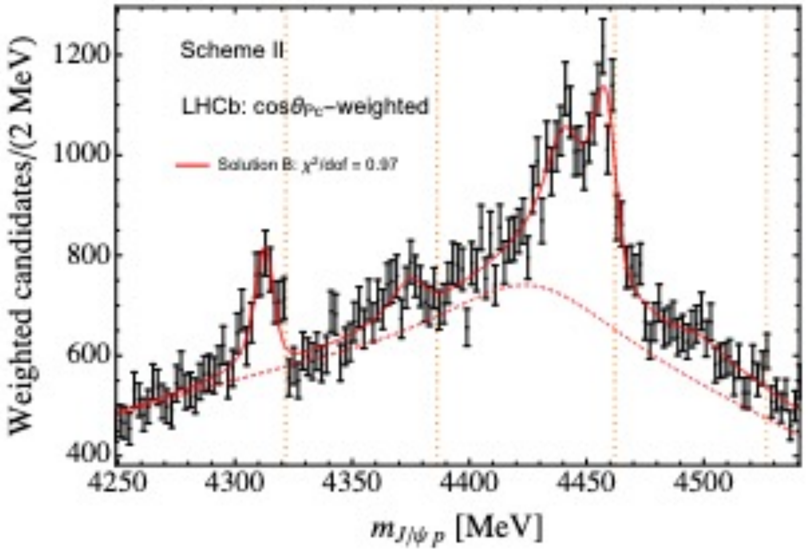
  - Updated data show evidence of cusps, but are still not conclusive
    - Analysis by JPAC JPAC, PRD 108 (2023) 054018



J/ψ-nucleon scattering and photoproduction

- J/ψ-nucleon scattering
  - Coupled-channel mechanism
    - ➢ $\Lambda_c \bar{D}^{(*)}$ contribution: $\mathcal{O}(0.2 \ldots 3\ \mathrm{am})$ — M.-L. Du et al., EPJC 80 (2020) 1053
    - ➢ $\Sigma_c^{(*)} \bar{D}^{(*)}$ contribution: $\mathcal{O}(0.1 \ldots 10\ \mathrm{am})$, from coupled-channel ($\Sigma_c^{(*)} \bar{D}^{(*)}$-$J/\psi N$) fits to LHCb data on P_c
  - How about gluon exchange?

- Photoproduction of charmonium-like states?

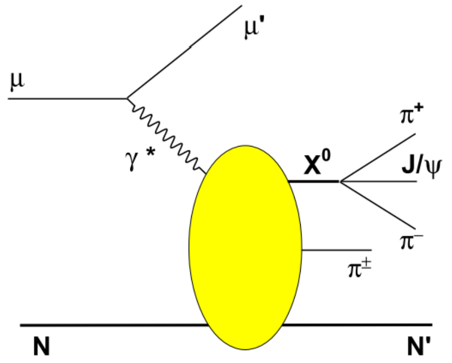


M.-L. Du et al., JHEP 08 (2021) 157

X(3872) photoproduction

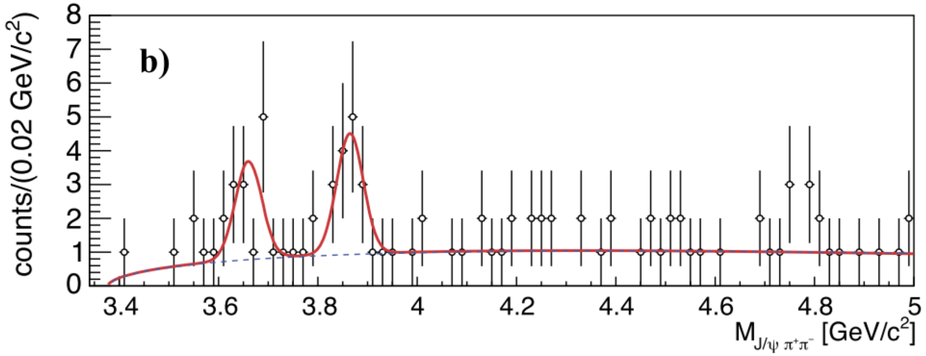
- Searched for at COMPASS, but not seen
  - Evidence of $\tilde{X}(3872)$ in $\gamma^* N \to X^0 \pi^\pm N'$ with 4.1σ

COMPASS, PLB 783 (2018) 334

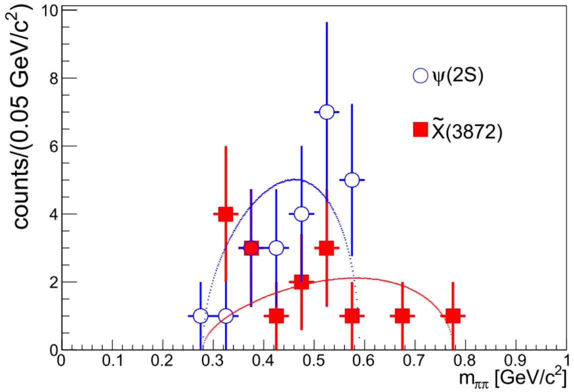


$\sqrt{s_{\gamma N}} \in [8, 18]$ GeV

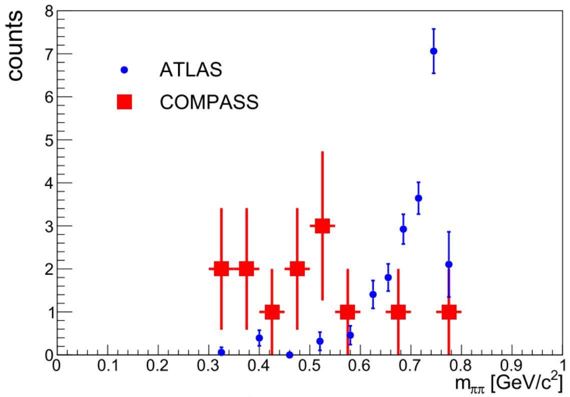
$M_{\tilde{X}} = (3860.4 \pm 10.0)$ MeV



  - The $\pi\pi$ invariant mass suggests $C(\tilde{X}) = -1$



(a)



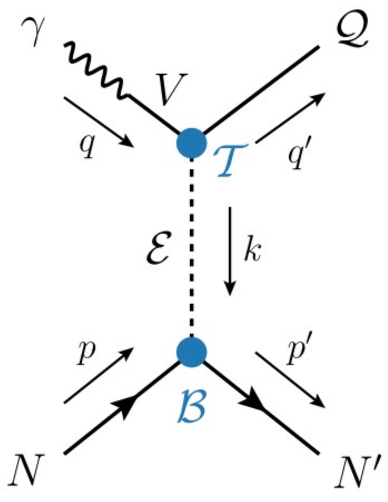
(b)

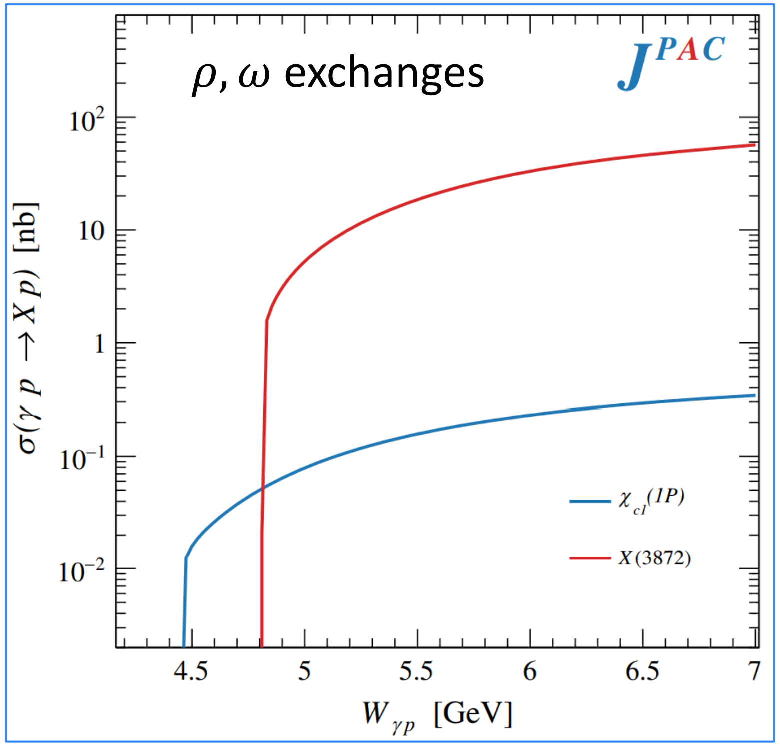
  - Cross sections at $\sqrt{s_{\gamma N}} = 13.7$ GeV : $\sigma(\gamma N \to \tilde{X}\pi N') \times \mathcal{B}(\tilde{X} \to J/\psi\pi^+\pi^-) = (71 \pm 28 \pm 39)$ pb

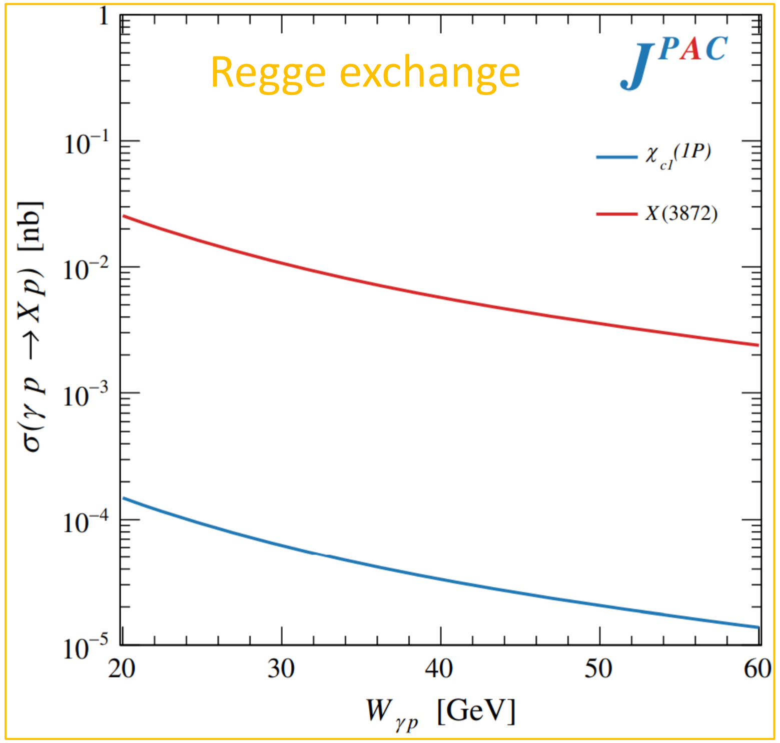
$\sigma(\gamma N \to X(3872)N') \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 2.9$ pb (CL = 90%)

X(3872) photoproduction with VMD

- Existing estimate for the X(3872) photoproduction
  - Vector-meson-dominance (VMD) model: $\gamma^* \to J/\psi$ JPAC, PRD 102 (2020) 114010
  - Low energy: ρ, ω exchanges, $\mathcal{O}(10\ \mathrm{nb})$
  - High energy: Regge exchange





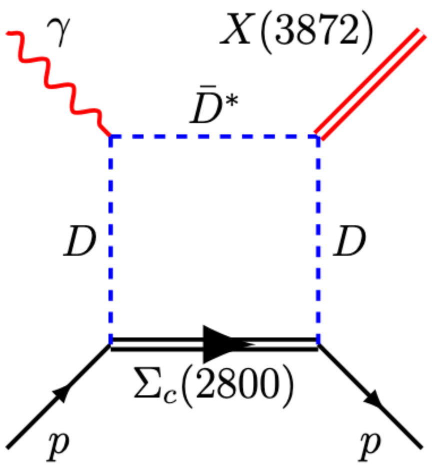


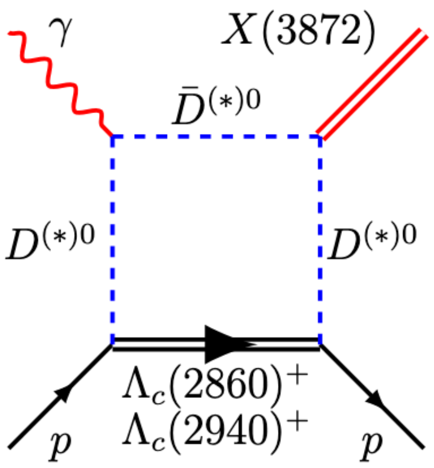
X(3872) photoproduction with coupled channels

- Coupled-channel mechanism for the X(3872) photoproduction in the near-threshold region
  - X(3872) couples strongly to $D\bar{D}^*$
  - Nearby open-charm thresholds:

$m_p + m_X = 4810$ MeV

$\bar{D}^0\Lambda_c(2940)^+ : 4804^{+2}_{-1}$ MeV
$\bar{D}^{*0}\Sigma_c(2800)^+ : 4799^{+14}_{-5}$ MeV
$D^{*-}\Sigma_c(2800)^{++} : 4811^{+4}_{-6}$ MeV
$\bar{D}^{*0}\Lambda_c(2860)^+ : 4863^{+2}_{-6}$ MeV
$\bar{D}^{*0}\Lambda_c(2940)^+ : 4946^{+1}_{-1}$ MeV



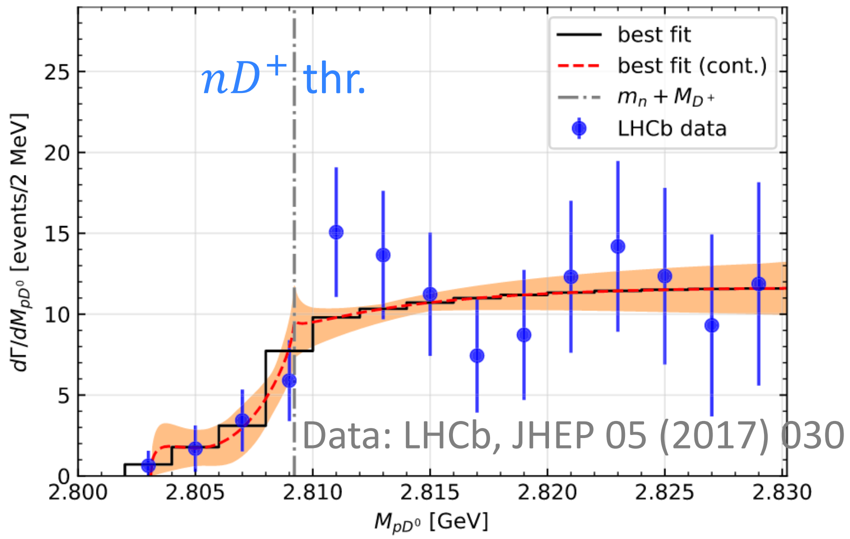


$\Lambda_c(2860)\ [3/2^+]$
$\Lambda_c(2940)\ [3/2^-]$
$\Sigma_c(2800)$: ½$^-$ from the analysis of $\Lambda_b \to \pi^- p D^0$

S. Sakai, FKG, B. Kubis, PLB 808 (2020) 135623

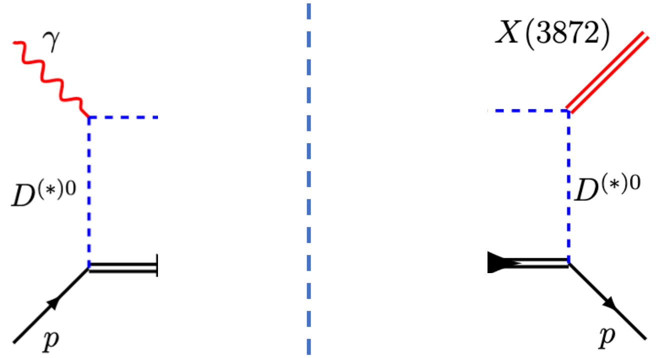
Coupling constants

- Measured widths
- Heavy quark spin symmetry
- $XD\bar{D}^*$ coupling consistent with hadronic molecular picture



X(3872) photoproduction with coupled channels

- Evaluate the box diagrams with a dispersive approach:



$$\mathcal{A}^{(J)}_{\ell S;\bar{\ell}\bar{S}(\gamma p\to\chi_{c1}p)}(s) = \sum_{\ell',S'}\frac{1}{\pi}\int_{s_{\rm th}}^{s_{\rm cut}} ds' \frac{\mathcal{A}^{(J)}_{\ell' S';\bar{\ell}\bar{S}(\gamma p\to\bar{D}^*\Sigma_c/\Lambda_c)}(s')\rho(s')\mathcal{A}^{(J)}_{\ell' S';\ell S(\chi_{c1}p\to\bar{D}^*\Sigma_c/\Lambda_c)}(s')}{s'-s}$$

consider S-wave for open-charm channels, S-, P- and D-waves for $\gamma p, Xp$

- Only limited channels, hard cutoff: $s_{\rm cut} = \sqrt{q_{\rm max}^2 + m_{\Sigma_c/\Lambda_c}^2} + \sqrt{q_{\rm max}^2 + m_{D^{(*)}}^2}$ with $q_{\rm max} = 1$ GeV

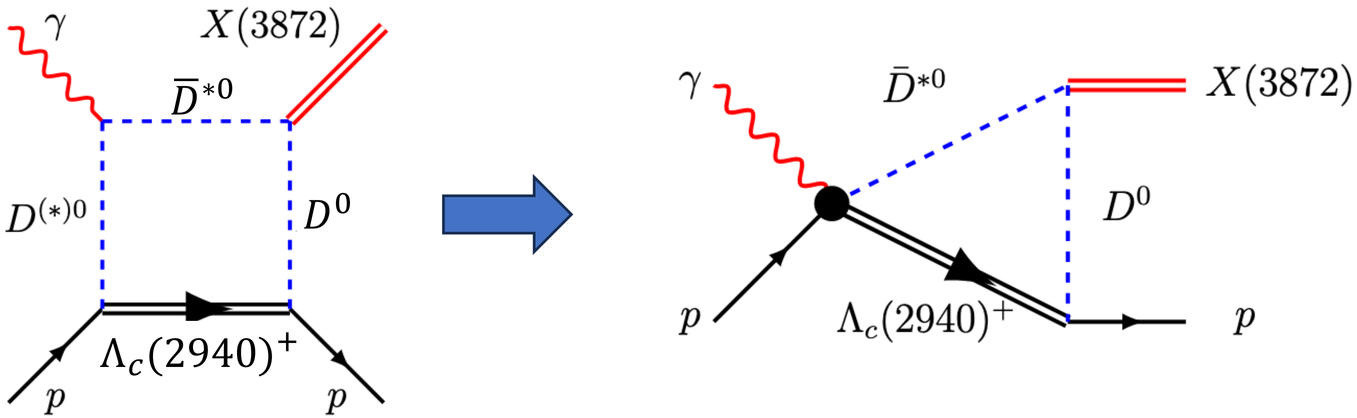
- Monopole form factor for exchanged particles with $\Lambda = m_{\rm ex} + \eta\Lambda_{\rm QCD}$

$$F(t) = \frac{\Lambda^2 - m_{\rm ex}^2}{\Lambda^2 - t}$$

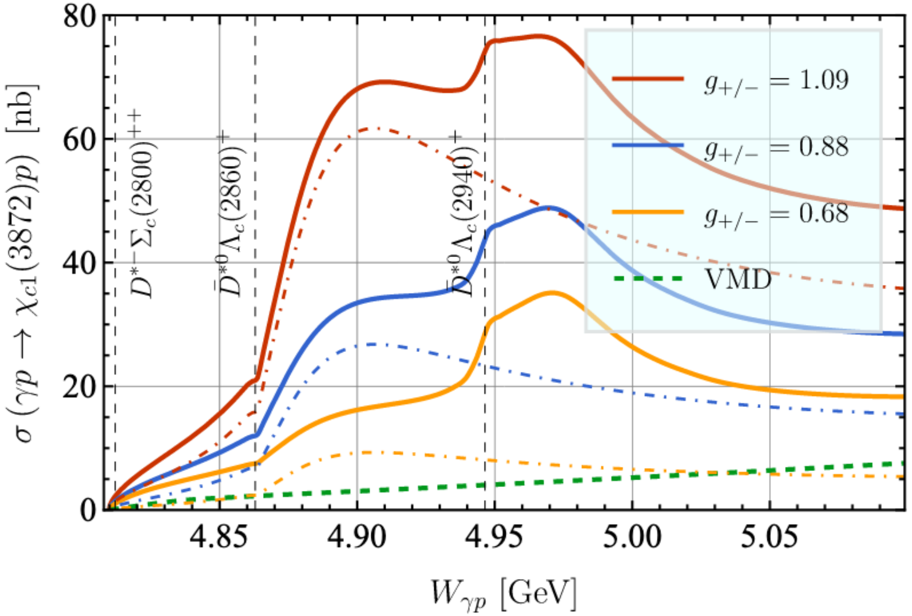
X(3872) photoproduction with coupled channels

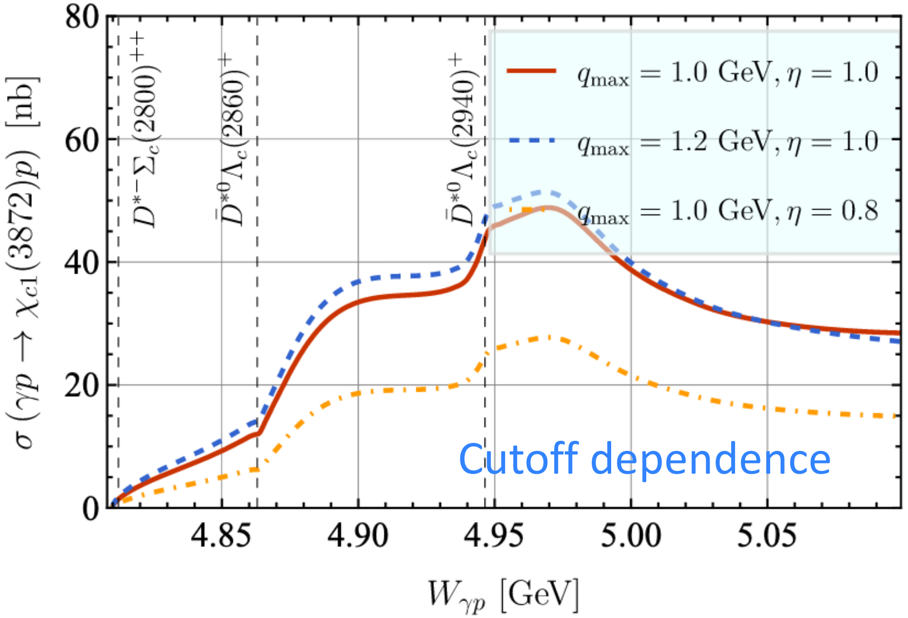
- Triangle singularity: subleading Landau singularity of the box diagram

For review on TS: FKG, X.-H.Liu, S.Sakai, PPNP 112 (2020) 103757



- Total cross section



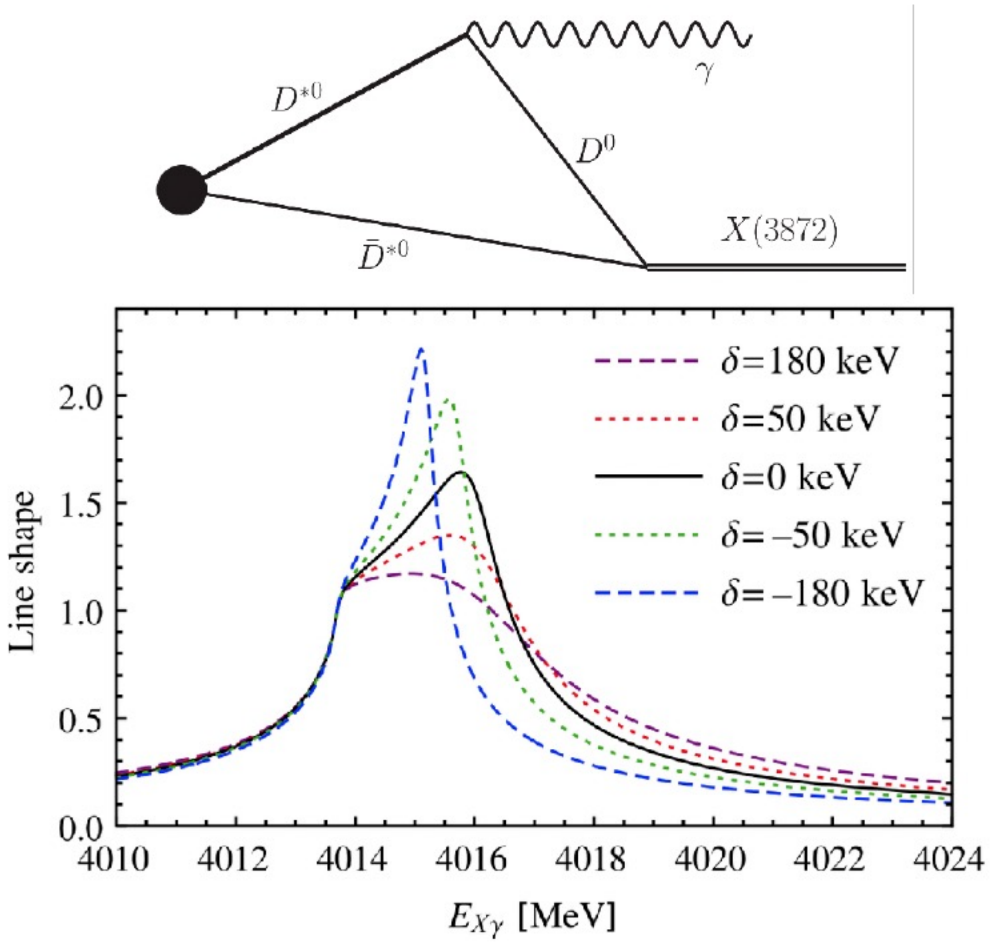


Here $g_{+/-}$ is the ratio of the $\Lambda(2860)D^{(*)}p$ and $\Lambda(2940)D^{(*)}p$ coupling constants constrained by the measured widths

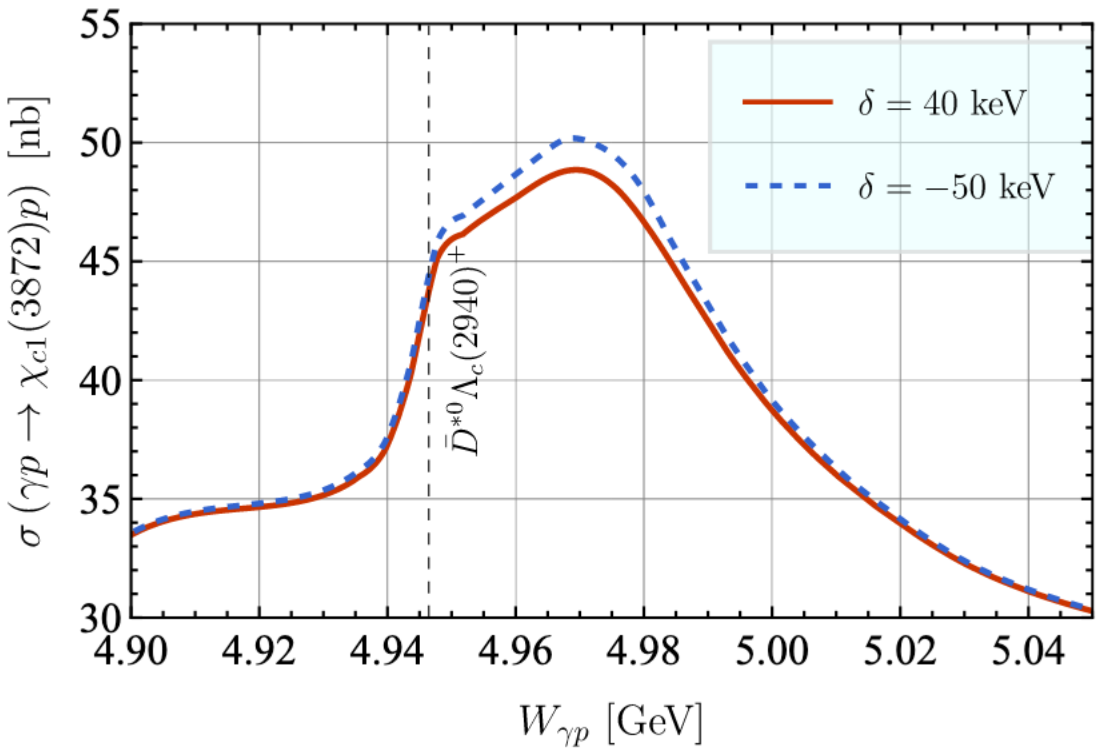
X(3872) photoproduction with coupled channels

- Triangle singularity induced structure may be used to measure the X(3872) binding energy (δ)

FKG, PRL 122 (2019) 202002

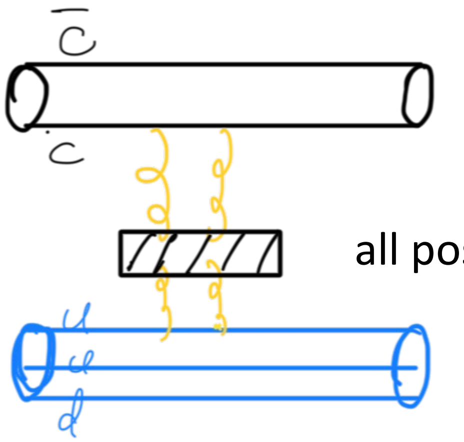


- However, here the sensitivity is smeared out by the $\Lambda(2940)$ width (~ 20 MeV)

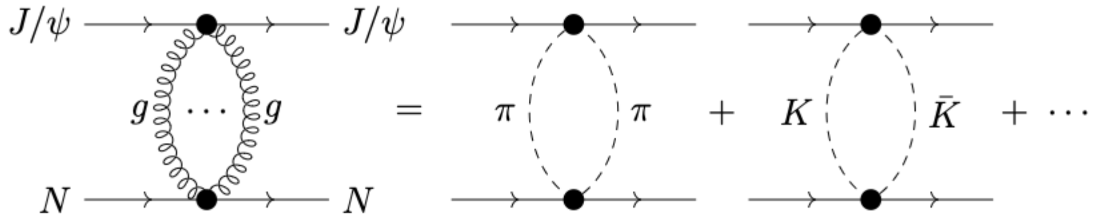


J/ψ-nucleon scattering: contribution from gluon exchange

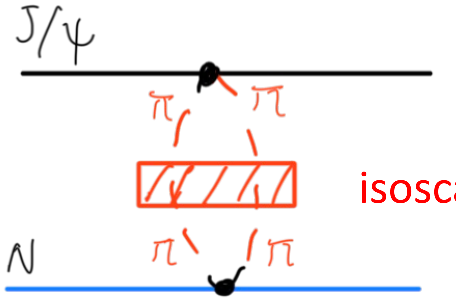
- We focus on the $J/\psi - N$ scattering at low energies, the scattering length
  - Gluon exchange from the unitarity point of view



all possible color-singlet states that can couple to gluons: $\pi\pi, KK$, ...



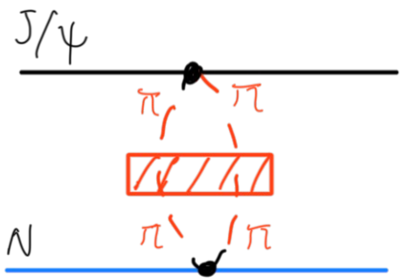
  - The longest-distance (lightest exchange particles) contribution: $\pi\pi$
    - contribution of correlated $\pi\pi$ exchanges



isoscalar scalar $\pi\pi$ rescattering: can be computed using dispersive approach

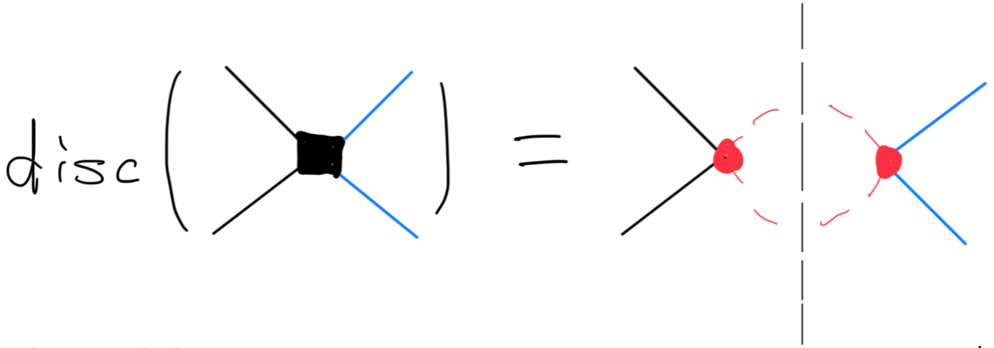
Dispersive approach

- $J/\psi N \to J/\psi N$ scattering amplitude satisfies the dispersion relation
  - Lowest intermediate states from gluon exchange: $\pi\pi \Rightarrow$ cut from the $\pi\pi$ threshold



$$\mathcal{M}(s,t) = \frac{1}{\pi}\int_{4m_\pi^2}^{+\infty} dt' \frac{\mathrm{Im}\,\mathcal{M}(s,t')}{t'-t-i\epsilon} \Rightarrow$$ S-wave $J/\psi N$ scattering amplitude

  - Unitarity $\Rightarrow$ imaginary part of the scattering amplitude



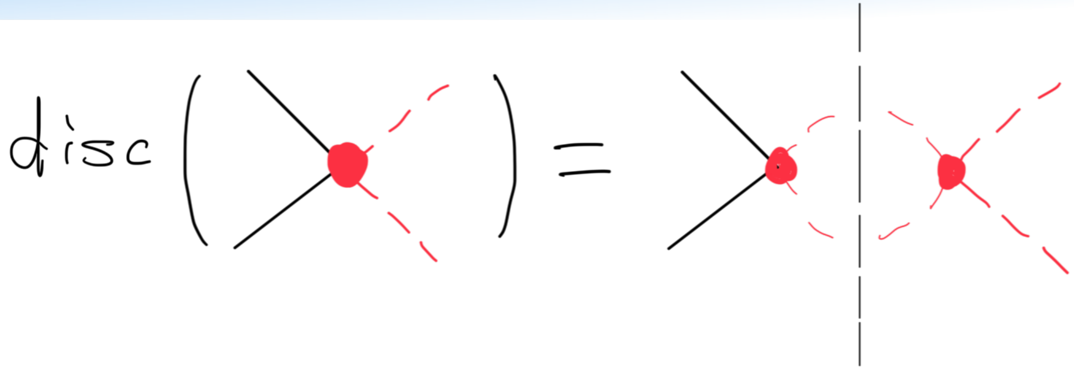
$$2i\,\mathrm{Im}\mathcal{M}_{J/\psi J/\psi\to N\bar{N}} = T_{J/\psi J/\psi\to\pi\pi}\; 2i\rho_\pi\; T^*_{\pi\pi\to N\bar{N}}$$

$\pi\pi$ phase space factor

  - $J/\psi J/\psi \to \pi\pi$ and $\pi\pi \to N\bar{N}$ amplitudes are again expressed using dispersion relation

Dispersive approach

- $J/\psi J/\psi \to \pi\pi$ amplitude
  - $\pi\pi$ scattering well-known
  - equation for $T_{J/\psi J/\psi\to\pi\pi}$ in a closed form
  - Solution is formally known as the Muskhelishvili-Omnès (MO) representation



$$2i\,\mathrm{Im}T_{J/\psi J/\psi\to\pi\pi} = \quad T_{J/\psi J/\psi\to\pi\pi} \quad 2i\rho_\pi \quad T^*_{\pi\pi\to\pi\pi}$$

- $N\bar{N} \to \pi\pi$ amplitude can be similarly obtained
  - The MO solution with both $\pi\pi$ and $K\bar{K}$ channels

Ω_0: $\pi\pi - K\bar{K}$ Omnès matrix

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

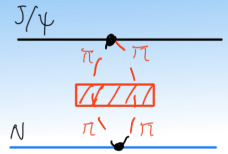
with

$$\vec{T}_0(s) = \begin{pmatrix} T_{N\bar{N}\to\pi\pi,0}(s) \\ \frac{2}{\sqrt{3}}T_{N\bar{N}\to K\bar{K},0}(s) \end{pmatrix}, \quad \vec{L}_0(s) = \begin{pmatrix} L_{N\bar{N}\to\pi\pi,0}(s) \\ \frac{2}{\sqrt{3}}L_{N\bar{N}\to K\bar{K},0}(s) \end{pmatrix}, \quad \vec{P}_{n-1}(s) = \begin{pmatrix} P_{n-1}^{N\bar{N}\to\pi\pi}(s) \\ \frac{2}{\sqrt{3}}P_{n-1}^{N\bar{N}\to K\bar{K}}(s) \end{pmatrix}$$

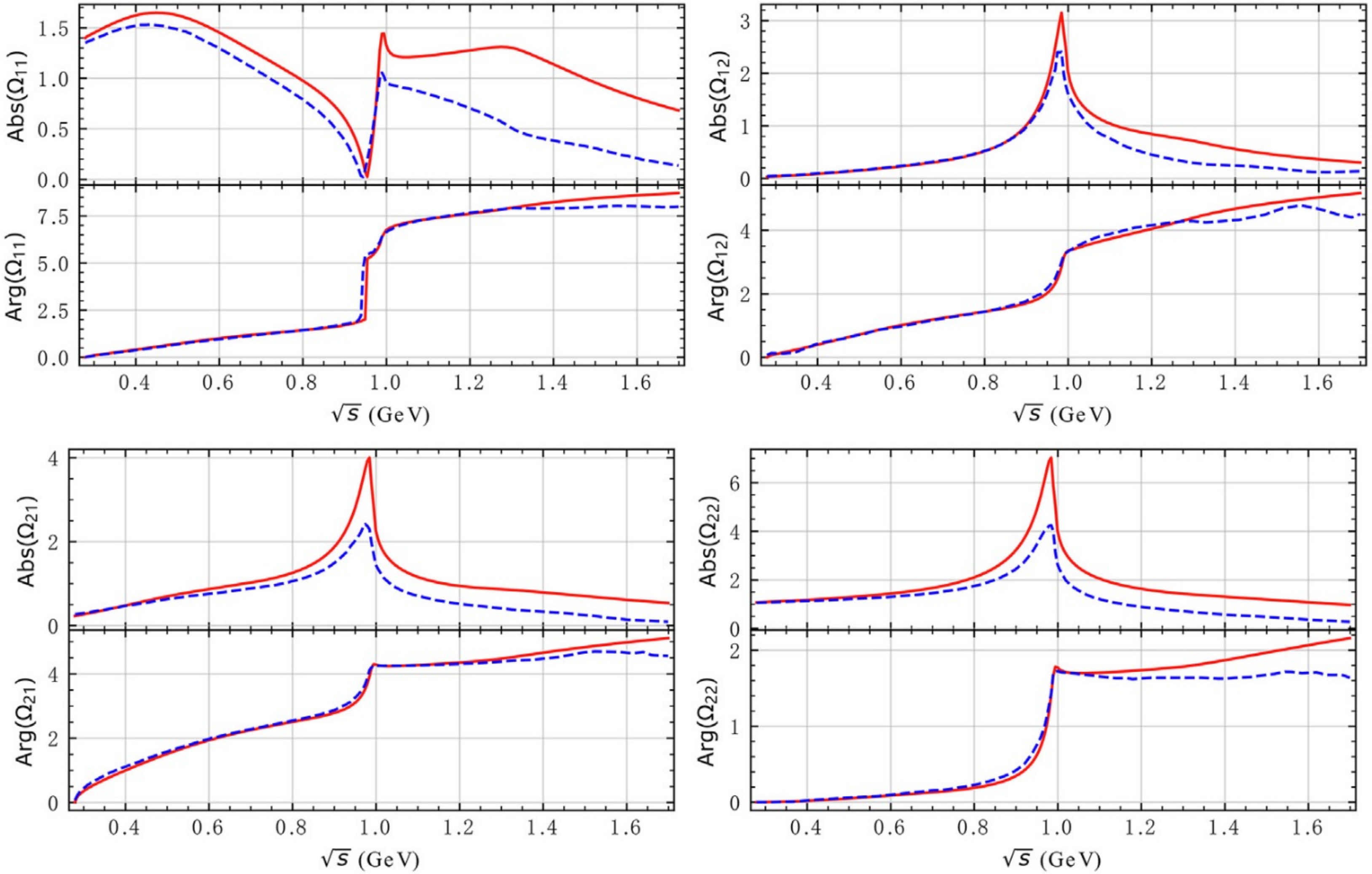
Do not have the right-hand cut

Subtraction polynomials, fixed by matching to chiral amplitudes

Inputs to the dispersive approach: Omnès matrix

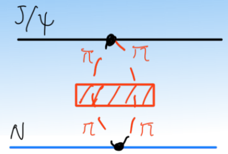


- $\pi\pi - K\bar{K}$ Omnès matrix: the $f_0(500)$ or σ, $f_0(980)$ contributions are included automatically



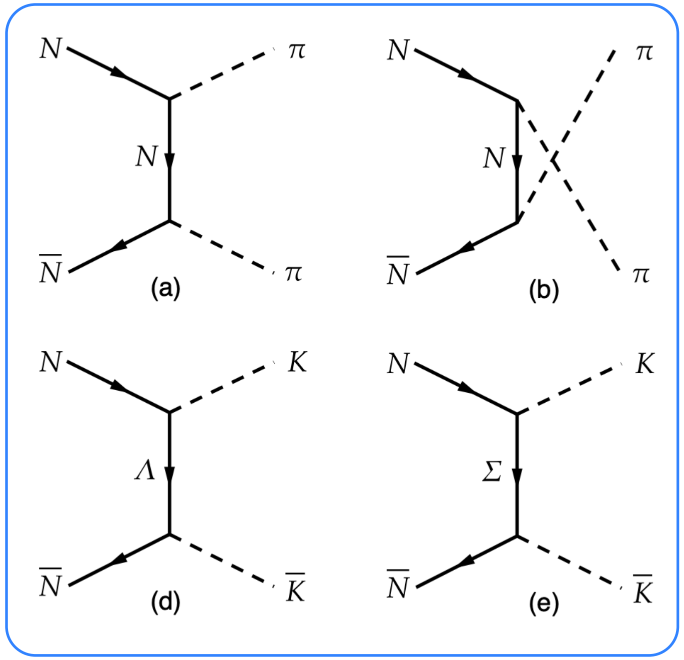
Red: S. Ropertz et al., EPJC 78 (2018) 1000; blue: M. Hoferichter et al., JHEP 06 (2012) 063

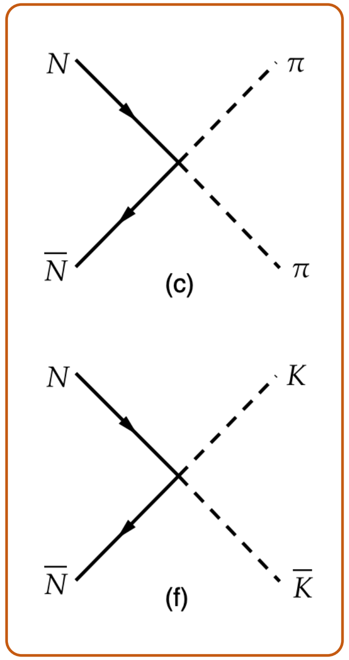
Inputs to the dispersive approach: $NN\pi\pi$



- $N\bar{N} \to \pi\pi$ without $\pi\pi - K\bar{K}$ rescattering: L_0, P_{n-1}

Vertices from LO chiral Lagrangian





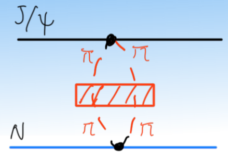
Vertices from NLO chiral Lagrangian
Low-energy constants (LECs) fixed in
X.-L. Ren et al., JHEP 12 (2012) 073

- The hadron-hadron-σ couplings can be systematically derived in this way; results for octet baryons

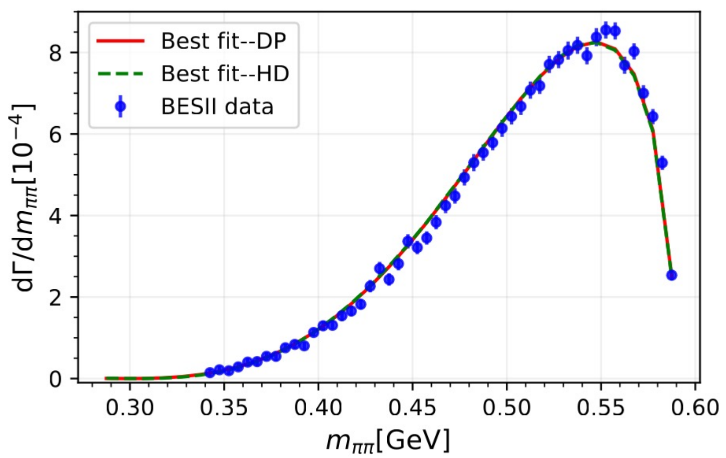
B. Wu, X.-H. Cao, X.-K. Dong, FKG, PRD 109 (2024) 034026

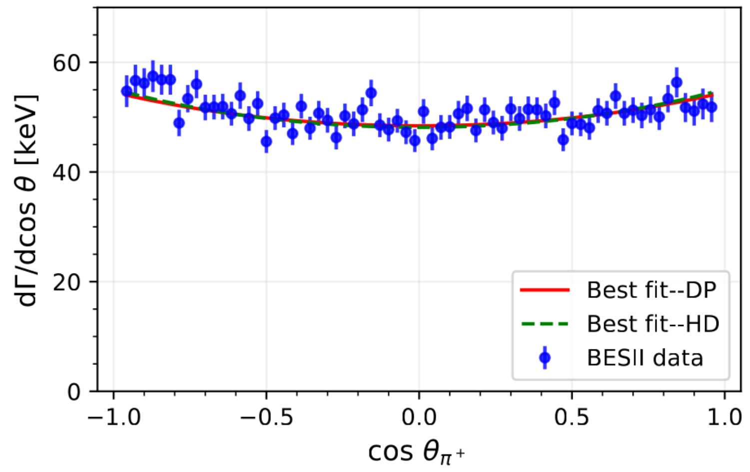
	LHC	RHC	Total	[33]	[18]	[34]	[37]	[36]	[24]	[23]	m_σ
$g_{\Sigma\Sigma\sigma}$	$1.8^{+0.5}_{-0.5}$	$3.5^{+2.0+0.8}_{-1.8-0.9}$	$3.5^{+1.8+0.4}_{-1.3-0.4}$	⋯	⋯	10.85(8.92)	4.65	⋯	⋯	⋯	519^{+50}_{-48}
$g_{\Xi\Xi\sigma}$	$0.2^{+0.1}_{-0.1}$	$2.6^{+1.5+0.5}_{-1.4-0.6}$	$2.5^{+1.5+0.5}_{-1.3-0.6}$	⋯	⋯	⋯	⋯	⋯	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}
$g^{\mathrm{SU(2)}}_{NN\sigma}$	$2.7^{+0.8}_{-0.8}$	$12.5^{+0.2+2.6}_{-0.2-3.2}$	$12.2^{+0.2+1.9}_{-0.2-2.3}$								586^{+38}_{-48}

Inputs to the dispersive approach: $\psi\psi\pi\pi$ vertex



- Two LECs for the $J/\psi\pi \to J/\psi\pi$ scattering:
  - $J/\psi\pi \to J/\psi\pi$ scattering unknown
  - Use $\psi' \to J/\psi\pi\pi$ data to extract similar LECs (off-diagonal from $\psi(2S)$ to J/ψ)





- Tree amplitude:

$$-\frac{4}{F_\pi^2}\left(c_1^{(21)} p_1^\mu p_{2\mu} + c_2^{(21)} p_1^0 p_2^0 + c_m^{(21)} M_{\mathcal{P}}^2\right)$$

- Final-state interaction with Omnès

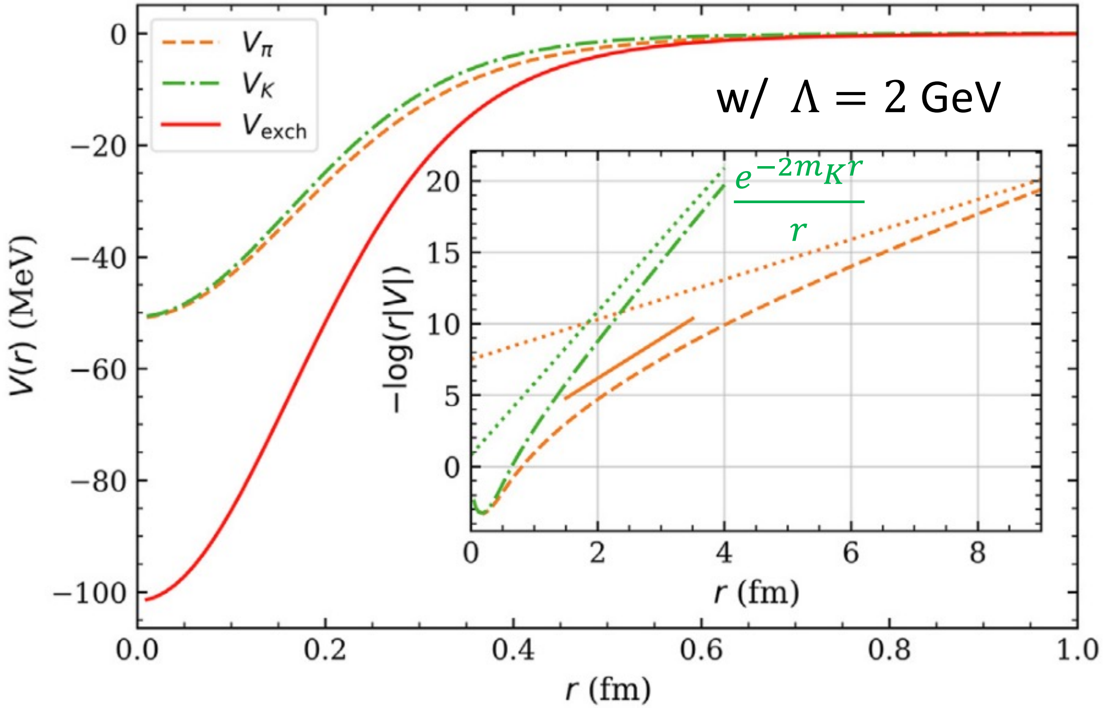
➢ Fit to BESII data for $\psi' \to J/\psi\pi^+\pi^-$
  - ✓ $\pi^+\pi^-$ invariant mass distribution
  - ✓ helicity angular distribution
  - ✓ $\pi\pi$ final state interaction considered using dispersion relation

➢ Assume the LECs for $J/\psi\pi \to J/\psi\pi$ scattering to be the same as those for $\psi'\pi \to J/\psi\pi$ (in reality, the former should be even larger)

$J/\psi J/\psi$ scattering

- $J/\psi J/\psi$ scattering calculated in the same manner X.-K. Dong et al., Sci. Bull. 66 (2021) 1577
  - $J/\psi J/\psi$ scattering potential given by a dispersive integral (regularized with a form factor)

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

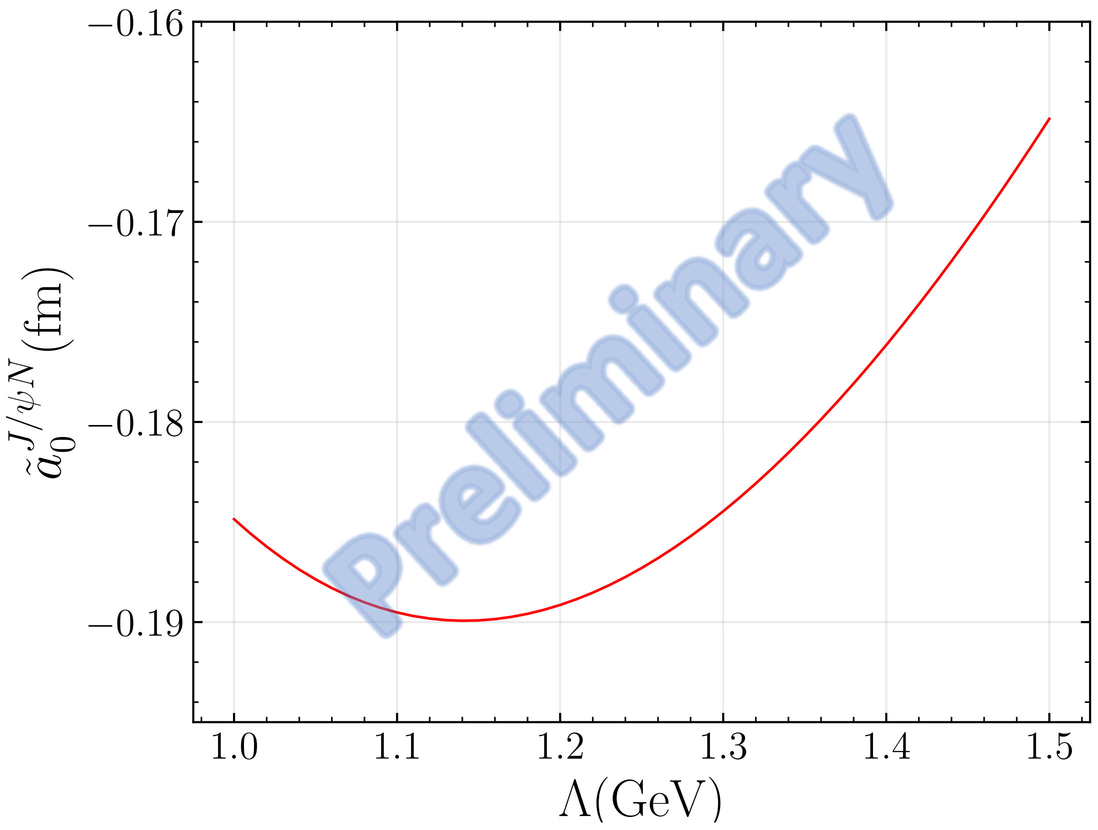


Long-distance behavior $\propto \frac{e^{-2m_\pi r}}{r}$

$\Rightarrow$ existence of $J/\psi J/\psi$ bound state is plausible

Results on the $J/\psi N$ scattering length

- S-wave scattering length: $\propto J/\psi N$ S-wave scattering amplitude at the threshold
  - $|a_{J/\psi N,0}|$ from the gluon exchange mechanism: $\mathcal{O}(\gtrsim 0.15\ \mathrm{fm})$
  - Significantly larger than that from the coupled-channel mechanism ($\lesssim \mathcal{O}(0.01\ \mathrm{fm})$)



$$c_1^{(ij)} = -\frac{\pi^2\sqrt{m_{\psi_i}m_{\psi_j}}F_\pi^2}{\beta_0}(4+3\kappa)\alpha^{(ij)}$$

$$c_2^{(ij)} = \frac{12\pi^2\sqrt{m_{\psi_i}m_{\psi_j}}F_\pi^2}{\beta_0}\kappa\alpha^{(ij)}$$

$$c_m^{(ij)} = -\frac{6\pi^2\sqrt{m_{\psi_i}m_{\psi_j}}F_\pi^2}{\beta_0}\alpha^{(ij)}$$

Schwarz inequality for chromopolarizabilities

$$\alpha_{J/\psi}\alpha_{\psi'} \geq \alpha^2_{\psi' J/\psi}$$

A. Sibirtsev, M. Voloshin, PRD 71 (2005) 076005

Thus, we expect the following inequality:

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

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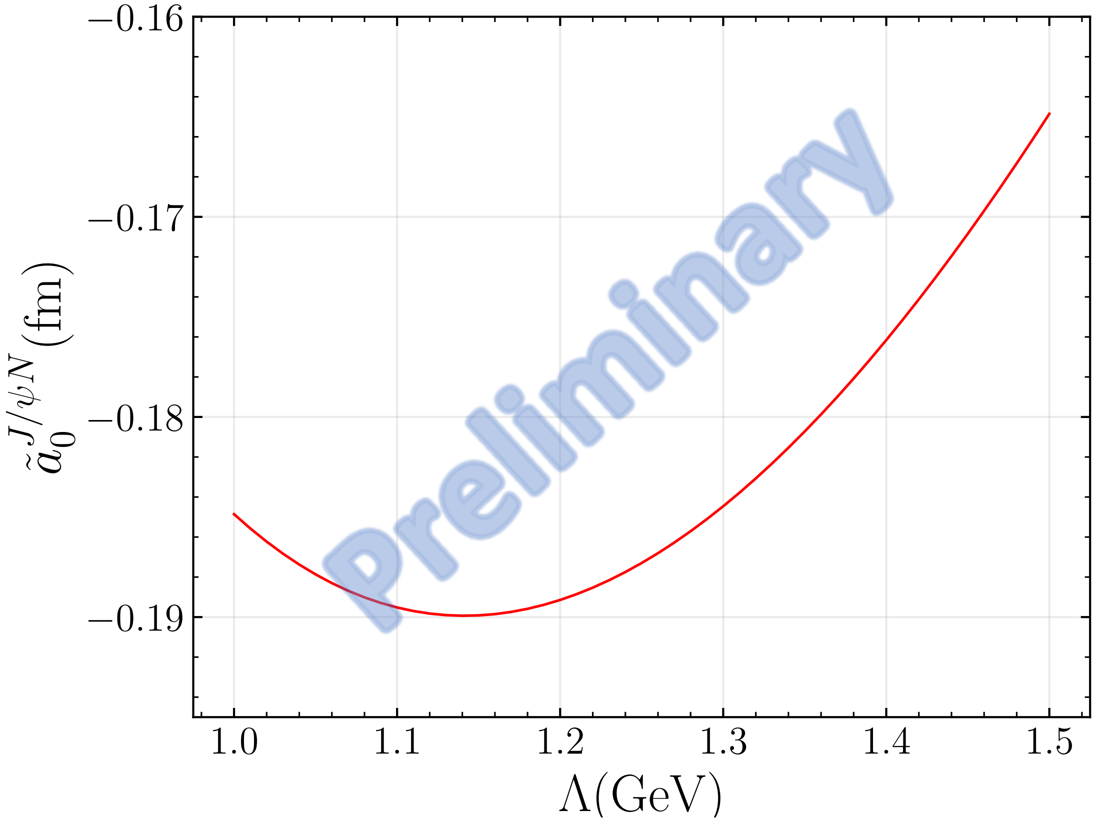

In line with lattice QCD results in:

- L. Liu et al., PoS LATTICE2008 (2008) 112

  $\eta_c N$: $-0.18(9)$ fm;

  $J/\psi N$ $\left(J=\frac{1}{2}\right)$: $0.05(77)$ fm

  $J/\psi N$ $\left(J=\frac{3}{2}\right)$: $-0.24(35)$ fm

- HALQCD, EPJ Web. Conf. 175 (2018) 05011

  $\eta_c N$: $-0.44(34)$ fm;

  $J/\psi N$ $\left(J=\frac{1}{2}\right)$: $-0.68(44)$ fm

  $J/\psi N$ $\left(J=\frac{3}{2}\right)$: $-0.63(42)$ fm

Summary and outlook

- Mechanism for charmonium near-threshold photoproduction not well understood
  - Unique prediction of coupled-channel mechanism for J/ψ: $\Lambda_c\bar{D}^{(*)}$ threshold cusps
  - Nontrivial line shape for $\gamma p \to X(3872)p$: thresholds + triangle singularities

- $J/\psi N$ scattering length from the gluon-exchange mechanism estimated to be significantly larger than that from the open-charm coupled-channel mechanism
  - Possible check:
    - Behavior of the long-distance potential from lattice QCD (HAL QCD did that for DD^* scattering)
    - We expect that the scaling of long-distance potential from gluon exchange for OZI suppressed scattering potential should be dominated by $2m_\pi$

Thank you for your attention!