Exclusive J/ψ photoproduction on nucleon and nuclei

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OMEG Origin of Matter and Evolution of Galaxies 우주 물질 중점연구소

In collaboration with T.-S.H.Lee (ANL)

East Asian Workshop on Exotic Hadrons 2024
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Contents

1. $\gamma\, p \to \varphi\, p$, $\gamma\, {}^4He \to \varphi\, {}^4He$

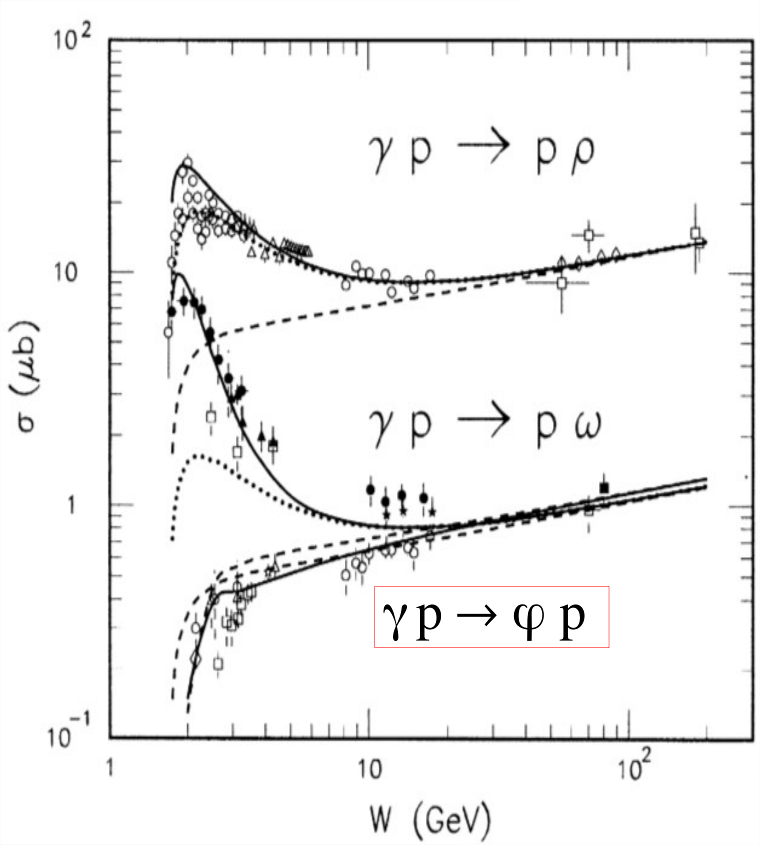
2. $\gamma\, p \to J/\psi\, p$, $\gamma\, A \to J/\psi\, A$ ($A = d, {}^4He, {}^{16}O, {}^{40}Ca$)

- ❑ Introduction
- ❑ Formalism
- ❑ Results
- ❑ Summary & Future work

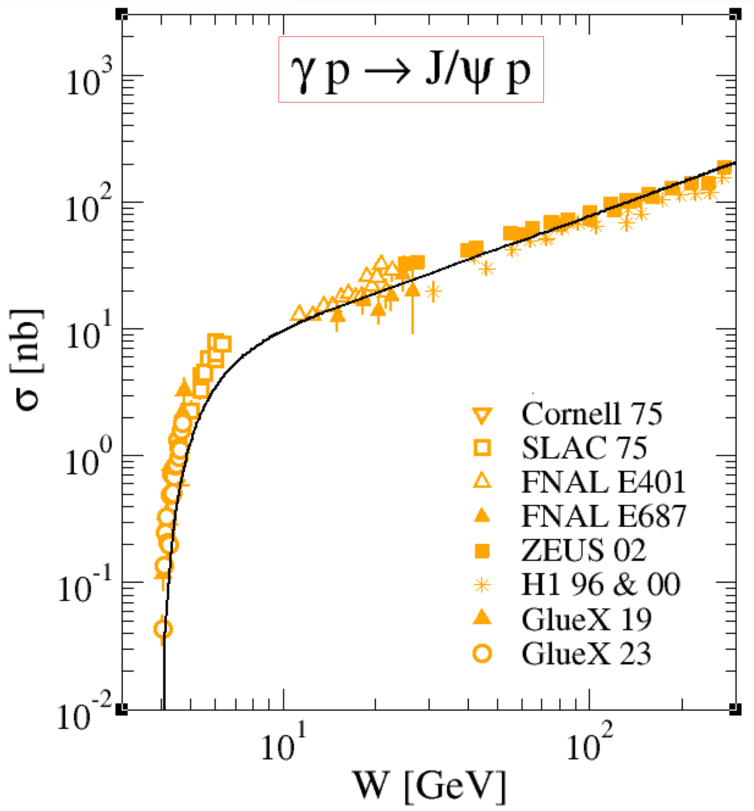
Contents based on

a [S.H.Kim, T.-S.H.Lee, S.i.Nam, Y.Oh, PRC.104.045202 (2021)]
b [S.H.Kim, T.-S.H.Lee, R.B.Wiringa, arXiv:2411.12187 (2024)]

□ Photoproduction of light vector mesons offers an ideal opportunity for studying gluonic interactions at high energies.
□ Pomeron exchange is responsible for describing slow rising total cross section.
□ The production mechanism at low energies should be investigated with the recent experimental data.

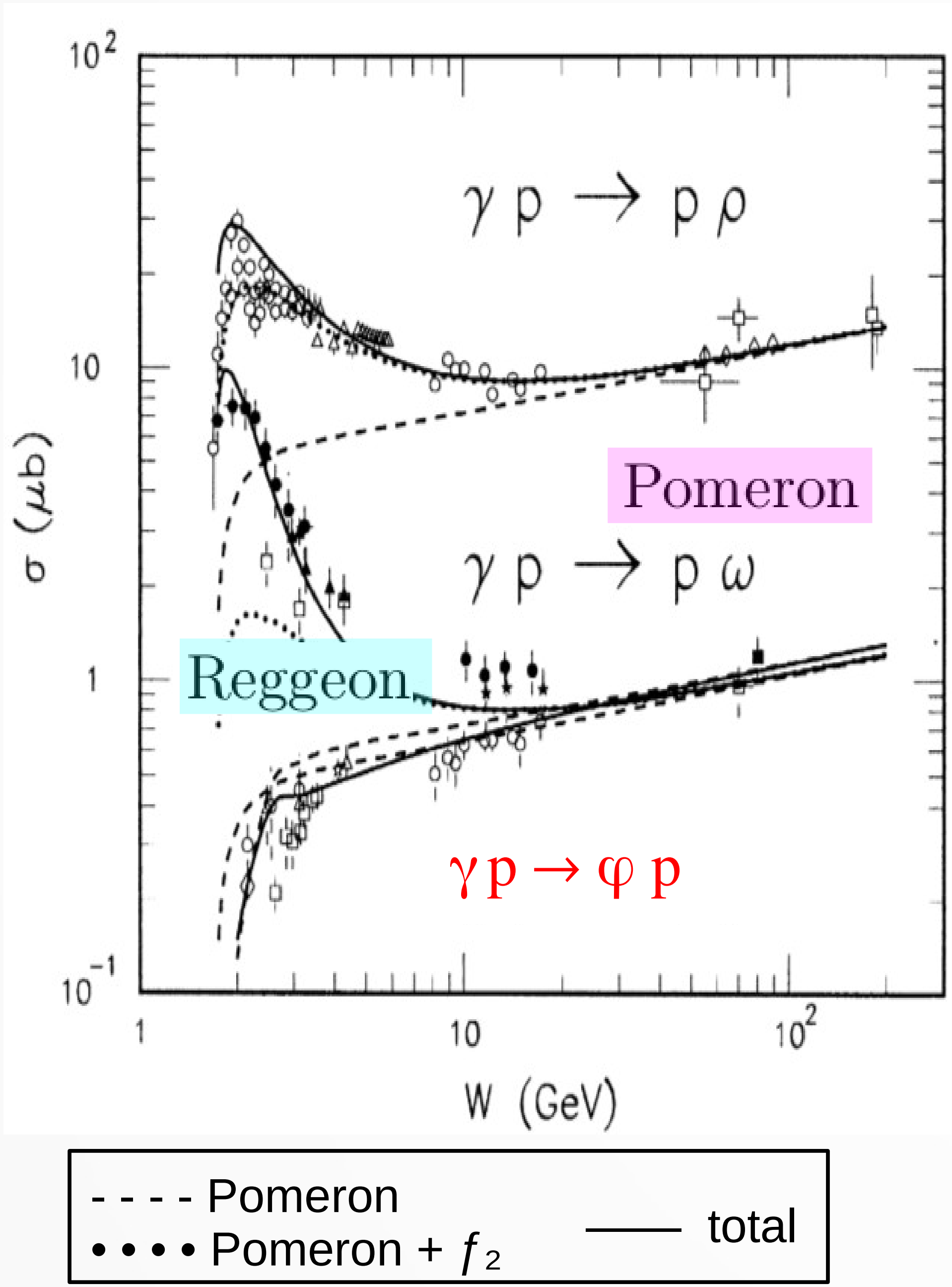


low energy : data [Dey, CLAS, PRC.89. 055208 (2014)
Seraydaryan, CLAS, PRC.89.055206 (2014)
Mizutani, LEPS, PRC.96.062201 (2017)]

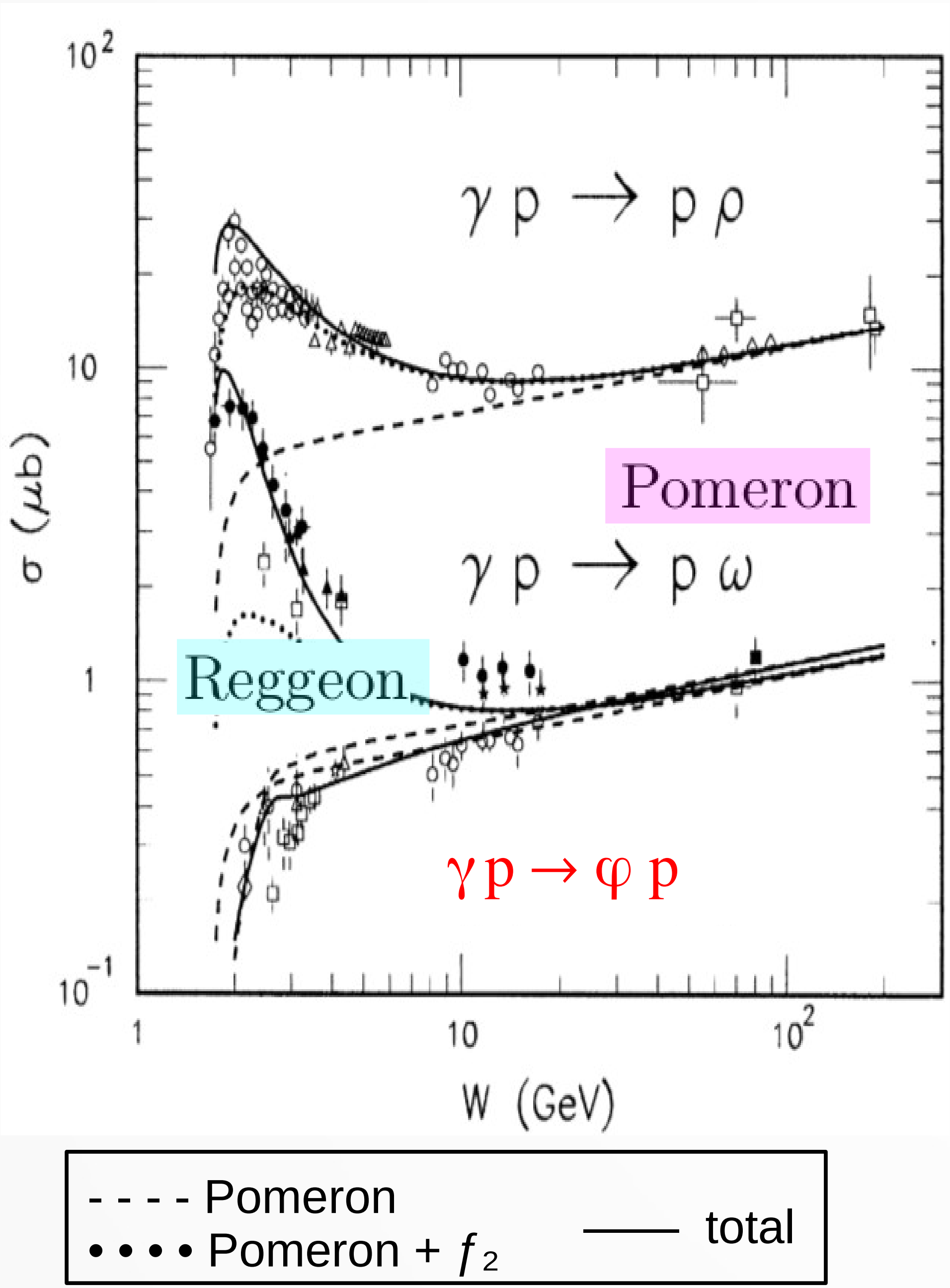


low energy : data [Pentchev, GlueX, PRL.123.072001 (2019)
Duran, JLab, Nature.615.813 (2023)
Pentchev, GlueX, PRC.108.025201 (2023)]

1. $\gamma\, p \rightarrow \varphi\, p, \quad \gamma\, {}^4He \rightarrow \varphi\, {}^4He$

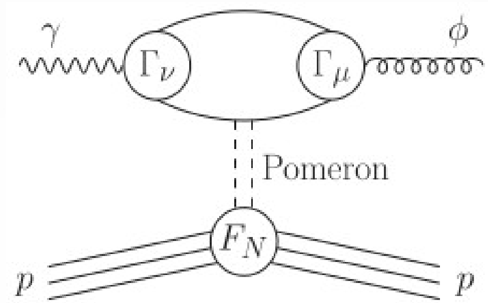


[Laget,PLB.489.313(2000)]



[Laget,PLB.489.313(2000)]

- We focus on γ p → φ p.
- high energy



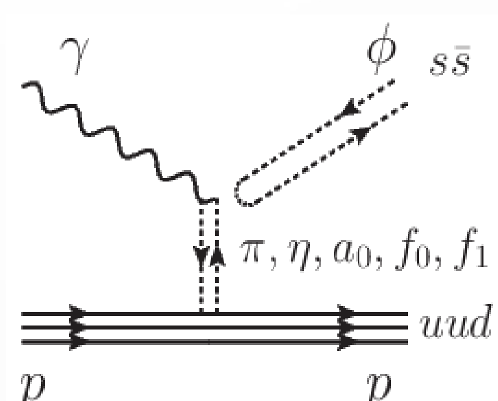
□ σ [γp → φp] ≈ σ [γp → ωp]

□ F_N: isoscalar EM form factor of the nucleon

$$F_N(t) = \frac{4M_N^2 - a_N^2 t}{(4M_N^2 - t)(1 - t/t_0)^2}$$

□ $_{P}(t) = 1.08 + 0.25t$

- low energy



□ σ[γp → φp] << σ[γp → (ρ,ω)p] due to the OZI rule

❑ high energy:

The two-gluon exchange is simplified by the Donnachie-Landshoff (DL) model which suggests that the Pomeron couples to the nucleon like a C = +1 isoscalar photon and its coupling is described in terms of $F_N(t)$.

[Pomeron Physics and QCD (Cambridge University, 2002)]

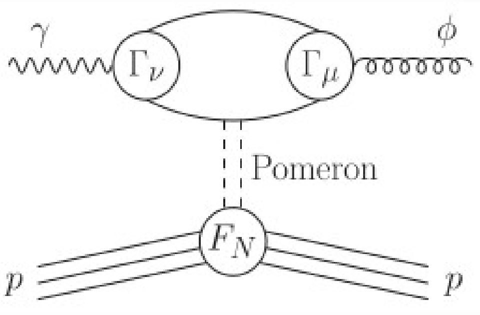
❑ low energy:

We need to clarify the reaction mechanism.

[Exp: Dey, CLAS, PRC.89. 055208 (2014)
Seraydaryan, CLAS, PRC.89.055206 (2014)
Mizutani, LEPS, PRC.96.062201 (2017)]

❑ We focus on γ p → φ p.

❑ high energy



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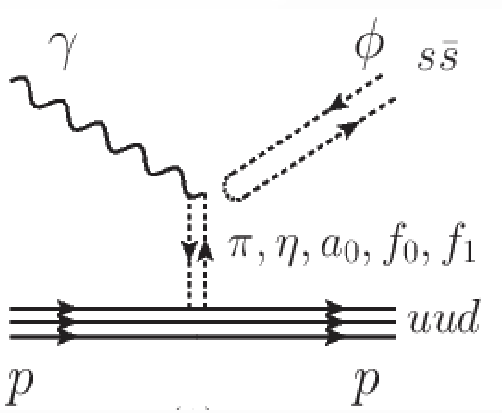
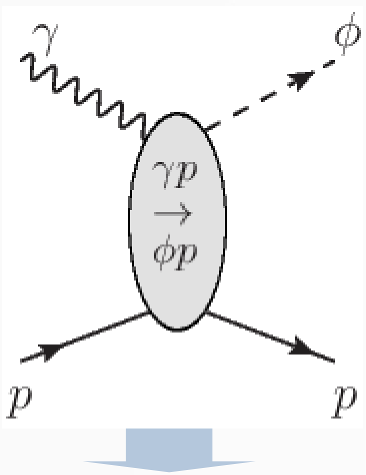
❑ low energy

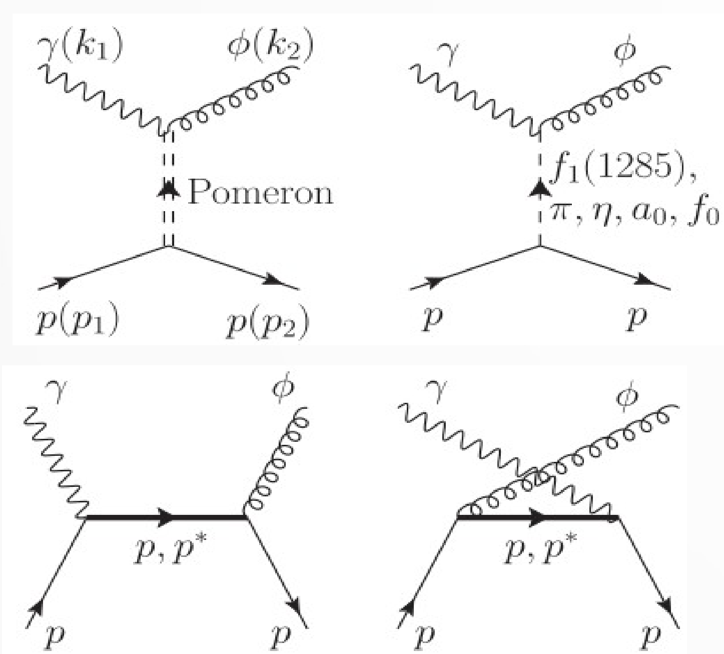


□ σ[γp → φp] << σ[γp → (ρ,ω)p] due to the OZI rule

Born term

❑ Scattering amplitude: $T_{\phi N,\gamma N}(E) = [B_{\phi N,\gamma N} \quad]$





□ We employ a dynamical approach based on a Hamiltonian.

$$H = H_0 + B_{\phi N,\gamma N} + \Gamma_{N^*,\gamma N} + \Gamma_{N^*,\phi N} + \sum_{MB=K\Lambda,K\Sigma,\pi N,\rho N} (v_{MB,\phi N} + \text{H.c.})$$

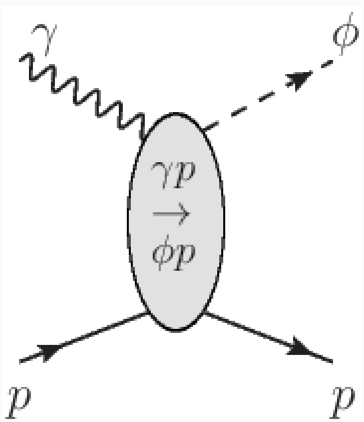
□ Ward-Takahashi identity

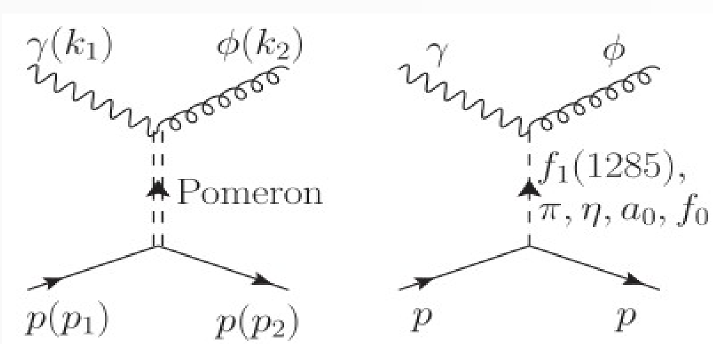
$$\mathcal{M}(k) = \epsilon_\mu(k)\mathcal{M}^\mu(k)$$

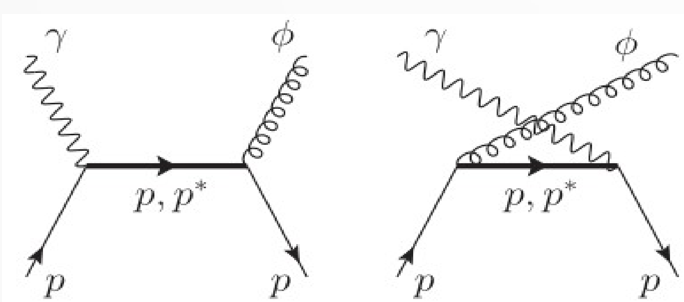
if we replace ϵ_μ with k_μ: $k_\mu \mathcal{M}^\mu(k) = 0$

Born term

❑ Scattering amplitude: $T_{\phi N,\gamma N}(E) = [B_{\phi N,\gamma N} \qquad]$







❑ Effective Lagrangians

□ EM vertex

$$\mathcal{L}_{\gamma\phi f_1} = g_{\gamma\phi f_1}\epsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu \partial^\lambda \partial_\lambda \phi_\alpha f_{1\beta}$$

$$\mathcal{L}_{\gamma\Phi\phi} = \frac{e g_{\gamma\Phi\phi}}{M_\phi}\epsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu \partial_\alpha \phi_\beta \Phi$$

$$\mathcal{L}_{\gamma S\phi} = \frac{e g_{\gamma S\phi}}{M_\phi} F^{\mu\nu}\phi_{\mu\nu} S$$

□ strong vertex

$$\mathcal{L}_{f_1 NN} = -g_{f_1 NN}\bar{N}\left[\gamma_\mu - i\frac{\kappa_{f_1 NN}}{2M_N}\gamma_\nu\gamma_\mu\partial^\nu\right] f_1^\mu \gamma_5 N$$

$$\mathcal{L}_{\Phi NN} = -i g_{\Phi NN}\bar{N}\Phi\gamma_5 N$$

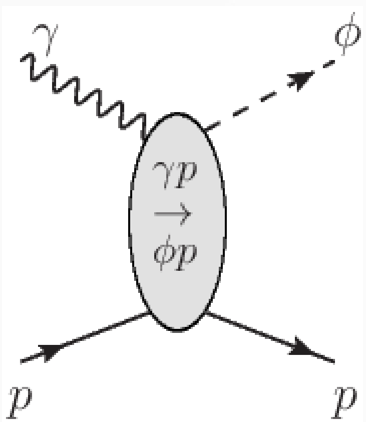
$$\mathcal{L}_{SNN} = -g_{SNN}\bar{N}SN$$

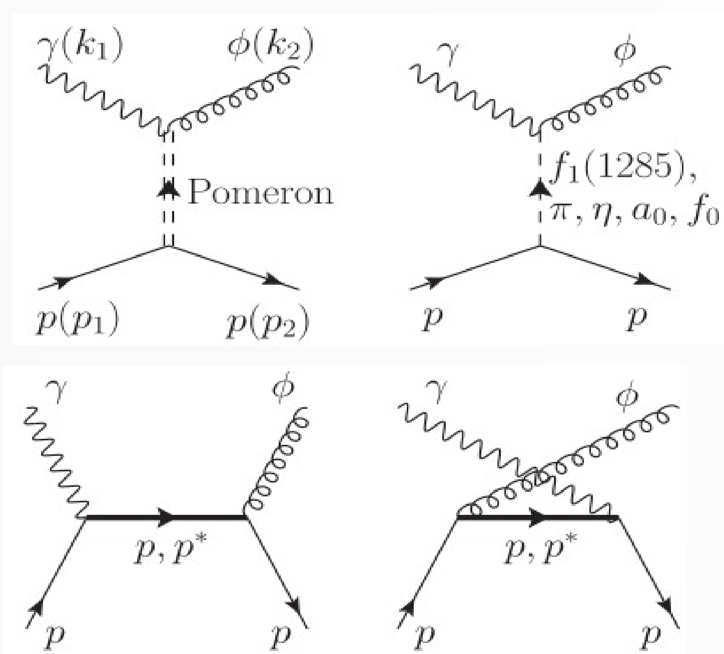
$$\mathcal{L}_{\gamma NN} = -e\bar{N}\left[\gamma_\mu - \frac{\kappa_N}{2M_N}\sigma_{\mu\nu}\partial^\nu\right] N A^\mu$$

$$\mathcal{L}_{\phi NN} = -g_{\phi NN}\bar{N}\left[\gamma_\mu - \frac{\kappa_{\phi NN}}{2M_N}\sigma_{\mu\nu}\partial^\nu\right] N \phi^\mu$$

Born term

❑ Scattering amplitude: $T_{\phi N,\gamma N}(E) = [B_{\phi N,\gamma N} \quad]$





$$\mathcal{M} = \varepsilon_\nu^* \bar{u}_{N'} \mathcal{M}^{\mu\nu} u_N \epsilon_\mu$$

$$\mathcal{M}_{f_1}^{\mu\nu} = i\frac{M_\phi^2 g_{\gamma f_1 \phi} g_{f_1 NN}}{t - M_{f_1}^2} \epsilon^{\mu\nu\alpha\beta}\left[-g_{\alpha\lambda} + \frac{q_{t\alpha} q_{t\lambda}}{M_{f_1}^2}\right] \times \left[\gamma^\lambda + \frac{\kappa_{f_1 NN}}{2M_N}\gamma^\sigma \gamma^\lambda q_{t\sigma}\right]\gamma_5 k_{1\beta},$$

$$\mathcal{M}_{\Phi}^{\mu\nu} = i\frac{e}{M_\phi}\frac{g_{\gamma\Phi\phi} g_{\Phi NN}}{t - M_\Phi^2}\epsilon^{\mu\nu\alpha\beta} k_{1\alpha} k_{2\beta}\gamma_5,$$

$$\mathcal{M}_{S}^{\mu\nu} = \frac{e}{M_\phi}\frac{2 g_{\gamma S\phi} g_{SNN}}{t - M_S^2 + i\Gamma_S M_S}\left(k_1 k_2 g^{\mu\nu} - k_1^\mu k_2^\nu\right),$$

$$\mathcal{M}_{\phi\,\mathrm{rad},s}^{\mu\nu} = \frac{e g_{\phi NN}}{s - M_N^2}\left(\gamma^\nu - i\frac{\kappa_{\phi NN}}{2M_N}\sigma^{\nu\alpha} k_{2\alpha}\right)(\not{q}_s + M_N) \times \left(\gamma^\mu + i\frac{\kappa_N}{2M_N}\sigma^{\mu\beta} k_{1\beta}\right),$$

$$\mathcal{M}_{\phi\,\mathrm{rad},u}^{\mu\nu} = \frac{e g_{\phi NN}}{u - M_N^2}\left(\gamma^\mu + i\frac{\kappa_N}{2M_N}\sigma^{\mu\alpha} k_{1\alpha}\right)(\not{q}_u + M_N) \times \left(\gamma^\nu - i\frac{\kappa_{\phi NN}}{2M_N}\sigma^{\nu\beta} k_{2\beta}\right),$$

❑ Effective Lagrangians

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$$\mathcal{L}_{\gamma\Phi\phi} = \frac{e g_{\gamma\Phi\phi}}{M_\phi}\epsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu \partial_\alpha \phi_\beta \Phi$$

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□ strong vertex

$$\mathcal{L}_{f_1 NN} = -g_{f_1 NN}\bar{N}\left[\gamma_\mu - i\frac{\kappa_{f_1 NN}}{2M_N}\gamma_\nu \gamma_\mu \partial^\nu\right] f_1^\mu \gamma_5 N$$

$$\mathcal{L}_{\Phi NN} = -i g_{\Phi NN}\bar{N}\Phi\gamma_5 N$$

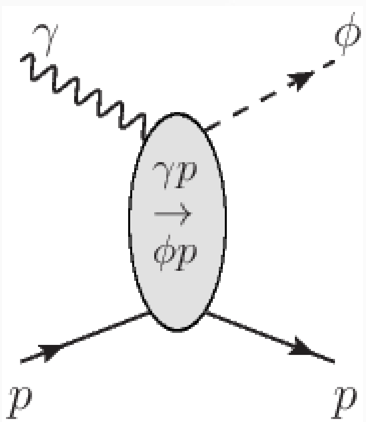
$$\mathcal{L}_{SNN} = -g_{SNN}\bar{N} S N$$

$$\mathcal{L}_{\gamma NN} = -e\bar{N}\left[\gamma_\mu - \frac{\kappa_N}{2M_N}\sigma_{\mu\nu}\partial^\nu\right] N A^\mu$$

$$\mathcal{L}_{\phi NN} = -g_{\phi NN}\bar{N}\left[\gamma_\mu - \frac{\kappa_{\phi NN}}{2M_N}\sigma_{\mu\nu}\partial^\nu\right] N \phi^\mu$$

final state interaction (FSI)

❑ Scattering amplitude: $T_{\phi N,\gamma N}(E) = [B_{\phi N,\gamma N} + T^{FSI}_{\phi N,\gamma N}(E)]$



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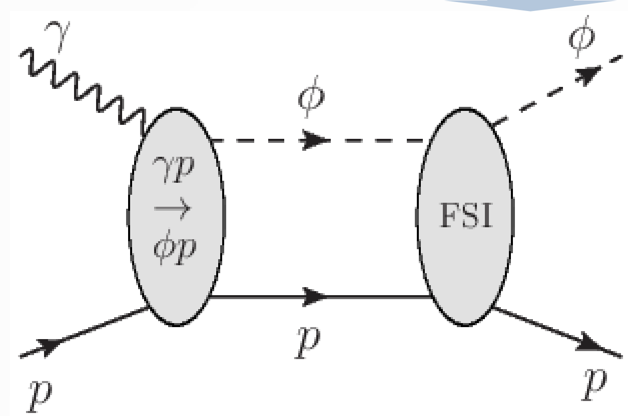

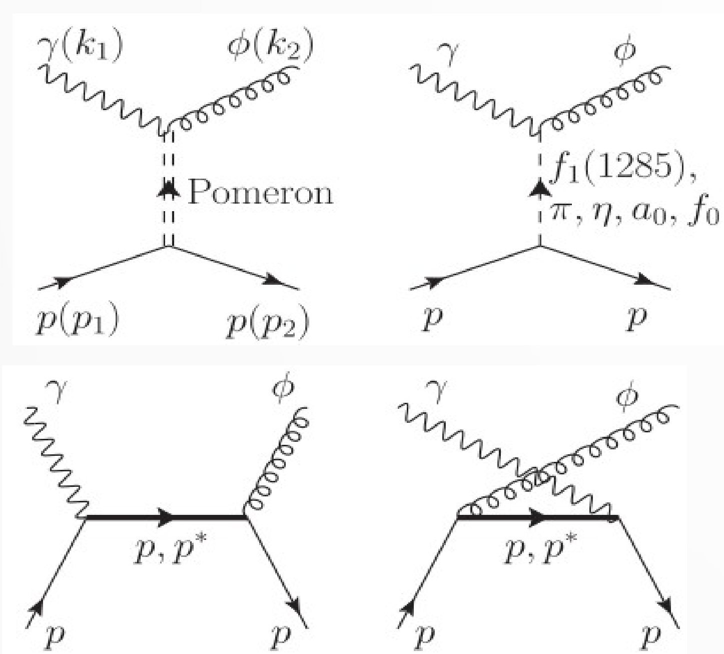

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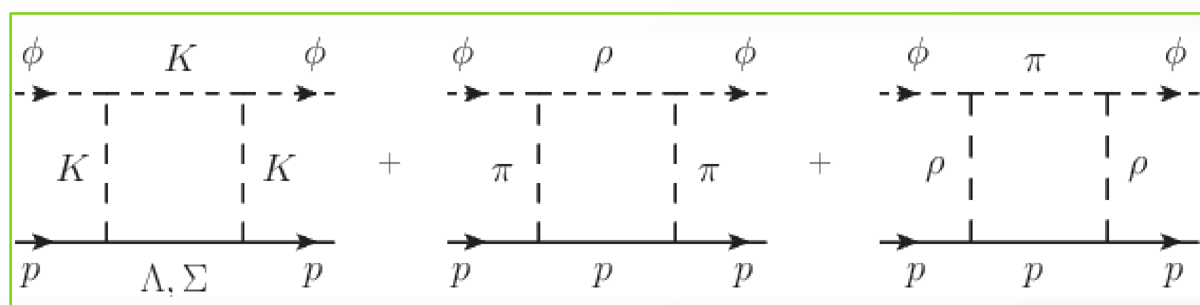
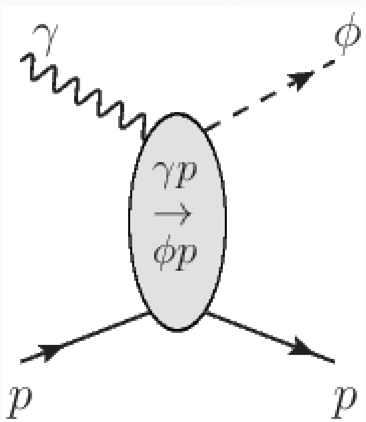


□ decay mode of φ-meson

Γ_1	K^+K^-	$(49.2 \pm 0.5)\%$
Γ_2	$K^0_L\ K^0_S$	$(34.0 \pm 0.4)\%$
Γ_3	$\rho\pi + \pi^+\pi^-\pi^0$	$(15.24 \pm 0.33)\%$
Γ_4	$\rho\pi$	
Γ_5	$\pi^+\pi^-\pi^0$	
Γ_6	$\eta\gamma$	$(1.303 \pm 0.025)\%$
Γ_7	$\pi^0\gamma$	$(1.32 \pm 0.06) \times 10^{-3}$
Γ_8	$\ell^+\ell^-$	
Γ_9	e^+e^-	$(2.974 \pm 0.034) \times 10^{-4}$
Γ_{10}	$\mu^+\mu^-$	$(2.86 \pm 0.19) \times 10^{-4}$
Γ_{11}	ηe^+e^-	$(1.08 \pm 0.04) \times 10^{-4}$
Γ_{12}	$\pi^+\pi^-$	$(7.3 \pm 1.3) \times 10^{-5}$
Γ_{13}	$\omega\pi^0$	$(4.7 \pm 0.5) \times 10^{-5}$
Γ_{14}	$\omega\gamma$	$< 5\%$
Γ_{15}	$\rho\gamma$	$< 1.2 \times 10^{-5}$

final state interaction (FSI)

❑ Scattering amplitude: $T_{\phi N,\gamma N}(E) = [B_{\phi N,\gamma N} + T^{FSI}_{\phi N,\gamma N}(E)]$



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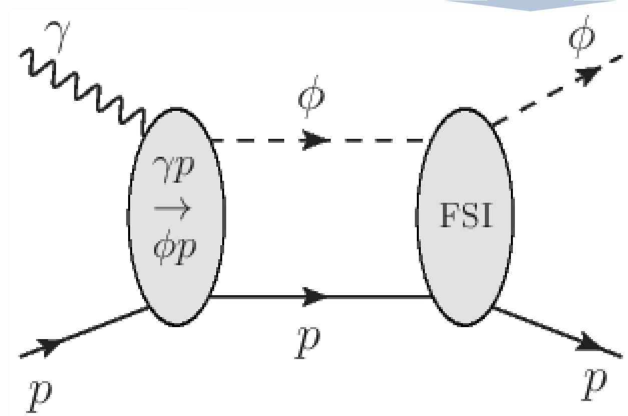

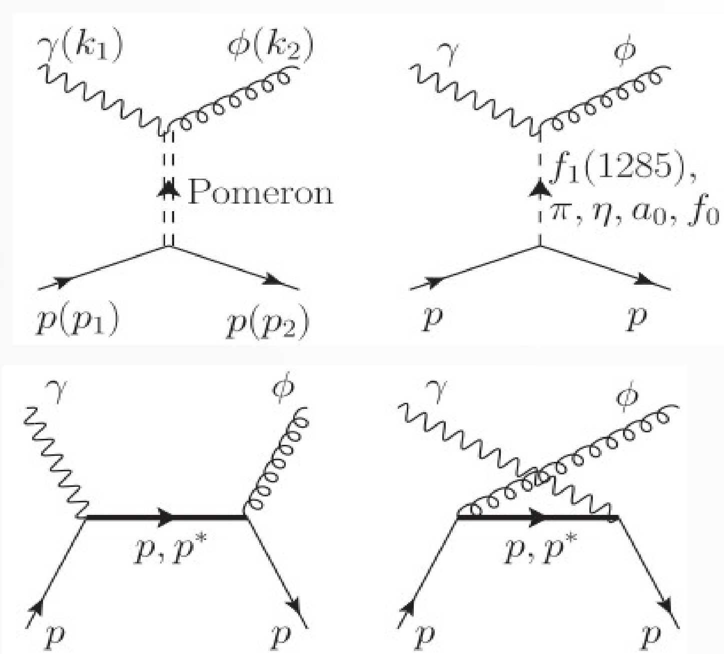

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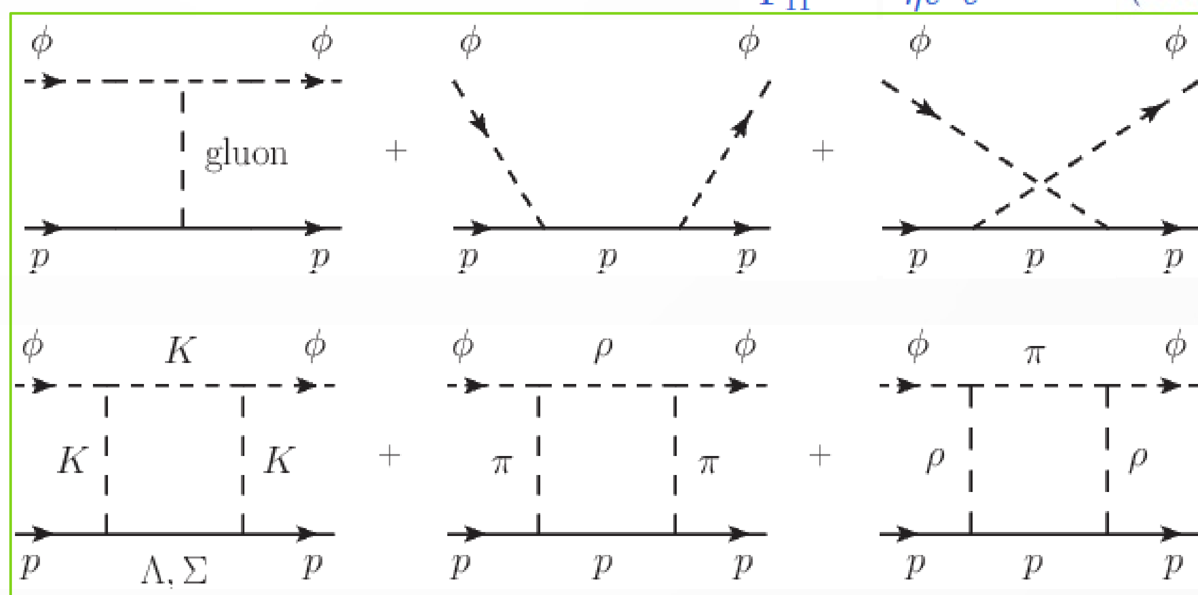

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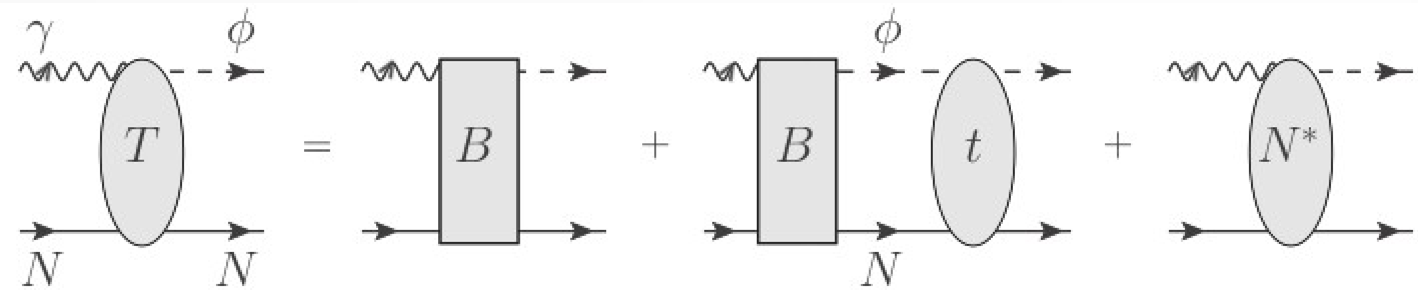
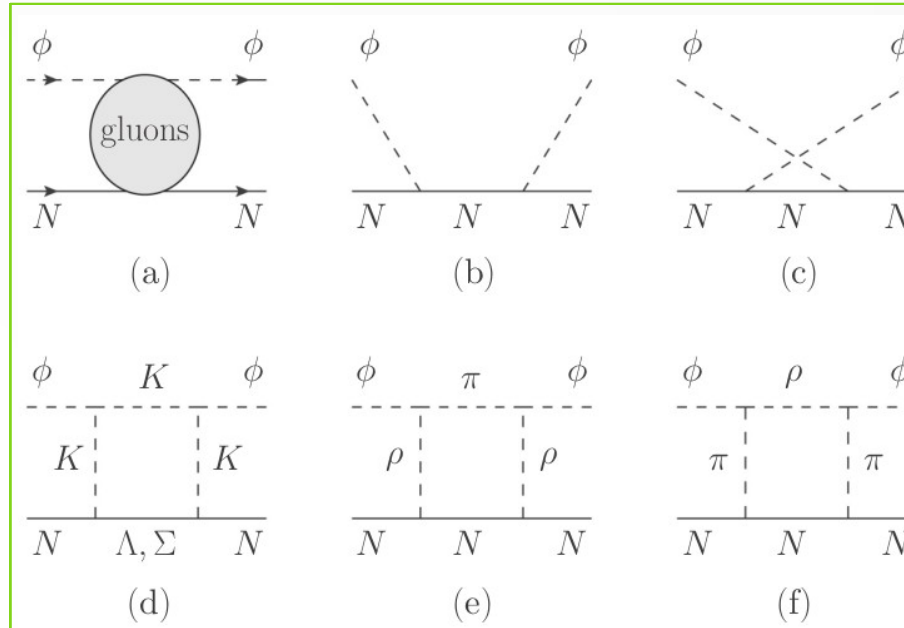
Γ_{11}	ηe^+e^-	$(1.08 \pm 0.04) \times 10^{-4}$
		$1.3) \times 10^{-5}$
		$0.5) \times 10^{-5}$
		$\times 10^{-5}$

final state interaction (FSI)



$$T_{\phi N,\gamma N}(E) = B_{\phi N,\gamma N} + T^{\mathrm{FSI}}_{\phi N,\gamma N}(E) + T^{N^*}_{\phi N,\gamma N}(E)$$

$t_{\phi N,\phi N}(E)$



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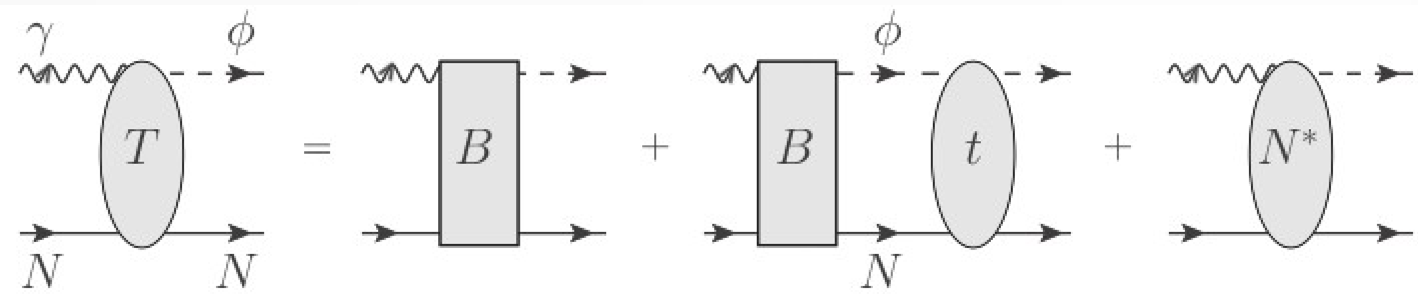
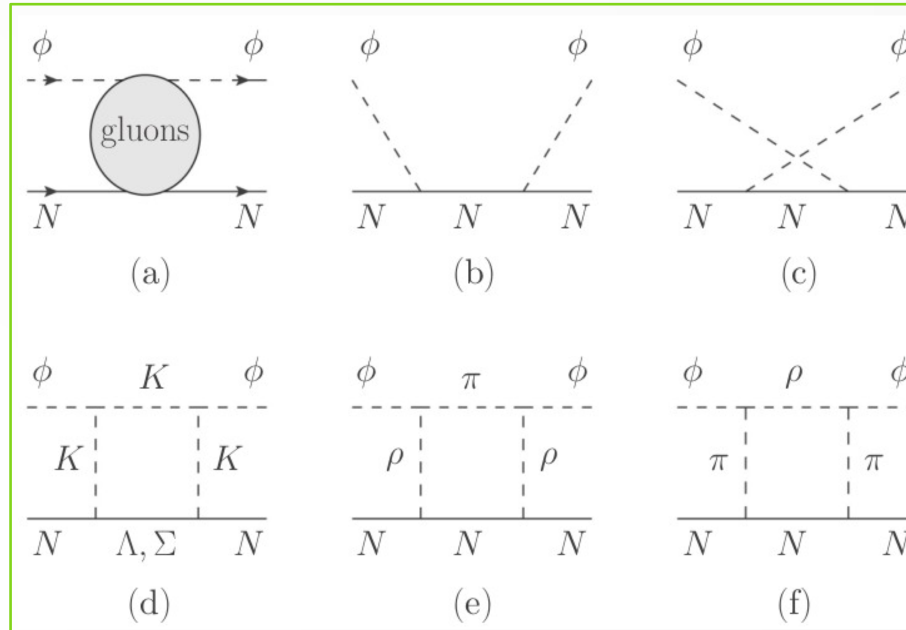


$$T_{\phi N,\gamma N}(E) = B_{\phi N,\gamma N} + \underbrace{T^{\mathrm{FSI}}_{\phi N,\gamma N}(E)}_{t_{\phi N,\phi N}(E) G_{\phi N}(E) B_{\phi N,\gamma N}} + T^{N^*}_{\phi N,\gamma N}(E)$$

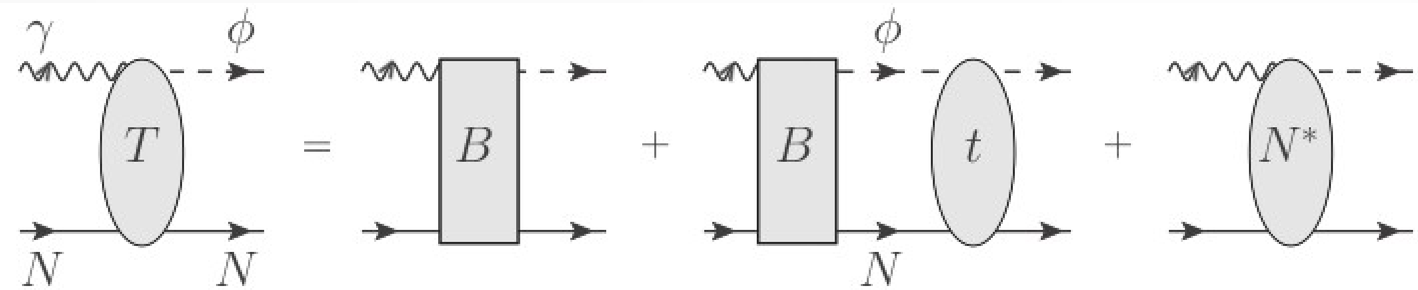
$$G_{MB}(E) = \frac{|MB\rangle\langle MB|}{E - H_0 + i\epsilon}$$: meson-baryon propagator

$$t_{\phi N,\phi N}(E) = V_{\phi N,\phi N}(E) + V_{\phi N,\phi N} G_{\phi N}(E) t_{\phi N,\phi N}(E)$$

$t_{\phi N,\phi N}(E)$



final state interaction (FSI)



$$T_{\phi N,\gamma N}(E) = B_{\phi N,\gamma N} + T^{\rm FSI}_{\phi N,\gamma N}(E) + T^{N^*}_{\phi N,\gamma N}(E)$$

$$T^{\rm FSI}_{\phi N,\gamma N}(E) = t_{\phi N,\phi N}(E) G_{\phi N}(E) B_{\phi N,\gamma N}$$

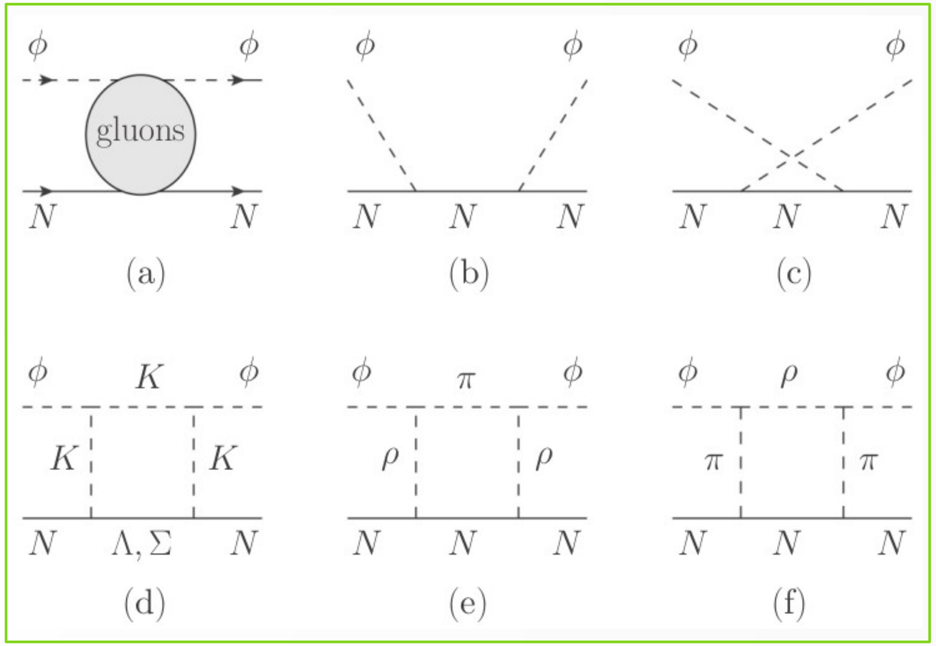
$$G_{MB}(E) = \frac{|MB\rangle \langle MB|}{E - H_0 + i\epsilon}$$: meson-baryon propagator

$$t_{\phi N,\phi N}(E) = V_{\phi N,\phi N}(E) + V_{\phi N,\phi N} G_{\phi N}(E) t_{\phi N,\phi N}(E)$$

$$V_{\phi N,\phi N}(E) = v^{\rm Gluon}_{\phi N,\phi N} + v^{\rm Direct}_{\phi N,\phi N} + \sum_{MB} v_{\phi N,MB} G_{MB}(E) v_{MB,\phi N}$$

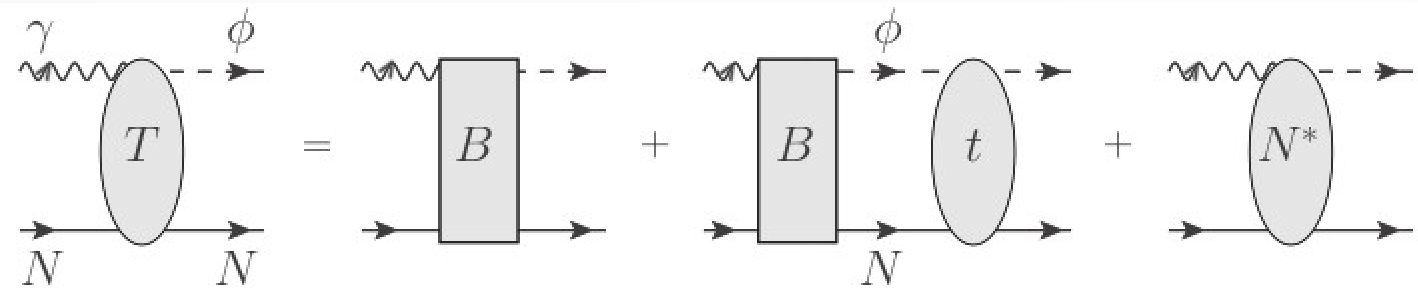
(a) (b,c) (d,e,f) MB = (KΛ, KΣ, πN, ρN)

$t_{\phi N,\phi N}(E)$

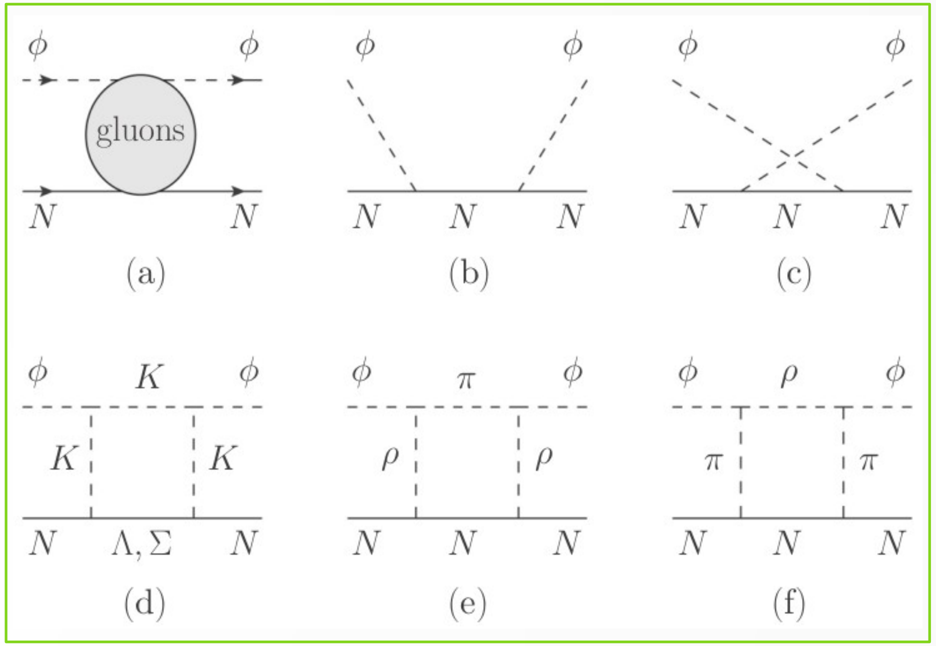


□ To leading order, we obtain these FSI diagrams.

final state interaction (FSI)



$t_{\phi N,\phi N}(E)$



$$T_{\phi N,\gamma N}(E) = B_{\phi N,\gamma N} + T^{\mathrm{FSI}}_{\phi N,\gamma N}(E) + T^{N^*}_{\phi N,\gamma N}(E)$$

$$t_{\phi N,\phi N}(E) G_{\phi N}(E) B_{\phi N,\gamma N}$$

$$G_{MB}(E) = \frac{|MB\rangle\langle MB|}{E - H_0 + i\epsilon}$$: meson-baryon propagator

$$\frac{1}{E - H_0 + i\epsilon} = P\frac{1}{E - H_0} - i\pi\delta(E - H_0)$$

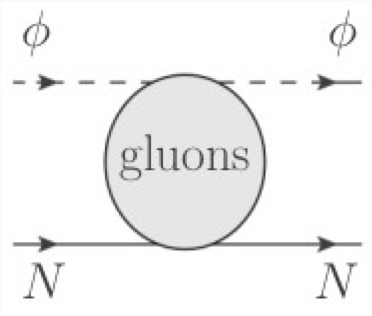
□ We consider both parts numerically.

$$t_{\phi N,\phi N}(E) = V_{\phi N,\phi N}(E) + V_{\phi N,\phi N} G_{\phi N}(E) t_{\phi N,\phi N}(E)$$

$$v^{\mathrm{Gluon}}_{\phi N,\phi N} + v^{\mathrm{Direct}}_{\phi N,\phi N} + \sum_{MB} v_{\phi N,MB} G_{MB}(E) v_{MB,\phi N}$$

(a) (b,c) (d,e,f) MB = (KΛ, KΣ, πN, ρN)

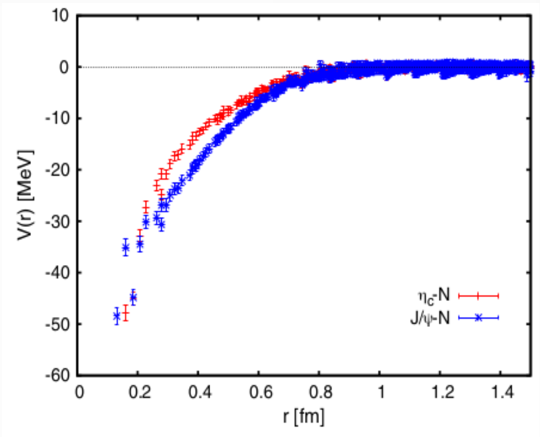
final state interaction (FSI)



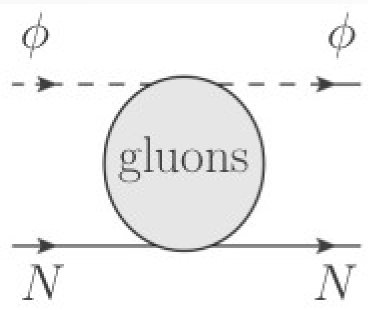
- □ The J/ψ-N potential from the LQCD data
  ~ Yukawa form (υ_0 = 0.1, α = 0.3 GeV)
  [Kawanai, Sasaki, PRD.82.091501(R) (2010)]

$$\mathcal{V}_{\mathrm{gluon}} = -\upsilon_0 \frac{e^{-\alpha r}}{r}$$

- □ which is assumed in our work, φ-N potential
  The best fit was obtained by (υ_0 = 0.2, α = 0.5 GeV).



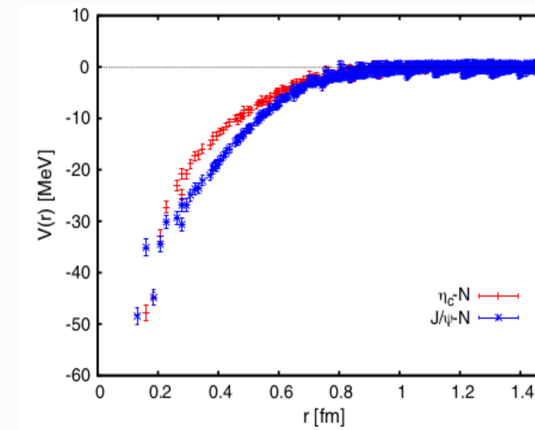
final state interaction (FSI)



□ The J/ψ-N potential from the LQCD data
~ Yukawa form (υ_0 = 0.1, α = 0.3 GeV)

[Kawanai, Sasaki, PRD.82.091501(R) (2010)]

$$\mathcal{V}_{\text{gluon}} = -\upsilon_0 \frac{e^{-\alpha r}}{r}$$



□ which is assumed in our work, φ-N potential
The best fit was obtained by (υ_0 = 0.2, α = 0.5 GeV).

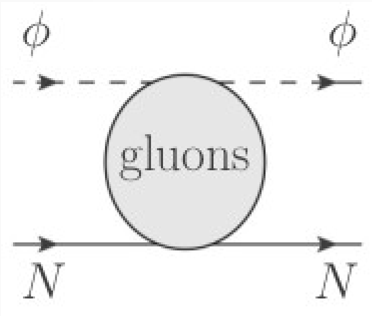
□ The potential is obtained by taking the nonrelativistic limit of the scalar-meson exchange amplitude calculated from the Lagrangian:

$$\mathscr{L}_\sigma = V_0(\bar{\psi}_N \psi_N \Phi_\sigma + \phi^\mu \phi_\mu \Phi_\sigma)$$

Φ_σ is a scalar field with mass α ($V_0 = -8\upsilon_0 \pi M_\varphi$).

□ $$\mathcal{V}_{\text{gluon}}\left(k\lambda_\phi, pm_s; k'\lambda'_\phi, p'm'_s\right) = \frac{V_0}{(p-p')^2 - \alpha^2}[\bar{u}_N(p, m_s)u_N(p', m'_s)][\epsilon^*_\mu(k, \lambda_\phi)\epsilon^\mu(k', \lambda'_\phi)]$$

final state interaction (FSI)



□ The J/ψ-N potential from the LQCD data
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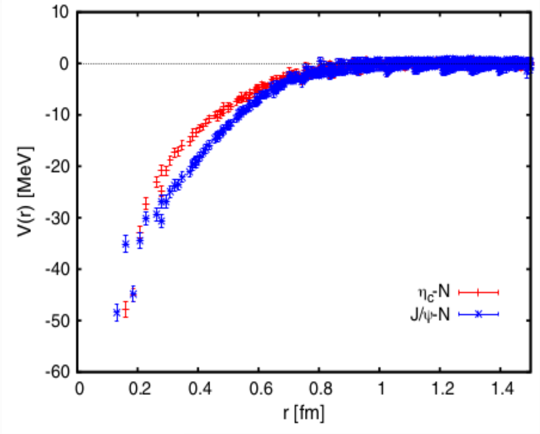
$$\mathcal{V}_{\text{gluon}} = -v_0 \frac{e^{-\alpha r}}{r}$$



□ which is assumed in our work, φ-N potential
The best fit was obtained by (υ_0 = 0.2, α = 0.5 GeV).

□ The φ-N potential from the LQCD [Lyu, PRD.106.074507 (2022)]

Attractive N-ϕ Interaction and Two-Pion Tail from Lattice QCD near Physical Point

Yan Lyu,[1,2,*] Takumi Doi,[2,†] Tetsuo Hatsuda,[2,‡] Yoichi Ikeda,[3,§]
Jie Meng,[1,4,¶] Kenji Sasaki,[3,**] and Takuya Sugiura[2,††]

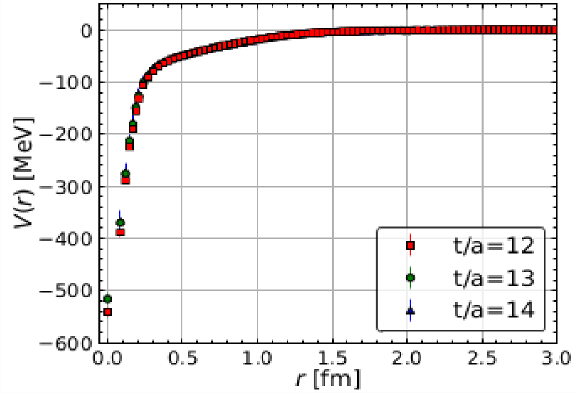


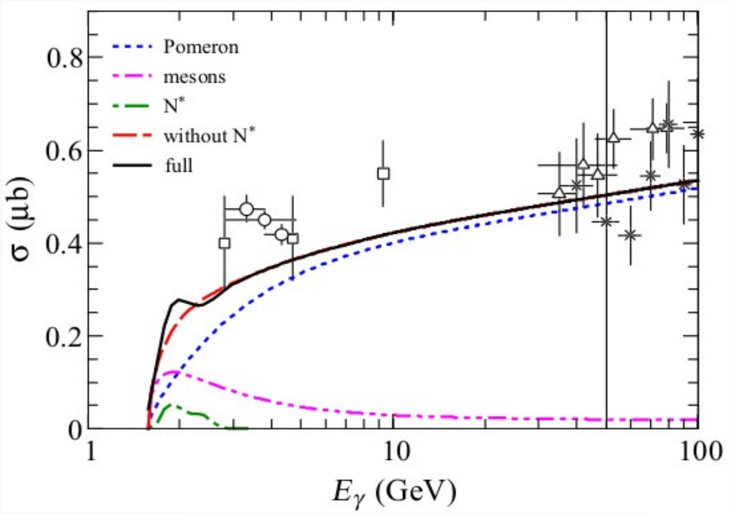
FIG. 1. (Color online). The N-ϕ potential $V(r)$ in the $^4S_{3/2}$ channel as a function of separation r at Euclidean time t/a = 12 (red squares), 13 (green circles) and 14 (blue triangles).

□ The simple fitting functions such as
"the Yukawa form" and "the van der Waals form ~ $1/r^k$ with k=6(7)"
cannot reproduce the lattice data.

> We need to update our results based on the LQCD data.

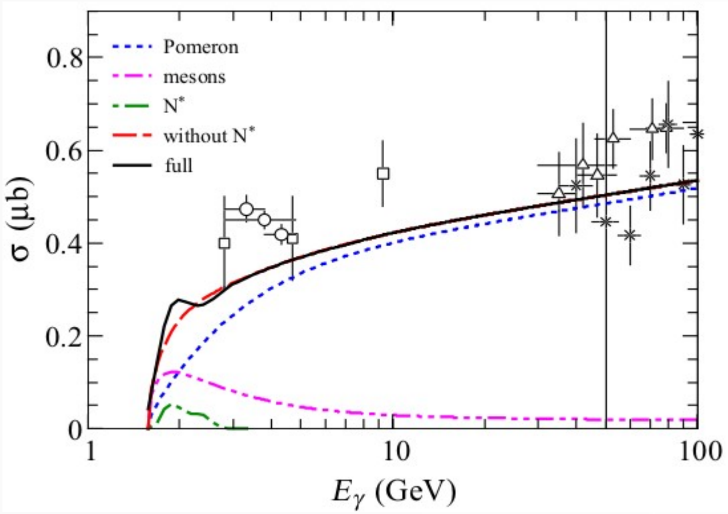
Born term

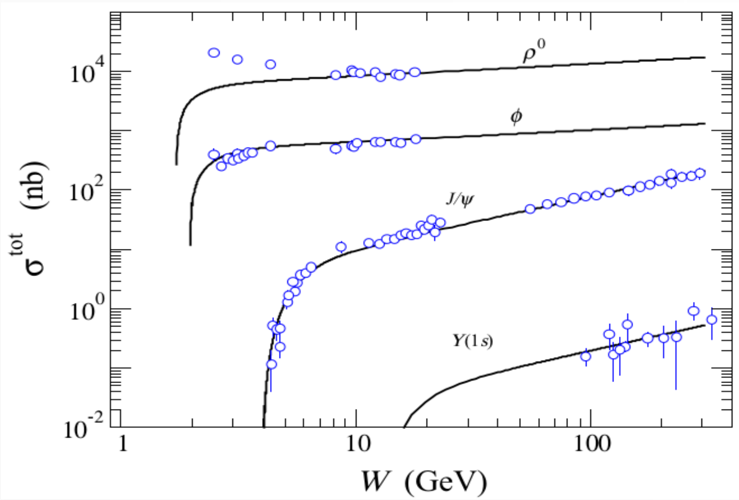
total cross section [γ p → φ p]



Born term

total cross section [γ p → φ p]

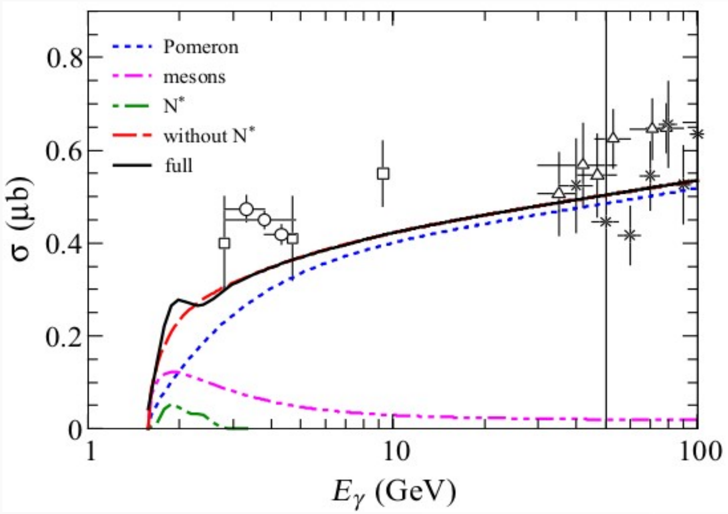


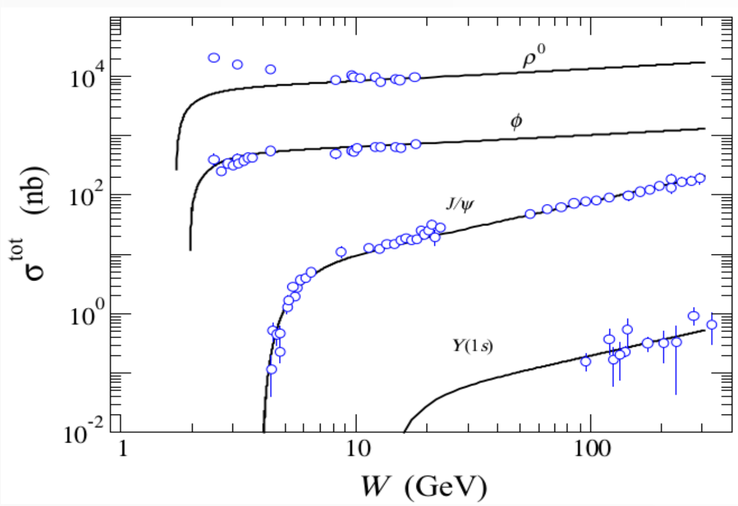


γ p →
ρ^0
ω
φ
J/ψ
ϒ(1s)

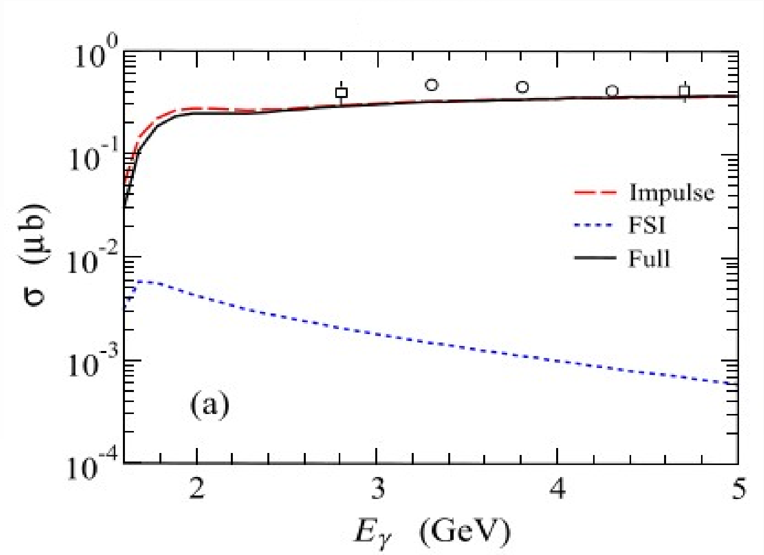
□ Our Pomeron model describes the high energy regions quite well.

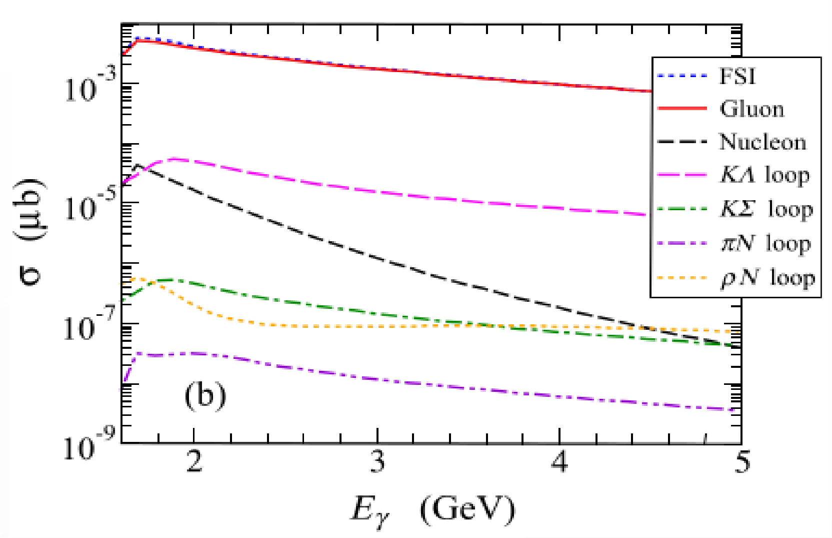
Born term — total cross section [γ p → φ p] — with FSI



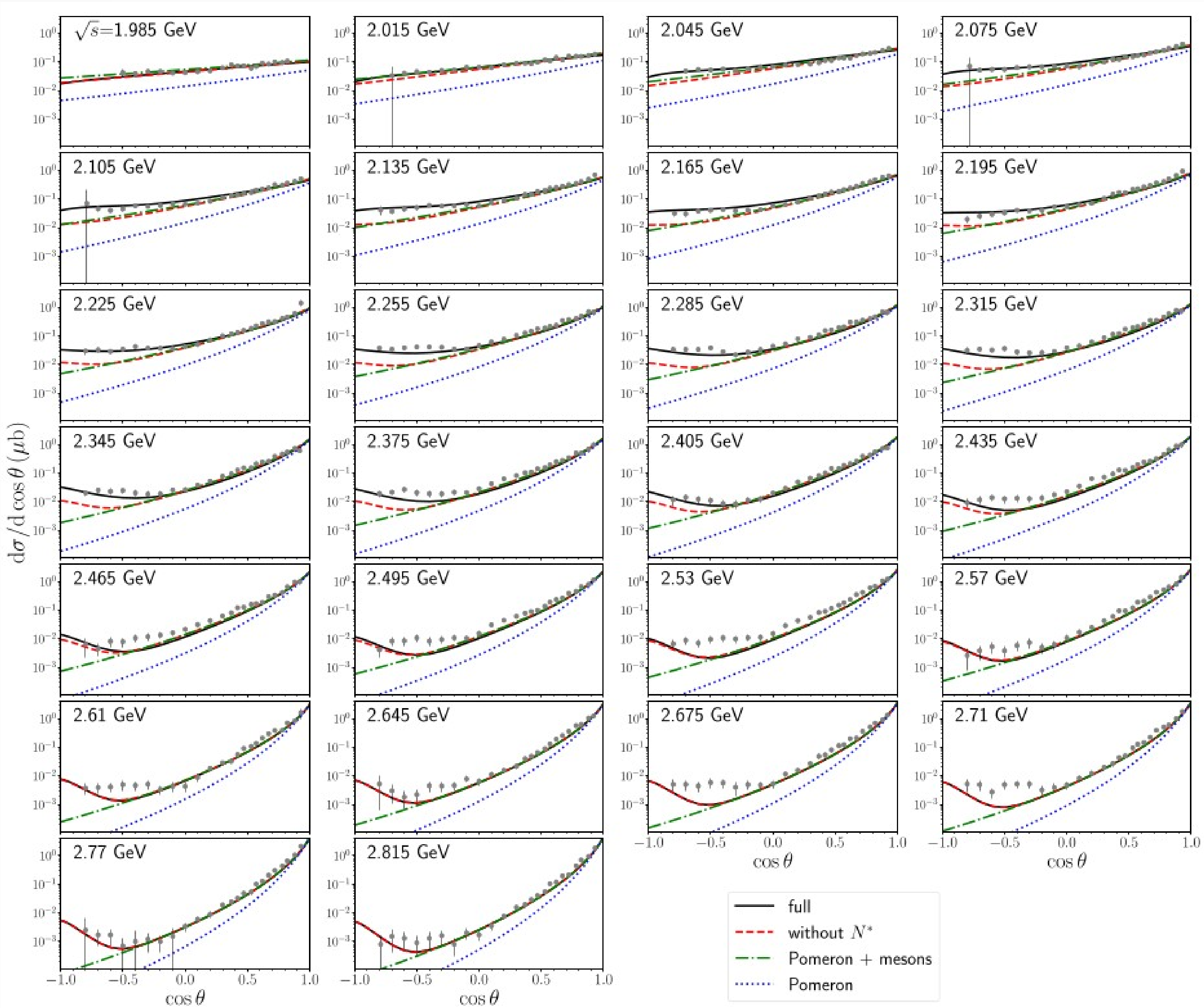


γ p →
ρ^0
ω
φ
J/ψ
Υ(1s)





- □ Our Pomeron model describes the high energy regions quite well.
- □ The contributions of the FSI terms are almost very small.



differential cross sections

[γ p → φ p]

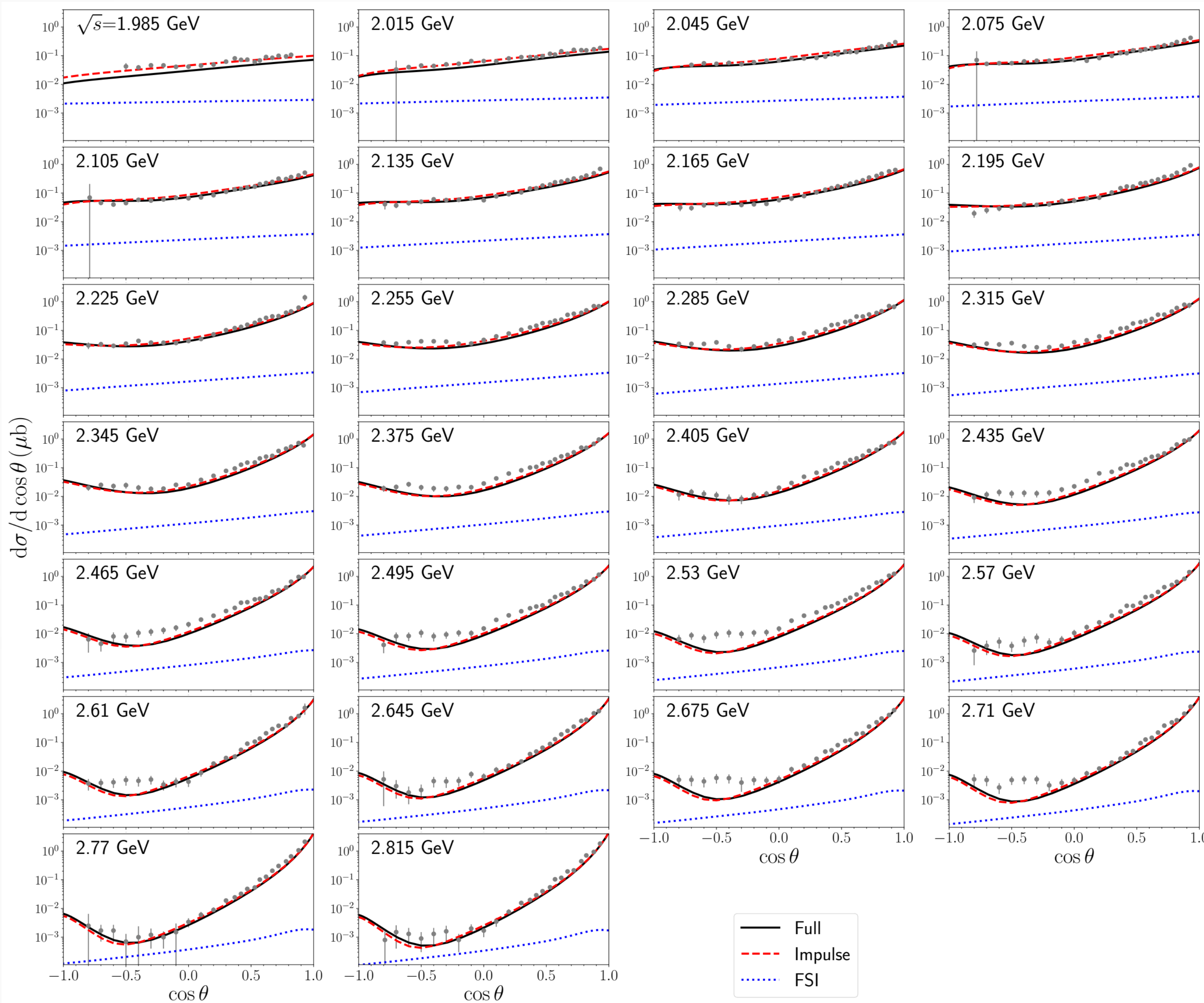
Born term

□ Forward: Pomeron exchange

□ Backward: mesons, nucleon, N^* exchanges

play crucial roles.

[Exp: Dey (CLAS), PRC.89. 055208 (2014)]

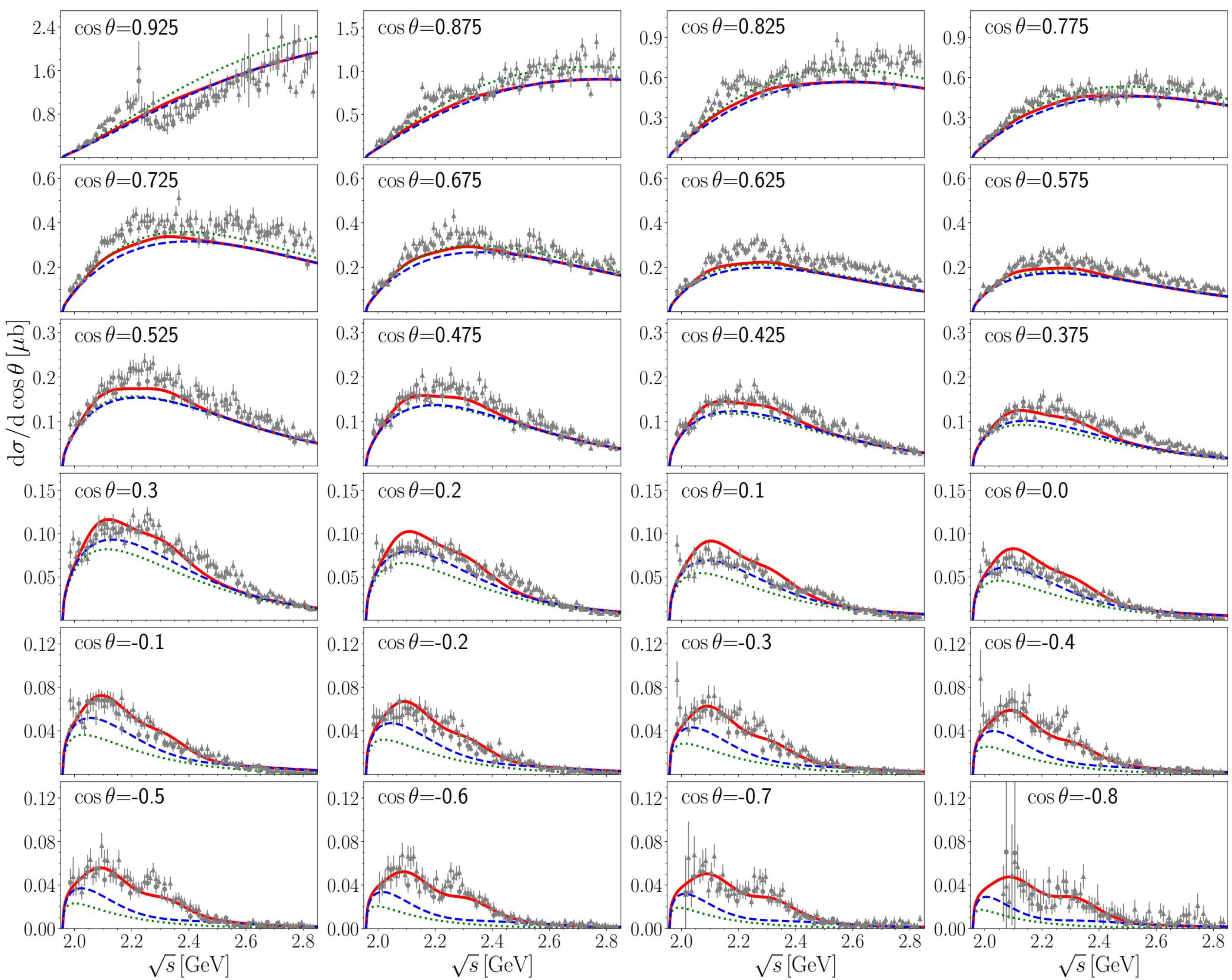


differential cross sections [γ p → φ p]

with FSI

- □ The contributions of the FSI terms are very small.

[Exp: Dey (CLAS), PRC.89. 055208 (2014)]



differential cross sections

[γ p → φ p]

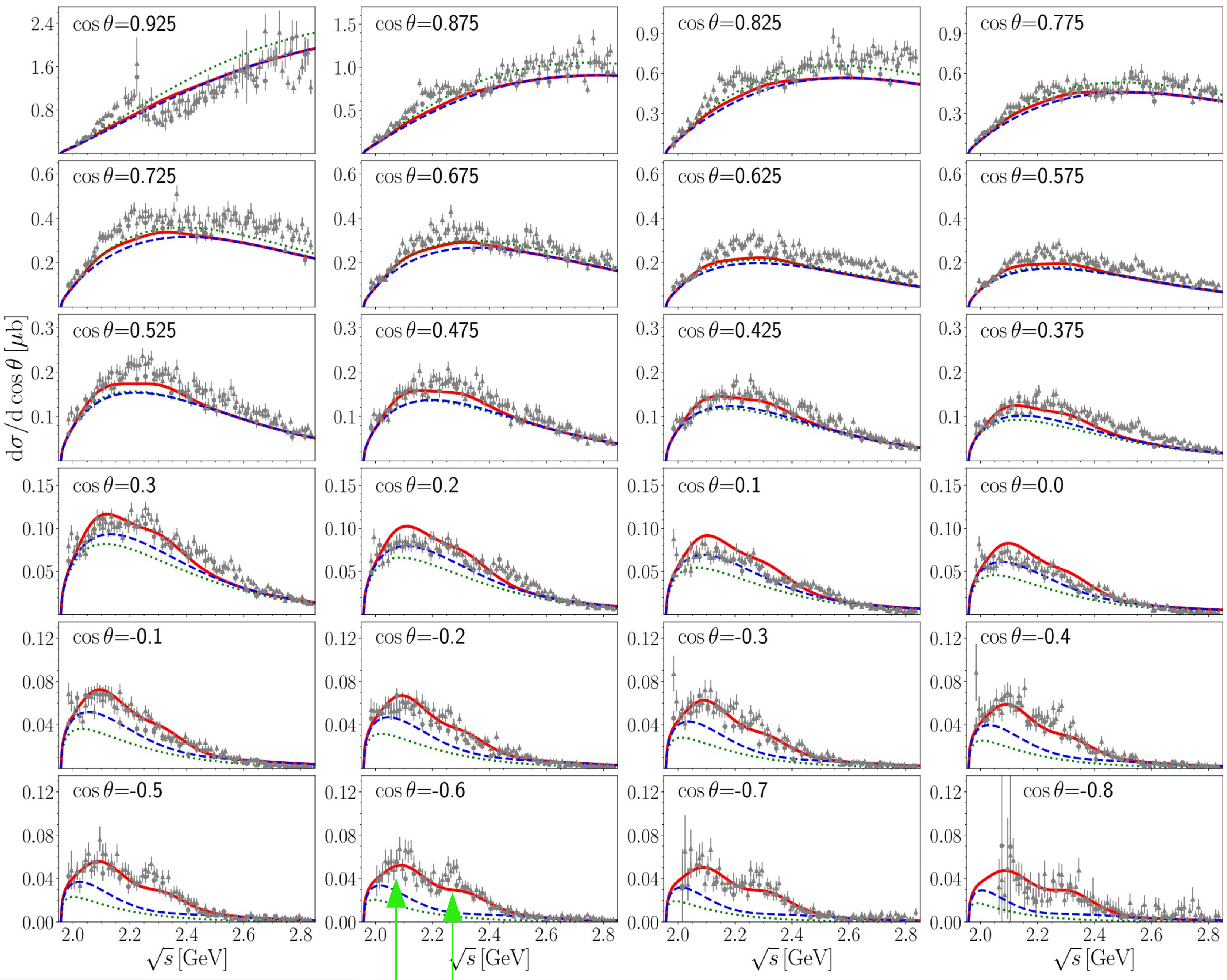
Born term

Pomeron

Born

total

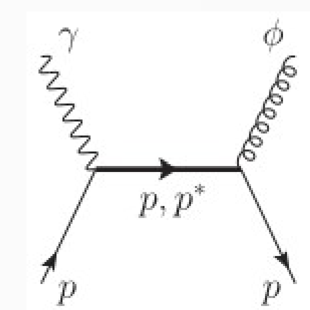
[Exp: Dey (CLAS), PRC.89. 055208 (2014)]



N*(2000,5/2⁺) N*(2300,1/2⁺)

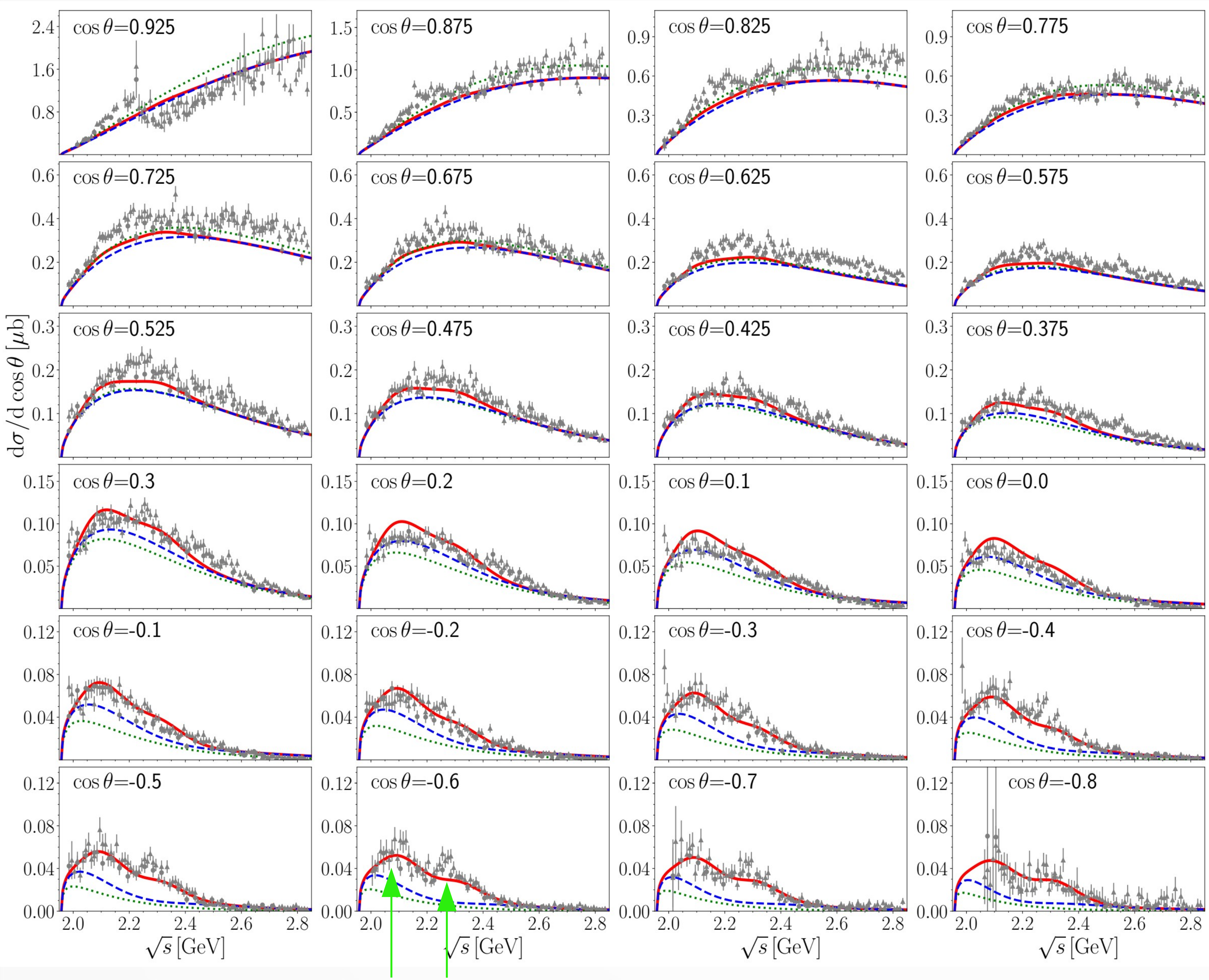
differential cross sections [γ p → φ p]

- □ The strong peak at √s ≃ 2.2 GeV persists only in cosθ = 0.925 & vanishes around cosθ = 0.8.
- □ The backward peaks at √s ≃ 2.1 & 2.3 GeV are due to two N*'s although the magnitudes are far more suppressed.
- □ None of the N* → φN decay is observed firmly experimentally.



Pomeron
Born
total

[Exp: Dey (CLAS), PRC.89. 055208 (2014)]

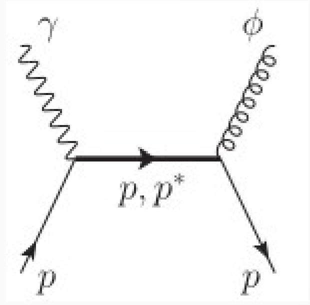


$N^*(2000,5/2^+)$ $N^*(2300,1/2^+)$

differential cross sections

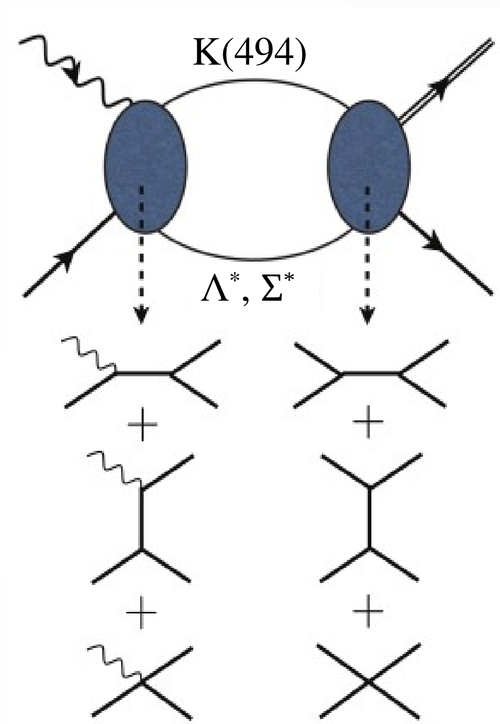
[γ p → φ p]

- The strong peak at √s ≃ 2.2 GeV persists only in cosθ = 0.925 & vanishes around cosθ = 0.8.
- The backward peaks at √s ≃ 2.1 & 2.3 GeV are due to two N^*'s although the magnitudes are far more suppressed.
- None of the $N^* \to \varphi N$ decay is observed firmly experimentally.



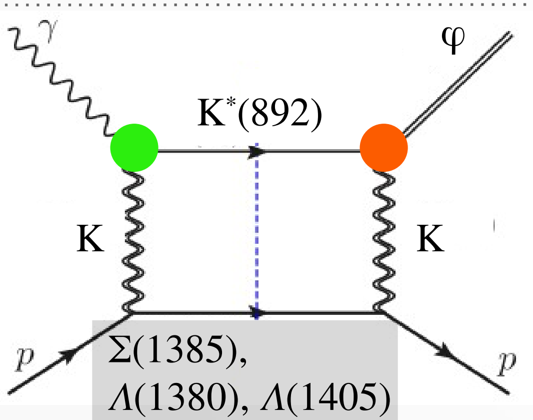
← Pentaquark $P_s[uuds\bar{s}]$ can be studied in this region.

Rescattering diagram
[γ p → φ p]



□ To satisfy the gauge invariance, we should include the t-, s-channels, and contact terms simultaneously.

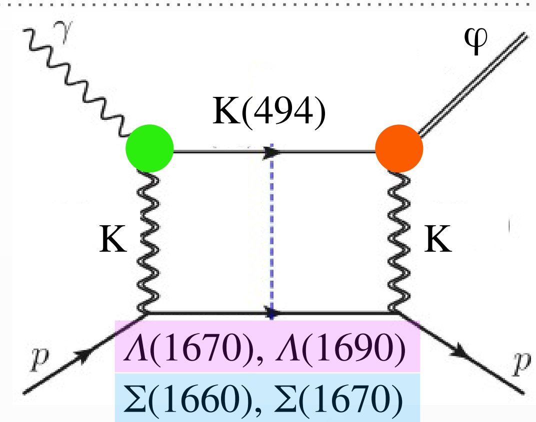
□ It satisfies the gauge invariance by itself.



● $\Gamma\,[K^{*\pm} \to K^{\pm}\gamma] = 9.8 \cdot 10^{-2}$ %
$\Gamma\,[K^{*0} \to K^{0}\gamma] = 2.46 \cdot 10^{-1}$ %

● SU(3) flavor symmetry

$$g_{\phi K^* K} = g_{\rho\omega\pi}/\sqrt{2}$$
$$g_{\rho\omega\pi} = 14.4\,\mathrm{GeV}^{-1}$$



● electric charge

● $\Gamma\,[\varphi \to K^{+}K^{-}] = 49.1$ %

❑ We employ a distorted-wave impulse approximation.

$$F_c(q^2) = F_N(q^2)F_T(q^2 = t)$$

Fc (FN) : nuclear (nucleon) charge FF

□ Including the FSI term, we can write DCS for spin J=0 nuclei:

$$\frac{d\sigma}{d\Omega_{\text{Lab}}} = \frac{(2\pi)^4|\mathbf{k}|^2 E_V(\mathbf{k})E_A(\mathbf{q}-\mathbf{k})}{|E_A(\mathbf{q}-\mathbf{k})|\mathbf{k}| + E_V(\mathbf{k})(|\mathbf{k}| - |\mathbf{q}|\cos\theta_{\text{Lab}})|}\,|AF_T(t)\bar{t}(\mathbf{k},\mathbf{q}) + T^{\text{FSI}}(\mathbf{k},\mathbf{q},E)|^2$$

$$T(E) = T^{\text{IMP}}(E) + T^{\text{FSI}}(E)$$

$$T^{\text{IMP}} = \sum_{i=1,A}\left[B_{\phi N_i,\gamma N_i} + T^{N^*}_{\phi N_i,\gamma N_i}\right]$$

γ ^{4}He → φ ^{4}He

γ p → φ p

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γ ^{4}He → φ ^{4}He   γ p → φ p

$$T(E) = T^{\text{IMP}}(E) + T^{\text{FSI}}(E)$$

$$T^{\text{IMP}} = \sum_{i=1,A}[B_{\phi N_i,\gamma N_i} + T^{N^*}_{\phi N_i,\gamma N_i}]$$

$$T^{FSI}(\mathbf{k},\mathbf{q},E) = \int d\mathbf{k}' T_{\phi A,\phi A}(\mathbf{k},\mathbf{k}',E)\frac{AF(t')\bar{t}(\mathbf{k}',\mathbf{q})}{E - E_V(\mathbf{k}') - E_A(\mathbf{q}-\mathbf{k}') + i\epsilon}$$

$$T^{\text{FSI}}(E) = T_{\phi A,\phi A}(E)\frac{1}{E - H_0}T^{\text{IMP}}$$

□ T^{IMP}: the term that φ meson is produced from a single nucleon in the nucleus

□ T^{FSI}: the effect due to the scattering of the outgoing φ with the recoiled nucleus

□ We solve the Lippmann-Schwinger equation:

$$T_{\phi A,\phi A}(\boldsymbol{\kappa},\boldsymbol{\kappa}',E) = U_{\phi A,\phi A}(\boldsymbol{\kappa},\boldsymbol{\kappa}',E) + \int d\boldsymbol{\kappa}'' U_{\phi A,\phi A}(\boldsymbol{\kappa},\boldsymbol{\kappa}'',E)\frac{1}{E - E_V(\boldsymbol{\kappa}'') - E_A(\boldsymbol{\kappa}'') + i\epsilon}T_{\phi A,\phi A}(\boldsymbol{\kappa}'',\boldsymbol{\kappa}',E) \quad \text{(in c.m.)}$$

□ Within multiple-scattering theory, φA potential is expressed in terms of φN scattering amplitude:

$$U_{\phi A,\phi A}(E) = \sum_{i=1,A} t_{\phi N_i,\phi N_i}(\omega)$$

❑ We employ a distorted-wave impulse approximation.

$$F_c(q^2) = F_N(q^2)F_T(q^2 = t)$$

F_c (F_N) : nuclear (nucleon) charge FF

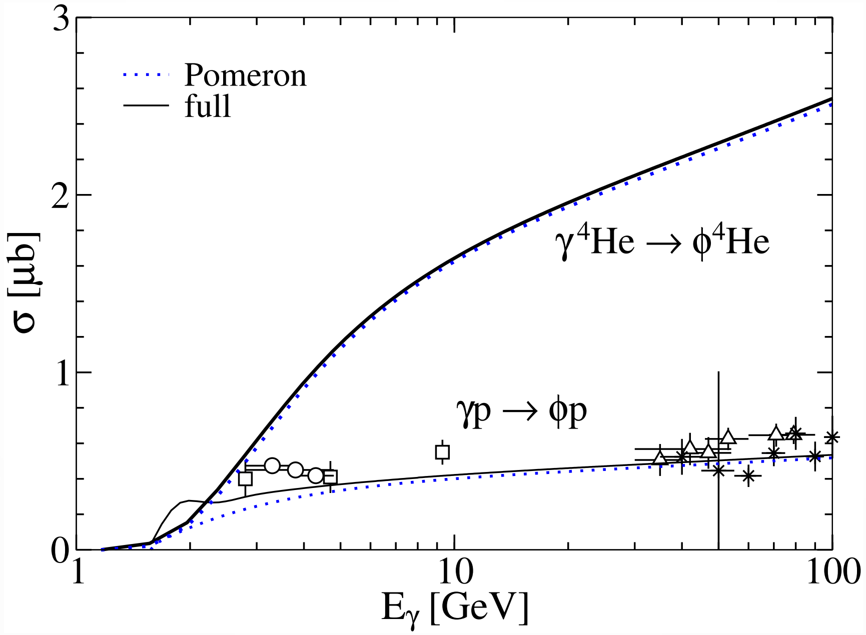
□ Including the FSI term, we can write DCS for spin J=0 nuclei:

$$\frac{d\sigma}{d\Omega_{\rm Lab}} = \frac{(2\pi)^4|\mathbf{k}|^2 E_V(\mathbf{k})E_A(\mathbf{q}-\mathbf{k})}{|E_A(\mathbf{q}-\mathbf{k})|\mathbf{k}| + E_V(\mathbf{k})(|\mathbf{k}| - |\mathbf{q}|\cos\theta_{\rm Lab})|} |AF_T(t)\bar{t}(\mathbf{k},\mathbf{q}) + T^{\rm FSI}(\mathbf{k},\mathbf{q},E)|^2$$

γ ^{4}He → φ ^{4}He γ p → φ p

$$T(E) = T^{\rm IMP}(E) + T^{\rm FSI}(E)$$

$$T^{\rm IMP} = \sum_{i=1,A}[B_{\phi N_i,\gamma N_i} + T^{N^*}_{\phi N_i,\gamma N_i}]$$



□ The total cross section for φ^{4}He production is about 4 times larger than φN production.

❑ We employ a distorted-wave impulse approximation.

$$F_c(q^2) = F_N(q^2)F_T(q^2 = t)$$

F_c (F_N) : nuclear (nucleon) charge FF

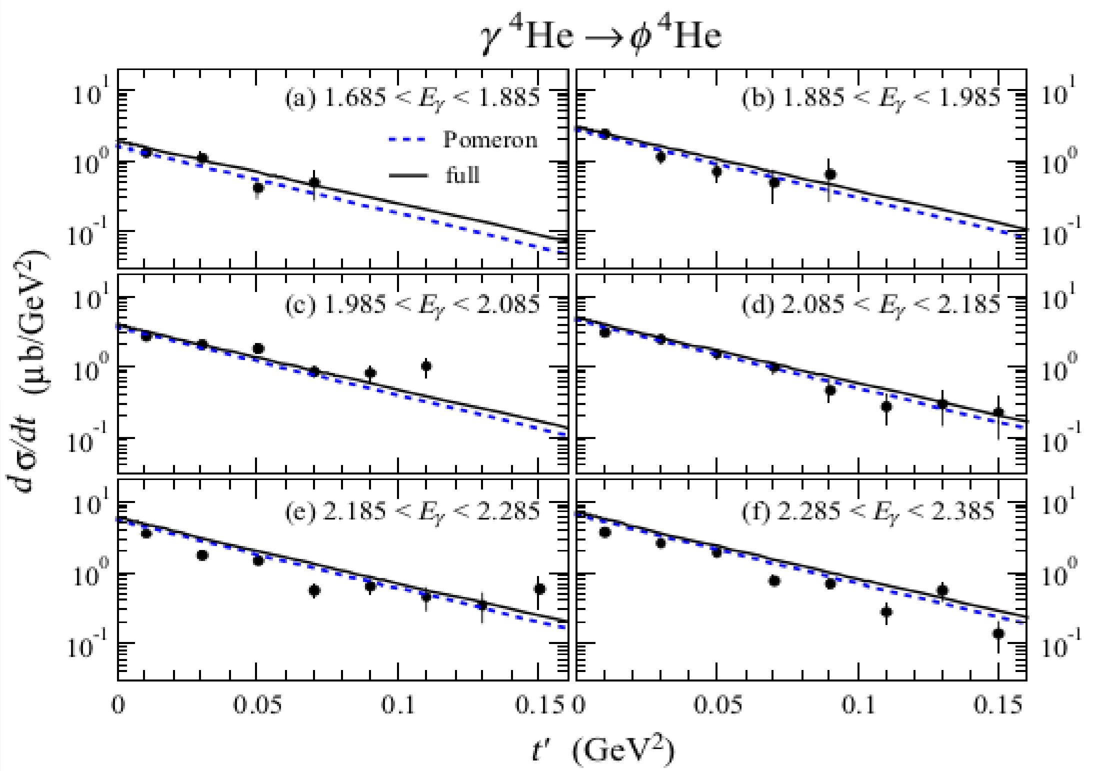
□ Including the FSI term, we can write DCS for spin J=0 nuclei:

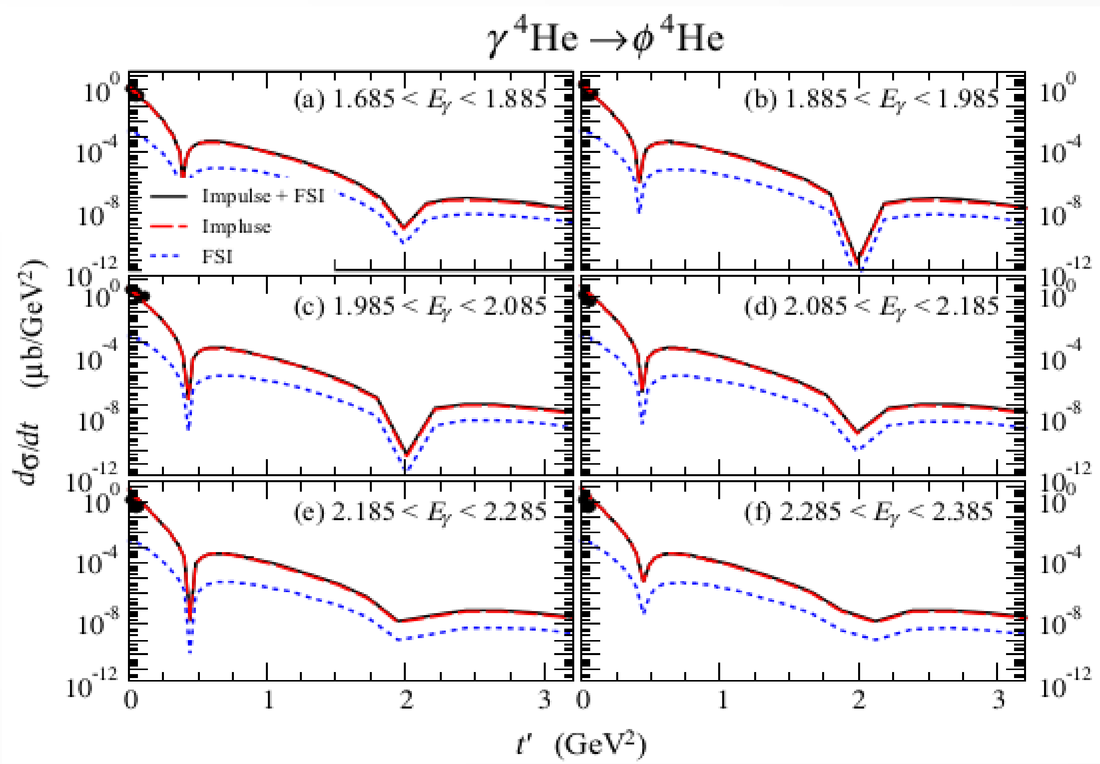
$$\frac{d\sigma}{d\Omega_{\rm Lab}} = \frac{(2\pi)^4|\mathbf{k}|^2E_V(\mathbf{k})E_A(\mathbf{q}-\mathbf{k})}{|E_A(\mathbf{q}-\mathbf{k})|\mathbf{k}| + E_V(\mathbf{k})(|\mathbf{k}| - |\mathbf{q}|\cos\theta_{\rm Lab})|}|AF_T(t)\bar{t}(\mathbf{k},\mathbf{q}) + T^{\rm FSI}(\mathbf{k},\mathbf{q},E)|^2$$

$\gamma\ ^4He \to \varphi\ ^4He$ $\gamma\ p \to \varphi\ p$

$$T(E) = T^{\rm IMP}(E) + T^{\rm FSI}(E)$$

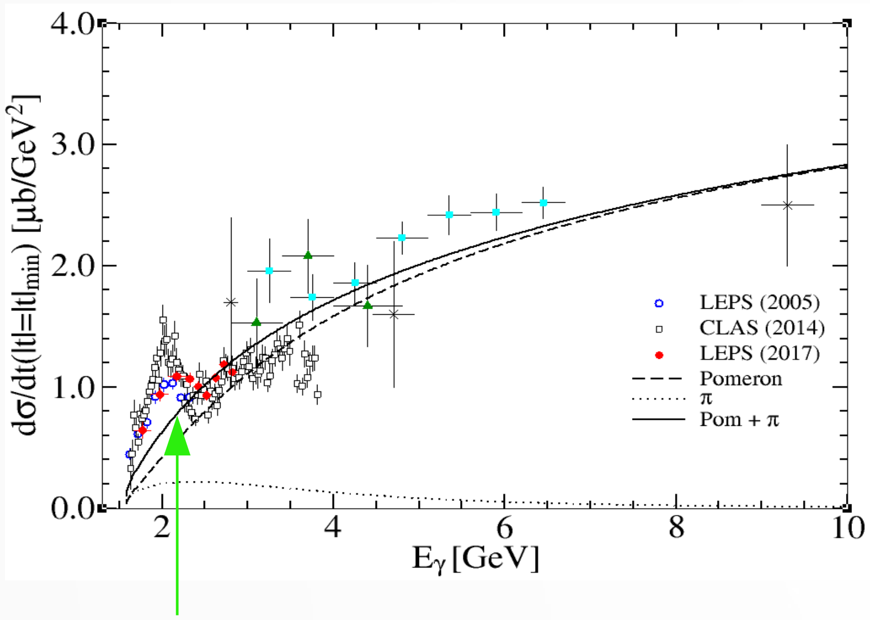
$$T^{\rm IMP} = \sum_{i=1,A}[B_{\phi N_i,\gamma N_i} + T^{N^*}_{\phi N_i,\gamma N_i}]$$





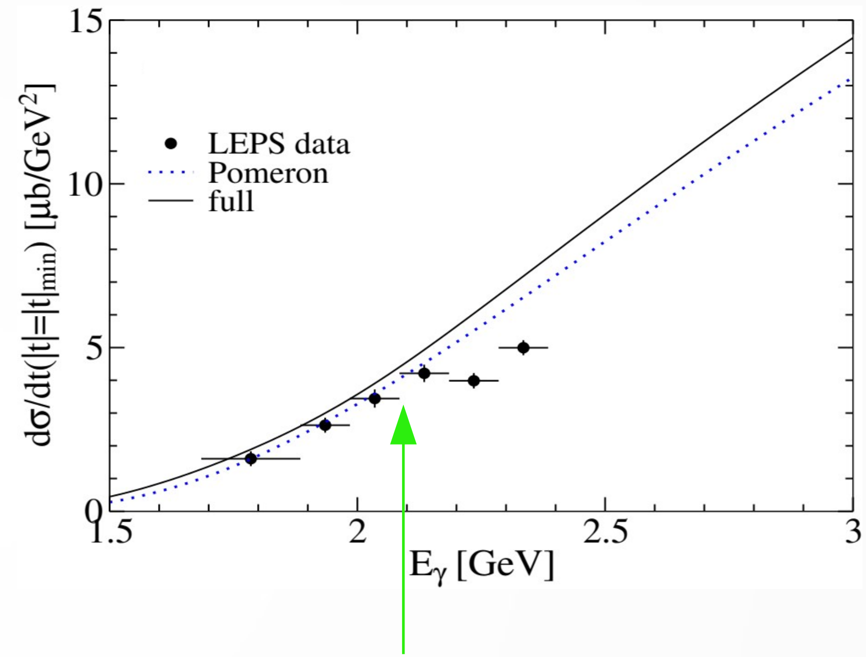
□ The FSI contributions are relatively suppressed by factors of $10^1 - 10^3$.

γ p → φ p



- is not due to the N^* contribution.
- may arise from another mechanism.

γ ^{4}He → φ ^{4}He



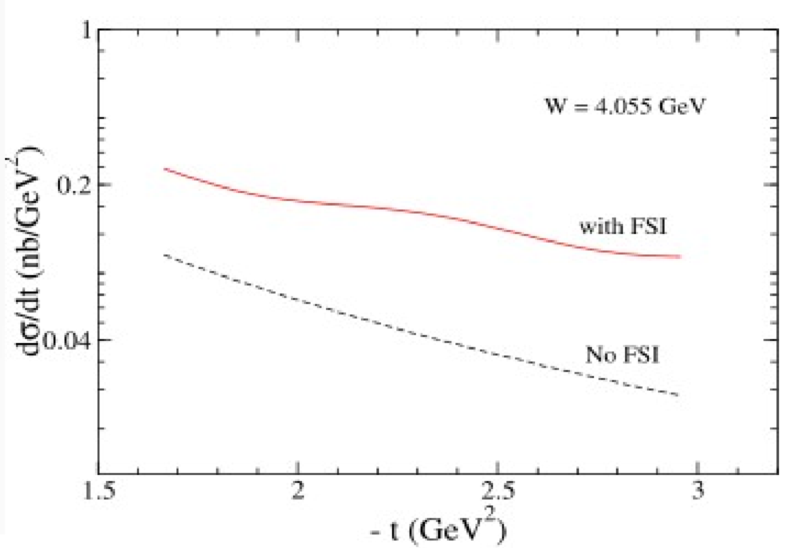
[Exp: Hiraiwa (LEPS), PRC.035208.5 (2017)]

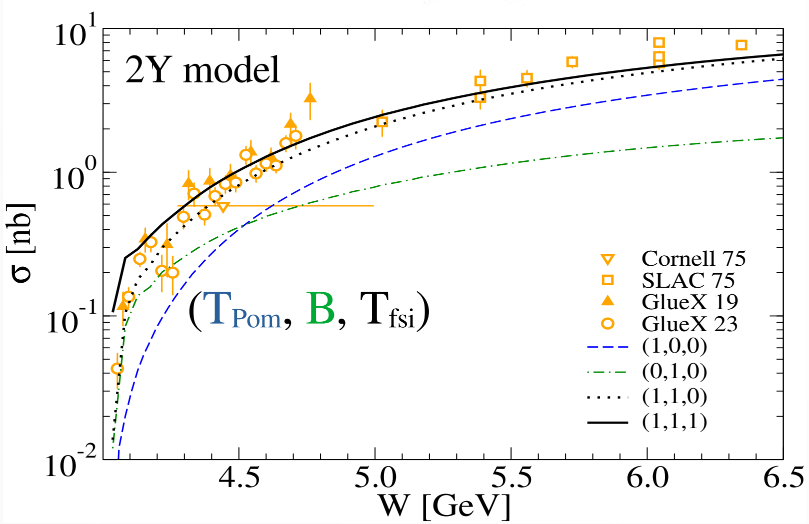
□ The peak position is similar to each other.
Any relation between them?

2. $\gamma\, p \rightarrow J/\psi\, p$, $\gamma\, A \rightarrow J/\psi\, A$

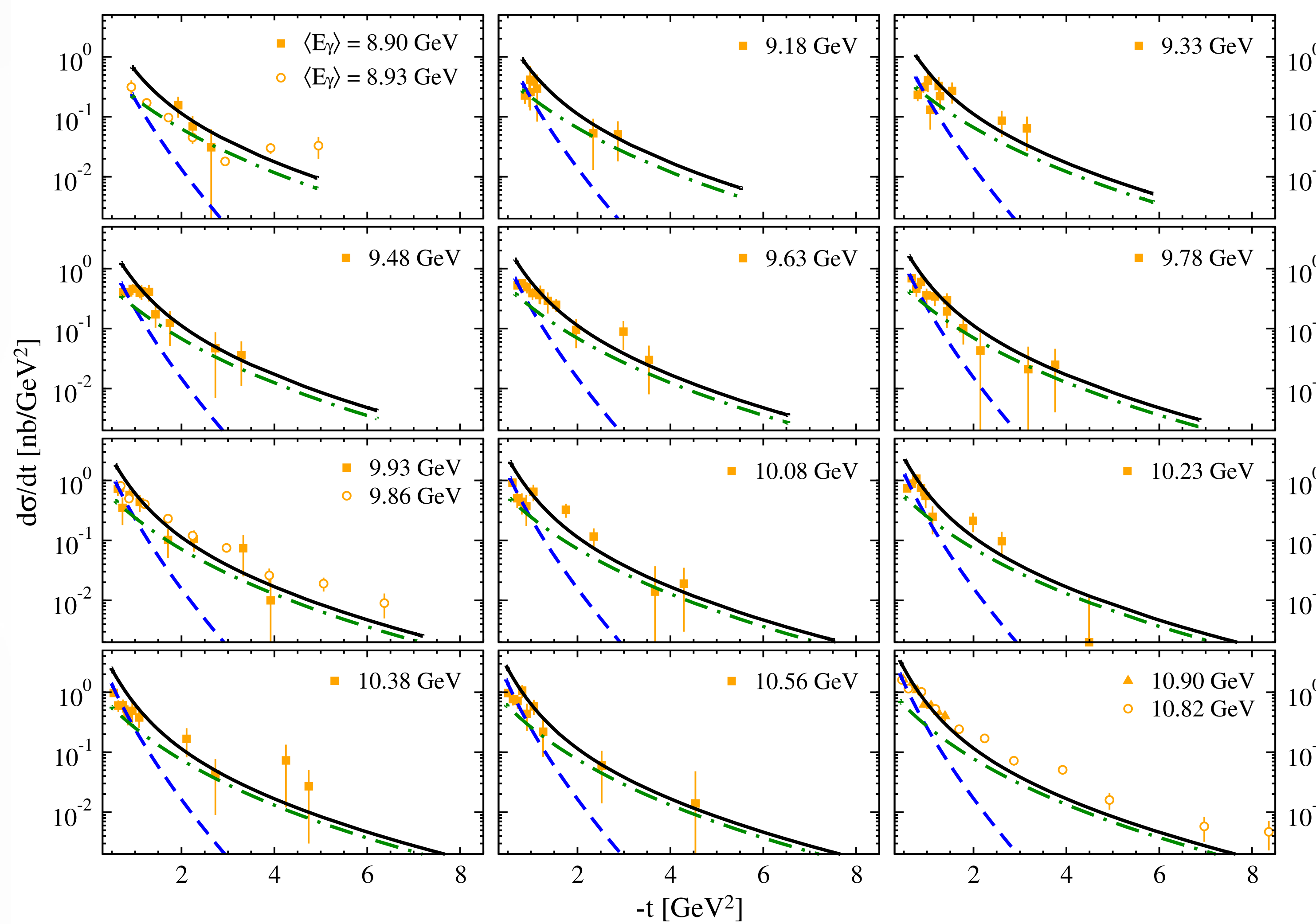
$\gamma\, d \rightarrow J/\psi\, d$

[Sakinah, Lee, Choi, PRC.109.065204 (2024)]





γ p → J/ψ p



□ DL Pomeron exchange alone is not sufficient for describing the diff. cross section data.

□ A dynamical model based on c-N potential v_{cN} and the $\varphi_{J/\psi}$ generated from CQM, B model, the diff. cross section data could be well reproduced at low energies.

Theoretical Framework

❑ Scattering amplitude: $T_{VA,\gamma A}(E) = T^{\rm IMP}_{VA,\gamma A}(E) + T^{\rm FSI}_{VA,\gamma A}(E)$

$$\langle \mathbf{k} m_V, \Phi^{J_d}_{\mathbf{P}',M_d'} | T^{\rm IMP}_{Vd,\gamma d}(E) | \mathbf{q}\lambda, \Phi^{J_d}_{\mathbf{P},M_d}\rangle$$

$$= \sum_{i=1}^{2} \langle \Phi^{J_d}_{\mathbf{P}',M_d'} | \, \langle \mathbf{k} m_V | t_{VN,\gamma N}(i) | \mathbf{q}\lambda\rangle \, | \Phi^{J_d}_{\mathbf{P},M_d}\rangle$$

$$= \sum_{m_{s_1},m_{s_2},m_{s_1'},m_{s_2'}} A_d \int d\mathbf{p}\, \phi^{J_d *}_{M_d'}(\mathbf{p}', m_{s_1'} m_{s_2'})$$

$$\times \Gamma(\mathbf{P}'\mathbf{p}', \mathbf{p}_1'\mathbf{p}_2') \phi^{J_d}_{M_d}(\mathbf{p}, m_{s_1} m_{s_2})$$

$$\times \langle \mathbf{k} m_V, \mathbf{p}_1' m_{s_1'} | t_{VN,\gamma N}(\omega) | \mathbf{q}\lambda, \mathbf{p} m_{s_1}\rangle ,$$

↓ Fixed scatter approximation (FSA)
Let initial momentum **p** = 0

$$\sim A_d \langle \mathbf{k} m_V, \mathbf{t}\bar{m}_{s_1'} | \bar{t}_{VN,\gamma N}(\omega_0) | \mathbf{q}\lambda, \mathbf{0}\bar{m}_{s_1}\rangle$$

$$\times F_{M_d',M_d}(t)$$

□ Deuteron form factor

$$F_{M_d',M_d}(t) = \sum_{m_{s_1},m_{s_2},m_{s_1'},m_{s_2'}}$$

$$\times \int d\mathbf{p}\, \phi^{J_d *}_{M_d'}(\mathbf{p} + \tfrac{\mathbf{t}}{2}, m_{s_1'} m_{s_2'})\, \phi^{J_d}_{M_d}(\mathbf{p}, m_{s_1} m_{s_2})$$

❑ Deuteron wave function

$$\Phi^{J_d}_{\mathbf{P},M_d}(\mathbf{p}_1 m_{s_1}, \mathbf{p}_2 m_{s_2})$$

$$= \delta(\mathbf{P} - \mathbf{p}_1 - \mathbf{p}_2)\Gamma(\mathbf{P}\mathbf{p}, \mathbf{p}_1\mathbf{p}_2)\phi^{J_d}_{M_d}(\mathbf{p}, m_{s_1} m_{s_2})$$

relativistic effect of *d*

$$\phi^{J_d}_{M_d}(\mathbf{p}, m_{s_1} m_{s_2}) = \sum_{L,M_L,M_S} \langle J_d M_d | L S M_L M_S\rangle$$

$$\times \langle S M_S | \tfrac{1}{2}\tfrac{1}{2} m_{s_1} m_{s_2}\rangle Y_{LM_L}(\hat{p}) R_L(|\mathbf{p}|),$$

□ $J_d = 1$, $S = 1$, $L = (0, 2)$

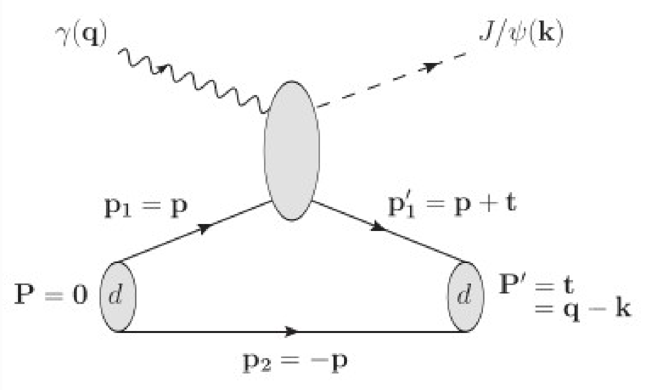
□ By choosing **t** in the z-direction

$$F_{0,0}(t) = \sqrt{4\pi}[F_0(t) - \sqrt{2}F_2(t)],$$

$$F_{1,1}(t) = F_{-1,-1}(t) = \sqrt{4\pi}[F_0(t) + \tfrac{1}{\sqrt{2}}F_2(t)],$$

$$F_{M_d',M_d}(t) = 0 \ \text{if} \ M_d' \neq M_d,$$

γ d → J/ψ d



$$\mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2,$$

$$\mathbf{p} = \frac{1}{2}(\mathbf{p}_1 - \mathbf{p}_2),$$

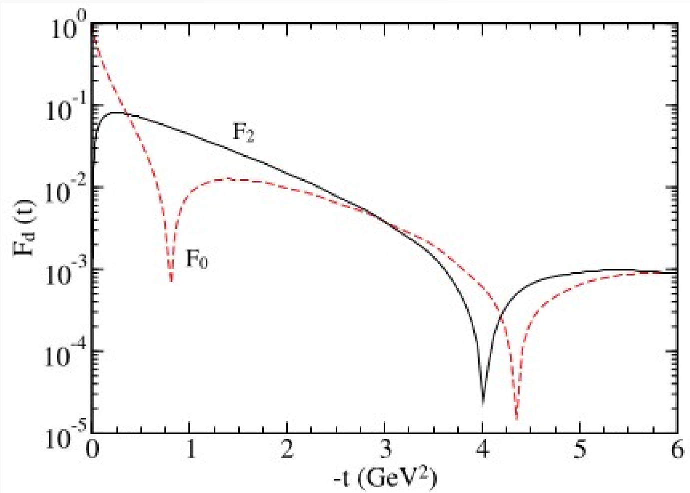
$$\mathbf{p}' = \frac{1}{2}(\mathbf{p}_1' - \mathbf{p}_2') = \mathbf{p} + \frac{1}{2}\mathbf{t}$$

rest frame of *d* — Lab frame

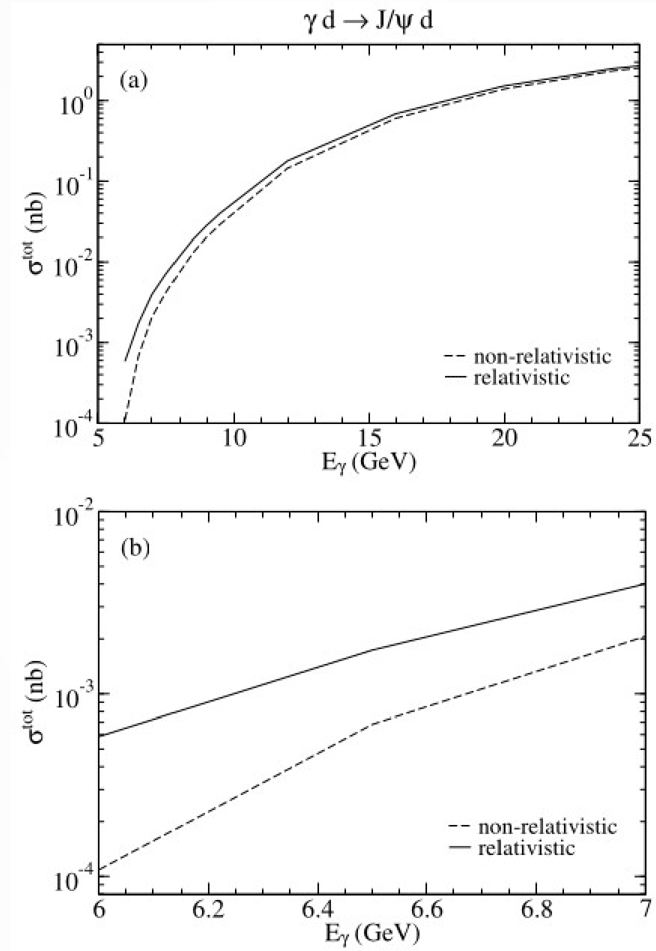
Numerical Results

□ Deuteron form factor

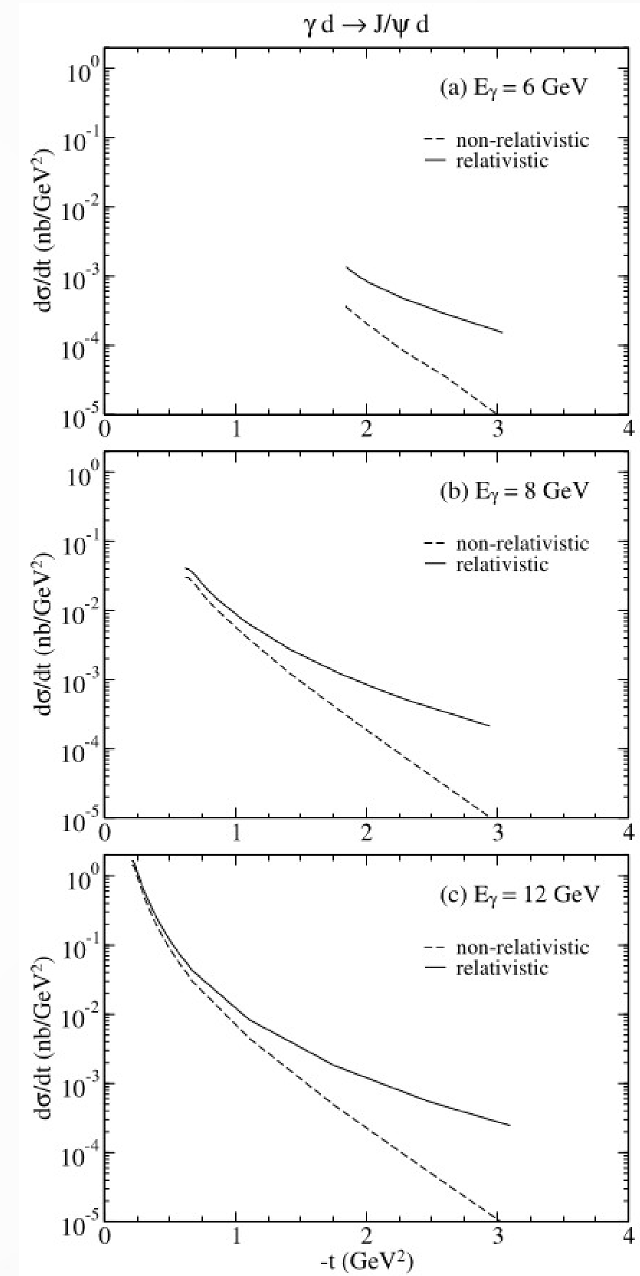
$$F_{0,0}(t) = \sqrt{4\pi}[F_0(t) - \sqrt{2}F_2(t)],$$
$$F_{1,1}(t) = F_{-1,-1}(t) = \sqrt{4\pi}[F_0(t) + \tfrac{1}{\sqrt{2}}F_2(t)],$$
$$F_{M_d',M_d}(t) = 0 \text{ if } M_d' \neq M_d,$$



Total Cross Section



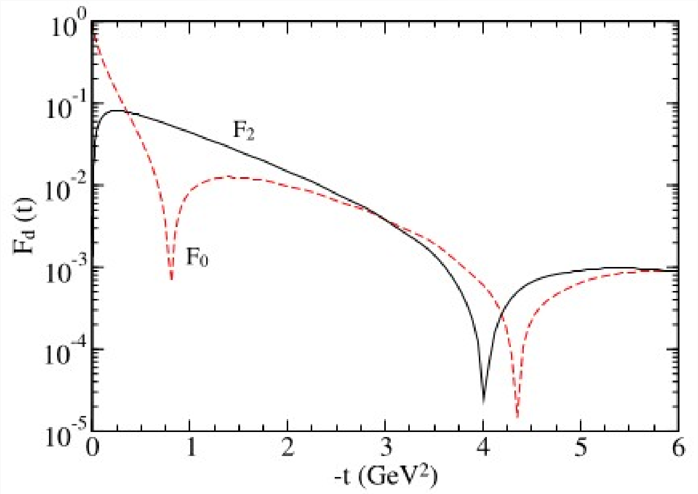
Differential Cross Section



Numerical Results

□ Deuteron form factor

$$F_{0,0}(t) = \sqrt{4\pi}[F_0(t) - \sqrt{2}F_2(t)],$$
$$F_{1,1}(t) = F_{-1,-1}(t) = \sqrt{4\pi}[F_0(t) + \tfrac{1}{\sqrt{2}}F_2(t)],$$
$$F_{M'_d,M_d}(t) = 0 \text{ if } M'_d \neq M_d,$$



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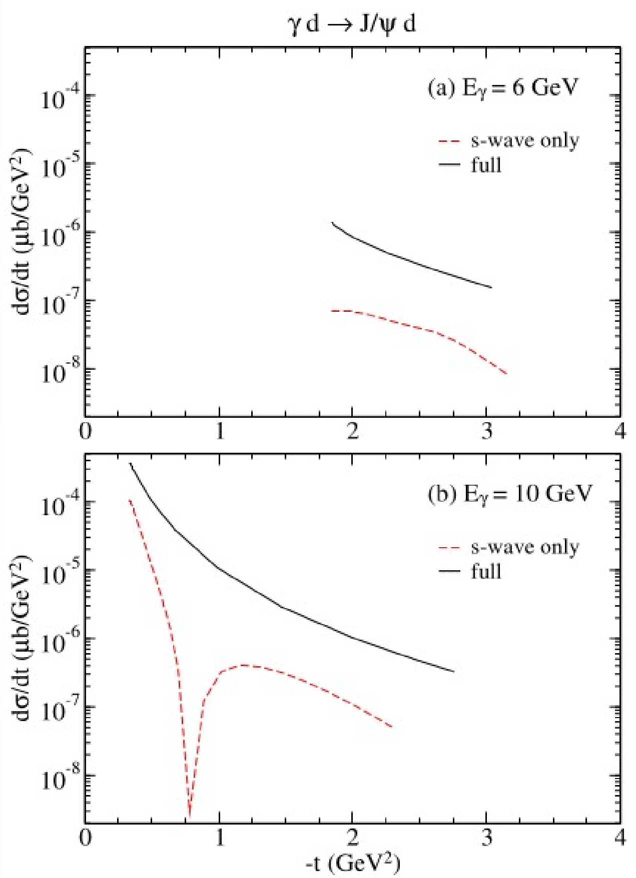

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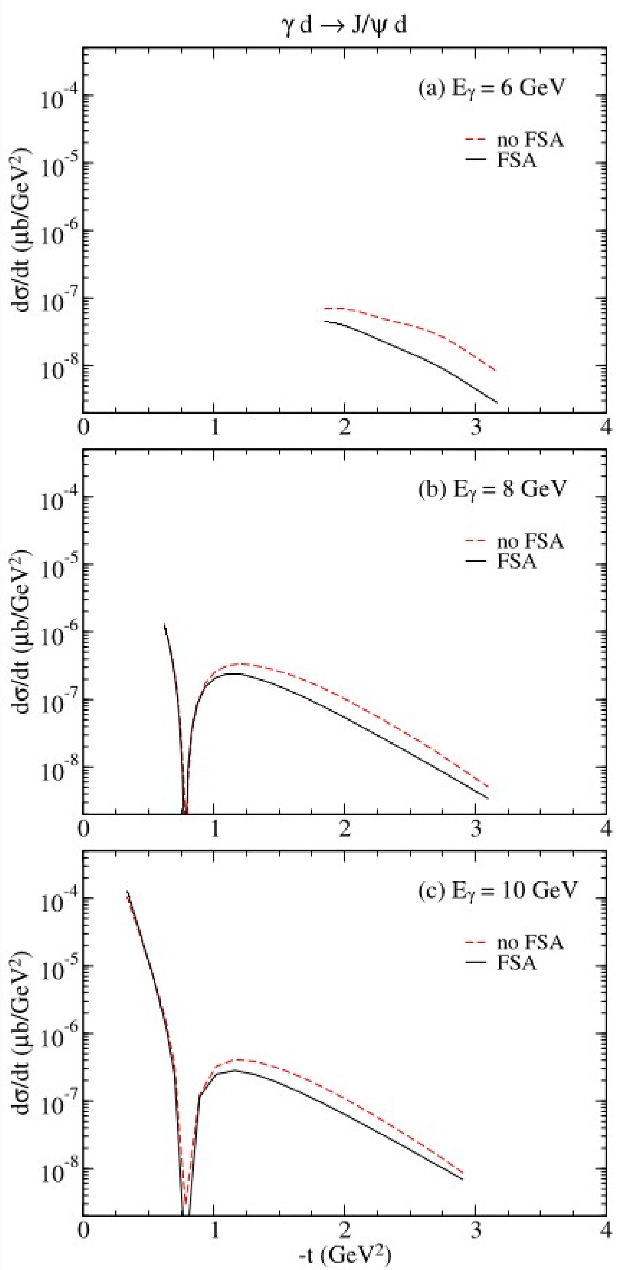

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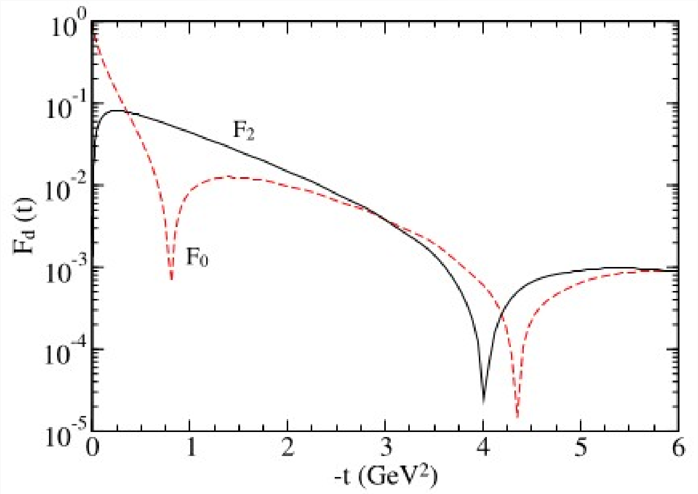

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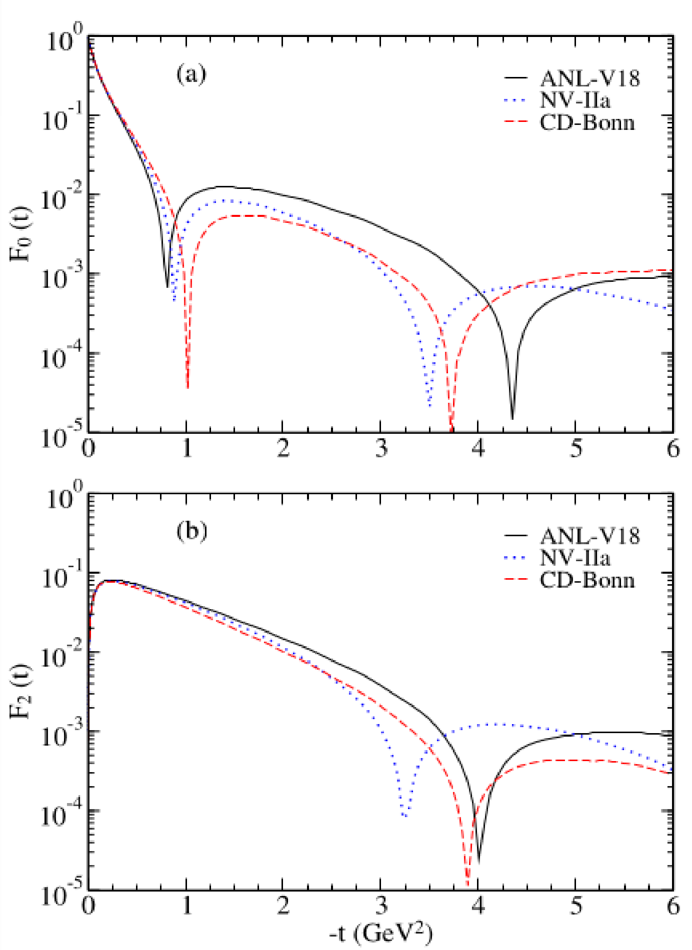

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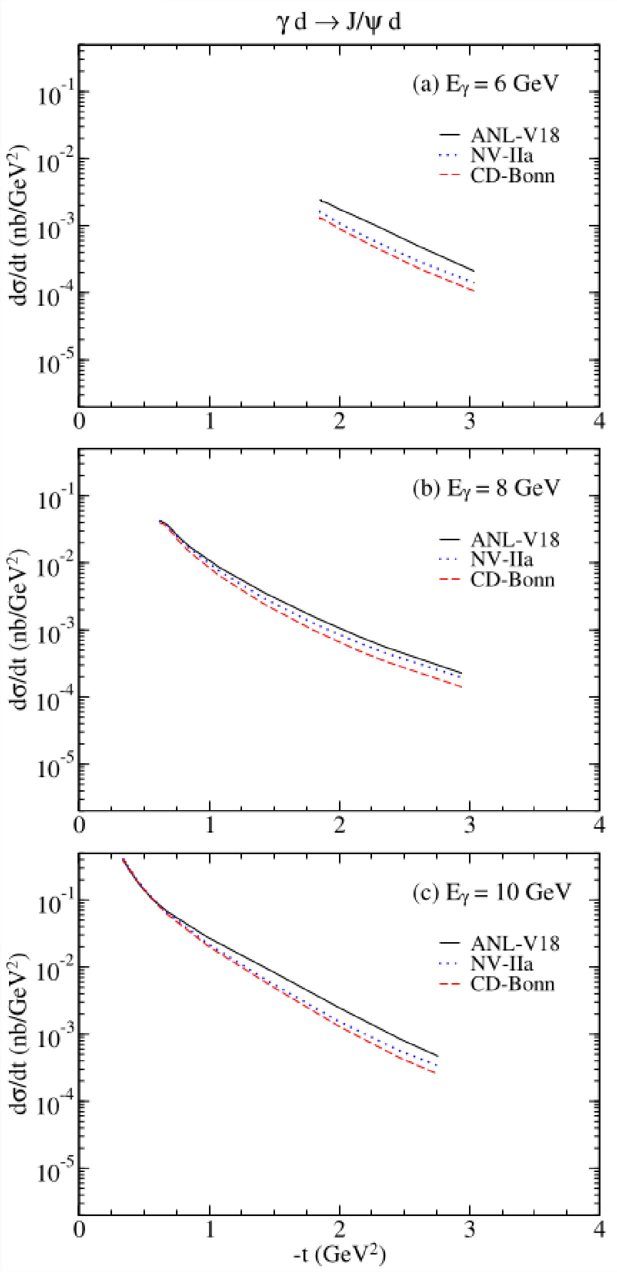


❑ We employ a distorted-wave impulse approximation.

$$F_c(q^2) = F_N(q^2) F_T(q^2 = t)$$

Fc (FN) : nuclear (nucleon) charge FF

□ Including the FSI term, we can write DCS for spin J=0 nuclei:

$$\frac{d\sigma}{d\Omega_{\rm Lab}} = \frac{(2\pi)^4 |\mathbf{k}|^2 E_V(\mathbf{k}) E_A(\mathbf{q}-\mathbf{k})}{|E_A(\mathbf{q}-\mathbf{k})|\mathbf{k}| + E_V(\mathbf{k})(|\mathbf{k}| - |\mathbf{q}|\cos\theta_{\rm Lab})|} |A F_T(t) \bar{t}(\mathbf{k},\mathbf{q}) + T^{\rm FSI}(\mathbf{k},\mathbf{q},E)|^2$$

γ A → J/ψ A

γ p → J/ψ p

$$T(E) = T^{\rm IMP}(E) + T^{\rm FSI}(E)$$

$$T^{\rm IMP} = \sum_{i=1,A} [B_{\phi N_i,\gamma N_i} + T^{N^*}_{\phi N_i,\gamma N_i}]$$

$$T^{FSI}(\mathbf{k},\mathbf{q},E) = \int d\mathbf{k}' T_{\phi A,\phi A}(\mathbf{k},\mathbf{k}',E) \frac{A F(t') \bar{t}(\mathbf{k}',\mathbf{q})}{E - E_V(\mathbf{k}') - E_A(\mathbf{q}-\mathbf{k}') + i\epsilon}$$

$$T^{\rm FSI}(E) = T_{\phi A,\phi A}(E) \frac{1}{E - H_0} T^{\rm IMP}$$

□ $T^{\rm IMP}$: the term that φ meson is produced from a single nucleon in the nucleus

□ $T^{\rm FSI}$: the effect due to the scattering of the outgoing J/ψ with the recoiled nucleus

□ We solve the Lippmann-Schwinger equation:

$$T_{\phi A,\phi A}(\boldsymbol{\kappa},\boldsymbol{\kappa}',E) = U_{\phi A,\phi A}(\boldsymbol{\kappa},\boldsymbol{\kappa}',E) + \int d\boldsymbol{\kappa}'' U_{\phi A,\phi A}(\boldsymbol{\kappa},\boldsymbol{\kappa}'',E) \frac{1}{E - E_V(\boldsymbol{\kappa}'') - E_A(\boldsymbol{\kappa}'') + i\epsilon} T_{\phi A,\phi A}(\boldsymbol{\kappa}'',\boldsymbol{\kappa}',E) \quad \text{(in c.m.)}$$

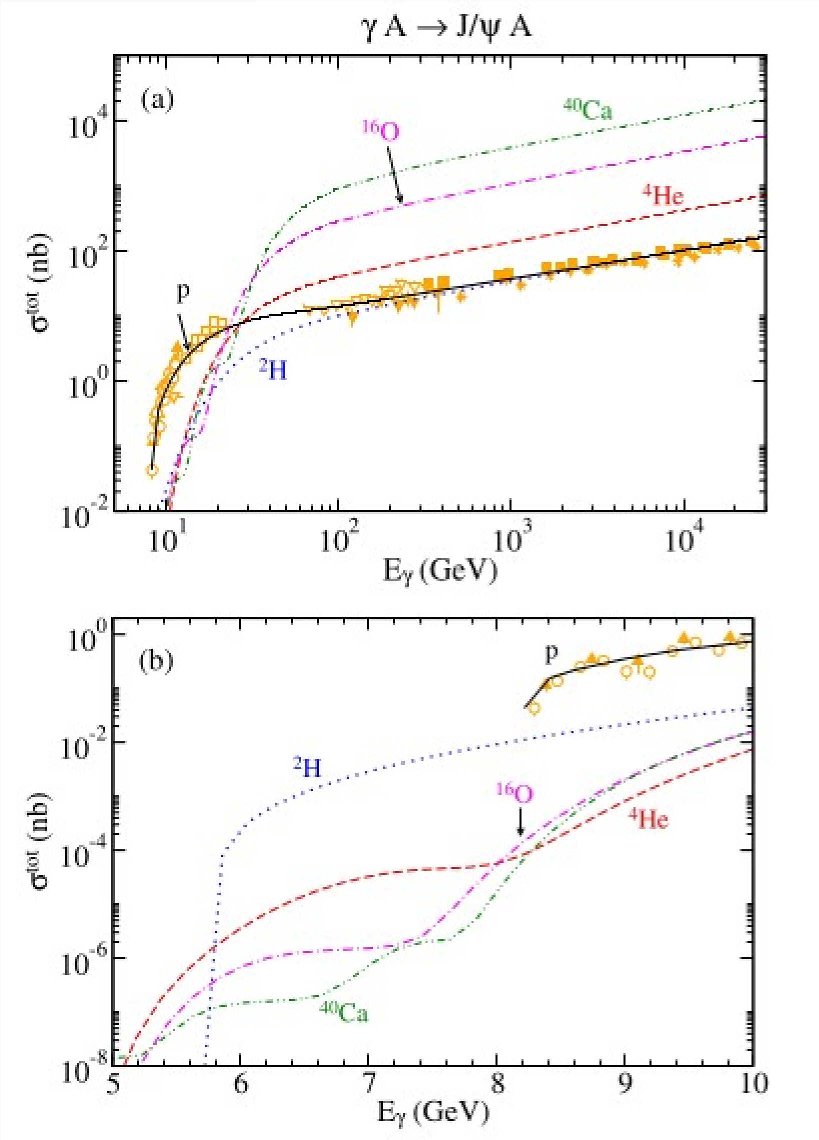
□ Within multiple-scattering theory, J/ψA potential is expressed in terms of J/ψN scattering amplitude:

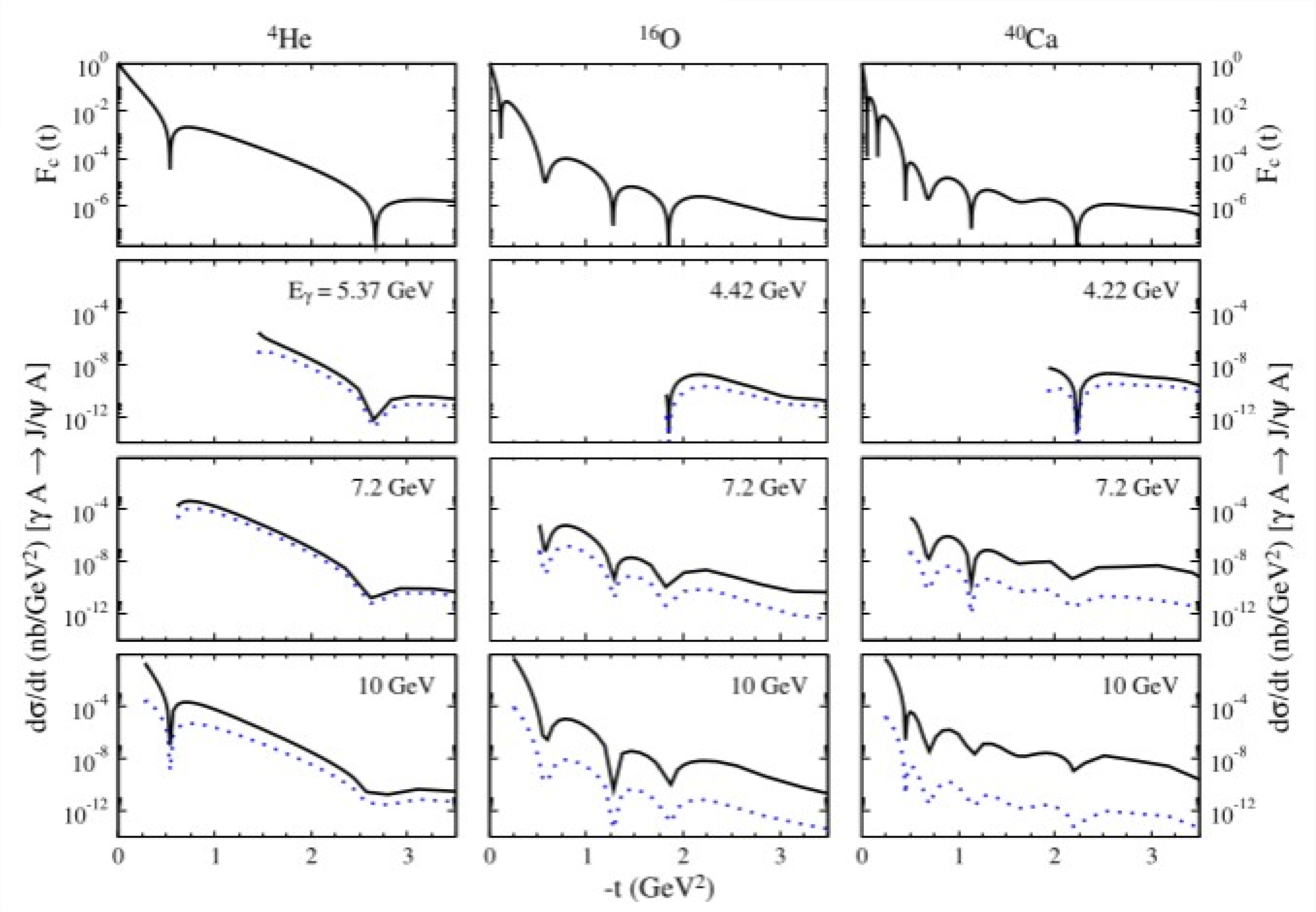
$$U_{\phi A,\phi A}(E) = \sum_{i=1,A} t_{\phi N_i,\phi N_i}(\omega)$$

❑ We employ a distorted-wave impulse approximation.

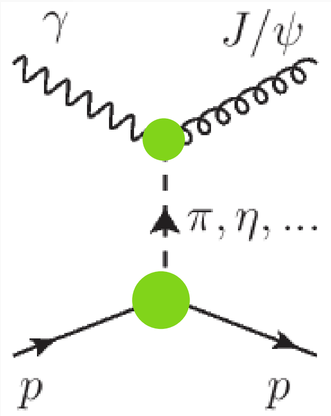
γ A → J/ψ A

□ Including the FSI term, we can write DCS for spin J=0 nuclei:

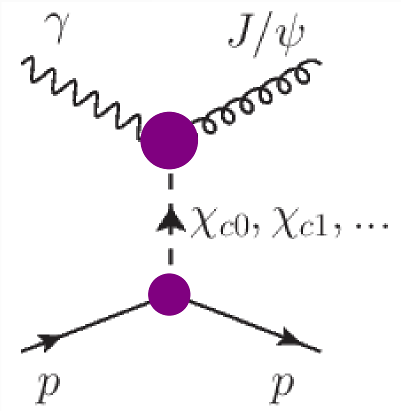




[S.H.Kim, in progress]



light mesons



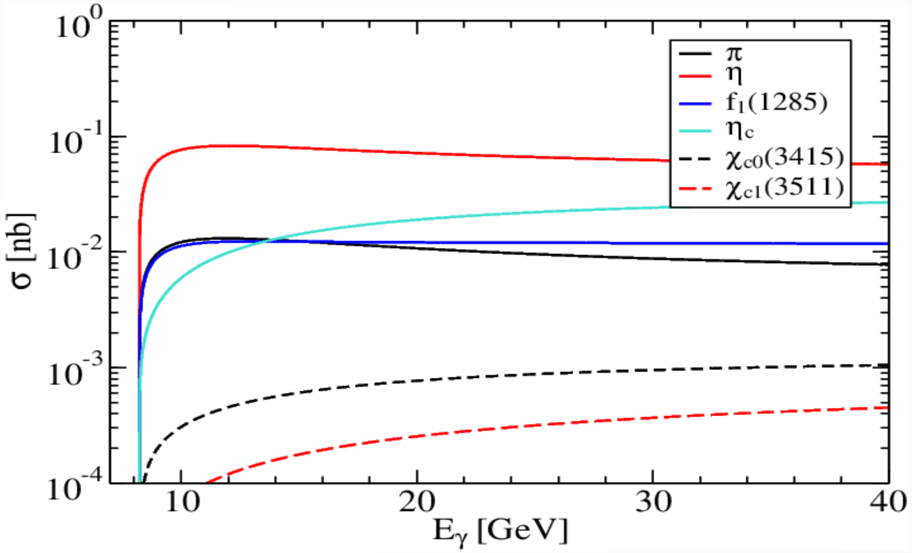
$c\bar{c}$ mesons

Mesons	Mass (J^P)
π	134 (0^-)
η	548 (0^-)
η'	958 (0^-)
f_1	1285 (1^+)
$\eta_c(1S)$	2984 (0^-)

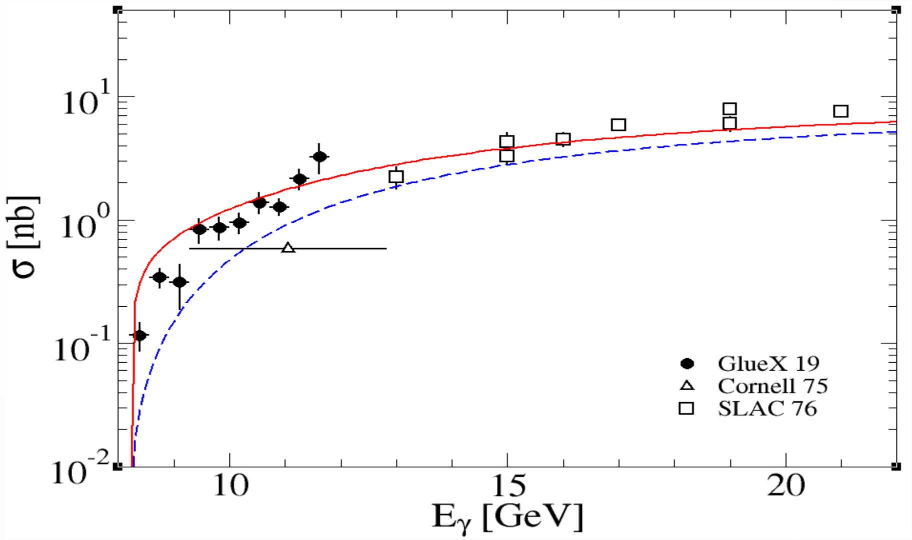
Mesons	Mass (J^P)
$\chi_{c0}(1P)$	3415 (0^+)
$\chi_{c1}(1P)$	3511 (1^+)
$\eta_c(2S)$	3638 (0^-)
$\chi_{c1}(3872)$	3872 (1^+)

□ σ (PS mesons) > σ (S mesons)
[by one ~ two orders of magnitudes]

□ Each Contribution



□ Total cross section with light mesons included



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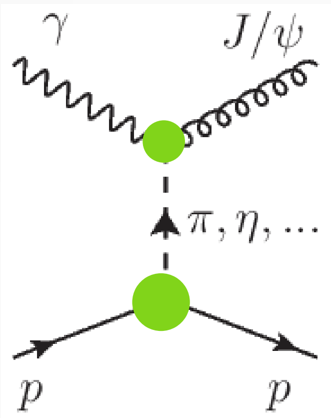
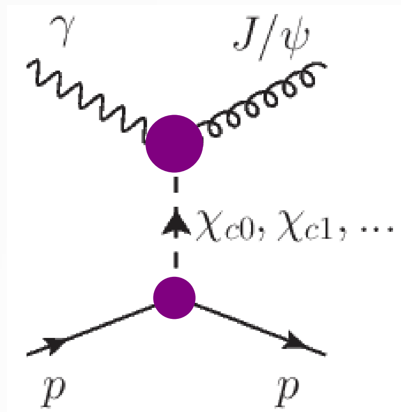


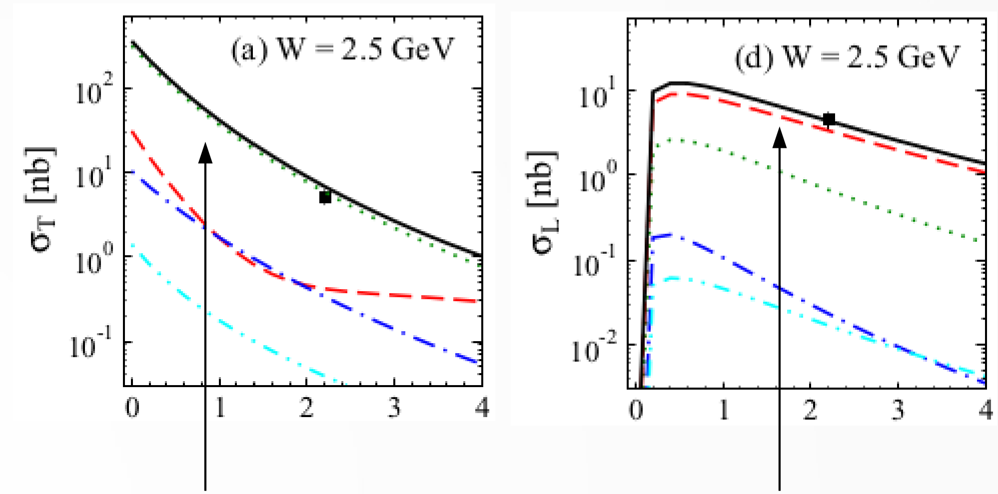
σ (PS mesons)



σ (S mesons)

← dominant →

$\gamma^* p \to \varphi p$ [S.H.Kim, PRC.101.065201 (2020)]

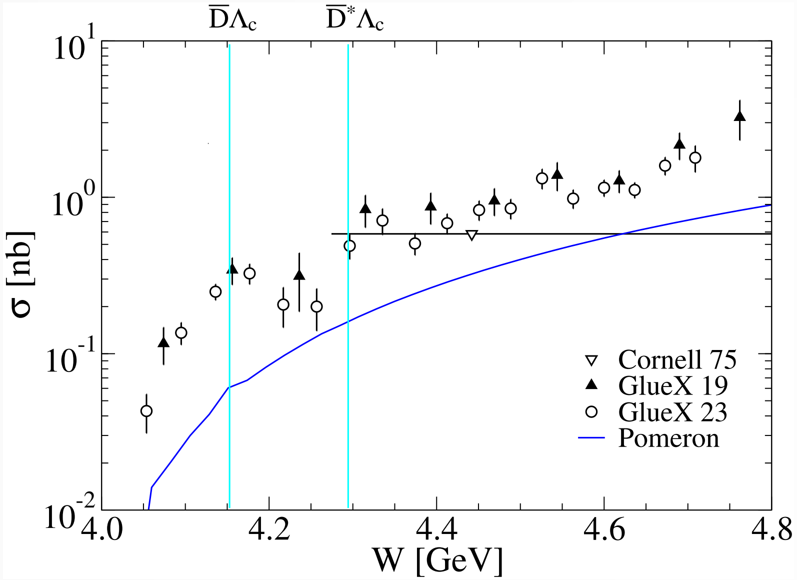


- The dominant mechanism can be verified by the future EIC and JLab data for the spin polarization observables, e.g., beam asymmetry.
- In vector-meson (φ) electroproduction, $\gamma^* p \to \varphi p$, we know that S-meson plays an important role at low W and low Q^2 for σ_L.

$$\frac{d\sigma}{d\Phi} = \frac{1}{2\pi}\left(\sigma + \varepsilon\sigma_{TT}\cos 2\Phi + \sqrt{2\varepsilon(1+\varepsilon)}\sigma_{LT}\cos\Phi\right) \quad \sigma = \sigma_T + \varepsilon\sigma_L$$

- The role of $\chi_{c0}(3415,0^+)$ can be found from the future EIC and JLab data for $\gamma^* p \to J/\psi\, p$ reaction at low W and low Q^2.

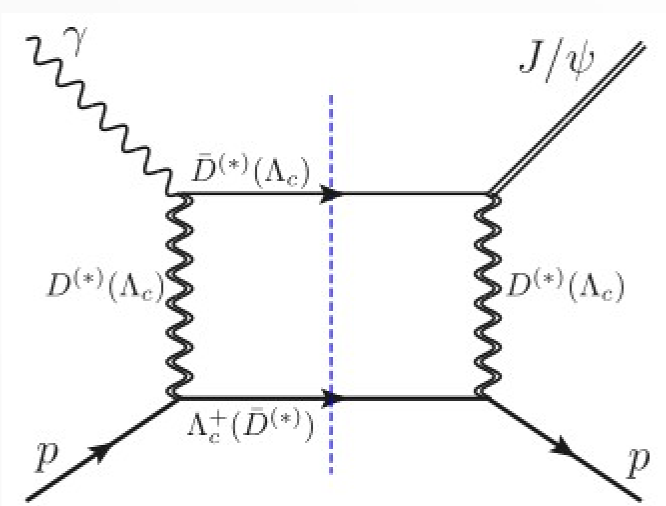
□ Two pronounced cusp structures are located at the $\bar{D}_c$ and $\bar{D}^*_c$ thresholds.



$$
\begin{aligned}
\mathcal{L}_{\Lambda_c DN} = & -g_{D^*N\Lambda_c}\bar{\Lambda}_c\gamma_\mu N D^{*\mu} - i g_{DN\Lambda_c}\bar{\Lambda}_c\gamma_5 N D \\
& -g_{D^*N\Lambda_c}\bar{N}\gamma_\mu \Lambda_c D^{*\mu\dagger} - i g_{DN\Lambda_c}\bar{N}\gamma_5\Lambda_c D^\dagger,
\end{aligned}
$$

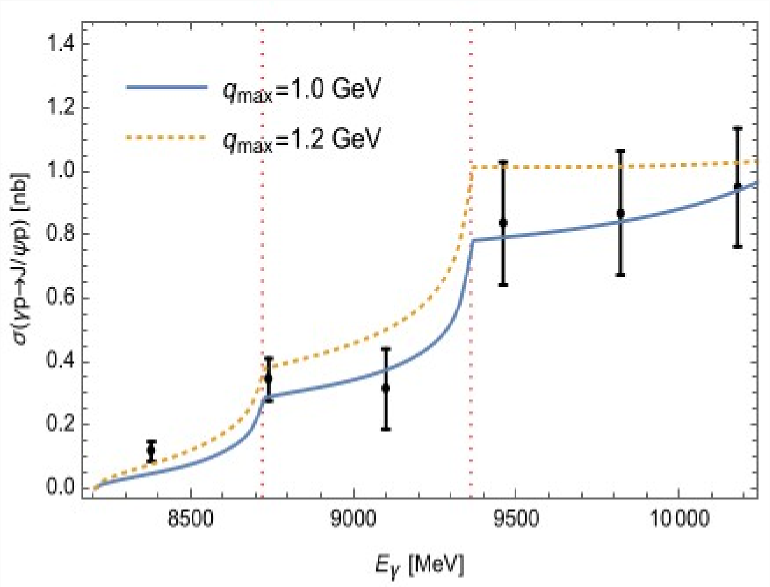
$$
\begin{aligned}
\mathcal{L}_\psi = & -g_{\psi DD^*}\psi_\mu\epsilon_{\mu\nu\alpha\beta}\left(\partial_\nu D^*_\alpha\partial_\beta D^\dagger - \partial_\nu D\partial_\beta D^{*\dagger}_\alpha\right) \\
& + i g_{\psi D^*D^*}\psi^\mu\left(D^{*\nu}\partial_\nu D^{*\dagger}_\mu - \partial_\nu D^*_\mu D^{*\nu\dagger}\right. \\
& \left. - D^{*\nu}\overleftrightarrow{\partial}_\mu D^{*\dagger}_\nu\right) - i g_{\psi DD} D^\dagger\overleftrightarrow{\partial}_\mu D\psi^\mu \\
& + g_{\psi\Lambda_c\Lambda_c}\bar{\Lambda}_c\gamma_\mu\psi^\mu\Lambda_c,
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_\gamma = & -g_{\gamma DD^*}F_{\mu\nu}\epsilon^{\mu\nu\alpha\beta}(D^*_\alpha\overleftrightarrow{\partial}_\beta D^\dagger - D\overleftrightarrow{\partial}_\beta D^{*\dagger}_\alpha) \\
& - i g_{\gamma D^*D^*}F^{\mu\nu}D^{*\dagger}_\mu D^*_\nu - e\bar{\Lambda}_c\gamma_\mu A^\mu\Lambda,
\end{aligned}
$$

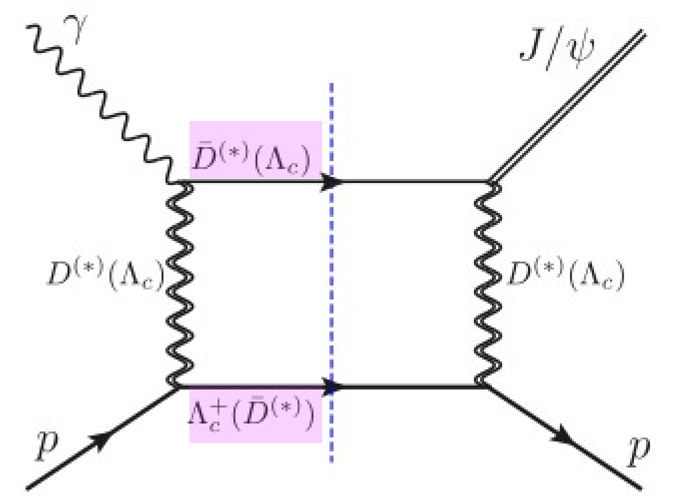


Coupling	$g_{\gamma DD^*}$	$g_{\gamma D^*D^*}$	$g_{DN\Lambda_c}$	$g_{D^*N\Lambda_c}$	$g_{\psi\Lambda_c\Lambda_c}$	$g_{\psi DD}$
Value	0.134 GeV^{-1}	0.641	−4.3	−13.2	−1.4	7.44
Source	Experimental data [46]		SU(4) [47,48]			VMD [47,48]

□ The presence of such cusps can be a clear indication of the importance of the charm loops.



[Du, EPJC.80.1053 (2020)]



□ We calculate
$\overline{D}_c$: 3 terms
$\overline{D}^*_c$: 5 terms

□ We are trying to calculate this region by using the 3-dimensional reduction of the integral equation for both principal and singular parts.

$$T_{MB}(p,p') = \sum_i \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{m_{B_i}}{E_{B_i}} T_{\gamma p\to M_iB_i}(p,q) \frac{1}{s-(E_{M_i}+E_{B_i})^2+i\epsilon} T_{M_iB_i\to J/\psi p}(q,p')$$
$$= -i\sum_i \frac{q_{\rm c.m.}}{16\pi^2}\frac{m_{B_i}}{\sqrt{s}}\int d\Omega\,[T_{\gamma p\to M_iB_i}(p,q)T_{M_iB_i\to J/\psi p}(q,p')] + \mathcal{P}$$

◇ For $\gamma\, p \to \varphi\, p$,

we studied relative contributions between the Pomeson and various meson exchanges.

> The light-meson (π, η, a_0, f_0,...) contribution is crucial to describe the data at low energies.

The final φN interactions are described by the gluon-exchange, direct φN couplings, and the box diagrams arising from the couplings with πN, ρN, $K\Lambda$, and $K\Sigma$ channels. > suppressed by $10^2 - 10^3$.

◇ For $\gamma\, {}^4He \to \varphi\, {}^4He$,

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> The FSI effects are suppressed compared to the Born term by $10^1 - 10^3$.

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◇ We investigated $\gamma\, A \rightarrow J/\psi\, A$ ($A = d$, ${}^4He$, ${}^{16}O$, ${}^{40}Ca$) reaction.
> The FSI effects are sizable near the threshold.

◇ We introduced two models for $\gamma\, A \rightarrow J/\psi\, A$: meson-exchange model, rescattering-diagram model

◇ For $\varphi\, p$ and $J/\psi\, p$ photoproduction, the meson-baryon loops seem to be the dominant.

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Thank you very much for your attention