Photo- and electro-production of φ meson off the nucleon and ^{4}He

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Contents

Contents based on

[S.H.Kim, S.i.Nam, PRC.100.065208 (2019)]
[S.H.Kim, S.i.Nam, PRC.101.065201 (2020)]
[S.H.Kim, T.S.H.Lee, S.i.Nam, Y. Oh, PRC.104.045202 (2021)]

Introduction

◇ photoproduction ⇨ electroproduction

$\gamma\, p \to (\varphi, \rho, \omega, J/\psi, \ldots)\, p$ ⇨ $\gamma^{*}\, p \to (\varphi, \rho, \omega, J/\psi, \ldots)\, p$

Regge model, at low W and Q^2

production off nuclear targets

⇨ $\gamma^{(*)}\, A \to (\varphi, \rho, \omega, J/\psi, \ldots)\, A$, $[A = {}^{2}H, {}^{4}He, {}^{12}C, \ldots]$

distorted-wave impulse approximation

Introduction

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distorted-wave impulse approximation

◇ Approved 12 GeV era experiments to date at Jafferson Labarotory:

[E12-09-003] Nucleon Resonances Studies with CLAS

[E12-11-002] Proton Recoil Polarization in the ${}^{4}He(e,e'p){}^{3}H$, ${}^{2}He(e,e'p)n$, ${}^{1}He(e,e'p)$

[E12-11-005] Meson spectroscopy with low Q^2 electron scattering in CLAS12

[E12-12-006] Near Threshold Electroproduction of J/ψ at 11 GeV

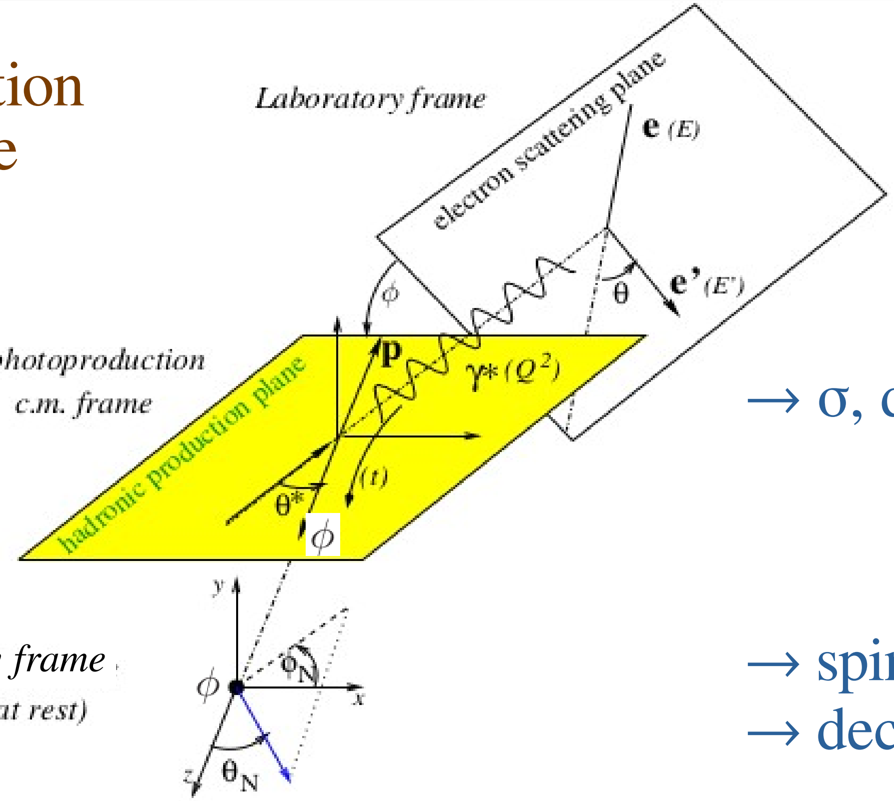
[E12-12-007] Exclusive Phi Meson Electroproduction with CLAS12

◇ Electron-Ion Collider (EIC) will carry out the relevant experiments in the future.

Exclusive electroproduction of vector mesons

$\gamma^{(*)}\, p \rightarrow V\, p$

reaction plane



□ Photon(γ) polarization vector
Transverse comp. ($\lambda_\gamma=\pm1$) [photo-, electro-]
Longitudinal comp. ($\lambda_\gamma=0$) [electro-]

→ σ, dσ/dΩ, dσ/dt [photo-, electro-]

→ spin-density matrices (ρ_{ij}) [photo-, electro-]
→ decay angular distributions (W) [photo-, electro-]

Exclusive electroproduction of vector mesons

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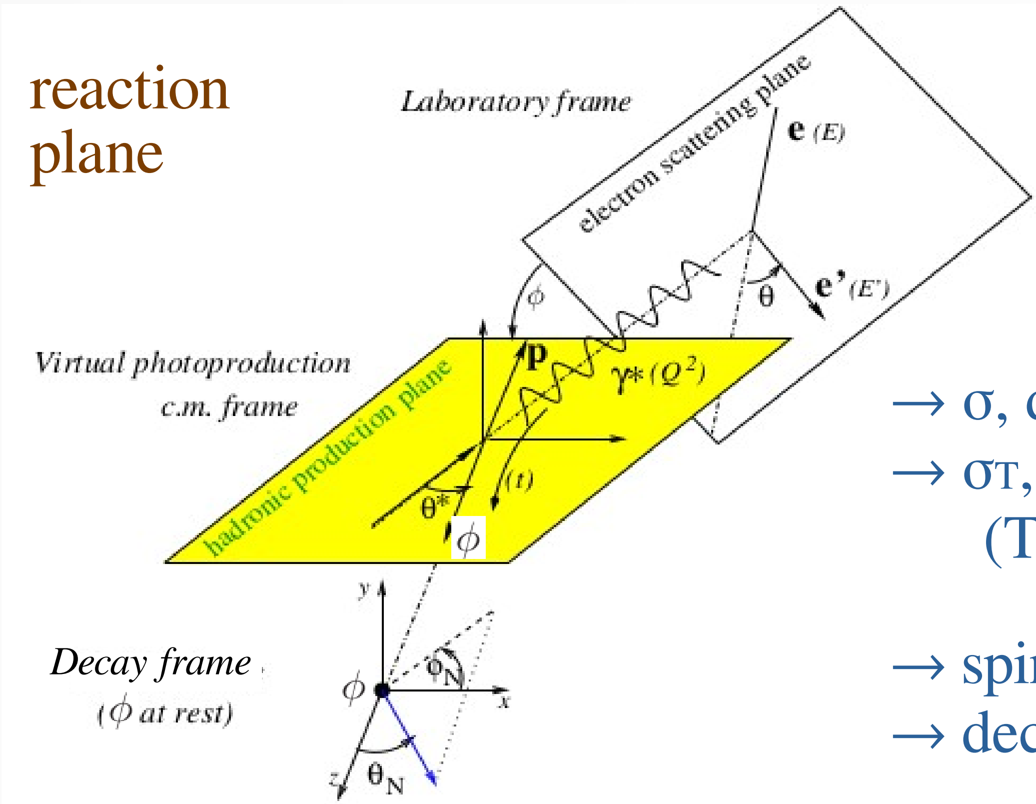

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→ σ_T, σ_L, σ_{TT}, σ_{LT}, $R=\sigma_L/\sigma_T$ ... [electro-]
(T-L separated cross sections)

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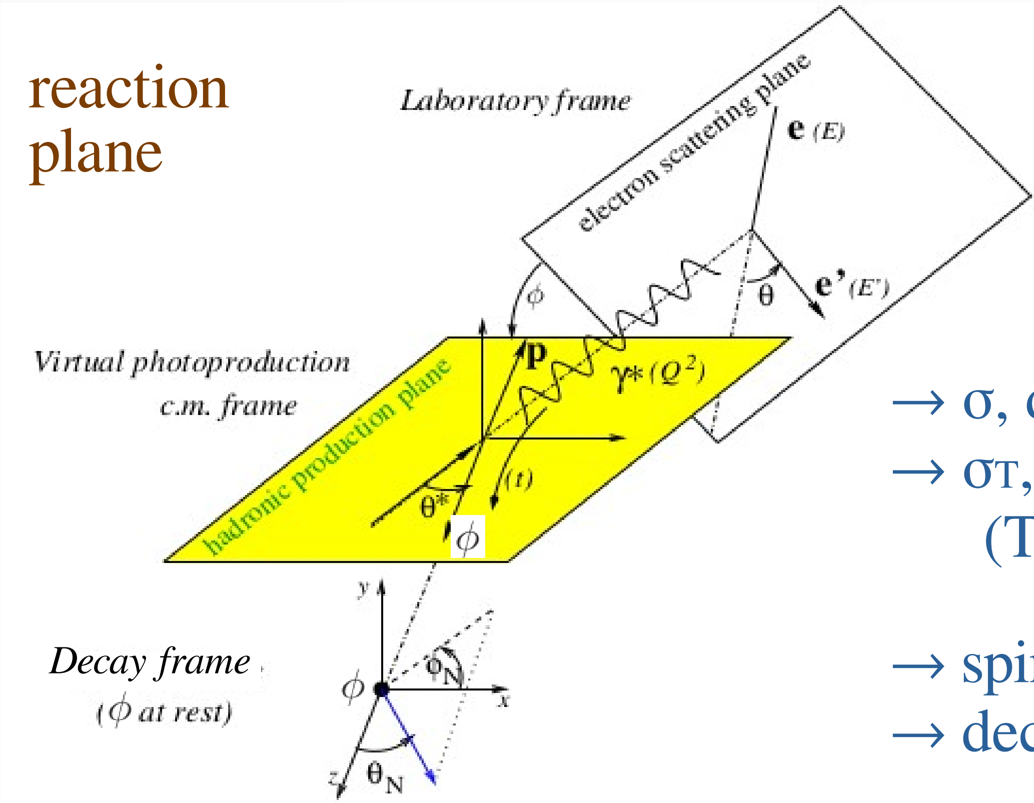

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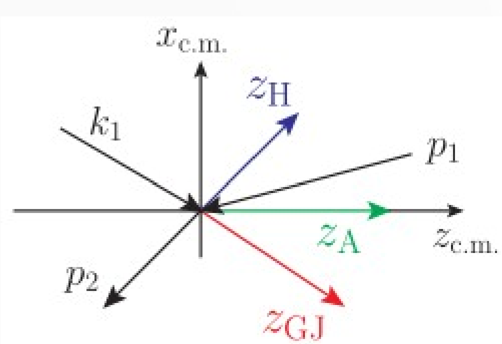
→ spin-density matrices (ρ_{ij}) [photo-, electro-]

→ decay angular distributions (W) [photo-, electro-]

❑ Decay frame



Adair frame

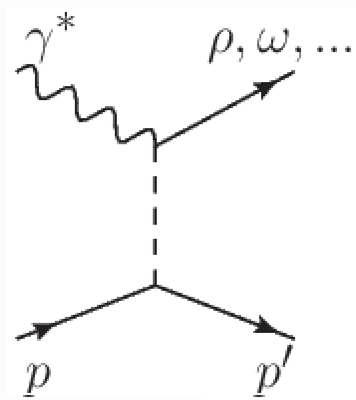
Helicty frame: in favor of s-channel helicity conservation (SCHC)

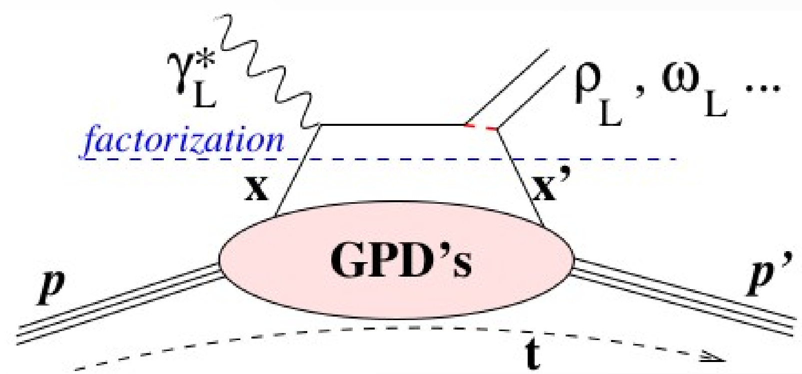
Gottfried-Jackson frame: in favor of t-channel helicity conservation (TCHC)

$\gamma^* p \to V(\rho, \omega, \varphi, J/\psi)\ p$

theoretical framework

Q^2=0 <---> low Q^2	<<----->>	high Q^2





t-channel Regge trajectory exchange	<<----->>	handbag diagram

Exclusive electroproduction of vector mesons

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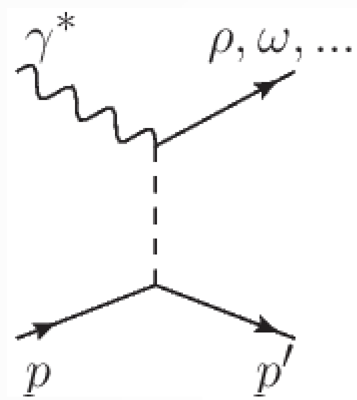
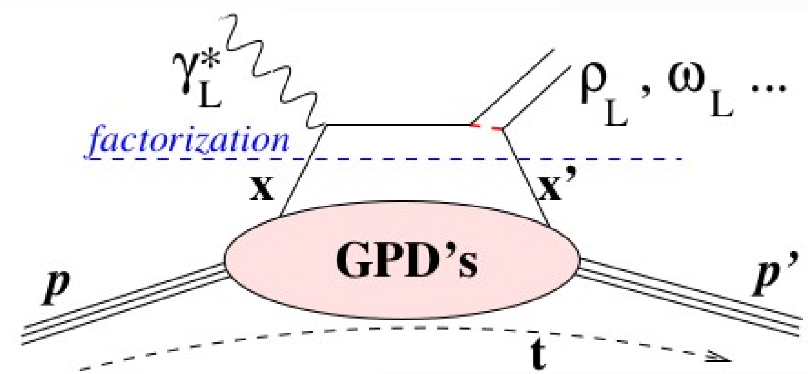


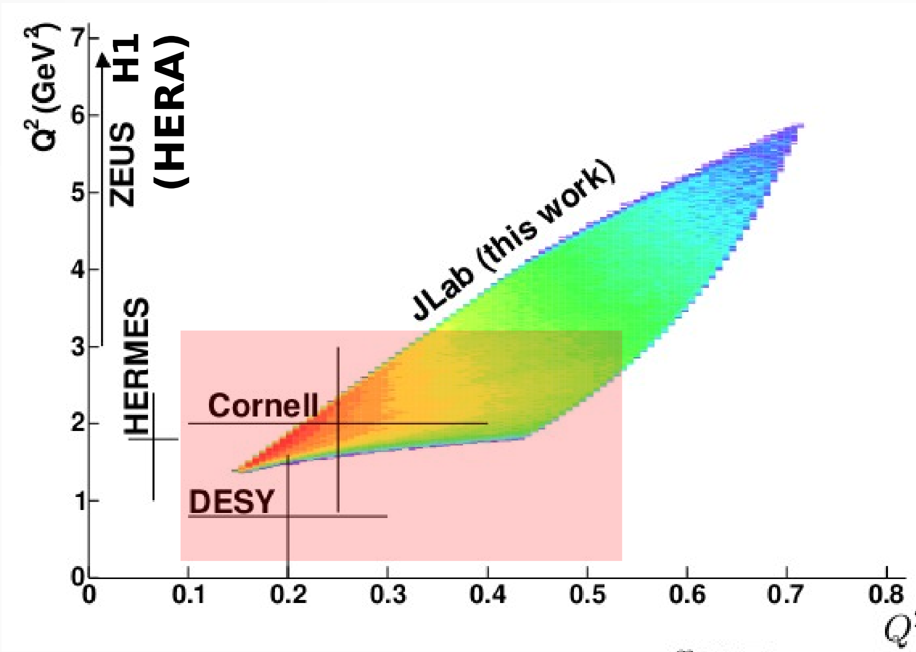


t-channel Regge trajectory exchange <<----->> handbag diagram

❑ Extending to "the virtual-photon sector" opens the way
> to tune hadronic component of the exchanged photon
> to explore to what extent meson exchange survives
> to observe hard-scattering mechanisms,
with a second hard scale, "photon virtuality $-(k_e - k_{e'})^2 = Q^2$".

Exclusive electroproduction of vector mesons

$\gamma^* p \to V(\rho, \omega, \varphi, J/\psi)\, p$

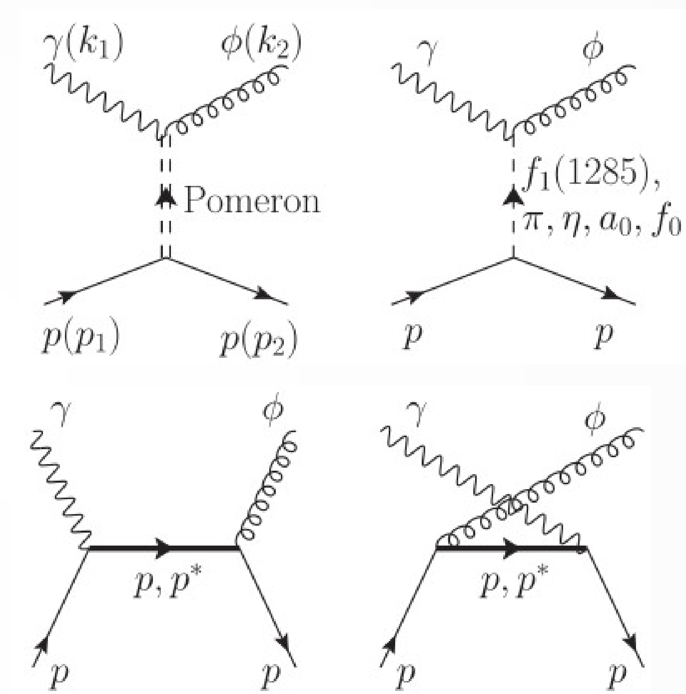


$$x_{\mathrm{Bj}} = \frac{Q^2}{W^2 + Q^2 - m^2}$$

[Kinematical range covered by vector meson electoproduction experiments]

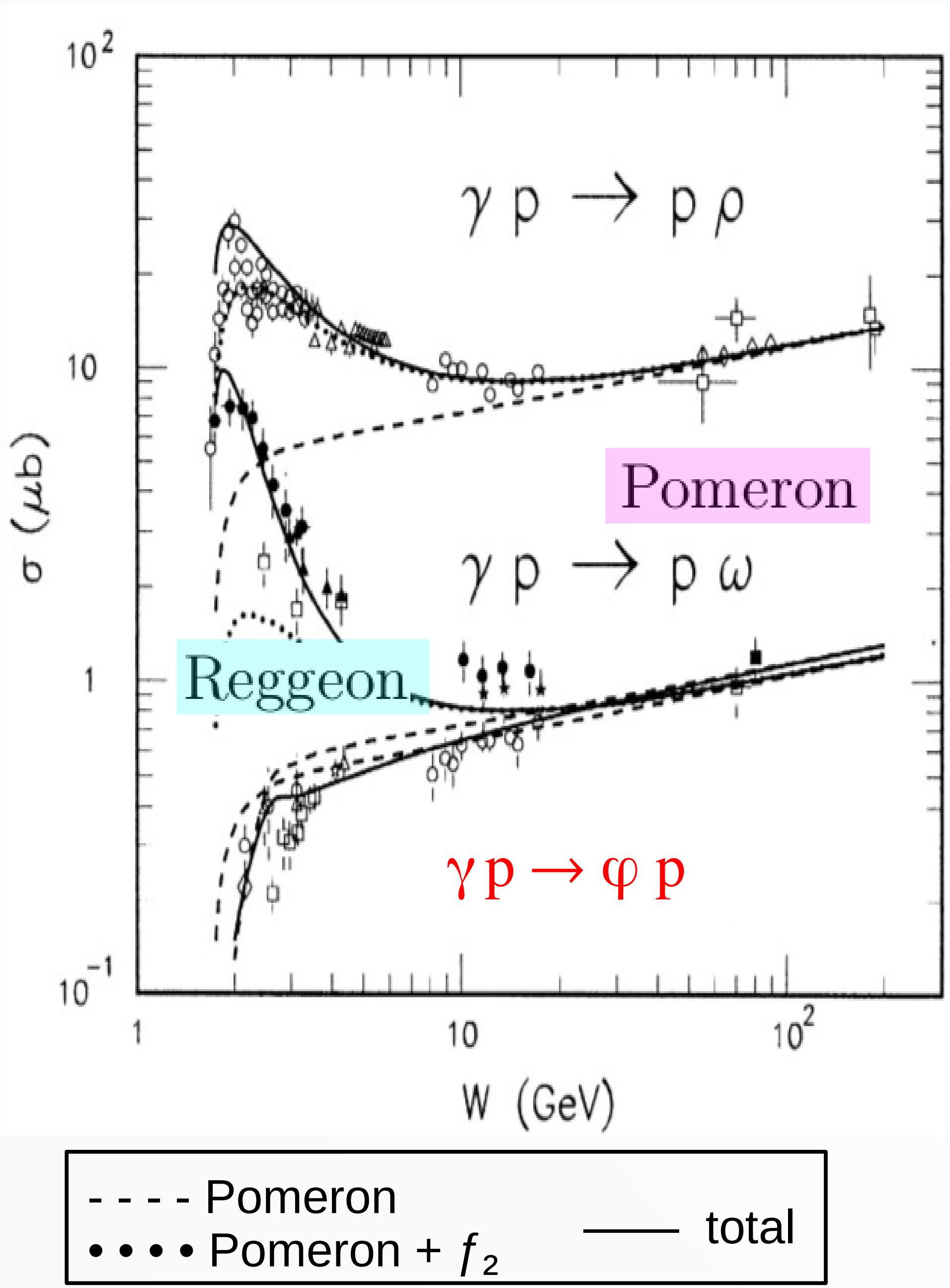
[Morand (CLAS), EPJ.A24.445 (2005)]

Feynman diagrams



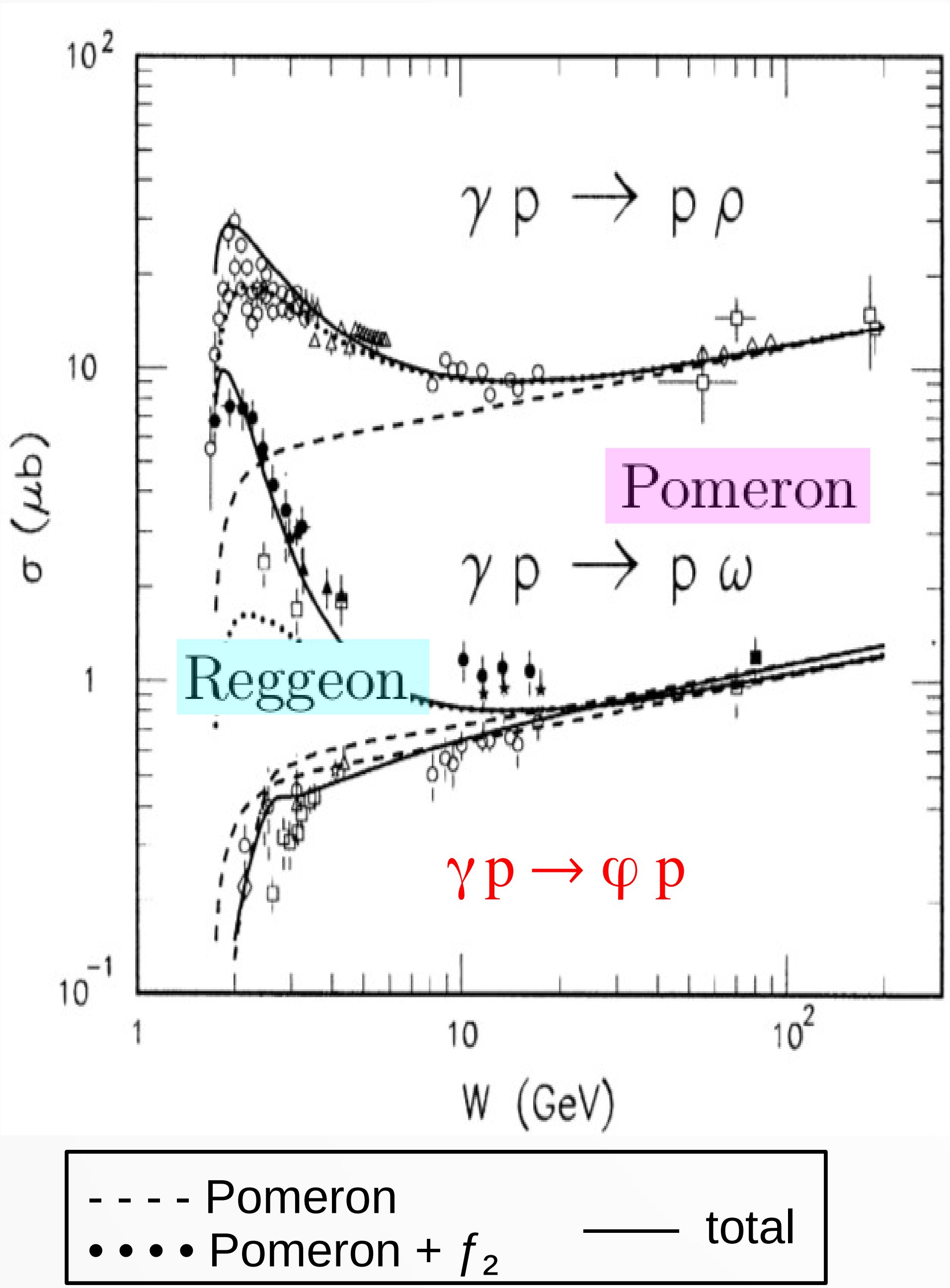
- ❑ We can test which of the two descriptions - with “hadronic” or “quark” degrees of freedom - applies in the considered kinematical domain.
- ❑ At low photon virtualities ($Q^2 \lesssim M_V^2$) and low energies ($W \lesssim$ several GeV), our hadronic effective model is applicable.

Exclusive photoproduction of vector mesons



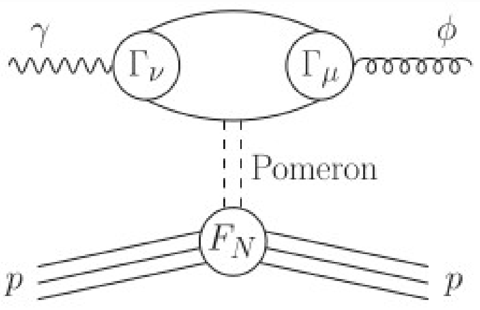
[Laget,PLB.489.313(2000)]

Exclusive photoproduction of vector mesons



[Laget,PLB.489.313(2000)]

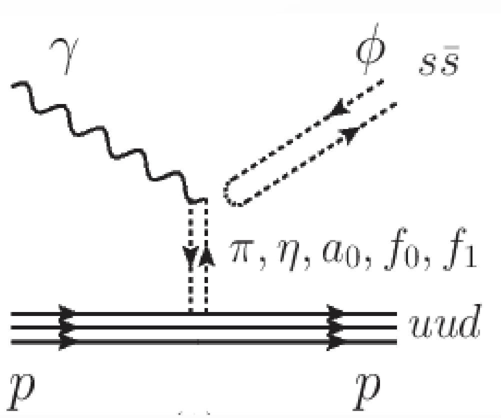
- ❑ We focus on $\gamma p \to \varphi p$.
- ❑ high energy



- □ $\sigma[\gamma p \to \varphi p] \approx \sigma[\gamma p \to \omega p]$
- □ F_N: isoscalar EM form factor of the nucleon

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

- ❑ low energy



- □ $\sigma[\gamma p \to \varphi p] \ll \sigma[\gamma p \to (\rho,\omega)p]$ due to the OZI rule

Exclusive photoproduction of vector mesons

❑ 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)]

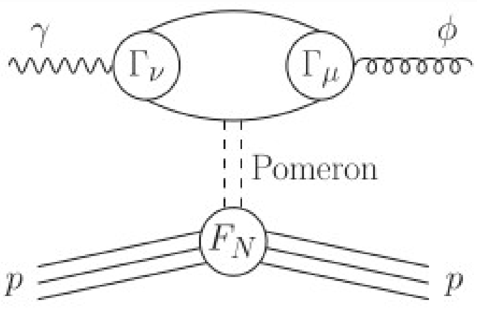
❑ low energy:

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 $\gamma\, p \to \varphi\, p$.

❑ high energy



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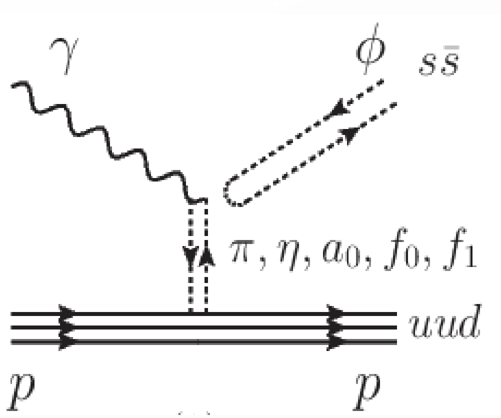
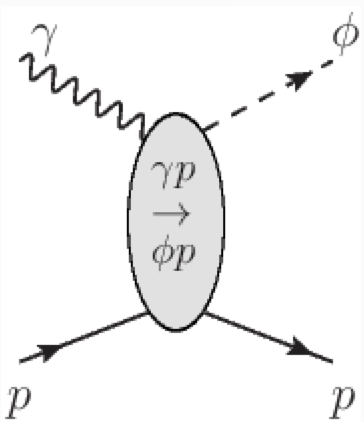
❑ low energy

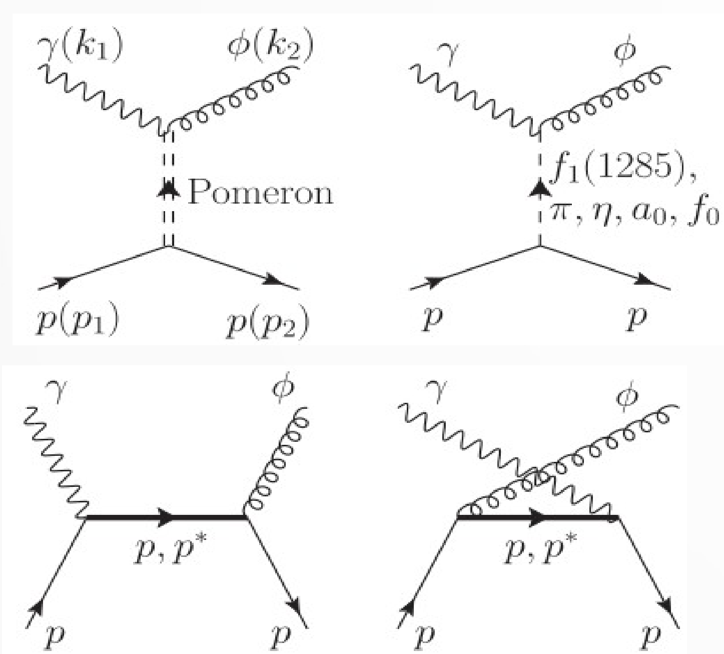


□ $\sigma[\gamma p \to \varphi p] \ll \sigma[\gamma p \to (\rho,\omega)p]$ due to the OZI rule

Born term

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





- 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

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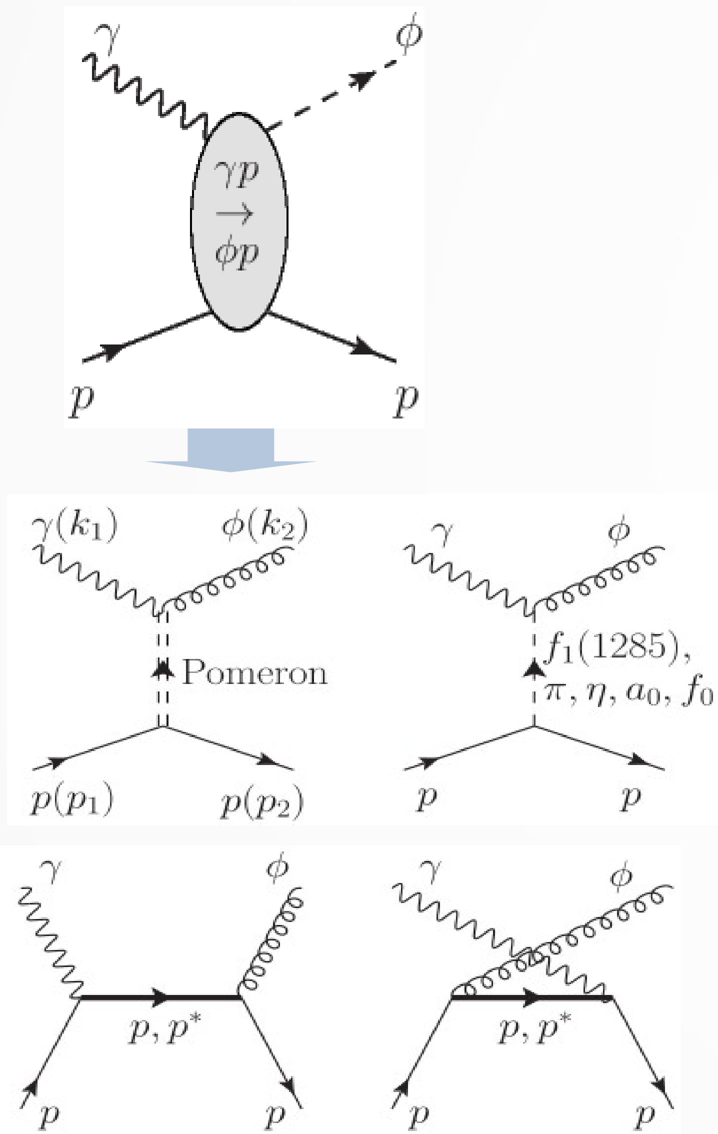

❑ Effective Lagrangians

□ 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

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

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

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

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

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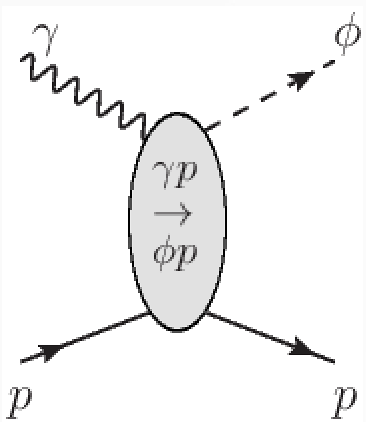

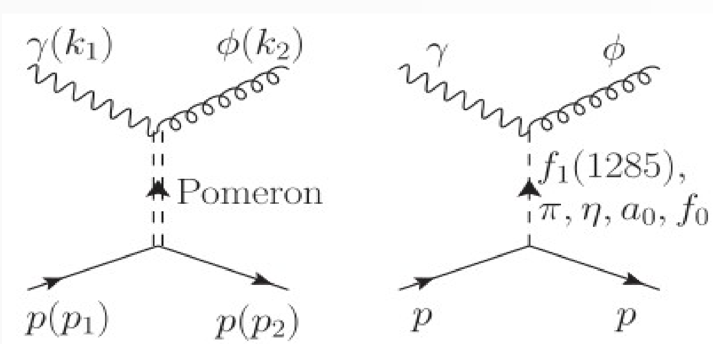

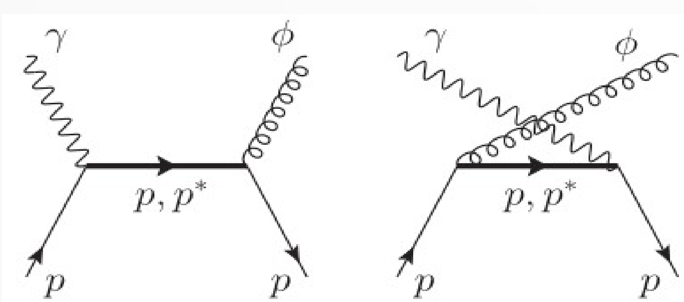

$$\mathcal{M} = \varepsilon^*_\nu \bar{u}_{N'} \mathcal{M}^{\mu\nu} u_N \epsilon_\mu$$

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

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

$$\mathcal{M}^{\mu\nu}_{S} = \frac{e}{M_\phi}\frac{2 g_{\gamma S\phi} g_{SNN}}{t - M^2_S + i\Gamma_S M_S}(k_1 k_2 g^{\mu\nu} - k^\mu_1 k^\nu_2),$$

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

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

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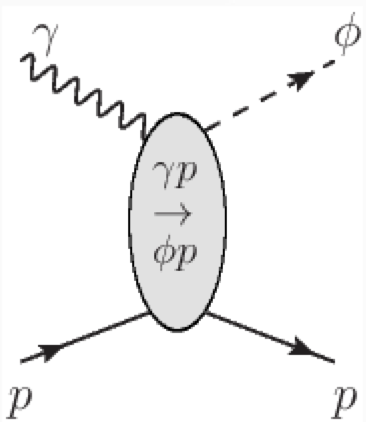
$$\mathcal{L}_{\phi NN} = -g_{\phi NN}\bar{N}\left[\gamma_\mu - \frac{\kappa_{\phi NN}}{2M_N}\sigma_{\mu\nu}\partial^\nu\right] N \phi^\mu$$

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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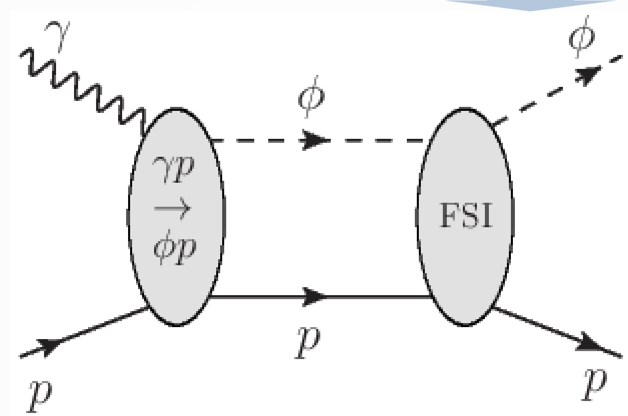
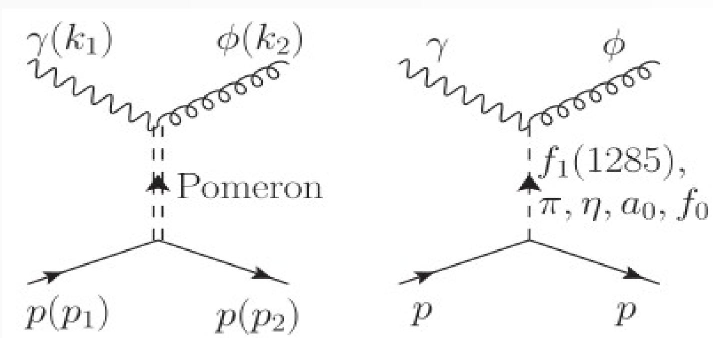
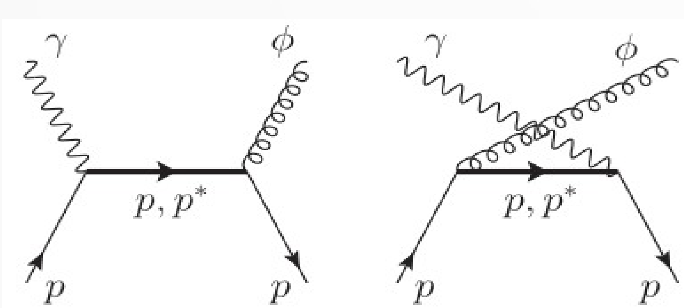
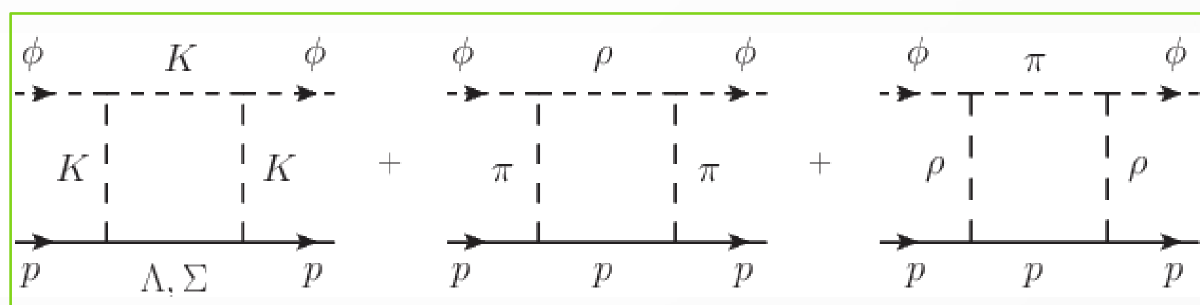






FSI=



□ 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}	$\rho\gamma$	$< 1.2 \times 10^{-5}$

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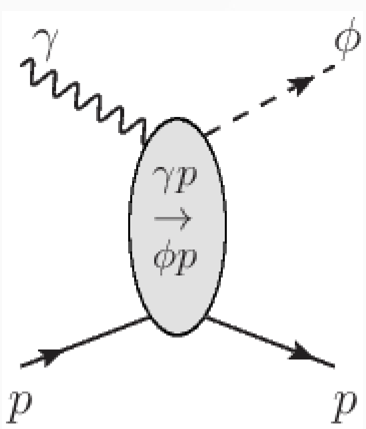

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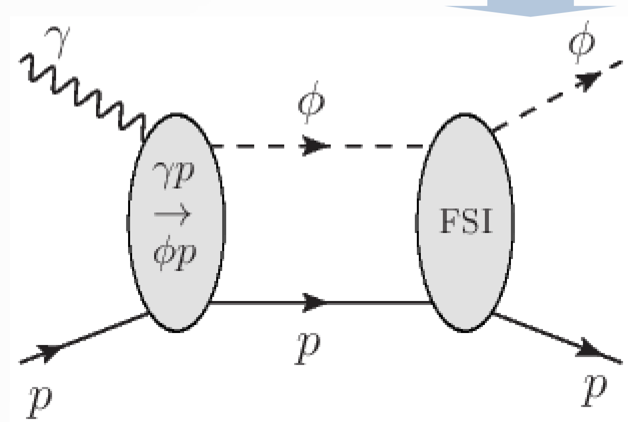

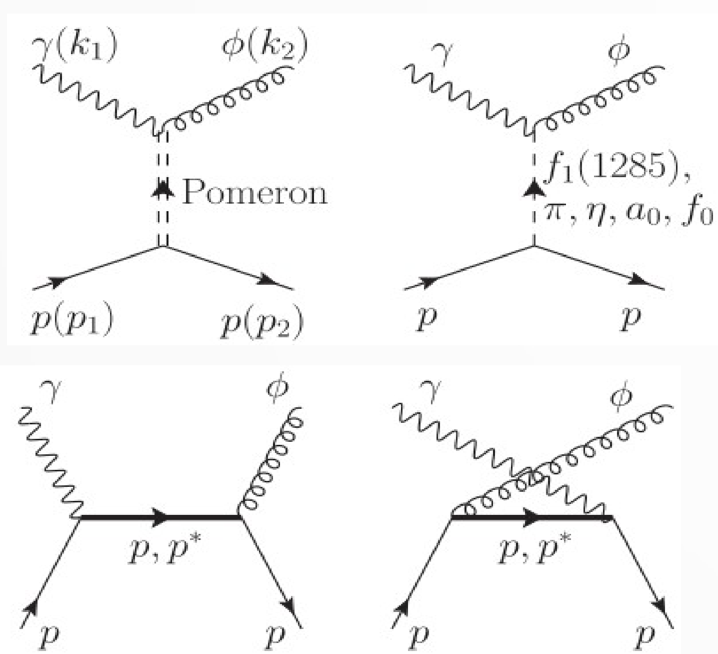

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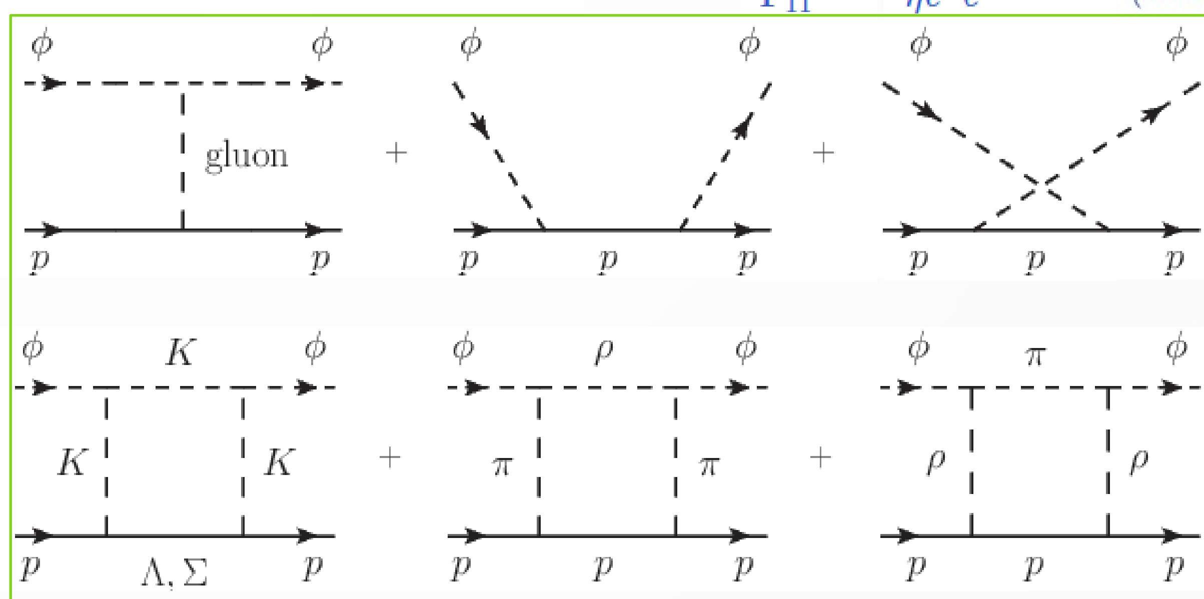

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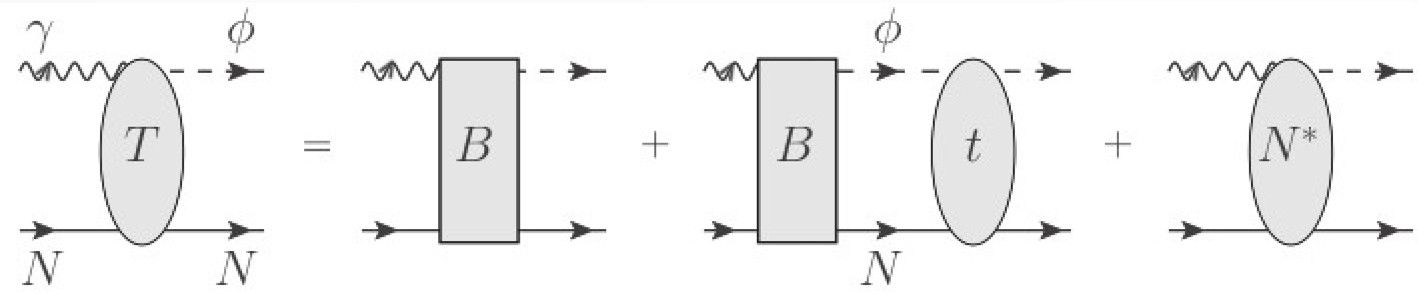
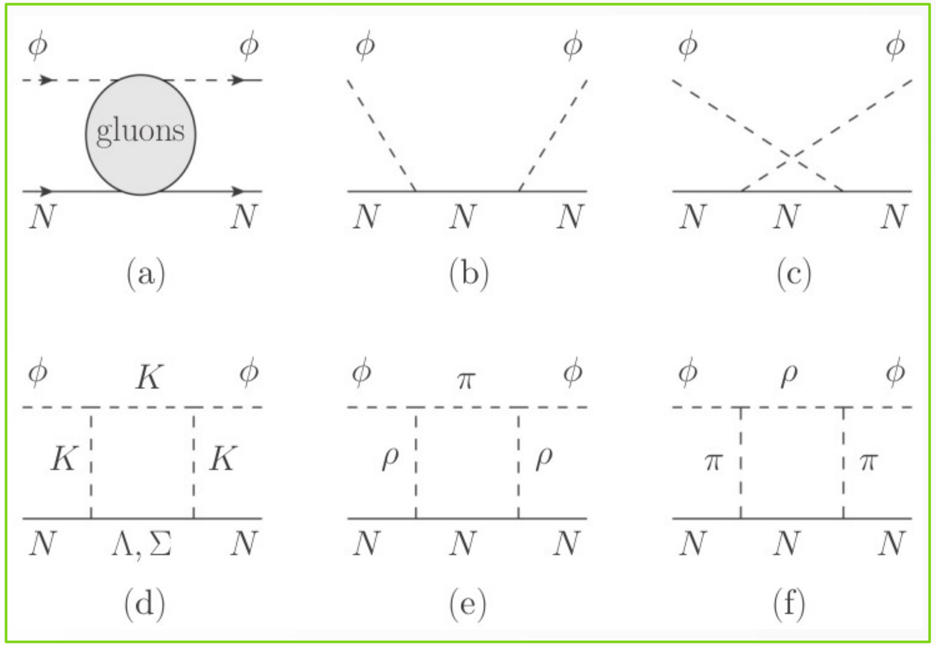
Γ_{11}	ηe^+e^-	$(1.08 \pm 0.04) \times 10^{-4}$
		$1.3) \times 10^{-5}$
		$0.5) \times 10^{-5}$
		$\times 10^{-5}$

final state interaction (FSI)



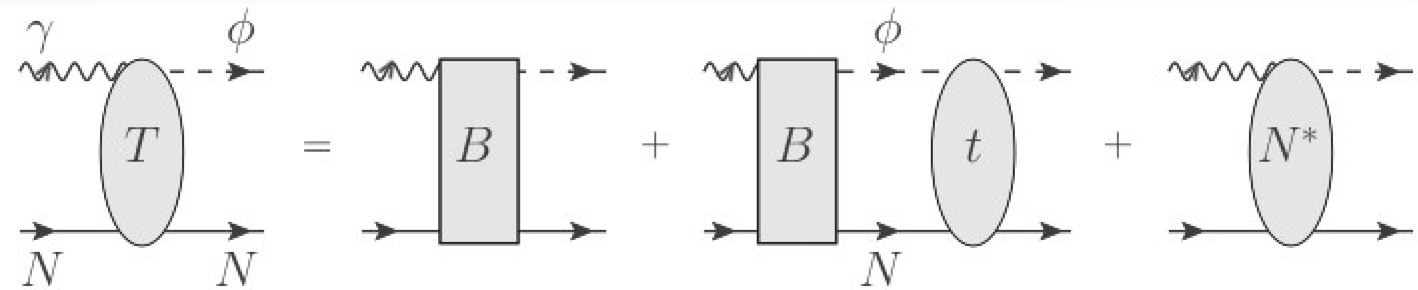
$$T_{\phi N,\gamma N}(E) = B_{\phi N,\gamma N} + T^{\mathrm{FSI}}_{\phi N,\gamma N}(E) + T^{N^*}_{\phi N,\gamma N}(E)$$

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



Exclusive photoproduction of vector mesons

final state interaction (FSI)

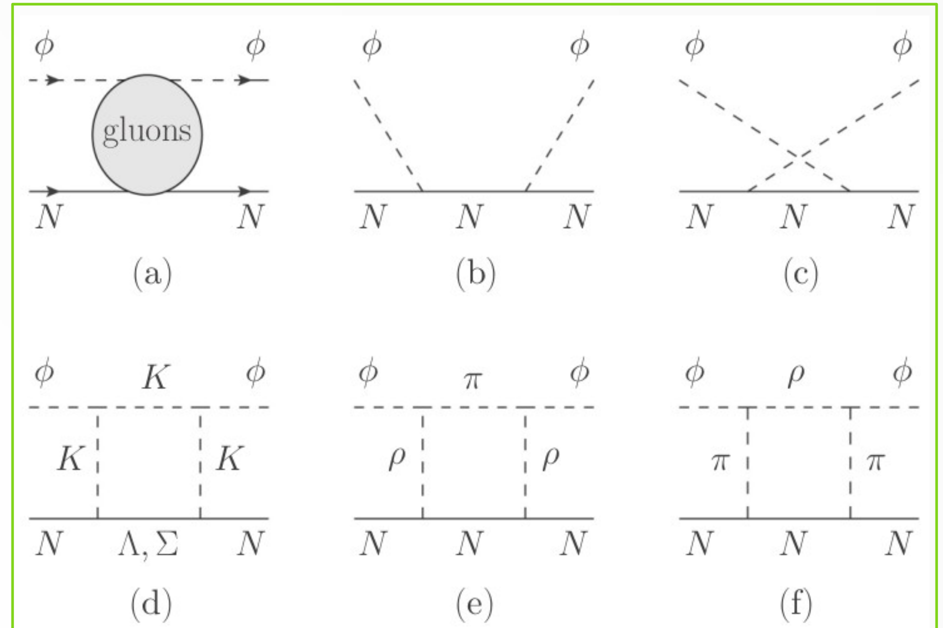


$$T_{\phi N,\gamma N}(E) = B_{\phi N,\gamma N} + \underbrace{T^{\mathrm{FSI}}_{\phi N,\gamma N}(E)}_{t_{\phi N,\phi N}(E) G_{\phi N}(E) B_{\phi N,\gamma N}} + T^{N^*}_{\phi N,\gamma N}(E)$$

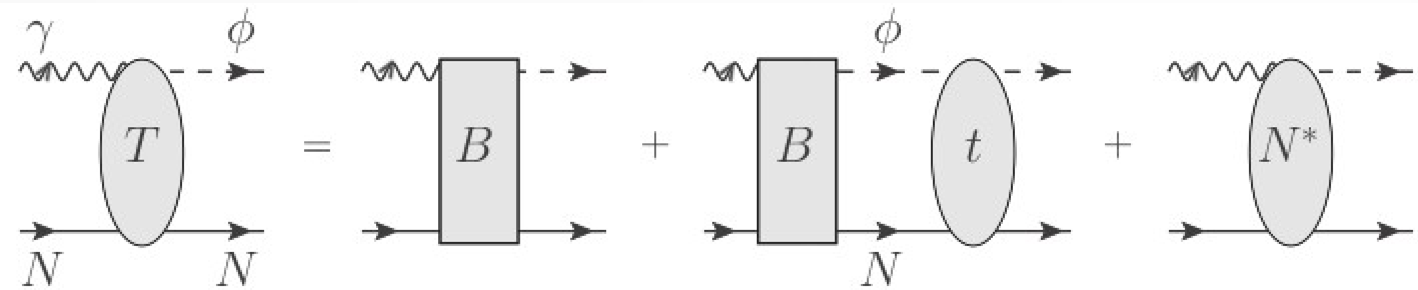
$$G_{MB}(E) = \frac{|MB\rangle \langle MB|}{E - H_0 + i\epsilon}$$: meson-baryon propagator

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

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



final state interaction (FSI)



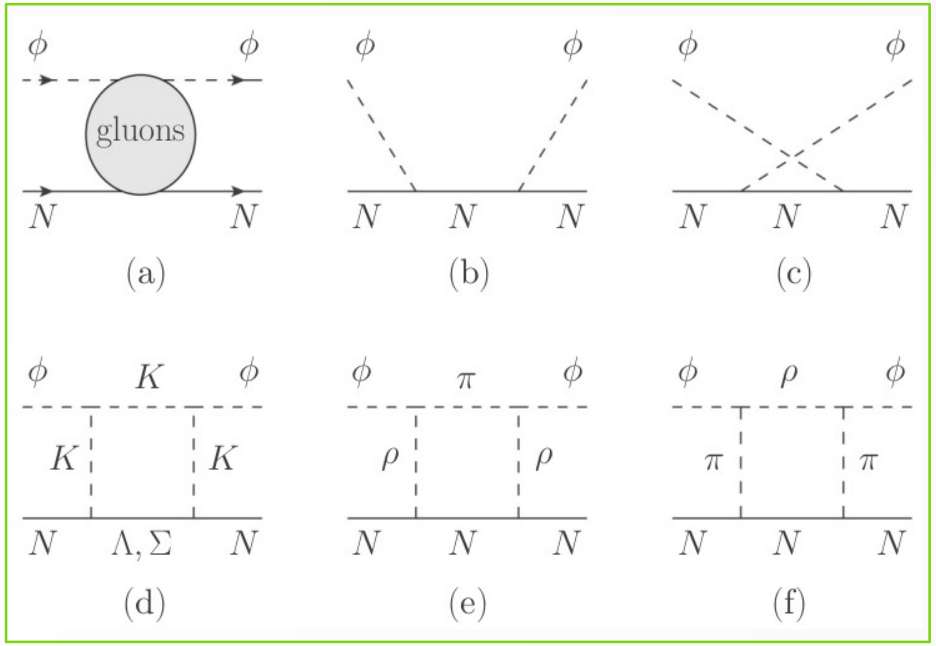
$$T_{\phi N,\gamma N}(E) = B_{\phi N,\gamma N} + \underbrace{T^{\mathrm{FSI}}_{\phi N,\gamma N}(E)}_{t_{\phi N,\phi N}(E) G_{\phi N}(E) B_{\phi N,\gamma N}} + T^{N^*}_{\phi N,\gamma N}(E)$$

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

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

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

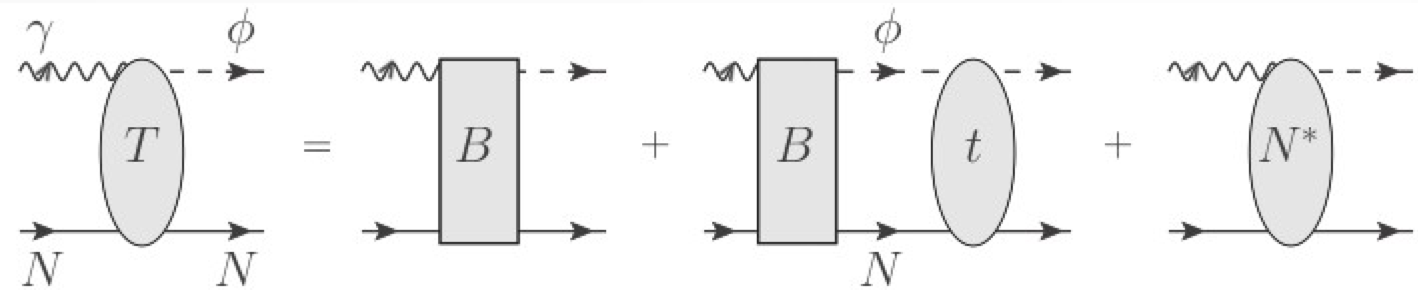
$t_{\phi N,\phi N}(E)$



□ To leading order, we obtain these FSI diagrams.

Exclusive photoproduction of vector mesons

final state interaction (FSI)



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

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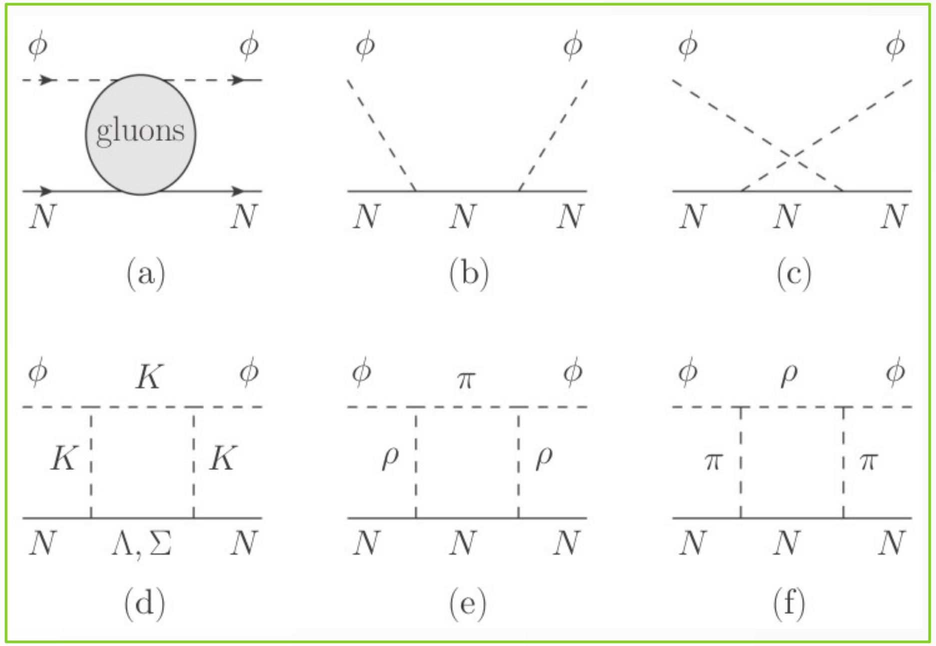
$$t_{\phi N,\phi N}(E) = \underbrace{V_{\phi N,\phi N}(E)}_{v^{\mathrm{Gluon}}_{\phi N,\phi N} + v^{\mathrm{Direct}}_{\phi N,\phi N} + \sum_{MB} v_{\phi N,MB} G_{MB}(E) v_{MB,\phi N}} + V_{\phi N,\phi N} G_{\phi N}(E) t_{\phi N,\phi N}(E)$$

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

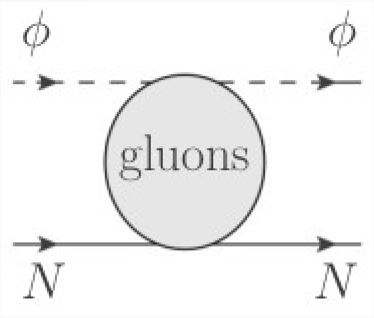
$t_{\phi N,\phi N}(E)$



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

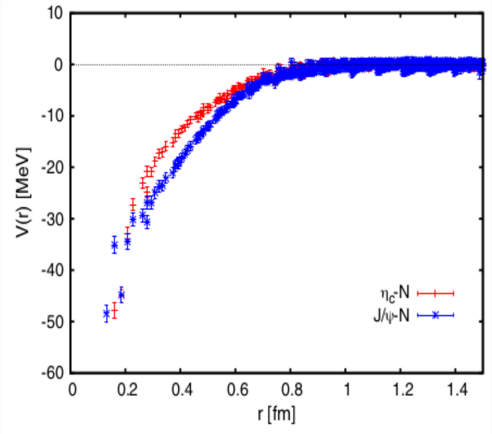
□ We consider both parts numerically.

final state interaction (FSI)



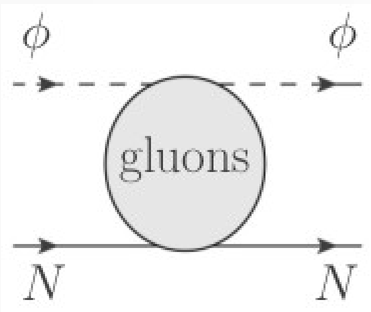
- The J/ψ-N potential from the LQCD data
  ~ Yukawa form ($\upsilon_0 = 0.1$, $\alpha = 0.3$ GeV)
  [Kawanai, Sasaki, PRD.82.091501(R) (2010)]

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



- which is assumed in our work, φ-N potential
  The best fit was obtained by ($\upsilon_0 = 0.2$, $\alpha = 0.5$ GeV).

final state interaction (FSI)



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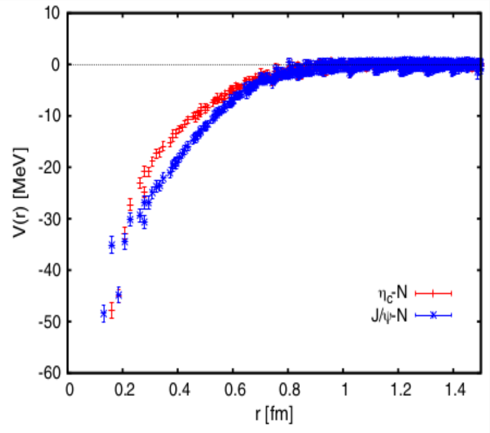


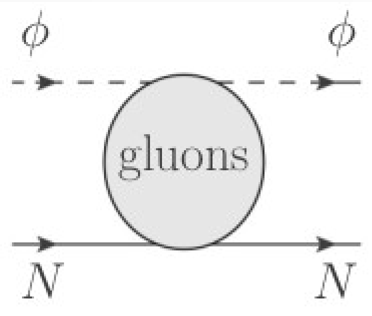
- The potential is obtained by taking the nonrelativistic limit of the scalar-meson exchange amplitude calculated from the Lagrangian:

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

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

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

final state interaction (FSI)



- The J/ψ-N potential from the LQCD data
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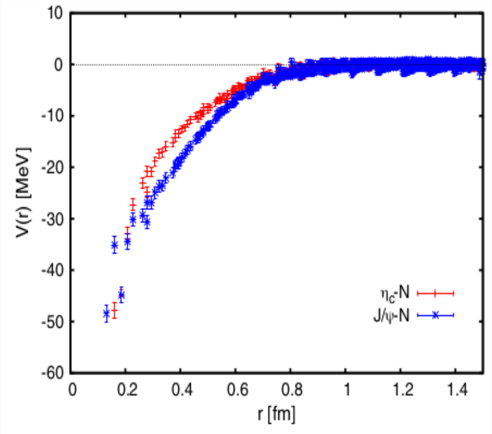
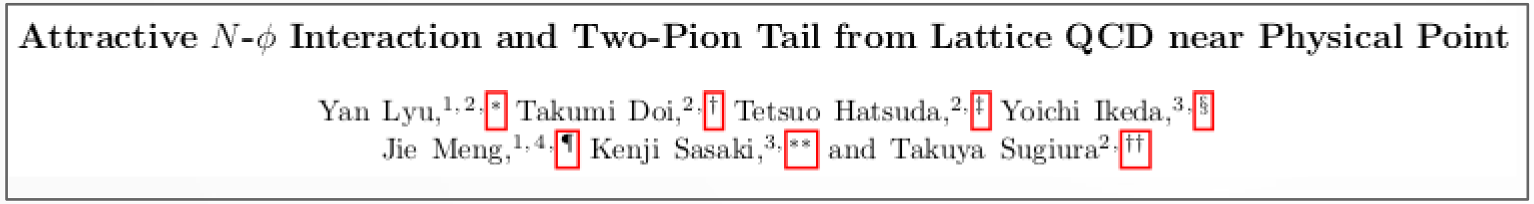
  [Kawanai, Sasaki, PRD.82.091501(R) (2010)]

$$\mathcal{V}_{\text{gluon}} = -v_0 \frac{e^{-\alpha r}}{r}$$



- 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 [hep-lat] 2205.10544



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,††]

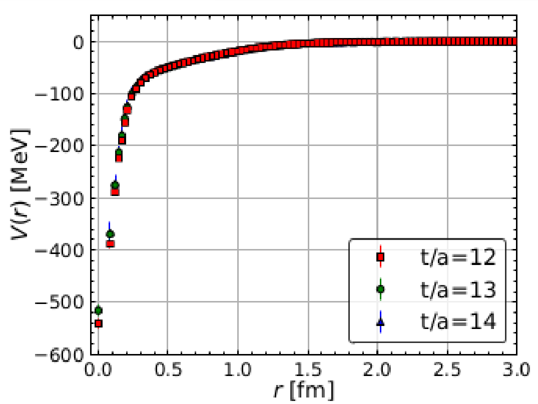


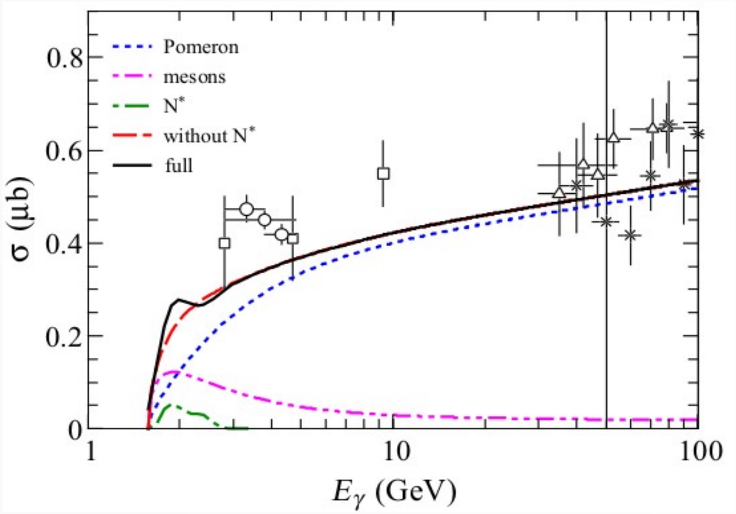
FIG. 1. (Color online). The N-ϕ potential $V(r)$ in the $^4S_{3/2}$ channel as a function of separation r at Euclidean time t/a = 12 (red squares), 13 (green circles) and 14 (blue triangles).

- 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.

Exclusive photoproduction of vector mesons [results]

Born term

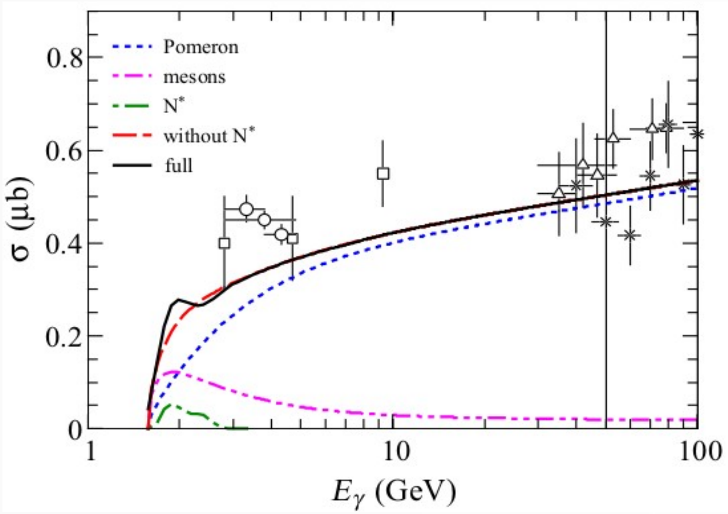


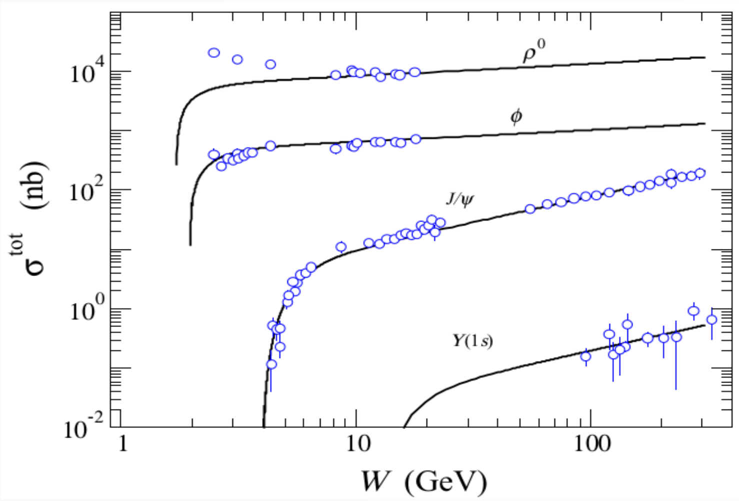
total cross section [$\gamma\, p \to \varphi\, p$]

Exclusive photoproduction of vector mesons [results]

Born term

total cross section [$\gamma\, p \to \varphi\, p$]





$\gamma\, p \to$
ρ^0
ω
φ
J/ψ
$\Upsilon(1s)$

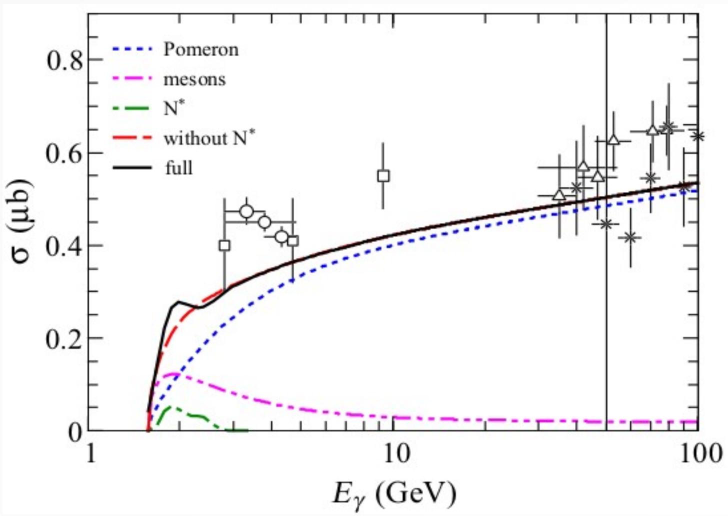
□ Our Pomeron model describes the high energy regions quite well.

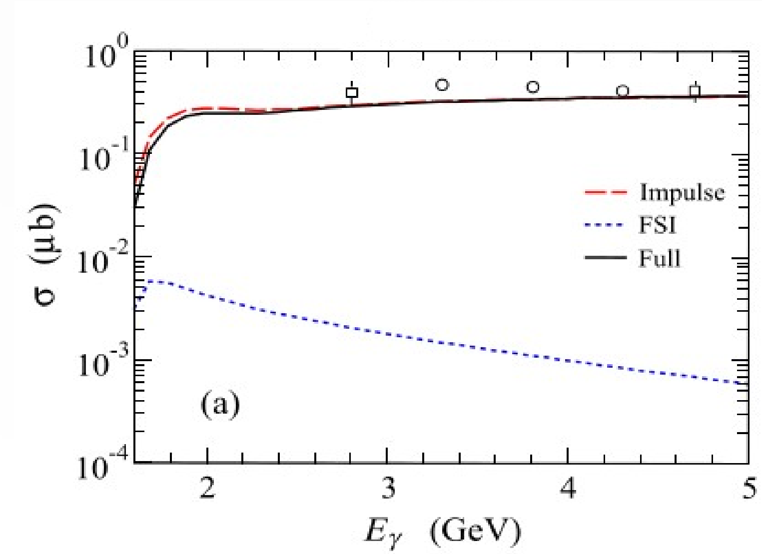
Exclusive photoproduction of vector mesons [results]

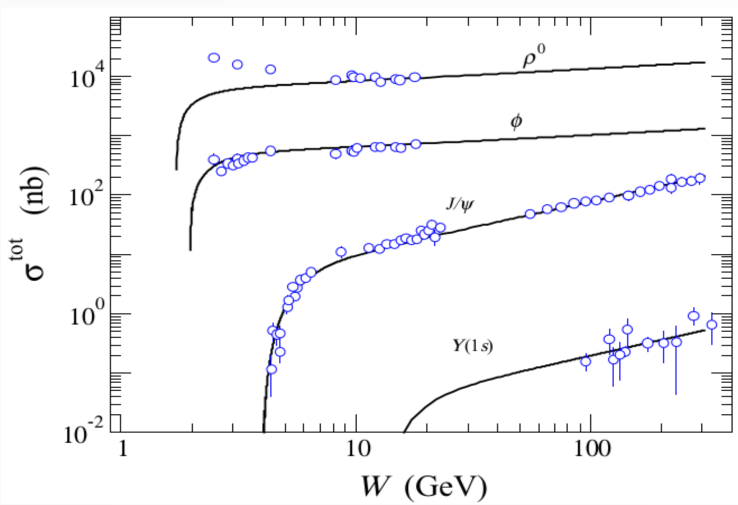
Born term

total cross section [$\gamma\, p \to \varphi\, p$]

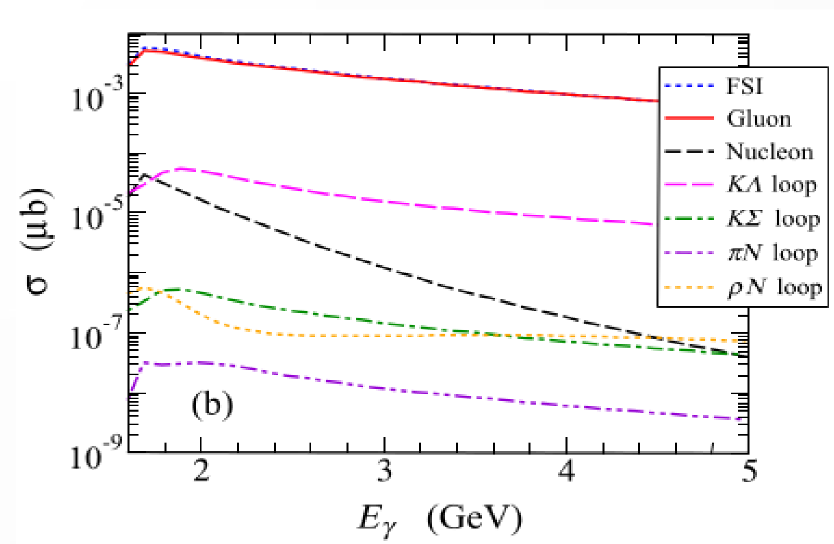
with FSI







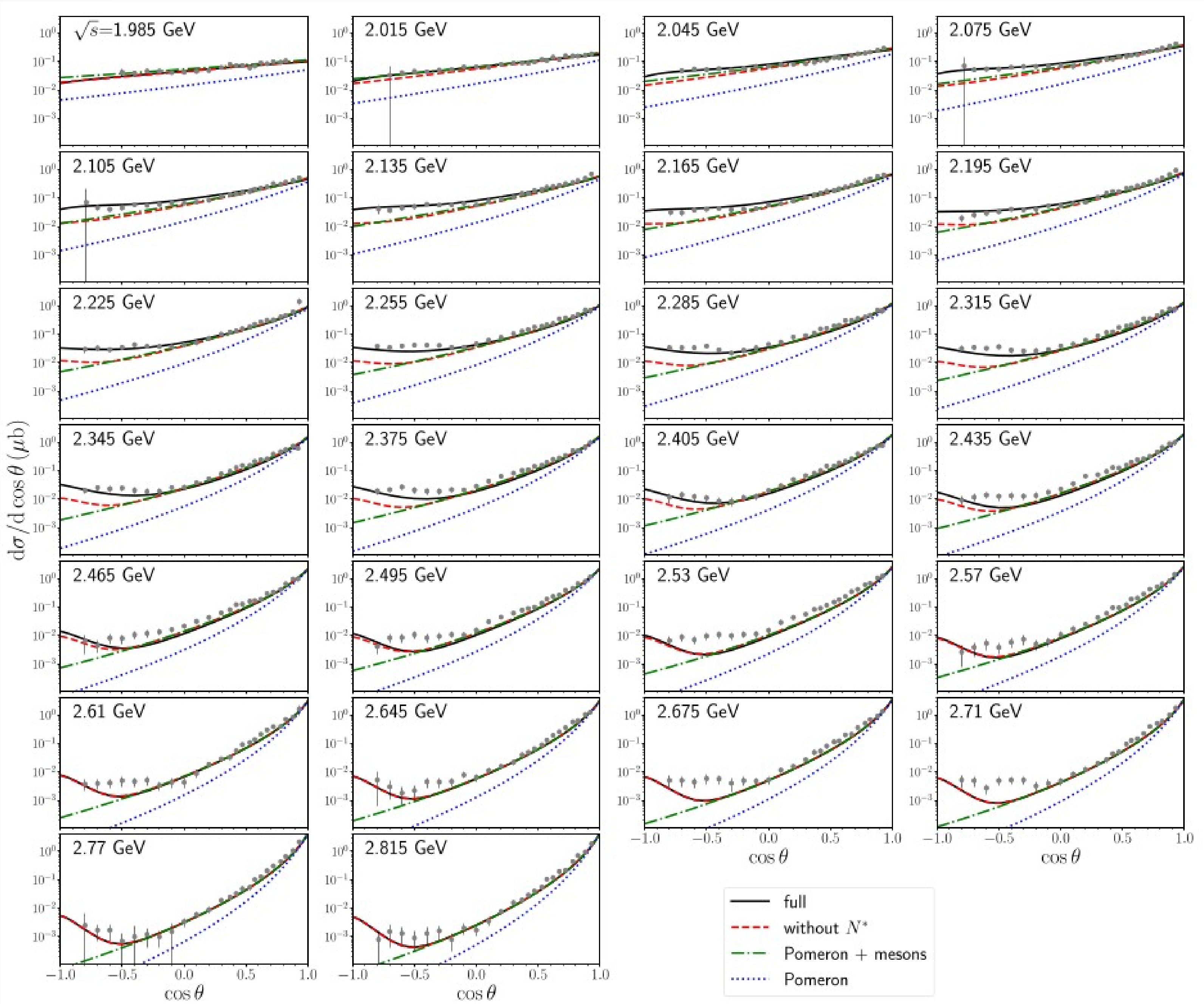
$\gamma\, p \to$
ρ^0
ω
φ
J/ψ
$\Upsilon(1s)$



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

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

Exclusive photoproduction of vector mesons [results]



differential cross sections
[$\gamma\, p \to \varphi\, p$]

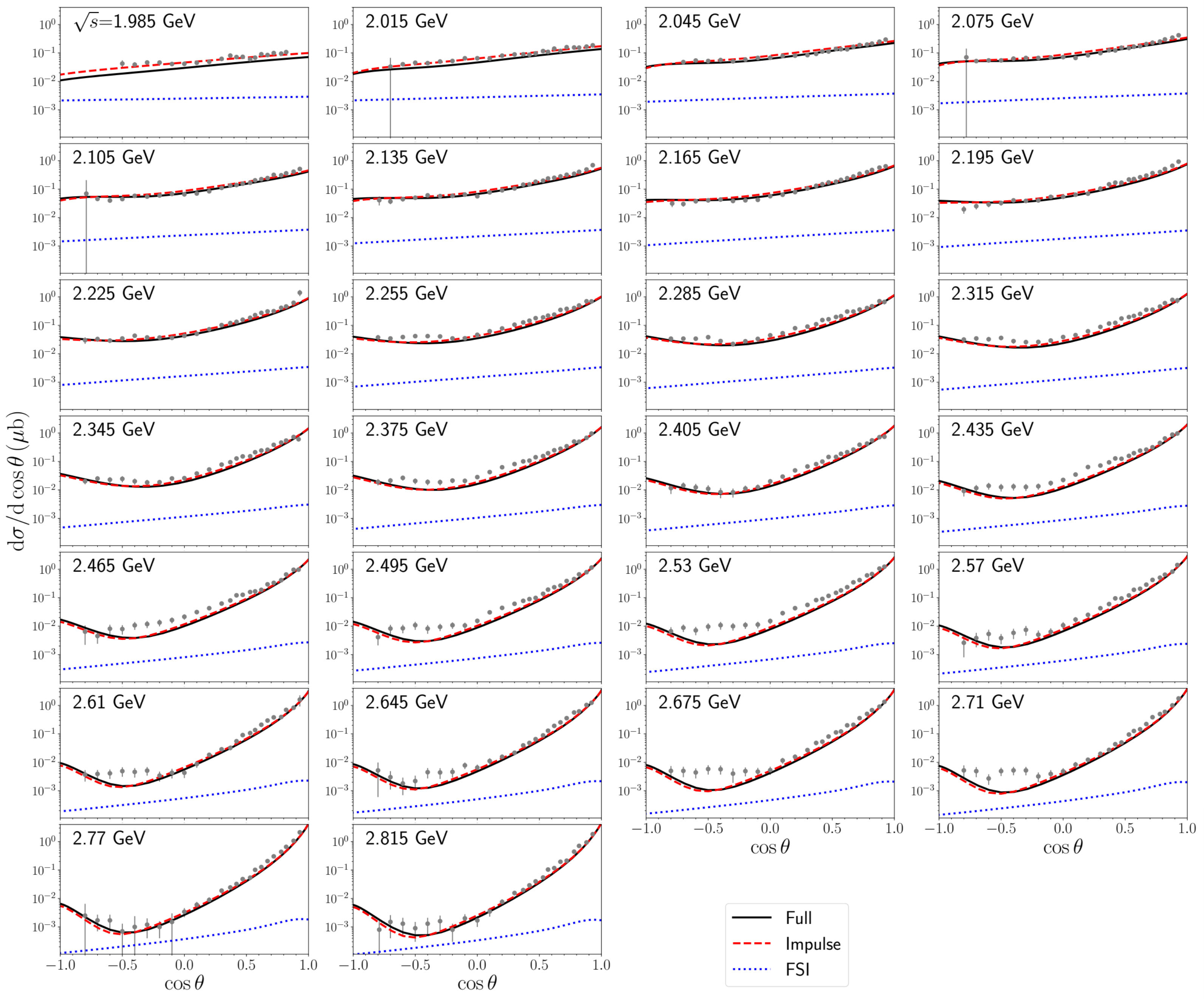
Born term

- □ Forward: Pomeron exchange
- □ Backward: mesons, nucleon, N^* exchanges

play crucial roles.

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

Exclusive photoproduction of vector mesons [results]



differential cross sections
$[\gamma\, p \to \varphi\, p]$

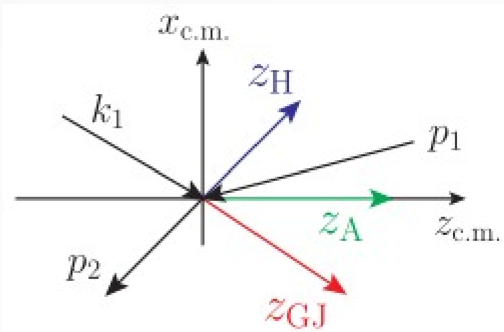
with FSI

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

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

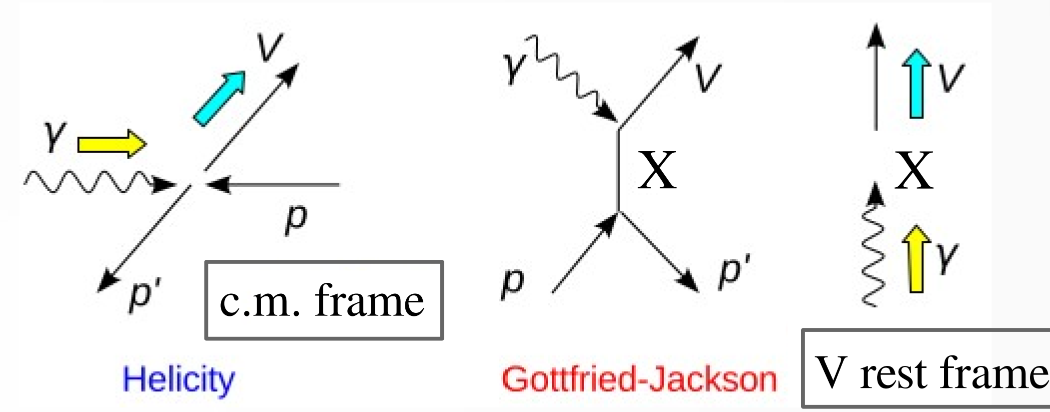
spin-density matrices

❑ Decay frame



V rest frame

Adair frame
Helicty frame
Gottfried-Jackson frame



Definition

$$\rho^0_{\lambda\lambda'} = \frac{1}{N} \sum_{\lambda_\gamma,\lambda_i,\lambda_f} \mathcal{M}_{\lambda_f\lambda;\lambda_i\lambda_\gamma} \mathcal{M}^*_{\lambda_f\lambda';\lambda_i\lambda_\gamma},$$

$$\rho^1_{\lambda\lambda'} = \frac{1}{N} \sum_{\lambda_\gamma,\lambda_i,\lambda_f} \mathcal{M}_{\lambda_f\lambda;\lambda_i-\lambda_\gamma} \mathcal{M}^*_{\lambda_f\lambda';\lambda_i\lambda_\gamma},$$

$$\rho^2_{\lambda\lambda'} = \frac{i}{N} \sum_{\lambda_\gamma,\lambda_i,\lambda_f} \lambda_\gamma \mathcal{M}_{\lambda_f\lambda;\lambda_i-\lambda_\gamma} \mathcal{M}^*_{\lambda_f\lambda';\lambda_i\lambda_\gamma},$$

$$\rho^3_{\lambda\lambda'} = \frac{1}{N} \sum_{\lambda_\gamma,\lambda_i,\lambda_f} \lambda_\gamma \mathcal{M}_{\lambda_f\lambda;\lambda_i\lambda_\gamma} \mathcal{M}^*_{\lambda_f\lambda';\lambda_i\lambda_\gamma},$$

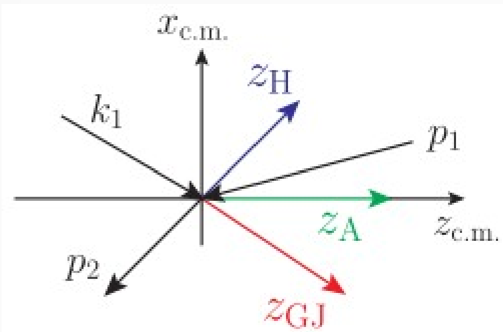
□ λ, λ' : Helicity states of the vector-meson

□ For a *t*-channel exchange of X,
the momentum of γ and V is collinear in the GJ frame.

Thus, the ρij^k elements measure the degree of helicity flip due to the *t*-channel exchange of X in the GJ frame.

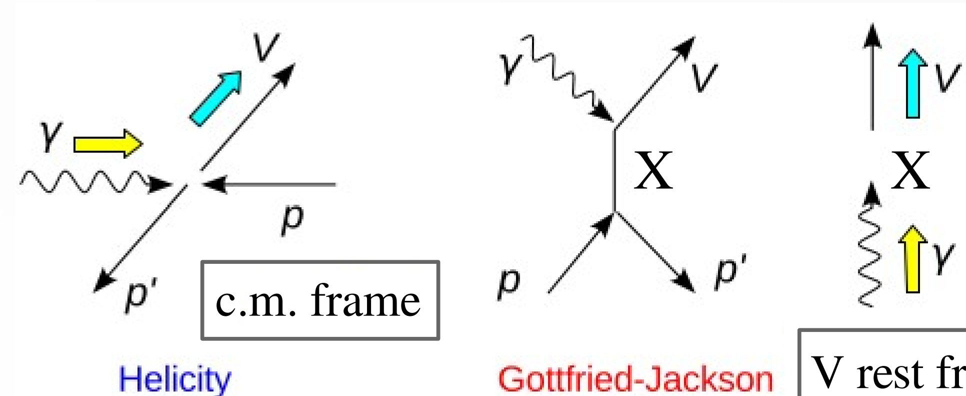
spin-density matrices

❑ Decay frame



V rest frame

Adair frame
Helicty frame
Gottfried-Jackson frame



Definition

$$\rho^0_{\lambda\lambda'} = \frac{1}{N}\sum_{\lambda_\gamma,\lambda_i,\lambda_f} \mathcal{M}_{\lambda_f\lambda;\lambda_i\lambda_\gamma}\mathcal{M}^*_{\lambda_f\lambda';\lambda_i\lambda_\gamma},$$

$$\rho^1_{\lambda\lambda'} = \frac{1}{N}\sum_{\lambda_\gamma,\lambda_i,\lambda_f} \mathcal{M}_{\lambda_f\lambda;\lambda_i-\lambda_\gamma}\mathcal{M}^*_{\lambda_f\lambda';\lambda_i\lambda_\gamma},$$

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$$\rho^3_{\lambda\lambda'} = \frac{1}{N}\sum_{\lambda_\gamma,\lambda_i,\lambda_f} \lambda_\gamma\mathcal{M}_{\lambda_f\lambda;\lambda_i\lambda_\gamma}\mathcal{M}^*_{\lambda_f\lambda';\lambda_i\lambda_\gamma},$$

$$\rho^0_{00} \propto \left|\mathcal{M}_{\lambda_\gamma=1,\lambda_\phi=0}\right|^2 + \left|\mathcal{M}_{\lambda_\gamma=-1,\lambda_\phi=0}\right|^2$$

- Single helicity-flip transition between γ & V

$$-\mathrm{Im}[\rho^2_{1-1}] \approx \rho^1_{1-1} = \frac{1}{2}\frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}$$

- Relative contribution between Natural & Unnatural parity exchanges

□ Convert into other frames by applying Wigner rotations:

$$\alpha_{\rm A\to H} = \theta_{\rm c.m.},$$

$$\alpha_{\rm H\to GJ} = -\cos^{-1}\left(\frac{v - \cos\theta_{\rm c.m.}}{v\cos\theta_{\rm c.m.} - 1}\right)$$

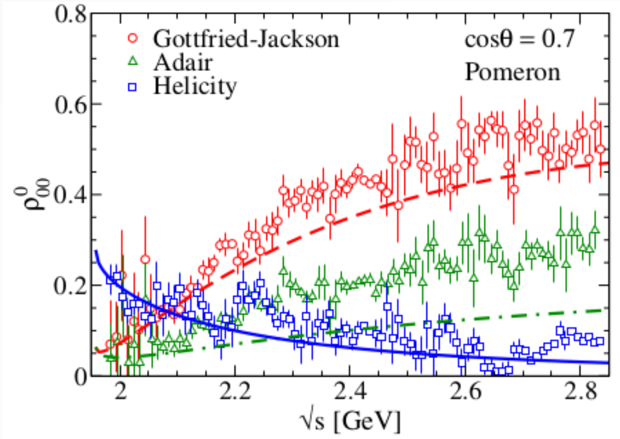
$$\alpha_{\rm A\to GJ} = \alpha_{\rm A\to H} + \alpha_{\rm H\to GJ}$$

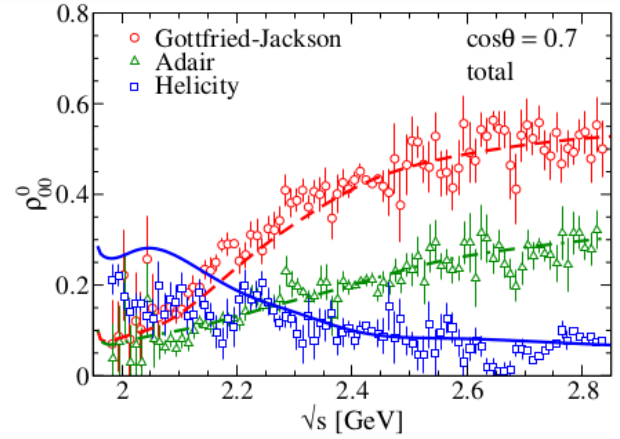
v : The velocity of the K meson in the φ rest frame (φ → K$\overline{\rm K}$ decay)

Exclusive photoproduction of vector mesons [results]

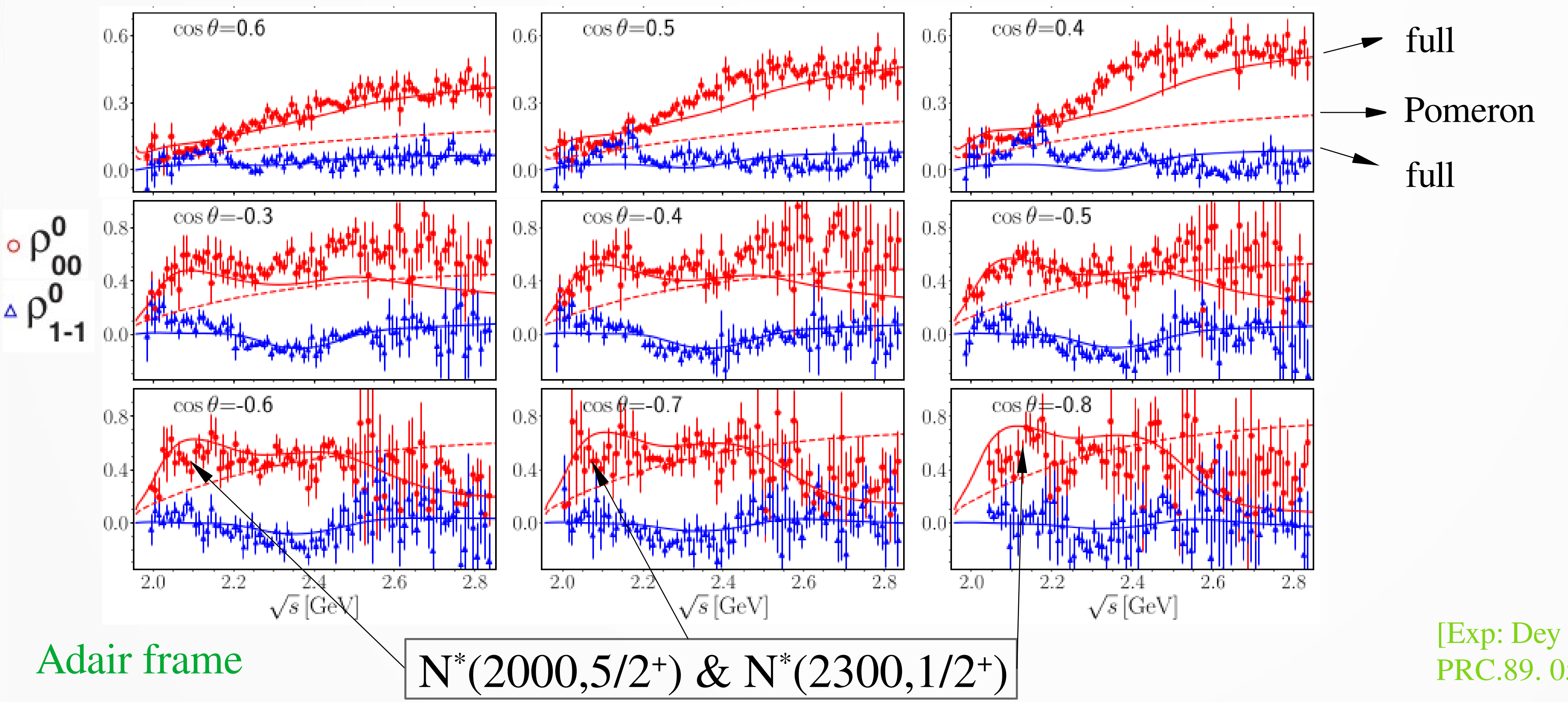
spin-density matrices

$\gamma\, p \to \varphi\, p$





- TCHC & SCHC are broken.

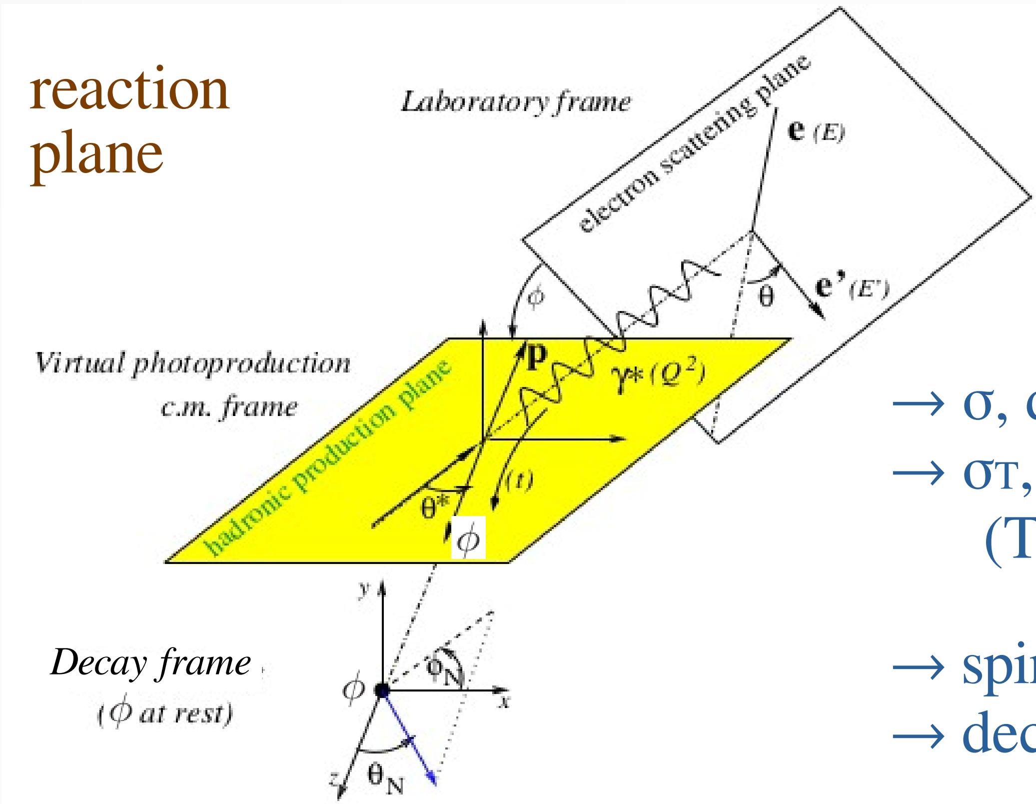


Adair frame

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

Exclusive electroproduction of vector mesons

$\gamma^* p \to V p$



□ Photon(γ) polarization vector
Transverse comp. ($\lambda_\gamma=\pm1$) [photo-, electro-]
Longitudinal comp. ($\lambda_\gamma=0$) [electro-]

→ σ, $d\sigma/d\Omega$, $d\sigma/dt$ [photo-, electro-]
→ σ_T, σ_L, σ_{TT}, σ_{LT}, $R=\sigma_L/\sigma_T$ ... [electro-]
(T-L separated cross sections)

→ spin-density matrices (ρ_{ij}) [photo-, electro-]
→ decay angular distributions (W) [photo-, electro-]

total cross section

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

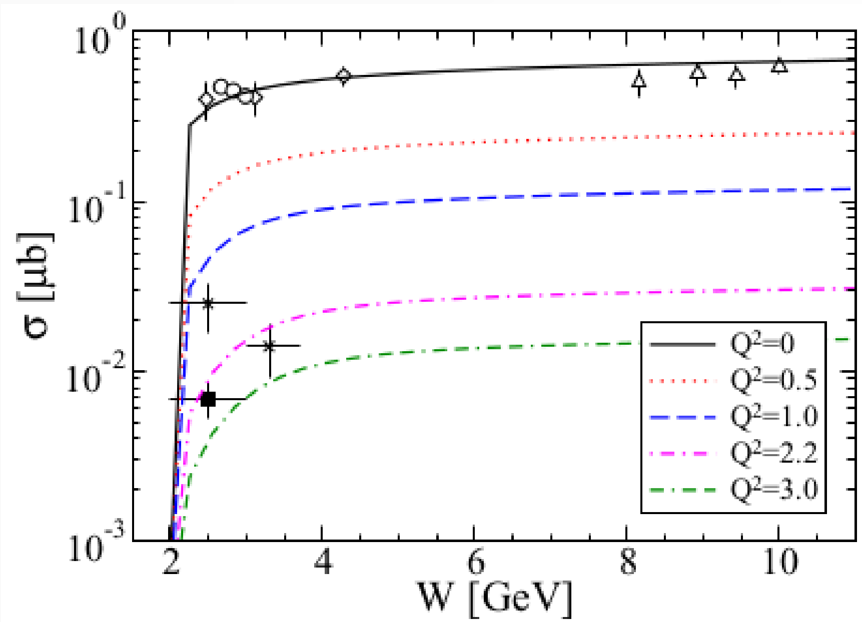
ε: Virtual-photon polarization parameter

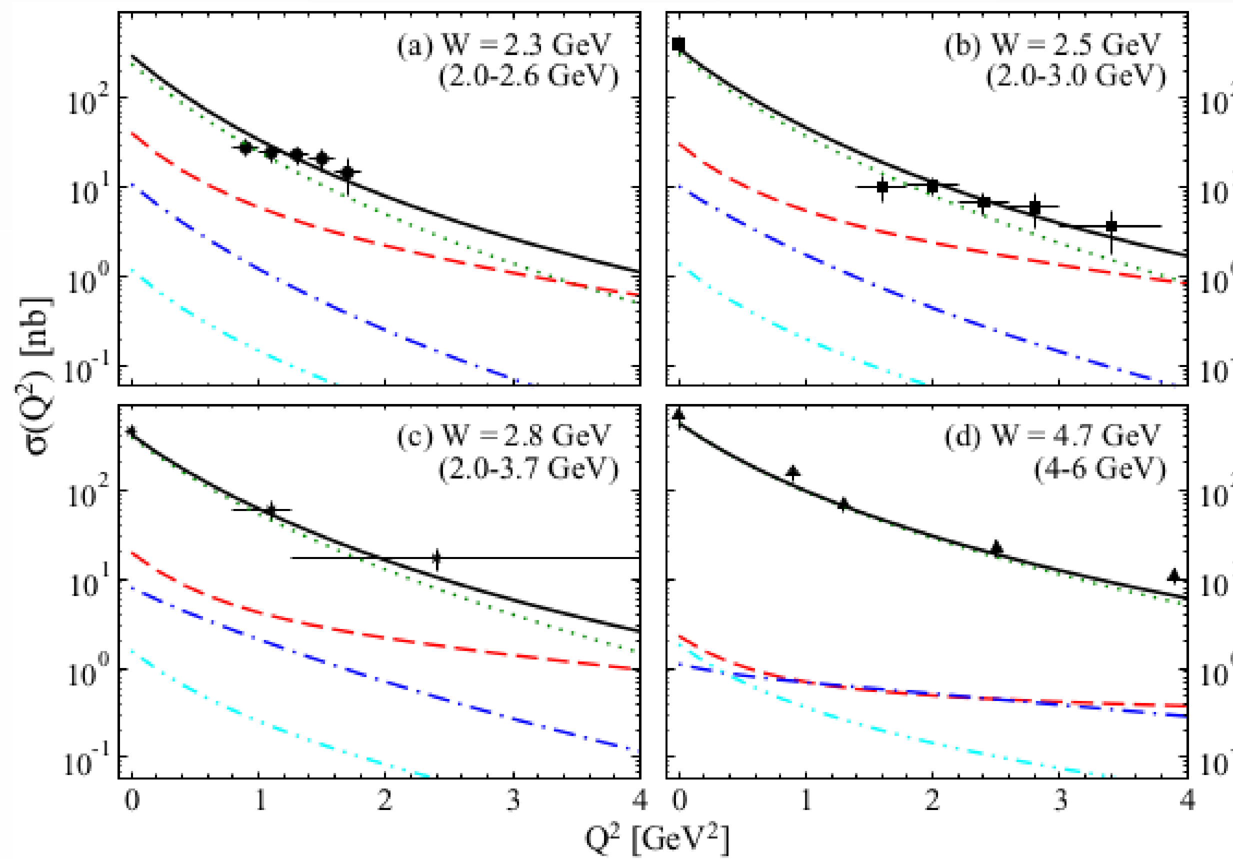
Exclusive electroproduction of vector mesons [results]

unpolarized cross sections

[Exp: Dixon (Cornell), PRL.39.516 (1977)] et al.

$\gamma^* p \to \varphi\, p$





Pomeron | PS (π,η) | total

S (a_0,f_0) | AV (f_1)

$$\sigma = \sigma_T + \varepsilon\sigma_L$$

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

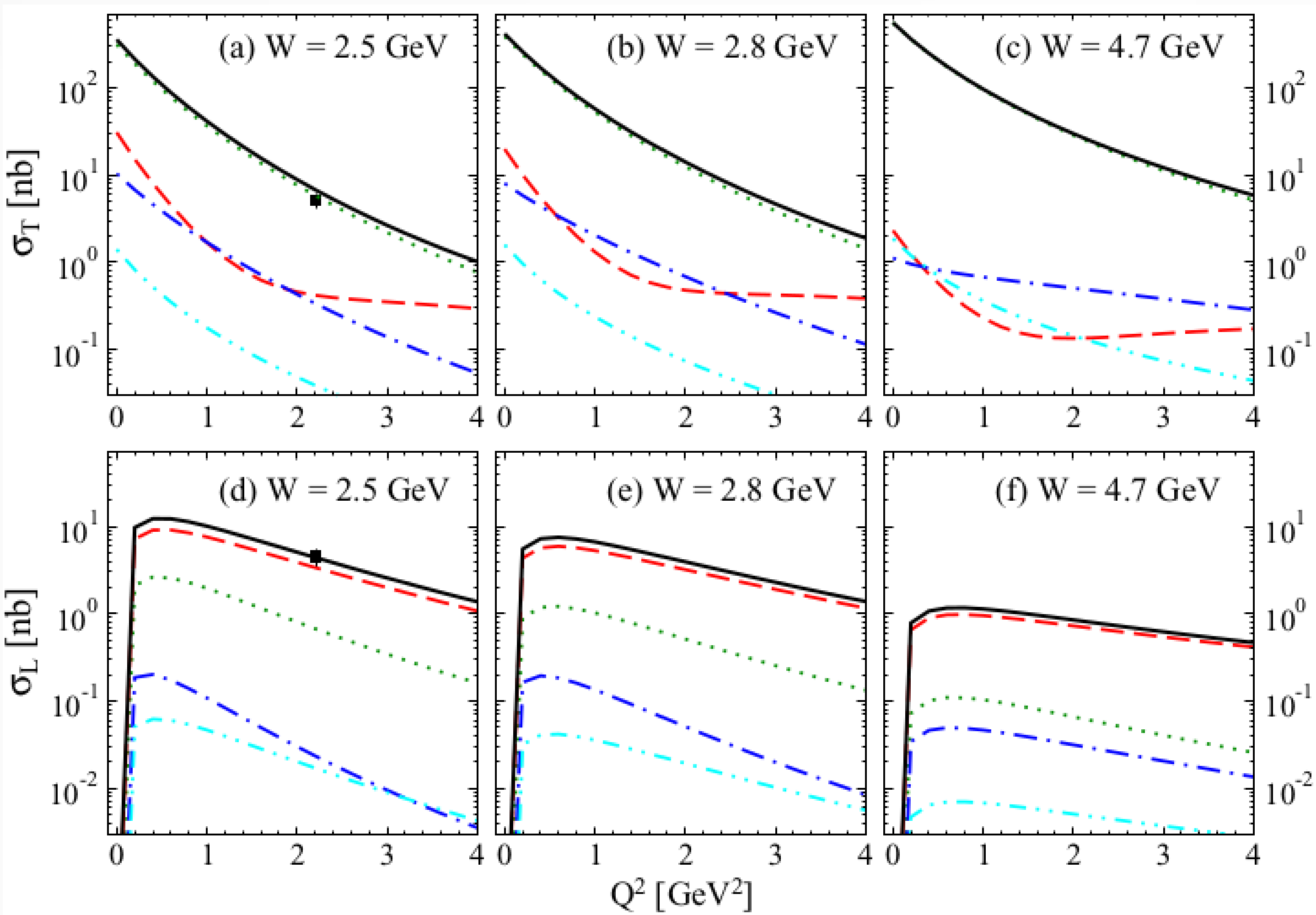
ε: Virtual-photon polarization parameter

- □ The Q^2 dependence of the cross sections is well described.
- □ The agreement with the exp. data is good at the real photon limit $Q^2=0$.

Exclusive electroproduction of vector mesons [results]

T-L separated cross sections

$\gamma^* p \to \varphi p$



[Exp: Santoro (CLAS), PRC.78.025210 (2008)]

$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\rm T}}{dt} = \frac{1}{2}\sum_{\lambda_\gamma=\pm1}\overline{|\mathcal{M}^{(\lambda_\gamma)}|^2},$$

$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\rm L}}{dt} = \overline{|\mathcal{M}^{(\lambda_\gamma=0)}|^2},$$

$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\rm TT}}{dt} = -\frac{1}{2}\sum_{\lambda_\gamma=\pm1}\overline{\mathcal{M}^{(\lambda_\gamma)}\mathcal{M}^{(-\lambda_\gamma)*}},$$

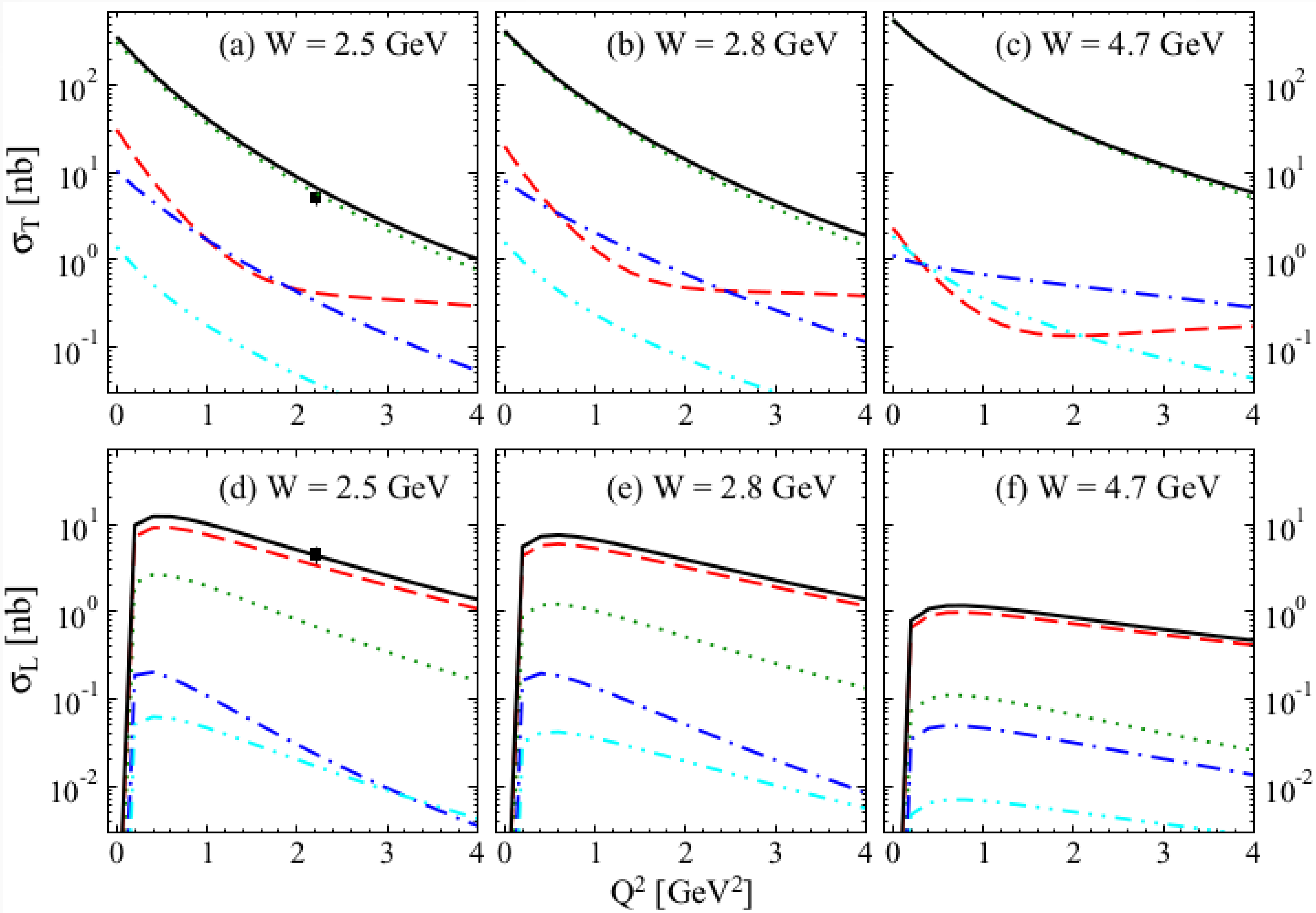
$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\rm LT}}{dt} = -\frac{1}{2\sqrt{2}}\sum_{\lambda_\gamma=\pm1}\lambda_\gamma\left(\overline{\mathcal{M}^{(0)}\mathcal{M}^{(\lambda_\gamma)*}} + \overline{\mathcal{M}^{(\lambda_\gamma)}\mathcal{M}^{(0)*}}\right)$$

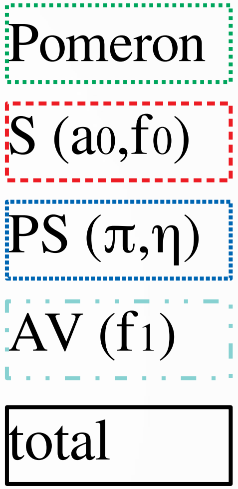
- Pomeron and S-meson exchanges dominate transverse (T) and longitudinal (L) cross sections, respectively.

Exclusive electroproduction of vector mesons [results]

T-L separated cross sections

$\gamma^* p \to \varphi p$





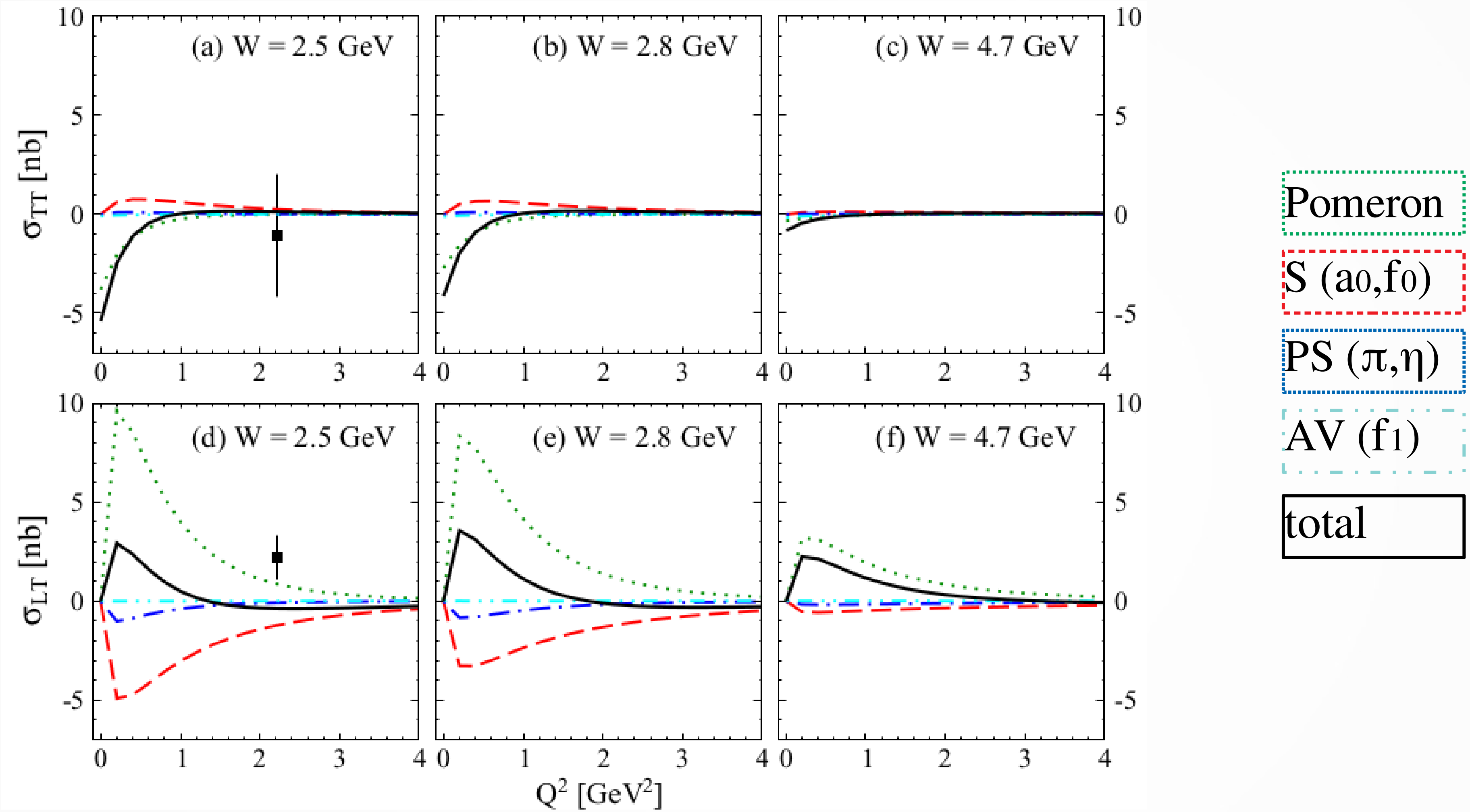
[Exp: Santoro (CLAS), PRC.78.025210 (2008)]

□ Pomeron and S-meson exchanges dominate transverse (T) and longitudinal (L) cross sections, respectively.

Exclusive electroproduction of vector mesons [results]

T-L separated cross sections

$\gamma^* p \rightarrow \varphi p$



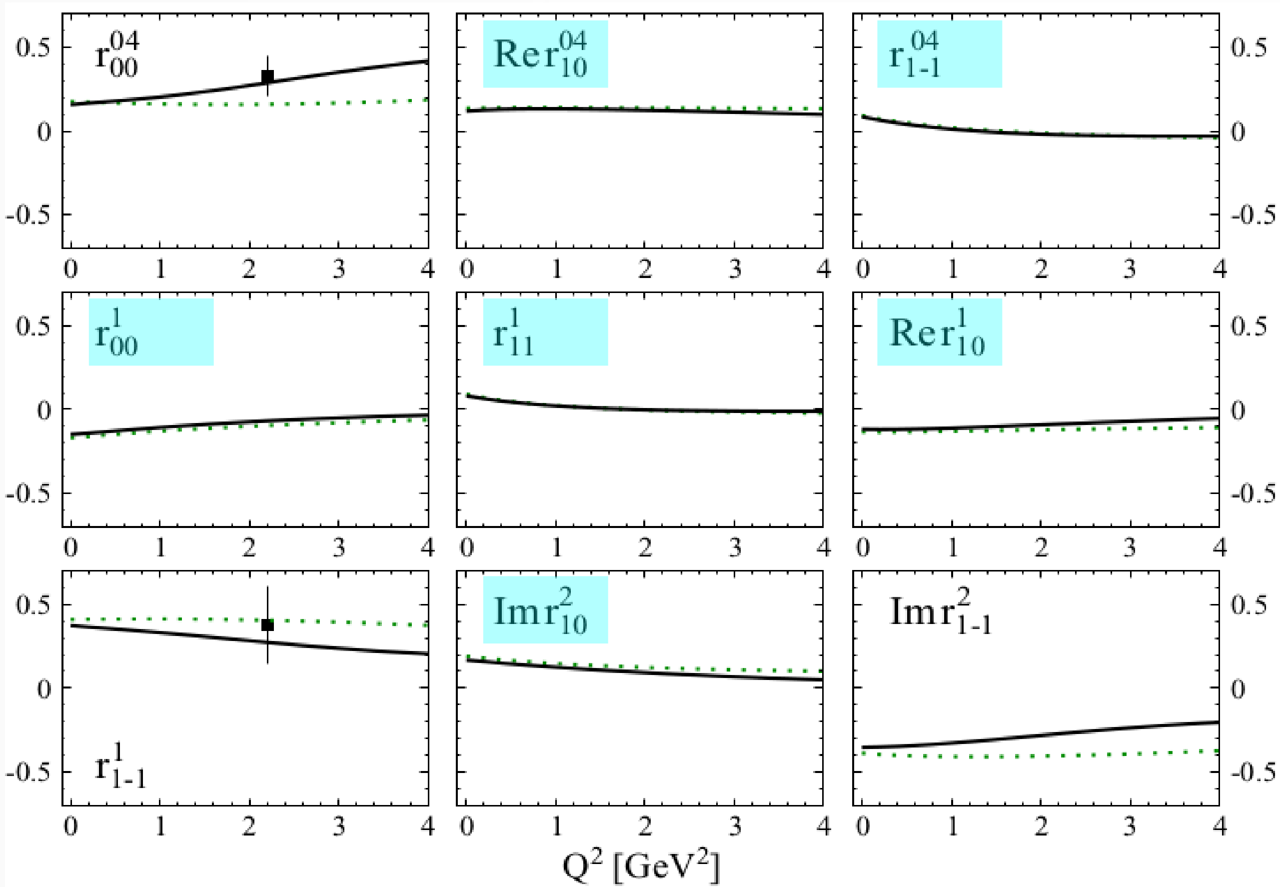
[Exp: Santoro (CLAS), PRC.78.025210 (2008)]

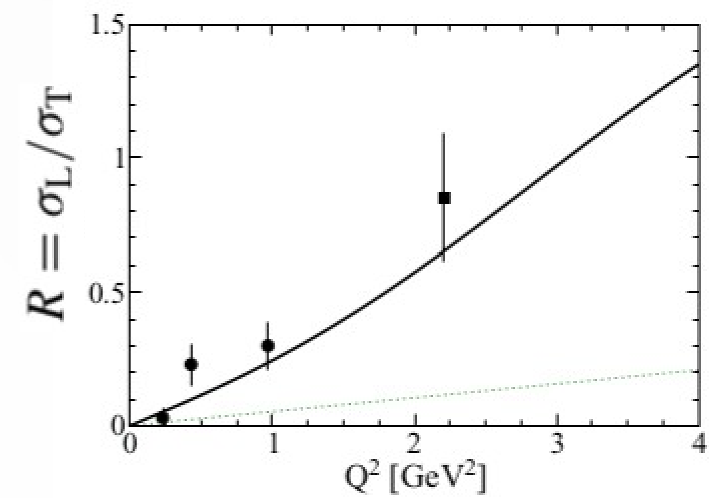
- □ The signs of Pomeron and **meson** contributions are opposite to each other.
- □ σ_{TT} and σ_{LT} become zero as W and Q^2 increases, indicating SCHC.

Exclusive electroproduction of vector mesons [results]

spin-density matrix elements (r_k^{ij})

$\gamma^* p \to \varphi p$





$$r_{ij}^{04} = \frac{\rho_{ij}^{0} + \varepsilon R \rho_{ij}^{4}}{1+\varepsilon R},$$

$$r_{ij}^{\alpha} = \frac{\rho_{ij}^{\alpha}}{1+\varepsilon R}, \quad \text{for } \alpha = (0-3),$$

$$r_{ij}^{\alpha} = \sqrt{R}\frac{\rho_{ij}^{\alpha}}{1+\varepsilon R}, \quad \text{for } \alpha = (5-8)$$

□ By definition, if SCHC holds, $r_{ij}^{k} = 0$.

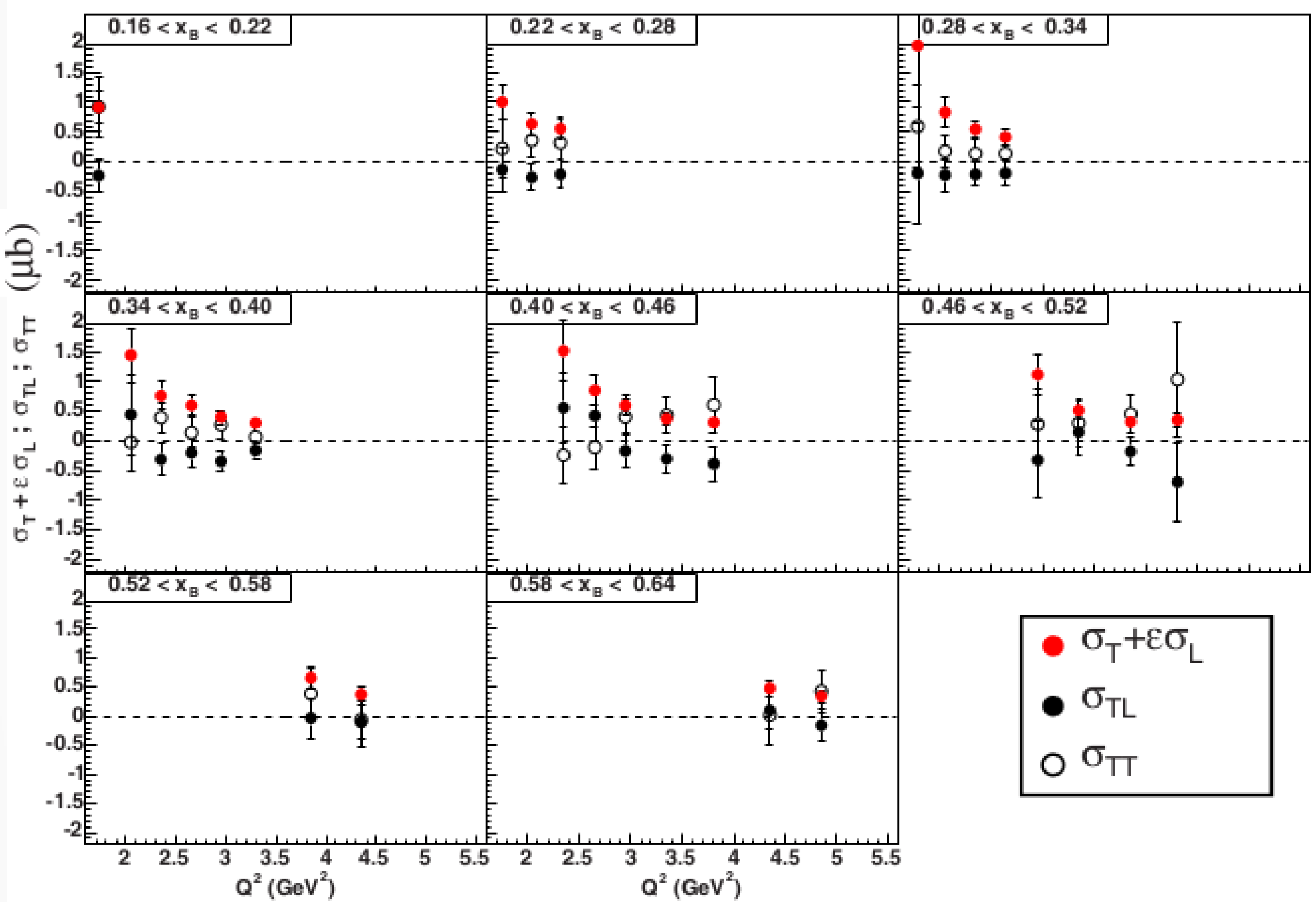
□ The relative contributions of different meson exchanges are verified.

□ Our hadronic approach is very successful for describing the data at Q^2=(0-4) GeV^2, W=(2-5) GeV, t=(0-2) GeV^2.

Exclusive electroproduction of vector mesons

T-L separated cross sections

$\gamma^* \, p \to \rho(770) \, p$



[Exp: Morrow (CLAS), EPJA.39.5 (2009)]

$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\mathrm{T}}}{dt} = \frac{1}{2}\sum_{\lambda_\gamma=\pm1}\overline{|\mathcal{M}^{(\lambda_\gamma)}|^2},$$

$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\mathrm{L}}}{dt} = \overline{|\mathcal{M}^{(\lambda_\gamma=0)}|^2},$$

$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\mathrm{TT}}}{dt} = -\frac{1}{2}\sum_{\lambda_\gamma=\pm1}\overline{\mathcal{M}^{(\lambda_\gamma)}\mathcal{M}^{(-\lambda_\gamma)*}},$$

$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\mathrm{LT}}}{dt} = -\frac{1}{2\sqrt{2}}\sum_{\lambda_\gamma=\pm1}\lambda_\gamma\left(\overline{\mathcal{M}^{(0)}\mathcal{M}^{(\lambda_\gamma)*}} + \overline{\mathcal{M}^{(\lambda_\gamma)}\mathcal{M}^{(0)*}}\right)$$

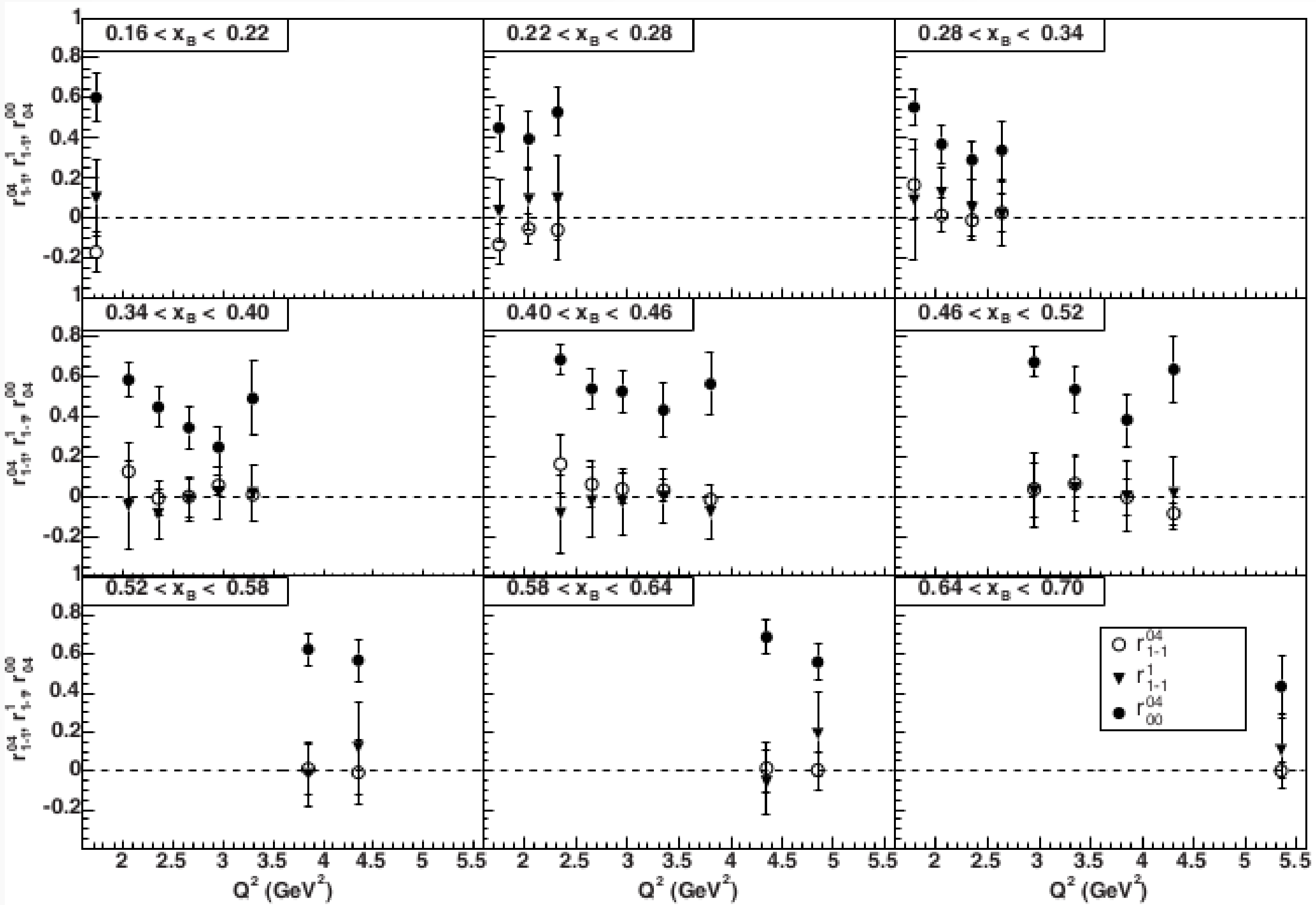
□ If SCHC holds, σ_{TT} and σ_{LT} become zero.

- Pomeron > meson-exchange ($\gamma^* \, p \to \varphi \, p$)
  Pomeron < meson-exchange ($\gamma^* \, p \to \rho \, p, \omega \, p$)

Exclusive electroproduction of vector mesons

spin-density matrix elements (r_k^{ij})

$\gamma^* p \to \rho(770)\, p$



[Exp: Morrow (CLAS), EPJA.39.5 (2009)]

○ r^{04}_{1-1}
▼ r^{1}_{1-1}
● r^{04}_{00}

r^{04}_{1-1} = 0 if SCHC holds

$$r_{ij}^{04} = \frac{\rho_{ij}^0 + \varepsilon R \rho_{ij}^4}{1+\varepsilon R},$$

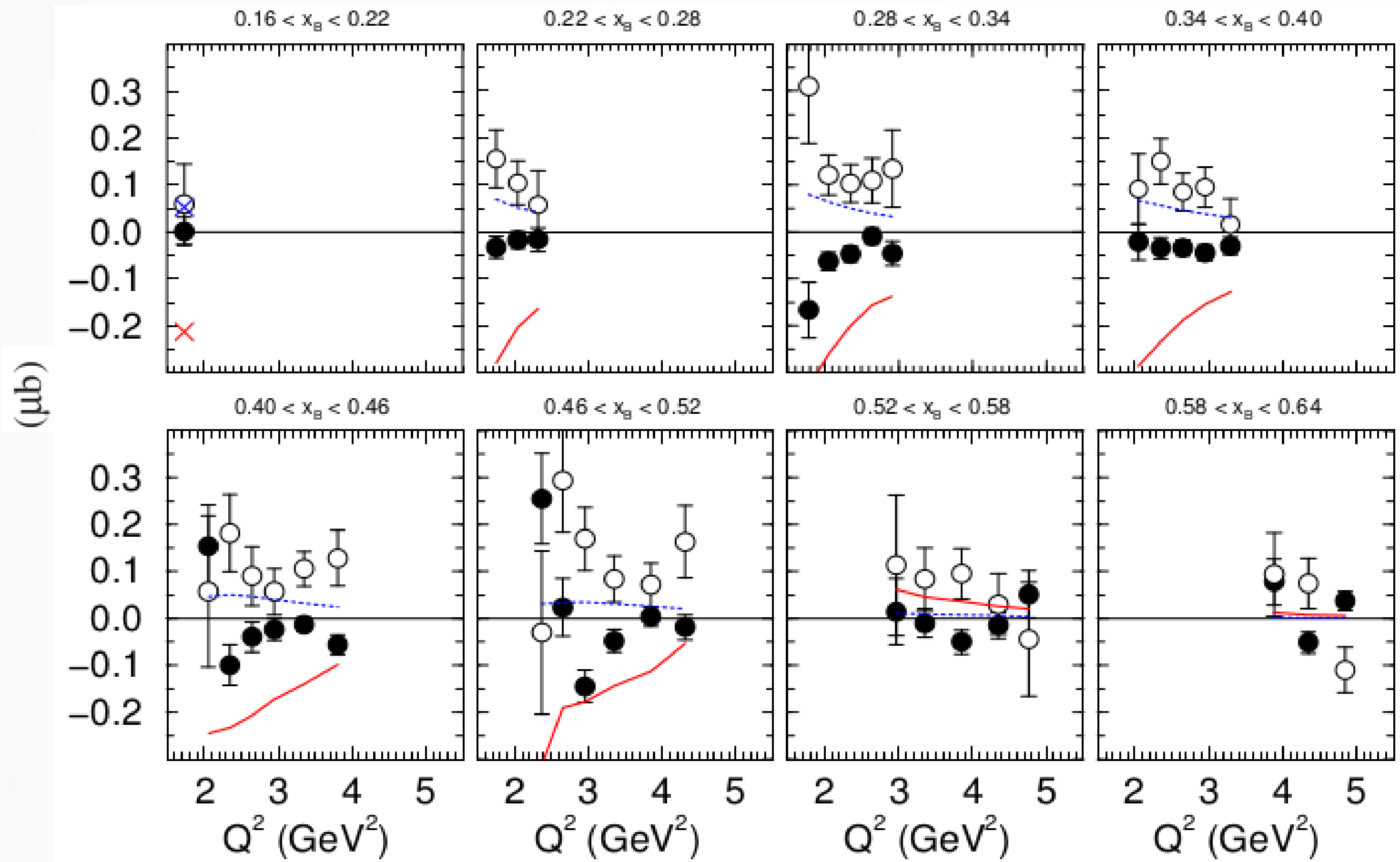
$$r_{ij}^{\alpha} = \frac{\rho_{ij}^{\alpha}}{1+\varepsilon R}, \quad \text{for } \alpha = (0-3),$$

$$r_{ij}^{\alpha} = \sqrt{R}\,\frac{\rho_{ij}^{\alpha}}{1+\varepsilon R}, \quad \text{for } \alpha = (5-8)$$

- Parity asymmery $P \equiv \dfrac{\sigma_T^N - \sigma_T^U}{\sigma_T^N + \sigma_T^U} = (1+\varepsilon R)\big(2r^1_{1-1} - r^1_{00}\big)$

T-L separated cross sections

$\gamma^* \, p \to \omega(782) \, p$



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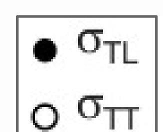
$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\rm TT}}{dt} = -\frac{1}{2}\sum_{\lambda_\gamma=\pm1}\overline{\mathcal{M}^{(\lambda_\gamma)}\mathcal{M}^{(-\lambda_\gamma)*}},$$

$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\rm LT}}{dt} = -\frac{1}{2\sqrt{2}}\sum_{\lambda_\gamma=\pm1}\lambda_\gamma\left(\overline{\mathcal{M}^{(0)}\mathcal{M}^{(\lambda_\gamma)*}} + \overline{\mathcal{M}^{(\lambda_\gamma)}\mathcal{M}^{(0)*}}\right)$$

Regge-based model
[Laget, PRD70.054023 (2004)]

[Exp: Morrow (CLAS), EPJA.39.5 (2009)]



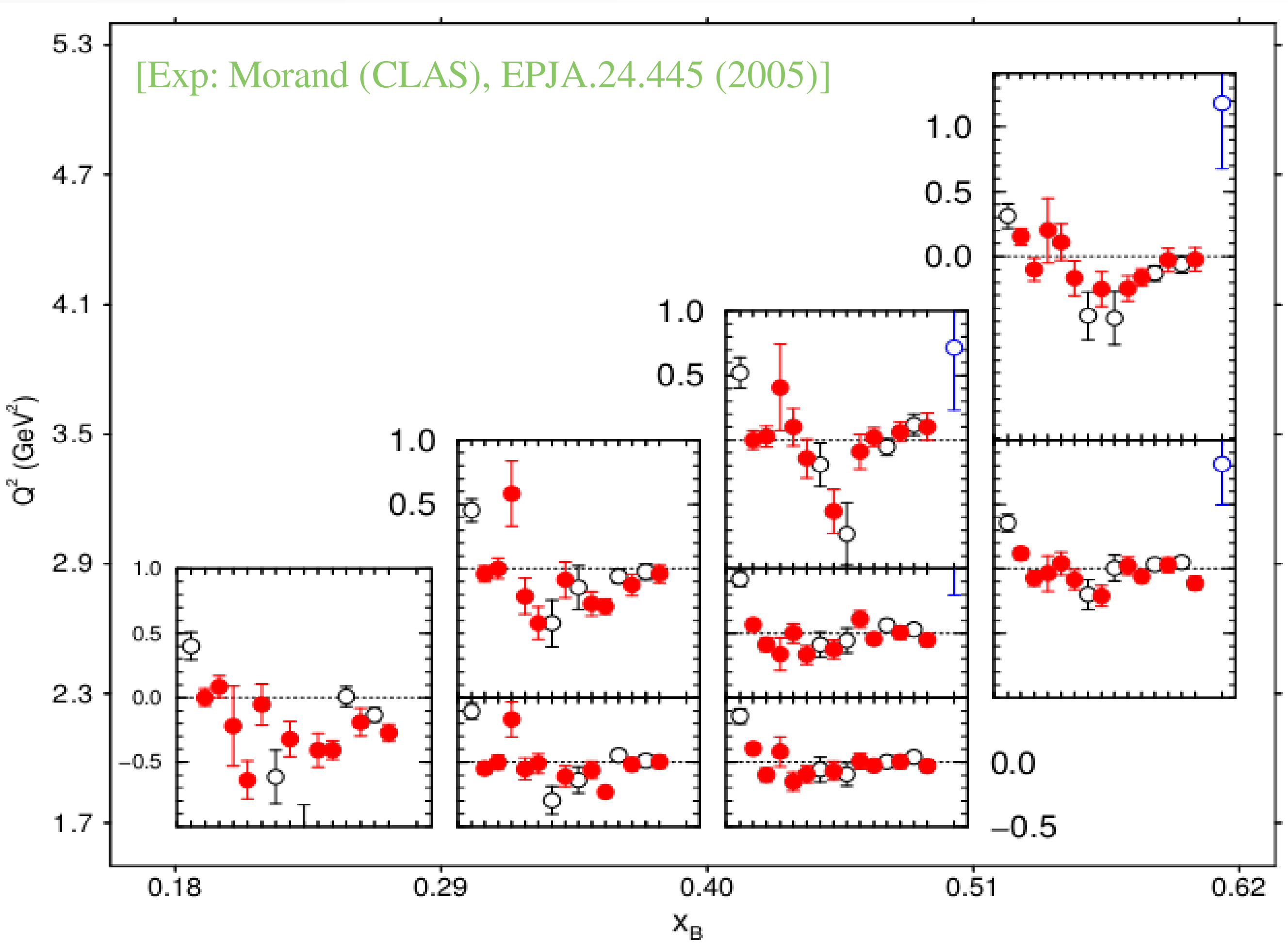
□ If SCHC holds, σ_{TT} and σ_{LT} become zero.

- Pomeron > meson-exchange ($\gamma^* \, p \to \varphi \, p$)
  Pomeron < meson-exchange ($\gamma^* \, p \to \rho \, p$, $\omega \, p$)

Exclusive electroproduction of vector mesons

spin-density matrix elements (r_k^{ij})

$\gamma^* p \to \omega(782)\, p$



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$$r_{ij}^{\alpha} = \frac{\rho_{ij}^{\alpha}}{1 + \varepsilon R}, \quad \text{for } \alpha = (0-3),$$

$$r_{ij}^{\alpha} = \sqrt{R}\frac{\rho_{ij}^{\alpha}}{1 + \varepsilon R}, \quad \text{for } \alpha = (5-8)$$

- r_{00}^{04}, $\mathrm{Re}\,r_{10}^{04}$, r_{1-1}^{04}, r_{00}^{1}, r_{11}^{1}, $\mathrm{Re}\,r_{10}^{1}$, r_{1-1}^{1}, $\mathrm{Im}\,r_{10}^{2}$, $\mathrm{Im}\,r_{1-1}^{2}$, r_{00}^{5}, r_{11}^{5}, $\mathrm{Re}\,r_{10}^{5}$, r_{1-1}^{5}, $\mathrm{Im}\,r_{10}^{6}$, $\mathrm{Im}\,r_{1-1}^{6}$
- SCHC holds, if $r_{ij}^{k} = 0$. It seems that SCHC is broken.

Coherent φ photoproduction off ^{4}He

❑ We employ a distorted-wave impulse approximation.

□ The contribution from the impulse term for spin J=0 nuclei:

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

γ ^{4}He → φ ^{4}He

γ p → φ p

$$\boxed{F_c(q^2) = F_N(q^2)F_T(q^2 = t)}$$

F_c (F_N) :
nuclear (nucleon) charge FF

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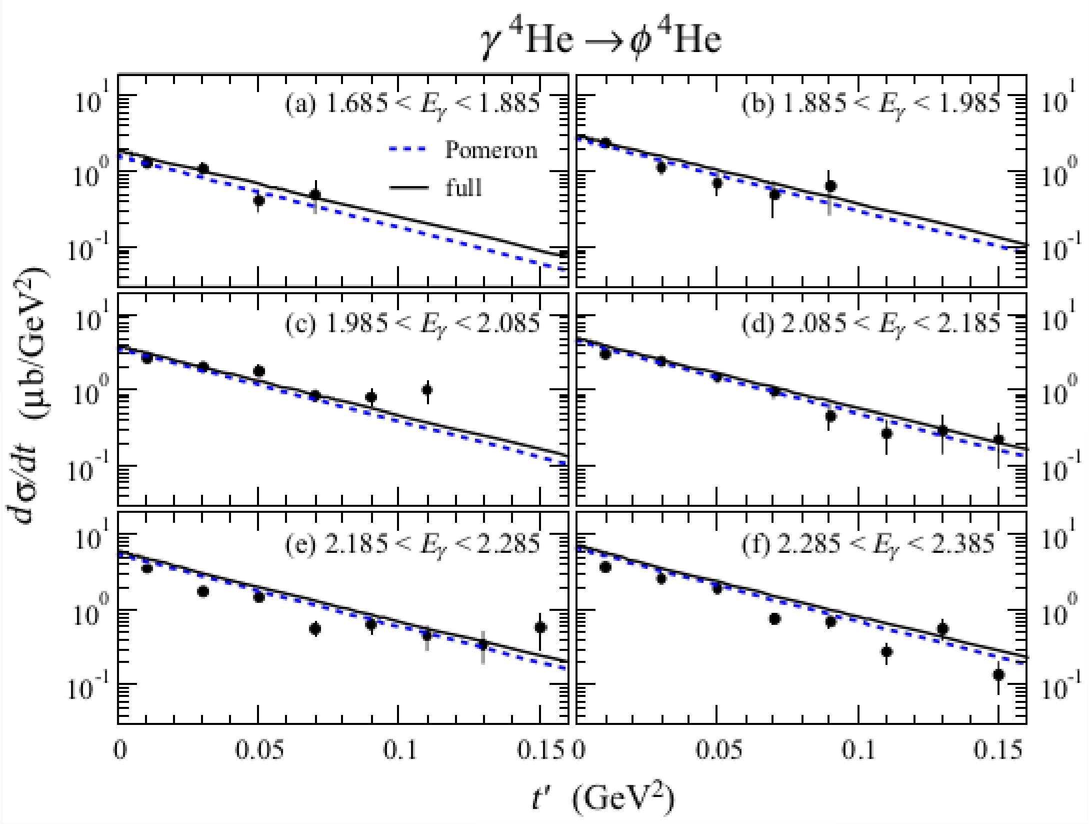
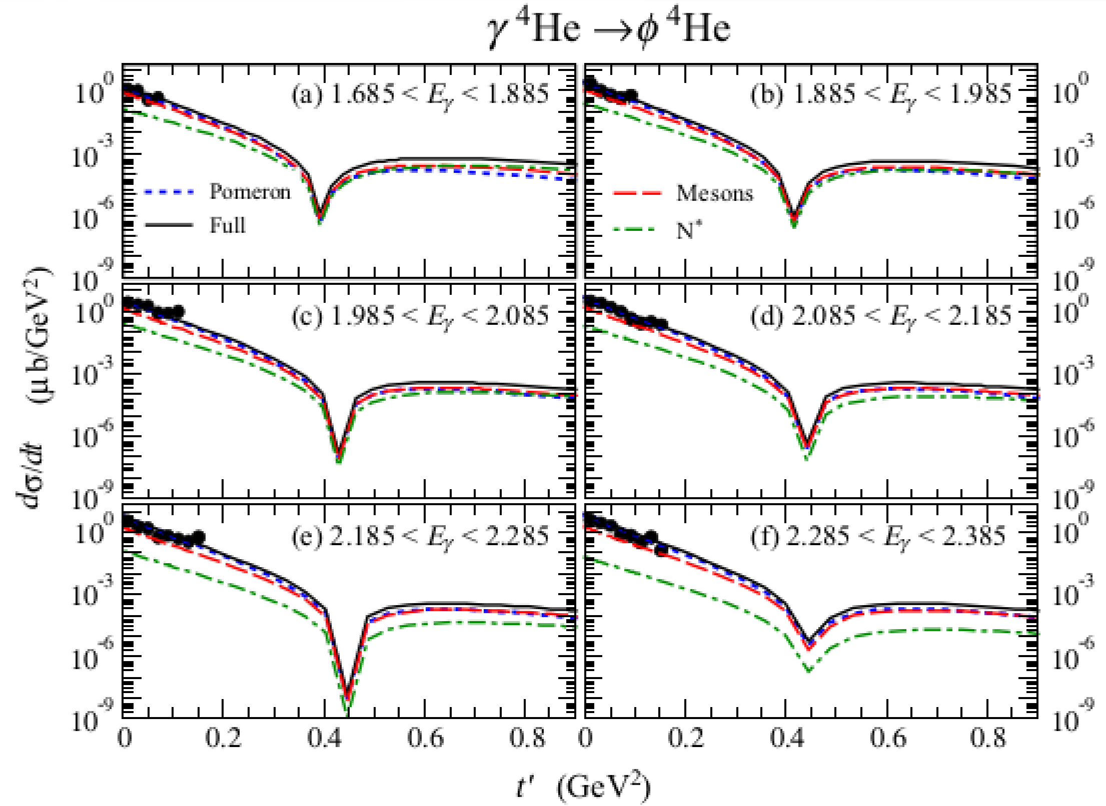
$\gamma\, ^4$He → φ ^{4}He

γ p → φ p

$$\boxed{F_c(q^2) = F_N(q^2)F_T(q^2=t)}$$

Fc (FN) :
nuclear (nucleon) charge FF





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

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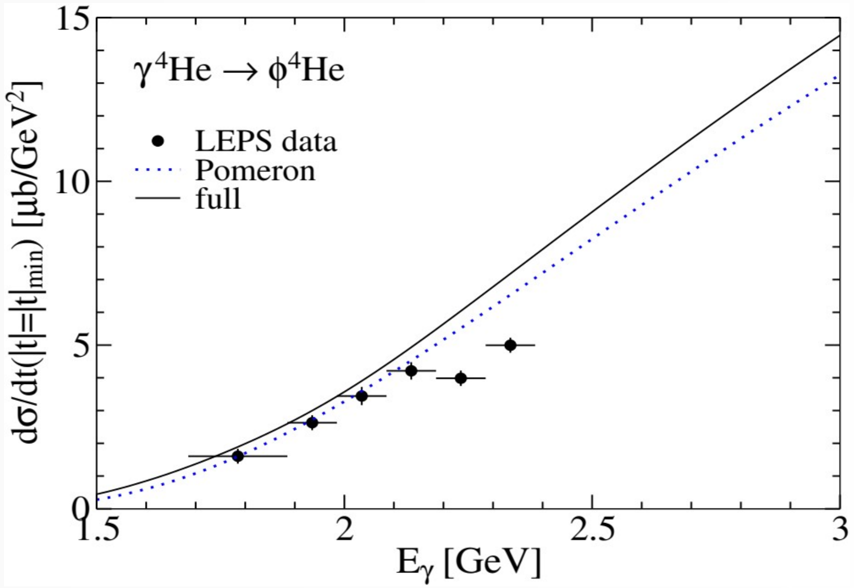
$\gamma\ {}^4\mathrm{He} \rightarrow \varphi\ {}^4\mathrm{He}$



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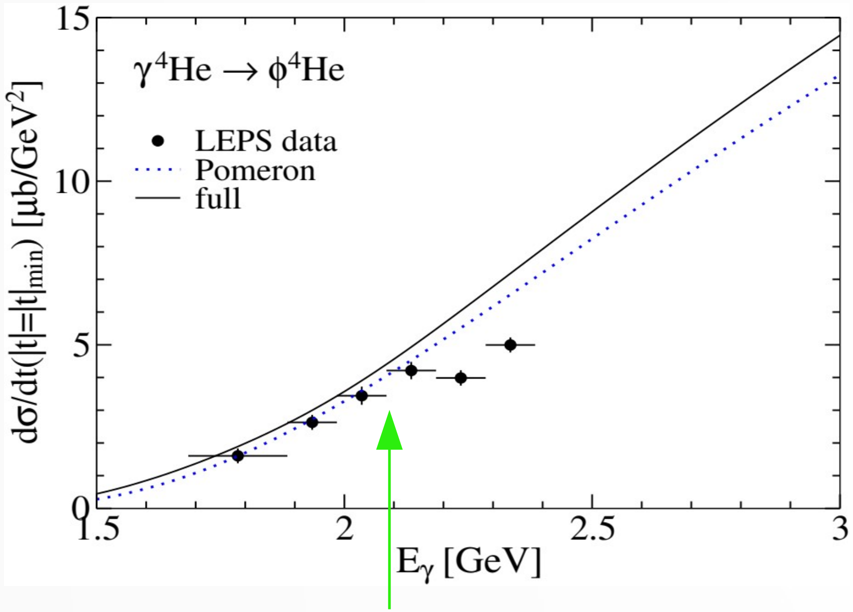
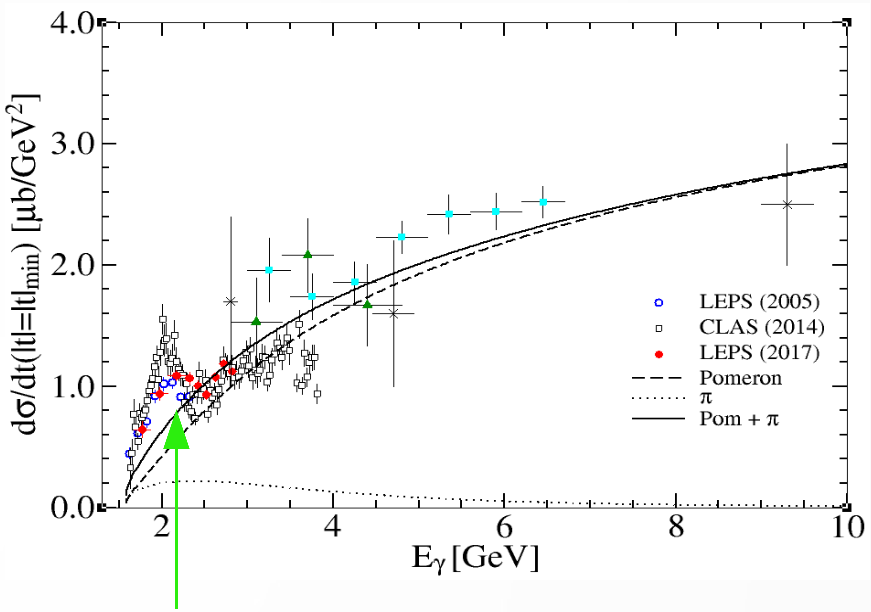


[Exp: Hiraiwa (LEPS), PRC.035208.5 (2017)]

$\gamma\ p \rightarrow \varphi\ p$



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

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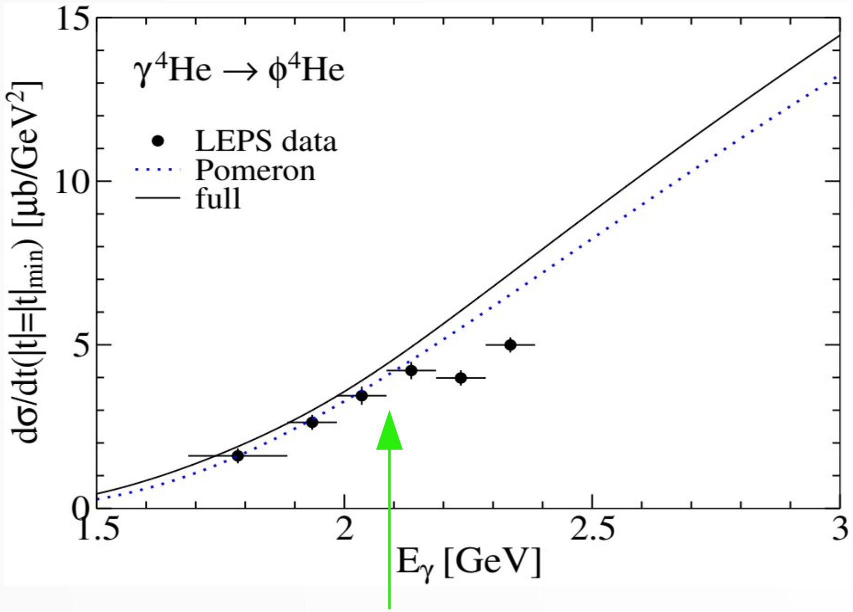

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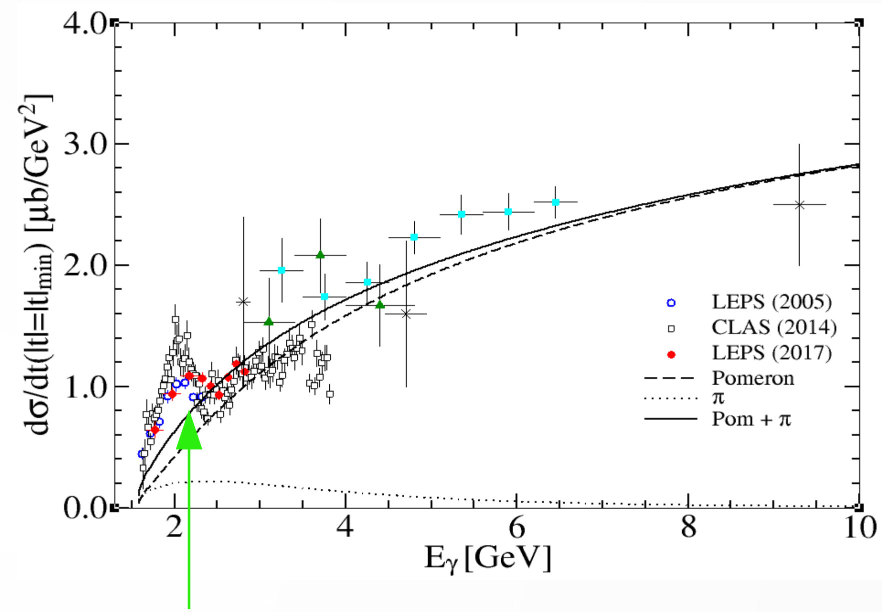

- is not due to the N^* contribution.
- may arise from another mechanism.

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

Summary & Future work

◇ For $\gamma\, p \rightarrow \varphi\, p$ & $\gamma^*\, p \rightarrow \varphi\, p$, we studied the 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.
> Regge model

◇ Extension to $\gamma^{(*)}\, A \rightarrow V[\varphi, J/\psi, \Upsilon(1S)]\, A$, [A = ^{2}H, ^{4}He, ^{12}C,…]
$\gamma\, {}^4\mathrm{He} \rightarrow \varphi\, {}^4\mathrm{He}$
> A distorted-wave impulse approximation within the multiple scattering formulation

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◇ For $\gamma\, p \to \varphi\, p$ & $\gamma^*\, p \to \varphi\, p$, we studied the relative contributions between the Pomeson and various meson exchanges.
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$\gamma\, {}^4He \to \varphi\, {}^4He$
> A distorted-wave impulse approximation within the multiple scattering formulation

◇ Approved 12 GeV era experiments to date at Jafferson Labarotory:
[E12-09-003] Nucleon Resonances Studies with CLAS
[E12-11-002] Proton Recoil Polarization in the ${}^4He(e,e'p){}^3H$, ${}^2He(e,e'p)n$, ${}^1He(e,e'p)$
[E12-11-005] Meson spectroscopy with low Q^2 electron scattering in CLAS12
[E12-12-006] Near Threshold Electroproduction of J/ψ at 11 GeV
[E12-12-007] Exclusive Phi Meson Electroproduction with CLAS12

◇ Electron-Ion Collider (EIC) will carry out the relevant experiments in the future.

Thank you very much for your attention