Hadron Physics (HaPhy) Meeting , 13-14, November, 2020

Photo- and electro-production of vector-mesons off nucleon and nuclei and UPC

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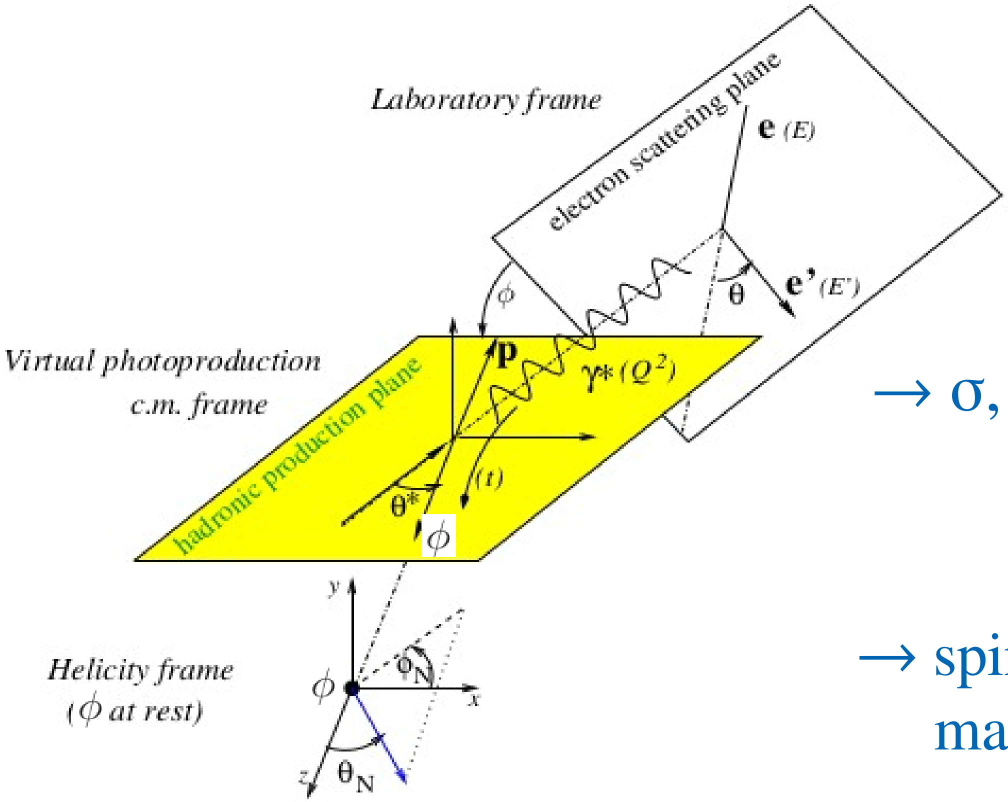
   [$\gamma\, {}^4\mathrm{He} \rightarrow \varphi(1020)\, {}^4\mathrm{He}$]
3. Vector-meson production in ultra-peripheral collision (UPC)
   [$A\, A \rightarrow A\, A\, V$]

In collaboration with
Seung-il Nam (PKNU)
Tsung-Shung H. Lee (ANL)
Yongseok Oh (KNU)

1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^{(*)}$ p → V p], V = φ, ρ, ω, J/ψ

reaction plane



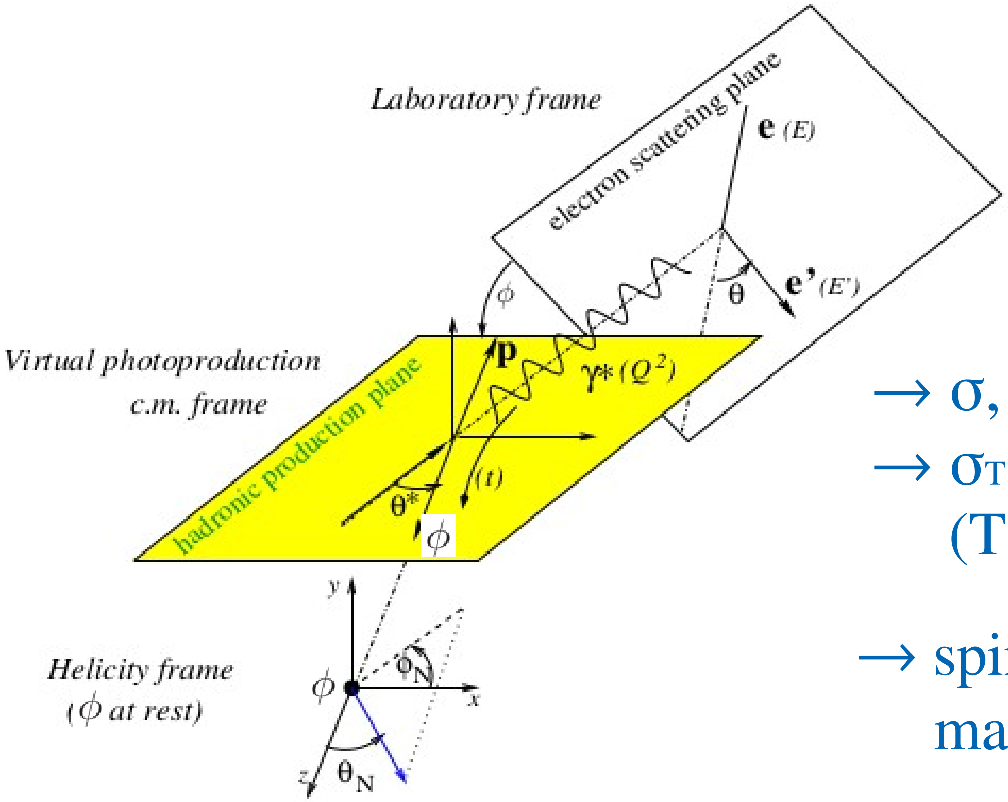
▸ photon(γ) polarization vector
Transverse comp. ($\lambda_\gamma=\pm1$) [photo-, electro-]
Longitudinal comp. ($\lambda_\gamma=0$) [electro-]

→ σ, dσ/dΩ, dσ/dt [photo-, electro-]

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

1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^{(*)}$ p $\rightarrow$ V p], V = φ, ρ, ω, J/ψ

reaction plane



- photon(γ) polarization vector

Transverse comp. ($\lambda_\gamma=\pm1$) [photo-, electro-]

Longitudinal comp. ($\lambda_\gamma=0$) [electro-]

$\rightarrow$ σ, $d\sigma/d\Omega$, $d\sigma/dt$ [photo-, electro-]

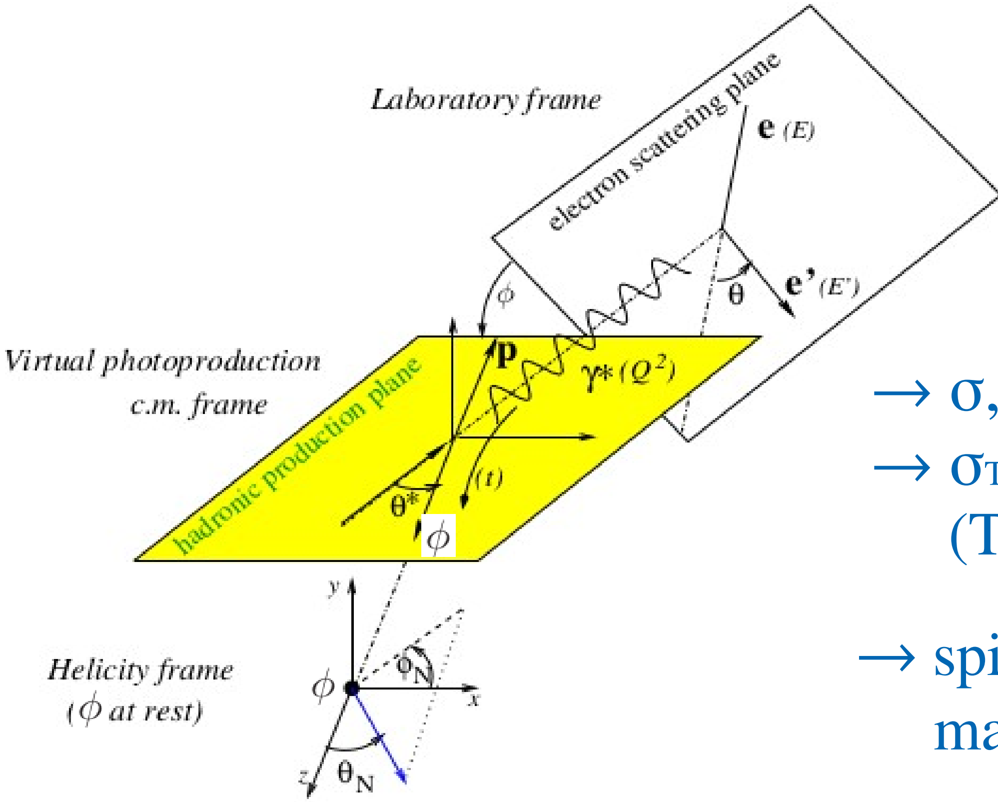
$\rightarrow$ σ_T, σ_L, σ_{TT}, σ_{LT}, $R=\sigma_L/\sigma_T$ ... [electro-]

(T-L separated cross sections)

$\rightarrow$ spin-density matrix elements (ρ_{ij}) [photo-, electro-]

1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^{(*)}$ p → V p], V = φ, ρ, ω, J/ψ

reaction plane

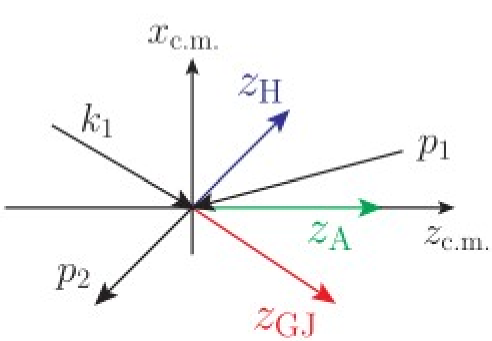


- ▸ photon(γ) polarization vector
Transverse comp. (λ_γ=±1) [photo-, electro-]
Longitudinal comp. (λ_γ=0) [electro-]

→ σ, dσ/dΩ, dσ/dt [photo-, electro-]

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

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



• V-meson rest frame

Adair frame

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

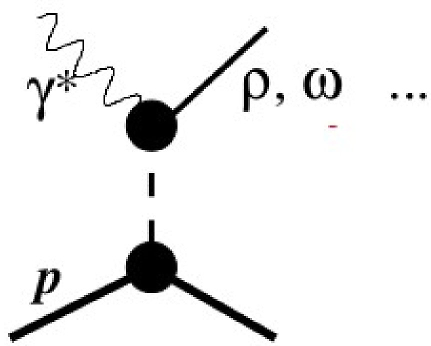
Gottfried-Jackson frame:
in favor of t-channel helicity conservation (TCHC)

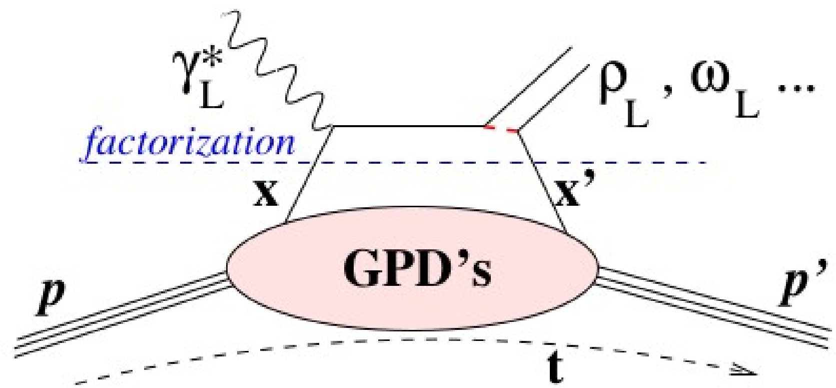
1. Photo- and electro-production of vector-mesons off nucleons $[\gamma^{(*)}\, p \to V\, p]$, $V = \varphi, \rho, \omega, J/\psi$

theoretical framework

photoproduction

Q²=0 <---> low Q²	<<----->>	high Q²



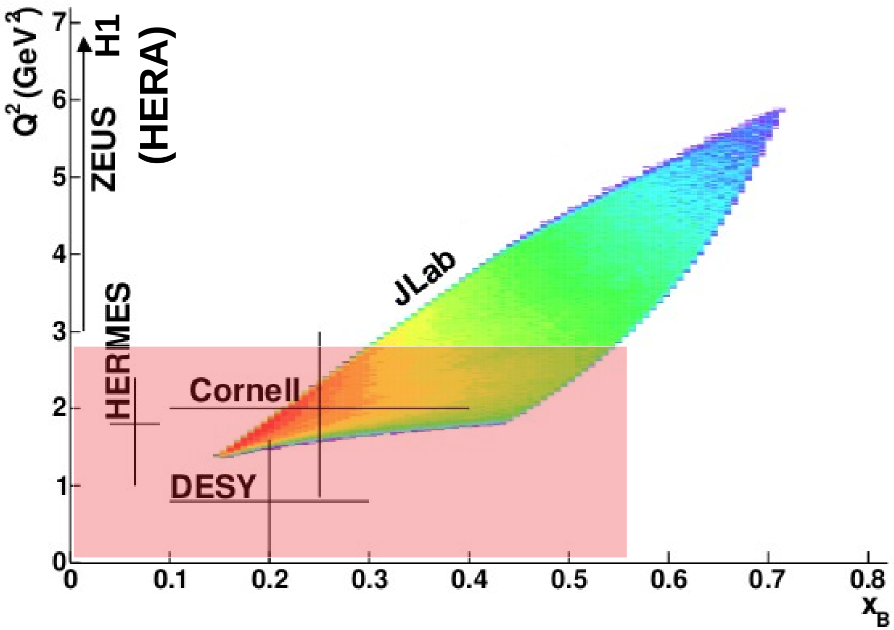


t-channel Regge trajectory exchange	<<----->>	handbag diagram

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

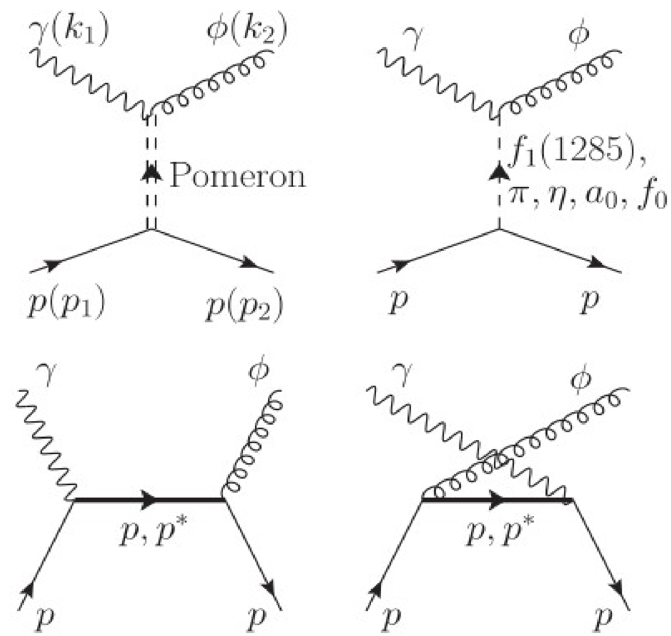
1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^{(*)}$ p $\rightarrow$ V p], V = φ, ρ, ω, J/ψ

theoretical framework



[Kinematical range covered by vector meson electoproduction experiments]

Feynman diagrams

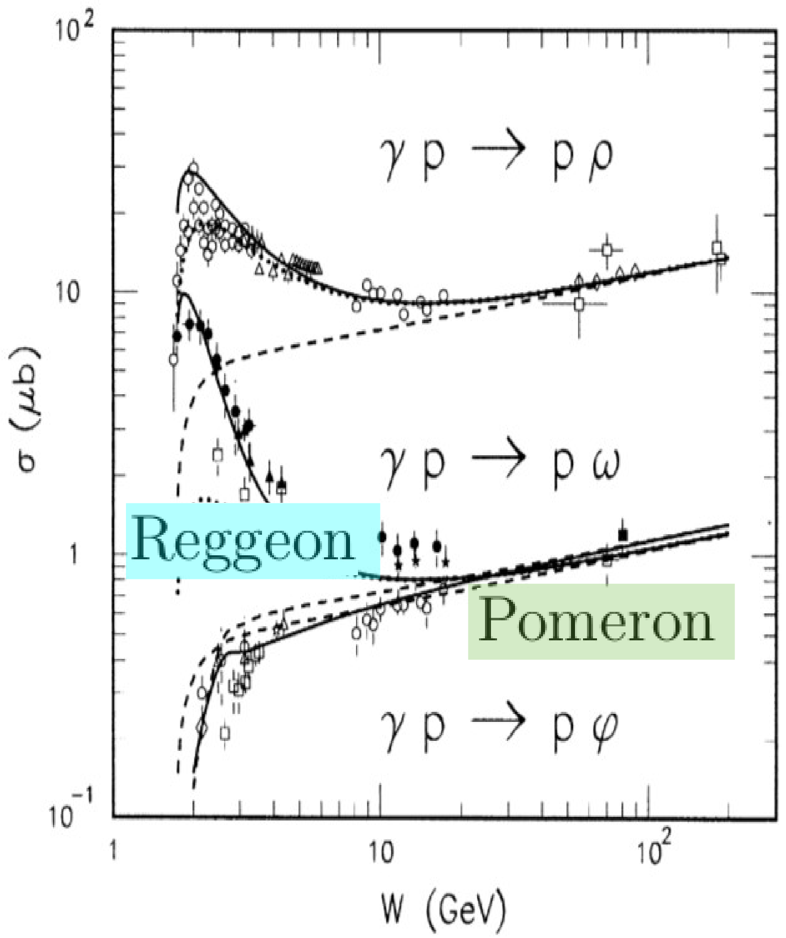


- We can test which of the two descriptions – with “quark” or “hadronic” degrees of freedom - applies in the considered kinematical domain.
  $2.5 \lesssim Q^2 \lesssim 60$ GeV^2 & $35 \lesssim W \lesssim 180$ GeV at H1
  $1.0 \lesssim Q^2 \lesssim 7.0$ GeV^2 & $3.0 \lesssim W \lesssim 6.3$ GeV at HERMES

- At low photon virtualities ($Q^2 \lesssim M_V^2$) and low energies ($W \lesssim$ several GeV), our hadronic effective model is applicable.

1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^{(*)}$ p → V p], V = φ, ρ, ω, J/ψ

total cross section for vector-meson photoproduction



[Laget, PLB.489.313 (2000)]

- Pomeron exchange (two-gluon exchange) dominates at "high energies".
- Clarifying the role of various meson exchanges at "low energies" is important.

1. Photo- and electro-production of vector-mesons off nucleons
$[\gamma^{(*)}\, p \to V\, p]$, V = φ, ρ, ω, J/ψ

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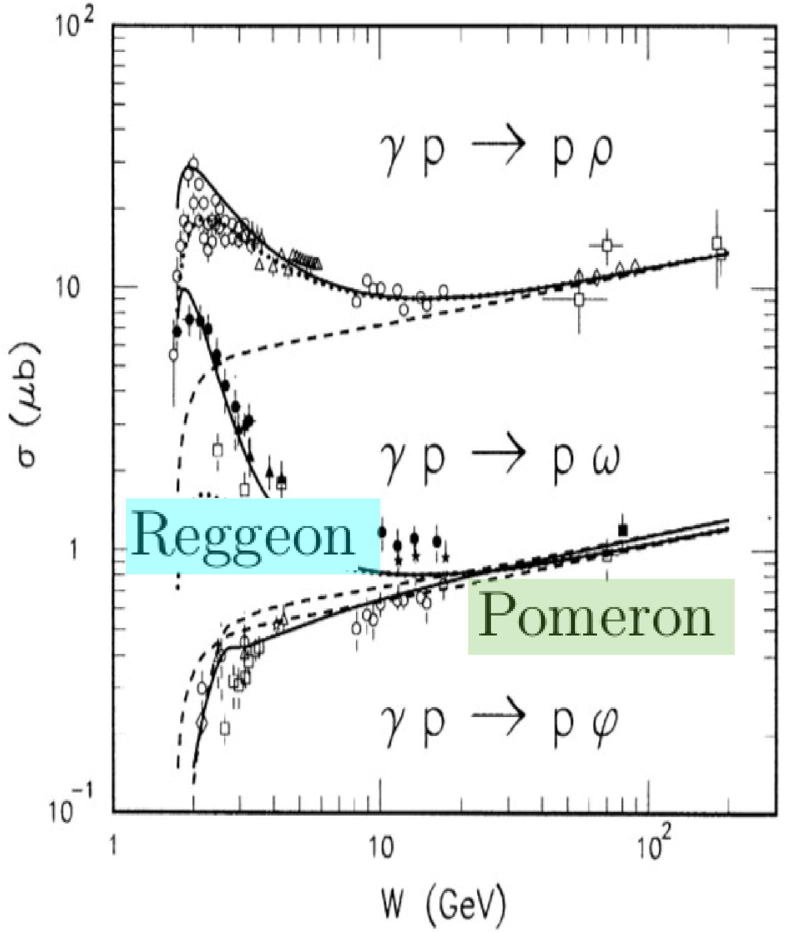

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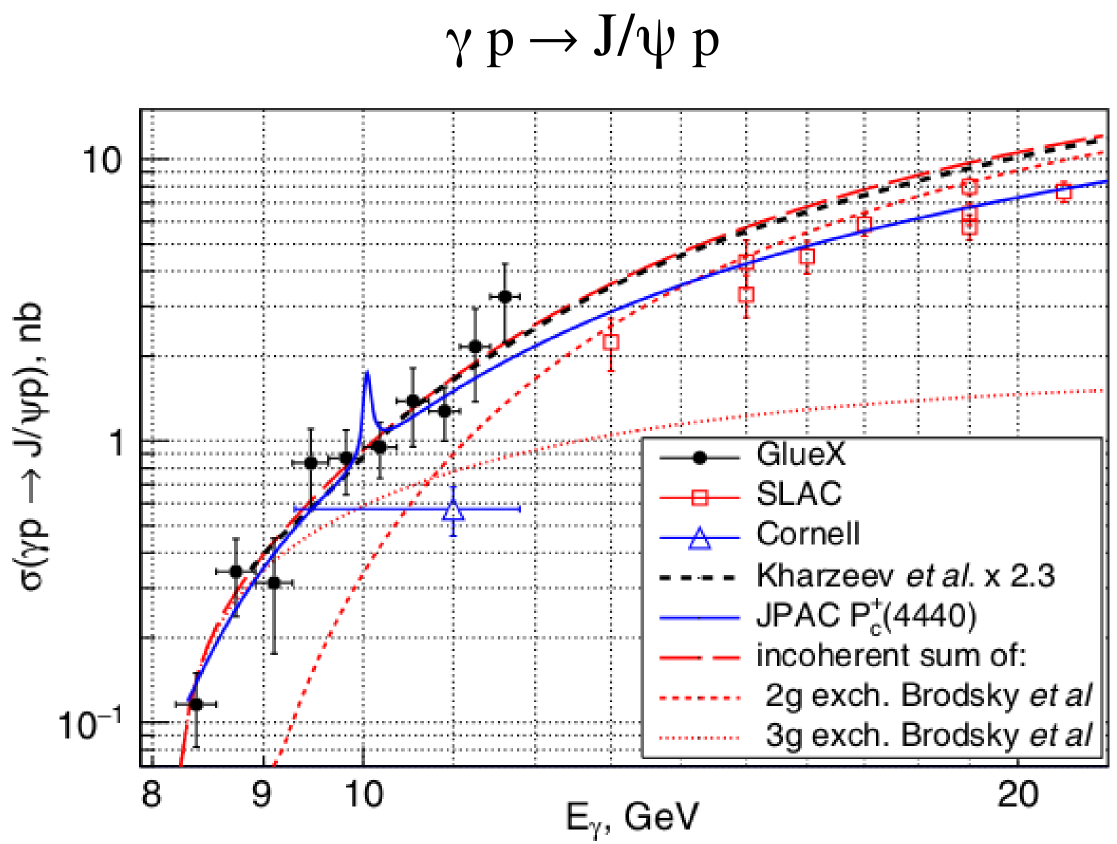


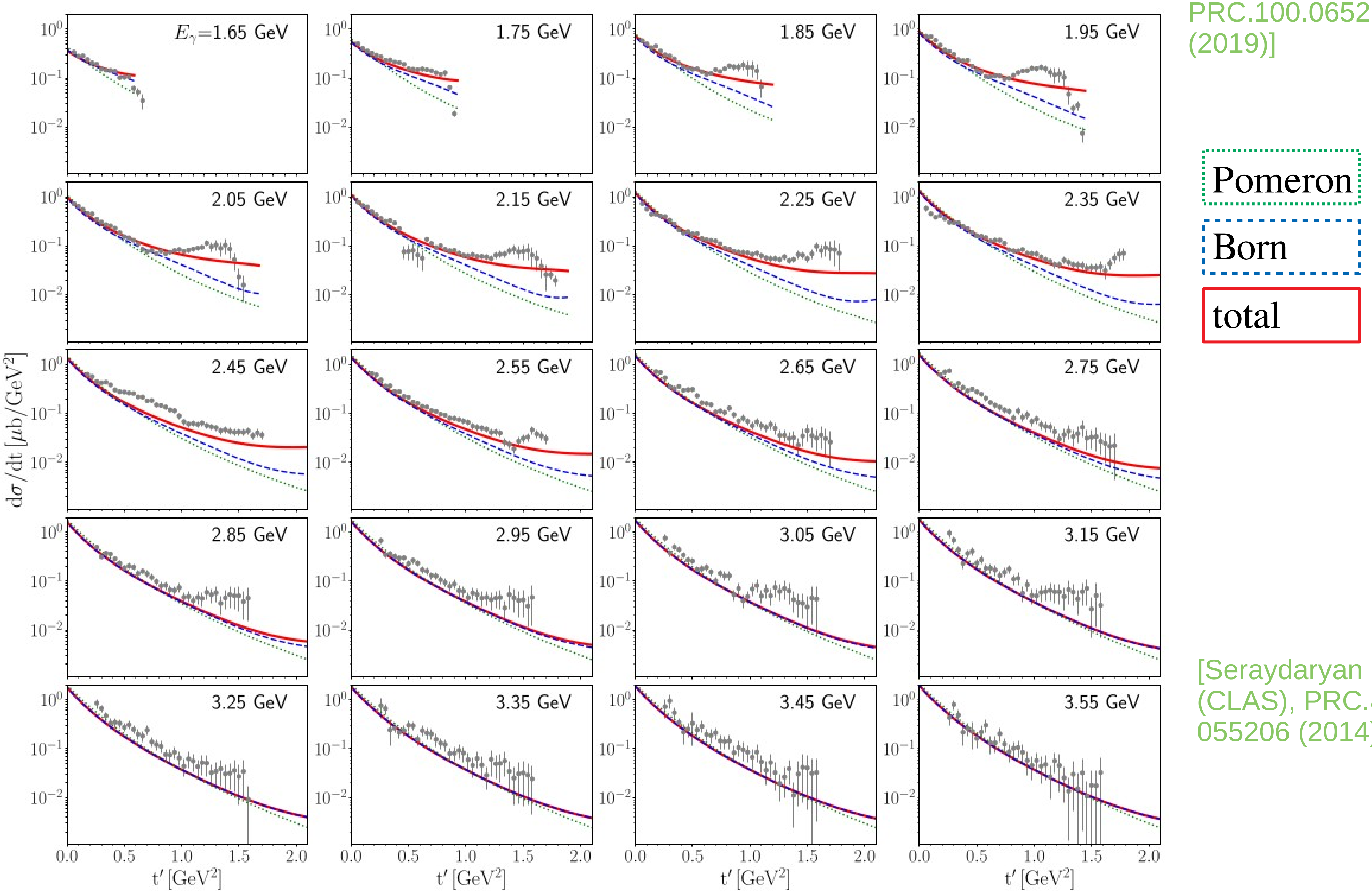
[Ali (GlueX), PRL.123.072001 (2019)]

- Pomeron exchange (two-gluon exchange) dominates at “high energies”.
- Clarifying the role of various meson exchanges at “low energies” is important.

1-1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma\, p \rightarrow V\, p$], V = φ, ρ, ω, J/ψ

differential cross sections

[S.H.Kim, S.i.Nam, PRC.100.065208 (2019)]

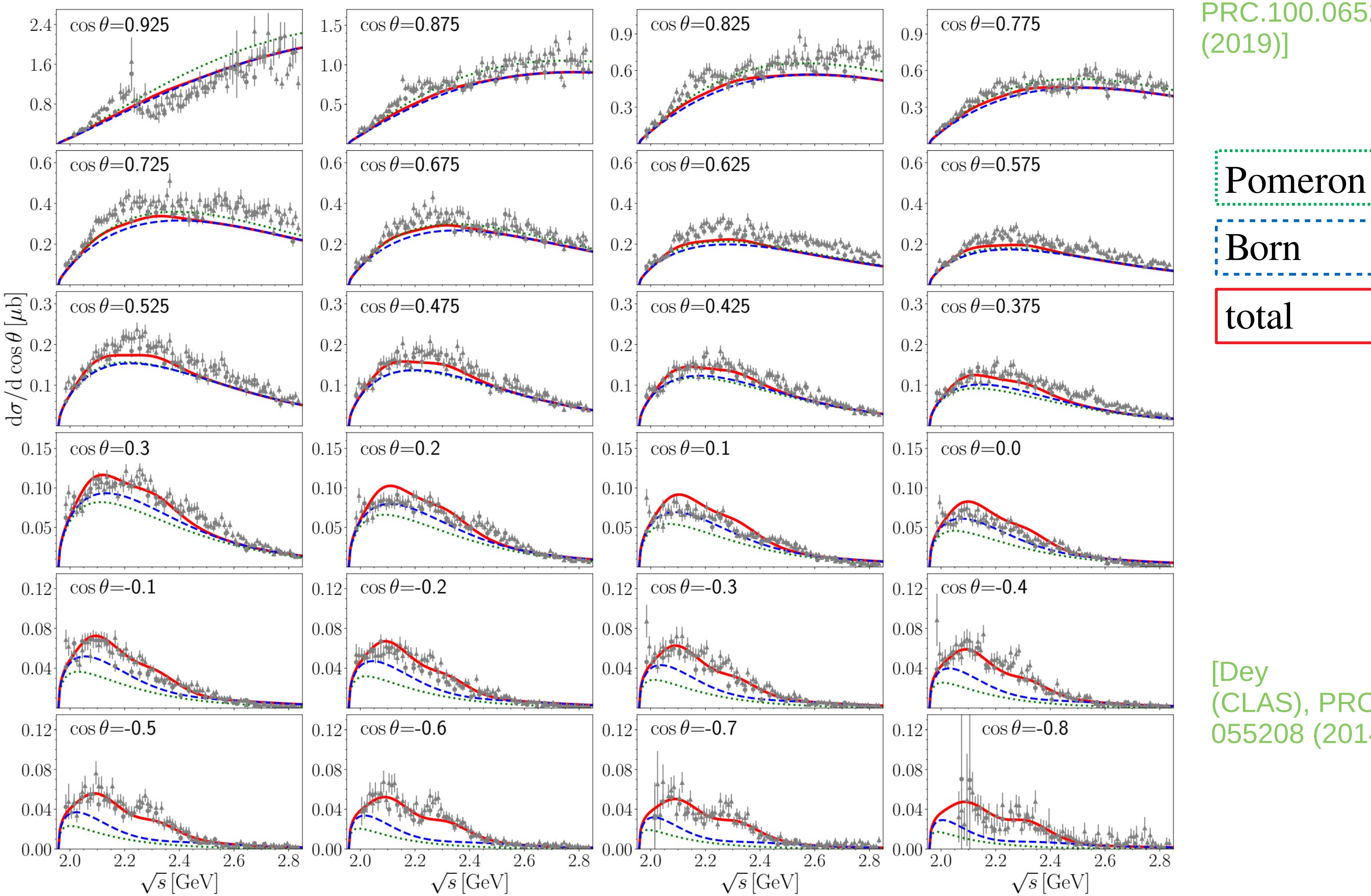


[Seraydaryan (CLAS), PRC.89. 055206 (2014)]

1-1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma\, p \to V\, p$], V = φ, ρ, ω, J/ψ

differential cross sections

[S.H.Kim, S.i.Nam, PRC.100.065208 (2019)]



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

spin-density matrix elements

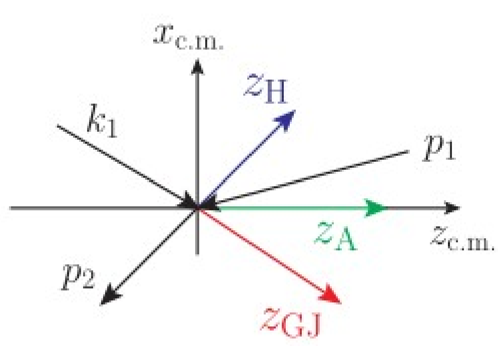
$$\rho^0_{\lambda\lambda'} = \frac{1}{N}\sum_{\lambda_\gamma,\lambda_i,\lambda_f} \mathcal{M}_{\lambda_f\lambda;\lambda_i\lambda_\gamma}\mathcal{M}^*_{\lambda_f\lambda';\lambda_i\lambda_\gamma},$$

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

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

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

$$N = \sum|\mathcal{M}_{\lambda_f\lambda;\lambda_i\lambda_\gamma}|^2$$



Adair frame

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

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

1-1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma\, p \to V\, p$], V = φ, ρ, ω, J/ψ

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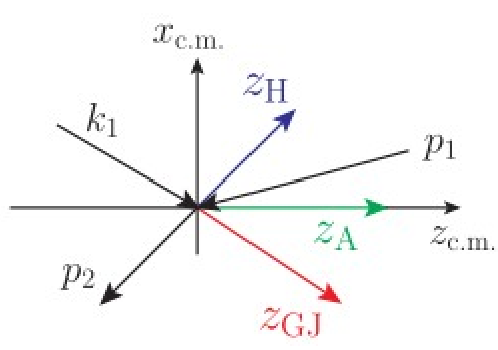
$$N = \sum |\mathcal{M}_{\lambda_f\lambda;\lambda_i\lambda_\gamma}|^2$$

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

- single helicity-flip transition between γ & φ

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

- relative contribution between Natural & Unnatural parity exchanges



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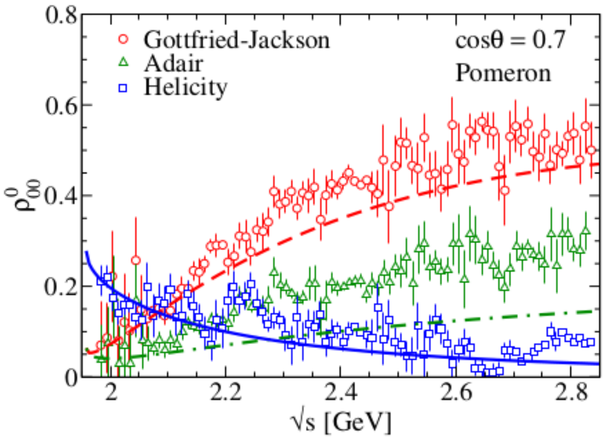
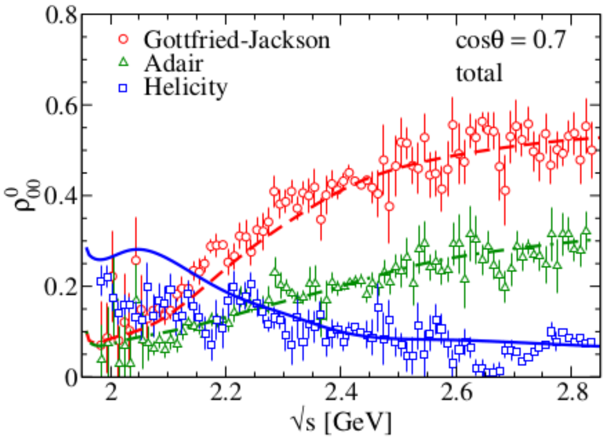
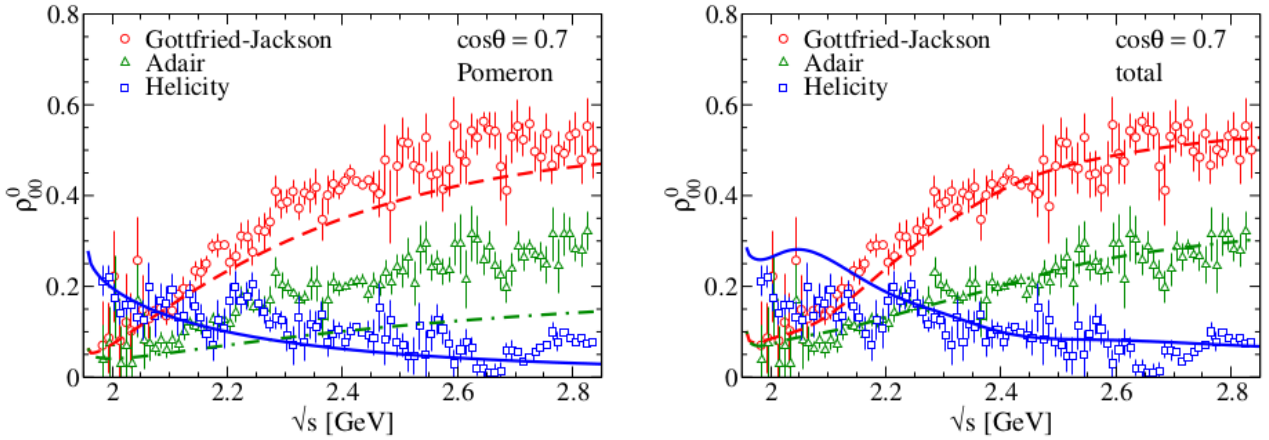
[γ $p \to V$ p], V = φ, ρ, ω, J/ψ



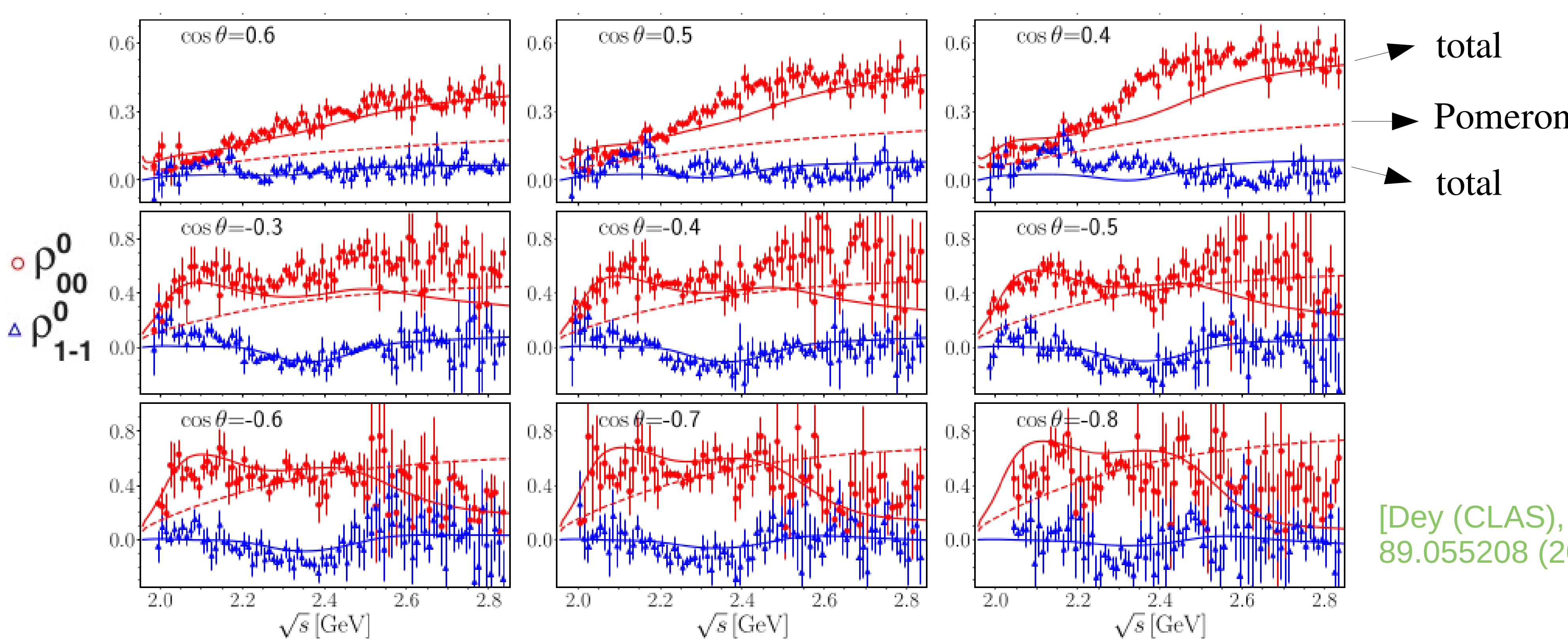


- TCHC &SCHC are broken.

1-1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma\, p \rightarrow V\, p$], V = φ, ρ, ω, J/ψ



▸ TCHC &SCHC are broken.



[Dey (CLAS), PRC. 89.055208 (2014)]

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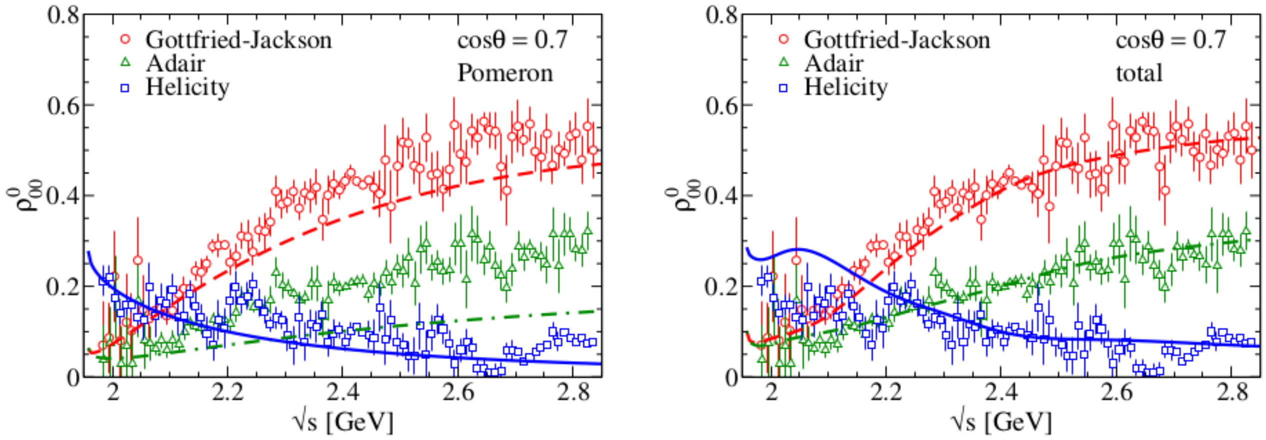

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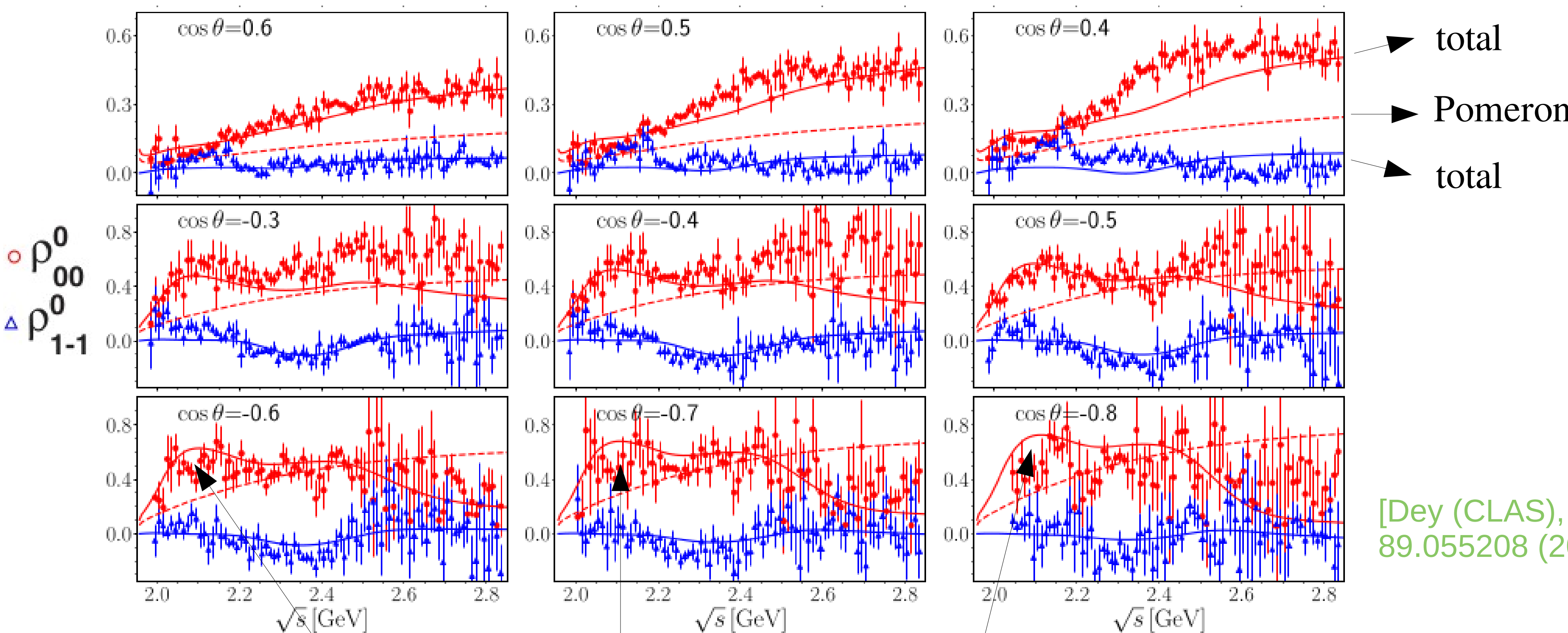


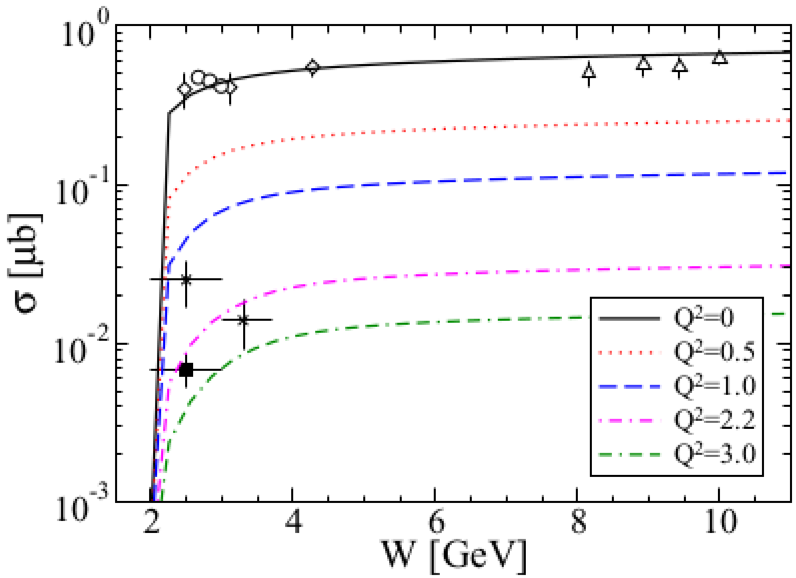
N*(2000,5/2+) & N*(2300,1/2+)

[Dey (CLAS), PRC. 89.055208 (2014)]

unpolarized cross sections

(1a) $\gamma^* p \to \varphi(1020)\, p$

[S.H.Kim, S.i.Nam,
PRC.101.065201 (2020)]



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

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

1-2. Photo- and electro-production of vector-mesons off nucleons
$[\gamma^* p \to V\, p]$, $V = \varphi, \rho, \omega, J/\psi$

unpolarized cross sections

(1a) $\gamma^* p \to \varphi(1020)\, p$

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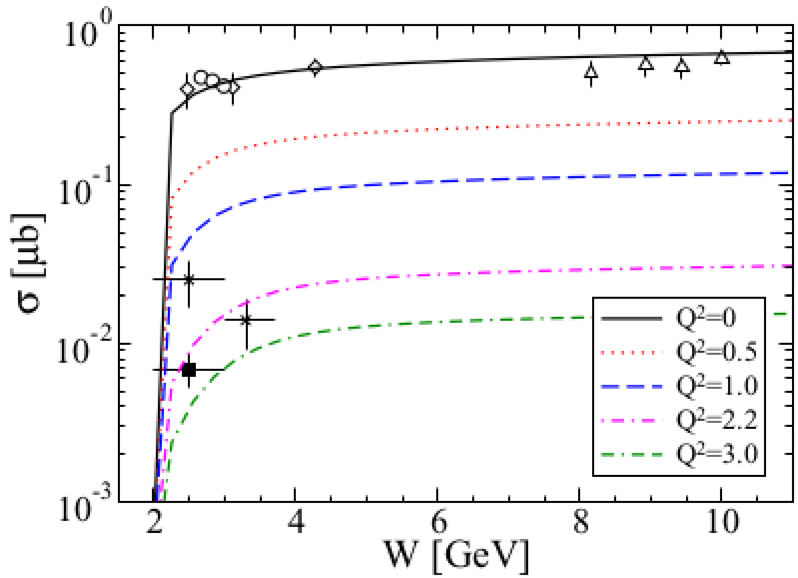
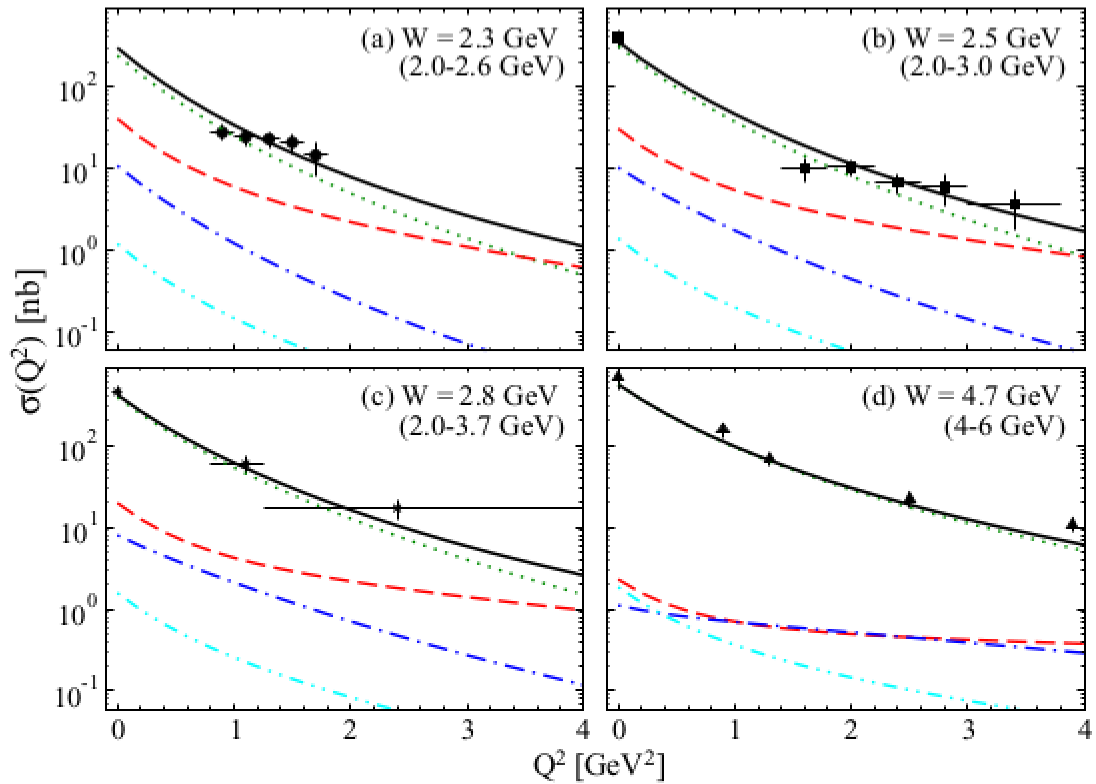




[Cornell (Dixon et al.) PRL.39.516 (1977)]

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

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

Pomeron | PS (π,η) | total
S (a_0, f_0) | AV (f_1)

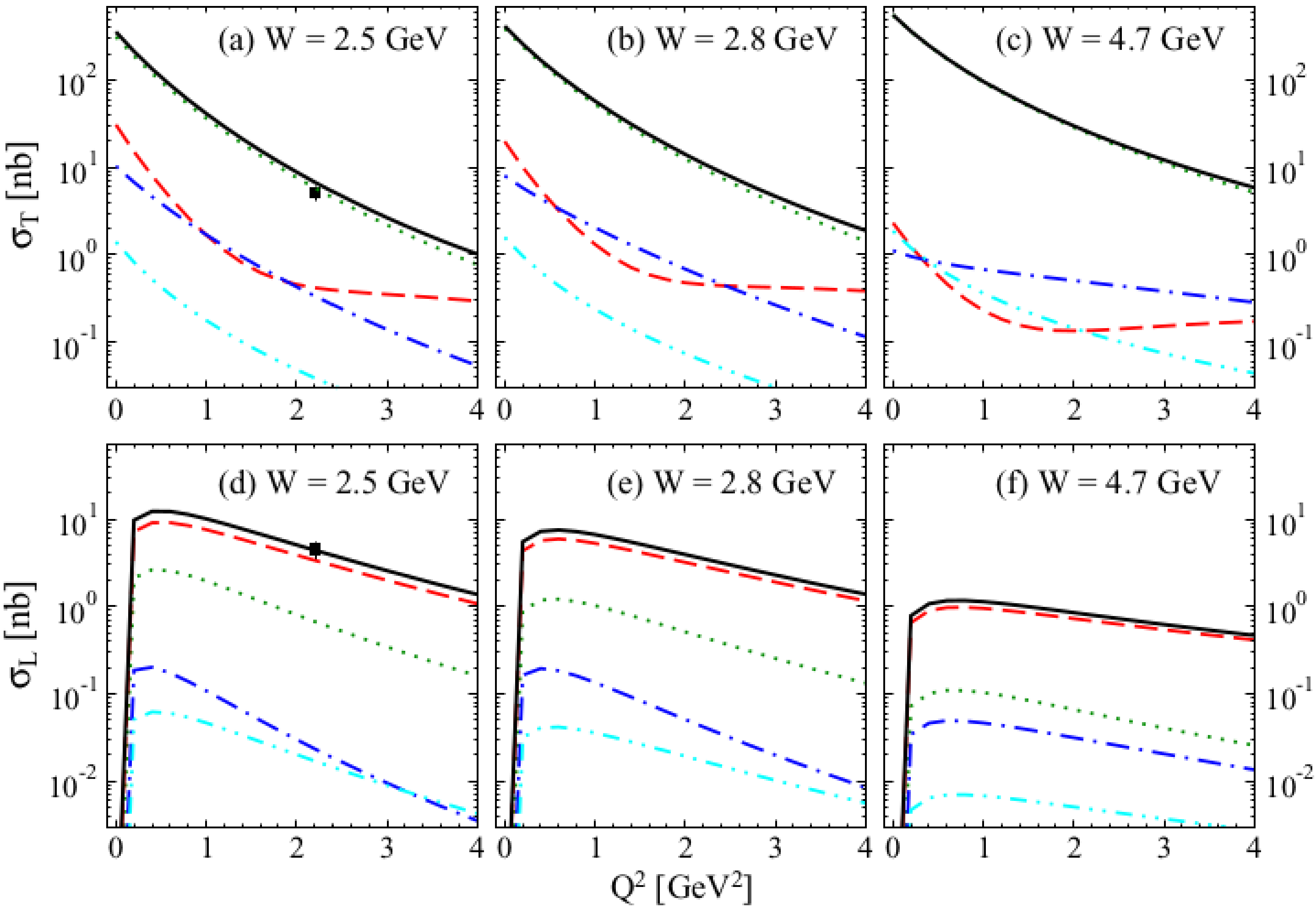
- The Q^2 dependence of the cross sections is well described.
- The agreement with the exp. data is good at the real photon limit $Q^2=0$.

1-2. Photo- and electro-production of vector-mesons off nucleons
$[\gamma^* p \to V\, p]$, V = φ, ρ, ω, J/ψ

T-L separated differential cross sections

(1b) $\gamma^* p \to \varphi(1020)\, p$

[S.H.Kim, S.i.Nam, PRC.101.065201 (2020)]



[CLAS (Santoro et al.) PRC.78.025210 (2008)]

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

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

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

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

$$\mathcal{N} = \left[32\pi\left(W^2 - M_N^2\right)Wk\right]^{-1}$$

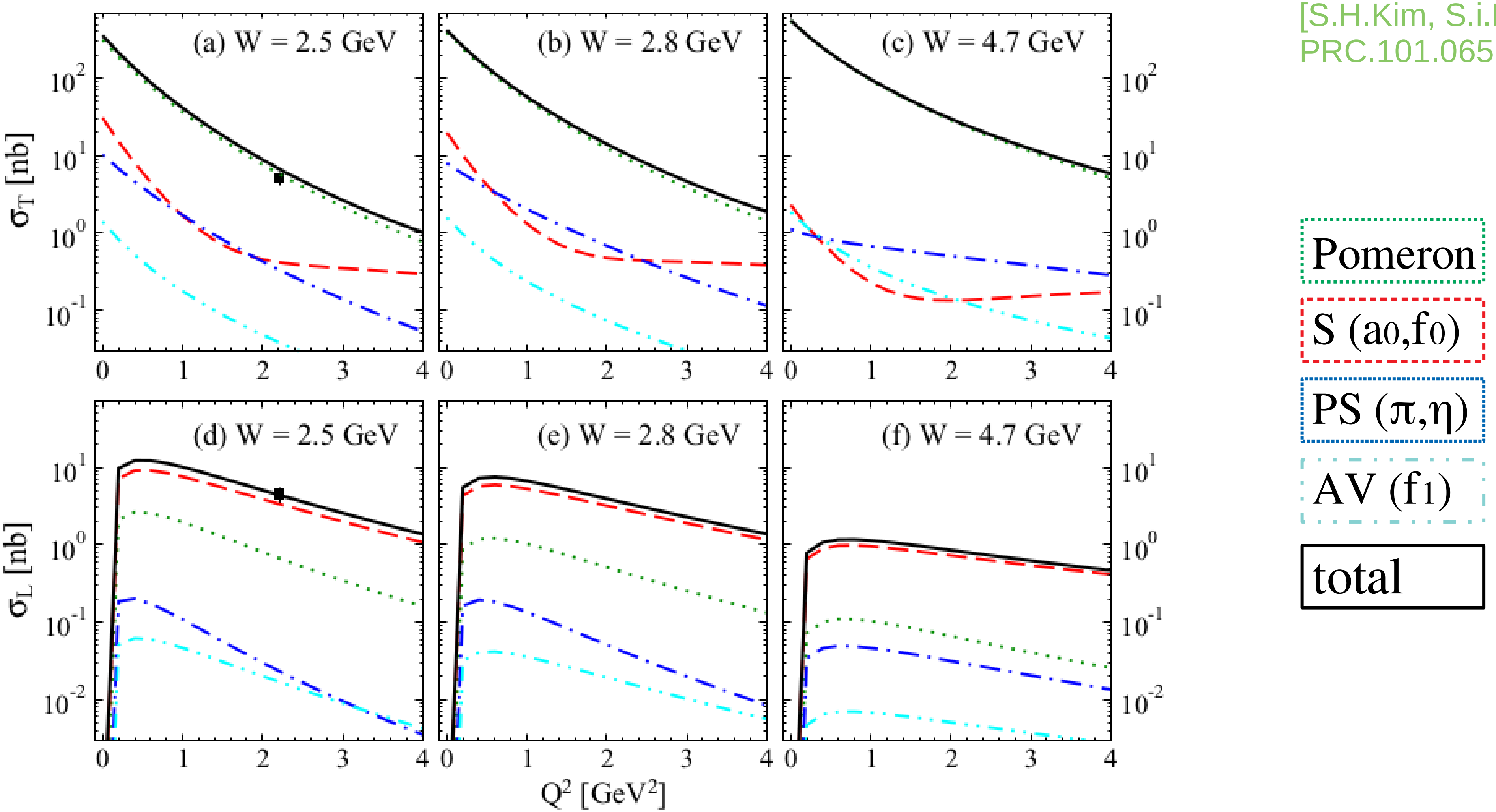
- Pomeron and S-meson exchanges dominate transverse (T) and longitudinal (L) cross sections, respectively.

1-2. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^* p \to V\, p$], V = φ, ρ, ω, J/ψ

T-L separated differential cross sections

(1b) $\gamma^* p \to \varphi(1020)\, p$

[S.H.Kim, S.i.Nam, PRC.101.065201 (2020)]



[CLAS (Santoro et al.) PRC.78.025210 (2008)]

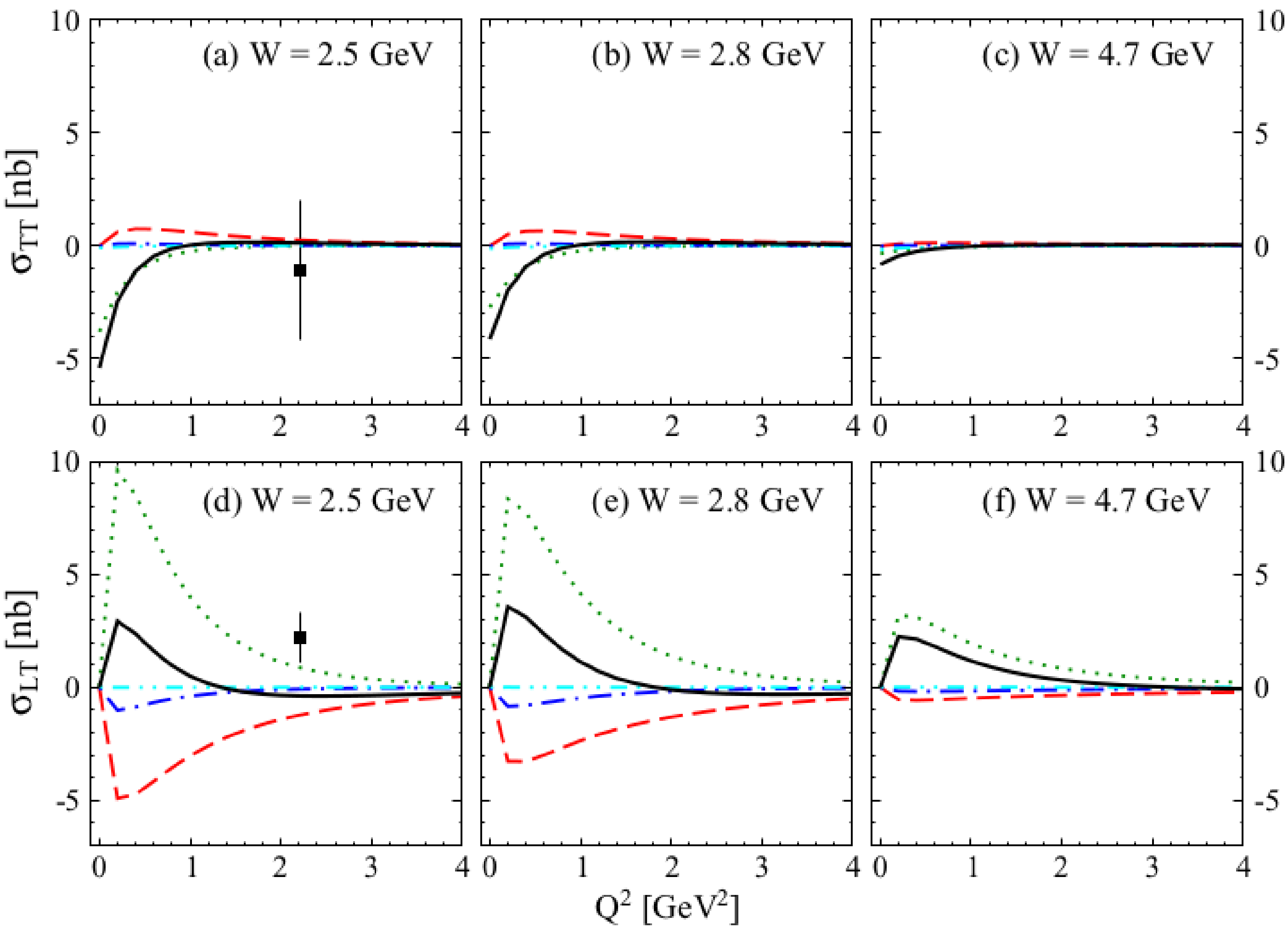
- Pomeron and S-meson exchanges dominate transverse (T) and longitudinal (L) cross sections, respectively.

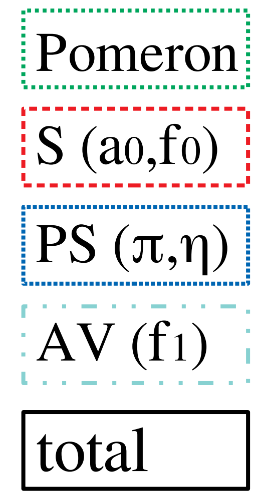
1-2. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^* p \to V p$], $V = \varphi, \rho, \omega, J/\psi$

T-L separated differential cross sections

(1c) $\gamma^* p \to \varphi(1020)\, p$

[S.H.Kim, S.i.Nam, PRC.101.065201 (2020)]



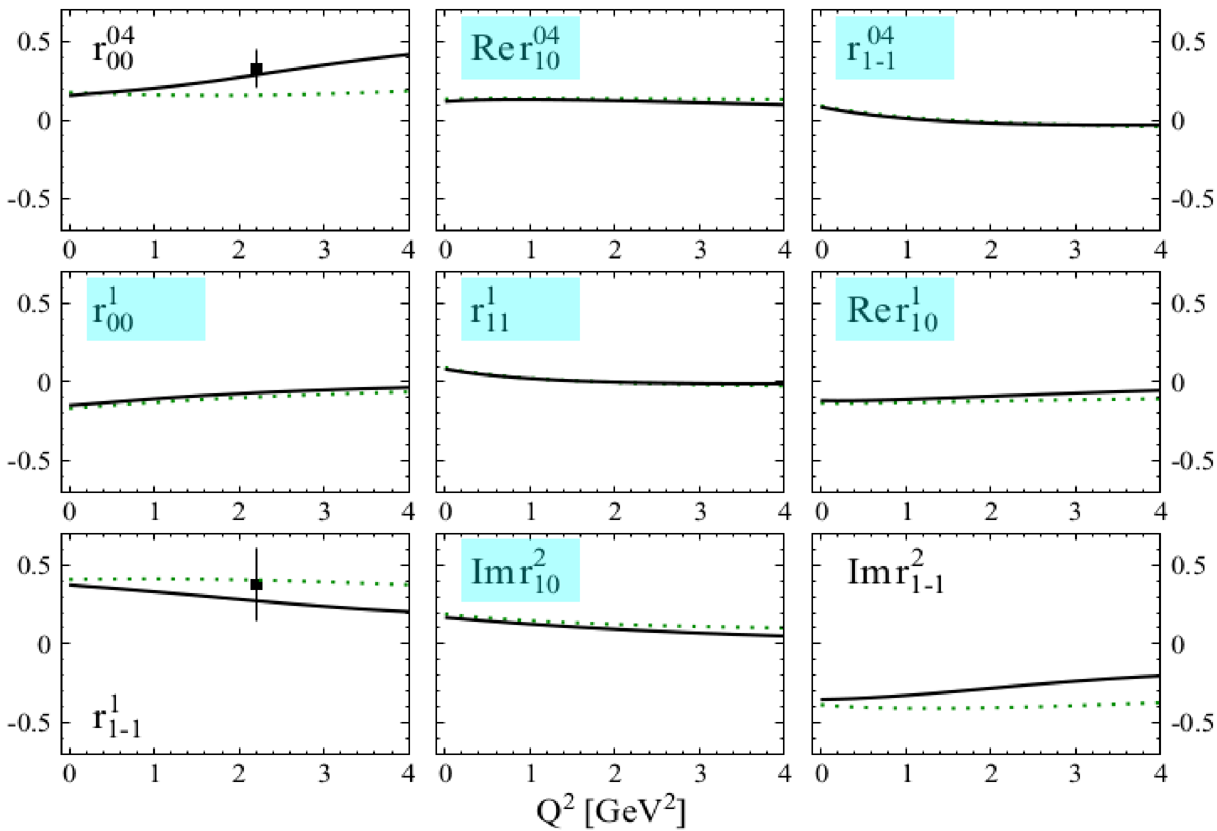


[CLAS (Santoro et al.) PRC.78.025210 (2008)]

- 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.

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

(1d) $\gamma^* p \to \varphi(1020)\, p$



$$r^{04}_{ij} = \frac{\rho^0_{ij} + \varepsilon R \rho^4_{ij}}{1 + \varepsilon R},$$

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

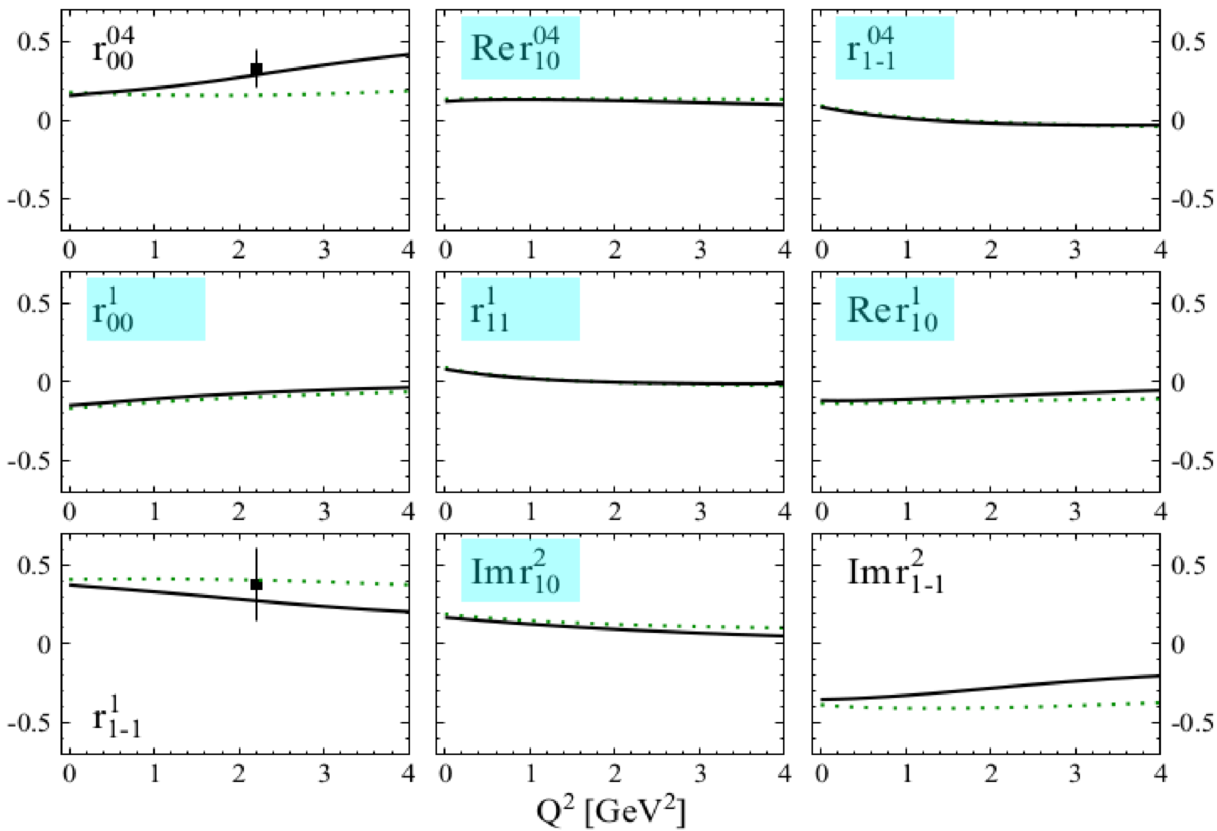
$$r^{\alpha}_{ij} = \sqrt{R}\frac{\rho^{\alpha}_{ij}}{1 + \varepsilon R}, \quad \text{for } \alpha = (5-8)$$

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

1-2. Photo- and electro-production of vector-mesons off nucleons
$[\gamma^* p \to V p]$, V = φ, ρ, ω, J/ψ

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

(1d) $\gamma^* p \to \varphi(1020)\, p$



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

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

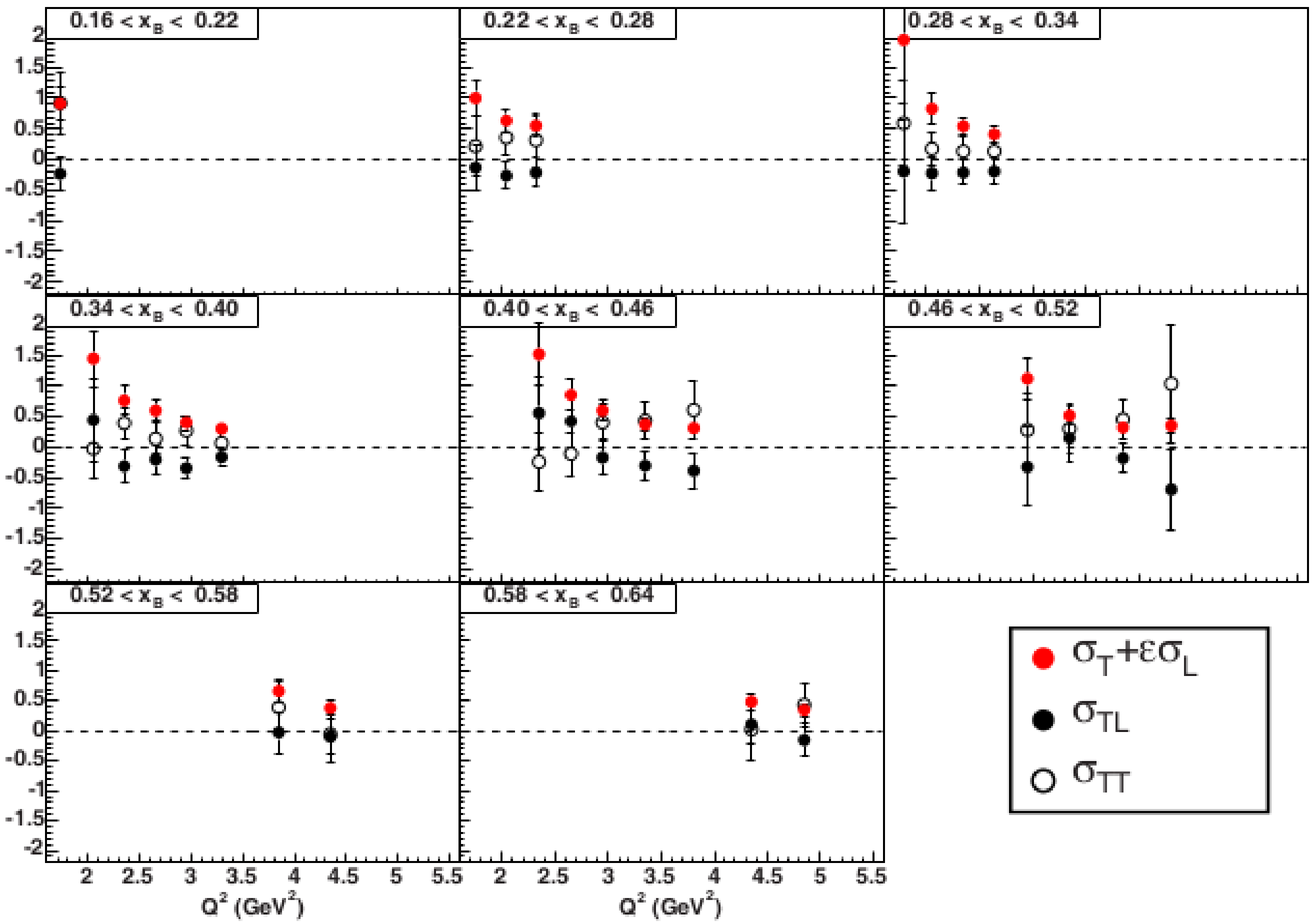
$$r_{ij}^{\alpha} = \sqrt{R}\frac{\rho_{ij}^{\alpha}}{1+\varepsilon R}, \quad \text{for } \alpha = (5-8)$$

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.

T-L separated differential cross sections

(2a) $\gamma^* p \to \rho(770)\, p$



[CLAS (Morrow et al.) EPJA.39.5 (2009)]

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

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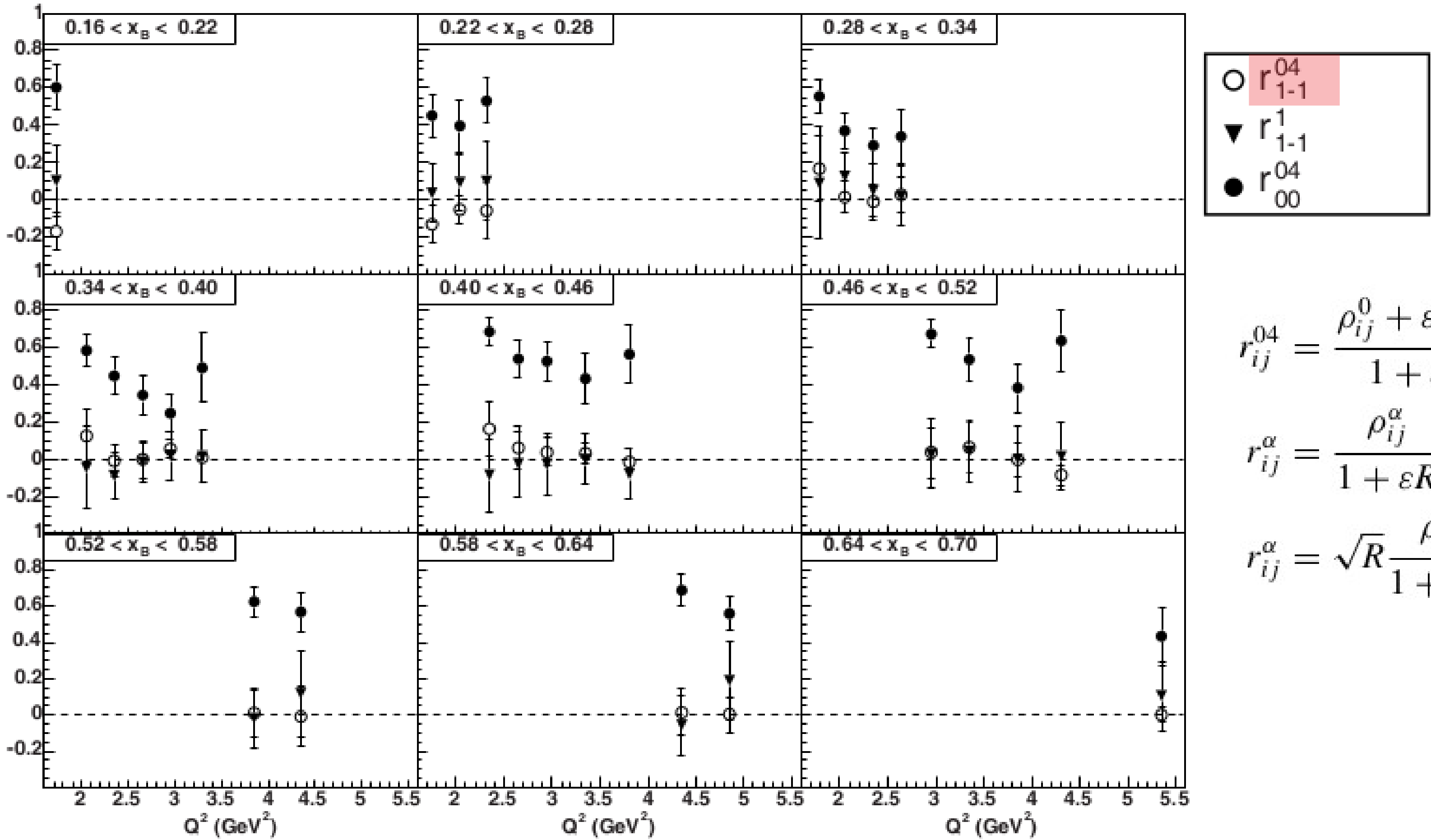
$$\mathcal{N} = \left[32\pi\left(W^2 - M_N^2\right)Wk\right]^{-1}$$

- If SCHC holds, σ_{TT} and σ_{LT} become zero.
- Pomeron > meson-exchange ($\gamma^* p \to \varphi\, p$)
  Pomeron < meson-exchange ($\gamma^* p \to \rho\, p$, $\omega\, p$)

1-2. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^* p \to V\, p$], V = φ, ρ, ω, J/ψ

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

(2b) $\gamma^* p \to \rho(770)\, p$



= 0 if SCHC holds

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

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

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

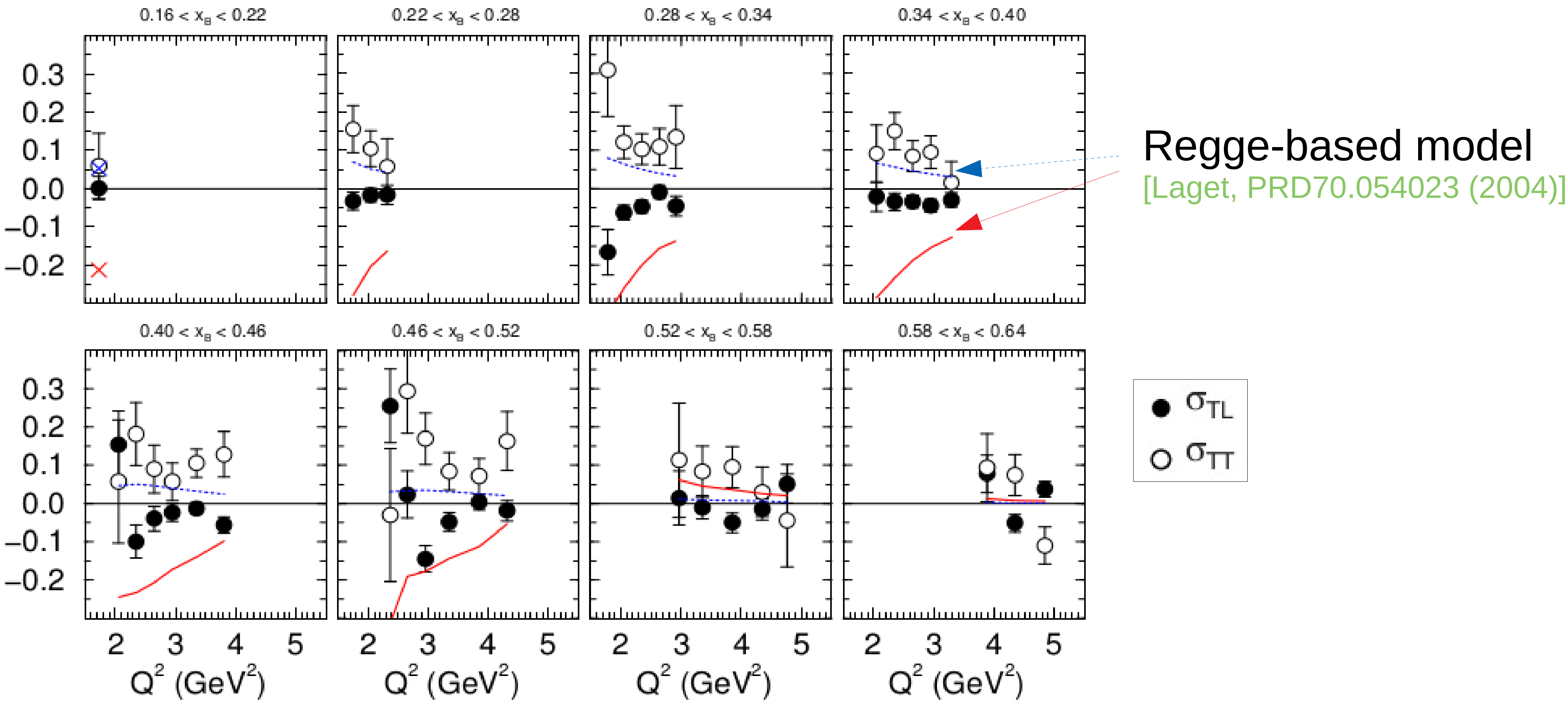
[CLAS (Morrow et al.) EPJA.39.5 (2009)]

- Parity asymmery $P \equiv \dfrac{\sigma_T^N - \sigma_T^U}{\sigma_T^N + \sigma_T^U} = (1+\varepsilon R)\left(2r_{1-1}^1 - r_{00}^1\right)$

1-2. Photo- and electro-production of vector-mesons off nucleons
$[\gamma^* p \to V p]$, $V = \varphi, \rho, \omega, J/\psi$

T-L separated differential cross sections

(3a) $\gamma^* p \to \omega(782)\, p$



[CLAS (Morand et al.) EPJA.24.445 (2005)]

- If SCHC holds, σ_{TT} and σ_{LT} become zero.
- Pomeron > meson-exchange ($\gamma^* p \to \varphi p$)
  Pomeron < meson-exchange ($\gamma^* p \to \rho p, \omega p$)

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

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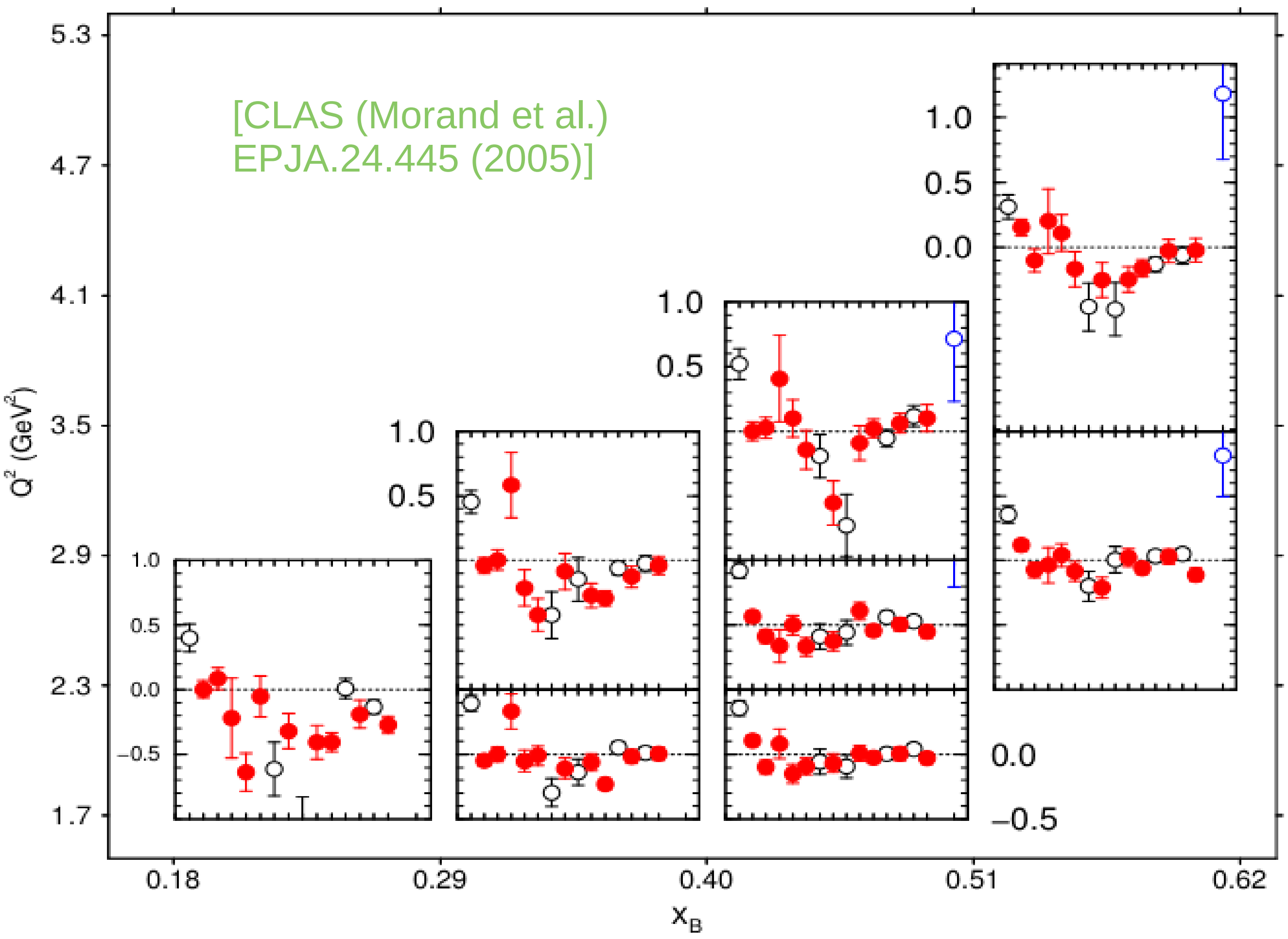

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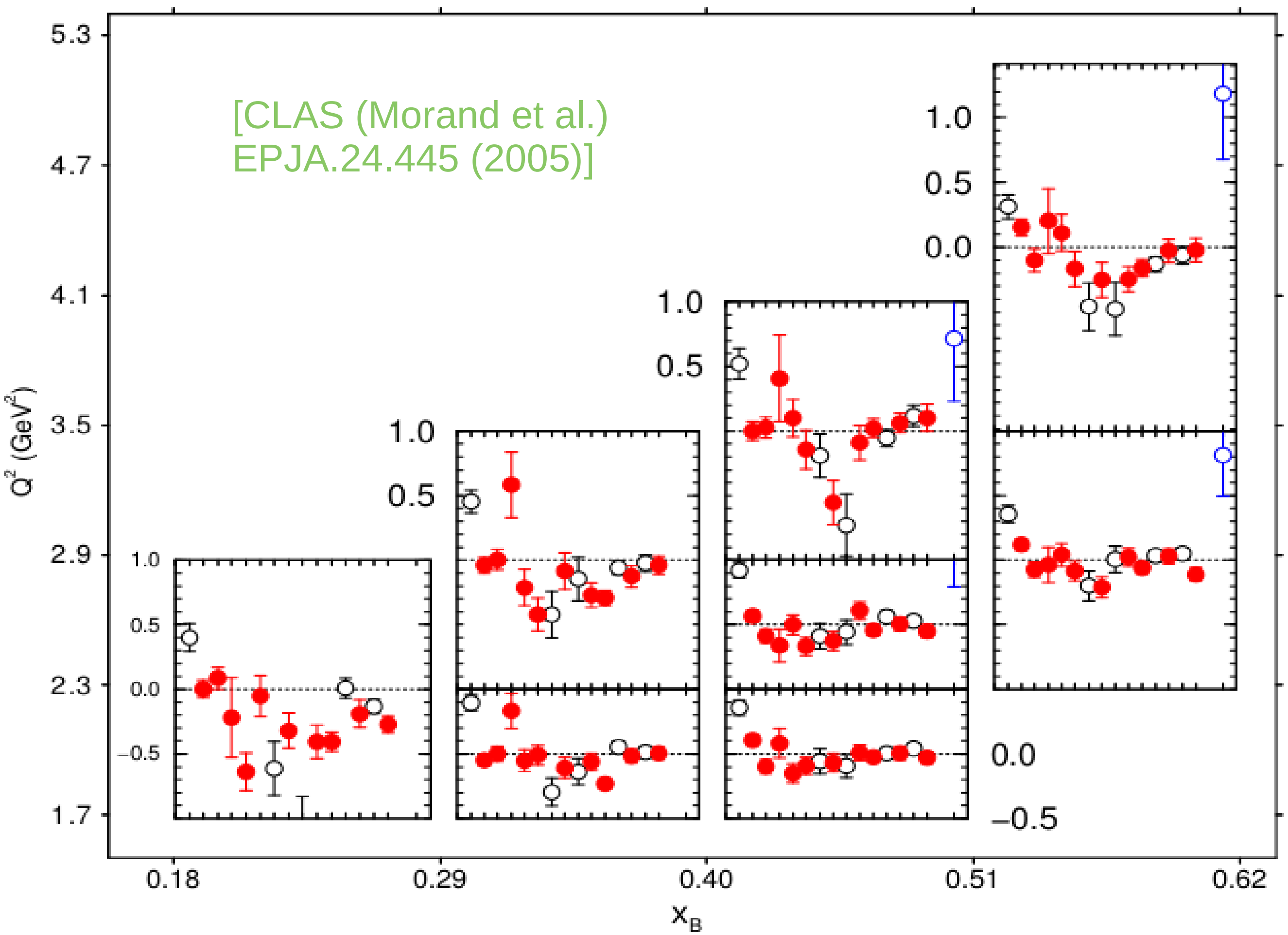

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- r_{00}^{04}, $\mathrm{Re}\, r_{10}^{04}$, r_{1-1}^{04}, r_{00}^{1}, r_{11}^{1}, $\mathrm{Re}\, r_{10}^{1}$, r_{1-1}^{1}, $\mathrm{Im}\, r_{10}^{2}$, $\mathrm{Im}\, r_{1-1}^{2}$, r_{00}^{5}, r_{11}^{5}, $\mathrm{Re}\, r_{10}^{5}$, r_{1-1}^{5}, $\mathrm{Im}\,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

1. Photo- and electro-production of vector-mesons off nucleons $[\gamma^{(*)} p \to V p]$, $V = \varphi, \rho, \omega, J/\psi$

(1) $\gamma^{(*)} p \to \varphi p$

- We employed an effective Lagrangian approach combined with a Regge model.
- The role of Pomeron- and meson-contributions is clearly verified.
- Our hadronic approach is very successful for describing the data at $Q^2=(0\text{-}4)$ GeV^2, $W=(2\text{-}5)$ GeV, $t=(0\text{-}2)$ GeV^2.

(2,3) $\gamma^{(*)} p \to \rho p, \omega p$ (4) $\gamma^{(*)} p \to J/\psi p$

- The theoretical analyses are very rare.
- Will be measured at JLab and EIC (Electron-Ion Collider).

1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^{(*)}$ p $\to$ V p], V = φ, ρ, ω, J/ψ

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We can extend these elementary processes
to the $\gamma^{(*)}$ A $\to$ V A processes.

2. Photoproduction of φ(1020) vector-meson off ^{4}He targets
[γ ^{4}He $\to$ φ(1020) ^{4}He]

2. Photoproduction of φ(1020) vector-meson off ^{4}He targets
[$\gamma\ ^4He \rightarrow \varphi(1020)\ ^4He$]

introduction

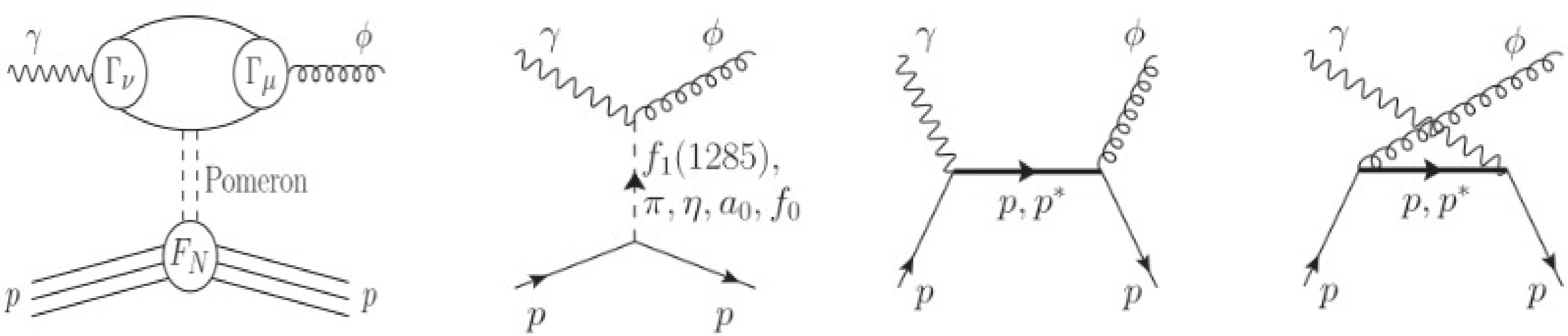
PHYSICAL REVIEW C **97**, 035208 (2018)

First measurement of coherent ϕ-meson photoproduction from ^{4}He near threshold

(LEPS Collaboration)

- Coherent photoproduction: "The incident nuclei" primarily remain intact, so the final state consists of "incident nuclei" + "a vector meson".

- The reaction mechanism of the elementary process is investigated using our hadronic effective Lagrangian method:
  $\gamma\ p \rightarrow \varphi\ p$ [S.H.Kim, S.i.Nam, PRC.100.065208 (2020)]
  $\gamma^*\ p \rightarrow \varphi\ p$ [S.H.Kim, S.i.Nam, PRC.101.065201 (2020)]



- The scattering amplitudes are constructed to conserve gauge invariance.

2. Photoproduction of φ(1020) vector-meson off ^{4}He targets [$\gamma\, ^4\text{He} \to \varphi(1020)\, ^4\text{He}$]

introduction

- We extend the elementary processes to reactions on nuclei targets: $\gamma\, ^4\text{He} \to \varphi\, ^4\text{He}$

- For coherent photoproduction on nuclei targets at low energies,
  the momentum transfer is large:
  $-t \simeq 0.9$ [GeV^2] for φ production $-t \simeq 3.6$ [GeV^2] for J/ψ production
  Thus the reactions probe the nuclear form factors.

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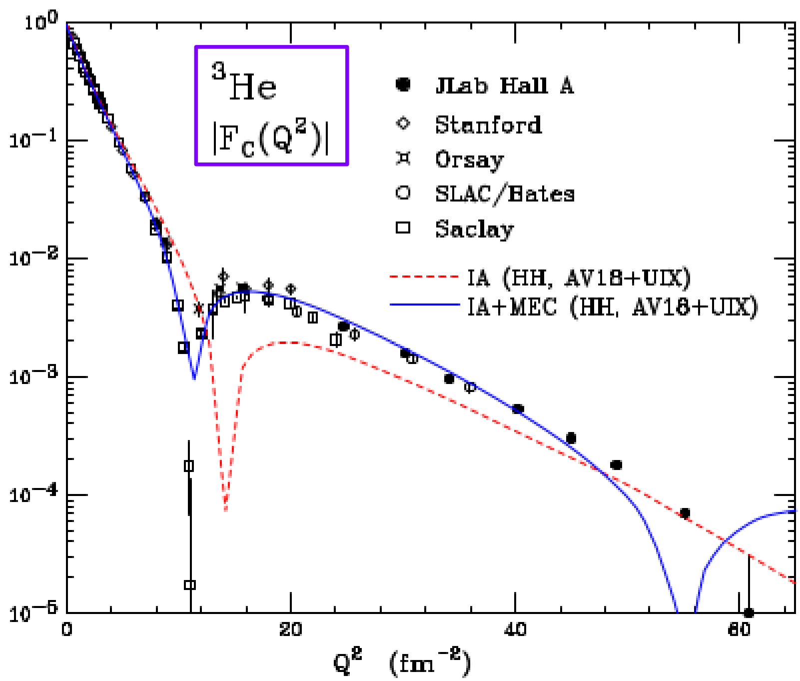
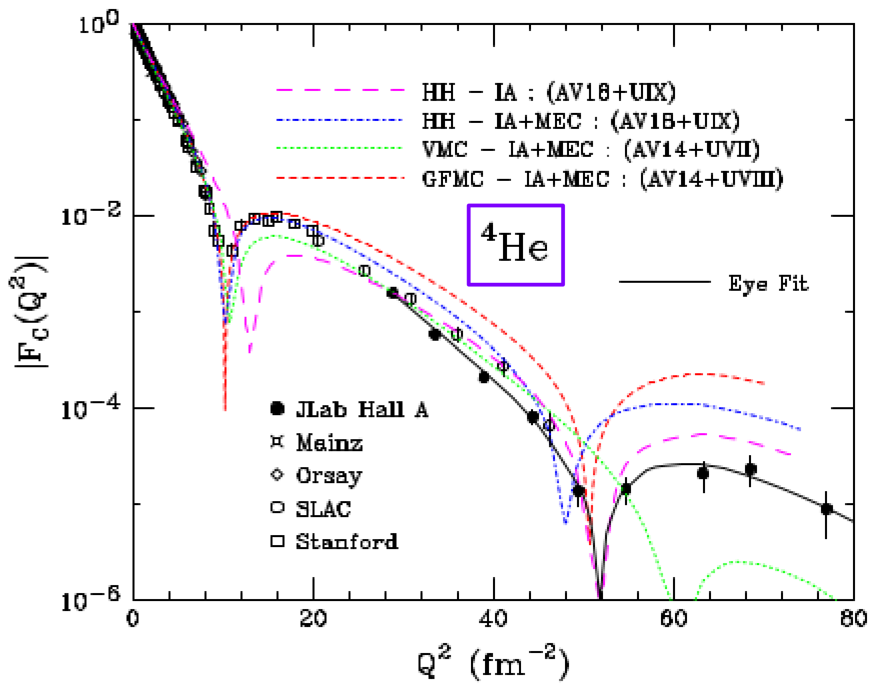
charge form factor



[Camsonne (JLab Hall A), PRL.119.162501 (2017)]



[Camsonne (JLab Hall A), PRL.112.132503 (2014)]

2. Photoproduction of φ(1020) vector-meson off ^{4}He targets
[$\gamma\, ^4\text{He} \rightarrow \varphi(1020)\, ^4\text{He}$]

theoretical framework

- We apply a distorted wave impulse approximation (DWIA) within the multiple scattering formulation, which treats the nucleus as a collection of free nucleons.

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

$$\frac{d\sigma}{d\Omega_{Lab}} = \text{[Phase factor]} \times |AF_T(t)|^2 \times [\frac{1}{4}\sum_{m_s,\lambda_\gamma}\sum_{m'_s,\lambda_V} |< k\lambda_V; p_f m'_s|T_{\mathbb{P}}|q\lambda_\gamma, p_i m_s >|^2]$$

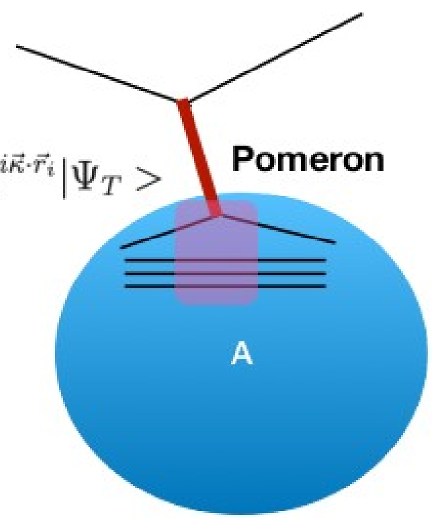
- Factorization approximation

$$-t = \vec{\kappa}^{\,2} - \omega^2$$

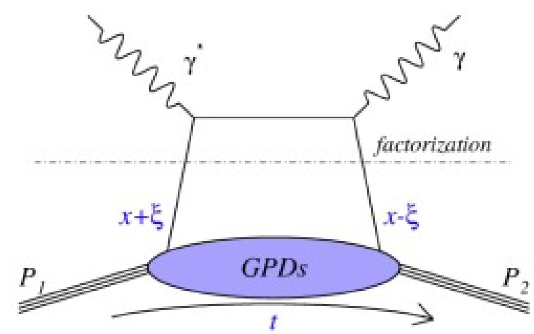
$$\omega = \sqrt{\vec{\kappa}^{\,2} + m_T^2} - m_T$$

$$F_T(t) = < \Psi_T| \sum_{i=1,A} e^{i\vec{\kappa}\cdot\vec{r}_i}|\Psi_T >$$

(nuclear form factor)



cf)



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

Argonne AV18 (AV)
Norfolk-Virginia (NV)

2. Photoproduction of φ(1020) vector-meson off ^{4}He targets [$\gamma\ ^4He \to \varphi(1020)\ ^4He$]

theoretical framework

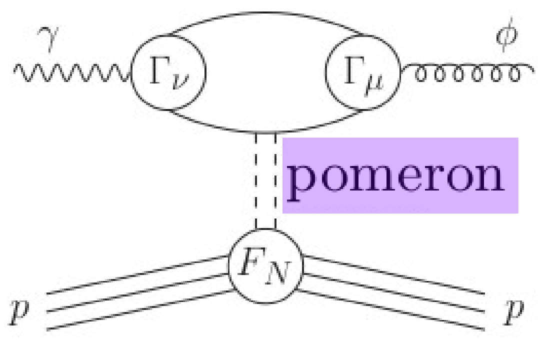
- We employ a Donnachie-Landshoff (DL) model.

[NPB.244.322 (1984)]

: Pomeron couples to the nucleon like a C=+1 isoscalar photon and its coupling is described in terms of a nucleon isoscalar EM form factor $F_N(t)$.

$$F_\phi(t) = \frac{2\mu_0^2}{(1-t/M_\phi^2)(2\mu_0^2 + M_\phi^2 - t)}, \quad F_N(t) = \frac{4M_N^2 - a_N^2 t}{(4M_N^2 - t)(1-t/t_0)^2}$$

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



- scattering amplitude: $\mathcal{M} = \varepsilon_\nu^* \bar{u}_{N'} \mathcal{M}^{\mu\nu} u_N \epsilon_\mu \quad \mathcal{M}^{\mu\nu} = -M(s,t)\Gamma^{\mu\nu}$

- transition operator:

$$\Gamma^{\mu\nu} = \not{k}_1 \left(g^{\mu\nu} - \frac{k_2^\mu k_2^\nu}{k_2^2} \right) - \gamma^\mu \left(k_1^\nu - \frac{k_1 \cdot k_2 k_2^\nu}{k_2^2} \right) - \left[k_2^\mu - \frac{k_1 \cdot k_2 (p_1^\mu + p_2^\mu)}{k_1 \cdot (p_1 + p_2)} \right] \left(\gamma^\nu - \frac{\not{k}_2 k_2^\nu}{k_2^2} \right)$$

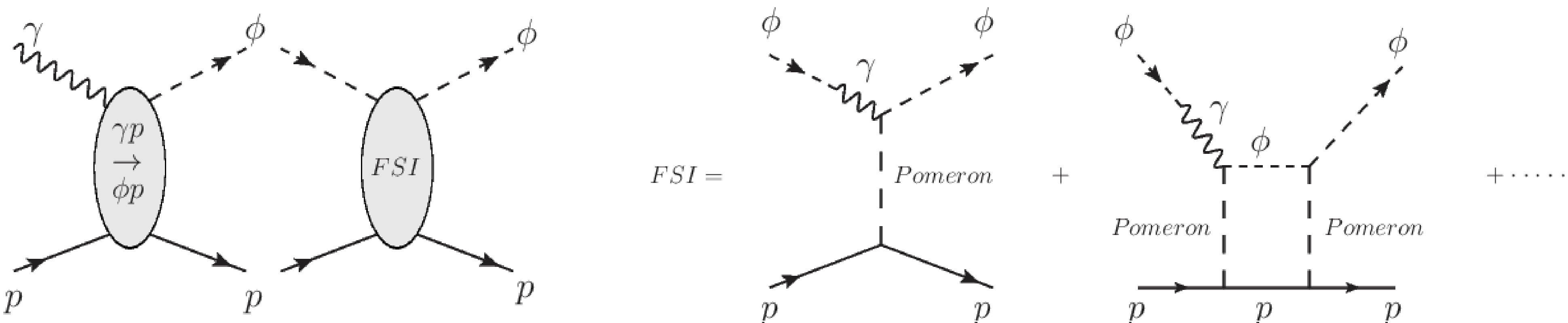
- scalar function: $M(s,t) = C_P F_1(t) F_2(t) \frac{1}{s} \left(\frac{s - s_{\text{th}}}{s_P} \right)^{\alpha_P(t)} \exp\left[-\frac{i\pi}{2} \alpha_P(t) \right]$

$\alpha_P(t)$	s_P [GeV^2]	s_{th} [GeV^2]	C_P	a_N^2	μ_0^2	t_0 [GeV^2]
1.08+0.25t	4	0	3.65	2.8	1.1	0.7

2. Photoproduction of $\varphi(1020)$ vector-meson off ^{4}He targets
[$\gamma\, ^4\mathrm{He} \rightarrow \varphi(1020)\, ^4\mathrm{He}$]

theoretical framework

- The effect of the final state interaction (FSI) is considered.
- We solve the Lippman-Schwinger equation and use a vector-meson dominance.



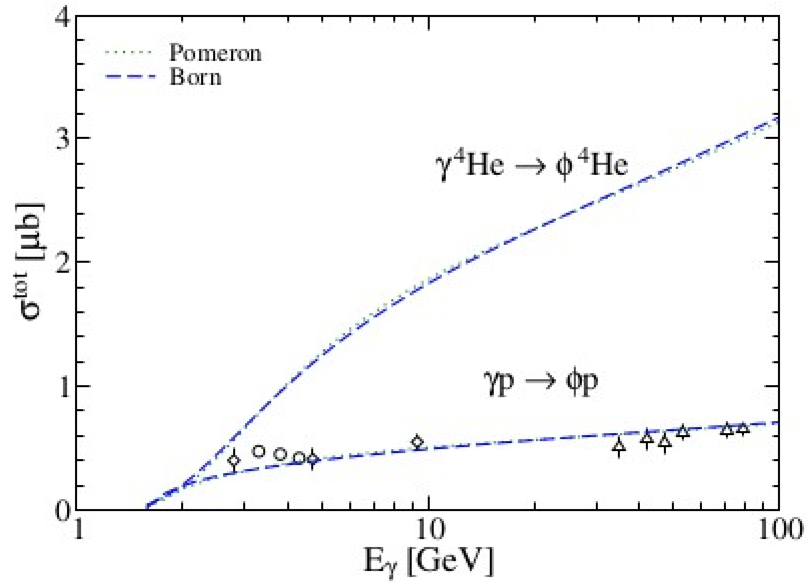
$$< \vec{k}, \lambda'_V m'_{s_A} | T_{fsi}(W) | \vec{q}, \lambda_\gamma m_{s_A} > = \sum_{\lambda_V, m''_{s_A}} \int d\vec{p} < \vec{k}, \lambda'_V m'_{s_A} | T_{V'N',VN}(W) | \vec{p} \lambda_V m''_{s_A} >$$

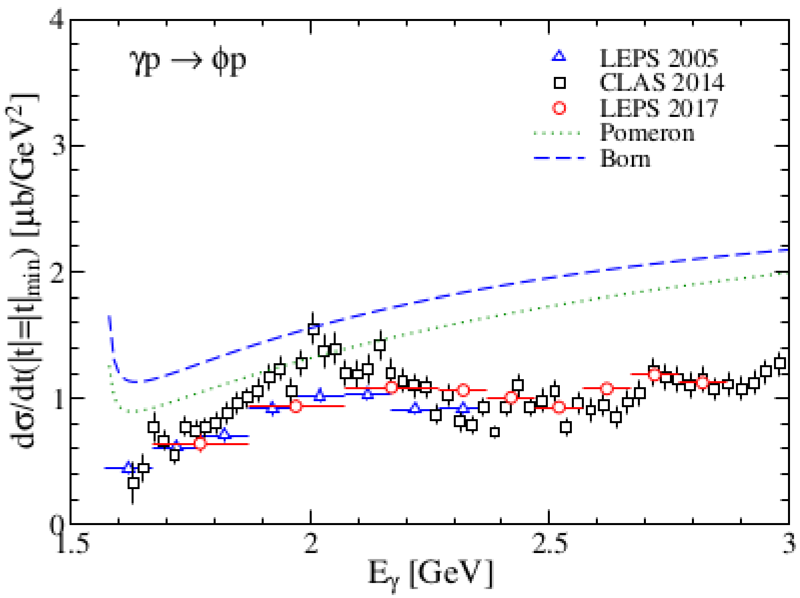
$$\times \frac{1}{W - E_V(\vec{p}) - E_A(\vec{p}) + i\epsilon} < \vec{p}, \lambda_V m''_{s_A} | T_{imp}(W) | \vec{q}, \lambda_\gamma m_{s_A} >$$

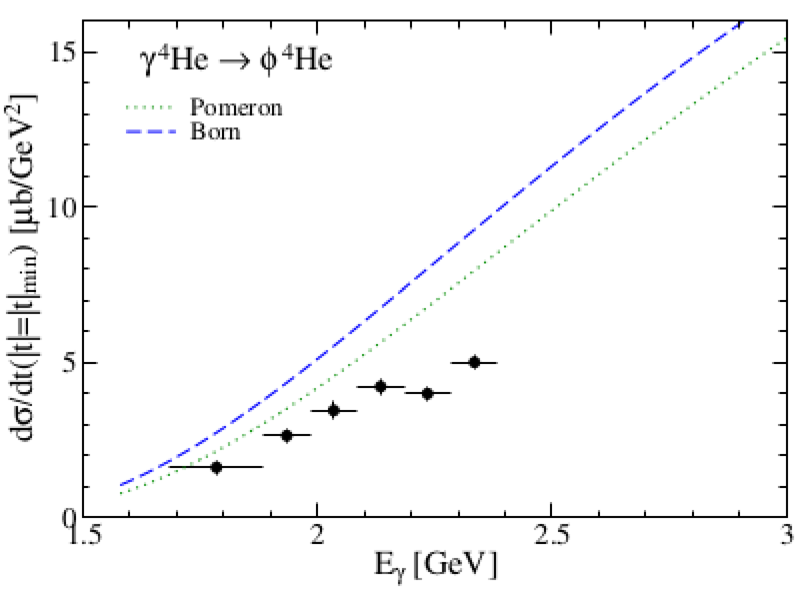
2. Photoproduction of φ(1020) vector-meson off ^{4}He targets [$\gamma\,^4\text{He} \rightarrow \varphi(1020)\,^4\text{He}$]

total & differential cross sections

preliminary

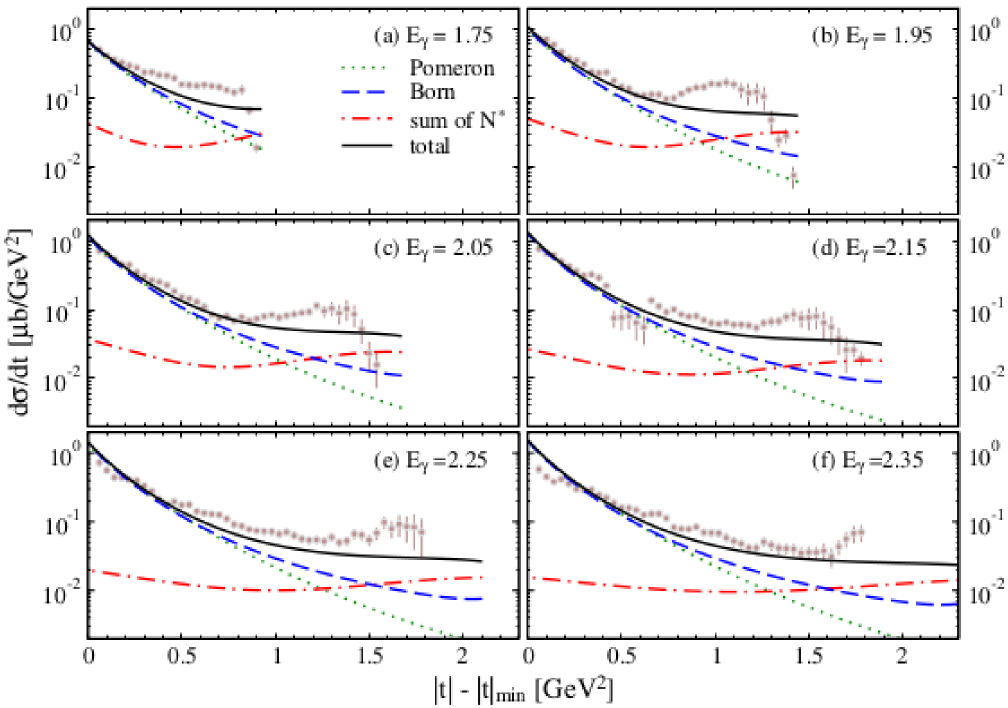




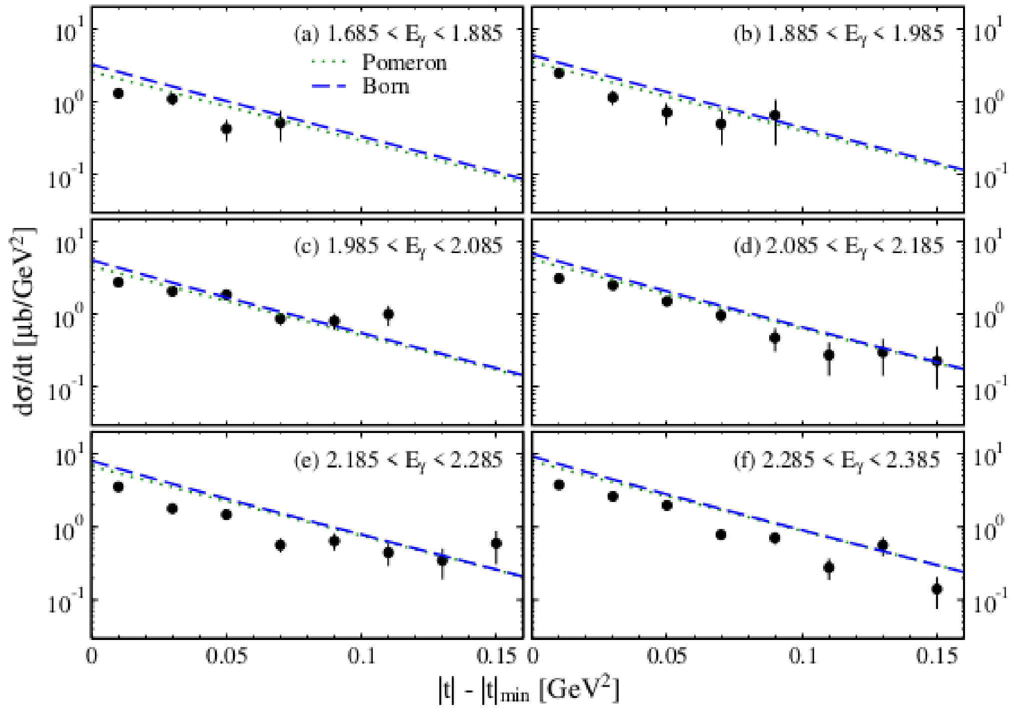


2. Photoproduction of φ(1020) vector-meson off ^{4}He targets
[$\gamma\ ^4\text{He} \to \varphi(1020)\ ^4\text{He}$]

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



$\gamma\ ^4\text{He} \to \varphi\ ^4\text{He}$



2. Photoproduction of φ(1020) vector-meson off ^{4}He targets

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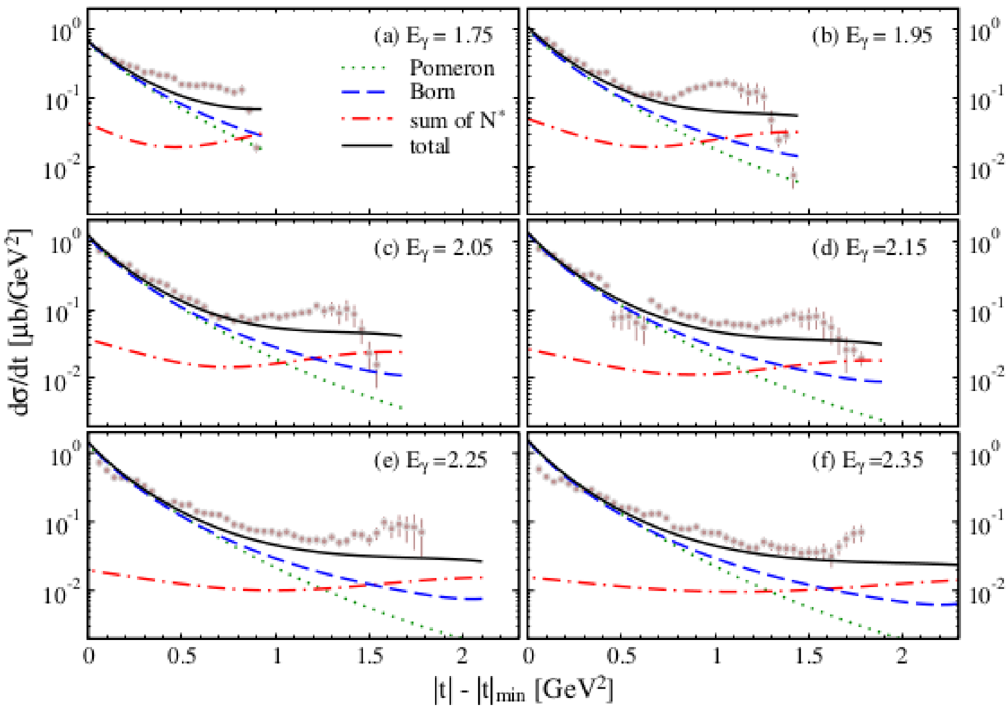

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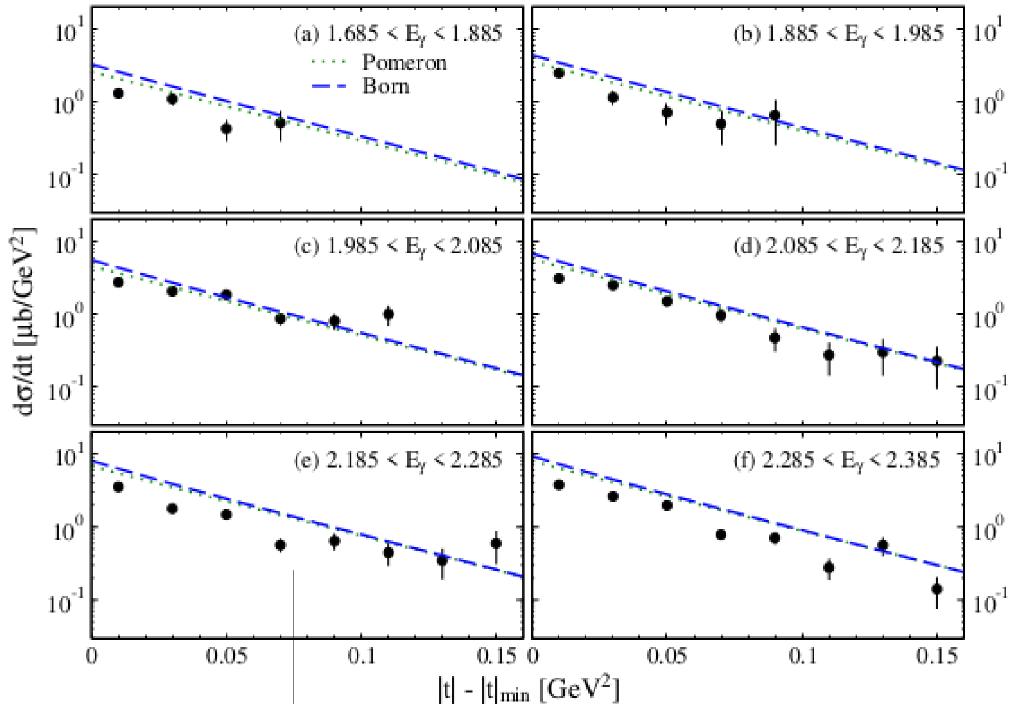
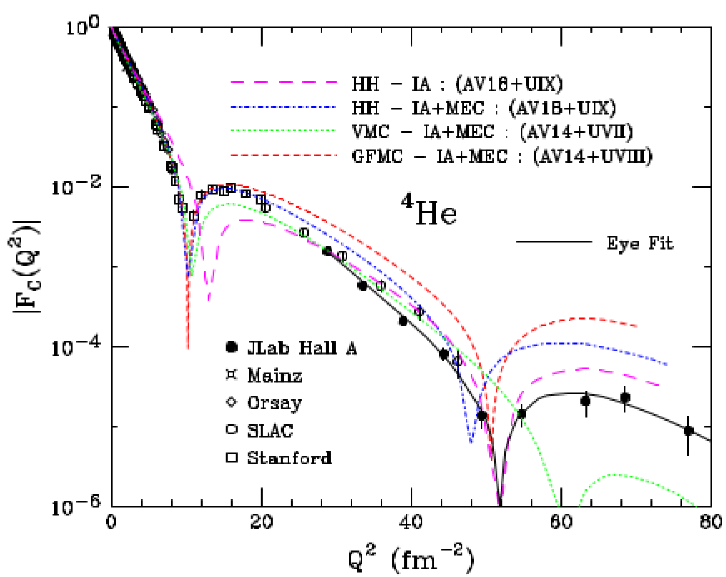
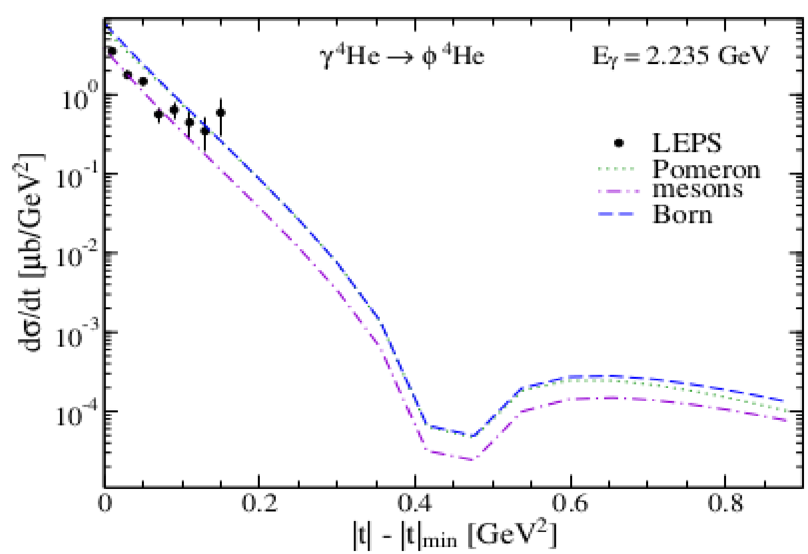


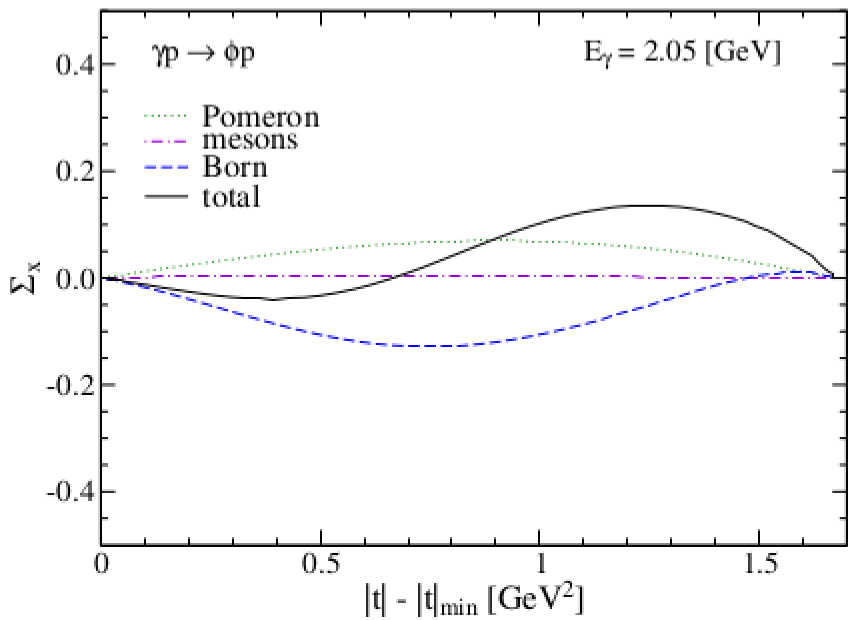




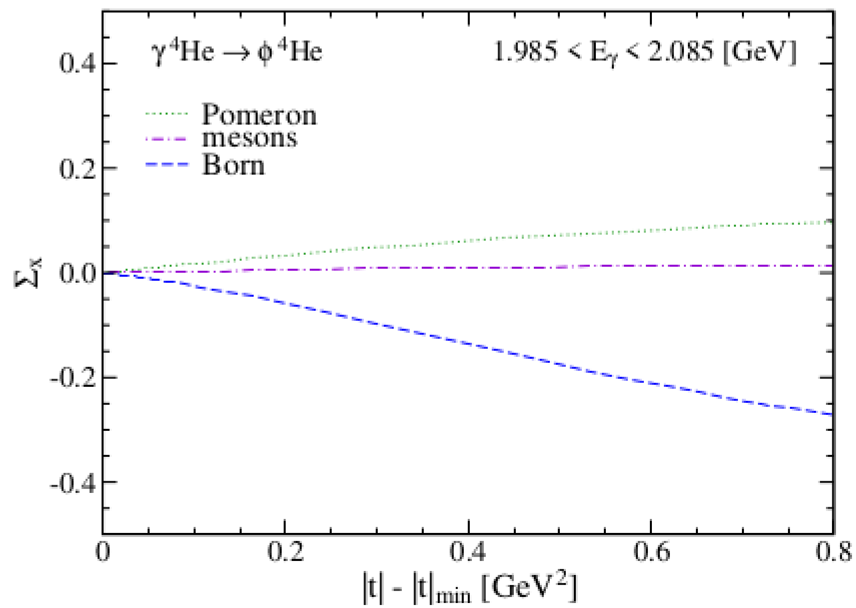
2. Photoproduction of φ(1020) vector-meson off ^{4}He targets [$\gamma\, ^4\mathrm{He} \to \varphi(1020)\, ^4\mathrm{He}$]

beam asymmetry

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



$\gamma\, ^4\mathrm{He} \to \varphi\, ^4\mathrm{He}$

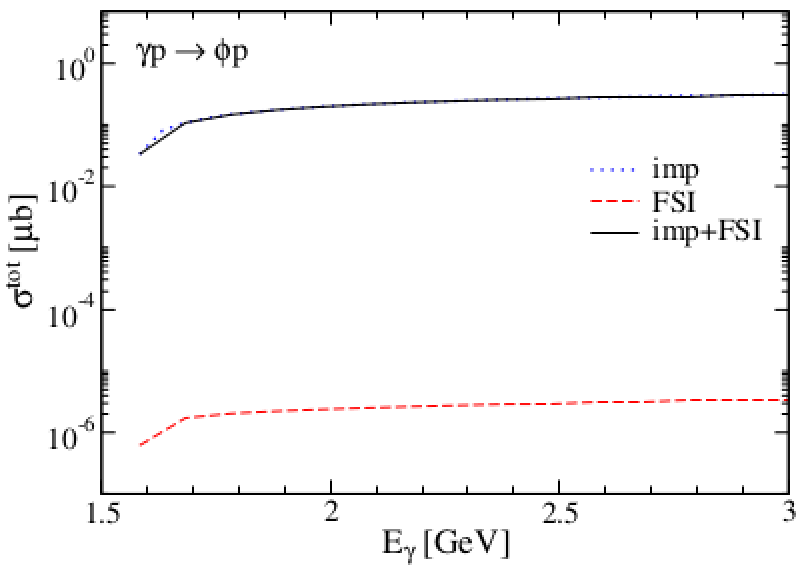


- Polarization observables are useful to shed light on the reaction mechanism.

2. Photoproduction of φ(1020) vector-meson off ^{4}He targets
[$\gamma\ ^4\mathrm{He} \to \varphi(1020)\ ^4\mathrm{He}$]

final state interaction

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



- The effect of the FSI is small when a vector-meson dominance is considered.

$$\sigma_{\gamma p \to \phi p} = \frac{e}{2\gamma_\phi} \sigma_{\phi p \to \phi p}$$

2. Photoproduction of φ(1020) vector-meson off ^{4}He targets
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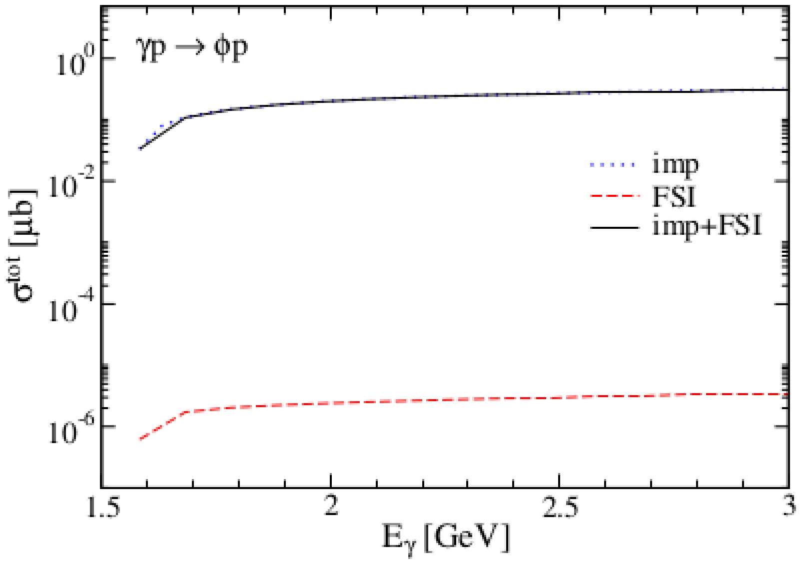

The results will come soon.

- The effect of the FSI is small when a vector-meson dominance is considered.

$$\sigma_{\gamma p\to\phi p} = \frac{e}{2\gamma_\phi}\sigma_{\phi p\to\phi p}$$

- We will consider the VN-VN interaction directly with a gluon-exchange model.

1. Photo- and electro-production of vector-mesons off nucleons
[$\gamma^{(*)}\, p \rightarrow V\, p$], $V = \varphi, \rho, \omega, J/\psi$

We can extend these elementary processes
to the $\gamma^{(*)}\, A \rightarrow V\, A$ processes.

2. Photoproduction of $\varphi(1020)$ vector-meson off ^{4}He targets
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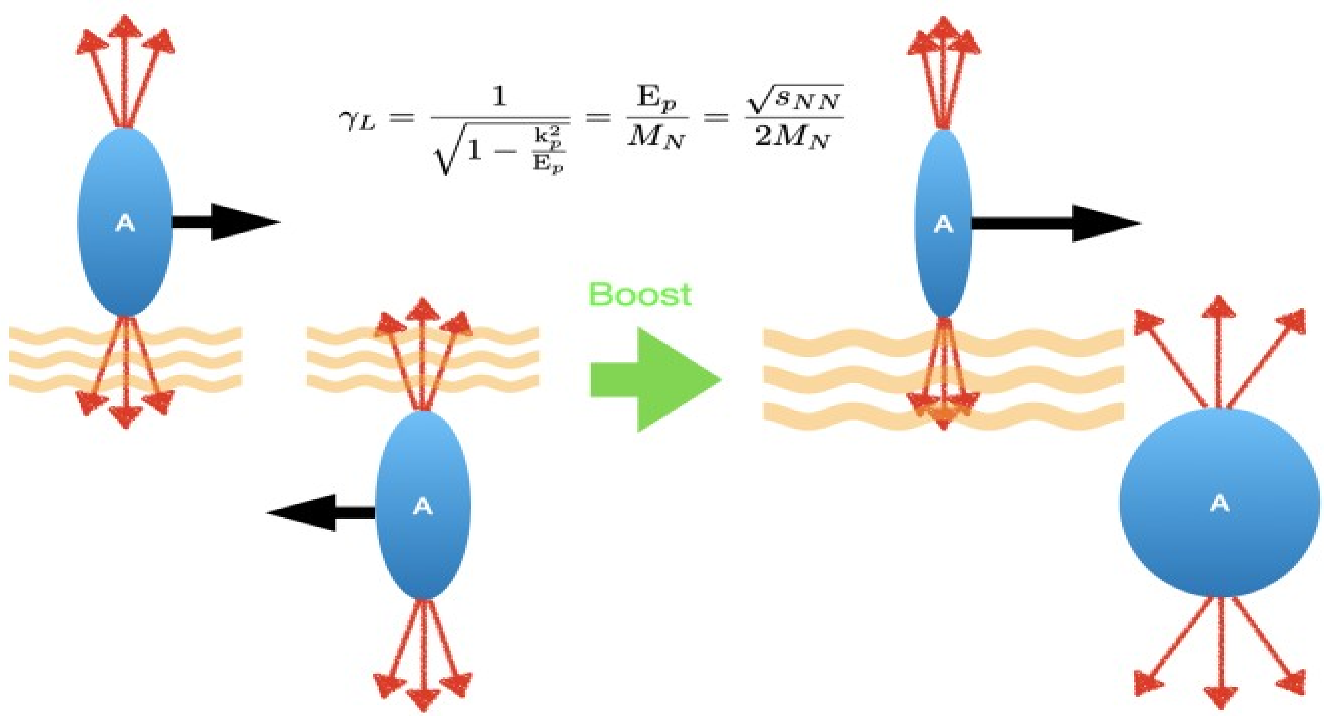
3. Vector-meson production in ultra-peripheral collision (UPC)
[$A\, A \rightarrow A\, A\, V$]

3. Vector-meson production in ultra-peripheral collision (UPC) [A A → A A V]

- Ultra-peripheral collisions (UPCs) involves collisions of relativistic nuclei when the impact parameters are large enough so that there are no hadronic interactions.
- The ions interact electromagnetically, via photonuclear or two-photon interactions.
- The transverse comp.s of the EM waves can be considered as a photon-flux distribution in terms of the equivalent photon approximation (EPA).
- In UPC's, the photons are nearly real, with virtuality $Q^2 < (\hbar/R_A)^2$.

[collider lab. frame]



[nucleus-target (nt) frame]

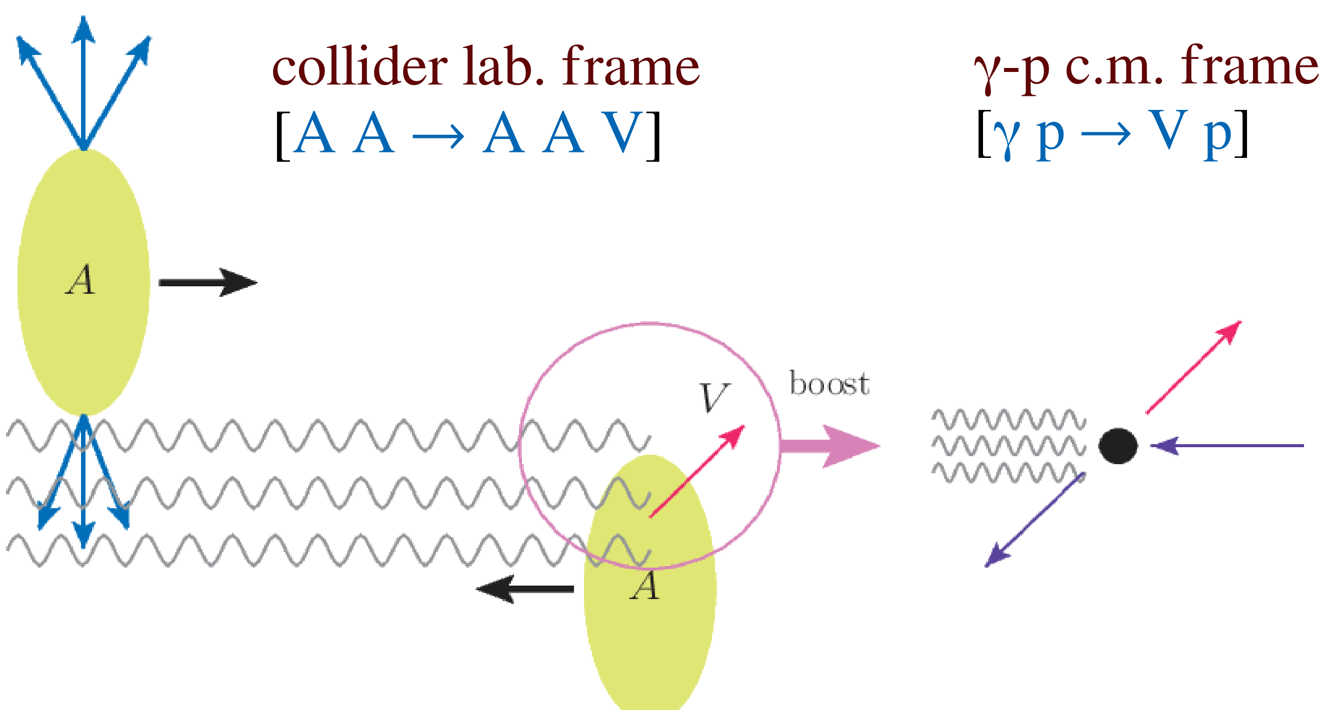
no hadron interaction if $b > 2R_A$

3. Vector-meson production in ultra-peripheral collision (UPC) [A A → A A V]

- In the collider lab. frame, we consider that an emitted photon inside the left nucleus hits the proton on the right.

$$k_\gamma^{\rm lab} = (\mathrm{k}_\gamma, 0, 0, \mathrm{k}_\gamma)\,, \quad k_p^{\rm lab,right} = (\mathrm{E}_p, 0, 0, -\mathrm{k}_p)$$

- We can boost from "the collider lab. frame" to "the γ-p c.m. frame ($\mathrm{k}_\gamma = \mathrm{k}_p$)".



3. Vector-meson production in ultra-peripheral collision (UPC) [A A → A A V]

$$E_\gamma = (W_{\gamma p}^2 - M_p^2)/(2M_p)$$

Facility	System	$\sqrt{s_{NN}}$ or $\sqrt{s_{eN}}$	Max. E_γ	Max. $W_{\gamma p}$	Max $\sqrt{s_{\gamma\gamma}}$
RHIC	AuAu	200 GeV	320 GeV	25 GeV	6 GeV
	pAu	200 GeV	1.5 TeV	52 GeV	30 GeV
	pp	500 GeV	20 TeV	200 GeV	150 GeV
LHC [17]	PbPb	5.1 TeV	250 TeV	700 GeV	170 GeV
	pPb	8.16 TeV	1.1 PeV	1.5 TeV	840 GeV
	pp	14 TeV	16 PeV	5.4 TeV	4.2 TeV
FCC-hh [18]	PbPb	40 TeV	13 PeV	4.9 TeV	1.2 TeV
SPPC [7]	pPb	57 TeV	58 PeV	10 TeV	6.0 TeV
	pp	100 TeV	800 PeV	39 TeV	30 TeV
eRHIC [19]	eAu	89 GeV	4.0 TeV	89 GeV	15 GeV
LHeC [20]	ePb	820 GeV	360 TeV	820 GeV	146 GeV

capabilities of different colliders

ArXiv:2005.01872 [nucl-ex]

- RHIC: The photon energies are well suited for photonuclear interactions involving meson (Reggeon) exchange.
- LHC: The energy frontier for photonuclear & two-photon physics.

3. Vector-meson production in ultra-peripheral collision (UPC) [A A → A A V]

- Glauber model [Annu.Rev.Nucl.Part.Sci.2007. 57:205-43]
  Nucleons at high energies are not deflected due to large momentum.
  Motions of nucleons are independent of nucleus.
  Overall cross sections are described in terms of nucleon-nucleon cross sections.

- The emitted photon from a nucleus can have various energies and its distribution is characterized by the photon-flux distribution:

$$\frac{dN_\gamma(E_\gamma)}{dE_\gamma} \approx \frac{2Z^2\alpha}{\pi E_\gamma}\left[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}[K_1^2(\zeta) - K_0^2(\zeta)]\right], \quad \zeta = \frac{2R_A E_\gamma}{\gamma}$$

$$\boxed{\sigma_{AA\to\phi AA} = \int_0^\infty dE_\gamma \frac{dN_\gamma(E_\gamma)}{dE_\gamma}\sigma_{\gamma^* A\to\phi A}}$$

no hadron interaction
if b > $2R_A$ ($R_A = 1.2A^{1/3}$ fm)

$$\boxed{\sigma_{\gamma^* A\to\phi A}(W_{\gamma p}) = \int d^2\boldsymbol{b}\,[1 - \exp[-\sigma_{\gamma^* p\to\phi p}(W_{\gamma p})T_A(\boldsymbol{b})]]}$$

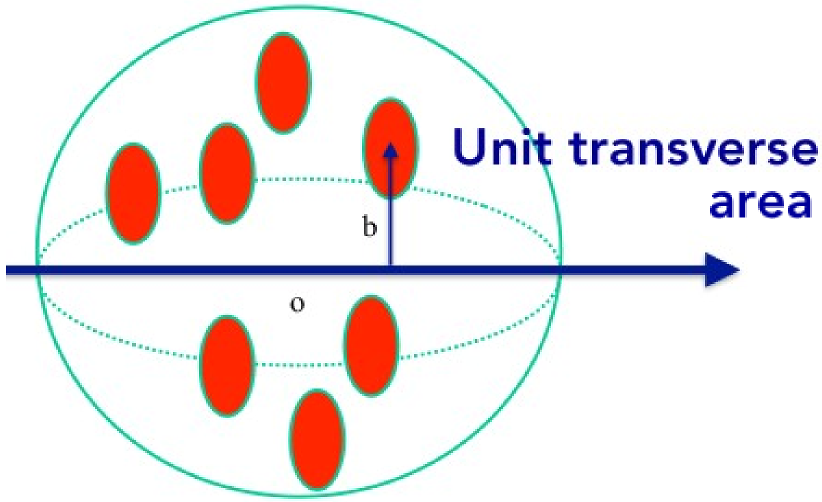
- With the eikonal Glauber model, we can write the γ A → V A cross section in terms of the elementary γ p → V p reaction process.

3. Vector-meson production in ultra-peripheral collision (UPC) [A A → A A V]

$$\sigma_{\gamma^* A\to\phi A}(W_{\gamma p}) = \int d^2\boldsymbol{b}\,[1-\exp[-\sigma_{\gamma^* p\to\phi p}(W_{\gamma p})\,T_A(\boldsymbol{b})]]$$

$$T_A(\boldsymbol{b}) = \int_{-\infty}^{\infty} dz\rho_A(\sqrt{|\boldsymbol{b}|^2+z^2})$$

- "Nuclear shape function" describes the transverse reaction probability at **b**.



$$\rho_A(s) = \frac{\rho_0\left[1+c\,(s/R_A)^2\right]}{1+\exp[(s-R_A)/d]}$$

- "Woods-Saxon density" is normalized by

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3. Vector-meson production in ultra-peripheral collision (UPC) [A A → A A V]

$$\boxed{\sigma_{\gamma^* A\to\phi A}(W_{\gamma p}) \;=\; \int d^2\boldsymbol{b}\,[1-\exp[-\sigma_{\gamma^* p\to\phi p}(W_{\gamma p})\,T_A(\boldsymbol{b})]]}$$

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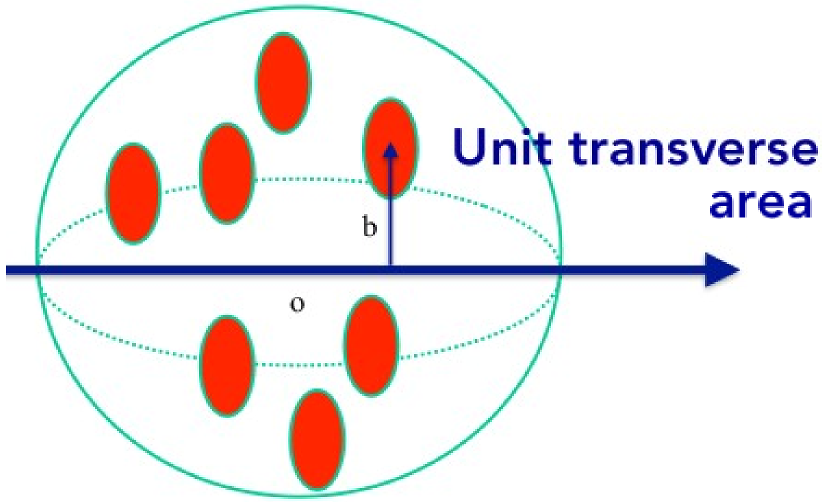

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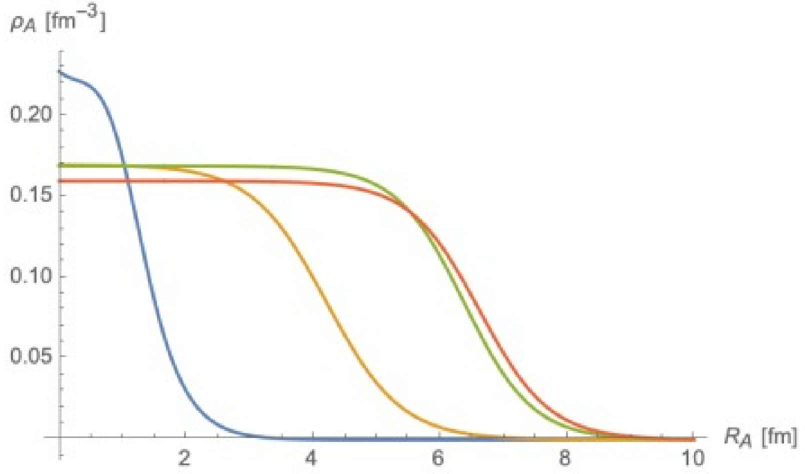
- inputs:

Nucleussxt	A	Z_A	R_A [fm]	d [fm]	ρ_0 [fm^{-3}]	c
He	4	2	1.01	0.327	0.2381	0.445
Cu	63	29	4.21	0.586	0.1701	0
Au	197	79	6.38	0.535	0.1693	0
Pb	208	82	6.62	0.549	0.1600	0

- Woods-Saxon density profiles (ρ_A)



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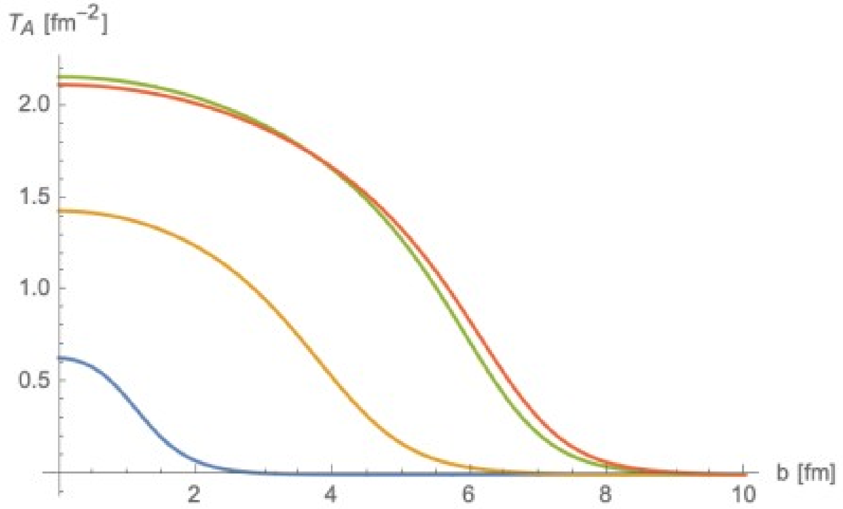

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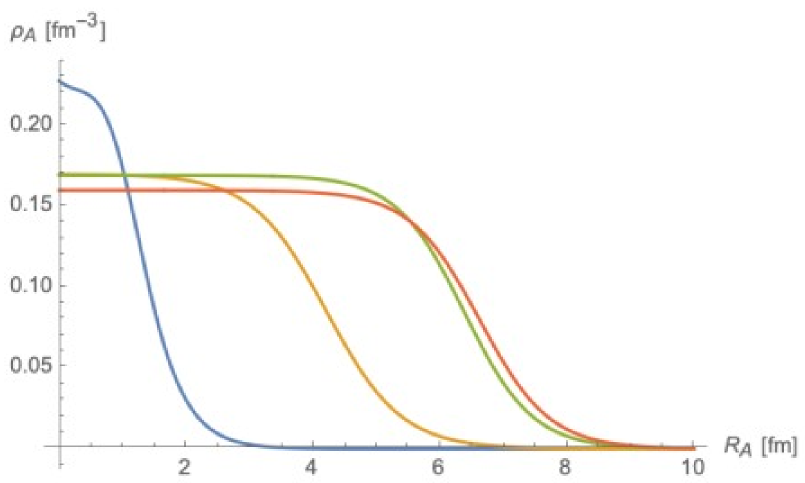

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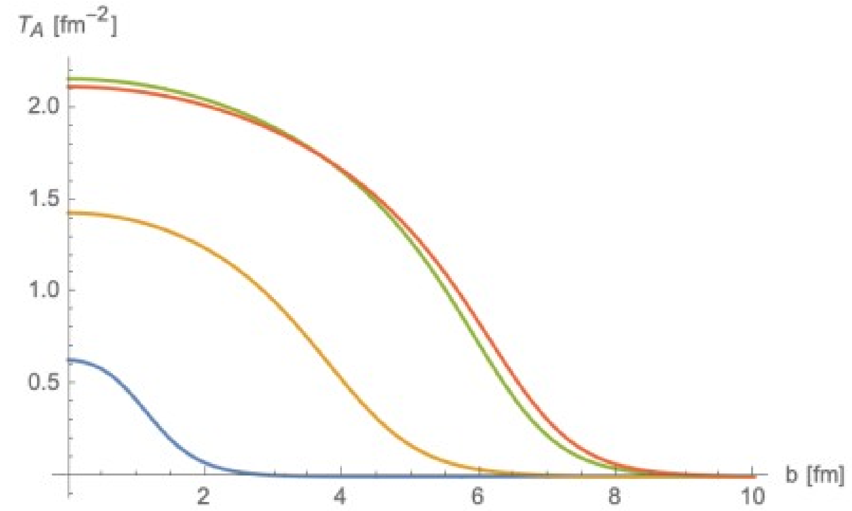

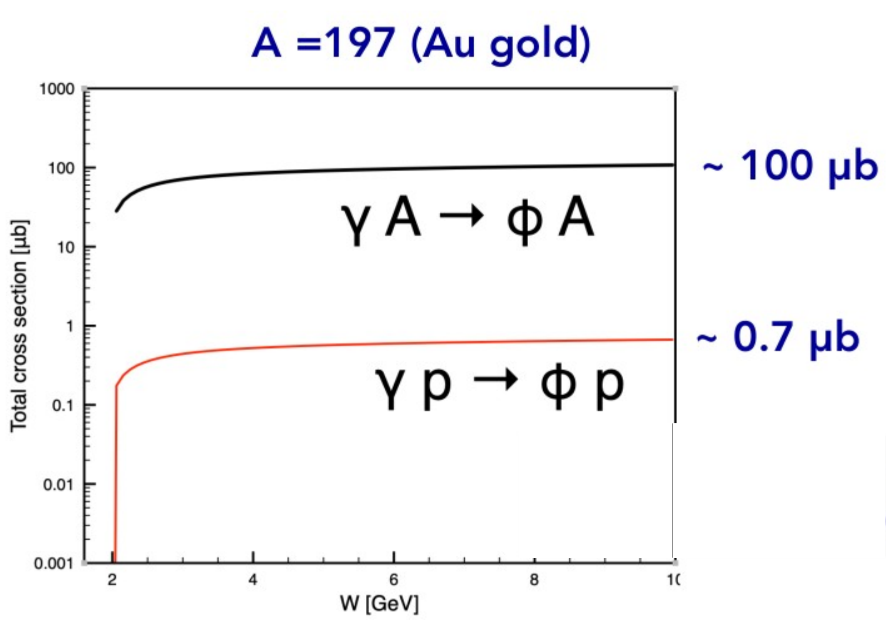

$$\frac{d\sigma_{AA\to\phi AA}}{dy} =$$

$$N_\gamma(y)\,\sigma_{\gamma^* A\to\phi A}(y) + N_\gamma(-y)\,\sigma_{\gamma^* A\to\phi A}(-y)$$

very preliminary !!!

Summary

1. Photo- and electro-production of vector-mesons off nucleons

(1) $\gamma^{(*)}\, p \to \varphi\, p$ [S.H.Kim, S.i.Nam] ▸PRC.100.065208 (2019) ▸PRC.101.065201 (2020)

- We employed an effective Lagrangian approach combined with a Regge model.
- The role of Pomeron- and meson-contributions is clearly 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.

(2,3) $\gamma^{(*)}\, p \to \rho\, p$, $\omega\, p$ (4) $\gamma^{(*)}\, p \to J/\psi\, p$

- The theoretical analyses are very rare.
- Will be measured at JLab and EIC (Electron-Ion Collider).

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2. Photoproduction of φ(1020) vector-meson off ^{4}He targets [$\gamma\, {}^4\mathrm{He} \to \varphi\, {}^4\mathrm{He}$]

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- The elementary process can be used to the UPC with a Glauber model.

Thank you very much
for your attention