# Exclusive electroproduction of vector mesons

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In collaboration with
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2nd APCTP Workshop on the Physics of Electron Ion Collider
11.30 - 12.02, 2023, Daegu Grand Hotel

# 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

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

Regge model, at low W & $Q^2$

pQCD model, at high W & $Q^2$

production off nuclear targets

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

distorted-wave impulse approximation

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distorted-wave impulse approximation

◇ These reactions are a rich source of information on soft and hard diffractive processes as well as the hadronic properties of the virtual photon.

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distorted-wave impulse approximation

◇ These reactions are a rich source of information on soft and hard diffractive processes as well as the hadronic properties of the virtual photon.

◇ 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 $J/\psi$ at 11 GeV

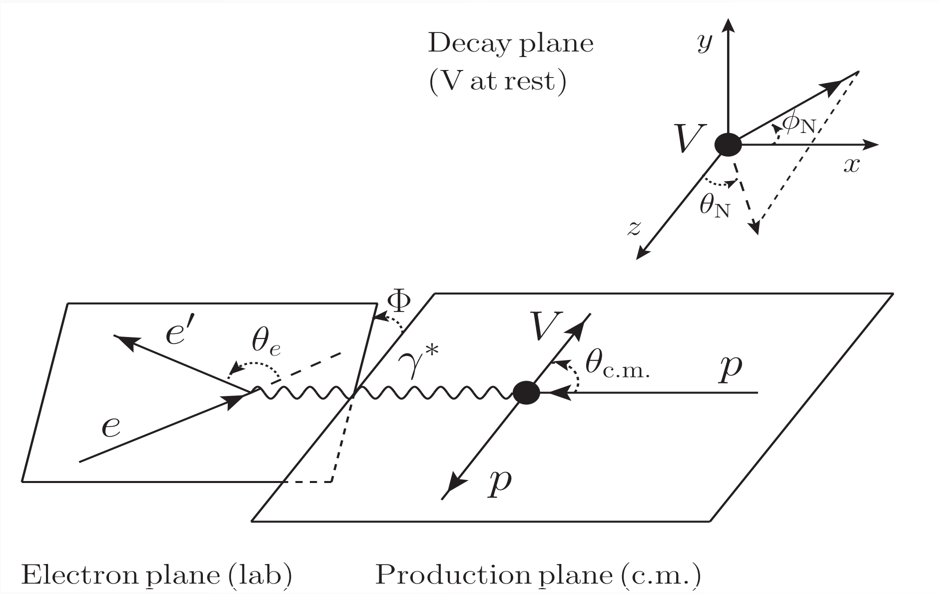
[E12-12-007] Exclusive Phi Meson Electroproduction with CLAS12

◇ 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-]

→ spin-density matrices ($\rho_{ij}$) [photo-, electro-]

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

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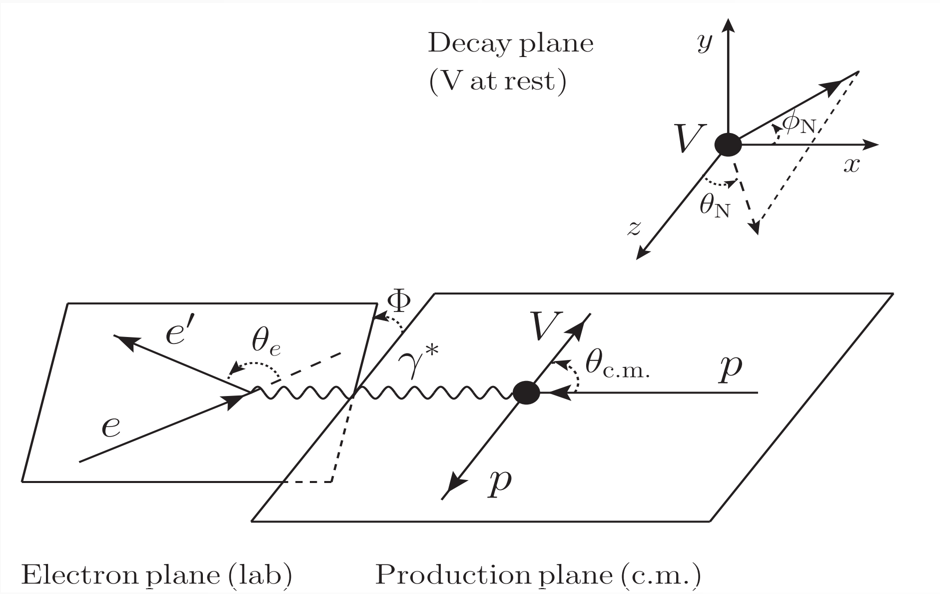


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→ $\sigma$, $d\sigma/d\Omega$, $d\sigma/dt$ [photo-, electro-]
→ $\sigma_T$, $\sigma_L$, $\sigma_{TT}$, $\sigma_{LT}$, $R=\sigma_L/\sigma_T$ ... [electro-]
(T-L separated cross sections)

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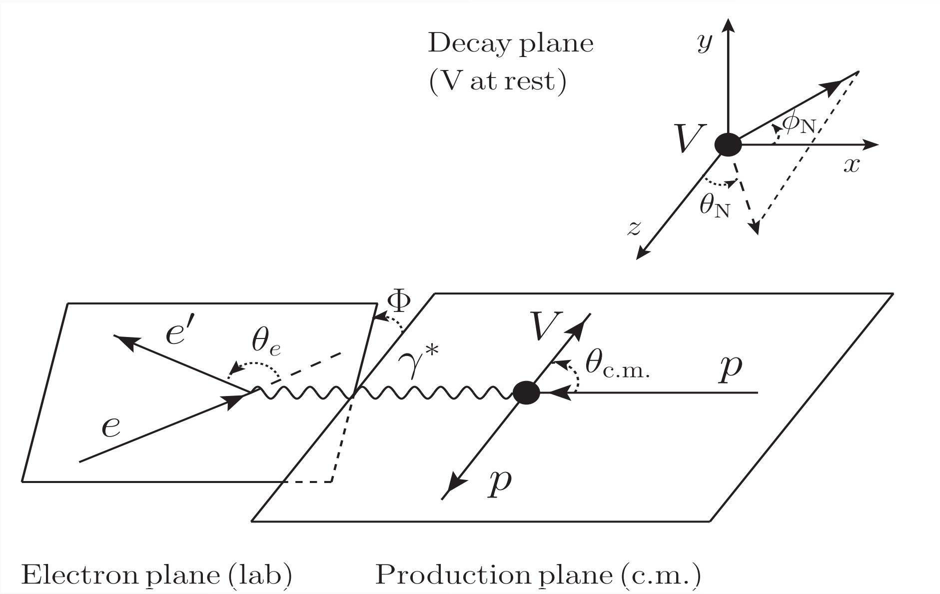


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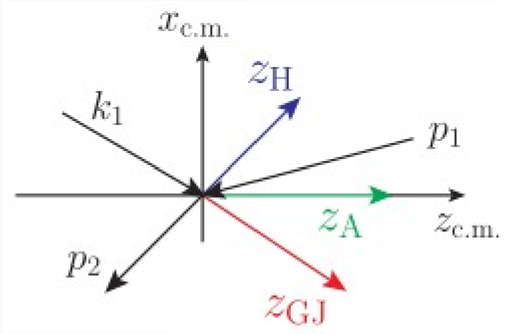
## ❑ Decay frame



Adair frame

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

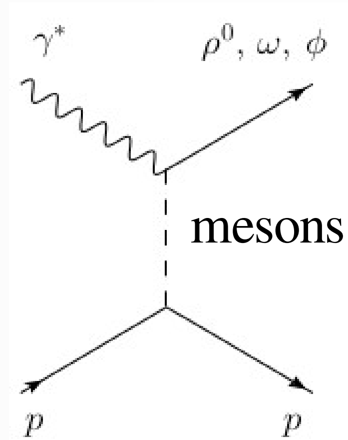
Gottfried-Jackson frame: in favor of t-channel helicity conservation (TCHC)

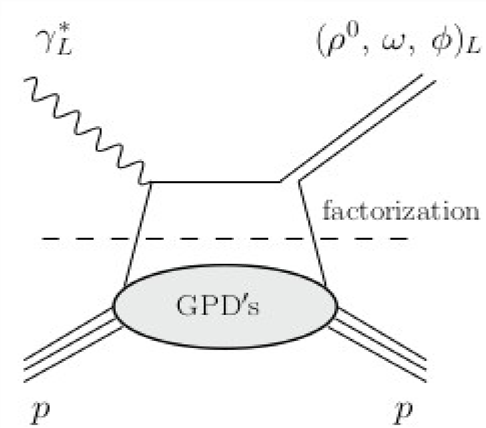
# Exclusive electroproduction of vector mesons

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

## theoretical framework

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

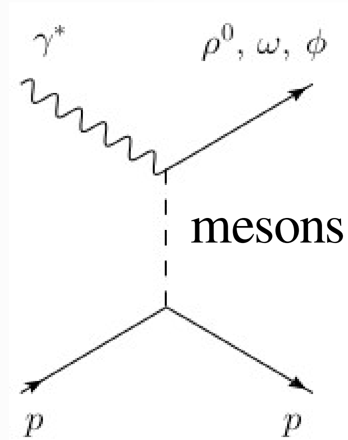
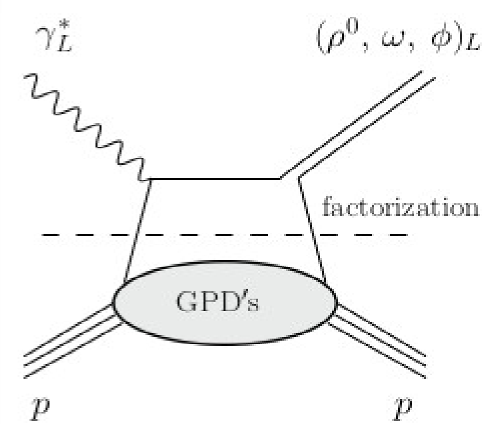



*t*-channel Regge trajectory exchange <<----->> handbag diagram

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

## theoretical framework

| $Q^2$=0 <---> low $Q^2$ | <<----->> | high $Q^2$ |
|---|---|---|
|  | |  |
| *t*-channel Regge trajectory exchange | <<----->> | handbag diagram |



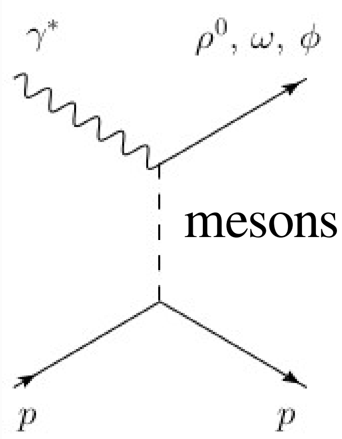


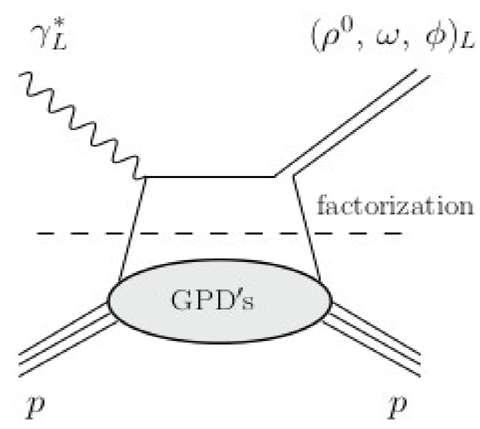
- Extending to "the virtual-photon sector" opens the way
  - > to tune hadronic component of the exchanged photon
  - > to explore to what extent meson exchange survives
  - > to observe hard-scattering mechanisms, with a second hard scale, "photon virtuality $-(k_e-k_{e'})^2=Q^2$".

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

theoretical framework

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




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

JML Regge model

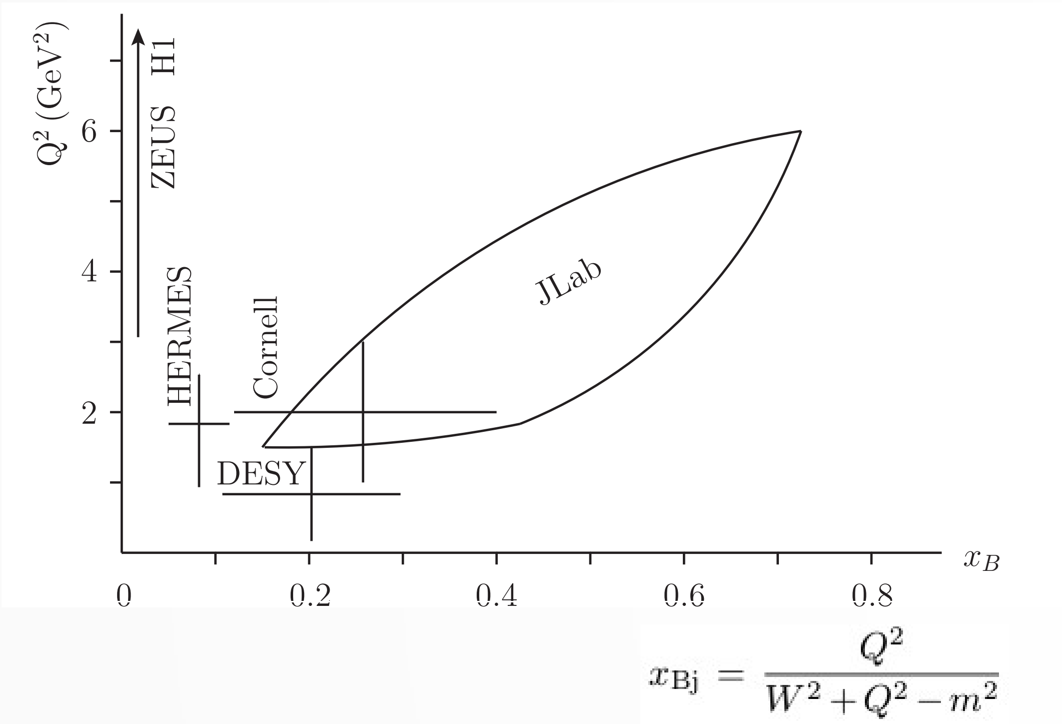
PLB.489.313 (2000)
PRD.70.054023 (2004)

VGG GPD-based model

PRL.80.5064 (1998)
PRD.60.094017 (1999)

# Exclusive electroproduction of vector mesons

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




[Kinematical range covered by vector meson electoproduction experiments]

❑ We can test which of the two descriptions - with “hadronic” or “quark” degrees of freedom - applies in the considered kinematical domain.

Exclusive electroproduction of vector mesons

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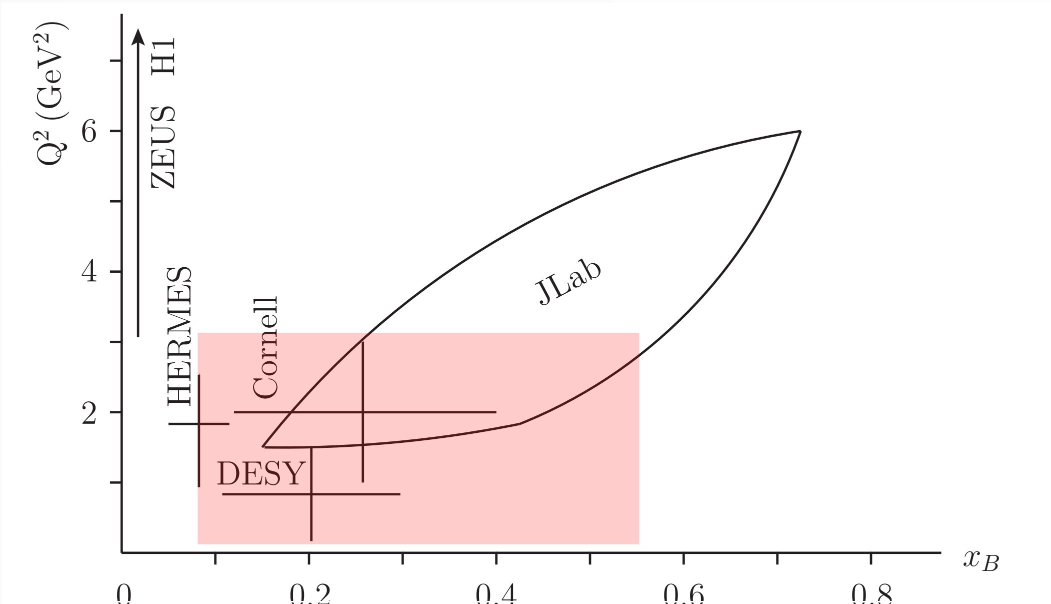
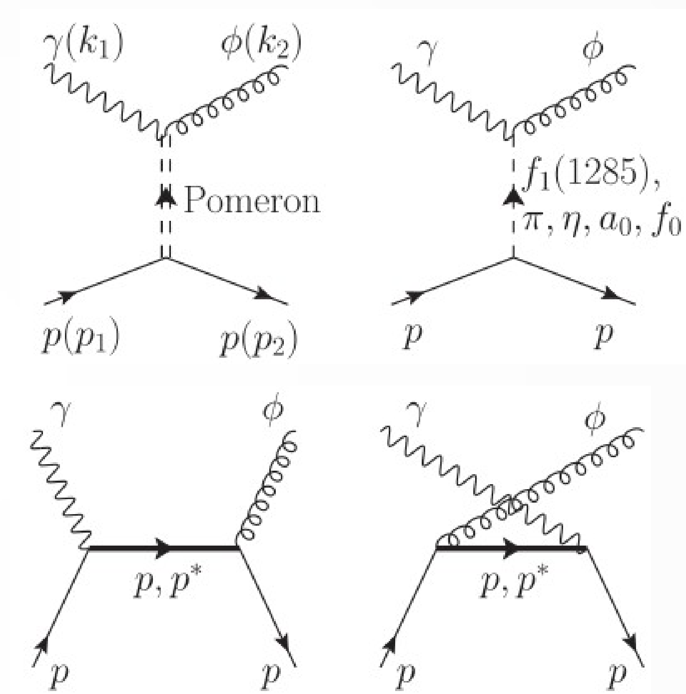



$$x_{\rm Bj} = \frac{Q^2}{W^2 + Q^2 - m^2}$$

[Kinematical range covered by vector meson electoproduction experiments]

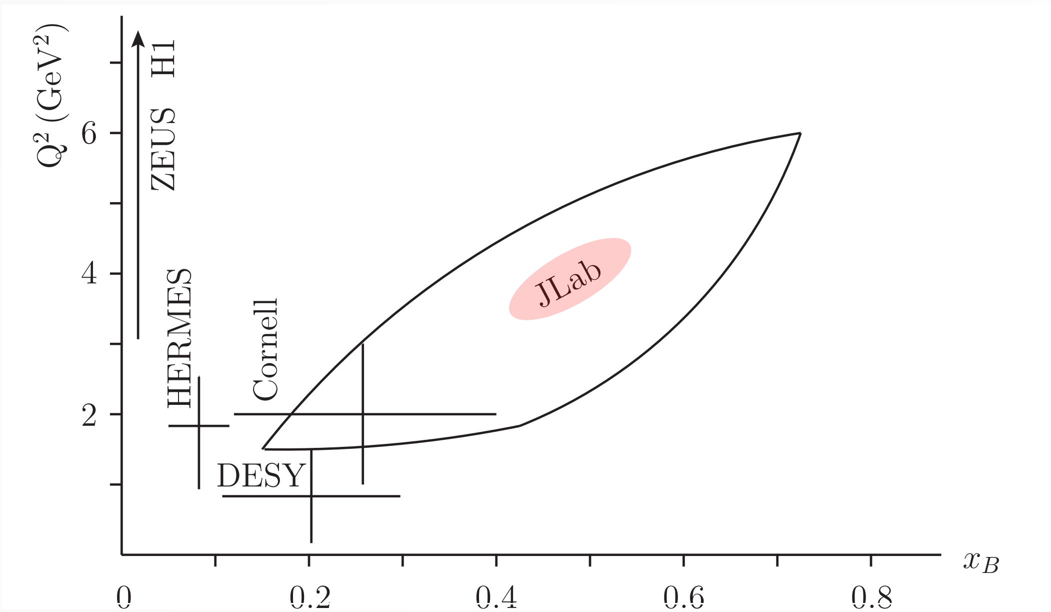
Feynman diagrams




- ❑ 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 ($Q^2 \lesssim Mv^2$) and low energies ($W \lesssim$ several GeV), our hadronic effective model is applicable.

# Exclusive electroproduction of vector mesons

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

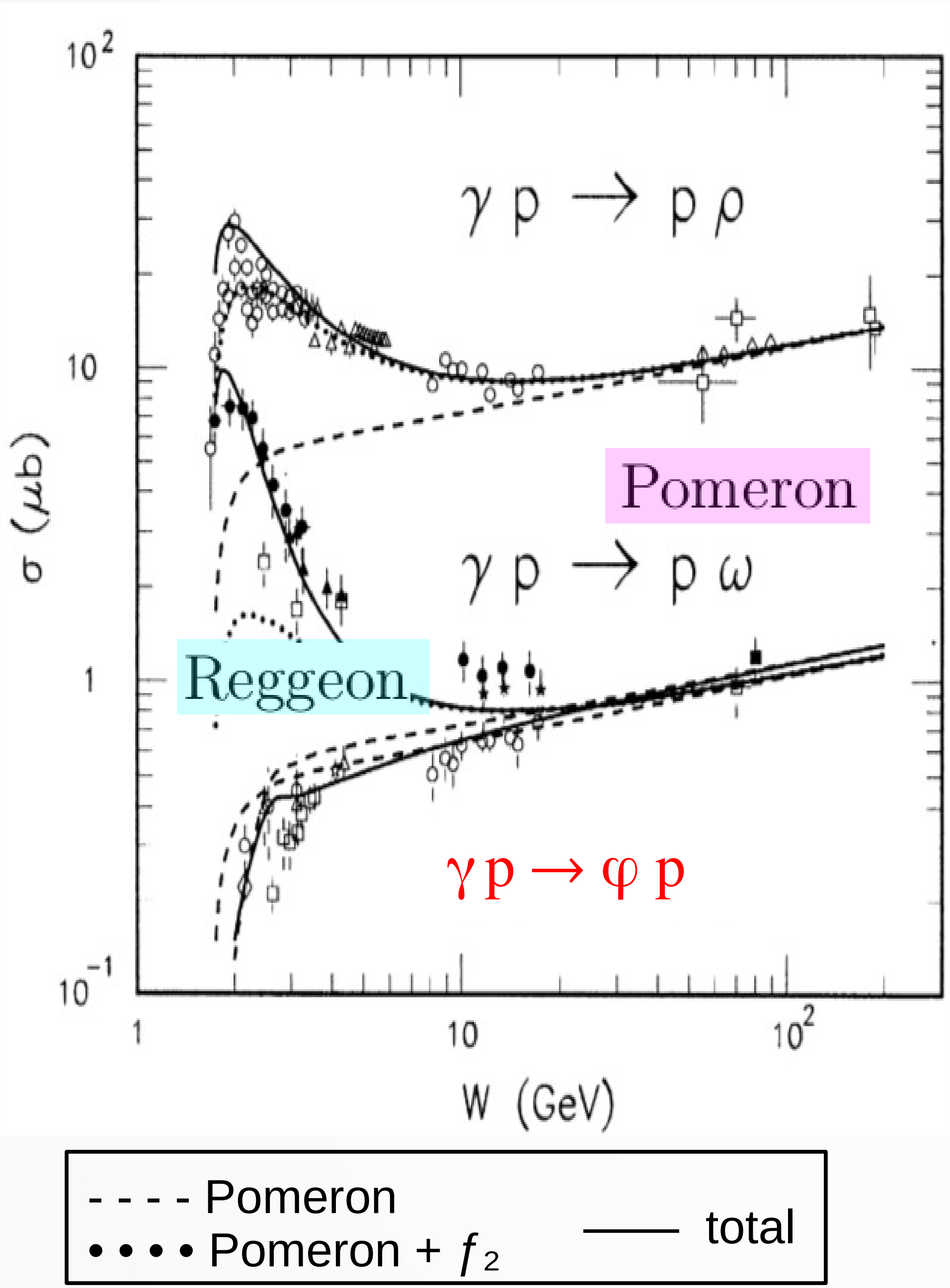



$$x_{\mathrm{Bj}} = \frac{Q^2}{W^2 + Q^2 - m^2}$$

[Kinematical range covered by vector meson electoproduction experiments]

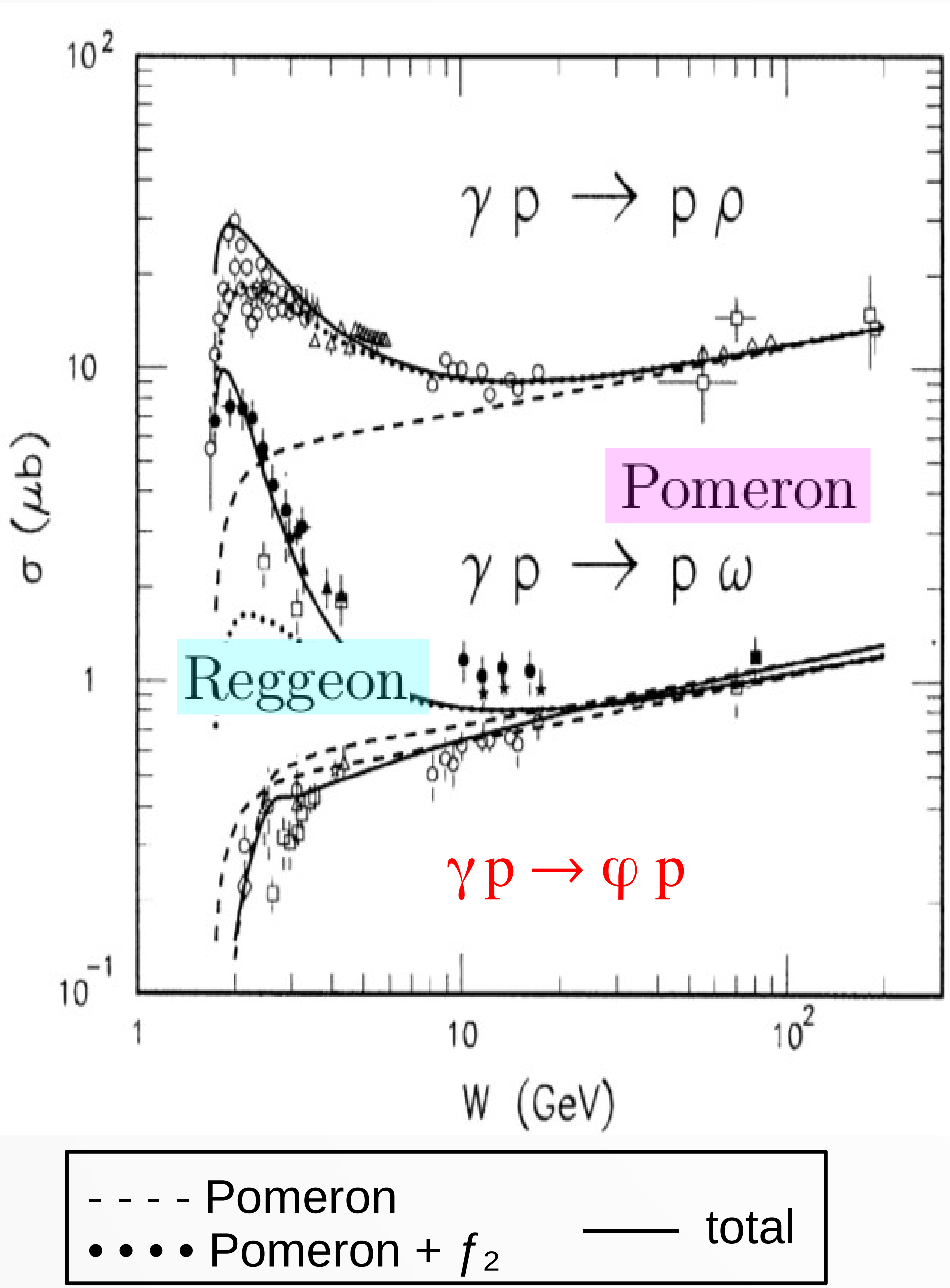
- The upcoming data from Jefferson Laboratory are particularly promising because they cover wide kinematical ranges of $Q^2$ and $x_B$ and thus provide a unique opportunity to test the two models.
- Electron-Ion Collider (EIC) will carry out the relevant experiments in the future.

# Exclusive photoproduction of vector mesons



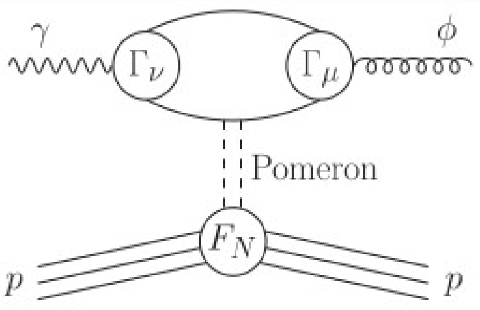

[Laget, PLB.489.313 (2000)]

# Exclusive photoproduction of vector mesons




[Laget, PLB.489.313 (2000)]

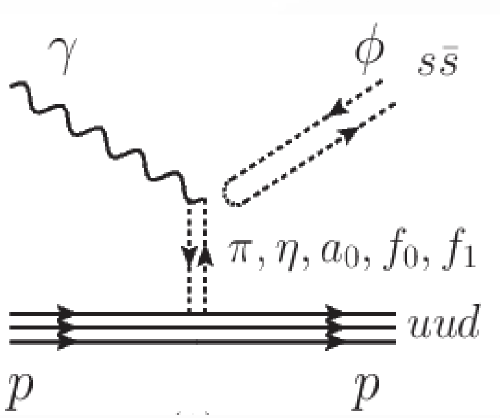
- We focus on γ p → φ p.
- high energy




- □ σ [γp → φp] ≈ σ [γp → ωp]
- □ FN: 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




- □ σ[γp → φp] << σ[γp → (ρ,ω)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)]

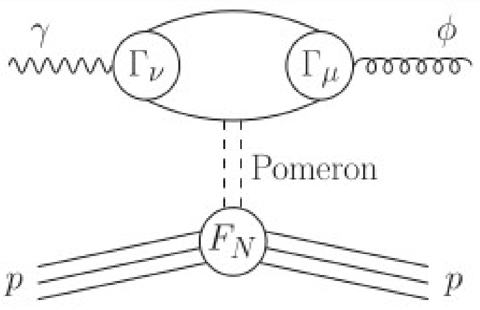
❑ low energy:

We need to clarify the reaction mechanism.

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

❑ We focus on $\gamma p \rightarrow \varphi p$.

❑ high energy

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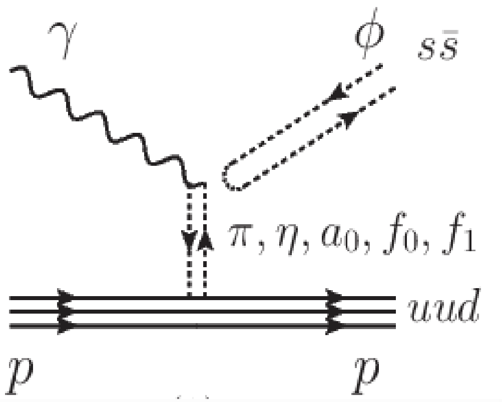
❑ low energy



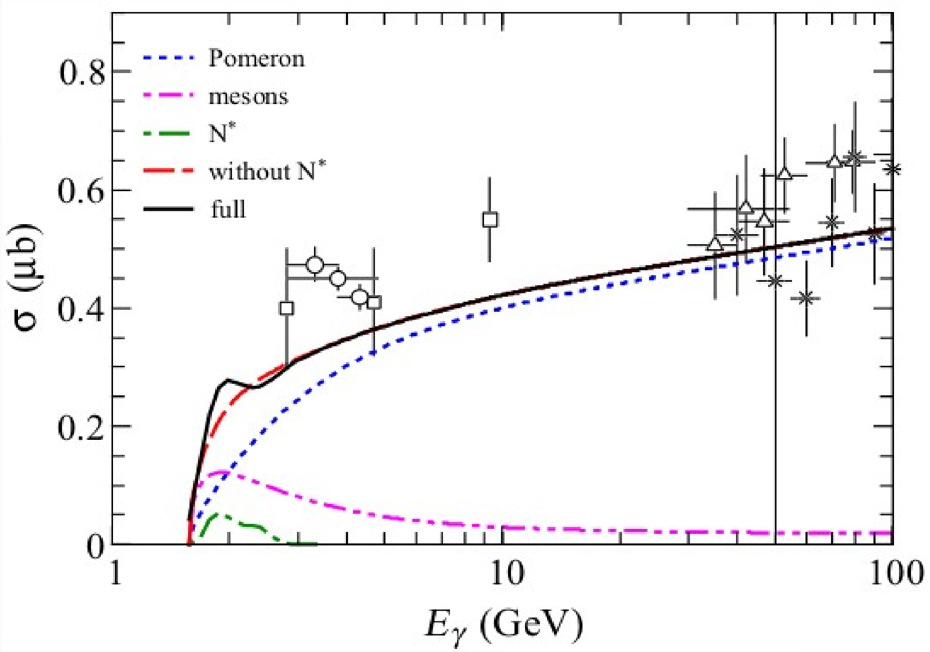

□ σ[γp → φp] << σ[γp → (ρ,ω)p] due to the OZI rule

# Exclusive photoproduction of vector mesons [results]

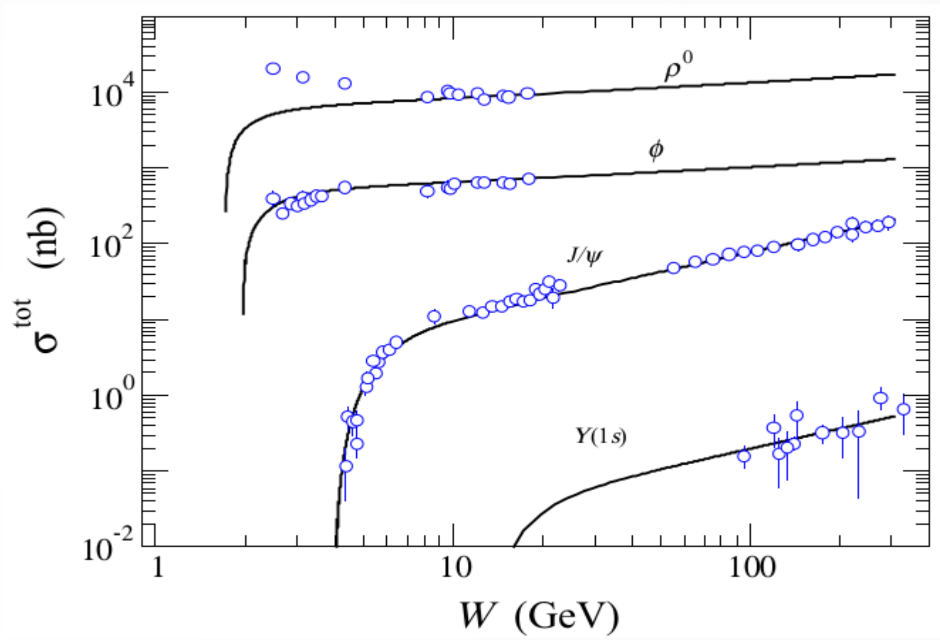
## Born term

## total cross section

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

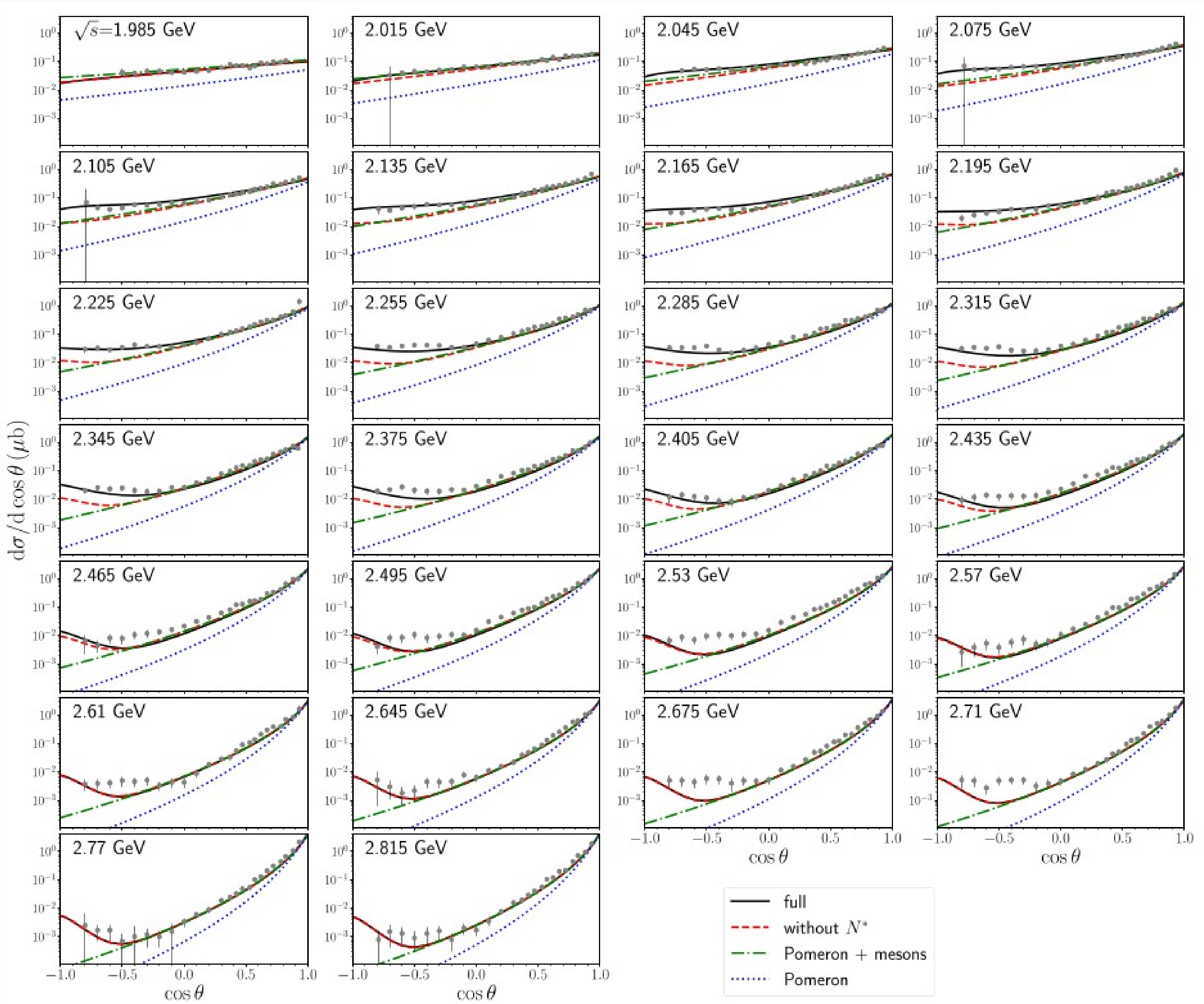



$\gamma\, p \to \rho^0, \omega, \varphi, J/\psi, \Upsilon(1s)$




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

# Exclusive photoproduction of vector mesons [results]




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

Born term

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

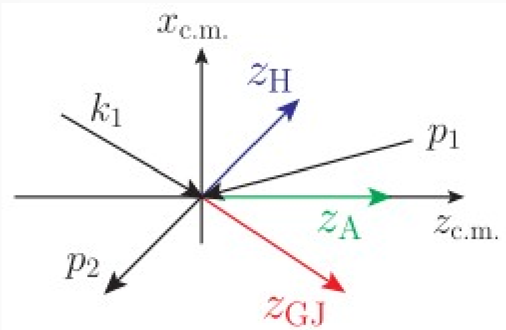
play crucial roles.

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

# Exclusive photoproduction of vector mesons

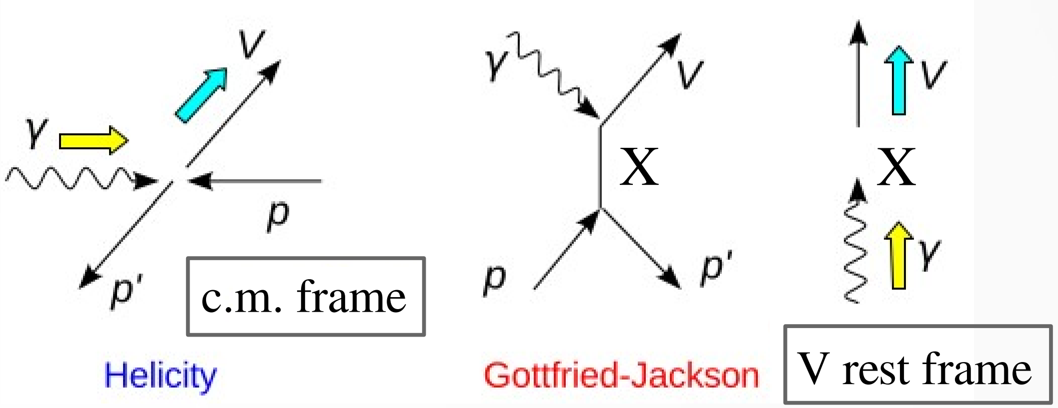
## spin-density matrices

❑ Decay frame




V rest frame

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

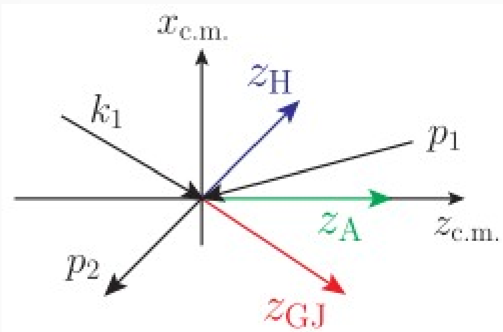
□ λ, λ' : Helicity states of the vector-meson

□ 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

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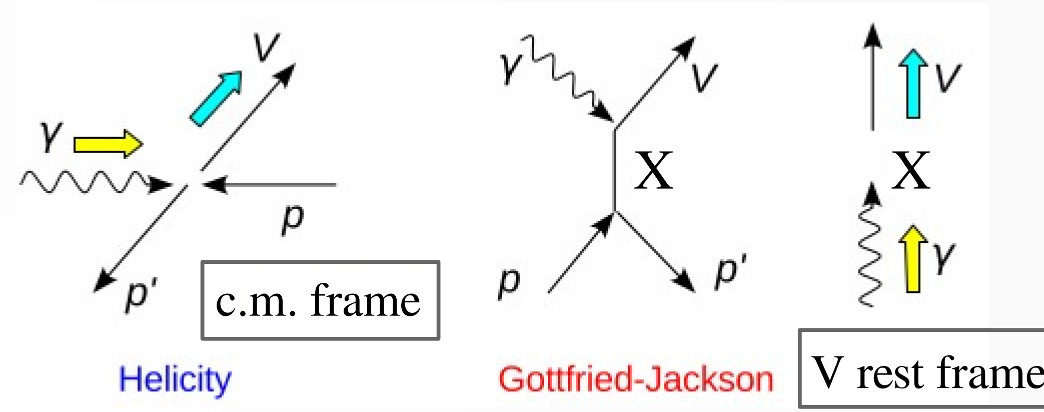


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$$\rho^0_{00} \propto \left|\mathcal{M}_{\lambda_\gamma=1,\lambda_\phi=0}\right|^2 + \left|\mathcal{M}_{\lambda_\gamma=-1,\lambda_\phi=0}\right|^2$$

- 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:

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

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

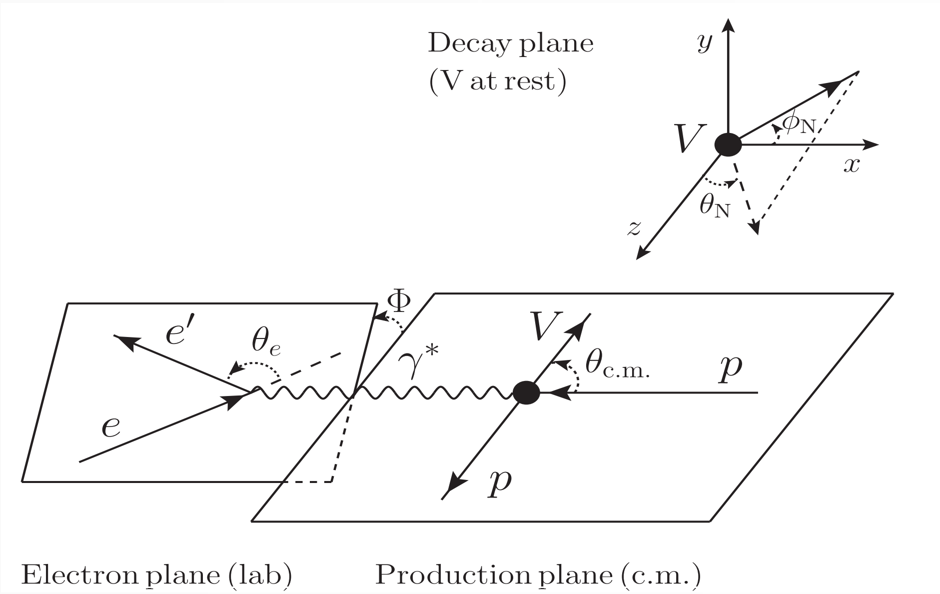
$$\alpha_{\rm A\to GJ} = \alpha_{\rm A\to H} + \alpha_{\rm H\to GJ}$$

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

# Exclusive electroproduction of vector mesons

$\gamma^{*}\, p \to V\, p$

reaction plane

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(T-L separated cross sections)

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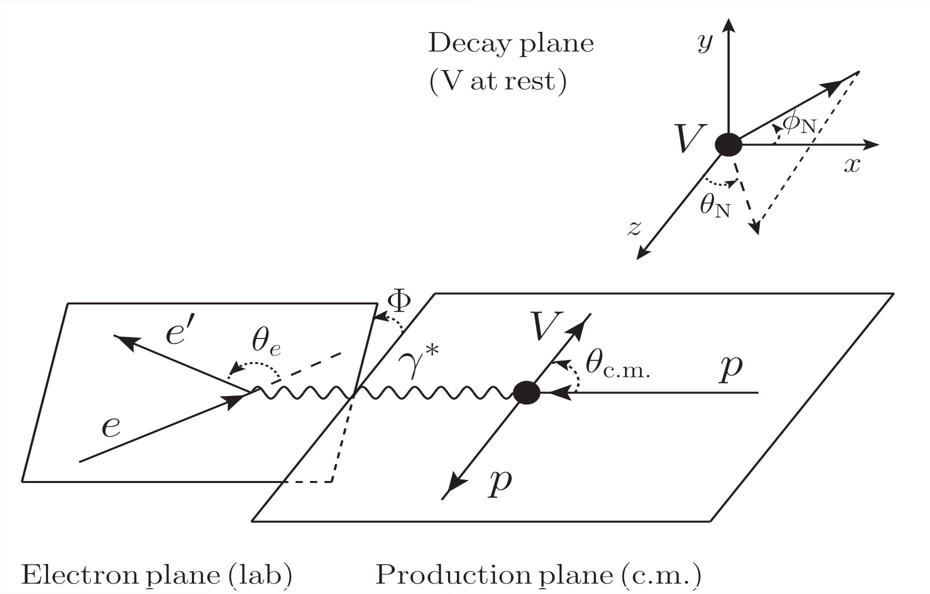


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→ $\sigma_T$, $\sigma_L$, $\sigma_{TT}$, $\sigma_{LT}$, $R=\sigma_L/\sigma_T$ … [electro-]
(T-L separated cross sections)

total cross section

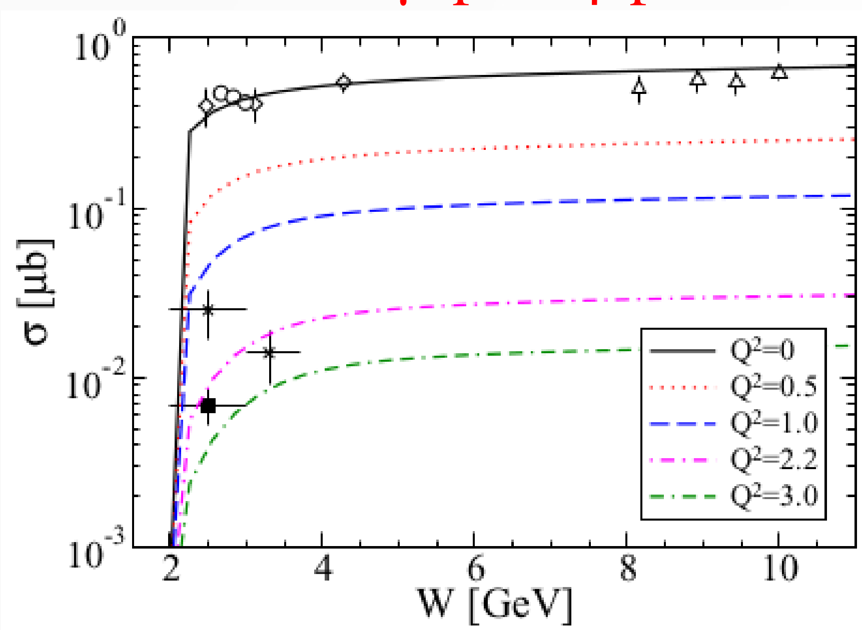
$$\sigma = \sigma_T + \varepsilon\sigma_L \qquad \frac{d\sigma}{d\Phi} = \frac{1}{2\pi}\left(\sigma + \varepsilon\sigma_{TT}\cos 2\Phi + \sqrt{2\varepsilon(1+\varepsilon)}\sigma_{LT}\cos\Phi\right)$$

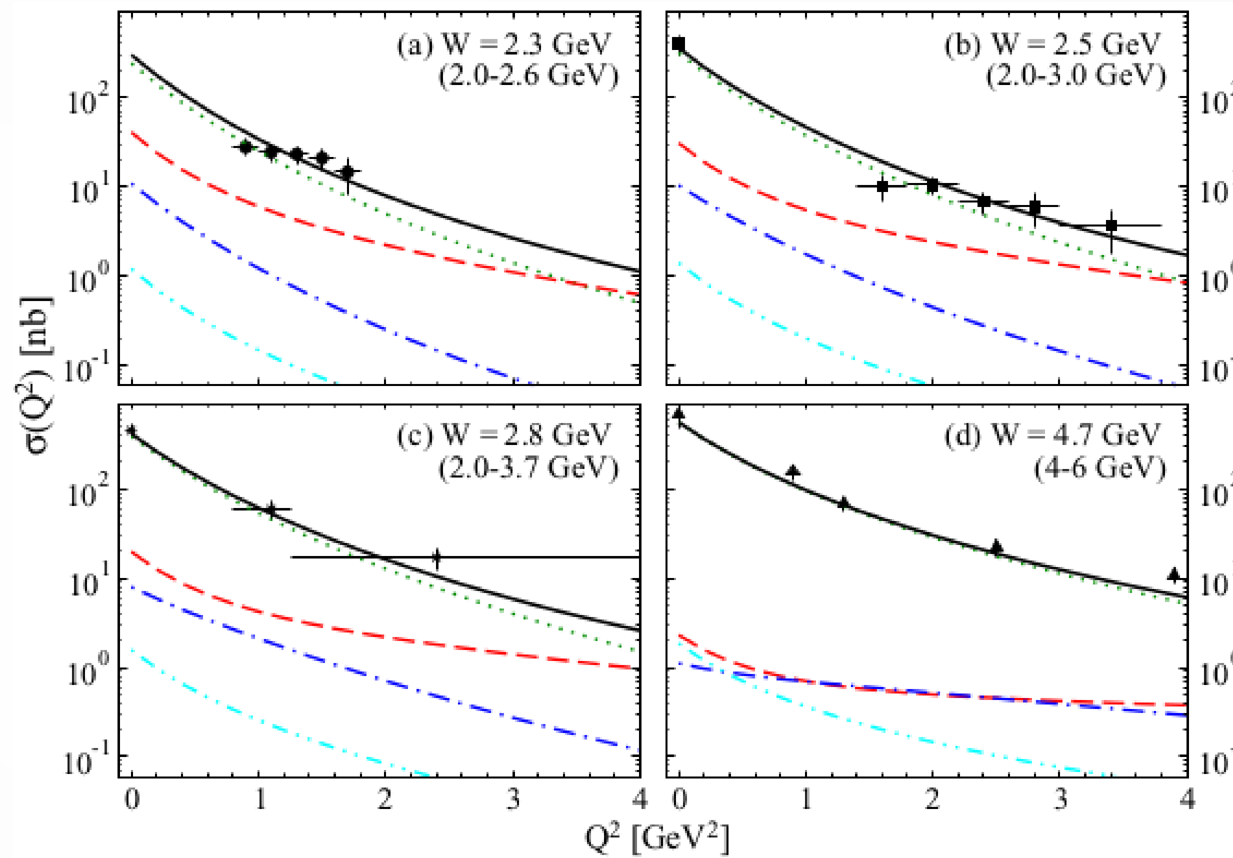
ε: Virtual-photon polarization parameter

## unpolarized cross sections

Exp: [CLAS] PRC.63.065205 (2001), PRC.78.025210 (2008)
[Cornell] PRD.24.2787 (1981)
[HERMES] ActaPhys.Pol.B.31.2353 (2000)

a-1 $\gamma^* p \rightarrow \varphi\, p$




Pomeron | PS (π,η) | total
S (a0,f0) | AV (f1)

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

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

ε: Virtual-photon polarization parameter

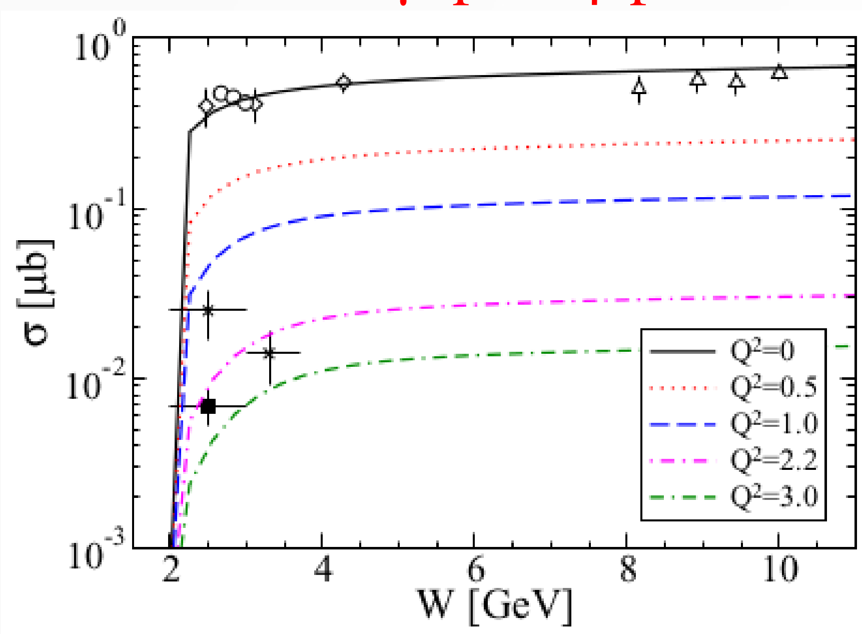
- □ The $Q^2$ dependence of the cross sections is well described.
- □ The agreement with the exp. data is good at the real photon limit $Q^2=0$.

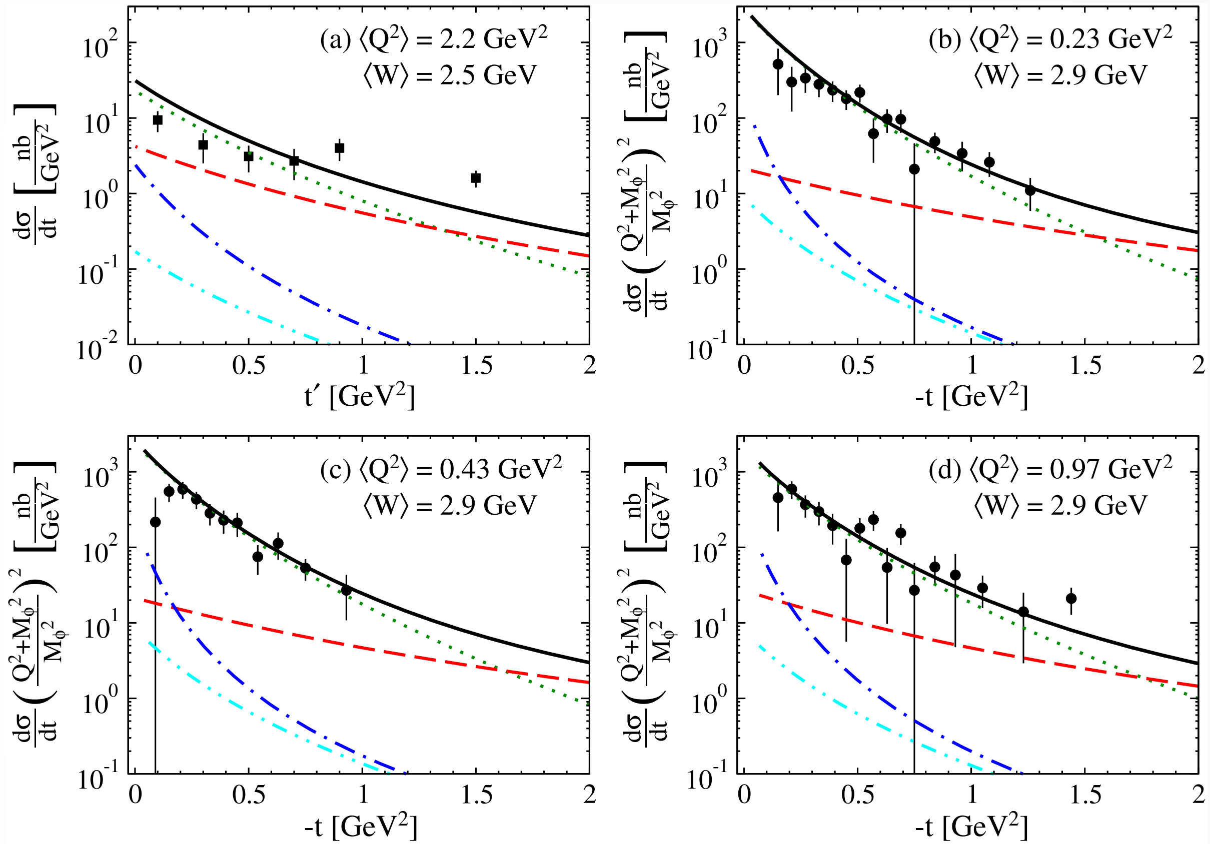
# Exclusive electroproduction of vector mesons

## unpolarized cross sections

Exp: [CLAS] PRC.78.025210 (2008)
[Cornell] PRL.39.516 (1977), PRD.19.3185 (1979)

a-2 $\gamma^* p \to \varphi\, p$




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

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

ε: Virtual-photon polarization parameter

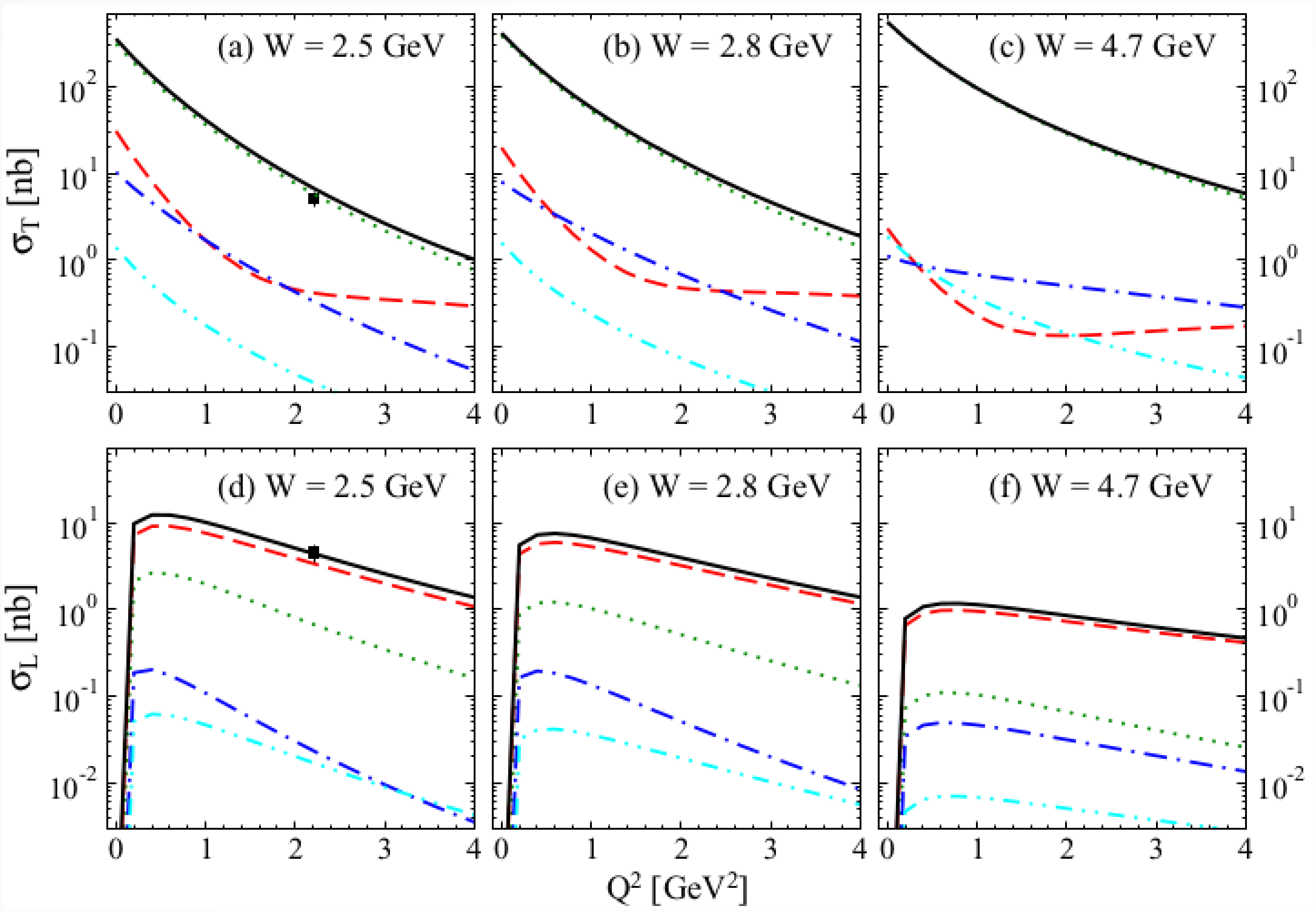
Pomeron | PS (π,η) | total
S ($a_0$,$f_0$) | AV ($f_1$)

- 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.

# Exclusive electroproduction of vector mesons

## T-L separated cross sections at low W

a-3 $\gamma^* p \to \varphi p$




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

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

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

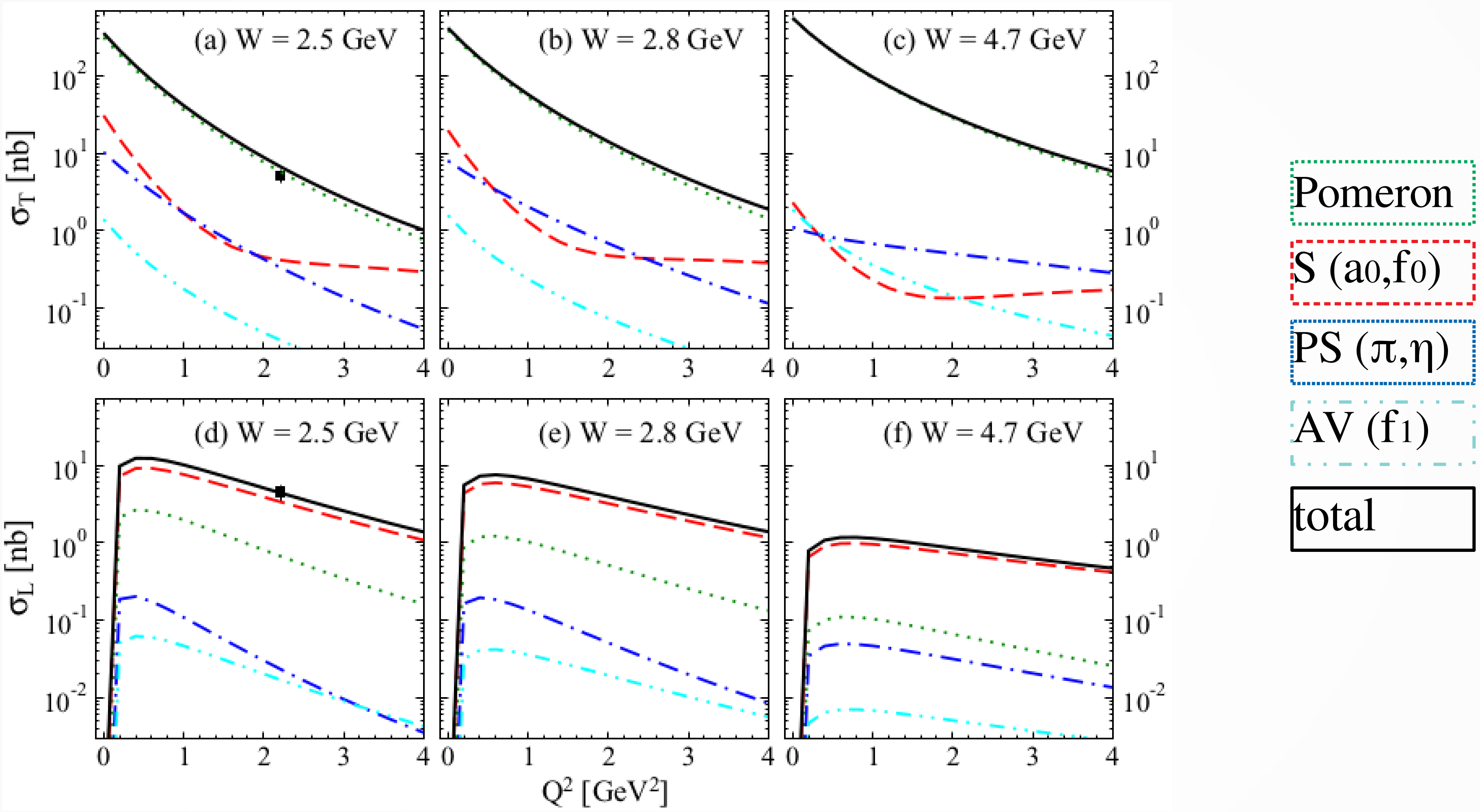
$$\frac{1}{\mathcal{N}}\frac{d\sigma_{LT}}{dt} = -\frac{1}{2\sqrt{2}}\sum_{\lambda_\gamma=\pm1}\lambda_\gamma\left(\overline{\mathcal{M}^{(0)}\mathcal{M}^{(\lambda_\gamma)^*}} + \overline{\mathcal{M}^{(\lambda_\gamma)}\mathcal{M}^{(0)^*}}\right)$$

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

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

## T-L separated cross sections at low W

a-3 $\gamma^* p \rightarrow \varphi p$



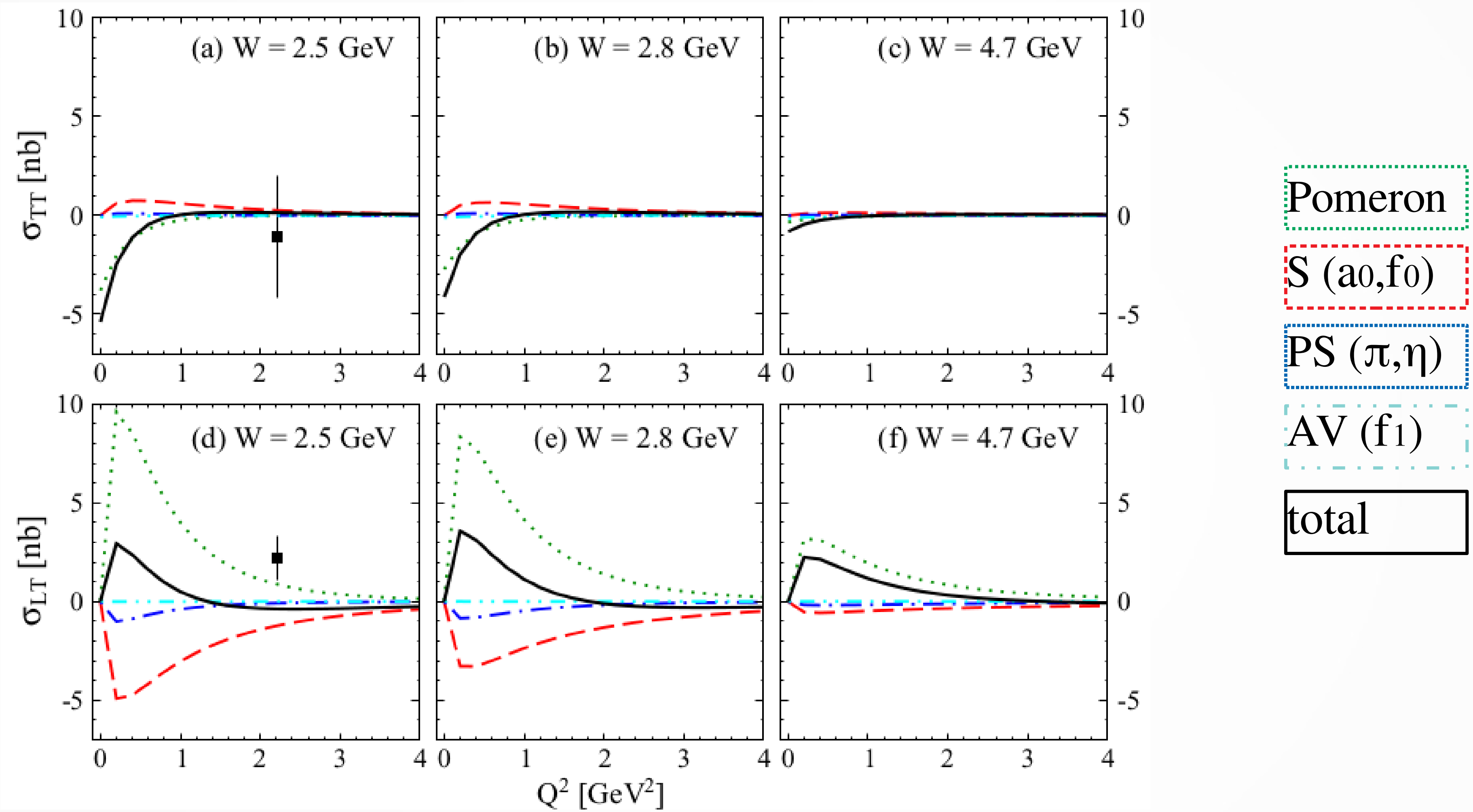

[Exp: CLAS, Santoro, PRC.78.025210 (2008)]

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

# Exclusive electroproduction of vector mesons

## T-L separated cross sections at low W

a-4 $\gamma^* p \to \varphi p$




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

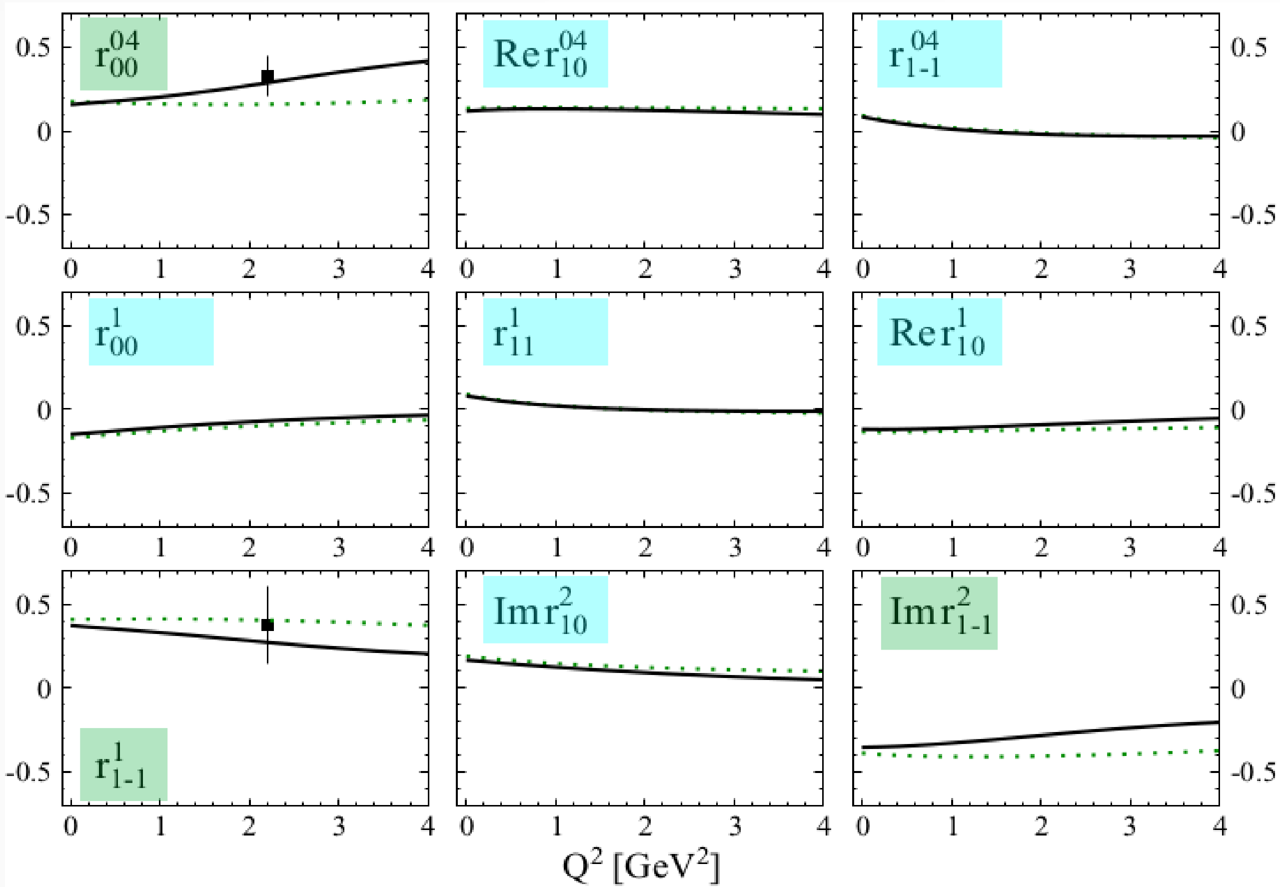
□ The signs of Pomeron and **meson** contributions are opposite to each other.

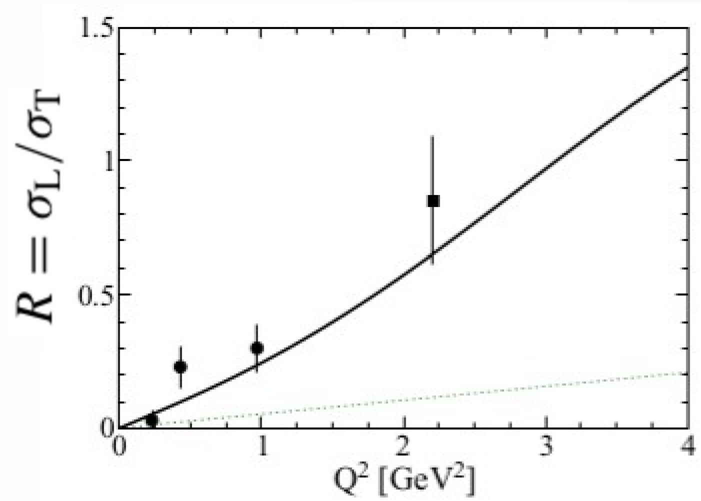
□ $\sigma_{TT}$ and $\sigma_{LT}$ become zero as W and $Q^2$ increases, indicating SCHC.

Exclusive electroproduction of vector mesons

spin-density matrix elements ($r_{ij}^{k}$) at W = 2.5 GeV

a-5 $\gamma^{*} p \to \varphi p$




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

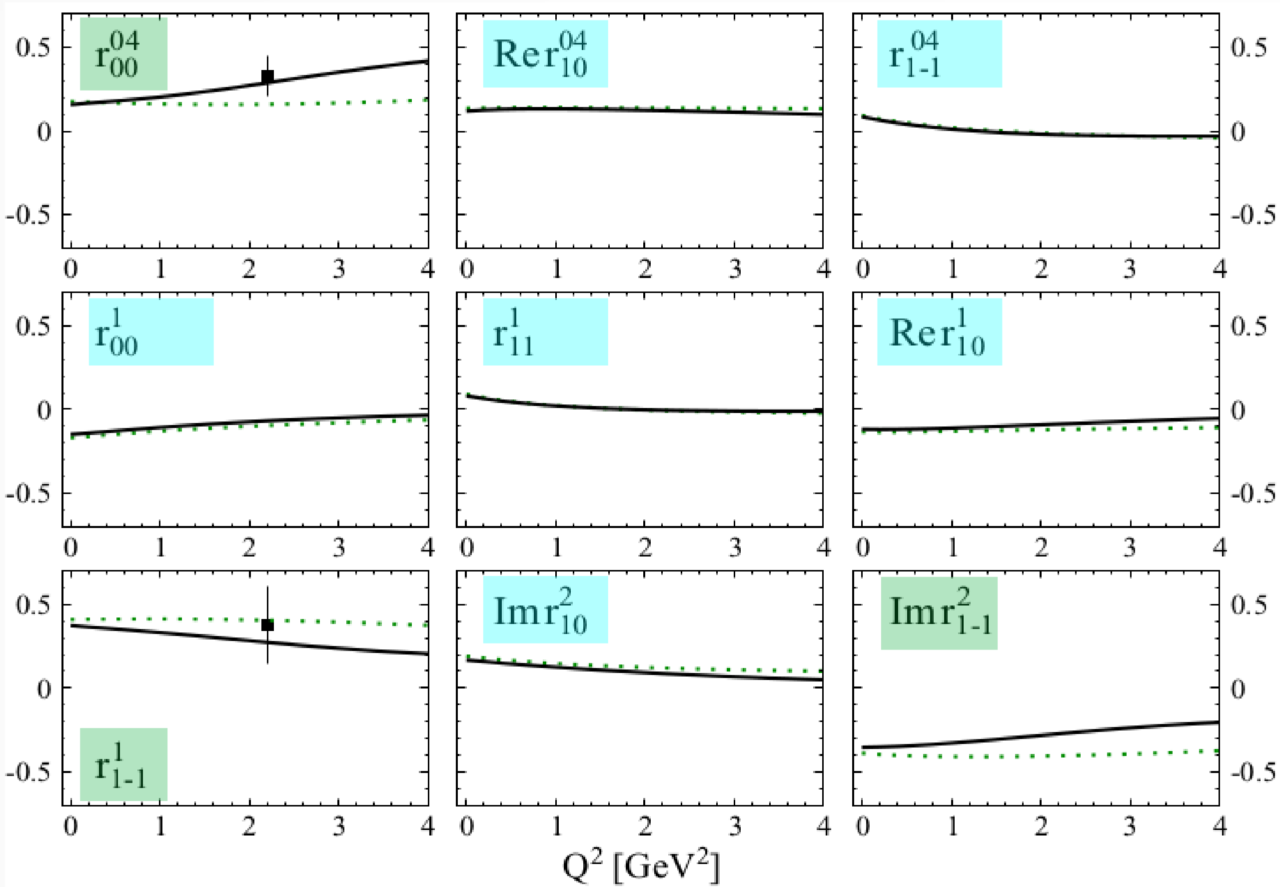
$$r_{ij}^{\alpha} = \frac{\rho_{ij}^{\alpha}}{1+\varepsilon R}, \quad \text{for } \alpha = (0-3),$$

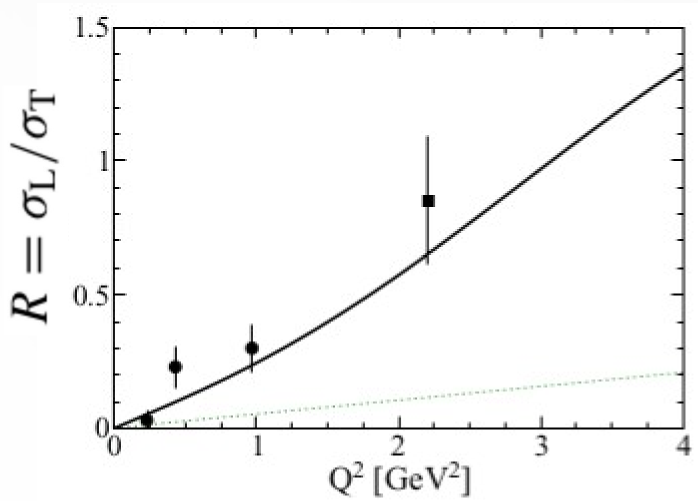
$$r_{ij}^{\alpha} = \sqrt{R}\frac{\rho_{ij}^{\alpha}}{1+\varepsilon R}, \quad \text{for } \alpha = (5-8)$$

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

spin-density matrix elements ($r_{ij}^{k}$) at W = 2.5 GeV

a-5 $\gamma^* p \to \varphi p$




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

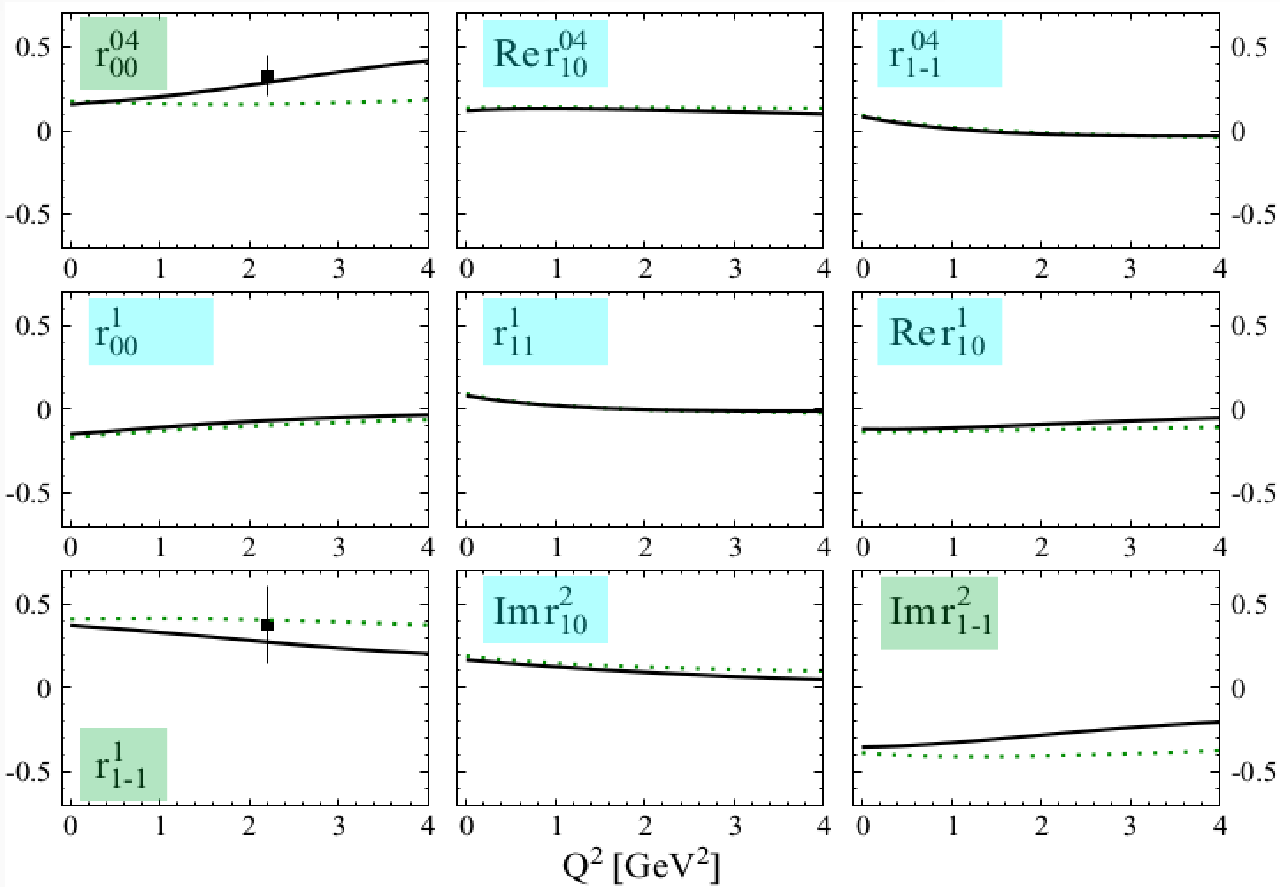
$$r_{ij}^{\alpha} = \frac{\rho_{ij}^{\alpha}}{1+\varepsilon R}, \quad \text{for } \alpha = (0-3),$$

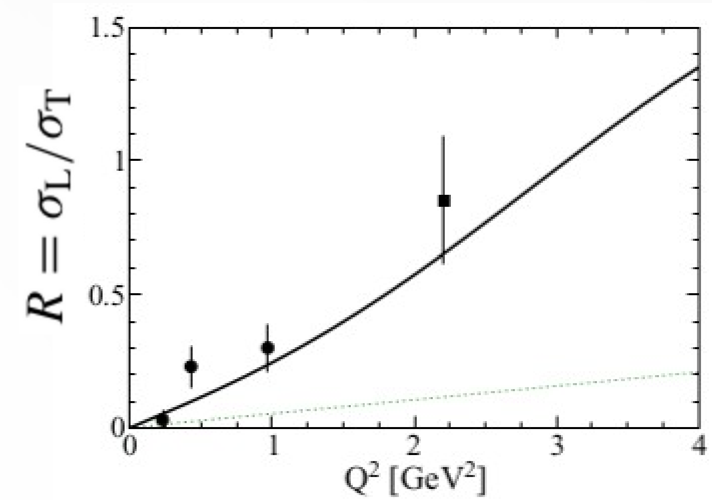
$$r_{ij}^{\alpha} = \sqrt{R}\frac{\rho_{ij}^{\alpha}}{1+\varepsilon R}, \quad \text{for } \alpha = (5-8)$$

- □ By definition, if SCHC holds, $r_{ij}^{k} = 0$, $r_{ij}^{k} \neq 0$.
- □ $P \equiv \frac{\sigma_T^N - \sigma_T^U}{\sigma_T^N + \sigma_T^U} = (1+\varepsilon R)(2r_{1-1}^{1} - r_{00}^{1})$ : Parity asymmery Our result ≃ 0.9
- □ $1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1} = 0$ only if Natural parity exchange ($\sigma^N$). Our result ≃ 0.1

## spin-density matrix elements ($r_{ij}^{k}$) at W = 2.5 GeV

a-5 $\gamma^* p \to \varphi p$




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

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

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

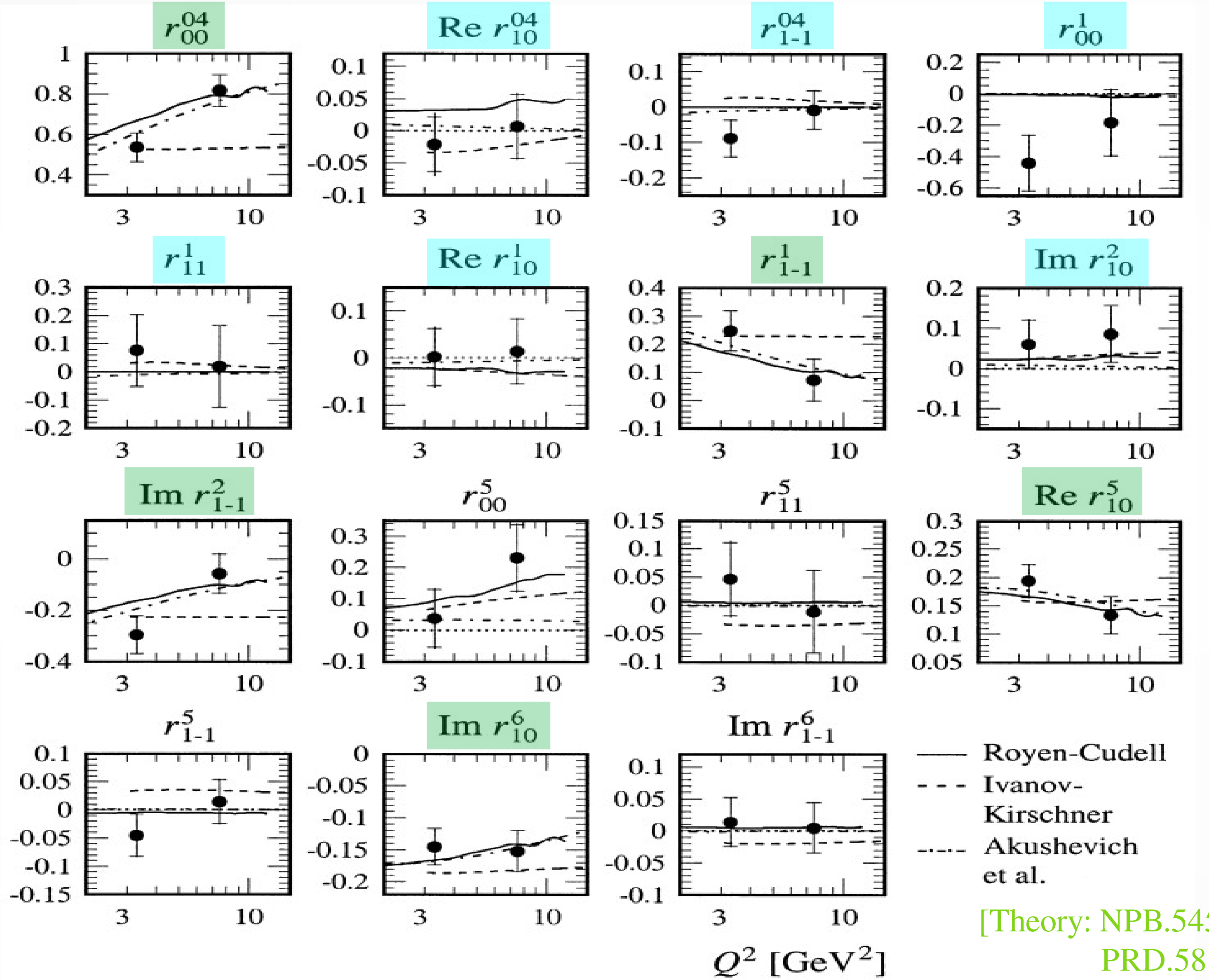
□ By definition, if SCHC holds, $r_{ij}^{k} = 0$, $r_{ij}^{k} \neq 0$.

□ The relative contributions of different meson exchanges are verified. □ SCHC seems to hold.

□ Our hadronic approach is very successful for describing the data at $Q^2 = (0\text{-}4)$ GeV², W = (2-5) GeV, t = (0-2) GeV².

## spin-density matrix elements ($r_{ij}^{k}$) at W ~ 100 GeV

a-6 $\gamma^{*}$ p → φ p




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

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

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

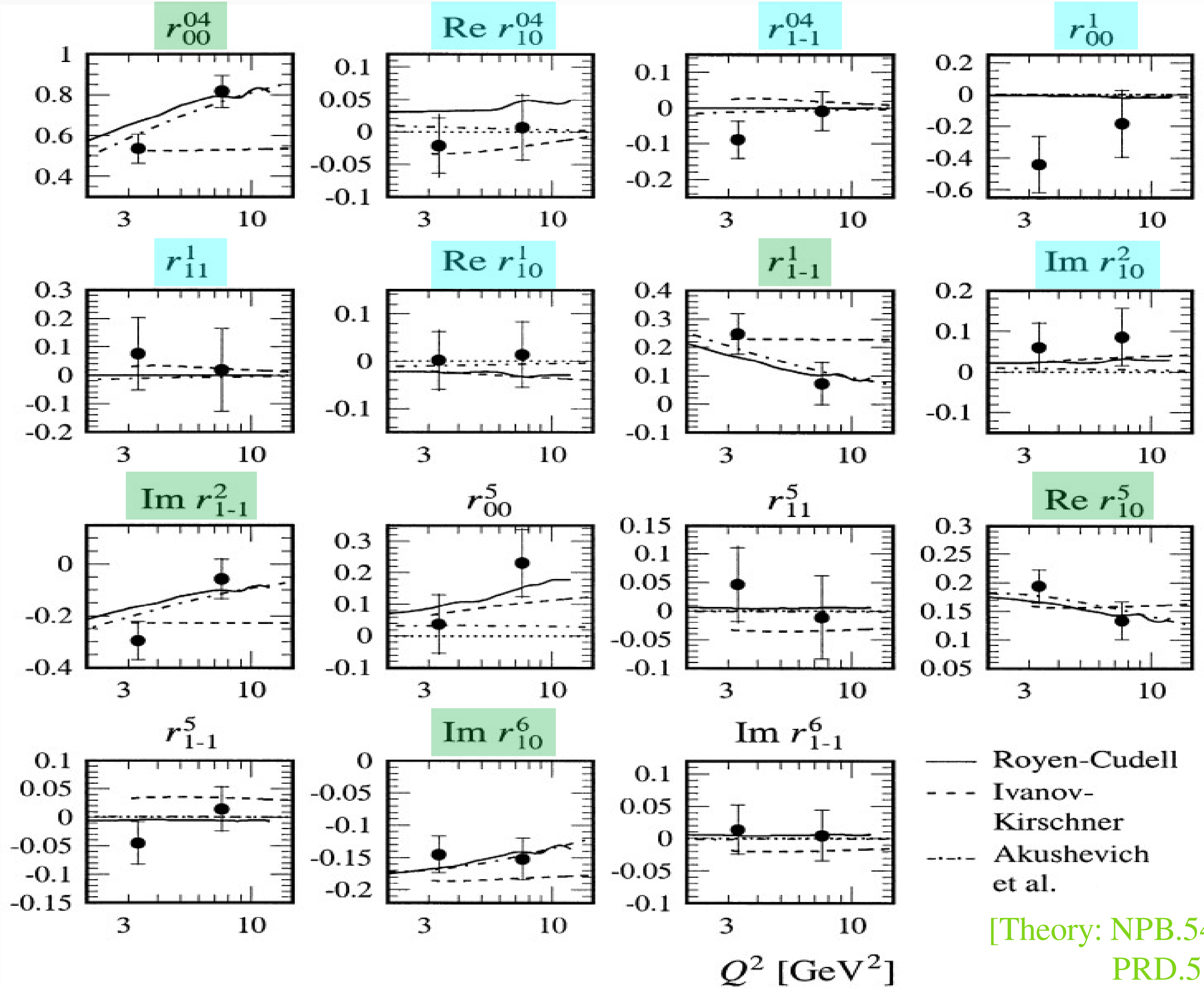
[Theory: NPB.545.505 (1999)
PRD.58.114026 (1998)
JETP.L.69.294 (1999)]

[Exp: H1, Adloff, PLB.483.360 (2000)]

# Exclusive electroproduction of vector mesons

spin-density matrix elements ($r_{ij}^k$) at W ~ 100 GeV

a-6 $\gamma^* p \rightarrow \varphi p$




[Exp: H1, Adloff, PLB.483.360 (2000)]

[Theory: NPB.545.505 (1999)
PRD.58.114026 (1998)
JETP.L.69.294 (1999)]

- By definition, if SCHC holds, $r_{ij}^k = 0$, $r_{ij}^k \neq 0$.
- A small but significant violation of SCHC is found from the H1 data.
- A Pomeron, represented by the hard two-gluon exchange, can reproduce the main features of the HERA data for hard diffraction.
- We need more complete reaction theories to describe the HERA data.

# Exclusive electroproduction of vector mesons

◇ Hard exclusive diffractive processes are the source of valuable information on the origin of small $x$ processes, i.e., on the origin of the phenomenon known as Pomeron.

# Exclusive electroproduction of vector mesons

◇ Hard exclusive diffractive processes are the source of valuable information on the origin of small $x$ processes, i.e., on the origin of the phenomenon known as Pomeron.

◇ Collaboration with T.-S.H.Lee (Argonne Natl. Lab.) and S.Sakinah (Kyungpook Natl. Univ.)
We have various theoretical tools to deal with the Pomeron exchange mechanism.
[T.-S.H.Lee, S.Sakinah, Yongseok Oh, EPJA.58.252(2022)]

□ Non-perturbative approach

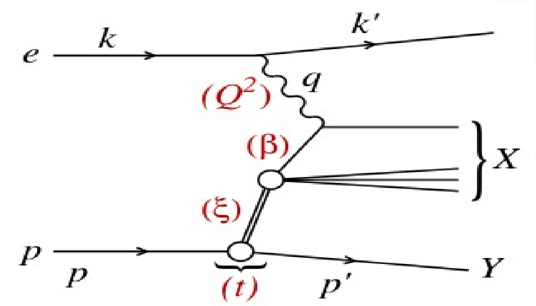
- Donnachie and Landshoff (Pom-DL) [NPB.244.322 (1983)]
- Its extension to include V-N potential extracted from LQCD (Pom-pot) [T.-S.H.Lee, arXiv:2004.13934]
- Constituent quark model (CQM) to account for the quark substructure of V (Pom-CQM) [T.-S.H.Lee]

□ Perturbative QCD approach

- Two-gluon exchange using the GPD of the nucleon (GPD-based) [T.-S.H.Lee]
- Two- & three-gluon exchanges using the parton distribution of the nucleon (2g+3g) [Brodsky, PLB.498.23 (2001)]
- Exchanges of scalar & tensor glueballs within the holographic formulation (holog) [Mamo, PRD.104.066023 (2021)]

 Inclusive diffraction

- Inclusive diffraction has been extensively studied at HERA.
- There are number of areas where the EIC can significantly expand our knowledge of QCD diffraction.



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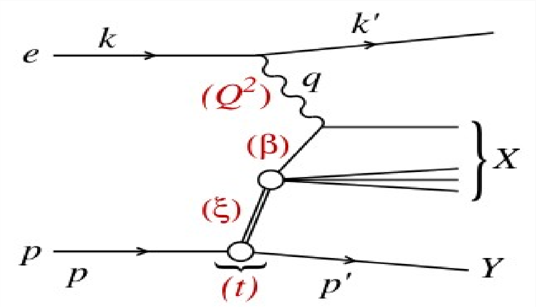
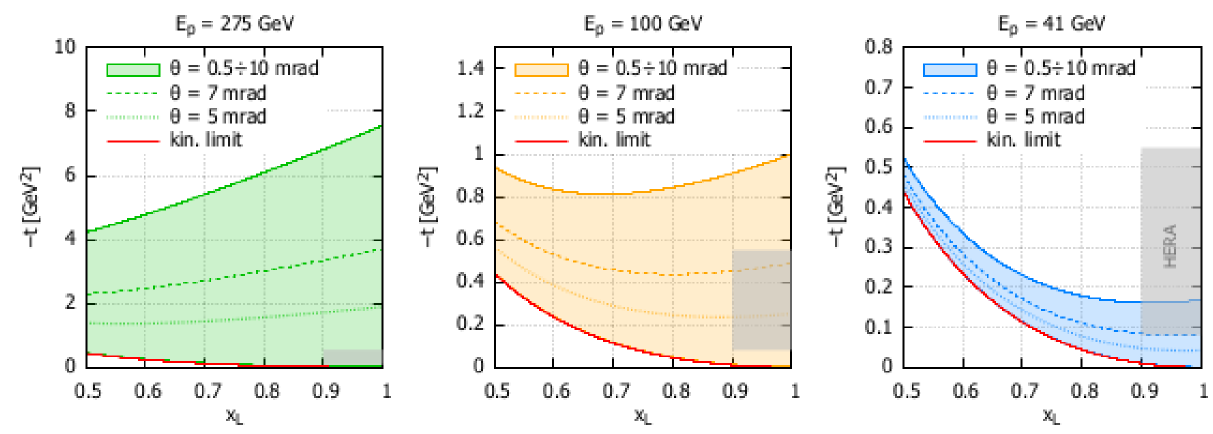
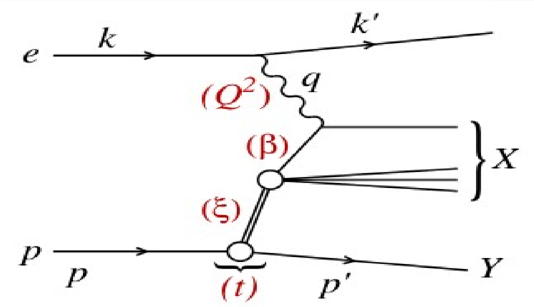



**First**, thanks to the instrumentation in forward Region, EIC will be able to measure leading protons in a much wider range of $t$ and $x_L$ than at HERA.



- Inclusive diffraction has been extensively studied at HERA.
- There are number of areas where the EIC can significantly expand our knowledge of QCD diffraction.

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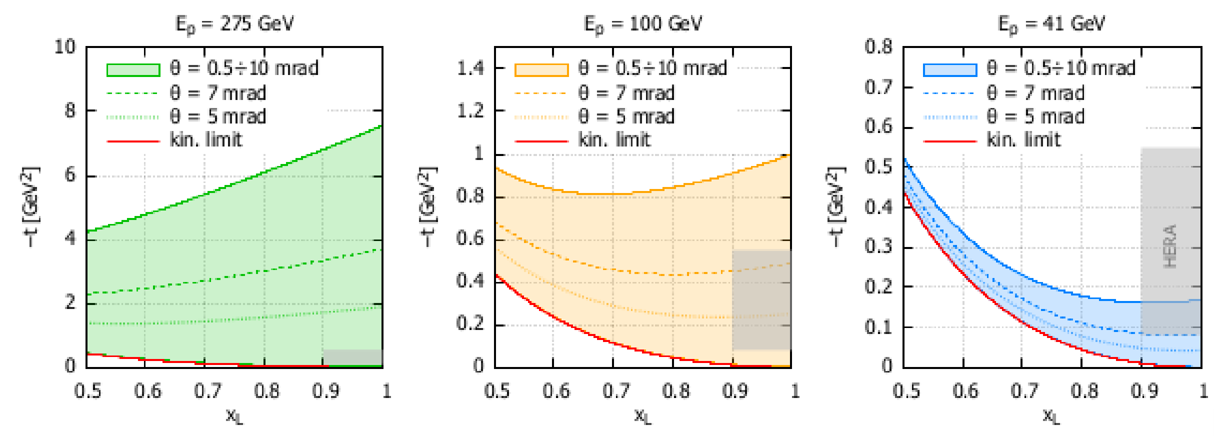
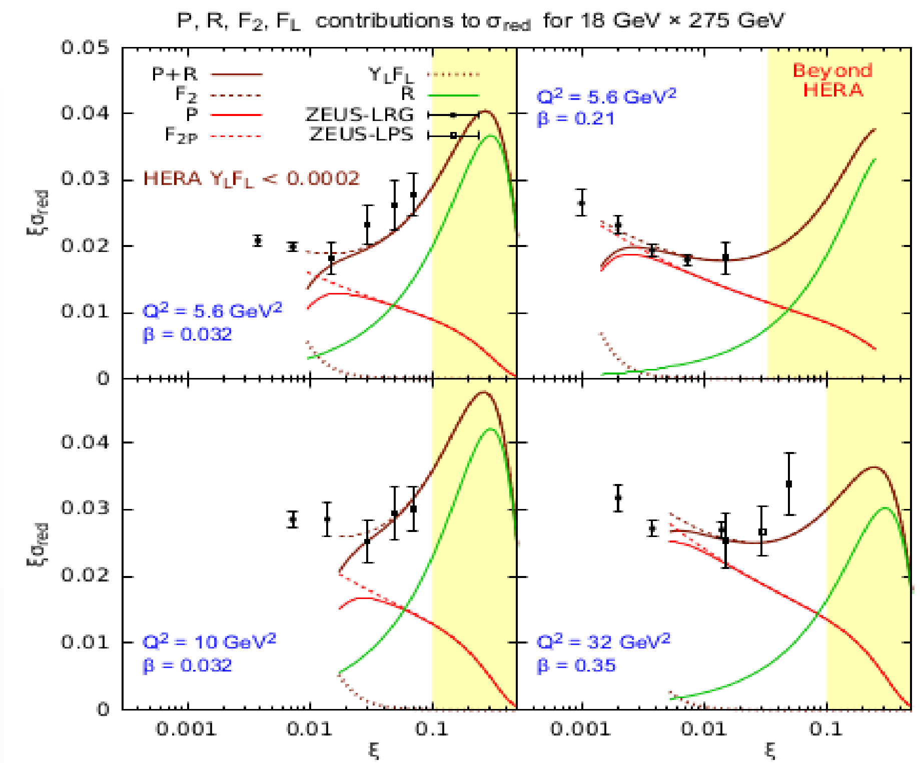


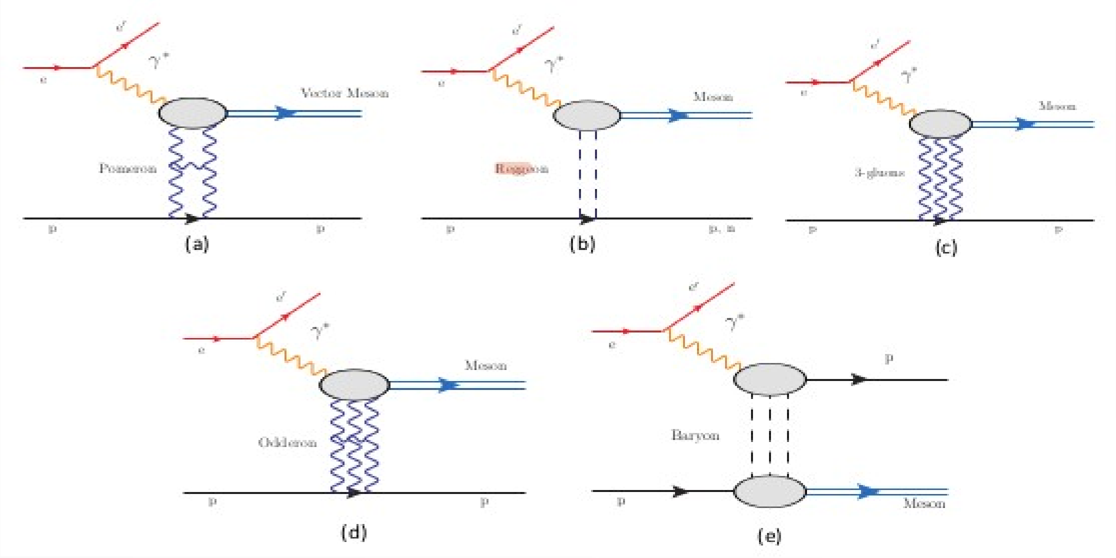

EIC has the potential to explore the region ($\zeta > 0.1$) to disentangle the two components.

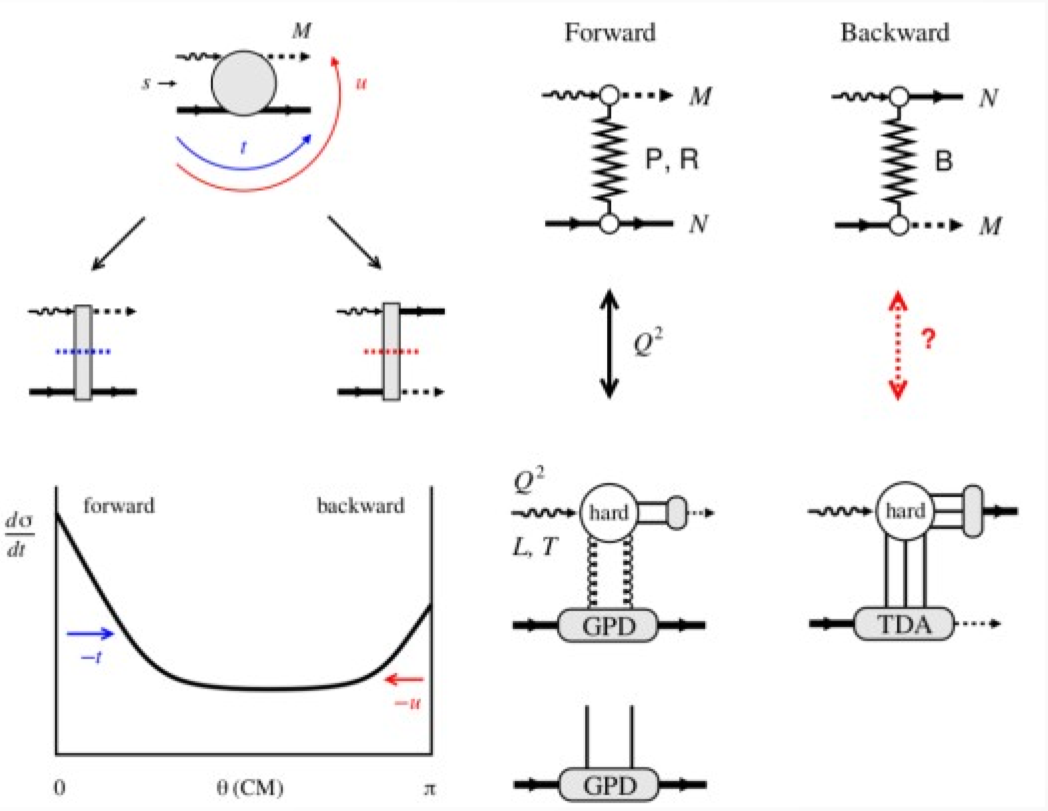
EIC will provide excellent opportunities to perform precise measurements of the longitudinal diffractive SF.

The **second** area where EIC could provide valuable information are the Pomeron & Reggeon contributions. At HERA, the *t*-dep. of the Reggeon contribution could not be tested at all.



- Odderon exchange, $u$-Channel exclusive meson electroproduction ...

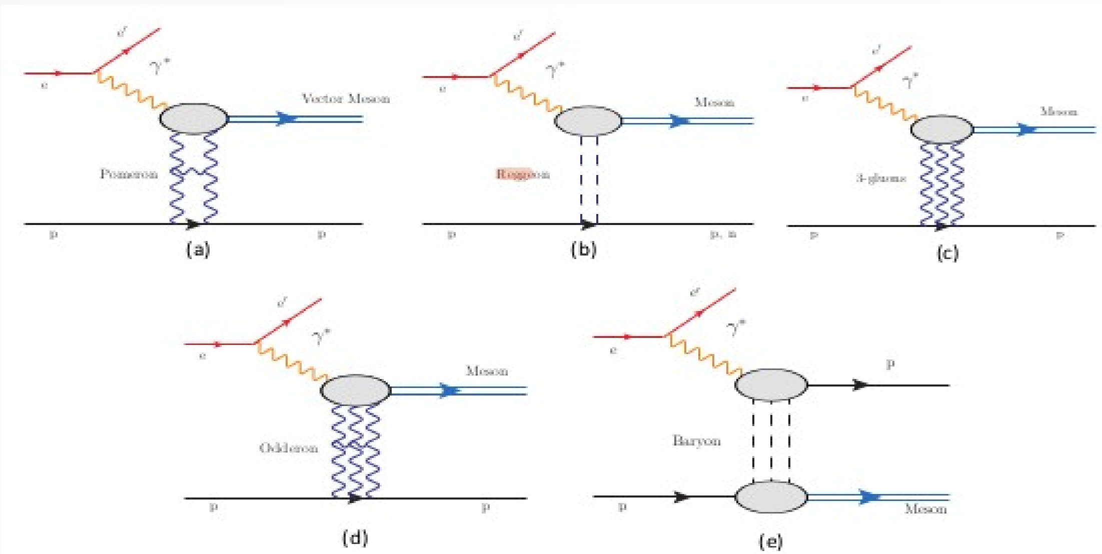


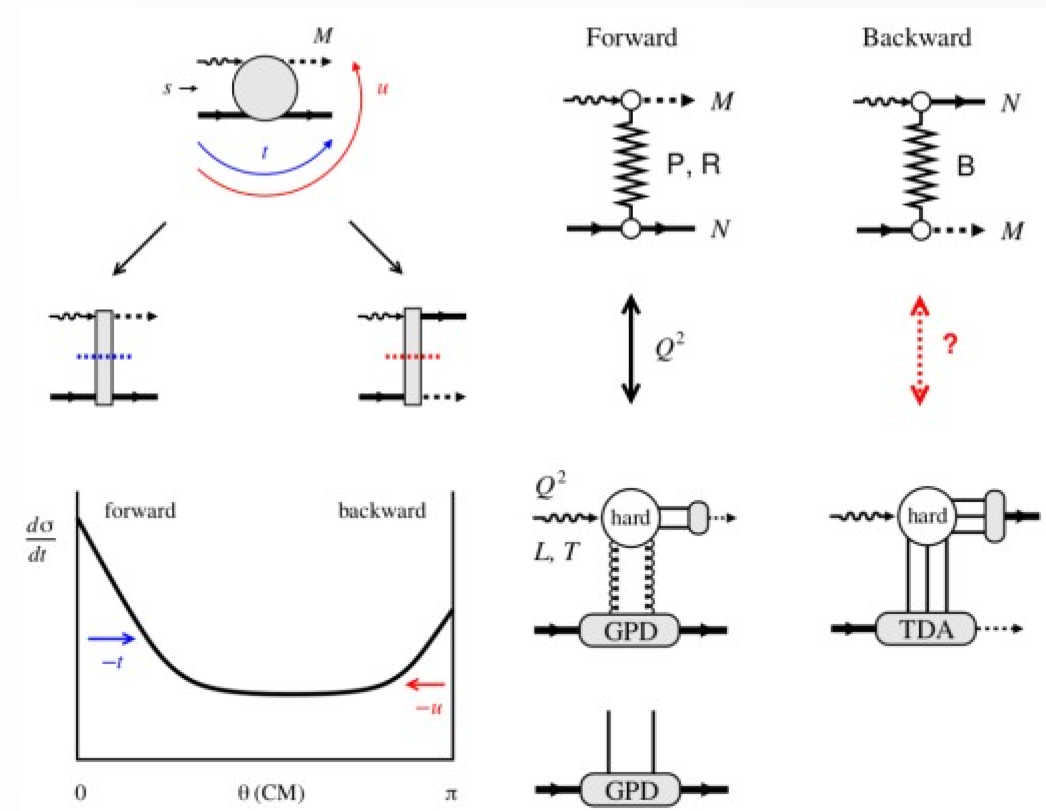




(left) Soft-hard-soft structure transition
(right) Forward-backward factorization scheme

# [EIC Yellow Report] 7.4.5. New particle production mechanisms

□ Odderon exchange, $u$-Channel exclusive meson electroproduction …




(left) Soft-hard-soft structure transition
(right) Forward-backward factorization scheme

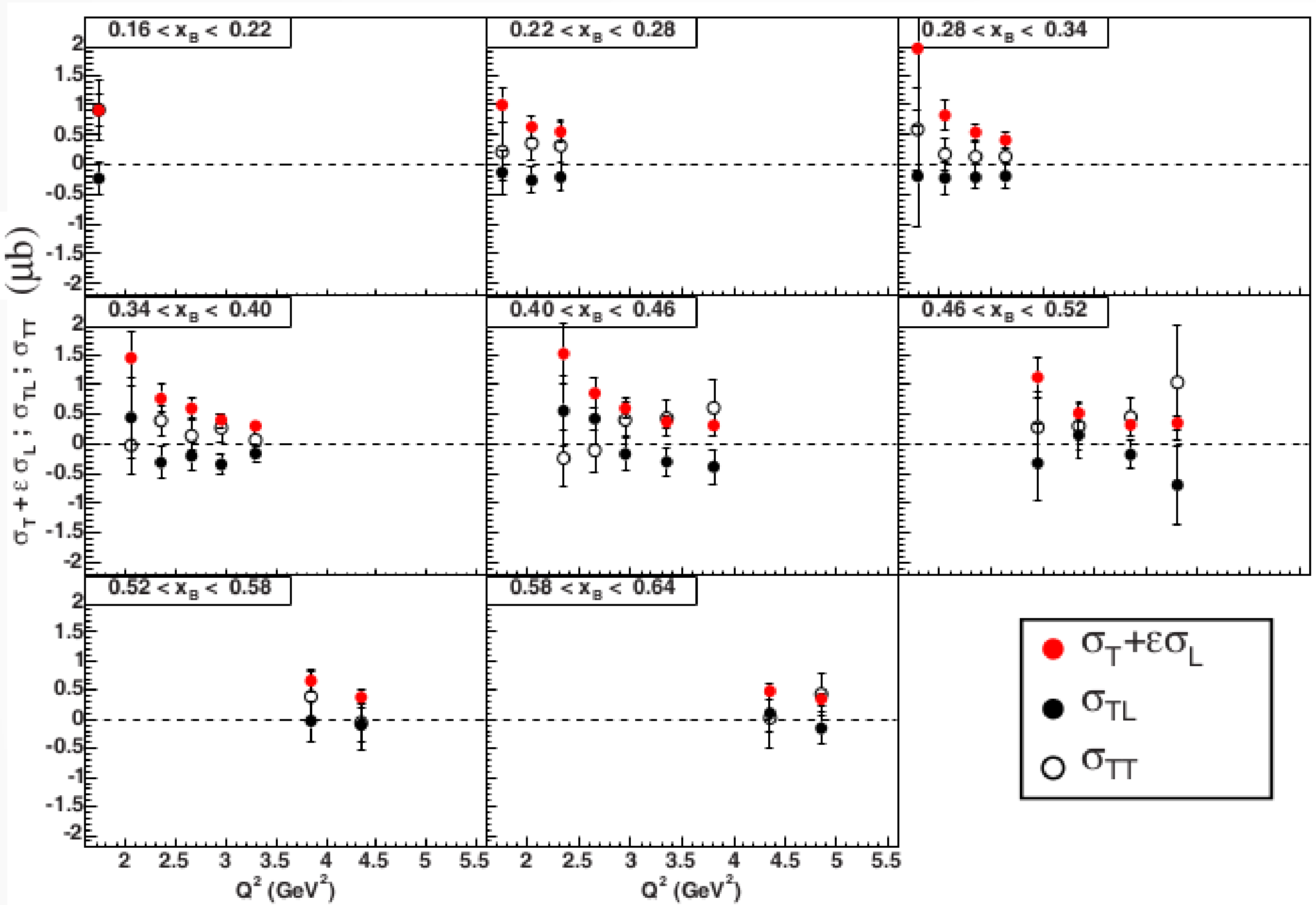
Combining the data collected at JLab 12 GeV and EIC, we aim to accomplish the following objectives to unveil the complete physics meaning of $u$-channel interactions:

- At low $Q^2$ limit: $Q^2 < 2\ \text{GeV}^2$, mapping out the $W$ dependence for electroproduction of all mesons at near-backward kinematics.
- Extracting the $u$-dependence ($\sigma \propto e^{-b \cdot u}$) as a function of $Q^2$. This could be used to study the transition from a "soft" Regge-exchange type picture (transverse size of interaction is of order of the hadronic size) to the "hard" QCD regime.
- Studying the model effectiveness between the hadronic Regge based (exchanges of mesons and baryons) and the partonic description through Transition Distribution Amplitudes (exchanges of quarks and gluons), is equivalent to studying the non-perturbative to perturbative QCD transition.

# Exclusive electroproduction of vector mesons

## T-L separated cross sections at low W

b-1 $\gamma^* \; p \to \rho(770) \; p$




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

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

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

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

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

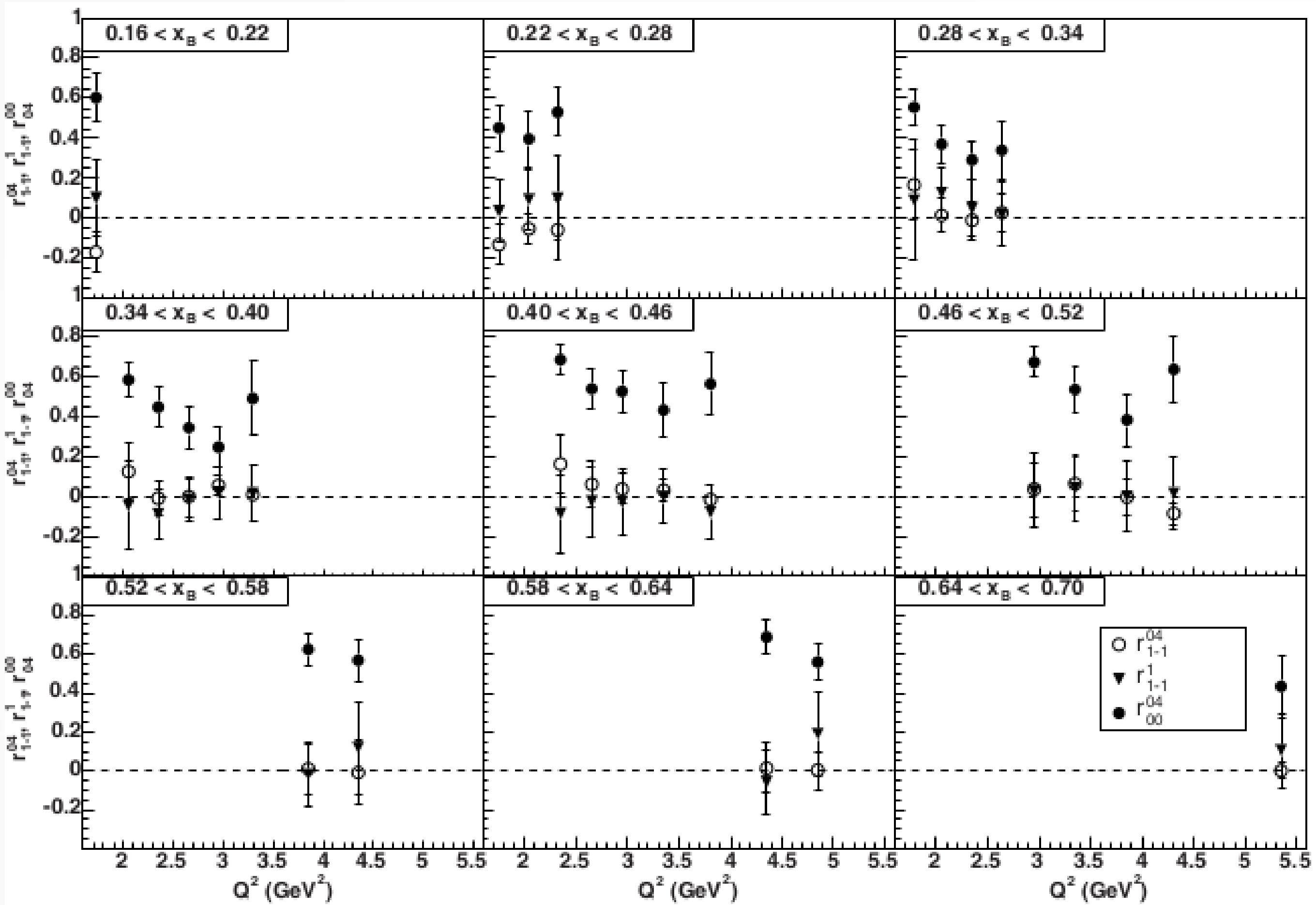
□ If SCHC holds, $\sigma_{TT}$ and $\sigma_{LT}$ become zero.

- 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 ($r_{ij}^{k}$) at low W

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




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

○ $r_{1-1}^{04}$ = 0 if SCHC holds

▼ $r_{1-1}^{1}$

● $r_{00}^{04}$

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

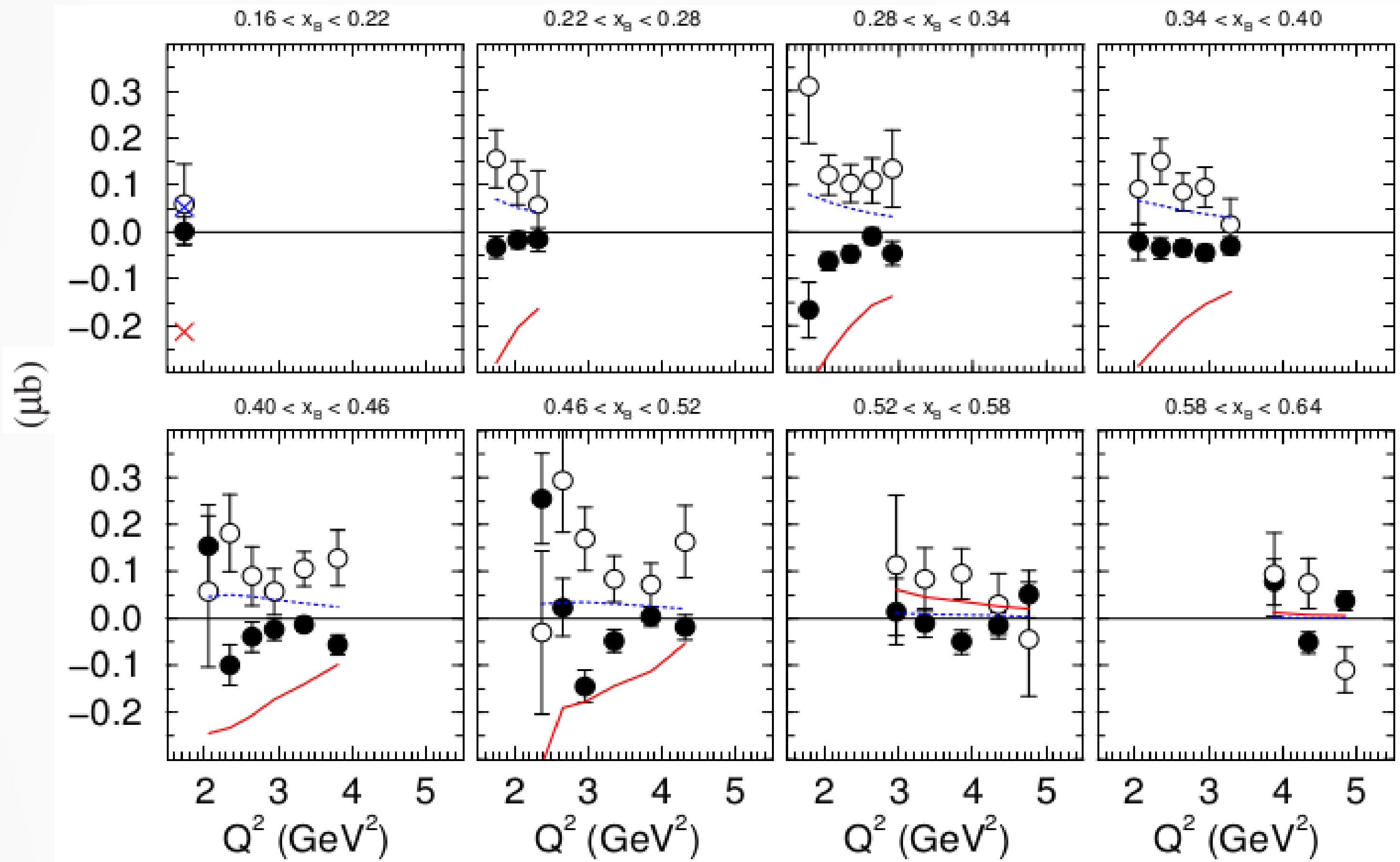
$$r_{ij}^{\alpha} = \frac{\rho_{ij}^{\alpha}}{1 + \varepsilon R}, \quad \text{for } \alpha = (0-3),$$

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

□ It is difficult to draw a firm conclusion concerning SCHC although most physical observables seem to support SCHC.

## T-L separated cross sections at low W

c-1 $\gamma^* \, p \to \omega(782) \, p$




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

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

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

Regge-based model
[Laget, PRD.70.054023 (2004)]

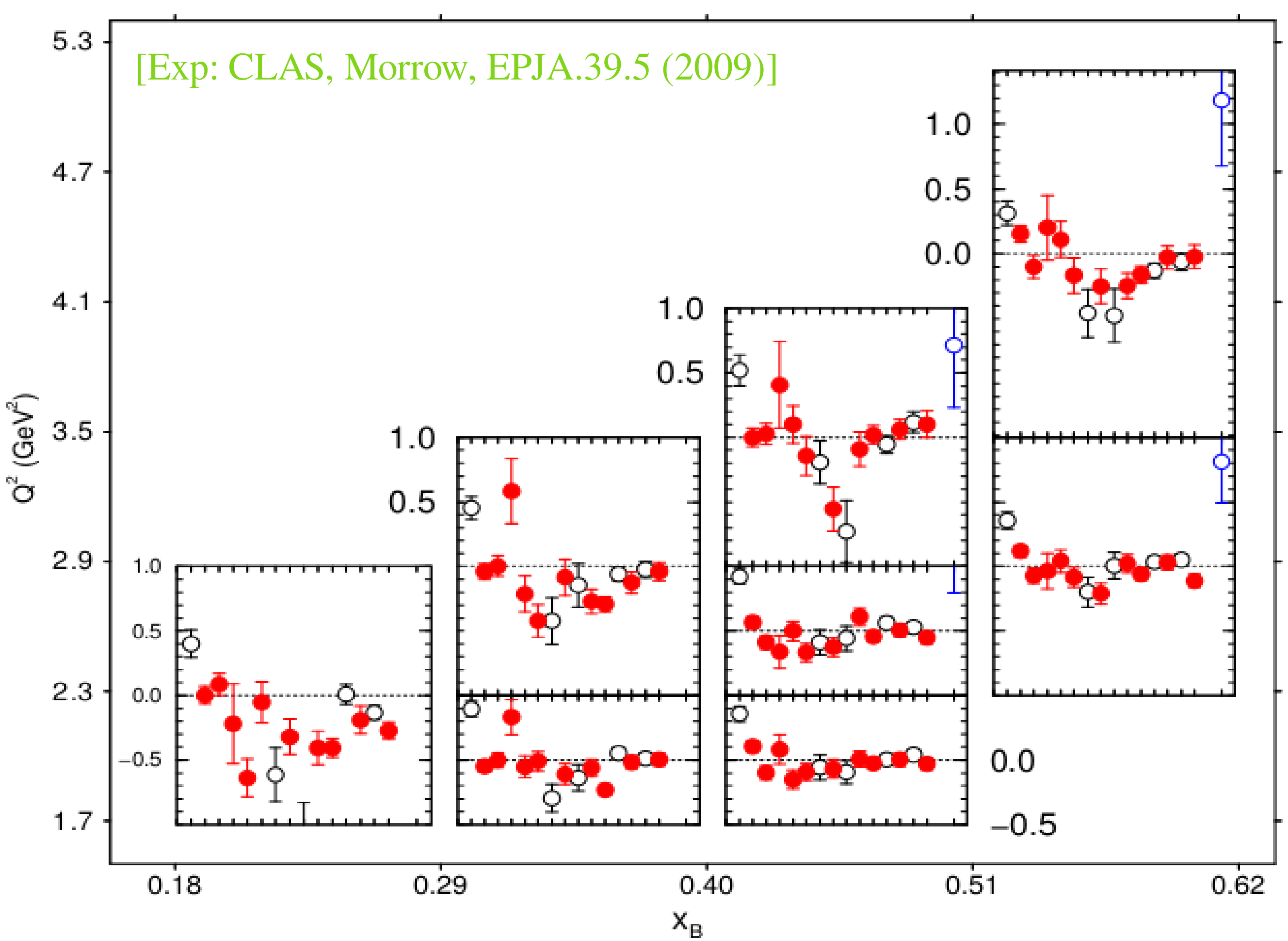
□ If SCHC holds, $\sigma_{TT}$ and $\sigma_{LT}$ become zero.

‣ 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 ($r_{ij}^k$) at low W

c-2 $\gamma^* p \to \omega(782)\, p$



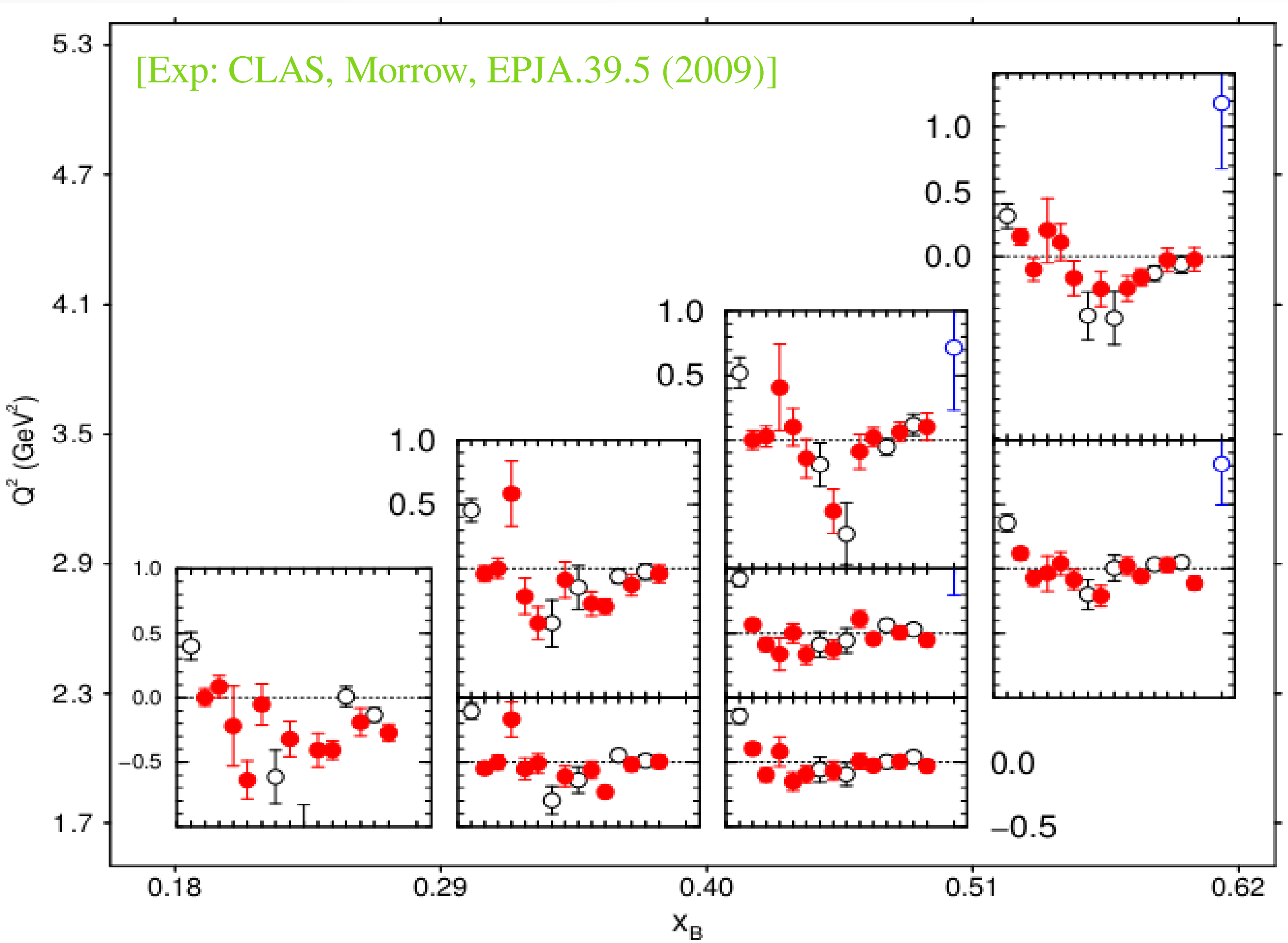

$$r_{ij}^{04} = \frac{\rho_{ij}^0 + \varepsilon R \rho_{ij}^4}{1 + \varepsilon R},$$
$$r_{ij}^{\alpha} = \frac{\rho_{ij}^{\alpha}}{1 + \varepsilon R}, \quad \text{for } \alpha = (0-3),$$
$$r_{ij}^{\alpha} = \sqrt{R}\frac{\rho_{ij}^{\alpha}}{1 + \varepsilon R}, \quad \text{for } \alpha = (5-8)$$

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

# Exclusive electroproduction of vector mesons

spin-density matrix elements ($r_{ij}^{k}$) at low W

c-2 $\gamma^* p \to \omega(782)\, p$




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

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

□ Theoretical studies on $\gamma^* p \to (\rho, \omega)\, p$ at low $Q^2$ and W are very rare. We need further investigation.

□ $r_{00}^{04}$, $\mathrm{Re}\, r_{10}^{04}$, $r_{1-1}^{04}$, $r_{00}^{1}$, $r_{11}^{1}$, $\mathrm{Re}\, r_{10}^{1}$, $r_{1-1}^{1}$, $\mathrm{Im}\, r_{10}^{2}$, $\mathrm{Im}\, r_{1-1}^{2}$, $r_{00}^{5}$, $r_{11}^{5}$, $\mathrm{Re}\, r_{10}^{5}$, $r_{1-1}^{5}$, $\mathrm{Im}\, r_{10}^{6}$, $\mathrm{Im}\, r_{1-1}^{6}$

□ SCHC holds, if $r_{ij}^{k} = 0$. It seems that SCHC is broken.

## Summary & Future work

◇ For $\gamma\, p \to \varphi\, p$ & $\gamma^*\, p \to \varphi\, p$, we studied the relative contributions between the Pomeron and various meson exchanges.
The light-meson ($\pi$, $\eta$, $a_0$, $f_0$,...) contribution is crucial to describe the data at low W & $Q^2$.

◇ For $\gamma^*\, p \to V\, p$, from the data of separated cross sections ($\sigma_{TT}$, $\sigma_{LT}$) and SDMEs ($r_{ij}^k$), we can test whether helicity is conserved or not in three different frames.

$\gamma^*\, p \to \varphi\, p$ : SCHC is conserved (low W & $Q^2$), is broken (high W & $Q^2$ at HERA).
$\gamma^*\, p \to \rho\, p$ : SCHC seems to hold (low W & $Q^2$).
$\gamma^*\, p \to \omega\, p$ : SCHC is broken (low W & $Q^2$).

◇ Extension to $\gamma^{(*)}\, A \to V[\varphi, J/\psi, \Upsilon(1S)]\, A$, [A = $^2$H, $^4$He, $^{12}$C,…]
$\gamma\, ^4\text{He} \to \varphi\, ^4\text{He}$ [S.H.Kim, T.S.H.Lee, S.i.Nam, Y. Oh, PRC.104.045202 (2021)]
> A distorted-wave impulse approximation within the multiple scattering formulation

◇ We plan to employ various Pomeron models to the soft and hard diffractive processes.

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

# Summary & Future work

◇ For $\gamma\, p \rightarrow \varphi\, p$ & $\gamma^*\, p \rightarrow \varphi\, p$, we studied the relative contributions between the Pomeron and various meson exchanges.
The light-meson ($\pi$, $\eta$, $a_0$, $f_0$,...) contribution is crucial to describe the data at low W & $Q^2$.

◇ For $\gamma^*\, p \rightarrow V\, p$, from the data of separated cross sections ($\sigma_{TT}$, $\sigma_{LT}$) and SDMEs ($r_{ij}^k$), we can test whether helicity is conserved or not in three different frames.

$\gamma^*\, p \rightarrow \varphi\, p$ : SCHC is conserved (low W & $Q^2$), is broken (high W & $Q^2$ at HERA).
$\gamma^*\, p \rightarrow \rho\, p$ : SCHC seems to hold (low W & $Q^2$).
$\gamma^*\, p \rightarrow \omega\, p$ : SCHC is broken (low W & $Q^2$).

◇ Extension to $\gamma^{(*)}\, A \rightarrow V[\varphi, J/\psi, \Upsilon(1S)]\, A$, [A = $^2$H, $^4$He, $^{12}$C,…]
$\gamma\, ^4\text{He} \rightarrow \varphi\, ^4\text{He}$ [S.H.Kim, T.S.H.Lee, S.i.Nam, Y. Oh, PRC.104.045202 (2021)]
> A distorted-wave impulse approximation within the multiple scattering formulation

◇ We plan to employ various Pomeron models to the soft and hard diffractive processes.

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

Thank you very much for your attention