Photo- and Electroproduction of Vector Mesons

Sang-Ho Kim (金相鎬)

Pukyong National University, Busan

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asia pacific center for theoretical physics

https://www.apctp.org/plan.php/nps2021

Contents

- ❑ QCD, the field theory of quark and gluon interactions,
  > is expected to describe the strong force between hadrons.
  > is a successful theory in the limit of short distances (perturbative QCD).

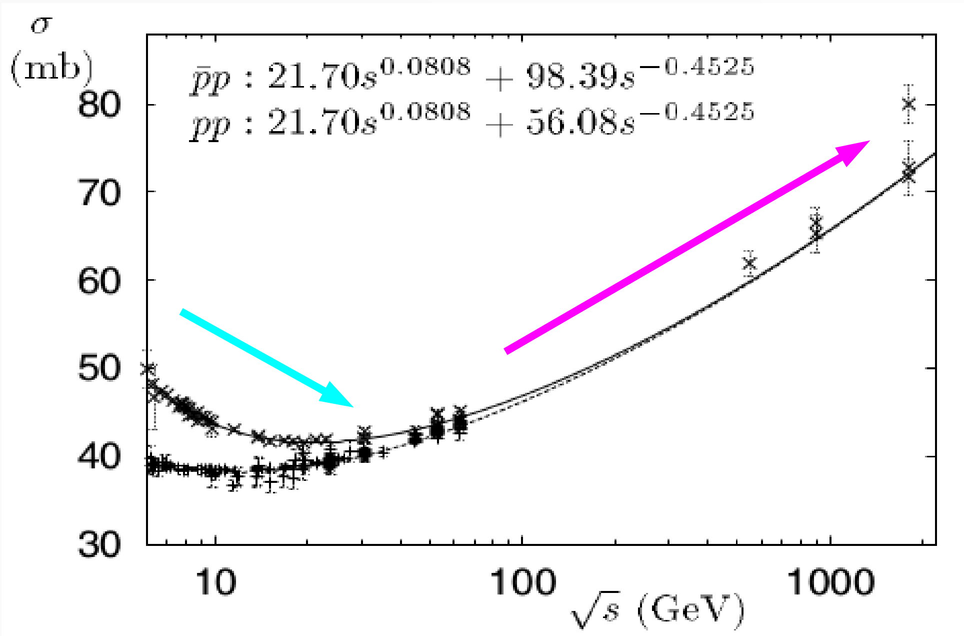
- ❑ Many of the scattering processes of hadrons are dominated by long-range forces ("soft interactions").

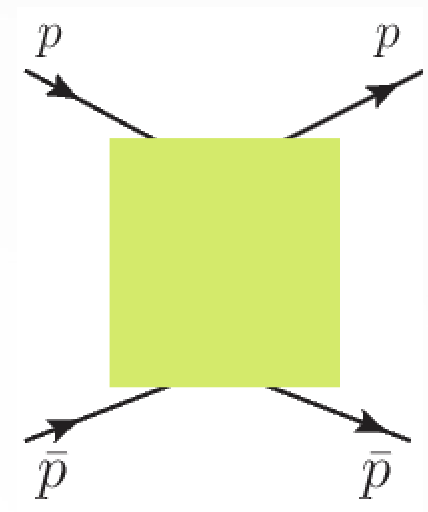
- ❑ A large fraction of these soft interactions is mediated by vacuum quantum number ($J^{PC} = 0^{++}$) exchange and is termed "diffractive".

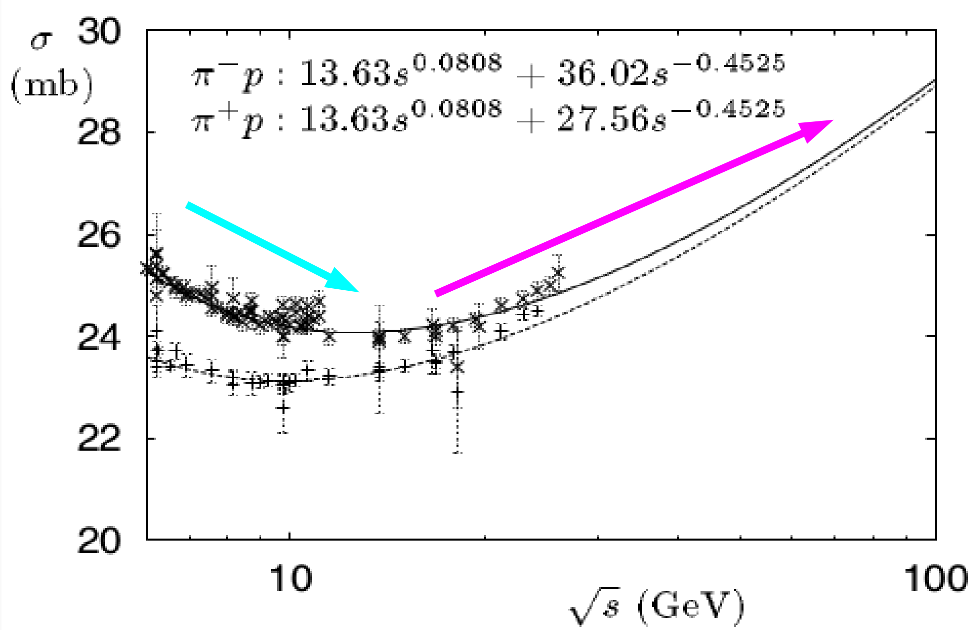
- ❑ In hadronic interactions, diffraction is well described by Regge theory.

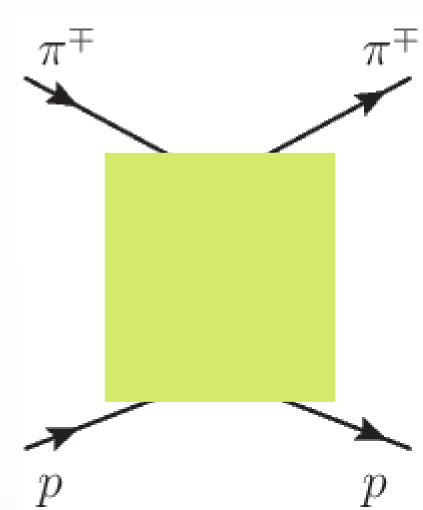
- ❑ Examples of diffractive scattering processes
  > $\bar{p}\,p \rightarrow \bar{p}\,p$, $\pi^{\pm}p \rightarrow \pi^{\pm}p$, $\gamma\, p \rightarrow (\rho, \omega, \varphi, J/\psi)\, p$ ...

Soft hadronic processes





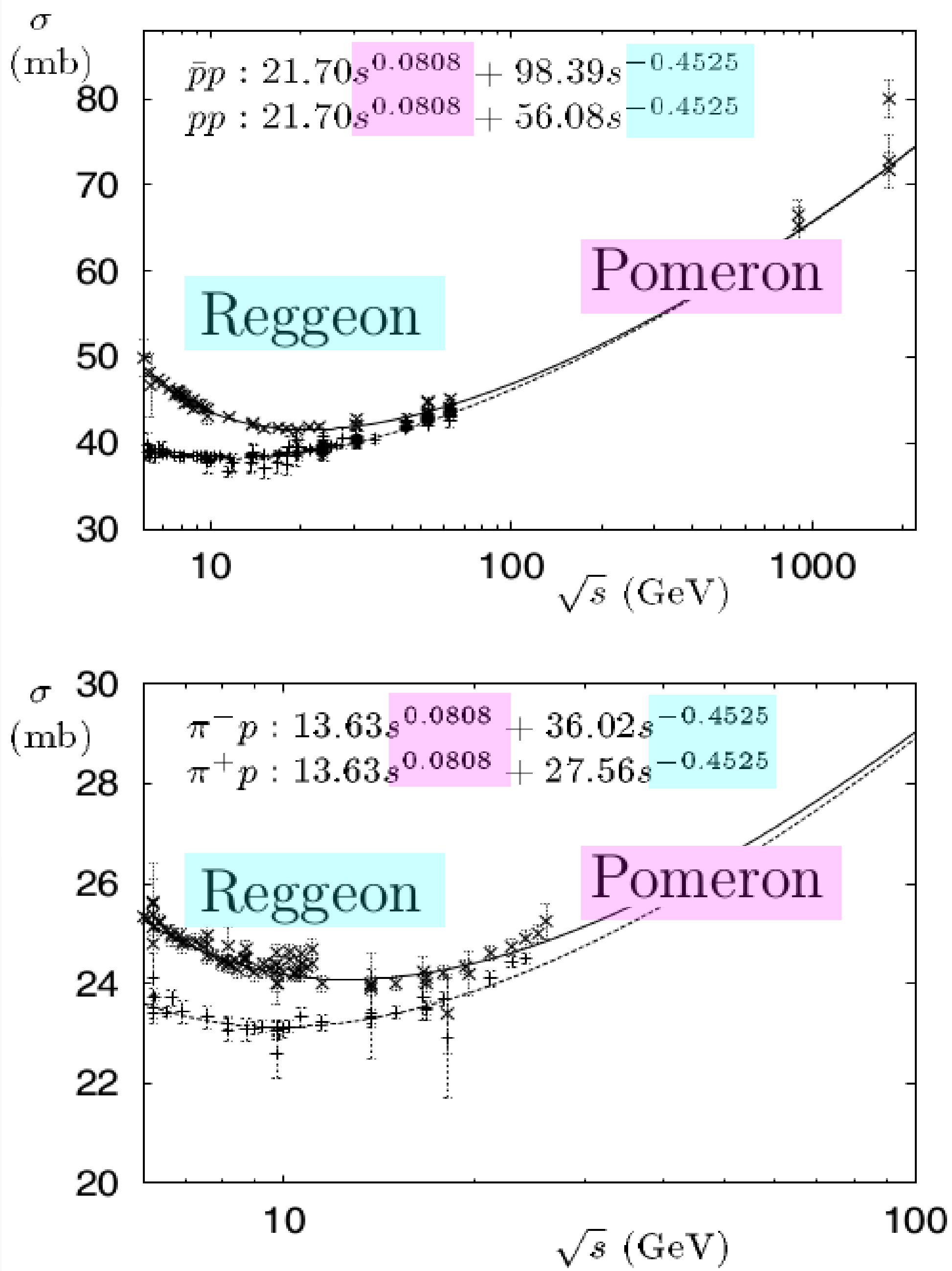




What is
the reaction
mechanism?

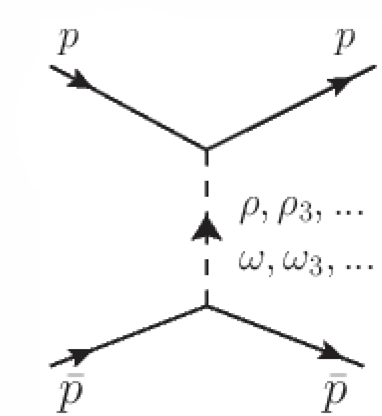
Donnachie, Pomeron Physics and QCD (2002)

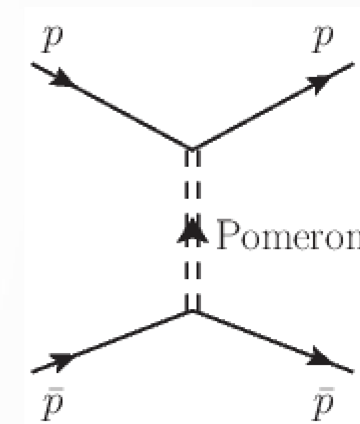
Soft hadronic processes



Reggeon
(Meson exchanges)

Pomeron
(Two-gluon exchange)





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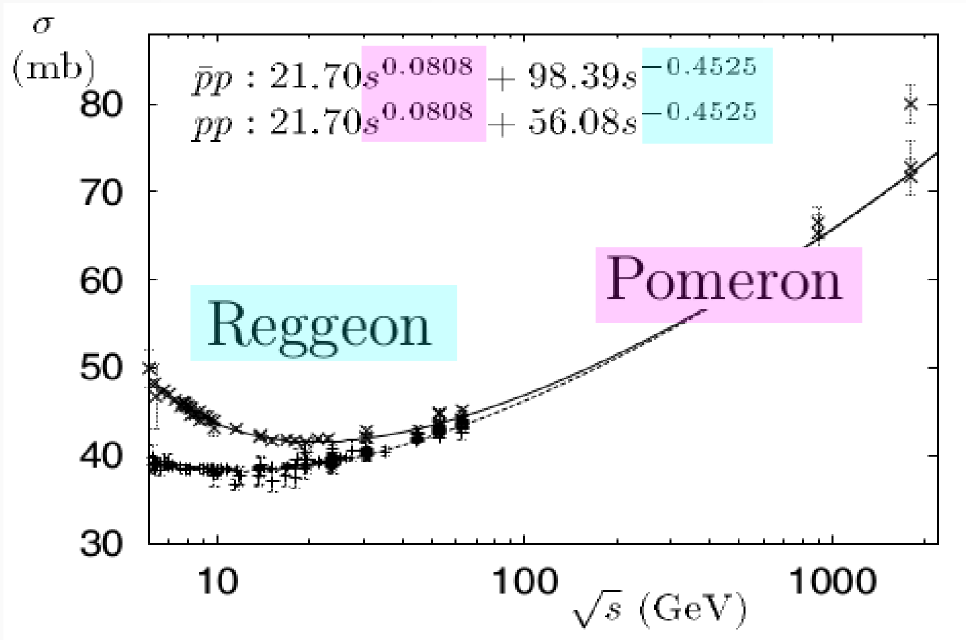
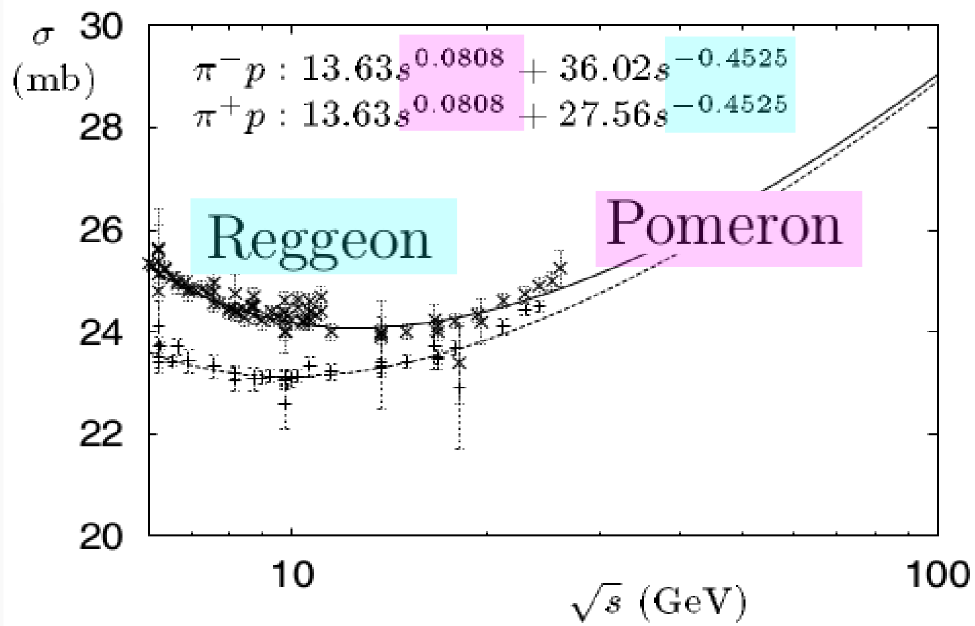


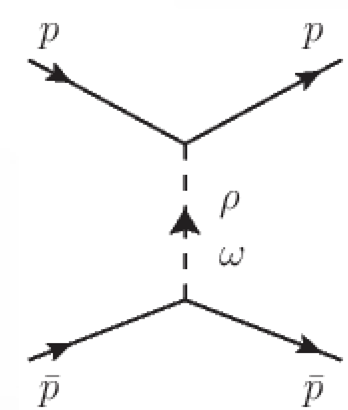


Donnachie, Pomeron Physics and QCD (2002)

Reggeon (Meson exchanges)

- ❑ an exchange of a family of ordinary mesons.
- ❑ Governs relatively low energy regions.
- ❑ Exchanges of (π, η, ρ, ω, ...) mesons and their resonances are possible in the *t* channel.

A single particle exchange in the *t* channel of spin J

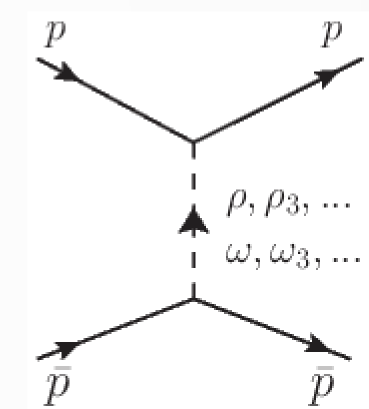


$$\sigma \sim s^{J-1}$$

It violates unitarity for large J.
Froissart bound :

$$\sigma^{\text{Tot}}(s) \leq \text{constant} \times \log^2(s/s_0)$$

Sum up all meson exchanges of various J

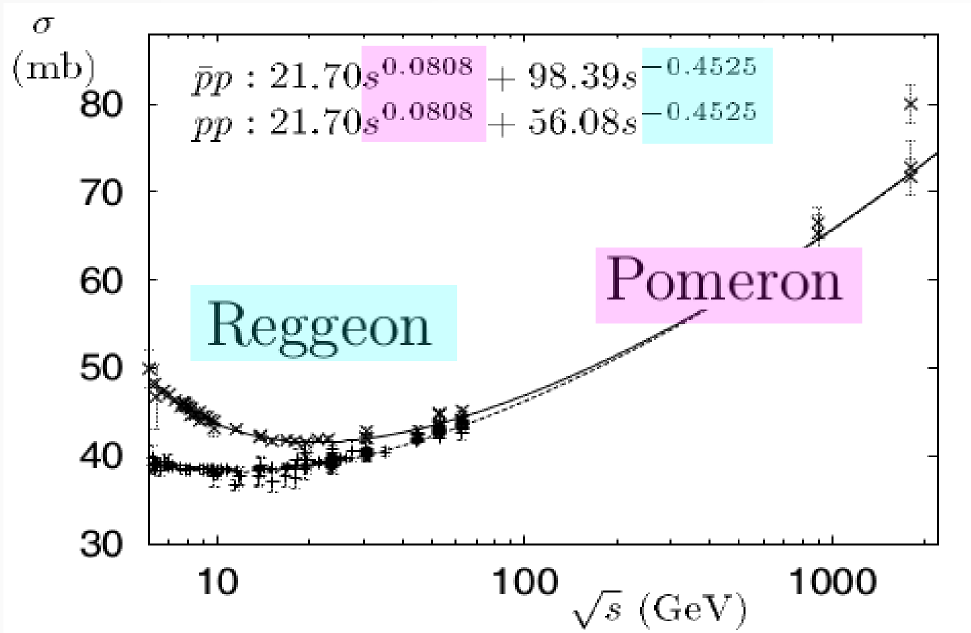


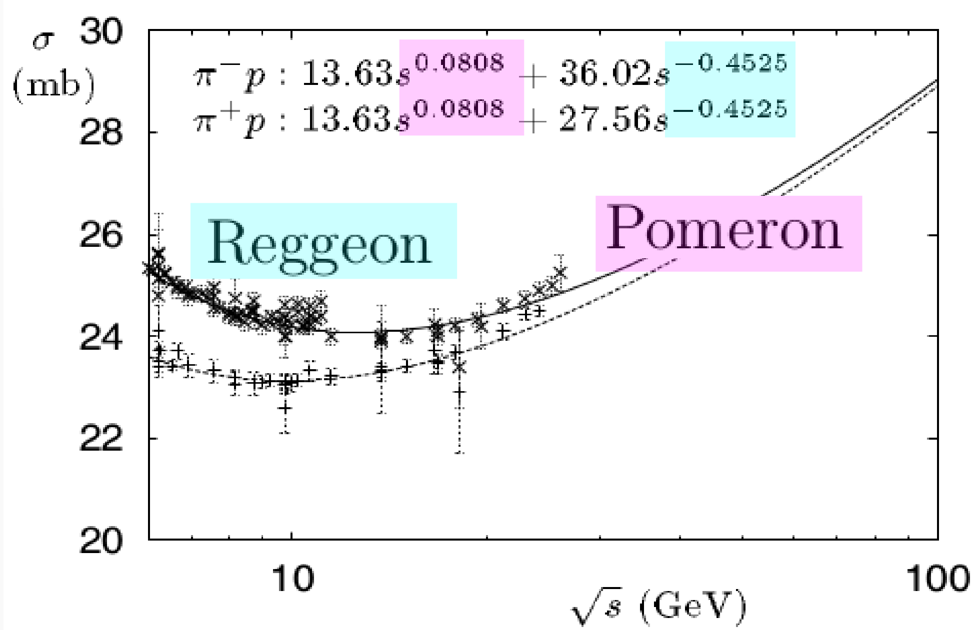
$$\sigma \sim s^{\alpha(0)-1}$$

α(*t*) is called a Regge trajectory.

$$\alpha(t) = \alpha(0) + \alpha' t$$

Soft hadronic processes

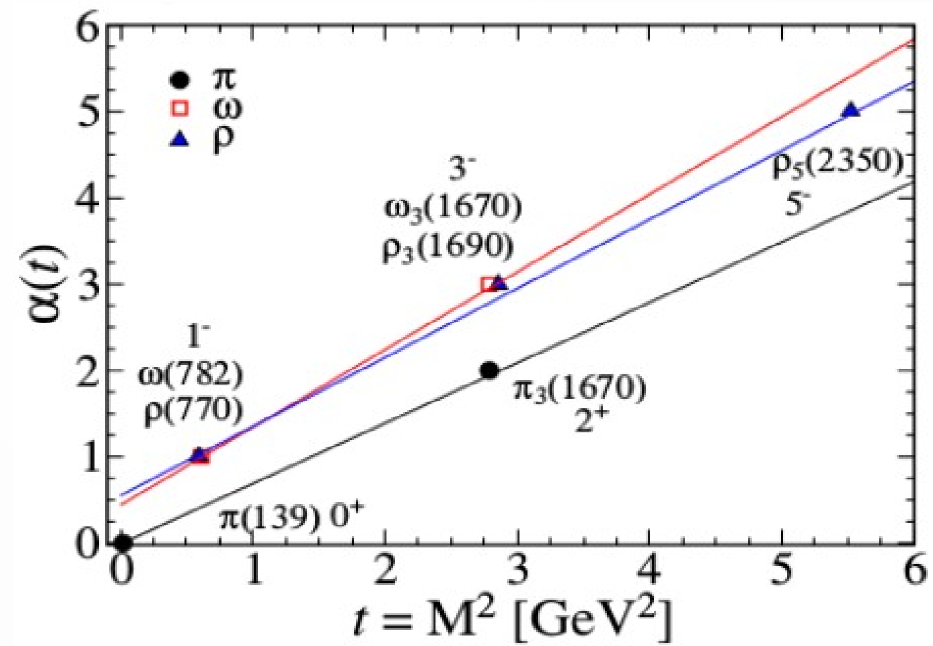




Donnachie, Pomeron Physics and QCD (2002)

Reggeon (Meson exchanges)

- ❑ an exchange of a family of ordinary mesons.
- ❑ Governs relatively low energy regions.
- ❑ (ρ,ω) trajectories (C=-1, natural parity) & (f_2,a_2) trajectories (C=+1, natural parity) are all degenerate.



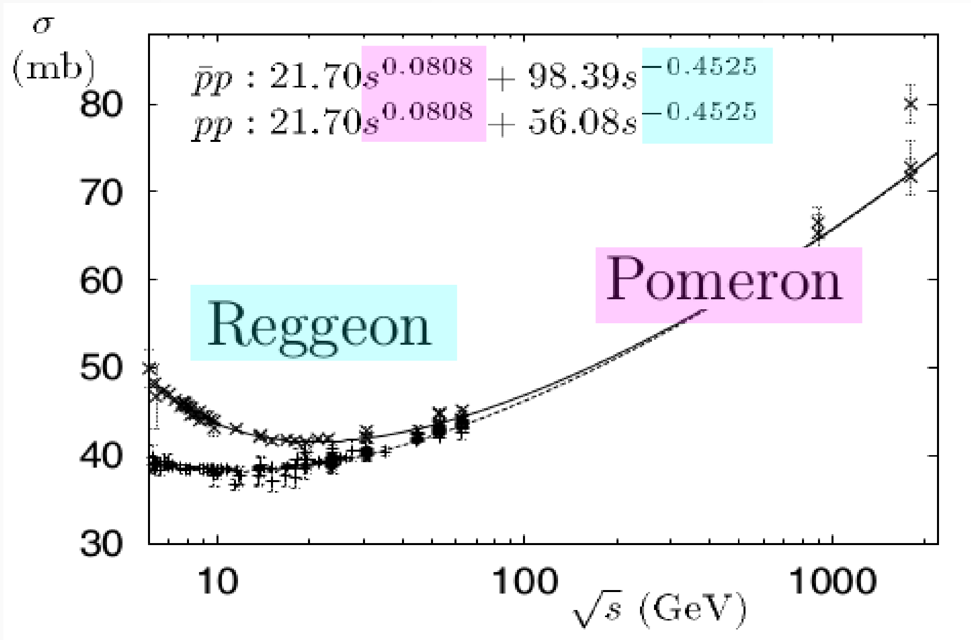
$$\alpha(M^2) = J$$

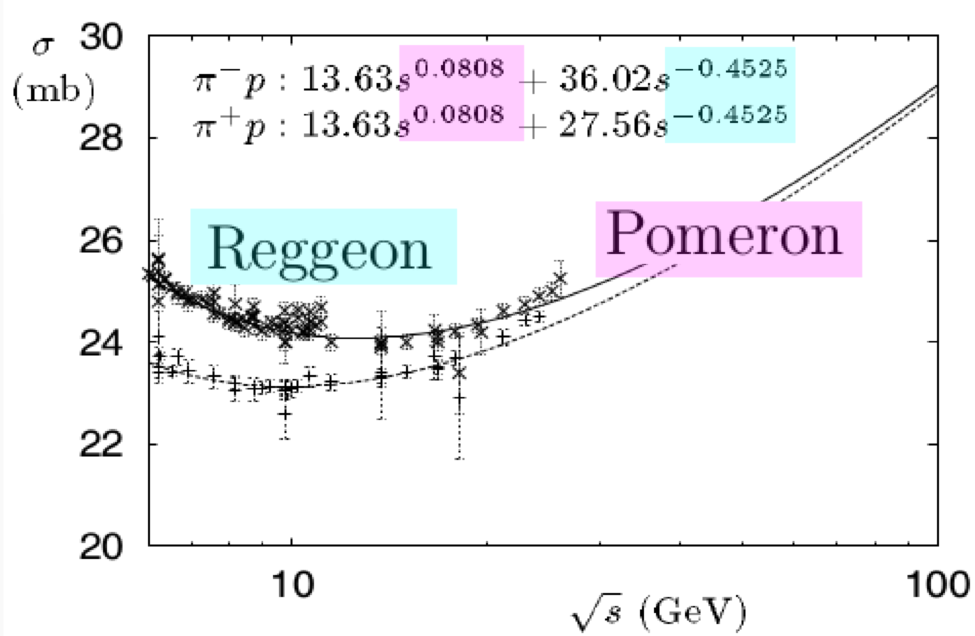
$$\alpha_\pi(t) = 0.7(t - M_\pi^2),$$
$$\alpha_\rho(t) = 0.55 + 0.8t,$$
$$\alpha_\omega(t) = 0.44 + 0.9t.$$

- ❑ α(t) categorizes hadrons with the same internal quantum numbers.

$$\sigma \propto s^{\alpha(0)-1} = s^{-0.5}$$

Soft hadronic processes





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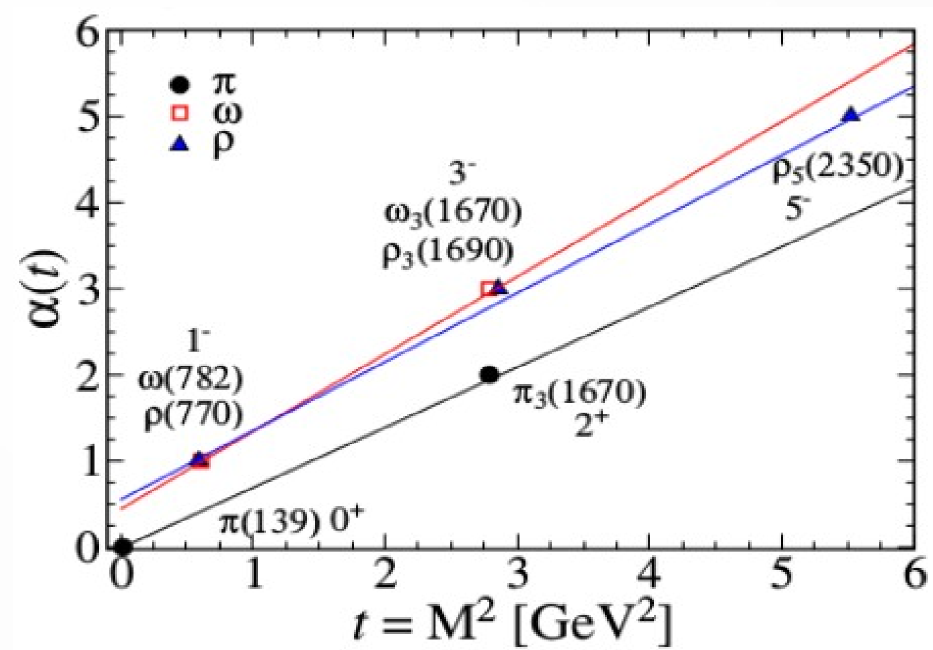

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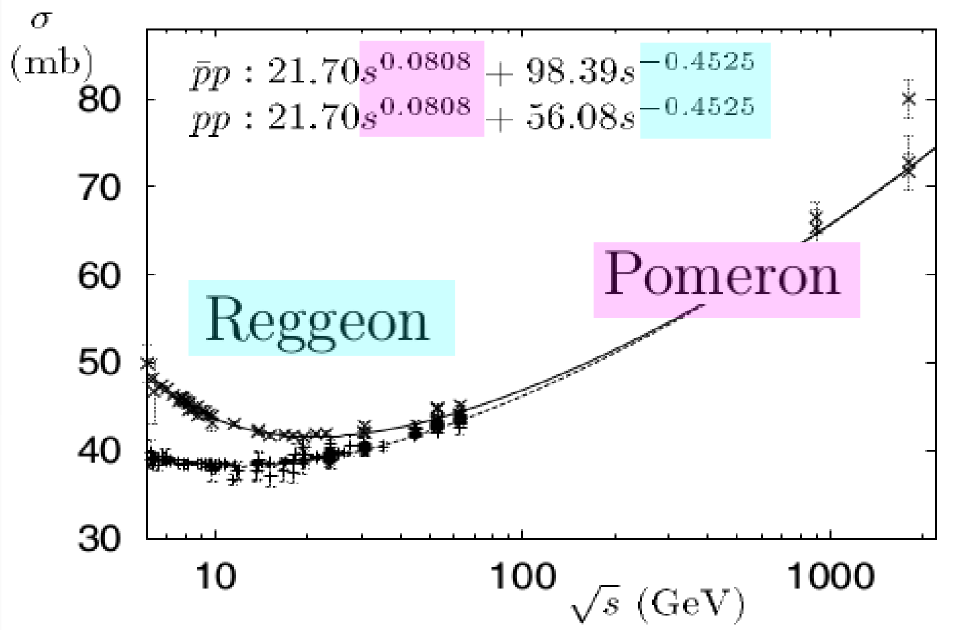
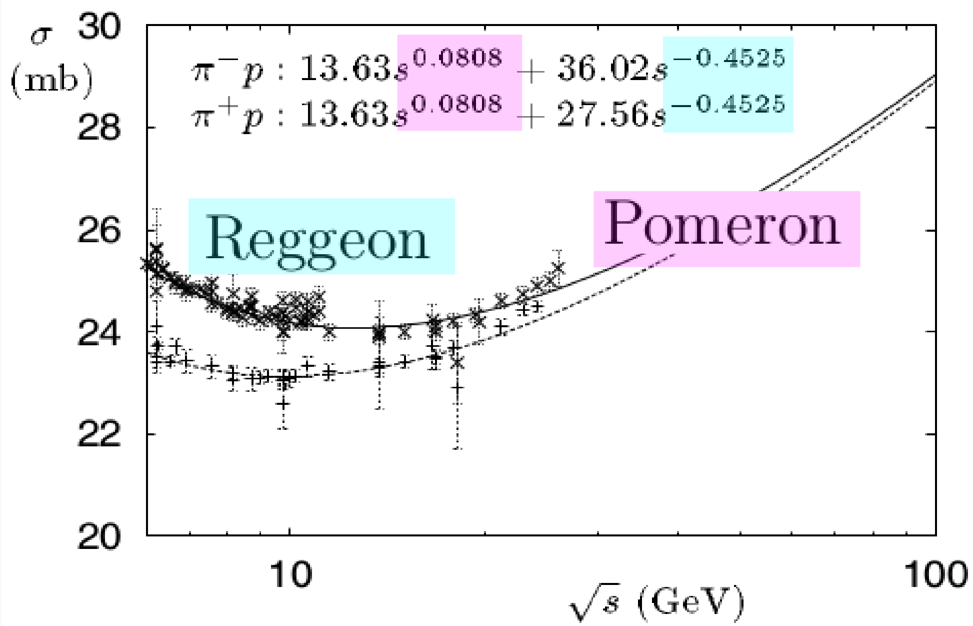
Regge trajectories of Baryons

Baryon exchange processes
Storrow, Phys Rept. 103.317 (1984)



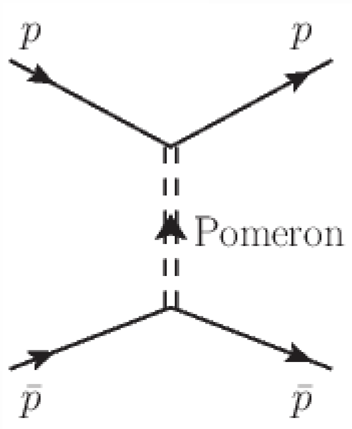


Donnachie, Pomeron Physics and QCD (2002)

Pomeron

- Is not associated with the meson trajectories.
- Has the vacuum quantum number, I=0 and C=+1.
- Governs relatively high energy regions.

- Donnachie & Landshoff (DL) model:
  The two-gluon exchange mechanism is parametrized as a Pomeron exchange within the Regge phenomenology.



- Pomeron trajectory: $\alpha_P(t) = 1.08 + 0.25t$

$$\sigma \propto s^{\alpha(0)-1} = s^{0.08}$$

1. Exclusive photoproduction of vector mesons

❑ Diffractive scattering processes

> $\bar{p}\,p \rightarrow \bar{p}\,p$, $\pi^{\pm} p \rightarrow \pi^{\pm} p$

> $\gamma\, p \rightarrow (\rho, \omega, \varphi, J/\psi)\, p$

❑ Particle Data Group 2020 (https://pdg.lbl.gov)

Mesons reviews

- Light Unflavored
  - Further States
- Strange
- Charmed
- Charmed, Strange (including possibly non-$q\bar{q}$ states)
- Bottom
- Bottom, Strange
- Bottom, Charmed
- $c\bar{c}$ (including possibly non-$q\bar{q}$ states)
- $b\bar{b}$ (including possibly non-$q\bar{q}$ states)
- Non $q\bar{q}$ Candidates

→

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;

for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

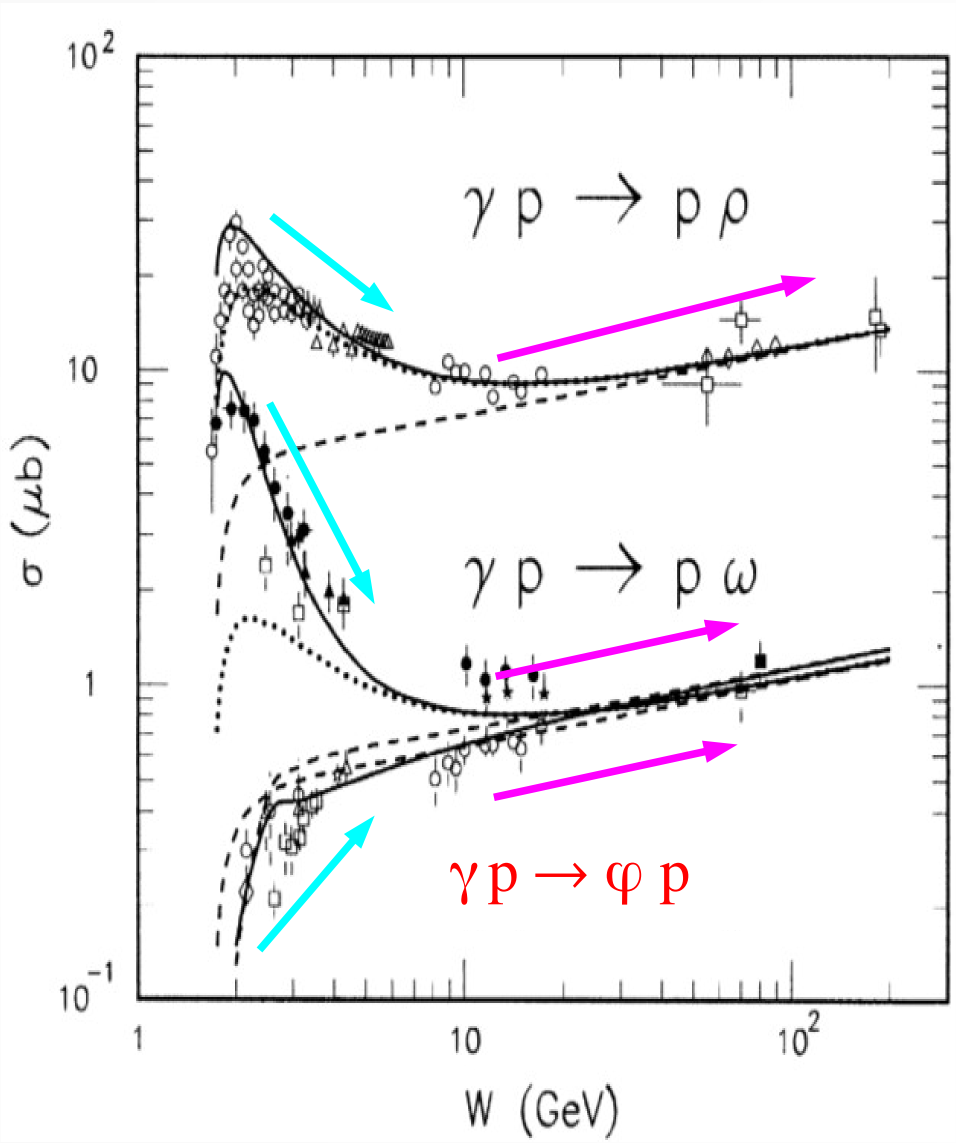
$\rho(770)$	$I^G(J^{PC}) = 1^+(1^{--})$
$\omega(782)$	$I^G(J^{PC}) = 0^-(1^{--})$
$\phi(1020)$	$I^G(J^{PC}) = 0^-(1^{--})$

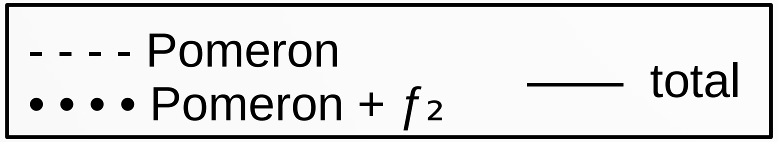
→

$c\bar{c}$ MESONS (including possibly non-$q\bar{q}$ states)

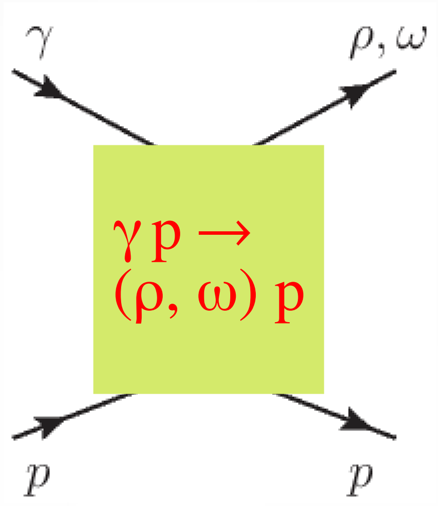
$J/\psi(1S)$ $\quad I^G(J^{PC}) = 0^-(1^{--})$

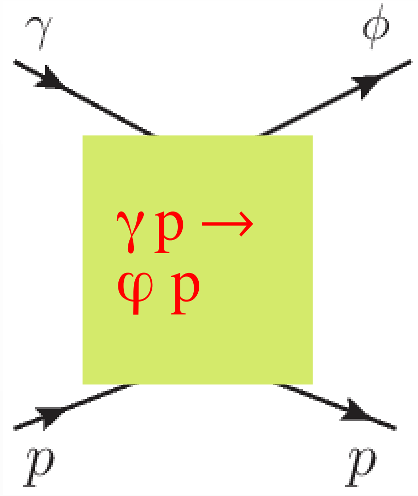
1. Exclusive photoproduction of vector mesons



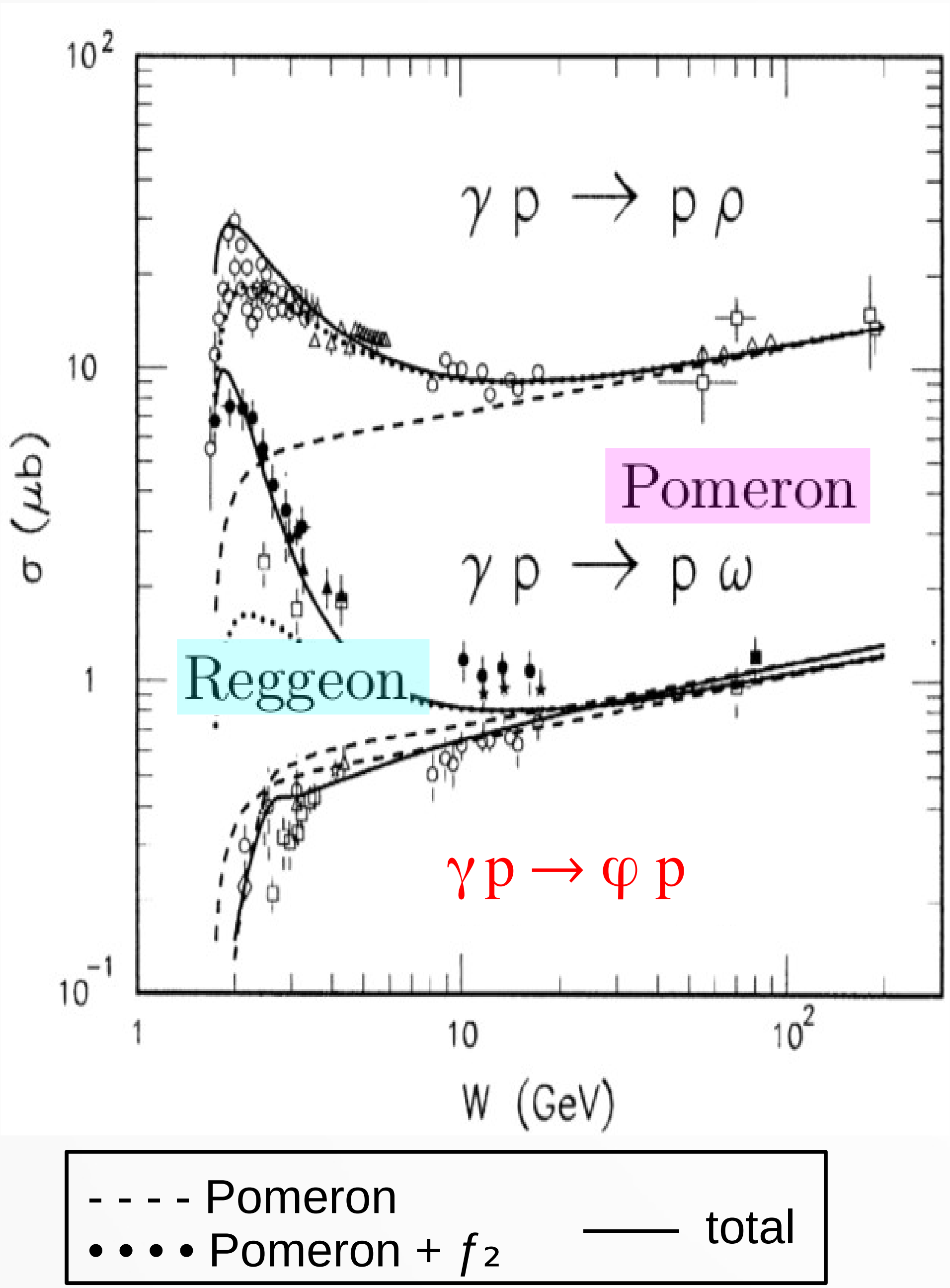


Laget,PLB.489.313(2000)





1. Exclusive photoproduction of vector mesons



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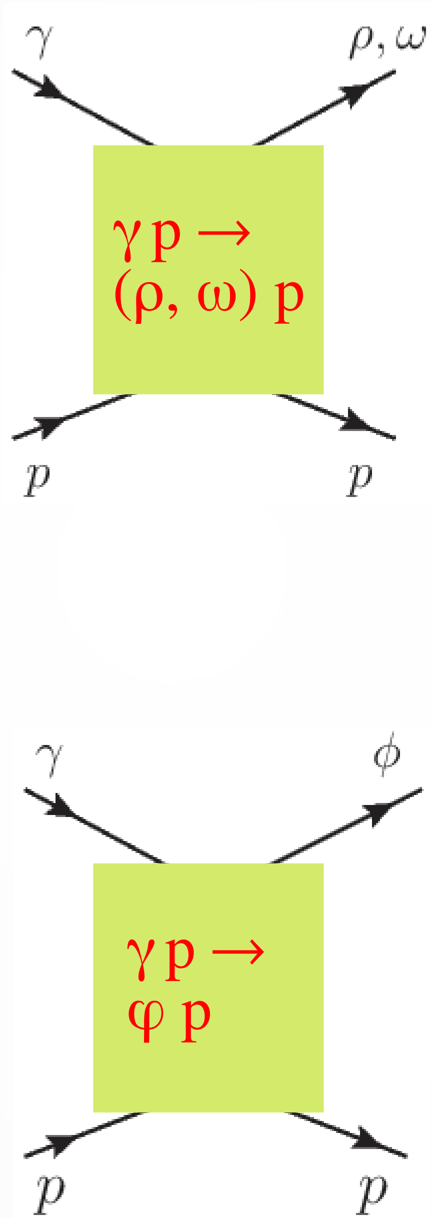
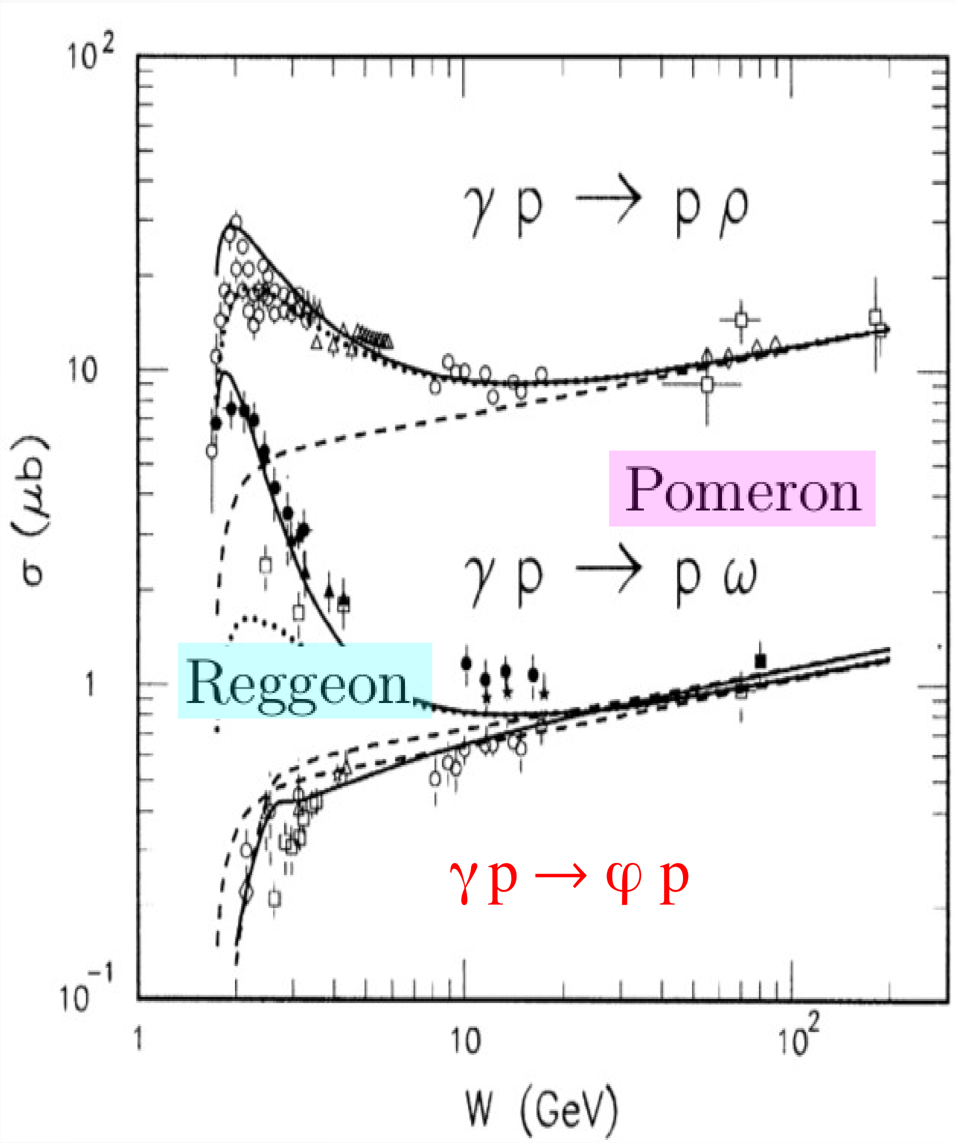


- At low energies, Reggeon (meson) exchanges are much more suppressed for γ p → φ p relative to γ p → (ρ, ω) p.

1. Exclusive photoproduction of vector mesons

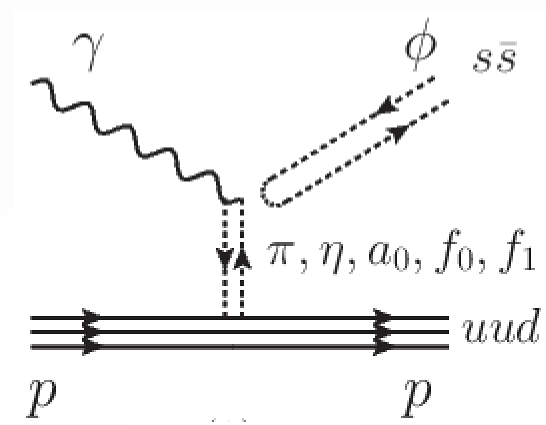


- - - - Pomeron
• • • • Pomeron + f_2
—— total

Laget,PLB.489.313(2000)

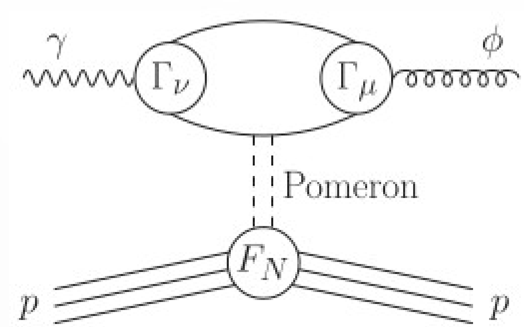
❑ We focus on γ p → φ p.

❑ Low energy



□ σ [γp → φp] << σ [γp → (ρ,ω)p] due to the OZI rule (The Feynman diagram is disconntected.)

❑ High energy



□ σ [γp → φp] ≈ σ [γp → ωp]

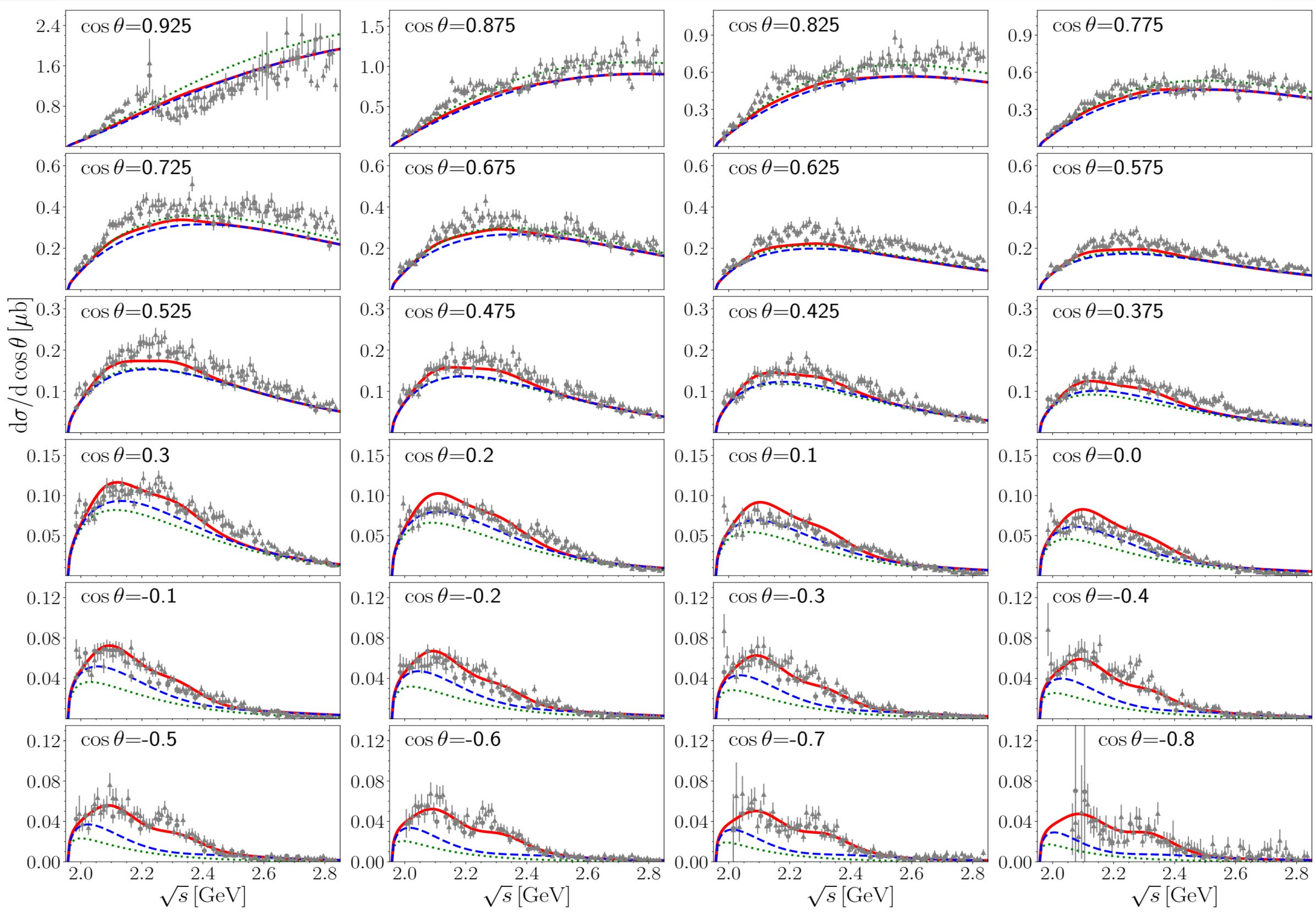
□ F_N: Isoscalar EM form factor of the nucleon

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

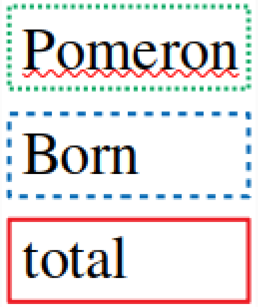
❑ General vector meson exchanges (ρ,ω) [$J^{PC}(1^{--})$] are not allowed due to their negative charge conjugations (C=-1).

1. Results: γ p → φ p

differential cross sections



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

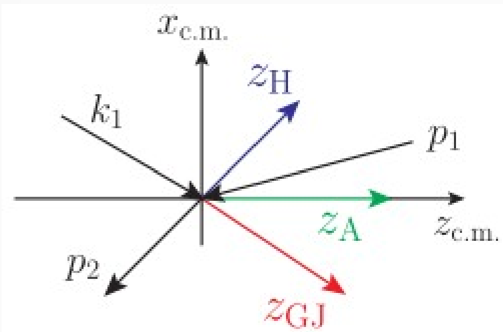


[Dey (CLAS), PRC.89. 055208 (2014)]

1. Results: γ p → φ p

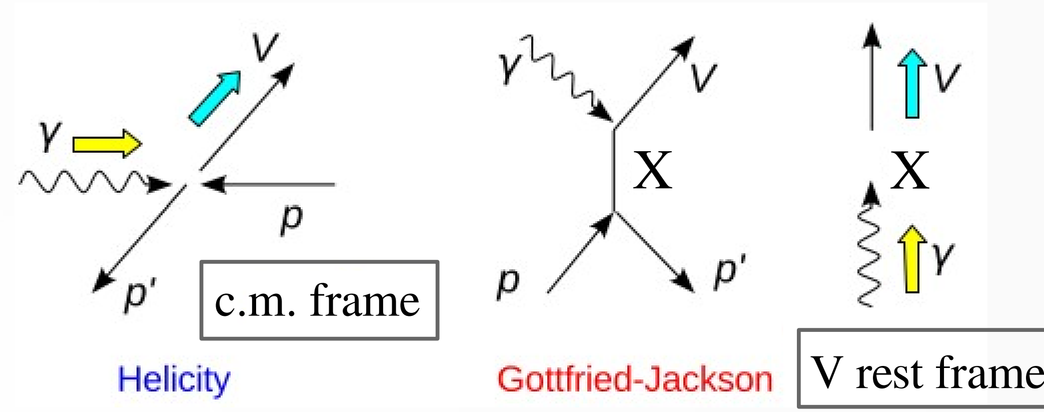
spin-density matrices

❑ 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

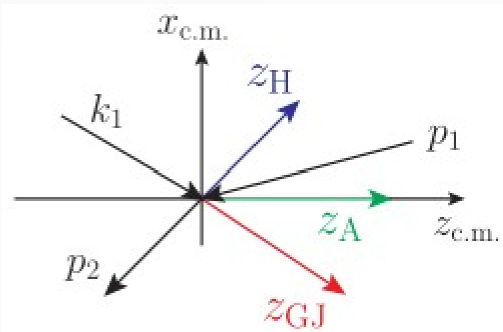
❑ For a *t*-channel exchange of X,
the momentum of γ and V is collinear in the GJ frame.

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

1. Results: γ p → φ p

spin-density matrices

❑ Decay frame



V rest frame

Adair frame
Helicty frame
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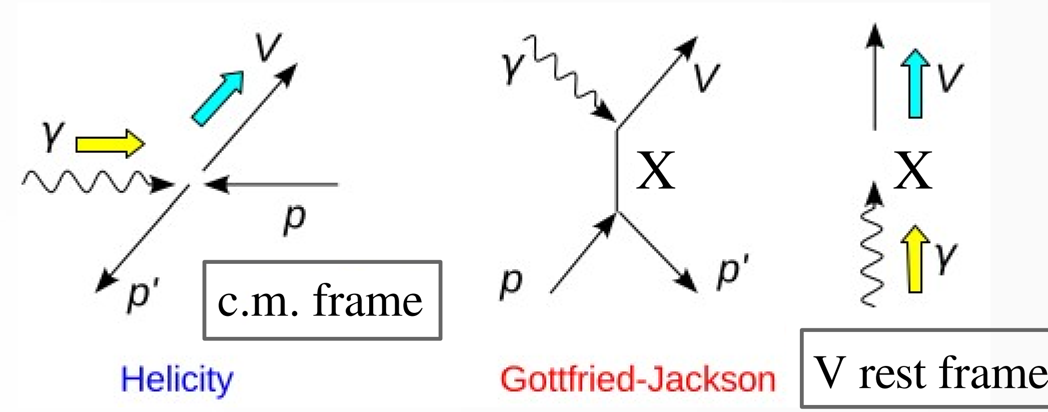

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$$\rho^0_{00} \propto \left|\mathcal{M}_{\lambda_\gamma=1,\lambda_\phi=0}\right|^2 + \left|\mathcal{M}_{\lambda_\gamma=-1,\lambda_\phi=0}\right|^2$$

- 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:

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

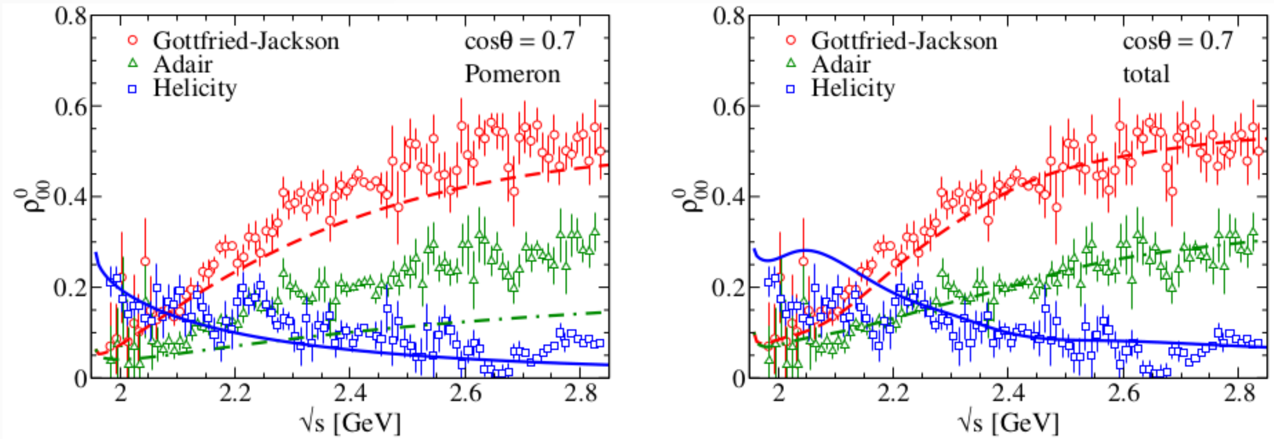
$$\alpha_{\mathrm{H}\to\mathrm{GJ}} = -\cos^{-1}\left(\frac{v - \cos\theta_{\mathrm{c.m.}}}{v\cos\theta_{\mathrm{c.m.}} - 1}\right)$$

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

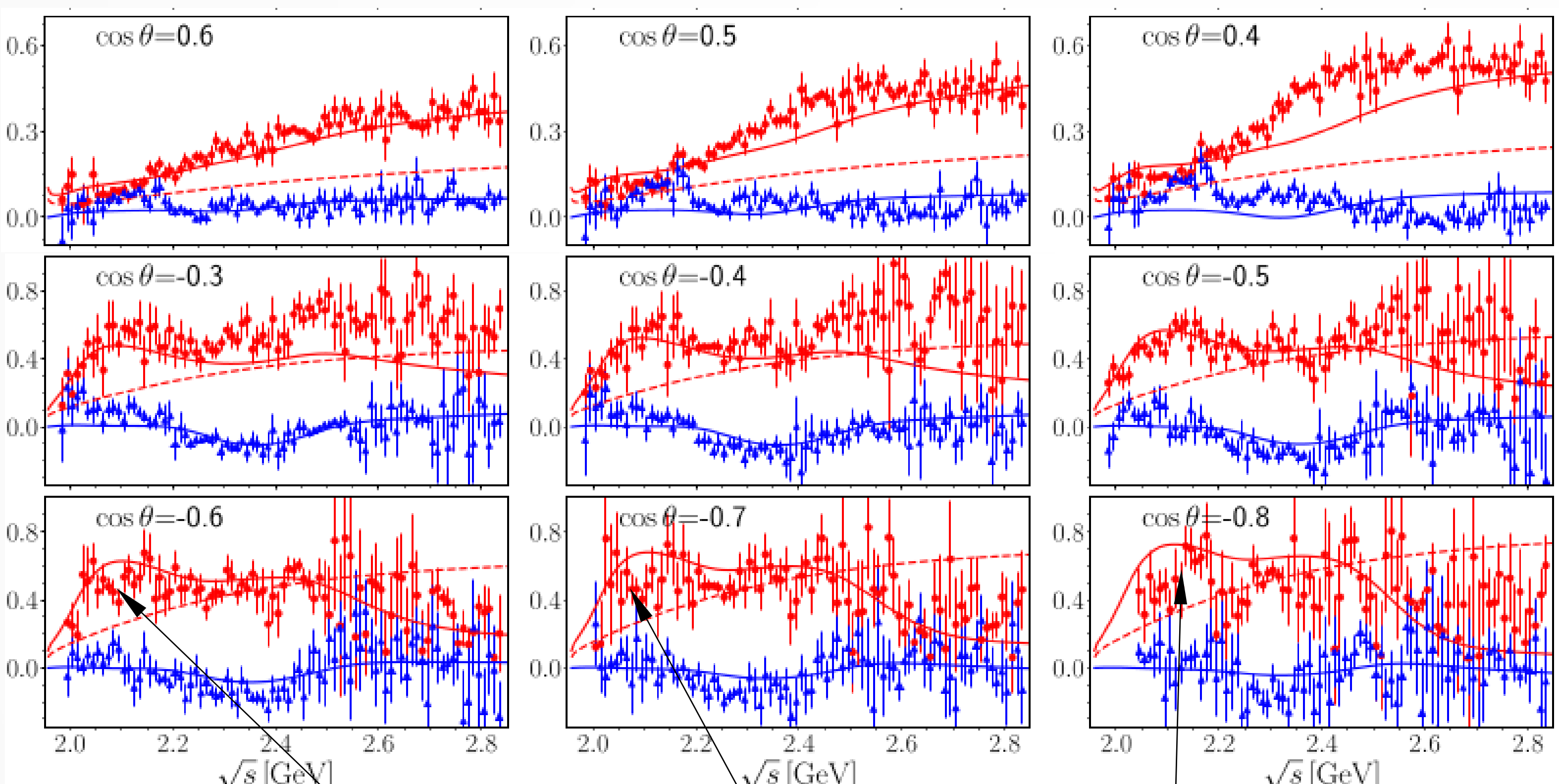
v : The velocity of the K meson in the φ rest frame (φ → K$\overline{\mathrm{K}}$ decay)

1. Results: $\gamma p \to \phi p$

spin-density matrices



- TCHC & SCHC are broken.



full

Pomeron

full

○ ρ^0_{00}

△ ρ^0_{1-1}

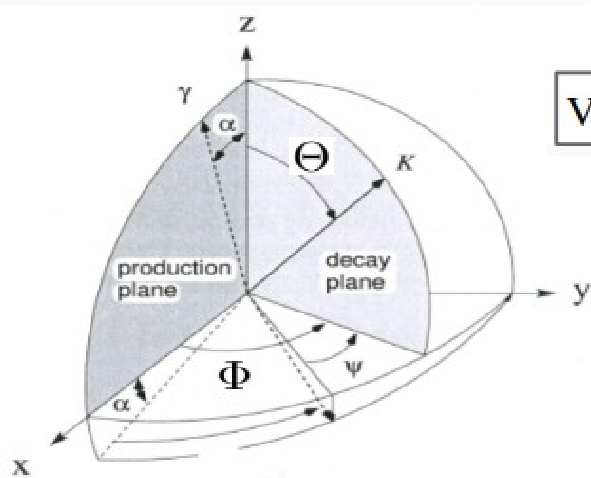
Adair frame

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

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

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

decay angular distributions (φ → K$\bar{K}$ decay)

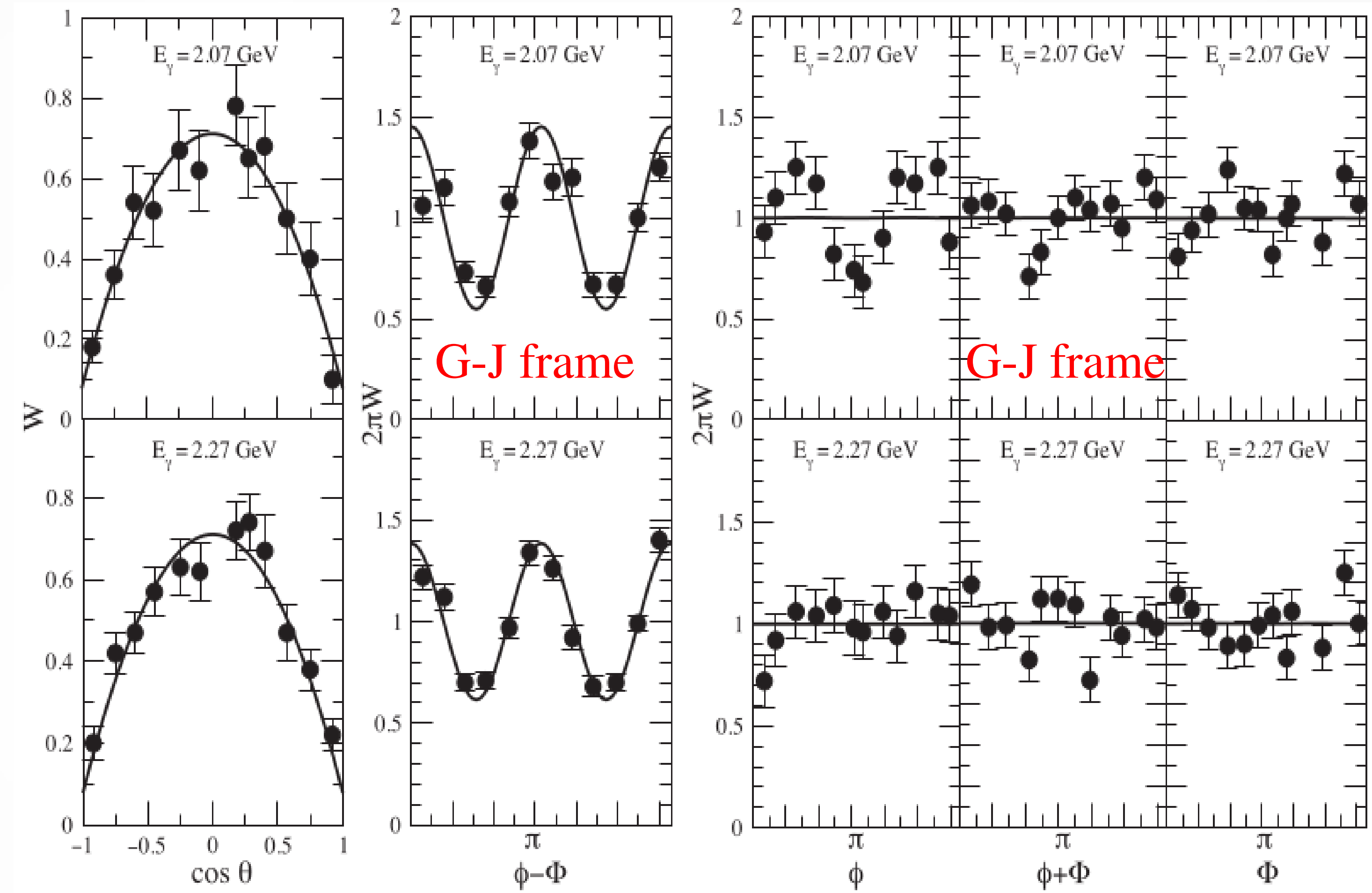


V rest frame

polar angle: Θ
azimuthal angle: Φ

$$W(\Omega_f) = \sum_{\lambda,\lambda'} \rho_{\lambda,\lambda'} Y_{1\lambda}(\Omega_f) Y^*_{1\lambda'}(\Omega_f)$$
$$= \rho_{00} Y_{10} Y^*_{10} + \rho_{11} Y_{11} Y^*_{11} + \rho_{-1-1} Y_{1-1} Y^*_{1-1}$$
$$+ \rho_{-11} Y_{1-1} Y^*_{11} + \rho_{1-1} Y_{11} Y^*_{1-1} + \rho_{01} Y_{10} Y^*_{11}$$
$$+ \rho_{10} Y_{11} Y^*_{10} + \rho_{0-1} Y_{10} Y^*_{1-1} + \rho_{-10} Y_{1-1} Y^*_{10}$$

$$W(\Omega_f) = \frac{3}{4\pi}\left[\rho_{00}\cos^2\Theta + \rho_{11}\sin^2\Theta - \rho_{1-1}\sin^2\Theta\cos 2\Phi - \sqrt{2}\mathrm{Re}\rho_{10}\sin 2\Theta\cos\Phi\right]$$



$$\rho_{\lambda\lambda'} = (-1)^{\lambda-\lambda'}\rho_{-\lambda-\lambda'}$$
$$\rho^0_{00} + \rho^0_{11} + \rho^0_{-1-1} = 1$$
$$\rho^0_{11} = \rho^0_{-1-1}$$

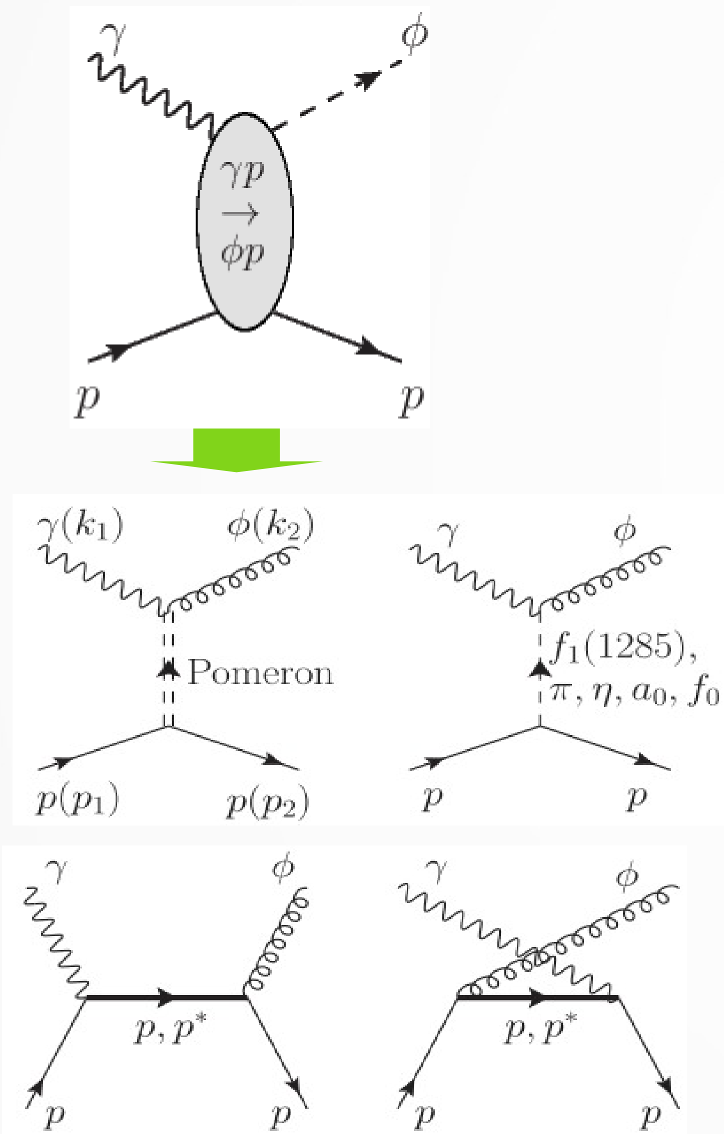
[Ryu et al., PTEP. 2014.023D03 (2014)]

□ Differential cross section

$$\frac{d\sigma}{dt\,d\Omega_f} = \frac{d\sigma}{dt} W(\Omega_f)$$

final state interaction (FSI)

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



❑ Ward-Takahashi identity

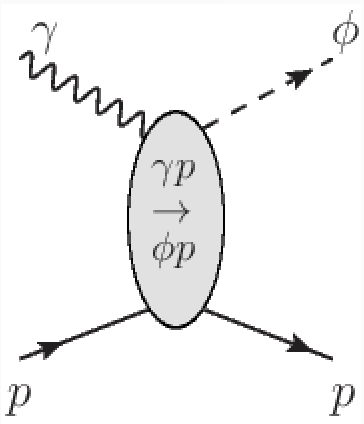
$$\mathcal{M}(k) = \epsilon_\mu(k)\mathcal{M}^\mu(k)$$

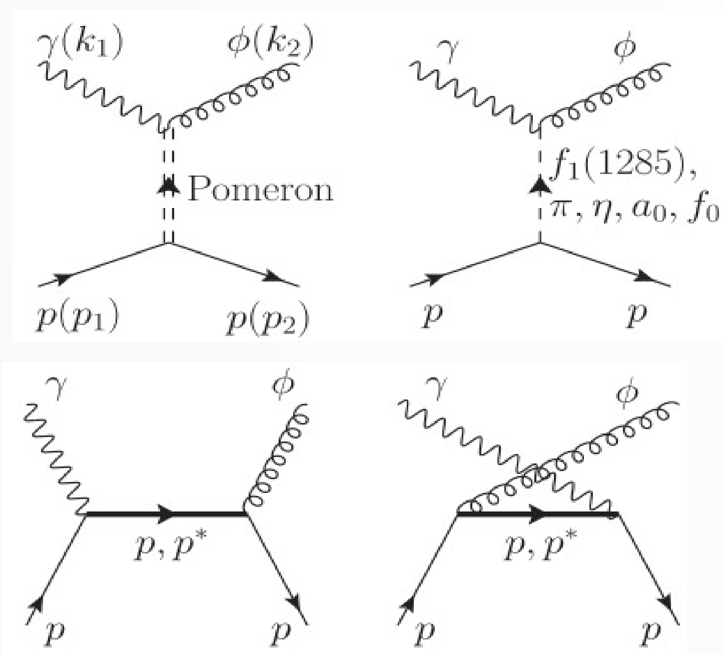
if we replace ϵ_μ with k_μ:

$$k_\mu \mathcal{M}^\mu(k) = 0$$

final state interaction (FSI)

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





❑ Effective Lagrangians

□ EM vertex

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

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

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

□ strong vertex

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

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

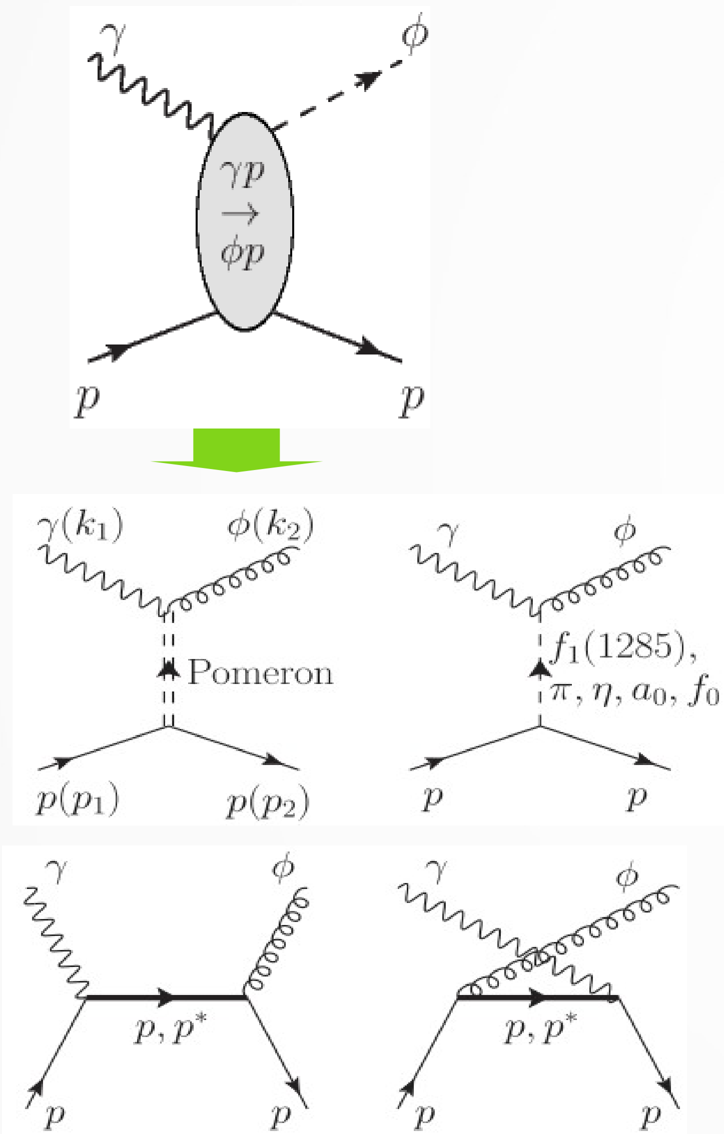
$$\mathcal{L}_{SNN} = -\, g_{SNN}\bar{N}SN$$

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

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

final state interaction (FSI)

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



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

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

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

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

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

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

❑ Effective Lagrangians

□ EM vertex

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

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

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

□ strong vertex

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

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

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

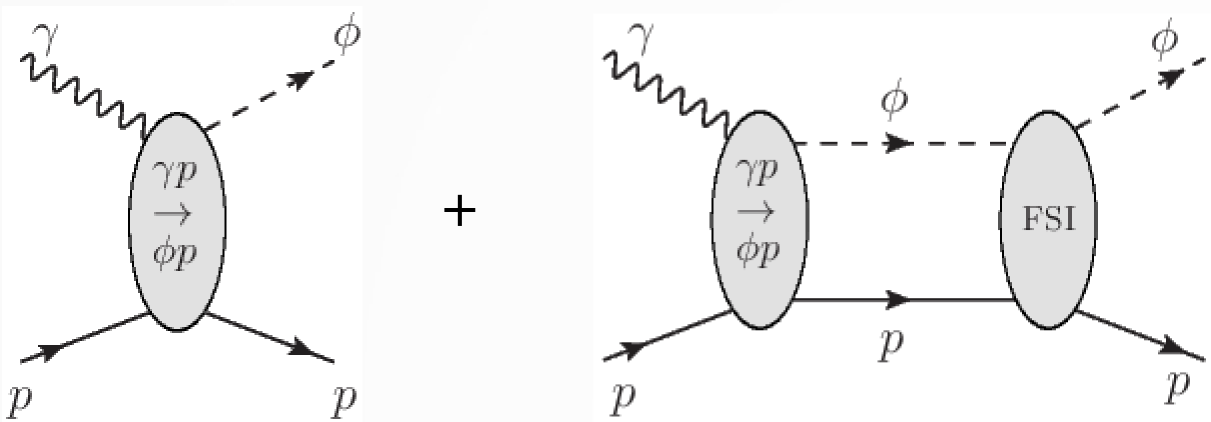
$$\mathcal{L}_{\gamma NN} = -e\bar{N}\left[\gamma_\mu - \frac{\kappa_N}{2M_N}\sigma_{\mu\nu}\partial^\nu\right]NA^\mu$$

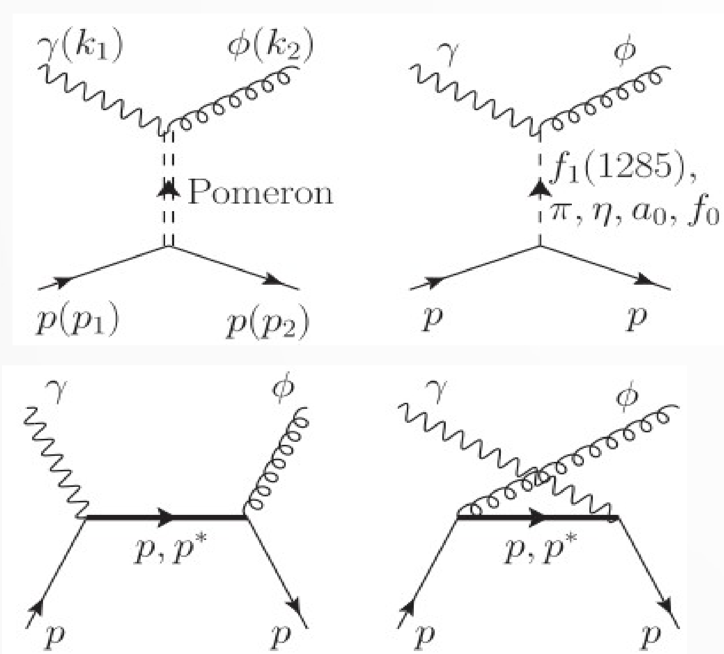
$$\mathcal{L}_{\phi NN} = -g_{\phi NN}\bar{N}\left[\gamma_\mu - \frac{\kappa_{\phi NN}}{2M_N}\sigma_{\mu\nu}\partial^\nu\right]N\phi^\mu$$

1. Results: γ p → φ p

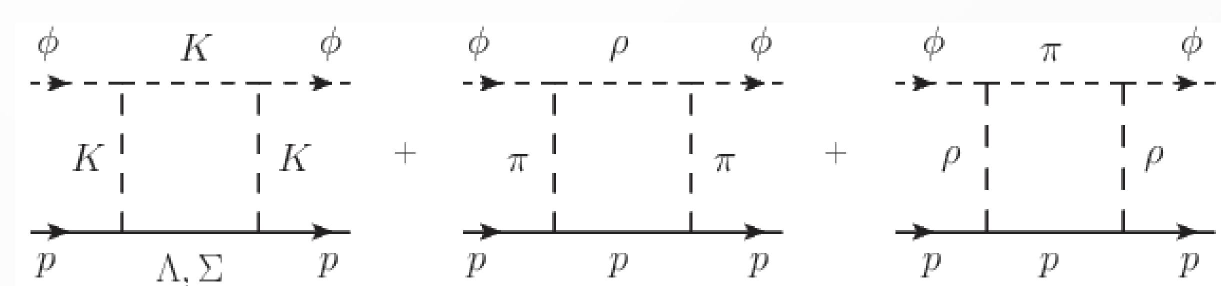
final state interaction (FSI)

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





FSI=



box diagrams

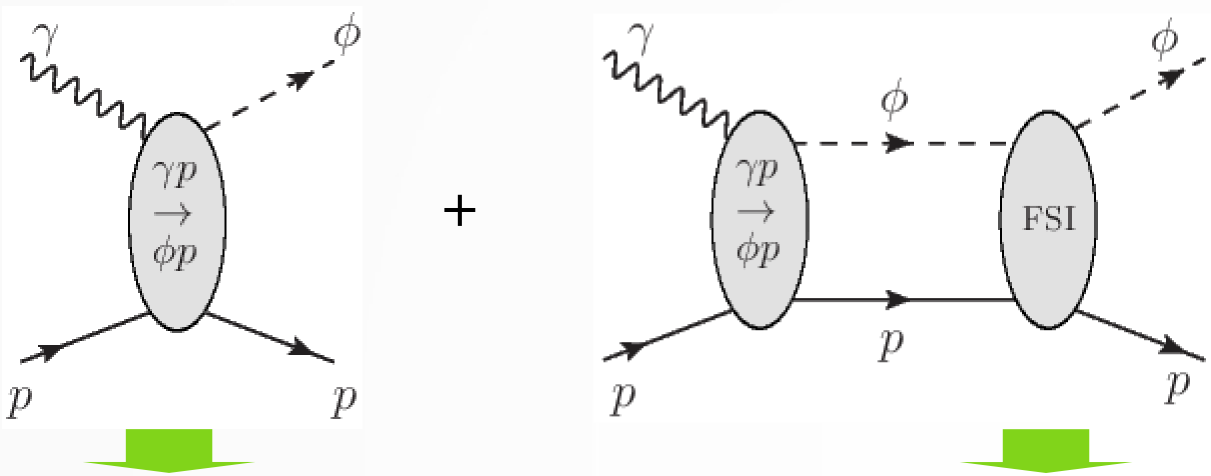
□ decay mode of φ-meson

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

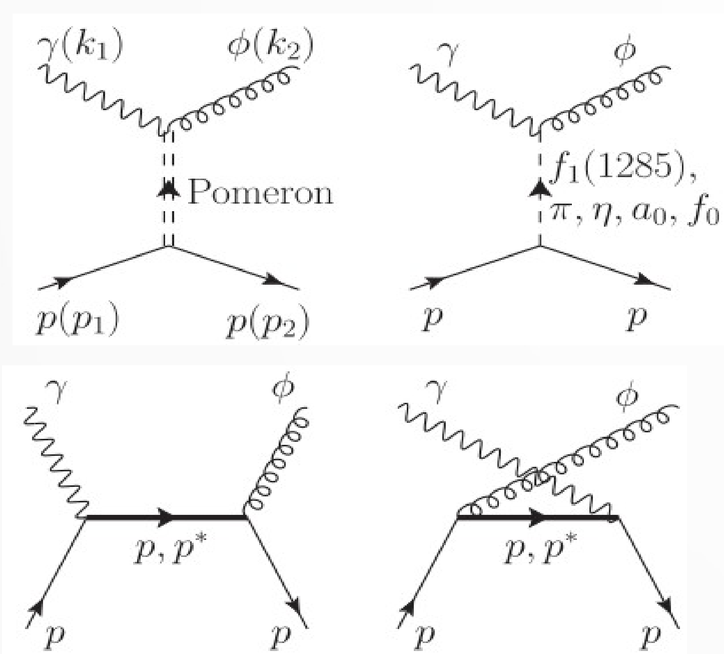
final state interaction (FSI)

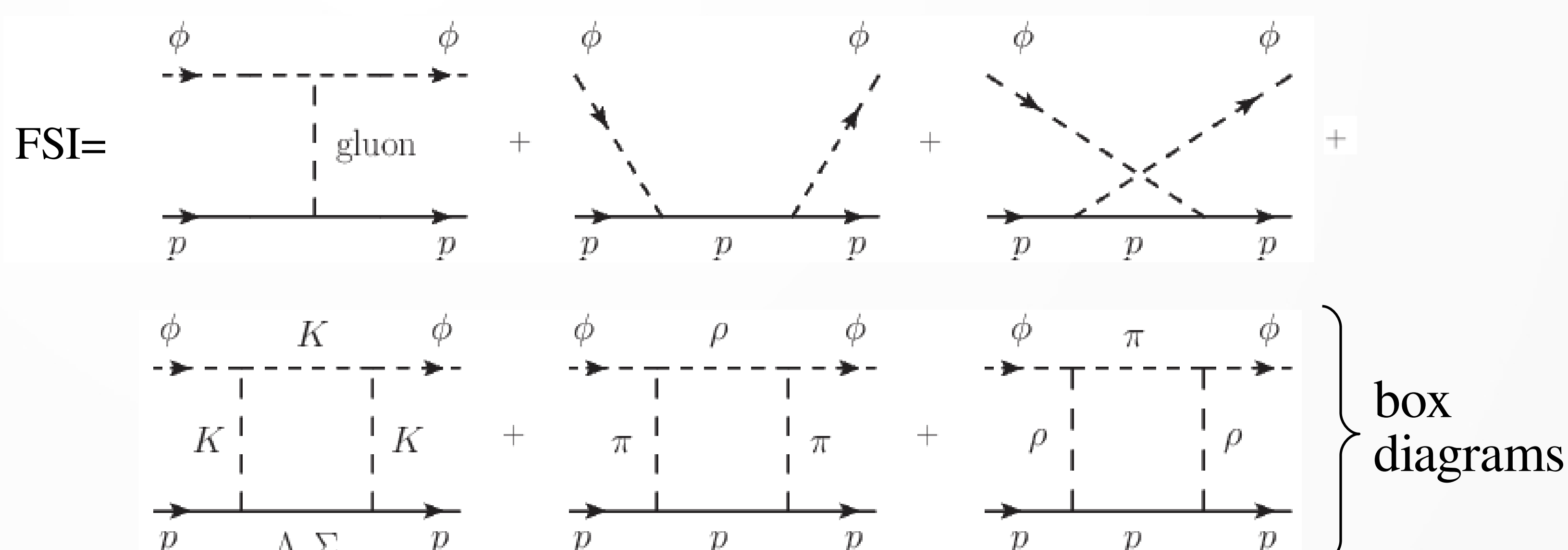
❏ Scattering amplitude: $T_{\phi N,\gamma N}(E) = [B_{\phi N,\gamma N} + T^{FSI}_{\phi N,\gamma N}(E)]$

$$T^{FSI}_{\phi N,\gamma N}(E) = t_{\phi N,\phi N}(E) \frac{|\phi N >< \phi N|}{E - H_0 + i\epsilon} B_{\phi N,\gamma N}$$



$$v_{\phi N,\phi N}(E) + \sum_{MB=K\Lambda,K\Sigma,\pi N,\rho N} v_{\phi N,MB}\, G_{MB}(E)\, v_{MB,\phi N}$$

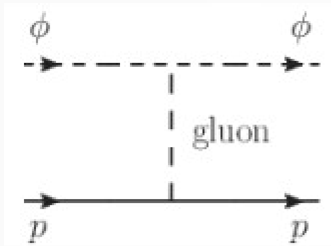


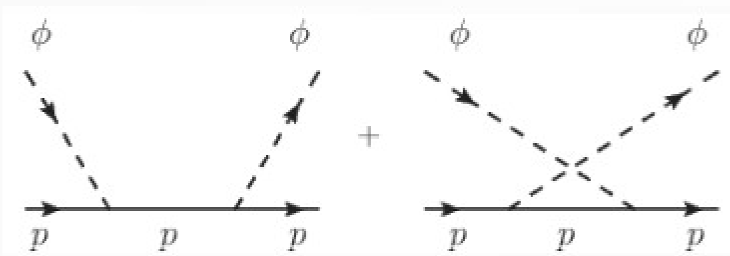


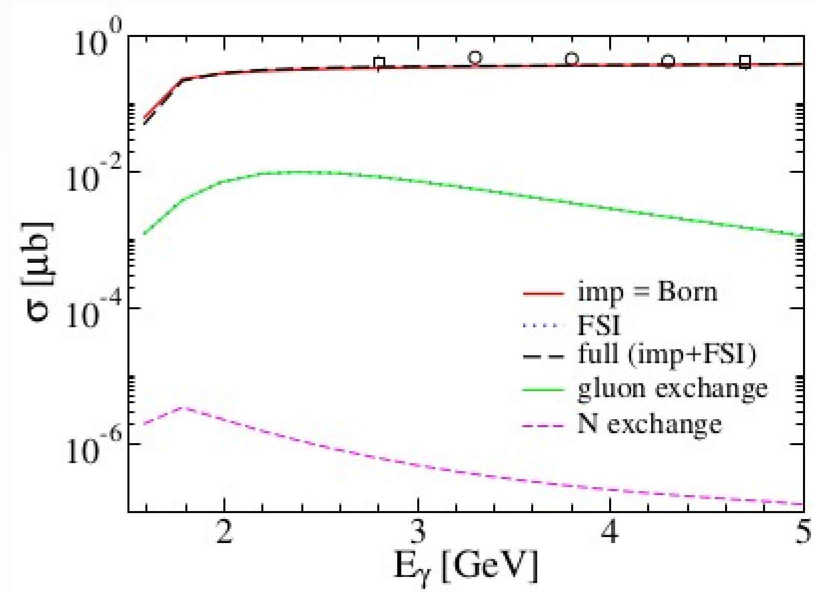
1. Results: $\gamma\, p \to \phi\, p$

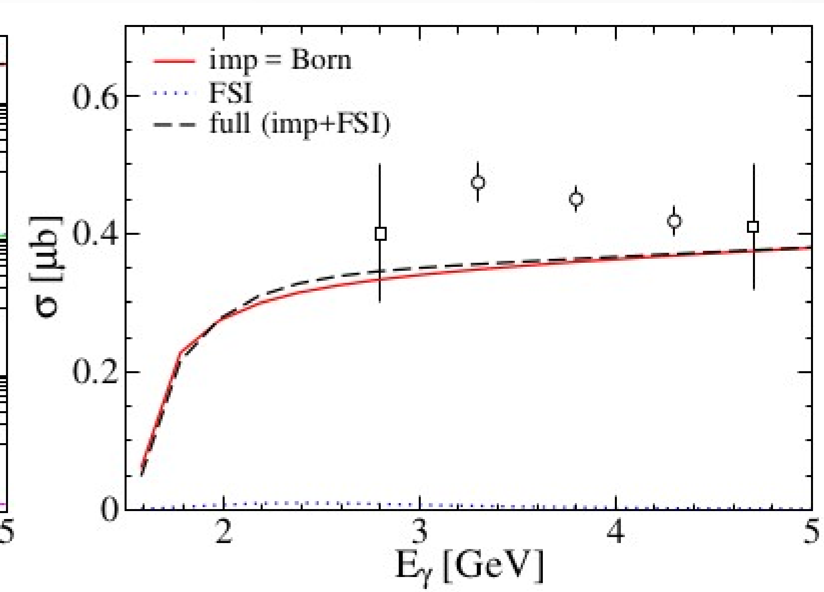
final state interaction (FSI)

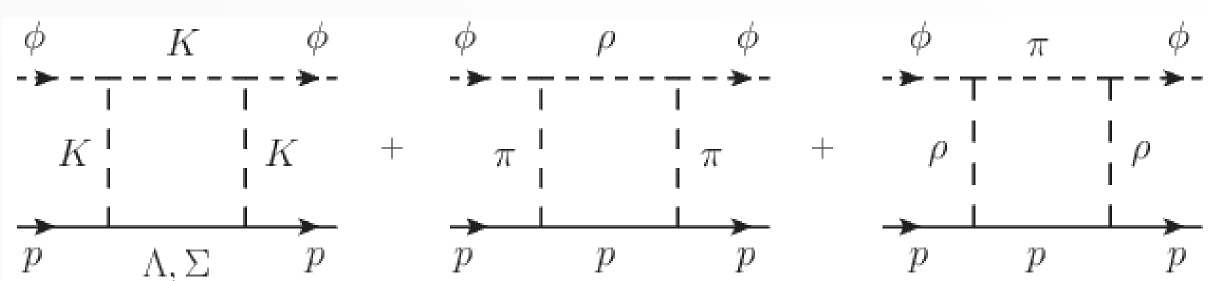
FSI=

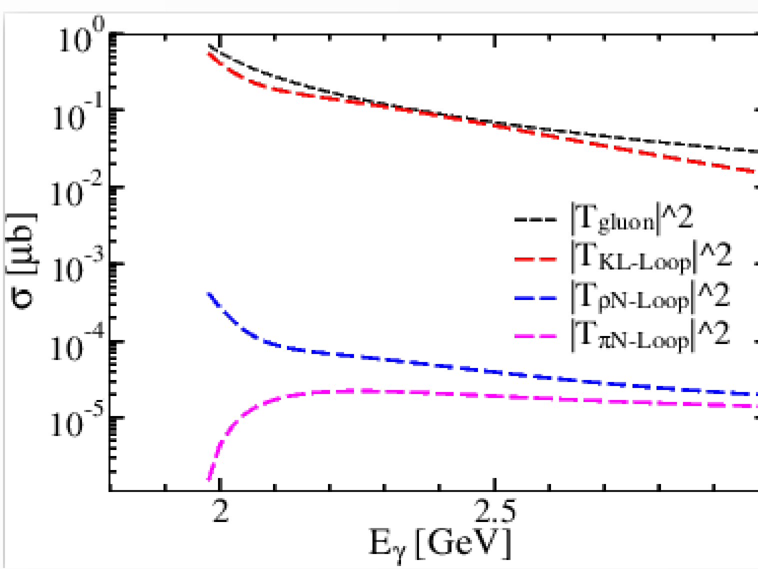






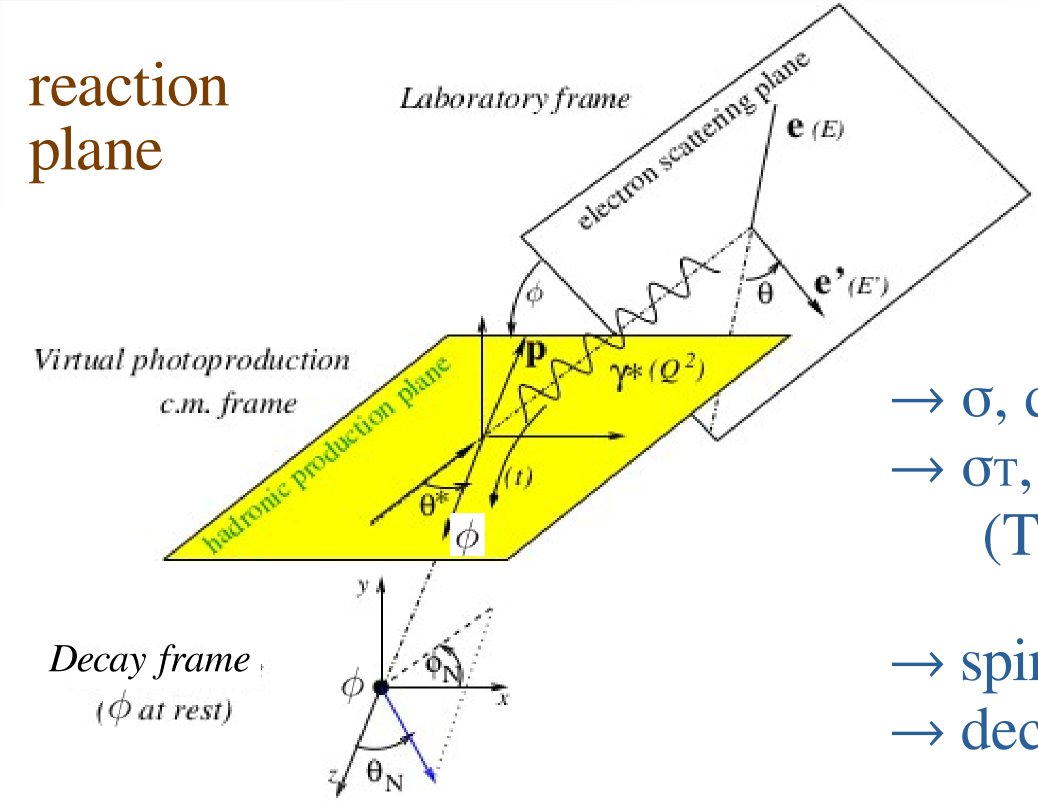






2. Exclusive electroproduction of vector mesons

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

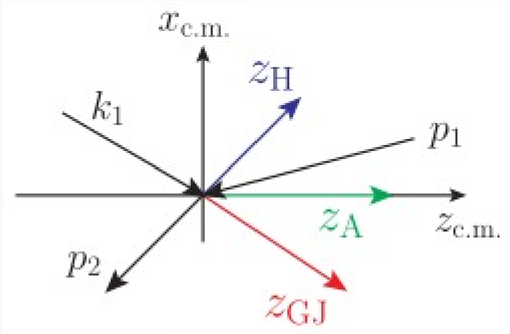


□ Photon(γ) polarization vector
Transverse comp. ($\lambda_\gamma=\pm1$) [photo-, electro-]
Longitudinal comp. ($\lambda_\gamma=0$) [electro-]

→ 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-]

❑ Decay frame



Adair frame

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

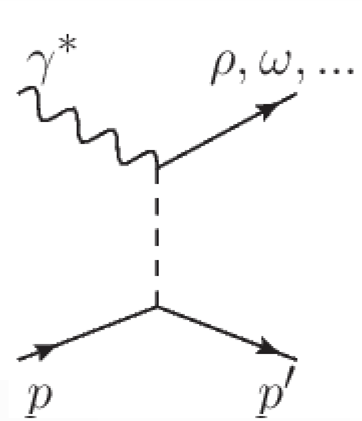
Gottfried-Jackson frame: in favor of t-channel helicity conservation (TCHC)

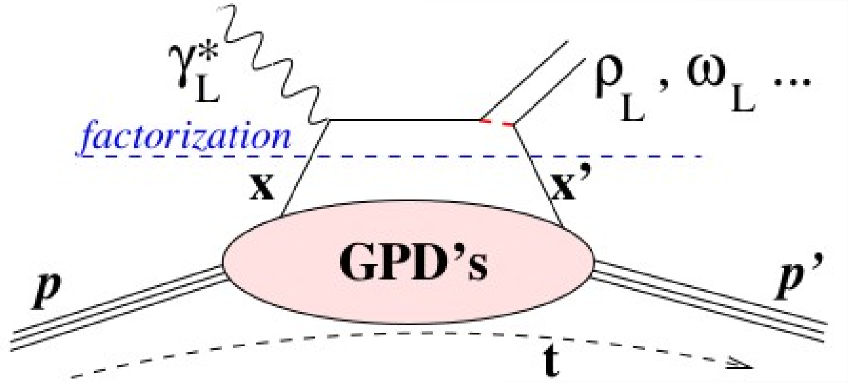
2. Exclusive electroproduction of vector mesons

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

theoretical framework

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

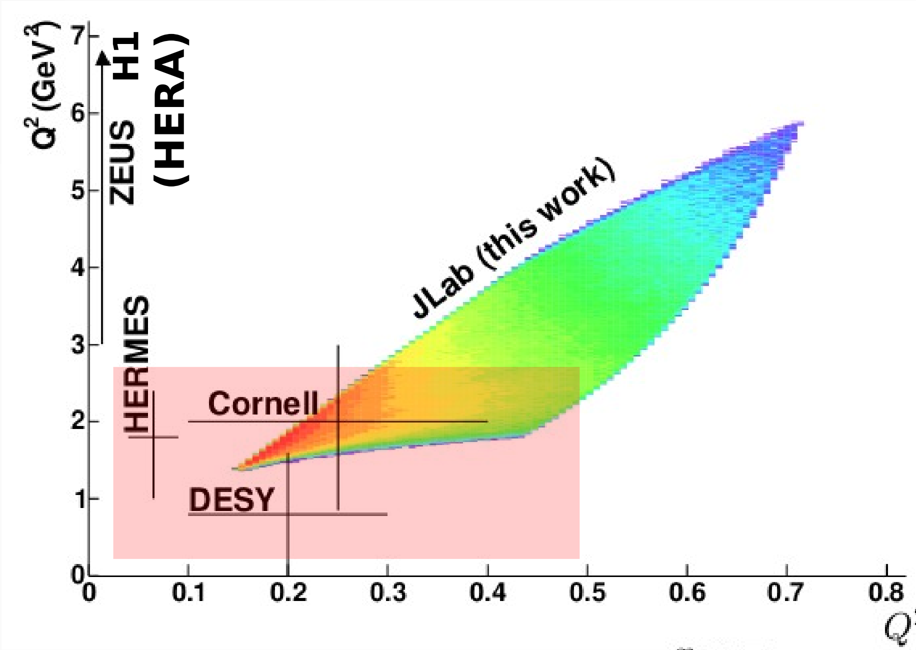




t-channel Regge trajectory exchange	<<----->>	handbag diagram

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

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

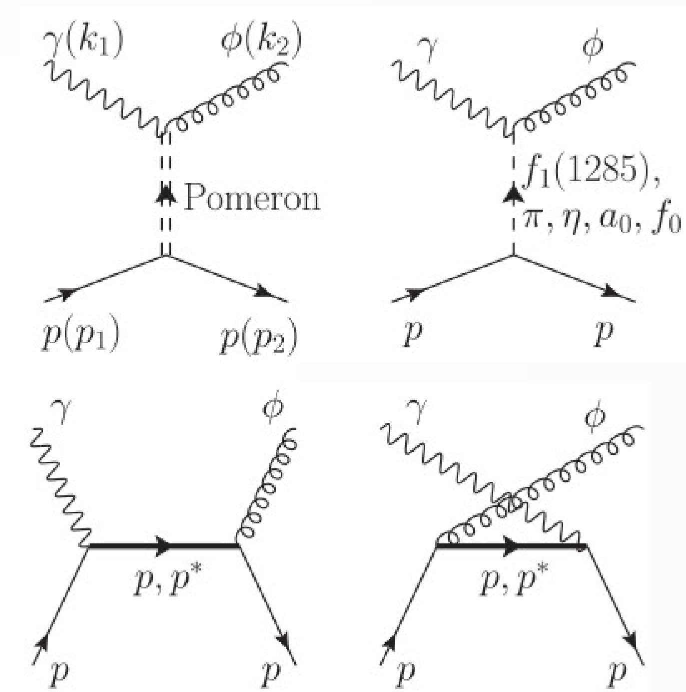


$$x_{\rm Bj} = \frac{Q^2}{W^2 + Q^2 - m^2}$$

[Kinematical range covered by vector meson electoproduction experiments]

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

Feynman diagrams

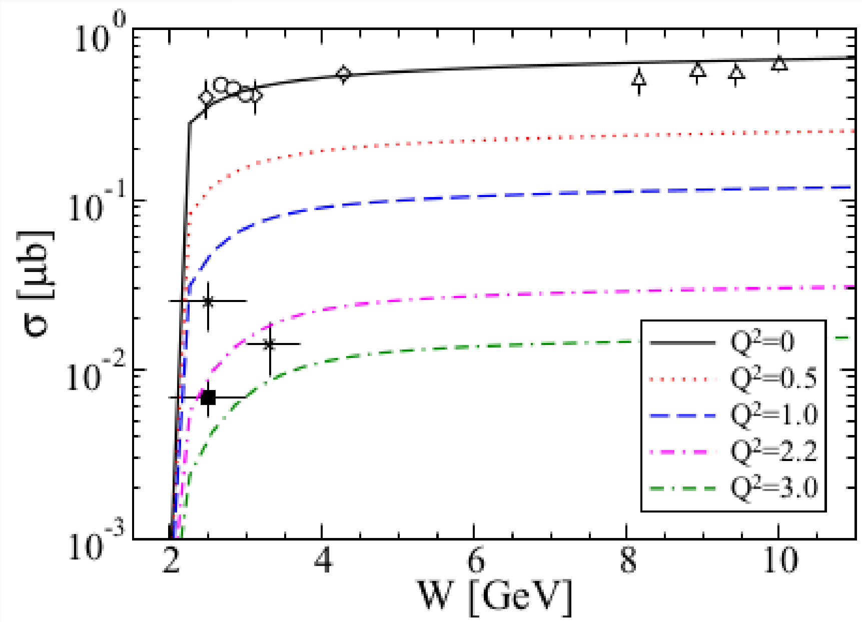


- ❑ We can test which of the two descriptions - with “hadronic” or “quark” degrees of freedom - applies in the considered kinematical domain.
- ❑ At low photon virtualities ($Q^2 \lesssim M_V^2$) and low energies ($W \lesssim$ several GeV), our hadronic effective model is applicable.

2. Results: $\gamma^* p \rightarrow \phi p$

unpolarized cross sections

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

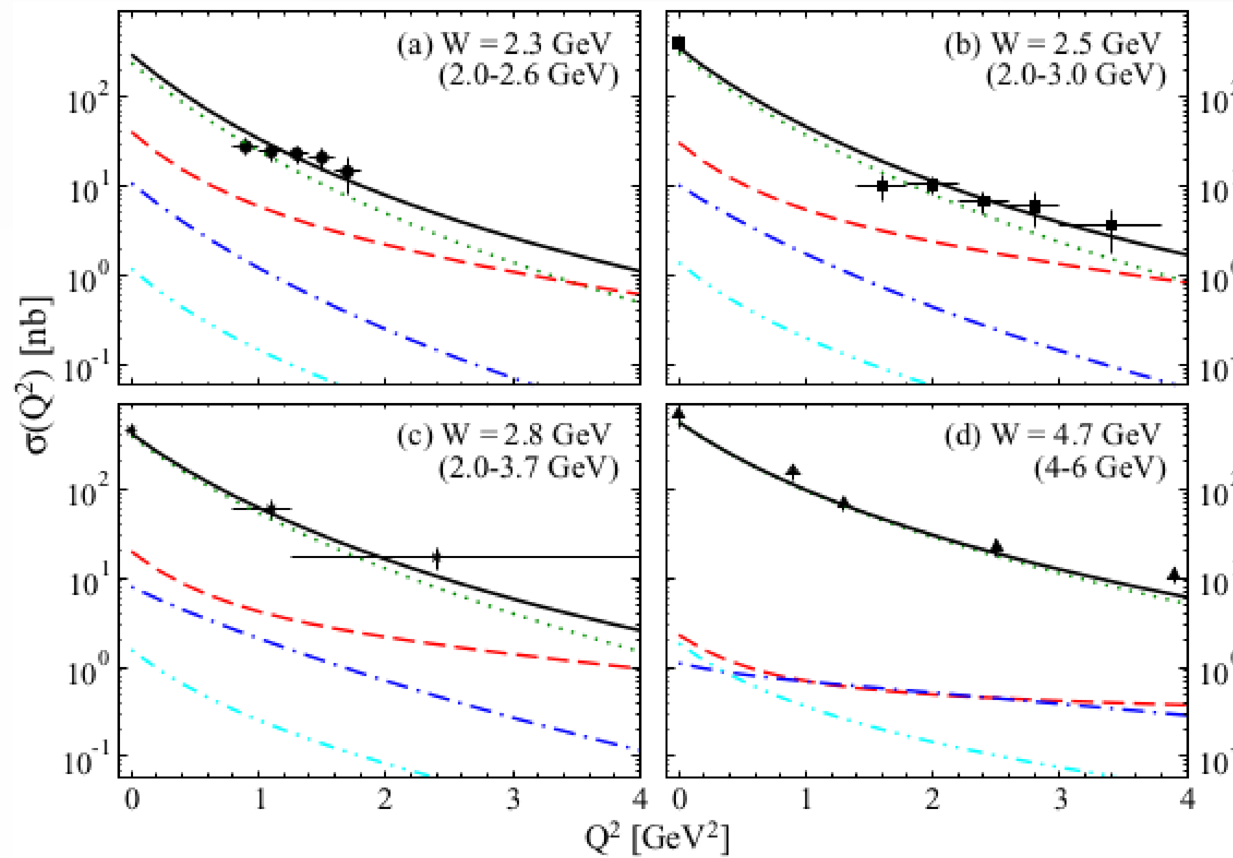


$$\sigma = \sigma_T + \varepsilon \sigma_L$$

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

ε: Virtual-photon polarization parameter

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

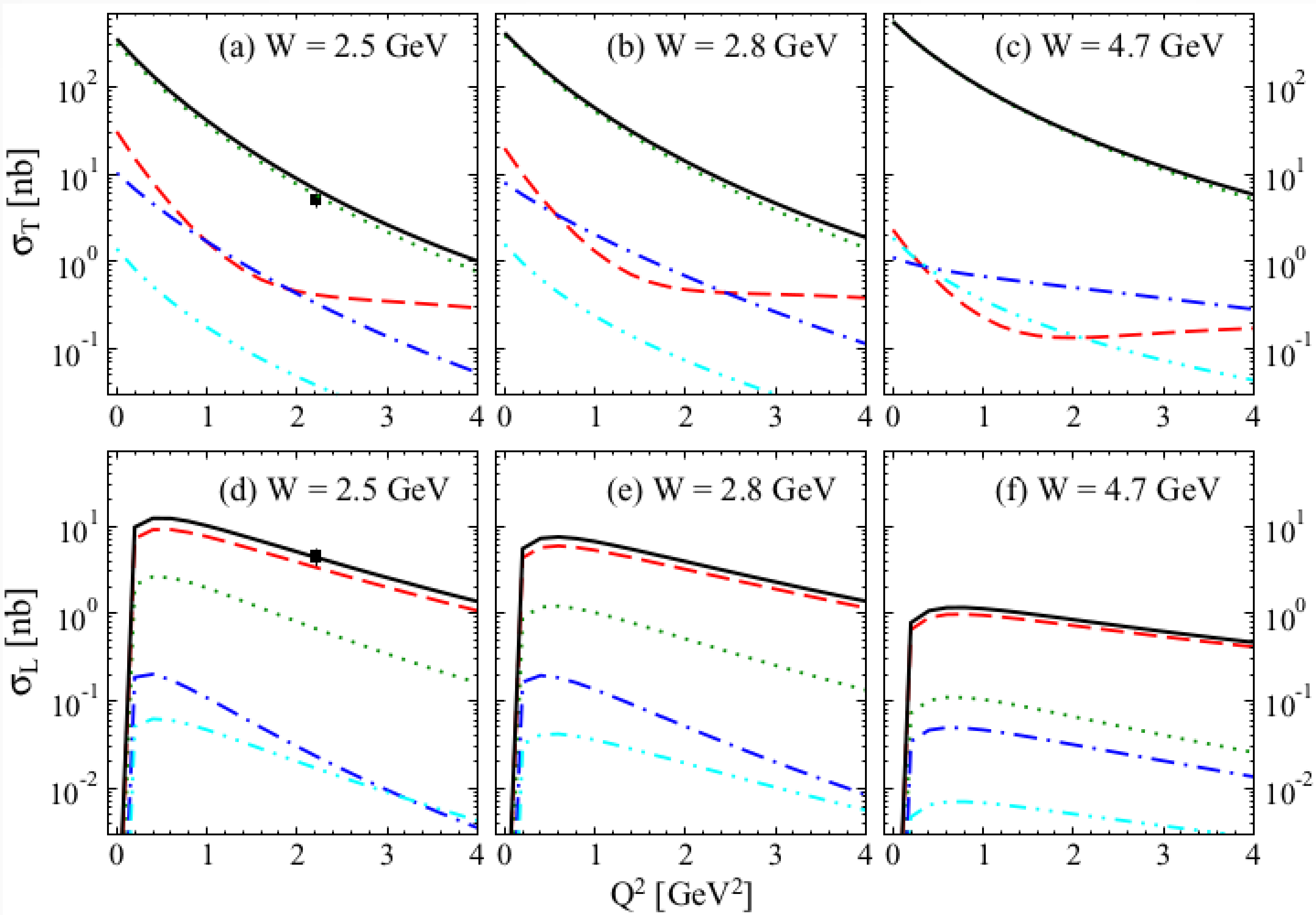


Pomeron | PS (π,η) | total
S (a_0,f_0) | AV (f_1)

❑ 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.

2. Results: $\gamma^* p \to \phi p$

T-L separated cross sections



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

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

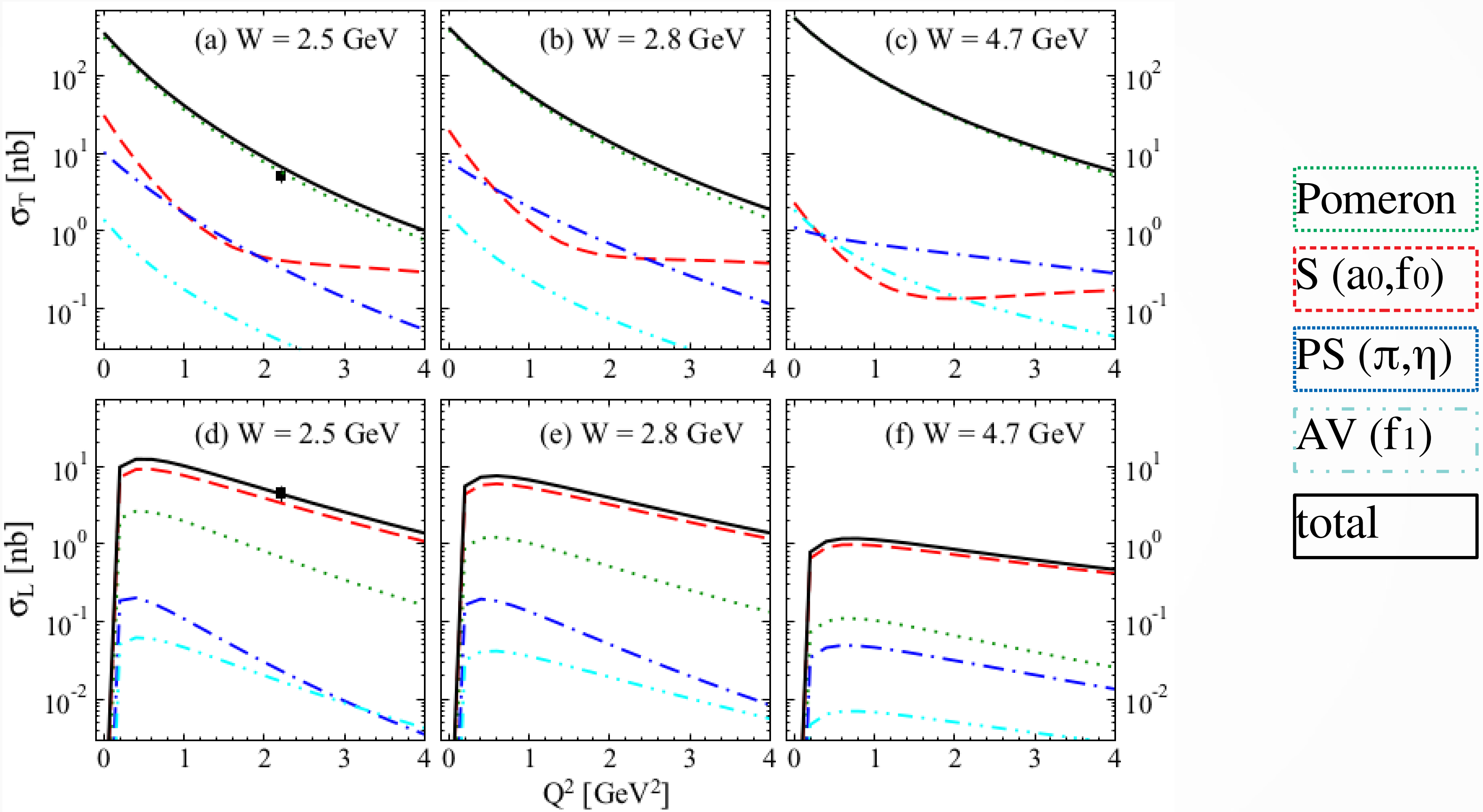
$$\frac{1}{\mathcal{N}}\frac{d\sigma_{\mathrm{TT}}}{dt} = -\frac{1}{2}\sum_{\lambda_\gamma=\pm1}\overline{\mathcal{M}^{(\lambda_\gamma)}\mathcal{M}^{(-\lambda_\gamma)*}},$$

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

[CLAS (Santoro et al.) PRC.78.025210 (2008)]
[S.H.Kim, S.i.Nam, PRC.101.065201 (2020)]

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

T-L separated cross sections

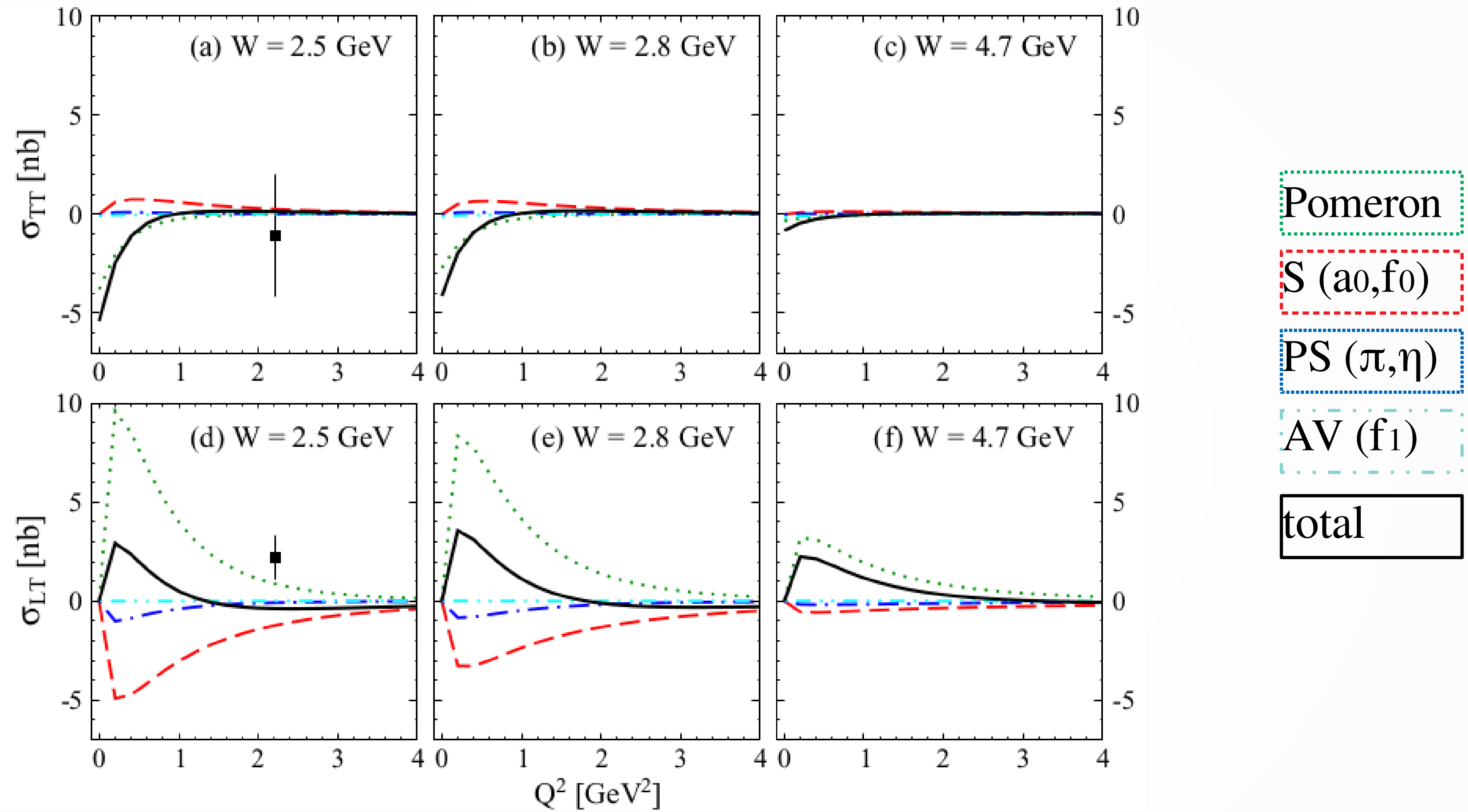


[CLAS (Santoro et al.) PRC.78.025210 (2008)]
[S.H.Kim, S.i.Nam, PRC.101.065201 (2020)]

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

2. Results: $\gamma^* p \to \varphi p$

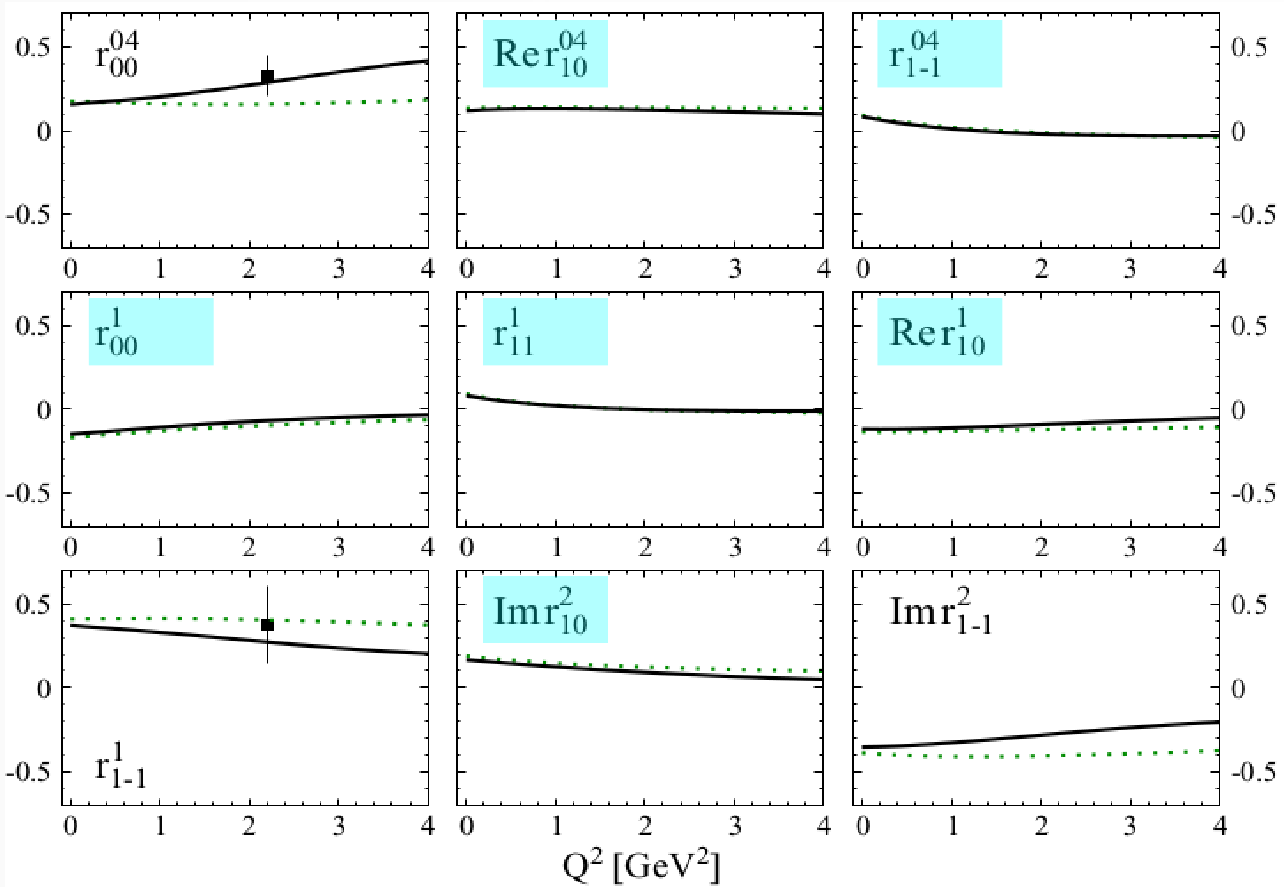
T-L separated cross sections

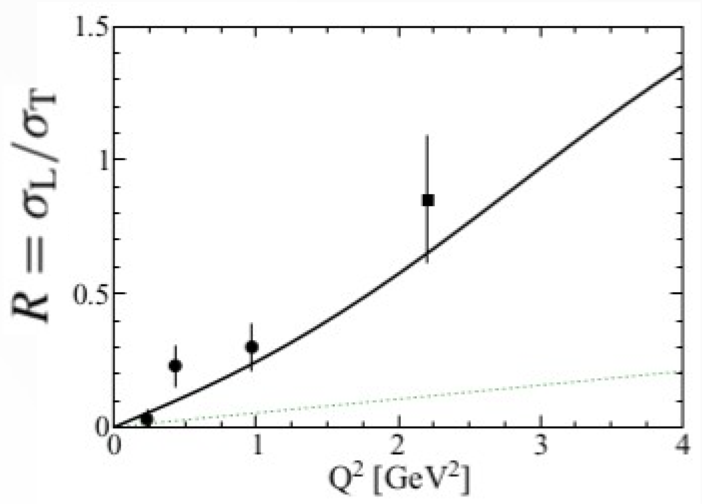


- The signs of Pomeron and **meson** contributions are opposite to each other.
- σ_{TT} and σ_{LT} become zero as W and Q^2 increases, indicating SCHC.

2. Results: $\gamma^* p \rightarrow \phi p$

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





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

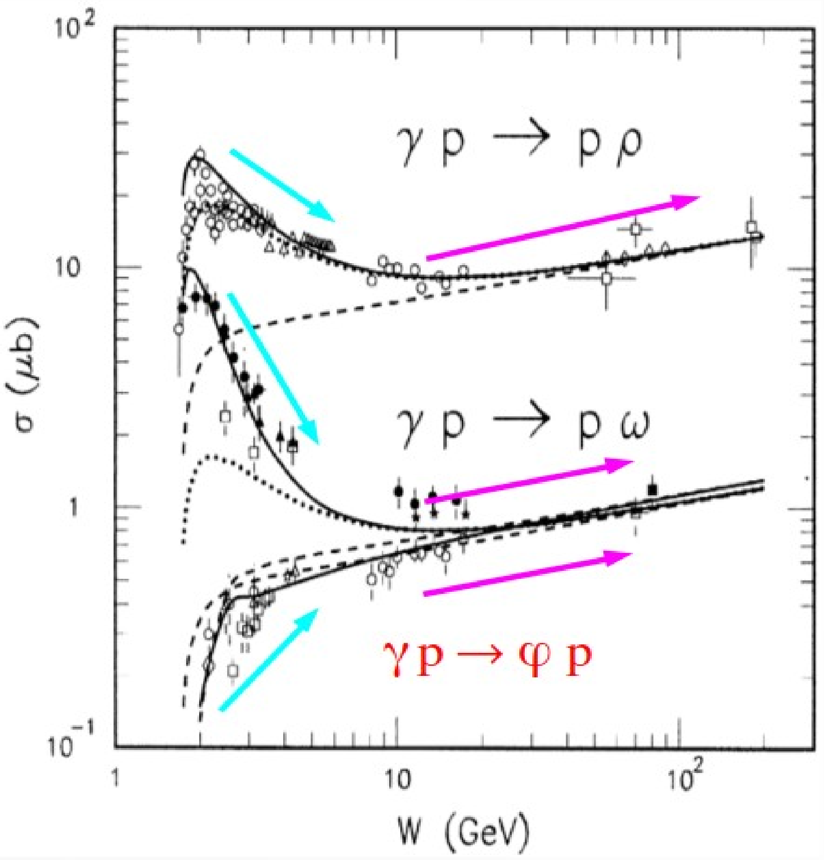
$$r^{\alpha}_{ij} = \frac{\rho^{\alpha}_{ij}}{1+\varepsilon R}, \quad \text{for } \alpha = (0-3),$$

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

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

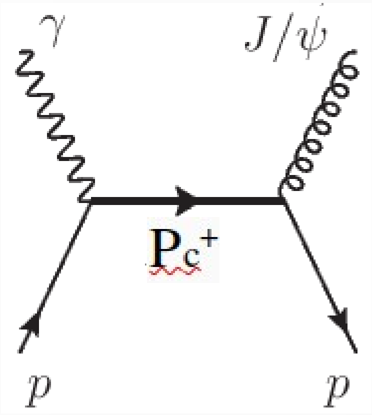
- The relative contributions of different meson exchanges are verified.
- Our hadronic approach is very successful for describing the data at Q^2=(0-4) GeV^2, W=(2-5) GeV, t=(0-2) GeV^2.

3. Exclusive photoproduction of J/ψ-meson

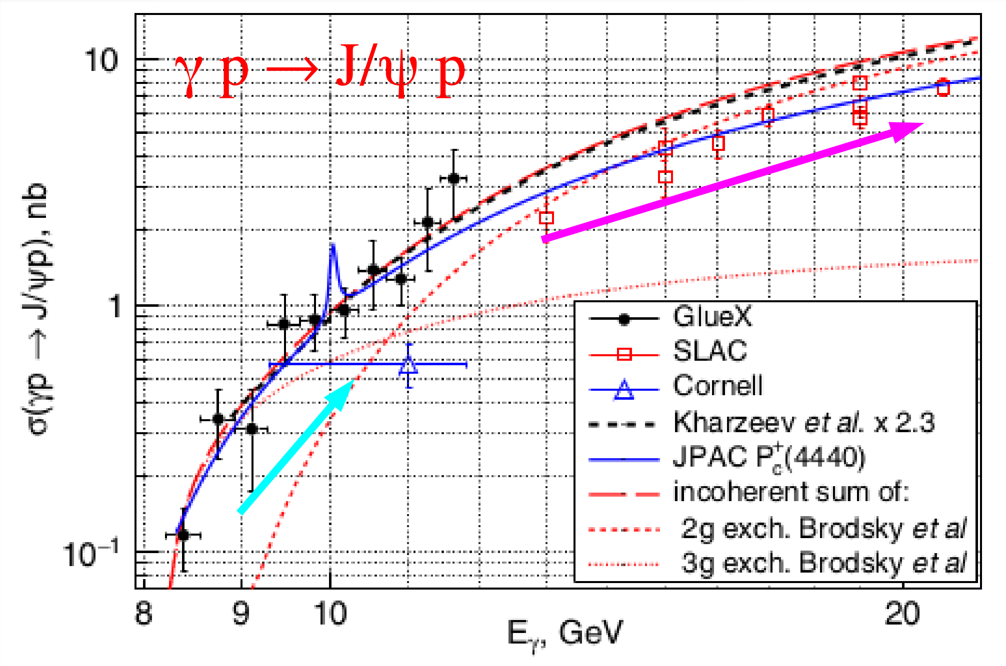


- The LHCb Collaboration reported the pentaquark states P_c^+(4312, 4440, 4457) with the quark content $uudc\bar{c}$.

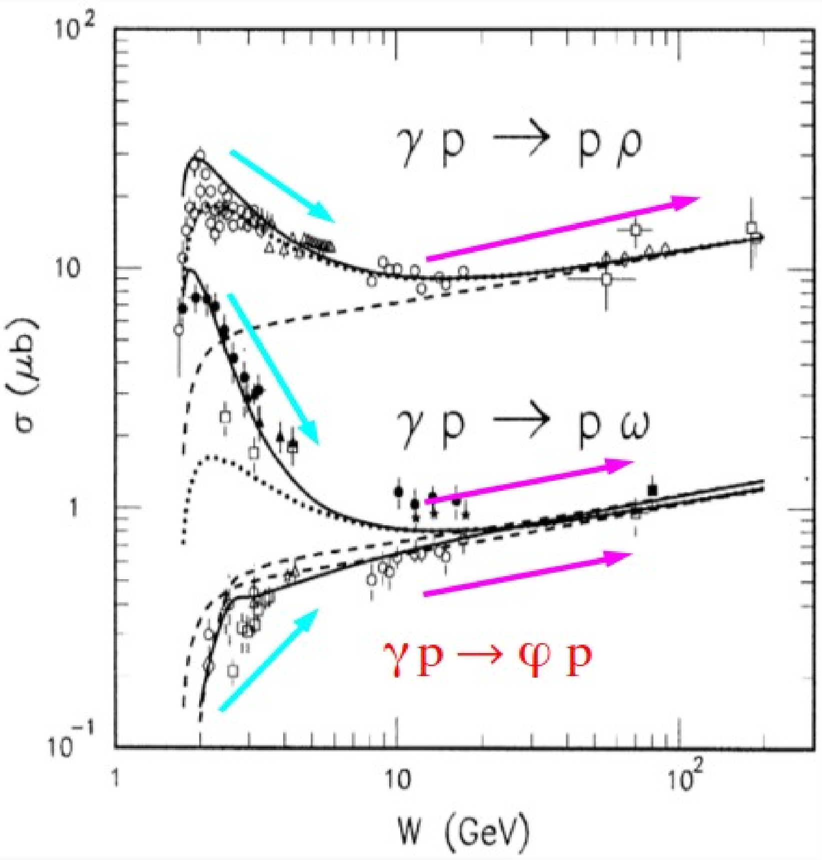
  > Its existence can be verified in γ p → J/ψ p in the *s* channel.
  > Not clear signal from the "Hall D" experiment.
  > The "Hall C" experiment at the 12 JLab GeV will produce new results .



3. Exclusive photoproduction of J/ψ-meson



[Exp: GlueX, PRL.123.072001 (2019)]
[Theory: Brodsky et al, PLB.498.23 (2001)
based on PQCD and effective HQ field theory]



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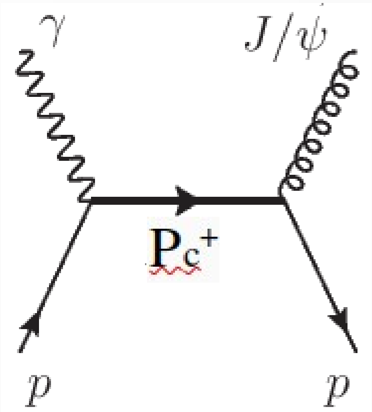
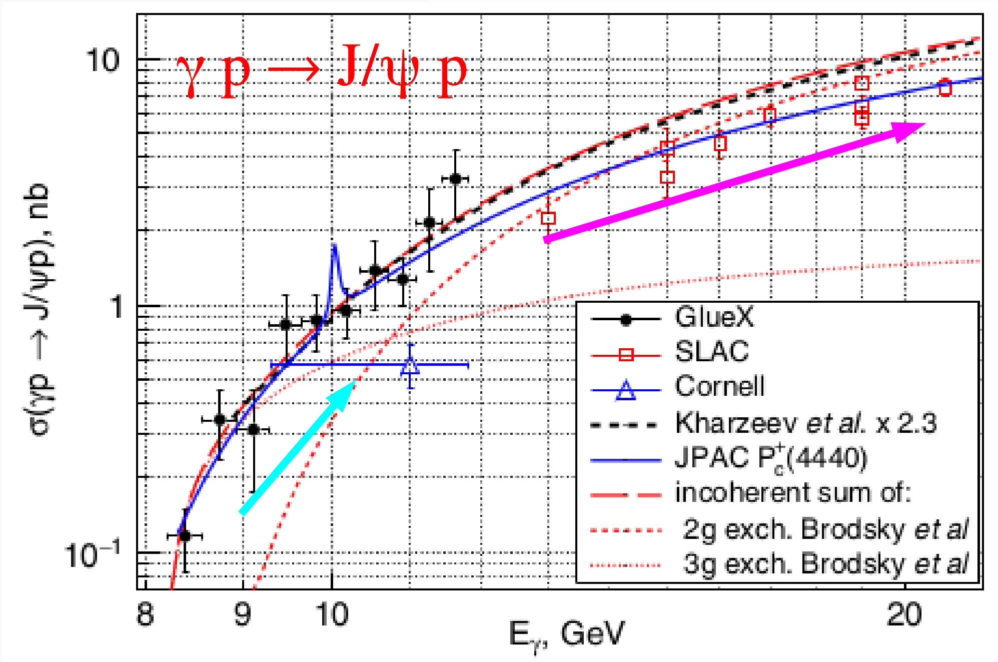


3. Exclusive photoproduction of J/ψ-meson



[Exp: GlueX, PRL.123.072001 (2019)]
[Theory: Brodsky et al, PLB.498.23 (2001)
based on PQCD and effective HQ field theory]

❑ Particle Data Group 2020 (https://pdg.lbl.gov)

Mesons reviews

Light Unflavored
Further States
Strange
Charmed
Charmed, Strange (including possibly non-$q\bar{q}$ states)
Bottom
Bottom, Strange
Bottom, Charmed
$c\bar{c}$ (including possibly non-$q\bar{q}$ states) →
$b\bar{b}$ (including possibly non-$q\bar{q}$ states)
Non $q\bar{q}$ Candidates

- $\eta_c(1S)$ $0^+(0^{-+})$
- $J/\psi(1S)$ $0^-(1^{--})$
- $\chi_{c0}(1P)$ $0^+(0^{++})$
- $\chi_{c1}(1P)$ $0^+(1^{++})$
- $h_c(1P)$ $0^-(1^{+-})$
- $\chi_{c2}(1P)$ $0^+(2^{++})$
- $\eta_c(2S)$ $0^+(0^{-+})$
- $\psi(2S)$ $0^-(1^{--})$
- $\psi(3770)$ $0^-(1^{--})$
- $\psi_2(3823)$ $0^-(2^{--})$
  was $\psi(3823)$, $X(3823)$
- $\psi_3(3842)$ $0^-(3^{--})$

❑ The LHCb Collaboration reported the pentaquark states P_c^+(4312, 4440, 4457) with the quark content uud$c\bar{c}$.

> Its existence can be verified in γ p → J/ψ p in the *s* channel.
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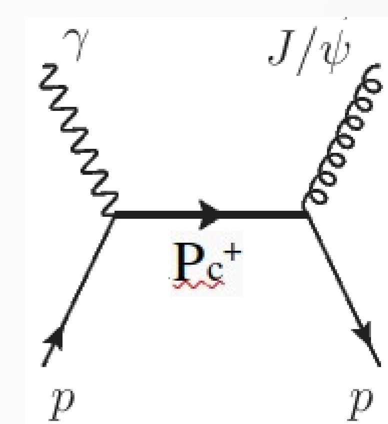
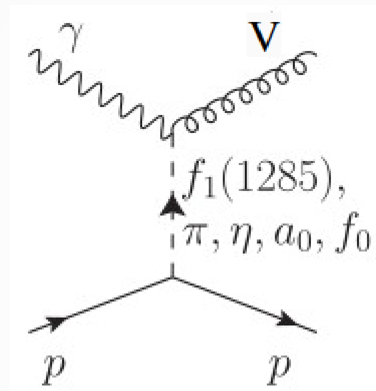


3. Exclusive photoproduction of J/ψ-meson

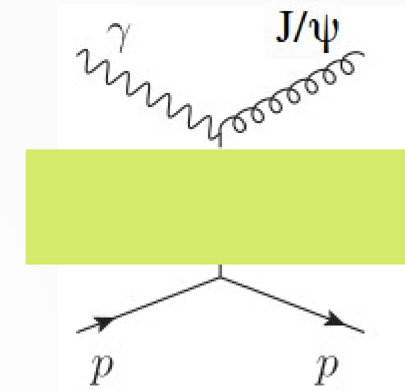
$\gamma\, p \to V(\rho, \omega, \varphi)\, p$

❑ The exchanges of the light unflavored mesons are crucial.

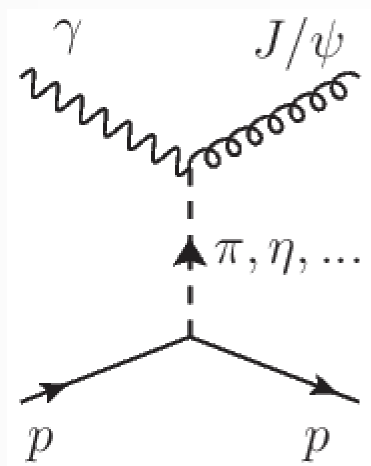


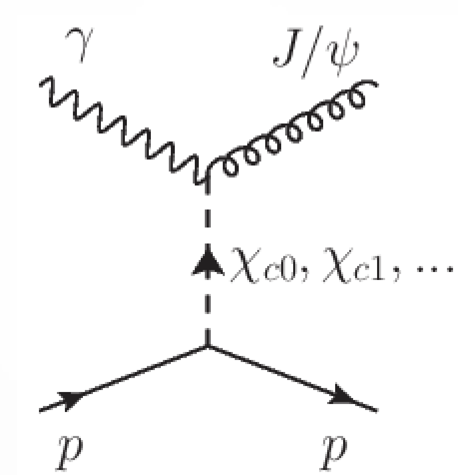
$\gamma\, p \to J/\psi\, p$

❑ Which mechanism is dominant?



Exchanges of □ light mesons □ $c\bar{c}$ mesons





$\gamma\, p \to J/\psi\, p$

❑ Which mechanism is dominant?

❑ Effective Lagrangians

$$\mathcal{L}_{J/\psi\Phi\gamma} = \frac{e g_{J/\psi\Phi\gamma}}{M_{J/\psi}} \epsilon^{\mu\nu\alpha\beta} \partial_\mu A_\nu \partial_\alpha \psi_\beta \Phi,$$

$$\mathcal{L}_{J/\psi S\gamma} = \frac{e g_{J/\psi S\gamma}}{M_{J/\psi}} F^{\mu\nu} \psi_{\mu\nu} S,$$

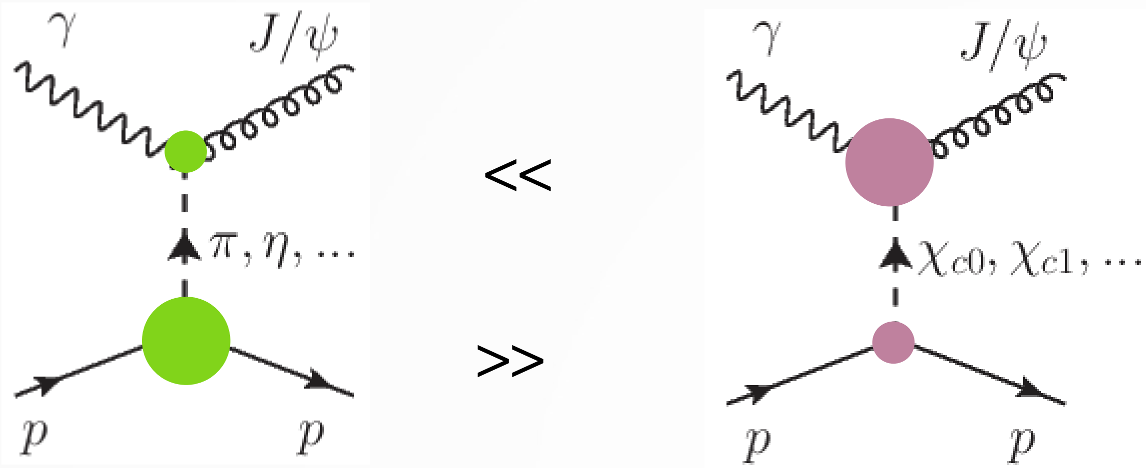
$$\mathcal{L}_{\gamma\phi f_1} = g_{\gamma\phi f_1} \epsilon^{\mu\nu\alpha\beta} \partial_\mu A_\nu \partial^\lambda \partial_\lambda \phi_\alpha f_{1\beta},$$

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

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

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

❑ coupling constants



Which is more dominant?

- $\eta_c(1S)$ $0^+(0^{-+})$
- $J/\psi(1S)$ $0^-(1^{--})$
- $\chi_{c0}(1P)$ $0^+(0^{++})$
- $\chi_{c1}(1P)$ $0^+(1^{++})$
- $h_c(1P)$ $0^-(1^{+-})$
- $\chi_{c2}(1P)$ $0^+(2^{++})$
- $\eta_c(2S)$ $0^+(0^{-+})$
- $\psi(2S)$ $0^-(1^{--})$
- $\psi(3770)$ $0^-(1^{--})$
- $\psi_2(3823)$ $0^-(2^{--})$
  was $\psi(3823)$, $X(3823)$
- $\psi_3(3842)$ $0^-(3^{--})$

□ light mesons

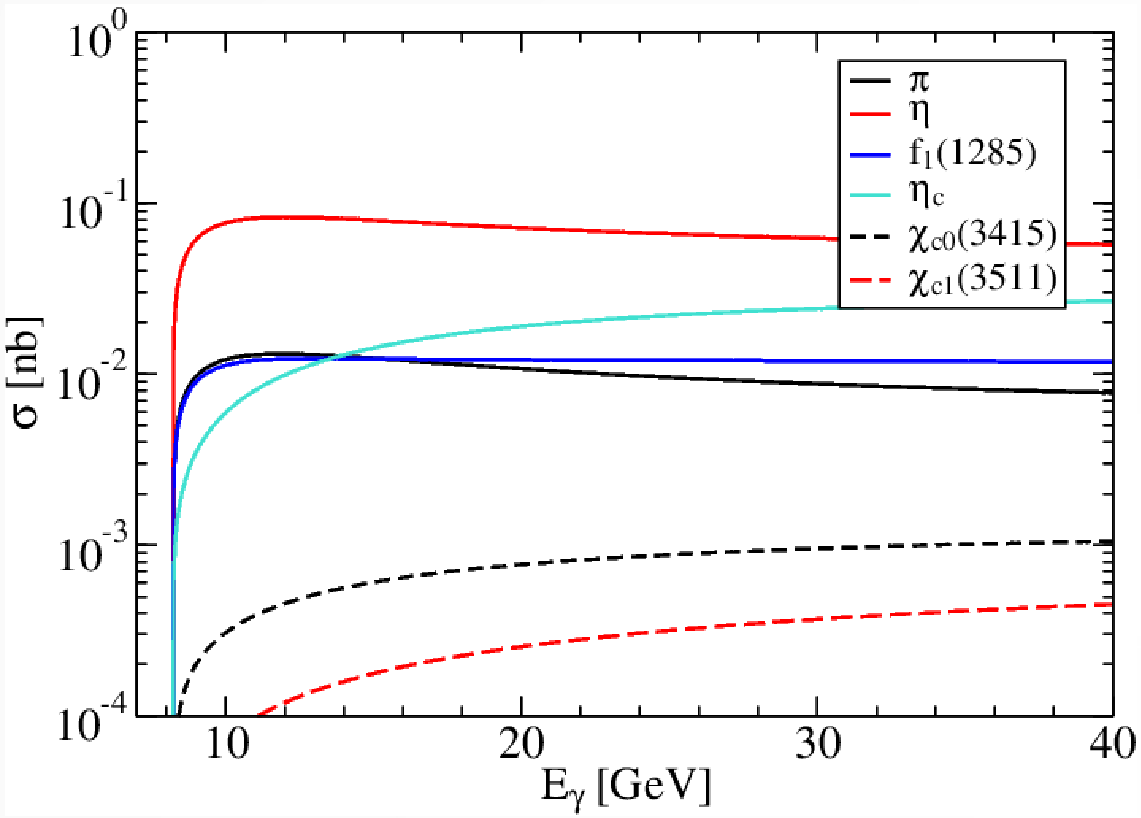
Mesons	Mass (J^P)	$\mathrm{Br}_{J/\psi\to M\gamma}$	$g_{J/\psi\to M\gamma}$	g_{MNN}
π	134 (0^-)	$(3.56 \pm 0.17) \cdot 10^{-5}$	0.002	13.0
η	548 (0^-)	$(1.108 \pm 0.027) \cdot 10^{-3}$	0.011	6.34
η'	958 (0^-)	$(5.25 \pm 0.07) \cdot 10^{-3}$	0.026	6.87
f_1	1285 (1^+)	$(6.1 \pm 0.8) \cdot 10^{-4}$	0.0007	2.5±0.5
$\eta_c(1S)$	2984 (0^-)	$(1.7 \pm 0.4) \cdot 10^{-2}$	2.14	0.0289

□ $c\bar{c}$ mesons

Mesons	Mass (J^P)	Γ_M [MeV]	$\mathrm{Br}_{M\to J/\psi\gamma}$ [%]	$g_{M\to J/\psi\gamma}$	$\mathrm{Br}_{M\to p\bar{p}}$	$g_{M\to p\bar{p}}$
$\chi_{c0}(1P)$	3415 (0^+)	10.8	1.40 ± 0.05	1.47	$(2.21 \pm 0.08) \cdot 10^{-4}$	0.0046
$\chi_{c1}(1P)$	3511 (1^+)	0.84	34.3 ± 1.0	0.10	$(7.60 \pm 0.34) \cdot 10^{-5}$	0.00084
$\eta_c(2S)$	3638 (0^-)	11.3	< 1.4	< 1.51	seen	–
$\chi_{c1}(3872)$	3872 (1^+)	< 1.2	> 0.7	> 0.008	not seen	–

3. Results: $\gamma p \to J/\psi\, p$

total cross section (each contribution)



light mesons

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❑ σ (light mesons) > σ (tetraquark states) [by one ~ two orders of magnitudes]
PS mesons S mesons ← mostly

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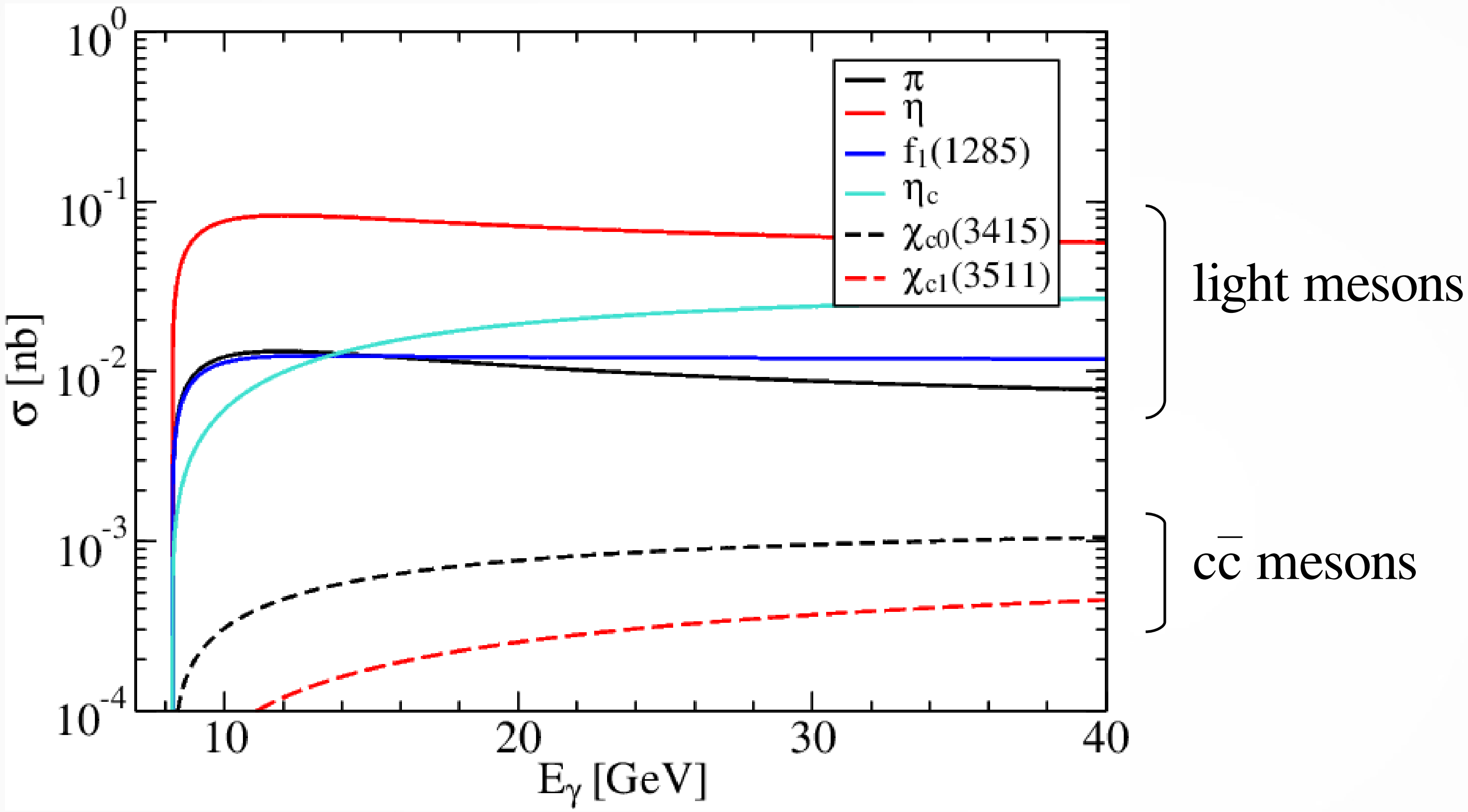
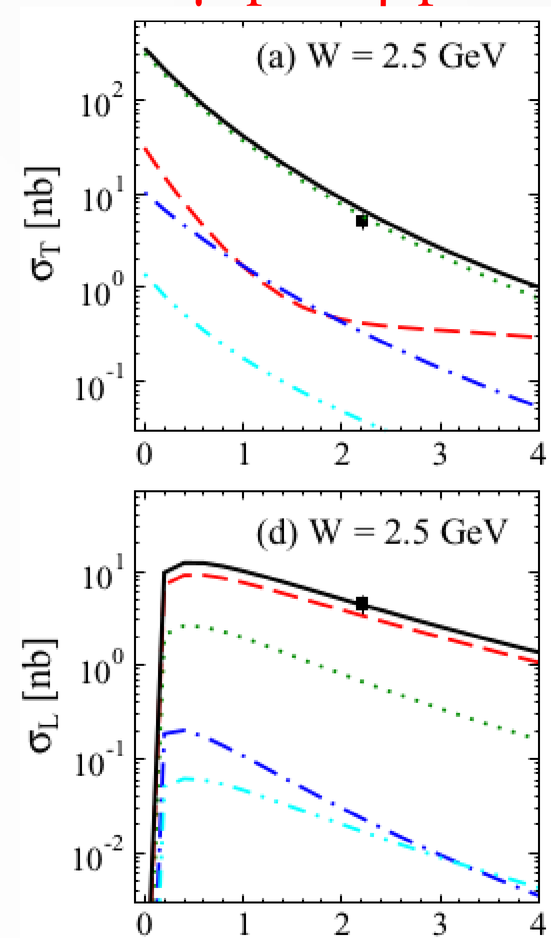


$\gamma^* p \to \varphi p$



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❑ Thus the tetraquark states will become important for the longitudinal part σ_L for $\gamma^* p \to J/\psi\, p$.

Summary

◇ For $\gamma\, p \to \varphi\, p$ & $\gamma^*\, p \to \varphi\, p$, 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.

◇ For $\gamma\, p \to J/\psi\, p$, the light-meson contribution is not negligible to the cross sections and can be confirmed by the upcoming GlueX data at Hall C.
The tetraquark state $\chi_{c0}\,(3415, 0^+)$ is important for the longitudinal part σ_L for $\gamma^*\, p \to J/\psi\, p$.

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◇ Extension of these elementary processes to reactions off nuclei targets [$\gamma^{(*)}\, A \to V\, A$]

> A distorted-wave impulse approximation within the multiple scattering formulation is used to analyze the low-energy LEPS data [$\gamma\, {}^4He \to \varphi\, {}^4He$].
> Extension to $\gamma^{(*)}\, A \to V[\varphi, J/\psi, \Upsilon(1S)]\, A$, [$A = {}^2H, {}^{12}C, \ldots$]

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◇ 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 $^4He(e,e'p)^3H$, $^2He(e,e'p)n$, $^1He(e,e'p)$
[E12-12-006] 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