The 1st CENuM Workshop for Hadronic Physics,
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The Pomeron, Odderon, and N* resonances in φ(1020) photoproducion

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Contents based on
arXiv: 1904.05133 [hep-ph]

In collaboration with
Seung-il Nam (PKNU)

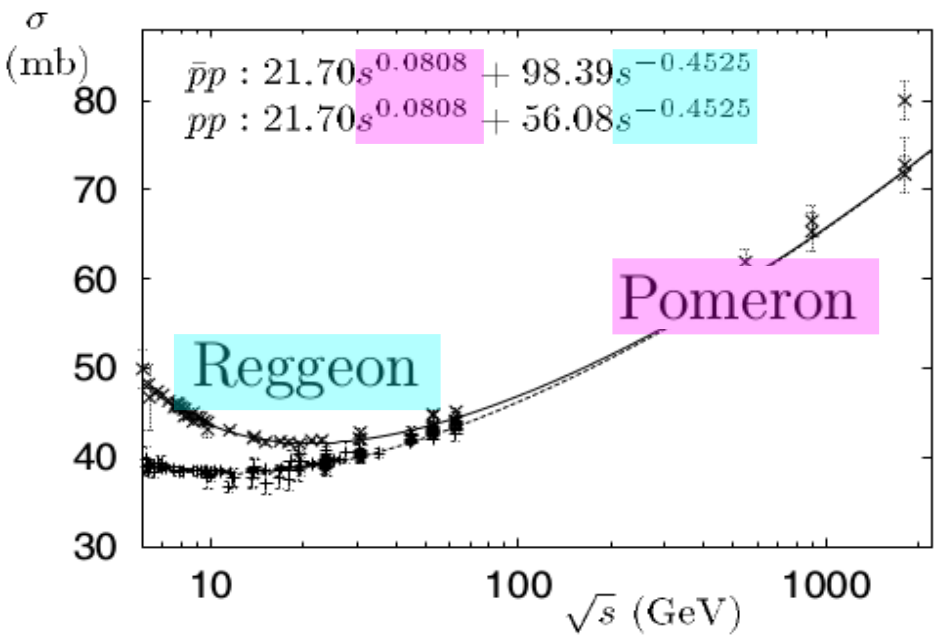
Contents

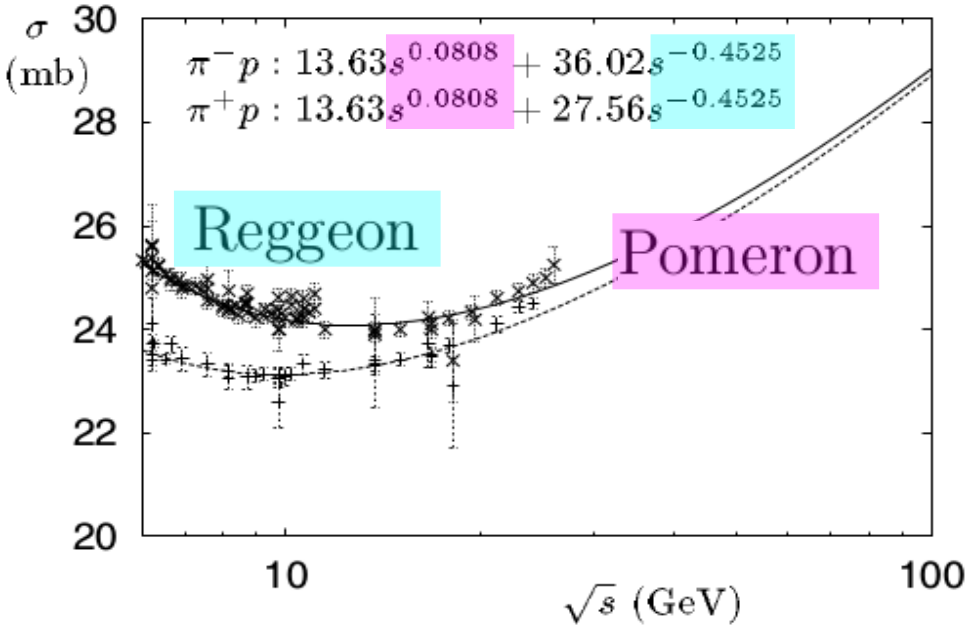
$$\gamma p \to \phi p$$

- Background
- Formalism
- Numerical Results
- Summary

Background

Soft hadronic processes



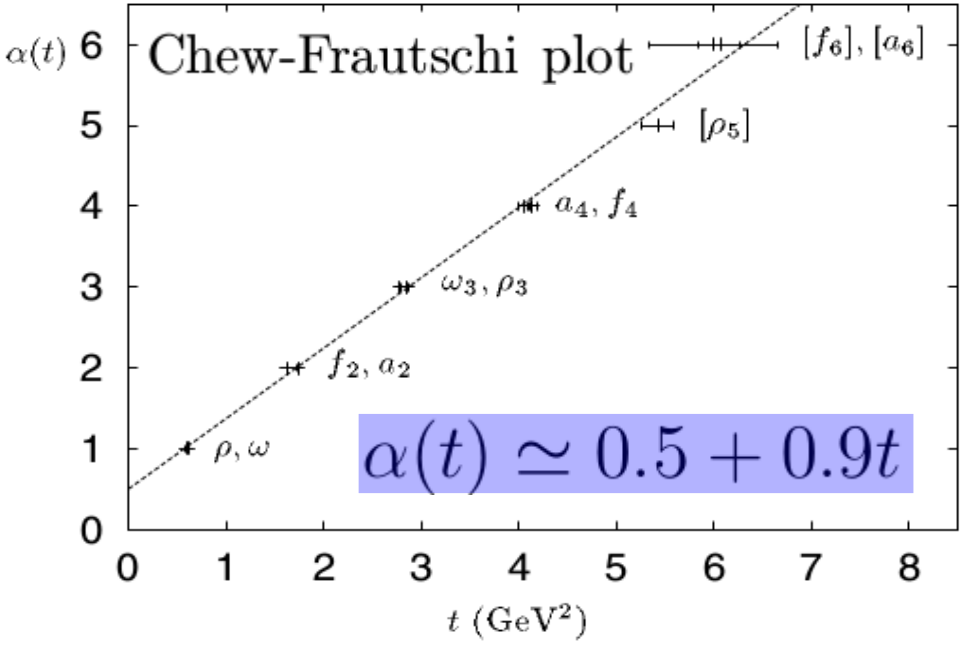


Donnachie, Pomeron Physics and QCD (2002)

Reggeon (Meson exchange)

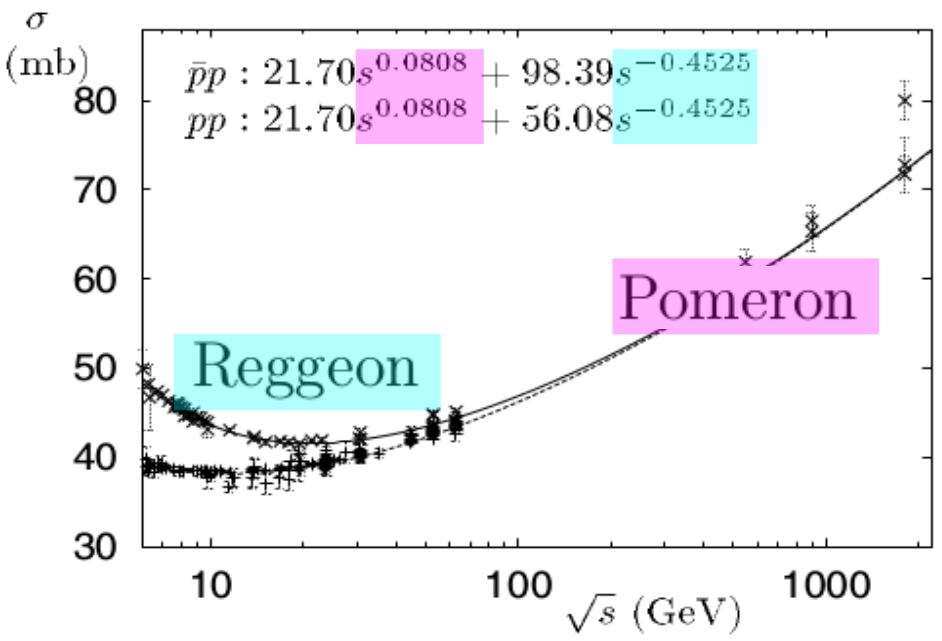
- Describes an exchange of a family of ordinary mesons.
- Governs relatively low energy regions.

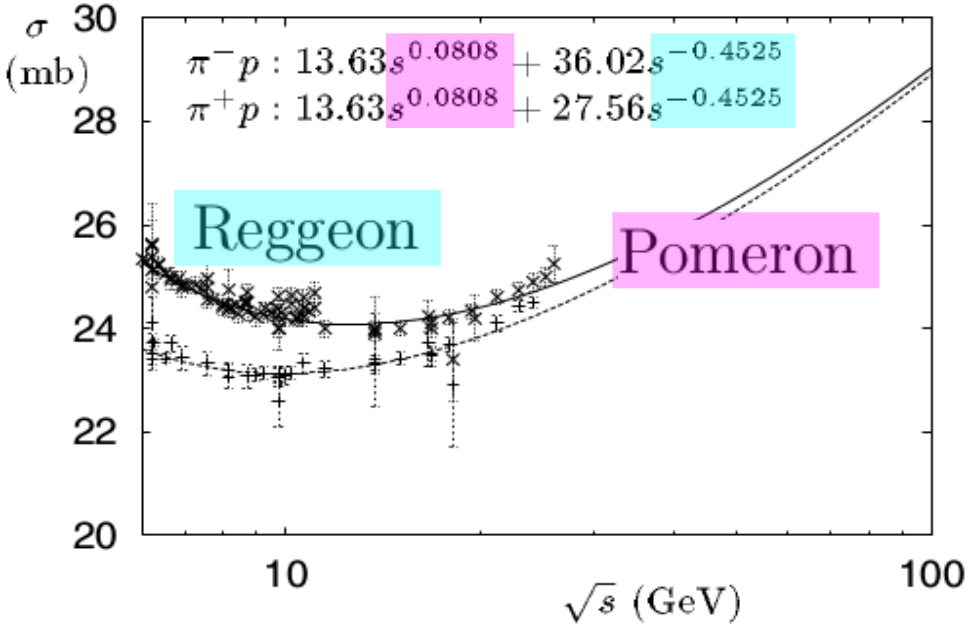
- (ρ,ω) trajectories (C=-1,natural parity) & (f_2,a_2) trajectories (C=+1,natural parity) are all degenerate.



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

Soft hadronic processes





Donnachie, Pomeron Physics and QCD (2002)

Pomeron

- Is not associated with meson trajectories.
- Is known as a gluon-rich Regge trajectory with vacuum quan. number, ($J^{PC} = 0^{++}$).
- Governs relatively high energy regions.

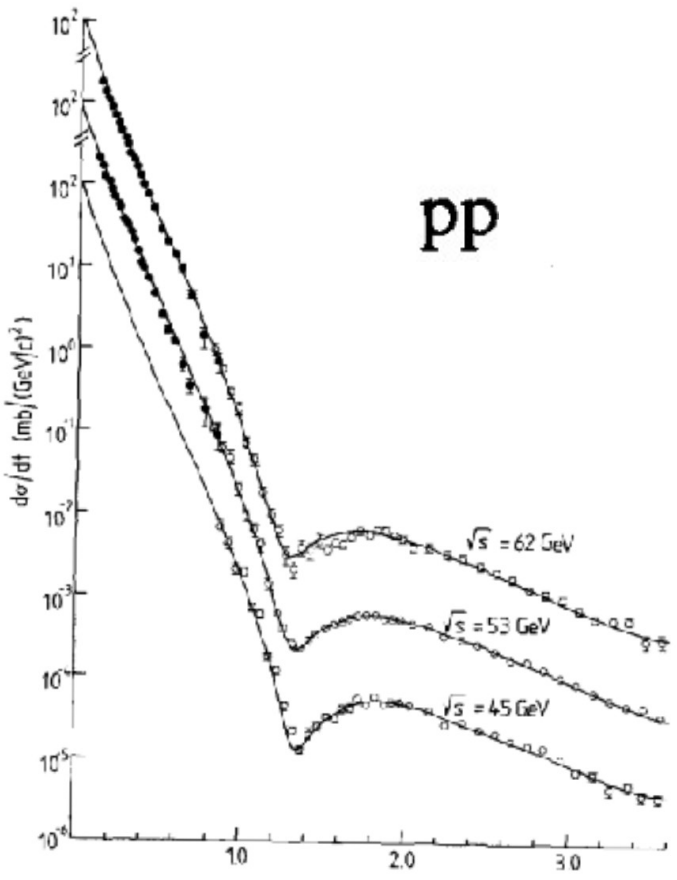
- There is no deep theory reason for the Pomeron hypothesis, but the phenomenology based on which turns out to be very successful.

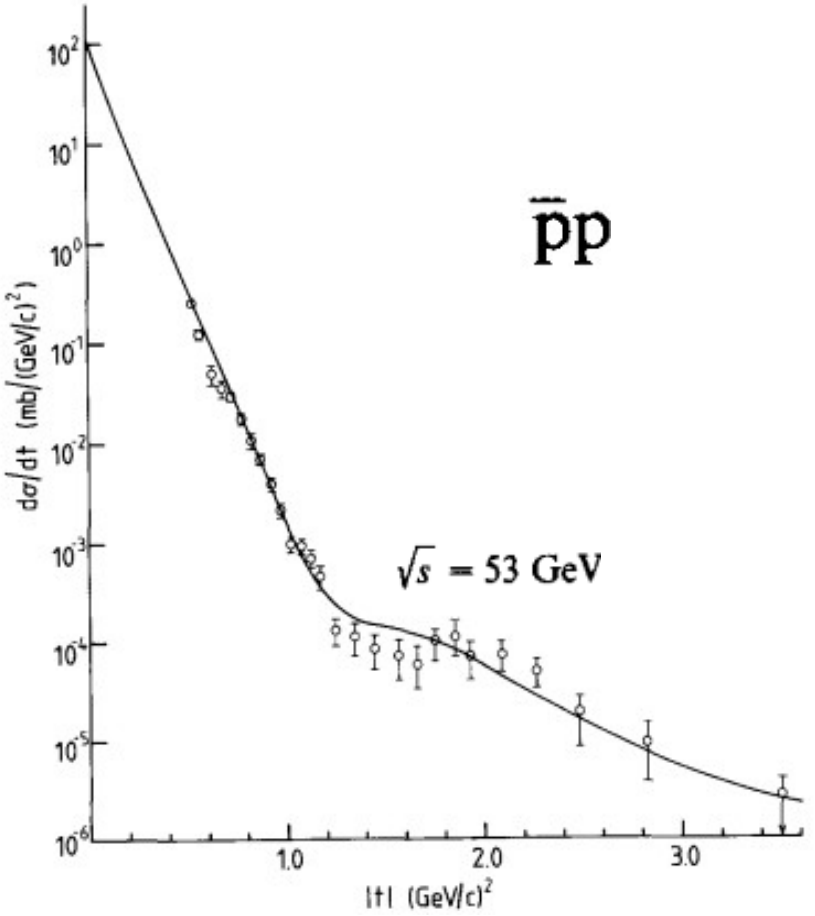
- Pomeron trajectory:

$$\alpha_P(t) \simeq 1.08 + 0.25t$$

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

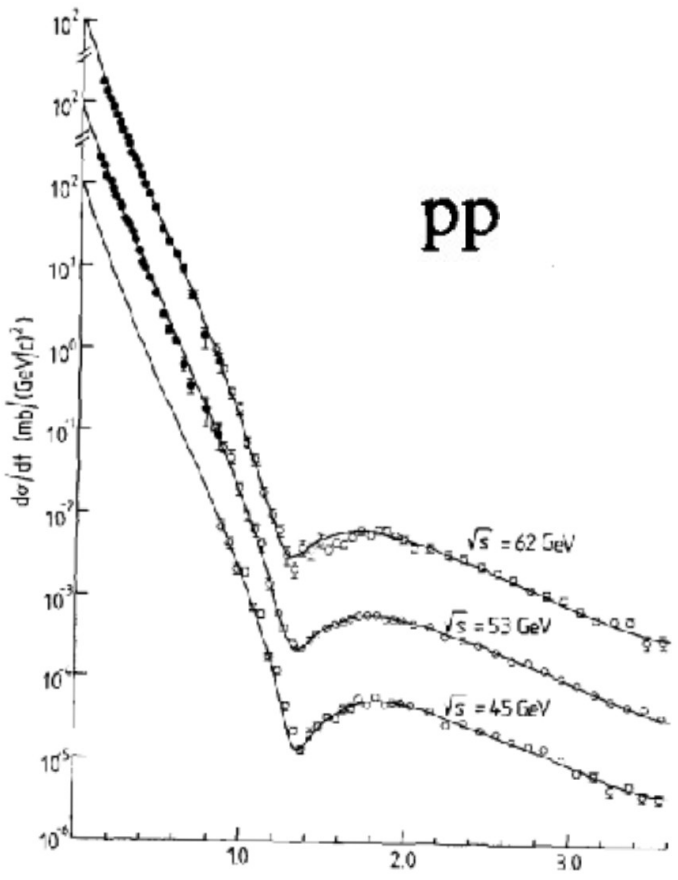
Soft hadronic processes

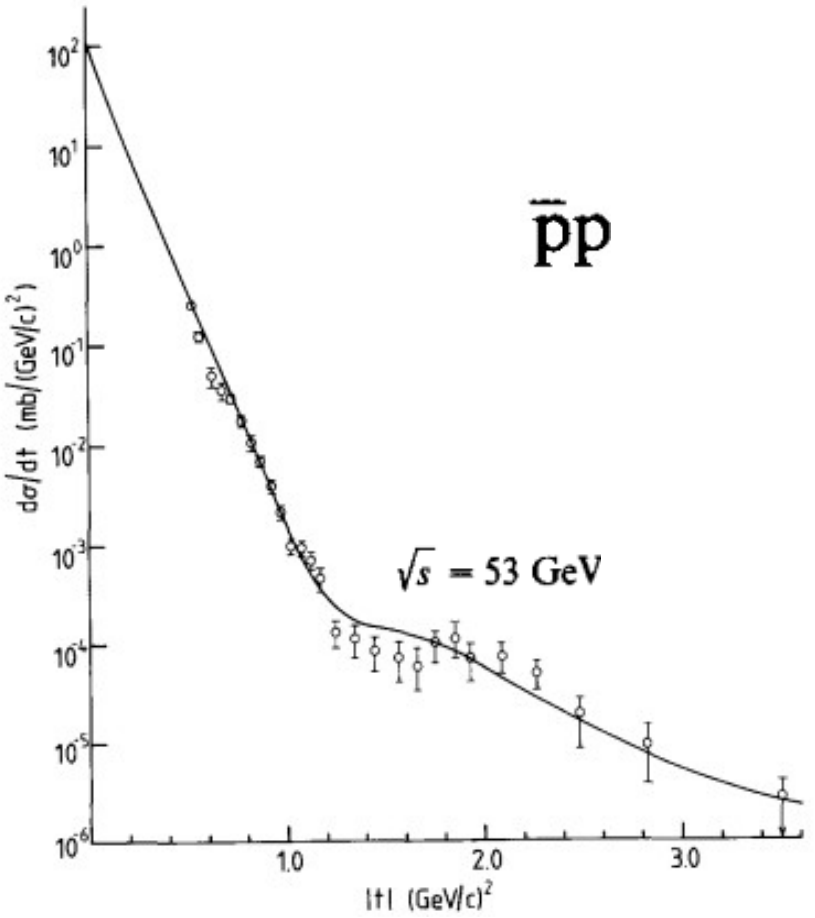




Donnachie & Landshoff, NPB267.690 (1986)

Soft hadronic processes

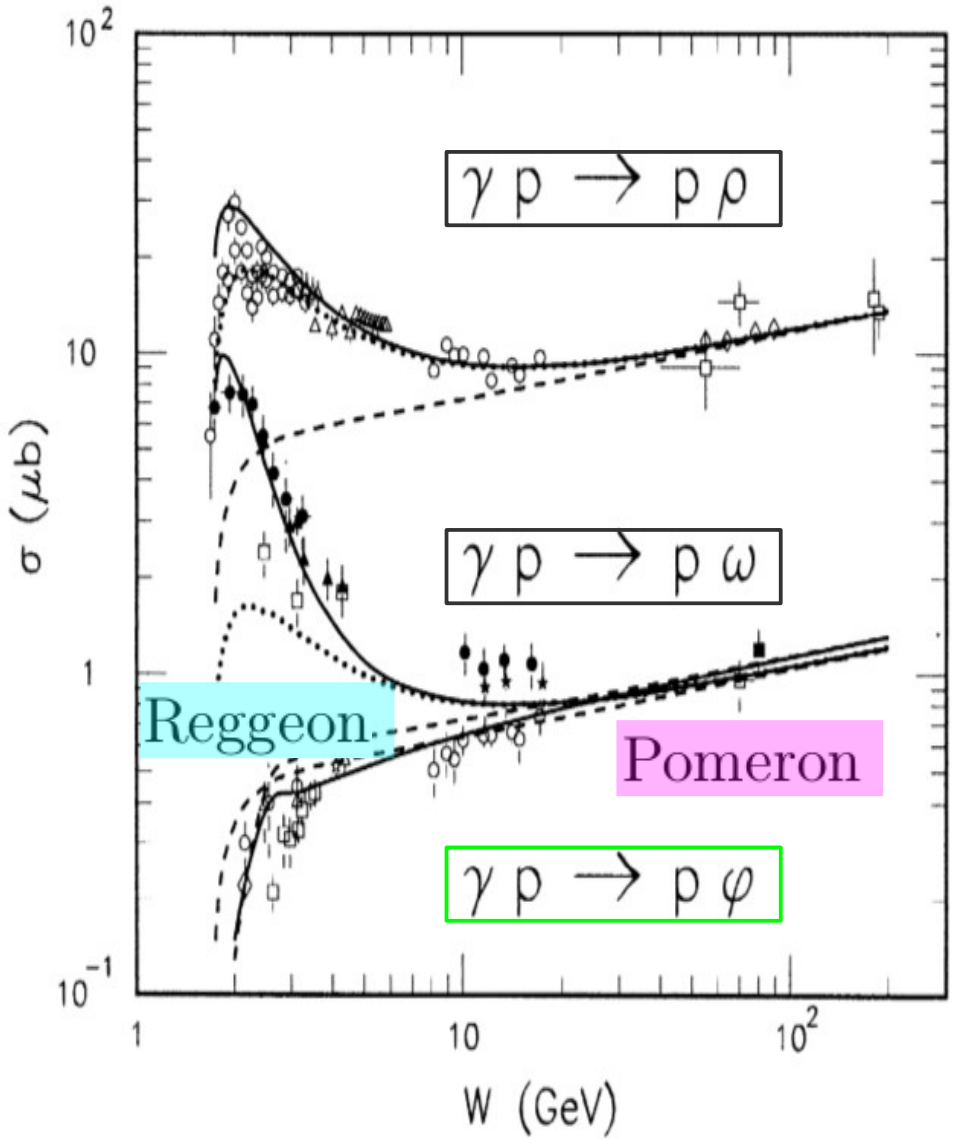




- A maximal Odderon model is proposed to describe the dip and shoulder region for pp and $\bar{p}p$ scatterings, respectively.
- This behavior is determined by delicate interference effects.

Donnachie & Landshoff, NPB267.690 (1986)

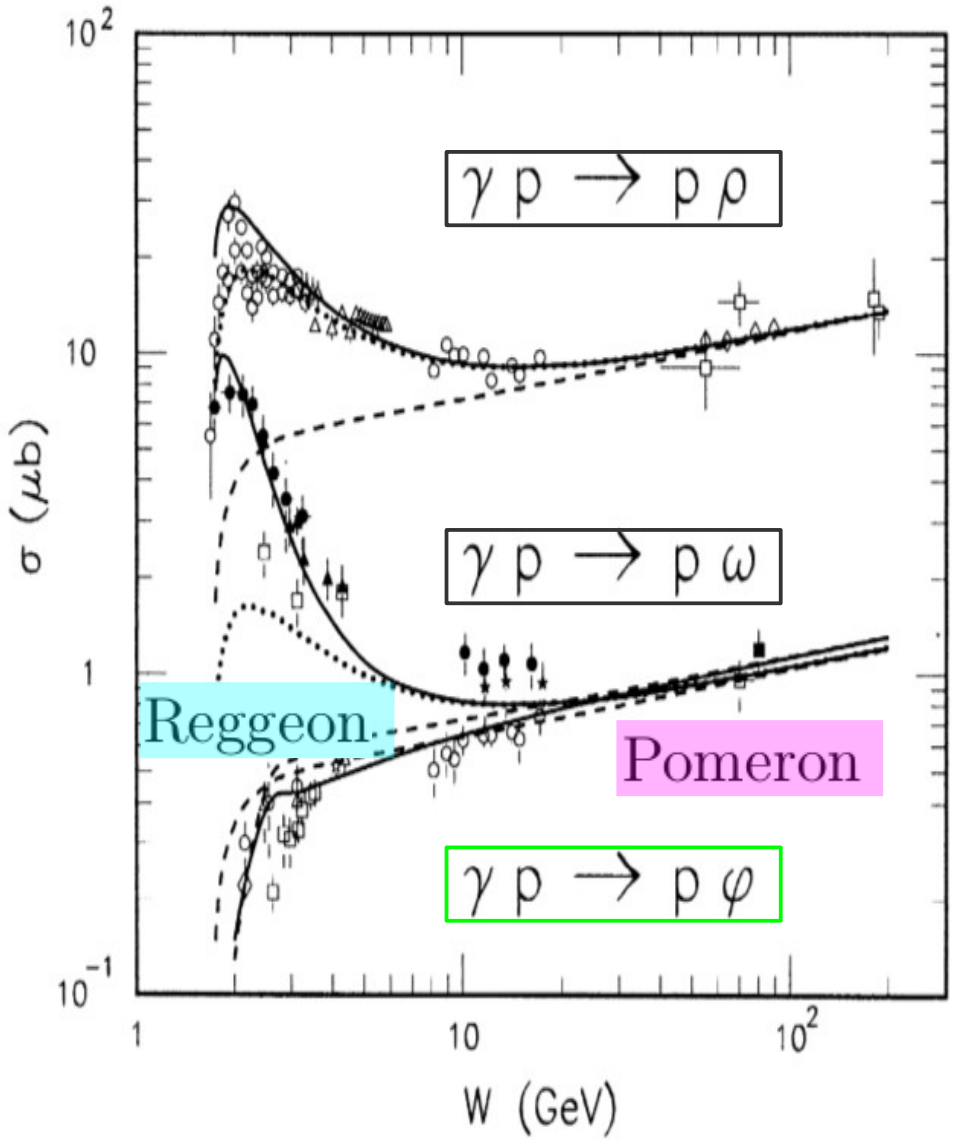
Elastic photoproduction of vector mesons



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

Laget,PLB.489.313(2000)

Elastic photoproduction of vector mesons



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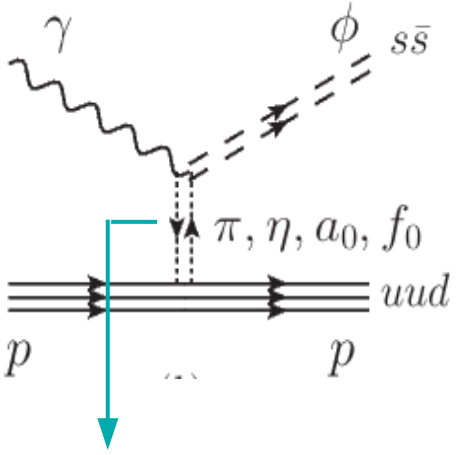
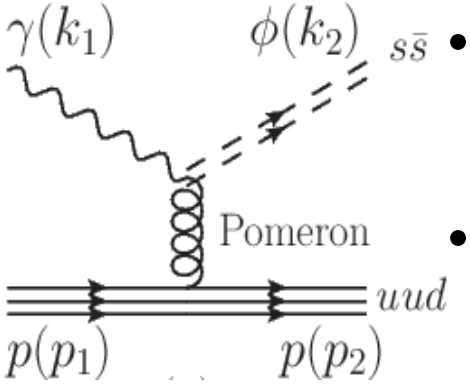
Low energy



light unflavored mesons

- The dynamics of Reggeon is related to non-perturabtive QCD in q-$\bar{q}$ sector.
- OZI suppressed.
- PS(0^-) π & η exchange
- S(0^+) a0 & f0 exchange

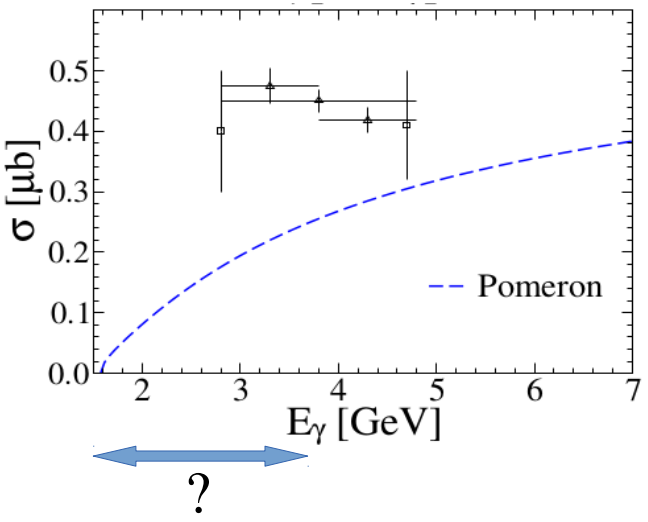
High energy



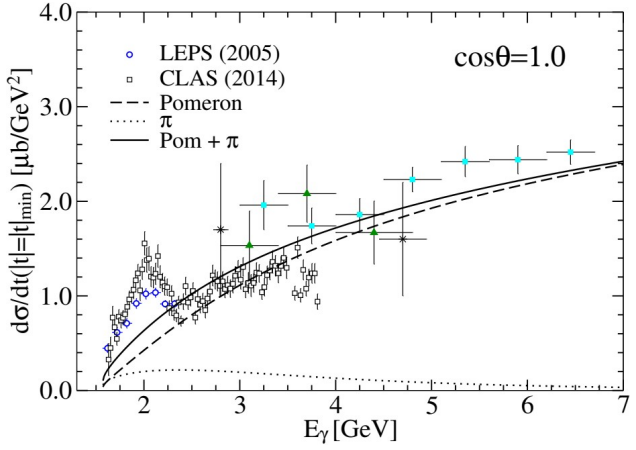
- Pomeron is the result of non-perturbative QCD interaction in gluon sector.
- Natural parity (+1).

φ photoproduction in low energy regions

- Pomeron alone is not sufficient to describe low energy regions.



- Only forward angle data existed before.



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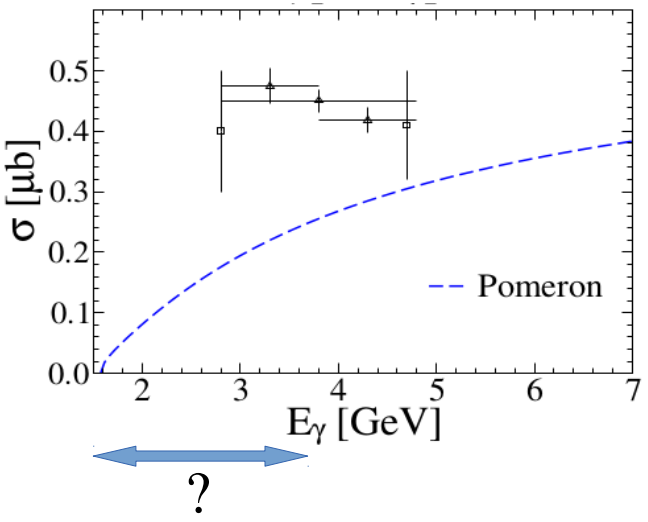

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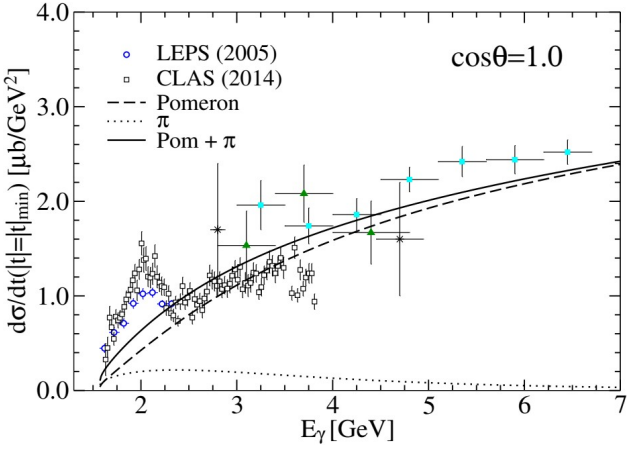
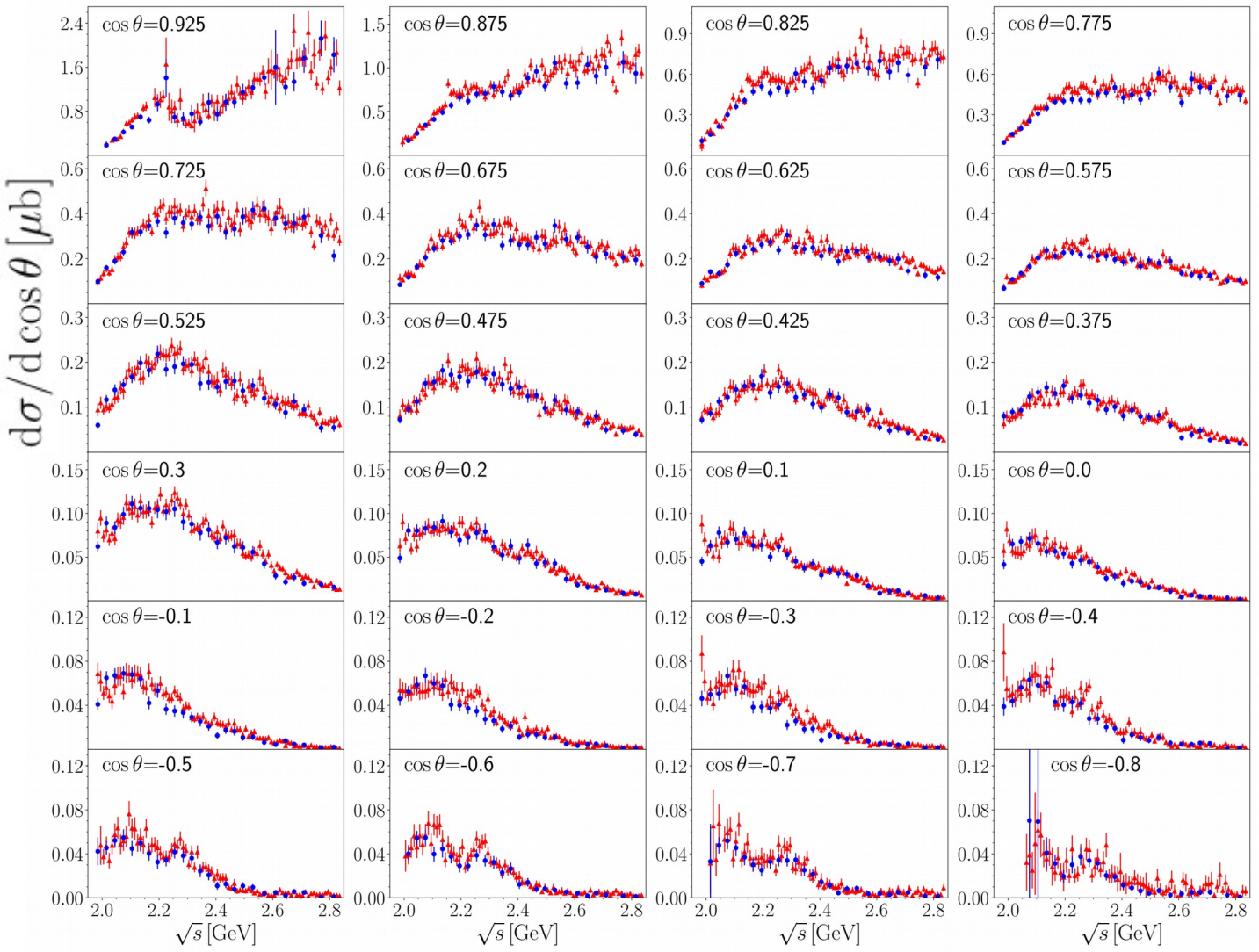


- Abundant data are reported at CLAS at full scattering angles & low energies (√s = 1.9-2.8 GeV).

[Seraydaryan, PRC.89.055206] & [Dey, PRC.89.055208] (2014)



Sangho Kim
(PKNU)

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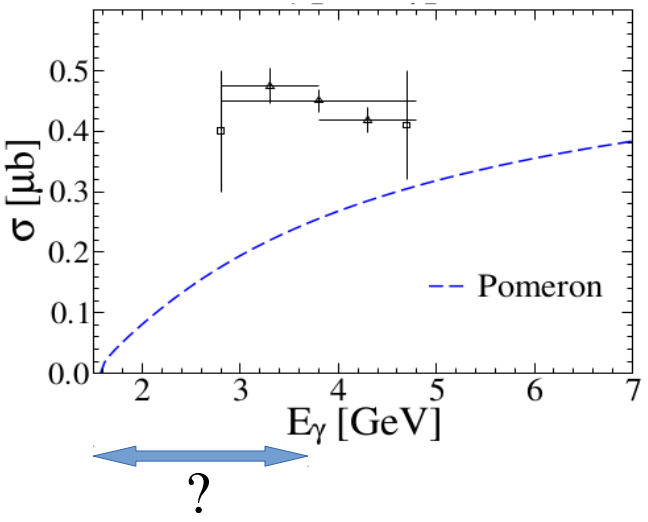

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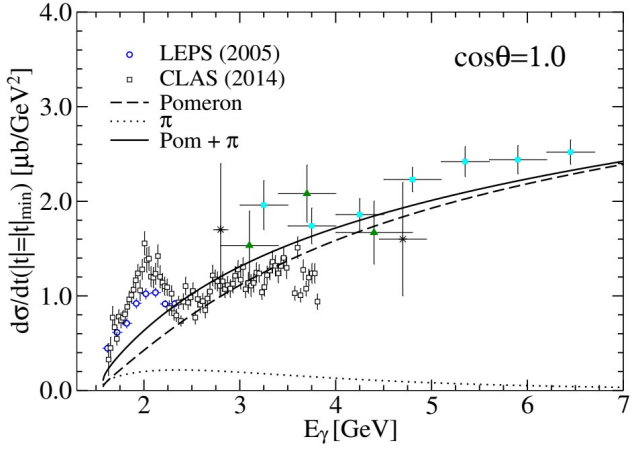

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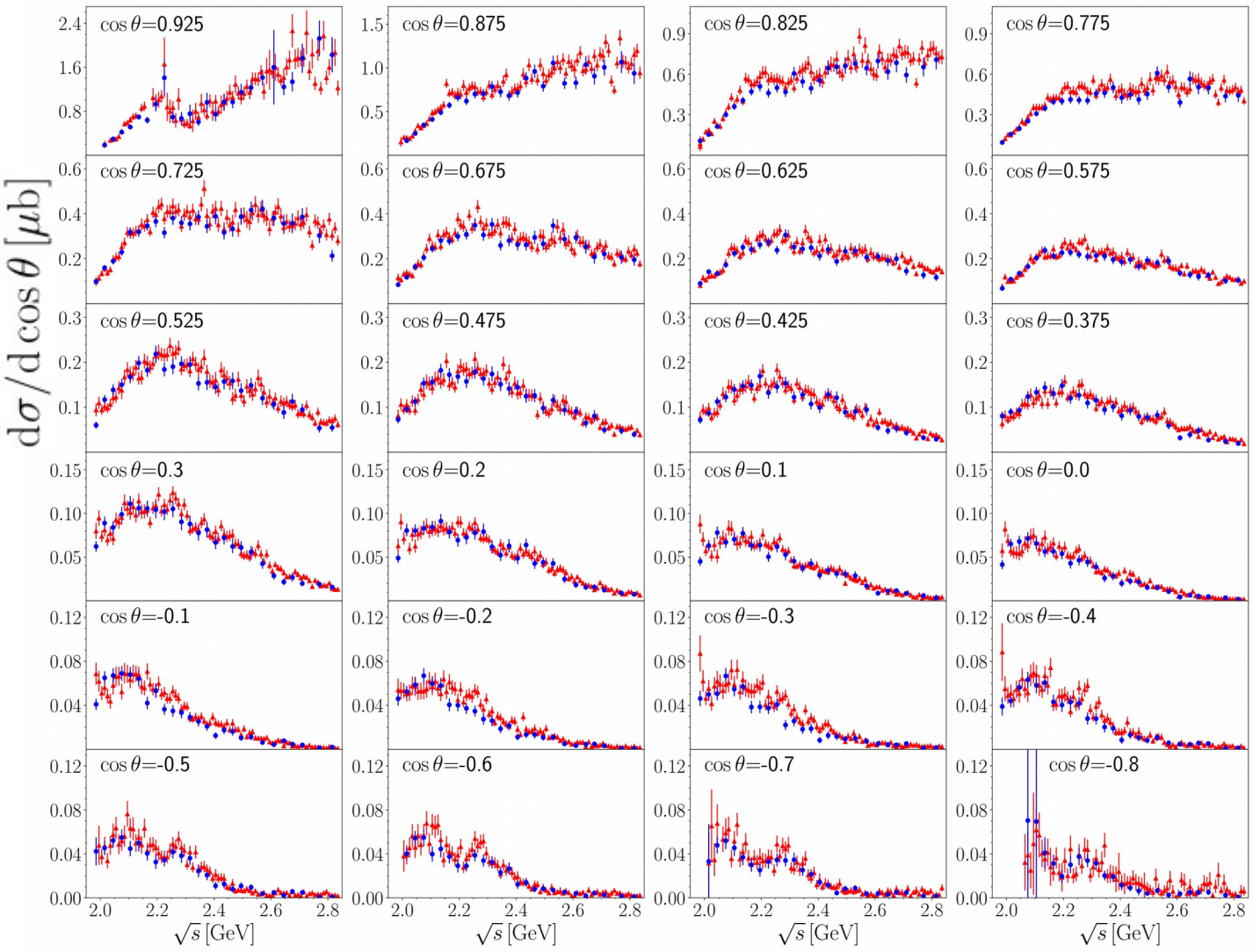
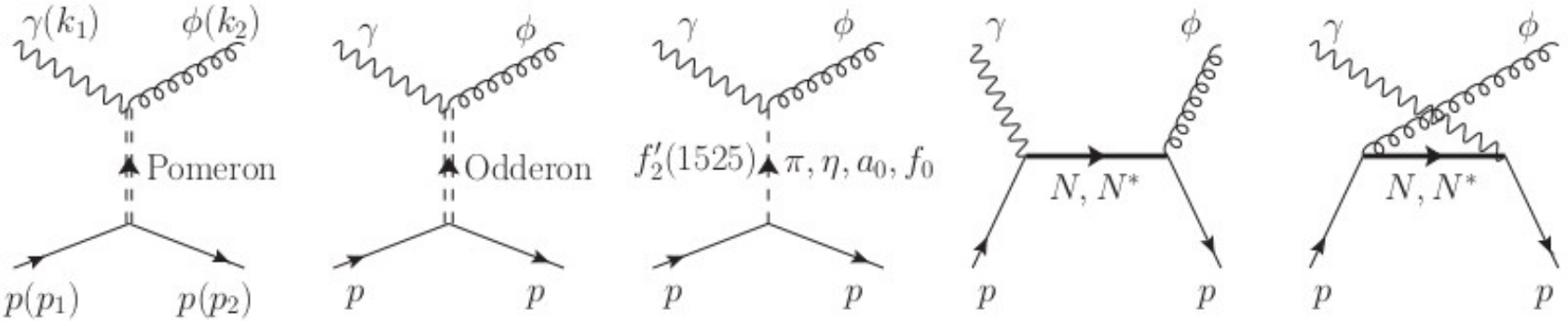


- We need a systematic analysis on φ photoproduction.

Formalism

Pseusoscalar(π,η) & Scalar(a_0,f_0) mesons, Nucleon

• Feynman diagrams for γp → φ(1020)p



Previous work: Pomeron + PS(π,η) + N + assumed N^*
Our work: Pomeron + PS(π,η) + N + Odderon + S(a_0,f_0) + f_2' + PDG N^*

Pomeron: two-gluon exchange (C=P= 1)
Odderon: three-gluon exchange (C=P=-1)

• A number of high-energy reactions have been proposed for detecting the Odderon, e.g. "$\boldsymbol{\gamma^{(*)} + p \rightarrow \eta_c + p}$" & "$\boldsymbol{\gamma + \gamma \rightarrow M + M}$".

Pseusoscalar(π,η) & Scalar(a_0,f_0) mesons, Nucleon

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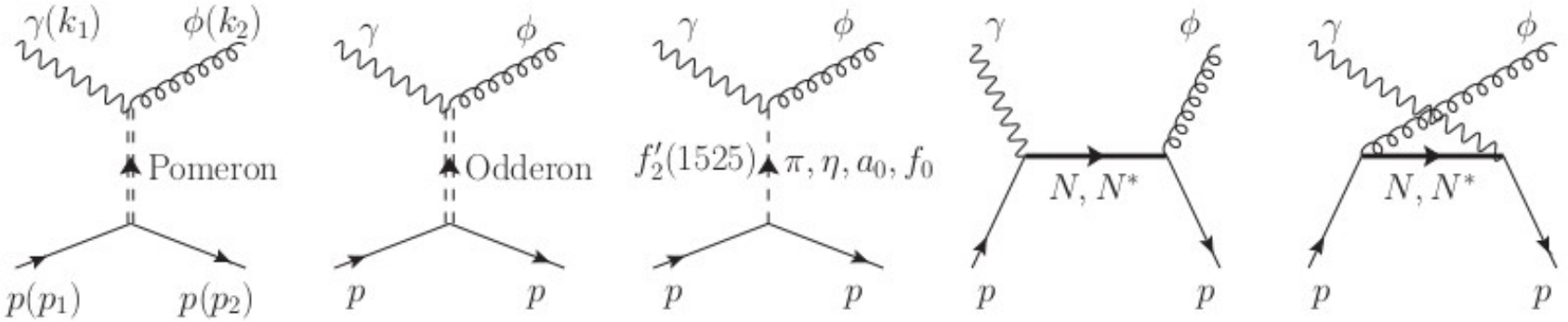

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• Effective Lagrangians

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

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

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

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

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

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

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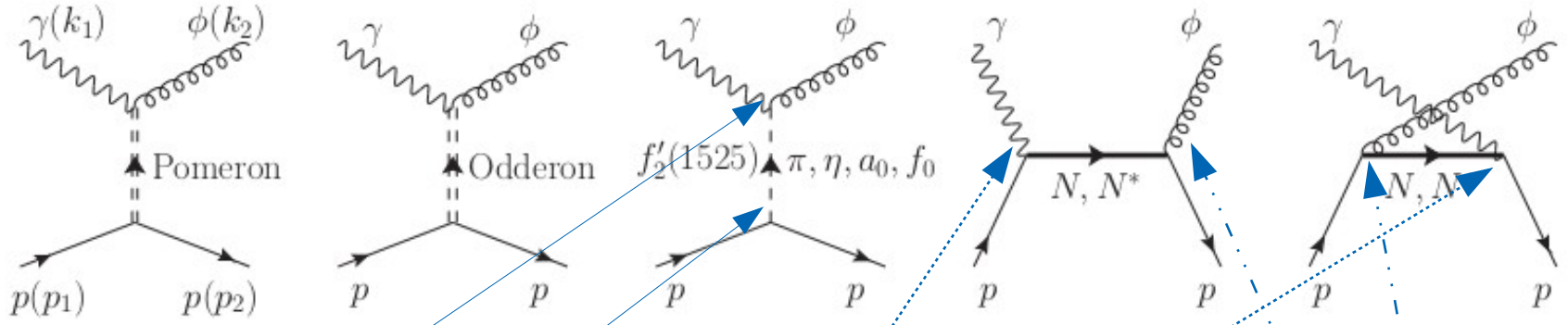

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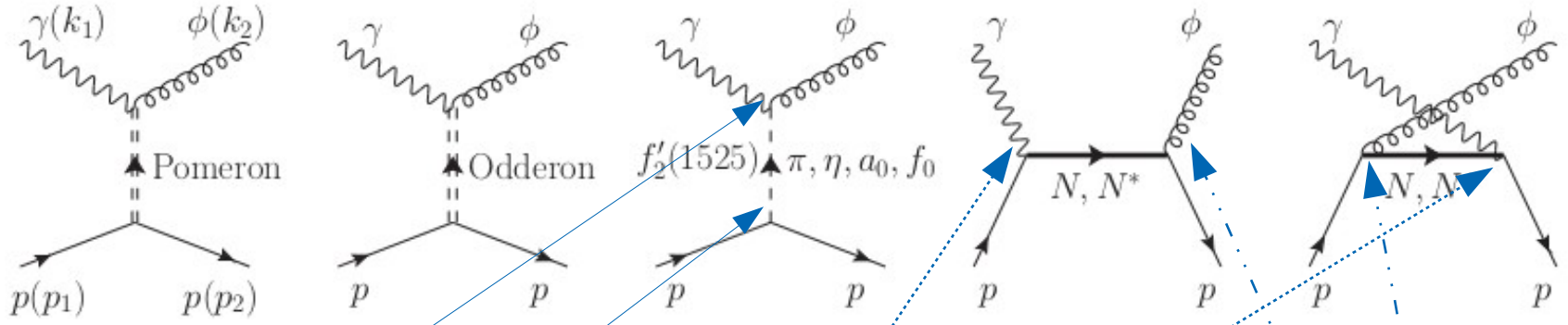

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$$\mathcal{L}_{\phi NN} = -g_{\phi NN}\bar{N}\left[\gamma_\mu - \frac{\kappa_{\phi NN}}{2M_N}\sigma_{\mu\nu}\partial^\nu\right] N \phi^\mu$$

• Form factors are considered to dress the interaction vertices.

meson exchange

$$F_{\Phi,S}(t) = \frac{\Lambda_{\Phi,S}^2 - M_{\Phi,S}^2}{\Lambda_{\Phi,S}^2 - t}$$

N exchange

$$F_N(x) = \frac{\Lambda_N^4}{\Lambda_N^4 + (x - M_N^2)^2}$$

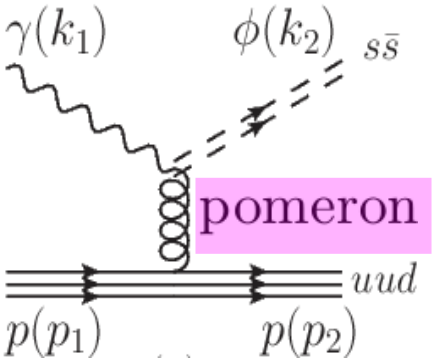
N^* exchange (Gaussian form)

$$F_{N^*}(x) = \exp\left[-\frac{(x - M_{N^*}^2)^2}{\Lambda_{N^*}^4}\right]$$

Pomeron & Odderon

- 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:

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

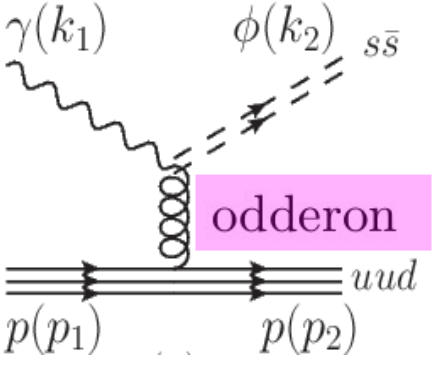
- scalar function: $M(s,t) = C_P F_1(t) F_2(t) \frac{1}{s} \left(\frac{s - s_{\rm th}}{s_P} \right)^{\alpha_P(t)} \exp\left[-\frac{i\pi}{2} \alpha_P(t) \right]$

- form factors: $F_1(t) = \frac{4M_N^2 - a_N^2 t}{(4M_N^2 - t)(1 - t/t_0)^2}, \quad F_2(t) = \frac{2\mu_0^2}{(1 - t/M_\phi^2)(2\mu_0^2 + M_\phi^2 - t)}$

	$\alpha_P(t)$	s_P [GeV^2]	$s_{\rm th}$ [GeV^2]	C_P	a_N^2	μ_0^2	t_0 [GeV^2]
Titov(2003)	1.08+0.25t	4	0	3.65	2.8	1.1	0.7
Titov(2007)	〃	〃	〃	3.20	4	〃	〃
Kiswandhi(2012)	〃	$(M_N + M_\phi)^2$	1.3	3.65	2.8	〃	〃
In this work	〃	〃	0	3.0	6.0	〃	〃

- scattering amplitude:

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

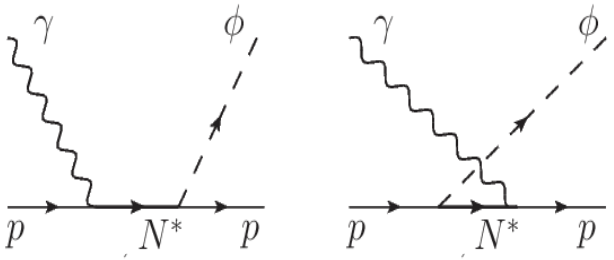


- Pomeron & Odderon trajectories:

$$\alpha_{\mathbb{P}}(t) = 1.08 + (0.25\,\text{GeV}^{-2})t, \quad \alpha_{\mathbb{O}}(t) = 0.95 + (0.25\,\text{GeV}^{-2})t$$

Nucleon resonances

- We choose N(2100), N(2120) & N(2300) from "PDG 2018" to describe two bump structures at backward angles.



- Effective Lagrnagians

$$\mathcal{L}_{\gamma NN^*} = \frac{e g_{\gamma NN^*}}{2M_N} \bar{N}^* (\sigma \cdot F) N + \text{h.c.}$$

$$\mathcal{L}_{\phi NR} = g_{\phi NN^*} \bar{N} \not{\phi} N^* + \text{h.c.}$$

- Γ_{N^*} = (200-300) MeV

PDG 2018

$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	***
➡ $N(2100)$	$1/2^+$	***
➡ $N(2120)$	$3/2^-$	***
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
➡ $N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

Nucleon resonances

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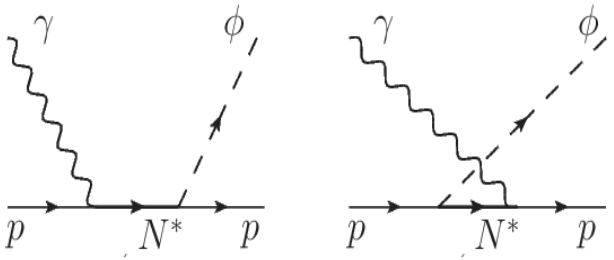

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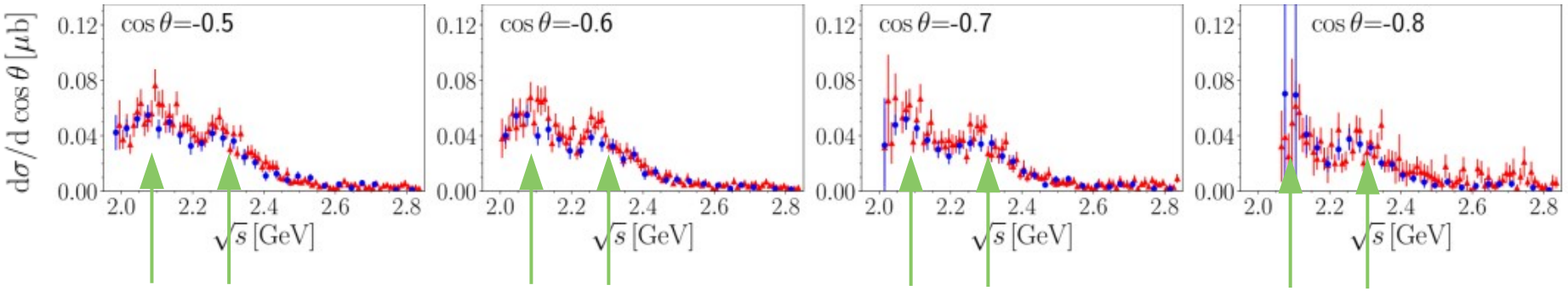
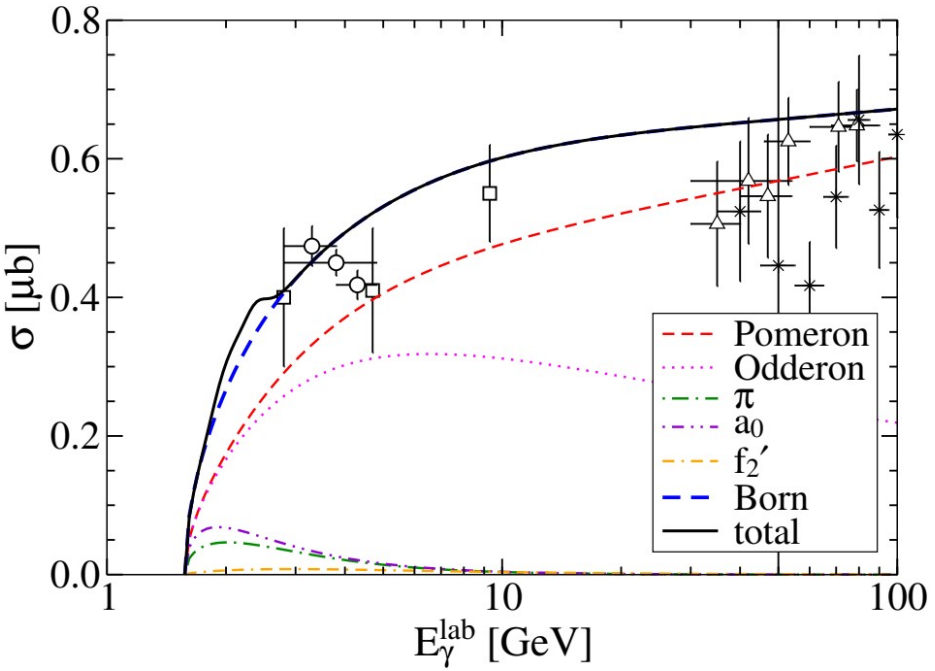
	$N(2570)$	$5/2^-$	**
	$N(2600)$	$11/2^-$	***
	$N(2700)$	$13/2^+$	**

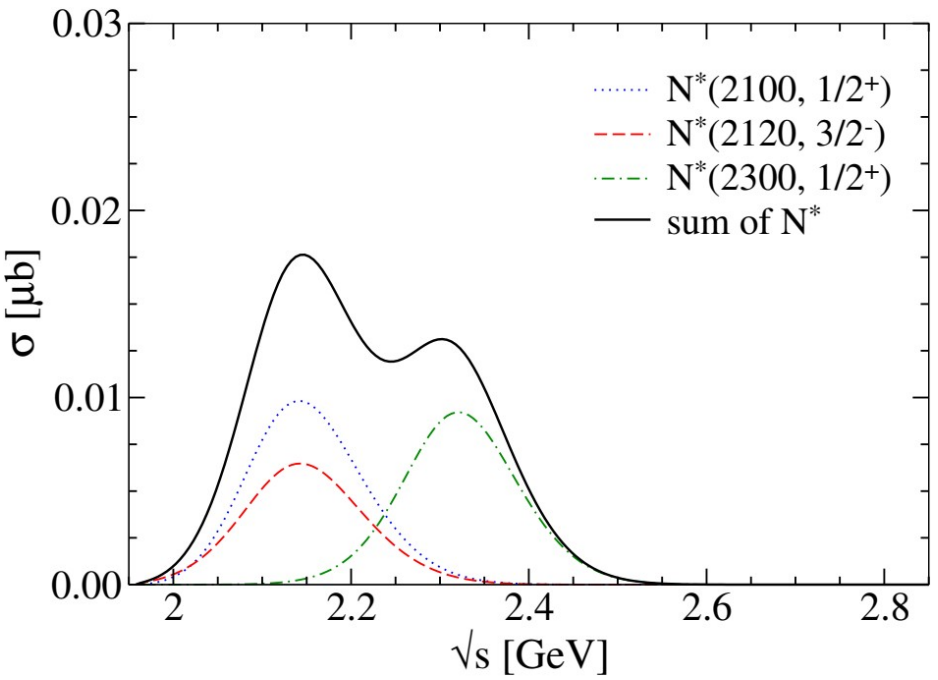
1. Two bump structures are located near their pole positions, i.e. $\sqrt{s} \approx 2.1$ & 2.3 GeV.
2. We expect only lower partial waves would be important.



Numerical Results

Total cross section





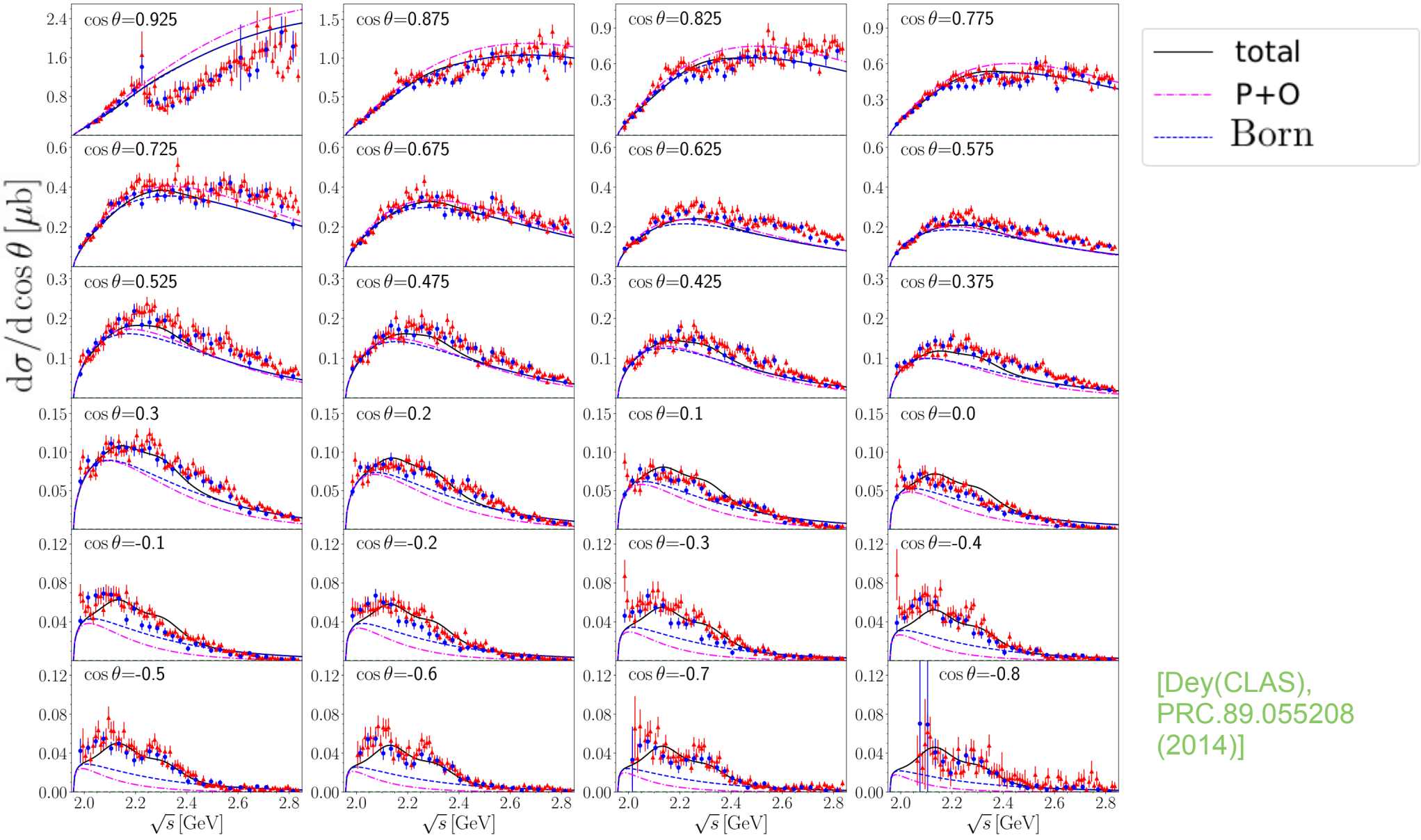
$$\mathcal{M}_{\rm total} = \sum_i \mathcal{M}_i^{\rm Born} + \sum_j C_j \mathcal{M}_j^{N^*}$$

$$i = (\mathbb{P}, \mathbb{O}, \pi, \eta, a_0, f_0, f_2')$$

$$j = (N^*(2100, 1/2^+), N^*(2120, 3/2^-), N^*(2300, 1/2^+))$$

- The total cross section is almost governed by Pomeron and Odderon exchanges.
- Other contributions are small to the total cross section but come into play significantly for the “differential cross sections” and “spin-density matrices”.

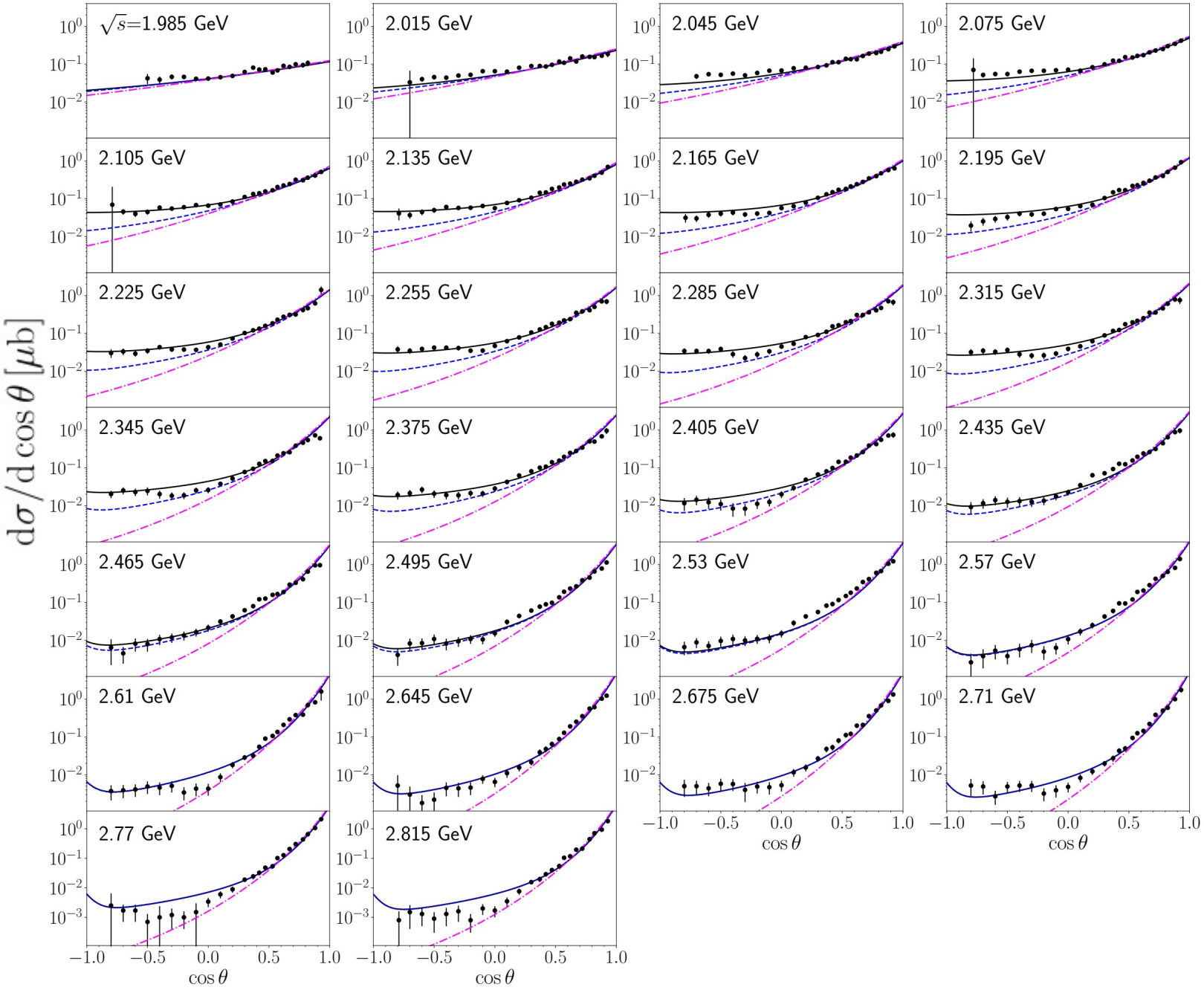
Differential cross sections (1)



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

- PS- and S-meson exchanges, respectively, make constructive and destructive interference effects with the dominant Pomeron and Odderon contributions.
- Three N* contributions improve the results at backward angles remarkably.

Differential cross sections (2)



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

Spin-density matrix elements

- SDMEs in terms of the helicity amplitudes

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

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

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

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

- normalization factor

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

- symmetry relation

$$\rho^\alpha_{\lambda\lambda'} = (-1)^{\lambda-\lambda'}\rho^\alpha_{-\lambda-\lambda'} \quad \text{for} \quad (\alpha = 0, 1),$$
$$\rho^\alpha_{\lambda\lambda'} = -(-1)^{\lambda-\lambda'}\rho^\alpha_{-\lambda-\lambda'} \quad \text{for} \quad (\alpha = 2, 3)$$

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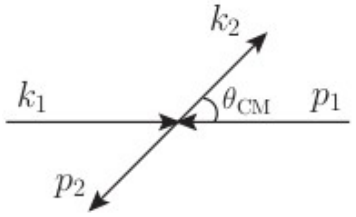
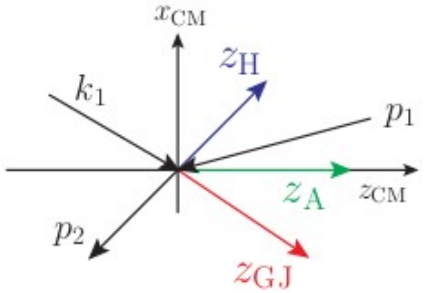


• center of mass frame



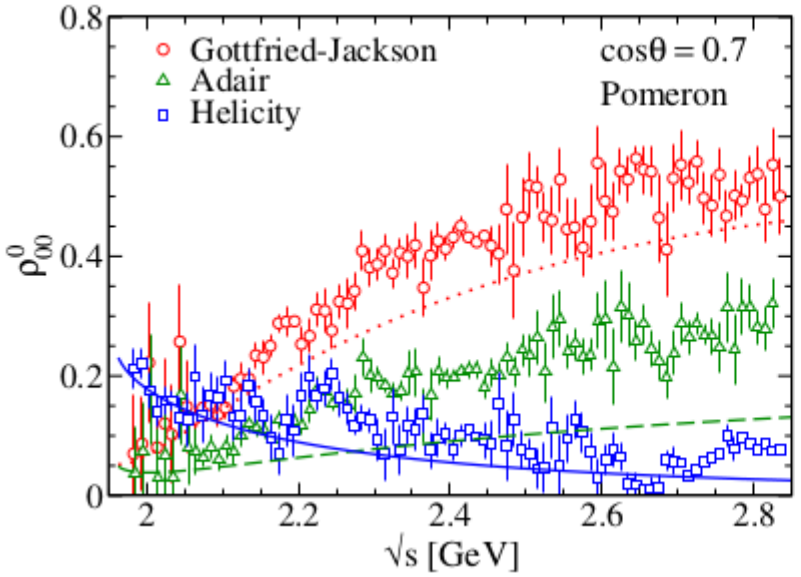
• φ-meson rest frame

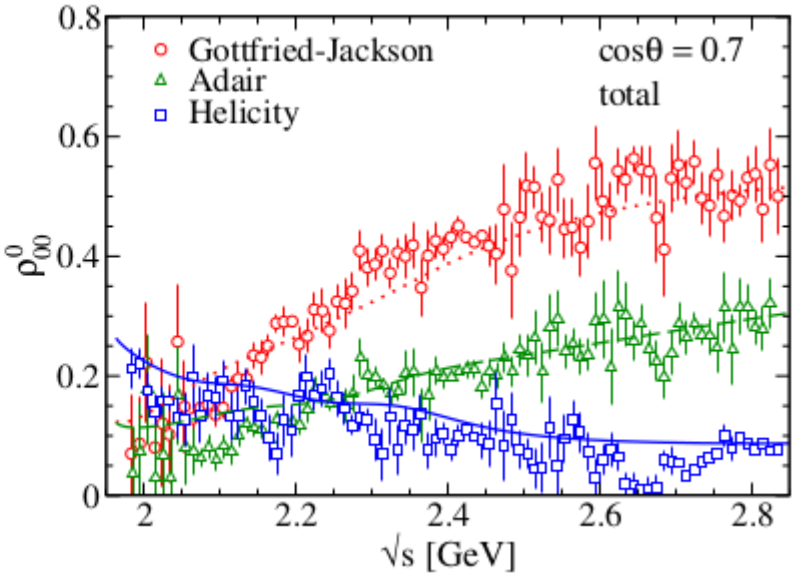
Adair frame: z axis is parallel to the incoming photon momentum in the CM frame.

Helicty frame: z axis is antiparallel to the momentum of the outgoing nucleon.
It is in favor of s-channel helicity conservation (SCHC).

Gottfried-Jackson frame: z axis is parallel to the momentum of the incoming photon.
It is in favor of t-channel helicity conservation (TCHC).

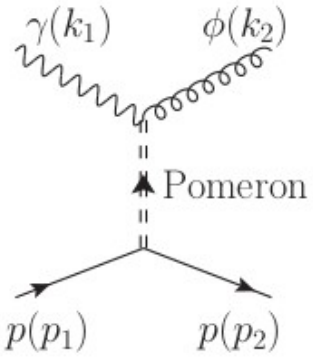
Spin-density matrix elements (1)





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

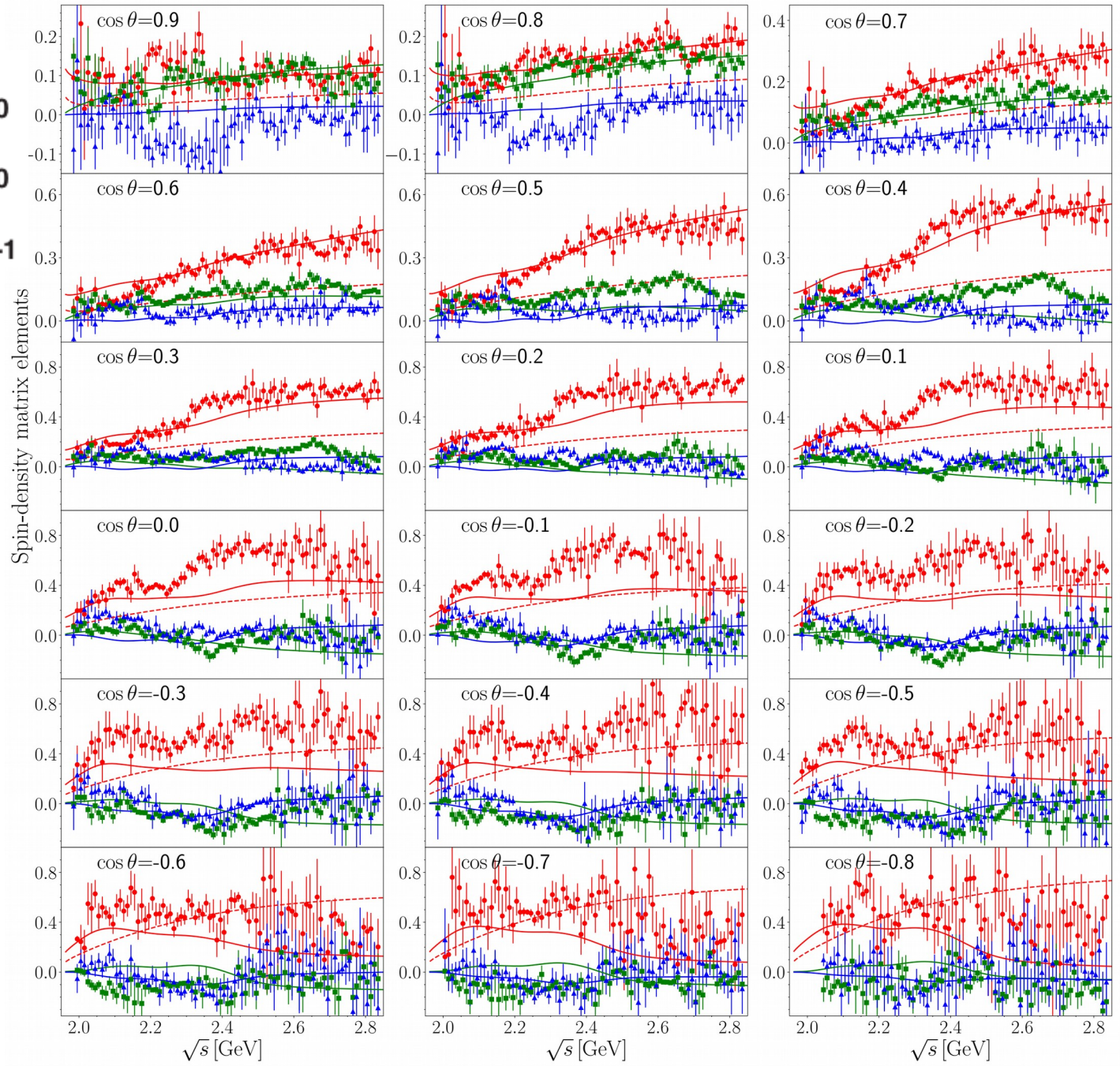
- ρ^0_{00} is nonzero in all three frames and thus exhibits strong deviation from TCHC, implying nonzero helicity flip ($\rho^0_{00} \propto |\mathcal{M}_{\lambda_\gamma=1,\lambda_\phi=0}|^2 + |\mathcal{M}_{\lambda_\gamma=-1,\lambda_\phi=0}|^2$).
- Pomeron alone is not sufficient.



- The inclusion of S(a_0,f_0)- & f_2'-mesons is essential to improve the results.

Spin-density matrix elements (2)

[Adair frame]

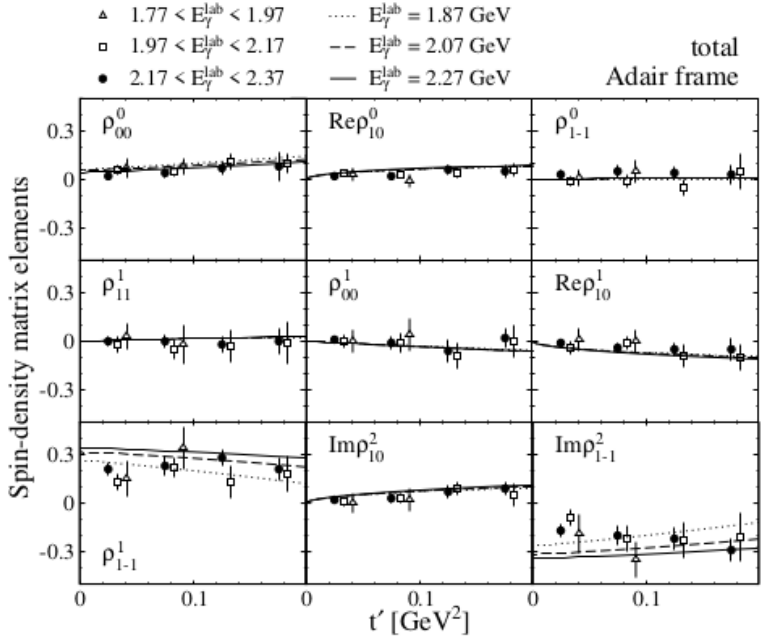


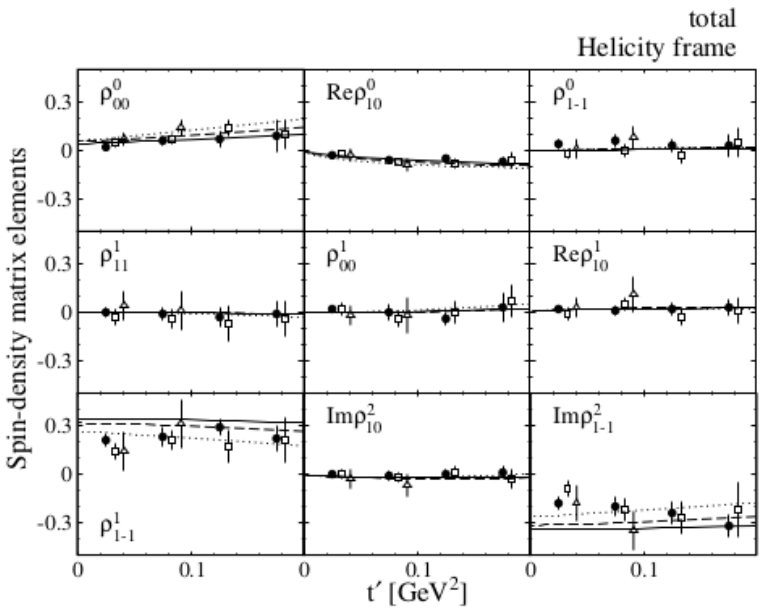
- forward angle:
  Pomeron alone is not enough.
  S(a_0,f_0)- & f2'-mesons improves the results.

- backward angle:
  N^* exchange describes the bump structure.

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

Spin-density matrix elements (3)





[Chang(LEPS), PRC.82.015205 (2010)]

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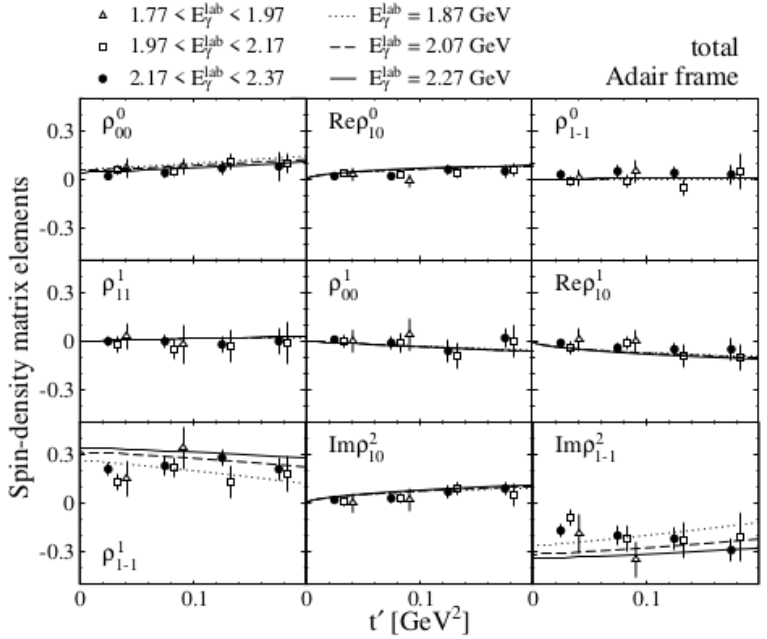

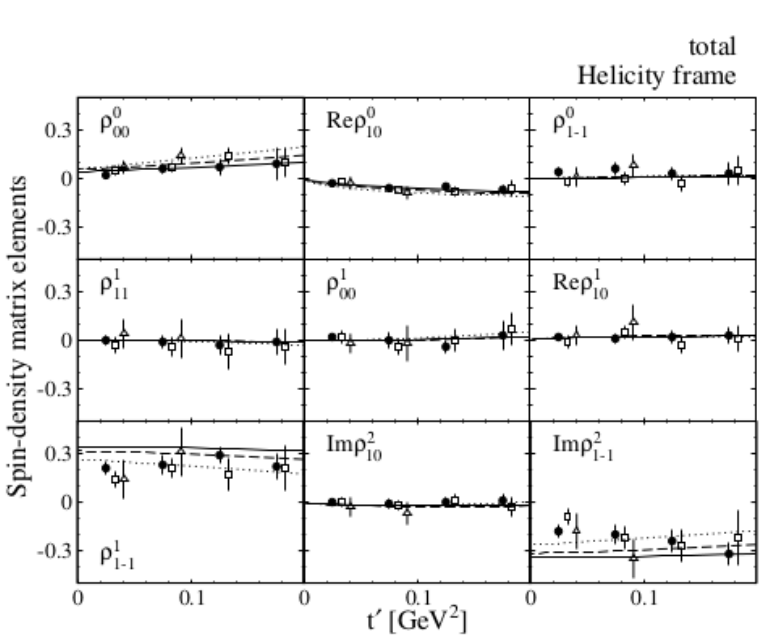

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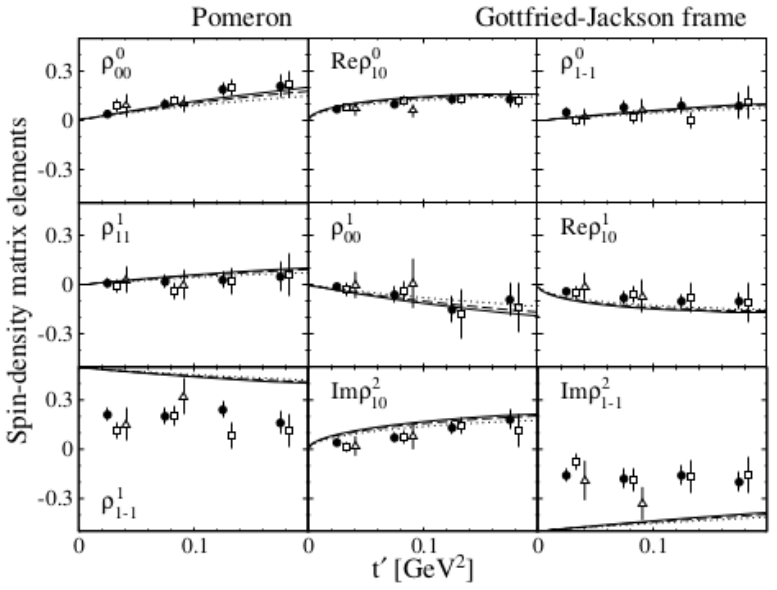

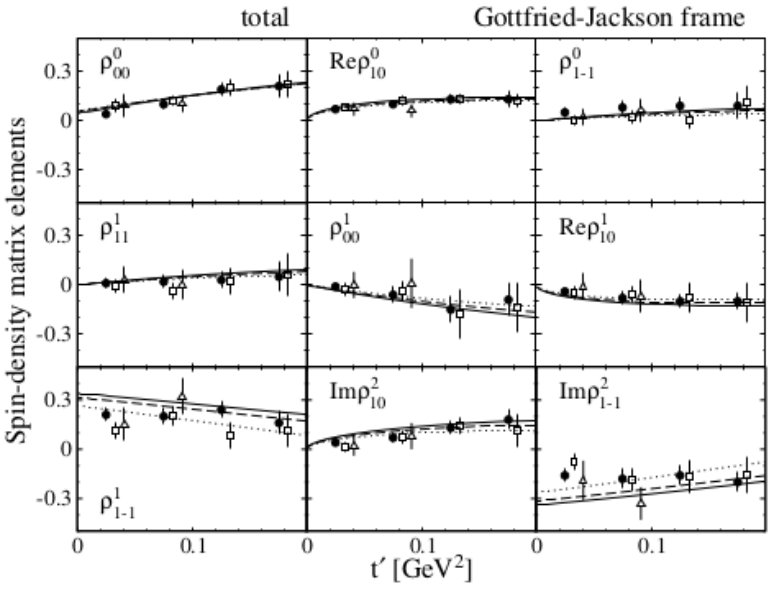

- Pomeron exchange

$$\rho^1_{1-1} \simeq \frac{1}{2}(1-\rho^0_{00})$$

- Relative strength of N & U parity exchange processes

$$\rho^1_{1-1} = \frac{1}{2}\frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}$$

- GJ frame is useful to test TCHC.

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◇ φ photoproduction, $\gamma p \rightarrow \phi(1020)p$, is reanalyzed with effective Lagrangians .

◇ Abundant CLAS(2014) data are reported at full angles & low energies.

◇ Various contributions from t-channel exchanges and N^* exchange
are considered in addition to the dominant Pomeron exchange.

⇨ Odderon ⇨ $f'_2(1525)$ trajectories

⇨ pseudoscalar meson (π,η) ⇨ scalar meson (a_0,f_0)

◇ Extension to other vector-meson (ρ,ω) photo- and electro-production mechanisms.

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Thank you very much

Back Up

Previous theoretical works

- Nagano, Toki, Proceedings (**1998**)

: scalar glueball ($J^{\pi}=0^{+}$, $M_{gl}^{2}\simeq 3\ GeV^{2}$).

- Williams, PRC, 57, 223 (**1998**)

: $s\bar{s}$ knockout, nonzero φNN couplings.

- Titov et al., PRC, 60, 035205 (**1999**)

: scalar mesons (σ, a_0, f_0).

- Laget, PLB, 489, 313 (**2000**)

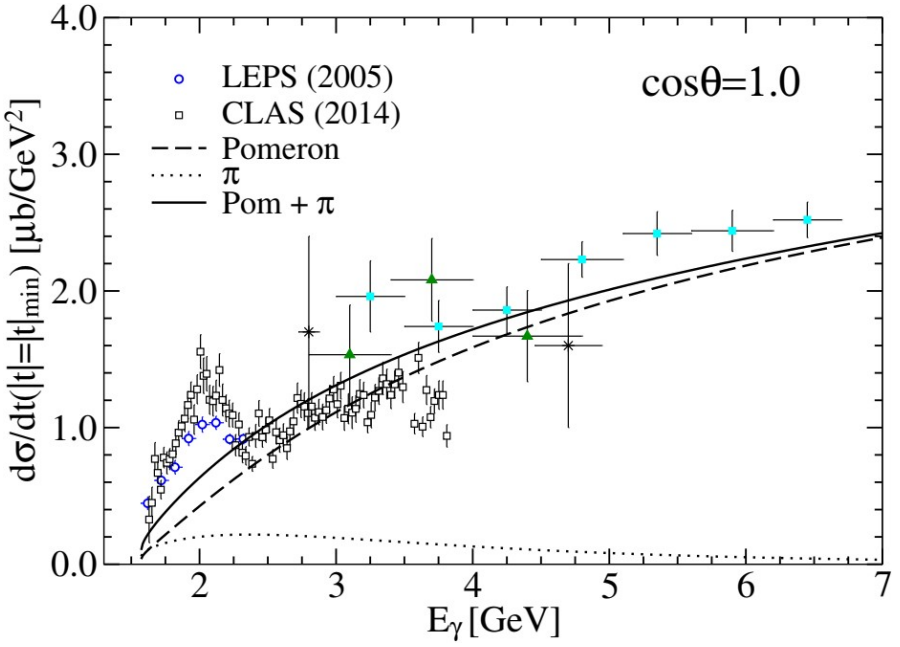
: $f_2(1270)$ meson, two gluon exchange.

- Titov, Lee, PRC, 67, 065205 (**2003**)

: $f_2(1270)$, $f'_2(1525)$ mesons, N^*.

∴ Pomeron & pseudoscalar mesons (π^0,η) in common.

t-channel contributions are widely studied.



Mibe(LEPS)PRL.95.182001(2005)

After an observation of the bump structure, most of works have moved on to the N^* scenario.

Previous theoretical works

• Titov, Kampfer, PRC,76, 035202 (**2007**)
: Pomeron + (π,η) mesons.

a. Ozaki, Hosaka, Nagahiro, Scholten, PRC, 80, 035201 (**2009**)
: coupled-channel effective-Lagrangian method based on the K-matrix approach.
Suggest the existence of a N^*, $J^P=1/2^-$ resonance (M=2.250, Γ=0.100 [GeV]).

b. Kiswandhi, Xie, Yang, PLB, 691, 214 (**2010**)
: Assume a N^* resonance of $J^P=3/2^-$ (M=2.10±0.03, Γ=0.465±0.141 [GeV]).

c. Kiswandhi, Yang, PRC, 86, 015203 (**2012**)
: N^* of $J^P=3/2^{\pm}$ (M=2.08±0.04, Γ=0.501±0.117(P=+), 0.570±0.159(P=-) [GeV]).

d. Ryu, Titov, Hosaka, Kim, PTEP, 2014, 023D03 (**2014**)
: various hadronic rescattering contributions, focusing on the KΛ(1520) channel.

Previous theoretical works