# The Pomeron, Odderon, and N* resonances in φ-meson photoproducion

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Contents based on
arXiv: 1904.05133 [hep-ph]

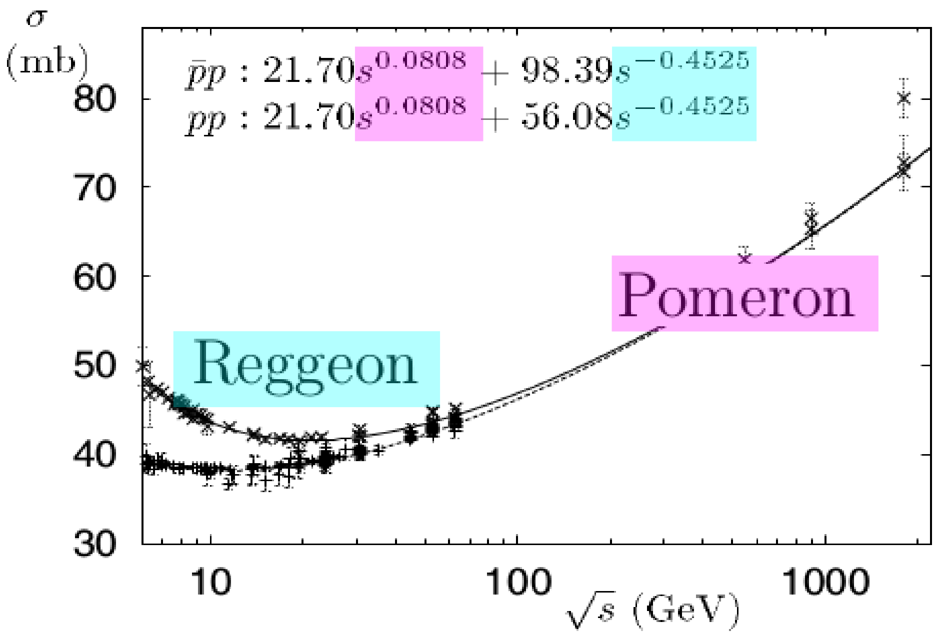
In collaboration with
Seung-il Nam (PKNU)

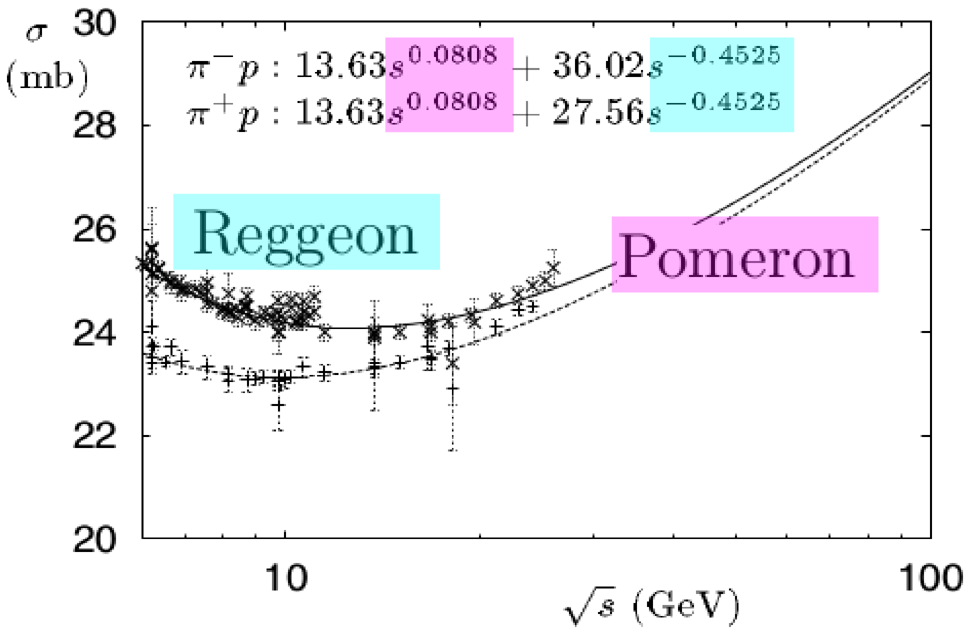
# Contents

$$\gamma p \rightarrow \phi p$$

# Background

# Soft hadronic processes

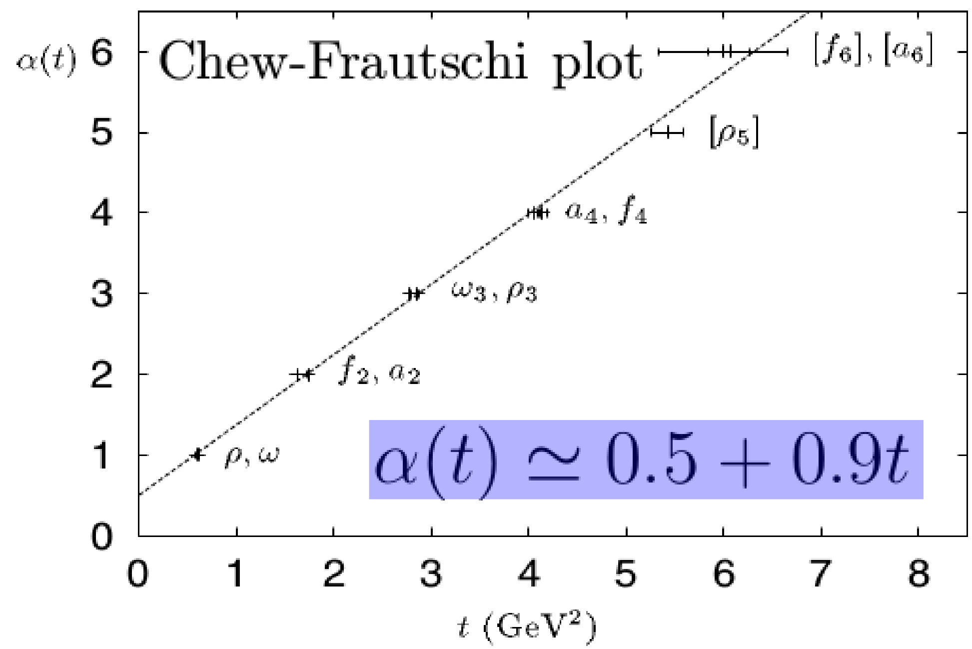



Donnachie, Pomeron Physics and QCD (2002)

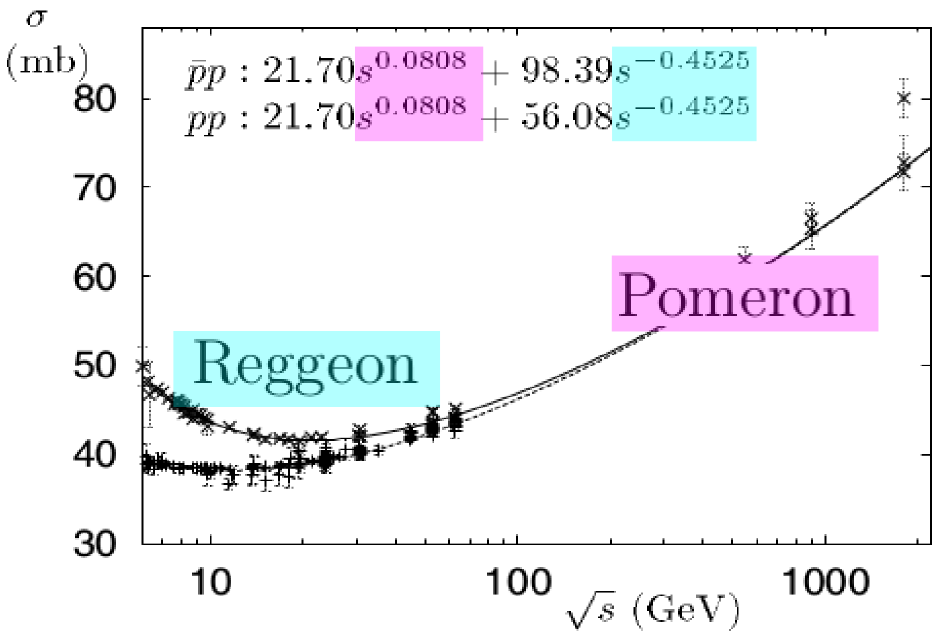
## Reggeon (Meson exchange)

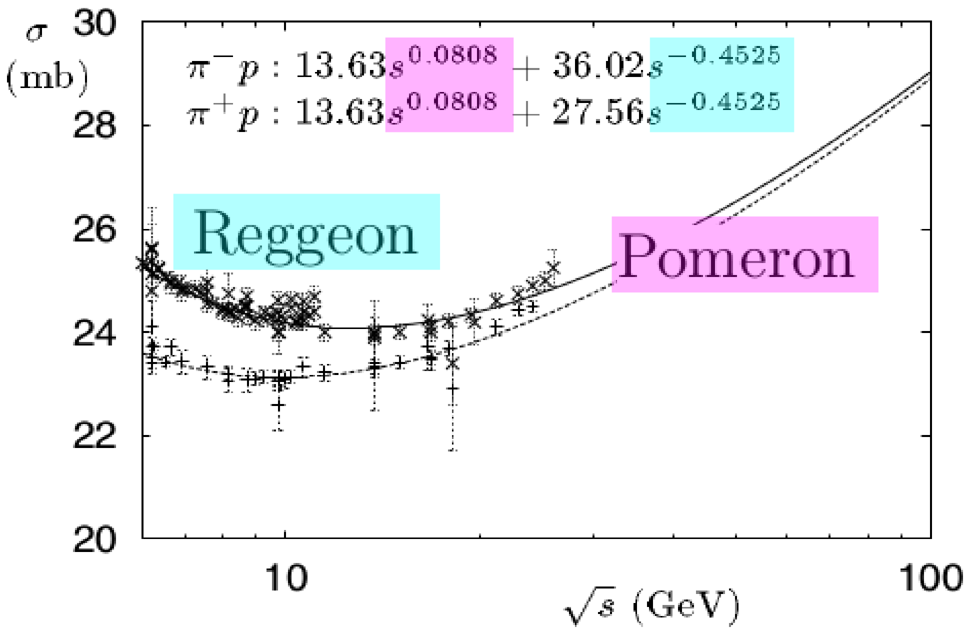
- Describes an exchange of a family of ordinary mesons.
- Governs relatively low energy regions.
- (ρ,ω) trajectories (C=-1,natural parity) & ($f_2$,$a_2$) trajectories (C=+1,natural parity) are all degenerate.




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

# 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.

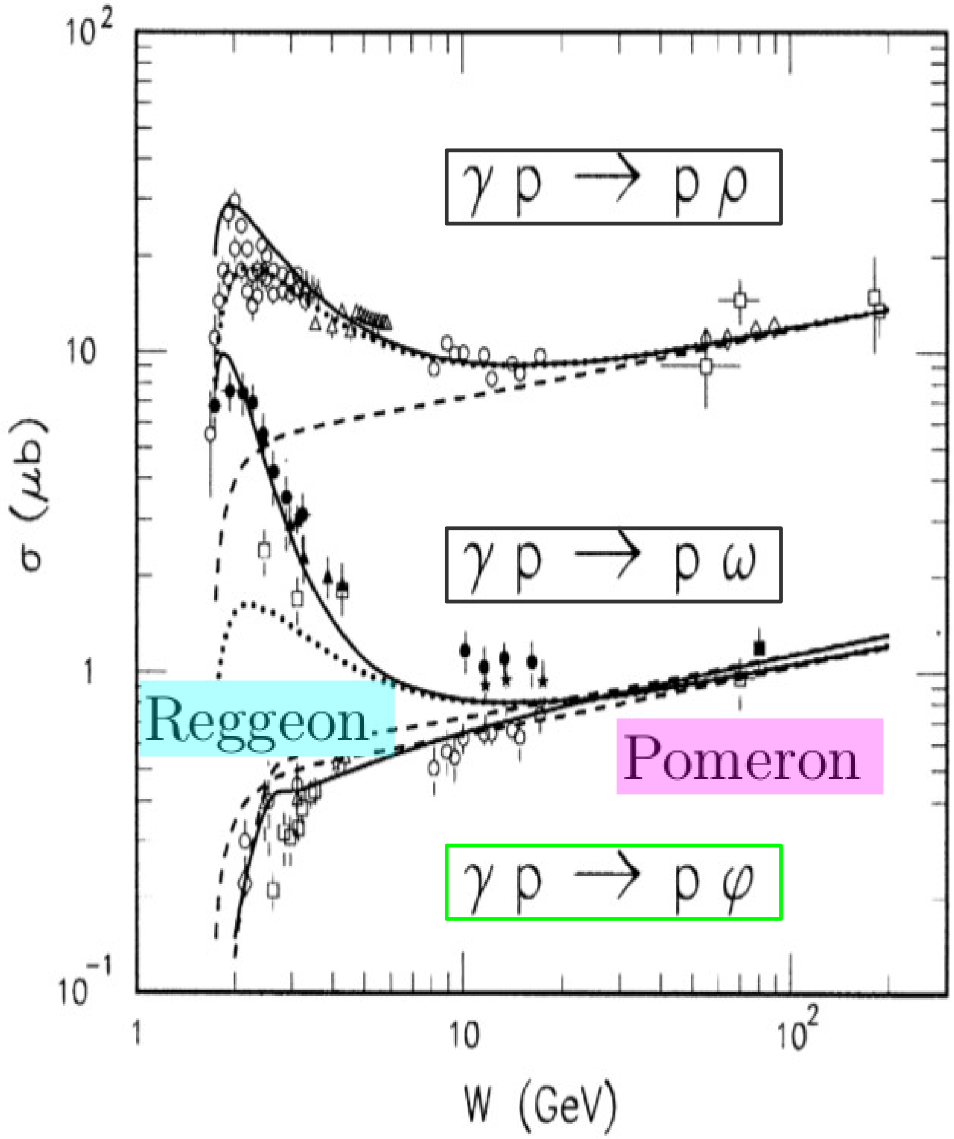
- There is no deep theory reason for the Pomeron hypothesis, but the phenomenology based on which turns out to be very successful.

- Pomeron trajectory:

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

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

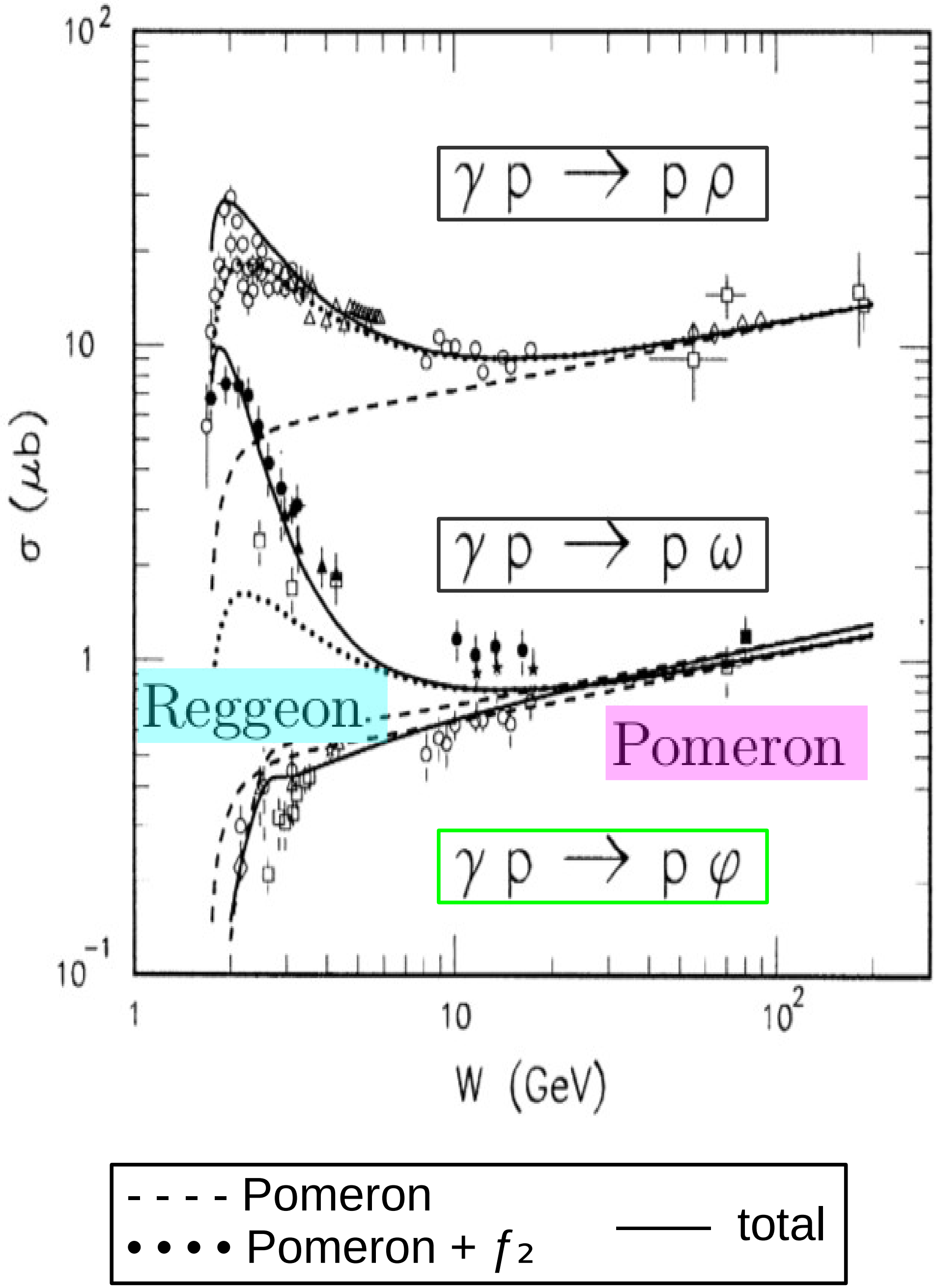
# Elastic photoproduction of vector mesons




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

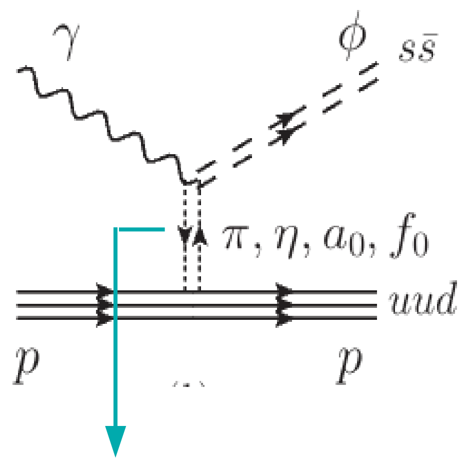
Laget,PLB.489.313(2000)

# Elastic photoproduction of vector mesons




Laget,PLB.489.313(2000)

## Low energy

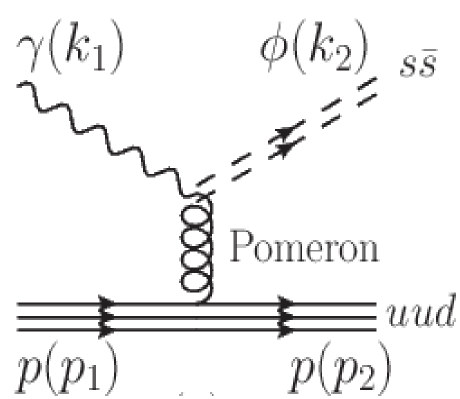



light unflavored mesons

- The dynamics of Reggeon is related to non-perturabtive QCD in $q\text{-}\bar{q}$ sector.
- OZI suppressed.

- PS($0^-$) $\pi$ & $\eta$ exchange
- S($0^+$) $a_0$ & $f_0$ exchange

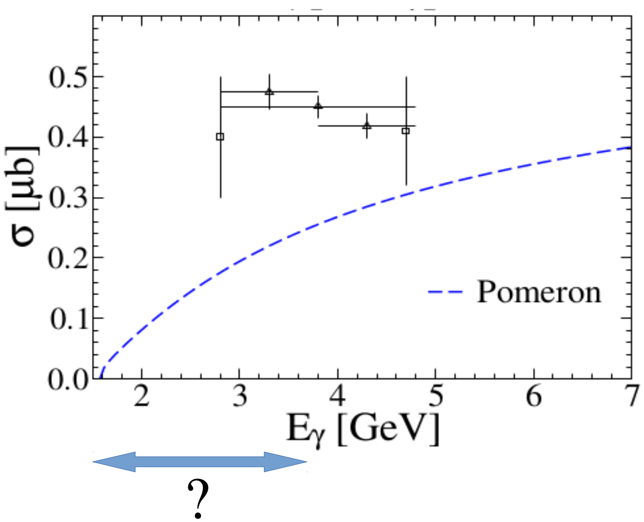
## High energy



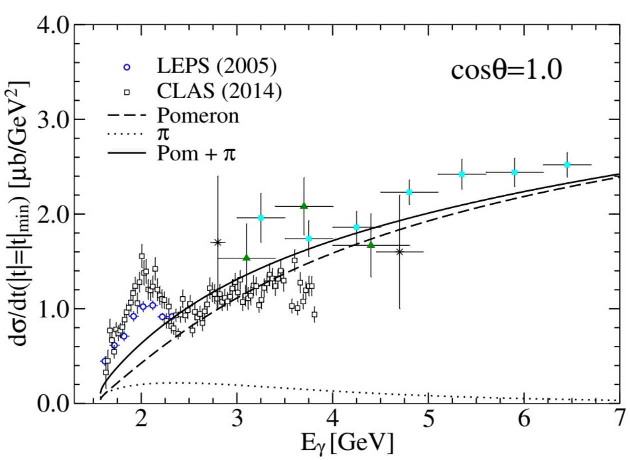

- Pomeron is the result of non-perturbative QCD interaction in gluon sector.
- Natural parity (+1).

# 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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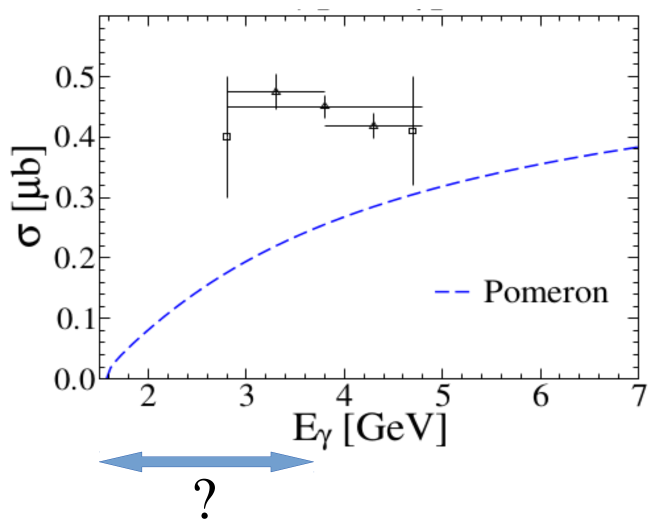


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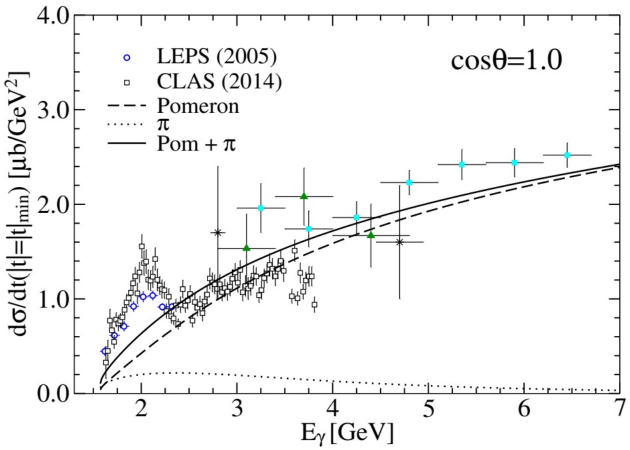
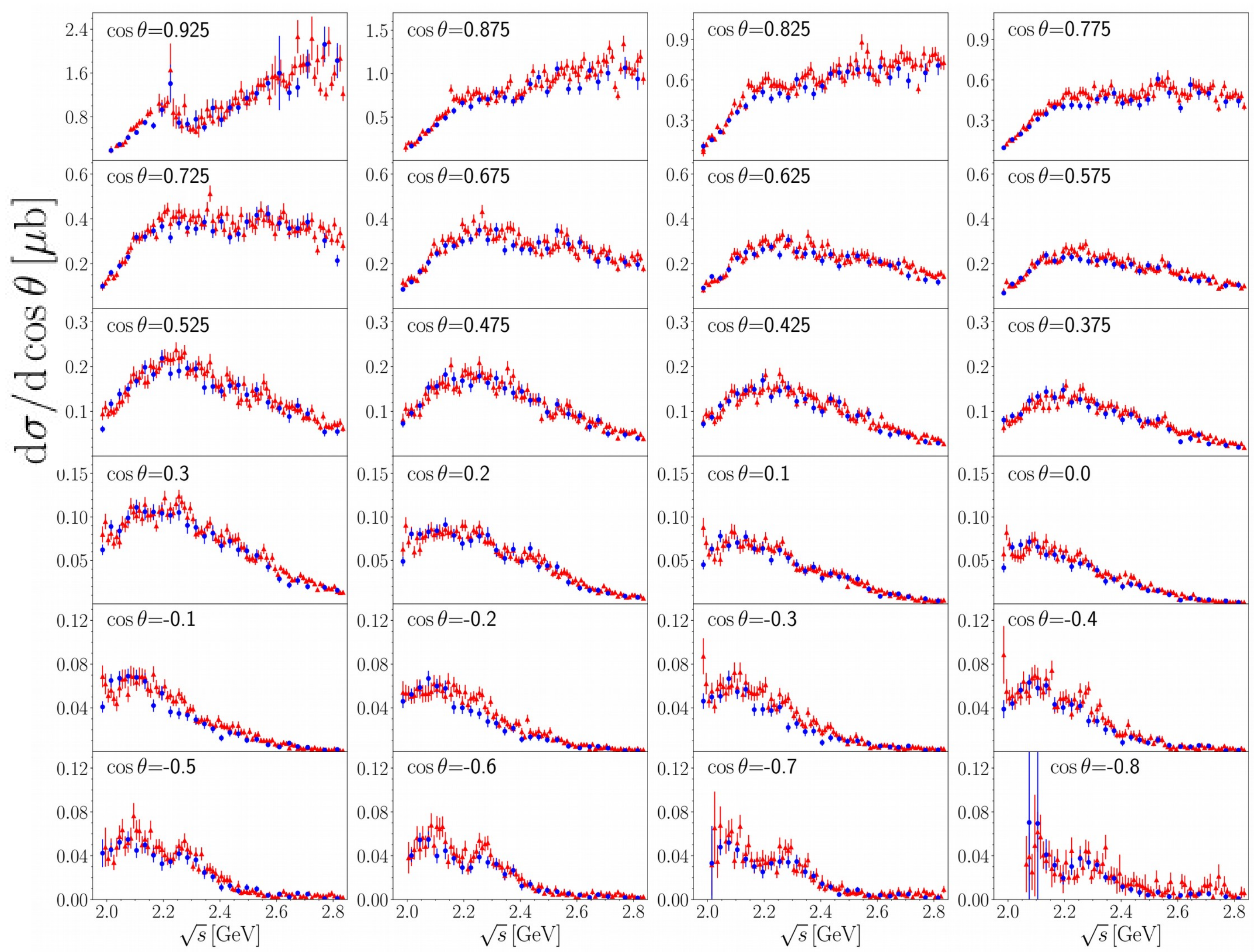



- Abundant data are reported at CLAS at full scattering angles & low energies (√s = 1.9-2.8 GeV).

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



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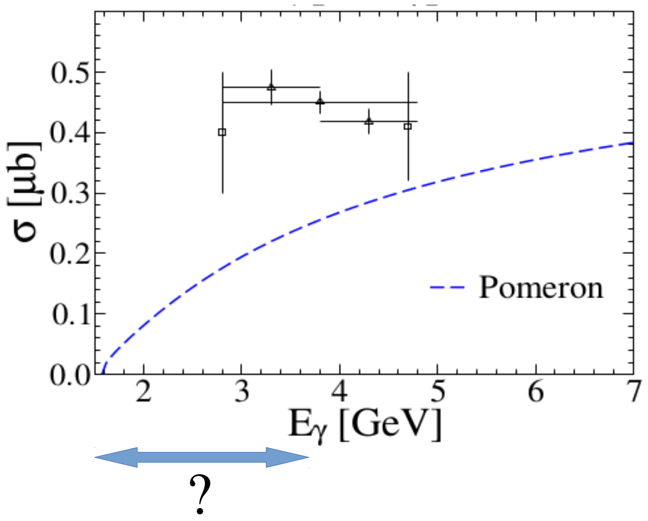


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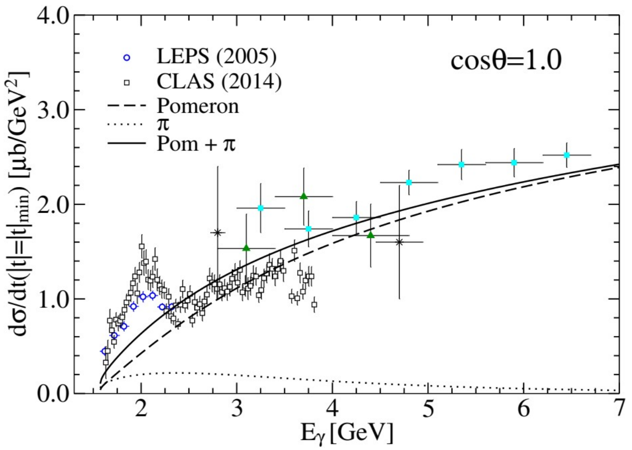


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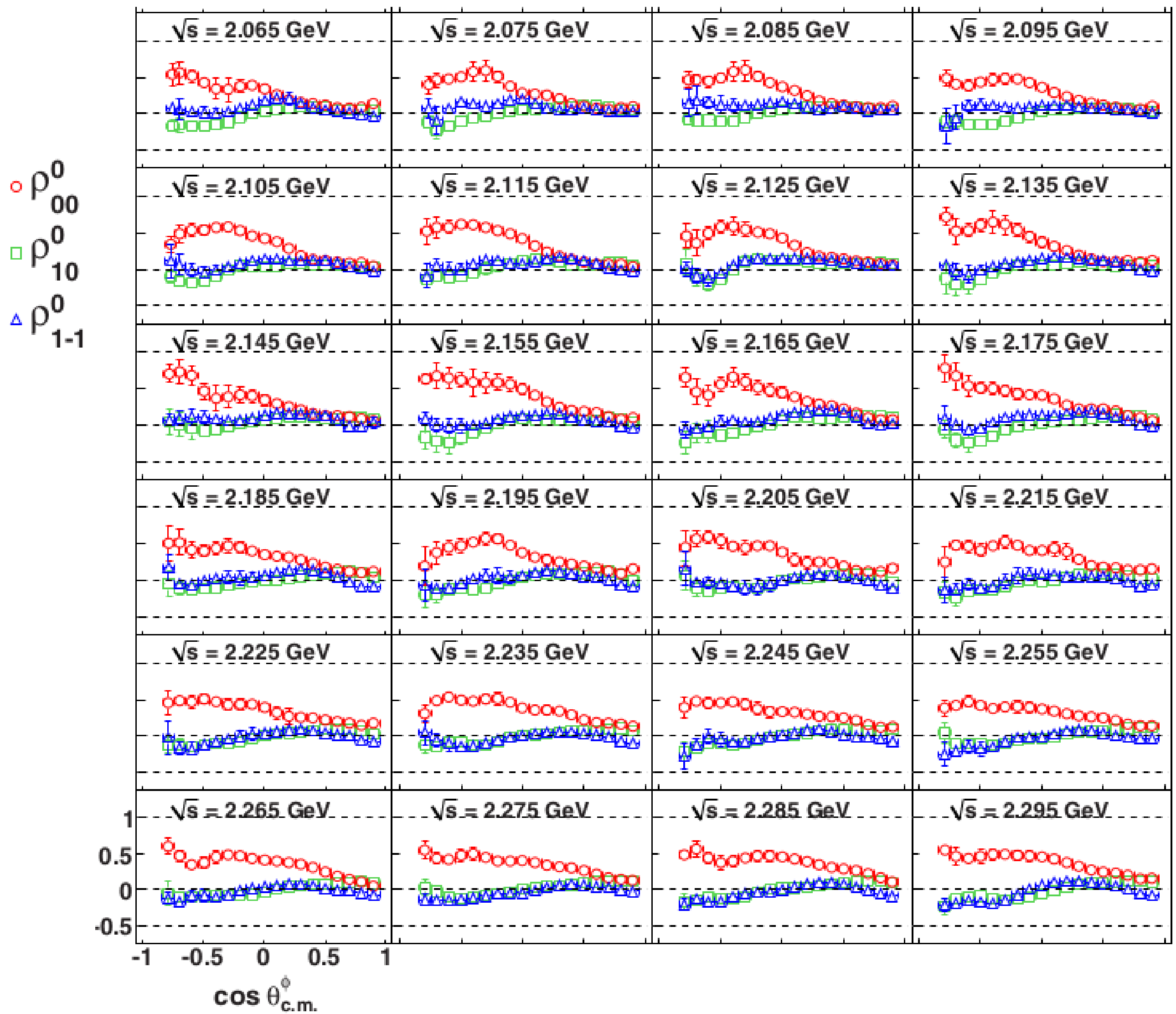
[Seraydaryan, PRC.89.055206] & [Dey, PRC.89.055208] (2014)



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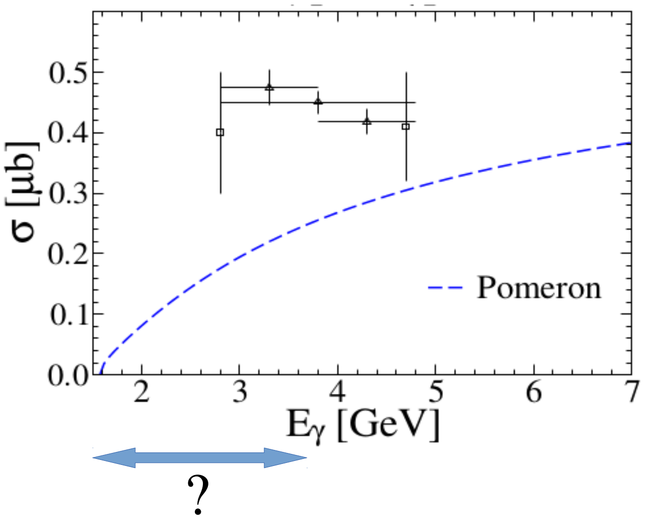


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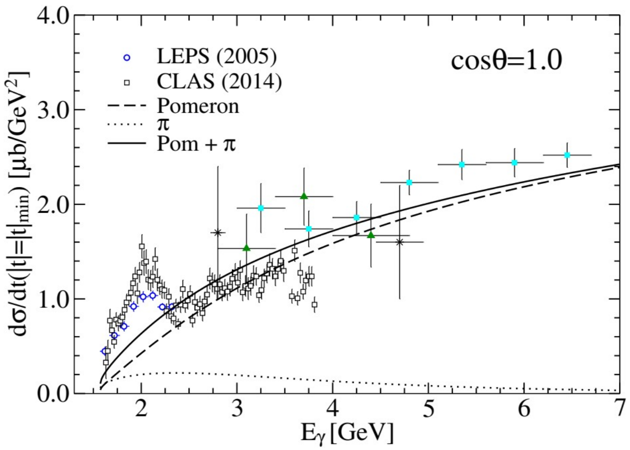


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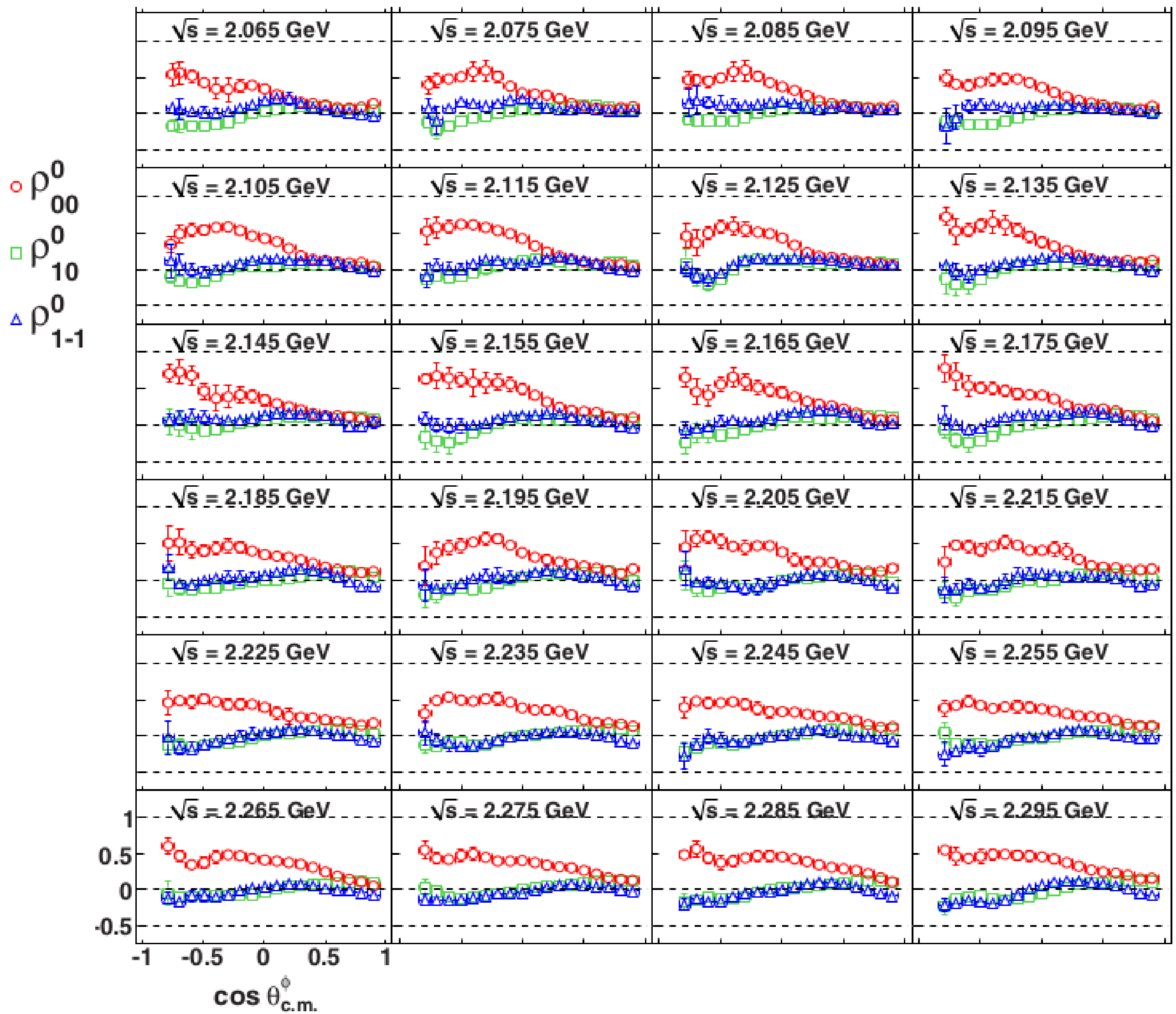
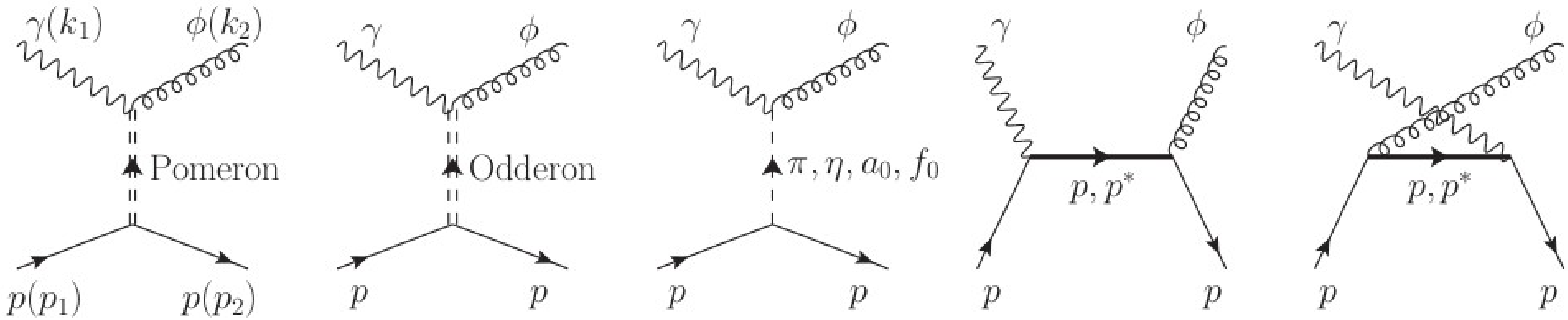



- We need a systematic analysis on φ photoproduction.

# 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($a_0$,$f_0$) + PDG N*

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

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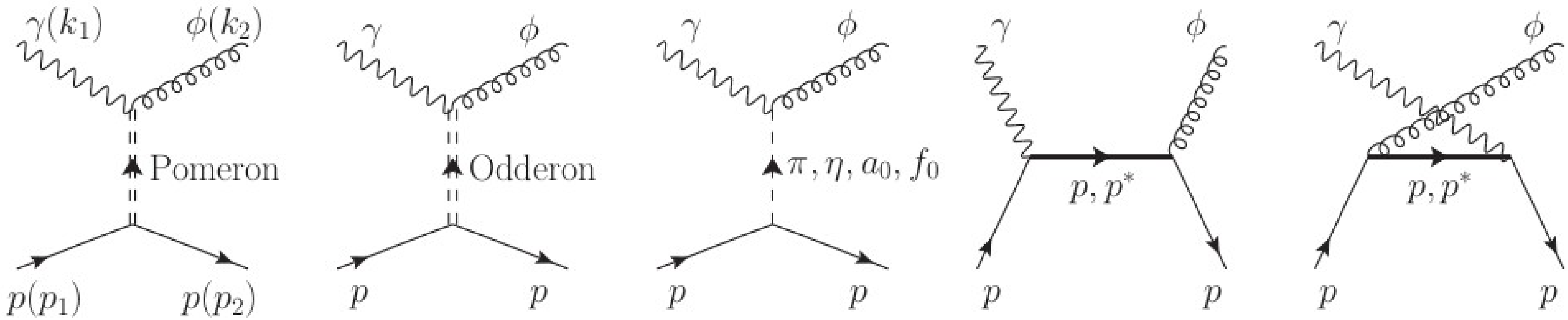


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- Effective Lagrangians

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

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

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

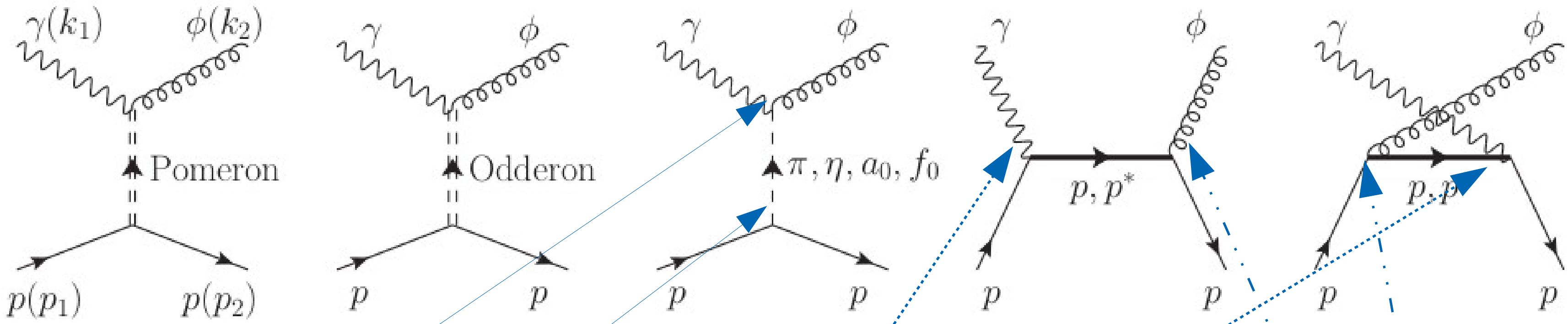
$$\mathcal{L}_{SNN} = -g_{SNN}\bar{N}NS,$$

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

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

# Pseusoscalar(π,η) & Scalar(a0,f0) mesons, Nucleon

• Feynman diagrams for γp → φ(1020)p

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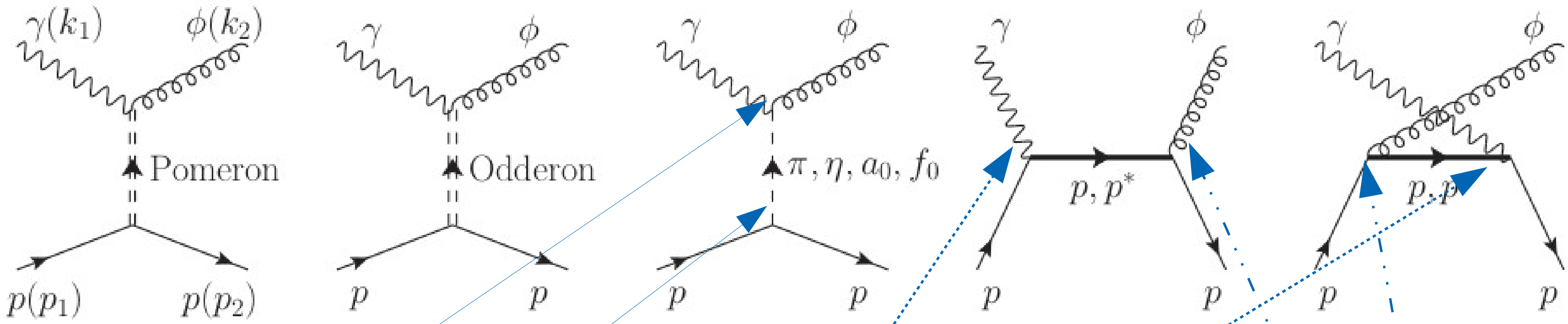
- Feynman diagrams for $\gamma p \to \varphi(1020)p$

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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

$$F_{\Phi,S}(t) = \frac{\Lambda^2_{\Phi,S} - M^2_{\Phi,S}}{\Lambda^2_{\Phi,S} - t}$$

N exchange

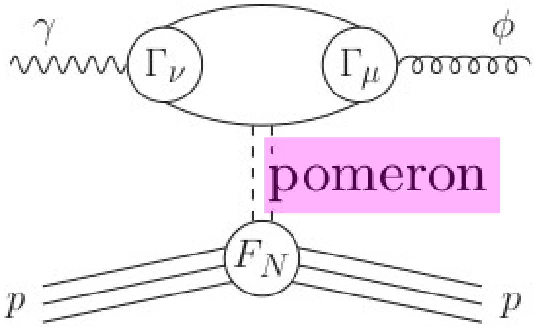
$$F_N(x) = \frac{\Lambda^4_N}{\Lambda^4_N + (x - M^2_N)^2}$$

N* exchange (Gaussian form)

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

# Pomeron & Odderon

We employ a Donnachie-Landshoff (DL) model.




- scattering amplitude:

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

- transition operator:

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

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

- 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$^2$] | $s_{\text{th}}$ [GeV$^2$] | $C_P$ | $a_N^2$ | $\mu_0^2$ | $t_0$ [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 | 〃 | 〃 |

- Pomeron & Odderon trajectories:

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

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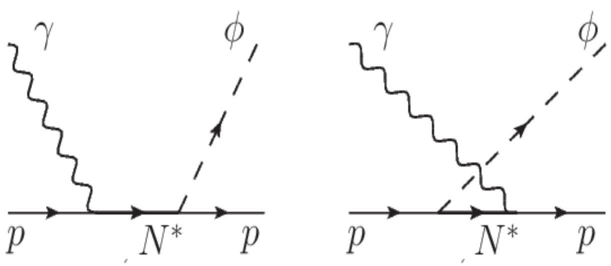
# Nucleon resonances

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




- Effective Lagrnagians

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

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

- $\Gamma_{N^*}$ = (200-300) MeV

PDG 2018

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

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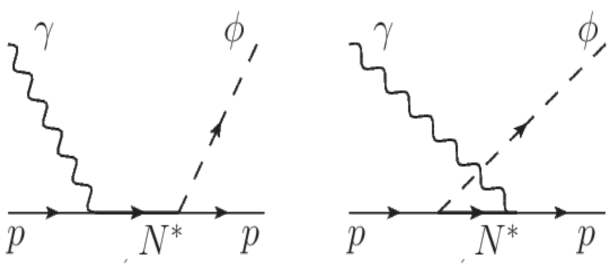


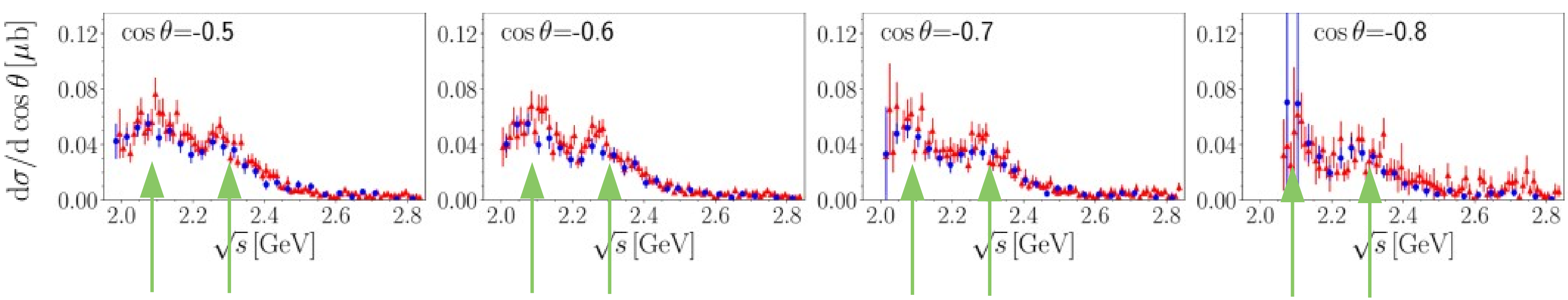

- Effective Lagrnagians

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

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

- $\Gamma_{N^*}$ = (200-300) MeV

1. Two bump structures are located near their pole positions, i.e. √s ≈ 2.1 & 2.3 GeV.
2. We expect only lower partial waves would be important.



# Numerical Results

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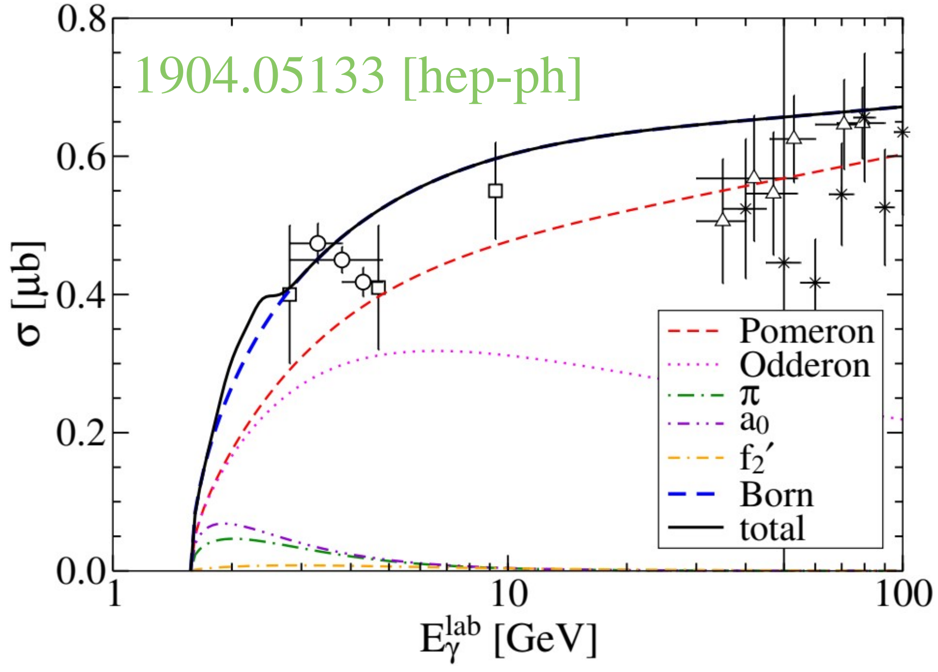
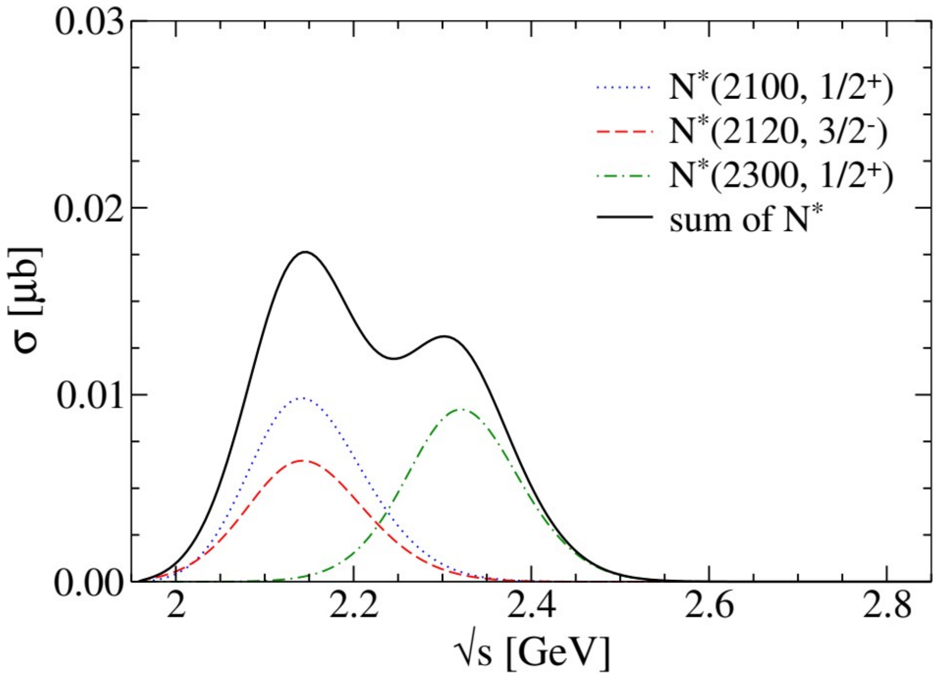
# Total cross section




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

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

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

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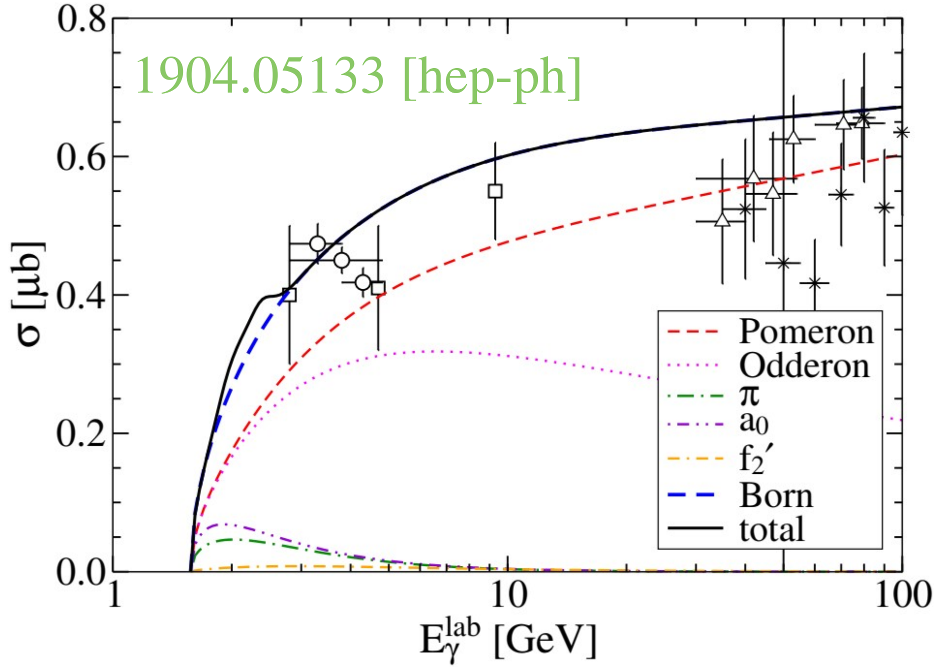
# Total cross section

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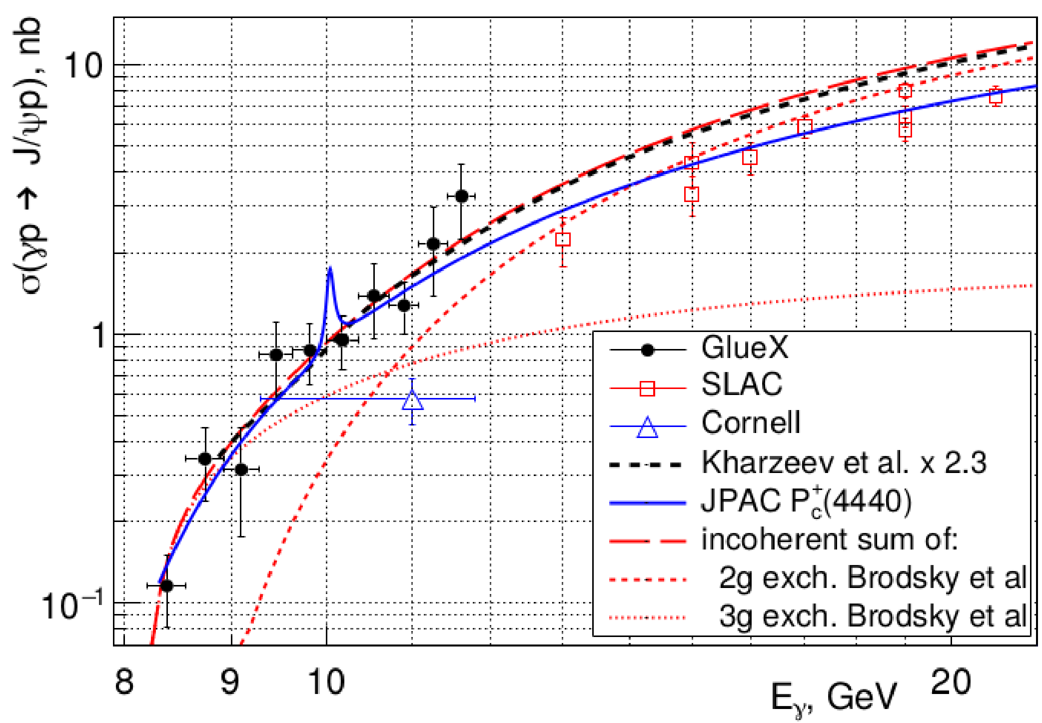
"First measurement of near-threshold J/ψ exclusive photoproduction off the proton" [GlueX Collaboration]
1905.10811 [nucl-ex]



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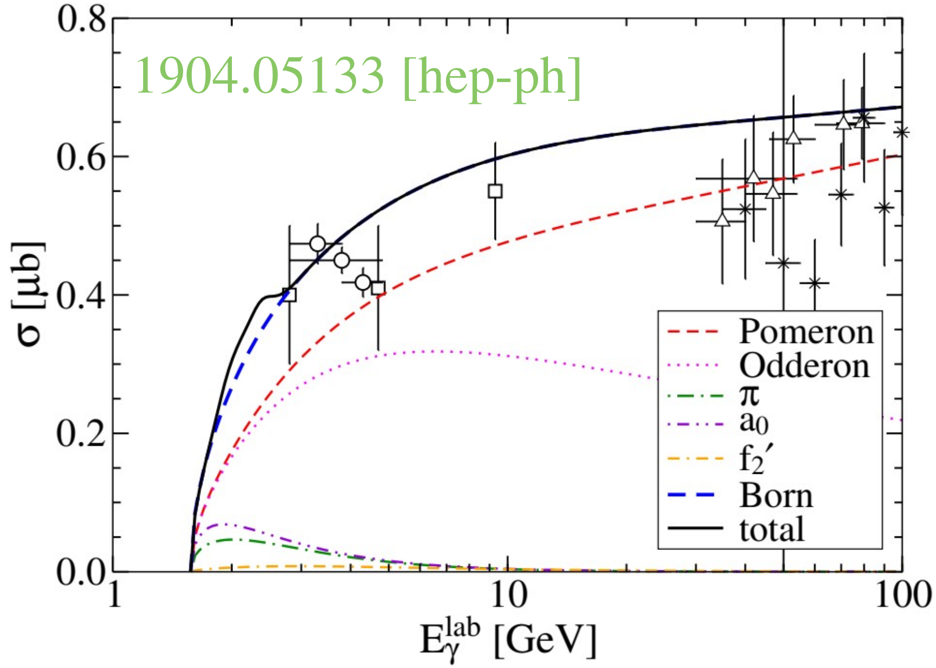


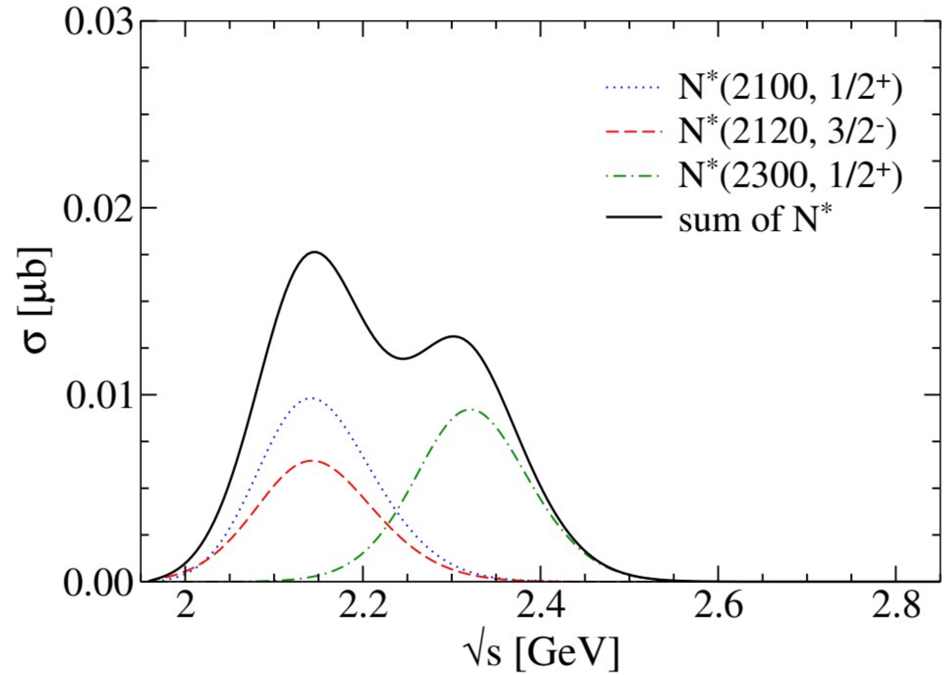


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- The total cross section is almost governed by Pomeron and Odderon exchanges.

- Other contributions are small to the total cross section but come into play significantly for the "differential cross sections" and "spin-density matrices".

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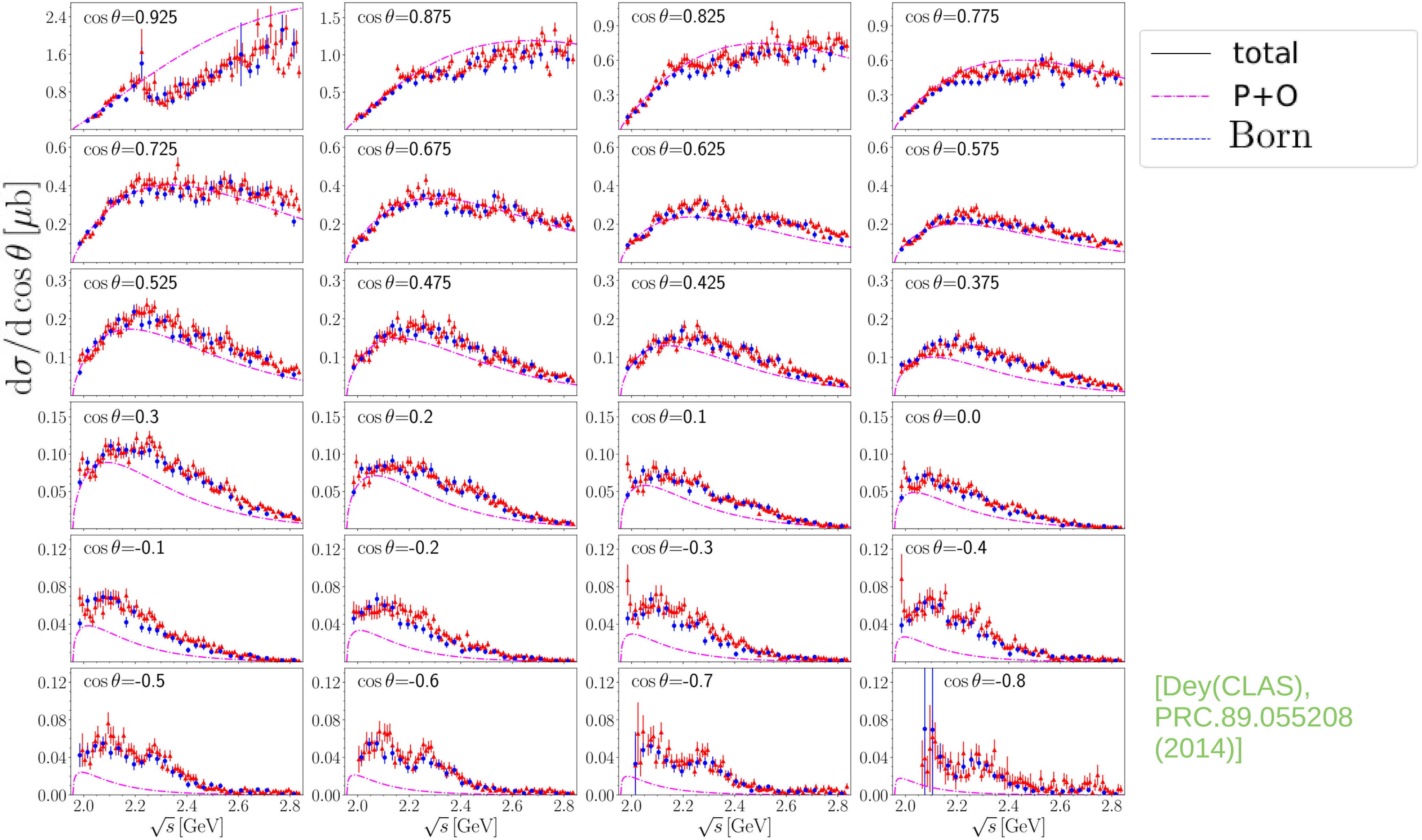
# Differential cross sections (1-1)




[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.

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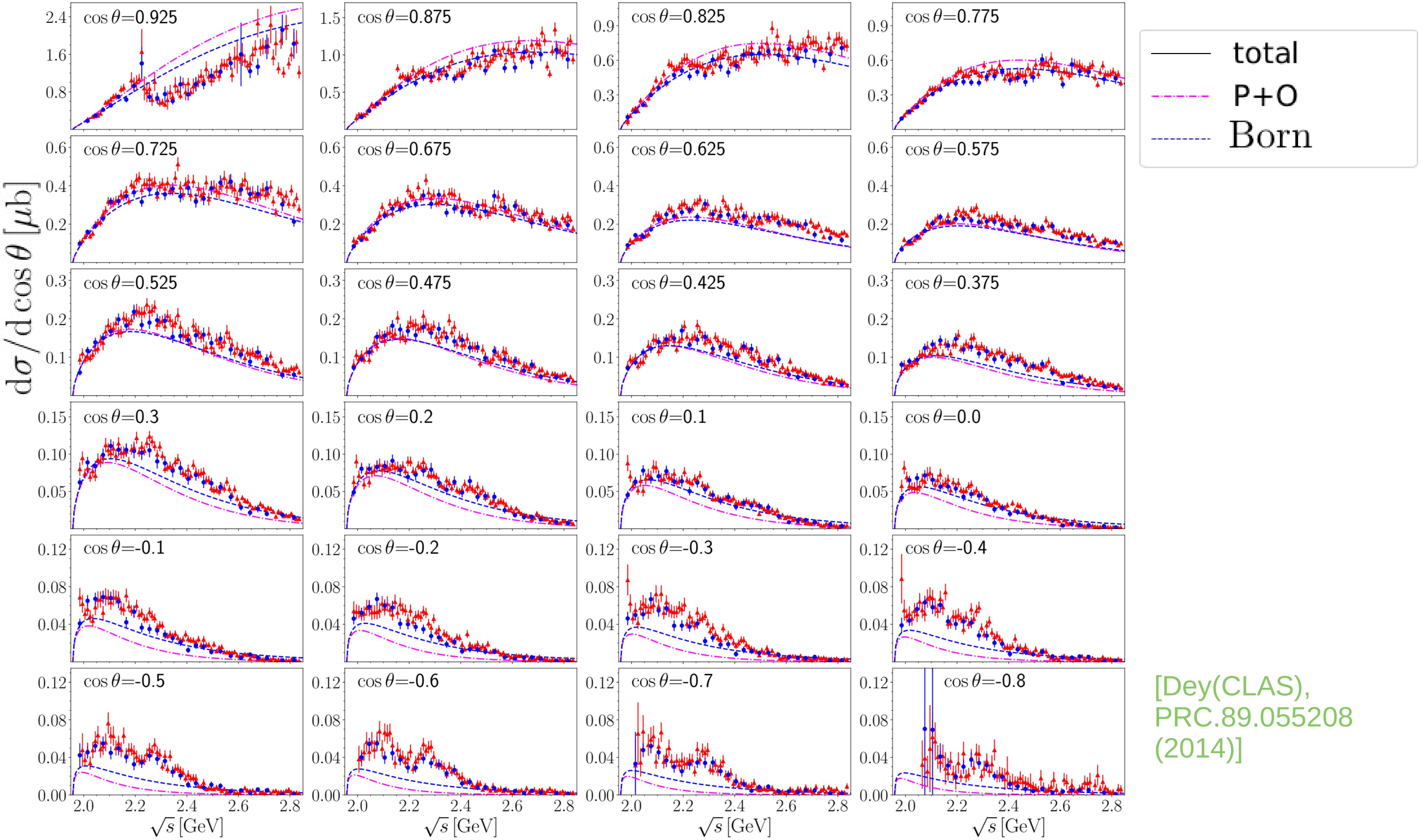
# Differential cross sections (1-2)




[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.

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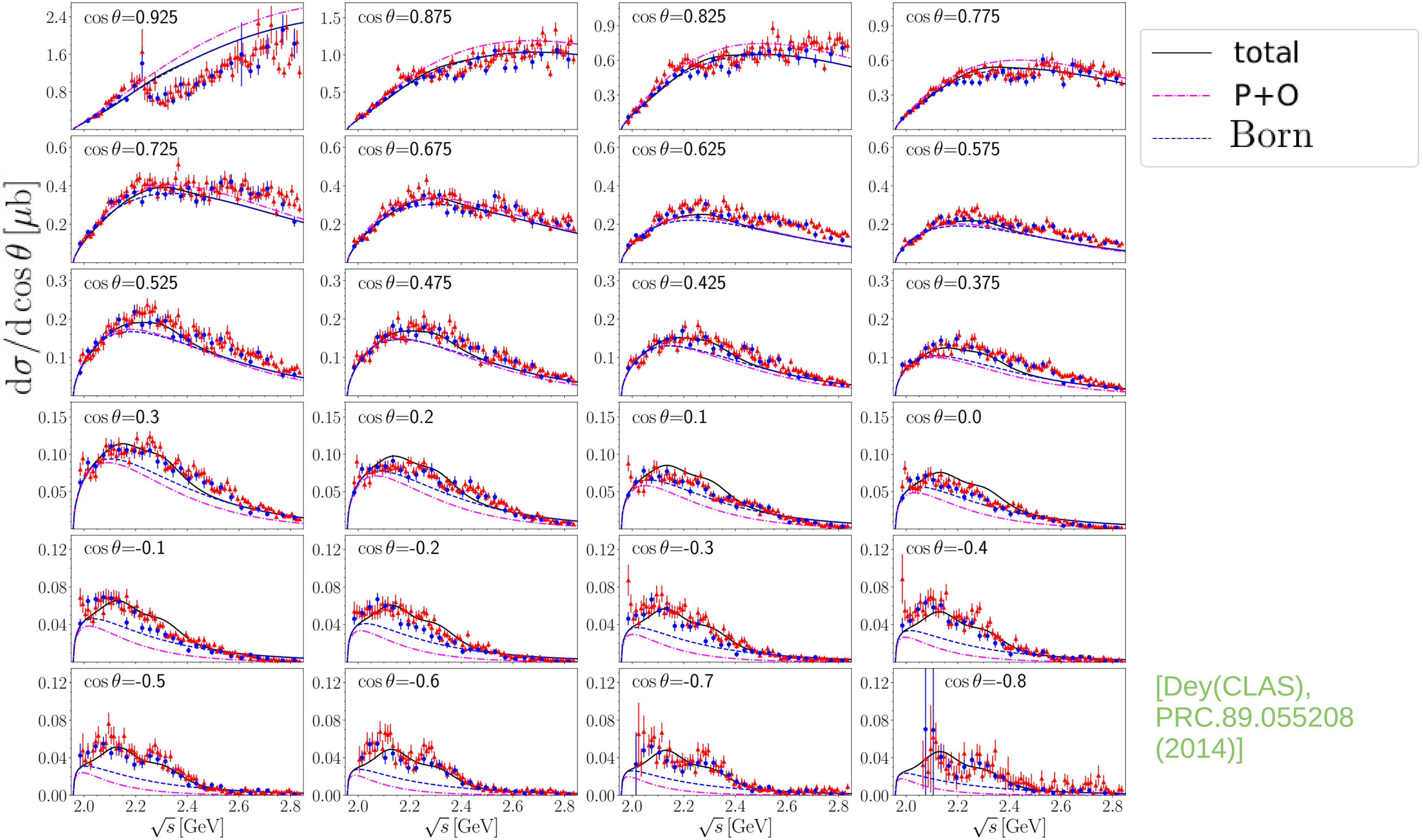
# Differential cross sections (1-3)

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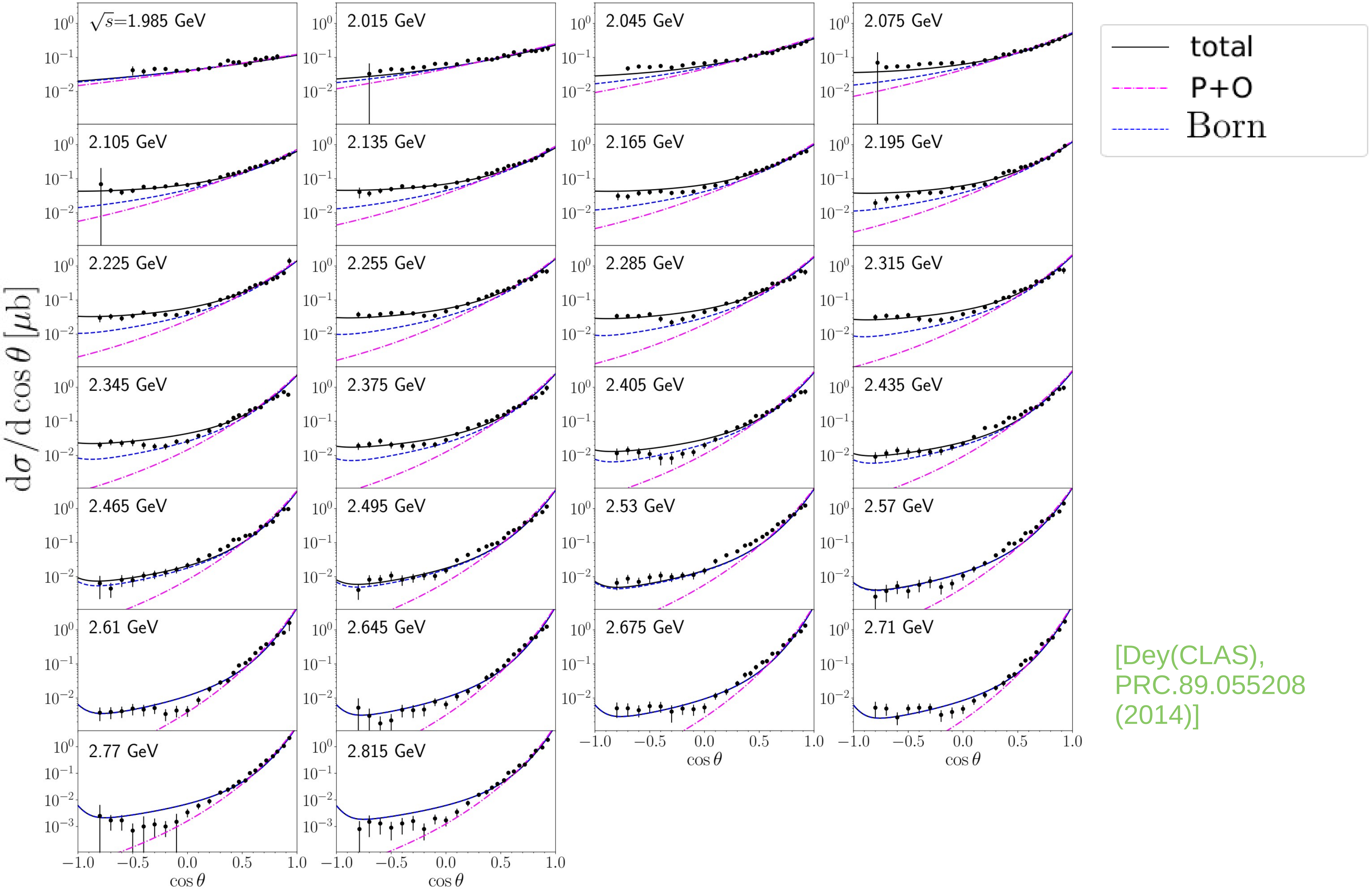
# Differential cross sections (2)




[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

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

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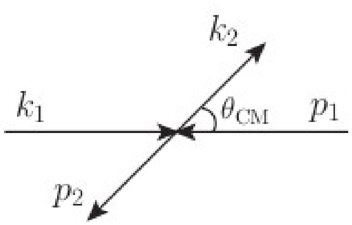
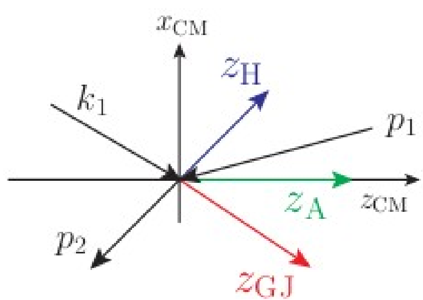



- center of mass frame



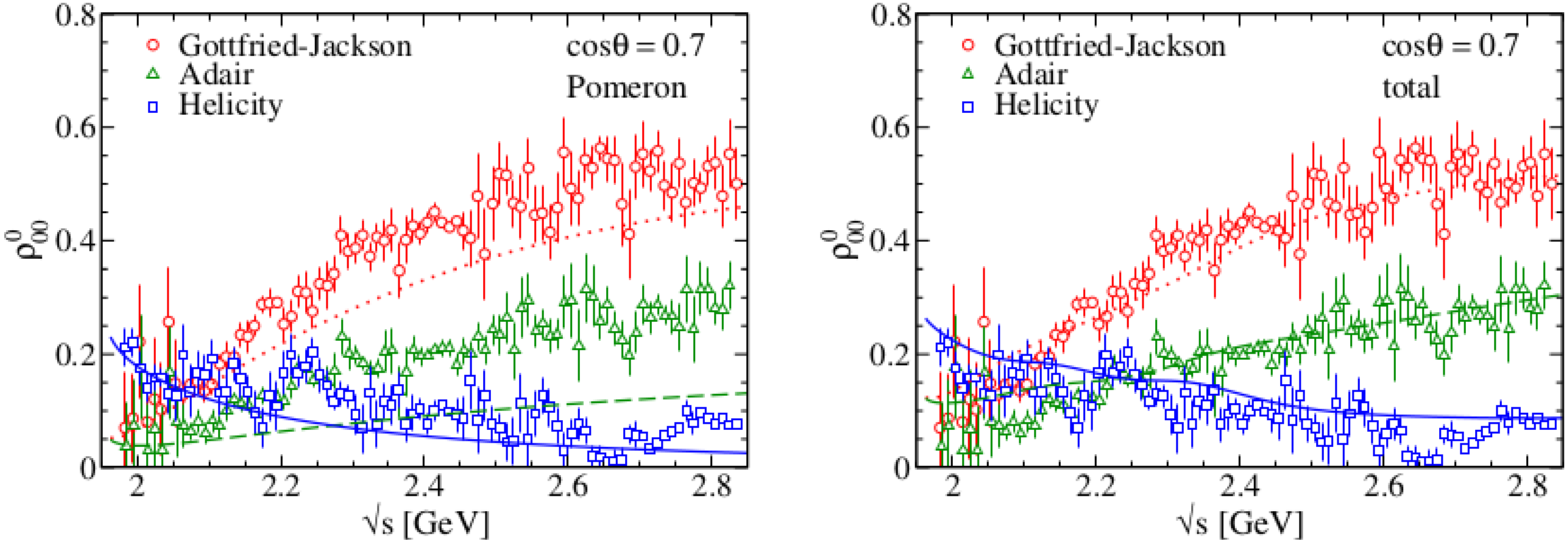

- φ-meson rest frame

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).

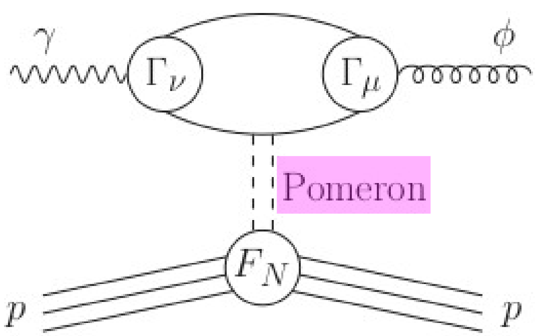
# Spin-density matrix elements (1)




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

- $\rho^0_{00}$ 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($a_0$,$f_0$)-mesons is essential to improve the results.

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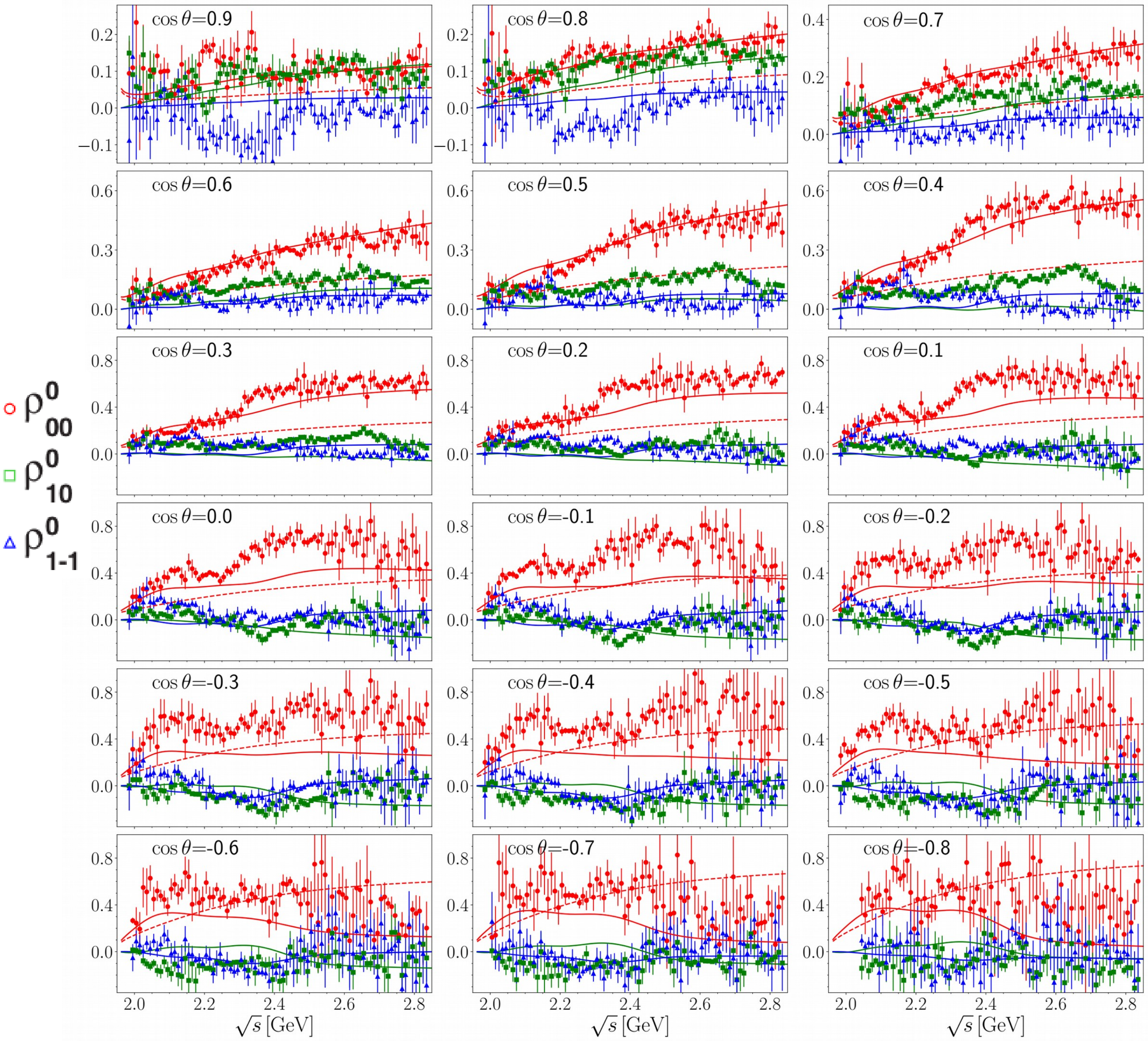
# Spin-density matrix elements (2)



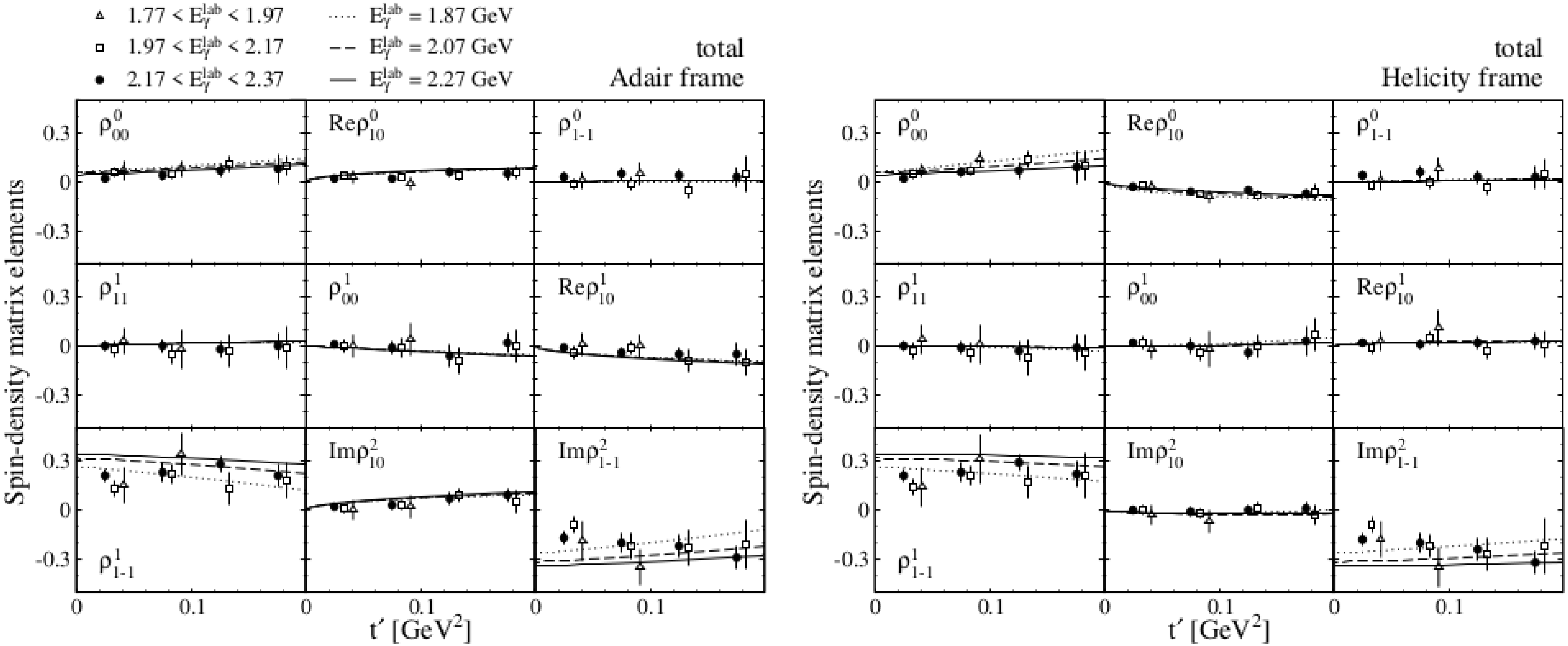

[Adair frame]

- forward angle: Pomeron alone is not enough.
- S(a0,f0)- mesons improves the results.

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

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

# Spin-density matrix elements (3-1)

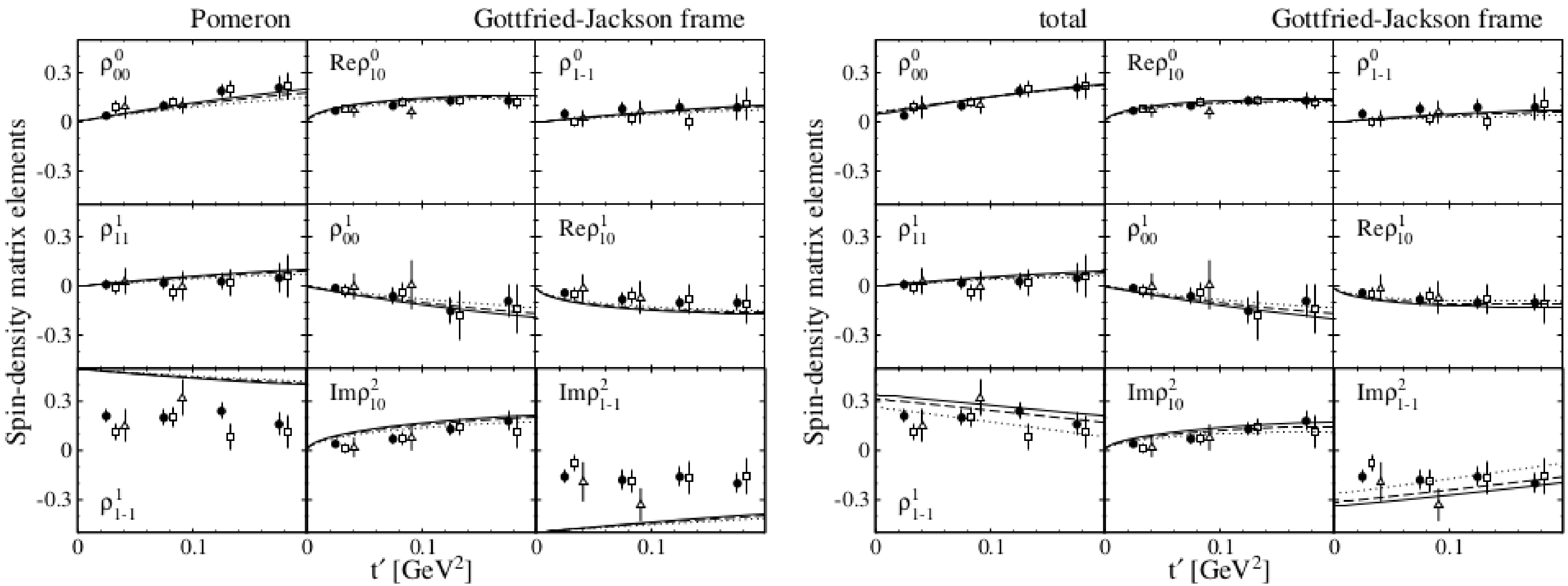



- Pomeron exchange:

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

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

# Spin-density matrix elements (3-2)




- Pomeron exchange:

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

- GJ frame is useful to test TCHC.
- Relative strength of N & U parity exchange processes:

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

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

# Summary

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◇ φ photoproduction, $\gamma p \rightarrow \varphi(1020)p$, 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 ⇨ 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

Sangho Kim
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# 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 ($\sigma, a_0, f_0$).

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

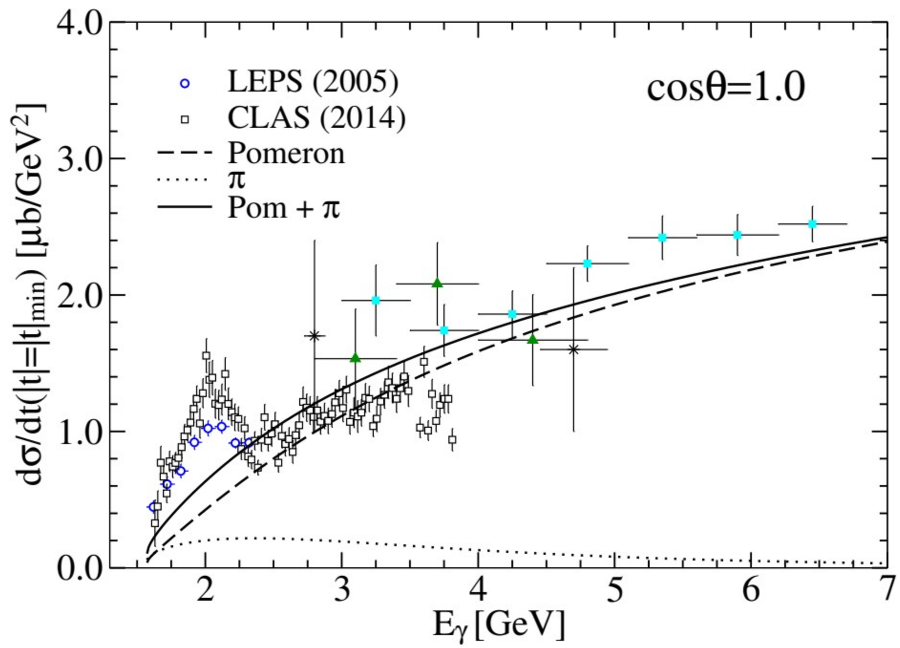
: $f_2(1270)$ meson, two gluon exchange.

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

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

∴ Pomeron & pseudoscalar mesons ($\pi^0$,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 + $(\pi,\eta)$ 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 ($M=2.250$, $\Gamma=0.100$ [GeV]).

**b.** Kiswandhi, Xie, Yang, PLB, 691, 214 (**2010**)
: Assume a $N^*$ resonance of $J^P=3/2^-$ ($M=2.10\pm0.03$, $\Gamma=0.465\pm0.141$ [GeV]).

**c.** Kiswandhi, Yang, PRC, 86, 015203 (**2012**)
: $N^*$ of $J^P=3/2^\pm$ ($M=2.08\pm0.04$, $\Gamma=0.501\pm0.117$(P=+), $0.570\pm0.159$(P=-) [GeV]).

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

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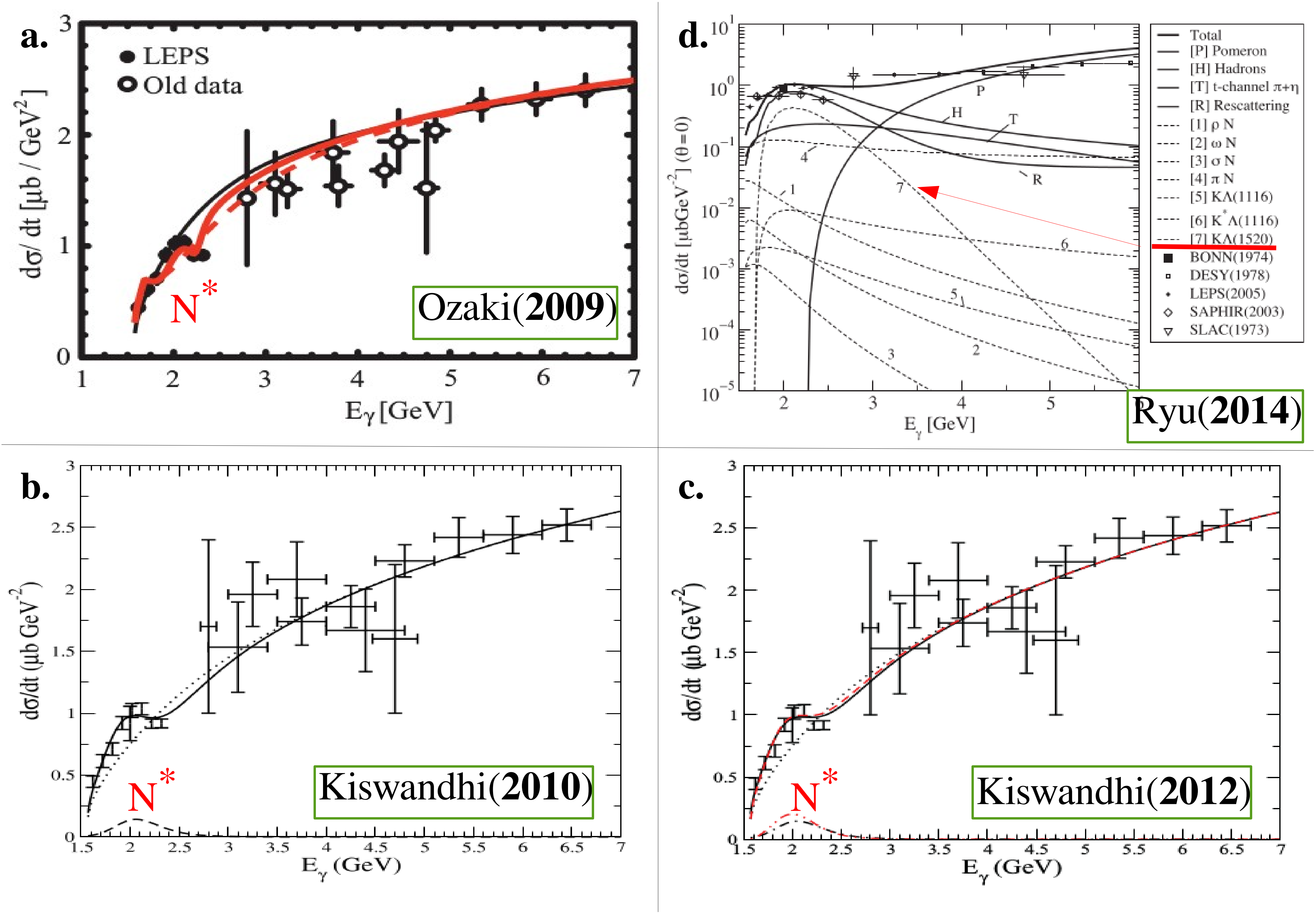
# Previous theoretical works



# Previous theoretical works