Reanalysis of the reaction $\gamma p \to \phi(1020)p$ with the recent CLAS data

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In collaboration with
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O u t l i n e

Investigation of strange sector

Extension (Prediction) to charm sector

PRODUCTION of HADRONS

$$\pi^- p \rightarrow K^{*0}\Lambda$$
$$\pi^- p \rightarrow K^{*0}\Sigma^0$$
$$\pi^- p \rightarrow K^{*+}\Sigma^-$$

$$\pi^- p \rightarrow K^0\Lambda$$
$$\pi^- p \rightarrow K^0\Sigma^0$$
$$\pi^- p \rightarrow K^+\Sigma^-$$

$$\gamma p \rightarrow K^{*+}\Lambda$$
$$\gamma p \rightarrow K^{*+}\Sigma^0$$
$$\gamma p \rightarrow K^{*0}\Sigma^+$$

$$\gamma p \rightarrow K^+\Lambda$$
$$\gamma p \rightarrow K^+\Sigma^0$$
$$\gamma p \rightarrow K^0\Sigma^+$$

$$\pi^- p \rightarrow \phi n$$
$$\gamma p \rightarrow \phi p$$

Outline

PRODUCTION of HADRONS

Investigation of strange sector		Extension (Prediction) to charm sector
$\pi^- p \to K^{*0}\Lambda$		$\pi^- p \to D^{*-}\Lambda_c^+$
$\pi^- p \to K^{*0}\Sigma^0$		$\pi^- p \to D^{*-}\Sigma_c^+$
$\pi^- p \to K^{*+}\Sigma^-$		$\pi^- p \to \bar{D}^{*0}\Sigma_c^0$
$\pi^- p \to K^0\Lambda$		$\pi^- p \to D^-\Lambda_c^+$
$\pi^- p \to K^0\Sigma^0$		$\pi^- p \to D^-\Sigma_c^+$
$\pi^- p \to K^+\Sigma^-$		$\pi^- p \to \bar{D}^0\Sigma_c^0$
	s $\Rightarrow$ c	
$\gamma p \to K^{*+}\Lambda$		$\gamma p \to \bar{D}^{*0}\Lambda_c^+$
$\gamma p \to K^{*+}\Sigma^0$		$\gamma p \to \bar{D}^{*0}\Sigma_c^+$
$\gamma p \to K^{*0}\Sigma^+$		$\gamma p \to D^{*-}\Sigma_c^{++}$
$\gamma p \to K^+\Lambda$		$\gamma p \to \bar{D}^0\Lambda_c^+$
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$\pi^- p \to \phi n$		$\pi^- p \to J/\Psi n$
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s → c

PRODUCTION of HADRONS

→ (O) PRD92.094021(2015) with J-PARC collaborators

→ (O) Drafting

→ (O) Only strange sector (N* physics)

→ (Δ) Preliminary (strange sector) with LEPS collaborators

Pc(4380), Pc(4450) ?

→ PRD93.034009(2016), IHEP

→ PRD92.034022(2015), Julich

O u t l i n e

Investigation of strange sector	Extension (Prediction) to charm sector	PRODUCTION of HADRONS
$\pi^- p \rightarrow K^{*0}\Lambda$	$\pi^- p \rightarrow D^{*-}\Lambda_c^+$	(O) PRD92.094021(2015) with J-PARC collaborators
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$\pi^- p \rightarrow \phi n$	$\pi^- p \rightarrow J/\Psi n$	PRD93.034009(2016), IHEP
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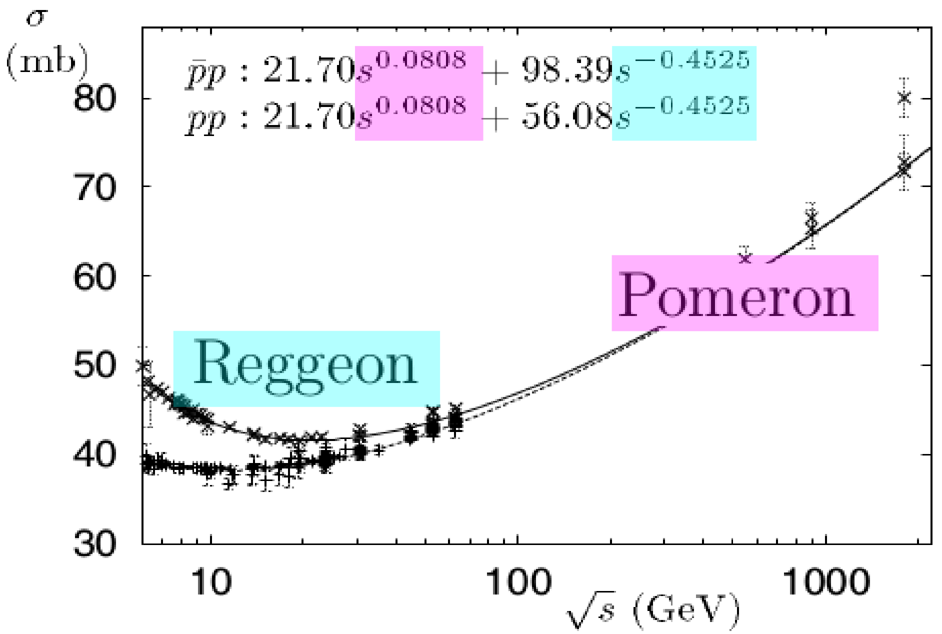
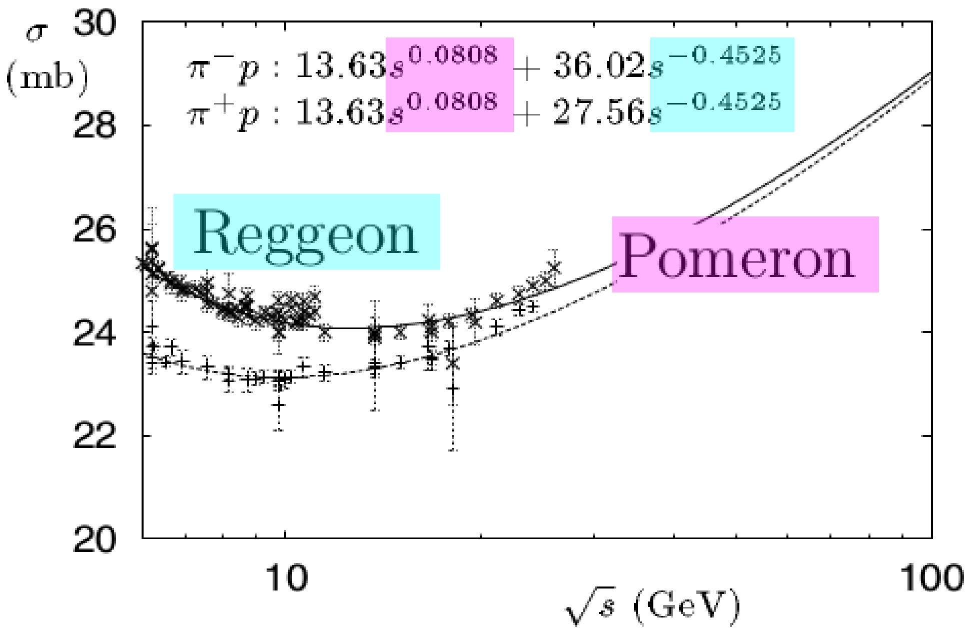
Contents

$$\boxed{\gamma p \to \phi p}$$

- ◈ Background
- ◈ Previous analyses
- ◈ Problems of current theoretical works
- ◈ Results : · total cross sections (σ)
  · differential cross sections ($d\sigma/d\Omega$, $d\sigma/dt$)
- ◈ Summary



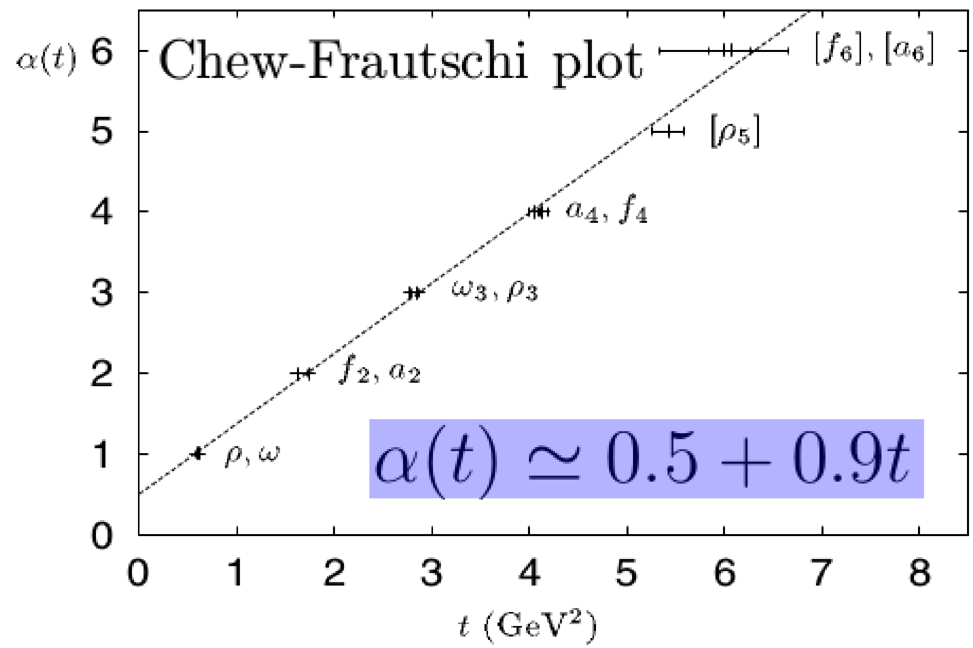


Donnachie, Pomeron Physics and QCD (2002)

Reggeon (Meson exchange)

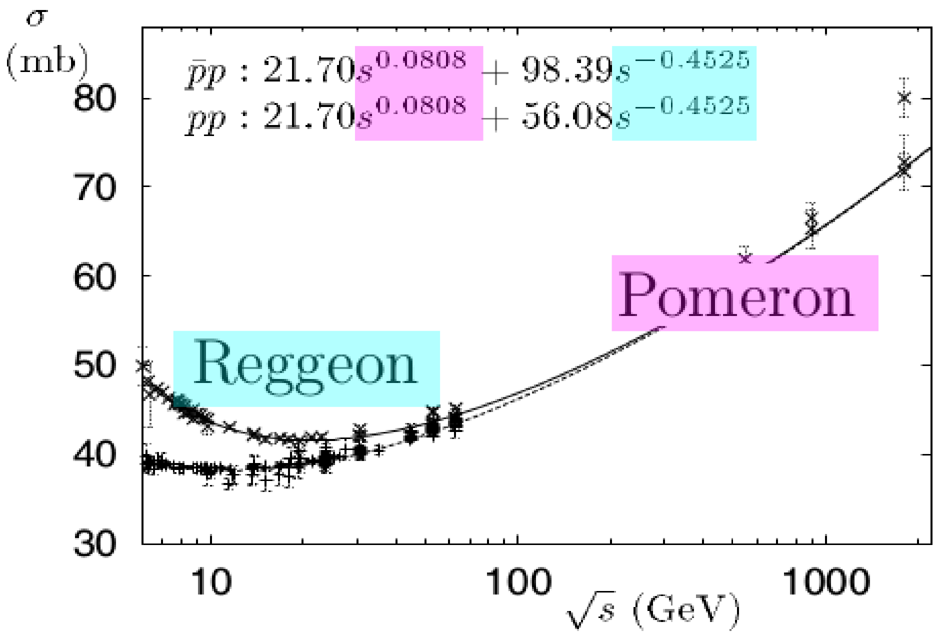
- Describes an exchange of a family of ordinary mesons.
- Governs relatively low energy regions.

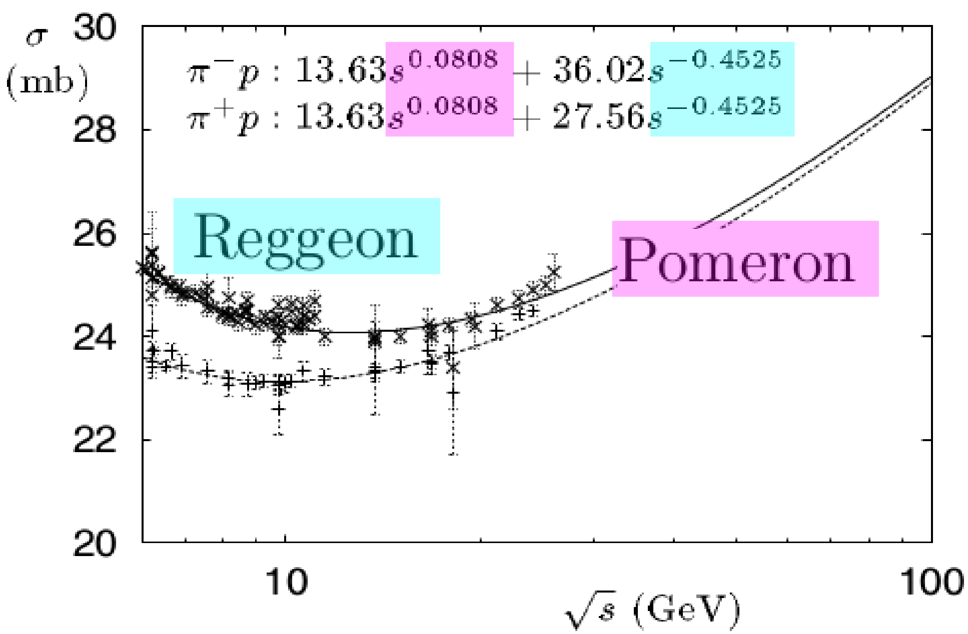
- (ρ,ω) trajectories (C=-1,natural parity) & (f_2,a_2) trajectories (C=+1,natural parity) are all degenerate.



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

Soft hadronic processes





Donnachie, Pomeron Physics and QCD (2002)

Pomeron

- Is not associated with the meson traj.s.
- Has the q.n.s of the vacuum, I=0 and C=+1.
- Governs relatively high energy regions.

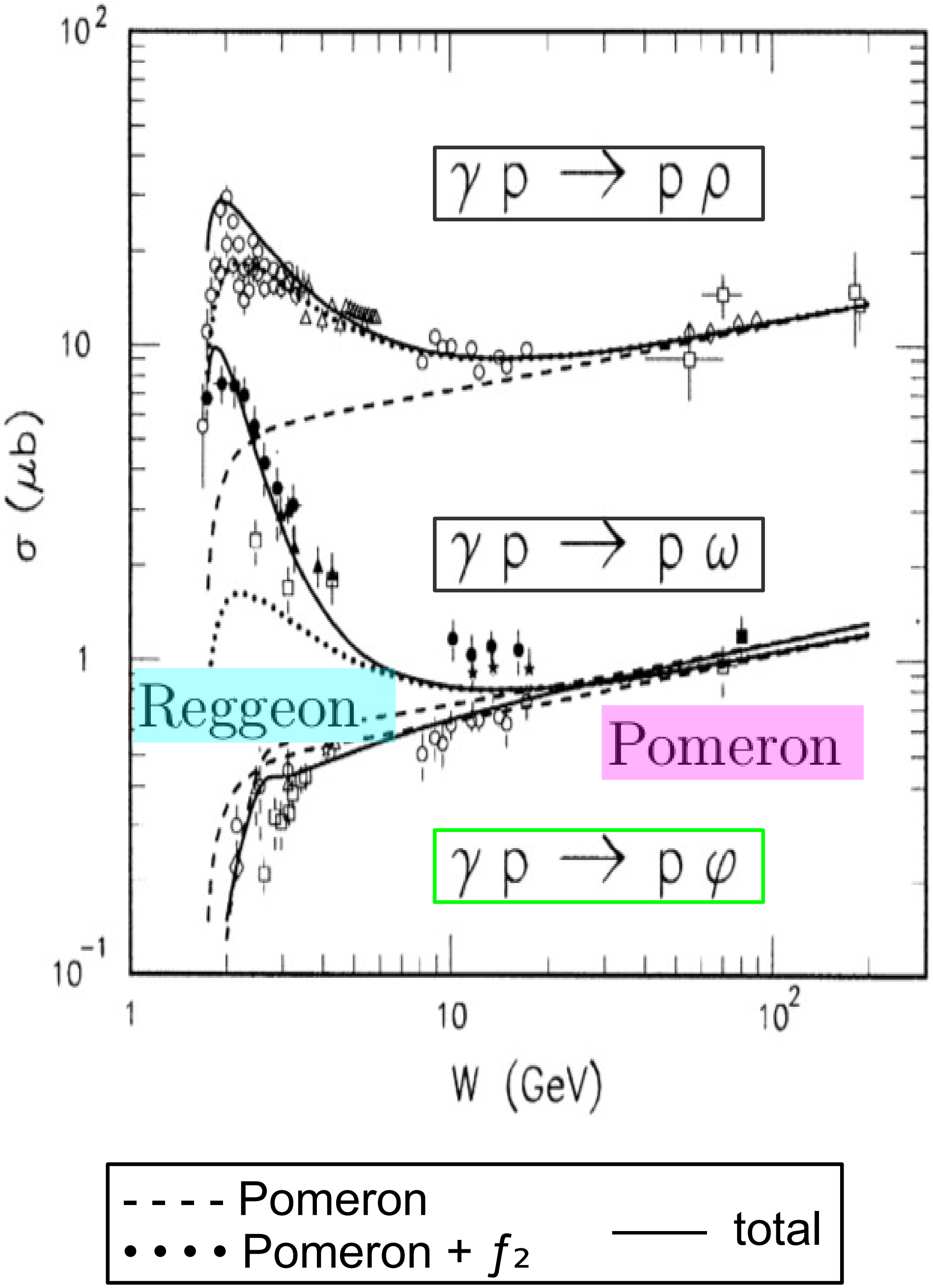
- There is no deep theory reason for the Pomeron hypothesis, but the phenomenology based on which turns out to be very successful.

- Assuming the trajectory:

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

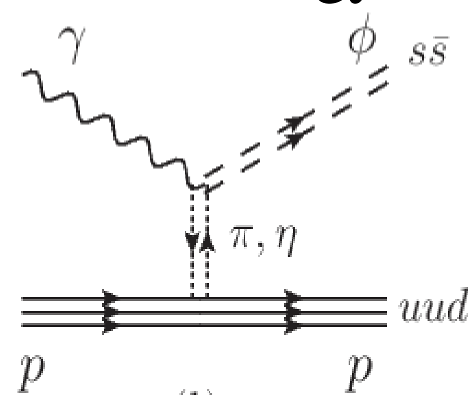
$$\sigma \propto s^{\alpha(0)-1} = s^{0.08}$$

Elastic photoproduction of vector mesons



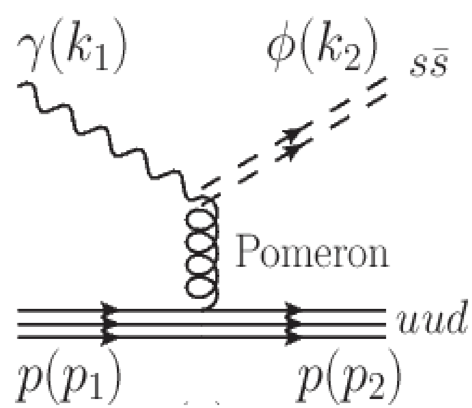
Laget, PLB.489.313(2000)

Low energy



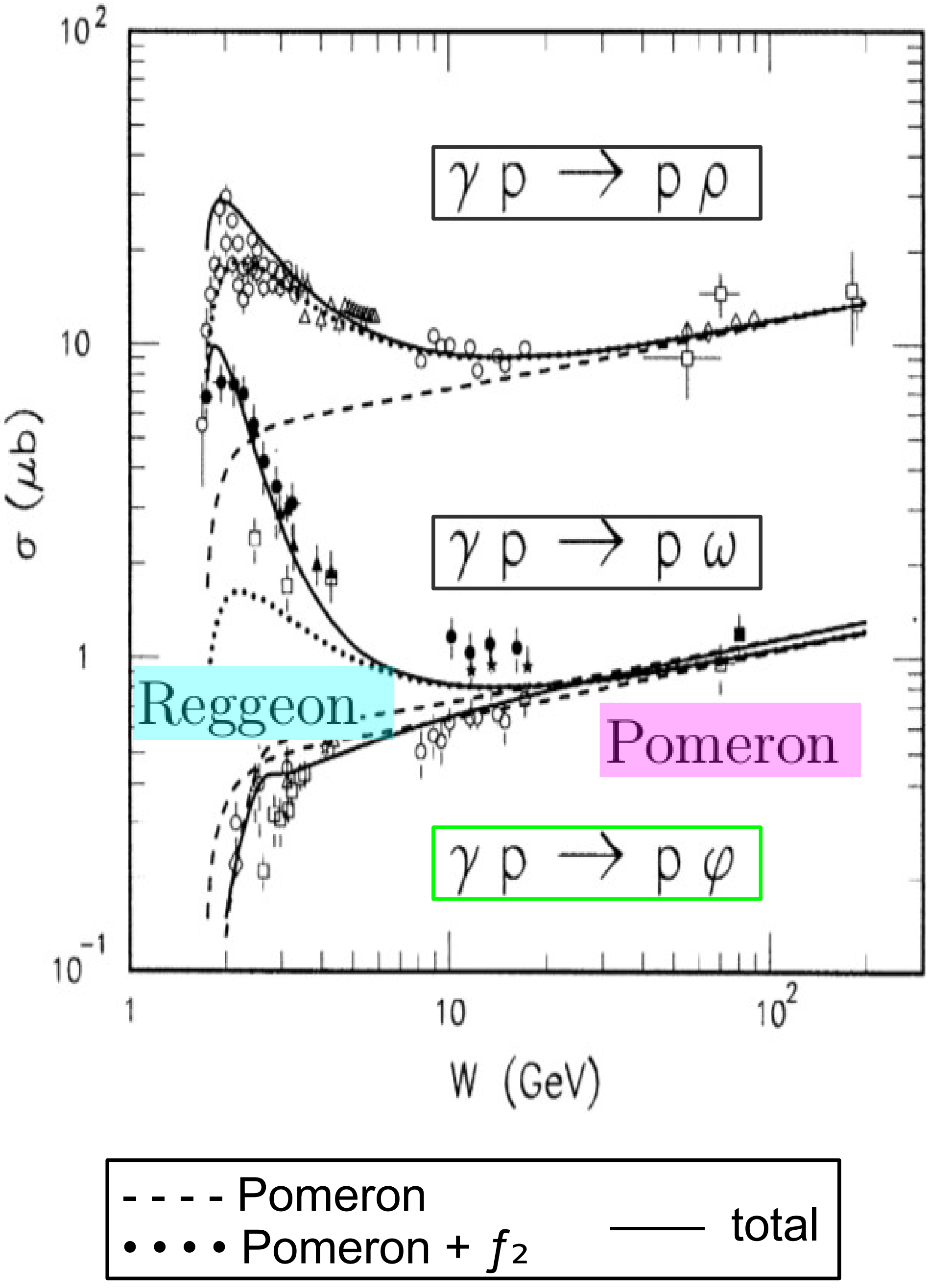
- The dynamics of Reggeon is related to non-perturabtive QCD in q-q sector.
- Unnatural parity (-1).
- OZI suppressed.

High energy



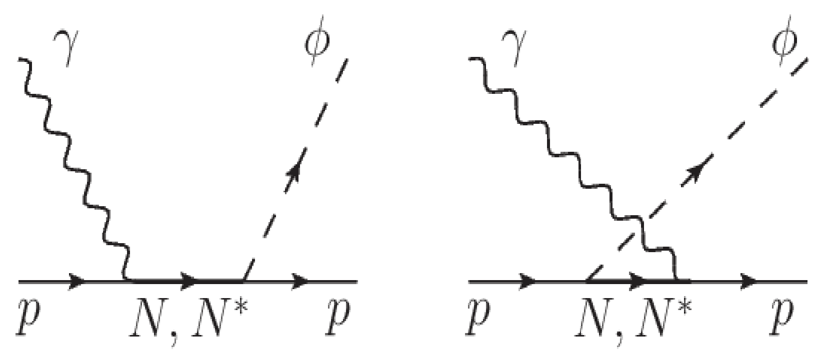
- Pomeron is the result of non-perturbative QCD interaction in gluon sector.
- Natural parity (+1).

Elastic photoproduction of vector mesons

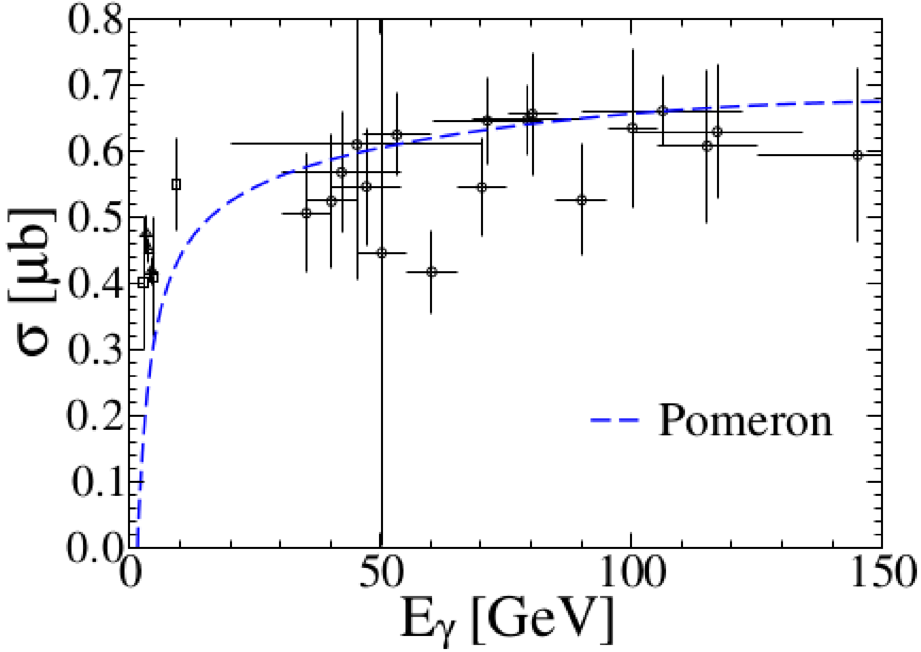


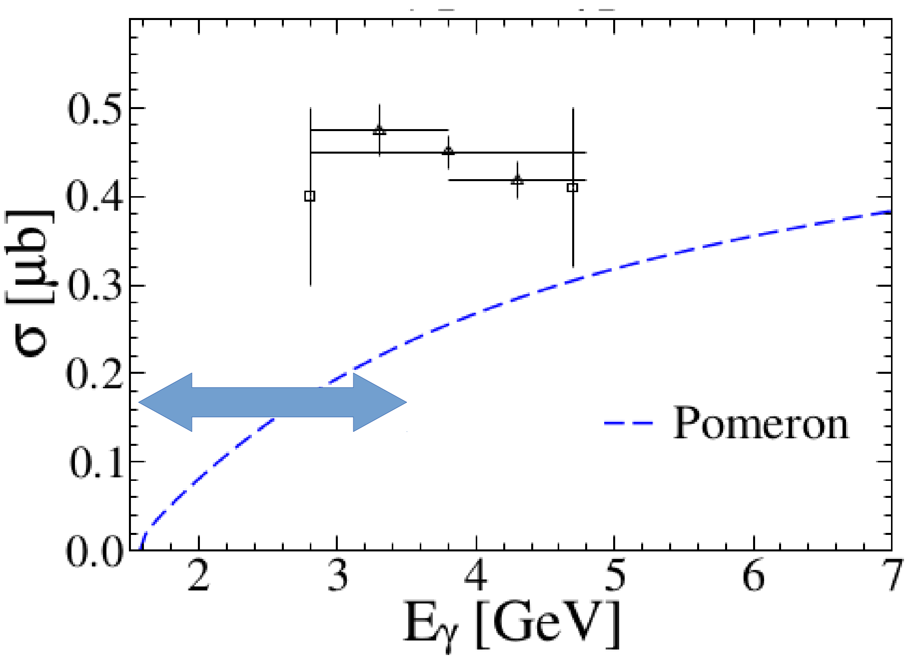
Laget, PLB.489.313(2000)

- General vector meson exchanges (ρ,ω) [$J^{PC}(1^{--})$] are not allowed due to their negative charge conjugations (C=-1).
- Vector mesons with exotic q.n. [$J^{PC}(1^{-+})$] are possible but they, possibly hybrid exotic mesons, are not much known experimentally.
- s- and u- channel exchanges



$$\boxed{\gamma p \to \phi(1020) p}$$





- Meson photoproduction has been a very useful experimental tool to investigate QCD as a hadronic degrees of freedom.
- Abundant exp.al data are reported recently at CLAS in low energy regions (E_γ = 1.6~3.6 GeV).
  [Seraydaryan, PRC.89.055206 (2014)] & [Dey, PRC.89.055208 (2014)].
- Pomeron alone is not sufficient to describe low energy regions.
- Our goal is to reanalyze them theoretically.

Previous theoretical works for the $\gamma p \to \phi(1020)p$

- 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.

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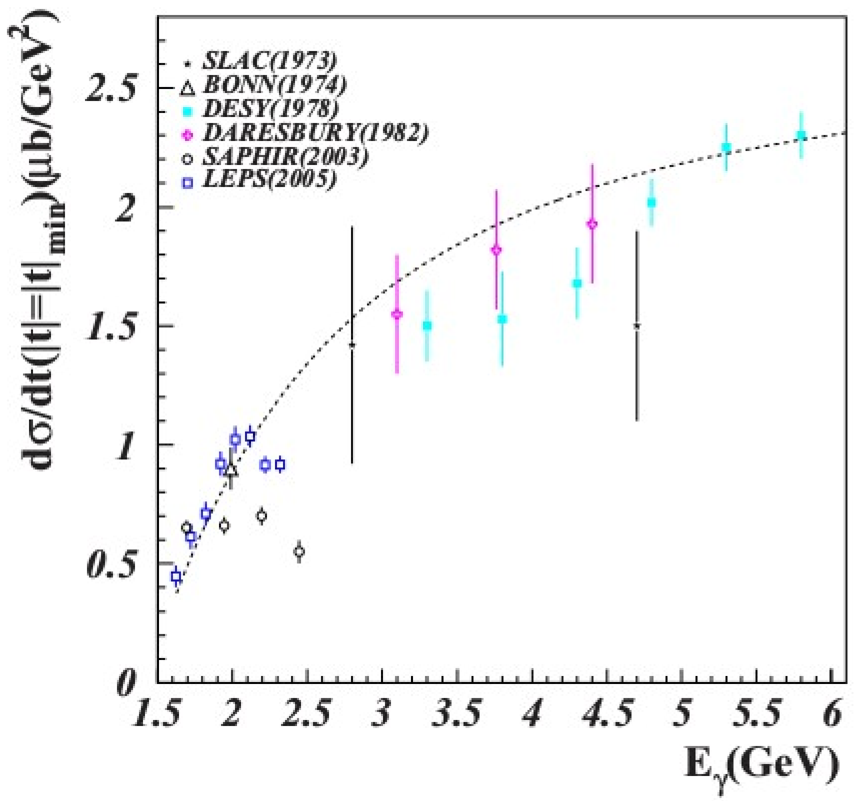

Mibe(LEPS)PRL.95.182001(**2005**)

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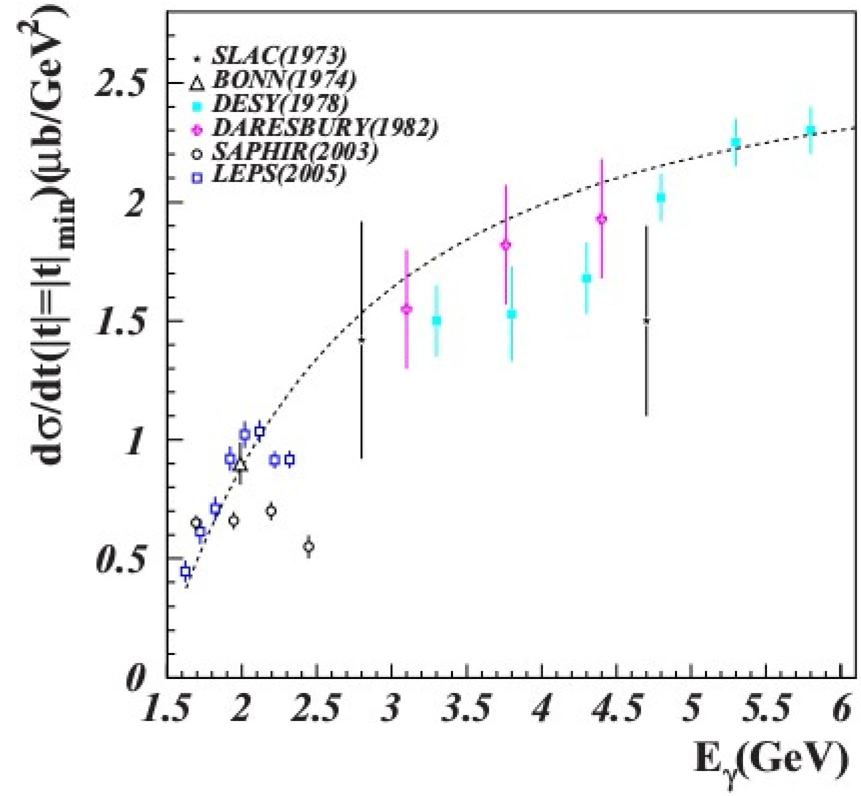


Mibe(LEPS)PRL.95.182001(**2005**)

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

- Titov, Kampfer, PRC,76, 035202 (**2007**)

: Pomeron + (π^0,η) mesons.

- 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]).

- 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]).

- Kiswandhi, Yang, PRC, 86, 015203 (**2012**)

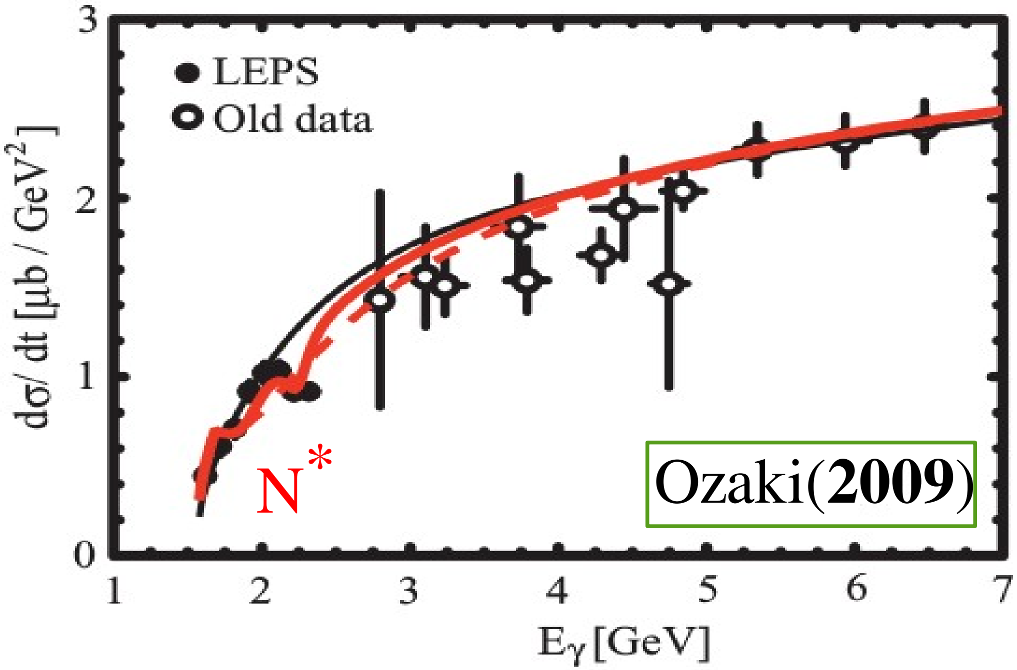
: N^* of J^P=3/2$^\pm$ (M=2.08±0.04, Γ=0.501±0.117(P=+), 0.570±0.159(P=-) [GeV]).

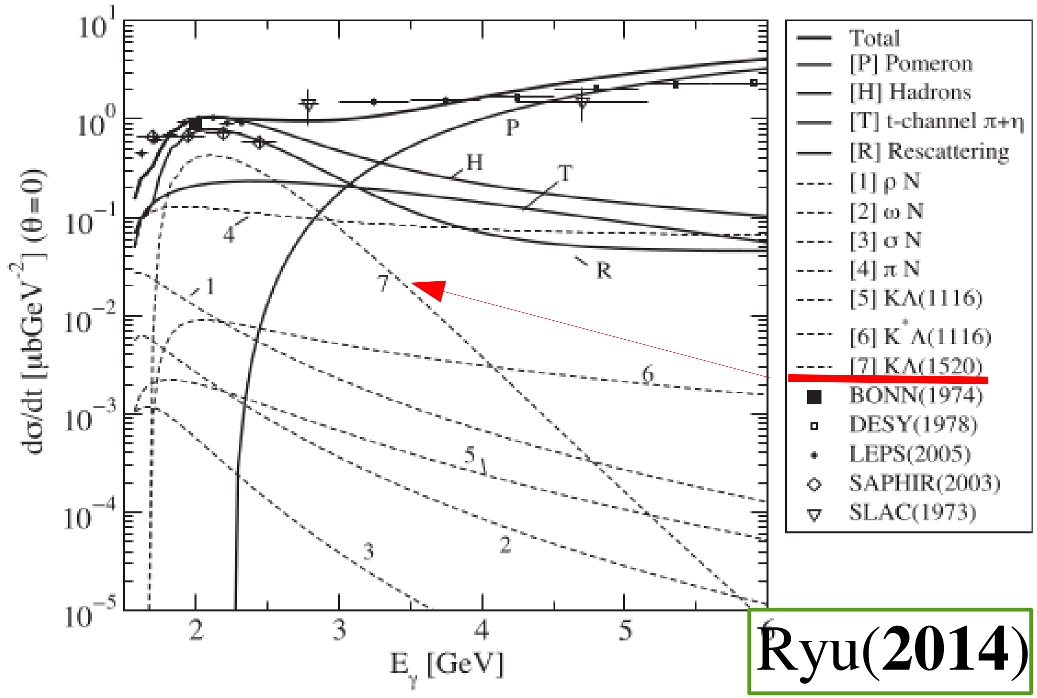
- Ryu, Titov, Hosaka, Kim, PTEP, 2014, 023D03 (**2014**)

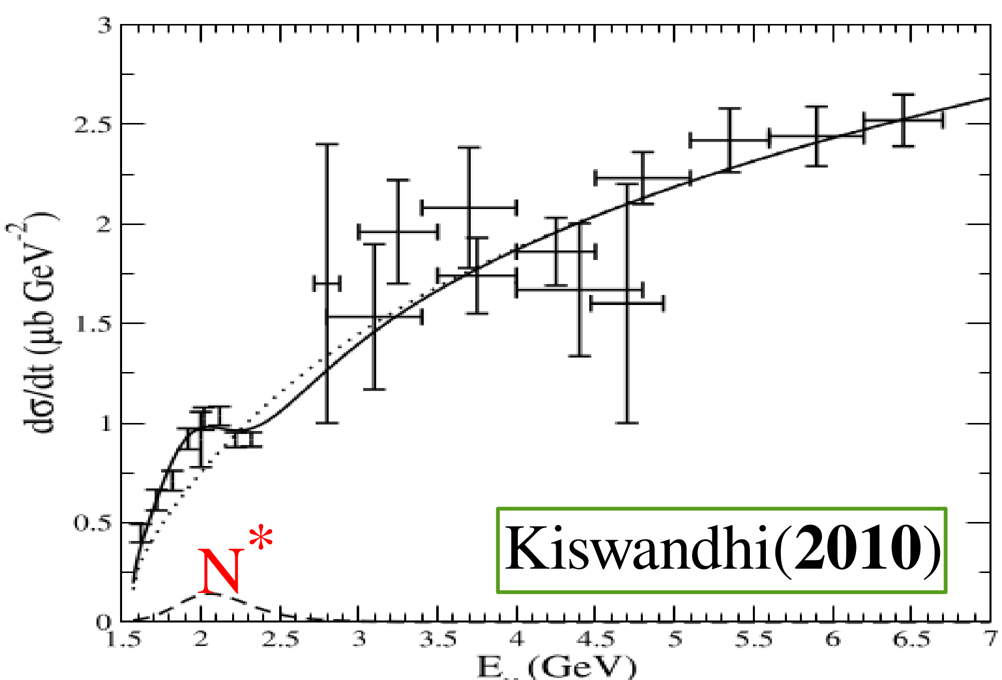
: various hadronic rescattering contributions, focusing on the KΛ(1520) channel.

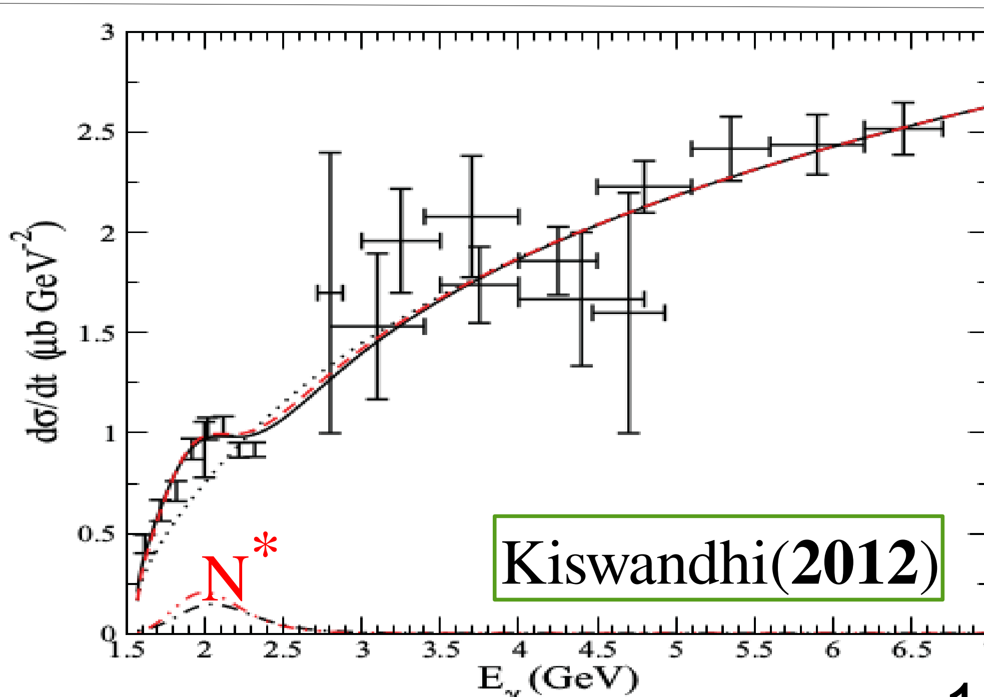
Sangho Kim (APCTP)

Previous theoretical works for the $\gamma p \to \phi(1020)p$









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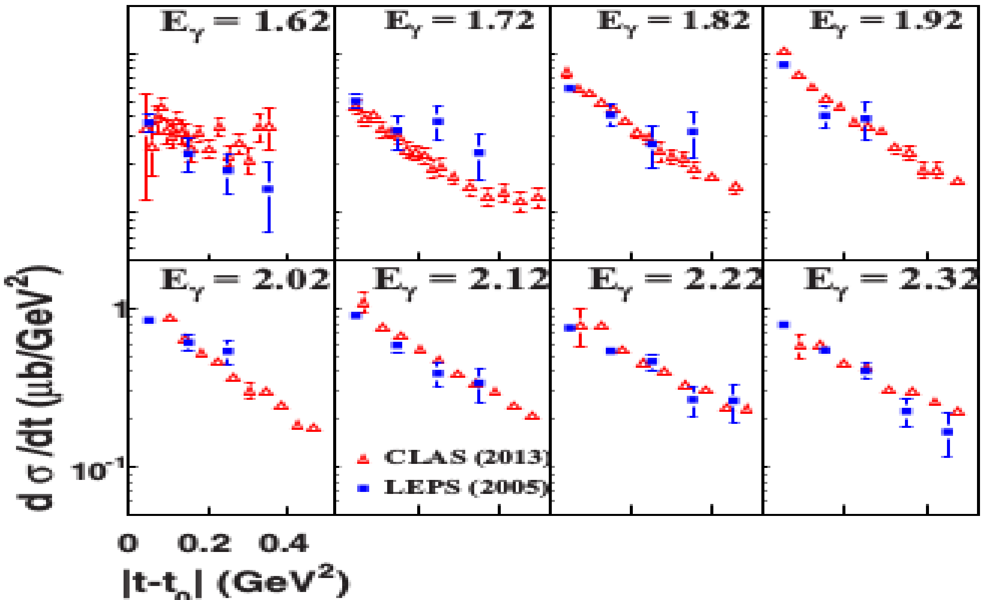
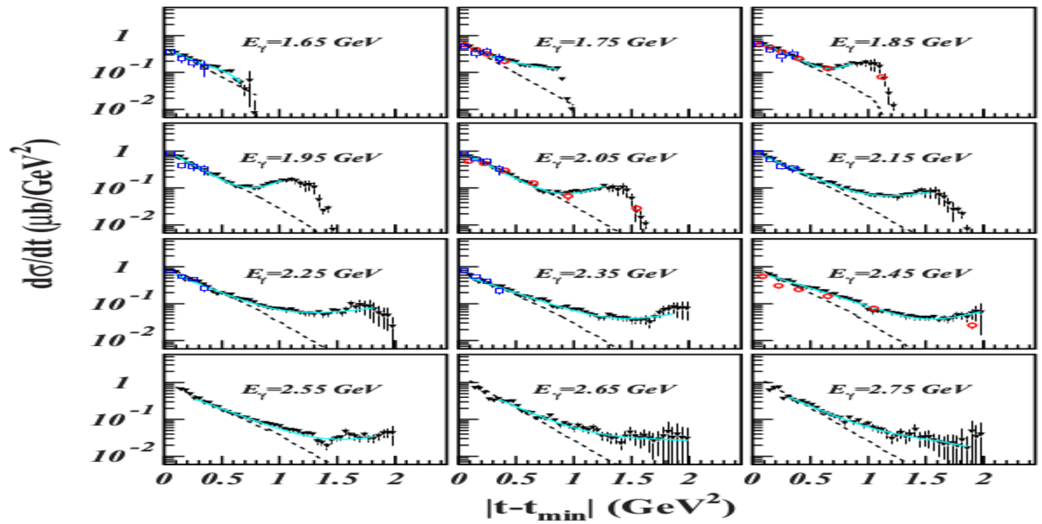
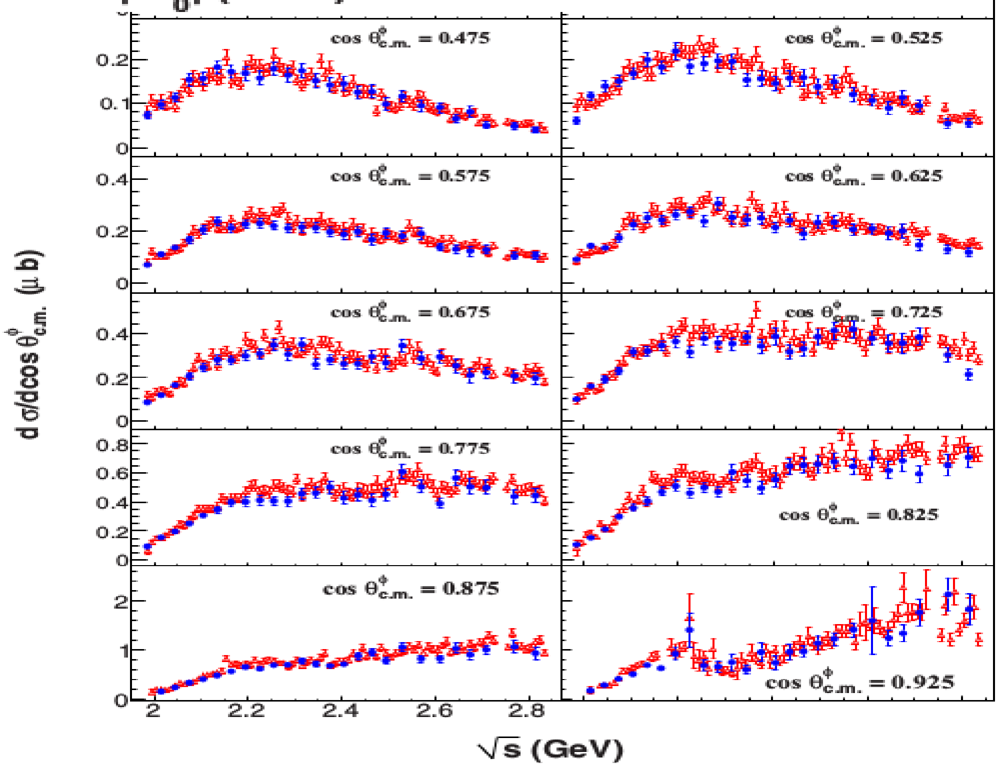
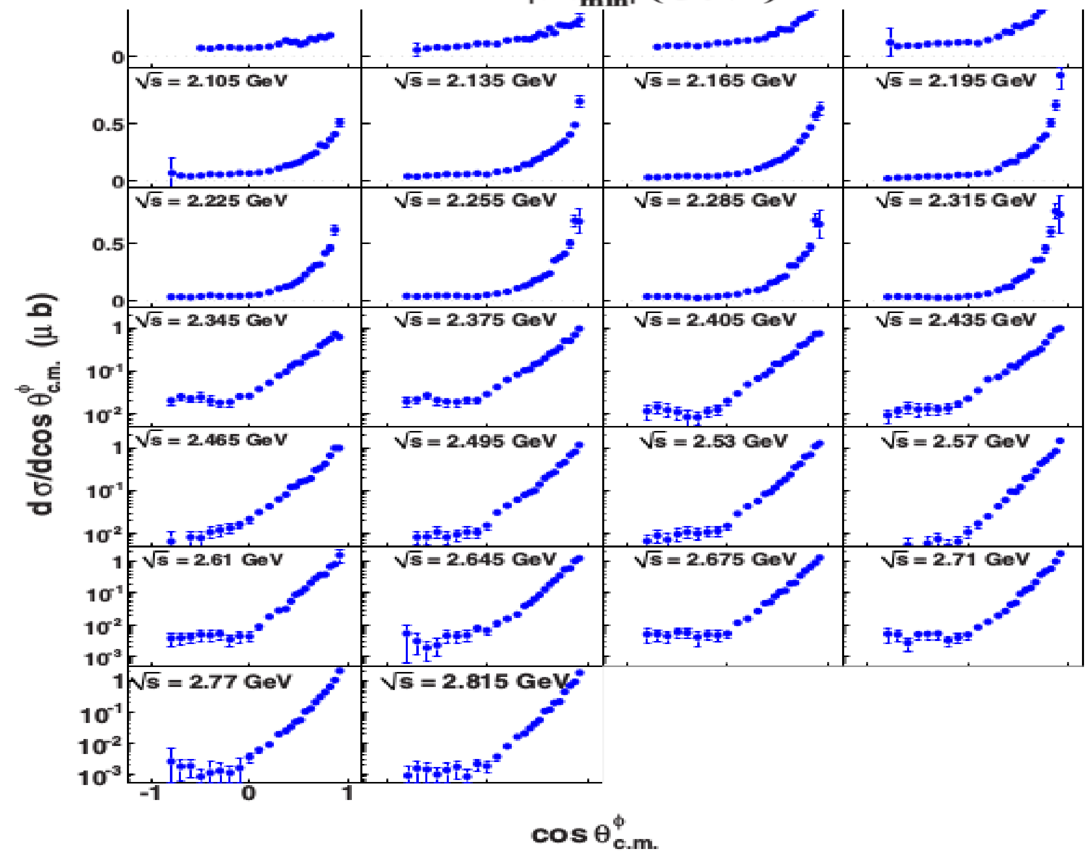


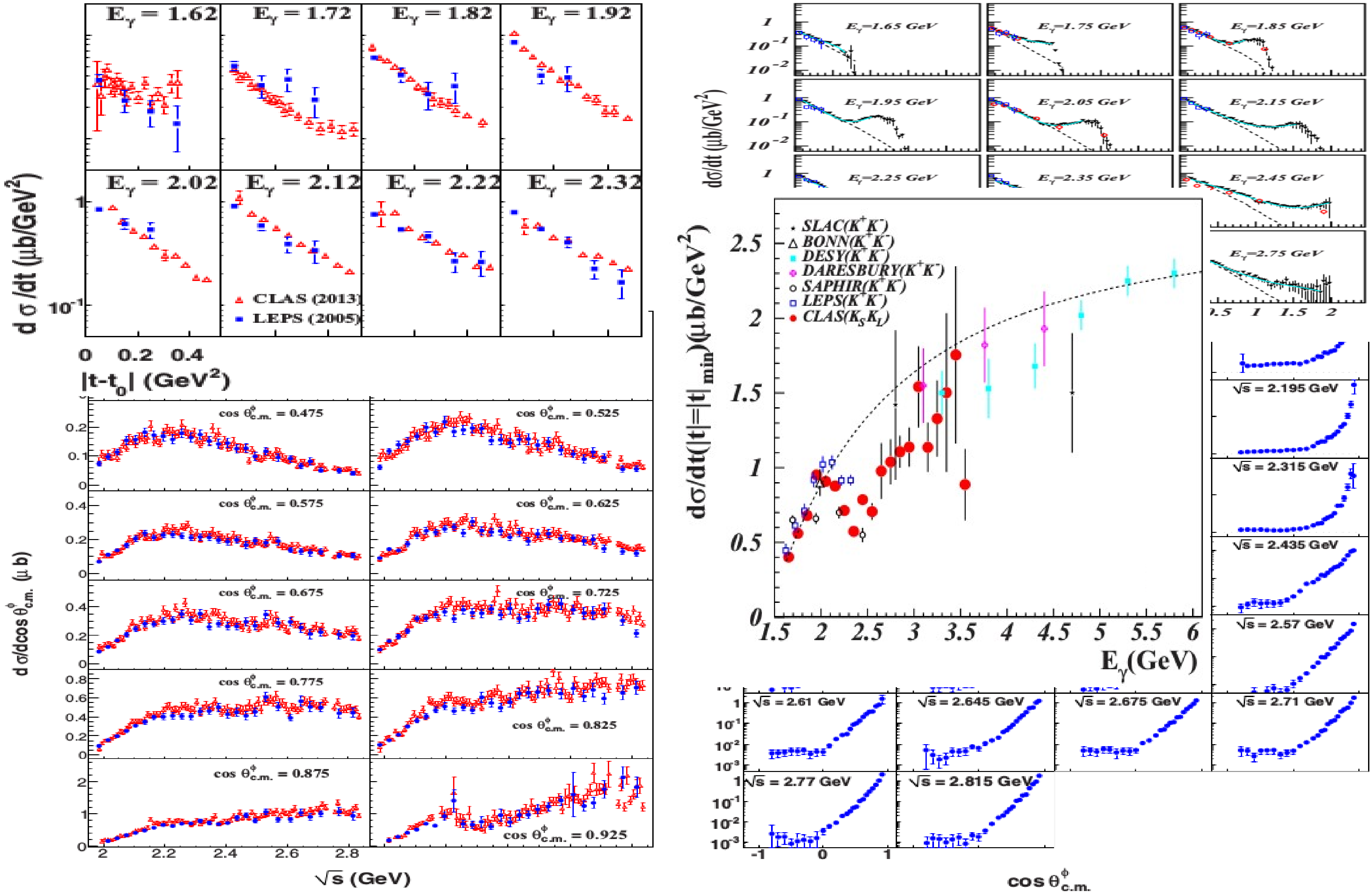






Do these theories describe the recent CLAS data well?

Previous theoretical works for the $\gamma p \to \phi(1020)p$



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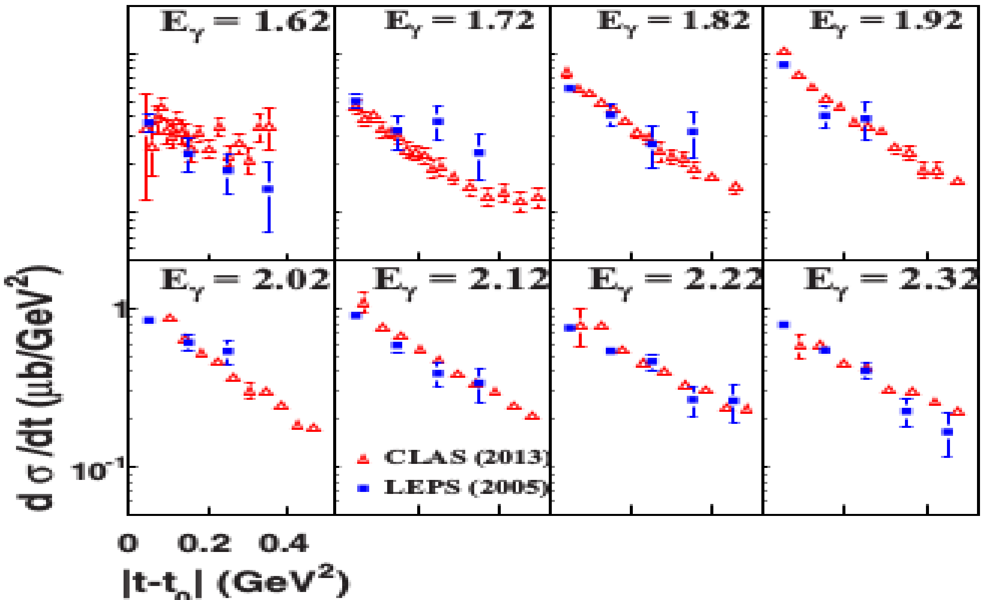
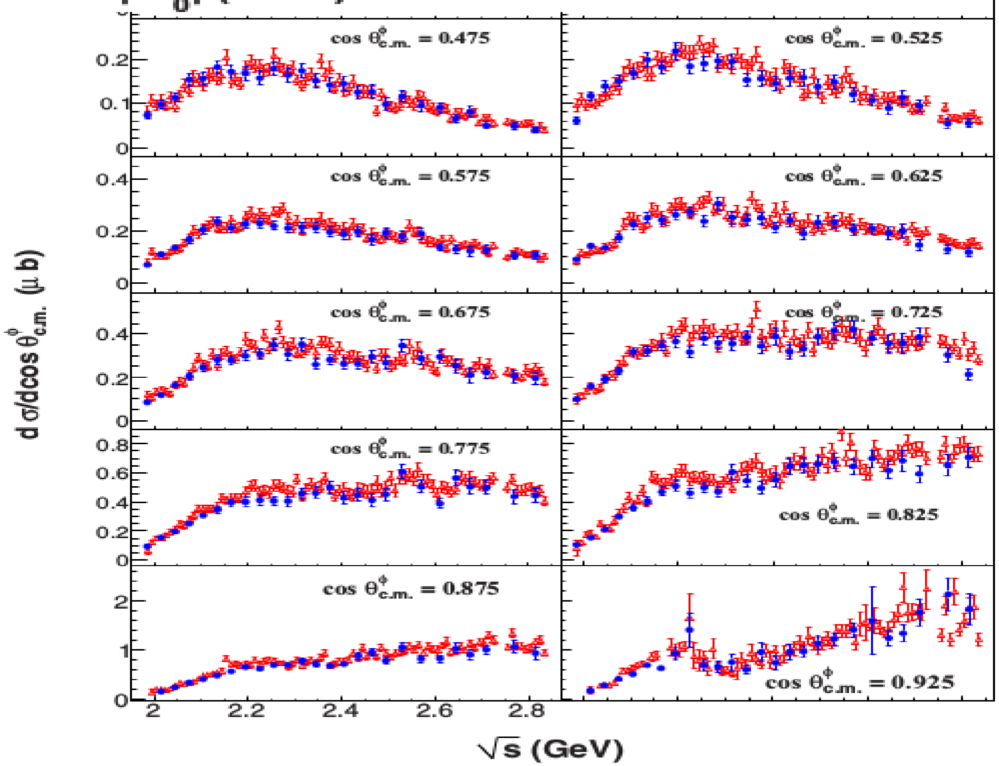
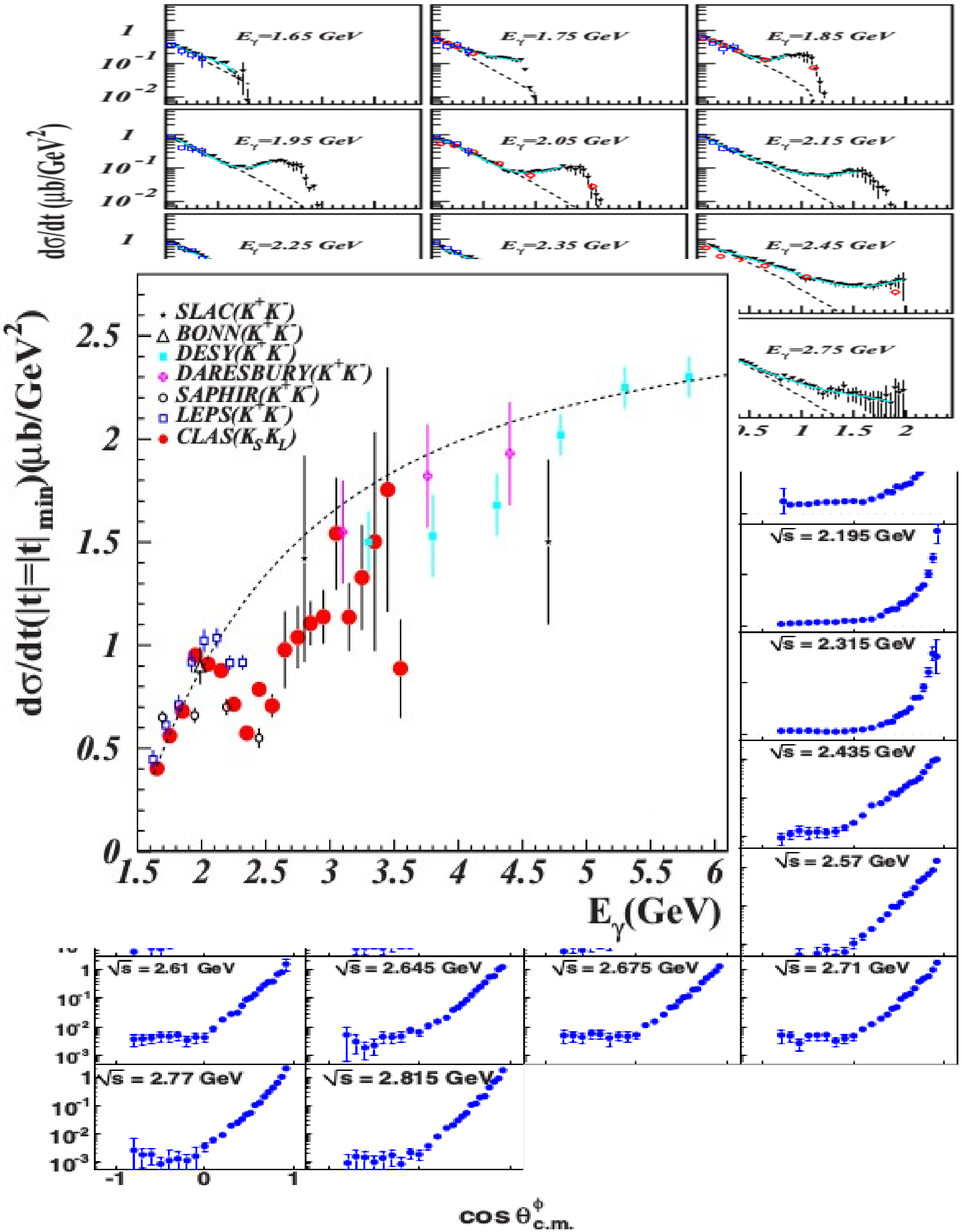




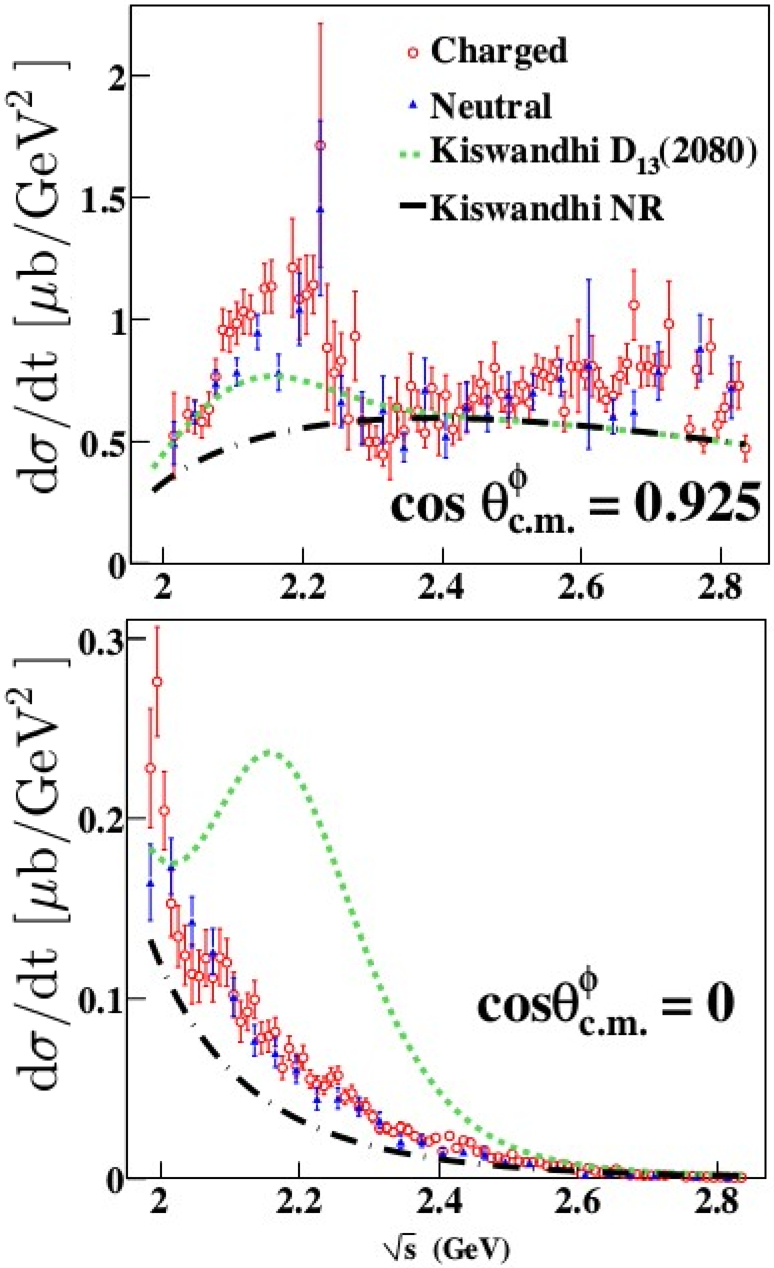


Do these theories describe the recent CLAS data well?

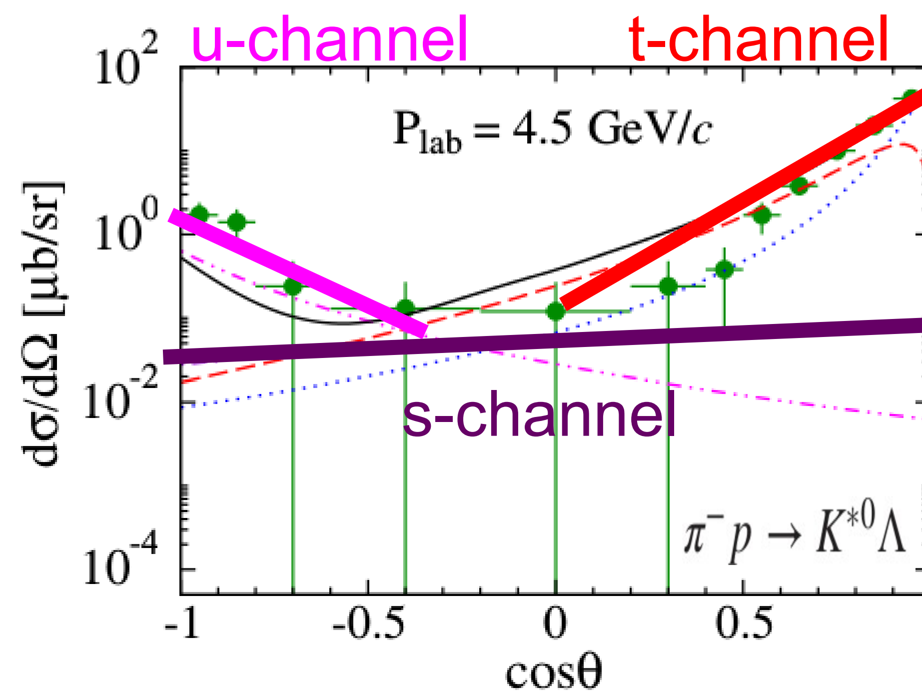
No!

Theoretical problem for the γp → φ(1020)p

$\gamma p \to \phi(1020) p$



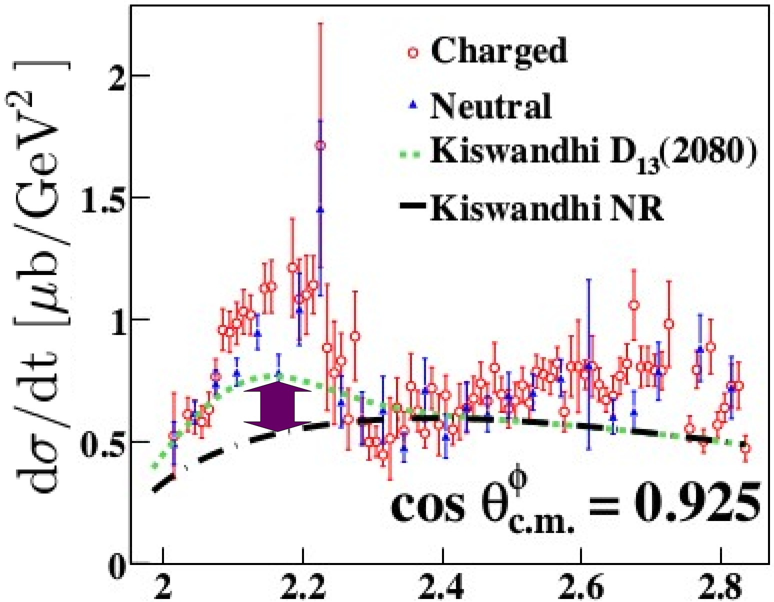
arXiv:1403.3730, Dey

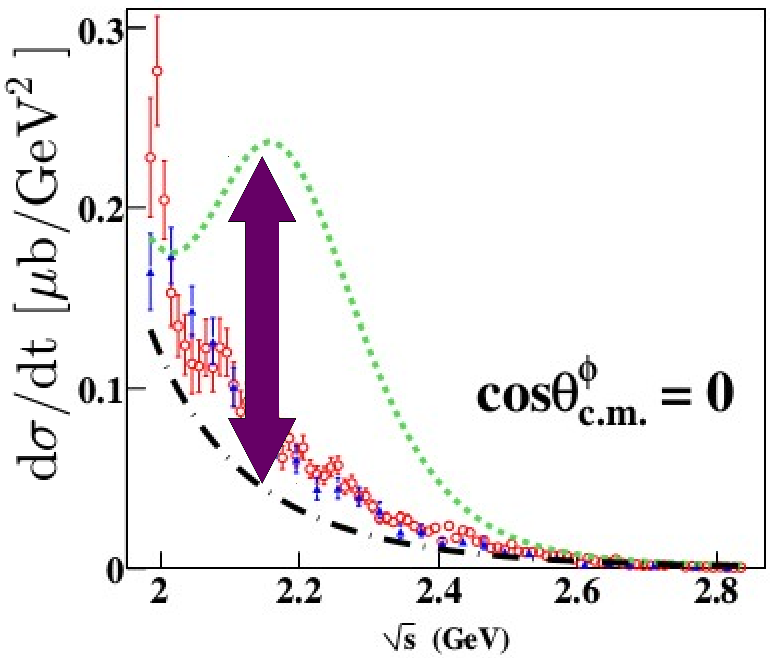


Kim et al, PRD92.094021 (2015)

Theoretical problem for the γp → φ(1020)p

$\gamma p \to \phi(1020) p$





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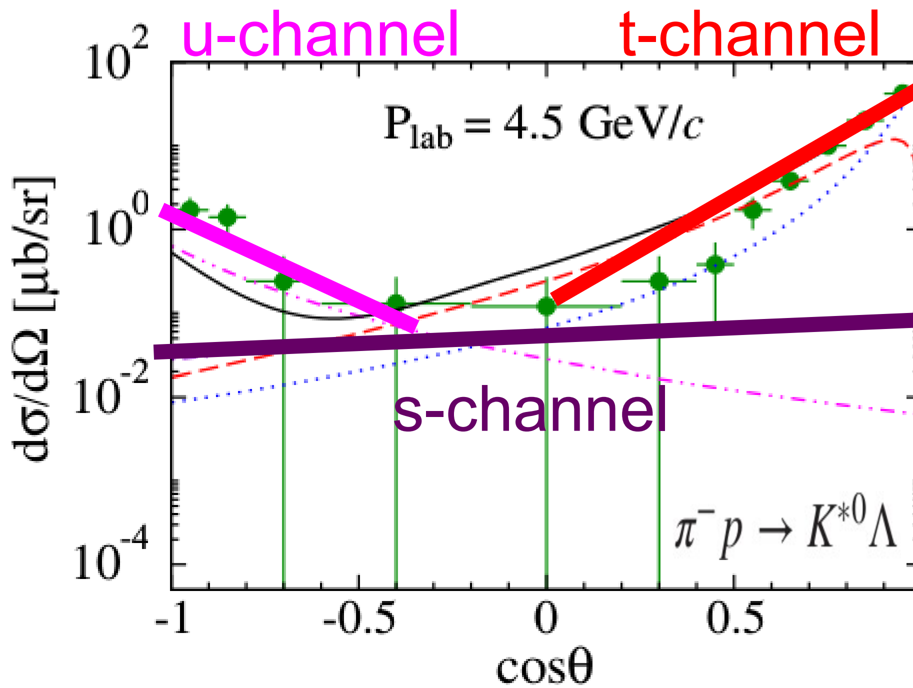
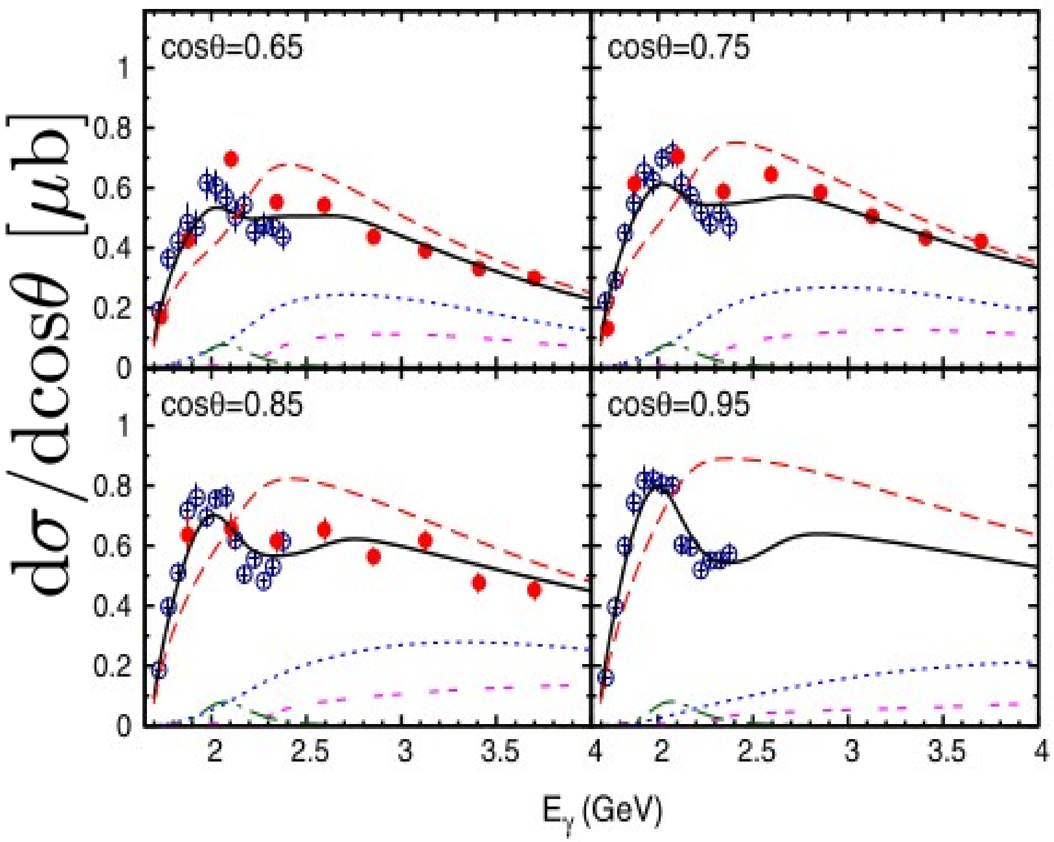


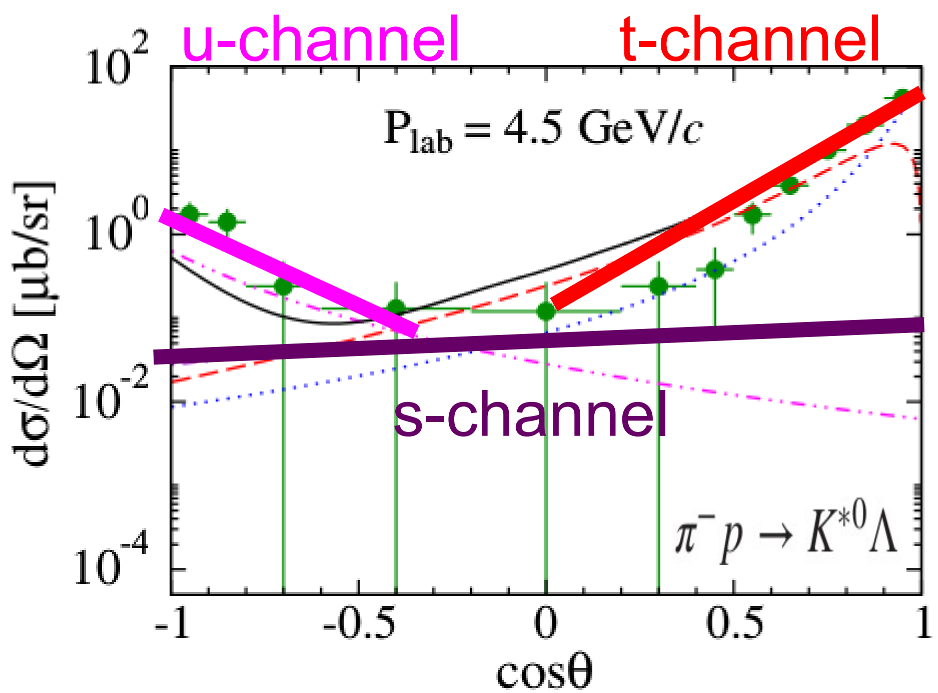
Kim et al, PRD92.094021 (2015)

Theoretical problem for the γp → φ(1020)p

$$\boxed{\gamma p \to K\Lambda(1520)}$$



He, NPA.927.24 (2014)



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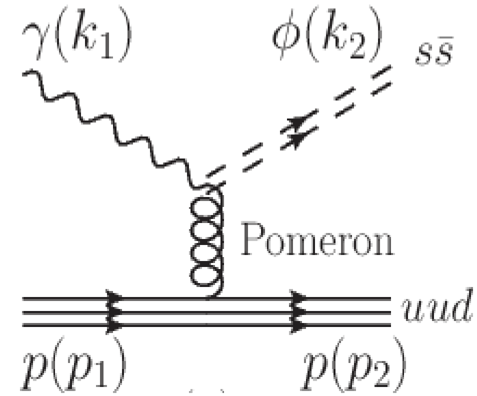
Numerical results: Pomeron



- scattering amplitude:

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

- transition operator:

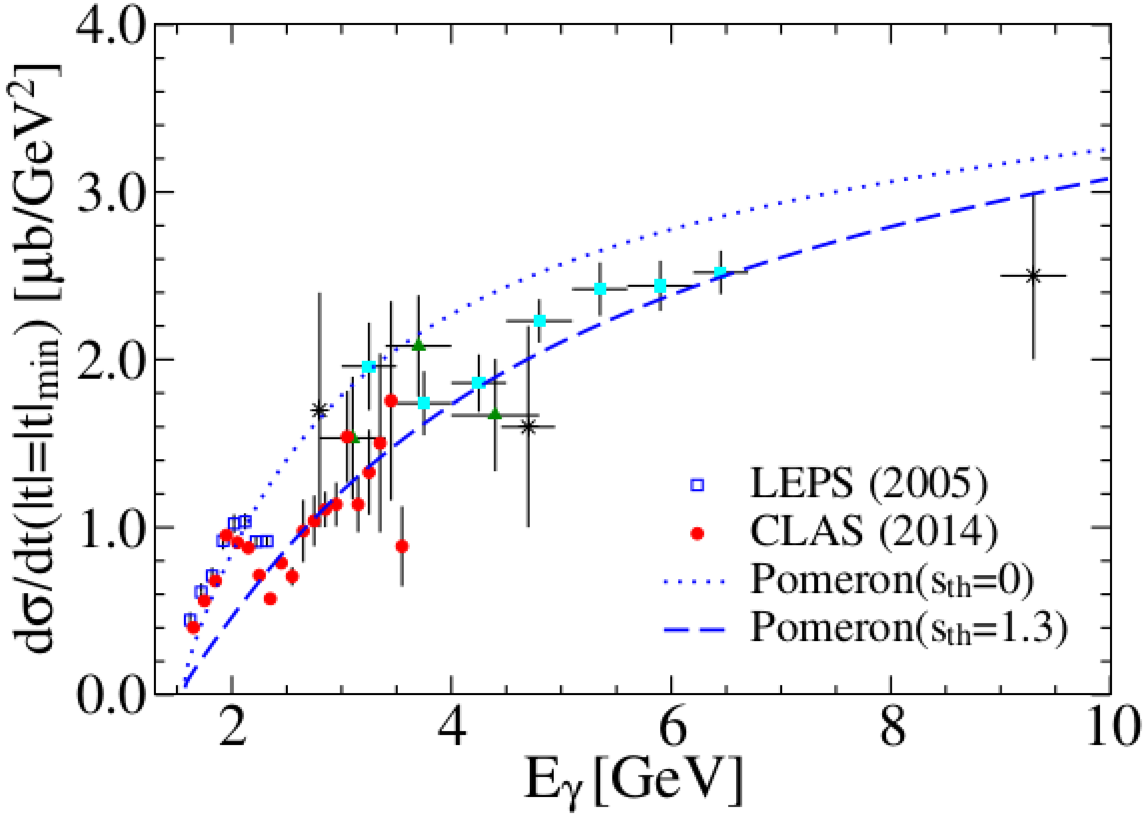
$$\Gamma^{\mu\nu} = \not{k}_1 \left(g^{\mu\nu} - \frac{k_2^\mu k_2^\nu}{k_2^2} \right) - \gamma^\mu \left(k_1^\nu - \frac{k_1 \cdot k_2 k_2^\nu}{k_2^2} \right) - \left[k_2^\mu - \frac{k_1 \cdot k_2 (p_1^\mu + p_2^\mu)}{k_1 \cdot (p_1 + p_2)} \right] \left(\gamma^\nu - \frac{\not{k}_2 k_2^\nu}{k_2^2}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

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

- 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_{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	"	"

Numerical results: Pomeron



	$\alpha_P(t)$	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	"	"
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Numerical results: Meson exchange

$$\mathcal{L}_{\phi P\gamma} = g_{\phi P\gamma}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu P \partial_\alpha \phi_\beta, \quad \mathcal{L}_{PNN} = -ig_{PNN}\bar{N}\gamma_5 PN,$$
$$\mathcal{L}_{\phi S\gamma} = g_{\phi S\gamma}A_{\mu\nu}S\phi^{\mu\nu}, \quad \mathcal{L}_{SNN} = -g_{SNN}\bar{N}SN.$$

	State	Fraction$(\Gamma_\mathrm{i}/\Gamma)$	$g_{\phi P(S)\gamma}$
	$\pi(139)$	$(1.27 \pm 0.06) \times 10^{-3}$	-0.040
P	$\eta(548)$	$(1.309 \pm 0.024) \times 10^{-2}$	-0.210
	$\eta'(958)$	$(6.25 \pm 0.21) \times 10^{-5}$	-0.217
S	$f_0(980)$	$(3.22 \pm 0.19) \times 10^{-4}$	0.727
	$a_0(980)$	$(7.6 \pm 0.6) \times 10^{-5}$	0.230

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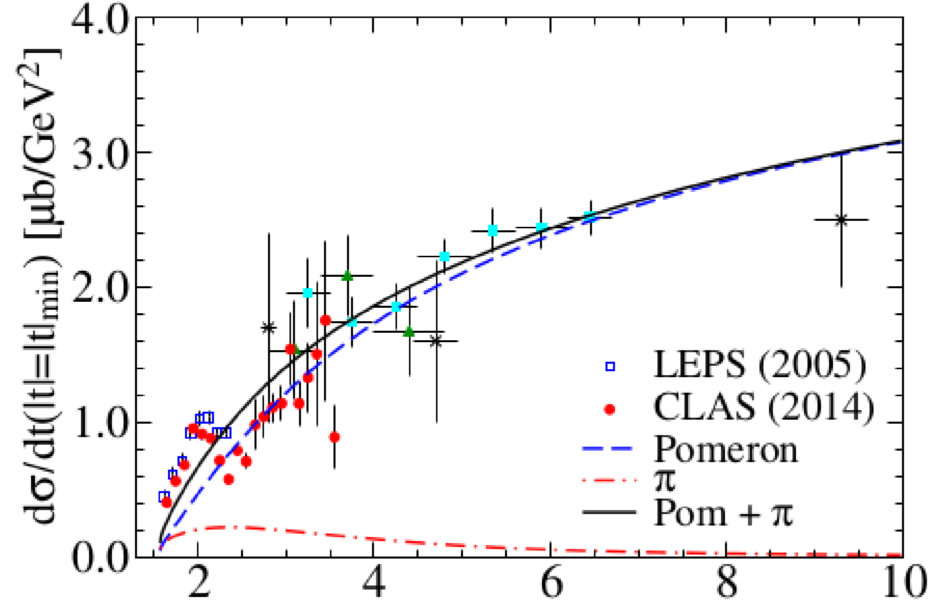
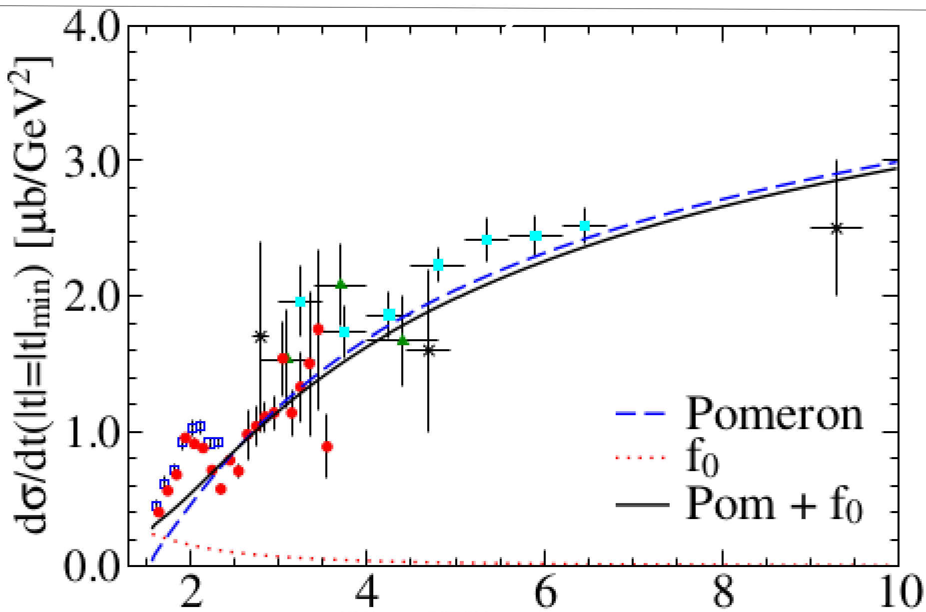
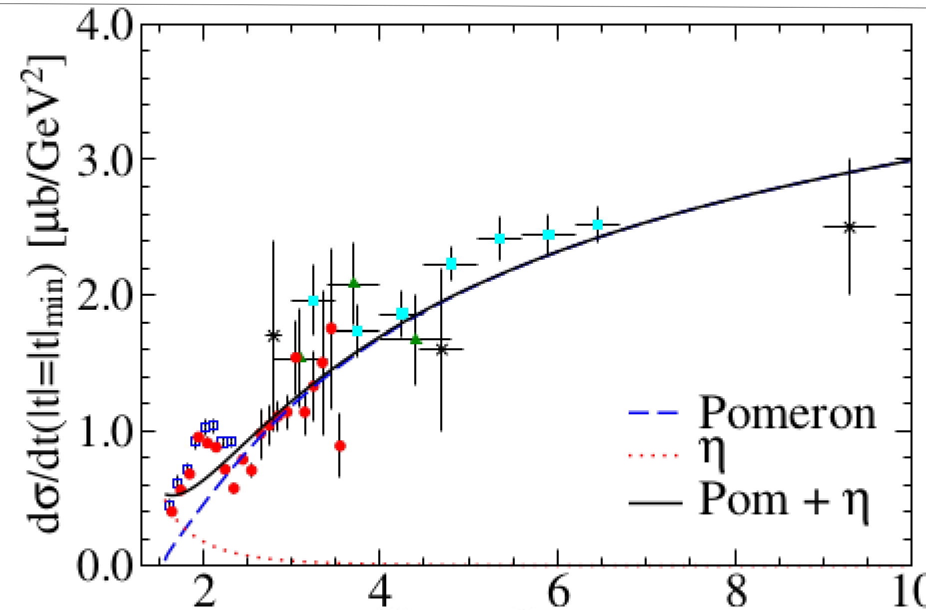


$$F_P = \left(\frac{\Lambda_P^2 - M_P^2}{\Lambda_P^2 - t}\right)^2, \quad \Lambda_{\pi(\eta)} = 1.05$$



$$F_\eta = \frac{\Lambda_\eta^2 - M_\eta^2}{\Lambda_\eta^2 - t}, \quad \Lambda_\eta = 2.0$$



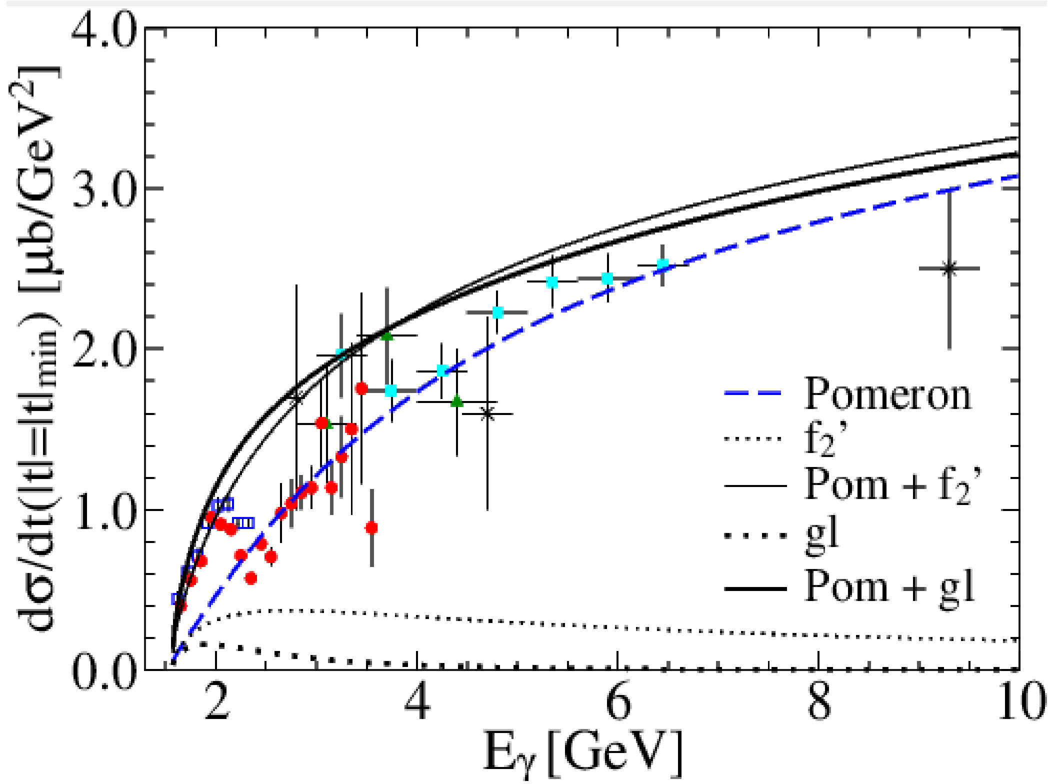
$$F_{f_0} = \frac{\Lambda_{f_0}^2 - M_{f_0}^2}{\Lambda_{f_0}^2 - t}, \quad \Lambda_{f_0} = 2.0$$

Numerical results: glueball & f_2 trajectories

- scattering amplitude: $\mathcal{M} = \varepsilon^*_\nu \bar{u}_{N'} \mathcal{M}^{\mu\nu} u_N \epsilon_\mu \qquad \mathcal{M}^{\mu\nu} = -M(s,t)\Gamma^{\mu\nu}$
- effective Lagrangians for VVξ interactions, (V,ξ) => (0^+,2^+) fields

$$\mathcal{L}_{0+} = \frac{1}{4} g_{\alpha\beta}(\Lambda^{\alpha\beta} + \Lambda^{\beta\alpha})\xi,$$
$$\mathcal{L}_{2+} = \frac{1}{4}(\Lambda^{\alpha\beta} + \Lambda^{\beta\alpha})\xi_{\alpha\beta} + \frac{1}{4}(\Lambda^{\alpha\beta} - \Lambda^{\beta\alpha})\xi_{\alpha\beta}$$
$$\Lambda^{\alpha\beta} = \partial_\mu V_1^\alpha \partial^\mu V_2^\beta + \partial^\alpha V_1^\mu \partial^\beta V_{2\mu} - \partial^\alpha V_1^\mu \partial_\mu V_2^\beta - \partial_\mu V_1^\alpha \partial^\beta V_2^\mu$$

$$N_{0+} \simeq M_N M_V^2,\ \alpha_{gl} = -0.75 + 0.25t,\ s_{gl} = \alpha'^{-1}_{gl}$$
$$N_{2+} \simeq 2sM_V,\quad \alpha_{f_2'} = 0.55 + 0.7t,\qquad s_{f_2'} = 1\,\mathrm{GeV}^2$$



- transition operator:

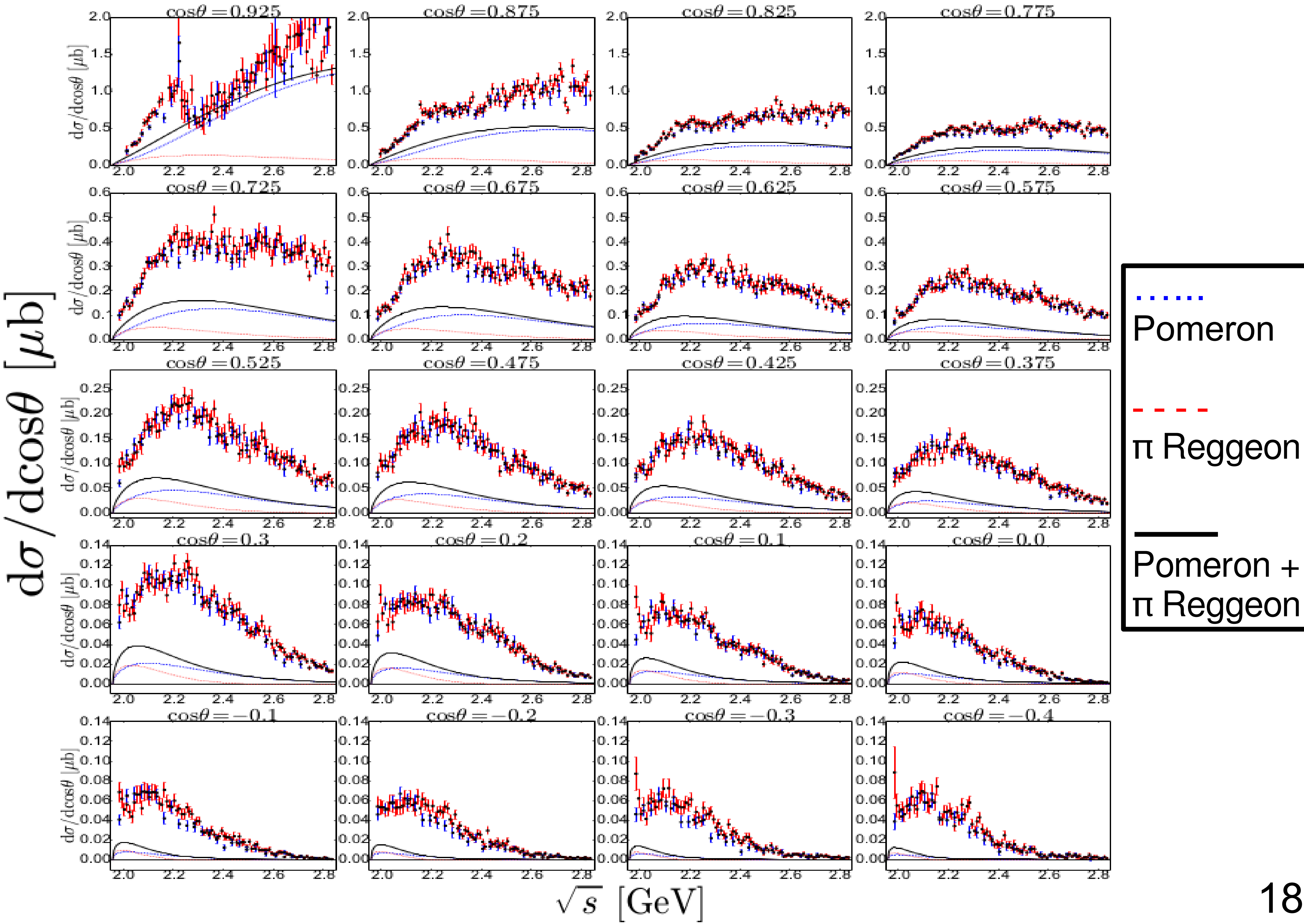
$$\Gamma^{\mu\nu}_{0+} = g^{\mu\nu} k_1 \cdot k_2 - k_1^\mu k_2^\nu,$$
$$\Gamma^{\mu\nu}_{2+} = \Gamma^{\mu\nu}_{0+} - 2i\sigma_{\alpha\beta}[g^{\alpha\mu} g^{\beta\nu} k_1 \cdot k_2 + k_2^\alpha k_1^\beta g^{\mu\nu} + g^{\alpha\nu} k_2^\beta k_1^\mu + g^{\beta\nu} k_1^\alpha k_2^\nu]$$

- scalar function:

$$M(s,t) = C_R F_1(t) F_V(t) \frac{1}{N_R} \left(\frac{s}{s_R}\right)^{\alpha_R(t)} \times \frac{\eta_R}{2}(1 + e^{-i\pi\alpha_R(t)})\Gamma(1 - \alpha_R(t)\alpha'_R$$

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

Numerical results: Pomeron + π Reggeon



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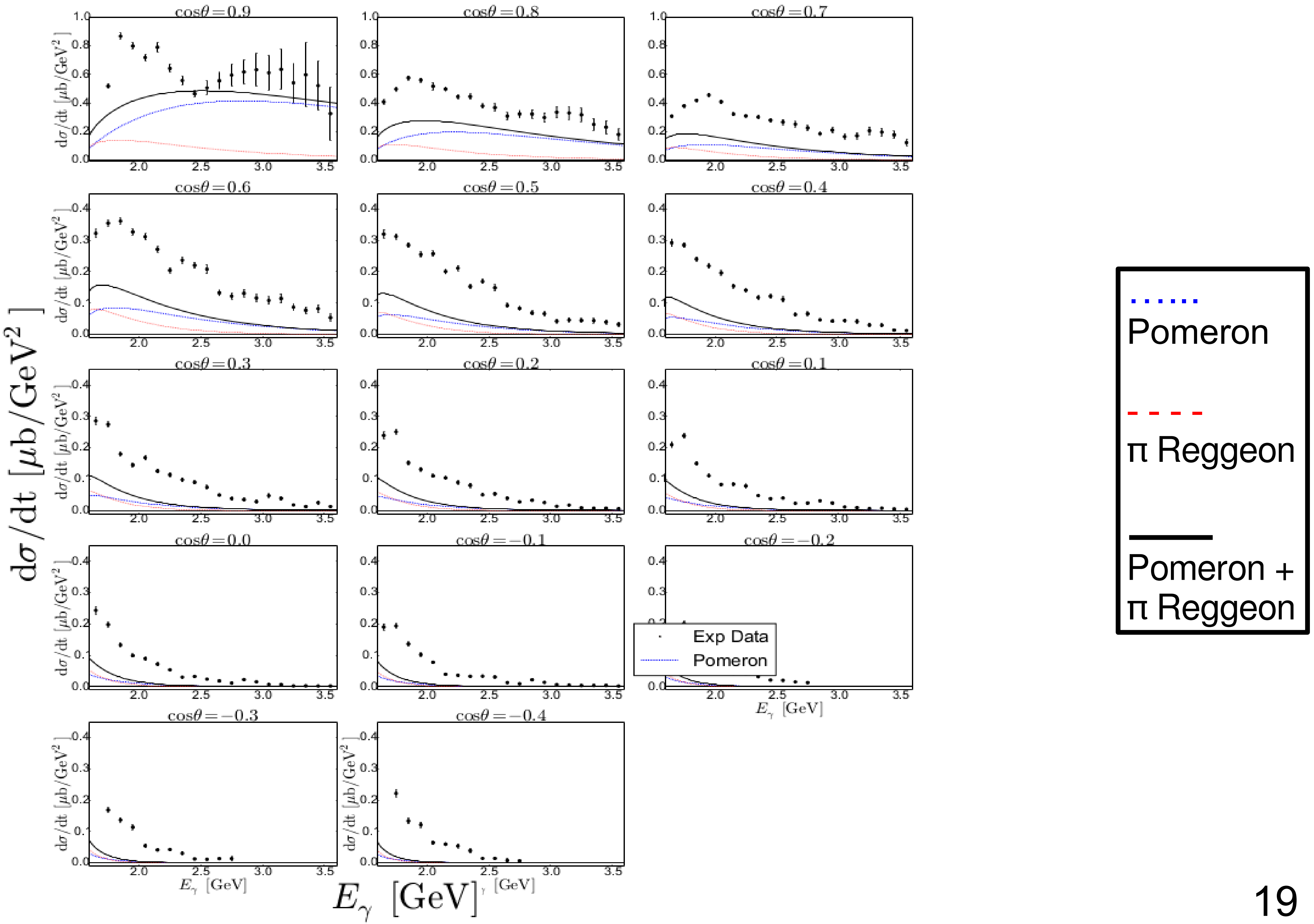

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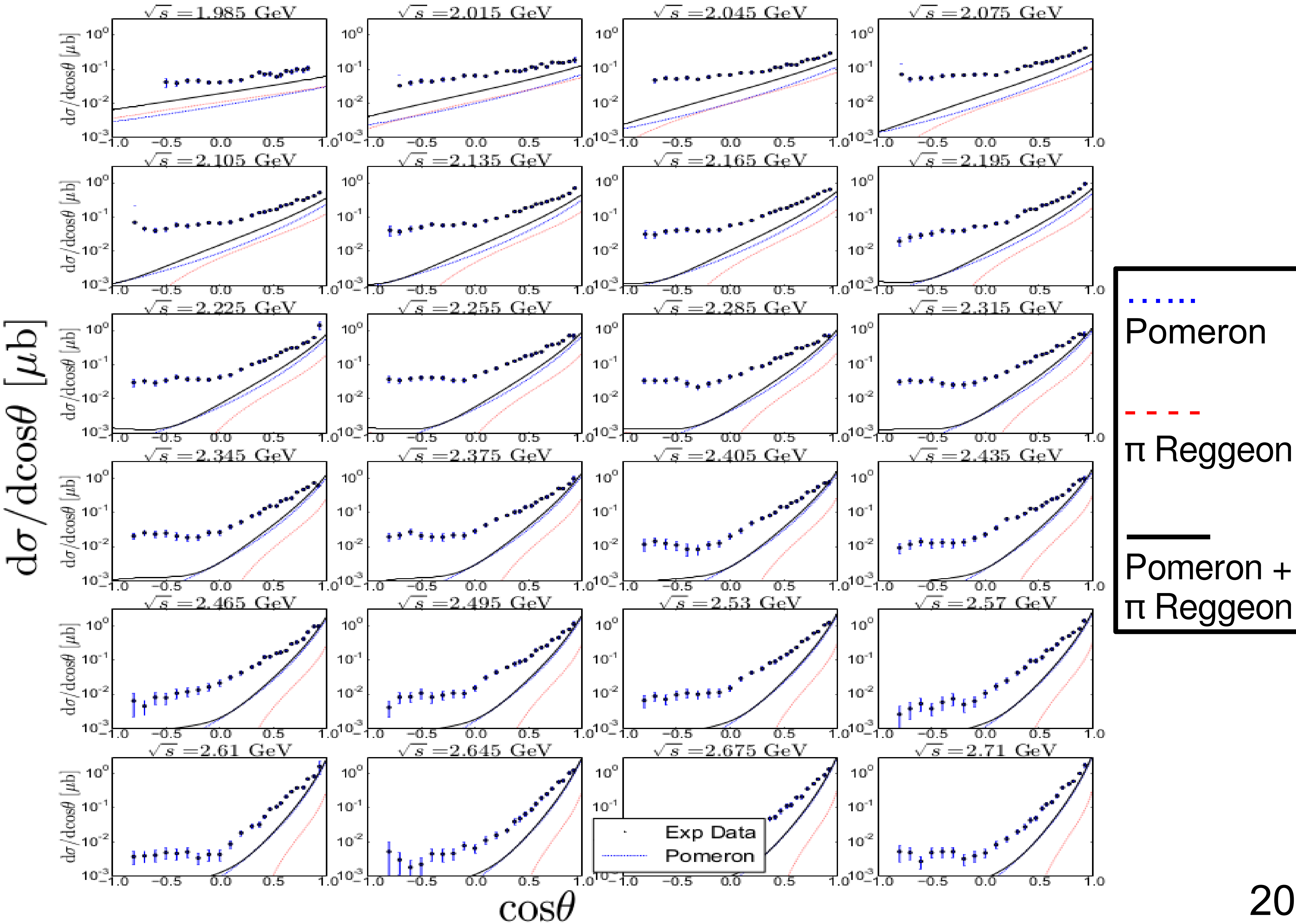

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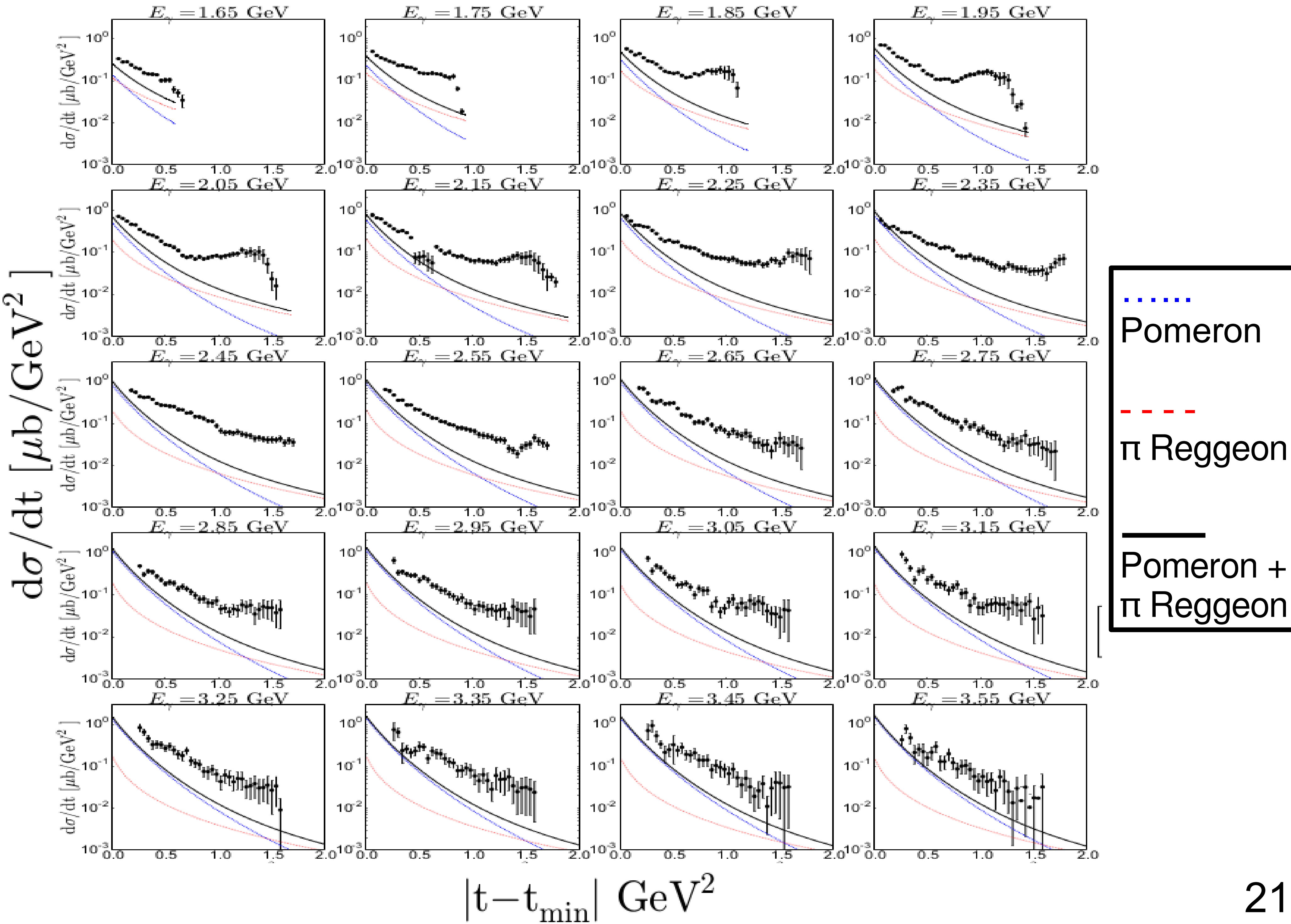
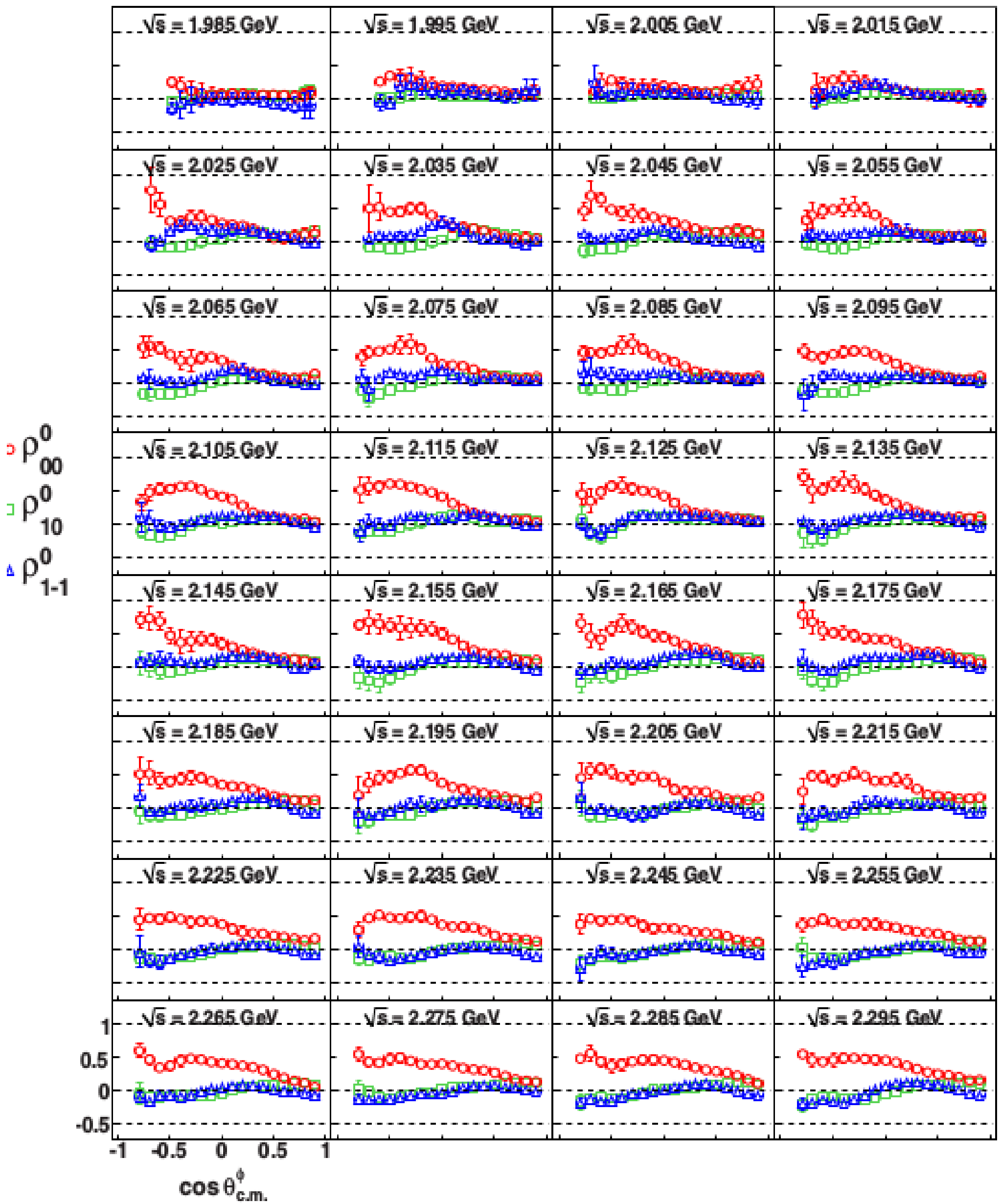
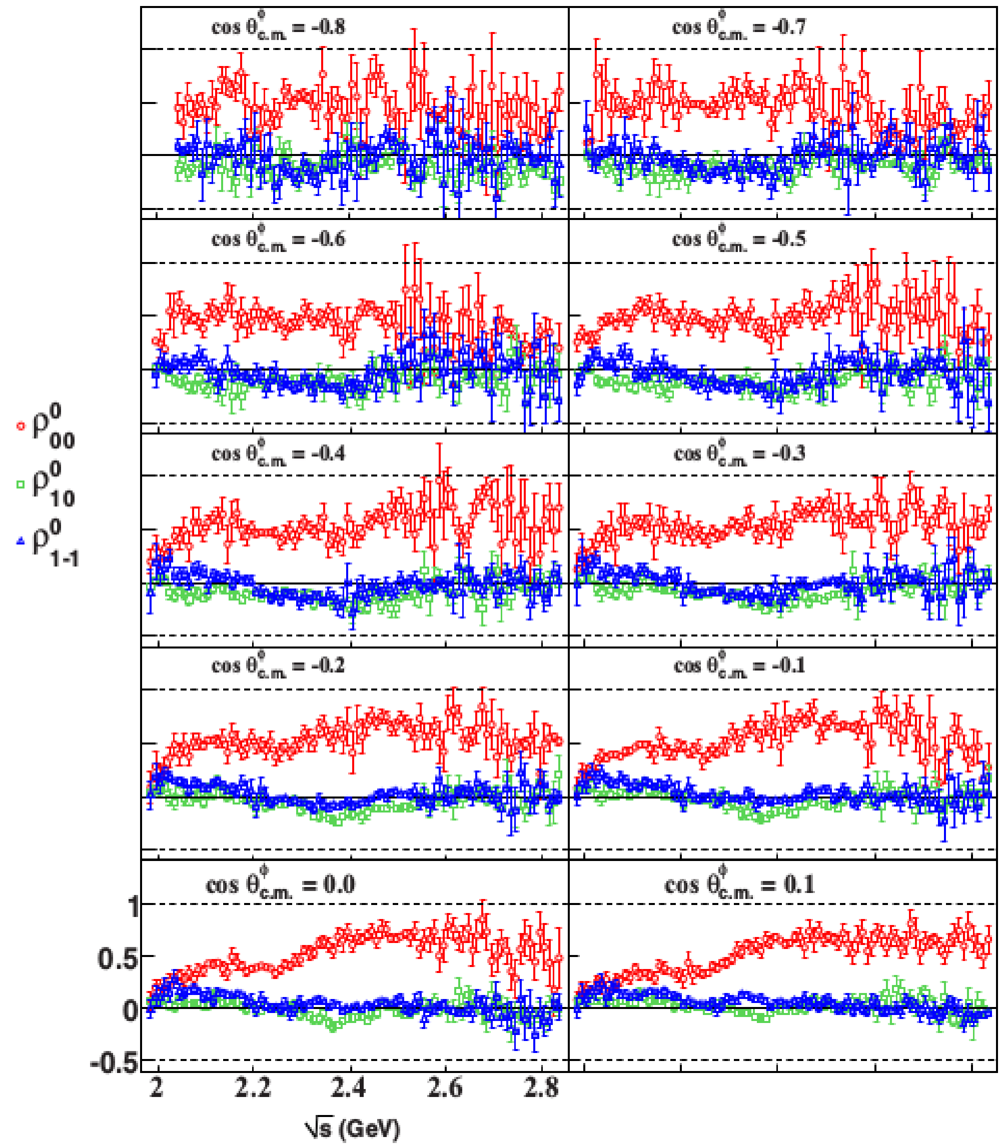


Spin density matrices





Summary

◇ φ photoproduction, $\gamma p \rightarrow \varphi(1020)p$, is reanalyzed.

◇ A bump structure is observed at both LEPS(2005) & CLAS(2014) Collaborations in forward angle region.

◇ N* scenario may not be a correct answer for this description.

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

⇨ pseudoscalar meson (π,η)

⇨ scalar meson (σ,a_0,f_0)

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

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◇ More extensive studies are required.

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Thank you very much