Photo- and electro-production of $J^P = 1/2^-$ hyperons and of φ(1020) and J/ψ(3097) mesons

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Introduction: Exotic hadrons

❑ Although several quark-gluon configurations could build hadrons within the theory of strong interactions, until about two decades ago, most hadrons were considered within the traditional quark model of Gell-mann and Zweig.

> Baryons are treated as states of three quarks and mesons as states of a quark and antiquark. The resonances are described by considering radial/orbital excitations.

baryon

meson

❑ Nowadays, there exist clear examples of hadrons whose properties cannot be explained within the naive quark model.

> Such hadrons are often referred to as "exotic hadrons" and their structures are under discussions, such as tetraquarks, pentaquarks, mixed states, etc.

tetraquark

pentaquark

※ The introduction part is based on the presentation by K.P.Khemchandani.

Introduction: Molecular hadrons

- Yet another possibility exists, which is the formation of hadrons (bound states/resonance) from the dynamics of the constituent hadrons.

- Such states are sometimes referred to as "dynamically generated states" or "molecular resonances".

- Such hadrons do not possess exotic quantum numbers.

- The occurrence of such a phenomenon seems naturally plausible in some cases, where the generation of a $q\bar{q}$ pair may be more economical than exciting a quark to a higher radial/orbital state.

- The name "molecular states" is used in analogy with atomic physics, where Van der Waals forces between atoms lead to formation of weakly bound states.

- Similarly, interactions of hadrons can sometimes lead to formation of "bound" states (strictly speaking, such states are resonances, they have finite widths, they are more like Feshbach resonances).

- The interactions among the constituent hadrons are long range.

Introduction: Molecular hadrons

- Discussions on the molecular nature of the states is not new.
  The possibility of such a description for $\Lambda(1405)$ by
  Dalitz in 1960s. [Phys Rev 153, 1617 (1967)]

- In the classical constituent quark models (B=qqq) [Capstick,Isgur, PRD.34.2809 (1986)],
  the lowest excitation of baryons is L=1 excitation of a quark, $J^P=1/2^-$,~ 450 MeV.

- Experimentally observed is

N(938)	$N^*(1535,1/2^-)$	(****)	$\rightarrow \Delta M$ = 596 MeV
$\Lambda(1116)$	$\Lambda(1405,1/2^-)$	(****)	$\rightarrow$ = 290 MeV
$\Sigma(1189)$	$\Sigma(1620,1/2^-)$	(*)	$\rightarrow$ = 431 MeV

- Why $N^*(1535) > \Lambda(1405)$?

- (a) pentaquark model [Helminen et al. NPA.699.624 (2002)]
  $N^*(1535)$ is mainly a $[ud][us]\bar{s}$ state.
  $\Lambda(1405)$ is mainly a $[ud][sq]\bar{q}$ state with $q\bar{q} = (u\bar{u}+d\bar{d})/\sqrt{2}$.
  (b) meson cloud model [Kaiser et al. PLB.362.23 (1995)]
  $N^*(1535)$ is explained as a $K\Lambda$-$K\Sigma$ quasibound state.
  $\Lambda(1405)$ is a dynamically generated state of coupled KN-$\Sigma\pi$ channels.

Introduction: Molecular hadrons

- Since then $\Lambda(1405)$ has been within a variety of models

- **An incomplete list of references:**

Kaiser et. al. NPA 594, 325 (1995)
Oset et. al. NPA 635, 99 (1998)
Oller et. al. PLB 500, 263 (2001)
Jido et. al. NPA 725, 181 (2003)
Hyodo et. al. Prog. Part. Nucl. Phys. 67, 55 (2012)
CLAS Collaboration, PRC 88, 045202 (2013)
Kamano et. al. PRC 90, 065204 (2014)
C.Wang et. al. PRD 96, 056002 (2017)
Kamiya et. al. NPA 954, 41 (2016)
Molina et. al. PRD 94, 056010 ; 079901 (2016)
Miyahara, et. al. PRC 98, 025201(2018)

- Some other examples of hadrons which seem to be strong candidates of molecular states: $D_s(2317)$, $X(3872)$

- **Theoretical/phenomenological (D_s):**

Beveren et. al. PRL 91, 012003 (2003)
Kolomeitsev et. al. PLB 582, 39 (2004)
Gamermann et. al. PRD 76, 074016 ; EPJA 33, 119 (2007)
Guo et. al. PLB 641,278 (2006) ; EPJA 40, 171 (2009)
Wang et. al. PRD 86, 014030 (2012)
Liu et. al. PRD 87, 014508 (2013)
Cleven et. al. EPJA 50, 149 (2014)
Altenbuchinger et. al. PRD 89, 014026 ; 89, 054008 (2014)

- **Finite volume and lattice (D_s):**

Mohler et. al. PRL 111, 222001 (2013)
C.B.Lang et. al. PRD 90, 034510 (2014)
Bali et. al. PRD 96, 074501 (2017)
Martinez Torres et. al. JHEP 05, 153 (2015)

- **Theoretical/phenomenological (X):**

Close et. al. PLB 578, 119 (2004)
Tornqvist et. al. PLB 579, 316 (2004)
Swanson et. al. PLB 588, 189 (2004)
Barnes et. al. PRD 69, 054008 (2004)
Braaten et. al. PRD 69, 074005 (2004)
Matheus et. al. PRD 75, 014005 (2007)
Hanhart et. al. PRD 76, 034007 (2007)
D.Gamermann et. al. PRD 81, 014029 (2010)
F.K.Guo et. al. PRD 88, 054007 (2013)
Karliner et. al. PRL 115, 122001 (2015)
Esposito et. al. Phys. Rept. 668, 1 (2017)

- **Finite volume and lattice (X):**

Prelovsek et. al. PRL 111, 192001 (2013)
Padmanath et. al. PRD 92, 034501 (2015)
Wallbott et. al. PRD 100, 014033 (2019)

Introduction: Recent findings

❑ Many discussions on Z_c [$c\bar{c}q\bar{q}$]
> doubly charmed compact tetqaquark, $D^{(*)}D^{(*)}$ molecules ?

❑ [BESIII, PRL 126, 103001 (2021)]

> First observation of exotic states with a new quark content $c\bar{c}s\bar{u}$
from $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$, $Z_{cs}(3985, 1^+)^-$, width $\Gamma \sim 12.8$ MeV

❑ [LHCb, 2103.01803 [hep-ex]]

> First observation with a $c\bar{c}u\bar{s}$ content
decaying to the "J/ψ K^+" final state, $Z_{cs}(4000, 1^+)^+$, width $\Gamma \sim 131$ MeV

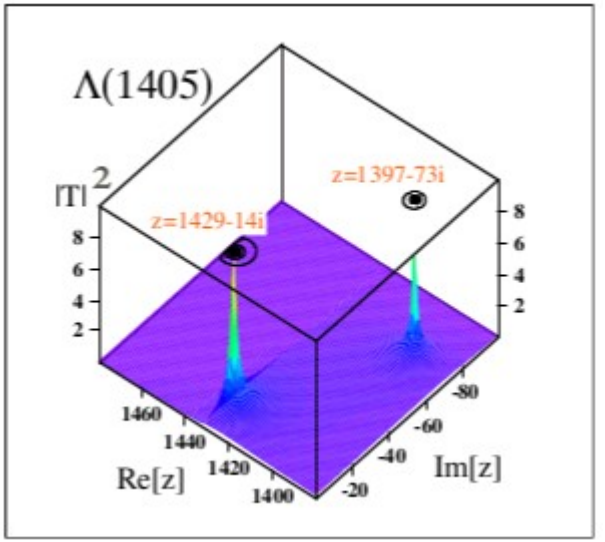
> A broader 1^+ or 1^- $Z_{cs}(4220)^+$

> A new $X(4685, 1^+)$ state decaying to "J/ψ φ"

❑ The interpretation of their structures is under discussion.
(compact object, molecular state, threshold effect ...)

Introduction: Hyperons

- Coming back to Λ(1405), although it has been within different models, it is still not clear if it is associated to one or two poles in the complex plane.



- Some studies suggest the existence of its isovector partner, i.e., Σ(1400,1/2⁻), but the case is less studied.

Oller, Meißner, PLB 500, 263 (2001)
Wu, Dulat, Zou, PRD 80, 017503 (2009)
Wu, Dulat, Zou, PRC 81, 045210 (2010)
Gao, Wu, Zou, PRC 81, 055203 (2010)
Guo, Oller, PRC 87, 035202 (2013)
Xie, Wu, Zou, PRC 90, 055204 (2014)
Xie, Geng, PRD 95, 074024 (2017)

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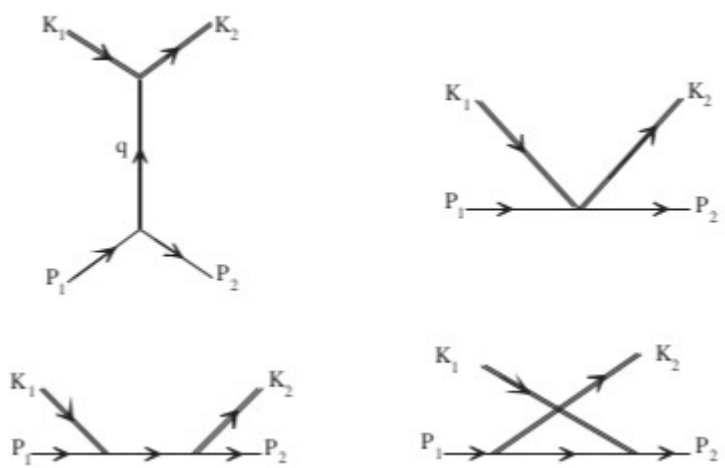
Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1775)$	$5/2^-$	****

Model: strangeness -1 meson-baryon system

- Strangeness -1 meson baryon dynamics is important, to understand the properties of $\Lambda(1405)$ and, due to its implications like kaonic-nuclear bound states.

- The importance of the topic:
  [K.P.Khemchandani, A.M.Torres, and J.A.Oller, PRC 100, 015208 (2019)]
  studied meson baryon dynamics in detail, considering the coupled channels $\bar{K}N$, $K\Xi$, $\pi\Sigma$, $\eta\Lambda$, $\pi\Lambda$, $\eta\Sigma$, $\bar{K}^*N$, $K^*\Xi$, $\rho\Sigma$, $\omega\Lambda$, $\varphi\Lambda$, $\rho\Lambda$, $\omega\Sigma$, $\varphi\Sigma$ following diagrams:



Model: strangeness -1 meson-baryon system

❑ Pseudoscalar-baryon interaction (standard, lowest order chiral Lagrangian):

- $$\mathscr{L}_{PB} = \langle \bar{B} i\gamma^\mu \partial_\mu B + \bar{B} i\gamma^\mu [\Gamma_\mu, B] \rangle - M_B \langle \bar{B} B \rangle + \frac{1}{2} D' \langle \bar{B} \gamma^\mu \gamma_5 \{u_\mu, B\} \rangle + \frac{1}{2} F' \langle \bar{B} \gamma^\mu \gamma_5 [u_\mu, B] \rangle$$

$$u_\mu = i u^\dagger \partial_\mu U u^\dagger, \; \Gamma_\mu = \frac{1}{2}\left(u^\dagger \partial_\mu u + u \partial_\mu u^\dagger\right), \; U = u^2 = exp\left(i\frac{P}{f_P}\right)$$

D'=0.8, $F' = 0.46$

$$P = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & \frac{-2}{\sqrt{3}}\eta \end{pmatrix}, \quad B = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}$$

Model: strangeness -1 meson-baryon system

❑ Vector meson baryon interactions (Hidden local symmetry):

$$\mathscr{L}_{VB} = -g\left\{\langle\bar{B}\gamma_\mu\left[V_8^\mu, B\right]\rangle + \langle\bar{B}\gamma_\mu B\rangle\langle V_8^\mu\rangle + \frac{1}{4M}\left(F\langle\bar{B}\sigma_{\mu\nu}\left[V_8^{\mu\nu}, B\right]\rangle + D\langle\bar{B}\sigma_{\mu\nu}\left\{V_8^{\mu\nu}, B\right\}\rangle\right) + \langle\bar{B}\gamma_\mu B\rangle\langle V_0^\mu\rangle + \frac{C_0}{4M}\langle\bar{B}\sigma_{\mu\nu}V_0^{\mu\nu}B\rangle\right\}$$

$$\mathscr{L}_{V_0BB} = -g\left\{\langle\bar{B}\gamma_\mu B\rangle\langle V_0^\mu\rangle + \frac{C_0}{4M}\langle\bar{B}\sigma_{\mu\nu}V_0^{\mu\nu}B\rangle\right\}$$ D=2.4, F=0.82

$$V^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu + ig\left[V^\mu, V^\nu\right]$$

$$V^\mu = \frac{1}{2}\begin{pmatrix} \rho^0 + \omega & \sqrt{2}\rho^+ & \sqrt{2}K^{*+} \\ \sqrt{2}\rho^- & -\rho^0 + \omega & \sqrt{2}K^{*0} \\ \sqrt{2}K^{*-} & \sqrt{2}\bar{K}^{*0} & \sqrt{2}\phi \end{pmatrix}^\mu \qquad B = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}$$

❑ All amplitudes are projected on s-wave and used as an input in the equation T = V + VGT

Model: strangeness -1 meson-baryon system

❑ Following data were considered to constrain the parameters:

> Total cross sections on 175 data points

[Landolt and Börsntein, Numerical data and Functional Relationships in Science and Technology, Group I, Volume 12, Sub-volume a, Total Cross-Sections for Reactions of High Energy Particles]:

$K^- p \rightarrow K^- p, \bar{K}^0 n, \eta\Lambda, \pi^0\Lambda, \pi^0\Sigma^0, \pi^\pm\Sigma^\mp$

> Kaonic hydrogen (Siddharta Collaboration)

$\Delta E = 283 \pm 36 \pm 6$ eV and $\Gamma = 549 \pm 89 \pm 22$ eV

[M. Bazzi et al., PLB 704, 113 (2011)]

> Cross section ratios near threshold

$$\gamma = \frac{\sigma\left(K^- p \rightarrow \pi^+\Sigma^-\right)}{\sigma\left(K^- p \rightarrow \pi^-\Sigma^+\right)} = 2.36 \pm 0.12,$$

$$R_c = \frac{\sigma\left(K^- p \rightarrow \textbf{charged particles}\right)}{\sigma\left(K^- p \rightarrow \textbf{all}\right)} = 0.664 \pm 0.033,$$

$$R_n = \frac{\sigma\left(K^- p \rightarrow \pi^0\Lambda\right)}{\sigma\left(K^- p \rightarrow \textbf{all neutral states}\right)} = 0.189 \pm 0.015,$$

Model: strangeness -1 meson-baryon system

❑ Following data were considered to constrain the parameters:

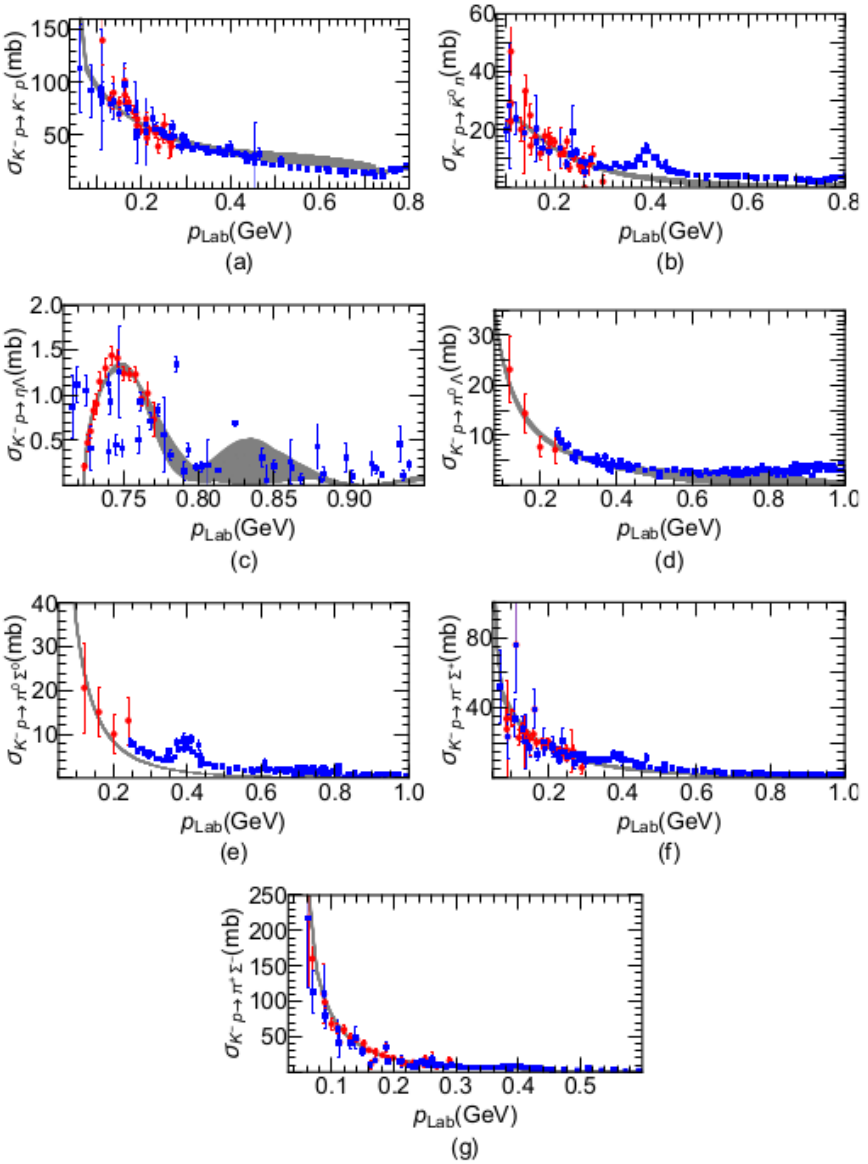
> Scattering length from Siddharta data

$a_{\text{K-p}} = (-0.65 \pm 0.10) + i\,(0.81 \pm 0.15)\ fm$

❑ Model results (fm)

a_{K^-p}	$-0.74^{+0.07}_{-0.02} + i\,0.73^{+0.03}_{-0.08}$
$a^0_{\bar{K}N}$	$-1.60^{+0.03}_{-0.01} + i\,0.89^{+0.04}_{-0.13}$
$a^1_{\bar{K}N}$	$0.12^{+0.10}_{-0.04} + i\,0.55^{+0.02}_{-0.04}$

[K.P.Khemchandani, A.M.Torres, and J.A.Oller, PRC 100, 015208 (2019)]



Model: strangeness -1 meson-baryon system

❑ As a result, two poles were obtained for Λ(1405):

(1385 ± 5) – i (124 ± 10) MeV
(1426 ± 1) – i (15 ± 2) MeV

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	Λ	$1/2^+$	****
new →	$\Lambda(1380)$	$1/2^-$	**
	$\Lambda(1405)$	$1/2^-$	****
	$\Lambda(1520)$	$3/2^-$	****
	$\Lambda(1600)$	$1/2^+$	****
	$\Lambda(1670)$	$1/2^-$	****
	$\Lambda(1690)$	$3/2^-$	****

❑ Comparison with other works:

> CLAS analysis of electroproduction data; poles ~ 1368 MeV, ~ 1423 MeV

> [Roca, Oset, PRC 88, 055206 (2013)]
(1352 – i48) MeV, (1419 – i29) MeV

> [Mai, Meißner, EPJA 51, 30 (2015)]
$(1325^{+15}_{-15} - i90^{+12}_{-18})$ MeV, $(1429^{+8}_{-7} - i12^{+2}_{-3})$ MeV

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Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
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$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1775)$	$5/2^-$	****

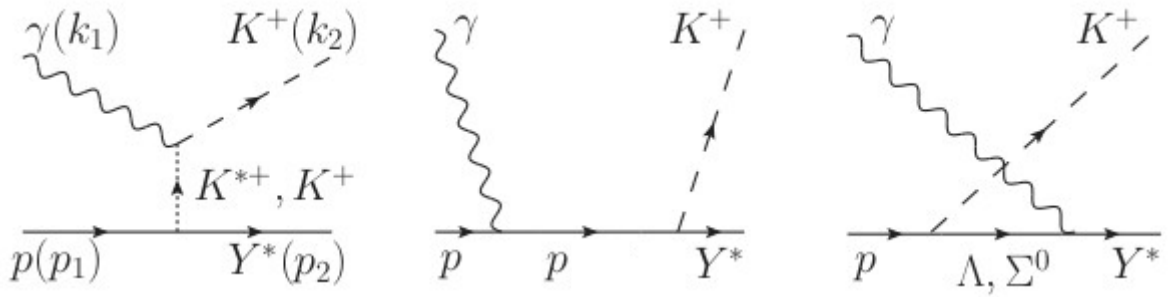
❑ In addition to the Λ(1405) pole, a state in the isovector case was also found at (1399 ± 35) - i (36 ± 9) MeV. We shall refer to this state as Σ(1400).

Model: Photoproduction

❑ We studied the photoproduction $\gamma\, p \to K^+ \Lambda(1405)$, $K^+ \Sigma(1400)$ using effective Lagrangians combined with a Regge model.

[S.H.Kim, K.P.Khemchandani, A.M.Torres, S.i.Nam, A. Hosaka, 2101.08668 [hep-ph]]

> t-, s-, and u-channel Born diagrams



> Data on $\Lambda(1405)$ are already available from CLAS.

[Moriya et al. CLAS, PRC 87, 035206 ; PRC 88, 045201 (2013)]

> Data with high statistics are expected to be released from ELSA facility in Bonn.

[G.Scheluchin, et al. EPJ Web Conf. 241, 01014 (2020)]

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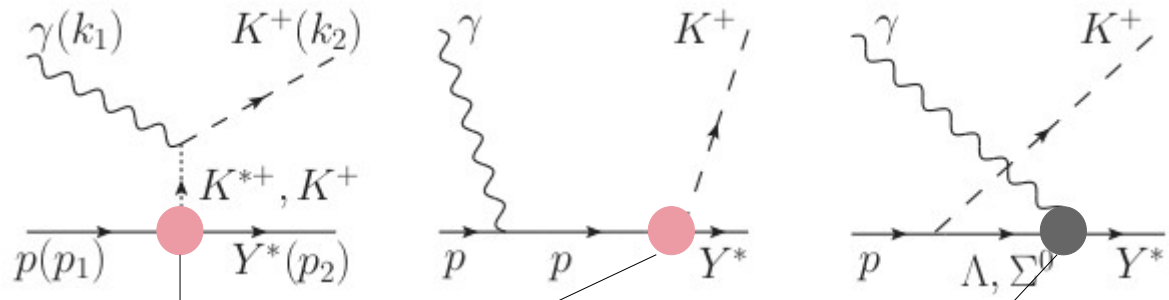
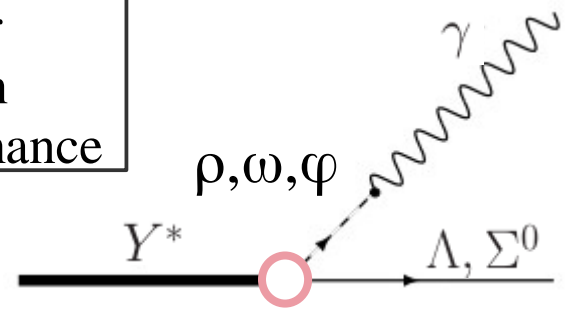


Y^*MB coupling
[K.P.Khemchandani et al. PRC 100, 015208 (2019)]

vector meson dominance



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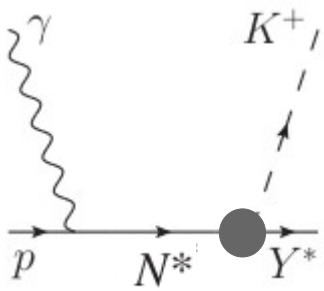
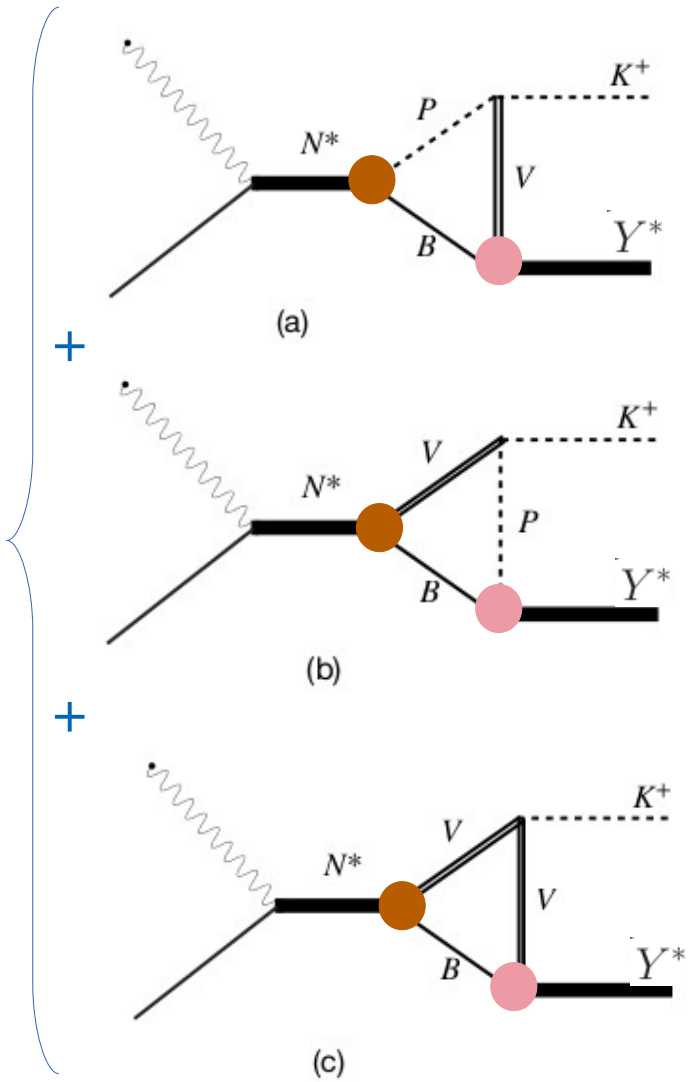
> s-channel $N^*(1895)$ contribution





[Khemchandani et al. PRD 103. 016015 (2021)]

Decay channel	Partial width [MeV]
$N_1^* \to K\Lambda_1^*$	10.4 ± 1.3
$N_1^* \to K\Lambda_2^*$	6.4 ± 0.8
$N_1^* \to K\Sigma^*$	11.4 ± 1.5
$N_2^* \to K\Lambda_1^*$	1.9 ± 0.1
$N_2^* \to K\Lambda_2^*$	1.1 ± 0.2
$N_2^* \to K\Sigma^*$	12.1 ± 1.2

	Branching ratios (%)		Experimental
	$N_1^*(1895)$	$N_2^*(1895)$	data [1]
πN	9.4	10.8	2–18
ηN	2.7	18.1	15–40
$K\Lambda$	10.9	19.4	13–23
$K\Sigma$	0.7	26.0	6–20
ρN	5.6	3.5	<18
ωN	25.7	6.2	16–40
ϕN	8.9	1.1	...
$K^*\Lambda$	12.1	14.0	4–9
$K^*\Sigma$	6.1	0.3	...

[Khemchandani et al. PRD 88.114016 (2013)]

Model: $N^*(1895, 1/2^-)$

- $N^*(1895)$ is the highest mass nucleon known with $J^P = 1/2^-$. PDG lists all $1/2^-$ structures found above 1800 MeV together, under the label of $N^*(1895)$.

- $N^*(1895)$ cannot be described within the naive quark model.
  An S_{11} resonance, within quark models based on the harmonic oscillator potential, after **$N^*(1535)$** & **$N^*(1650)$**, is expected to appear with mass > 2100 MeV.

> Hadron interactions may play an important role in describing $N^*(1895)$.

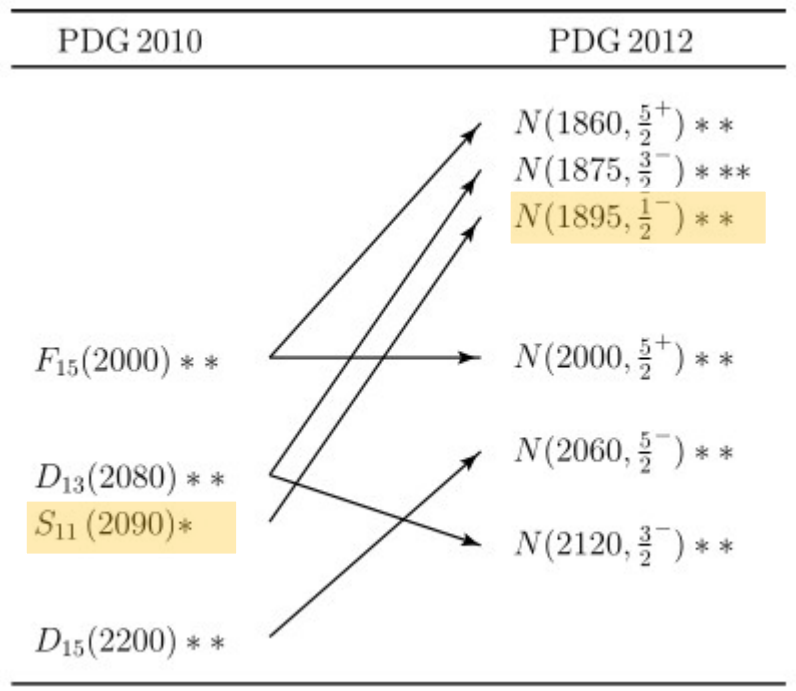
- A clustering of N^*'s around 1890 MeV: $N^*(1895)$, **$N^*(1880, 1/2^+)$**, **$N^*(1900, 3/2^+)$**.

> The properties of N^*'s around 1900 MeV are under continuous debate.

- $N^*(1895)$ used to be listed as **$S_{11}(2090)$** before PDG 2012.

- Several different descriptions have been provided for a peak present around 1900 MeV in the $\gamma\, p \rightarrow K\, \Lambda$ total cross sections.

[PRD 49, 4570 (1994)
PRC 61, 012201 (2000)
EPJA 41, 361 (2009)
PRC 86, 022201 (2012)
EPJA 48, 15 (2012)
PLB 771, 142 (2017)
PRD 100, 056008 (2019)]



Model: $N^*(1895, 1/2^-)$

PHYSICAL REVIEW D **103,** 016015 (2021)

Decay properties of $N^*(1895)$

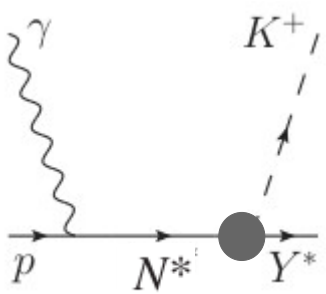
K. P. Khemchandani,[1,2,*] A. Martínez Torres,[3,2,†] H. Nagahiro,[4,2,‡] and A. Hosaka[2,§]

- A recent work found two poles with overlapping widths associated with $N^*(1895)$.

> 1801 – *i* 96 MeV 1912 – *i* 54 MeV

- The PS/V meson-baryon coupled channel amplitudes reproduce, for example, the isospin 1/2 and 3/2 πN amplitudes extracted from PWA of the exp. data and the $\pi^- p \to \eta n$ and $\pi^- p \to K^0 \Lambda$ cross sections up to a total energy of about 2 GeV.

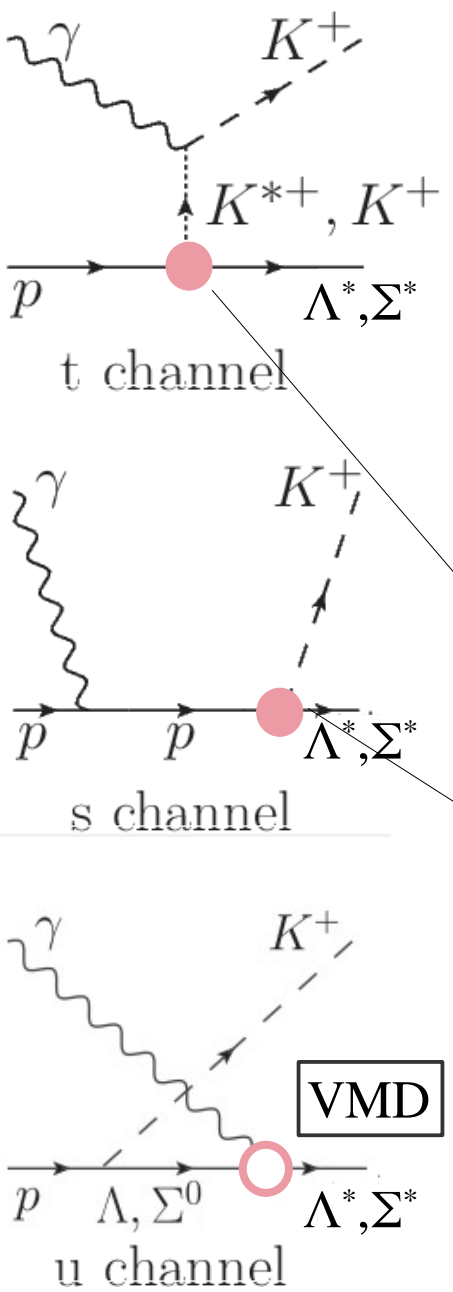
- A recent work obtained the couplings of the meson-baryon channels to $N^*(1895)$ to study its decays to light hyperon resonances.



[Khemchandani et al. PRD 103, 016015 (2021)]

Model: Effective Lagrangians

1. Background contributions



❑ Electromagnetic interactions

$$\mathcal{L}_{\gamma KK} = -ie_K[K^\dagger(\partial_\mu K) - (\partial_\mu K^\dagger)K]A^\mu,$$

$$\mathcal{L}_{\gamma KK^*} = g_{\gamma KK^*}\epsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu[(\partial_\alpha K^{*-}_\beta)K^+ + K^-(\partial_\alpha K^{*+}_\beta)],$$

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

$$\mathcal{L}_{\gamma\Lambda^*\Lambda^*} = \frac{e\kappa_{\Lambda^*}}{2M_N}\bar{\Lambda}^*\sigma_{\mu\nu}\partial^\nu A^\mu\Lambda^*,$$

$$\mathcal{L}_{\gamma Y\Lambda^*} = \frac{e\kappa_{\Lambda^*\to Y\gamma}}{2M_N}\bar{Y}\gamma_5\sigma_{\mu\nu}\partial^\nu A^\mu\Lambda^* + \text{H.c.},$$

❑ Strong interactions

$$\mathcal{L}_{KNY} = -ig_{KNY}\bar{N}\gamma_5 YK + \text{H.c.},$$

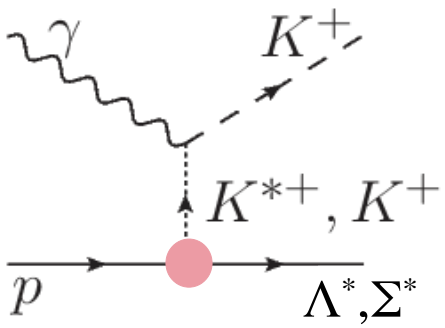
$$\mathcal{L}_{KN\Lambda^*} = -ig_{KN\Lambda^*}\bar{N}\Lambda^* K + \text{H.c.},$$

$$\mathcal{L}_{K^*N\Lambda^*} = -g_{K^*N\Lambda^*}\bar{N}\gamma_5\gamma_\mu\Lambda^* K^{*\mu} + \text{H.c.}$$

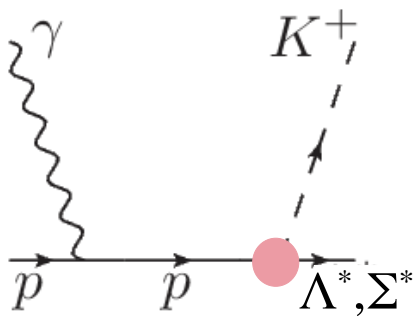
form factor: $F_B(q^2) = \left[\frac{\Lambda_B^4}{\Lambda_B^4 + (q^2 - M_B^2)^2}\right]^2$

Model: Effective Lagrangians

1. Background contributions



t channel



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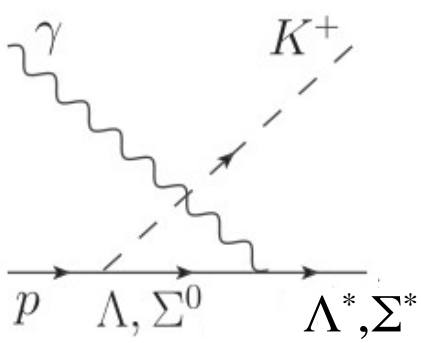


u channel

Coupling constants

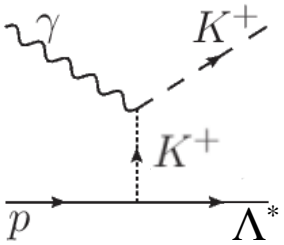
[K.P.Khemchandani, A.M.Torres, and J.A.Oller, PRC 100, 015208 (2019)]

	$\Lambda(1405)$		Σ's around 1400 MeV	
	$1385^{\pm5} - i\,124^{\pm10}$	$1426^{\pm1} - i\,15^{\pm2}$	–	$1399^{\pm35} - i\,36^{\pm9}$
KN	$0.66^{\pm0.35} - i\,1.93^{\pm0.12}$	$2.43^{\pm0.16} + i\,0.63^{\pm0.23}$	–	$0.50^{\pm0.29} + i\,0.33^{\pm0.18}$
$\bar{K}^*N$	$0.62^{\pm0.28} - i\,0.18^{\pm0.14}$	$0.04^{\pm0.36} + i0.23^{\pm0.19}$	–	$-3.46^{\pm0.21} - i\,0.06^{\pm0.15}$

	$\Lambda(1405)$	Σ's around 1400 MeV
KN	$1.75 - i\,0.7$	$0.50 + i\,0.33$
$\bar{K}^*N$	$0.3 + i0.03$	$-3.46 - i\,0.06$

$g_{KN\Lambda^*} > g_{KN\Sigma^*}$

$g_{K^*N\Lambda^*} < g_{K^*N\Sigma^*}$



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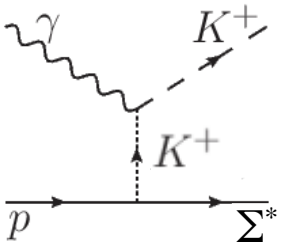

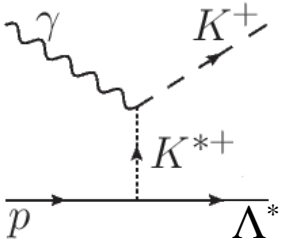

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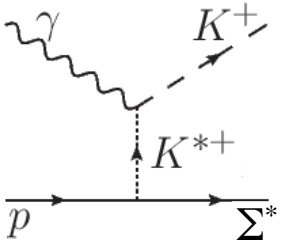
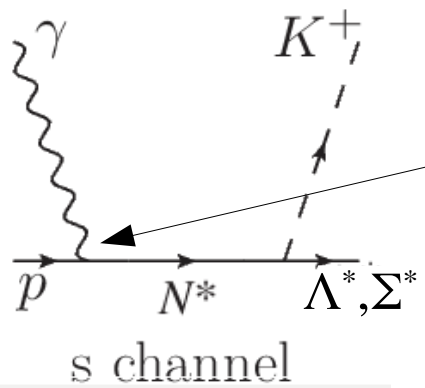


2 (a). N*(1895) contribution



❑ Electromagnetic interactions are well known.

$$\mathcal{L}^{1/2^\pm}_{\gamma N N^*} = \frac{e h_1}{2M_N} \bar{N}\Gamma^\mp \sigma_{\mu\nu}\partial^\nu A^\mu N^* + \text{H.c.},$$

$$\mathcal{L}^{3/2^\pm}_{\gamma N N^*} = -ie\left[\frac{h_1}{2M_N}\bar{N}\Gamma^\pm_\nu - \frac{ih_2}{(2M_N)^2}\partial_\nu \bar{N}\Gamma^\pm\right] F^{\mu\nu} N^*_\mu + \text{H.c.},$$

$$\mathcal{L}^{5/2^\pm}_{\gamma N N^*} = e\left[\frac{h_1}{(2M_N)^2}\bar{N}\Gamma^\mp_\nu - \frac{ih_2}{(2M_N)^3}\partial_\nu \bar{N}\Gamma^\mp\right] \partial^\alpha F^{\mu\nu} N^*_{\mu\alpha} + \text{H.c.},$$

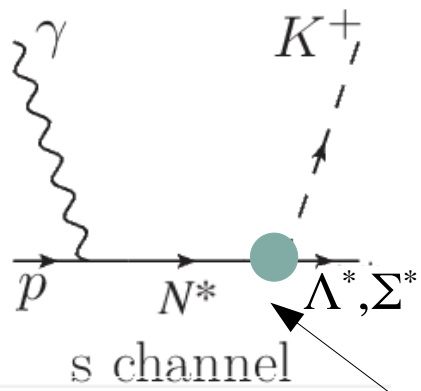
$$\mathcal{L}^{7/2^\pm}_{\gamma N N^*} = ie\left[\frac{h_1}{(2M_N)^3}\bar{N}\Gamma^\pm_\nu - \frac{ih_2}{(2M_N)^4}\partial_\nu \bar{N}\Gamma^\pm\right] \partial^\alpha\partial^\beta F^{\mu\nu} N^*_{\mu\alpha\beta} + \text{H.c.}$$

$$\Gamma^\pm = \begin{pmatrix} \gamma_5 \\ I_{4\times4} \end{pmatrix}, \quad \Gamma^\pm_\nu = \begin{pmatrix} \gamma_\nu\gamma_5 \\ \gamma_\nu \end{pmatrix}$$

Gaussian form factor:

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

2 (a). N*(1895) contribution



$$\Gamma^{\pm} = \begin{pmatrix} \gamma_5 \\ I_{4\times4} \end{pmatrix}, \quad \Gamma^{\pm}_{\nu} = \begin{pmatrix} \gamma_\nu\gamma_5 \\ \gamma_\nu \end{pmatrix}$$

❑ Electromagnetic interactions are well known.

$$\mathcal{L}^{1/2^\pm}_{\gamma NN^*} = \frac{eh_1}{2M_N}\bar{N}\Gamma^{\mp}\sigma_{\mu\nu}\partial^\nu A^\mu N^* + \text{H.c.},$$

$$\mathcal{L}^{3/2^\pm}_{\gamma NN^*} = -ie\left[\frac{h_1}{2M_N}\bar{N}\Gamma^{\pm}_{\nu} - \frac{ih_2}{(2M_N)^2}\partial_\nu\bar{N}\Gamma^{\pm}\right]F^{\mu\nu}N^*_\mu + \text{H.c.},$$

$$\mathcal{L}^{5/2^\pm}_{\gamma NN^*} = e\left[\frac{h_1}{(2M_N)^2}\bar{N}\Gamma^{\mp}_{\nu} - \frac{ih_2}{(2M_N)^3}\partial_\nu\bar{N}\Gamma^{\mp}\right]\partial^\alpha F^{\mu\nu}N^*_{\mu\alpha} + \text{H.c.},$$

$$\mathcal{L}^{7/2^\pm}_{\gamma NN^*} = ie\left[\frac{h_1}{(2M_N)^3}\bar{N}\Gamma^{\pm}_{\nu} - \frac{ih_2}{(2M_N)^4}\partial_\nu\bar{N}\Gamma^{\pm}\right]\partial^\alpha\partial^\beta F^{\mu\nu}N^*_{\mu\alpha\beta} + \text{H.c.}$$

❑ No direct information

$$\mathcal{L}^{1/2^\pm}_{K\Lambda^*N^*} = -ig_{K\Lambda^*N^*}\bar{K}\bar{\Lambda}^*\Gamma^{\mp}N^* + \text{H.c.},$$

$$\mathcal{L}^{3/2^\pm}_{K\Lambda^*N^*} = \frac{g_{K\Lambda^*N^*}}{M_K}\partial^\mu\bar{K}\bar{\Lambda}^*\Gamma^{\pm}N^*_\mu + \text{H.c.},$$

$$\mathcal{L}^{5/2^\pm}_{K\Lambda^*N^*} = \frac{ig_{K\Lambda^*N^*}}{M_K^2}\partial^\mu\partial^\nu\bar{K}\bar{\Lambda}^*\Gamma^{\mp}N^*_{\mu\nu} + \text{H.c.},$$

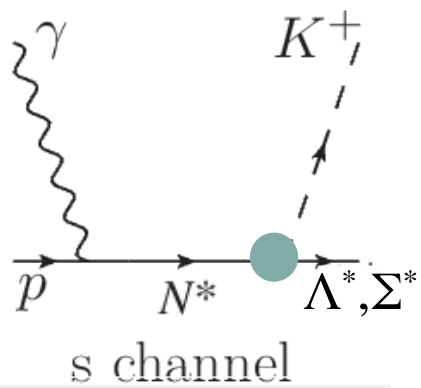
$$\mathcal{L}^{7/2^\pm}_{K\Lambda^*N^*} = -\frac{g_{K\Lambda^*N^*}}{M_K^3}\partial^\mu\partial^\nu\partial^\alpha\bar{K}\bar{\Lambda}^*\Gamma^{\pm}N^*_{\mu\nu\alpha} + \text{H.c.}$$

Gaussian form factor:

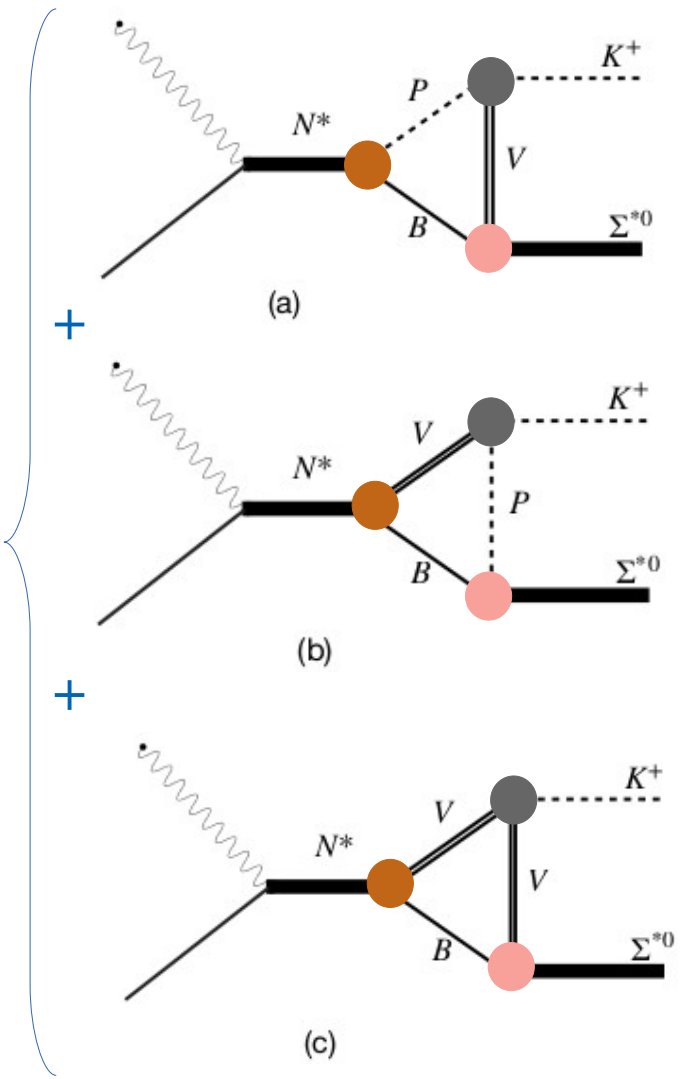
$$F_{\mathrm{N}^*}(q_s^2) = \exp\left\{-\frac{(q_s^2 - M_{N^*}^2)^2}{\Lambda_{N^*}^4}\right\}$$

Model: Effective Lagrangians

2 (a). N*(1895) contribution



[Khemchandani et al. PRD 103, 016015 (2021)]



Channel in the loop
$\rho^0 p K^+$
$\omega p K^+$
$\phi p K^+$
$\rho^+ n K^0$
$K^{*+}(892)\Lambda\pi^0$
$K^{*+}(892)\Sigma^0\pi^0$
$K^{*+}(892)\Sigma^0\eta$
$K^{*0}(892)\Sigma^+\pi^+$

: The couplings are well known.

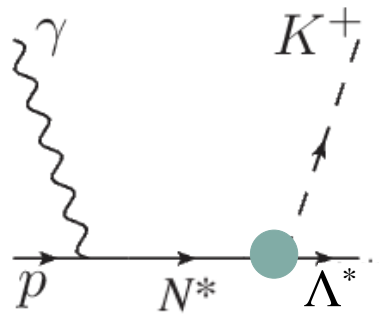
[Khemchandani et al. PRD.88.114016 (2013)]

[Khemchandani et al. PRC.100.015208 (2019)]

❑ For γ p → K⁺ Λ(1405), we include other N*'s besides N*(1895).

Model: Effective Lagrangians

2 (b). N^* contributions



s channel

$$m_l + m_f = m_j$$

$$\Gamma(N^* \to K\Lambda^*) = \sum_\ell |G(\ell)|^2$$

$N^*(2000, 5/2^+)$	PDG resonances
$N^*(2100, 1/2^+)$	PDG 〃
$N^*(2030, 1/2^-)$	missing resonances
$N^*(2055, 3/2^-)$	missing 〃
$N^*(2095, 3/2^-)$	missing 〃

[S.H.Kim et al. PRD.96.014003 (2017)]

"Strong coupling constants" $g_{K\Lambda^* N^*}$ &
"Decay amplitudes" $G(\ell)$

$$\langle K(\mathbf{q})\Lambda^*(-\mathbf{q}, m_f)| - i\mathcal{H}_{int}|N^*(\mathbf{0}, m_j)\rangle$$
$$= 4\pi M_{N^*}\sqrt{\frac{2}{q}}\sum_{l,m_l}\langle l m_l \tfrac{1}{2} m_f | j m_j\rangle Y_{l m_l}(\hat{\mathbf{q}}) G(\ell)$$

$$\begin{cases} G(0) = \sqrt{\dfrac{|\vec{q}|(E_{\Lambda^*} + M_{\Lambda^*})}{4\pi M_{N^*}}}\, g_{K\Lambda^* N^*} & j = \frac{1}{2}^+ \\ G(1) = -\sqrt{\dfrac{|\vec{q}|(E_{\Lambda^*} - M_{\Lambda^*})}{4\pi M_{N^*}}}\, g_{K\Lambda^* N^*} & j = \frac{1}{2}^- \end{cases}$$

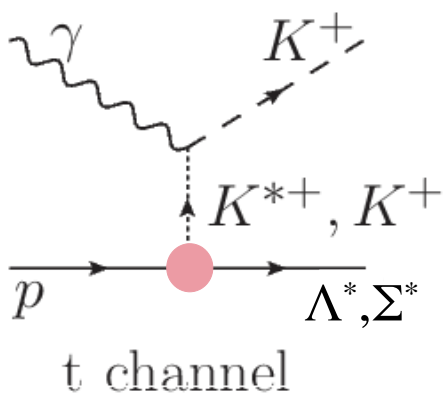
$$\begin{cases} G(2) = -\sqrt{\dfrac{|\vec{q}|^3(E_{\Lambda^*} - M_{\Lambda^*})}{12\pi M_{N^*}}}\, \dfrac{g_{K\Lambda^* N^*}}{M_K} & j = \frac{3}{2}^+ \\ G(1) = \sqrt{\dfrac{|\vec{q}|^3(E_{\Lambda^*} + M_{\Lambda^*})}{12\pi M_{N^*}}}\, \dfrac{g_{K\Lambda^* N^*}}{M_K} & j = \frac{3}{2}^- \end{cases}$$

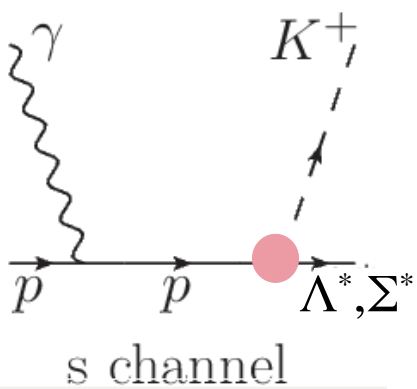
$$\begin{cases} G(2) = \sqrt{\dfrac{|\vec{q}|^5(E_{\Lambda^*} + M_{\Lambda^*})}{30\pi M_{N^*}}}\, \dfrac{g_{K\Lambda^* N^*}}{M_K^2} & j = \frac{5}{2}^+ \\ G(3) = -\sqrt{\dfrac{|\vec{q}|^5(E_{\Lambda^*} - M_{\Lambda^*})}{30\pi M_{N^*}}}\, \dfrac{g_{K\Lambda^* N^*}}{M_K^2} & j = \frac{5}{2}^- \end{cases}$$

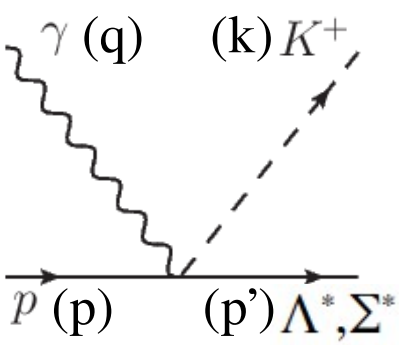
- For $\gamma\, p \to K^+\, \Lambda(1405)$,
  we include other N^*'s besides $N^*(1895)$.

constituent quark model
Capstick, PRD 58. 074011 (1998)

Model: Gauge invariance







❑ Scalar scheme $\mathcal{L}_{KNY^*} = g_{KNY^*}\bar{K}\bar{Y}^* N + \text{H.c.}$

$$\mathcal{M} = \underline{(\mathcal{M}_K + \mathcal{M}_N^{\text{elec}})}\,(t - M_K^2)P_K^{\text{Regge}} + \mathcal{M}_{K^*}(t - M_{K^*}^2)P_{K^*}^{\text{Regge}}$$

❑ Vector scheme $\mathcal{L}^V_{KNY^*} = i f_{KNY^*}\partial^\mu \bar{K}\bar{Y}^*\gamma_\mu N + \text{H.c.}$

> Contact term is additionally needed. ($\partial^\mu \rightarrow -ieA^\mu$)

A. Global gauge invariance by multiplying common FF

$\hat{F} = f_t + f_s - f_t f_s$

[R.M.Davidson, R.Workman, PRC 63. 025210 (2011)]

$$\mathcal{M}^V = \underline{\left(\mathcal{M}_K^V + \mathcal{M}_N^{\text{elec,V}} + \mathcal{M}_C\right)} \cdot \hat{F}$$

B. Local gauge invariance

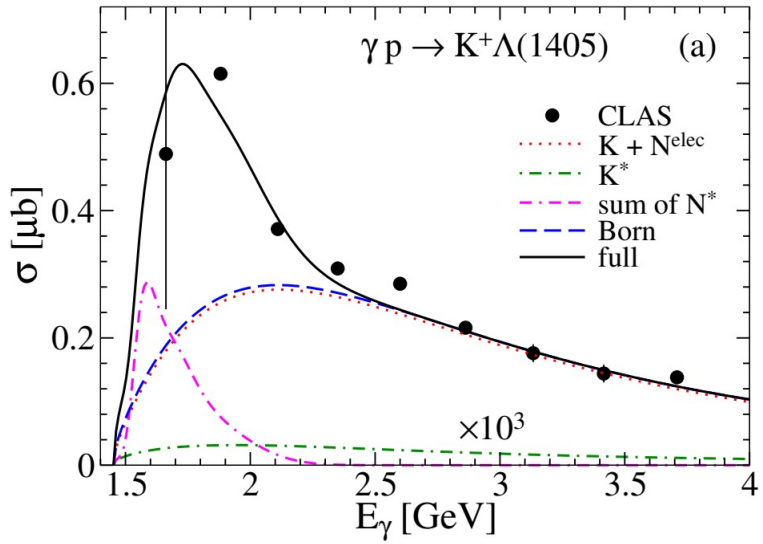
[H.Haberzettl, K.Nakayama,S.Krewald, PRC 74. 045202 (2006)]

[Y.Oh, C.M.Ko, K.Nakayama, PRC 77, 045204 (2008) $\gamma p \rightarrow K^+\Sigma^*(1385)$]

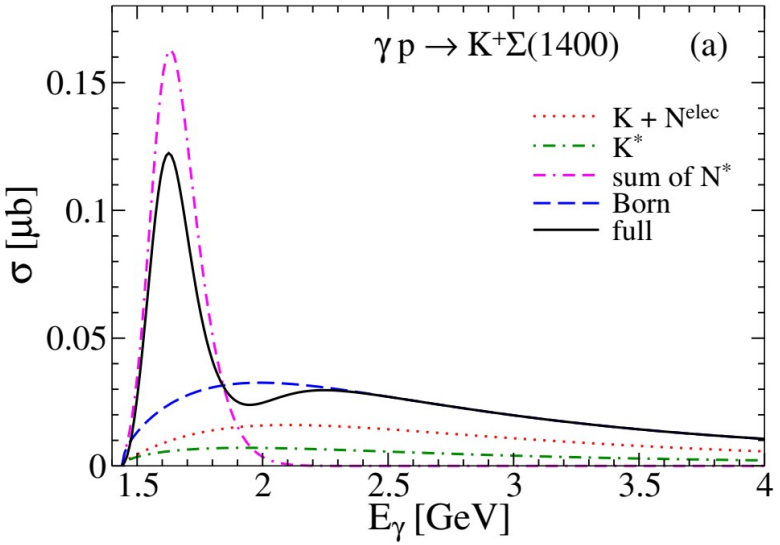
$$\mathcal{M}^V = \underline{\mathcal{M}_K^V} f_t + \underline{\mathcal{M}_N^{\text{elec,V}}} f_s + \underline{\mathcal{M}_C} f_t + C^\mu A_\mu$$

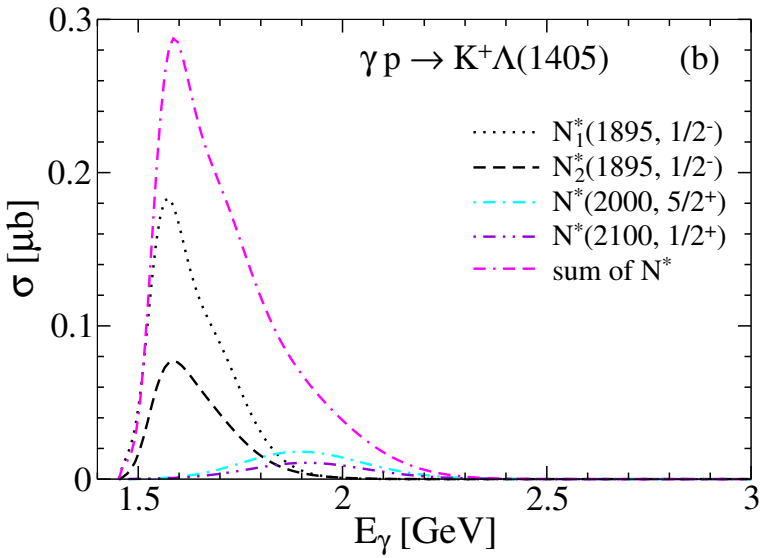
$$C^\mu = -e\frac{f_t - \hat{F}}{t - q^2}(2q - k)^\mu - e\frac{f_s - \hat{F}}{s - p^2}(2p + k)^\mu$$

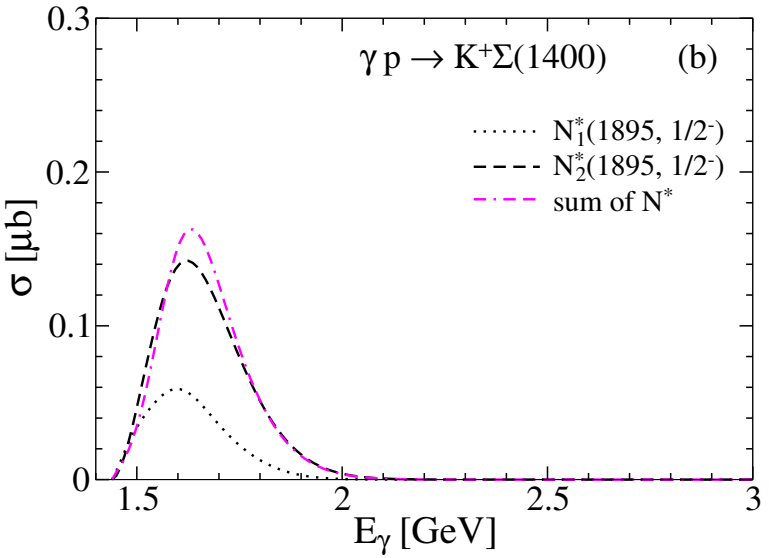
Results: Total & differential cross sections



10 ×

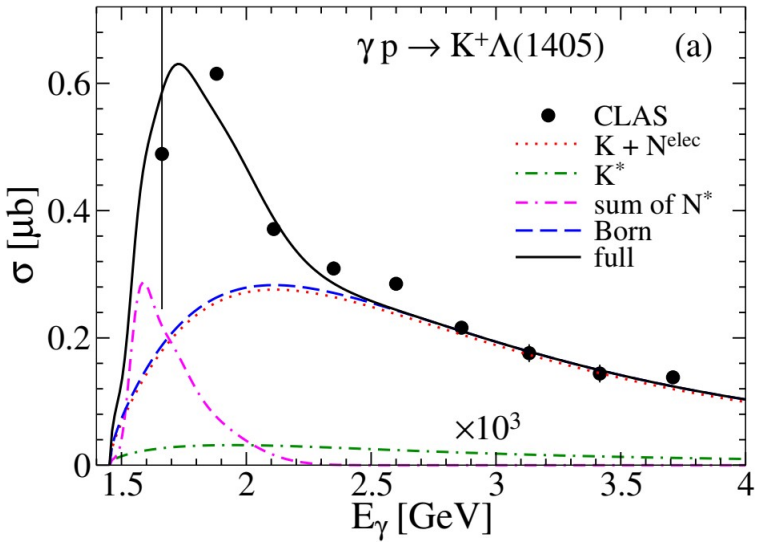




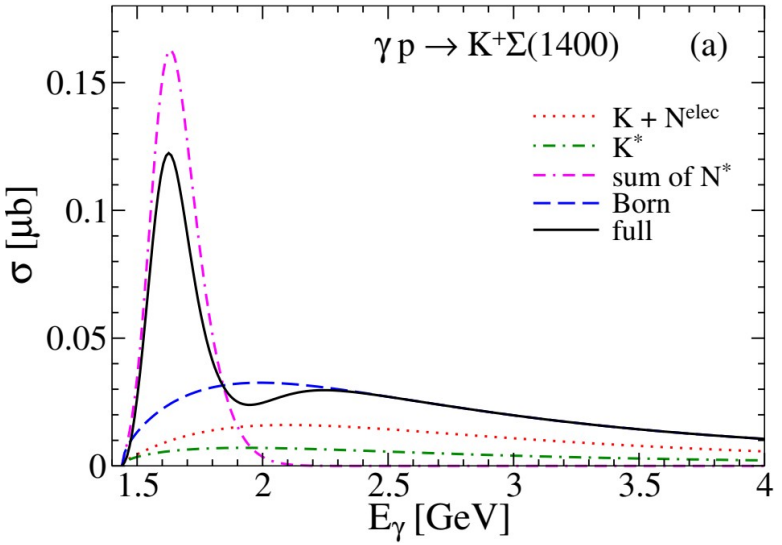


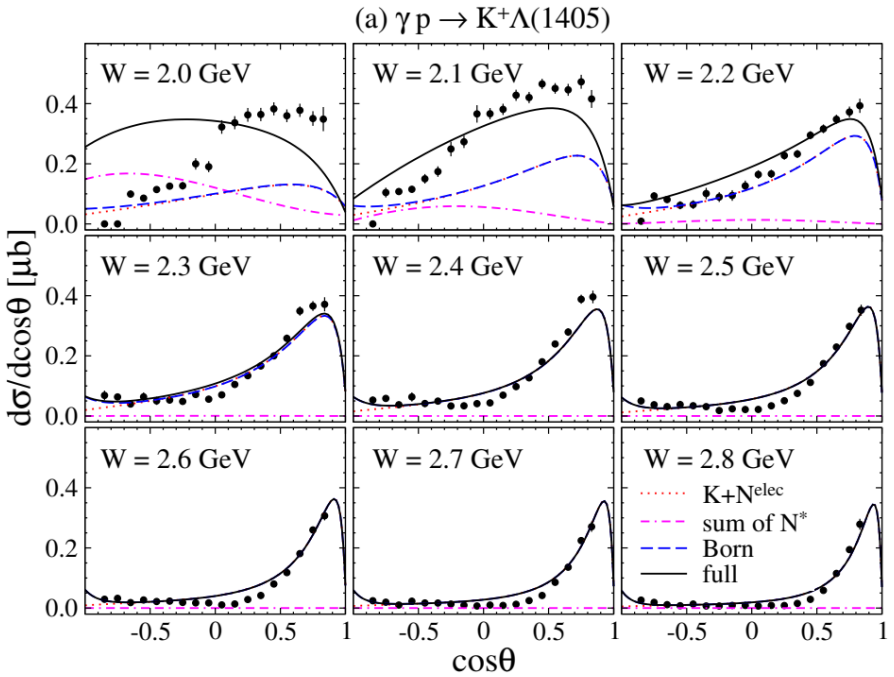
- **$N^*(2000, 5/2^+)$ & $N^*(2100, 1/2^+)$** are much suppressed than $N^*(1895, 1/2^-)$.

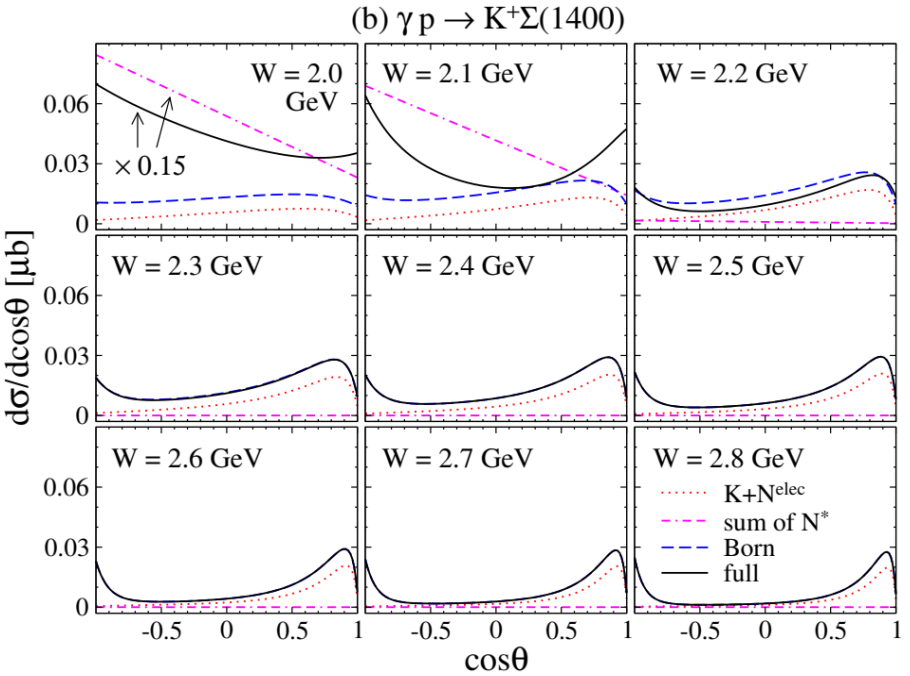
Results: Total & differential cross sections



10 ×



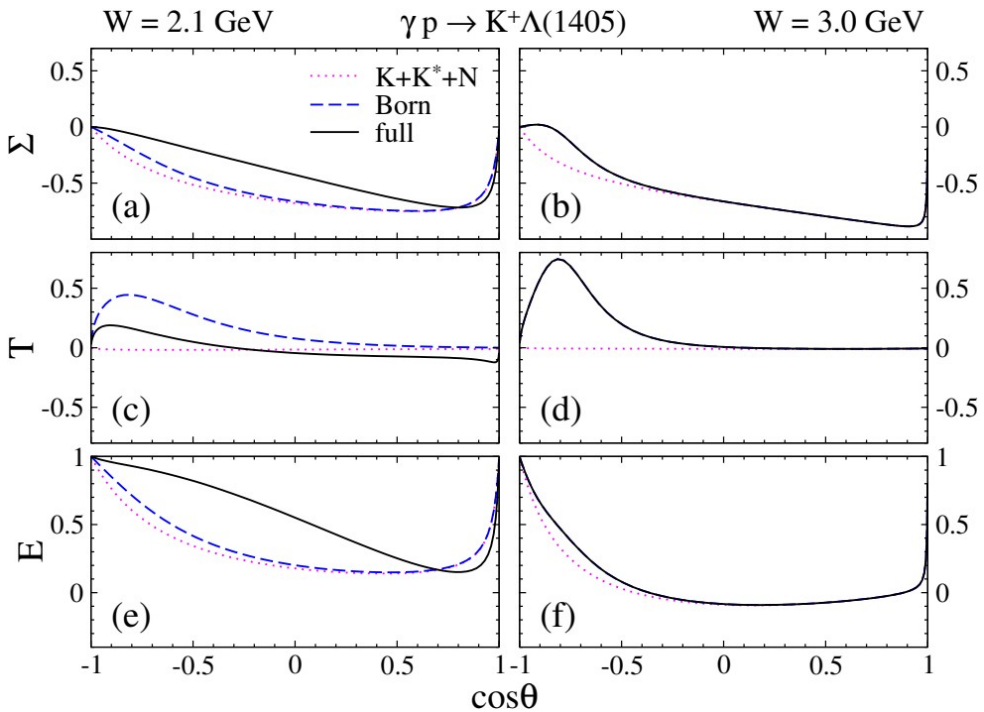


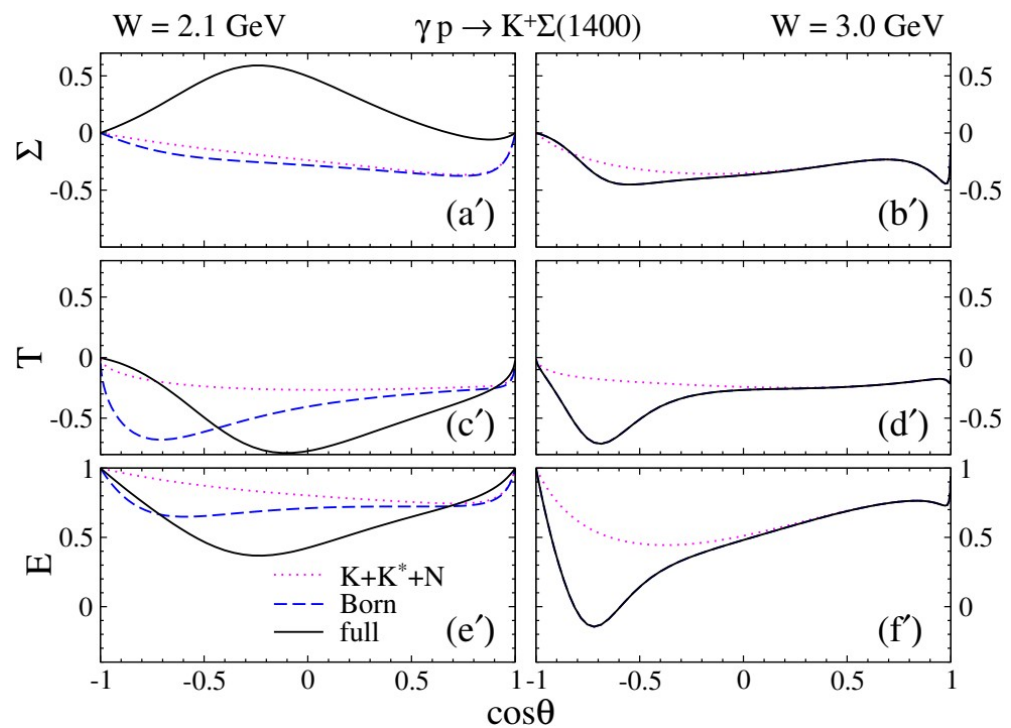


- ❑ K-Regge exchange is the main contribution for both reactions.
- ❑ K^*-Regge exchange is much enhanced for $K^+\Sigma(1400)$ production.

[Moriya (CLAS) PRC.88.045201 (2013)]

Results: Spin polarization observables

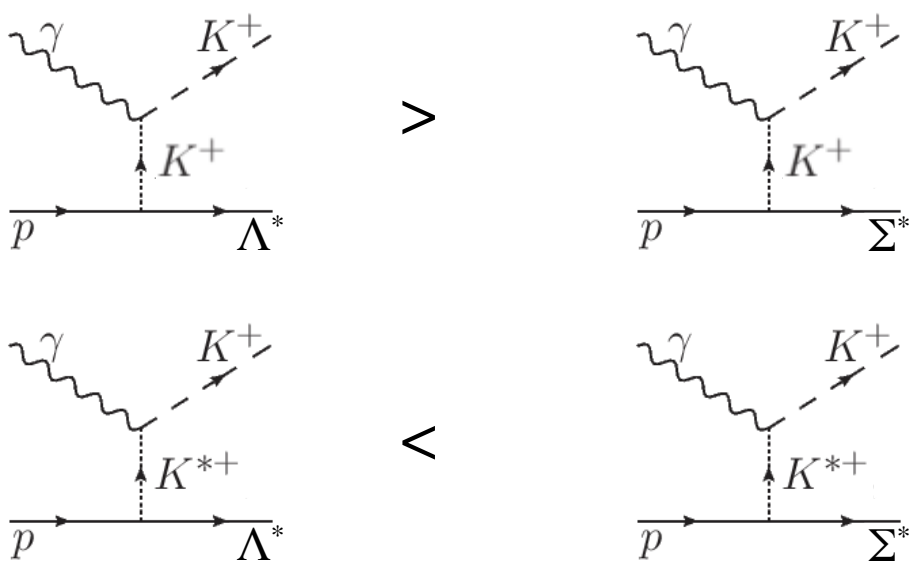




$$\Sigma = \frac{\sigma^{(\perp,0,0)} - \sigma^{(\parallel,0,0)}}{\sigma^{(\perp,0,0)} + \sigma^{(\parallel,0,0)}},$$

$$T = \frac{\sigma^{(0,+y,0)} - \sigma^{(0,-y,0)}}{\sigma^{(0,+y,0)} + \sigma^{(0,-y,0)}},$$

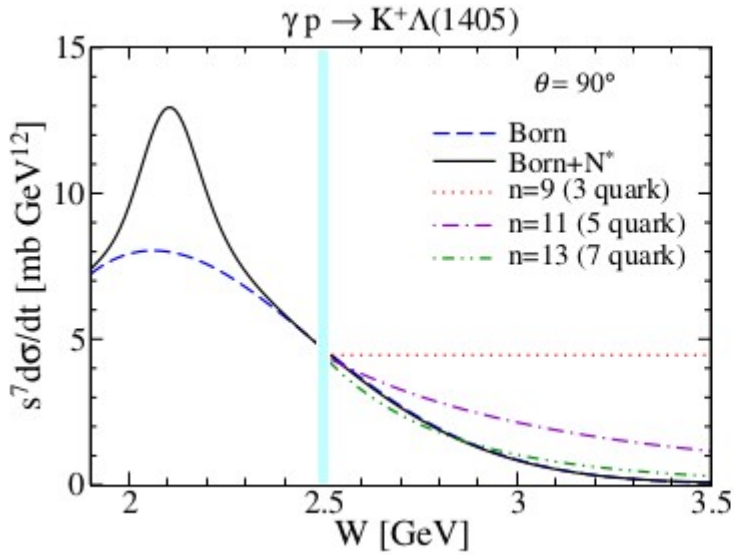
$$E = \frac{\sigma^{(r,+z,0)} - \sigma^{(r,-z,0)}}{\sigma^{(r,+z,0)} + \sigma^{(r,-z,0)}},$$

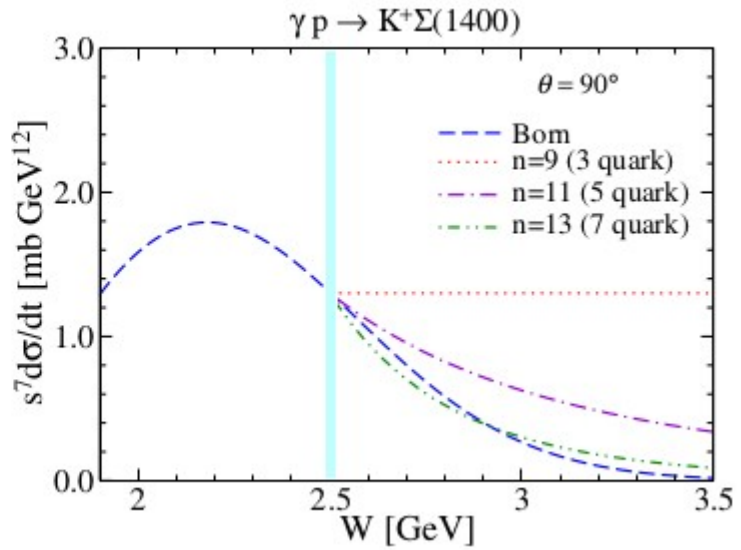


❑ The reactions can be distinguished by measuring the spin asymmetries.

Results: Constituent counting rule

- CCR is a method to analyze the internal structure of the hadrons by dimensional considerations of the reaction amplitude in terms of the quark and gluon propagators at the large angle as well as the high energy.





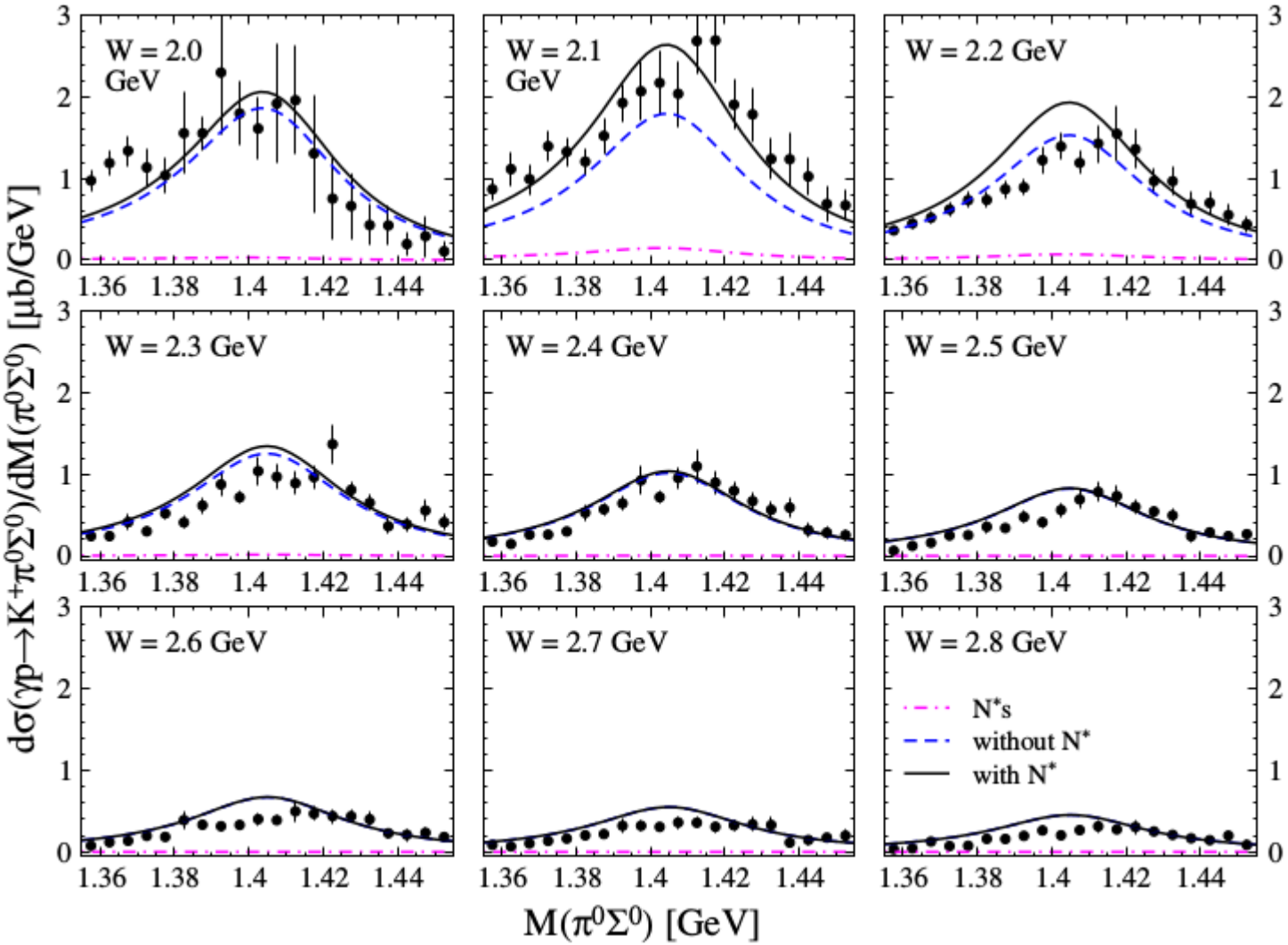
$$\frac{d\sigma_{ab\to cd}}{dt} \propto \frac{1}{s^{n-2}}$$

- If Λ^* & Σ^* are composed of three quarks, $1\gamma + 3N + 2K + 3(\Lambda^*,\Sigma^*) = 9$
  〃 five , $1\gamma + 3N + 2K + 5(\Lambda^*,\Sigma^*) = 11$

- Λ^* & Σ^* are possibly distinctive from the simple *uds*-quark state.

Results: Invariant mass distributions

$\gamma\, p \rightarrow K^{+}\, \Lambda(1405)$



[Moriya (CLAS) PRC.88.045201 (2013)]
[S.H.Kim et al. PRD.96.014003 (2017)]

$$\frac{d\sigma_{\gamma p\to K^{+}\pi^{0}\Sigma^{0}}}{dM_{\pi^{0}\Sigma^{0}}} \approx \frac{2M_{\Lambda^{*}}M_{\pi^{0}\Sigma^{0}}}{\pi} \frac{\sigma_{\gamma p\to K^{+}\Lambda^{*}}\Gamma_{\Lambda^{*}\to\pi^{0}\Sigma^{0}}}{(M^{2}_{\pi^{0}\Sigma^{0}}-M^{2}_{\Lambda^{*}})^{2}+M^{2}_{\Lambda^{*}}\Gamma^{2}_{\Lambda^{*}}}$$

Assumptions

- ❑ The decay widths for the decaying resonances are sufficiently narrow.
- ❑ The interference between the different resonances in the Dalitz plot is negligible.

Summary – 1

◇ The photoproduction $\gamma p \to K^+\Lambda(1405)$ & $\gamma p \to K^+\Sigma(1400)$ is studied using an effective Lagrangian approach combining with a Regge model.

◇ K-Reggeon exchange is a dominant contribution to both reactions.
◇ K^*-Reggeon exchange is sizable only for the $K^+\Sigma(1400)$ production.

◇ The cross section of $K^+\Sigma(1400)$ is an order of magnitude suppressed relative to $K^+\Lambda(1405)$, but is sizable to be measured in the future experiments.

◇ $N^*(1895, 1/2^-)$ is crucial to reproduce the CLAS data for $K^+\Lambda(1405)$ production.

Contents

1. Photoproduction of $J^P = 1/2^-$ hyperons off nucleons:
   $\gamma\, p \rightarrow K^+\, \Lambda(1405)$ & $K^+\, \Sigma(1400)$

   > Introduction
   > Model
   > Results
   > Summary

2. Photo- & electro-production of φ and J/ψ mesons off nucleons:
   $\gamma^{(*)}\, p \rightarrow V\, p$, $V = \varphi, J/\psi$

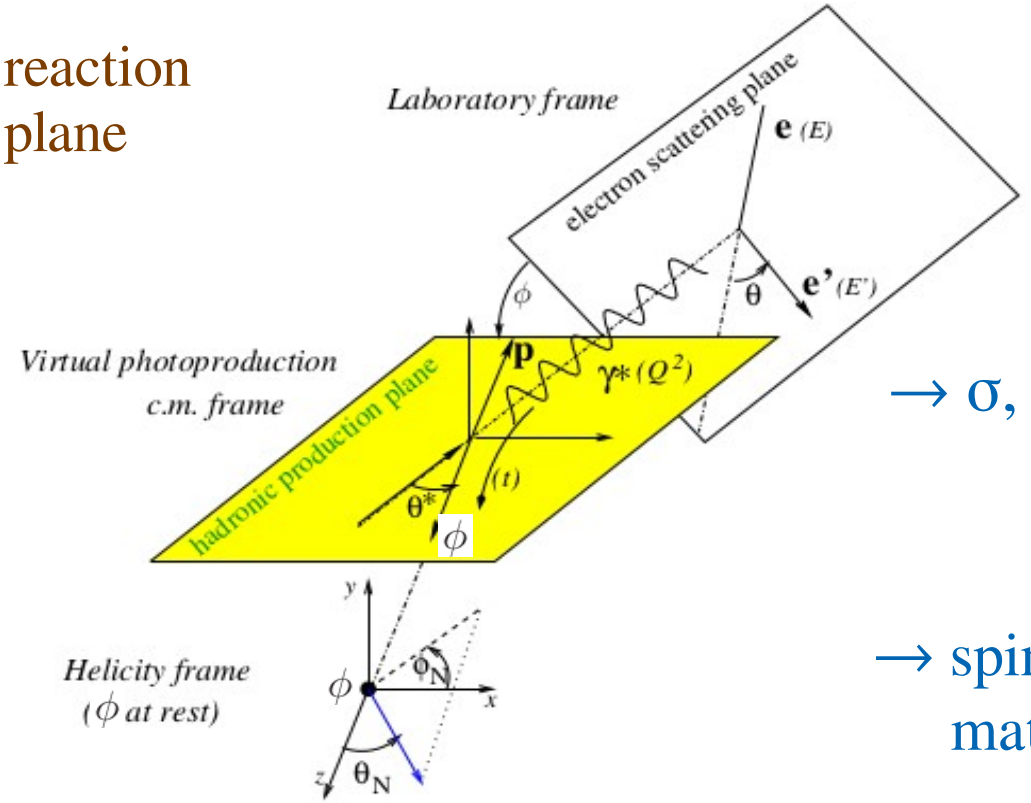
   > Introduction
   > Results: A. $\gamma\, p \rightarrow \varphi\, p$
   B. $\gamma^*\, p \rightarrow \varphi\, p$
   C. $\gamma\, p \rightarrow J/\psi\, p$
   > Summary

※ Current and future works

Introduction: Photo- and electro-production of vector-mesons

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

reaction plane



- photon(γ) polarization vector

Transverse comp. ($\lambda_\gamma = \pm 1$) [photo-, electro-]

Longitudinal comp. ($\lambda_\gamma = 0$) [electro-]

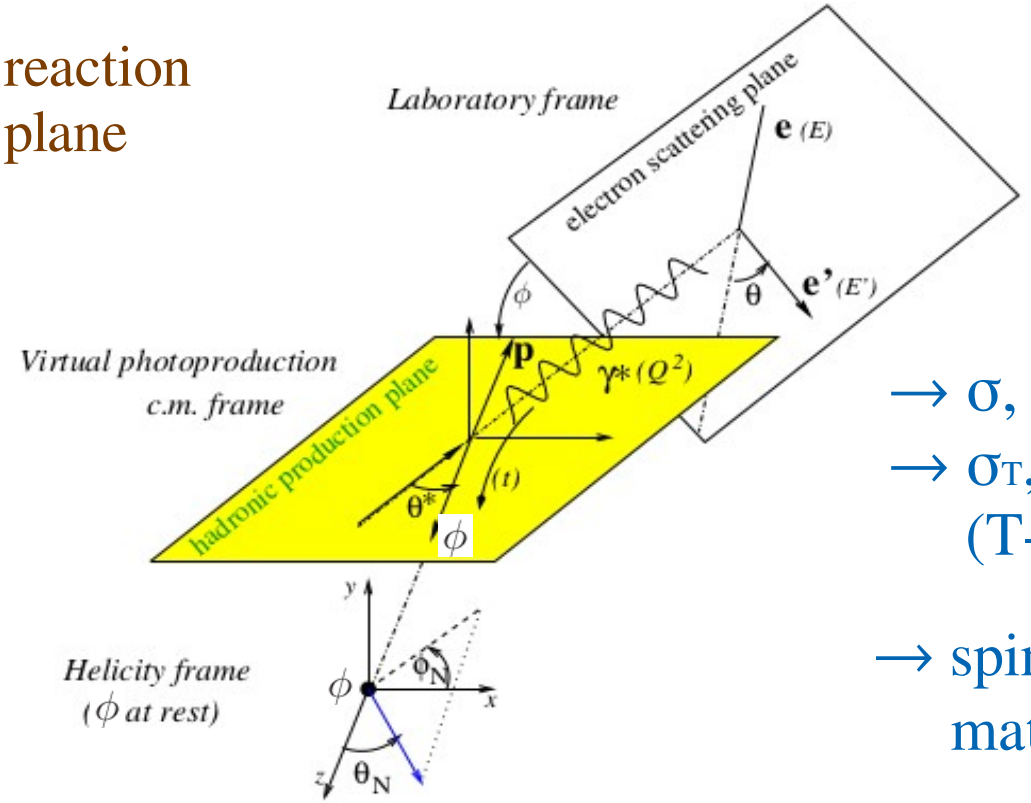
→ σ, $d\sigma/d\Omega$, $d\sigma/dt$ [photo-, electro-]

→ spin-density matrix elements (ρ_{ij}) [photo-, electro-]

Introduction: Photo- and electro-production of vector-mesons

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

reaction plane



- photon(γ) polarization vector

Transverse comp. ($\lambda_\gamma = \pm 1$) [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-]

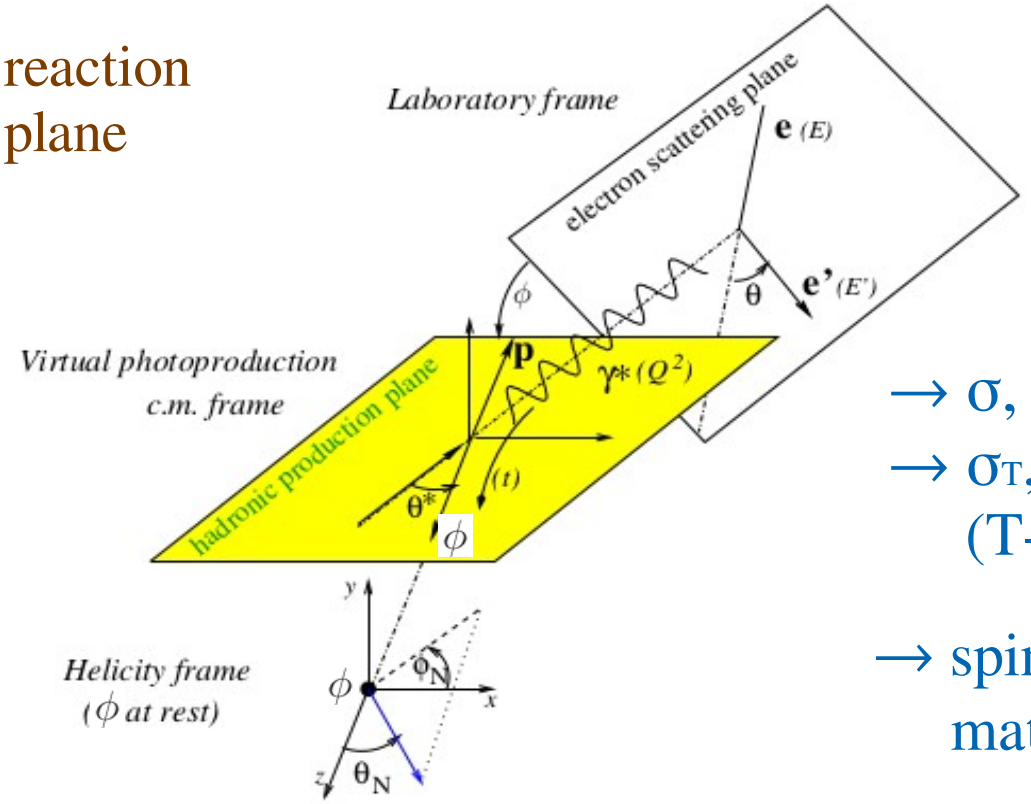
(T-L separated cross sections)

→ spin-density matrix elements (ρ_{ij}) [photo-, electro-]

Introduction: Photo- and electro-production of vector-mesons

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

reaction plane



- 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-]

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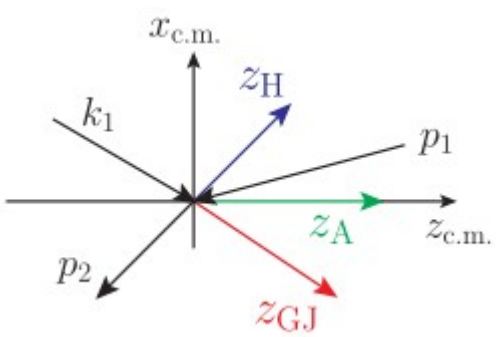
→ spin-density matrix elements (ρ_{ij}) [photo-, electro-]



• V-meson rest frame

Adair frame

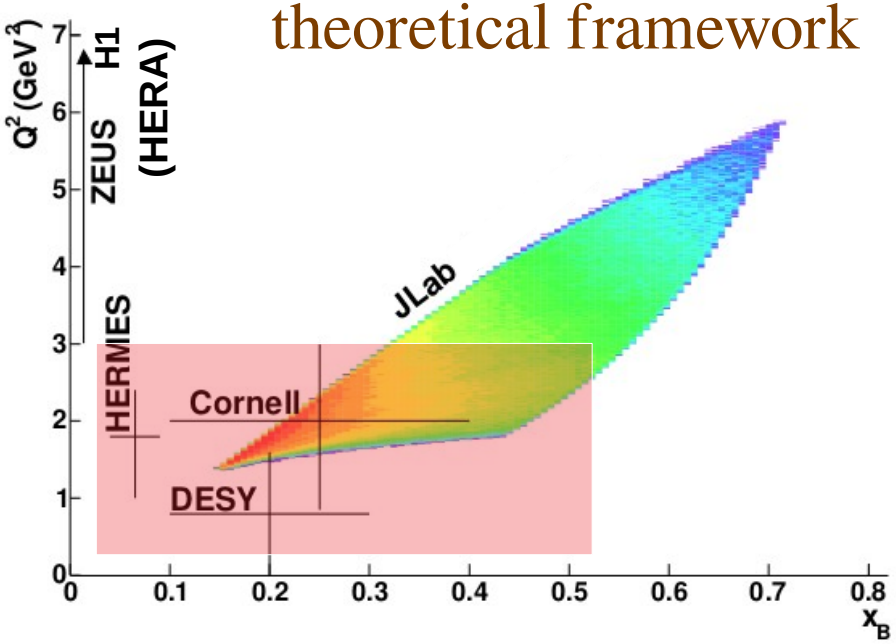
Helicty frame:
in favor of s-channel helicity conservation (SCHC)

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

Introduction: Photo- and electro-production of vector-mesons

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

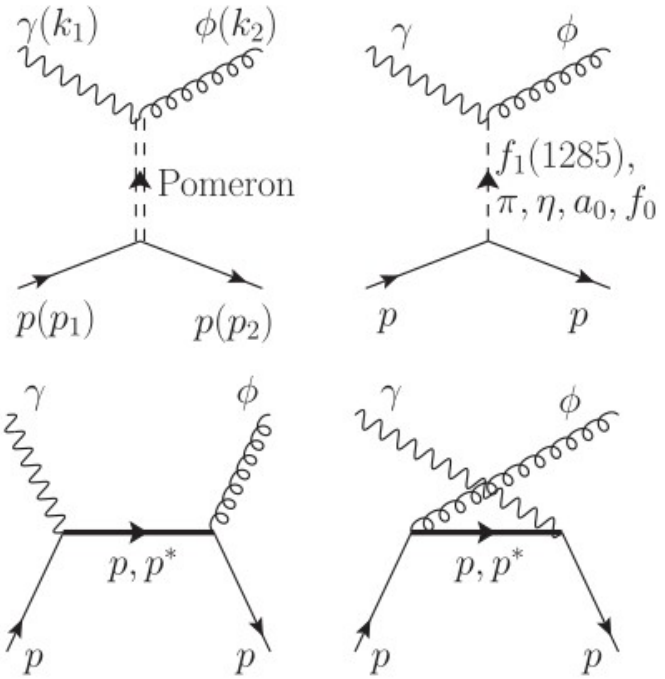
theoretical framework



[Kinematical range covered by vector meson electoproduction experiments]

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

Feynman diagrams



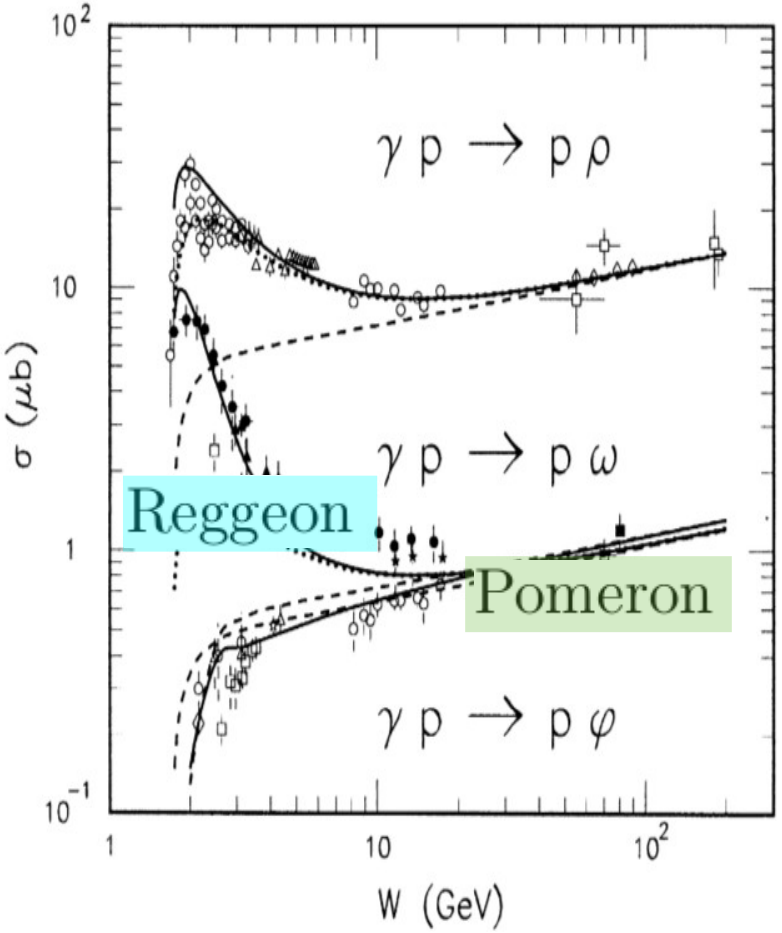
- We can test which of the two descriptions - with "hadronic" or "quark" degrees of freedom - applies in the considered kinematical domain.

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

Introduction: Photo- and electro-production of vector-mesons

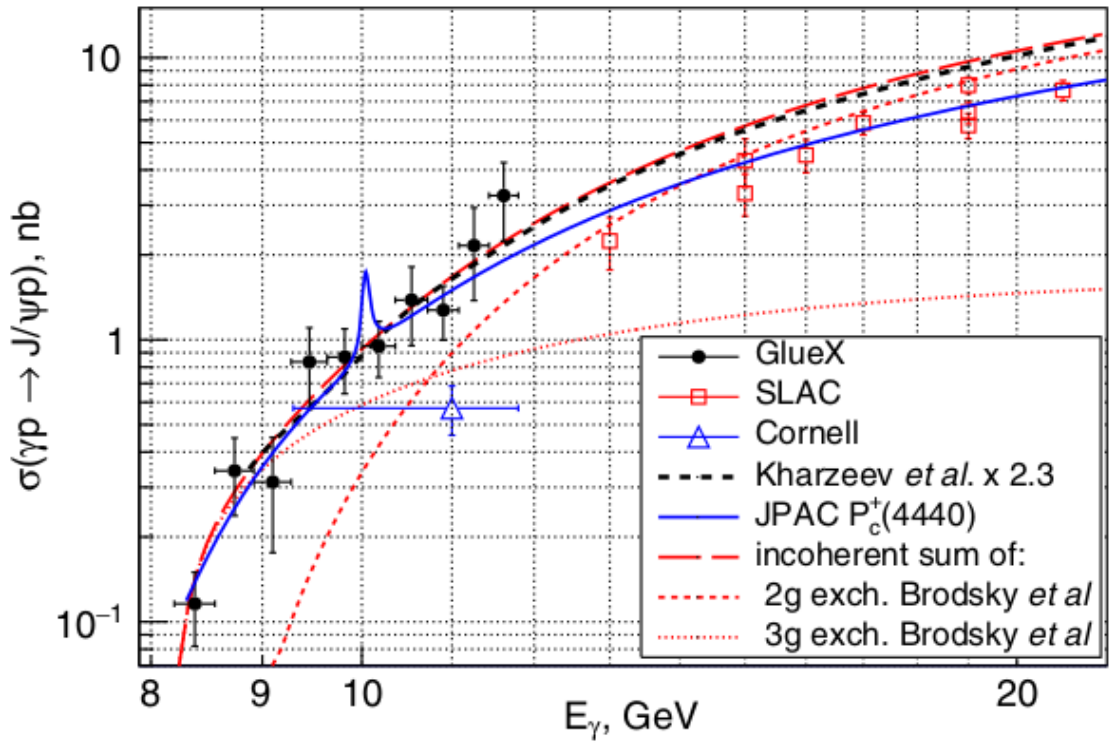
$\gamma\, p \rightarrow V\, p$, $V = \varphi, \rho, \omega, J/\psi$

total cross section



[Laget, PLB 489.313 (2000)]

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

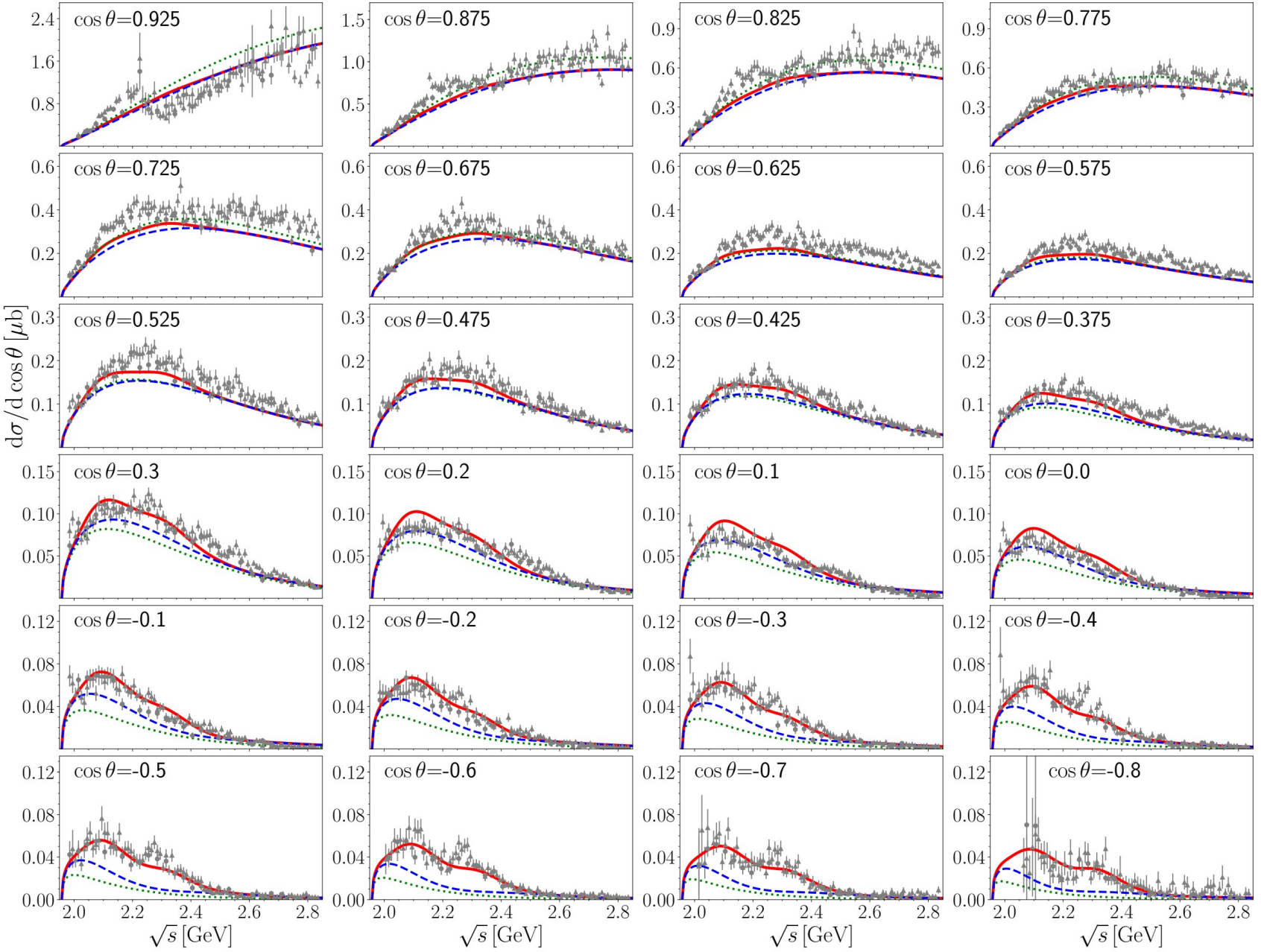


[Ali (GlueX), PRL.123.072001 (2019)]

- Pomeron exchange (two-gluon exchange) dominates at "high energies".
- Clarifying the role of various meson exchanges at "low energies" is important.

A. $\gamma p \rightarrow \varphi p$

differential cross sections



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

Pomeron

Born

total

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

spin-density matrix elements

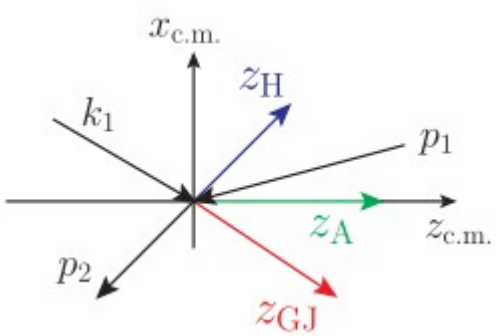
$$\rho^0_{\lambda\lambda'} = \frac{1}{N} \sum_{\lambda_\gamma,\lambda_i,\lambda_f} \mathcal{M}_{\lambda_f\lambda;\lambda_i\lambda_\gamma} \mathcal{M}^*_{\lambda_f\lambda';\lambda_i\lambda_\gamma},$$

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

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

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

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



Adair frame

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

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

spin-density matrix elements

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

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

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

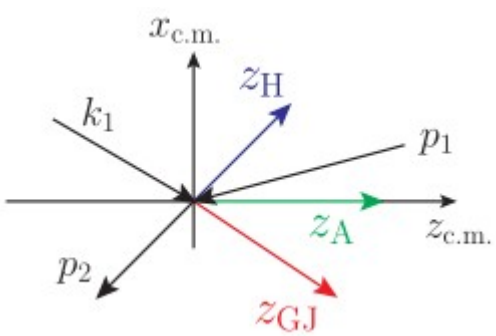
$$N = \sum |\mathcal{M}_{\lambda_f\lambda;\lambda_i\lambda_\gamma}|^2$$

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

- single helicity-flip transition between γ & φ

$$-\mathrm{Im}[\rho^2_{1-1}] \approx \rho^1_{1-1} = \frac{1}{2}\frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}$$

- relative contribution between Natural & Unnatural parity exchanges

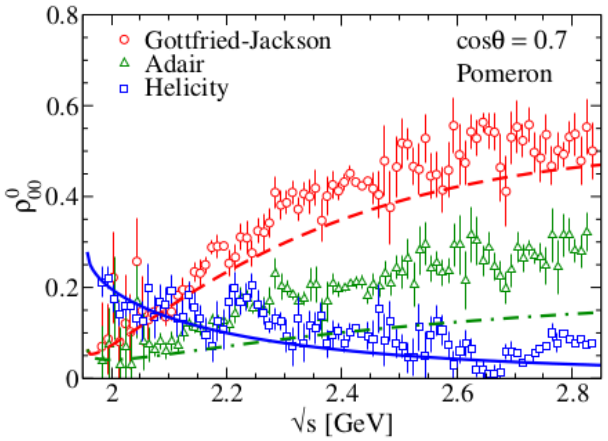


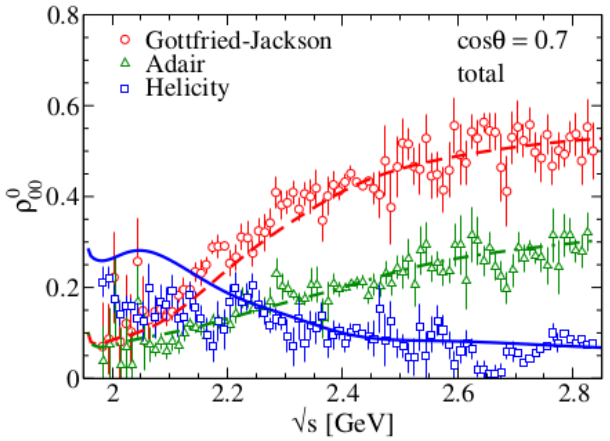
Adair frame

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

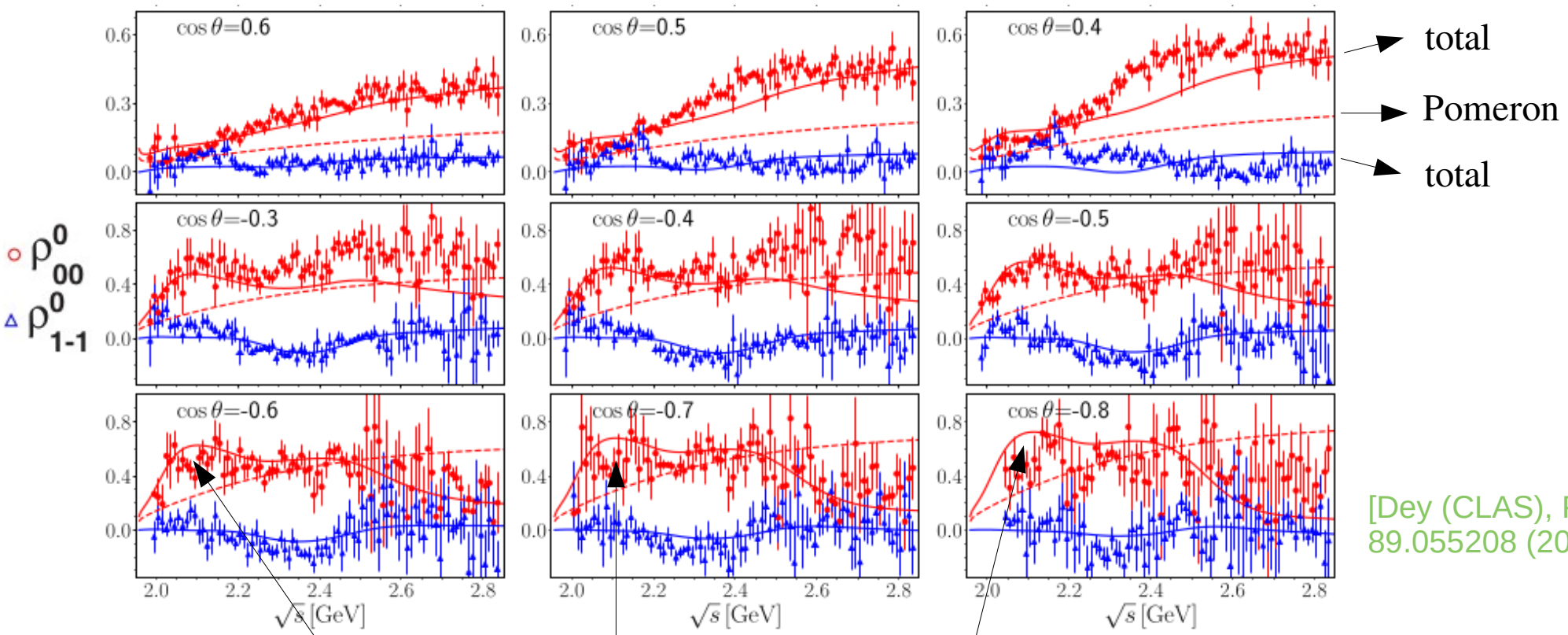
Gottfried-Jackson frame:
in favor of t-channel helicity conservation (TCHC)

Results A. $\gamma p \rightarrow \varphi p$





- TCHC &SCHC are broken.

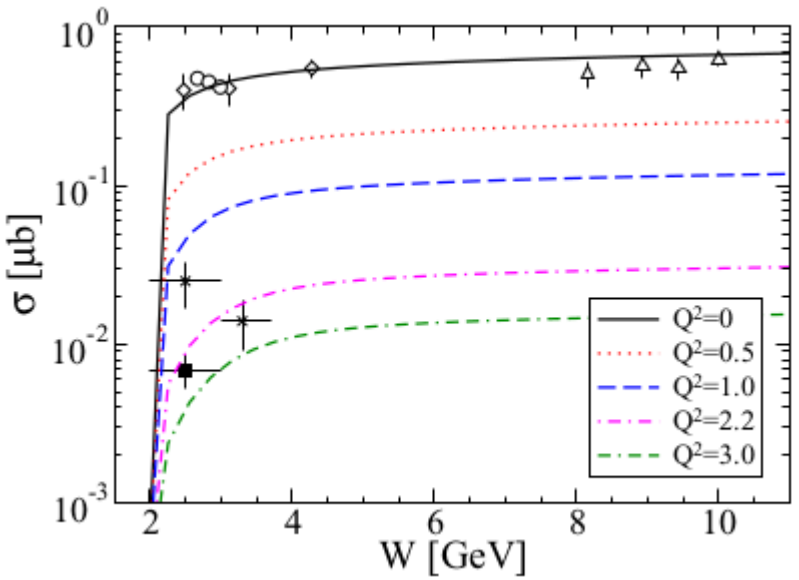


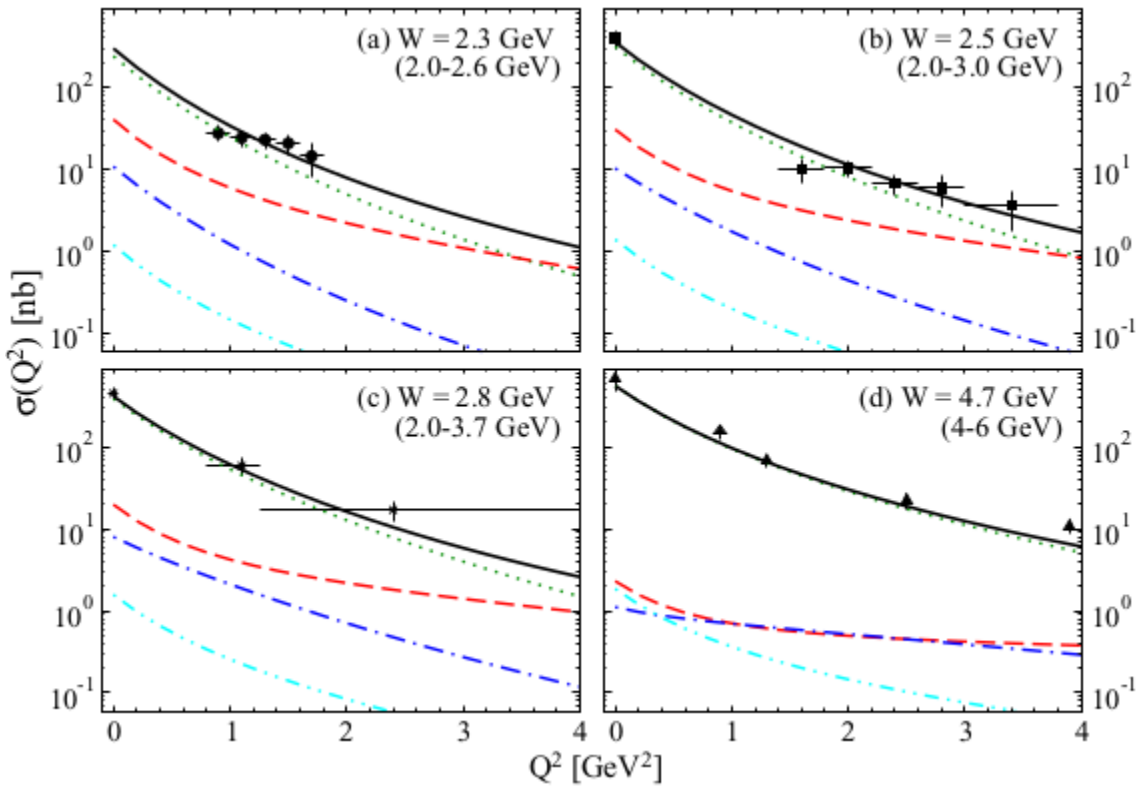
$N^*(2000,5/2^+)$ & $N^*(2300,1/2^+)$

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

unpolarized cross sections

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





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

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

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

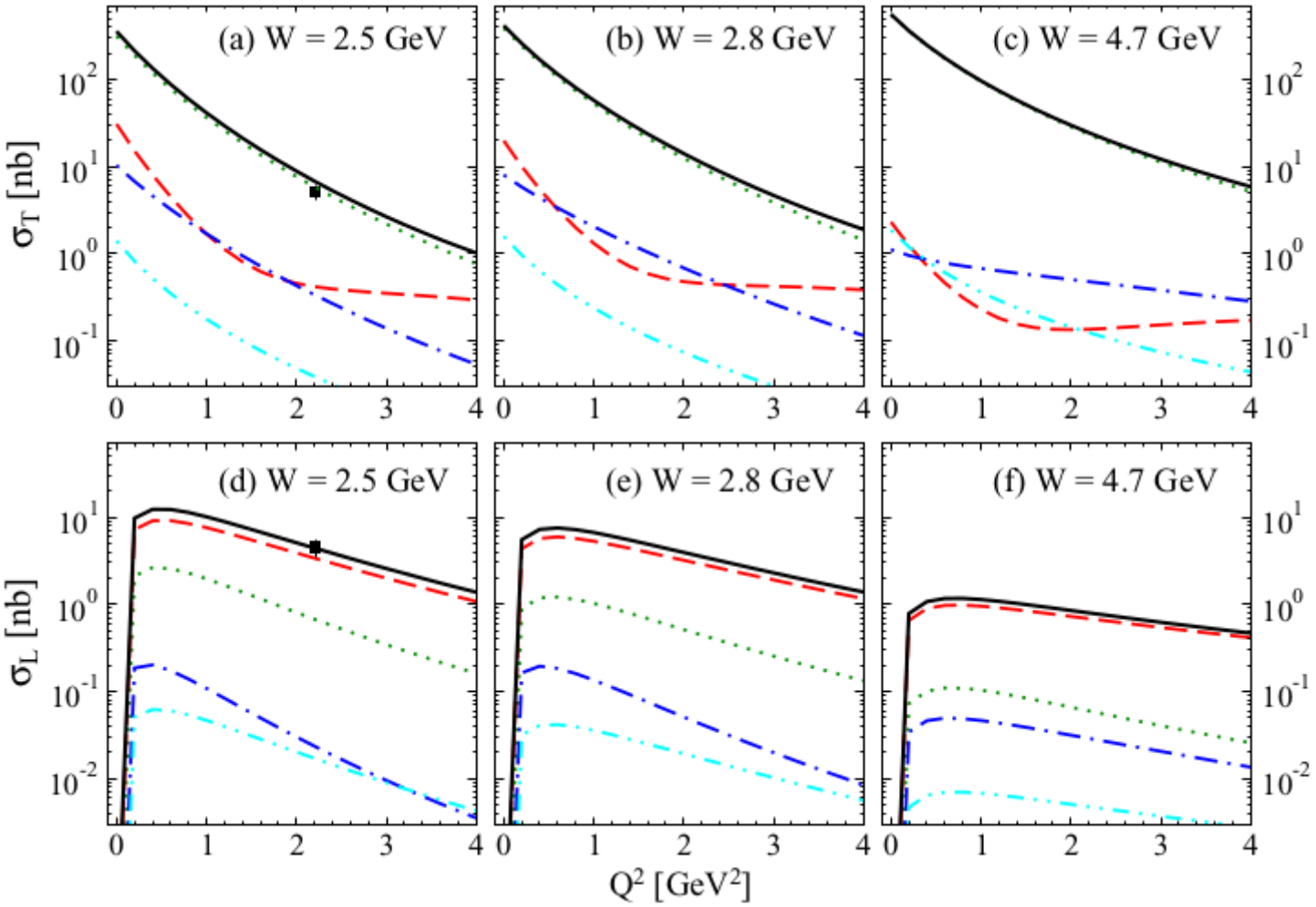
Pomeron | PS (π,η) | total

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.

T-L separated differential cross sections

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



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

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

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

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

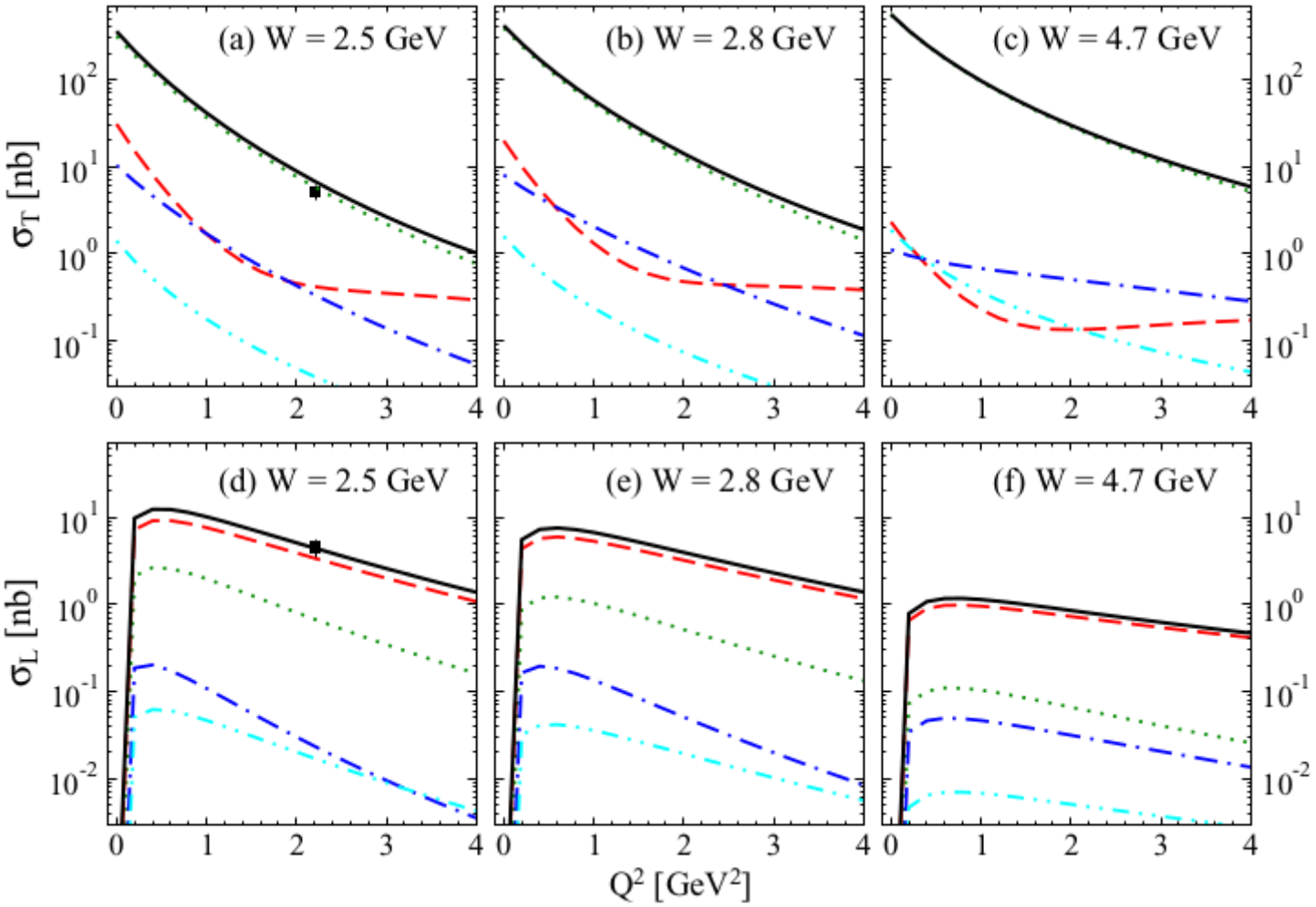
$$\mathcal{N} = \left[32\pi\left(W^2 - M_N^2\right)Wk\right]^{-1}$$

[CLAS (Santoro et al.) PRC.78.025210 (2008)]

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

T-L separated differential cross sections

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



Pomeron

S (a_0,f_0)

PS (π,η)

AV (f_1)

total

[CLAS (Santoro et al.) PRC.78.025210 (2008)]

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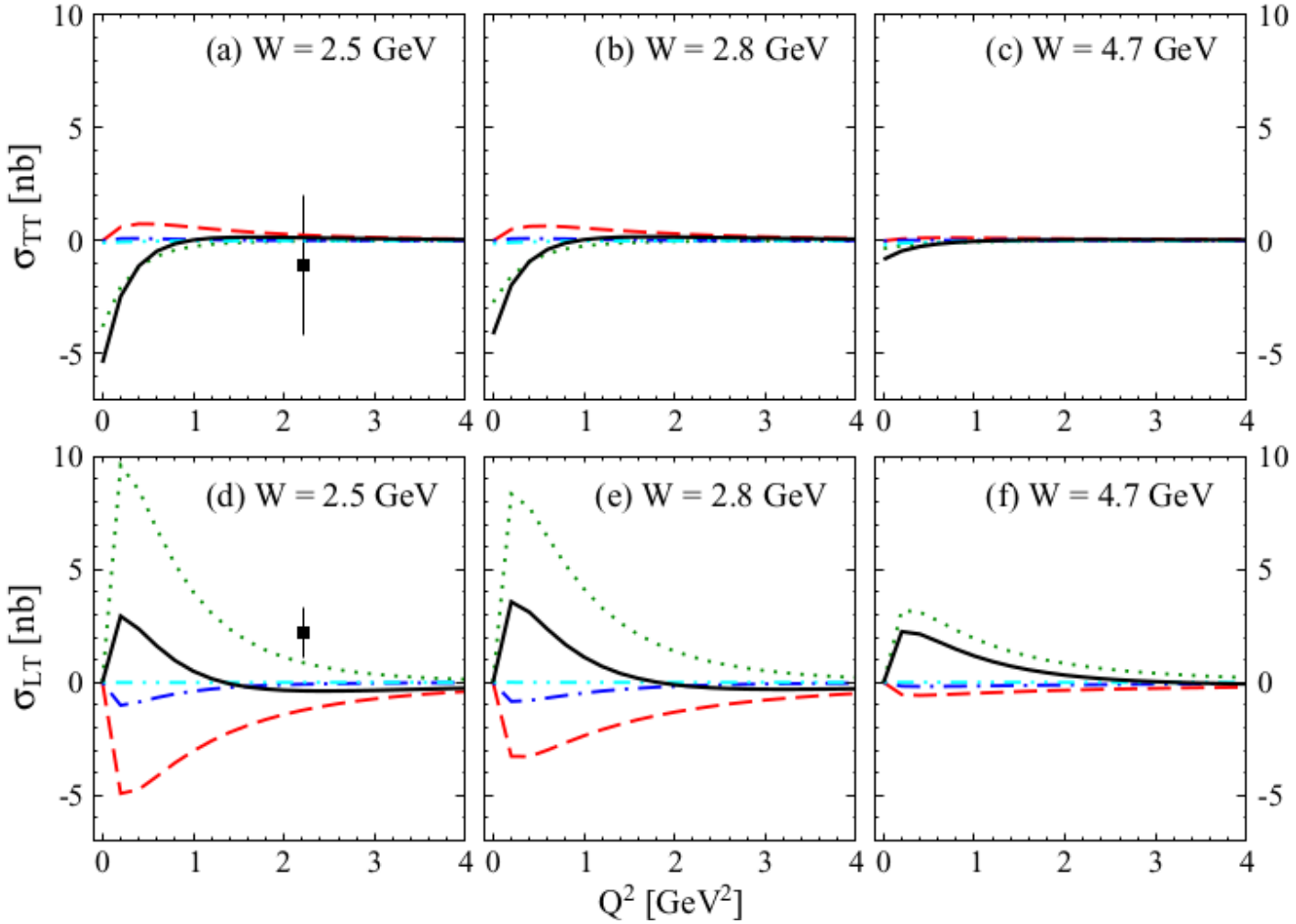
T-L separated differential cross sections



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

Pomeron

S (a_0,f_0)

PS (π,η)

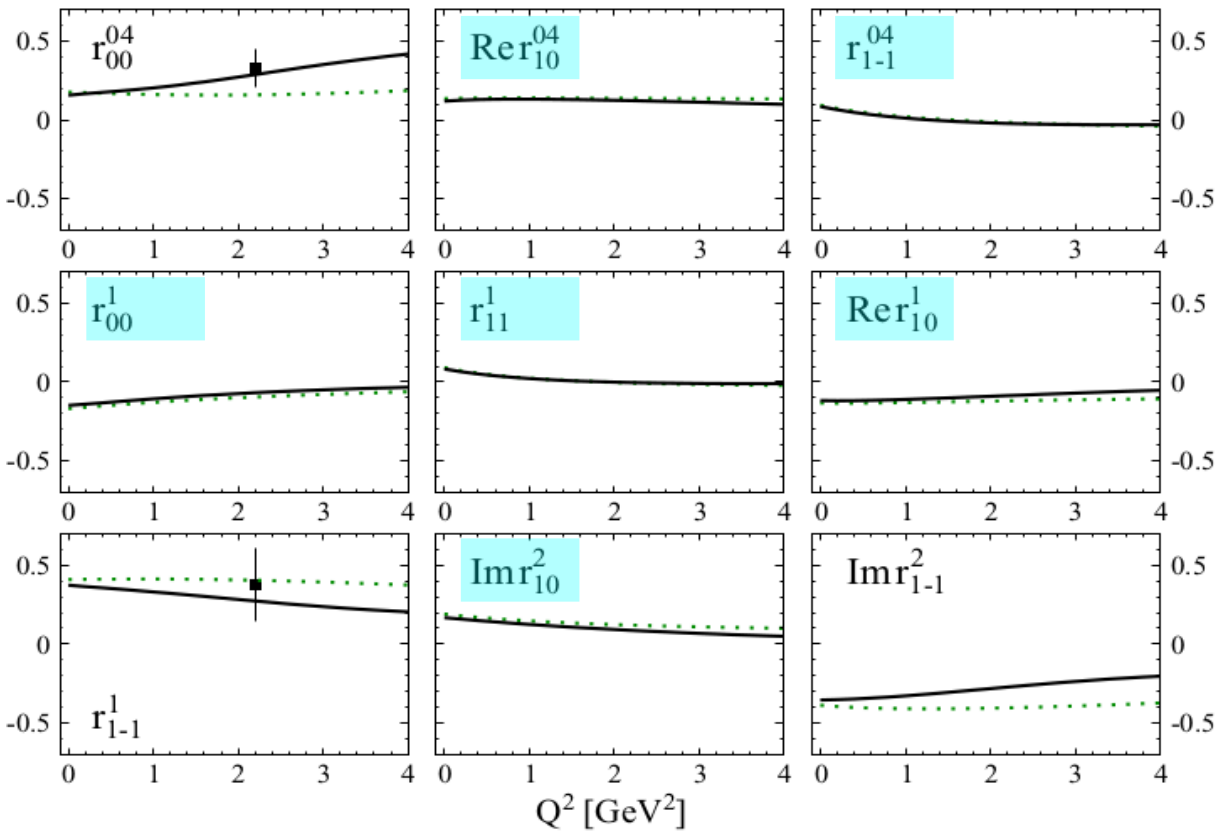
AV (f_1)

total

[CLAS (Santoro et al.) PRC.78.025210 (2008)]

- 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.

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



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

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

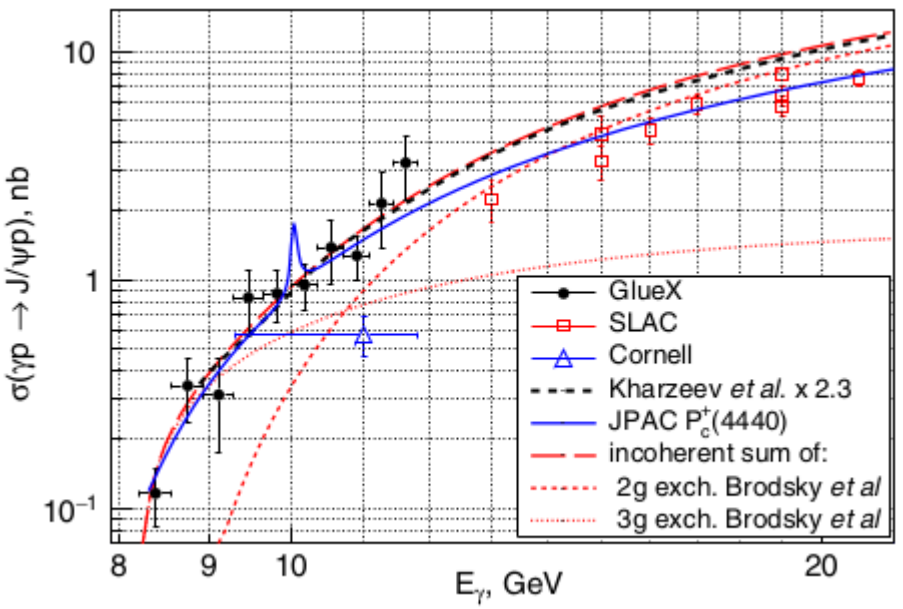
$$r^{\alpha}_{ij} = \sqrt{R}\frac{\rho^{\alpha}_{ij}}{1 + \varepsilon R}, \quad \text{for } \alpha = (5-8)$$

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.

C. $\gamma\, p \rightarrow J/\psi\, p$

- Many of the radiative decay proceed through the production of multi mesonic resonant and non-resonant states.



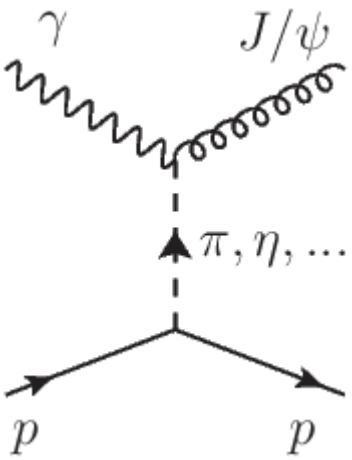
[Exp: GlueX, PRL.123.072001 (2019)]
[Theory: Brodsky et al, PLB.498.23 (2001)
based on PQCD and effective HQ field theory]

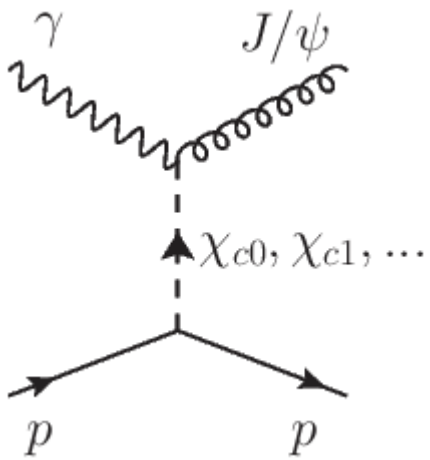
- The main reaction mechanism?

Radiative decays of J/ψ

Γ_{203}	$3\,\gamma$	$(1.16 \pm 0.22) \times 10^{-5}$
Γ_{204}	$4\,\gamma$	$< 9 \times 10^{-6}$
Γ_{205}	$5\,\gamma$	$< 1.5 \times 10^{-5}$
Γ_{206}	$\gamma\pi^0\pi^0$	$(1.15 \pm 0.05) \times 10^{-3}$
Γ_{207}	$\gamma\eta\pi^0$	$(2.14 \pm 0.31) \times 10^{-5}$
Γ_{208}	$\gamma a_0(980)^0 \rightarrow \gamma\eta\pi^0$	$< 2.5 \times 10^{-6}$
Γ_{209}	$\gamma a_2(1320)^0 \rightarrow \gamma\eta\pi^0$	$< 6.6 \times 10^{-6}$
Γ_{210}	$\gamma K_S^0\, K_S^0$	$(8.1 \pm 0.4) \times 10^{-4}$
Γ_{211}	$\gamma\eta_c(1S)$	$(1.7 \pm 0.4)\%$
Γ_{212}	$\gamma\eta_c(1S) \rightarrow 3\,\gamma$	$(3.8^{+1.3}_{-1.0}) \times 10^{-6}$
Γ_{213}	$\gamma\pi^+\pi^-\,2\,\pi^0$	$(8.3 \pm 3.1) \times 10^{-3}$
Γ_{214}	$\gamma\eta\pi\pi$	$(6.1 \pm 1.0) \times 10^{-3}$
Γ_{215}	$\gamma\eta_2(1870) \rightarrow \gamma\eta\pi^+\pi^-$	$(6.2 \pm 2.4) \times 10^{-4}$
Γ_{216}	$\gamma\eta(1405/1475) \rightarrow \gamma K\overline{K}\pi$	$(2.8 \pm 0.6) \times 10^{-3}$
Γ_{217}	$\gamma\eta(1405/1475) \rightarrow \gamma\gamma\rho^0$	$(7.8 \pm 2.0) \times 10^{-5}$
Γ_{218}	$\gamma\eta(1405/1475) \rightarrow \gamma\eta\pi^+\pi^-$	$(3.0 \pm 0.5) \times 10^{-4}$
Γ_{219}	$\gamma\eta(1405/1475) \rightarrow \gamma\gamma\phi$	$< 8.2 \times 10^{-5}$
Γ_{220}	$\gamma\eta(1405) \rightarrow \gamma\gamma\gamma$	$< 2.63 \times 10^{-6}$
Γ_{221}	$\gamma\eta(1475) \rightarrow \gamma\gamma\gamma$	$< 1.86 \times 10^{-6}$
Γ_{222}	$\gamma\rho\rho$	$(4.5 \pm 0.8) \times 10^{-3}$
Γ_{223}	$\gamma\rho\omega$	$< 5.4 \times 10^{-4}$
Γ_{224}	$\gamma\rho\phi$	$< 8.8 \times 10^{-5}$
Γ_{225}	$\gamma\eta'(958)$	$(5.25 \pm 0.07) \times 10^{-3}$

❑ coupling constants





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

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

▫ Effective Lagrangians

EM coupling

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

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

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

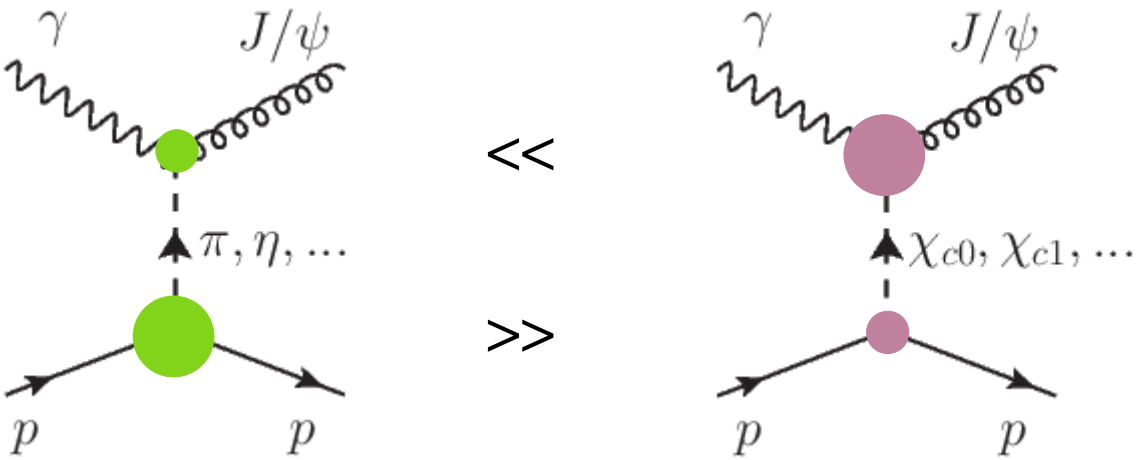
Strong coupling

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

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

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

❑ coupling constants



Which is more dominant?

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

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

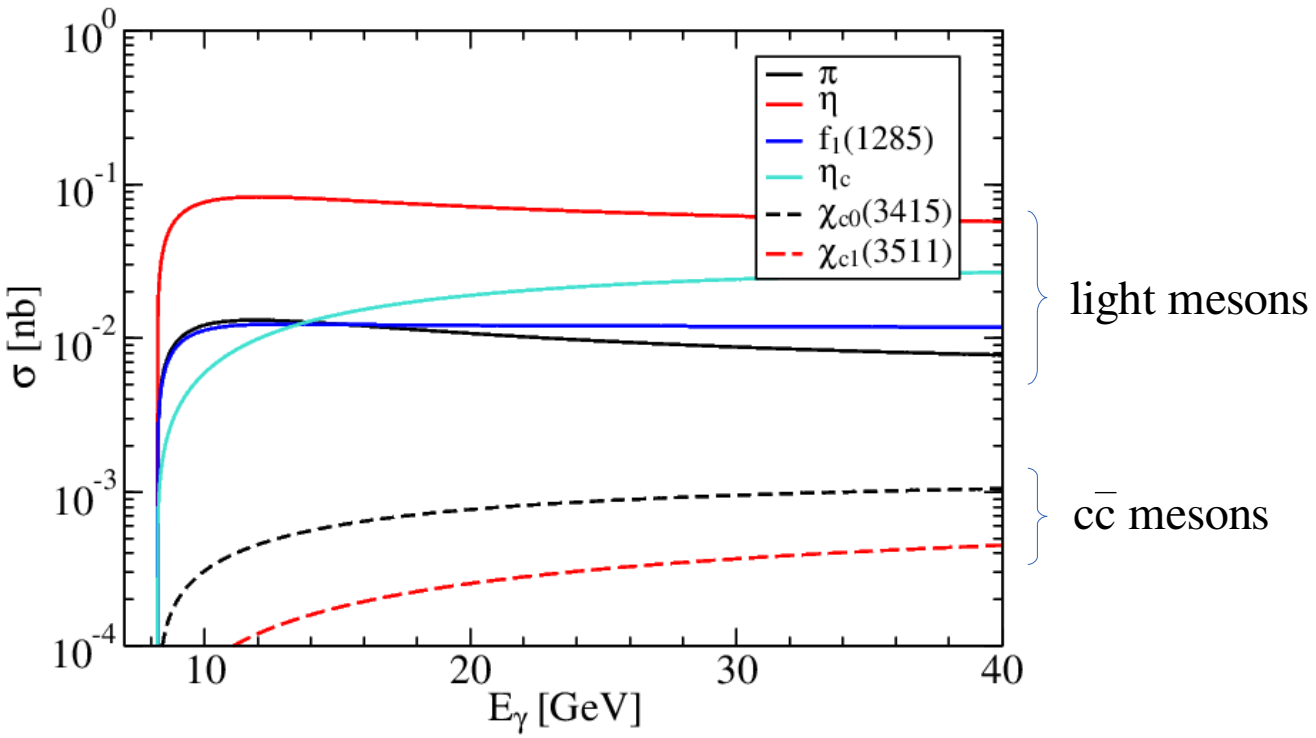
light mesons

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	–

❑ total cross section (each contribution)



Mesons	Mass (J^P)
π	134 (0^-)
η	548 (0^-)
η'	958 (0^-)
f_1	1285 (1^+)
$\eta_c(1S)$	2984 (0^-)

Mesons	Mass (J^P)
$\chi_{c0}(1P)$	3415 (0^+)
$\chi_{c1}(1P)$	3511 (1^+)
$\eta_c(2S)$	3638 (0^-)
$\chi_{c1}(3872)$	3872 (1^+)

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

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

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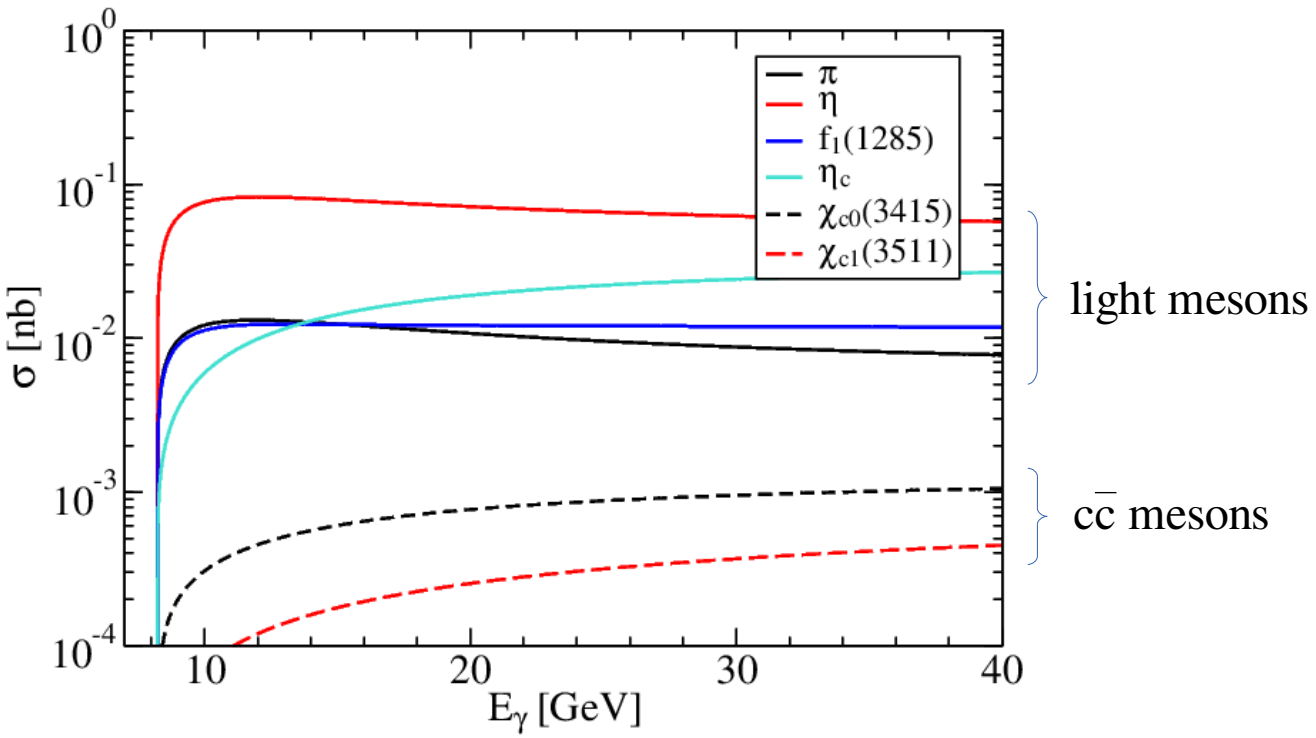
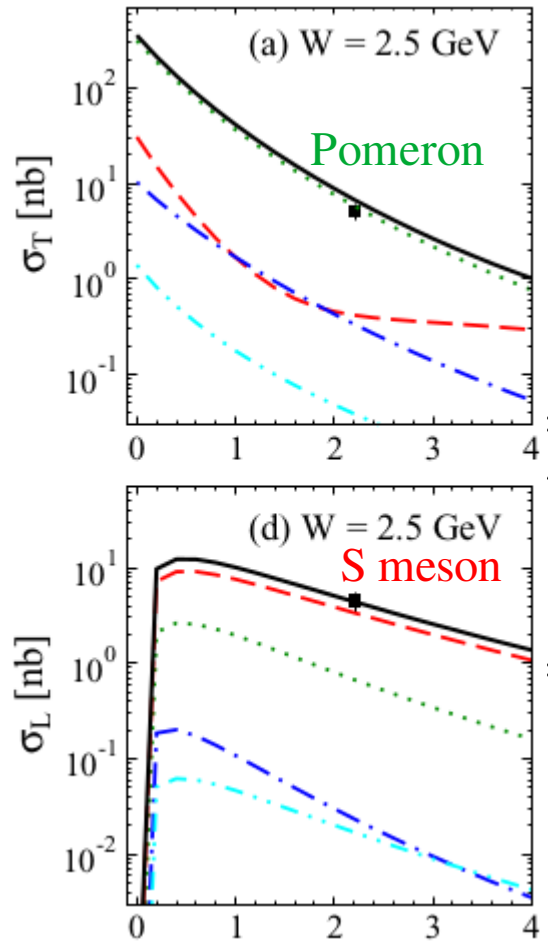


$\gamma\, p \to \varphi\, p$



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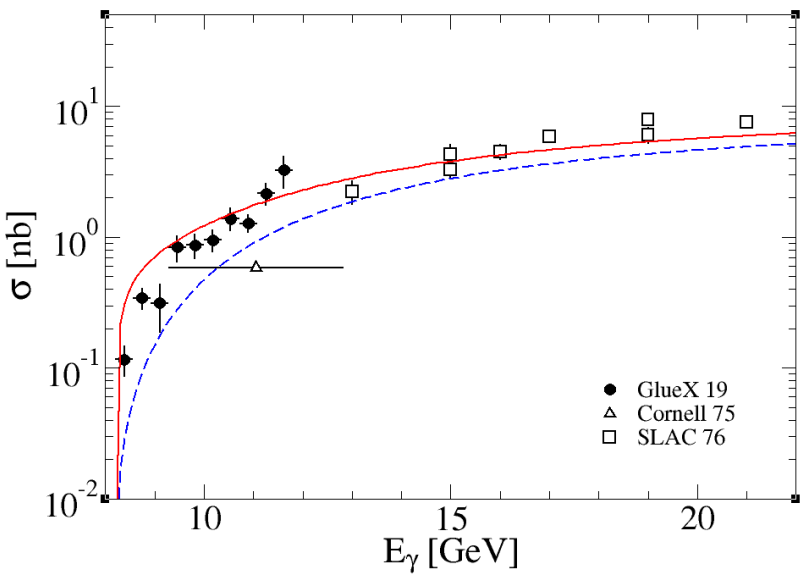
C. $\gamma\, p \rightarrow J/\psi\, p$

❑ total cross section

▫ Donnachie & Landshoff model



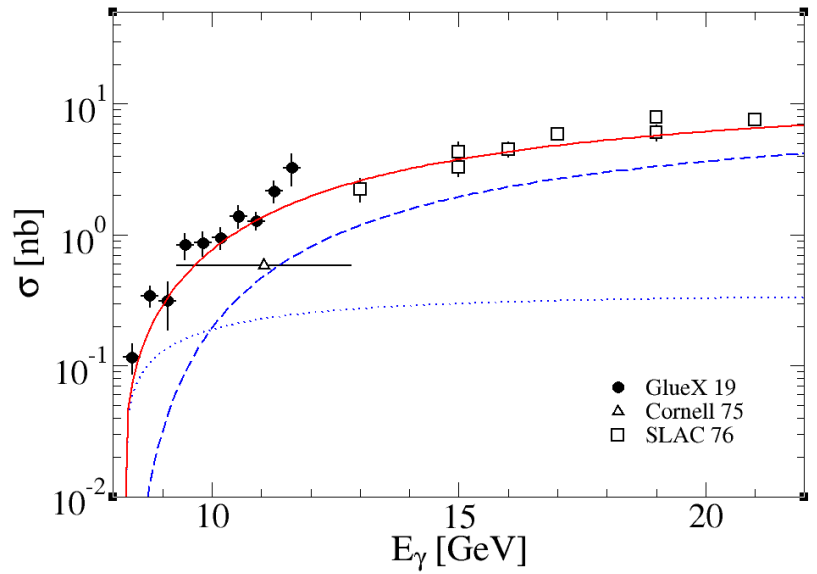
soft Pomeron

soft Pomeron
+ light mesons

$$\mathcal{T}_{\mathbb{P}}^{\mu\nu}(q,p,q',p') = [i12\frac{eM_V^2}{f_V}][\beta_{q_V}F_V(t)]][\beta_{u/d}F_1(t)]\{\not{q}\, g^{\mu\nu} - q^{\mu}\gamma^{\nu}\}$$
$$\left(\frac{s}{s_0}\right)^{\alpha_P(t)-1} \exp\left\{-\frac{i\pi}{2}\left[\alpha_P(t)-1\right]\right\}$$

[Donnachie et al, NPB.244.322 (1984)]

▫ Brodsky model



two-hard gluon

three-hard gluon

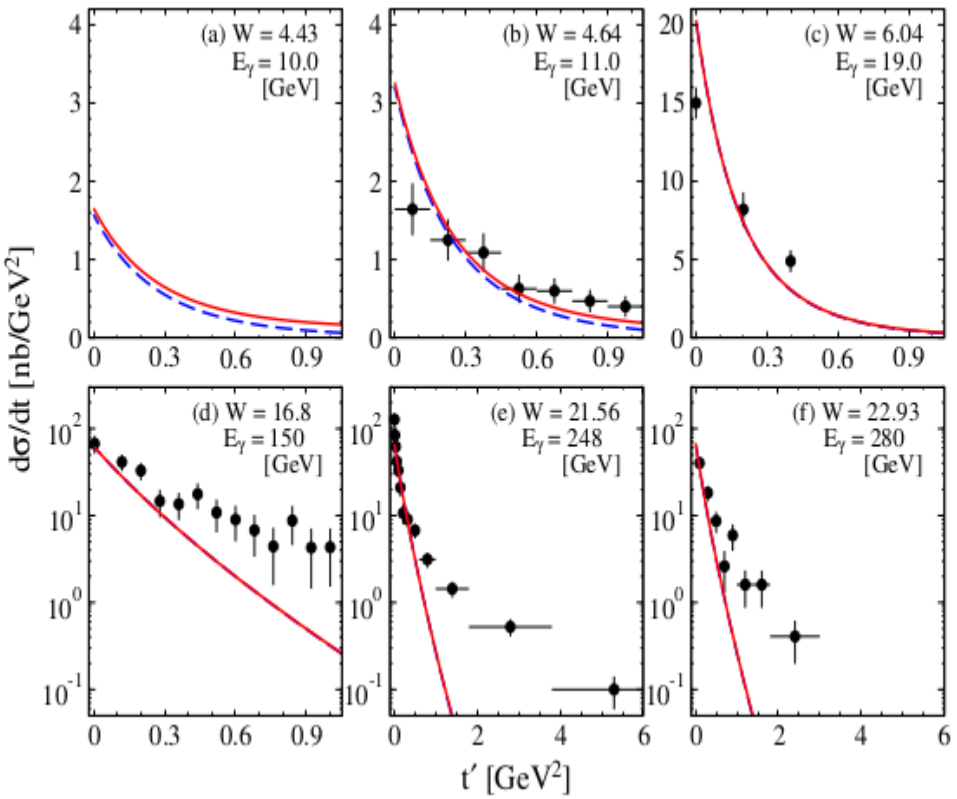
$$\frac{d\sigma}{dt} = \mathcal{N}_{2g}\, v\, \frac{(1-x)^2}{R^2\mathcal{M}^2} F_{2g}^2(t)\left(s-m_p^2\right)^2$$

$$\frac{d\sigma}{dt} = \mathcal{N}_{3g}\, v\, \frac{(1-x)^0}{R^4\mathcal{M}^4} F_{3g}^2(t)\left(s-m_p^2\right)^2$$

[Brodsky et al, PLB.498.23 (2001)
based on PQCD and effective HQ field theory]

❑ differential cross sections

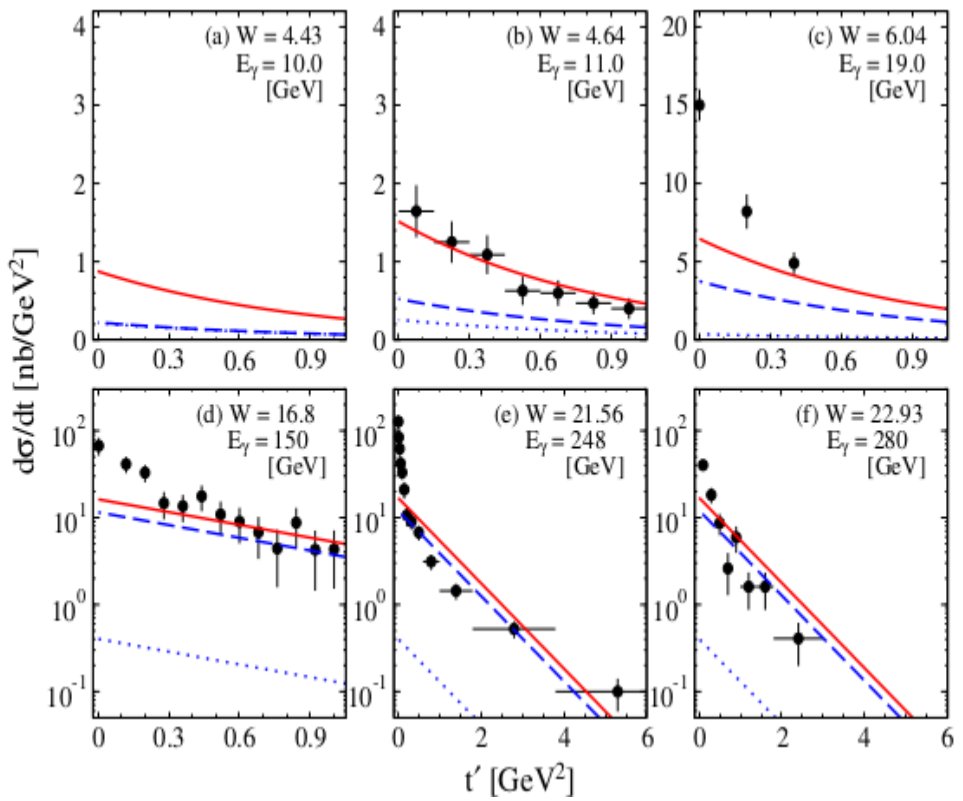
▫ Donnachie & Landshoff model



soft Pomeron

soft Pomeron
+ light mesons

▫ Brodsky model



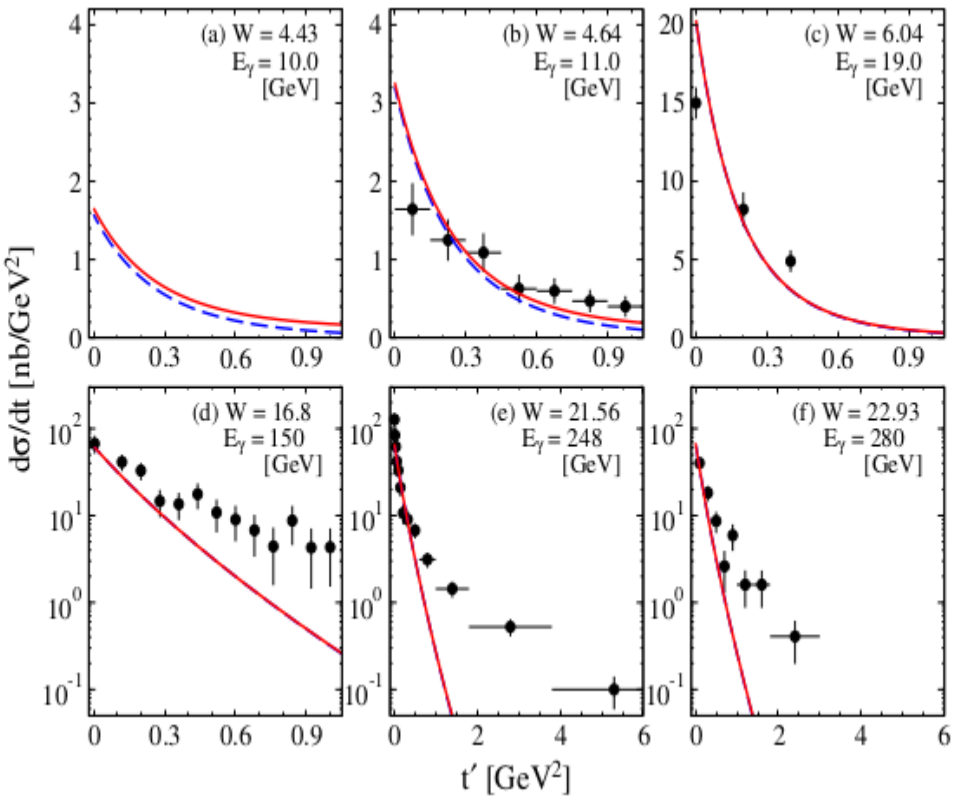
two-hard gluon

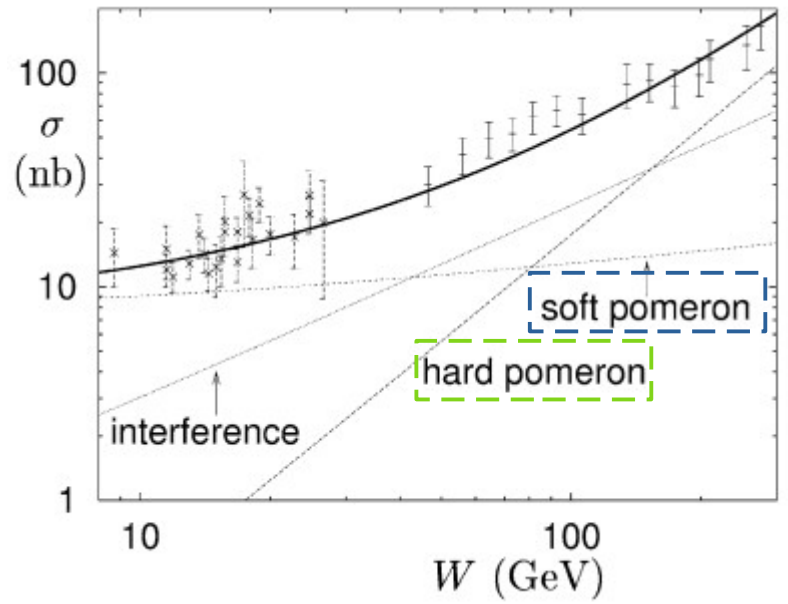
three-hard gluon

▫ At low energies, both models describe the GlueX data well.
▫ At high energies, we need the hard Pomeron for the DL model.

❑ differential cross sections

▫ Donnachie & Landshoff model





soft Pomeron

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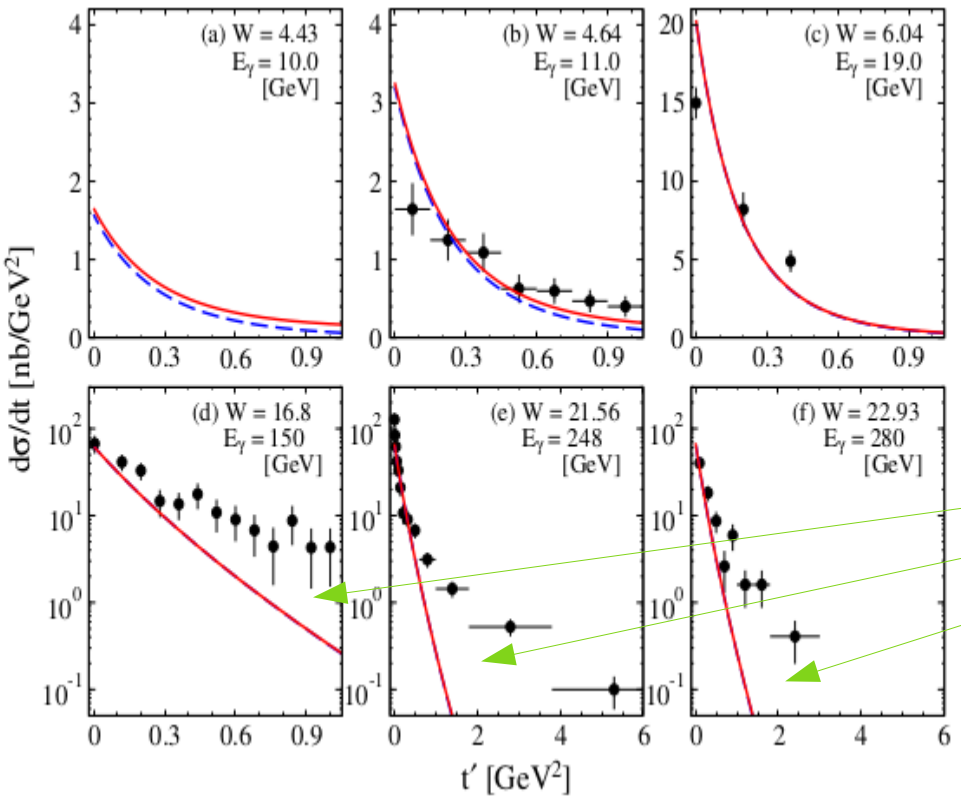

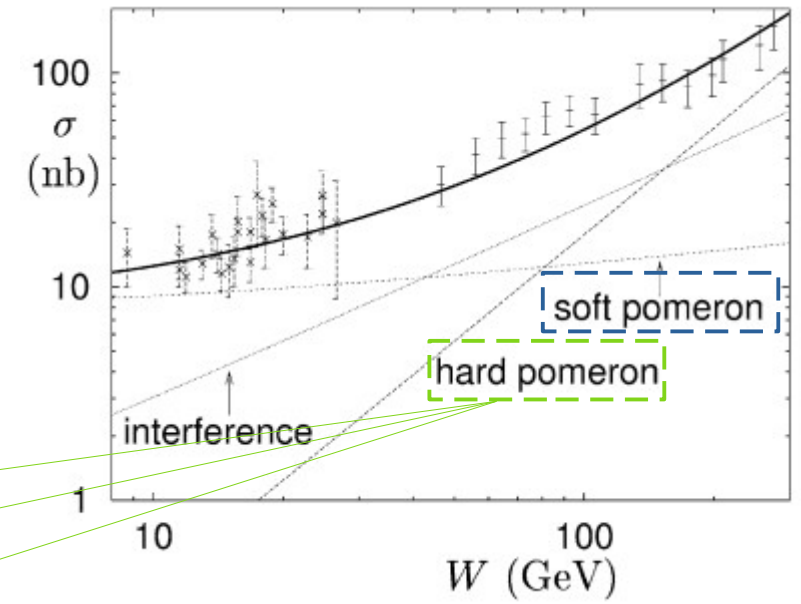

$\alpha_{soft}(t) = 1.08 + 0.25t$
$\alpha_{hard}(t) = 1.44 + 0.1t$

soft Pomeron

soft Pomeron
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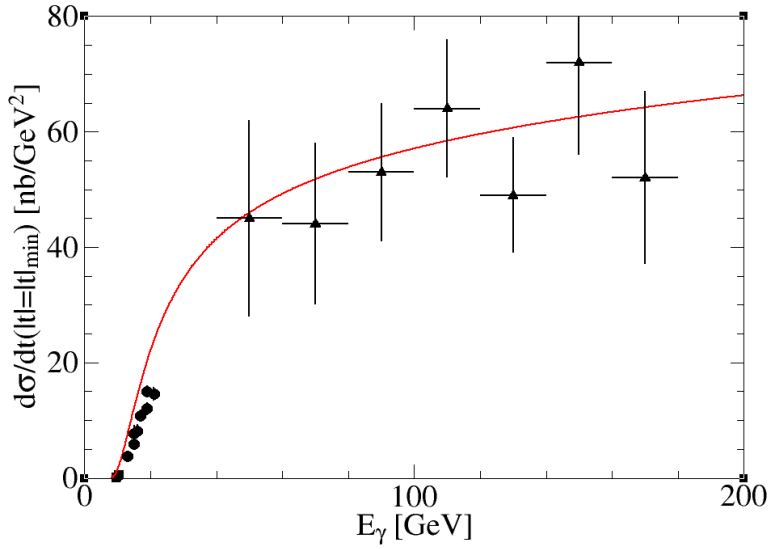
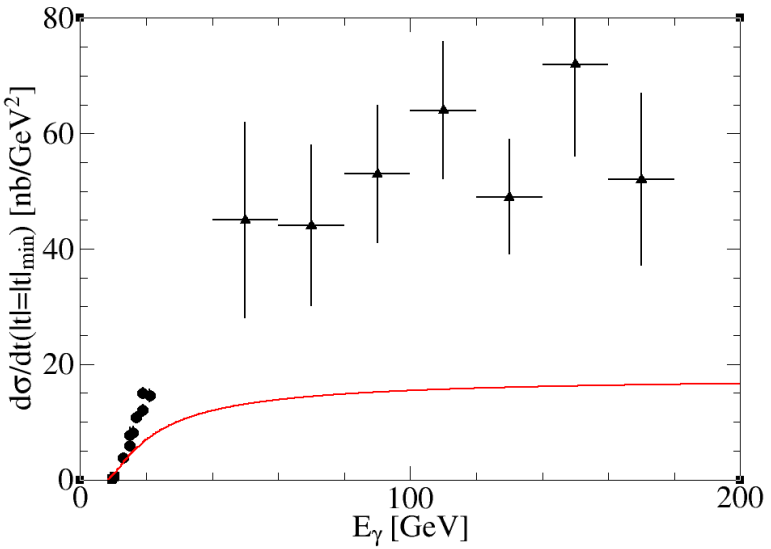


▫ Brodsky model



▫ The DL model is more adequate to describe the high energy data.

Summary – 1 & 2

◇ The photoproduction $\gamma p \to K^+\Lambda(1405)$ & $\gamma p \to K^+\Sigma(1400)$ is studied using an effective Lagrangian approach combining with a Regge model.

◇ K-Reggeon exchange is a dominant contribution to both reactions.
◇ K^*-Reggeon exchange is sizable only for the $K^+\Sigma(1400)$ production.

◇ The cross section of $K^+\Sigma(1400)$ is an order of magnitude suppressed relative to $K^+\Lambda(1405)$, but is sizable to be measured in the future experiments.

◇ $N^*(1895, 1/2^-)$ is crucial to reproduce the CLAS data for $K^+\Lambda(1405)$ production.

◇ For $\gamma\, p \to \varphi\, p$ & $\gamma^*\, p \to \varphi\, p$, we studied the relative contributions between the Pomeson and various meson exchanges.

◇ 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. (cross section as well as spin polarization observables)
◇ The tetraquark state χ_{c0} $(3415, 0^+)$ is important for the longitudinal part σ_L for "$\gamma^*\, p \to J/\psi\, p$".

Current and Future works

◇ Extension of these elementary processes to reactions off nuclei targets
[$\gamma^{(*)}$ A → V A]
[T.-S. H. Lee (Argonne NL), Y. Oh (Kyungpook NU), S.i. Nam (Pukyong NU)]

- A distorted-wave impulse approximation within the multiple scattering formulation is used to analyze the low-energy LEPS data. [$\gamma\ ^4He \rightarrow \varphi\ ^4He$]
- Planning to extend to $\gamma^{(*)}$ A → V[φ, J/ψ, Υ(1S)] A, [A = ^{2}H, ^{12}C, …]

◇ Approved 12 GeV era experiments to date at JLab
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[E12-11-002] Proton Recoil Polarization in the ^{4}He(e,e'p)^{3}H, ^{2}He(e,e'p)n, ^{1}He(e,e'p)

[E12-12-006] Near Threshold Electroproduction of J/ψ at 11 GeV

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

◇ Electron-Ion Collider (EIC)

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Thank you very much for your attention