

The Θ^+ Photoproduction in a Regge Model

Herry Kwee

College of William and Mary

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Jefferson Lab

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1. Introduction

2. Photoproduction

- $\gamma n \rightarrow \Theta^+ K^-$ for spin-1/2 Θ^+
- $\gamma p \rightarrow \Theta^+ \overline{K^0}$ for spin-1/2 Θ^+
- $\gamma n \rightarrow \Theta^+ K^-$ for spin-3/2 Θ^+

3. Results

- Total cross sections (σ)
- Differential cross sections ($\frac{d\sigma}{dt}$)
- Photon asymmetries (Σ)
- Decay angular distributions

4. Conclusions

Pentaquarks ($q^4\bar{q}$)

QCD does not prohibit pentaquarks

Known: Baryon (qqq) and Meson ($q\bar{q}$)

Other possibility: $(qqq)(qqq)$, $(q\bar{q})(q\bar{q})$, glueball, and **Pentaquark** ($q^4\bar{q}$)

Questions:

Where should we look?

How can we distinguish pentaquark from (qqq) resonance?

and How stable? (width)

Theoretical prediction: Diakanov et. al.
(hep-ph/9703373)

- lightest pentaquark: antidecuplet
- no ordinary baryon (qqq) has $s = +1$
- mass around 1530 MeV
- width $\simeq 15$ MeV

Hidden Strangeness:

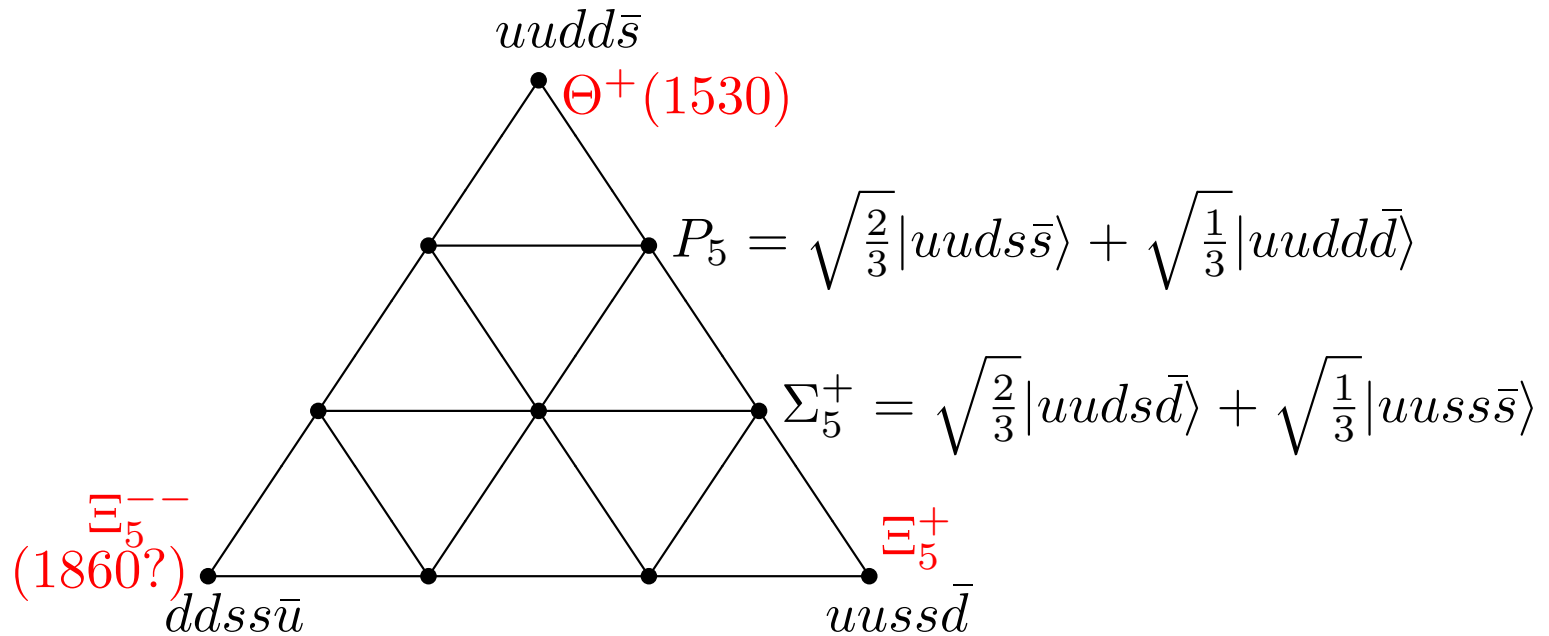


Figure 1: $SU(3)_F$ Antidecuplet for Pentaquark

- naively, $m(\Xi_5^+) - m(\Theta^+) = m_s \approx 150$ MeV.
- Mixing: effect only on N_5 and Σ_5 .

Experimental Evidence

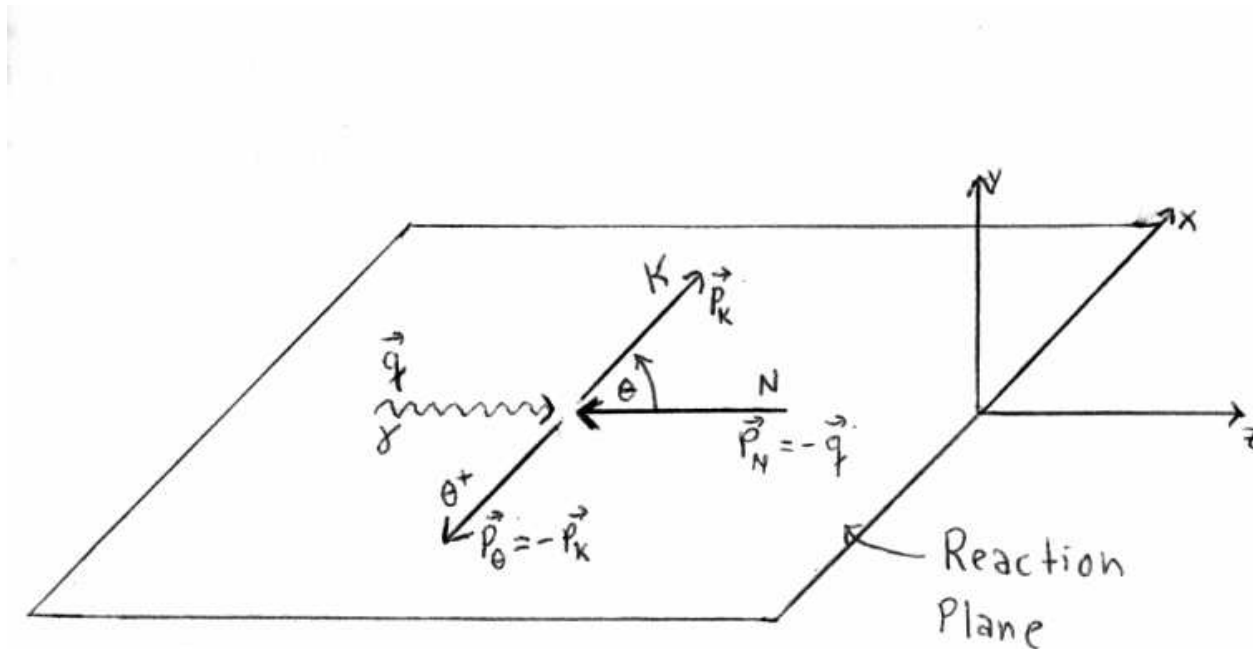
- First experimental sign: Nakano et. al. (LEP collaboration, hep-ex/0301020)
 - mass 1540 ± 10 MeV
 - width less than 25 MeV
- Other experiment: V.V. Barmin et al. (hep-ex/0304040) → very narrow width (≤ 9 MeV)
- Current experimental status:
 - positive signal: 10 published experiments
 - non-observing experiment: 11 published results
- LEP still see signal (see talk by Nakano at International Conference on QCD and Hadronic Physics, Beijing).

Quantum Numbers

- $SU(3)_F : 3 \otimes 3 \otimes 3 \otimes 3 \otimes \bar{3} \rightarrow$ many possibilities (multiplets).
- Θ^+ ($s = +1$) can be member of 35plet, 27plet or antidecuplet.
- **Antidecuplet??**
 $\text{isospin} = 0$ (searches for $\theta^{++} \rightarrow$ no result, J. Barth et al., hep-ex/0307083)
- result has been ruled out by new CLAS g11 experiment
- also STAR see signal for Θ^{++} (see talk by Huang at International Conference on QCD and Hadronic Physics, Beijing).
- The spin and parity of the Θ^+ is currently unknown

Θ^+ Photoproduction

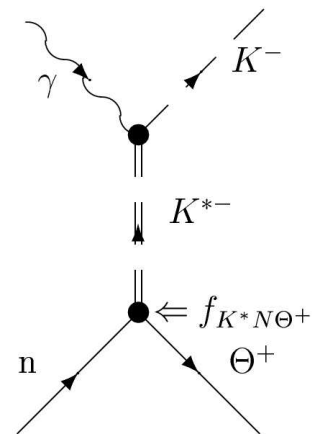
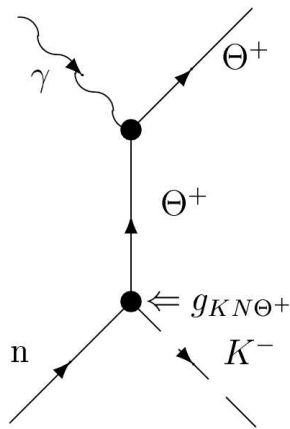
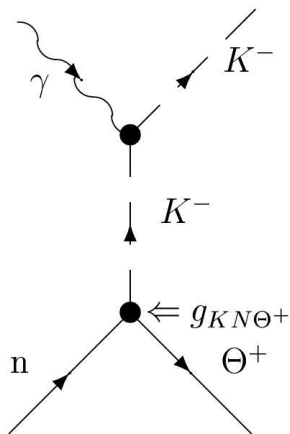
$$\gamma(q) + N(p_N) \longrightarrow K(p_K) + \Theta^+(p_\Theta)$$



$$s \equiv (p_N + q)^2, \quad t \equiv (q - p_K)^2, \quad \text{and} \quad u \equiv (q - p_\Theta)^2$$

(M. Guidal, HJK, M.V. Polyakov, M. Vanderhaeghen,
hep-ph/0507180)

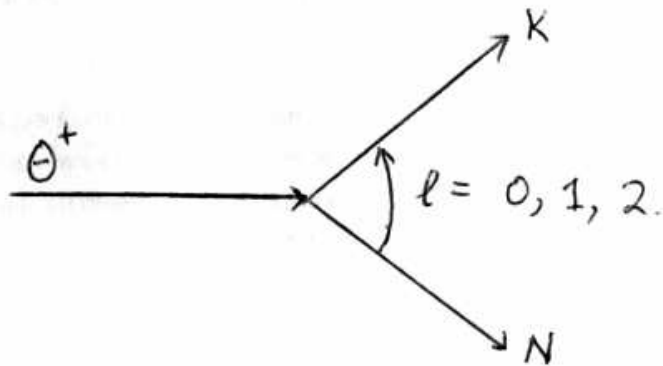
$$\gamma n \rightarrow K^- \Theta^+ : J_{\Theta}^P = \frac{1}{2}^+ \left(\frac{1}{2}^- \right)$$



$$\begin{aligned}
\mathcal{M}_K &= (-i) e g_{KN\Theta} \cdot \mathcal{P}_{Regge}^K(s, t) \cdot \varepsilon_\mu(q, \lambda) \\
&\times \left[F_K(t) \cdot (2p_K - q)^\mu \cdot \bar{\Theta} \gamma^5 N \right. \\
&\quad - F_\Theta(u) \cdot (t - m_K^2) \cdot \bar{\Theta} \gamma^\mu \frac{(\gamma \cdot p_u + M_\Theta)}{u - M_\Theta^2} \gamma^5 N \\
&\quad + 2p_K^\mu \cdot (\hat{F}(s, t, u) - F_K(t)) \cdot \bar{\Theta} \gamma^5 N \\
&\quad \left. - \left(\frac{t - m_K^2}{u - m_\Theta^2} \right) \cdot 2p_\Theta^\mu \cdot \{\hat{F}(s, t, u) - F_\Theta(u)\} \cdot \bar{\Theta} \gamma^5 N \right]
\end{aligned}$$

- difference between (+) and (-) parity: only in γ^5 and (\pm, i)
- t- and u-channel reggeized the same way (required by gauge invariance)
- the last 2 terms: required contact terms

Θ Decay and $KN\Theta$ Vertex



$$J^P = \frac{1}{2}^- \iff l = 0, \text{ S-wave}$$

$$J^P = \frac{1}{2}^+ \iff l = 1, \text{ P-wave}$$

$$J^P = \frac{3}{2}^+ \iff l = 1, \text{ P-wave}$$

$$J^P = \frac{3}{2}^- \iff l = 2, \text{ D-wave}$$

KN Θ^+ vertex and Θ^+ Width

- $J^P = \frac{1}{2}^+$

$$\mathcal{L}_{KN\Theta} = i g_{KN\Theta} \left(K^\dagger \bar{\Theta} \gamma_5 N + \bar{N} \gamma_5 \Theta K \right)$$

$$\Gamma_{\Theta \rightarrow KN} = \frac{g_{KN\Theta}^2}{2\pi} \frac{|\bar{p}_K|}{M_\Theta} \left(\sqrt{\bar{p}_K^2 + M_N^2} - M_N \right)$$

- $|\bar{p}_K| \simeq 0.267 \text{ GeV}$
- with $\Gamma_{\Theta \rightarrow KN} = 1 \text{ MeV} \rightarrow g_{KN\Theta} \simeq 1.056$

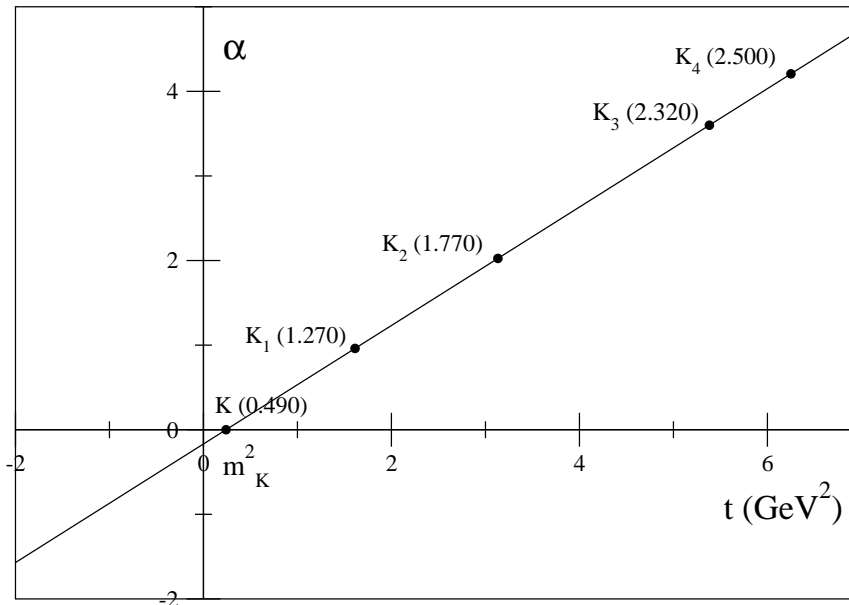
- $J^P = \frac{1}{2}^-$

$$\mathcal{L}_{KN\Theta} = g_{KN\Theta} \left(K^\dagger \bar{\Theta} N + \bar{N} \Theta K \right)$$

$$\Gamma_{\Theta \rightarrow KN} = \frac{g_{KN\Theta}^2}{2\pi} \frac{|\bar{p}_K|}{M_\Theta} \left(\sqrt{\bar{p}_K^2 + M_N^2} + M_N \right)$$

- $\Gamma_{\Theta \rightarrow KN} = 1 \text{ MeV} \rightarrow g_{KN\Theta} \simeq 0.1406$

K Regge Exchange



- imagine K as a tube (rod) with 2 quarks at the end \rightarrow rotate \rightarrow higher angular momentum
- higher-spin excitation of Kaons lie on K Regge trajectory
- K Regge trajectory for t-channel:
$$\alpha_K(t) = \alpha_K^0 + \alpha'_K \cdot t$$
- trajectories can be either non-degenerate or degenerate

Non-degenerate Regge Trajectory

$$\frac{1}{t - m_K^2} \implies \mathcal{P}_{Regge}^K(s, t) = \left(\frac{s}{s_0}\right)^{\alpha_K(t)} \frac{\pi \alpha'_K}{\sin(\pi \alpha_K(t))} \times \frac{\mathcal{S}_K + e^{-i\pi \alpha_K(t)}}{2} \frac{1}{\Gamma(1 + \alpha_K(t))}$$

- $s_0 \simeq 1 \text{ GeV}$
- standard linear trajectory for K is:

$$\alpha_K(t) = 0.7 (t - m_K^2)$$

- as $t \rightarrow m_K^2$, $\alpha_K \rightarrow 0$ and $\mathcal{P}_{Regge}^K(s, t) \rightarrow \frac{1}{t - m_K^2}$
- $\Gamma(1 + \alpha(t))$ suppresses propagator poles in the unphysical region
- $J^P = 0^-, 2^-, 4^-, \dots$ correspond with $\mathcal{S} = +1$
- $J^P = 1^+, 3^+, 5^+, \dots$ correspond with $\mathcal{S} = -1$

Degenerate Regge Trajectory

Degenerate trajectory: obtained by adding or subtracting the two non-degenerate trajectories with the two opposite signatures

1. a constant (1) phase
2. a rotating ($e^{-i\pi\alpha(t)}$) phase: strong degeneracy assumption

$$\frac{1}{t - m_K^2} \implies \mathcal{P}_{Regge}^K(s, t) = \left(\frac{s}{s_0}\right)^{\alpha_K(t)} \frac{\pi\alpha'_K}{\sin(\pi\alpha_K(t))} \times e^{-i\pi\alpha_K(t)} \frac{1}{\Gamma(1 + \alpha_K(t))}$$

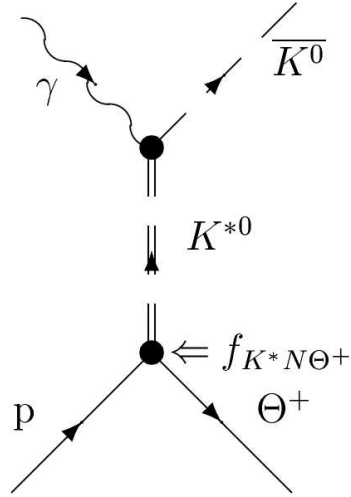
- Regge vertex functions (Regge residues) away from the pole position, need form factors $F_K(t)$, $F_\Theta(u)$, and \hat{F} .
- We choose monopole forms for F_K and F_u :

$$F_K(t) = \left(1 + \frac{-t + m_K^2}{\Lambda^2} \right)^{-1},$$

$$F_\Theta(u) = \left(1 + \frac{-u + M_\Theta^2}{\Lambda^2} \right)^{-1},$$

- where cut-off Λ is chosen to be 1 GeV,
- and $\hat{F} = F_K(t) + F_\Theta(u) - F_K(t) \cdot F_\Theta(u)$ to cancel the poles in the contact terms.

$$\gamma p \rightarrow \bar{K}^0 \Theta^+ : J_{\Theta}^P = \frac{1}{2}^+ \left(\frac{1}{2}^- \right)$$



$$\begin{aligned} \mathcal{M}_{K^*} &= (i) e f_{K^{*0} K^0 \gamma} f_{K^* N \Theta} \cdot \mathcal{P}_{Regge}^{K^*}(s, t) \cdot \varepsilon^\mu(q, \lambda) \\ &\times \varepsilon_{\mu\nu\lambda\alpha} q^\nu (q - p_K)^\lambda \bar{\Theta} \left[\frac{i \sigma^{\alpha\beta} (q - p_K)_\beta}{M_N + M_\Theta} \right] \gamma_5 N \end{aligned} \quad (1)$$

- $f_{K^{*0} K^0 \gamma}$ is determined from radiative K^* decay experiment
- similar term contributes to $\gamma n \rightarrow \Theta^+ K^-$ if K^* is considered

$K^*N\Theta^+$ vertex

- $J^P = \left(\frac{1}{2}^+\right) \quad \left(\frac{1}{2}^-\right)$

$$\mathcal{L}_{K^*N\Theta} = -i f_{K^*N\Theta} \bar{\Theta} \left[\frac{i \sigma_{\mu\nu} p_{K^*}^\nu}{M_N + M_\Theta} \right] \gamma_5 N \cdot V^\mu(p_{K^*}) + \text{h.c.}$$

- Using $SU(3)$ symmetry for the vector meson couplings within the baryon octet and $SU(6)$ symmetry between the baryon octet and antidecuplet

$$g_{\rho^0 pp} + f_{\rho^0 pp} = \frac{7}{10} \left(V_0 + \frac{1}{2} V_1 \right) + \frac{1}{20} V_2 = 18.7(\text{input})$$

$$g_{\phi pp} + f_{\phi pp} = -\frac{1}{10} \left(V_0 + \frac{1}{2} V_1 \right) + \frac{7}{20} V_2 = 0(\text{input})$$

$$f_{K^{*0}\Theta+p} = \frac{3}{\sqrt{30}} \left(V_0 - V_1 - \frac{1}{2} V_2 \right)$$

- $g_{VNN}(f_{VNN})$: vector (tensor) coupling constants

$$f_{K^*0p\Theta^+} = (g_{\rho^0pp} + f_{\rho^0pp}) \frac{3\sqrt{3}}{\sqrt{10}} \frac{4/5 - r}{r + 2}$$

- where $r \equiv V_1/V_0 \simeq 0.35$ is obtained in the chiral quark soliton model

$$f_{K^*N\Theta} \equiv f_{K^*0p\Theta^+} \simeq 5.9$$

- rescaling r , corresponding to Θ^+ width of 1 MeV yields:

$$f_{K^*N\Theta} \equiv f_{K^*0p\Theta^+} \simeq 1.1$$

K* Regge Exchange

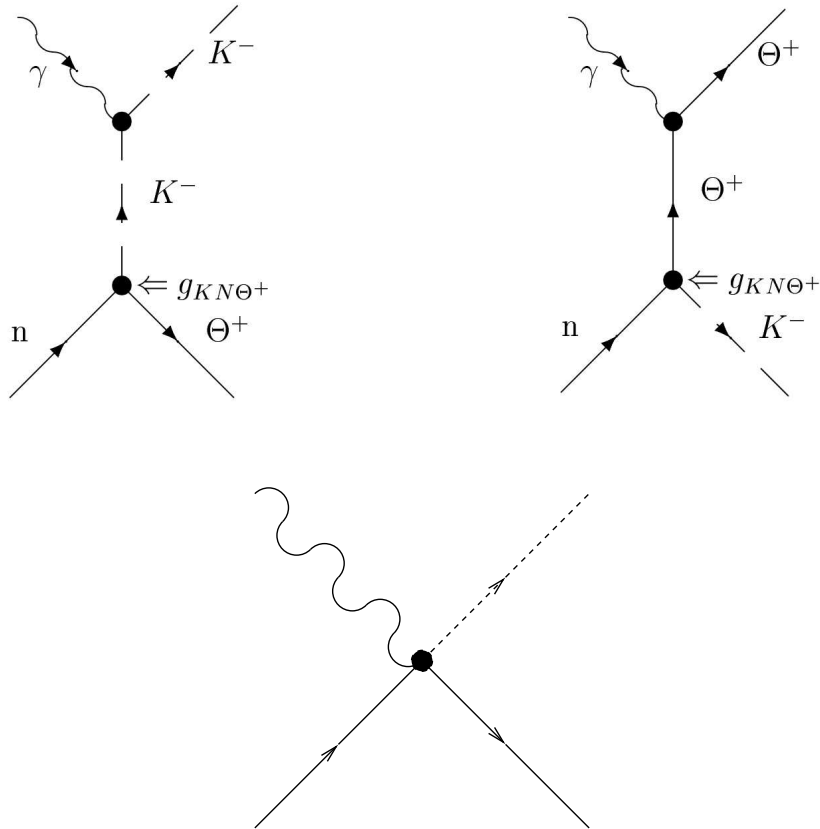
$$\frac{1}{t - m_{K^*}^2} \implies \mathcal{P}_{Regge}^{K^*} = \left(\frac{s}{s_0} \right)^{\alpha_{K^*}(t)-1} \frac{\pi \alpha'_{K^*}}{\sin(\pi \alpha_{K^*}(t))} \times \frac{\mathcal{S}_K^* + e^{-i\pi \alpha_{K^*}(t)}}{2} \frac{1}{\Gamma(\alpha_{K^*}(t))}$$

- Regge trajectory: $\alpha_{K^*}(t) = \alpha_{K^*}^0 + \alpha'_{K^*} \cdot t$
- standard linear trajectory for the $K^*(892)$ is :

$$\alpha_{K^*}(t) = 0.25 + \alpha'_{K^*} t$$

- where $\alpha'_{K^*} = 0.83 \text{ GeV}^{-2}$
- strong degeneracy assumption

$$\gamma n \rightarrow K^- \Theta^+ : J_{\Theta}^P = \frac{3}{2}^+ \left(\frac{3}{2}^- \right)$$



- additional contact term: to preserve gauge invariance
- $\Theta \rightarrow \Theta^\alpha$ (spin-3/2): change the vertex and propagator structure

$$\begin{aligned}
\mathcal{M}_K &= \frac{(-)(i) e g_{KN\Theta}}{m_K} \cdot \mathcal{P}_{Regge}^K(s, t) \cdot \varepsilon_\mu(q, \lambda) \\
&\times \left[F_K(t) \cdot (2p_K - q)^\mu \cdot (p_K - q)^\alpha \cdot \bar{\Theta}_\alpha \gamma^5 N \right. \\
&- F_\Theta(u) \cdot (t - m_K^2) \cdot \bar{\Theta}_\alpha \gamma^{\alpha\beta\mu} \frac{(\gamma \cdot p_u + M_\Theta)}{u - M_\Theta^2} \\
&\quad \cdot S_{\beta\nu} \cdot \gamma^{\nu\sigma\rho} \frac{(p_K)_\sigma \cdot (p_u)_\rho}{M_\Theta^2} \gamma^5 N \\
&+ (t - m_K^2) \cdot \bar{\Theta}_\alpha \gamma^{\alpha\mu\nu} \frac{(F_\Theta(u) \cdot p_K + F_K(t) \cdot p_\Theta)_\nu}{M_\Theta} \gamma^5 N \\
&+ 2p_K^\mu \cdot (\hat{F}(s, t, u) - F_K(t)) \cdot p_K^\alpha \cdot \bar{\Theta} \gamma^5 N \\
&\left. - \left(\frac{t - m_K^2}{u - m_\Theta^2} \right) \cdot 2p_\Theta^\mu \cdot \{\hat{F}(s, t, u) - F_\Theta(u)\} \cdot p_K^\alpha \cdot \bar{\Theta} \gamma^5 N \right]
\end{aligned}$$

with

$$S_{\beta\nu} = g_{\beta\nu} - \frac{\gamma_\beta \gamma_\nu}{3} - \frac{(\gamma_\beta (p_u)_\nu - \gamma_\nu (p_u)_\beta)}{3M_\Theta} - \frac{2((p_u)_\beta (p_u)_\nu)}{3M_\Theta^2}$$

- again difference between (+) and (-) parity: only in γ^5 and (\pm, i)

KN Θ^+ vertex

- $J^P = \frac{3}{2}^+$

$$\mathcal{L}_{KN\Theta} = \frac{g_{KN\Theta}}{m_K} \left\{ \bar{\Theta}^\alpha g_{\alpha\beta} N (\partial^\beta K) + \bar{N} \Theta^\alpha g_{\alpha\beta} (\partial^\beta K^\dagger) \right\}$$

$$\Gamma_{\Theta \rightarrow KN} = \frac{g_{KN\Theta}^2}{2\pi} \frac{|\bar{p}_K|}{M_\Theta} \frac{|\bar{p}_K|^2}{3m_K^2} \left(\sqrt{\bar{p}_K^2 + M_N^2} + M_N \right)$$

- with $\Gamma_{\Theta \rightarrow KN} = 1 \text{ MeV} \rightarrow g_{KN\Theta} \simeq 0.4741$

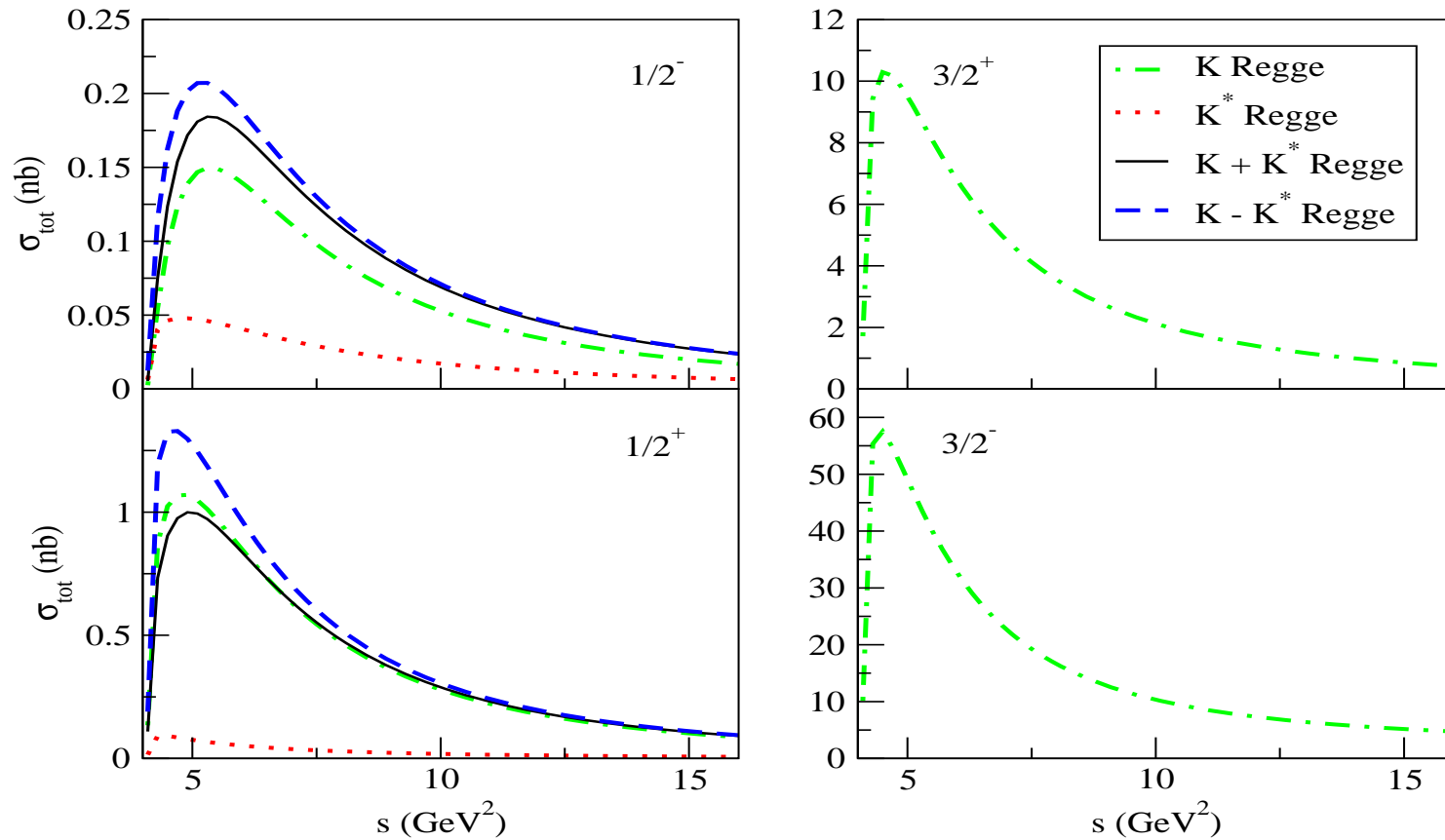
- $J^P = \frac{3}{2}^-$

$$\mathcal{L}_{KN\Theta} = \frac{g_{KN\Theta}}{m_K} \left\{ \bar{\Theta}^\alpha \gamma_5 N g_{\alpha\beta} (\partial^\beta K) + \bar{N} \gamma_5 \Theta^\alpha g_{\alpha\beta} (\partial^\beta K^\dagger) \right\}$$

$$\Gamma_{\Theta \rightarrow KN} = \frac{g_{KN\Theta}^2}{2\pi} \frac{|\bar{p}_K|}{M_\Theta} \frac{|\bar{p}_K|^2}{3m_K^2} \left(\sqrt{\bar{p}_K^2 + M_N^2} - M_N \right)$$

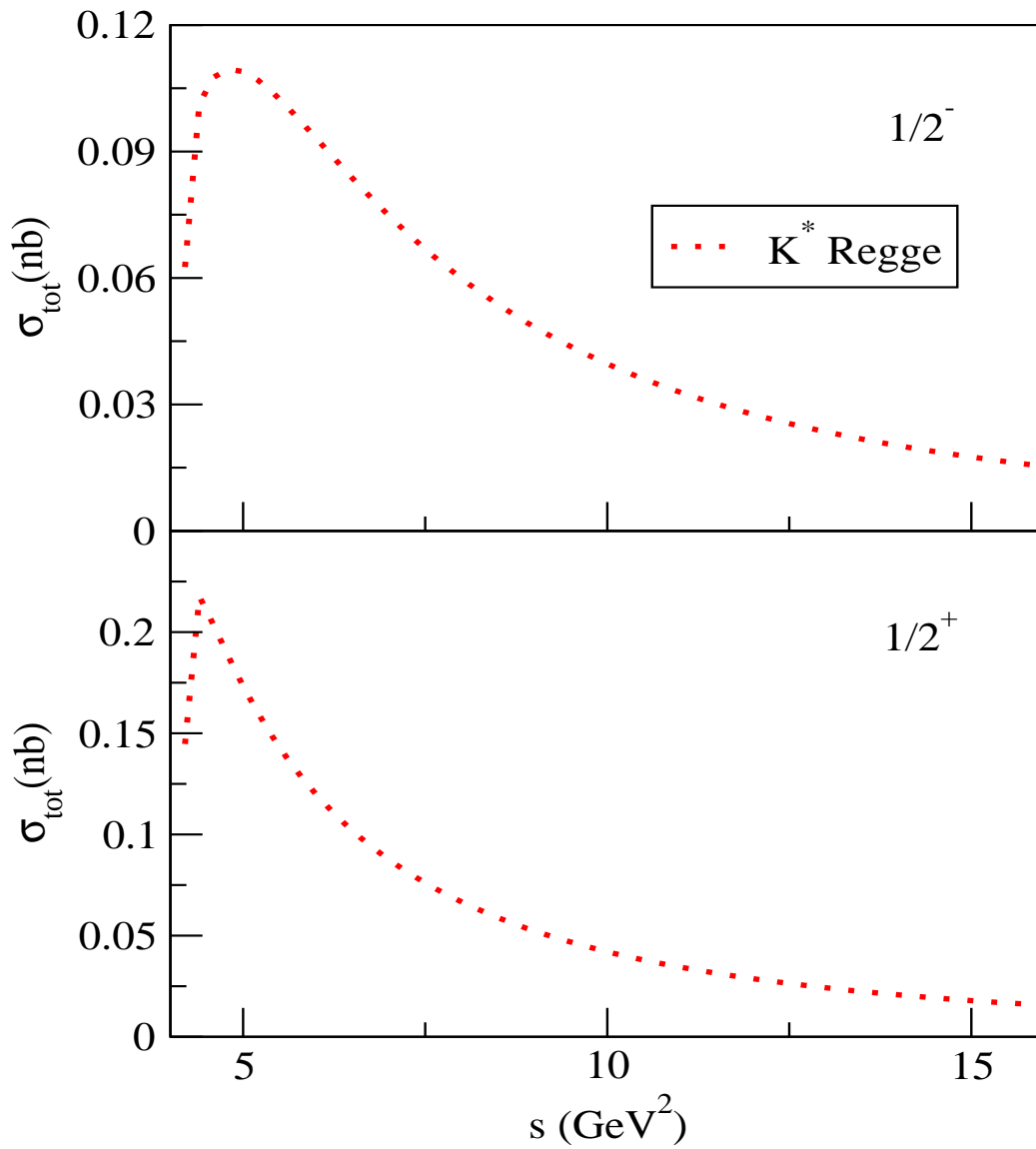
- $\Gamma_{\Theta \rightarrow KN} = 1 \text{ MeV} \rightarrow g_{KN\Theta} \simeq 3.558$

Cross Section for $\gamma n \rightarrow \Theta^+ K^-$

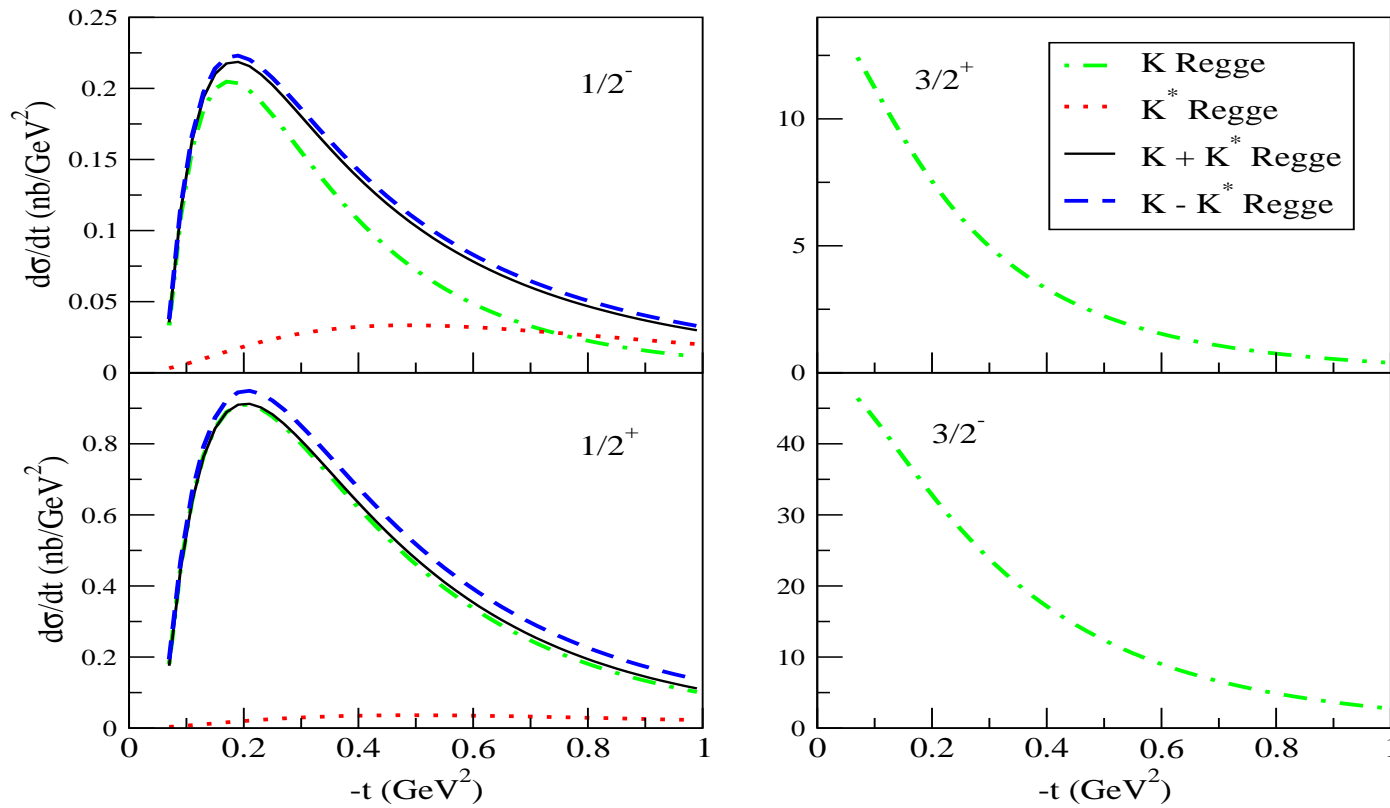


- Note the uncertainty in the sign of the coupling $f_{K^*0p\Theta^+}$

Cross section for $\gamma p \rightarrow \Theta^+ \overline{K^0}$

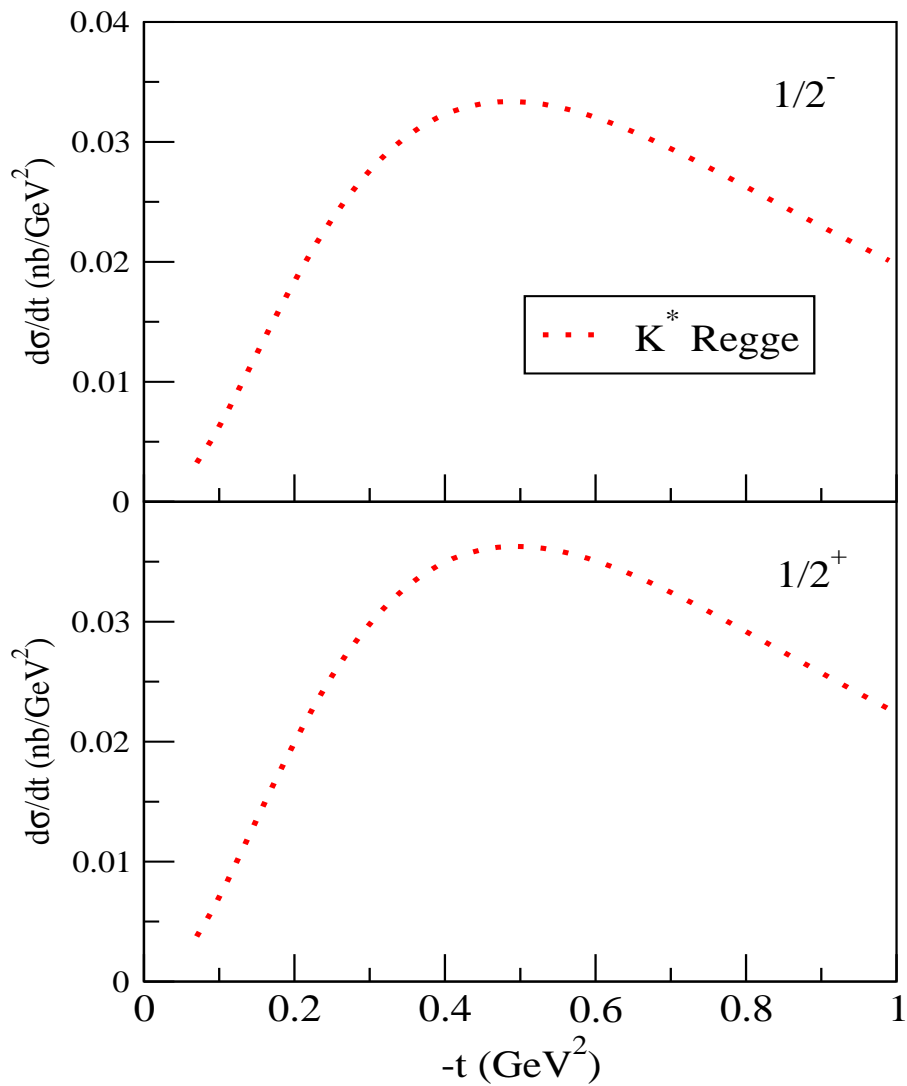


Differential Cross section for $\gamma n \rightarrow \Theta^+ K^-$,
 $s = 8.4 \text{ GeV}^2$



- spin- $1/2^-$ has peak around $-t \simeq 0.2 \text{ GeV}^2$

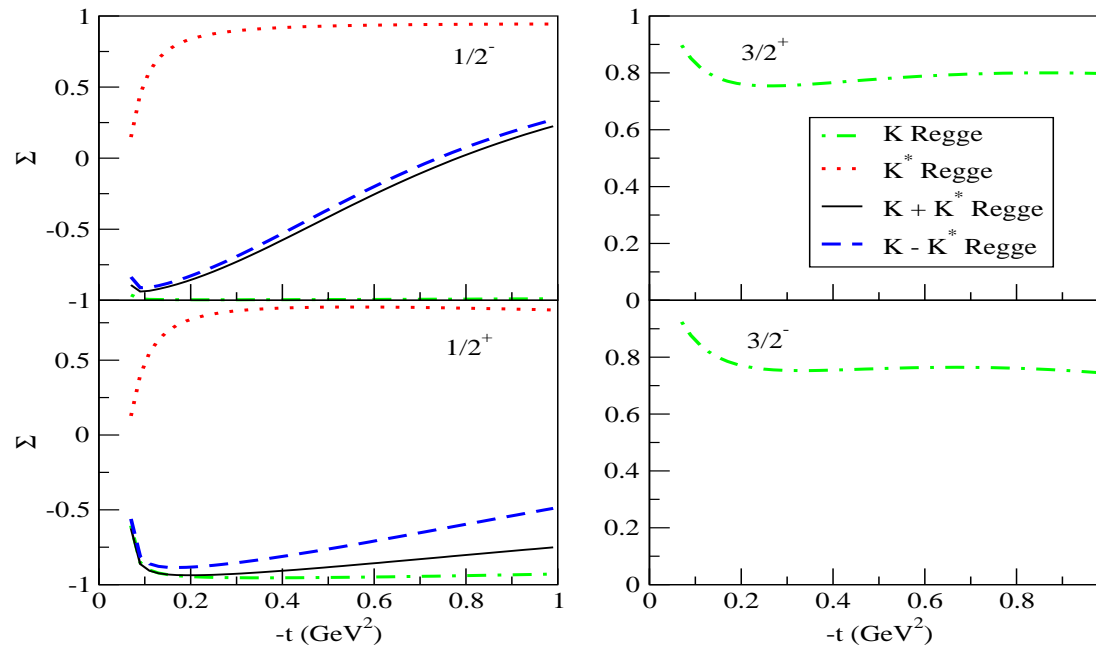
Differential Cross section $\gamma p \rightarrow \Theta^+ \bar{K}^0$,
 $s = 8.4 \text{ GeV}^2$



- γp has peak(from K^*) around $-t \simeq 0.4 - 0.5 \text{ GeV}^2$

Photon Asymmetries for $\gamma n \rightarrow \Theta^+ K^-$,

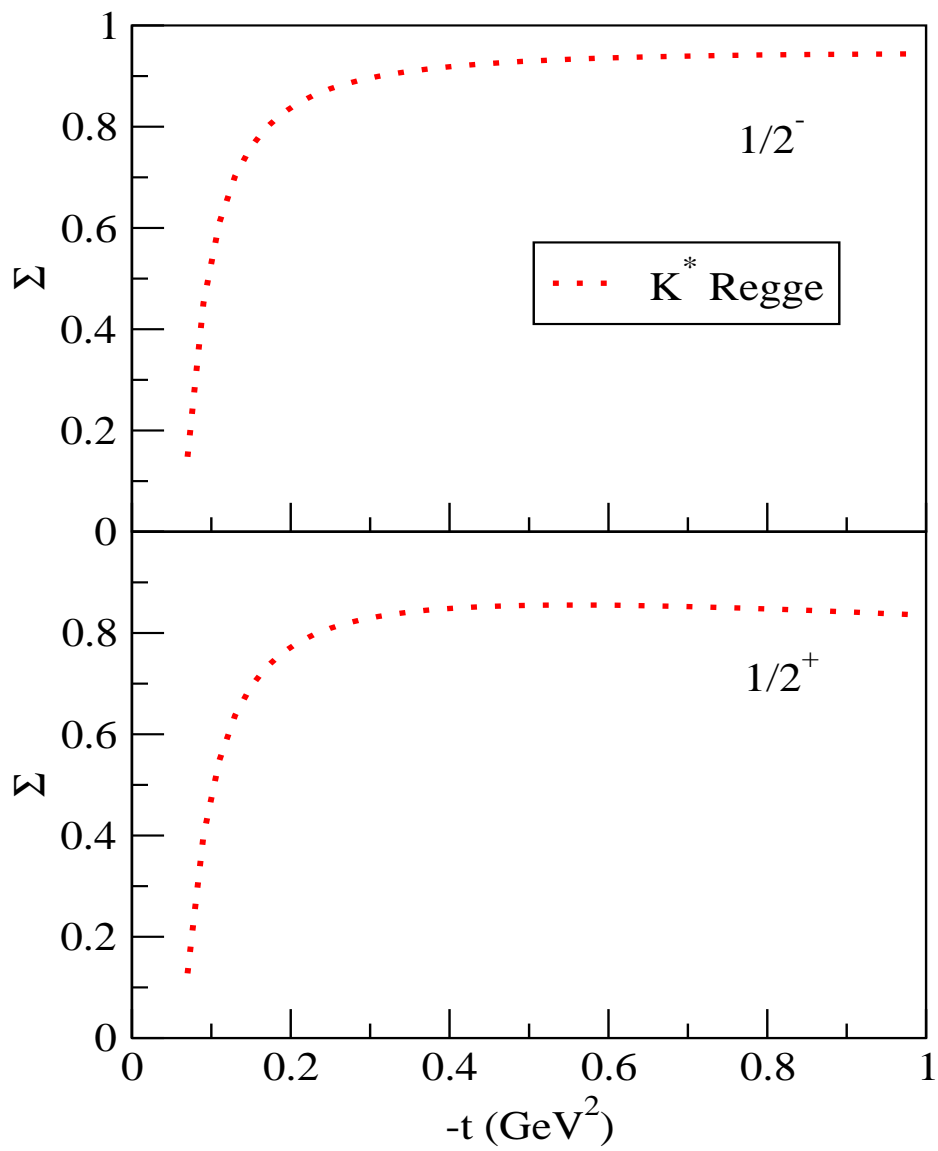
$s = 8.4 \text{ GeV}^2$



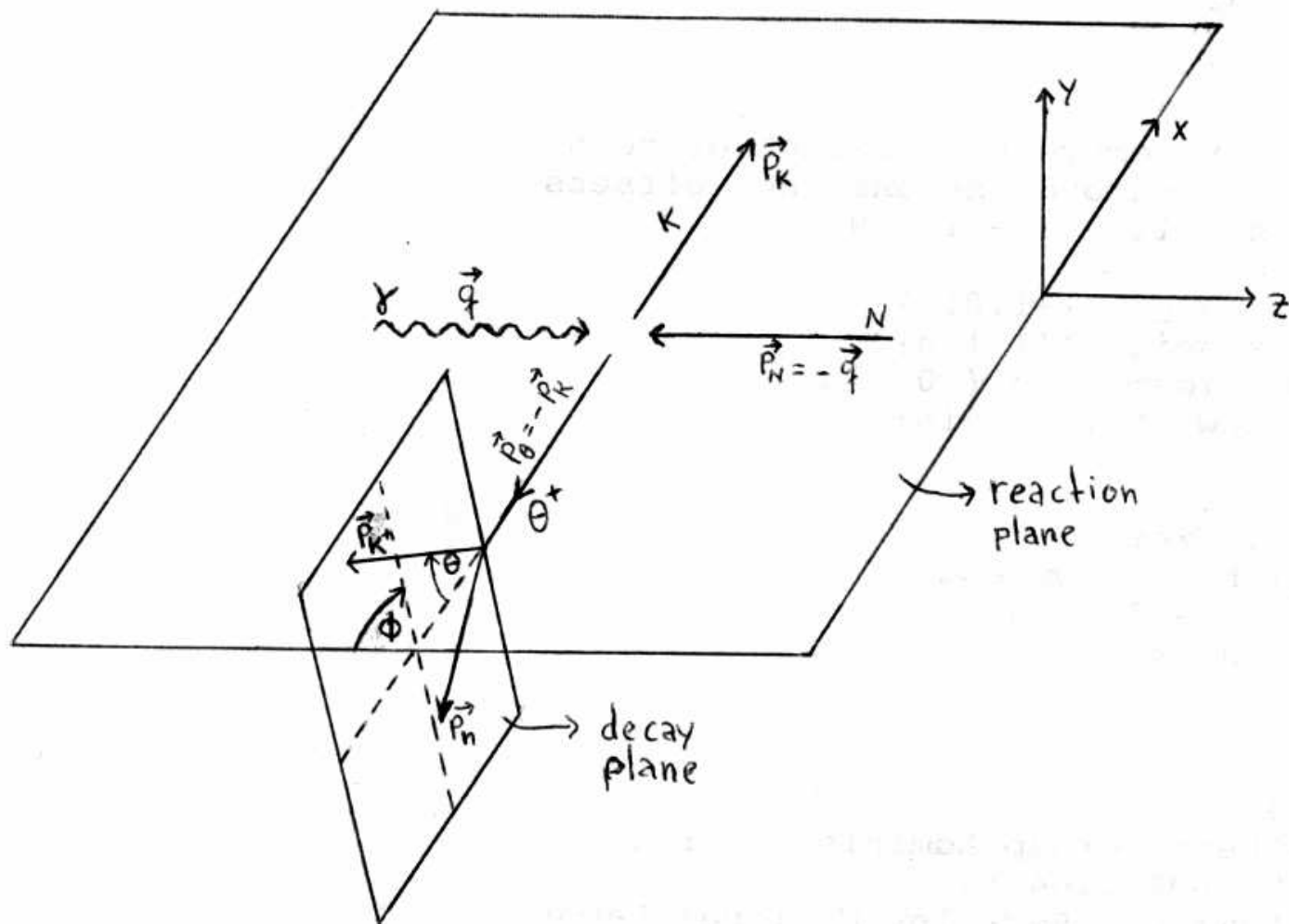
- $\Sigma = \frac{\sigma_{\perp} - \sigma_{\parallel}}{\sigma_{\perp} + \sigma_{\parallel}}$

- $K(K^*)$ exchange dominant, Σ go to $-1(1)$

Photon Asymmetries for $\gamma p \rightarrow \Theta^+ \overline{K^0}$,
 $s = 8.4 \text{ GeV}^2$



Decay Angular Distribution



- angular distribution of $\Theta^+ \rightarrow K^+ n$

$$\begin{aligned}
W(\theta, \phi) &= \sum_{s_f, s'_f; s_\theta, s'_\theta} \hat{R}_{s_f, s_\theta} \rho_{s_\theta, s'_\theta}(\Theta^+) \hat{R}_{s'_f, s'_\theta}^* \\
&= \sum_{s_\theta, s'_\theta} \left\{ \hat{R}_{-\frac{1}{2}, s_\theta} \rho_{s_\theta, s'_\theta} \hat{R}_{-\frac{1}{2}, s'_\theta}^* + \hat{R}_{\frac{1}{2}, s_\theta} \rho_{s_\theta, s'_\theta} \hat{R}_{-\frac{1}{2}, s'_\theta}^* \right. \\
&\quad \left. + \hat{R}_{\frac{1}{2}, s_\theta} \rho_{s_\theta, s'_\theta} \hat{R}_{\frac{1}{2}, s'_\theta}^* + \hat{R}_{-\frac{1}{2}, s_\theta} \rho_{s_\theta, s'_\theta} \hat{R}_{\frac{1}{2}, s'_\theta}^* \right\}
\end{aligned}$$

- The transition operator

$$\hat{R}_{s_f, s_\theta} \equiv \langle n, s_f, \mathbf{P}_\theta - \mathbf{p}' | \hat{t} | \Theta^+, s_\theta, \mathbf{P}_\theta = 0 \rangle$$

- $\rho_{s_\theta, s'_\theta}$: the photon density matrix elements in the Θ^+ production

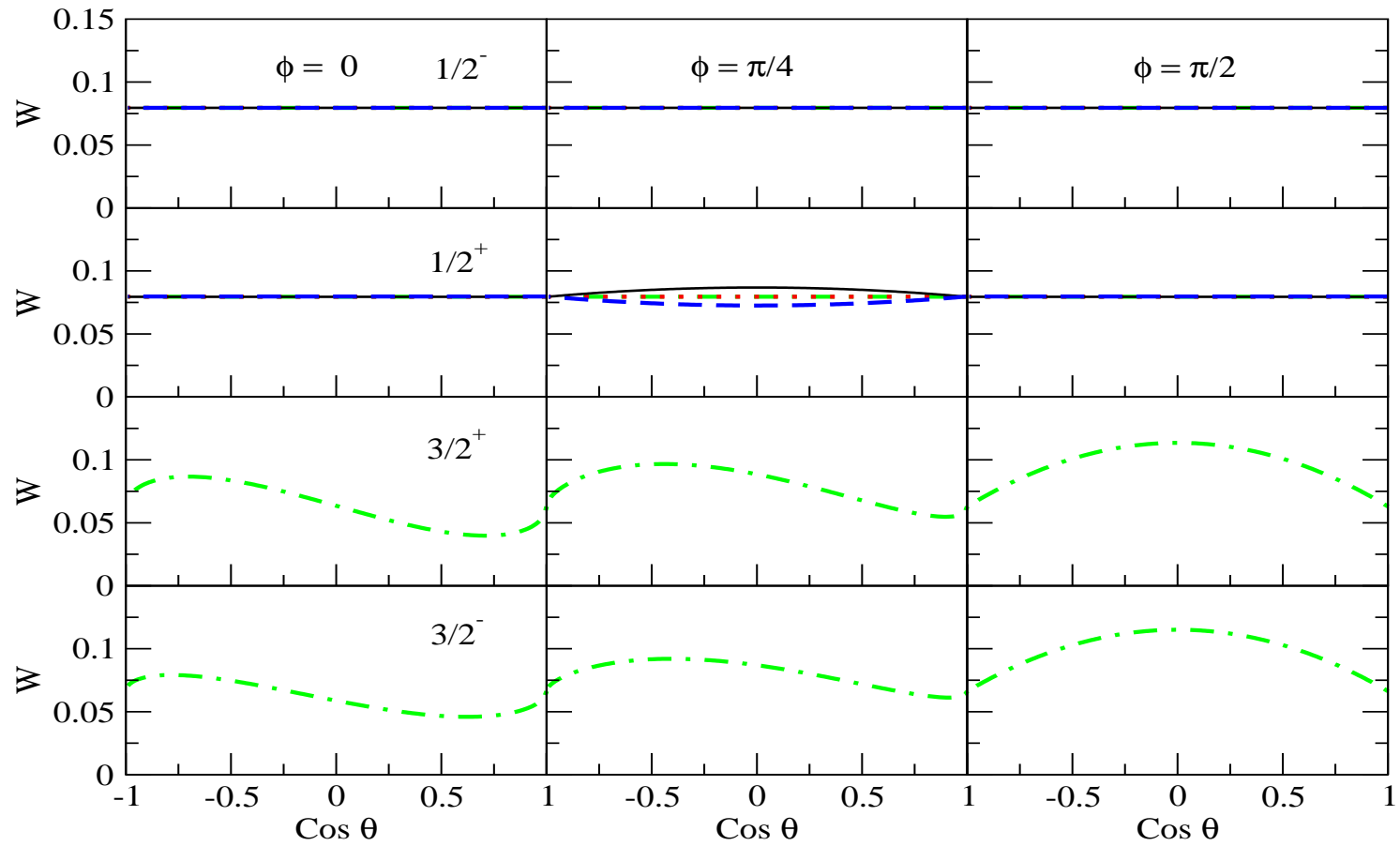


Figure 2: $\gamma n \rightarrow \Theta^+ K^-$, $\alpha = 0$, $s = 8.4 \text{ GeV}^2$, $t = -0.1 \text{ GeV}^2$

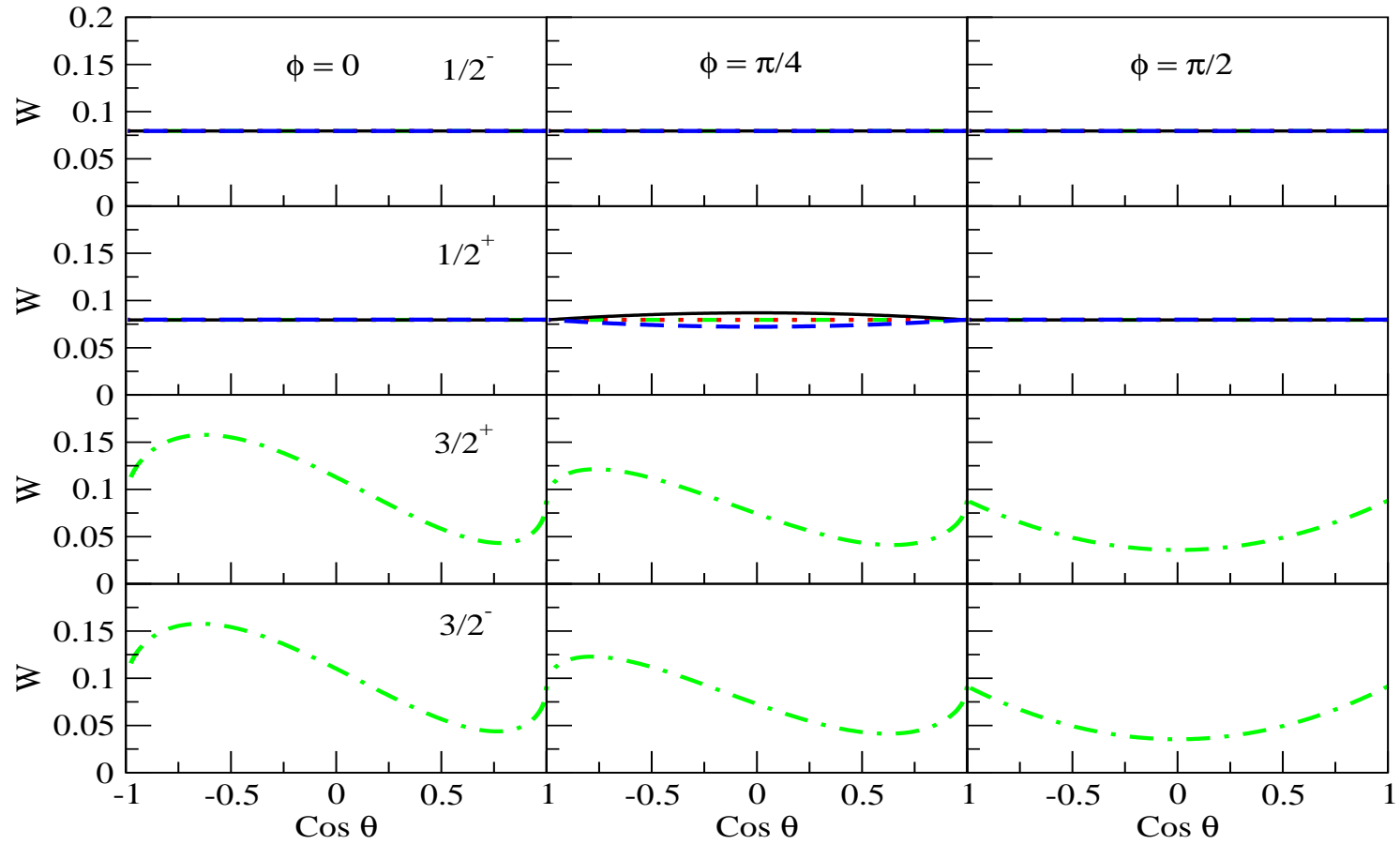


Figure 3: $\gamma n \rightarrow \Theta^+ K^-$, $\alpha = 1$, $s = 8.4 \text{ GeV}^2$, $t = -0.1 \text{ GeV}^2$

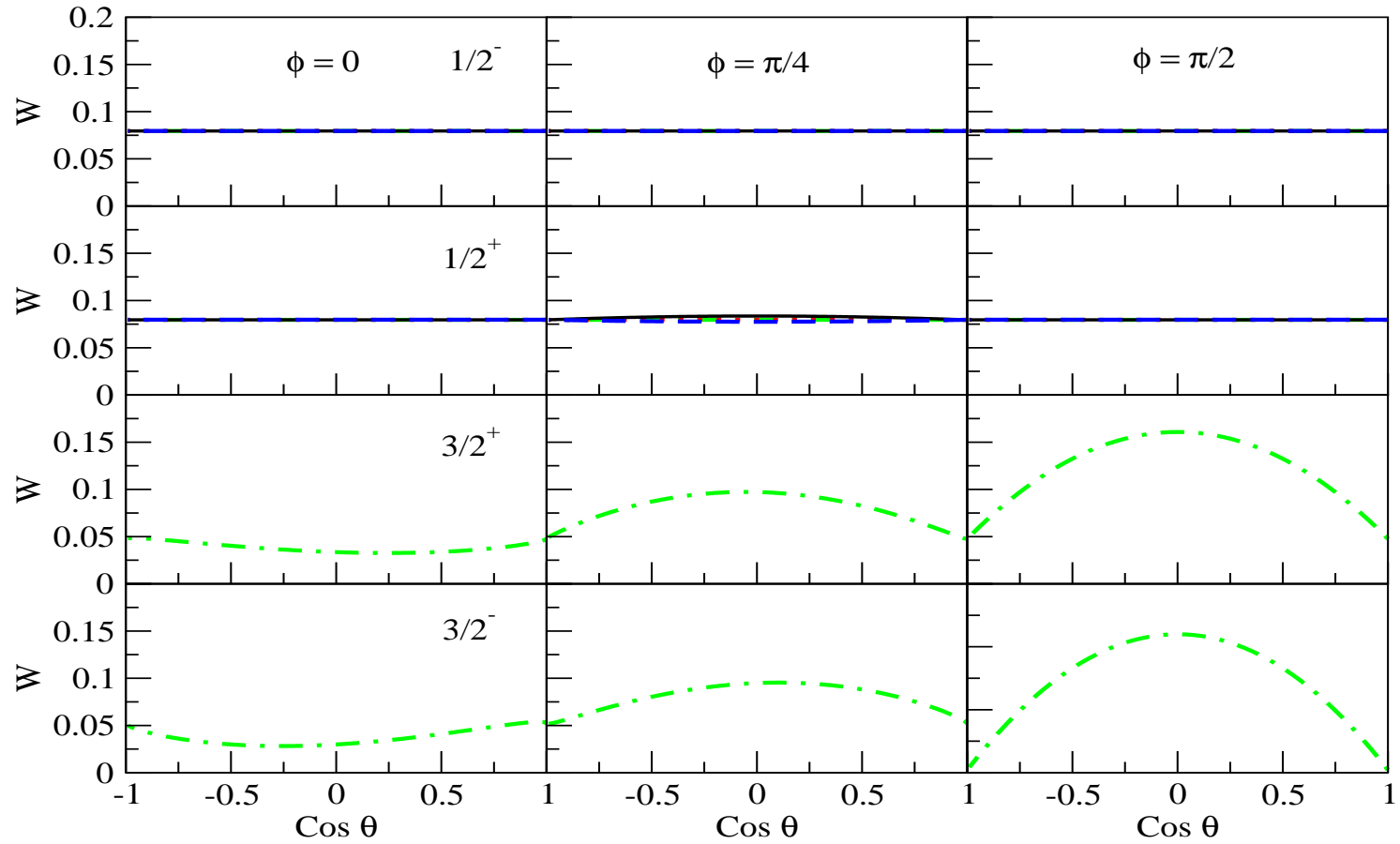


Figure 4: $\gamma n \rightarrow \Theta^+ K^-$, $\alpha = 2$, $s = 8.4 \text{ GeV}^2$, $t = -0.1 \text{ GeV}^2$

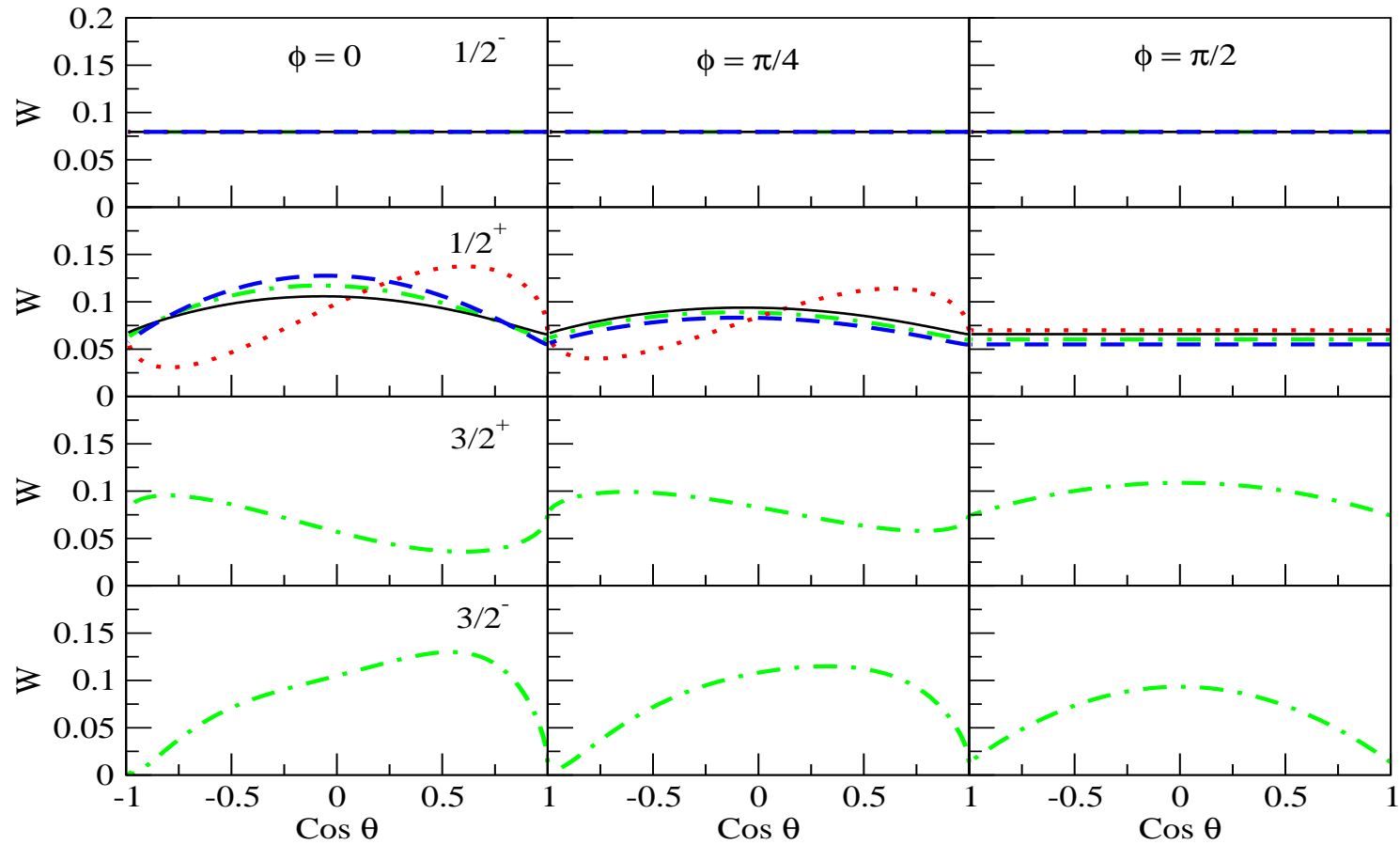


Figure 5: $\gamma n \rightarrow \Theta^+ K^-$, $\alpha = 3$, $\text{pol}_\gamma = -1$, $s = 8.4 \text{ GeV}^2$, $t = -0.1 \text{ GeV}^2$

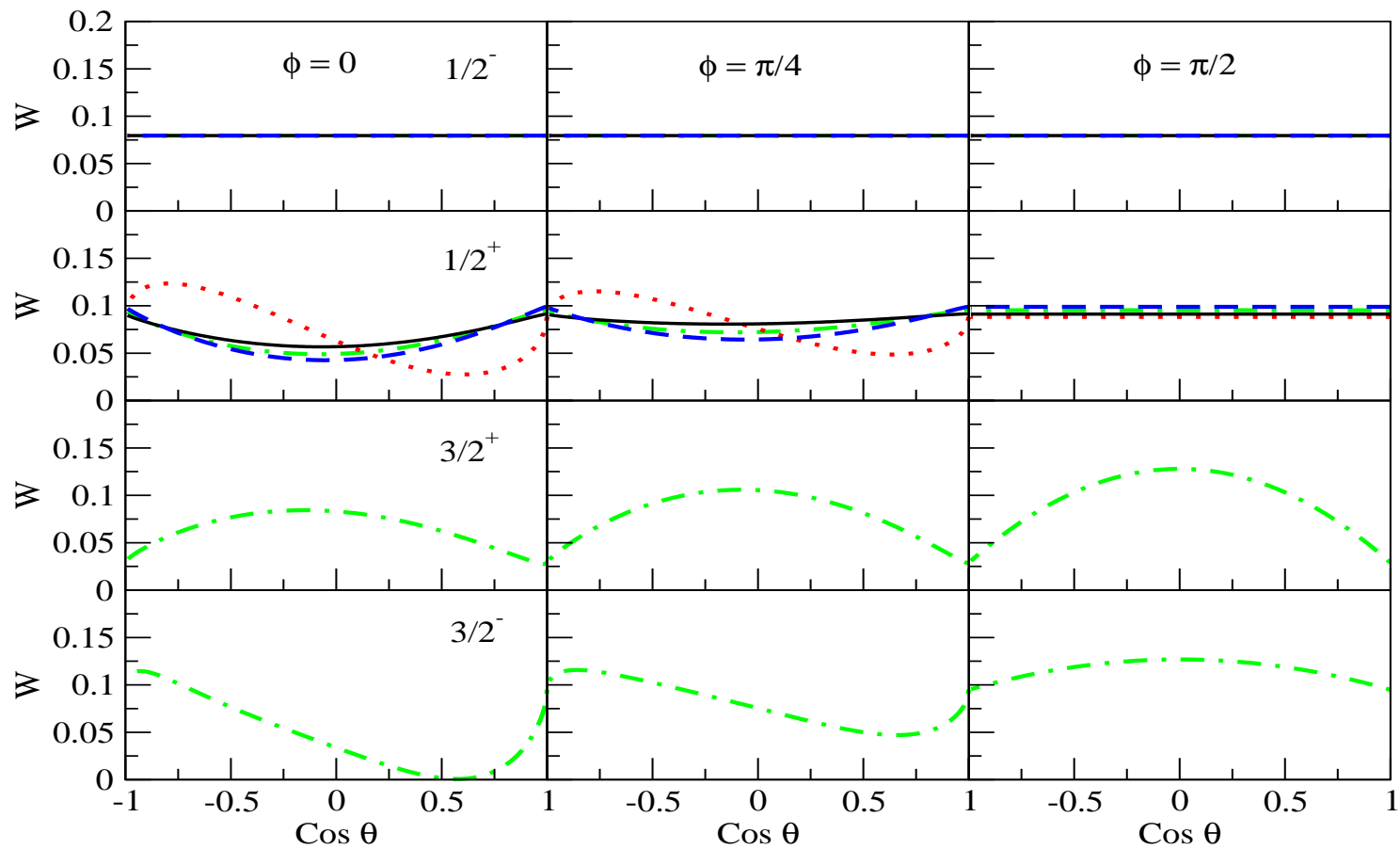


Figure 6: $\gamma n \rightarrow \Theta^+ K^-$, $\alpha = 3$, $\text{pol}_\gamma = 1$, $s = 8.4 \text{ GeV}^2$, $t = -0.1 \text{ GeV}^2$

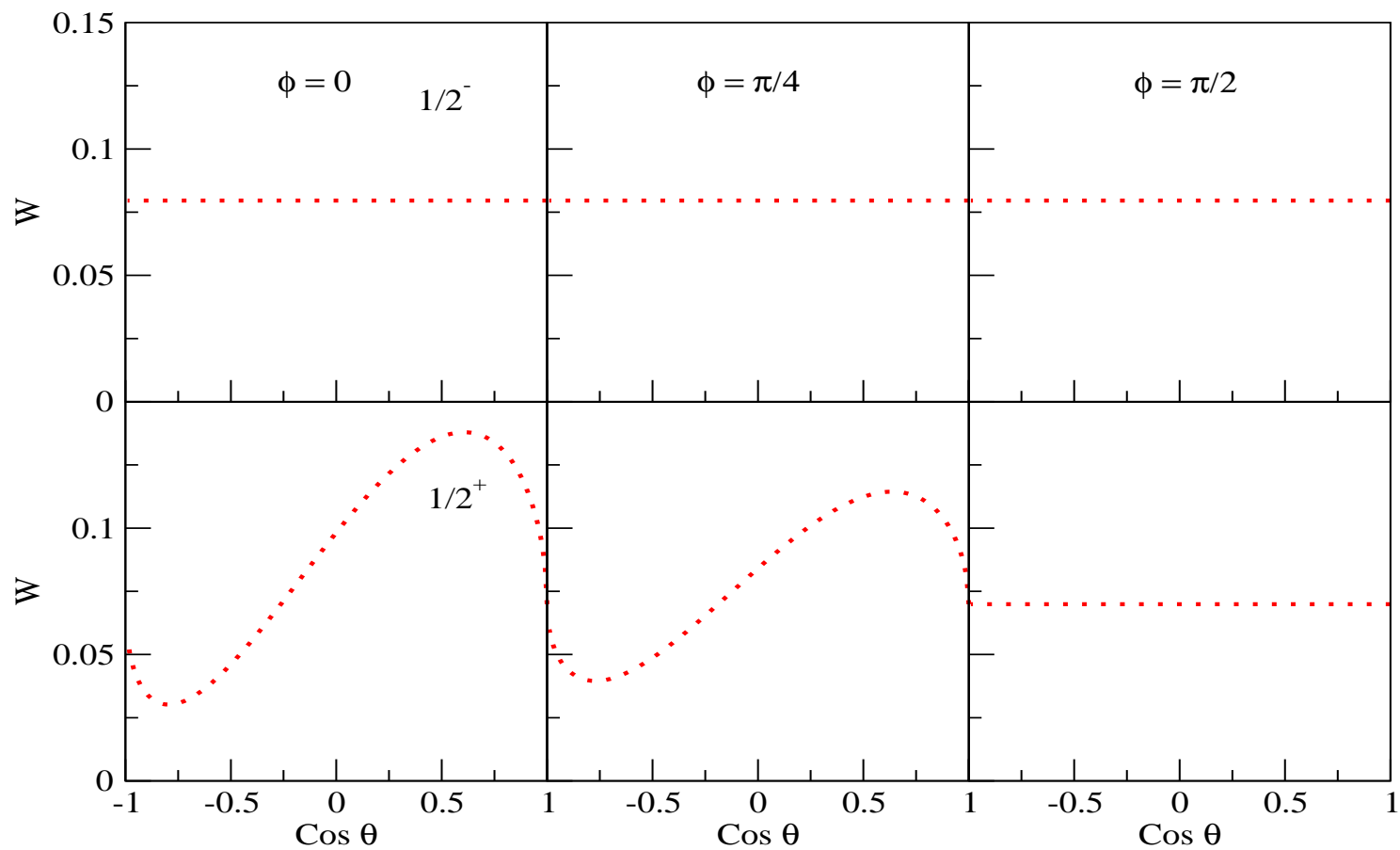


Figure 7: $\gamma p \rightarrow \Theta^+ \overline{K}^0$, $\alpha = 3$, $\text{pol}_\gamma = -1$, $s = 8.4 \text{ GeV}^2$, $t = -0.1 \text{ GeV}^2$

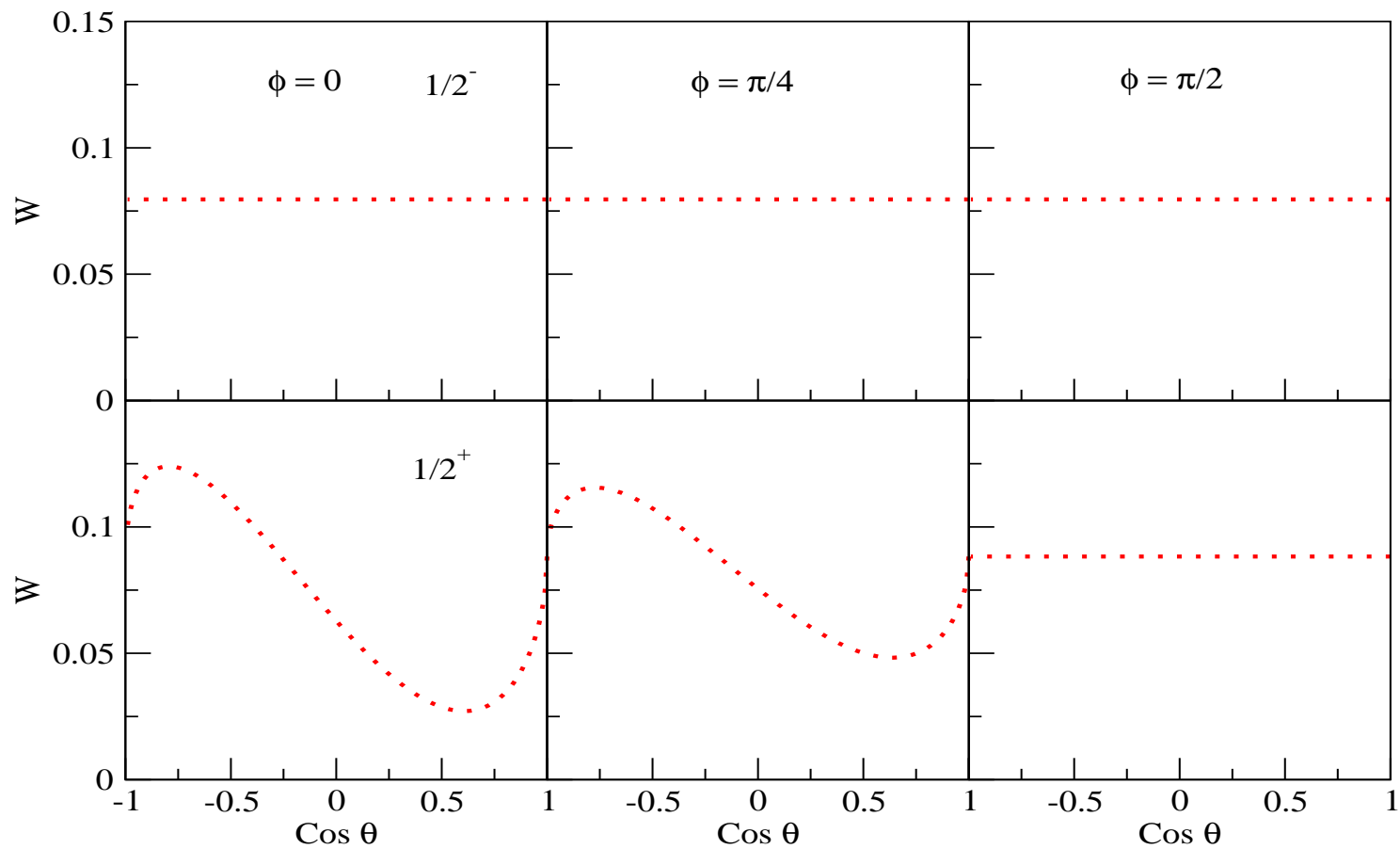


Figure 8: $\gamma p \rightarrow \Theta^+ \bar{K}^0$, $\alpha = 3$, $\text{pol}_\gamma = 1$, $s = 8.4 \text{ GeV}^2$, $t = -0.1 \text{ GeV}^2$

Some observable of the W (decay angular distribution):

- more variation in:
 - $\gamma n \rightarrow K^- \Theta^+$
 - circular polarization
- hard to miss spin-3/2 characteristic
- $\phi = \pi/2$ mostly not interesting

Conclusion

- theoretically both parity assignment of the Θ^+ are allowed
- the spin of the Θ^+ can be $1/2$ or $3/2$
- photoproduction experiments: good place to determine the spin and parity of the Θ^+
- if statistics allow, decay angular distribution is even better to determine the spin and parity of the Θ^+