The Θ^+ Photoproduction in a Regge Model

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1. Introduction
2. Photoproduction
   - $\gamma n \to \Theta^+ K^-$ for spin-1/2 Θ^+
   - $\gamma p \to \Theta^+ \overline{K^0}$ for spin-1/2 Θ^+
   - $\gamma n \to \Theta^+ K^-$ for spin-3/2 Θ^+
3. Results
   - Total cross sections (σ)
   - Differential cross sections ($\frac{d\sigma}{\mathrm{d}t}$)
   - 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

First experimental signature: Nakano et. al. (hep-ex/0301020)

- mass 1540 ± 10 MeV
- width less than 25 MeV

KN scattering experiments (e.g. V.V. Barmin *et al.*, hep-ex/0304040) $\rightarrow$ very narrow width ($\leq$ few MeV)

Up to now:

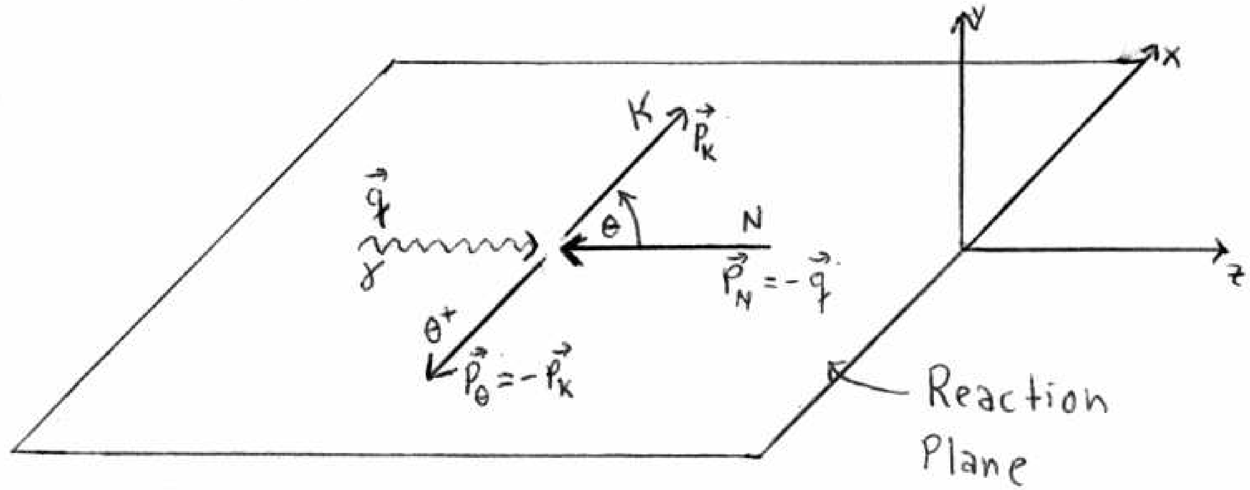
- 10 published experiments with positive signature for the Θ^+
- 11 published experiments with non-observing results for the Θ^+

Quantum Numbers

- $SU(3)_F : 3 \otimes 3 \otimes 3 \otimes 3 \otimes \bar{3} \rightarrow$ many possibilities (multiplets)
  Θ^+ (S $= +1$) member of 35plet, 27plet or antidecuplet.
- Why antidecuplet?
  isospin $= 0$ (searches for $\theta^{++} \rightarrow$ no result, J. Barth et al., hep-ex/0307083)
- The spin and parity of the Θ^+ is unknown

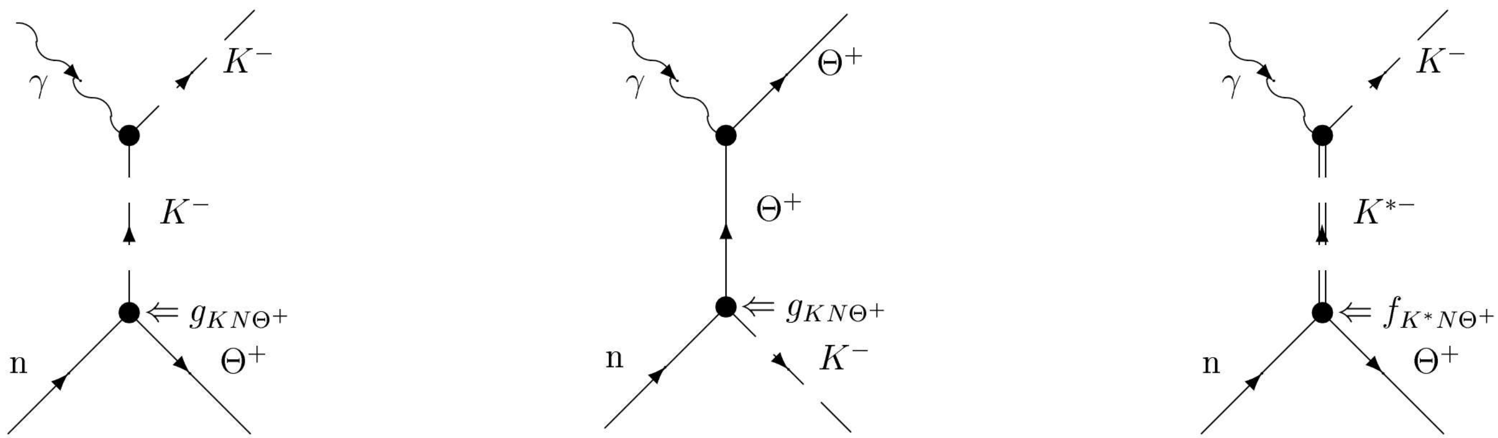
Θ^+ Photoproduction

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



$s \equiv (p_N + q)^2$, $t \equiv (q - p_K)^2$, and $u \equiv (q - p_\Theta)^2$
(M. Guidal, HJK, M. Vanderhaeghen, work in progress)

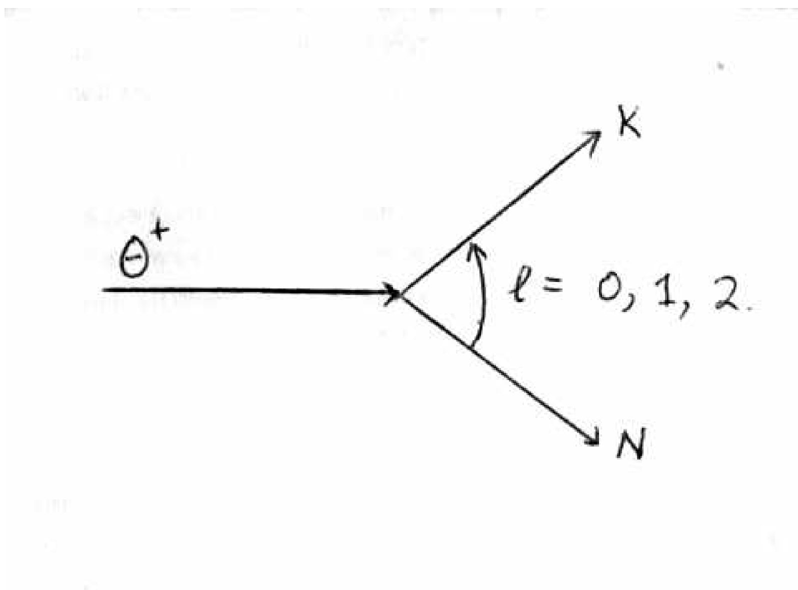
$$\gamma n \longrightarrow K^- \Theta^+ : J^P_\Theta = \frac{1}{2}^+ \ \left(\frac{1}{2}^-\right)$$



$$\begin{aligned} \mathcal{M}_K \quad &= \quad (-i)\, e\, g_{KN\Theta} \cdot \mathcal{P}^K_{Regge}(s,t) \cdot \varepsilon_\mu(q,\lambda) \\ &\times \quad \Big\{ (2p_K - q)^\mu \cdot \bar{\Theta}\, \gamma^5\, N \\ &- \quad (t - m_K^2) \cdot \bar{\Theta}\, \gamma^\mu \frac{(\gamma \cdot p_u + M_\Theta)}{u - M_\Theta^2} \gamma^5\, N \Big\} \end{aligned}$$

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

KNΘ Vertex and Θ Width



$$J^P = \tfrac{1}{2}^- \Longleftrightarrow l = 0, \text{ S-wave}$$
$$J^P = \tfrac{1}{2}^+ \Longleftrightarrow l = 1, \text{ P-wave}$$
$$J^P = \tfrac{3}{2}^+ \Longleftrightarrow l = 1, \text{ P-wave}$$
$$J^P = \tfrac{3}{2}^- \Longleftrightarrow l = 2, \text{ D-wave}$$

$KN\Theta^+$ vertex

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

$$\begin{aligned} \mathcal{L}_{KN\Theta} &= i\, g_{KN\Theta} \left(K^\dagger \bar{\Theta} \gamma_5 N + \bar{N} \gamma_5 \Theta K \right) \\ \Gamma_{\Theta \to KN} &= \frac{g^2_{KN\Theta}}{2\pi} \frac{|\bar{p}_K|}{M_\Theta} \left(\sqrt{\bar{p}_K^2 + M_N^2} - M_N \right) \end{aligned}$$

- $|\bar{p}_K| \simeq 0.267$ GeV

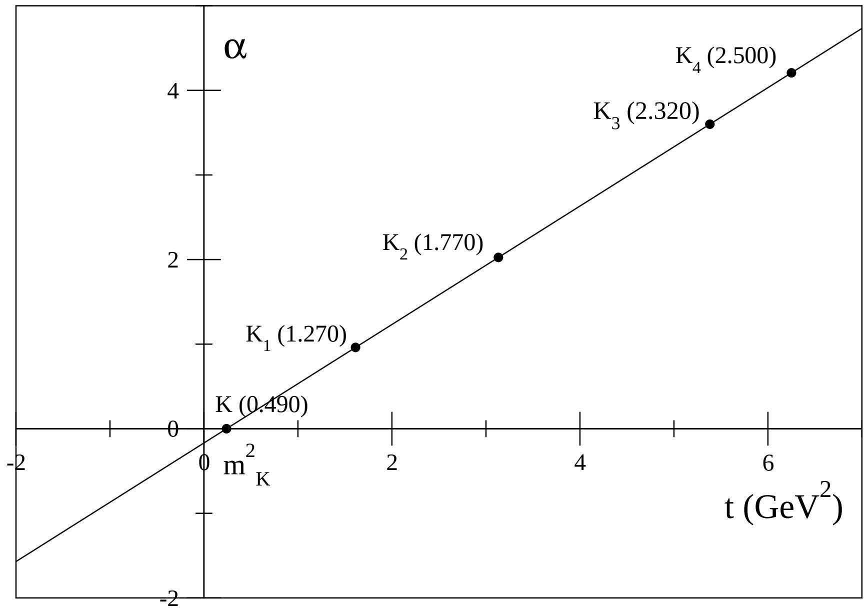
- $\Gamma_{\Theta \to KN} = 1$ MeV $\to g_{KN\Theta} \simeq 1.056$
  $\Gamma_{\Theta \to KN} = 3$ MeV $\to g_{KN\Theta} \simeq 1.829$

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

$$\begin{aligned} \mathcal{L}_{KN\Theta} &= g_{KN\Theta} \left(K^\dagger \bar{\Theta} N + \bar{N} \Theta K \right) \\ \Gamma_{\Theta \to KN} &= \frac{g^2_{KN\Theta}}{2\pi} \frac{|\bar{p}_K|}{M_\Theta} \left(\sqrt{\bar{p}_K^2 + M_N^2} + M_N \right) \end{aligned}$$

- $\Gamma_{\Theta \to KN} = 1$ MeV $\to g_{KN\Theta} \simeq 0.1406$
  $\Gamma_{\Theta \to KN} = 3$ MeV $\to g_{KN\Theta} \simeq 0.2435$

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

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

- $s_0 \simeq 1\ \mathrm{GeV}^2$
- standard linear trajectory for K is:

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

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

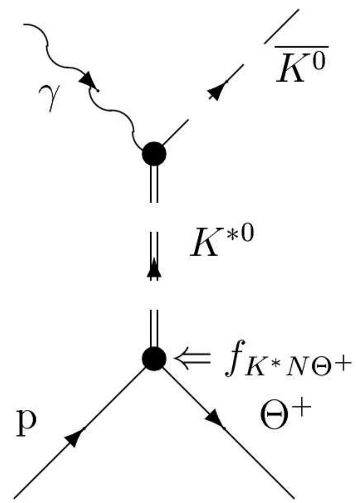
Degenerate Regge Trajectory

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

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

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



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

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

$K^* N \Theta^+$ vertex

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

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

- 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

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

- where $r \equiv V_1/V_0$
- From chiral quark soliton model we obtained $r \simeq 0.35$, corresponding to $\Gamma \simeq 15$ MeV and this gives:

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

- Rescaling chiral quark soliton model to yield $\Gamma \simeq 1$ MeV corresponds to $r \simeq 0.7$ and this gives:

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

$\mathbf{K}^*$ Regge Exchange

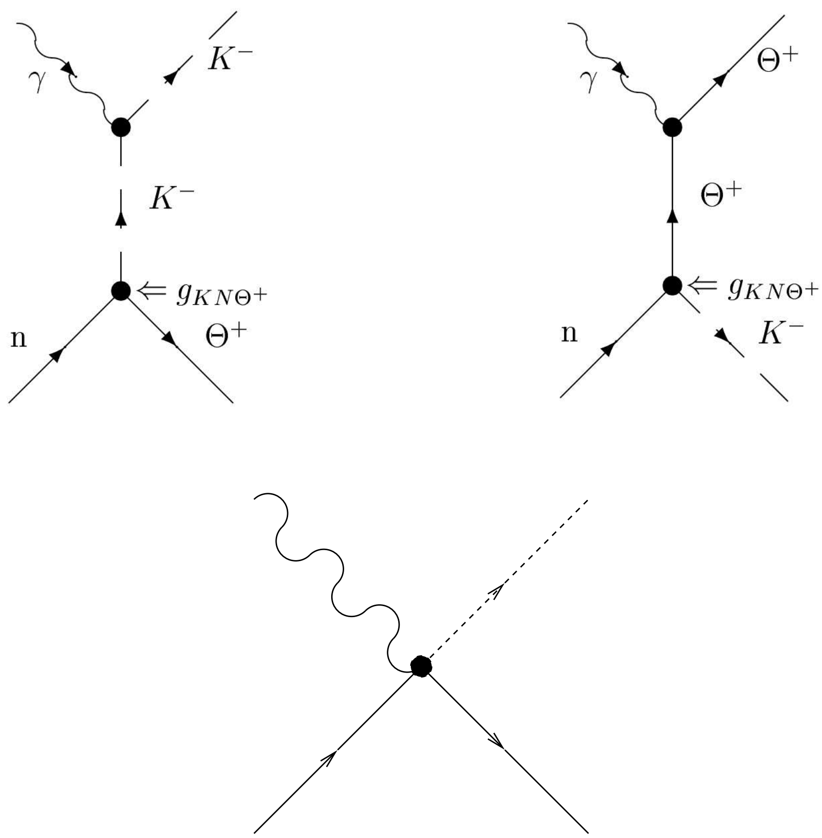
$$\frac{1}{t - m_{K^*}^2} \Longrightarrow \mathcal{P}_{Regge}^{K^*} = \left(\frac{s}{s_0}\right)^{\alpha_{K^*}(t)-1} \frac{\pi\alpha'_{K^*}}{\sin(\pi\alpha_{K^*}(t))} \times \frac{\mathcal{S}_K^* + e^{-i\pi\alpha_{K^*}(t)}}{2} \frac{1}{\Gamma(\alpha_{K^*}(t))}$$

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

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

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

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



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

$$
\begin{aligned}
\mathcal{M}_K \quad &= \quad \frac{(-)\,(i)\,e\,g_{KN\Theta}}{m_K} \cdot \mathcal{P}^K_{Regge}(s,t) \cdot \varepsilon_\mu(q,\lambda) \\
&\times \quad \Big\{ (2p_K - q)^\mu \cdot (p_K - q)^\alpha \cdot \bar{\Theta}_\alpha\, \gamma^5\, N \\
&- \quad (t - m_K^2) \cdot \bar{\Theta}_\alpha\, \gamma^{\alpha\beta\mu}\, \frac{(\gamma \cdot p_u + M_\Theta)}{u - M_\Theta^2} \\
&\qquad\qquad \cdot S_{\beta\nu} \cdot \gamma^{\nu\sigma\rho}\, \frac{(p_K)_\sigma \cdot (p_u)_\rho}{M_\Theta}\, \gamma^5 N \\
&+ \quad (t - m_K^2) \cdot \bar{\Theta}_\alpha\, \gamma^{\alpha\mu\nu}\, \frac{(p_K + p_\Theta)_\nu}{M_\Theta}\, \gamma^5 N \Big\}
\end{aligned}
$$

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 $(\pm, i)$

$KN\Theta^+$ vertex

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

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

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

- $\Gamma_{\Theta \to KN} = 1$ MeV $\rightarrow g_{KN\Theta} \simeq 0.4741$
  $\Gamma_{\Theta \to KN} = 3$ MeV $\rightarrow g_{KN\Theta} \simeq 0.8212$

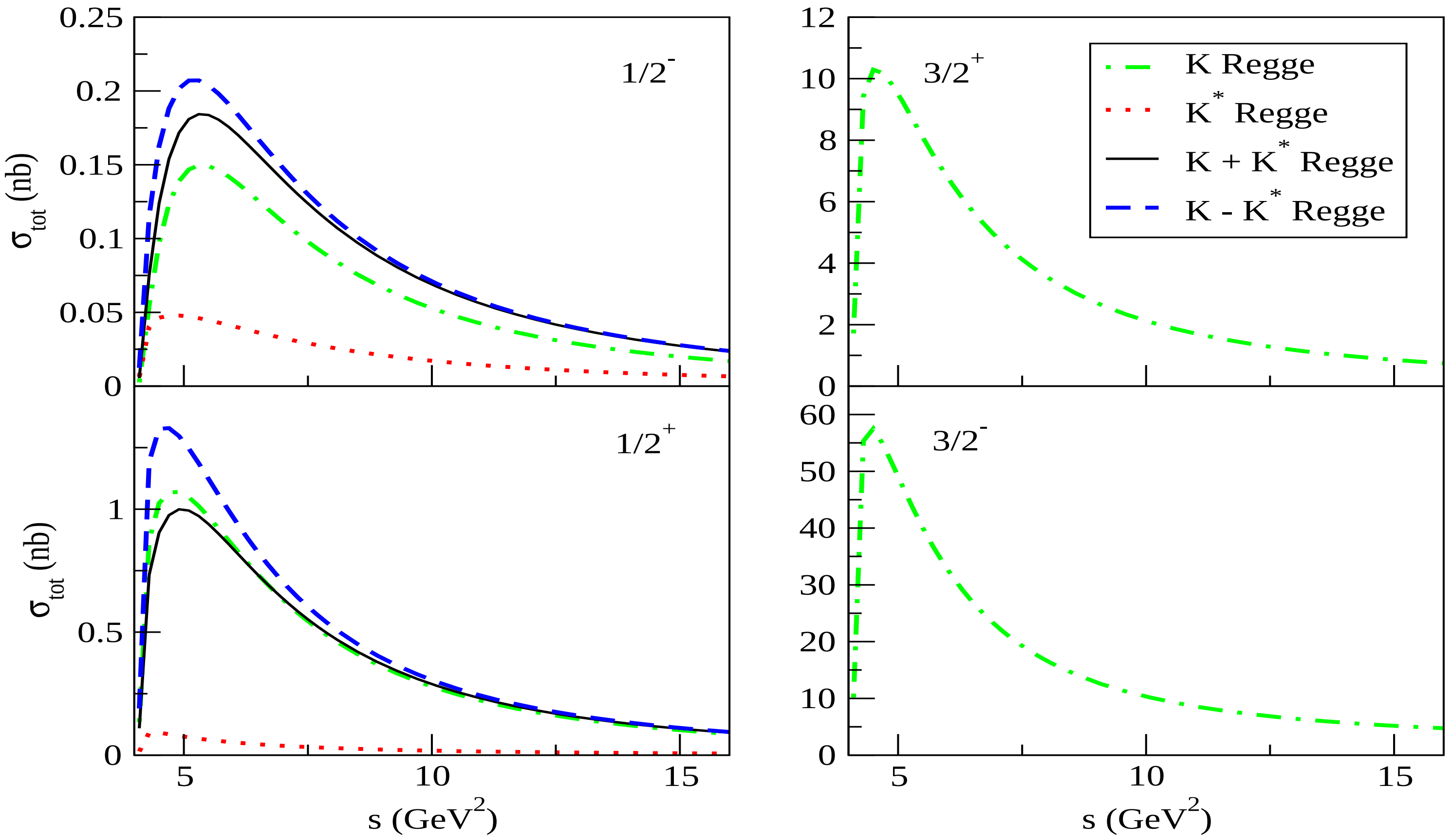
- $J^P = \frac{3}{2}^-$

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

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

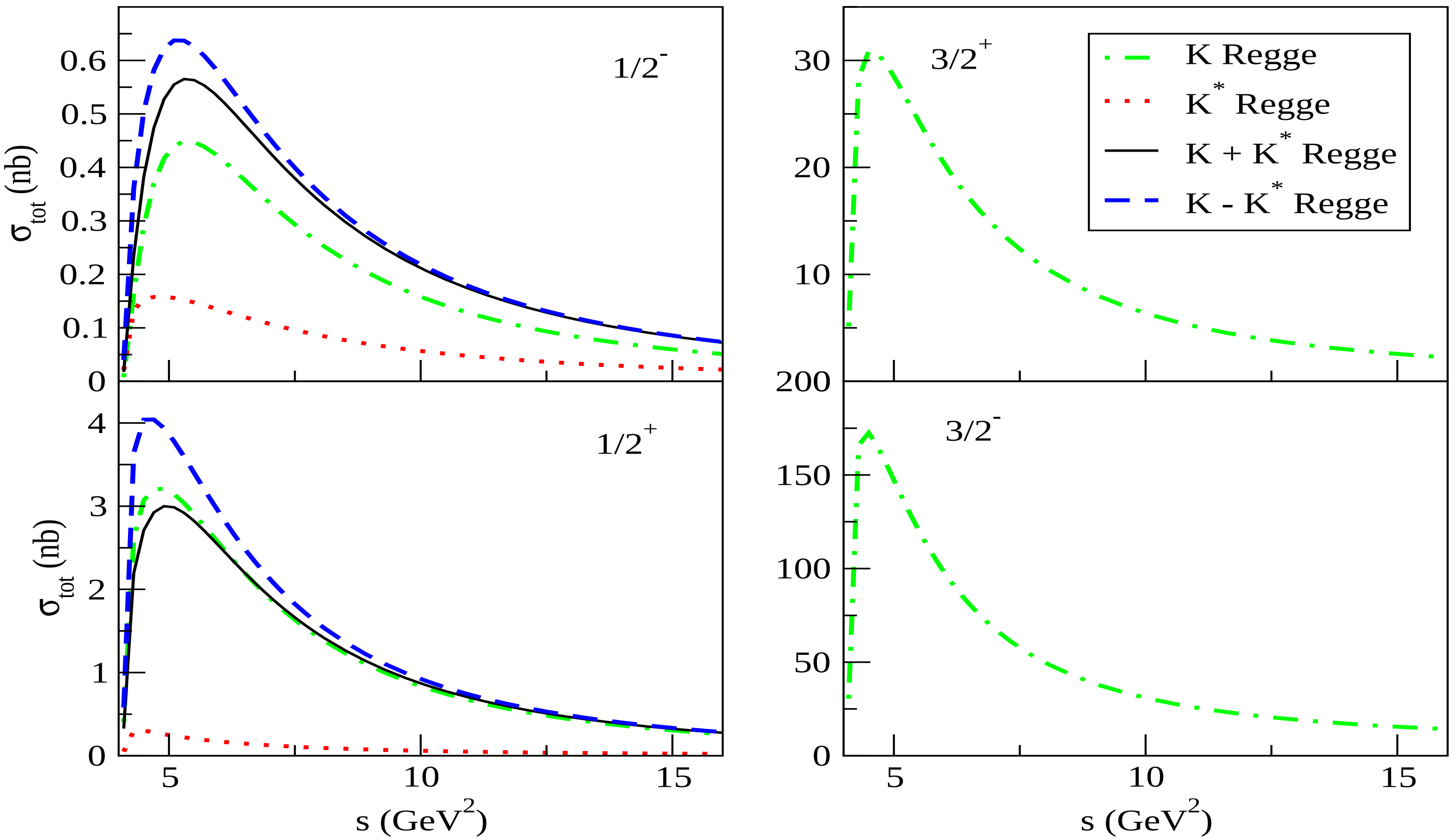
- $\Gamma_{\Theta \to KN} = 1$ MeV $\rightarrow g_{KN\Theta} \simeq 3.558$
  $\Gamma_{\Theta \to KN} = 3$ MeV $\rightarrow g_{KN\Theta} \simeq 6.162$

Cross Section for $\gamma n \to \Theta^+ K^- (\Gamma_\Theta = 1$ MeV)



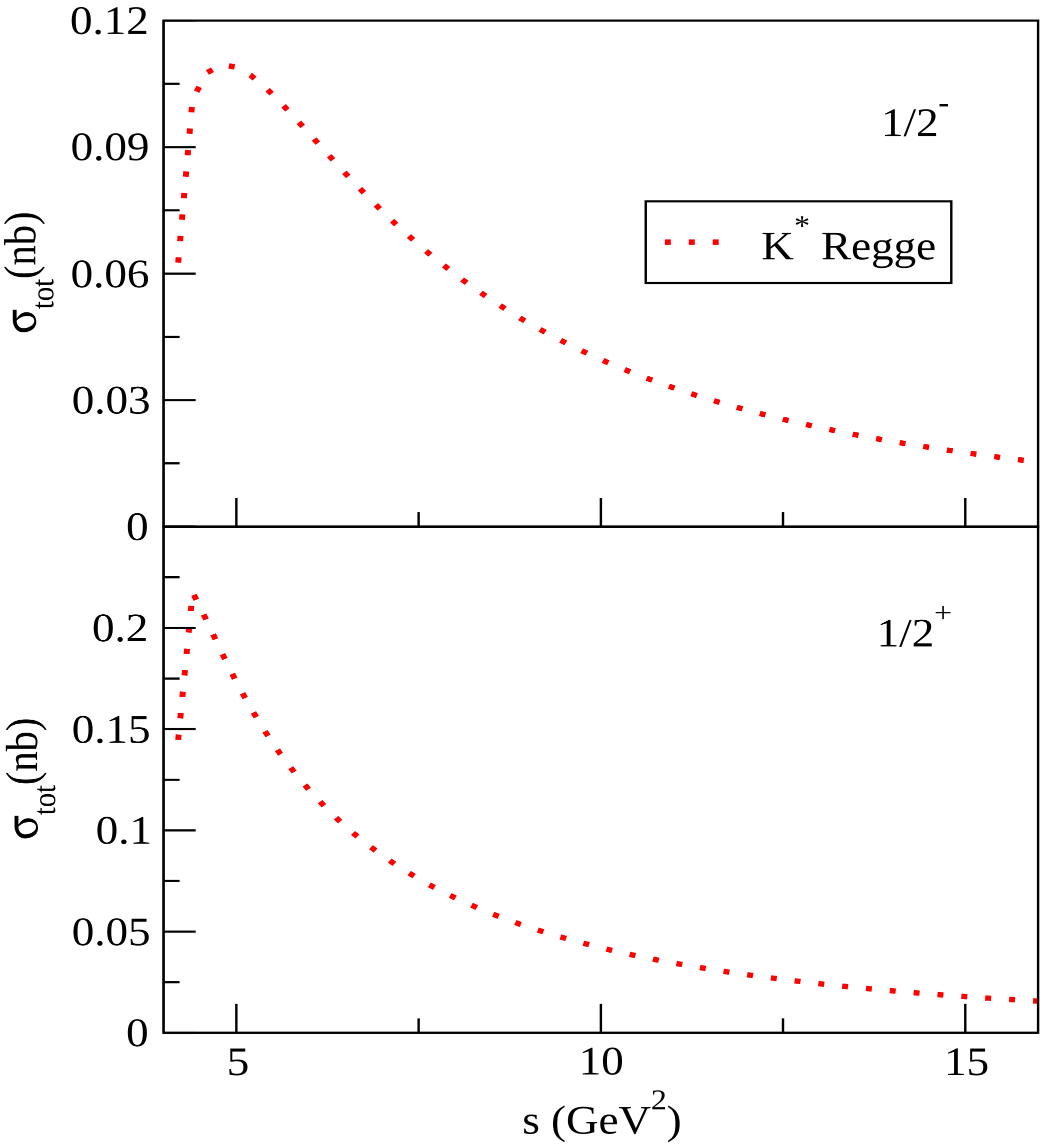
- Note the uncertainty in the sign of the coupling $f_{K^{*0} p \Theta^+}$

Cross Section for $\gamma n \to \Theta^+ K^- (\Gamma_\Theta = 3$ MeV)



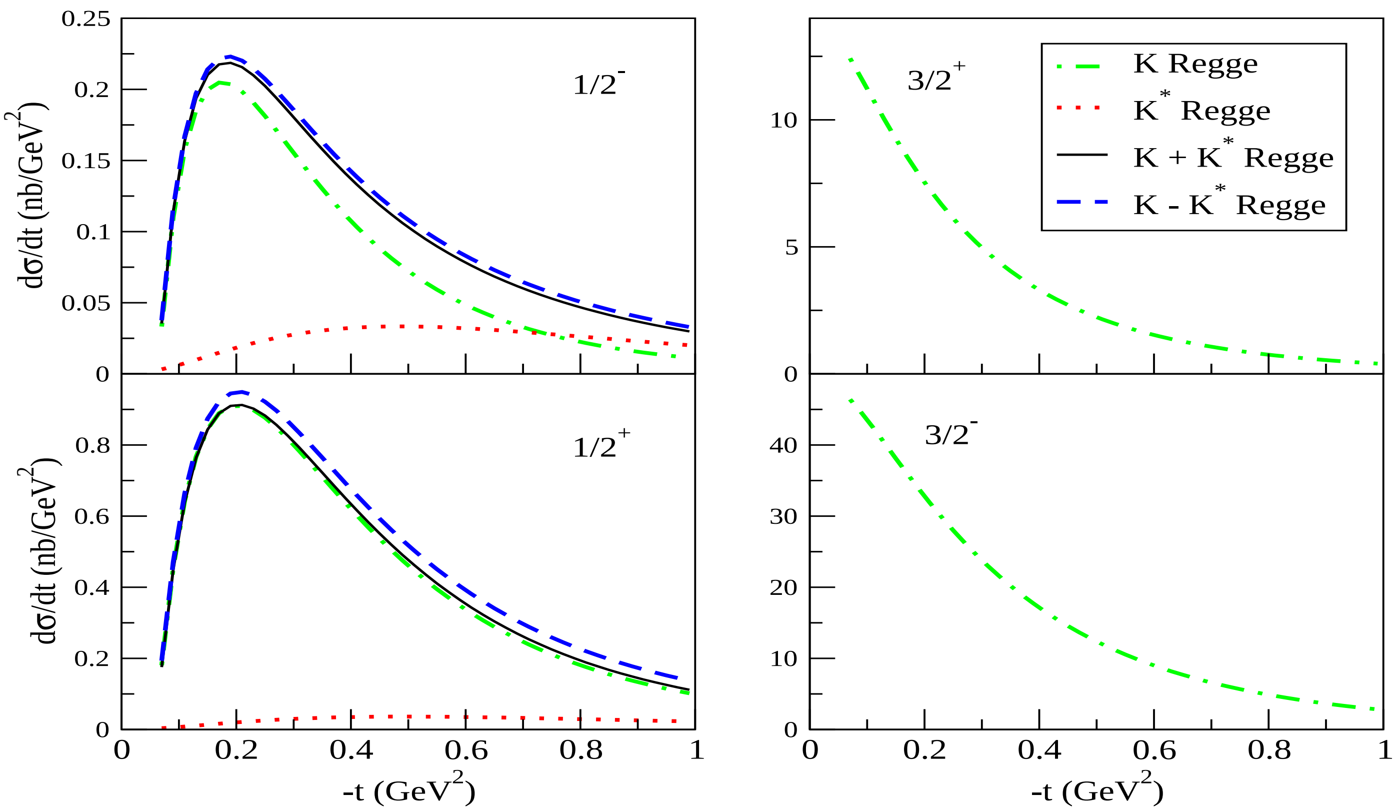
- Note the uncertainty in the sign of the coupling $f_{K^{*0}p\Theta^+}$

Cross section for $\gamma p \to \Theta^+ \overline{K^0} (\Gamma_\Theta = 1\ \text{MeV})$



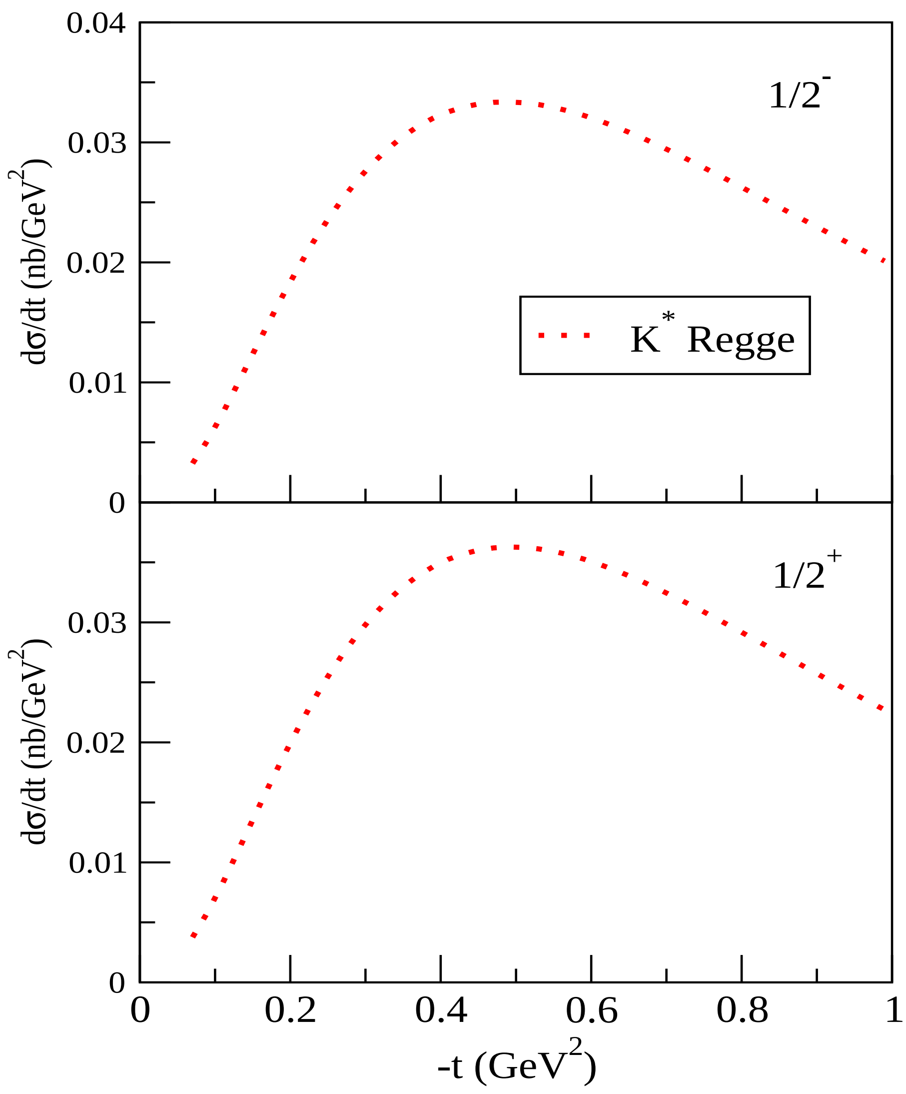
Differential Cross section for $\gamma n \to \Theta^+ K^-$,

$(\Gamma_\Theta = 1\ \mathrm{MeV})$, s= 8.4 GeV^2



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

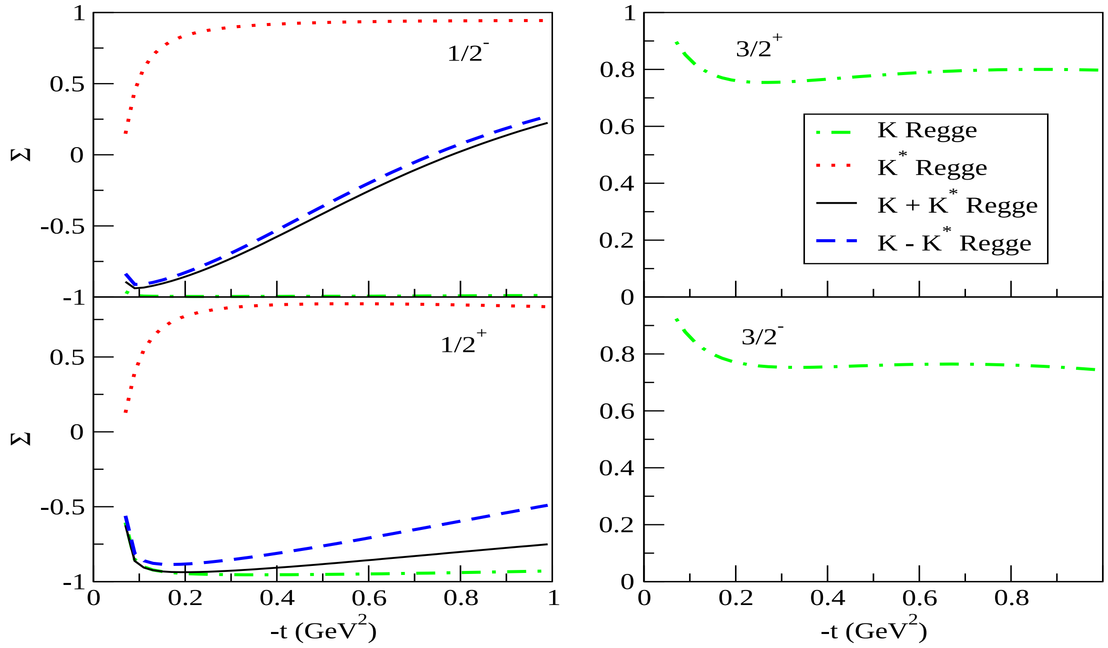
Differential Cross section $\gamma p \to \Theta^+ \overline{K^0}$, $(\Gamma_\Theta = 1\ \mathrm{MeV})$, s = 8.4 GeV^2



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

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

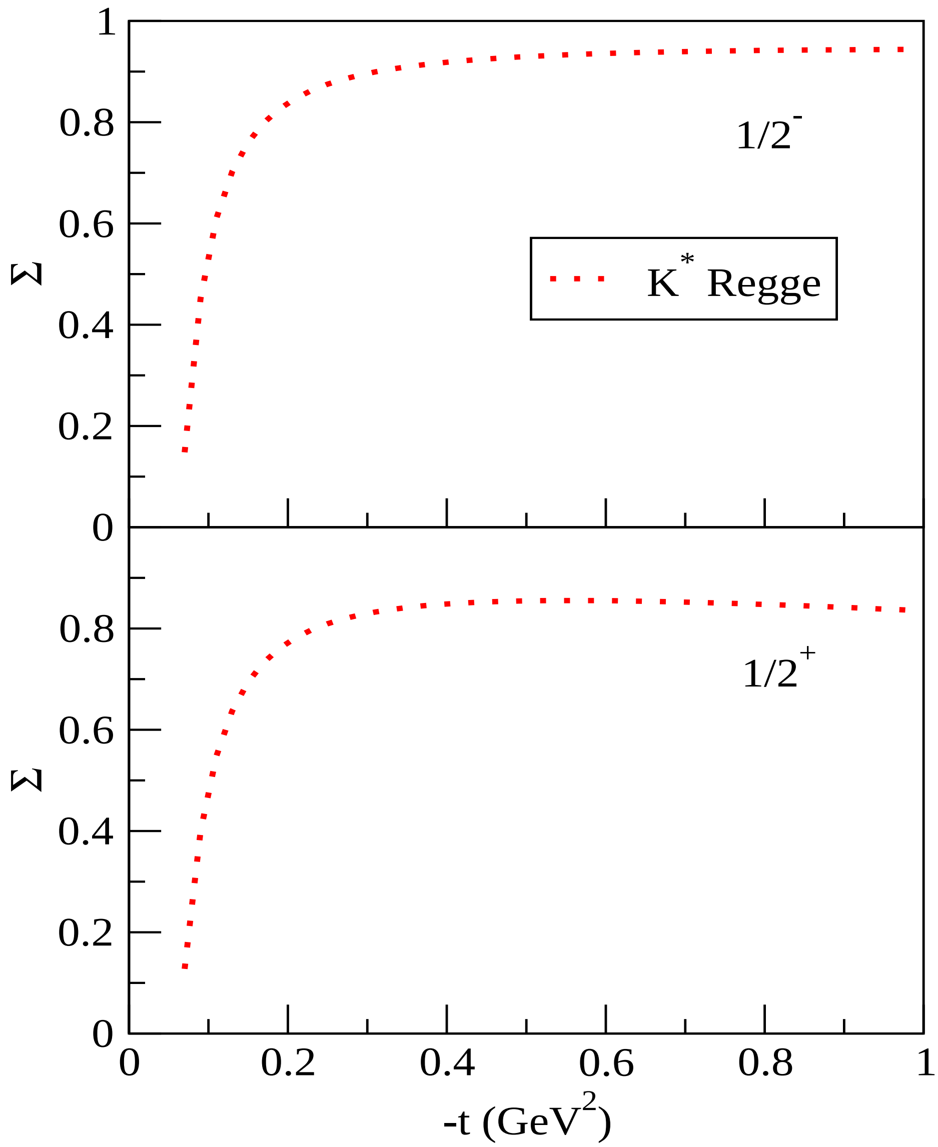
s= 8.4 GeV^2



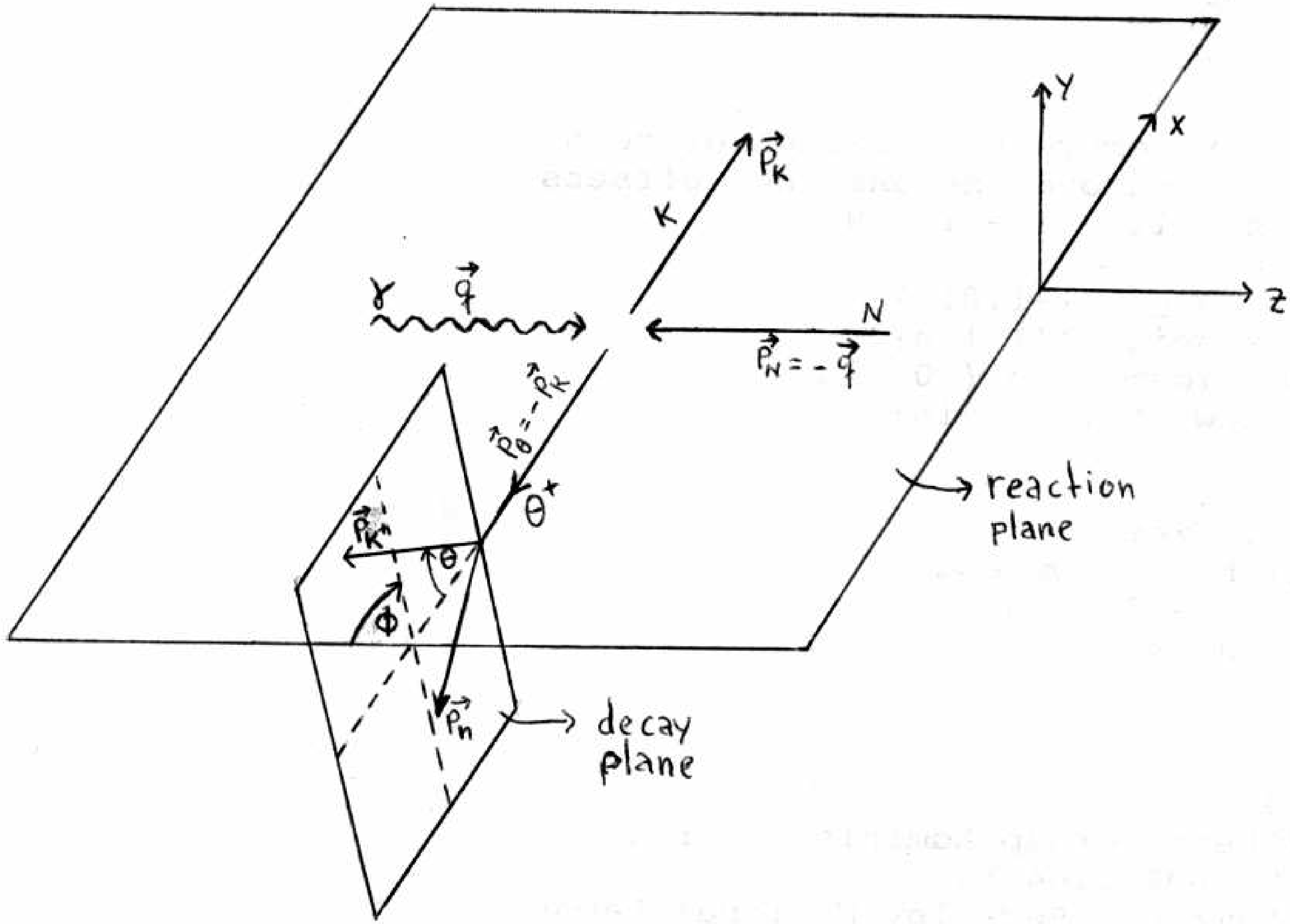
- $\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}$
- $K(K^*)$ exchange dominant, Σ go to -1(1)

Photon Asymmetries for $\gamma p \to \Theta^+ \overline{K^0}$,

s = 8.4 GeV^2



Decay Angular Distribution



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

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

- 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

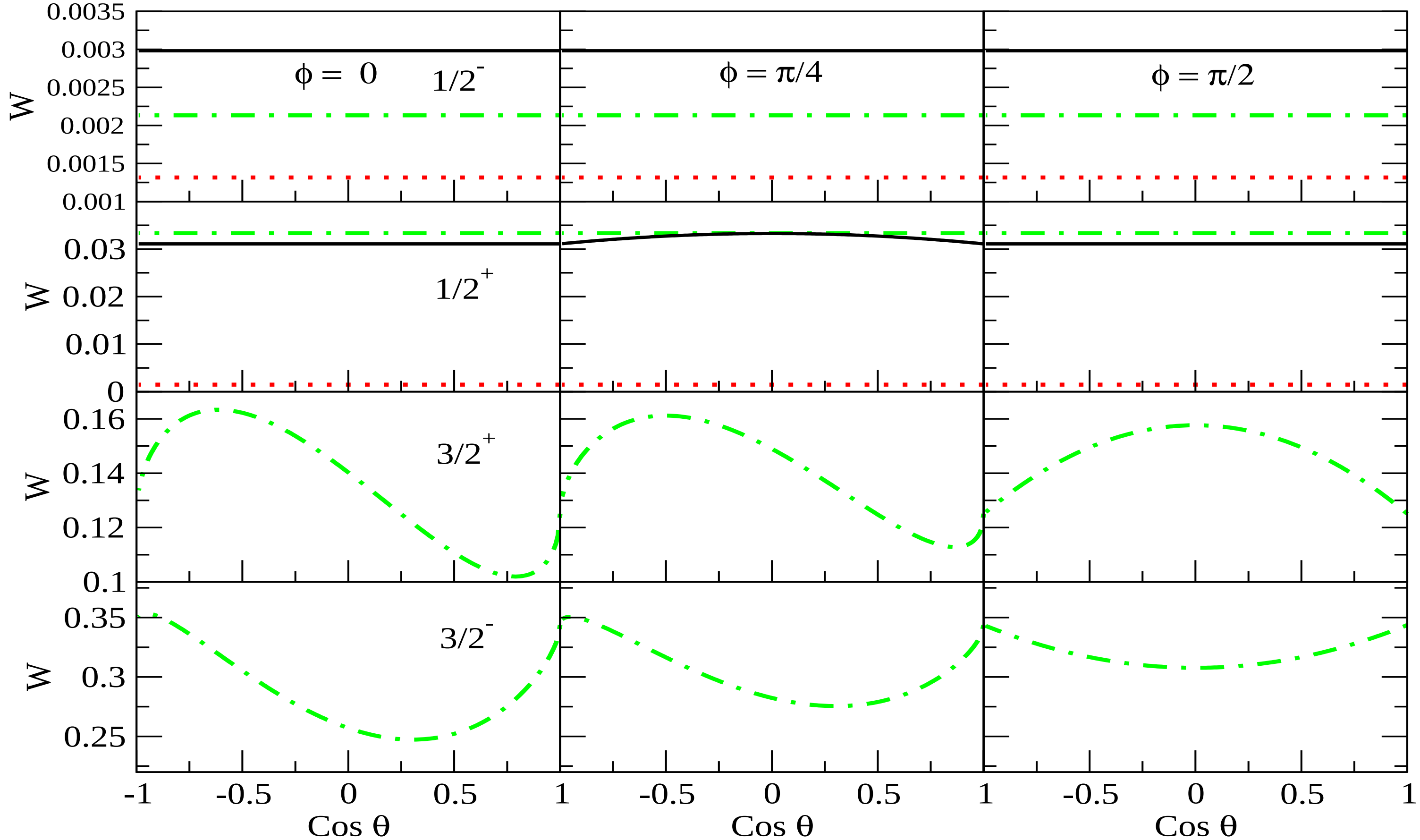


Figure 1: $\gamma n \to \Theta^+ K^-, \alpha = 0$, s$= 8.4$ GeV^2, $t = -0.1$ GeV^2

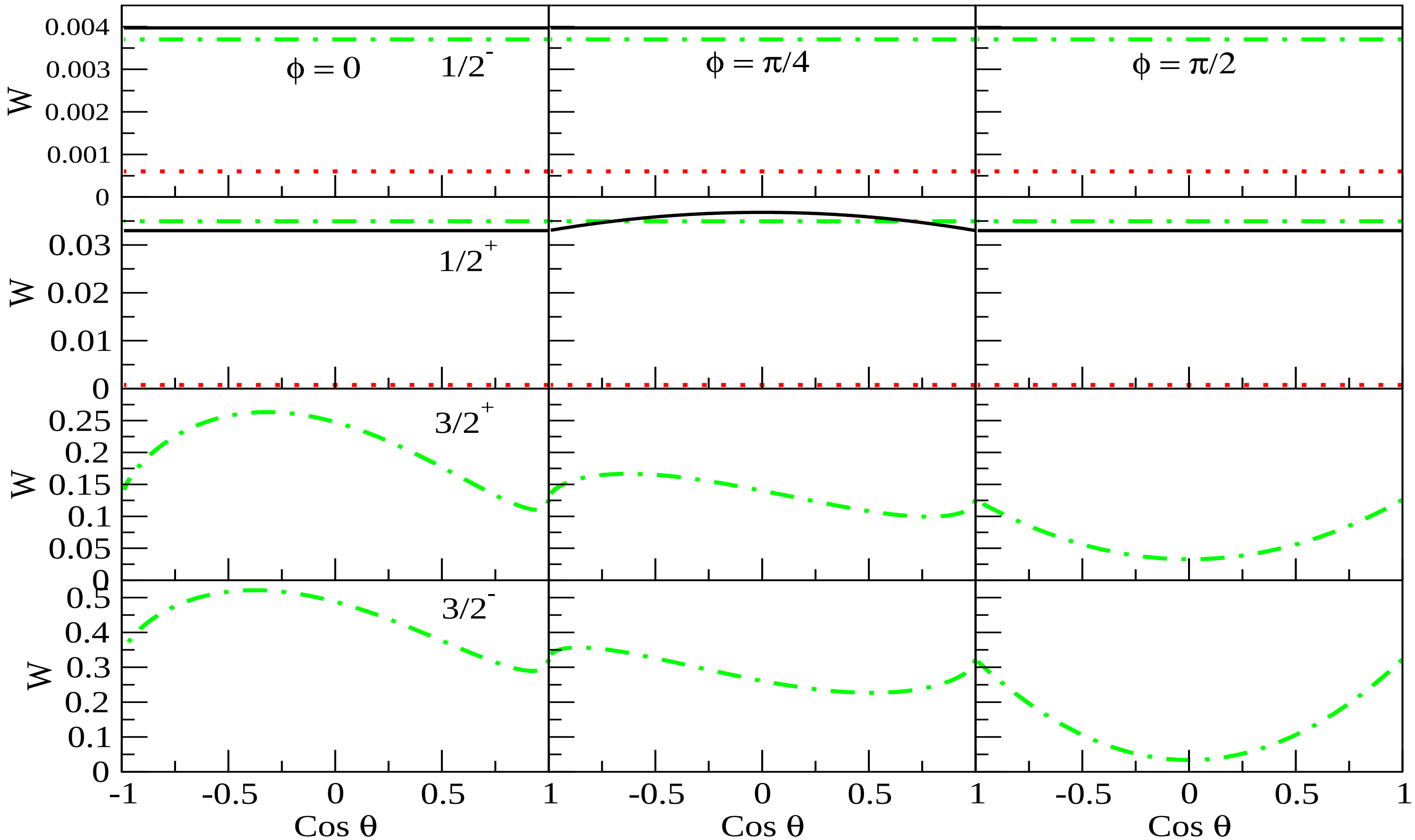


Figure 2: $\gamma n \to \Theta^+ K^-, \alpha = 1$, s= 8.4 GeV^2, $t = -0.1$ GeV^2

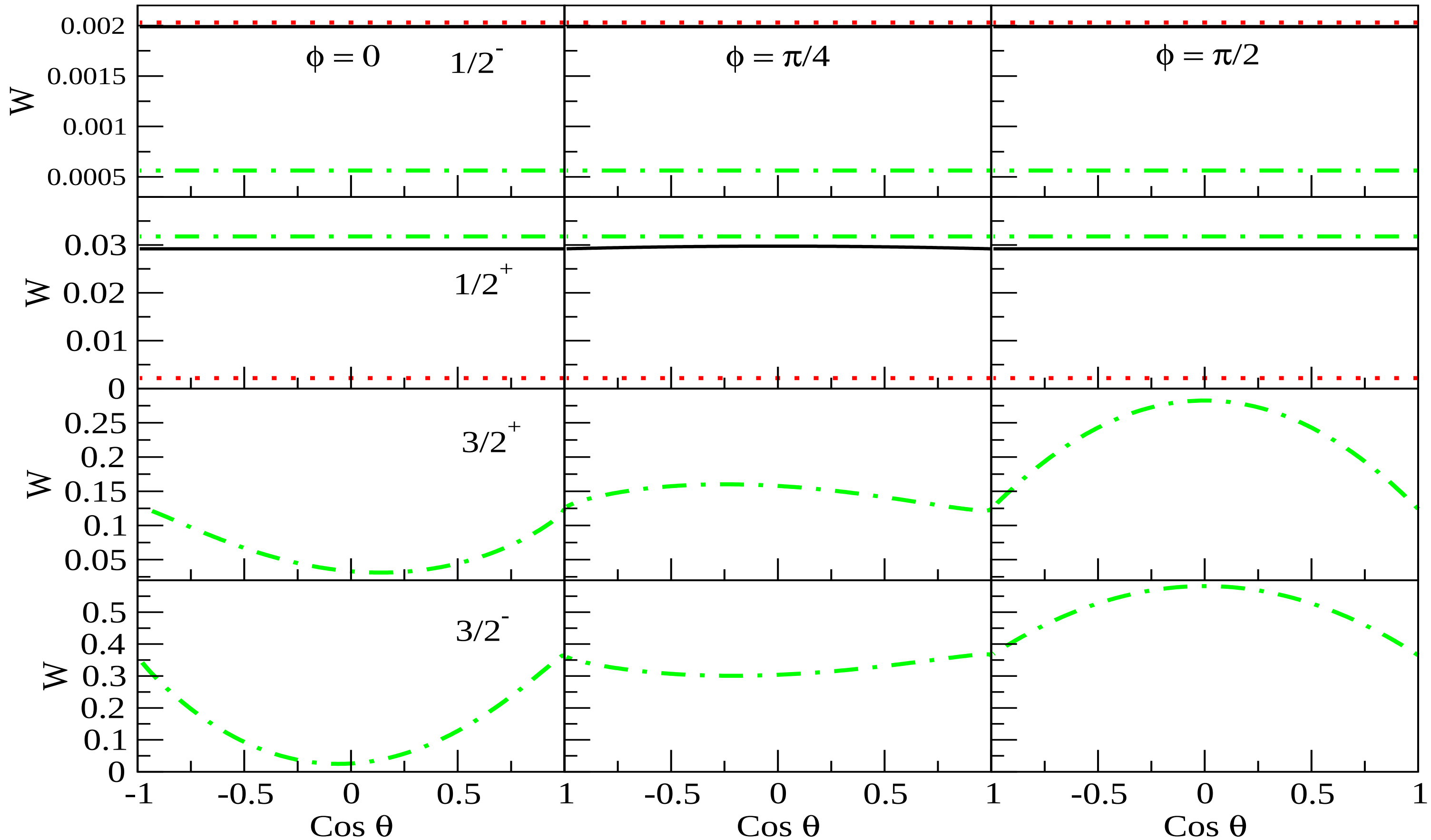


Figure 3: $\gamma n \rightarrow \Theta^+ K^-, \alpha = 2$, s= 8.4 GeV^2, $t = -0.1$ GeV^2

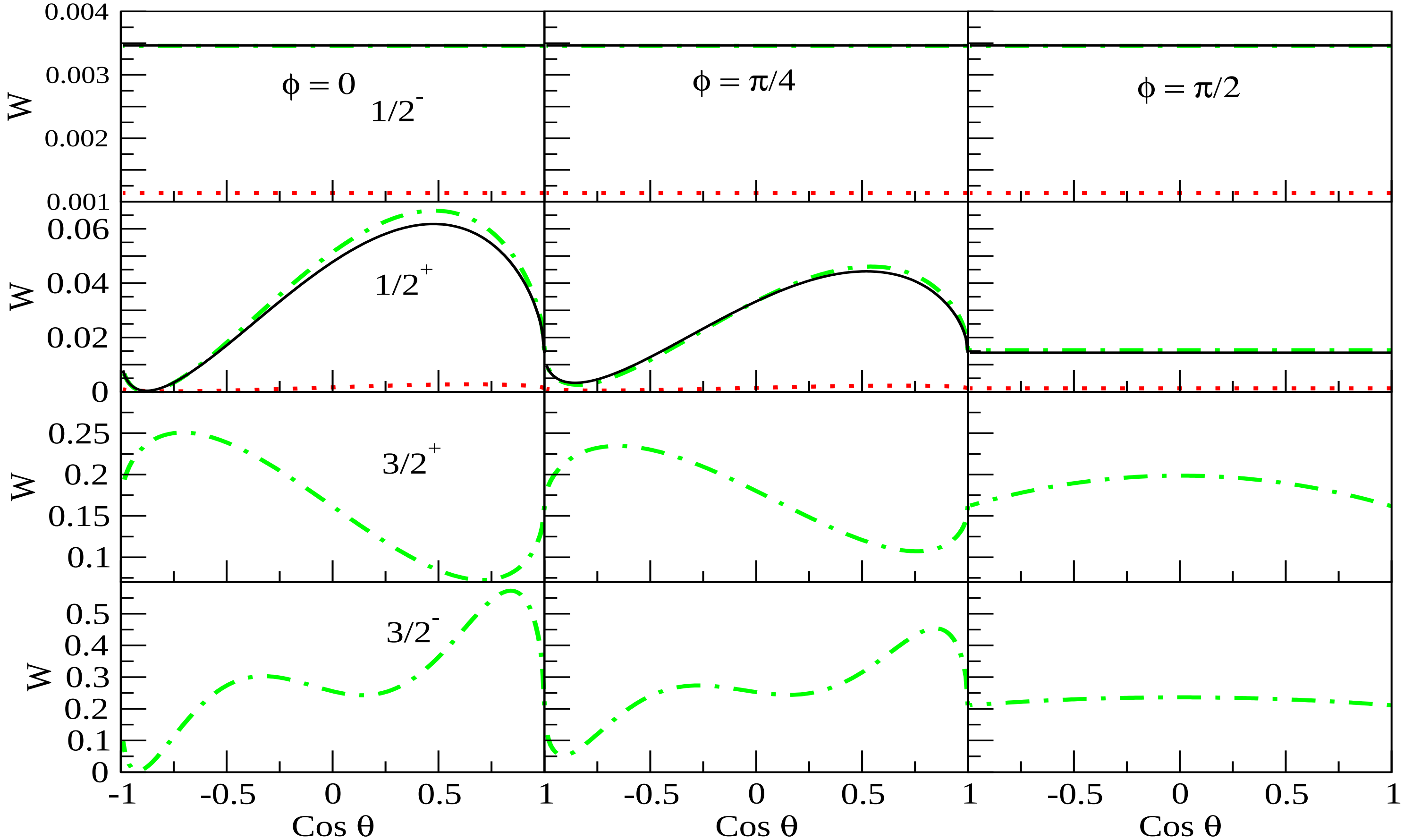


Figure 4: $\gamma n \rightarrow \Theta^+ K^-, \alpha = 3$, pol$_\gamma = -1$, s= 8.4 GeV^2, $t = -0.1$ GeV^2

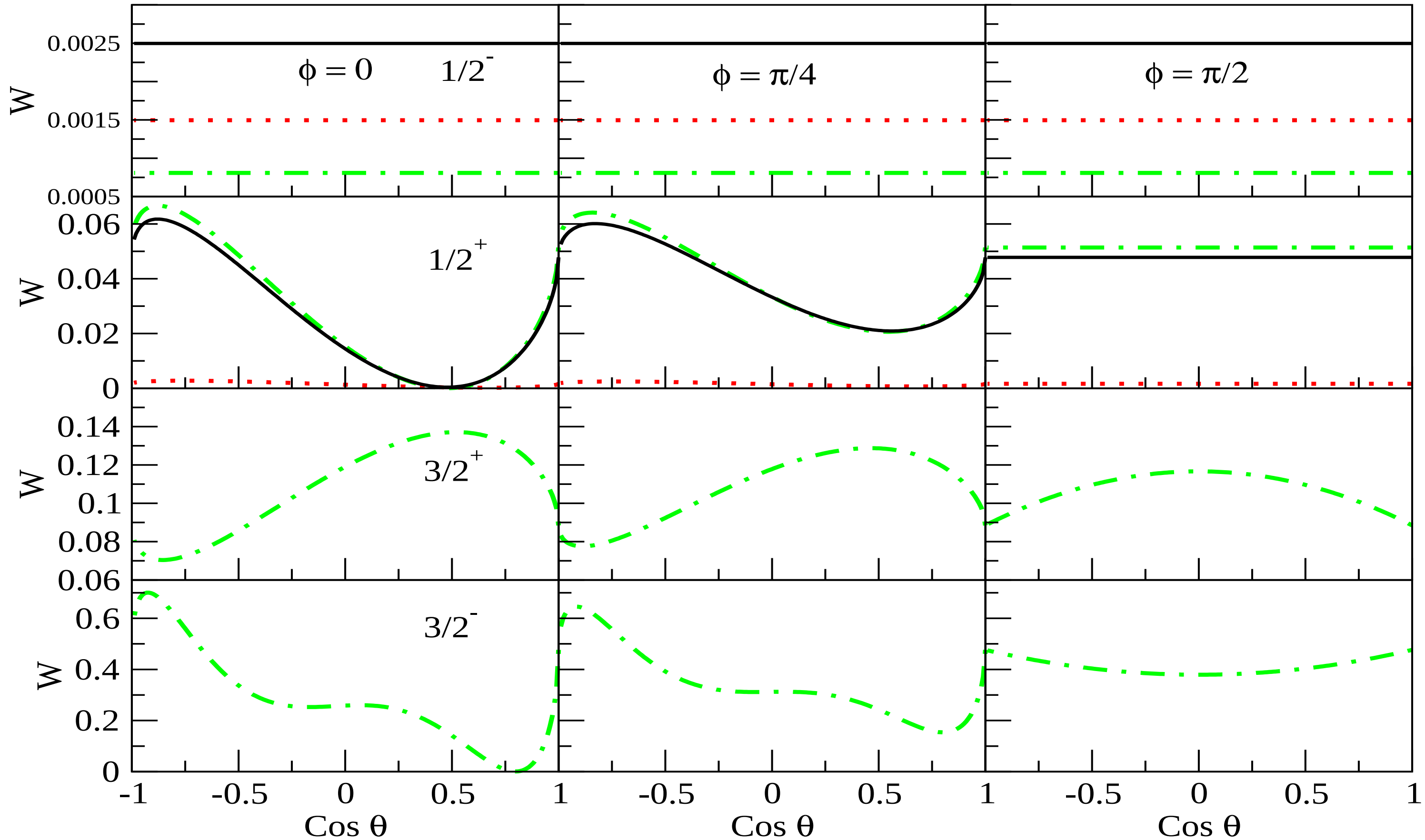


Figure 5: $\gamma n \to \Theta^+ K^-, \alpha = 3$, pol$_\gamma = 1$, s$= 8.4$ GeV^2, $t = -0.1$ GeV^2

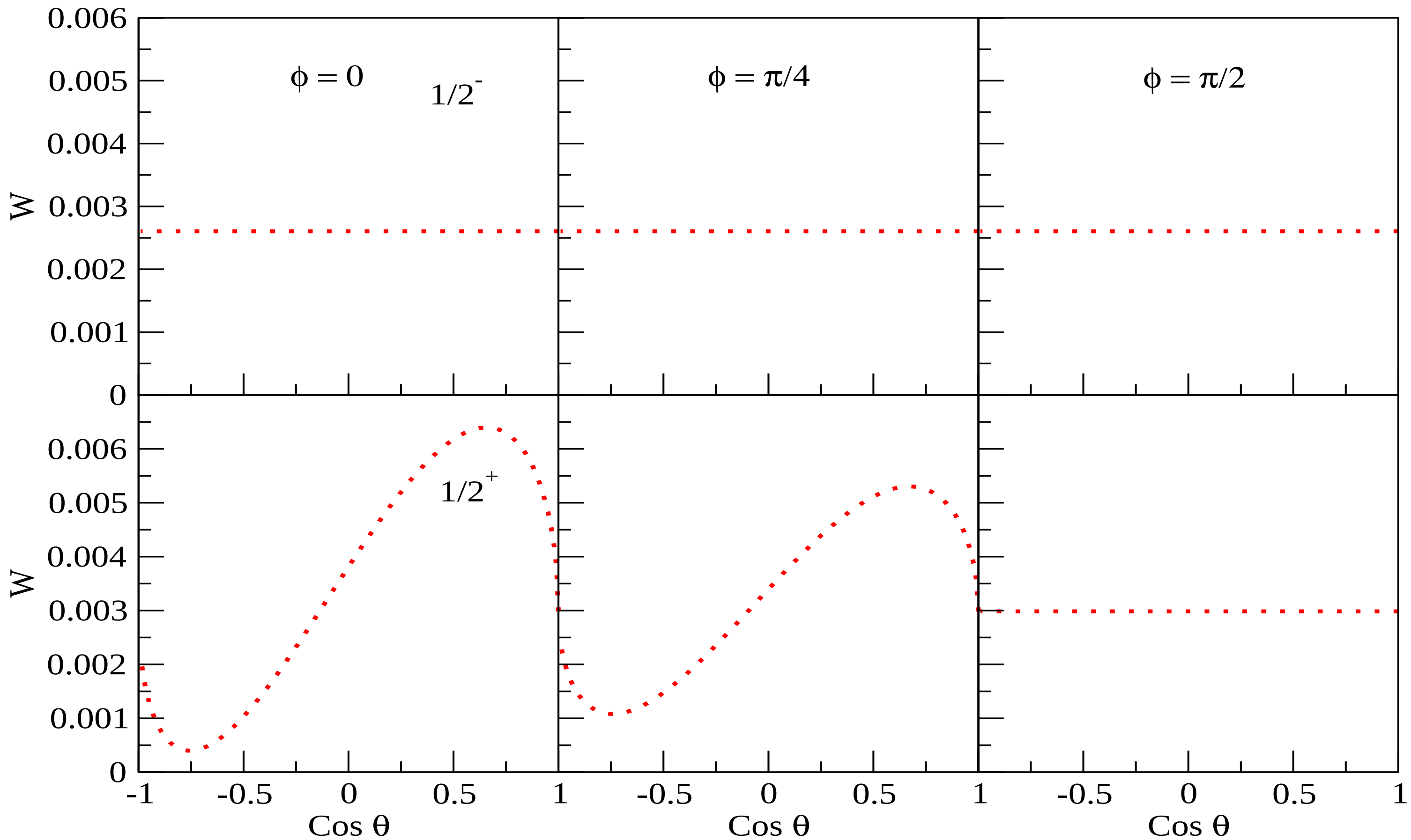


Figure 6: $\gamma p \rightarrow \Theta^+ \overline{K^0}, \alpha = 3$, pol$_\gamma = -1$, s $= 8.4$ GeV^2, t $= -0.1$ GeV^2

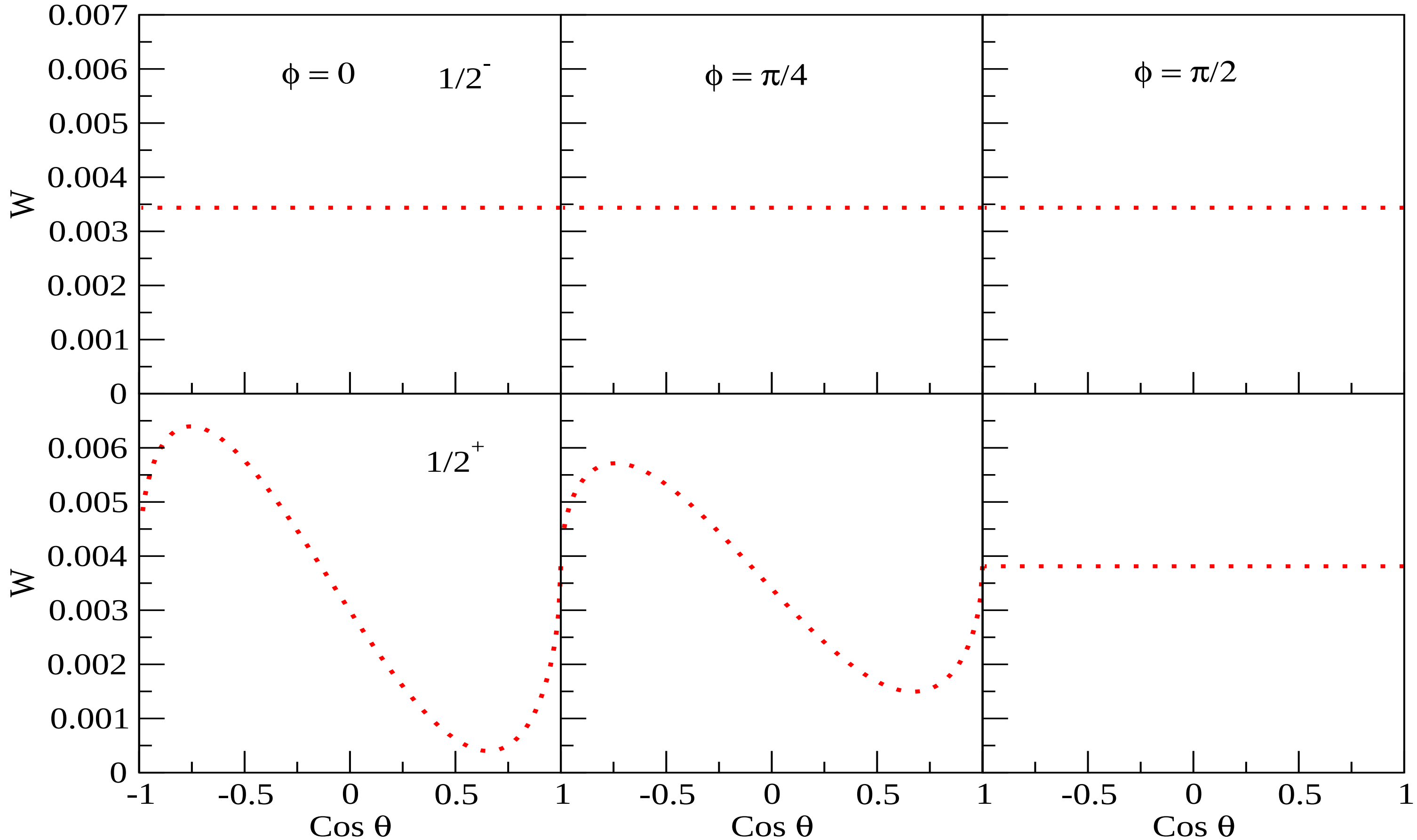


Figure 7: $\gamma p \to \Theta^+ \overline{K^0}, \alpha = 3$, pol$_\gamma$ = 1, s = 8.4 GeV^2, t = -0.1 GeV^2

Some observable of the W (decay angular distribution):

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

Conclusion

- the Θ^+ cross section (σ) correlates strongly with its width (Γ) e.g. $\mathrm{J}^{\mathrm{P}} = \frac{1}{2}^+$ Θ^+ state with $\Gamma_\Theta \leq 1$ MeV will have production $\sigma(\gamma n \to \Theta^+ \mathrm{K}^-) \leq 1.5$ nb.

- the process $\gamma n \to \Theta^+ \mathrm{K}^-$ is dominated by K Regge exchange and has larger σ compared to $\gamma p \to \Theta^+ \overline{\mathrm{K}^0}$ process.

- in the process $\gamma p \to \Theta^+ \overline{\mathrm{K}^0}$, K Regge exchange is absent, the leading mechanism is K^* Regge exchange and this leads to production cross section $\sigma \simeq 0.1$ nb ($1/2^+$ and $1/2^-$).

- photon asymmetries in photoproduction experiments are sensitive to the parity of the Θ^+ ($\mathrm{J}^{\mathrm{P}} = \frac{1}{2}^+$ or $\frac{1}{2}^-$).