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

Hidden Strangeness:

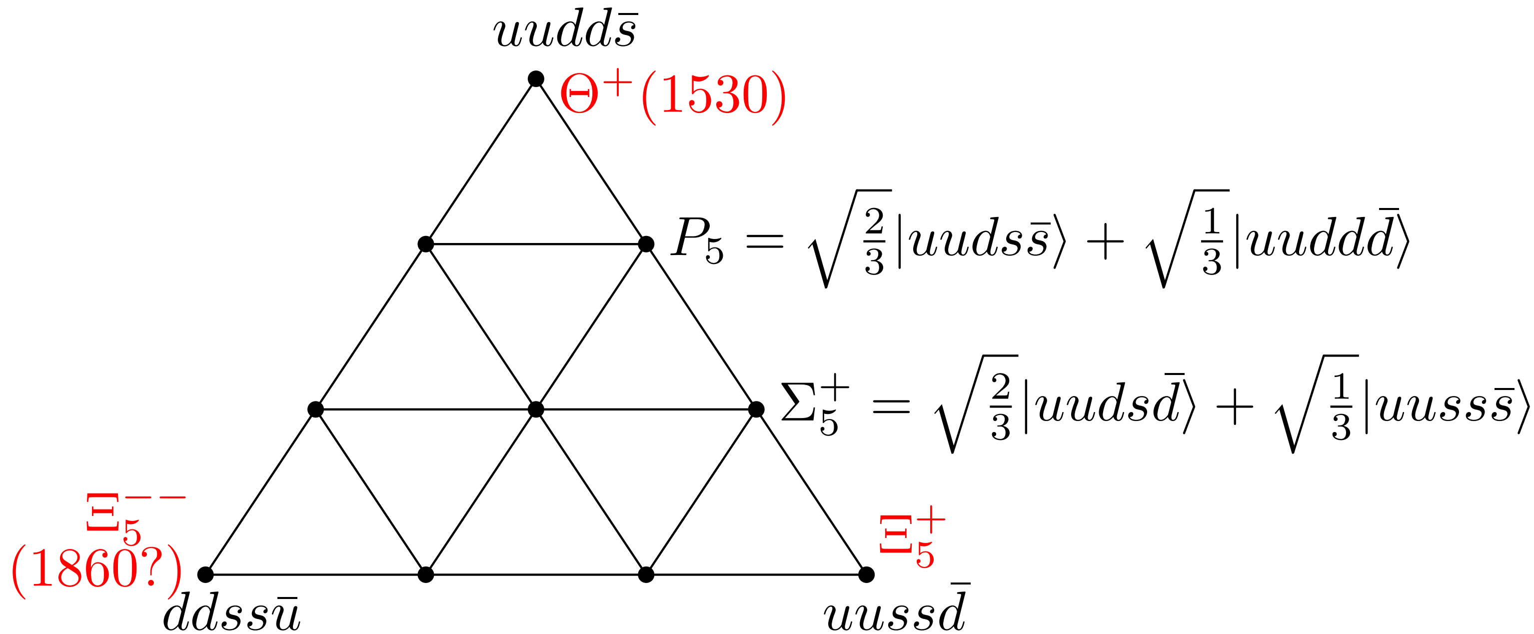


Figure 1: $SU(3)_F$ Antidecuplet for Pentaquark

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

Experimental Evidence

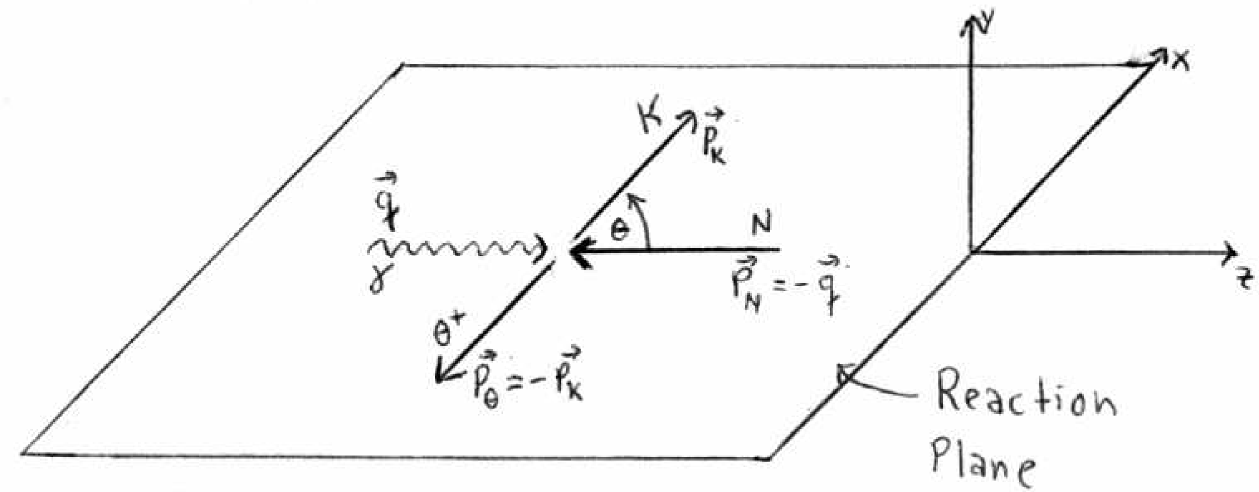
- First experimental sign: Nakano et. al. (LEP collaboration, hep-ex/0301020)
  - mass 1540 ± 10 MeV
  - width less than 25 MeV
- Other experiment: V.V. Barmin et al. (hep-ex/0304040) $\rightarrow$ very narrow width (≤ 9 MeV)
- Current experimental status:
  - positive signal: 10 published experiments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

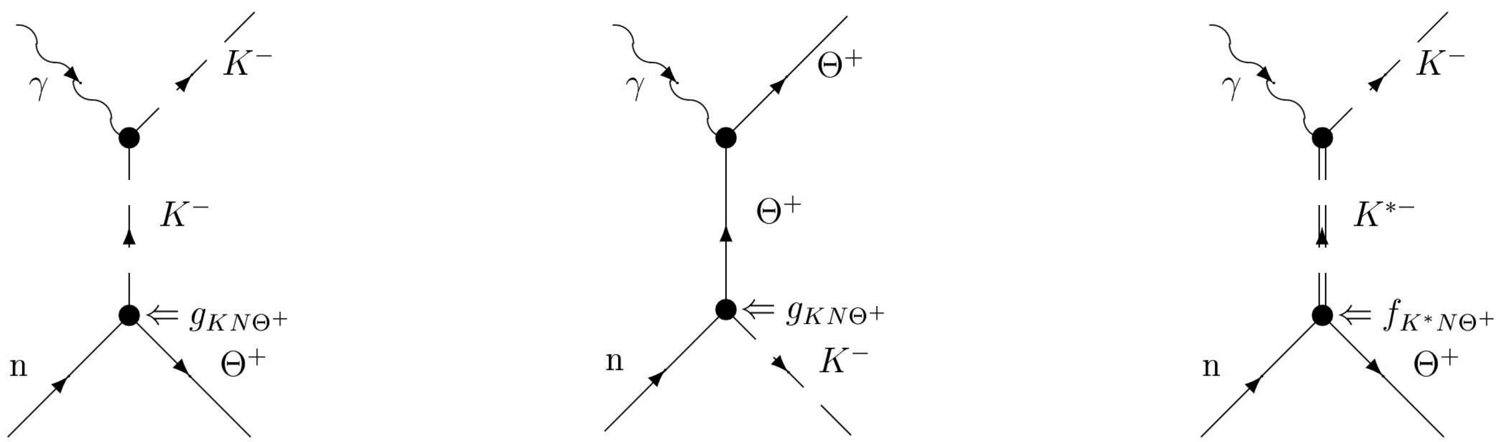
Θ^+ Photoproduction

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



$s \equiv (p_N + q)^2$, $t \equiv (q - p_K)^2$, and $u \equiv (q - p_\Theta)^2$
(M. Guidal, HJK, M.V. Polyakov, M. Vanderhaeghen, hep-ph/0507180)

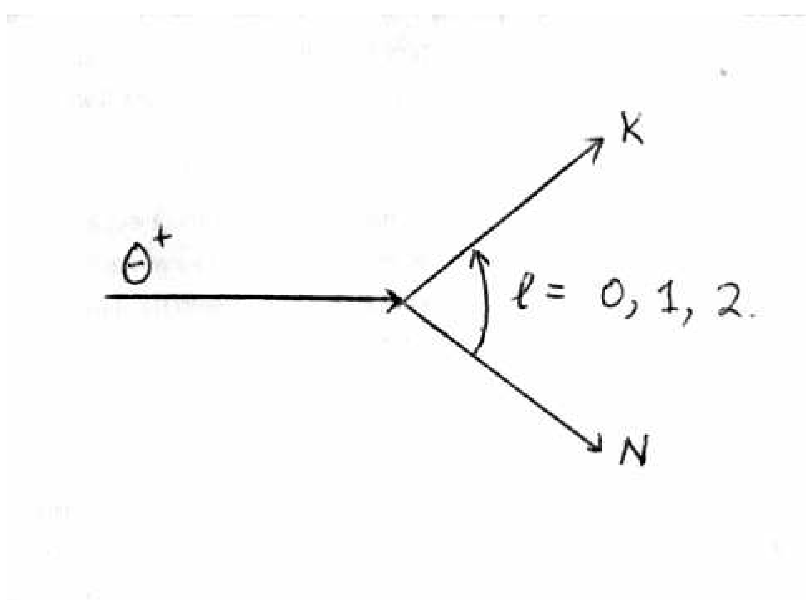
$$\gamma n \to K^- \Theta^+ : J_\Theta^P = \frac{1}{2}^+ \left(\frac{1}{2}^-\right)$$



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

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

Θ Decay and KNΘ Vertex



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

$KN\Theta^+$ vertex and Θ^+ Width

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

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

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

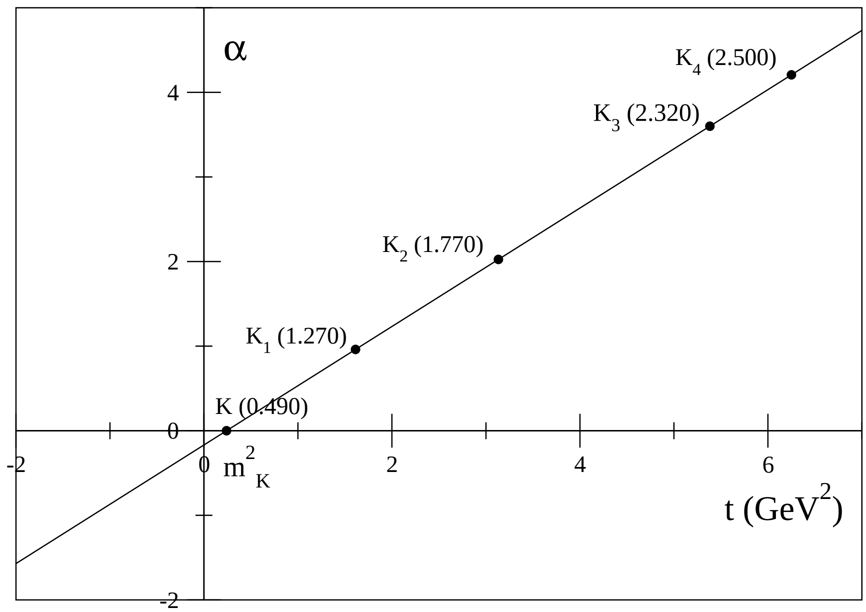
- with $\Gamma_{\Theta \to KN} = 1$ MeV $\to g_{KN\Theta} \simeq 1.056$

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

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

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

K Regge Exchange



- imagine K as a tube (rod) with 2 quarks at the end → rotate → 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

$$\frac{1}{t - m_K^2} \Longrightarrow \mathcal{P}_{Regge}^{K}(s,t) \quad = \quad \left(\frac{s}{s_0}\right)^{\alpha_K(t)} \frac{\pi \alpha'_K}{\sin(\pi \alpha_K(t))}$$

$$\times \quad \frac{\mathcal{S}_K + e^{-i\pi\alpha_K(t)}}{2} \frac{1}{\Gamma(1 + \alpha_K(t))}$$

- $s_0 \simeq 1$ 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
- $J^P = 0^-, 2^-, 4^-, \ldots$ correspond with $\mathcal{S} = +1$
- $J^P = 1^+, 3^+, 5^+, \ldots$ 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

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

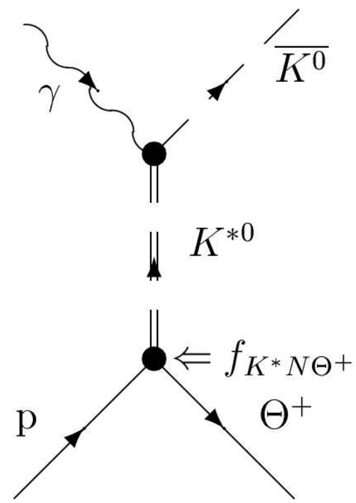
- Regge vertex functions (Regge residues) away from the pole position, need form factors $F_K(t)$, $F_\Theta(u)$, and $\hat{F}$.
- We choose monopole forms for F_K and F_u :

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

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

- 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.

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



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

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

$K^* N \Theta^+$ vertex

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

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

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

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

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

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

$\mathbf{K^*}$ Regge Exchange

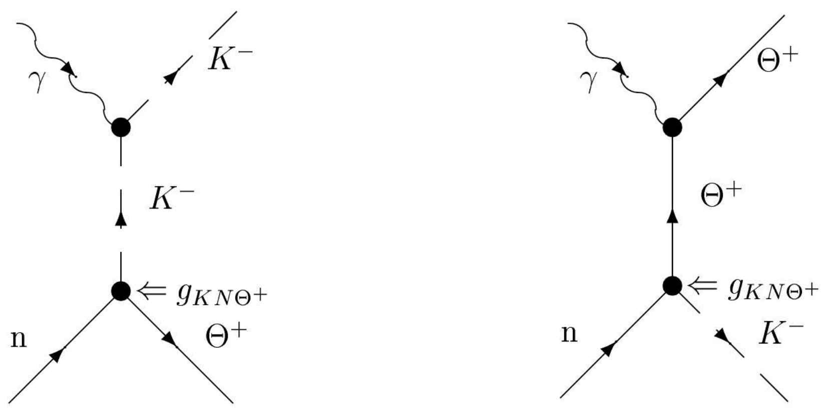
$$\frac{1}{t - m_{K^*}^2} \Longrightarrow \mathcal{P}_{Regge}^{K^*} = \left(\frac{s}{s_0}\right)^{\alpha_{K^*}(t)-1} \frac{\pi \alpha'_{K^*}}{\sin(\pi \alpha_{K^*}(t))}$$
$$\times \frac{\mathcal{S}_K^* + e^{-i\pi\alpha_{K^*}(t)}}{2} \frac{1}{\Gamma(\alpha_{K^*}(t))}$$

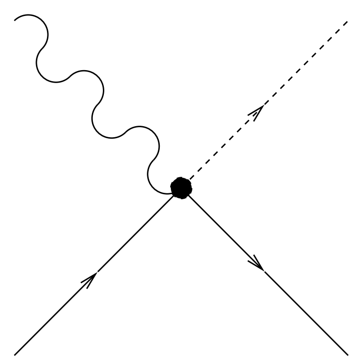
- Regge trajectory: $\alpha_{K^*}(t) = \alpha_{K^*}^0 + \alpha'_{K^*} \cdot t$
- standard linear trajectory for the $K^*(892)$ is :

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

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

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





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

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

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**

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

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

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

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

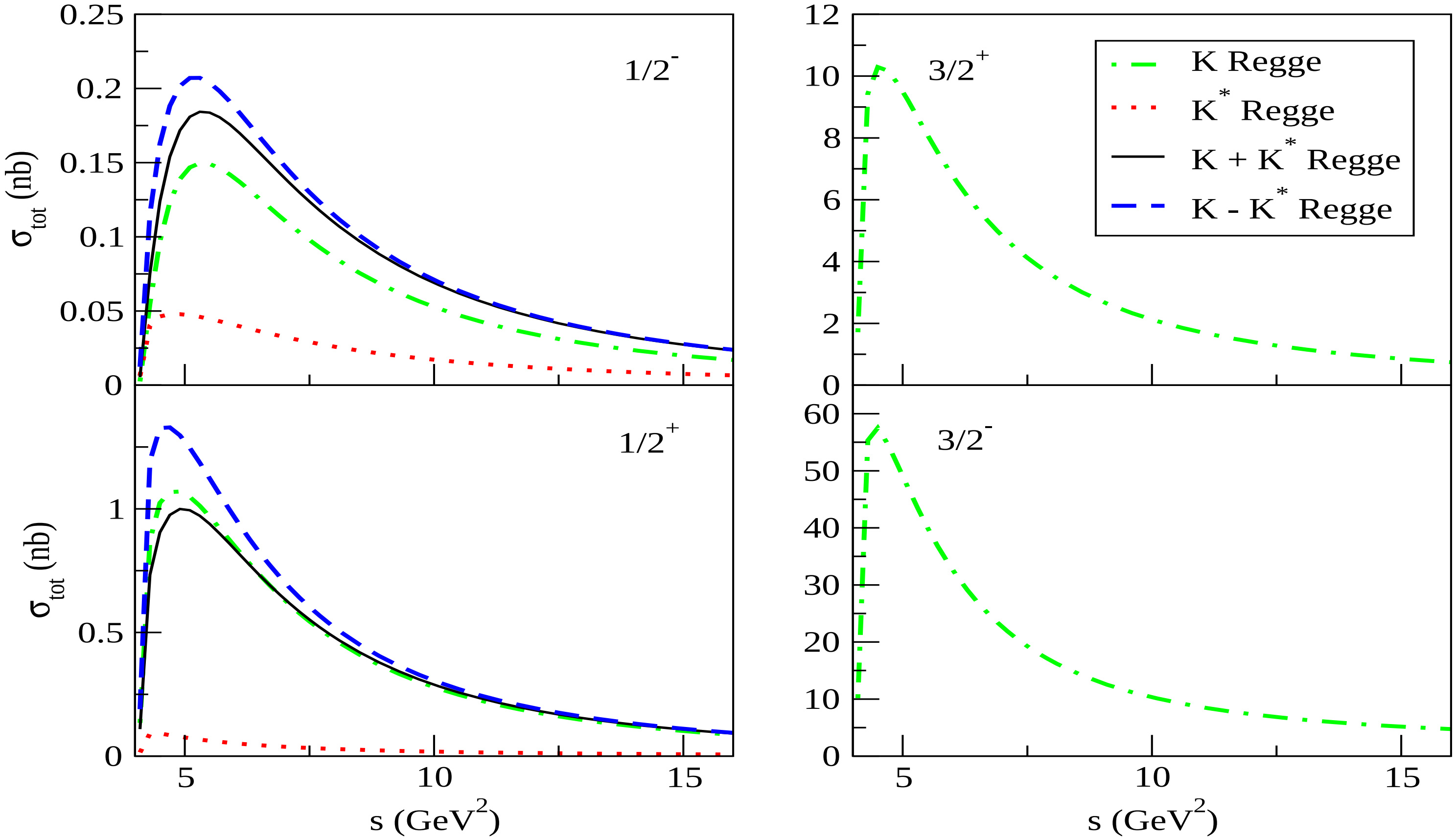
- $J^P = \frac{3}{2}^-$

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

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

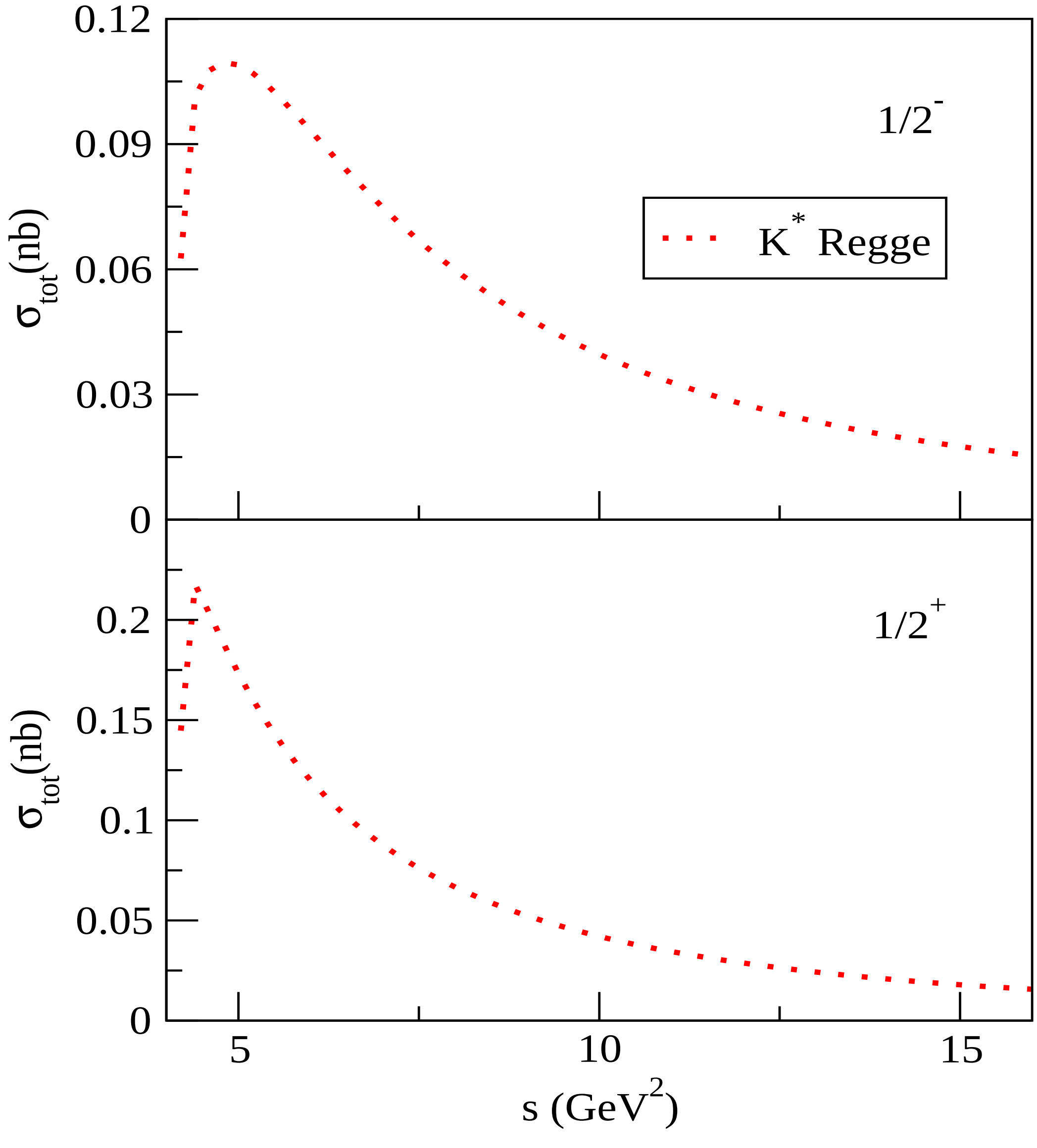
- $\Gamma_{\Theta\to KN} = 1$ MeV $\to g_{KN\Theta} \simeq 3.558$

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

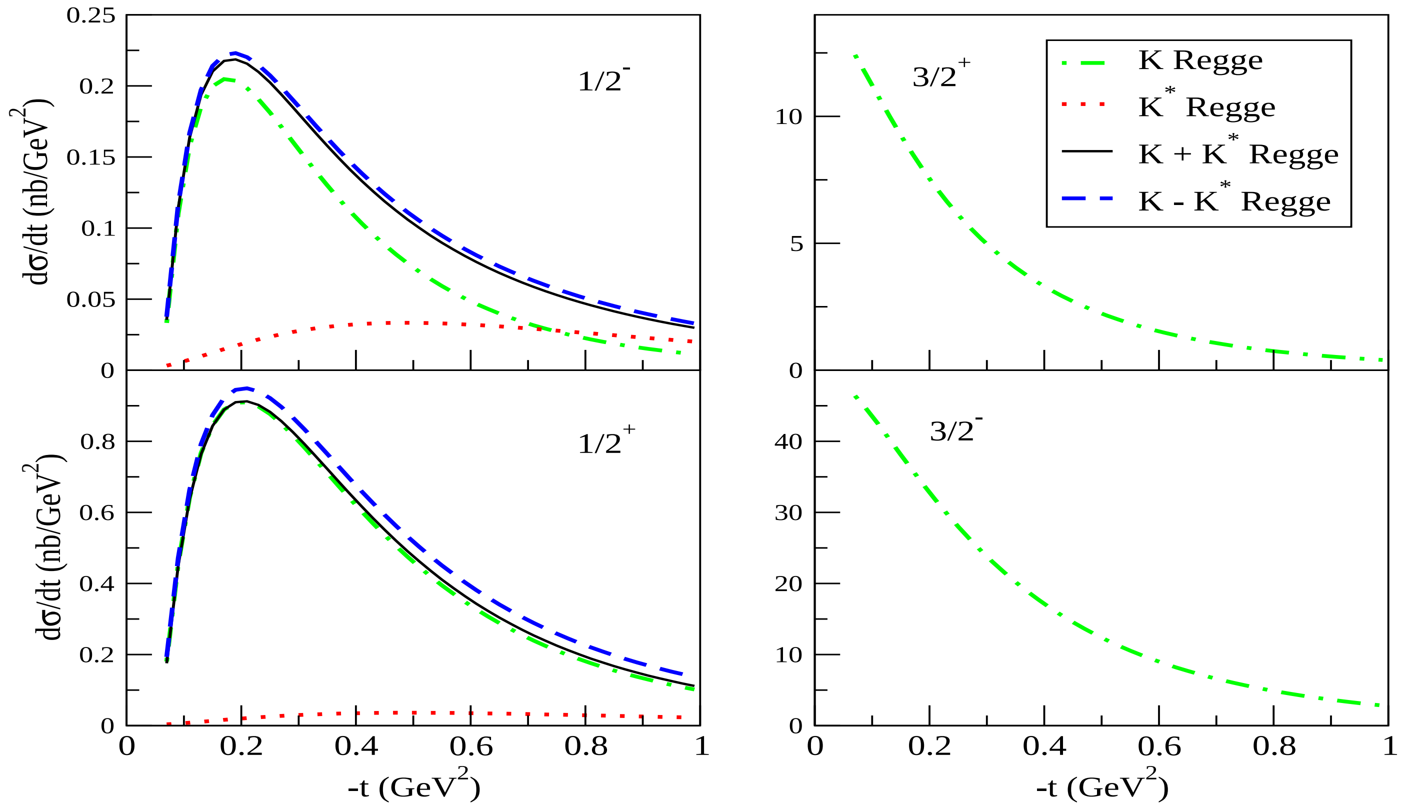


- Note the uncertainty in the sign of the coupling $f_{K^{*0}p\Theta^+}$

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



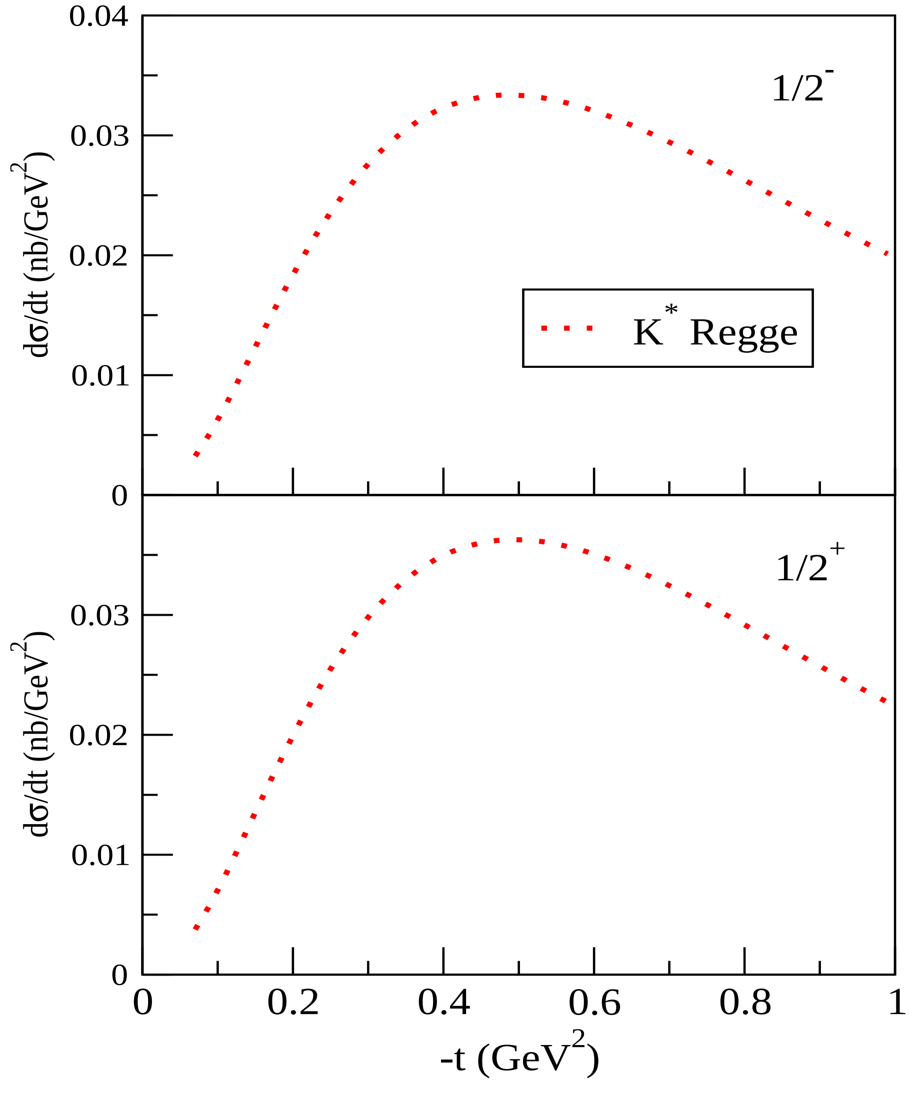
Differential Cross section for $\gamma n \to \Theta^+ K^-$, s= 8.4 GeV^2



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

Differential Cross section $\gamma p \to \Theta^+ \overline{K^0}$,

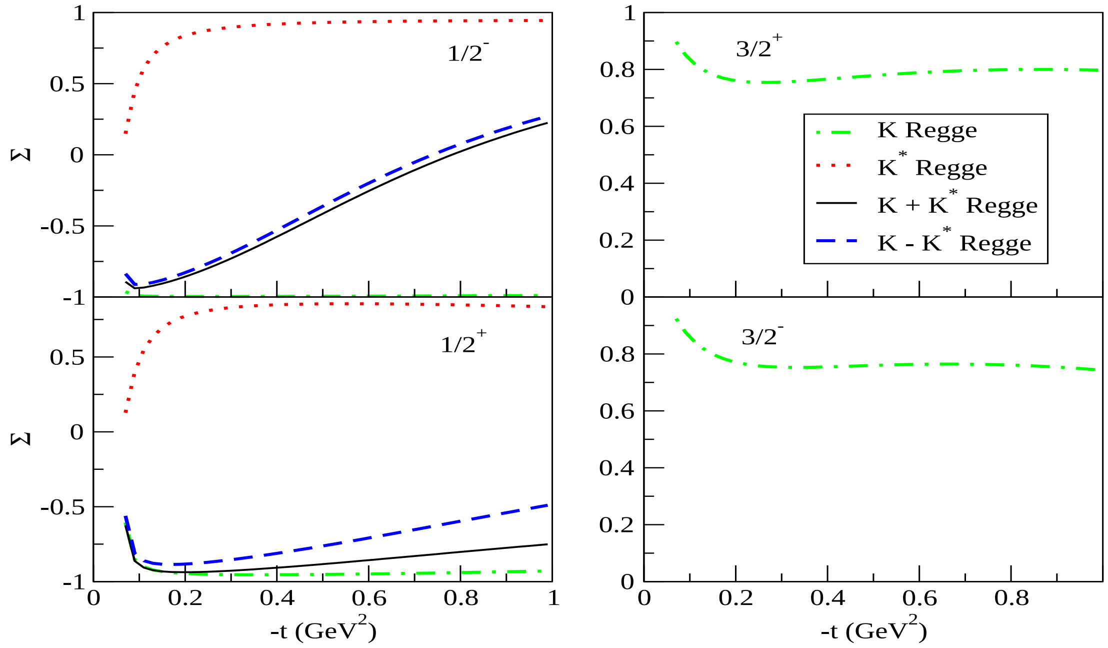
$s = 8.4\ \mathrm{GeV}^2$



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

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

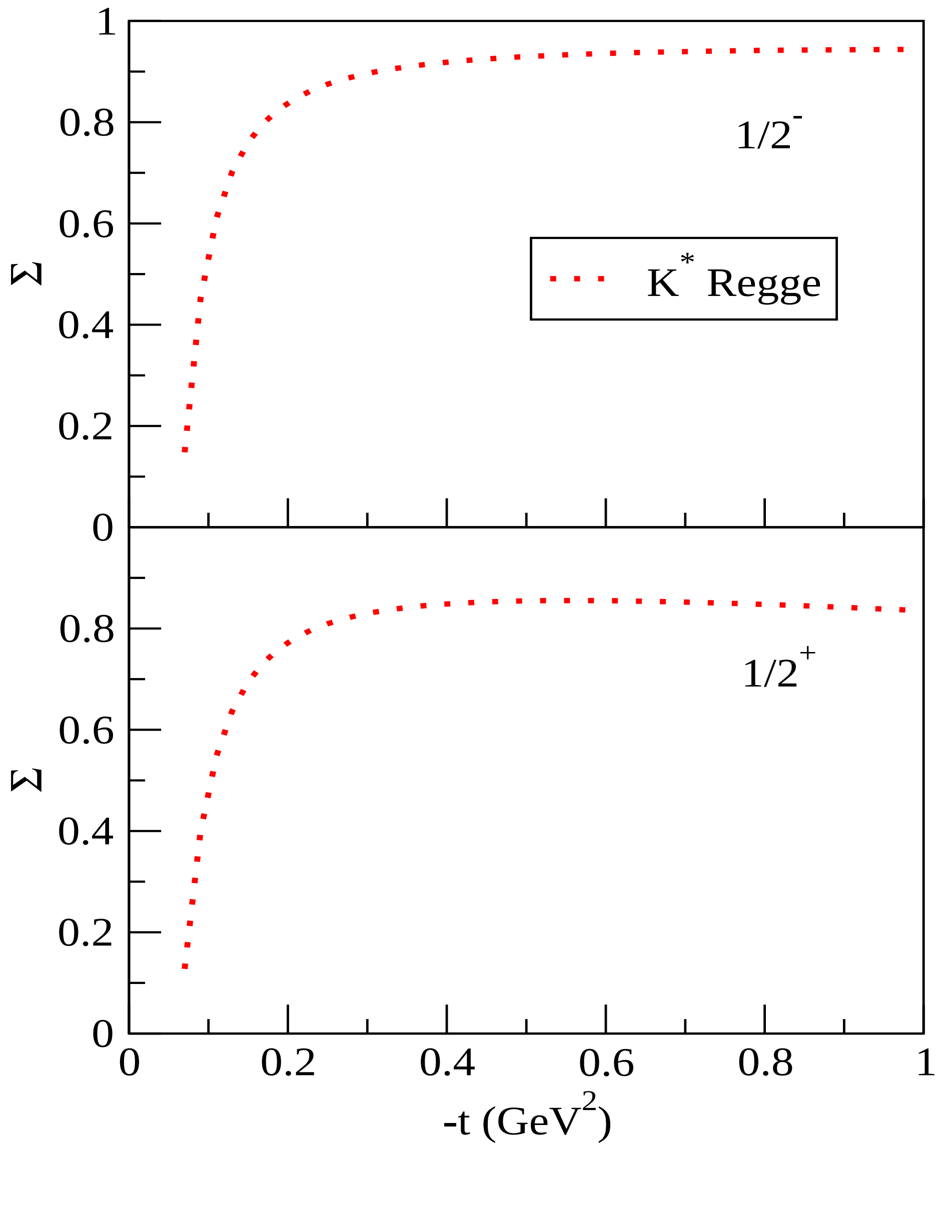
s= 8.4 GeV^2



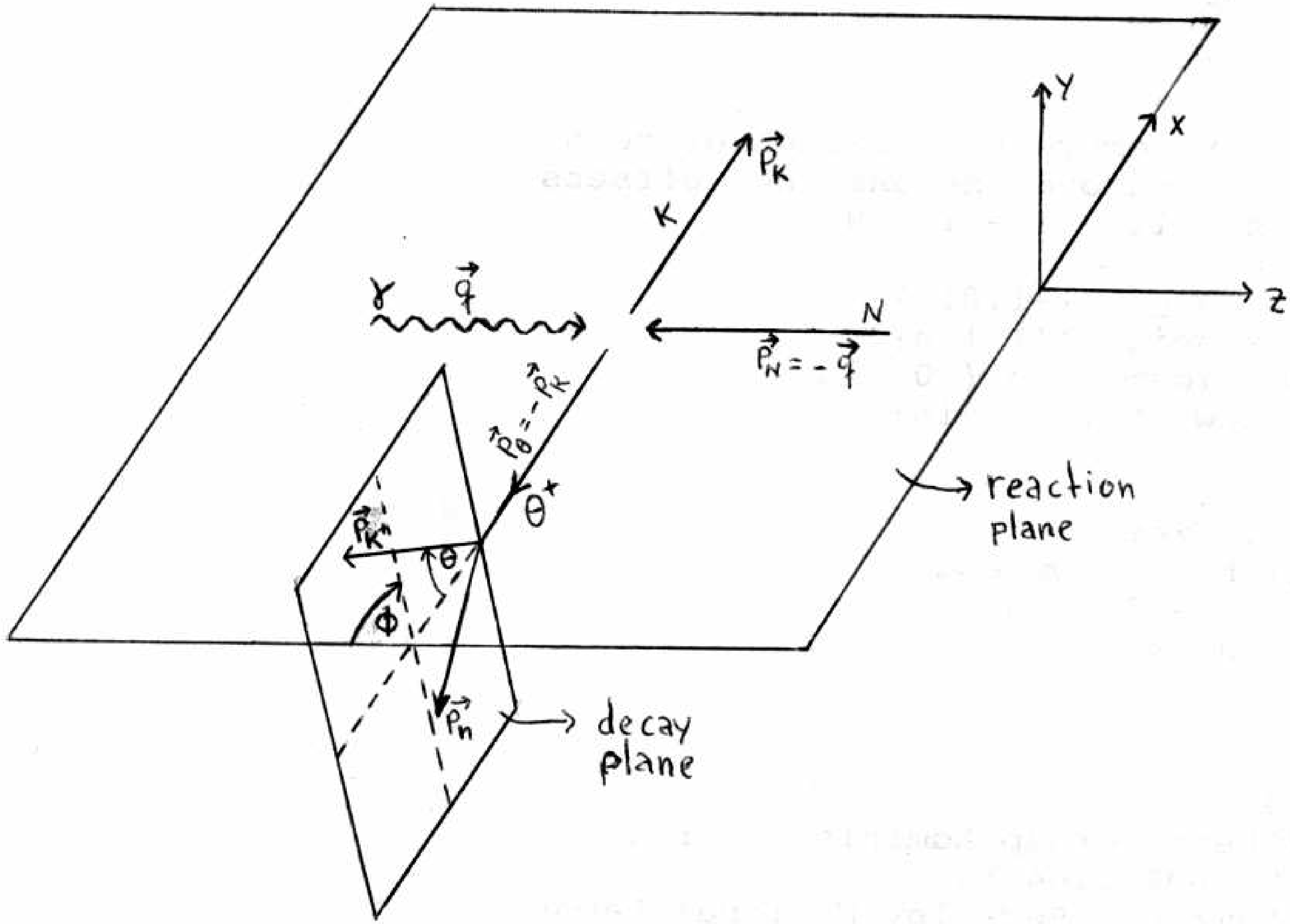
- $\Sigma = \frac{\sigma_\perp - \sigma_\|}{\sigma_\perp + \sigma_\|}$
- $K(K^*)$ exchange dominant, Σ go to -1(1)

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

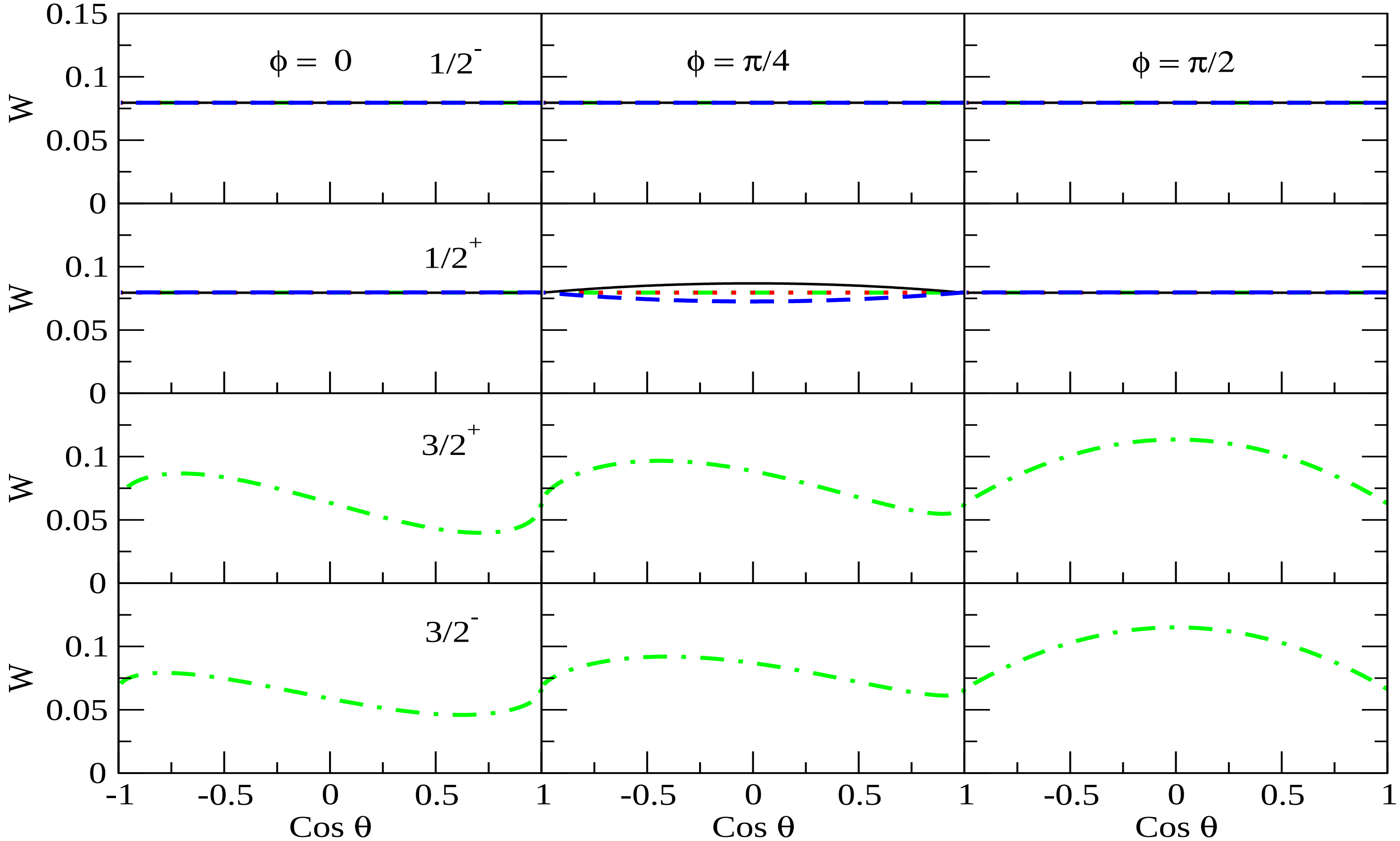


Figure 2: $\gamma n \rightarrow \Theta^+ K^-, \alpha = 0$, s= 8.4 GeV^2, $t = -0.1$ GeV^2

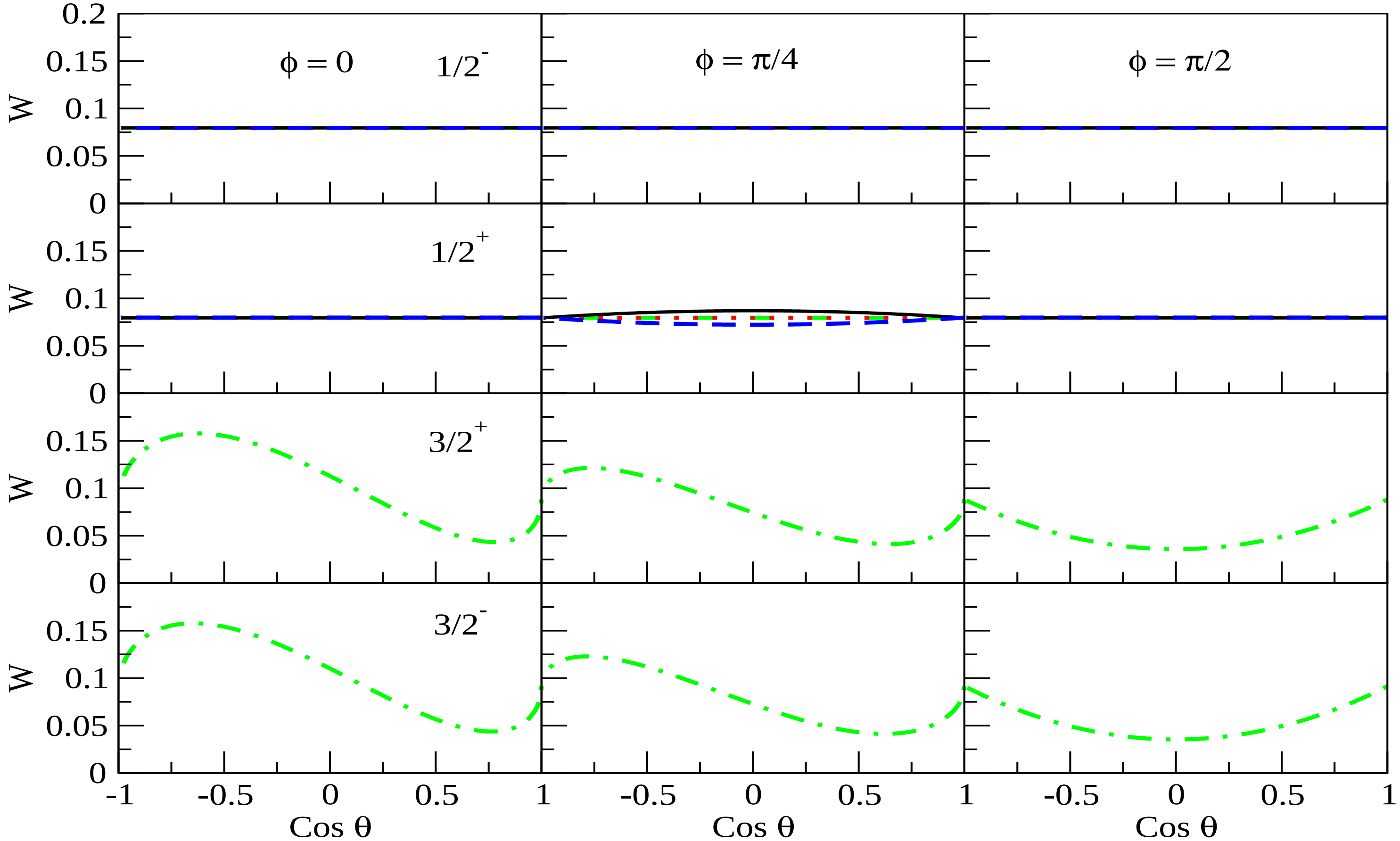


Figure 3: $\gamma n \rightarrow \Theta^+ K^-, \alpha = 1$, s= 8.4 GeV^2, $t = -0.1$ GeV^2

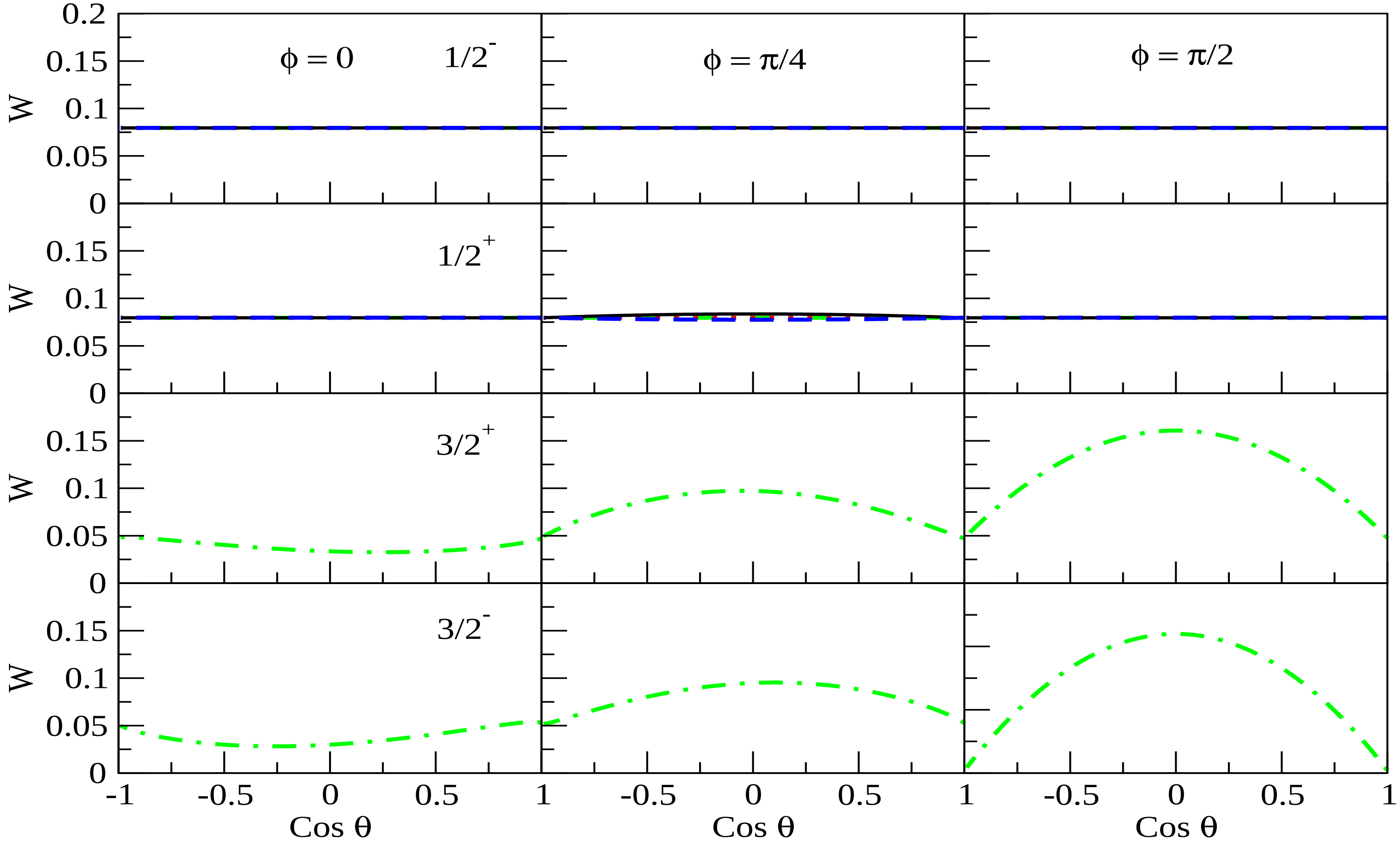


Figure 4: $\gamma n \to \Theta^+ K^-, \alpha = 2$, s$= 8.4$ GeV^2, $t = -0.1$ GeV^2

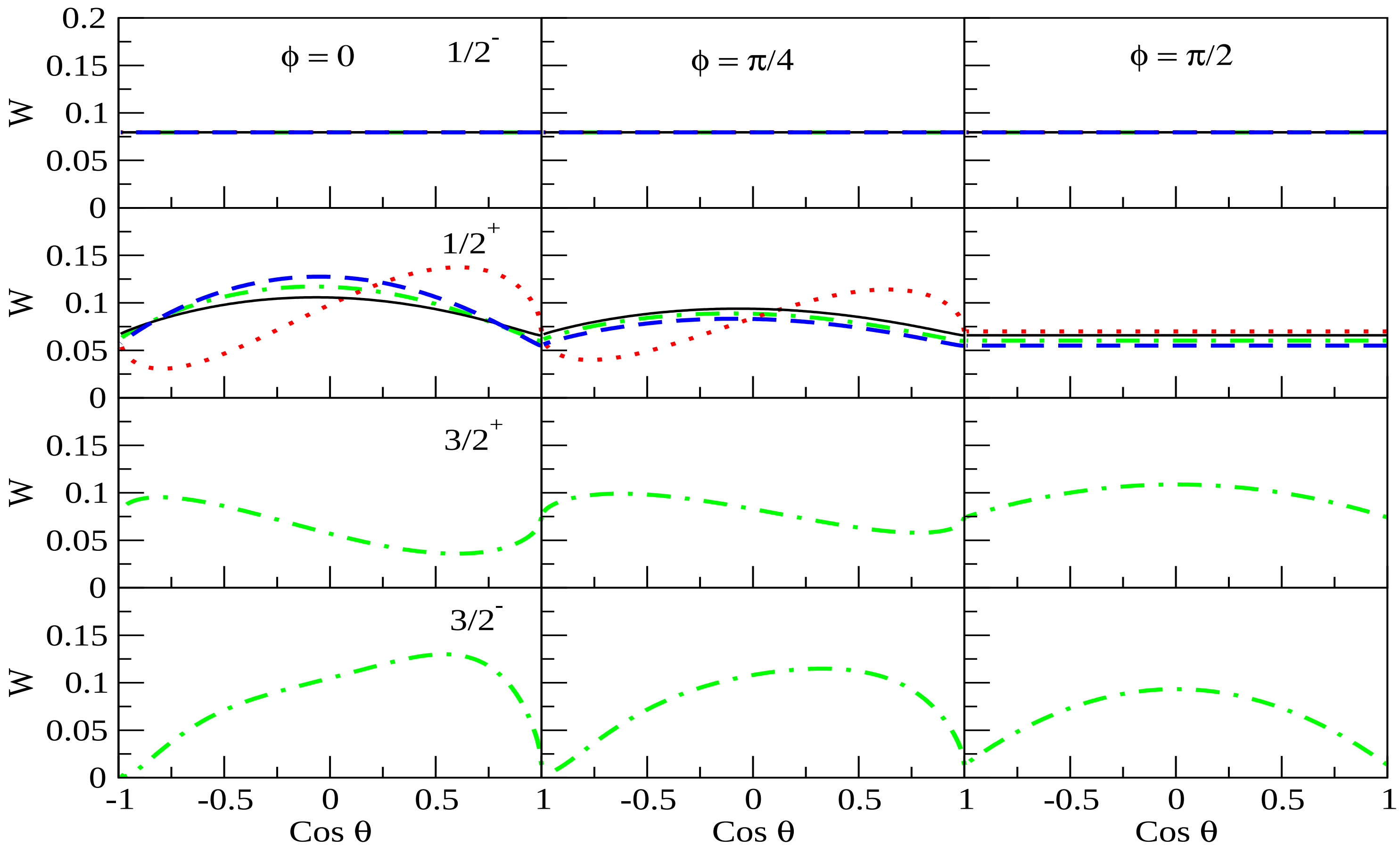


Figure 5: $\gamma n \to \Theta^+ K^-, \alpha = 3$, pol$_\gamma = -1$, s= 8.4 GeV^2, $t = -0.1$ GeV^2

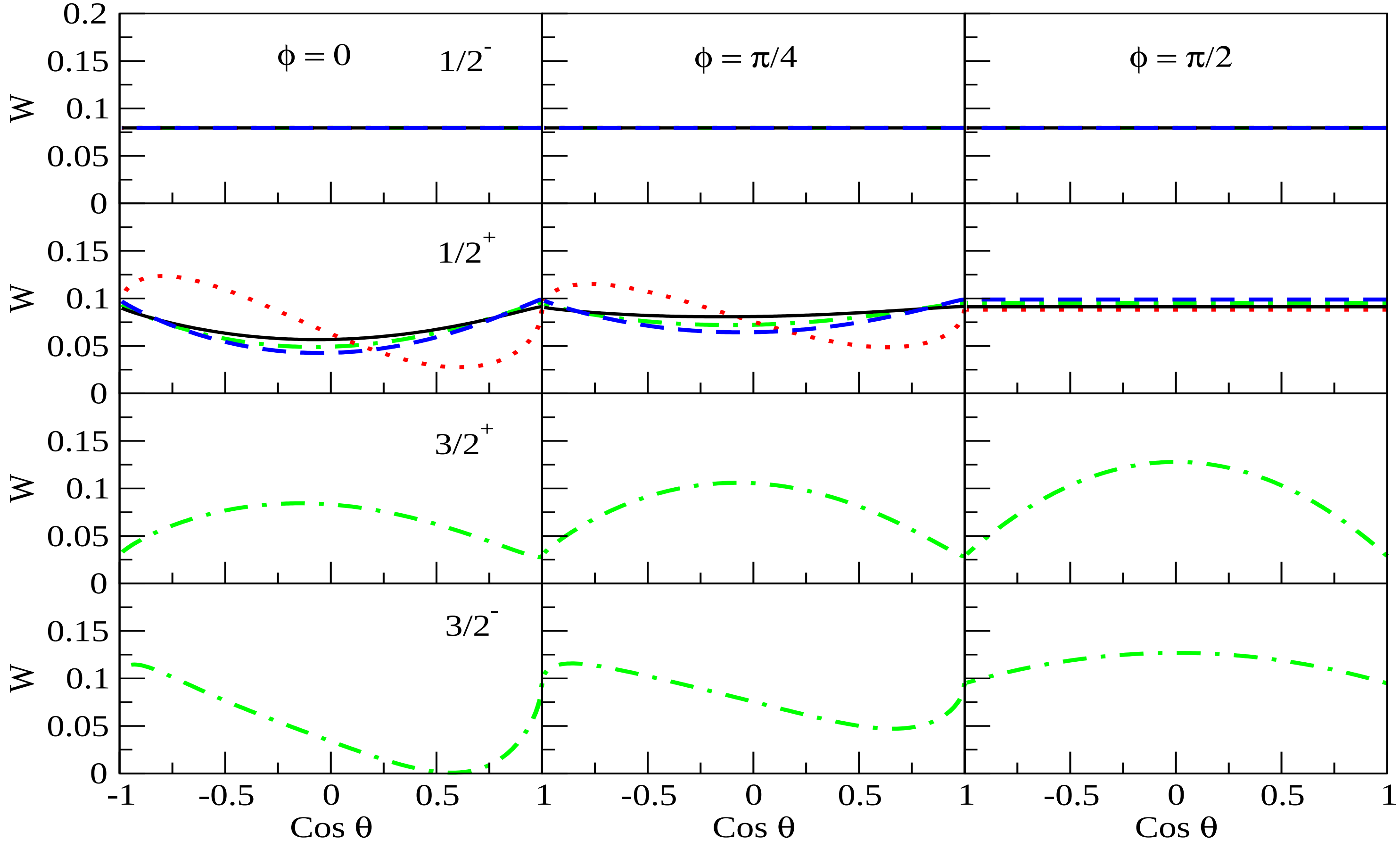


Figure 6: $\gamma n \to \Theta^+ K^-, \alpha = 3$, pol$_\gamma = 1$, s$= 8.4$ GeV^2, $t = -0.1$ GeV^2

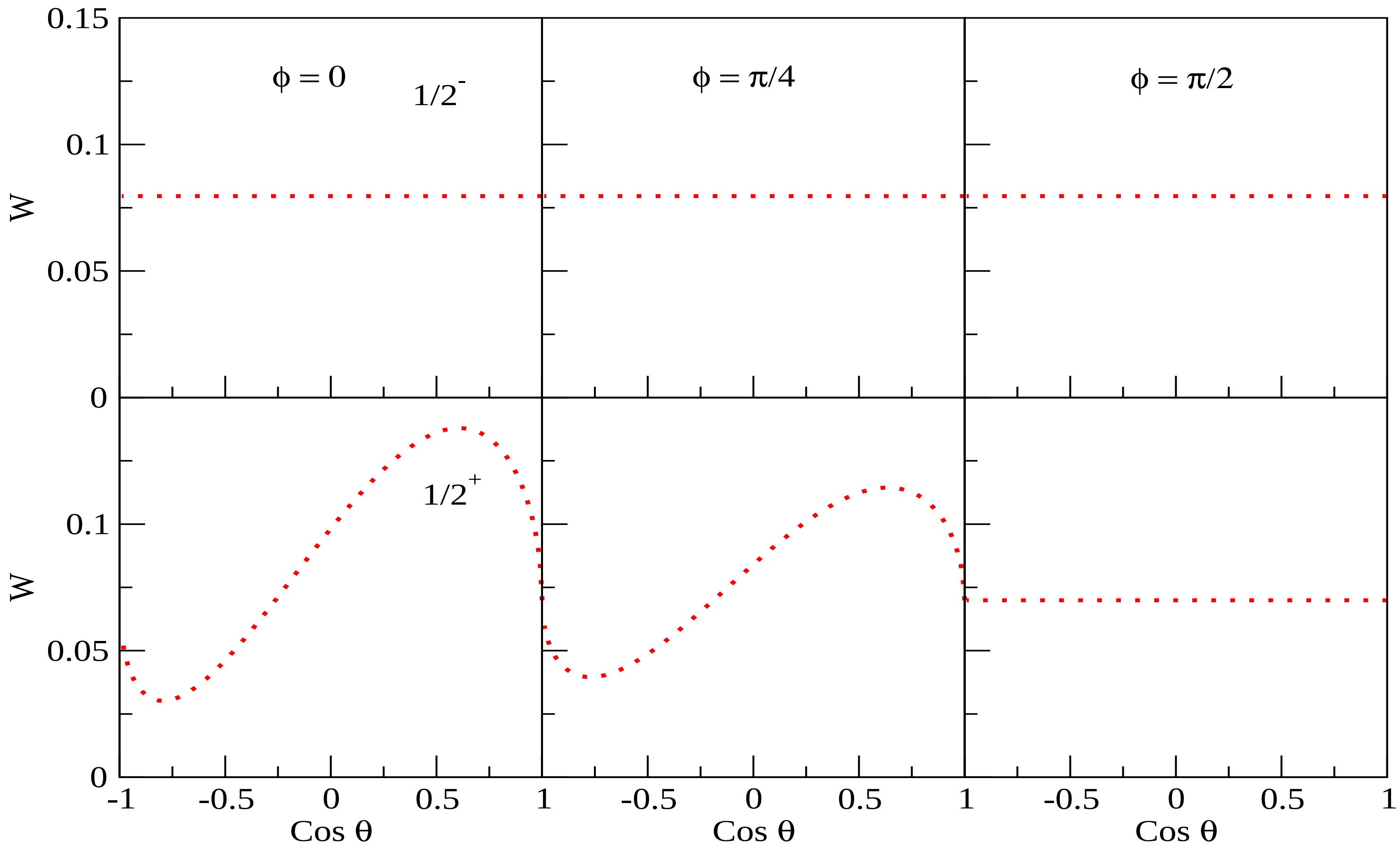


Figure 7: $\gamma p \rightarrow \Theta^+ \overline{K^0}, \alpha = 3$, pol$_\gamma = -1$, s $= 8.4$ GeV^2, t $= -0.1$ GeV^2

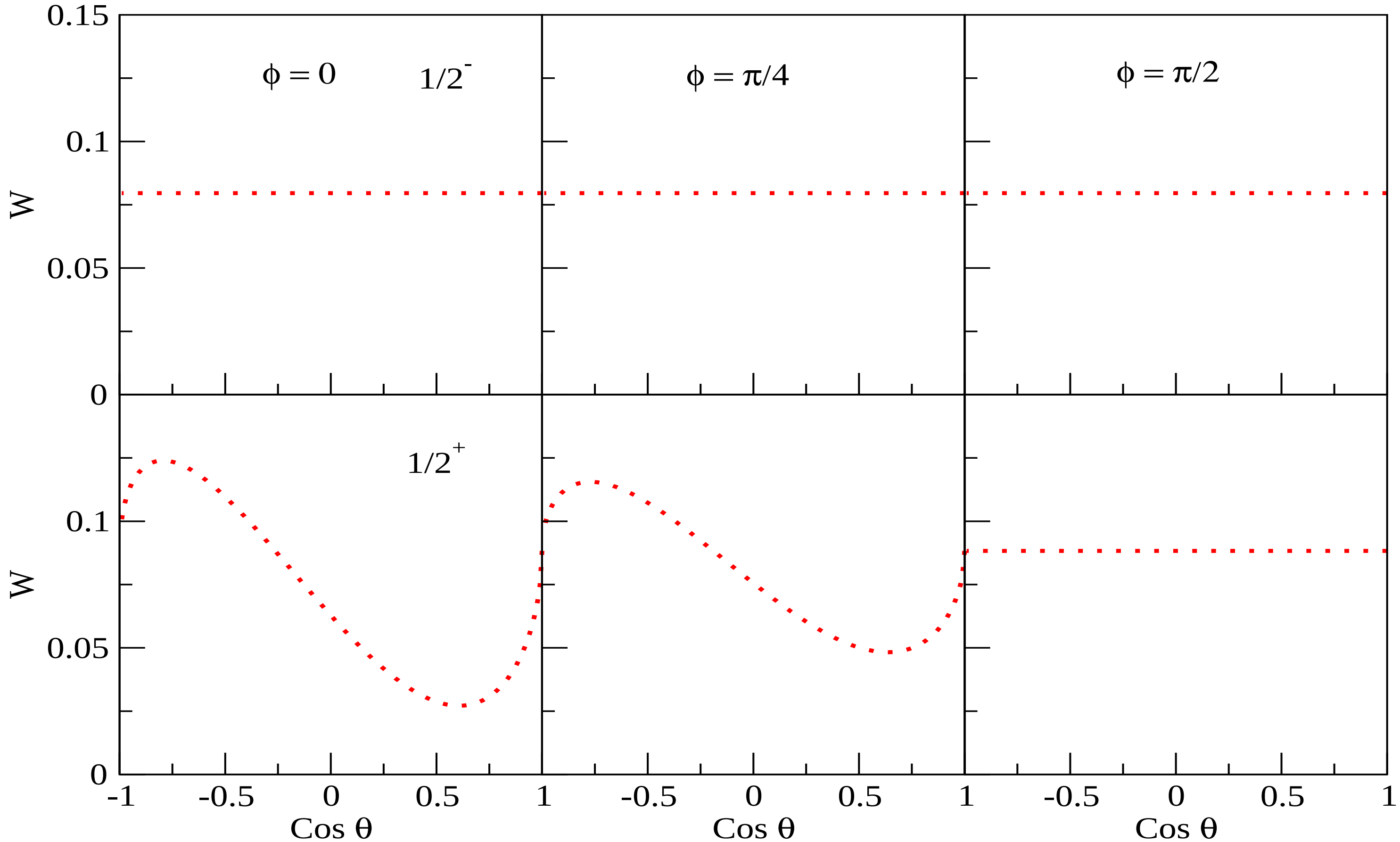


Figure 8: $\gamma p \rightarrow \Theta^{+}\overline{K^{0}}, \alpha = 3$, pol$_{\gamma} = 1$, s $= 8.4$ GeV^{2}, t $= -0.1$ GeV^{2}

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

- 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^+