Θ^+ production in photon-nucleon and meson-nucleon reactions

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Searching for Pentaquarks

- Light pentaquarks ($qqqq\bar{s}$ *q=u,d*

quark models, Y=2 exotics (1960's)
1970-1980's: KN scattering for Z^* (Golowich, PDG 86, …)
Soliton models: Diakonov, Petrov, Polyakov, Chemtob, Praszalowicz etc
2003: LEPS of Spring-8, first ***discovery*** of pentaquark, Θ^+ (1540) (PRL 91, 012002)
Confirmed by CLAS, DIANA, SAPHIR, HERMES, etc.
NA49: Ξ^{*--}(1862) – another exotic state

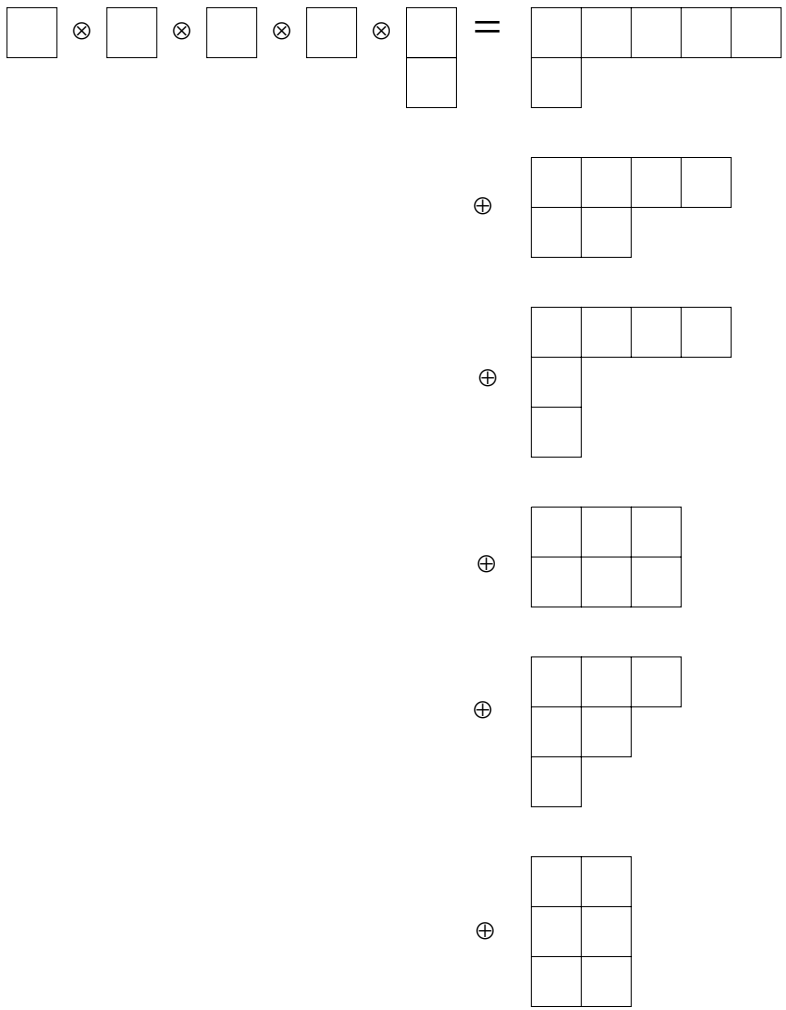
- Heavy pentaquarks ($qqqq\bar{Q}$ *q=u,d,s*

1987: quark models (Lipkin, Gignoux, Silvestre-Brac, Richard, …) $P_{\bar{Q}s}$ $P_{\bar{Q}}$
1990's: soliton model (Helsinki, Seoul, Syracuse, …)
Stable against strong decays? (mass < DN, D_sN threshold)

1998: E791 of Fermilab, search for P_{cs}(2750-2860) by weak decays into $\phi\pi p$, K^*Kp (PRL 81, 44):
no evidence

Many works on N^* for crypto-exotic pentaquark states (meson-nucleon quasi-bound states)
Many calculations in various models

Pentaquark states $(q^4\text{-}\bar{q})$ in SU(3)

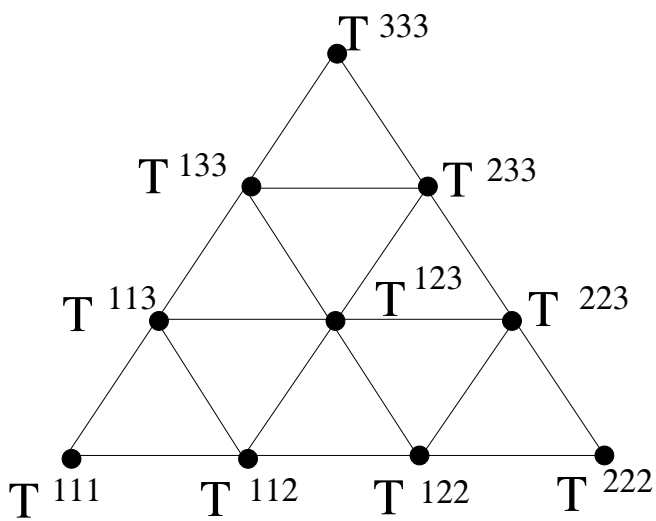


Multip.	#	
35	1	I = 2 Θ and I = 5/2, 3/2 N* (J=5/2?)
27	3	I = 1 Θ and I = 3/2, 1/2 N* (J=3/2?)
10	4	
$\overline{\mathbf{10}}$	2	I = 0 Θ and I = 1/2 N* (J=1/2?)
8	8	
1	3	

Cf. Θ has Y=2,
N* has Y=1

Skyrmion picture: Walliser +, hep-ph/0304058

Pentaquarks as anti-decuplet



Θ

N_{10}

Σ_{10}

Ξ_{10}

T^{333}	Y=2	I=0	Θ
T^{133}, T^{233}	Y=1	I=1/2	N_{10}
$T^{113}, T^{123}, T^{223}$	Y=0	I=1	Σ_{10}
$T^{111}, T^{112}, T^{122}, T^{222}$	Y=-1	I=3/2	Ξ_{10}

$\Theta^{+}(1540)$: observed by LEPS, CLAS, SAPHIR, DIANA, etc

$\Xi^{--}_{3/2}(1862)$ observed by NA49 and ??

Equal-spacing rule in anti-decuplet from GMO mass formula

mixing with pentaquark octet? N(1440) and N(1710) (?) Jaffe-Wilczek

Cf: N(1440) ~ σN quasi-bound state: Juelich Group in πN scattering,

PRC57,1464 (1998); PRC62,025207 (2000)

SU(3) symmetric Lagrangian

1.Baryon anti-decuplet – meson octet – baryon octet

$$\mathcal{L} = -ig\overline{T^{jkl}}\gamma_5 P_m^j B_n^k \varepsilon^{lmn} + \text{h.c.}$$

T : baryon anti-decuplet
P : meson octet
B : baryon octet

2.Baryon anti-decuplet – meson octet – baryon anti-decuplet

$$\mathcal{L} = g'\overline{T^{jkl}} P_m^j T^{mkl}$$

3.Baryon anti-decuplet – meson octet – baryon decuplet

Not allowed since $8 \otimes 10 = 35 \oplus 27 \oplus 10 \oplus 8.$ Thus the N_{10} cannot decay into $\pi\Delta$

BR[N(1710)->$\Delta\pi$] = 15-40% (PDG)

U-spin conservation $\mapsto$ the N_{10} can be produced by γn but not by γp

$\gamma N \mapsto K\Theta$

Quantum numbers of the $\Theta^+(1540)$:

❶ $I = 0$ if $\Theta(1540)$ belongs to anti-decuplet

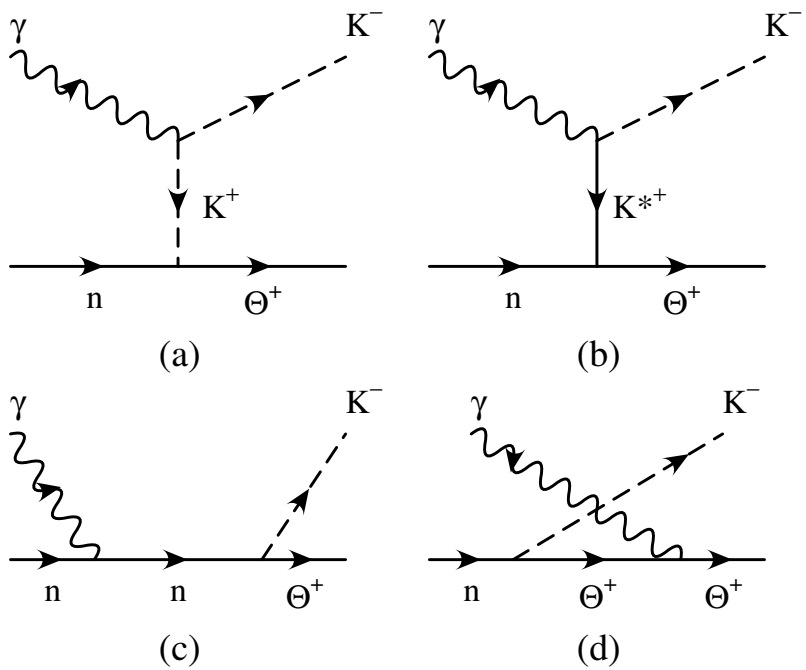
❷ Spin? - most models predict ½

❸ Parity?
- lattice, QCD sum rules $\mapsto$ odd parity
- quark models with orbital motion, soliton models $\mapsto$ even parity

Soliton models for heavy pentaquark gives
$1/2^+$: ground state
$1/2^-$: first excited state
$I=1,2$: higher states

we first assume $I = 0$ and $J^P = 1/2^+$ for $\Theta^+(1540)$.

$\gamma n \mapsto K\Theta$

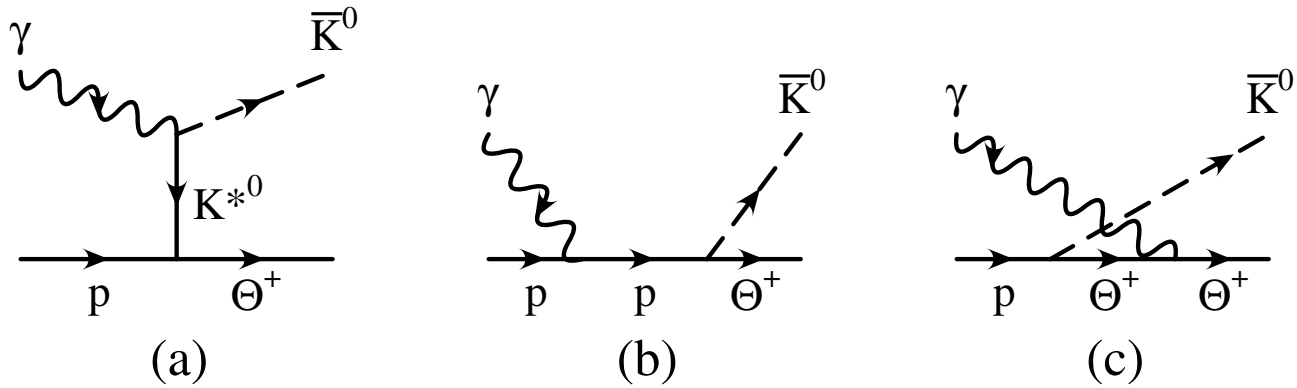


For I=1,2 Θ:
completely <u>different</u> production mechanisms

I=0 & I=1 Θ^+

Other resonances: Δ(no), N_{10} (yes), others….

$\gamma p \mapsto K\Theta$



Other resonance: Δ(no), N_{10}(no), others…

Lagrangian

SU(3) Lagrangian for $\overline{10}-8-8$ $\mathcal{L} = -ig\overline{T^{jkl}}\gamma_5 P_m^j B_n^k \varepsilon^{lmn} + \text{h.c.}$ gives

$$\mathcal{L}_{KN\Theta} = -ig_{KN\Theta}(\overline{\Theta}\gamma_5 K^+ n - \overline{\Theta}\gamma_5 K^0 p) + \text{h.c.}$$

$$\mathcal{L}_{K^*N\Theta} = -g_{K^*N\Theta}(\overline{\Theta}\gamma_\mu K^{*+\mu} n - \overline{\Theta}\gamma_\mu K^{*0\mu} p) + \text{h.c.} + \text{(tensor coup.)}$$

Other Lagrangian

$$\mathcal{L}_{\gamma KK},\ \mathcal{L}_{\gamma NN},\ \mathcal{L}_{K^*K\gamma},\quad \mathcal{L}_{\gamma\Theta\Theta} = -e\overline{\Theta}\left(A_\mu\gamma^\mu - \frac{\kappa_\Theta}{2M_\Theta}\sigma_{\mu\nu}\partial^\nu A^\mu\right)\Theta,$$

$$\mathcal{L}_{\pi NN} = \frac{g_{\pi NN}}{2M_N}\overline{N}\gamma^\mu\gamma_5\partial_\mu\pi N,$$

$$\mathcal{L}_{K^*K\pi} = -ig_{K^*K\pi}\left(\overline{K}\partial^\mu\pi K_\mu^* - \partial^\mu\overline{K}\pi K_\mu^*\right) + \text{h.c.}$$

Coupling constants

Coupling constants

$$\Gamma(\Theta)=\frac{g_{KN\Theta}^2\, p_K}{2\pi M_\Theta}(E_N - M_N)$$

$g_{KN\Theta}$: can be determined from $\Gamma(\Theta)$

expt. upper bound: 9-25 MeV

chiral soliton model: 5-15 MeV (Polyakov +, Diakonov +)

KN scattering analyses: a few (~5) MeV or even less (Nussinov, Arndt +, …)

we do not try to fix this coupling and set $g_{KN\Theta}$ = 1 ($\Gamma(\Theta)$ ~ 1 MeV)

leaving its determination to near future expt.

$g_{K^*N\Theta}$: unknown and cannot be inferred from $\Gamma(\Theta)$

some estimate based on several assumptions (not suppressed)

we give the results by varying $g_{K^*N\Theta}/g_{KN\Theta}$

κ_Θ : anomalous magnetic moment of the Θ

depends on the model for the pentaquark structure -0.9~+0.3 (?)

we take κ_Θ=0 (the results are *not so much dependent* on κ_Θ in the above range)

Form factors

$$F(r, M_{\rm ex})=\frac{\Lambda^4}{\Lambda^4+(r-M_{\rm ex}^2)^2}$$

Λ = 1.8 GeV from kaon photonproduction

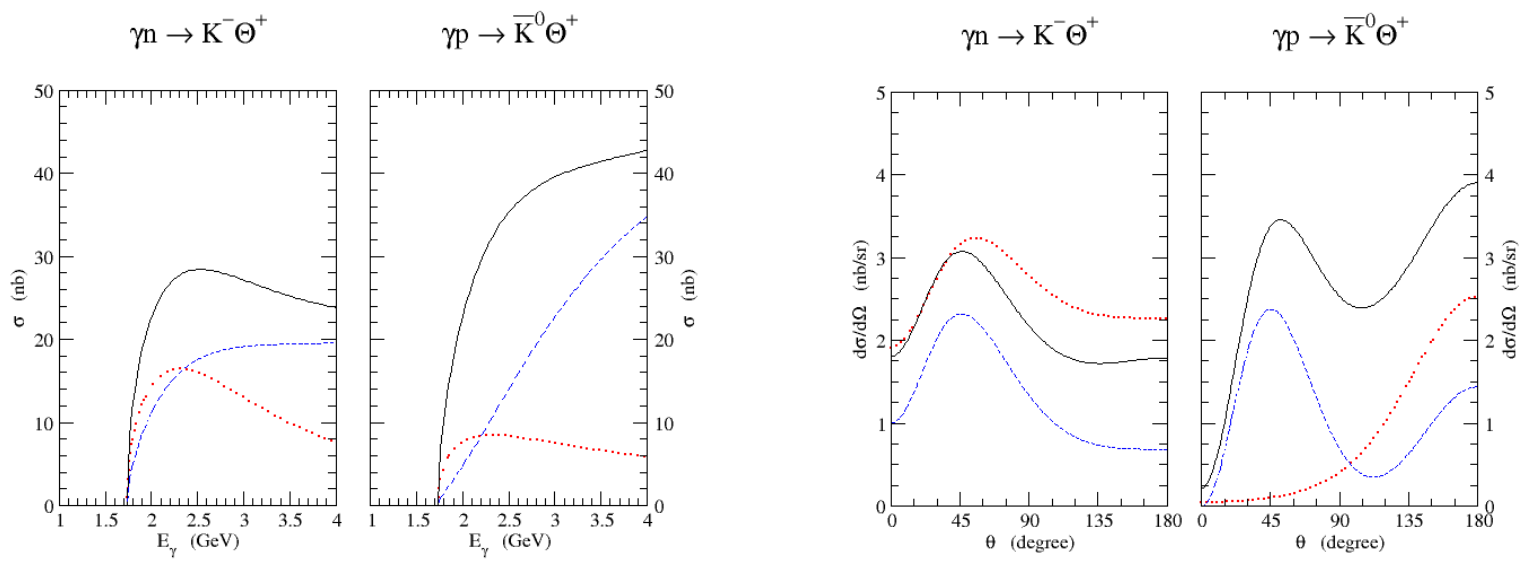
1.2 GeV from πN scattering

(Janssen et al., Giessen group)

$\gamma N \mapsto K\Theta$ (results)

Total cross sections

Diff. cross sections at E_γ=2.5 GeV

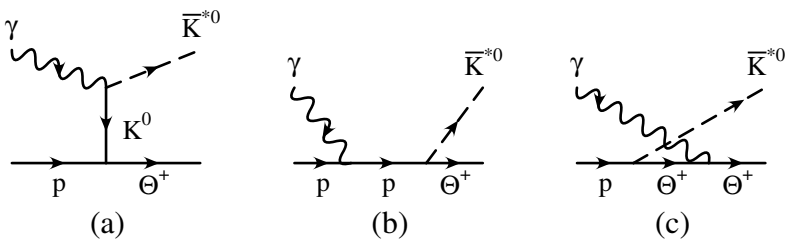


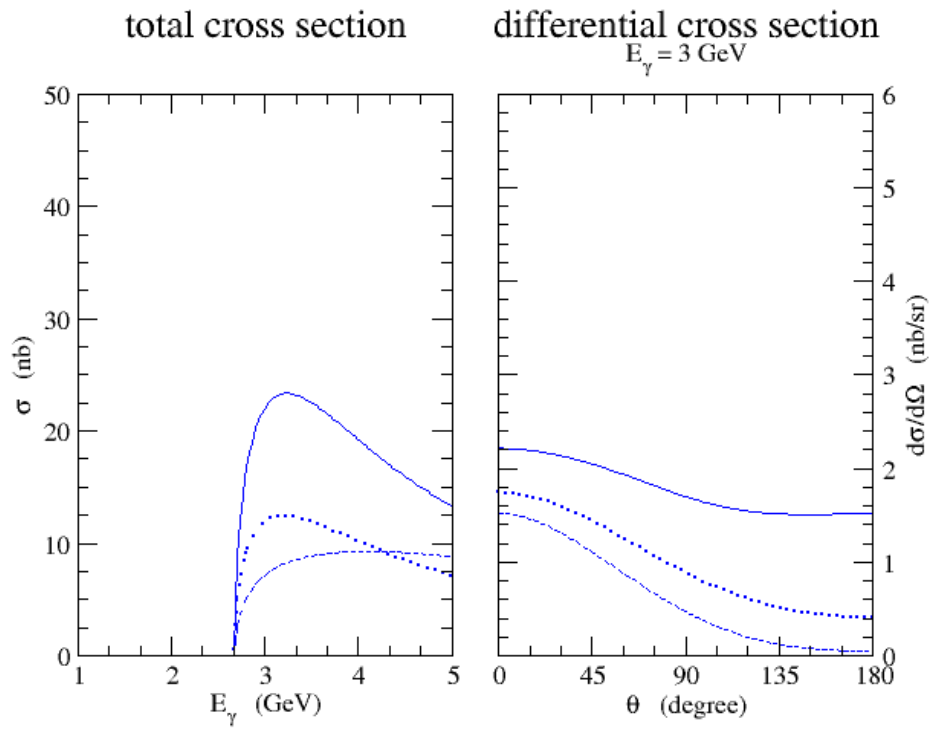
$g_{K^*N\Theta} = 0$

$g_{K^*N\Theta}/g_{KN\Theta} = 0.7$

$g_{K^*N\Theta}/g_{KN\Theta} = -0.7$

$\gamma N \mapsto K^* \Theta$

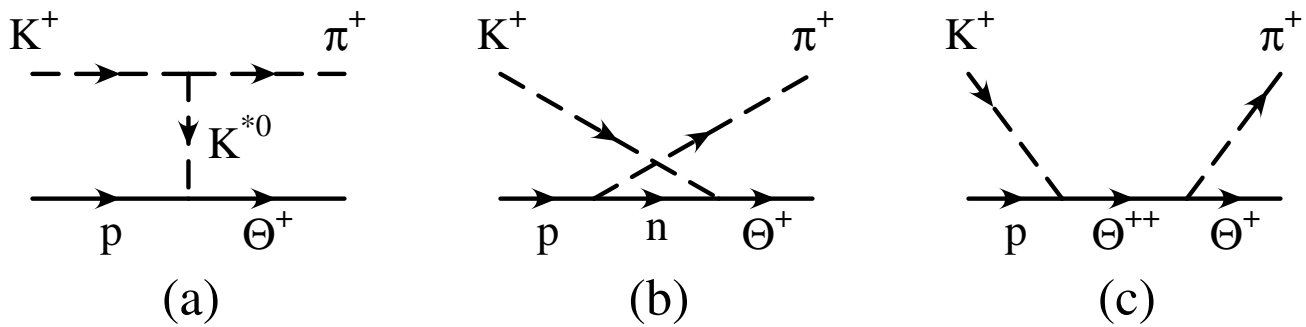




Dotted: $g_{K^*N\Theta} = 0$, Solid: $g_{K^*N\Theta}/g_{KN\Theta} = 0.7$,
Dashed: $g_{K^*N\Theta}/g_{KN\Theta} = -0.7$

$KN \mapsto \pi\Theta$

$K^+ p \to \pi^+ \Theta^+$



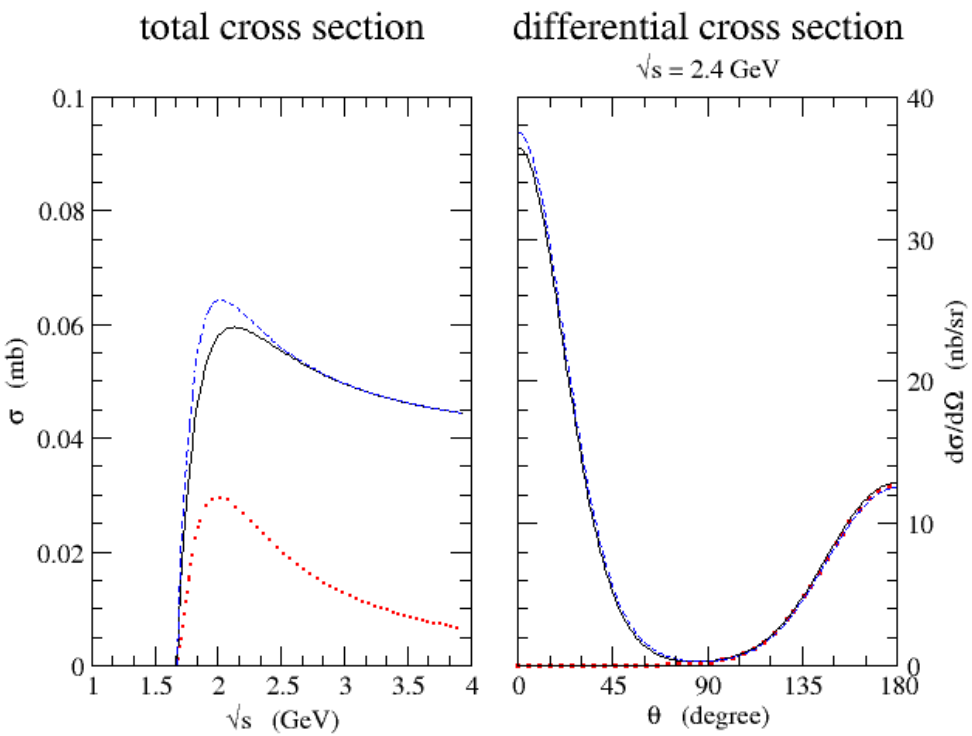
Isospin relation

Δ (no)

I=1 Θ (yes)
I=2 Θ (no)

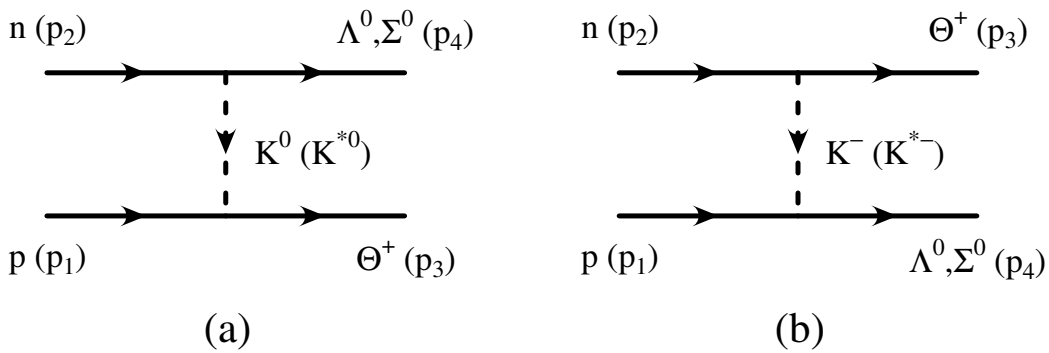
$$\mathcal{M}_{K^+p} = -\mathcal{M}_{K^0n} = -\sqrt{2}\mathcal{M}_{K^0p} = -\sqrt{2}\mathcal{M}_{K^+n}$$

$K^+p \mapsto \pi^+\Theta^+$



red: $g_{K^*N\Theta} = 0$
black: $g_{K^*N\Theta}/g_{KN\Theta} = 0.7$
blue: $g_{K^*N\Theta}/g_{KN\Theta} = -0.7$

$NN \mapsto \Lambda\Theta, \ \Sigma\Theta$



Isospin relation for $NN \mapsto \Sigma\Theta$

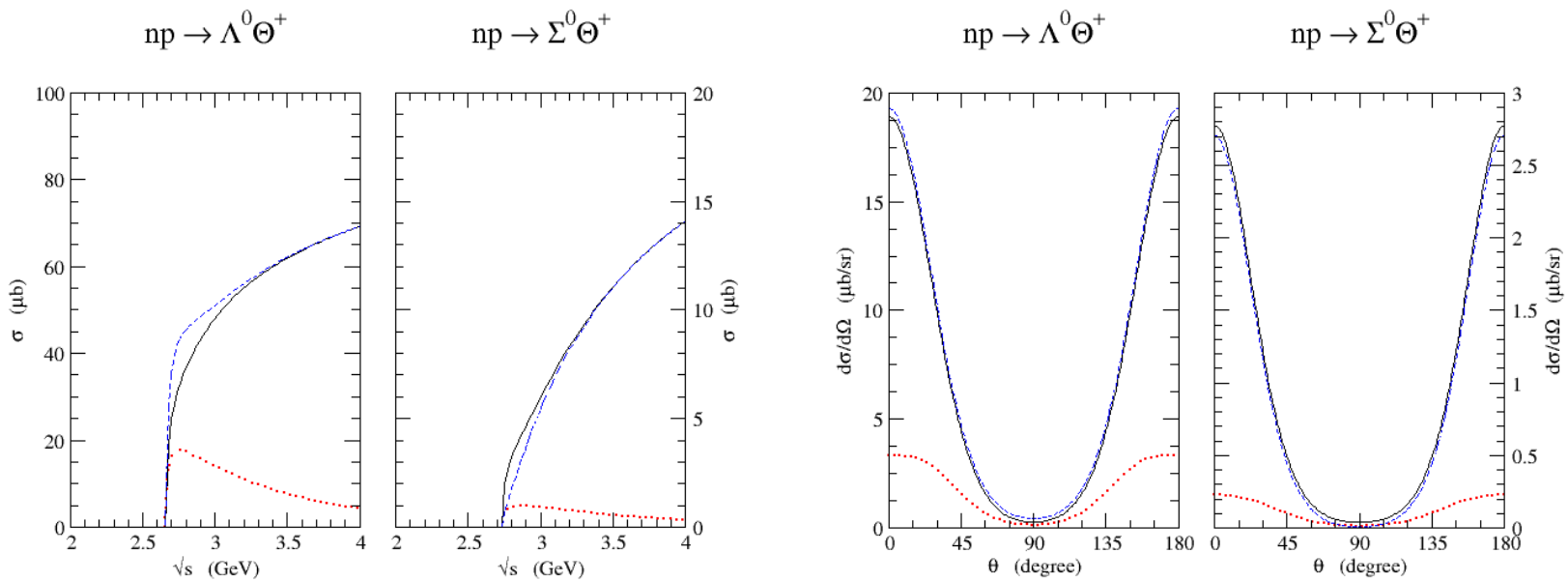
$$\mathcal{M}_{pp} = -\mathcal{M}_{nn} = -\sqrt{2}\mathcal{M}_{np}$$

SU(3) symmetry for KNY couplings

$$g_{KN\Lambda}/\sqrt{4\pi} \sim -3.7, \quad g_{KN\Sigma}/\sqrt{4\pi} \sim 1.0$$

Nijmegen potential (1999) for K^*NY couplings

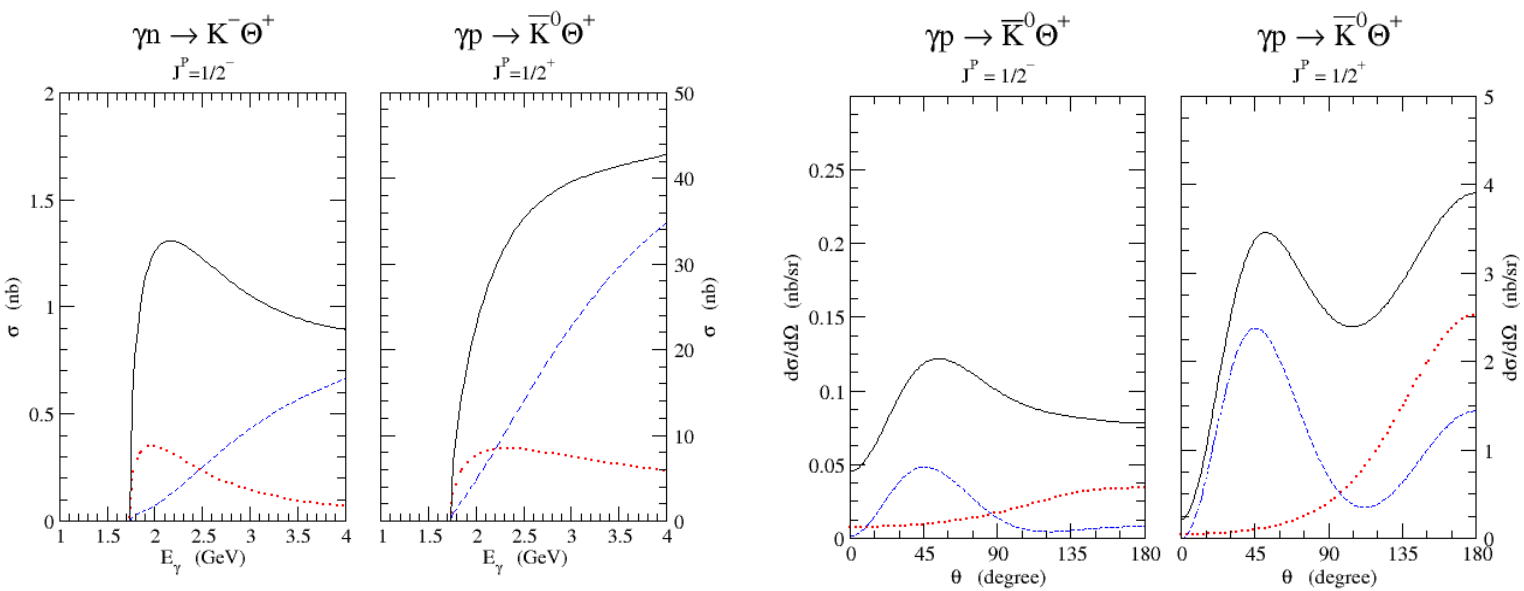
$np \mapsto \Lambda^0\Theta^+, \ \Sigma^0\Theta^+$



red: $g_{K^*N\Theta} = 0$
black: $g_{K^*N\Theta}/g_{KN\Theta}$ = 0.7
blue: $g_{K^*N\Theta}/g_{KN\Theta}$ = -0.7

Summary

- Exploratory study on $\Theta^+(1540)$ production in γN, KN (πN), and NN reactions
- N* contribution? Spin asymmetries?
- Other reactions with other final states? Liu & Ko, PRC68, nucl-th/0309023,0310087
- Other Θ particles? Quantum numbers?
  Total and diff. cross sections at E_γ = 2.5 GeV for odd-parity $\Theta^+(1540)$



red: $g_{K^*N\Theta} = 0$
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