Two Kaon Photoproduction and Λ(1520) and Θ(1540)

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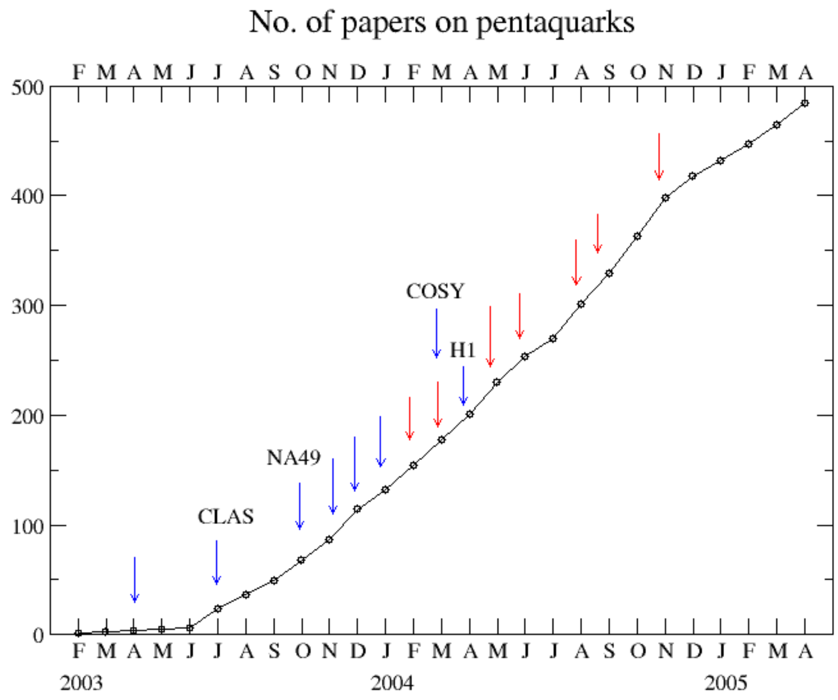

Blue: positive experimental results

Red: negative experimental results

Outline

- Introduction
  - Double kaon photoproduction
  - Radiative decays of $\Lambda(1520)$
  - Pentaquarks: expt. and theory (soliton model)
- The $\gamma N \to K \bar{K} N$ reaction: model
- Results
  - Radiative decay of $\Lambda(1520)$
  - Exotic $\Theta(1540)$ production
- Summary

1.Introduction

- $\gamma N \rightarrow K K N$ reaction at low energies
  - Provides a tool to study various hadron productions
  - In $K K$ channel
    - vector meson (especially ϕ meson) production
  - In $K N$ channel
    - hyperons (especially $\Lambda(1520)$) production
  - In $K N$ channel
    - exotic pentaquarks, if any. [putative $\Theta(1540)$]
    - First experiment which claimed the observation of $\Theta(1540)$
- Difficulties
  - Many resonances in each channel
    - Lots of parameters are introduced
  - Experimental data are not enough
    - Most of the limited data show the mass distribution in an arbitrary unit
  - Gauge invariance, Complicated rescattering processes

Introduction

- Previous theoretical works
  - K. Nakayama, K. Tsushima, PLB 583 (2004)
  - A.R. Dzierba et al., PRD 69 (2004)
  - W. Roberts, PRC 70 (2004)
  - A.I. Titov et al., PRC 71 (2005)
- In this work, (hep-ph/0412363) we consider
  - Kaon background diagrams
  - Vector meson production
  - Tensor meson production
  - Intermediate S=-1 hyperons and S=+1 $\Theta(1540)$
  - Form factors are included. Charge conservation is restored by extending the conventional method, i.e., by introducing contact diagrams.
  - Exp. data are used to constrain the cutoff parameters.

Radiative decay of Λ(1520)

- Various model predictions for the radiative decay of Λ(1520)
  - Show strong model dependence
  - Radiative decays into Λ(1405) and Σ* are suppressed

- Experimental measurements
  - Very limited and uncertain
  - Recent measurements
    - SPHINX: measure Γ(Λ(1520) Λ(1116)γ) from pN KΛγN (PLB 604, 2004)
    - CLAS: measure Γ(Λ(1520) Λ(1116)γ) from γp KΛγ (PRC71, 2005)
    - Larger values than most model predictions

- Motivation: What we can distinguish model predictions for Λ(1520) decay in double kaon photoproduction.

Status of Λ(1405) decay (in keV)

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Model	Λγ	Σγ	Λ(1405)γ	Σ*γ
NRQM (Darewych et al. PRD 28)	96	74	0.2	~0
MIT bag (Kaxiras et al., PRD 32)	46	17	0.1	3.6
SU(3) broken NRQM (Kaxiras et al., PRD 32)	156	55	0.7	0.07
RCQM (Warns et al., PLB 258)	215	293		
Chiral bag (Umino & Myhrer, NPA 554)	32	51		
Algebraic model (Bijker et al., AP 284)	85	180		
SPHINX (EPJA 21, 2004)	159 +/- 33			
CLAS (PRC71, 2005)	167 +/- 43			
PDG (PLB 592, 2004)		304 +/- 53*	***: not measured directly**	
Bertini (NPB 279, 1987)	33 +/- 11	47 +/- 17*		
Mast et al. (PRL 21, 1968)	134 +/- 23			

Exotic baryons

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- Exotic hadrons
  - Normal hadrons: minimal quark contents are qqq for baryons and $q\bar{q}$ for mesons
  - Exotic hadrons: not normal ones
    - Pure exotic: can be distinguished by unique quantum numbers
    - Cryptoexotic: whose quantum numbers can be generated by qqq or $q\bar{q}$
- Pentaquark exotic baryons: made of four quarks and one antiquark
  - Θ(1540): observed first by LEPS at Spring-8 $udud\bar{s}$ anti-strangeness, mass ~ 1540 MeV, width ~ 1 MeV (Particle Data Group)
  - Ξ(1862): exotic S=-2, I=3/2 baryon (NA49) $udds\bar{s}$
  - Θ_c(3099): anti-charmed baryon (H1) $udud\bar{c}$

Exotic baryons (II)

- Fact or Fiction? Experiment review by K. Hicks (hep-ex/0504027)
  Do they really exist?
  - Positive results
    LEPS, DIANA, CLAS, SAPHIR, ITEP, HERMES, ZEUS, COSY-TOF, SVD, NA49, H1, etc
  - Negative results
    BES, BaBar, Belle, LEP, HERA-B, SPHINX, HyperCP, CDF, FOCUS, PHENIX, WA89, etc
- If exists, then
  - Low mass, narrow width
    - hidden structure in baryons?
  - Quantum numbers: spin & parity?
  - Splitting in the multiplets –
    Where are the other members? Who are they?
  - Production mechanisms – Why can they be seen only in some places?

Exotic baryons (III)

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Existence problem: experimental work

- Recent results from JLab (JLab News, April 28, 2005)

(g11) Similar expt. as SAPHIR but 2 orders of magnitude better statistics

$\gamma p \longmapsto K^+ K^0 n$ no evidence of the Θ^+

(g10) the original expt. with higher statistics. (deuteron target)

$\gamma n \longmapsto K^+ K^- n$ coming soon

- Recent SPring-8 experiment (on deuteron target) confirms the Θ peak (T. Nakano: Pentaquark 2004, QCD 2005)
- Θ^{++}(?) by STAR Collaboration (Huang: QCD 2005)

History

- Earlier experiments for pentaquark Θ
  - $\gamma + p \to K^- + \Theta$ — J. Tyson et al. PRL 19, 255 (1967)
  - K^+p and K^+d — R.J. Abrams et al., PRL 19, 259 (1967), etc
  - $\pi^- + p \to K^- + \Theta$ — E.W. Anderson et al., PL 29B, 136 (1969)

Found peaks for Θ,
but concluded no resonance.

- Many crypto-exotic resonances were reported earlier, e.g.
  - Hirose et al. Nuovo Cim. 50A (1979) Amirzadeh et al. Phys. Lett. 89B (1979)
    Aref'ev et al. Yad. Fiz. 51 (1990) Karnaukhov et al. Phys. Lett. B 281 (1992)
  - most of them were found to have narrow widths, but their existence was not confirmed by later expt.
  - SPHINX: X(1810), X(2050), X(2400) ~ $uudss\,(?)$ Yad. Fiz. 65 (2002)

Early Expt. (π p reaction)

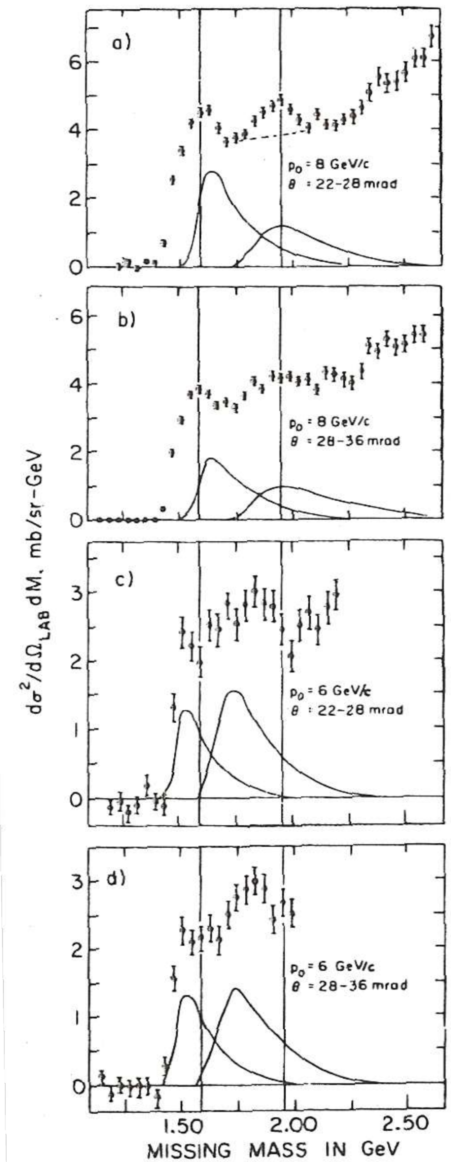
- Peaks at 1590 and 1950 MeV in $\pi^- p$ $K^- \Theta$ with 8 GeV beam :

  interpreted as kinematic reflection due to higher meson (spin-2 and 3) resonances since the peaks move to

  1500 and 1800 MeV with 6 GeV beams.

  E.W. Anderson et al., Phys. Lett. 29B, 136 (1969)

- A.R. Dzierba et al., PRD 69, 051901 (2004)
  - Claims that the peak observed at 1540 MeV in γN reaction may be kinematic reflection coming from tensor mesons.



8 GeV beam

6 GeV beam

Models for pentaquarks

- Diakonov et al. (chiral soliton model, 1997)
  - Equal spacing rule for antidecuplet (group theoretic relation)
  - Identify N(1710) as antidecuplet and δm=180 MeV (by fitting the parameters to the other baryons), which gives Θ at 1530 MeV
  - But 10 ? 10 ? 8 is not allowed

- Bound state model of soliton-meson (Callan and Klebanov, 1985)
  - Treat the strangeness sector differently from the light (u,d) quark sector
  - Repulsive interaction for KN (S=+1 channel)
  - Recent works: Itzhaki et al. (2004)
  - Park, Rho, Min (2004): consider the system of soliton, K, K*
    - test the formation of Θ(1540) vs a (KSRF parameter, $M_V^2 = a\, g^2 F_\pi^2$)
    - possible resonance at a~1 (a~2 in the real world)

Models for pentaquarks

- Heavy pentaquarks
  - Quark models: Lipkin (PLB 195, 1987), Gignoux et al. (PLB 193,1987)
    - Pentaquarks with anti-charm and strange quark may be bound
    - Fleck et al., Stancu etc: more sophisticated quark model

- Heavy pentaquarks in Skyrme model
  - Riska-Scoccola (PLB 299, 1993)
    - apply the Callan-Klebanov model to anti-charmed pentaquark
    - Bottom-up approach (chiral Lagrangian + symmetry breaking)
    - Bound states of soliton-Φ where Φ means heavy pseudoscalar meson (like D, B)
    - Bound nonstrange heavy pentaquarks (mass smaller than DN threshold)
    - Does not show heavy quark symmetry in a transparent way

Models for pentaquarks

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- Heavy quark symmetry
  - $J = S_Q + S_L$, $S_L = S_q + L$
    hadron with $J = S_L$ +/– ½
    should be degenerate in infinite heavy quark mass limit
  - In mesons, pseudoscalar (Φ) and vector (Φ^*) mesons (δM = 400   140   45 in MeV)
  - In baryons, Σ_Q and Σ_Q^* (δM = 190   65   ? in MeV)

S_Q: heavy quark spin
S_q: light quark spin
L: orbital ang. mom.

- Soliton-meson bound state model for heavy (exotic) baryons
  Oh, Park, Min (PLB 331, 1994; PRD 50, 1994)
  - Start from the infinite mass limit   (top-down approach)
  - Treat the heavy pseudoscalar and heavy vector mesons on equal footing

by introducing $H = \frac{1 - v\gamma}{2}\left(\Phi\gamma_5 - \Phi^*_\mu \gamma^\mu\right)$

v = four - velocity of H

$$\mathcal{L} = \mathcal{L}_M - i v_\mu \,\mathrm{Tr}\left[H\left(\partial^\mu - V^\mu\right)\bar{H}\right] + g\,\mathrm{Tr}\left(H\gamma^\mu\gamma_5 A_\mu \bar{H}\right) + ...$$

V, A : vector and axial - vector chiral field

g :   universal coupling constant $(D^* \to D\pi)$

Heavy-qaurk symmetric
& chirally invariant

Models for pentaquarks

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Lowest heavy pentaquark ($\bar{Q}qqqq$) states
in the infinite heavy quark mass limit

Table 3

i	j_ℓ^π	j^π	Mass Formula	$m_{P_{\bar{c}}}$	$m_{P_{\bar{b}}}$	b.e.*
0	0^-	$\frac{1}{2}^-$	$M_{sol} + \overline{m}_\Phi - \frac{1}{2}gF'(0) + 3/8\mathcal{I}$	2704	6042	210
0	1^-	$\frac{1}{2}^-, \frac{3}{2}^-$	$M_{sol} + \overline{m}_\Phi - \frac{1}{2}gF'(0) + 3/8\mathcal{I}$	2704	6042	210
1	1^-	$\frac{1}{2}^-, \frac{3}{2}^-$	$M_{sol} + \overline{m}_\Phi - \frac{1}{2}gF'(0) + 7/8\mathcal{I}$	2802	6140	112
0	1^+	$\frac{1}{2}^+, \frac{3}{2}^+$	$M_{sol} + \overline{m}_\Phi - \frac{1}{2}gF'(0) + 3/8\mathcal{I}$	2704	6042	210
1	0^+	$\frac{1}{2}^+$	$M_{sol} + \overline{m}_\Phi - \frac{1}{2}gF'(0) + 7/8\mathcal{I}$	2802	6140	112
1	1^+	$\frac{1}{2}^+, \frac{3}{2}^+$	$M_{sol} + \overline{m}_\Phi - \frac{1}{2}gF'(0) + 7/8\mathcal{I}$	2802	6140	112

* binding energy below the nucleon-heavy meson threshold.

Shows heavy quark symmetry

Oh, Park, Min (PLB 331, 1994; PRD 50, 1994)

Lesson: do not integrate out heavy vector meson degrees of freedom in the heavy quark sector in favor of heavy pseudoscalar mesons

Models for pentaquarks

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- Two expansion parameters
  - $1/N_c$: soliton
  - $1/m_Q$: heavy quark mass
- $1/N_c$ only. $M_{sol} = O(N_c)$, $m_Q = O(N_c^0)$
  - We may estimate 1/m corrections in the soliton-fixed frame. (Oh, Park, PRD 51, 1995)

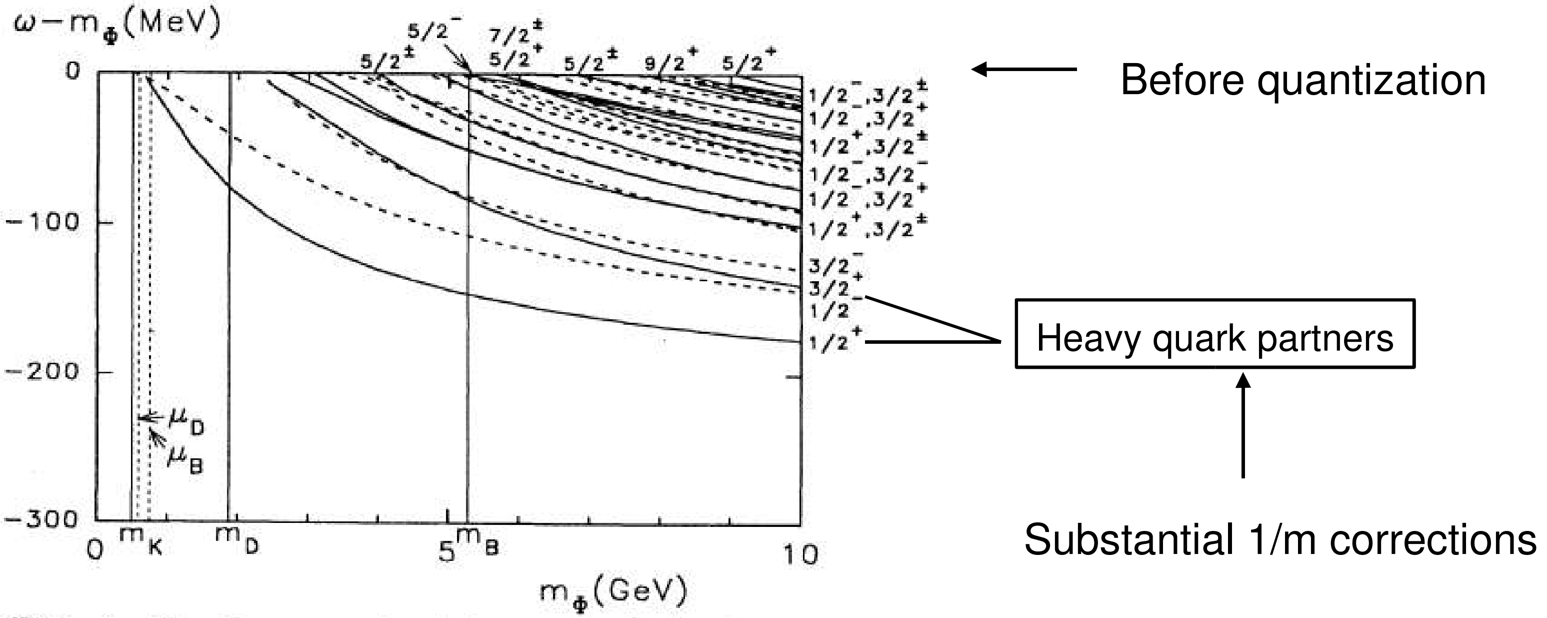


FIG. 6. Binding energies $|\omega| - m_\Phi$ of the bound states as functions of the antiflavored heavy-meson mass. Solid (dashed) lines denote the positive (negative) parity states.

Models for pentaquarks

- In nature, $m_Q >> M_{sol}$
  - Spectrum for the heavy-meson—soliton system in the heavy-meson fixed frame (Oh. Park. ZPA 359. 1997)

Table 2. Numerical results on the bound states. Energies are given in MeV unit

(n, k_ℓ^π)	Set I	Set II	Set III	Set IV	Exp.
$(0, 0^+)$	−287	−461	−366	−588	−610
$(1, 0^+)$	−12	−62	−15	−79	–
$(0, 1^-)$	−89	−196	−113	−250	−320
$(0, 1^+)$[a]	−17	−54	−21	−69	–

[a] Bound state of soliton to antiflavored heavy meson

← $\Lambda_c(1/2+)$

← $\Lambda_c(1/2–)$ and $\Lambda_c(3/2–)$

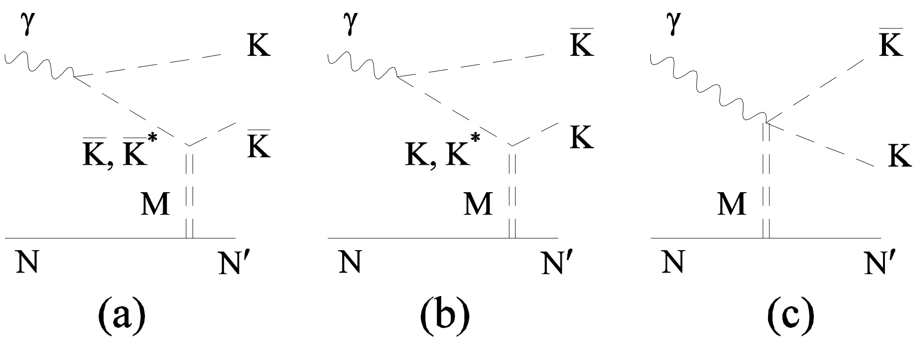
← $\Theta_c(1/2+)$

Only one bound state for (nonstrange) heavy pentaquark states

pentaquark states depend on the details of the model

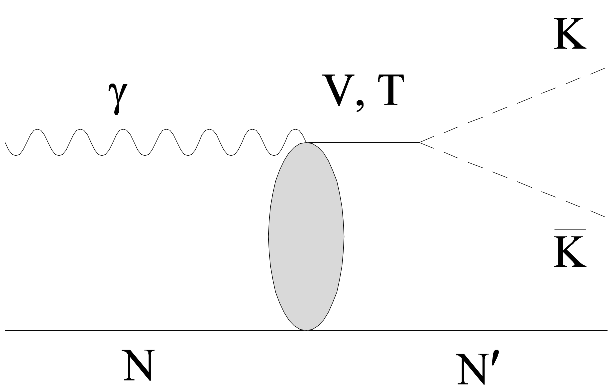
Model for double kaon photoproduction: Diagrams (I)

(1) Kaon background diagrams



M: mesons

(2) Vector meson & tensor meson productions

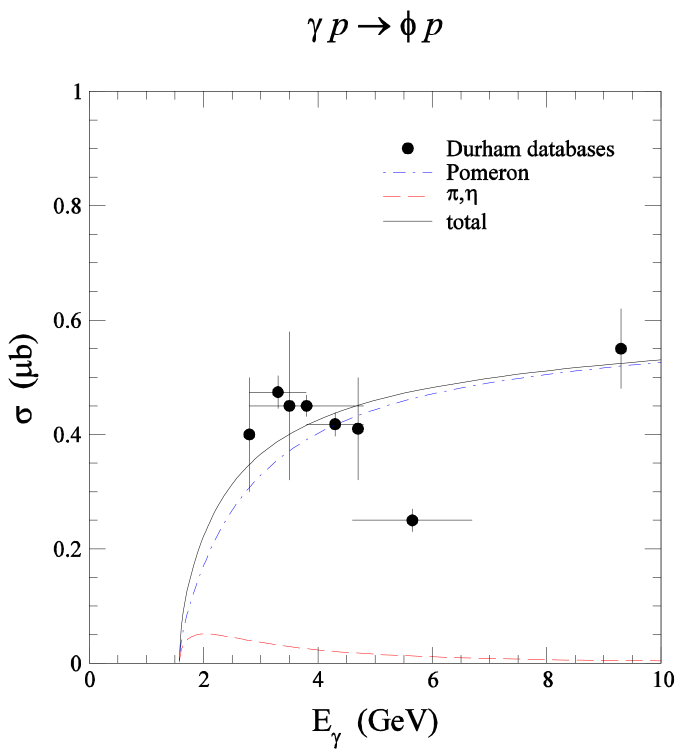


V = ρ, ω, ϕ

T = $a_2(1320)$, $f_2(1275)$

Vector meson production

- ρ, ω, and ϕ mesons
- Considered diagrams include
  - Pomeron exchange
  - Pseudoscalar meson exchange
  - f_2 meson exchange
  - Nucleon diagrams
  - All parameters are fixed by the experimental data for vector meson photoproduction.



ϕ meson photoproduction

Tensor meson production

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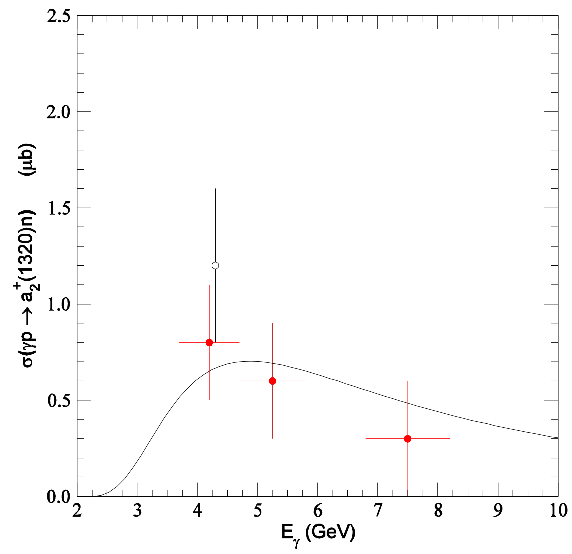
- Tensor meson photoproductions
  - a_2^+ and a_2^- productions: pion exchange is the dominant process.
    - consistent with the data.
  - a_2^0 and f_2 productions: pion exchange is not allowed by C-parity
    $C(a_2) = C(\pi^0) = +1$, $C(\rho^0) = -1$
    vector meson exchange is expected to be the dominant mechanism at low energies.

    Odderon exchange at high energies(?)

    - expt. data: very limited and very uncertain

    (cf. Dzierba et al. used one-pion-exchange for neutral tensor meson photoproductions.)

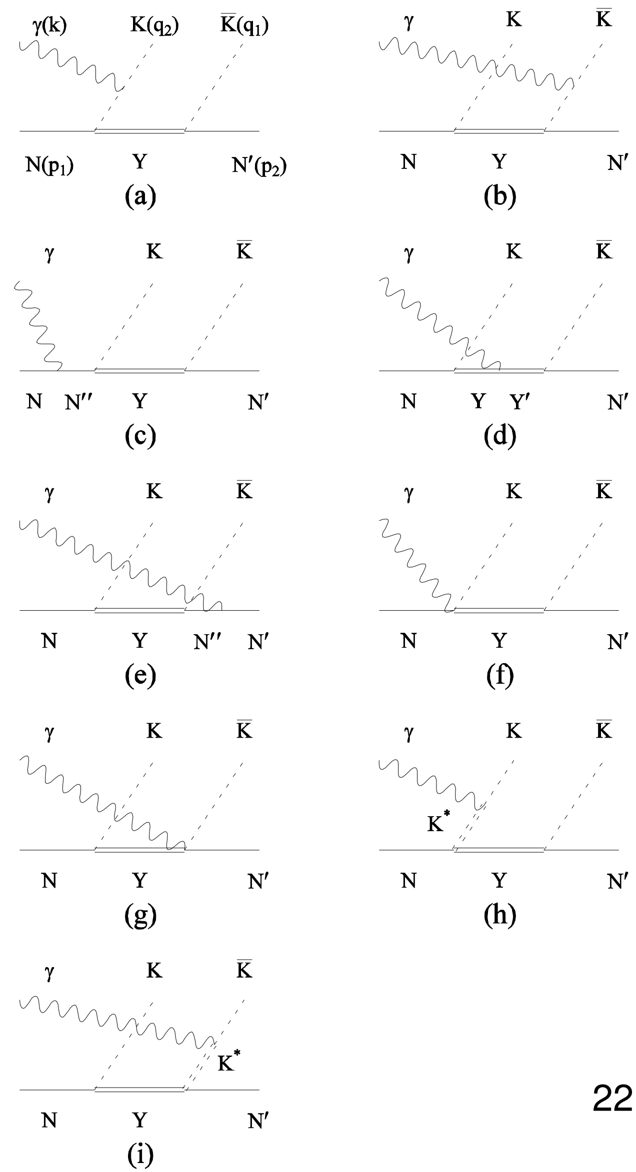


$\gamma p \; a_2^+(1320)n$

Diagrams (II)

(3) Intermediate S=-1 hyperons

- Λ baryons
  $\Lambda(1116)$, $\Lambda(1405)$, $\Lambda(1520)$
- Σ baryons
  $\Sigma(1193)$, $\Sigma(1385)$
- photo-transitions such as
  $N\Delta$ and YY' (such as $\Lambda\Sigma$, $\Sigma\Sigma^*$, $\Lambda\Lambda^*$, etc)
- couplings
  - exp. information is used if available.
  - otherwise, quark model and SU(3) relations are used



Diagrams (III)

(4) Intermediate Θ

mass: 1540 MeV, width: 1 MeV

for positive parity,

$$g_{K^*N\Theta} = \sqrt{3}\, g_{KN\Theta}$$

for negative parity,

$$g_{K^*N\Theta} = 1/\sqrt{3}\, g_{KN\Theta}$$

Isospin = 0 (antidecuplet)

Θ can be formed in $\gamma n \to K^+ K^- n$

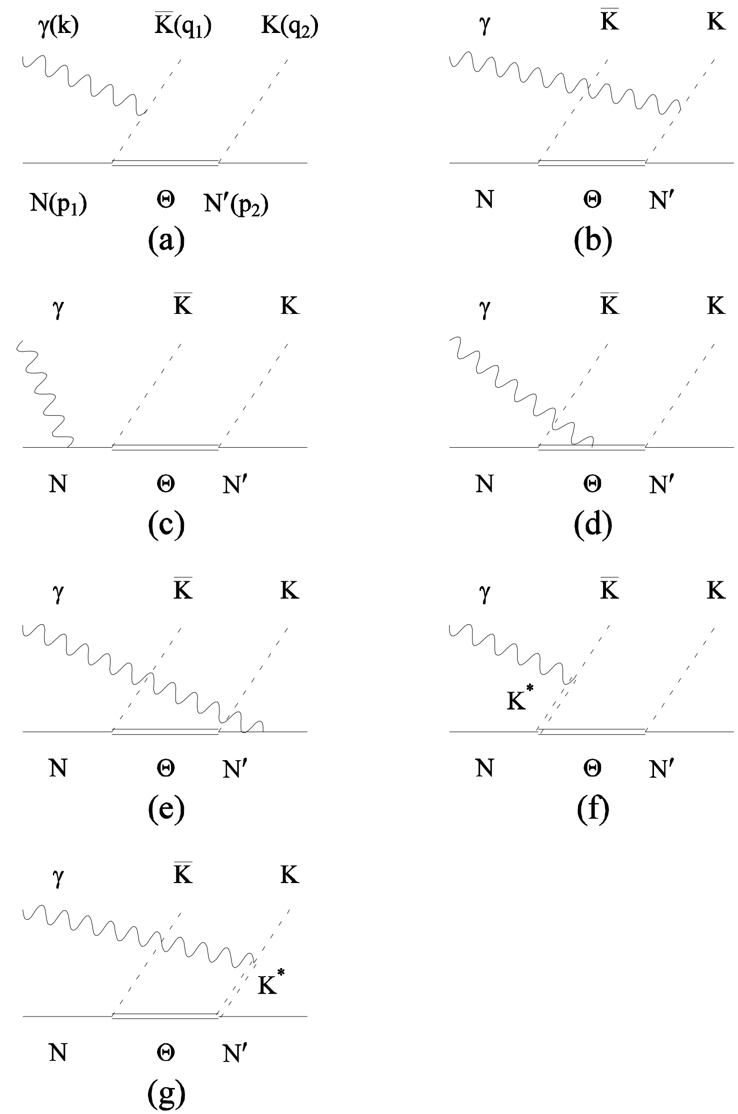
and $\gamma p \to K^0 \bar{K}^0 p$

(5) Form factors

charge conservation ($q ? J = 0$) is restored by adding contact terms.

In effect, e.g.,

$$F_1, F_2 \;?\; 1-(1-F_1)(1-F_2)$$



Θ(1540) production

- $\gamma N \to \Theta K$: studied by various groups
- SU(3) symmetric interactions of pentaquarks (Oh, Kim, PRD 70, 2004)
- Total and differential cross sections (Oh, Kim, Lee, PRD 69; NPA 745, 2004)

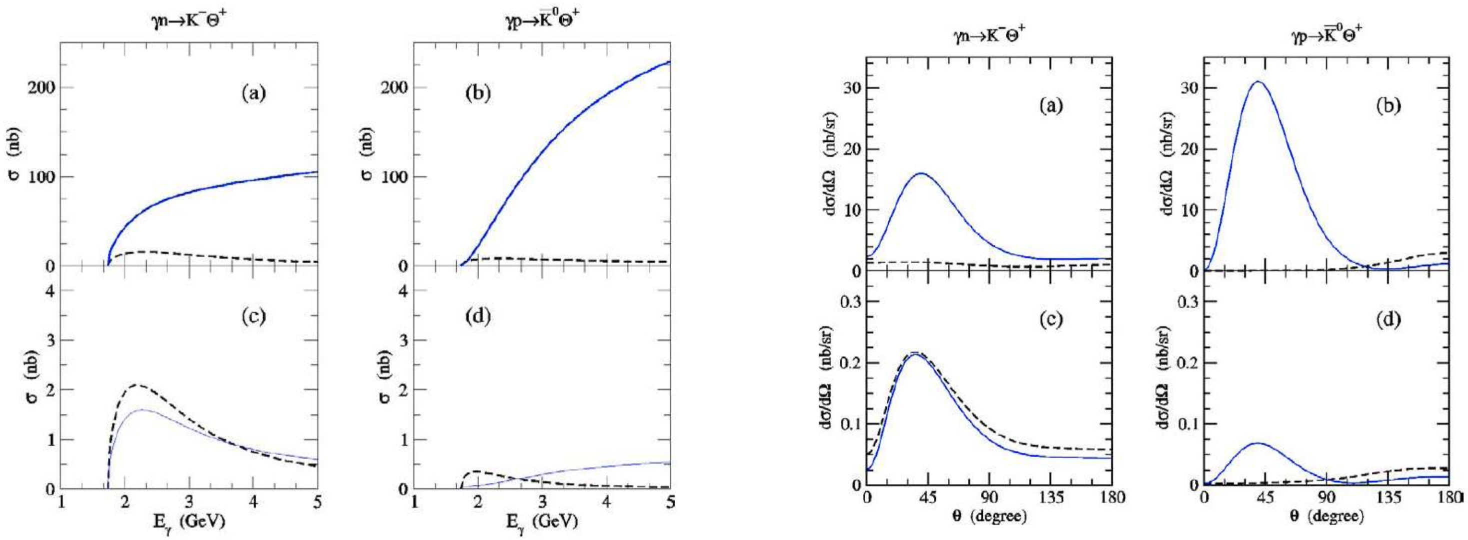


Fig. 5. Cross sections for $\gamma + N \to \bar{K} + \Theta^+$. Total cross sections (upper panel) and differential cross sections at $E_\gamma = 3.0$ GeV (lower panel). (a), (c) for $\gamma + n \to K^- + \Theta^+$ and (b), (d) for $\gamma + p \to \bar{K}^0 + \Theta^+$. In (a), (b), even-parity is assumed for Θ^+, and in (c), (d), odd-parity of Θ^+ is assumed. The dashed lines are obtained with $g_{K^*N\Theta} = 0$, and the solid lines are with $g_{K^*N\Theta}/g_{KN\Theta} = \sqrt{3}\ (1/\sqrt{3})$ for positive (negative) parity Θ^+ as in Eq. (13).

3. Results

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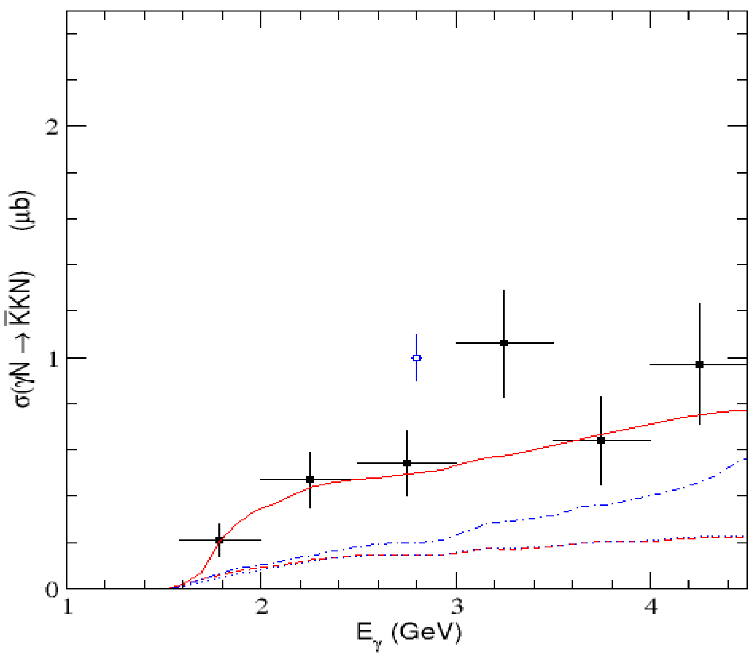
- Total cross sections of 4 processes in γ N K $\bar{K}$ N, where the isospin of the nucleon is not changed.



Form factors $$F(q^2) = \frac{\Lambda^4}{\Lambda^4 + (q^2 - M_{ex}^2)^2}$$

Fit the cutoff parameter of the form factors; Λ = 0.9 GeV

Expt. data are for γp K^+K^-p

Erbe et al., Phys. Rev. 188 (1969)
Ballam et al., Phys. Rev. D5 (1972)

red solid: $\gamma p \rightarrow K^+ K^- p$

blue dot-dashed: $\gamma n \rightarrow K^+ K^- n$

red dashed: $\gamma p \rightarrow K^0 \bar{K}^0 p$

blue dotted: $\gamma n \rightarrow K^0 \bar{K}^0 n$

Results for $\gamma N \quad K\bar{K}N$

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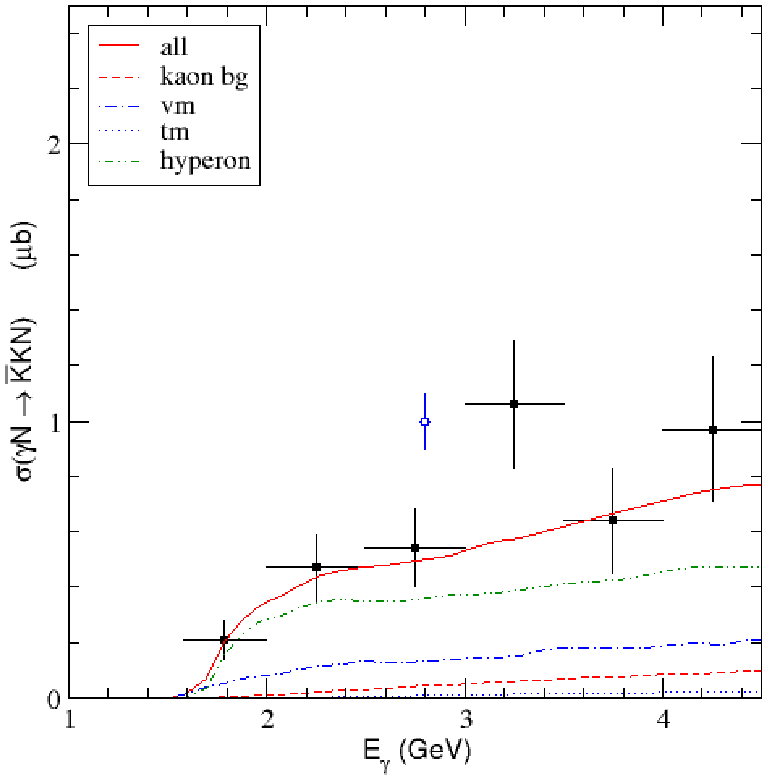
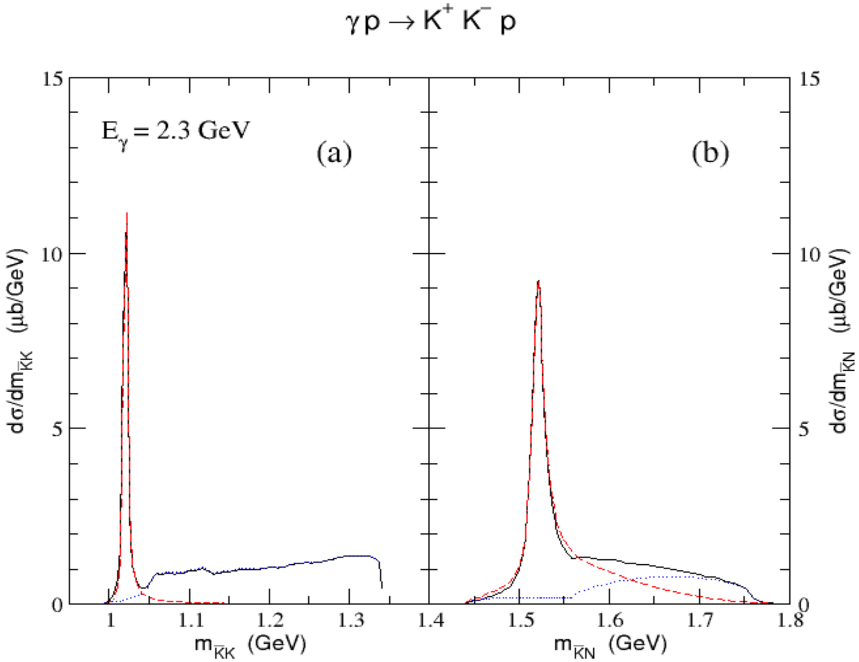
- $\gamma p \mid\!\rightarrow K^+ K^- p$

  main contribution comes from $\Lambda(1520)$ production.
  Study the properties of $\Lambda(1520)$,

  ıd Σ.



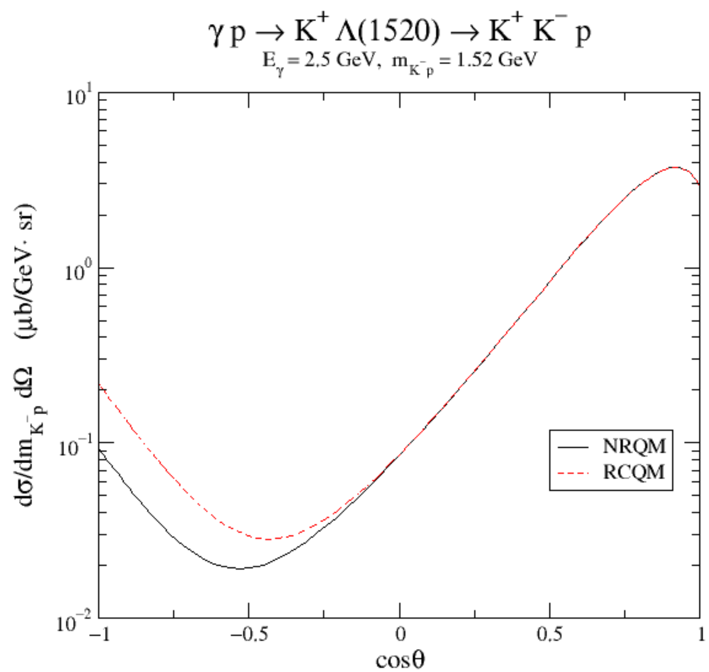
Λ(1520)



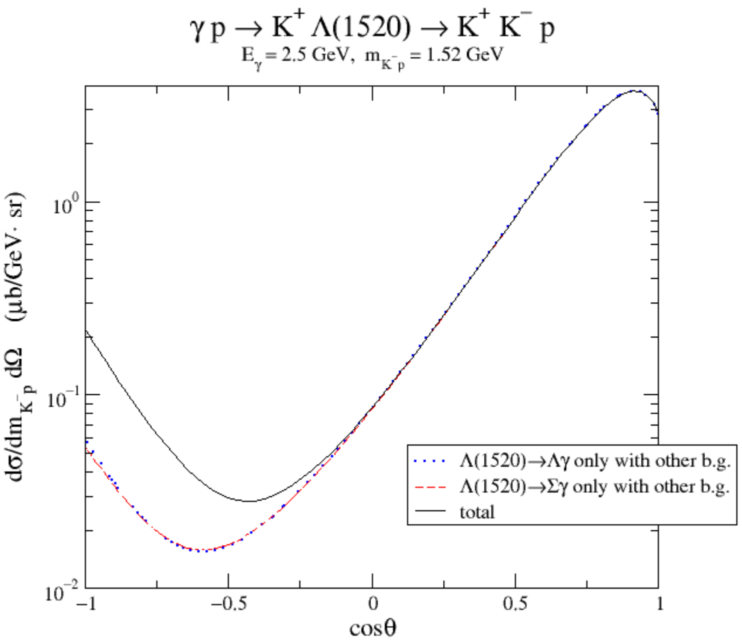
Red line: ϕ   Red line: Λ(1520)

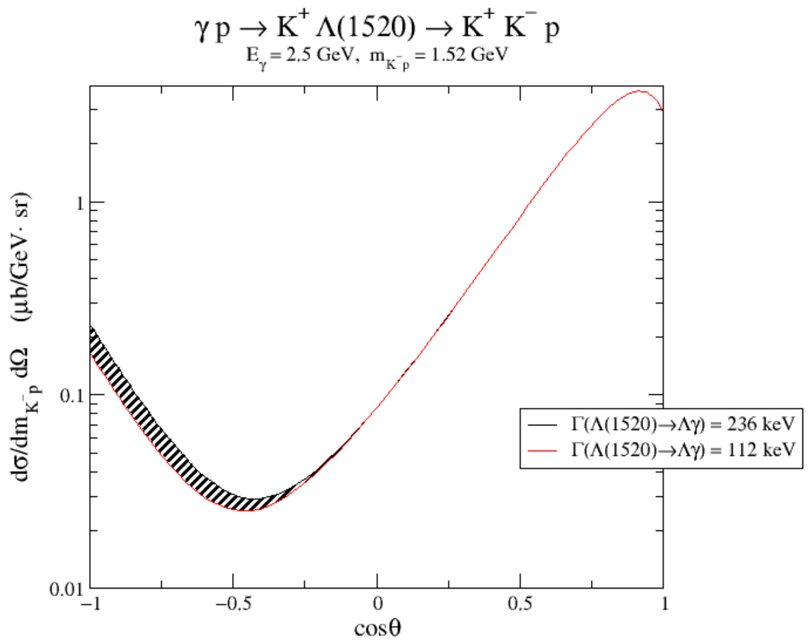
Model	Λγ	Σγ	Λ(1405)γ	Σ*γ
SU(3) broken NRQM (Kaxiras et al., PRD 32)	156	55	0.7	0.07
RCQM (Warns et al., PLB 258)	215	293		

CLAS (2005) $\Gamma(\Lambda\gamma) = 167 \pm 43^{+25}_{-12}$ keV



$\Lambda(1520)$


γ p → K⁺ Λ(1520) → K⁺ K⁻ p
Eγ = 2.5 GeV, mK⁻p = 1.52 GeV
dσ/dmK⁻p dΩ (μb/GeV· sr)
cosθ
Λ(1520)→Λγ only with other b.g.
Λ(1520)→Σγ only with other b.g.
total


γ p → K⁺ Λ(1520) → K⁺ K⁻ p
Eγ = 2.5 GeV, mK⁻p = 1.52 GeV
dσ/dmK⁻p dΩ (μb/GeV· sr)
cosθ
Γ(Λ(1520)→Λγ) = 236 keV
Γ(Λ(1520)→Λγ) = 112 keV

Other hyperons (PDG)

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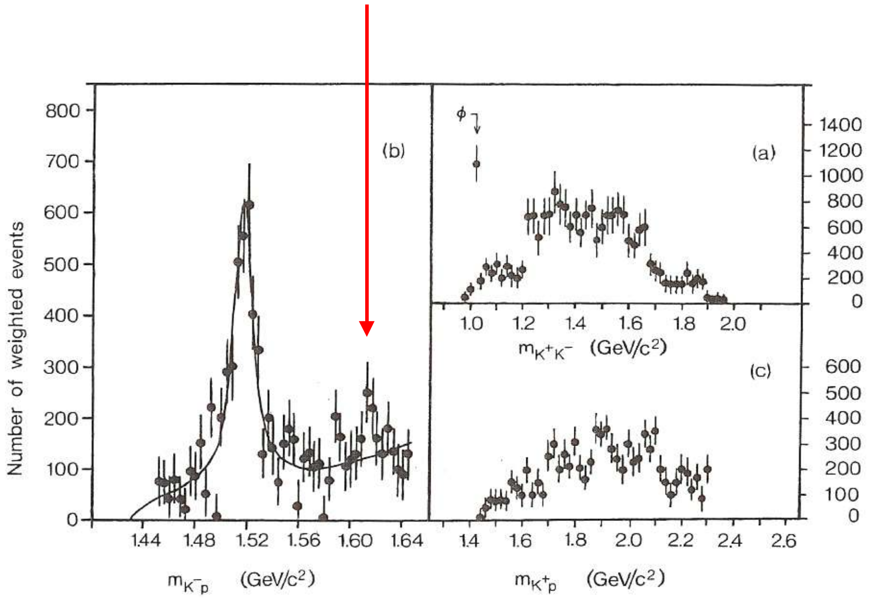
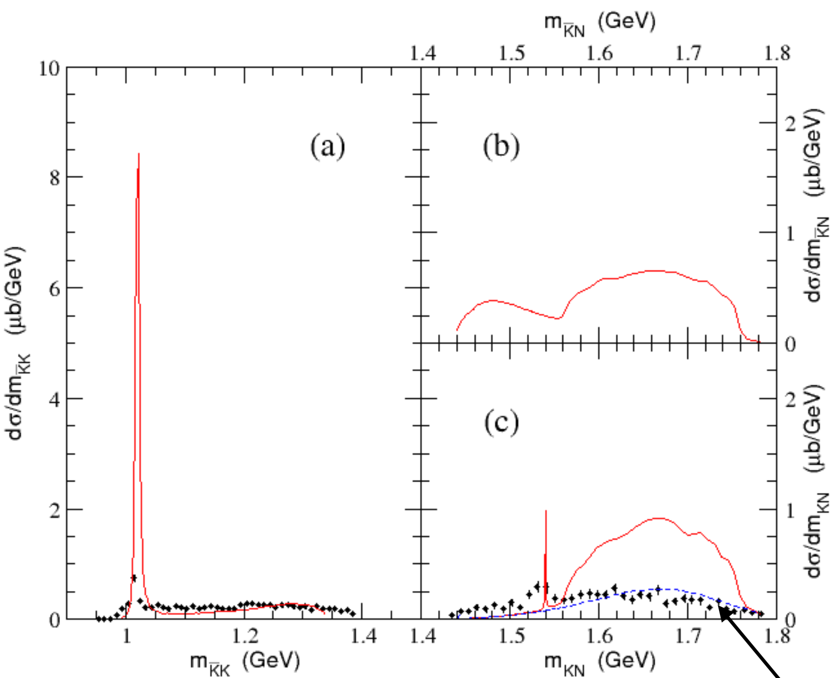
- Λ resonances Γ in MeV
  - Λ(1600) 1/2+ *** 50-250
  - Λ(1670) 1/2- **** 25-50
  - Λ(1690) 3/2- **** 50-70
  - Λ(1800) 1/2- *** 200-400
- Σ resonances
  - Σ(1560) Bumps **
  - Σ(1580) 3/2- **
  - Σ(1620) 1/2- **
  - Σ(1660) 1/2+ *** 40-200



LAMP2 Collab. Z. Phys. C 7, 17 (1980)

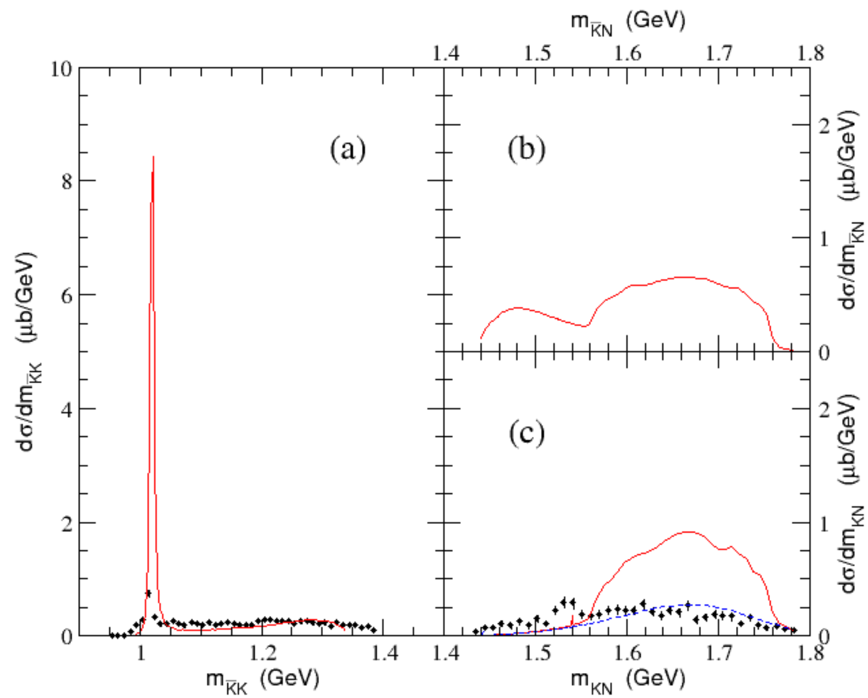
Results for $\gamma N \to K\bar{K}N$

- : reactions where Θ can be formed
- $\gamma n \to K^+ K^- n$: reaction with CLAS data (cf. data are not normalized. compare the shape only)



positive parity Θ

without φ and Θ



negative parity Θ

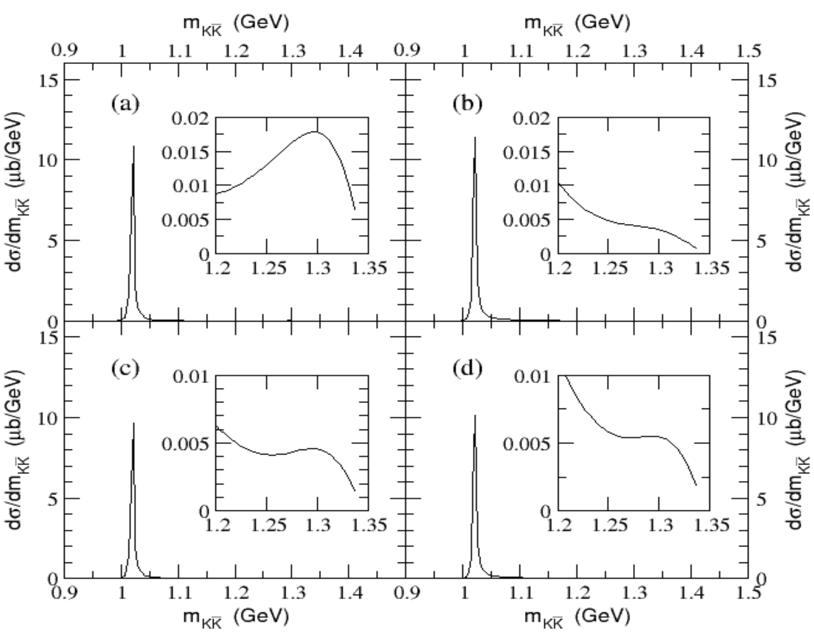
E_γ = 2.3 GeV

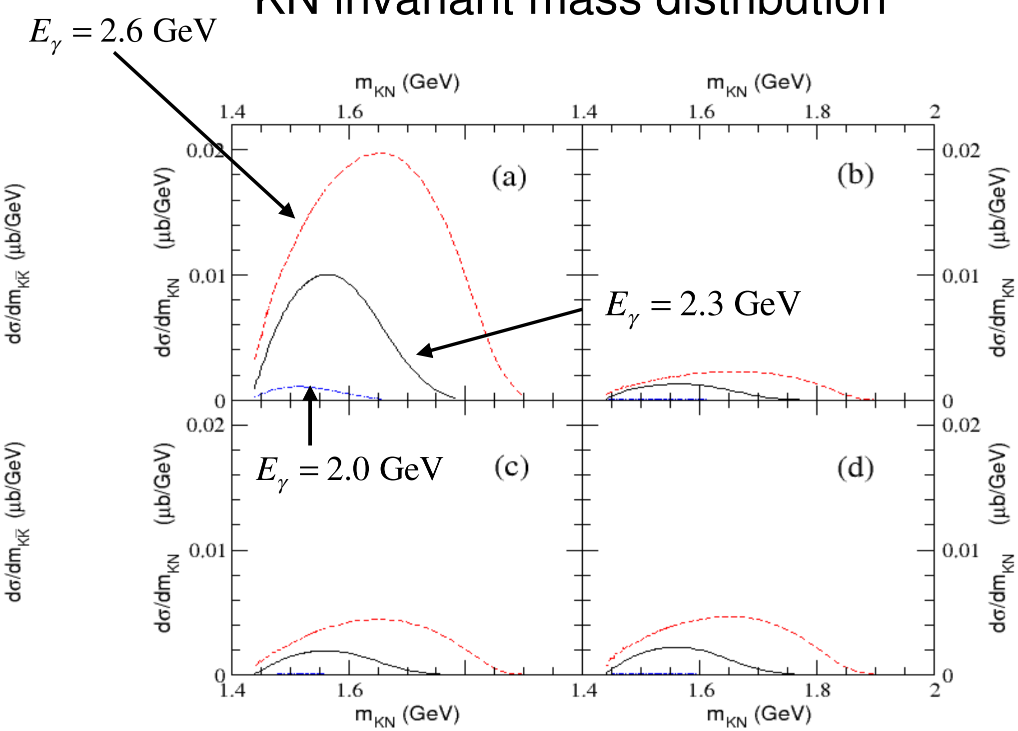
Results for $\gamma N \quad K\bar{K}N$

Vector & tensor meson contributions

$\bar{K}K$ invariant mass distribution
at E_γ = 2.3 GeV

KN invariant mass distribution





vector & tensor mesons only

tensor mesons only

Differential cross sections for γn K^+K^-n

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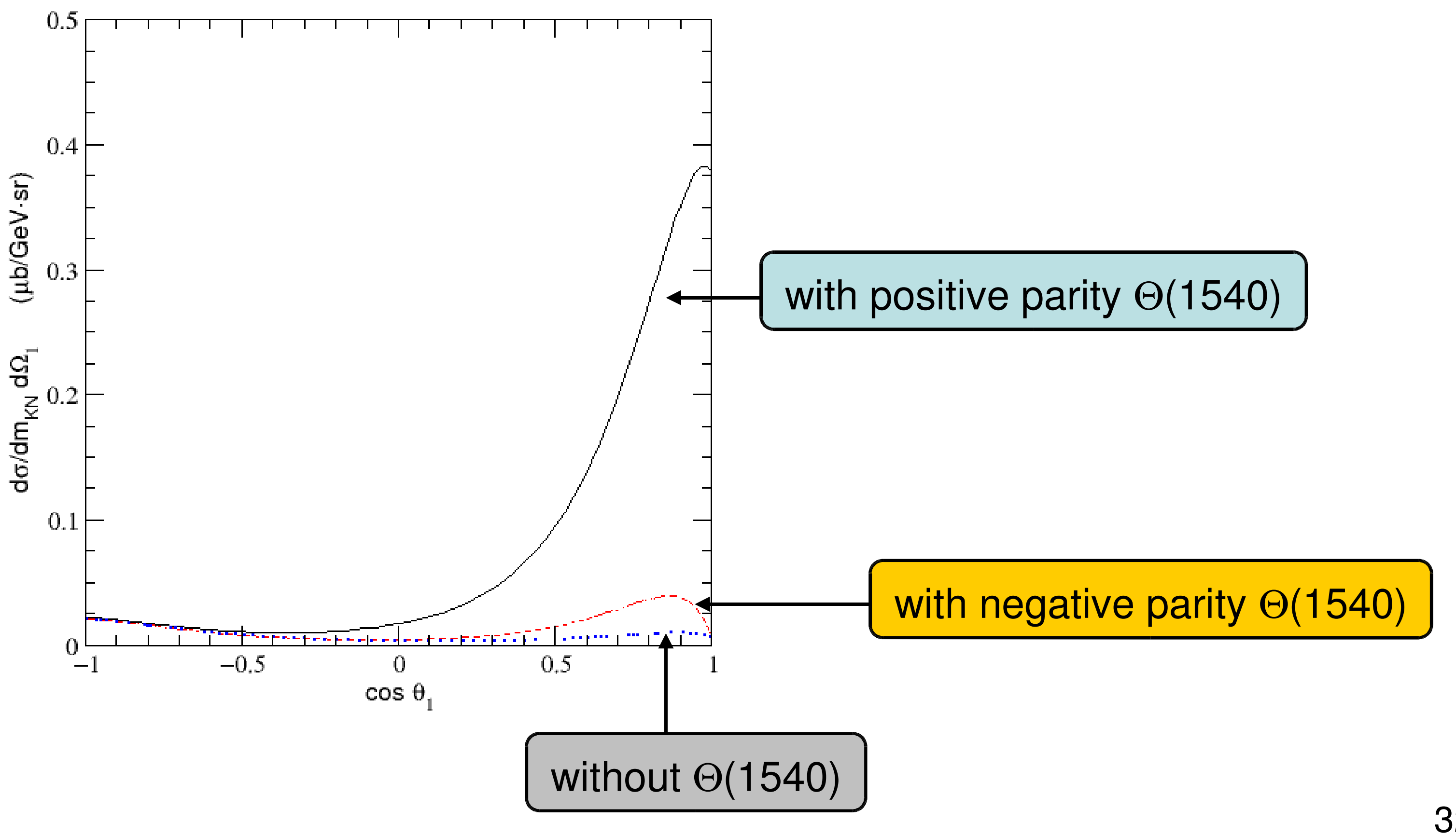
Differential cross section at E_γ=2.3 GeV and M_{KN}=1.54 GeV as a function of the angle of K^- in the CM frame



Spin asymmetries for γn K^+K^-n

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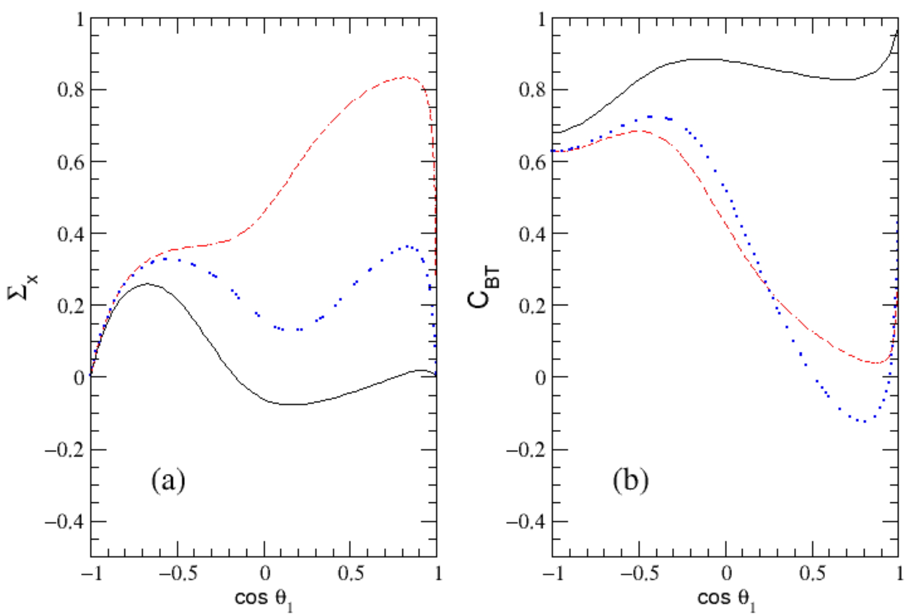
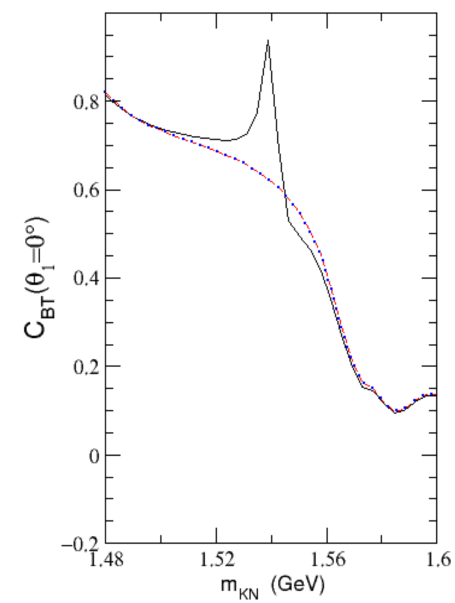
Single photon beam asymmetry Σ_x and beam-target double asymmetry C_{BT}

blue lines: without $\Theta(1540)$
black lines: with positive parity $\Theta(1540)$
red lines: with negative parity $\Theta(1540)$

At E_γ = 2.3 GeV and M_{KN} = 1.54 GeV



At E_γ = 2.3 GeV for a given angle



4. Summary

- We studied $\gamma N \rightarrow K\bar{K}N$ reactions in a model including kaon backgrounds, vector and tensor meson productions, intermediate hyperon states for studying the production and the parity of $\Theta(1540)$.
- Form factor parameters are fitted to the total cross section data for $\gamma p \rightarrow K^+K^-p$.
- Dominant contributions come from $\Lambda(1520)$ and $\phi(1020)$.
- Tensor meson part is small in the considered kinematic region.
- It is difficult to make a conclusion about the peak observed in experiments.
- Spin asymmetries would be useful to study the formation (and the parity) of $\Theta(1540)$: however, model-dependence is unavoidable.
- More precise and accurate experimental data are required. (JLab, Spring-8, etc)