European Centre for Theoretical Studies in Nuclear Physics and Related Areas

Pentaquark states: structure and properties

February 10 - 12 2004

Spectroscopy of Exotic Baryons with CLAS: Search for Ground and First Excited States

- **Theoretical motivations**
- **CLAS@JLab**
- $\gamma\ p \to\ \Theta^+ \bar{K}^0 \to \pi^+ \pi^-\ K^+ (n)$ (preliminary)
- **Planned experiment**

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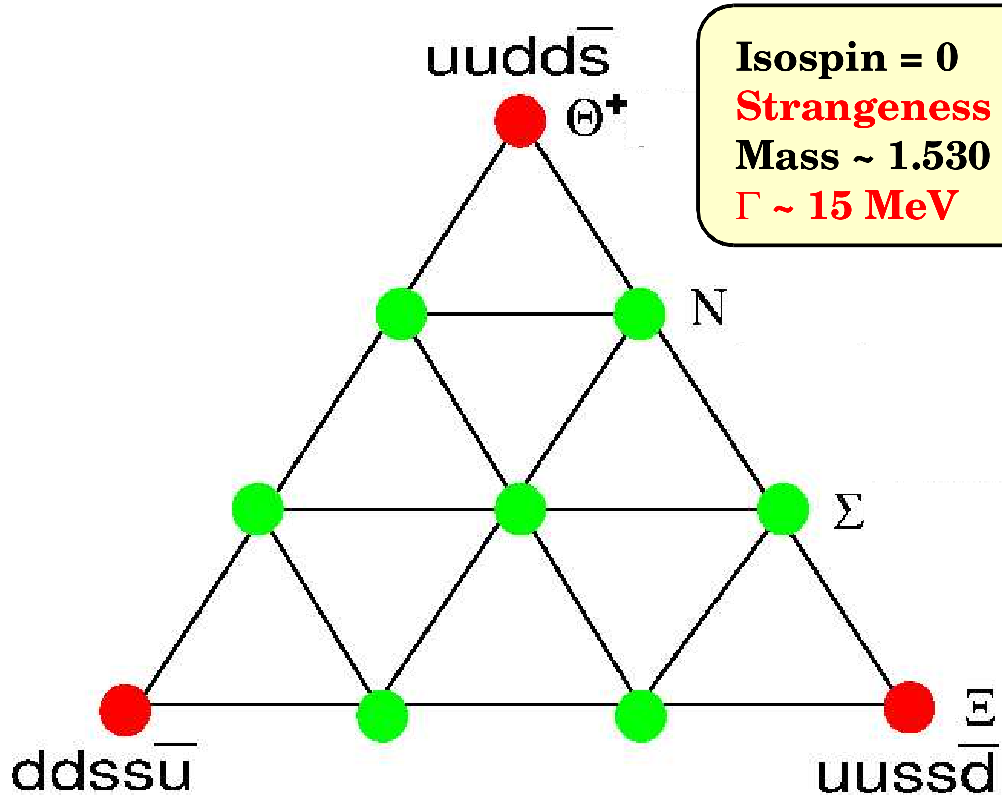
Physics motivation

- QCD DOES NOT forbid pentaquark states
- Theoretical and experimental activity started several decades ago
- Interested renewed by *Diakonov et al.* Soliton Model predictions

$[\overline{10}]$ Spin = ½ NEW MULTIPLET

D.Diakonov et al. Z. Phys A359, 1997, 305



Isospin = 0
Strangeness = +1
Mass ~ 1.530 MeV
Γ ~ 15 MeV

5-quark states are also predicted in many other theoretical models

- Skyrme model
- MIT bag model
- CQM
- Lattice QCD
- Clustered CQM
- QCD Sum rules

Pentaquark searches in 2003

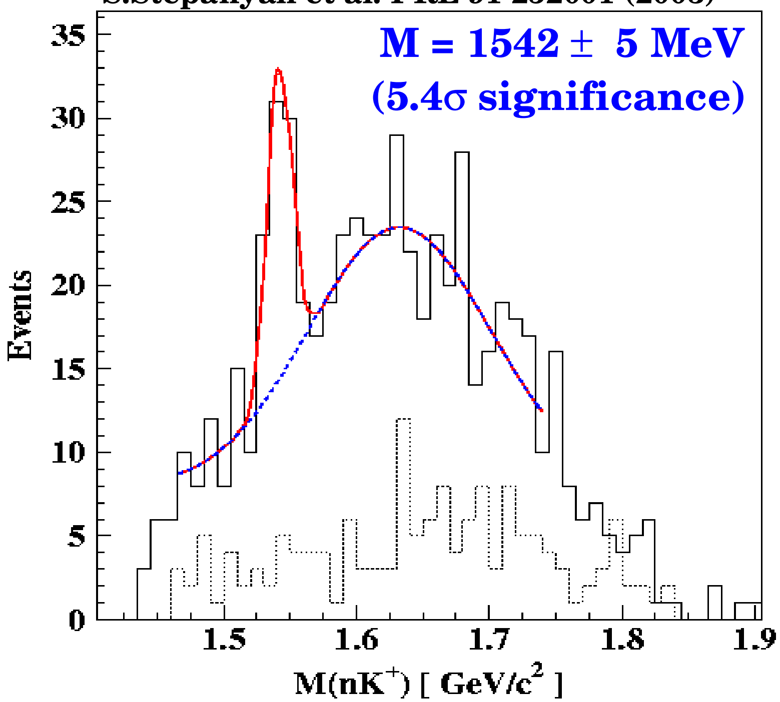
- First evidence for the Θ^+ was found by the LEPS/Spring-8 Collaboration
- Results confirmed by several experiments using different probes and nuclear targets (DIANA, CLAS, CERN/FNAL, HERMES) with statistical significance of 4-6σ
- Signal seen on proton target by SAPHIR and ZEUS

CLAS results

Photon beam on deuterium

$$\gamma\ d \to \Theta^+\ K^-\ p_s$$

S.Stepanyan et al. PRL 91 252001 (2003)



Photon beam on proton

High energy ($3.0 < E_\gamma < 5.4$ GeV)

$$\gamma\ p \to \Theta^+ \pi^+ K^- \to \pi^+ K^-\ K^+ (n)$$

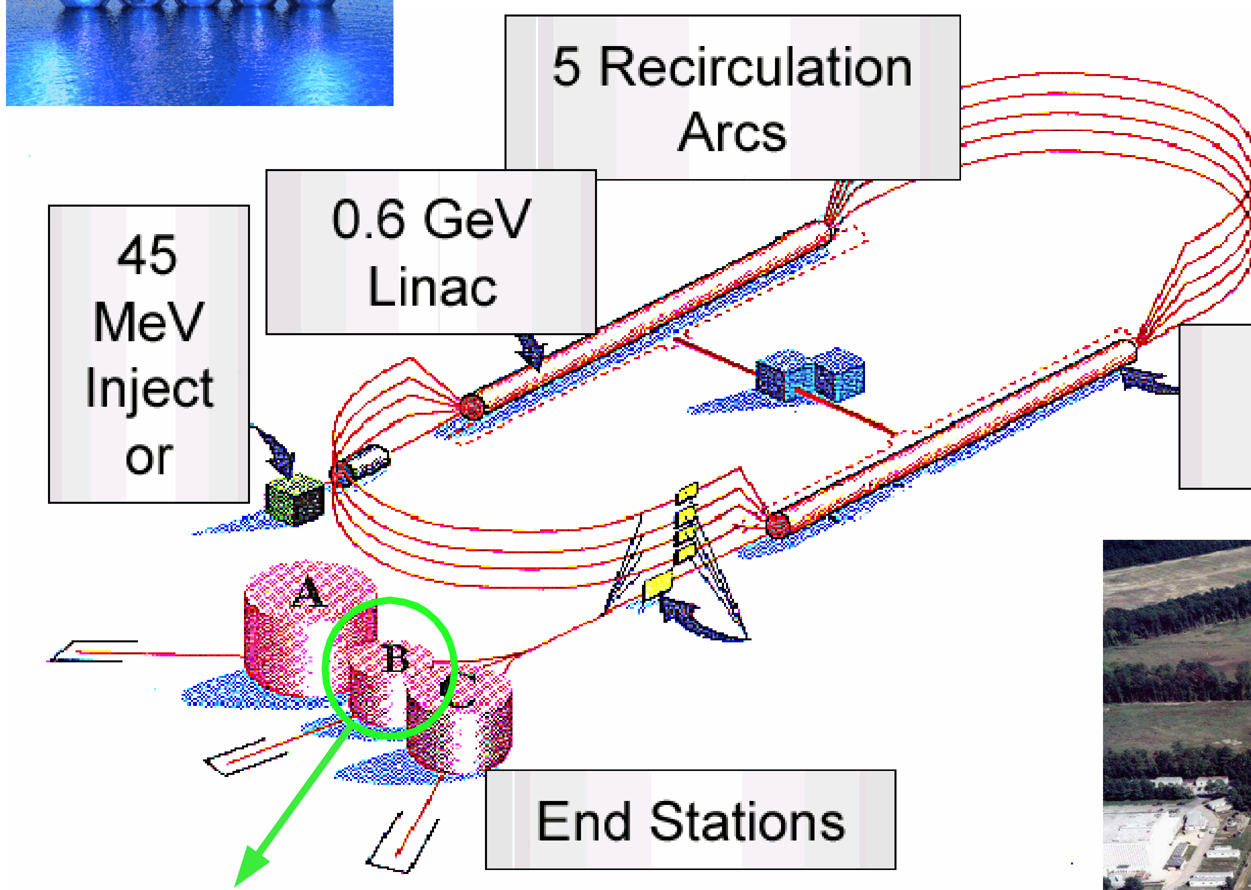
(pubblished)

Low energy ($1.6 < E_\gamma < 3.0$ GeV)

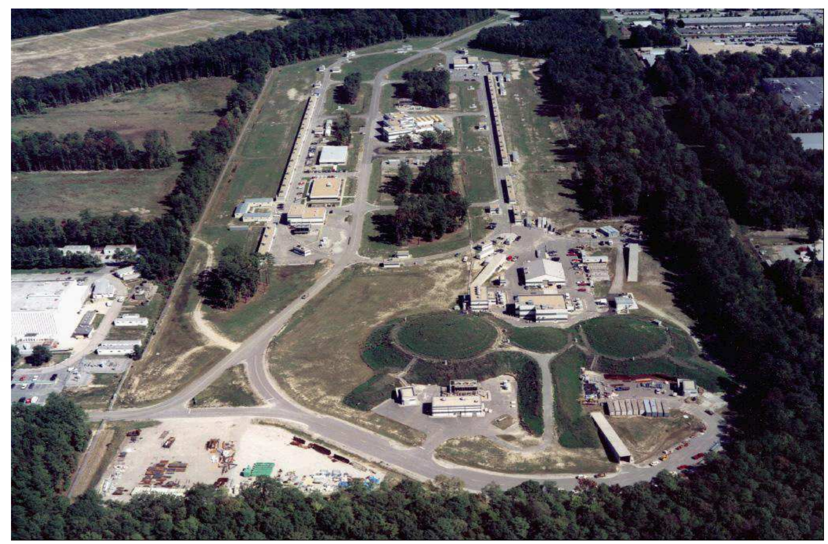
$$\gamma\ p \to \Theta^+ \bar{K}^0 \to \pi^+ \pi^-\ K^+ (n)$$

The Continuous Electron Beam Accelerator Facility
CEBAF @ Jefferson Laboratory

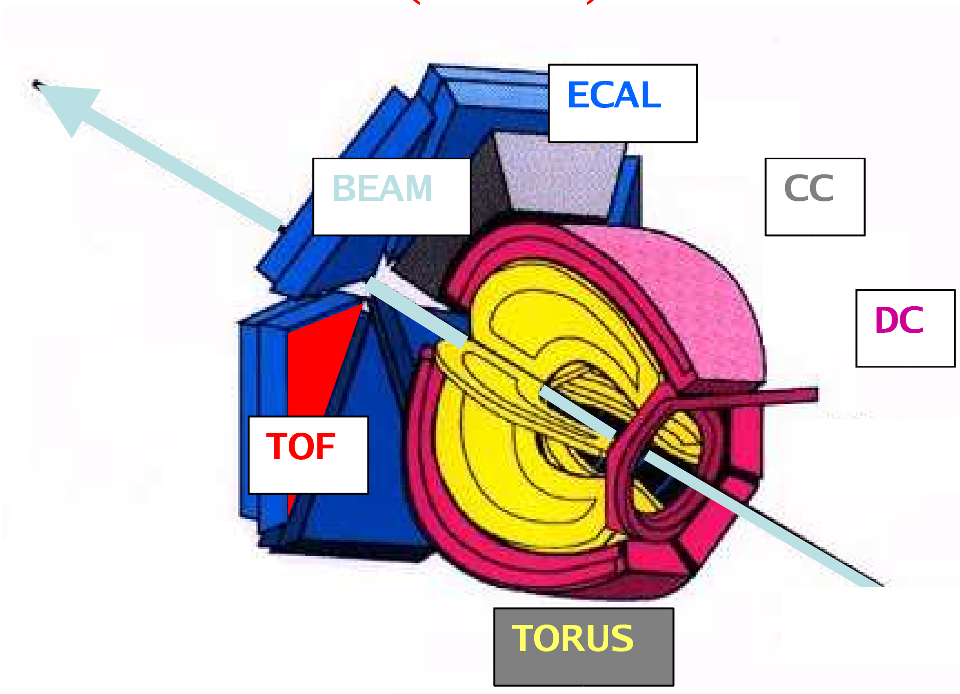
E_{max}	~ 6 GeV
I_{max}	~ 200 mA
Duty Factor	~ 100%
σ_E/E	~ 2.5 10^{-5}
Beam $\mathcal{P}$	~ 80%
E_γ(Bremsstrahlung)	~ 0.8- 5.5 GeV

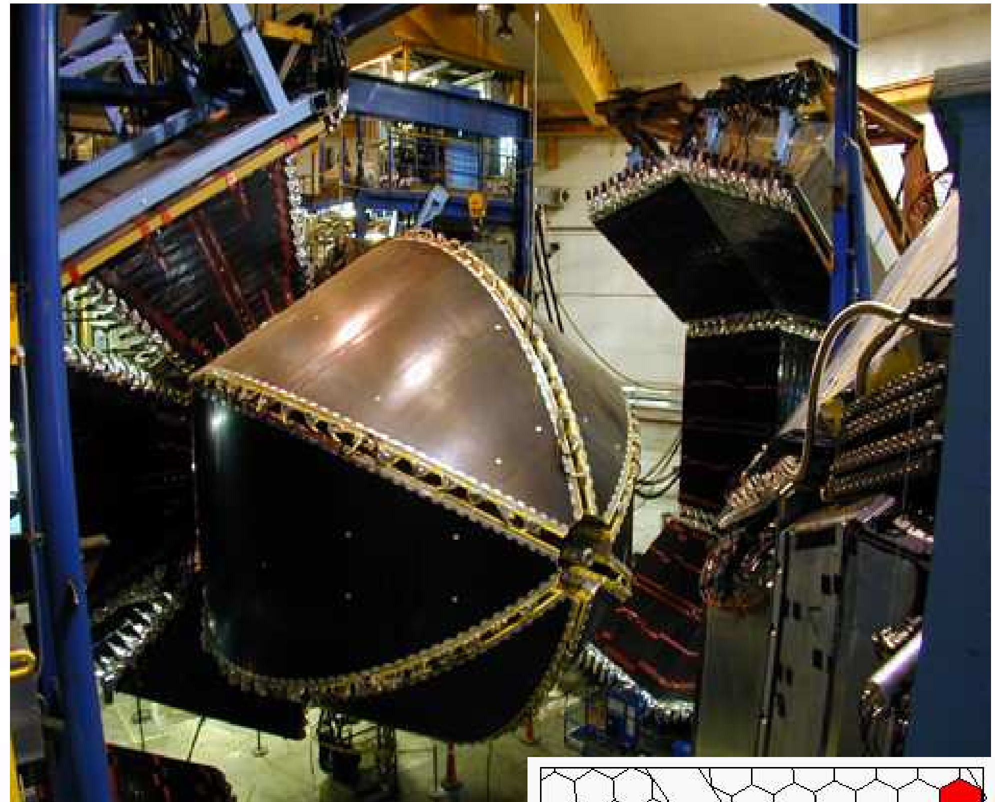


Hall B with CLAS detector



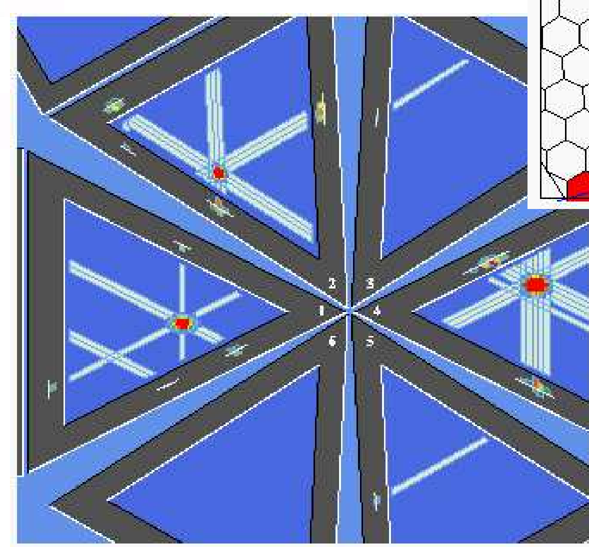
The CEBAF Large Acceptance Spectrometer (CLAS)

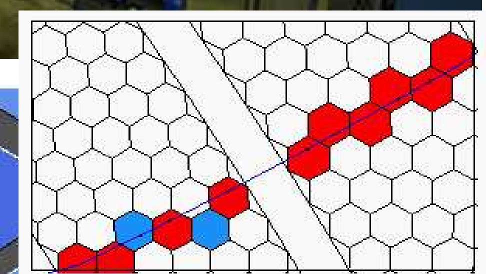




Performance

- 6 independent sectors
- ~ 4π acceptance
- $L = 10^{34}\ cm^{-2}\ s^{-1}$
- $\int B\,dl = 2.5$ T m
- $\Delta p/p \sim 1\ \%$

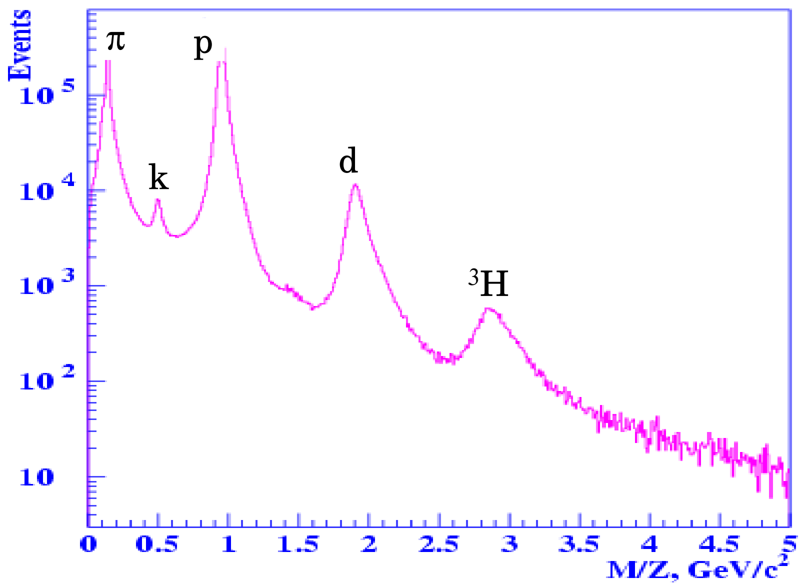


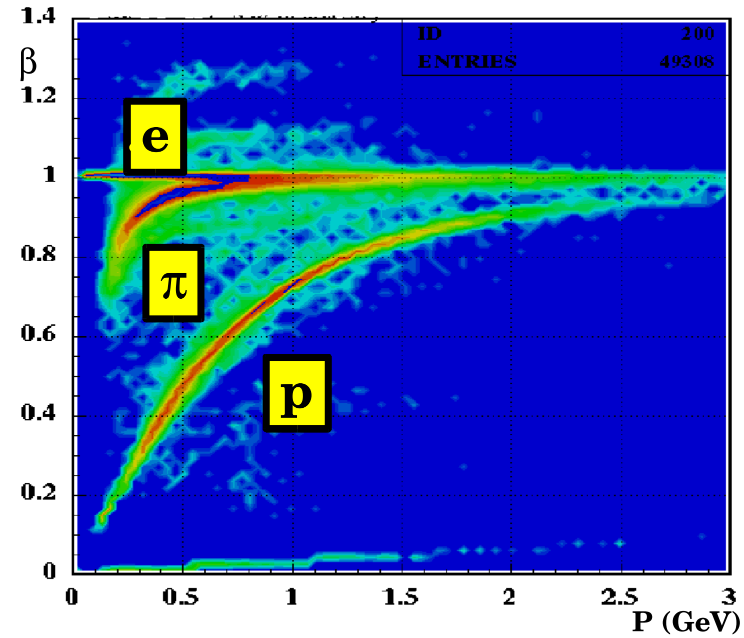


Best suited for multihadron final states (p, π, K)

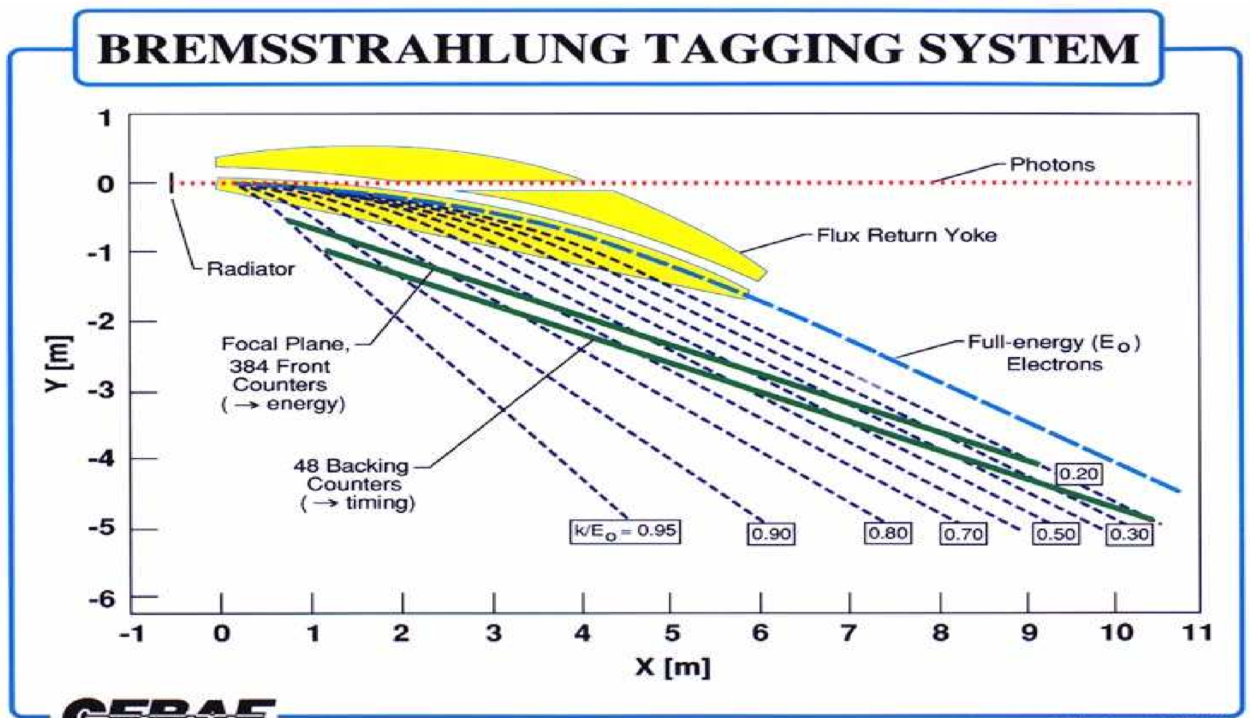
The Jefferson Lab and the CLAS detector

Hadron detection efficiency and kinematic coverage





Photons @ JLAB

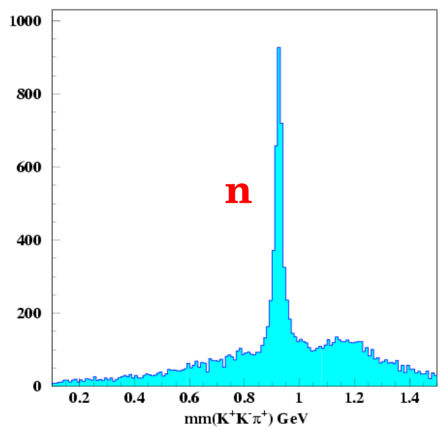


CLAS measurements

$\gamma\ p \rightarrow\ \Theta^+ K^-\ \pi^+$

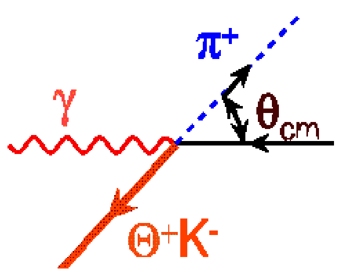
- **Decay mode: $\Theta^+ \rightarrow K^+ n$**
  Final state: $K^+ K^- \pi^+$ (n)

- **High energy photons**
  3.0 - 5.4 GeV



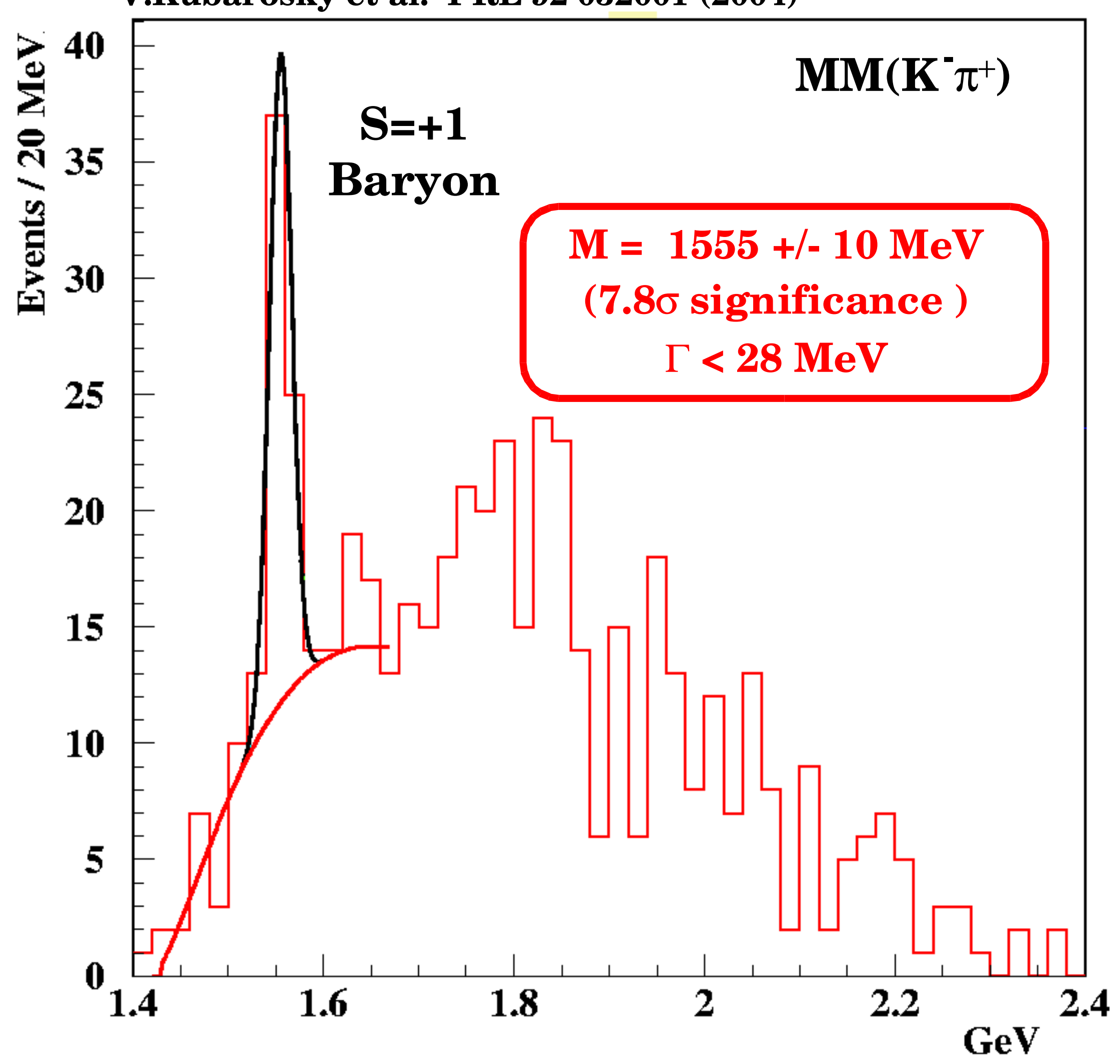
- **Neutron as a 'missing particle'**

- **Angular cuts to reduce meson production:**
  $\cos\vartheta_{CM}^{(\pi+)} > 0.8$
  $\cos\vartheta_{CM}^{(K+)} < 0.6$



- **Signal shows up as a peak in the ($K^- \pi^+$) missing mass**

V.Kubarosky et al. PRL 92 032001 (2004)



Data analysis

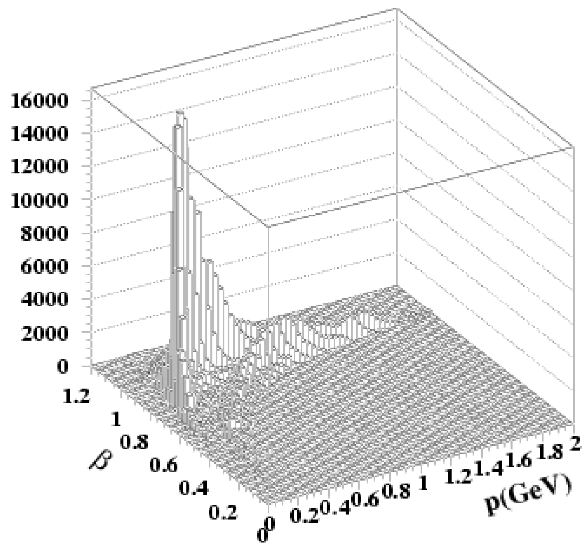
- Hydrogen target
- Photon energy: 1.6 - 3.0 GeV

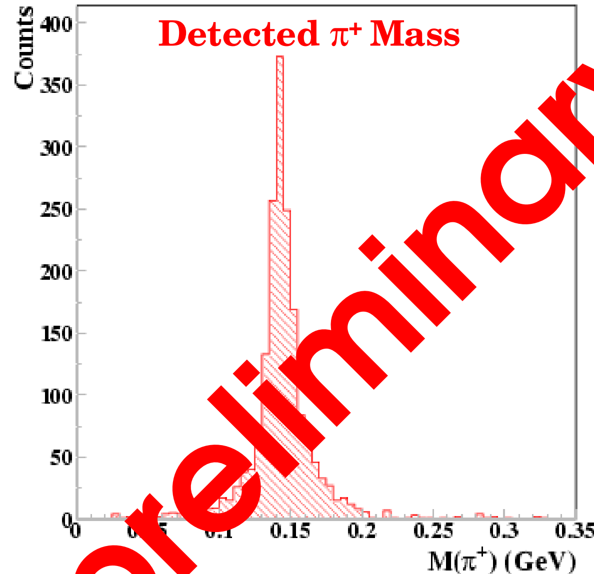
$$\gamma\ p \rightarrow \Theta^+ K^0 \rightarrow K^+\, n\, \pi^+\, \pi^-$$

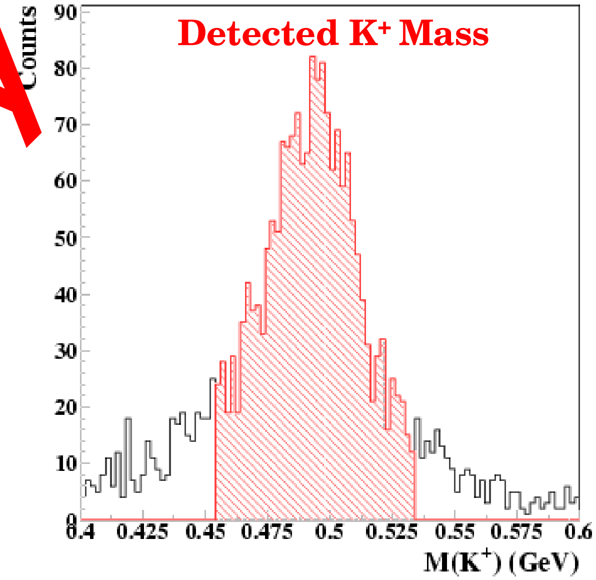
$$\Theta^+ \rightarrow K^+\, n \qquad K^0 \rightarrow K_S^0 \rightarrow \pi^+\, \pi^-$$

Red: detected particles

Particle Identification

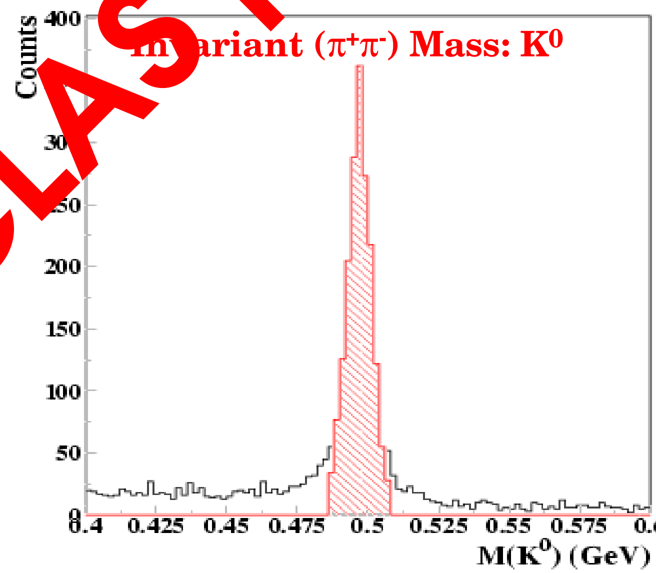


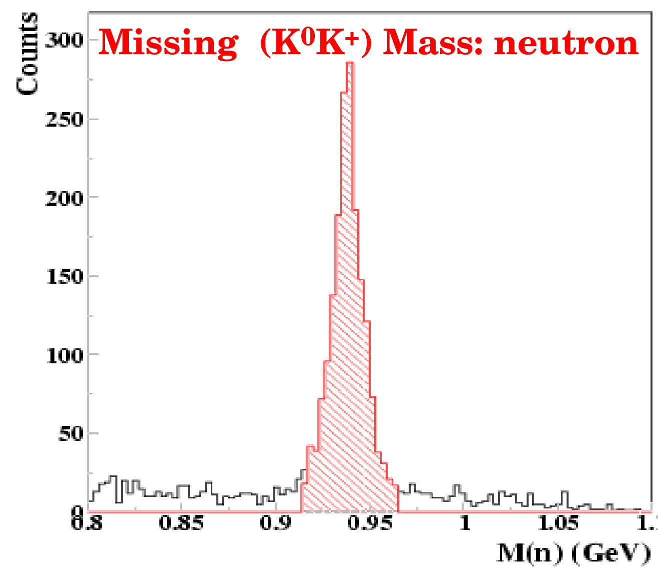




Channel Identification

- Closed kinematics
- Tagged strangeness





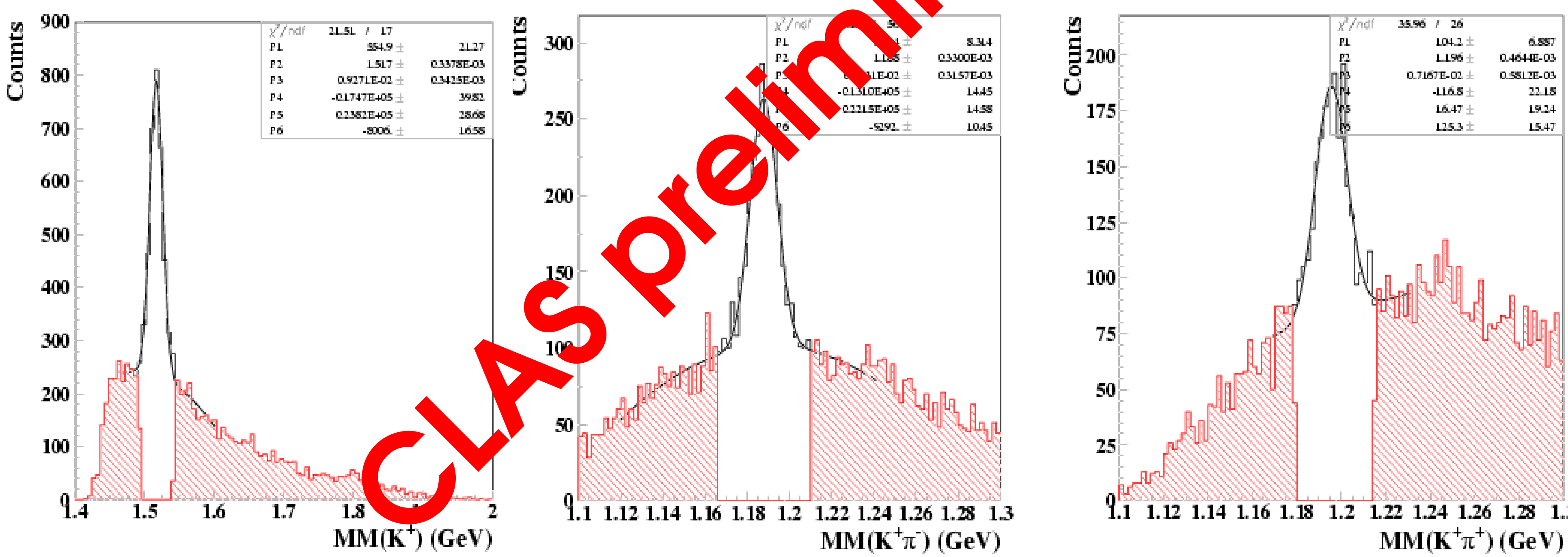
Background rejection

$\gamma\ p \rightarrow \Lambda^*(1520)\ K^+$

$\Lambda^*(1520) \rightarrow n\ K^0$

$\gamma\ p \rightarrow \Sigma^{+(-)}\ \pi^{-(+)}\ K^+$

$\Sigma^{+(-)} \rightarrow n\ \pi^{+(-)}$



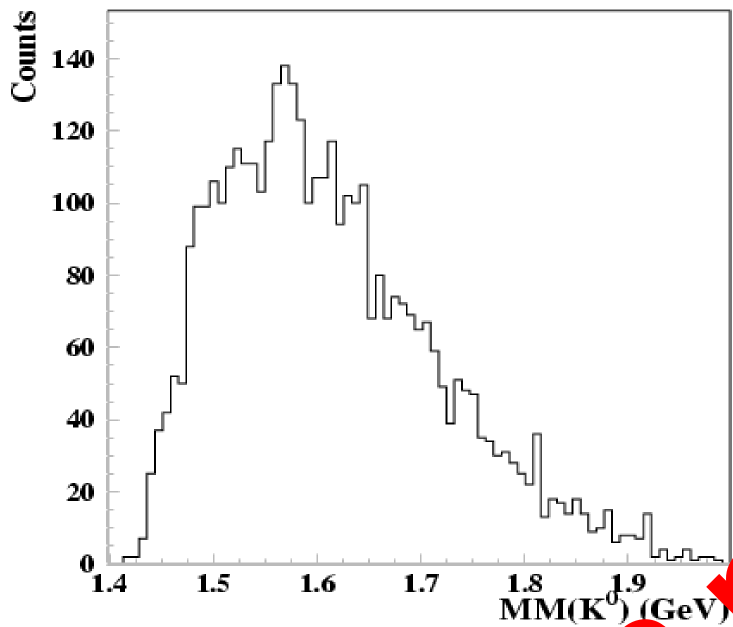
Results

- Θ^+ should show up as a peak in the K^0 missing mass

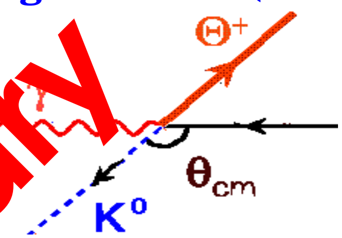
Results

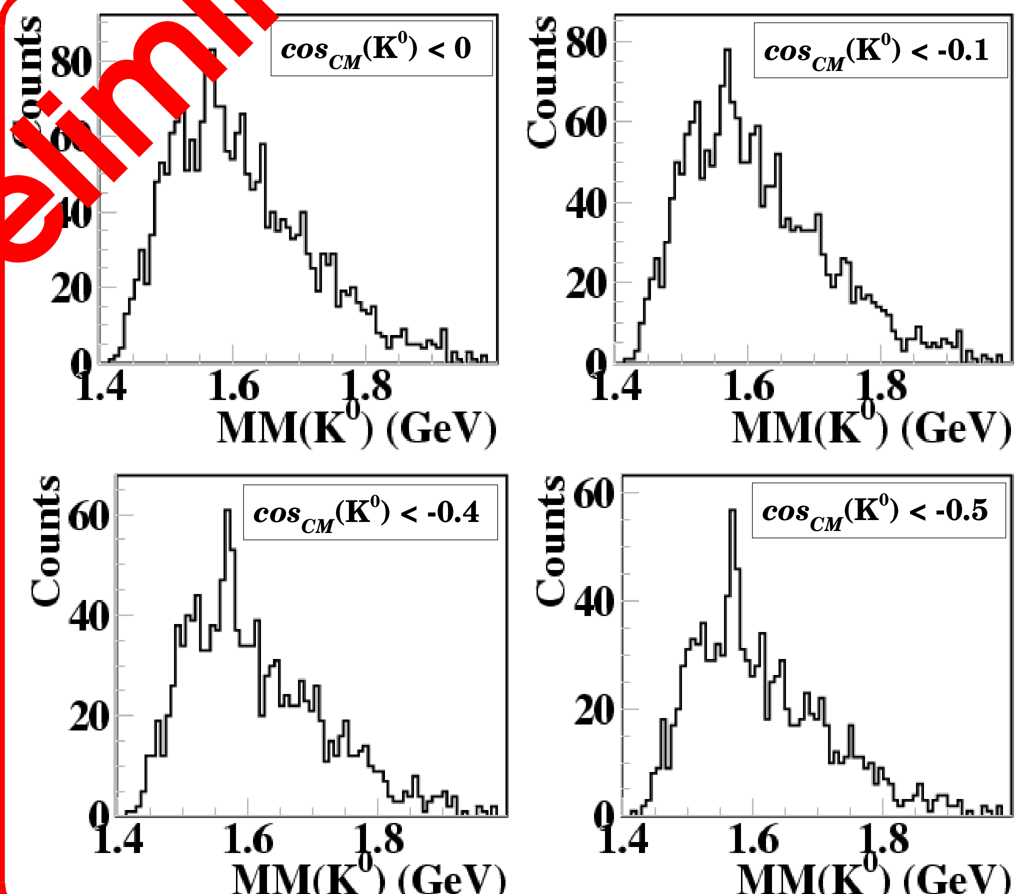
$$\gamma\ p \rightarrow \Theta^+ K^0$$

All angles, all energies



- The peak is enhanced when the K^0 is selected at backward angles in the (K^0-Θ^+) C.o.M.

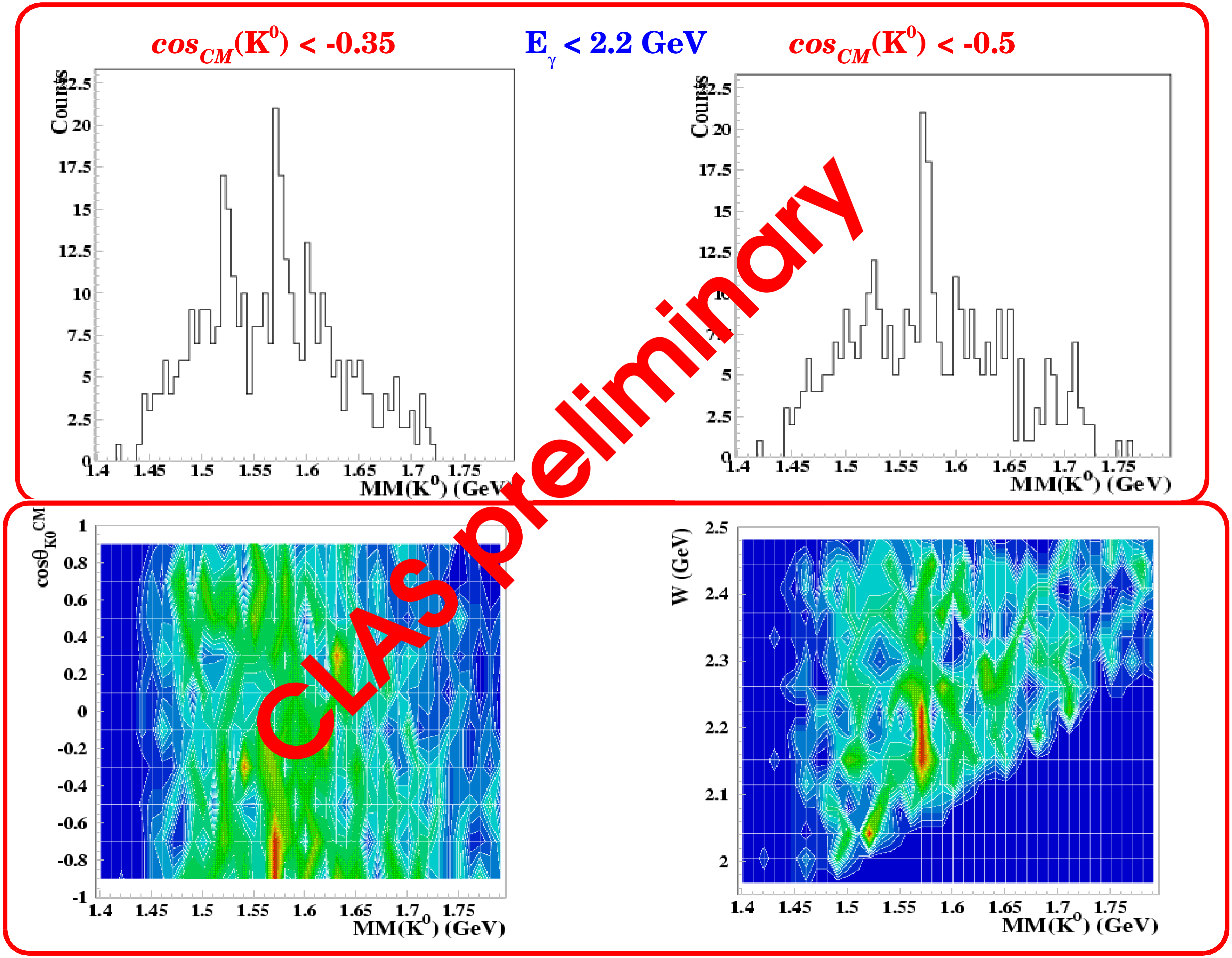




The best peak/bg ratio is obtained for:

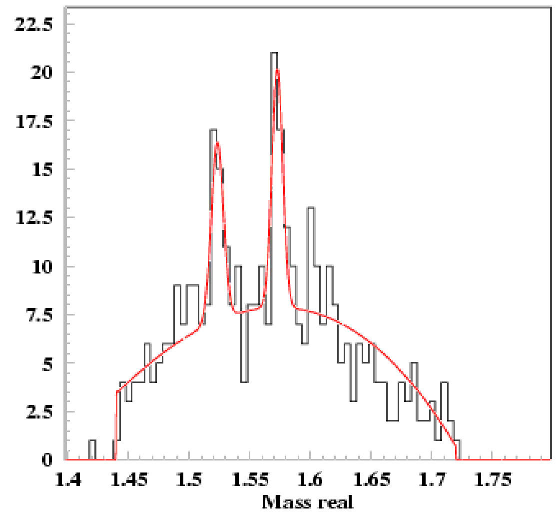
- $cos_{CM}(K^0) < -0.35$
- $1.6 < E_\gamma < 2.2$ GeV

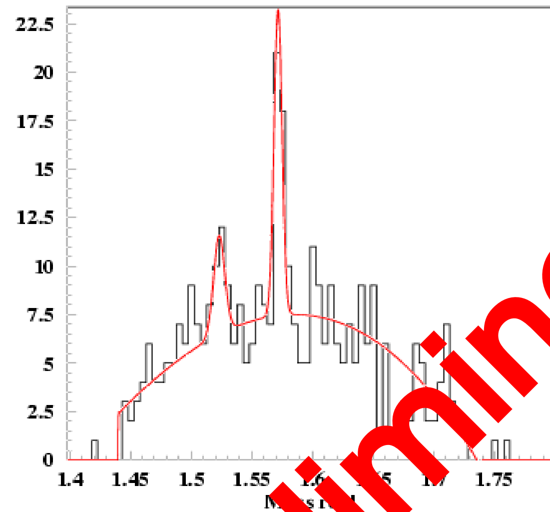
Results



cos$_{CM}$(K^0) < -0.35
E$_\gamma$ < 2.2 GeV
cos$_{CM}$(K^0) < -0.5
Counts
MM(K^0) (GeV)
CLAS preliminary
cosθ_{K0}^{CM}
W (GeV)

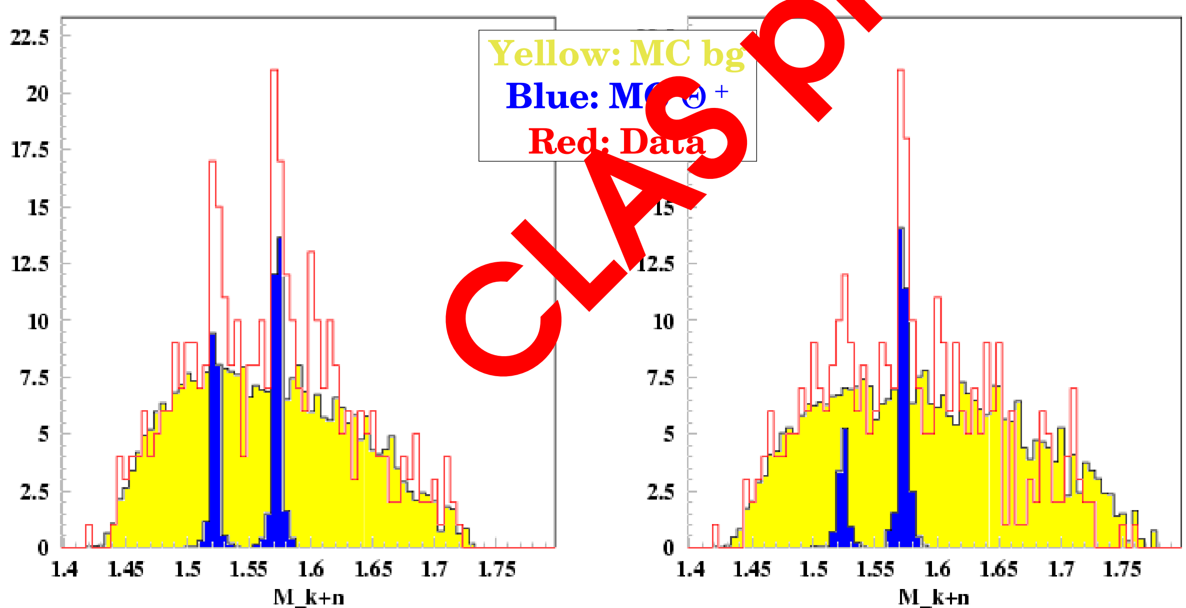
- The spectrum has been fitted to a (Gaussian + 5th order polynomial) using an unbinned Likelihood procedure





- A side-band subtraction method (2 and 4 nearest bins) was applied giving similar results

- The spectrum has been compared to MC simulation



All methods give similar results

$N_{peak} \pm \mathrm{sqrt}(N_{bg})$
$22 \pm \mathrm{sqrt}(30)$
stat. sig. = $(3.9 \pm 0.2)\sigma$
Mass = 1523 +/- 5 MeV
FWHM ~ 9 MeV

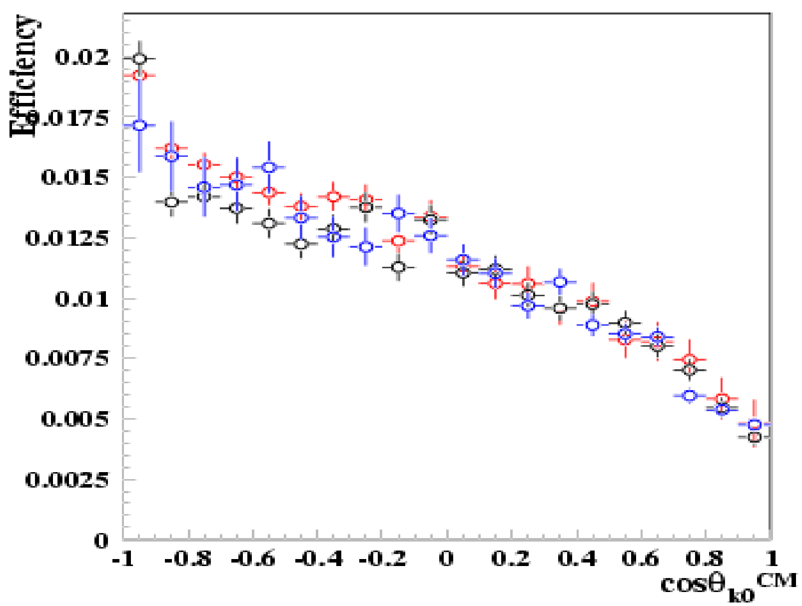
$N_{peak} \pm \mathrm{sqrt}(N_{bg})$
$27 \pm \mathrm{sqrt}(26)$
stat. sig. = $(6.0 \pm 0.2)\sigma$
Mass = 1573 +/- 5 MeV
FWHM ~ 9 MeV

MC simulations

- Full GSIM simulations using a realistic event generator
- The same analysis chain used for data

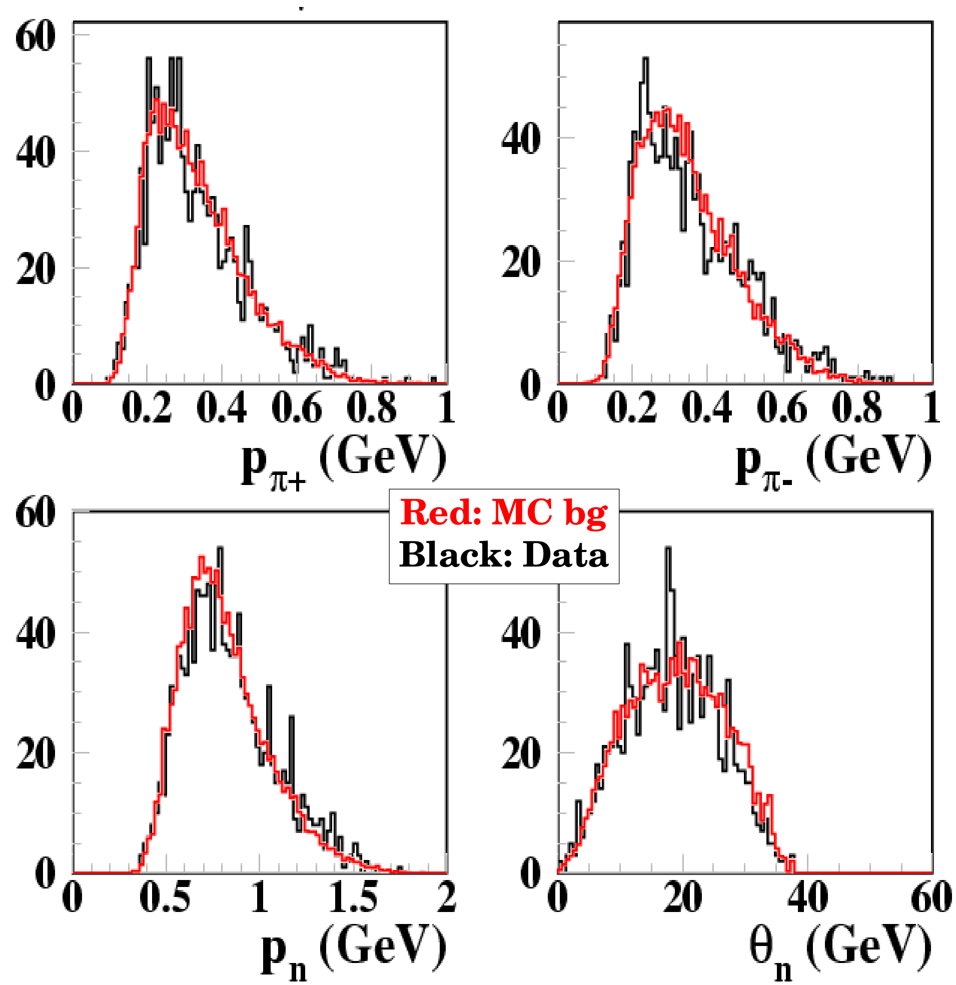
Signal

- $\gamma\ p \rightarrow\ \Theta^+ K^0 \rightarrow\ K^+ n\ \pi^+ \pi^-$
- $M = 1.523$ and 1.573 $\Gamma = 0$
- Different production mechanisms:
  - *u-exchange* (K^0 backward peaked in CM)
  - *t-exchange* (K^0 forward peaked in CM)
  - *flat* in CM
- cuts optimization/effect on mass spectra
- CLAS efficiency evaluation (similar for the two masses)



Background

- Phase space $\gamma\ p \rightarrow K^+ K^0 n \rightarrow K^+\ n\ \pi^+ \pi^-$
- Tuned on E_γ, p_n and p_{K+} spectra
- Good agreement with other variables



Luminosity

I step: getting L from φ production $\gamma\, p \to p\,\varphi \to p\, K^+K^-$

$$L(E_\gamma\ 1.6\text{-}2.2\ \mathrm{GeV}) = \frac{N_\varphi(E_\gamma\ 1.6\text{-}2.2\mathrm{GeV})}{\sigma_\varphi(E_\gamma\sim 2\ \mathrm{GeV})\ \ b.r._{\varphi\to K+K-}\ \ \varepsilon_\varphi} = 2.3\ \mathrm{pb}^{-1}$$

- $\varepsilon_\varphi \sim 2.4\%$ with a realistic angular distribution
- $\sigma_\varphi(E_\gamma\sim 2\ \mathrm{GeV}) = 200$ nb
- b.r. $\varphi \to K^+K^- = 49\%$
- $N_\varphi(E_\gamma\ 1.6\text{-}2.2\mathrm{GeV}) = 5530$

II step: getting the $\Lambda^*(1520)$ cross section ($\gamma\, p \to \Lambda^*(1520)\, K^+ \to p\, K^-K^+$)

$$\sigma_{\Lambda*(1520)}(E_\gamma\sim 2\ \mathrm{GeV}) = \frac{N_{\Lambda*(1520)}(E_\gamma\ 1.6\text{-}2.2\mathrm{GeV})}{L(E_\gamma\ 1.8\text{-}2.3\ \mathrm{GeV})\ b.r._{\Lambda*(1520)\to pK-}\ \ \varepsilon_{\Lambda*(1520)}} = 180\ \mathrm{nb}$$

- $\varepsilon_{\Lambda*(1520)} \sim 3.9\%$ with a realistic angular distribution
- $L(E_\gamma\ 1.6\text{-}2.2\ \mathrm{GeV}) = 2.3\ \mathrm{pb}^{-1}$
- b.r. $\Lambda^*(1520) \to pK^- = 22.5\%$
- $N_{\Lambda*(1520)}(E_\gamma\ 1.6\text{-}2.2\ \mathrm{GeV}) = 3630$

III step: checking the Λ^* cross section in the same final state of Θ^+

$\gamma\, p \to \Lambda^*(1520)\, K^+ \to n\, K^0\, K^+ \to n\ \pi^+\pi^-\, K^+$

$$\sigma_{\Lambda*(1520)}(E_\gamma\sim 2\ \mathrm{GeV}) = \frac{N_{\Lambda*(1520)}(E_\gamma\ 1.6\text{-}2.2\mathrm{GeV})}{L(E_\gamma\ 1.8\text{-}2.3\ \mathrm{GeV})\ b.r._{\Lambda*\to nK0}\ b.r._{K0\to Ks}\ b.r._{Ks\to\pi+\pi-}\ \varepsilon_{\Lambda*(1520)}} = 186\ \mathrm{nb}$$

- $\varepsilon_{\Lambda*(1520)} \sim 2\%$ with a realistic angular distribution
- $L(E_\gamma\ 1.6\text{-}2.2\ \mathrm{GeV}) = 2.3\ \mathrm{pb}^{-1}$
- b.r. $\Lambda^*(1520) \to nK^0 = 22.5\%$
- b.r. $K^0 \to K_S = 50\%$
- b.r. $K_S \to \pi^+\pi^- = 68\%$
- $N_{\Lambda*(1520)}(E_\gamma\ 1.6\text{-}2.2\ \mathrm{GeV}) = 650$

- **The $\Lambda^*(1520)$ cross sections agree at 5% level**
- **5% (method) + 5% ($\delta\sigma_\varphi$) = 10% on Luminosity: $L = 2.3 \pm 0.2\ \mathrm{pb}^{-1}$**

Total Cross section estimate

Efficiency

- Few % difference in angular distribution
- Factor 2 of difference
  when integrated for $cos_{CM}(K^0) < -0.35$:

Luminosity = $2.3 \pm 0.2\ pb^{-1}$
b.r. $\Theta^+ \rightarrow K^+ n = 50\%$
b.r. $K^0 \rightarrow K_S = 50\%$
b.r. $K_S \rightarrow \pi^+ \pi^- = 68\%$

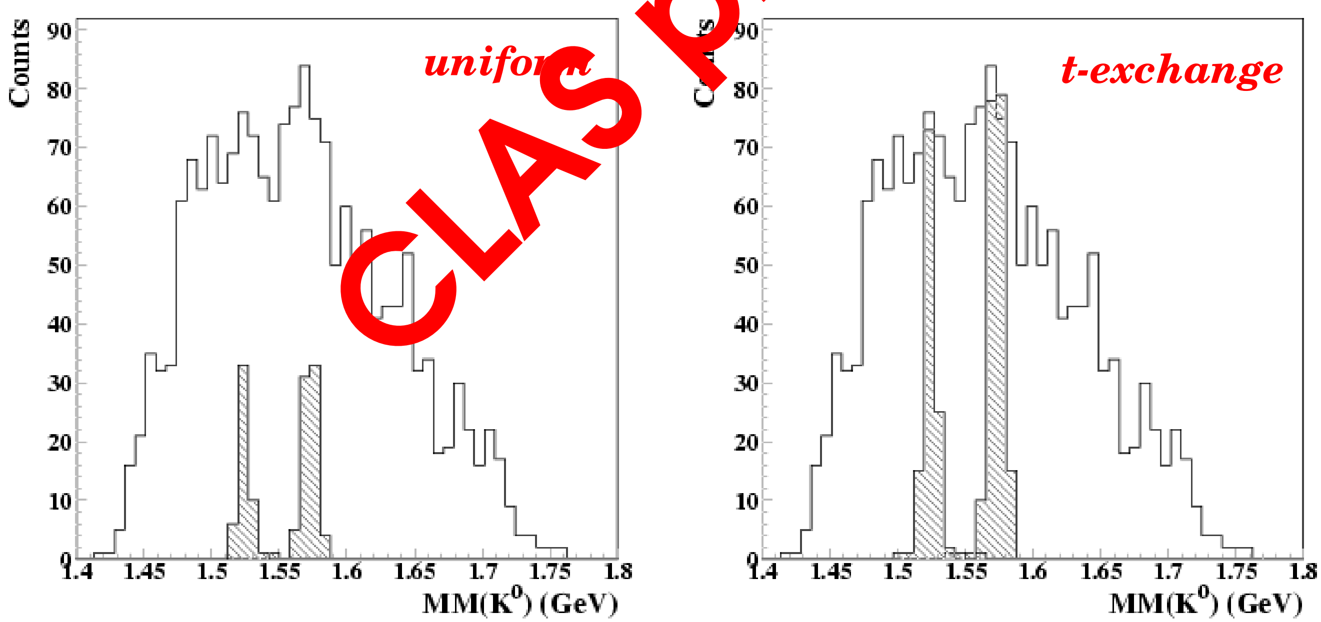
- **Low mass peak (5 - 12 nb)**

$\sigma_{Tot} = 36 \pm 9 \pm 4$ nb (t-exchange integrated eff.)
$\sigma_{Tot} = 12 \pm 3 \pm 1$ nb (flat integrated eff.)
$\sigma_{Tot} = 5 \pm 1 \pm 1$ nb (u-exchange integrated eff.)

- **High mass peak (8 - 18 nb)**

$\sigma_{Tot} = 35 \pm 14 \pm 6$ nb (t-exchange integrated eff.)
$\sigma_{Tot} = 18 \pm 4 \pm 2$ nb (flat integrated eff.)
$\sigma_{Tot} = 8 \pm 2 \pm 1$ nb (u-exchange integrated eff.)

- (t-exchange) ruled out by consistency with theall-angle spectrum

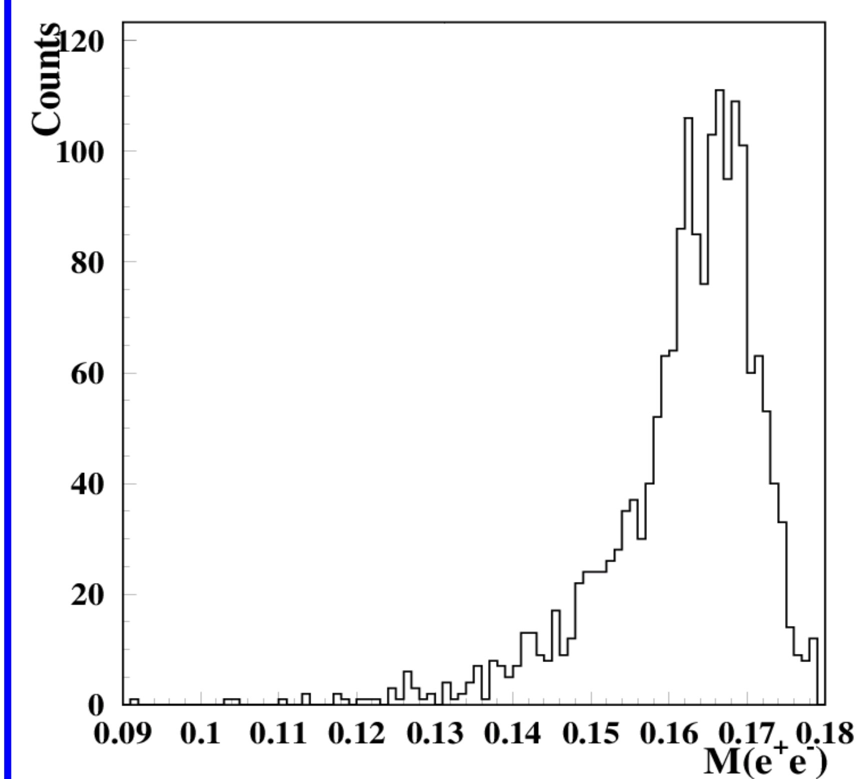


Particle Identification

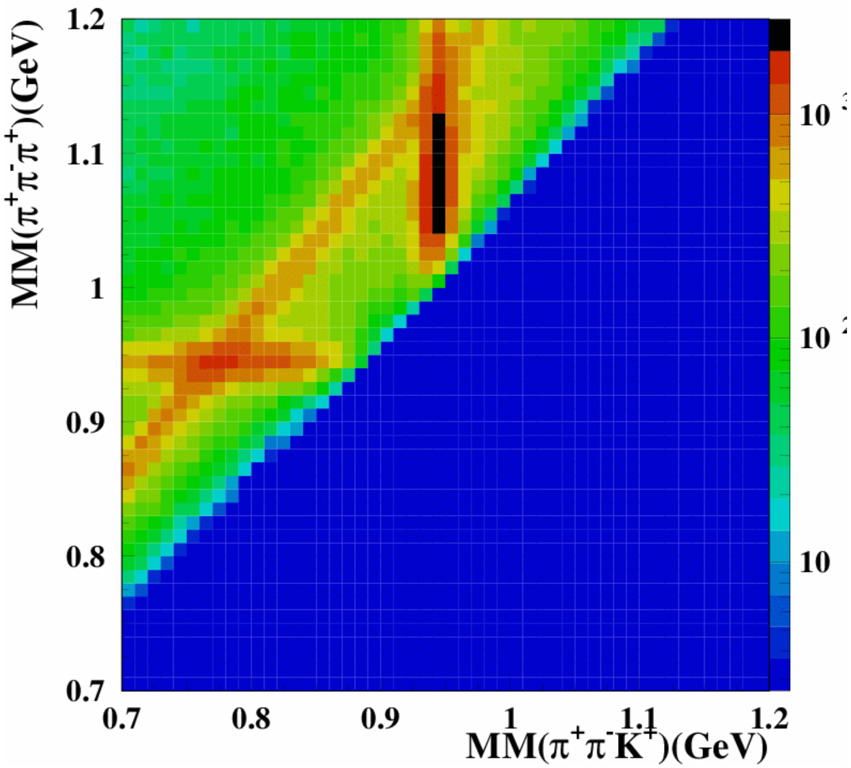
Contamination to the $\pi^+\pi^-K^+$ event sample may came, e.g. from:

e^+e^- identified as $\pi^+\pi^-$

π^+ identified as K^+



The selected $\pi^+\pi^-$ are not compatible with $\gamma \to e^+e^-$



$\pi^+\pi^-\pi^+$ (n) events are kinematically separated from $\pi^+\pi^-K^+$ (n)

Systematic checks

MC simulations

Θ^+ Mass and kinematical corrections
Peak position stability

Varying pion momentum by 1%

$p_\pi = p_\pi \cdot 1.01$

M_{K0} ~ + 3 MeV
M_n ~ - 4 MeV
$M_{\Lambda*}$ ~ 0 MeV
$M_{\Theta+}$ ~ 0 MeV

Varying pion momentum by +10 MeV

$p_\pi = p_\pi + 10$ MeV

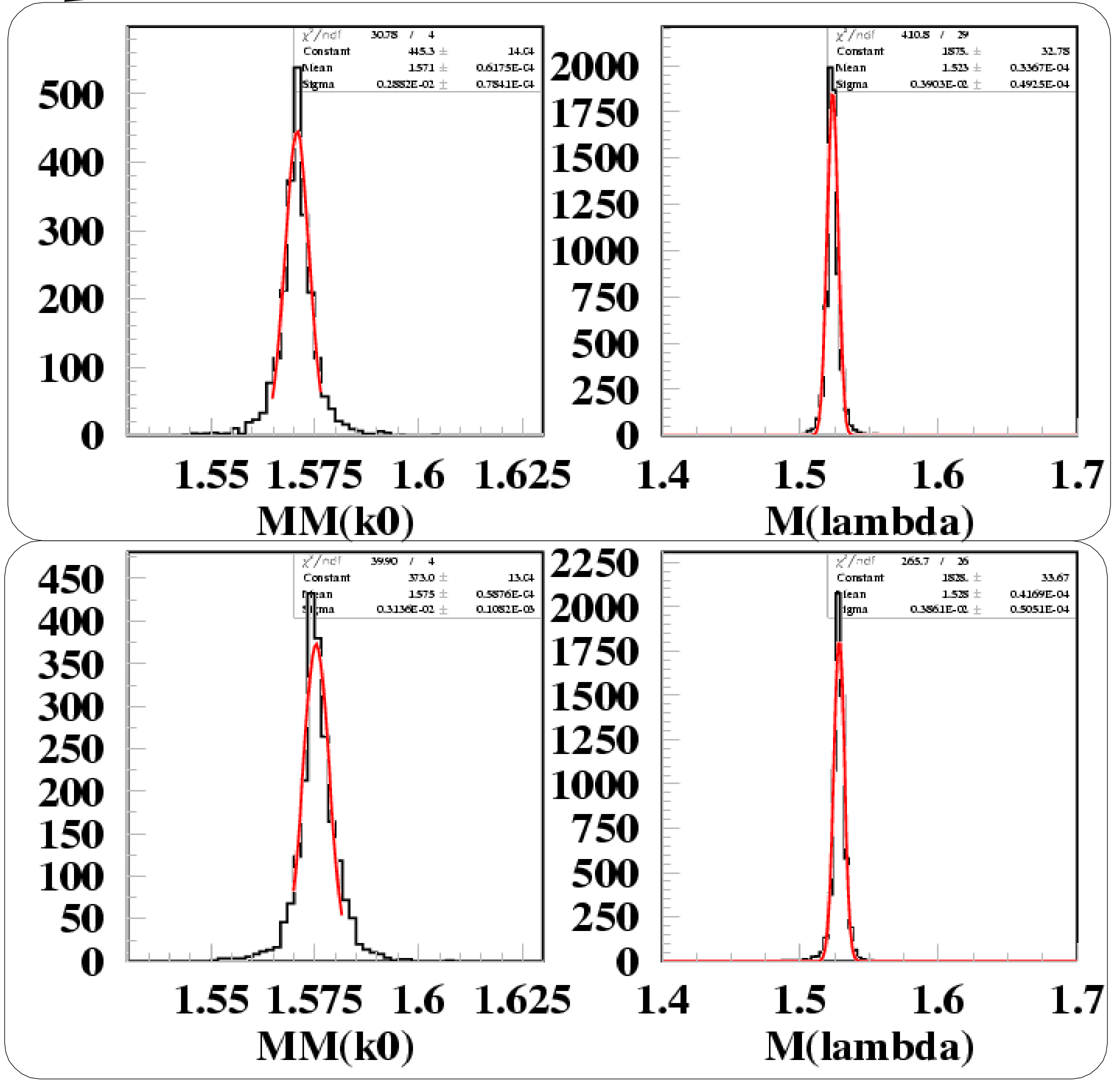
M_{K0} ~ + 10 MeV
M_n ~ - 10 MeV
$M_{\Lambda*}$ ~ 0 MeV
$M_{\Theta+}$ ~ 0 MeV

Varying pion angles by $\pm 0.5^o$

M_{K0} ~ 0 MeV
M_n ~ 0 MeV
$M_{\Lambda*}$ ~ 0 MeV
$M_{\Theta+}$ ~ 0 MeV

Varying photon energy by +10 MeV

M_{K0} ~ 0 MeV
M_n ~ +4 MeV
$M_{\Lambda*}$ ~ +4 MeV
$M_{\Theta+}$ ~ +4 MeV



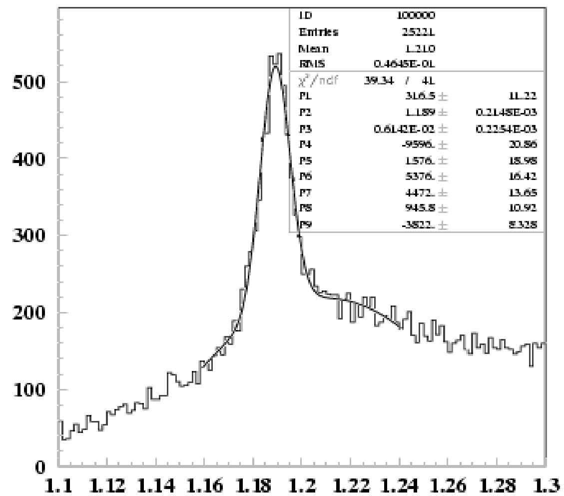
- All reasonable shifts of π variables leave the final mass unchanged
- A photon energy shift shows up in ALL missing mass

Systematic checks

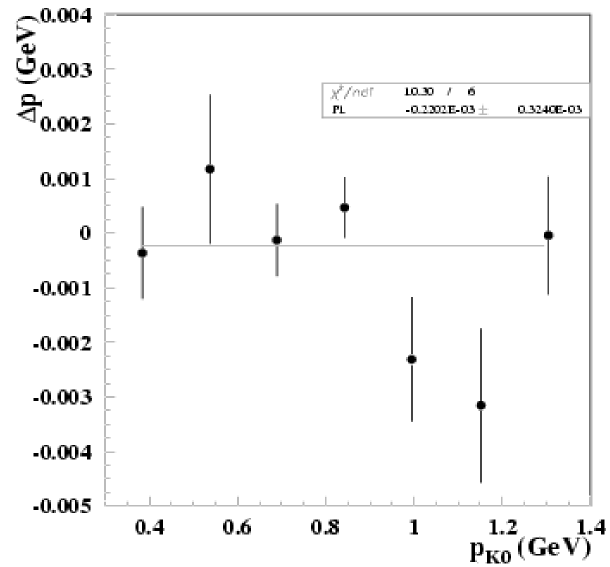
DATA

Θ^+ Mass and kinematical corrections
Peak position stability

- **Θ^+ should show up as a peak in the K^0 missing mass**
- **Studing the reaction $\gamma\, p \rightarrow \Sigma^+ K^0$ we can verify the mass calibration**



- **The Σ^+ peak shows no shift depending on the K^0 momentum**



- **Known hyperons were used to check energy/momentum calibration**

Peak	Mass spectrum	No corrections	E_{loss}	E_{loss} + γ energy	(PDG value)
$\bar{K}^0$	$\pi^+\pi^-$ invariant mass	(494.6 ± 0.1)	(497.4 ± 0.1)	(497.4 ± 0.1)	(497.7 ± 0.1)
n	$\pi^+\pi^-K^+$ missing mass	(943.3 ± 0.1)	(936.6 ± 0.1)	(938.5 ± 0.1)	939.6
Λ^*	K^+ missing mass	(1518 ± 0.5)	(1516 ± 0.5)	(1518 ± 0.5)	(1519 ± 1)
Σ^+	π^-K^+ missing mass	(1191 ± 0.3)	(1186 ± 0.3)	(1188 ± 0.3)	1189.4
Σ^-	π^+K^+ missing mass	(1199 ± 0.4)	(1194 ± 0.4)	(1196 ± 0.5)	1197.4
Θ^+	$\pi^+\pi^-$ missing mass	(1522 ± 2)	(1522 ± 1)	(1523 ± 1)	/
Θ^*	$\pi^+\pi^-$ missing mass	(1572 ± 2)	(1572 ± 1)	(1573 ± 1)	/

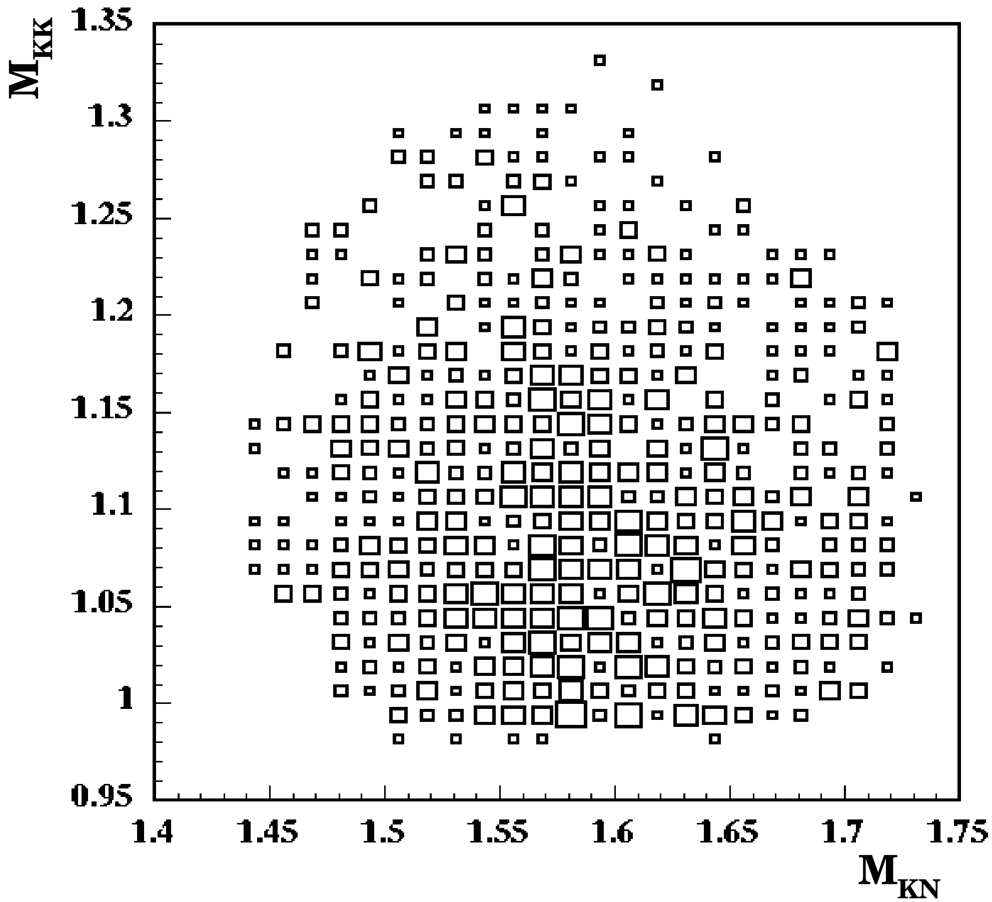
An absolute Θ^+ mass calibration < 5 MeV is quoted with a resolution ($1.6 < E_\gamma < 2.2$ GeV): FWHM = 9 MeV

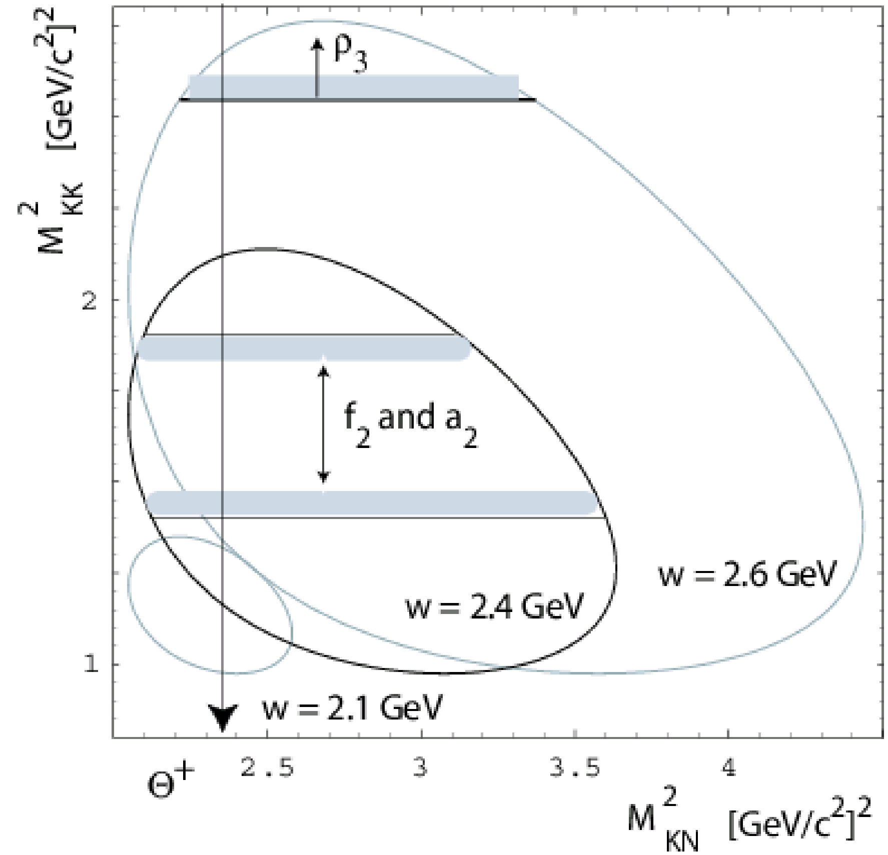
Systematic checks

- **Checking for possible kinematic reflections from meson decays:**

$$\gamma\ p \rightarrow n\ a^+_2(1320) \rightarrow n\ \bar{K}^0\ K^+$$

$$\gamma\ p \rightarrow n\ \rho^+(1690) \rightarrow n\ \bar{K}^0\ K^+$$





Low energy

W < 2.3 (subthreshold)

Pentaquarks spectrum

- Existence of excited pentaquark states is predicted by theory
- Several models predicts Θ^+ spin partners in the same mass range

Skyrme-soliton model

Borisyuk et al. hep-ph/0307370

- Θ^+: T=0, J^P= 1/2$^+$ state
- New series of baryons Θ_1^{++}, Θ_1^{+}, Θ_1^{0} with T=1, J^P= 3/2$^+$

ΔM(3/2-1/2) ~ 55 MeV

QCD sum-rules

Zhu hep-ph/0307345

- T = 0, 1, and 2 lie close to each other:
- $\Theta_{T=0}(1.56 \pm 0.15)$, $\Theta_{T=1}(1.59 \pm 0.15)$, and $\Theta_{T=2}(1.53 \pm 0.15)$

ΔM(3/2-1/2) ~ 30-50 MeV

Constituent quark model

Dudek and Close hep-ph/0311258

- Spin-Orbit forces (L·S) responsible for the mass splitting

ΔM(3/2-1/2) ~ 40 MeV $[(ud)_{S=0}\,(ud)_{S=0}\,\bar{s}]$ Jaffe and Wilczek hep-ph/0307341

ΔM(3/2-1/2) ~ 35-65 MeV $[(ud)_{S=0}\,((ud)_{S=1}\,\bar{s})]$ Karliner and Lipkin hep-ph/0307243

Bijker Giannini Santopinto hep-ph/0310281

- Complete classification of $qqqq\bar{q}$ state in spin-flavour SU(6) representation

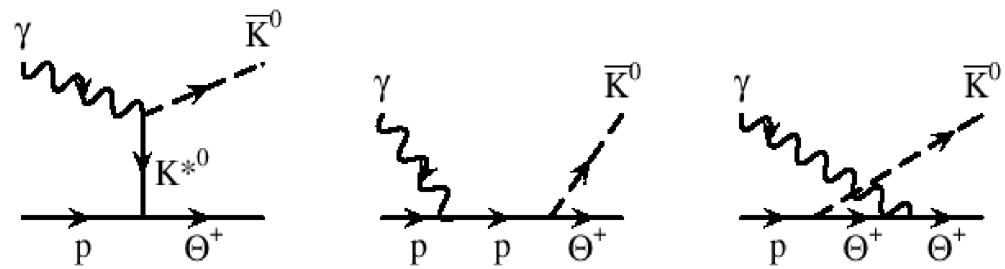
ΔM(3/2-1/2) ~ 120 MeV

Theta⁺ production mechanisms

Effective Lagrangian

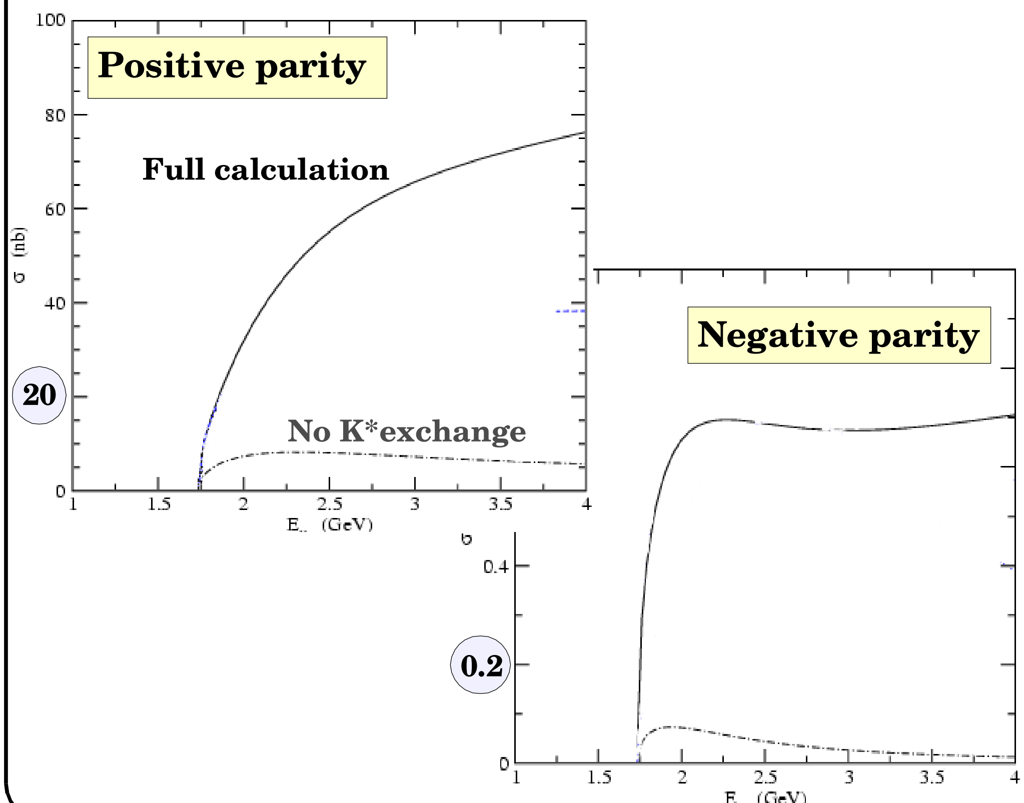
$$\gamma\ p \rightarrow \Theta^+ \bar{K}^0$$

Y.Oh et al. Hep-ph/0310019



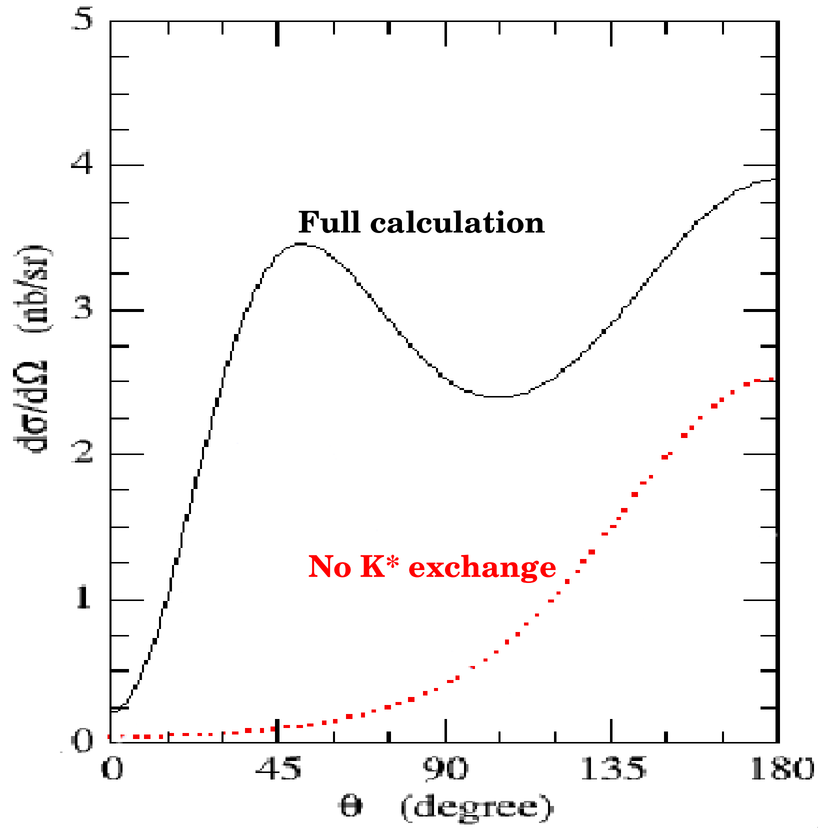
Total cross section

- strongly depends on parity
- strongly depends on coupling constants
- is predicted to be in the range σ~5-40 nb



Differential cross section

shows sensitivity to the production mechanisms



Questions we have to answer in the short term with a high statistics experiment

- Can we confirm the presence of the two peaks?
- Are there any other excited pentaquarks?
- What are their masses?
- What are the production mechanisms in terms of hadron dynamics?

This would set the groundwork for a comprehensive study of pentaquark properties

- **Mass:** the mass measured in different experiments ranges from 1526 MeV to 1550 MeV
- **Width:** the experimental width (FWHM) ranges from 9 to 27 MeV, dominated by the experimental resolution
- **Strangeness and charge:** S=+1, Q=+1 fixed by measuring fully exclusive processes as $\gamma\ p \rightarrow \Theta^+ \bar{K}^0 \rightarrow K^+ (n) \pi^+ \pi^-$
- **Isospin Spin and Parity:** still unknown

E-04-021

The JLab PAC just approved with the highest priority a new run on hydrogen running for 25 days (two months)

Two production channels:

$\gamma\ p \rightarrow \Theta^+ \bar{K}^0$

$\gamma\ p \rightarrow \Theta^+ K^+ \pi^-$

Two decay modes:

$\Theta^+ \rightarrow K^+ n$

$\Theta^+ \rightarrow K^0 p$

Will collect more than 10 times the current CLAS statistics

Primary goals

- Establish the Θ^+ mass spectrum
- Measure total and differential cross sections
- Study decay angular distributions

Requirements

- **Broad energy range**

  from Θ^+ production threshold (~1.6 GeV) up to 4 GeV

- **High Luminosity**

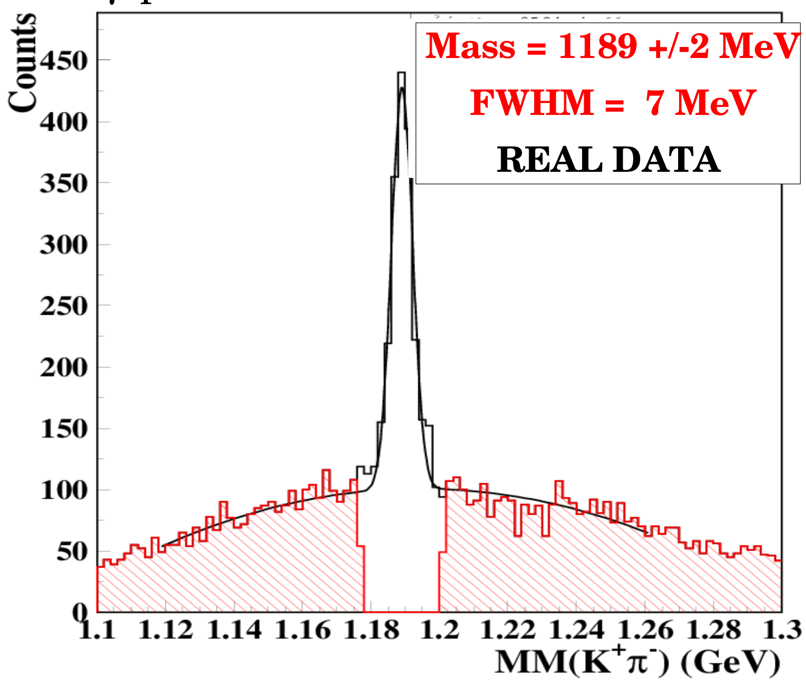
  Large photon flux

  Longer target

Mass accuracy and resolution

- In CLAS different final states are measured simultaneously
- Known hyperons can be used to check energy/momentum calibration

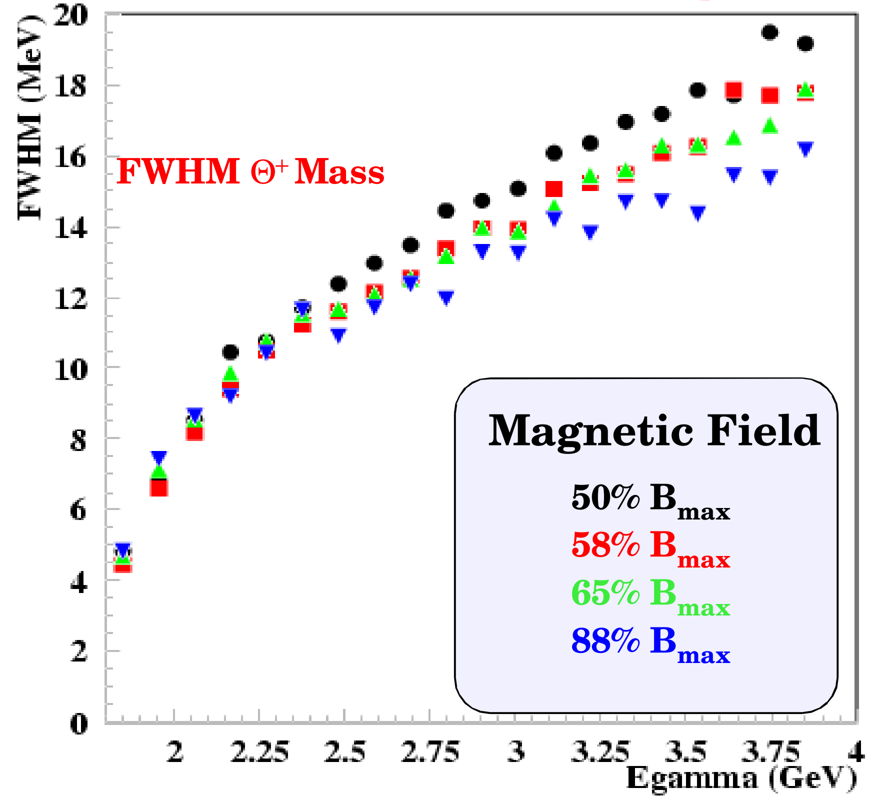
$\gamma\ p \rightarrow \Sigma^+\ \pi^-\ K^+ \qquad \Sigma^+ \rightarrow n\ \pi^+$



- MC study of resolution as a function of E_γ

$\gamma\ p \rightarrow \Theta^+ \bar{K}^0$

$\rightarrow K^+\ \pi^+\ \pi^-\ (n)$ Red: detected particles



An absolute Θ^+ mass calibration < 4 MeV is expected with a resolution ($1.6 < E_\gamma < 2.2$ GeV): FWHM = 6 - 8 MeV

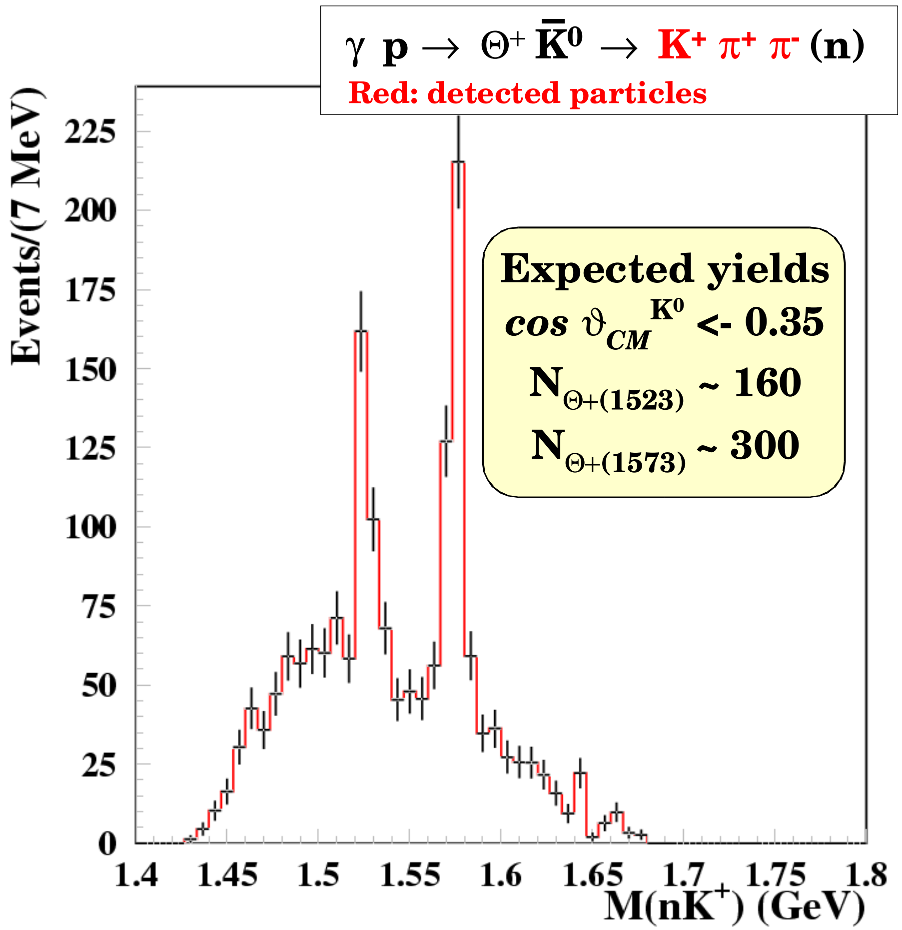
Statistical accuracy

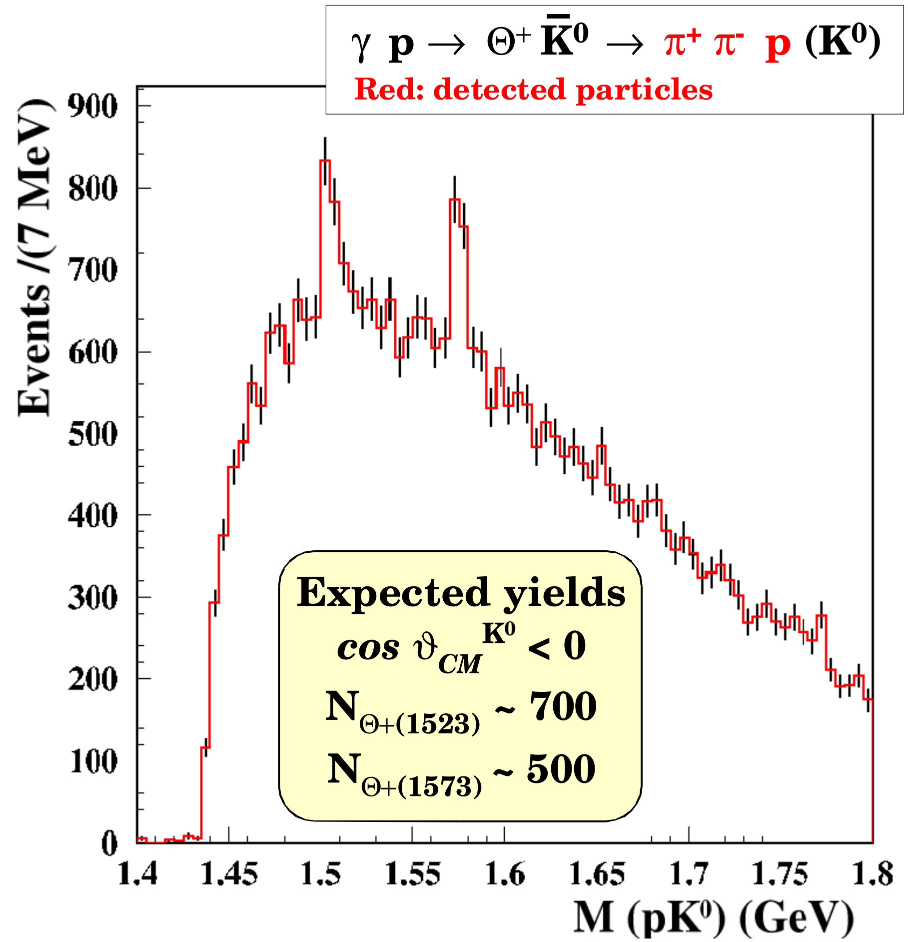
Assuming the following run conditions:

- 4 GeV electron beam
- Magnetic Field = 50% B_{max}
- 25 days data taking

Projected results for $1.6 < E_\gamma < 2.2$ GeV

10x the existing data



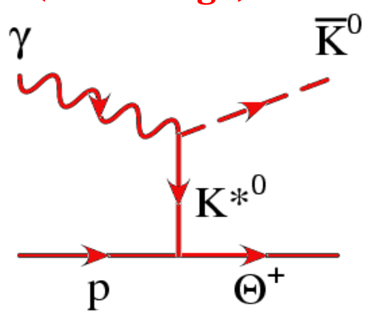


Projected results for
$1.6 < E_\gamma < 2.2$ GeV
300 events in the *cos* $\vartheta_{CM}^{K^0} < -0.35$ range

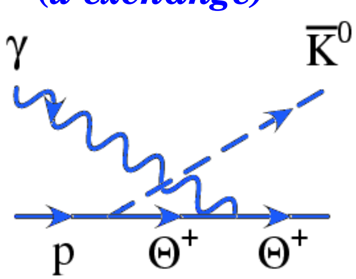
Statistical accuracy
Differential cross section

Sensitivity to different production mechanisms

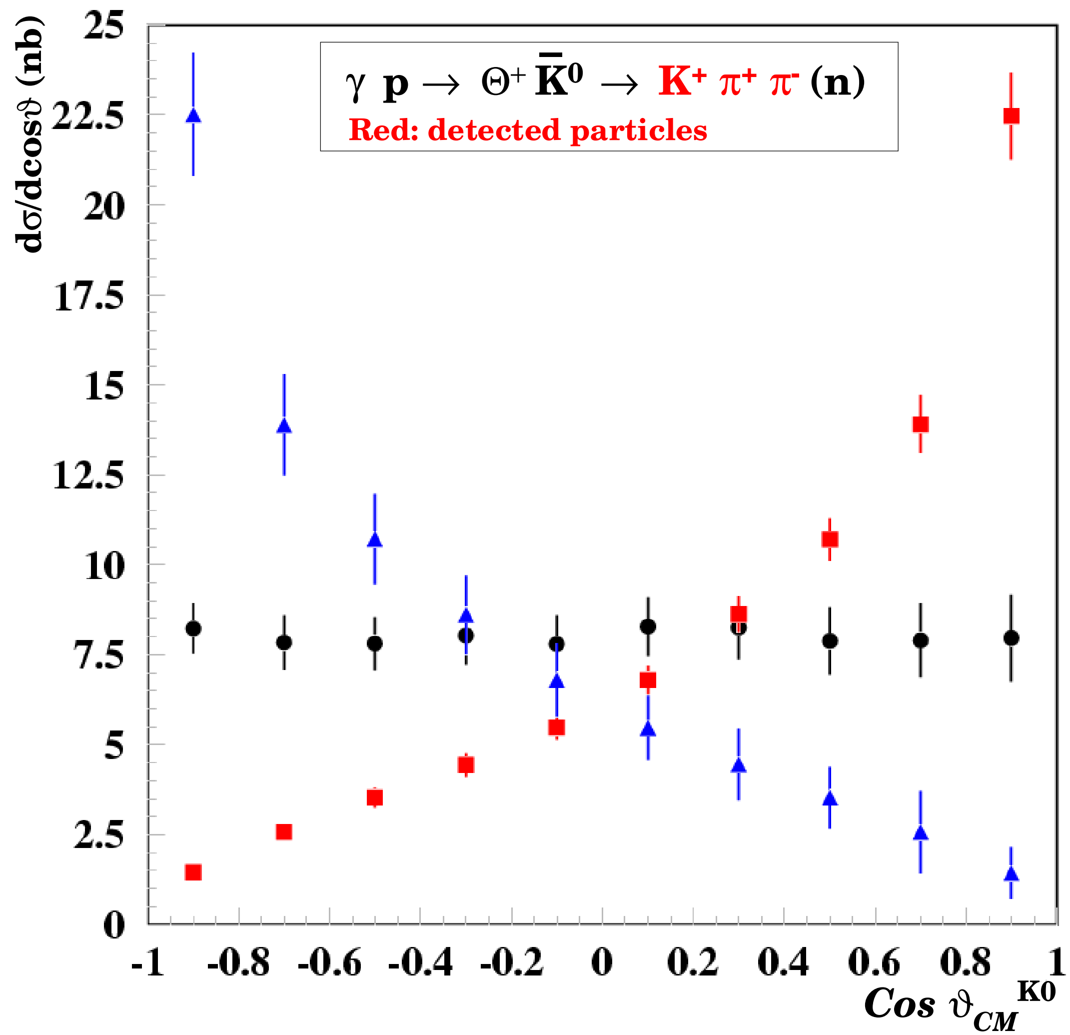
Red = forward production *(t-exchange)*



Blue = backward production *(u-exchange)*



Black = uniform distribution in the cm



Statistical accuracy
Decay angular distribution

Projected results for
$1.6 < E_\gamma < 2.2$ GeV

300 events in the *cos* $\vartheta_{CM}^{K^0} < -0.35$ range

Sensitivity to Θ^+ spin and parity

- **Decay angular distributions reflects Θ^+ spin and parity:**

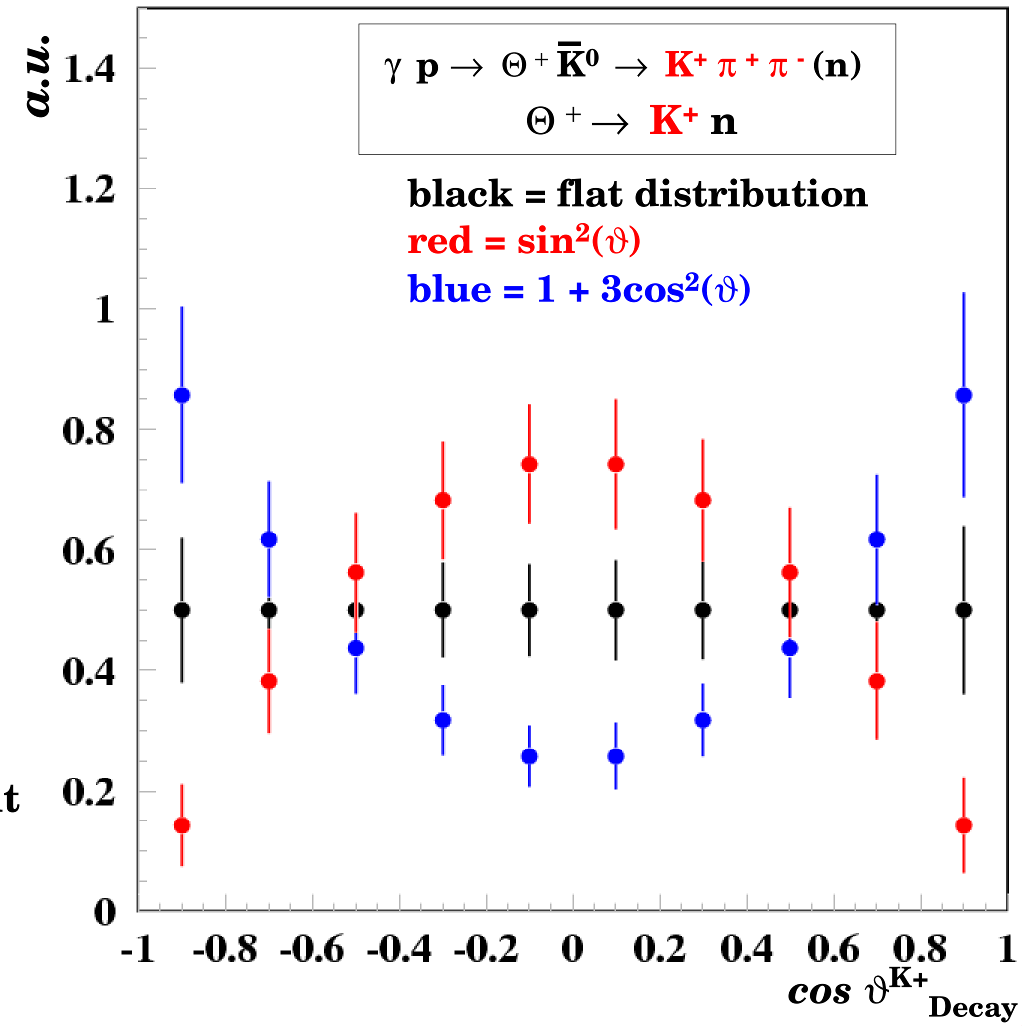
  $J^P = 1/2^-$ $J_z = \pm 1/2 \rightarrow$ flat distribution

  $J^P = 3/2^+$ $J_z = \pm 1/2 \rightarrow [1 + 3\cos^2(\vartheta)]$

  $J^P = 3/2^+$ $J_z = \pm 3/2 \rightarrow \sin^2(\vartheta)$

- **CLAS measures full angular decay distributions**

- **If the Θ^+ is polarized, the measurement of this observable is the first step to infer quantum numbers**



Conclusions

- The reaction $\gamma\, p \rightarrow n\, K^0\, K^+$ was studied at JLab
- The CLAS data show a very good Pid with little bg
- The K^0 missing mass shows some structures enhanced at backward K^0 CM angles
- Cutting at backward angles two peaks are identified at:

1523+- 5 MeV	FWHM~9 MeV	statistical significance of 4.0 σ
1573+- 5 MeV	FWHM~9 MeV	statistical significance of 6.0 σ

- Full MC simulations (phase space + signal) indicate:
  - no peaks are expected in that mass spectrum (bg only)
  - the CLAS resolution is compatible with the observed peak width

A total cross section in the range 5 - 12 nb for the low mass peak and 8-18 nb fro the high mass peak was derived

- Systematic checks indicate that the peak position is stable, the kinematical corrections may affect it only within few MeV, no kinematical reflections are found to be present in the mass spectra

A new experiment that will collect 10x the present statistics has been recently approved by the JLab PAC