New Results from the CLAS Pentaquark Search Experiments

KEK Seminar

June 24, 2005

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Outline

- Short Introduction
- The published CLAS deuterium data
- The new CLAS deuterium data
- The new CLAS proton data
- New STAR data for Θ^{++} pentaquark
- Conclusions

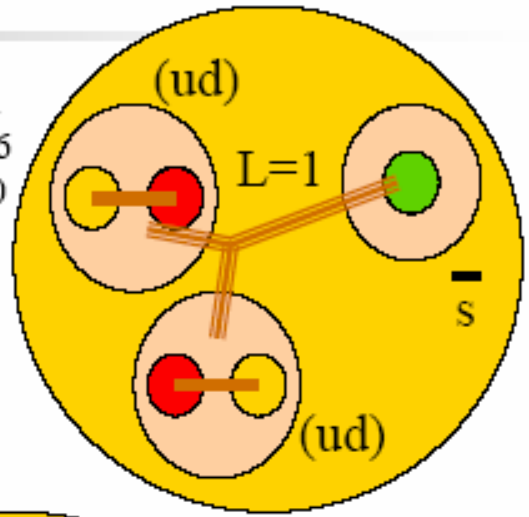
Short Introduction

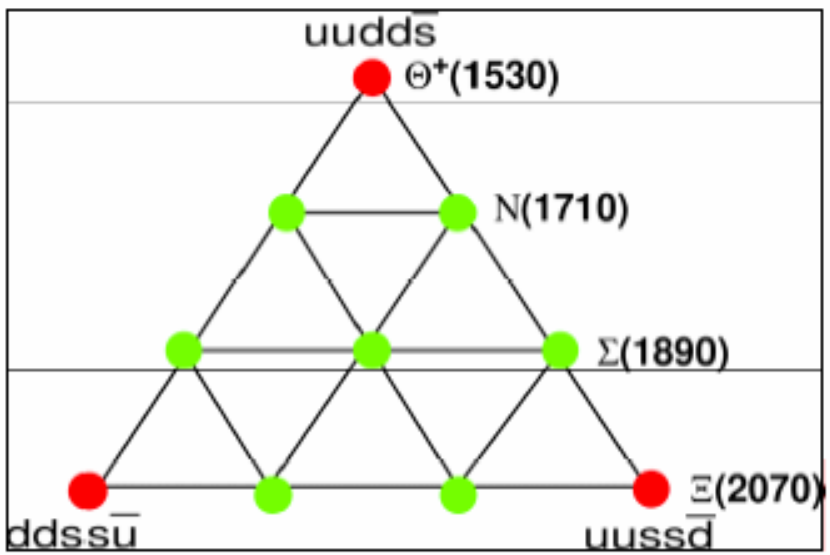
Pentaquark Structure

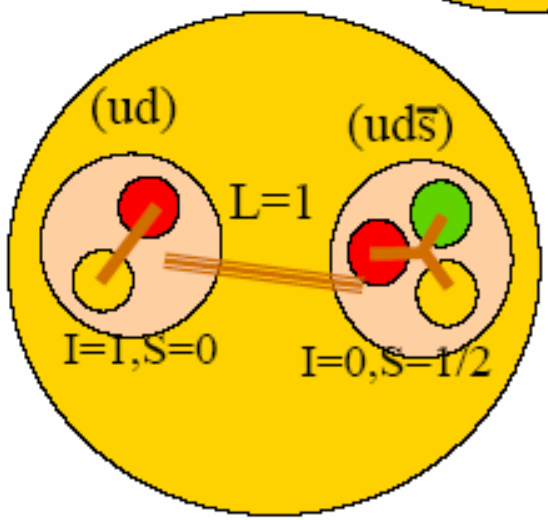
Pentaquarks:
rotational excitations of the soliton [rigid core surrounded by chiral (meson) fields]

Diakonov *et al.*, *Z.* Phys A **359**, 305 (1997).

JW hep-ph/0307341
JM hep-ph/0308286
SZ hep-ph/0310270







Karliner, Lipkin, hep-ph/0307243

Why is searching for the Θ^+ important?

- QCD does not prohibit $q^4\bar{q}$ states.
- Early searches have failed to produce evidence for pentaquarks. Is the Θ^+ too broad to see in experiments?
- If the Θ^+ exists with a narrow width, what is the mechanism of non-perturbative QCD that supresses "fall-apart" to KN with a short lifetime?
- Naïve quark models cannot explain a narrow width; the soliton model or correlated quark models can.
- If it exists, the Θ^+ would be the first evidence for a new class of particle type. If it doesn't exist, we have further constrained QCD.

PDG Review Table

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B 592, 1 (2004) (URL: http://pdg.lbl.gov)

EXOTIC BARYONS

Minimum quark content: $\Theta^+ = uudd\overline{s}$, $\Phi^{--} = ssdd\overline{u}$, $\Phi^+ = ssuu\overline{d}$.

$\Theta(1540)^+$

$I(J^P) = 0(?^?)$

It is difficult to deny a place in the Summary Tables for a state that six experiments claim to have seen. Nevertheless, we believe it reasonable to have some reservations about the existence of this state on the basis of the present evidence.

Mass $m = 1539.2 \pm 1.6$ MeV
Full width $\Gamma = 0.90 \pm 0.30$ MeV

NK is the only strong decay mode allowed for a strangeness $S=+1$ resonance of this mass.

$\Theta(1540)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
KN	100%	270

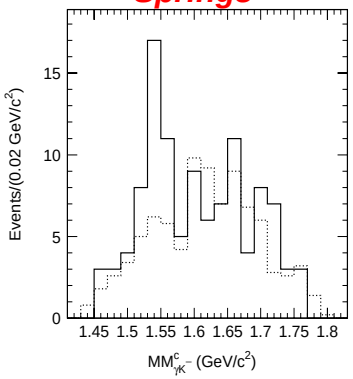
Comparison of Θ^+ Experiments

Where	Reaction	Mass	Width	σ's*
LEPS	$\gamma C \rightarrow K^+K^- X$	1540 +- 10	< 25	4.6
DIANA	$K^+Xe \rightarrow K^0p X$	1539 +- 2	< 9	4.4
CLAS	$\gamma d \rightarrow K^+K^-p(n)$	1542 +- 5	< 21	5.2
SAPHIR	$\gamma p \rightarrow K^+K^0(n)$	1540 +- 6	< 25	4.8
ITEP	$\nu A \rightarrow K^0p X$	1533 +- 5	< 20	6.7
CLAS	$\gamma p \rightarrow \pi^+K^-K^+(n)$	1555 +- 10	< 26	7.8
HERMES	$e^+d \rightarrow K^0p X$	1526 +- 3	13 +- 9	~5
ZEUS	$e^+p \rightarrow e'K^0p X$	1522 +- 3	8 +- 4	~5
COSY	$pp \rightarrow K^0p\Sigma^+$	1530 +- 5	< 18	4-6

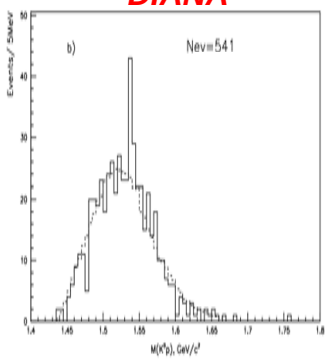
*Gaussian statistical significance: estimated background fluctuation

Evidence for Pentaquark States

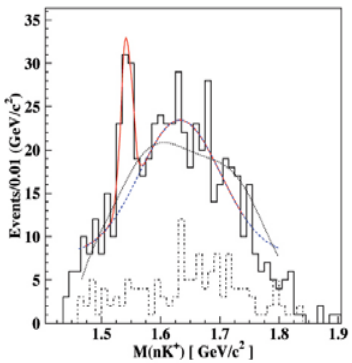
Spring8



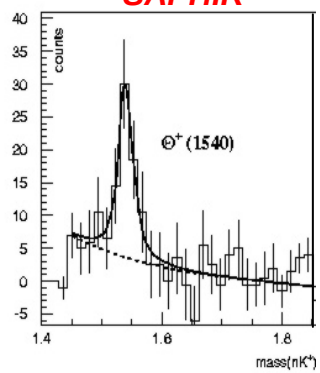
DIANA



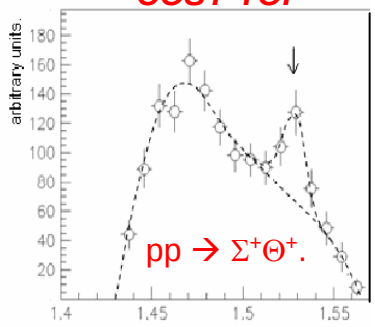
JLab-d

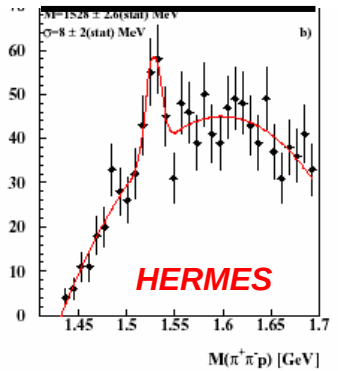


SAPHIR

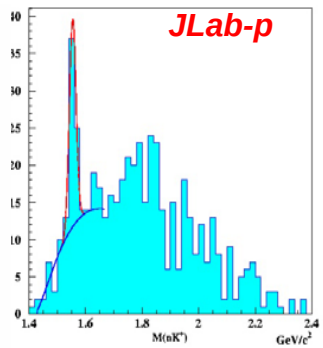


COSY-TOF

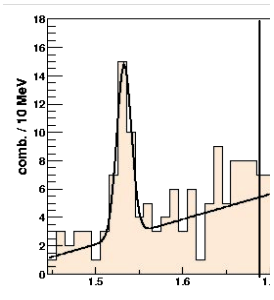




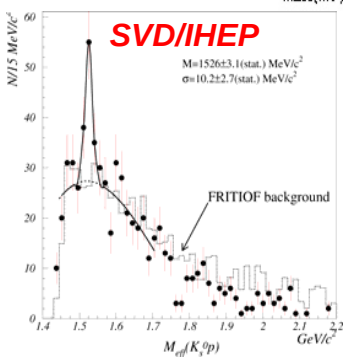
JLab-p



ITEP

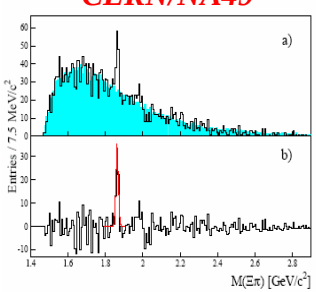


SVD/IHEP

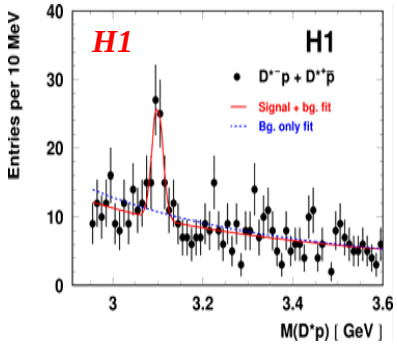


This is a lot of evidence

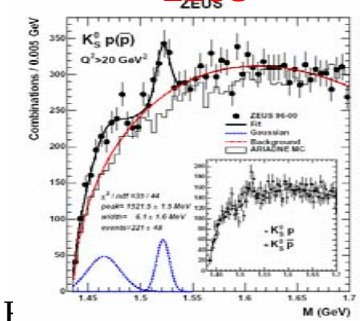
CERN/NA49



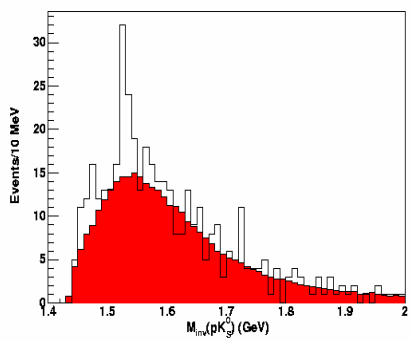
H1



ZEUS



Nomad



Critical Comments

- For many experiments, the background shape is not clearly known.
- Some experiments have harsh angle cuts that could affect the mass spectra.
- In all cases, the signal is weak compared with standard resonances.
  - Cuts are necessary to lower background.

Null Results

Production Mechanism?

- If the Θ^+ exists, data suggests it likely favors certain production mechanisms.
  - This is an exotic baryon.
  - It may have an exotic production mechanism.

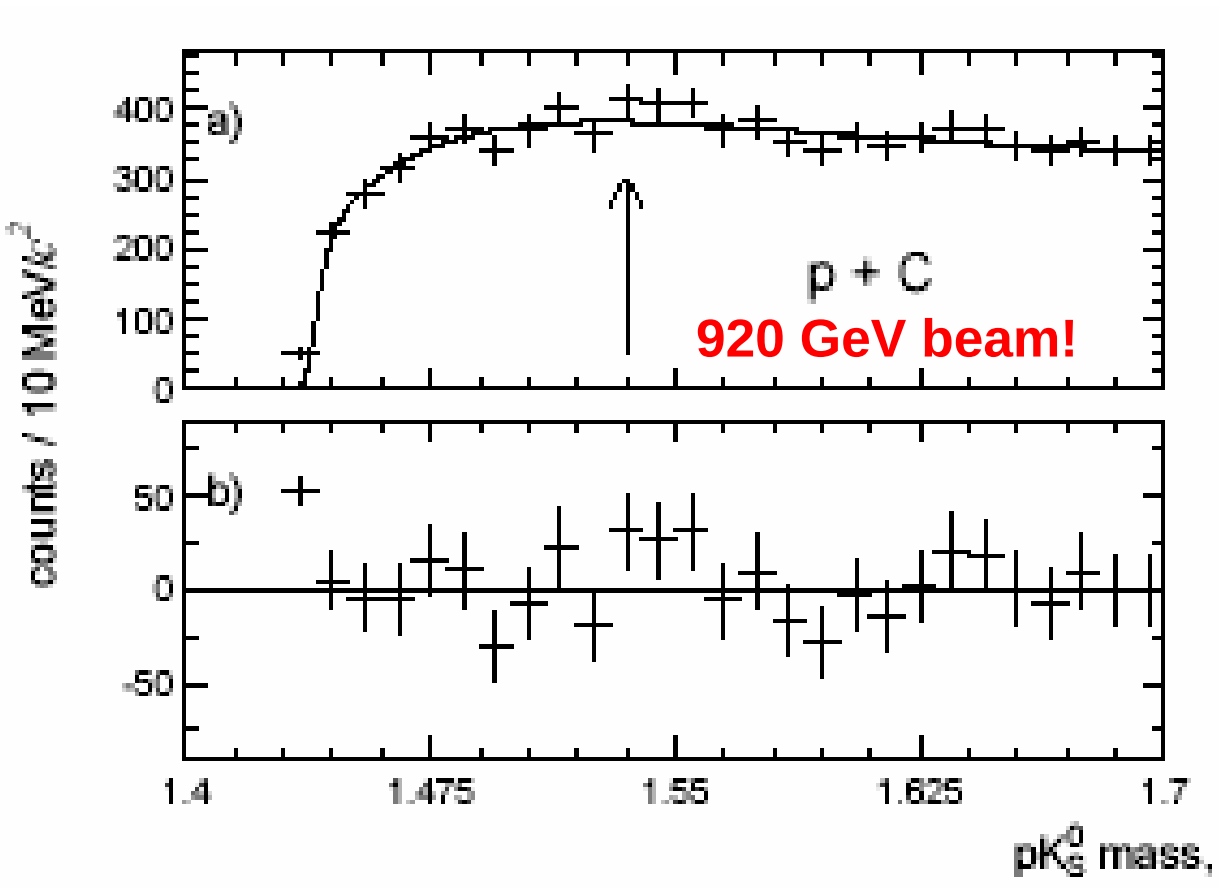
Published Null Experiments

Group	Reaction	Limit	Sensitivity?
BES e^+e^-	$J/\Psi \rightarrow \Theta\Theta^*$	$<1.1\times10^{-5}$	No?
Belle e^+e^-	$\Psi(2S) \rightarrow pK^0$	$<0.6\times10^{-5}$	??
BaBar e^+e^-	$\Upsilon(4S) \rightarrow pK_s^0$	$<1.1\times10^{-4}$	??
ALEPH	$e^+e^- \rightarrow Z \rightarrow pK_s^0$	$<0.6\times10^{-5}$	??
HERA-B	$pA \rightarrow pK_s^0X$	$<0.02\times\Lambda^*$	No?
CDF	$pp^* \rightarrow pK_s^0X$	$<0.03\times\Lambda^*$	No?
HyperCP	$pCu \rightarrow pK_s^0X$	$<0.3\%\ K^0p$	No?
PHENIX	$AuAu \rightarrow n^*K^-$	not given	??
Belle	$K^+Si \rightarrow pK_s^0X$	$<0.02\times\Lambda^*$	Yes?

Θ^+: Null Results

HERA-B data on Carbon target: invariant mass of pK^0 shows no Θ^+ peak.

Could kinematics be an issue? If Θ^+ is not produced by fragmentation, HERA-B may not see it.



Critical Comments

- Inclusive versus Exclusive measurement
  - inclusive has better resolution, but more background (especially at higher energy)
- Backgrounds: combinatorial and from other resonances. Can we estimate?
- Production mechanism: projectile or target fragmentation?
  - Is it calculable in some model?

Titov: inclusive production

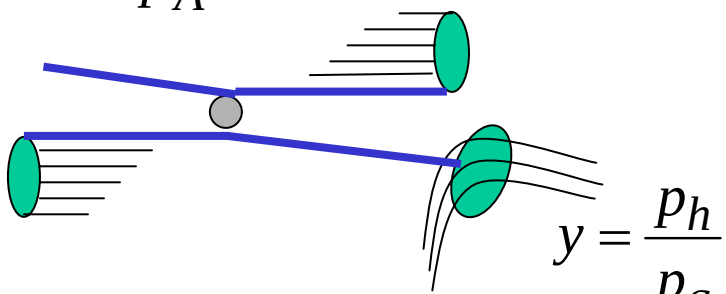
(fragmentation region)

$$x = \frac{p_q}{p_A}$$

fast slow

$$NN \to (N\ldots)(\Theta^+ \overline{K}\ldots)$$

$$NN \to (N\ldots)(\Lambda K\ldots)$$



$$y = \frac{p_h}{p_q}$$

Ratio: pentaquark to baryon production

Regge exchange dominates

(2 = diquarks as quasi-partons)

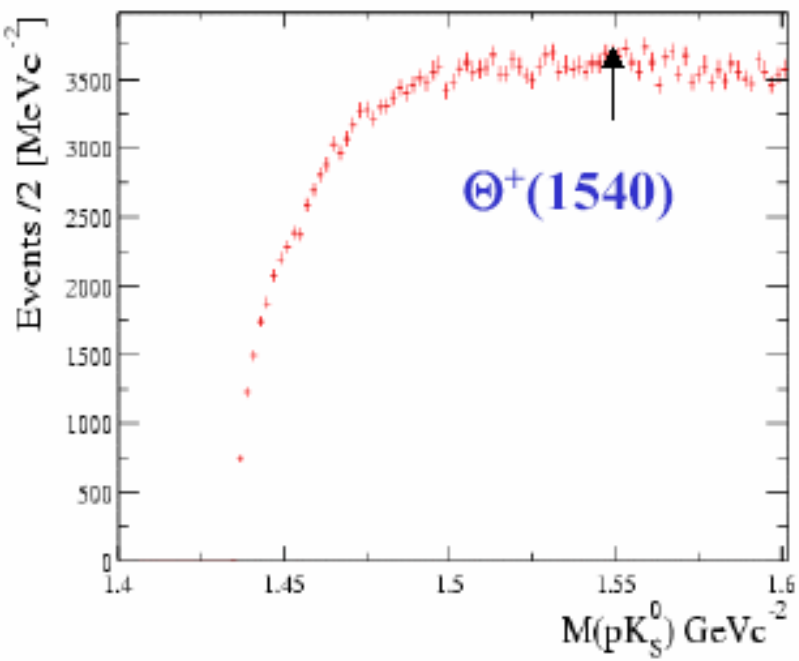
$$R_{\Theta\Lambda} \propto (1-z)^{4(2)}; \quad z = \frac{p_h}{p_{h\max}}; \qquad z \approx 0.7$$

$$10^{-3} \le R_{\Theta\Lambda} < 2.4 \cdot 10^{-2}$$

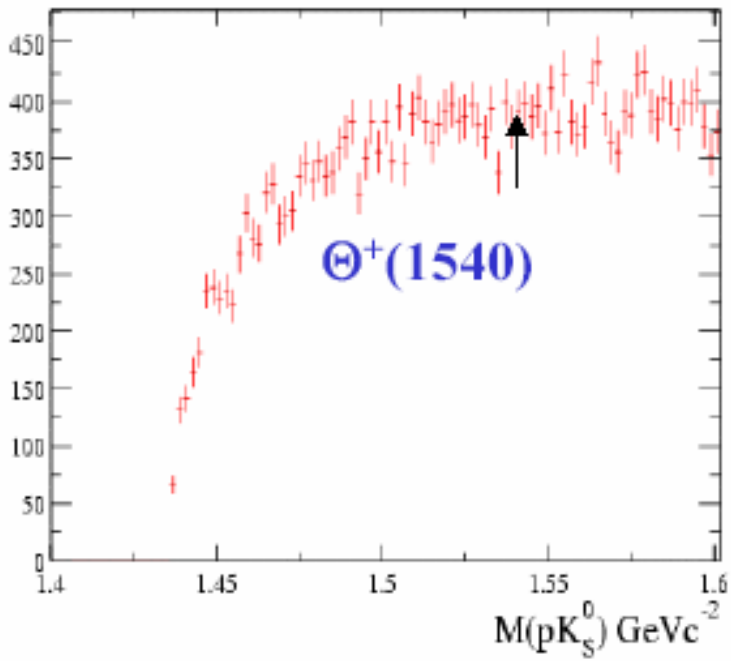
$\Theta^+(p\,K_s)(1540)$ Invariant Mass

No signal observed in any p* region (SFL > 0.0 cm)

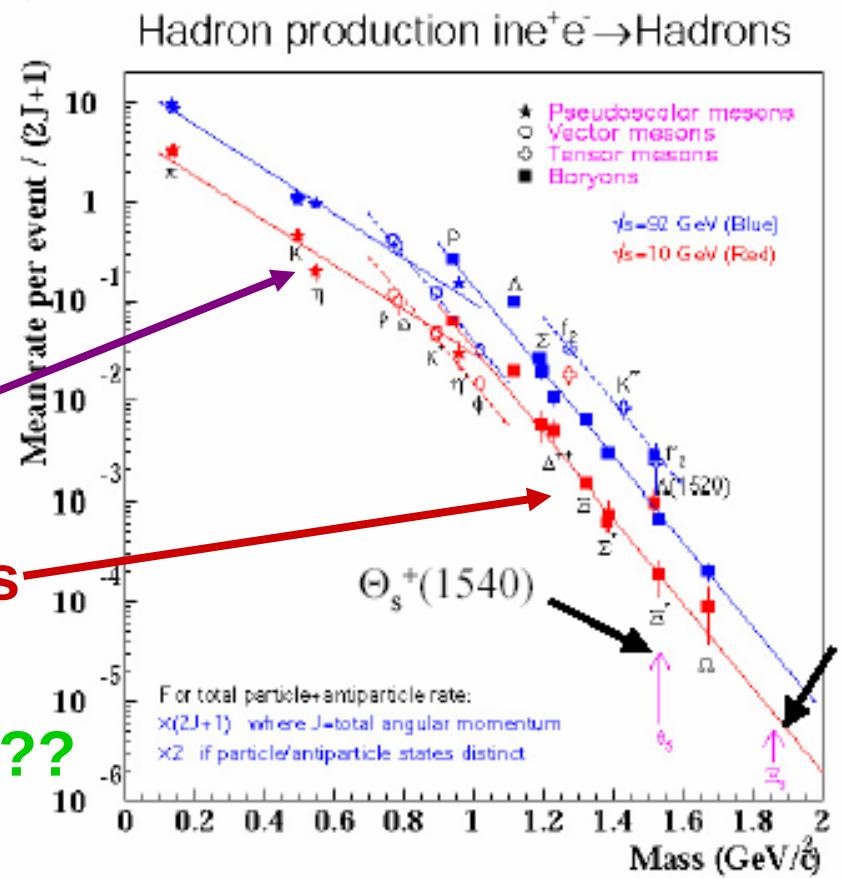
0.0 < p* < 0.5 GeV/c



3.5 < p* < 4.0 GeV/c



Hadron Rate in e^+e^- → Hadron



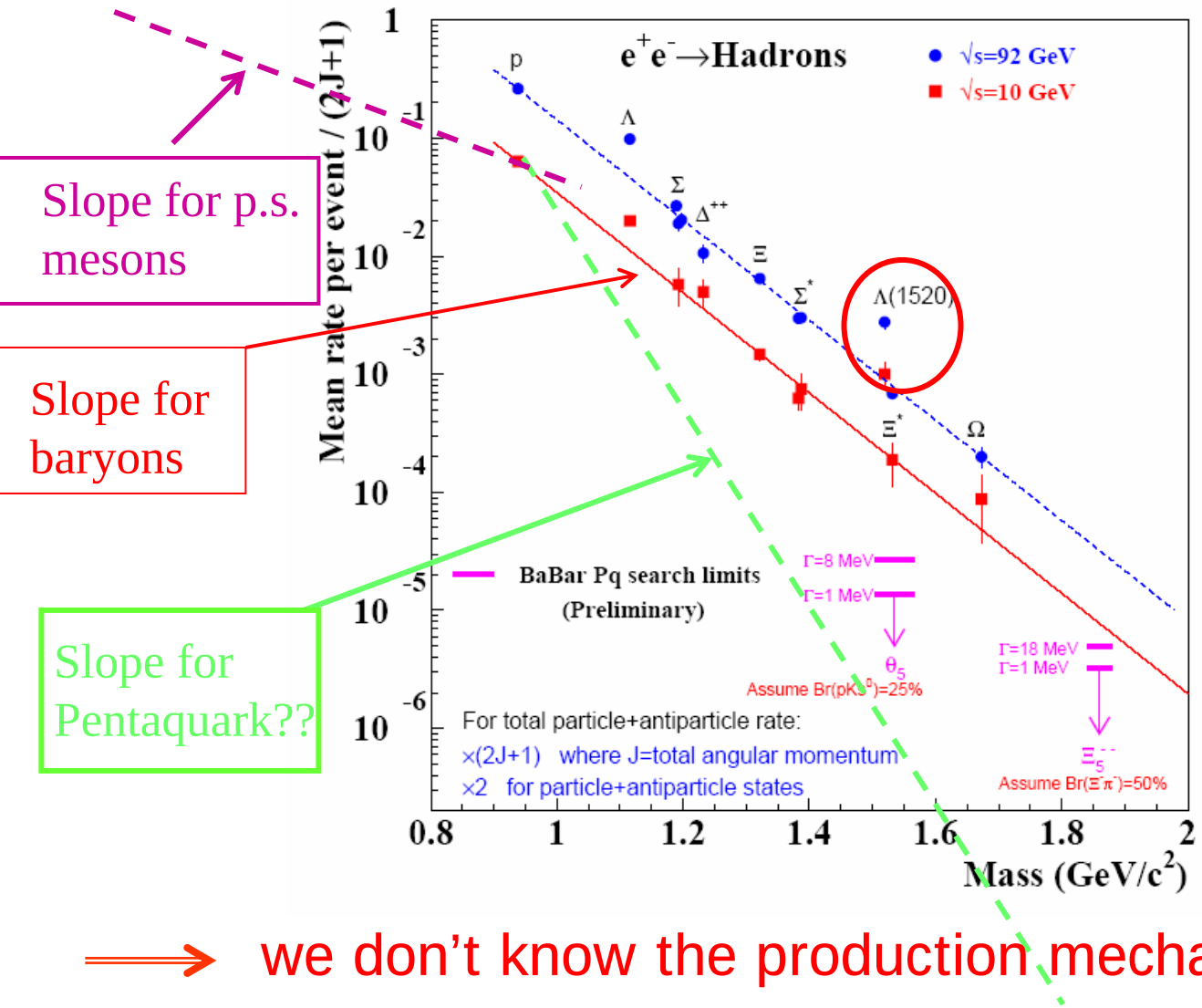
Slope for mesons

Slope for baryons

Slope for pentaquarks??

Assuming the Pentaquark production is the same as baryon production we expect the total production of Θ_s^+, Ξ_5^{--} per event continuum to be $\Theta_s^+ = 7 \times 10^{-4}$, $\Xi_5^{--} = 3. \times 10^{-5}$

Hadron production in e^+e^-



Slope:

Pseudoscalar mesons:

~ 10^{-2}/GeV/c^2 (need to generate one $q\bar{q}$ pair)

Baryons:

~ 10^{-4} /GeV/c^2

(need two more pairs)

Pentaquarks:

~ 10^{-6} /GeV/c^2 (?)

(need 4 more pairs)

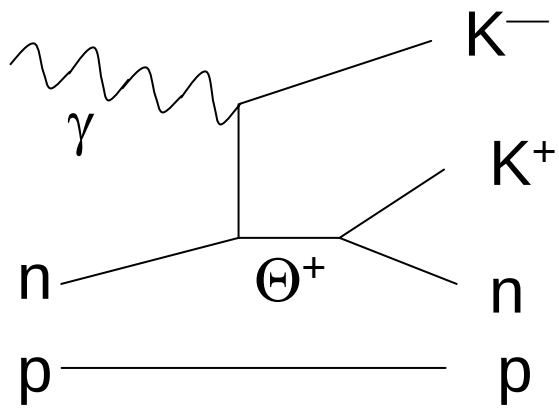
⟹ we don't know the production mechanism!!

The published CLAS data

Detected nuclear reactions

$$\gamma n\,(p) \rightarrow \Theta^{+} K^{-}\,(p)$$

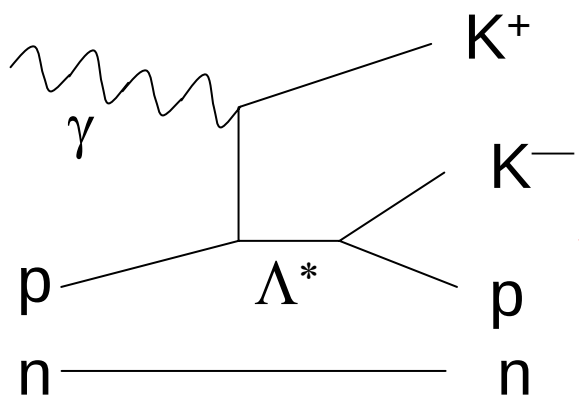
$$\Theta^{+} \rightarrow K^{+} n$$



S = -1

$$\gamma p\,(n) \rightarrow \Lambda^{*}(1520) K^{+}\,(n)$$

$$\Lambda^{*}(1520) \rightarrow K^{-} p$$

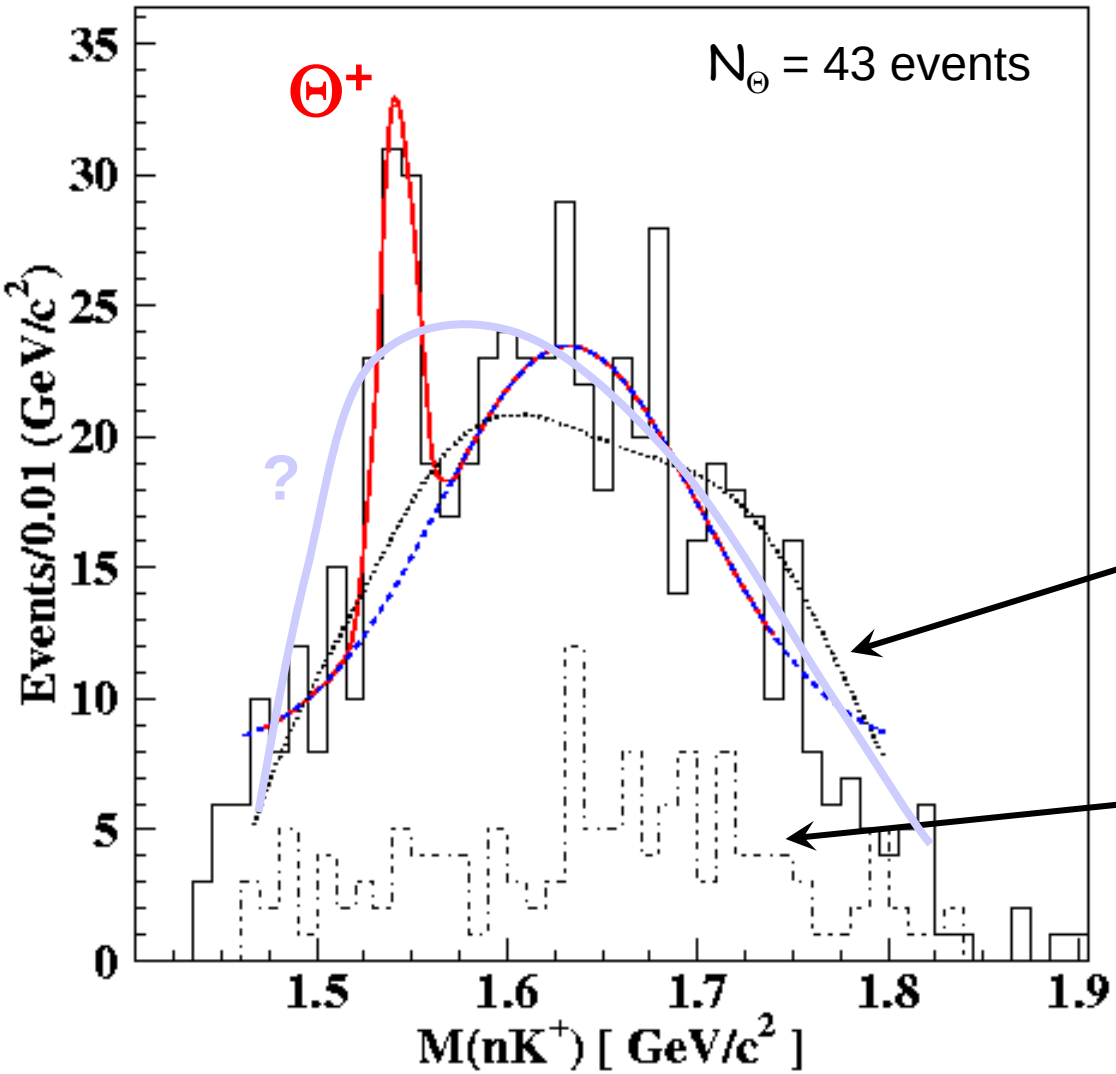


S = +1

$$\gamma N \rightarrow \phi(1020)\, N \rightarrow K^{+} K^{-}\, N$$

background

CLAS: γ d --> K^+ K^- p (n)



Mass = 1.542 GeV

Γ< 21 MeV

Significance 5.2±0.6 σ

Significance = ?

Two different background shapes

Events in the Λ(1520) peak.

Official CLAS statement

- "Further analysis of the deuterium data find that the significance of the observed peak may not be as large as indicated."
  - We really need a calculation of the background before the statistical significance of the peak can be known.
- **Eventually the new experiment, with much higher statistics, will settle the question.**
  - The g10 experiment (x10 statistics) is now finished.

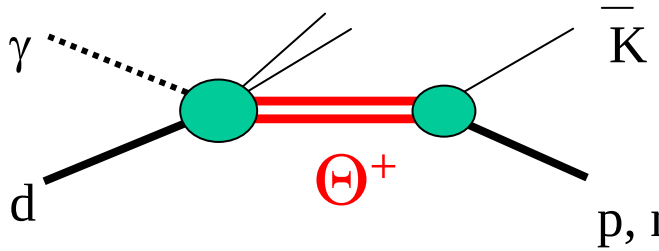
New CLAS deuterium data

"G10" run: March 13 - May 16, 2004

- Tagged photons in the energy range from 0.8 GeV to 3.59 GeV;
- Target – 24 cm long liquid deuterium at Z=-25cm;
- Trigger – two charged particles in CLAS.
- Data are taken at 2 settings of CLAS toroidal magnet.
- At each setting integrated luminosity ($25 pb^{-1}$) is about 10 times higher than in published deuterium data.

Analysis strategy for the Θ^+:

- Independent analysis of several reactions by different groups;



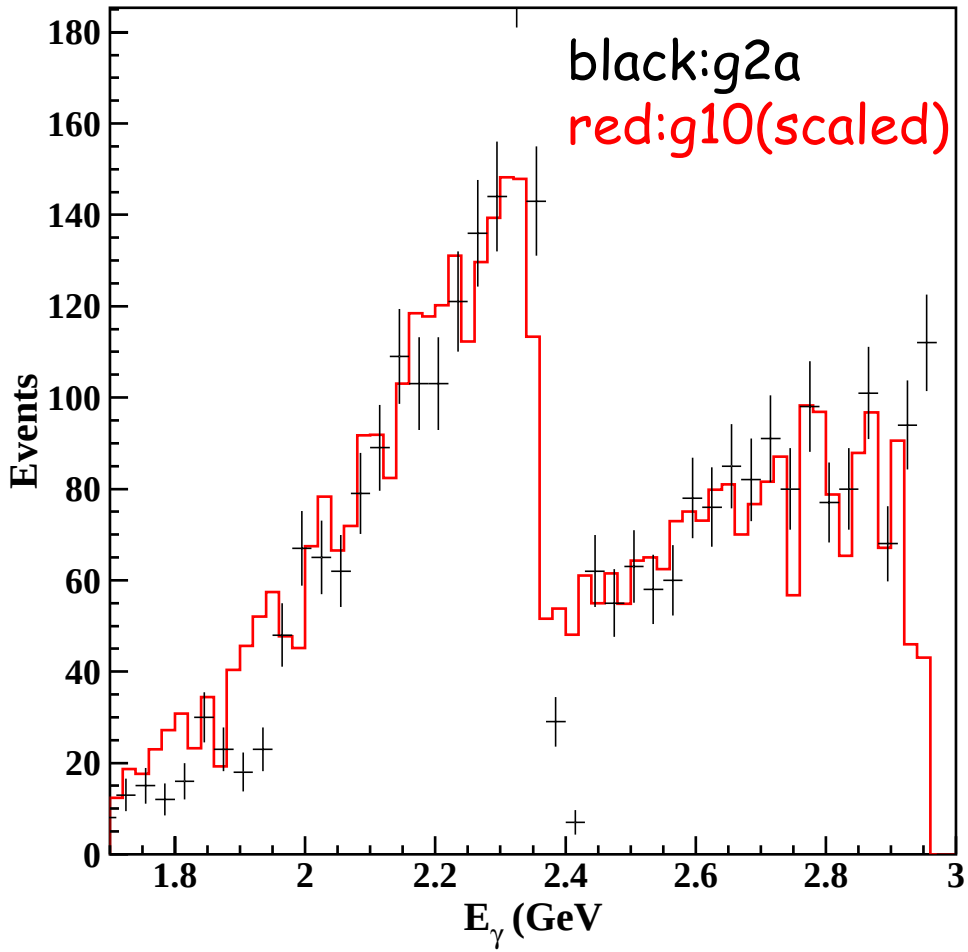
detected final states

$\gamma + d \to p + K^- + K^+ + n; \Theta^+ \to nK^+$	pK^-K^+
$\gamma + d \to \Lambda^0 + K^{+(0)} + n(p); \Theta^+ \to nK^+, pK_S^0$	$p\pi^-K^+; pp\pi^+\pi^-$
$\gamma + d \to p + \pi^+ + \pi^- + K^-; \Theta^+ \to pK_S^0; K_S^0 \to \pi^+\pi^-$	$p\pi^-\pi^+K^-$
$\gamma + "n" \to K^- + K^+ + n; \Theta^+ \to nK^+$ Fermi momentum corrections	K^-K^+

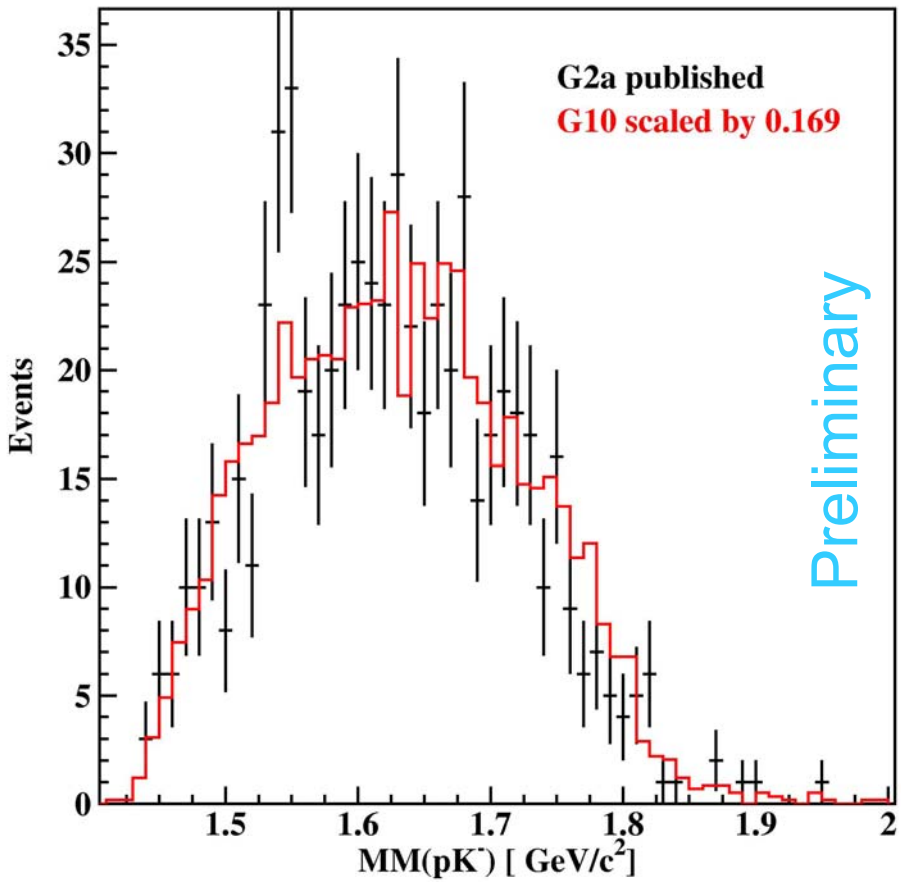
- Work on cross section upper limit estimate in other channels is in progress. Requires acceptance simulations for each final state.

Comparison with published data

- Nearly identical event selections are applied to g10 data.
  - Timing cuts, missing neutron mass cut are momentum dependent in g10 analysis.
  - Fiducial cut on K- to take into account the difference of acceptance due to the target position.
  - Other cuts are same.
- Photon energy is matched to the g2a beam energy.
  - g10 ran in higher photon energy than g2a.



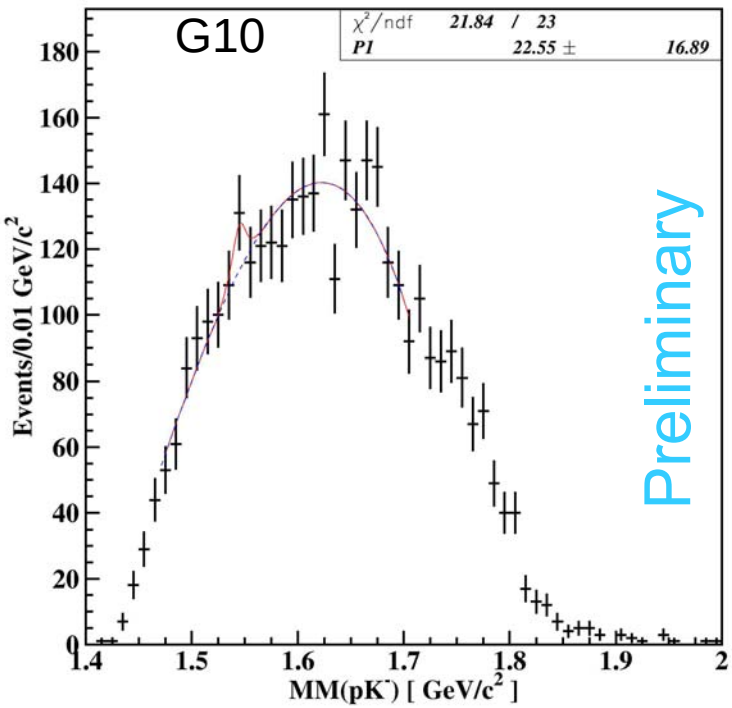
MM(pK^-) distributions

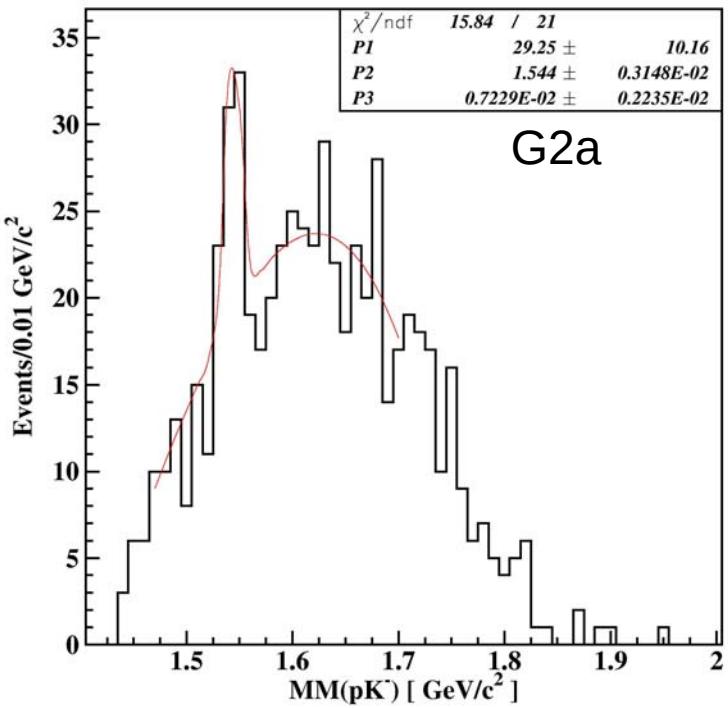


- Two distributions statistically consistent with each other:
  - 26% c.l. for null hypothesis from the Kolmogorov test (two histograms are compatible).
  - Reduced χ^2=**1.15** for the fit in the mass range from 1.47 to 1.8 GeV/c^2
- G10 mass distribution can be used as a background for refitting the published spectrum.

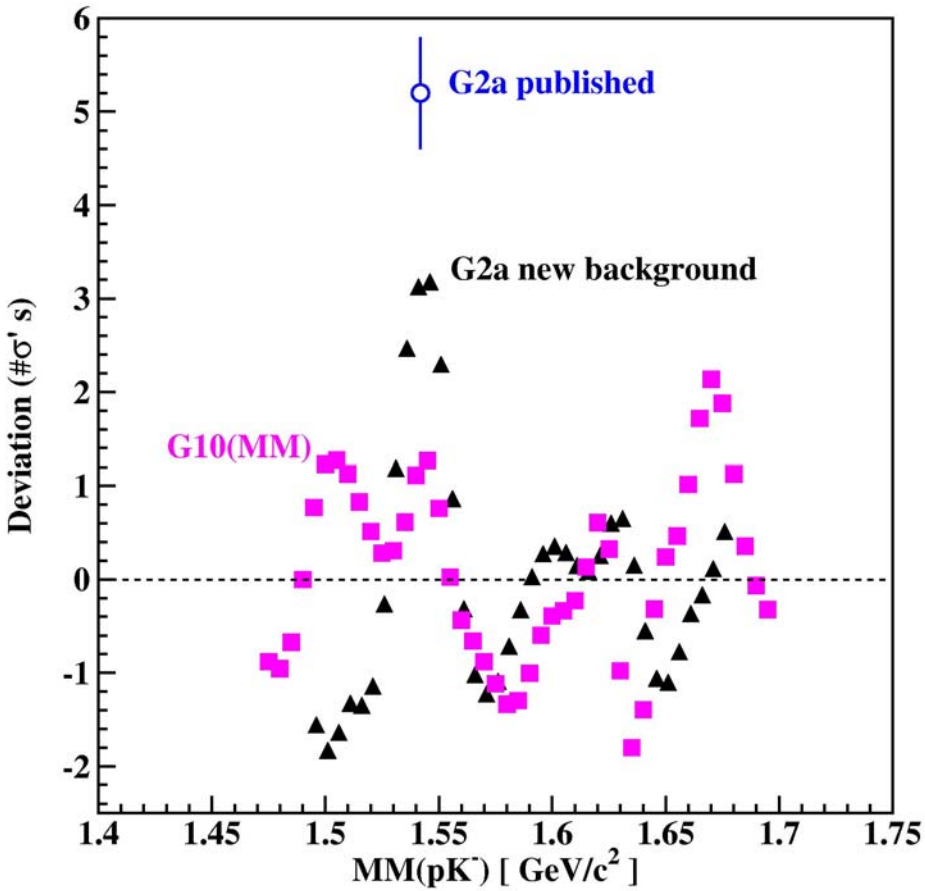
Fit to the MM(pK$^-$) distributions

- The same 3rd degree polynomial as a background in both fits (for g2a function was scaled by x5.9).
- For the fit to the g10 distribution Gaussian, the sigma was fixed to the known CLAS resolution (determined from MC and fits to other peaks).





Can the peak seen in the g2a data be reproduced at higher statistics?



- Published results on Θ^+ from analysis of g2a data cannot be reproduced in the analysis of high statistics g10 data.
- The statistical significance in the published data is an unlucky coincidence of a statistical fluctuation and an underestimate of the background in the mass region of 1.54 GeV/c^2.

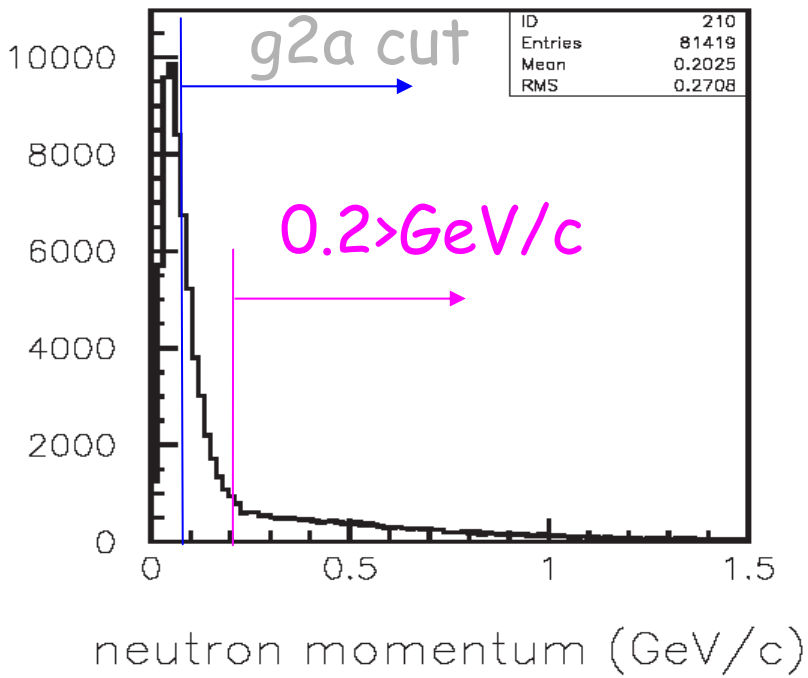
The second question

- Beyond g2a conditions, is there statistically significant evidence for the Θ^+?

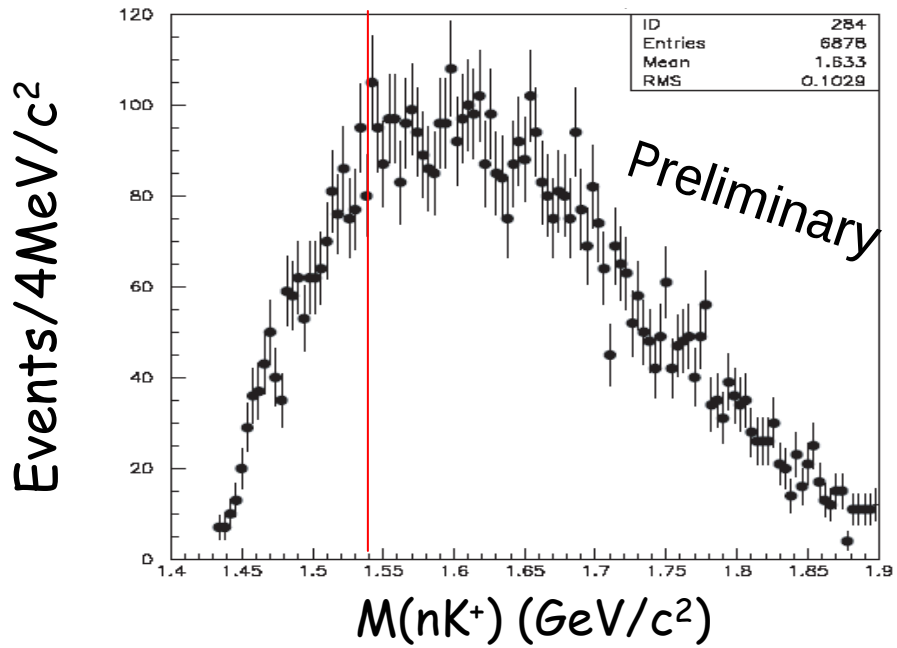
Data Set	Electron Beam Energy	Torus Current	Triggers
g2a	2.478 GeV	3375 A	1477.7 M
	3.115 GeV	3375 A	547.1 M
g10	3.767 GeV	2250 A	4495.6 M
	3.767 GeV	3375 A	4936.9 M

Missing momentum cut

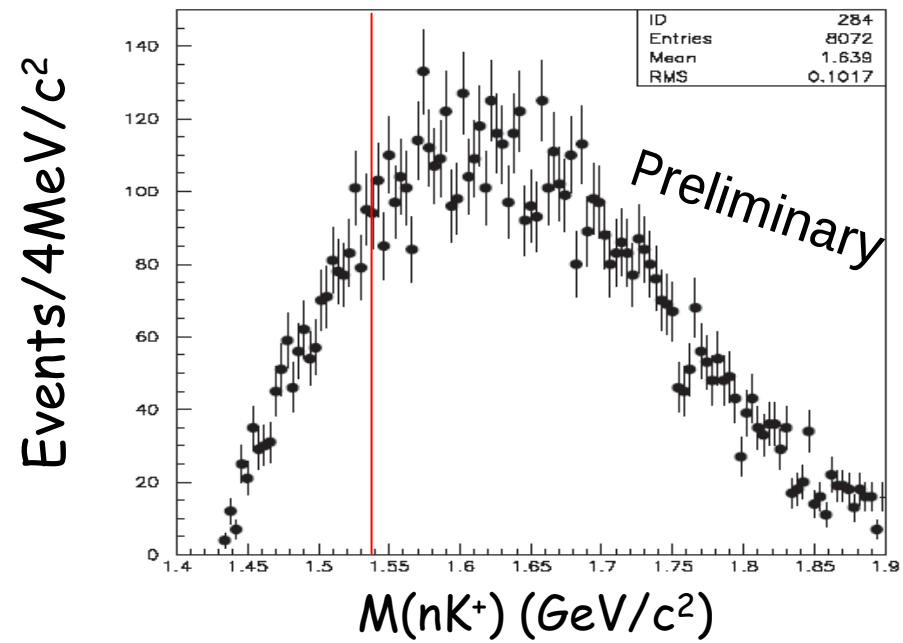
G10 (3375A), All E_γ



G10 (3375A), pmis>0.2 GeV/c

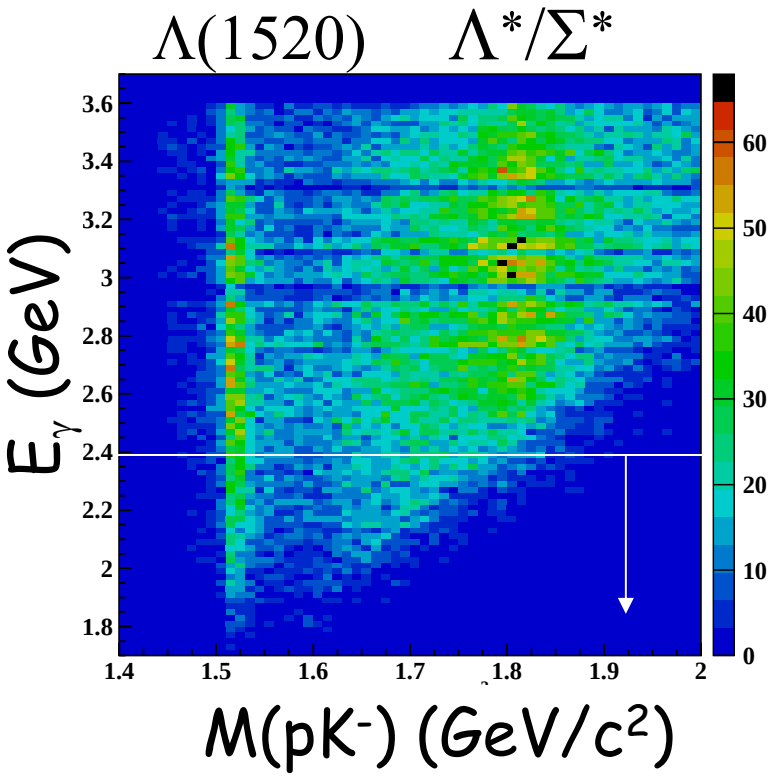


G10 (2250A), pmis>0.2 GeV/c

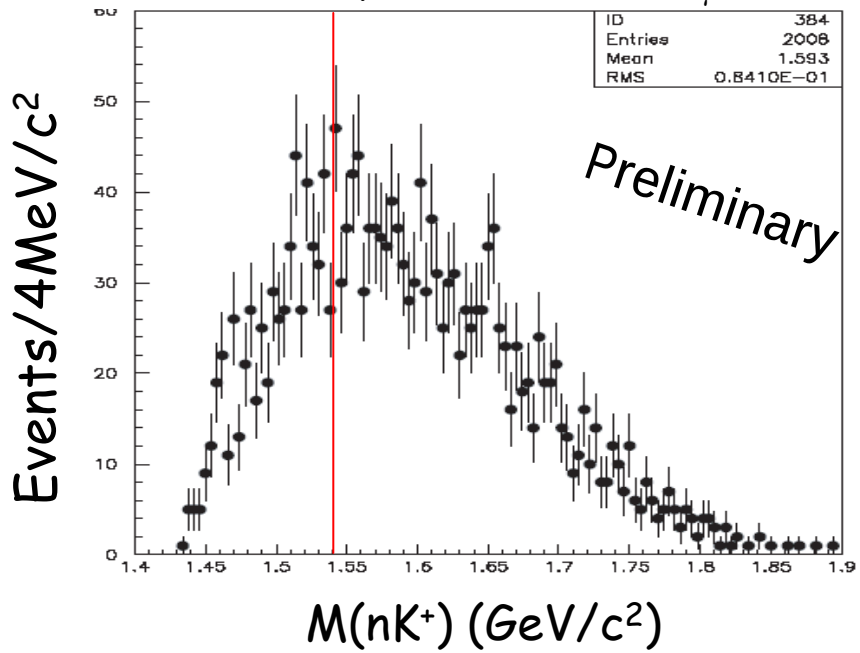


Photon energy cut

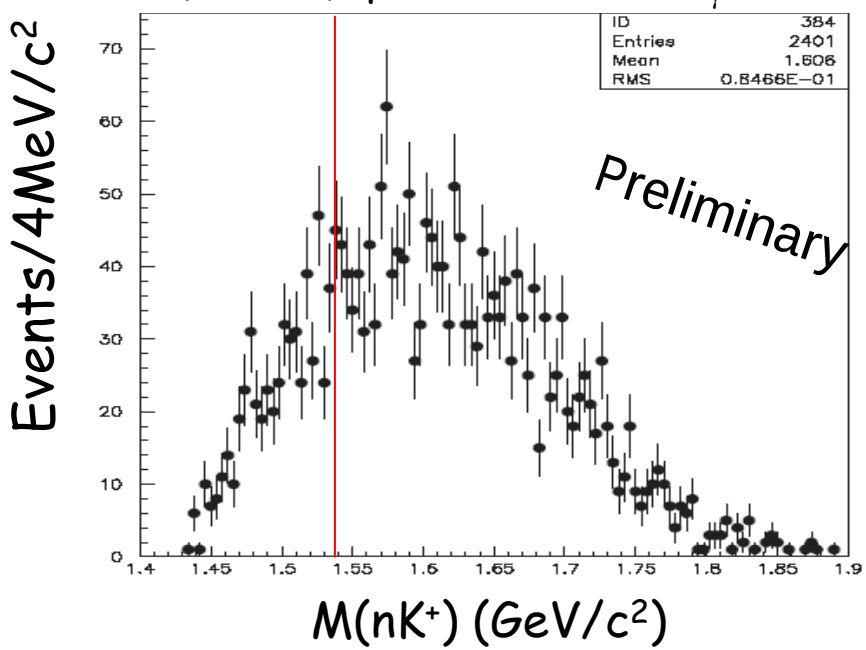
G10 (3375A)



G10 (3375A), pmis>0.2 GeV/c,E_γ<2.4 GeV



G10 (2250A), pmis>0.2 GeV/c E_γ<2.4 GeV



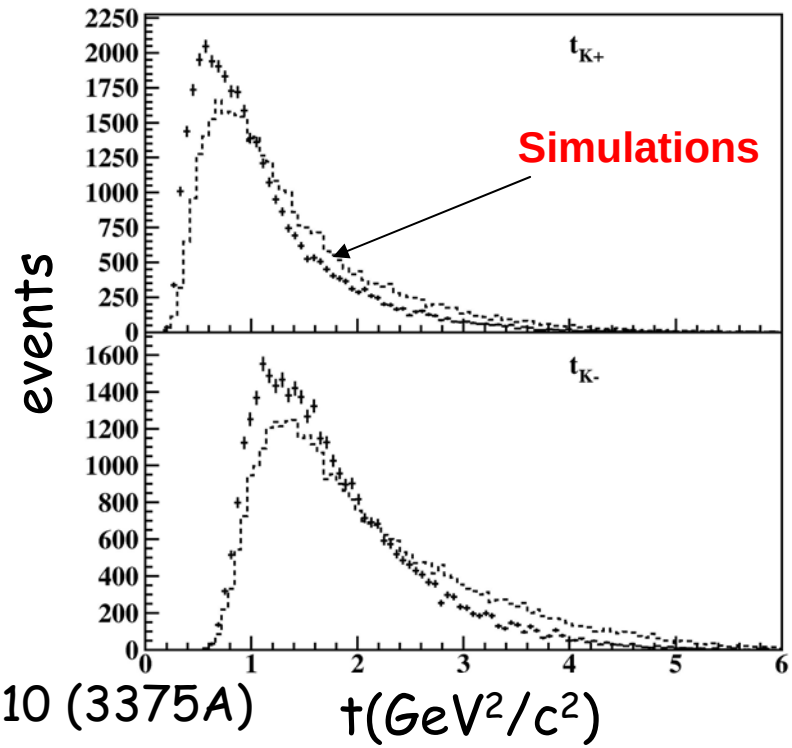
Beyond g2a conditions, is there statistically significant evidence for the Θ^+?

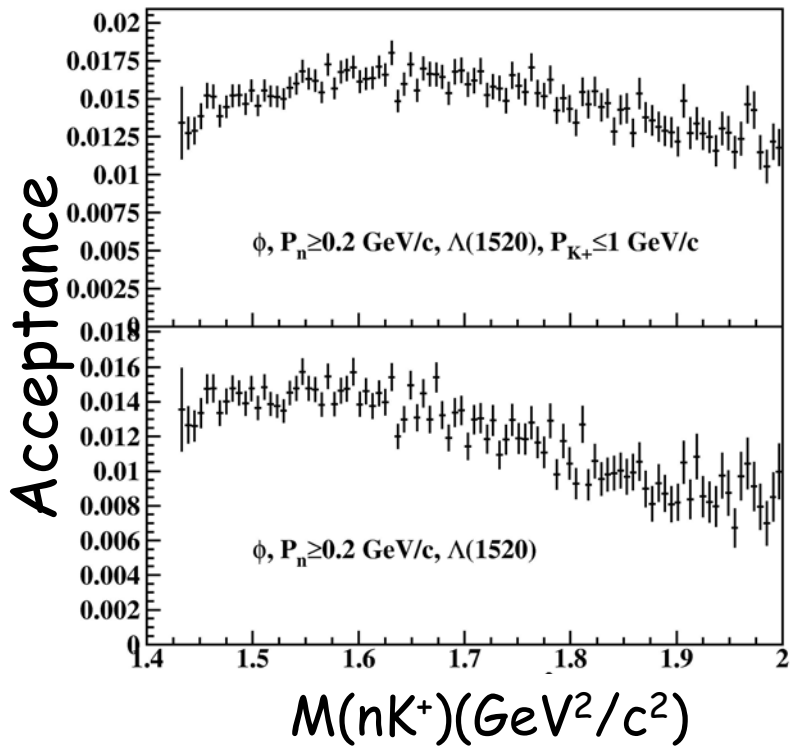
- No peak is found under more constrained kinematical cuts (but not all physically justifiable cuts have been tried).

- Any statistically significant peak must be seen in both the low-field data and the high-field data to be “real”.

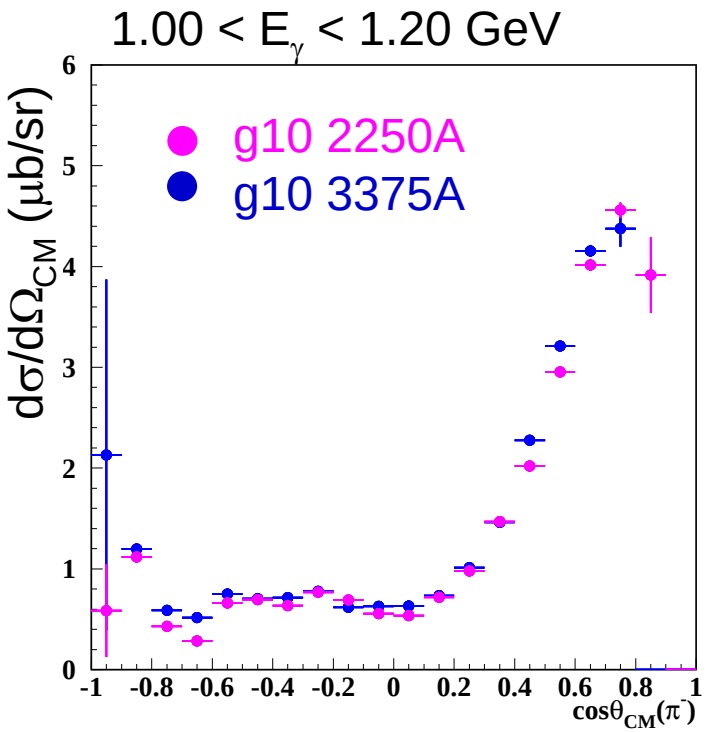
Upper limit of the Θ^+ production cross section in the reaction $\gamma d \rightarrow pK^+K^-(n)$

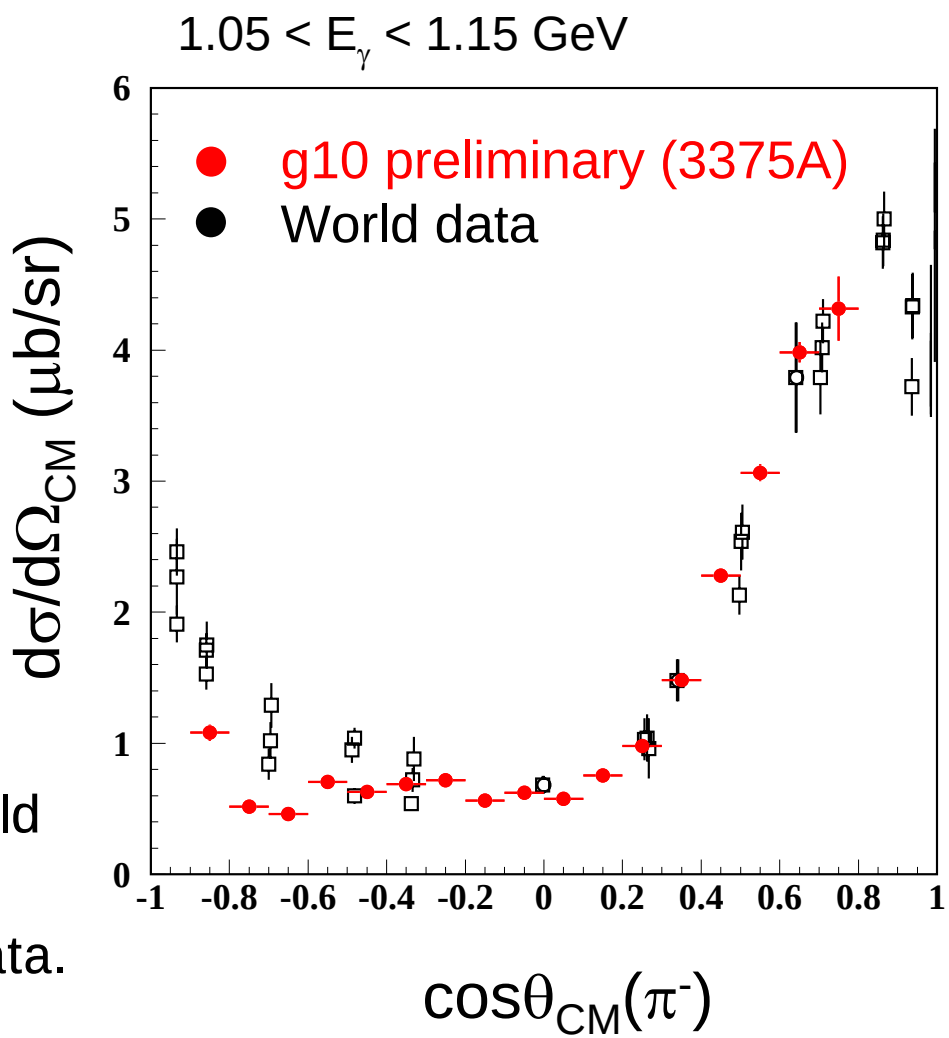
- Number of "signal" events – number of events fluctuating into Gaussian peak over a smooth background (3rd degree polynomial).
- Acceptance calculation – 4 body phase space event generator, modified to match kinematics of detected particles with data.





γ n → p π^- cross section

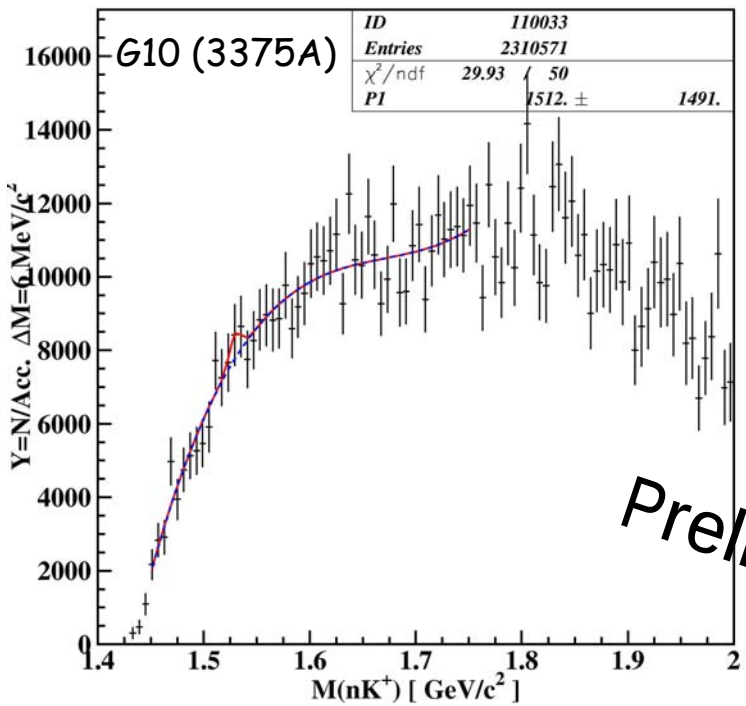


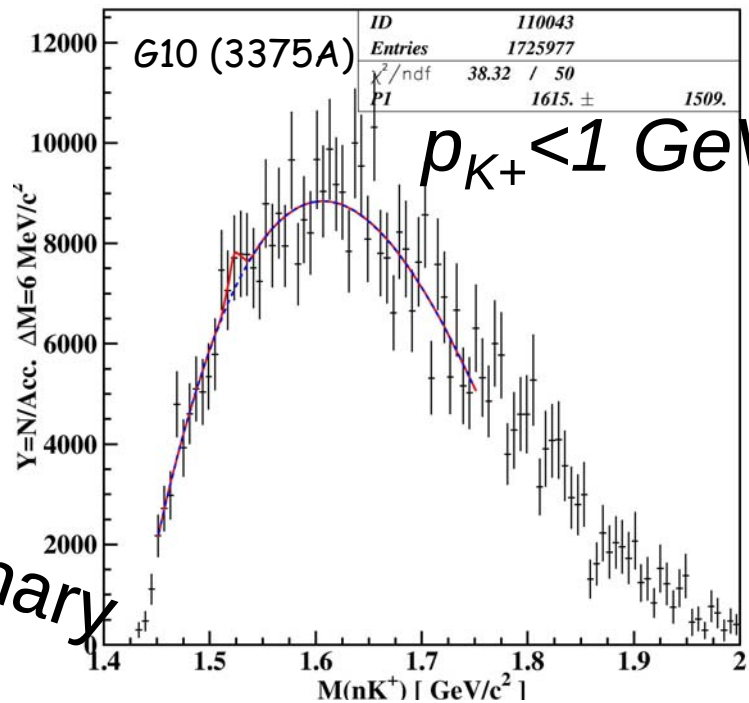


- Consistency between high field and low field data.
- g10 data agree with world data.
- 0.5 % of statistics

Upper limit on cross section for $\gamma d \rightarrow \Theta^+ p K^-$, with $P_p > 0.35$ GeV/c

- Fit with the sum of 3rd degree polynomial and a Gaussian function with fixed width. Gaussian σ=5.5 MeV/c^2, mean running from 1.48 to 1.72 GeV/c^2.
- Cross section upper limit around M(nK^+)=1.525 GeV/c^2 for the reaction **$\gamma d \rightarrow \Theta^+ p K^-$, with $P_p > 0.35$ GeV/c, σ^u=450pb (95.4% CL).**

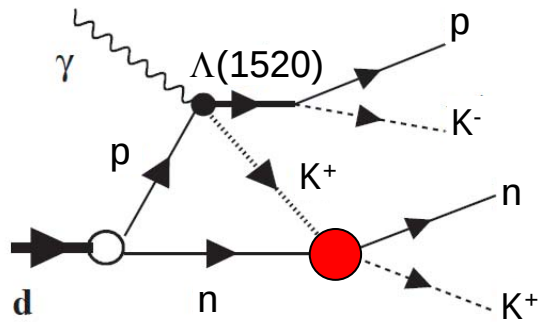




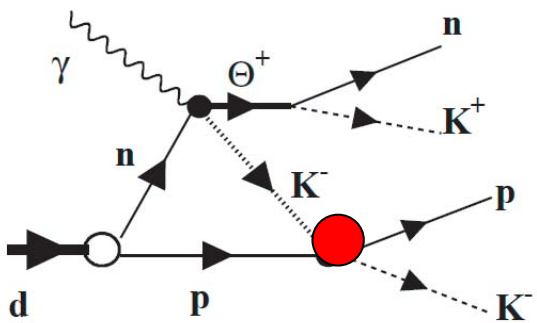
Preliminary

The elementary cross section: $\gamma n \rightarrow \Theta^+ K^-$

- With Fermi momentum being the only source of an energetic spectator proton, the cross section upper limit is **20nb**, $Y/Y_0(0.35)=0.02$.
- A more sophisticated model for an energetic spectator: take the L(1520) production as a guide, the cross section upper limit is **4-5 nb**, $Y/Y_0(0.35)=0.1$.

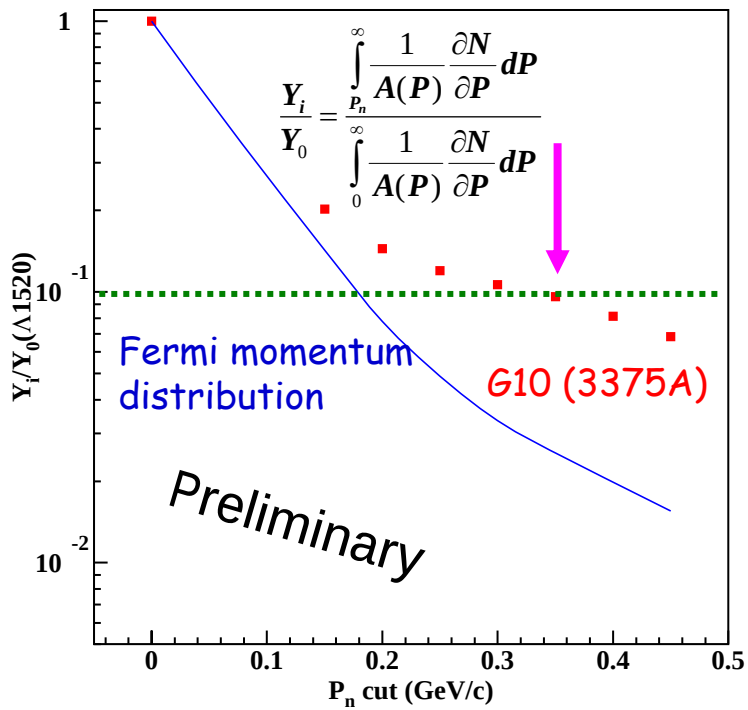


Λ(1520) is produced on the proton, neutron is a spectator.



Θ^+ is produced on the neutron, proton is a spectator.

$$\sigma(\gamma n) = (Y_0 / Y)\sigma(\gamma d)$$



Summary of Deuterium Data

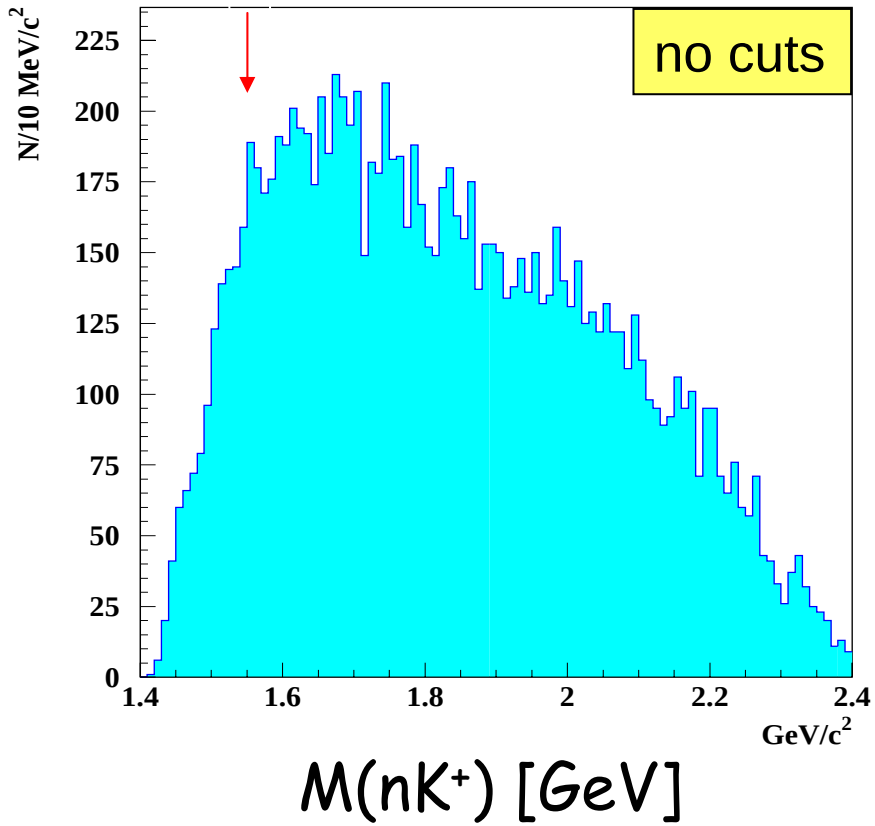
- A search for the Θ^+ in the photon-induced reactions using photons with energies up to 3.6 GeV has been carried out with the CLAS.
- g2a peak cannot be reproduced. No peak is found under more constrained kinematical cuts.
- The upper limit on the measured cross section in the reaction $\gamma d \rightarrow \Theta^+ p K^-$, with $P_p > 0.35$ GeV/c, is about 450 pb (95.4% CL).
- The upper limit on the cross section of the elementary process $\gamma n \rightarrow \Theta^+ K^-$ is 4-20 nb, model dependent.

The CLAS proton data

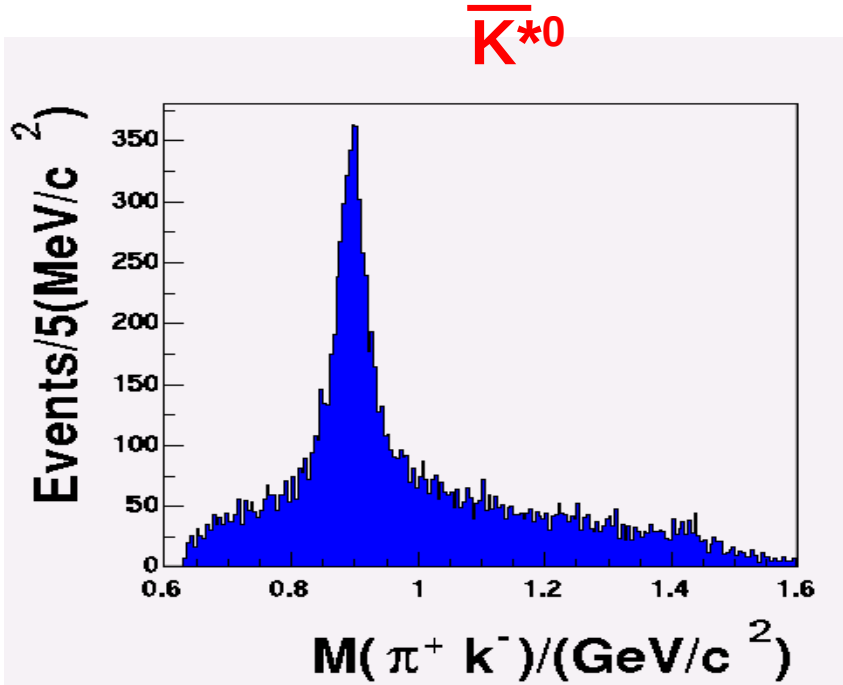
Published: Θ^+ from the proton

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

Prominent $\overline{K}^{*0}$

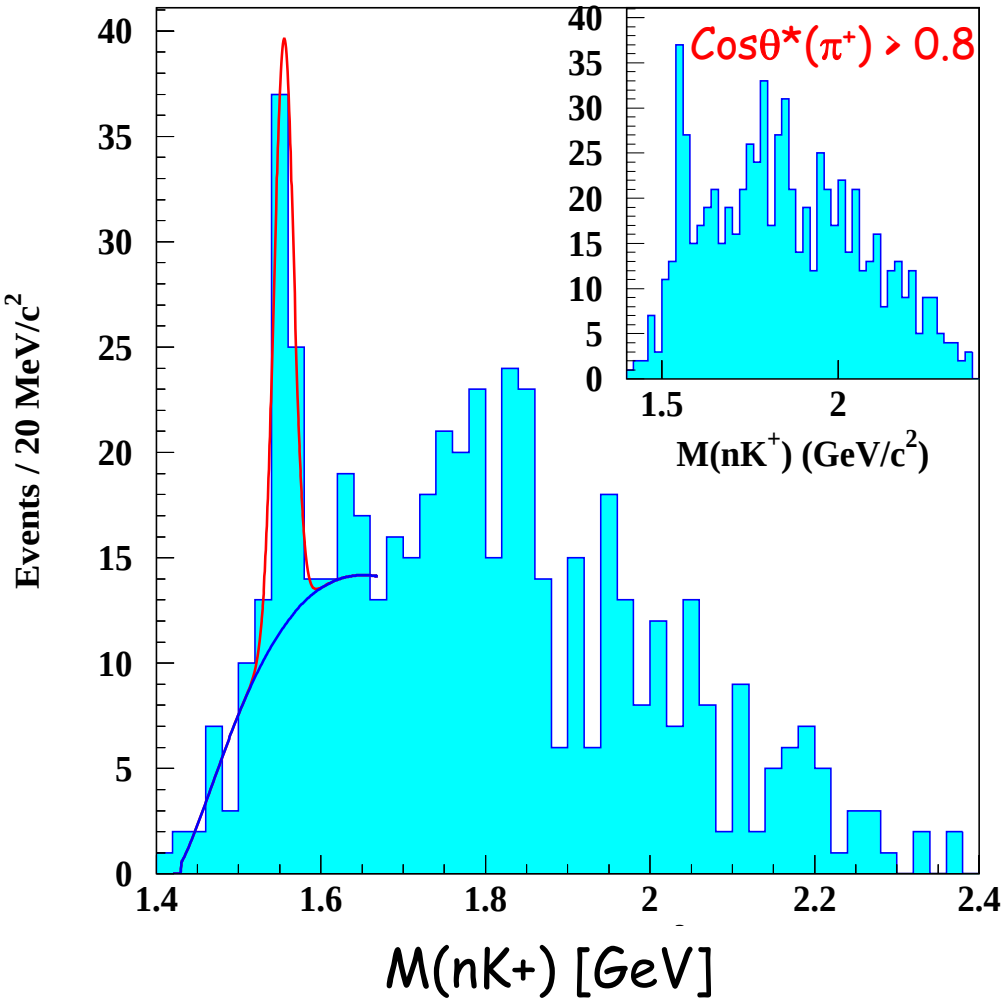


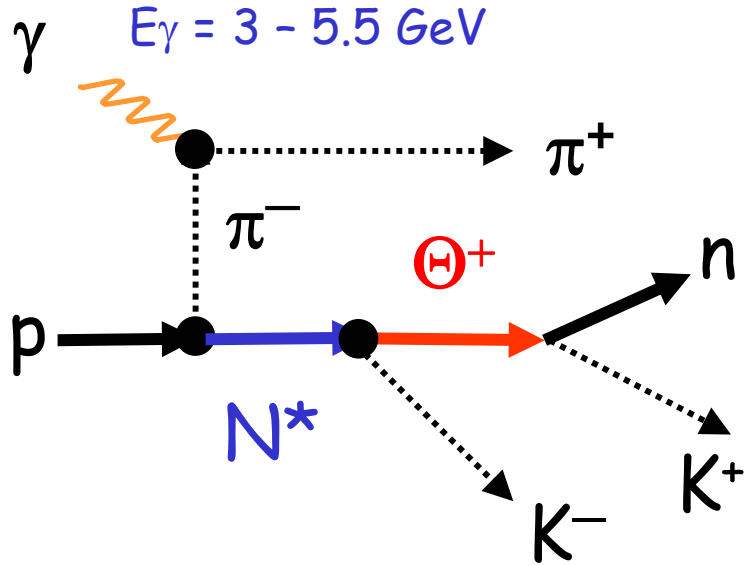
$M(nK^+)$ [GeV]



Published: Θ^+ from the proton

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





M=1555±10 MeV
Γ< 26 MeV

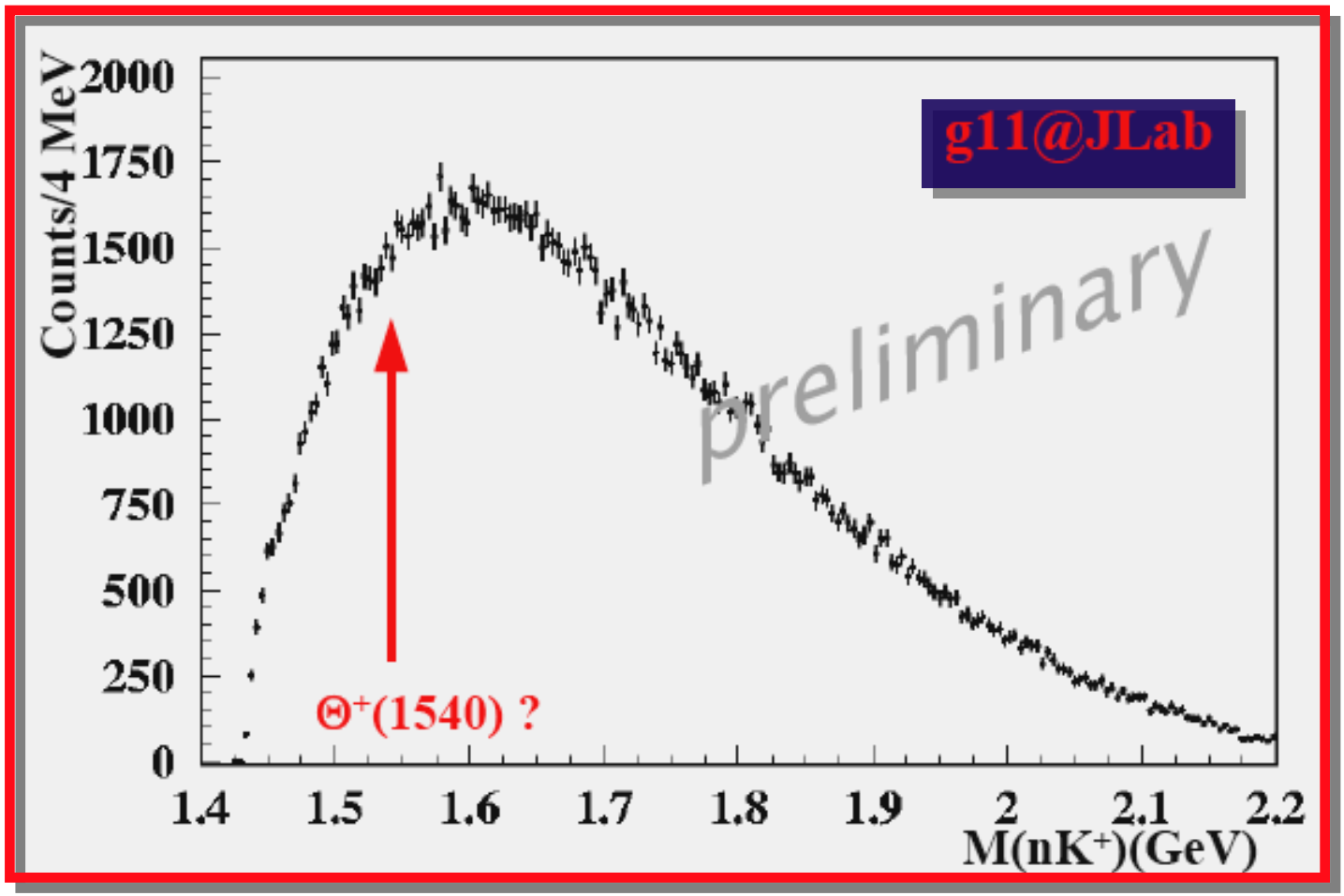
Cosθ*(π+) > 0.8
Cosθ*(K+) < 0.6

CLAS Collaboration
PRL 92, 032001-1 (2004).

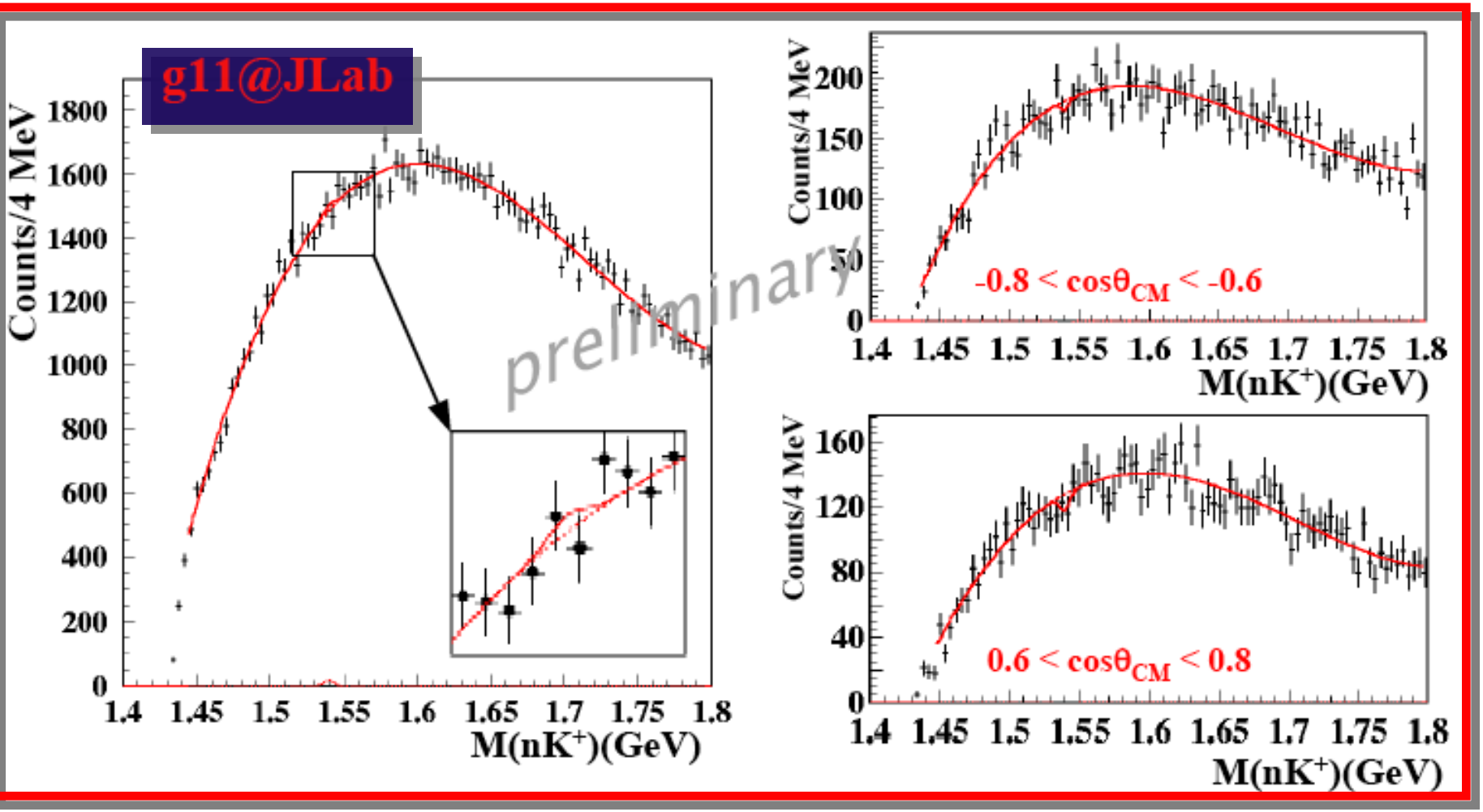
New CLAS Proton Data

γ p --> K^+ K^0 (n)

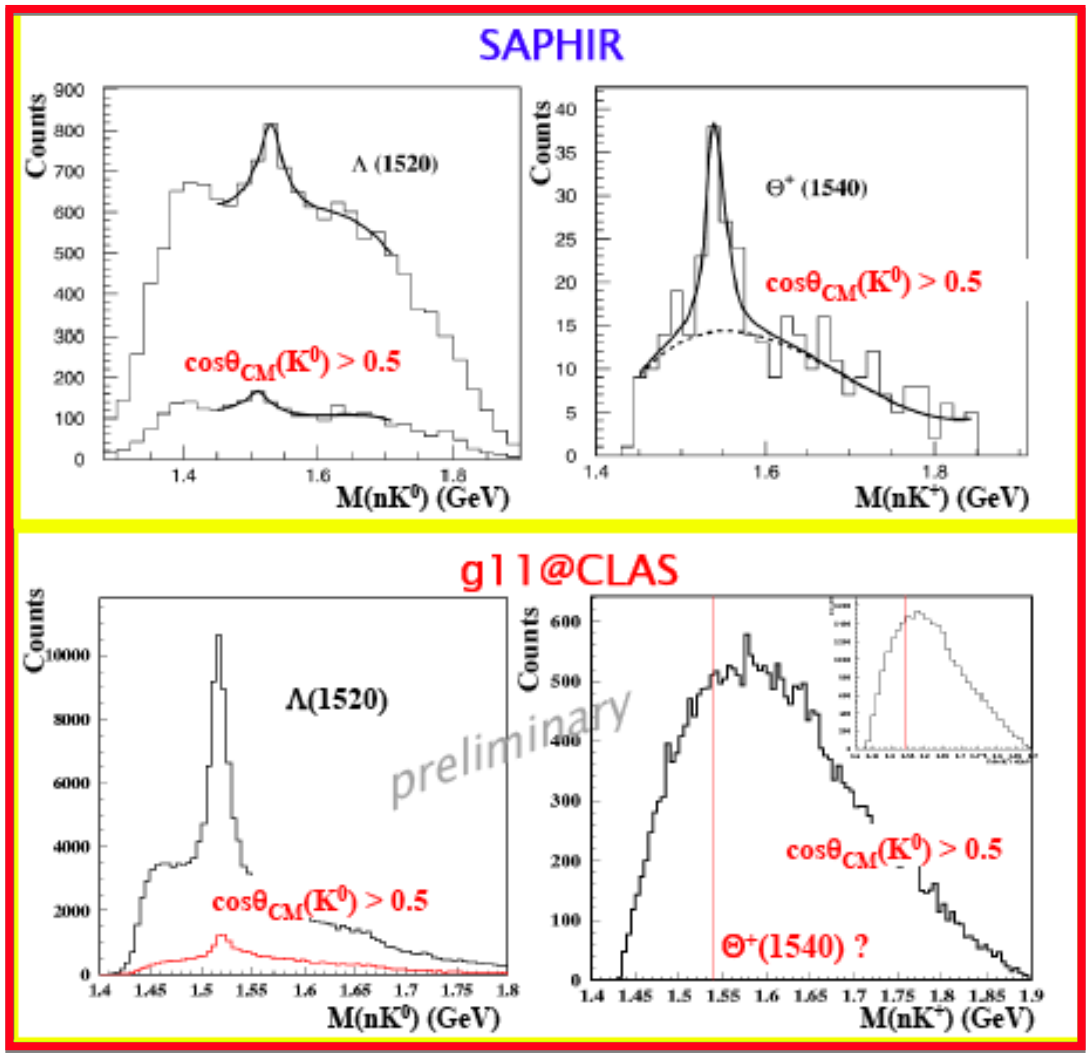
talk by R. DeVita, Tampa APS meeting



Estimating the Upper Limit



Comparison to SAPHIR



SAPHIR

$N(\Theta^+)/N(\Lambda^*) \sim 9\%$

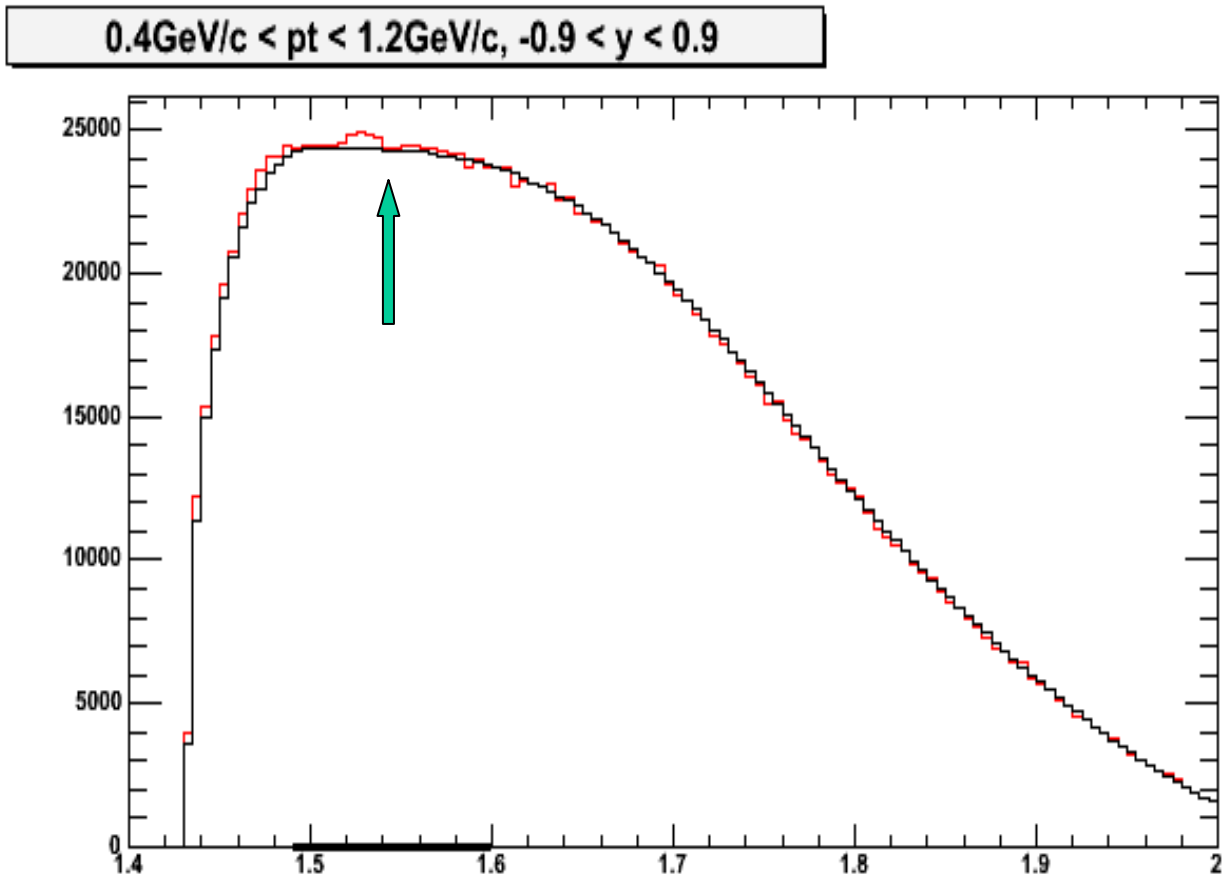
CLAS

$N(\Theta^+)/N(\Lambda^*) < 0.5\%$ (95%CL)

New Claims since April 2005

- STAR Collaboration (Θ^{++})
  - J. Ma, APS meeting, Tampa FL, April 2005
  - Huang, International Conference on QCD and Hadronic Physics, Beijing, June, 2005.
- LEPS Collaboration, SPring-8
  - Reaction γd --> Θ^{+} Λ*(1520)
  - Chiral 2005 (Nakano), APS Tampa (Hicks), QCD Beijing (Nakano).

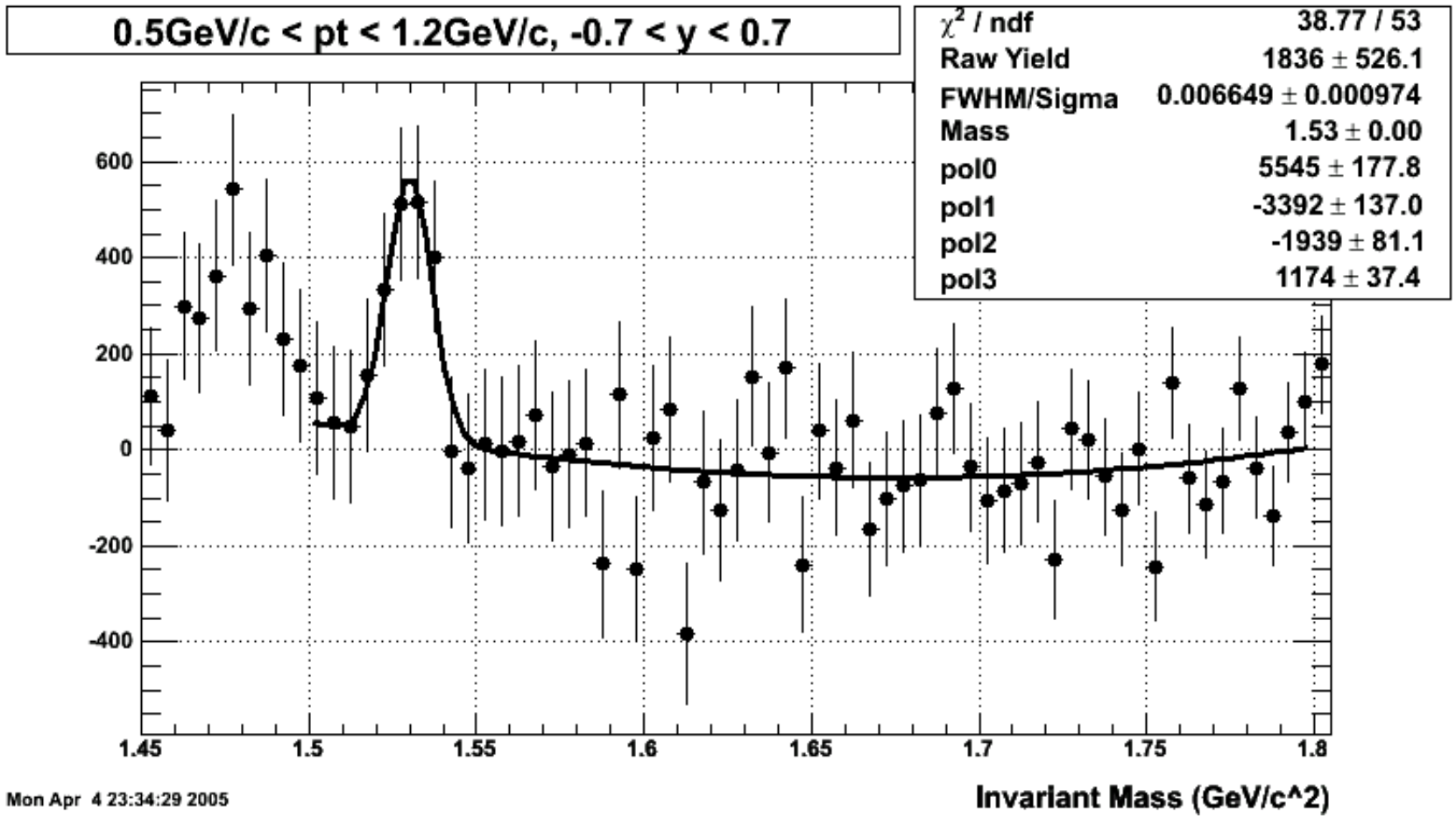
STAR: d+Au results



pK^+ and $\bar{p}K^-$ from 18.4 M d+Au at 200 GeV

Background – Combinatorial and Correlated Pairs

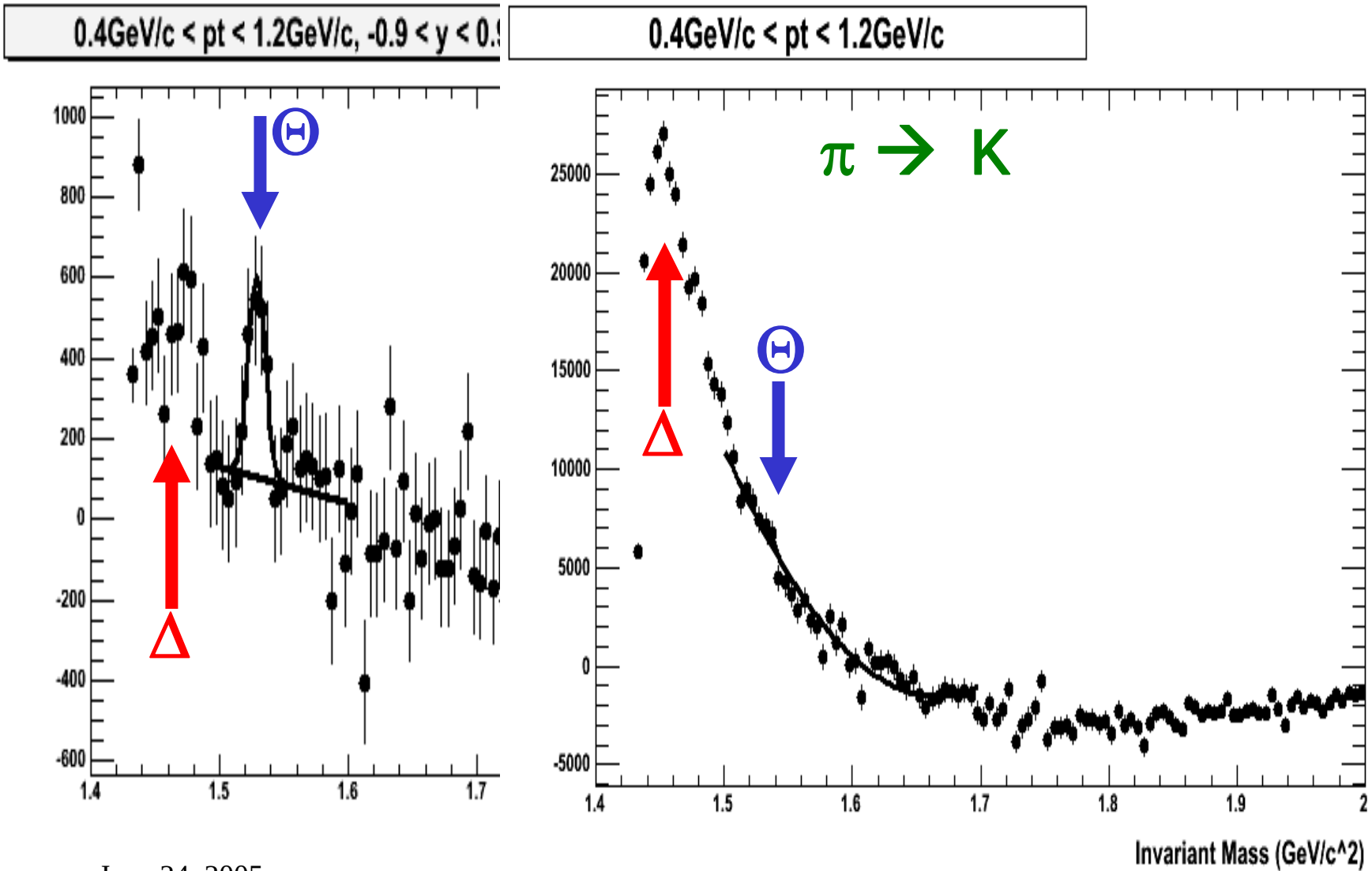
STAR: d+Au background-sub.



The invariant mass distribution: a 3.5-5.0 sigma signal is seen

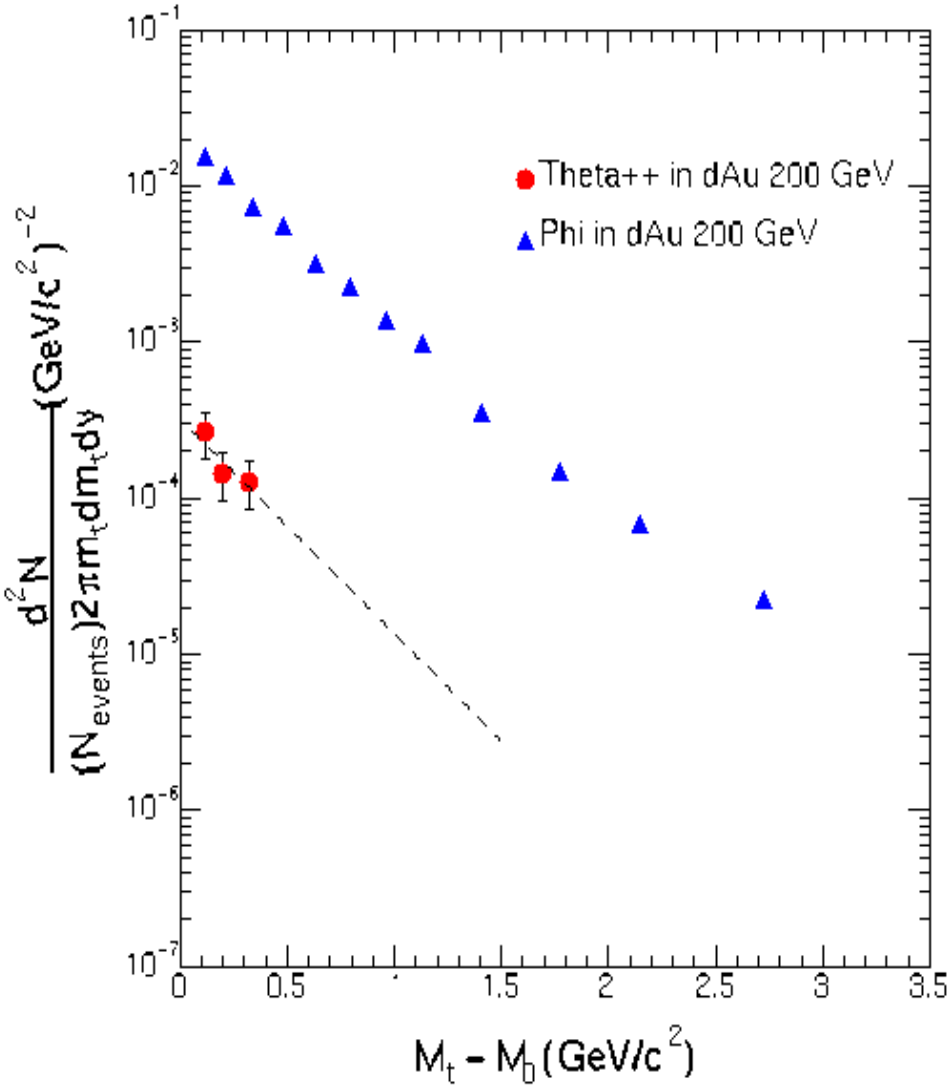
Measured mass is about 1.53 GeV/c^2. Full width is about 15 MeV

Particle mis-ID background



Comparison with known states

After acceptance and efficiency correction



Assuming 100% branching ratio

Spectrum includes Θ^{++} and Θ^{--}

Mt-exponential fit yields:

dN/dy = 0.0012 +- 0.0006

T = 315 +- 30 MeV

Yields for some particles in dAu

K_s: 0.321 +- 0.006 +- 0.03

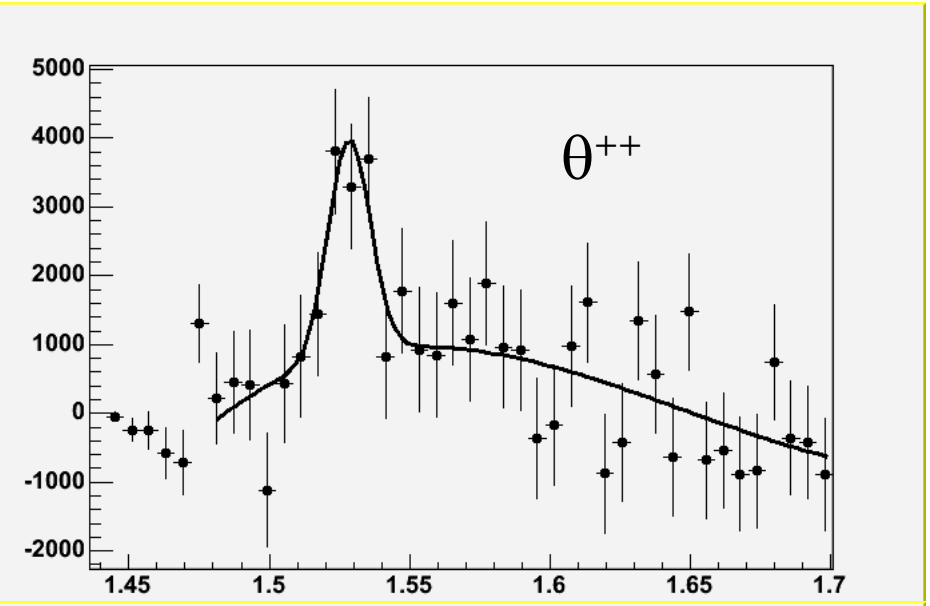
$\Lambda+\bar{\Lambda}$: 0.339 +- 0.007

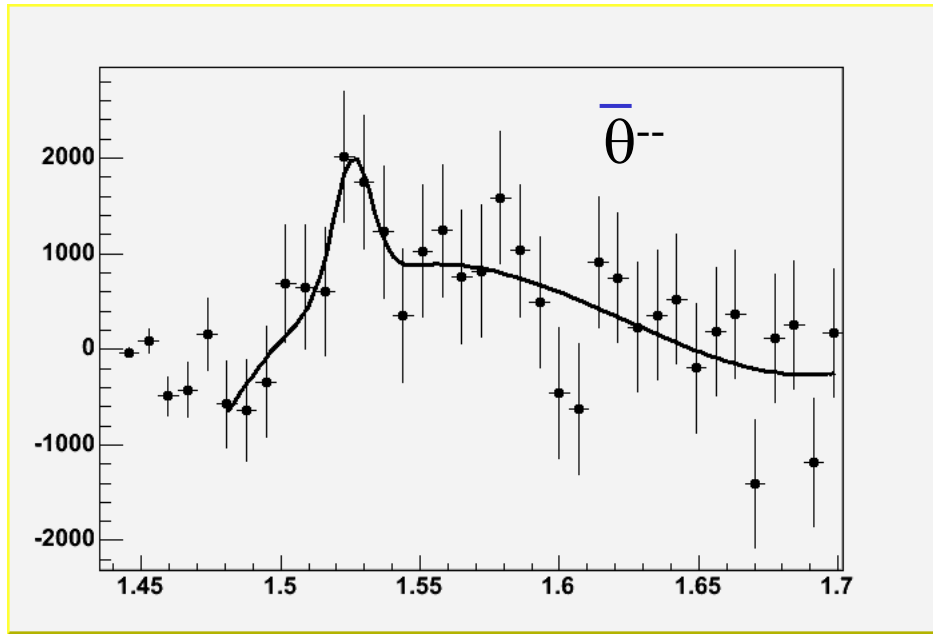
$\Xi+\bar{\Xi}$: 0.0251 +- 0.0006

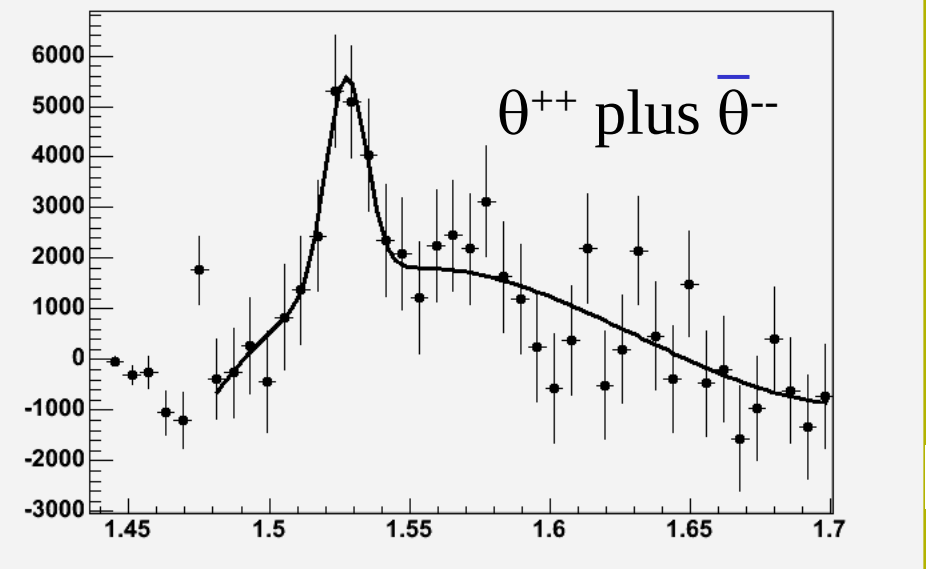
ϕ: 0.0642

$\Theta^{++}/\phi \sim 2\%$

STAR: Au+Au 62.4 GeV







- A nice signal is also seen in AuAu 62.4 GeV data from 20-80% centrality bin, 5.1 M events.
- θ^{--}/θ^{++} = 0.47 +- 0.2

STAR: Conclusions

1) **If pK^+ peak at 1530 MeV/c^2 is a real pentaquark, then I = 1 likely, there must be a θ^+. But the recent JLab null result on θ^+ casts serious doubt on the θ^{++}.**

2) **The STAR observed yield is so small such that many experiments would not have the sensitivity to see it.**

Summary

- There is reason for caution about the existence of the Θ^+.
  - Need better experiments (pos. and null).
- Experiments need to have better control over the background shape.
  - Can backgrounds be calculated?
- The new high-statistics data:
  - CLAS $\gamma p \rightarrow K^+K^0(n)$ shows no signal
  - CLAS $\gamma d \rightarrow K^+K^-p(n)$ shows no signal
- We're left with a mystery:
  - Is it an exotic production mechanism?