Searchs for Pentaquarks

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- Introduction
- Evidences and Counter evidences for the Θ^+
- Other pentaquarks
- Summary and outlook

PIC2004@ Boston University, June 27, 2004

What are penta-quarks?

- Minimum quark content is 5 quarks.
- "Exotic" penta-quarks are those where the antiquark has a different flavor than the other 4 quarks $\left(qqqq\overline{Q}\right)$
- Quantum numbers cannot be defined by 3 quarks alone.

Example: $uudd\bar{s}$

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

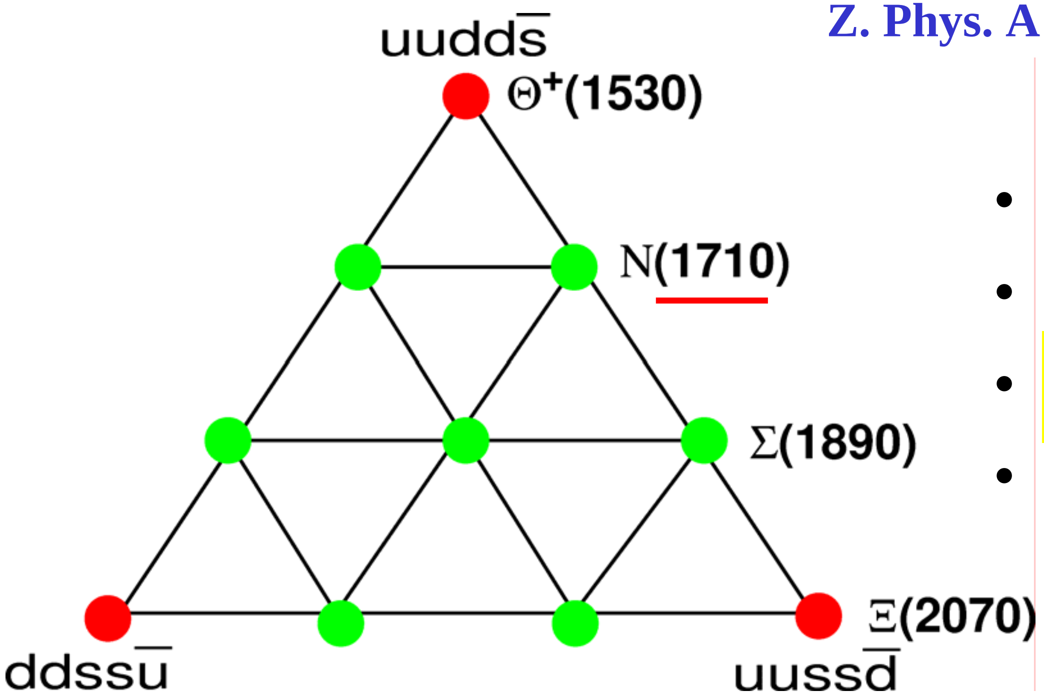
Strangeness = 0 + 0 + 0 + 0 + 1 = 1

e.g. $uudd\bar{c}$, $uuss\bar{d}$

c.f. $\Lambda(1405)$: $uuds\bar{u}$ or uds

Θ^+ Baryon

D. Diakonov, V. Petrov, and M. Polyakov, Z. Phys. A 359 (1997) 305.



- Exotic: S=+1
- Low mass: 1530 MeV
- Narrow width: ~ 15 MeV
- J^p=1/2$^+$

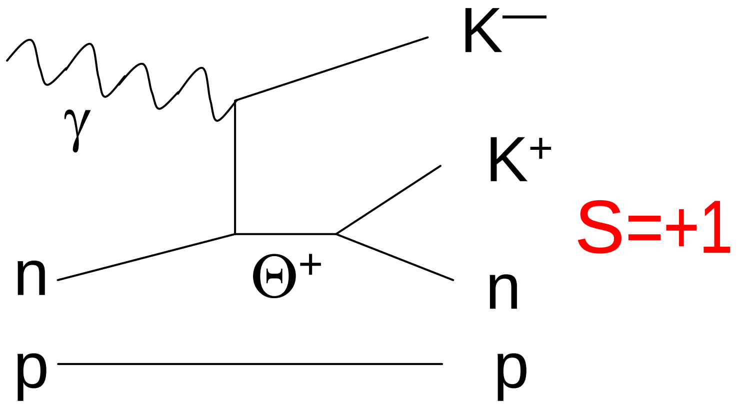
M = [1890-180*Y] MeV

Reaction diagrams

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

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

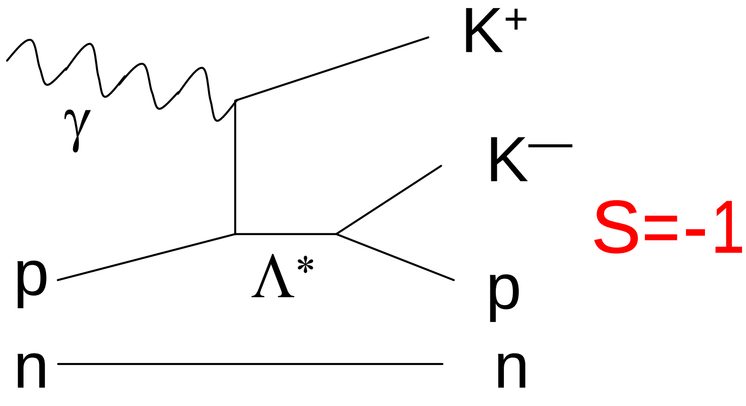
"Exotic"



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

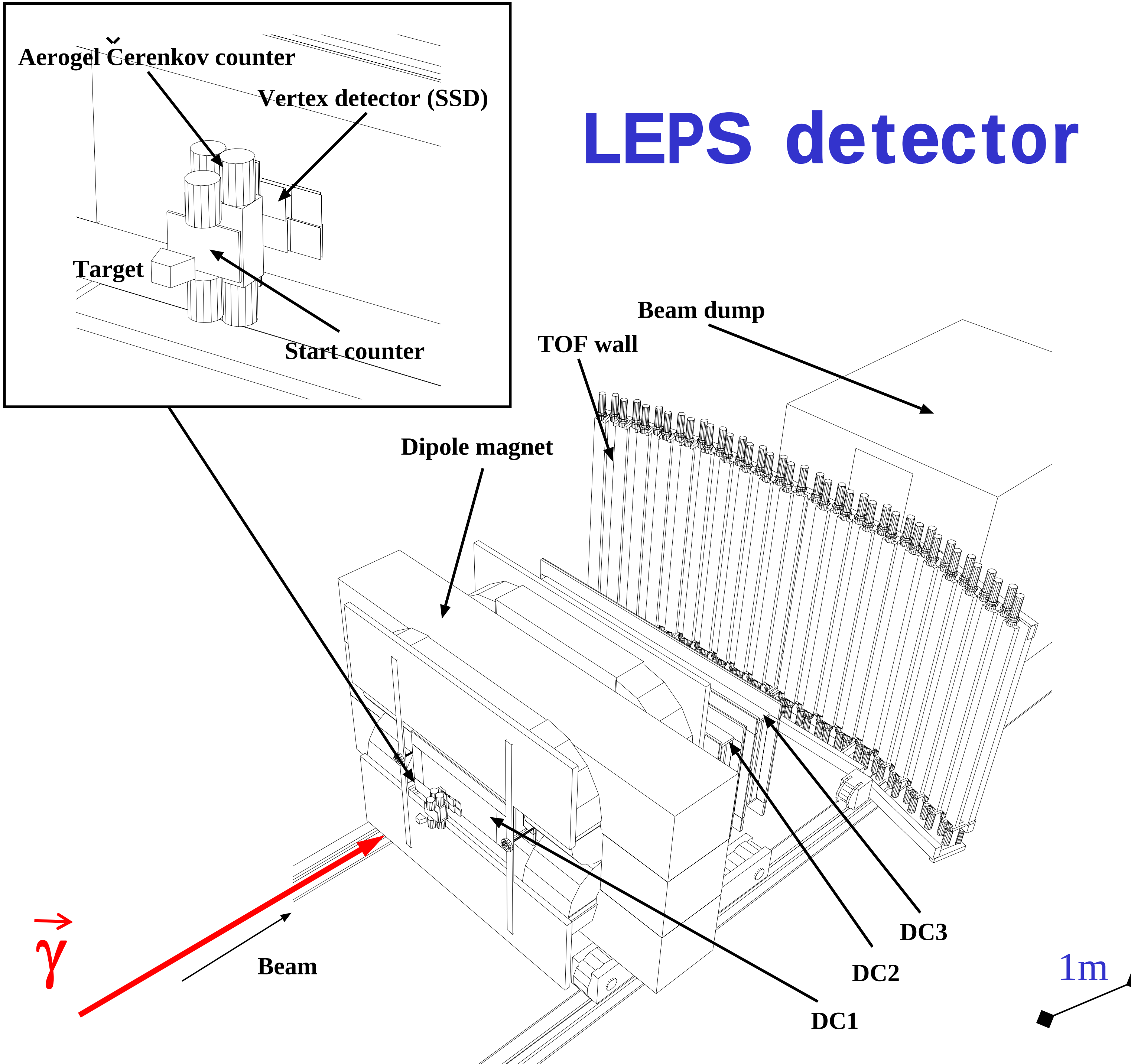
$$\Lambda^{*}(1520) \rightarrow K^{-} p$$

"Standard" baryon



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

LEPS detector



First evidence from LEPS

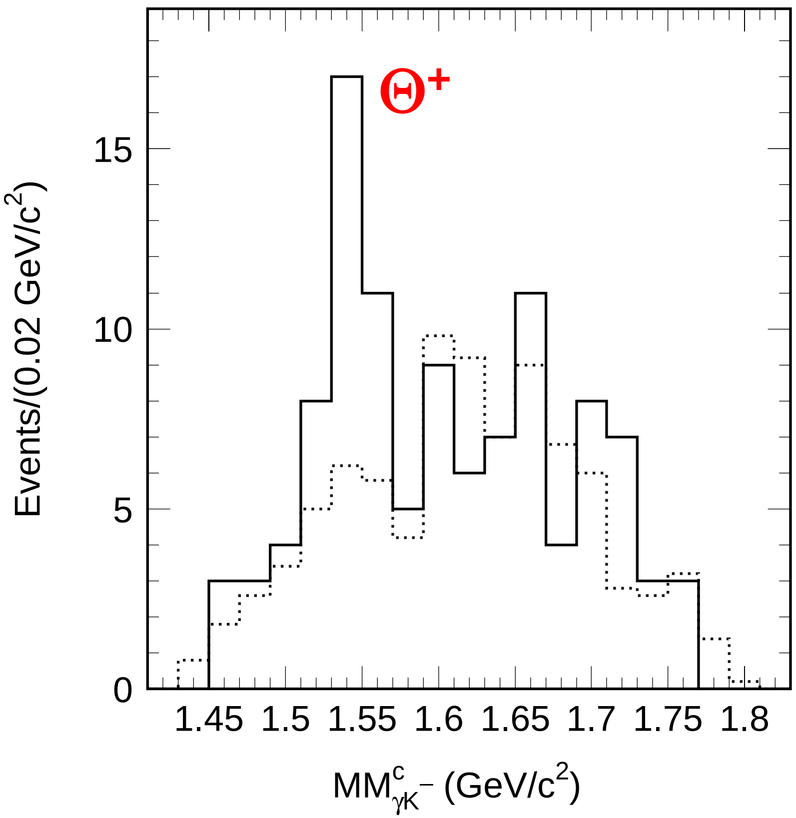
$\gamma\, n \rightarrow K^+ K^- n$

$M = 1.54 \pm 0.01$ **MeV**
Γ **< 25 MeV**
Gaussian significance 4.6σ

Background level is estimated by a fit in a mass region above 1.59 GeV.

Assumption:

- **Background is from non-resonant K^+K^- production off the neutron/nucleus**
- **… is nearly identical to non-resonant K^+K^- production off the proton**



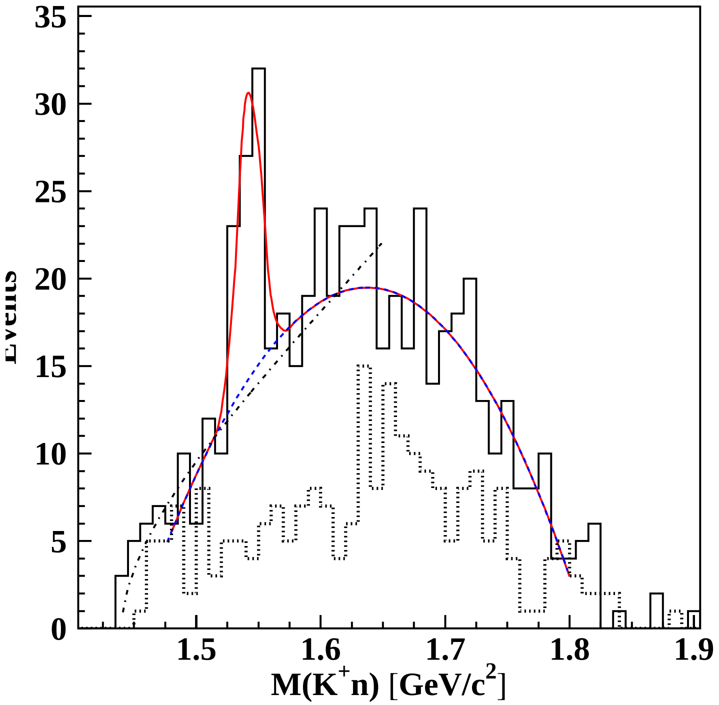
Phys.Rev.Lett. 91 (2003) 012002

hep-ex/0301020

CLAS/JLAB Exclusive process

hep-ex/0307018

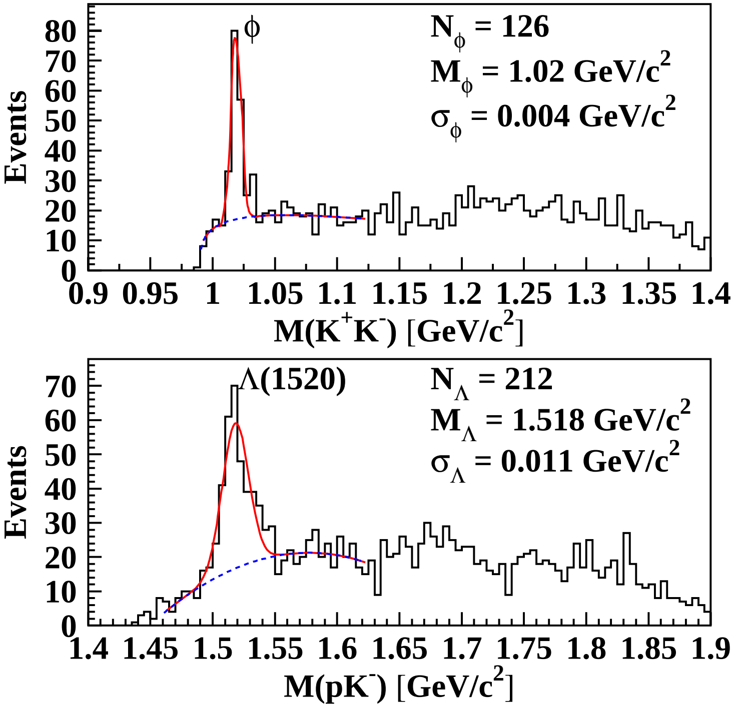
$\gamma\, d \rightarrow p\, K^+\, K^-\, n$



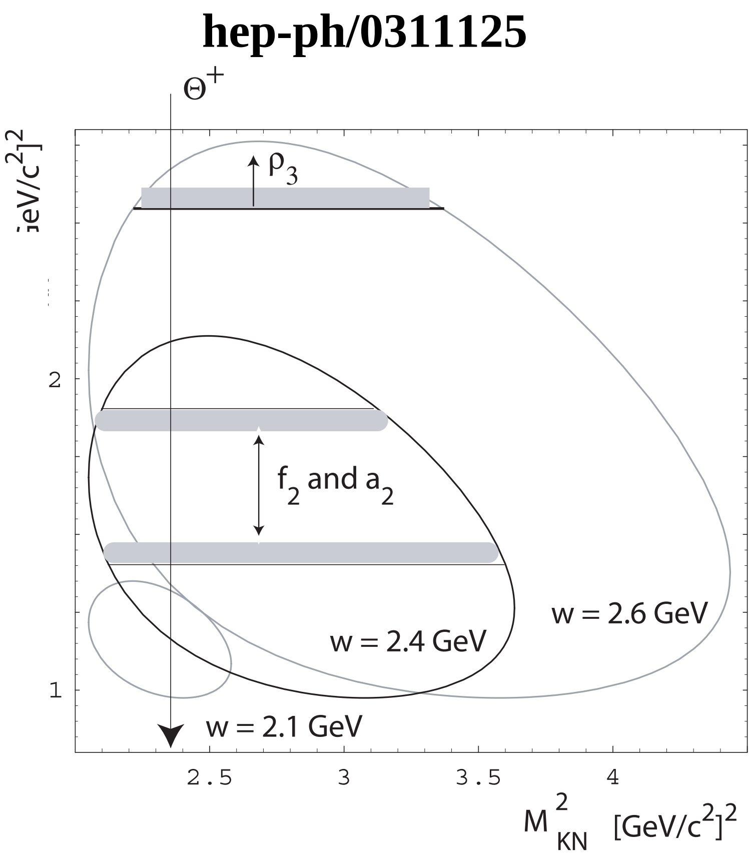
M = 1542±5 MeV

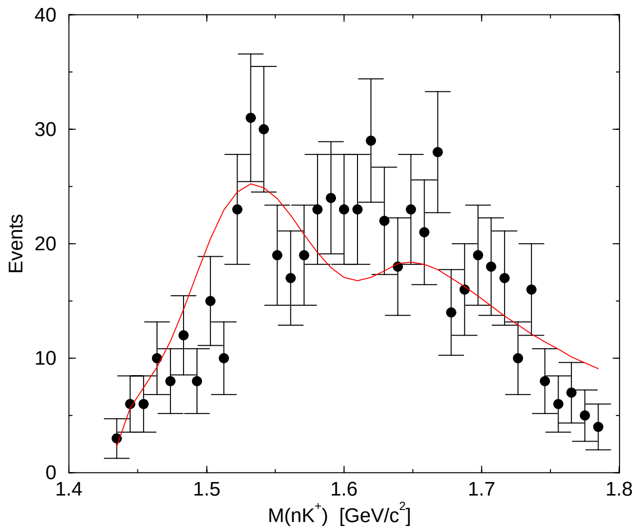
Γ < 21 MeV

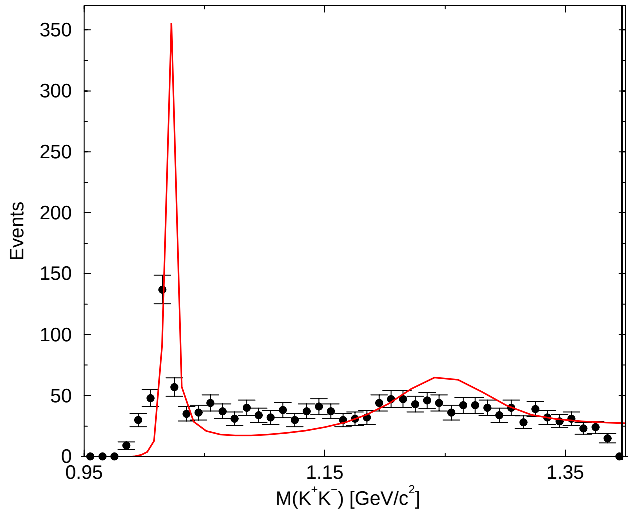
- **Detect $K^+ K^-$ p**
- **Reconstruct neutron via missing mass.**
- **Remove ϕ and Λ(1520).**



Kinematic reflections





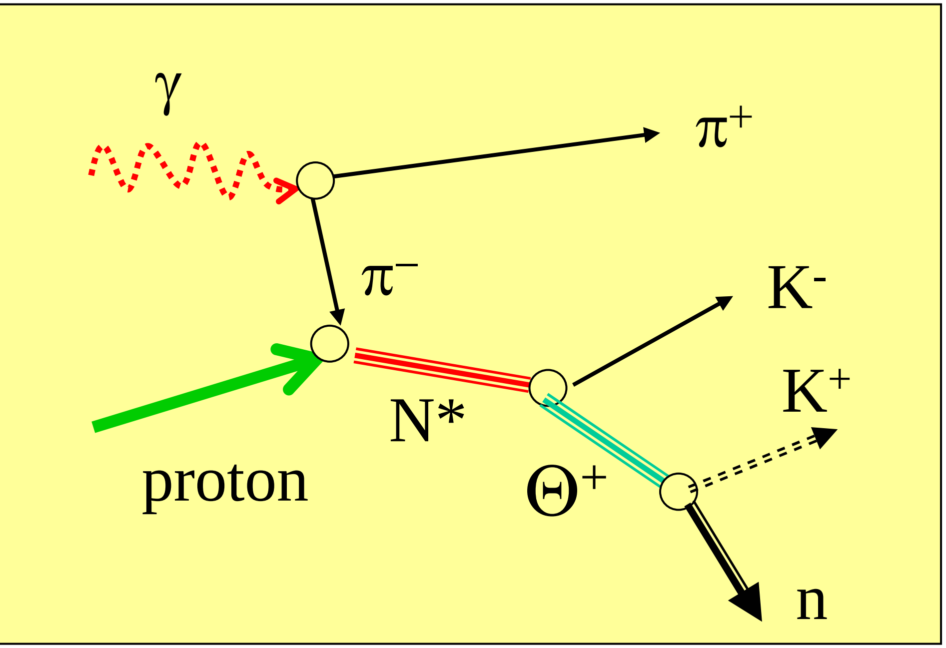


- **Kinematic reflections due to $f_2(1275)$, $a_2(1320)$ and $\rho_3(1690)$ can generate a narrow enhancement in K^+n effective mass.**

CLAS/JLAB on protons

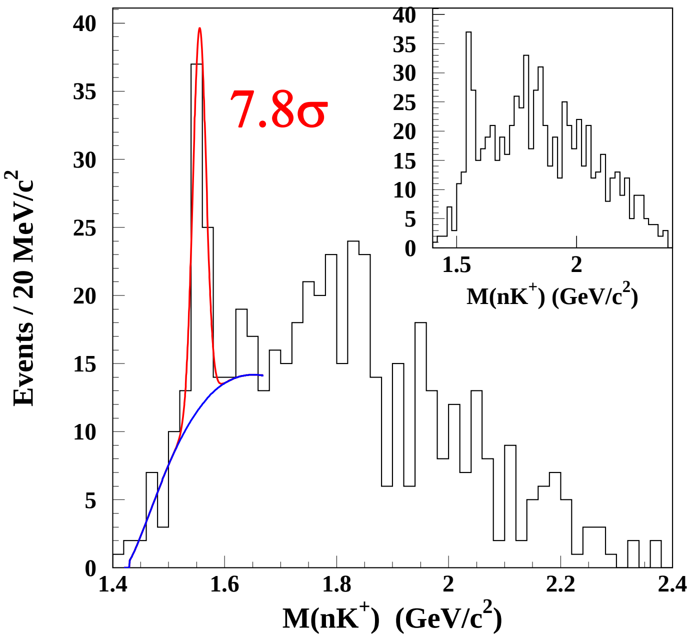
CLAS Collaboration
PRL 92, 032001-1 (2004).

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

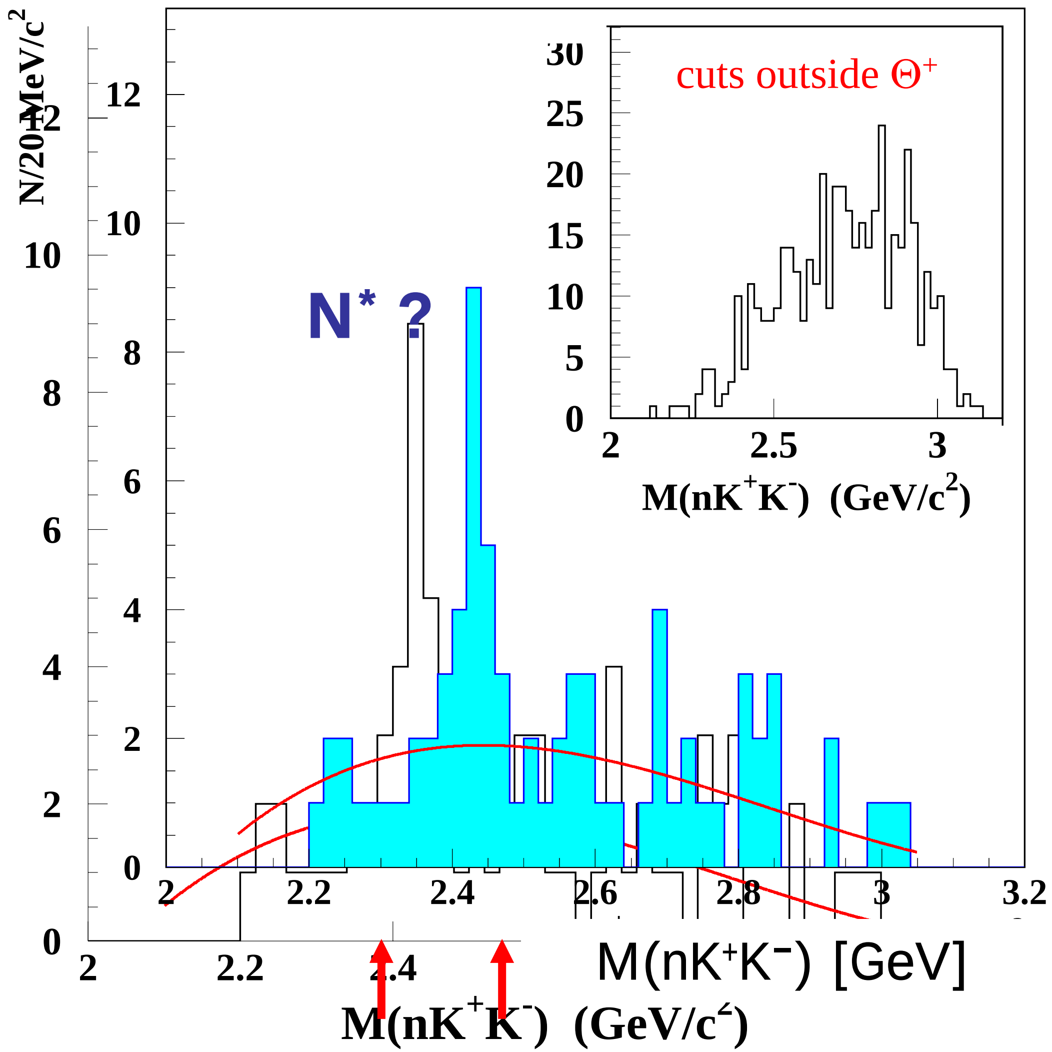


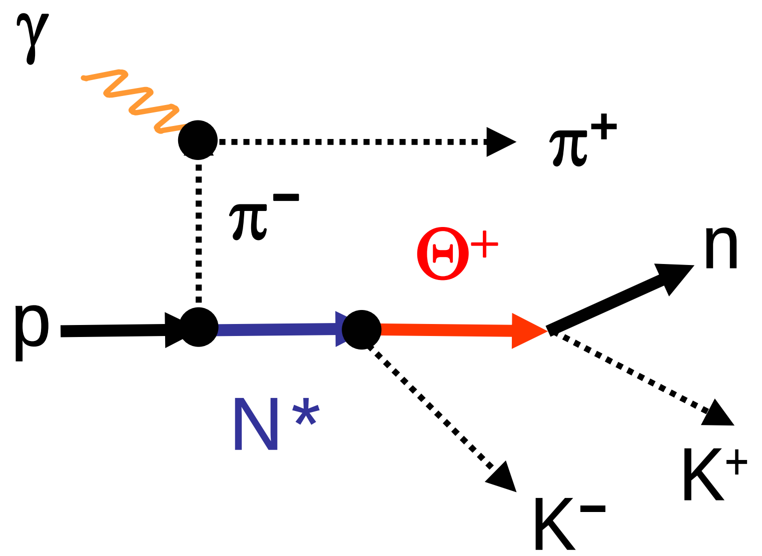
$M = 1555 \pm 1 \pm 10$ MeV
$\Gamma < 26$ MeV

- **Detect $K^+ K^- \pi^+$**
- **Reconstruct neutron from missing 4-momentum.**
- **Require $\cos\theta\pi > 0.8$ & $\cos\theta_K < 0.6$**



N* production mechanism?

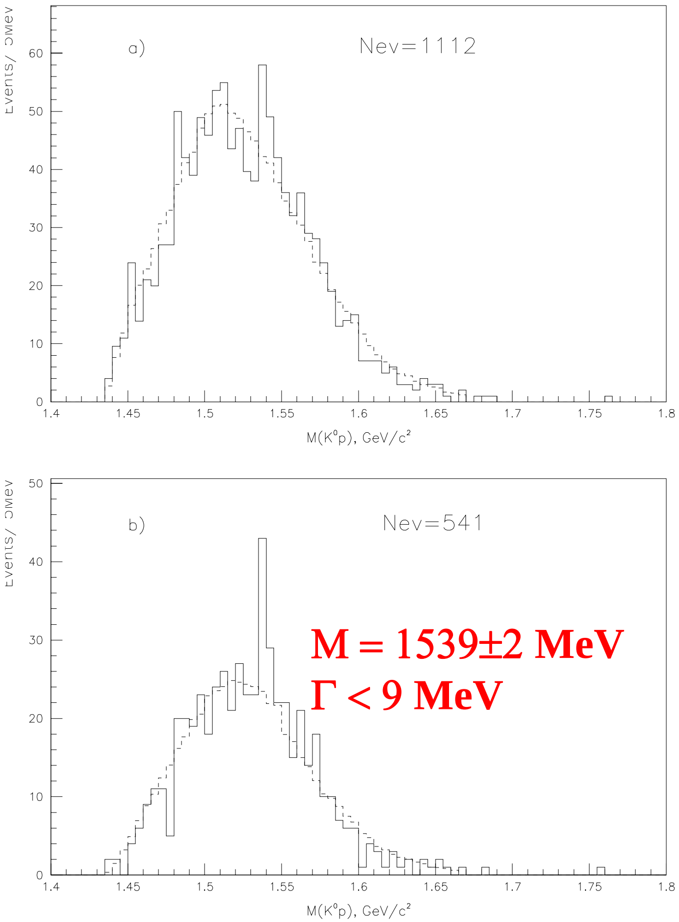




- **What do π^-p scattering data say?**
- π^-p cross section data in PDG have a gap in the mass range 2.3–2.43 GeV.

DIANA/ITEP Result

K^+ Xe → K^0 p X
(K^+ n → K^0 p)



hep-ex/0304040

- **P_{K+} < 530 MeV/c**
- **Require θ_K<100deg. & θ_p<100 deg.**
- **Remove cos ϕ_{pK} <0 ← back-to-back**

K^+ n → Θ^+ ⟷ Θ^+ → K^+ n

$\Gamma = 0.9 \pm 0.3$ MeV

Cahn and Trilling hep-ph/0311245

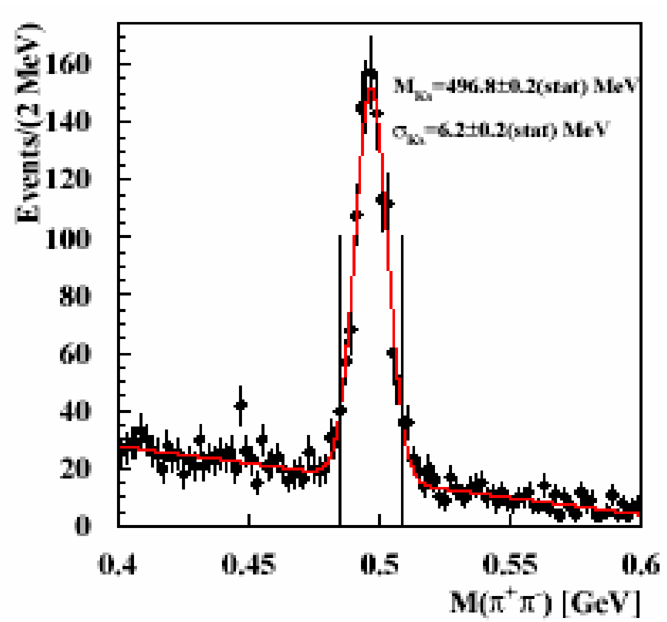
consistent with KN phase shift analysis by Arndt et. al.

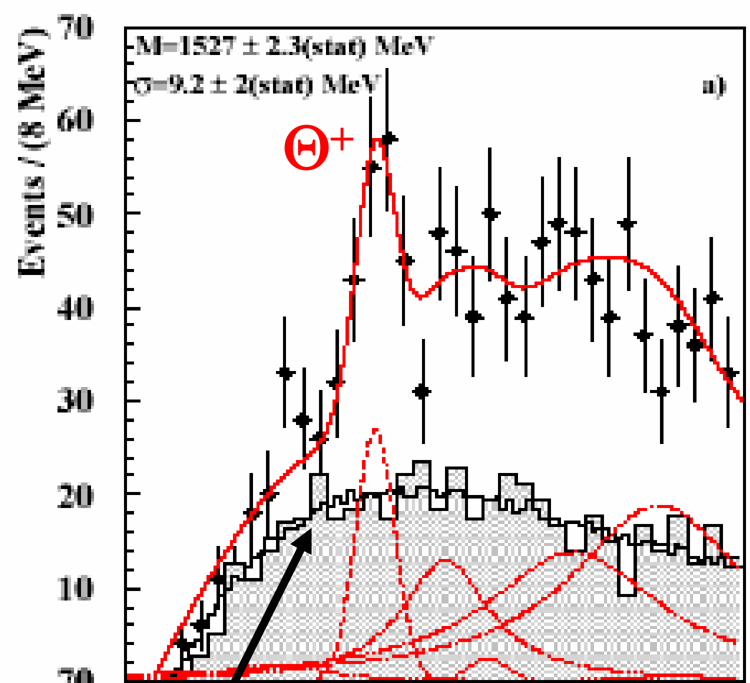
Phys. Rev. C68, 042201(R)

HERMES: $e^+d \rightarrow K^0 p\ X$

Detect $K^0 \rightarrow \pi^+\pi^-$
Nice clean peak.

Complicated background
due to Σ^* resonances

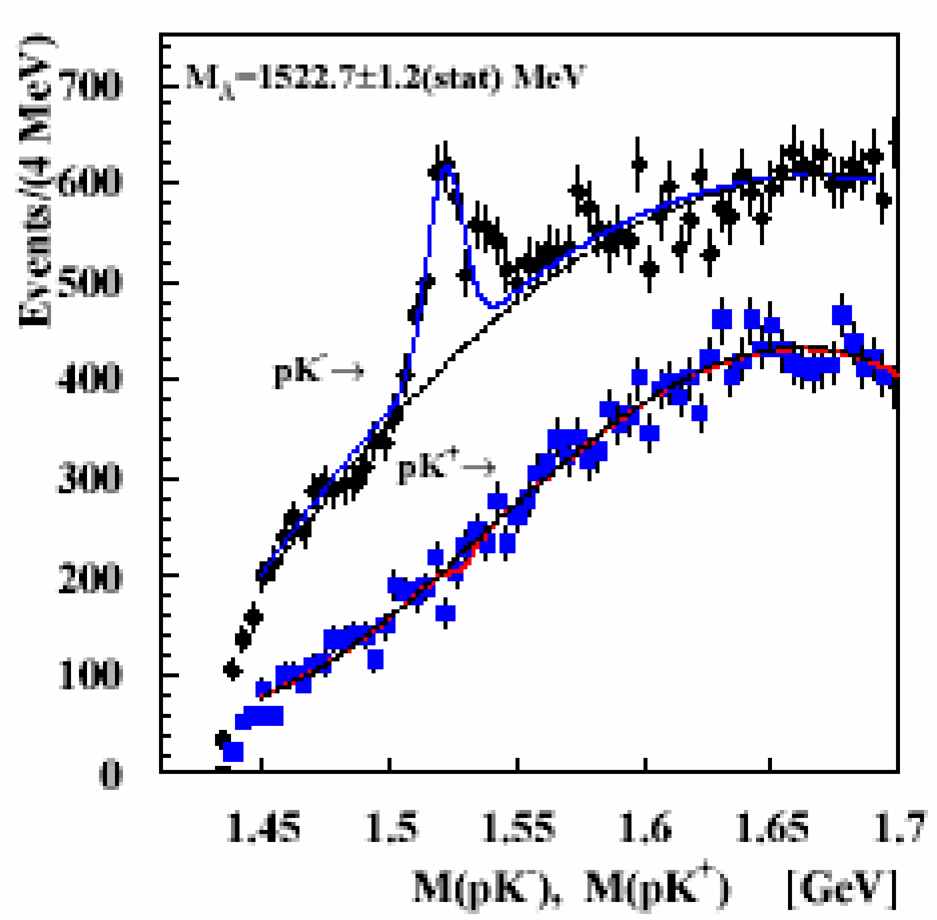




mixed events **shaded: Pythia MC**

HERMES: $e^+d \rightarrow K^0 p\ X$

Clear Λ(1520) peak is seen. This is a crucial test, as it has similar mass.

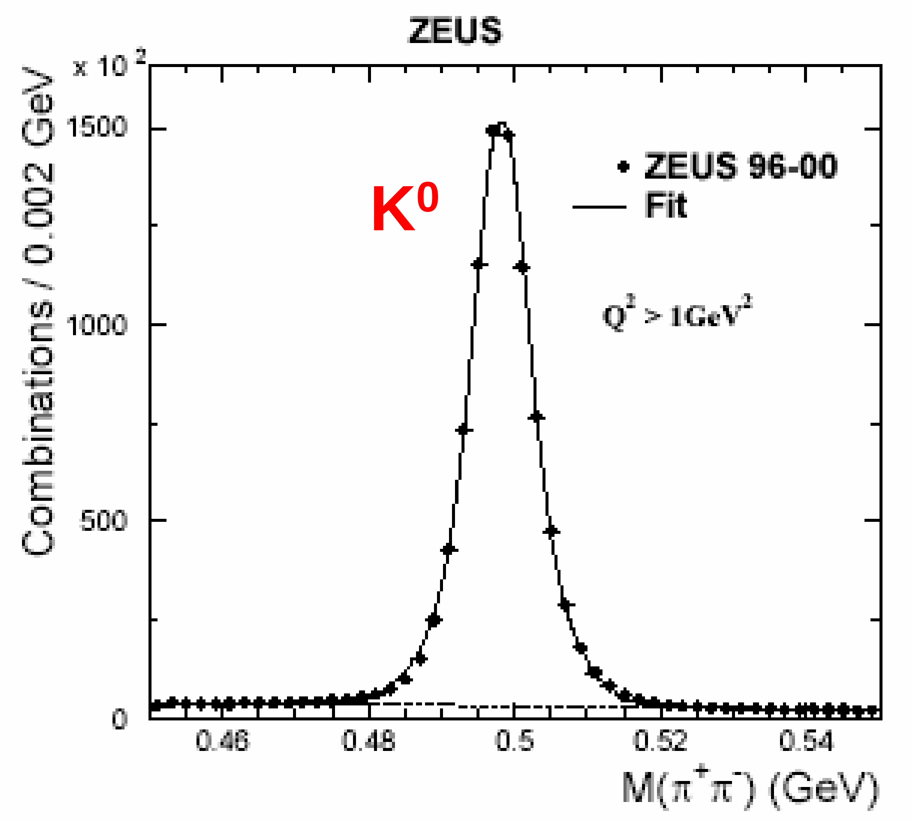


No peak is seen in the pK+ spectrum.

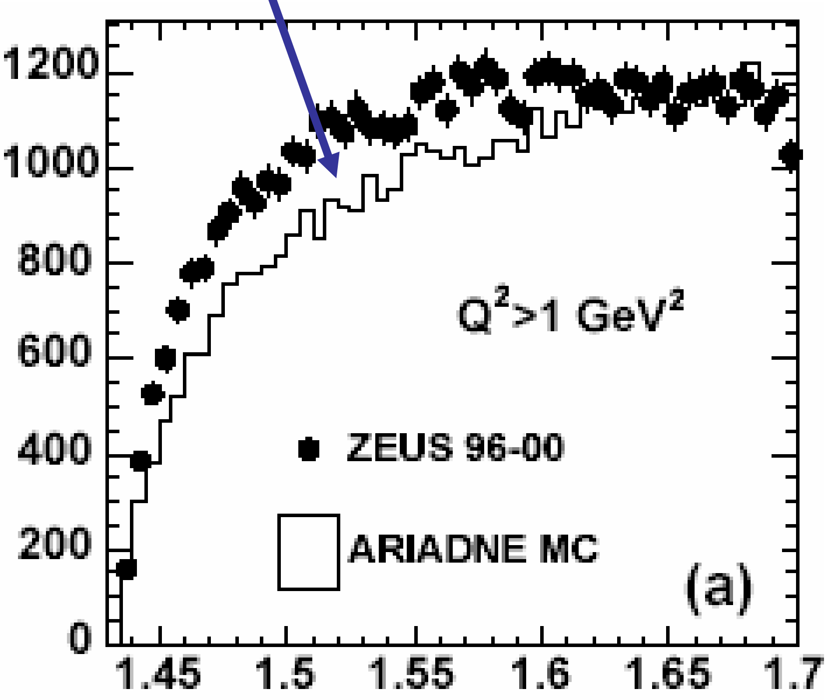
→ no Θ^{++} !

ZEUS: $e^+p \rightarrow e'K^0p\ X$

Huge statistics!



Hint of excess for $Q^2 > 1$.

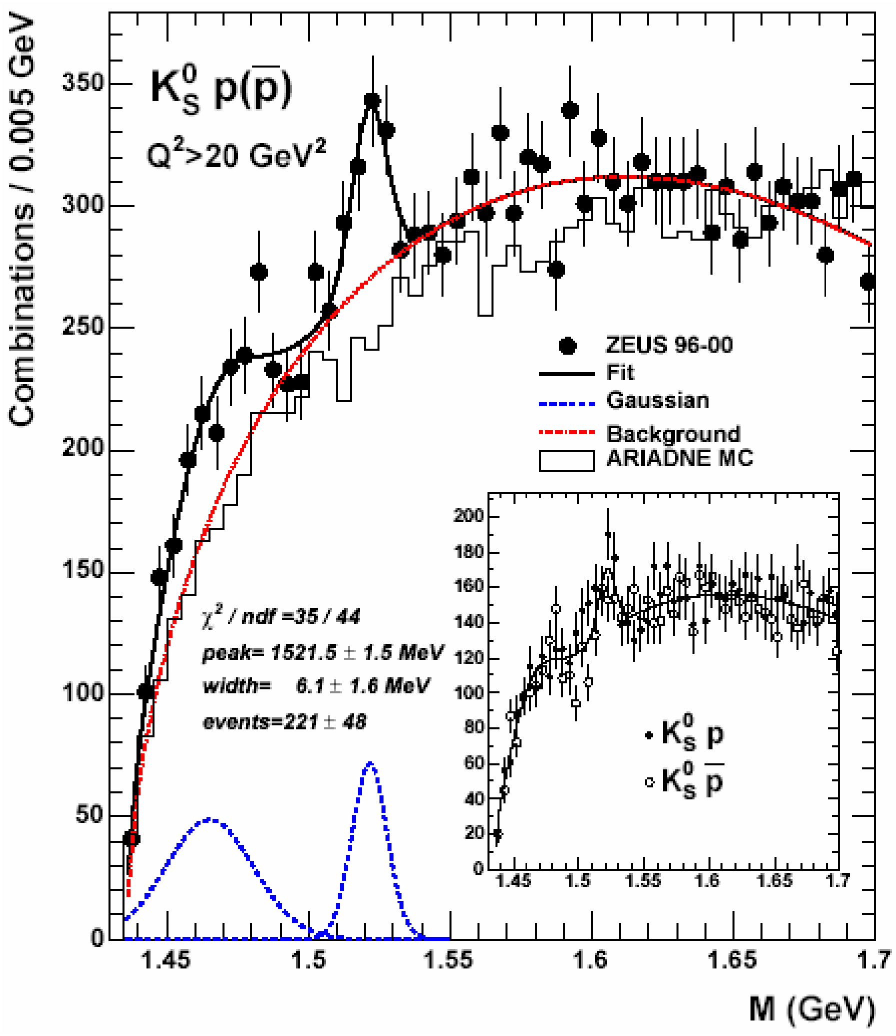


Note: they see a clear peak for the Λ(1520) in the pK- spectrum.

ZEUS: $e^+p \rightarrow e'K^0p\,X$

The peak only shows up clearly for $Q^2 > 20$ GeV^2.

Note (inset) that the peak appears in both K^0p and $K^0\bar{p}$ albeit with different widths.

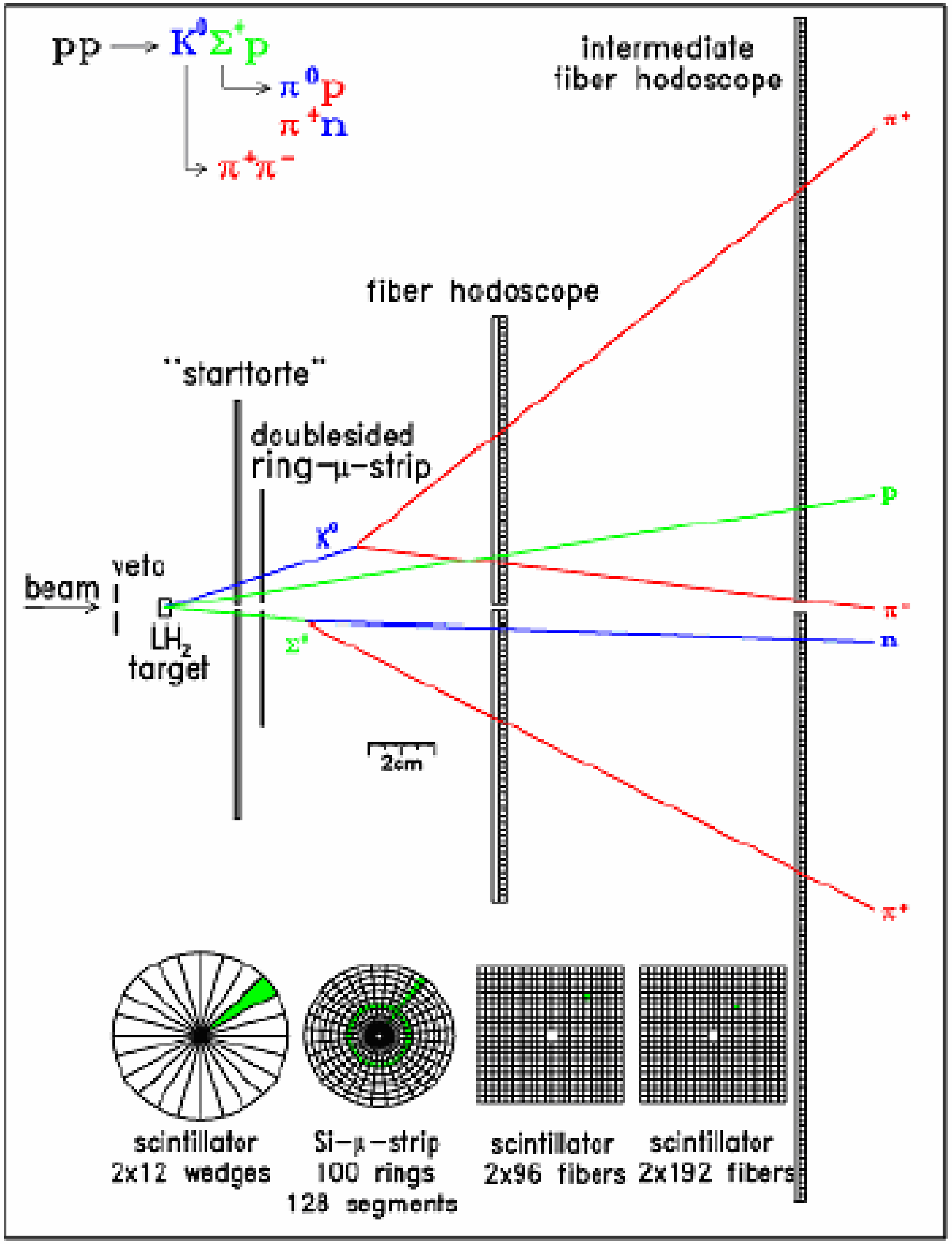


COSY:

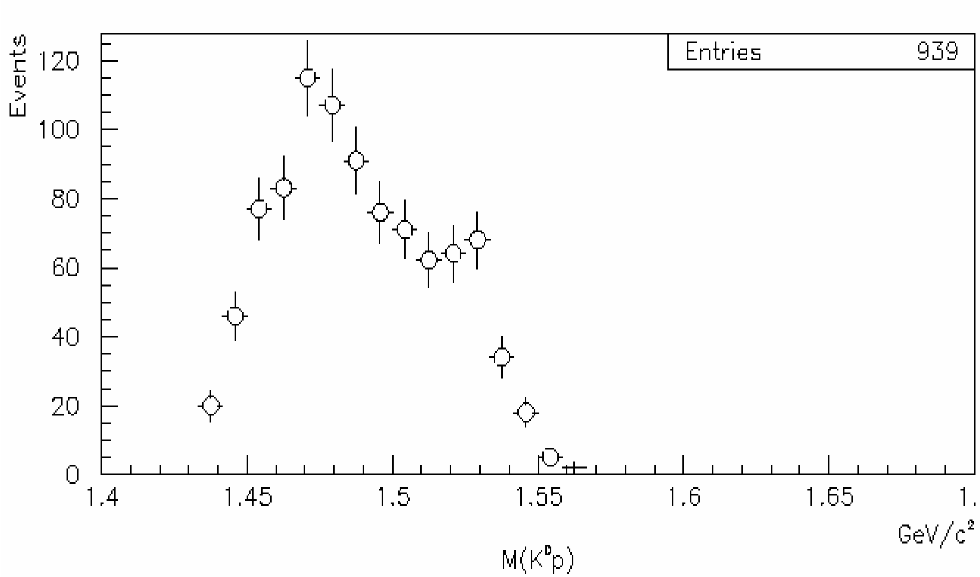
$pp \rightarrow K^0 p \Sigma^+$

The COSY-TOF detector uses scintillators and microstrips to get good vertex reconstruction.

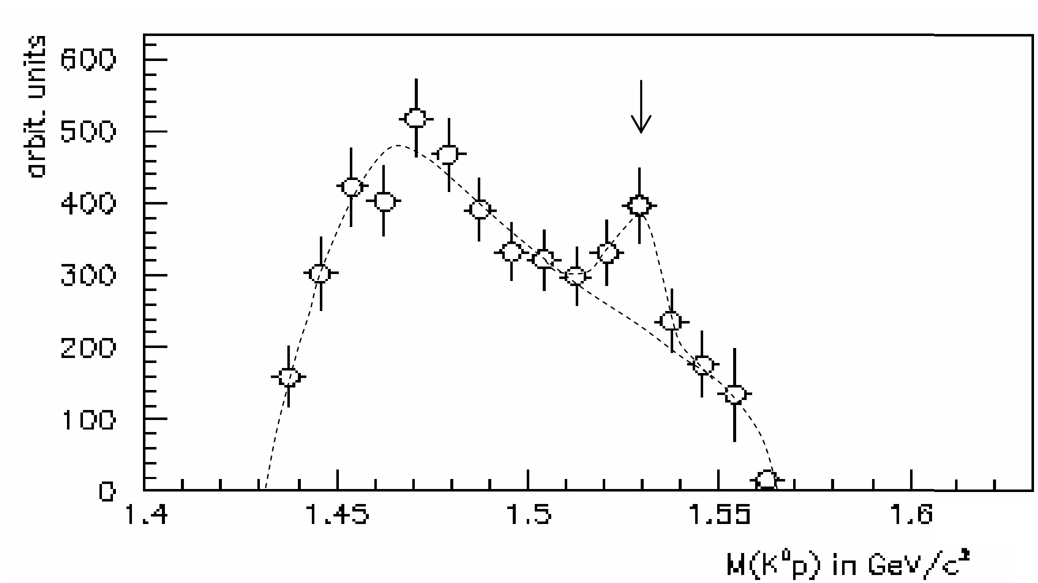
Finding a detached vertex easy in the low-multiplicity environment.



COSY result



Before the acceptance correction.



M = 1530±5 MeV

Γ < 18 MeV

$\sigma = 0.4 \pm 0.1 \pm 0.1$ μb

Summary of 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	$e^+d \rightarrow K^0p X$	1528 +- 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

Mass

- **M = 1.54 GeV: SPring-8, ITEP, CLAS-d**
  - **These were the first 3 publications**
- **M = 1.555 GeV: CLAS-p**
  - **This one has over 7 σ significance!**
- **M = 1.53 GeV: HERMES, ZEUS, COSY**
  - **These are the most recent ones…**
- **Can all of these be the same resonance?**
  - **We need to find better ways to estimate the experimental uncertainties.**

Width

- **Again, there is inconsistency:**
  - **Most measurements are only upper limits.**
  - **DIANA has Γ < 9 MeV.**
  - **The cross-section implies Γ=0.9 MeV.**
  - **HERMES: Γ = 13 +- 9 stat. (+- 3 sys.) MeV**
  - **ZEUS: Γ = 8 +- 4 stat. (+- 5 sys.) MeV**
  - **Arndt *et al.* and Cahn *et al.* analysis of KN phase shifts suggests that Γ < 1 MeV !!**
- **The small width is the hardest feature for theorists to understand…**

Negative Results

- HERA-B (Germany):
  - reaction: p+A at 920 GeV
  - measured: K^-p and K^0p invariant mass
  - Clear peak for $\Lambda(1520)$, no peak for Θ^+
  - production rate: $\Theta^+/\Lambda(1520)<0.02$
- BES (China):
  - reaction: $e^+e^- \rightarrow J/\psi \rightarrow \Theta^+\bar{\Theta}^-$
  - limit on B.R. of $\sim 10^{-5}$

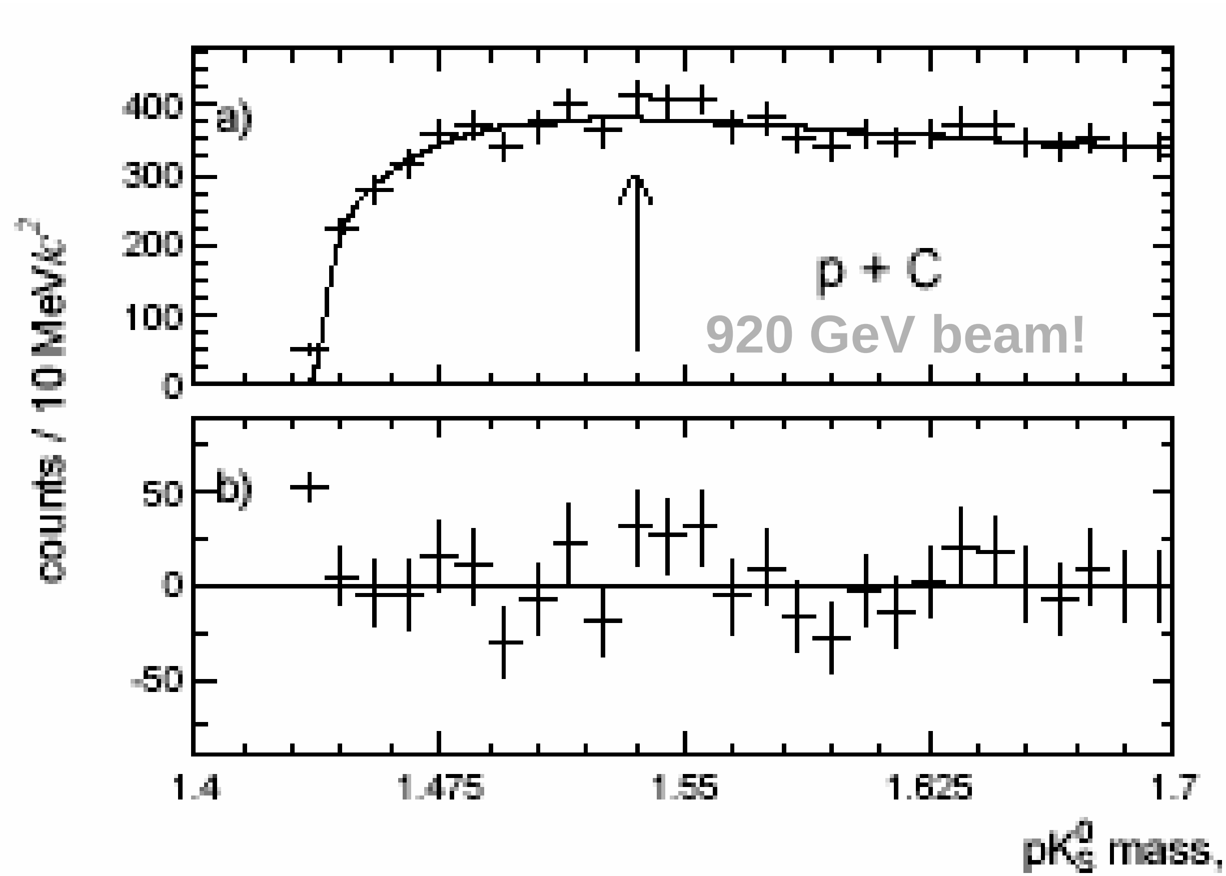
And many unpublished negative results

(HyperCP, CDF, E690, BaBar, LEP,,,).

HERA-B result

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

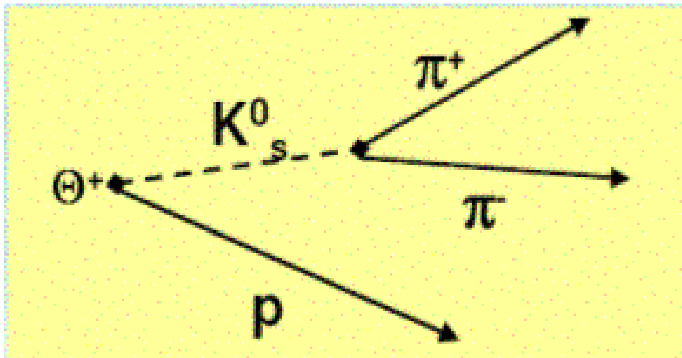
Could it be due to reaction mechanism?

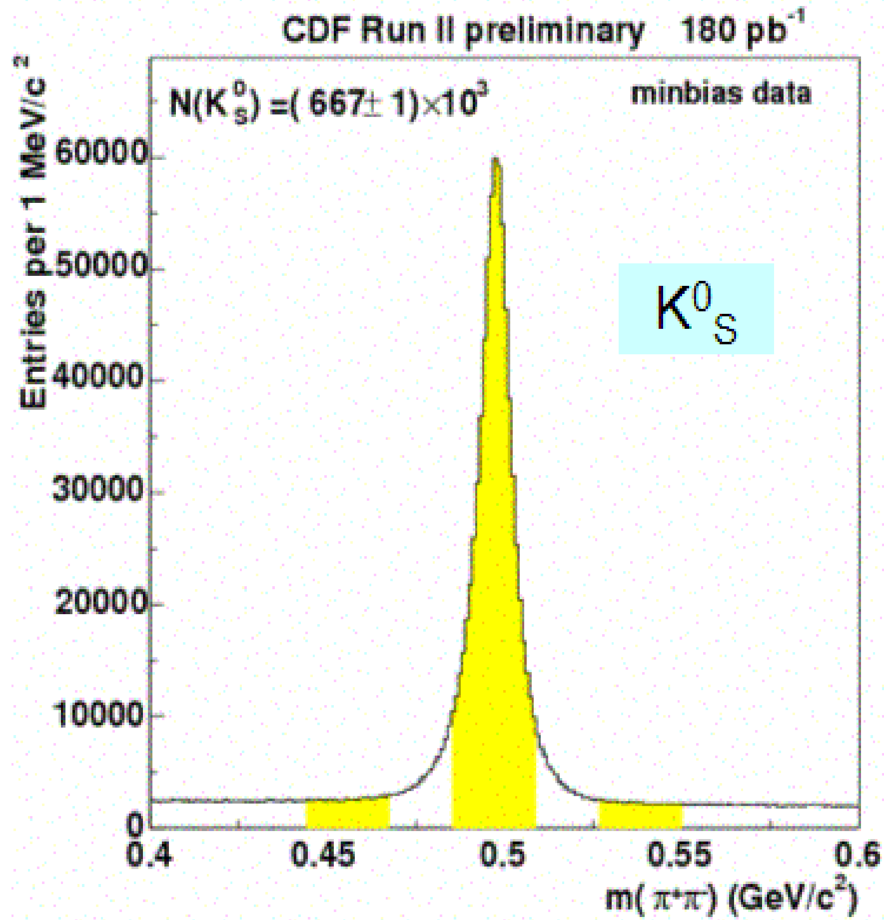


sensitivity: better than 5 μb/nucleon

Θ^+ Search at CDF: Strategy & Samples

$p\,K^0_S \rightarrow p\,\pi^+\,\pi^-$





Two energy ranges:

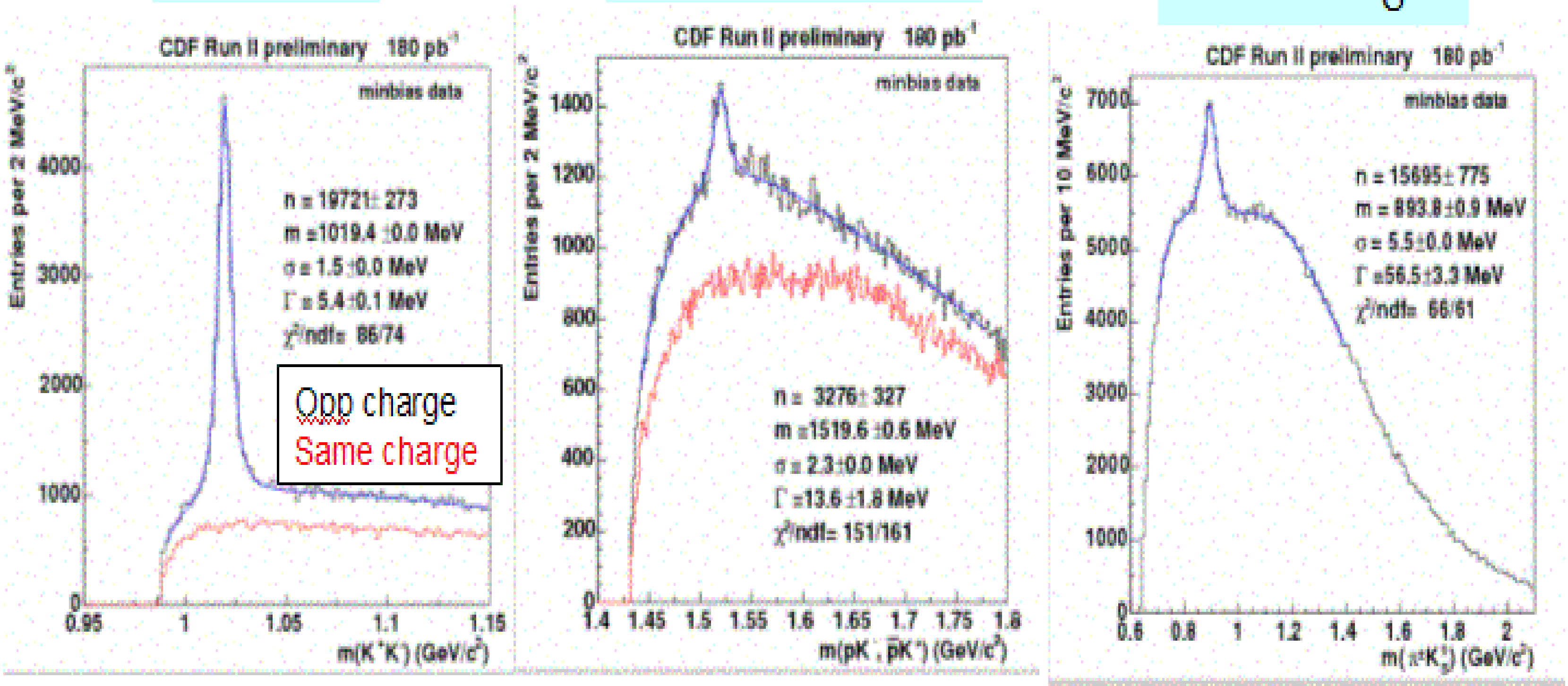
- ***minbias***! $23£10^6$ events
- ***jet20***! $16£10^6$ events

to remove $\Lambda \rightarrow p\pi^-$: m($\pi$p) and m(p$\pi$)¸ 1.13 GeV

Presented at QNP2004 by M.J. Wang

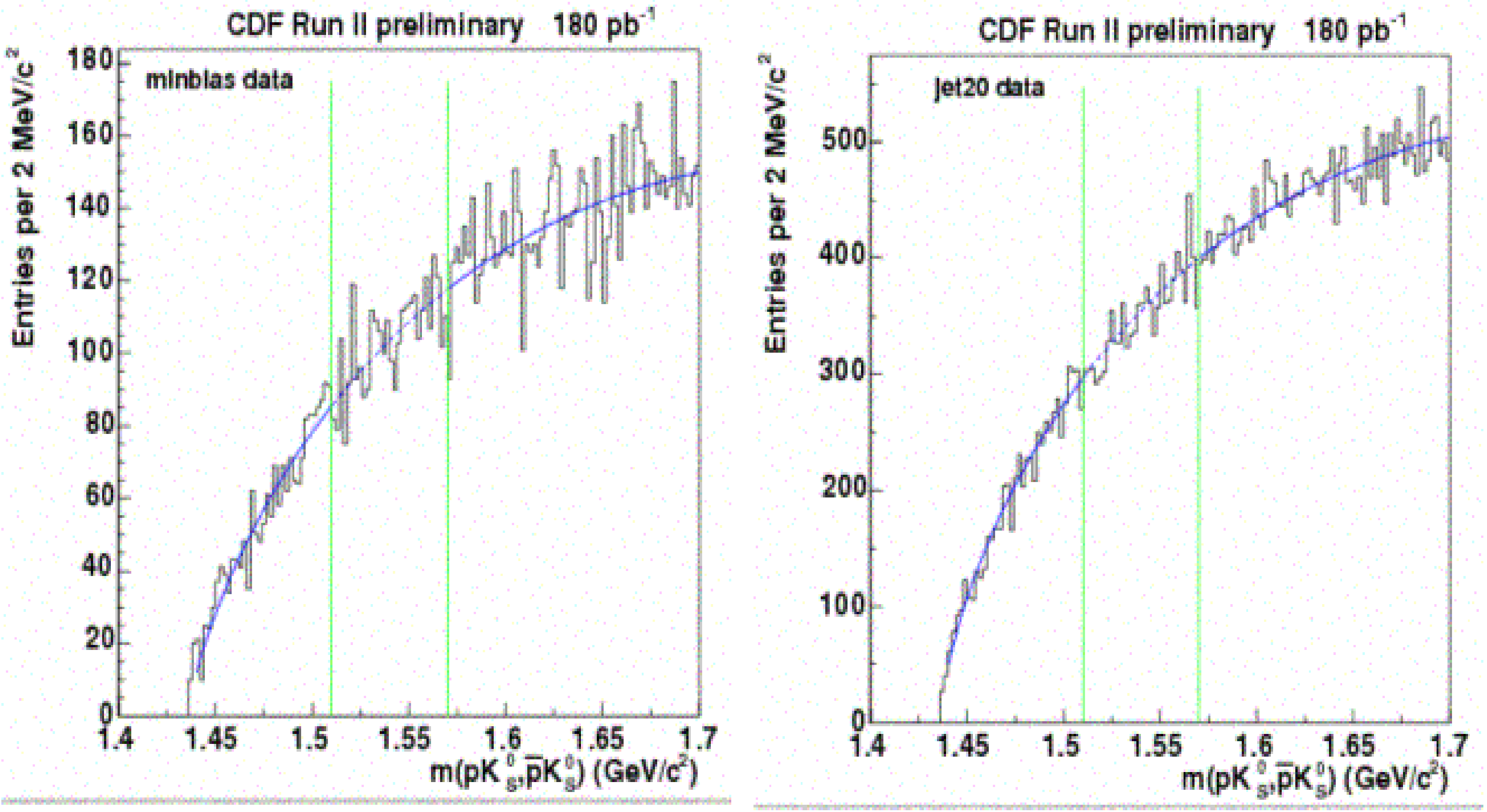
Θ^+ Search at CDF: Known Resonances

$\phi \rightarrow K^+K^-$ | $\Lambda(1520) \rightarrow pK^-$ | $K^{*+} \rightarrow K^0_S\pi^+$



Acceptance limited by TOF cuts: *(determined with MC)*

Θ^+ Search at CDF: pK^0_S Mass Spectrum



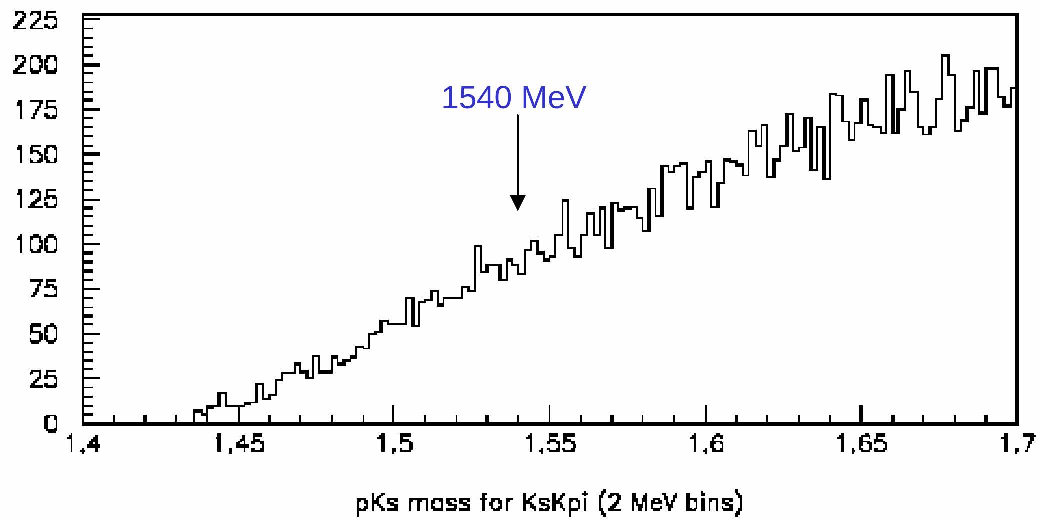
No evidence of narrow resonance

pK_s in $pp \rightarrow p_{slow}K_sK^-\pi^+p_{fast}$

- Low multiplicity *exclusive* reaction → limited combinatorics.
- K_s is correct strangeness for Θ^+ (assuming strangeness conservation in production).
- Events selected by topology, and energy and momentum conservation.
  - Loose cut on p_L conservation (5 GeV).
  - Tight cut on p_T^2 conservation (.002 GeV^2 ~ (45 MeV)^2).
  - Tight cut on (E-p_L) conservation (-.02 - .015 GeV).
    - Errors on E & p_L are highly correlated.
  - Events eliminated that have $\Delta(E-p_L)$ consistent with $p_{slow}K_s\mathbf{K^+}\pi^-p_{fast}$
- 68,050 events selected.
  - 63,945 with one solution.
  - 4105 (6%) with 2 solutions (π^+/p_{slow} ambiguity).

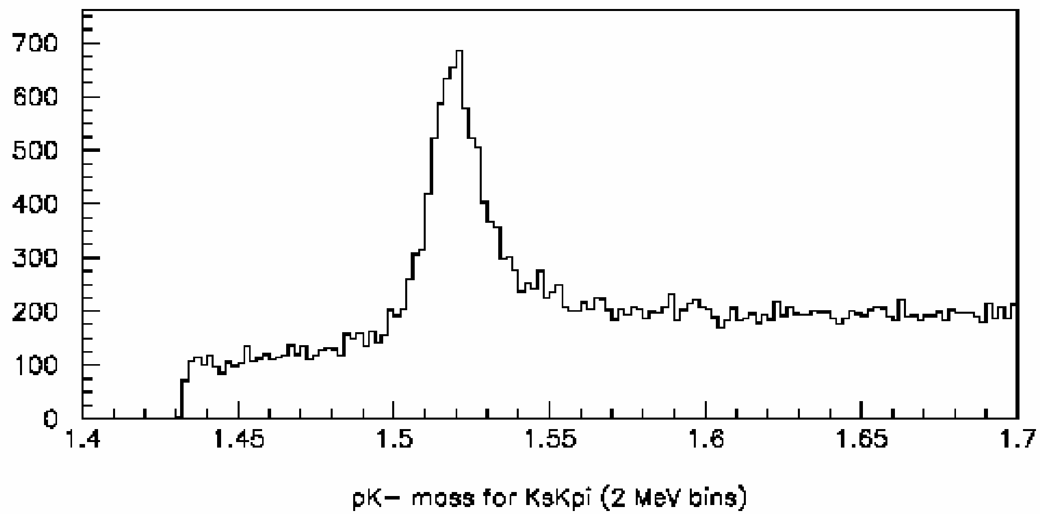
pK_s and pK^- (Preliminary)

Monte Carlo
pK_s mass
resolution (σ)
at 1540 MeV
is 1.5 MeV.



Yield of narrow
(pK_s) at 1540 MeV
is less than 25
events (95% CL).

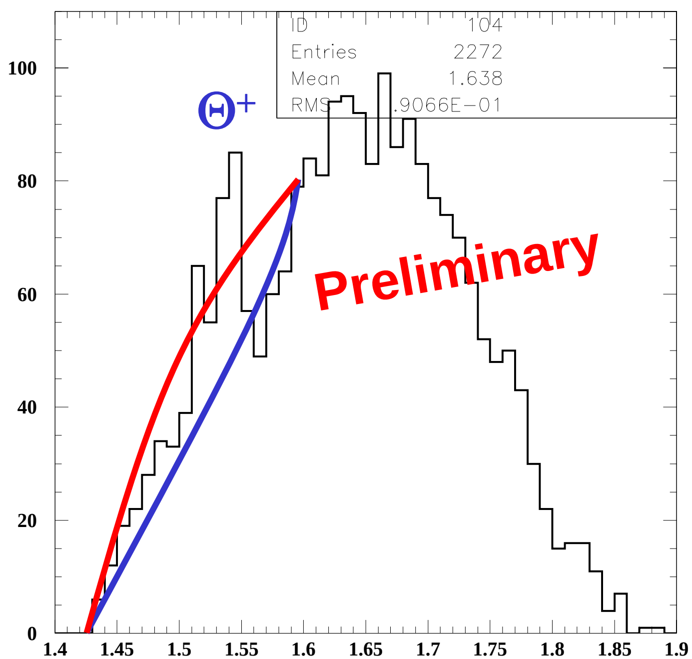
~5000 Λ(1520)
above background;
FWHM ~ 14 MeV



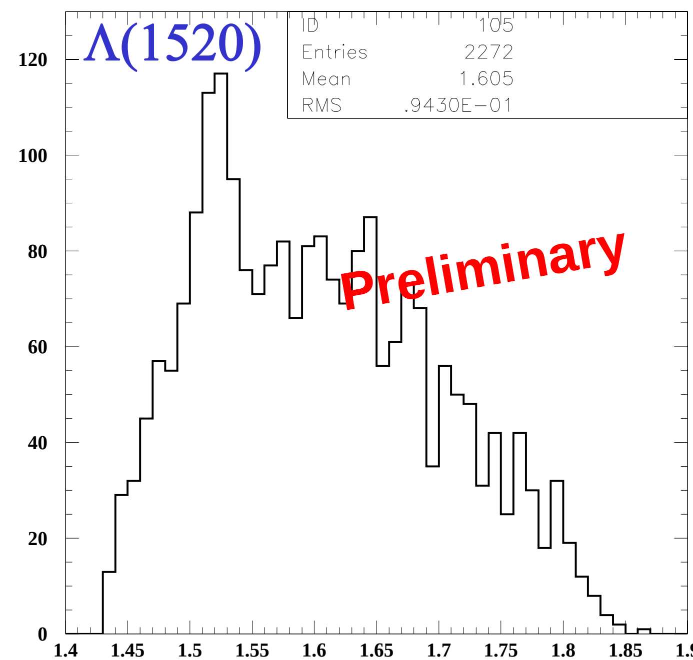
New LEPS data

~2x10^{12} photons on a 15cm-long LD2 target.

Minimal cuts: vertex, $MM_{\gamma KK}=M_N$, no ϕ, E_γ < 2.35 GeV



$MM_{\gamma K-}$ (GeV)

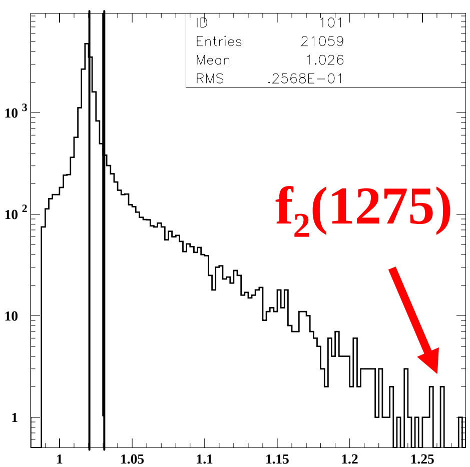


$MM_{\gamma K+}$ (GeV)

$$(MM^c_{\gamma K-})^2 = (MM_{\gamma K-})^2 - P_{(K+n)}/P_n(MM^2_{\gamma K+K-} - M_n^2)$$

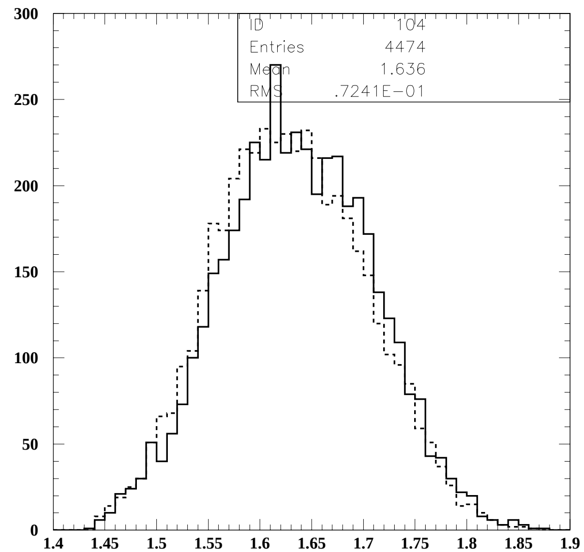
Missing mass for ϕ-tail events

$1.02 < M_{KK} < 1.03$



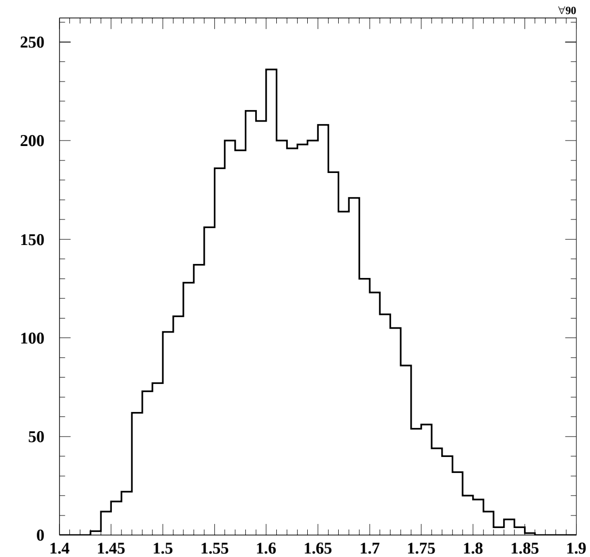
M_{KK} (GeV)

Real data: ϕ tail



$MM_{\gamma K-}$ ($MM_{\gamma K+}$)(GeV)

MC: $M_{KK} > 1.03$

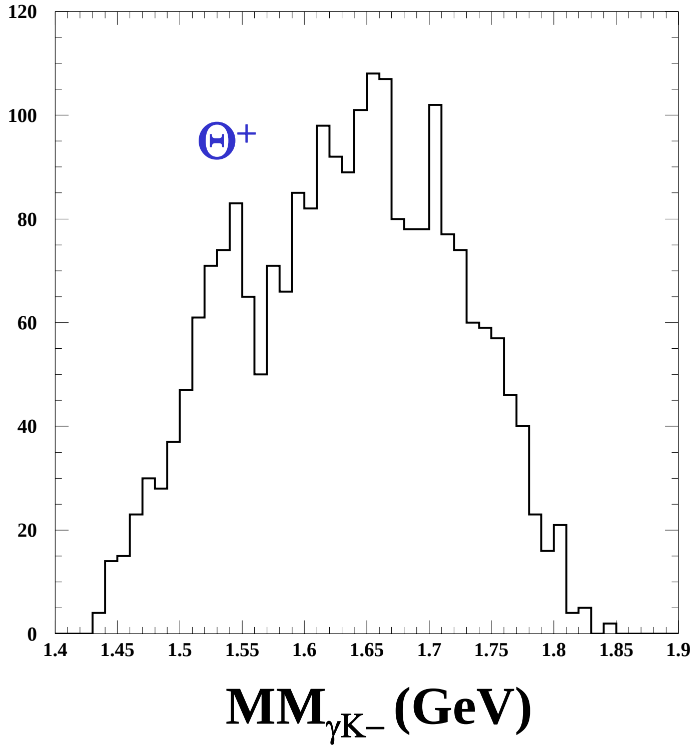


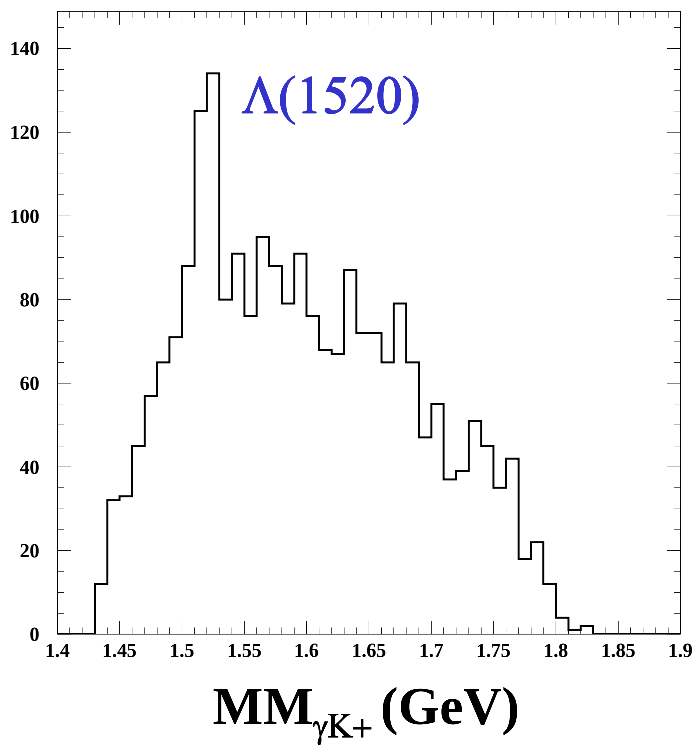
$MM_{\gamma K-}$ (GeV)

Other way to correct Fermi motion

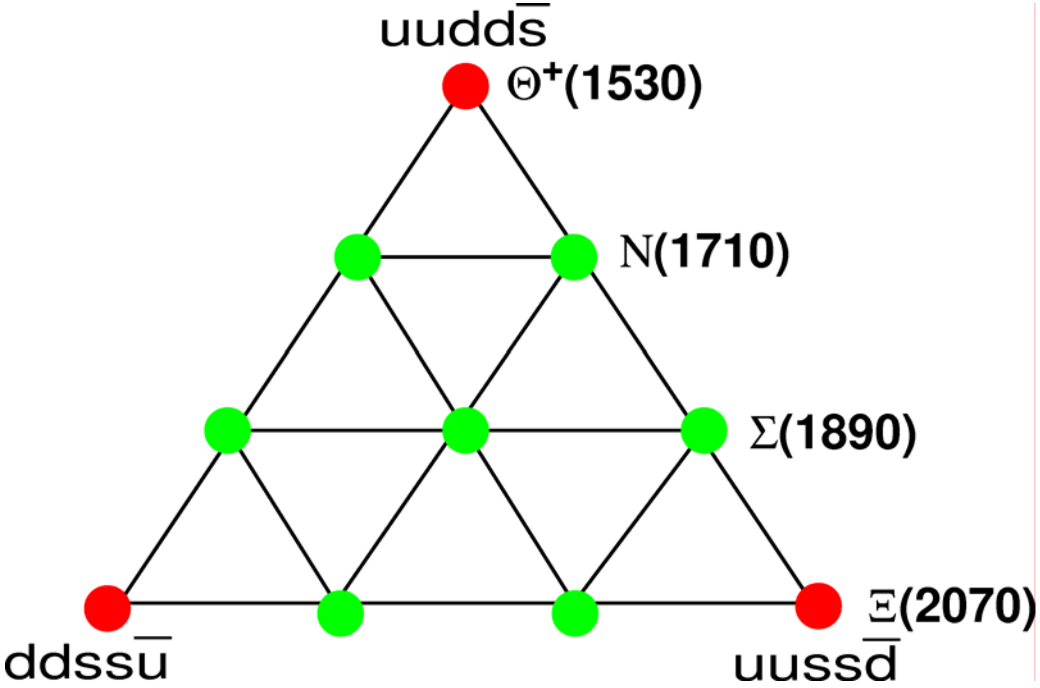
Assumption:

neutron(proton) momentum = missing momentum

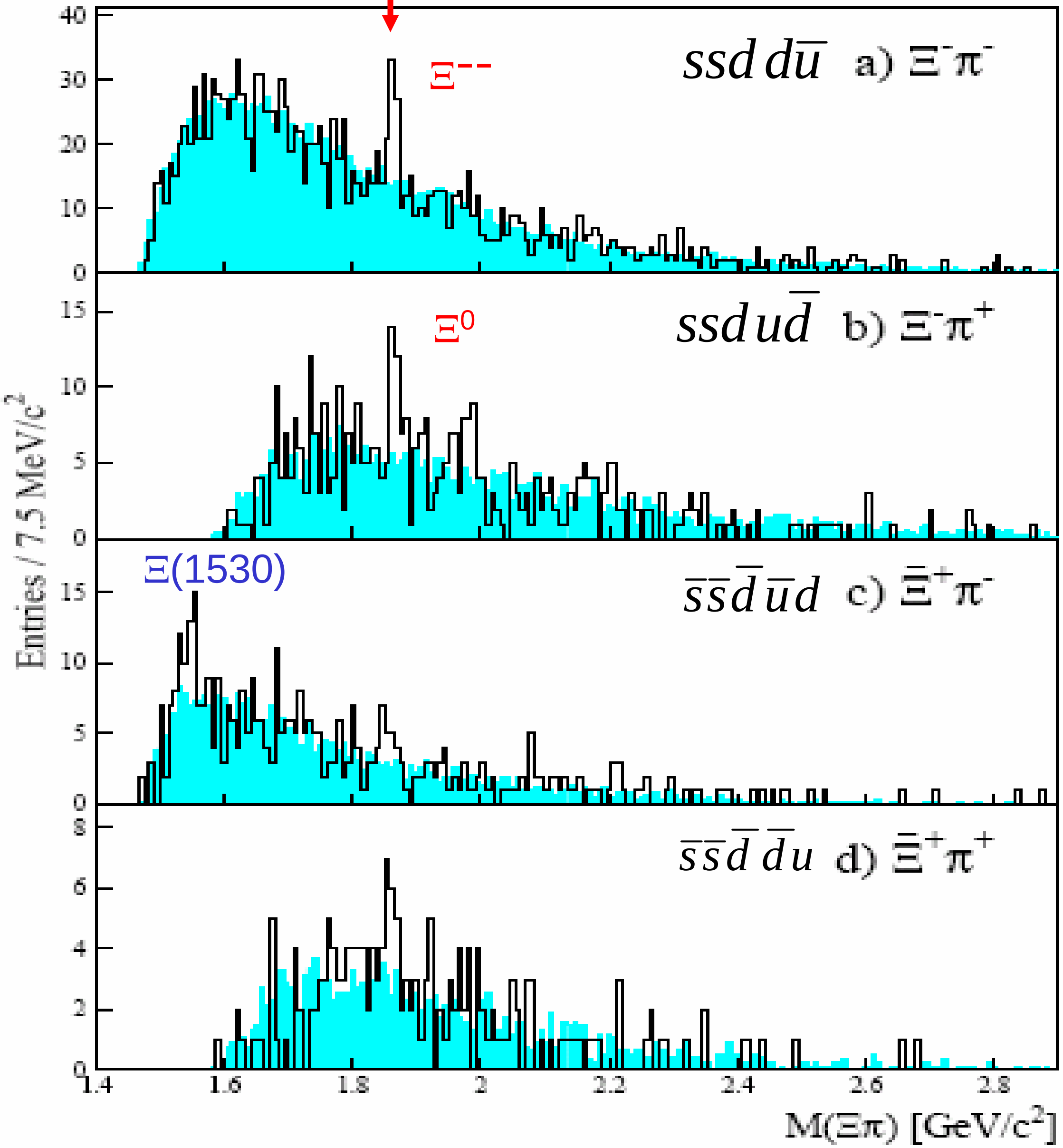




Other Pentaquarks



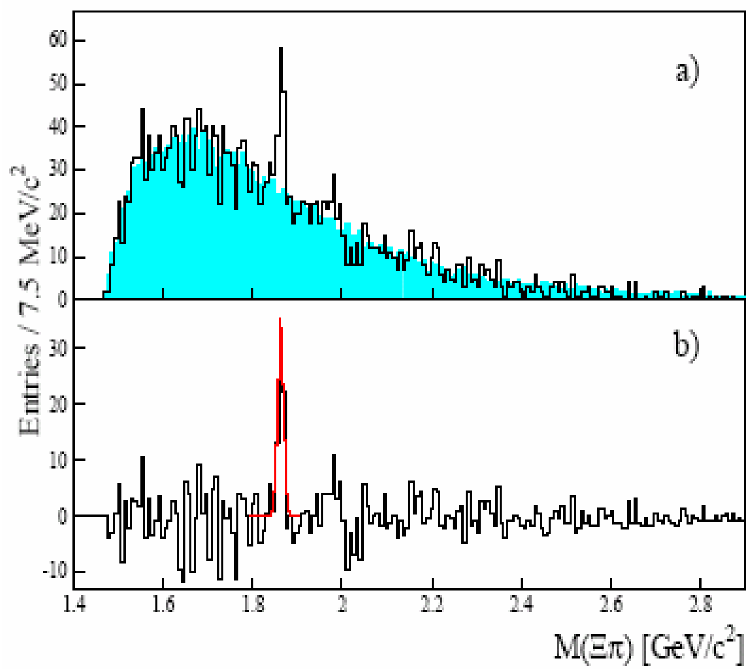
Observation of Exotic Ξ^{--}



M=1.862 ± 0.002 GeV

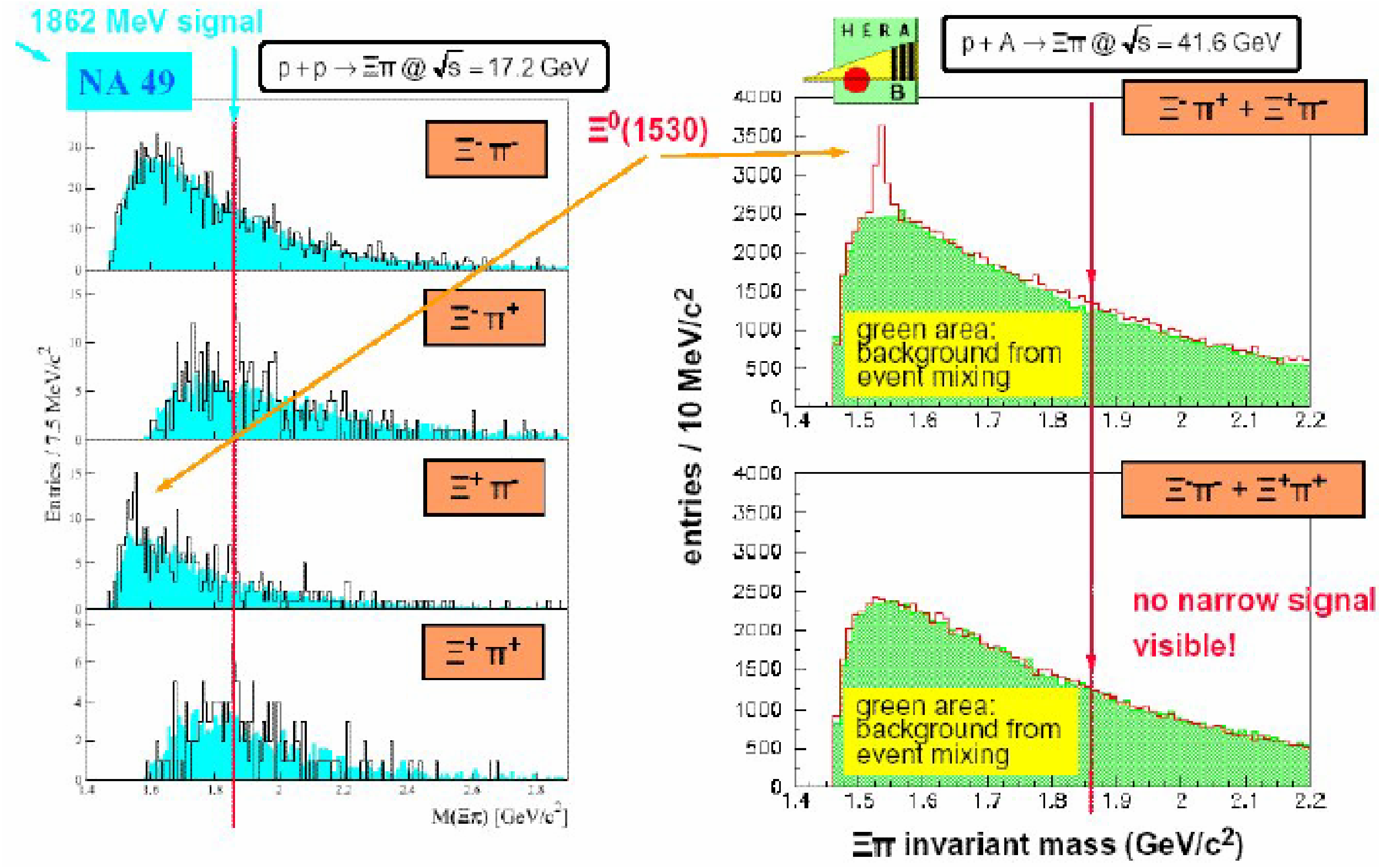
Γ<0.018 GeV

Combined spectra



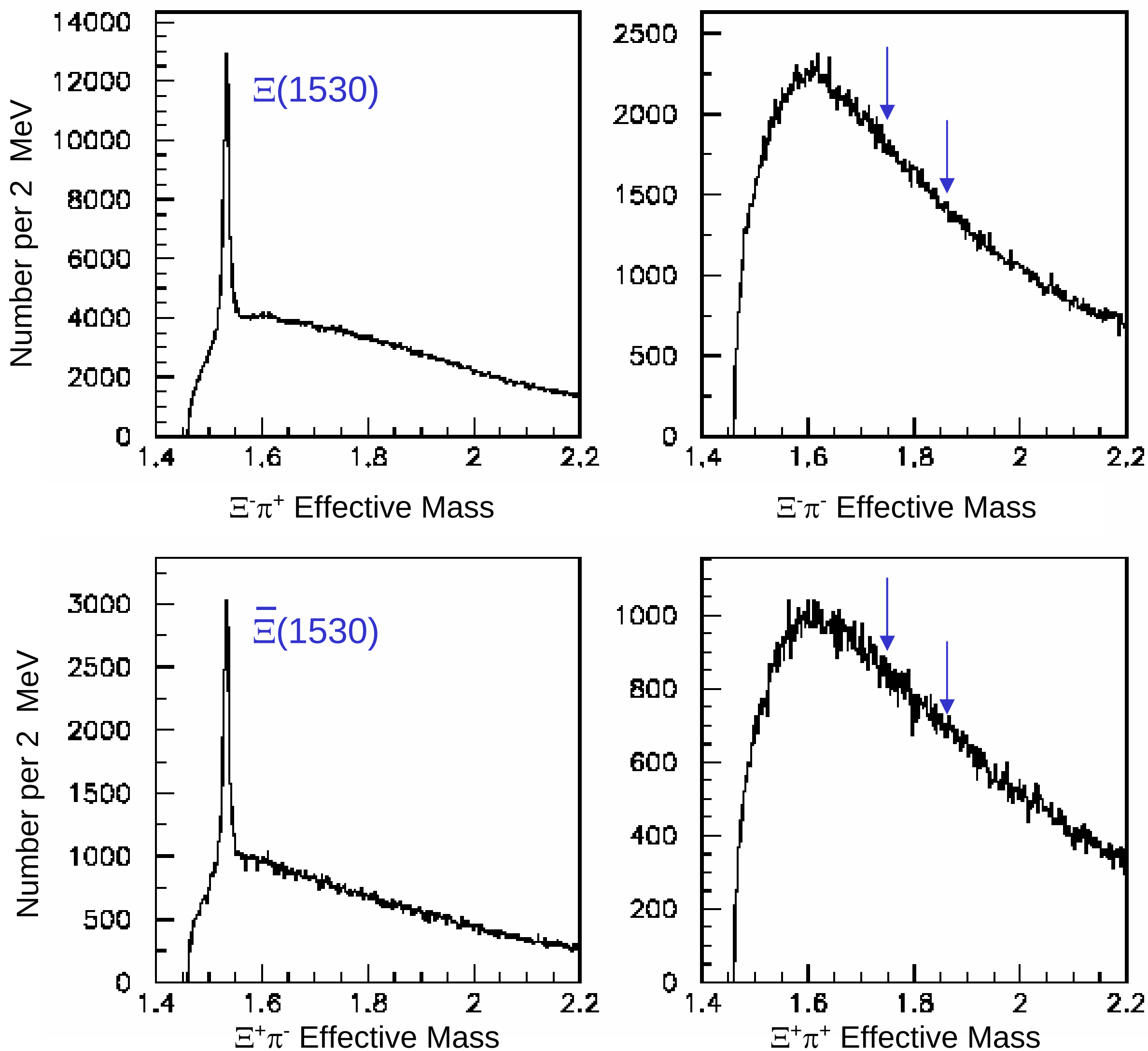
CERN SPS hep-ex/0310014

Negative result: HERA-B



Also not seen by CDF, BaBar and E690.

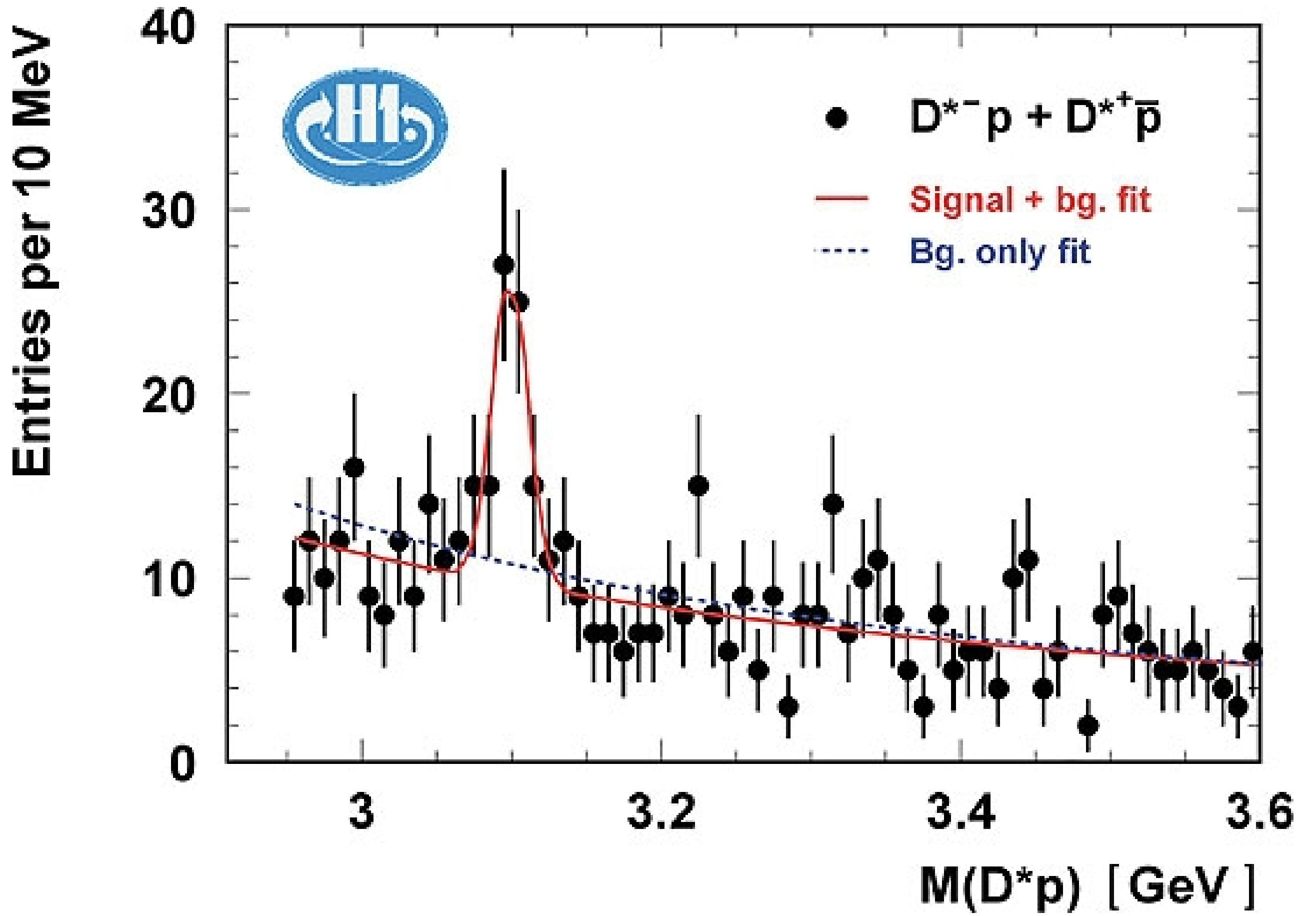
$\Xi^{\pm}\pi^{\pm}$ Effective Mass Spectra



Arrows at 1750 MeV & 1860 MeV

Monte Carlo mass resolution (σ) for $\Xi\pi$: 3.3 MeV at 1750 MeV; 4.5 MeV at 1862 MeV.

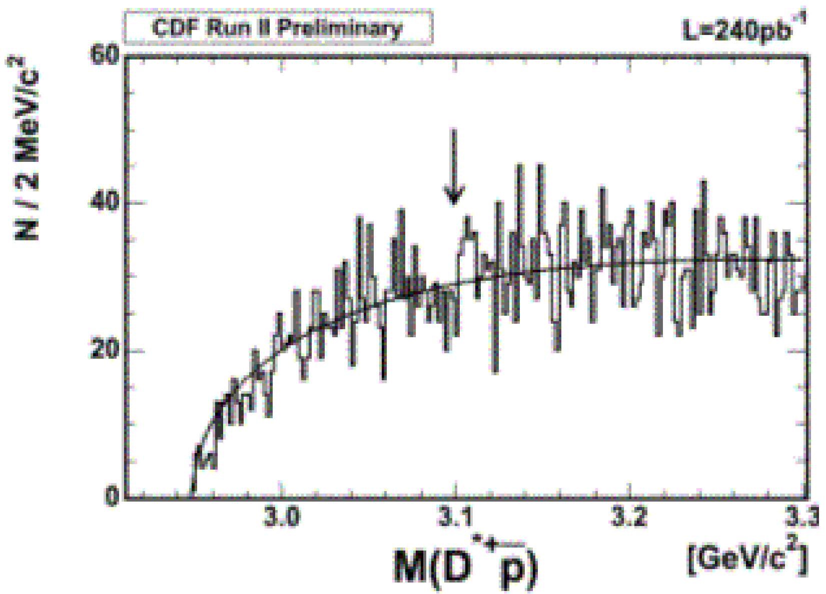
Charmed pentaquark

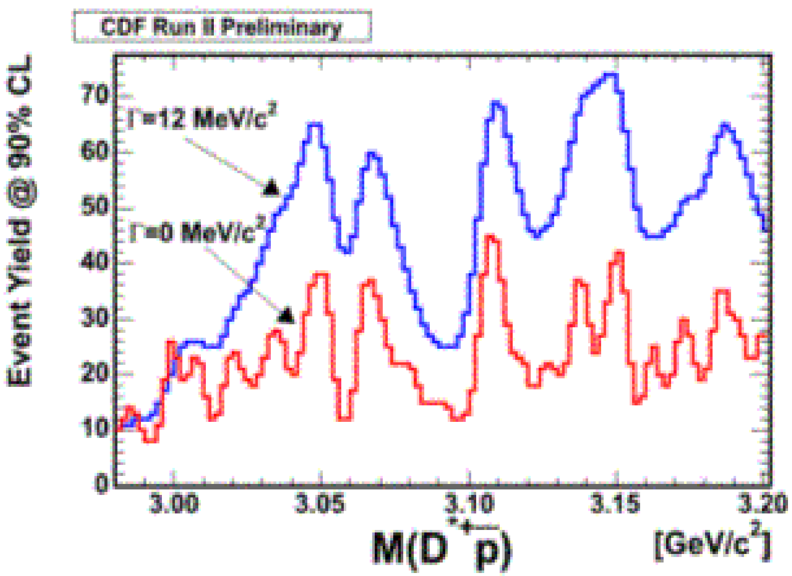


- The H-1 collaboration at DESY (Germany)
- It is a possible (uuddc̄) quark configuration.

Θc search at CDF: D*p Mass Spectrum

D*proton mass with TOF





- Proton pass all tracking cuts
- 0.5 GeV/c < Pt(proton) <2.75 GeV/c
- D+ and proton form a good vertex with vertex χ^2 < 30
- 142.5 <M(D+)–M(D^0) < 148.5 MeV/c^2
- TOF : (measured–expected)/error <2.0

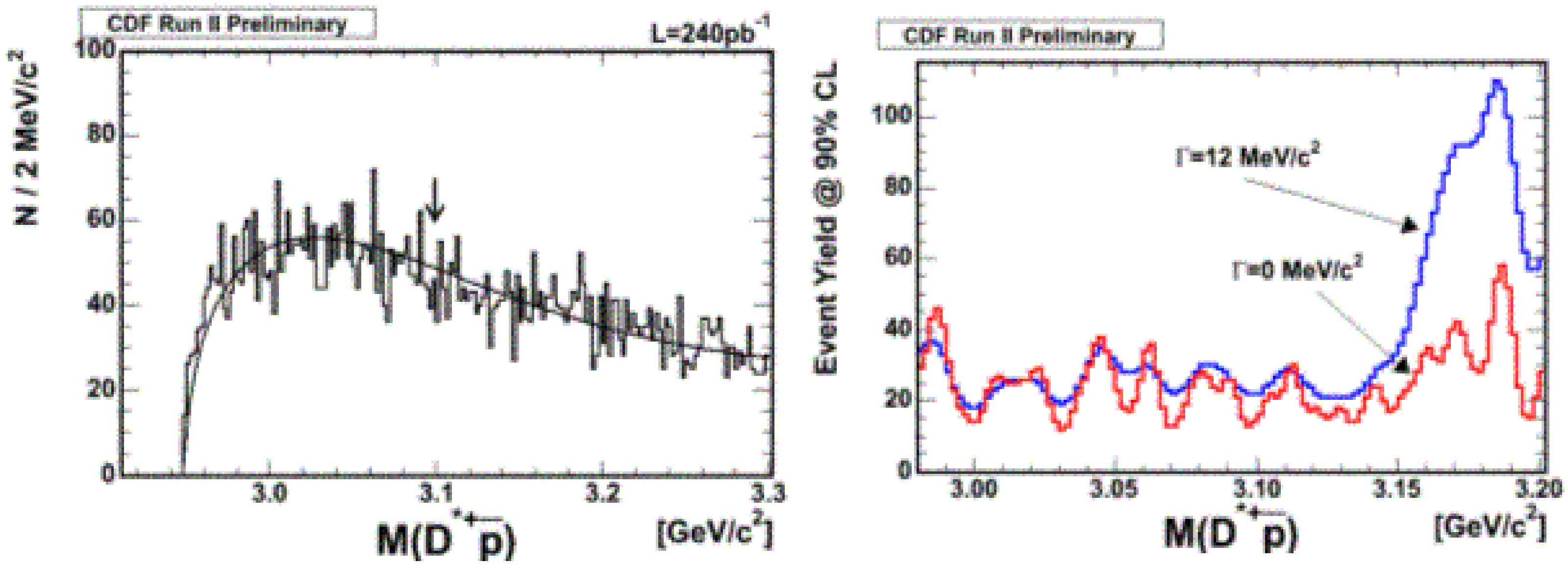
For M=3.099 GeV/c^2,

<12 events for Γ=0.0 MeV/c^2 @90% C.L.

<25 events for Γ=12.0 MeV/c^2 @90% C.L.

Θc search: D*p Mass Spectrum

D*proton mass with dEdX



- Proton pass all tracking cuts
- 2.75 GeV/c < Pt(proton)
- D* and proton form a good vertex with vertex χ^2 < 30
- 142.5 <M(D*)−M(D°) < 148.5 MeV/c²
- dEdX : (measured−expected)/error <1.3

For M=3.099 GeV/c²,

<19 events for Γ=0.0 MeV/c² @90% C.L.

<30 events for Γ=12.0 MeV/c² @90% C.L.

Also not seen by Zeus and Focus.

Summary

- Evidence for an S=+1 baryon around 1.54 GeV with a narrow width has been observed by several experimental groups.
- There are some inconsistencies in the measured masses and widths.
- No signal has been observed in high energy experiments with high statistics and good mass resolution.
- The Θ^+ does not exist or its production in high energy reactions must be highly suppressed.
- Other pentaquarks have been observed only one experiment and in doubt.

Outlook

- LEPS new exp. re-observed the peak.
  - Unlikely to be due to statistical fluctuations.
  - Further checks are in progress.
- New dedicated experiments with high statistics are on-going, scheduled, or planned at several labs (Jlab, KEK, BNL, e.t.c.).
- The issue will be settled in near future.

Exotic S=+1 Baryon

NOTE ON THE S = + 1 BARYON SYSTEM

(PDG 1986; Phys. Lett. B170, 289)

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and more recently by Kelly[2] and by Oades.[3] Two new partial-wave analyses[4] have appeared since our 1984 edition. Both claim that the P_{13} and perhaps other waves resonate.

However, the results permit no definite conclusion- the same story heard for 15 years. The standards of proof must simply be much more severe here than in a channel in which many resonances are already known to exist. The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

References

- **1. Particle Data Group, Rev. Mod. Phys. 48, SI88 (1976).**
- **2. R.L. Kelly, in Proceedings of the Meeting on Exotic Resonances (Hiroshima, 1978), ed. I. Endo et al.**
- **3. G.C. Oades, in Low and Intermediate Energy Kaon-Nucleon Physics (1981), ed. E. Ferrari and G. Violini.**
- **4. K. Hashimoto, Phys. Rev. C29, 1377 (1984); and R.A. Arndt and L.D. Roper, Phys. Rev. D31, 2230 (1985).**

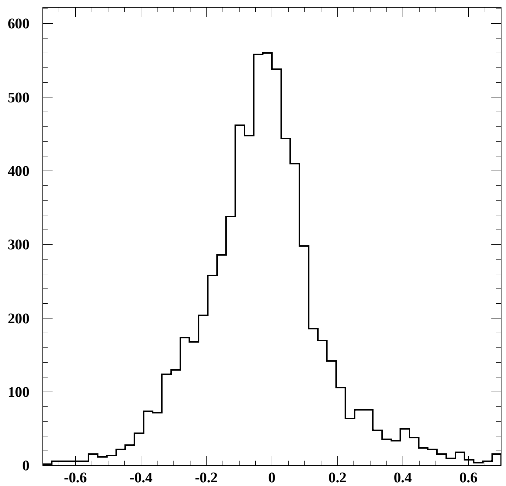
Fermi motion correction

1st order: $MM^{c}_{\gamma K-} = MM_{\gamma K-} - MM_{\gamma K+K-} + M_n$

2nd order: $(MM^{c}_{\gamma K-})^2 = (MM_{\gamma K-})^2 - \underline{P_{(K+n)}/P_n(MM^2_{\gamma K+K-} - M_n^2)}$

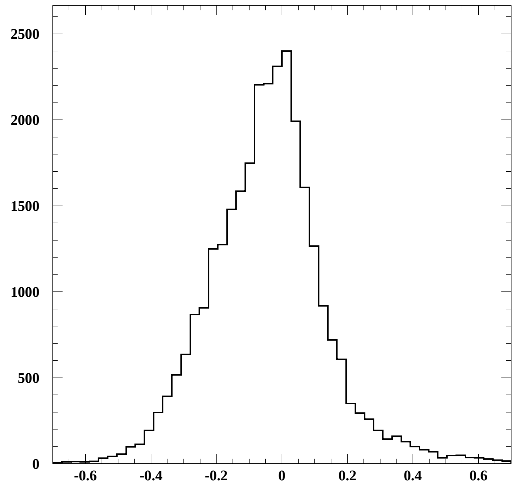
ΔM^2

$M_{KK} > 1.03$



ΔM^2 (GeV^2)

$1.01 < M_{KK} < 1.03$



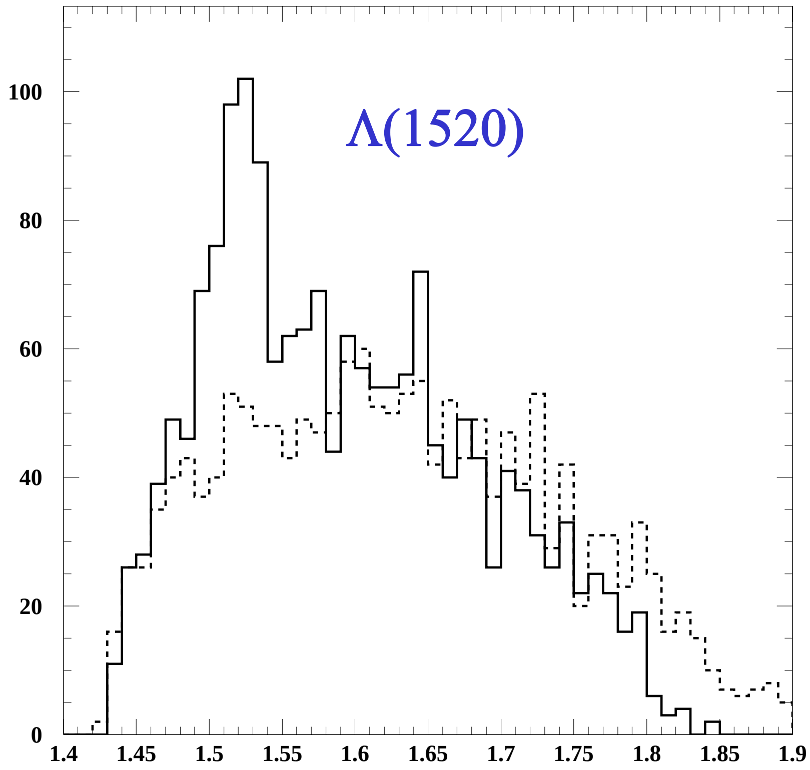
ΔM^2 (GeV^2)

We expect

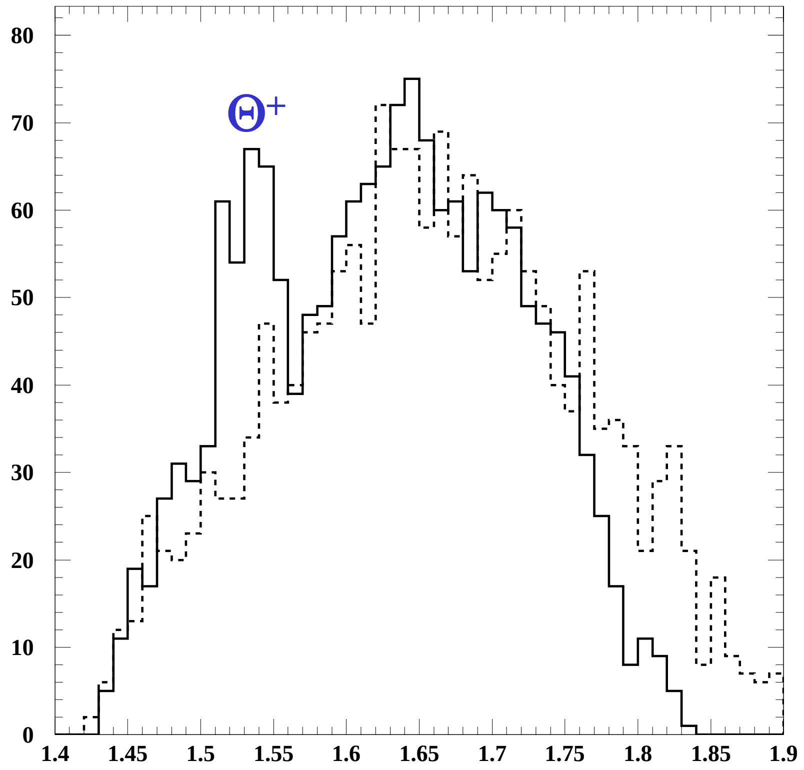
Smaller ΔM^2 → Better correction → Better S/N

if the peak is real.

$|\Delta M^2| < 0.10$ GeV^2



$MM_{\gamma K+}$ (GeV)



$MM_{\gamma K-}$ (GeV)