Exotic Baryons at HERMES

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Overview

Introduction

- QCD
- Exotic hadrons

Experimental overview

- Positive results
- Null results

HERMES

- The HERMES spectrometer
- Θ analysis
- Ξ^{--} analysis
- Additional Θ^{+} studies

Recent results

QCD in a nutshell

Interactions of quarks and gluons

- All q carry a color charge r, g, b and $\overline{q}$ carry anticolor
- All g carry a combined color charge, *i.e.* $r\overline{b}$
- Only colorless objects, *i.e.* $q\overline{q}$, qqq $\Rightarrow$ confinement

Multiquark states

- $q\overline{q} \rightarrow$ mesons (integer spin)
- $qqq \rightarrow$ baryons (half-integer spin)

States with only light quarks (u, d, s)

- Light mesons: $\mathbf{3}_f \times \overline{\mathbf{3}}_f = \mathbf{1} + \mathbf{8}$
- Light baryons: $\mathbf{3}_f \times \mathbf{3}_f \times \mathbf{3}_f = \mathbf{1} + \mathbf{8} + \overline{\mathbf{8}} + \mathbf{10}$

Exotic hadrons

More than 3 quarks $\longrightarrow$ *exotics*

Can also be colorless!

- *Exotic mesons* ($qq\bar{q}\bar{q}$): $\geq$ 4 quarks, integer spin
- *Exotic baryons* ($qqqq\bar{q}$): $\geq$ 5 quarks, half-integer spin

Surprise? No, this happens all the time in the quark sea!

Manifestly versus crypto-exotic

- *Crypto-exotic*: quantum numbers also possible with non-exotics (*e.g.* sea quark fluctuations, $uudd\bar{u}$)
  $\longrightarrow$ mix with corresponding non-exotic states
- *Manifestly exotic*: quantum numbers can only be obtained with more than three quarks (*e.g.* $uudd\bar{s}$)

Exotic hadrons

Experimental situation

- Searches and sightings in the early years of QCD
- No clear evidence for exotic mesons or baryons

Particle Data Group in 1988

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.

Once again: PDG is right!

Chiral Quark Soliton model

Diakonov, Petrov, Polyakov (1997)

- Extension of Skyrme model:
  rotations in flavor space and in real space equivalent
- Mass states are rotational excitations with $E \sim J(J+1)$

For light quarks u, d, s:

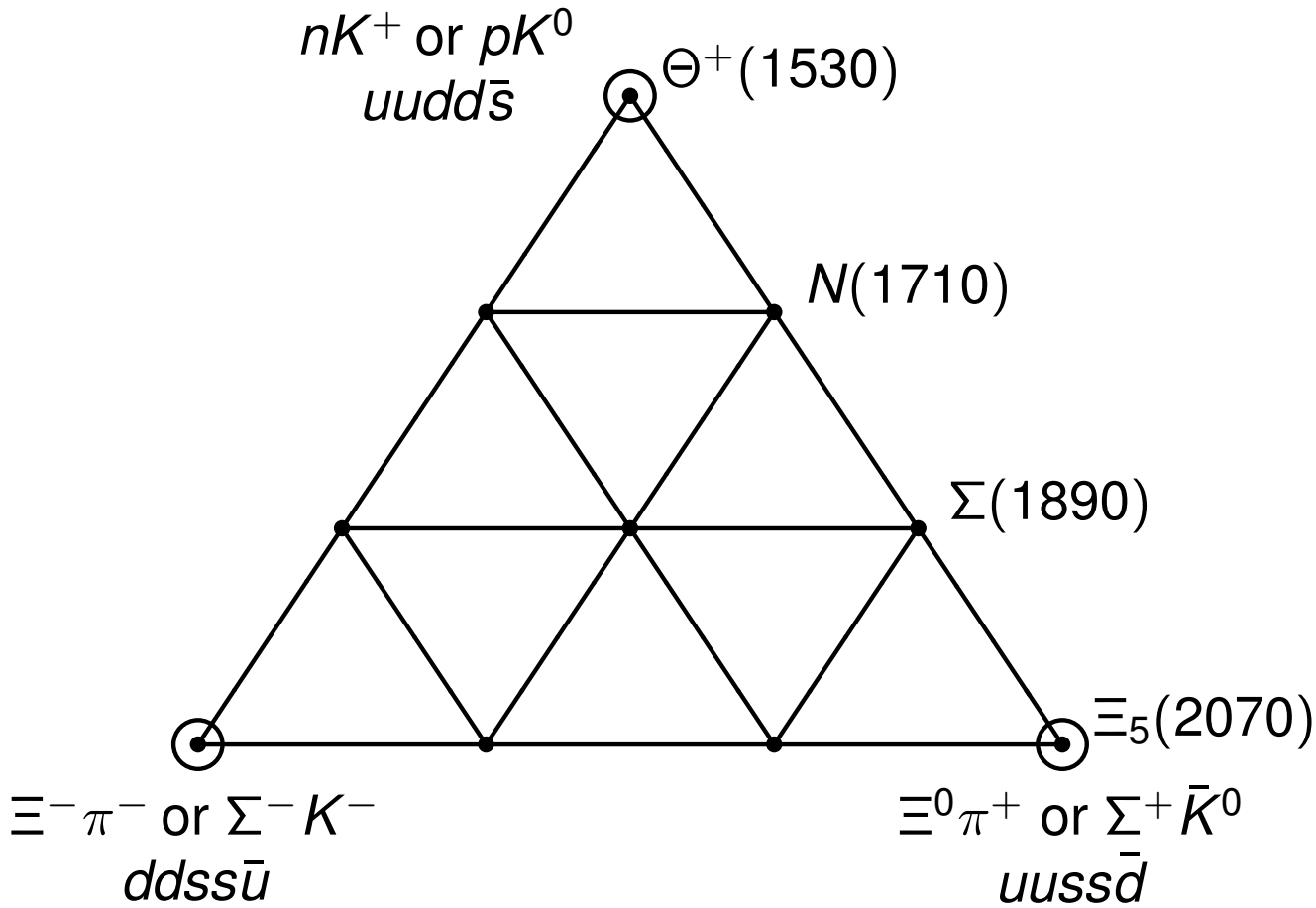
Baryons in multiplets $\mathbf{8} + \mathbf{10} + \overline{\mathbf{10}} + \mathbf{27} + \cdots$

- **8** (octet): non-exotic spin $\frac{1}{2}$ baryons
- **10** (decuplet): non-exotic spin $\frac{3}{2}$ baryons
- $\overline{\mathbf{10}}$ (anti-decuplet): exotic spin $\frac{1}{2}$ baryons
- **27**: exotic spin $\frac{3}{2}$ baryons

Mass splittings for **8** and **10** are correctly reproduced!

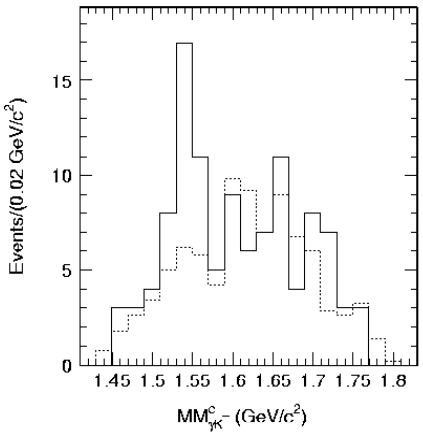
Chiral Quark Soliton model

- Exotic anti-decuplet $\overline{\mathbf{10}}$

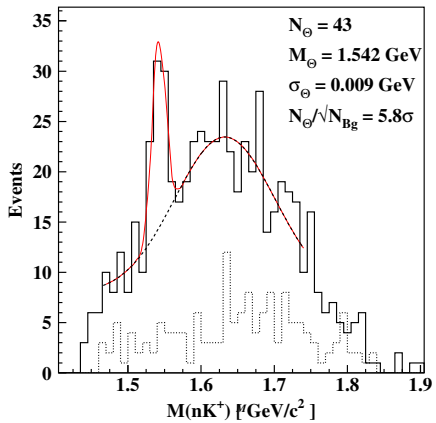


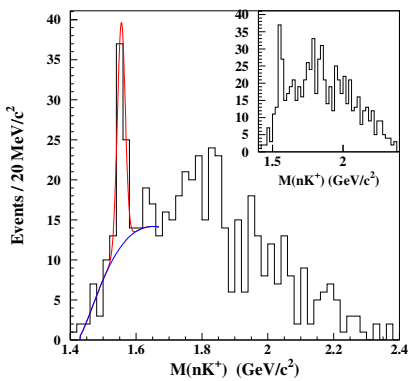
Experimental status: positive results

LEPS

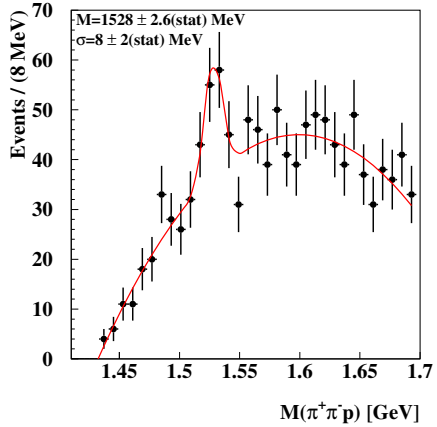


CLAS (*p* and *d*)

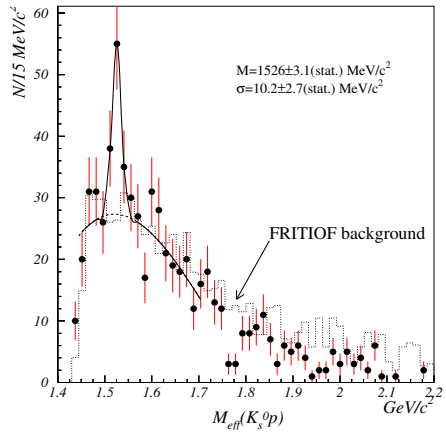




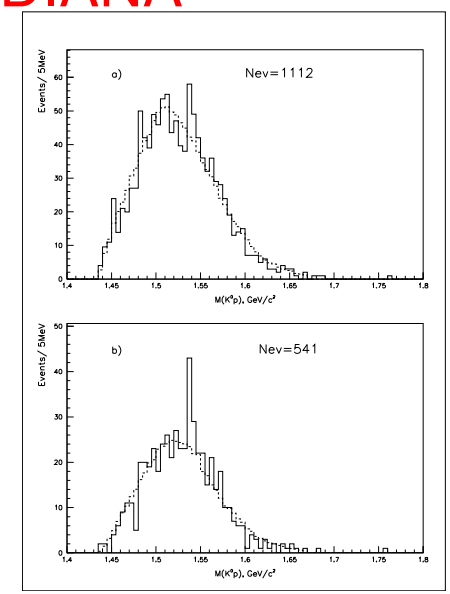
HERMES



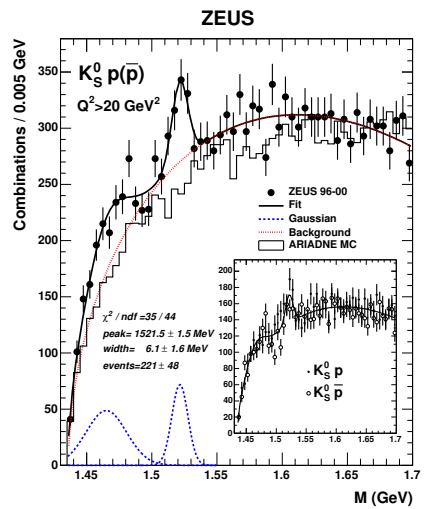
SVD-2

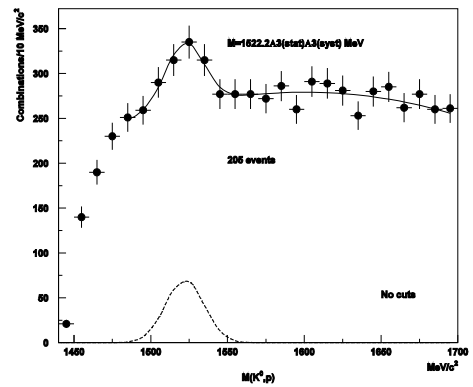


DIANA



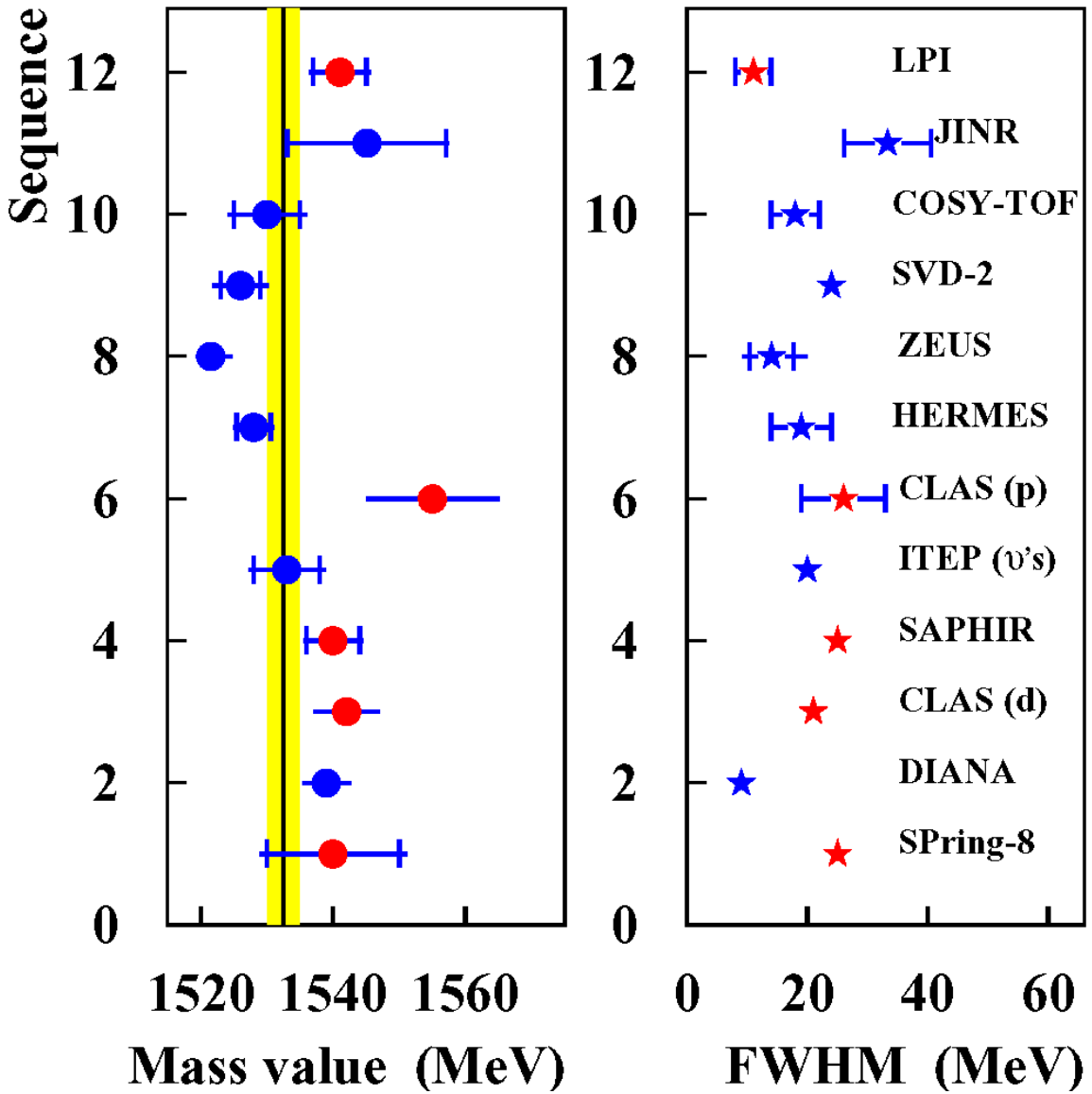
Zeus





. . . and more!

Experimental status: positive results



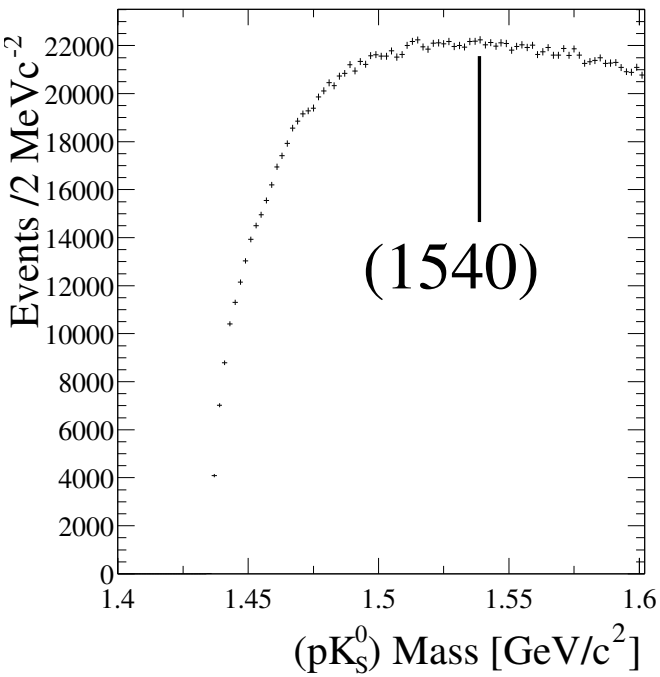
Legend
- $K^+ n$
- $K^0_S p$

World average:
1532.5 ± 2.4 MeV
(yellow band)

Experimental status: null results

BaBar

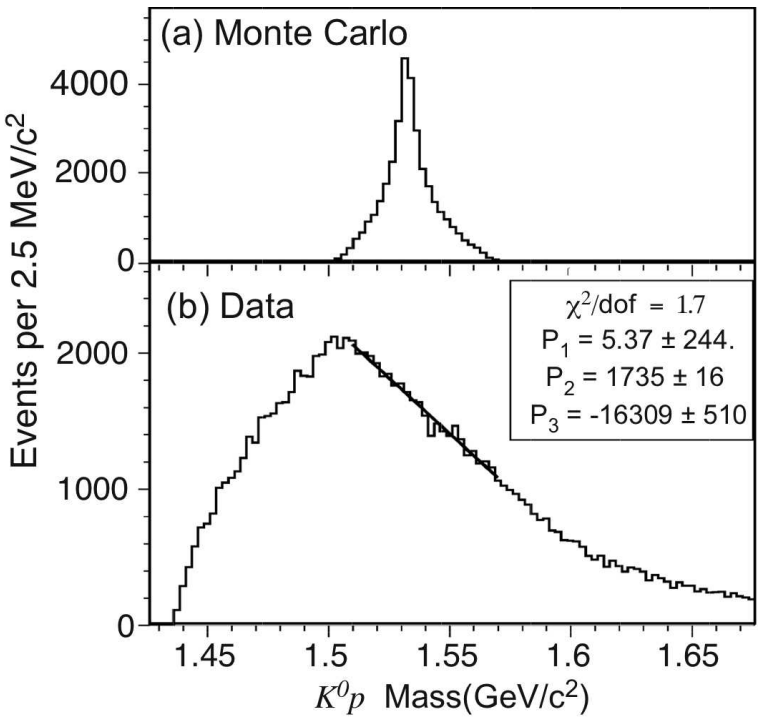
- $e^+e^- \rightarrow pK^0_S X$



- BES, Belle, LEP

HyperCP

- $pCu \rightarrow pK^0_S X$



- H1, Hera-B, Sphinx, CDF, FOCUS, Belle, Phenix

Experimental status: comments

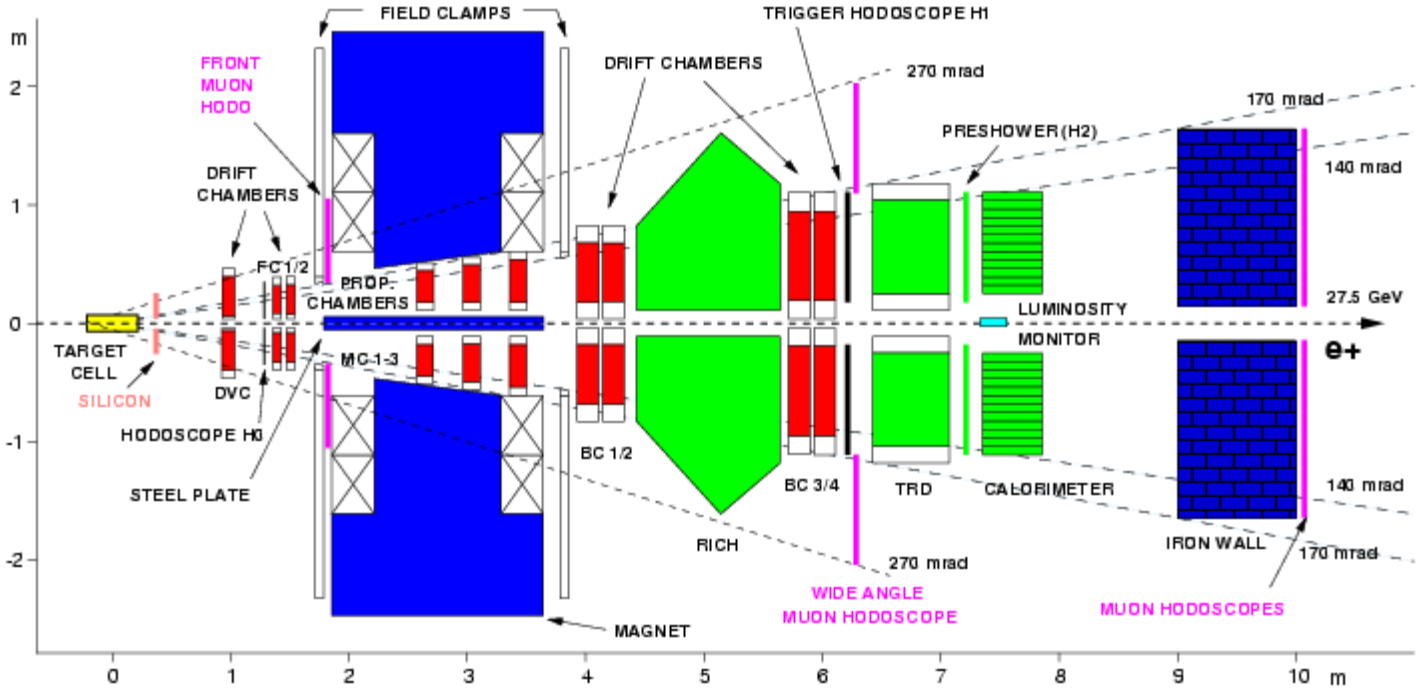
Θ^+ could be false peak

- Background unknown, statistical fluctuation
- Significance is blown up
- Strangeness unknown (in pK^0_S channel)
- Kinematic reflections
- Ghost tracks

Null results are not sensitive

- High multiplicity
- No structure for Σ's
- In e^+e^- difficult to produce baryons
- Large isospin asymmetry
- Acceptance effects

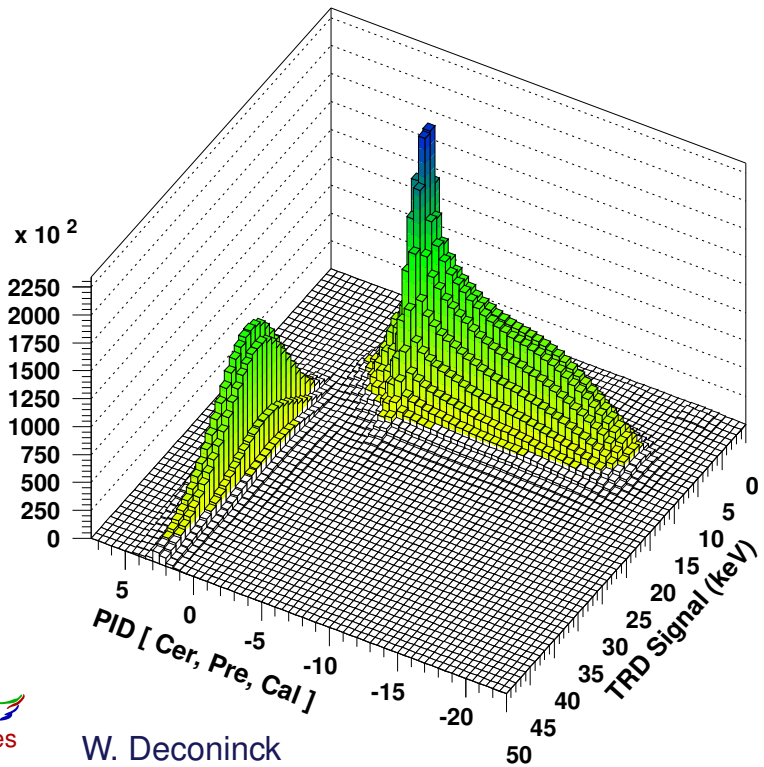
The HERMES spectrometer: overview



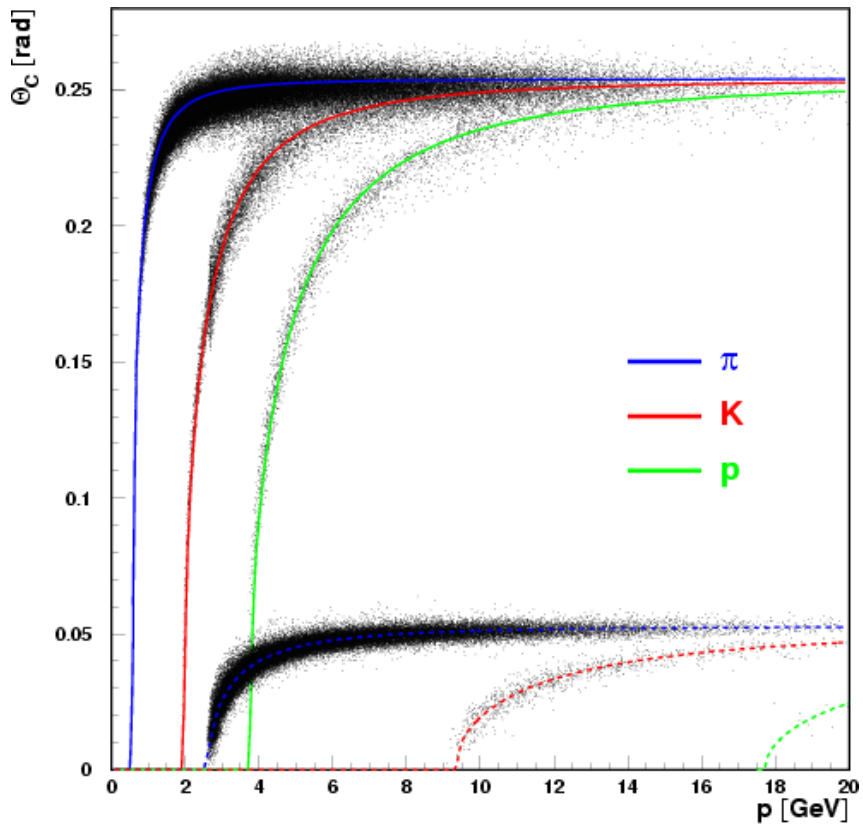
- 27.6 GeV $e^{\pm}$ HERA beam on $\overrightarrow{H}$, $\overrightarrow{He}$, $\overrightarrow{D}$ or H_2, D_2, He,...
- Resolution: $\frac{\Delta p}{p} = 1.4 - 2.5\%$, $\Delta\vartheta \lesssim 0.6$ mrad
- RICH: identification hadrons (p, π, K)
- TRD, Calo and Preshower: hadron/lepton separation

The HERMES spectrometer: PID

- **Hadron/lepton separation:**
  Combination of
  - TRD
  - Calorimeter
  - Preshower
  - RICH

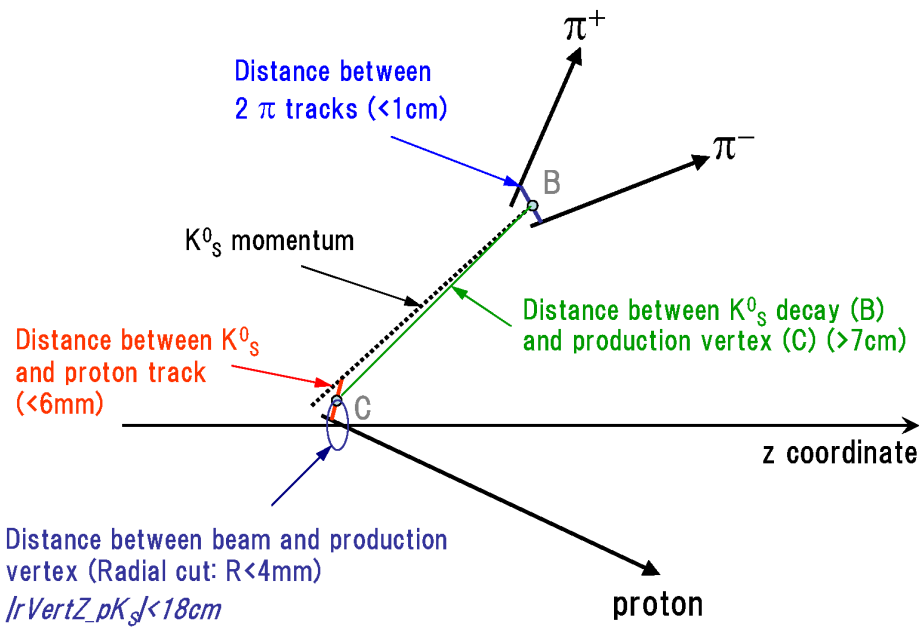


- **Hadron identification:**
  Dual radiator RICH
  - aerogel: $n = 1.03$
  - C_4F_{10} gas: $n = 1.0014$



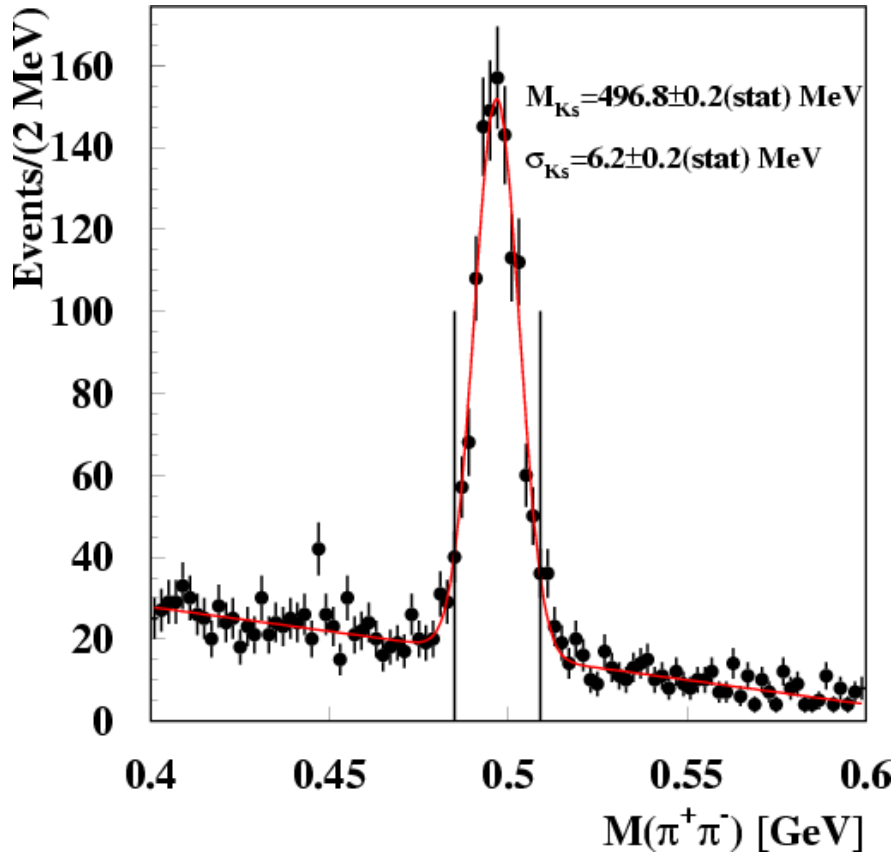
Θ^+ analysis: event selection

- Channel: $\Theta^+ \rightarrow pK^0_S \rightarrow p\pi^+\pi^-$
- Topology:



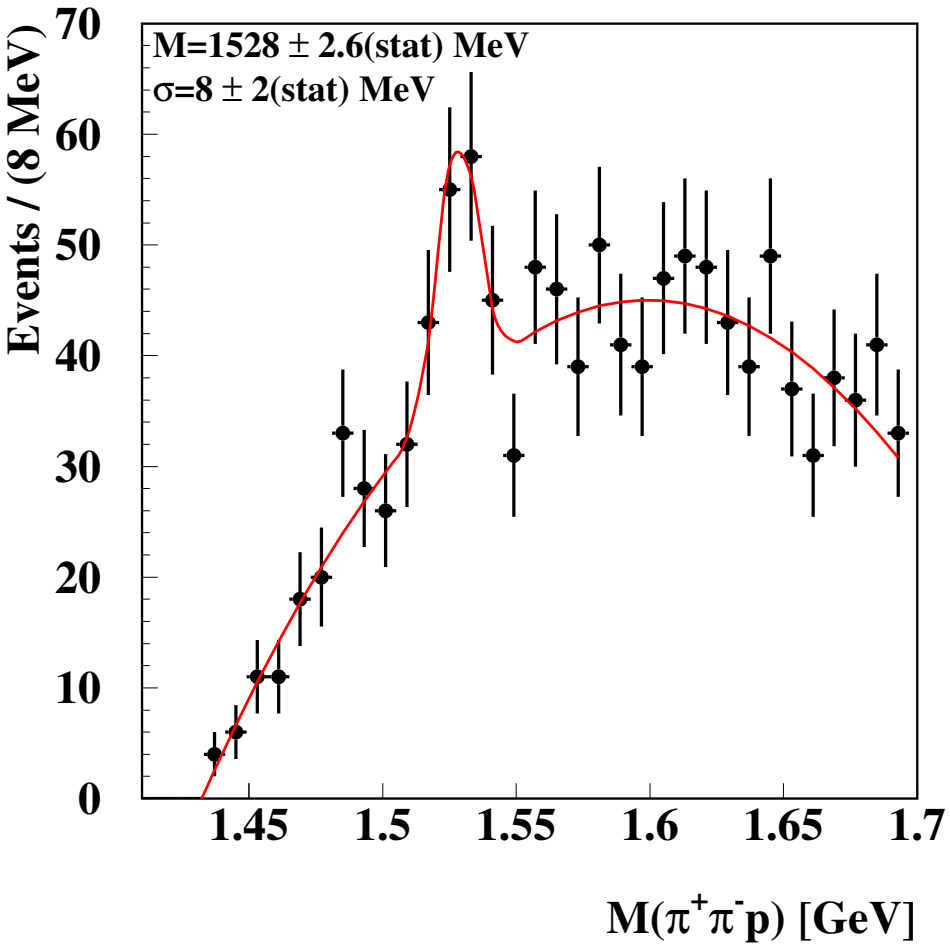
- Select K^0_S events ($2\,\sigma$ window)
- Remove Λ events ($3\,\sigma$ window)

- $M(\pi^+\pi^-)$ mass spectrum
  K^0_S peak at 496.8 MeV



Θ^+ analysis: final spectrum

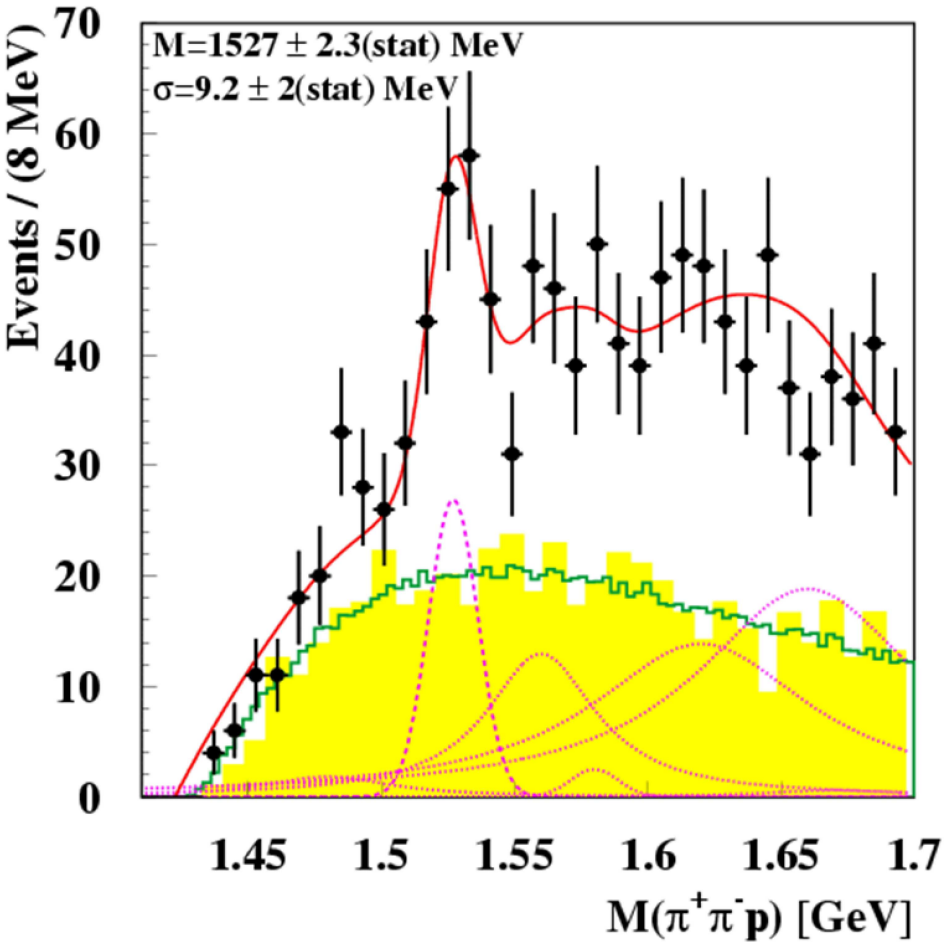
- Spectrum with polynomial fit



- Unbinned fit with 3rd order polynomial and Gaussian
- Θ^+ peak:
  - M = 1528 ± 2.6 MeV
  - σ = 8 ± 2 MeV
- Significance 3.7 σ

Θ^+ analysis: understanding the background

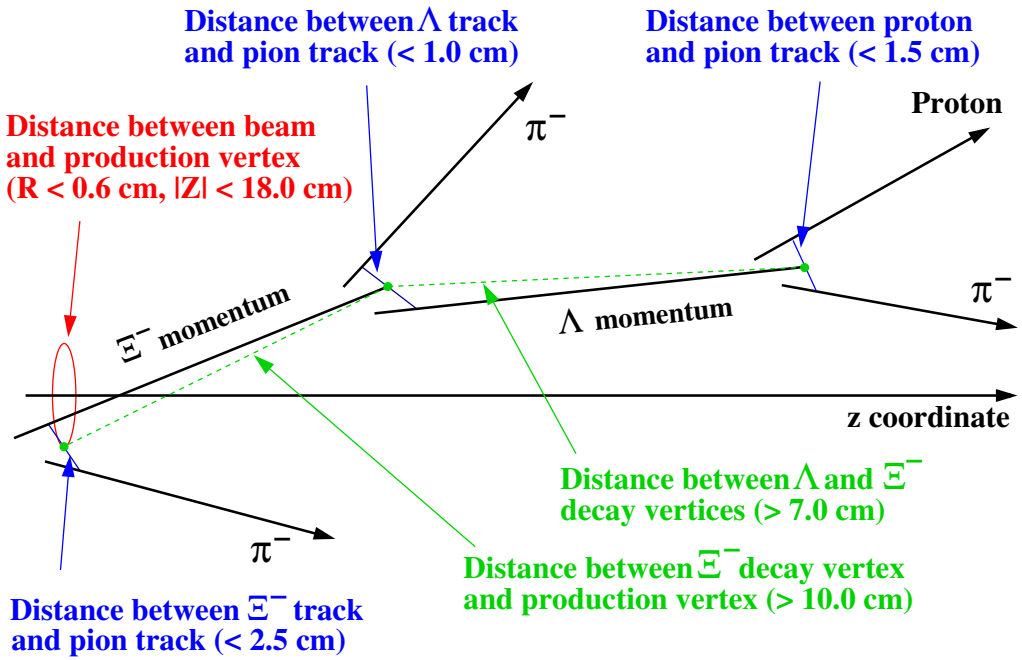
- Spectrum with MC background



- Mixed-event background
  - p from one event
  - K^0_S from other event
- PYTHIA6 Monte Carlo
  - No Σ^{*+} resonances
  - Added by hand (*cfr.* PDG)
- Θ^+ peak:
  - M = 1527 $\pm$ 2.3 MeV
  - σ = 9.2 $\pm$ 2 MeV
- Significance 4.3 σ

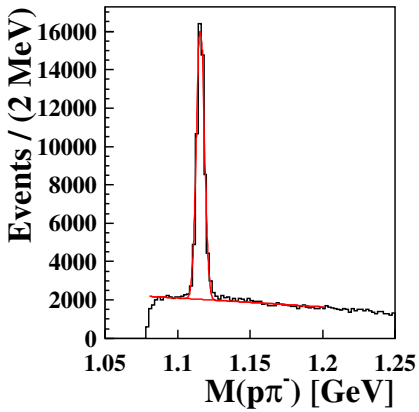
Ξ^{--} analysis: event selection

- Channel: $\Xi^{--} \rightarrow \Xi^{-}\pi^{-} \rightarrow \Lambda\pi^{-}\pi^{-}$
- Topology:

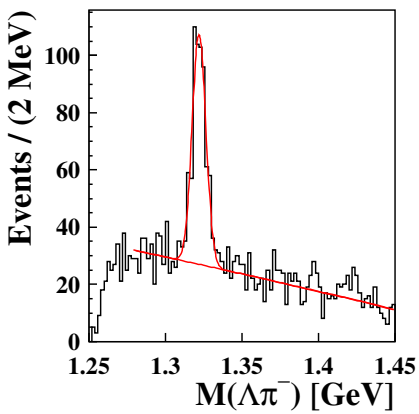


- Select Λ events ($2\,\sigma$ window)
- Select Ξ^{-} events ($2\,\sigma$ window)

- $M(p\pi^{-})$ with Λ

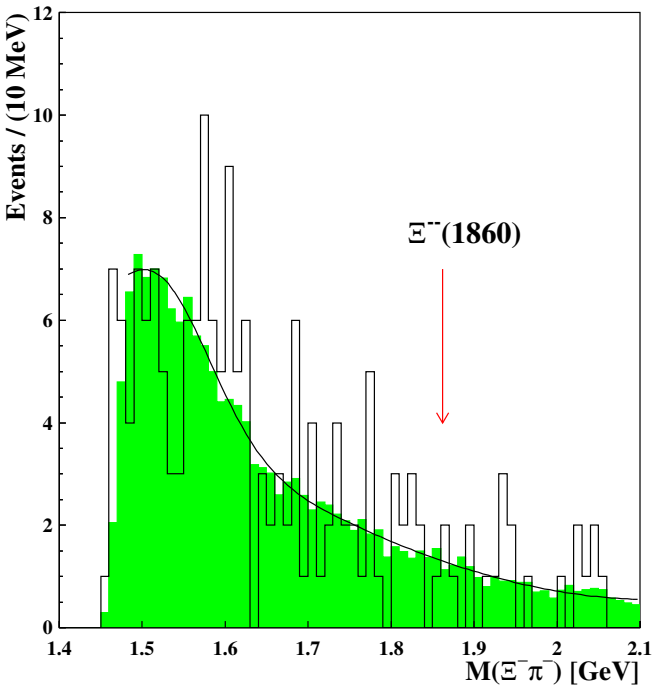


- $M(p\pi^{-}\pi^{-})$ with Ξ^{-}

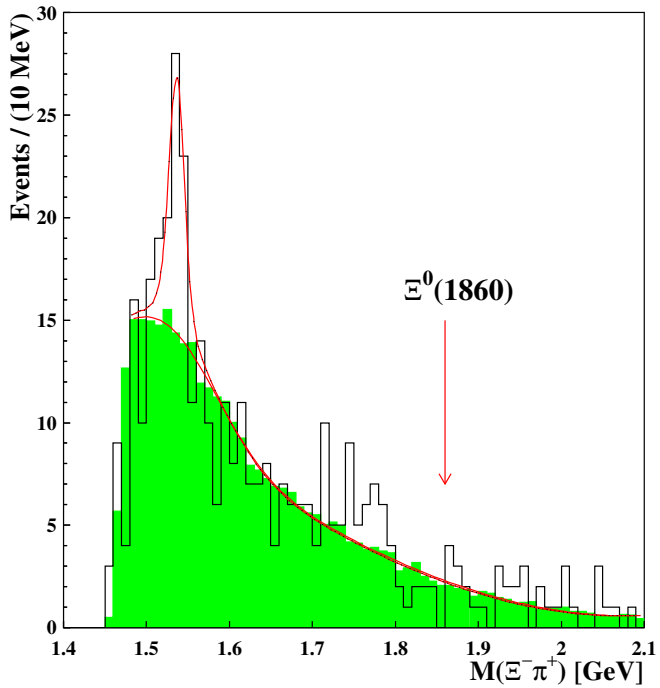


Ξ^{--} analysis: results

- $M(p\pi^-\pi^-\pi^-)$ spectrum



- $M(p\pi^+\pi^-\pi^-)$ spectrum



- Mixed-event background
- No Ξ peaks around 1860 MeV
- $\Xi^0(1530)$ seen, as expected

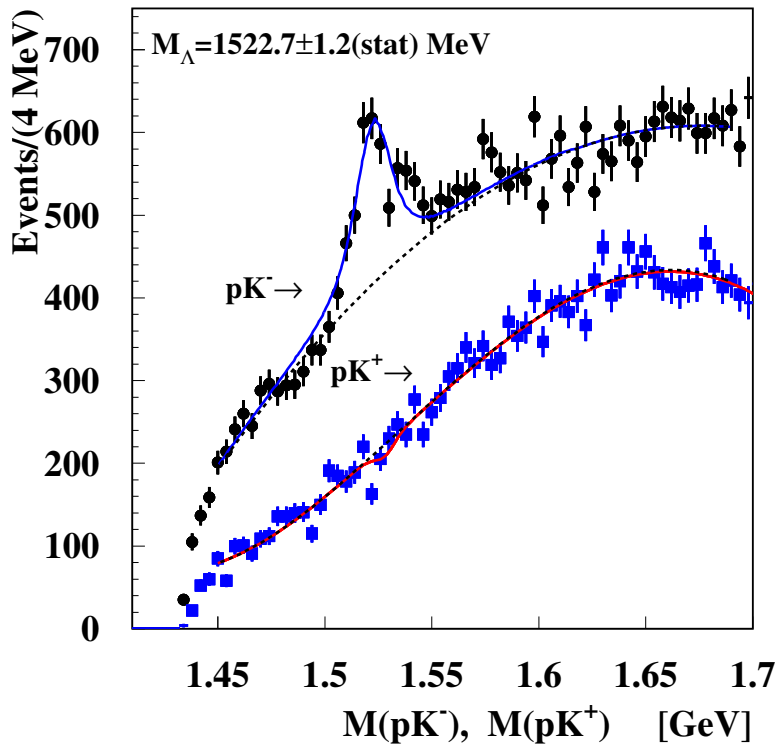
- Upper limit $\sigma^{90\%}_{\Xi^{--}} = 1.0 - 2.1$ nb
- Upper limit $\sigma^{90\%}_{\Xi^0} = 1.2 - 2.5$ nb
- $\sigma_{\Xi^0(1530)} = 8.8 - 24$ nb

Additional Θ^+ studies: isospin

In the decay channels:

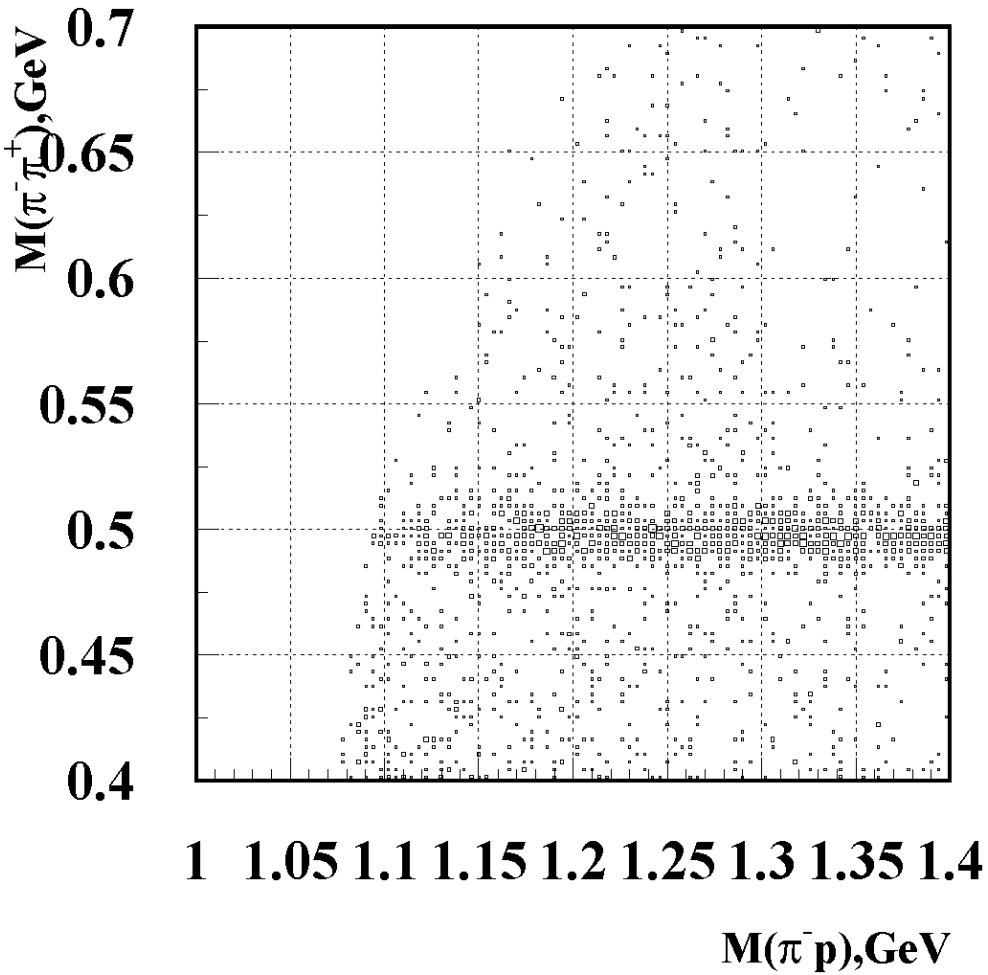
- pK^-: Clear Λ peak at 1522.7 MeV
- pK^+: no peak, zero counts (91% C.L.)

Not isotensor, probably isosinglet



Additional Θ^+ studies: PID problems

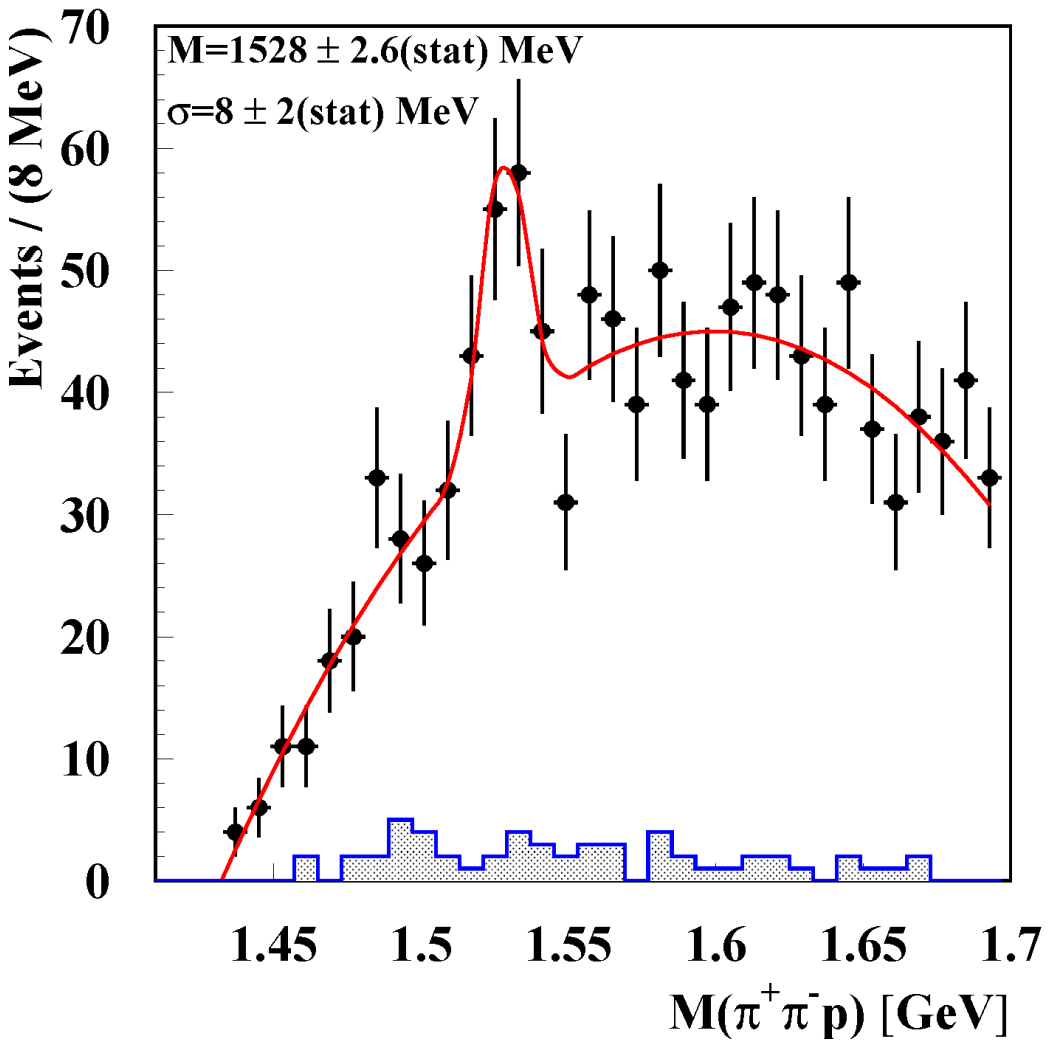
- Correlation $M_{\pi\pi}$ vs. $M_{p\pi}$



- PID leaks
  - π^+ is actually p (mis-ID)
  - K_S combination is a Λ
  - Λ peak at $M_\Lambda = 1116\,\text{MeV}$ not seen
  - No significant mis-ID of p tracks as π^+!
- Ghost tracks
  - No correlations
  - Examined data files
  - No ghost tracks!

Additional Θ^+ studies: inefficient cuts

- $\Lambda(1116)$ contribution



PID leaks

- π^+ is a p (mis-ID)
- K_S is actually $\Lambda(1116)$

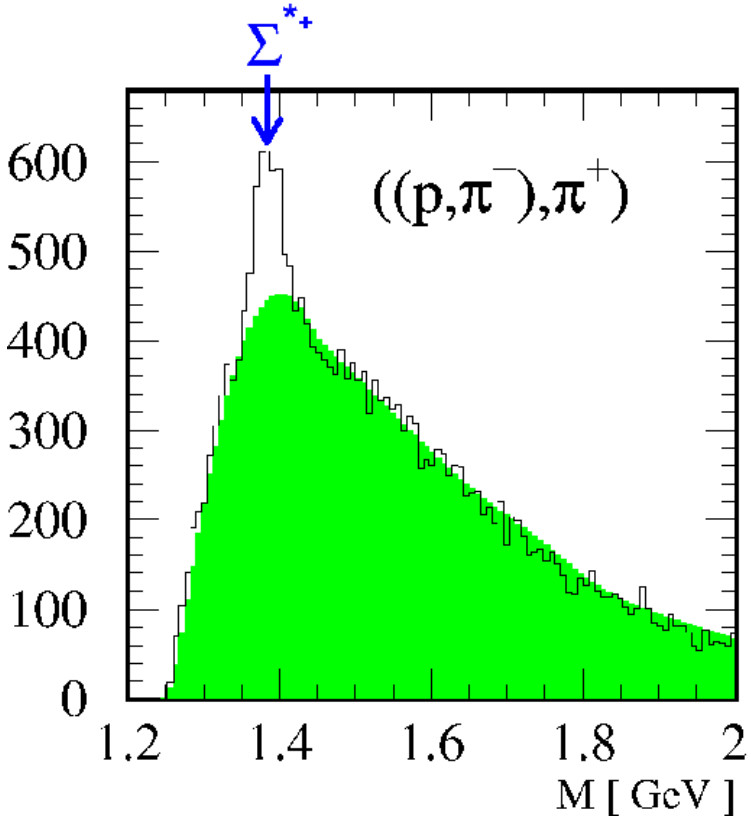
Maybe Λ cut inefficient

Contribution of Λs

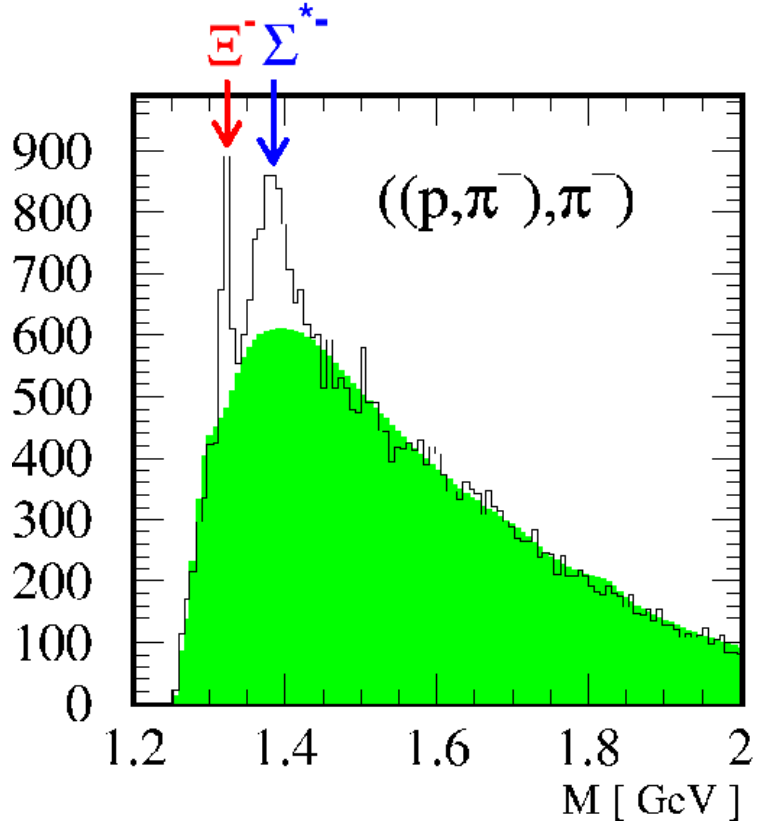
- Events with Λ (blue)
- Peak not from Λ!

Additional Θ^+ studies: is Θ^+ a Σ^{*+}?

- Σ^{*+} would decay to $\Lambda\pi^+$
- $Br(K_S\pi)/Br(\Lambda\pi^+) = 2/3$

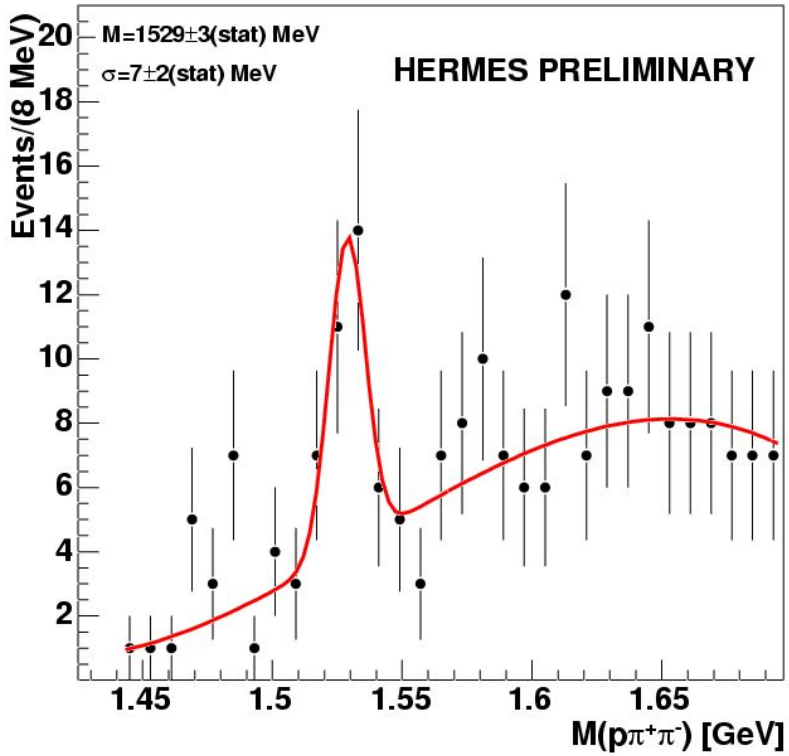


- $M_{p\pi\pi}$ spectrum (black)
- Mixed events (green)



→ Not a Σ^{*+} resonance!

Additional Θ^+ studies: require extra hadron



- With 4th hadron (black)
- 4th hadron $= \pi$ (red)
- 4th hadron $\neq \pi$ (green)

Require extra π

- Background down
- Signal stays!

Additional Θ^+ studies: require extra hadron

Why does the additional π help?

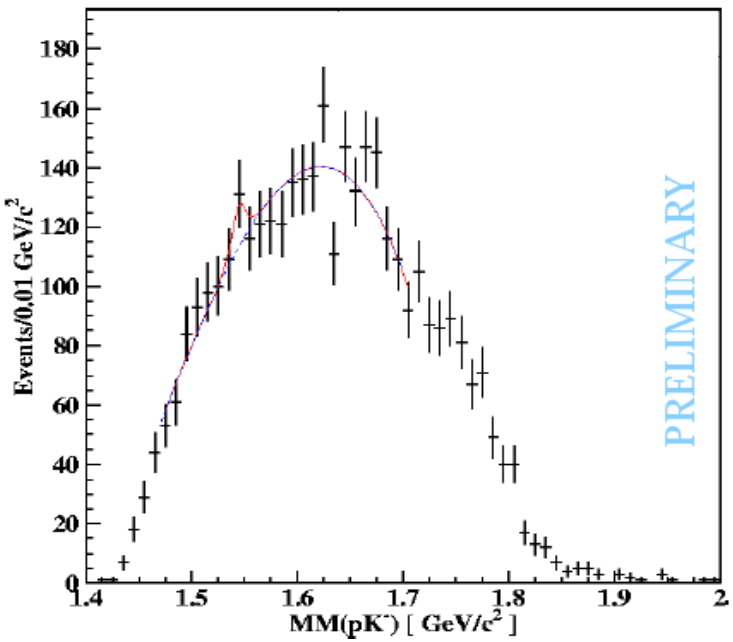
- ϕ production: $p\gamma \rightarrow p\phi \rightarrow pK^0_S K^0_L \rightarrow p\pi^+\pi^-(K^0_L)$
- Requiring extra π removes this $p\pi\pi$-only process

Can we clean even more?

- Remove $K^{*\pm} \rightarrow K_S\pi^\pm \rightarrow \pi^+\pi^-\pi^\pm$
- Remove $\Lambda \rightarrow p\pi_4$ from $K^0_S\Lambda \rightarrow p\pi\pi\pi$

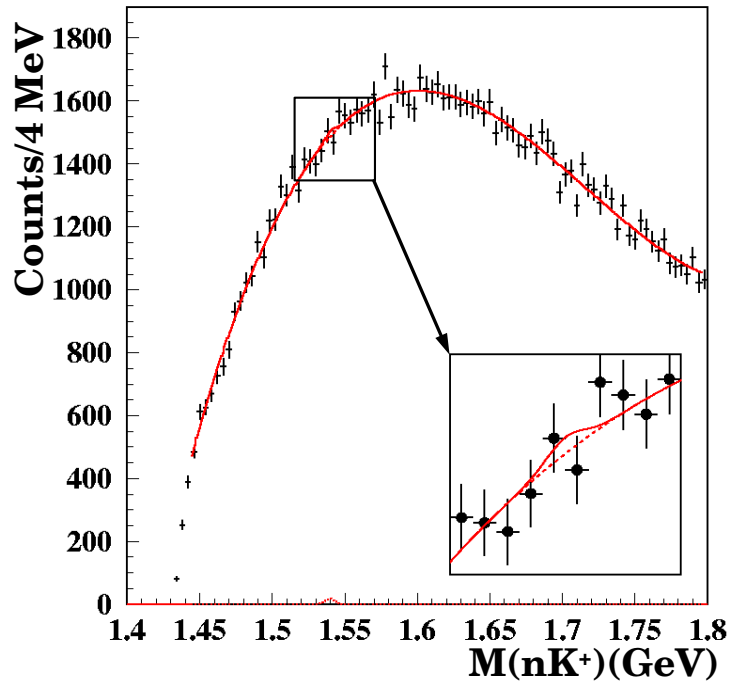
New results: CLAS g10 and g11

- g10: $\gamma d \to n K^+ K^- p$



- Preliminary!
- $\sigma_{\gamma n \to \Theta^+ K^-} < 5\,\text{nb}$ (95% C.L.)

- g11: $\gamma p \to n K^+ K^0_S$

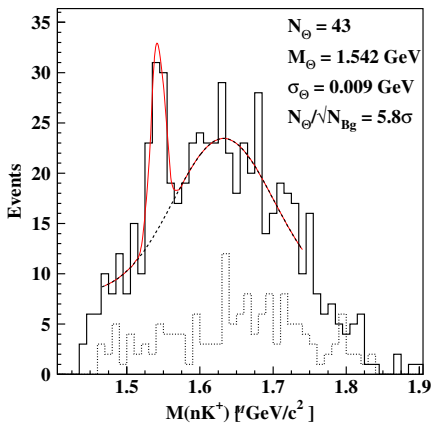


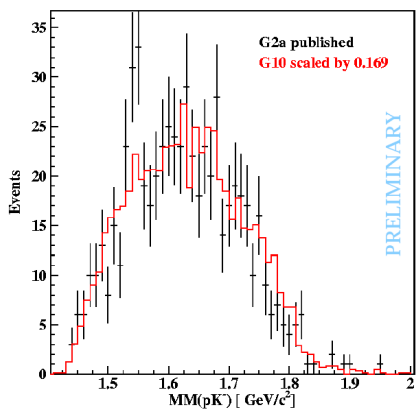
- $\sigma_{\gamma p \to \Theta^+ K^0_S} < 2\,\text{nb}$ (95% C.L.)
- $\frac{N(\Theta^+)}{N(\Lambda(1520))} < 0.2\%$ (95% C.L.)

New results: CLAS g10 and g11

g10 vs. CLAS-d

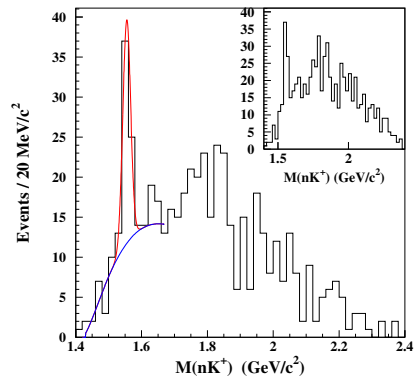
- Background underestimated
- Now only 3 σ signal. . .



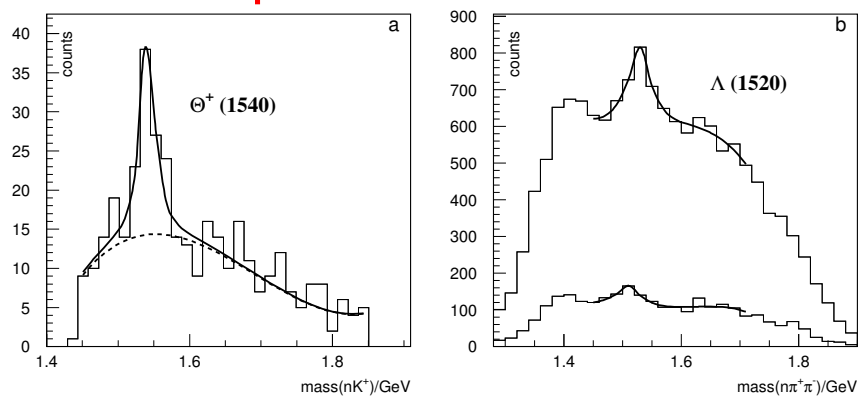


g11 vs. CLAS-p

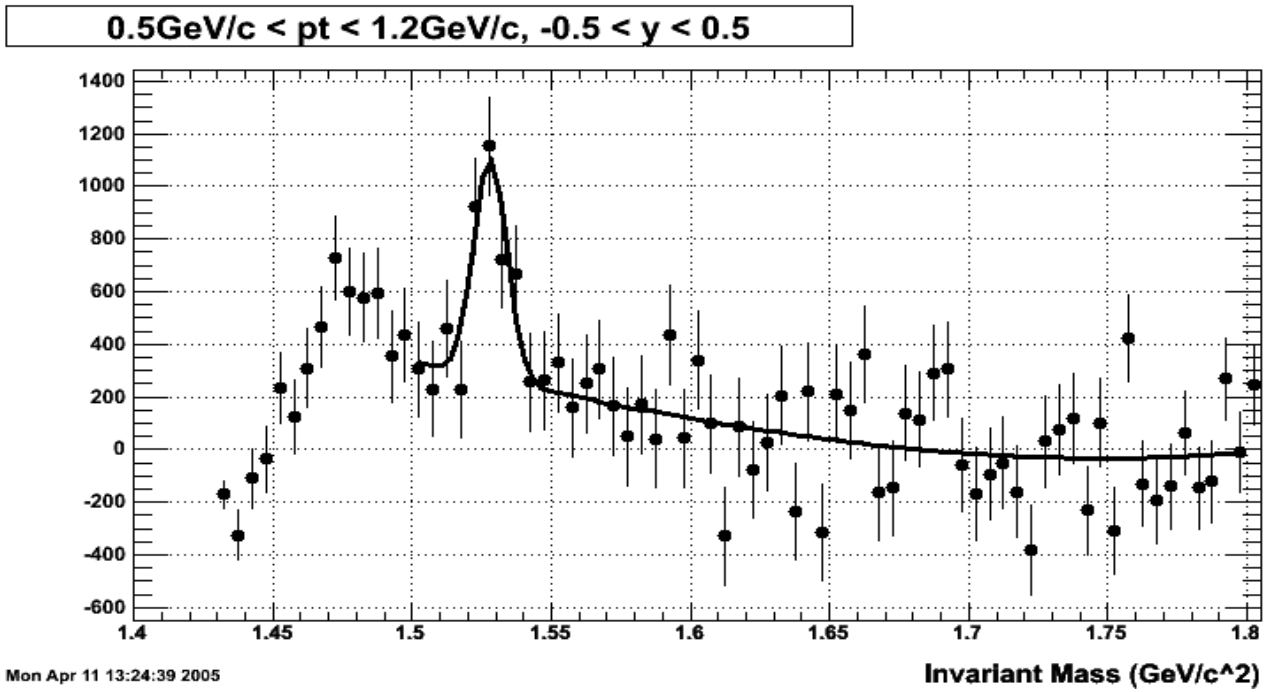
- 5 σ turned out to be wrong



g11 vs. Saphir



New results: STAR at RHIC



- Preliminary!
- High statistics, good resolution, minimal cuts
- $5\,\sigma$ observation of Θ^{++}, also Θ^{+} with lower significance

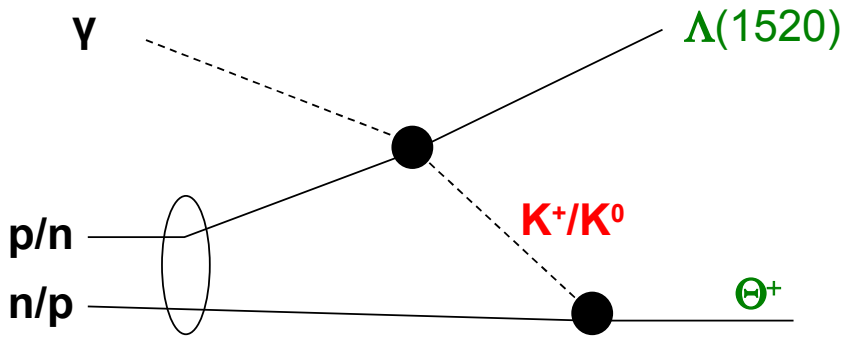
"The observed yield at STAR is so small, such that many experiments would not have the sensitivity to see it."

New results: LEPS at SPring-8

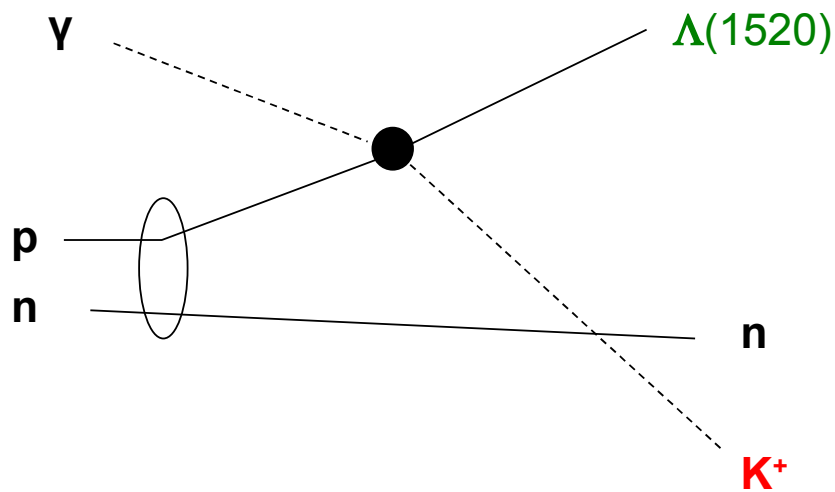
Reaction: $\gamma d \to \Lambda(1520)\Theta^+ \to pK^- X$

- Liquid D_2 target
- E_γ known between 1.5 – 2.4 GeV
- Missing mass technique

- Possible reaction mechanism

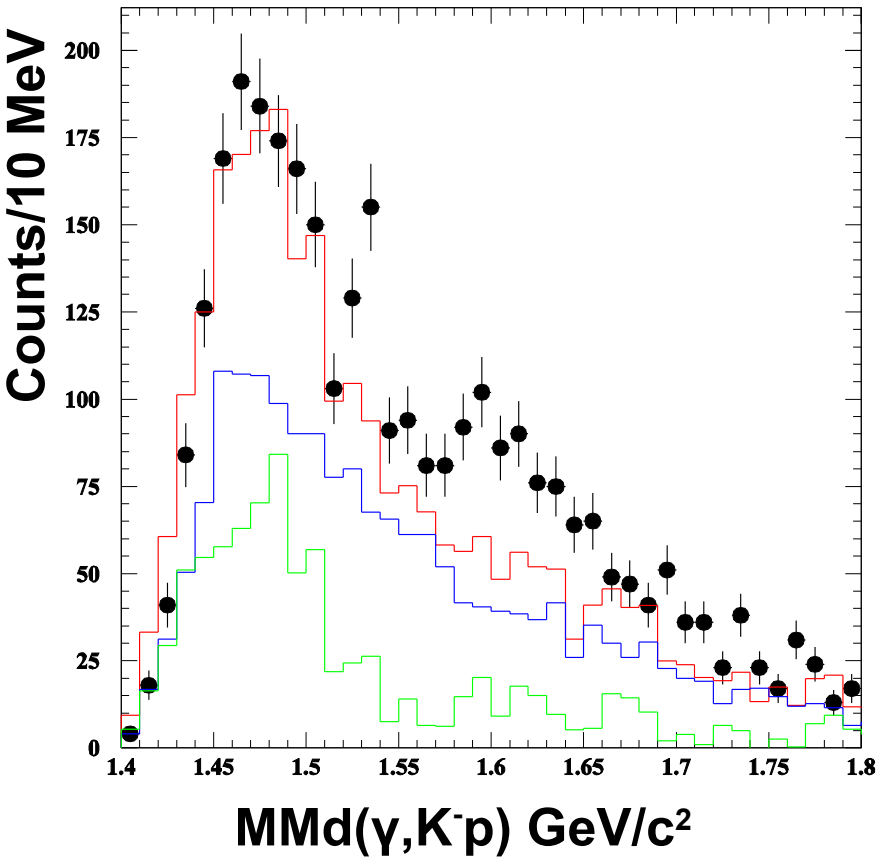


- Main source of background



New results: LEPS at SPring-8

- pK^- missing mass



Background determination:

- $\Lambda(1520)$ on H_2(*l*) target
- Contribution $\Lambda(1520)$ sidebands
- Total background (sum)

Excess around 1.53 GeV

- Naïve significance: $5\,\sigma$
- Width consistent with resolution
- Mostly from $p_{nK} \approx 0.42$ GeV
  Outside CLAS acceptance...

- Preliminary!

Conclusions

Experimental status:

- Θ^+: ± 10 sightings $\leftrightarrow$ ± 10 null results
- Ξ^{--}: 1 sighting, several null results
- Θ_C: 1 sighting, several null results

Contributions of HERMES:

- Θ^+ is seen
- Isotensor is unlikely
- Extra π improves signal $\rightarrow$ production mechanism
- Ξ^{--} is not seen $\rightarrow$ upper limit on cross-section

Recent results:

- Small K^* coupling
- Large isospin asymmetry (Karliner-Lipkin)

Pentaquarks are in very bad shape, but they are still alive.
Both experimental and theoretical study should continue.