Pentaquarks: Much Ado About Nothing?

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Nuclear Physics Seminar
University of Virginia
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Outline

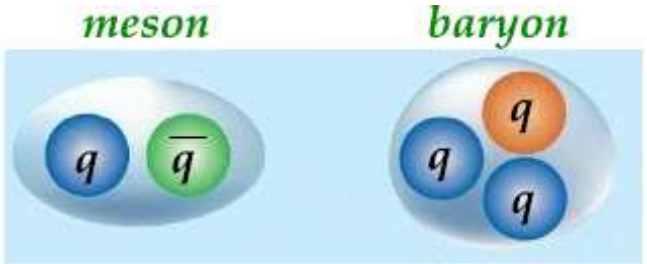
QCD in a Nutshell

QCD describes interactions of quarks and gluons

- Quarks q carry color charge (r, g, b)
  Anti-quarks $\overline{q}$ carry anticolor charge ($\overline{r}$, $\overline{g}$, $\overline{b}$)
- Gluons g carry combined color charge, *i.e.* $r\overline{b}$
- Only colorless objects, *i.e.* $q\overline{q}$, qqq $\longrightarrow$ color confinement

Multiquark states: hadrons

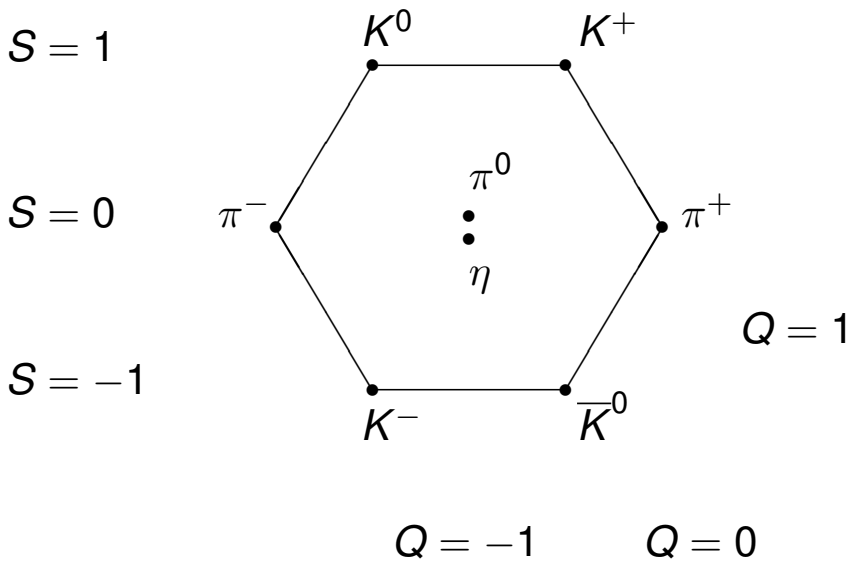
- $q\overline{q}$ $\longrightarrow$ mesons (integer spin)
- qqq $\longrightarrow$ baryons (half-integer spin)



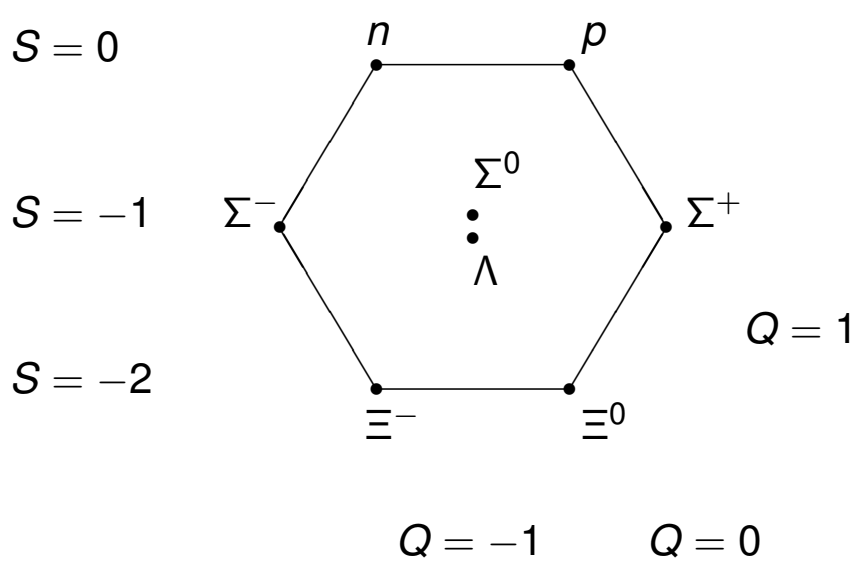
QCD in a Nutshell

Multiplets of states with only *u*, *d*, *s* quarks

- Light mesons ($q\overline{q}$)
  $\mathbf{3}_f \times \overline{\mathbf{3}}_f = \mathbf{1} + \mathbf{8}$



- Light baryons (qqq)
  $\mathbf{3}_f \times \mathbf{3}_f \times \mathbf{3}_f = \mathbf{1} + \mathbf{8} + \overline{\mathbf{8}} + \mathbf{10}$



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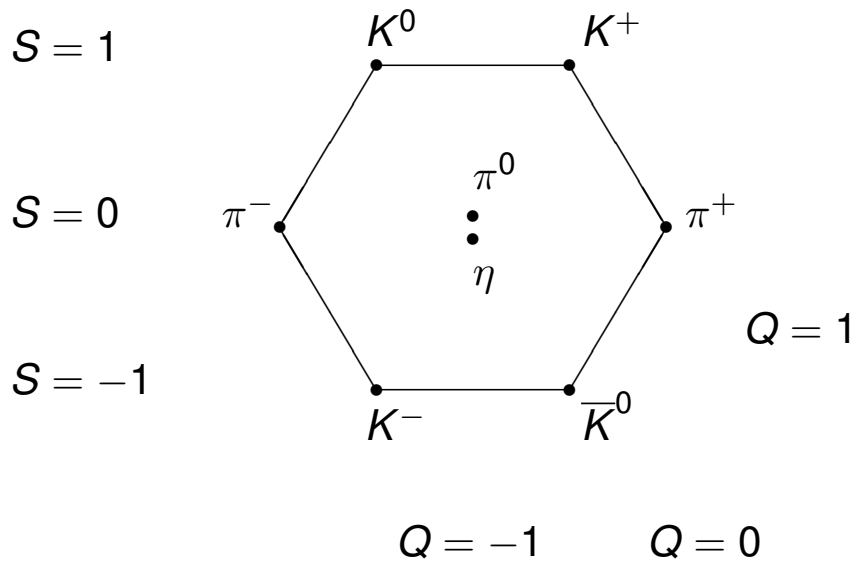

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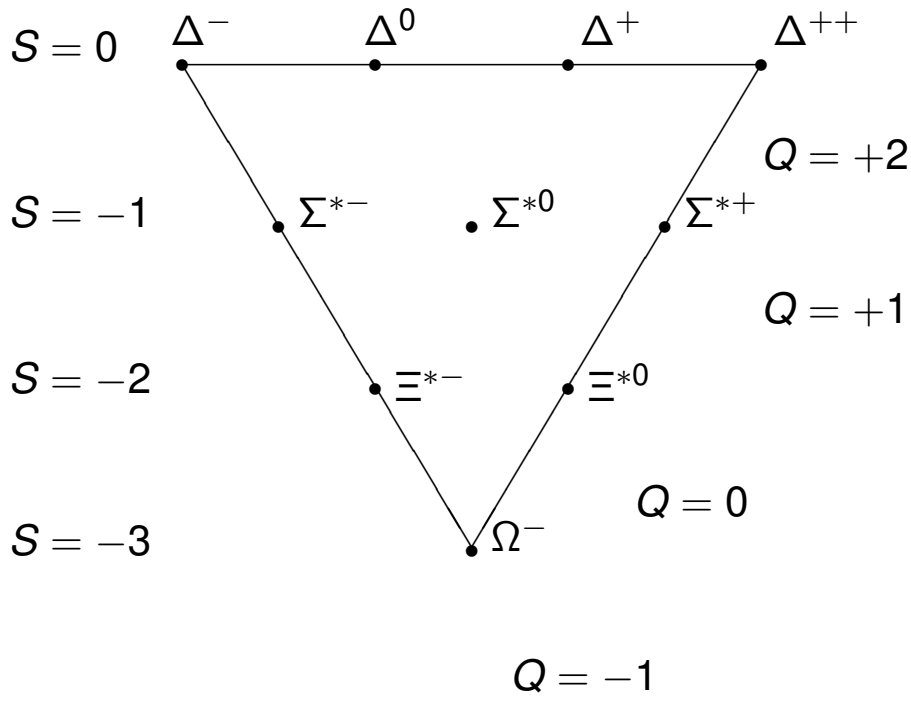


Exotic Hadrons

More than 3 quarks:

- *Exotic mesons* ($qq\overline{q}\overline{q}$) have ≥ 4 quarks, integer spin
- *Exotic baryons* ($qqqq\overline{q}$) have ≥ 5 quarks, half-integer spin

Surprised? Look at the quark sea!

A proton can also be $uud + s\overline{s}$ (*crypto-exotic*), but mixes with the normal uud state.

Manifestly exotic "pentaquarks" (Z^*, Θ^+, Ξ^{--}, Θ_c)

- Minimum quark content: 4 q and 1 $\overline{q}$
- $\overline{q}$ has a different flavor!
- Quantum numbers can only be obtained with five or more quarks, *e.g.* $\Theta^+(uudd\overline{s})$ has strangeness $S = +1$

Exotic Hadrons

Expected characteristics of pentaquarks

- Quick fall-apart (short life-time) $\rightarrow$ large resonance width
- Difficult to observe in invariant mass spectra

Early Z^* sightings (late 60s, 70s)

- Scattering of kaon beams on protons or deuterons
- Several Z^* resonances ($S = +1$, isoscalar and isovector)
- Widths of 100 MeV at masses of 1800–1900 MeV
- Various contradictory and unconfirmed results

Issue of Z^* never unambiguously resolved, abandoned in 80s.

Exotic Hadrons: Chiral Quark Soliton Model

Diakonov, Petrov, Polyakov (1997)

- Extension of Skyrme model
- Treat rotations in flavor space as equivalent to real space, mass states are rotational excitations with $E \sim J(J+1)$
- Successful in various aspects of QCD
- Applicability to exotic spectroscopy debated

For light quarks u, d, s:

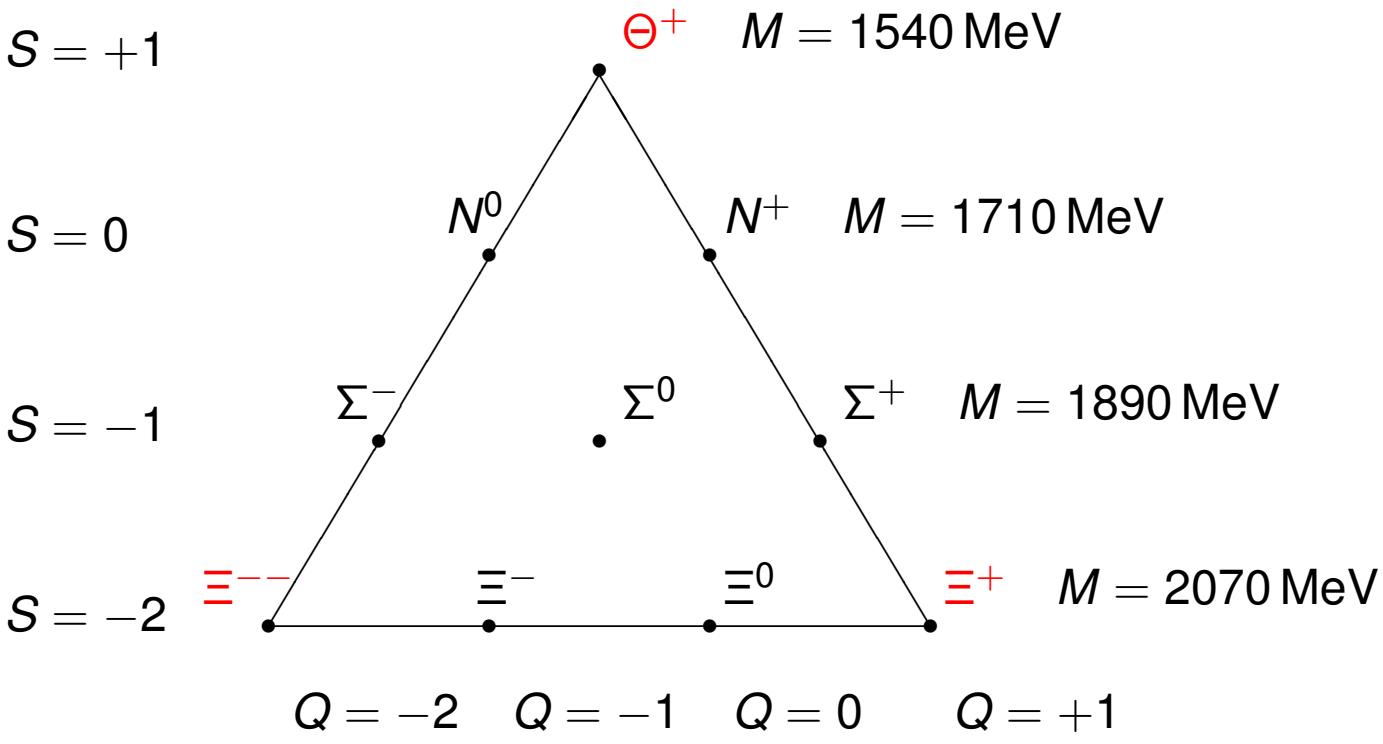
Baryons reproduced in multiplets $\mathbf{8} + \mathbf{10} + \overline{\mathbf{10}} + \mathbf{27} + \cdots$

- **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

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

Exotic Hadrons: Chiral Quark Soliton Model

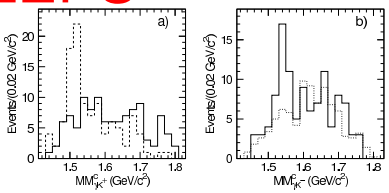
Anti-decuplet $\overline{\mathbf{10}}$ with masses predicted by QSM

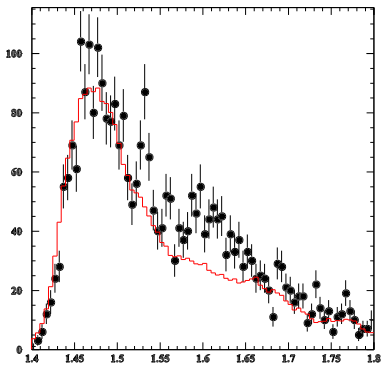


- $\Theta^+ \to pK^0$ or nK^+
- Quark content $uudd\bar{s}$
- $\Xi^{--} \to \pi^-\Xi^-$ or $K^-\Sigma^-$
- $\Xi^+ \to \pi^+\Xi^0$ or $\overline{K}^0\Sigma^+$

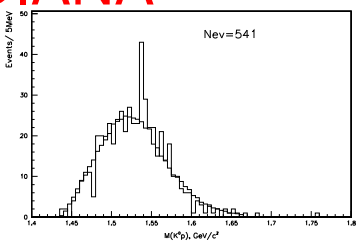
Experimental Status: Since 2003…

LEPS

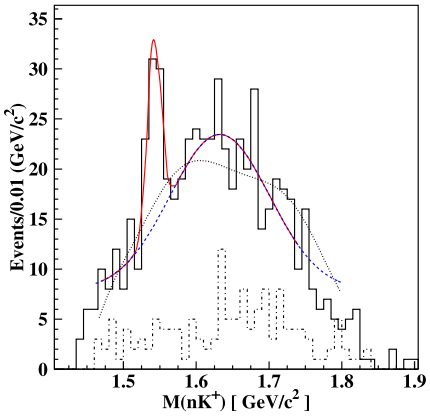




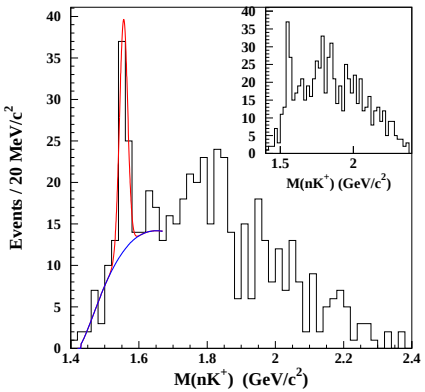
DIANA



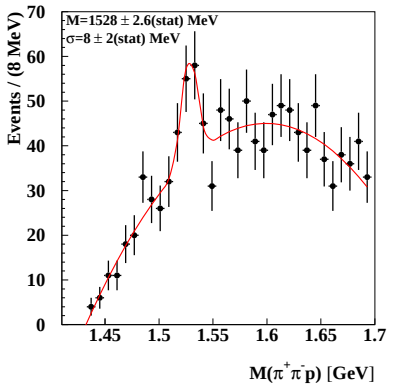
CLAS (*d*)



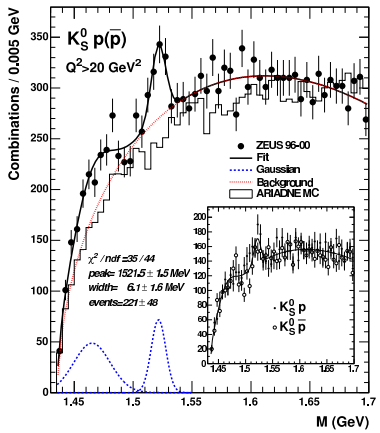
CLAS (*p*)



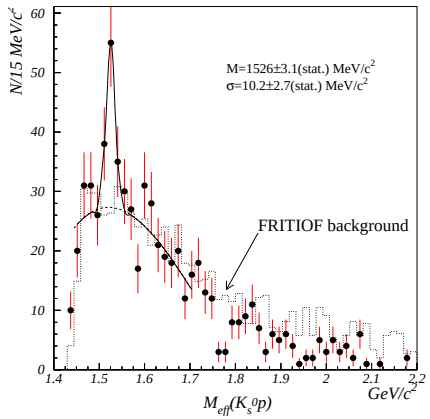
HERMES

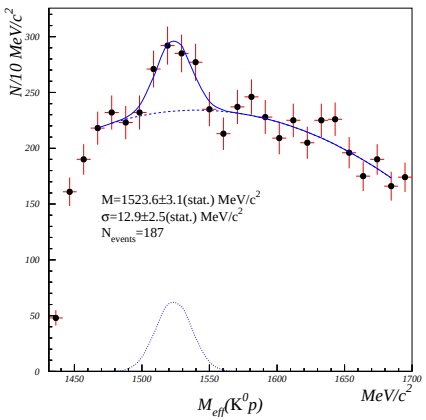


Zeus



SVD-2





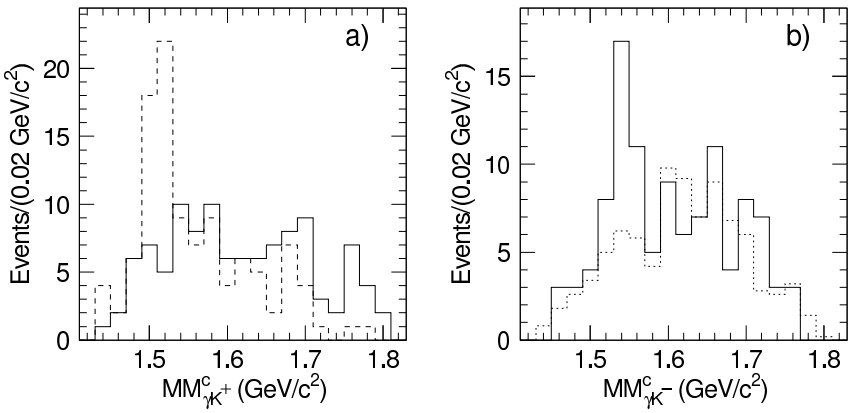
Experimental Status

Reaction mechanisms for Θ(1540) production

- Photoproduction with E_γ few GeV on fixed targets
  - Exclusive reactions on p (or n from missing mass) (SAPHIR, CLAS-p, CLAS-g11)
  - Inclusive reactions on A (d, C, Si): Fermi-motion correction (LEPS, CLAS-g10)
- Θ formation by K on n (DIANA, old data, Belle)
- High energy e on p, A (ZEUS, HERMES, BaBar, Belle)
- High energy p on p, A (SVD-2, HyperCP, HERA-B)

Photoproduction on *A*

LEPS



Original experiment on C

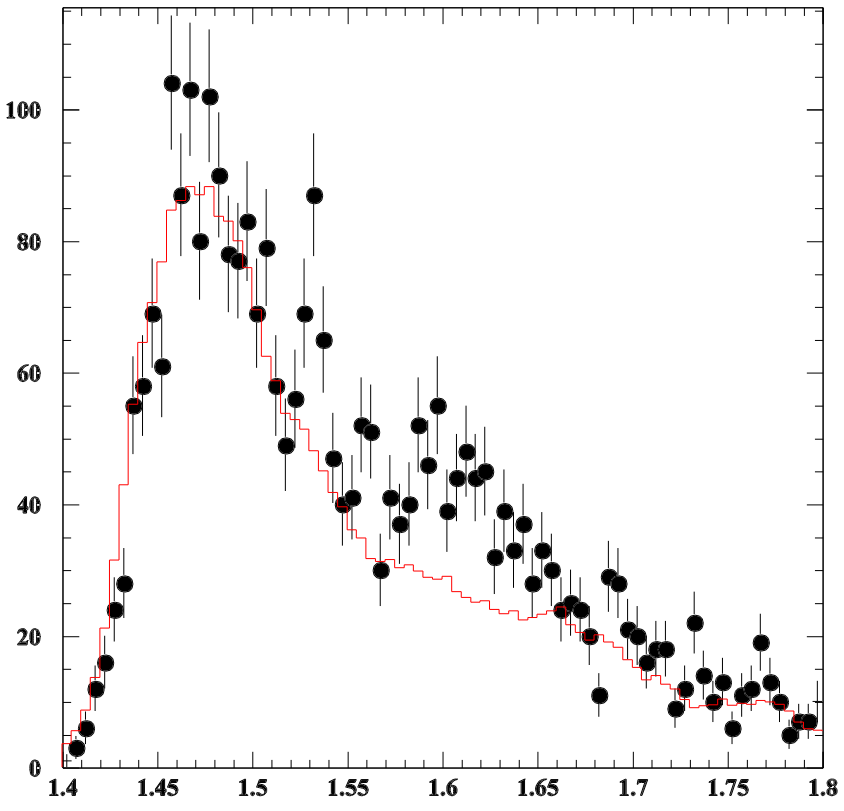
- First report of Θ^+
- Reaction $\gamma C \rightarrow K^+ K^- X$
- Fermi-motion correction
- Background poorly understood

Experiment repeated on *d*

- No Fermi-motion
- Background seems understood (from *p* target)
- Second bump at higher *M*
- Still no publication...

Photoproduction on *A*

LEPS



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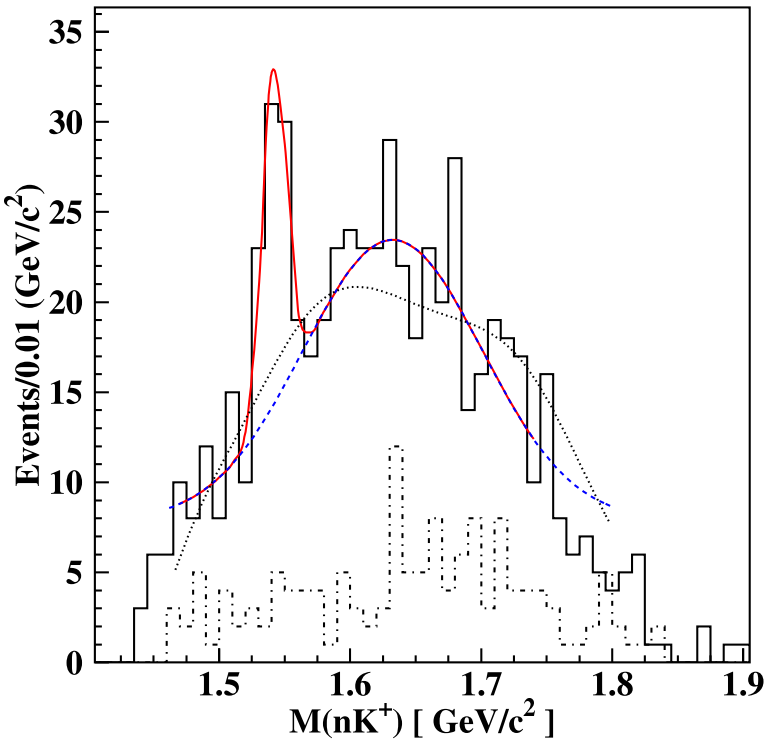
Photoproduction on A

CLAS-d



$\gamma d \to pK^+K^-(n)$

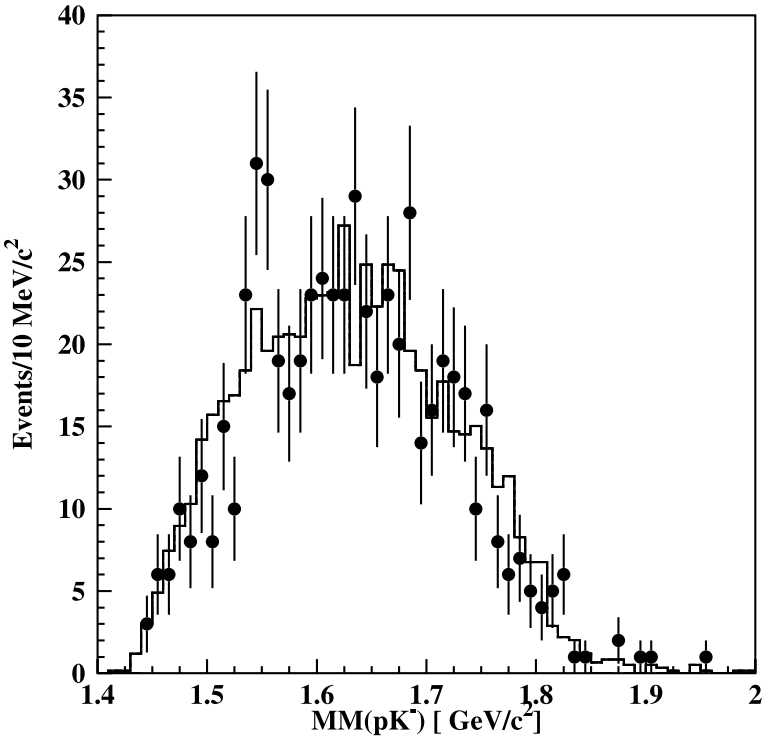
- Significance $\frac{S}{\sqrt{B}}$ around $5\,\sigma$
- Final state interactions
- Background difficult to estimate

Experiment repeated

- Repeated with CLAS-g10
- Better background estimation
- Significance now only $3\,\sigma\ldots$

Photoproduction on A

CLAS-d



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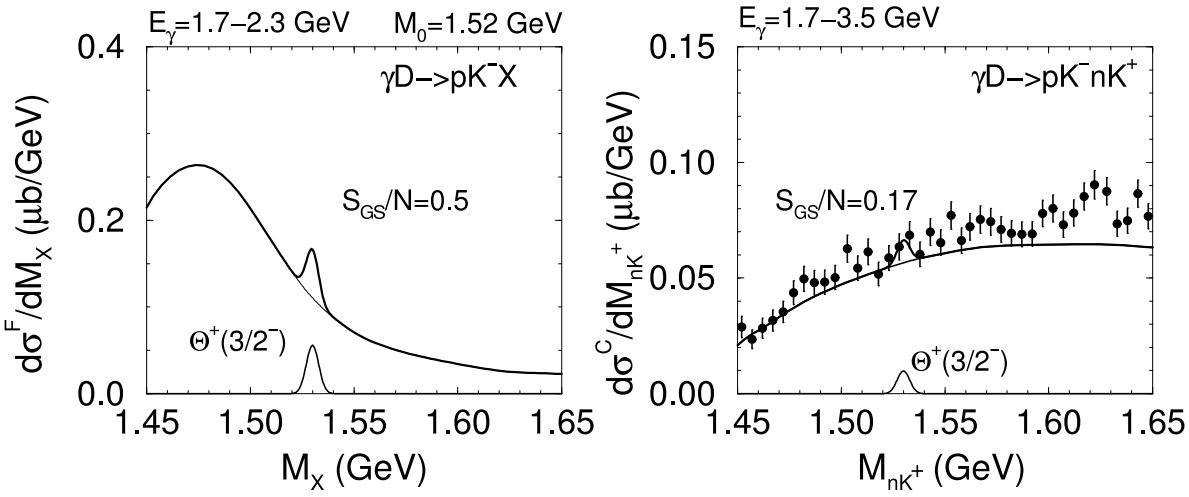
Photoproduction on *A*: CLAS versus LEPS

Differences in acceptance (Titov, nucl-th/0607054)

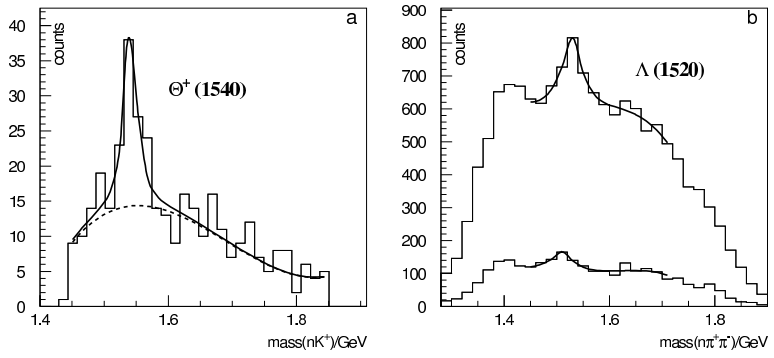


Interference with other processes (Guzey, hep-ph/0608129)

- Identical final states interfere in total cross section
- Selection criteria, experimental conditions important
- More details in talk Moskov Amarian (November 27)

Photoproduction on p

SAPHIR



Exclusive Θ^+ production

- $\gamma p \to K^0 \Theta^+ \to \pi^+ \pi^- K^+ n$
- Cross section for Θ^+ estimated as 300 nb

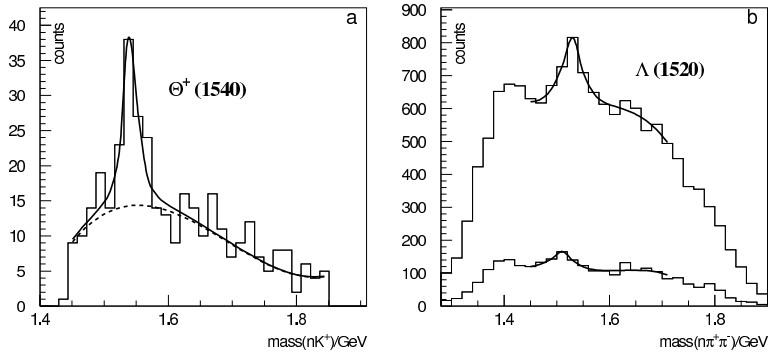
CLAS-g11

Experiment repeated

- Cross section upper limit determined as 0.8 nb
- This is in disagreement with SAPHIR

Photoproduction on *p*

SAPHIR



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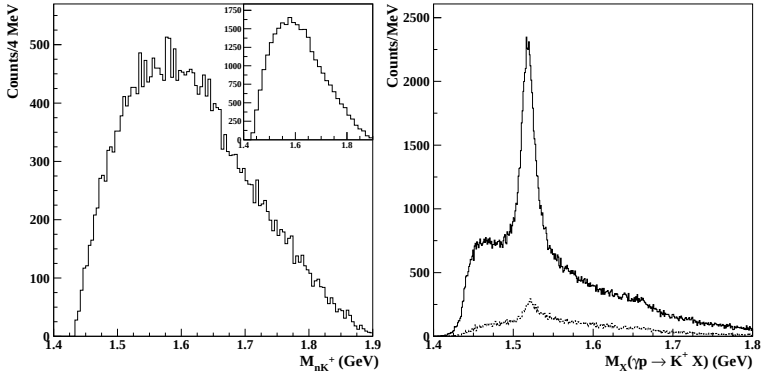

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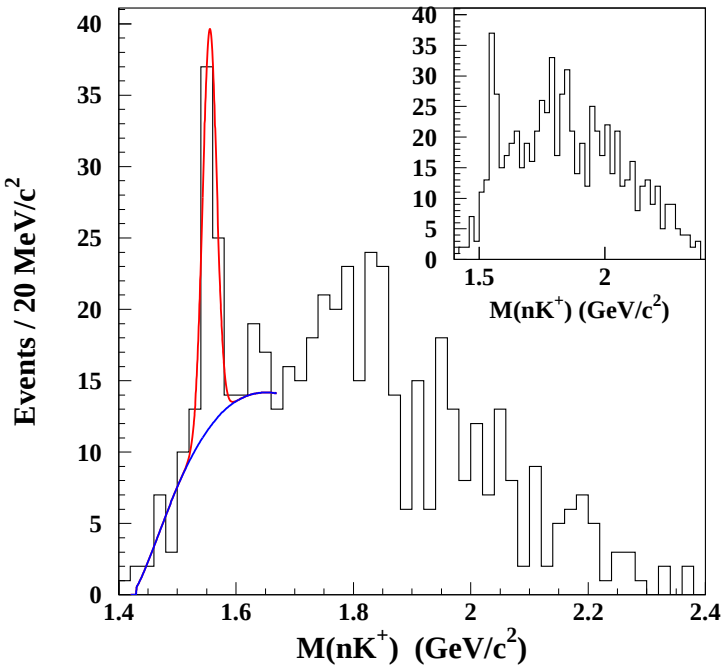
Photoproduction on p: $nK^+K^-\pi^+$



CLAS-p

- $\gamma p \rightarrow \Theta^+ K^- \pi^+ \rightarrow nK^+K^-\pi^+$
- n reconstructed by missing mass
- π^+ forward, K^- backward (CMS)
- Peak in $M(nK^+)$ with $\frac{S}{\sqrt{B}} \approx 7\,\sigma$
- Will be tested in CLAS-g12 experiment (April 2008)

NK scattering: Formation of Θ

Ideal way to study Θ resonance

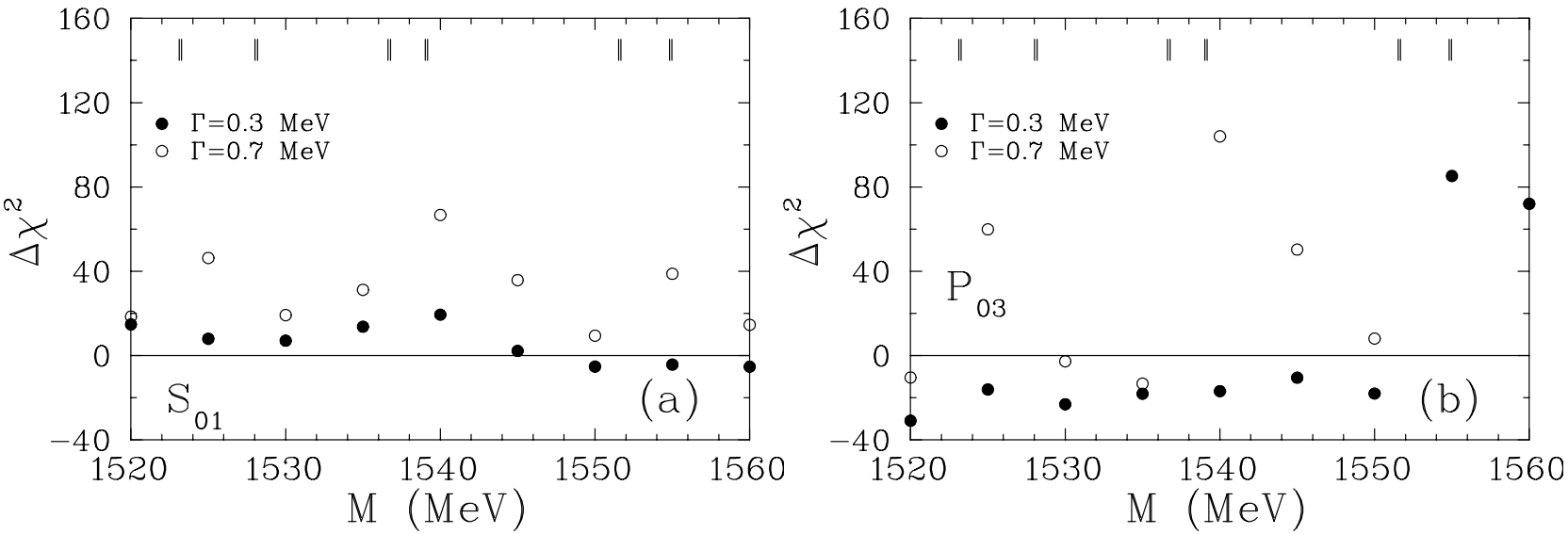
- NK scattering: nK^+ or pK^0
- Take K of appropriate energy on fixed target N
- $E_K \approx 430\,\text{MeV}$ for Θ formation

Unfortunately, no low energy K beam facilities anymore:

- Re-analysis of partial wave analysis results
- Direct formation with slowed down beam of higher energy
- Secondary K^+ produced in e^+e^- collisions
- Quasi-formation: quasi-free K^+ on quasi-free n
  (see photoproduction reactions at LEPS)

NK scattering: Re-analysis Partial Wave Data

Look at the change in χ^2 by inclusion of Θ as S_{01} or P_{03}



- Possible Θ^+ must have $\Gamma < 1$ MeV
- Decrease in χ^2 mostly due to limited data in PWA

Figure: Arndt, `nucl-th/0308012`

NK scattering: Direct formation with slow K^+ beam

DIANA experiment

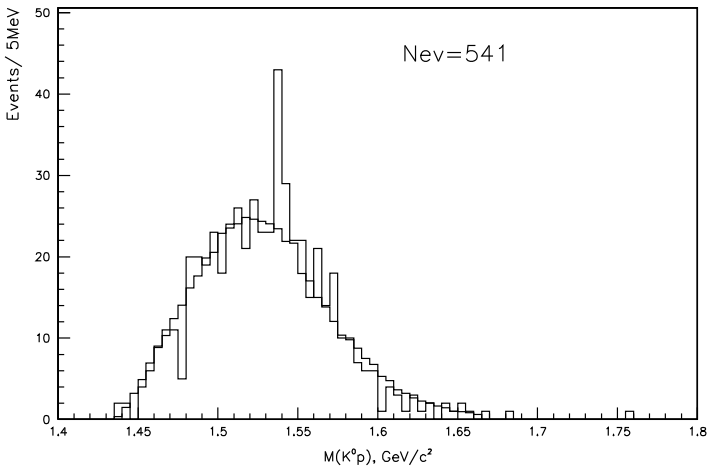


Figure: Barmin, `hep-ex/0304040`

$$K^+ n(Xe) \rightarrow \Theta^+ \rightarrow p K^0_S$$

- Energy E_{K^+} around 500 MeV
- Definite $S = 1$ (initial state)
- Rescattering of p or K^0_S in Xe nucleus
- Only direct formation experiment

Experiment repeated

- Rescattering suppression studied with MC
- No peak at higher/lower E_{K^+}
- $\Gamma = 0.36 \pm 0.11$ MeV

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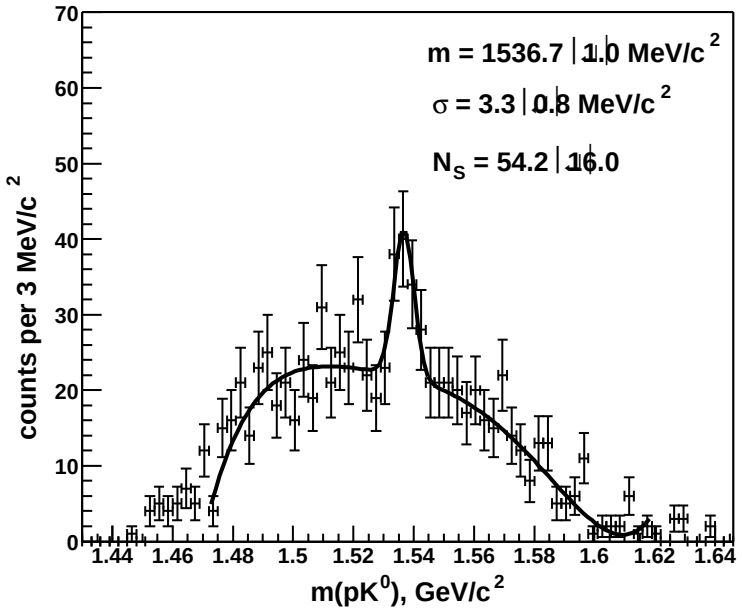

Figure: Barmin, `hep-ex/0603017`

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NK scattering: Secondary K^+ beams

BELLE

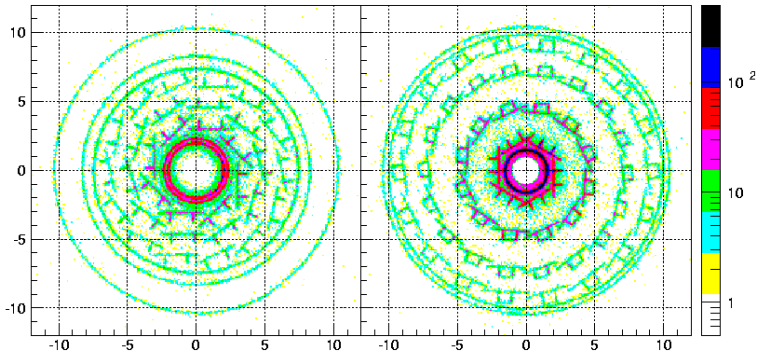

Figure: Abe, `hep-ex/0507014`

$$K^+ n(Si) \rightarrow \Theta^+ \rightarrow p K^0_S$$

- K^+ from the reaction $D^{*-} \rightarrow \overline{D}^0 \pi^- \rightarrow K^+ \pi^- \pi^-$
- Most probable $E_{K^+} = 600\,\text{MeV}$
- $n(Si)$ from vertex detector
- Other reactions contribute $\rightarrow$ selection criteria

Upper limits

- Yield DIANA: solid line
- $\Gamma < 0.9 \pm 0.3\,\text{MeV}$
- Does not support DIANA

NK scattering: Secondary K^+ beams

BELLE

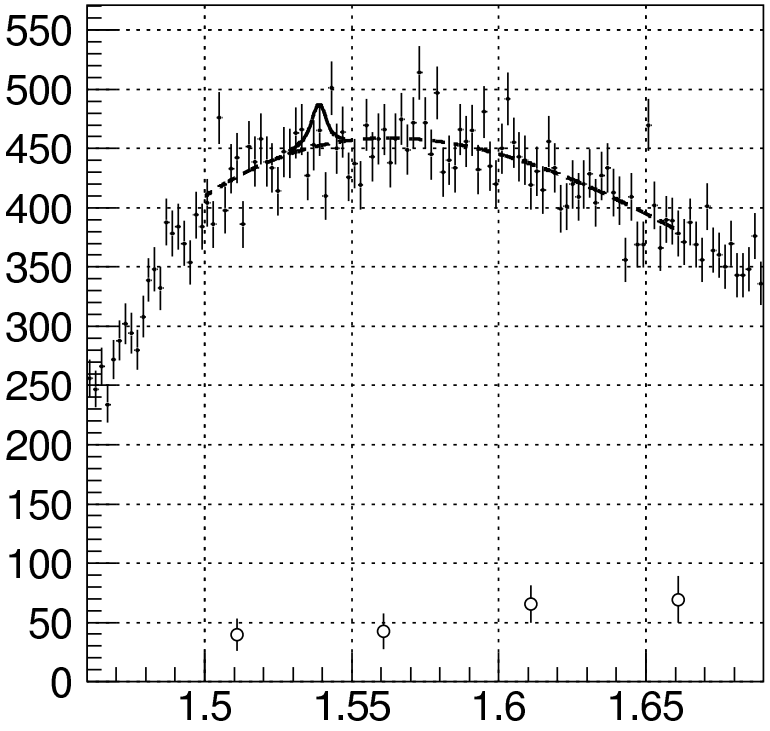

Figure: Abe, `hep-ex/0507014`

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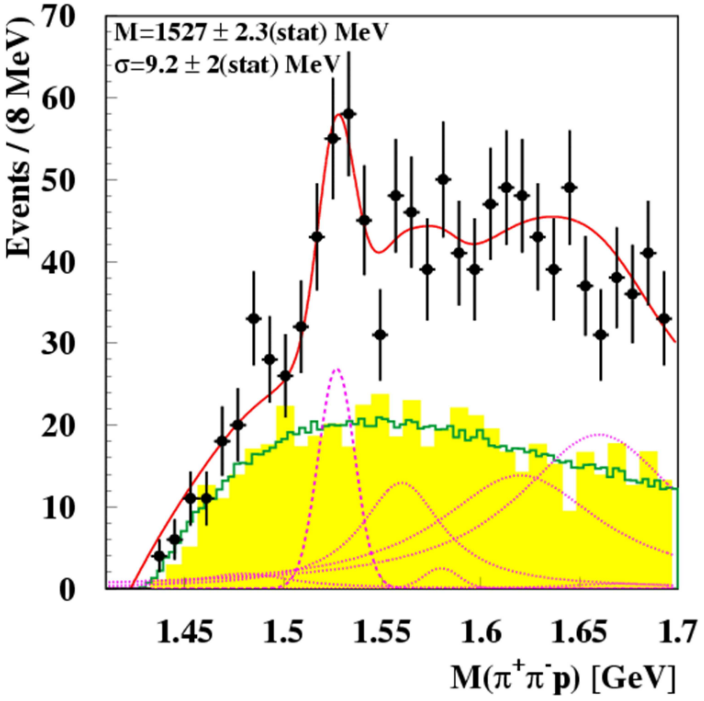
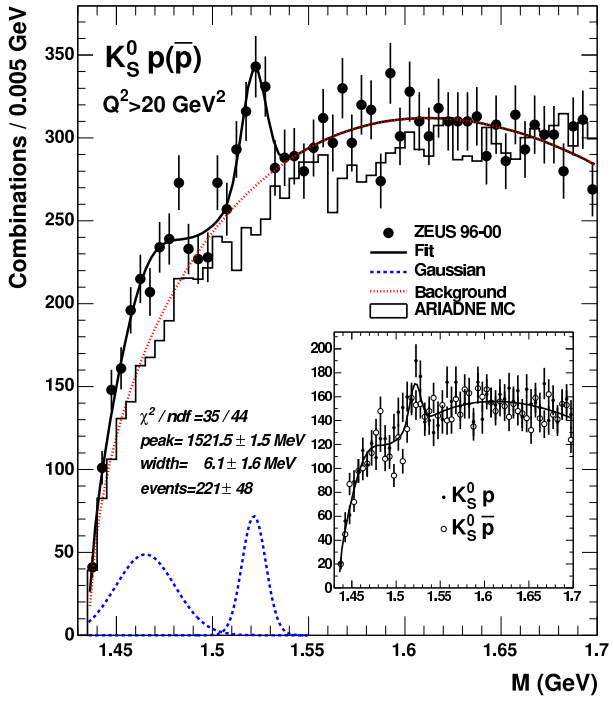
High energy Θ^+ production: *ep* at HERA

HERMES



- For $Q^2 \approx 0\,\text{GeV}$
- More about this later!

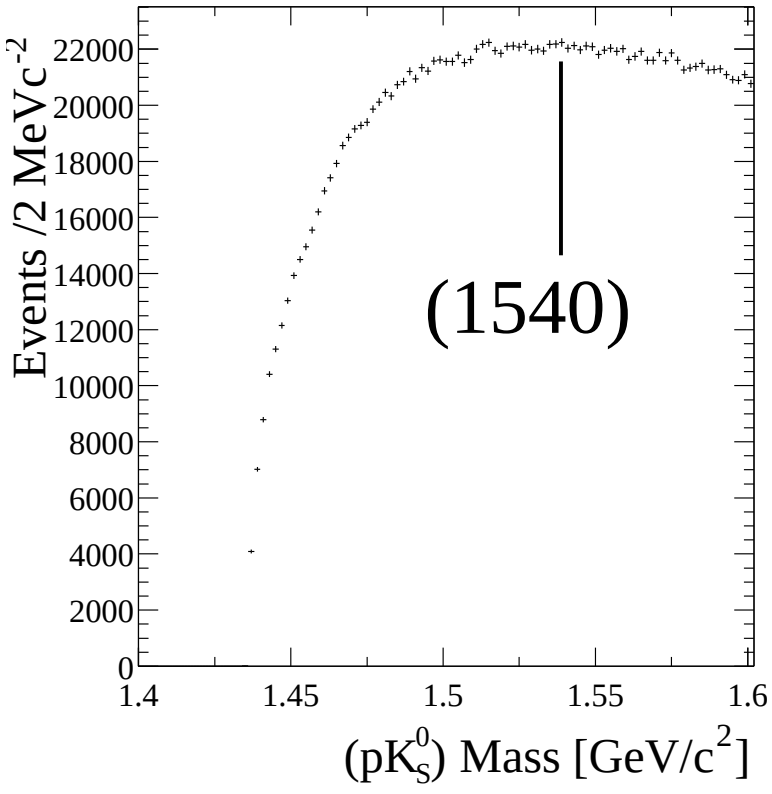
ZEUS



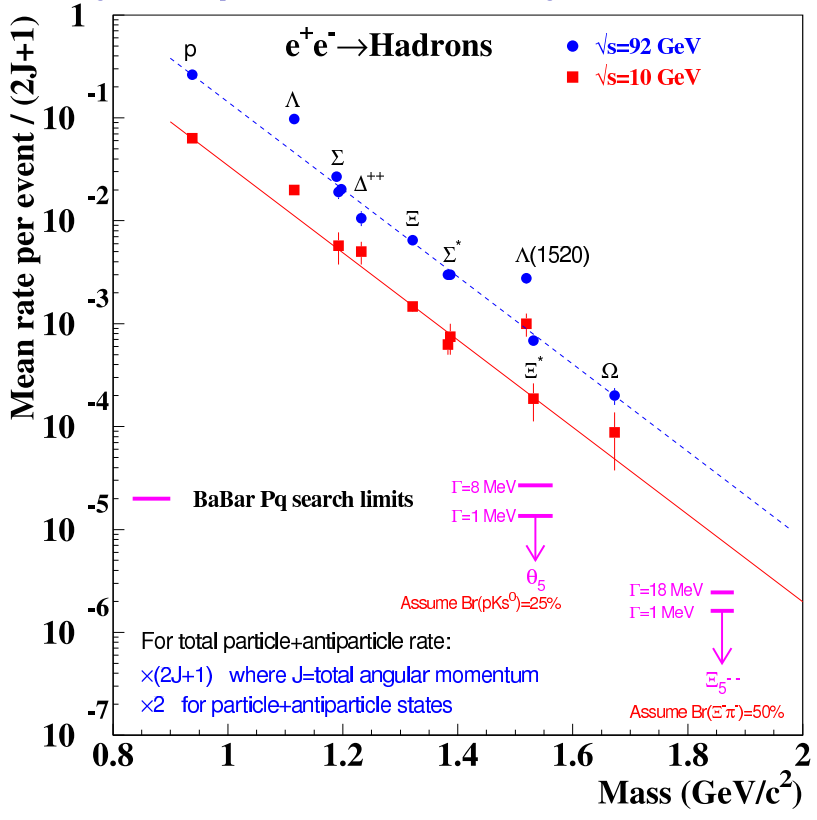
- Only for $Q^2 > 20\,\text{GeV}$
- Not seen at H1…

High energy Θ^+ production: e^+e^- at BaBar

Inclusive pK^0_S channel



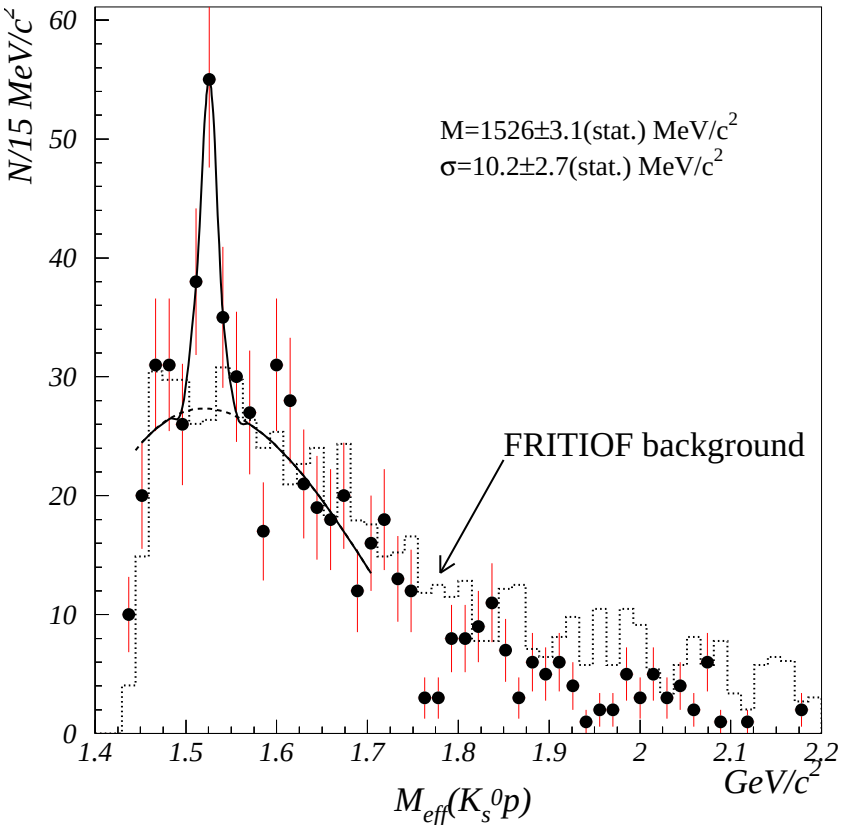
Baryon production yields



- Θ yield order or magnitude below ordinary hadrons
- But do we really expect a 5-*q* state to behave similar?

High energy Θ^+ production: *pp*

SVD-2



Original result

- 70 GeV $pA \rightarrow pK_S^0$
- Background unknown

Experiment repeated

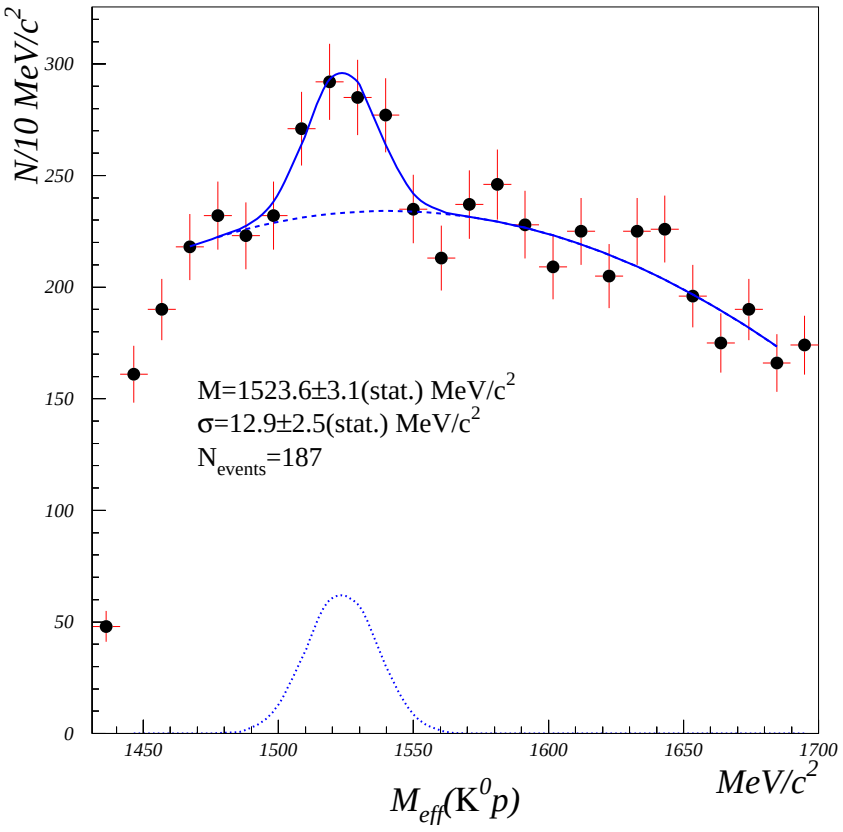
- Statistics increased
- Mixed event background

But

- No confirmation from SPHINX

High energy Θ^+ production: *pp*

SVD-2



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Experimental Status: Overview

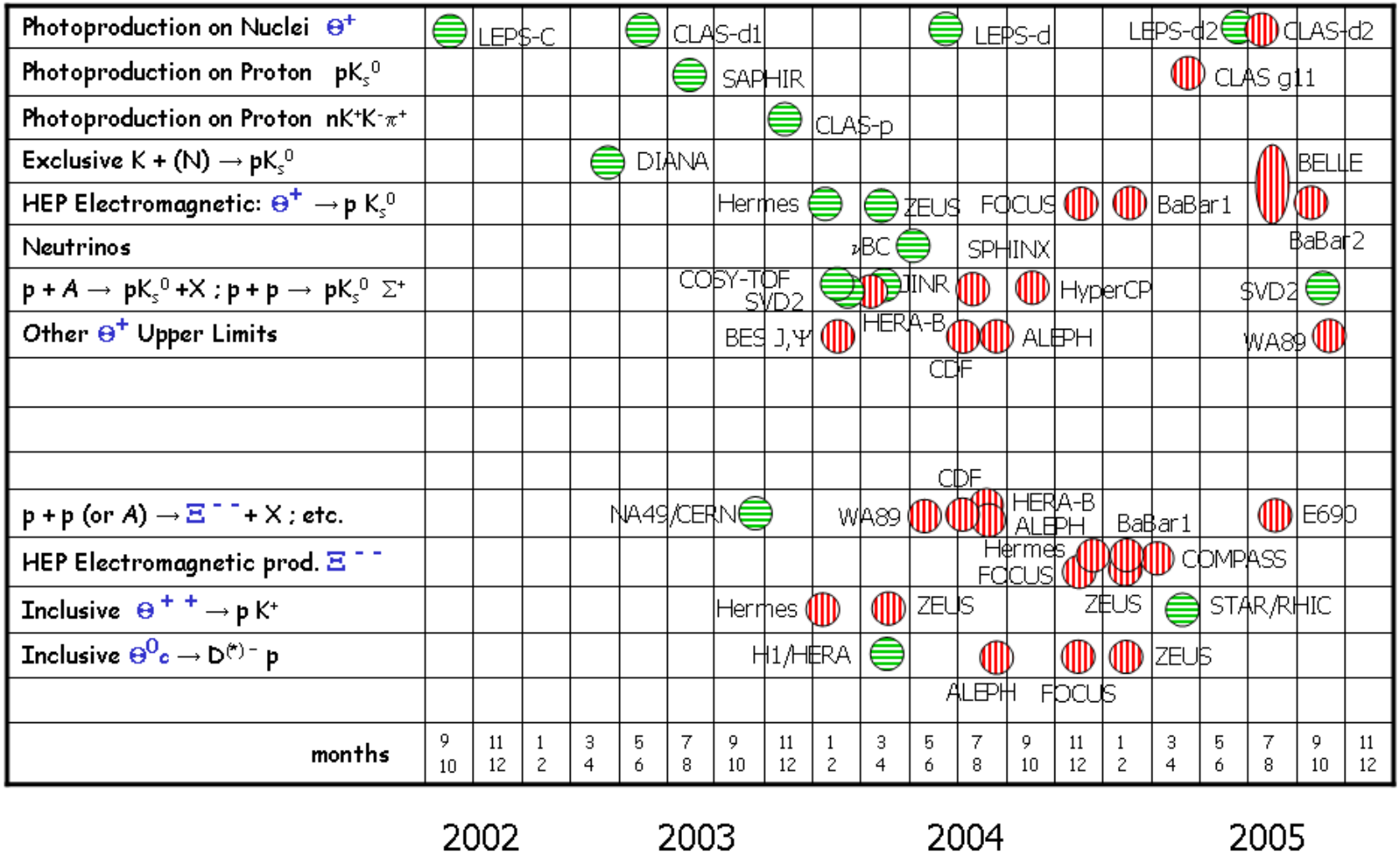


Figure: Schumacher, `nucl-ex/0512042`

The HERMES Experiment

High-energy electrons on fixed target

- Polarized electron beam, polarized gas target
- Main goal: spin structure of the nucleon (spin puzzle)
- But many more interesting analyses: DVCS, transversity, nuclear effects...

Quasi-real photoproduction

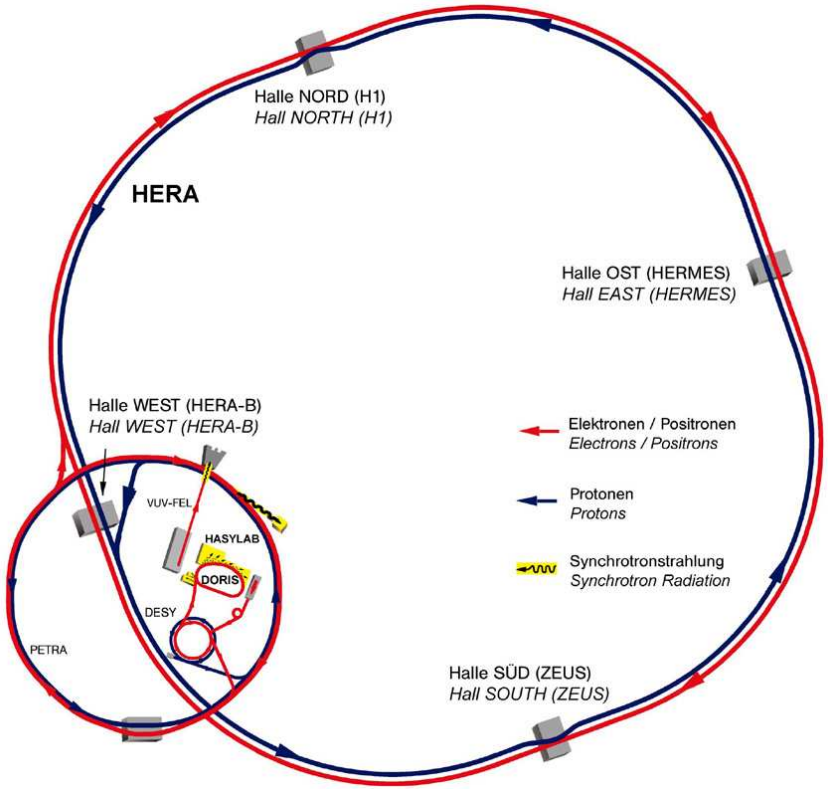
- Electron emits photon with $Q^2 \approx 0$
- Photon interacts with nucleon
- Produced hadrons detected in forward spectrometer
- Electron not detected, bending angle too small

The HERA Storage Ring

DESY physics institute in Hamburg, Germany
with the HERA and PETRA storage rings

The HERA Storage Ring

Overview of DESY



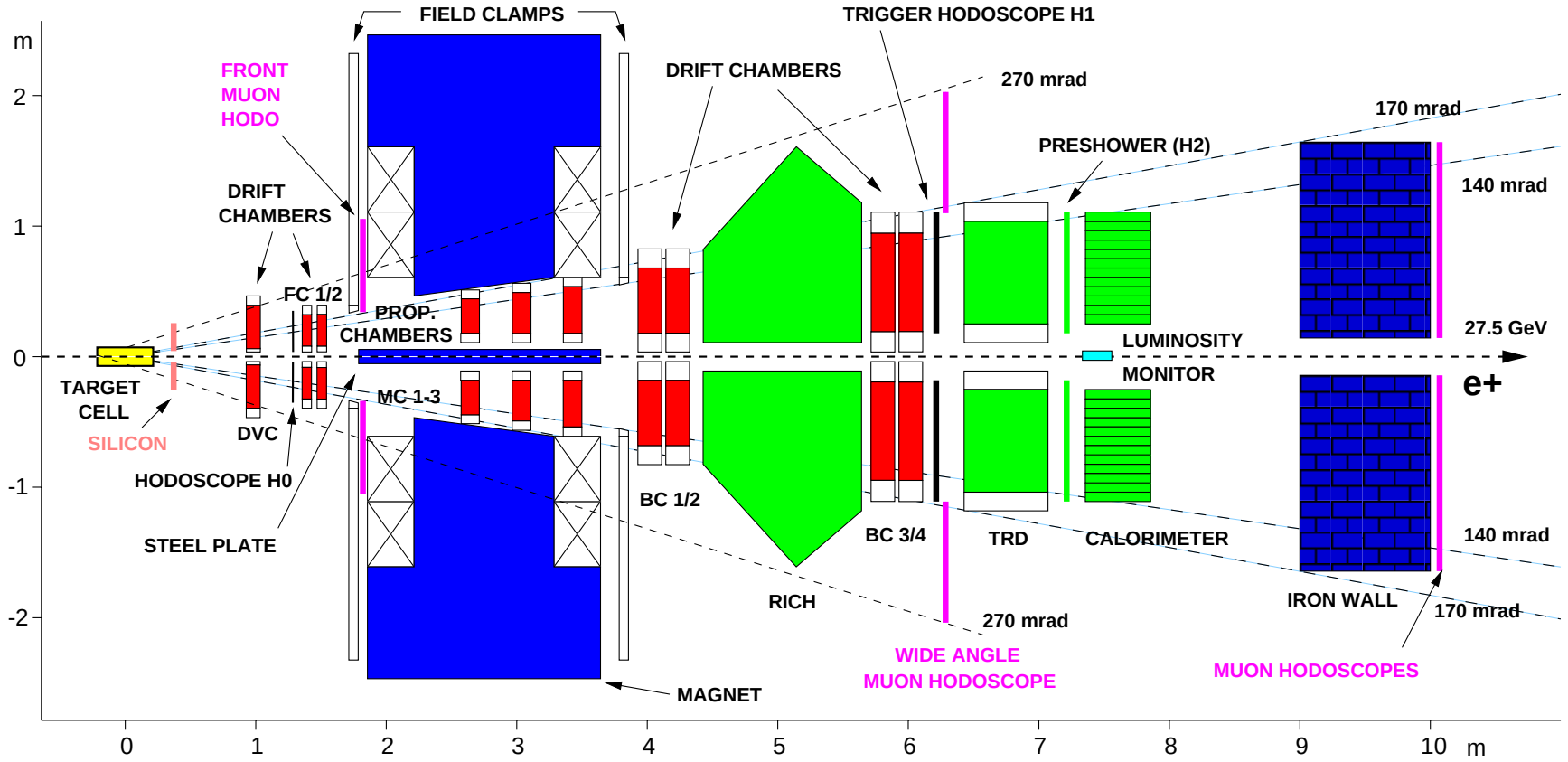
HERA: particle physics

- Collider for H1, ZEUS: 27.5 GeV e on 920 GeV p
- HERMES: 27.5 GeV e on A
- HERA-B: 920 GeV p on A
- Last beam in June 2007
- Analysis of data continues

Also synchrotron radiation

- HASYLAB
- VUV-FEL/FLASH
- PETRA III
- XFEL (ready: 2013)

The HERMES Spectrometer



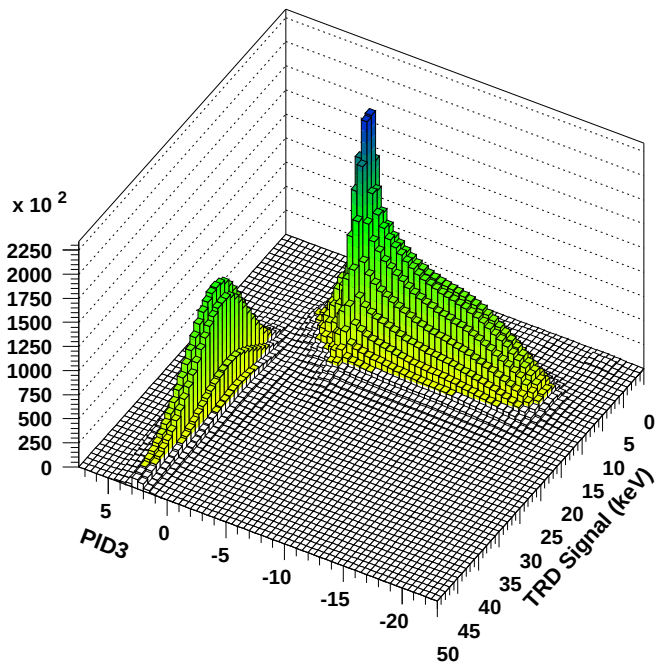
- 27.6 GeV $e^{\pm}$ HERA beam on $\overrightarrow{H}$, $\overrightarrow{He}$, $\overrightarrow{D}$ or H_2, D_2, He,...
- Resolution: $\frac{\Delta p}{p}$ = 1.4 – 2.5%, $\Delta\vartheta \lesssim 0.6$ mrad
- TRD, Preshower, Calorimeter: hadron/lepton separation
- RICH: hadron identification (π, K, p)

The HERMES Spectrometer

Hadron/lepton separation:

with combination of

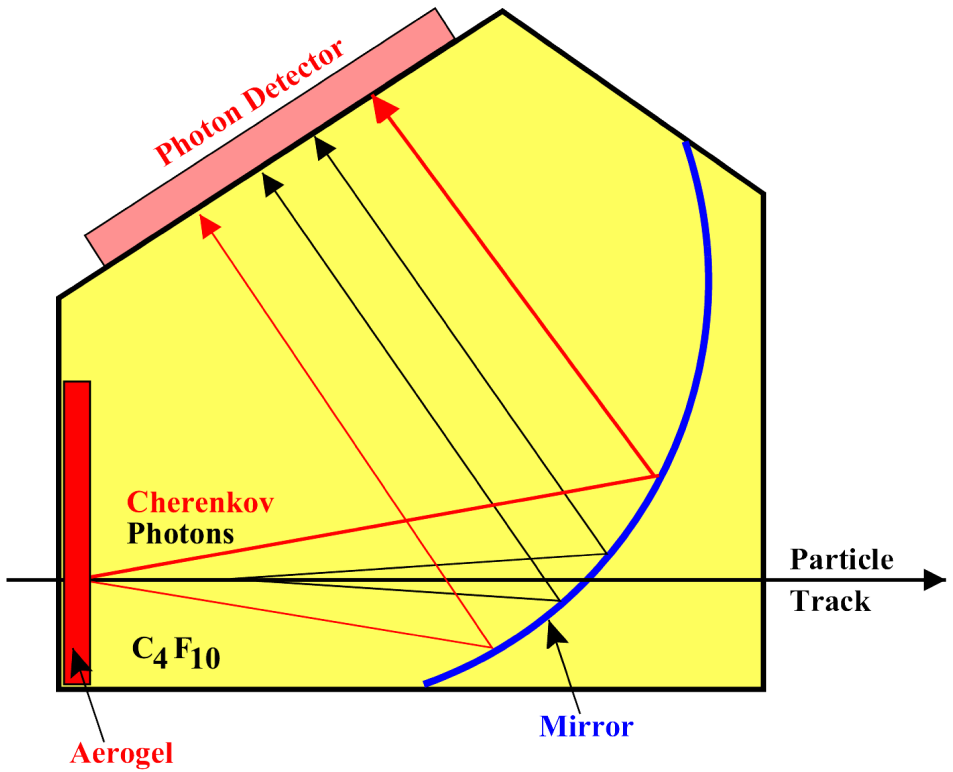
- TRD
- Calorimeter
- Preshower
- RICH



Hadron identification:

Ring-Imaging Čerenkov detector (RICH)

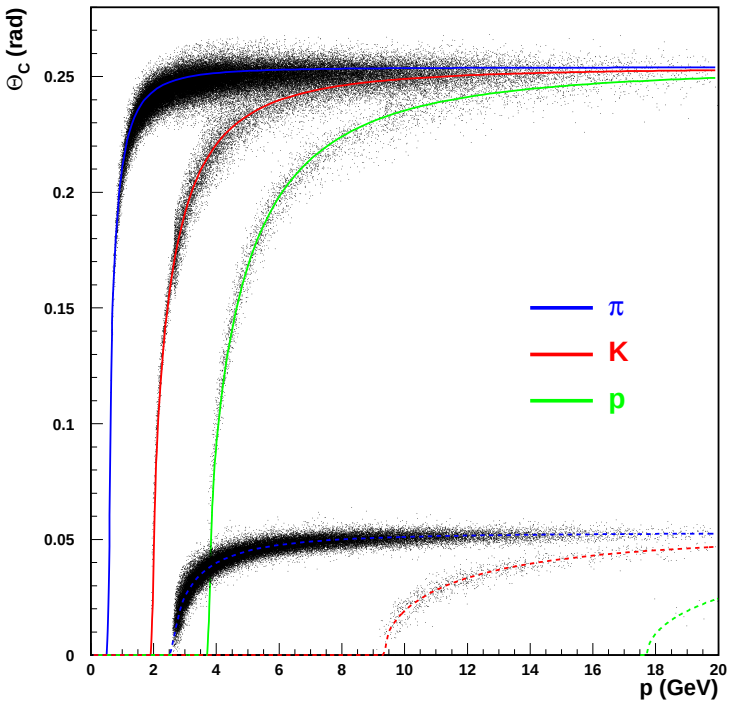
- Two radiators for larger kinematic coverage



The HERMES Spectrometer: RICH Detector

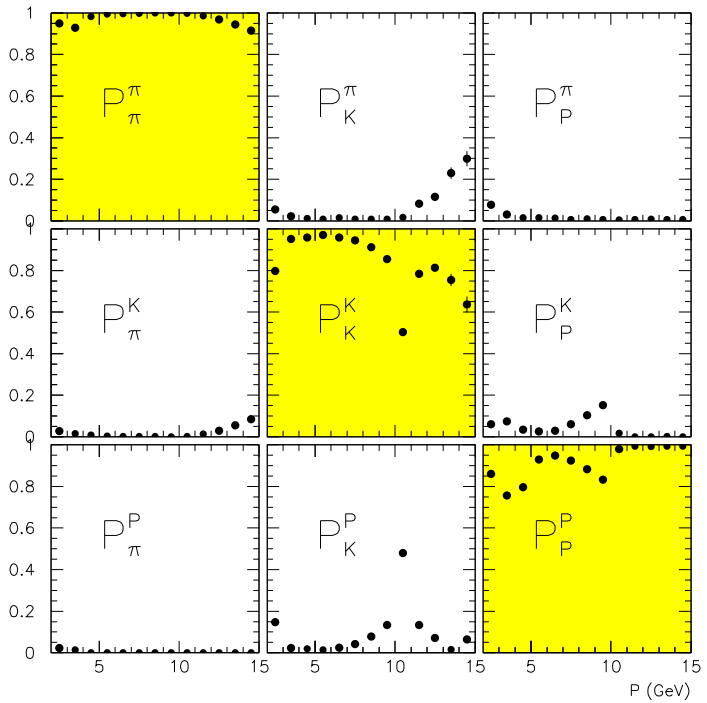
Dual radiator:

- Aerogel: $n = 1.03$
- C_4F_{10} gas: $n = 1.0014$



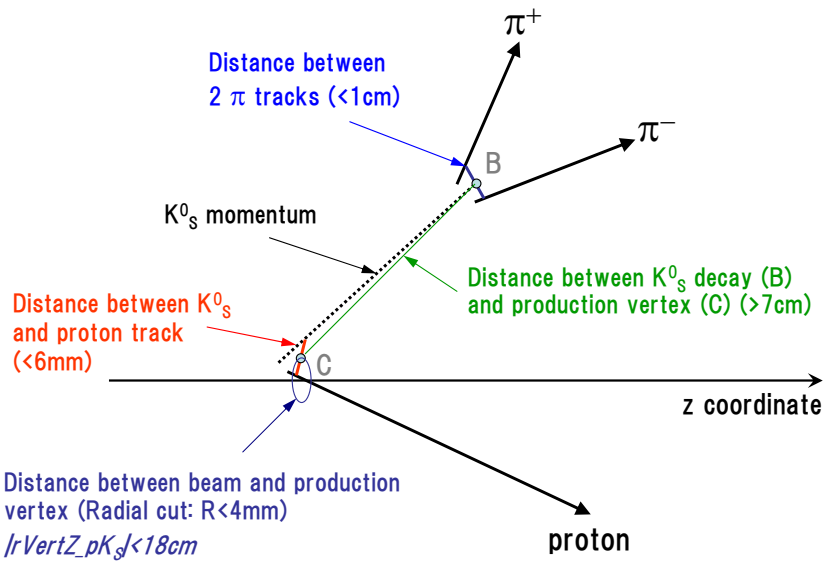
Identification efficiency

- Momentum dependence
- Range 4–9 GeV for protons



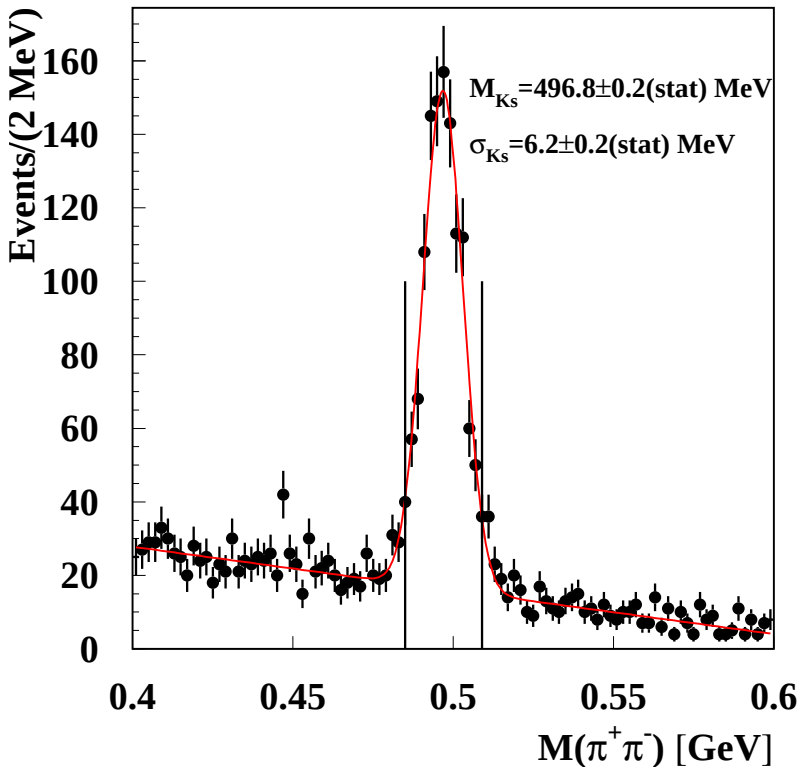
$\Theta^+(1540)$ at HERMES

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



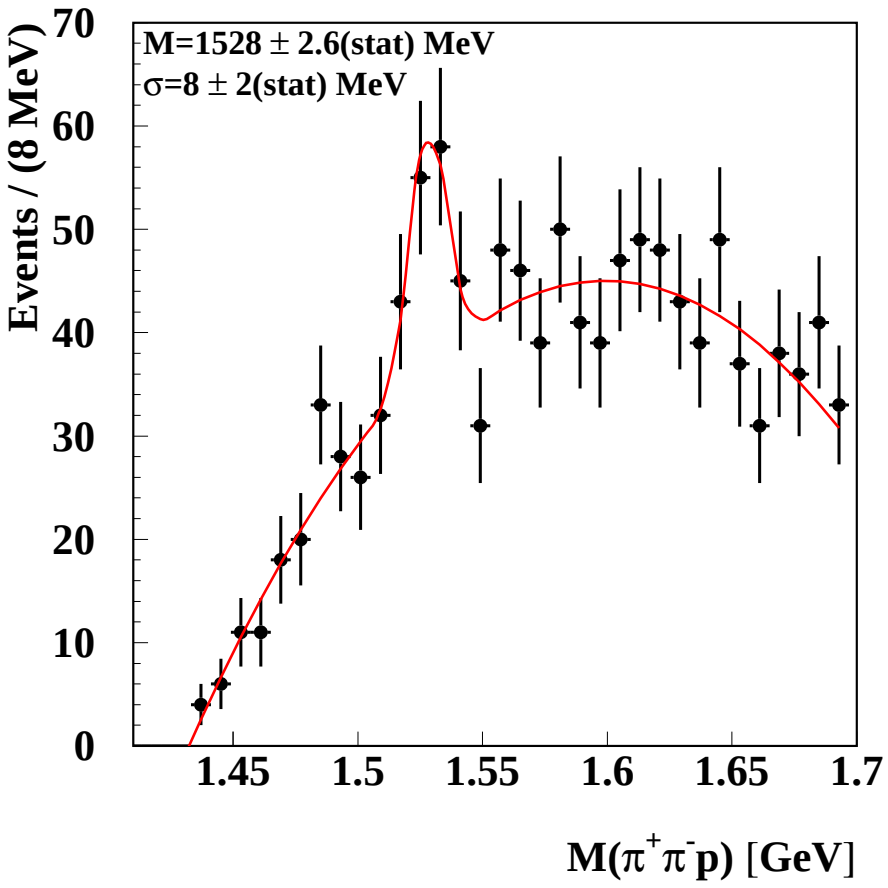
- Select K^0_S events
- Remove Λ events

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



$\Theta^+(1540)$ at HERMES

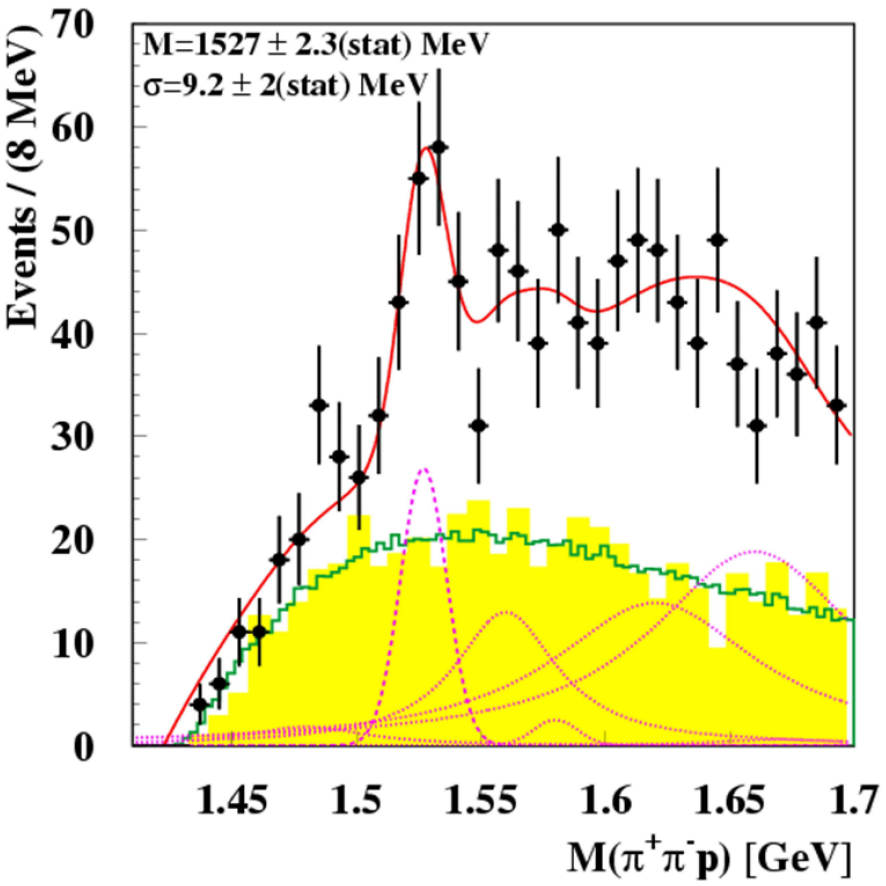
- Spectrum with polynomial fit



- Unbinned fit with 3rd order polynomial and Gaussian
- Θ^+ peak:
  - M = 1528 ± 2.6 MeV
  - σ = 8 ± 2 MeV
- Significance $\frac{S}{\delta S} \approx 3.7\,\sigma$

$\Theta^+(1540)$ at HERMES: Understanding the Background

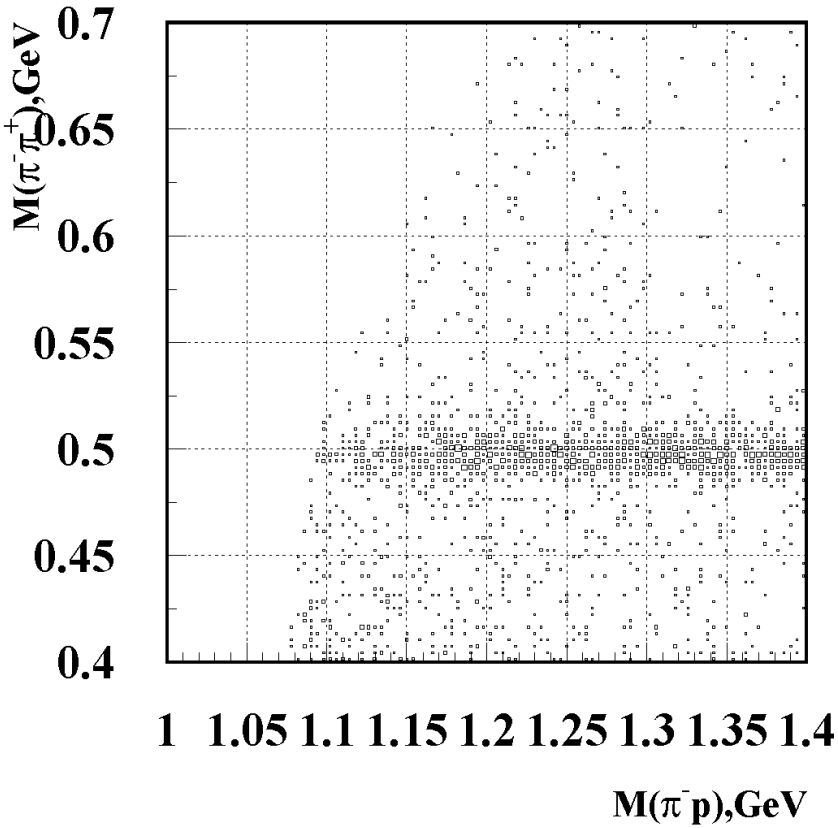
- Spectrum with MC background



- Mixed-event background
  - p from one event
  - K^0_S from other event
- PYTHIA6 Monte Carlo
  - No Σ^{*+} resonances
  - Added by hand
- Θ^+ peak:
  - M = 1527 ± 2.3 MeV
  - σ = 9.2 ± 2 MeV
- Significance $\frac{S}{\delta S} \approx 4.3\,\sigma$

Additional Θ^+ studies: Tracking or PID problems

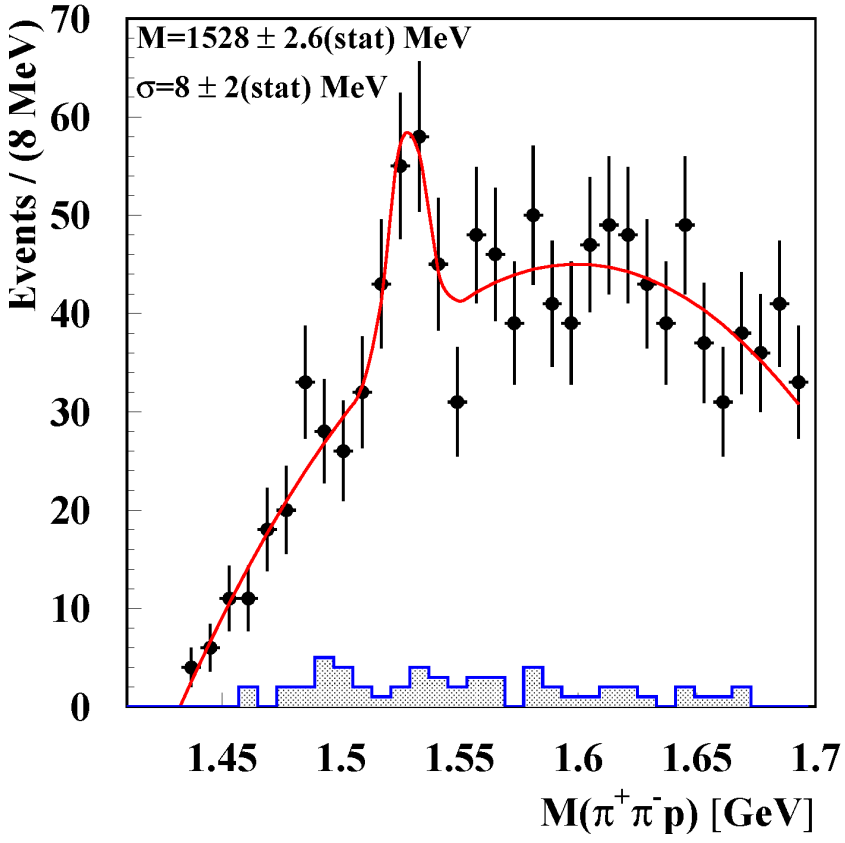
- Correlation $M_{\pi\pi}$ vs. $M_{p\pi}$



- Ghost tracks
  - No correlations
  - Examined data files
  - No ghost tracks!
- 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^+!

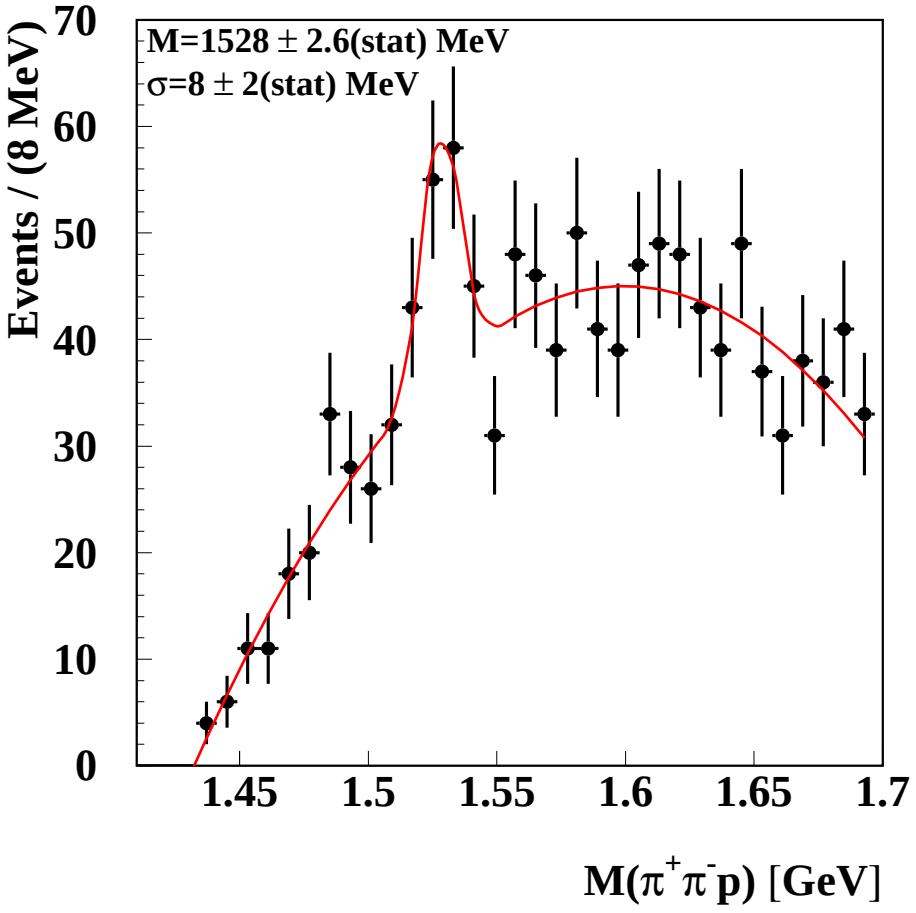
Additional Θ^+ Studies: Tracking or PID Problems

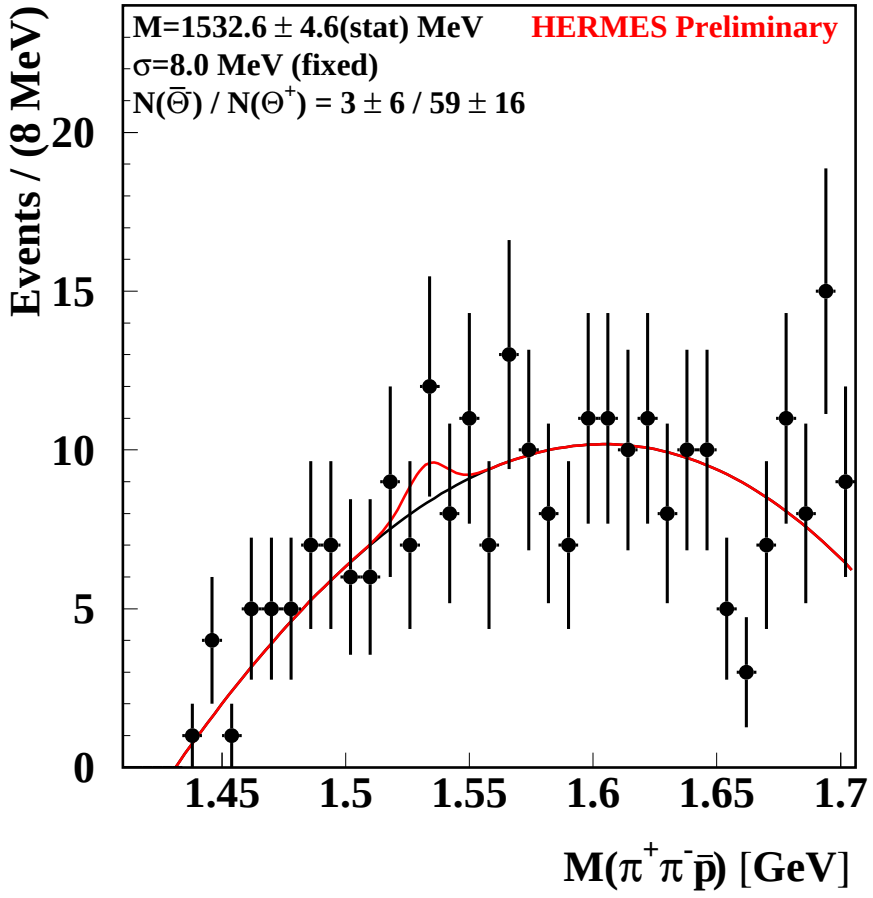
- Λ(1116) contribution



- Ghost tracks
  - No correlations
  - Examined data files
  - No ghost tracks!
- PID leaks
  - π^+ is actually p (mis-ID)
  - K_S combination is a Λ
  - Λ events are cut out from spectrum
  - Inefficient Λ cut not reason for peak!

Anti-Particle $\bar{\Theta}(1540)$

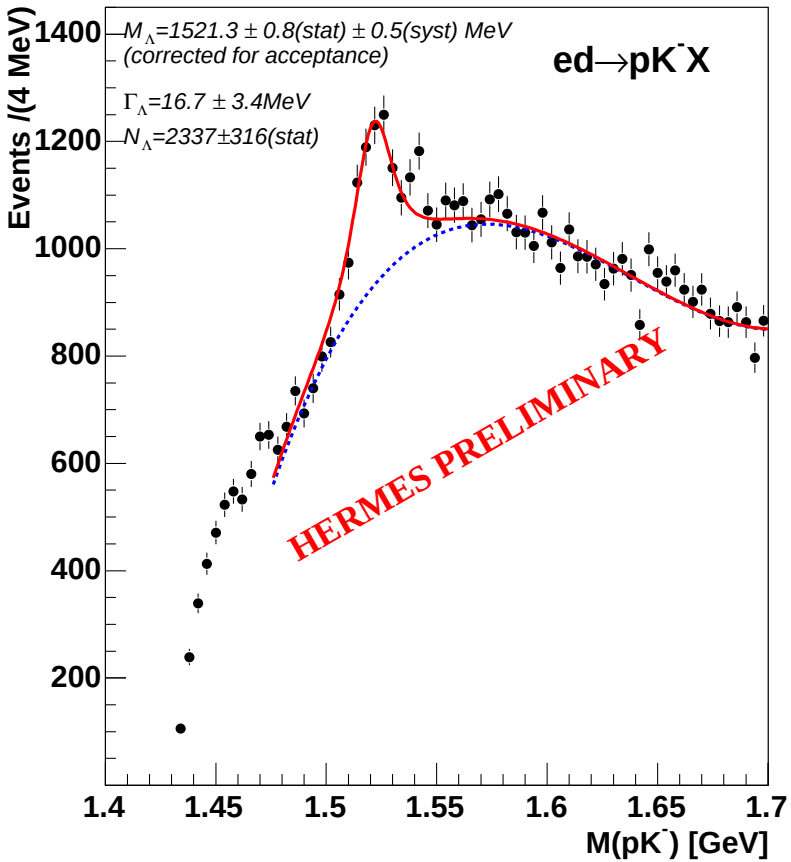




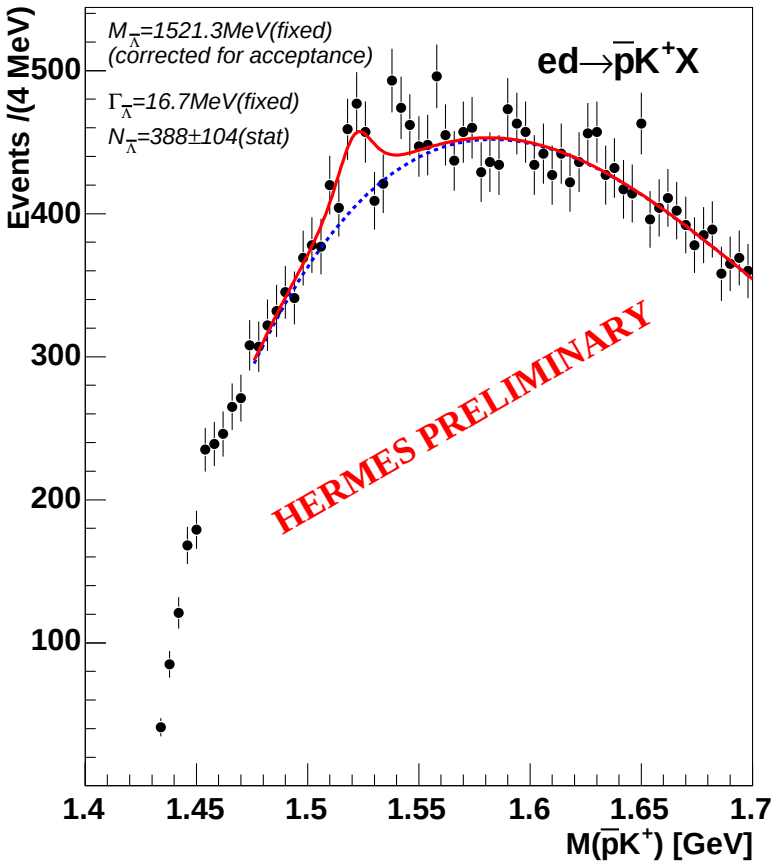
- No $\bar{\Theta}(1540)$ peak visible, ratio $\bar{\Theta}/\Theta = (3 \pm 6)/(59 \pm 16)$
- Do we expect to see many $\bar{\Theta}(1540)$? Our target favors particles!

Anti-Particle $\bar{\Theta}(1540)$: Comparison with $\Lambda(1520)$

$\Lambda(1520) \rightarrow pK^-$

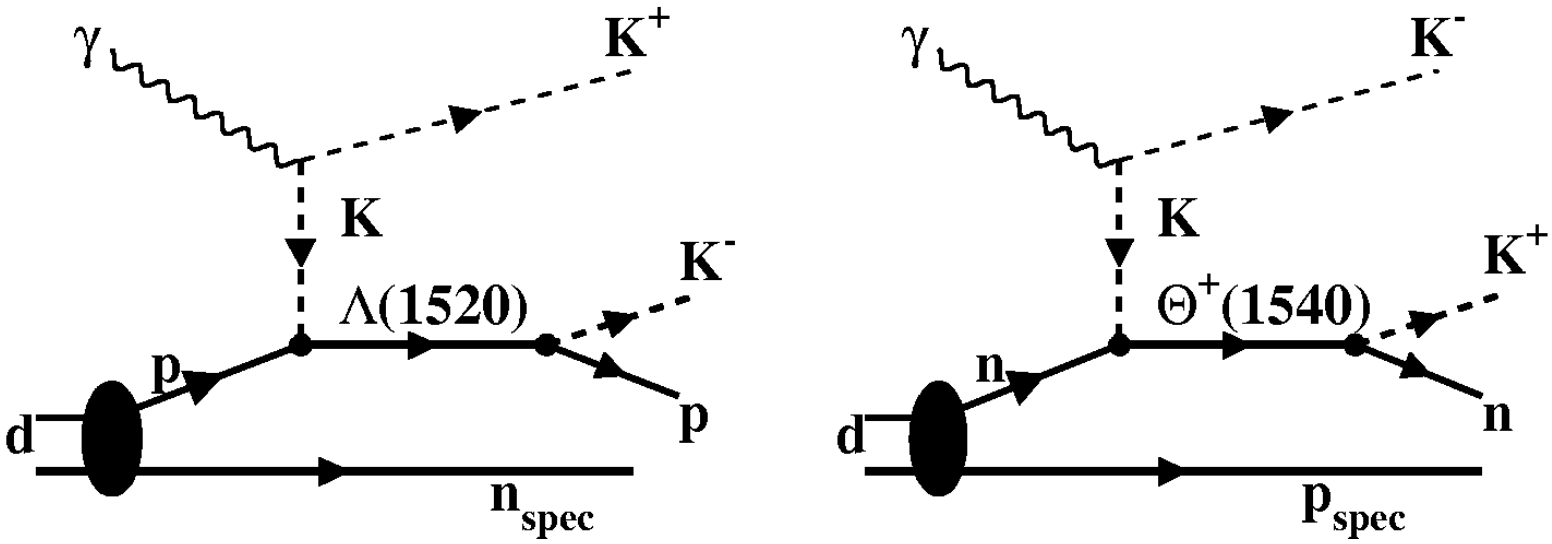


$\bar{\Lambda}(1520) \rightarrow \bar{p}K^+$



- $M = 1521.3 \pm 0.8(\text{stat}) \pm 0.5(\text{syst})$ MeV (acceptance effect)
- In HERMES acceptance for $\Lambda(1520)$ ($P_z > 6$ GeV):
  $R_{\bar{\Lambda}/\Lambda} = 0.15 \pm 0.05(\text{stat}) \pm 0.02(\text{syst})$

Anti-Particle $\bar{\Theta}(1540)$: Comparison with $\Lambda(1520)$



Expected number of $\bar{\Theta}(1540)$

- 59 ± 16 $\Theta(1540)$ observed
- 10 ± 4 $\bar{\Theta}(1540)$ are expected when $R_{\bar{\Theta}/\Theta} = R_{\bar{\Lambda}/\Lambda}$
- 3 ± 6 $\bar{\Theta}(1540)$ were observed
- Both numbers are consistent with each other

Work in Progress at HERMES

Transversely polarized hydrogen data

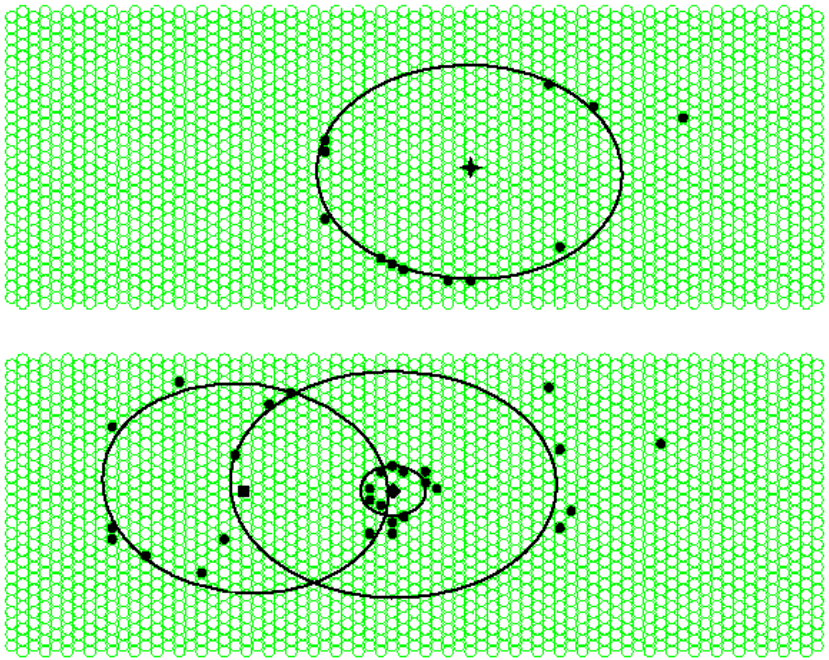
- Large amount of data, taken in 2002–2005
- Transverse magnetic field around polarized target
- Correction method for DIS electron from target available
- For displaced K^0_S vertices: development of different code

Data taken in 2006–2007

- Higher target densities (unpolarized)
- Solenoidal field does not affect forward tracks
- Approximately doubled statistics on D, five times on H
- Data still being calibrated (run ended June 2007)

Improvements in Particle Identification

RICH hit pattern



- Low intensity of Čerenkov light: few PMT hits
- Ambiguities exist when multiple tracks in one half
- Algorithm for event-level PID developed (by UIUC), previously only track-level existed
- Effects in certain momentum ranges seem substantial

Event Mixing as Background Estimator

Method

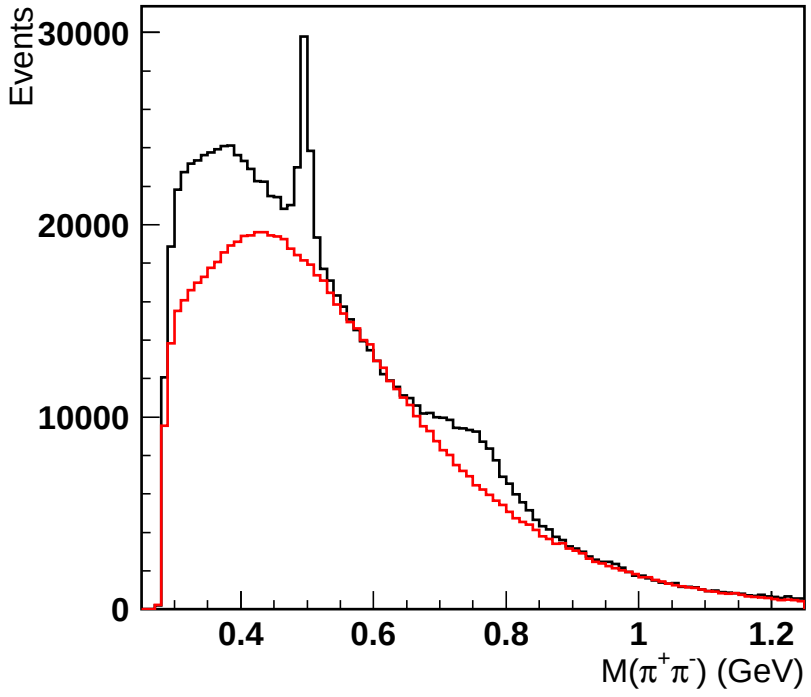
- Combine one daughter from one event with the other daughter from another event
- No resonances will appear (in theory…)

But only if

- equal multiplicity
- same region of detector
- …

Demonstrated on $K^0_S \rightarrow$

- changing buffer size



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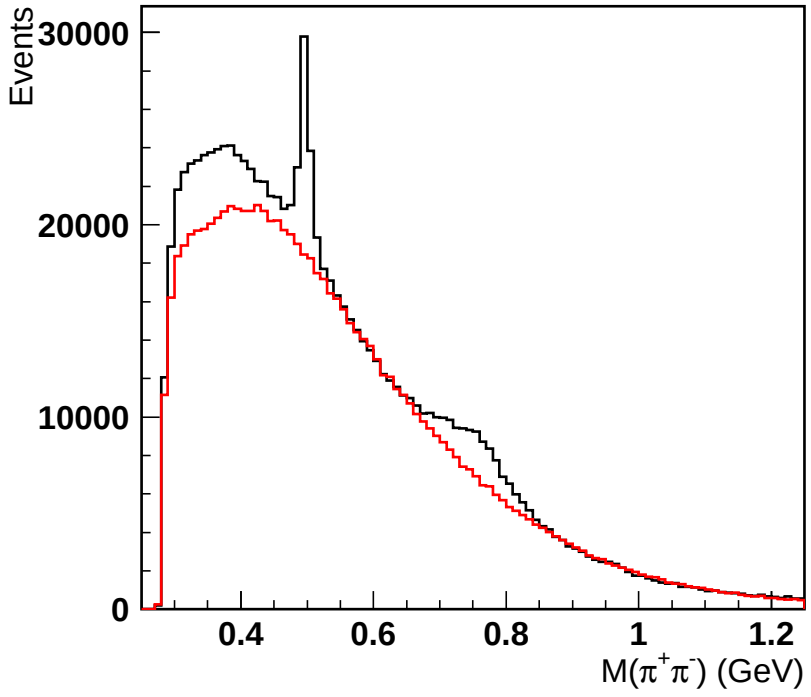

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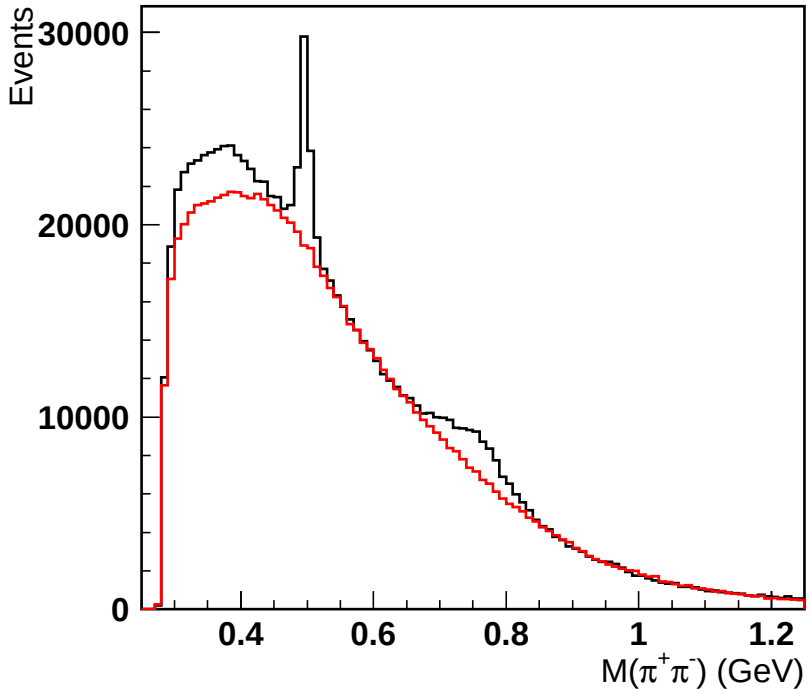

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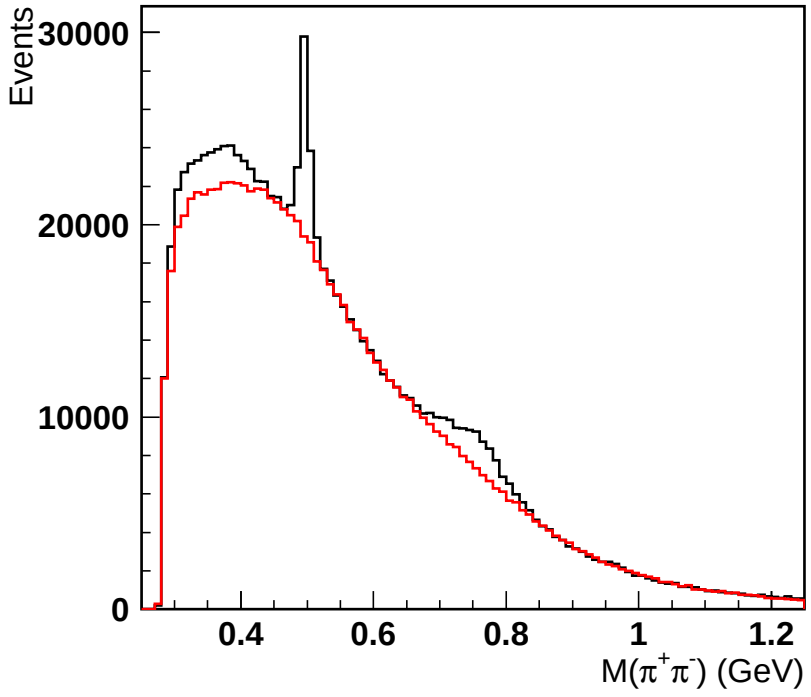
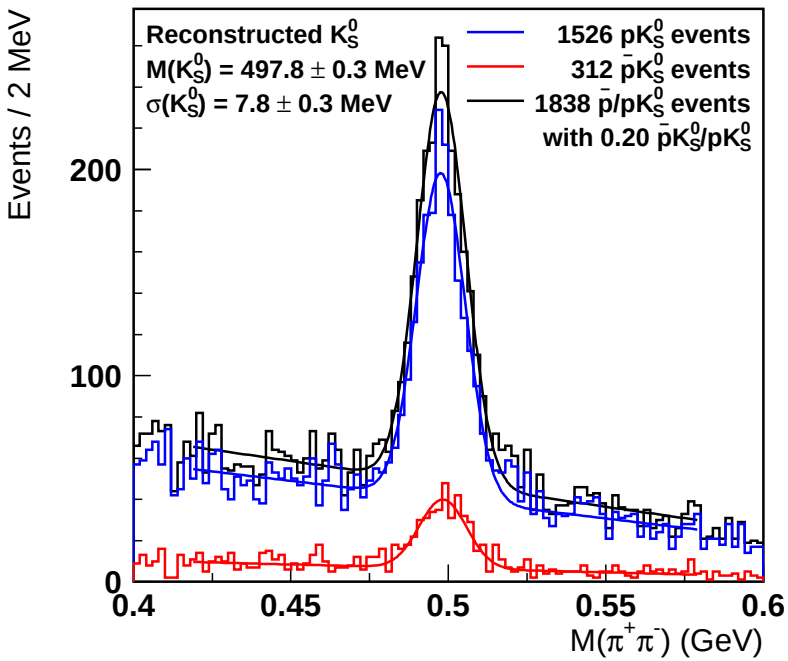
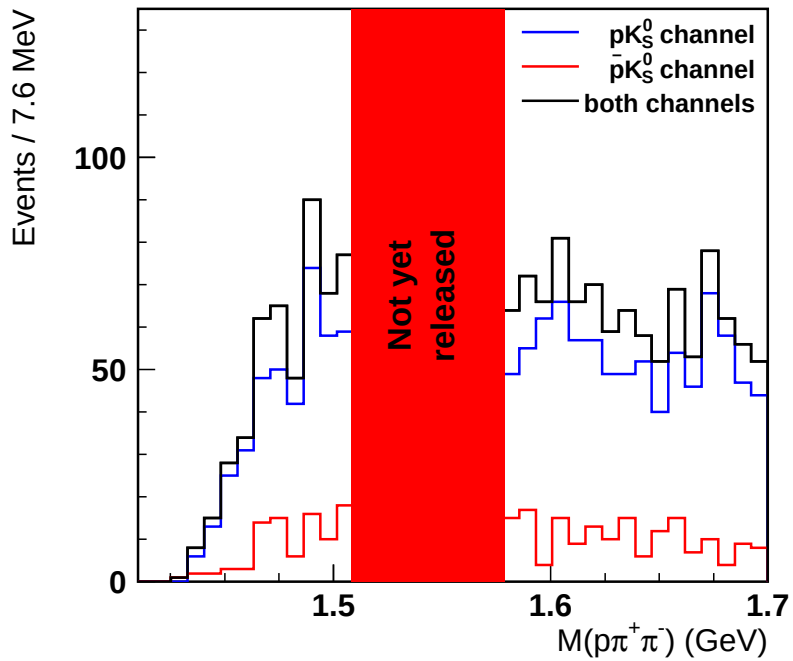


Full Data Set 2002–2007

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



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



- Published data set: approximately 1000 events
- 2006–2007, deuterium target: two times more events
- 2006–2007, hydrogen target: five times more events

Resolution will improve with fully calibrated data!

Full Data Set 2002–2007

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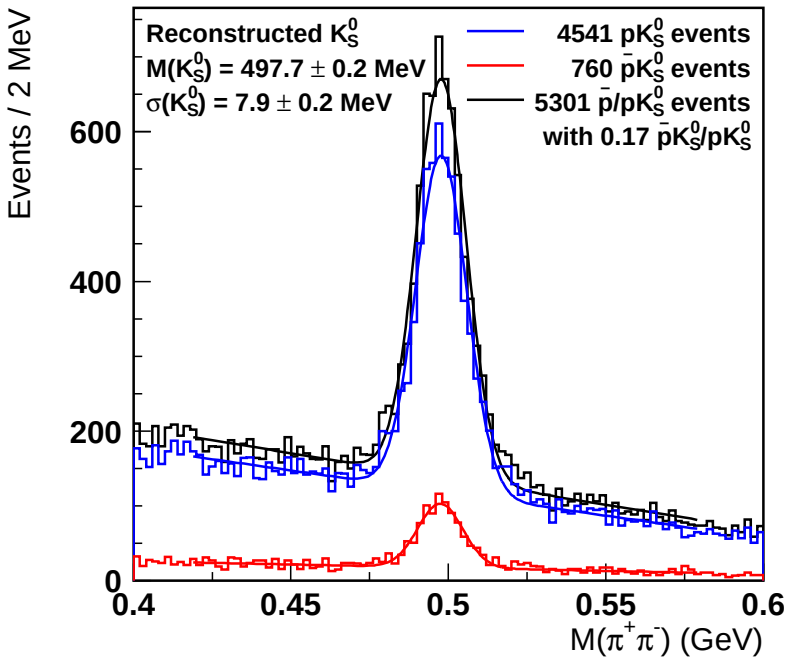
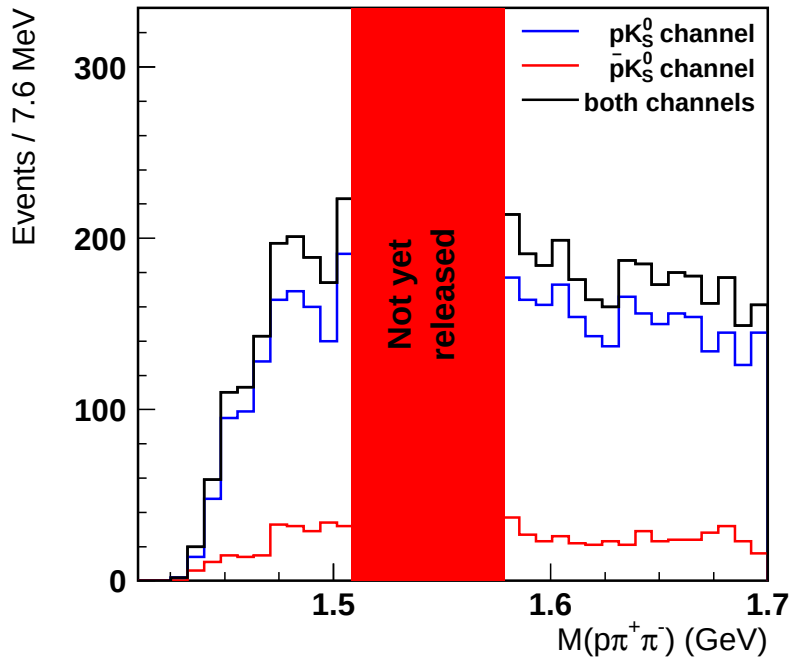


$M(p\pi^+\pi^-)$ spectrum



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Summary

Overview of HERMES contributions

- Θ^+ observed at 1528 MeV, with low statistics
- Lots of systematic studies on result: peak is robust
- No Θ^{++} observed $\rightarrow$ isosinglet
- No Ξ^{--} observed (other pentaquark, not shown here)
- No $\bar{\Theta}$ observed, but from the $\Lambda(1520)$ we expect this

Plans at HERMES

- All data taking completed, five-fold increased number of events
- Analysis continuing and heading towards publication

Summary

Experimental status: status

- Few results stand unchallenged in their reaction channels (CLAS-*p*)
- CLAS and COSY could not confirm their earlier positive sightings
- Other repeat experiments suffer from the same low statistics, and low significance

Theoretical status

- Acceptance difference between experiments large enough (Titov)
- Interference between Θ and other processes (Guzey, Amarian)