Pentaquarks: Much Ado About Nothing?

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Outline

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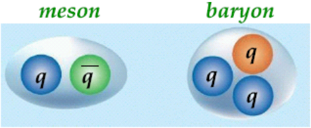
QCD in a Nutshell

QCD describes interactions of quarks and gluons

- Quarks q carry color charge (r, g, b; their sum cancels)
  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 bound states allowed $\rightarrow$ color confinement
- Simplest colorless combinations: $q\overline{q}$, qqq

Multiquark bound states: hadrons

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

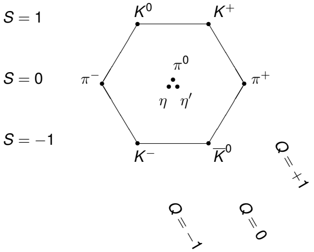


QCD in a Nutshell

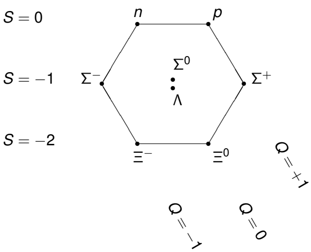
Lightest hadrons

- Ground states without internal orbital momentum ($\ell = 0$)
- Composed of the three lightest quarks (u, d, s) $\rightarrow$ $SU(3)_f$

- Light mesons ($q\overline{q}$)
  $\mathbf{3}_f \times \overline{\mathbf{3}}_f = \mathbf{1} + \mathbf{8}$ with $J = 0$



- Light baryons (qqq)
  $\mathbf{6}_{fs} \times \mathbf{6}_{fs} \times \mathbf{6}_{fs} = \mathbf{56}_S + \ldots$



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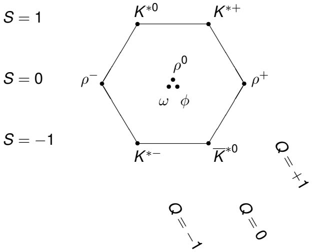

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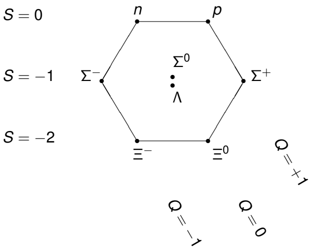

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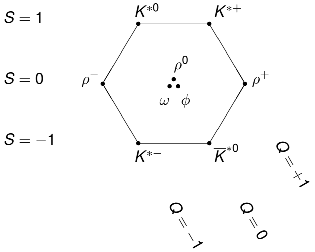

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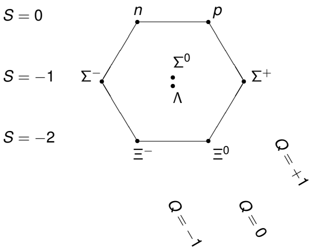

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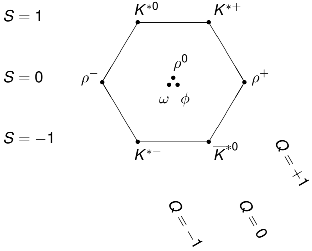

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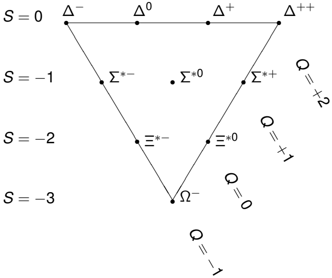

Exotic Hadrons

More than 3 quarks:

- *Exotic mesons* ($qq\overline{q}\overline{q}$) have $\geq$ 4 quarks, integer spin
- *Exotic baryons* ($qqqq\overline{q}$) have $\geq$ 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 than the quarks
- 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 (bag model)

- Quick fall-apart (short life-time) $\rightarrow$ large resonance width
- Difficult to observe in invariant mass spectra
- More suitable for partial wave analysis

Early Z^* sightings (late 1960s, 1970s)

- 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^*s never unambiguously resolved and abandoned in the 1980s, but now understood as pseudo-resonances due to opening up of $K\pi N$ channels.

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Chiral Quark Soliton Model

Diakonov, Petrov, Polyakov (1997)

- Based on Skyrme model: hadrons are regarded as spherically symmetric solitonic solutions of the pion field
- Rotations in flavor space equivalent to real space, and mass states equivalent to rotational excitations
- Only mass differences between states can be predicted
- Applicability to exotic spectroscopy debated

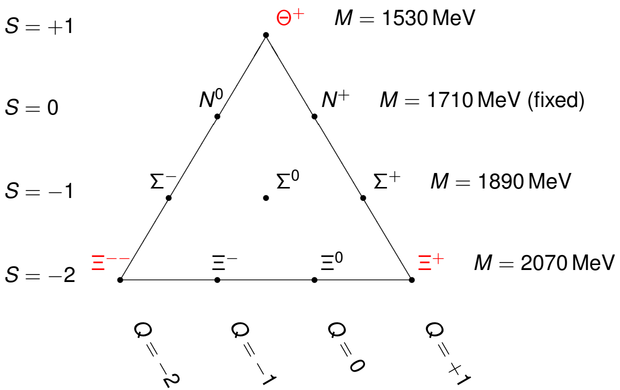
For the lightest quarks *u*, *d*, *s*:

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

- **8** and **10**: non-exotic baryons (with correct mass splittings)
- Antidecuplet $\overline{\mathbf{10}}$: exotic spin $\frac{1}{2}$ baryons, $N(1710)$ as anchor

Chiral Quark Soliton Model

Predicted masses in antidecuplet $\overline{\mathbf{10}}$



Manifestly exotic baryons on the corners (Θ^+, Ξ^{--}, Ξ^+), others predicted states have crypto-exotic quantum numbers

Exotic Baryons Θ^+, Ξ^{--}, and Ξ^+

Exotic baryon Θ^+ ($uudd\bar{s}$)

- Predicted at 1530 MeV and narrower than 15 MeV
- Positive strangeness $S = +1$ (only possible when exotic)
- Decay modes to nK^+ or pK^0 (only $|S| = 1$)
- First observation by LEPS experiment at SPring-8 in Japan
- Several confirmations, numerous null results since then

Exotic baryons Ξ^{--} ($ddss\bar{u}$) and Ξ^+ ($uuss\bar{d}$)

- Predicted with a mass of 2070 MeV and width of 140 MeV
- Decay modes of Ξ^{--} to $\pi^-\Xi^-$ or $K^-\Sigma^-$
- Decay modes of Ξ^+ to $\pi^+\Xi^0$ or $\overline{K}^0\Sigma^+$
- First (and only) observation by NA49 experiment at CERN
- Observed at 1862 MeV with width smaller than 18 MeV

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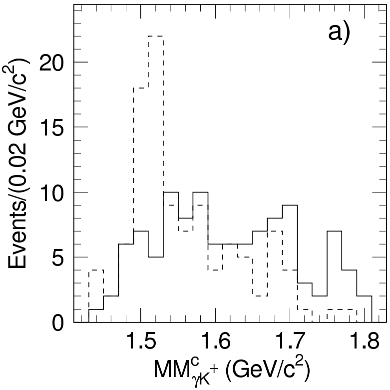
Observation of Θ^+ in Photoproduction at LEPS

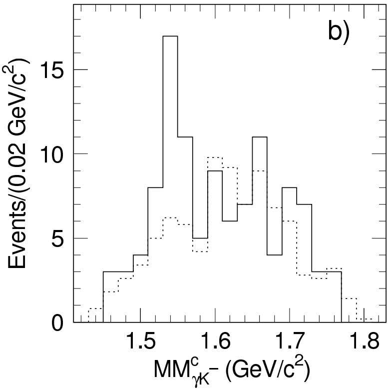
LEPS at SPring-8 in Japan

- Photons on nuclear targets
- E_γ between 1.4–2.5 GeV
- $\gamma n(\mathrm{C}) \to K^+ K^- (n)$

First observation exotic Θ^+

- Fermi-motion correction
- Background poorly understood





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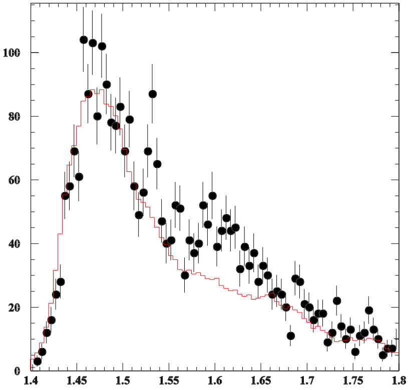


First observation exotic Θ^+

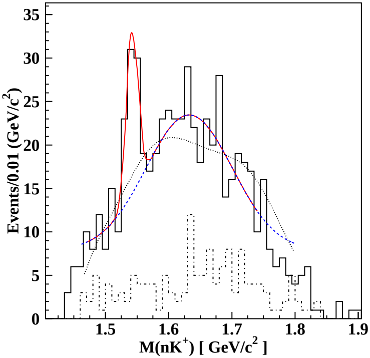
- Fermi-motion correction
- Background poorly understood

Experiment repeated with deuterium target

- Fermi-motion reduced
- Background seems better understood (with p target)
- Second bump at higher M
- Still no publication. . .

Photoproduction on A

CLAS-d



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

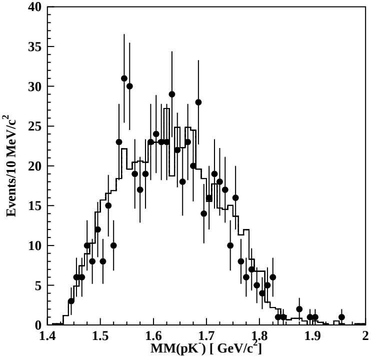
- Significance $\frac{S}{\sqrt{B}}$ around 5 σ
- Final state interactions
- Background difficult to estimate

Experiment repeated

- Repeated with CLAS-g10
- Better background estimation
- Significance now only 3 σ...

Photoproduction on A

CLAS-d



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

- Significance $\frac{S}{\sqrt{B}}$ around $5\,\sigma$
- Final state interactions
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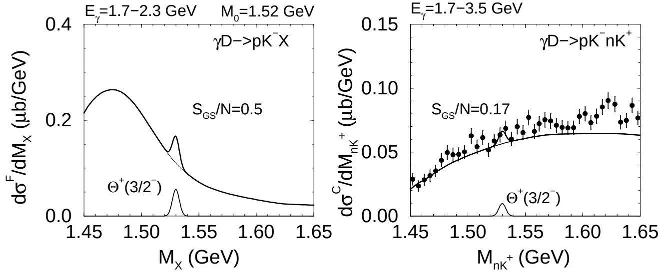
Photoproduction on *A*: CLAS versus LEPS

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

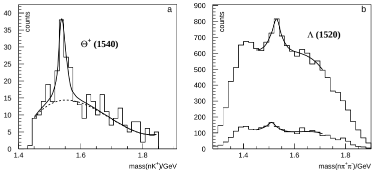


Interference other processes (Guzey, `hep-ph/0608129`)

- Identical final states interfere in total cross section
- Selection criteria, experimental conditions important

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

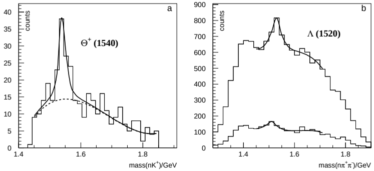
CLAS-g11

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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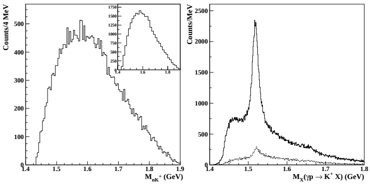

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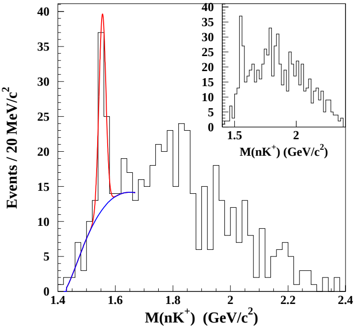
Photoproduction on p: $nK^+K^-\pi^+$



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)

Outline

NK scattering: Formation of Θ

Ideal way to study Θ resonance

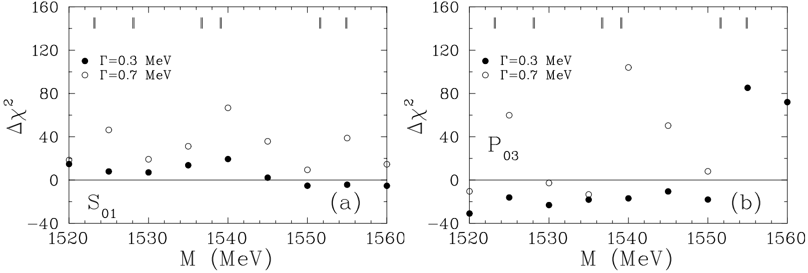
- NK scattering: nK^+ or pK^0
- Take K of appropriate energy on fixed target N
- $E_K \approx 430\,\text{MeV}$ for Θ formation

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

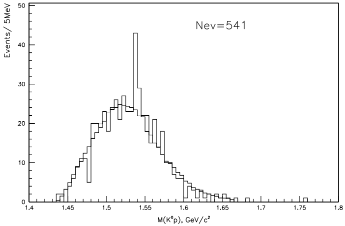


Figure: Barmin, `hep-ex/0304040`

$$K^+n(Xe) \to \Theta^+ \to pK^0_S$$

- 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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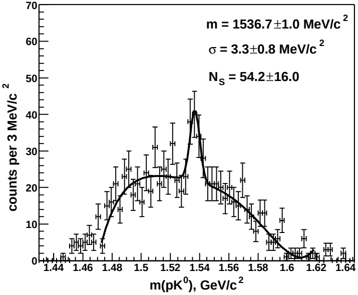

Figure: Barmin, `hep-ex/0603017`

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NK scattering: Secondary K^+ beams

BELLE

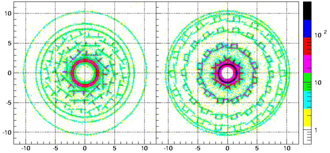

Figure: Abe, `hep-ex/0507014`

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

- 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

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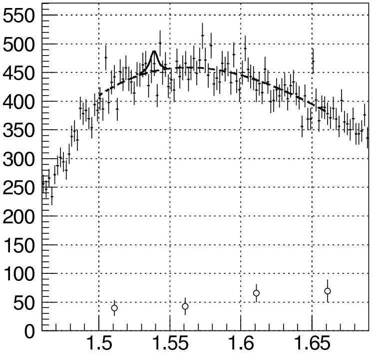

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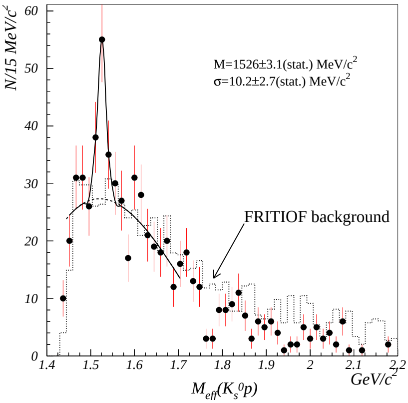
High energy Θ^+ production: *pp*

SVD-2



Original result

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

Experiment repeated

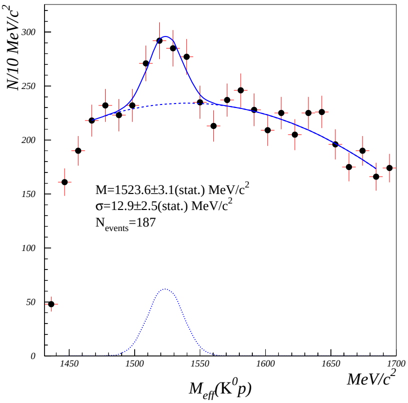
- Statistics increased
- Mixed event background

But

- No confirmation from SPHINX

High energy Θ^+ production: *pp*

SVD-2



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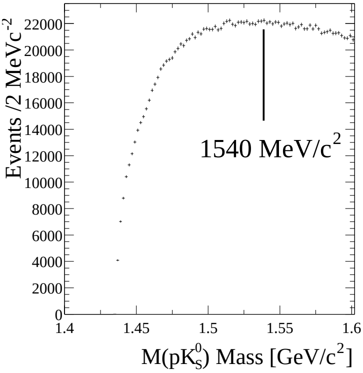
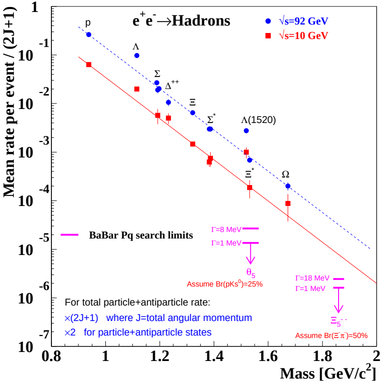
High energy Θ^+ production: e^+e^- at BaBar

Inclusive pK^0_S channel



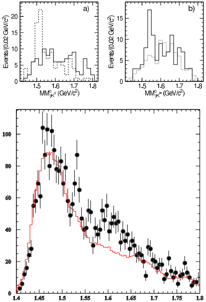
Baryon production yields



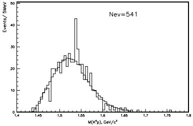
- Θ yield order or magnitude below ordinary hadrons
- But do we really expect a 5-q state to behave similar?

Observation of Θ^+ at Other Experiments

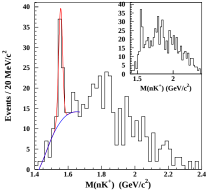
LEPS



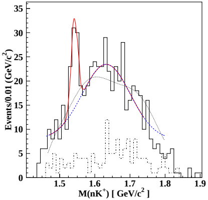
DIANA



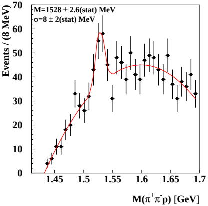
CLAS *p* (JLab)



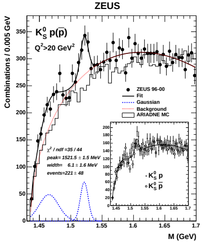
CLAS *d* (JLab)



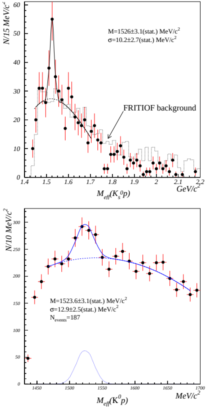
HERMES



ZEUS (HERA)



SVD-2



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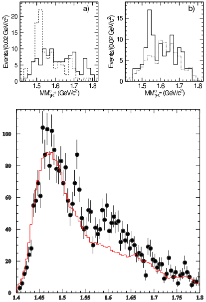

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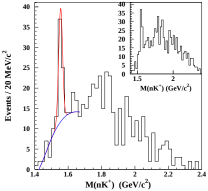

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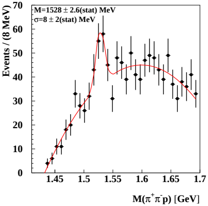
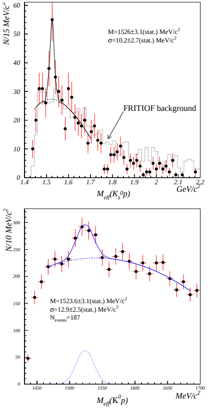
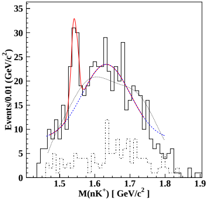


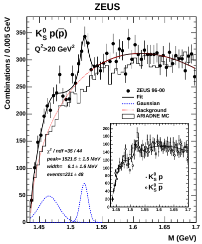
SVD-2



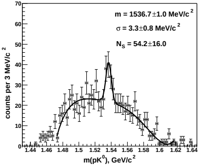
CLAS *d* (JLab)



ZEUS (HERA)

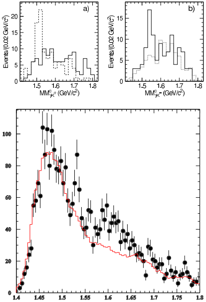


DIANA

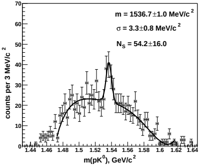


Observation of Θ^+ at Other Experiments

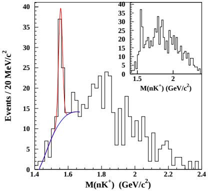
LEPS



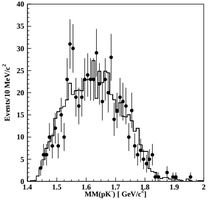
DIANA



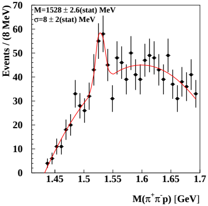
CLAS *p* (JLab)



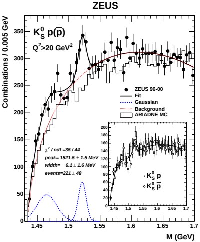
CLAS *d* (JLab)



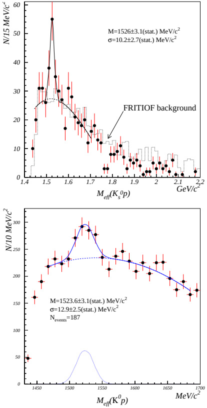
HERMES



ZEUS (HERA)



SVD-2



Outline

The HERMES Experiment

High energy electrons on fixed gas target

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

Exotic production in quasi-real photoproduction

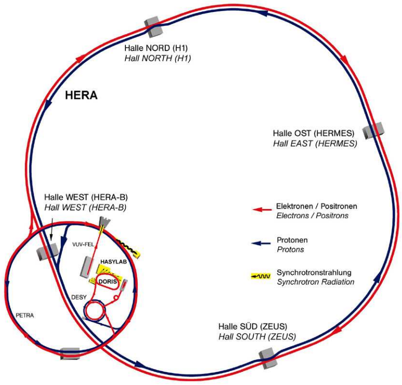
- Electron emits photon with $Q^2 \approx 0$
- Photon interacts with nucleon
- Produced hadrons are detected in forward spectrometer
- Electron not detected, bending angle too small

The HERA Storage Ring

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

The HERA Storage Ring

Schematic overview DESY



Particle physics with HERA

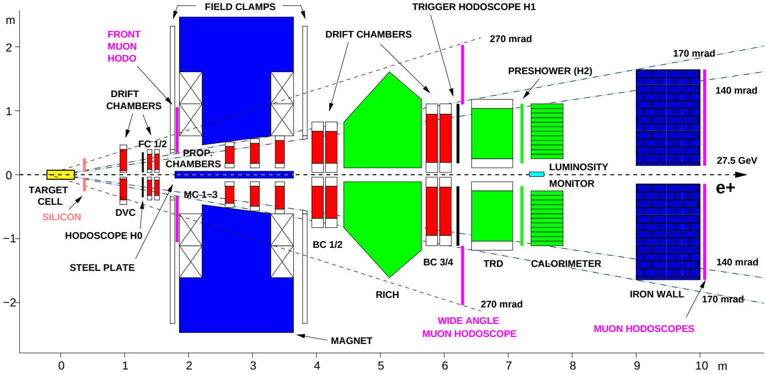
- Collider for H1, ZEUS: 27.5 GeV *e* on 920 GeV *p*
- HERMES: 27.5 GeV *e* on *A*
- HERA-B: 920 GeV *p* on *A*
- Last beam in June 2007
- Analysis of data continues

Synchrotron radiation facility

- HASYLAB
- VUV-FEL/FLASH
- PETRA III, XFEL (by 2013)

Outline

The HERMES Spectrometer

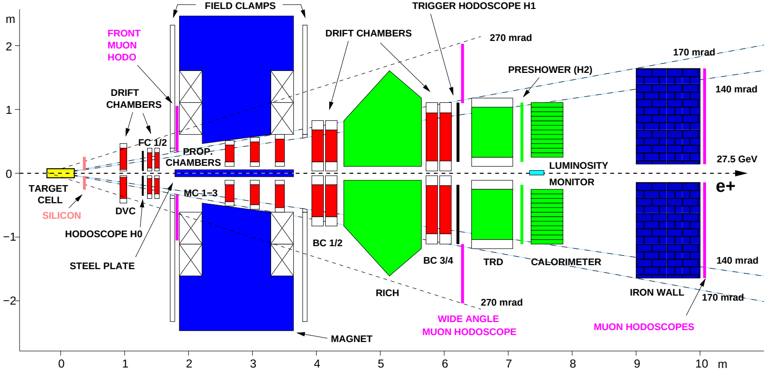


27.6 GeV $e^{\pm}$ HERA beam on $\overrightarrow{H}$, $\overrightarrow{He}$, $\overrightarrow{D}$ or H_2, D_2, He,...

Tracking detectors

- Tracking resolution: $\frac{\Delta p}{p} = 1.4 - 2.5\%$, $\Delta\vartheta \lesssim 0.6$ mrad
- Invariant mass resolution: 6 MeV for K^0, 2.5 MeV for Λ

The HERMES Spectrometer

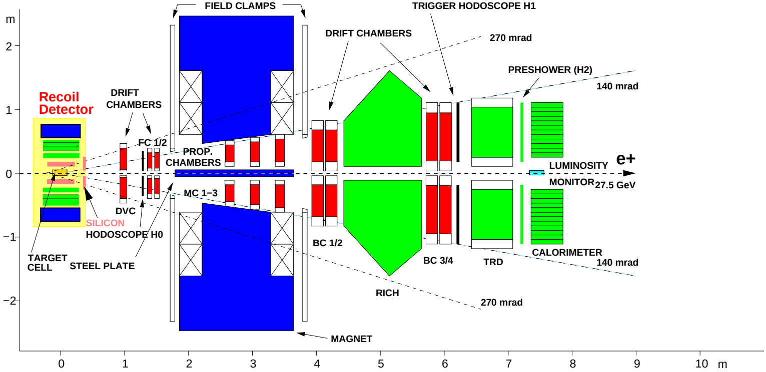


27.6 GeV $e^{\pm}$ HERA beam on $\vec{H}$, $\vec{He}$, $\vec{D}$ or H_2, D_2, He,...

Particle identification detectors

- TRD, Preshower, Calorimeter: hadron/lepton separation
- RICH: hadron identification (π, K, p)

The HERMES Spectrometer



27.6 GeV $e^{\pm}$ HERA beam on $\vec{H}$, $\vec{He}$, $\vec{D}$ or H_2, D_2, He,…

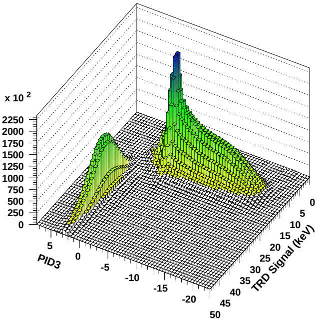
Recoil detector during 2006 and 2007

- Unpolarized target with higher density
- Estimated $\mathcal{L} \approx 400\mathrm{pb}^{-1}$ on deuterium, more on hydrogen

The HERMES Spectrometer

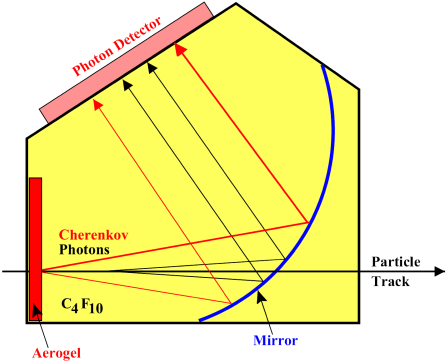
Hadron/lepton separation:
with combination of

- TRD
- Calorimeter
- Preshower
- RICH



Hadron identification:
Ring-Imaging Čerenkov detector (RICH)

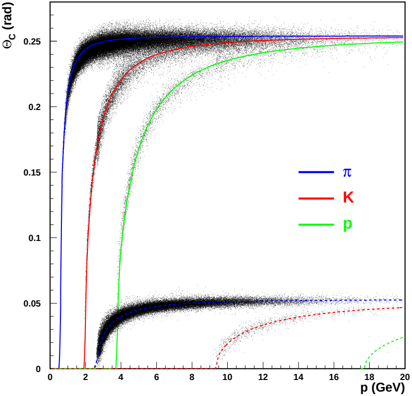
- Two radiators for larger kinematic coverage



The HERMES Spectrometer: RICH Detector

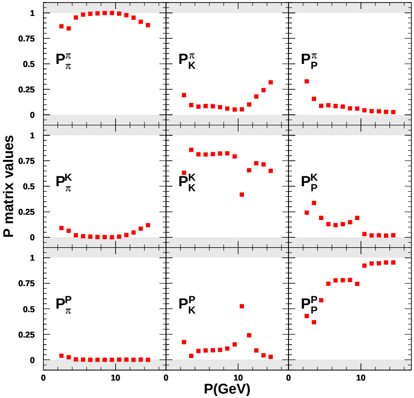
Dual radiator

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



Identification efficiency

- Momentum dependence
- Range 4–9 GeV for protons

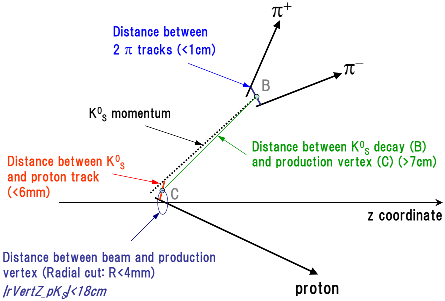


Outline

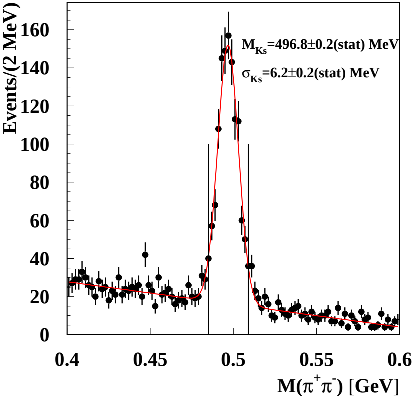
Observation of the Exotic Baryon Θ^+ at HERMES

Inclusive reaction

- Decay channel
  $\Theta^+ \to pK^0_S \to p\pi^+\pi^-$
- Event selection



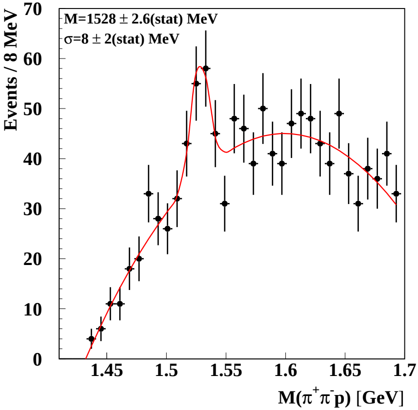
Invariant mass $M(\pi^+\pi^-)$



K^0_S meson at 496.8 MeV with width of 6.2 MeV

Observation of the Exotic Baryon Θ^+ at HERMES

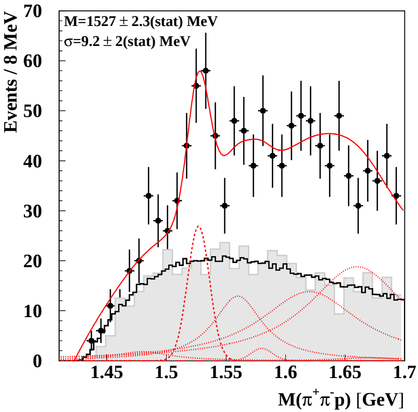
- Spectrum with polynomial fit



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

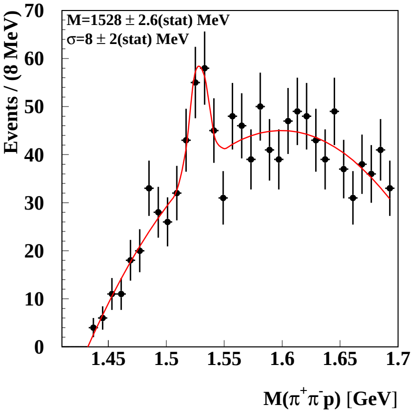
Observation of the Exotic Baryon Θ^+ at HERMES

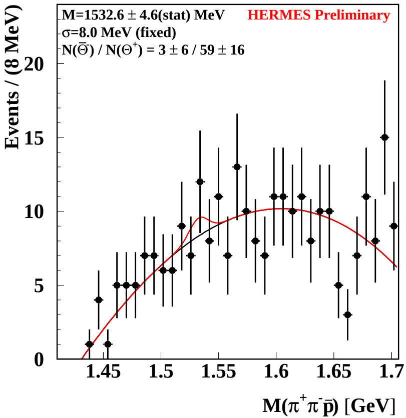
- Spectrum with Monte Carlo



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

Search for the Exotic Antibaryon Θ^- at HERMES



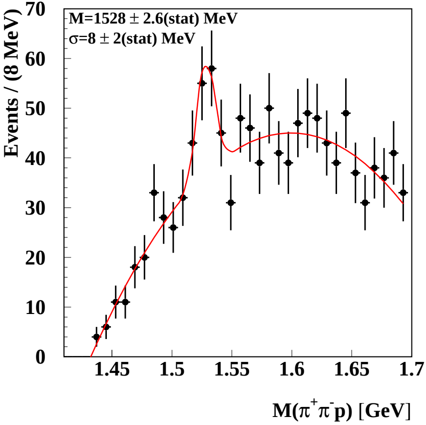


- No Θ^- peak visible, ratio $\Theta^-/\Theta^+ = (3 \pm 6)/(59 \pm 16)$
- But how many Θ^- do we expect to observe?

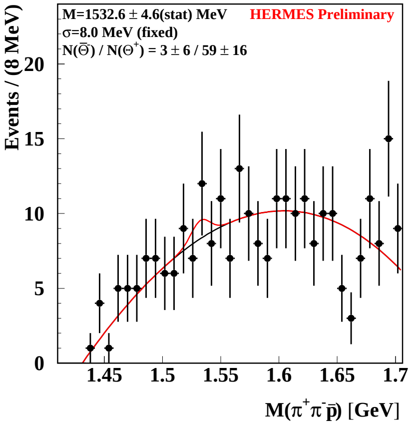
Outline

Cross Section Ratio of the Hyperon $\Lambda(1520)$

Observation of exotic Θ^+



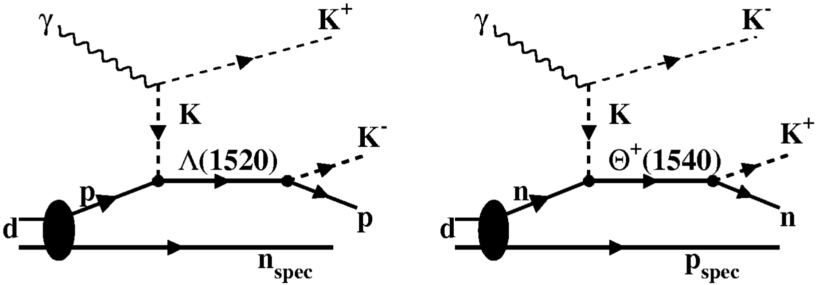
Search for antiparticle Θ^-



- No exotic Θ^- observed, ratio $\Theta^-/\Theta^+ = (3 \pm 6)/(59 \pm 16)$
- But how many Θ^- do we expect? Target favors particles!

Cross Section Ratio of the Hyperon $\Lambda(1520)$

Production of hyperon $\Lambda(1520)$ and exotic $\Theta^+(1540)$

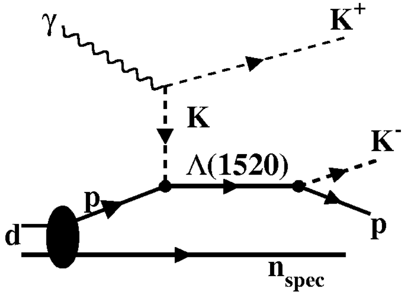


Expected number of Θ^-

- Determine cross section ratio of $\overline{\Lambda}(1520)$ to $\Lambda(1520)$
- Assumption that $R_{\Theta^-/\Theta^+} = R_{\overline{\Lambda}(1520)/\Lambda(1520)}$
- Is expected number of Θ^- consistent with null result 3 ± 6 ?

Cross Section Ratio of the Hyperon $\Lambda(1520)$

Production of hyperon $\Lambda(1520)$



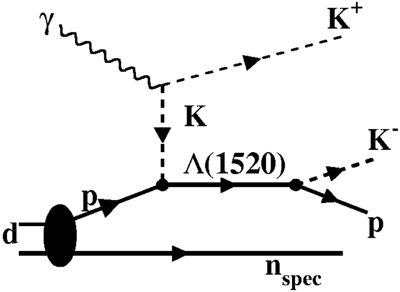
- $\Lambda(1520) \to pK^-$
- $\overline{\Lambda}(1520) \to \overline{p}K^+$
- Identical data sample as for the observation of exotic baryon Θ^+

Event selection criteria

- Not optimized on $\Lambda(1520)$
- Investigated with Monte Carlo

Cross Section Ratio of the Hyperon $\Lambda(1520)$

Production of hyperon $\Lambda(1520)$



- $\Lambda(1520) \rightarrow pK^-$
- $\overline{\Lambda}(1520) \rightarrow \overline{p}K^+$
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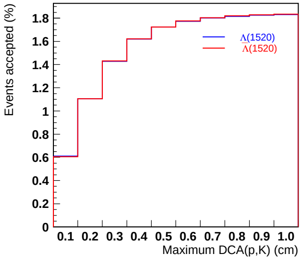
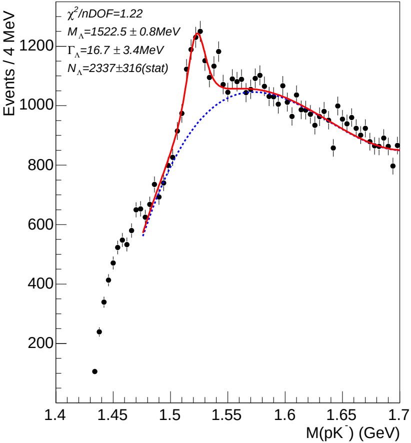


Event selection criteria

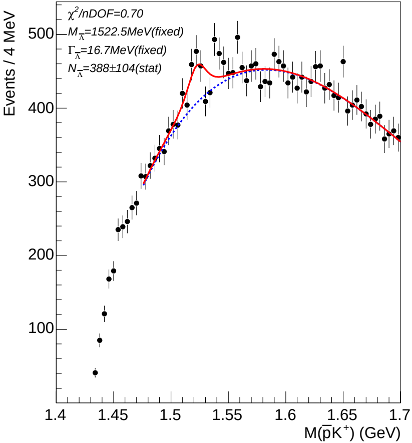
- Not optimized on $\Lambda(1520)$
- Investigated with Monte Carlo

Cross Section Ratio of the Hyperon $\Lambda(1520)$

Invariant mass $M(pK^-)$

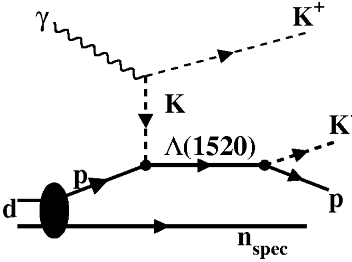


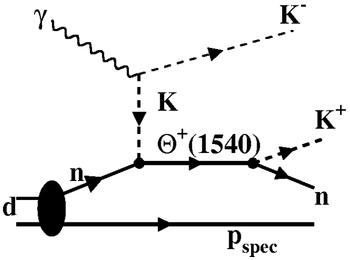
Invariant mass $M(\bar{p}K^+)$



- $M = 1522.5 \pm 0.8(\text{stat})$ MeV affected by acceptance effect

Cross Section Ratio of the Hyperon Λ(1520)





Hyperon Λ(1520)

- Cross section ratio $R_{\bar{\Lambda}/\Lambda} = 0.15 \pm 0.05$
- Assumption that $R_{\bar{\Theta}/\Theta} = R_{\bar{\Lambda}/\Lambda}$

Exotic baryon Θ^+

- 59 ± 16 Θ^+ observed
- 10 ± 4 Θ^- expected
- 3 ± 6 Θ^- observed
- Consistent within one σ

Outline

Event Mixing

Procedure for background estimation

- Combine track in one event with track in different event
- Normalize distributions or scale by a combinatoric factor
- No correlations or resonances will be present

Original method used in searches for exotic Θ^+ and Ξ^{--}

- Select the events based on all selection criteria
- Do the event mixing between the selected events
- Mixed events do not satisfy the selection criteria anymore
- Distance of closest approach between tracks changed!

Improved method

Event Mixing

Procedure for background estimation

- Combine track in one event with track in different event
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Original method used in searches for exotic Θ^+ and Ξ^{--}

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Improved method

Event Mixing

Procedure for background estimation

- Combine track in one event with track in different event
- Normalize distributions or scale by a combinatoric factor
- No correlations or resonances will be present

Original method incorrect

Improved method

- Select tracks based on the track selection criteria (*e.g.* charge, momentum, fiducial volume)
- Do the event mixing between all selected tracks
- Select events based on the event selection criteria (*e.g.* distance of closest approach, vertex separation)

Event Mixing

Kinematic mismatch

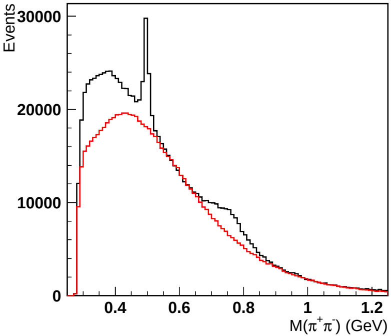
- Track with high momentum can be replaced by track with low momentum in the opposite detector half
- Distribution of the mixed events not representative

Event mixing buffer

- Replace by most similar track among last N events
- Larger N will give better agreement

Invariant mass $M(\pi^+\pi^-)$

(with η, K_S^0 and ρ resonances)



Buffer size $N = 1$

Event Mixing

Kinematic mismatch

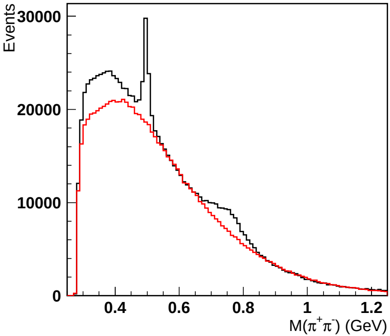
- Track with high momentum can be replaced by track with low momentum in the opposite detector half
- Distribution of the mixed events not representative

Event mixing buffer

- Replace by most similar track among last N events
- Larger N will give better agreement

Invariant mass $M(\pi^+\pi^-)$

(with η, K_S^0 and ρ resonances)



Buffer size $N = 22$

Event Mixing

Kinematic mismatch

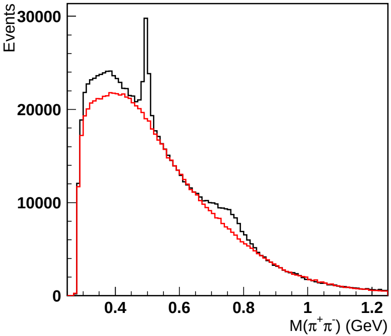
- Track with high momentum can be replaced by track with low momentum in the opposite detector half
- Distribution of the mixed events not representative

Event mixing buffer

- Replace by most similar track among last N events
- Larger N will give better agreement

Invariant mass $M(\pi^+\pi^-)$

(with η, K_S^0 and ρ resonances)



Buffer size $N = 47$

Event Mixing

Kinematic mismatch

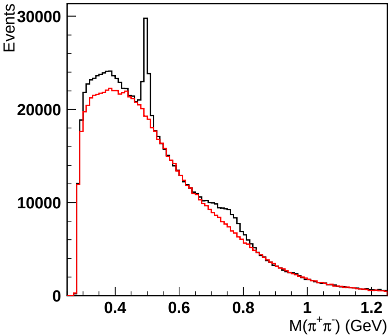
- Track with high momentum can be replaced by track with low momentum in the opposite detector half
- Distribution of the mixed events not representative

Event mixing buffer

- Replace by most similar track among last *N* events
- Larger *N* will give better agreement

Invariant mass $M(\pi^+\pi^-)$

(with η, K^0_S and ρ resonances)

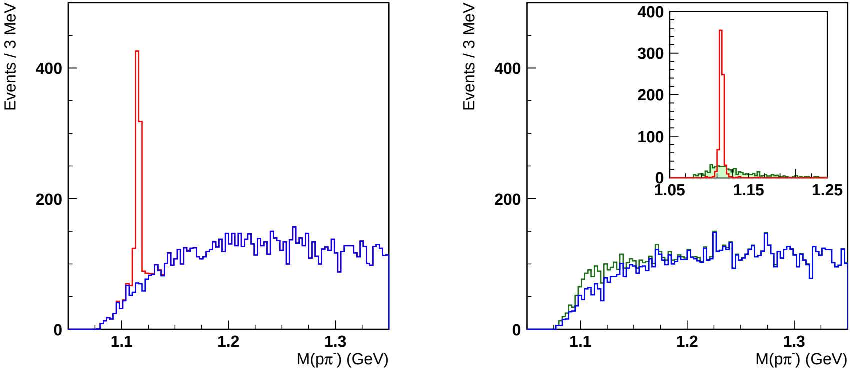


Buffer size $N = 80$

Event Mixing

Mixed resonance events (in Monte Carlo)

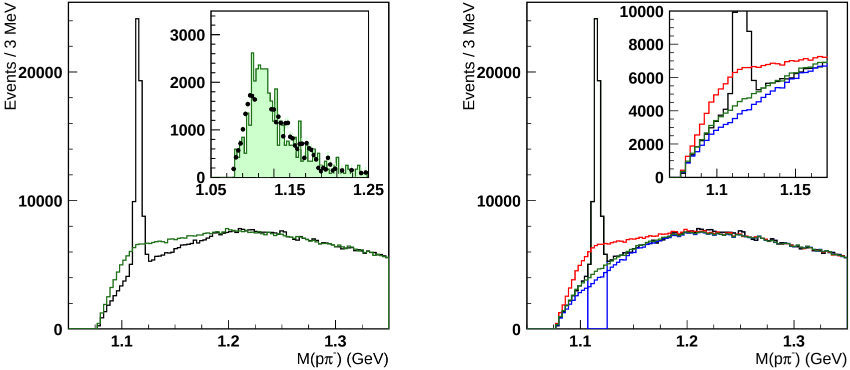
- Background events $\xrightarrow{\text{mixing}}$ identical background shape
- Resonance events $\xrightarrow{\text{mixing}}$ smeared resonance shape
- Mixed resonance shape different from background shape!



Event Mixing

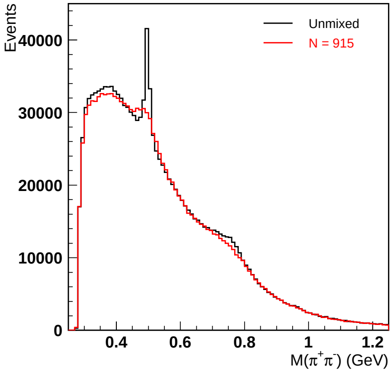
Mixed resonance events (in data)

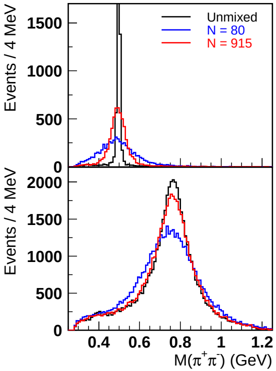
- Difference between mixed events described by MC
- Requires the availability of a Monte Carlo simulation
- Including and discarding invariant mass window



Event Mixing

Mixed resonance events (overfit)

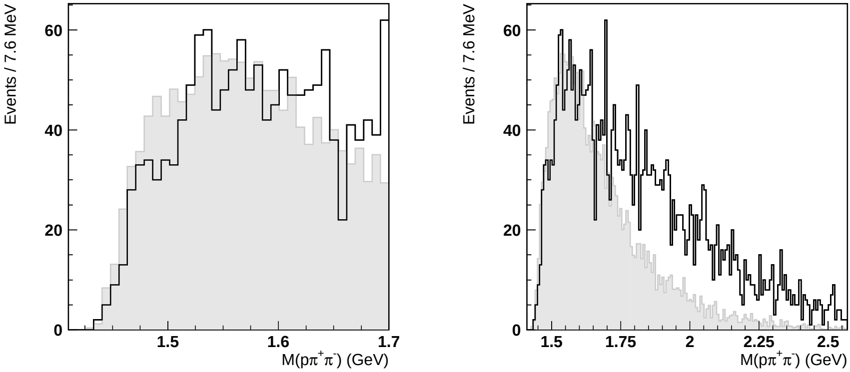




- When buffer size *N* larger, smeared resonances narrower
- Too large *N* will just reproduce the resonances
- Keep *N* small enough to have normalization region

Event mixing

Application to search for exotic Θ^+

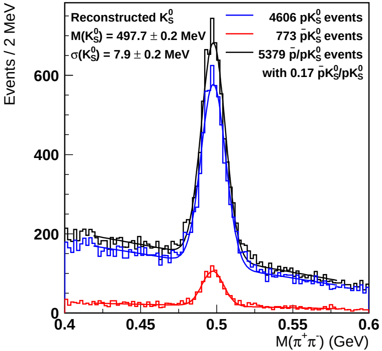


- Mixed event background describes background poorly
- Correlations between tracks? Contribution of Σ^* hyperons?
- Mixed event background highest at 1540 MeV

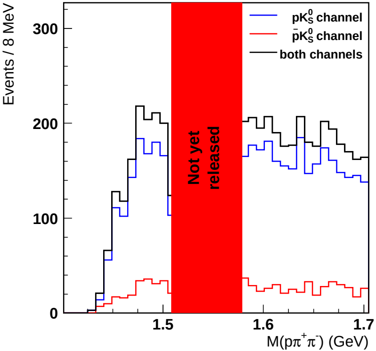
Outline

Search in Data Collected in 2006–2007

Invariant mass $M(\pi^+\pi^-)$



Invariant mass $M(p\pi^+\pi^-)$

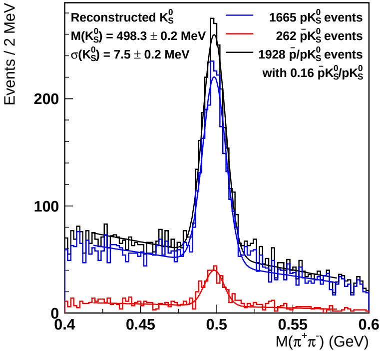


- Low density hydrogen target (ld): largest available data set
- High density hydrogen target (hd)
- Deuterium target: conditions identical to 1998–2000

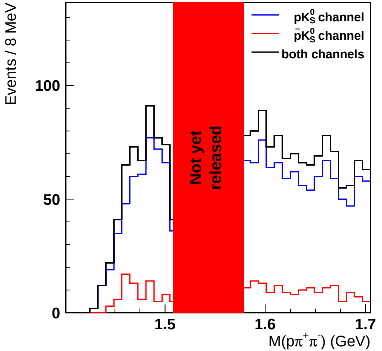
Resolution will (hopefully) improve with fully calibrated data!

Search in Data Collected in 2006–2007

Invariant mass $M(\pi^+\pi^-)$



Invariant mass $M(p\pi^+\pi^-)$



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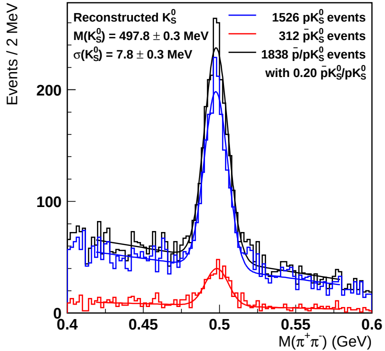
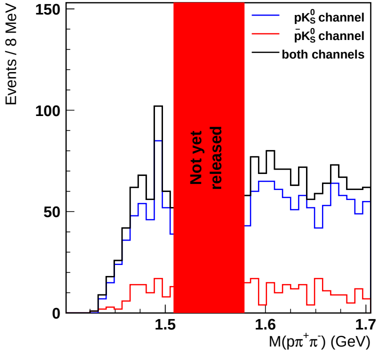
Search in Data Collected in 2006–2007

Invariant mass $M(\pi^+\pi^-)$



Invariant mass $M(p\pi^+\pi^-)$



- Low density hydrogen target (ld): largest available data set
- High density hydrogen target (hd)
- Deuterium target: conditions identical to 1998–2000

Resolution will (hopefully) improve with fully calibrated data!

Outline

Transverse Magnet Correction

Search for exotic baryons on hydrogen

- Until 2005 only possible on low density deuterium target
- Data set collected on hydrogen had not been analyzed

Transversely polarized hydrogen target

- Transverse magnetic holding field of 0.3 T in target region
- Correction methods TMC developed by collaboration, but only for vertex with lepton beam
- Displaced K_S^0, Λ vertices need different approach

Transverse magnetic holding field

- Approximation as homogenous field in rectangular region

Transverse Magnet Correction

Search for exotic baryons on hydrogen

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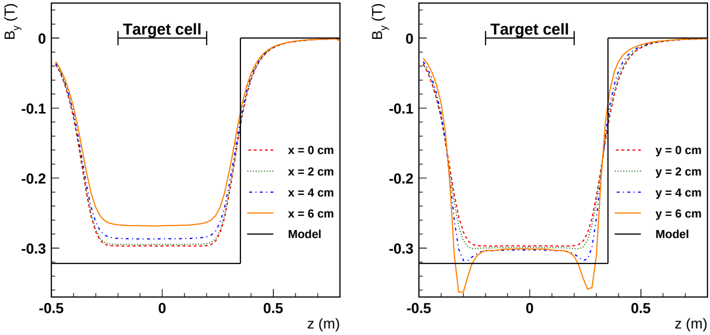
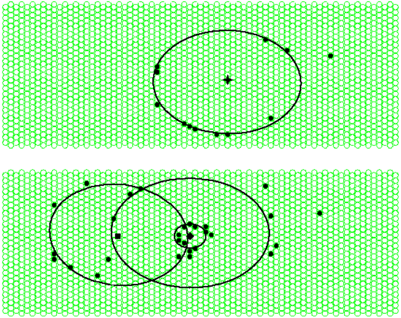
- Data set collected on hydrogen had not been analyzed

Transverse magnetic holding field



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

Outline

Summary

Overview of HERMES contributions

- Evidence for resonance at 1528 MeV, low number of events
- Several systematic studies confirm: peak is robust
- No Θ^{++} observed $\rightarrow$ isosinglet
- No Ξ^{--} observed, upper limit of 3 nb (not part of this talk)
- No $\overline{\Theta}$ observed, but this is consistent with the $\Lambda(1520)$
- Event mixing (used in the original publication) needs to be improved

Upcoming results at HERMES

- Data taking completed, 5-fold increase of number of events
- Analysis in final and heading towards publication

Conclusions

Experimental status

- CLAS and COSY could not confirm their earlier evidence
- Other repeat experiments suffer from the same low statistics, and low significance

Theoretical status

- Acceptance difference between experiments large enough
- Interference between Θ^+ and other processes

Conclusion

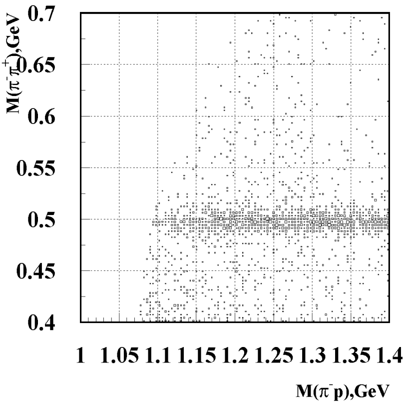
- Incredible amount of experimental and theoretical activity was definitely worth it, even if in the end no exotic baryons are found

Outline

Outline

Additional Θ^+ studies: Tracking or PID problems

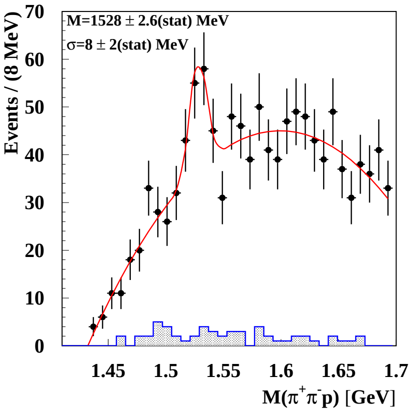
- Correlation $M_{\pi\pi}$ vs. $M_{p\pi}$



- 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

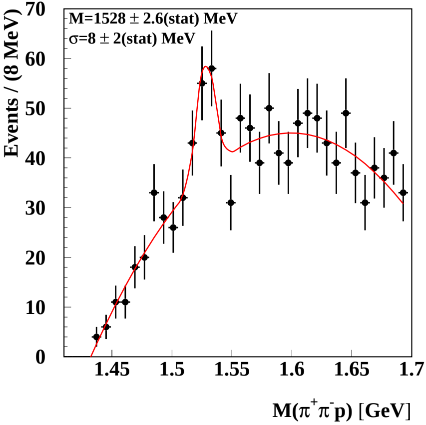


- Ghost tracks
  - No correlations
  - Examined data files
  - No ghost tracks!
- PID leaks
  - π^+ is actually p (mis-ID)
  - K_S combination is a Λ
  - Λ events are cut out from spectrum
  - Inefficient Λ cut not reason for peak!

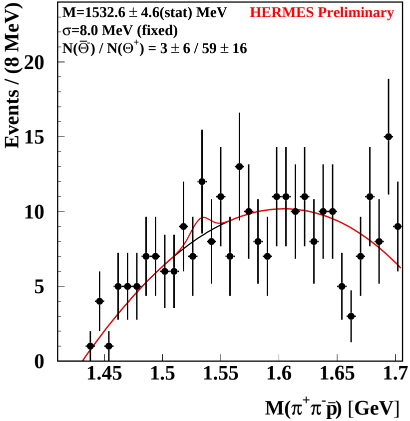
Outline

Cross Section Ratio of the Hyperon Λ(1520)

Observation of exotic Θ^+



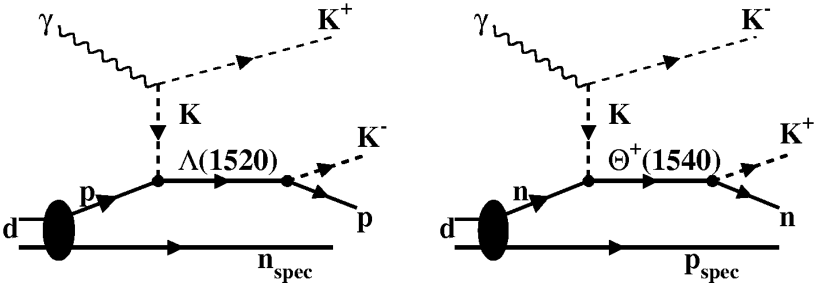
Search for antiparticle Θ^-



- No exotic Θ^- observed, ratio $\Theta^-/\Theta^+ = (3 \pm 6)/(59 \pm 16)$
- But how many Θ^- do we expect? Target favors particles!

Cross Section Ratio of the Hyperon Λ(1520)

Production of hyperon Λ(1520) and exotic $\Theta^+(1540)$

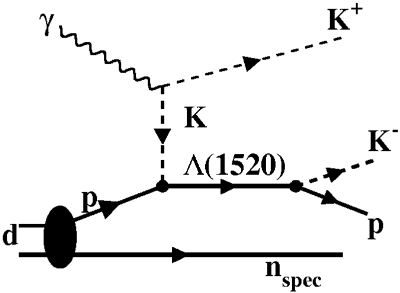


Expected number of Θ^-

- Determine cross section ratio of $\overline{\Lambda}(1520)$ to Λ(1520)
- Assumption that $R_{\Theta^-/\Theta^+} = R_{\overline{\Lambda}(1520)/\Lambda(1520)}$
- Is expected number of Θ^- consistent with null result 3 ± 6 ?

Cross Section Ratio of the Hyperon Λ(1520)

Production of hyperon Λ(1520)



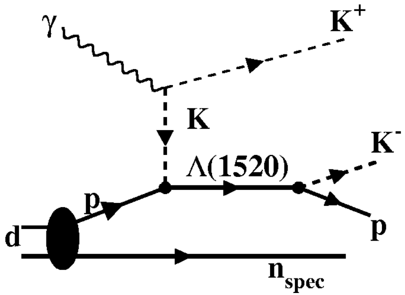
- $\Lambda(1520) \rightarrow pK^-$
- $\overline{\Lambda}(1520) \rightarrow \overline{p}K^+$
- Identical data sample as for the observation of exotic baryon Θ^+

Event selection criteria

- Not optimized on Λ(1520)
- Investigated with Monte Carlo

Cross Section Ratio of the Hyperon Λ(1520)

Production of hyperon Λ(1520)



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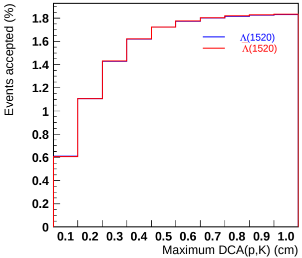
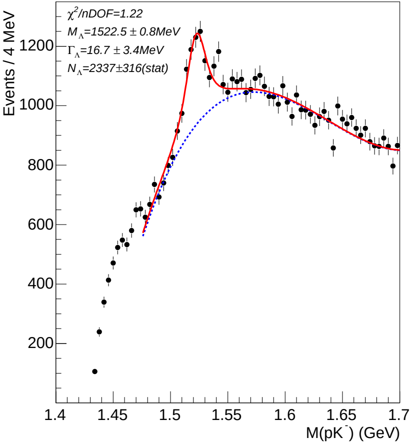
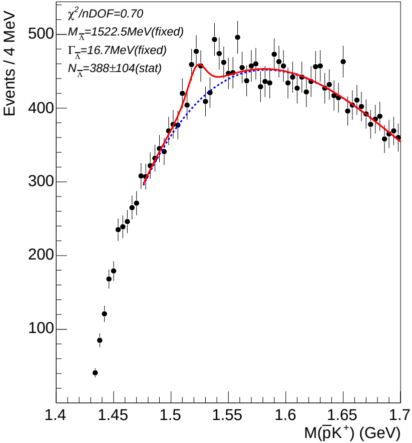


Cross Section Ratio of the Hyperon $\Lambda(1520)$

Invariant mass $M(pK^-)$



Invariant mass $M(\bar{p}K^+)$

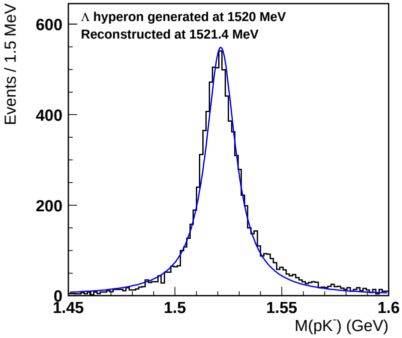


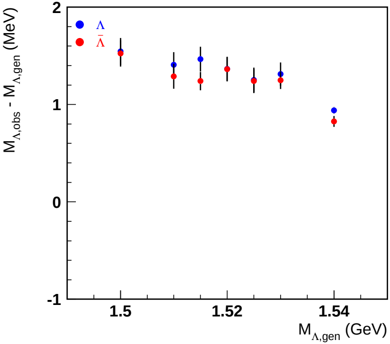
- $M = 1522.5 \pm 0.8(\text{stat})$ MeV affected by acceptance effect

Cross Section Ratio of the Hyperon Λ(1520)

Acceptance correction for Λ(1520) hyperon

- Acceptance varies in Λ(1520) mass region
- Shape of peak changes to skewed Breit-Wigner
- Mass from simple Breit-Wigner 1.5 ± 0.5 MeV too high





Cross Section Ratio of the Hyperon Λ(1520)

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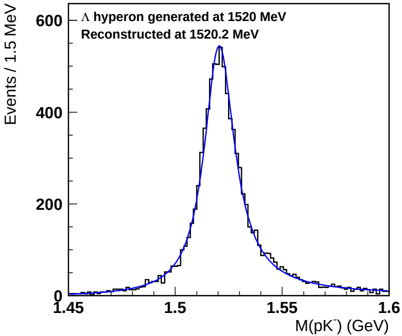
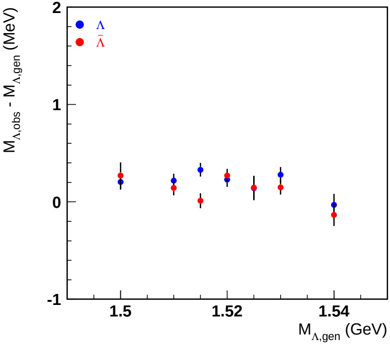


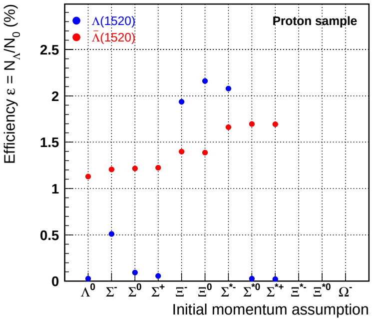


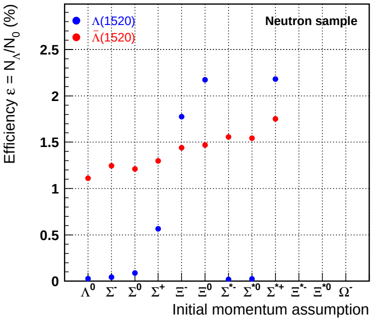
Cross Section Ratio of the Hyperon Λ(1520)

Acceptance for Λ(1520) events using Monte Carlo

- PYTHIA Monte Carlo: Λ(1520) hyperon not simulated
- gmc_dcay Monte Carlo: initial momentum unknown

Initial momentum distributions





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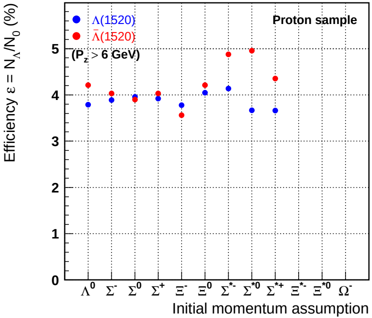
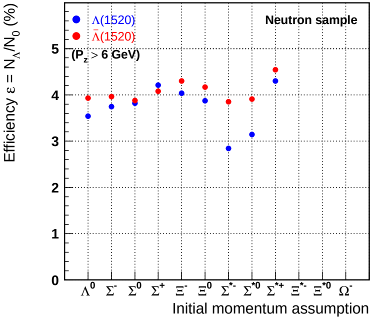
Initial momentum distributions with $P_z > 6\,\mathrm{GeV}$





Cross Section Ratio of the Hyperon $\Lambda(1520)$

Acceptance for $\Lambda(1520)$ events using Monte Carlo

- PYTHIA Monte Carlo: $\Lambda(1520)$ hyperon not simulated
- gmc_dcay Monte Carlo: initial momentum unknown

Initial momentum distributions with $P_z > 6\,\mathrm{GeV}$

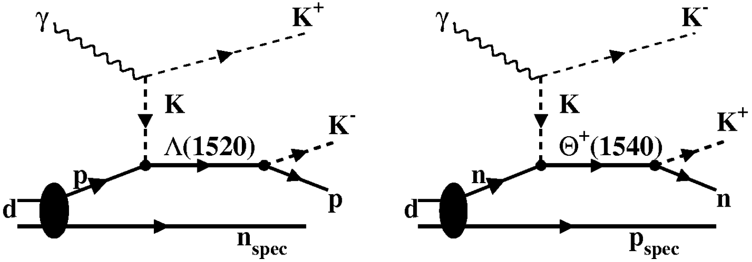
Cross section for $\Lambda(1520)$ and $\overline{\Lambda}(1520)$ production

- $\sigma_{\gamma^* D \to \Lambda(1520) X} = 65.3 \pm 8.8(\mathrm{stat}) \pm 6.9(\mathrm{syst})\,\mathrm{nb}$
- $\sigma_{\gamma^* D \to \bar{\Lambda}(1520) X} = 9.8 \pm 2.6(\mathrm{stat}) \pm 0.9(\mathrm{syst})\,\mathrm{nb}$

Cross section ratio of $\Lambda(1520)$ to $\overline{\Lambda}(1520)$

- $R_{\bar{\Lambda}/\Lambda} = 0.15 \pm 0.05(\mathrm{stat}) \pm 0.02(\mathrm{syst})$

Cross Section Ratio of the Hyperon Λ(1520)



Hyperon Λ(1520)

- Cross section ratio $R_{\bar{\Lambda}/\Lambda} = 0.15 \pm 0.05$
- Assumption that $R_{\bar{\Theta}/\Theta} = R_{\bar{\Lambda}/\Lambda}$

Exotic baryon Θ^+

- 59 ± 16 Θ^+ observed
- 10 ± 4 Θ^- expected
- 3 ± 6 Θ^- observed
- Consistent within one σ