Search for strange pentaquarks in ep collisions at HERA

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- **Motivation**
- **ZEUS K^0p peak near 1530 MeV – new developments**
- **Comparisons with H1 results**
- **Searches for strange pentaquarks (PQ) decaying to Ξπ**

Papers:

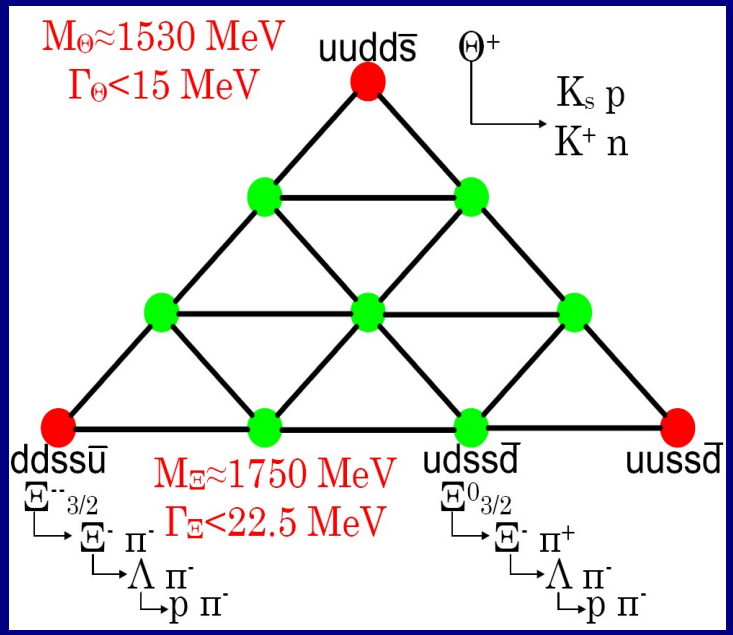
- 644 (H1) Search for a Narrow Baryonic Resonance Decaying to K^0p
- 363 (ZEUS) Search for Pentaquarks Decaying to Ξπ in Deep Inelastic Scattering at HERA
- 392 (ZEUS) Cross section measurements of Θ^+ candidates
- 369 (ZEUS) Production properties of states decaying to strange particles in ep collisions at HERA

Motivation

- Triggered by recent observations of possible PQ at 1530 MeV (width <15 MeV)
- Many experiments observed peaks in Kn and K^0p channels at ~1530 MeV consistent with PQ predictions -
  - LEPS, DIANA, CLAS, SAPHIR, HERMES, SVD - all are low-energy experiments
- In this study, we attempt to find such states by reconstructing $K^0\,p$ final state in ep colliding experiment

Note: K^0p decay channel is not exotic
Example: Σ states

Thus this measurement has to be complemented with those based on K^+n decay mode



Why $\Theta^+ \rightarrow K^0_s p$ channel?

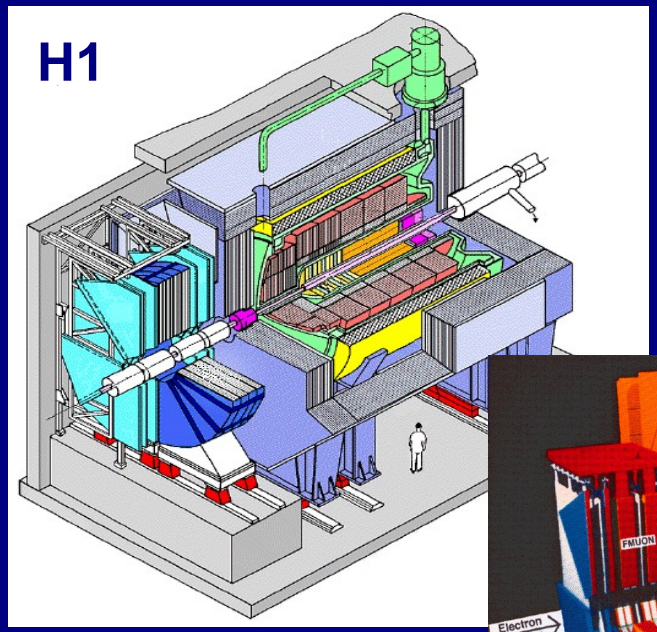
- K^0p decay mode can be well reconstructed (no chance for Kn)
- No K^0p resonance near 1530 MeV in e^+e^- (LEP, BaBar, Belle, BES).
  → PQ suppressed in quark fragmentation?
- No corresponding peak in Λπ channel. Not a new Σ?

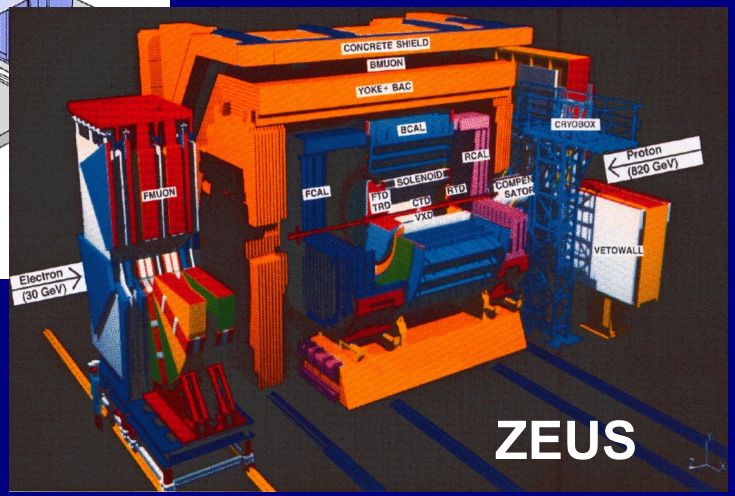
favor PQ explanation of $K^0_s p$ signal?

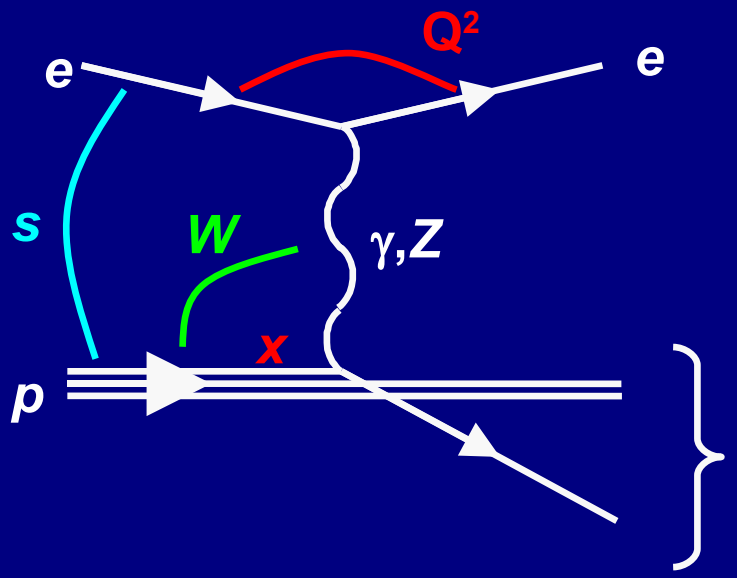
Event kinematics

e^- / e^+ → ← p

27.6 GeV 820/920 GeV







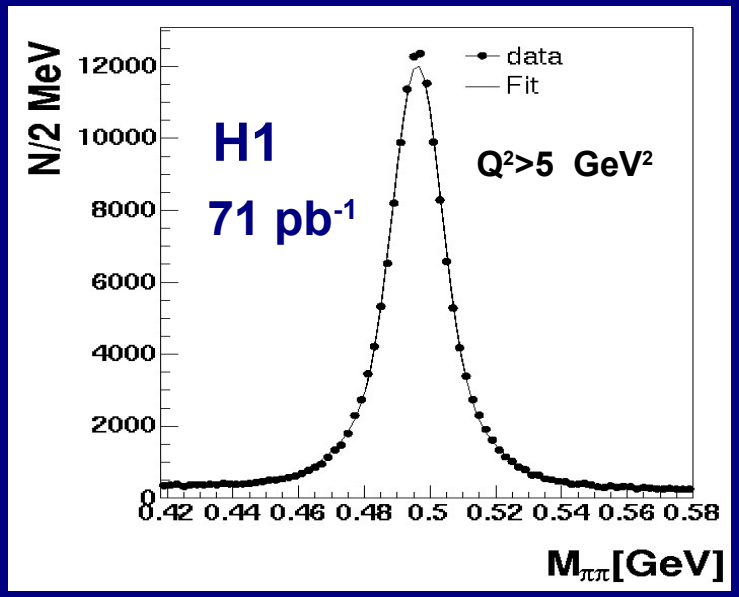
- ***s*:** *ep* c.m. energy

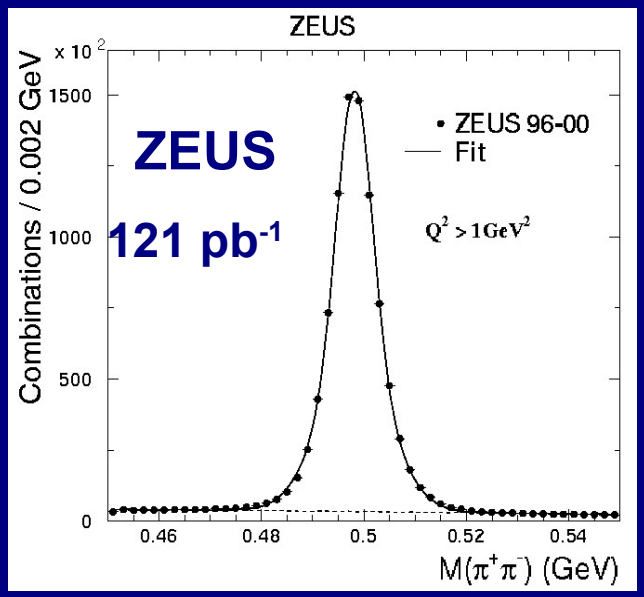
  $\sqrt{s} = 300 - 318$ GeV

- $Q^2 = -q^2$: 4-momentum transfer squared
- ***x*:** fraction of proton momentum carried by quark
- ***y*:** inelasticity parameter
- ***W*:** γ*-*p* c.m. energy

DIS events are triggered by observing scattered electron in calorimeters
→ unbiased hadronic final-state data sample

Reconstruction of $K^0_s p$ in DIS





K^0_s reconstruction:

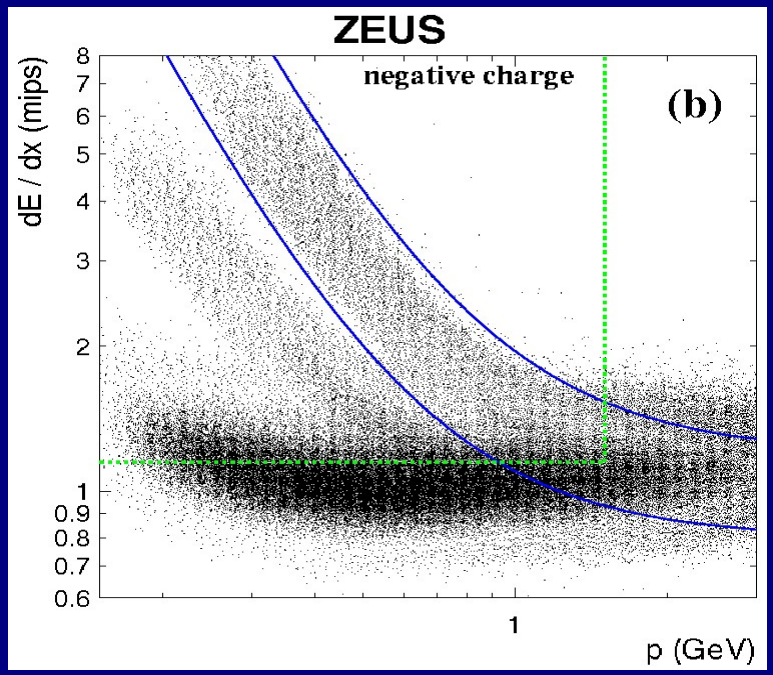
- $K^0_s \rightarrow \pi^+\pi^-$ using secondary-vertex
- $p_T(K^0_s)>0.3$ GeV
- $\eta(K^0_s)|<1.5$
- Dalitz e^+e^- pairs and Λ's removed

Proton reconstruction:

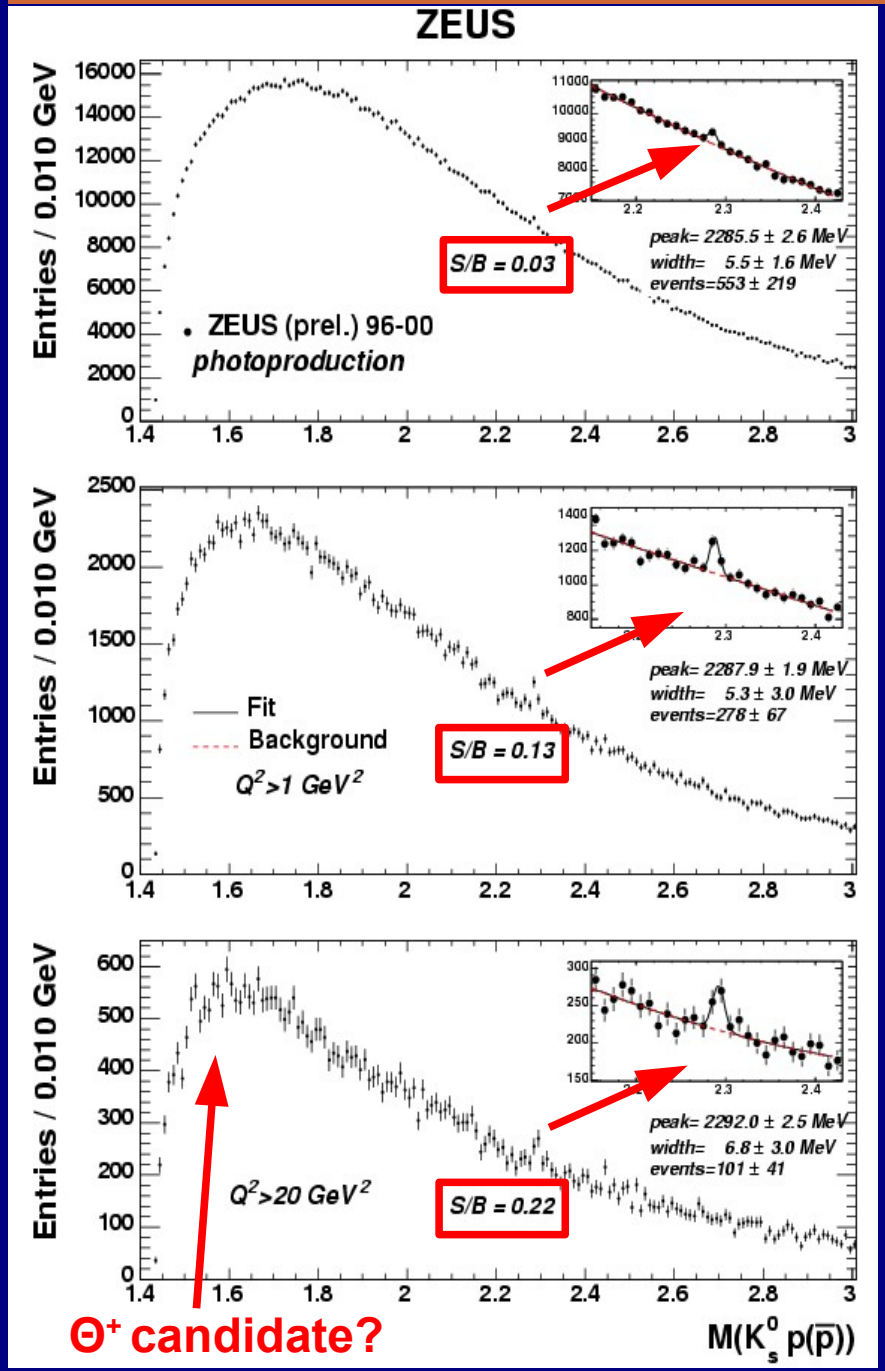
- tracks originate from primary vertex
- dE/dx identification:
  - ZEUS: "region method"
    - dE/dx>1.15, p<1.5 GeV
  - H1: "likelihood" method

K^0_s p mass resolution:

H1: 5 MeV ZEUS: 2.4 MeV



$K^0_s p$ invariant mass



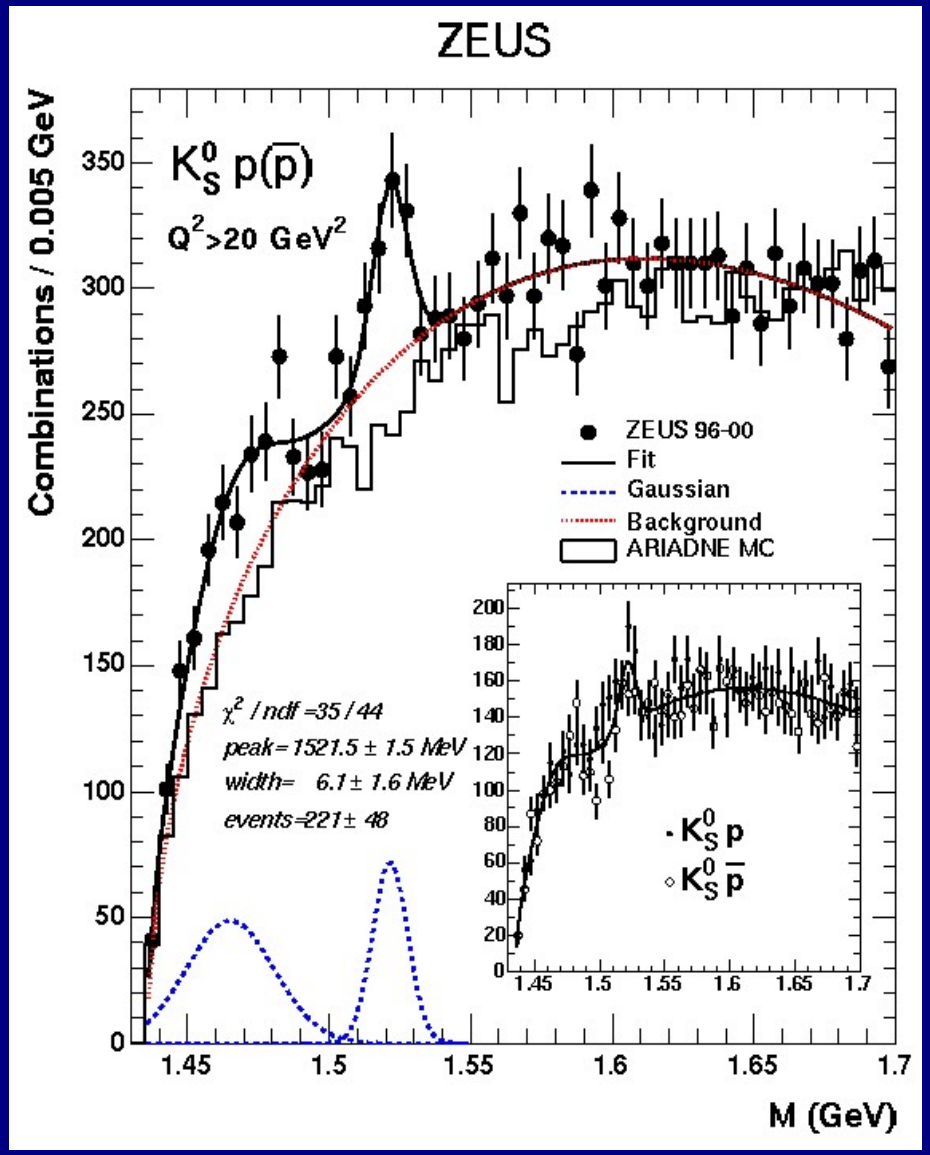
- Peak near 1522 MeV for DIS at Q^2>20 GeV^2
- $\Lambda_c^+ \rightarrow K^0_s p$ peak near 2285 MeV for photoproduction and DIS:
  - signal-over-background (S/B) ratio is very small for photoproduction
  - such S/B is expected for c-quark fragmentation driven by boson-gluon-fusion process $g \rightarrow c\bar{c}$

Note: ZEUS triggers photoproduction events using jets with E_T>6-8 GeV:

→ ZEUS photoproduction events are enriched with K^0_s and (anti)protons from fragmentation of light quarks

Absence of Θ^+ peak in photoproduction data could be due to small S/B ratio (significant combinatorial background and particle multiplicity)

$K^0_s p$ peak near 1522 MeV in details

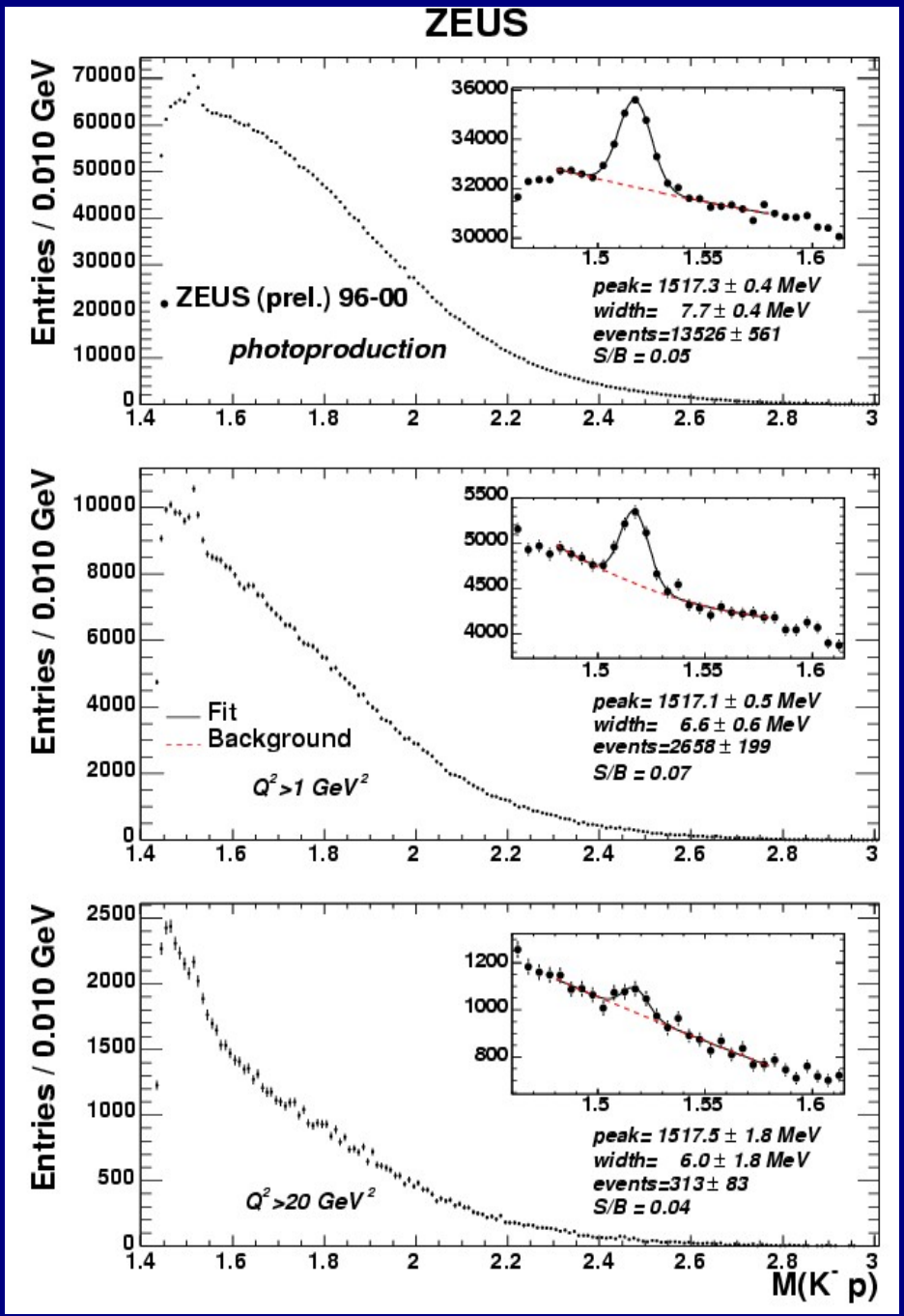


Fit: Double-Gaussian + threshold background function

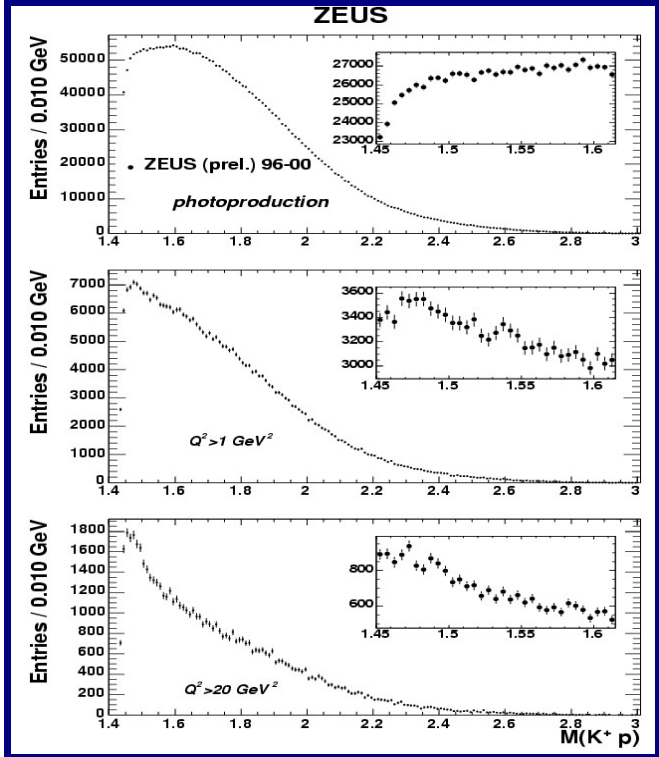
- 4.6σ signal near 1522 MeV
- Narrow width Γ=8±4 MeV
- For low proton momenta p<1.5 GeV
- Not in MC simulation
- Exits in DIS for Q^2>20-50 GeV^2
- Double-peak restructure?
  - evidence for PDG Σ(1480) bump (*)?

see more details in
ZEUS Coll. PL B591 (2004) 7

$\Lambda(1520) \rightarrow K^- p$



- Significant number of Λ(1520) (~16.5K)
- S/B ratio is the same for photoproduction and DIS
- Indicates light-quark fragmentation origin (unlike Λ_c^+)
  - Rate of Λ(1520) ~ average charge multiplicity.



K^+p spectrum does not have statistically significant peak near 1530 MeV

no Θ^{++} signal

Looking at production properties

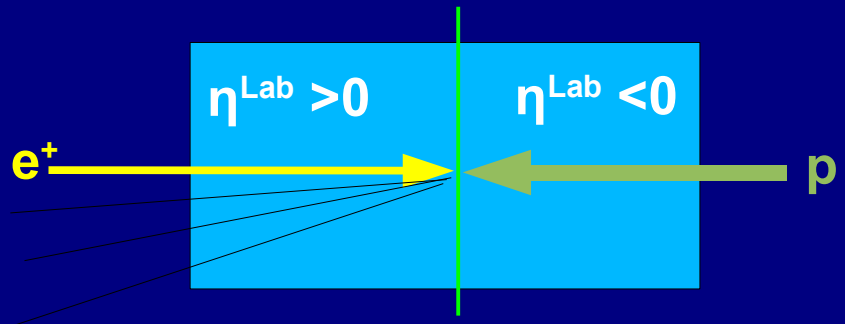
Non-observations of Θ^+ in e^+e^- may indicate that ZEUS Θ^+ signal could be related to the proton fragmentation

If this is the case (S.C. hep-ph/0502098):

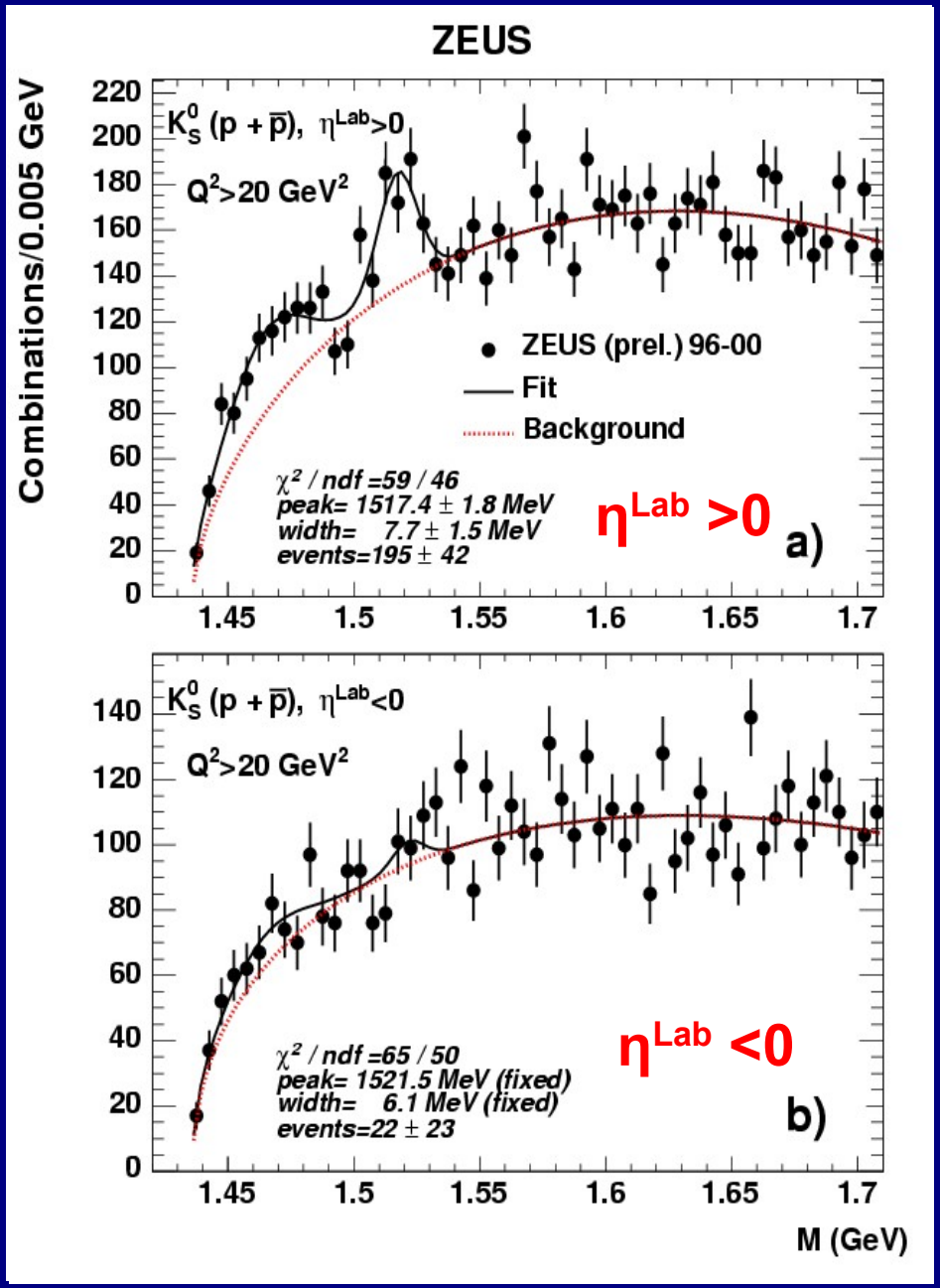
1) high-Q^2 events are more favorable
2) Θ^+ mainly in the forward region ($\eta^{Lab} > 0$)
3) Θ^+ rate should be larger than for $\overline{\Theta^+}$

Check this by reconstructing the $K^0_s p$ signal:

- in forward and rear pseudorapidity regions
- for proton and antiproton combinations

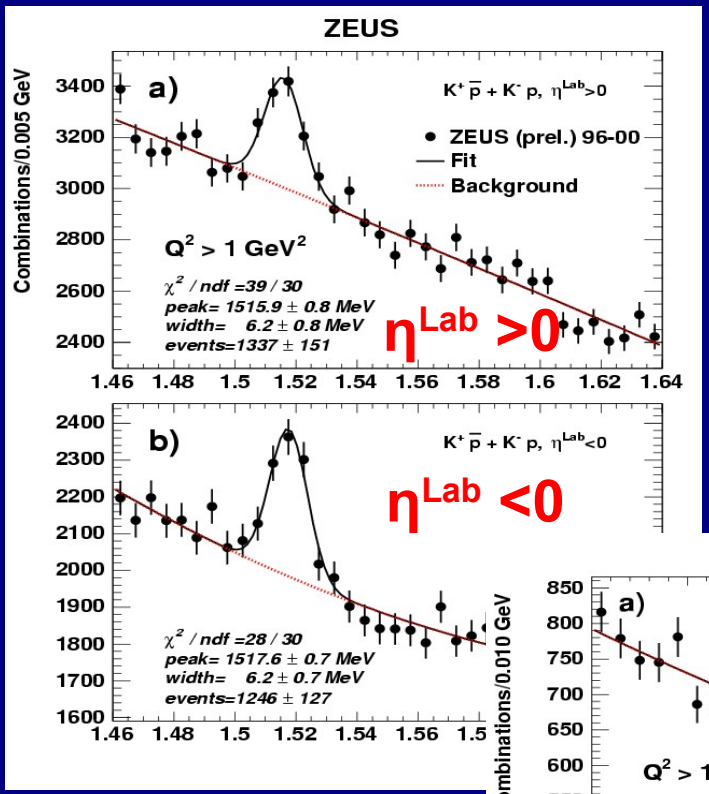


peak is predominantly for $\eta^{Lab} > 0$

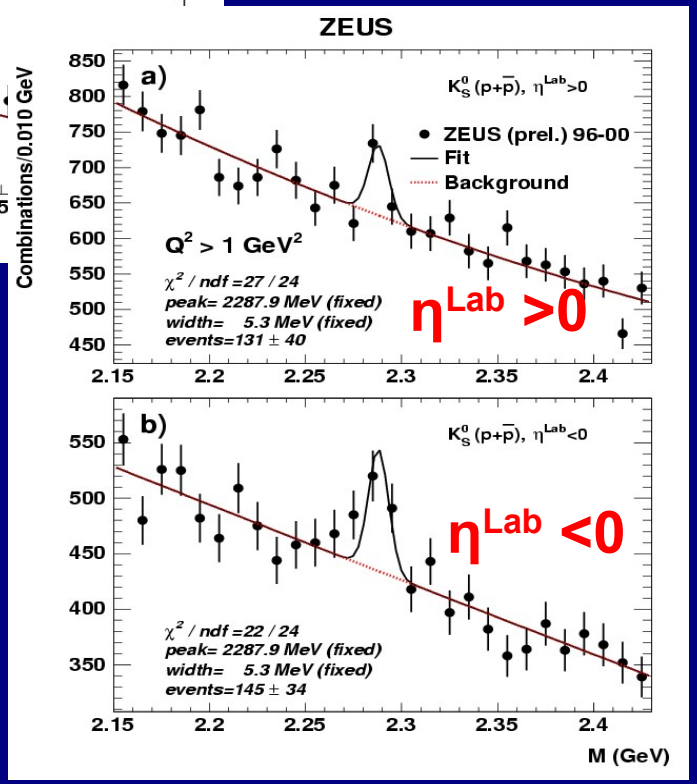


Looking at production properties

- What about known states?
  - Λ(1520) - from u,d,s-quark fragmentation
  - Λ_c^+ - from c-quark fragmentation after the hard process $g \to c\bar{c}$
- Good reference for comparison with Θ^+ candidate



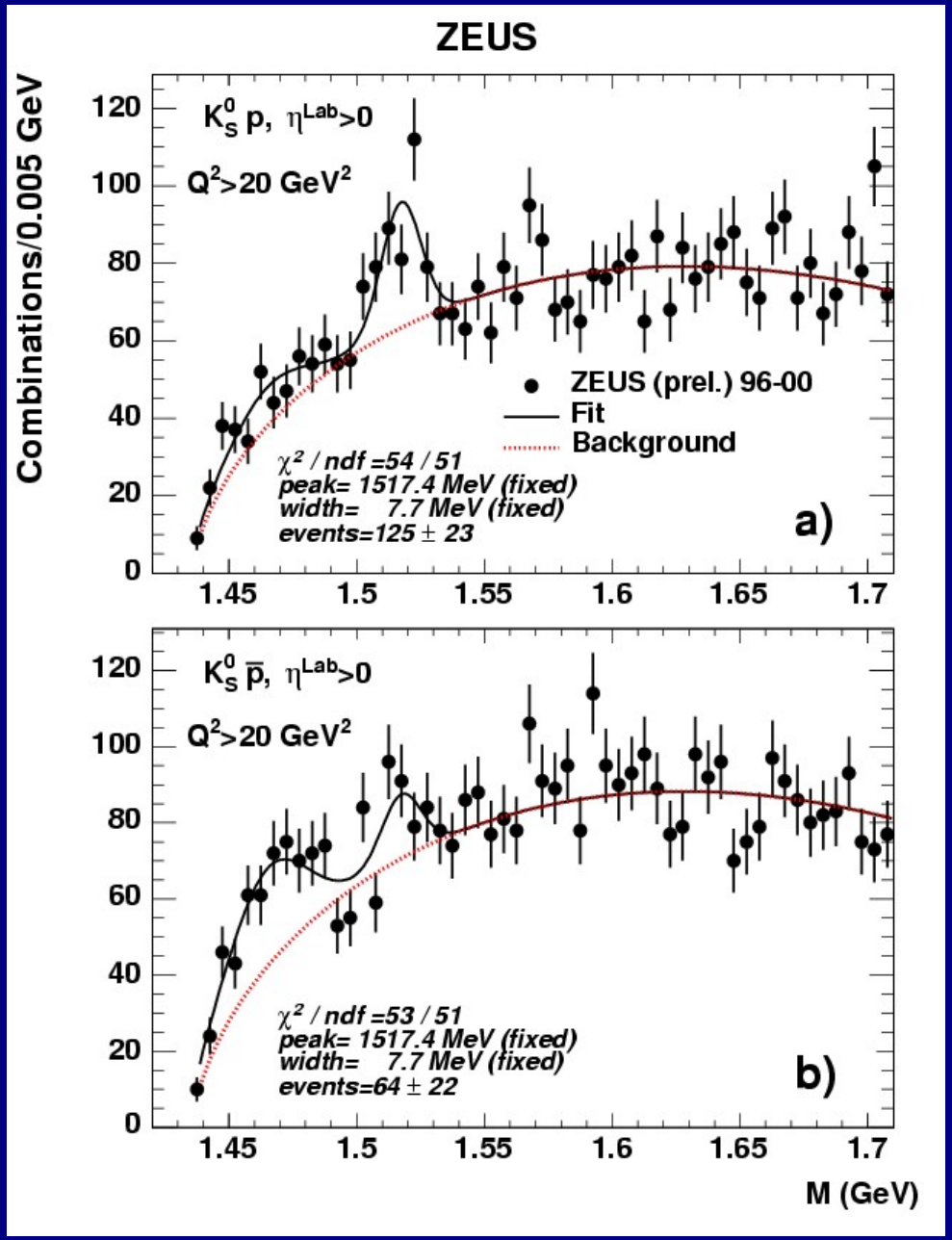
same numbers of baryons for $\eta^{Lab}>0$ and $\eta^{Lab}<0$



unlike Θ^+ candidate, Λ(1520) and Λ_c^+ are democratically produced in $\eta^{Lab}>0$ and $\eta^{Lab}<0$ pseudorapidity regions

Looking at production properties

- Split the signal to K^0_S-proton and K^0_S-antiproton combinations for $\eta^{Lab} > 0$
- Double-Gaussian fit gives 5.4σ statistical significance for the proton channel
- Background is simpler than for the sum of the two distributions



Notes on the fitting procedure:

- peak and width are fixed to the sum of the two distributions

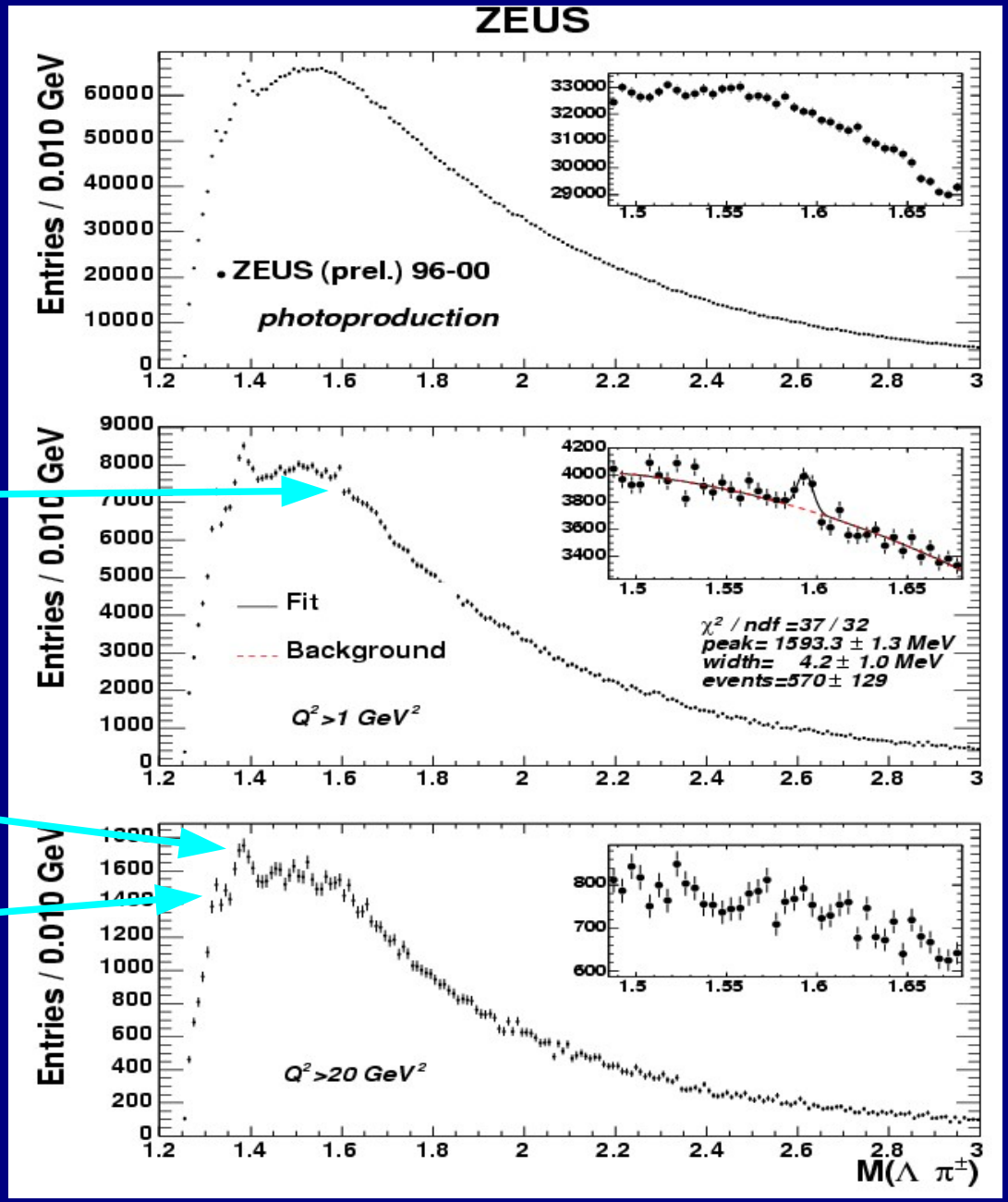
- fit using continuous background is also fine

Looking at production properties

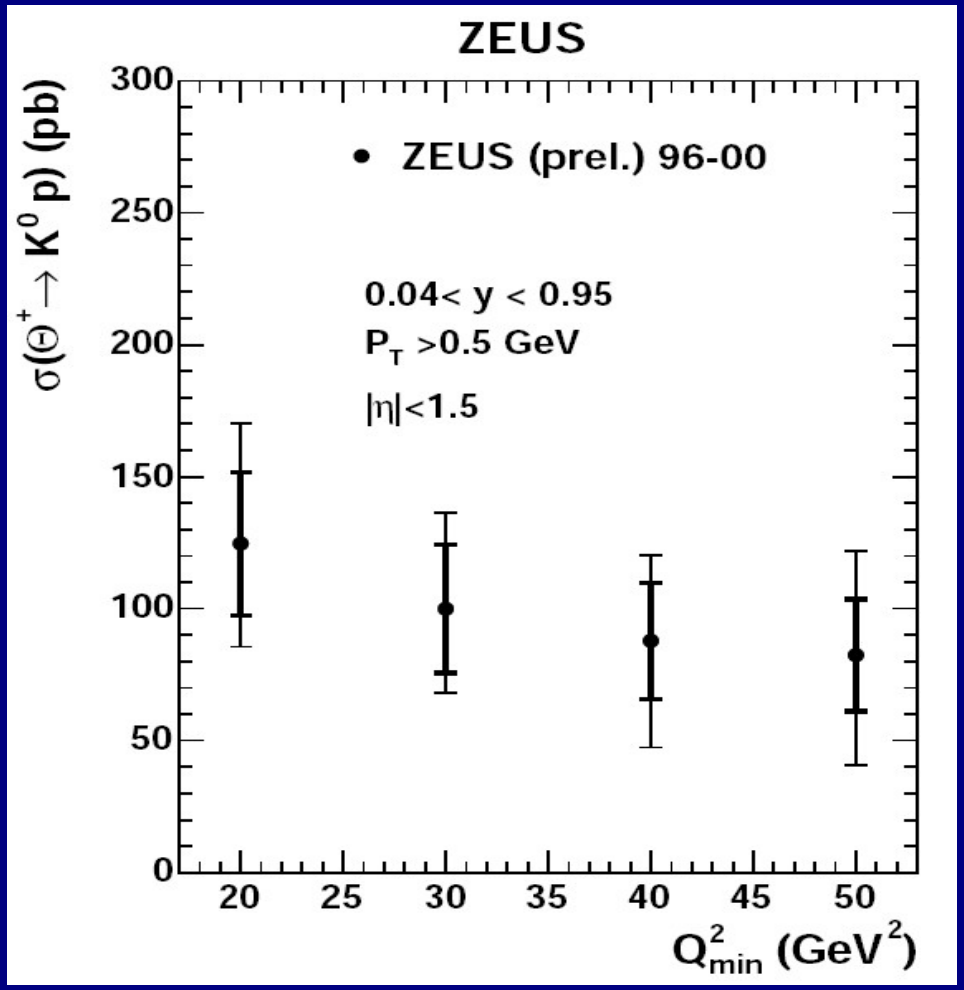
- if ZEUS Θ^+ candidate is a new Σ state, it can decay to $\Lambda\pi$
- No signal near 1530 MeV
- Peak near 1600 MeV consistent with a PDG Σ state (**)
  - statistical significance is low

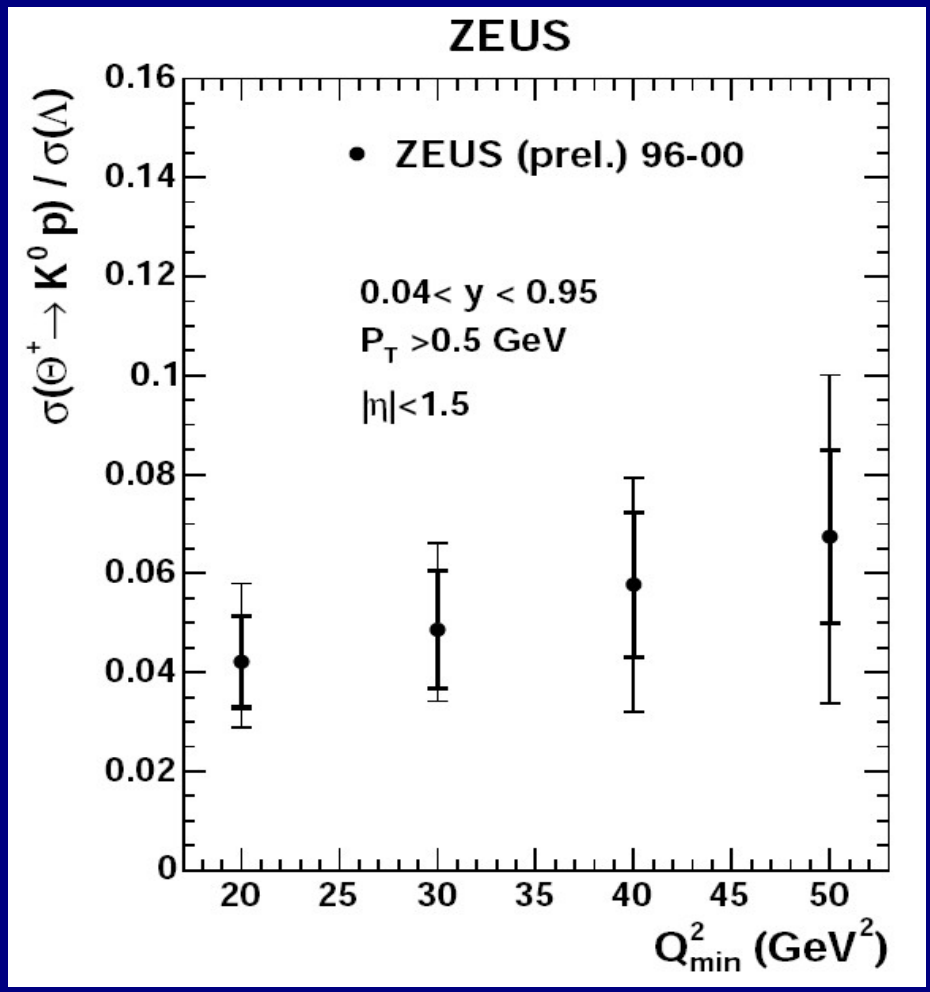
$\Sigma(1385)$

Ξ^-



Cross-section measurement

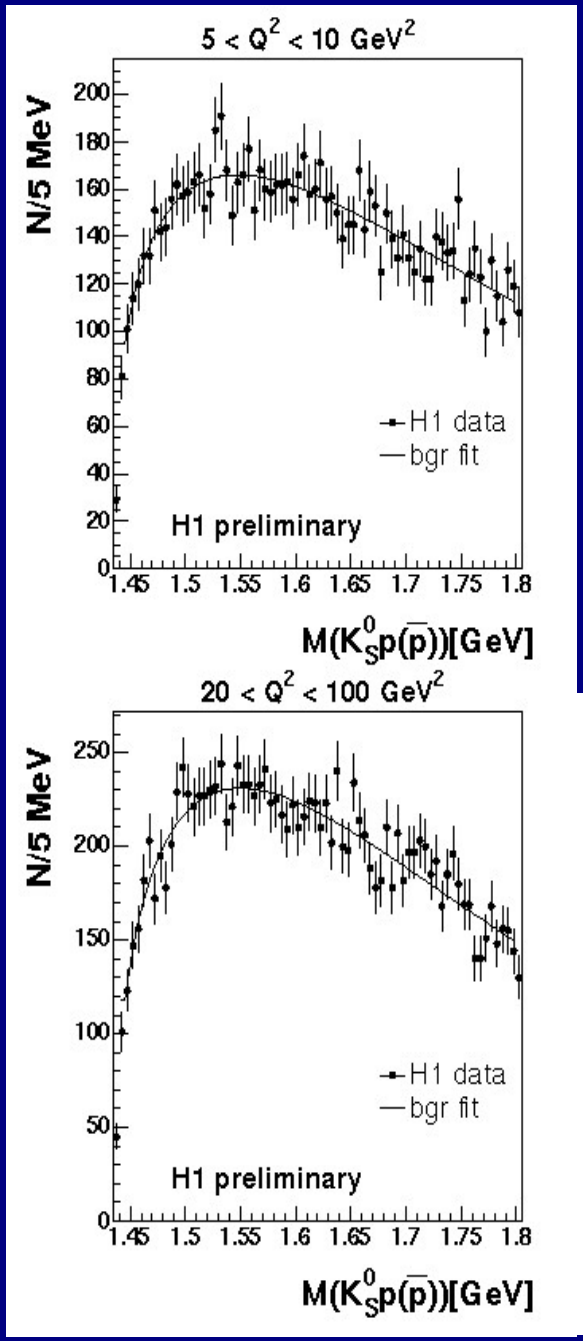


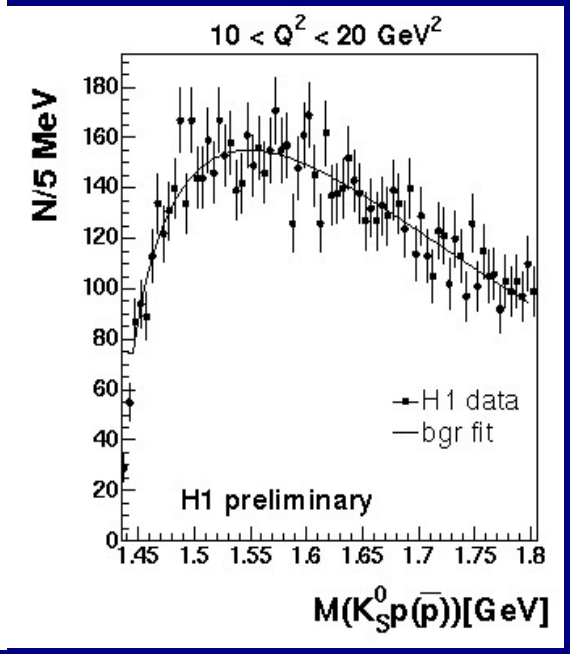


- assume Σ kinematics for Θ⁺ (as for quark fragmentation)
- estimate acceptance using RAPGAP model (for DIS process)

Q^2>20 GeV^2 $\sigma(e^{\pm}p \to e^{\pm}\,\Theta^{+}\,X \to e^{\pm}\,K^{0}p\,X) = 125 \pm 27(\mathrm{stat.})^{+36}_{-28}(\mathrm{syst.})\ \mathrm{pb}.$

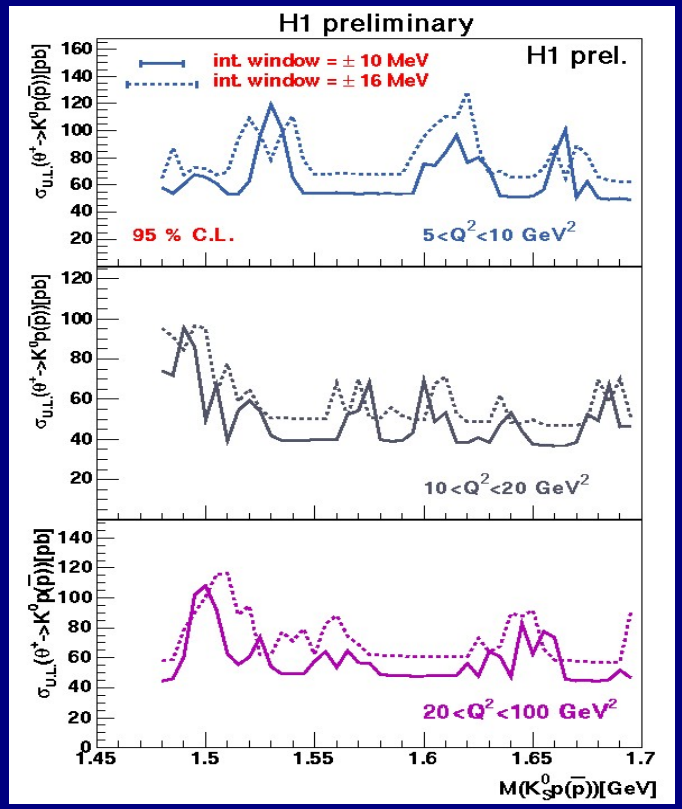
H1 results





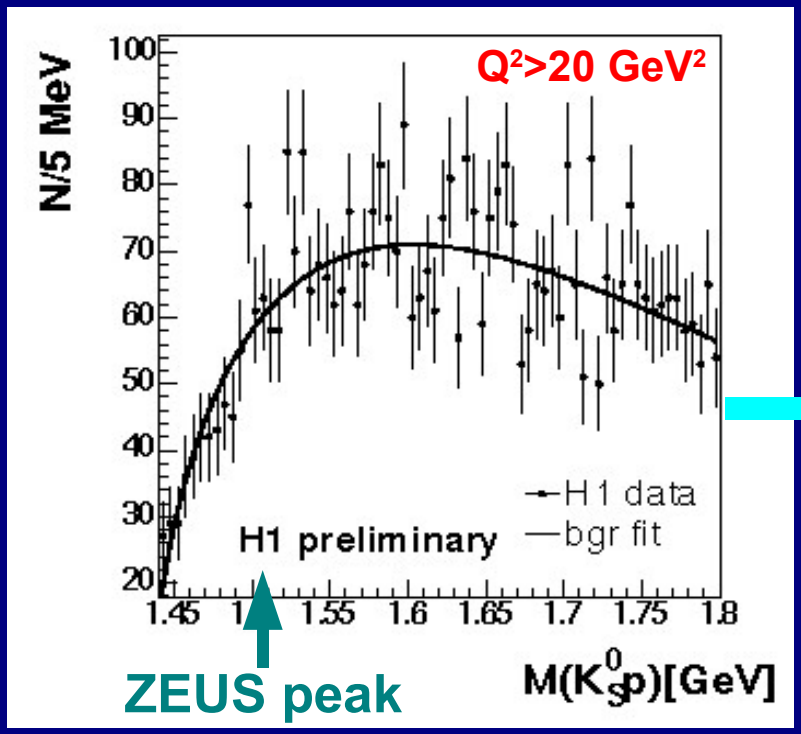
- H1: DIS Q^2>5 GeV^2 0.1<y<0.6 (ZEUS: 0.01<y<0.95)
- Protons are selected using the dE/dx likelihood method without explicit cut on the proton momenta (allows to use protons with p>1.5 GeV)
- Similar K^0_S reconstruction as for ZEUS

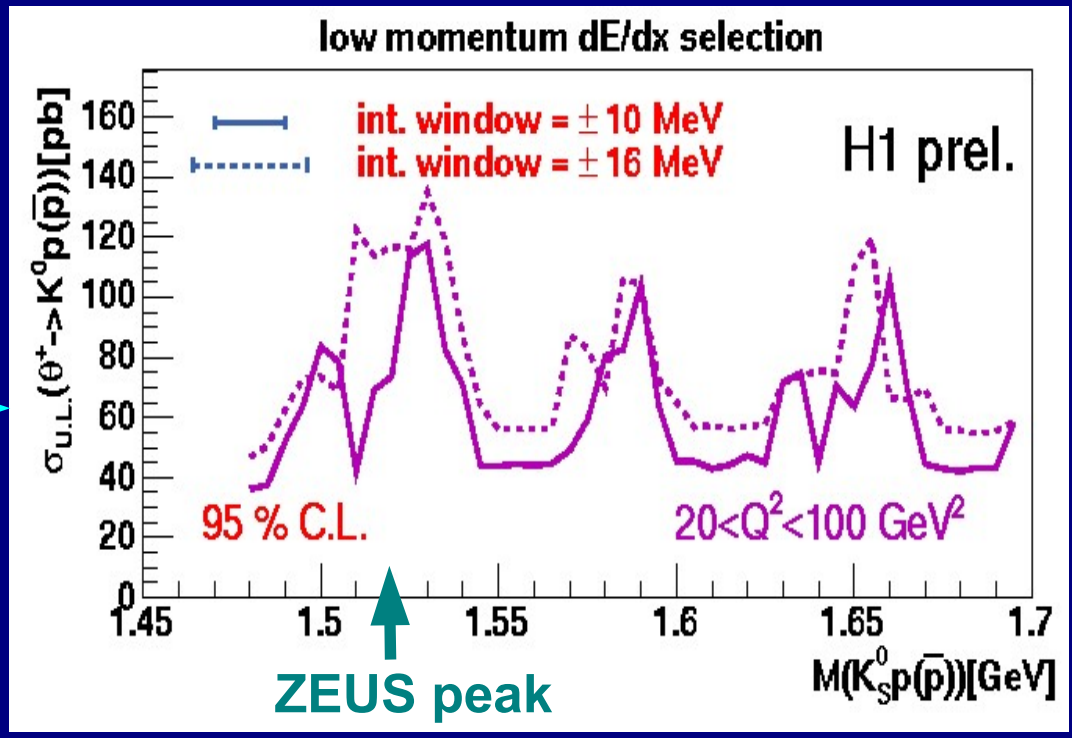
no PQ signal



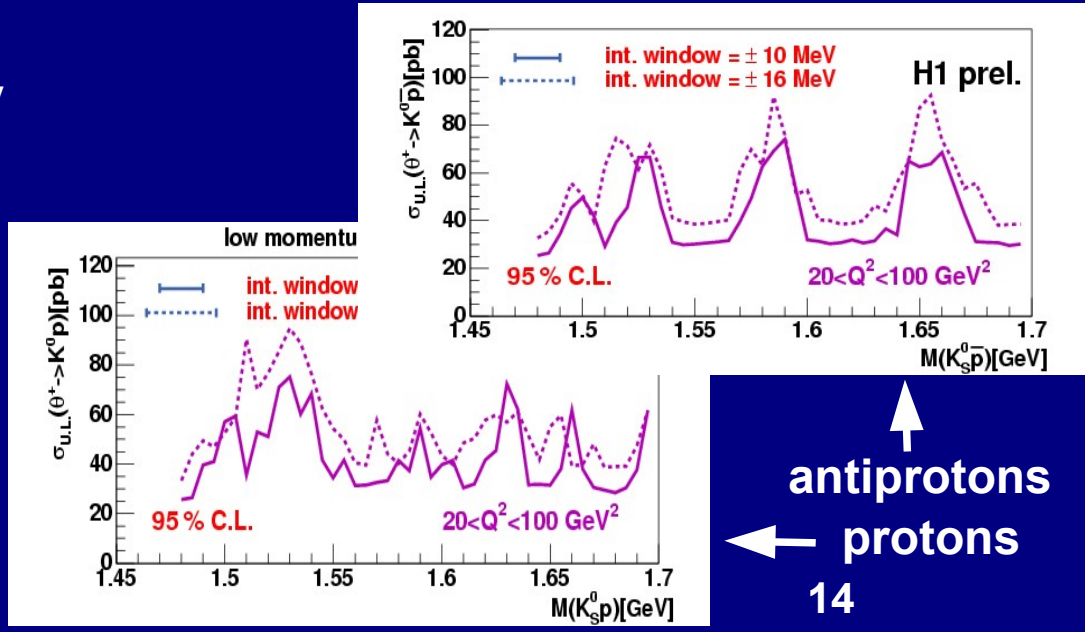
upper limits on σ(Θ⁺) assuming quark fragmentation of Θ⁺

H1 results





- Use low-momentum protons as in ZEUS case (p<1.5 GeV) – a better proton purity
- Still no ZEUS signal
- Statistics is lower than in ZEUS case
- Upper limit does not contradict to the ZEUS observation
  - σ(Θ⁺)~120 pb for Q²>20 GeV²
- Need more data

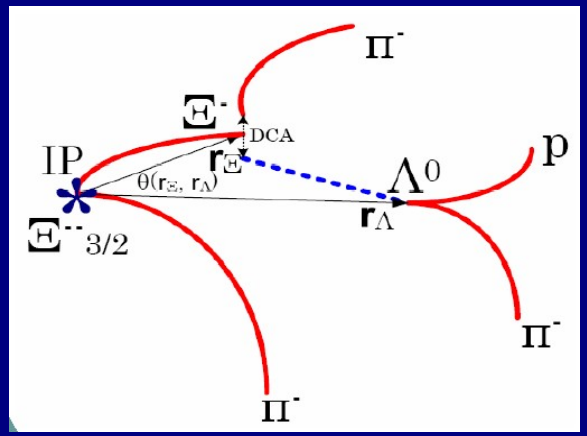


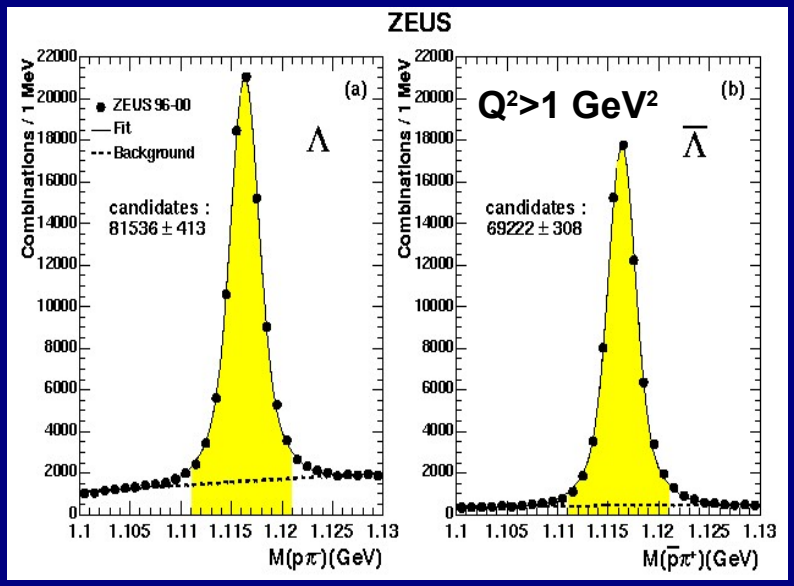
Heavy strange PQ in DIS

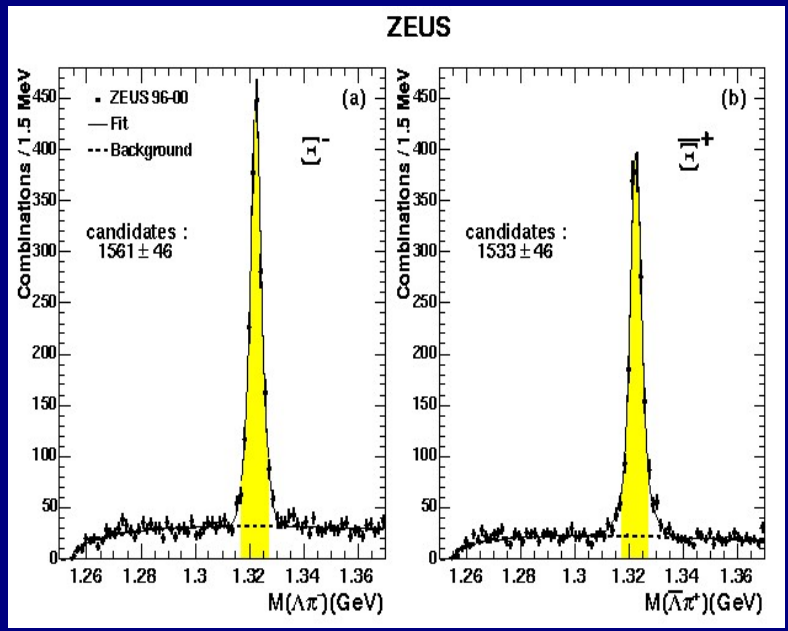
- Observed by NA49 Collab.
- Consistent with $\Xi^{--}_{3/2}$ (dsdsū)
- narrow width, mass ~1862 MeV

Reconstruction:

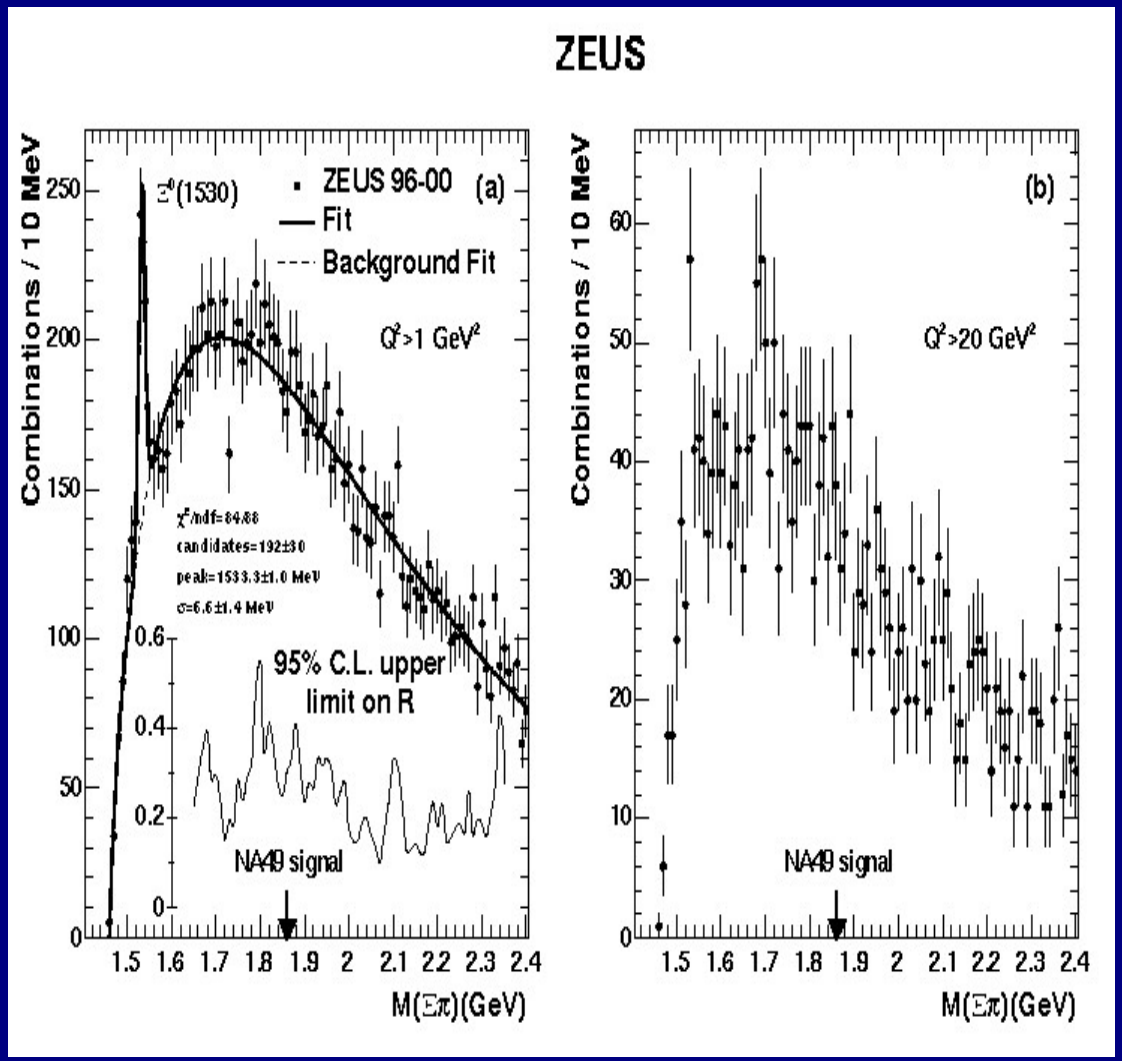
- Λ from secondary vertex
- combine with tracks which have small DCA from Λ
- combine Ξ candidates with pions from primary vertex
  - ~3100 Ξ candidates

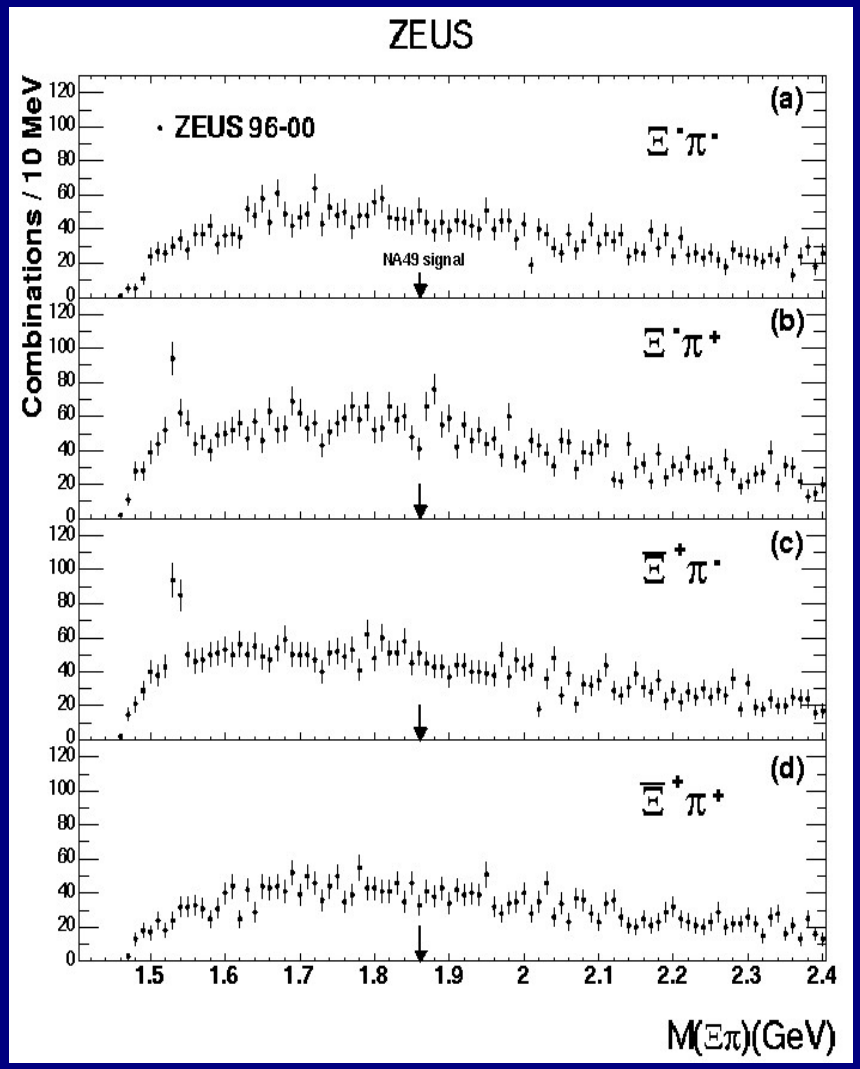






Heavy strange PQ



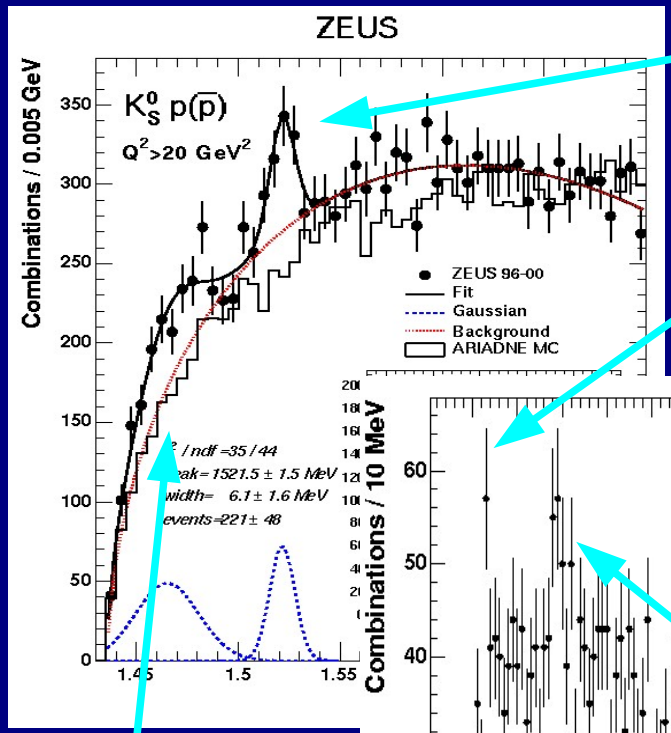


- Competitive number of $\Xi^0(1530)$ candidates (192±30)
- No signal near 1862 MeV
- Upper limit on the ratio $R = \Xi^{--(0)}_{3/2} / \Xi^0(1530) \sim 0.2\text{-}0.5$

Summary

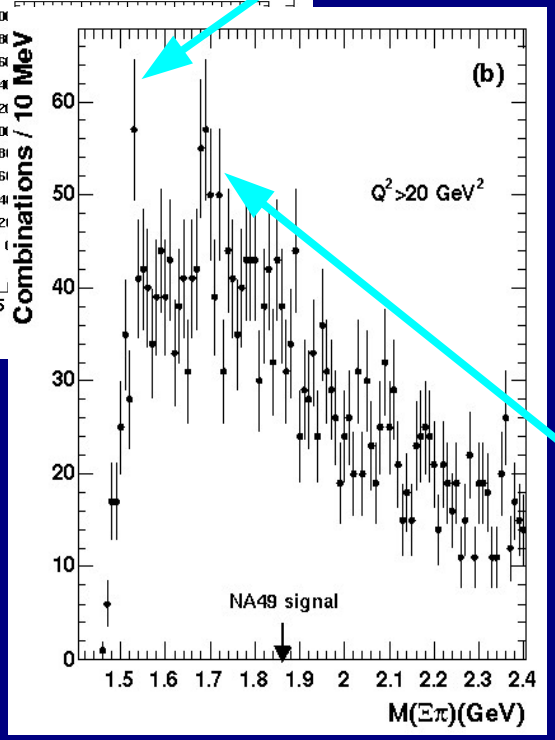
- ZEUS Θ^+ candidate is predominantly produced in the forward region, $\eta^{Lab} > 0$ (towards incoming proton)
  - neither $\Lambda(1520)$ (from light-quark fragmentation) nor Λ_c^+ (from c-quark fragmentation after $g \rightarrow c\bar{c}$) has such property
- Absence of the Θ^+ signal in photoproduction data dominated by jets with $E_T > 6$-8 GeV. Small S/B ratio due to proton fragmentation origin of Θ^+ ?
  - $\Lambda(1520)$ cannot be used as a "reference" state for other experiments
  - may explain non-observations of Θ^+ in e^+e^- and TEVATRON
- H1 did not find the Θ^+ peak. However H1 upper limit does not contradict to the ZEUS observation
- No NA49 PQ signal... No Θ^{++} signal...
- HERAII data is necessary for further studies

A few other unexpected peaks..

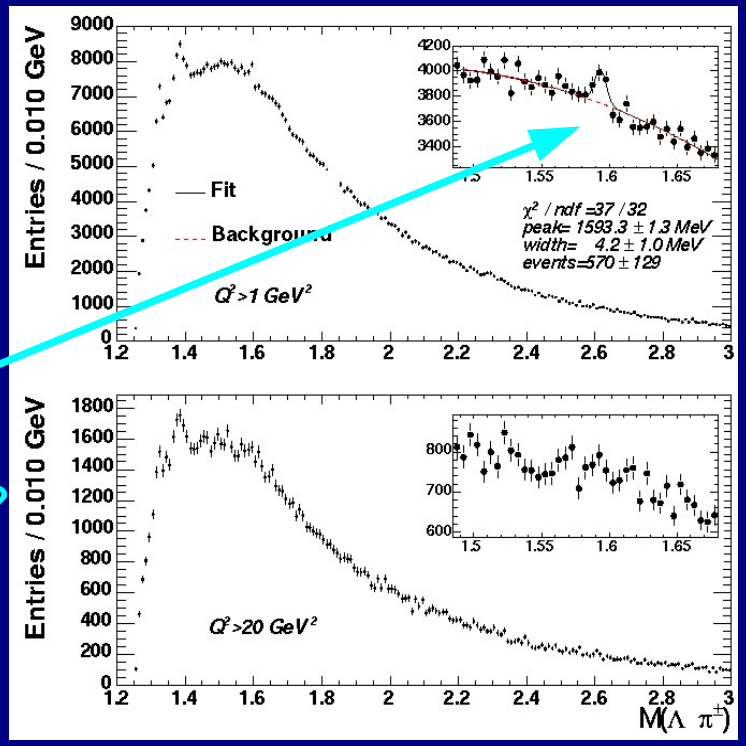


PQ candidate

Ξ(1530)



non well-established PDG Σ(1580) or Σ(1620) states?



non well-established PDG Ξ(1690) state?

double-peak structure?
Evidence for PDG Σ(1480) bump (*)?

- Stat. significance below 5σ in all cases
- No signals in ZEUS photoproduction data
- See more details in ZEUS contributed papers

Summary of experiments

LEPS	$\gamma n \to K^-(K^+n)$	1540 ± 10	< 25	4.6	$K^+n\ (S=+1)$
CLAS	$\gamma d \to pK^-(K^+n)$	1542 ± 5	< 21	5.2	$K^+n\ (S=+1)$
CLAS	$\gamma p \to \pi^+K^-(K^+n)$	1555 ± 10	< 26	7.8	$K^+n\ (S=+1)$
SAPHIR	$\gamma p \to K^0_S\ (K^+n)$	1540 ± 6	< 25	4.8	$K^+n\ (S=+1)$
DIANA	$K^+Xe \to Xe'(K^0_S\ p)$	1539 ± 2	< 9	4.4	$K^0_Sp\ (\lvert S\rvert=1)$
ITEP	$\nu A^* \to X(K^0_S\ p)$	1533 ± 5	< 20	6.7	$K^0_Sp\ (\lvert S\rvert=1)$
SVD	$pA^{**} \to X(K^0_S\ p)$	1526 ± 5	< 24	5.6	$K^0_Sp\ (\lvert S\rvert=1)$
HERMES	$e^+d \to X(K^0_S\ p)$	1526 ± 3	13 ± 9	~ 5	$K^0_Sp\ (\lvert S\rvert=1)$
COSY-TOF	$pp \to \Sigma^+(K^0_S\ p)$	1530 ± 5	< 18	4-6	$K^0_Sp\ (\lvert S\rvert=1)$
YEREVAN	$pC_3H_8 \to Xp(K^0_S\ p)$	1545 ± 12	< 34	5.5	$K^0_Sp\ (\lvert S\rvert=1)$
ZEUS	$e^\pm p \to e^\pm X(K^0_S\ p(\bar{p}))$	1522 ± 2	8 ± 4	~ 5	$K^0_Sp\ (\lvert S\rvert=1)$

: positive results

Negative results:

BES	$e^+e^- \to J/\Psi(\Psi(2S)) \to K^0_Sp\bar{K}^-\bar{n}\ \&\ K^0_S\bar{p}K^+n$	$< 1.1 \times 10^{-5}$ B.R.
Belle	$e^+e^- \to \Psi(2S) \to B^0\bar{B}^0 \to \bar{p}(K^0_S\ p)$	$< 2.3 \times 10^{-7}$ B.R.
BaBar	$e^+e^- \to \Upsilon(4S) \to B\bar{B} \to X(K^0_S\ p)$	$< 1.0 \times 10^{-4}$ B.R.
ALEPH	$e^+e^- \to Z \to (K^0_S\ p)$	$< 6.2 \times 10^{-4}$ B.R.
CDF	$p\bar{p} \to X(K^0_S\ p)$	$< 0.03 \times \Lambda^*$
E871	$pCu \to X(K^0_S\ p)$	$< 2.5 \times 10^{-3}$ B.R.
HERA-B	$pA^* \to X(K^0_S\ p)$	$< 0.02 \times \Lambda^*$
PHENIX	$AuAu \to X(K^-\bar{n})$	(not given)
CLAS	$\gamma p \to K^0_S(K^+n)$	(not given)
H1	$e^\pm p \to e^\pm X(K^0_S\ p(\bar{p}))$	< 120 pb**

suppressed? No net baryon number in initial state?

consistent with ZEUS PHP data

isospin forbidden? M.Karliner, H.Lipkin hep-ph/0506084

limit is consistent with ZEUS observation