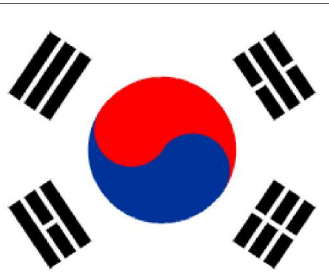
BARYONS07
Seoul, South Korea
11. – 15. June 2007



Exotic Baryons production in *ep* collisions at HERA

Marc Del Degan

ETH Institute for Particle Physics

Overview

- Introduction: Pentaquarks (PQ)
- Experimental search at HERA for the:
  - Θ^{+}
  - $\Xi^{--/0}$
  - Θ^{0}_{c}
- Conclusion

Pentaquarks: first observation

- In 2003 observation of a narrow resonance with flavour exotic quantum numbers (B = +1, S = +1) by the LEPS Collaboration:
- Reaction: $\gamma\, n \rightarrow K^- K^+ n$
- minimal quark content: $uudu\bar{d}s \rightarrow \Theta^+(1540)$
- Successively confirmed by 10 experiments in various reactions:

Experiment	Reaction	Energy (GeV)	Mass (MeV/c^2)	significance
LEPS	$\gamma\, ^{12}C \rightarrow K^- X$	$E_\gamma \approx 2$	1540 ± 10	4.6σ
DIANA	$K^+ Xe \rightarrow p K^0_s X$	$E_{K^+} < 0.5$	1539 ± 2	4σ
CLAS(d)	$\gamma d \rightarrow p K^- K^+ n$	$E_\gamma < 3.8$	1542 ± 5	5.2
SAPHIR	$\gamma p \rightarrow K^0_s K^+ n$	$E_\gamma < 2.65$	$1540 \pm 4 \pm 2$	4.4σ
CLAS(p)	$\gamma p \rightarrow \pi^+ K^- K^+ n$	$E_\gamma = 4.8 - 5.5$	1555 ± 10	7.8σ
νBC	$\nu A \rightarrow p K^0_s X$	range	1533 ± 5	6.7σ
ZEUS	$ep \rightarrow ep K^0_s X$	$\sqrt{s} = 320$	1522 ± 1.5	4.6σ
HERMES	$ed \rightarrow p K^0_s X$	$E_e = 27.6$	$1528 \pm 2.6 \pm 2.1$	5.2σ
COSY	$pp \rightarrow \Sigma^+ p K^0_s$	$P_p = 3$	1530 ± 5	3.7σ
SVD	$pA \rightarrow p K^0_s X$	$E_p = 70$	$1526 \pm 3 \pm 3$	5.6σ
NA49	$pp \rightarrow \Xi^- \pi^- X$	$E_p = 158$	1862 ± 2	4σ
H1	$ep \rightarrow D^{*-} p D^{*+} \bar{p} X$	$\sqrt{s} = 320$	$3099 \pm 3 \pm 5$	5.4σ

Adapted from V.D.Burkert, hep-ph/0510309

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but also several negative results

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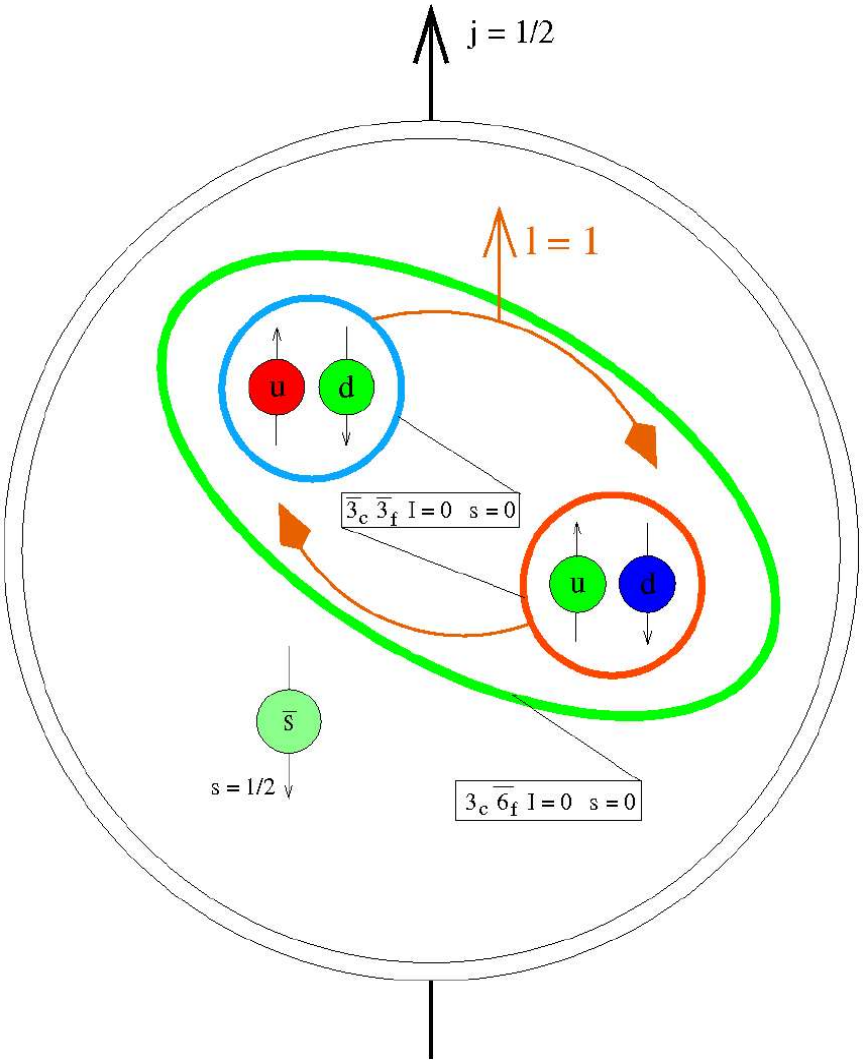
Group	Reaction
BES	$e^+e^- \rightarrow J/\Psi \rightarrow \bar{\Theta}\Theta$
BaBar	$e^+e^- \rightarrow \Upsilon(4S) \rightarrow pK^0 X$
Belle	$e^+e^- \rightarrow B^0\bar{B}^0 \rightarrow p\bar{p}K^0 X$
LEP	$e^+e^- \rightarrow Z \rightarrow pK^0 X$
HERA-B	$pA \rightarrow K^0 pX$
SPHINX	$pC \rightarrow K^0\Theta^+ X$
HyperCP	$pCu \rightarrow K^0 pX$
CDF	$p\bar{p} \rightarrow K^0 pX$
FOCUS	$\gamma BeO \rightarrow K^0 pX$
Belle	$\pi + Si \rightarrow K^0 pX$
PHENIX	$Au + Au \rightarrow K^- \bar{n} X$

K. Hicks, hep-ph/0504027

Pentaquarks: models

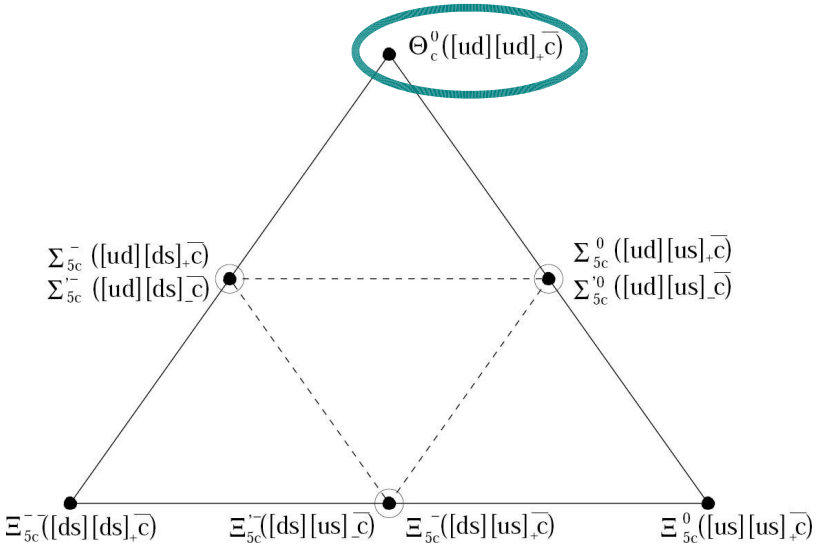
- Hypothetical 5 quark state: $4q\,\overline{q}$
- Various theoretical models:
  - Jaffe Wilczek diquark model:
    $PQ = \overline{q}\,(qq)\,(qq)$
  - Karliner Lipkin triquark model:
    $PQ = (qq)(qq\overline{q})$
    - Both models predicts
      $8_f \oplus \overline{10}_f$ for the light PQ
    - and for the heavy PQ: $\overline{6}_f \oplus 3_f$
  - Chiral soliton model (Diakonov *et al.*)
  - Lattice QCD, …

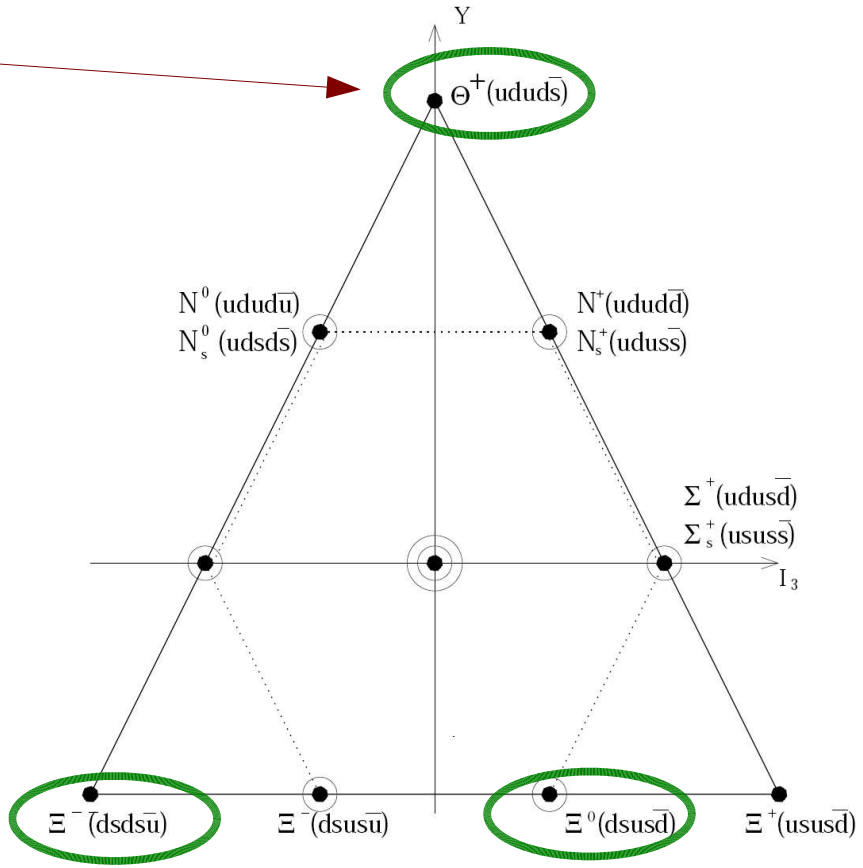


The $\Theta^+(1540)$ in the JW model

Representation of the PQ's

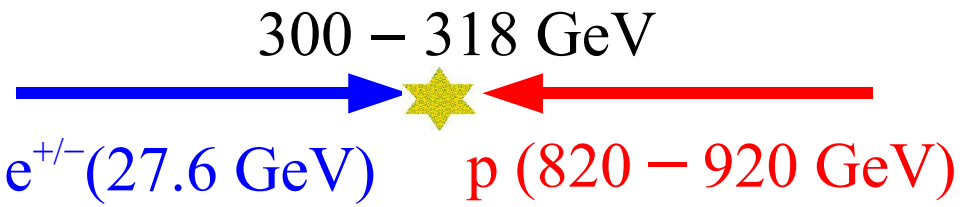
- If the $\Theta^+(1540)$ really exists → expect several other states



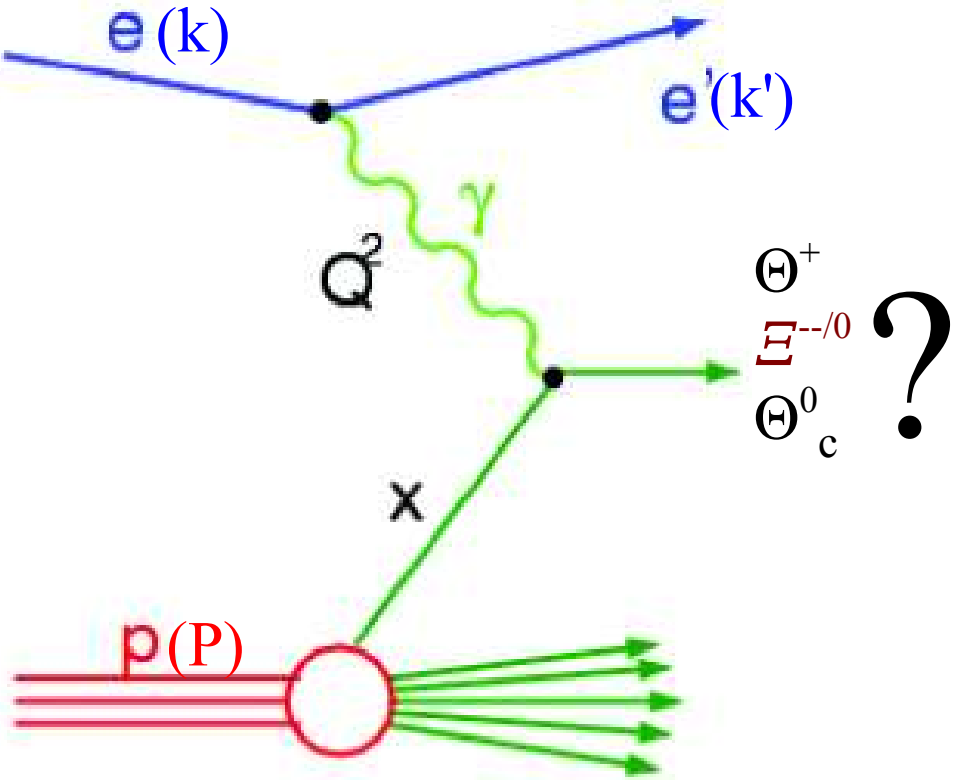


- This talk:
  Θ^+ and $\Xi^{--/0}$ at HERA
  Θ^0_c at HERA

HERA: ZEUS and H1



Main process at HERA

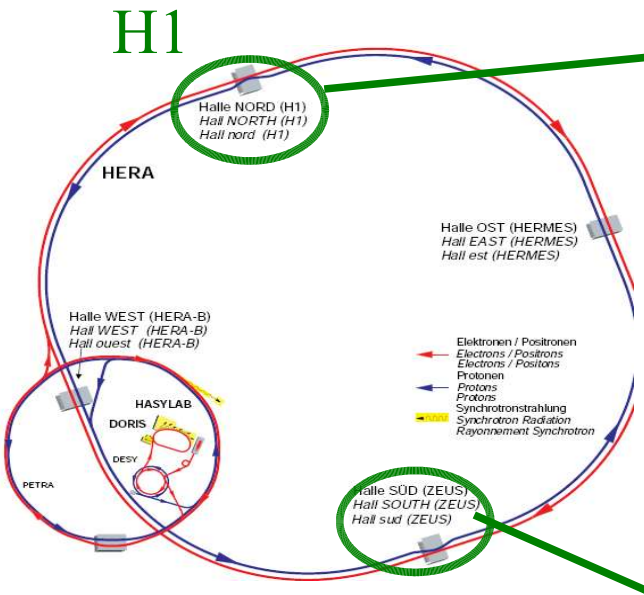


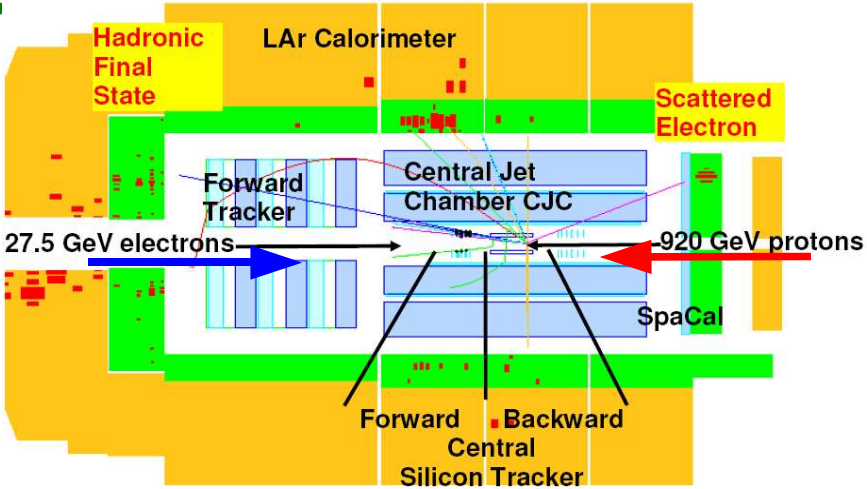
All studies presented are done in deep inelastic scattering (DIS):

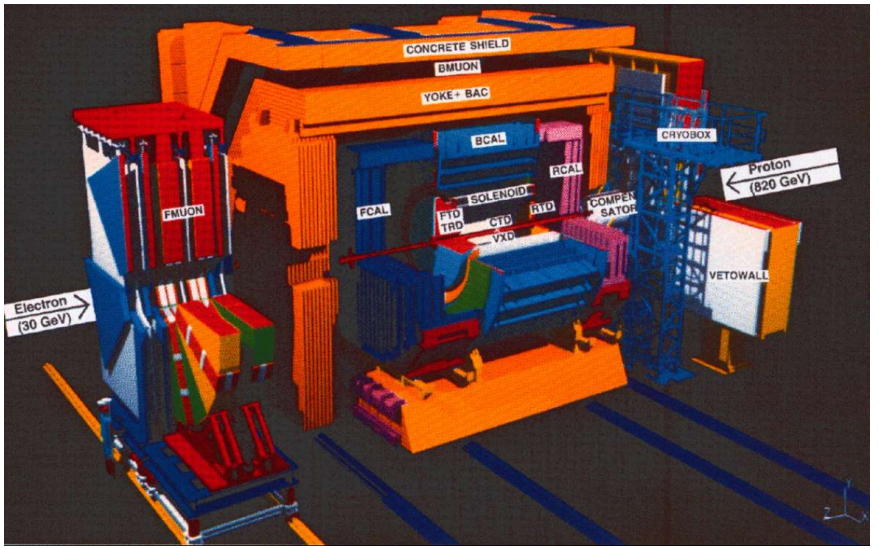
- $Q^2 = -q^2 = -(k - k')^2$
  $= 4EE'\cos(\theta/2) > 1\ \mathrm{GeV}^2$
- $y = P \cdot q / P \cdot k$
  $= 1 - E'/(2E) * (1 - \cos(\theta/2))$

→ Reconstructed from Energy E' and angle θ of the scattered electron

HERA: ZEUS and H1



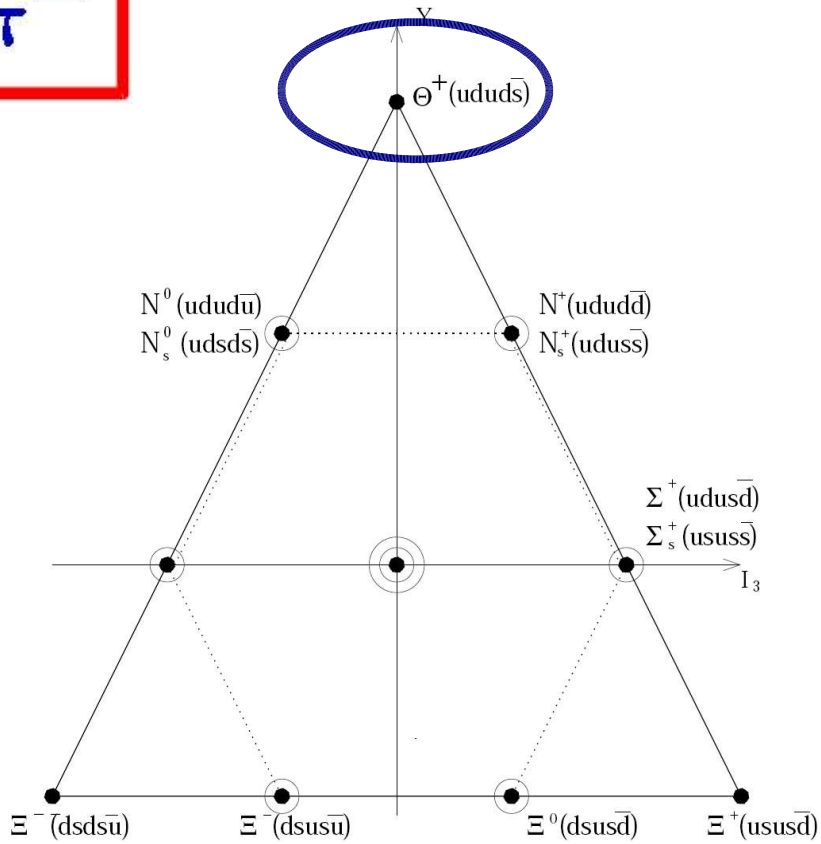




HERA I Data: 1996 – 2000
Lumi: O(100 pb^{-1})

Experimental search for the Θ^+

$$\Theta^+(1530) \longrightarrow p\,K^\circ_S \longrightarrow p\,\pi^+\pi^-$$



$\Theta^+ \rightarrow K^0_s\, p$: K^0_s and p selection

$L = 121\ pb^{-1}$

Event selection

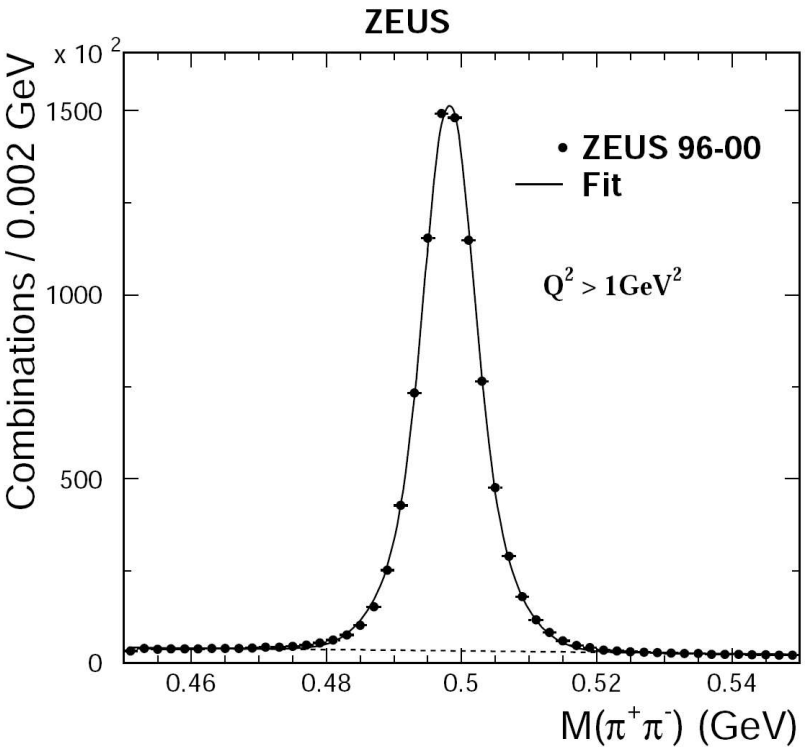
$Q^2_e > 1\ GeV^2$

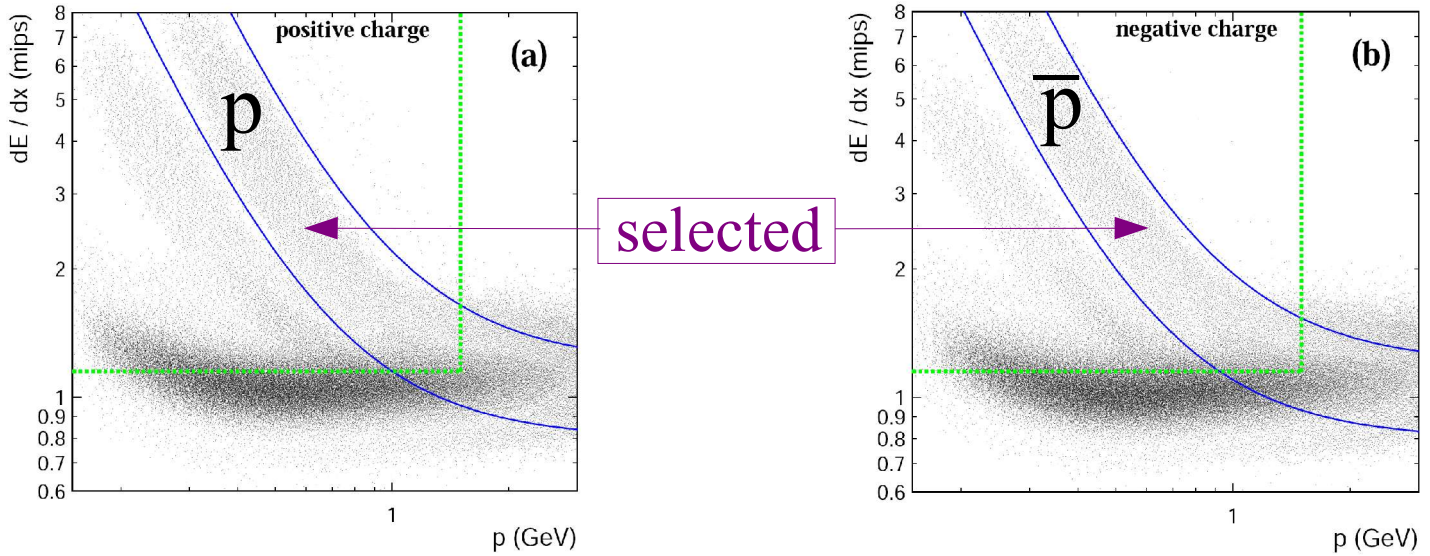
$y_e < 0.95$

K^0_s selection

$p_T(K^0_s) > 0.3\ GeV$, $|\eta(K^0_s)| < 1.5$

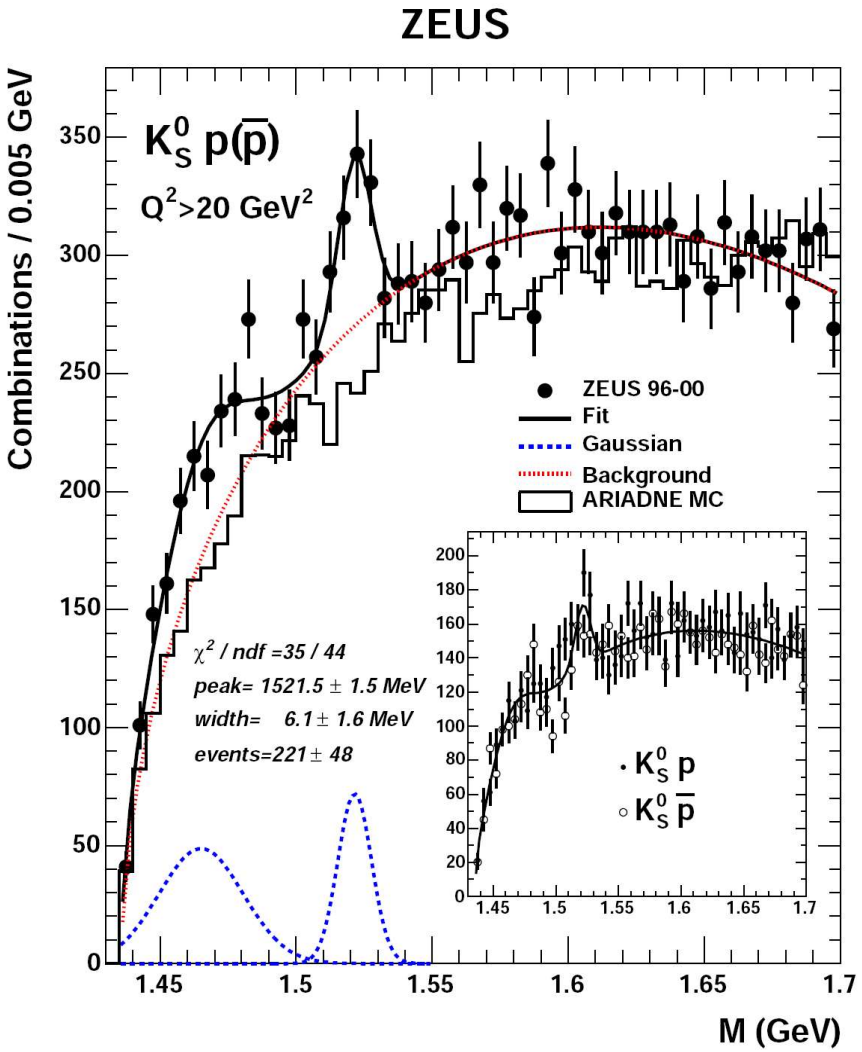
$N \approx 887k$, BG: ~ 6%



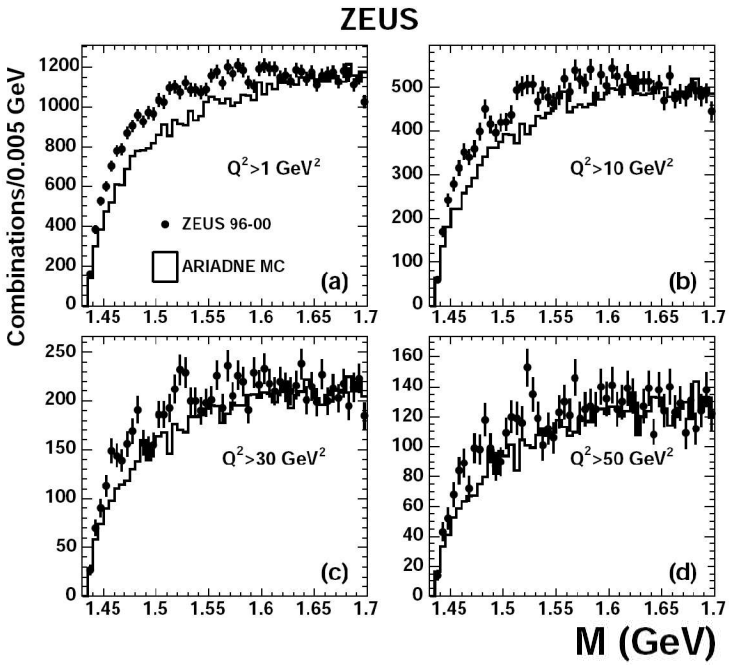


Search for the Θ^+ at ZEUS

ZEUS Collab., PLB 591 (2004)



$$f_{fit} = P_1(M\text{-}M_{th})^{P_2} \bullet [1+P_3(M\text{-}M_{th})]$$
$$M_{th} = m_p + m_\pi$$



→ Signal only visible at larger Q^2

Signal for $Q^2 > 20$ GeV
- $S = 221 \pm 48$
- $M = (1521.5 \pm 1.5)$ MeV
- $\sigma = (6.1 \pm 1.6)$ MeV
- Significance: 3.9 – 4.6 σ

X-section (ZEUS prelim.)

$\sigma(ep \rightarrow e\Theta^+X \rightarrow e(K^0_S p)X) = 125 \pm 27\ ^{+36}_{-28}$ pb

$\Theta^+ \rightarrow K^0_s\, p$: K^0_s and p selection

$L = 74\ pb^{-1}$

Event selection

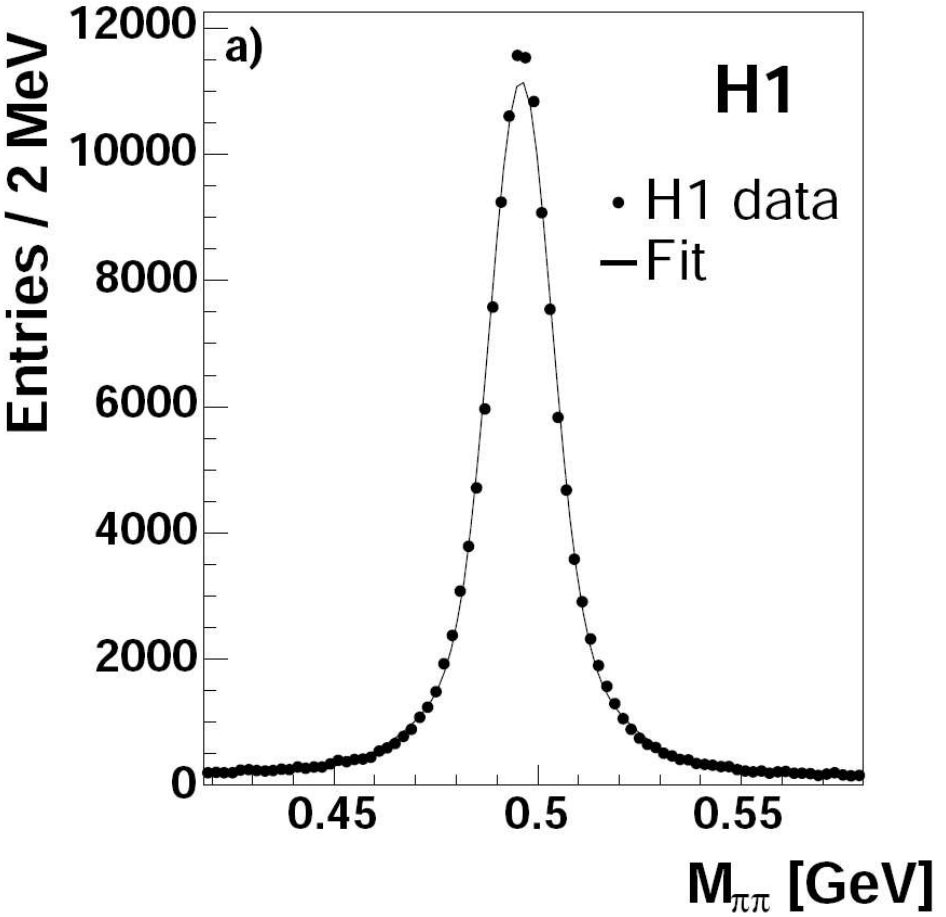
$5 < Q^2_e < 100\ GeV^2$

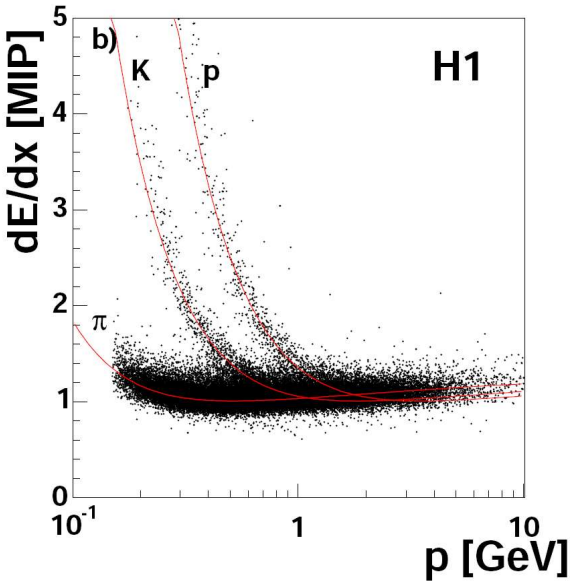
$0.1 < y_e < 0.6$

K^0_s selection (like ZEUS selection)

$p_T(K^0_s) > 0.3$ GeV, $|\eta(K^0_s)| < 1.5$

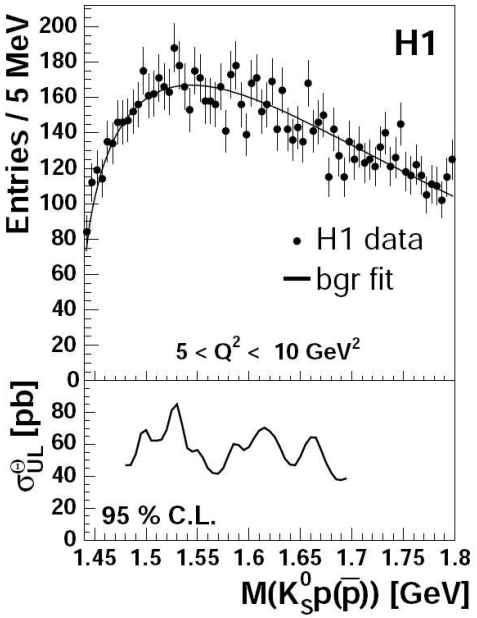
N ≈ 133k, BG: ~ 3%

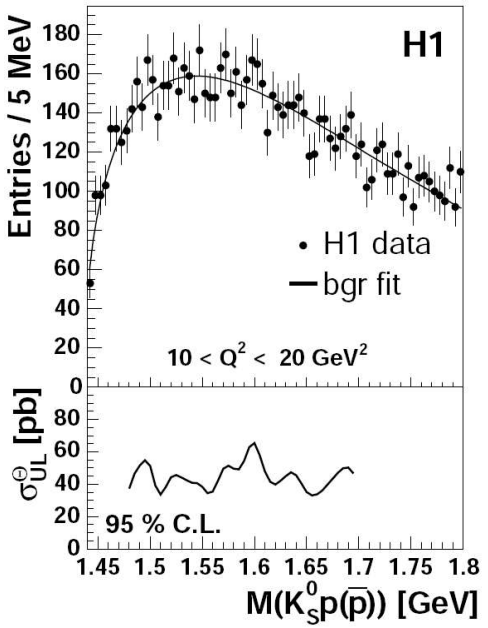


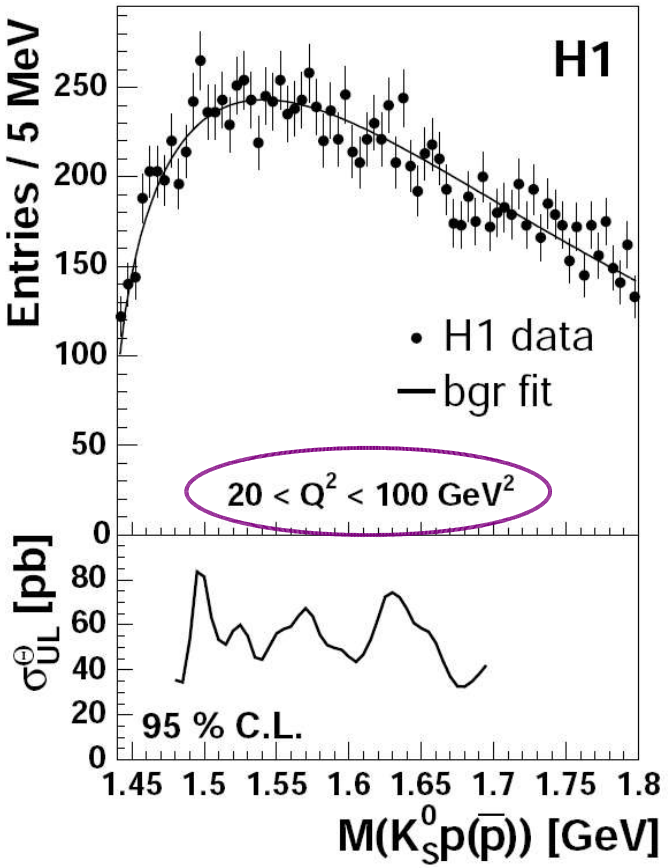


Search for the Θ^+ at H1

H1 Collab., PL B 639 (2006)







No significant signal in any Q^2 bin

→ extract upper limit at 95 % C.L. on the X-section $\sigma(ep \rightarrow e\Theta^+X \rightarrow e(K^0_s p)X)$, using modified Frequentist approach, based on likelihood ratios

H1 can not confirm the ZEUS result

Comparison with ZEUS

$\sigma_{ZEUS} = 125 \pm 27^{+36}_{-28}$ pb

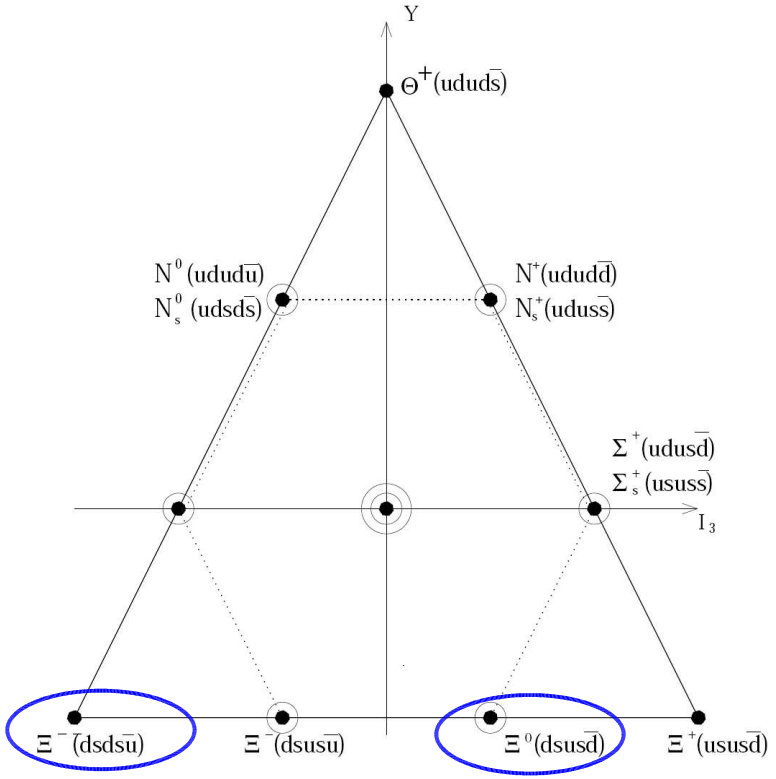
$\sigma_{H1}(M=1.52) < 72$ pb 95% C.L.

extrapolate to $y < 0.95$:

$\sigma_{H1}(M=1.52) < 100$ pb @ 95% C.L.

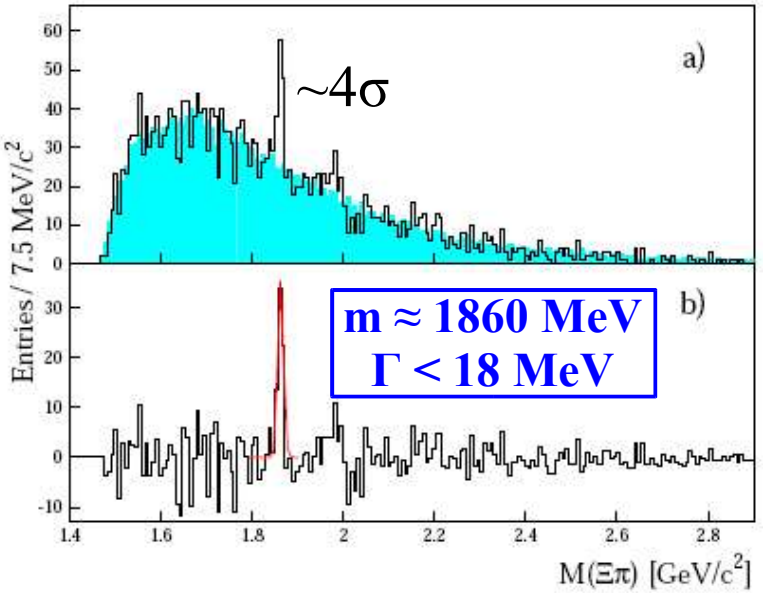
Experimental search for the $\Xi^{--/0}$

$$\Xi^{--/0} \rightarrow \Xi^{-}\pi_3^{\pm}$$
$$\Xi^{-} \rightarrow \Lambda\pi_2^{-}$$
$$\Lambda \rightarrow p\pi_1^{-}$$



Reminder: The NA49 Signal

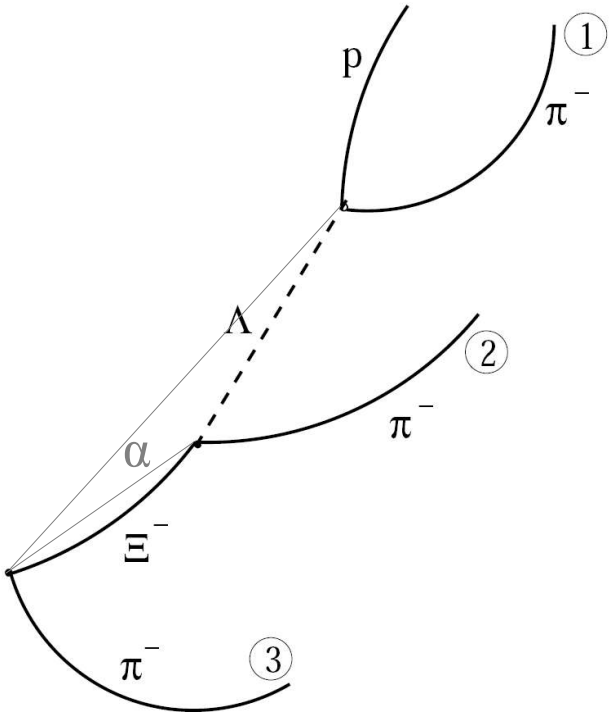
NA49 Collab., PRL 92 (2004)



Not seen by any other experiment
(WA89, ALEPH, BES, FOCUS, COMPASS, CDF,...)

$\Xi^{--/0} \rightarrow \Xi^-\pi^{\pm}$: Baryon selection

$L = 101\ pb^{-1}$



DIS-selection:

$2 < Q^2 < 100\ GeV^2$

$0.05 < y < 0.7$

Λ selection:

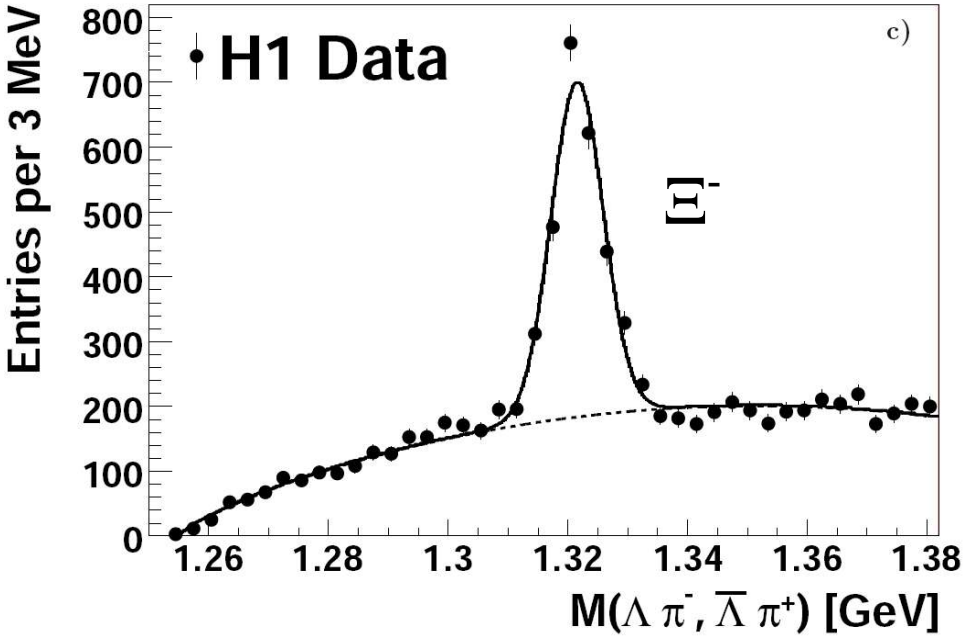
$p_T > 0.3$ GeV

Decay length > 0.75 cm

Ξ^- selection:

$|Dca'(\Xi^-)| < 2.5$ mm

$\alpha < 0.6$ rad

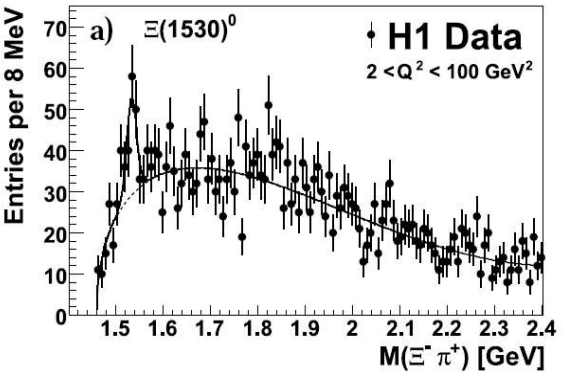


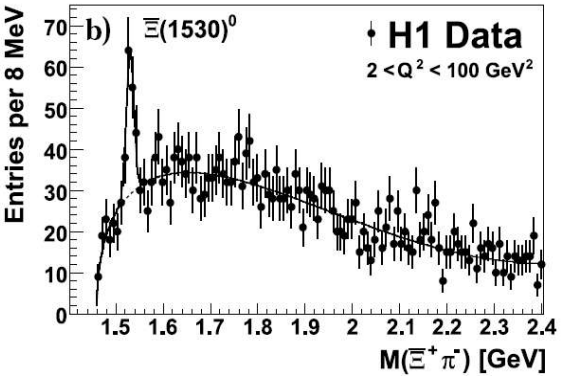
Search for the $\Xi^{--/0}$ at H1

Apart from $\Xi(1530)^0$ signal, **no other significant signal** observed

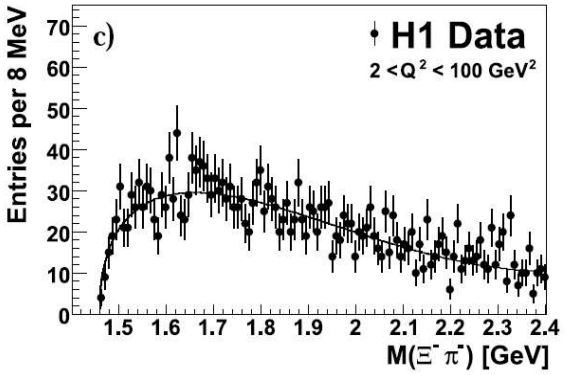
Extract upper limit on R(M) at 95% C.L., using modified Frequentist approach

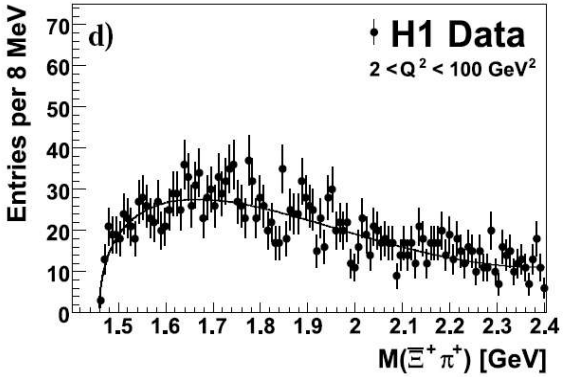
$\Xi^- \pi^+$ $\quad$ $\bar{\Xi}^+ \pi^-$





$\Xi^- \pi^-$ $\quad$ $\bar{\Xi}^+ \pi^+$





$$R(M) = \frac{N^{res}(M,q)}{N(1530,0)} \times \frac{\epsilon(1530,0)}{\epsilon(M,q)}$$

$\Xi(1530)^0$

N $= 163 \pm 24$

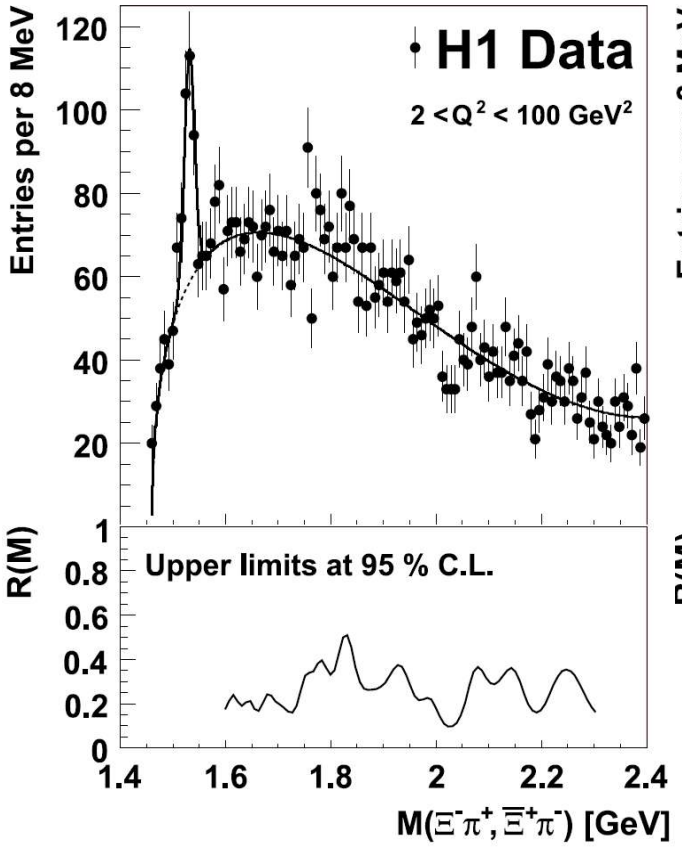
M $= (1532 \pm 2)$ MeV

$\sigma = (9.4 \pm 1.5)$ MeV

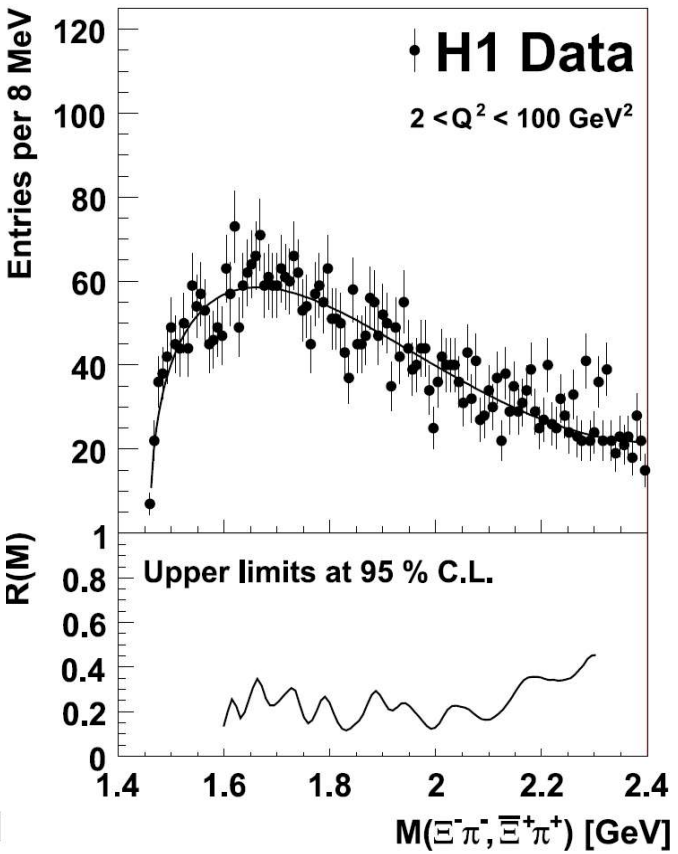
Limit on the $\Xi^{--/0}$

hep-ex:0704.3594
ZEUS Collab., PL B610 (2005)

neutral comb.



charged comb.



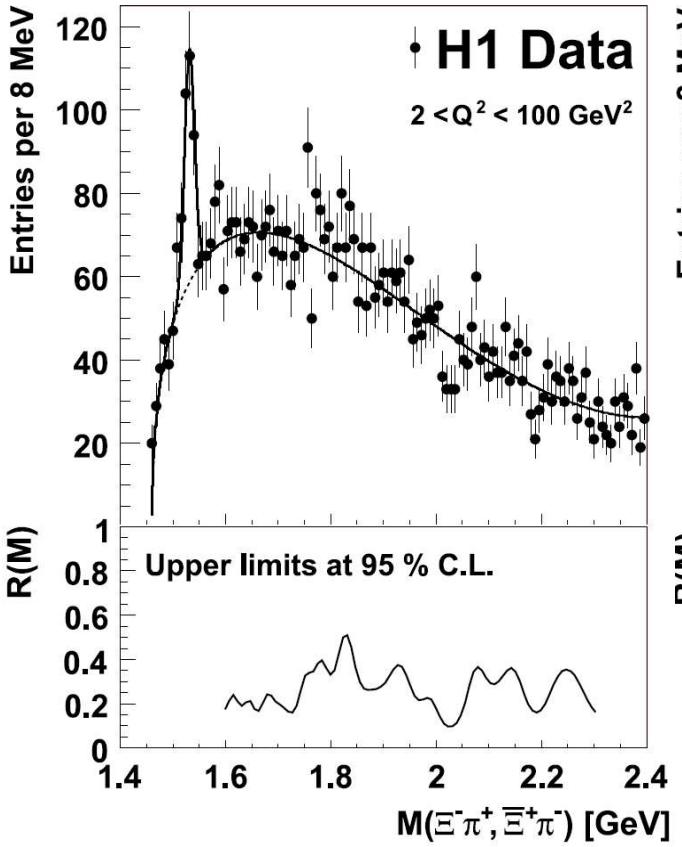
$0.1 < R(M) < 0.5$

$0.12 < R(M) < 0.45$

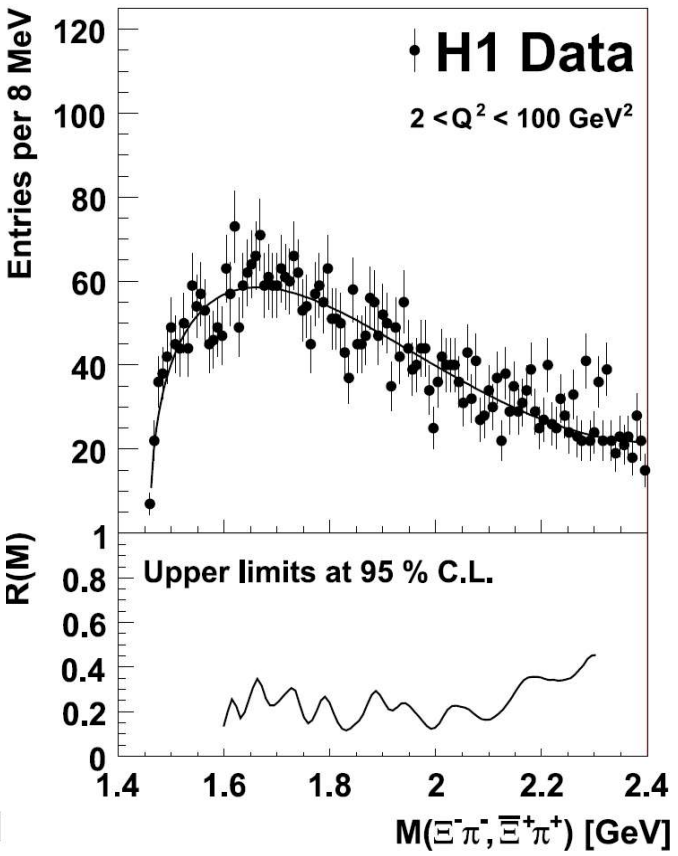
Limit on the $\Xi^{--/0}$

hep-ex:0704.3594
ZEUS Collab., PL B610 (2005)

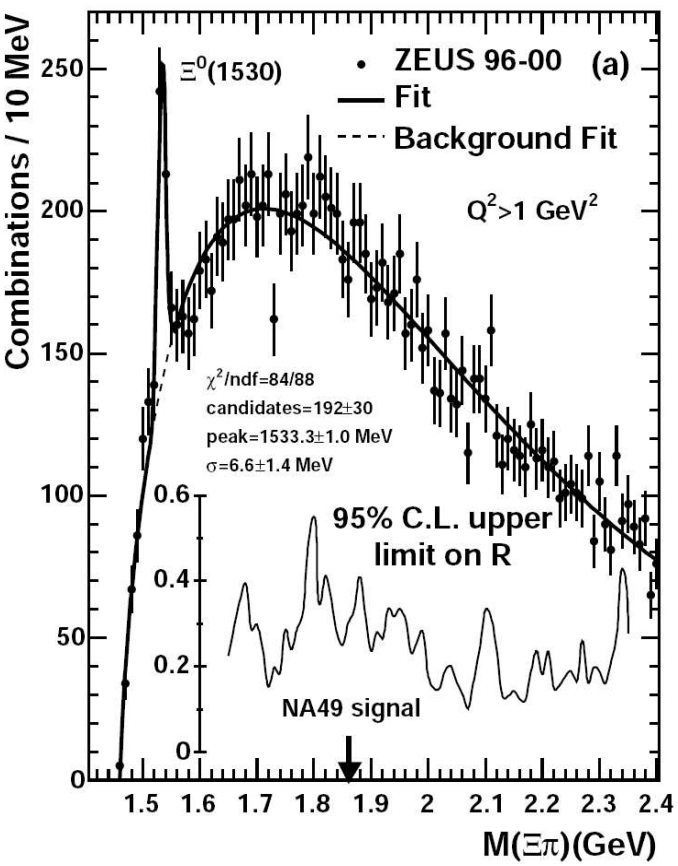
neutral comb.



charged comb.



all comb.



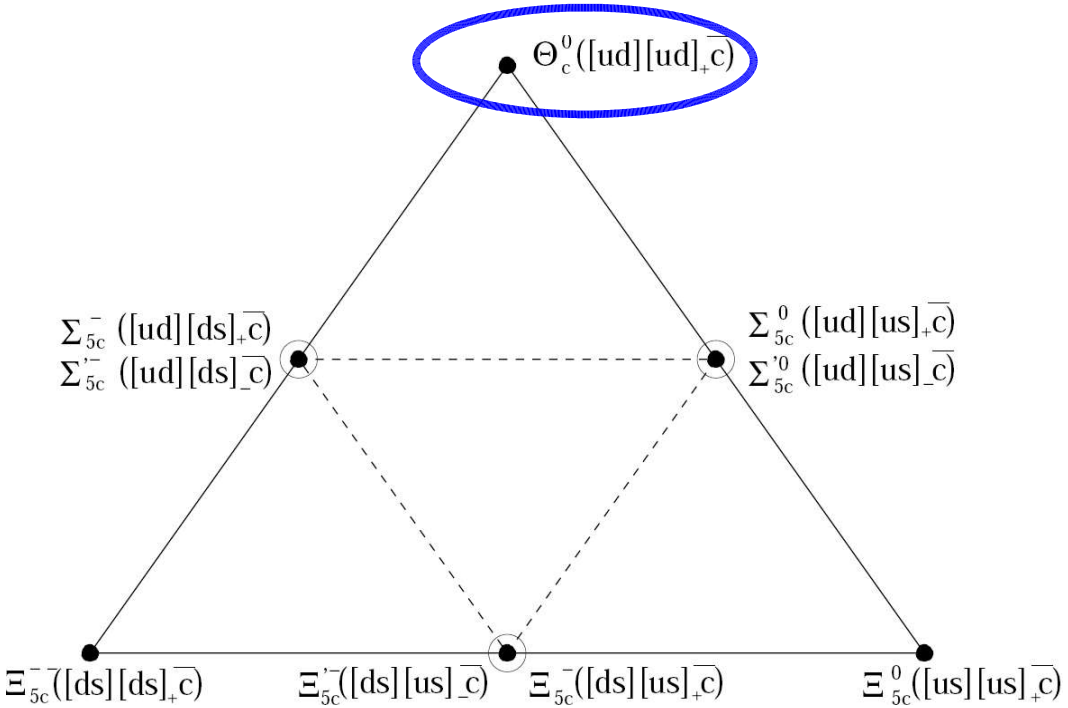
$0.1 < R(M) < 0.5$

$0.12 < R(M) < 0.45$

$0.1 < R(M) < 0.5$

Experimental search for the Θ^0_c

$$\Theta^0_c \rightarrow D^{*-} p$$



$\Theta^0_c \rightarrow D^{*-} p$: D^{*+} reconstruction

H1 Collab., PL B588 (2004)
ZEUS Collab., EPJ C38 (2004)

ZEUS: $L = 126\ pb^{-1}$

H1: $L = 75\ pb^{-1}$

DIS-selection:

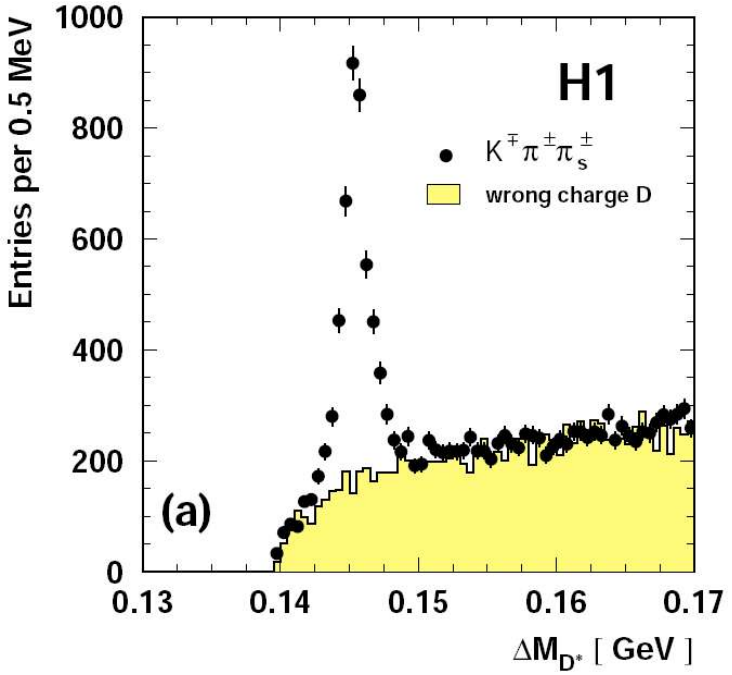
$Q^2 > 1 GeV^2$
$Q^2 < 100\ GeV^2$ (H1 only)
$0.05 < y < 0.7$ (H1)
$y < 0.95$ (ZEUS)

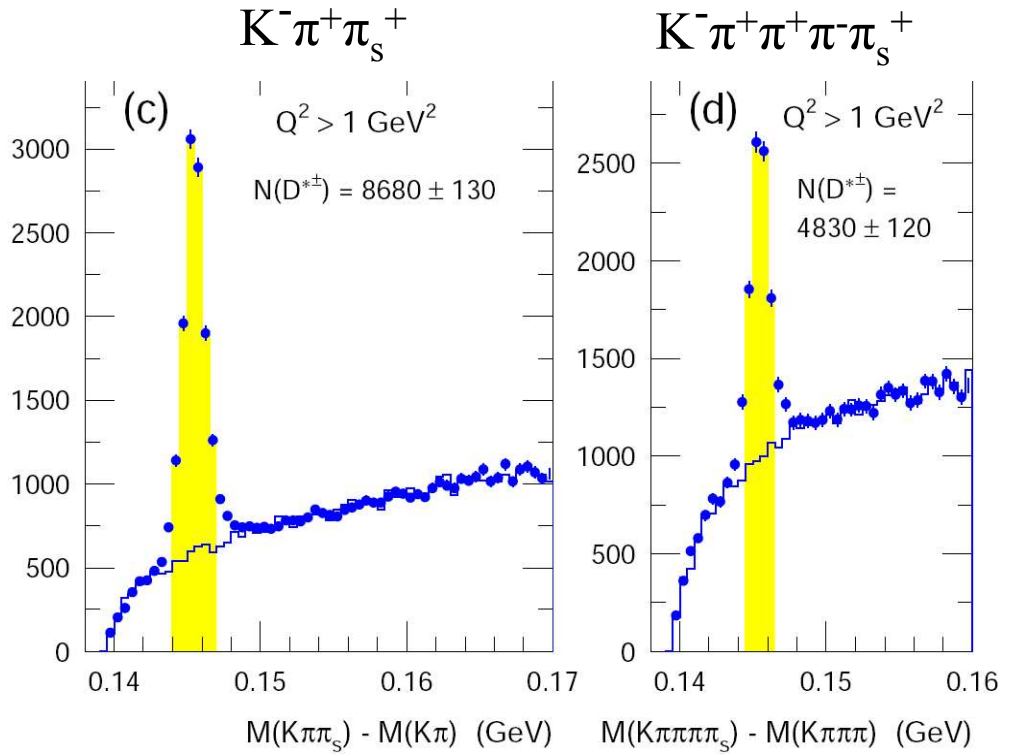
Reconstruction of D^{*+} mesons:

$D^{*+} \rightarrow D^0 \pi_s^+$

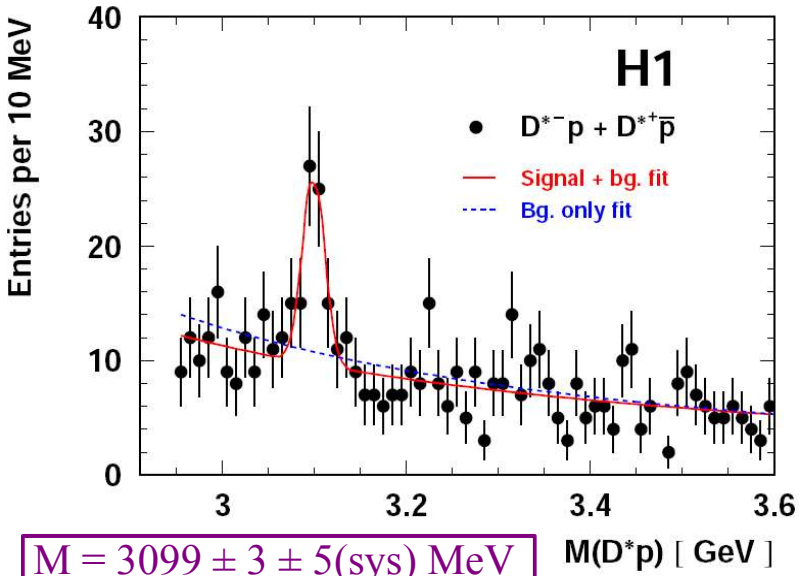
$D^0 \rightarrow K^-\pi^+$

$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ (ZEUS only)





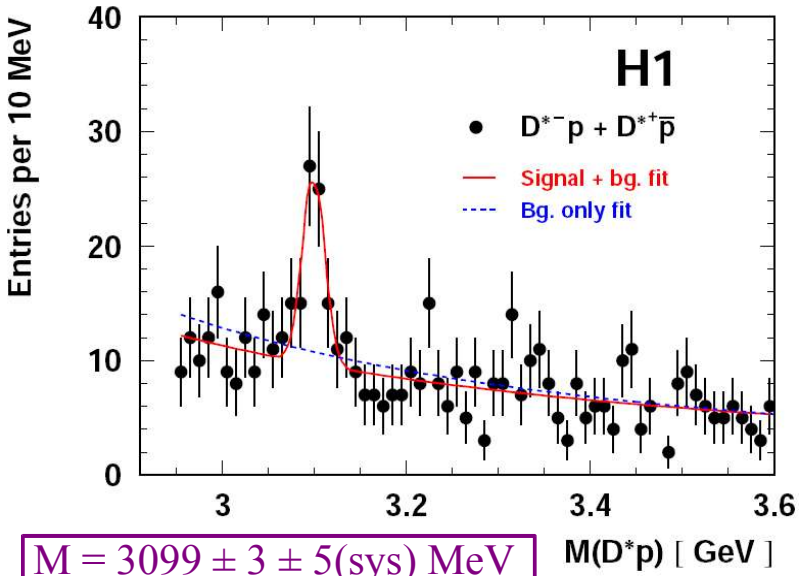
Search for the Θ^0_c



M = 3099 ± 3 ± 5(sys) MeV
σ = 12 ± 3 MeV
N = 51 ± 11
Significance: 5.4 – 6.2 σ

Signal so far not confirmed by any other experiment!

Search for the Θ^0_c



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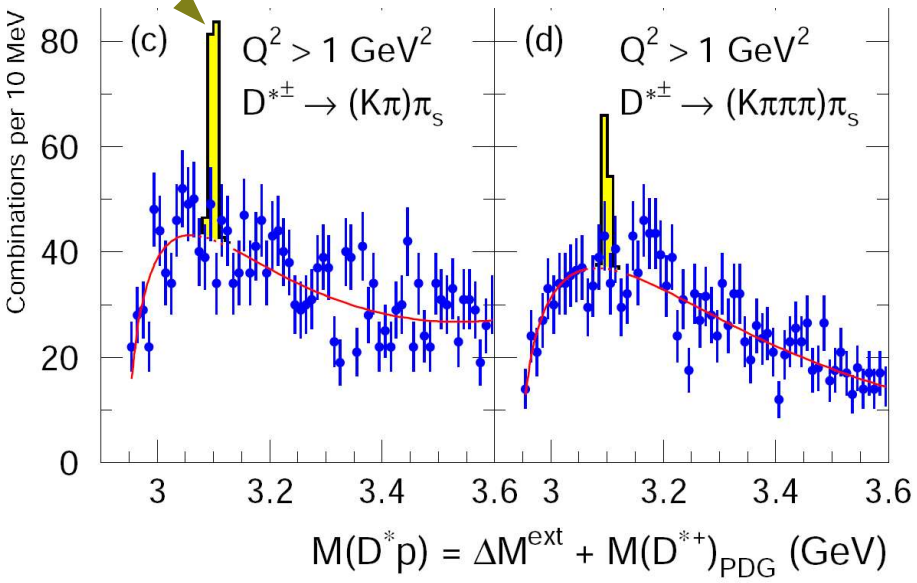
MC expec.



Acceptance corrected **yield ratio (D*p) / D^*_{inc}**:

Visible range: $p_T > 1.5$ GeV, $-1.5 < \eta < 1.0$

H1: $R_{cor}(D^*p(3100)/D^*) = (1.59 \pm 0.33\ ^{+033}_{-0.45})\%$

ZEUS: $R_{cor}(D^*p(3100)/D^*) < 0.51\%$ **(@95%C.L.)**

Signal so far not confirmed by any other experiment!

Conclusion

- $\Theta^+(1530)$:
  - ZEUS sees a signal for $Q^2 > 20$ GeV:
    $\sigma(ep \rightarrow e\Theta^+X \rightarrow e(K^0_s p)X) = 125 \pm 27\ ^{+36}_{-28}$ pb
  - H1 does not see a signal, upper limit at 95% C.L compatible with ZEUS measurement

- $\Xi^{--/0}(1860)$:
  - Not seen, neither by ZEUS nor by H1
  - Upper limit at 95% C.L. on production ratio with respect to the $\Xi(1530)^0$ vary from 10 to 50%
  - ZEUS and H1 are compatible

- $\Theta^0_c(3100)$:
  - H1 sees a signal in DIS and in γp
  - ZEUS can not confirm, upper limit on acceptance corrected yield is not compatible with H1

Outlook: HERAII data should resolve the open questions

Additional material

$\Xi^{--/0} \rightarrow \Xi^-\pi^\pm$: Baryon selection

$L = 121\ pb^{-1}$

DIS-selection:

$Q^2 > 1 GeV^2$

$E_e' > 5$ GeV

$35 < E-pz < 60$ GeV

$|z\text{-vertex}| < 50$ cm

Λ selection:

dE / dx for proton candidate

fit to secondary vertex

Ξ^- selection:

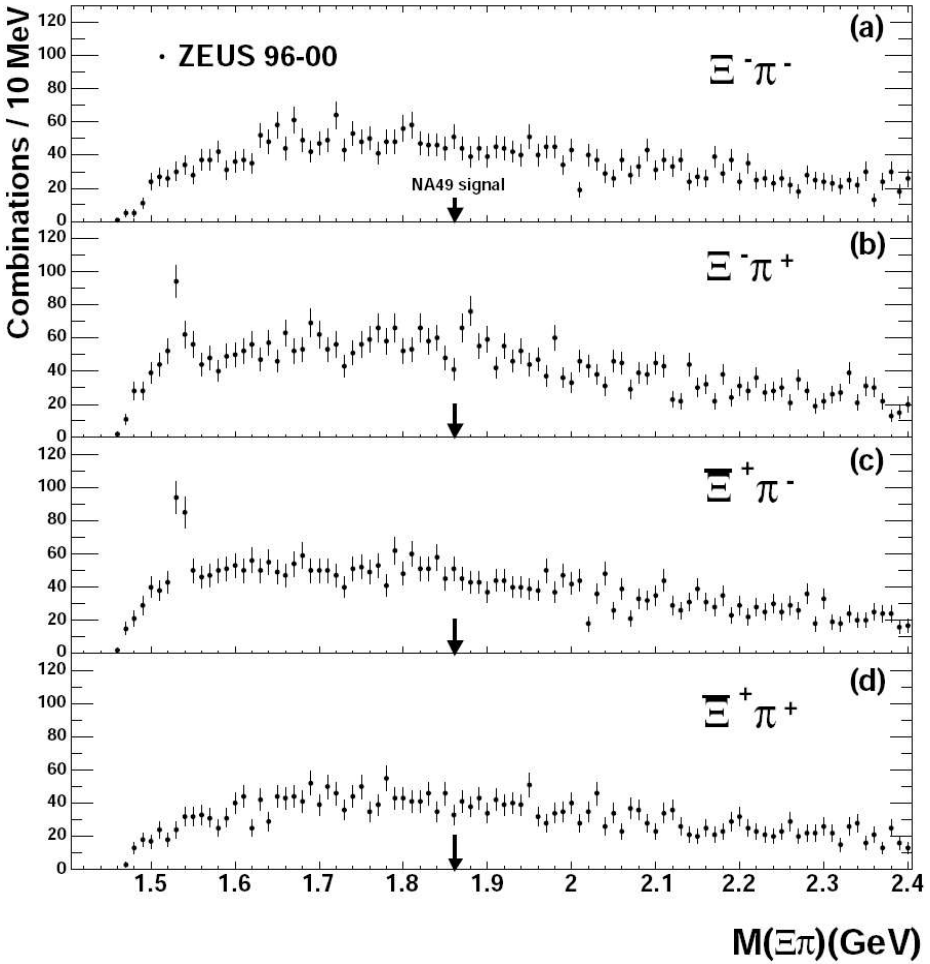
$|m_{inv}(p,\pi) - m_\Lambda| < 5$ MeV

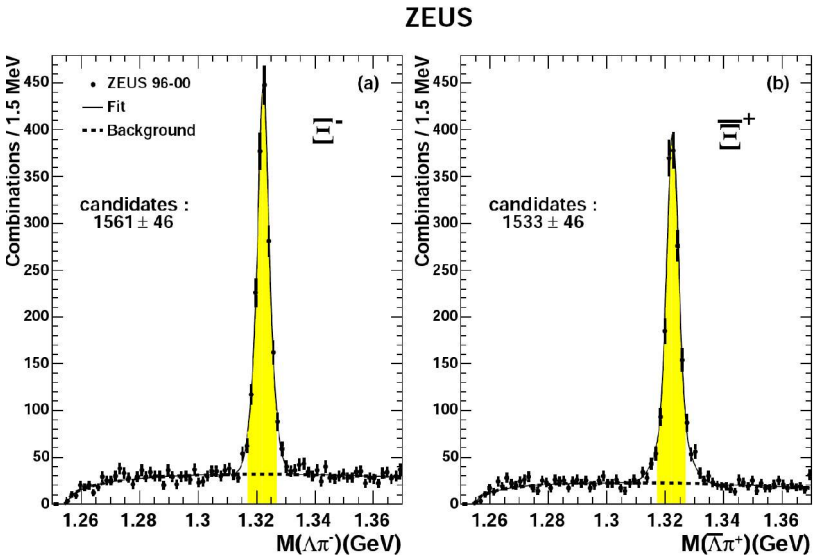
$|Dca'(\Xi^-)| < 1$ cm

Decay length (L) > 1.75 cm

$L(\Lambda) > L(\Xi)$

$p(\pi) < p(\Lambda)$





($\Xi\pi$)-selection:

$|m_{inv}(\Lambda\pi) - m_\Xi| < 6$ MeV

$p(\pi) < p(\Xi)$

Search for the $\Xi^{--/0}$ at ZEUS

ZEUS Collab., PL B610 (2005)

Apart from $\Xi(1530)^0$ signal, **no other significant signal** observed

→ extract upper limits on R(M)

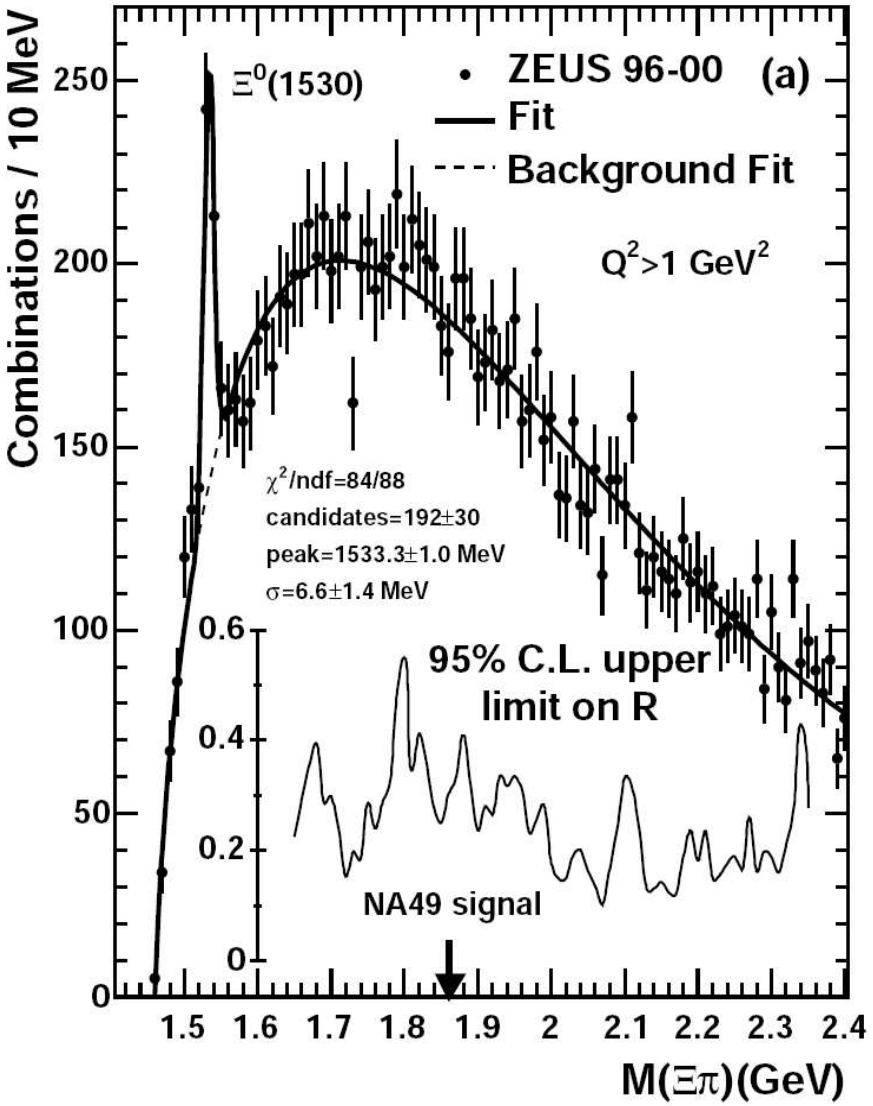
$\Xi(1530)^0$

N = 192 ± 30

M = (1533 ± 1) MeV

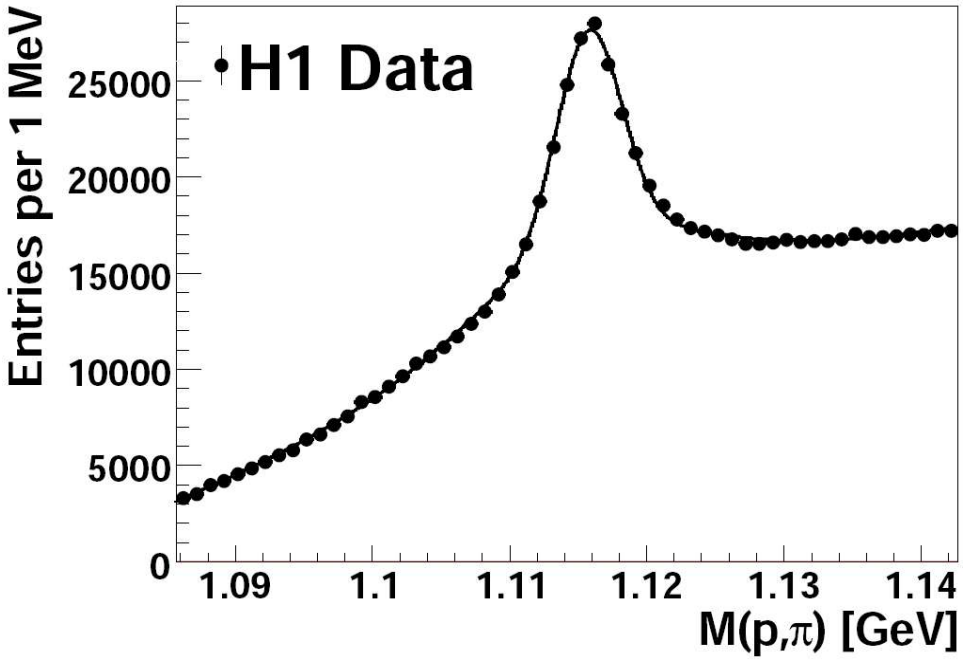
σ = (6.6 ± 1.4) MeV

$0.1 < R(M) < 0.5$

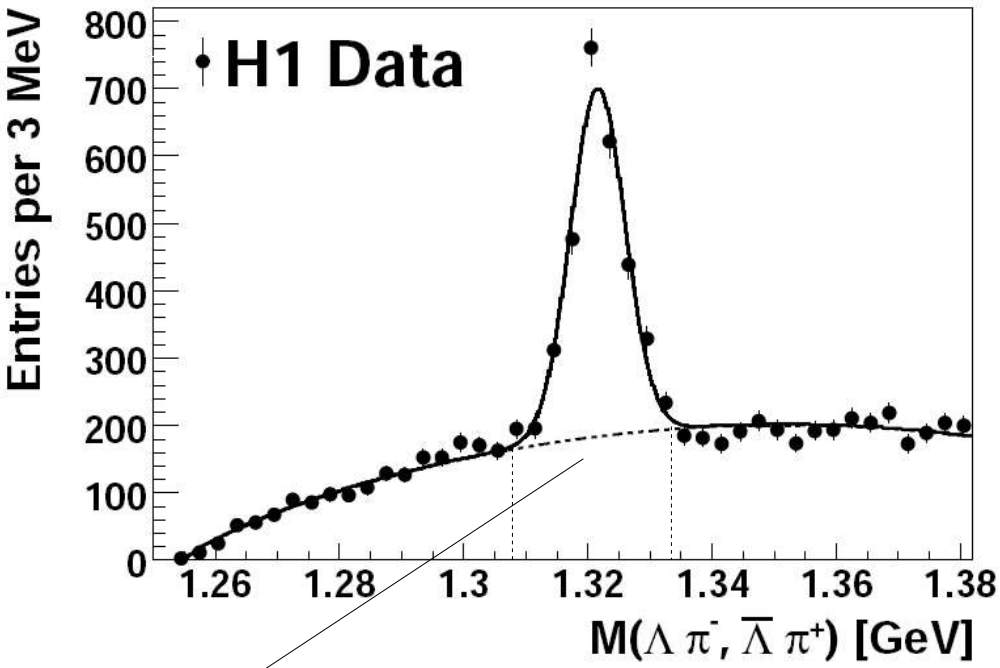


Search for new baryonic states @ H1

$\Lambda \rightarrow p\pi^-$

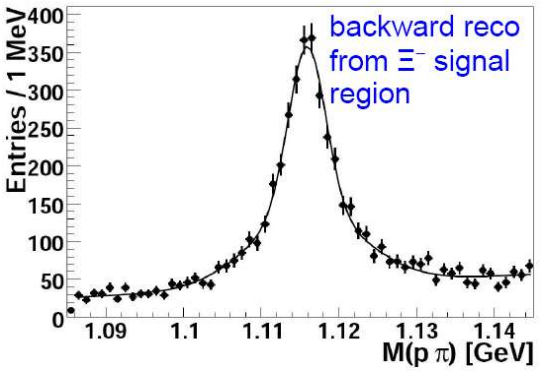


$\Xi^- \rightarrow \Lambda\pi^-$



150k reconstructed Λ:

m = 1115.8 MeV
$\sigma \approx 5$ MeV
$c\tau = (7.6 \pm 0.9)$ cm



1870 reconstructed Ξ^-:

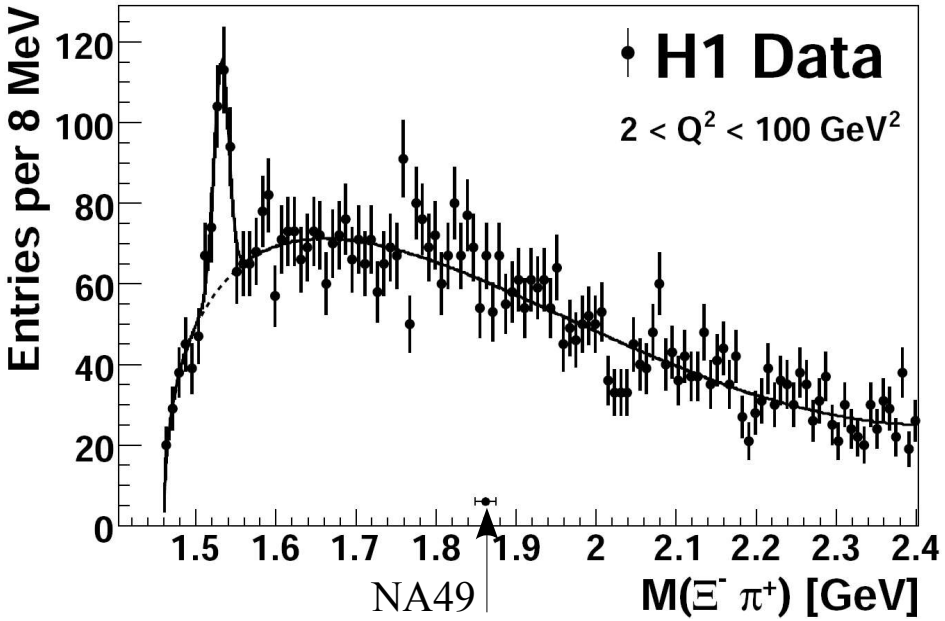
m = 1321.6 MeV
$\sigma \approx 4.3$ MeV
$c\tau = (5.1 \pm 0.3)$ cm

→ PDG compliant

Search for new baryonic states @ H1

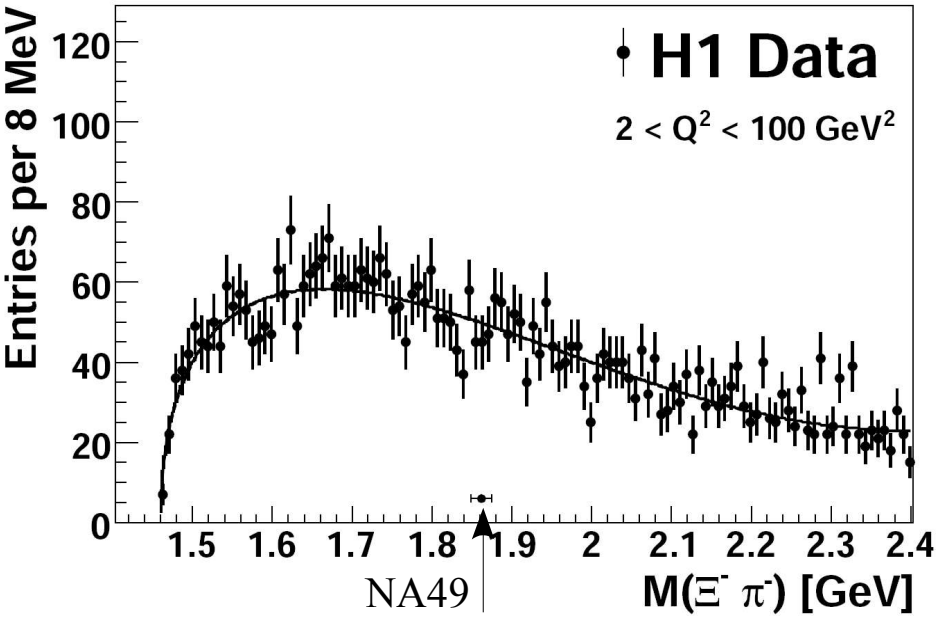
Combine Ξ^- candidates with additional (primary vertex-fitted) track assumed to be π

neutral combinations:
$\Xi^-\pi^+$ and $\overline{\Xi}^+\pi^-$



Clear signal of 163 ± 24 $\Xi(1530)^0$
m = (1532.1 ± 1.6) MeV
σ = (9.4 ± 1.5) MeV

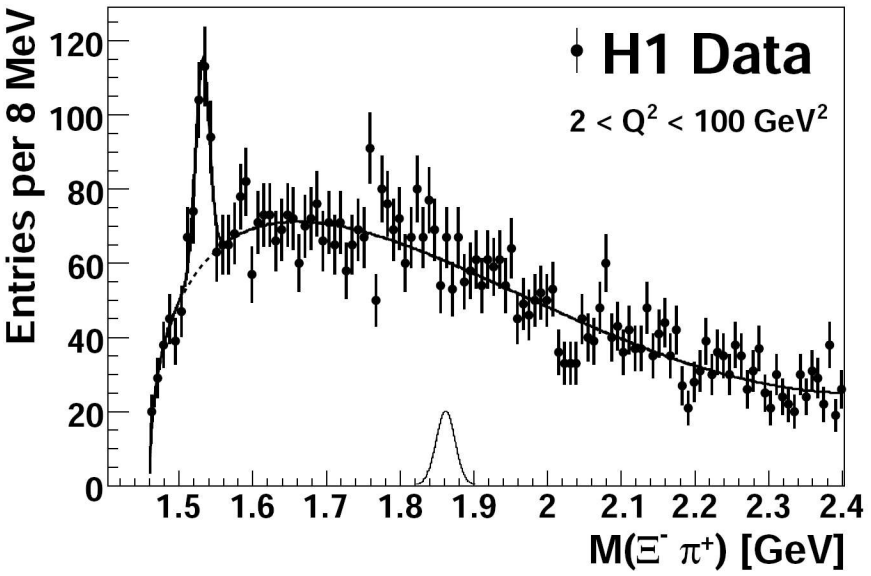
charged combinations:
$\Xi^-\pi^-$ and $\overline{\Xi}^+\pi^+$



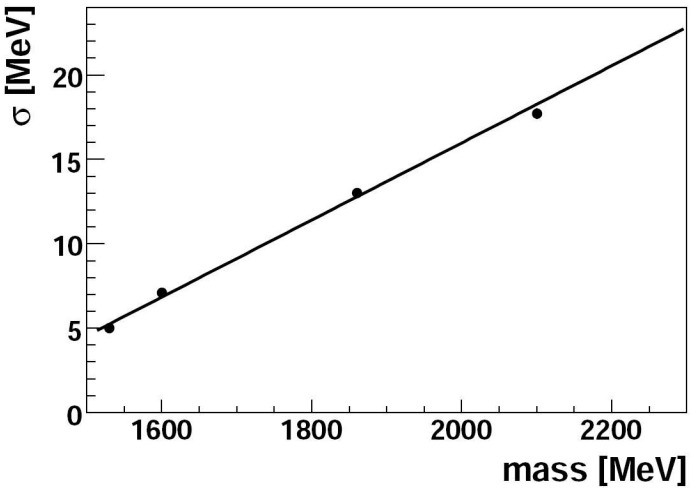
No significant signal
→ **no hint for the NA49 resonance**

Limit calculation I

- Modified frequentist approach (T.Junk)
- Assumptions:
  - BR($X \to \Xi\pi$) = 100 %
  - Small width
  - Production similar to $\Xi(1530)^0$
- Mass-dependent upper limit for possible $\Xi^-\pi^\pm$ signal at 95 % C.L.: $N_{u.l.}(\Xi^-\pi^\pm)$
- Neutral and charged combinations for simultaneous BG determination
- Gaussian for the possible signal, width from MC (mass-dependent)
- Separate limits for neutral and charged combinations
- Normalise upper limit wrt number of $\Xi(1530)^0$ → systematics mostly cancel:



resolution



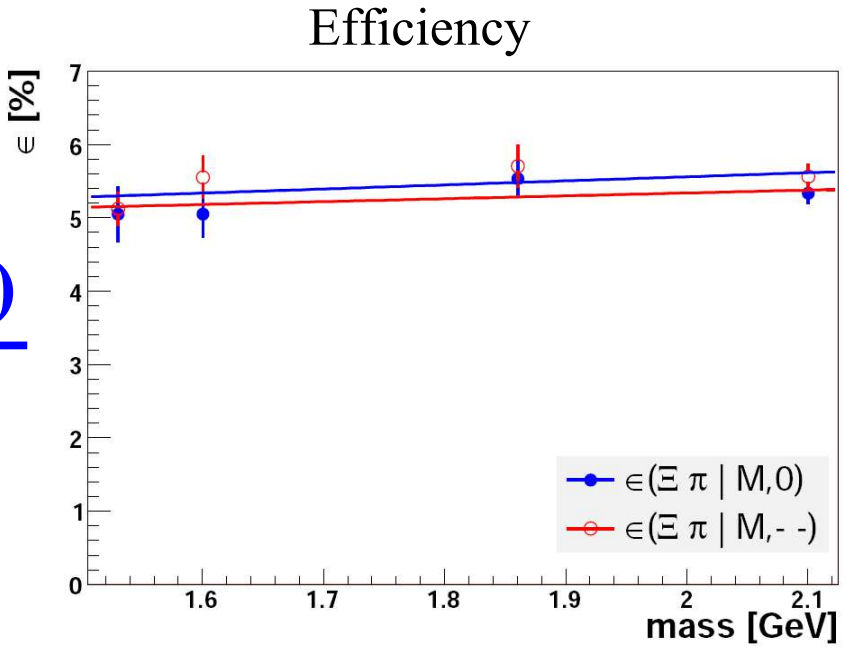
$$R^*_{u.l.}(M) = \frac{N_{u.l.}(\Xi^-\pi^\pm)}{N(\Xi(1530)^0)}$$

Limit calculation II

- Correct $R^*_{u.l.}$ for small differences in efficiency (mass-dependent):

$$R_{u.l.}(M) = R^*_{u.l.}(M) \cdot \frac{\epsilon(\Xi(1530)^0)}{\epsilon(M, q)}$$

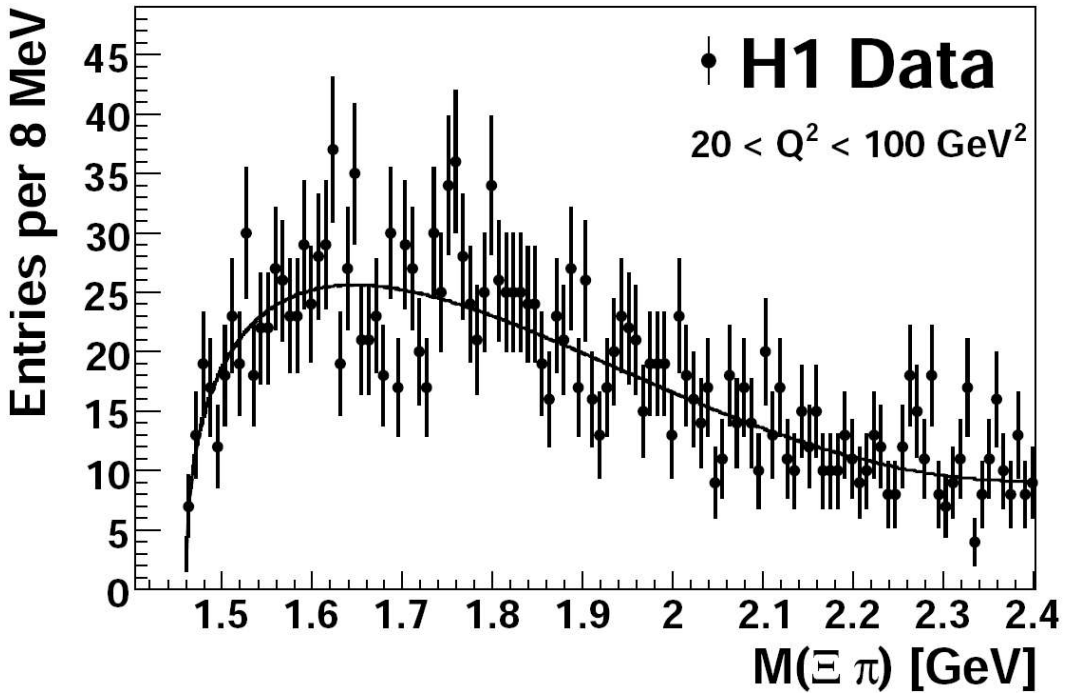
  - Efficiency correction new wrt ICHEP06

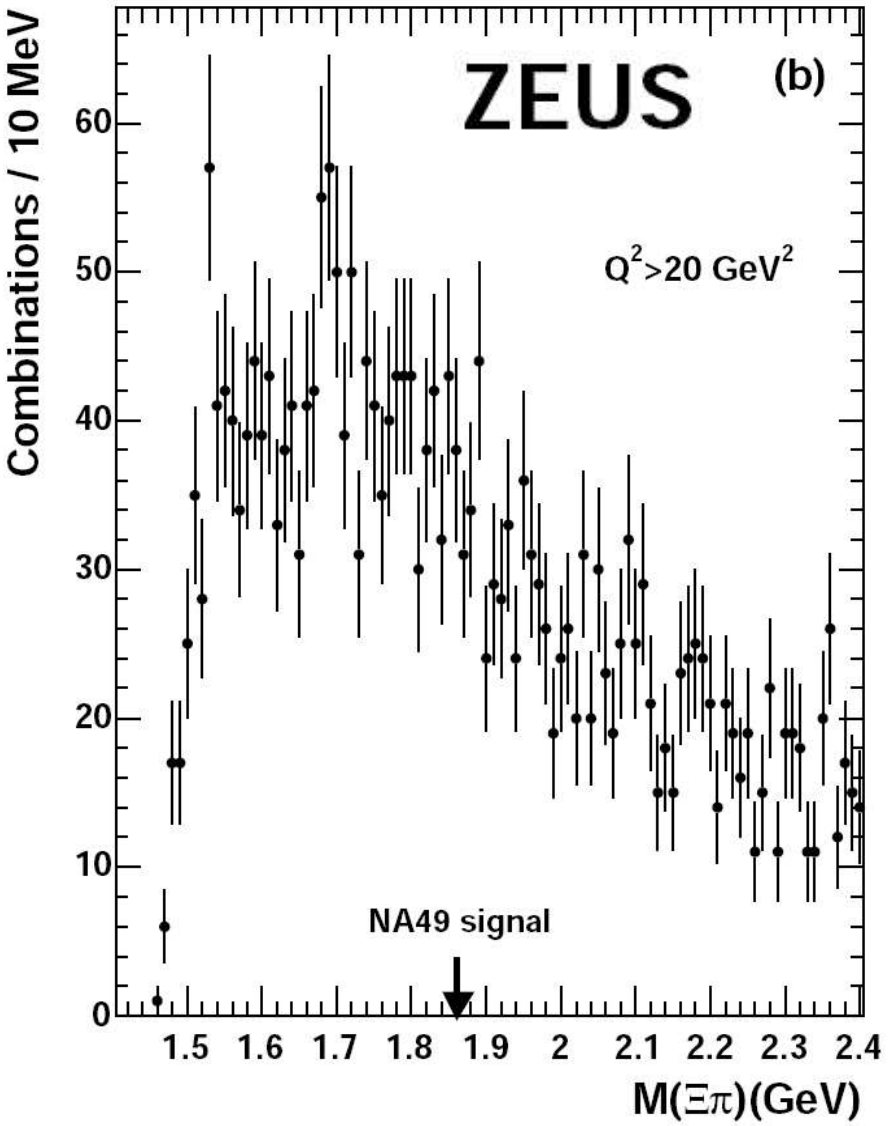


- Uncertainties considered:
  - Number of $\Xi(1530)^0$: 15% (from fit)
  - Width of signal: 5% (diff $\sigma(\Xi(1530)^0)$ data-MC)
  - Efficiency correction factor: 8%
  - BG: 2% (performing BG determination under different assumption)

Search for the $\Xi^{--/0}(1860)$ pentaquark

All charge combinations, $20 < Q^2 < 100$ GeV^2





$\Theta^0_c \rightarrow D^{*-} p$: D^{*+} selection

$L = 126\ pb^{-1}$

DIS-selection:

$Q^2 > 1 GeV^2$

$y < 0.95$

$E_e' > 8$ GeV

$40 < E-pz < 65$

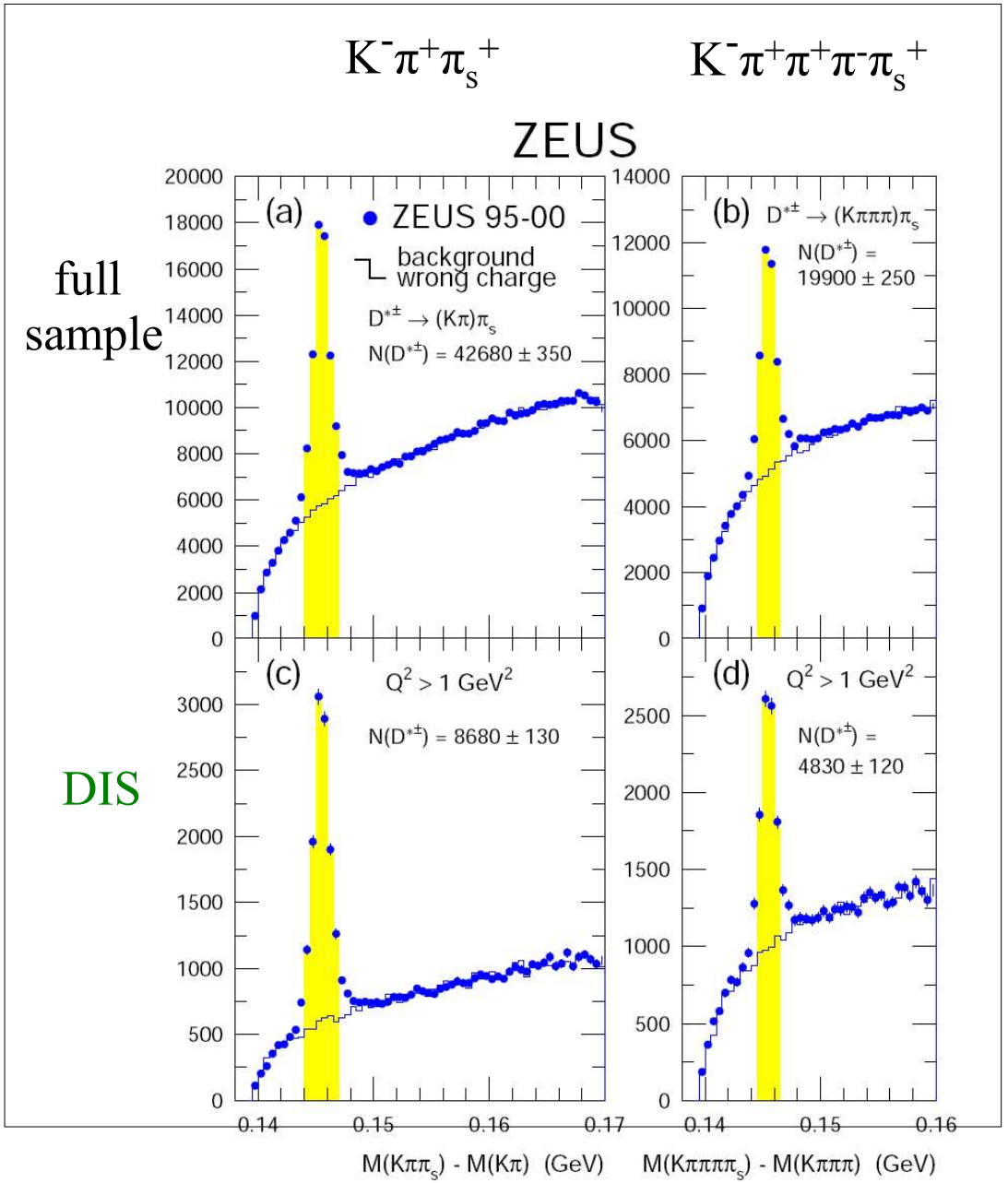
$|z\text{-vertex}| < 50$ cm

Reconstruction of D^{*+} mesons:

$D^{*+} \rightarrow D^0 \pi_s^+$,

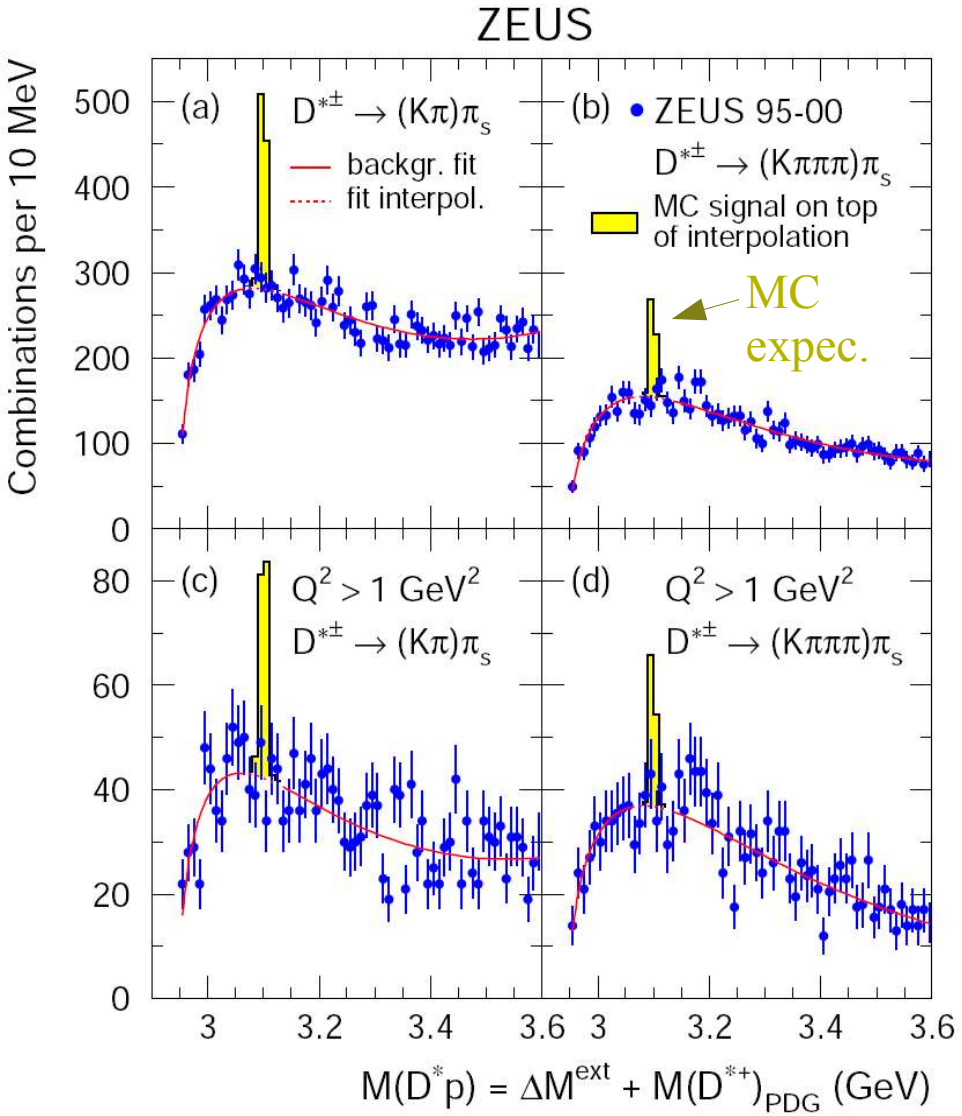
$D^0 \rightarrow K^-\pi^+$ and

$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$



Search for the Θ^0_c at ZEUS

ZEUS Collab., EPJ C38 (2004)



No significant signal in any channel, neither in DIS nor in γp

Acceptance corrected **yield ratio (D*p) / D^*_{inc}**:

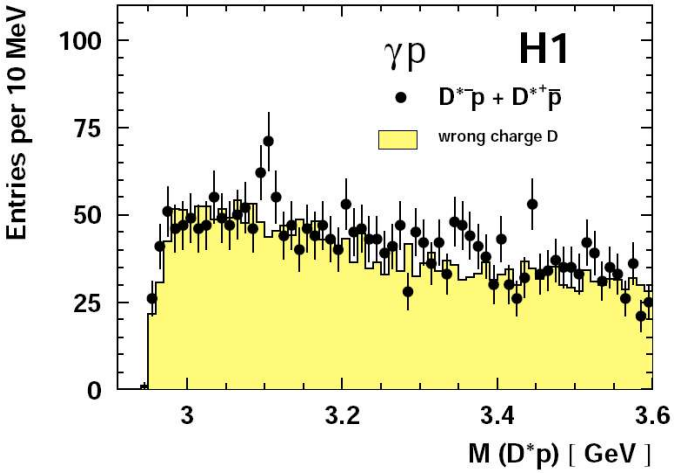
$R_{cor}(D^*p(3100)/D^*) < 0.51\%$ (@95%C.L.)

for $Q^2 > 1$ GeV and $D^0 \to K^-\pi^+$

→ ZEUS data not compatible with H1 signal

Search for the Θ^0_c at H1

Signal also visible in photoproduction



Acceptance corrected **yield ratio (D*p) / D^*_{inc}**:

Visible range: $p_T > 1.5$ GeV, $-1.5 < \eta < 1.0$

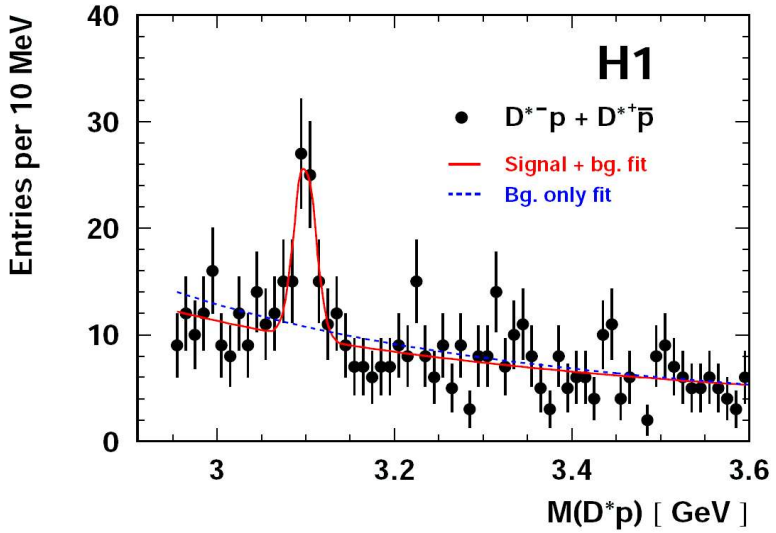
$R_{cor}(D^*p(3100)/D^*) = (1.59 \pm 0.33\ ^{+033}_{-0.45})\%$

Visible corss section (extrapolate to full D* phase space):

$\sigma_{vis}(D^*p(3100)) / \sigma_{vis}D^* = (2.48 \pm 0.52\ ^{+0.85}_{-0.64})\%$

The Θ_c at H1 and FOCUS

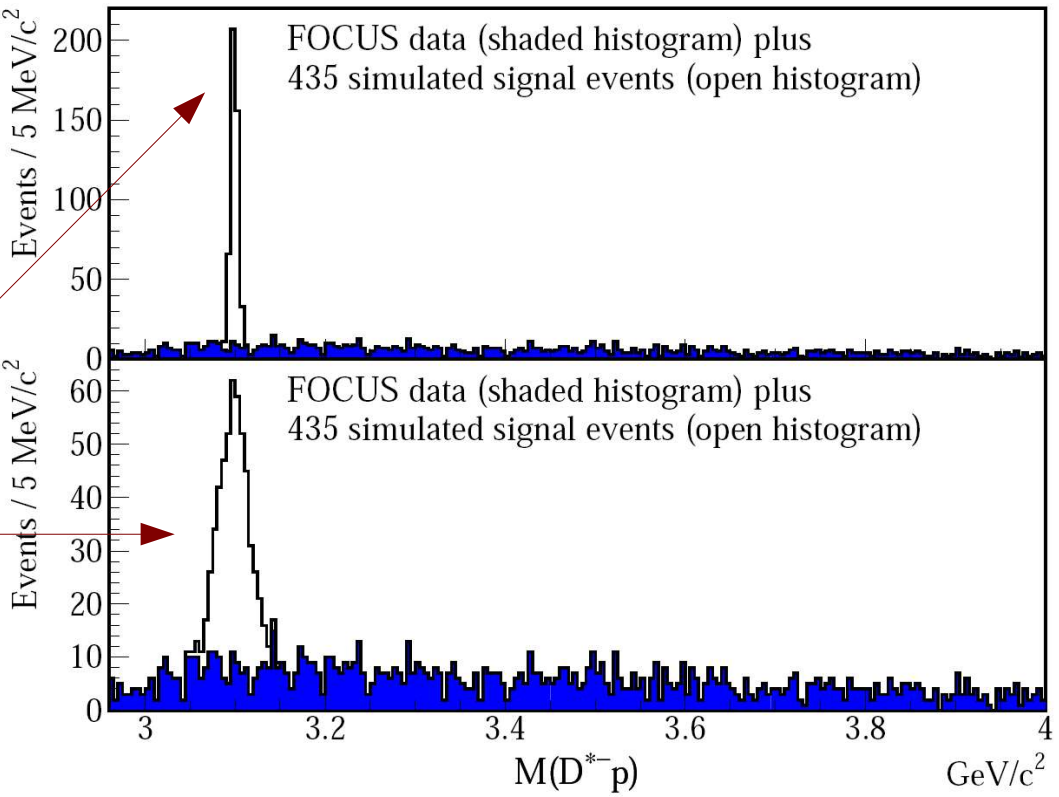
- The H1 signal $\Theta_c \rightarrow D^*p$:
  - ZEUS and FOCUS claimed incompatibility



expected signal at FOCUS extrapolated from H1

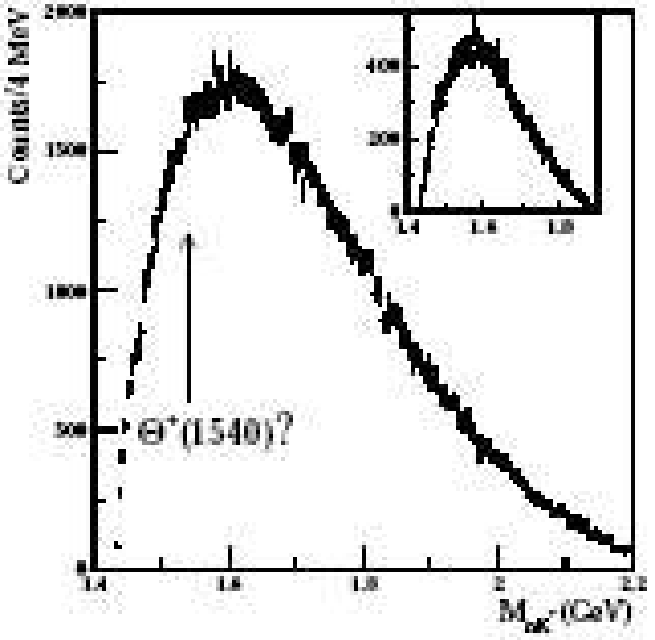
σ=4.15 MeV

σ=17 MeV



The new CLAS experiments

- $\gamma p \rightarrow K^0_s K^+ (n)$
  - No Signal observed
  - Upper limit on production cross section: (0.85-1.3)nb at 95% CL and m ≈ 1.54GeV
  - Contradicts SAPHIR experiment by two orders of magnitude (300nb)
  - Implies very small coupling of Θ^+ to NK*; but in many models major source of Θ^+ production



- $\gamma d \rightarrow p K^- K^+ (n)$
  - Previous CLAS results claimed ~ 5 σ for Θ^+ in the same channel and same energy
  - New high statistics results see no hint for a Θ^+ state!
  - Clearly contradicts the previous data
  - New fit of old data with improved BG (from new data) yields a significance of only 3 σ, previous: (5.2 ± 0.6) σ
  - The new CLAS data leaves room only for a Θ^+ state with intrinsic width of less than 0.5 MeV