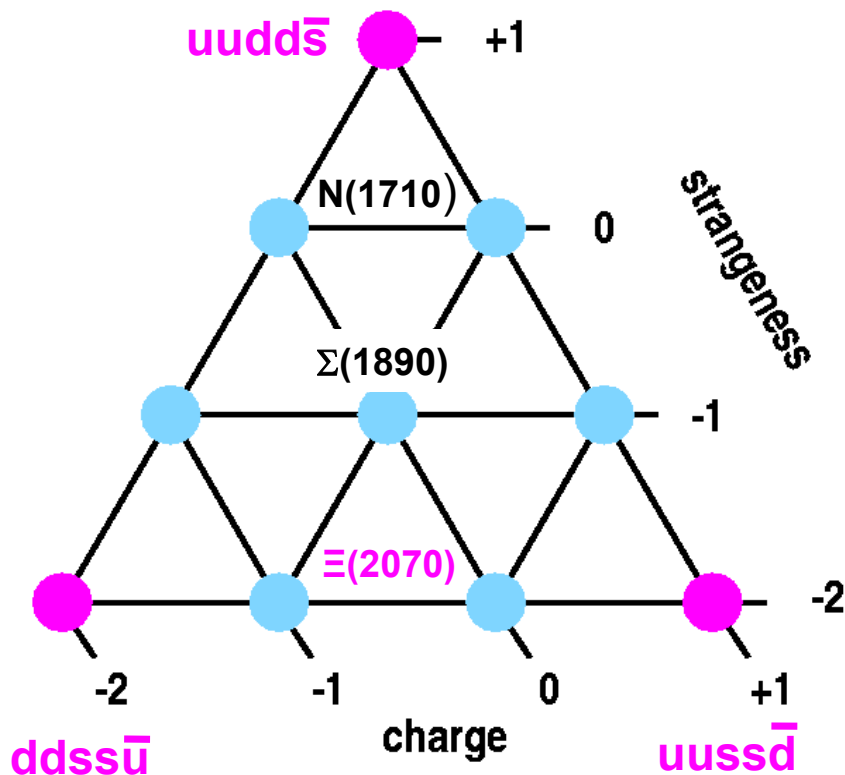# Pentaquarks a HERA

A. Zoccoli
Università and INFN - Bologna

<u>Outline:</u>
-Introduction
-Pentaquark search at HERA:
    - Strange sector
    - Charm sector
-Conclusions (?)

The strange pentaquark

$\Theta^+(1530) \rightarrow nK^+$ or pK^0

uudd$\bar{s}$

N(1710)

Σ(1890)

Ξ(2070)

ddss$\bar{u}$

uuss$\bar{d}$

charge

strangeness

$\Xi^{--} \rightarrow \Xi^-\pi^-$ or Σ^-K^- $\Xi^+ \rightarrow \Xi^0\pi^+$ or Σ^+K^0

The anti-decuplet proposed by Diakonov, Petrov & Polyakov (Z.Phys.A359 (1997) 305) with the three exotic baryons at the corners - requiring the indicated five valence quarks - and their decay modes. Masses in MeV are given in parentheses.
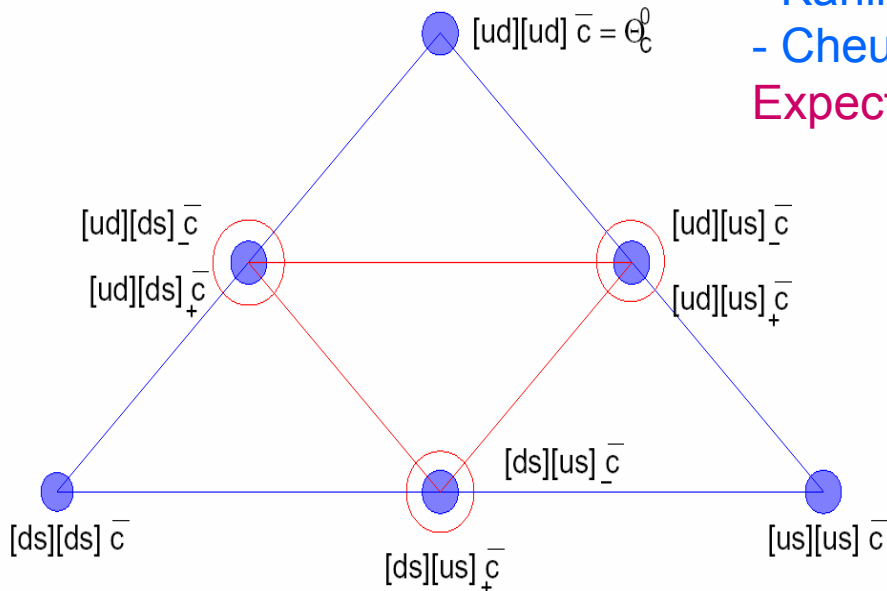
Most exciting for experimental investigations is the prediction of a width of less than 15 MeV for the $\Theta^+(1530)$ state.

The charm pentaquark

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

$uudd\bar{c}$

Many recent theoretical predictions:
- Jaffe-Wilczek → M~2710 MeV
- Wu-Ma   → M~2704 MeV
- Karliner-Lipkin → M~2985 MeV
- Cheung   → M~2938-2997 MeV
Expected width ~ 20 MeV

Decay modes:
- M < 2807 MeV $\theta^0_c \rightarrow \theta^+ \pi^-$
- M < 2948 MeV $\theta^0_c \rightarrow D^- p$
- M > 2948 MeV $\theta^0_c \rightarrow D^{*-} p$
because of mass thresholds.
Main search decay channel :

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

Studied channels

🌐 **Strange pentaquark**

$$\theta^+ \rightarrow \begin{cases} nK^+ \\ pK^0 \end{cases}$$

M~ 1530 MeV

$$\Xi^{--} \rightarrow \Xi^-\pi^- \rightarrow (\Lambda\pi^-)\pi^-$$

M ~ 1860 MeV

Narrow peaks expected

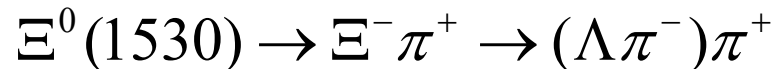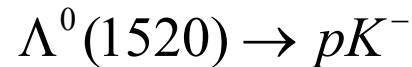→ Need particle ID for proton/kaon identification

🌐 **Charm Pentaquark**

$$\theta_C^0 \rightarrow D^{*-}\, p \rightarrow (D^0\pi^-)p$$

M > 2950 MeV
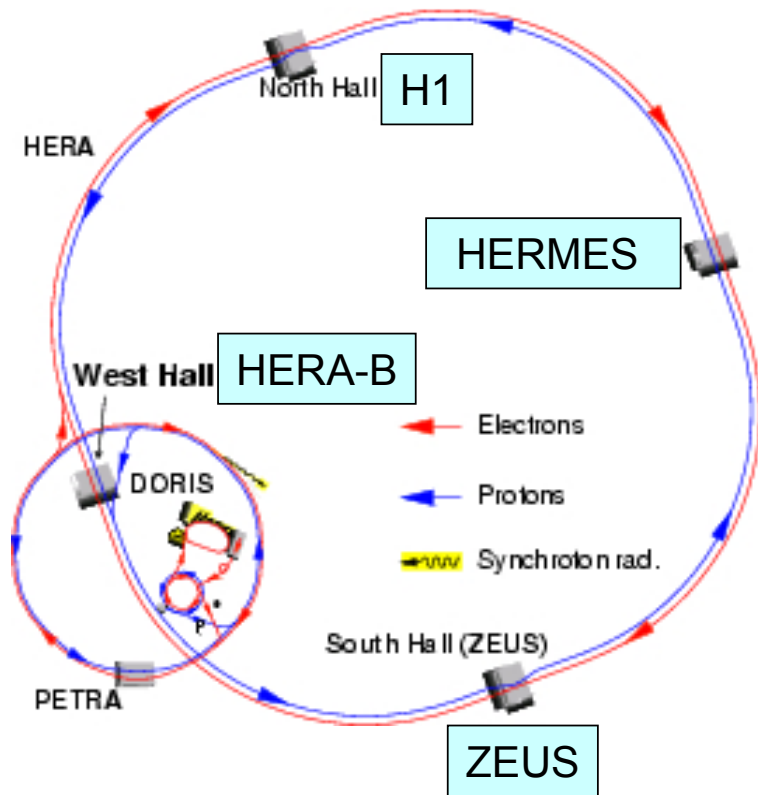
Studied channels

- **Different production mechanisms:**
  - photoproduction, neutrino, p-p, p-A, e-scatt, e-p, etc.

- **Control channels for checking detector sensitivity and particle ID capabilities:**

$$\Lambda^0(1520) \to pK^-$$

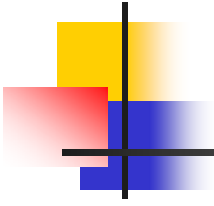$$\Xi^0(1530) \to \Xi^-\pi^+ \to (\Lambda\pi^-)\pi^+$$

→ Production ratios & cross sections useful for the comparison of the results.

The HERA experiments

Different interaction mechanisms, energies and detectors (PiD):

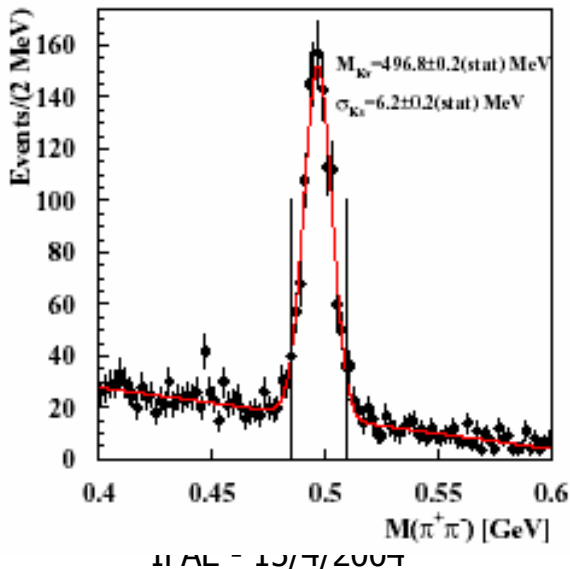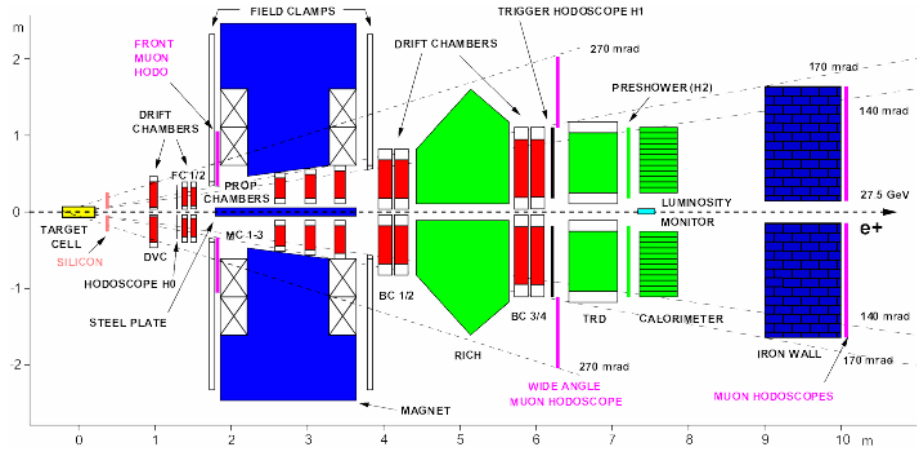|		
-HERMES	$e^{\pm}$-d	gas target
	PiD	RICH
-ZEUS/H1	$e^{\pm}$-p	collider
	PiD	dE/dx
-HERA-B	p-A	wire target
	PiD	RICH

$$\theta^+ \rightarrow pK_S^0 \rightarrow p(\pi^+\pi^-) + cc$$

- HERMES   positive result
- ZEUS   positive result
- HERA-B   negative result
- H1   negative result (NOT shown)

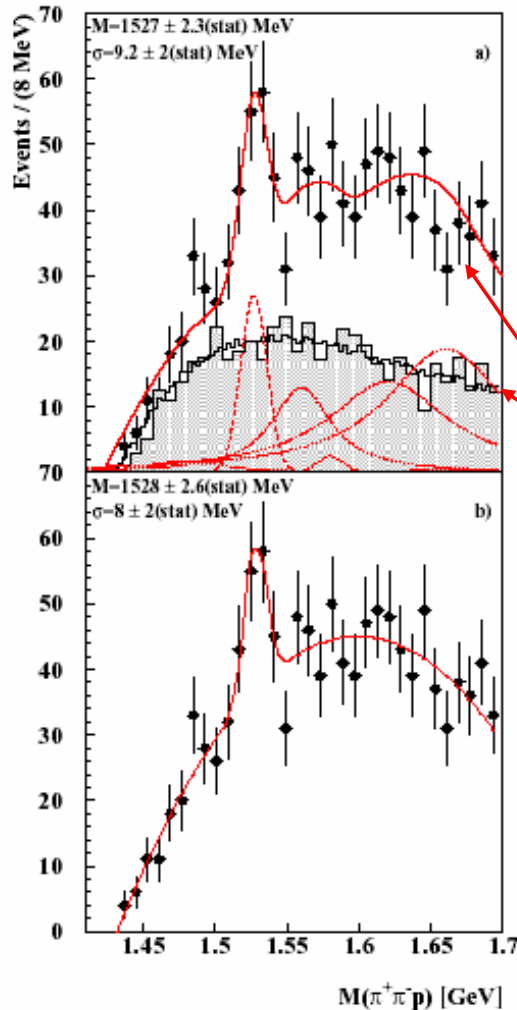Seen by: Spring-8, CLAS, SAPHIR, DIANA, Neutrino, SVD-2, Cosy-TOF

HERMES search

e$^{\pm}$-d int. (gas target)
Integrated Lumi: 250 pb^{-1}
PiD based on RICH:
→ p(p) ϵ [4,9] GeV
→ p(π) ϵ [1,15] GeV

K$_S$ statistics:
        ~ 1000 ev.
with strong lifetime cut.

Able to reconstruct Λ, Ξ and
~1000 Λ(1520)→ pK$^-$.

IPAL - 15/4/2004

HERMES ($\theta^+ \to pK_s$)

M=1527 ± 2.3(stat) MeV
σ=9.2 ± 2(stat) MeV

a)

M=1528 ± 2.6(stat) MeV
σ=8 ± 2(stat) MeV

b)

$M(\pi^+\pi^-p)$ [GeV]
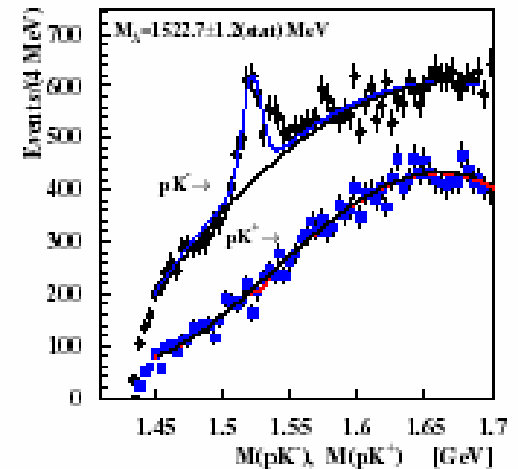
Quoted results :

- $N(\theta^+)$ = 78 ± 18 events
- $M(\theta^+)$= 1528 ± 3 MeV
- $\sigma(\theta^+)$ = 19 ± 5 MeV
- Significance: 4.2- 6.3 σ

Discrepancy with MC predictions:
$\to$ explained as Σ production

Production ratio
Λ(1520) / θ^+ :
~ 1.6 – 3.5

M_{Λ}=1522.7±1.2(stat) MeV

$pK^-\to$

$pK^+\to$

M(pK^-), M(pK^+)   [GeV]

ZEUS

e$^{\pm}$-p collisions: √s~320 GeV
Integrated lumi: 121 pb^{-1}
PiD based on dE/dx
→p(p) <1.5 GeV

dE/dx for p/p̄ candidates

Kinematic variables:
Q^2 :4-momentum transfer
→ Q^2>1 GeV
W: γ-p c.m. energy

Analyses on: pK$_S$, Ξπ channels
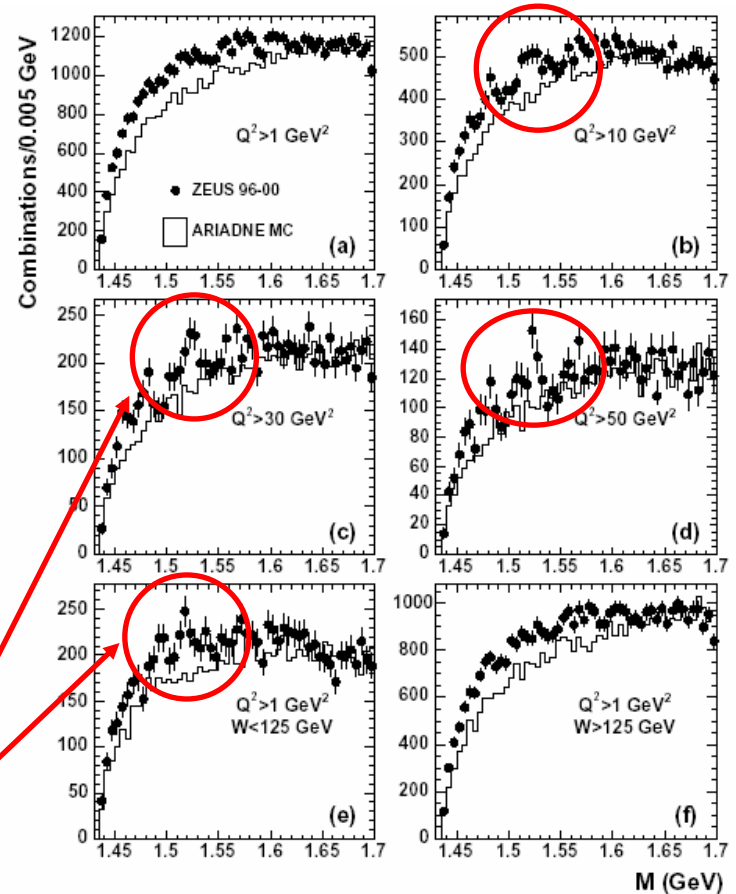D*$^-$p channel

IFAE - 15/4/2004

ZEUS ($\theta^+ \to pK_s$)

<u>K_S signal</u>: 866800 ± 1000
800 times larger than Hermes

<u>pK_s combination</u>:
• many different cuts applied
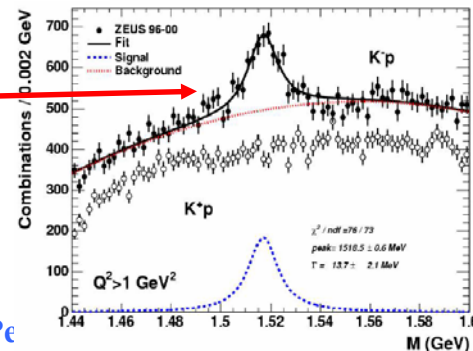• structures at ~ 1520 MeV
→ Increase with Q^2 decrease with W
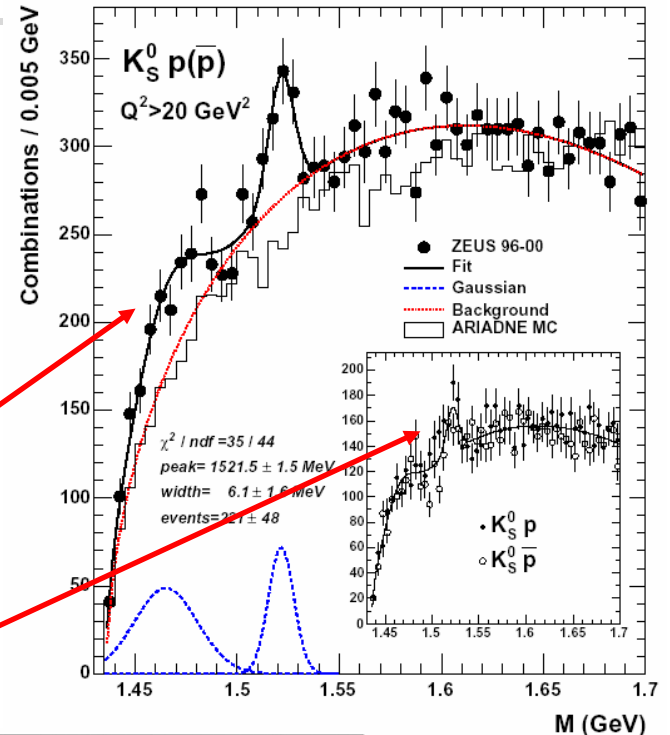
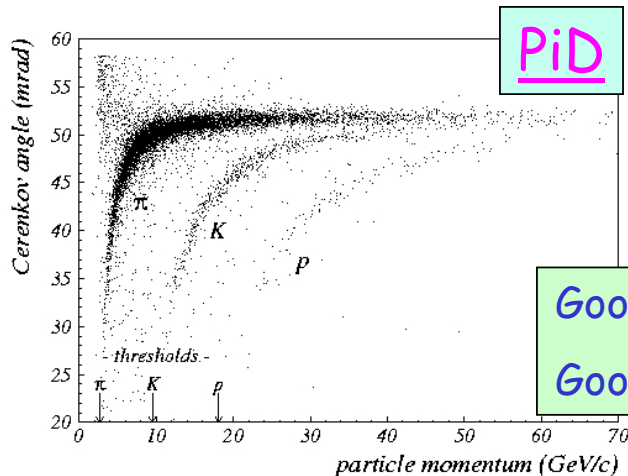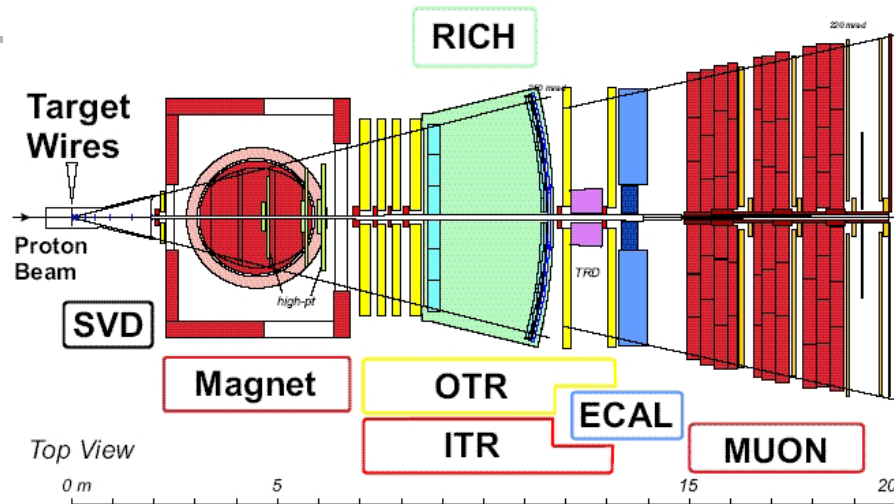# ZEUS ($\theta^+ \rightarrow pK_s$) results

Quoted results:

- N(θ^+) = 211 ± 48 events
- M(θ^+)= 1521.5 ± 1.5 MeV
- σ(θ^+) = 6.1 ± 1.6 MeV
- Significance: 3.9-4.6 σ

- Production of Σ(1480) ?
- production seen in pK_S and p̄K_S (96±34 ev)
- Λ(1520) → pK^- seen (~10σ)
- no production ratio or cross section quoted

$K_S^0 p(\bar{p})$
$Q^2 > 20$ GeV^2

- ZEUS 96-00
— Fit
---- Gaussian
···· Background
☐ ARIADNE MC

χ^2 / ndf =35 / 44
peak= 1521.5 ± 1.5 MeV
width= 6.1 ± 1.6 MeV
events=221 ± 48

· K_S^0 p
∘ K_S^0 p̄

- ZEUS 96-00
— Fit
---- Signal
···· Background

K^-p

K^+p

$Q^2 > 1$ GeV^2

χ^2 / ndf =76 / 73
peak= 1518.5 ± 0.6 MeV
Γ = 13.7 ± 2.1 MeV

HERA-B searches

- p-A interaction

$\sqrt{s}$ = 41.6 GeV and

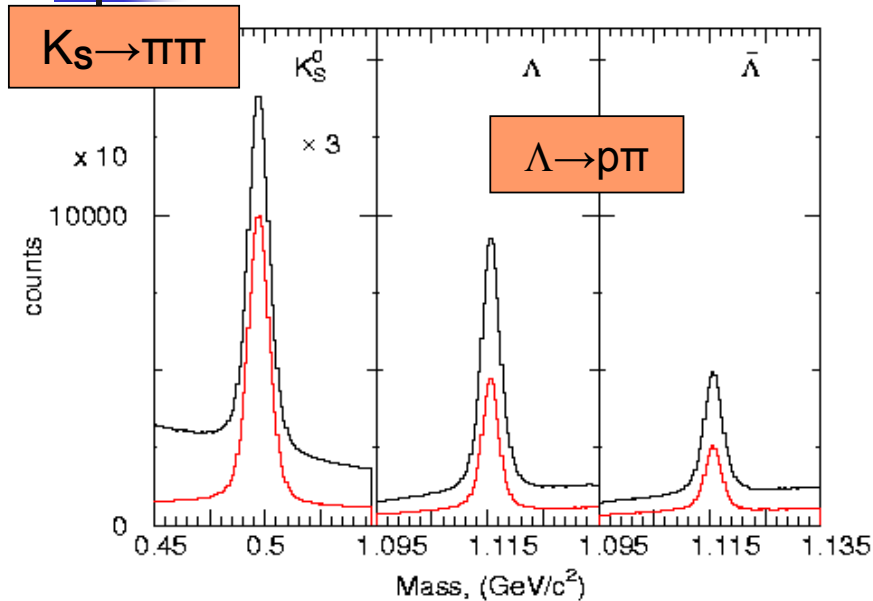IR ~ 5 MHz

- Large acceptance at mid-rapidity

- PiD with RICH

PiD

Statistics:

220 x10^6 Minimum Bias events
(^{12}C, ^{184}W and ^{48}Ti)

Good kaon   ID: 10< p <60 GeV

Good proton ID: 20< p <60 GeV

HERA-B: K_S, Λ reconstruction

$K_S \rightarrow \pi\pi$

$\Lambda \rightarrow p\pi$

Applied cuts:
- CDA < 300 μm
- $p_t c\tau$ > 0.02 (Gev/c)×cm

Backgound rejection: 95%
Signal efficiency: 90%

Armenteros plot

Statistics:

~3.400.000 K_s σ ~ 4,9 MeV

~ 940.000 Λ σ ~ 1,8 MeV

~ 450.000 $\overline{\Lambda}$

4 times larger than ZEUS.

HERA-B: the Λ(1520) → p K⁻

Carbon target

Applied PiD cuts:

p likelihood > 0.95

K likelihood > 0.95

A strong signal visible at 1520 GeV for both particle and antiparticle.

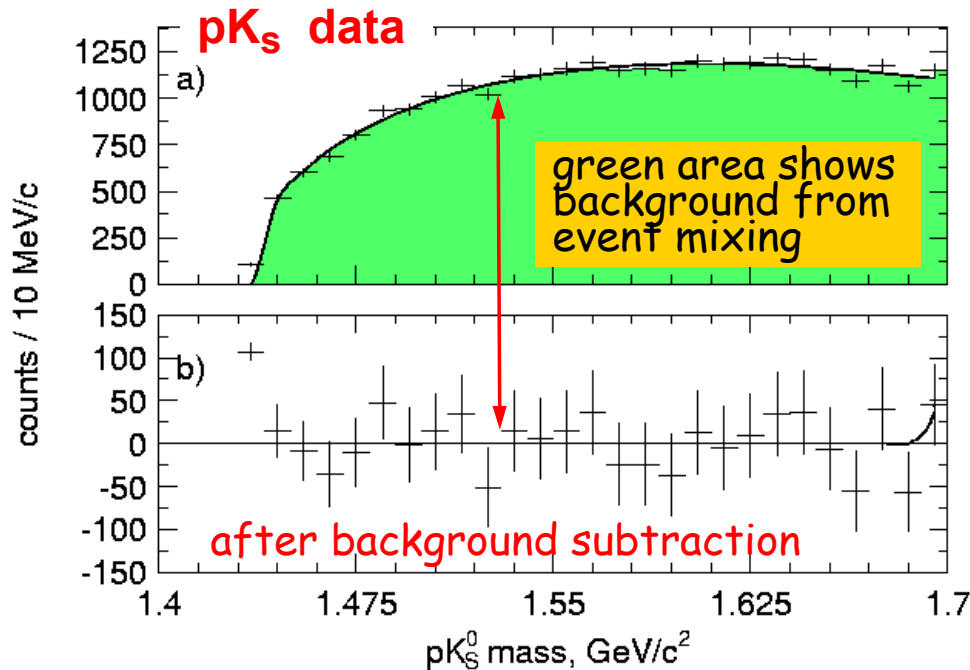Simulation of kinematic reflections of two-body decays are also shown.

Λ: ~ 2000, σ ~ 8 MeV
$\overline{\Lambda}$: ~ 1000, σ ~ 8 MeV

→ Good proton/kaon identification

p-K^0: invariant mass

Preliminary!

Carbon target

pK$_S$ data

green area shows background from event mixing

after background subtraction

pK$_S$ combination:
- p likelihood > 0,95
- analysis performed on 3 different samples/targets (C,Ti,W)
- Many sistematic checks:
  - low multiplicity,
  - s-tag
  - PiD
  - Kinematic cuts

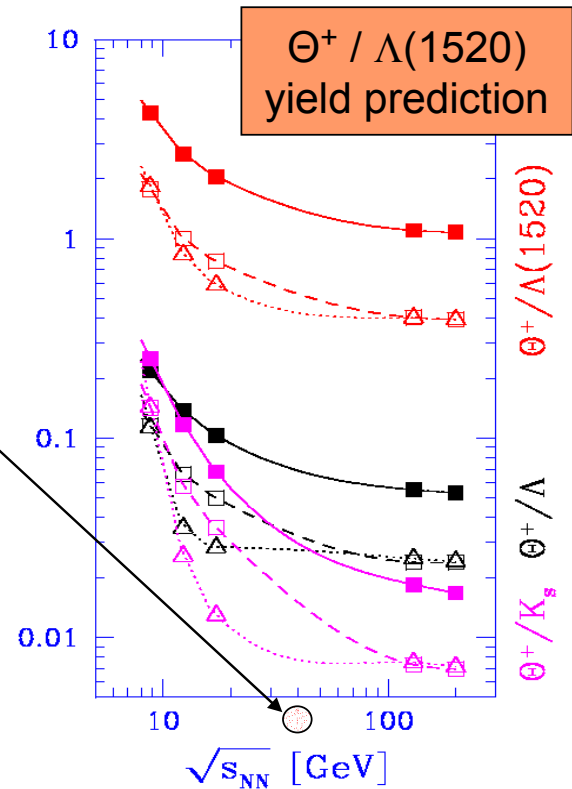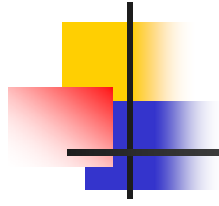No evidence of resonances in the mass region around 1.530 GeV.

HERA-B Results: Θ^+

• At mid-rapidity the sensitivity in BR * $d\sigma/dx_f$ is about 5μb/nucleon. An upper limit for the cross section will be provided.

• At mid-rapidity the acceptance for Θ^+ (1530) is very similar to Λ (1520), a preliminary upper limit for the particle yield ratio is:

Θ^+ (1530)/Λ (1520) < 0.002 at 95% C.L.

• This value differs significantly from the existing theoretical prediction based on statistical hadronization (Letessier et al., hep-ph/0310188) and from the HERMES result.

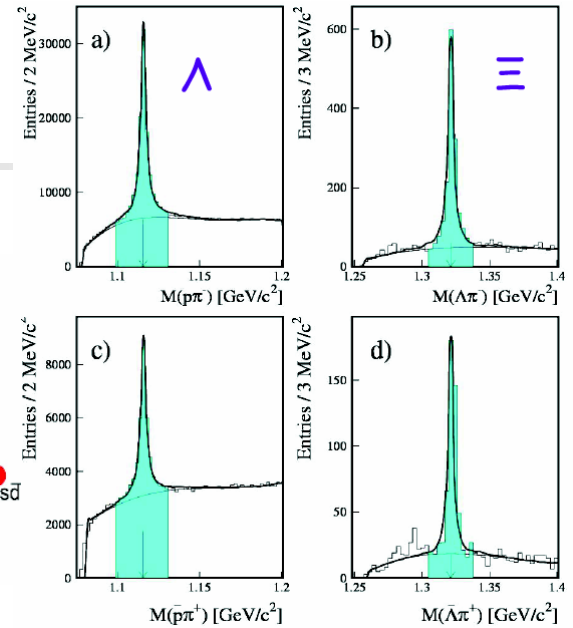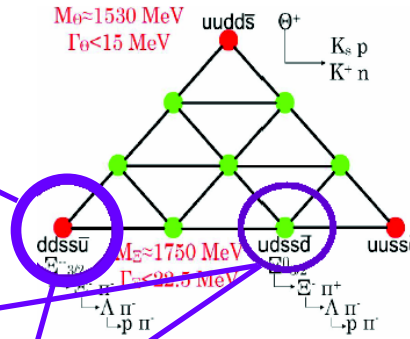Θ^+ / Λ(1520) yield prediction
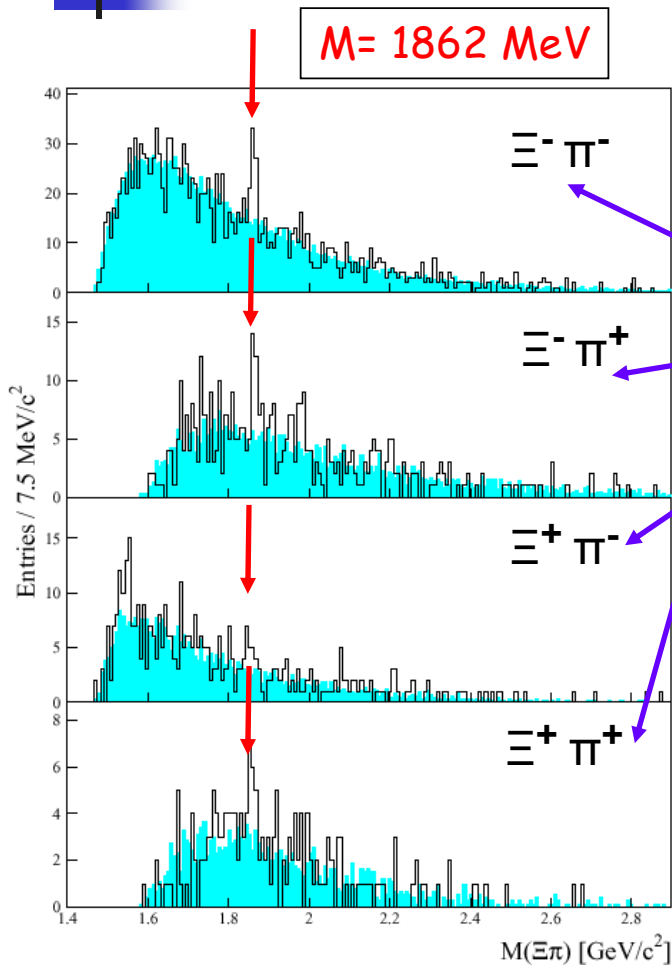
$$\Xi^{--} \rightarrow \Xi^- \pi^- \rightarrow (\Lambda \pi^-) \pi^- \rightarrow (p \pi^- \pi^-) \pi^- + cc$$

- HERMES   ??
- ZEUS: negative result
- HERA-B   negative result
- H1   ??

Seen only by the NA49 experiment

NA49: Ξ⁻⁻ results

M= 1862 MeV

Ξ⁻ π⁻

Ξ⁻ π⁺

Ξ⁺ π⁻

Ξ⁺ π⁺

M(Ξπ) [GeV/c²]

$M_\theta \approx 1530$ MeV
$\Gamma_\theta < 15$ MeV

$M_\Xi \approx 1750$ MeV
$\Gamma_\Xi < 22.5$ MeV

Λ

Ξ

- Ξ⁻ π⁺ channel: weak Ξ⁰(1530) signal. Less than in previous published results

• Ξ⁻ π⁻ channel:

signal: 75,5 events
significance: 5,6 σ

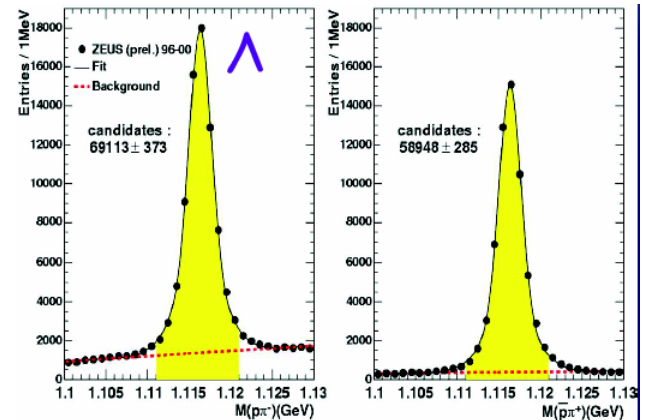Unique positive result on Ξ⁻⁻ !!

ZEUS: Ξ^{--} search

Strategy:

- reconstruct Λ from V_0 decay
- reconstruct $\Xi^{\pm}$ from $\Lambda\pi$ decay
- reconstruct Ξ^{--} from $\Xi\pi$ decay
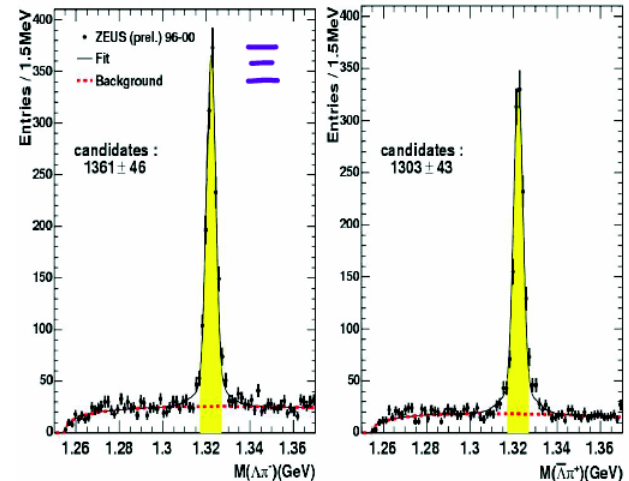
PiD needed for p reconstruction
Same sample as before

Statistics:

69113 ± 373 Λ
58948 ± 285 $\bar{\Lambda}$
1361 ± 45 Ξ^-
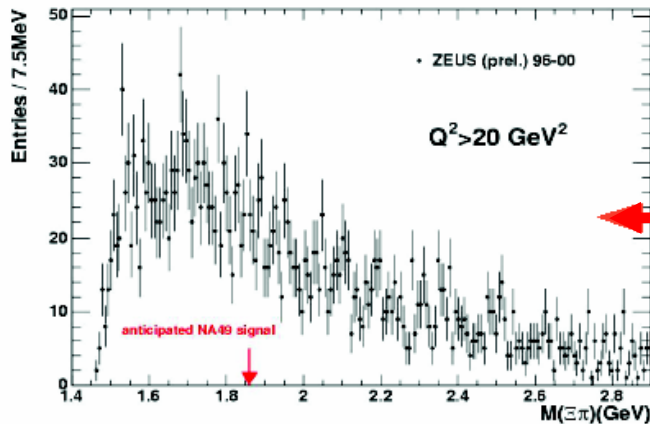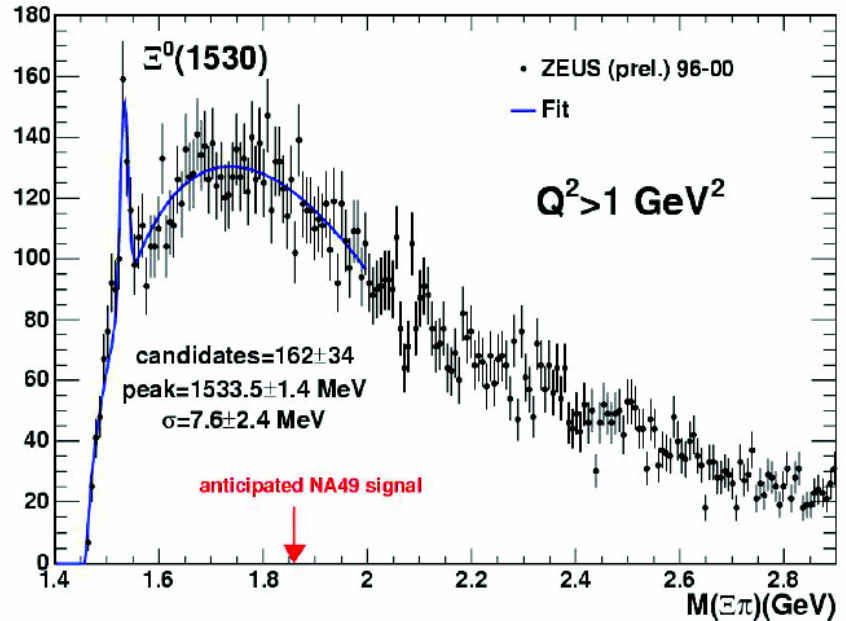1303 ± 43 $\bar{\Xi}^+$

Small background & large statistics

ZEUS: $\Xi \to \Lambda\pi$ reconstruction

$\Xi^- \pi^+$ channel: clean $\Xi^0(1530)$ signal (162 ± 34 ev.), larger than NA49.

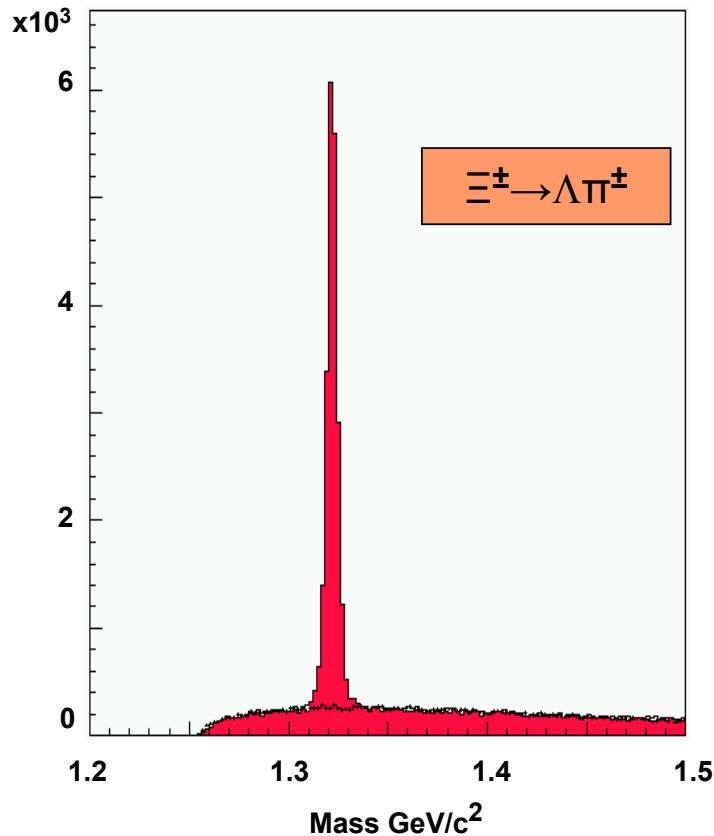$\Xi^- \pi^-$ channel: **no evidence** for narrow signal between 1.8 and 1.9 GeV.

- ZEUS (prel.) 96-00
— Fit

$\Xi^0(1530)$

$Q^2 > 1$ GeV^2

candidates=162 ± 34
peak=1533.5 ± 1.4 MeV
$\sigma=7.6\pm2.4$ MeV

anticipated NA49 signal

$M(\Xi\pi)$(GeV)

Entries / 7.5MeV

- ZEUS (prel.) 96-00

$Q^2 > 20$ GeV^2

anticipated NA49 signal

$M(\Xi\pi)$(GeV)

No signal for $Q^2 > 20$ GeV^2 as well !

HERA-B: $\Xi \to \Lambda\pi$ reconstruction

All targets

x10³

6

4

2

0

$\Xi^{\pm} \to \Lambda\pi^{\pm}$

1.2   1.3   1.4   1.5

Mass GeV/c²

Selection criteria:

• Same strategy as before

• Λ and π have large impact to primary

• Ξ^- candidate point to the primary.

→ Small background, Ξ peaks at the correct position.

<u>Statistics:</u>

~11.300 Ξ^-, $\sigma \sim$ 2,6 MeV

~ 7.700 Ξ^+, $\sigma \sim$ 2,6 MeV

→ One of the largest available statistics.

Ξ-π: invariant mass

-Ξ⁻ π⁺ channel: prominent
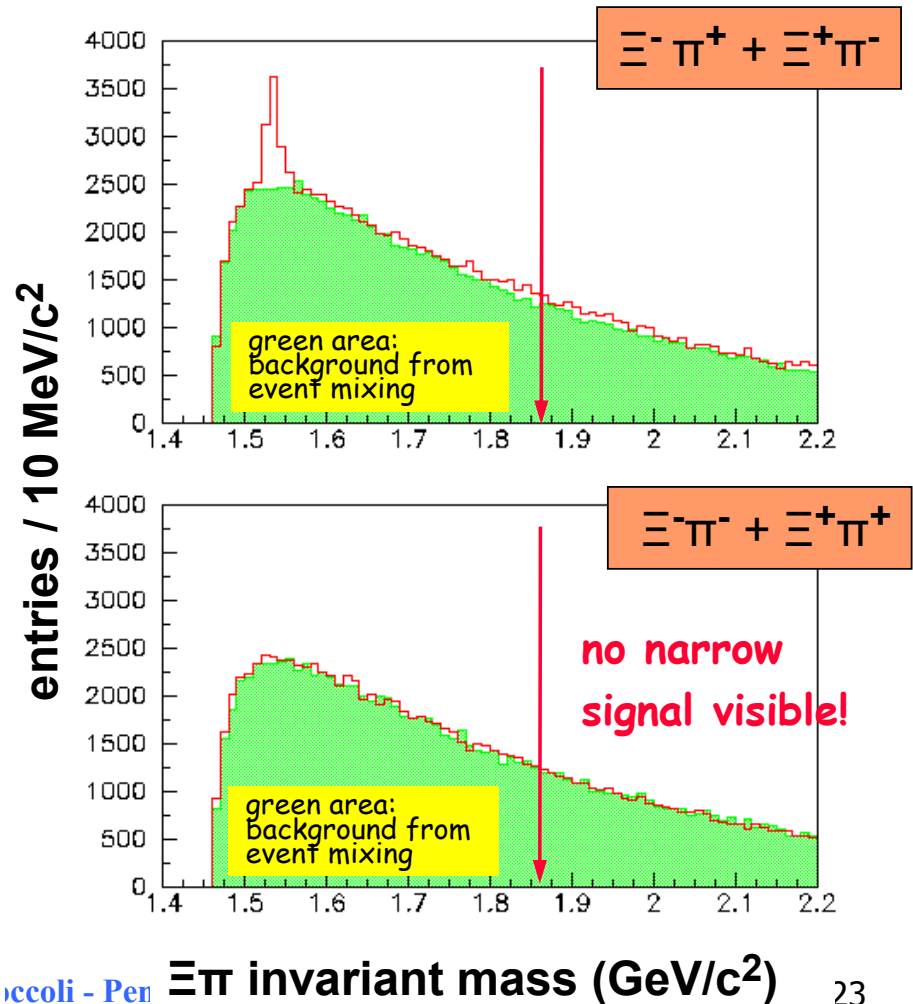Ξ⁰(1530) (~ 3000 ev) signal and
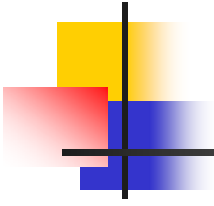possible weak evidence for
known higher Ξ* resonances.

• Ξ⁻ π⁻ channel: **no evidence** for
narrow signal between 1.8 and
1.9 GeV. Sensitivity for Ξ⁻⁻
(1862) signal at mid-rapidity is
Br· dσ/dx$_F$ ~ 10 μbarn/nucleon.

• Preliminary values: for the
upper limits of the relative
production yields

Ξ⁻⁻(1862) / Ξ⁰(1530) < 0.04
Ξ⁺⁺(1862) / Ξ⁰(1530) < 0.055

Ξ⁻π⁺ + Ξ⁺π⁻

green area:
background from
event mixing

Ξ⁻π⁻ + Ξ⁺π⁺

**no narrow
signal visible!**

green area:
background from
event mixing

entries / 10 MeV/c²

Ξπ invariant mass (GeV/c²)

$$\theta_C^0 \rightarrow D^{*-} p \rightarrow (D^0 \pi^-) p \rightarrow (K^- \pi^+ \pi^-) p + cc$$

- HERMES   ??
- ZEUS: negative result
- HERA-B   ??
- H1   positive result
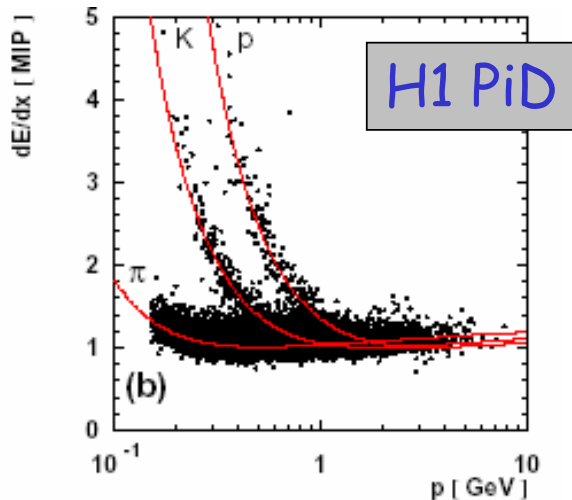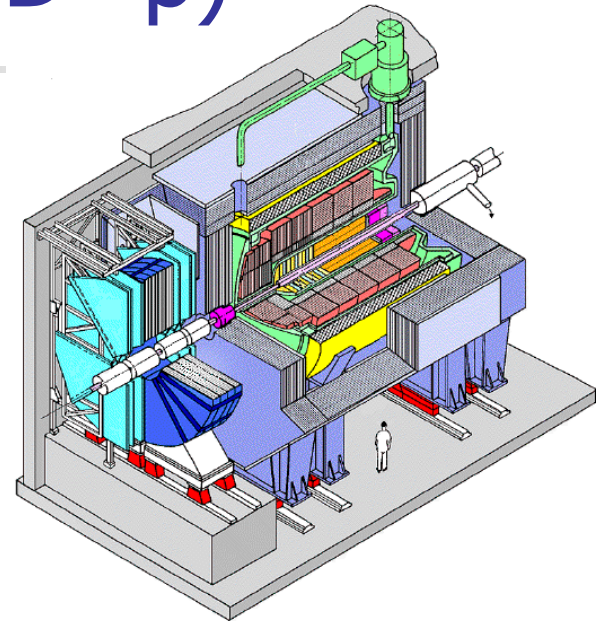
Seen only by the H1 experiment

H1 search for $(\theta^0_C \to D^{*-}p)$

$e^{\pm}$-p collisions
Integrated Lumi: 75 pb^{-1}
PiD based on dE/dx good
perfomances $\to$ p(p)<2 GeV

NO SIGNAL in the pK$_s$ channel !!

H1 PiD

The procedure:
D* selected in the decay channel:
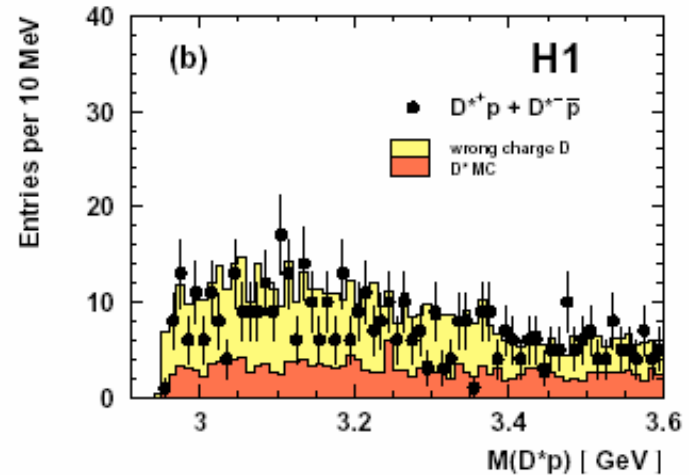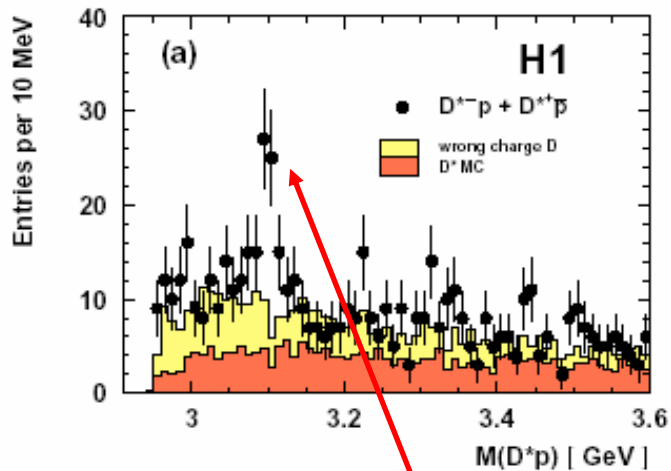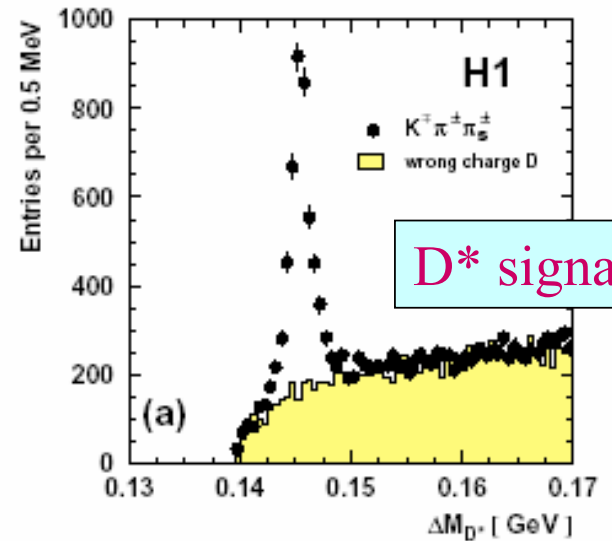$$D^{*-} \to D^0 \pi^- \to (K^- \pi^+)\pi^-$$
and then combined with a proton.

H1 ($\theta^0_c \rightarrow D*^-p$)

D* signal

D* Statistics:
  N(D*$^\pm$) ~ 3000 ev
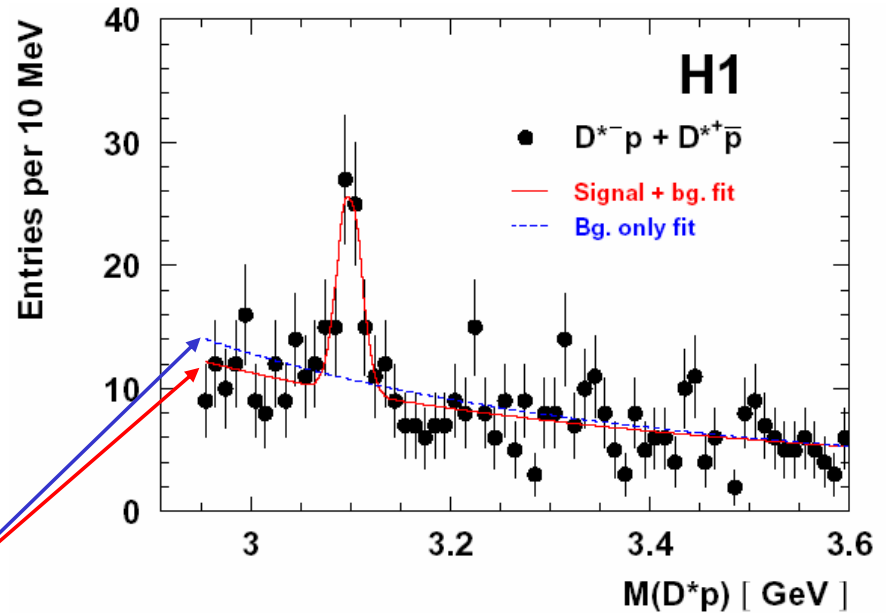
then after the combination with proton:

Peak seen in the right charge combination.

H1 ($\theta^0_c \rightarrow D^{*-}p$)

Quoted Results:

- $N(\theta^0_c)$ = 50.6 ± 11.2 ev.
- $M(\theta^0_c)$= 3099 ± 3 MeV
- $\sigma(\theta^0_c)$ = 12 ± 3 MeV
- Seen both in the D*⁻p (26 ev) and in the D*⁺p̄ (23 ev) channels.
- Significance: 5.4-6.2 σ

Tests performed on PiD, on kinematic and on reflections. Small excess seen also in photoproduction.

ZEUS ($\theta^0_C \rightarrow D^{*-}p$)

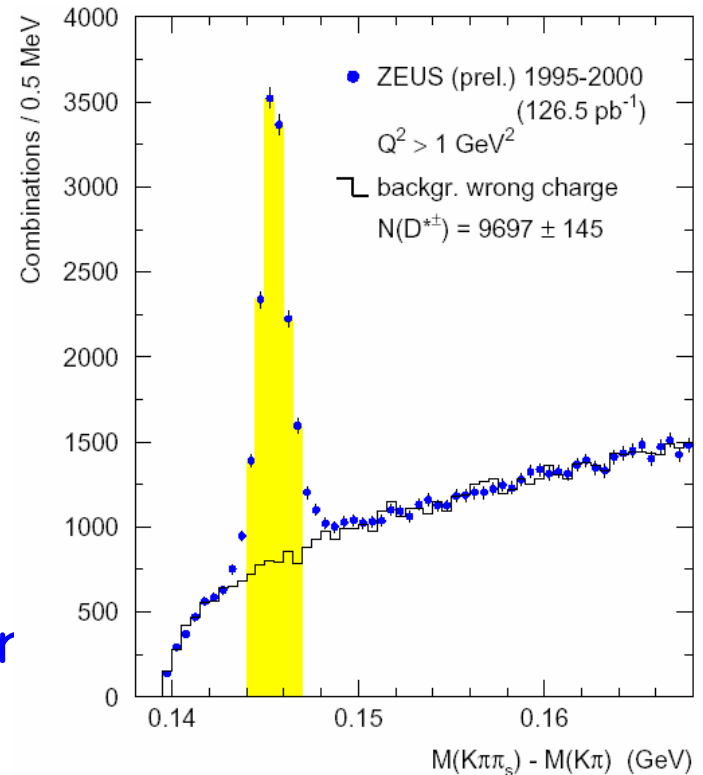Integrated Lumi.: 126,5 pb^{-1} (1.7 larger than H1 !)
Same strategy as before.
PiD based on dE/dx.
Selection cuts similar to H1.
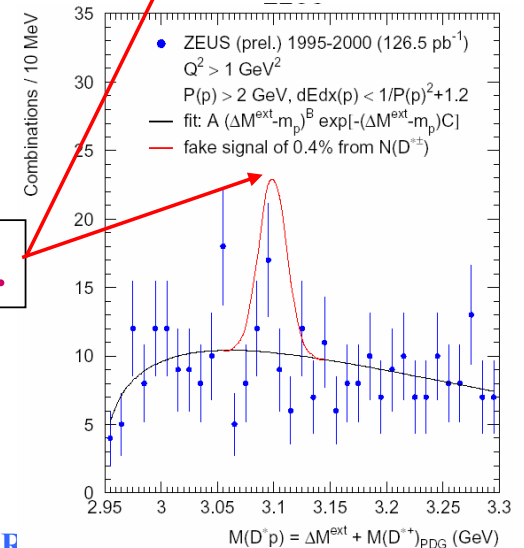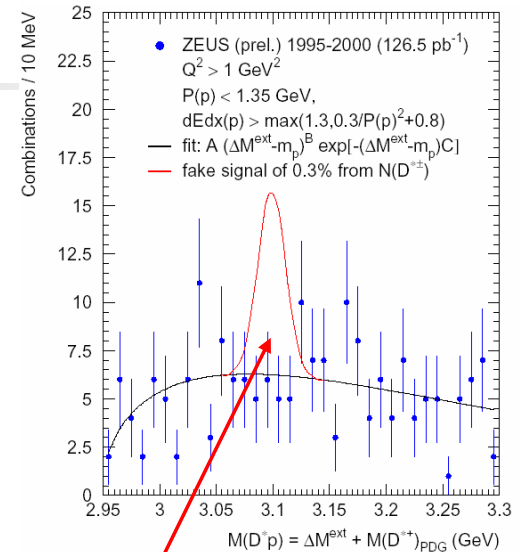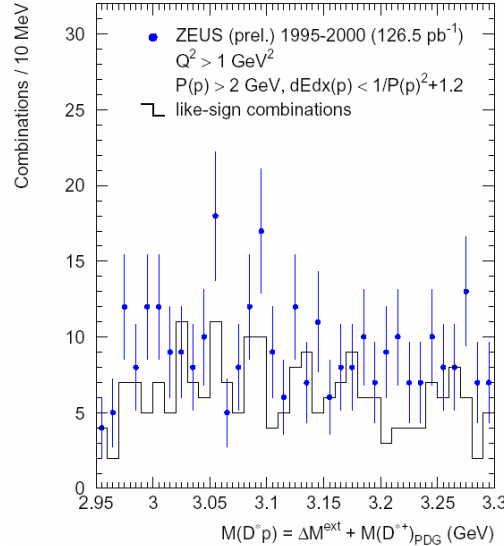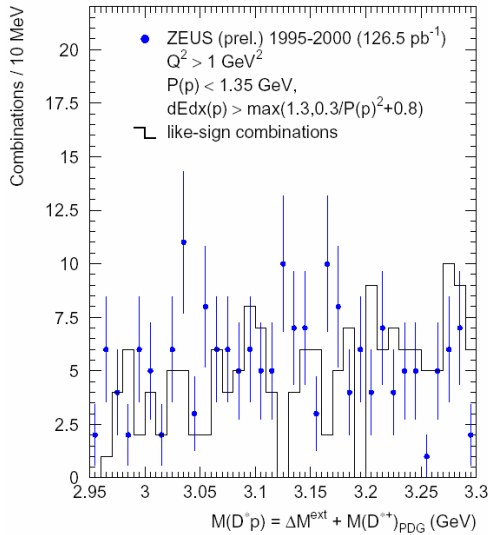
Statistics:
    N(D$^{*\pm}$) = 9697 ± 145
a factor 3 larger than H1 (a factor 4.5 smaller than in inclusive case).

Detailed studies with different dE/dx and momentum ranges

ZEUS ($\theta^0_c \rightarrow D^{*-}p$)

$Q^2 > 1$ GeV

Signal expectation based on the H1 result.

🌍 NO visible signals !!
🌍 Not compatible with the H1 result.

Summary @ HERA

Situation from the 4 HERA experiments:

	Inter.	# Ks	# Λ(1520)	# θ+	# X	# X--	# D*	# θc
HERMES	e-d	~ 1.000	~ 1.000	76 ± 18		??		??
HERA-B	p-A	~ 3.400.000	~ 10.000	NO	~ 19.000	NO		??
ZEUS	e-p	~ 110.000	~ 10 σ	221 ± 48	~ 2.600	NO	~ 10.000	NO
H1	e-p	??	??	NO (?)		??	~ 3.000	50.6 ± 11.2

➢ $\theta^+(1530)$: 2 positive results (2-4.5σ) + 2 negative results

➢ $\Xi^{--}(1860)$: 2 negative results (agreement !!)

➢ $\theta^0_C(3100)$: 1 positive (5-6σ) + 1 negative result

Situation still unclear. Clear discrepancies between ZEUS and H1

Conclusions

- $\Xi^{--}(1860)$: NOT confirmed by any experiment, but should be there if θ^+ is a pentaquark
- $\theta^+(1530)$: many positive results (few σ), still to clarify:
    - Mass and width
    - Production ratio vs $\Lambda(1520)$
    - Production cross section
- $\theta^0_c(3100)$: seen by H1 NOT confirmed by ZEUS

Conclusions-II

🌐 Why such a differences ?

- 🔴 Production mechanism
- 🔴 Detector performances/acceptances
- 🔴 PiD kinematic cuts

🌐 Still needed solid comparisons between different experiments

🌐 Is there a conclusion? In my opinion not yet !