The experimental search for CHARM pentaquarks (ZEUS)

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O U T L I N E

- **I:** Introduction: Narrow pentaquarks
- **II:** The ZEUS D* Data
- **III:** Zeus search for Charm pentaquark
- **IV:** Conclusions

Exotic Hadronic Pentaquarks

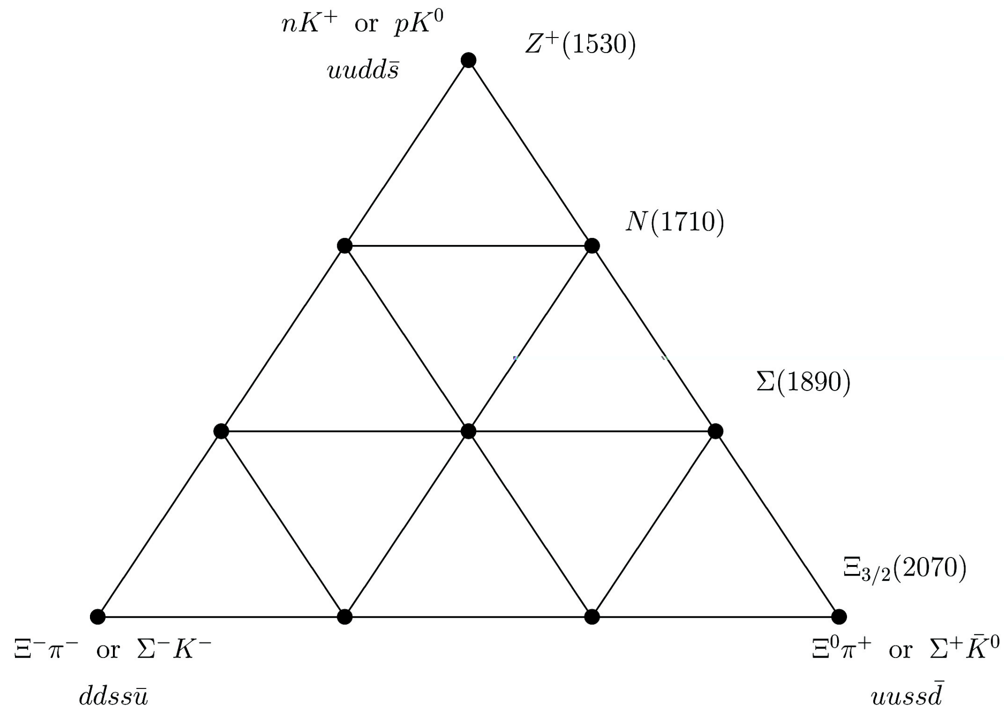
Observations of narrow states were recently reported. The significance was always between 3-7σ. Some examples:

- BaBar, CLEO, Belle: New D_s mesons $D_s(2317)$ and $D_s(2457)$ with masses lower than quark model expectations
- Many experiments, mainly fixed target at low energy, observe a narrow exotic baryon state $\Theta^+(1530) \to K^+n$ or K^0p with $S = +1$.
  See also report of the CLAS collaboration at Jlab, in this conference.
- ZEUS also reported observing $\Theta^+(1530)$ (Update in previous talk). $\Theta^+(1530)$ cannot be made of 3 quarks but it can be made of 5 quarks $uudd\bar{s}$.
  Such Pentaquarks do not exist in the naive quark model, but QCD does not forbid 5-quark hadronic states
- Many other experiments have searched but have NOT seen the $\Theta^+(1530)$
- H1 reported in March 2004 the observation of a narrow charm pentaquark $\Theta_c^0(= uudd\bar{c}) \to D^{*\pm}p^{\mp}$ at 3.1 GeV (Update,previous talk) ZEUS reported no observation of this resonance.
- Sept. 2004: ZEUS published the NO observation of $\Theta_c^0(3099)$

Many high statistics experiments searched but did NOT see the Θ_c^0.
Many theory papers discuss the new resonances-so far NO conclusions !

The Skyrme model prediction

A narrow ($\Gamma < 15$ MeV) exotic state with strangeness $S = +1$, $J^P = 1/2^+$ and $I = 0$ was predicted by Diakonov et al. (Z.Phys.A359,305,1997) on top of a $SU(3)$ anti-decuplet of baryons



With linear SU(3) breaking in $Y = B - S$ (as in the SU3 decuplet) and ASSUMIMG the $N(1710)$ to be S=0 member of the anti-decuplet, the $S = 1$ member is predicted to have $M \approx 1.53$ GeV. The $S = -2$ $\Xi_{3/2}$ anti-decuplet members are predicted to have $M \approx 2.07$ GeV

Charm Pentaquarks

If $\Theta^+ = uudd\bar{s}$ **exists, heavy pentaquarks, such as** $\Theta_c^0 = uudd\bar{c}$ **should also exist**

Several Theoretical Predictions:

Jaffe-Wilczek (hep-ph/0307341); Wu-Ma (hep-ph/0402244):
$M(\Theta_c^0) \approx 2700$ **MeV** $\Rightarrow$ **too light to decay to** D **mesons**

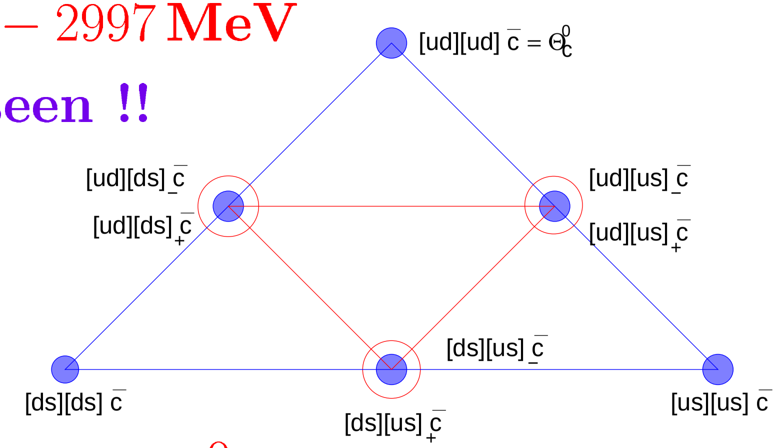
can decay weakly to $\Theta^+\pi^-$

Karliner-Lipkin (hep-ph/0307343):

$M(\Theta_c^0) = 2985 \pm 50$ **MeV ;** $\Gamma(\Theta_c^0) \sim 21$ **MeV**

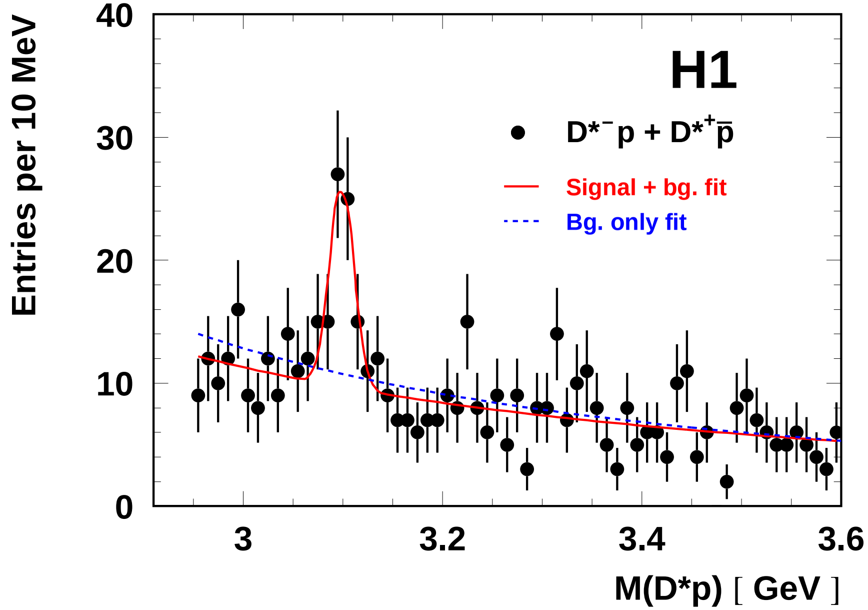
Cheung (hep-ph/0308176): $M(\Theta_c^0) = 2938 - 2997$ **MeV**
decays dominantly to D^-p^+ **or** D^0n **Not seen !!**

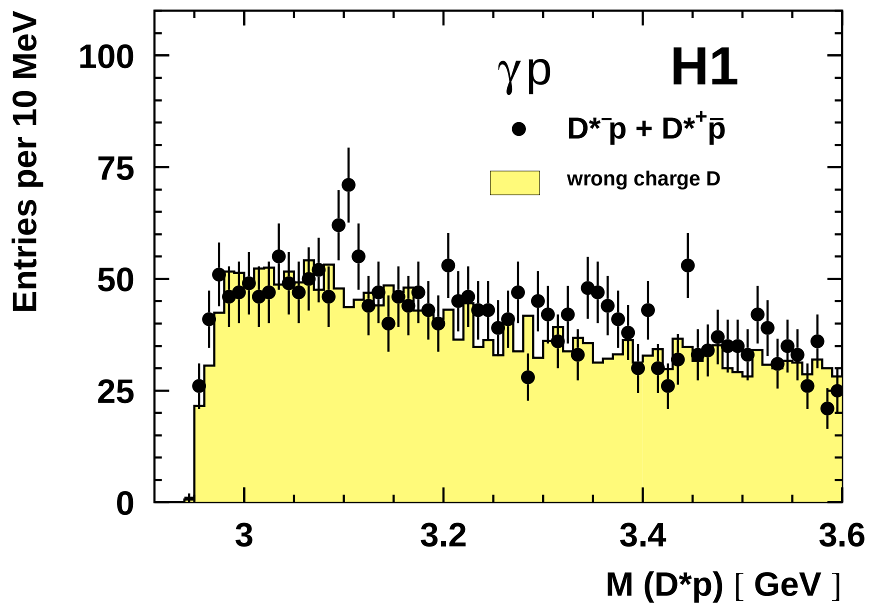
If $M(\Theta_c^0) > M(D^{*\pm}) + M(p) = 2948$ **MeV,**
Θ_c^0 **can decay to** $D^{*\pm}p$



H1 and ZEUS at HERA searched for Θ_c^0 **signal in** $M(D^{*-}p)$ **(+ c.c.) spectra, where** $D^{*+} \rightarrow D^0\pi_s^+$ **(+ c.c.)**

The H1 Charm Pentaquark





In a DIS sample of ≈ 3400 $D^{*\pm}$ H1 reported observation of a narrow resonance in $M(D^{*-}p)$ (+ c.c.) in the D^0 decay mode $D^0 \to K^\mp\pi^\pm$ at a mass of $M = 3099 \pm 3(stat.) \pm 5(syst.)$ MeV

C. Atkas et al., Phys. Lett. B 588, 17 (2004)

The measured Gaussian width $12 \pm 3(stat.)$ MeV
The quoted mass resolution (in talks) was about 7 MeV.

The signal consists of 50.6 ± 11.2 events (see previous talk)

Roughly 1% of the total D^* production rate.($(1.46 \pm 0.32)\%$, Beijing'04)

Signal also seen in photoproduction sample with $\approx$ same ratio to D^*

ZEUS search for the Θ_c^0 - D^* selection

All ZEUS HERA-I data was examined (126.5 pb^{-1})

The $D^{*\pm}(2010)$ mesons were identified using the two decay channels

$$D^{*+} \rightarrow D^0\pi_s^+ \rightarrow (K^-\pi^+)\pi_s^+ + (c.c.). \quad (1)$$

$$D^{*+} \rightarrow D^0\pi_s^+ \rightarrow (K^-\pi^+\pi^+\pi^-)\pi_s^+ + (c.c.). \quad (2)$$

The mass difference $\Delta M = M(K\pi\pi_s) - M(K\pi)$ for channel (1) and $\Delta M = M(K\pi\pi\pi\pi_s) - M(K\pi\pi\pi)$ for channel (2) selected the D^* candidates. The efficiency of the D^* trigger was above 95%.

Peaks at 145.5 MeV in $M(D^{*+}) - M(D^0)$ demonstrate the D^* signals. The background under the peak, is given by the wrong-charge combinations. Following cuts were used to reduce the combinatorial background:
$p_T(K,\pi) > 0.45\,\text{GeV},\ ,p_T(\pi_s) > 0.1\,\text{GeV}$ **for channel (1), and** $p_T(K) > 0.5\,\text{GeV},\ p_T(\pi) > 0.2\,\text{GeV},\ p_T(\pi_s) > 0.15\,\text{GeV}$ **for channel (2).**

Kinematic D^* region: $-1.6 < \eta(D^*) < 1.6$, $p_T(D^*) > 1.35\text{GeV}$ **or** $p_T(D^*) > 2.8\text{GeV}$ **for channels (1) and (2) respectively.**

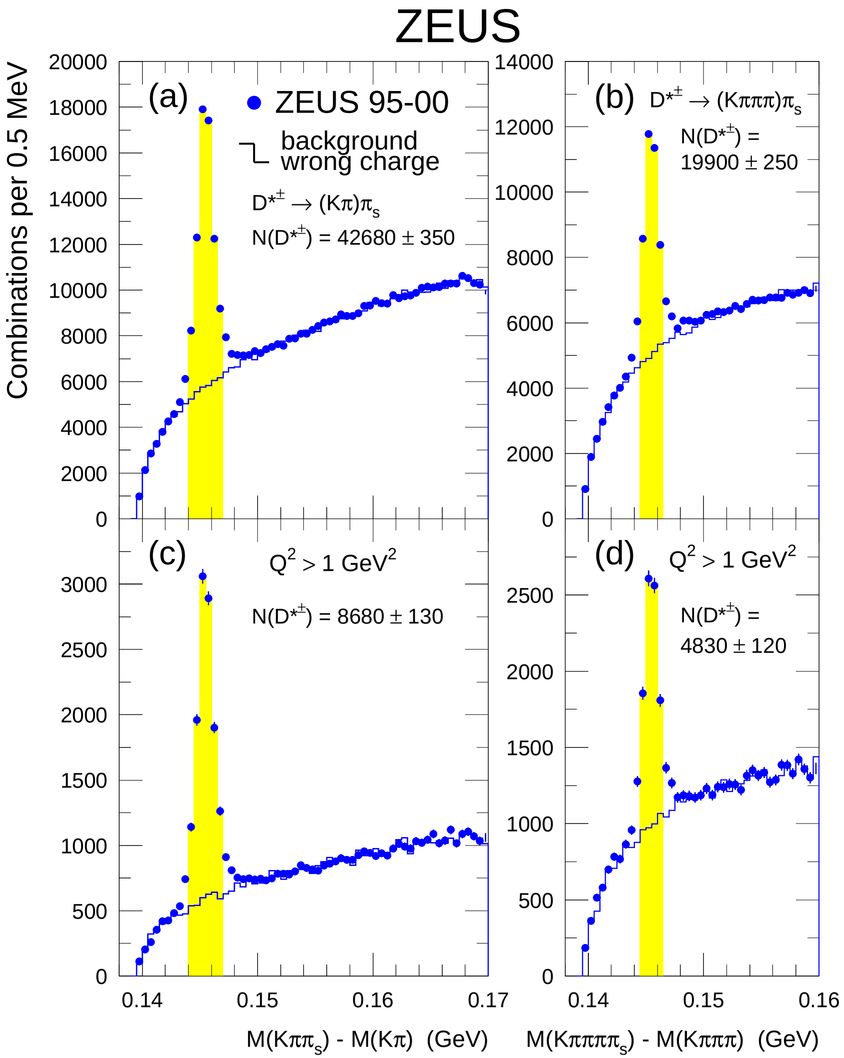
Mass windows for the D^0 selection:

$$1.83 < M(K\pi) < 1.90\,\text{GeV},\ 1.845 < M(K\pi\pi\pi) < 1.885\,\text{GeV}$$

$0.144 < \Delta M < 0.147\text{GeV}$,$0.1445 < \Delta M < 0.1465\text{GeV}$ **for channels (1,2) respectively.**

ZEUS search for the Θ_c^0

Publication: S. Chekanov et al., Eur.Phys.J.C 38 (2004) 29



$\Delta M = M(D^{*+}) - M(D^0) \sim m_\pi$

Clean D^* signals in 2 D^0 decay modes

$D^0 \to K^-\pi^+$; $D^0 \to K^-\pi^+\pi^+\pi^-$ **(+ c.c.)**

Θ_c^0 searched for with D^*'s from yellow bands $N(D^{*\pm}) \approx 62,000$

For the DIS sub-sample $Q^2 > 1$ **GeV^2**

$N(D^{*\pm}) \approx 13,500$

Proton selection: $P_T(p) > 0.15$ **GeV**

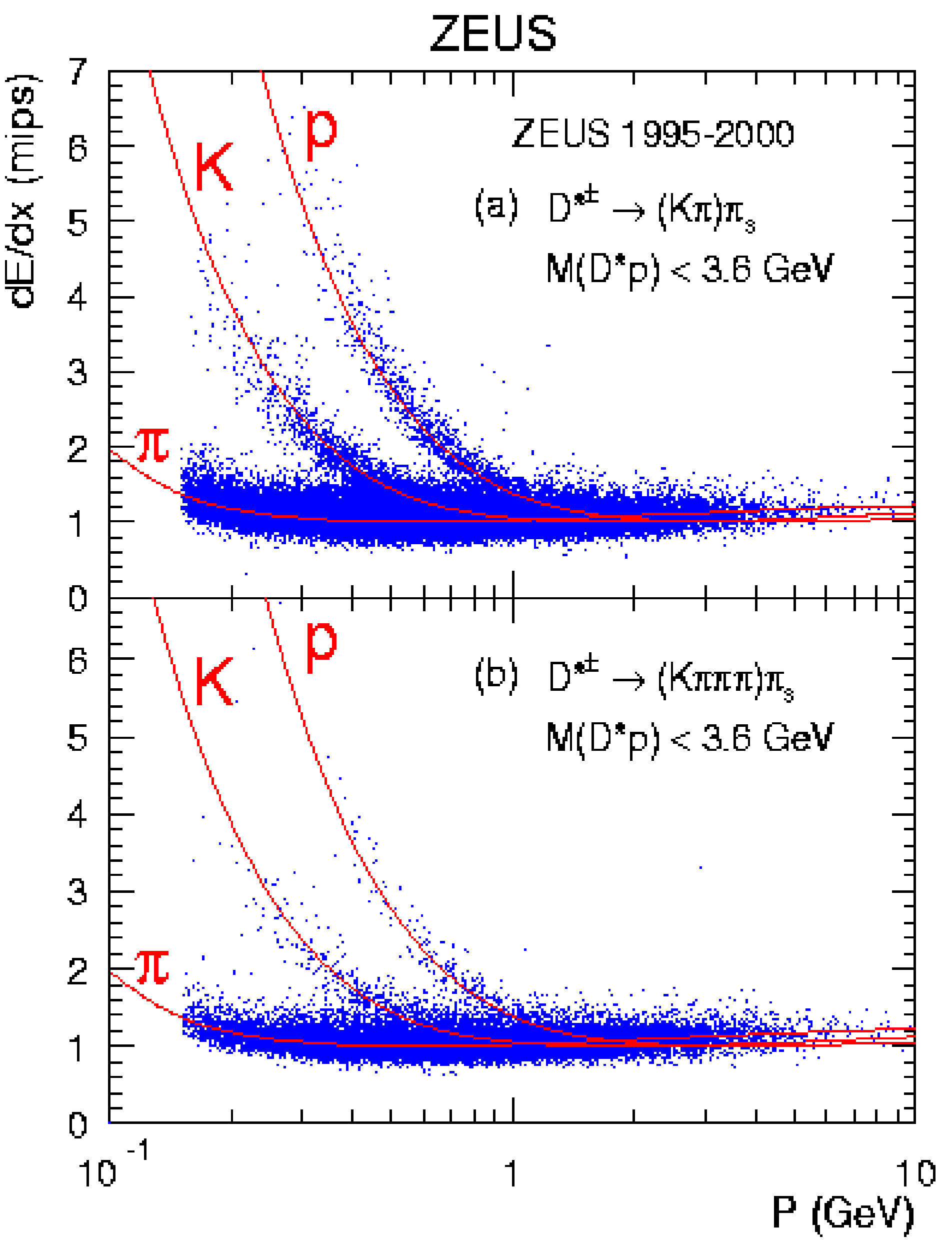
dE/dx **applied for protons.**

3 methods of p usage: (1) All Protons.

2) Low-P_p : $(dE/dx)_p$ **band;** $P < 1.35$ **GeV;** $dE/dx > 1.3$ **(Clean p's from** dE/dx**)**

3) High-P_p : $(dE/dx)_p$ **band;** $P > 2$ **GeV** **(Like H1 selection, without** dE/dx **cut)**

ZEUS search for the Θ_c^0: dE/dx



Plots of dE/dx for $M(D*p) < 3.6GeV.$

To ensure good dE/dx resolution at least 8 CTD hits were used.

P, K and π bands separated well at low momentum for both D^0 decay modes:

$D^0 \rightarrow K^- \pi^+$ **(+ c.c.)**

$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ **(+ c.c.)**

ZEUS search for the Θ_c^0: use of dE/dx

A χ_1^2 method was used for dE/dx selection. (O.Deppe,PhD Thesis,1999)

For each particle, a χ_1^2 value that estimates the deviation of the measured dE/dx from the expectation was calculated as:

$$\chi_1^2 = \frac{[\ln(dE/dx) - \ln(dE/dx)_{\text{expected}}]^2}{\sigma^2_{\ln(dE/dx)}}.$$

The resolution was parameterised empirically as $\sigma_{\ln(dE/dx)} = a/\sqrt{n}$, where n is the number of hits used for the dE/dx measurement and a is a constant determined from the sample of tagged protons. The χ_1^2 probability of the proton hypothesis, l_p, (l_p=0.0-1.0) is given by the probability for a proton to produce the observed or a larger value of χ_1^2.

The distribution of l_p for proton candidates shows a sharp peak at $l_p \sim 0$ and becomes relatively flat towards $l_p \sim 1$.

Cut to optimize the signal/background: $l_p > 0.15$.

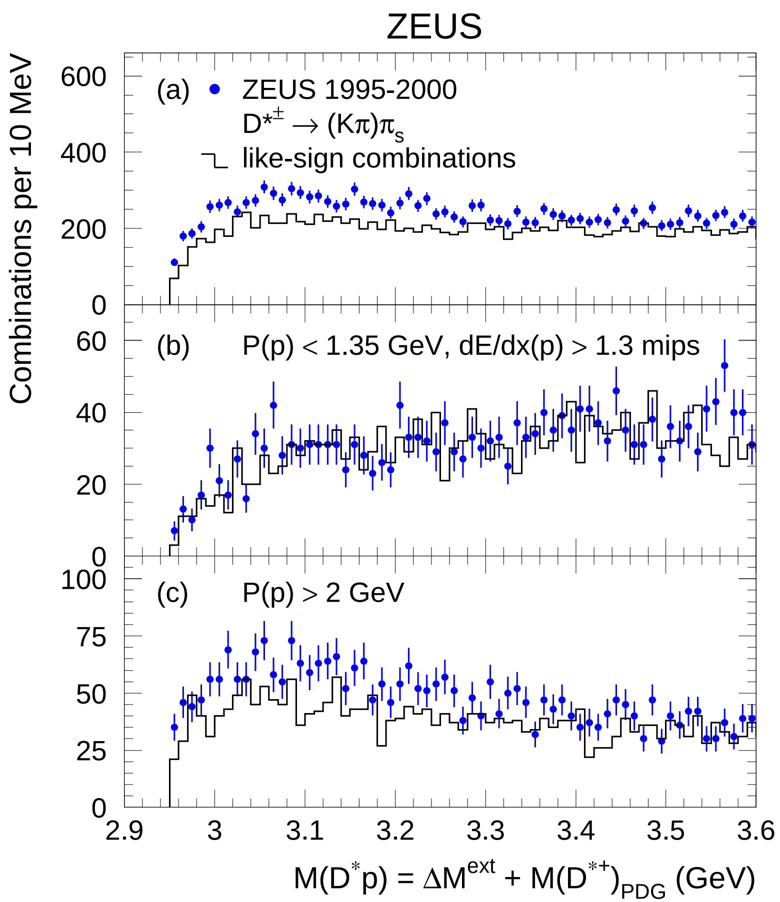
The acceptance of the protons before the cut l_p, was, using the Θ_c^0 MC, 85% and 89% for samples with D^*'s in channels (1) and (2), respectively.

After the cut $l_p > 0.15$ it became $(85.0 \pm 0.1)\%$, independent of the p momenta spectrum.

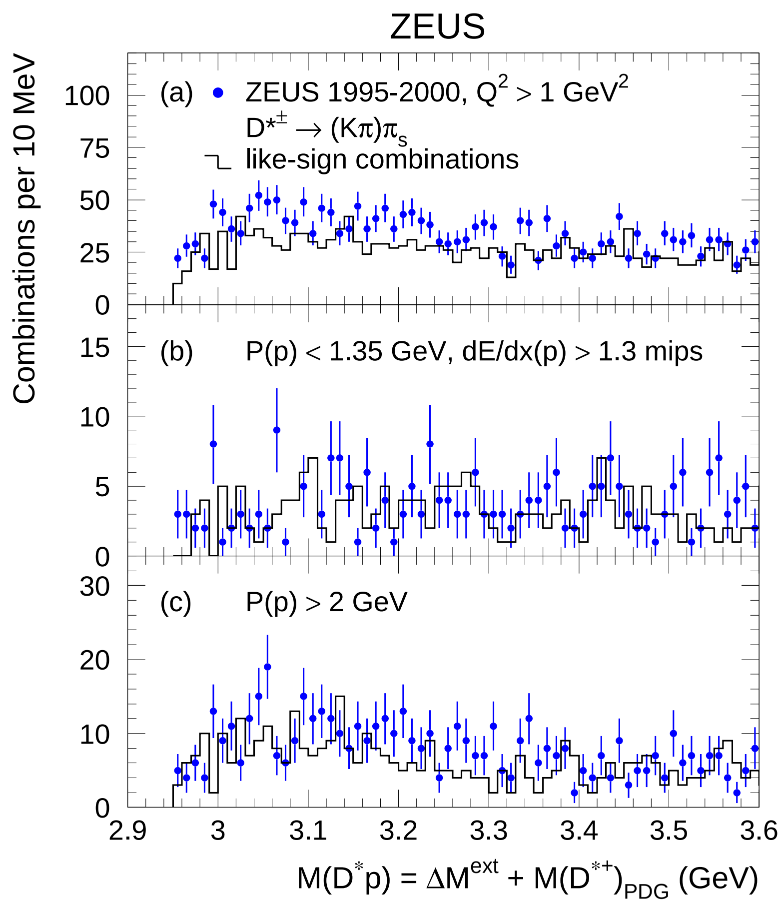
ZEUS $M(D^*p)$ spectra for the $D^0 \to K^-\pi^+$ channel

$$M(D^*p) = M(K\pi\pi_s p) - M(K\pi\pi_s) + M(D^{*+})_{\mathrm{PDG}}$$

full sample



DIS sample



All protons

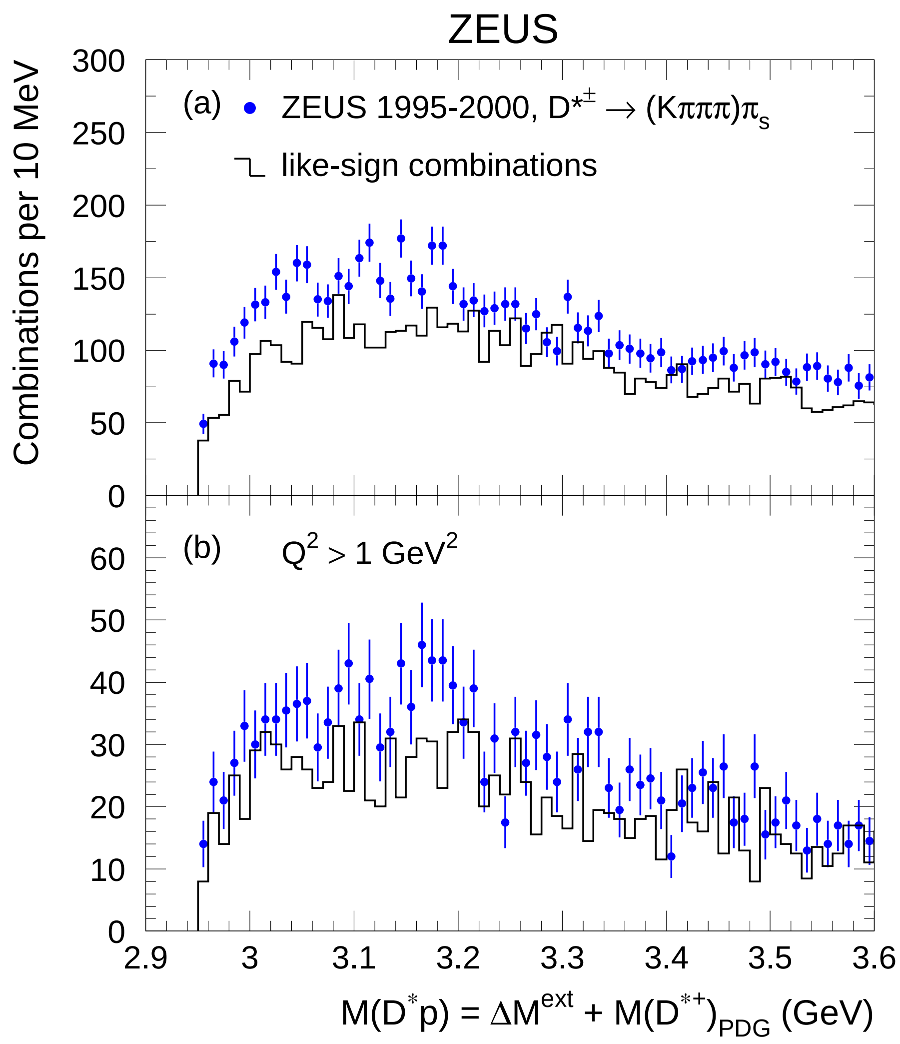
Low-P_p

High-P_p

Histograms are like-sign combinations. Mass resolution from MC: 4 MeV.

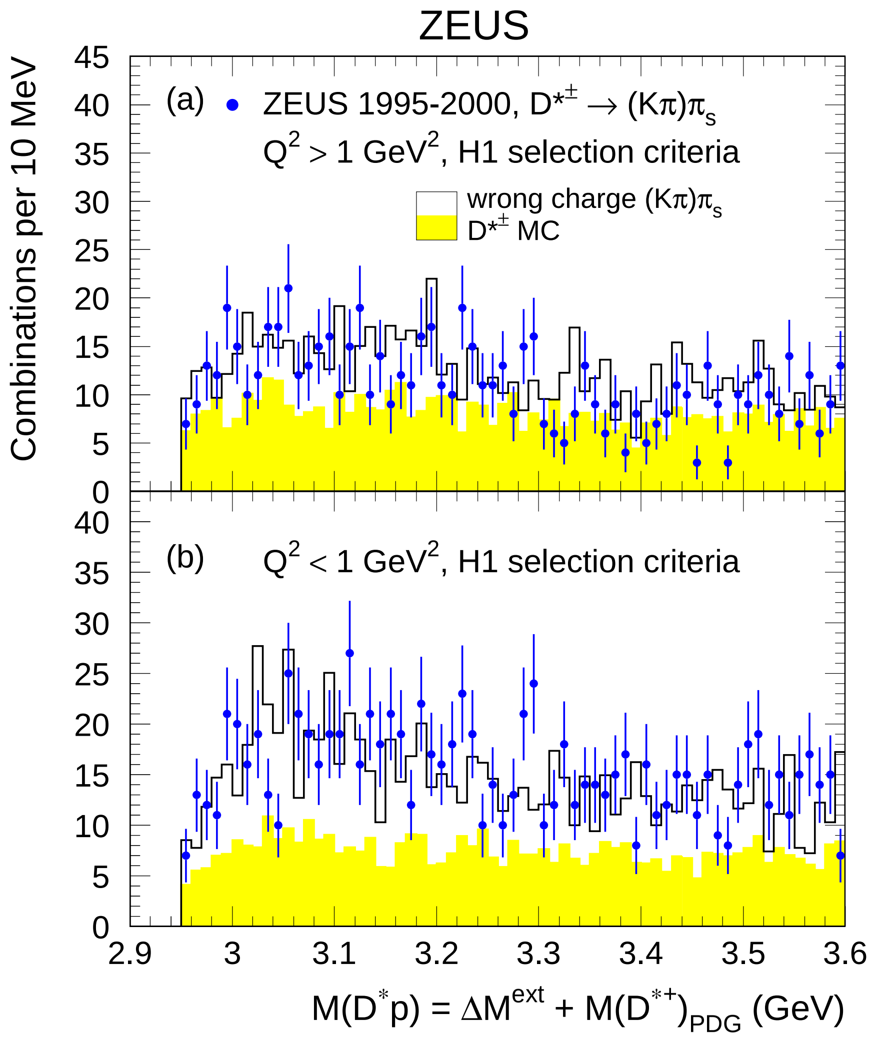
No evidence for a signal at 3.1 GeV **$D^0 \to K^-\pi^+$ analysis repeated with very similar cuts to H1 $\Rightarrow$ no signal**

ZEUS $M(D^*p)$ spectra for the $D^0 \to K^-\pi^+\pi^+\pi^-$ channel



No evidence for Θ_c^0 also in the $D^0 \to K^-\pi^+\pi^+\pi^-$ channel.

ZEUS $M(D^*p)$ spectra $D^0 \to K^-\pi^+$ channel,H1 selection



ZEUS RATE relative to H1 is proportional to relative D^* nos.

No evidence for Θ_c^0 using H1 ΔM and $D^0 \to K^-\pi^+$ cuts.

ZEUS upper limits for Θ_c^0 production I

Upper limits on the fraction of D^* mesons originating from the Θ_c^0 decays were set in the signal window $3.07 < M(D^*p) < 3.13$ GeV. This window covers the H1 measurement taking into account the uncertainties of the measured Θ_c^0 mass and width. The upper limits were calculated for the full D^*-meson samples obtained with D^* reconstructed in channels (1) and (2):

$$(1) D^0 \to K^-\pi^+ \qquad (2) D^0 \to K^-\pi^+\pi^+\pi^-$$

Each $M(D^*p)$ distribution was fitted outside the signal window to the functional form $x^a \exp(-bx + cx^2)$, where $x = \Delta M^{\text{ext}} - m_p$, m_p is the proton mass and:

$$\Delta M^{\text{ext}} = M(K\pi\pi_s p) - M(K\pi\pi_s) \text{ or } \Delta M^{\text{ext}} = M(K\pi\pi\pi\pi_s p) - M(K\pi\pi\pi\pi_s).$$

The fitted curves describe the $M(D^*p)$ distributions reasonably well in the whole range (see following Figures)
The number of reconstructed Θ_c^0 baryons was estimated by subtracting the background function, integrated over the signal window, from the observed number of candidates in the window. This number was divided by the number of reconstructed D^* mesons, yielding the fraction of D^* mesons originating from the Θ_c^0 decays: $R(\Theta_c^0 \to D^*p/D^*)$.

ZEUS upper limits for Θ_c^0 production II

The upper limits are the frequentist confidence bounds calculated for a Gaussian probability function (Feldman and Cousins,P.R.D57,3873(1998)).

The 95% C.L. upper limits on $R(\Theta_c^0 \to D^*p/D^*)$ are 0.29% and 0.33% for channels (1) and (2), respectively. The combined upper limit for both channels is 0.23%. The combined upper limit for DIS with $Q^2 > 1\mathrm{GeV}^2$ is 0.35%

To correct the fraction of D^* mesons originating from the Θ_c^0 decays for detector effects, we also calculated the relative acceptance of the above ratio R:

$$R^{cor}(\Theta_c^0 \to D^*p/D^*) = \frac{A(\Theta_c^0 \to D^*p)}{A^{\mathrm{inc}}(D^*)} = \frac{A^{\Theta_c^0}(D^*)}{A^{\mathrm{inc}}(D^*)} \cdot A(p) \cdot A(l_p > 0.15).$$

With our number of D^* mesons in our kinematic region and assuming a 1% Θ_c^0 production rate a signal of 626 Θ_c^0 baryons should have been seen in our samples of both decay channels.

Assuming Gaussian statistics, a 1% signal with the expected number of background events could produce 626 Θ_c^0 events in the signal window only in cases of statistical fluctuations larger than $9\,\sigma$. For our DIS ($Q^2 > 1\mathrm{GeV}^2$) sample the exclusion is about $5\,\sigma$.

A plot of such expected number of events is shown in the following figures and the detailed results of both channels are given in the following table

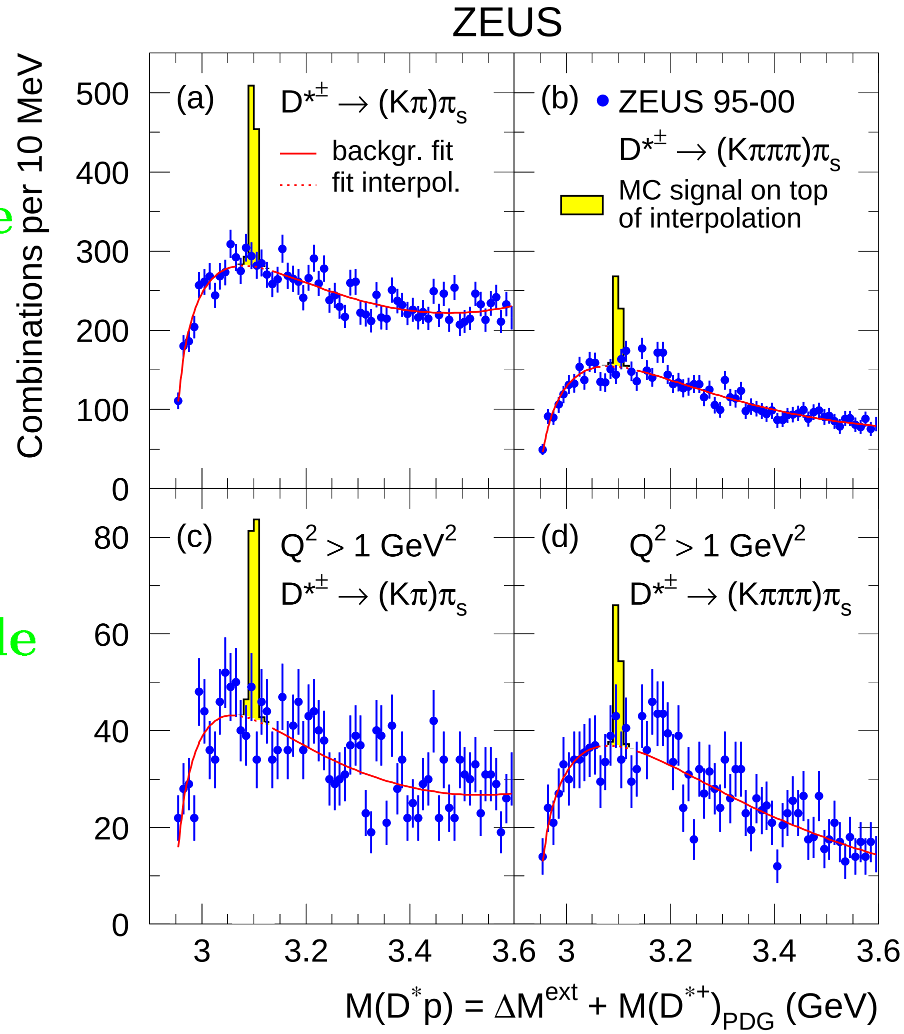
ZEUS upper limits for Θ_c^0 production III

$$M(D^*p) = M(K\pi\pi_s p) - M(K\pi\pi_s) + M(D^{*+})_{\rm PDG}$$

$$D^0 \to K^-\pi^+ \qquad D^0 \to K^-\pi^+\pi^+\pi^-$$

Full sample

DIS sample



Yellow histograms are MC Θ_c^0 signals normalized to $\Theta_c^0/D^* = 1\%$ after H1 on top of a background fit (solid curves)

95% C.L. upper limits on $R(\Theta_c^0 \to D^*p/D^*)$ calculated in D^*p window 3.07-3.13GeV. A visible rate of $R = 1\%$ is excluded by **9 s.d. (5 s.d)** for the full (DIS) sample. $R < 0.23\%$ $(< 0.35\%)$ for full (DIS) sample.

Accepted-corrected limits: $< 0.37\% (< 0.51\%)$ for full (DIS) sample.

$f(c \to \Theta_c^0) \cdot B_{\Theta_c^0 \to D^*p} < 0.16\%$ $(< 0.19\%)$ for the full (DIS) combined sample

D^* decay channel	$(K\pi)\pi_s$	$(K\pi\pi\pi)\pi_s$	Both channels
Full data sample			
N_{window}	1710	914	
N_{backgr}	1678 ± 23	919 ± 19	
$N(D^*)$	42680 ± 350	19900 ± 250	
$R(\Theta_c^0 \to D^*p/D^*)$	$< 0.29\%$	$< 0.33\%$	$< 0.23\%$
$R^{\text{cor}}(\Theta_c^0 \to D^*p/D^*)$	$< 0.47\%$	$< 0.50\%$	$< 0.37\%$
$f(c \to \Theta_c^0) \cdot B_{\Theta_c^0 \to D^*p}$	$< 0.18\%$	$< 0.33\%$	$< 0.16\%$
DIS with $Q^2 > 1\text{GeV}^2$			
N_{window}	252	220	
N_{backgr}	252.8 ± 9.2	219.8 ± 8.8	
$N(D^*)$	8680 ± 130	4830 ± 120	
$R(\Theta_c^0 \to D^*p/D^*)$	$< 0.41\%$	$< 0.69\%$	$< 0.35\%$
$R^{\text{cor}}(\Theta_c^0 \to D^*p/D^*)$	$< 0.59\%$	$< 1.06\%$	$< 0.51\%$
$f(c \to \Theta_c^0) \cdot B_{\Theta_c^0 \to D^*p}$	$< 0.20\%$	$< 0.56\%$	$< 0.19\%$
Photoproduction with $Q^2 < 1\text{GeV}^2$			
N_{window}	1458	695	
N_{backgr}	1422 ± 21	694 ± 15	
$N(D^*)$	34000 ± 330	15070 ± 220	
$R(\Theta_c^0 \to D^*p/D^*)$	$< 0.36\%$	$< 0.40\%$	$< 0.29\%$
$R^{\text{cor}}(\Theta_c^0 \to D^*p/D^*)$	$< 0.60\%$	$< 0.60\%$	$< 0.47\%$
$f(c \to \Theta_c^0) \cdot B_{\Theta_c^0 \to D^*p}$	$< 0.23\%$	$< 0.43\%$	$< 0.21\%$

Table 1: Numbers of the $M(D^*p)$ combinations in the signal window, N_{window}; fit background estimations, N_{backgr}; numbers of reconstructed D^* mesons, $N(D^*)$; 95% C.L. upper limits on the uncorrected, $R(\Theta_c^0 \to D^*p/D^*)$, and corrected, $R^{\text{cor}}(\Theta_c^0 \to D^*p/D^*)$, fractions of D^* mesons originating from Θ_c^0 decays; and 95% C.L. upper limits on the product of the fraction of c quarks hadronising as a Θ_c^0 baryon, $f(c \to \Theta_c^0)$, and the branching ratio of the Θ_c^0 decay to D^*p, $B_{\Theta_c^0 \to D^*p}$. The results are shown for the full data sample, for DIS with $Q^2 > 1\text{GeV}^2$ and for photoproduction with $Q^2 < 1\text{GeV}^2$.

Summary of ZEUS search for Θ_c^0 in $e-p$ at HERA

ZEUS has searched for a resonance in the $D^{*\pm}p^{\mp}$ invariant-mass spectrum at HERA using an integrated luminosity of $126pb^{-1}$. The decay channels

$$D^0 \to K^-\pi^+ \qquad D^0 \to K^-\pi^+\pi^+\pi^- \text{ (+c.c.)}$$

were used to identify $D^{*\pm}$ mesons.

No resonance structure was observed in the $M(D^{*\pm}p^{\mp})$ spectrum from more than $60\,000$ reconstructed $D^{*\pm}$ mesons. The upper limit on the fraction of D^* mesons originating from Θ_c^0 decays is 0.23% (95% C.L.). The upper limit for DIS with $Q^2 > 1\,\text{GeV}^2$ is 0.35% (95% C.L.). Using the corrected ratios, R^{cor}, the limits become 0.37% and 0.51% respectively.

CONCLUTION : the ZEUS data are not compatible with the H1 report of Θ_c^0 baryon production in DIS and photoproduction, with a rate, in DIS, of roughly 1% of the D^* production rate.

FUTURE RESULTS FROM HIGH STATISTICS HERA II DATA MAY RESOLVE THE ZEUS/H1 Θ_c^0 DISCREPANCY

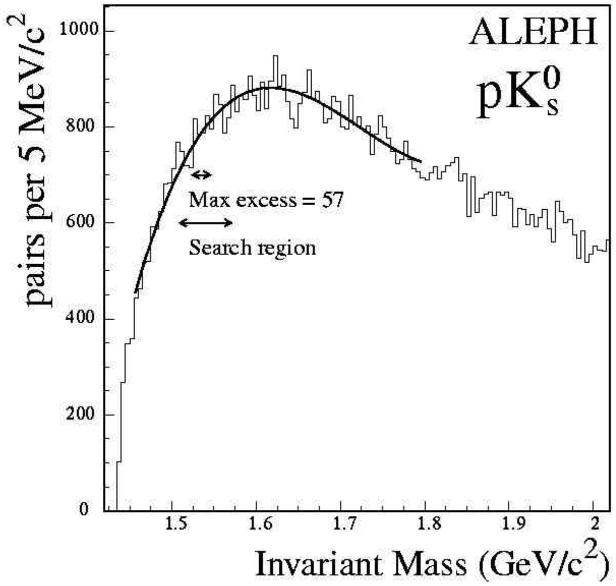
SPARE SLIDES: Repeating the Θ_c^0 analysis with the H1 cuts

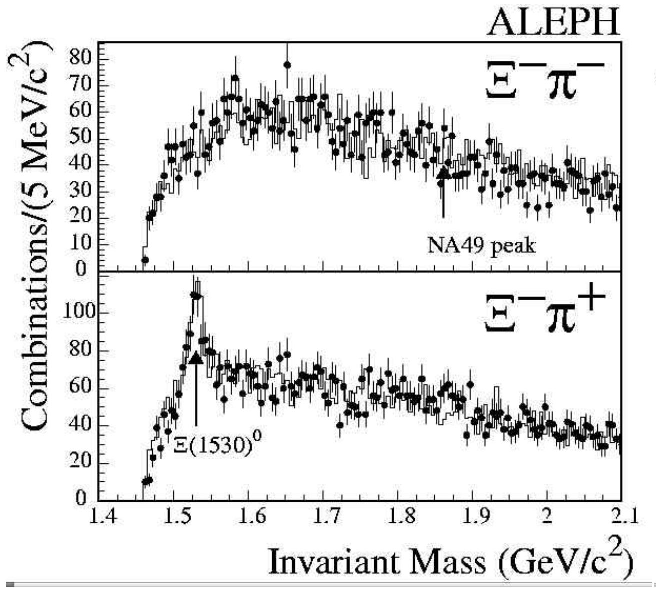
The D^* in channel (1) $D^0 \to K^-\pi^+$ analysed using the H1 criteria:

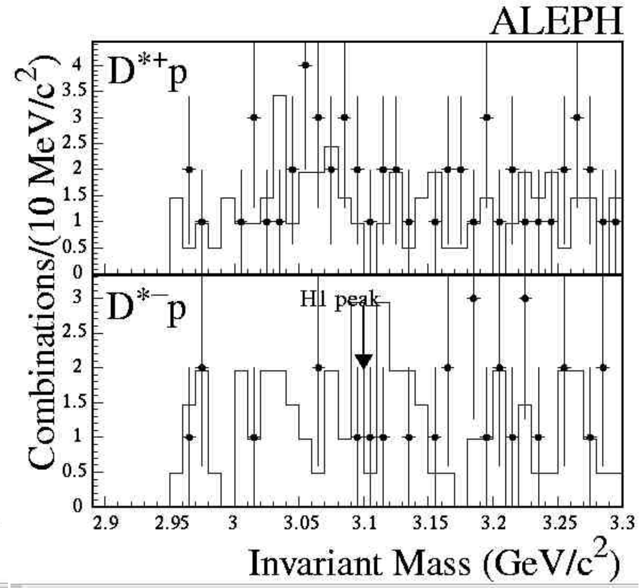
(1). The minimum P_T of the D^* tracks were set to the H1 values.
(2). The cut $p_T(D^*)/E_T^{10} > 0.12$ was replaced by the cut $z(D^*) > 0.2$, where $z(D^*) = P \cdot p(D^*)/P \cdot q$ and P, $p(D^*)$ and q are the four-momenta of the incoming proton, the D^* meson and the exchanged photon. In the proton rest frame, $z(D^*)$ is the fraction of the photon energy carried by the $D^{*\pm}$ meson. The requirements on $M(K\pi)$ and ΔM were kept as in the nominal ZEUS analysis since they were determined by the mass resolution of the ZEUS CTD.[1]
(3). The DIS events were selected with $Q^2 > 1\,\mathrm{GeV}^2$ and $0.05 < y < 0.7$, while the photoproduction events were selected with $Q^2 < 1\,\mathrm{GeV}^2$ and $0.2 < y < 0.8$
(4). The D^* candidates were required to have $-1.5 < \eta(D^*) < 1.0$ and $p_T(D^*) >$ $1.5\mathrm{GeV}$ or $p_T(D^*) > 2.0\mathrm{GeV}$ in DIS or photoproduction selections, respectively.
(5). No. of D^*'s became 5920 ± 90 and 11670 ± 140 for DIS and photoprod.
(6) The cut $l_p > 0.15$ was replaced by the H1 cut of normalised proton likelihood. P_p range $1.6 - 2.0\,\mathrm{GeV}$ was excluded for photoproduction.

NO $\Theta_c^0(3.1GeV)$ seen in the ZEUS data with the H1 CUTS.

Other pentaquark searches: LEP- in e^+e^- annihilations







No evidence for $\Theta^+(1530)$, $\Xi^{--}(1862)$, $\Xi^0(1862)$, $\Theta_c^0(3099)$
from 3.5 million hadronic Z **decays in the ALEPH detector**

ALEPH 95% **C.L. limits:**

$BR(\Theta^+ \to pK_S^0) \cdot N(\Theta^+)/N(\Lambda(1520)) < 0.019$

$BR(\Xi^{--}(1862) \to \Xi^-\pi^-) \cdot N(\Xi^{--}(1862))/N(\Xi^0(1530)) < 0.058$

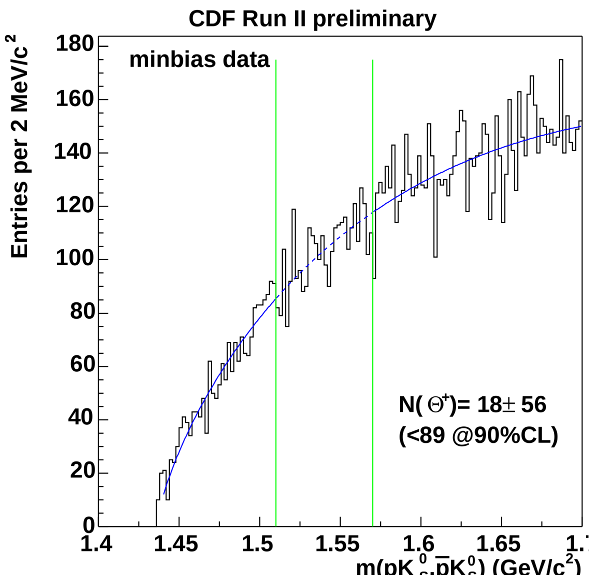
$BR(\Xi^0(1862) \to \Xi^-\pi^+) \cdot N(\Xi^0(1862))/N(\Xi^0(1530)) < 0.12$

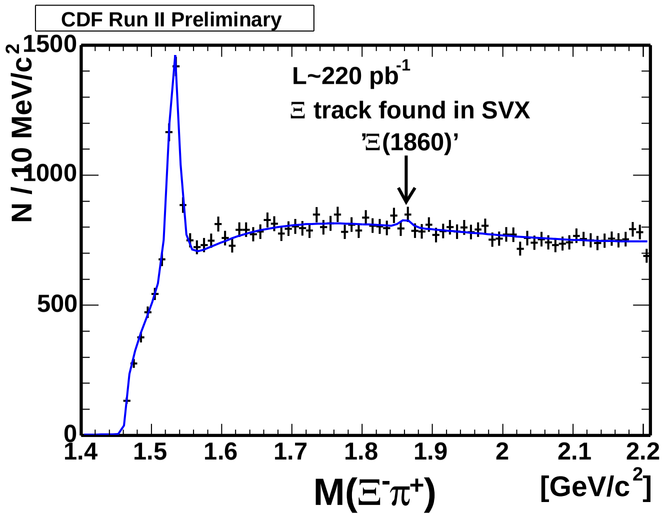
$N(\Theta_c^0) \cdot BR(\Theta_c^0 \to D^{*-}p) < 6.3 \cdot 10^{-4}$

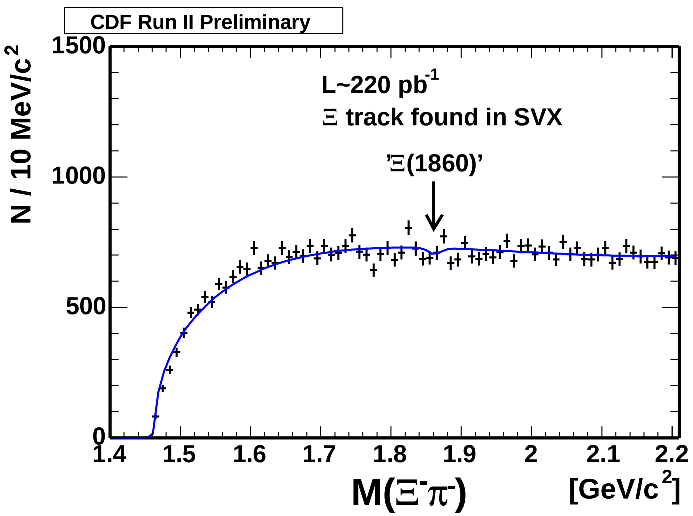
$N(\Theta_c^0) \cdot BR(\Theta_c^0 \to D^-p) < 3.1 \cdot 10^{-3}$

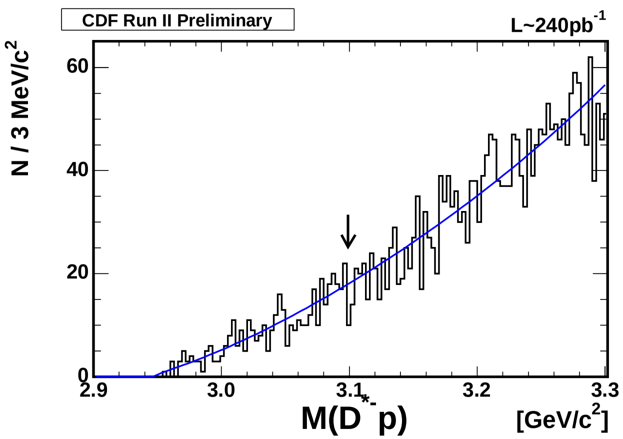
Also no evidence for $\Theta^+(1530)$ **at DELPHI and OPAL**

Other pentaquark searches: CDF, in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ GeV









CDF Run II at the TEVATRON $(220\ \text{pb}^{-1})$

No evidence for
$\Theta^+(1530)$, $\Xi^{--}(1862)$, $\Xi^0(1862)$, $\Theta_c(3099)$

CDF 90% **C.L. limits:**

$$BR(\Theta^+ \to pK_S^0) \cdot N(\Theta^+)/N(\Lambda(1520)) < 0.0034$$

$$BR(\Xi^0(1862) \to \Xi^-\pi^+) \cdot N(\Xi^0(1862))/N(\Xi^0(1530)) < 0.06$$

$$N(\Theta_c^0) \cdot BR(\Theta_c^0 \to D^{*-}p) < 3.9 \cdot 10^{-5}$$

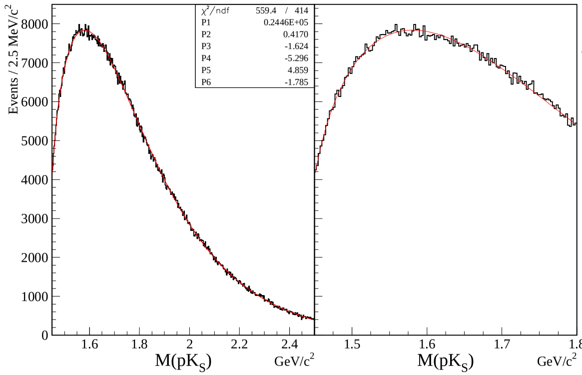
Other pentaquark searches: FOCUS

FOCUS: Fixed-target Fermilab experiment

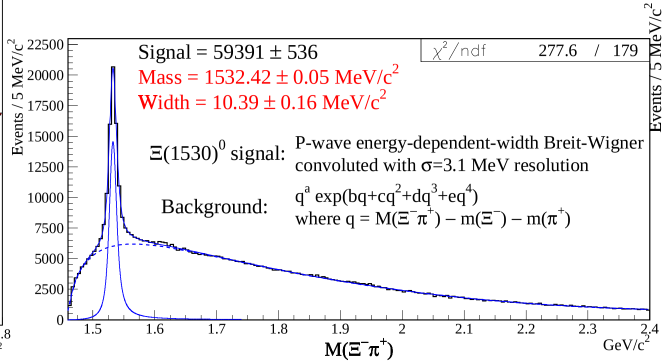
Photon beam from 300 GeV $e^{\pm}$ beam on BeO targets

Search for Θ^+, $\Xi(1862)$ and Θ_c^0 (hep-ex/0412021)

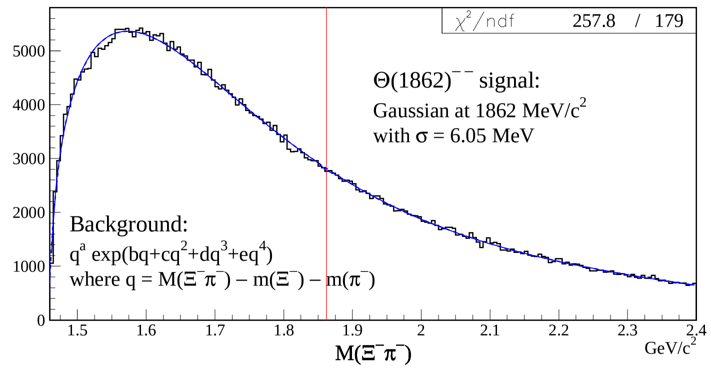
$\Theta^+(1530) \to pK_S^0$



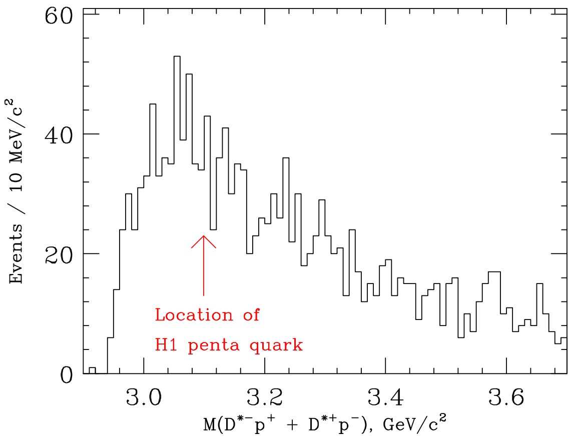
$\Xi^0(1862) \to \Xi^-\pi^+$



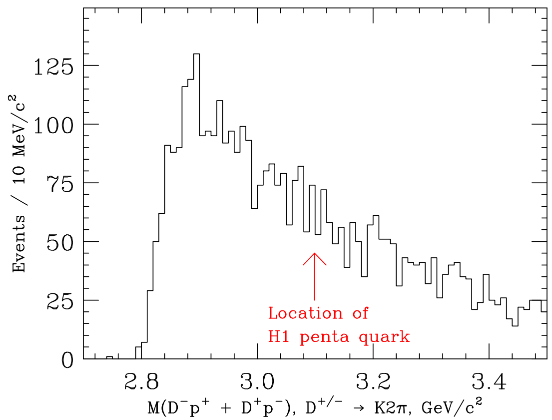
$\Xi^{--}(1862) \to \Xi^-\pi^-$



$\Theta_c^0(3099) \to D^{*-}p$



$\Theta_c^0(3099) \to D^-p$



Sample: 63 million K_S^0

800,000 Ξ^-

$\approx 60,000\ \Xi^0(1530)$

$\approx 36,000 D^{*-}$

$\approx 84,000 D^-$

No evidence for $\Theta^+(1530)$, $\Xi^{--}(1862)$, $\Xi^0(1862)$, $\Theta_c(3099)$

95% C.L. limits (assuming $BR(\Theta^+ \to pK_S^0) = 0.25$):

$\sigma(\Theta^+)/\sigma(\Sigma^{\pm}(1385)) < 2.1\%$; $\sigma(\Theta^+)/\sigma(K^{*-}(892)) < 0.17\%$

$BR(\Xi^{--}(1862) \to \Xi^-\pi^-) \cdot \sigma(\Xi^{--}(1862))/\sigma(\Xi^0(1530)) < 0.37\%$