Exotic Hadronic States at HERA

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- **Introduction**
- **Strange Pentaquarks: Θ^+ , Ξ^{--}**
- **Charm Pentaquark: Θ_c**
- **Summary**

PentaQuarks were theoretically anticipated...

D.Diakonov, V. Petrov and M. Polyakov (hep-ph/9703373)

"Exotic Anti-Decuplet of Baryons: predictions from Chiral Solitons"

Prediction of exotic baryon:

$m_{\Theta+} \approx 1530$ MeV

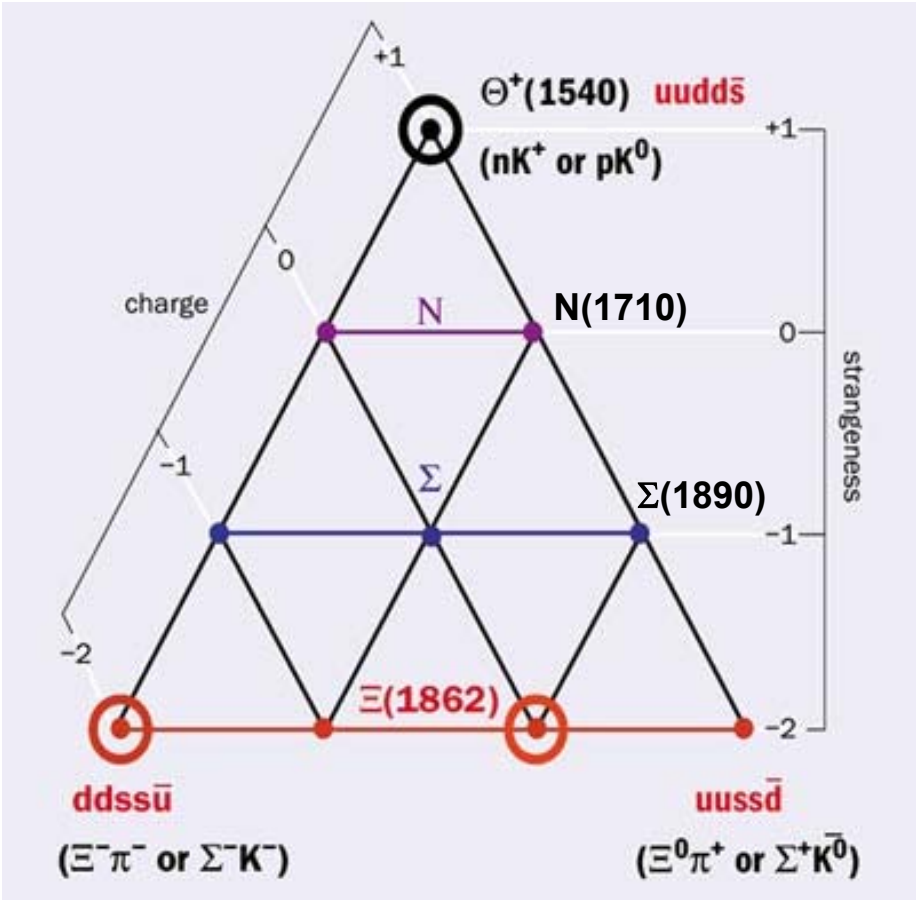
$\Gamma_{\Theta+} < 15$ MeV

$J^P = 1/2^+$

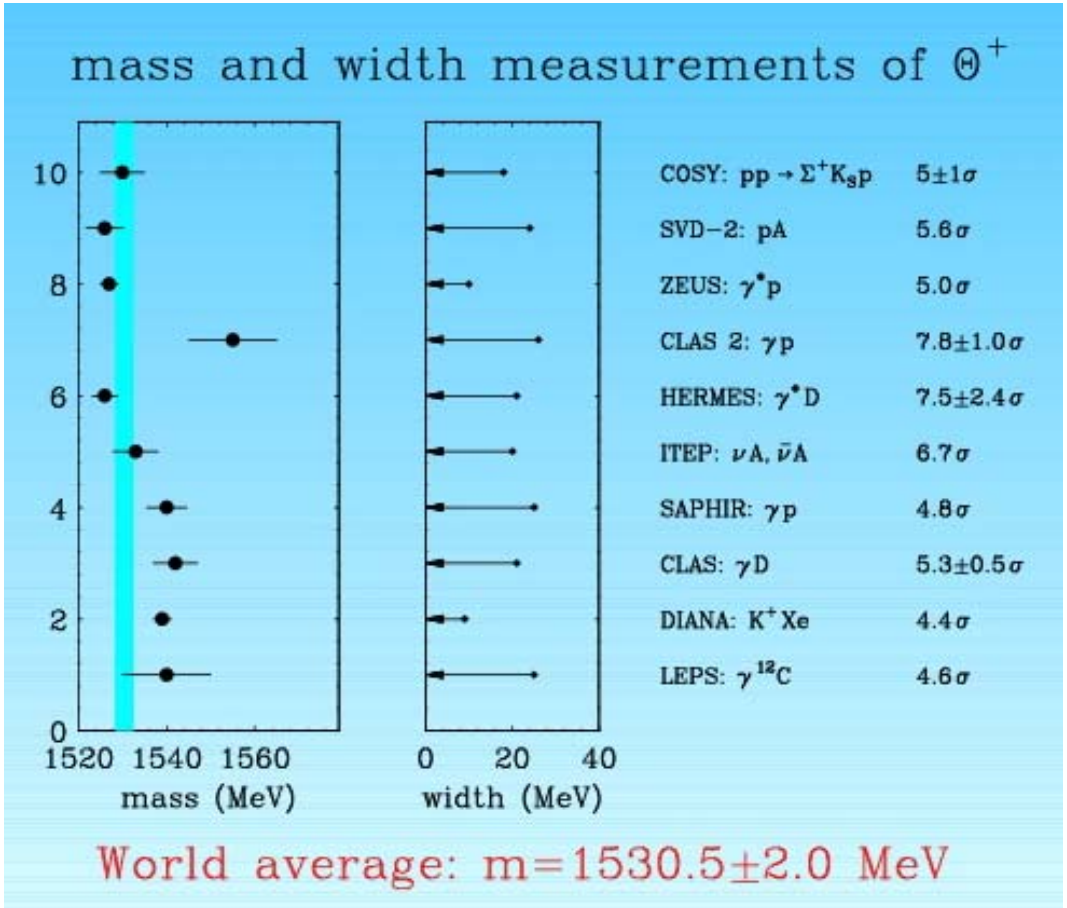
$I = 0$

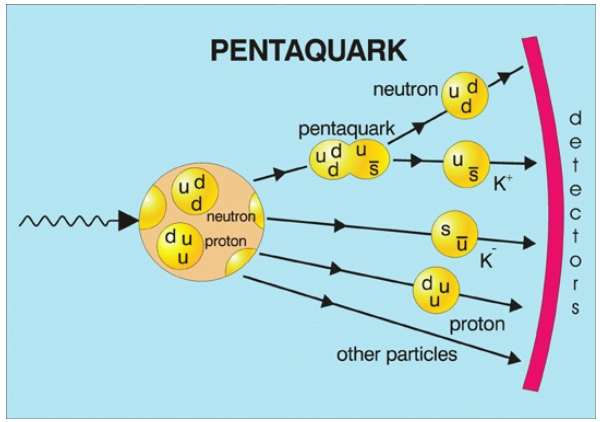
belonging to:

$\overline{10}$ of $SU(3)_f$

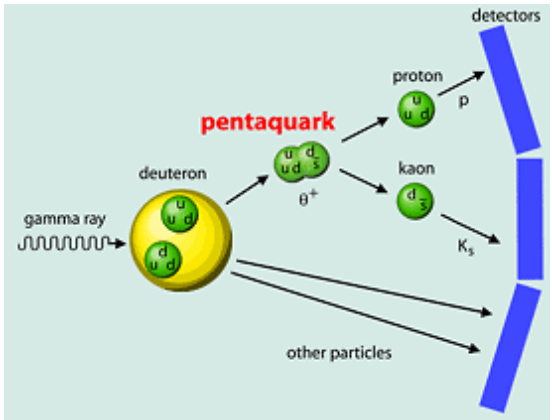


Experimental Evidence of Pentaquarks





$\Theta^+ \rightarrow nK^+$



$\Theta^+ \rightarrow pK_s$

Also evidence for:

NA49: Ξ^{--} (ddssū)

H1: Θ_c (uuddc̄)

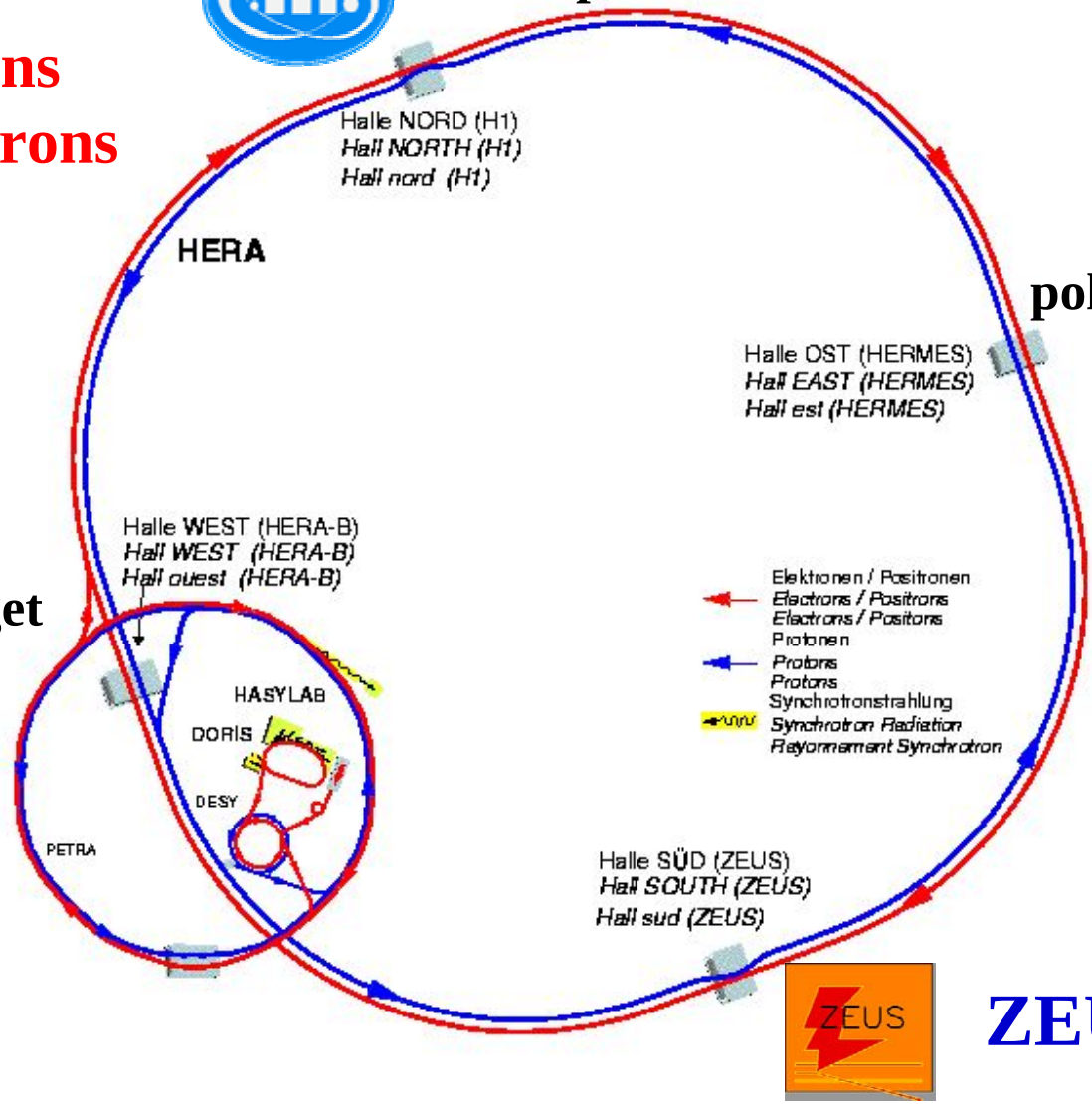
Fixed target: valence quarks

High energy: fragmentation

HERA: ep Collider

H1: ep interactions

920 GeV protons
27.5 GeV positrons



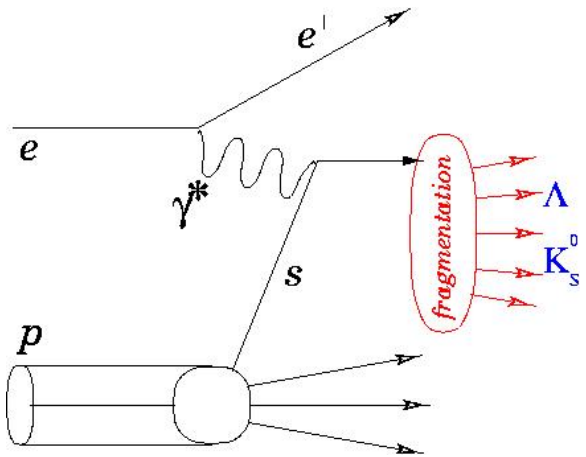
HERMES:
polarised e + fixed target

HERA-B:
p beam+fixed target

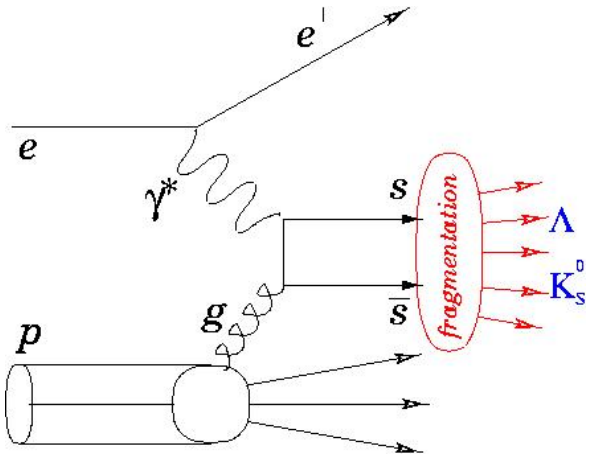
ZEUS: ep interactions

Strange quark production in DIS

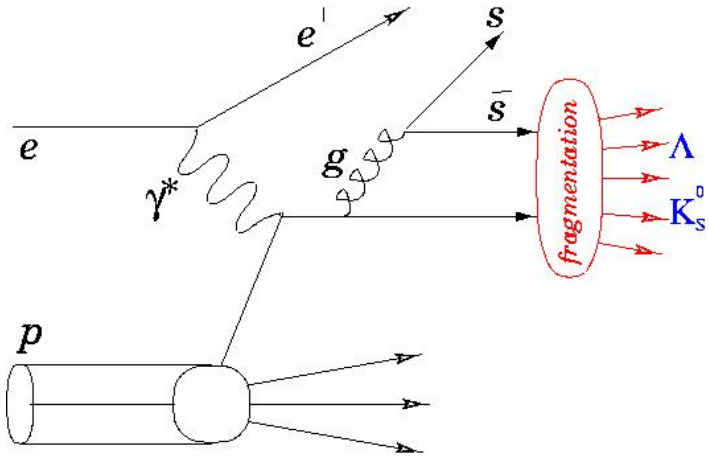
Flavour excitation



Boson-gluon fusion



Gluon-Splitting



Secondary scattering will mainly produce baryons

The anti-baryon $\bar{\Theta}^-$ pentaquark ($\bar{u}\bar{u}\bar{d}\bar{d}s$) can only be produced in fragmentation!!!

The Θ^+ search in ZEUS

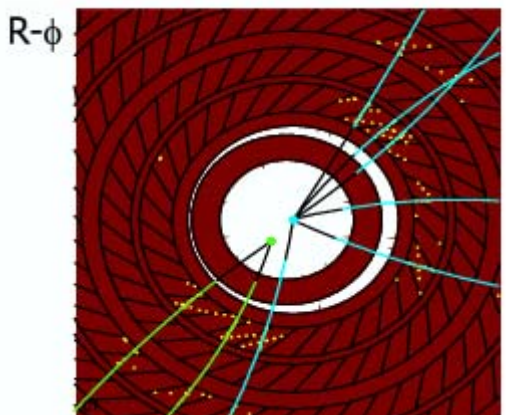
$$\Theta^+ \to K^0_S\, p \quad (\ \overline{\Theta}^- \to K^0_S\, \overline{p}\ )$$

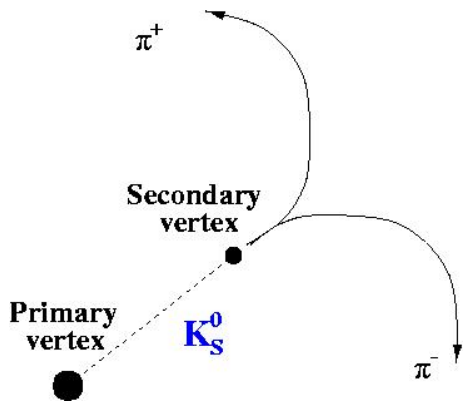
Reconstruct the $K^0_S\, p\, (\overline{p})$ inv. mass

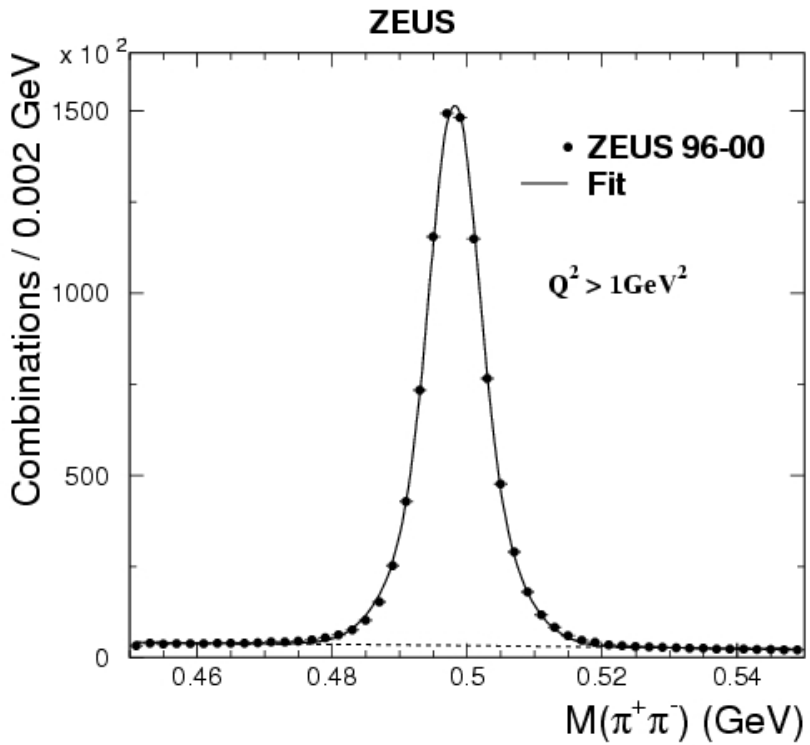
Inclusive DIS event sample (121 pb^{-1})

K_S selection: $p_T(K^0_s) > 0.3\,,\ |\eta(K^0_s)| \le 1.5$

remove Λ and γ conversions





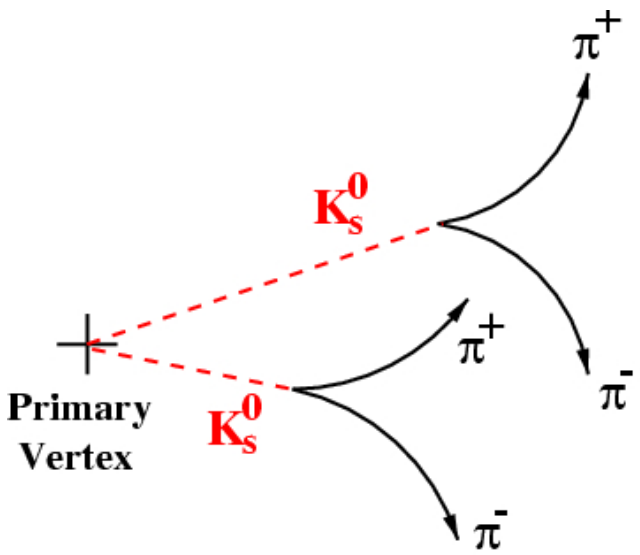


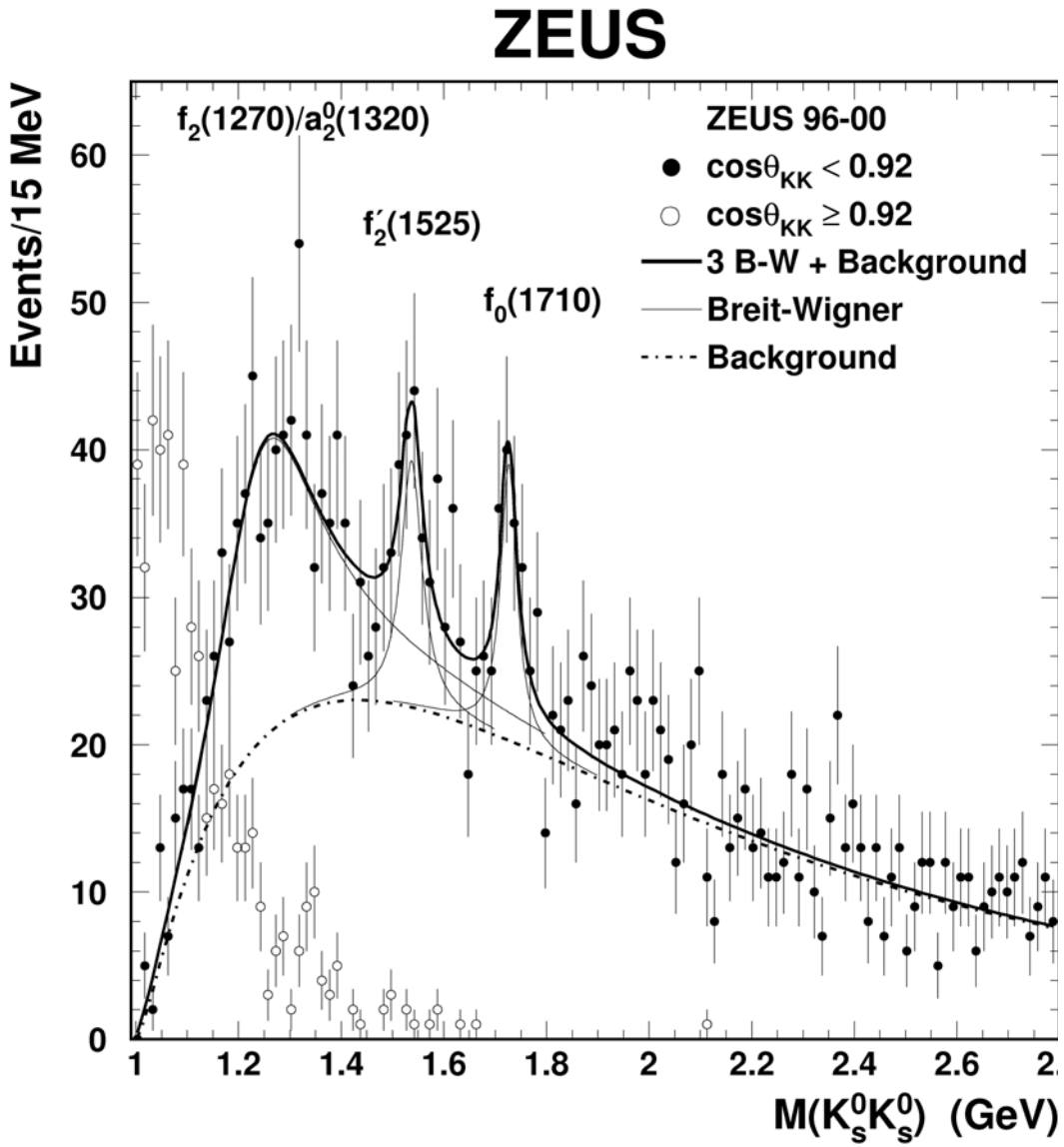
Peak: 498 ±0.01 MeV

Background: < 6%

Candidates: ~ 870,000

Parenthesis: $K_S K_S$ resonances in ZEUS





Several resonances observed

$f_0(1710)$: glueball?

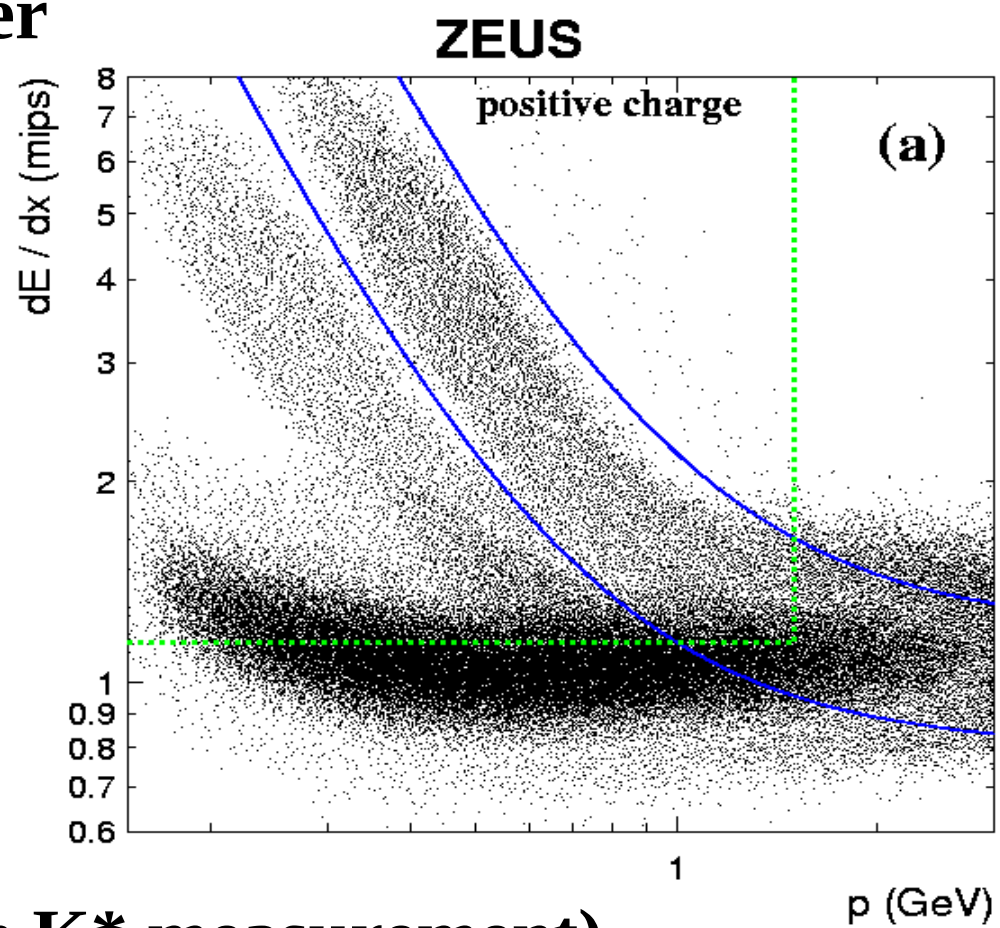
Gluon rich enviroment

Proton identification

Energy loss measurement dE/dx in the central tracking chamber

- **dE/dx > 1.15 mips**
- **momentum(p) < 1.5 GeV**

~ 60% proton purity



$K_S p$ Resolution: 2 ±0.5 MeV
(MC estimation consistent with K* measurement)

The Θ^+ search in ZEUS

$$Q^2 > 20\,\mathrm{GeV}^2$$

$$M : 1521.5 \pm 1.5(\mathrm{stat})\ ^{+2.8}_{-1.7}(\mathrm{syst})\ \mathrm{MeV}$$

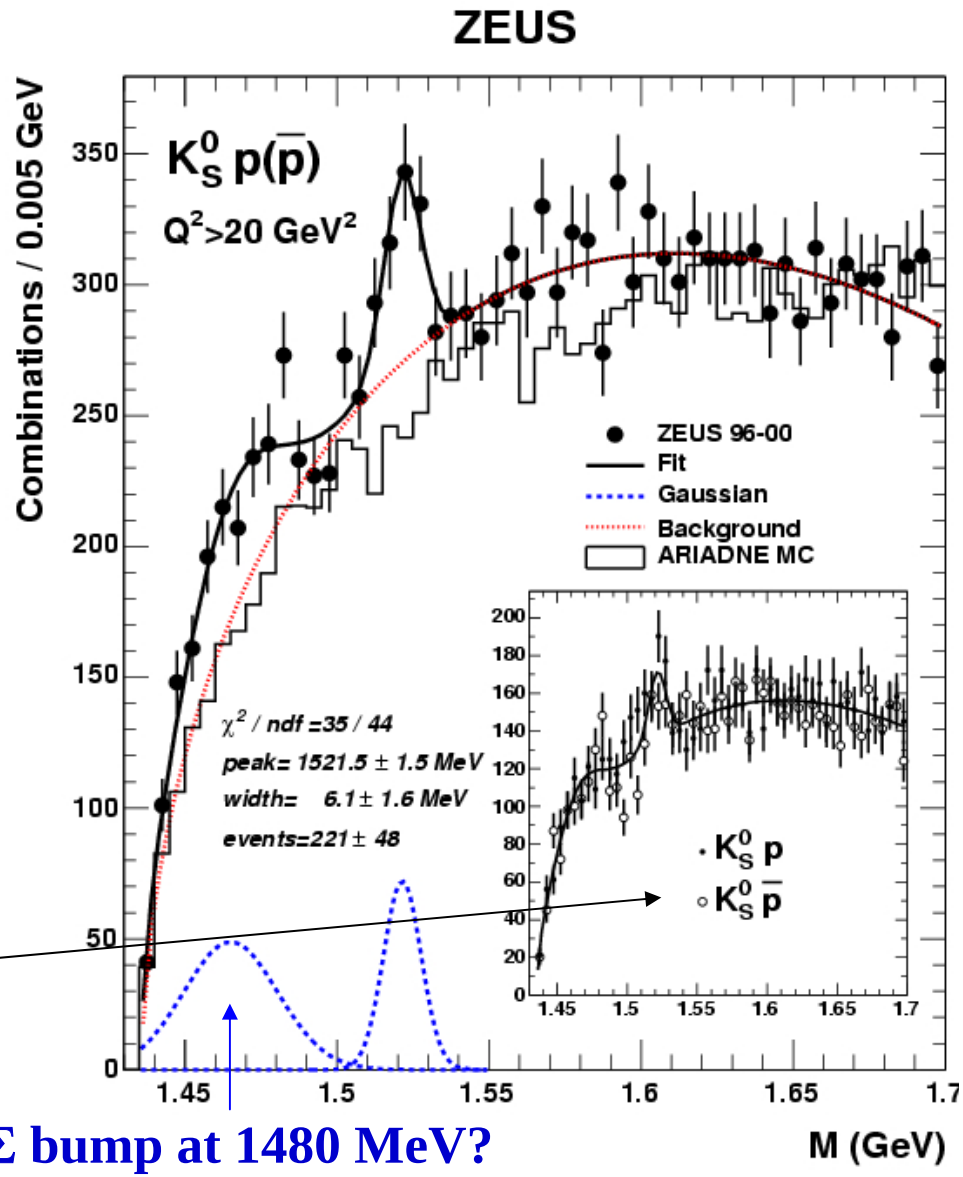
- Gaussian W: 6.1±1.6 MeV
- BW Fit: $\Gamma = 8 \pm 4$ MeV

$\Rightarrow$ compatible with experimental resolution ~ 2 MeV

- Fit: 3P Background + 2 Gaussians

$\Rightarrow \sim 4.6\,\sigma$

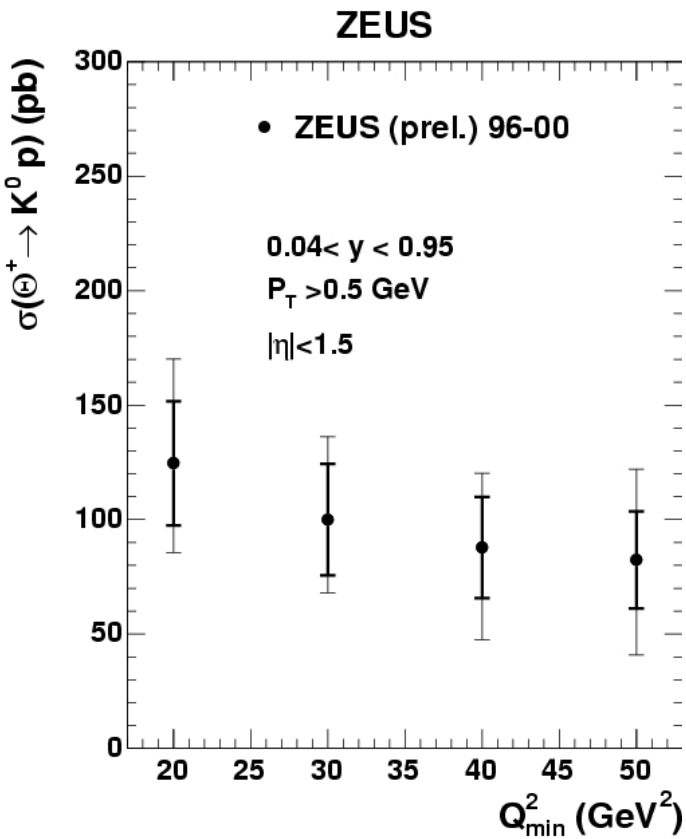
Signal seen in $K^0_S \bar{p} \equiv \overline{\Theta^-}$!?

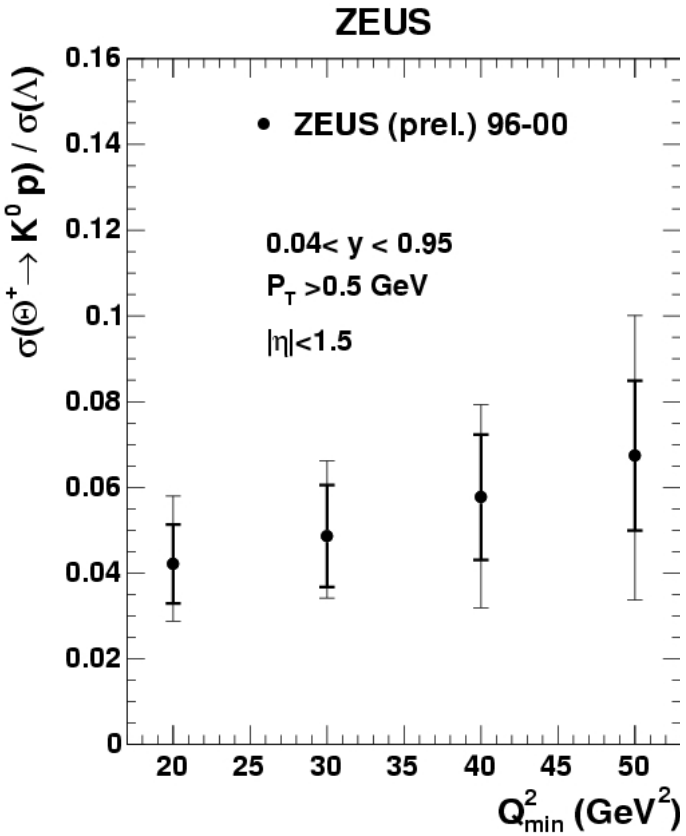


Σ bump at 1480 MeV?

Θ^+ cross sections and ratio $\sigma(\Theta^+ \to K_s\, p)/\sigma(\Lambda)$

$$p_T > 0.5\,\text{GeV}\,,\ |\eta| < 1.5\ ,\ Q^2 > 20\,\text{GeV}^2$$





Ratio shows no significant dependence on Q^2_{min}

$$\sigma(ep \to e\Theta^+ X \to eK^0_S pX) : 125 \pm 27(\text{stat})^{+36}_{-28}(\text{syst})\,\text{pb}$$

$$\sigma\left(\Theta^+ \to K^0_S\, p\right)/\sigma\left(\Lambda\right) = 4.2 \pm 0.9(\text{stat})^{+1.2}_{-0.9}(\text{syst})\,\%$$

The Θ^+ search in HERMES

$$e^+ + D \rightarrow \Theta^+ + X \rightarrow p K^0_S + X$$

Peak at:

M = 1527±2.3 MeV

σ = 9.2±2 MeV

Γ = 17 ± 9 ± 3 MeV

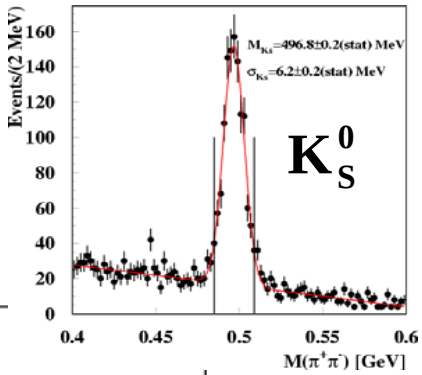
- **Significance: $N_S / \delta N_S = 4.3$**
- **Excellent hadron identification RICH:**

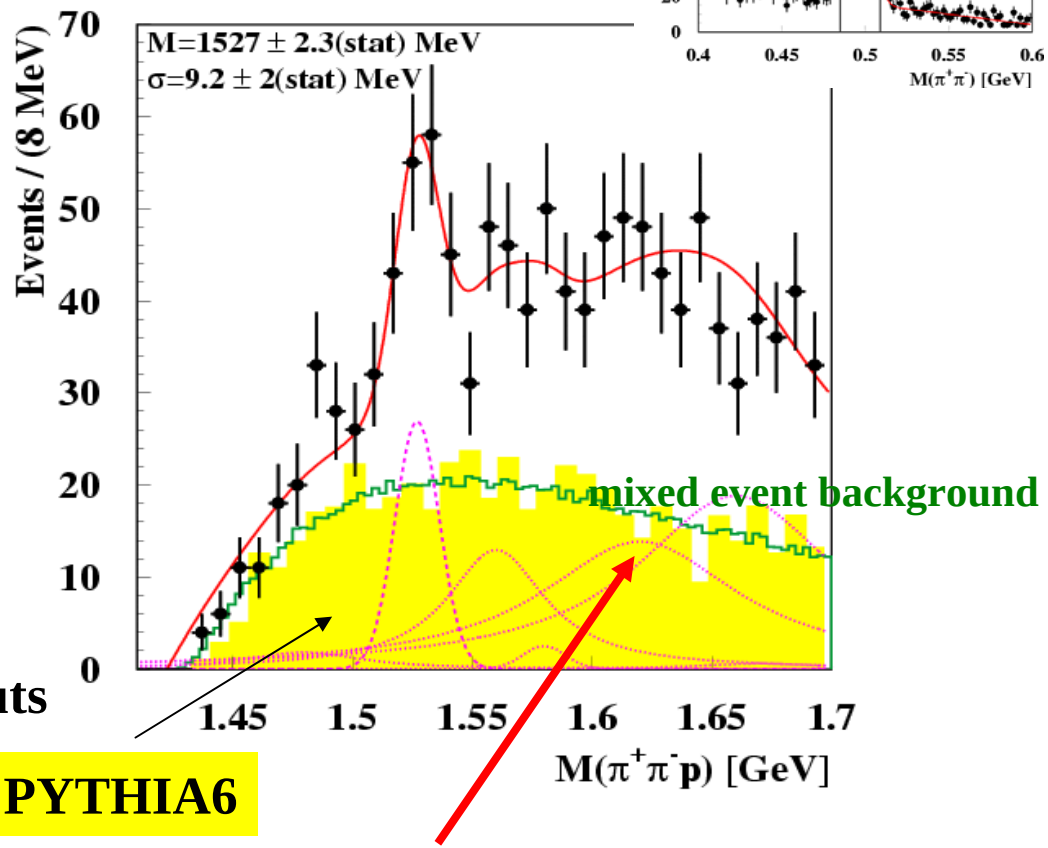
  π: 1-15 GeV, p: 4-9 GeV
- **Full MC simimulation**

→no peaks generated from acceptance & cuts

K_S peak after p id.

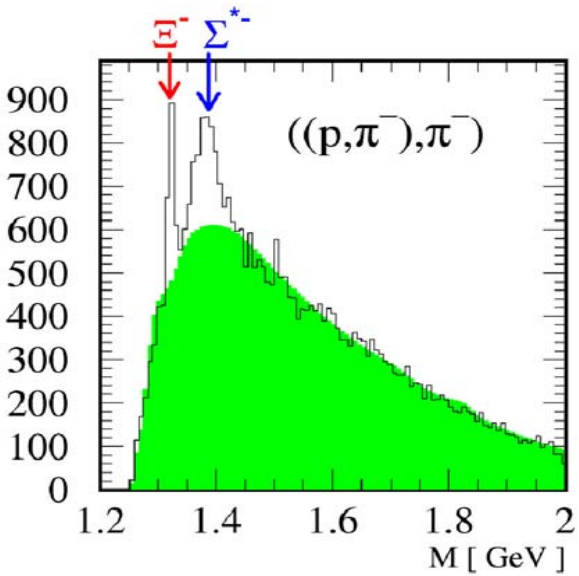
O(1000) K_S candidates

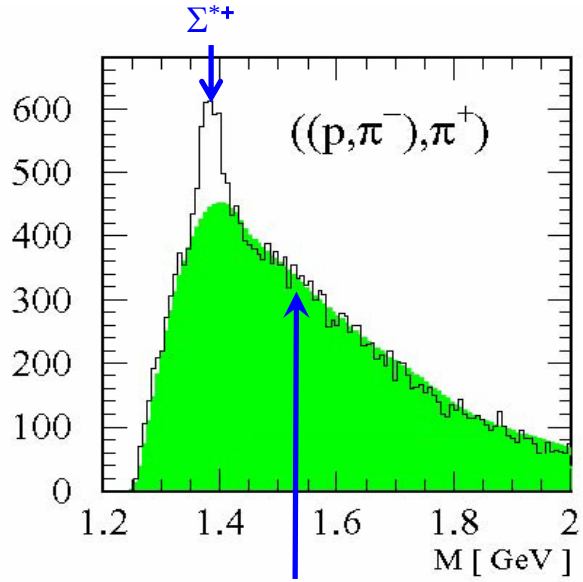




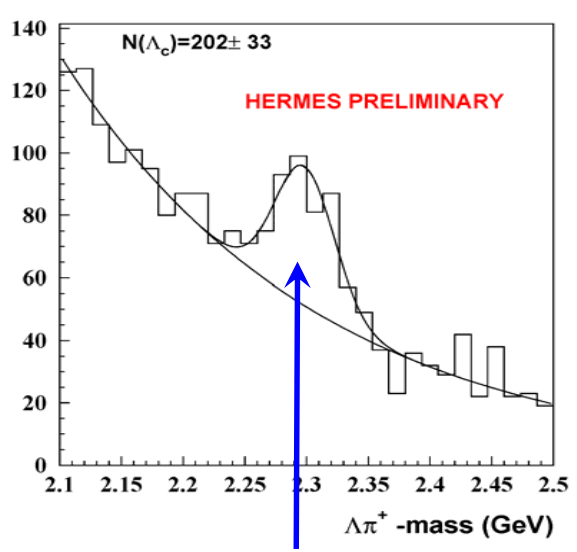
HERMES: Θ^+ vs Σ^{*+}

- Is peak a new Σ^{*+} or a pentaquark state
- If peak is $\Sigma^{*+} \Rightarrow$ also see a peak in $M(\Lambda\pi^+)$
  - member of baryon octect: b.r.$(\Lambda\pi^+)/(pK_s) \geq 3/2$
  - member of decuplet: b.r.$(\Lambda\pi^+)/(pK_s) \sim 3/2$ (M.Polyakov)





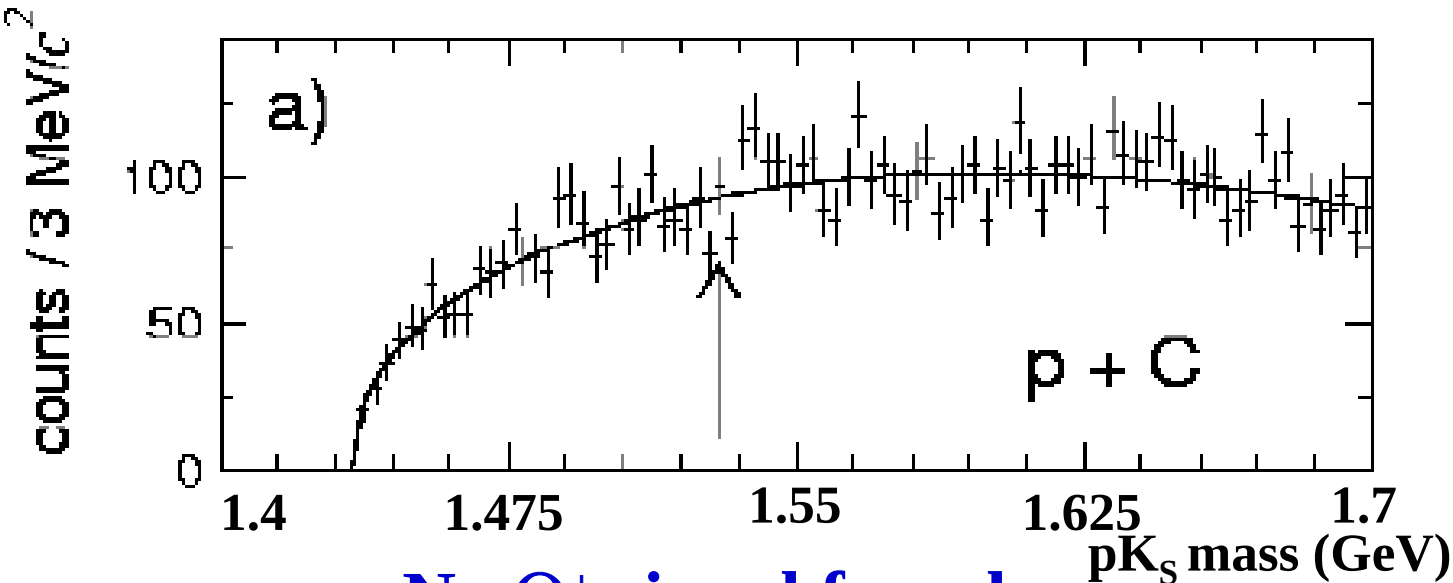
No peak in $\Lambda\pi^+$ spectrum near 1530 MeV



But Λ_C clearly seen

$\Rightarrow$ mass peak cannot be a sigma resonance

The Θ^+ search in HERA-B



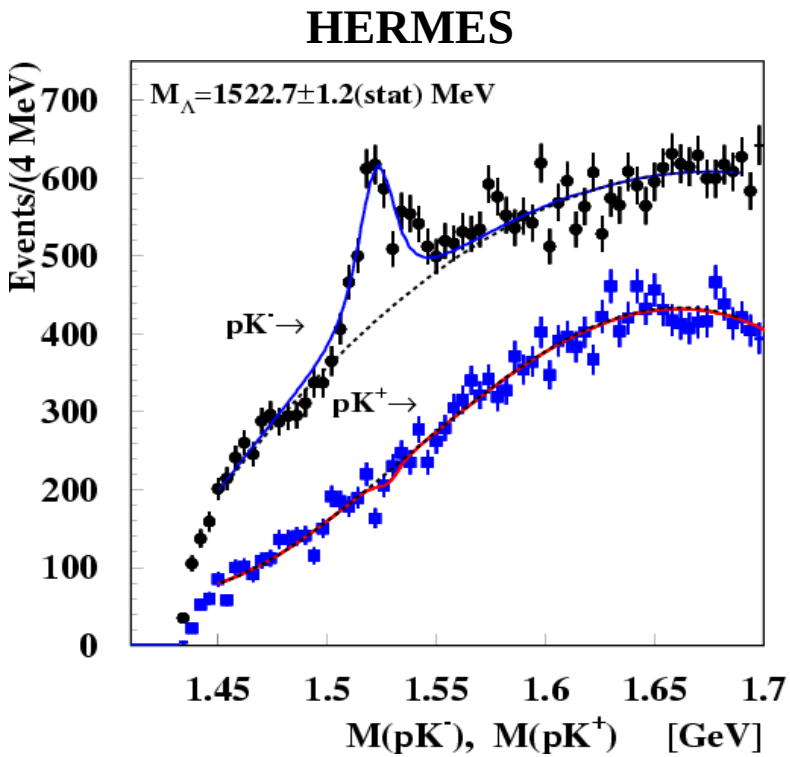
No Θ^+ signal found

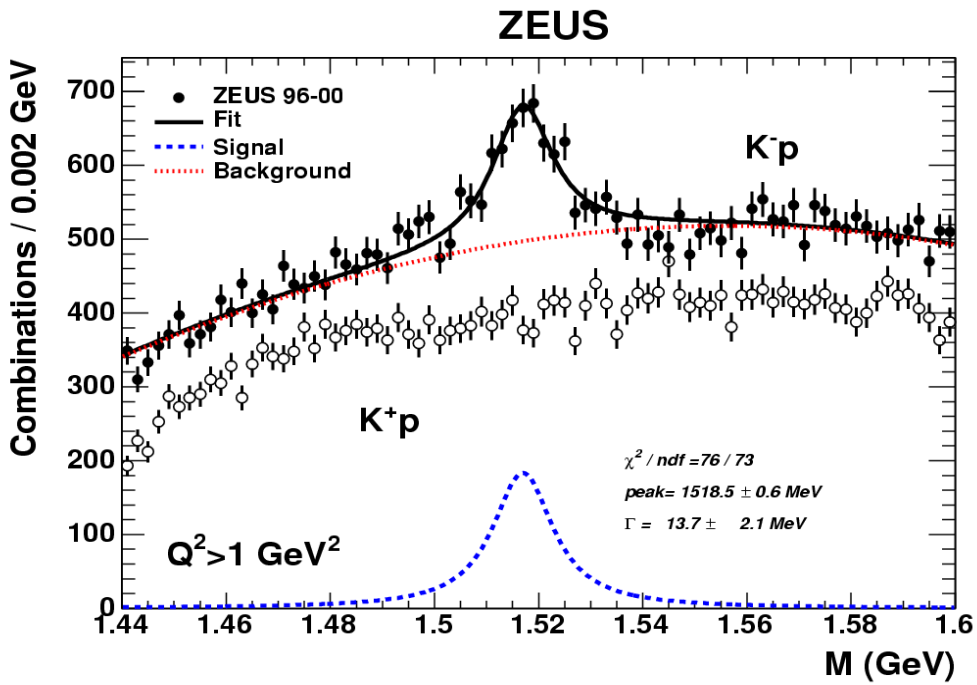
Assuming an atomic mass dependence of $\sigma_N \propto A^{0.7}$ for the production cross section,

the UL(95%) for $B \cdot d\sigma/dy|_{y=0}$ for Θ^+ production is:

- **3.7 μb/nucleon @ 1530 MeV**
- **22 μb/nucleon @ 1540 MeV**

Is there a Θ^{++} at HERA?



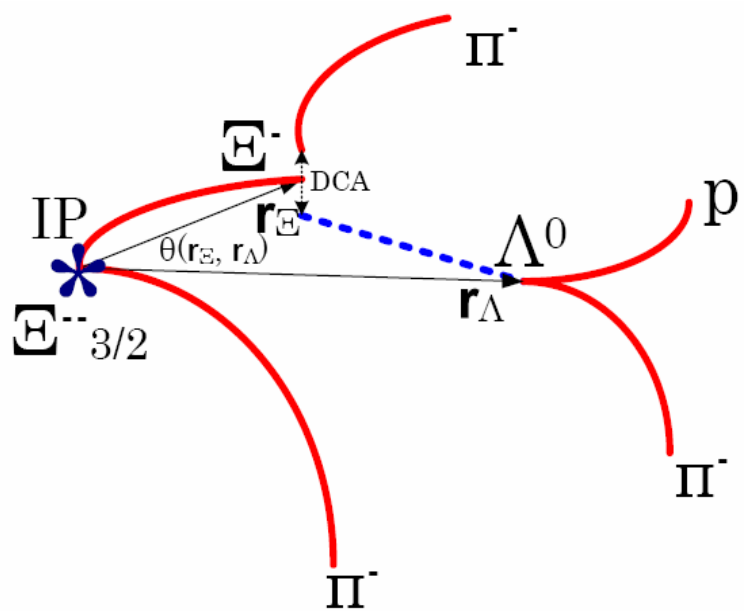


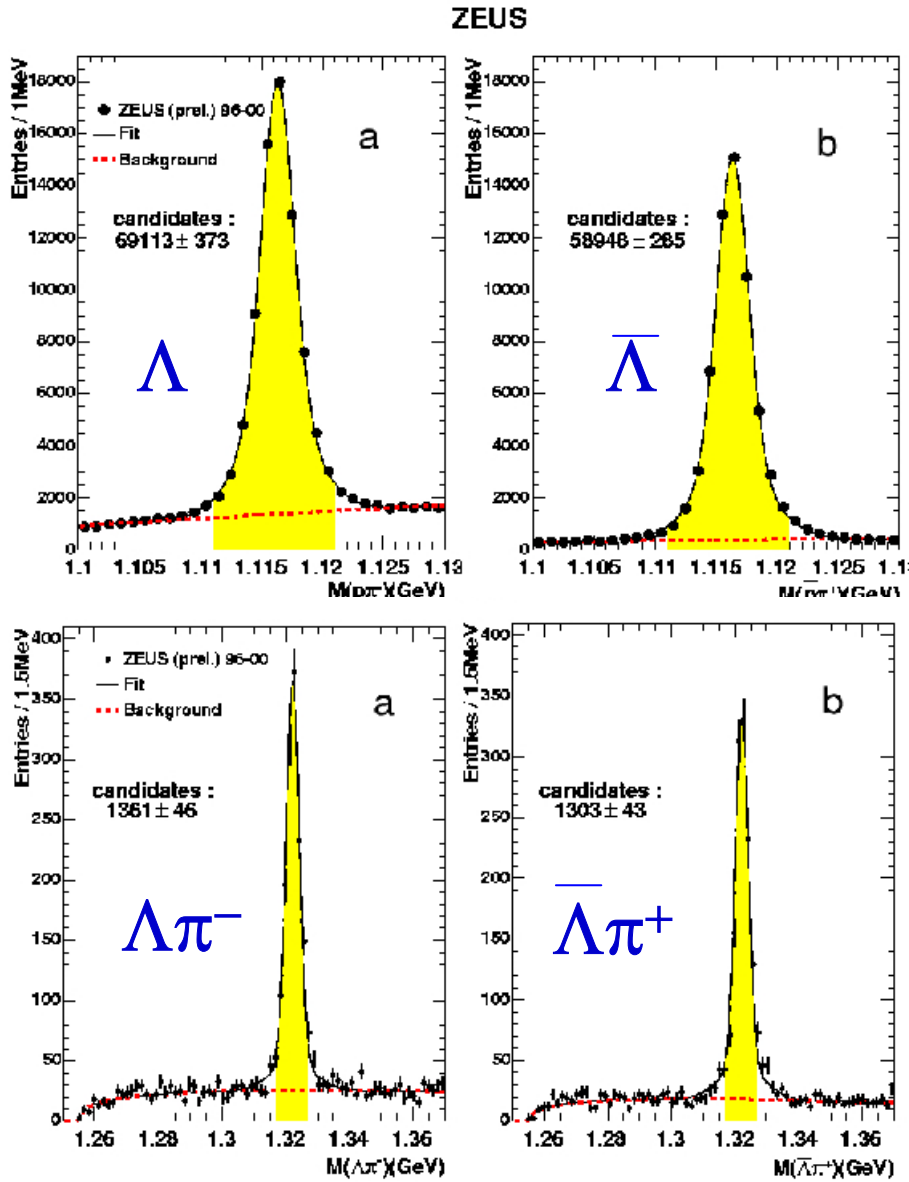
- **Clear Signal for well established $\Lambda(1520) \rightarrow pK^-$**
- **No Signal for $\Theta^{++} \rightarrow pK^+$ ⟶ Θ^+ isoscalar**

The NA49 signal (Ξ^{--}) search in ZEUS

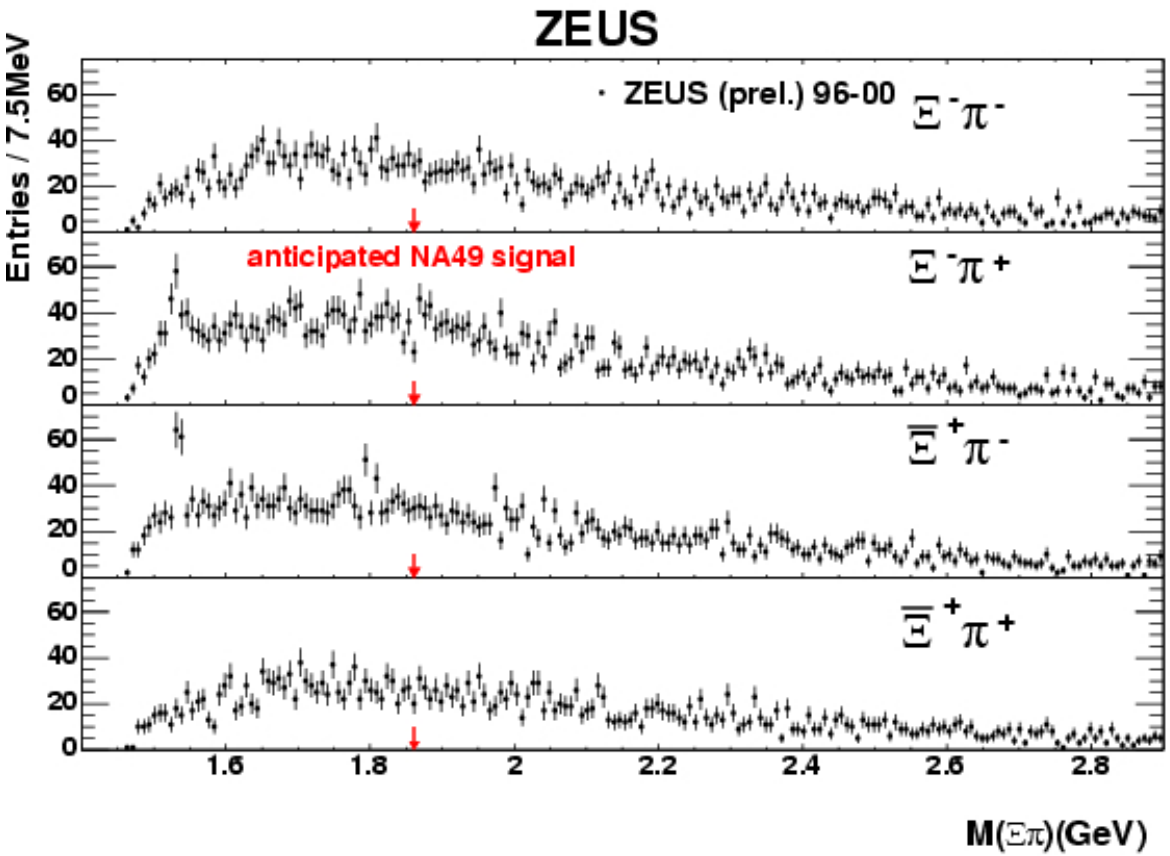
$$\Xi^{--} \rightarrow \Xi^{-}\pi^{-}$$
$$\rightarrow \Lambda^{0}\pi^{-}$$
$$\rightarrow p\pi^{-}$$

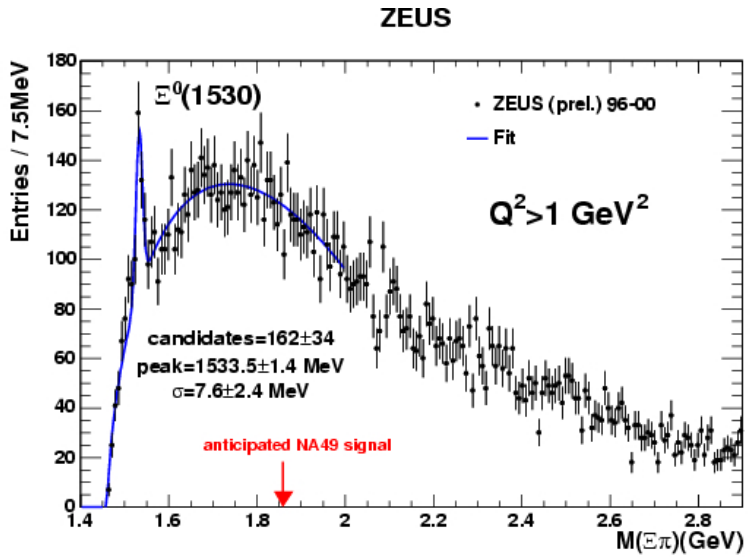
- **Inclusive DIS event sample (105 pb^{-1})**
- **High statistics, small background**

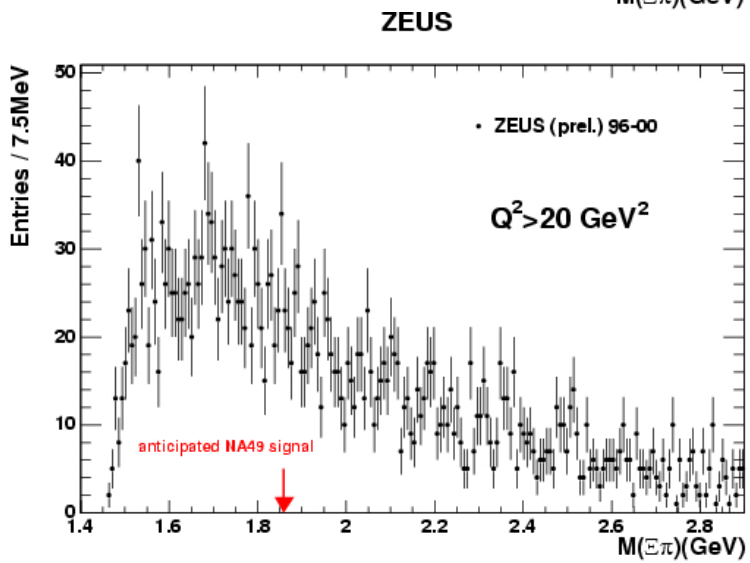




The NA49 signal (Ξ^{--}) search in ZEUS





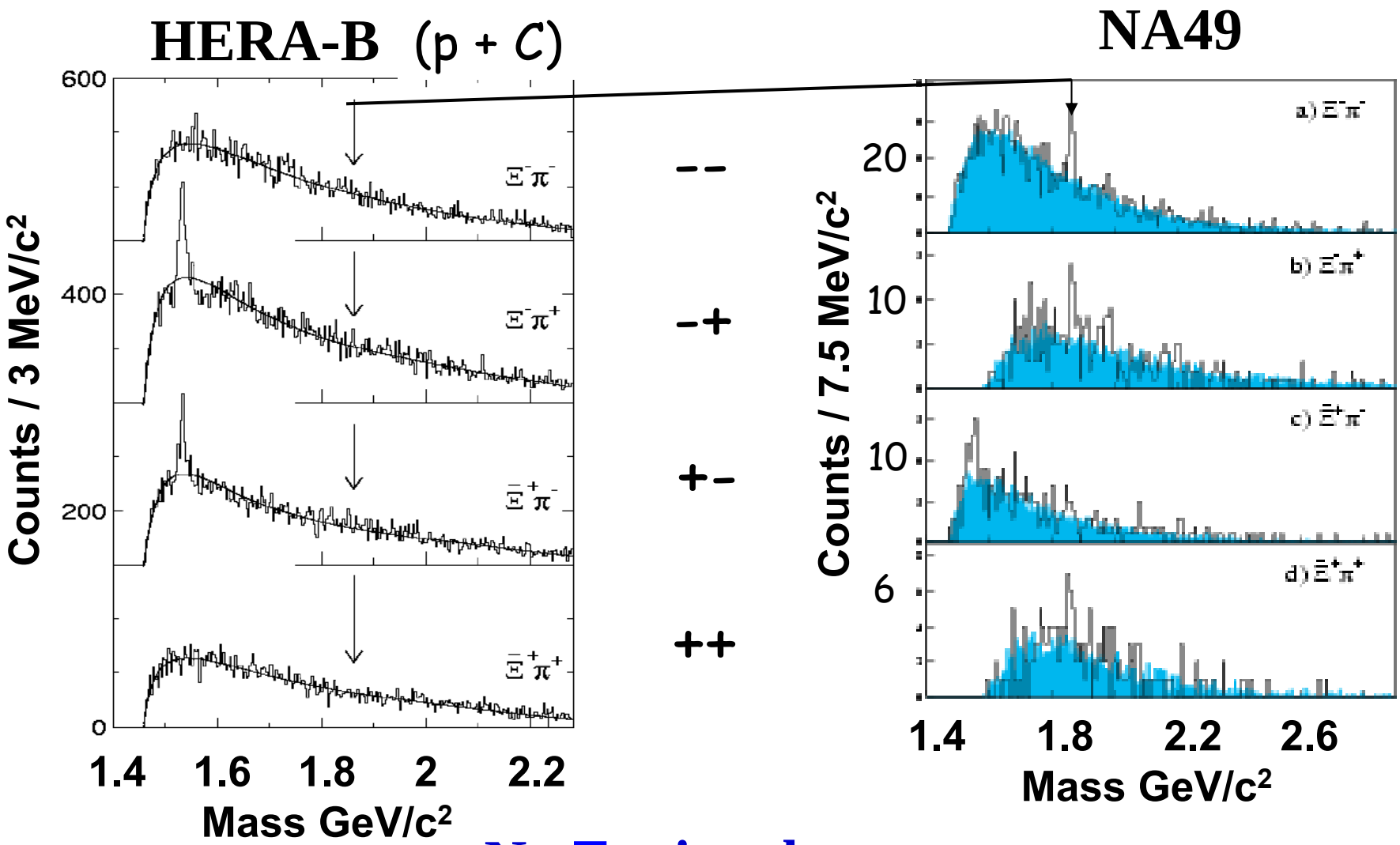


Clean $\Xi^0_{3/2}(1530)$ but ...

No pentaquark signal

Four channels combined

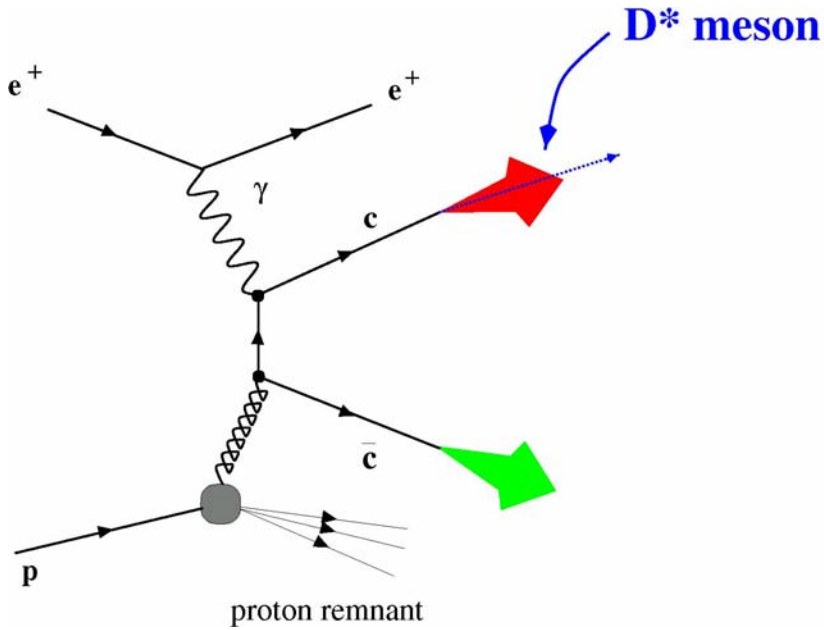
The NA49 signal (Ξ^{--}) search in HERA-B



No Ξ^{--} signal seen

Charm quark production in DIS

Main contribution comes from boson-gluon fusion



Charm tagging is efficiently done by reconstructing D*

Golden channel: $D^{*+} \rightarrow D^0 \pi_S \rightarrow (K\pi)\pi_S$

$D^{*+} \rightarrow D^0 \pi_S \rightarrow (K\pi\pi\pi)\pi_S$

The Charmed Pentaquark search in H1

$Q^2 > 1\,GeV^2$ (DIS)

96 – 00 H1 data ($75\,pb^{-1}$)

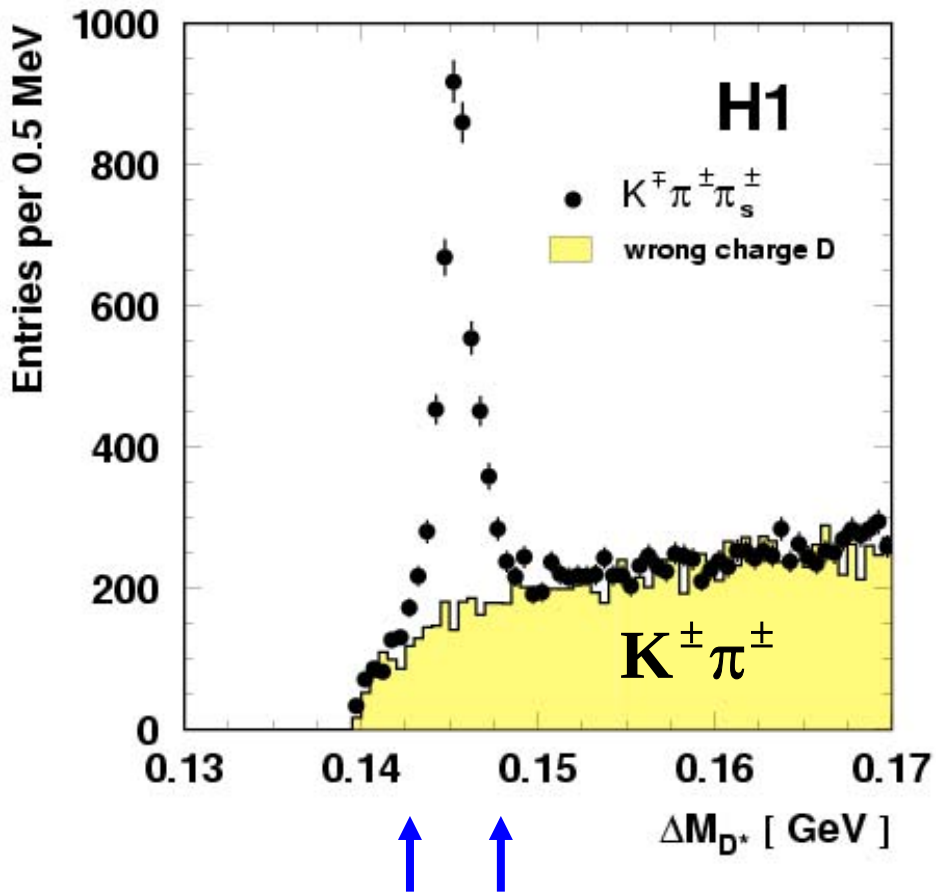
$p_T(D^*) > 1.5\,GeV$

$p_T(K) + p_T(\pi) > 2\,GeV$

$-1.5 < |\eta(D^*)| < 1$

$z(D^*) > 0.2$

$D^* \to D^0\pi_S \to (K\pi)\pi_S$



Signal region ~ 3400 D*

Good signal/background ratio

Signal region

Proton identification

Energy loss measurement dE/dx in the drift chamber

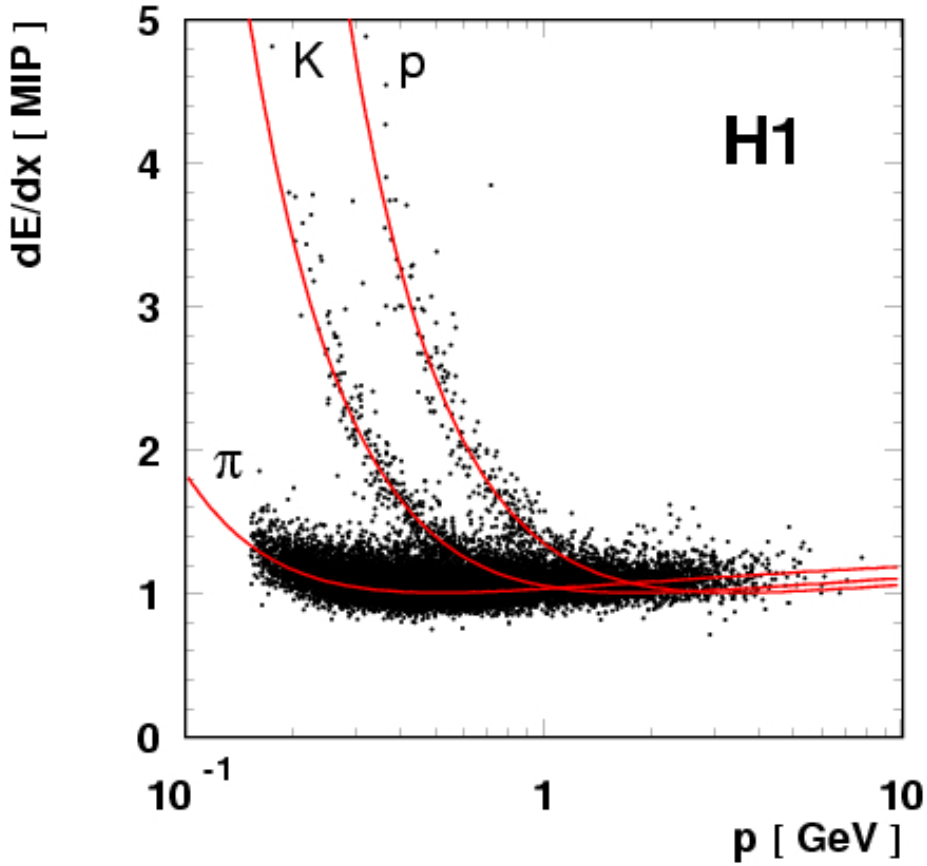
Parametrisation precision ~3-5%

MIP resolution ~8%

Use normalised likelihoods

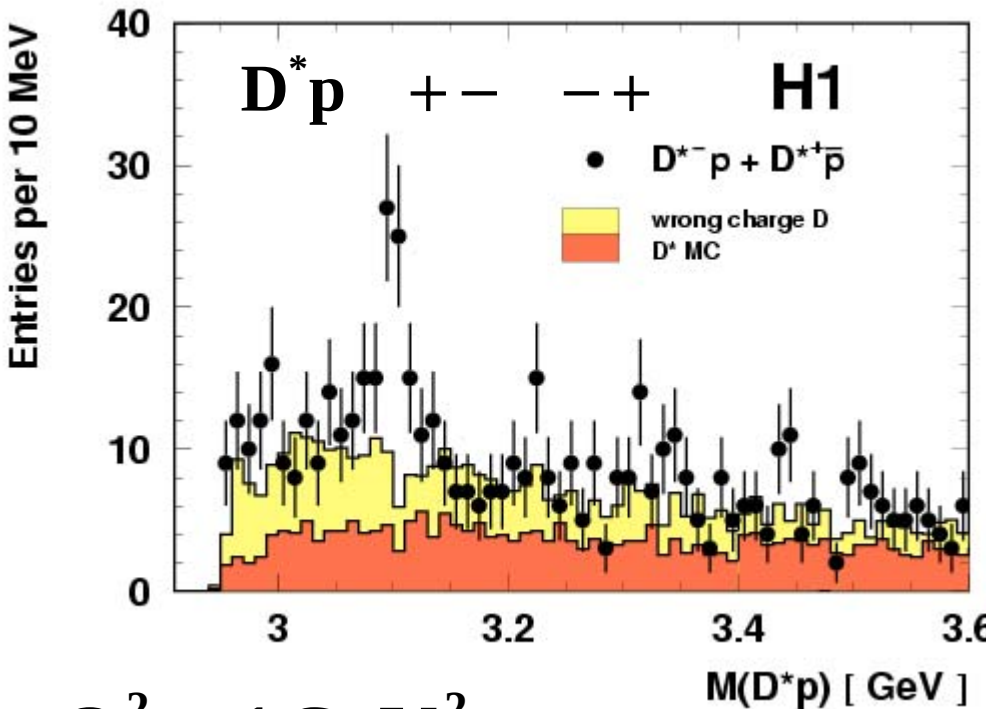
$L(\pi) + L(K) + L(p) = 1$

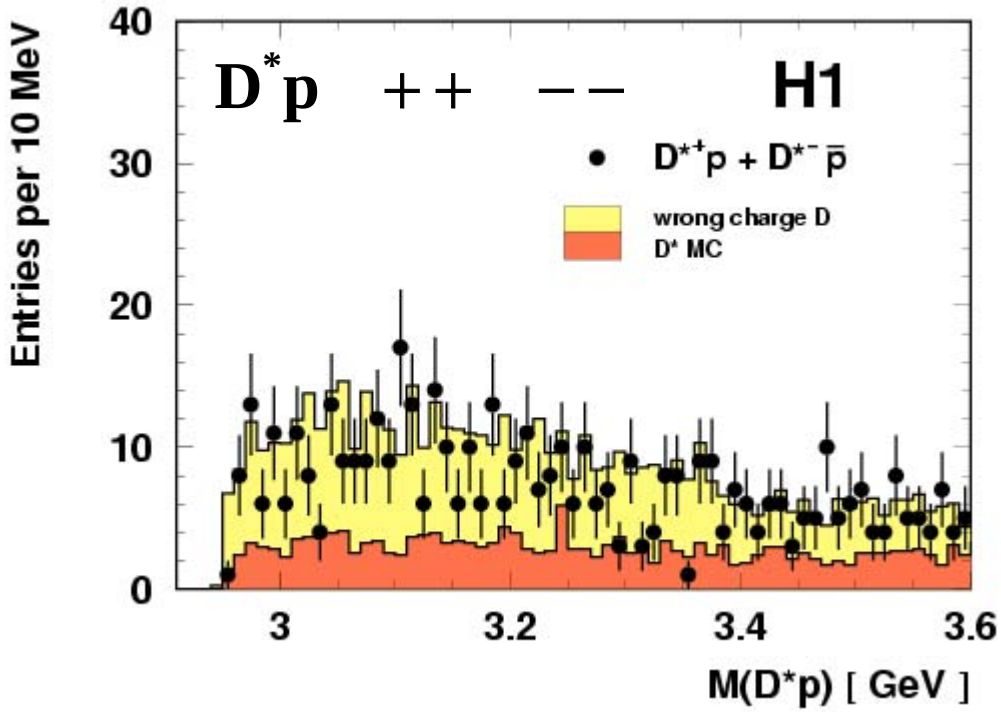
Use dE/dx for background suppression



The charmed pentaquark search in H1

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





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

No enhancement in D^* Monte Carlo

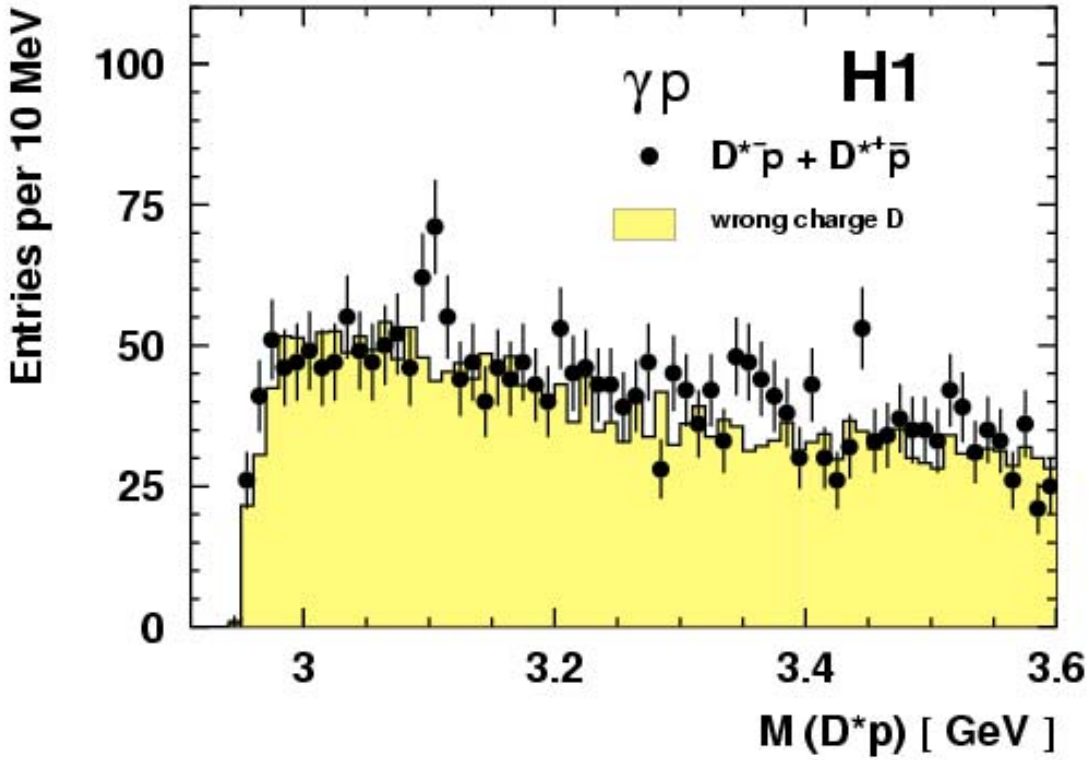
No enhancement in wrong charge D

Narrow resonance at M =3099 ±3(stat) ±5(syst) MeV

No significant signal in same charge combination

The charmed pentaquark search in H1

Signal also seen in independent sample of photoproduction



More combinatorial background

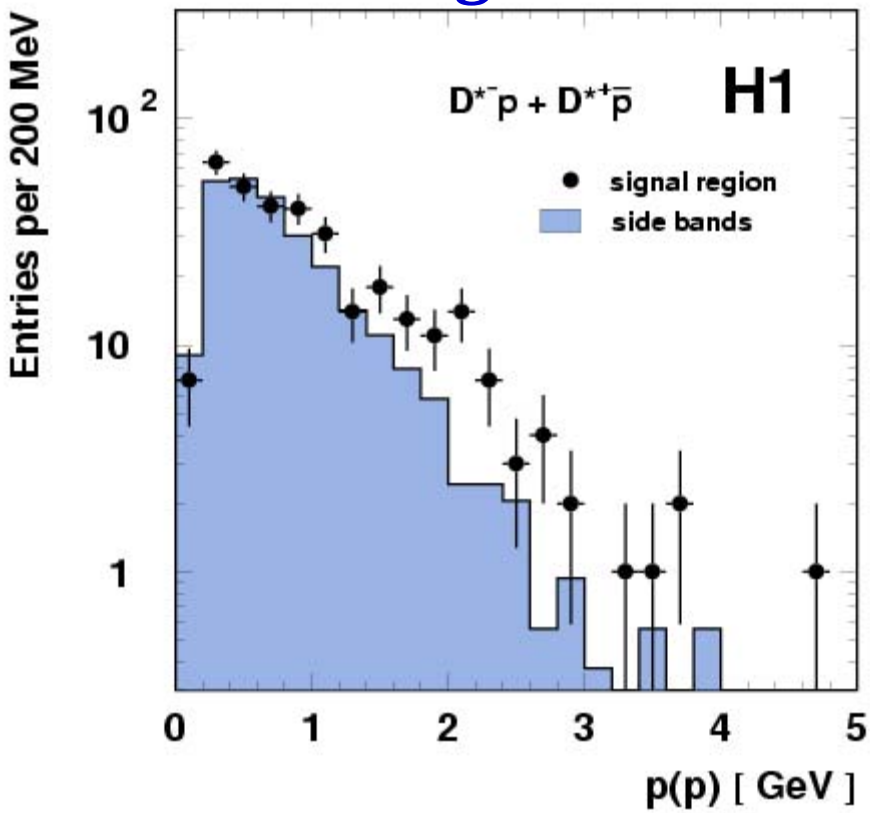
D^*p peak at the same mass

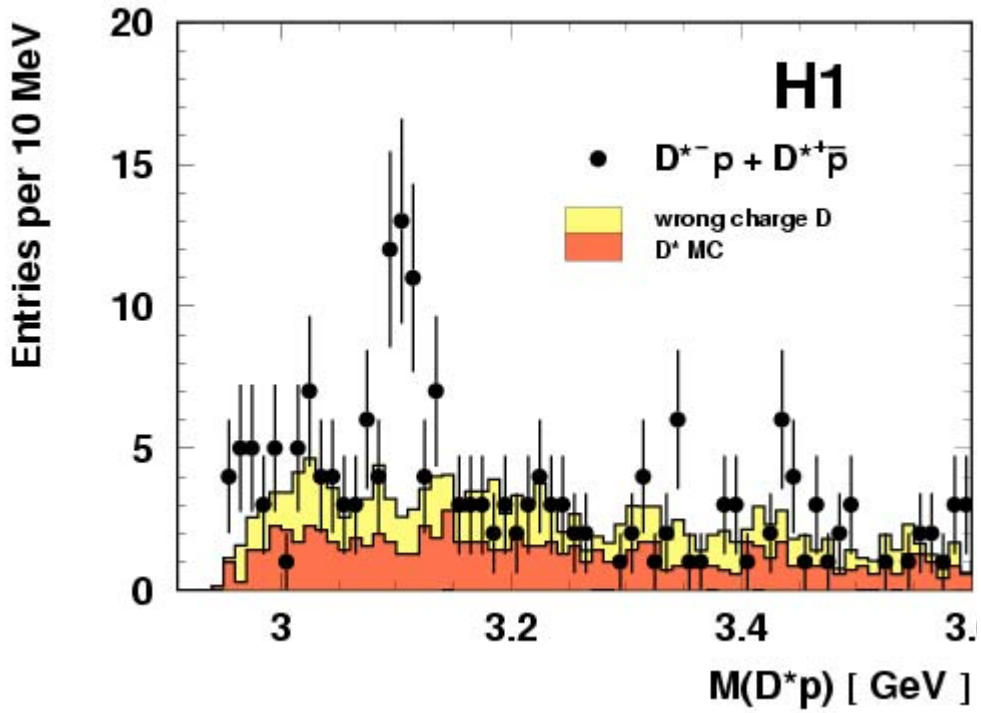
Narrow resonance at M =3103 ±4 MeV

The charmed pentaquark search in H1

$Q^2 > 1 GeV^2$

High momentum region: no dE/dx cuts



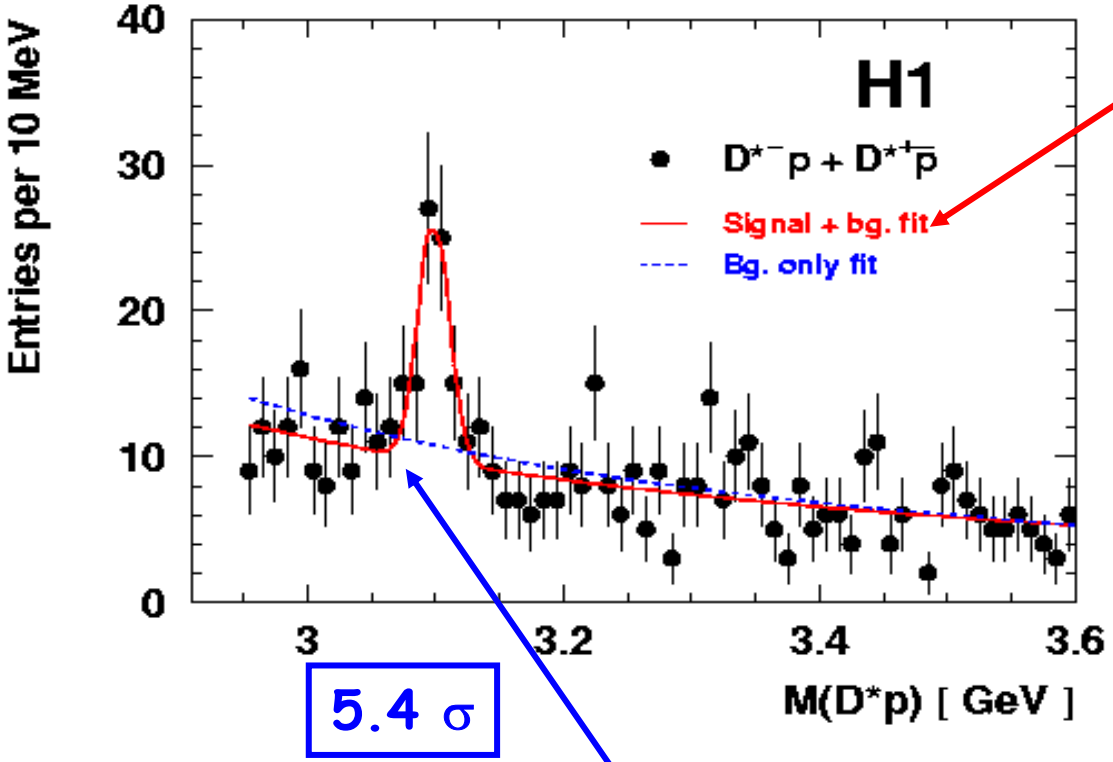


The momentum spectrum of the particles in the signal region is harder than in the $M(D^*p)$ side bands

At large proton momentum the signal is more pronounced

The charmed pentaquark search in H1

$Q^2 > 1 GeV^2$



background + signal hypothesis Fit:

Mass: 3099 ± 3(stat) ± 5(syst) MeV

Width: 12 ±3 MeV

(consistent with experimental resolution)

Numbers of signal and bg. within 2σ

N_b = 45.0 ± 2.8

N_s = 50.6 ± 11.2 (~ 1% of D* yield)

Background only hypothesis: N_b=51.7±2.7

Background fluctuation probability: $4x10^{-8}$ (Poisson)=5.4 σ (Gauss)

The charmed pentaquark search in ZEUS

95-00 ZEUS data (126 pb^{-1})

$D^* \rightarrow (K\pi)\pi_S$

$p_T(D^*) > 1.35$ GeV

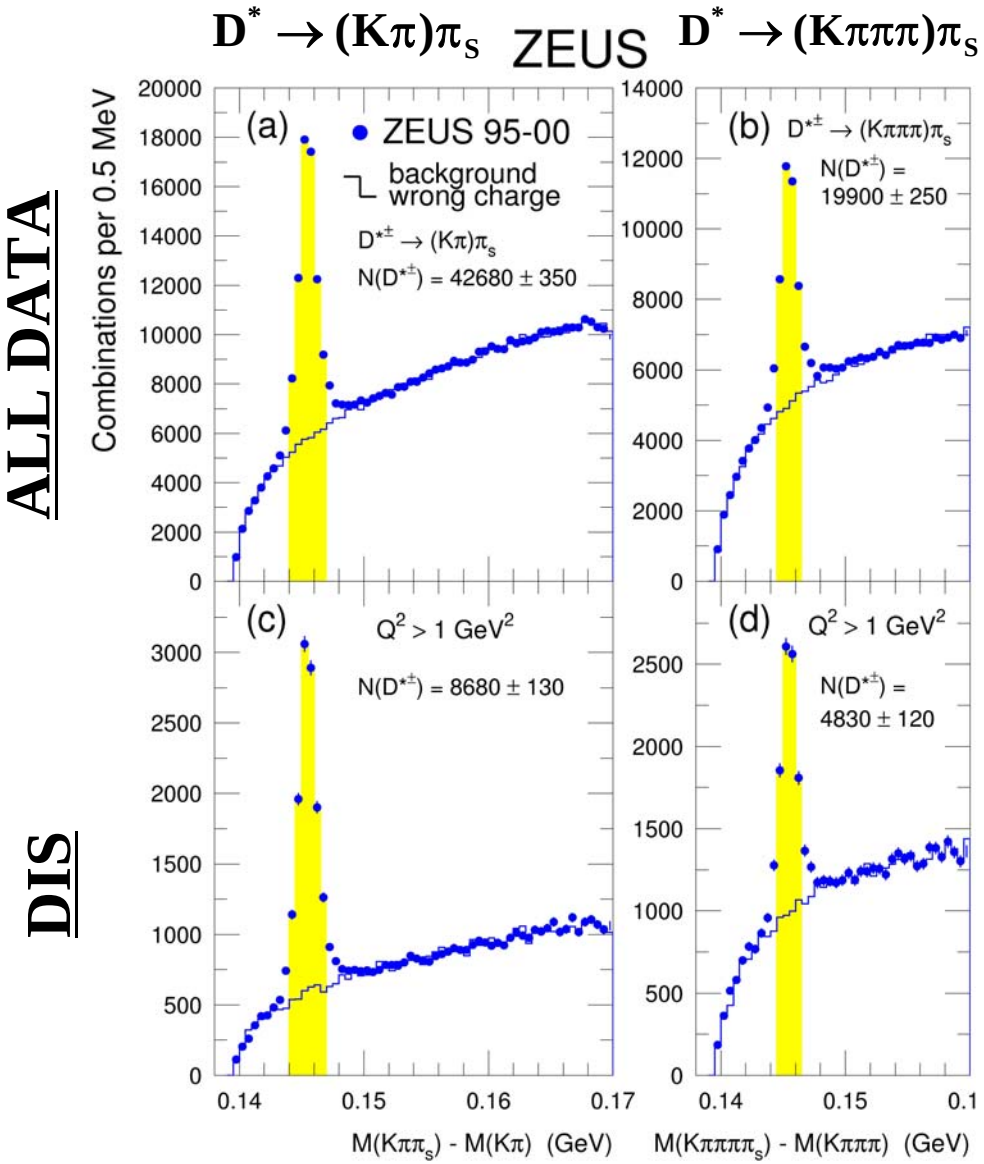
$D^* \rightarrow (K\pi\pi\pi)\pi_S$

$p_T(D^*) > 2.8$ GeV

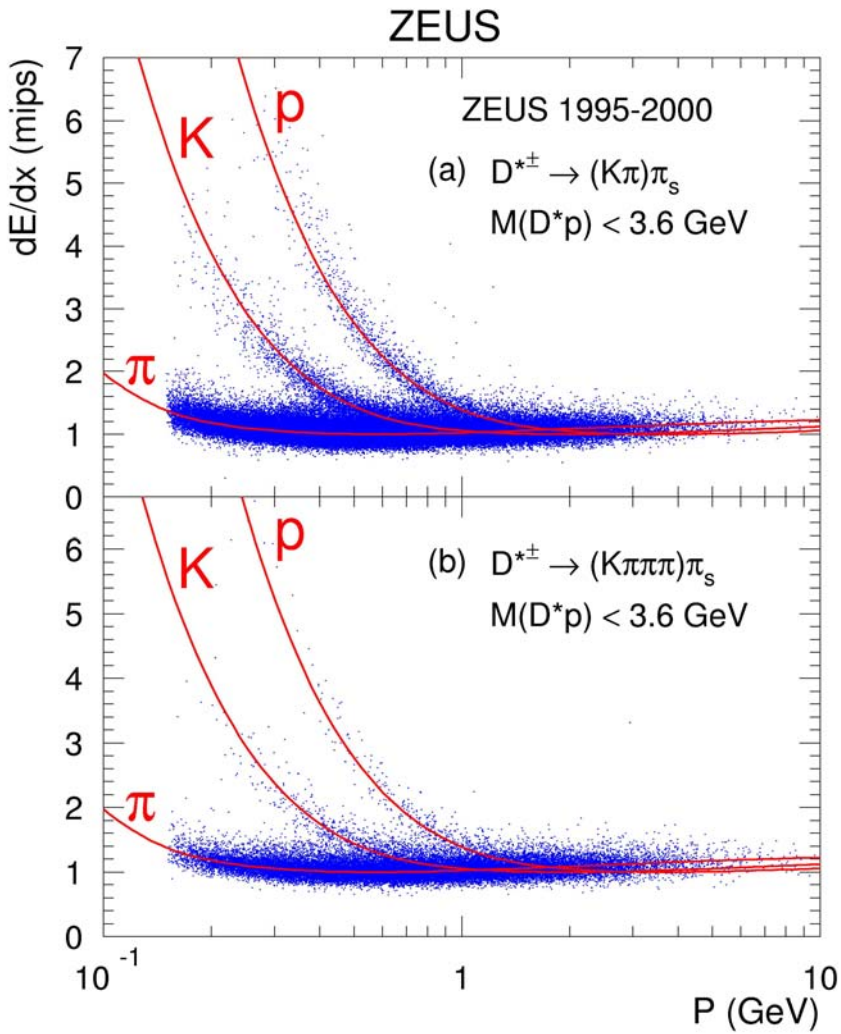
Number of D*

Total sample > 62000

DIS sample > 13000



Proton identification



Energy loss measurement dE/dx in the central tracking chamber

Expectations tuned using tagged protons and pions from Λ & K_s decays

$$\chi^2 = \frac{[\ln(dE/dx) - \ln(dE/dx)_{expected}]^2}{\sigma^2_{\ln(dE/dx)}}, \quad \sigma^2_{\ln(dE/dx)} = a/\sqrt{n_{hits}}$$

l_p: probability to produce the observed or larger value of χ^2

Acceptance A(l_p >0.15) = 85 ±0.1 %

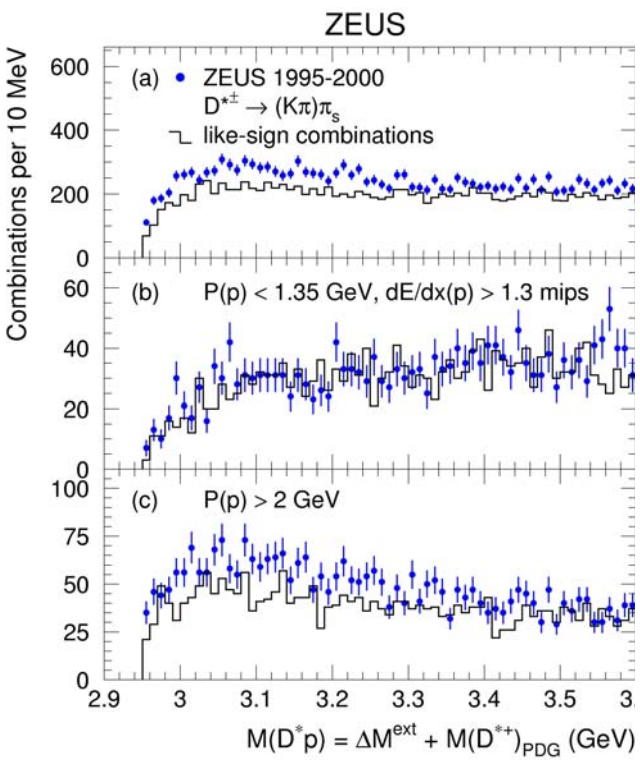
ZEUS finds NO charmed pentaquark ...

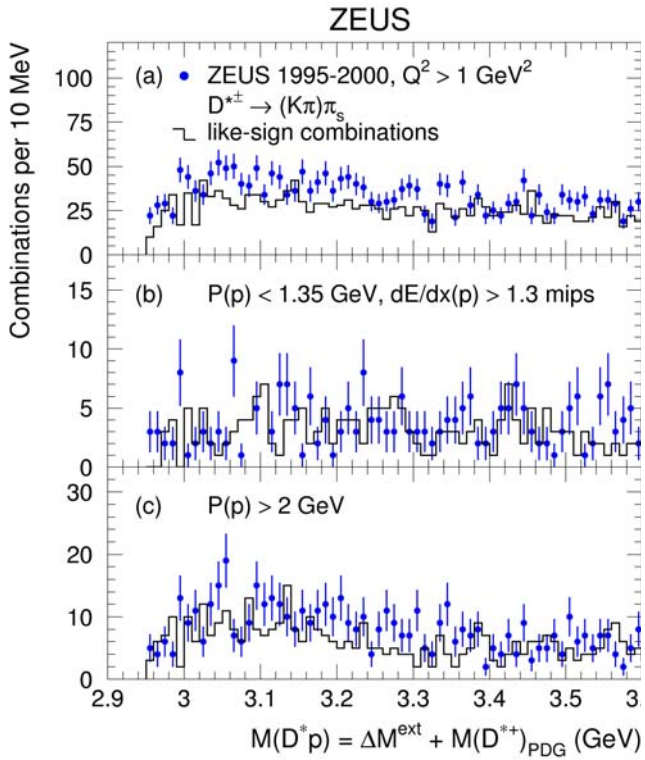
$D^* \rightarrow (k\pi)\pi_s$

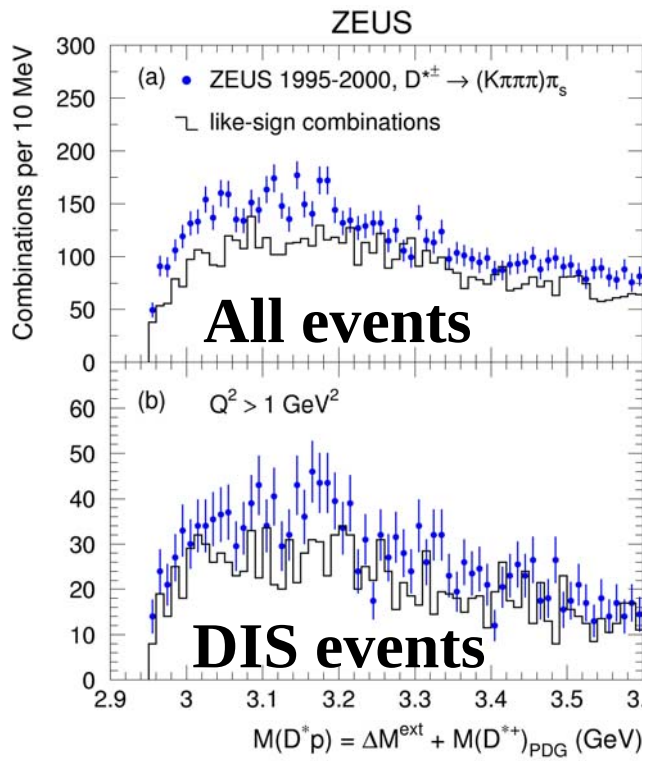
$D^* \rightarrow (k\pi\pi\pi)\pi_s$

All events

DIS events







No signal seen in different channels or selections

ZEUS upper limits for charmed pentaquark

No signal in either channel or for $Q^2 > 1$ GeV^2

Upper limit at 95% CL

$$R = N(\Theta_C \to D^* p) / N(D^*)$$

$R < 0.23$ %

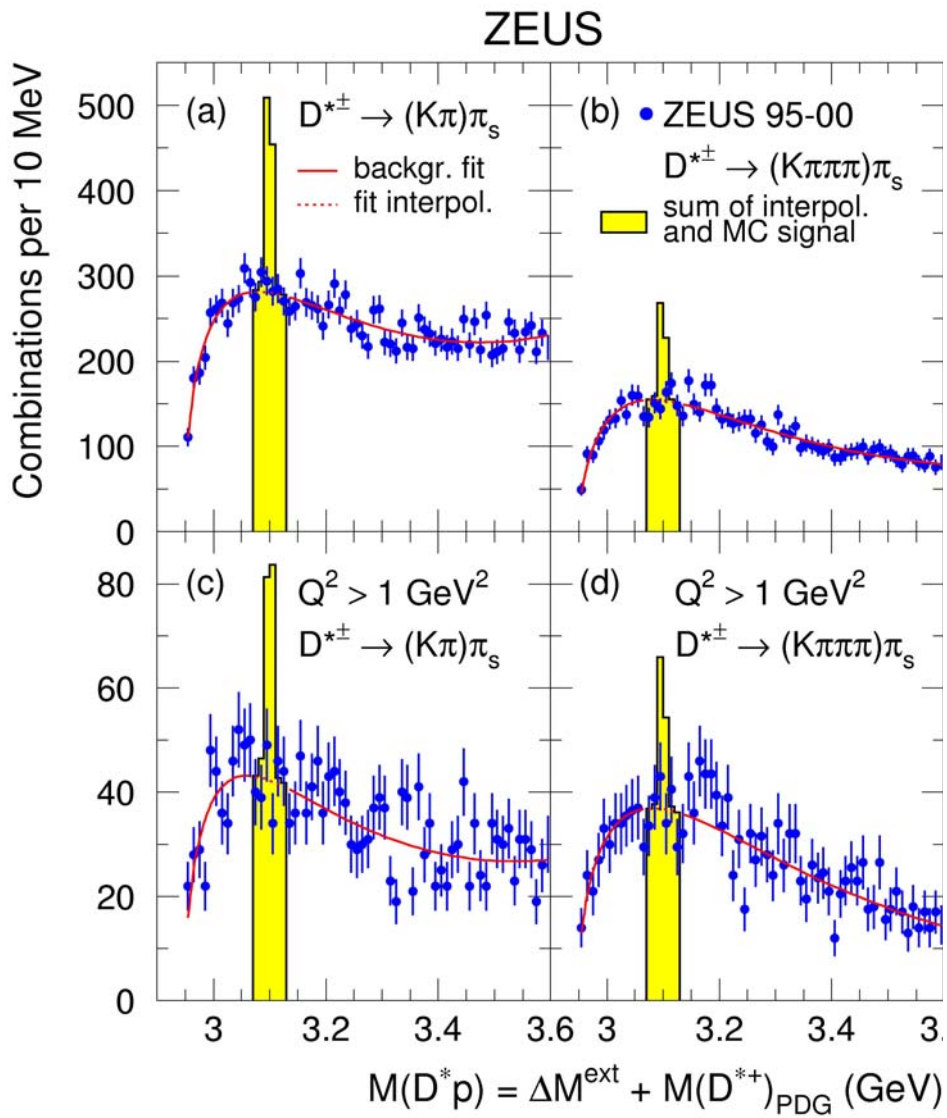
$R < 0.35\%$ for $Q^2 > 1$ GeV^2

$R < 0.29\%$ for $Q^2 < 1$ GeV^2

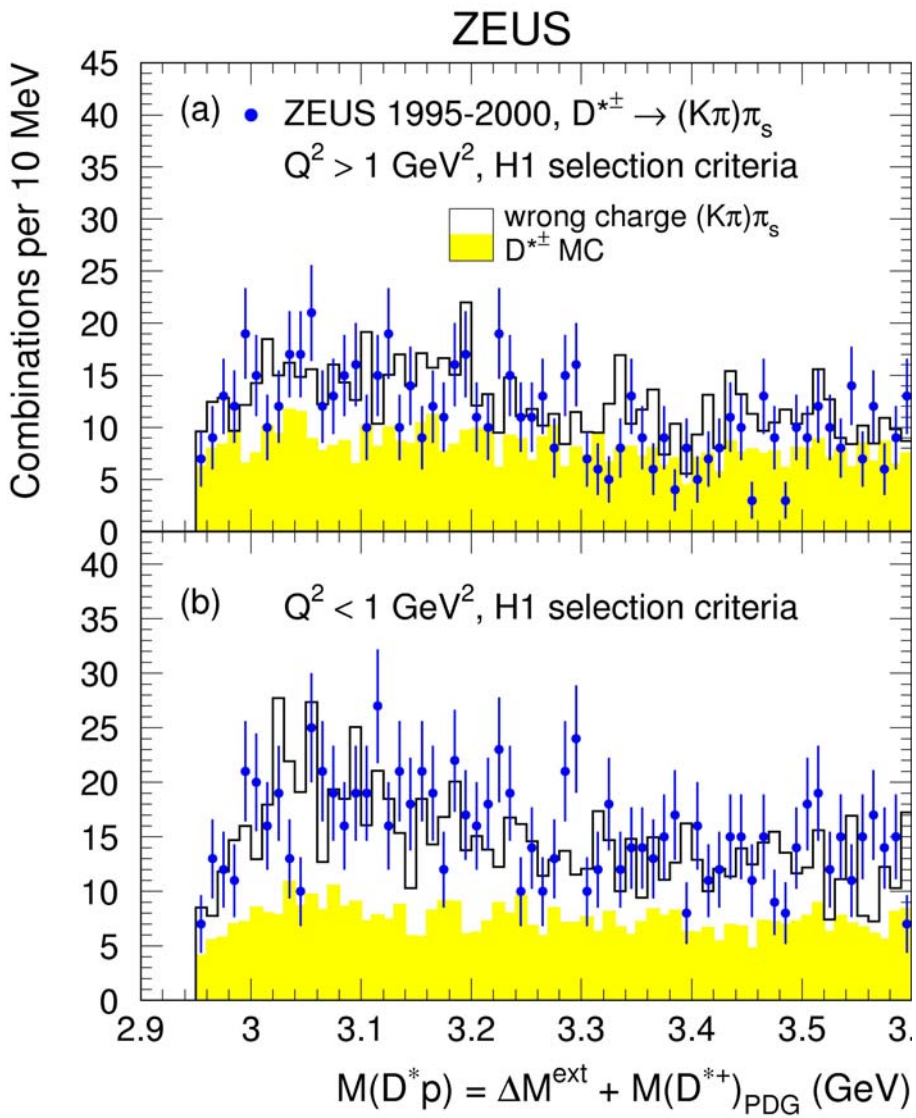
Universal upper limit

$$f(c \to \Theta_C) \cdot B_{\Theta_C \to D^* p} < 0.16\%$$

R~1% excluded at 9σ



ZEUS data with H1 selection cuts



NO CHARM PENTAQUARK!

$$Q^2 > 1\,\mathrm{GeV}^2$$

$$Q^2 < 1\,\mathrm{GeV}^2$$

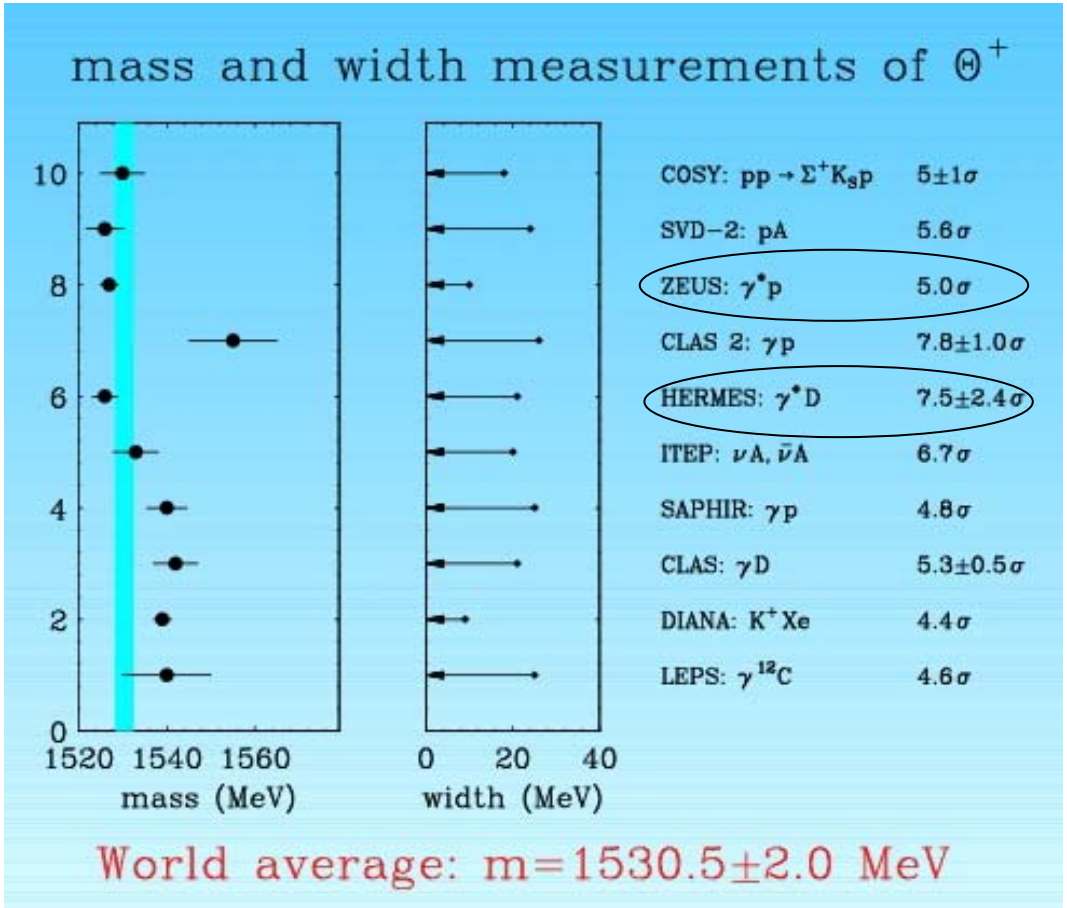
Number of D^*

$Q^2 > 1$ GeV^2: 5920±90

$Q^2 < 1$ GeV^2: 11670 ± 140

SUMMARY

Summary: the Θ^+ search at HERA



ZEUS

$M: 1521.5 \pm 1.5(\text{stat}) \,^{+2.8}_{-1.7}(\text{syst})$ MeV

$\Gamma: 8 \pm 4$ MeV

HERMES

$M: 1527 \pm 2.3$ MeV

$\Gamma: 17 \pm 9 \pm 3$ MeV

HERA-B

The UL(95%) for $B \cdot d\sigma/dy|_{y=0}$ for Θ+ production is:

3.7 μb/nucleon @ 1530 MeV

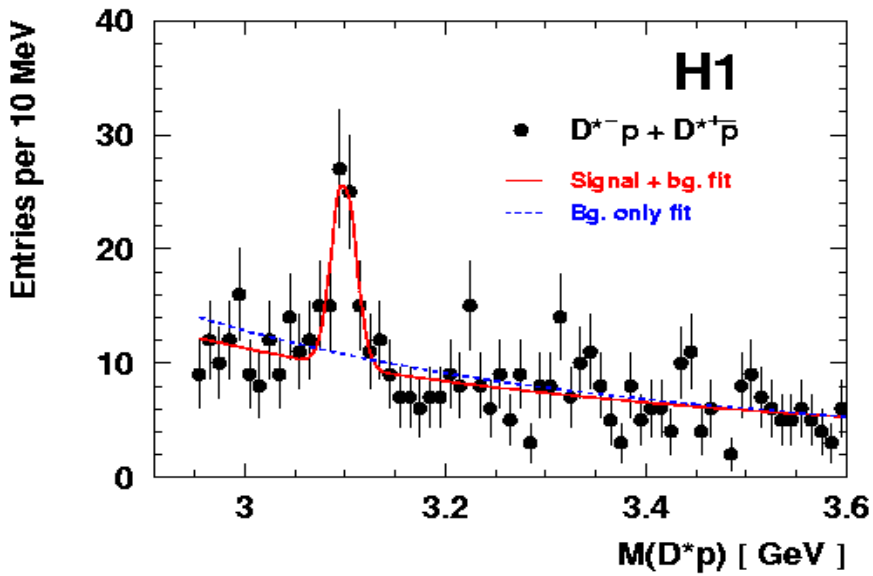
22 μb/nucleon @ 1540 MeV

ZEUS measurement:

- One of the most precise (largest number of candidates)
- Smallest width due to one of the best resolutions in the $K_S p$ channel

Summary: the Θ^+_C search at HERA

H1 sees narrow resonance at M =3099 ±3(stat) ±5(syst) MeV



background + signal hypothesis Fit:

Mass: 3099 ± 3(stat) ± 5(syst) MeV

Width: 12 ±3 MeV

(consistent with experimental resolution)

Numbers of signal and bg. within 2σ

$N_b = 45.0 \pm 2.8$

$N_s = 50.6 \pm 11.2$ (~ 1% of D* yield)

ZEUS does not see a narrow resonance

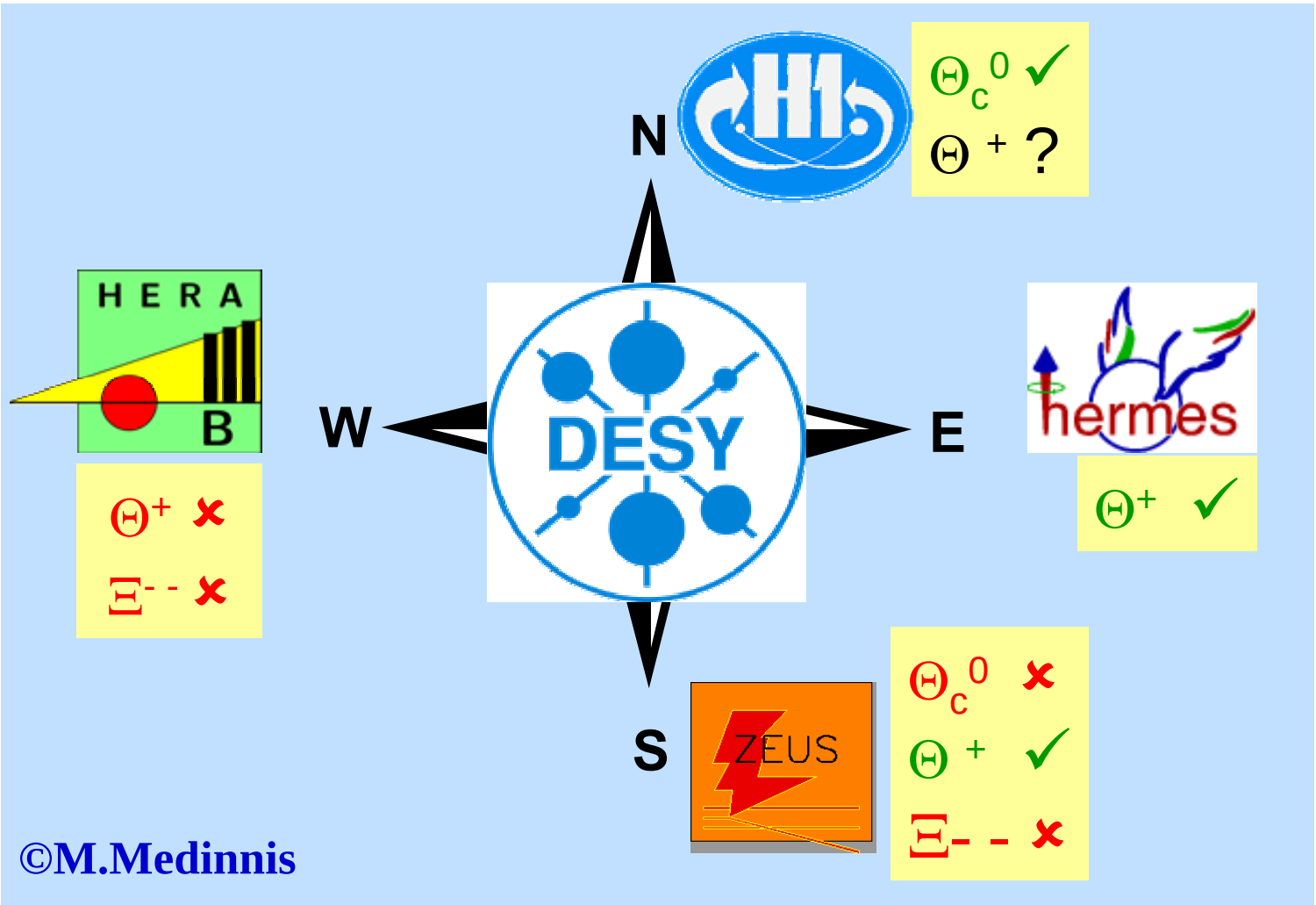
$$R = N(\Theta_C \to D^* p) / N(D^*) \sim 1\% \text{ excluded at } 9\sigma$$

$$f(c \to \Theta_C) \cdot B_{\Theta_C \to D^* p} < 0.16\%$$

$R < 0.35\%$ for $Q^2 > 1$ GeV^2

$R < 0.29\%$ for $Q^2 < 1$ GeV^2

Pentaquark searches at HERA



Puzzle!! : exciting times ahead