Particle production and spectroscopy in *ep* collisions

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On behalf of H1 and ZEUS Collaborations

Low-x meeting

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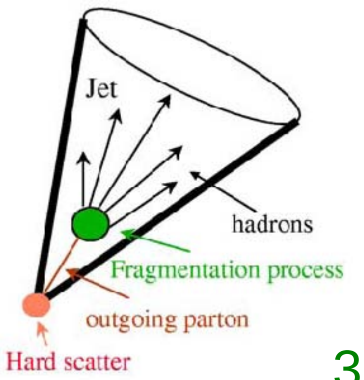
Outline

- Introduction
- Charm fragmentation: ratios, fractions & functions
- Strange production: K^0_S, Λ production, ratios…
- Search for pentaquarks□
- Summary

Charm fragmentation ratios and fractions



1. Are u- & d-quarks produced equally?

$$R_{u/d} = \frac{c\bar{u}}{c\bar{d}}$$

2. What is s-quark production suppression?

$$\gamma_s = \frac{2c\bar{s}}{(c\bar{d} + c\bar{u})}$$

3. Is the fraction of D mesons produced in a vector state in accordance with spin counting (=0.75)?

$$P_V = \frac{V}{(PS + V)}$$

4. What are the fractions of c-quarks hadronising in a charm hadron?

$$f(c \rightarrow D, \Lambda_c) = \frac{N(D, \Lambda_c)}{N(c)}$$

5. Are the charm fragmentation characteristics universal?

Charm hadrons cross sections needed to extract the ratios and fractions.

Charm hadrons reconstruction in DIS

Charm mesons D^0, $D^{*\pm}$, $D^{\pm}$, $D_s^{\pm}$ and the $\Lambda_c^{\pm}$ baryons are reconstructed in deep inelastic scattering at HERA with the **ZEUS** detector from the following decay modes:

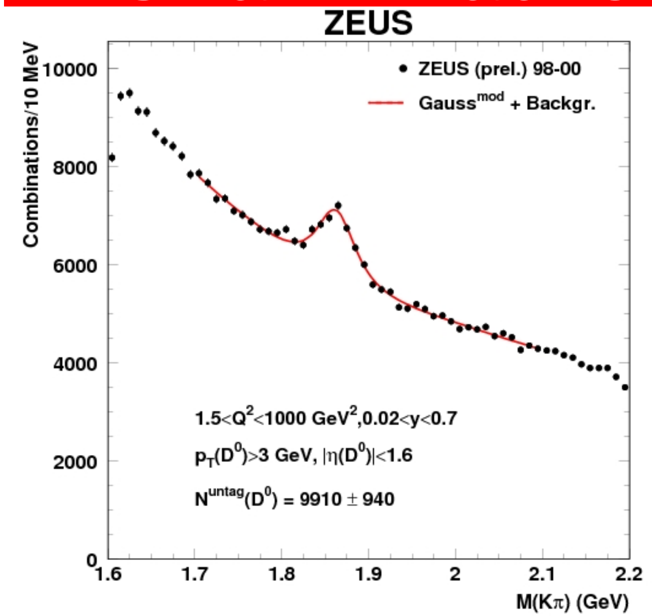
- **$D^0 \rightarrow K^- \pi^+$**
- **$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$**
- **$D^+ \square \rightarrow K^- \pi^+ \pi^+$**
- **$D_s^+ \square \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$**
- **$\Lambda_c^+ \rightarrow K^- p \pi^+$**

(+ c.c.)

Event selection

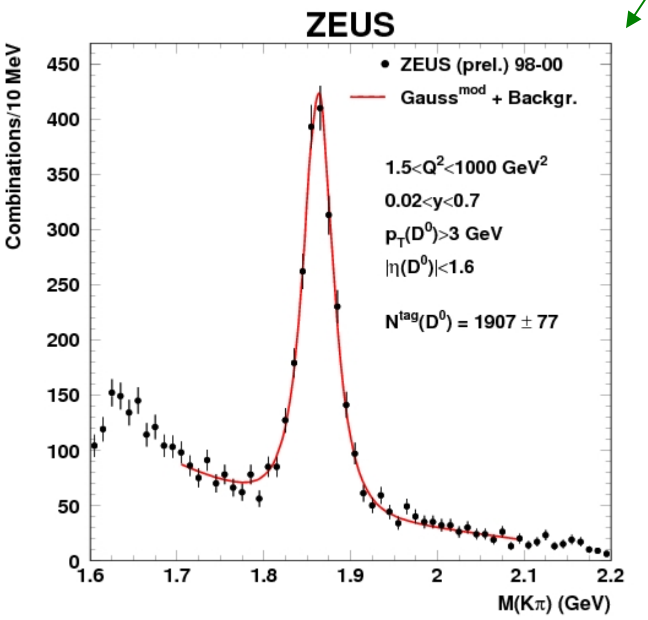
- **$1.5 < Q^2 < 1000$ GeV^2**
- **$0.02 < y < 0.7$**
- **$p_T(D,\Lambda_c) > 3$ GeV**
- **$|\eta(D,\Lambda_c)| < 1.6$**
- **$\mathcal{L} = 81.7$ (65.0) pb^{-1}**, 1998-2000 (1998-1999, for D^+ and Λ_c due to trigger availability)

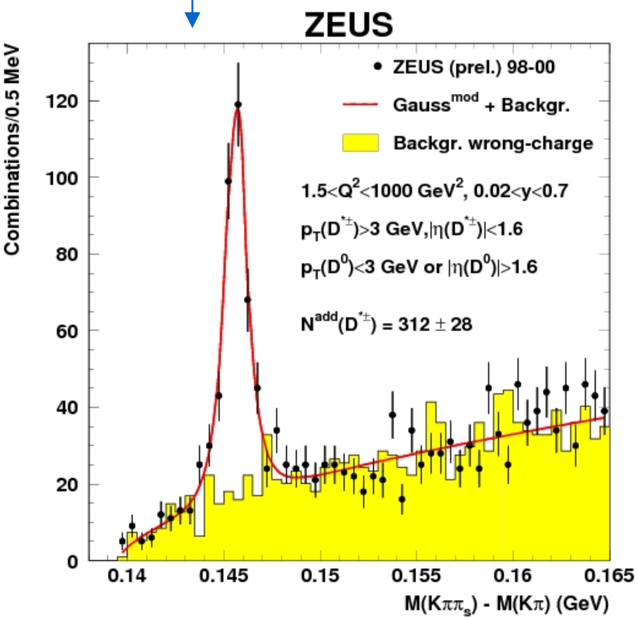
Charm hadrons reconstruction in DIS



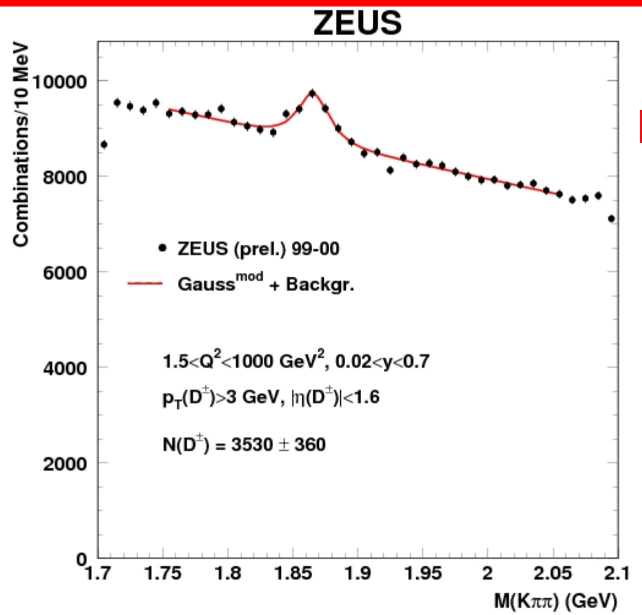
D^0 and D^* signals are splited in independent samples:

- D^0 not coming from D^* (D^0(untag))
- D^0 from D^* (D^0(tag))
- "Additional" D^*

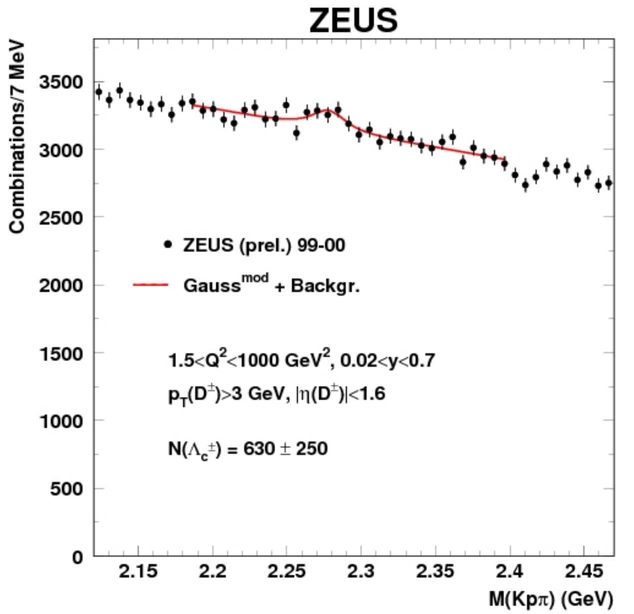




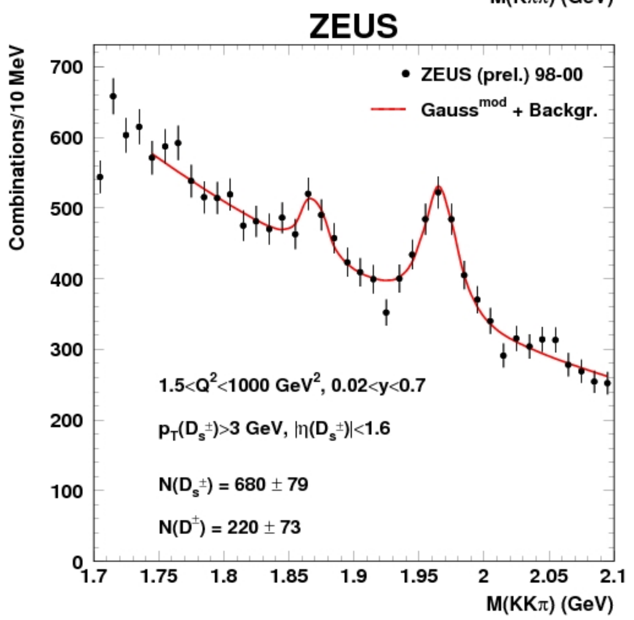
Charm hadrons reconstruction in DIS



D^+



Λ_c^+



D_s^+

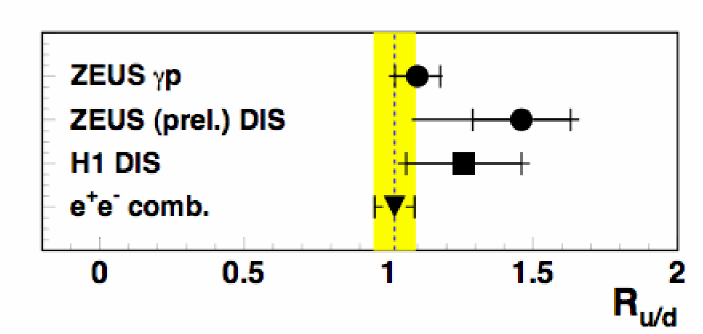
Clear signals from D^+ and D_s^+, but not for Λ_c.

Charm fragmentation ratios

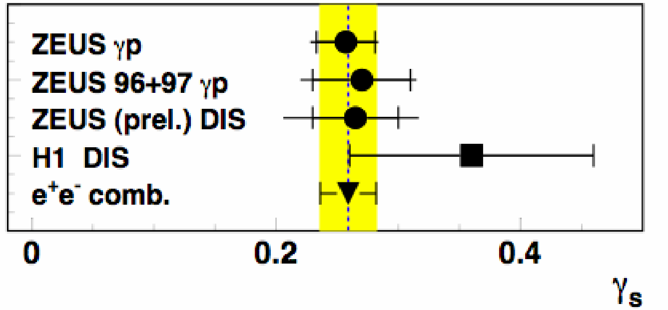
ZEUS preliminary results

$$R_{u/d} = \frac{\sigma^{untag}(D^0)}{\sigma(D^\pm) + \sigma^{tag}(D^0)} = \mathbf{1.46 \pm 0.17^{+0.10}_{-0.34}}$$

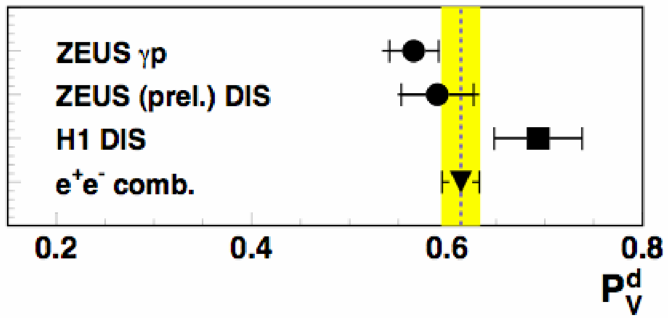
(Large systematic error from D^0(untag) signal extraction procedure, this has consequences in the other measurements.)



$$\gamma_s = \frac{2\sigma(D_s^\pm)}{\sigma(D^\pm) + \sigma^{untag}(D^0) + \sigma^{tag}(D^0) + 2\sigma^{add}(D^{*\pm})} = \mathbf{0.265 \pm 0.035^{+0.039}_{-0.048}}$$



$$P_V^d = \frac{\sigma^{tag}(D^0)/B_{D^* \to D^0\pi} + \sigma^{add}(D^{*\pm})}{\sigma(D^\pm) + \sigma^{tag}(D^0) + \sigma^{add}(D^{*\pm})} = \mathbf{0.590 \pm 0.037^{+0.022}_{-0.018}}$$



Measured P_V^d is smaller than spin-counting prediction P_V^d=0.75

Charm fragmentation fractions

$$f(c \to D^+) = \frac{\sigma(D^+) + \sigma^{add}(D^{*+}) \cdot (1 - B_{D^{*+} \to D^0 \pi^+})}{\sigma_{gs}}$$

$$f(c \to D^0) = \frac{\sigma^{untag}(D^0) + \sigma^{tag}(D^0) + \sigma^{add}(D^{*+}) \cdot (1 + B_{D^{*+} \to D^0 \pi^+})}{\sigma_{gs}}$$

$$f(c \to D^{*+}) = \frac{\sigma^{tag}(D^0) / B_{D^{*+} \to D^0 \pi^+} + \sigma^{add}(D^{*+})}{\sigma_{gs}}$$

$$f(c \to D_s^+) = \frac{\sigma(D_s^+)}{\sigma_{gs}} \qquad f(c \to \Lambda_c^+) = \frac{\sigma(\Lambda_c^+)}{\sigma_{gs}}$$

where

$$\sigma_{gs} = \sigma(D^+) + \sigma^{untag}(D^0) + \sigma^{tag}(D^0) + 2\sigma^{add}(D^{*+}) + \sigma(D_s^+) + \sigma(\Lambda_c^+) \times 1.14$$

is the total charm cross section.

Rates from $\Xi_c^{0,\pm}$ and Ω_c^0 are estimated from non-charm Ξ and Ω states to be 14±5% of Λ_c rate.

Charm fragmentation fractions

ZEUS preliminary results

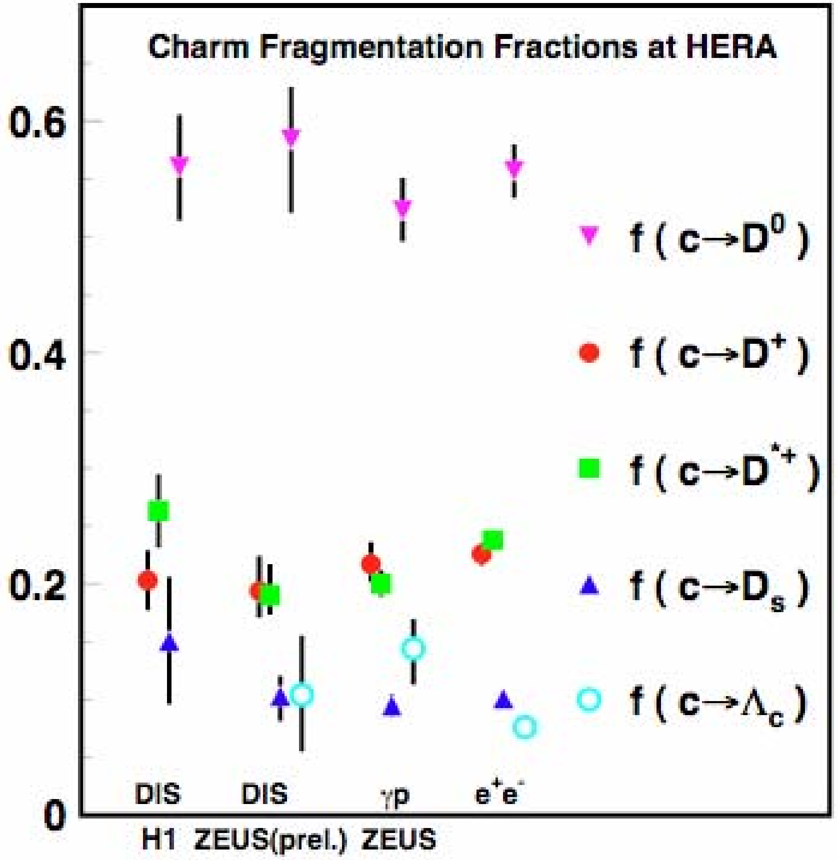
$$f(c \to D^0) = 0.584 \pm 0.039^{+0.024}_{-0.050}$$

$$f(c \to D^+) = 0.194 \pm 0.020^{+0.023}_{-0.011}$$

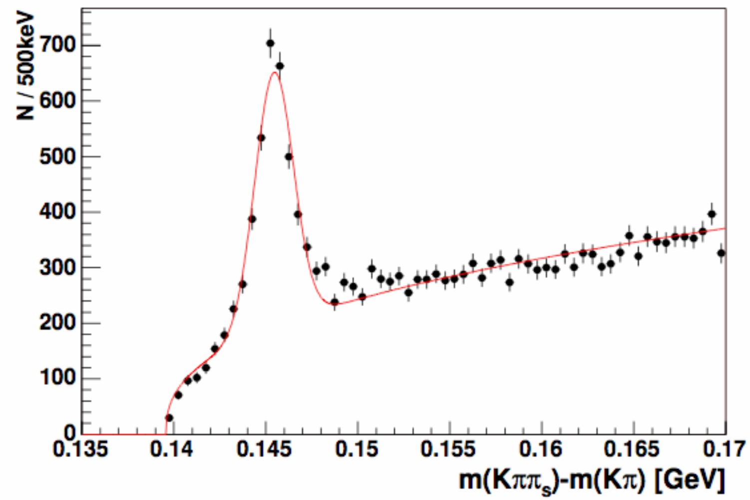
$$f(c \to D^{*+}) = 0.190 \pm 0.014^{+0.023}_{-0.009}$$

$$f(c \to D_s^+) = 0.103 \pm 0.013^{+0.012}_{-0.017}$$

$$f(c \to \Lambda_c^+) = 0.104 \pm 0.048^{+0.018}_{-0.010}$$



Charm fragmentation functions (H1)



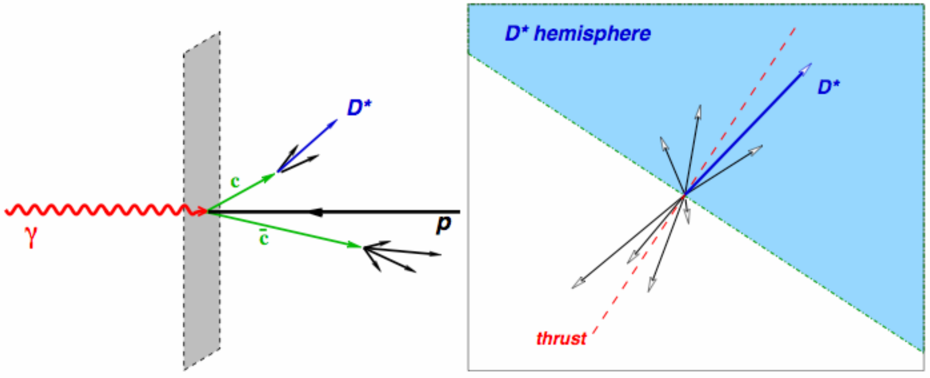
Event selection

- $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
- $2 < Q^2 < 100$ GeV^2; $0.05 < y < 0.7$
- $p_T(D^*) > 1.5$ GeV; $|\eta(D^*)| < 1.5$

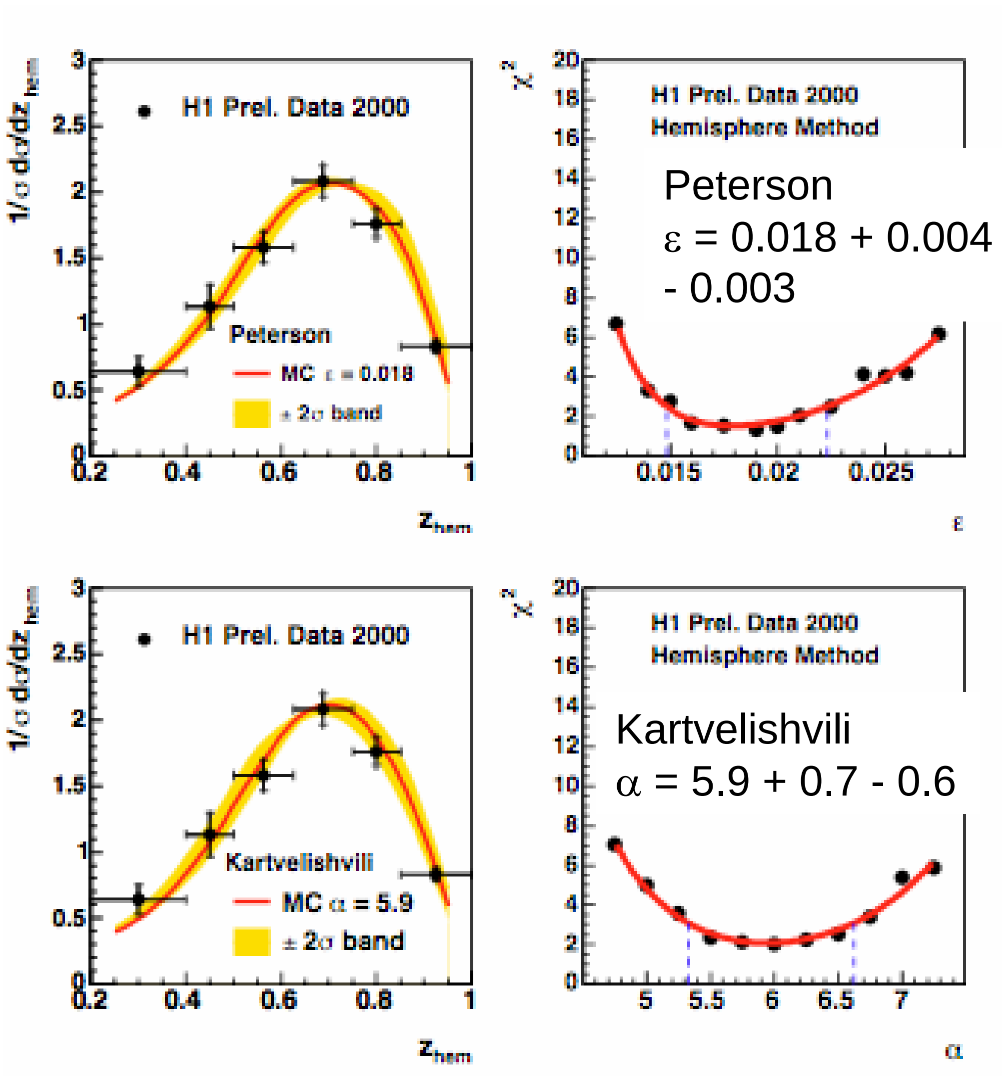
Hemisphere method:

In γp-frame cc pair is balanced in p_T

$$z = \frac{(E + p_L)_{D^*}}{\Sigma_{hem}(E + p)}$$



Charm fragmentation functions (H1)



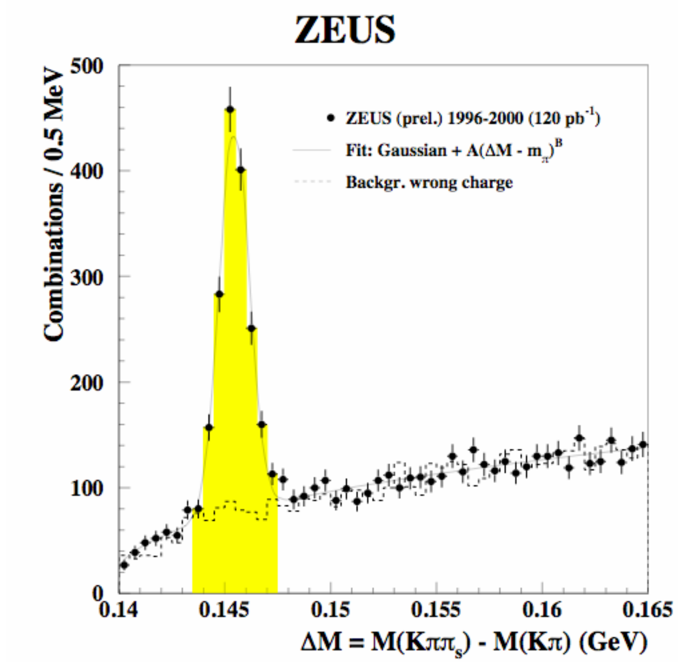
Charm fragmentation functions (ZEUS)

Event selection

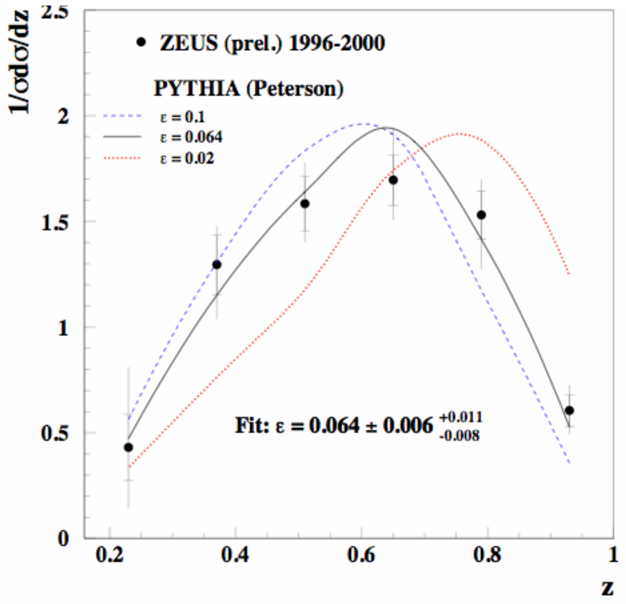
- $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$
- $Q^2 < 1$ GeV^2; $130 < W < 280$GeV
- p_T (D*) > 2 GeV; $|\eta(D^*)| < 1.5$
- $E_T^{jet} > 9$ GeV; $|\eta^{jet}| < 2.4$

Jet method: Energy of c-quark is approximated by the energy of the D* jet

$$z = \frac{(E + p_L)_{D^*}}{2E_{jet}}$$

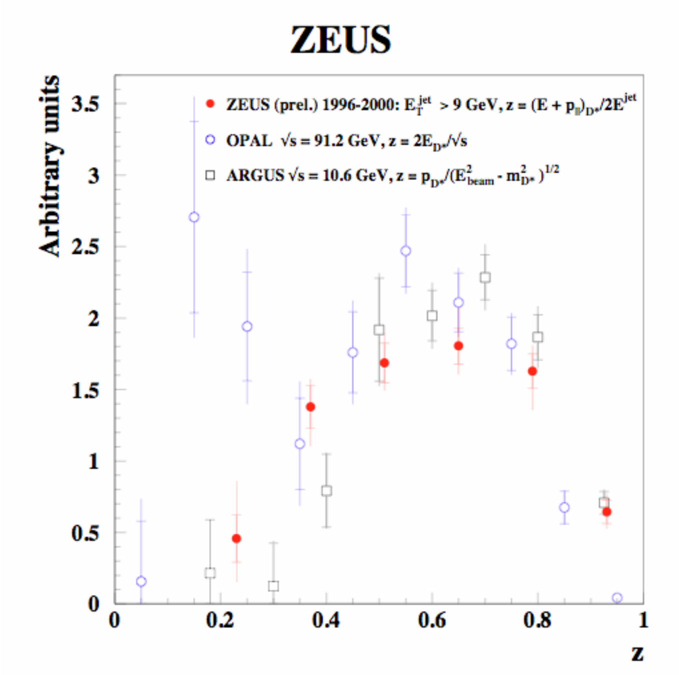


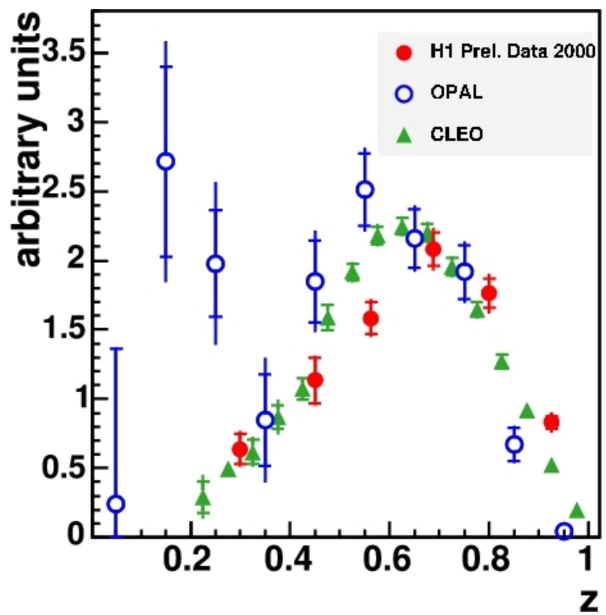
Peterson
$\varepsilon = 0.064 \pm 0.006\ ^{+0.011}_{-0.008}$



Charm fragmentation functions

ZEUS and H1 comparison with other experiments





H1 hemisphere method
$\langle\sqrt{s}\rangle \approx 10$ GeV,
$z = \frac{(E+p_L)_{D*}}{\sum_{hem}(E+p)}$

OPAL $\sqrt{s} = 91.2$ GeV,
$z = 2E_{D*}/\sqrt{s}$

CLEO $\sqrt{s} \approx 10$ GeV,
$z = p_{D*}/p_{max}$

- Different extraction methods and different scales involved, reasonable agreement between charm fragmentation function from different processes.

Strange production at HERA

Strangeness is largely produced at HERA providing a rich environment to study the fragmentation process by investigating production rates, relative yields, polarizations…

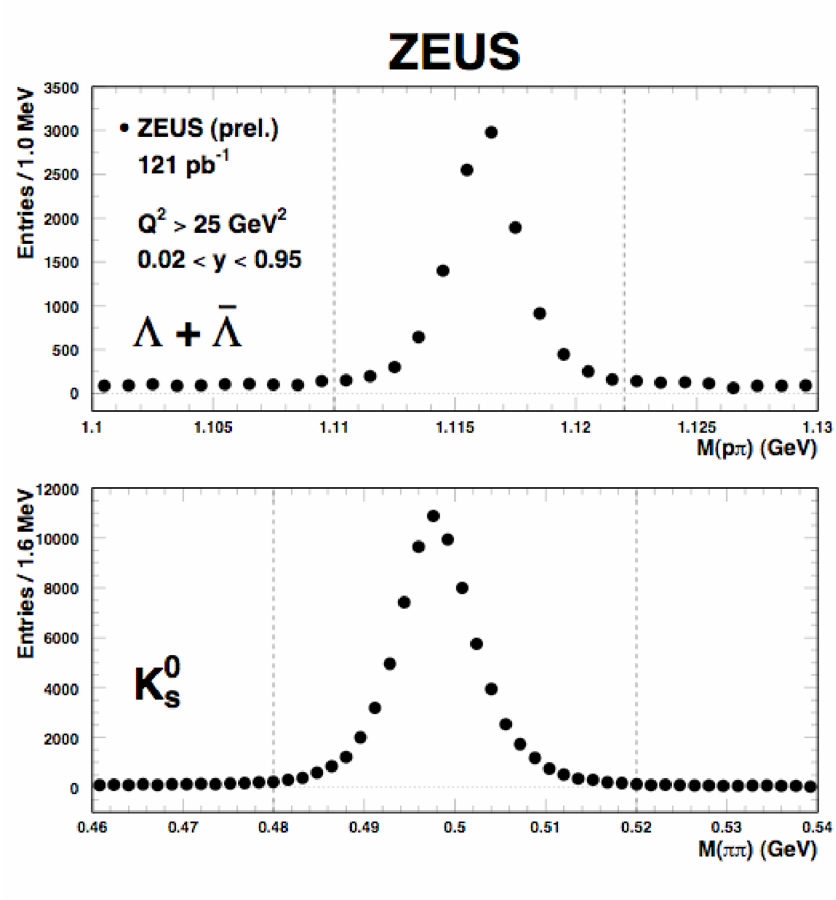
Measurements performed in the following phase spaces:

- Photoproduction, at least 2 jets
- DIS $5 < Q^2 < 25$ GeV^2
- DIS $Q^2 > 25$ GeV^2

For the three sets:

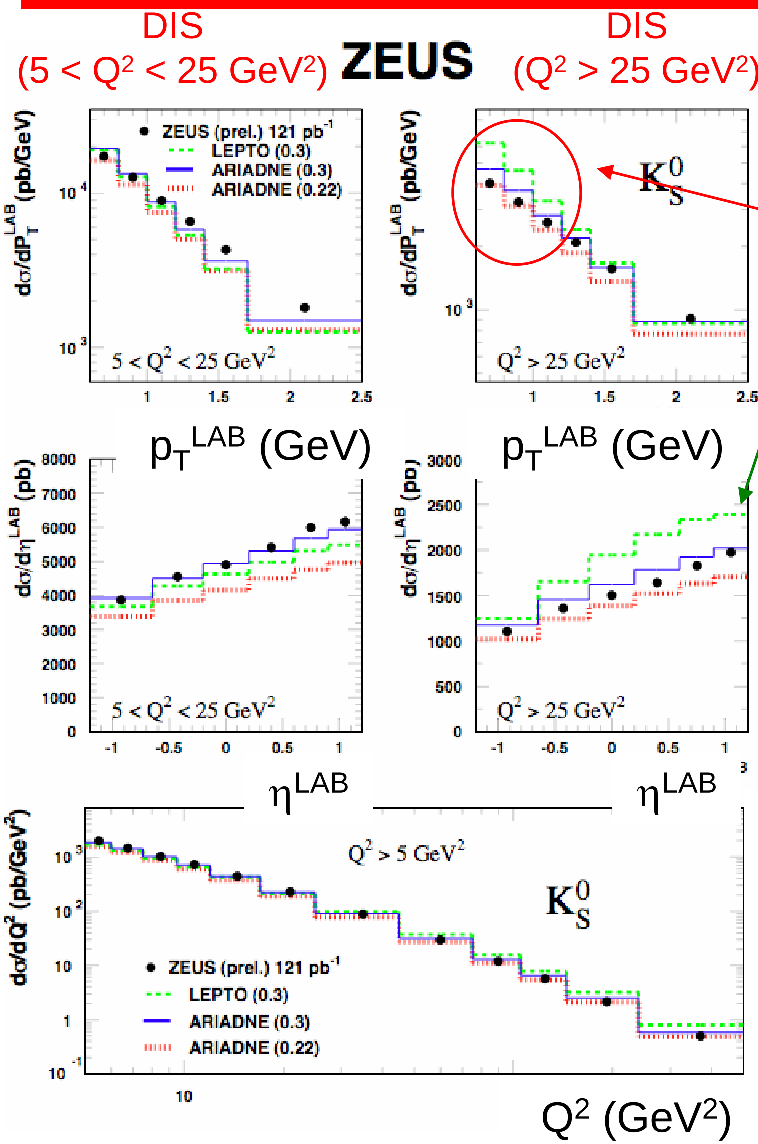
- $0.6 < p_T(K^0_s,\Lambda) < 2.5$□ GeV
- $|\eta(K^0_s,\Lambda)| < 1.2$

Reconstruction of K^0_s and Λ

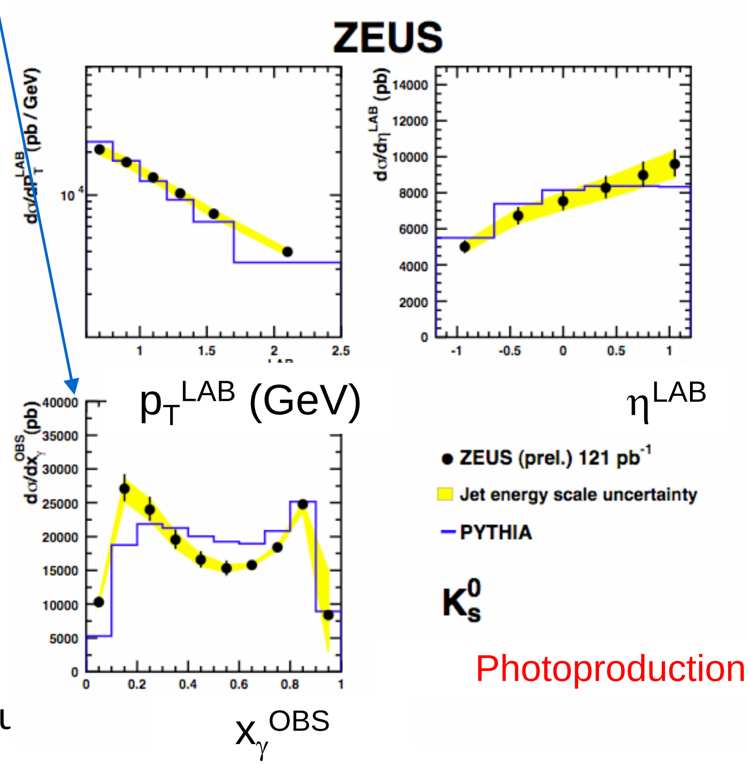


Clean background and high statistics

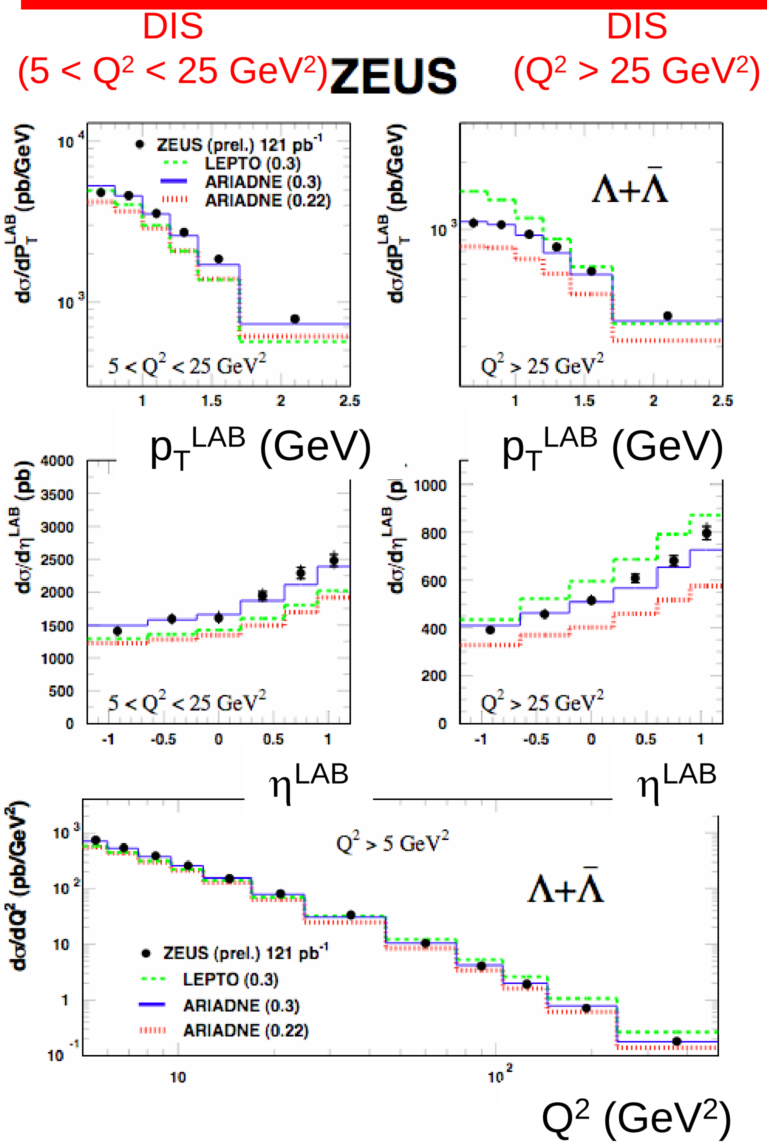
K^0_s production

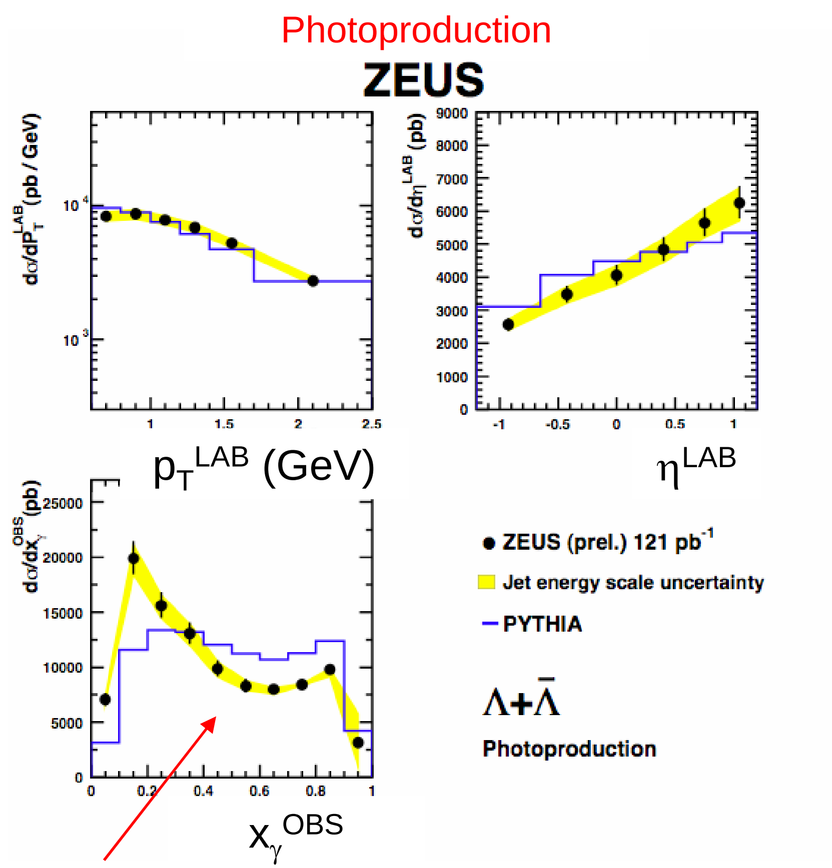


- In general, Ariadne describes reasonably well the data (λ_s=0.3).
- But for lower p_T, λ_s=0.22 describes better the data.
- Lepto does not reproduce the data.
- Pythia also fails to reproduce the data in PHP.



Λ and $\bar{\Lambda}$ production



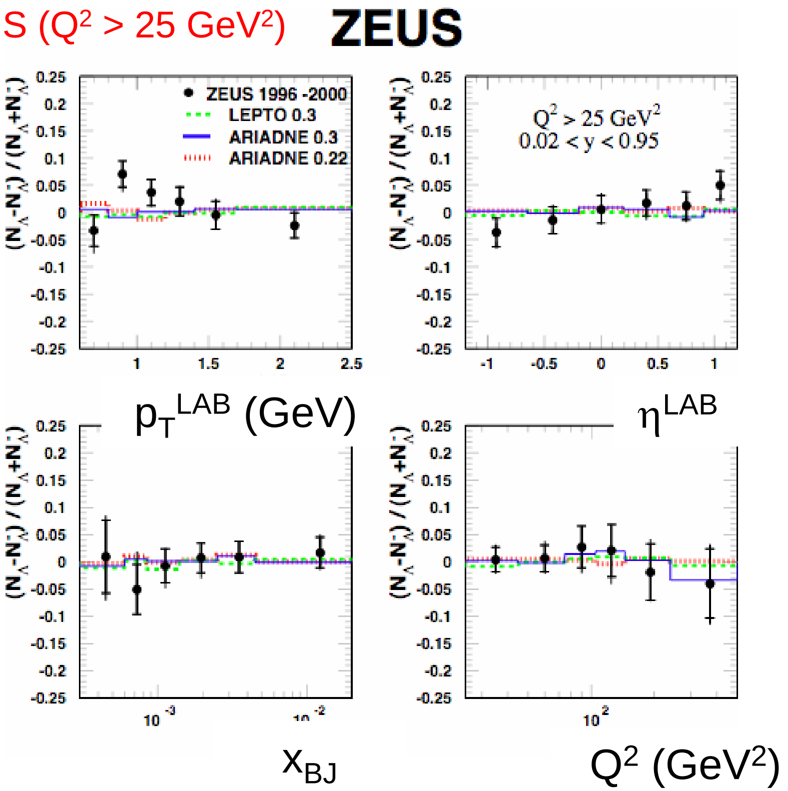


- Similar situation as in the K^0_s analysis.
- Adjusting a single parameter, λ_s, is not sufficient enough to describe the data simultaneously.

Λ to $\bar{\Lambda}$ asymmetry

$$A = \frac{N_\Lambda - N_{\bar{\Lambda}}}{N_\Lambda + N_{\bar{\Lambda}}}$$

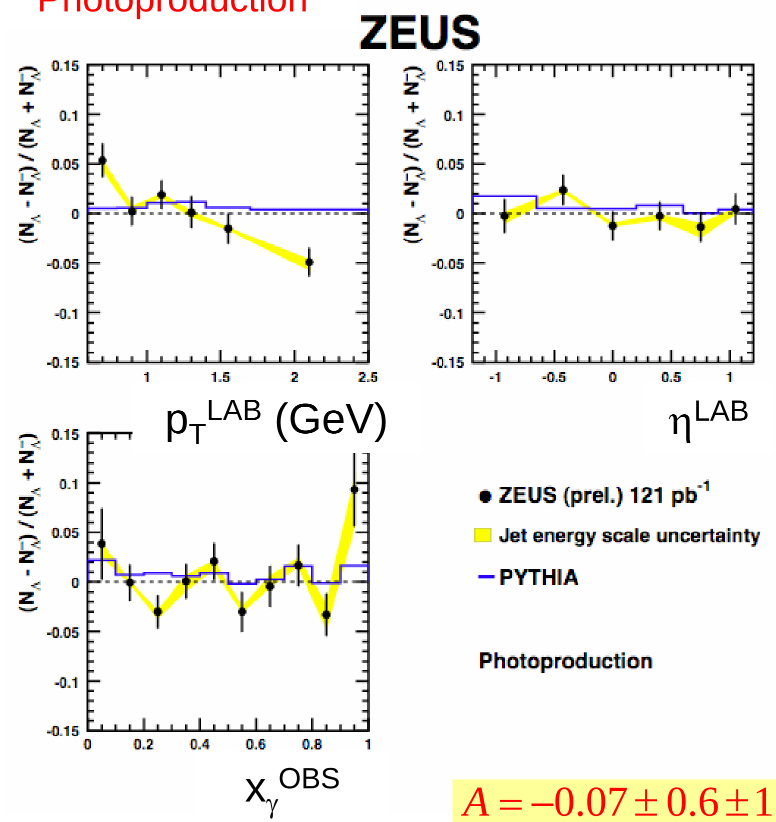
DIS ($Q^2 > 25$ GeV^2)



$A = +0.3 \pm 1.3^{+0.5}_{-0.8}$ %

$A = +0.4 \pm 0.2$ % (pred)

Photoproduction



$A = -0.07 \pm 0.6 \pm 1.0$ %

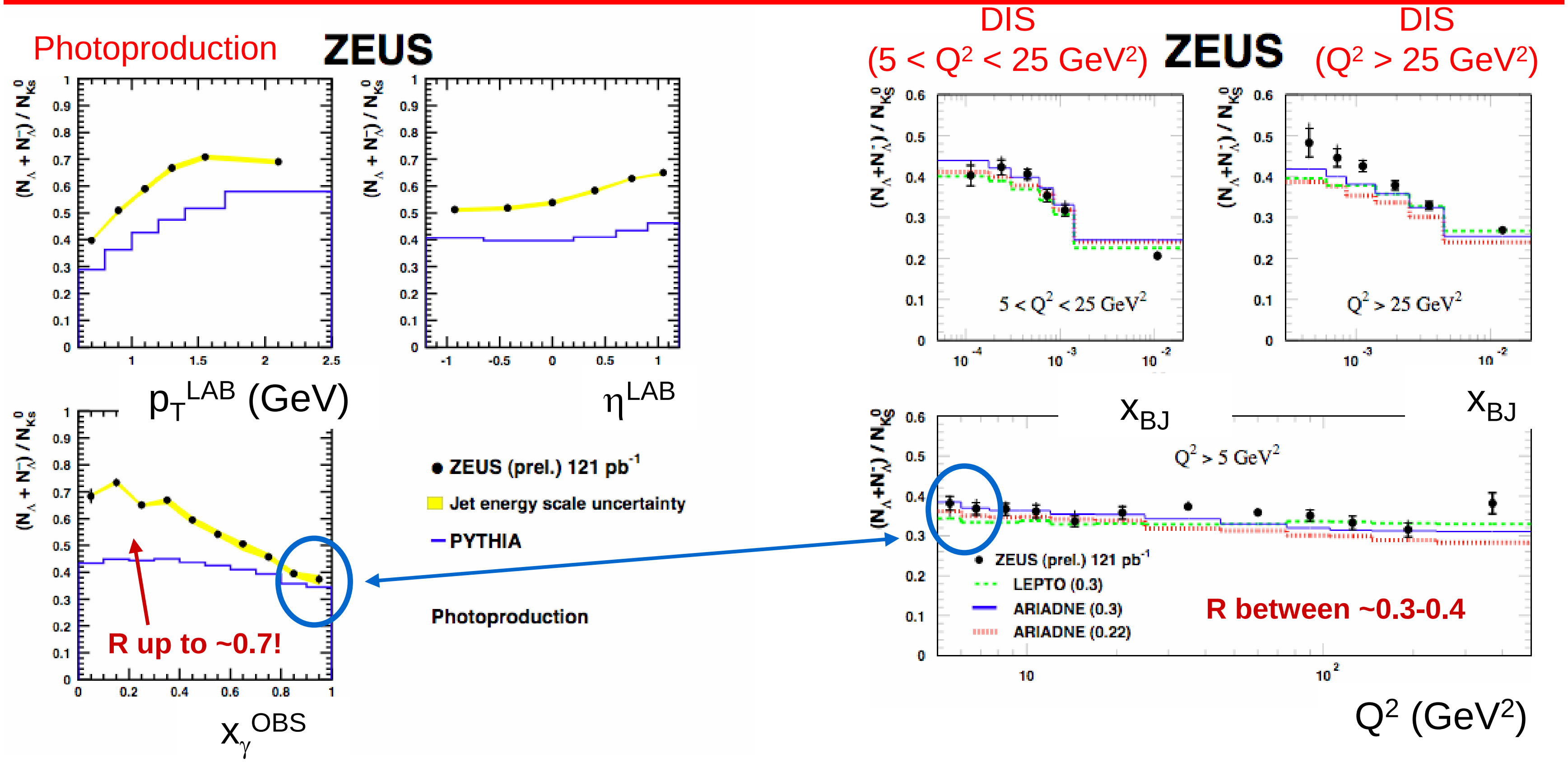
$A = +0.6 \pm 0.1$ % (pred)

- Results consistent with no asymmetry.
- Production of both baryons should follow the same mechanism.

R. • Influence from the initial proton should be small.

Baryon to meson ratio

$$R = \frac{N_{\Lambda} + N_{\bar{\Lambda}}}{N_{K_s^0}}$$



- Ariadne predicts R well in DIS, whereas in PHP Pythia underestimates R.
- R ~ 0.4 for both direct PHP and low Q^2 DIS
- R increases up to ~0.7 for lower values of x_{γ}, where resolved PHP is dominant.

Search for strange pentaquarks (ZEUS)

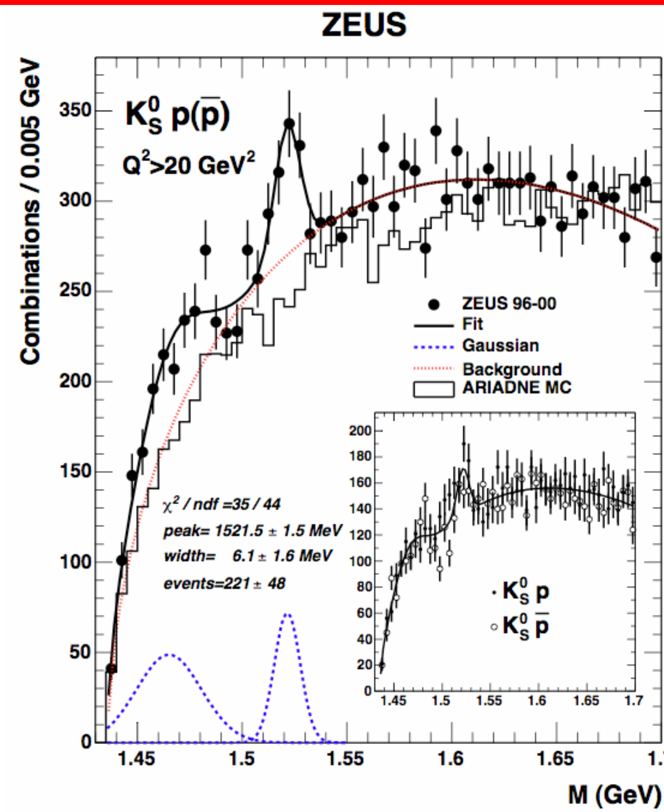
Search for $\Theta^+ \rightarrow K^0_s p$ - clear signal observed

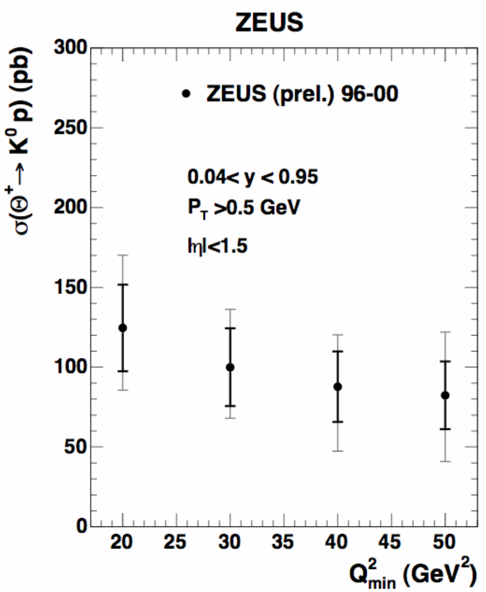
- $Q^2 > 20$ GeV^2, $0.04 < y < 0.95$
- $p_T(K^0_s p) > 0.5$ GeV, $|\eta(K^0_s p)| < 1.5$
- p(p) < 1.5 GeV, p selection with dE/dx

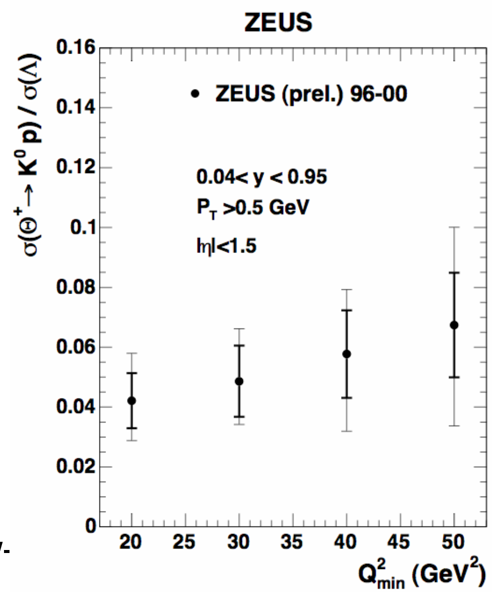
➢ 221±48 events

➢ $M(\Theta^+) = 1521.5 \pm 1.5^{+2.8}_{-1.7}$ MeV

➢ width = 6.1±1.6 MeV







Cross sections (ZEUS preliminary)

$\sigma(ep \rightarrow e\Theta^+X \rightarrow eK^0_s pX) =$

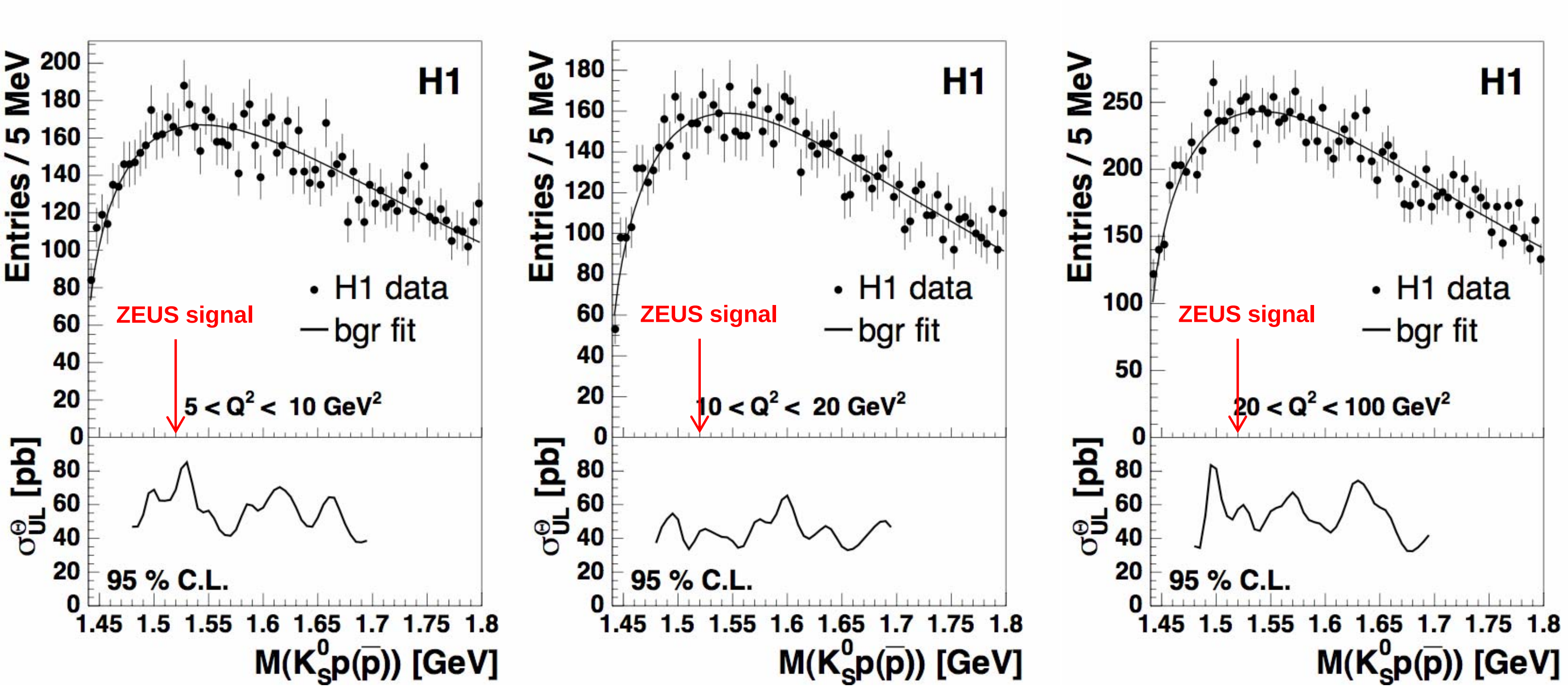
$125 \pm 27\ ^{+36}_{-28}$ pb

$\sigma(\Theta^+)/\sigma(\Lambda) =$ **$4.2 \pm 0.9\ ^{+1.2}_{-0.9}$ %**

Search for strange pentaquarks (H1)

Search for Θ^+ $\rightarrow$ $K^0_s p$ - NO signal observed by H1

- $5 < Q^2 < 100$ GeV^2, $0.1 < y < 0.6$
- $p_T(K^0_s p) > 0.5$ GeV, $|\eta(K^0_s p)| < 1.5$



Search for strange pentaquarks (H1)

Search for $\Theta^+ \rightarrow K^0_s p$

Applying an upper cut in the momentum of the proton for comparison with ZEUS

- $p(p) < 1.5$ GeV
- $20 < Q^2 < 100$ GeV^2
- notice different y ranges
  - $0.1 < y < 0.6$ (H1)
  - $0.04 < y < 0.95$ (ZEUS)

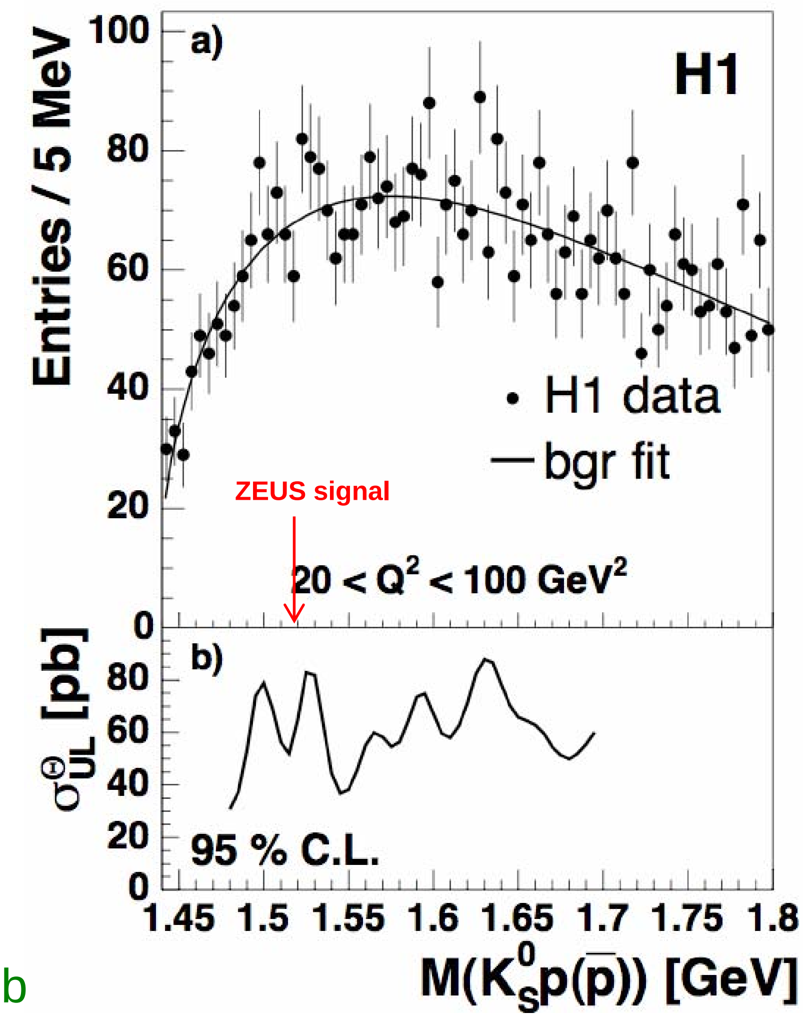
No Θ^+ signal obeserved!

Cross section upper limit @ 95% CL:

$\sigma(M=1.52 \text{ GeV}) < 72$ pb

(ZEUS preliminary)

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



Search for strange pentaquarks (ZEUS)

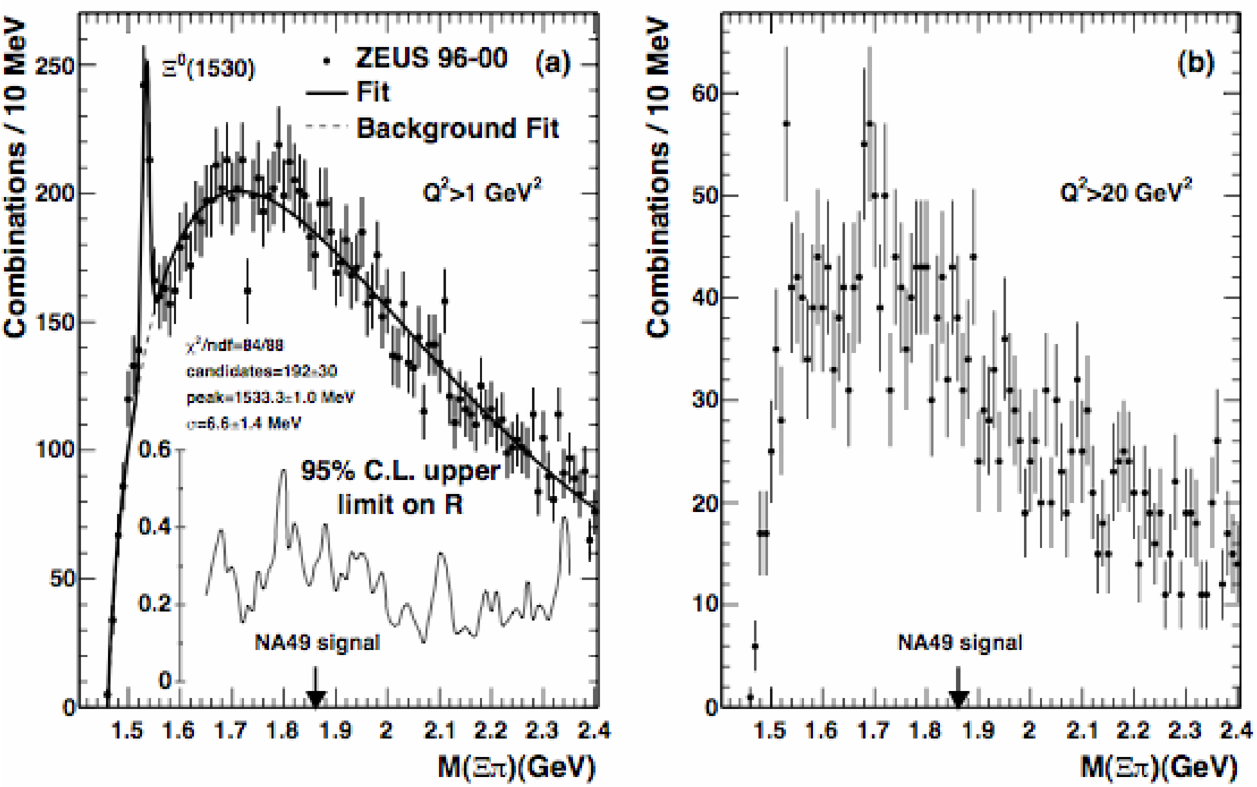
<u>Search for Ξ^{--}</u> $\rightarrow \Xi^{-} \pi^{-}$

No Ξ^{--} signal observed!

Upper limit @ 95% CL:

$N(\Xi^{--})/N(\Xi^{0}(1530)) < 0.29$

ZEUS



Signal observed by NA49:
mass = 1862 MeV
width < 18 MeV

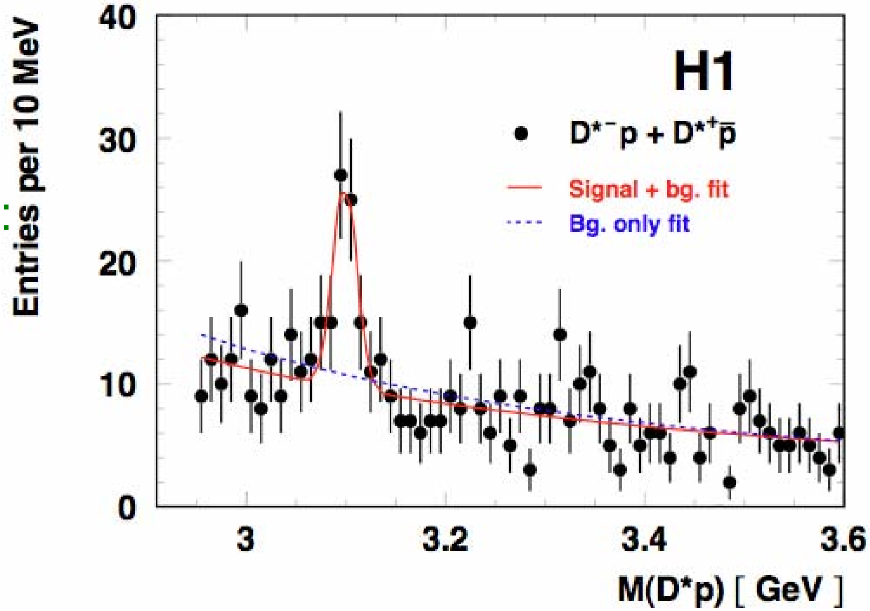
Searches from other experiments give negative results

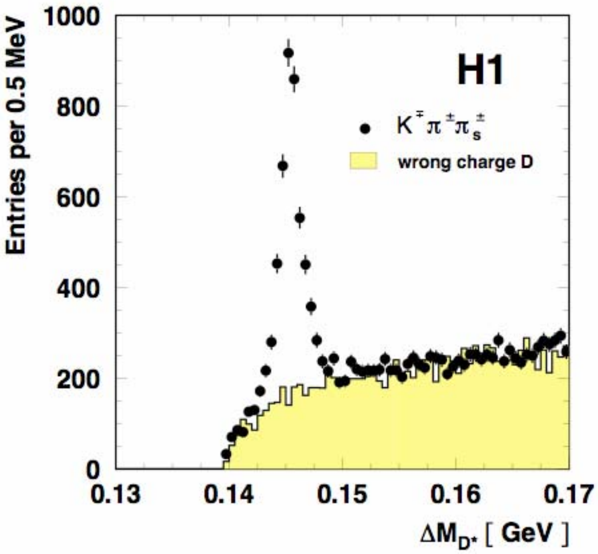
Search for charm pentaquarks (H1)

Search for $\Theta_c \rightarrow D^*p$

- DIS: $1 < Q^2 < 100$ GeV^2; $0.05 < y < 0.7$
- γp: $Q^2 < 1$ GeV^2; $0.2 < y < 0.8$

- D* reconstructed from the decay mode: $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
- protons selected using dE/dx measurements





- Mass = 3099 ± 3 ± 5 MeV
- Width = 12 ± 3 MeV
- 50.6±11.2 events

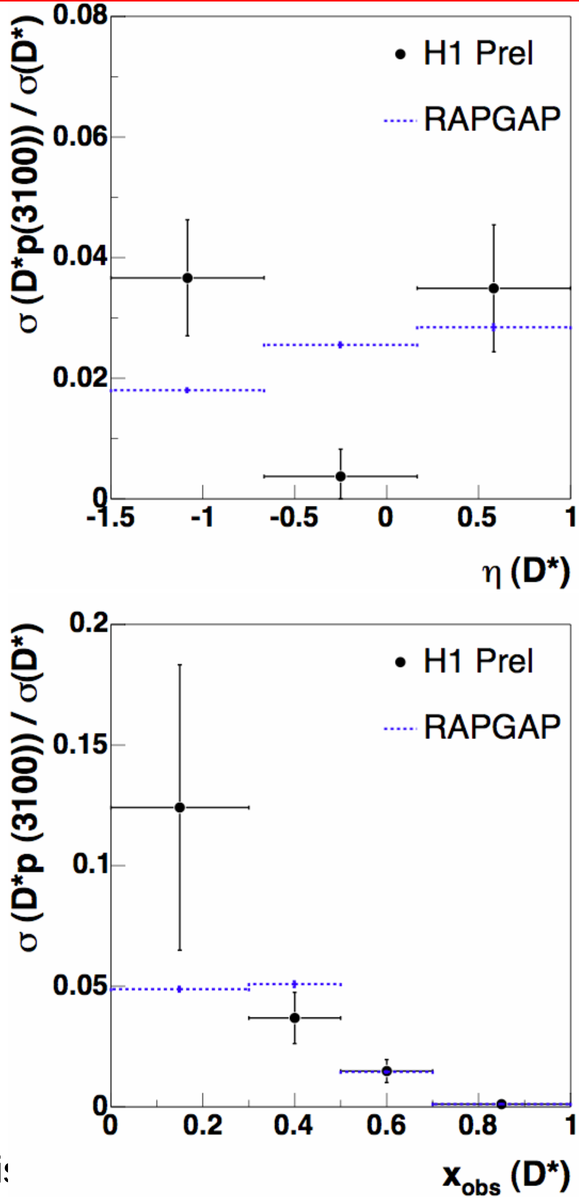
(5.4σ: background fluctuation probability of 4×10^{-8} (poissonian) converted to gaussian sigmas)

Search for charm pentaquarks (H1)

<u>Search for Θ_c</u> $\rightarrow$ D*p

- Acceptance corrected ratio D*p/D* for $1 < Q^2 < 100$ GeV^2 (preliminary)
R_{cor}(D*p/D*) = 1.59 ± 0.33 $^{+0.33}_{-0.45}$%

- Differential cross sections in DIS
  - D*p suppressed close to the central rapidity regions compared to inclusive D*.
  - D*p fragmentation function is hard as expected for a charm hadron of such mass. Hadronization function of D* from D*p is softer than inclusive D*.



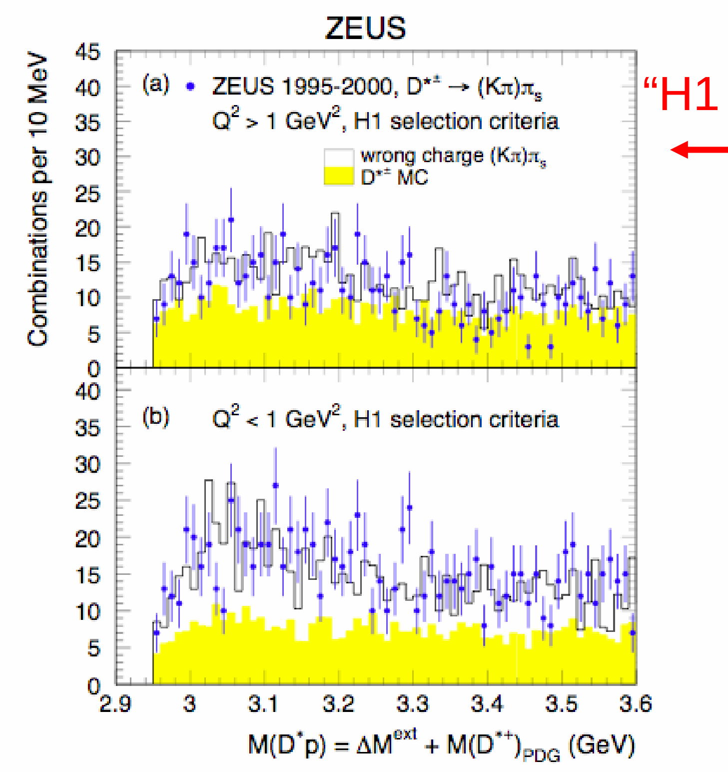
Search for charm pentaquarks (ZEUS)

Search for $\Theta_c \rightarrow D^*p$

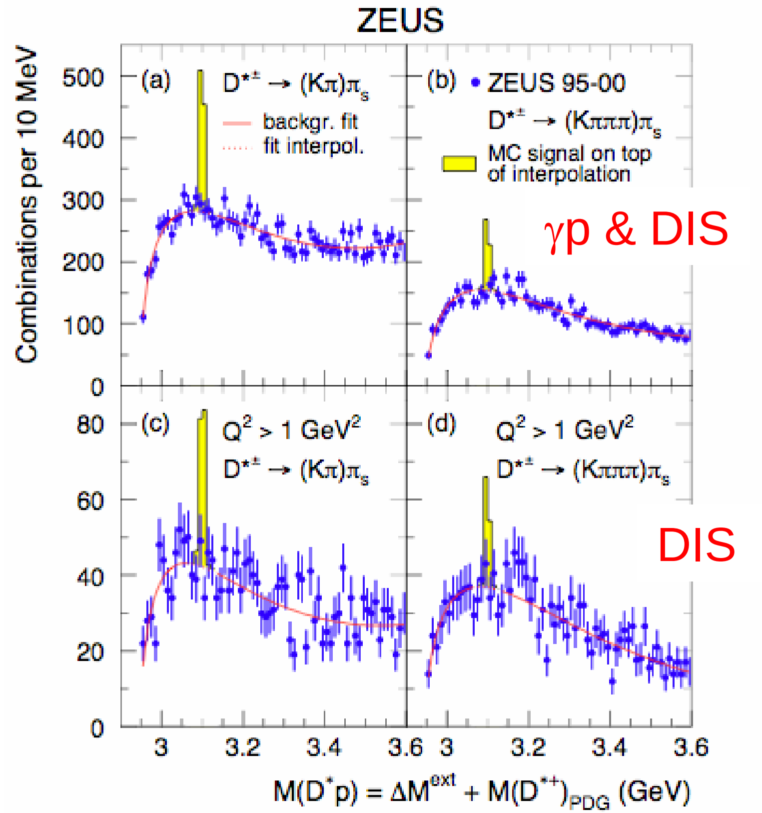
- γp and DIS

No signal observed!

- D^* reconstructed from the decay modes: $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$ and $\rightarrow K^-\pi^+\pi^+\pi^-\pi^+$



"H1 selection ⟵ criteria"



Shaded histogram is MC signal normalized to 1% of the inclusive D*

$R_{cor}(D^*p/D^*) < 0.59\ \%$ @95% CL
(DIS, $K2\pi$ mode)

Summary

- The charm fragmentation ratios and fractions were measured in deep inelastic scattering at HERA and results are consistent with universality.
- Charm fragmentation functions are measured. Reasonable agreement from different processes.
- K^0_s, Λ, $\bar{\Lambda}$ production at HERA
  - o Differential cross sections were measured in DIS and PHP. Data is reasonably well reproduced by Ariadne in DIS, where as Pythia fails to reproduce PHP.
  - o Λ to $\bar{\Lambda}$ production consistent with no asymmetry in the given phase space.
  - o Baryon to meson production ratio show an enhancement in resolved PHP. This is not predicted by Pythia.

Summary

- Strange pentaquark searches
  - Narrow state $K^0_s p$ observed by ZEUS at 1520 MeV.
    $\sigma(ep \rightarrow e\Theta^+ X \rightarrow eK^0_s pX) = 125 \pm 27\ ^{+36}_{-28}$ pb
    Not seen by H1.
  - ZEUS does not observe $\Xi^{--} \rightarrow \Xi^- \pi^-$, seen by NA49.
- Charm pentaquark searches
  - Narrow state D*p observed by H1 at 3099 MeV.
    $R_{cor}(D^*p/D^*) = 1.59 \pm 0.33\ ^{+0.33}_{-0.45}\%$ (in DIS)
    Not seen by ZEUS.