XII. INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY

Hadron Spectroscopy in ep Collisions

- Introduction
- Light quark production
- Strange production
- Charm production
- “Exotic” states
- Summary

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representing H1 and ZEUS

Introduction

Why talk about HERA at Hadron Conf ?

HERA is probably not *THE* optimal machine for spectroscopy …
however, information from ep-collisions (different environment) might be complementary, and thus we can:

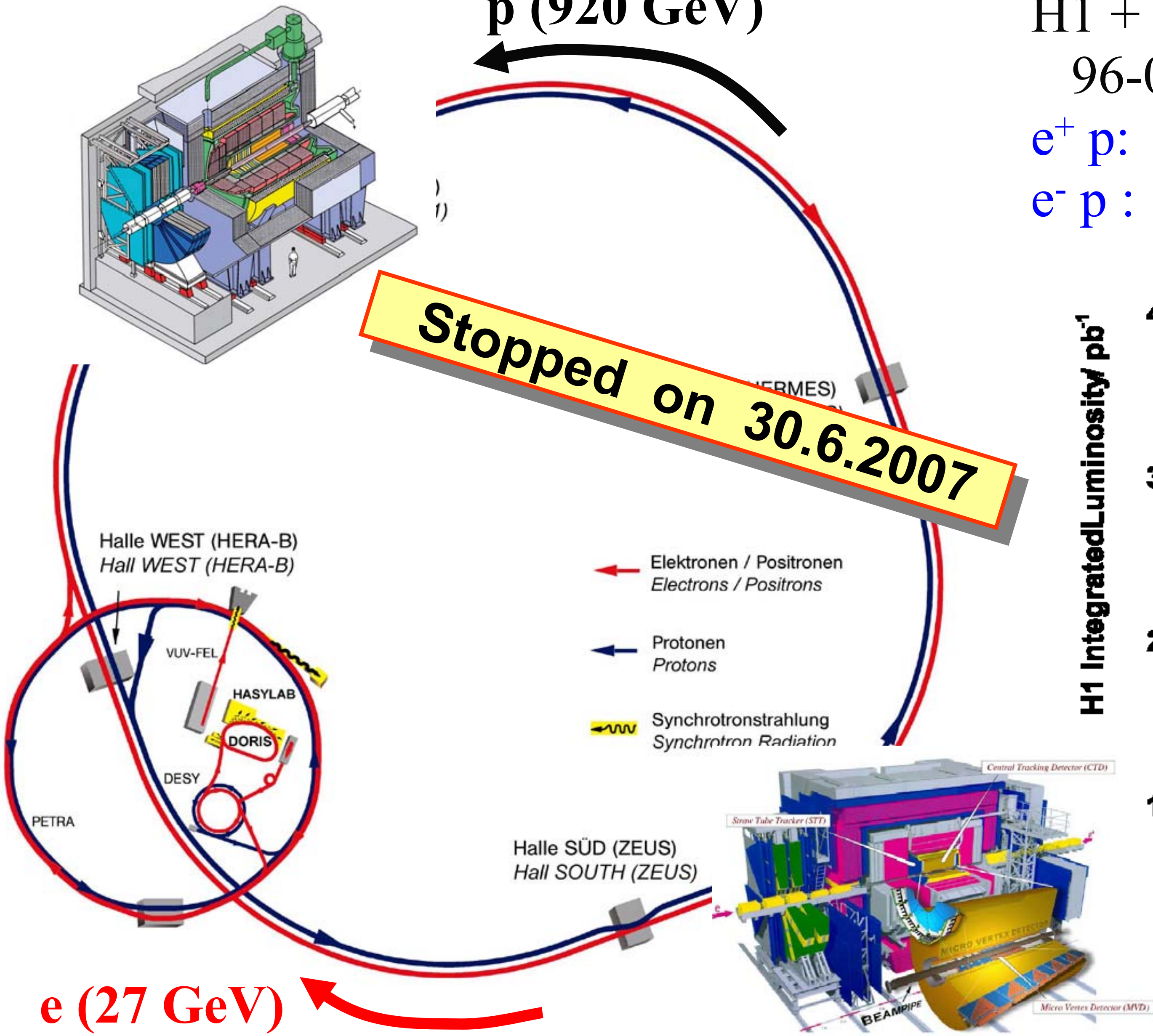
- Test various aspects of perturbative QCD, and
  build phenomenological models with predictive power.
- Study and find out what dominates the production processes?
  differences for mesons, baryons, antiparticles … ?
- Learn details about non-perturbative fragmentation processes,
  such as issues of fragmentation universality … ?

- Search and study excited states,
  look for "exotic" states: glueballs, pentaquarks, …
  and compare with others to increase overall understanding.

The HERA Collider

HERA: 318 GeV
p (920 GeV) e (27.6 GeV)

p (920 GeV)



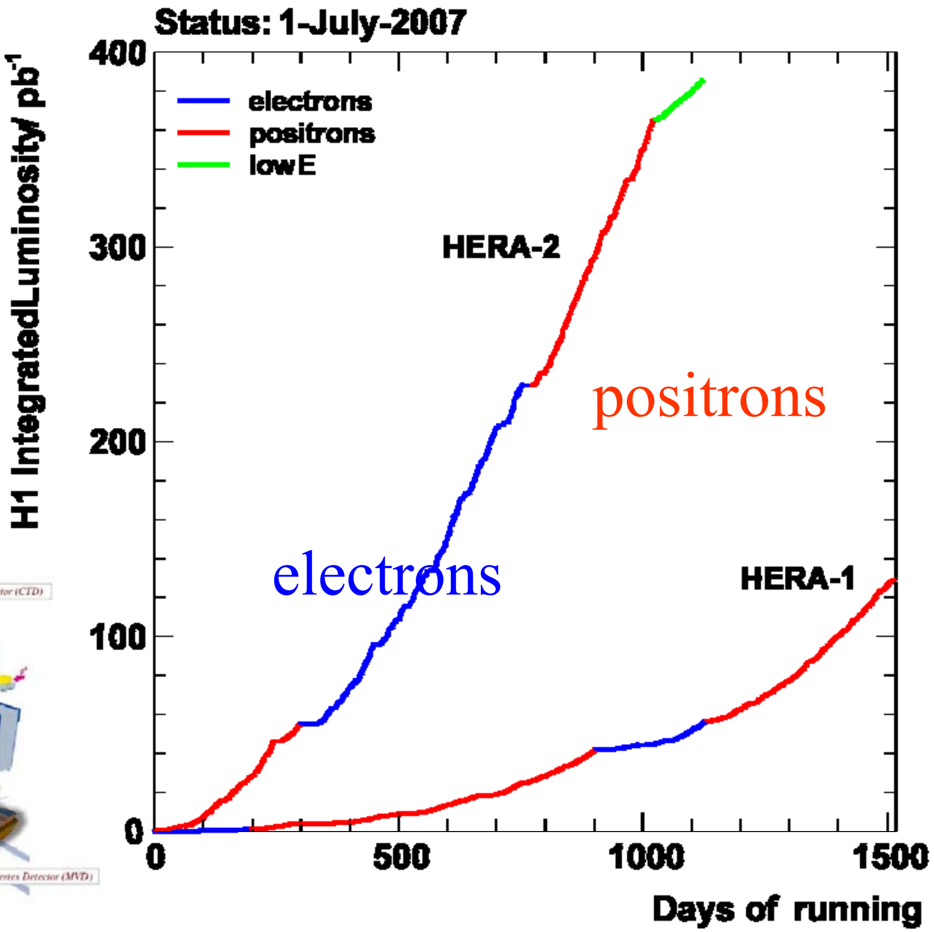
Stopped on 30.6.2007

e (27 GeV)

H1 + ZEUS integrated luminosity
96-00 + 03-07 (high energy)

$e^+ p$: ~ 300 pb^{-1}

$e^- p$: ~ 185 pb^{-1}



HERA Kinematics

HERA: 318 GeV

p (920 GeV) e (27.6 GeV)

e(k) + p(P) → e'(k') + X

$$\sigma_{hadron} = \int f(x,\mu) \cdot \hat{\sigma} \cdot D_q^h(x_F, \mu_F)\, dx$$

D_q^h : Fragmentation of quark q to hadron h

$$s = (P+k)^2$$

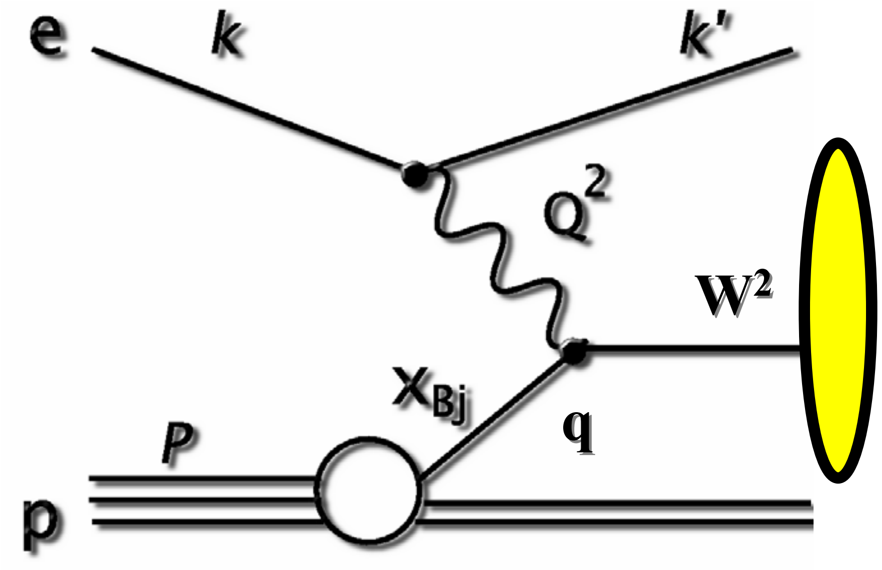
$$W^2 = (P+q)^2$$

$$Q^2 = -q^2 = -(k-k')^2$$

$$y = \frac{qP}{kP} \cong \frac{W^2 + Q^2}{s}$$

$$x_{Bj} = \frac{Q^2}{2qP} \cong \frac{Q^2}{sy}$$

$$x_\gamma = \frac{\sum_{jet1,jet2}(E-P_z)}{\sum_{hadrons}(E-P_z)}$$



- **Light hadrons**
- **Strange**
- **Charm**
- **Exotics**

Relevant Regimes:

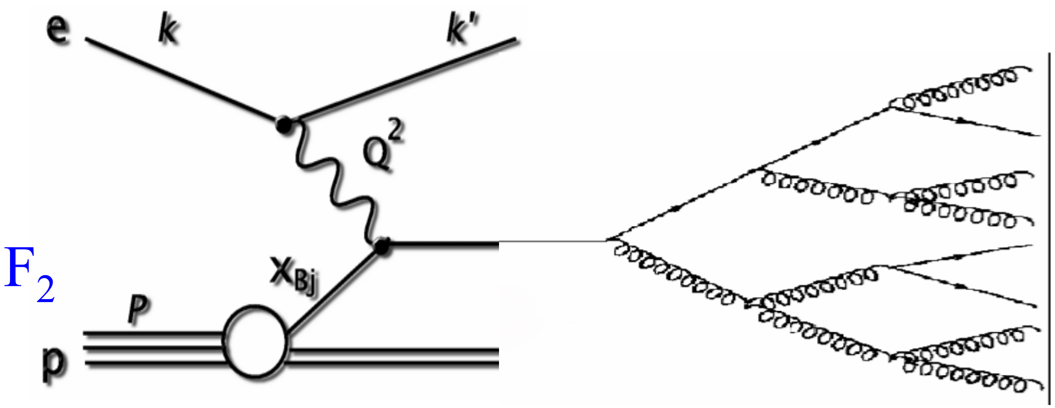
$Q^2 < 1$ GeV^2 : Photoproduction (γP): direct and resolved processes (x_γ to separate)

$Q^2 > 1$ GeV^2 : Deep Inelastic Scattering (DIS)

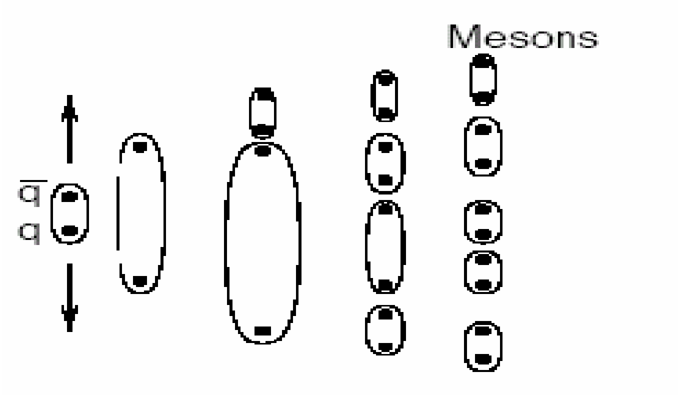
LO Description of ep-Scattering

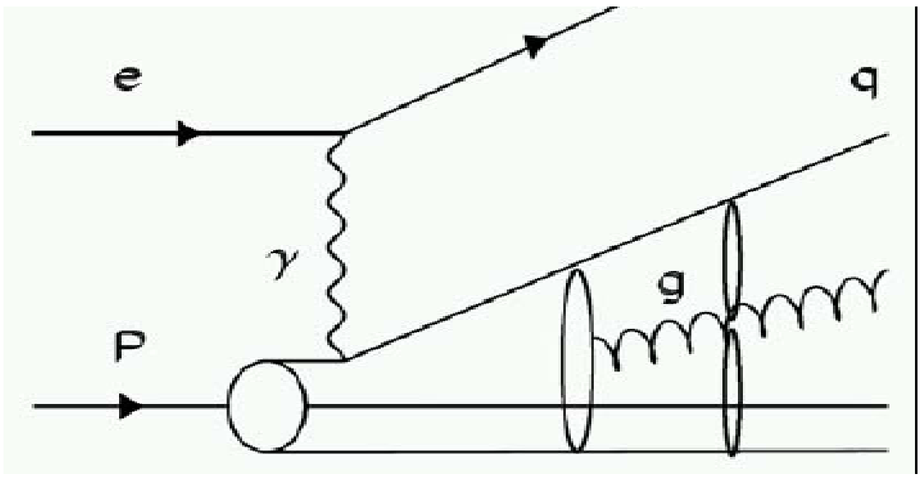
Hard Scattering: LO ME -- pQCD + Parton Showers pQCD + Hadronisation non-p QCD + Decay

F_2



String fragmentation
Django/Pythia/Rapgap
Monte Carlo programs





or Cluster fragmentation
HERWIG

Color Dipol Model (CDM) → Ariadne MC

Baryon Production

$ep \rightarrow \bar{p}, p, \bar{d}, d$ - Baryon Production

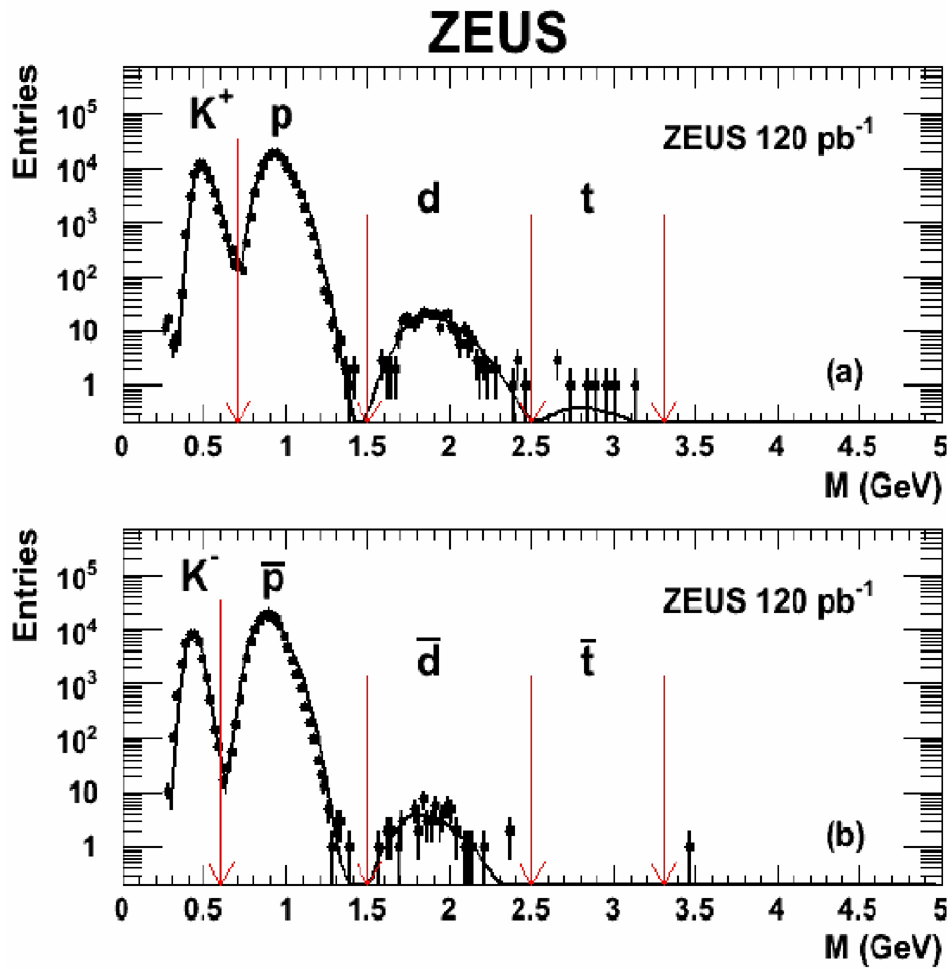
- **To better understand production.**
  e.g. coalescence model predicts

$$d\sigma_d \propto (d\sigma_p \cdot d\sigma_n) \propto (d\sigma_p)^2$$

- **Expect coalescence parameter to be equal for particle and antiparticle.**

- **Thus expect** $\bar{d}/d = (\bar{p}/p)^2$

- **HERA data:**
  ZEUS 120 pb^{-1}: 65 anti-d in DIS
  H1 6 pb^{-1}: 45 anti-d in photoproduction

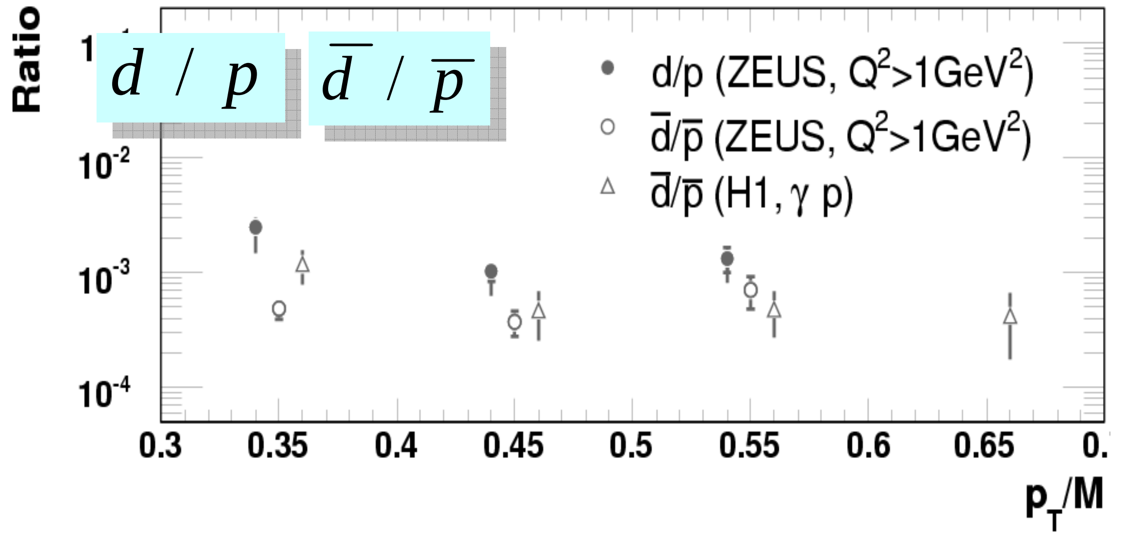


Good separation, based on p and dE/dx

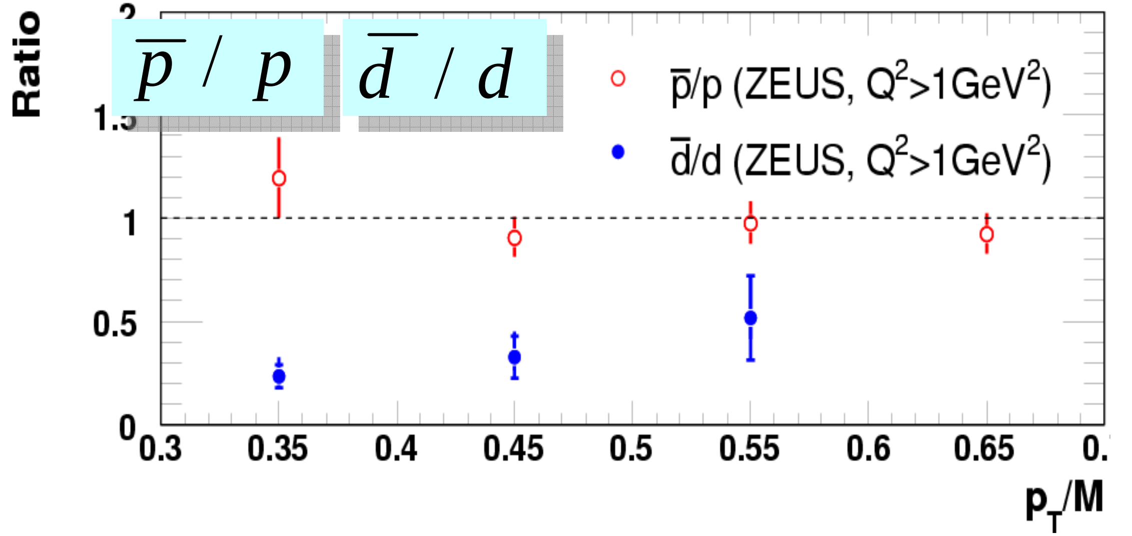
$ep \rightarrow \bar{p}, p, \bar{d}, d$ - Baryon Production

Results:

- **Proton and Anti-p yields are ~ 1000 x larger than d and anti-d**
- **anti-d / anti-p ratio : ZEUS and H1 are consistent**



- **anti-p/p ratio is consistent with unity; no sensitivity to model predictions at the 10% level**
- **surprisingly more d than anti-d ?**
  Q: difference in coalescence parameter for particle and anti-particles ?



ZEUS Collab., DESY 07-070 (120 pb^{-1})

H1 Collab., EPJ C36 (2004) 213 (5.5 pb^{-1})

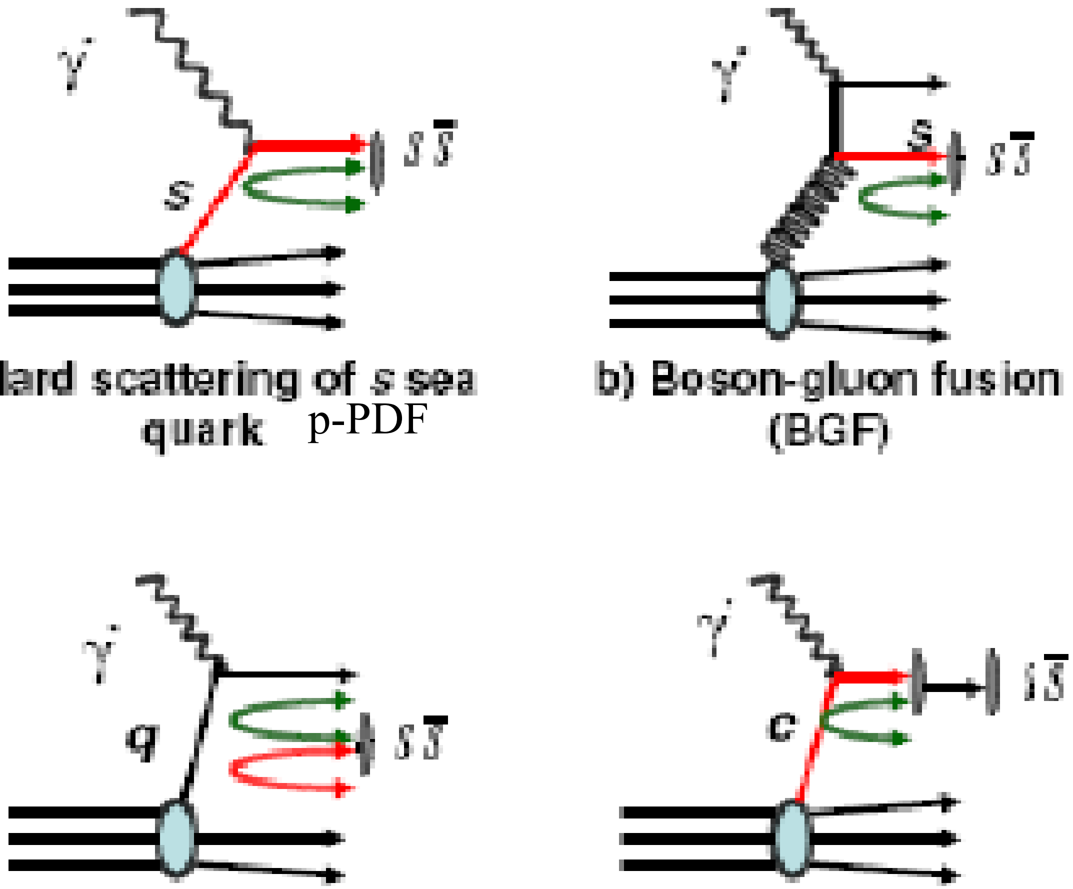
More details in talk by K.Daum

Strange Particle Production

Thine eyes will see strange things,
and your mind will imagine confusing things.
[Proverbs 23.:33]

Strangeness Production

Study of K^0_s and Λ production in DIS and γp



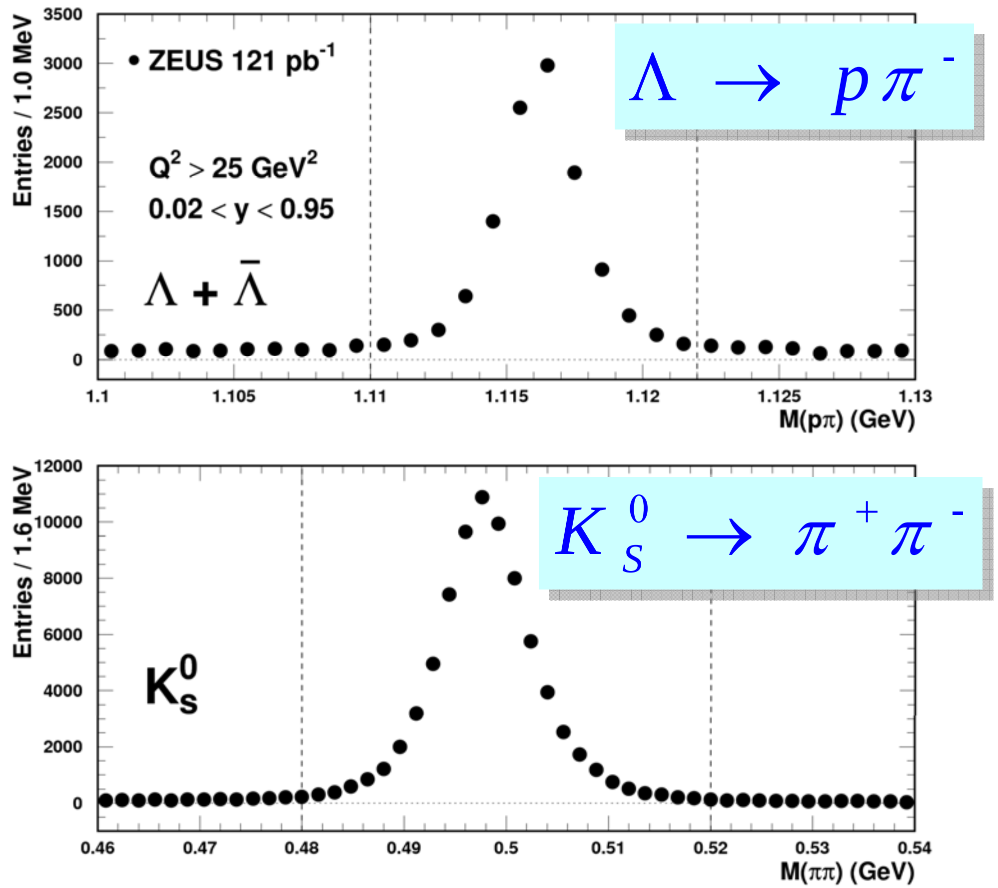
a) Hard scattering of *s* sea quark p-PDF

b) Boson-gluon fusion (BGF)

c) Parton pure fragmentation
g-splitting (pert.)
string fragmentation (non-p)

d) Heavy quark decay

Examples of K^0_s and Λ signals



➔ strangeness suppression parameter λ_s

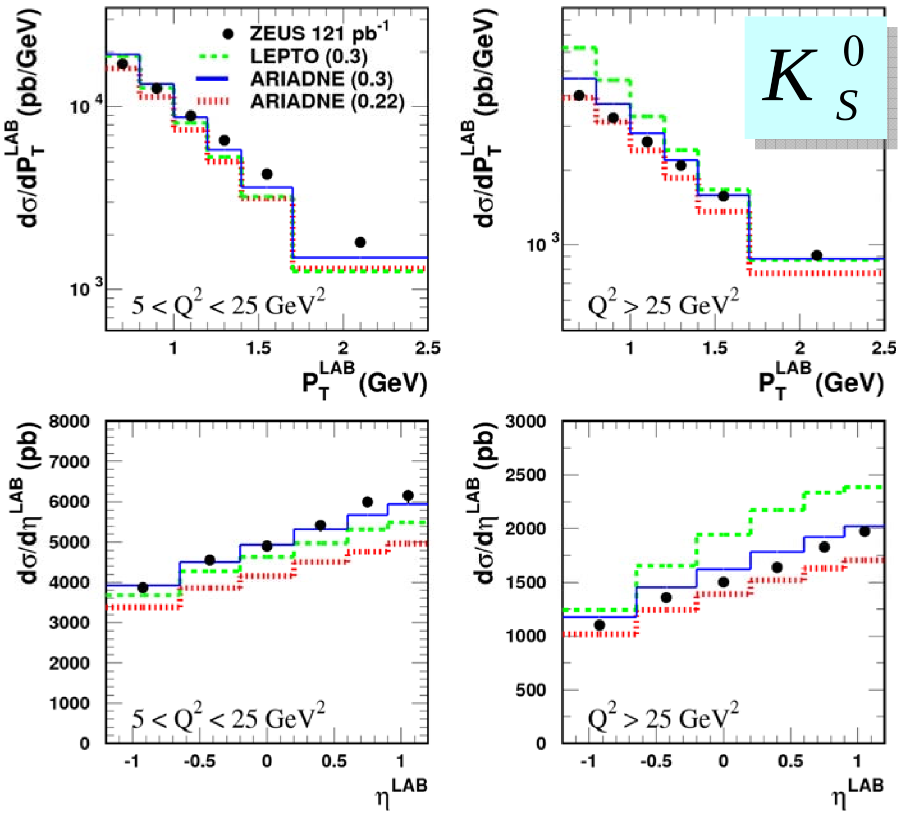
ZEUS Collab., EPJ C51 (2007) 1

K^0_s Production in DIS and γp

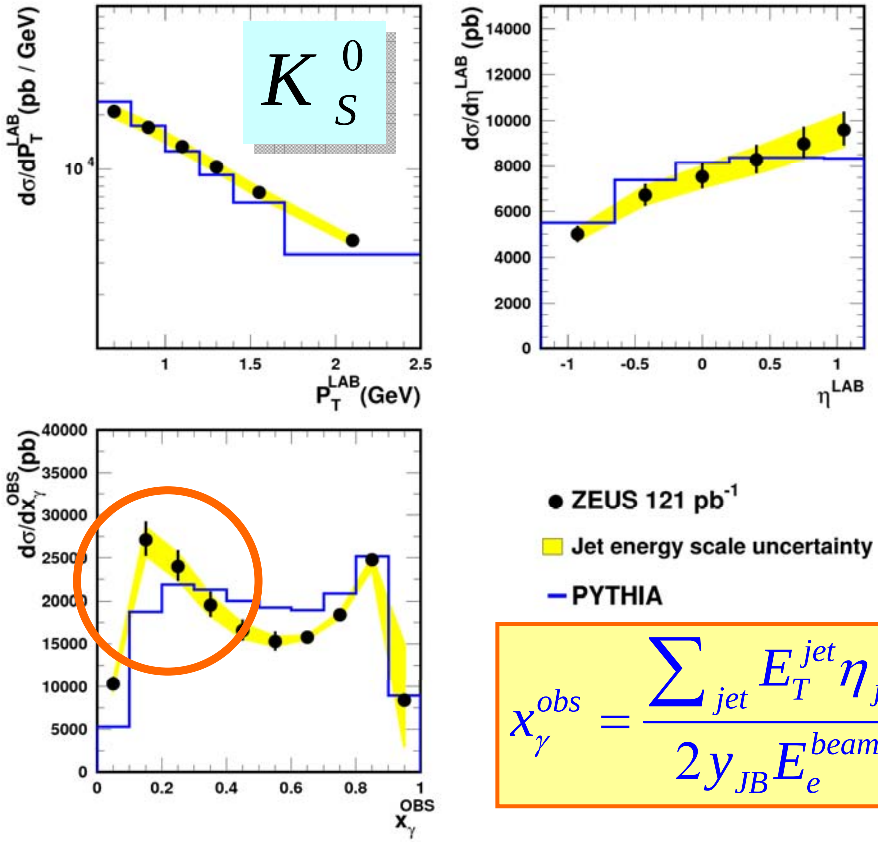
Cross sections in p_T^{lab} and η^{lab} (121 pb^{-1})

ZEUS Collab., EPJ C51 (2007) 1

$5<Q^2<25$ GeV^2 | $Q^2>25$ GeV^2



Photoproduction ($Q^2 \approx 0$ GeV^2) :



$$x_\gamma^{obs} = \frac{\sum_{jet} E_T^{jet} \eta_{jet}}{2 y_{JB} E_e^{beam}}$$

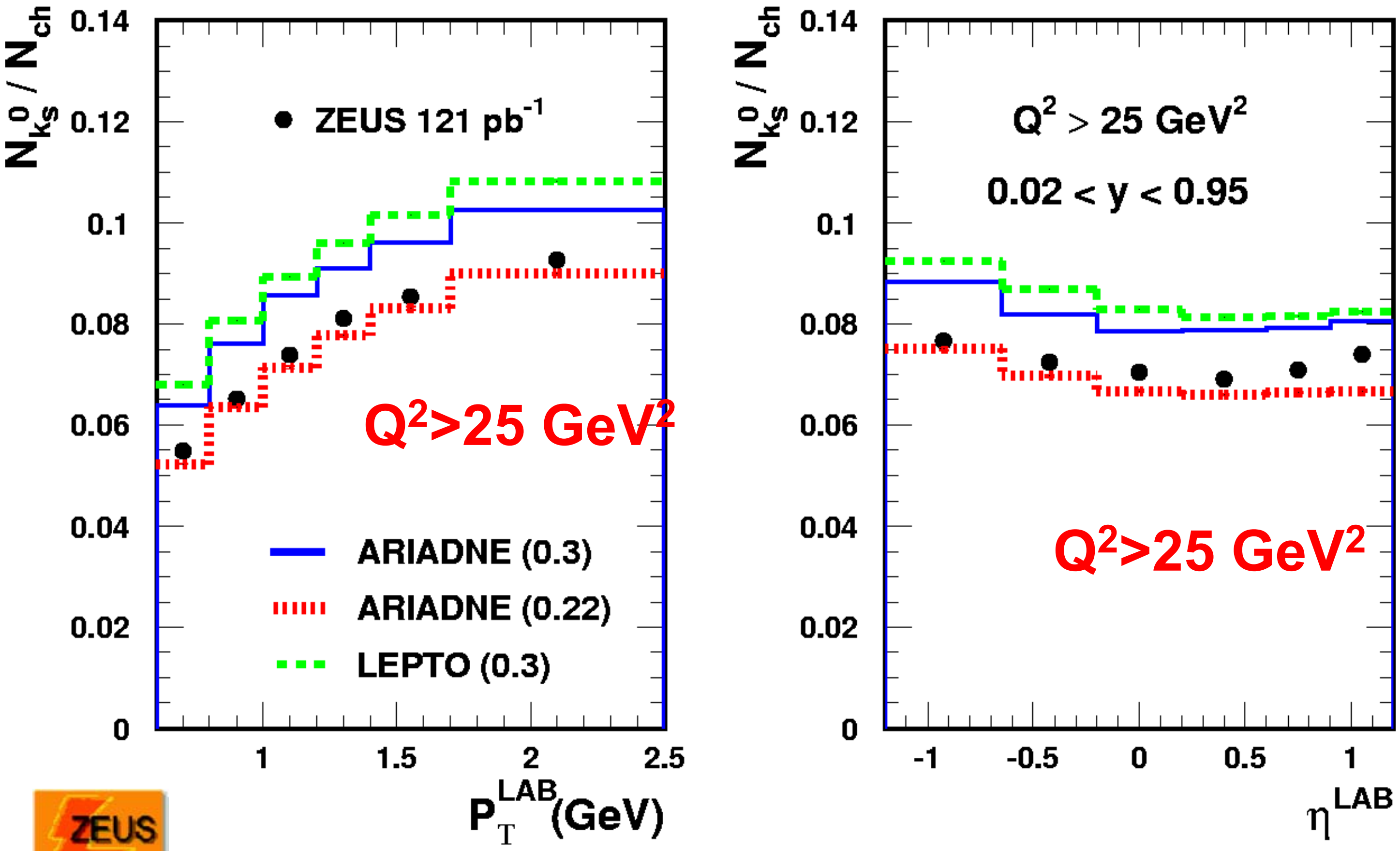
→ **ARIADNE describes data overall with λ_S=0.3;**
discrepancies in details: e.g. p_T-slope.

→ **PYTHIA (normalised to data) describes overall features, except low x_γ^{obs} (resolved)**

→ Similar conclusions for Λ production and in baryon to meson ratios.

Strangeness: Strange to Light Ratio

$$\frac{N_{K_S^0}}{N_{charged}} = \frac{N_{K_S^0}}{N_{K^\pm} + N_{\pi^\pm} + N_{p/\bar{p}}}$$



ZEUS Collab., EPJ C51 (2007) 1

- **strange/light ratio:** overall described by ARIADNE in DIS, but with smaller λ_s=0.22 favoured

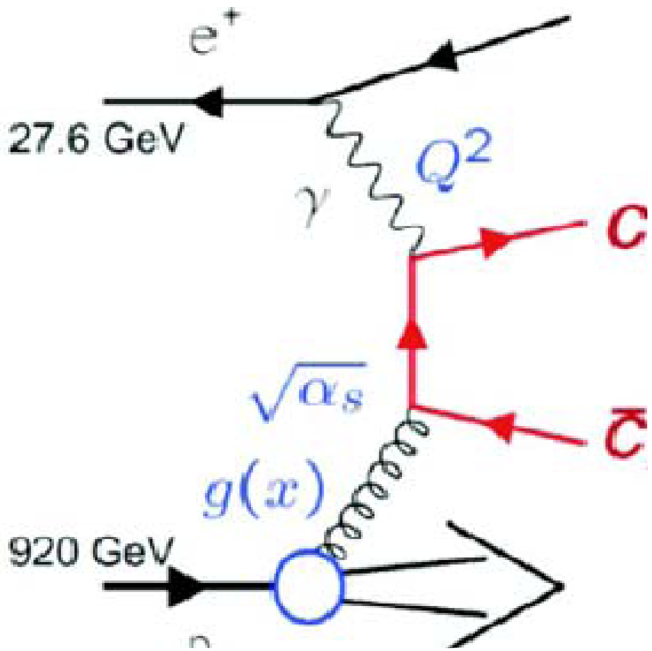
→ Overall features described, but more work needed to disentangle details. e.g. is single λ_S sufficient?

→ Need to better understand issues of fragmentation !

See talk by K.Daum

Charmed Particle Production

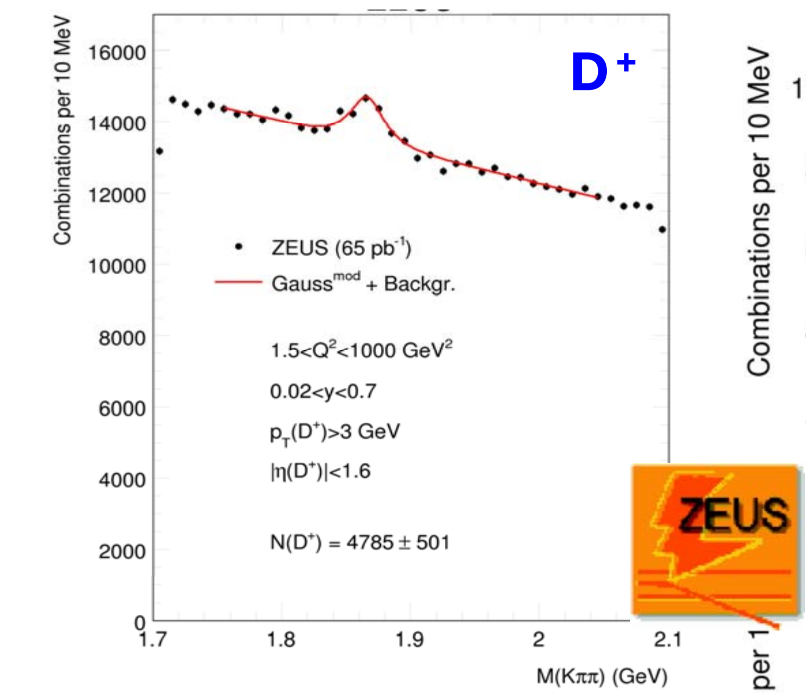
Dominated by photon-gluon fusion

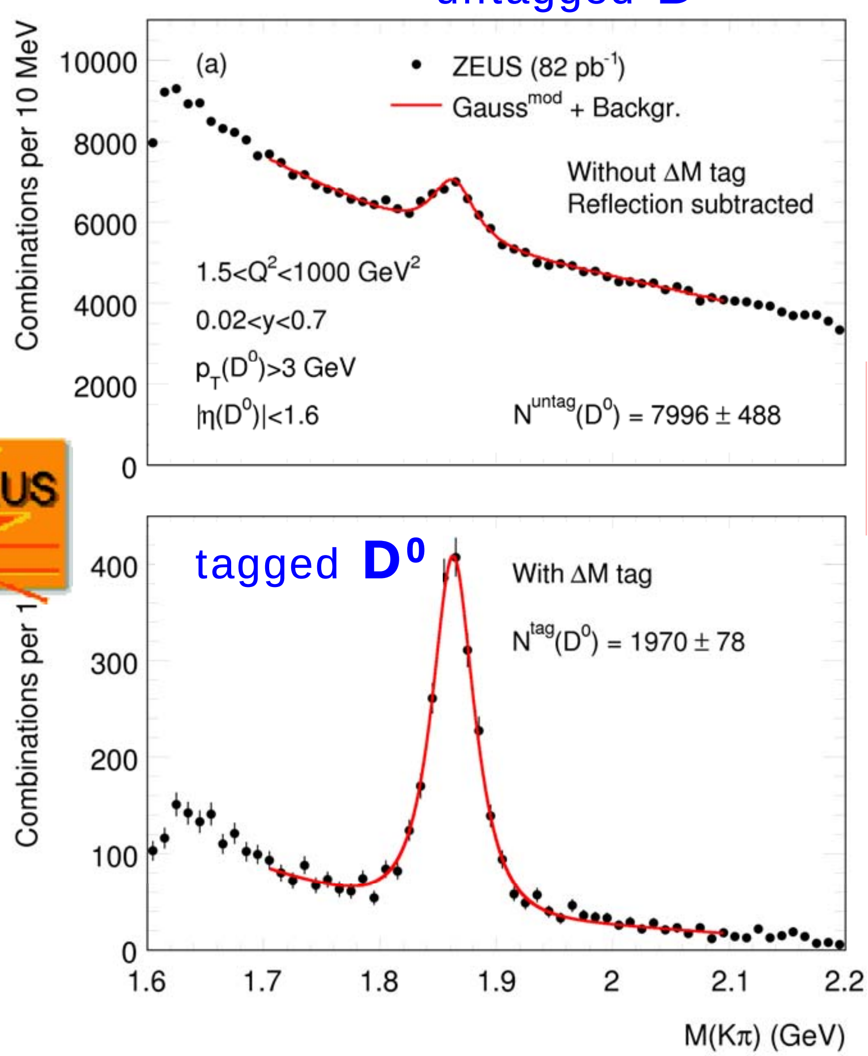


Charmed Particle Production (DIS)

study properties with D^0, D^*, D^+, D_S mesons (H1, new ZEUS data)

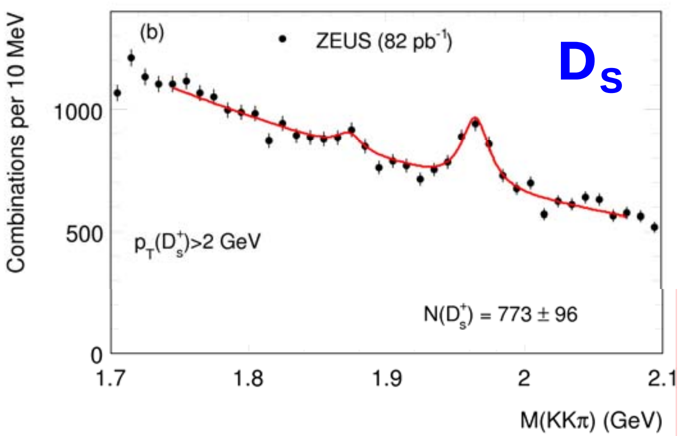
HERA-I - 82 pb^{-1}
HERA-II - 135 pb^{-1}

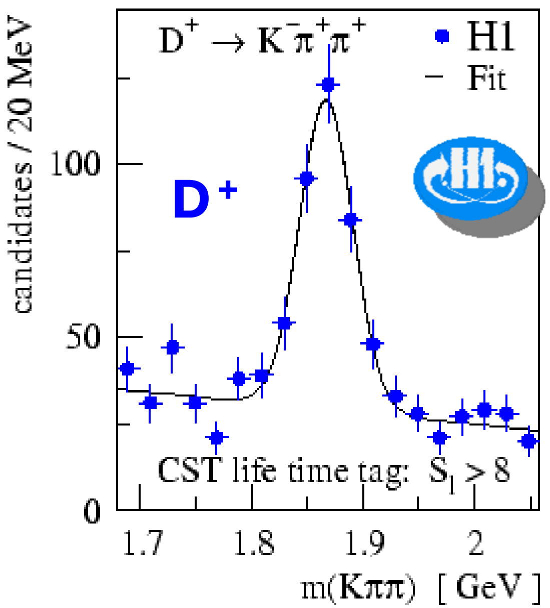




Clean signals (with vertex det.)

used for dσ , F2C (not shown)



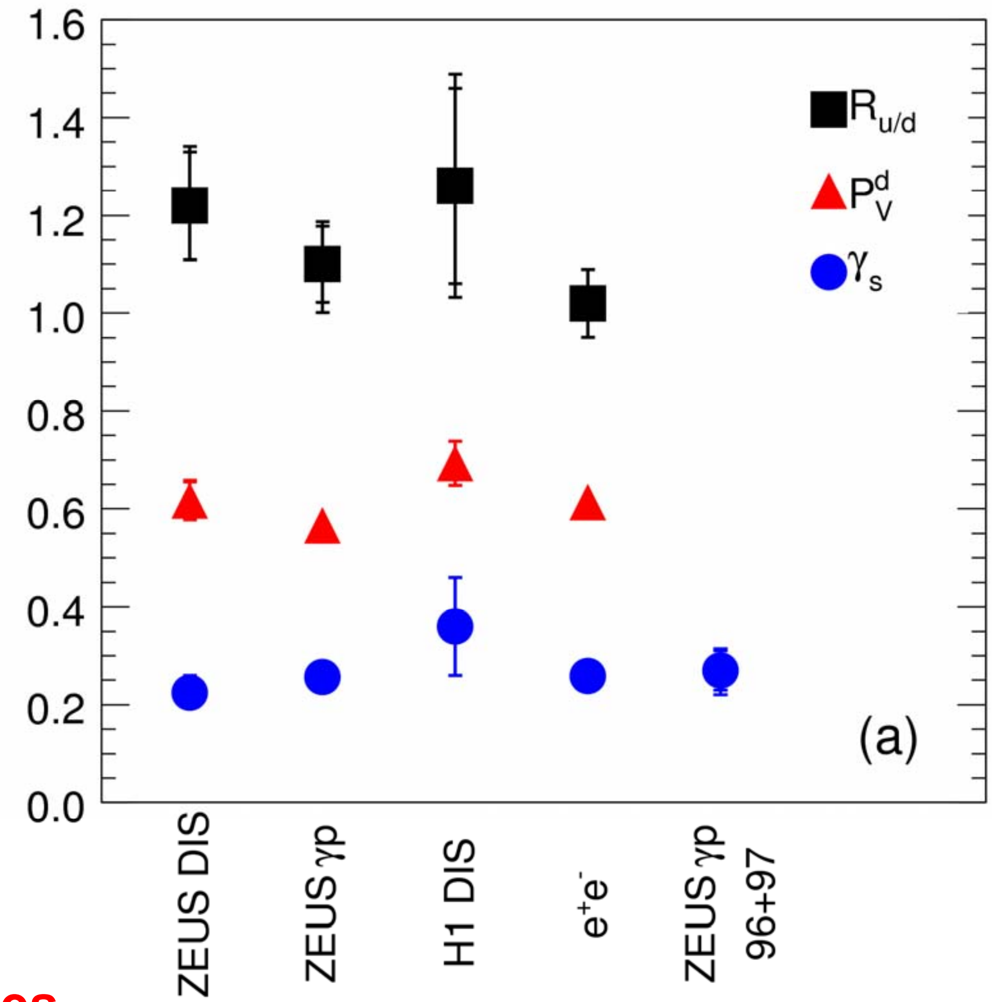


ZEUS Collab., DESY-07-052; subm. to JHEP

Charm: Fragmentation Properties

Results for D^0, D^*, D^+, D_S

- Neutral to charged meson ratio: R(u/d)
- Vector to scalar meson ratio: P_V^d
- Strangeness suppression factor: γ_S



➡ find consistency between all processes in ep(DIS, γp) and ee
➔ universality confirmed

ZEUS Collab., DESY-07-052; subm. to JHEP

H1 Collab., EPJ C38 (2005) 447.

Charm: Fragmentation Fractions

D^0, D^*, D^+, D_S, Λ_C : fragmentation fractions FF

= fractions of c-quarks hadronising

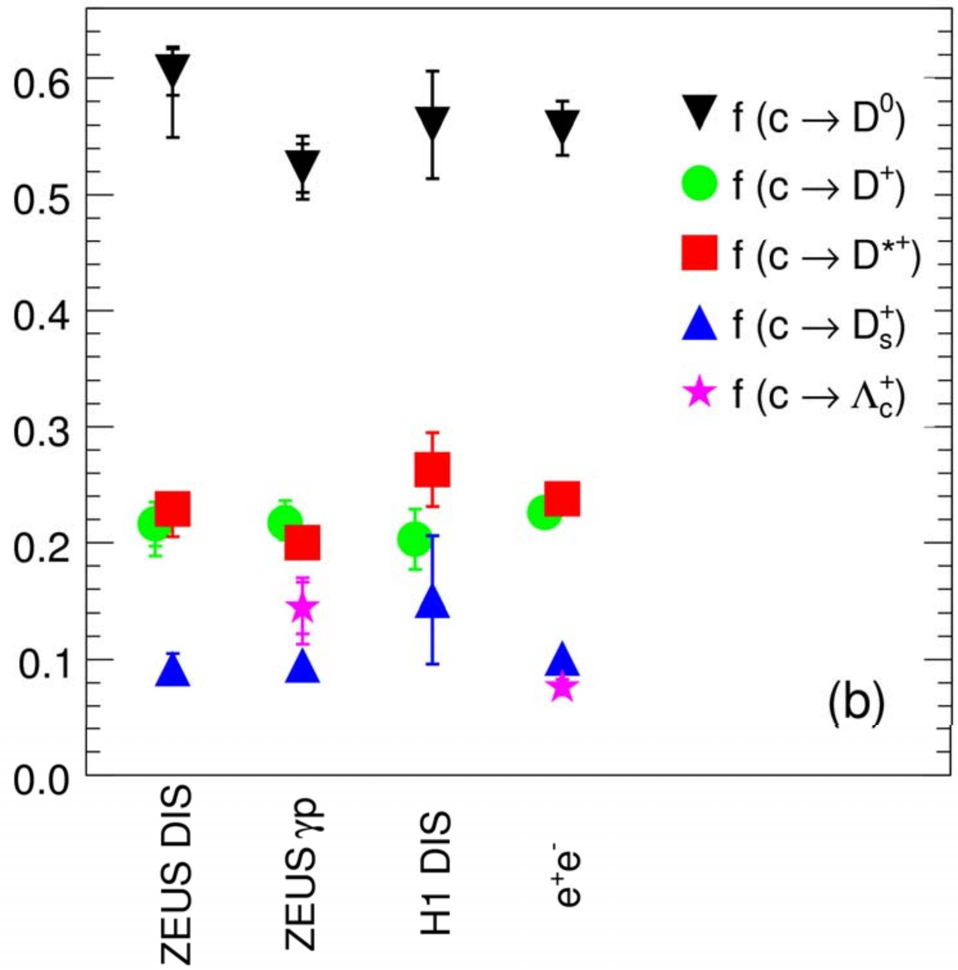
f (c → c- hadrons)

Comparing values for

- ZEUS (in DIS and photoproduction),

- H1 (DIS) (no Λ_C)

- e^+e^-



FF are same within errors,
- **independent of hard subprocess**
- **and consistent with frag. universality**

ZEUS Collab., DESY-07-052; subm. to JHEP

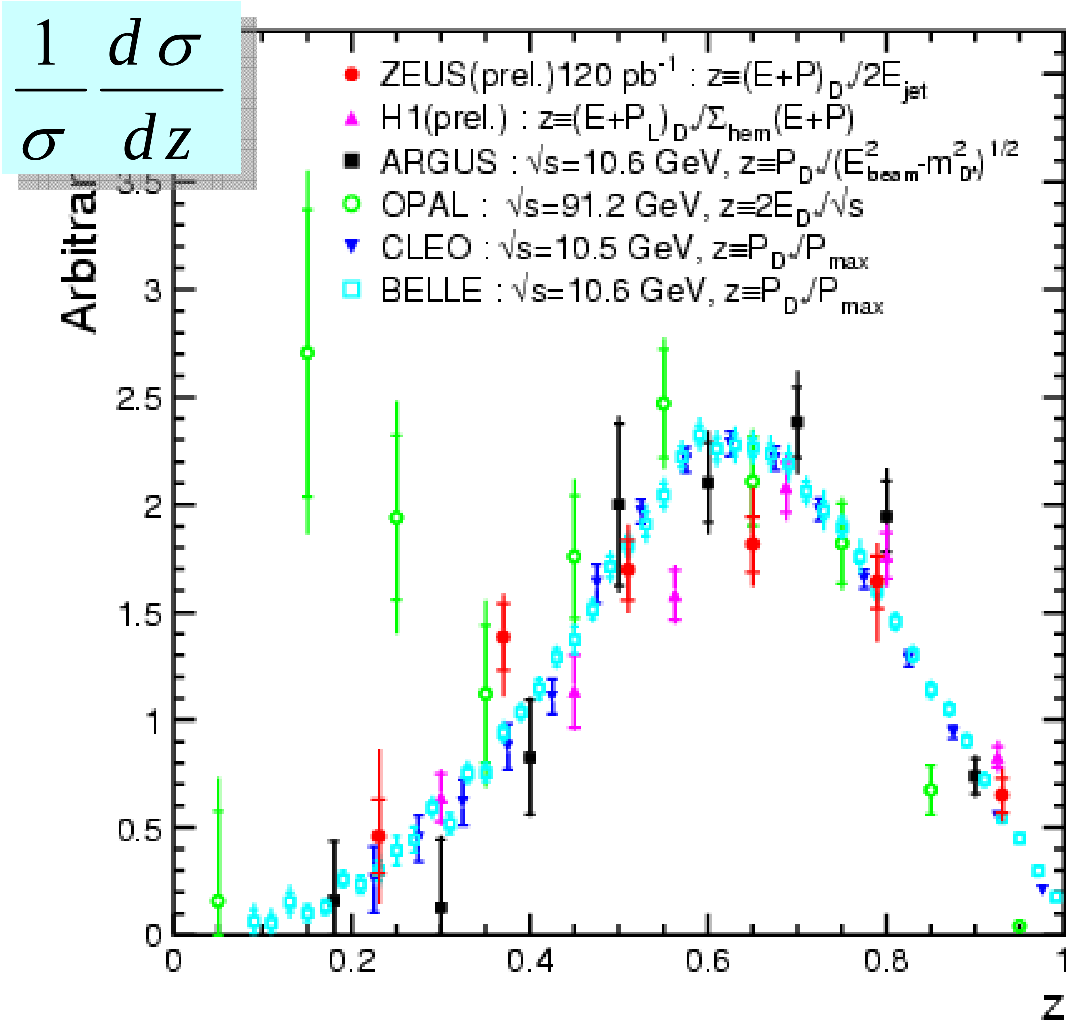
H1 Collab., EPJ C38 (2005) 447

Charm: D* Fragmentation Function

- **Fragmentation function measured with D* decays D* → D⁰ π**
- **Important non-perturbative ingredient to charm NLO calculations.**
- **z-definitions differ in detail**
- **BUT: overall features of data are similar to e⁺e⁻ experiments**

  (low z OPAL points contain large contributions of gluon splitting)

- Data are also used to extract parameters of fragmentation functions (e.g. Peterson, Kartvelishvili ...).



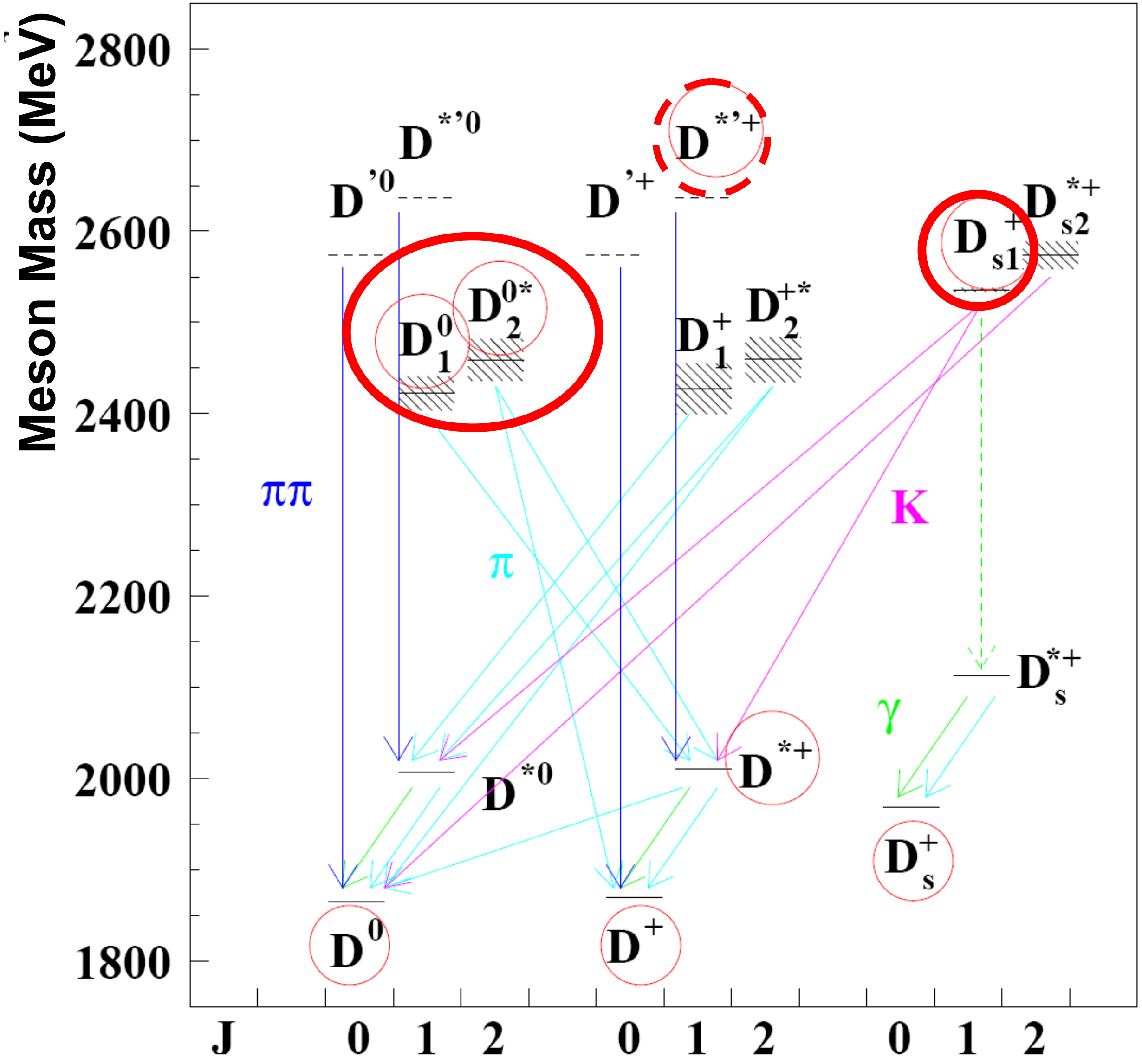
ZEUS Collab, Contrib. DIS07;
H1 Collab. Contrib.407 to EPS-conf.

Excited Charmed Mesons

- Study **orbitally excited D-mesons** (doublets) through decays :
  - $D_1(2420)^0 \rightarrow D^{*+} \pi^-$, $D^+ K^-$
  - $D_2^*(2460)^0 \rightarrow D^{*+} \pi^-$, $D^+ K^-$

  and
  - D_{S1} $(2536)^+ \rightarrow D^{*0} K^+$, $D^{*+} K^0$

- Search for **radially excited** state $D^{*\prime+}$ (2640) $\rightarrow D^{*+} \pi^- \pi^+$



Excited Charmed Mesons

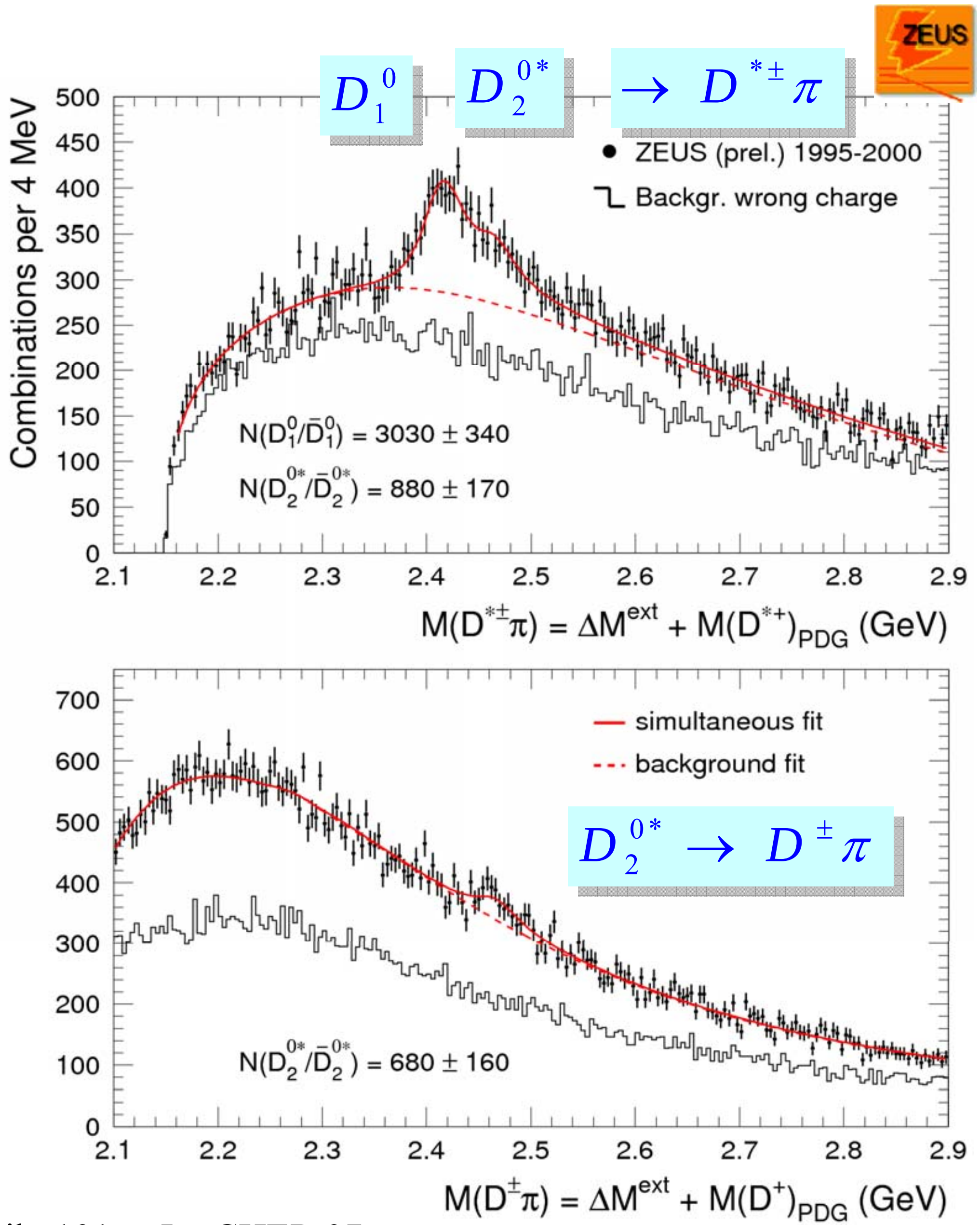
- **Orbitally excited P-wave mesons:**

  D^0_1, D^{*0}_2 → $D^{*+}\pi^-$ and $D^\pm\pi$

- **ZEUS observed :**
  $N(D^0_1)$ = 3030 ± 340 events
  $N(D^{*0}_2)$ = 1560 ± 233 events

- **and determined**
  - **masses,**
  - **rel. branching ratios,**
  - **fragmentation fractions,**
  - **helicity distributions, and**
  - **width of D^0_1**

- **NO signal seen in search for radially excited $D^{*\prime +}(2640)$ → $D^{*+}\pi^-\pi^+$**
  → upper limit on f*Br

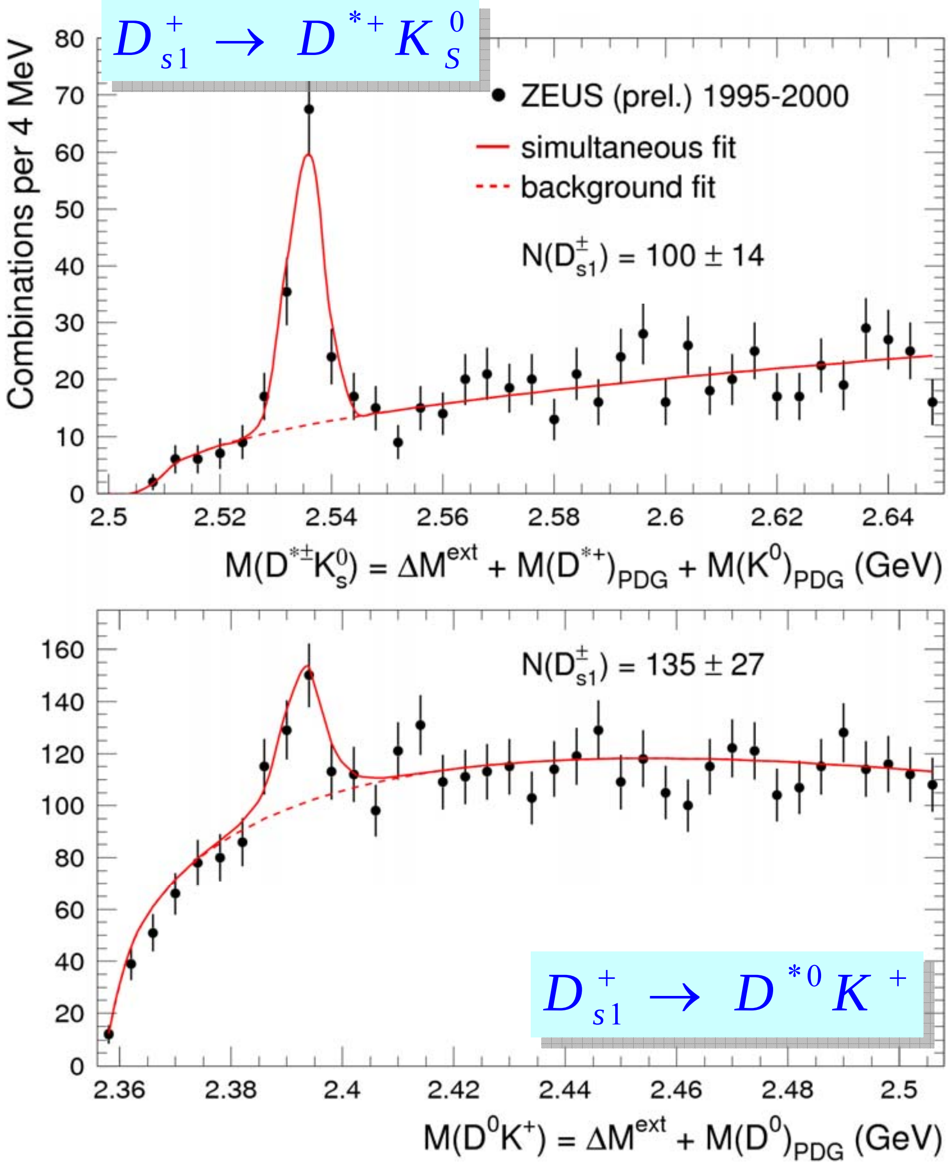


ZEUS Collab., Contrib. 101 to Int.CHEP-07.

Charmed Strange Particles

ZEUS Collab., Contrib. 101 to Int.CHEP-07.

- **Observed orbitally excited (cs) mesons D^+_{S1} (2536)**



ZEUS measured:

100 +- 14 events in $D^+_{S1} \rightarrow D^{*+} K^0_S$

135 +- 27 events in $D^+_{S1} \rightarrow D^0 K^+$

Fits to helicity angle between K^0_S and π_s in D* rf $dN \sim (1+R\cos^2\theta)$ gives

$$R(D^+_{s1}) = -0.74\left(^{+0.23}_{-0.17}\right)\left(^{+0.06}_{-0.05}\right)$$

→ this is consistent

- **with CLEO values (- 0.32±0.40)**
- **with prel. Belle (-0.7±0.03)**
- **with R=-1 as expected for 1^-, 2^+ …**
- **not really with R=0, as for 1^+**

R≠0 could suggest a mixture of two 1^+ states eg. $D_{s1}(2536)^+$ and $D_{s1}(2460)^+$

Summary: Excited Charm

ZEUS Collab., Contrib. 101 to Int.CHEP-07.

	Mass (Mev)
$D_1(2420)^0$	$2419.8 \pm 2.0(stat)^{+0.8}_{-1.0}(syst)$
$D_2^*(2460)^0$	$2468.4 \pm 3.6(stat)^{+1.1}_{-1.3}(syst)$
$D_{S1}\ (2536)^+$	$2535.30^{+0.44}_{-0.41}(stat)^{+0.09}_{-0.08}(syst)$

consistent with PDG values

	Fragmentation fraction%
$f(c \rightarrow D_1(2420)^{0)}$	$3.5 \pm 0.4^{+0.4}_{-0.6} \pm 0.2$
$f(c \rightarrow D_2^*(2460)^{0)}$	$3.8 \pm 0.7 \pm 0.6 \pm 0.2$
$f(c \rightarrow D_{S1}\ (2536)^{+)}$	$1.1 \pm 0.2 \pm 0.1 \pm 0.1$
$f(c \rightarrow D^{*\prime +} \times B)$	<0.45% at 95% C.L.

consistent with e^+e^- values

- **Width:** $\Gamma(D_1^0) = 51.6 \pm 7.0(stat)\ ^{+1.9}_{-4.1}$ (syst) MeV

- **Ratios:**

$$BR(D_{S1}^+ \rightarrow D^{*0}\ K^+ / D^{*+}\ K^0) = 2.2 \pm 0.6(stat)^{+0.4}_{-0.5}(syst) \pm 0.1(ext)$$

$$BR(D_2^{*0} \rightarrow D^+\pi^- / D^{*+}\pi^-) = 2.7 \pm 0.8(stat) \pm 0.6(syst) \pm 0.1(ext)$$

consistent with PDG values

- **Helicity par:**

$$R(D_{s1}^+) = -0.74^{+0.23}_{-0.17}(stat)^{+0.06}_{-0.05}(sys)$$

$$R(D_1^0) = +6.1 \pm 2.3(stat)^{+2.0}_{-0.8}(sys)$$

Pentaquark Particles

$qqqq\bar{q}$ - States

... a short status report ...

Pentaquarks – Reminder

Existence of pentaquark states within different theoretical approaches

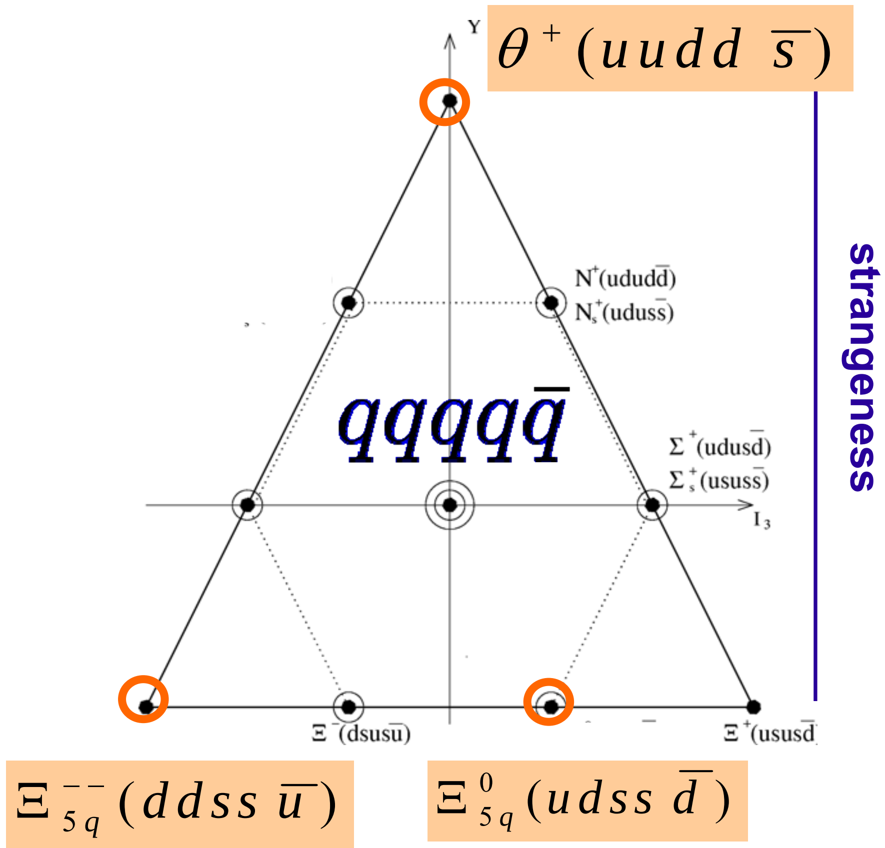
eg. Chiral Quark Soliton Model (D.Diakonov et al.) predicts an antidecuplet of pentaquarks:

- low mass (1.5–2.1 GeV)
- narrow (≤ 30 MeV)
- exotic quantum numbers

Experimental searches at HERA focused on Θ^{+}, Ξ^{--}, Ξ^{0}

→ **many positive and negative results exist on Θ^{+} besides HERA ...**

Pentaquark Anti-decuplet

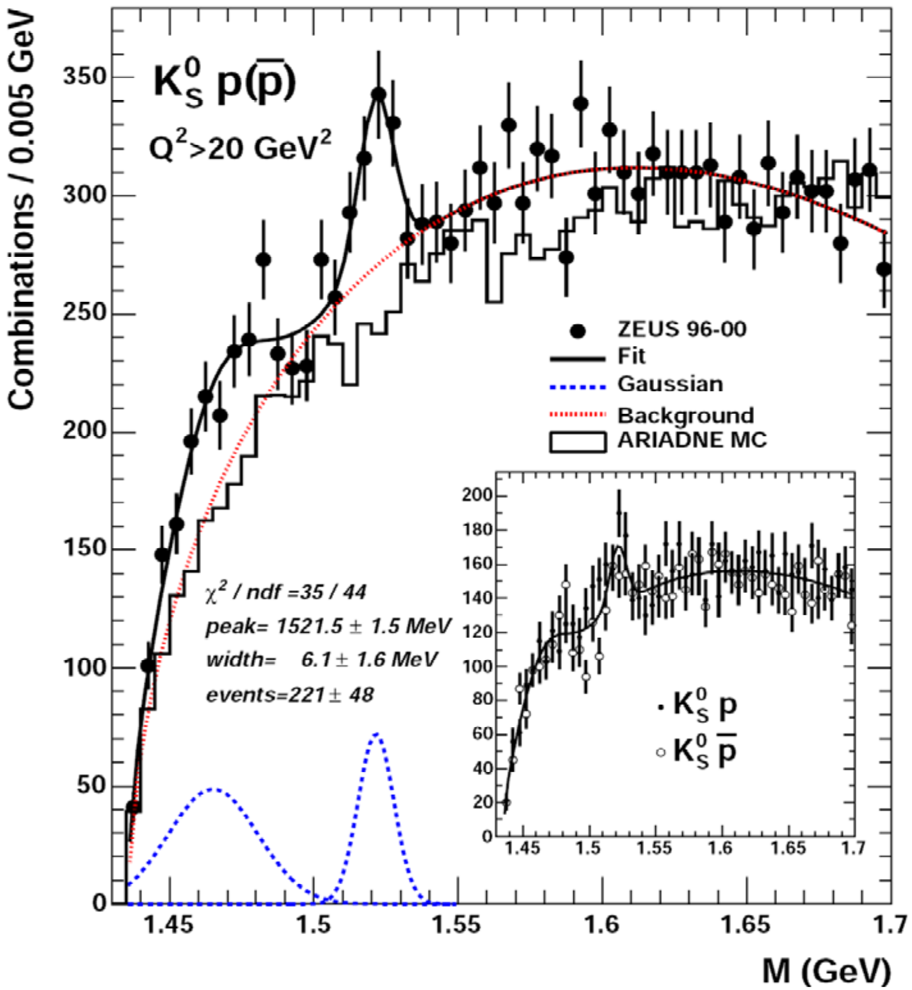


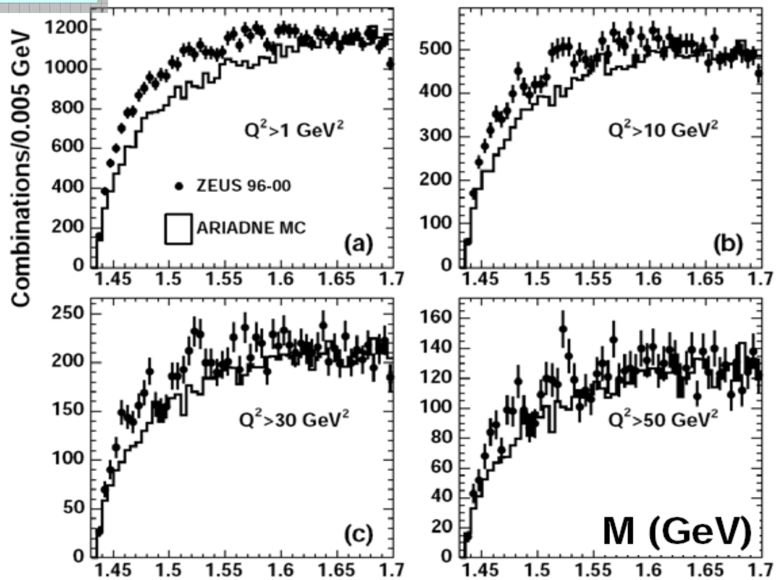
D.Diakonov et al. Z. Phys A359, 1997, 305;
D. Diakonov, V. Petrov, Phys. Rev. D69, 2004, 094011

Search for the strange Θ^+ : ZEUS

$$\Theta^+(1540) \to pK_S^0 \to p\pi^+\pi^-$$

L = 121 pb^{-1}





Signal SEEN for Q^2 > 20 GeV

S = 221 ± 48

M = (1521.5 ± 1.5) MeV

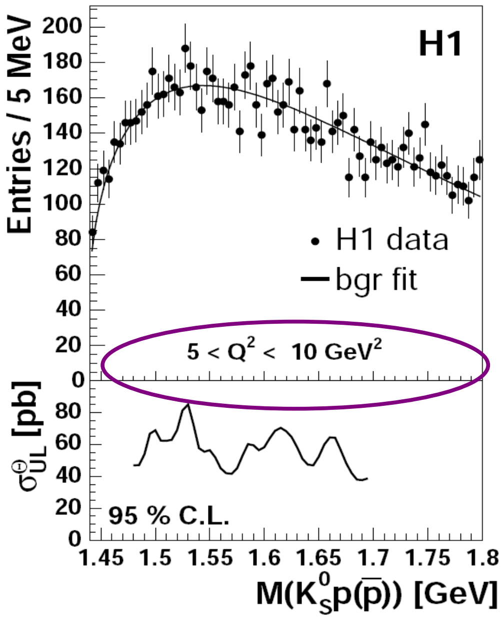
σ = (6.1 ± 1.6) MeV

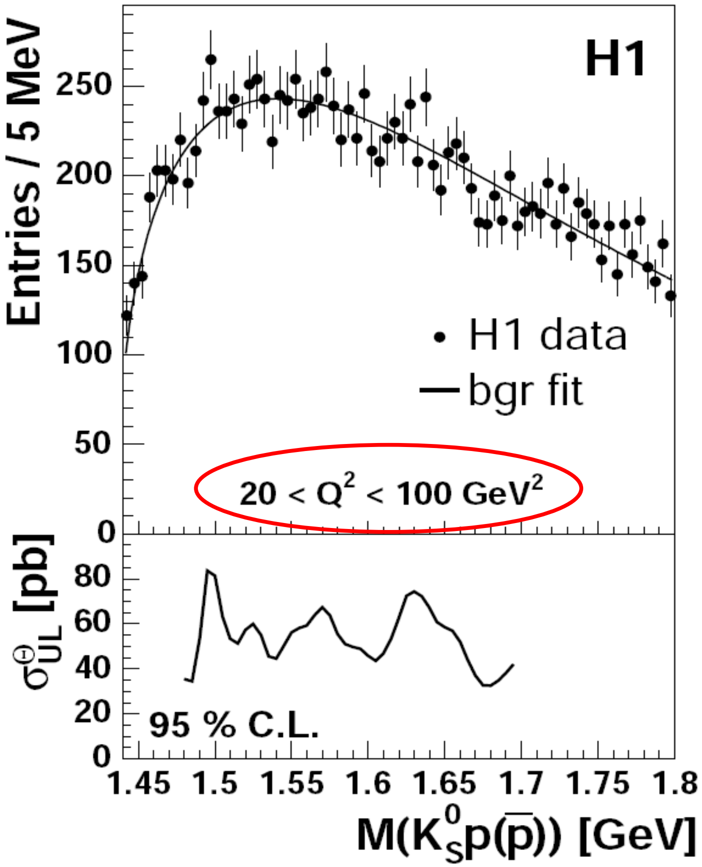
Significance: 3.9 – 4.6 σ

$p_t(p)<1.5$; $p_t(\Theta)>0.5$; $|\eta(\Theta)|<1.5$; $0.04<y<0.9$

ZEUS Collab., PLB 591 (2004) 7

Search for the strange Θ^+ : H1





$p_t(\Theta)>0.5$; $|\eta(\Theta)|<1.5$; $0.1<y<0.6$

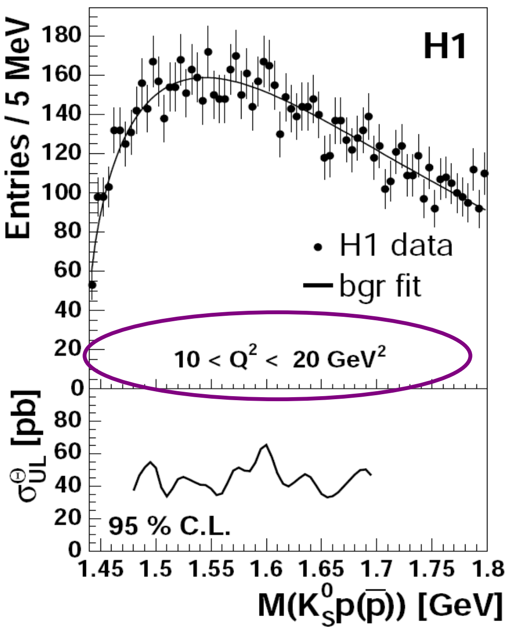
$5 < Q^2_e < 100$ GeV^2

$0.1 < y_e < 0.6$

$L = 74$ pb^{-1}

No significant signal

in any Q^2 bin



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

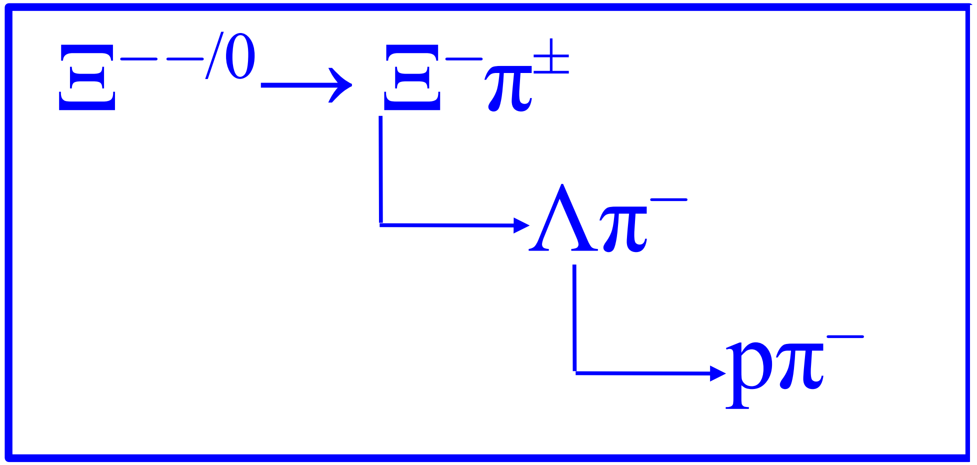
H1 extrapolated ZEUS range : $\sigma_{H1}(M=1.52) < 100$ pb @ 95% C.L.

H1 does not confirm ZEUS result

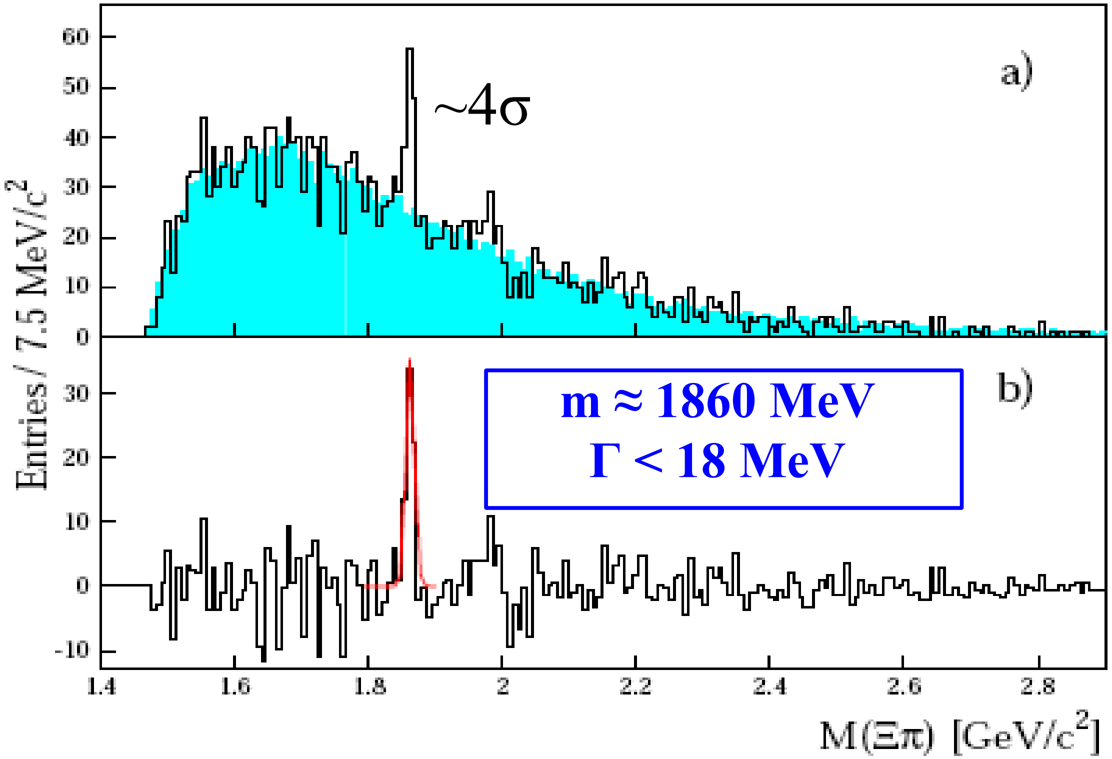
H1 Collab., PL B 639 (2006)

An S=-2 State $\Xi^{--/0} \rightarrow \Xi\pi$?

Remember the NA49 "4σ hint" at mass 1862 MeV ...



NA49 Collab., PRL 92 (2004)



➔ **H1+ZEUS** searched for doubly charged and neutral states Ξ^{--}_{5q} and Ξ^{0}_{5q} produced in ep

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

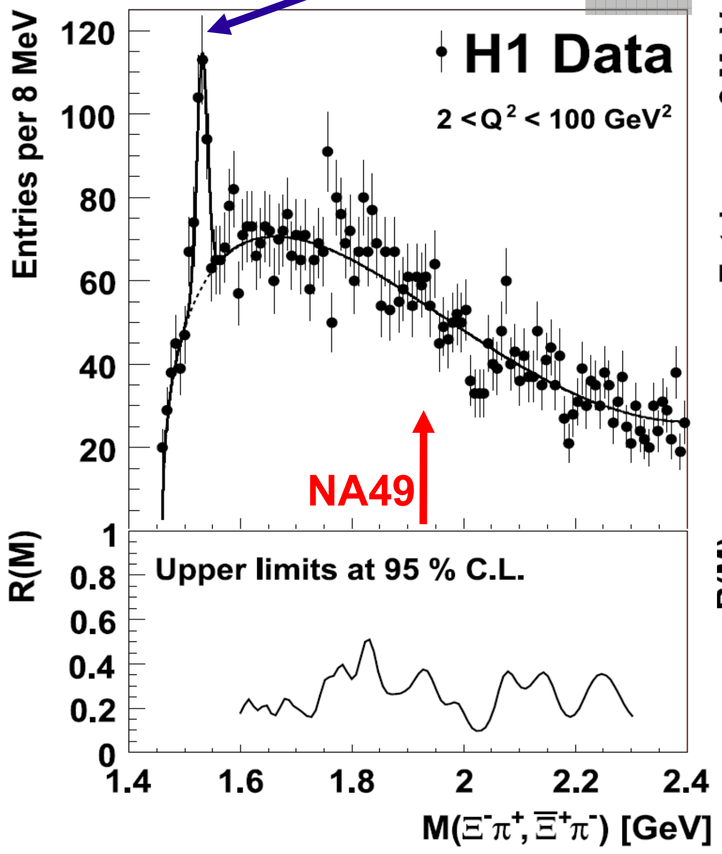
Baryonic States decaying → Ξπ in DIS

All upper limits relative to Ξ⁰ (1530)

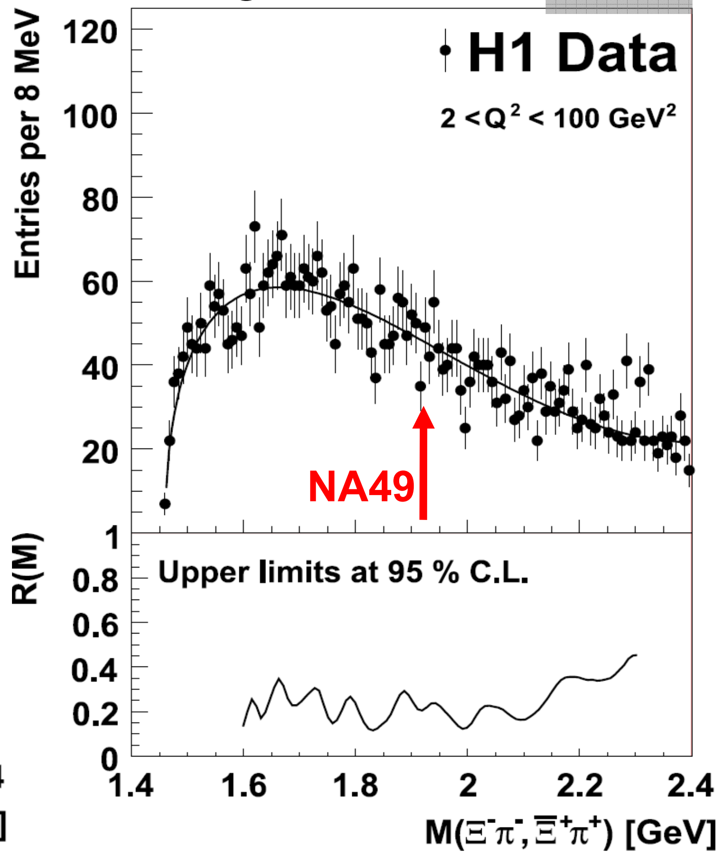
H1: hep-ex:0704.3594

ZEUS Collab., PL B610 (2005)

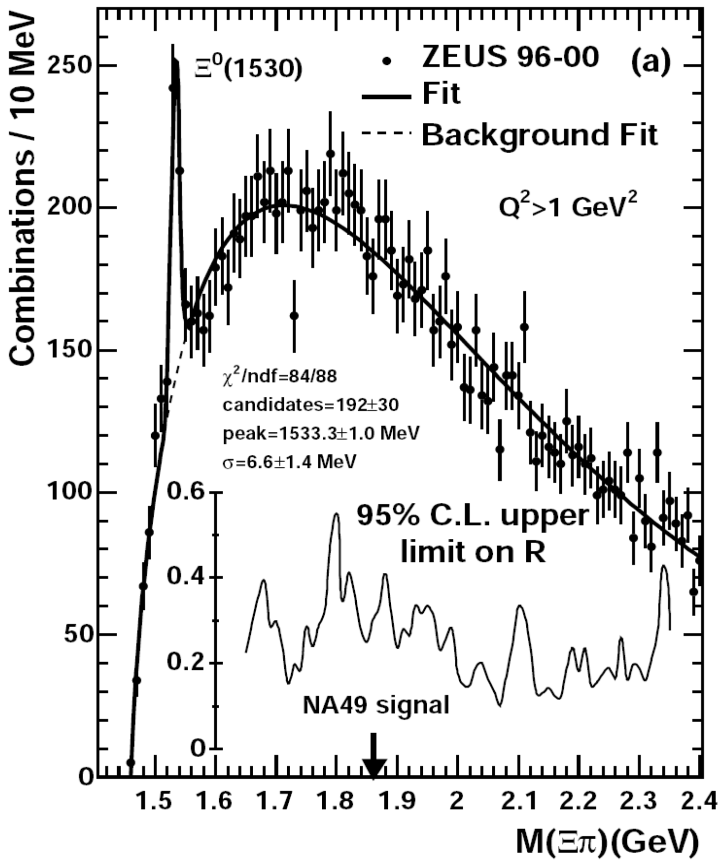
neutral comb. ± ∓



charged comb. ± ±



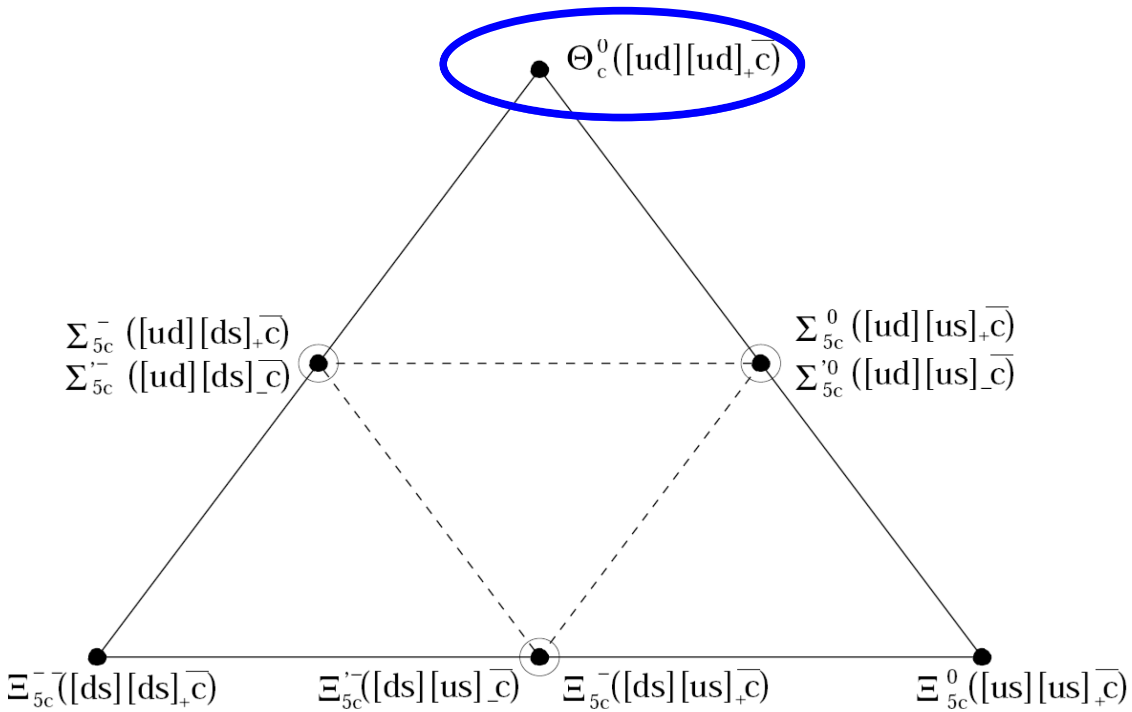
all comb.



- **NA49** observation at 1862 MeV not confirmed
- **H1+ZEUS:** Search for Ξ^{--}_{5q} and Ξ^0_{5q} decaying to Ξπ

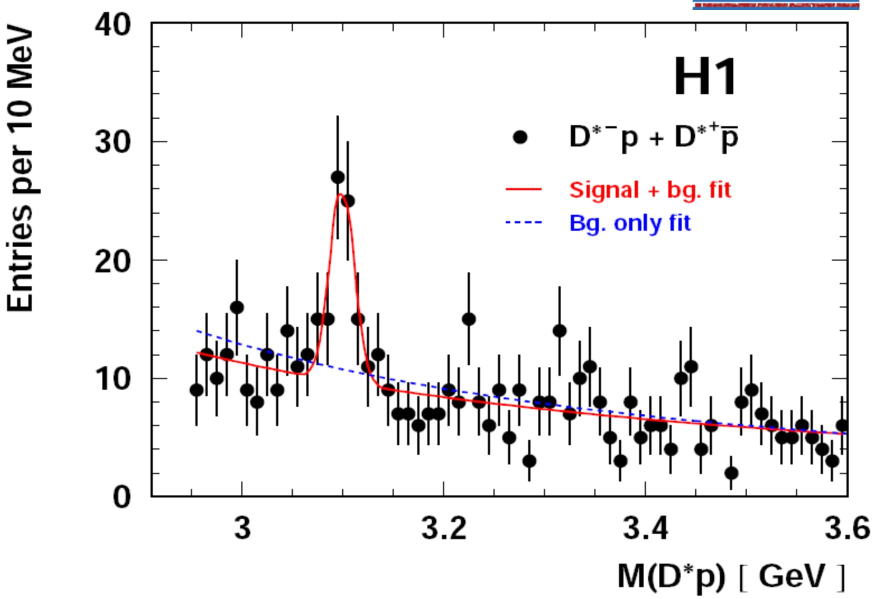
No evidence seen for any exotic 5q state

Is there a $\Theta^0_c \rightarrow D^{*-}\, p$?



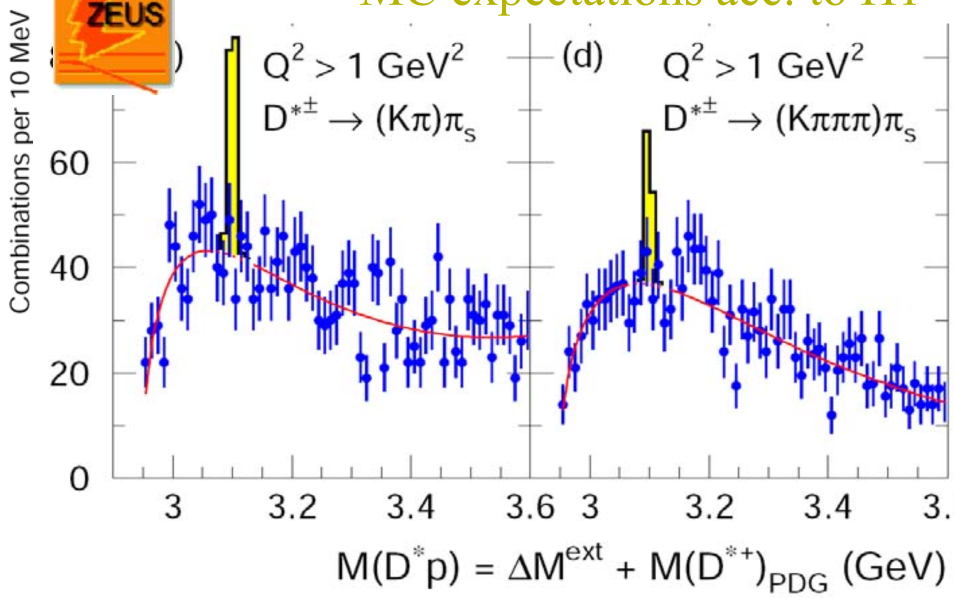
Search for a charmed $\Theta_c^0 \rightarrow D^*p$

→ No new information



H1 Collab., PL B588 (2004) Lumi =75 pb^{-1}

MC expectations acc. to H1



ZEUS Collab., EPJ C38 (2004) Lumi =126 pb^{-1}

ZEUS: NO Signal

H1: Signal with :
M = 3099 ± 3 ± 5(sys) MeV
σ = 12 ± 3 MeV ; N = 51 ± 11
Significance: 5.4 – 6.2 σ

Compare **acceptance corrected yield ratio (D*p) / D^*_{inc}**:
in vis.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.)

No evidence seen for Θ_c^0 by any other experiment

ZEUS does not confirm H1 result

"Pentaquark Score" at HERA ...

- $\Theta^+(1530)$:
  - ZEUS sees signal for $Q^2 > 20$ GeV:
    H1 does not see a signal, upper limit at 95% C.L compatible with ZEUS measurement

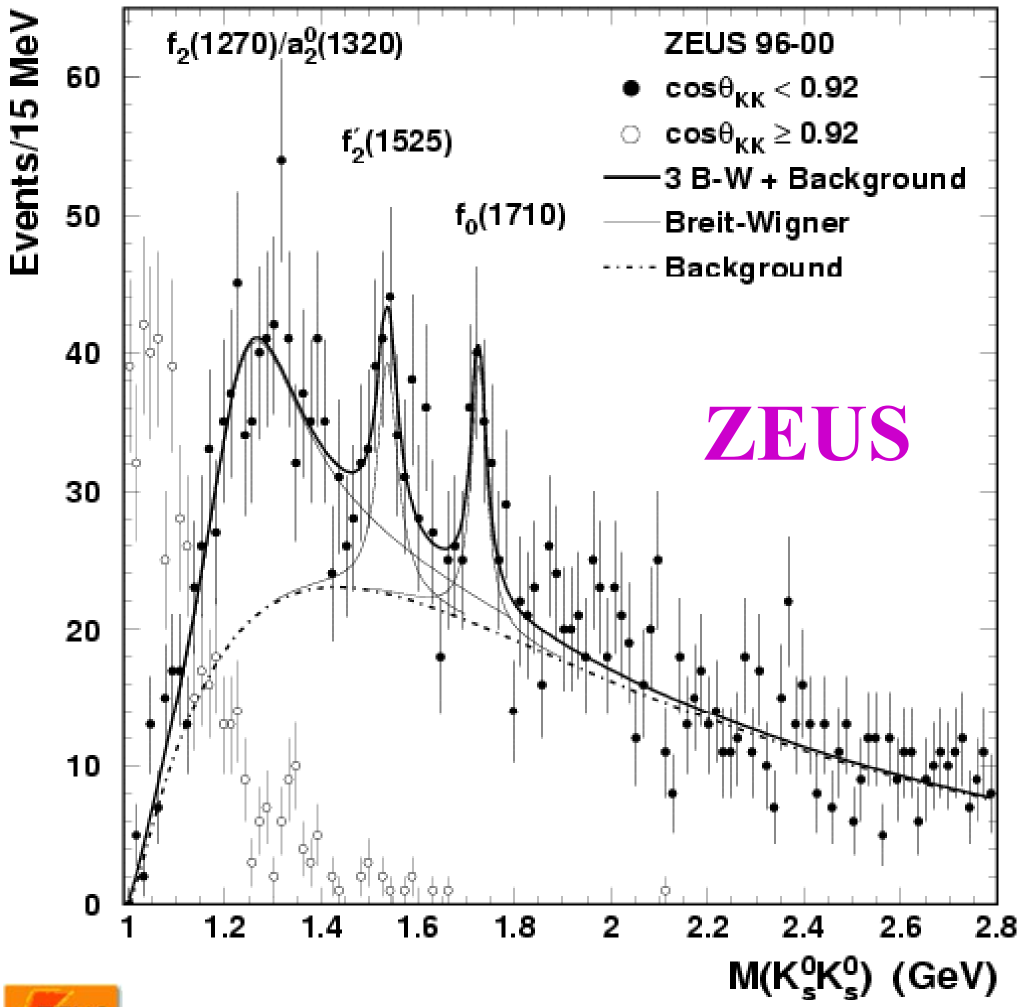
- $\Xi^{--/0}(1860)$:
  - Not seen, neither by ZEUS nor by H1
  - ZEUS and H1 are compatible

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

Glueball Candidates seen in ep-collisions ???

Structures in $K^0_S K^0_S$ Resonances

- Search for structure in $K^0_S K^0_S$ mass spectrum : HERA-I data 121 pb^{-1}
  $0.04 < y < 0.95$; $Q^2 > 4$ GeV^2



- lightest glueball candidate:
  $J^{PC} = 0^{++}$; M=1730 MeV
  eg. **WA102:** glueball candidate $f_0(1710)$

ZEUS observes 3 peaks:

- **M=1274 MeV ; Γ=44 MeV**
  broad peak $f_2(1270)/a2(1320)$
- **M=1537 MeV ; Γ=50 MeV**
  consistent with $f_2'(1525)$
- **M=1726 MeV ; Γ=38 MeV**
  $f_0(1710)$??? PDG: Γ=137±8 MeV

Is this the
Glueball candidate ?

ZEUS Collab., PL B578 (2004) 33

Summary

- **Light particle production:**
  - d (+anti-d) production ~1/1000 of p (+anti-p) production
  - possibly more d than anti-d ???
- **Strange particle production : ZEUS and H1 data agree** ☺
  - Overall features of the data are well described; but differences seen when looking in detail → need better understanding of fragmentation issues
- **Charmed particle production: ZEUS and H1 data agree** ☺
  - D mesons: fragmentation universality confirmed between ep and e^+e^- data;
  - orbital excited D-mesons observed (D^0_1, D^{*0}_2 , D^+_{S1}) in agreement with PDG; radial excited state $D^{*'+}$ not seen.
- **The HERA "pentaquark" story isn't over** ☹☹
  - Major differences between H1 and ZEUS observed
  - need final HERA-II data analysed to resolve the present inconsistencies ...

→ HERA provides mainly information about production and fragmentation issues – less on spectroscopy …

BUT then...

may be it is now time to apply A.Huxley's quote to the Pentaquark searches ?

"The great tragedy of science, …
the slaying of a beautiful hypothesis
by an ugly fact" !

Thanks - to all the HERA colleagues.