

Strangeness Production and Hadron Spectroscopy at HERA

- Strangeness production
- “Exotic” states
- Charm excited states production
- Baryon production

Christoph Grab
ETH Zurich



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



representing
and



Introduction

Note: various slides marked as “ref”
are included for reference purposes
and are NOT discussed in detail

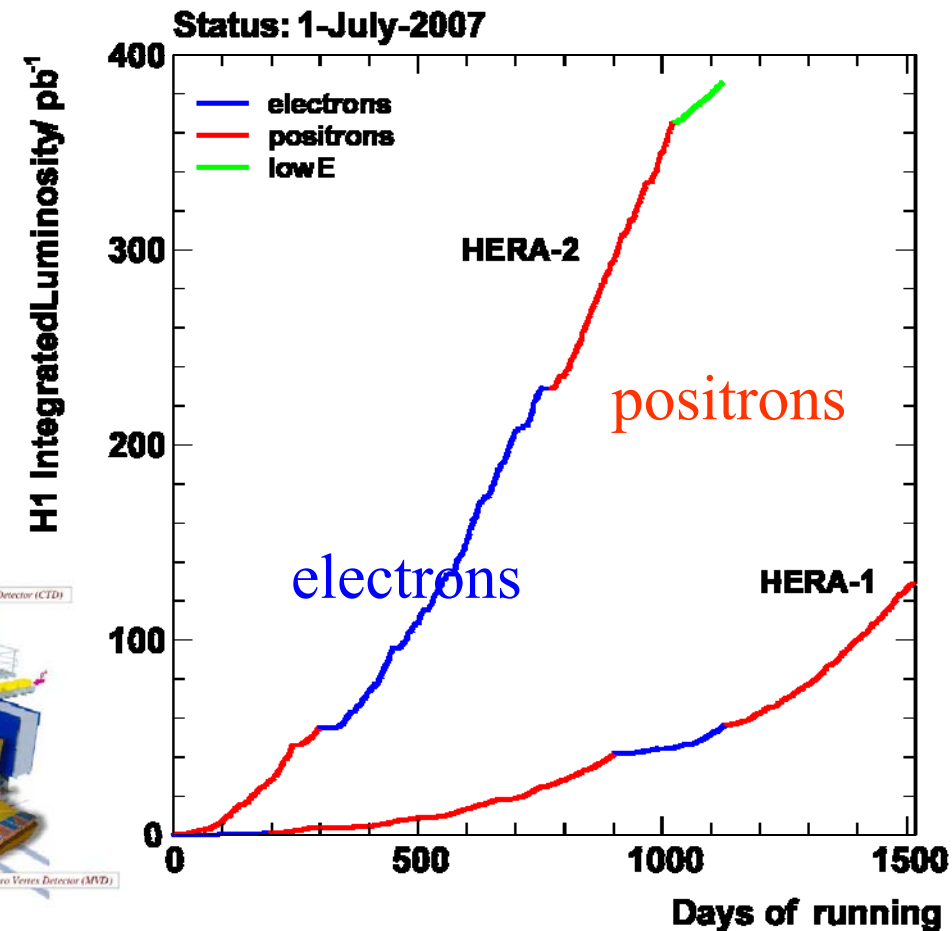
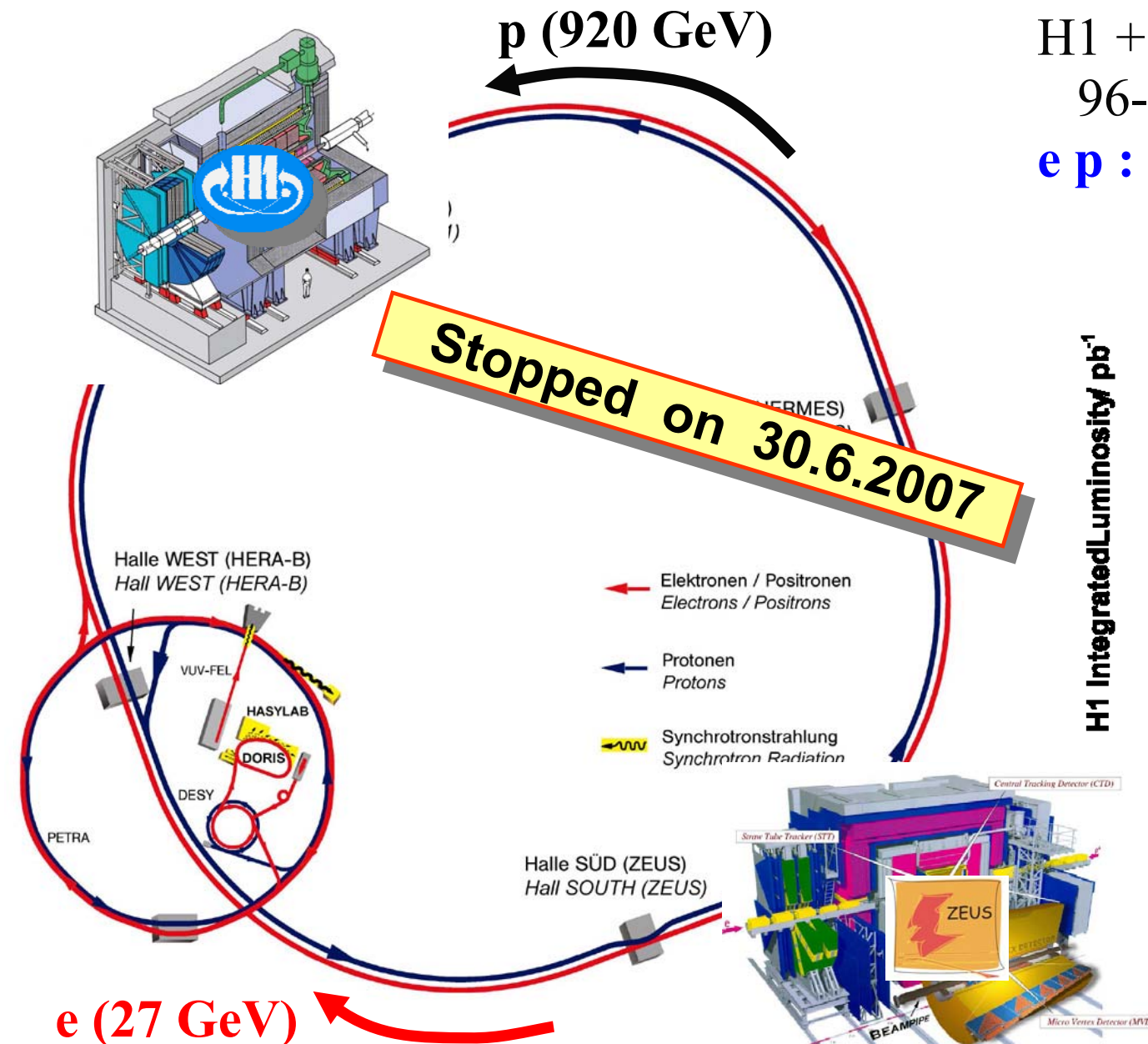
QCD : Abstracts to cover (14+4 min)

- 120 Measurement of K^0 s, Λ , anti- Λ production with ZEUS at HERA
ZEUS Collab., DESY-06-226, EPJ C51 (2007) 1
- 123 Measurement of Bose-Einstein correlations of charged and neutral kaons in DIS with ZEUS at HERA :
ZEUS Collab., DESY-07-069, PL B 652 (2007) 1
- 124 Measurement of (anti)deuteron and (anti)proton production in deep inelastic ep scattering with ZEUS
ZEUS Collab., DESY 07-070, Nucl. Phys. B 786 (2007) 181,
H1 Collab., EPJ C36 (2004) 213
- 135 Measurement of inclusive K^0 s K^0 s resonance production with ZEUS at HERA
ZEUS Collab. DESY-08-068
- 243 Measurement of excited charm and charm-strange meson production with ZEUS at HERA
ZEUS Collab., Contrib. 101 to Int.CHEP-07., DESY-08-093.
- 783 Search for Baryonic Resonances Decaying to Ξ π in Deep-Inelastic Scattering with H1 at HERA
H1 Collab. Eur.Phys.J.C52:507-514,2007.
- 847 Strangeness Production at low Q^2 in Deep-inelastic ep Scattering with H1 at HERA
H1 Collab. Prelim. DIS 2008, paper in progress;
- 848 Strangeness Production at High Q^2 in Deep-inelastic ep Scattering with H1 at HERA
H1 Collab. expected H1prelim-08-035 (J.Ruiz) **Cancelled**
- 866 Inclusive (non-diffractive) $\rho(770)$, $K^*(892)$ and $\phi(1020)$ photoproduction with H1 at HERA
H1 Collab. Prelim. DIS03, (A. Kropivnitskaya) **Cancelled**
- 867 Inclusive $K^{*+/-}$ production at low Q^2 with H1 at HERA
H1 Collab. expected H1prelim-08-032 (D.Sunar)

The HERA Collider (ref)

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

H1 + ZEUS integrated luminosity
 96-00 + 03-07 (high energy)
 $e p : \sim 500 \text{ pb}^{-1}$ (each expt.)



The HERA Kinematics (ref)

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

$$e(k) + p(P) \rightarrow e'(k') + X \quad \text{Lumi} \sim 500 \text{ pb}^{-1} \text{ (H1 and ZEUS each)}$$

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

D_q^h : Fragmentation
of quark q to hadron h

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

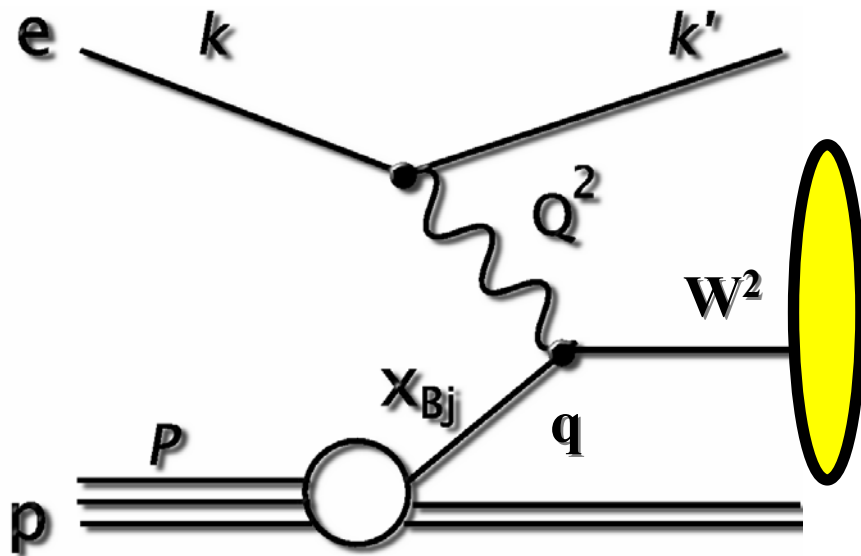
$$W^2 = (P + q)^2$$

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

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

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

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



- Light hadrons
- Strange
- Charm
- Exotics

Relevant Regimes:

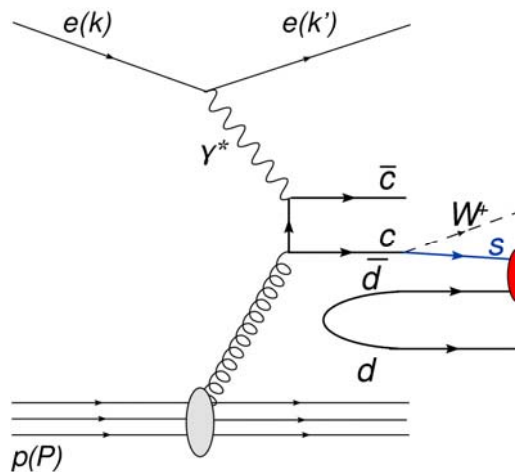
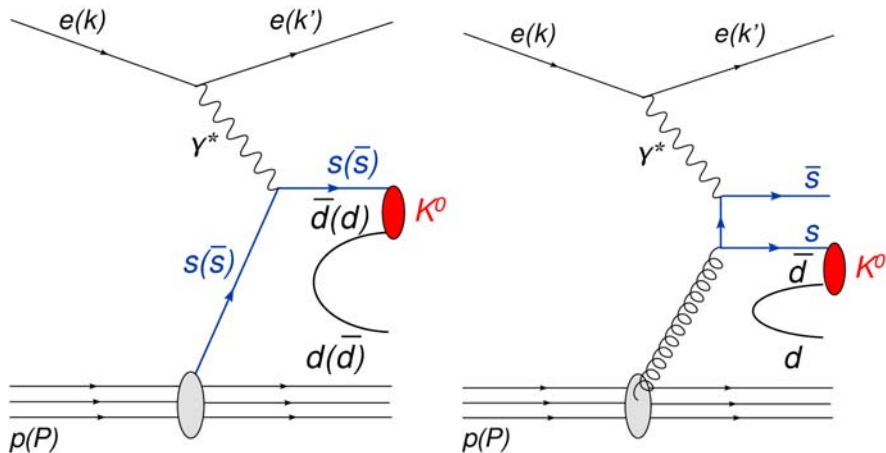
$Q^2 < 1 \text{ GeV}^2$: Photoproduction (γP): direct and resolved processes (x_γ to separate)
 $Q^2 > 1 \text{ GeV}^2$: Deep Inelastic Scattering (DIS)

Strangeness Production

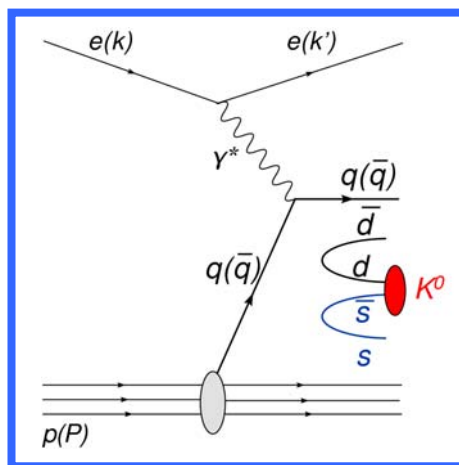
K_s , Λ and K^*

Strangeness Production: K_s , K^* , Λ

Hard processes : QPM, BGF (s,c), g-splitting (perturbative)

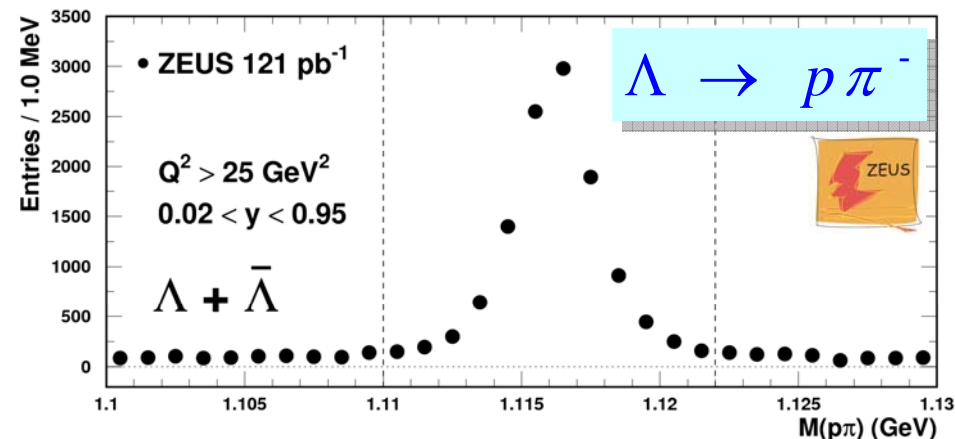


string fragmentation
(non-perturbative)

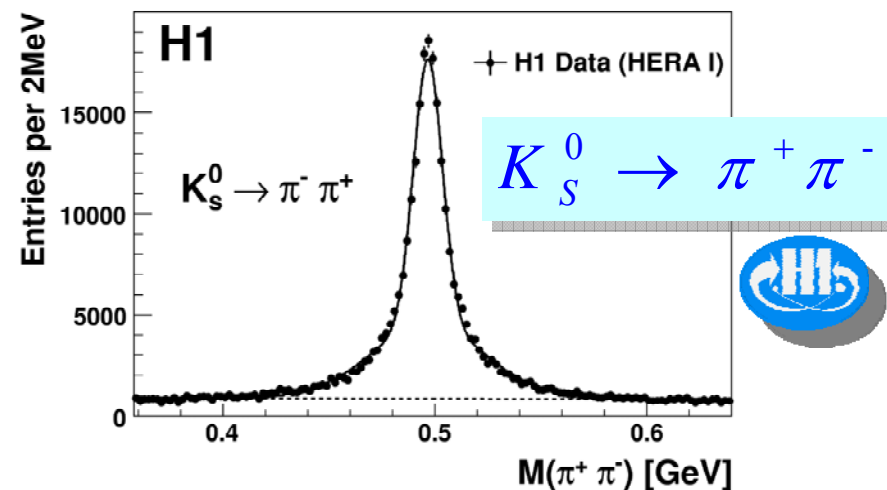


Examples of K_s^0 and Λ signals

ZEUS Collab., EPJ C51 (2007) 1



H1 Collab., Prelim 2008



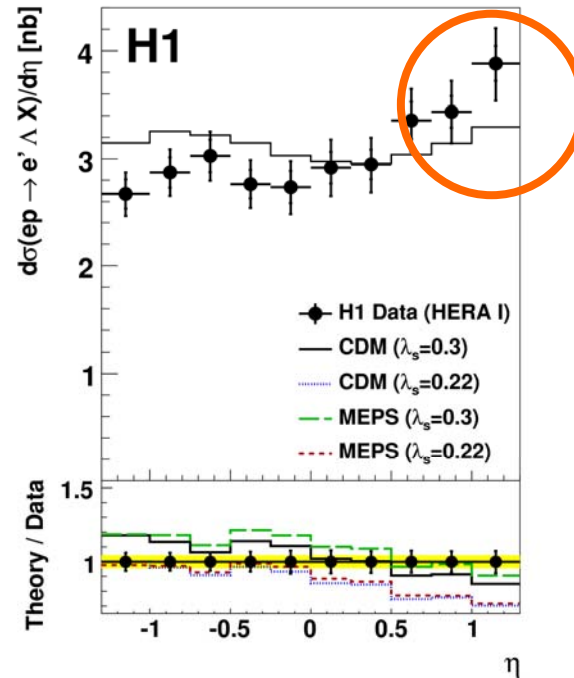
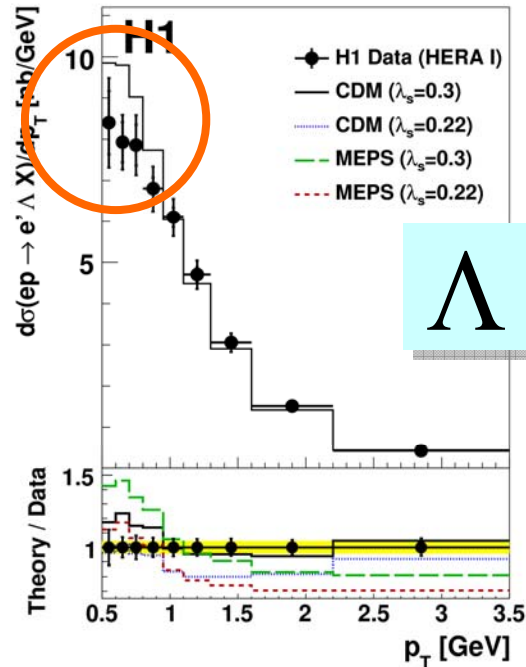
→ strangeness production parameters λ_s, λ_{sq}

K^0_s, Λ Production in DIS and γp : H1 and ZEUS

Cross sections in p_T^{lab} and $\eta^{\text{lab}}, x_\gamma$

DIS: $2 < Q^2 < 100 \text{ GeV}^2$

H1: Prelim. 2008

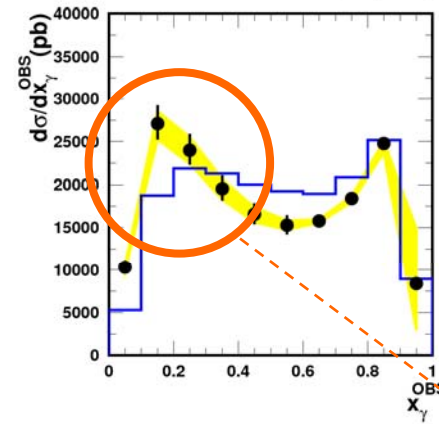
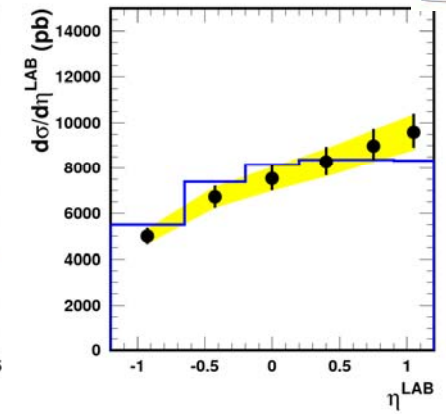
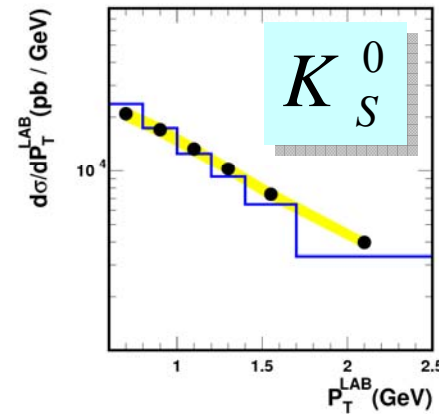


→ ARIADNE CDM overall agrees for $\lambda_s=0.3$;
discrepancies in details: e.g. p_T -slope.

→ Similar, consistent conclusions by H1, ZEUS for K and for Λ production

ZEUS Collab., EPJ C51 (2007) 1

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



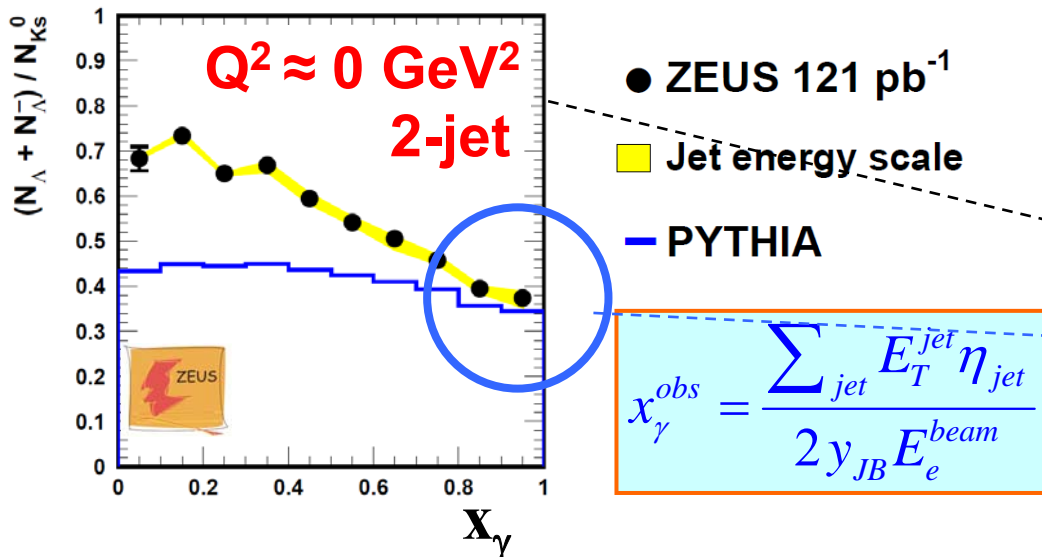
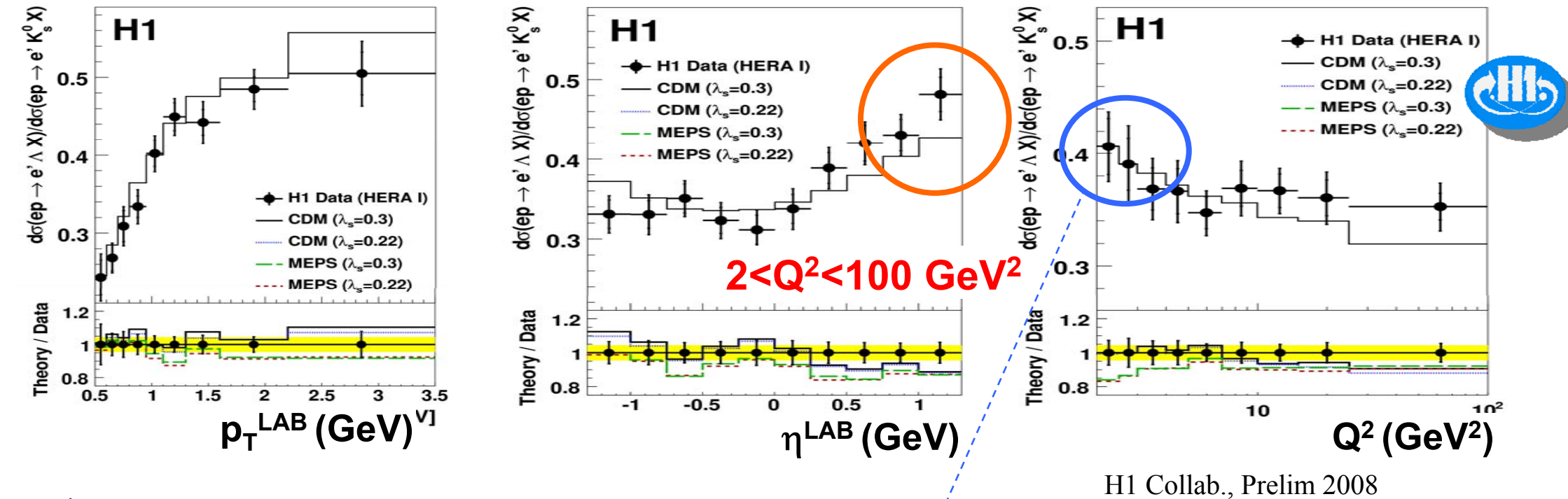
● ZEUS 121 pb⁻¹
■ Jet energy scale uncertainty
— PYTHIA

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

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

$$\frac{N_{\Lambda} + N_{\bar{\Lambda}}}{N_{K_S^0}}$$

Strange Baryon Λ to Meson K_S^0 Ratio

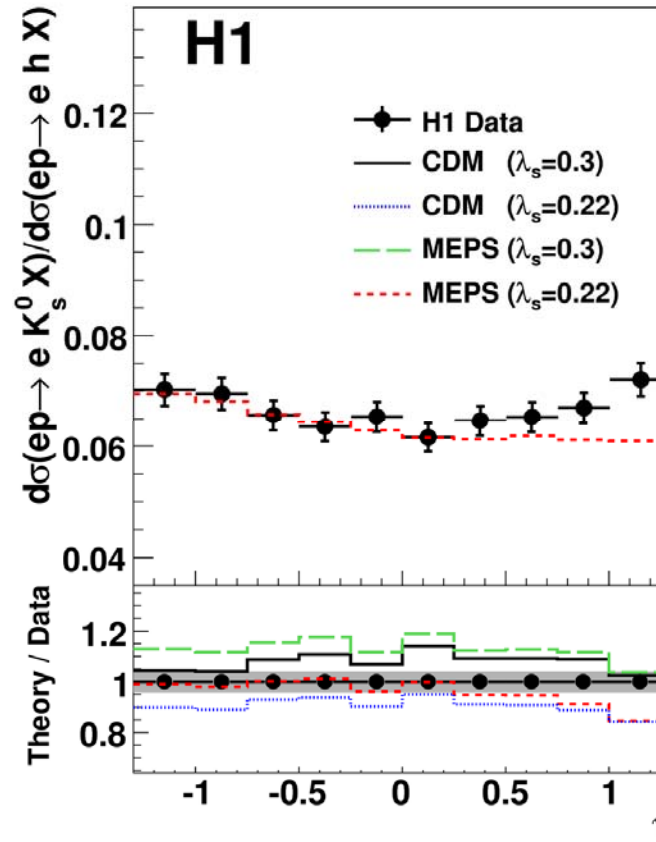
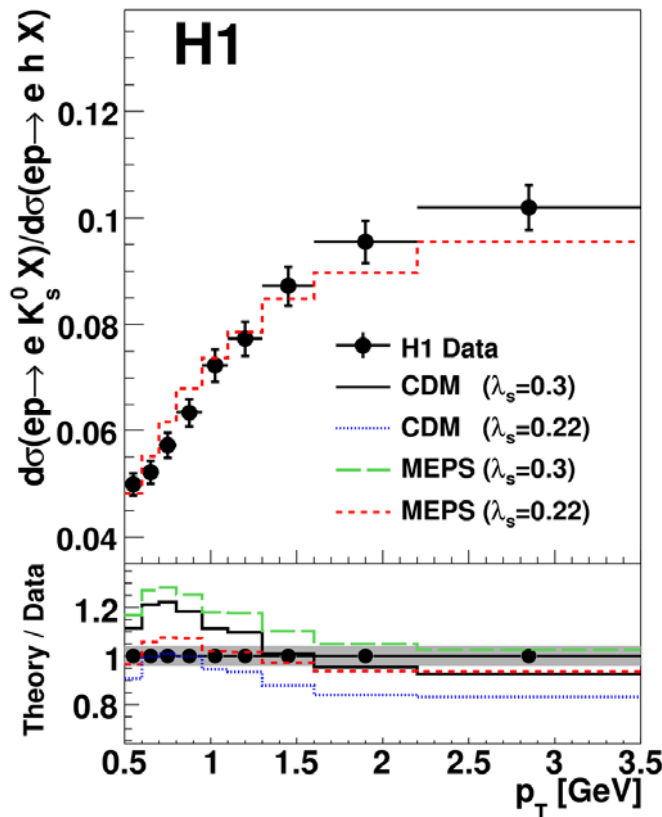


$$x_{\gamma}^{\text{obs}} = \frac{\sum_{\text{jet}} E_T^{\text{jet}} \eta_{\text{jet}}}{2y_{JB} E_e^{\text{beam}}}$$

- CDM ok at 10% level with $\lambda_s=0.3$
- x_{γ} not described by PYTHIA (incl. MI)
- At $x_{\gamma} \approx 1$ (direct) : ratio in γp is similar as in DIS at low Q^2 , and also similar to measurements in e^+e^-

ZEUS Collab., EPJ C51 (2007) 1

Strange K_S^0 to Light Hadrons h Ratio



h = all charged particles

$$\frac{N_{K_S^0}}{N_{charged}}$$

$2 < Q^2 < 100 \text{ GeV}^2$

H1: prelim. ICHEP08

- **→ K/hadrons** : overall described by CMD and MEPS, favour **smaller $\lambda_s=0.22$** !
- **$K_S, \Lambda, \bar{\Lambda}/K_S$** : better described by CMD with **larger $\lambda_s=0.3$** (ALEPH) and Pythia (in γp)
- **Λ : NO** asymmetry observed between Λ and anti- Λ (H1 and ZEUS)
- **General:** H1 and ZEUS consistent; overall features described, details NOT; single λ_s is NOT sufficient; need overall fit to extract λ_s and $\lambda_{qq}, \lambda_{qs}$

K* (892) Production in DIS

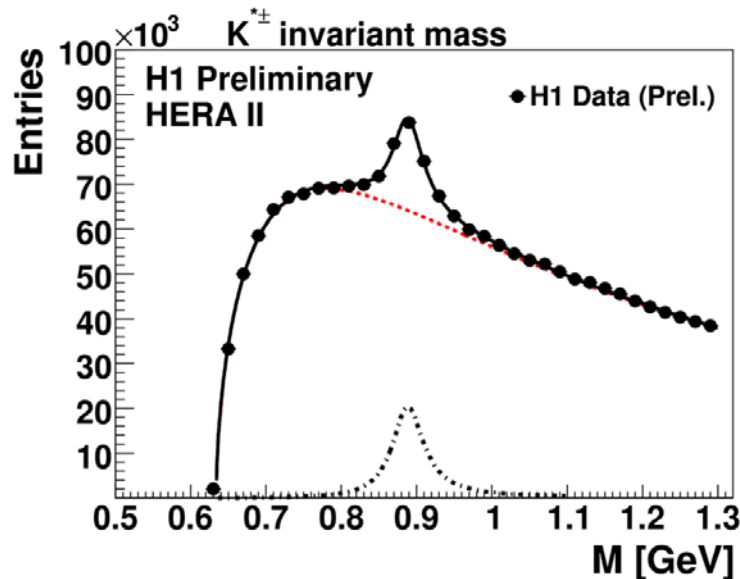


$5 < Q^2 < 100 \text{ GeV}^2$, 301 pb^{-1}

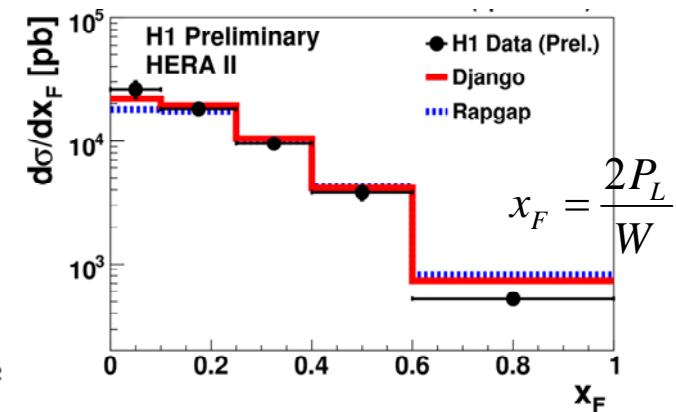
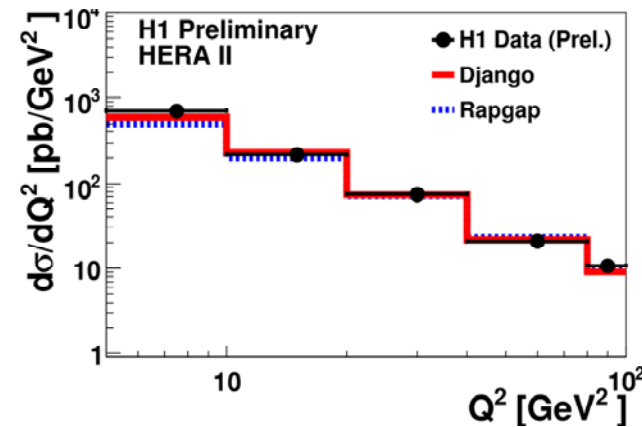
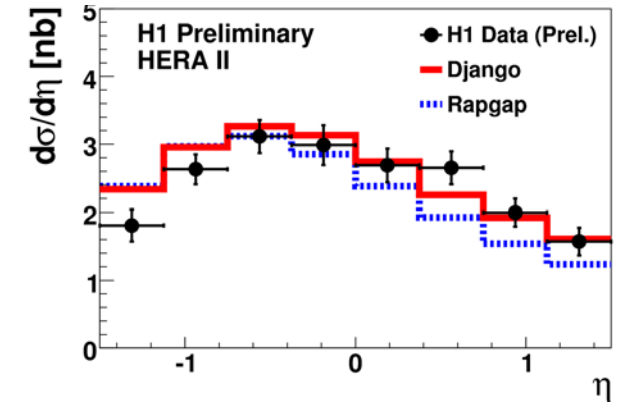
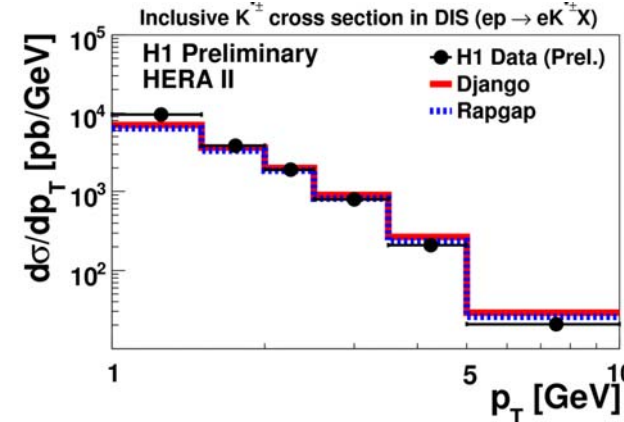
Inclusive cross sections

$$K^{*\pm} \rightarrow K_S^0 \pi^\pm$$

K* : fitted with relativ. BW



H1 Collab., Prelim 2008



- **K* cross sections measured first time at HERA** : overall features described by Django (CDM) and RAPGAP (MEPS), details NOT (eg. eta shape)
- Conclusions consistent with K_S , Λ data

Bose Einstein Correlations in Kaons

Bose-Einstein Correlations for $K^\pm K^\pm$, $K_S K_S$ (ref)

Measure size and shape of particle emitting source.
Identical bosons emission enhanced close in phase space.

Distance in phase space characterized by:

r = source size of particle emission

Q_{12} = distance in 4-momentum space

$$Q_{12} = \sqrt{-(p_1 - p_2)^2}$$

Correlation function $R(Q_{12})$, defined by
two-particle density functions $P(Q_{12})$:

$$R(Q_{12}) = P(Q_{12}) / P_{noBEC}(Q_{12})$$

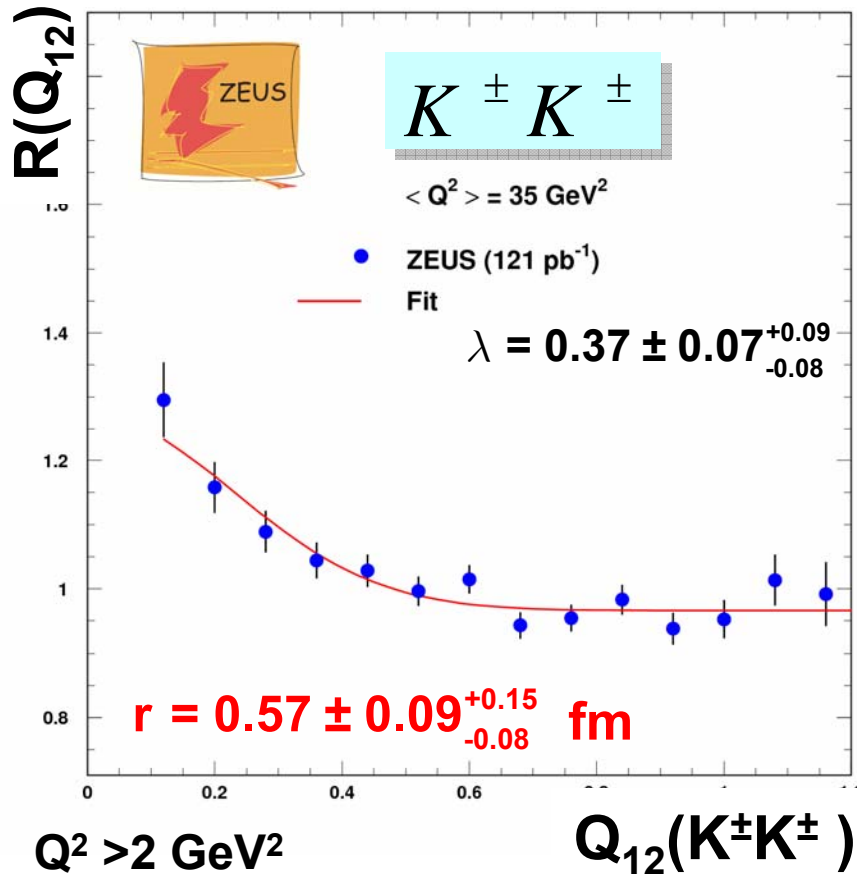
Static Gaussian source of strength λ :

$$R_{Gaus}(Q_{12}) = 1 + \lambda \exp(-r^2 Q_{12}^2)$$

Reduce model sensitivity via double ratios R :

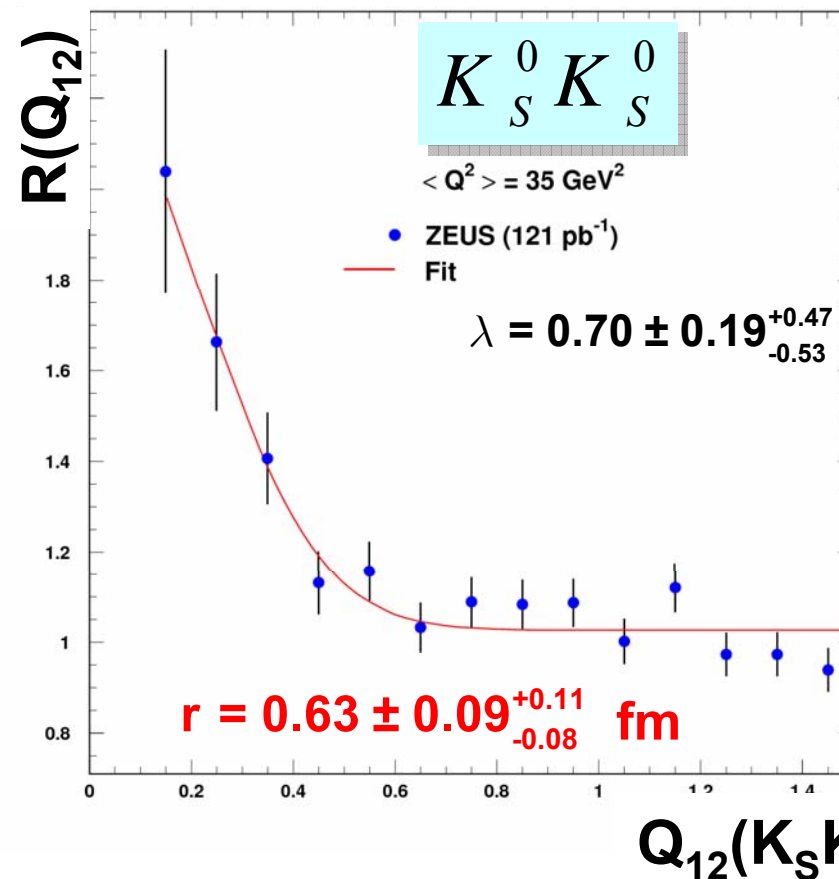
$$R(Q_{12}) = \frac{P(Q_{12})^{data}}{P_{mix}(Q_{12})^{data}} / \frac{P(Q_{12})^{MC,noBEC}}{P_{mix}(Q_{12})^{MC,noBEC}}$$

Bose-Einstein Correlations for $K^\pm K^\pm$, $K_S K_S$



$Q^2 > 2 \text{ GeV}^2$

121 pb⁻¹



$Q_{12}(K_S K_S)$

Source size r
 and
 distance Q_{12} in
 4-momentum
 space

$$Q_{12} = \sqrt{-(p_1 - p_2)^2}$$

λ = source
 strength

ZEUS Collab., PL B 652 (2007) 181

- Bose-Einstein correlations clearly established for $K^\pm K^\pm$ pairs
- $K_S K_S$ inconclusive, $f_0(980) \rightarrow K_S K_S$ background \rightarrow large systematics
- Source radius “ r ” found similar

BEC: Source Radius r

$K^\pm K^\pm$



ZEUS
(this paper)



$K^\pm K^\pm$



OPAL (LEP)
Eur. Phys. J. C 21 (2001) 23

$K^\pm K^\pm$



DELPHI (LEP)
Phys. Lett. B 379 (1996) 330

$K_S^0 K_S^0$



ZEUS
(this paper)



$K_S^0 K_S^0$



ALEPH (LEP)
Phys. Lett. B 611 (2005) 66

$K_S^0 K_S^0$



OPAL (LEP)
Z. Phys. C 67 (1995) 389

$K_S^0 K_S^0$



DELPHI (LEP)
Phys. Lett. B 379 (1996) 330

charged
particles

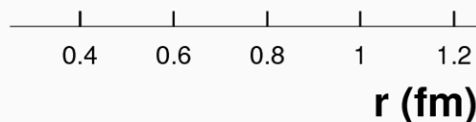


ZEUS
Phys. Lett. B 583 (2004) 231

charged
particles



H1
Z. Phys. C 75 (1997) 437



r values found consistent in :

- ep (DIS) vs. e^+e^-

- $K^\pm K^\pm$ and $K_S K_S$ (marginal)

- Kaons vs. charged particles

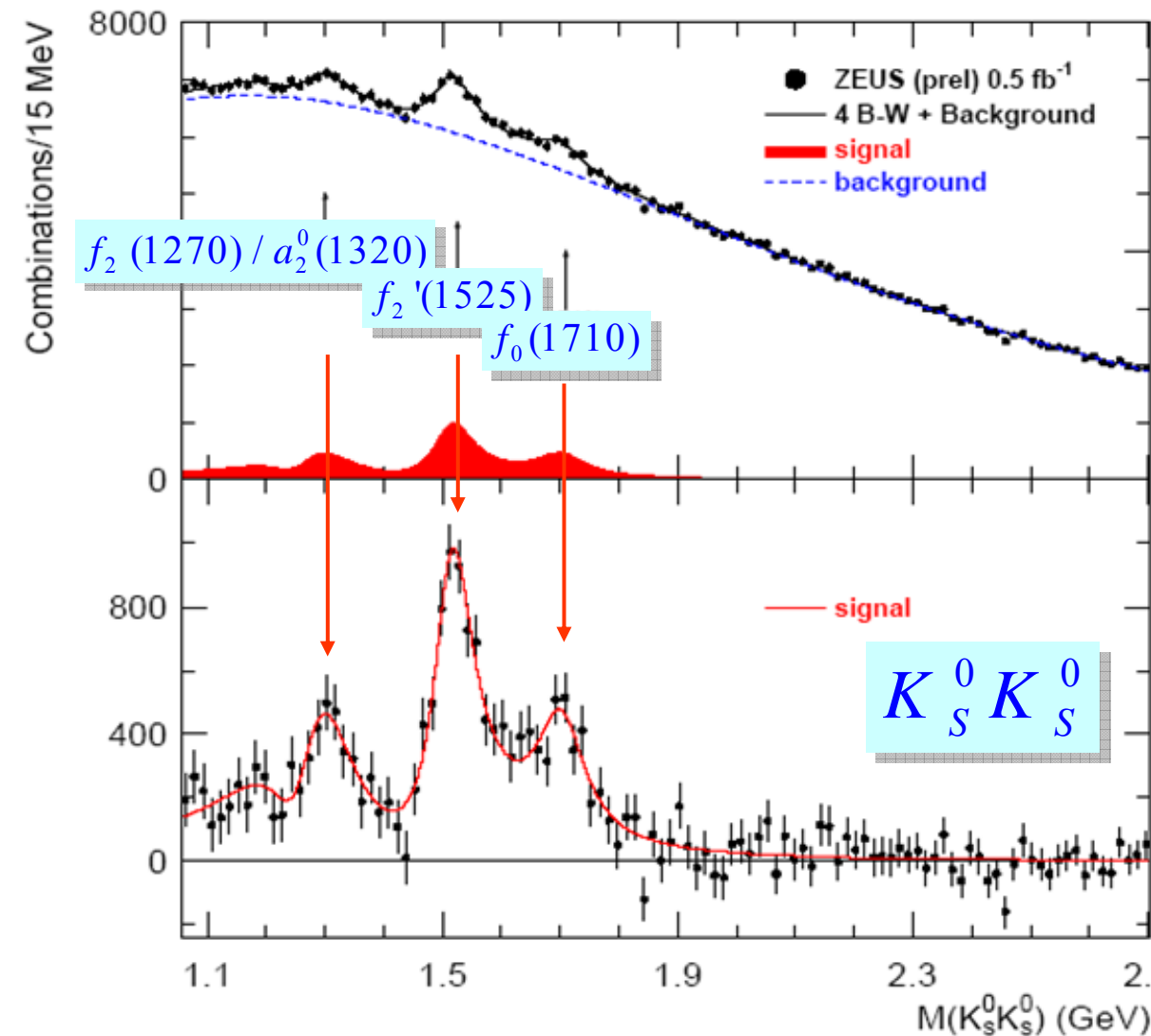
ZEUS Collab., PL B 652 (2007) 181

Glueball Candidates in $K^0_S K^0_S$ Mass Spectra ?

$K_S^0 K_S^0$: Glueball Candidate

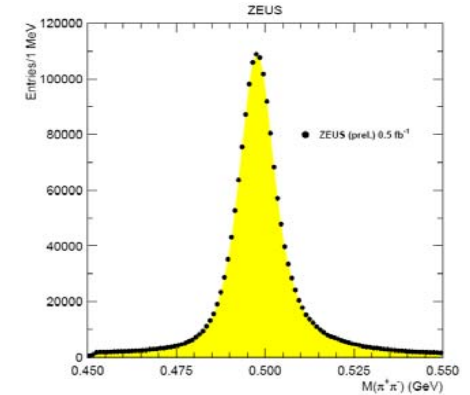


- $K_S^0 K_S^0$ spectrum (672418 comb) : HERA-I+II data $\sim 500 \text{ pb}^{-1}$; all Q^2



- lightest glueball candidate expected:**
 $J^{PC} = 0^{++}$; $M = 1730 \pm 100 \text{ MeV}$
 eg. seen by **WA102, L3** : $f_0(1710)$

$$K_S^0 \rightarrow \pi\pi$$



ZEUS observes 3 structures:

Interference fit of spectra with multiple relativ. BWs;
and determine mass and widths

ZEUS Collab., DESY 08-068

Structures in $K_S^0 K_S^0$ Resonances

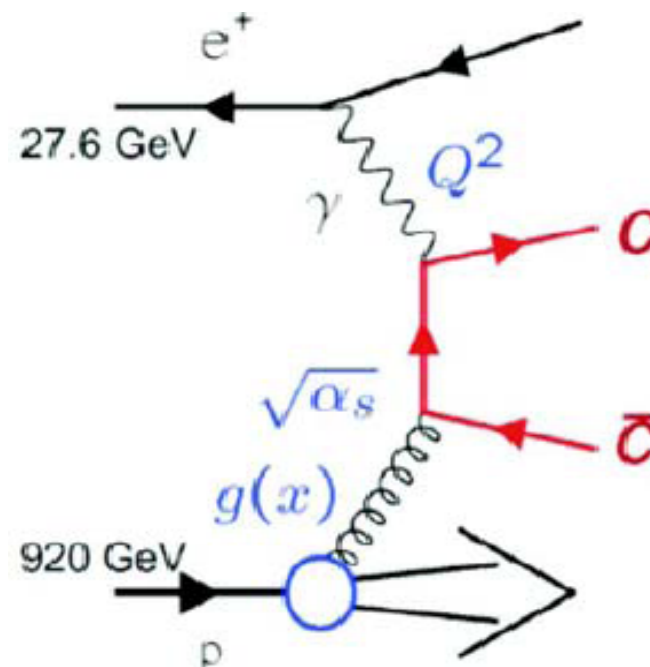


in MeV	$f_2'(1525)$	$f_0(1710)$
mass	$1512 \pm 3^{+1.4}_{-0.5}$	$1701 \pm 5^{+9}_{-2}$
width	$83 \pm 9^{+5}_{-4}$	$100 \pm 24^{+7}_{-22}$
Particle Data Group 2007 Values		
mass	1525 ± 5	1724 ± 7
width	73^{+6}_{-5}	137 ± 8

- Evidence for $f_2'(1525)$ and $f_0(1710)$ [at 5 sigma]
- Masses of $f_2'(1525)$ and $f_0(1710)$ found bit low, but widths consistent with PDG
- $f_0(1710)$ is consistent with $J^{PC}=0^{++}$ glueball candidate

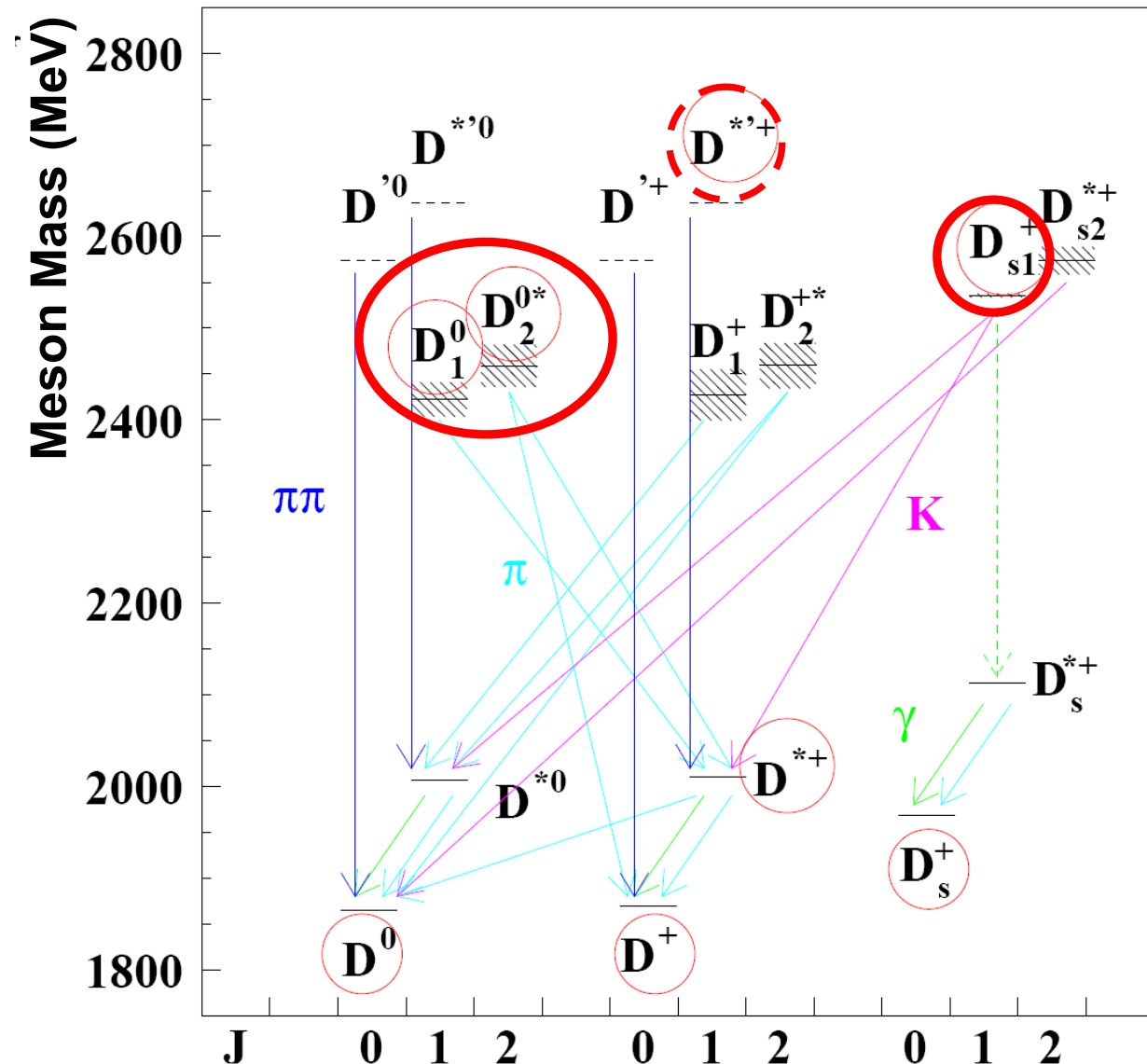
Charmed Particle Production

Dominated by photon-gluon fusion



Excited Charmed Mesons

- Measure **orbitally excited D-mesons** (doublets) through decays :
 - $D_1(2420)^0 \rightarrow D^{*+} \pi^-$
 - $D_2^*(2460)^0 \rightarrow D^{*+} \pi^- , D^+ \pi^-$
- and
- $D_{s1}(2536)^+ \rightarrow D^{*0} K^+ , D^{*+} K_S^0$
- Search for **radially excited state**
 $D^{*+}(2640) \rightarrow D^{*+} \pi^- \pi^+$



Excited Charmed Mesons



- Orbitally excited P-wave mesons:**

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

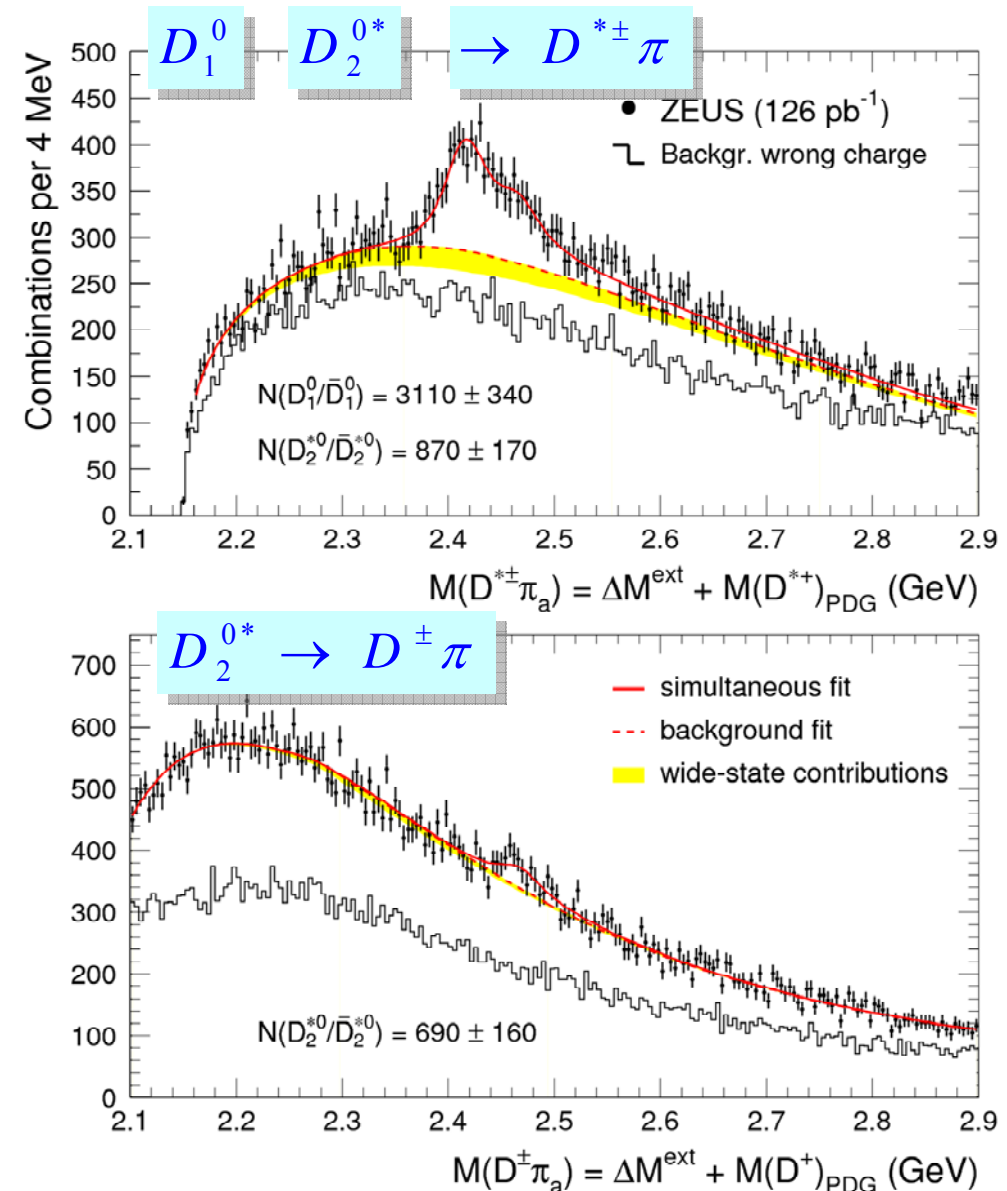
- ZEUS observed :**

$$N(D^0_1[2420]) = 3110 \pm 340 \text{ events}$$

$$N(D^{*0}_2[2460]) = 1560 \pm 233 \text{ events}$$

- and determined**

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

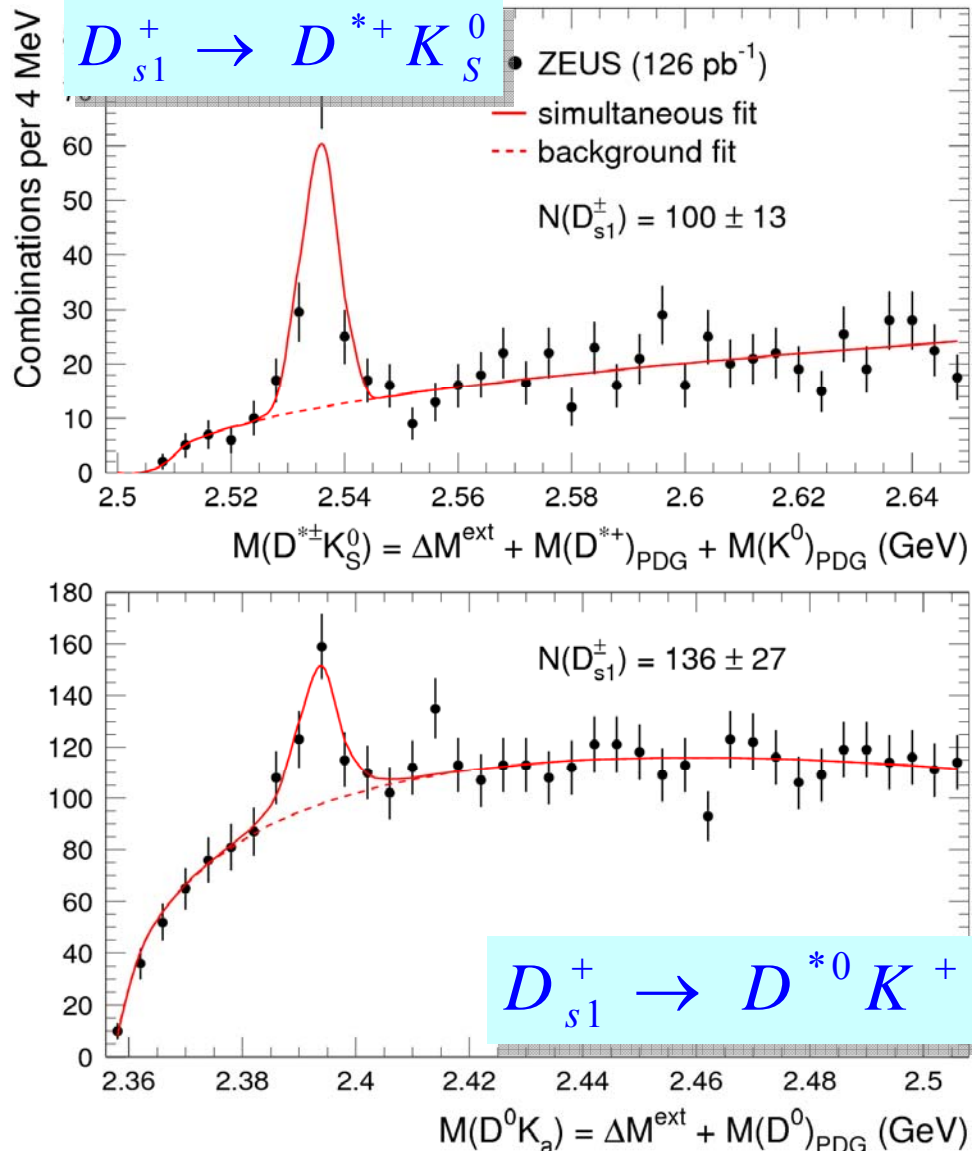


ZEUS DESY-08-093.

Charmed Strange Particles



Observed orbitally excited (cs) mesons D_{s1}^+ (2536)



ZEUS measured:

100 ± 13 events in $D_{s1}^+ \rightarrow D^{*+} K_S^0$

136 ± 27 events in $D_{s1}^+ \rightarrow D^{*0} K^+$

Fits for helicity parameter between K_S^0 and π_s in D^* rf $dN \sim (1+h \cos^2\theta)$ gives

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

$h \neq 0$ suggests mixture of two 1^+ states, eg. D+S waves to the $D_{s1}(2536)^+ \rightarrow D^{*+} K_S^0$

→ this is consistent

* with Belle value and CLEO range

* not with $h=3$ for pure D 1^+ state

* not really with $h=0$, for pure S 1^+

ZEUS DESY-08-093.

Excited Charmed Mesons



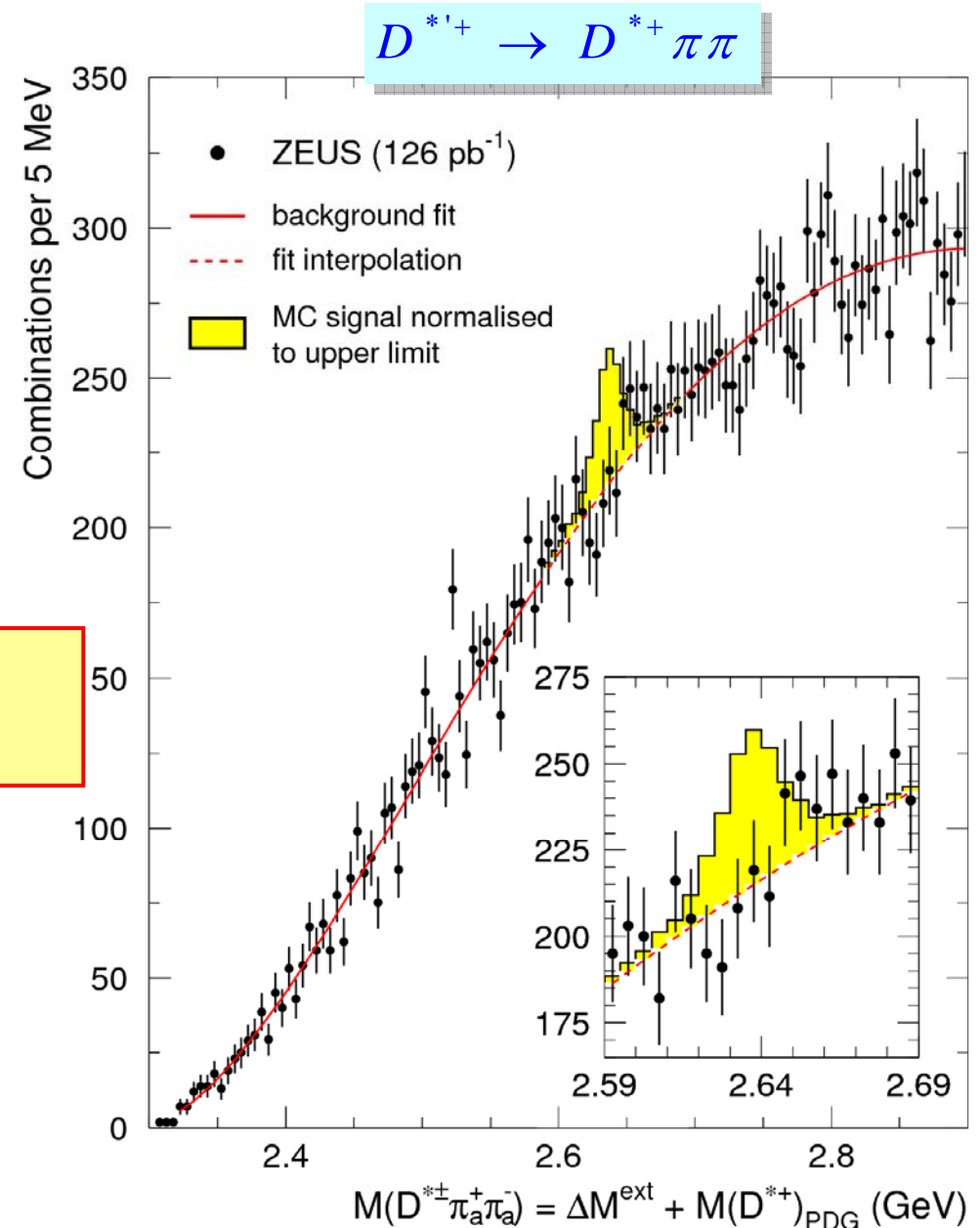
- NO signal seen in search for **radially excited**

$$D^{*'}(2640) \rightarrow D^{*+} \pi^- \pi^+$$

→ best upper limit on f^*Br

in $2.59 < M < 2.69$ GeV

$$f(c \rightarrow D^{*'}) \cdot B(D^{*'} \rightarrow D^* \pi \pi) < 0.4\% \text{ (95\% CL)}$$



ZEUS DESY-08-093.

Excited Charm (ref)



ZEUS DESY-08-093.

	Mass (Mev)
$D_1(2420)^0$	$2420.5 \pm 2.1(stat) \pm 0.9(syst) \pm .2(PDG)$
$D_2^*(2460)^0$	$2469.1 \pm 3.7(stat)_{-1.3}^{+1.2}(syst) \pm .2(PDG)$
$D_{s1}(2536)^+$	$2535.57_{-0.41}^{+0.44}(stat) \pm 0.1(syst) \pm 0.17(PDG)$

consistent with
PDG values

	Fragmentation fraction%
$f(c \rightarrow D_1(2420)^0)$	$3.5 \pm 0.4_{-0.6}^{+0.4}$
$f(c \rightarrow D_2^*(2460)^0)$	$3.8 \pm 0.7_{-0.6}^{+0.5}$
$f(c \rightarrow D_{s1}(2536)^+)$	$1.11 \pm 0.16_{-0.10}^{+0.08}$
$f(c \rightarrow D^{*++}) \times Br$	$<0.4\% \text{ at } 95\% \text{ C.L.}$

consistent with
 e^+e^- values

best limit to date

- Width: $\Gamma(D_1^0) = 53.2 \pm 7.2(stat)_{-4.9}^{+3.3}(syst)$

larger than world average

- Ratios: $BR(D_2^{*0} \rightarrow D^+ \pi^- / D^{*+} \pi^-) = 2.8 \pm 0.8(stat)_{-0.6}^{+0.5}(syst)$
 $BR(D_{s1}^+ \rightarrow D^{*0} K^+ / D^{*+} K^0) = 2.3 \pm 0.6(stat) \pm 0.3(syst)$

consistent with
PDG values

- Helicity par: $h(D_1^0) = +5.9_{-1.7}^{+3.0}(stat)_{-1.0}^{+2.4}(sys)$
 $h(D_{s1}^+) = -0.74_{-0.17}^{+0.23}(stat)_{-0.05}^{+0.06}(sys)$

consistent with pure D-wave (h=3)

inconsistent with pure S-wave (h=0)

Baryon Production

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

ZEUS Collab., DESY 07-070 (120 pb⁻¹)

- To better understand production, and test **coalescence model** prediction:

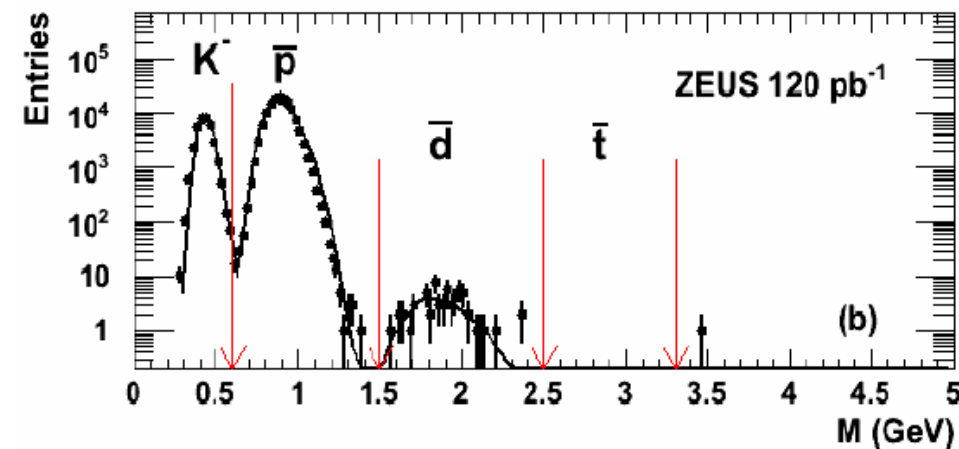
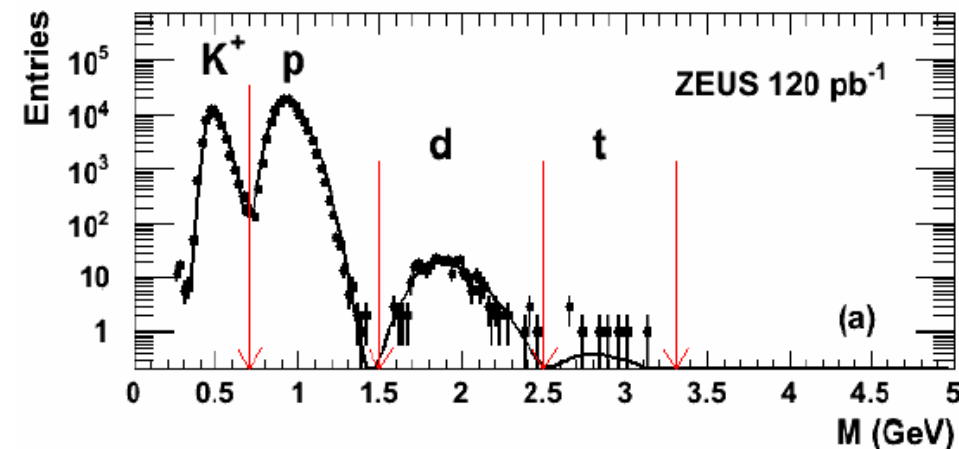
$$d\sigma_d \propto (d\sigma_p \cdot d\sigma_n) \propto (d\sigma_p)^2$$

- Expect coalescence parameter B2 (nucleon overlap) to be equal for particle and antiparticle, and

- 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

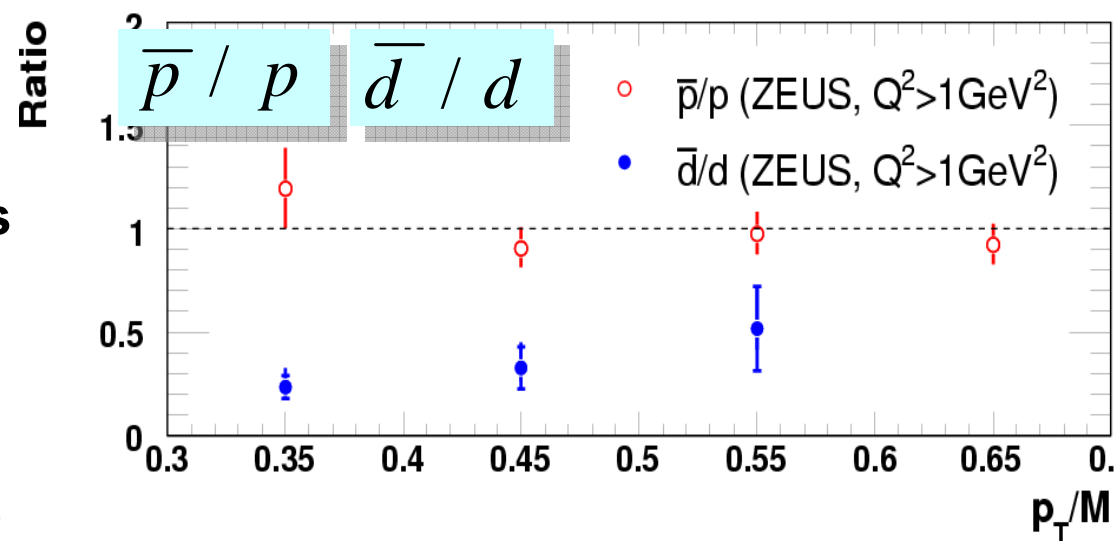
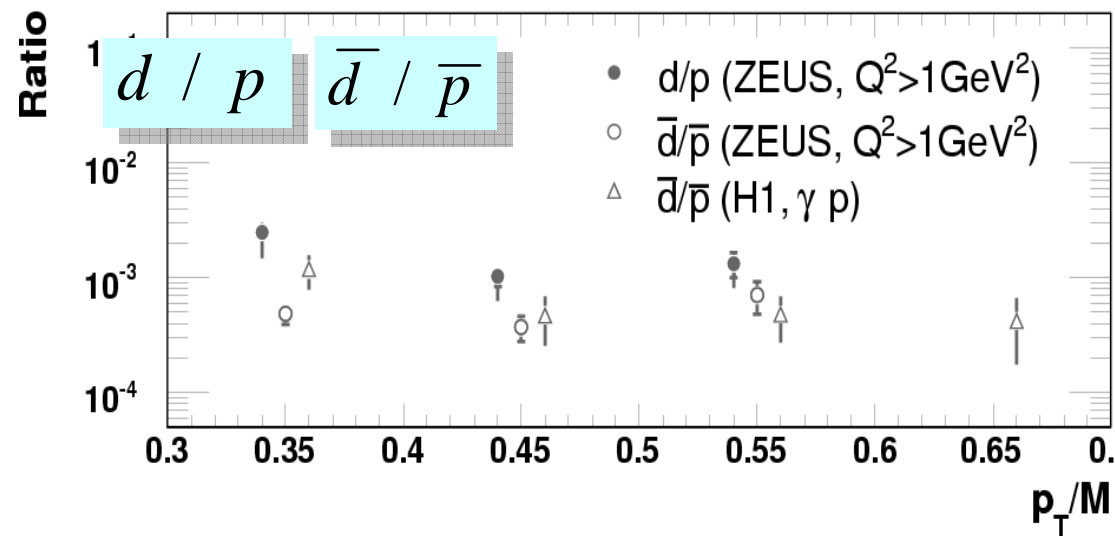


Good separation, based on p and dE/dx

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

Results:

- Proton and Anti-p yields are $\sim 1000 \times$ larger than d and anti-d
- anti-d / anti-p ratio :
ZEUS and H1 are consistent
- anti-p/p ratio is consistent with unity;
thus expect (anti-d / d) also ~ 1
 \rightarrow NOT seen
- But: no sensitivity to model predictions
at the necessary $<10\%$ level
- Q: are there more d than anti-d ?
- Is the coalescence parameter
different for particle and anti-particles?
 \rightarrow need confirmation



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

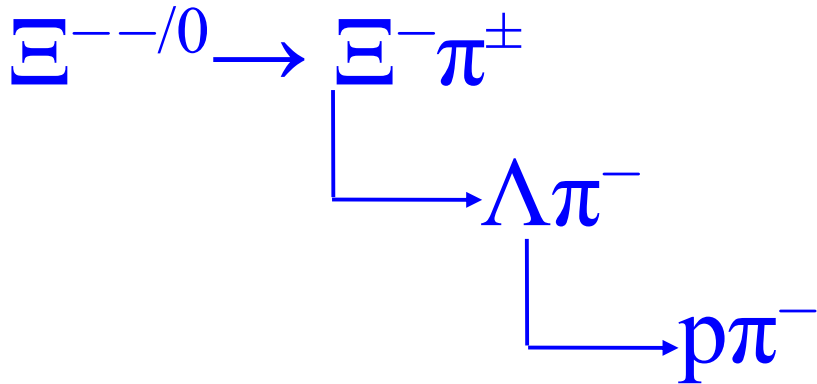
H1 Collab., EPJ C36 (2004) 213 (5.5 pb $^{-1}$)

Baryonic States decaying to $\Xi\pi$

Pentaquark candidate ?

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

Remember the NA49 “ 4σ hint” at mass 1862 MeV ...



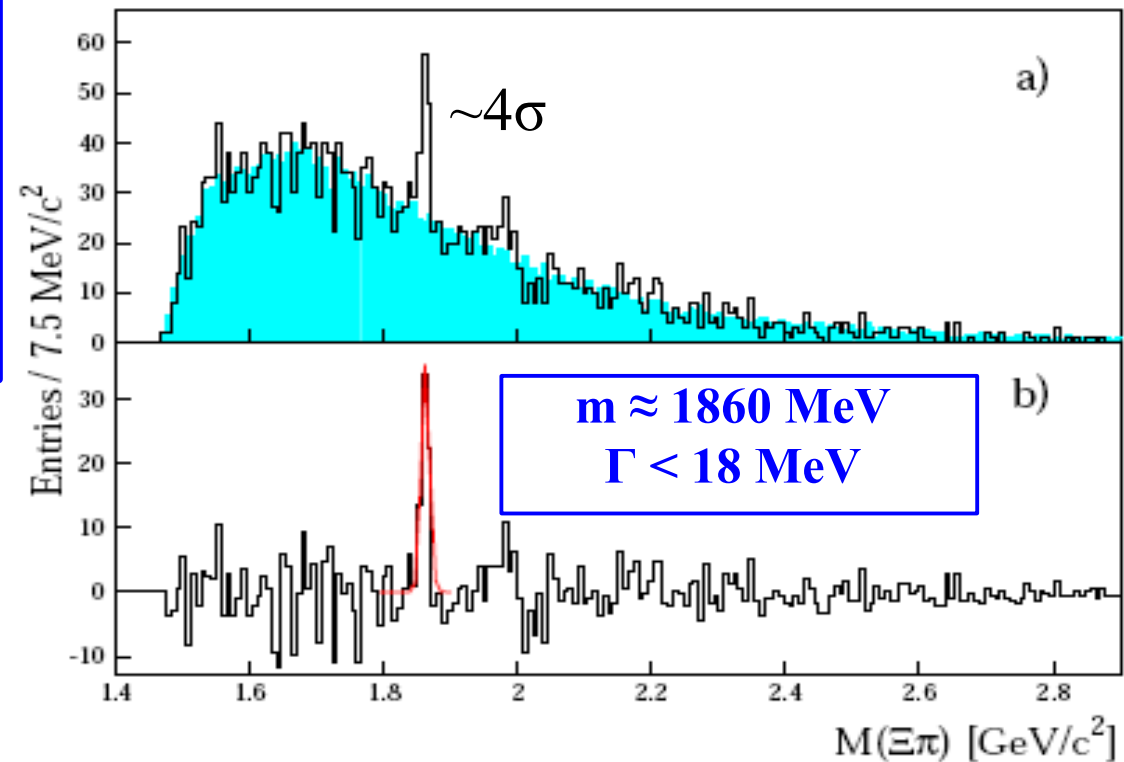
→ **H1+ZEUS** searched for doubly charged and neutral states

Ξ_{5q}^{--} and Ξ_{5q}^0
produced in DIS

H1:EPJ C52 (2007) 507

ZEUS: PL B610 (2005)

NA49 Collab., PRL 92 (2004)



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

Baryonic States decaying $\rightarrow \Xi\pi$ in DIS

All upper limits relative to Ξ^0 (1530)

H1:EPJ C52 (2007) 507

ZEUS: PL B610 (2005)

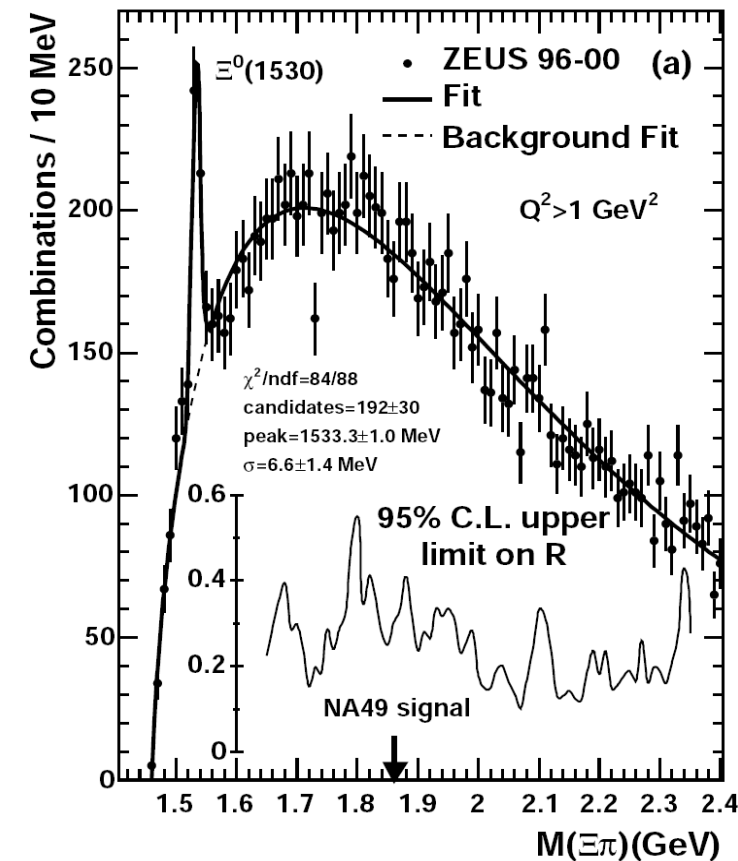
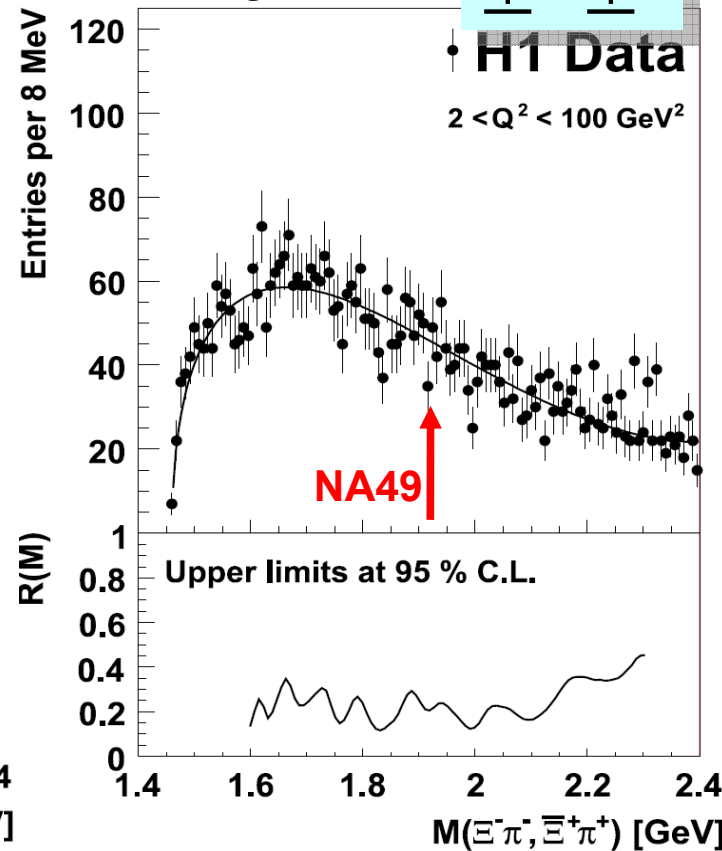
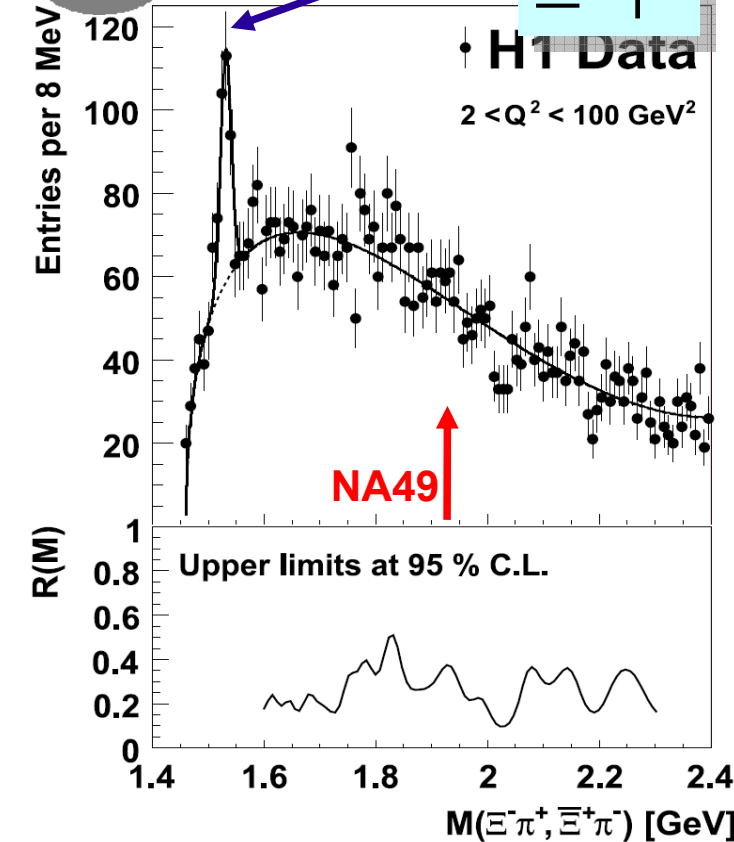


neutral comb $\pm \mp$

charged comb $\pm \pm$

$\Xi \pi$

all comb.



- NA49 observation at 1862 MeV not confirmed
- H1+ZEUS: Search for Ξ_{5q}^- and Ξ_{5q}^0 decaying to $\Xi\pi$

No evidence seen for any exotic 5q state in $\Xi\pi$

• Strange particle production

- K_S , Λ , Λ/K_S ratios: Zeus and H1 data agree 😊
CDM describes overall features well with $\lambda_S=0.3$ (ALEPH tune); differences seen in details
- K^* production : supports K_S , Λ messages
- $K^\pm K^\pm$ Bose-Einstein Correlations clearly observed;
source radius $r \sim 0.6$ consistent with e^+e^- data, and charged particles

• Glueball candidate in $K_S K_S$ resonance 😊

- Clear evidence for $f'_2(1525)$ and $f_0(1710)$ resonance state :
- interference fit yields (m, Γ) , consistent with PDG

• Charmed particle production: 😊

- orbital excited D-mesons measured (D^0_1 , D^{*0}_2 , D^{+}_{S1}):
masses in agreement with PDG; radial excited state D^{*+} not seen.

• Baryon production:

- d (+anti- d) production $\sim 1/1000$ of p (+anti- p) production; $p/\text{anti-}p$ is \sim unity.
- more d than anti- d ? is coalescence parameter not universal ?

➔ **HERA provides a wealth of complementary information ...**

Backup slides

K_s^0 and Λ Production in DIS

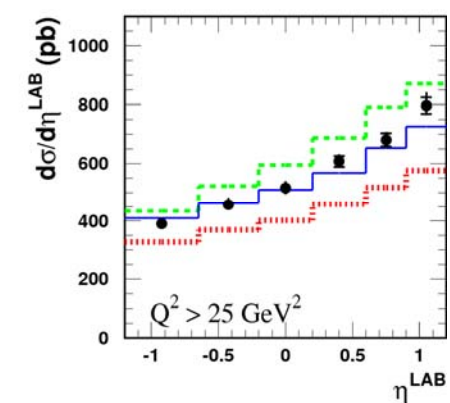
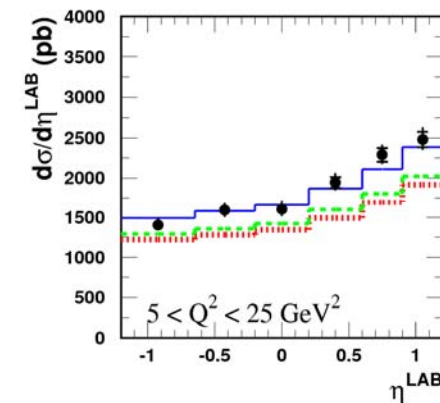
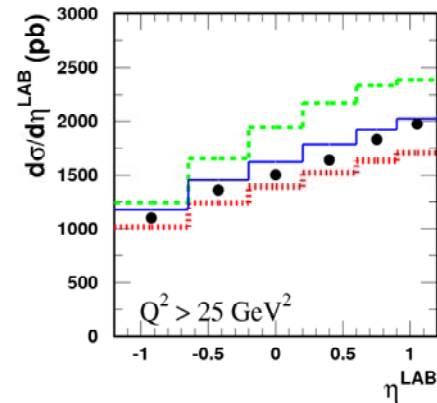
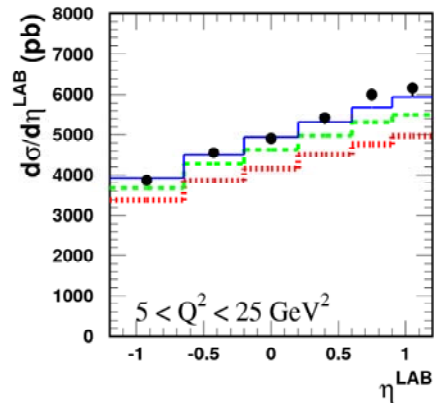
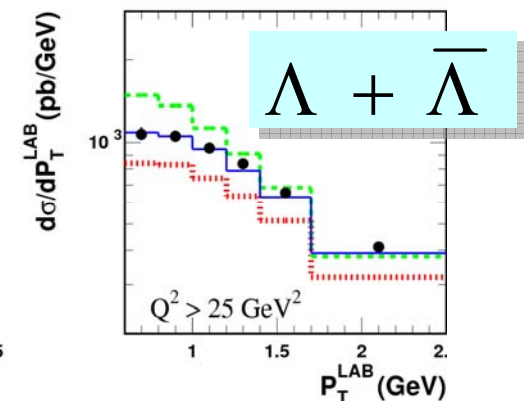
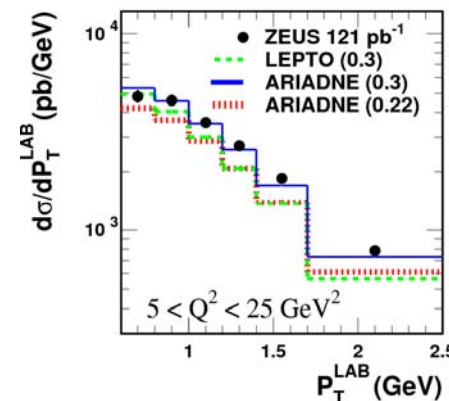
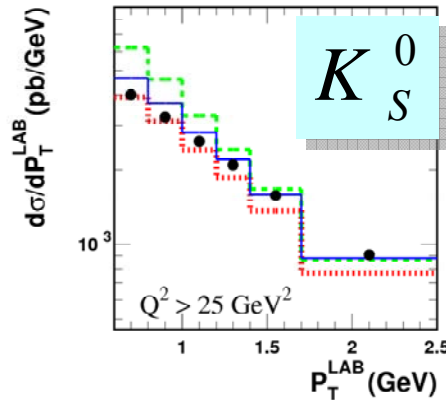
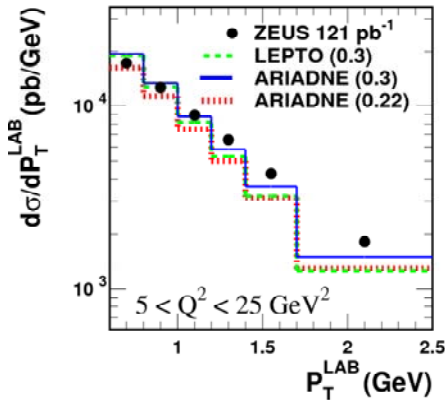
K_s^0 and Λ production cross sections in p_T^{lab} and η^{lab} (121 pb^{-1})

$5 < Q^2 < 25 \text{ GeV}^2$

$Q^2 > 25 \text{ GeV}^2$

$5 < Q^2 < 25 \text{ GeV}^2$

$Q^2 > 25 \text{ GeV}^2$

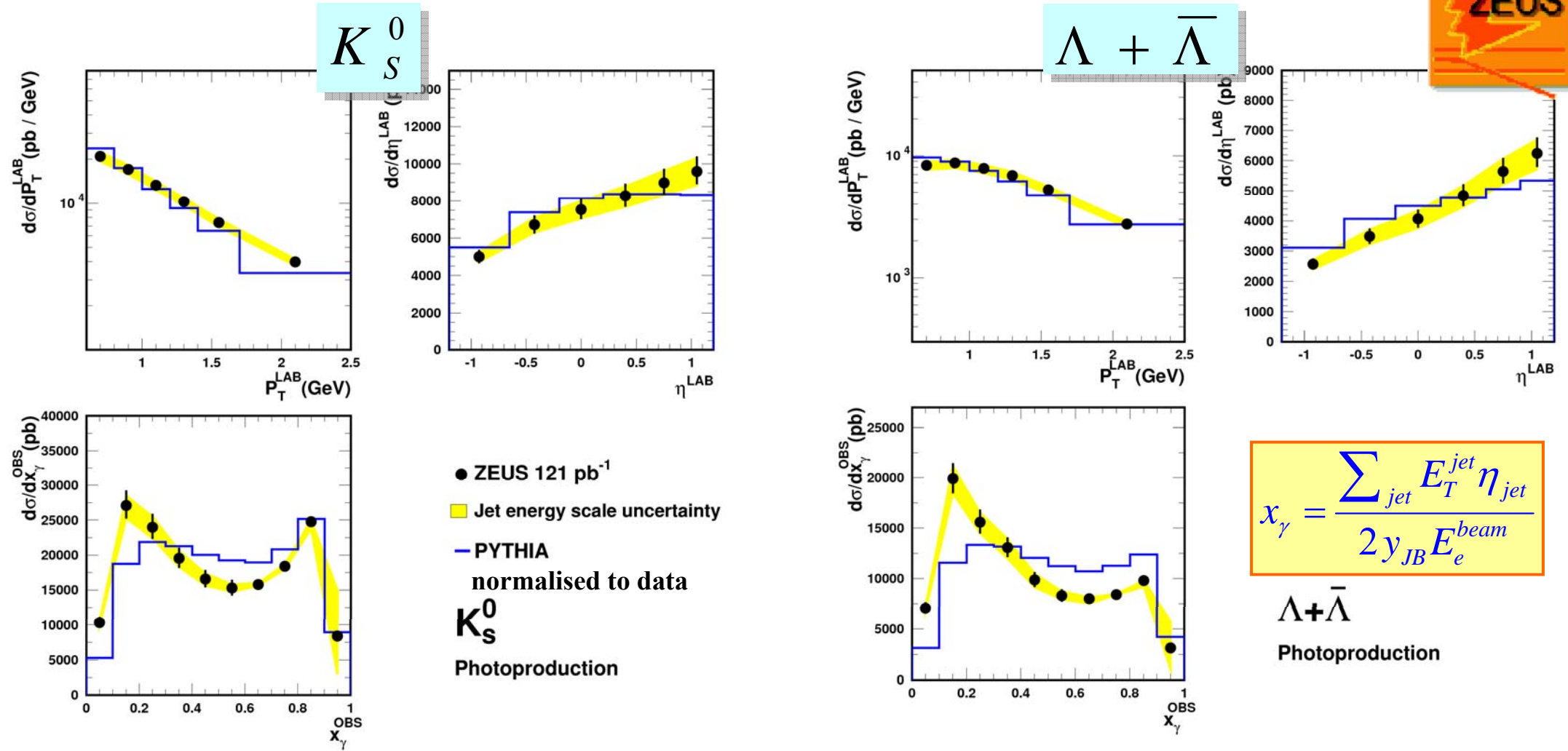


- **ARIADNE describes data overall with $\lambda_s=0.3$.
discrepancies in details: K_s at high Q^2 , low x_{Bj} , p_T -slope**

ZEUS Collab., EPJ C51 (2007) 1

K_S^0 and Λ Production in γP

Photoproduction ($Q^2 \approx 0 \text{ GeV}^2$) : **require 2 jets** ($E_T > 5 \text{ GeV}$; $|\eta| < 2.4$)



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

ZEUS Collab., EPJ C51 (2007) 1

K_s^0 Production in DIS and γp : H1 and ZEUS

Cross sections in p_T^{lab} and η^{lab}

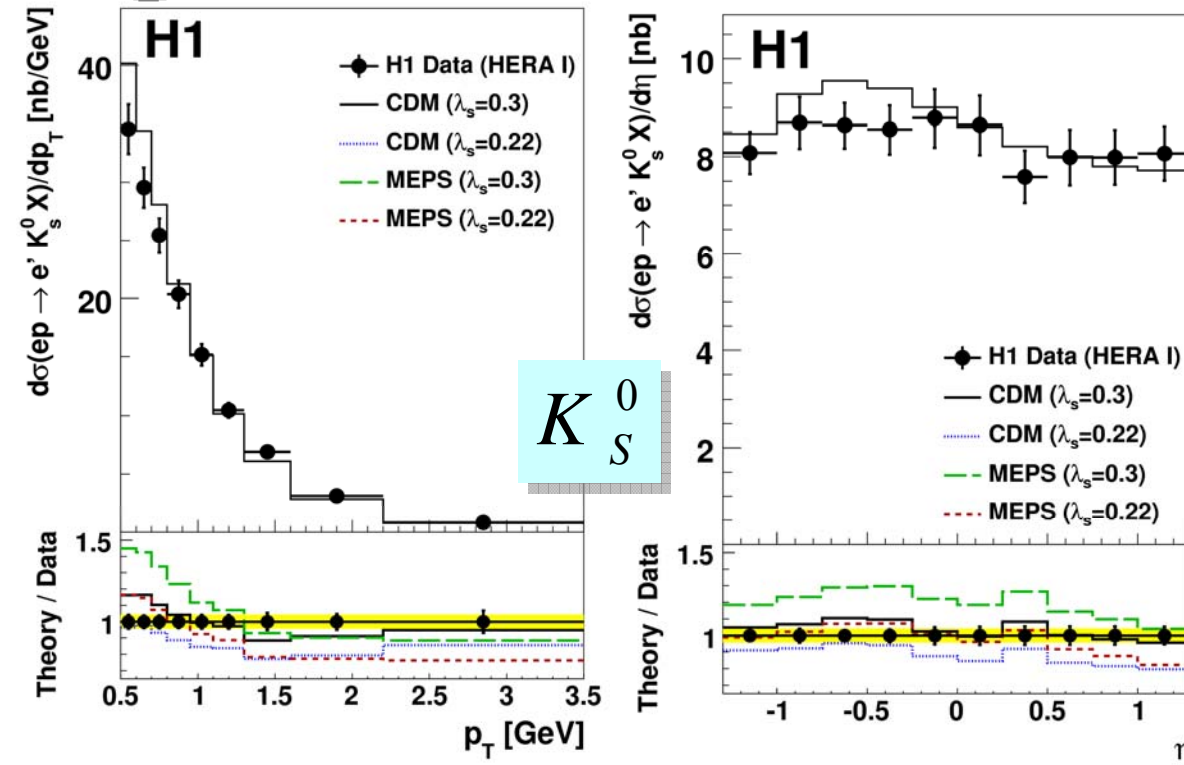
ZEUS Collab., EPJ C51 (2007) 1



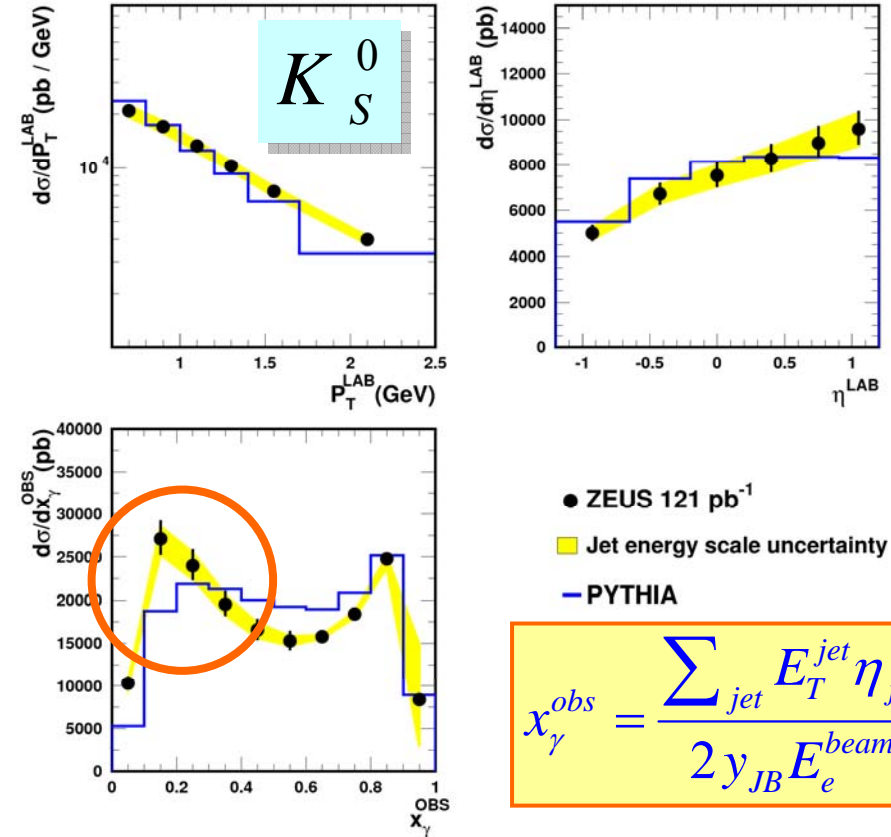
$2 < Q^2 < 100 \text{ GeV}^2$



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



H1: Prelim. 2008; submitted to EPJ



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

→ ARIADNE CDM overall agrees for $\lambda_s=0.3$; discrepancies in details: e.g. p_T -slope.

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

K_s^0 and Λ Production (opt)

- Production Mechanisms:
 - direct from proton PDG
 - via boson gluon fusion
 - by perturbative gluon splitting $g \rightarrow ss$
 - by non-perturbative string fragmentation
- strangeness suppression factor (γ_s) set to 0.3 (default)
- diquark-anti-diquark suppression = 0.1
- s-diquark/ s-quark suppression = 0.4
- spin-1 / spin-0 diquark suppression = 0.05
- PDF: CTEQ in DIS; GRV and SaS2D for photoproduction
- Monte Carlo : Ariadne (CDM), Lepto (MEPS in DIS), Pythia (MEPS, γp),
in general using the ALEPH tune



Pentaquarks – Reminder (opt)

Existence of **pentaquark states** within different theoretical approaches

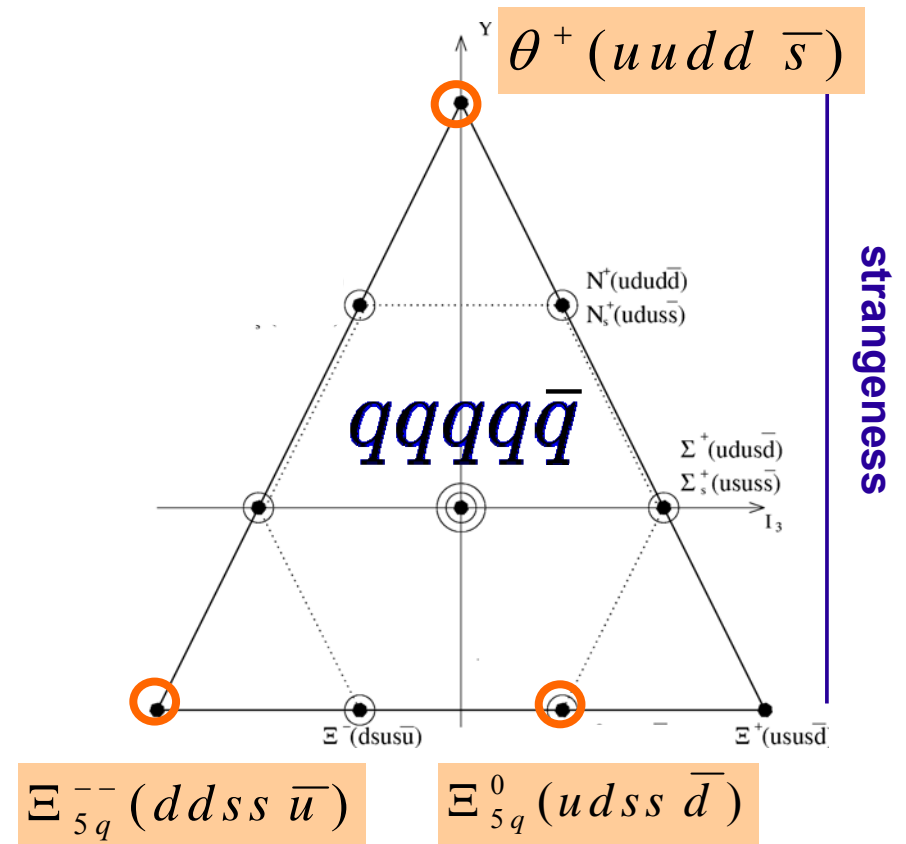
eg. Chiral Quark Soliton Model (D.Diakonov et al.) predicts an antidecuplet of pentaquarks:

- 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

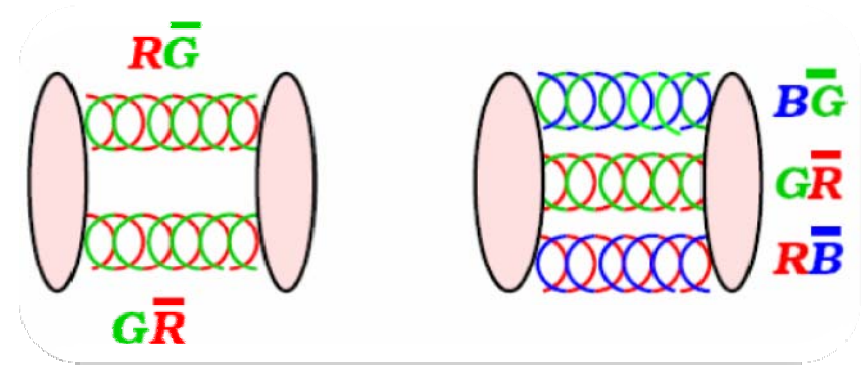
Glueballs in $K^0_s K^0_s$ Resonances ? (ref)

The $K^0_s K^0_s$ system is expected to couple to scalar and tensor glueballs

K^0_s : has $S=0$, $P=-1$, $C=+1$

$K^0_s K^0_s$: has $P=+1$, $C=+1 \rightarrow J = \text{even}$

$K^0_s K^0_s$ bound states $\rightarrow J^{PC}$: 0^{++} (scalar), 2^{++} (tensor) ...



● Lattice QCD predicts: Lightest glueball candidates:

→ $J^{PC} = 0^{++} \rightarrow \text{mass } 1730 \pm 100 \text{ MeV.}$

→ $J^{PC} = 2^{++} \rightarrow \text{mass } 2400 \pm 120 \text{ MeV.}$

● Experimentally, four states with $J^{PC} = 0^{++}$ and $I=0$ are established (PDG)

$f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$

$$P = (-1)^{(L+1)}$$

Parity

$$C = (-1)^{(L+S)}$$

Charge Conjugation

$$J = L \oplus S$$

J: Total Angular Momentum

L: Orbital Angular Momentum

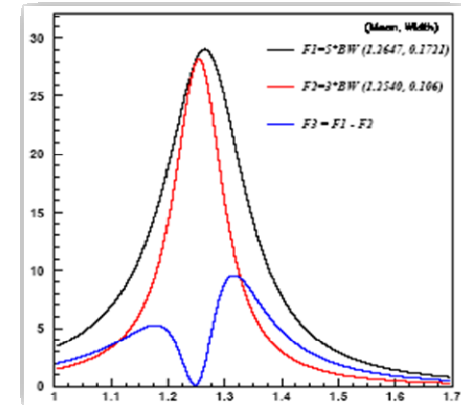
S: Total Spin ($q\bar{q} \Rightarrow 0, 1$)

● Question:
what's the mixing fraction of mesons and glueballs?

● Hybrids? Tetraquarks ? ...

Fitting: use Breit-Wigner with interference

Destructive interference



	Coherent States		
	$f_2(1270)$	$a_2(1320)$	$f_2(1525)$
Isospin I =	0	1	0
Quark Content	$(u\bar{u} + d\bar{d})/\sqrt{2}$	$(u\bar{u} - d\bar{d})/\sqrt{2}$	$s\bar{s}$
Charge Factor	$(\frac{2}{3} \times \frac{2}{3} + \frac{1}{3} \times \frac{1}{3})\frac{1}{2}$	$(\frac{2}{3} \times \frac{2}{3} - \frac{1}{3} \times \frac{1}{3})\frac{1}{2}$	$\frac{1}{3} \times \frac{1}{3}$
Amplitude ratio	5 BW	-3 BW	2 BW

$$\begin{aligned} \text{Function} = & a \{5 * \text{BW}_{f_2}(1270) - 3 * \text{BW}_{a_2}(1320) + 2 * \text{BW}_{f_2}(1525)\}^2 \\ & + b \{\text{BW}_{f_0}(1710)\}^2 \\ & + c \text{ Background } U(M) \end{aligned}$$

a b c are free parameters

BW is Relativistic Breit-Wigner function:

$$F(M) = \frac{m\sqrt{\Gamma}}{m^2 - M^2 - im\Gamma}$$

Faiman, D. and Lipkin, H. J. and Rubinstein, H. R., Phys. Lett. B59, 269 (1975)

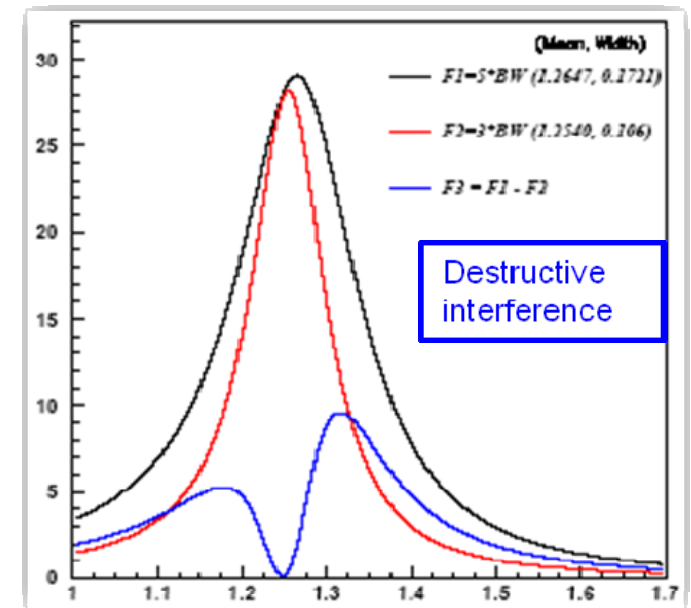
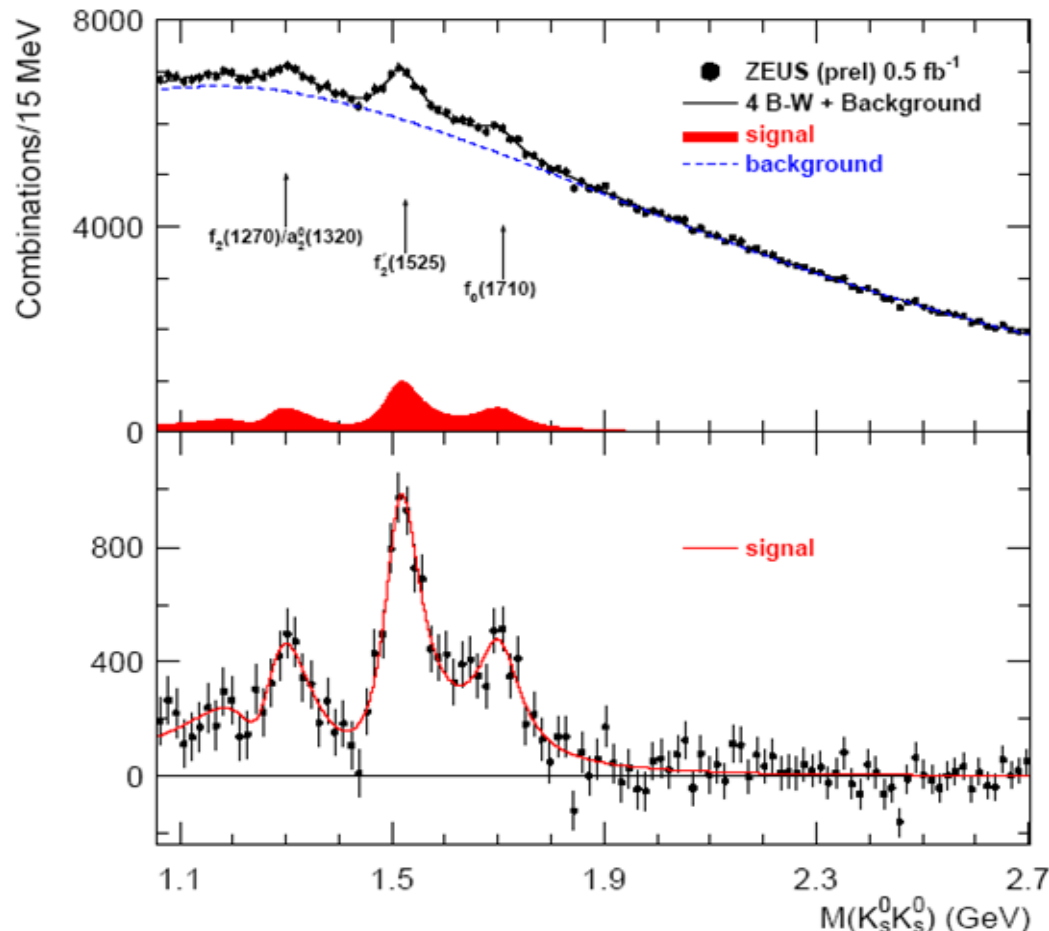
Fitting functions

➤ Modified Relativistic Breit-Wigner (MRBW) function $F(M)$ + BGRND $U(M)$:

$$F(M) = \sum_{i=1}^3 C_i \left(\frac{m_{*,i} \Gamma_{d,i}}{(m_{*,i}^2 - M^2)^2 + m_{*,i}^2 \Gamma_{d,i}^2} \right)$$

$$U(M) = A \cdot (M - 2m_{K_S^0})^B \cdot \exp \left(-C(M - 2m_{K_S^0}) \right)$$

- C_i is the amplitude of the resonance
- $m_{*,i}$ is the mass of resonance
- $\Gamma_{d,i}$ is the effective resonance width
- M is the $K_S^0 K_S^0$ invariant mass



$\chi^2/\text{ndf} =$
86/110

Improved fitting in 1270 and 1420 region,
where destructive and constructive
interference are well described.

Structures in $K_S^0 K_S^0$ Resonances

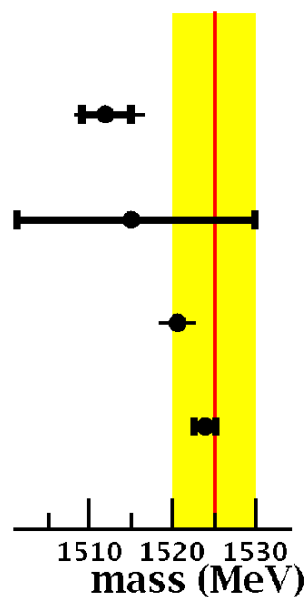
Fit	No interference		Interference		PDG 2007 Values	
χ^2/ndf	96/95		86/97			
in MeV	Mass	Width	Mass	Width	Mass	Width
$f_2(1270)$	1304 ± 6	61 ± 11	1268 ± 10	176 ± 17	1275.4 ± 1.1	$185.2^{+3.1}_{-2.5}$
$a_2^0(1320)$			1257 ± 9	114 ± 14	1318.3 ± 0.6	107 ± 5
$f_2'(1525)$	$1523 \pm 3^{+2}_{-8}$	$71 \pm 5^{+17}_{-2}$	$1512 \pm 3^{+1.4}_{-0.5}$	$83 \pm 9^{+5}_{-4}$	1525 ± 5	73^{+6}_{-5}
$f_0(1710)$	$1692 \pm 6^{+9}_{-3}$	$125 \pm 12^{+19}_{-32}$	$1701 \pm 5^{+9}_{-2}$	$100 \pm 24^{+7}_{-22}$	1724 ± 7	137 ± 8

Table 1: *The measured masses and widths for the $f_2(1270)$, $a_2^0(1320)$, $f_2'(1525)$ and $f_0(1710)$ states using $K_S^0 K_S^0$ decays as determined by one fit neglecting interference and another one with interference as predicted by $SU(3)$ symmetry arguments*

- Masses of $f_2'(1525)$ and $f_0(1710)$ found bit low, but widths consistent with PDG
- $f_0(1710)$ mass, seen at 5 sigma, is consistent with $J^{PC}=0^{++}$ glueball candidate

Summary $f_2(1525)$ and $f_0(1710)$ states

$f_2(1525)$



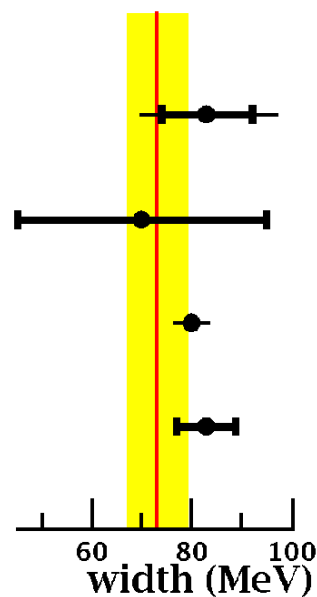
e p ZEUS

Central p p Production

e^+e^- experiments

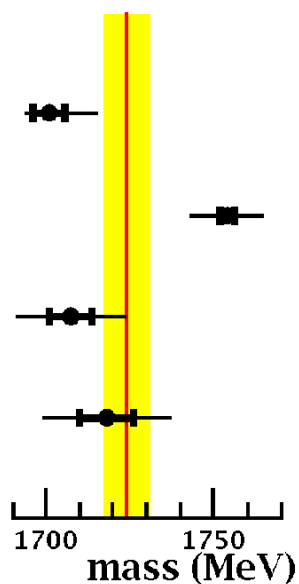
K-meson experiments

■ PDG 2007



← ZEUS low mass

$f_0(1710)$



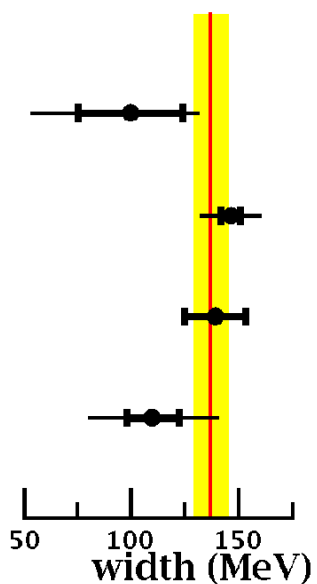
e p ZEUS

e^+e^- BES Collab.

e^+e^- other Collab.

p p, π p experiments

■ PDG 2007



← ZEUS low mass

← BES high

K* (892) Production in DIS



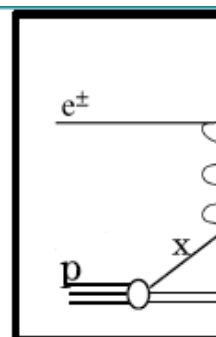
DATA 05&06&07 ($L = 301 \text{ pb}^{-1}$)
DST5 with 3.3.6 h100 version used
Electron Sigma Method used

Kinematic Cuts

- $5 < Q_e^2 < 100 \text{ GeV}^2$
- $0.1 < y_{e\Sigma} < 0.6$
- Scattered electron selection
 - $E_e > 11 \text{ GeV}$
 - $156^\circ < \theta_e < 173^\circ$
 - SPACAL fiducial cuts applied

Technical Cuts

- S61 Trigger
 - electron ($E_e > 6 \text{ GeV}$) SpaCal
 - at least 1 high momentum track candidate
- $35 < E - P_z < 70 \text{ GeV}$
- $-35 < z_{\text{vtx}} < 35 \text{ cm}$
- Scattered electron selection
- $E_{\text{had}} < 0.5 \text{ GeV}$, $R_\theta > 12 \text{ cm}$, $R_{\text{cluster}} < 4 \text{ cm}$



K_s⁰ Selection

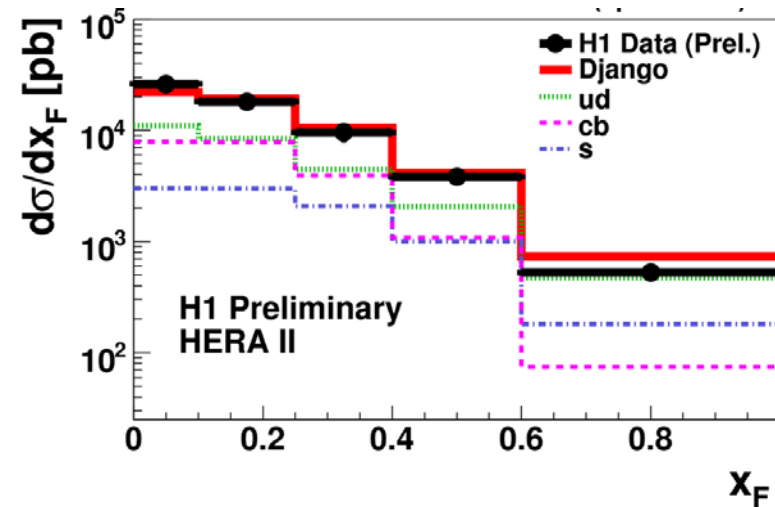
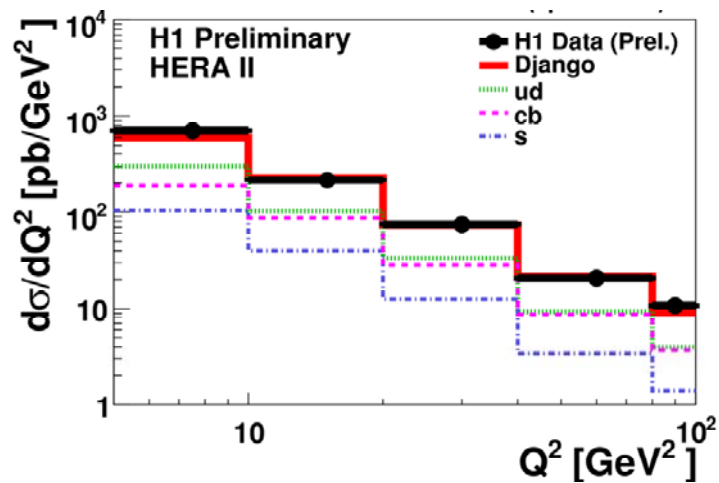
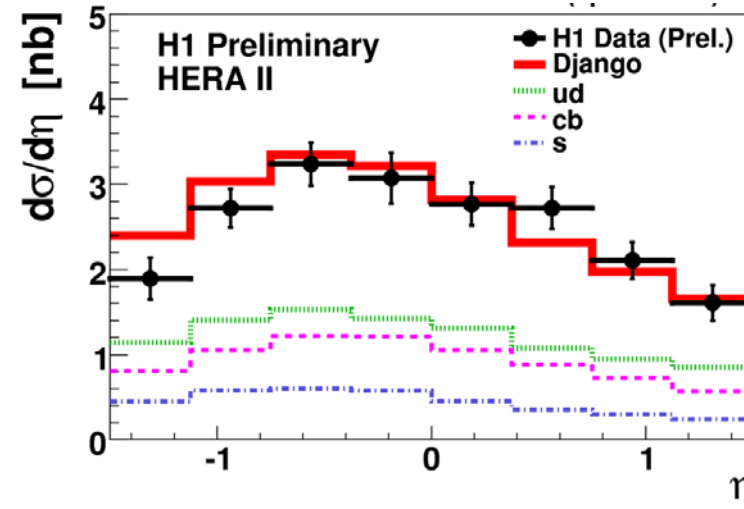
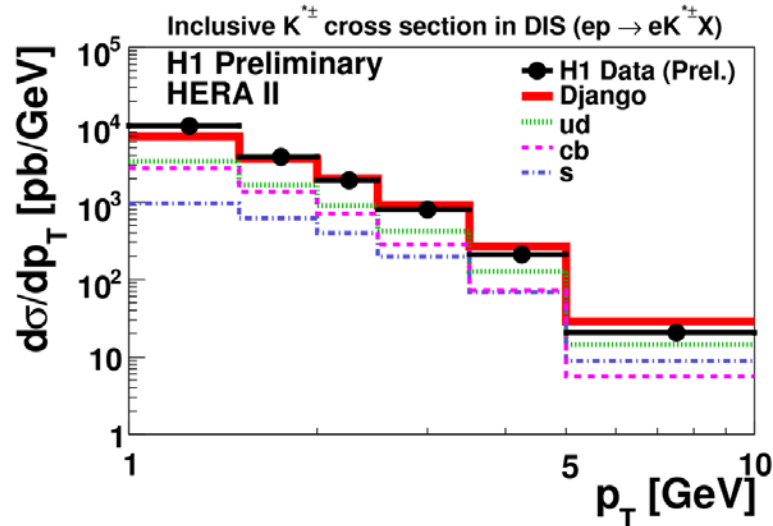
- Use h100 K0-Finder
- Pairs of oppositely charged secondary c
- $p_T > 0.12 \text{ GeV}/c$, $|\eta| < 1.5$
- Λ (cut on $(M_{p\pi} - 1.115) < 0.012 \text{ GeV}$)
- γ conversion cut on $M_{e^+e^-} > 0.05 \text{ GeV}$
- $p_{T(\pi\pi)} > 0.5 \text{ GeV}$
- Armenteros $p_\perp > 0.11 \text{ GeV}$
- $|\cos(\theta^*)| < 0.95$
- $\chi^2 < 5.4$
- $\Delta(\text{dca}) > 0.5$
- Radial decay length $> 2 \text{ cm}$
- $0.470 < M_{K0s} < 0.520 \text{ GeV}$

K* (892) Production: Quark contributions (opt)

H1 Collab., Prelim 2008

$$K^{*\pm} \rightarrow K_S^0 \pi^\pm$$

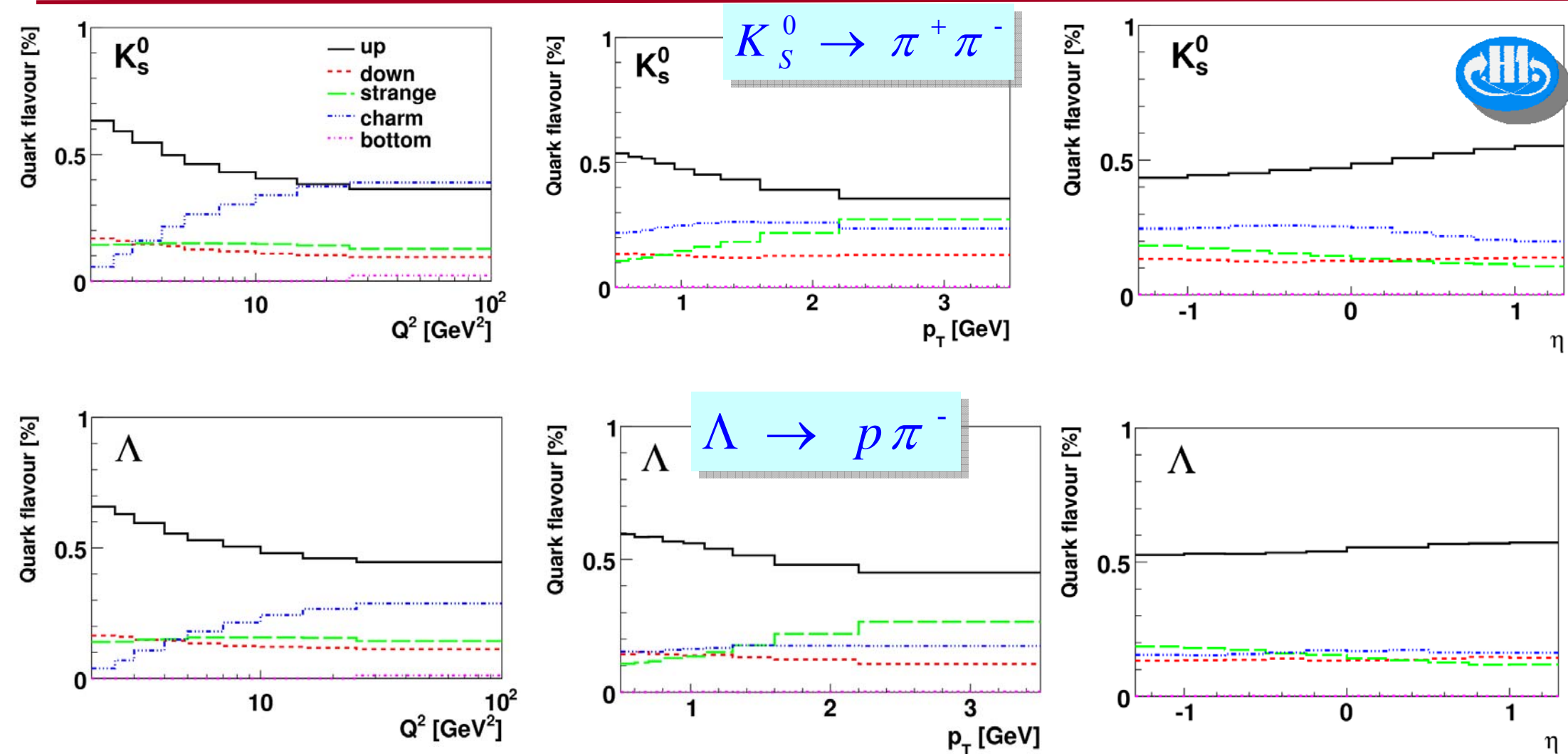
Inclusive cross sections



$$x_F = \frac{2P_L}{W}$$

● **quark contributions:** at low scales: u,d dominate; at large scales, charm and light quarks become equivalent → difficult to extract s-content of proton

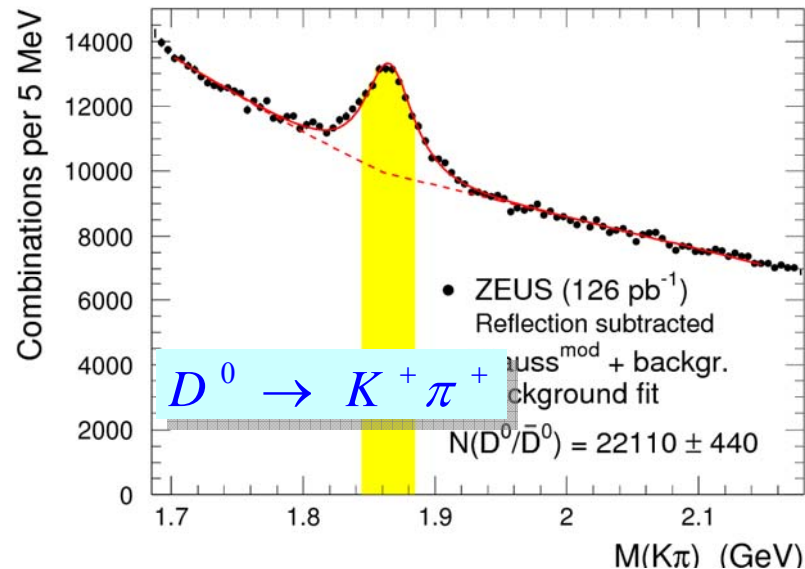
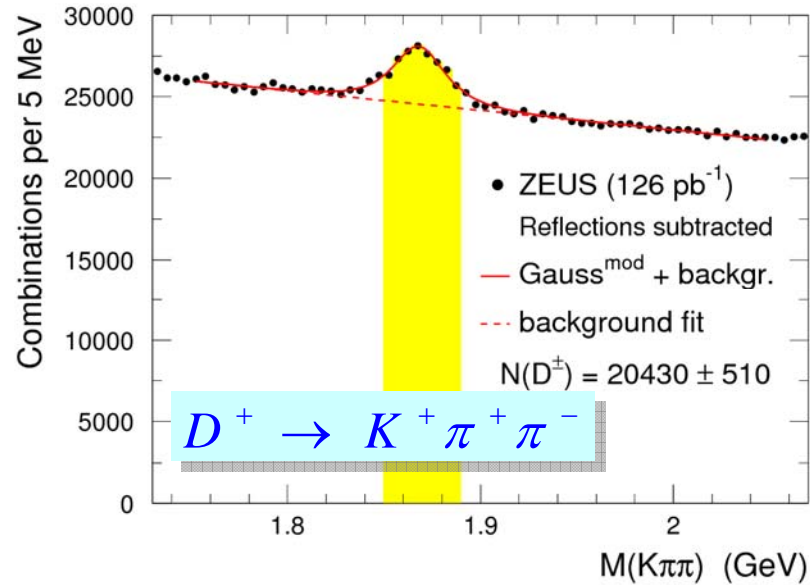
K_S , Λ Production: Quark contributions (opt)



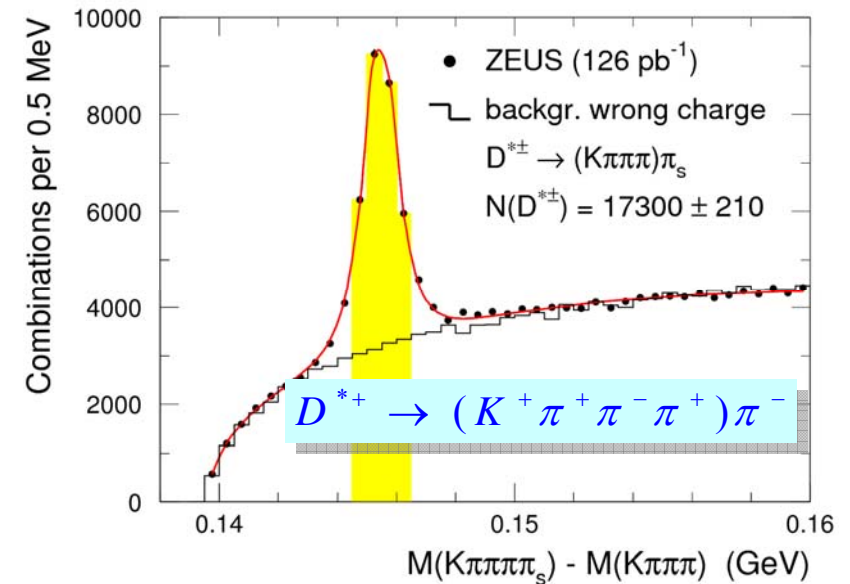
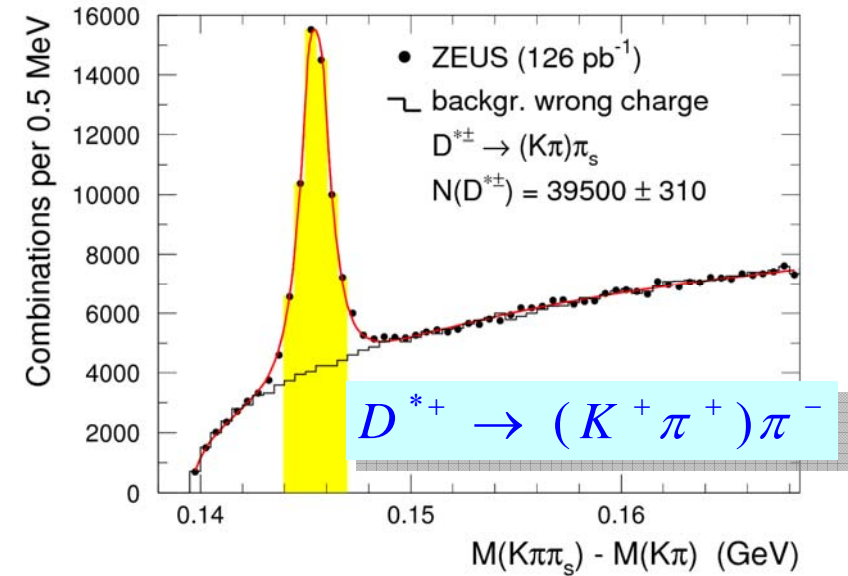
● **quark contributions:** at low scales: u,d dominate; at large scales, charm and light quarks become equivalent → difficult to extract s-content of proton

Excited Charmed Mesons (opt)

Signals used: $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^0 \rightarrow K^- \pi^+$



$D^{*+} \rightarrow (K^- \pi^+) \pi^+$ and $(K^- \pi^+ \pi^- \pi^+) \pi^+$



ZEUS DESY-08-093.

Excited Charmed Mesons (opt)



$\cos \phi$ vs $r = \Gamma_S/(\Gamma_S + \Gamma_D)$

- Cosine of relative phase of S- and D-wave amplitudes

ZEUS measured:

100 \pm 13 events in $D_{s1}^+ \rightarrow D^{*+} K_S^0$

Fits for helicity parameter between K_S^0 and π_S in D^* rf $dN \sim (1+h \cos^2\theta)$ gives

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

$h \neq 0$ suggests mixture of two 1^+ states, D+S waves, eg. $D_{s1}(2536)^+$ and $D_{s1}(2460)^+$

→ this is consistent

- * with Belle and CLEO values
- * not with $h=3$ for pure D 1^+ state
- * not really with $h=0$, for pure S 1^+

