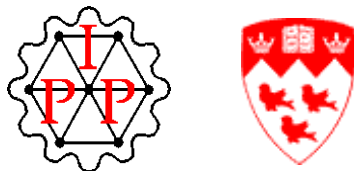


# Spectroscopy Results from HERA

François Corriveau, IPP/McGill



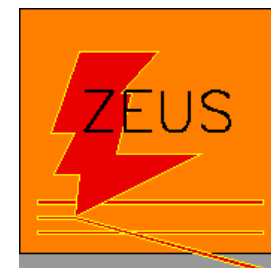
on behalf of the H1 and ZEUS Collaborations

*PhiPsi08 at Laboratori Nazionali di Frascati*

10 April 2008

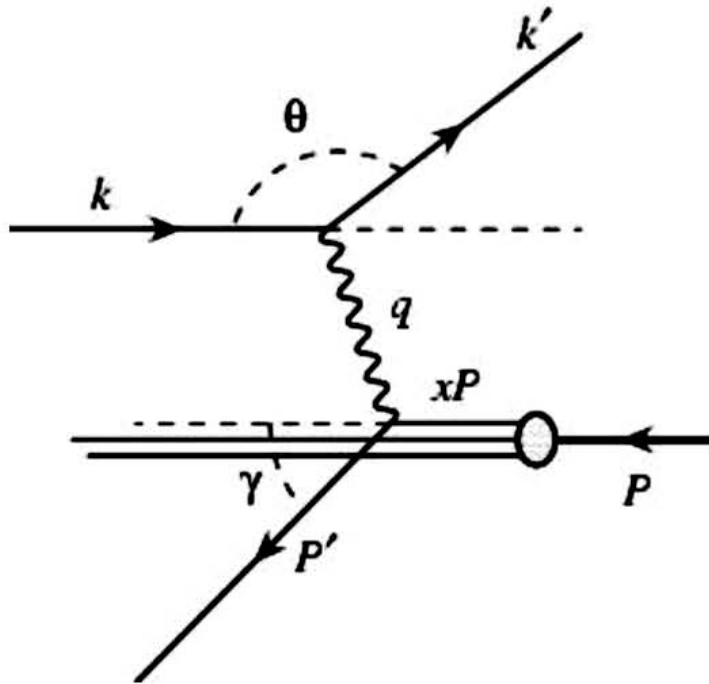


- **H1 and ZEUS at HERA**
- **Hadron production**
- **Tetraquark States ?**
- **Pentaquark States ?**
- **Outlook**



# $e^\pm p$ – Kinematics at HERA

27.6 GeV electrons/positrons on 920(820) GeV protons



## Deep Inelastic Scattering (DIS):

Neutral current (NC) via  $\gamma/Z^0$  exchange

Charged current (CC) via  $W^\pm$  exchange

**Photoproduction:**  $Q^2 \approx 0$

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

$$x = \frac{Q^2}{2p \cdot q} \quad y = \frac{p \cdot q}{p \cdot k}$$

$$s = (p + k)^2 \quad Q^2 = x \cdot y \cdot s$$

$Q^2$  = exchanged momentum (squared)

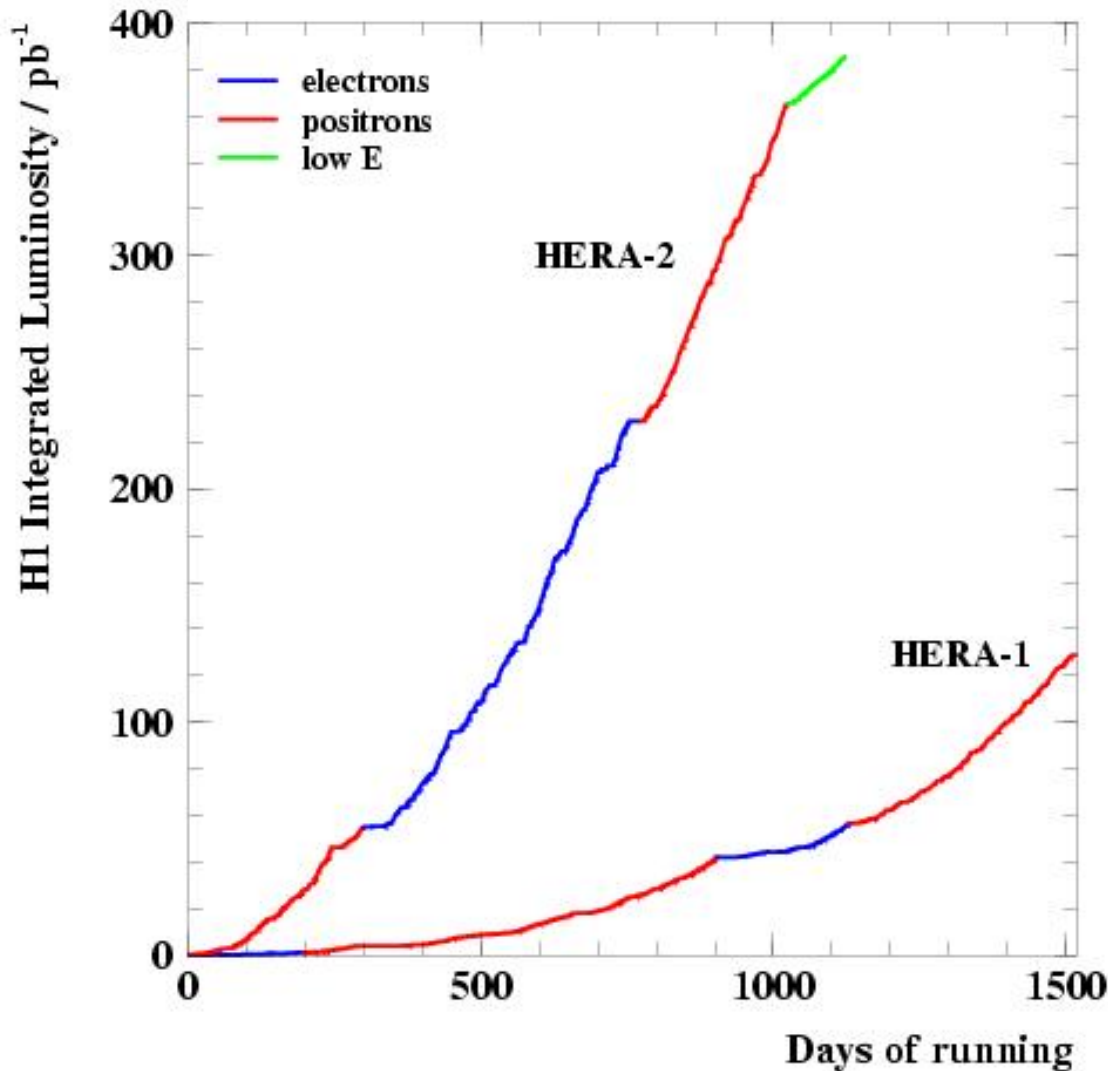
$x$  = Bjorken scaling variable

$y$  = inelasticity scaling variable

$\sqrt{s}$  = center of mass energy ( $\sim 320$  GeV)

$W$  = photon-proton center of mass energy

# HERA Luminosities



**HERA I:** unpolarised e<sup>±</sup> beams

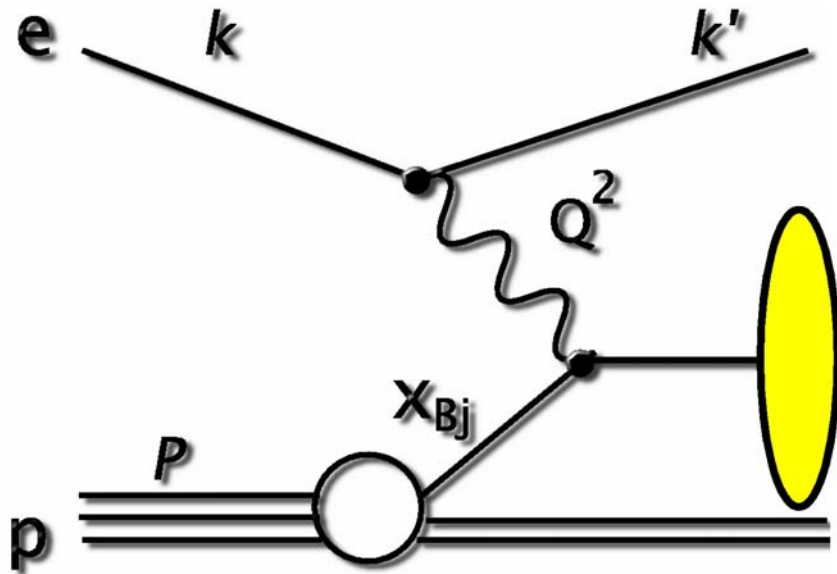
**HERA II:** polarised e<sup>±</sup> beams

Gated luminosities

e <sup>±</sup> p	H1	ZEUS
<b>HERA I</b>	128 pb <sup>-1</sup>	143 pb <sup>-1</sup>
<b>HERA II</b>	385 pb <sup>-1</sup>	407 pb <sup>-1</sup>

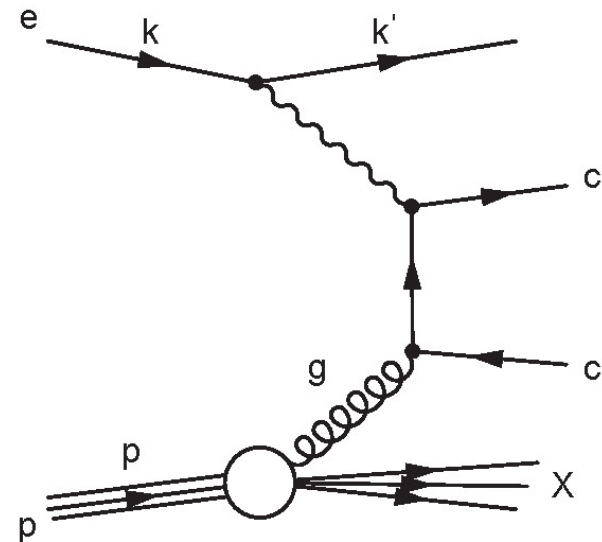
~ 0.5 fb<sup>-1</sup> per experiment

# Hadron Production at HERA



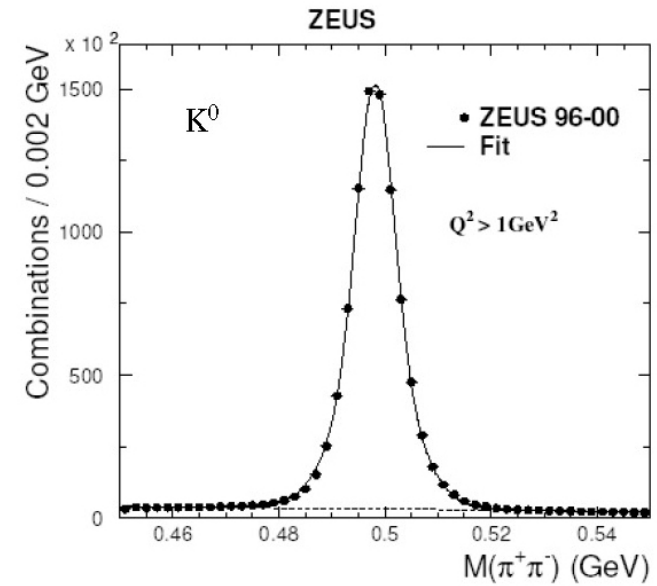
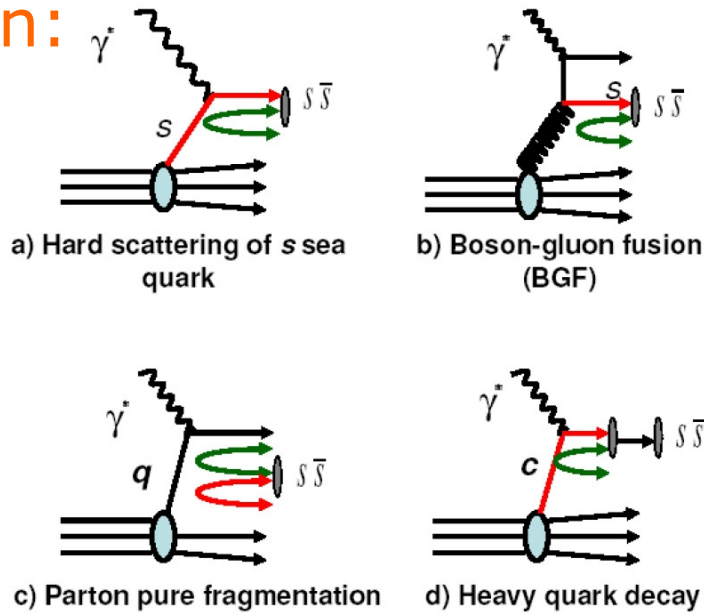
Hadronisation processes leading to hadronic final states (non-perturbative QCD)

Heavy quark production however dominated by photon-gluon processes (perturbative QCD)

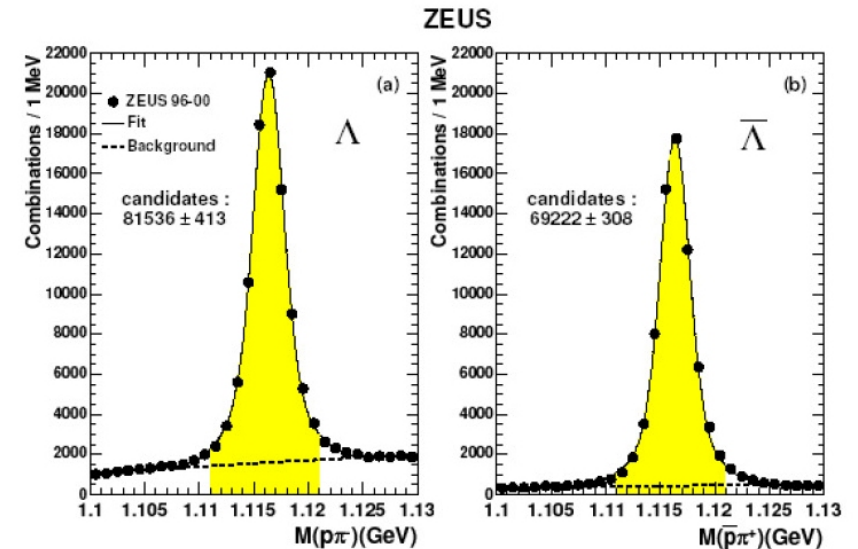
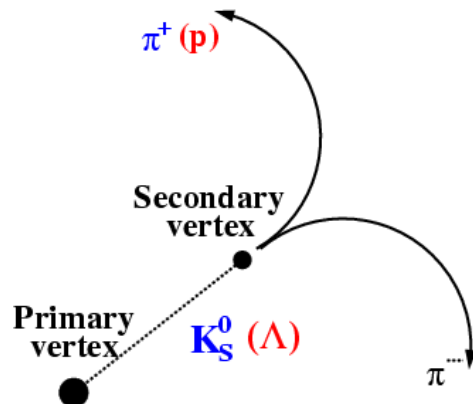


# Strangeness

## Production:

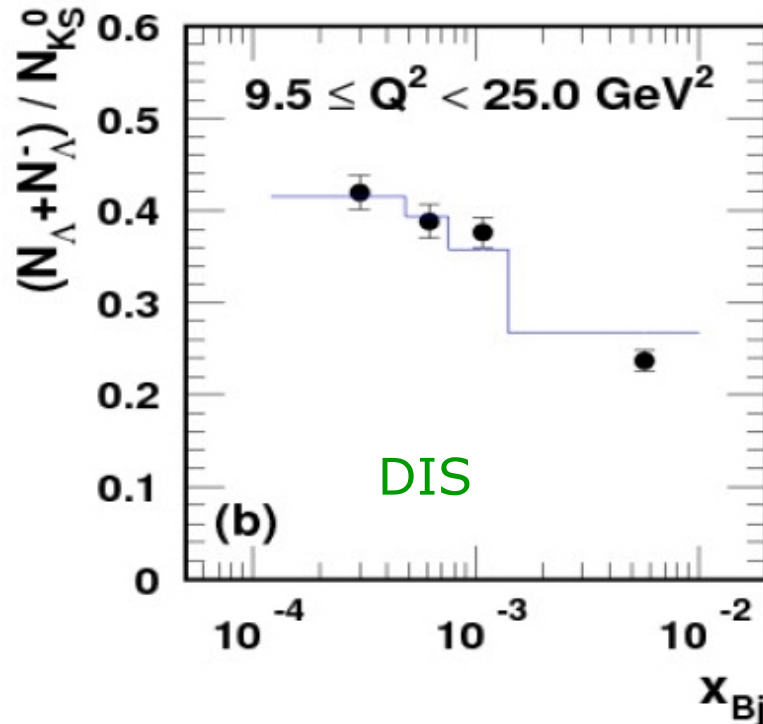


## Observation of $K_s^0$ 's and $\Lambda$ 's:



# Strangeness Results

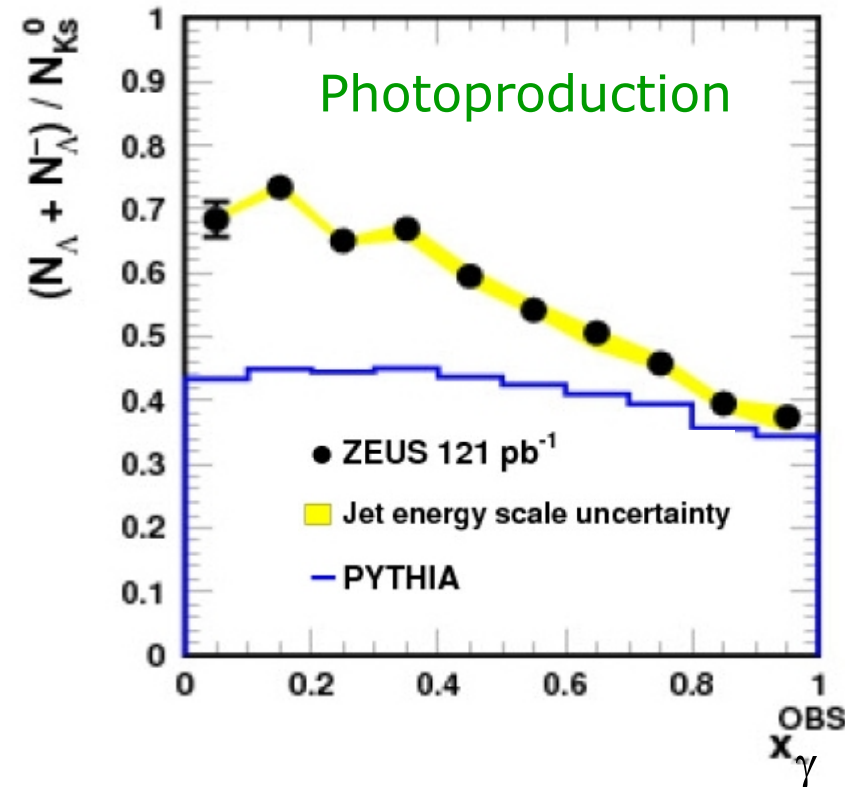
Baryon to meson ratio:  $(\Lambda + \bar{\Lambda})/K_s^0$



fairly well described by ARIADNE MC  
(strangeness suppression factor  $\lambda_s = 0.3$ )

Other results:  
(similar ones from H1)

full sets of cross sections vs event/particle variables  
baryon to meson ratio similar to  $e^+e^-$  measurements  
no baryon-antibaryon asymmetry observed  
no evidence for  $\Lambda$  transverse polarisation



new production mechanism  
needed at low  $x_\gamma^{\text{OBS}}$

# Charm Production

$$D^0 \rightarrow K^- \pi^+$$

$$D^{*+} \rightarrow D^0 \pi_s^+$$

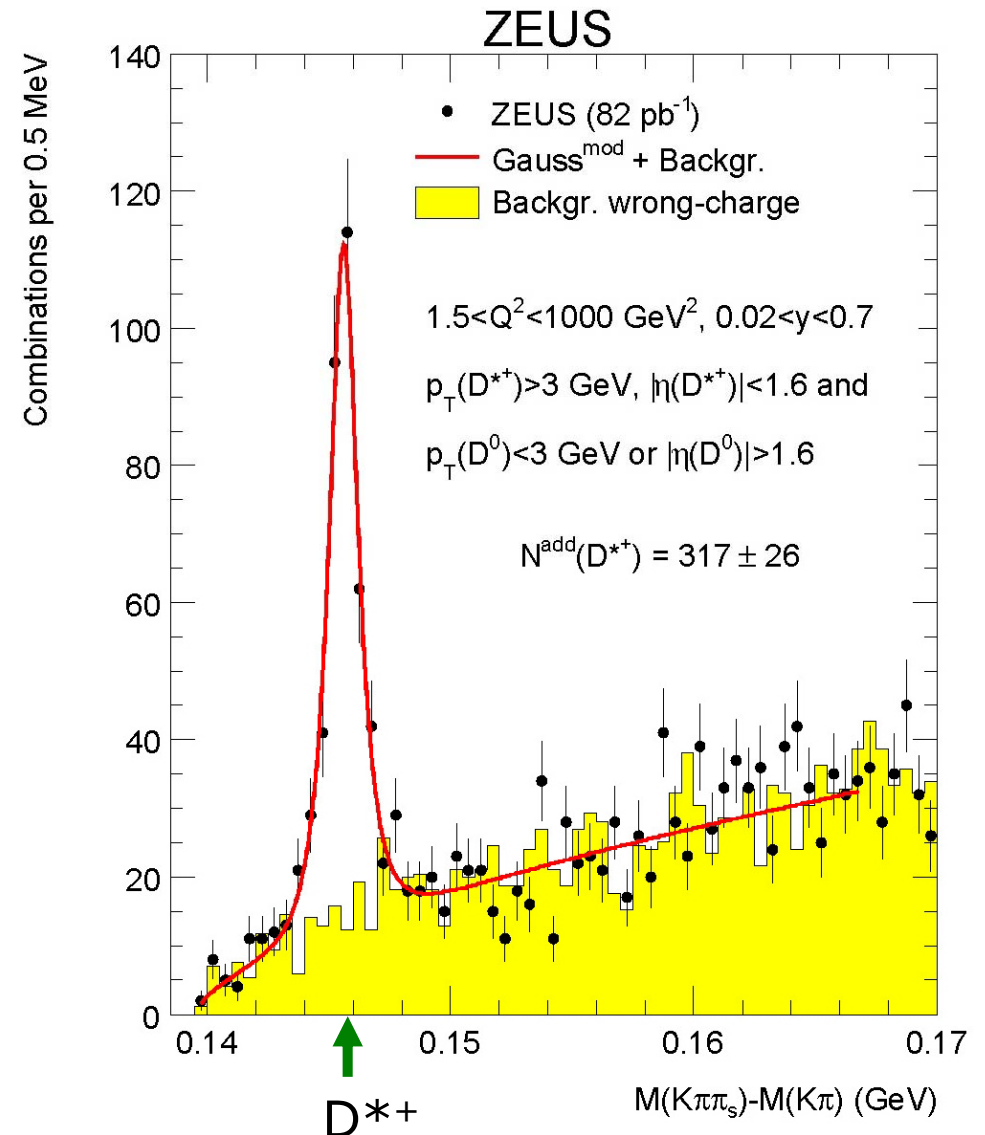
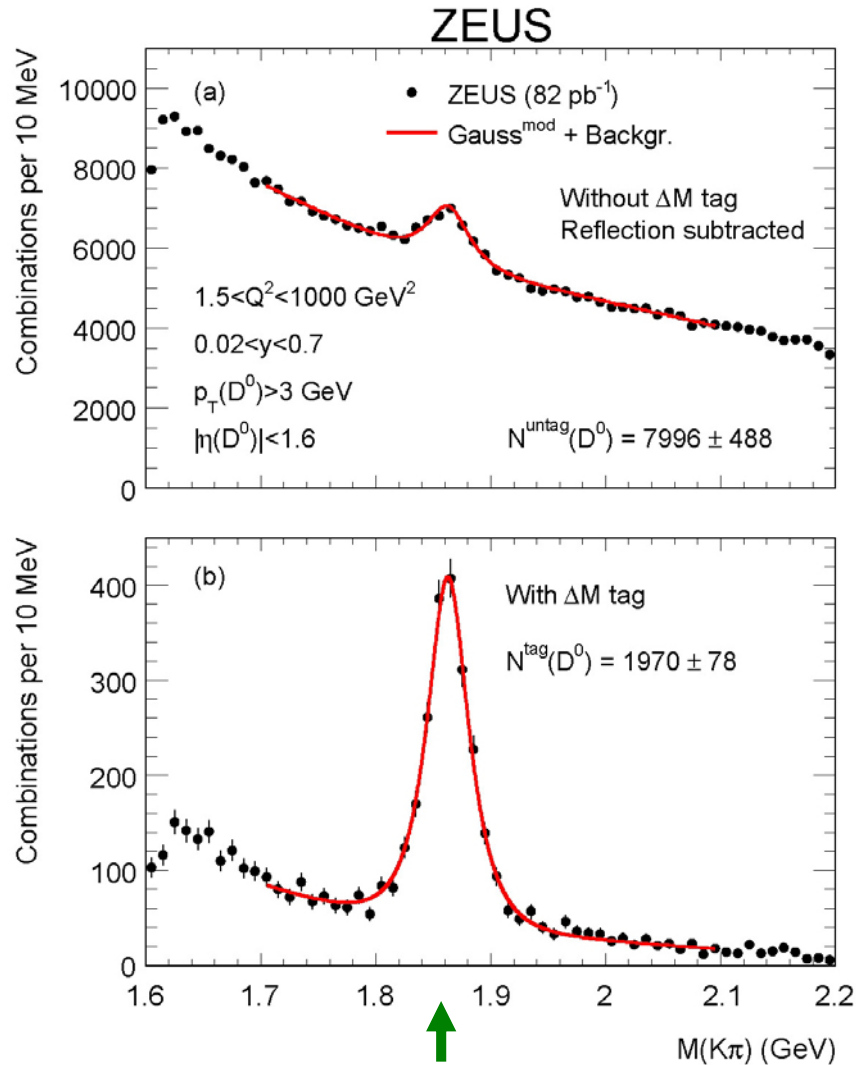
$$D^+ \rightarrow K^- \pi^+ \pi^+$$

$$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$$

$$\Lambda_c^+ \rightarrow K^- p \pi^+$$

- charm fragmentation ratios
- charm hadronisation fractions
- .. numerous other QCD results  
(cross sections vs QCD NLO,  $F_2^{cc}$ , ..)

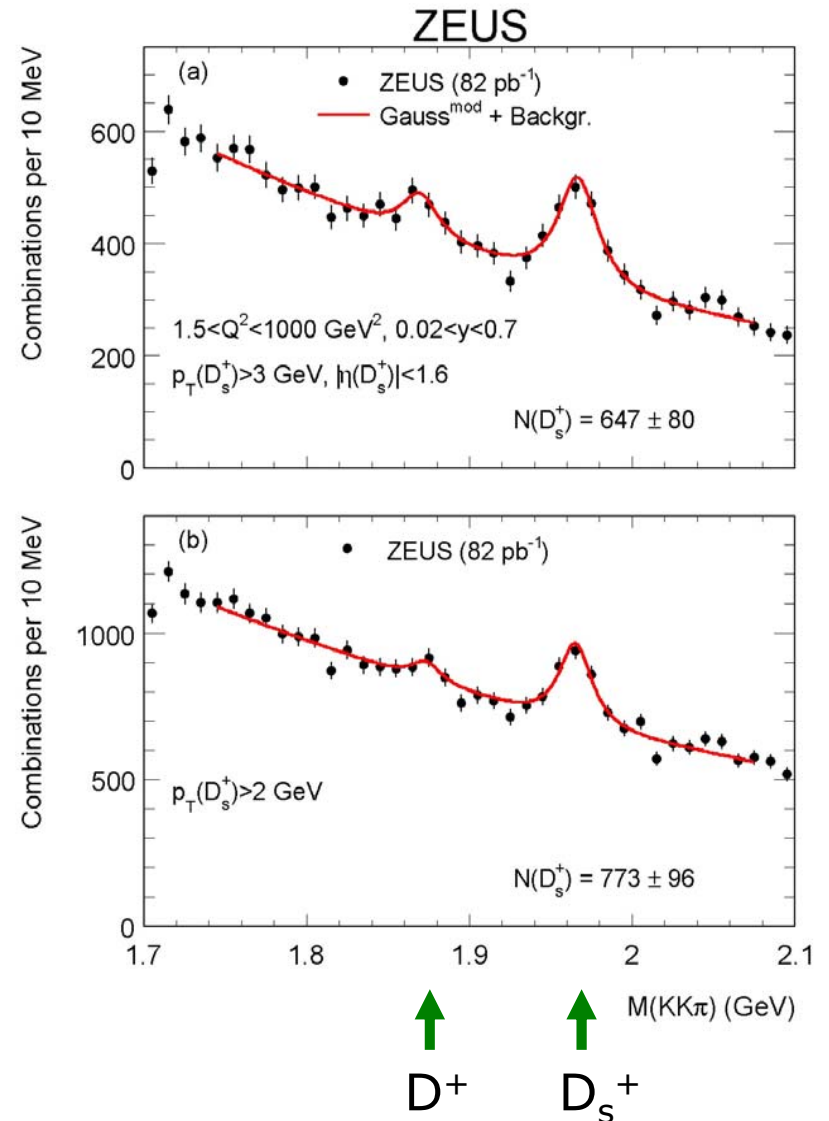
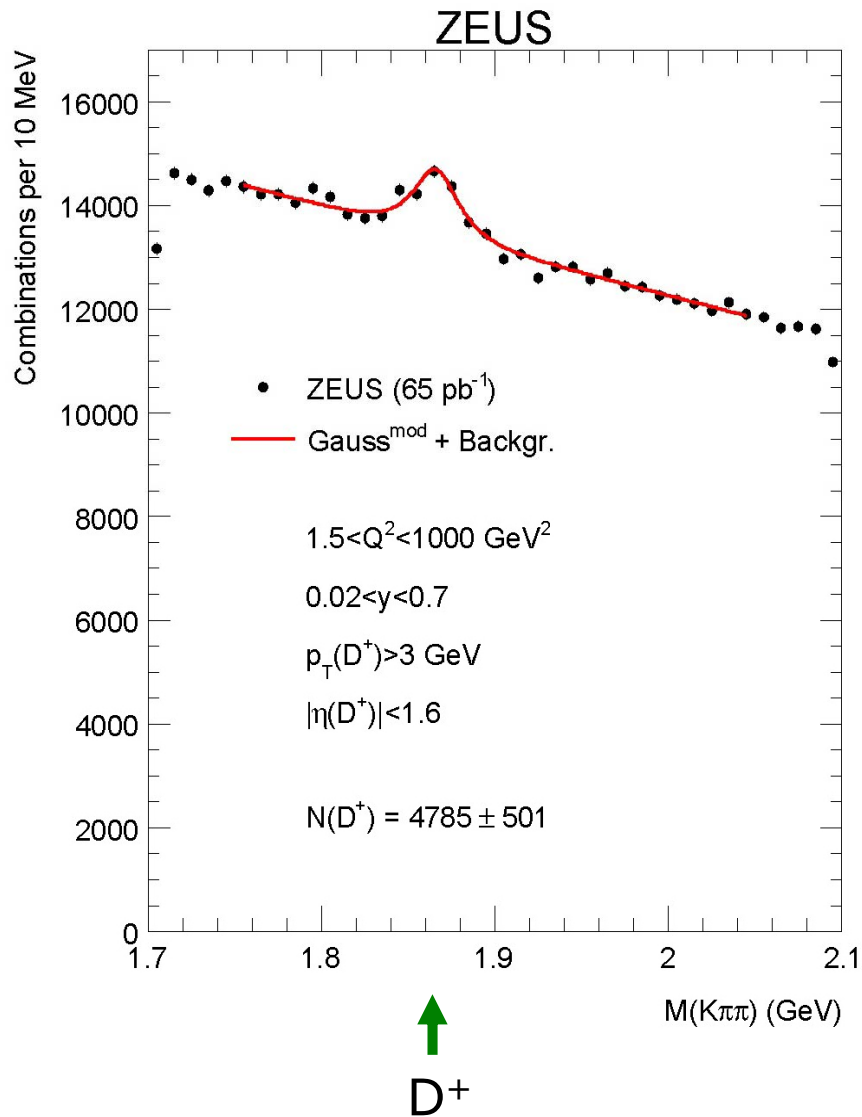
# D<sup>0</sup> and D\* Production



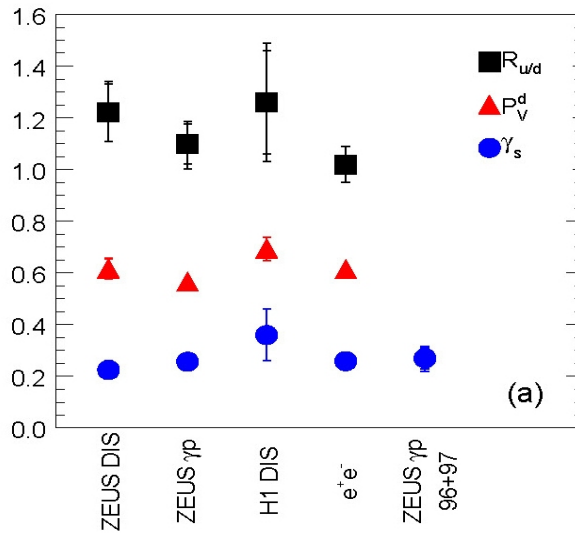
$\Delta M$  tag from  $D^{*+} \rightarrow D^0 \pi_s^+$  events



# D<sup>+</sup> and D<sub>s</sub><sup>+</sup> Production

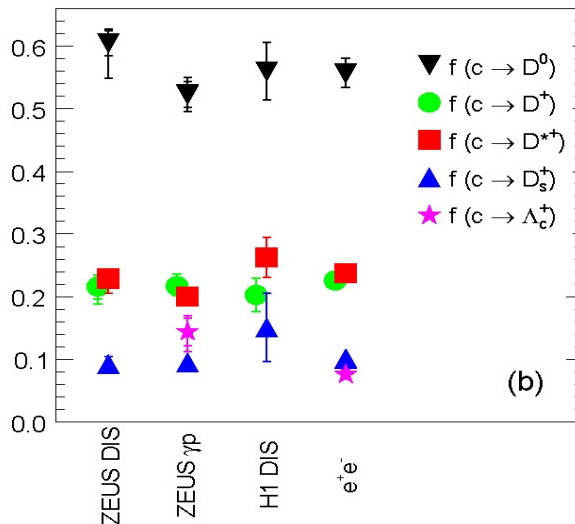


# Charm Fragmentation



## Ratios:

- neutral to charged D mesons  $\rightarrow u$  and  $d$  produced  $\sim$ equally in charm fragmentation
- fraction charged D's in vector state  $<$  naïve  $3/4$
- strangeness suppression factor



## Fractions:

- generally consistent with expectations
- agreements ZEUS – H1 –  $e^+e^-$
- fragmentation  $\sim$ independent of the hard subprocesses

# Gluon and Quark States

The best known hadrons are well explained by the Standard Model

Particles made only from gluons, or from more than 3 quarks are not excluded

Since gluons carry both color and anti-color, 2 or 3 may form color singlet “glueballs”

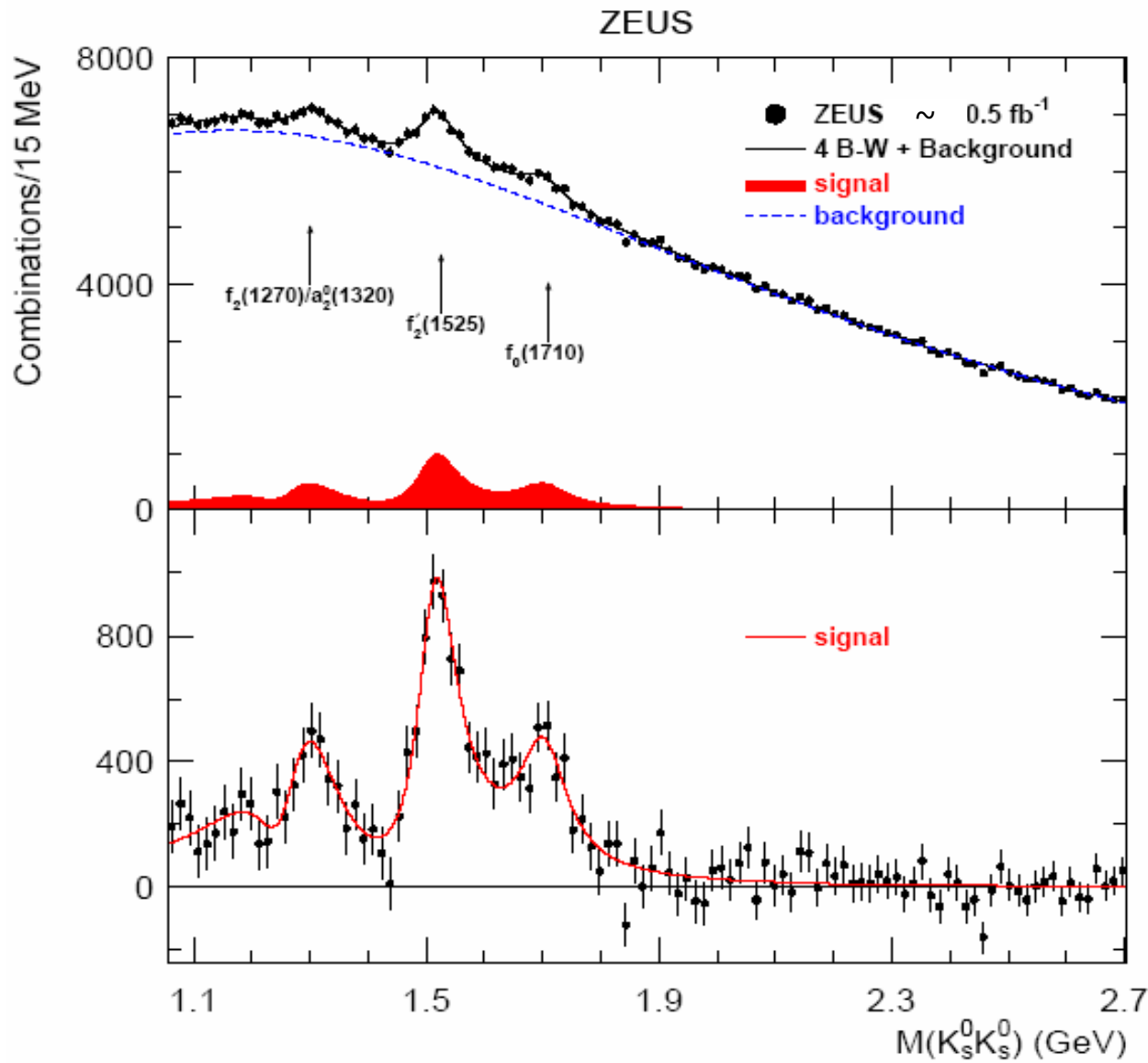
**Lattice QCD calculations predict:**

lightest glueball  $J^{PC} = 0^{++}$  in mass range 1450-1750 MeV

next:  $J^{PC} = 2^{++}$  in mass range 2300-2600 MeV

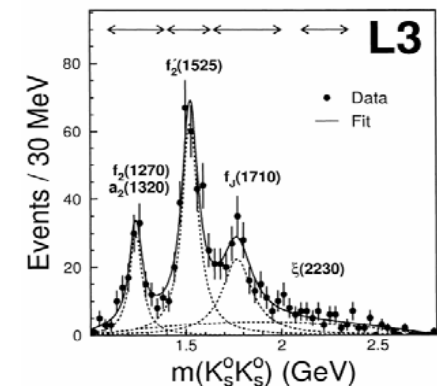
$K_s^0 K_s^0$  bound states:  $J^{PC} = 0^{++}$  (scalar),  $2^{++}$  (tensor), ..  
hence may couple to glueballs

# $K_S^0 K_S^0$ Resonant States



Bret-Wigner functions, with interference terms included

states  $f_2'(1525)$  and  $f_0(1710)$  clearly seen



# $K_s^0 K_s^0$ Resonance Results

## State $f_0(1710)$ :

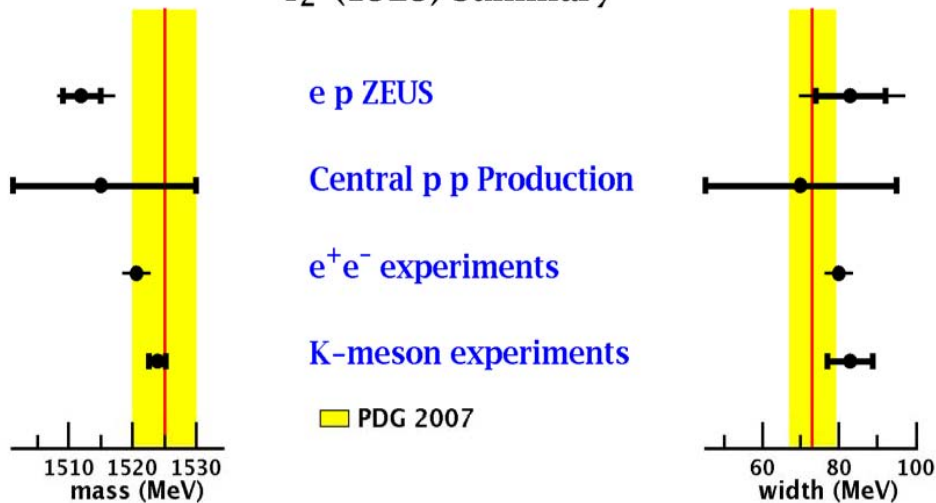
observed at  $5\sigma$   
significance

consistent with  
 $J^{PC}=0^{++}$

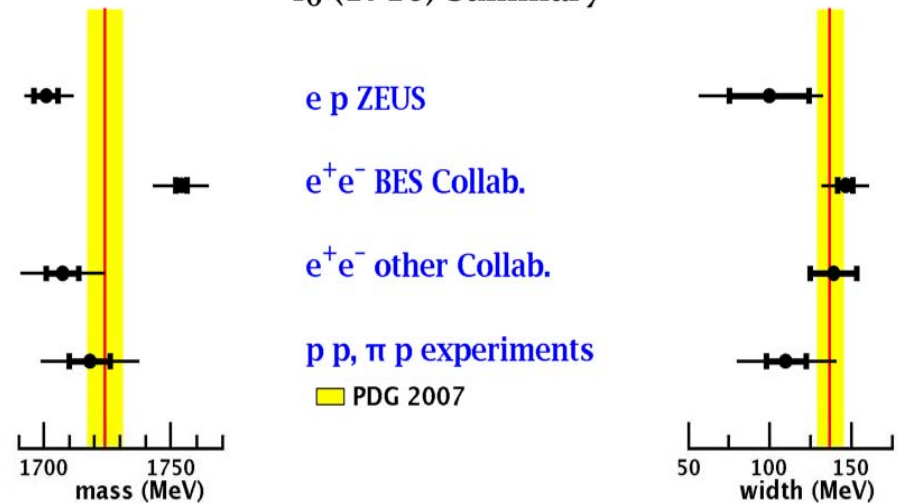
glueball candidate  $\rightarrow$

in MeV	Fit		PDG 2007 Values	
	Mass	Width	Mass	Width
$f_2(1270)$	$1268 \pm 10$	$176 \pm 17$	$1275.4 \pm 1.1$	$185.2^{+3.1}_{-2.5}$
$a_2^0(1320)$	$1257 \pm 9$	$114 \pm 14$	$1318.3 \pm 0.6$	$107 \pm 5$
$f_2'(1525)$	$1512 \pm 3^{+2}_{-0.6}$	$83 \pm 9^{+5}_{-4}$	$1525 \pm 5$	$73^{+6}_{-5}$
$f_0(1710)$	$1701 \pm 5^{+5}_{-3}$	$100 \pm 24^{+8}_{-19}$	$1724 \pm 7$	$137 \pm 8$

### $f_2'(1525)$ summary



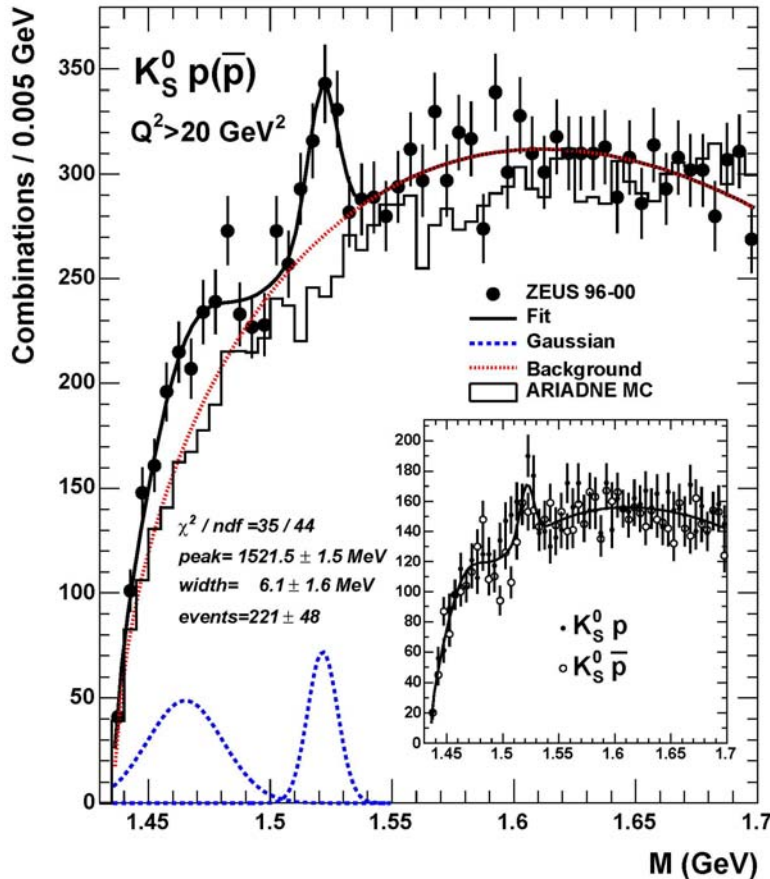
### $f_0(1710)$ summary



# Strangeness States

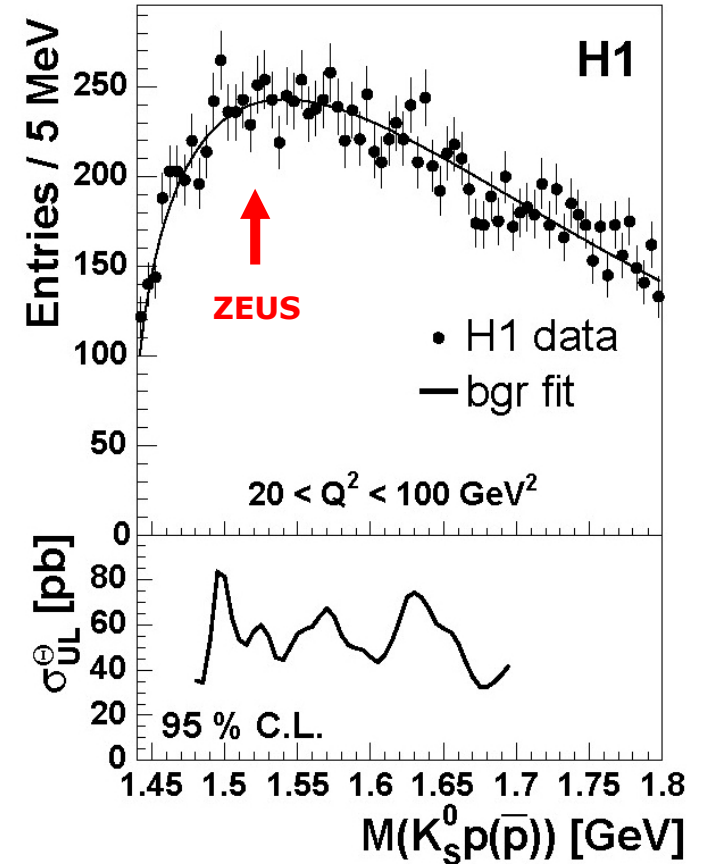
Search for:  $\Theta^+ \rightarrow K_s^0 p$  and  $\bar{\Theta}^+ \rightarrow K_s^0 \bar{p}$

ZEUS



ZEUS has a positive signal at 1522 MeV

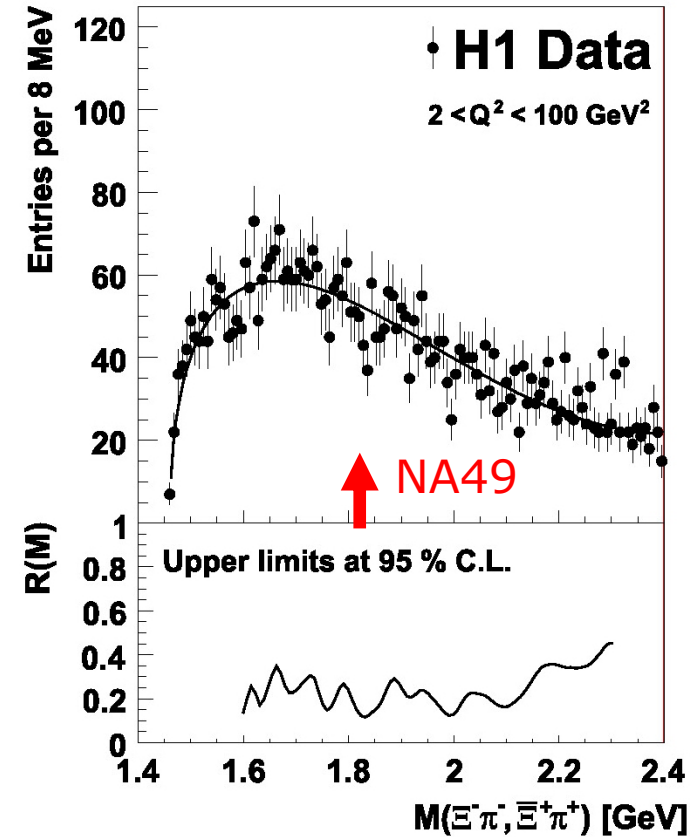
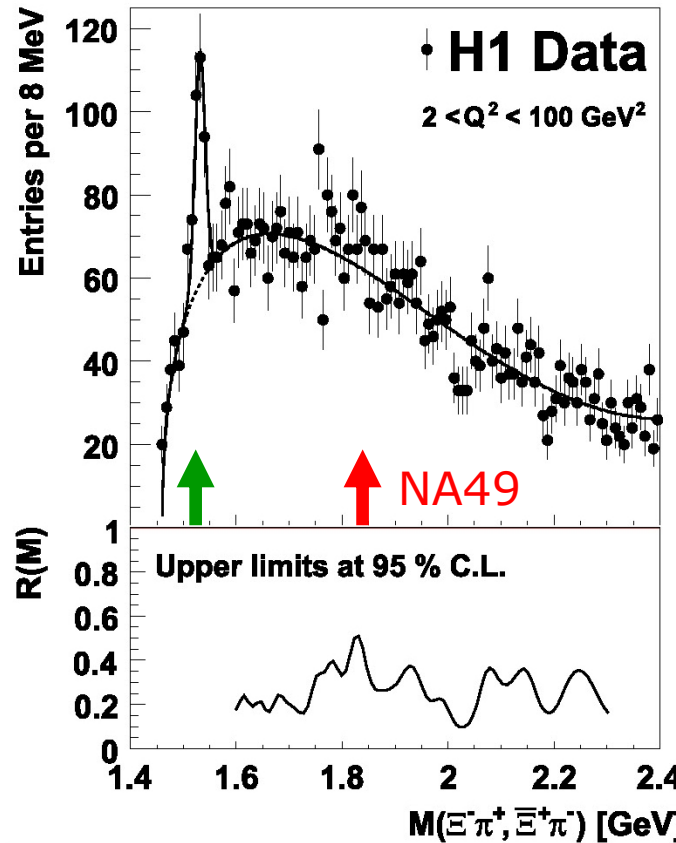
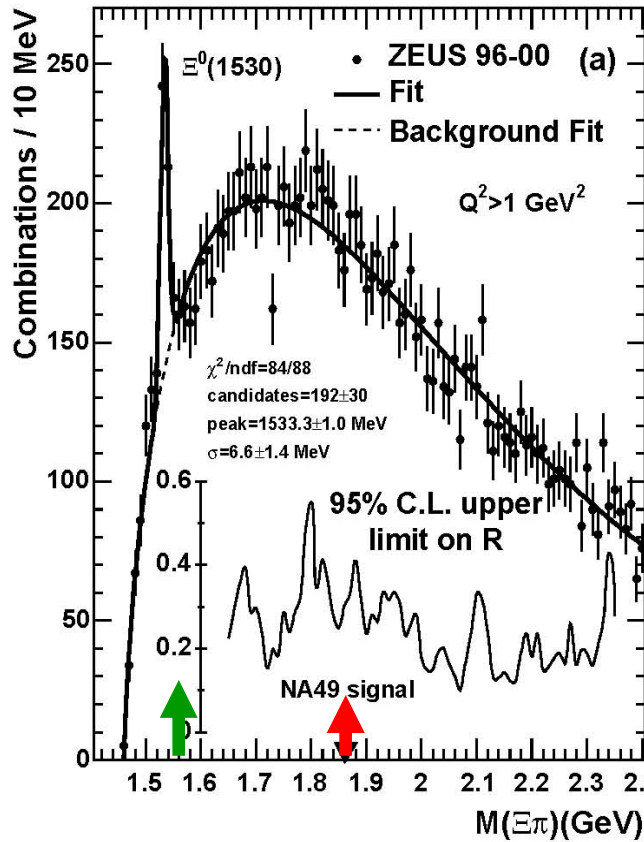
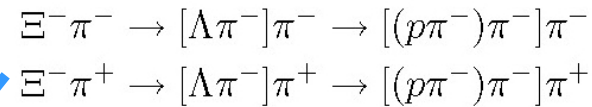
HERA I data



No signal observed in H1, upper limits set on cross sections.

# Strangeness States

Search for:  $\Xi_{5q}^{--}$  and  $\Xi_{5q}^0$



Known resonant state  $\Xi(1530 \text{ MeV})^0$ . No signal at 1862 MeV (NA49), cross section upper limits set relative to 1530 state.

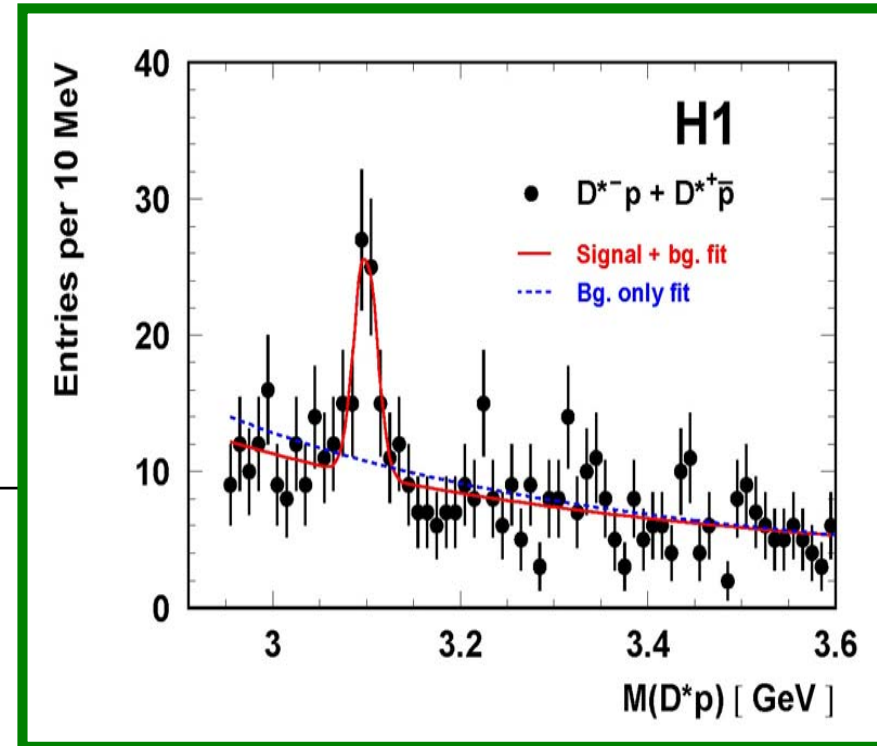
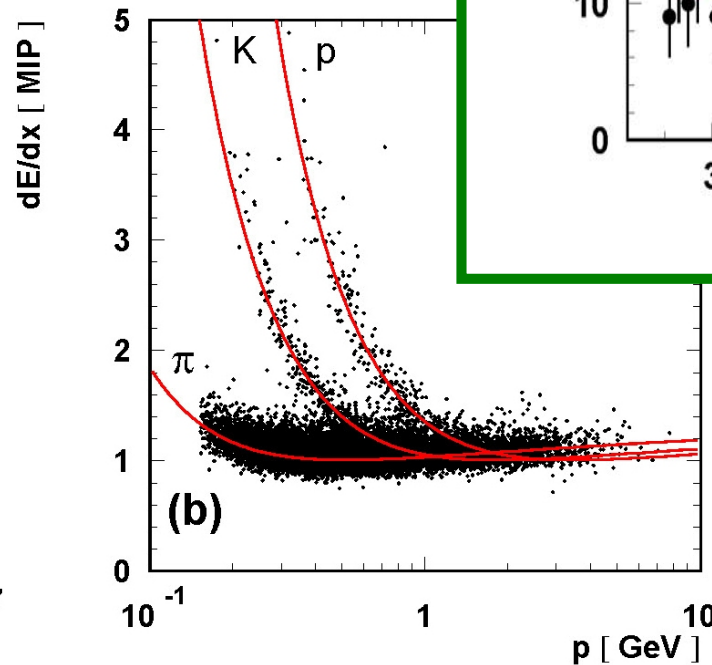
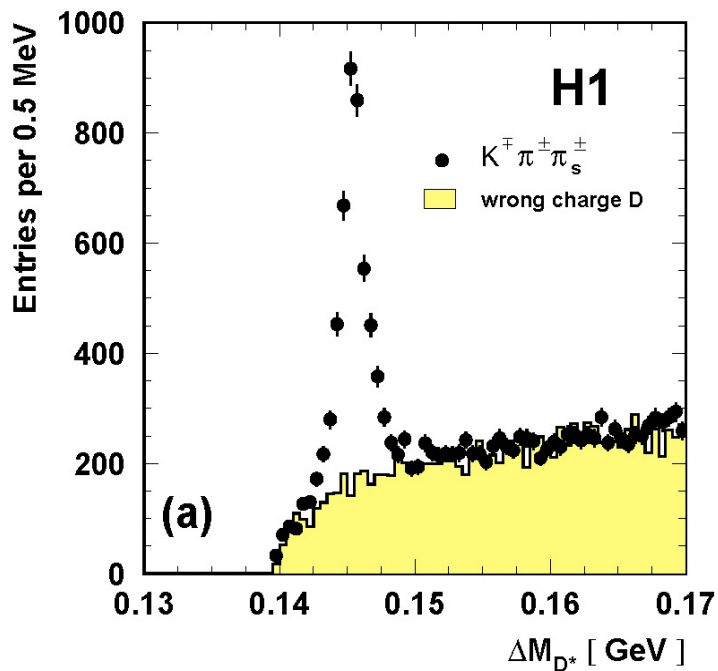


# D\*<sub>s</sub>p Resonance (2004)

A resonance was observed by H1  
with HERA I data (75 pb<sup>-1</sup>)

Invariant mass = 3099 ± 3 MeV

RMS = 12 ± 3 MeV



Minimum quark  
content:

$uudd\bar{c}$

anti-charm baryon.

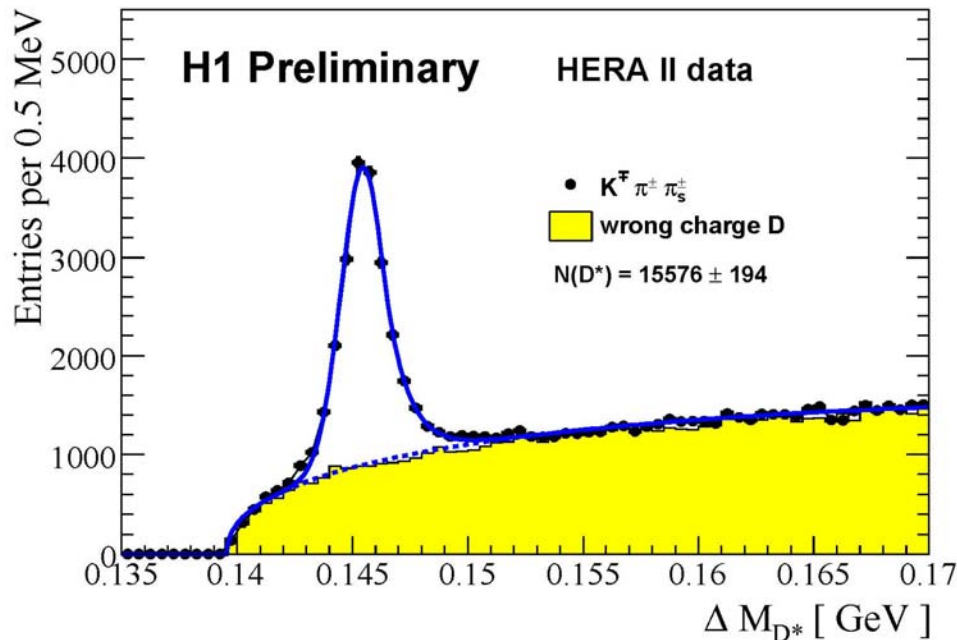
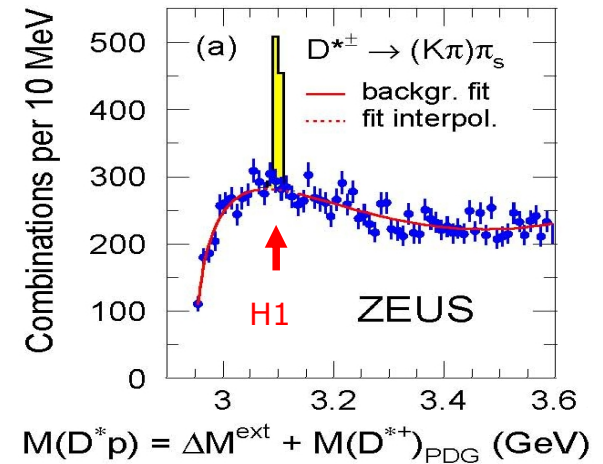
pentaquark candidate?



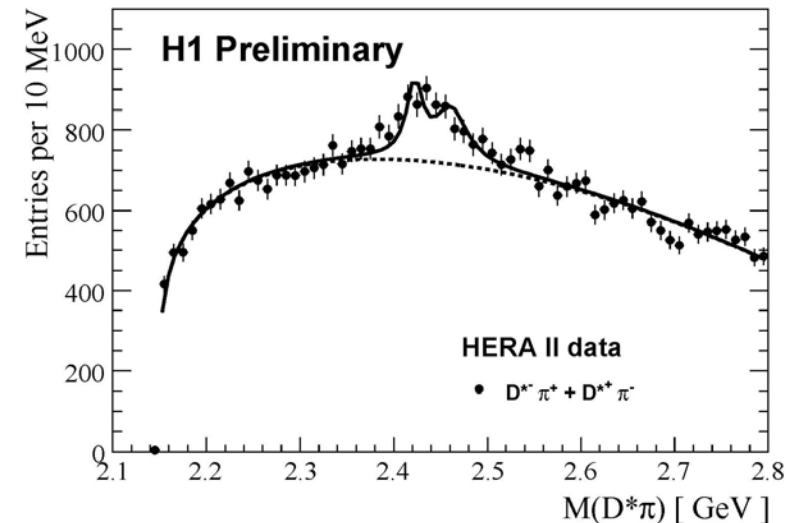
# D\*<sub>s</sub> p Resonance (2008)

Excess not observed in other experiments (BaBar, CDF, ZEUS, ALEPH, FOCUS), therefore:

Repeat measurement with HERA II data (348 pb<sup>-1</sup>) and nearly the same cuts: slightly reduced phase space.



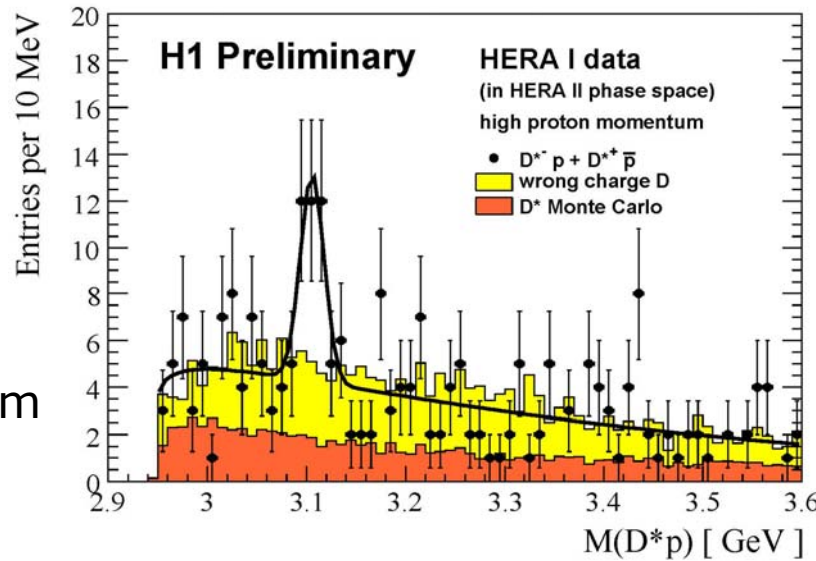
Check for sensitivity by observing  $D_1(2420)^0$  and  $D_2^*(2460)^0 \rightarrow D^*\pi$ : same  $D^*$  selection and  $\Delta M$  technique.



# New Analysis

## HERA I data

HERA II phase space  
high proton momentum

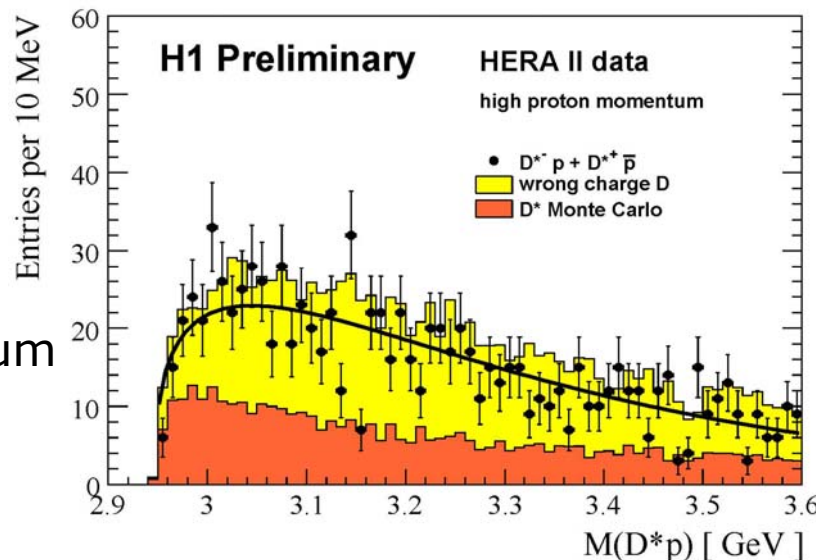


Signal observed  
in reduced  
phase space

ratio  $N(D^*p)/N(D^*)$   
of  $0.81 \pm 0.21\%$

## HERA II data

high proton momentum



No peak, 95% CL  
limit of 16.3 events.

ratio limit: 0.10%

In both cases:  
 $D^*$  Background  
well described  
(MC+wrong charge)

# Summary

- 23 years since conception and after 15 years of operation, **HERA** stopped on June 30<sup>th</sup>, 2007. An integrated luminosity of **1 fb<sup>-1</sup>** was taken by both experiments **H1** and **ZEUS** combined.
- **ZEUS** and **H1** have ongoing **spectroscopy programs**, from light quarks to beauty and for multi-parton resonant state searches.
- **HERA II** statistics are now being exploited to understand the **properties** of the investigated states.
- No positive signal observed in the most recent pentaquark searches.



*The End of an Era*

# Excited Charm Mesons

ZEUS:

$$D_1(2420)^0, D_2(2460)^0 \rightarrow D^{*+}\pi_a^-$$

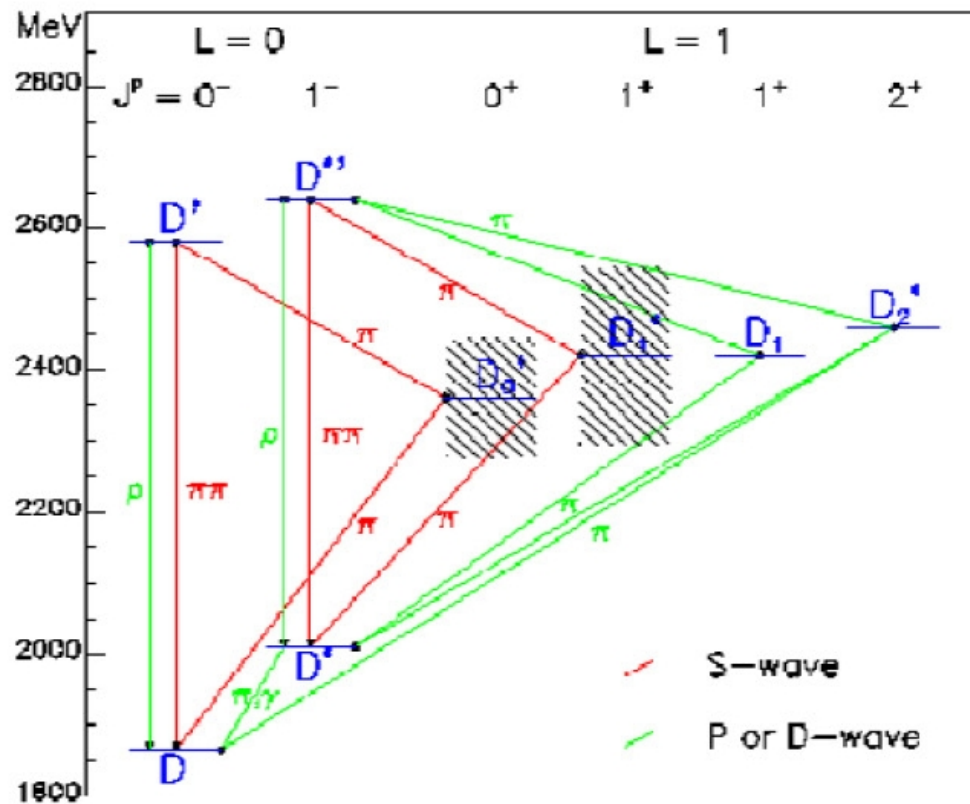
$$D_2(2460) \rightarrow D^+\pi_a^-$$

$$D_{s1}^+(2536) \rightarrow D^{*+}K_s^0$$

$$D_{s1}^+(2536) \rightarrow D^0K^+$$

measure masses, widths,  
fragmentation functions,  
helicity dependence, ..

Spectroscopy of D mesons



# “Backward Analysis”

Study  $D^*$  mass in the signal region and in side bands:

Excess is observed only for the signal region with HERA I: the sample is charm enriched.

