Charm Hadron Spectroscopy with ZEUS

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on behalf of the ZEUS Collaboration

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O U T L I N E

- Introduction
- P-wave Charm Mesons
- Search for a Charm Pentaquark decaying to $D^{*\pm}\pi^{\mp}$
- Summary

Introduction

The years 2003-2004 brought new life to the old hadron spectroscopy subject

New unexpected and surprising narrow states were found in various hadronic sectors

- **New D_s mesons $D_s(2317)$ and $D_s(2457)$ with masses lower than quark model expectations**
- **A puzzling new charmonium state $X(3872) \to \pi^+\pi^- J/\psi$**
  Candidate for DD^* molecule?
- **Many experiments see by now the exotic baryon state $\Theta^+(1530) \to K^+n$ or K^0p with $S = +1$ predicted by Diakonov et al. (Z.Phys.A359,305,1997) at the top of a SU(3) anti-decuplet of baryons**
  $\Theta^+(1530)$ cannot be made of 3 quarks $\Rightarrow$ Bound state of 5 quarks $uudd\bar{s}$
  Cannot be in the naive quark model, but QCD does not forbid 5-quark hadronic states
  (F.E.Close: "The End of the Constituent Quark Model?")
- **NA49 reported $\Xi\pi$ pentaquark candidates around 1860 MeV**
- **Last surprise came last month with H1 reporting observation of a narrow charm pentaquark $\Theta_c^0(= uudd\bar{c}) \to D^{*\pm}\pi^{\mp}$ at 3.1 GeV**

Very exciting times for resonance hunters

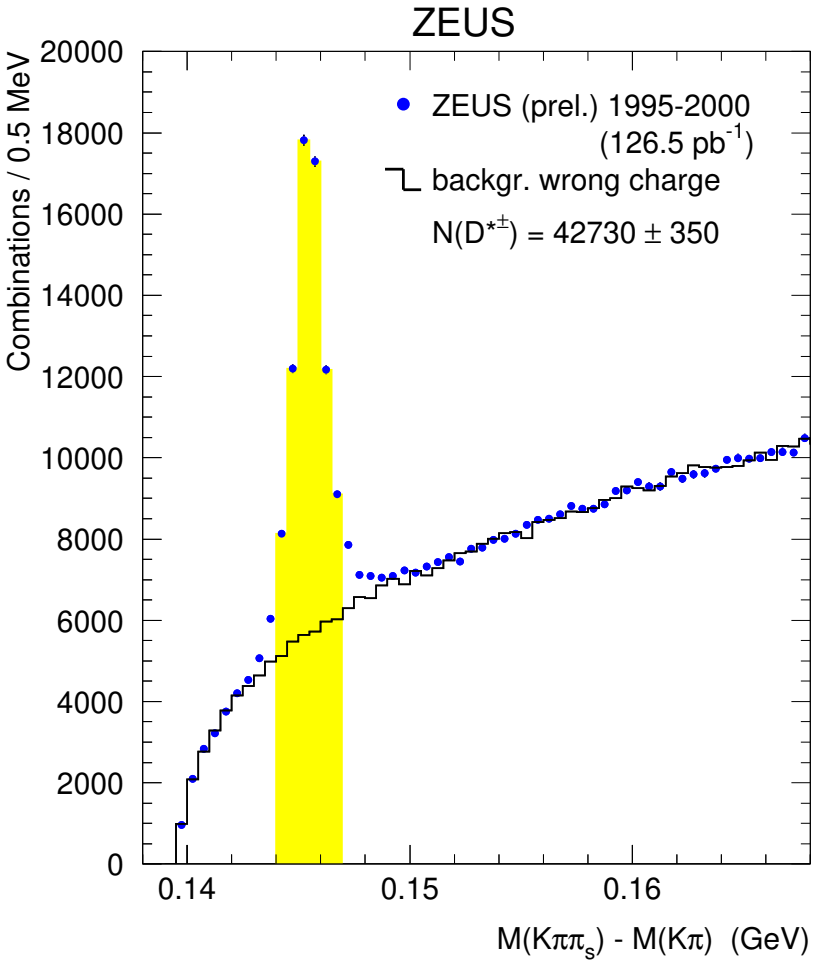
Hundreds of theory papers to try and understand the new narrow resonances

Charm Tagging for Spectroscopy

$D^{*+} \to D^0 \pi_s^+ \to (K^- \pi^+)\pi_s^+$ **(+ c.c.)**

$f(c \to D^{*+}) \approx 24\%$, $BR = 2.6\%$

$\Delta M = M(D^{*+}) - M(D^0) = 0.14542\,\mathbf{GeV} \sim m_\pi$



DATA 1995-2000 (126.5 pb^{-1})

$P_T(D^{*\pm}) > 1.35\,\mathbf{GeV}, \quad |\eta(D^{*\pm})| < 1.6$

Candidates with $144 < \Delta M < 147\,\mathbf{MeV}$ **(yellow band) were used. In this range after background subtraction:**

$$N(D^{*\pm}) = 42730 \pm 350$$

better than 1% **stat. precision**

Summary of cuts:

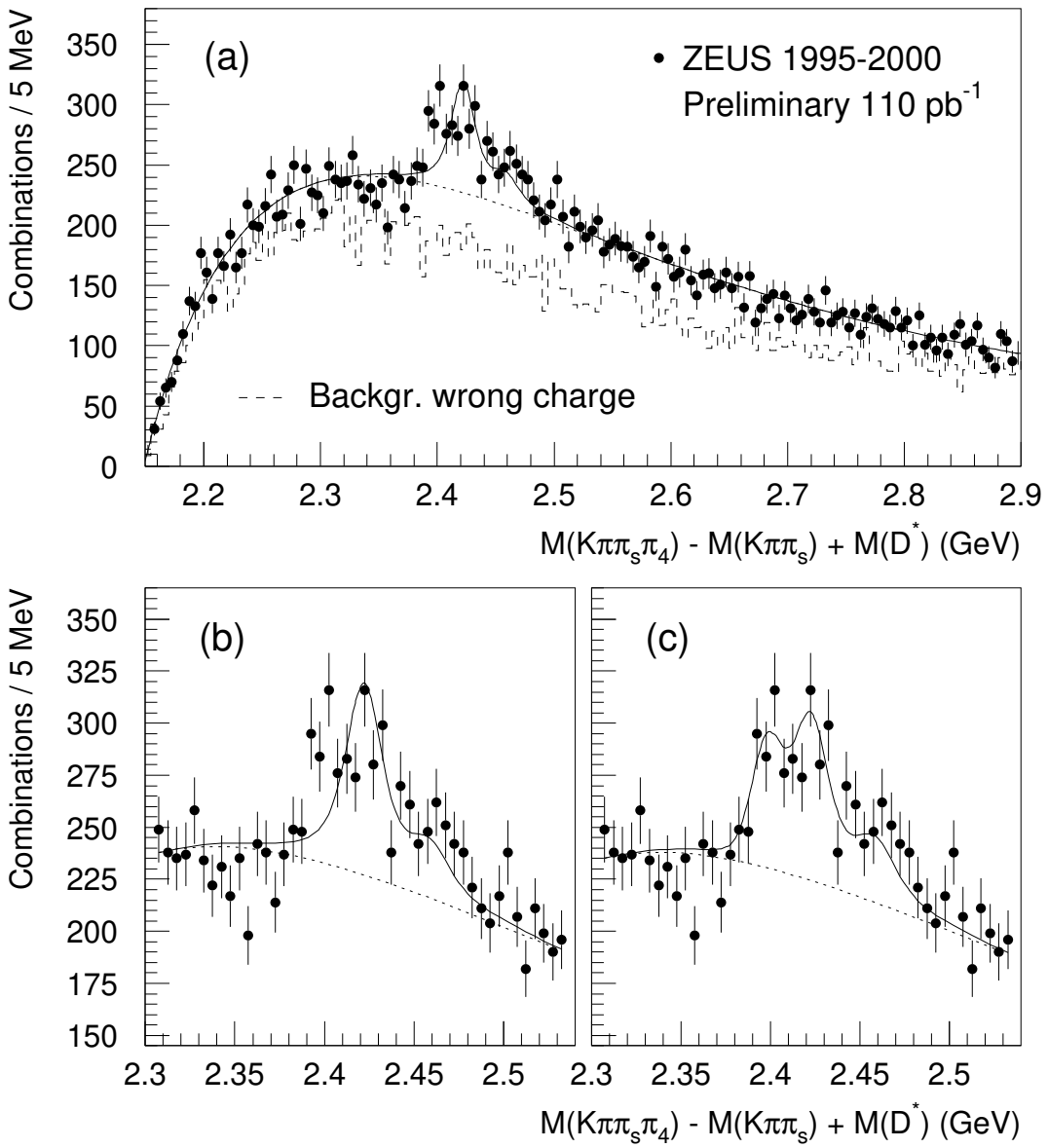
$P_T(K) > 0.45\,\mathbf{GeV}$, $P_T(\pi) > 0.45\,\mathbf{GeV}$

$P_T(\pi_s) > 0.10\,\mathbf{GeV}$

$P_T(D^{*\pm})/E_T^{\text{out } 10^\circ} > 0.12$

$1.83 < M(K\pi) < 1.90\,\mathbf{GeV}$ **(wider for high** $P_T(D^{*\pm})$**)**

Orbitally excited P-wave D mesons



$D_1^0(2420), D_2^{*0}(2460) \to D^{*\pm}\pi^{\mp}$

$\Delta M^{ext} = M(K\pi\pi_S\pi_4) - M(K\pi\pi_s)$

2-dimensional fit with fixed M, Γ, resolution and helicity distribution:

$\frac{dN}{d\cos\alpha} \propto 1 + 3\cos^2\alpha \qquad (1^+, L+s = 3/2)$

$\frac{dN}{d\cos\alpha} \propto 1 - \cos^2\alpha \qquad (2^+, L+s = 3/2)$

helicity angle α : between π_4 and π_s in $D^{*\pm}$ rest frame

$N(D_1^0) = 526 \pm 65$

$N(D_2^{*0}) = 203 \pm 60$

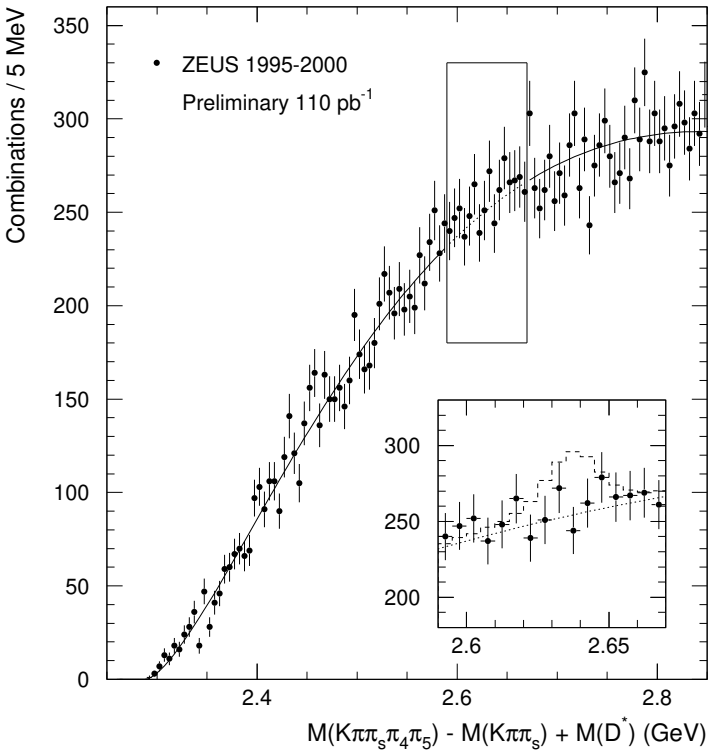
Additional narrow bump ?

$N = 211 \pm 49$

$M = 2398.1 \pm 2.1(\text{stat.})^{+1.6}_{-0.8}(\text{syst.})$ **MeV**

New D meson ? Interference ?

Search for radially excited $D^{*\prime\pm}$ meson



$\underline{D^{*\prime\pm} \to D^{*\pm}\pi^+\pi^-}$

Observed by DELPHI: 66 ± 14 **events** (4.7 **s.d.**)

$M = 2637\,\mathbf{MeV};\ \Gamma < 15\,\mathbf{MeV}$

CLEO and OPAL did not confirm

$\Longleftarrow$ **ZEUS search**

$\Delta M^{ext} = M(K\pi\pi_S\pi_4\pi_5) - M(K\pi\pi_s)$

Search window: $2.59 < \Delta M^{ext} + M(D^{*+}) < 2.67\,\mathbf{GeV}$

covers both predictions and DELPHI's observation

After backgr. subtraction: "$N(D^{*\prime\pm})$"$= 91 \pm 75$

A PYTHIA MC simulation was used for acceptance calculation

Using world average for $f(c \to D^*)$ **:**

$$f(c \to D^{*\prime+}) \cdot B_{D^{*\prime+} \to D^{*+}\pi^+\pi^-} < 0.7\% \quad (95\% \quad \text{C.L.})$$

(ZEUS prel.)

Limit is somewhat stronger than the 0.9% **limit obtained by OPAL**

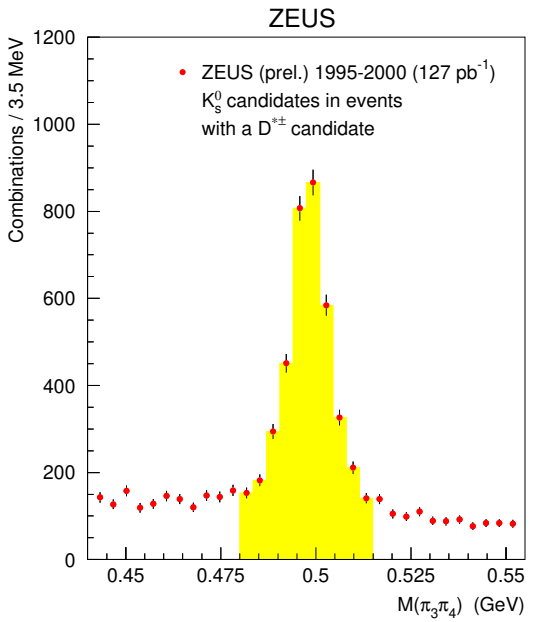
Charm-strange $D_{s1}^{\pm}(2536)$ meson

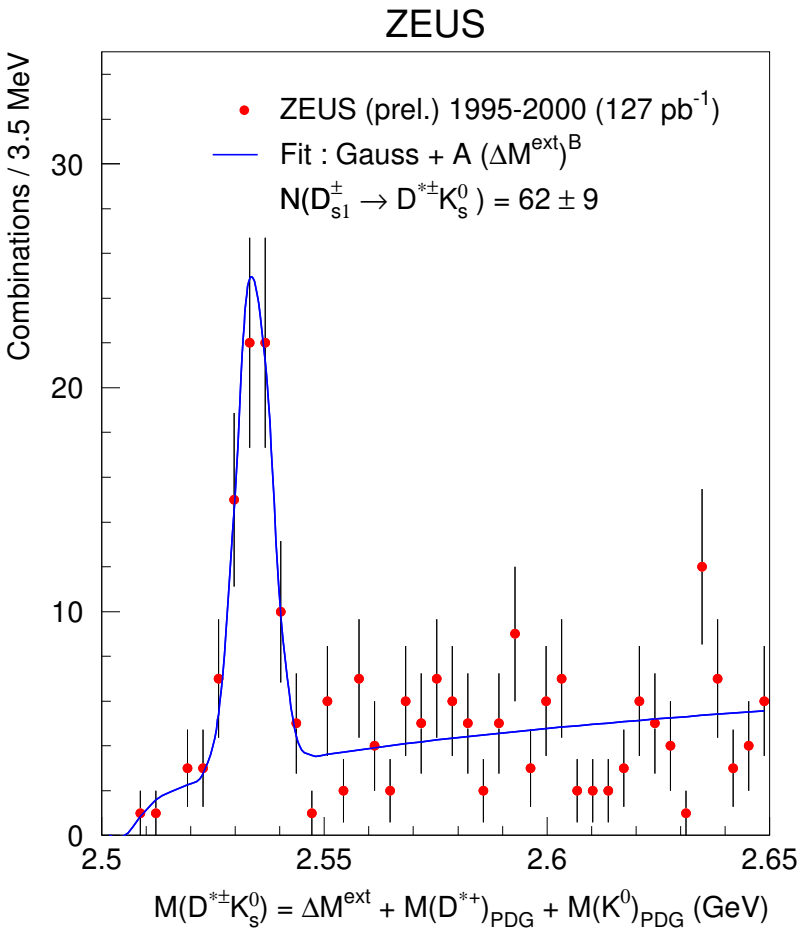
$$D_{s1}^{\pm}(2536) \to D^{*\pm}K_s^0 \ , \quad K_s^0 \to \pi^+\pi^-$$

$$\Delta M^{ext} = M(K\pi\pi_S\pi_3\pi_4) - M(K\pi\pi_s) - M(\pi_3\pi_4)$$

$$N(D_{s1}) = 62.3 \pm 9.3$$

$$M(D_{s1}) = 2534.2 \pm 0.6 \pm 0.5\,\mathbf{MeV} \quad (\sim M_{\rm PDG})$$





Helicity angle α : between K_s^0 and π_s in $D^{*\pm}$ r.f.

Fit to a form : $1 + R\cos^2\alpha$

$$\boxed{R = -0.53 \pm 0.32(\text{stat.})^{+0.05}_{-0.14}(\text{syst.})}$$ **(ZEUS prel.)**

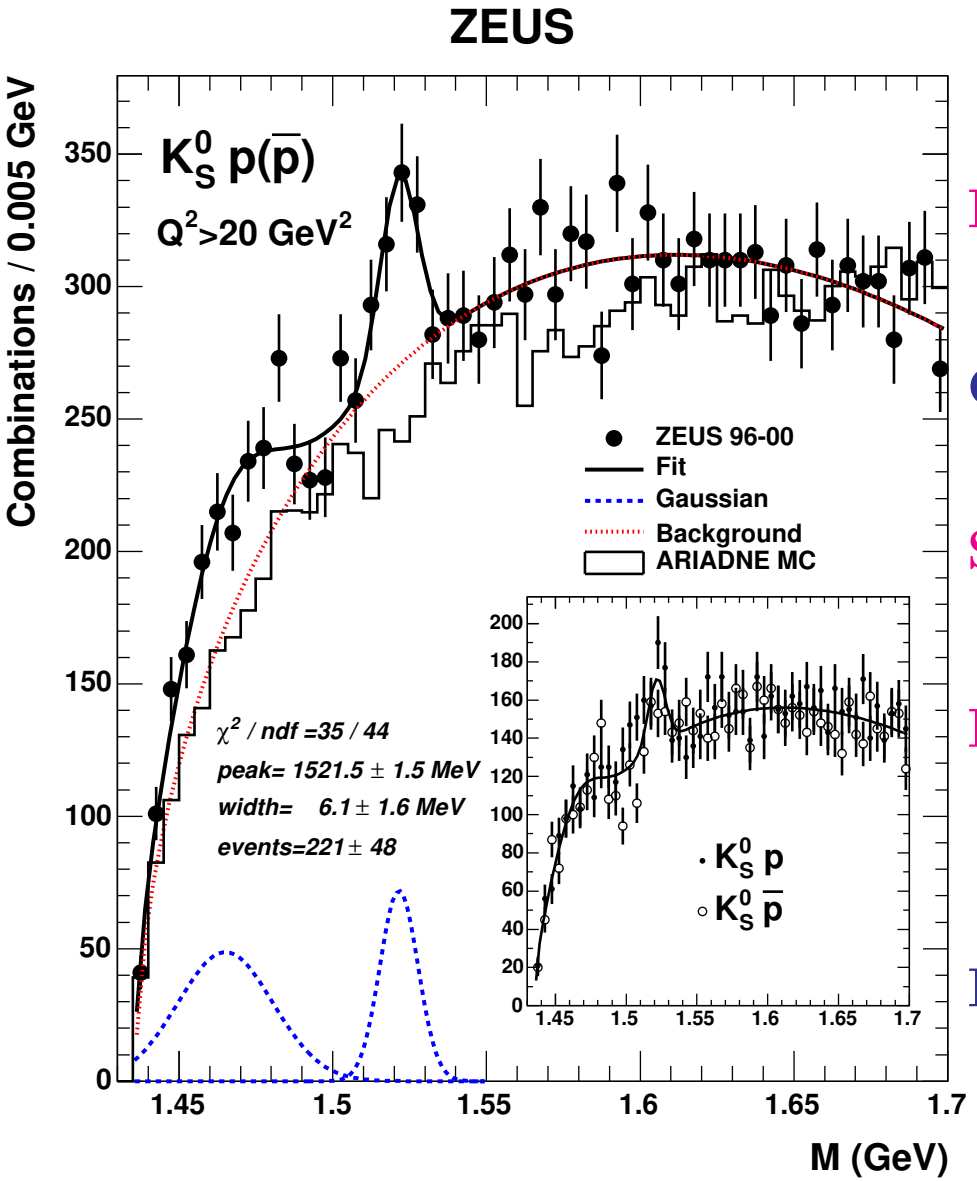
CLEO $(D_{s1}^+ \to D^{*0}K^+)$ **:** $R = -0.23^{+0.40}_{-0.32}$

ZEUS : consistent with $R = 0$, i.e. $J^P = 1^+$

does not contradict $R = -1$

expected for $J^P = 1^-,\ 2^+$

Evidence for the Strange Pentaquark $\Theta^+(1530)$



Resonances searched in $K^0_S p$ and $K^0_S \bar{p}$ spectra

Evidence for narrow baryon resonance at

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

Gaussian width consistent with experimental resolution (2 MeV)

Signal visible at high Q^2

221 ± 48 events for $Q^2 > 20$ GeV^2 (4.6 s.d.)

Probability of background fluctuating into signal in the range 1500-1560 MeV is below $6 \cdot 10^{-5}$

Resonance consistent with the predicted $\Theta^+(1530)$ pentaquark with $\Gamma < 15$ MeV

Signal in $K^0_S \bar{p}$ channel $\Rightarrow$ First evidence for antipentaquark $(\bar{u}\bar{u}\bar{d}\bar{d}s)$

First evidence for production of such state in kinematic region where hadron production dominated by fragmentation

Charm Pentaquarks

Since $\Theta^+ = uudd\bar{s}$ exists, heavy pentaquarks, such as $\Theta_c^0 = uudd\bar{c}$ should also exist

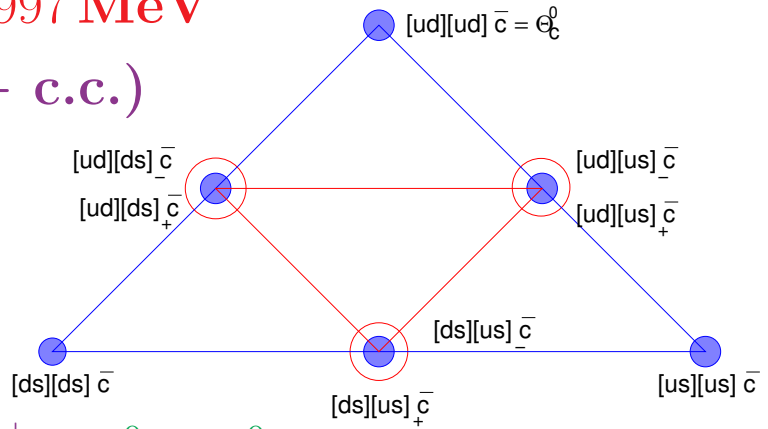
Predictions:

Jaffe-Wilczek (hep-ph/0307341); Wu-Ma (hep-ph/0402244):
$M(\Theta_c^0) \approx 2700$ **MeV $\Rightarrow$ too light to decay to D mesons**
can decay weakly to $\Theta^+(1530)\pi^-$

Karliner-Lipkin (hep-ph/0307343):
$M(\Theta_c^0) = 2985 \pm 50\,\mathbf{MeV}$; $\Gamma(\Theta_c^0) \sim 21\,\mathbf{MeV}$

Cheung (hep-ph/0308176): $M(\Theta_c^0) = 2938 - 2997\,\mathbf{MeV}$
decays dominantly to D^-p^+ or D^0n (+ c.c.)

If $M(\Theta_c^0) > M(D^{*\pm}) + M(p) = 2948\,\mathbf{MeV}$,
Θ_c^0 can decay to $D^{*\pm}p$



ZEUS is sensitive to resonances decaying to $D^{*\pm}$ $(D_1^0,\ D_2^{*0},\ D_{s1})$
very narrow resonances (Θ^+)

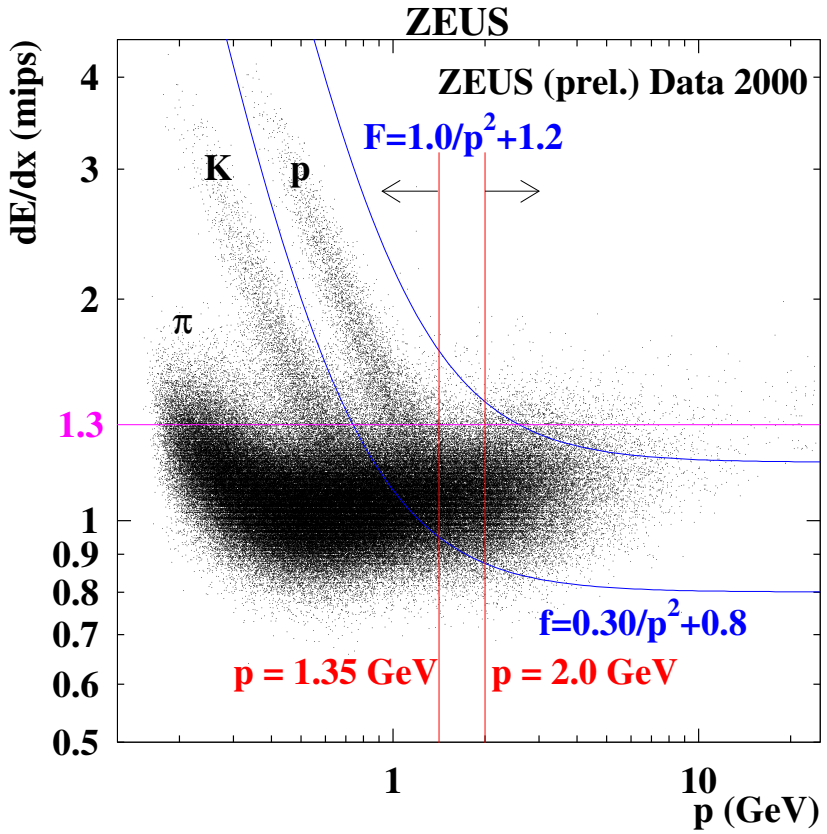
$\Rightarrow$ Search for Θ_c^0 signal in $M(D^{*-}p)$ (+ c.c.) spectra

Selection of p candidates

$P_T(p) > 0.15$ **GeV**

Define wide dE/dx **p-band:** $f < dE/dx < F$**, where**

$$f = 0.3/P^2 + 0.8 \ , \ F = 1.0/P^2 + 1.2$$



Scatter plot: subset of 2000 data for illustration

dE/dx proton selection effective mainly for low-P

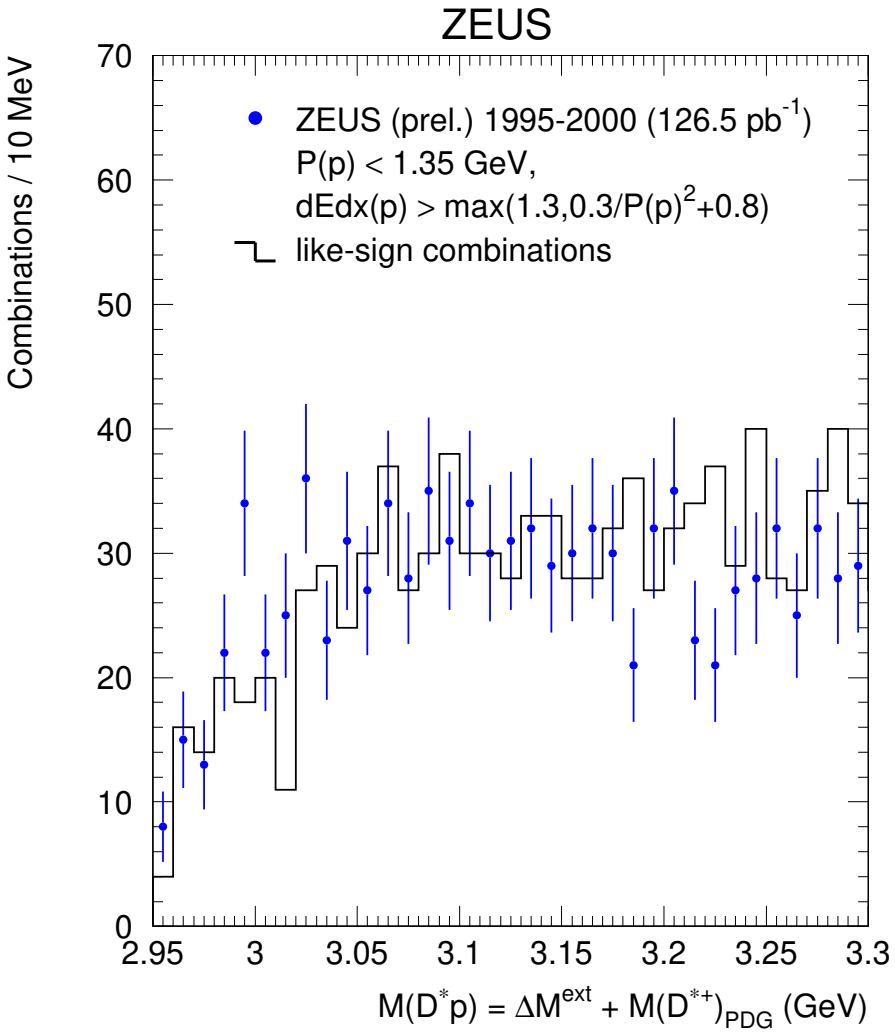
Protons from $5q$ decays can have higher momentum than the bulk of pions and kaons

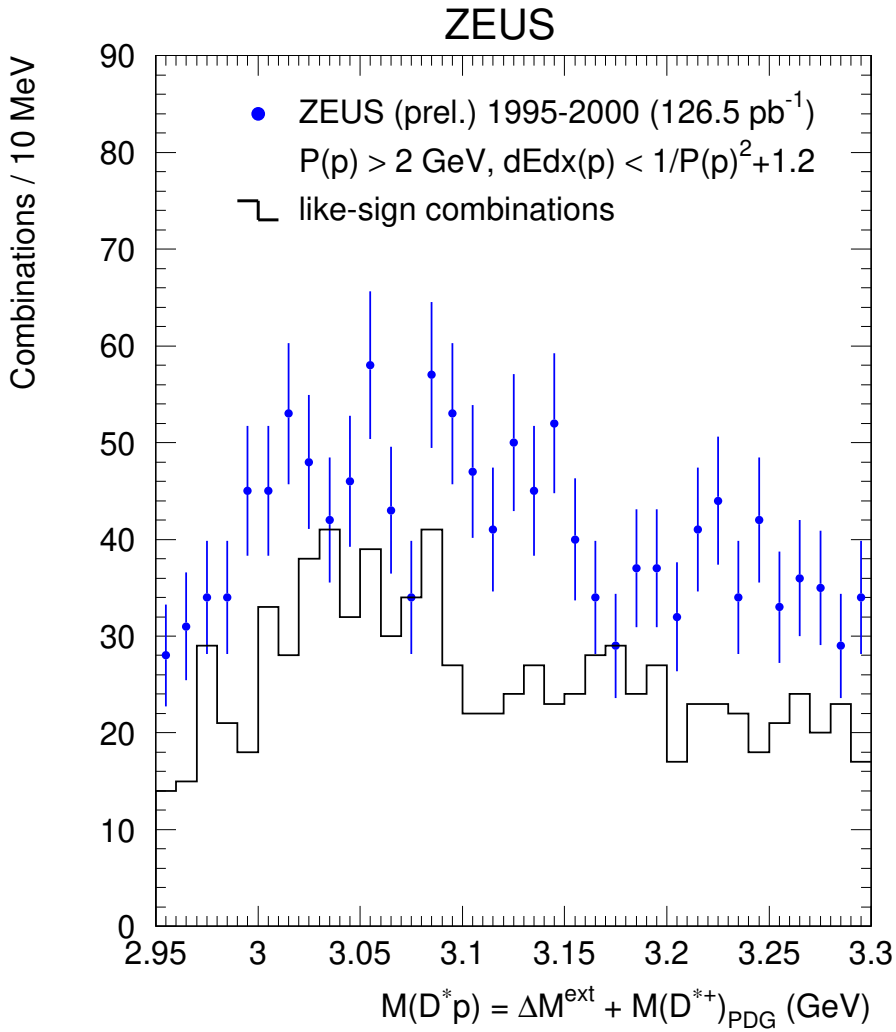
two strategies for p-selection:

1) $(dE/dx)_p$ **band with** $P < 1.35\,$**GeV and** $dE/dx > 1.3$

2) $(dE/dx)_p$ **band with** $P > 2\,$**GeV**

$M(D^*p)$ spectra





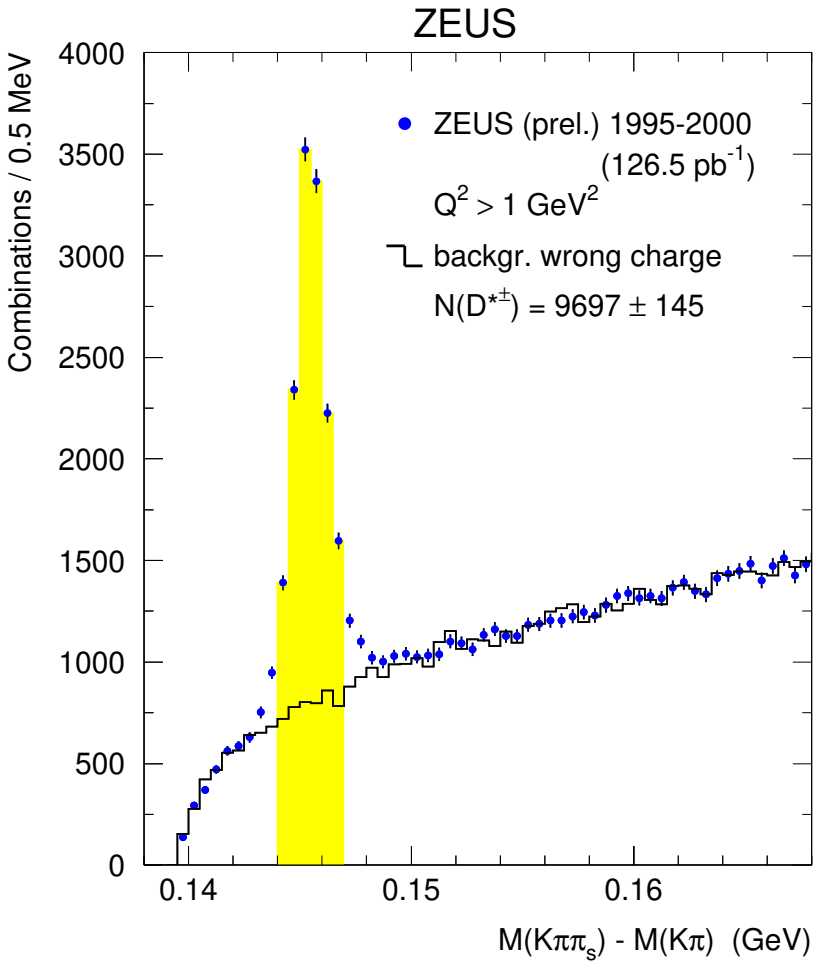
$$M(D^*p) = \Delta M^{\mathrm{ext}} + M(D^{*+})_{\mathrm{PDG}} = M(K\pi\pi_s p) - M(K\pi\pi_s) + M(D^{*+})_{\mathrm{PDG}}$$

No signal observed

$D^{*\pm}$ in DIS with $Q^2 > 1\,\mathrm{GeV}^2$

Charm fragmentation universality requires $f(c \to \Theta_c^0)$ to be the same in γp and ep collisions.

It is useful to check DIS alone because it permits cleaner selection (smaller $W_{\gamma p} \Longrightarrow$ smaller multiplicities)



DATA 1995-2000 ($126.5\ \mathrm{pb}^{-1}$)

$P_T(D^{*\pm}) > 1.35\,\mathbf{GeV}, \quad |\eta(D^{*\pm})| < 1.6$

$E_{e'} > 8\,\mathbf{GeV}, \quad Q^2 > 1\,\mathbf{GeV}^2$

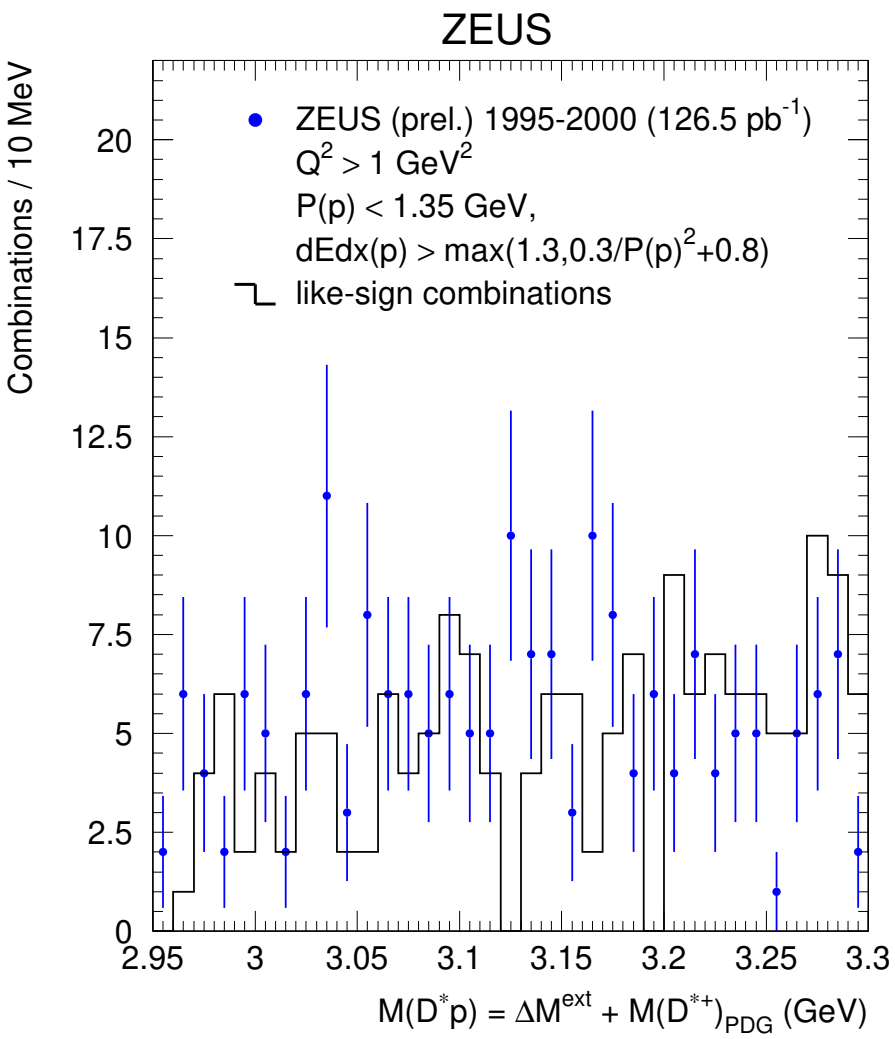
$N(D^{*\pm}) = 9697 \pm 145$

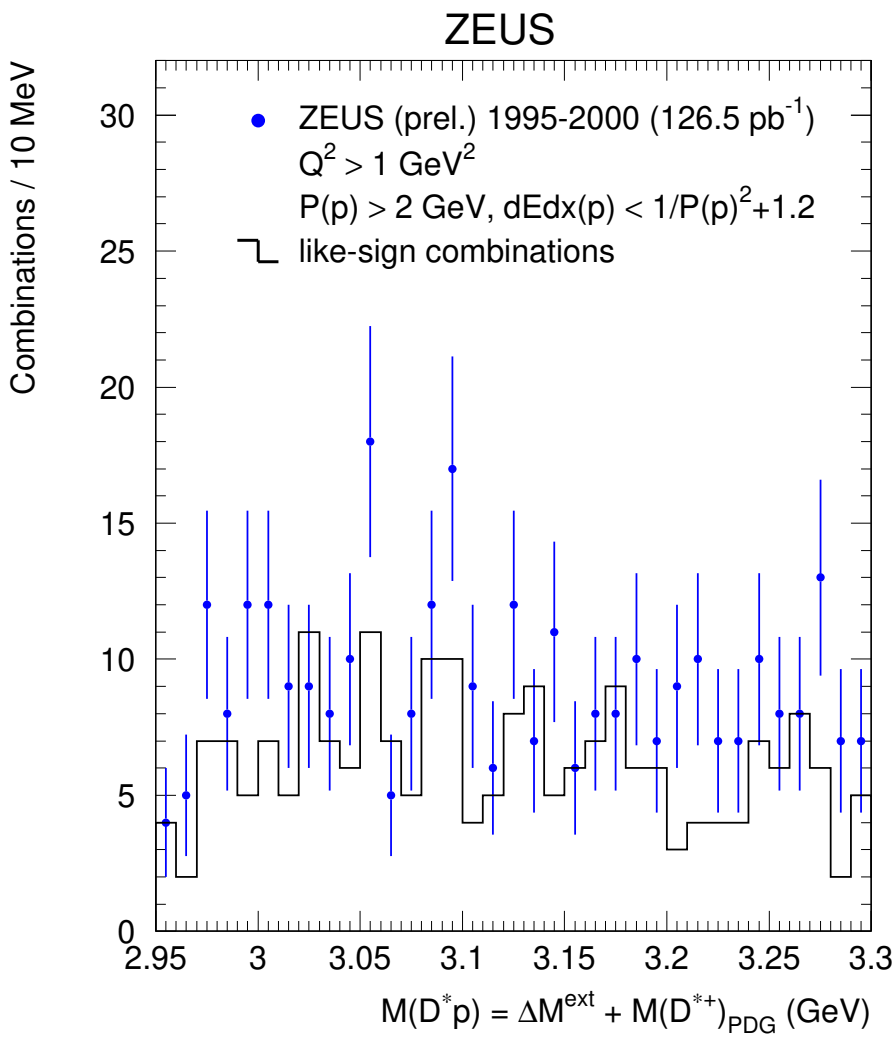
signal is cleaner

but ~ 4.5 times smaller

than in inclusive case

$M(D^*p)$ spectra in DIS with $Q^2 > 1\,\mathrm{GeV}^2$





$$M(D^*p) = \Delta M^{\mathrm{ext}} + M(D^{*+})_{\mathrm{PDG}} = M(K\pi\pi_s p) - M(K\pi\pi_s) + M(D^{*+})_{\mathrm{PDG}}$$

Again no visible signal

Systematic studies and expected signal estimation

Systematic studies

- selecting of DIS with $Q^2 > 15\,\mathrm{GeV}^2$
- varying dE/dx requirements for low-P selection
- no dE/dx requirements for high-P selection
- require $\cos\Theta^*(p) > -0.7$, where $\Theta^*(p)$ is the angle between p direction in $5q$ r.f. and $5q$ direction in the lab
- studying/removing reflections from $D_1^0, D_2^{*0} \to D^{*\pm}\pi^{\mp}$
- removing the cut on $P_T(D^{*\pm})/E_T^{\mathrm{out}\,10^\circ}$; using $z(D^{*\pm}) > 0.2$ instead
- making all cuts as close as possible to H1 selection

$$\Rightarrow \textbf{No signal}$$

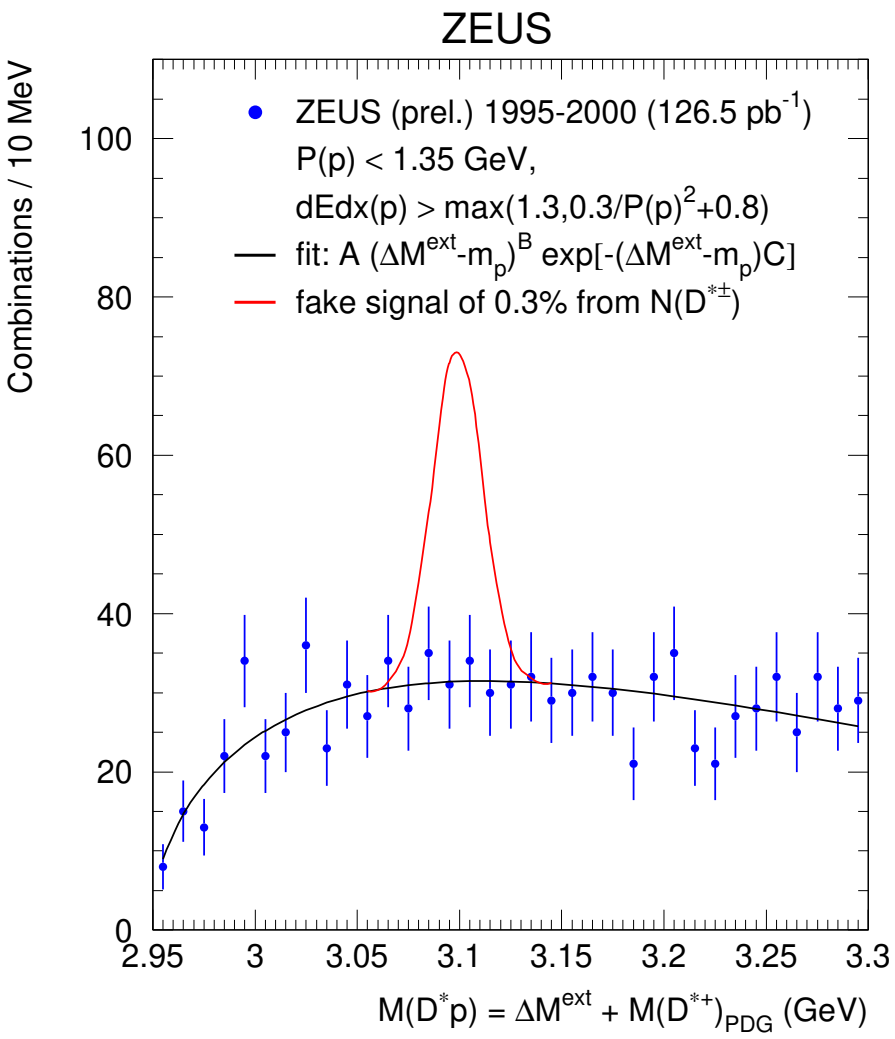
Estimation of expected signals (inspired by H1 observations):

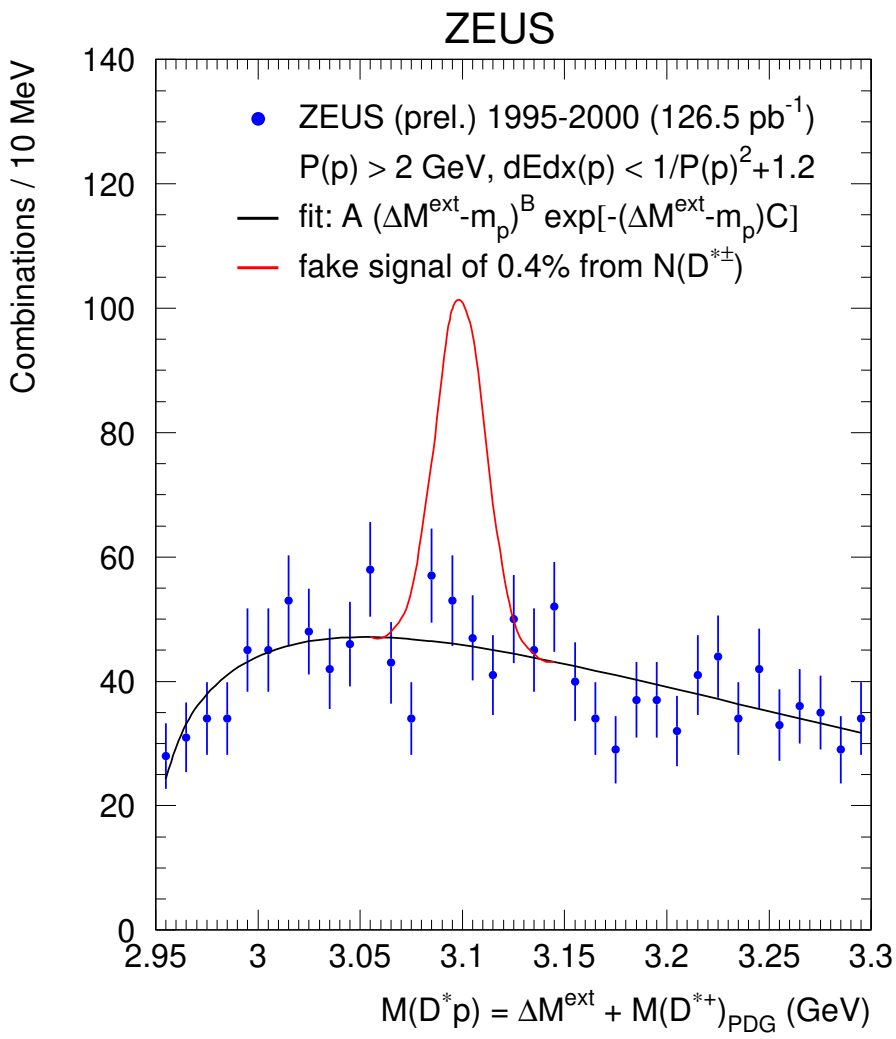
$$\frac{N^{\mathrm{rec}}(\Theta_c^0 \to D^{*-}p + c.c.)}{N^{\mathrm{rec}}(D^{*\pm})} \sim 1\%$$

$$\frac{N^{\mathrm{rec}}(P(p)<1.35\,\mathrm{GeV}, dE/dx(p)>1.3)}{N^{\mathrm{rec}}(\mathrm{all}\ p)} \sim 30\% \Rightarrow \text{low-}P \text{ selection : } 0.3\% \text{ from } N(D^{*\pm})$$

$$\frac{N^{\mathrm{rec}}(P(p)>2\,\mathrm{GeV})}{N^{\mathrm{rec}}(\mathrm{all}\ p)} \sim 40\% \Rightarrow \text{high-}P \text{ selection : } 0.4\% \text{ from } N(D^{*\pm})$$

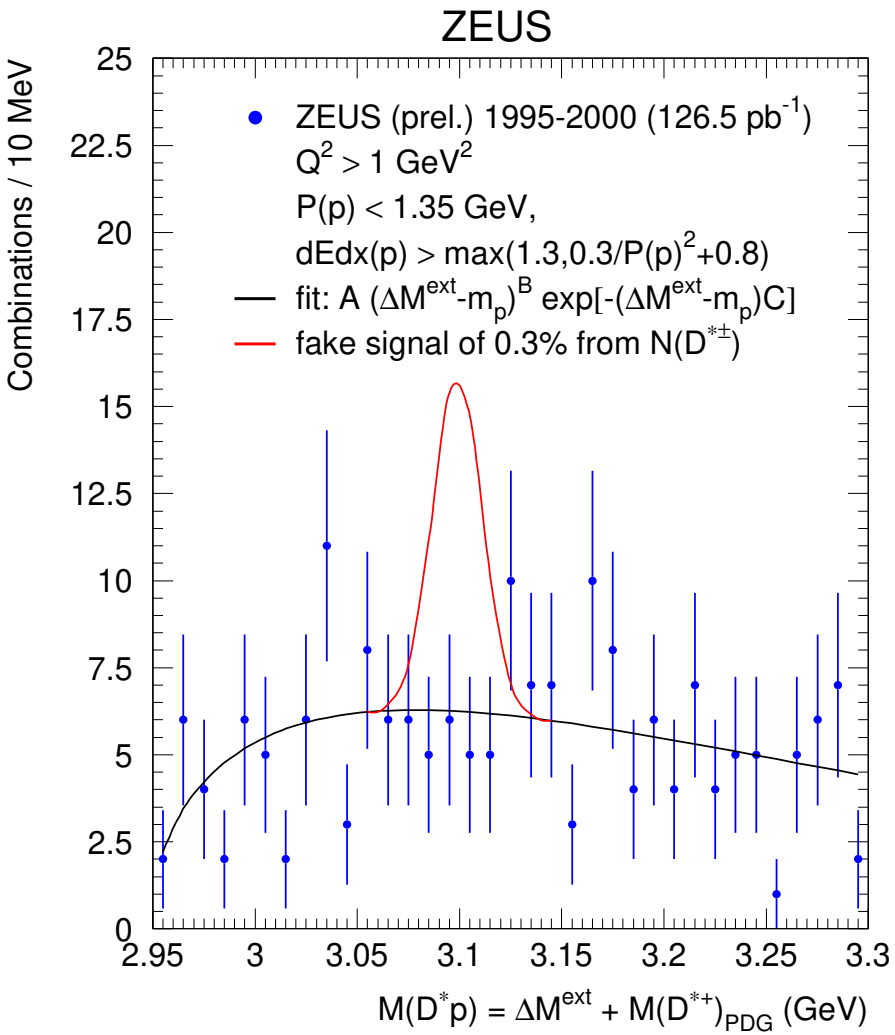
Estimated signal expectations

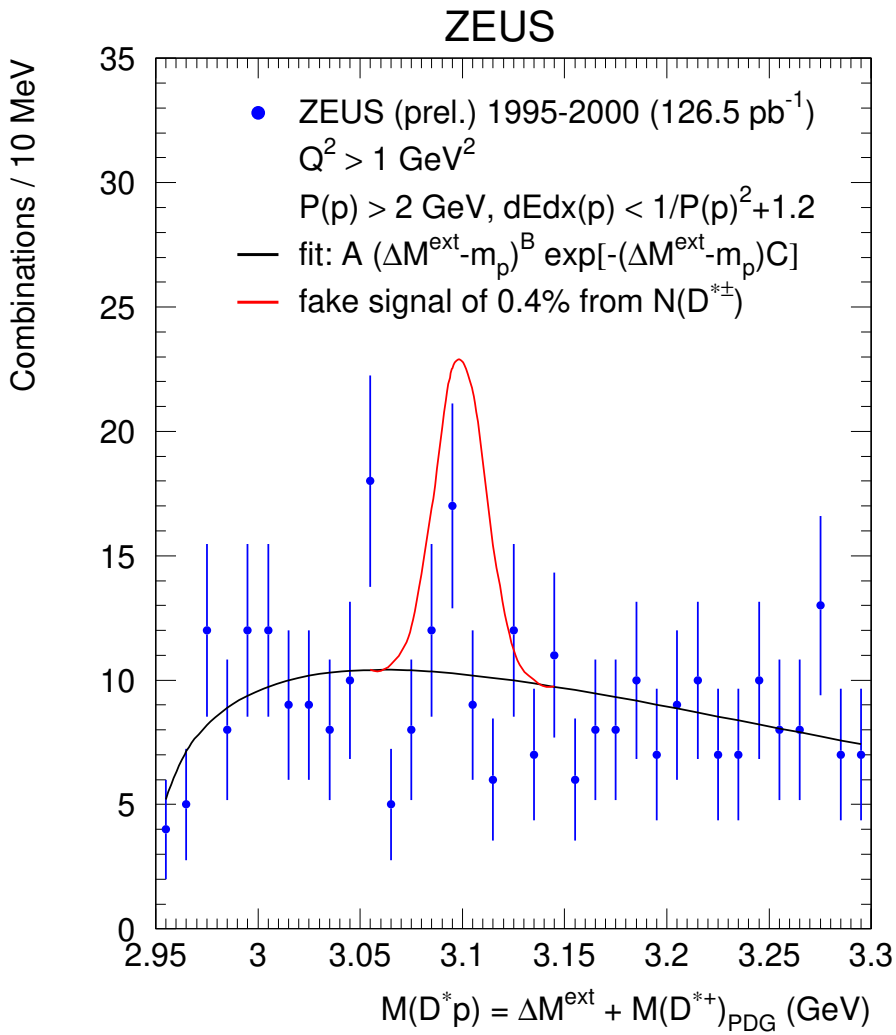




$\Rightarrow$ **Large signals are excluded**

Estimated signal expectations in DIS with $Q^2 > 1\,\mathrm{GeV}^2$





Sensitivity is smaller

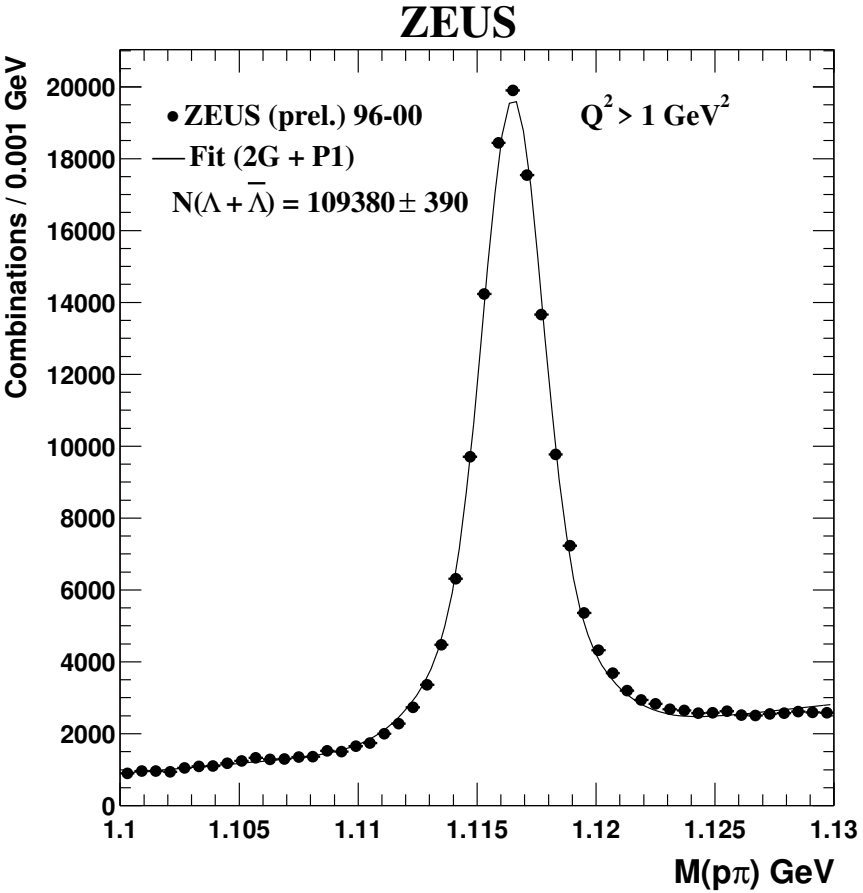
but no large signals are seen

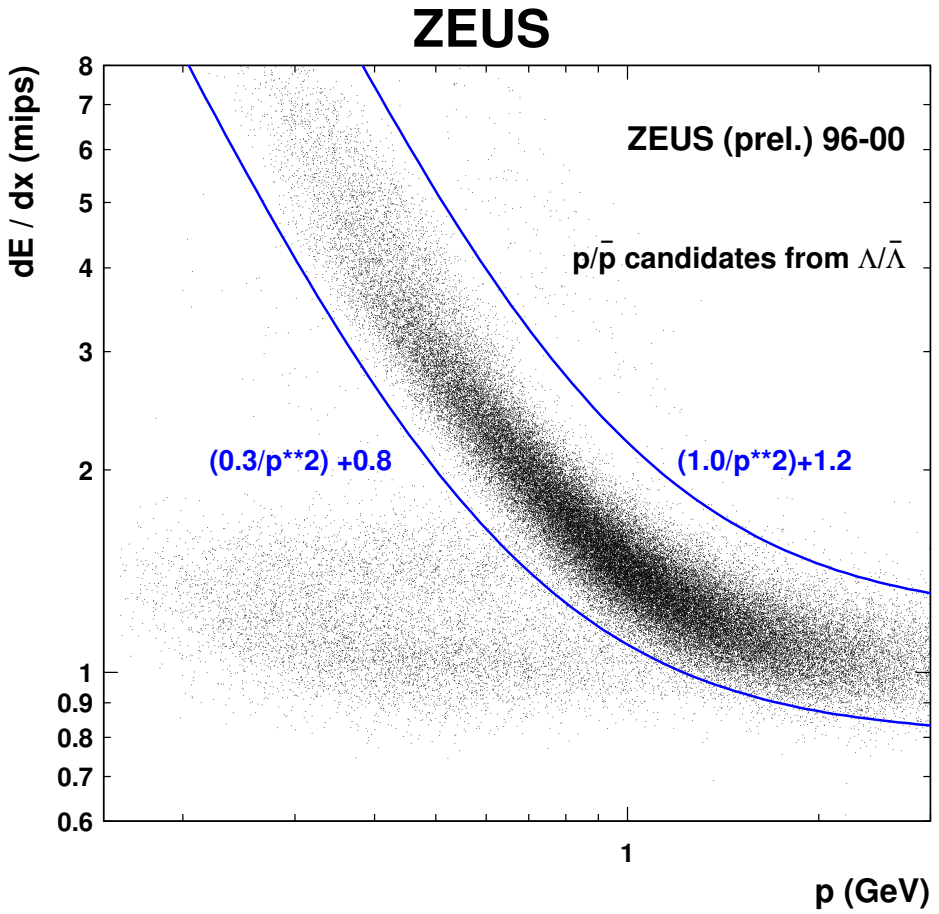
Summary

Using all HERA-I data ($126.5\,\mathrm{pb}^{-1}$)

- **The P-wave charm mesons** $D_1^0(2420)$, $D_2^{*0}(2460)$, $D_{s1}^{\pm}(2536)$ **are clearly seen**
- **No evidence for the radially excited state** $D^{*\prime\pm}(2637) \to D^{*\pm}\pi^+\pi^-$ **seen by DELPHI**
- **The strange (anti)pentaquark** $\Theta^+(1530) \to K_S^0 p(\bar{p})$ **is seen with a width consistent with resolution**
- **No resonance structure is seen in the** $M(D^*p)$ **spectra**
- **ZEUS data constrain the uncorrected fraction of** $D^{*\pm}$ **mesons originating from** Θ_c^0 **decays to be well below** 1%

Backup: Proton dE/dx band



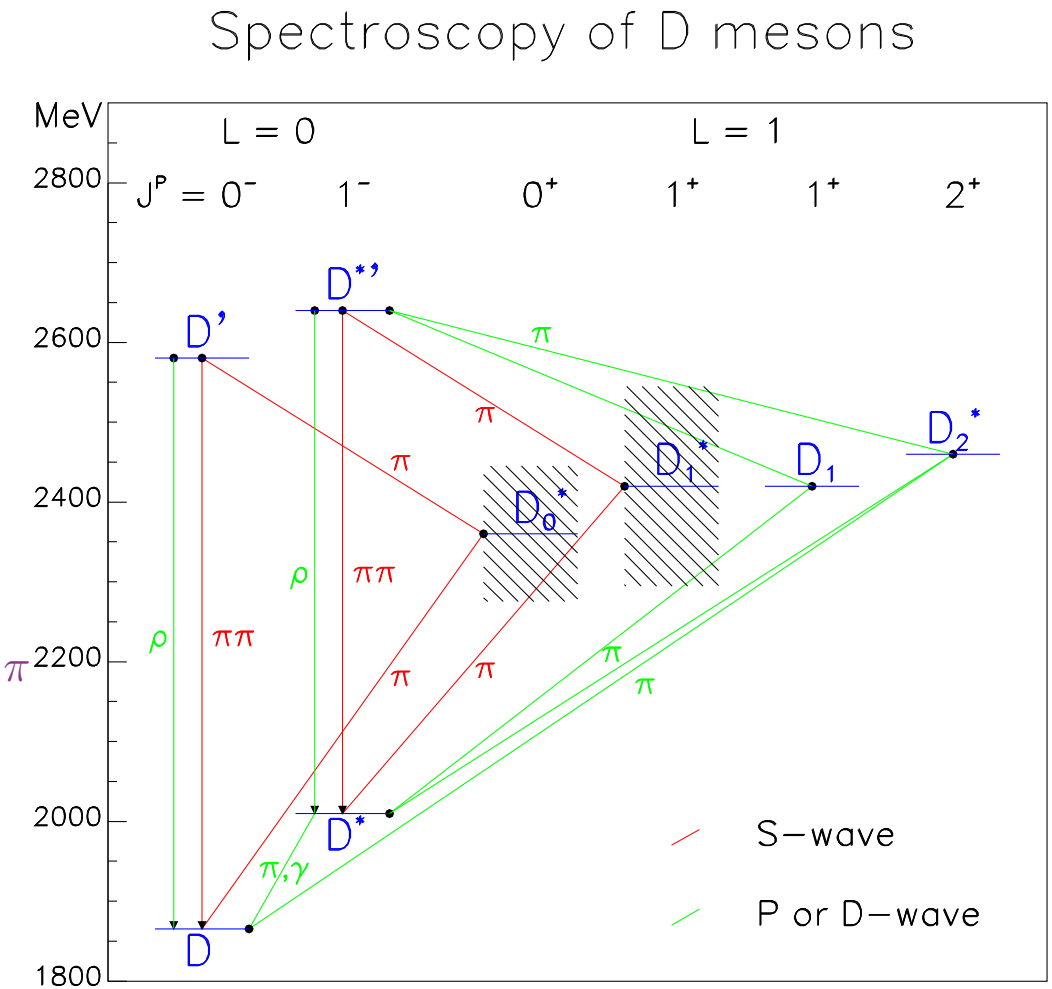


$\Lambda^0 \to p\pi$ **from sec.vert.**

dE/dx **for** $p/\bar{p}$ **candidates**

$$0.3/P^2 + 0.8 < dEdx < 1.0/P^2 + 1.2$$

Backup: Excited Charm Mesons



In HQET: two doublets of P-wave D mesons

Wide: D_0^* $(J^P = 0^+)$, D_1^* $(J^P = 1^+)$

Narrow: D_1 (1^+), D_2^* (2^+)

Non-strange P-wave mesons: $D_1^0(2420)$,$D_2^{*0}(2460)$

Both are narrow ($\approx$ 20 MeV) and decay to D^*

Charm-strange P-wave mesons:

$D_{s1}^{\pm}(2536)$,$J^P = 1^+(?)$

$D_{sJ}^{\pm}(2573)$,$J^P = 2^+(??)$

ZEUS 1995-2000 PHP+DIS

$$D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+)\pi_s^+ \ \textbf{(+c.c.)}$$

$$p_\perp^{D^*} > 2 \ \textbf{GeV} \ , \ |\eta^{D^*}| < \textbf{1.5}$$

Backup: trigger selection

First level trigger:

CAL-FLT: regional energy sums

CTD-FLT: "tracks" looking to the nominal interaction point

DIS : scattered electron (and CTD-FLT)

Untagged PhP : CTD-CAL and CTD-FLT

Tagged PhP : 44m and 35m taggers, CTD-CAL and CTD-FLT

Second level trigger:

DIS : scattered electron and CAL energies

Untagged PhP : CAL energies and SLT tracks (high-W)

Tagged PhP : 44/35m taggers, CAL energies and SLT tracks

Third level trigger:

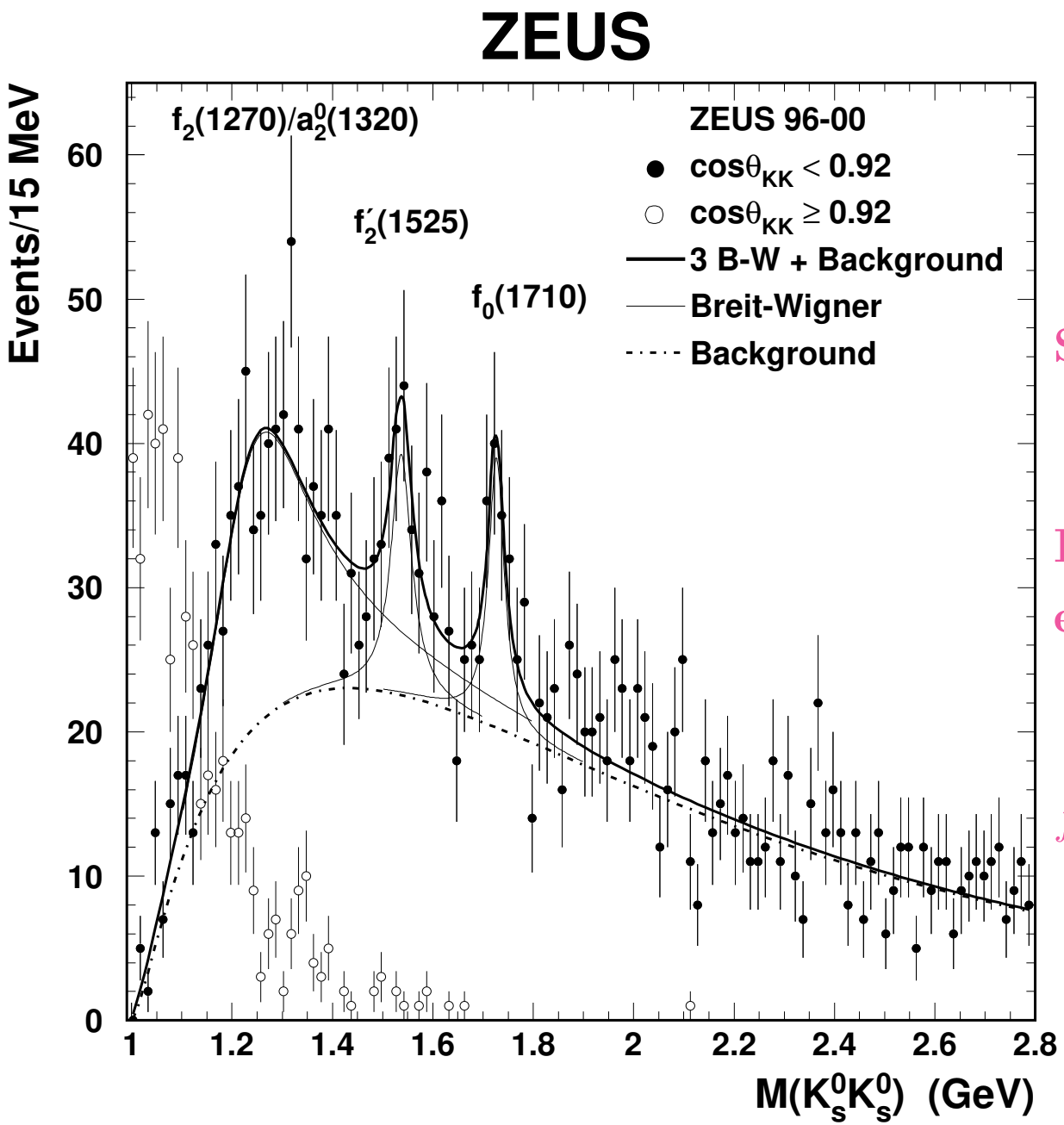
Inclusive DIS : almost offline selection

$D^{*\pm}$ in DIS : reconstructed $D^{*\pm}$ in DIS events (low Q^2)

Inclusive PhP : dijet events

$D^{*\pm}$ in PhP : reconstructed $D^{*\pm}$ in tagged/untagged PhP events

Backup: $K^0_S K^0_S$ Resonances in DIS



Several resonances observed

Produced in gluon-rich environment

$f_0(1710)$ = glueball candidate ??