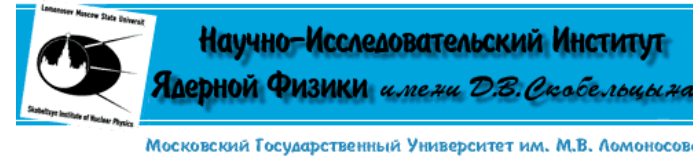


Charm spectroscopy and exotics at ZEUS



Leonid Gladilin
(SINP MSU)



ICHEP 06, 26.07 - 2.08, Moscow



OUTLINE :

HERA and HERA II

results on $\Theta^+ \rightarrow K_s^0 p$ (+c.c.)

d/\bar{d} production in DIS

search for $\Theta_c^0 \rightarrow D^{*-} p$ (+c.c.)

excited D mesons

Summary and Outlook

BACKUP :

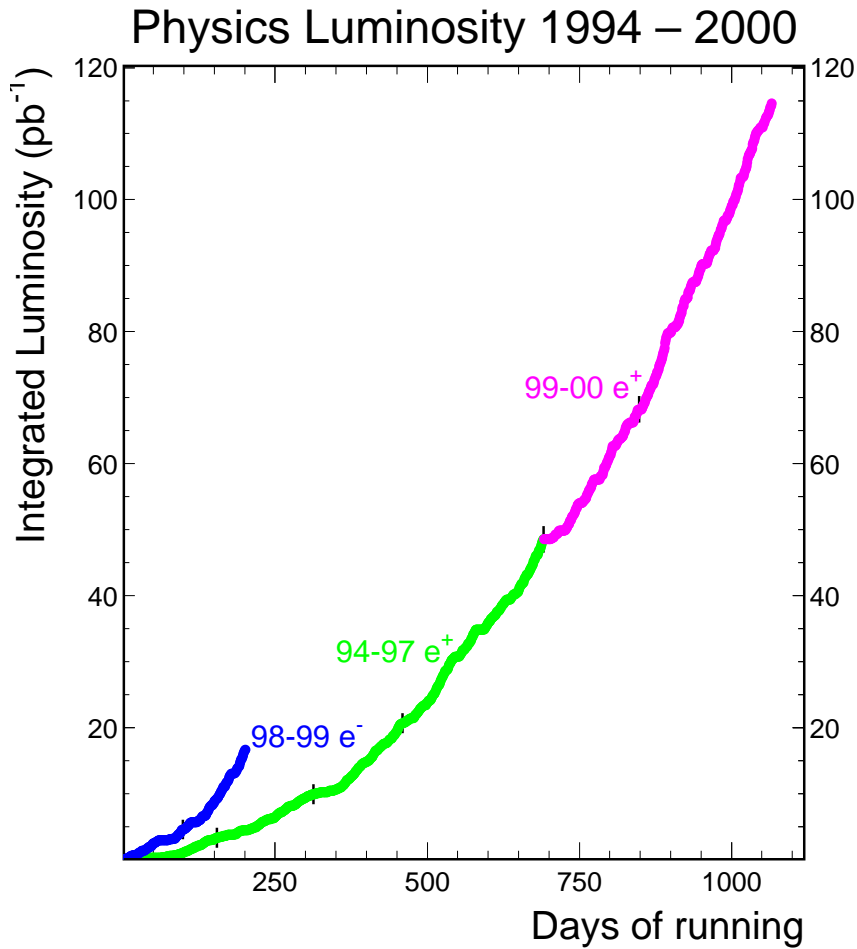
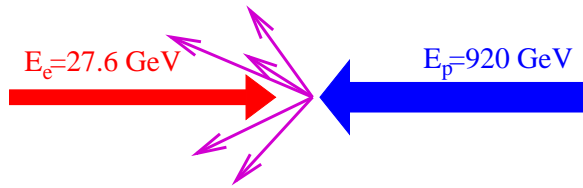
more on $\Theta^+ \rightarrow K_s^0 p$ (+c.c.)

Θ^{++} and $\Xi_{3/2}^{--,0}$ searches

more on $\Theta_c^0 \rightarrow D^{*-} p$ (+c.c.)

more on excited D mesons

HERA → HERA II



H1, ZEUS : > 100 pb⁻¹ each

	HERA	HERA II
1992-2000		2003-2007

\sqrt{s}	320 (300)	320 GeV
\mathcal{L}	$1.5 \cdot 10^{31}$	$7 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
\mathcal{L}_{int}	0.1	$\sim 0.5 \text{ fb}^{-1}$

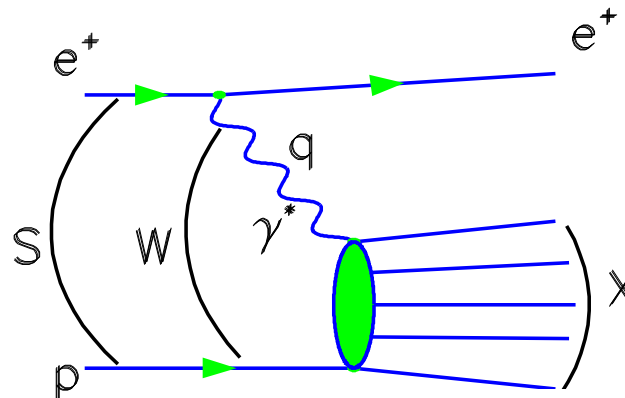
$$e(k) + p(P) \rightarrow e(k') + X \quad s = (P + k)^2$$

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

Photoproduction
DIS

$$Q^2 \simeq 0 \text{ GeV}^2$$

$$Q^2 > 1 \text{ GeV}^2$$

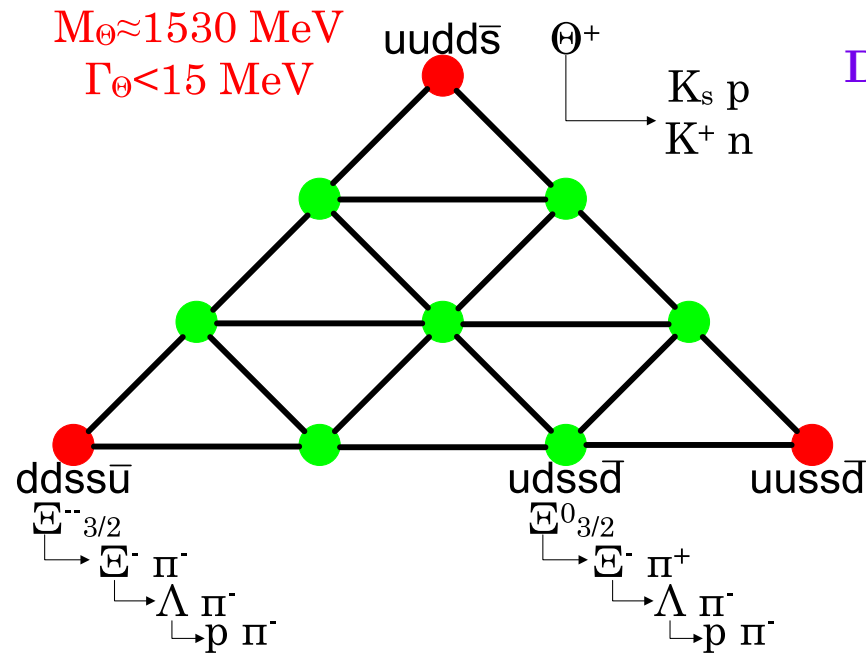


$$W^2 = (P + q)^2$$

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

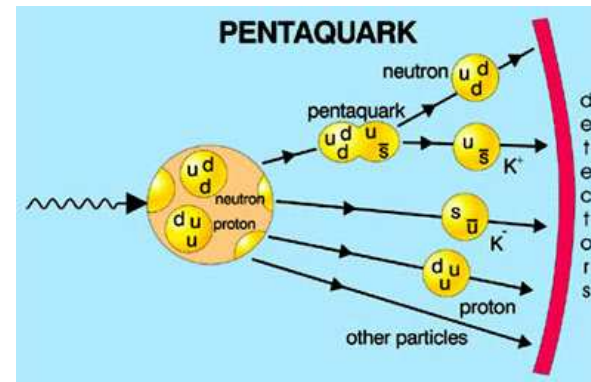
$$x = \frac{Q^2}{2qP} \simeq \frac{Q^2}{sy}$$

Strange pentaquarks



Diakonov, Petrov, Polyakov (hep-ph/9703373)

Exotic Anti-Decuplet of Baryons:
 predictions from Chiral Solitons



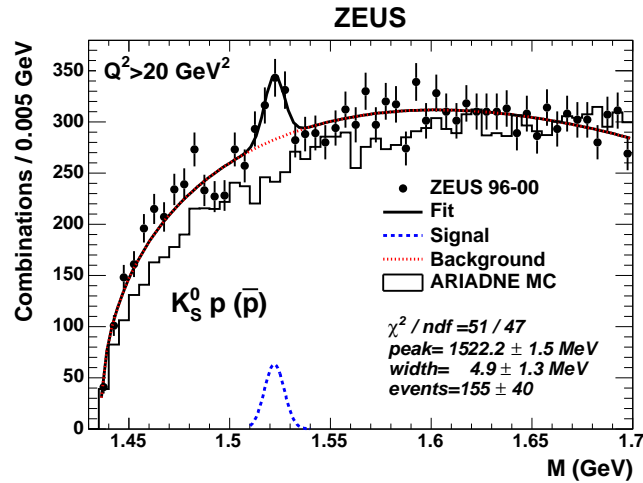
exotic ($S=B=+1$) narrow baryon $\Theta^+ \rightarrow K^+ n$ observed by **LEPS**, CLAS, SAPHIR
 non-exotic decay mode $\Theta^+ \rightarrow K_s^0 p$ seen by DIANA, HERMES, COSY-TOF, SVD, ZEUS, ITEP

negative results from **BES**, HERA-B, CDF, ALEPH, DELPHI, L3, BABAR, BELLE, SPHINX, HyperCP, PHENIX and ... CLAS ($\gamma p \rightarrow K_s^0 K^+ n$) with $50 \times$ SAPHIR

another exotic ($S=-2, B=+1$) narrow baryon $\Xi_{3/2}^{--} \rightarrow \Xi^- \pi^-$ reported by NA49

negative results from **WA89**, HERA-B, HERMES, CDF, ALEPH, BABAR, ZEUS, ...

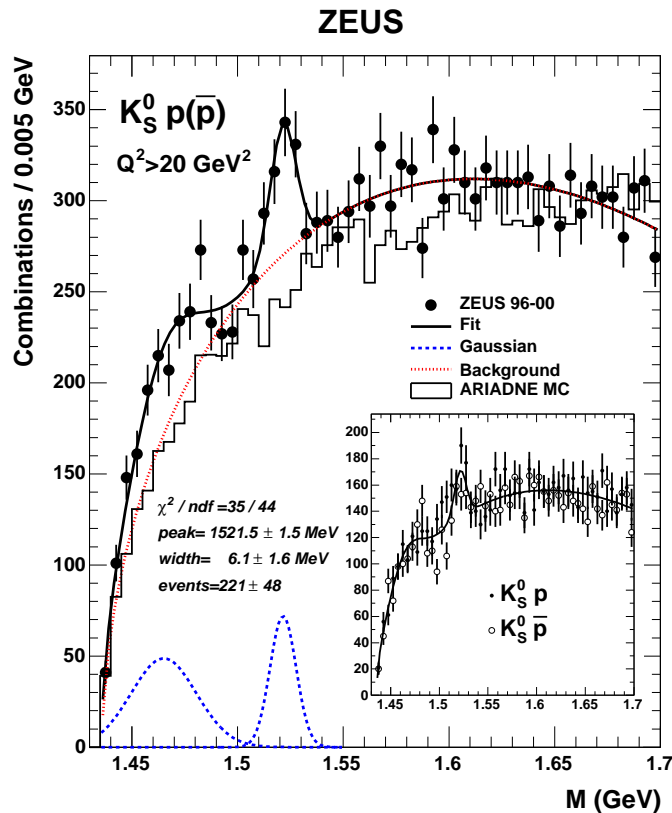
$M(K_s^0 p(\bar{p}))$ for $Q^2 > 20 \text{ GeV}^2$



$Q^2 > 20 \text{ GeV}^2$: best signal identification

Fit with Gaussian + background (3 par.)

$N = 155 \pm 40$, $M = 1522.2 \pm 1.5 \text{ MeV}$
width compatible with resolution



Fit with 2nd Gaussian for (Σ ?) bump around 1465 MeV

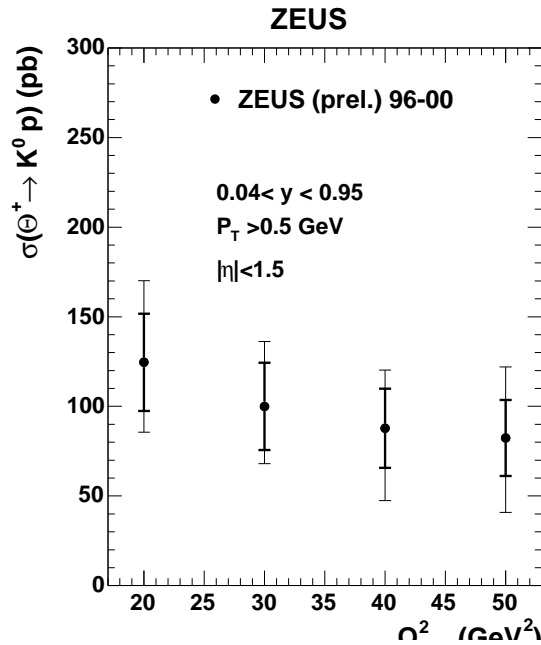
$N = 221 \pm 48$, $M = 1521.5 \pm 1.5 \text{ MeV}$
width compatible with resolution

For BW: $\Gamma = 8 \pm 4$ (stat.) MeV

⇐ signal seen in both charges

$N(\Theta^- \rightarrow K_s^0 \bar{p}) = 96 \pm 34$

Θ^+ cross section (ZEUS) and upper limit on it (H1)



Θ^\pm cross section in the visible range:

$$Q^2 > 20 \text{ GeV}^2, 0.04 < y < 0.95$$

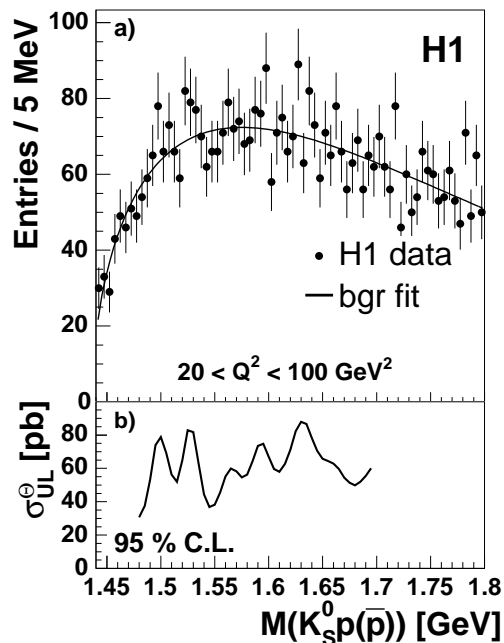
$$p_T(\Theta^\pm) > 0.5 \text{ GeV}, |\eta(\Theta^\pm)| < 1.5$$

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

$$R = \sigma(\Theta^+ \rightarrow K^0 p) / \sigma(\Lambda^0) = 4.2 \pm 0.9_{-0.9}^{+1.2} \%$$

$$\text{HERA-B: } R < 0.46 \%$$

$$\text{ALEPH: } R < 0.4 \%$$



H1 : no significant signal

in particular, for $Q^2 > 20 \text{ GeV}^2$

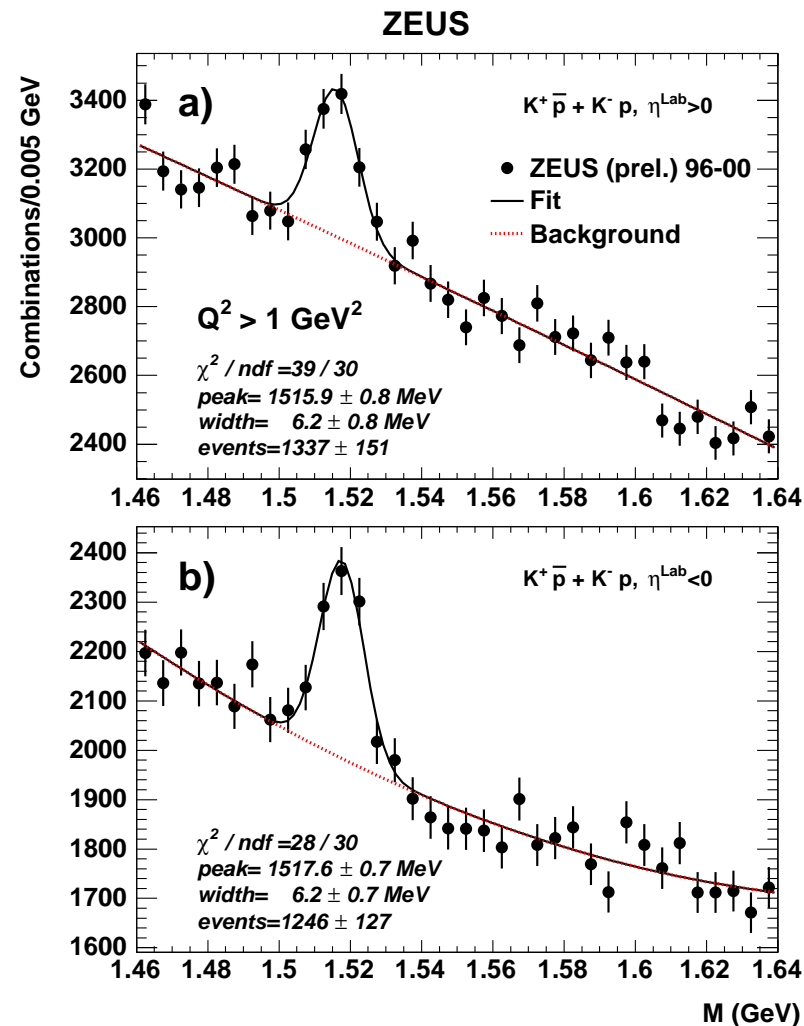
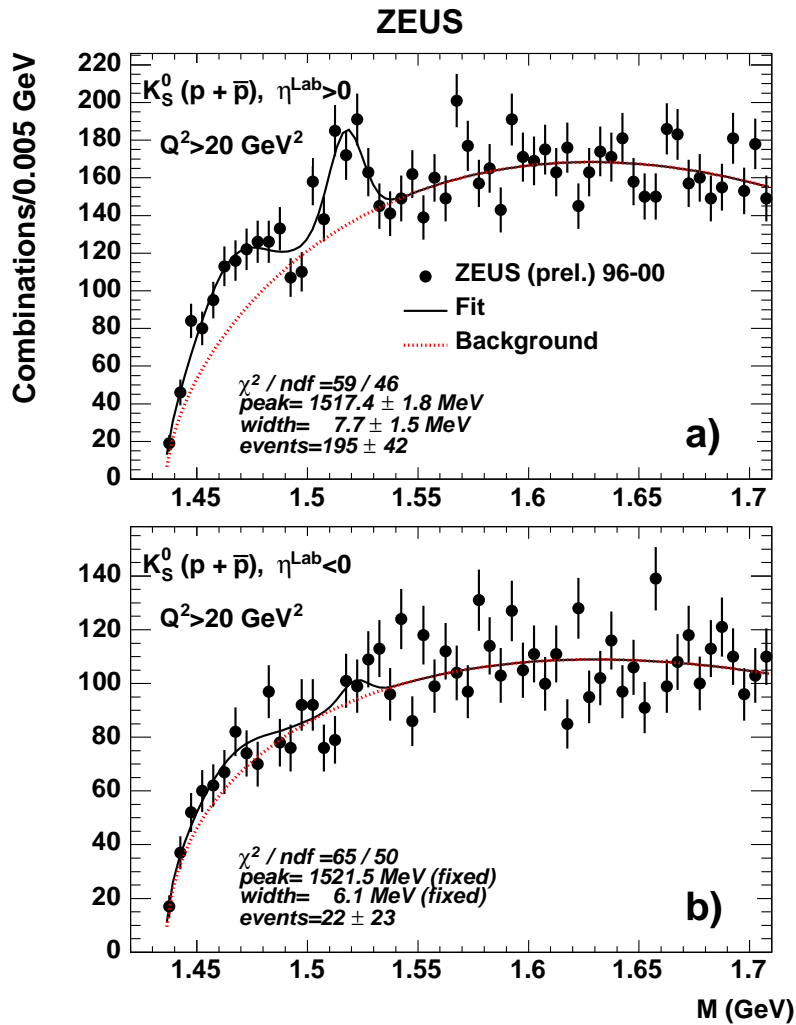
consistent with the ZEUS measurement

note : $\mathcal{L}_{int}(\text{ZEUS}) = 121 \text{ pb}^{-1}$

$$\mathcal{L}_{int}(\text{H1}) = 74 \text{ pb}^{-1}$$

larger luminosity is vital

Θ^+ production mechanism in ep collisions ?

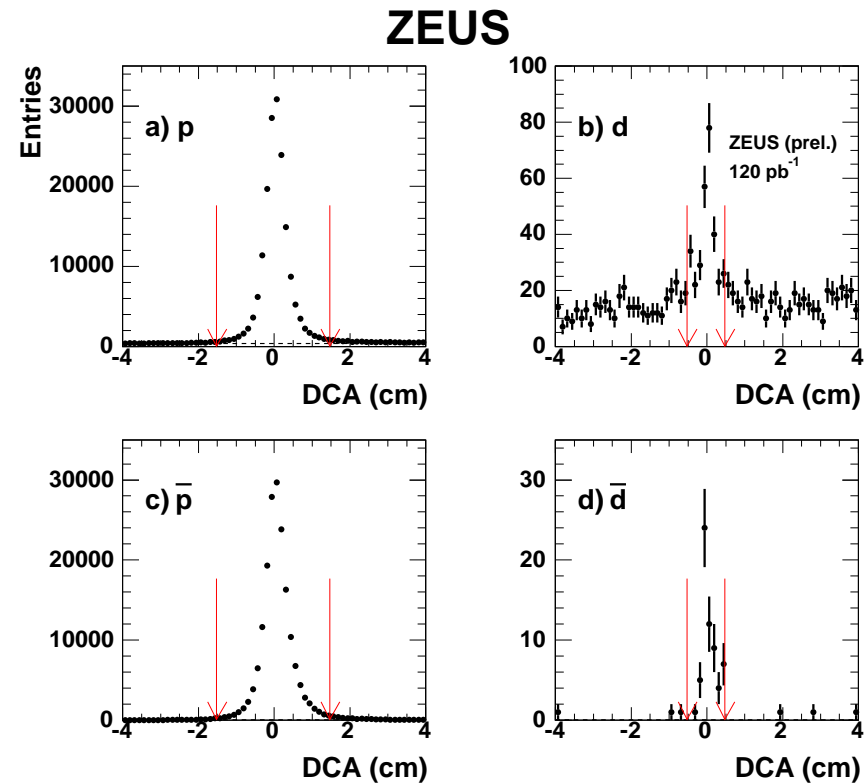
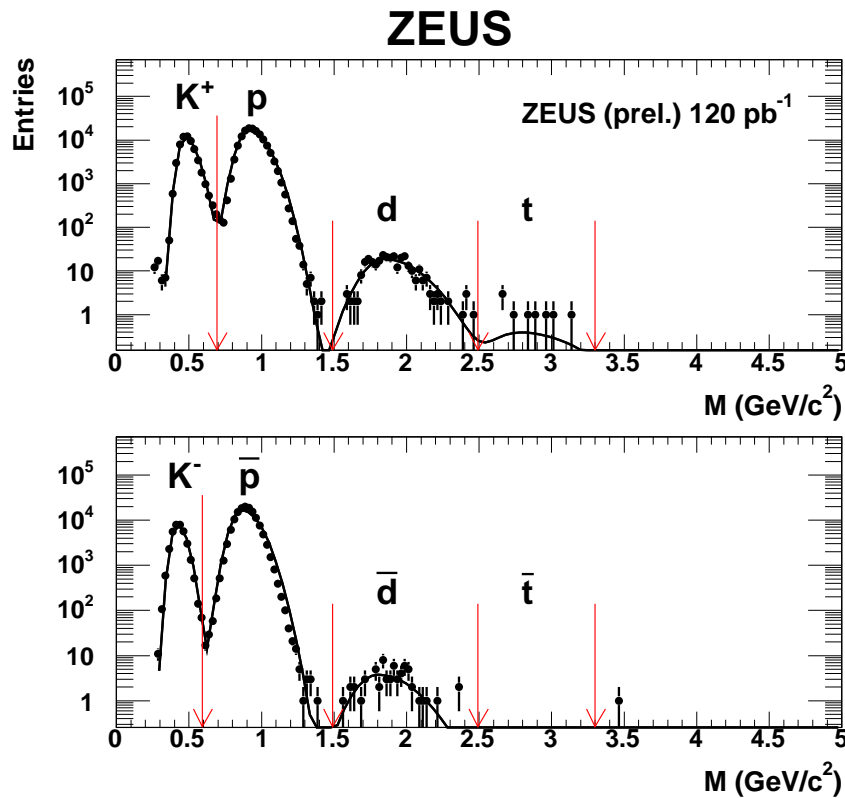


Θ^\pm produced mostly in forward (proton) direction

It is not a case for $\Lambda(1520)$ produced in q/g fragmentation

Θ^\pm may have unusual production mechanism related to p -remnant fragmentation ?
 in case of coalescence, should be sizeable d/\bar{d} production in DIS

d/\bar{d} production in DIS with $Q^2 > 1 \text{ GeV}^2$



$M = P / f_{BB}^{-1}(dE/dx)$
for tracks with $dE/dx > 2.5$

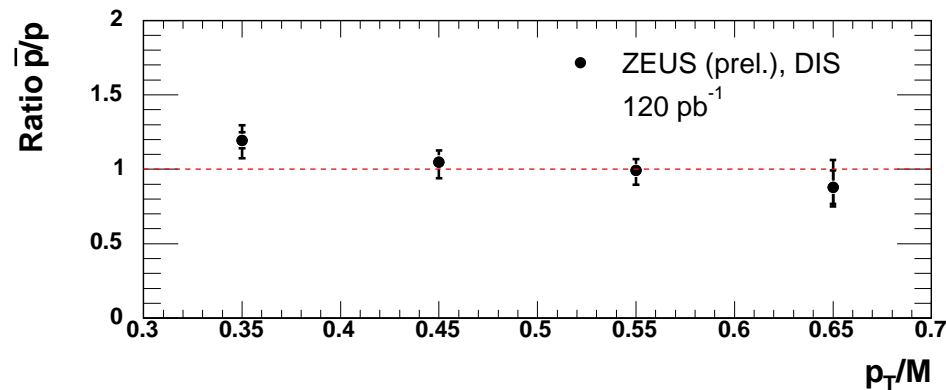
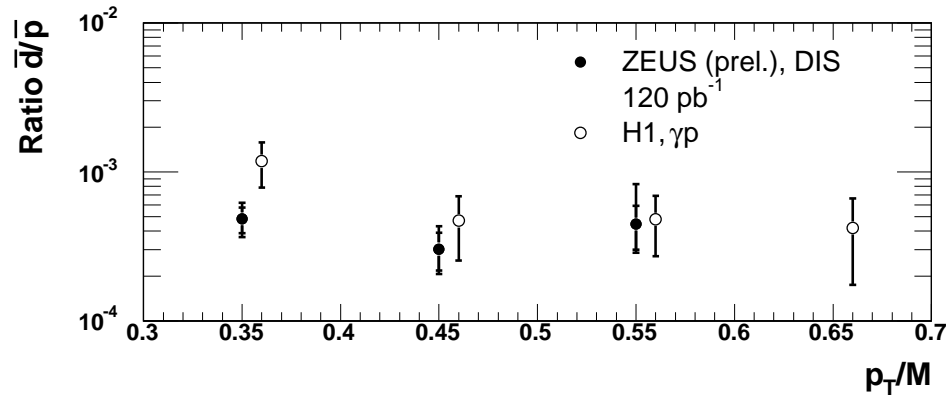
Distance of Closest Approach
to beam spot in transverse plane

Subtracting side-band background: $N(d) = 195 \pm 18$
 $N(\bar{d}) = 61 \pm 8$

Yes, d/\bar{d} are produced in DIS as well

\bar{d}/\bar{p} ratio in DIS with $Q^2 > 1 \text{ GeV}^2$

ZEUS



\bar{d}/\bar{p} ratio similar to H1 (γp)
and pp data

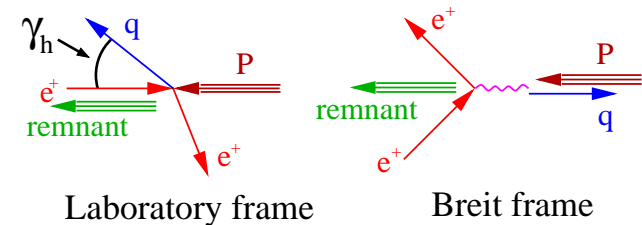
$$\frac{1}{\sigma} \frac{E_A d^3 \sigma_A}{d^3 P_A} = B_A \left(\frac{1}{\sigma} \frac{E_N d^3 \sigma_N}{d^3 P_N} \right) A$$

$$P_N = P_A/A$$

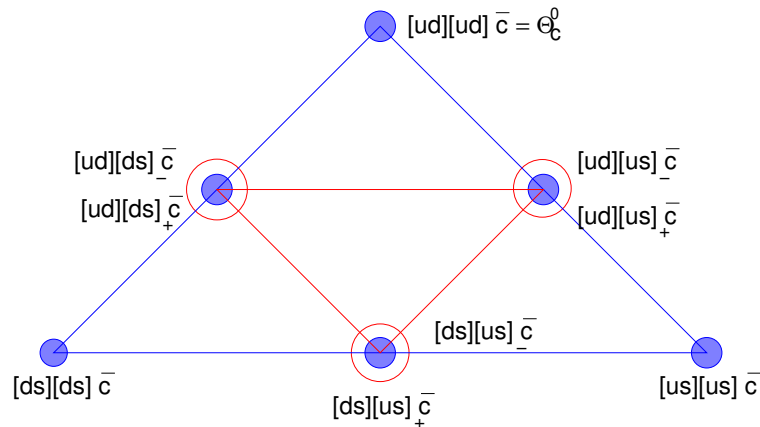
\bar{p}/p ratio ~ 1

Coalescence Model with $B_2 \approx (0.5 - 1) \cdot 10^{-2} \text{ GeV}^2$ works for \bar{d} production in DIS

no \bar{d} in current region of Breit frame \implies no contradiction with low \bar{d} rates in e^+e^-



Charm pentaquarks



What about $\Theta_c^0 = (ud)^2 \bar{c}$?

Jaffe-Wilczek (hep-ph/0307341): $M(\Theta_c^0) = 2710 \text{ MeV}$

Such Θ_c^0 would be too light to decay to D mesons
can decay weakly to $\Theta^+ \pi^-$, $p K^0 \pi^-$, $p K^+ \pi^- \pi^-$, ...

Karliner-Lipkin (hep-ph/0307343): $M(\Theta_c^0) = 2985 \pm 50 \text{ MeV}$

$\Gamma(\Theta_c^0) \sim 21 \text{ MeV}$

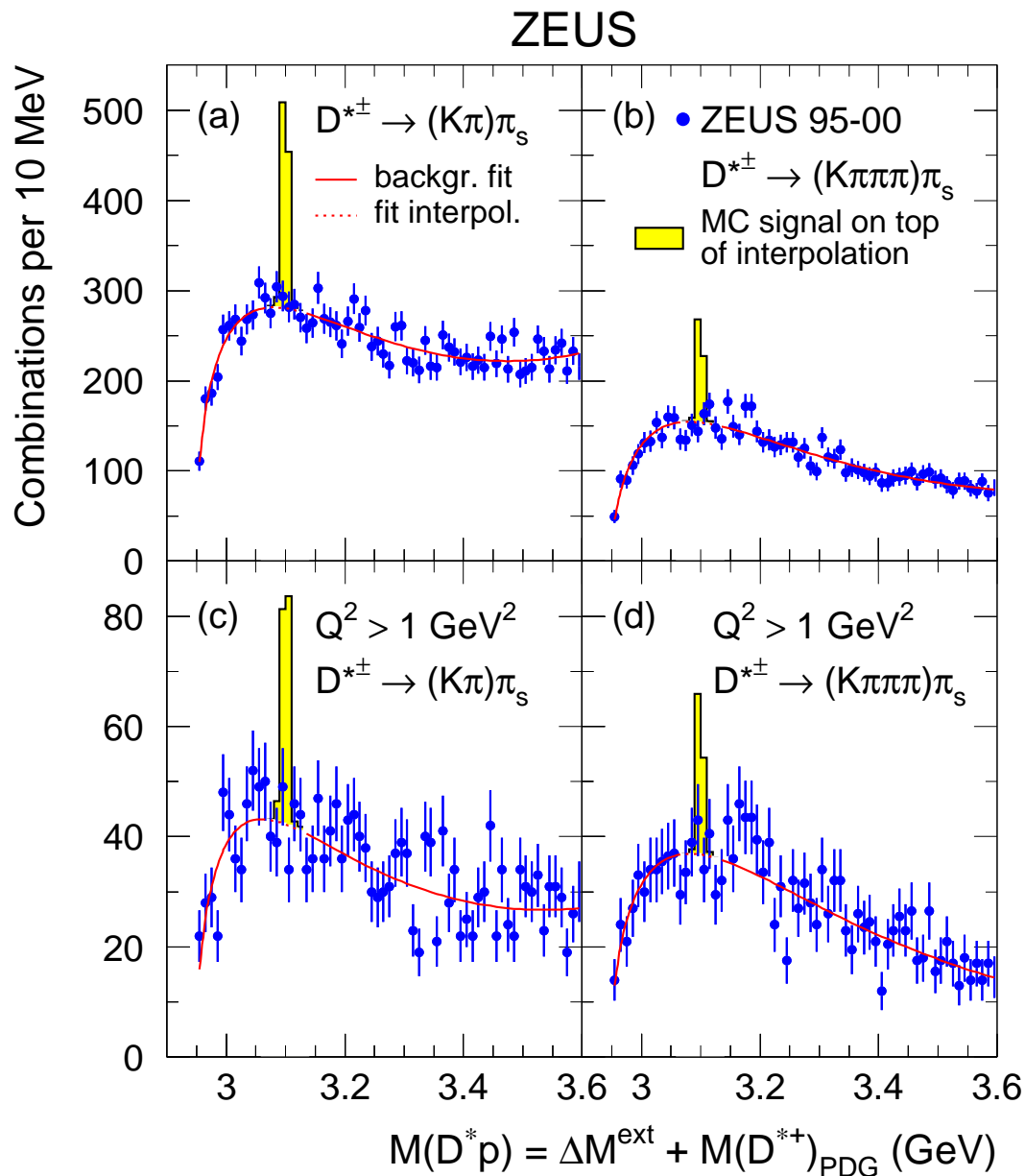
Such Θ_c^0 would decay to $D^{(*)-} p$ (+ c.c.)

H1 (hep-ex/0403017) observed a signal in $M(D^{*-} p)$ (+ c.c.)

contributed “roughly 1% to the visible $D^{*\pm}$ yield

negative results from ZEUS (hep-ex/0409033), ALEPH, BELLE,
FOCUS, CDF, ...

ZEUS limits on Θ_c^0 rate



yellow signals: MC signals
 normalised to 1% of obs. D^*
1% visible rate is excluded

at 9 σ for full sample
at 5 σ for $Q^2 > 1 \text{ GeV}^2$

95% C.L. upper limits:
 visible rate $R(\Theta_c^0 \rightarrow D^*p/D^*)$

< 0.23% for full sample
< 0.35% for $Q^2 > 1 \text{ GeV}^2$

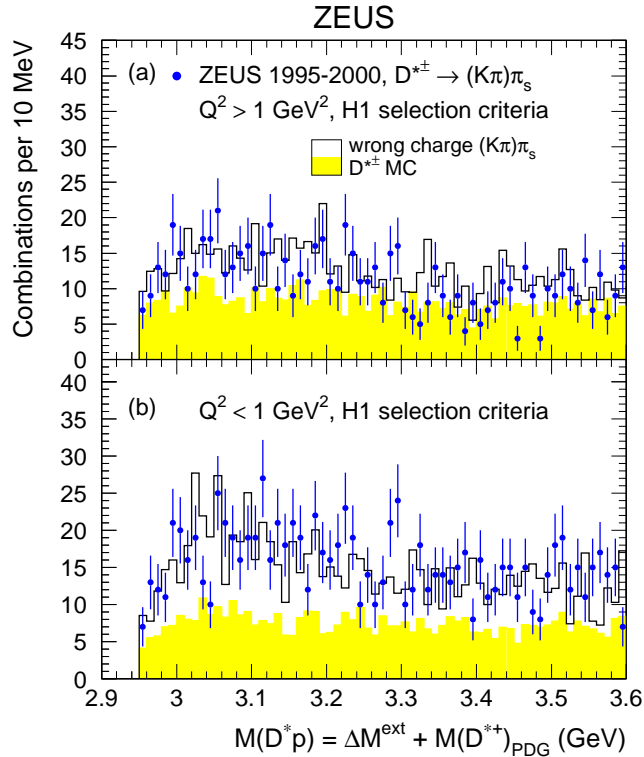
acceptance corrected rate

< 0.37% for full sample
< 0.51% for $Q^2 > 1 \text{ GeV}^2$

$f(c \rightarrow \Theta_c^0) \times B(\Theta_c^0 \rightarrow D^*p)$

< 0.16% for full sample
< 0.19% for $Q^2 > 1 \text{ GeV}^2$

H1 and ZEUS results on $\Theta_c^0 \rightarrow D^*p$ disagree



ZEUS $M(D^*p)$ with H1 selection criteria

$\Leftarrow Q^2 > 1 \text{ GeV}^2$

no signal

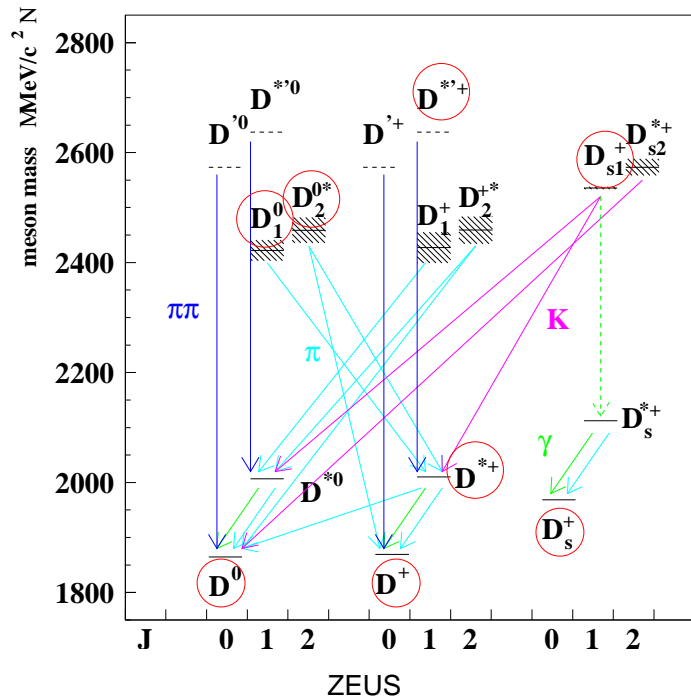
$\Leftarrow Q^2 < 1 \text{ GeV}^2$

no signal

	H1 prel.	ZEUS	ZEUS, $Q^2 > 1 \text{ GeV}^2$
visible rate $R(\Theta_c^0 \rightarrow D^*p/D^*)$	$(1.46 \pm 0.32)\%$	$< 0.23\%$ (95% C.L.)	$< 0.35\%$ (95% C.L.)
acceptance corrected rate	$(1.59 \pm 0.33_{-0.45}^{+0.33})\%$	$< 0.37\%$ (95% C.L.)	$< 0.51\%$ (95% C.L.)
$\sigma_{\text{vis}}(\Theta_c^0)/\sigma_{\text{vis}}(D^*)$	$(2.48 \pm 0.52_{-0.64}^{+0.85})\%$		
$f(c \rightarrow D^{*+}) \times \sigma_{\text{vis}}(\Theta_c^0)/\sigma_{\text{vis}}(D^*)$	$(0.58 \pm 0.12_{-0.15}^{+0.20})\%$		
$f(c \rightarrow \Theta_c^0) \times B(\Theta_c^0 \rightarrow D^*p)$		$< 0.16\%$ (95% C.L.)	$< 0.19\%$ (95% C.L.)

HERA II data can help to resolve the disagreement

Study of excited D mesons at HERA



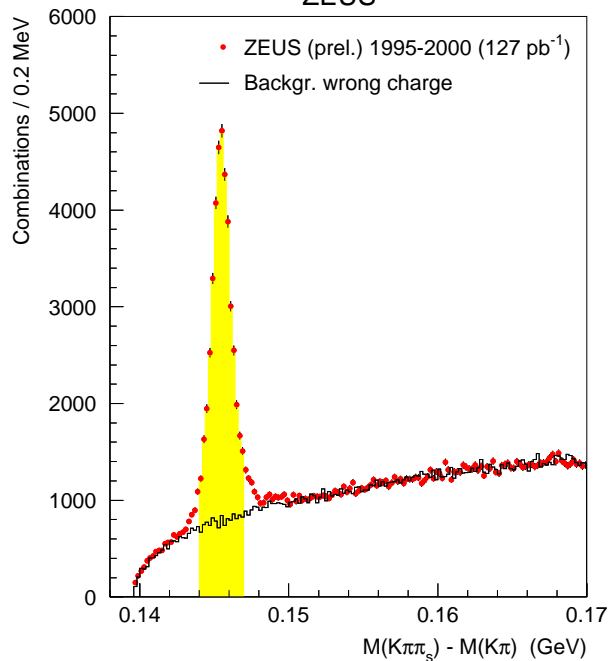
Orbitally excited:

$$1) D_1^0, D_2^{*0} \rightarrow D^{*+} \pi^- (+ \text{c.c.})$$

$$2) D_{s1}^+ \rightarrow D^{*+} K^0 (+ \text{c.c.}) \implies \text{discussion}$$

Search for radially excited:

$$3) D^{*'+} \rightarrow D^{*+} \pi^+ \pi^- (+ \text{c.c.})$$



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

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

$$P_\perp^{D^*} > 2 \text{ GeV} \text{ and } -1.5 < \eta^{D^*} < 1.5$$

In the yellow band under background:

$$N(D^{*\pm}) = 31350 \pm 240$$

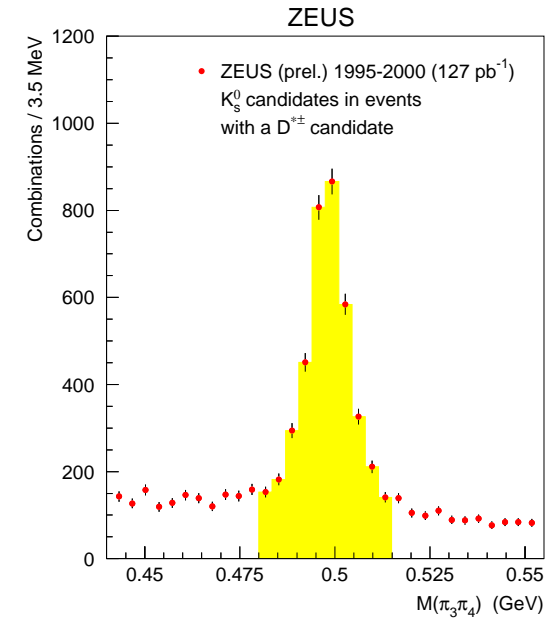
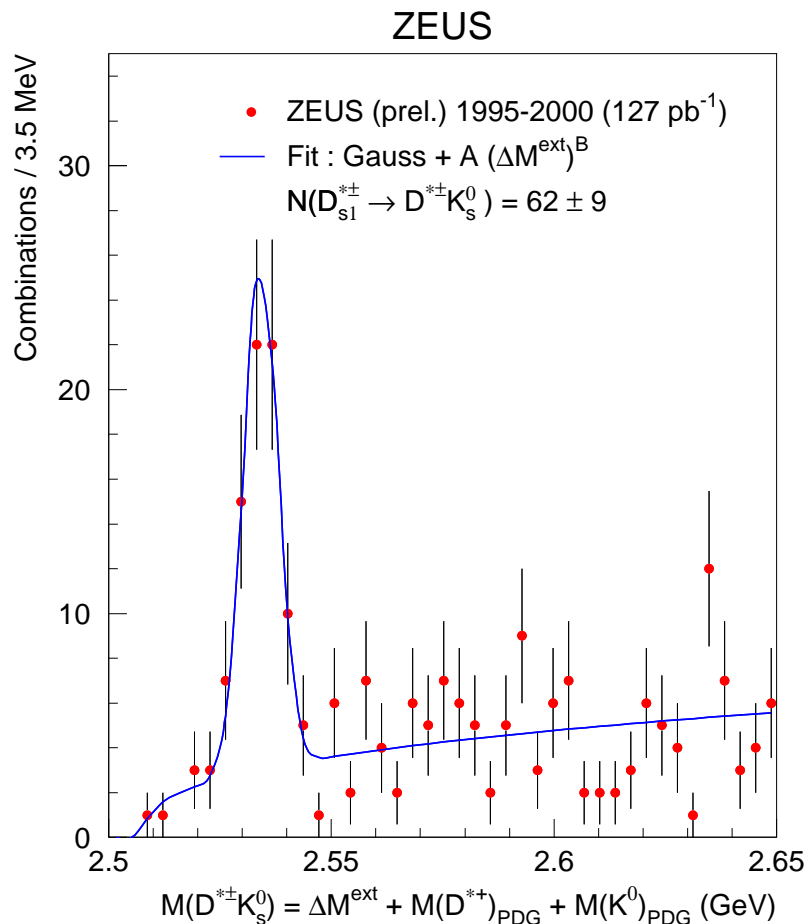
Charm-strange $D_{s1}^{\pm}(2536)$ meson

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

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

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

$$M(D_{s1}^+) = 2534.2 \pm 0.6 \pm 0.5 \text{ MeV} \quad (\sim M_{\text{PDG}})$$



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

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

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

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

ZEUS : consistent with $R = 0$, i.e. $J^P = 1^+$
 does not contradict to $R = -1$ expected for $1^-, 2^+$

Belle (recent) : $R = -0.70 \pm 0.03 \rightarrow$ mixture of D and S waves due to interf. with $D_{sJ}^+(2460)$?

Fragmentation fractions for excited D mesons

Using world average for $f(c \rightarrow D^{*+})$:

	$f(c \rightarrow D_1^0)$ [%]	$f(c \rightarrow D_2^{*0})$ [%]	$f(c \rightarrow D_{s1}^+)$ [%]
ZEUS (prel.)	$1.46 \pm 0.18^{+0.33}_{-0.27} \pm 0.06$	$2.00 \pm 0.58^{+1.40}_{-0.48} \pm 0.41$	$1.24 \pm 0.18^{+0.08}_{-0.06} \pm 0.14$
CLEO	1.8 ± 0.3	1.9 ± 0.3	
OPAL	2.1 ± 0.8	5.2 ± 2.6	$1.6 \pm 0.4 \pm 0.3$
ALEPH	1.6 ± 0.5	4.7 ± 1.0	$0.94 \pm 0.22 \pm 0.07$
DELPHI	1.9 ± 0.4	4.7 ± 1.3	

1) the same amounts of excited D mesons in e^+e^- and ep data

2) situation with $f(c \rightarrow D_2^{*0})$ is not clear

3) $f(c \rightarrow D_{s1}^+)$ is twice as large as the expectation :

$$\gamma_s \times f(c \rightarrow D_1^0) \approx 0.3 \times 2\% = 0.6\%$$

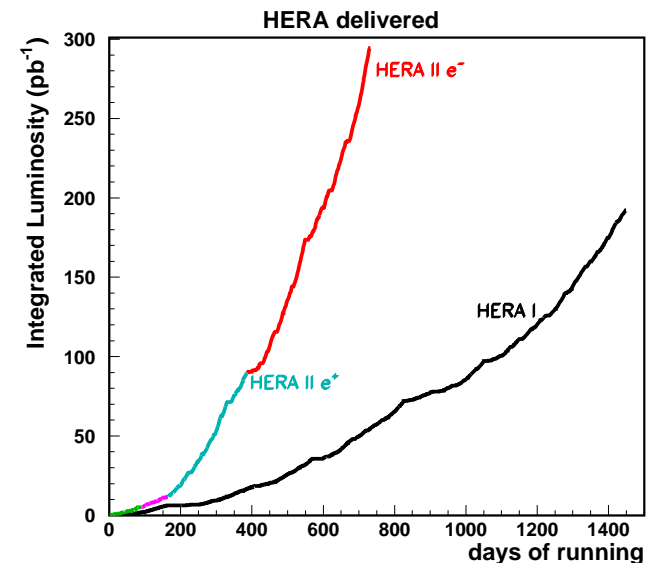
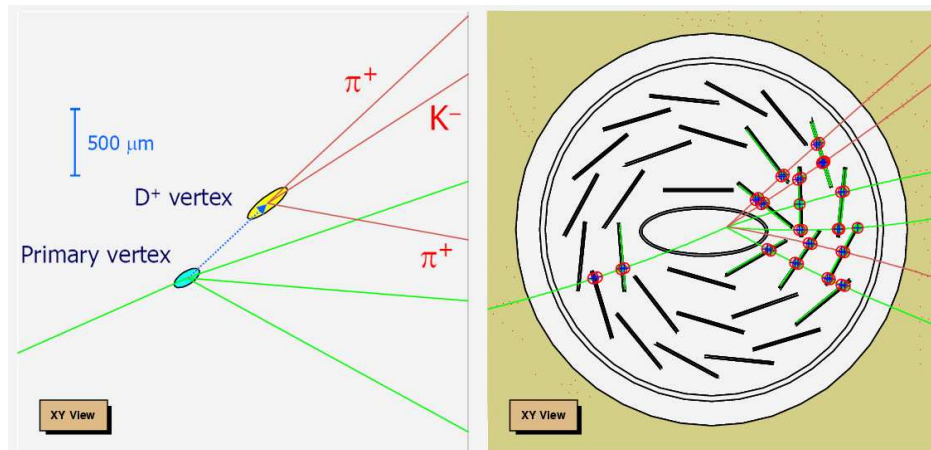
Why $f(c \rightarrow D_{s1}^+)$ is so large ?

Is it connected with its strange helicity ?

Summary and Outlook

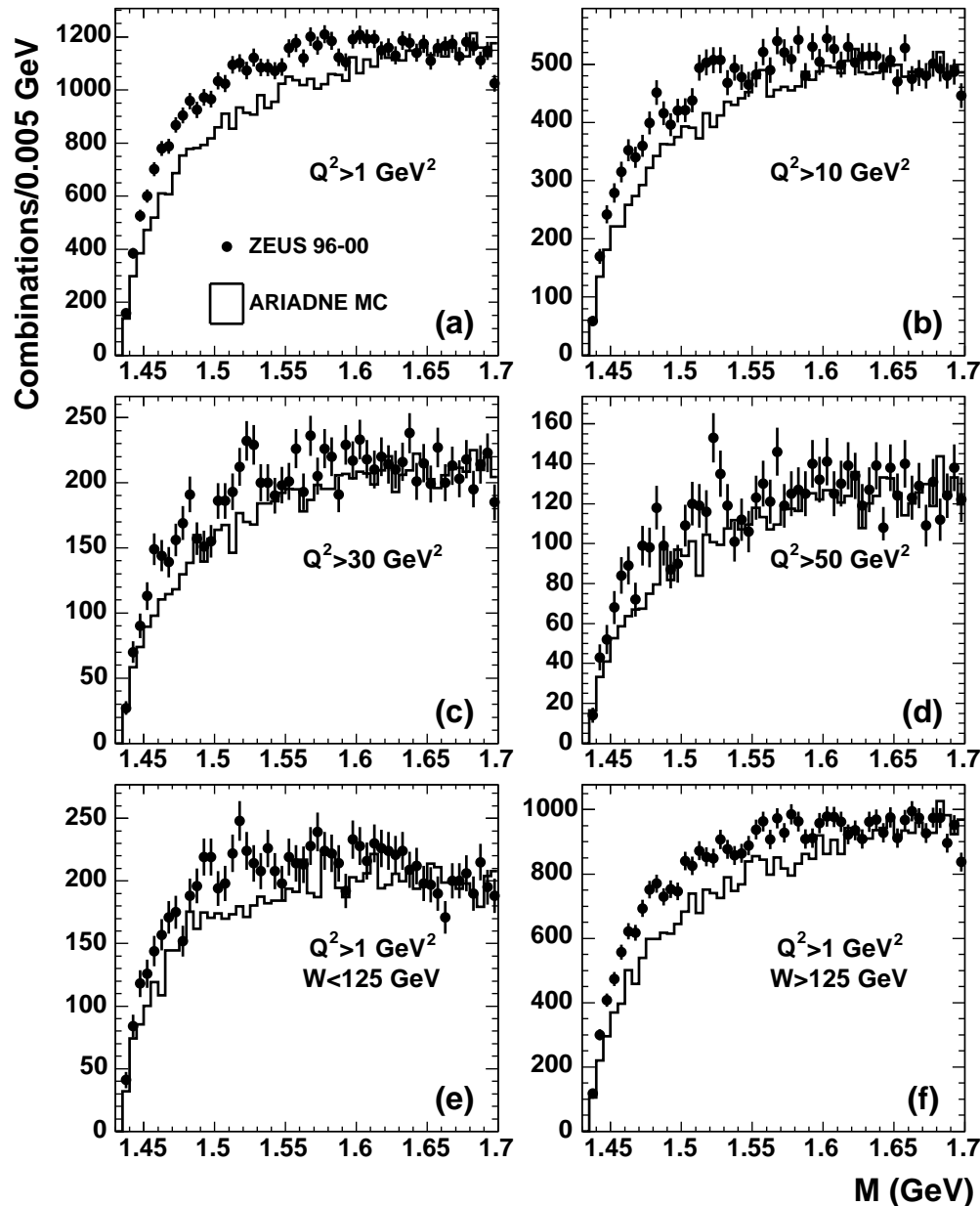
- $\Theta^+ \rightarrow K_s^0 p$ production observed in high- Q^2 DIS by ZEUS.
H1 does not see the signal that is not in statistical contradiction with ZEUS.
Studies suggest Θ^+ production in ep related to proton-remnant fragmentation
- Sizeable d/\bar{d} production observed in DIS.
 \bar{d}/\bar{p} ratio in DIS similar to γp (H1) and pp data,
corresponds to Coalescence Model with $B_2 \approx (0.5 - 1) \cdot 10^{-2} \text{ GeV}^2$
- H1 and ZEUS results on $\Theta_c^0 \rightarrow D^* p$ disagree.
Using larger statistics, ZEUS does not see a signal observed by H1
- Rates of excited D^{**} mesons are close in e^+e^- and ep data.
 $D_{s1}^\pm(2536)$ shows questionable helicity distribution and “too large” $f(c \rightarrow D_{s1}^+)$

Expect more from HERA II



$M(K_s^0 p(\bar{p}))$

ZEUS



large background

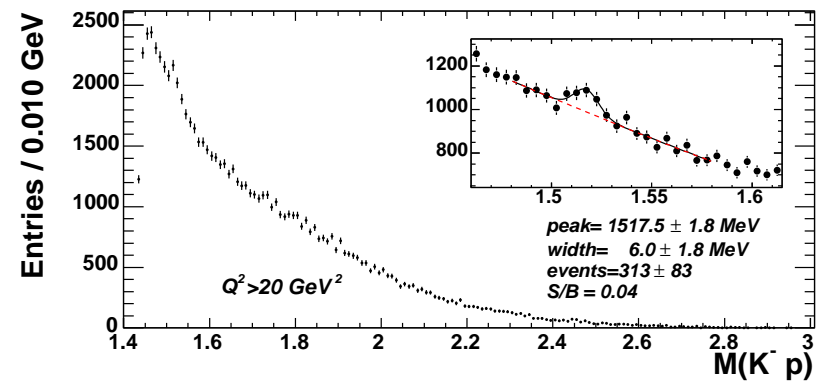
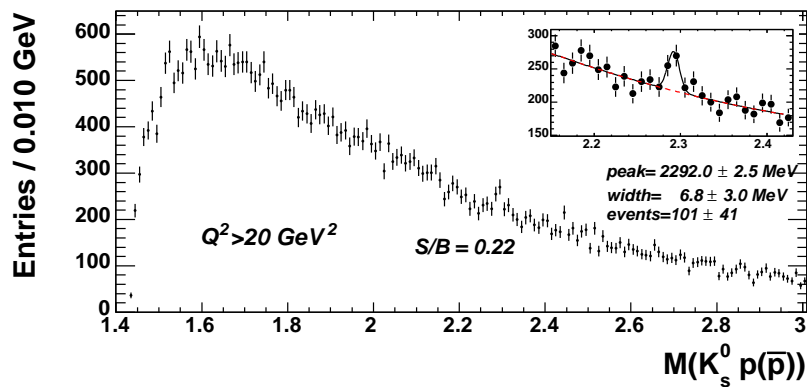
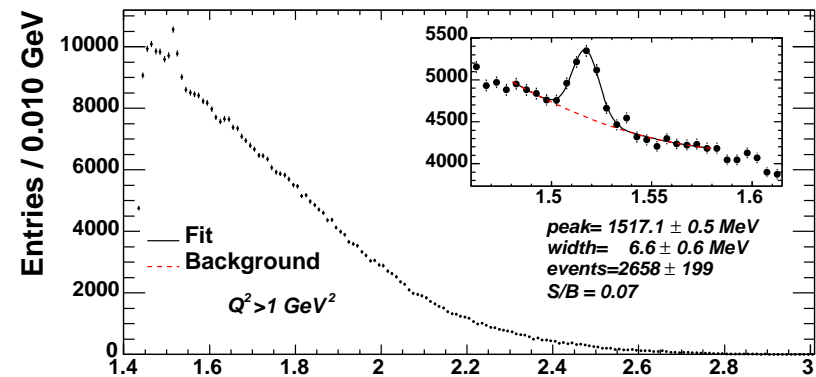
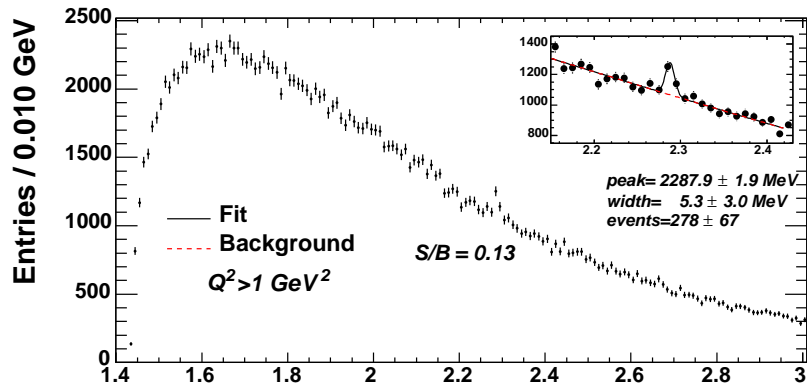
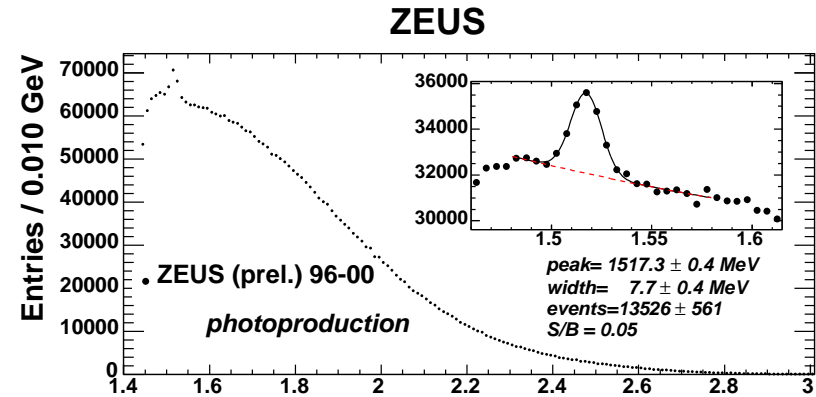
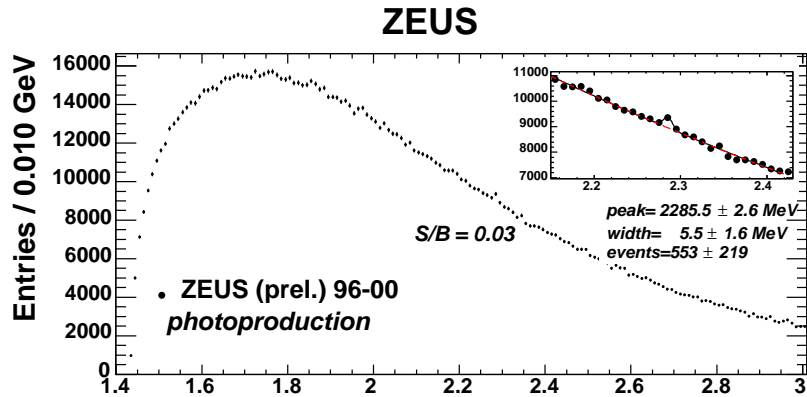
signal becomes visible
for $Q^2 > 10 \text{ GeV}^2$

ARIADNE (JETSET) MC
(normalized to data above 1.65 GeV)
does not reproduce the shape.

$\Sigma(1480)$, $\Sigma(1560)$ bumps ?

for $Q^2 > 1 \text{ GeV}^2$,
signal is visible
for $W < 125 \text{ GeV}$

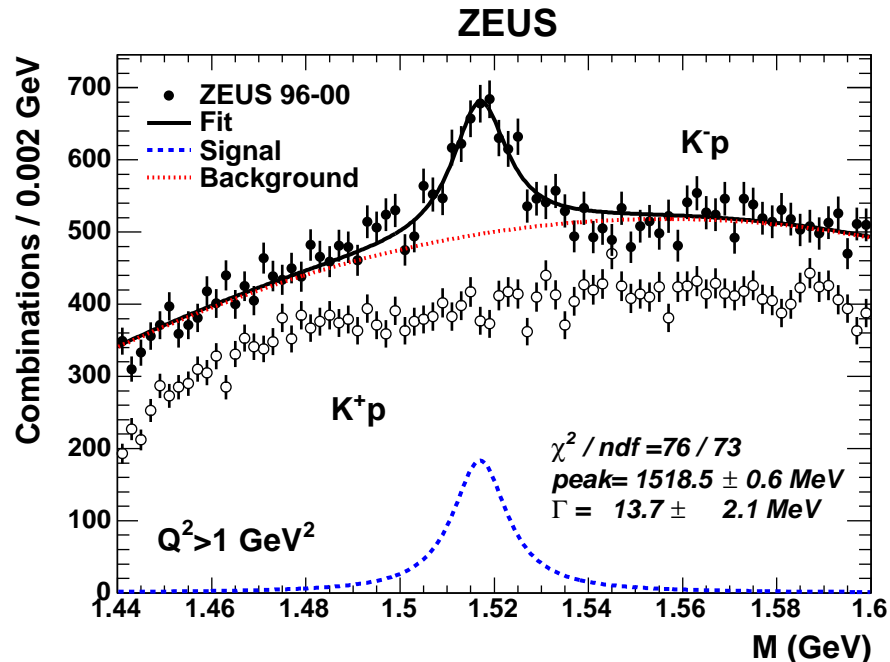
Λ_c and $\Lambda(1520)$



Λ_c seen better for $Q^2 > 20$ GeV²

It is not a case for $\Lambda(1520)$

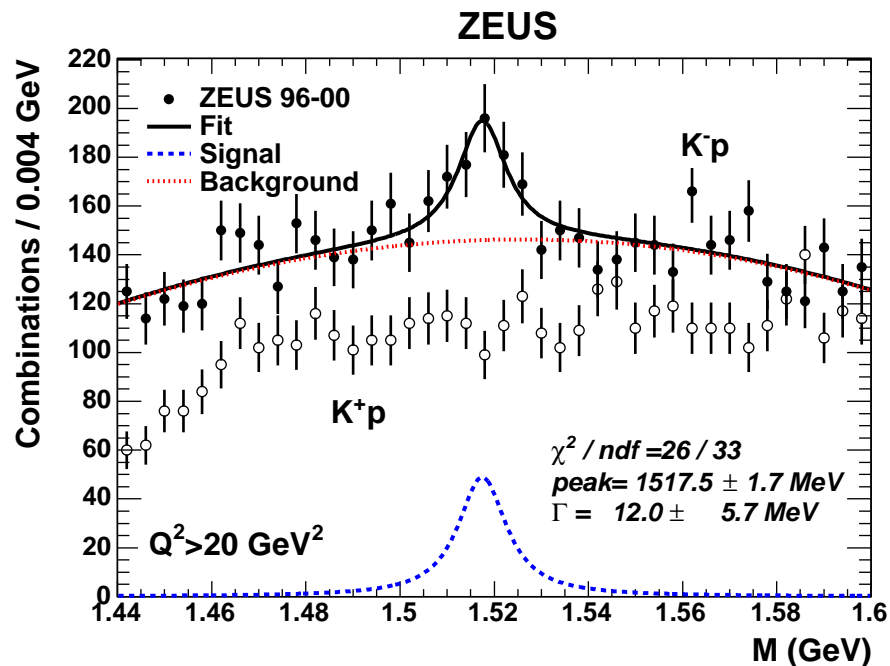
Search for $\Theta^{++} \rightarrow K^+ p (+c.c.)$



For NK bound state,
both $I = 0, 1$ are possible

$I = 1$: triplet $\Theta^0, \Theta^+, \Theta^{++}$

\Leftarrow search for $\Theta^{++} \rightarrow K^+ p (+c.c.)$
no signal

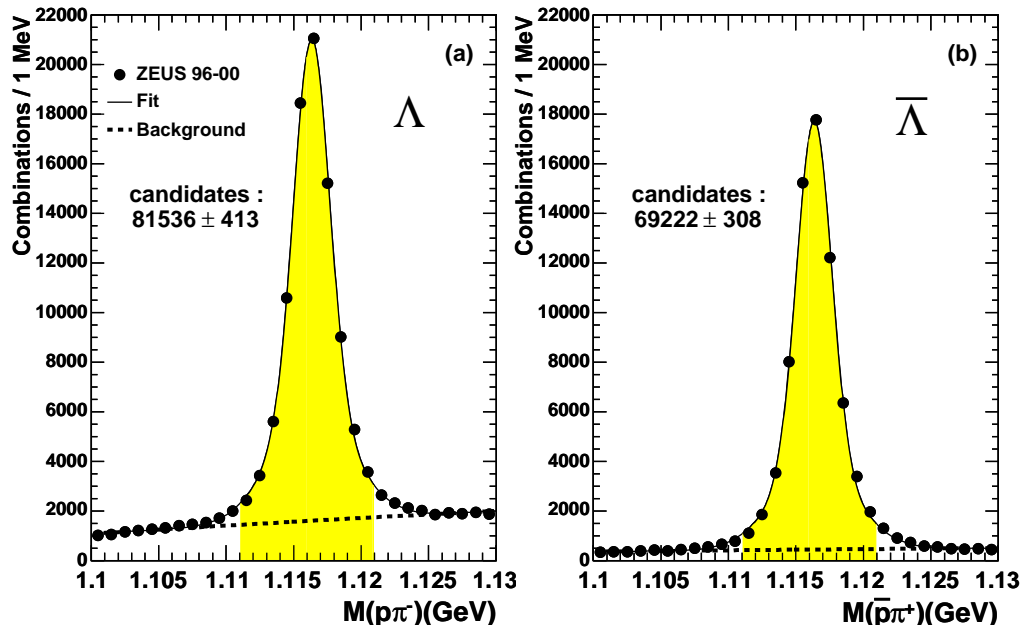


\Leftarrow no Θ^{++} signal for $Q^2 > 20 \text{ GeV}^2$
as well

Does not contradict to
 Θ^{++} observation by STAR
with $R(\Theta^{++} / \Lambda(1520)) \approx 0.1\%$

Search for pentaquarks with $S = \pm 2$

ZEUS



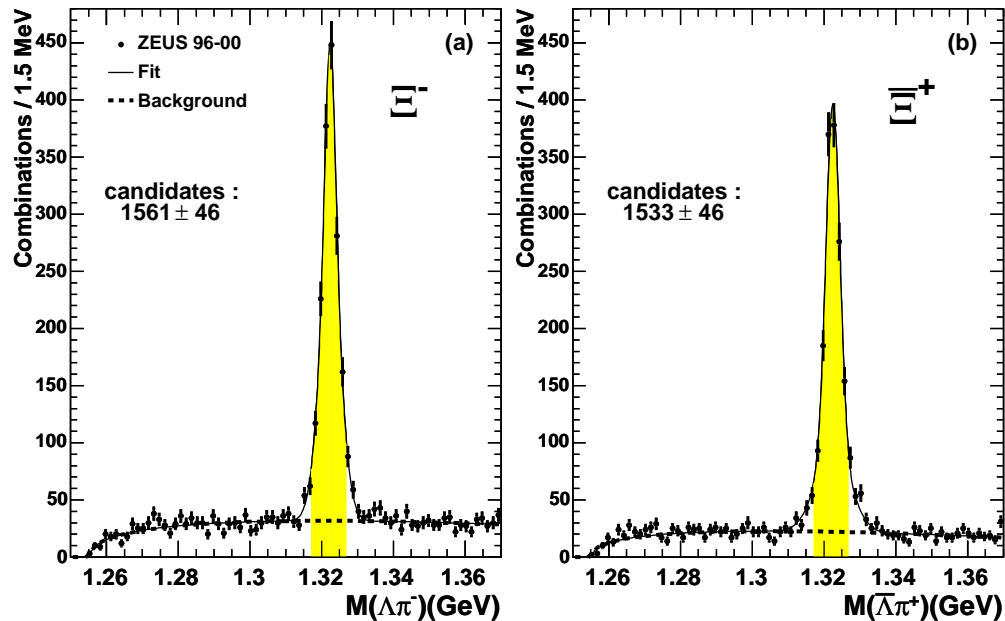
$\Xi_{3/2}^{--}, 0 \rightarrow \Xi \pi$ observed by NA49

ZEUS search in DIS, $Q^2 > 1 \text{ GeV}^2$

$\Lambda^0 \rightarrow p\pi^- (+c.c.)$ are well identified using the displaced vertices

$\Leftarrow \sim 150000$ candidates

ZEUS



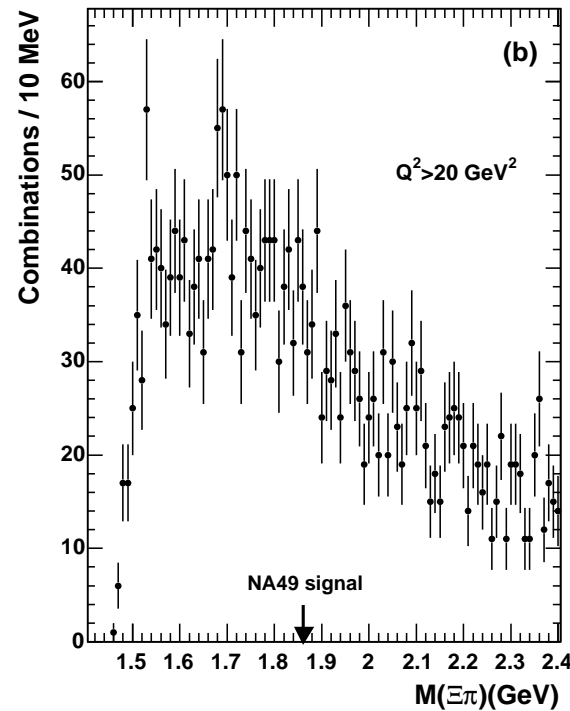
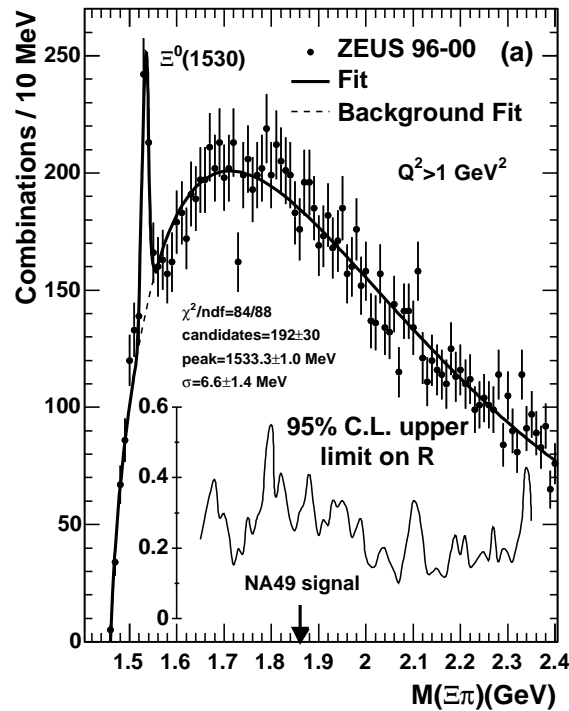
Combining with additional track

$\Xi^- \rightarrow \Lambda^0 \pi^- (+c.c.)$

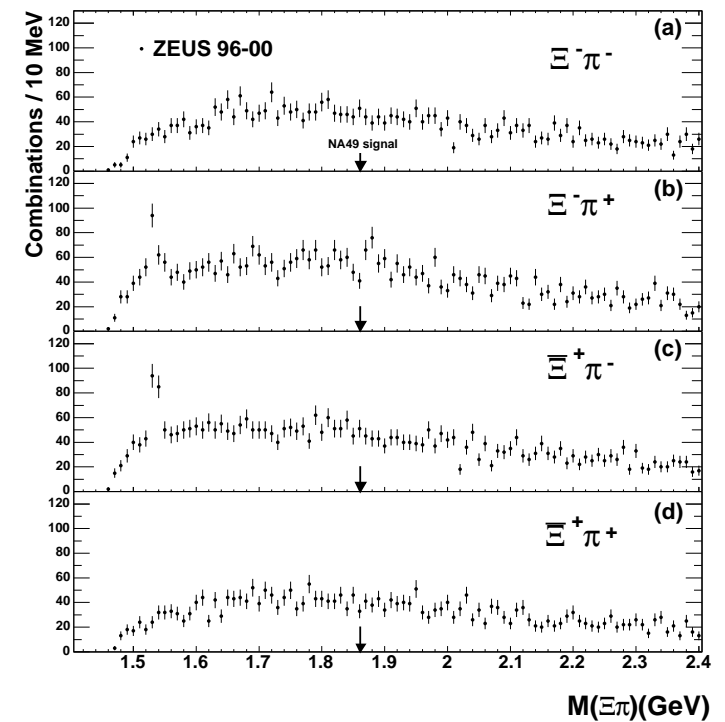
$\Leftarrow \sim 3000$ candidates

$M(\Xi\pi)$ and upper limit on $R(\Xi_{3/2}^{--},^0/\Xi^0(1530))$

ZEUS



ZEUS



approx. the same number of $\Xi^0(1530) \rightarrow \Xi^- \pi^+$ as in NA49

No $\Xi_{3/2}$ signal for $Q^2 > 1 \text{ GeV}^2$ and $Q^2 > 20 \text{ GeV}^2$; in all charge combinations

$R(\Xi_{3/2}^{--},^0/\Xi^0(1530)) < 0.29$ (95% C.L.) in the NA49 signal region

Note: ZEUS studies central production

NA49 covers forward production

$D^{*\pm}$ reconstruction for charm pentaquark searches

H1 96-00 data (75 pb^{-1})

$$Q^2 > 1 \text{ GeV}^2, 0.05 < y < 0.7$$

$$P_T(D^{*\pm}) > 1.5 \text{ GeV}, -1.5 < \eta(D^{*\pm}) < 1.0$$

$$N(D^{*\pm}) \sim 3400$$

$$\text{(for } Q^2 < 1 \text{ GeV}^2 : N(D^{*\pm}) \sim 4900)$$

ZEUS 95-00 data (126 pb^{-1})

two D^* decay channels:

$$p_T(D^*) > 1.35 \text{ GeV for } D^* \rightarrow (K\pi)\pi_s$$

$$p_T(D^*) > 2.8 \text{ GeV for } D^* \rightarrow (K\pi\pi\pi)\pi_s$$

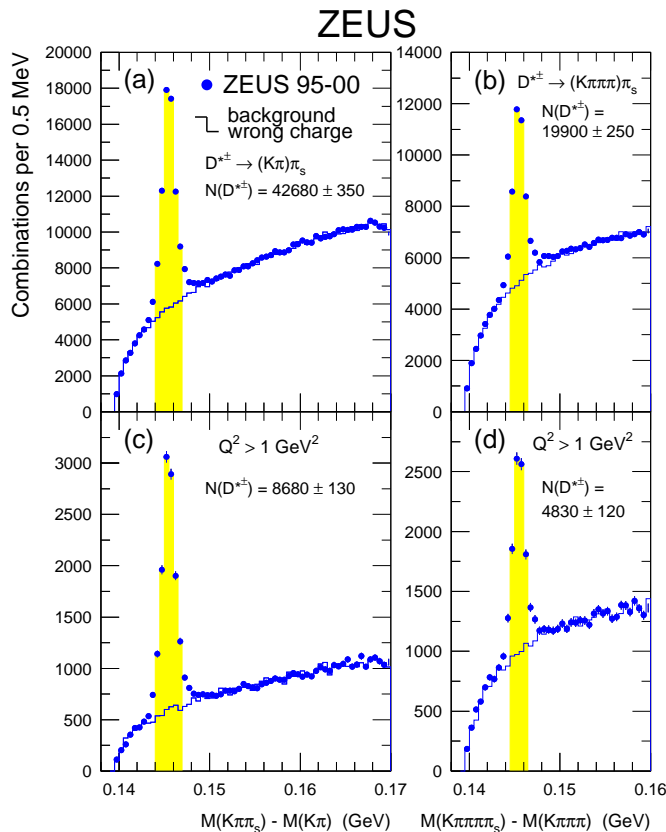
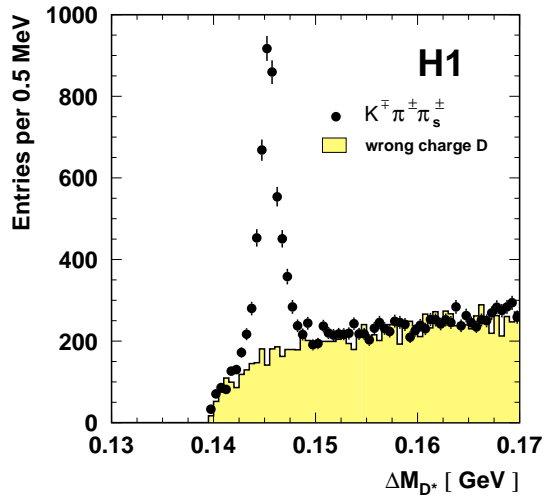
$$|\eta(D^*)| < 1.6 \text{ for both channels}$$

Yellow bands used

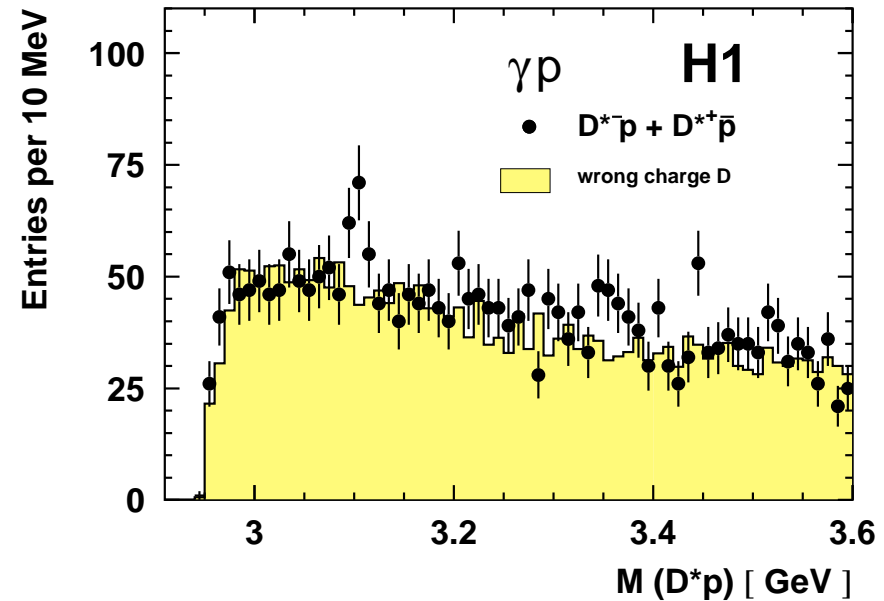
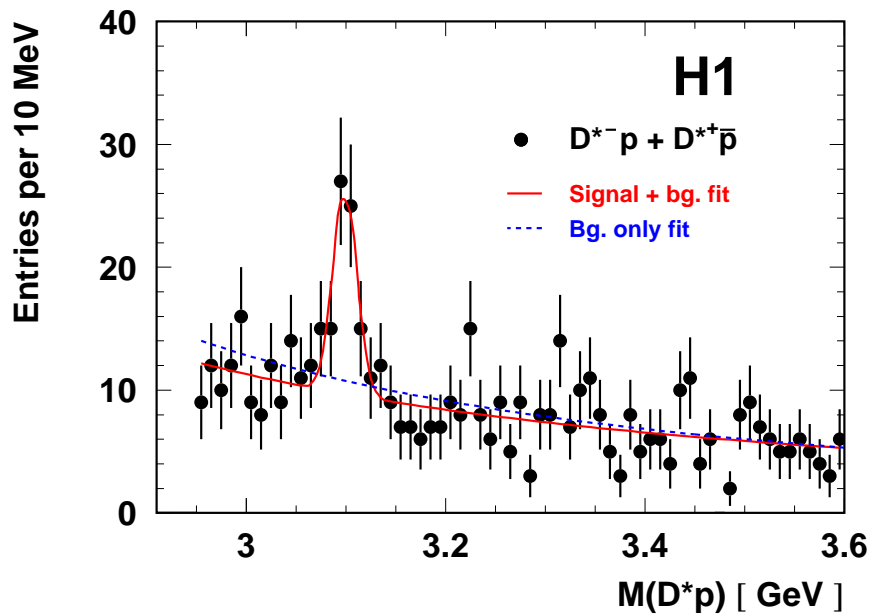
for Θ_c^0 search:

$$N(D^*) \sim 62500, \text{ full sample}$$

$$N(D^*) \sim 13500, Q^2 > 1 \text{ GeV}^2$$



$M(D^*p)$ in DIS and photoproduction



Clean signal in DIS
 (in both $D^{*+}\bar{p}$ and $D^{*-}p$)

Signal for $Q^2 < 1 \text{ GeV}^2$
 at the same mass

Fit Gaussian + background (2 par.):

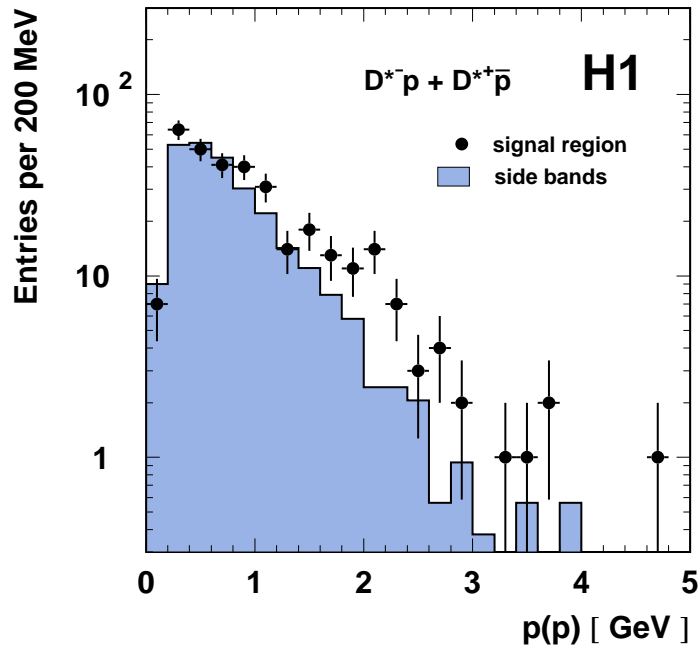
$$N(\Theta_c^0) = 50.6 \pm 11.2$$

$$M(\Theta_c^0) = 3099 \pm 3(\text{stat.}) \pm 5(\text{syst.}) \text{ MeV}$$

$$\sigma(\Theta_c^0) = 12 \pm 3 \text{ MeV (consist. with resolution)}$$

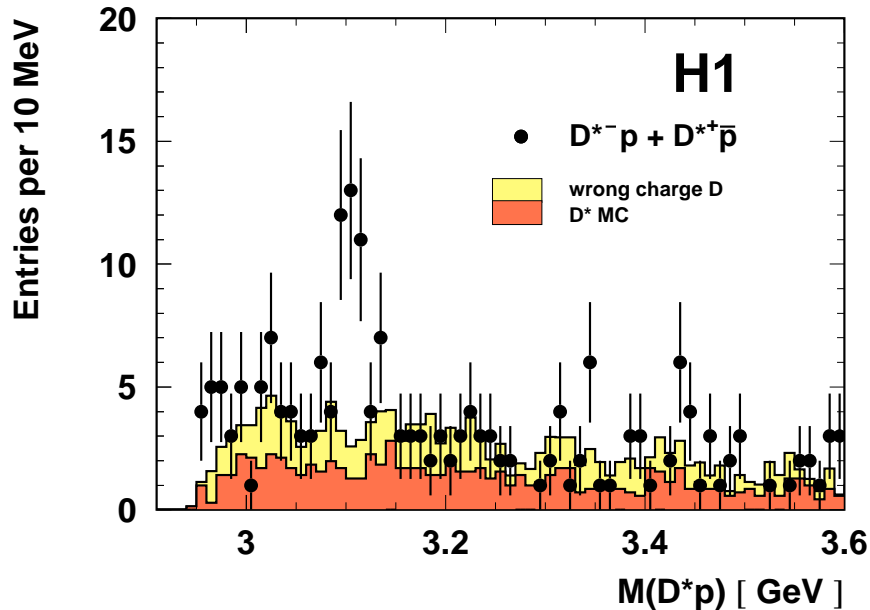
visible rate $R(\Theta_c^0 \rightarrow D^*p/D^*) = 1.46 \pm 0.32 \% \text{ (prel.)}$ or “roughly 1%”
 (paper)

$M(D^*p)$ for large proton momenta



particles taken as protons
w/o dE/dx requirements

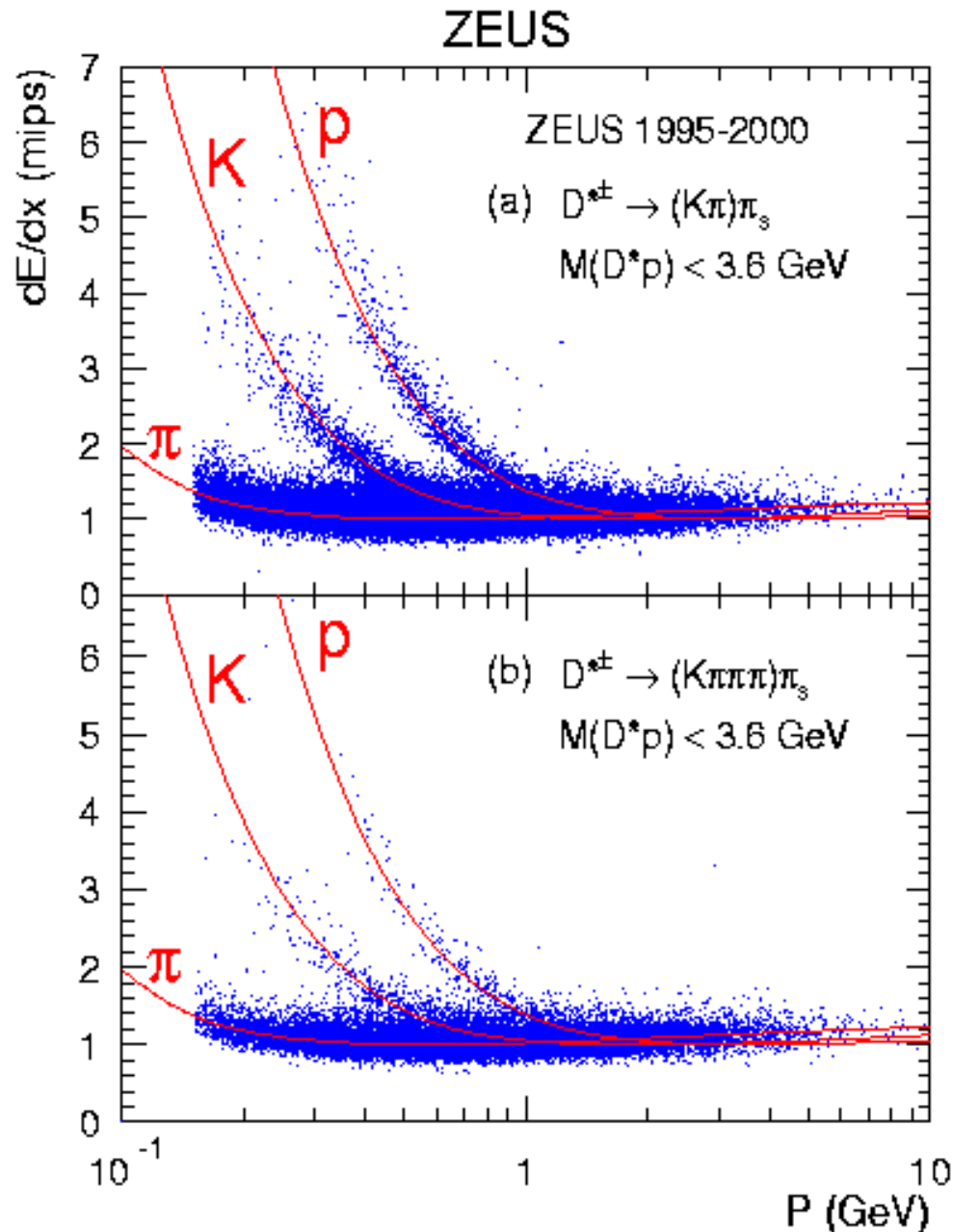
“protons” from signal region
($3.085 < M(D^*p) < 3.115$ GeV)
have harder momentum distribution
than “protons” from side bands



For $P(p) > 2$ GeV,
clean signal is seen
even w/o use of dE/dx

⇐ background is well described
by 2-component model

$p(\bar{p})$ identification, ZEUS



improved dE/dx calibration
w.r.t. Θ^+ analysis

resolution $\sim 9\%$

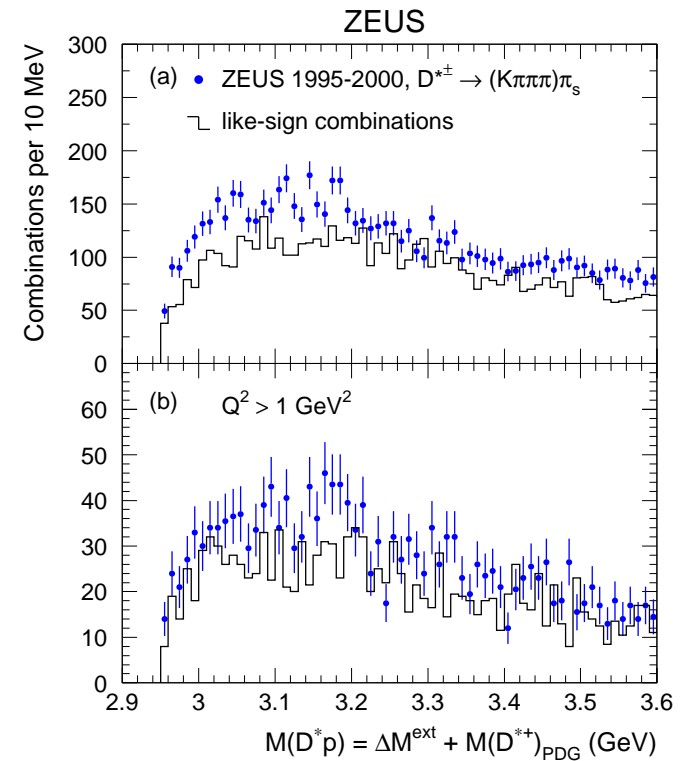
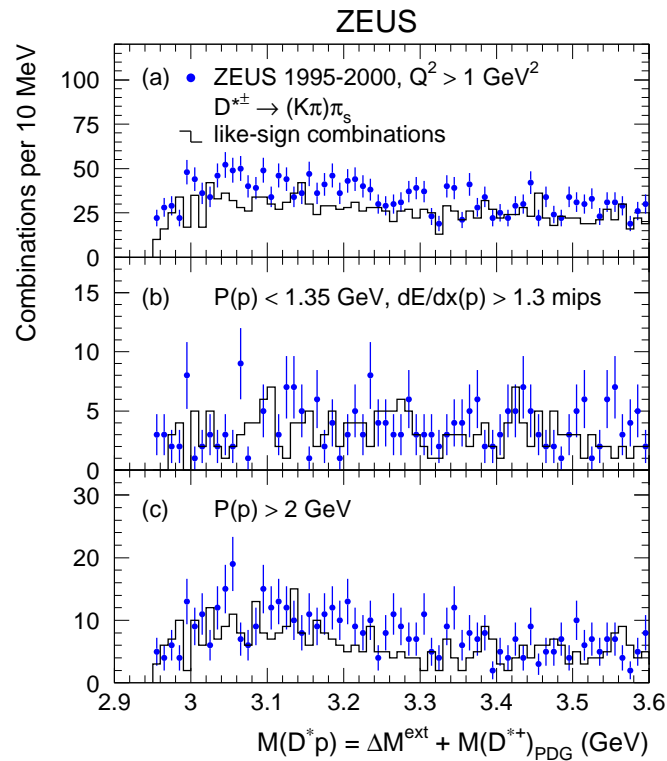
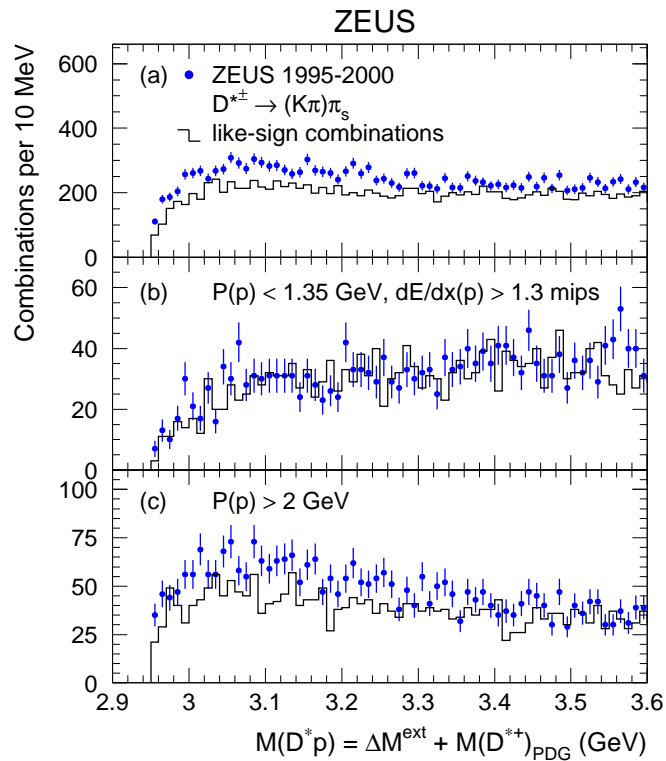
param. tuned using tagged $p(\bar{p})$
from Λ^0 decays

to select $p(\bar{p})$ candidates

$Prob(\chi^2) > 0.15$

$A(Prob(\chi^2) > 0.15) = 85.0 \pm 0.1\%$

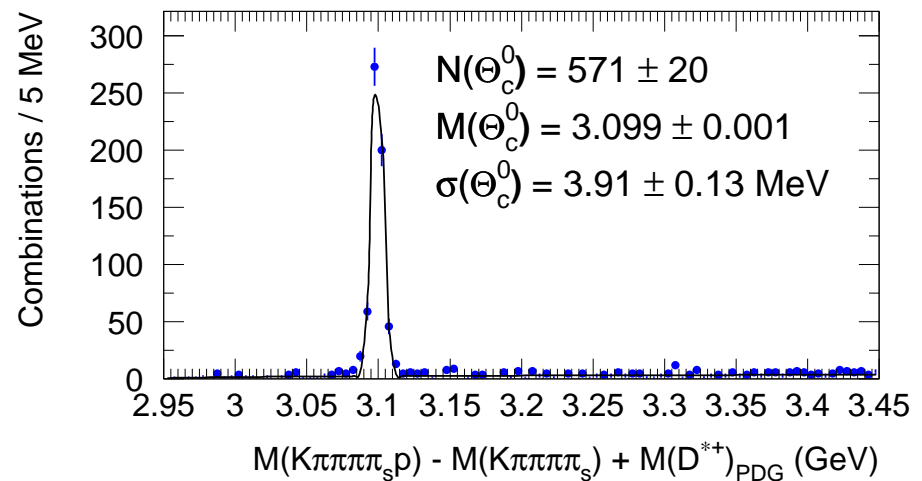
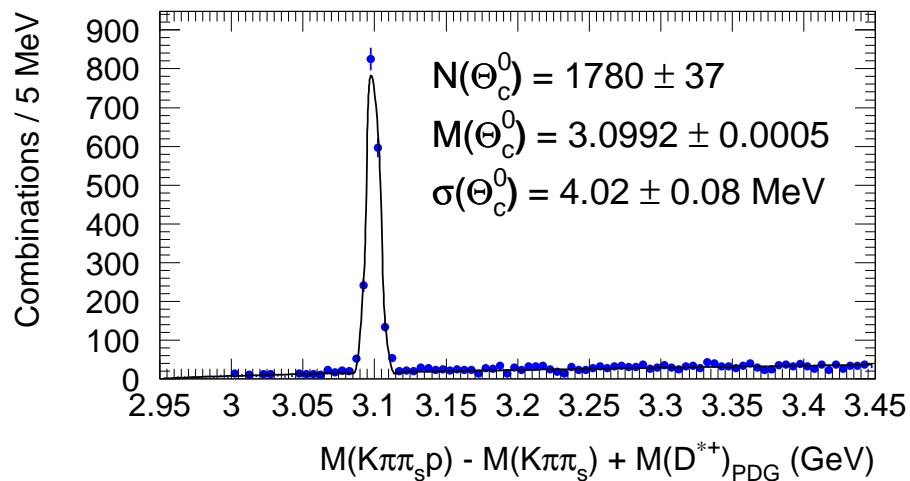
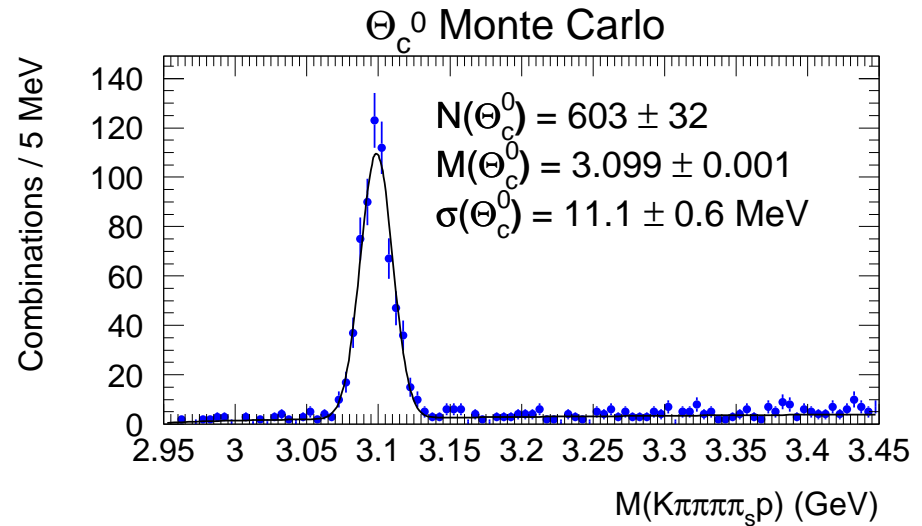
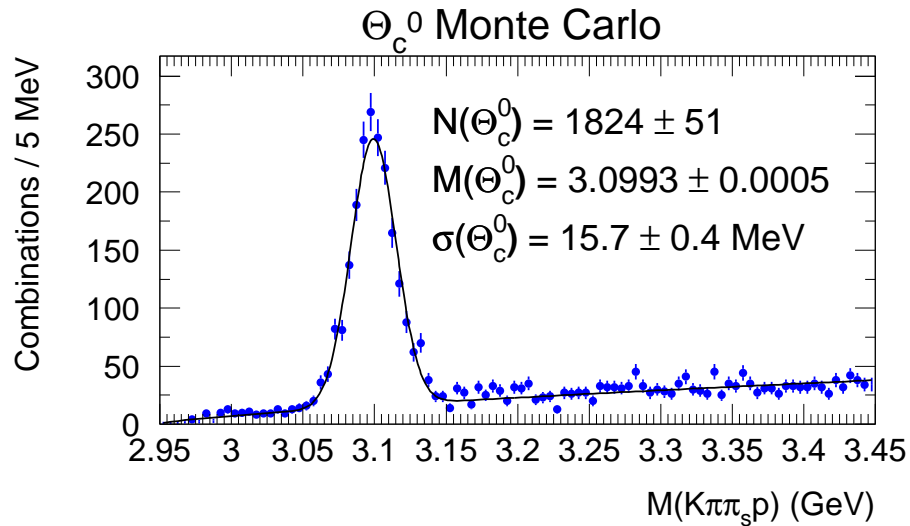
$M(D^*p)$, ZEUS



no signal in either distribution

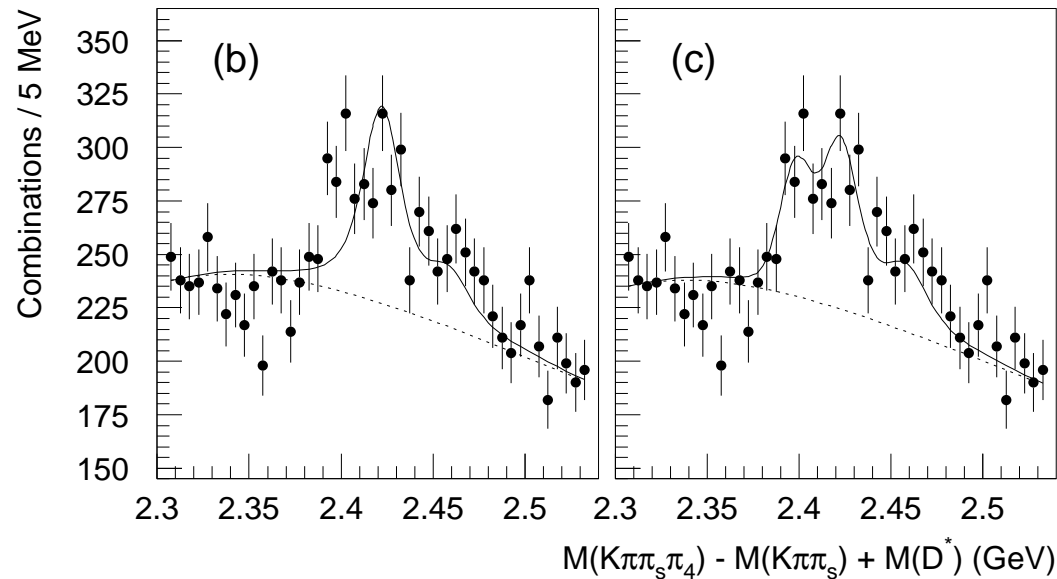
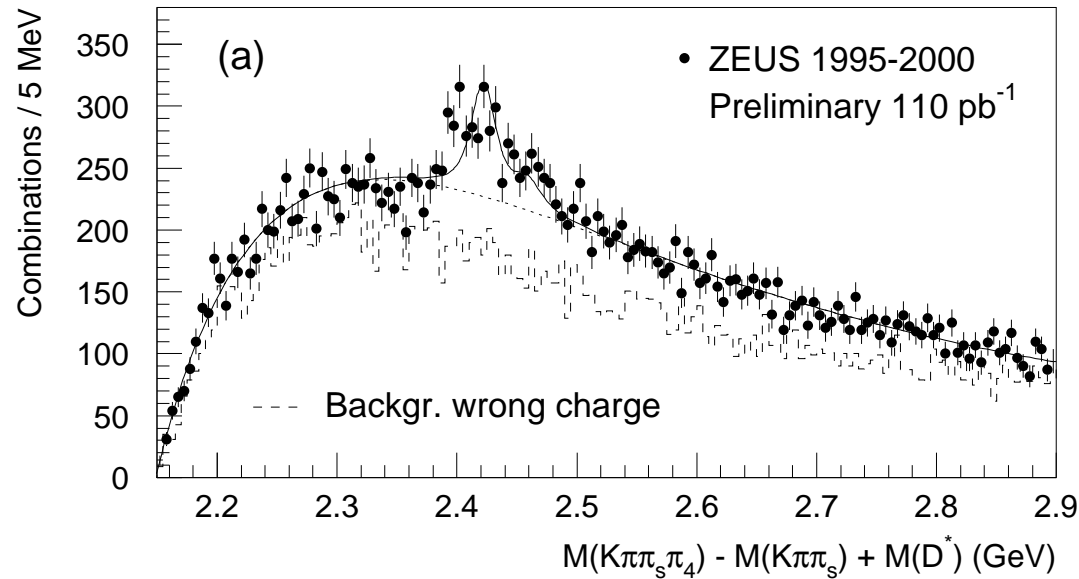
ZEUS Θ_c^0 MC and extended ΔM method

To prepare signal MC, Θ_c^0 was emulated by redefining mass, width and decay channel of $\Sigma_c^0(d\bar{d}c)$



resolution is ~ 4 MeV (w.r.t. ~ 7 MeV in H1 analysis)

Orbitally excited P-wave D mesons



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

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

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

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

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

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

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

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

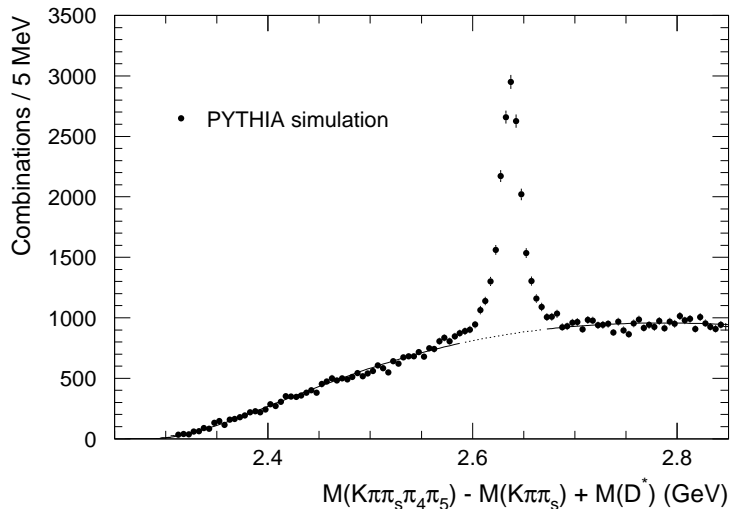
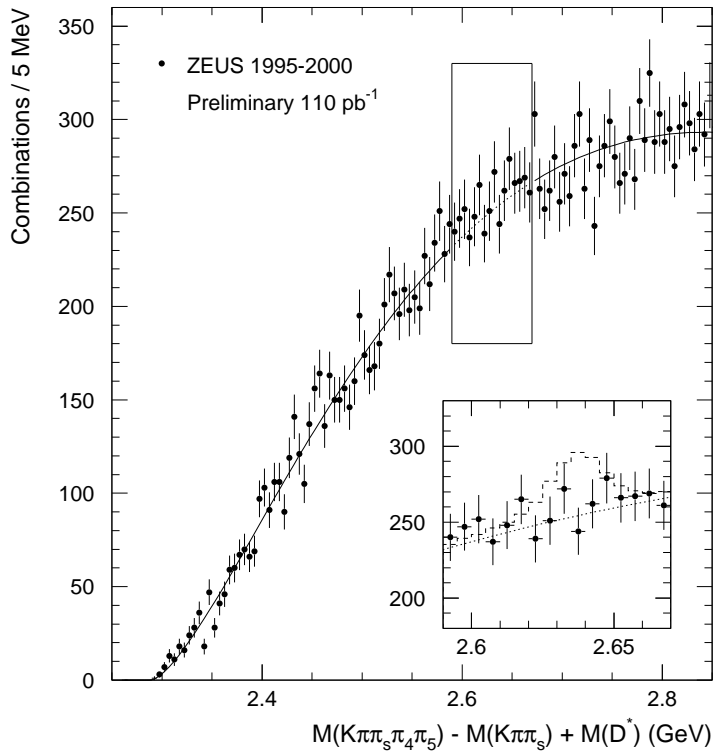
Additional narrow bump ?

$$N = 211 \pm 49$$

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

New D meson ? Interference ?

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



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

Observed by DELPHI ($\sim 5\sigma$): $M = 2637 \text{ MeV}$

$$\Gamma < 15 \text{ MeV}$$

CLEO and OPAL did not confirm

\Leftarrow ZEUS search

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

Search window: $2.59 < \Delta M^{ext} + M(D^{*+}) < 2.67 \text{ GeV}$
covers both predictions and DELPHI's observation

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

Using world average for $f(c \rightarrow D^{*+})$:

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

(ZEUS prel.)

somewhat stronger than the 0.9% limit
obtained by OPAL