Charm spectroscopy and exotics at ZEUS

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O U T L I N E :

HERA and HERA II

results on $\Theta^+ \to K^0_s p$ (+c.c.)

$d/\bar{d}$ production in DIS

search for $\Theta^0_c \to D^{*-} p$ (+c.c.)

excited D mesons

Summary and Outlook

B A C K U P :

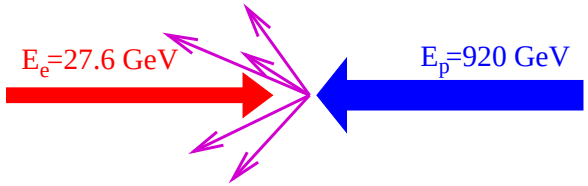
more on $\Theta^+ \to K^0_s p$ (+c.c.)

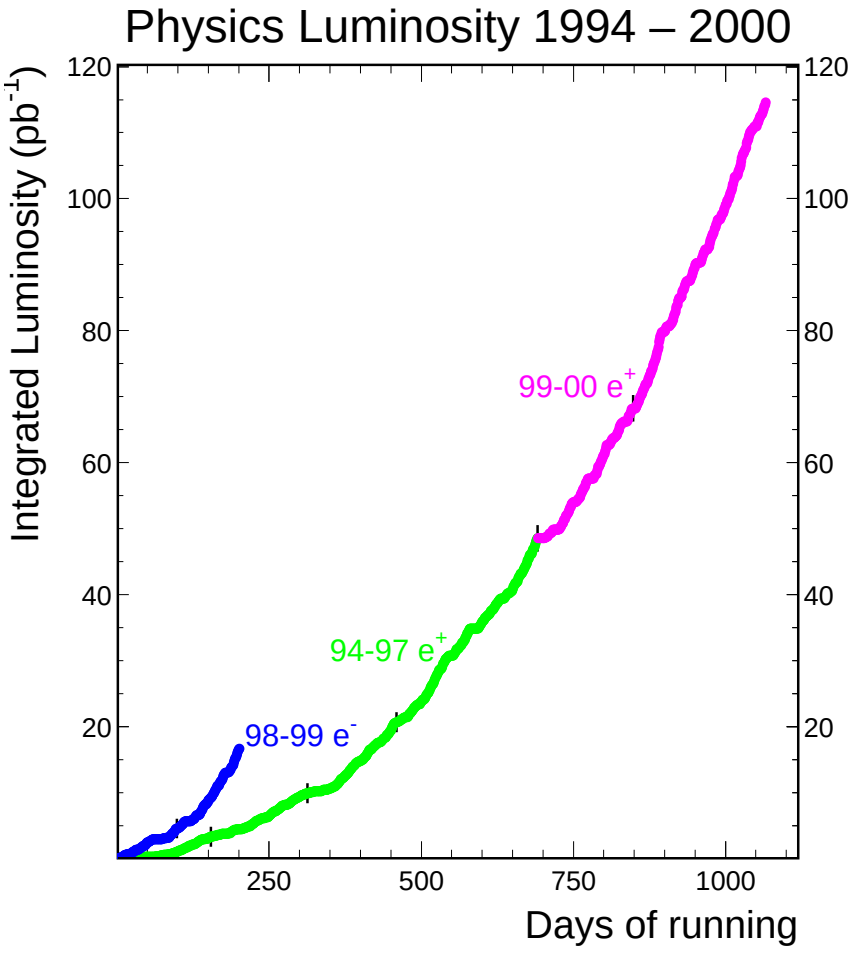
Θ^{++} and $\Xi^{--,0}_{3/2}$ searches

more on $\Theta^0_c \to D^{*-} p$ (+c.c.)

more on excited D mesons

HERA $\longrightarrow$ HERA II





H1, ZEUS : $> 100\,\mathrm{pb}^{-1}$ each

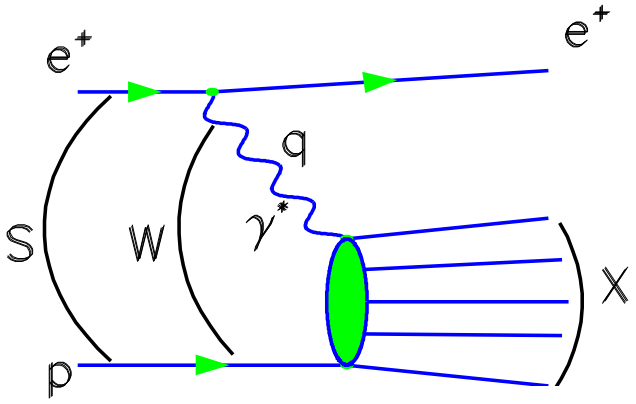
	HERA 1992-2000	**HERA II 2003-2007**
$\sqrt{s}$	320 **(300)**	320 **GeV**
$\mathcal{L}$	$1.5 \cdot 10^{31}$	$7 \cdot 10^{31}\, cm^{-2}\, s^{-1}$
$\mathcal{L}_{int}$	0.1	$\sim 0.5\, fb^{-1}$

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

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

Photoproduction $\quad Q^2 \simeq 0\, GeV^2$

DIS $\quad Q^2 > 1\, GeV^2$

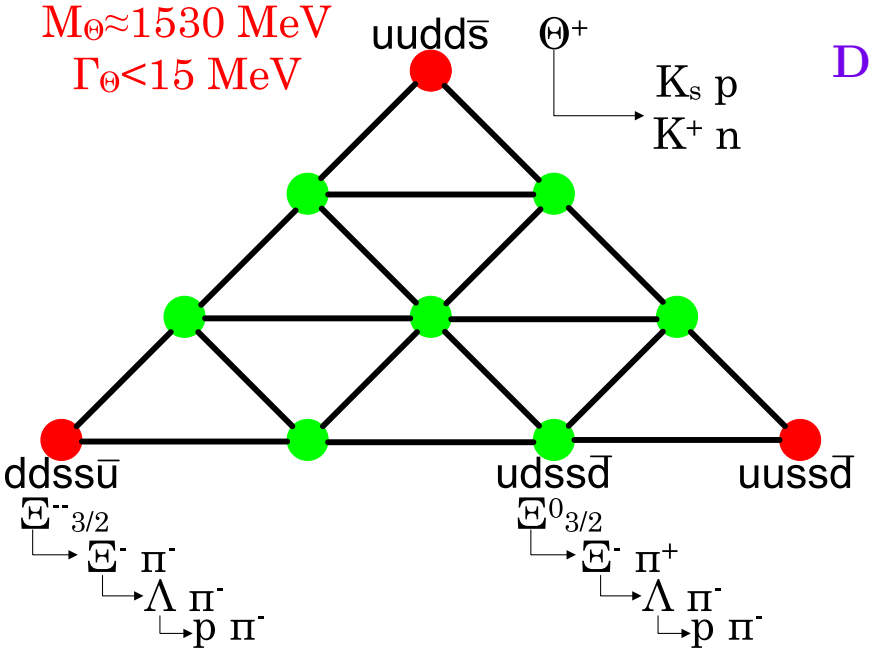


$$W^2 = (P+q)^2$$

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

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

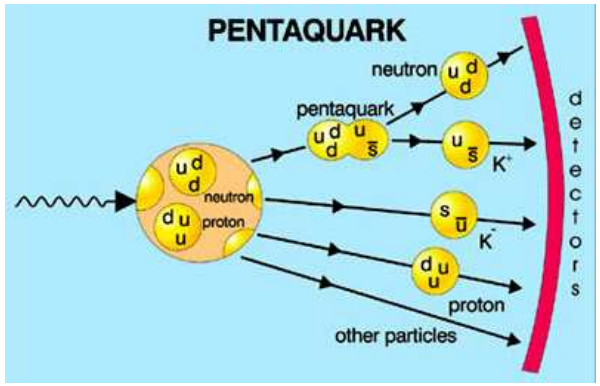
Strange pentaquarks



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

Exotic Anti-Decuplet of Baryons:

predictions from Chiral Solitons



exotic (S=B=+1) narrow baryon $\Theta^+ \to K^+ n$ observed by LEPS, CLAS, SAPHIR

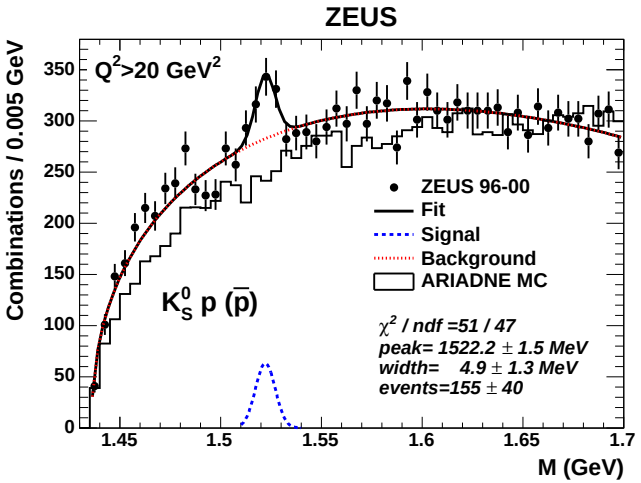
non-exotic decay mode $\Theta^+ \to K^0_s p$ seen by DIANA, HERMES, COSY-TOF, SVD, ZEUS, ITEP

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

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

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

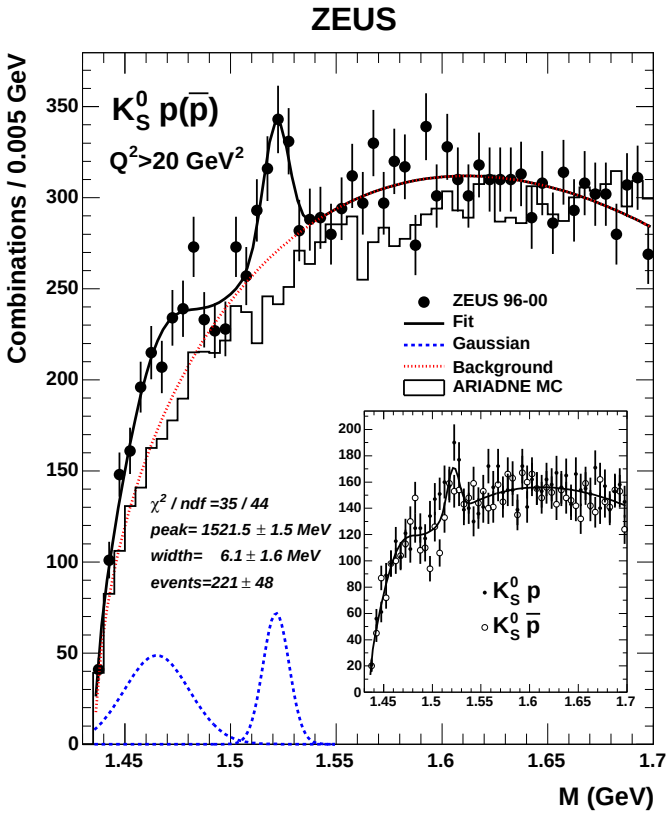
$M(K^0_s p(\bar{p}))$ for $Q^2 > 20\,\mathrm{GeV}^2$



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

Fit with Gaussian + background (3 par.)

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



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

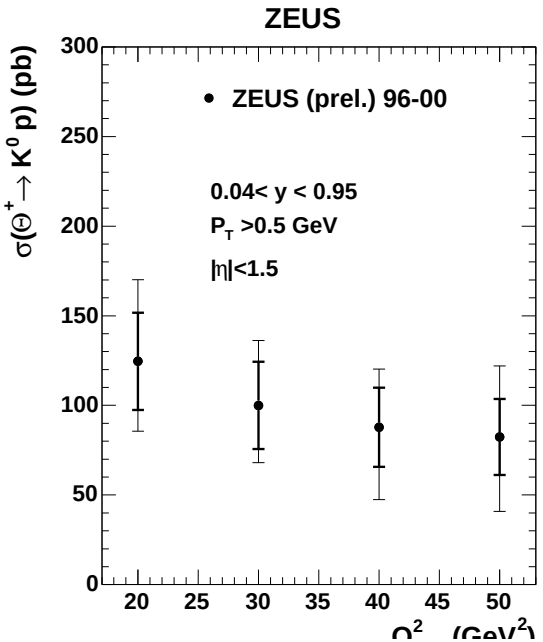
$N = 221 \pm 48$, $M = 1521.5 \pm 1.5\,\mathrm{MeV}$
width compatible with resolution

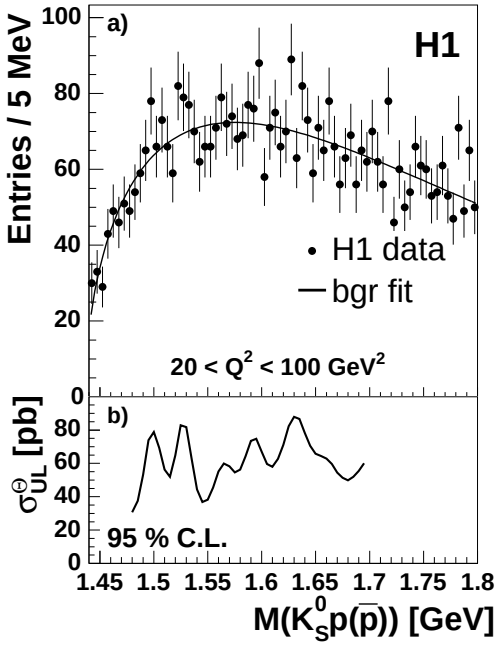
For BW: $\Gamma = 8 \pm 4$ (stat.) MeV

$\Longleftarrow$ signal seen in both charges

$N(\Theta^- \to K^0_s \bar{p}) = 96 \pm 34$

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





$\Theta^\pm$ cross section in the visible range:

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

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

$$\sigma(ep \to e\Theta^+ X \to eK^0 pX) = 125 \pm 27^{+36}_{-28}\,\mathrm{pb}$$

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

HERA-B: $R < 0.46\,\%$

ALEPH: $R < 0.4\,\%$

H1 : no significant signal

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

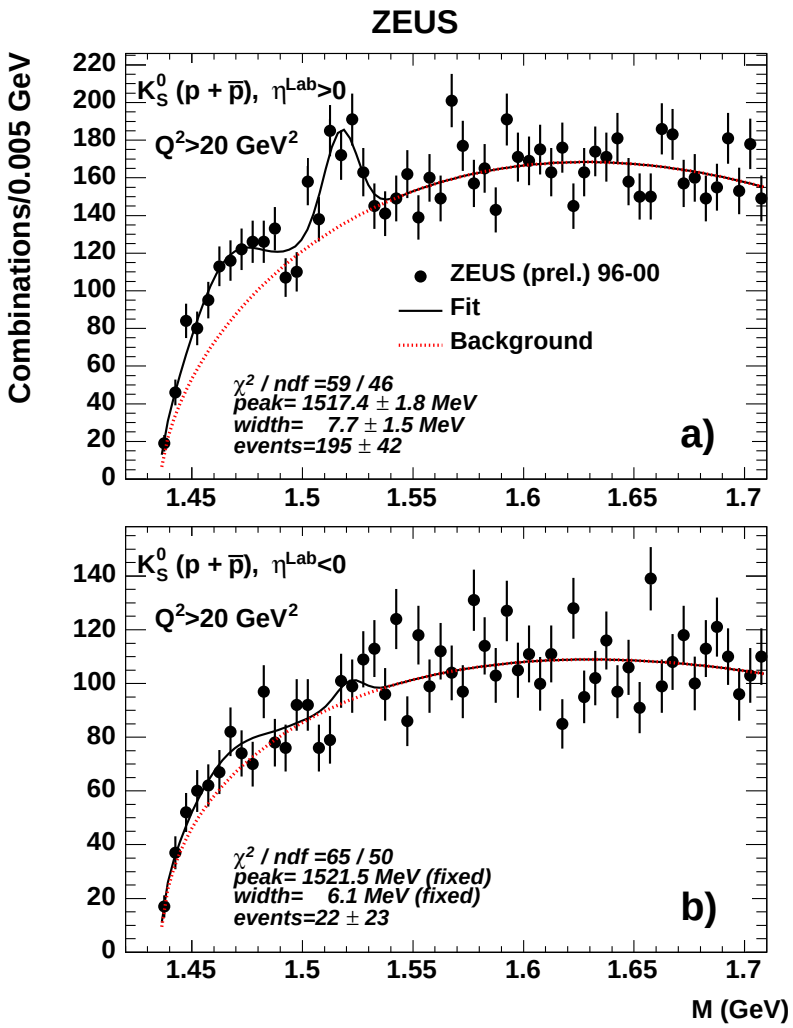
consistent with the ZEUS measurement

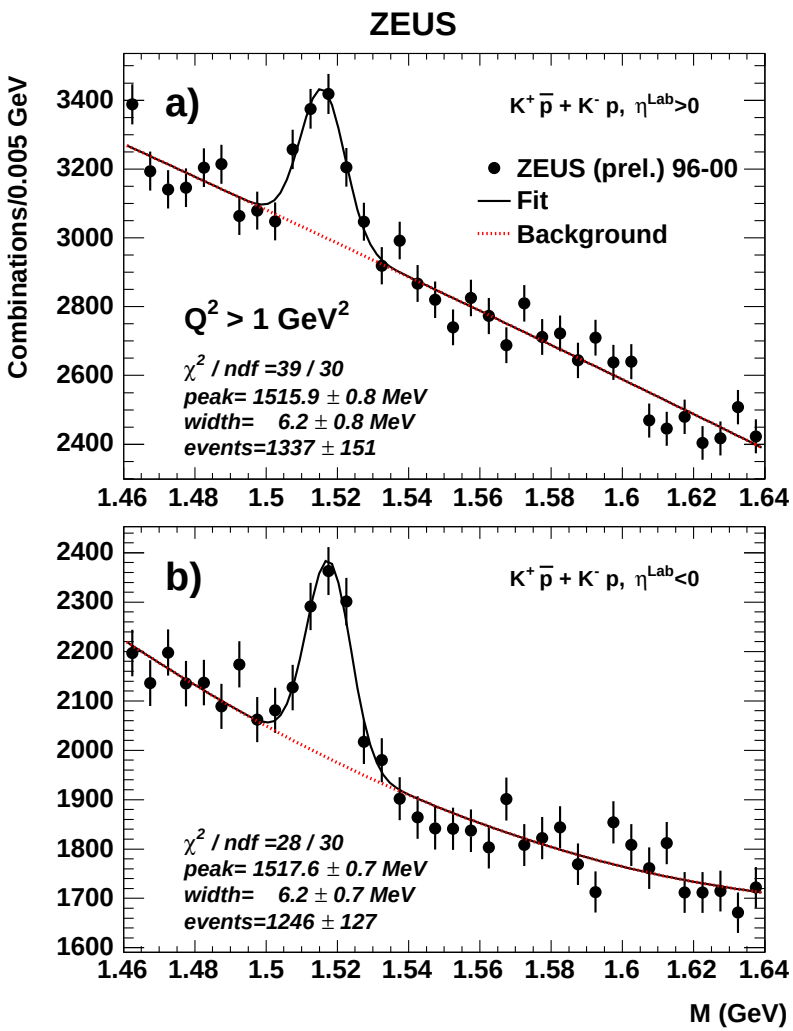
note : $\mathcal{L}_{int}(\mathrm{ZEUS}) = 121\,\mathrm{pb}^{-1}$

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

larger luminosity is vital

Θ^+ production mechanism in ep collisions ?





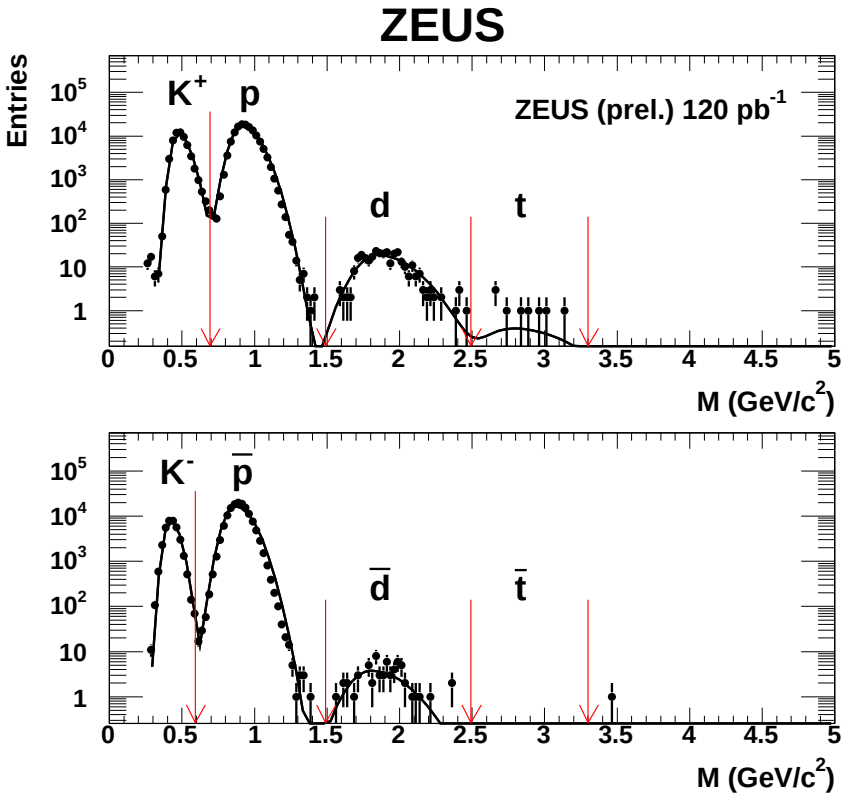
$\Theta^{\pm}$ produced mostly in forward (proton) direction

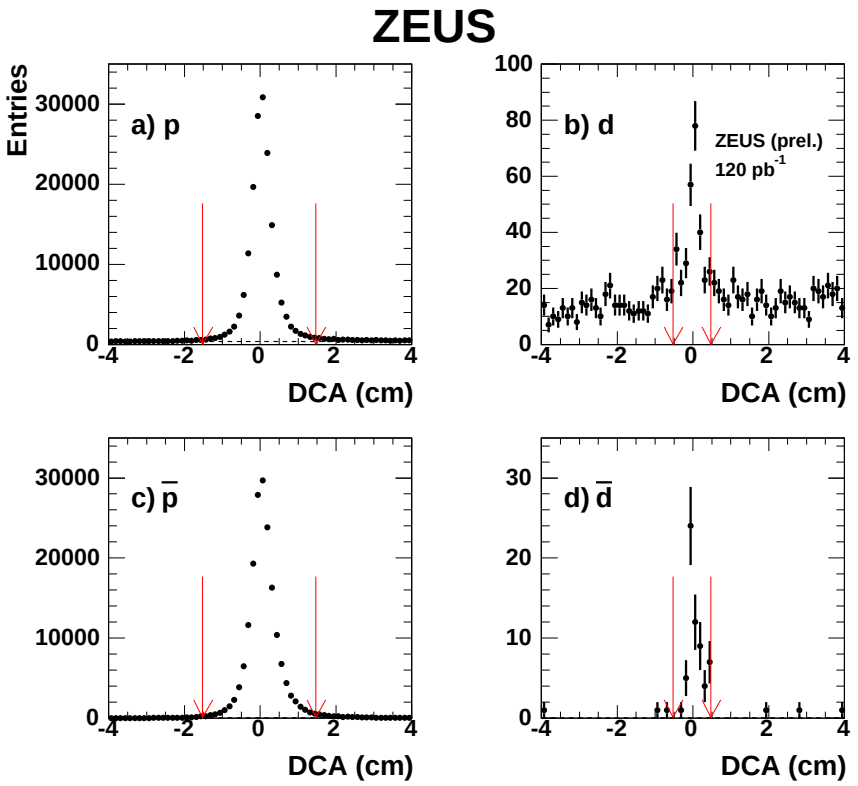
It is not a case for $\Lambda(1520)$ produced in q/g fragmentation

$\Theta^{\pm}$ 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 $Q^2 > 1\,\mathrm{GeV}^2$





$M = P/f_{BB}^{-1}(dE/dx)$

for tracks with $dE/dx > 2.5$

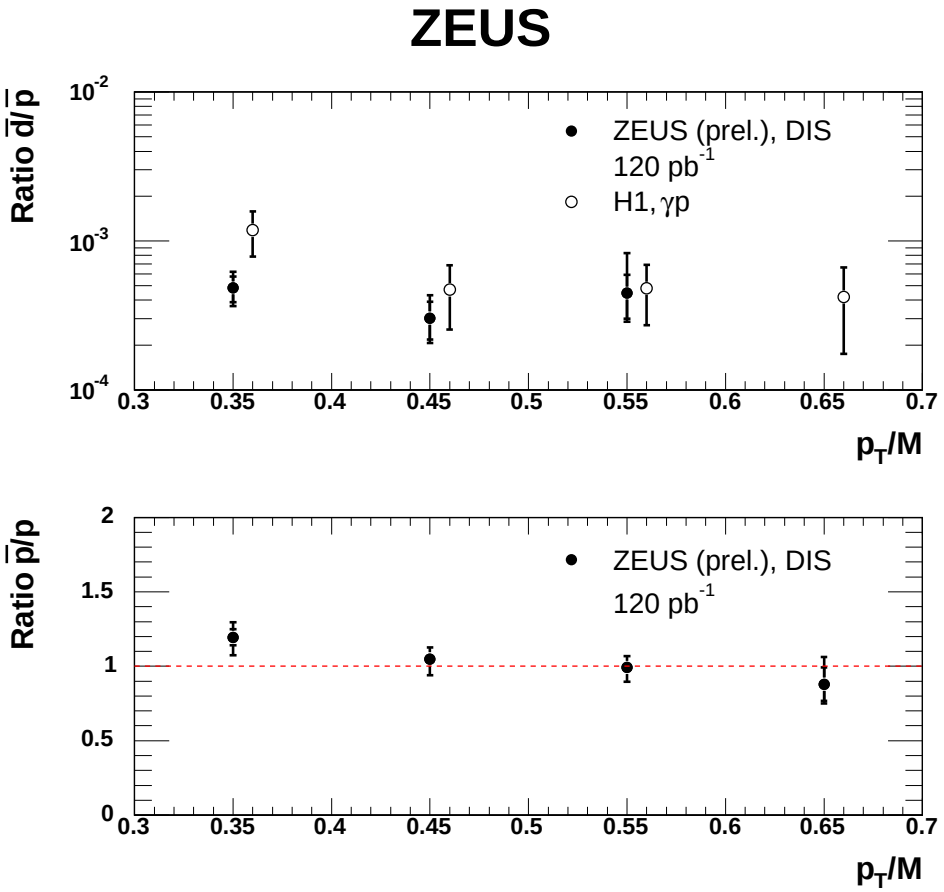
Distance of Closest Approach to beam spot in transverse plane

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 $Q^2 > 1\,\mathrm{GeV}^2$



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

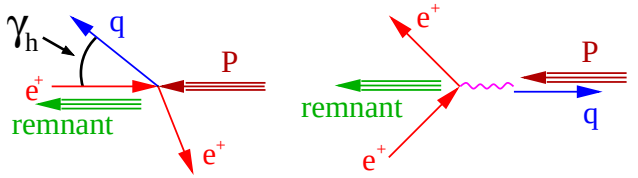
$$\frac{1}{\sigma}\frac{E_A d^3\sigma_A}{d^3P_A} = B_A\left(\frac{1}{\sigma}\frac{E_N d^3\sigma_N}{d^3P_N}\right)^A$$

$$P_N = P_A/A$$

$\bar{p}/p$ ratio ~ 1

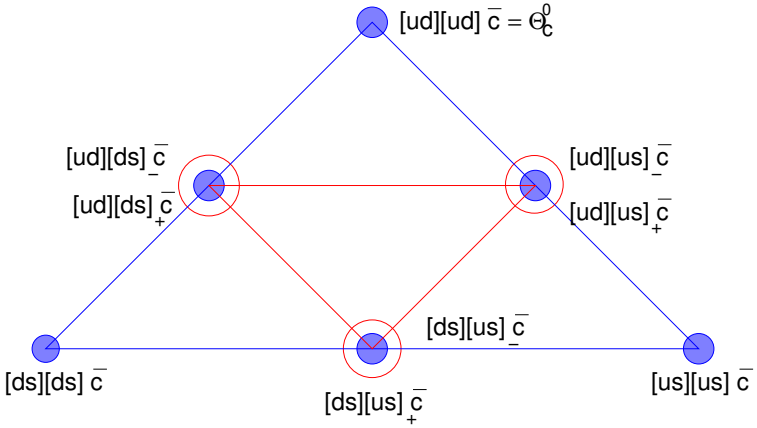
Coalescence Model with $B_2 \approx (0.5-1)\cdot 10^{-2}\,\mathrm{GeV}^2$ works for $\bar{d}$ production in DIS

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



Laboratory frame Breit frame

Charm pentaquarks



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

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

Such Θ_c^0 would be too light to decay to D mesons

can decay weakly to $\Theta^+\pi^-$, $pK^0\pi^-$, $pK^+\pi^-\pi^-$, ...

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

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

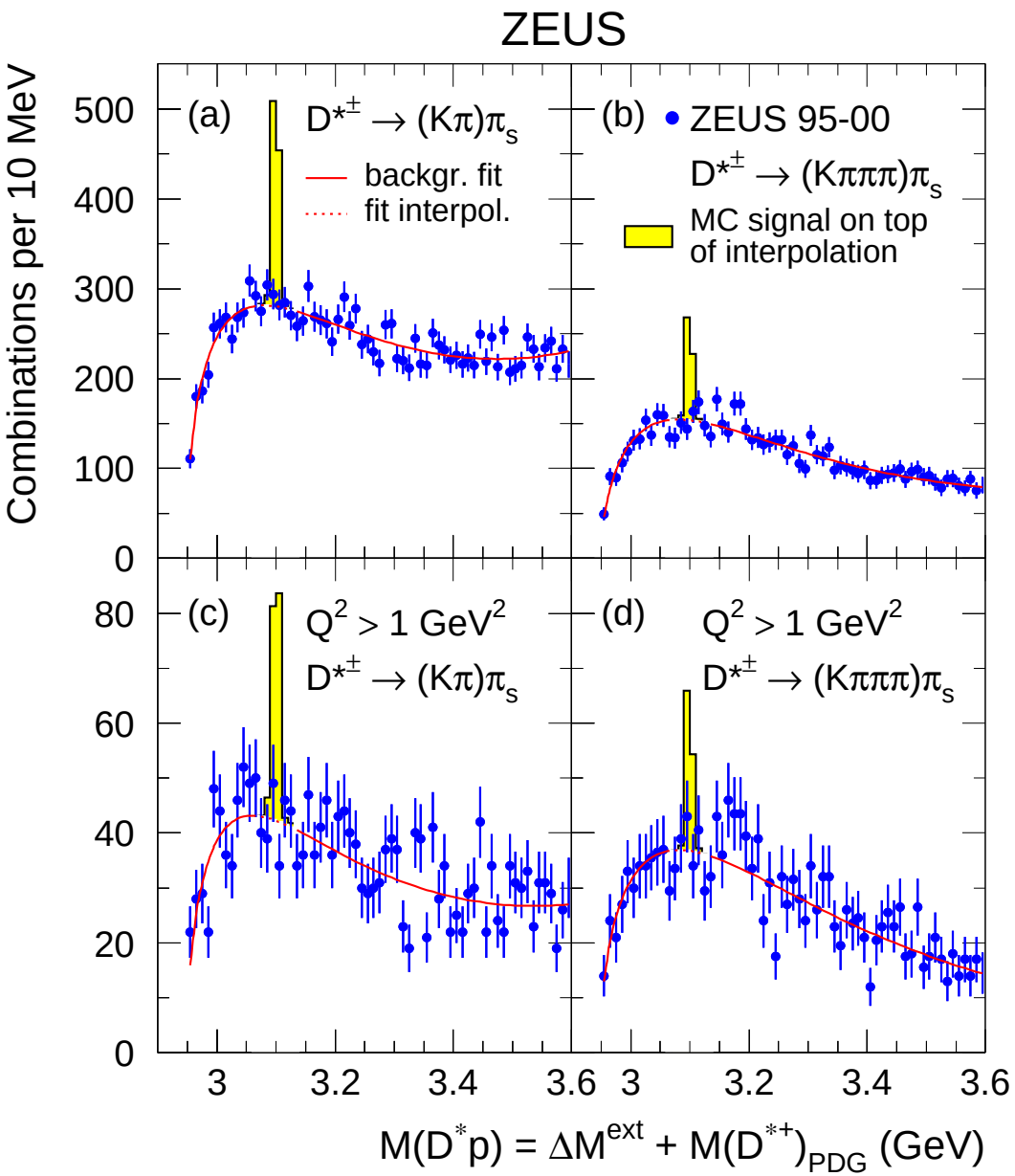
Such Θ_c^0 would decay to $D^{(*)-}p$ (+ c.c.)

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 $Q^2 > 1\,\mathrm{GeV}^2$

95% C.L. upper limits:

visible rate $R(\Theta_c^0 \to D^*p/D^*)$

$< 0.23\%$ for full sample

$< 0.35\%$ for $Q^2 > 1\,\mathrm{GeV}^2$

acceptance corrected rate

$< 0.37\%$ for full sample

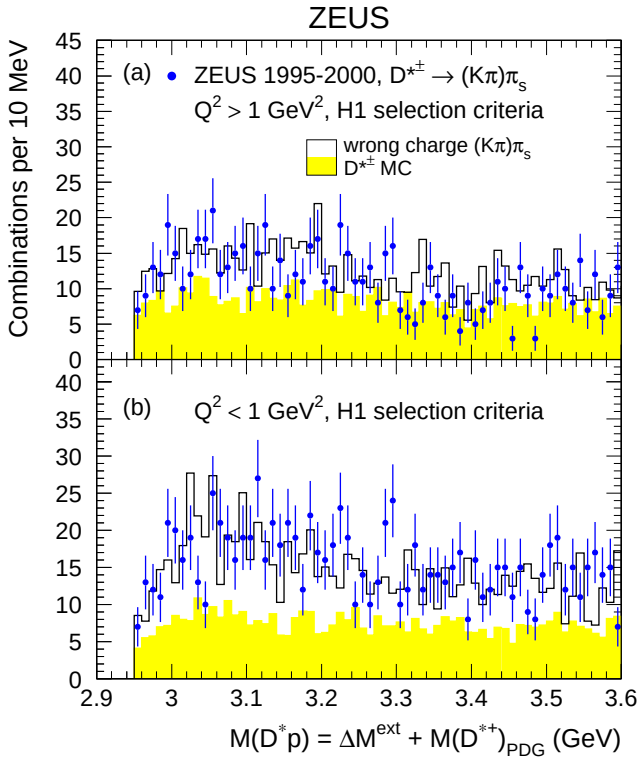
$< 0.51\%$ for $Q^2 > 1\,\mathrm{GeV}^2$

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

$< 0.16\%$ for full sample

$< 0.19\%$ for $Q^2 > 1\,\mathrm{GeV}^2$

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



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

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

no signal

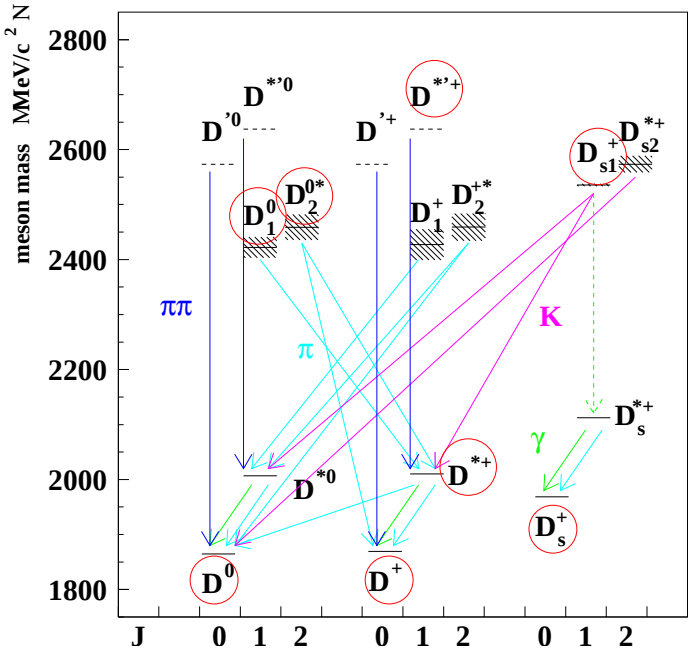
$\Longleftarrow Q^2 < 1\,\text{GeV}^2$

no signal

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

HERA II data can help to resolve the disagreement

Study of excited D mesons at HERA



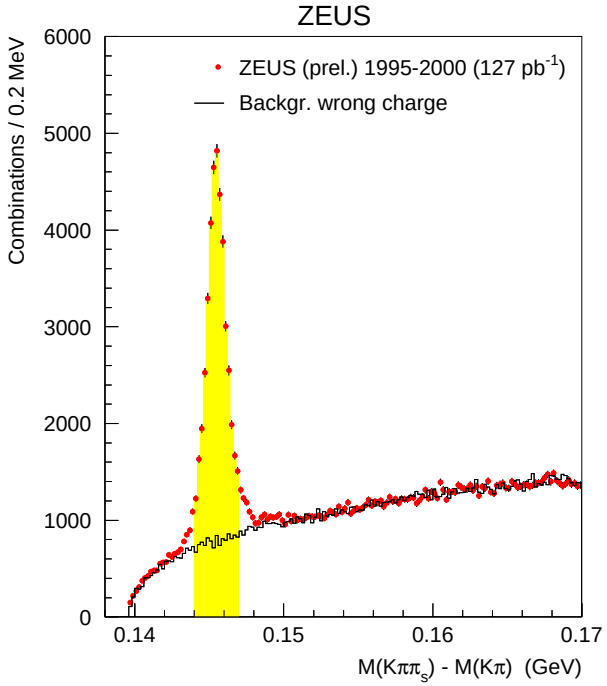
Orbitally excited:

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

2) $D_{s1}^+ \to D^{*+}K^0$ (+ c.c.) $\Longrightarrow$ discussion

Search for radially excited:

3) $D^{*\prime +} \to D^{*+}\pi^+\pi^-$ (+ c.c.)



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

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

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

In the yellow band under background:

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

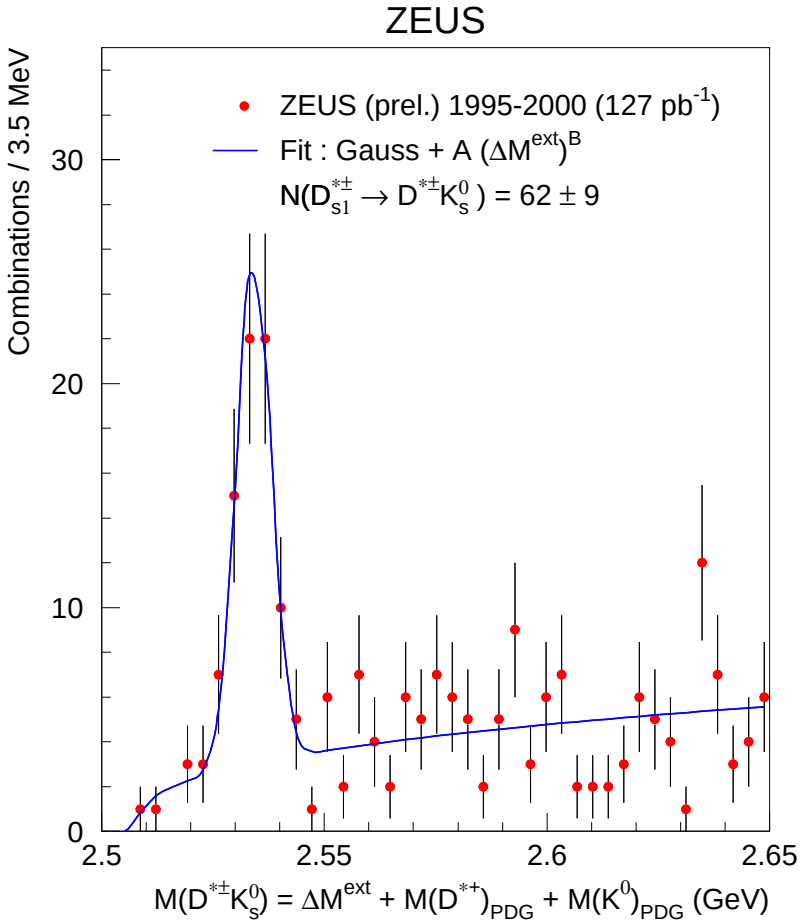
Charm-strange $D_{s1}^{\pm}(2536)$ meson

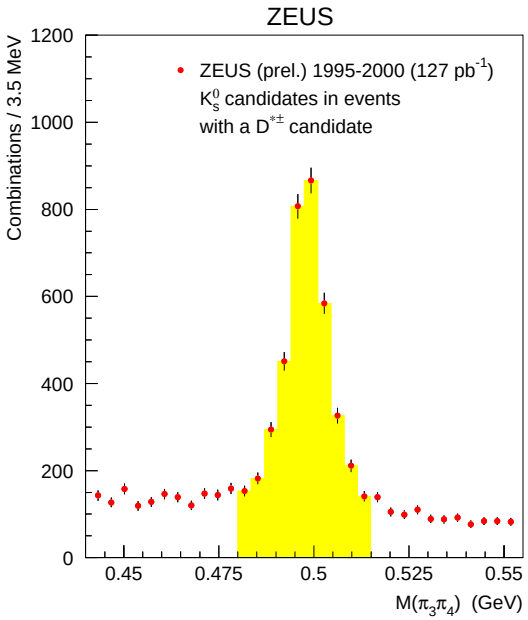
$$D_{s1}^{\pm}(2536) \to D^{*\pm}K_s^0\ , \quad K_s^0 \to \pi^+\pi^-$$

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

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

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





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

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

$$R = -0.53 \pm 0.32(\text{stat.})^{+0.05}_{-0.14}(\text{syst.})$$ (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 to $R = -1$ expected for 1^-, 2^+

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

Fragmentation fractions for excited D mesons

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

	$f(c \to D_1^0)$ [%]	$f(c \to D_2^{*0})$ [%]	$f(c \to D_{s1}^+)$ [%]
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 $f(c \to D_2^{*0})$ is not clear

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

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

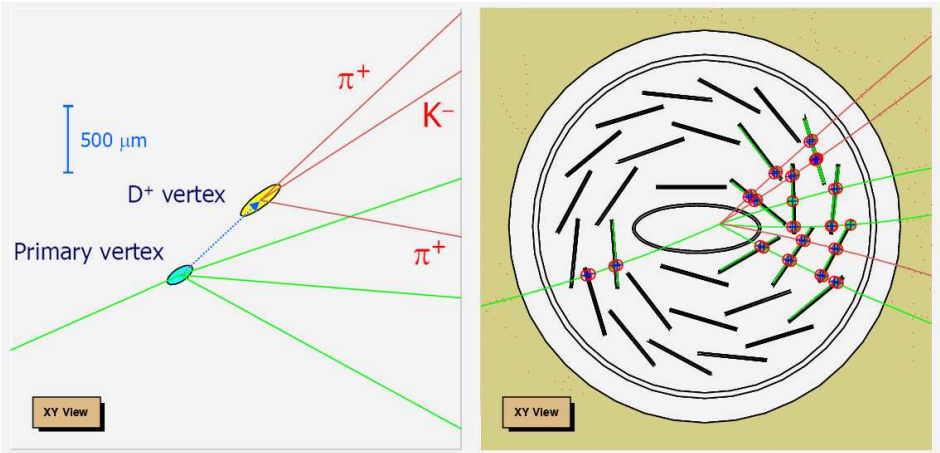
Why $f(c \to D_{s1}^+)$ is so large ?

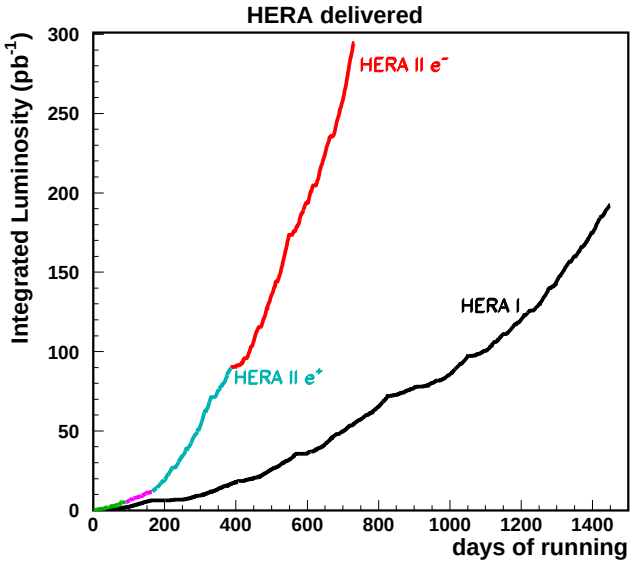
Is it connected with its strange helicity ?

Summary and Outlook

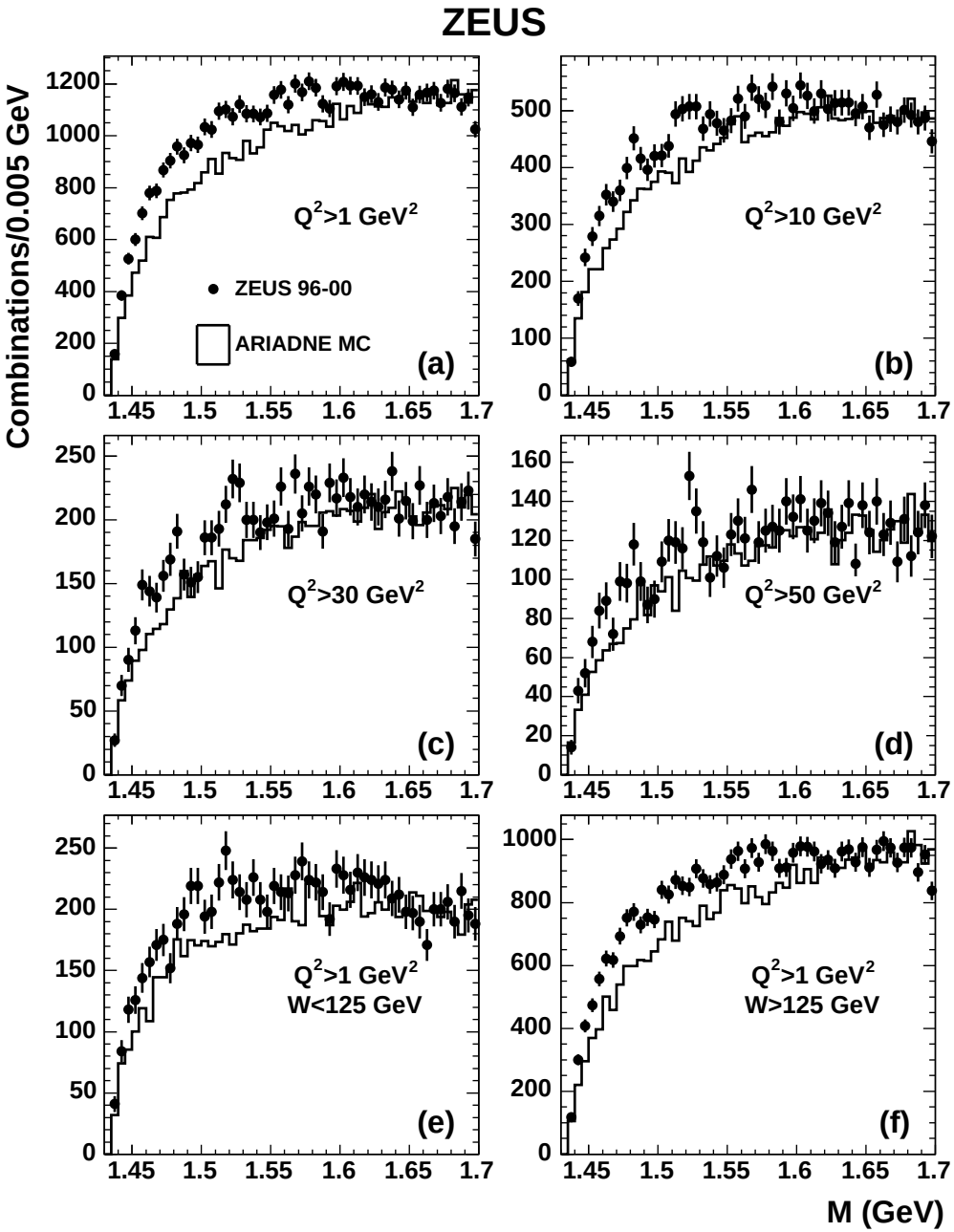
- $\Theta^+ \to K^0_s p$ production observed in high-Q^2 DIS by ZEUS.
  H1 does not see the signal that is not in statistical contradiction with ZEUS.
  Studies suggest Θ^+ production in ep related to proton-remnant fragmentation
- Sizeable $d/\bar{d}$ production observed in DIS.
  $\bar{d}/\bar{p}$ ratio in DIS similar to γp (H1) and pp data,
  corresponds to Coalescence Model with $B_2 \approx (0.5 - 1) \cdot 10^{-2}\,\mathrm{GeV}^2$
- H1 and ZEUS results on $\Theta^0_c \to D^* p$ 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.
  $D^{\pm}_{s1}(2536)$ shows questionable helicity distribution and "too large" $f(c \to D^+_{s1})$

Expect more from HERA II





$M(K^0_s p(\bar{p}))$



large background

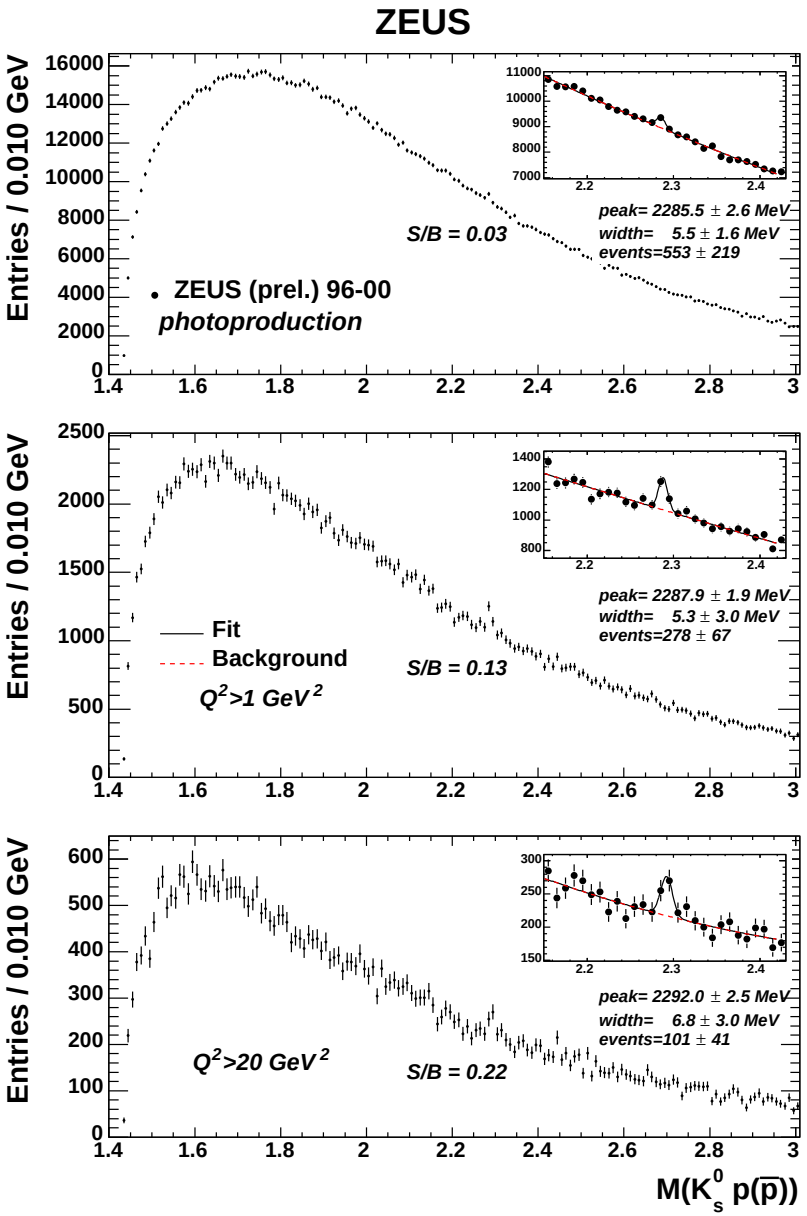
signal becomes visible
for $Q^2 > 10\,\mathrm{GeV}^2$

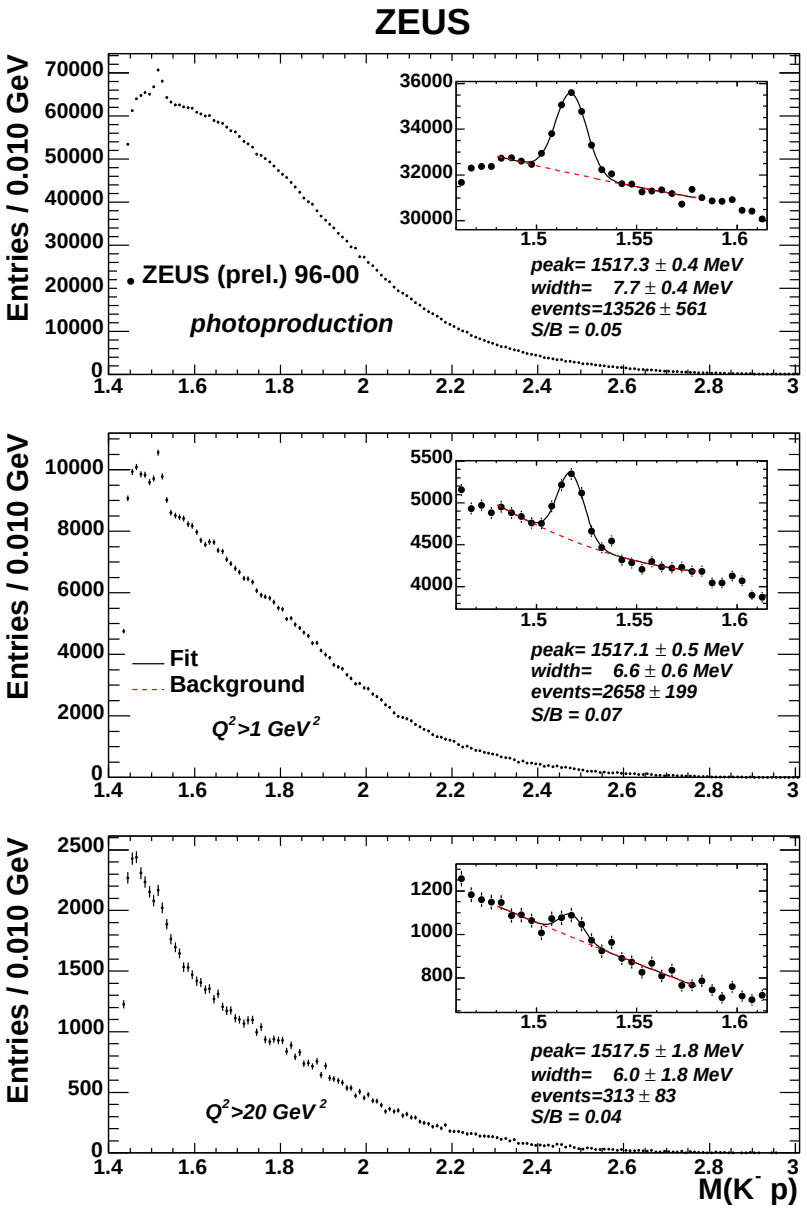
ARIADNE (JETSET) MC
(normalized to data above 1.65 GeV)
does not reproduce the shape.

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

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

Λ_c and $\Lambda(1520)$

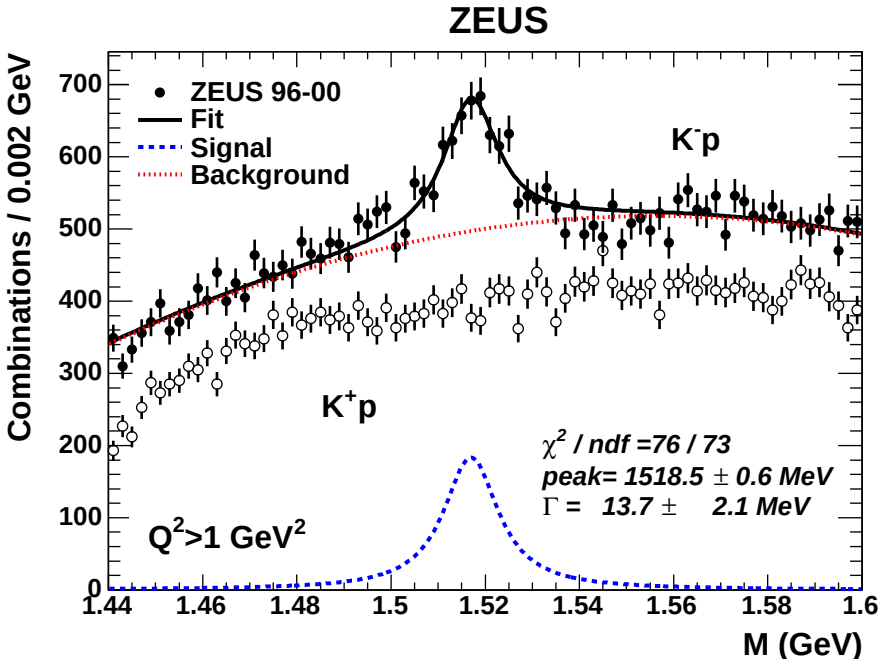


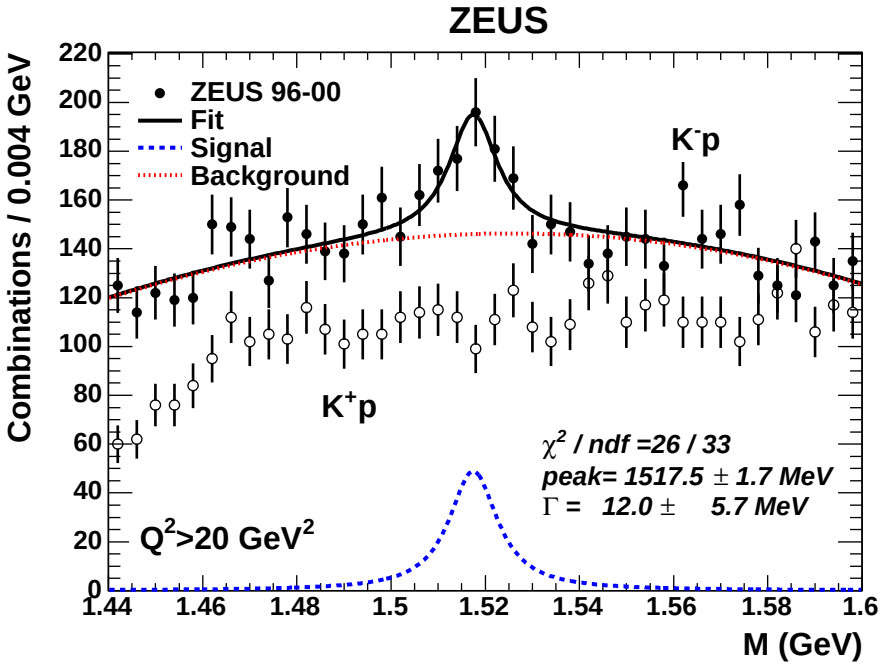


Λ_c seen better for $Q^2 > 20\,\mathrm{GeV}^2$

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

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





For NK bound state,

both $I = 0, 1$ are possible

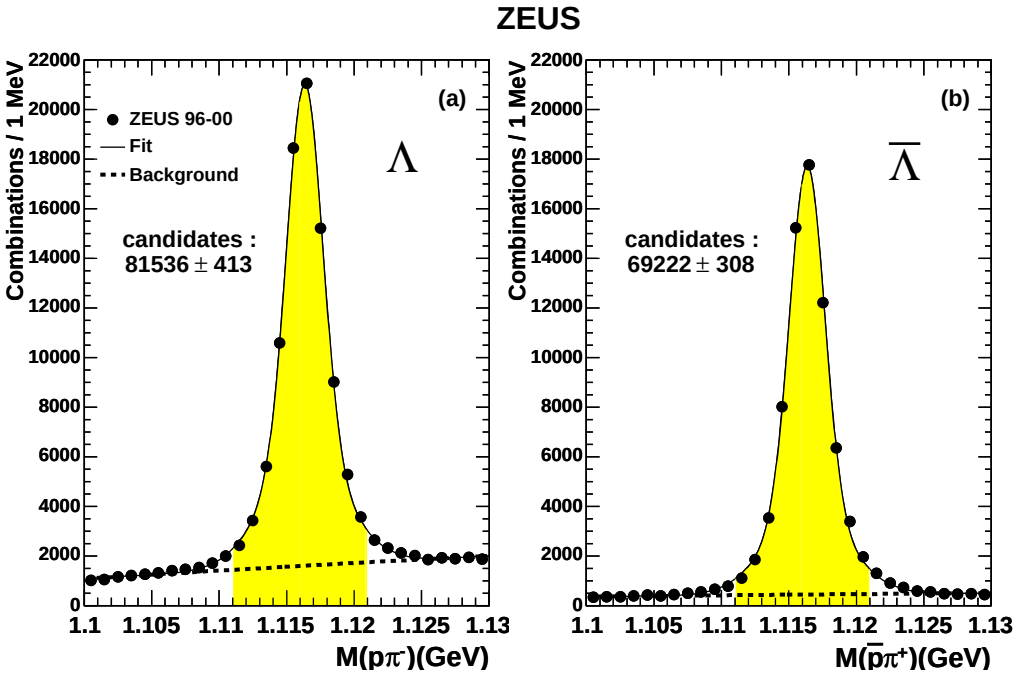
$I = 1$: triplet Θ^0, Θ^+, Θ^{++}

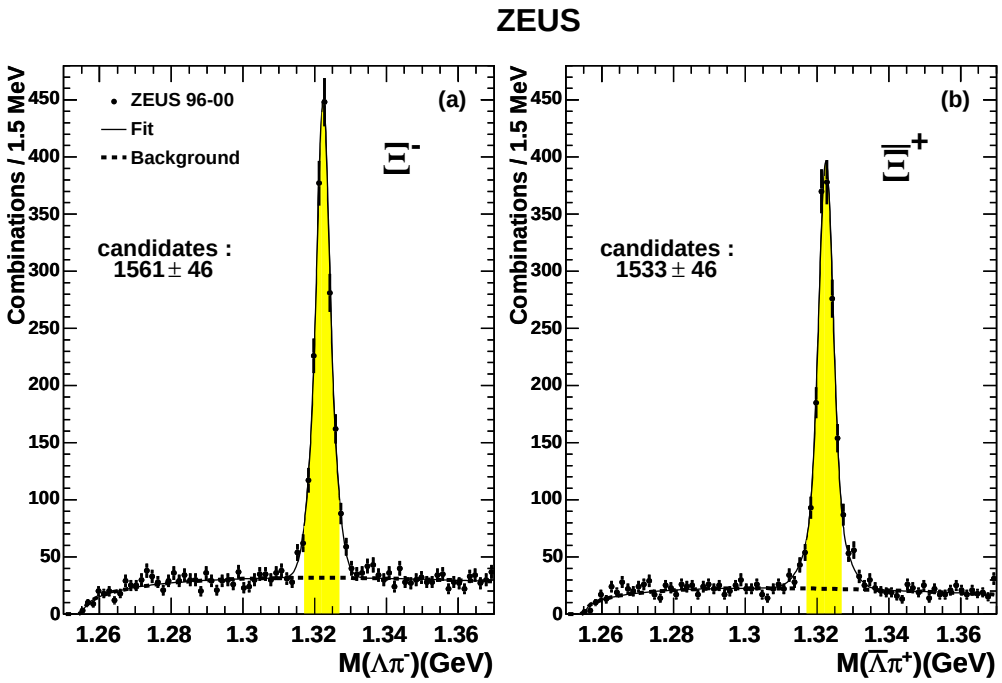
$\Longleftarrow$ search for $\Theta^{++} \to K^+p$ (+c.c.)
no signal

$\Longleftarrow$ no Θ^{++} signal for $Q^2 > 20\,\mathrm{GeV}^2$
as well

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

Search for pentaquarks with $S = \pm 2$





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

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

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

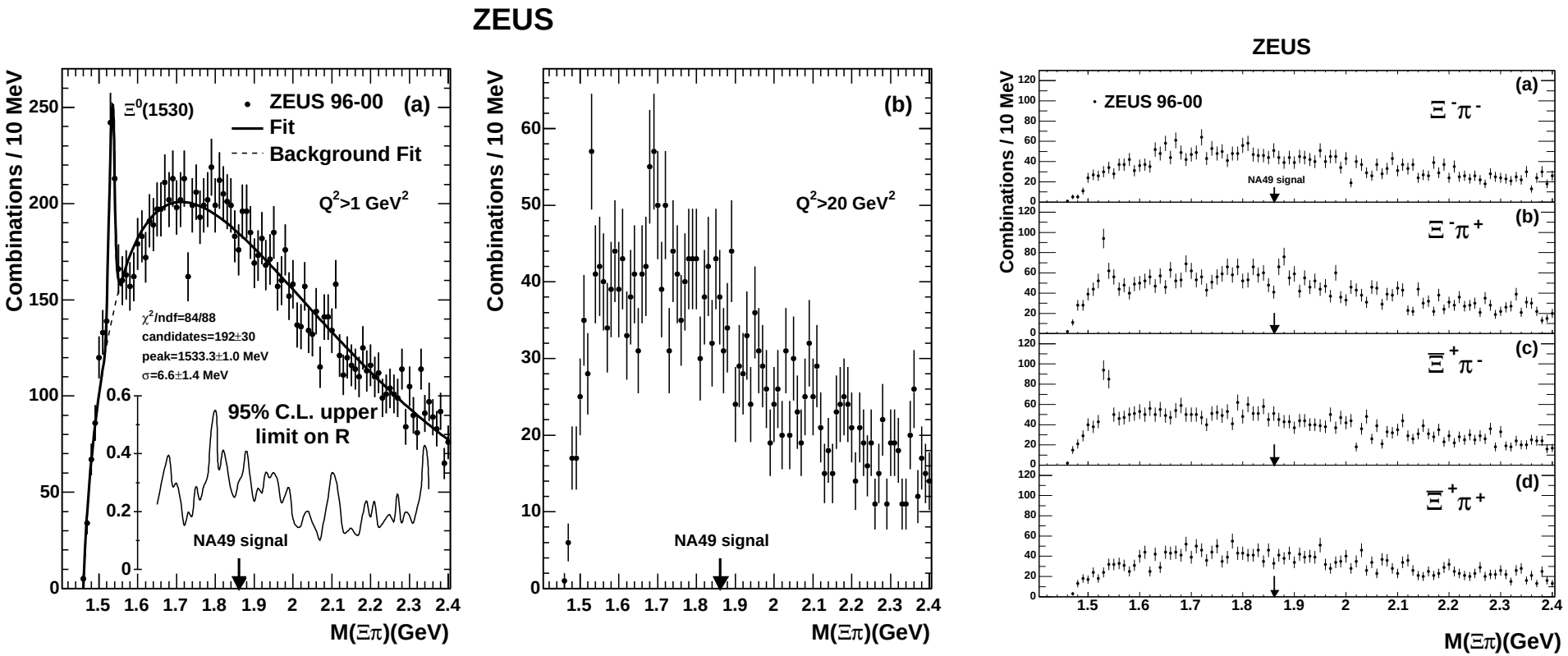
$\Longleftarrow \sim 150000$ candidates

Combining with additional track

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

$\Longleftarrow \sim 3000$ candidates

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



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

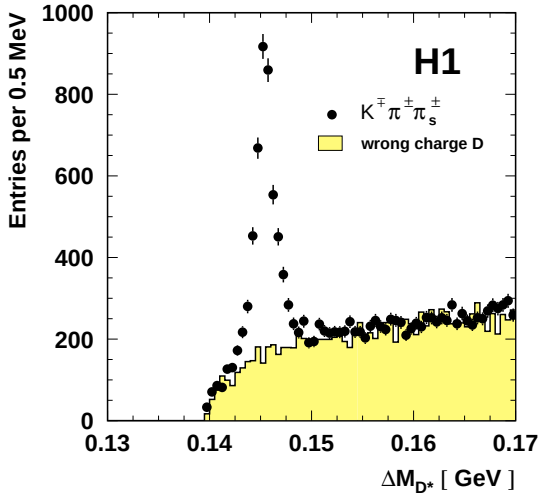
No $\Xi_{3/2}$ signal for $Q^2 > 1\,\mathrm{GeV}^2$ and $Q^2 > 20\,\mathrm{GeV}^2$; in all charge combinations

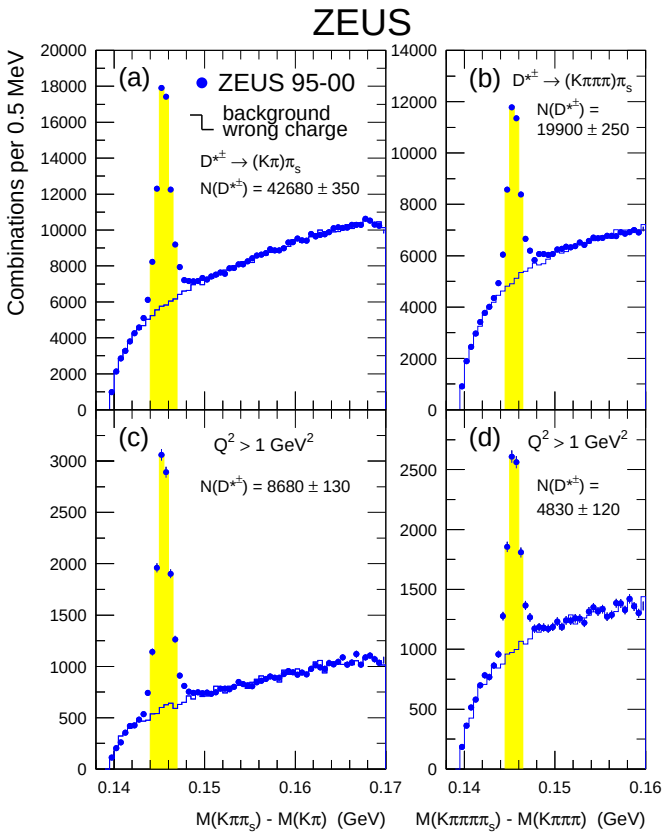
$R(\Xi_{3/2}^{--,0}/\Xi^0(1530)) < 0.29$ (95% C.L.) in the NA49 signal region

Note: ZEUS studies central production

NA49 covers forward production

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





H1 96-00 data ($75\,\mathrm{pb}^{-1}$)

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

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

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

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

ZEUS 95-00 data ($126\,\mathrm{pb}^{-1}$)

two D^* decay channels:

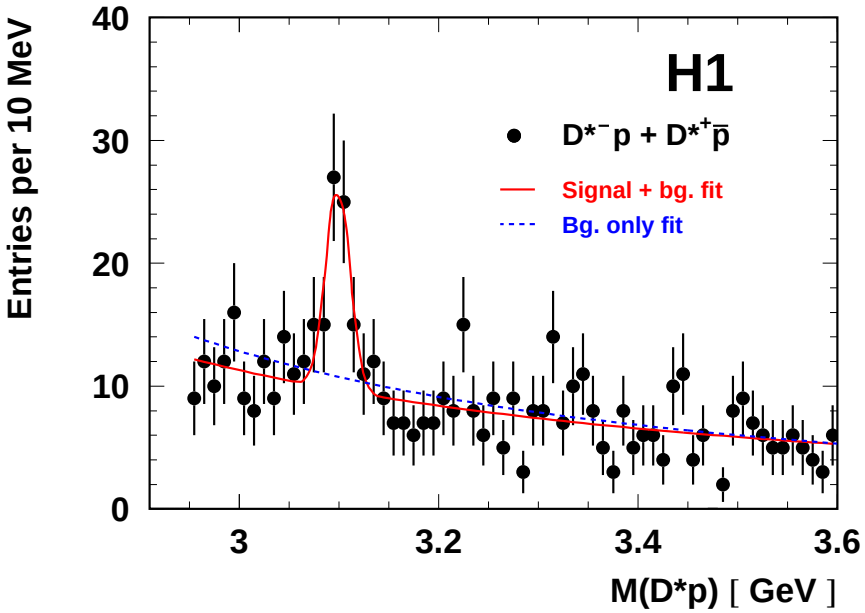
- $p_T(D^*) > 1.35\,\mathrm{GeV}$ for $D^* \to (K\pi)\pi_s$
- $p_T(D^*) > 2.8\,\mathrm{GeV}$ for $D^* \to (K\pi\pi\pi)\pi_s$
- $|\eta(D^*)| < 1.6$ for both channels

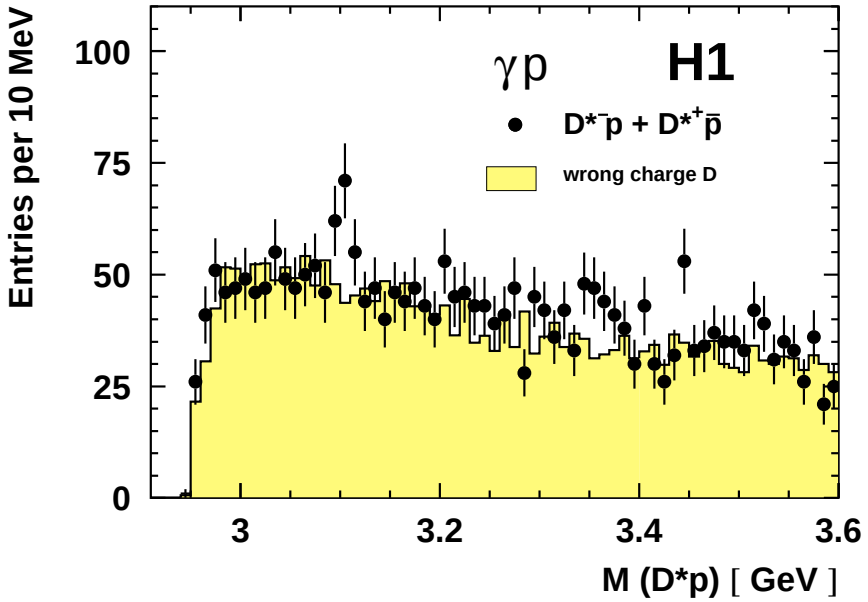
Yellow bands used for Θ_c^0 search:

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

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

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





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

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

Fit Gaussian + background (2 par.):

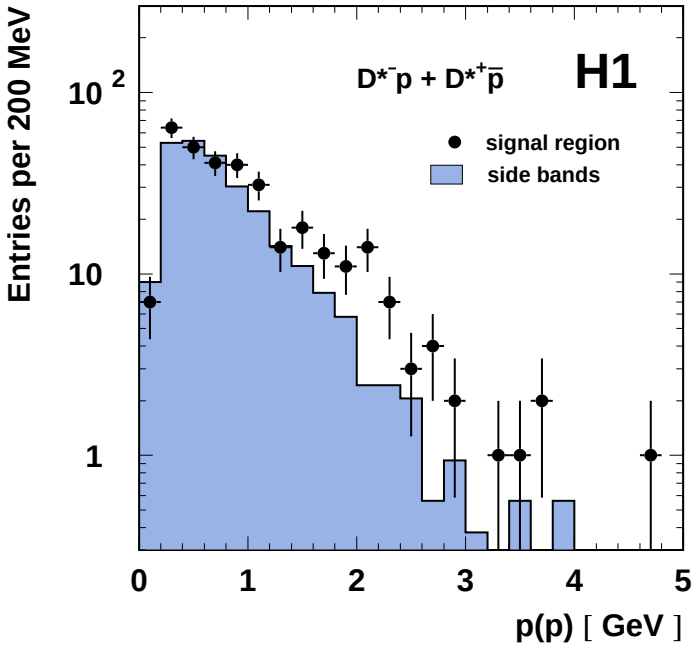
$$N(\Theta_c^0) = 50.6 \pm 11.2$$

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

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

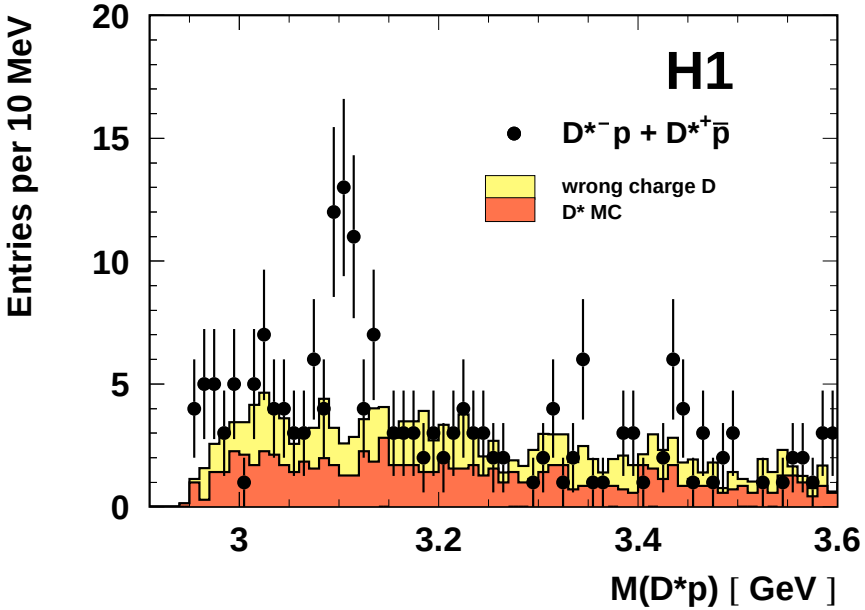
visible rate $R(\Theta_c^0 \to D^*p/D^*) = 1.46 \pm 0.32\,\%$ (prel.) or "roughly 1%" (paper)

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



particles taken as protons
w/o dE/dx requirements

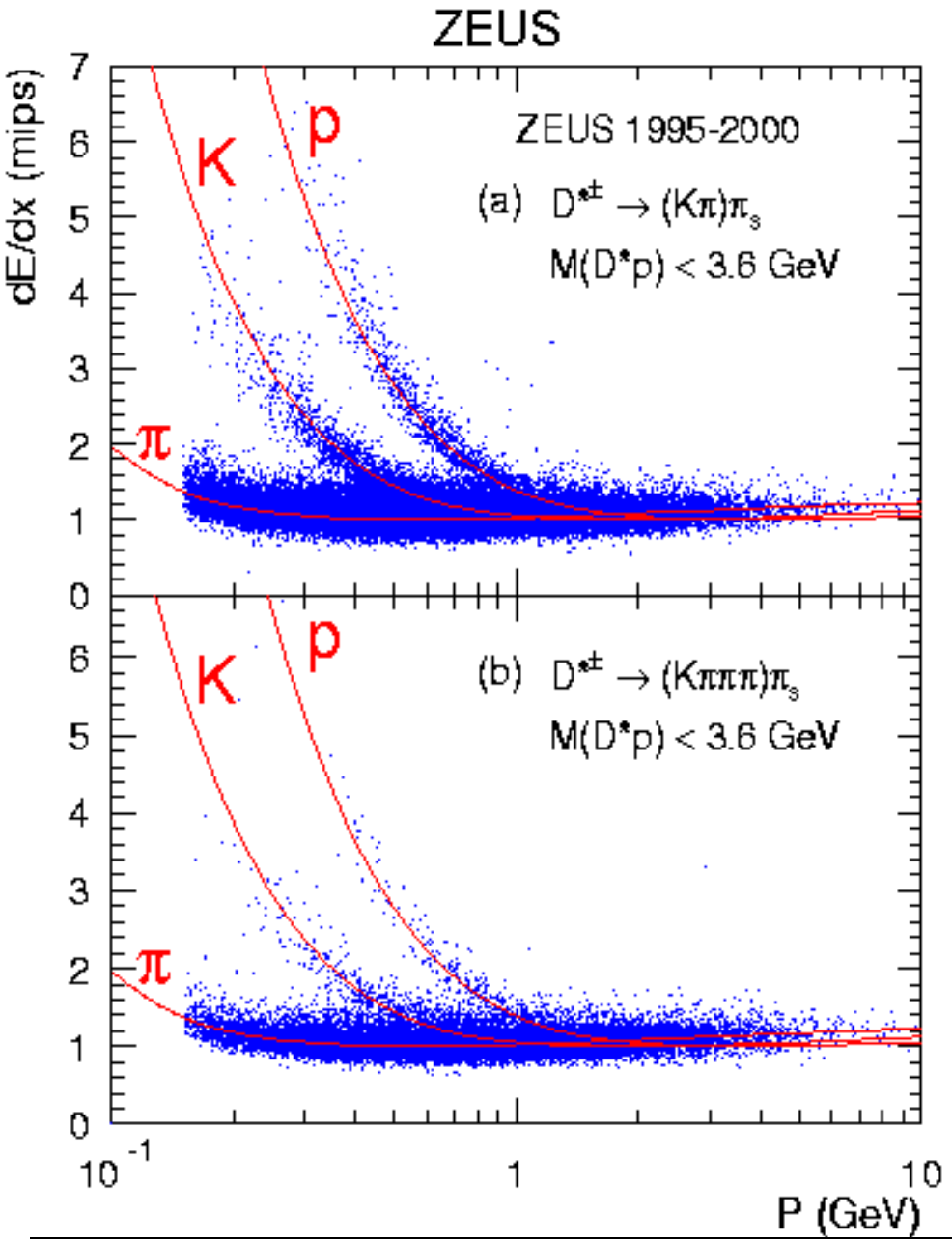
"protons" from signal region
$(3.085 < M(D^*p) < 3.115\,\text{GeV})$
have harder momentum distribution
than "protons" from side bands



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

$\Longleftarrow$ background is well described
by 2-component model

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



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

resolution $\sim 9\%$

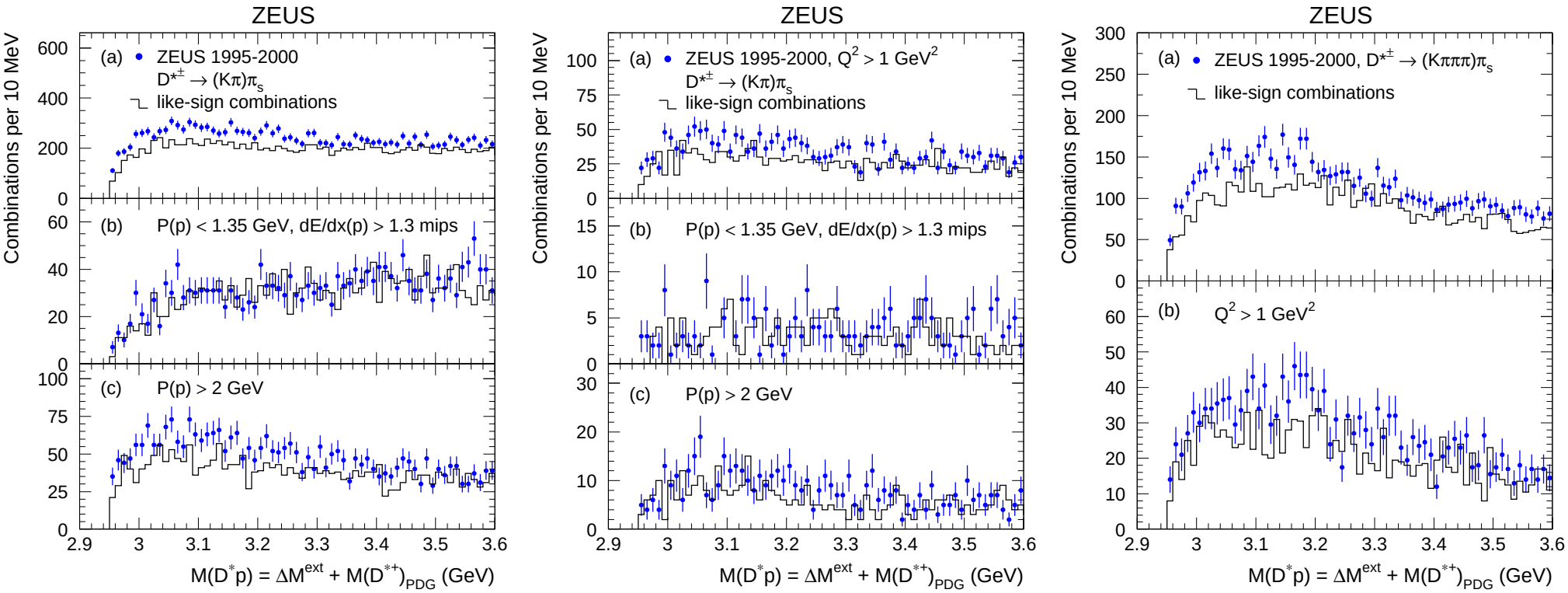
param. tuned using tagged $p(\bar{p})$ from Λ^0 decays

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

$Prob(\chi^2) > 0.15$

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

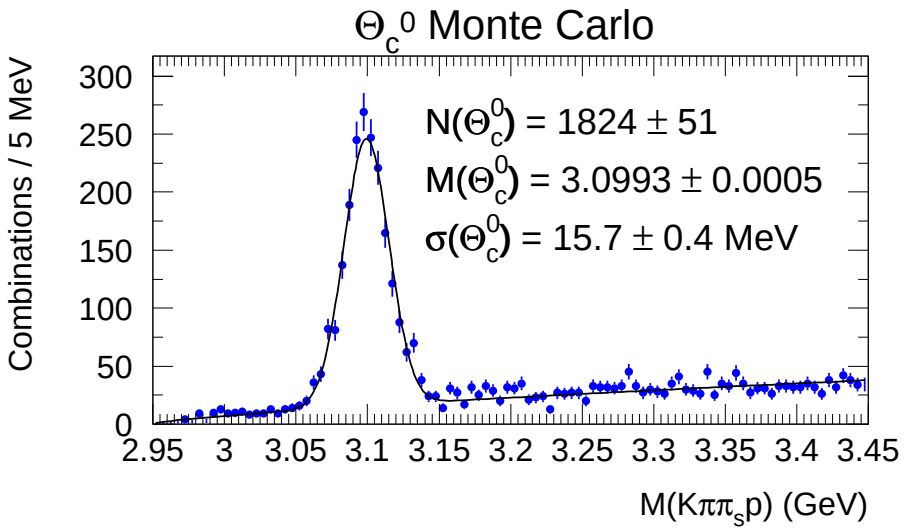
$M(D^*p)$, ZEUS

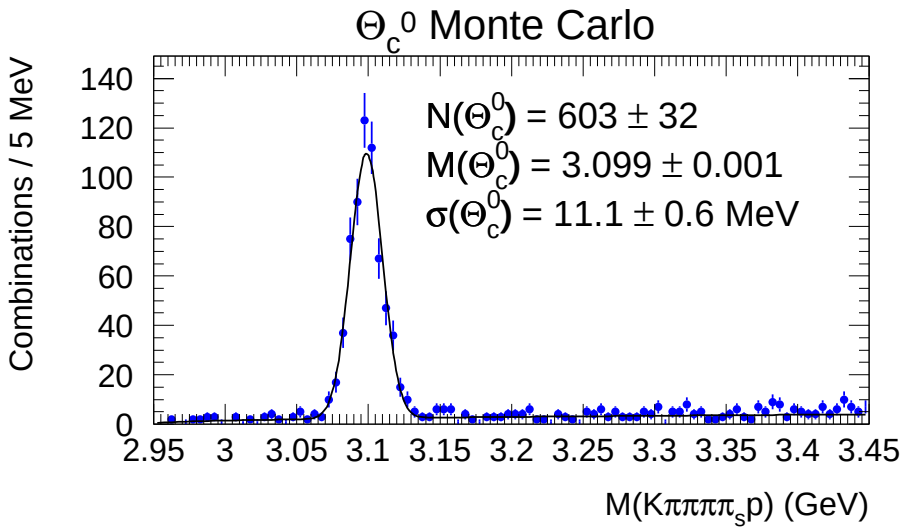


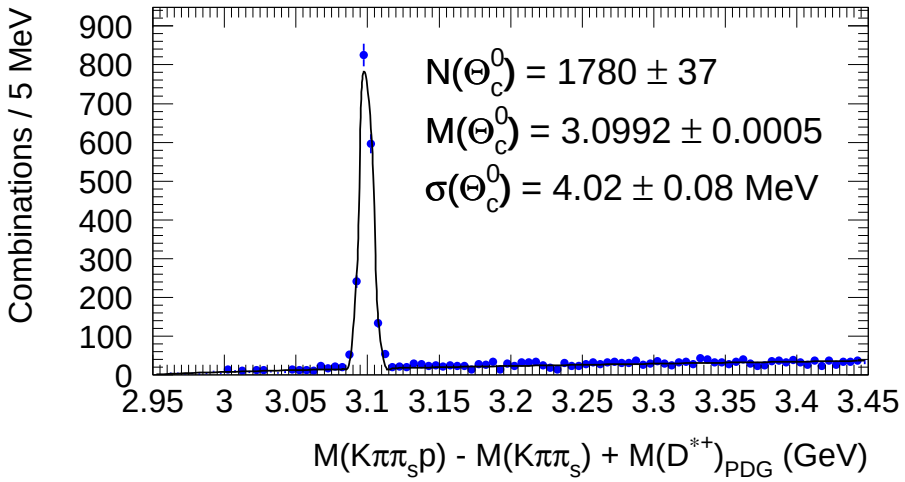
no signal in either distribution

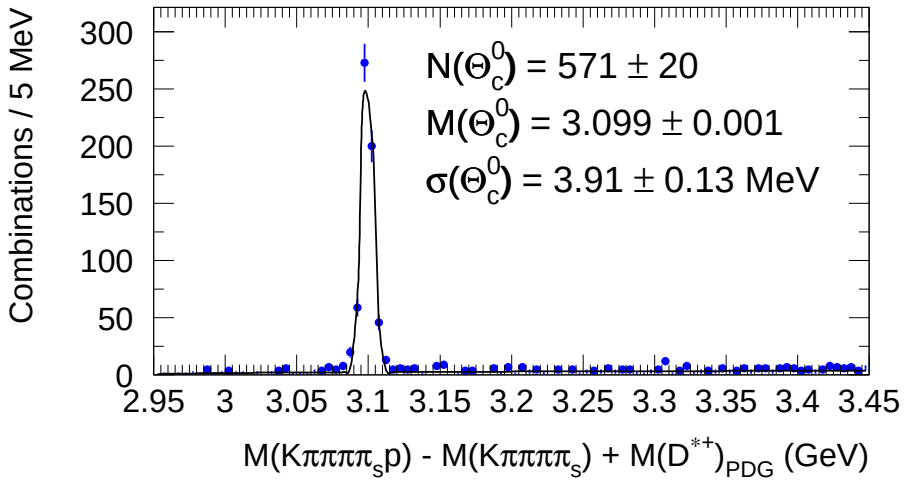
ZEUS Θ_c^0 MC and extended ΔM method

To prepare signal MC, Θ_c^0 was emulated by redefining mass, width and decay channel of $\Sigma_c^0(ddc)$



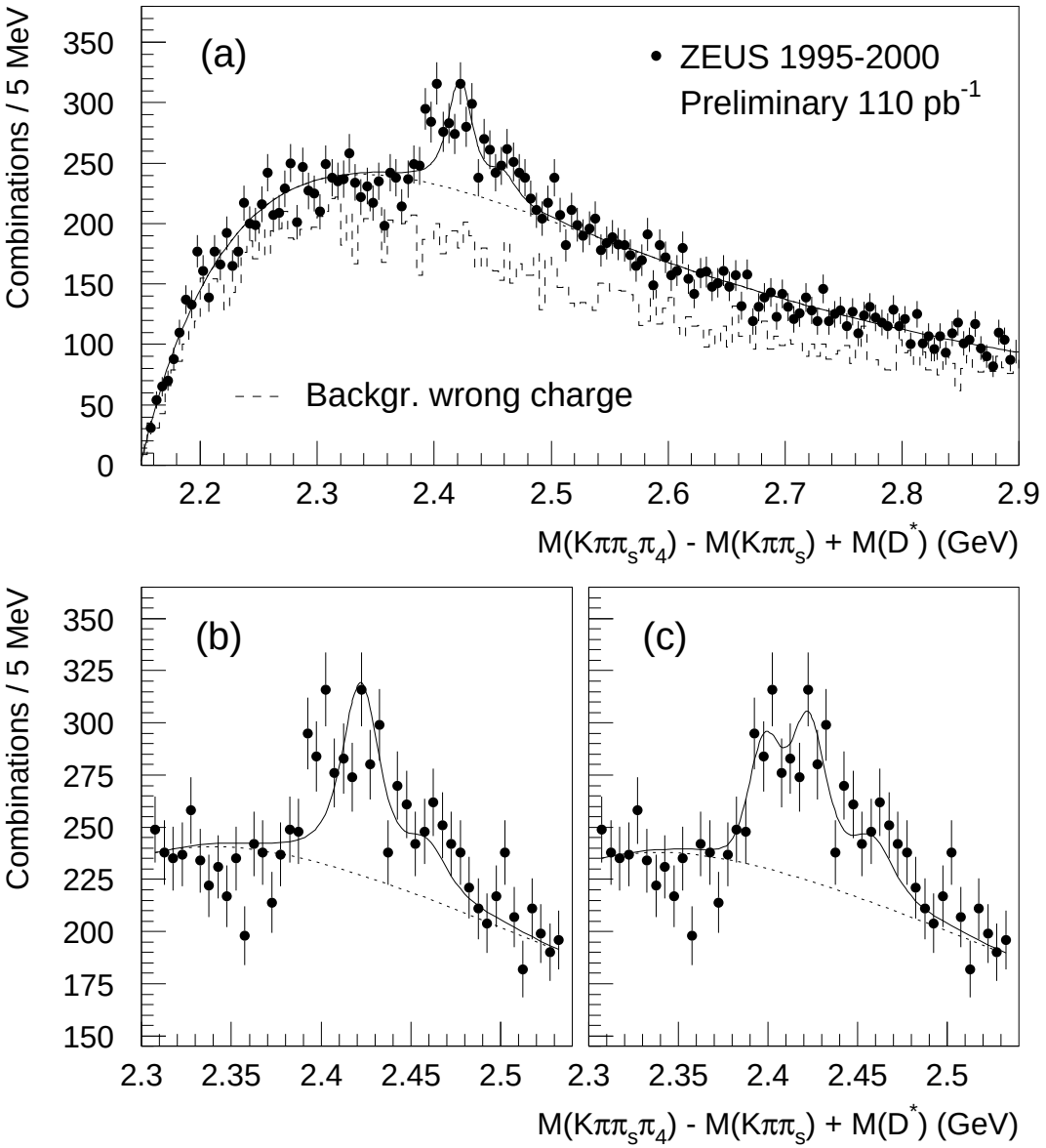






resolution is ~ 4 MeV (w.r.t. ~ 7 MeV in H1 analysis)

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 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

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

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

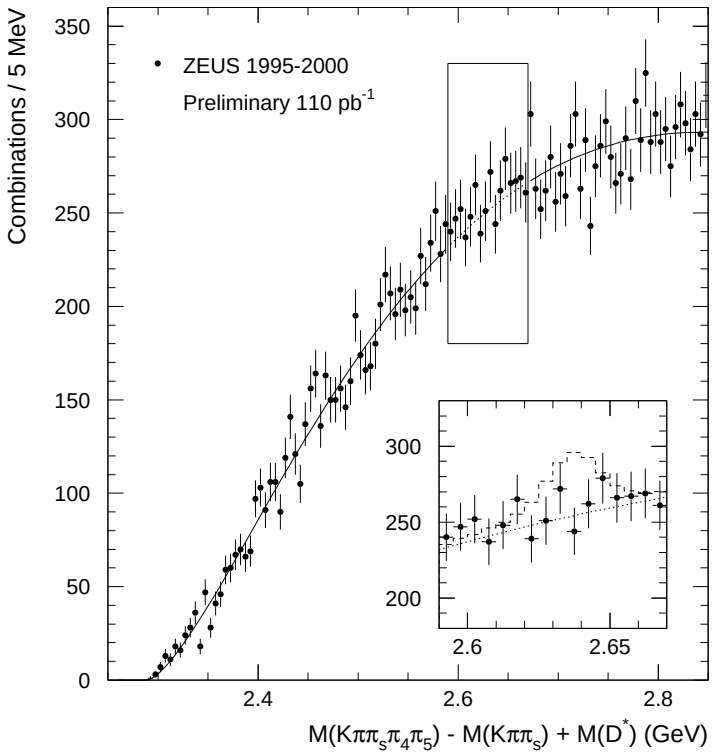
Additional narrow bump ?

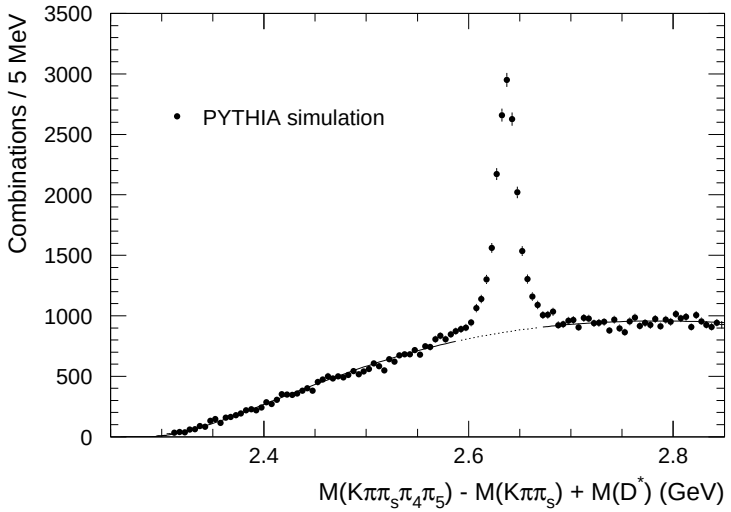
$N = 211 \pm 49$

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

New D meson ? Interference ?

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





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

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

$\Gamma < 15\,\mathbf{MeV}$

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

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

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

(ZEUS prel.)

somewhat stronger than the 0.9% **limit**

obtained by OPAL