Spectroscopy and charm fragmentation in ep collisions

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(sponsored by DESY)

September 20-24, St.Petersburg, Russia

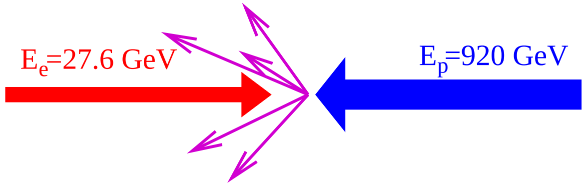
O U T L I N E :

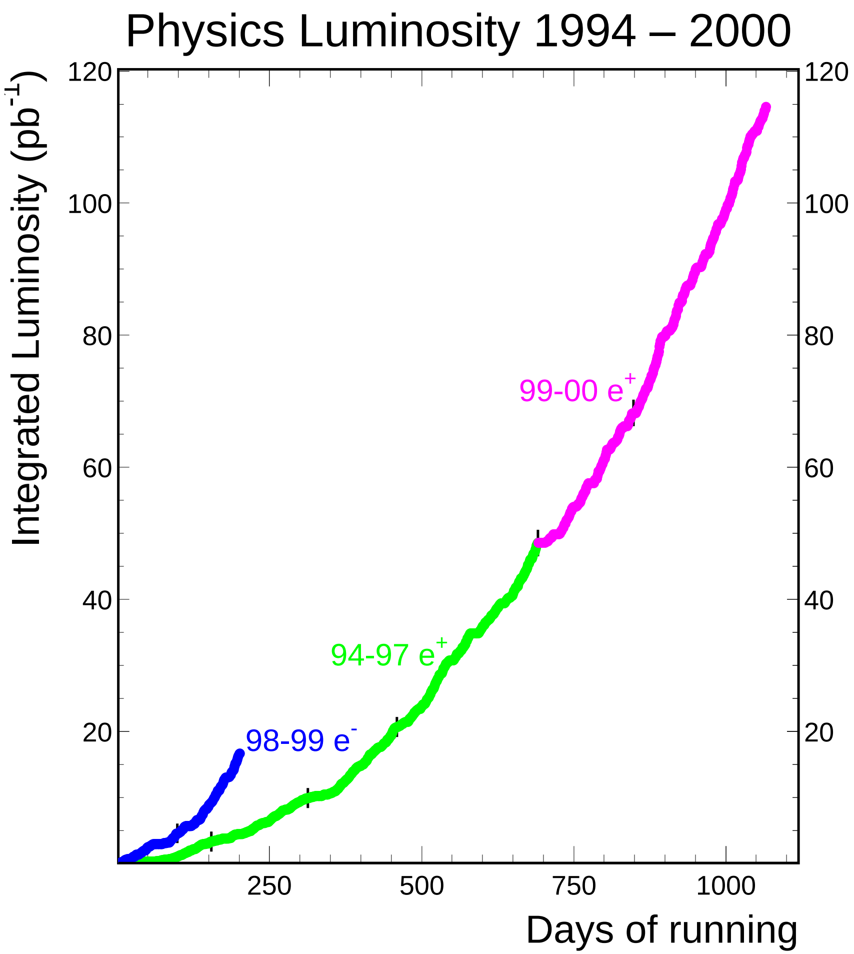
- HERA and its charm
- charm fragmentation
- excited D mesons
- Results on $\Theta^{+} \to K_s^0 p$ (+c.c.)
- Θ^{++} and $\Xi_{3/2}^{--,0}$ searches
- Results on $\Theta_c^0 \to D^{*-} p$ (+c.c.)
- Summary and Outlook

B A C K U P :

- light mesons in $M(\gamma\gamma)$ and $M(\pi^+\pi^-)$
- light mesons in $M(K_s^0 K_s^0)$
- more on excited D mesons
- more on $\Theta^{+} \to K_s^0 p$ (+c.c.)
- more on $\Theta_c^0 \to D^{*-} p$ (+c.c.)

HERA $\longrightarrow$ HERA II





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

	HERA	**HERA II**
	1992-2000	**2003-2007**
$\sqrt{s}$	320 **(300)**	320 **GeV**
$\mathcal{L}$	$1.5 \cdot 10^{31}$	$7 \cdot 10^{31}\, cm^{-2}\, s^{-1}$
$\mathcal{L}_{int}$	0.1	$\sim 0.5\, fb^{-1}$
beam spot	150×30	$80 \times 20\, \mu m^2$

$e^{\pm}$ **long. pol.** $(\approx 60\%)$

$\sigma_{c\bar{c}} \approx 1\,\mu\mathrm{b} \Longrightarrow 10^8$ **events** $(\mathcal{L}_{int} = 0.1\, f\mathrm{b}^{-1})$

$\sigma_{b\bar{b}} \approx 10\,\mathrm{nb} \Longrightarrow 10^6$ **events** $(\mathcal{L}_{int} = 0.1\, f\mathrm{b}^{-1})$

“QCD explorer” HERA

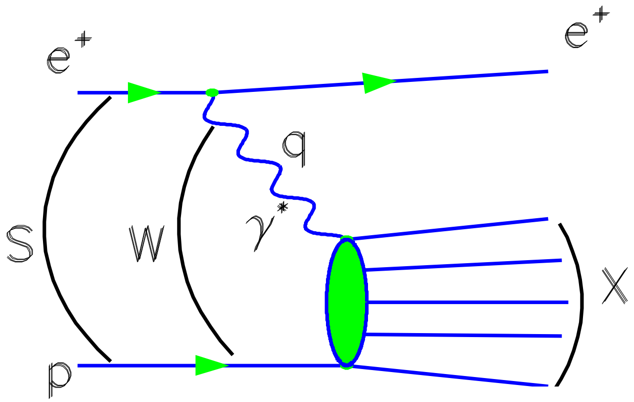
tests (p)QCD predictions

“Charm factory” HERA

studies charm fragmentation

Kinematic variables and charm production

$e(k) + p(P) \rightarrow e(k') + X$



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

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

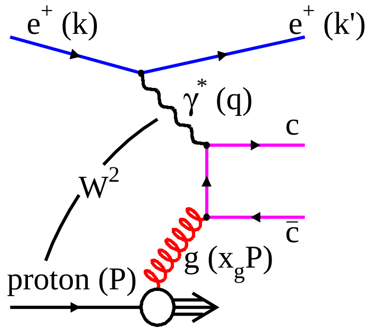
Photoproduction $\quad Q^2 \simeq 0\, GeV^2$

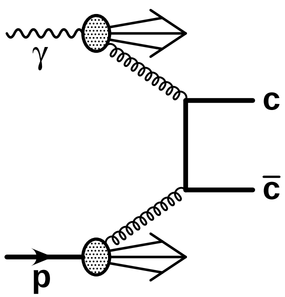
DIS $\quad Q^2 > 1\, GeV^2$

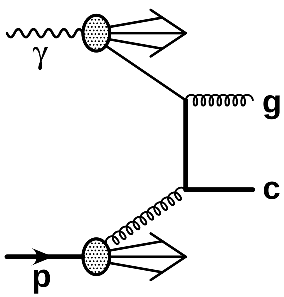
$$W^2 = (P+q)^2$$

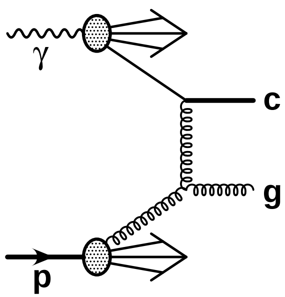
$$y = \frac{q \cdot P}{k \cdot P} \cong \frac{W^2}{s} \qquad x \cong \frac{Q^2}{sy}$$

Charm production is expected to be described by pQCD:

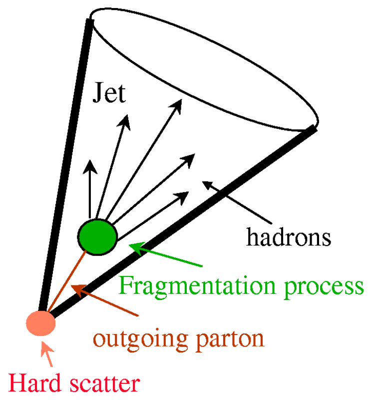








$c \Longrightarrow D$?



Charm fragmentation issues

Important to study charm fragmentation to find :

1) What is the proper parameterisation for the fractional transfer of c-quark energy/momentum to a given D-meson (z) ?
fragmentation function, $f(z)$

2) Are u and d quarks produced equally ? $R_{u/d} = \frac{c\bar{u}}{c\bar{d}}$

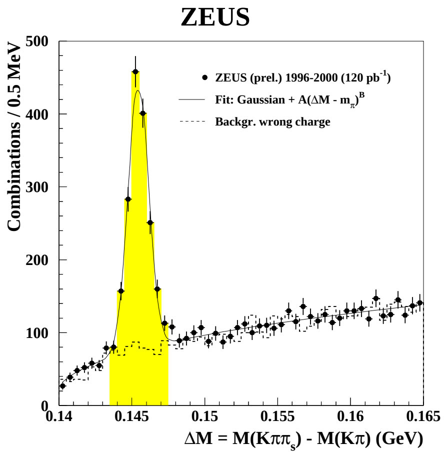
3) What is the s-quark production suppression ? $\gamma_s = \frac{2\,c\bar{s}}{c\bar{d}+c\bar{u}}$

4) Are vector (D^*) and pseudoscalar (D) mesons produced as predicted by spin counting ? $P_{\rm v} = \frac{V}{V+PS}$ $(= 0.75\ ?)$

5) What are the relative fragmentation fractions of charm hadrons ?
$f(c \to D) = \frac{N(D)}{N(c)} = \frac{\sigma(D)}{\sum_{\rm all} \sigma(D)}$

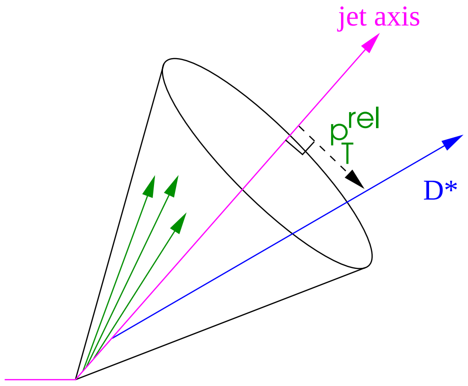
6) Are these functions, ratios and fractions universal ?
compare HERA results with those in e^+e^- annihilations

Measurement of $c \to D^{*+}$ fragmentation function



$\mathcal{L}_{int} = 120\,\mathrm{pb}^{-1}$

$N(D^{*\pm}) = 1268 \pm 52$



In e^+e^- annihilations, $D^{*\pm}$ energy is related to $\sqrt{s}/2$. In ep ?

1) ZEUS: find jet containing $D^{*\pm}$ and relate the $D^{*\pm}$ energy to the energy of this jet: $Q^2 < 1\,\mathrm{GeV}^2$, $P_T(D^{*\pm}) > 2\,\mathrm{GeV}$, $E_T^{\mathrm{jet}} > 9\,\mathrm{GeV}$

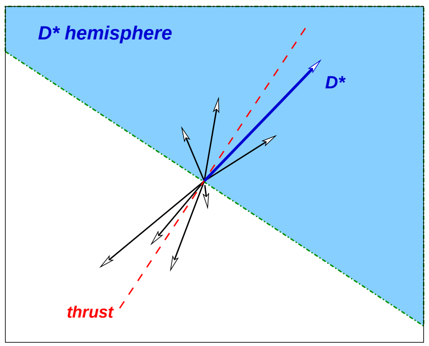
$$z = (E + p_{||})^{D^*} / (E + p_{||})^{\mathrm{jet}} \equiv (E + p_{||})^{D^*} / 2\,E^{\mathrm{jet}}$$

2) H1, jet method: $Q^2 > 2\,\mathrm{GeV}^2$, $P_T(D^{*\pm}) > 1.5\,\mathrm{GeV}$, $E_T^{\mathrm{jet}} > 3\,\mathrm{GeV}$

$$z_{\mathrm{jet}} = (E + p_{||})^{D^*} / (E + p)^{\mathrm{jet}} \quad \text{in } \gamma^* p$$

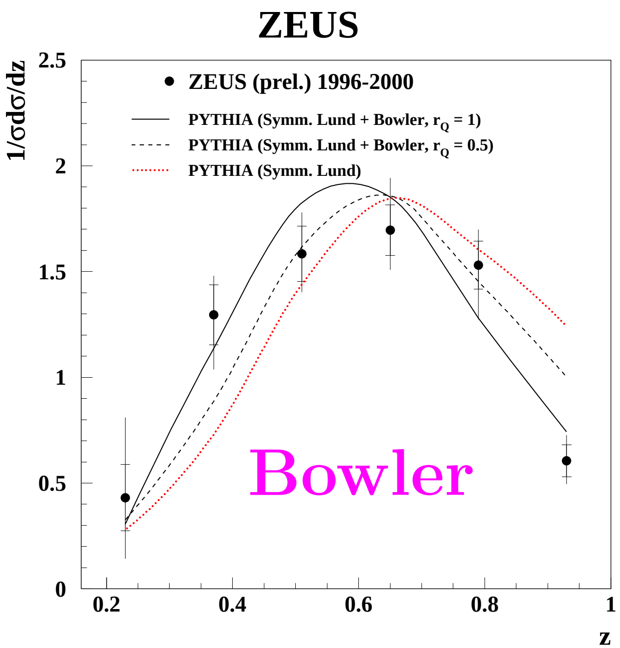
3) H1, hemisphere method:

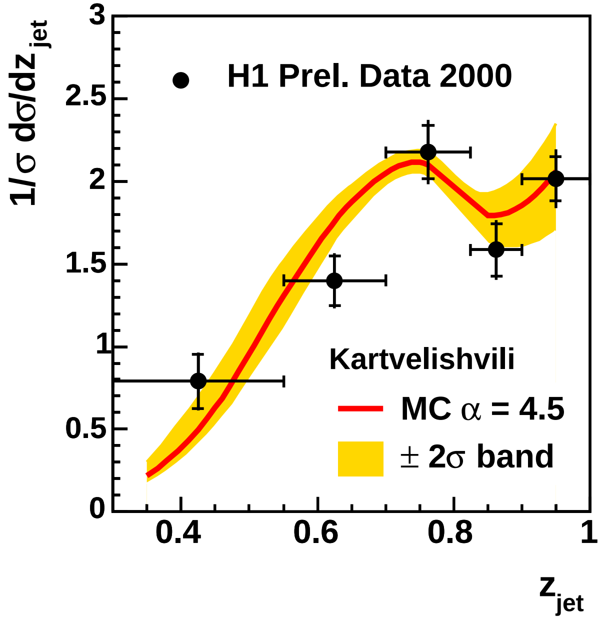
$$z_{\mathrm{hem}} = (E + p_{||})^{D^*} / \sum_{\mathrm{hem}} (E + p) \quad \text{in } \gamma^* p$$

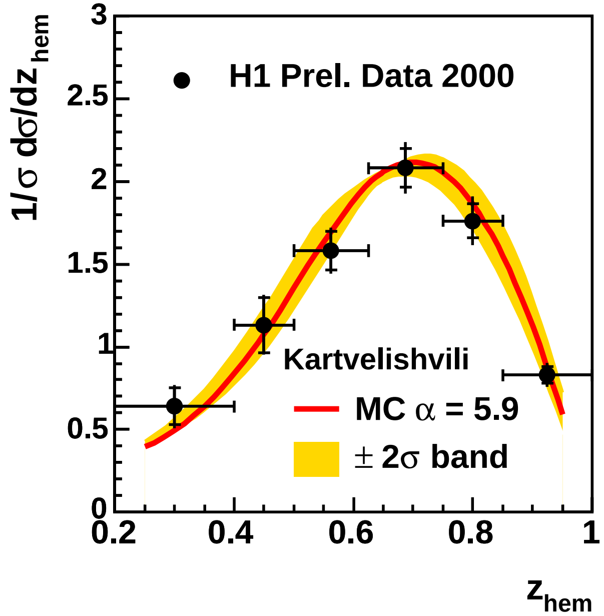


Bowler and Kartvelishvili parameterizations

Parameters are extracted using MC (Pythia or Rapgap+Pythia), i.e. they are optimized input parameters of the MC simulations







$$\frac{1}{z^{1+r_Q b m_Q^2}}(1-z)^a \exp\left(\frac{-b m_\perp^2}{z}\right)$$

$r_Q = 1$ (default) is preferable

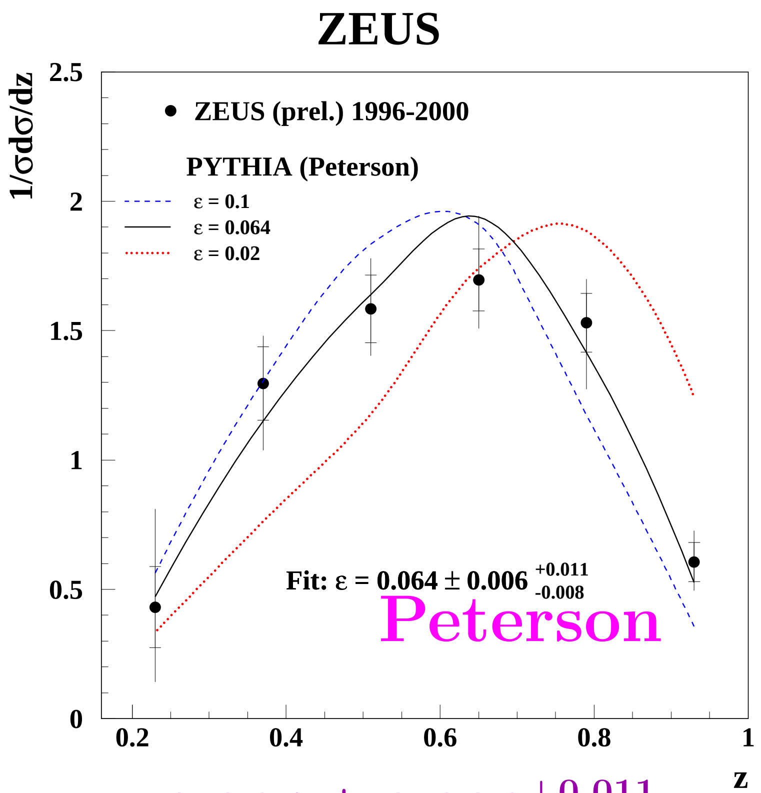
$$f(z) \propto z^{\alpha}(1-z)$$

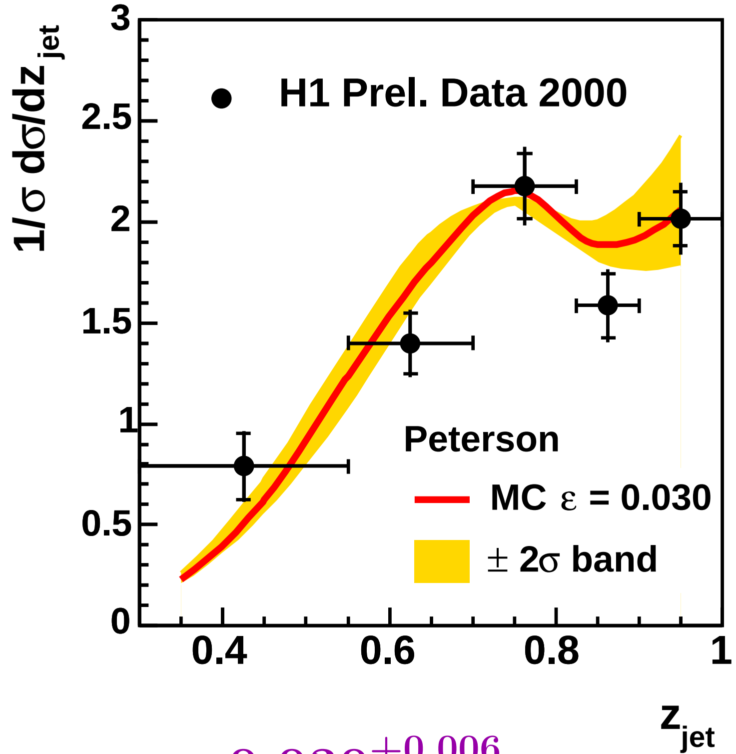
$\alpha = 4.5 \pm 0.5$ (H1 jet method)

$\alpha = 5.9^{+0.9}_{-0.6}$ (H1 hem. method)

$4.0 < \alpha < 6.8$ (H1 prel.)

Peterson parameterization: $f(z) \propto \frac{1}{z(1-1/z-\epsilon/(1-z))^2}$





$\epsilon = 0.064 \pm 0.006^{+0.011}_{-0.008}$ (ZEUS prel.)

$\epsilon = 0.05$ (PYTHIA default)

$\epsilon = 0.053$ (LL fit to ARGUS data by Nason and Oleari)

uncorrected for D^{**} decays

$\epsilon = 0.030^{+0.006}_{-0.005}$ (H1 jet method)

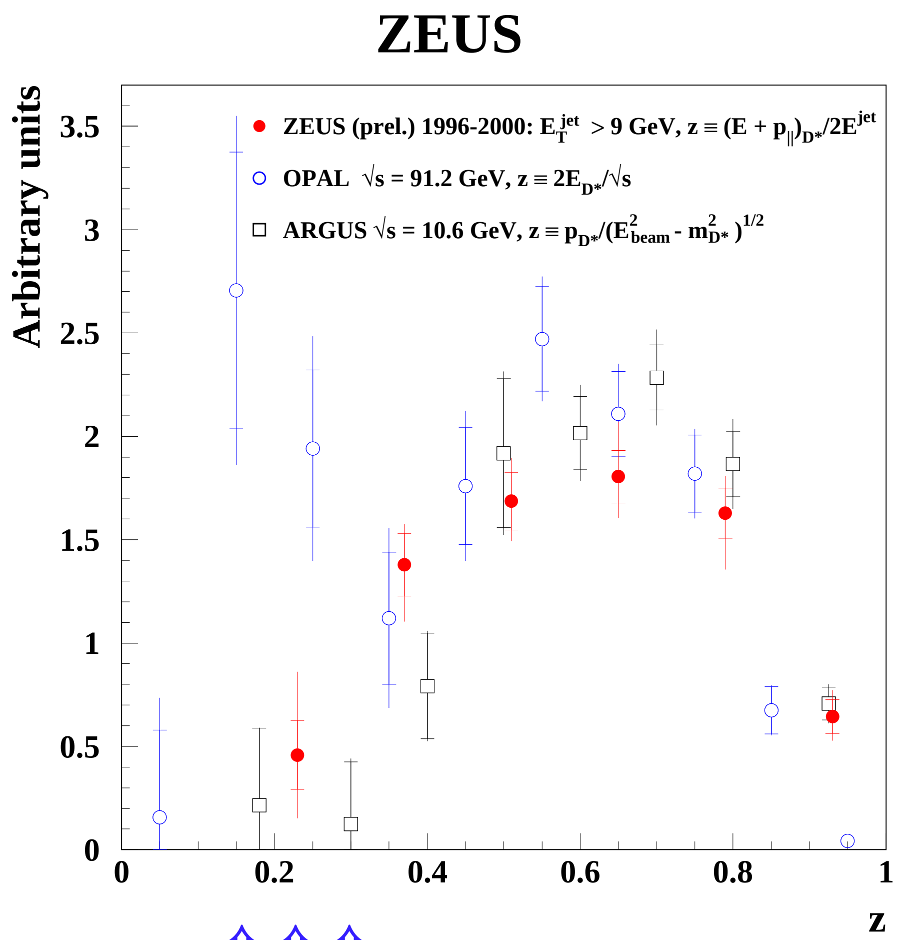
$\epsilon = 0.018 \pm 0.004$ (hem. method)

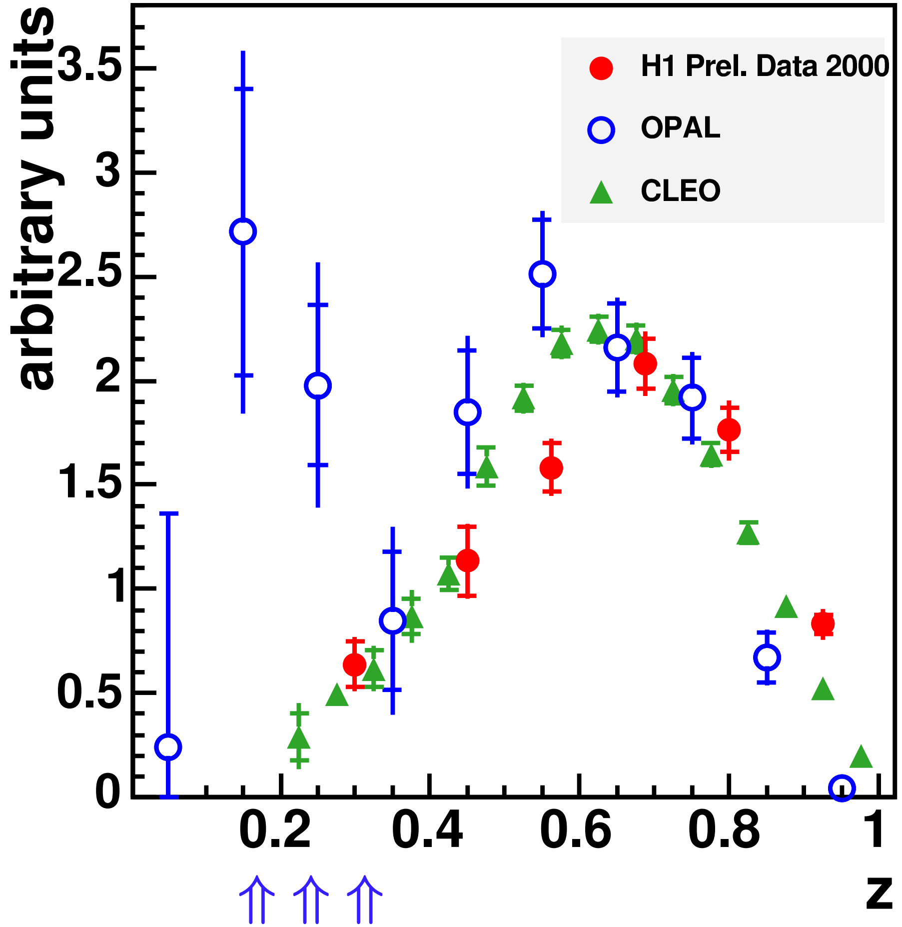
$0.014 < \epsilon < 0.036$ (H1 prel.)

corrected for D^{**} decays

NLO fits are needed !

Charm fragmentation function in ep and e^+e^- collisions





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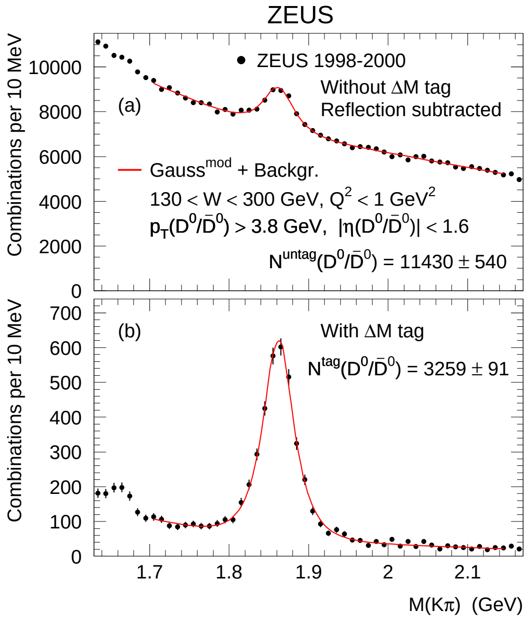
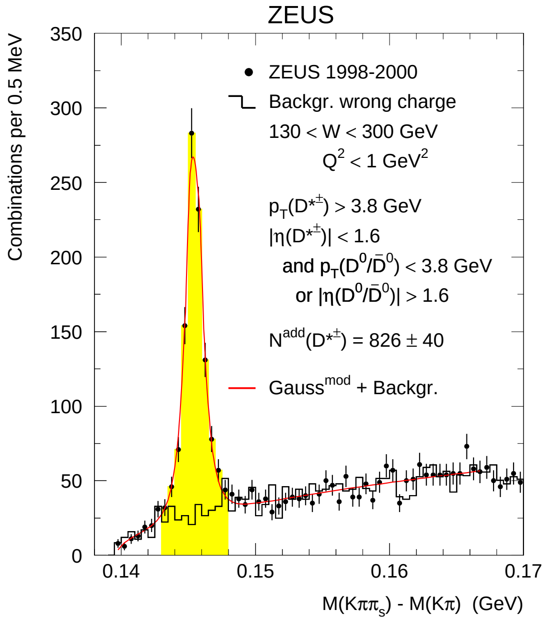
no gluon-splitting component in low-energy data

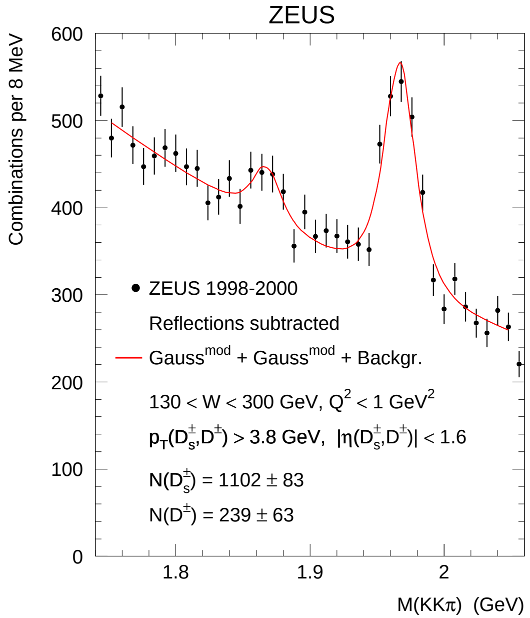
different z definitions

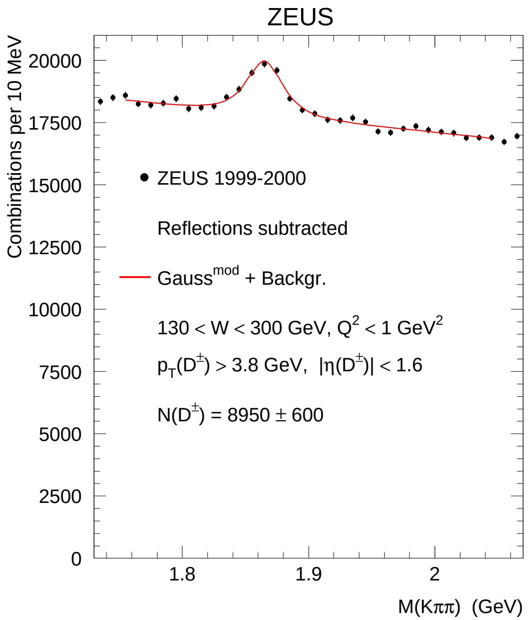
qualitative agreement

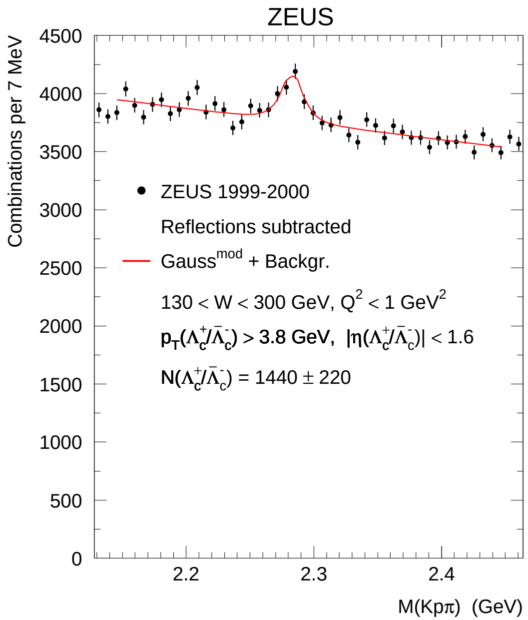
Measurement of c-fragmentation ratios and fractions $D^{*\pm}$ and c ground states: D^0, $D_s^{\pm}$, $D^{\pm}$ and $\Lambda_c^{\pm}$











Kinematic range of ZEUS γp analysis:

$P_T(D,\Lambda) > 3.8\,\text{GeV},\ |\eta(D,\Lambda)| < 1.6$

$130 < W < 280\,\text{GeV},\ Q^2 < 1\,\text{GeV}^2$

"Measured" x-sections:

$\sigma^{\text{untag}}(D^0),\ \sigma^{\text{tag}}(D^0),\ \sigma^{\text{add}}(D^{*\pm})$

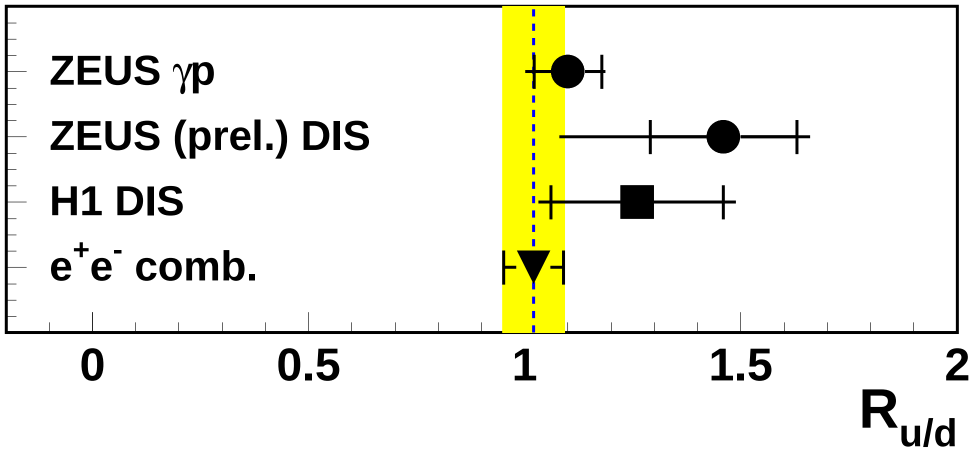
$\sigma(D_s^{\pm}),\ \sigma(D^{\pm}),\ \sigma(\Lambda_c^{\pm})$

$R_{u/d}$ measurement

$$R_{u/d} = \frac{c\bar{u}}{c\bar{d}} = \frac{\sigma^{dir}(D^{0,*0})}{\sigma^{dir}(D^{\pm,*\pm})} = \frac{\sigma(D^0)-\sigma(D^{*\pm})\times BR}{\sigma(D^{\pm})-\sigma(D^{*\pm})\times(1-BR)+\sigma(D^{*\pm})}$$

$$= \frac{\sigma(D^0)-\sigma(D^{*\pm})\times BR}{\sigma(D^{\pm})+\sigma(D^{*\pm})\times BR} = \frac{\sigma^{\mathrm{untag}}(D^0)}{\sigma(D^{\pm})+\sigma^{\mathrm{tag}}(D^0)} \quad , BR = B_{D^{*+}\to D^0\pi^+} = (67.7 \pm 0.5)\ \%$$

$$R_{u/d} = 1.100 \pm 0.078\ (\mathrm{stat})^{+0.038}_{-0.061}\ (\mathrm{syst})^{+0.047}_{-0.049}\ (\mathrm{br})$$ (ZEUS γp)



$$= \frac{f(c\to D^0)-f(c\to D^{*+})\times BR}{f(c\to D^+)+f(c\to D^{*+})\times BR}$$

for H1 and e^+e^-

consistent with isospin invariance

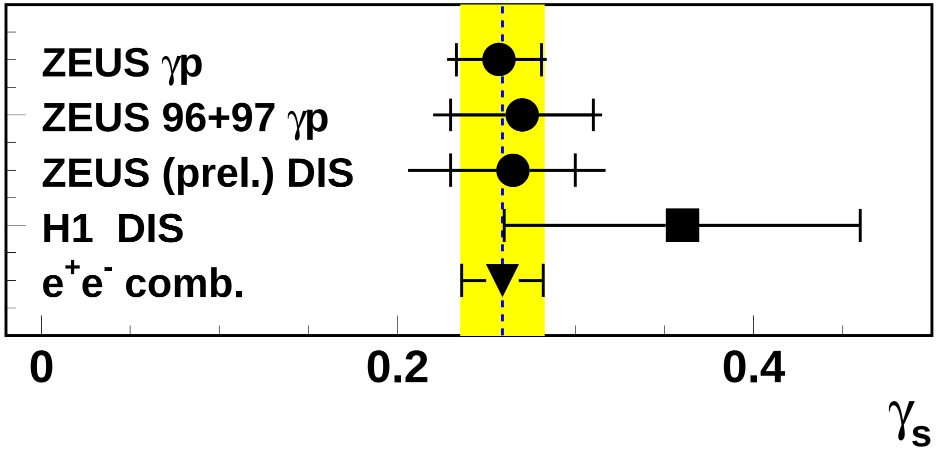
u and d quarks are produced equally in charm fragmentation

and what about more precise measurement in DIS ?

γ_s measurement

$$\gamma_s = \frac{2\,c\bar{s}}{c\bar{d}+c\bar{u}} = \frac{2\,\sigma(D_s^{\pm})}{\sigma(D^{\pm})+\sigma^{\rm untag}(D^0)+\sigma^{\rm tag}(D^0)+\sigma^{\rm add}(D^{*\pm})\cdot(1+R_{u/d})}$$

$$\gamma_s = 0.257 \pm 0.024\,(\text{stat})^{+0.013}_{-0.016}\,(\text{syst})^{+0.078}_{-0.049}\,(\text{br})$$ **(ZEUS γp)**



$$= \frac{2\,f(c\to D_s^+)}{f(c\to D^+)+f(c\to D^0)}$$

for H1 and e^+e^-

perfect agreement between measurements

D_s production suppressed by factor ≈ 3.9 in c-fragmentation

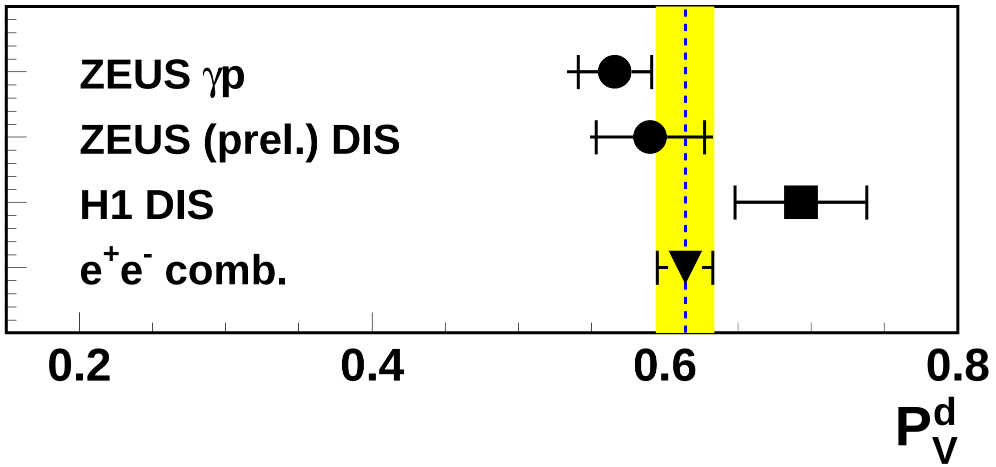
note: excited charm-strange mesons like to decay to non-strange D mesons

$\Longrightarrow$ Lund strangeness-suppression parameter is $10 - 30\%$ larger than the observable γ_s

$P_{\rm V}^d$ measurement ($P_{\rm V}^d \equiv P_{\rm V}$ for $c\bar{d}/\bar{c}d$ mesons)

$$P_{\rm V}^d = \frac{V}{V+PS} = \frac{\sigma(D^{*\pm})}{\sigma(D^{*\pm})+\sigma^{dir}(D^{\pm})} = \frac{\sigma^{\rm tag}(D^0)/BR+\sigma^{\rm add}(D^{*\pm})}{\sigma(D^{\pm})+\sigma^{\rm tag}(D^0)+\sigma^{\rm add}(D^{*\pm})}$$

$$P_{\rm V}^d = 0.566 \pm 0.025\,({\rm stat})^{+0.007}_{-0.022}\,({\rm syst})^{+0.022}_{-0.023}\,({\rm br})$$ **(ZEUS γp)**



$$= \frac{f(c \to D^{*+})}{f(c \to D^{+})+f(c \to D^{*+})\cdot BR}$$

for H1 and e^+e^-

$P_{\rm V} \neq 0.75 \quad \Longrightarrow \quad$ **naive spin counting does not work for charm**

challenge for fragmentation models:

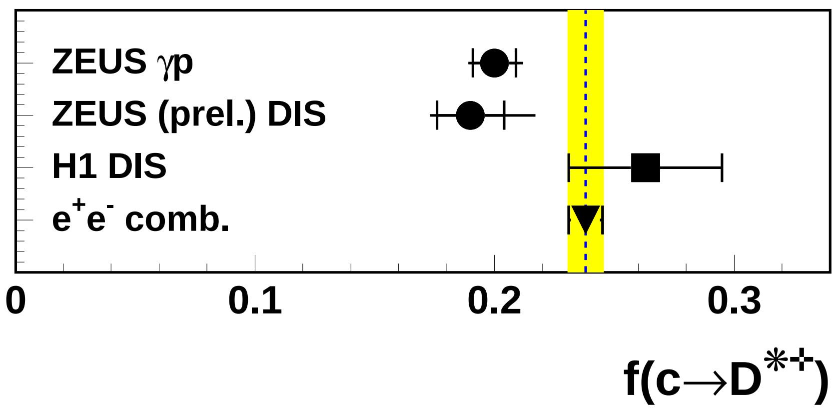
thermodynamics and string fragmentation predict $2/3$

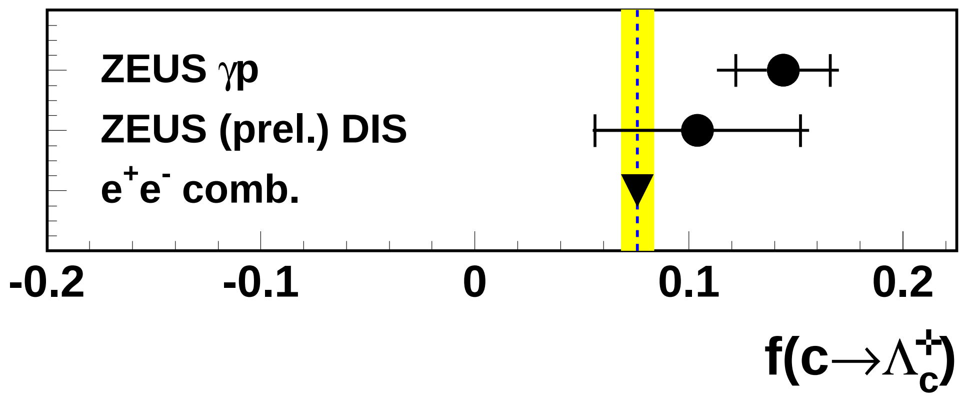
BKL predicts ≈ 0.6 **for** e^+e^- **where only fragmentation diagrams contribute**

for ZEUS γp **kinematic range, BKL prediction is** ≈ 0.66

Charm fragmentation fractions, $f(c \to D, \Lambda_c) = \sigma(D, \Lambda_c)/\sigma_{gs}$

ZEUS γp	Combined e^+e^- data
$f(c \to D^+) = 0.217 \pm 0.014^{+0.013}_{-0.005}{}^{+0.014}_{-0.016}$	$0.226 \pm 0.010^{+0.016}_{-0.014}$
$f(c \to D^0) = 0.523 \pm 0.021^{+0.018}_{-0.017}{}^{+0.022}_{-0.032}$	$0.557 \pm 0.023^{+0.014}_{-0.013}$
$f(c \to D_s^+) = 0.095 \pm 0.008^{+0.005}_{-0.005}{}^{+0.026}_{-0.017}$	$0.101 \pm 0.009^{+0.034}_{-0.020}$
$f(c \to \Lambda_c^+) = 0.144 \pm 0.022^{+0.013}_{-0.022}{}^{+0.037}_{-0.025}$	$0.076 \pm 0.007^{+0.027}_{-0.016}$
$f(c \to D^{*+}) = 0.200 \pm 0.009^{+0.008}_{-0.006}{}^{+0.008}_{-0.012}$	$0.238 \pm 0.007 \pm 0.003$

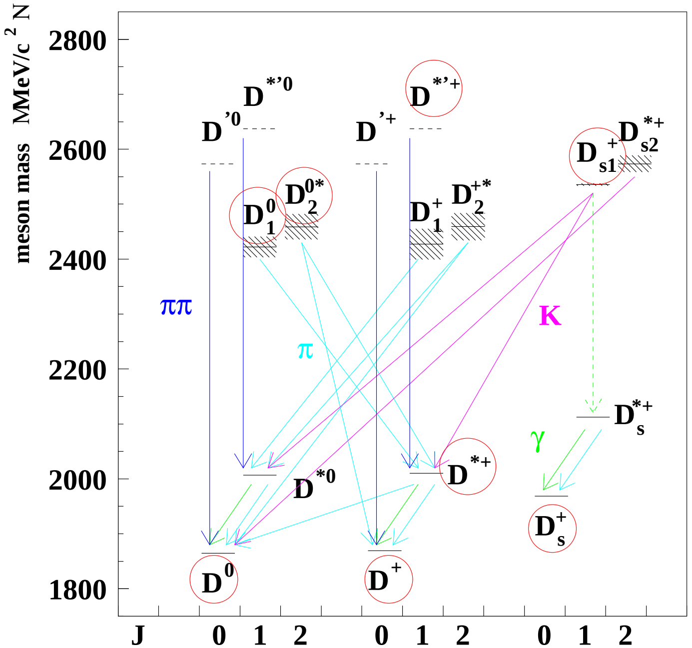




consistent with universality of charm fragmentation fractions

a half of the difference in $f(c \to D^{*+})$ is due to the difference in $f(c \to \Lambda_c^+)$

Study of excited D mesons at HERA



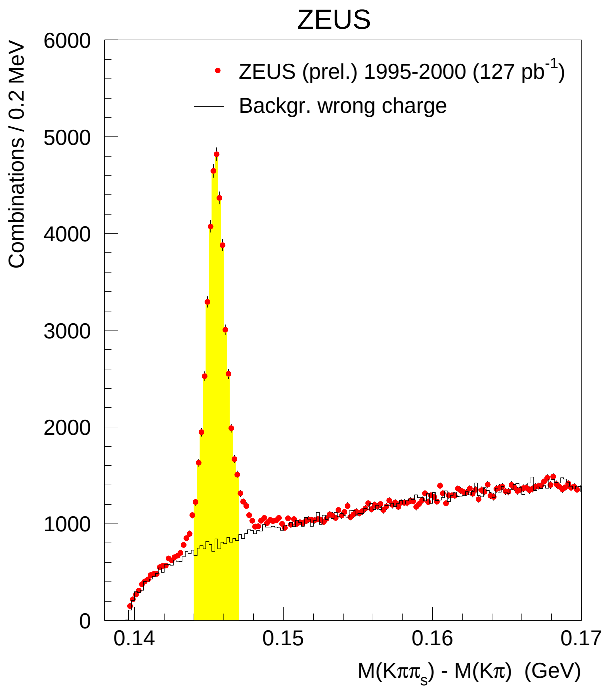
Orbitally excited:

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.)

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

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

In the yellow band under background:

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

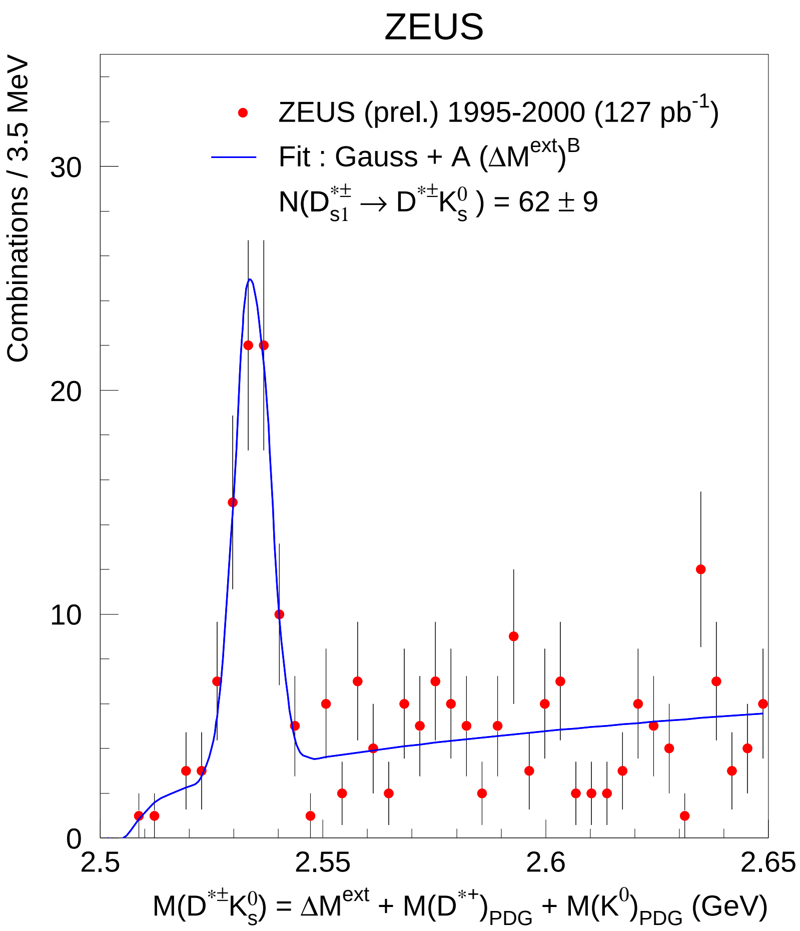
Charm-strange $D_{s1}^{\pm}(2536)$ meson

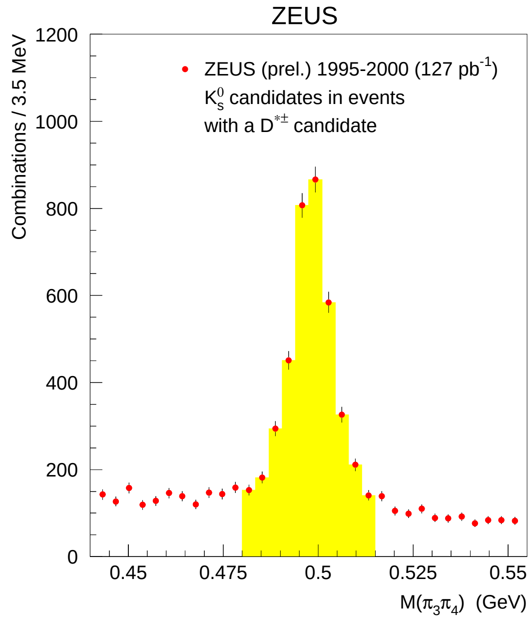
$$D_{s1}^{\pm}(2536) \to D^{*\pm} K_s^0 \ , \qquad K_s^0 \to \pi^+\pi^-$$

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

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

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





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

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

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

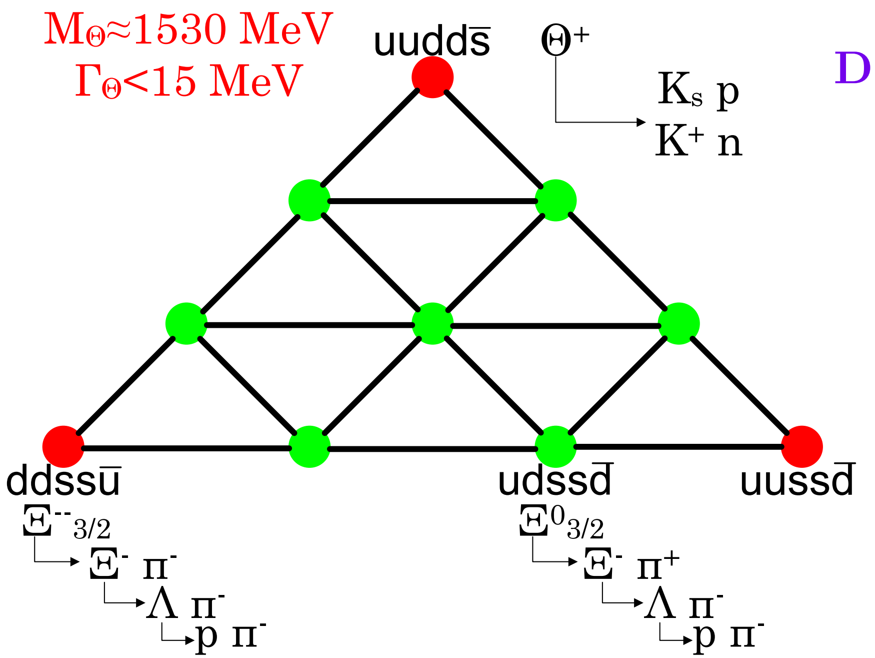
3) $f(c \to D_{s1}^+)$ is twice as large as the expectation :

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

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

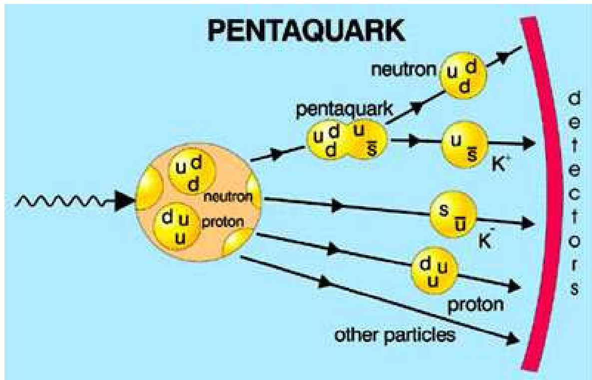
Is it connected wih its strange helicity ?

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

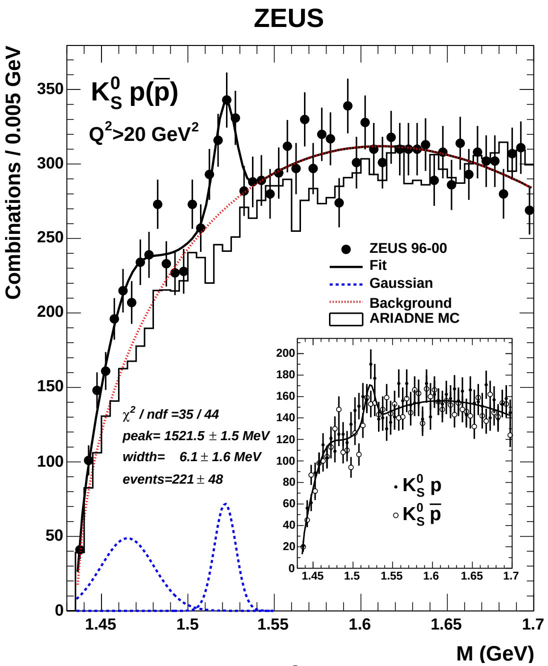
non-exotic decay mode $\Theta^+ \to K^0_s p$ seen by DIANA, HERMES, COSY-TOF, SVD, ZEUS, ITEP

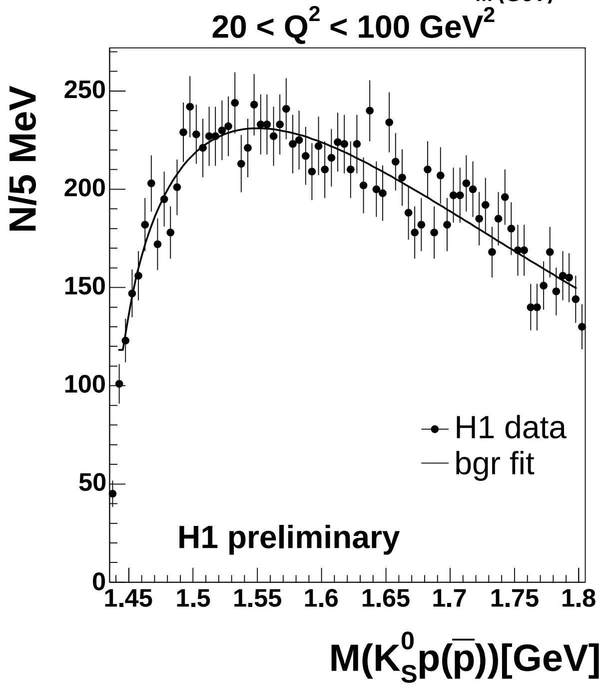
negative results from BES, HERA-B, CDF, ALEPH, DELPHI, L3, BABAR, BELLE, SPHINX, HyperCP, PHENIX and ... CLAS $(\gamma p \to K^0_s K^+ n)$ with $50\times$SAPHIR

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, ...

$\Theta^{\pm} \rightarrow K_s^0 p(\bar{p}))$ observation in ep collisions ?





ZEUS : best signal for $Q^2 > 20\,\mathbf{GeV}^2$

Fit with 2nd Gaussian for (Σ ?) bump around $1465\,\mathbf{MeV}$

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

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

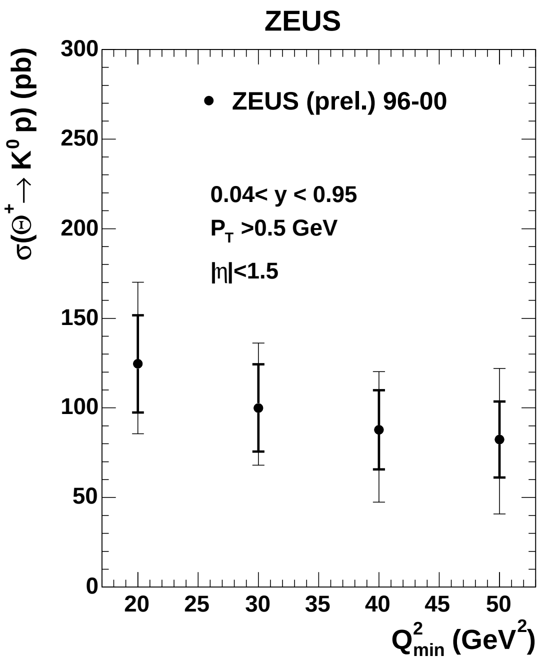
$\Longleftarrow$ **signal seen in both charges**

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

H1 : no significant signal
in particular, for $Q^2 > 20\,\mathbf{GeV}^2$

note : $\mathcal{L}_{int}(\mathrm{ZEUS}) = 121\,\mathbf{pb}^{-1}$
$\mathcal{L}_{int}(\mathrm{H1}) = 71\,\mathbf{pb}^{-1}$

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



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

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

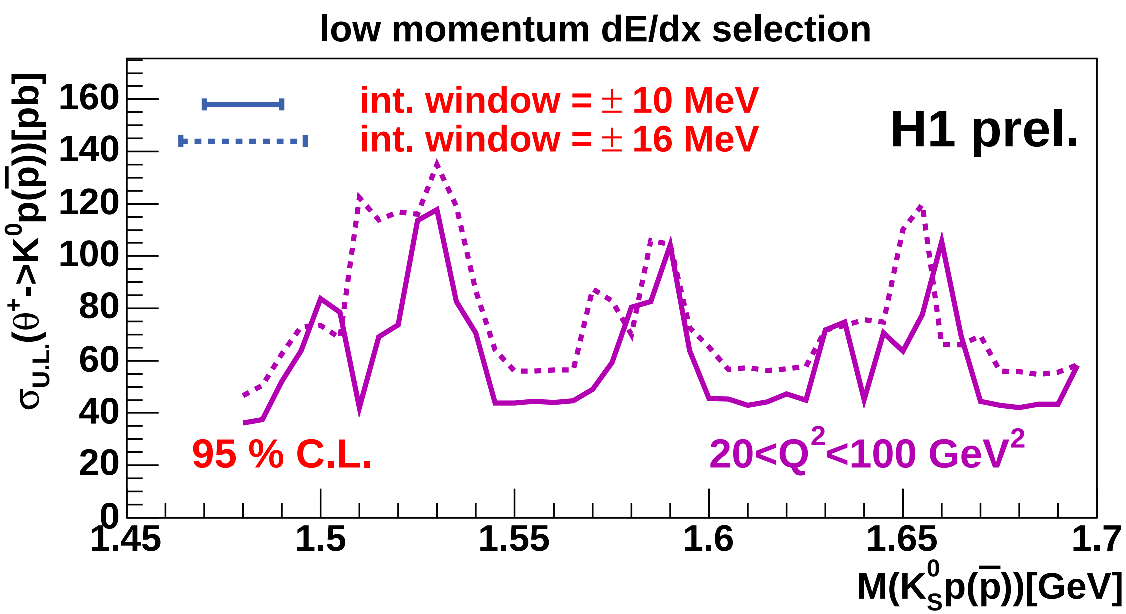
$p_T(\Theta^{\pm}) > 0.5\,\mathbf{GeV}$, $|\eta(\Theta^{\pm})| < 1.5$

$\sigma(ep \to e\Theta^+ X \to eK^0 pX) = 125 \pm 27^{+37}_{-28}\,\mathbf{pb}$

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

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

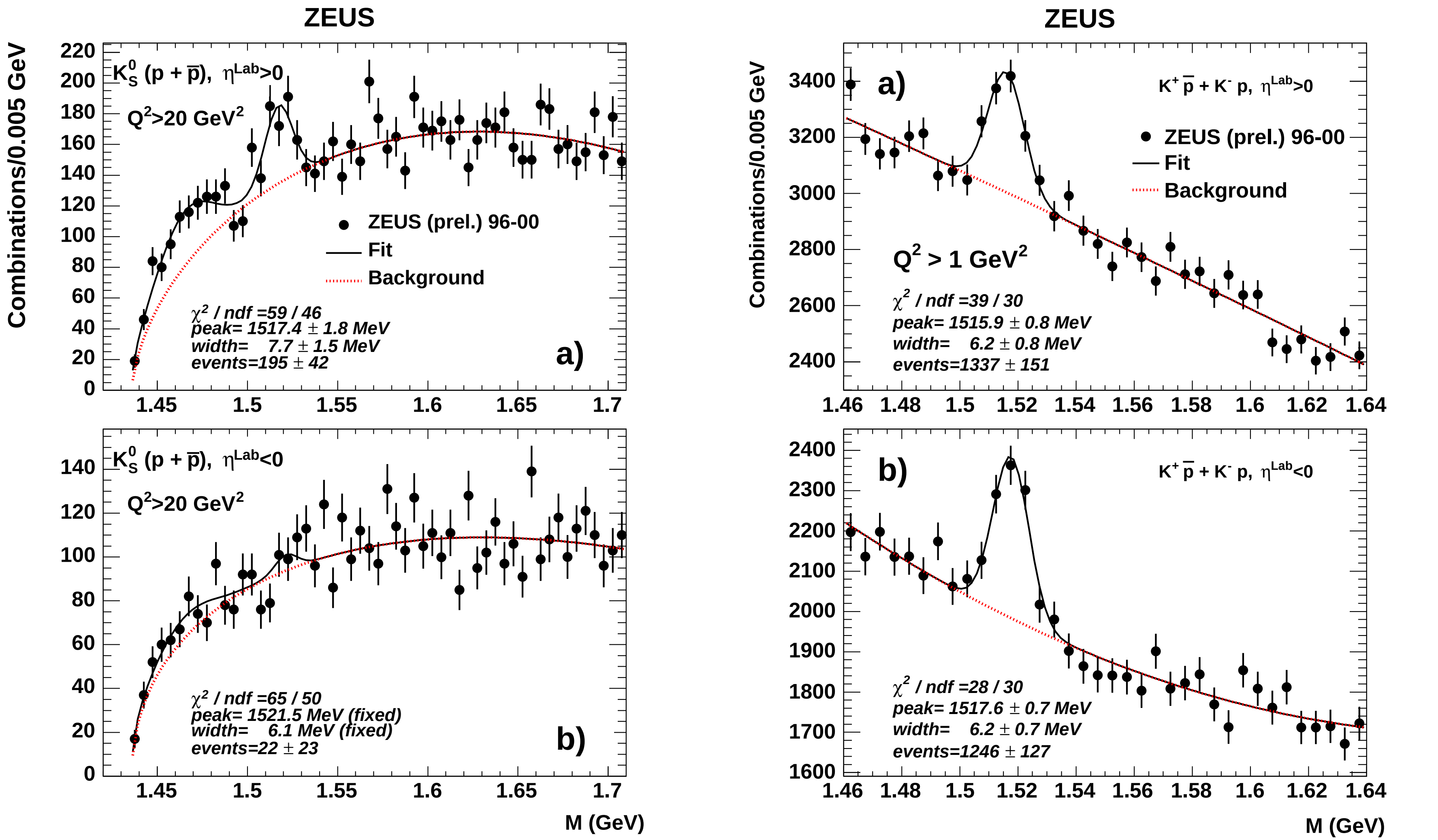
ALEPH: $R < 0.4\,\%$



no contradiction between ZEUS and H1 data

larger luminosity is vital

Θ^+ production mechanism in ep collisions ?

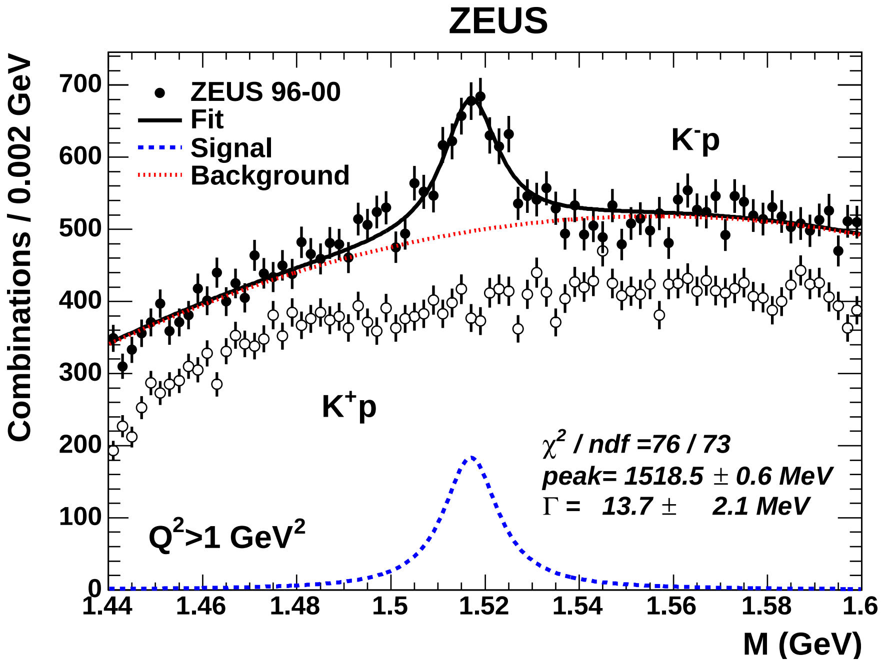


$\Theta^{\pm}$ produced mostly in forward (proton) direction

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

$\Theta^{\pm}$ may have unusual production mechanism related to proton-remnant fragmentation ?

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



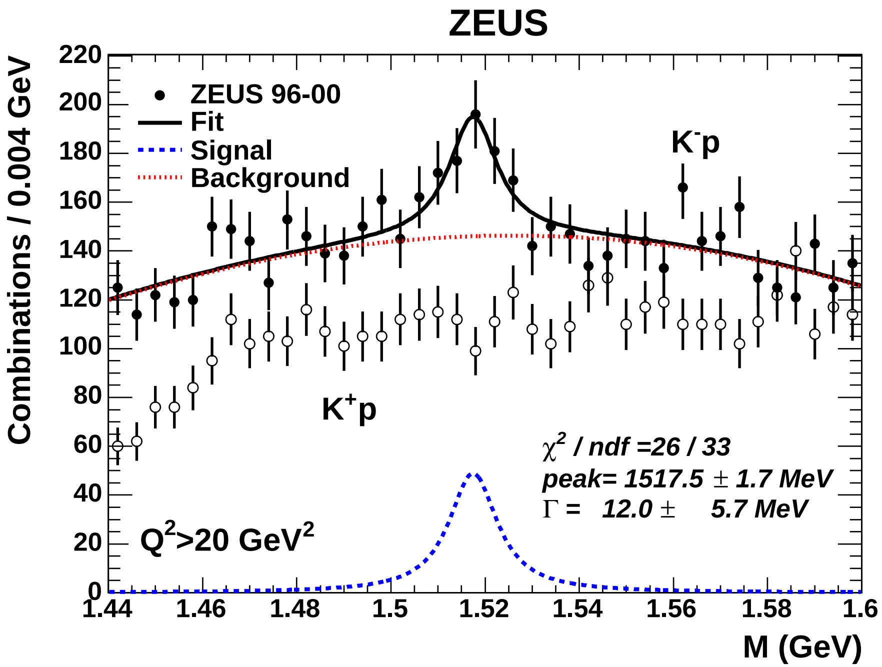
For NK bound state,

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 $Q^2 < 20\,\mathrm{GeV}^2$

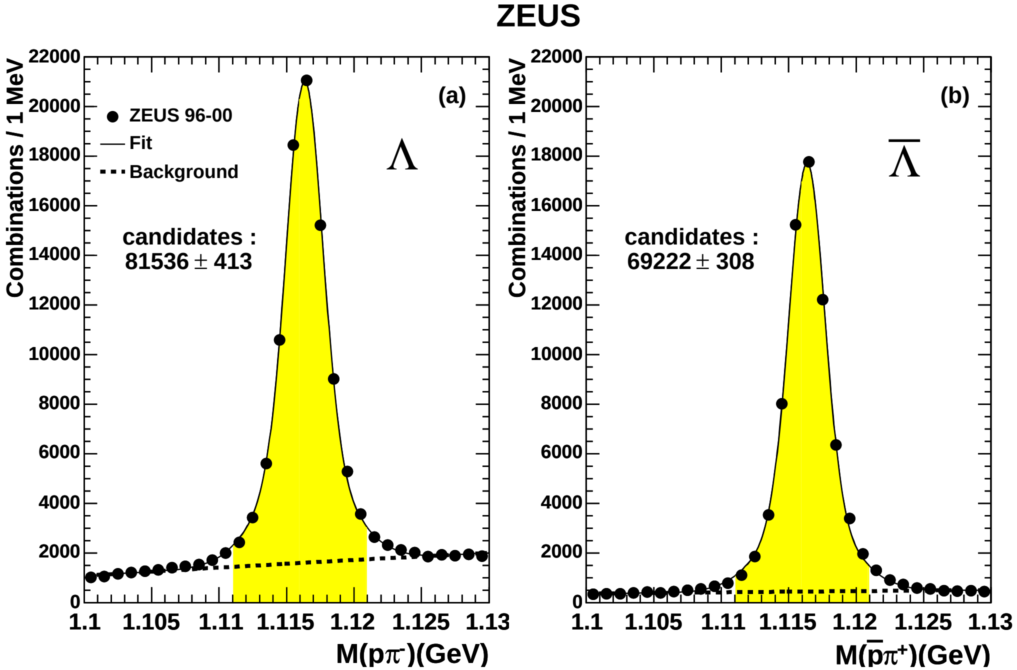
as well

Does not contradict to

Θ^{++} observation by STAR

with $R(\Theta^{++}/\Lambda(1520)) \approx 0.1\%$

Search for pentaquarks with $S = \pm 2$

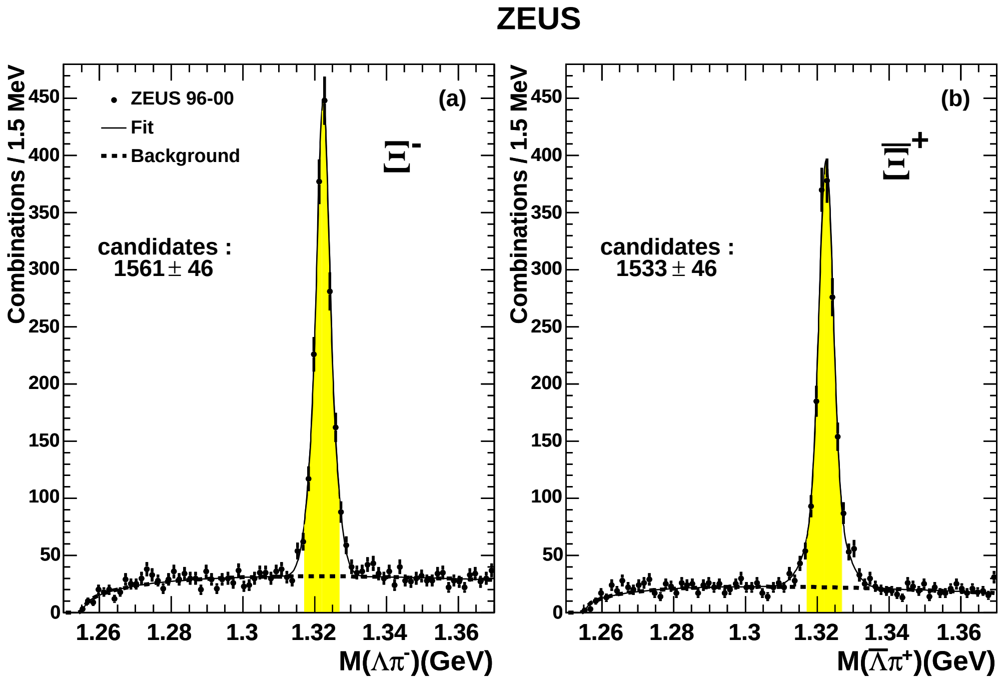


$\Xi_{5q}^{--,0} \rightarrow \Xi\pi$ **observed by NA49**

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

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

$\Longleftarrow \sim 150000$ **candidates**

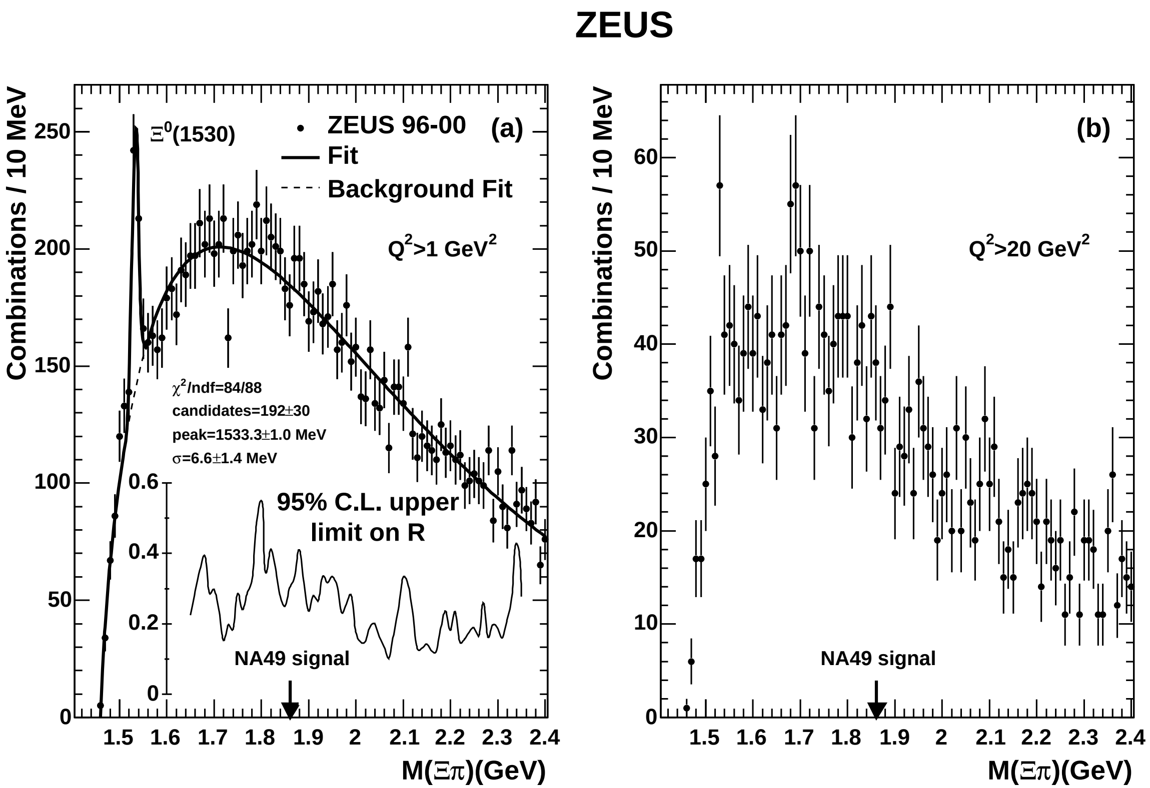


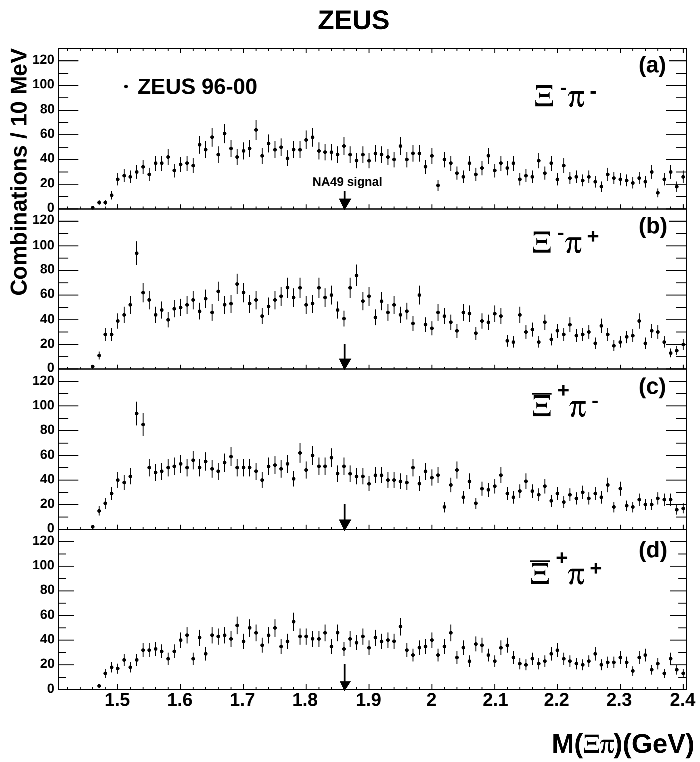
Combining with additional track

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

$\Longleftarrow \sim 3000$ **candidates**

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





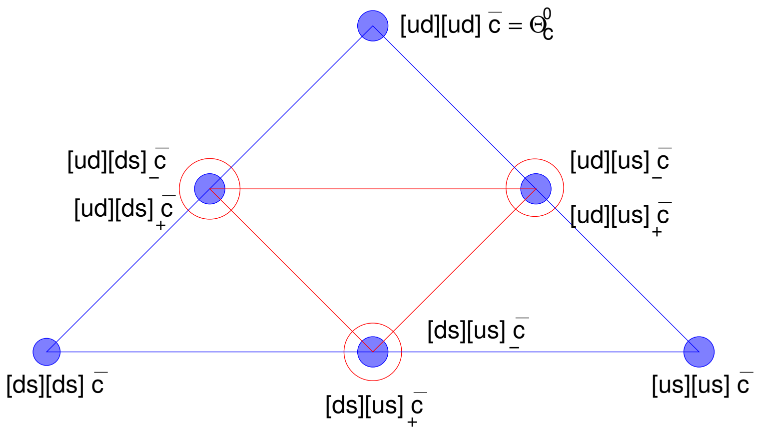
approx. the same number of $\Xi^0(1530) \to \Xi^-\pi^+$ as in NA49

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



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

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

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

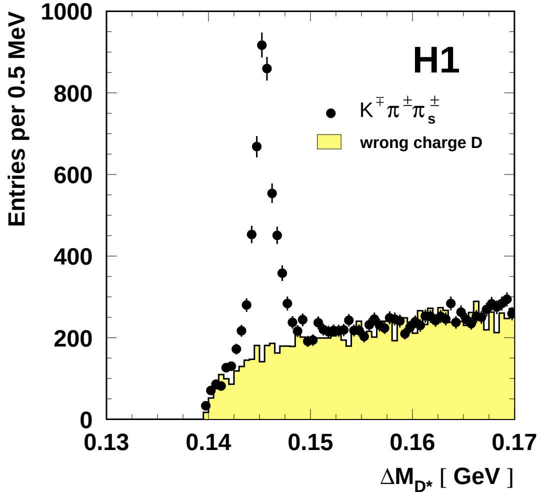
Karliner-Lipkin (hep-ph/0307343): $M(\Theta_c^0) = 2985 \pm 50\,$**MeV**
$\Gamma(\Theta_c^0) \sim 21\,$**MeV**

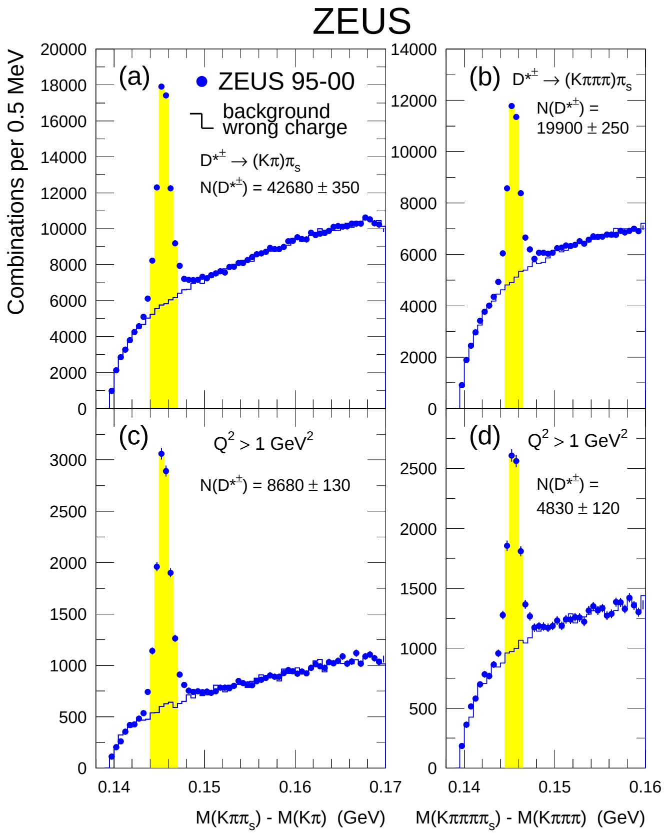
Such Θ_c^0 would decay to $D^{(*)-}p$ (+ c.c.)

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

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

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





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

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

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

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

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

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

two D^* decay channels:

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

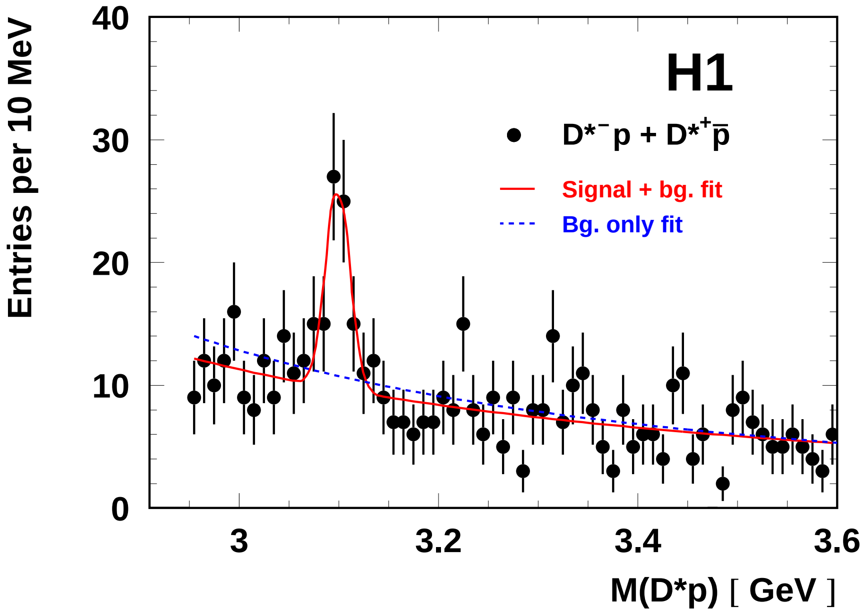
Yellow bands used

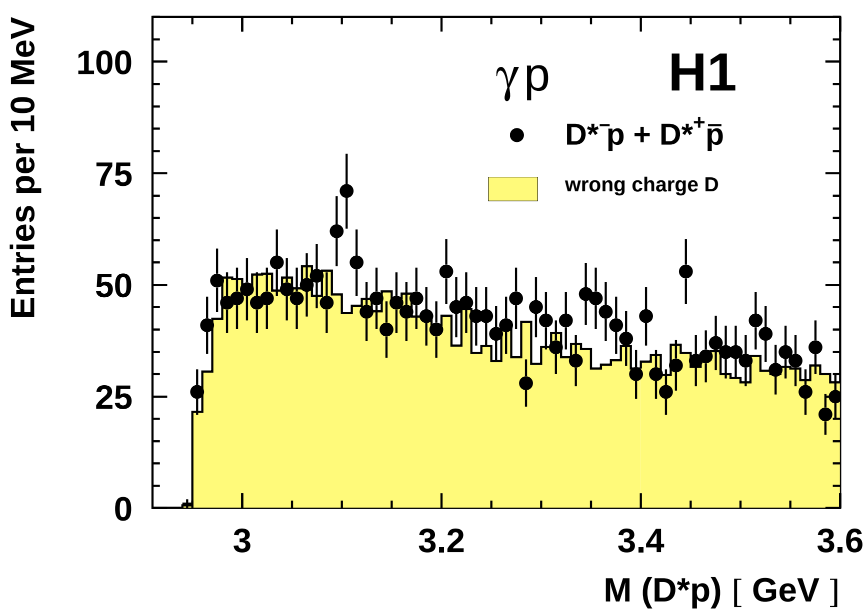
for Θ_c^0 search:

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

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

$M(D^*p)$ 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.):

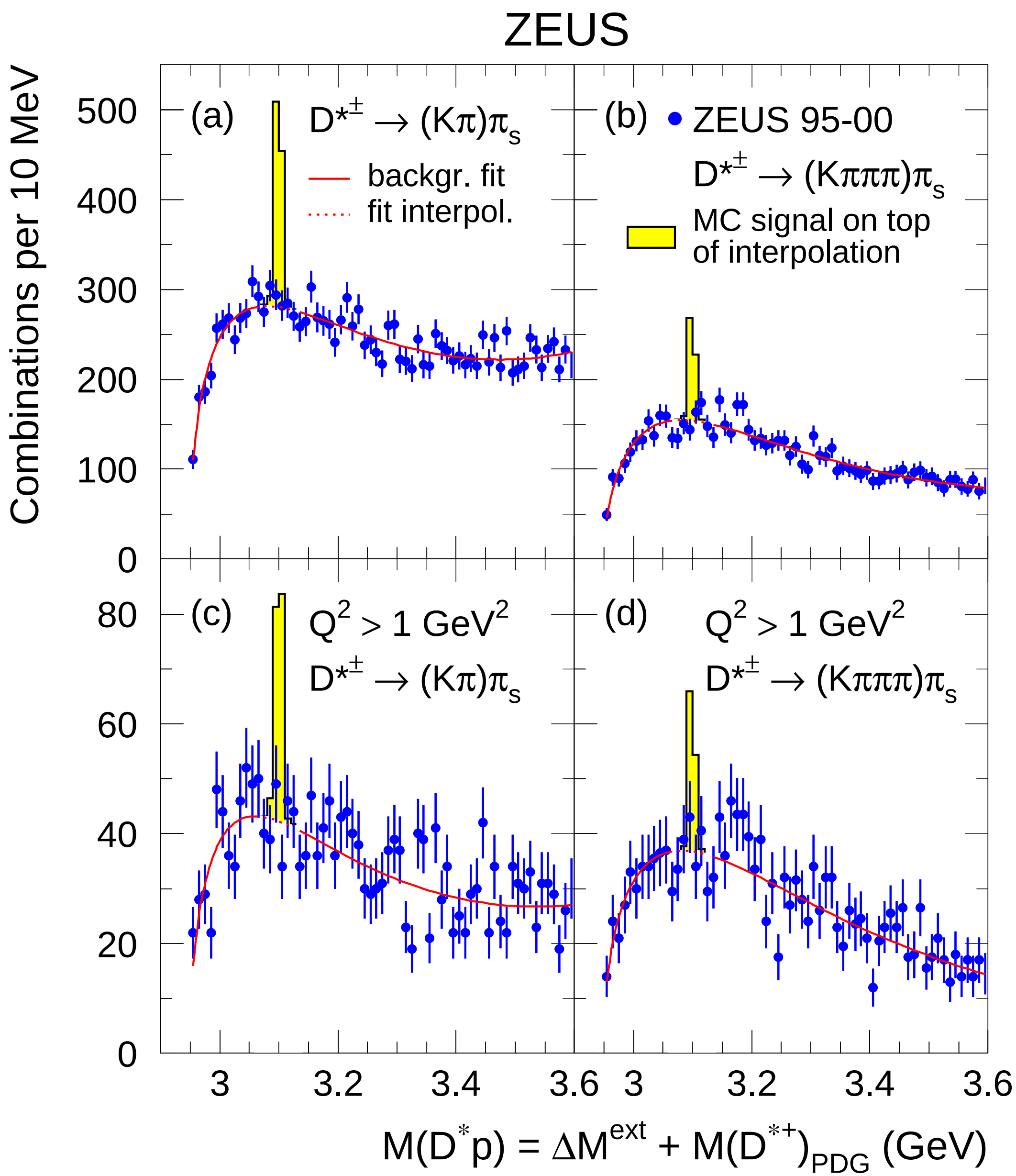
$$N(\Theta_c^0) = 50.6 \pm 11.2$$

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

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

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

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 $Q^2 > 1$ 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 $Q^2 > 1$ GeV^2

acceptance corrected rate

$< 0.37\%$ for full sample

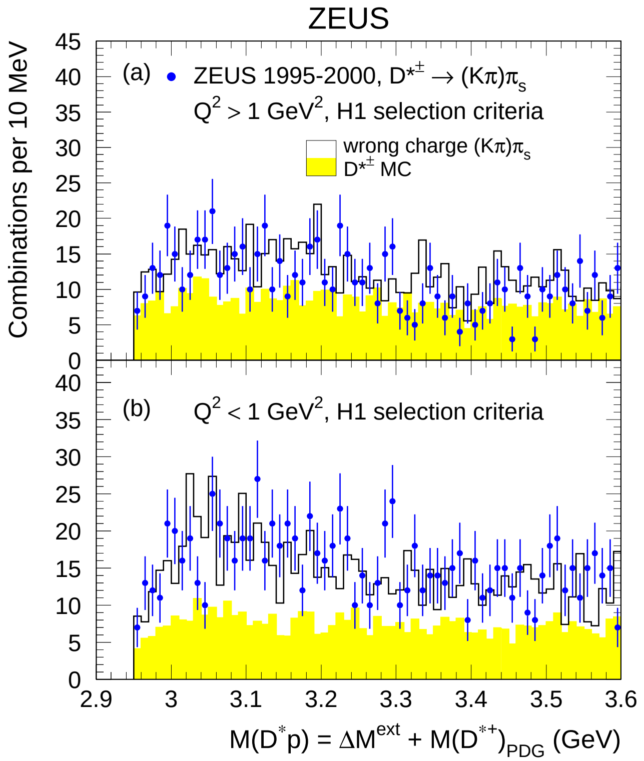
$< 0.51\%$ for $Q^2 > 1$ GeV^2

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

$< 0.16\%$ for full sample

$< 0.19\%$ for $Q^2 > 1$ GeV^2

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



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

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

no signal

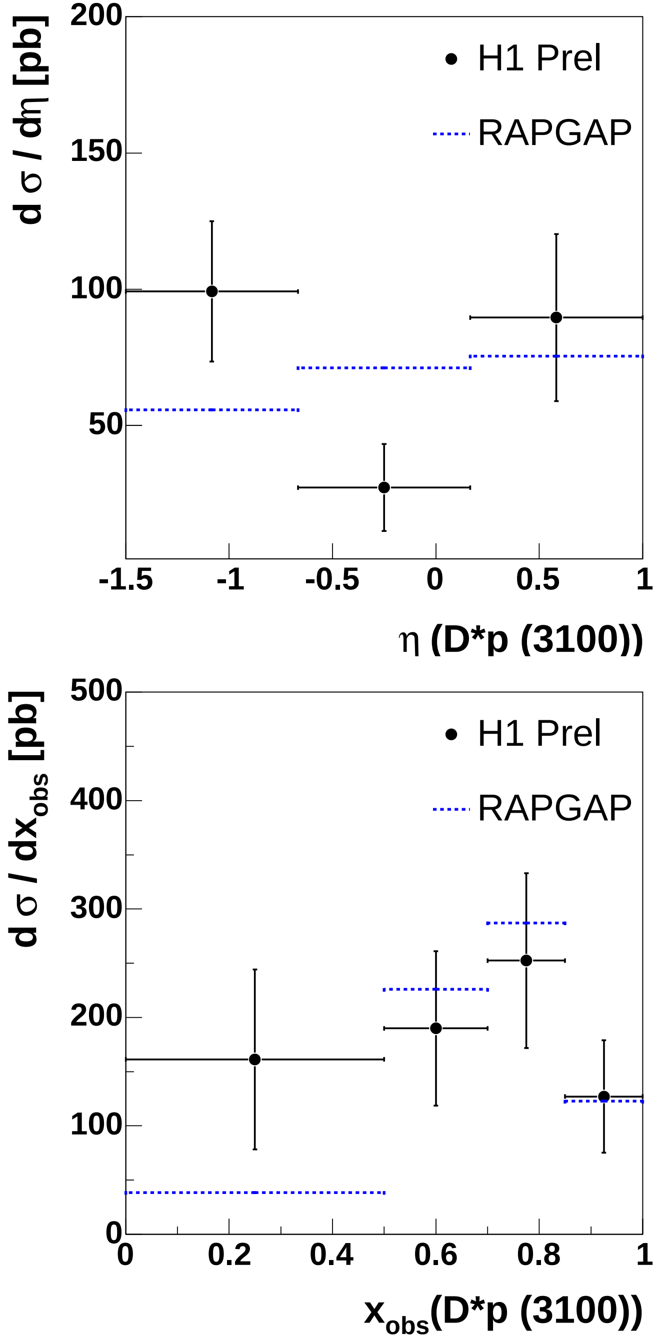
$\Leftarrow Q^2 < 1\,\mathrm{GeV}^2$

no signal

	H1 prel.	ZEUS	ZEUS, $Q^2 > 1\,\mathrm{GeV}^2$
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.)
$\sigma_{\mathrm{vis}}(\Theta_c^0)/\sigma_{\mathrm{vis}}(D^*)$	$(2.48 \pm 0.52^{+0.85}_{-0.64})\%$		
$f(c \to D^{*+}) \times \sigma_{\mathrm{vis}}(\Theta_c^0)/\sigma_{\mathrm{vis}}(D^*)$	$(0.58 \pm 0.12^{+0.20}_{-0.15})\%$		
$f(c \to \Theta_c^0) \times B(\Theta_c^0 \to D^*p)$		$< 0.16\%$ (95% C.L.)	$< 0.19\%$ (95% C.L.)

HERA II data can help to resolve the disagreement

Θ_c^0 production mechanism in ep collisions ?



⟸ fragmentation model : RAPGAP(+PYTHIA)
with Θ_c^0 from $D_1(2420), D_2^*(2460)$ resetting

⟸ $D^*p(3100)$ production suppressed
in the central rapidity region and
above the model in the photon direction

otherwise the fragmentation model
provide a reasonable description
of $D^*p(3100)$ cross section shapes

$D^*p(3100)$ fragmentation function

$$x_{\rm obs} = (E - p_z)^{D^*p} / \sum_{\rm hem}(E - p)$$

⟸ hard fragmentation function
consistent with the fragmentation model

Θ_c^0 seems to be produced in c-quark fragmentation

Summary

HERA produces competitive results on charm fragmentation and pentaquark searches

- **Measurements of charm fragmentation at HERA generally support the hypothesis that fragmentation proceeds independently of the hard sub-process**

- **Rates of excited D^{**} mesons are close in e^+e^- and ep data.**
  $D_{s1}^{\pm}(2536)$ shows questionable helicity distribution and "too large" $f(c \to D_{s1}^{+})$

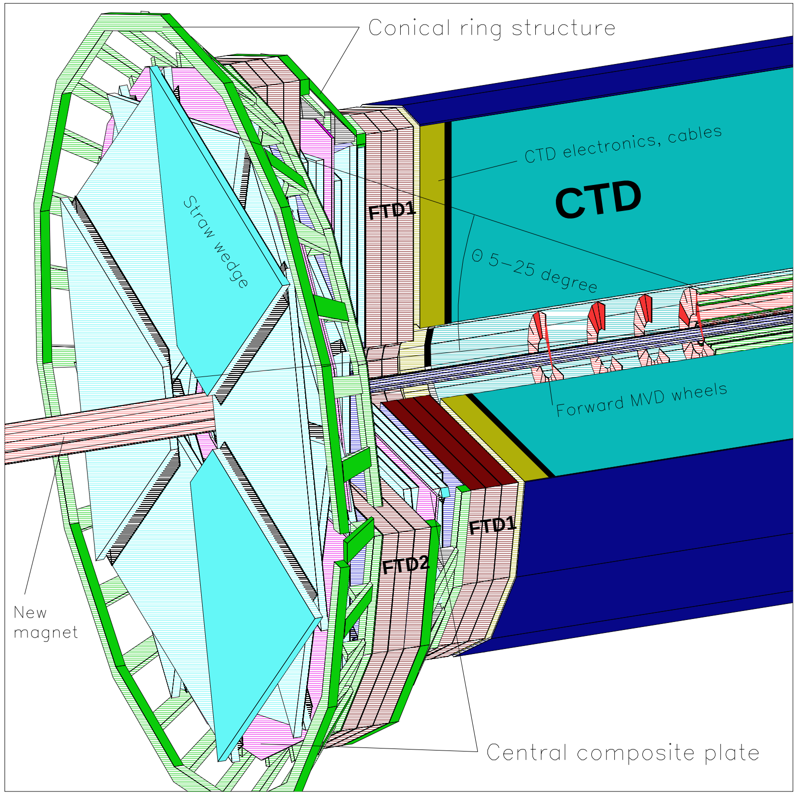
- **$\Theta^+ \to K_s^0 p$ production observed in high-Q^2 DIS by ZEUS.**
  H1 does not see the signal that is not in statistical contradiction with ZEUS.
  Studies suggest Θ^+ production in ep related to proton-remnant fragmentation

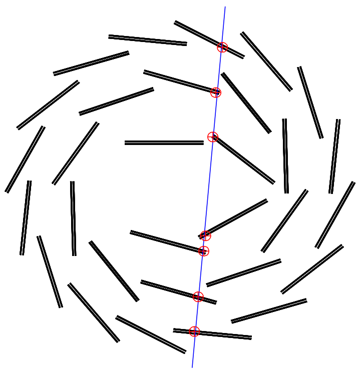
- **no signature of $\Theta^{++} \to Kp$ that does not contradict to STAR observation**

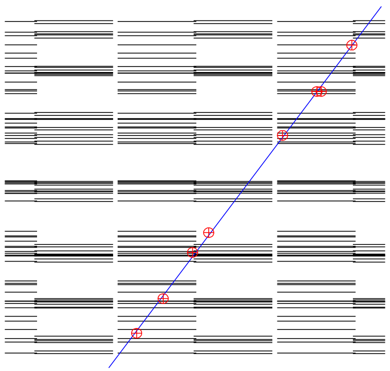
- **no signature of $\Xi_{3/2}^{--,0} \to \Xi\pi$ although sensitivity is similar to NA49**

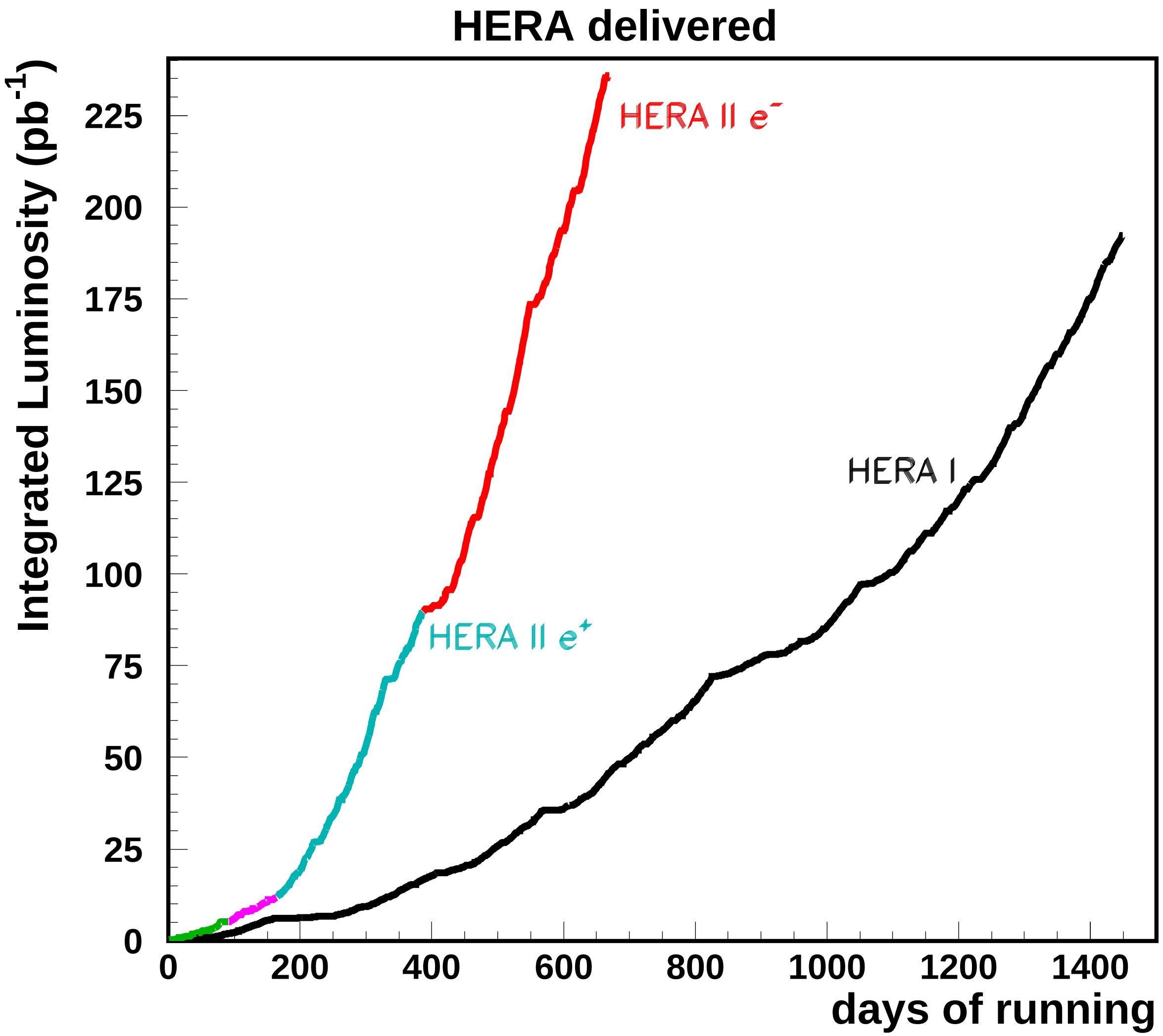
- **H1 and ZEUS results on $\Theta_c^0 \to D^*p$ disagree.**
  Using larger statistics, ZEUS does not see a signal observed by H1.
  H1 studies suggest Θ_c^0 produced in c-quark fragmentation

Outlook



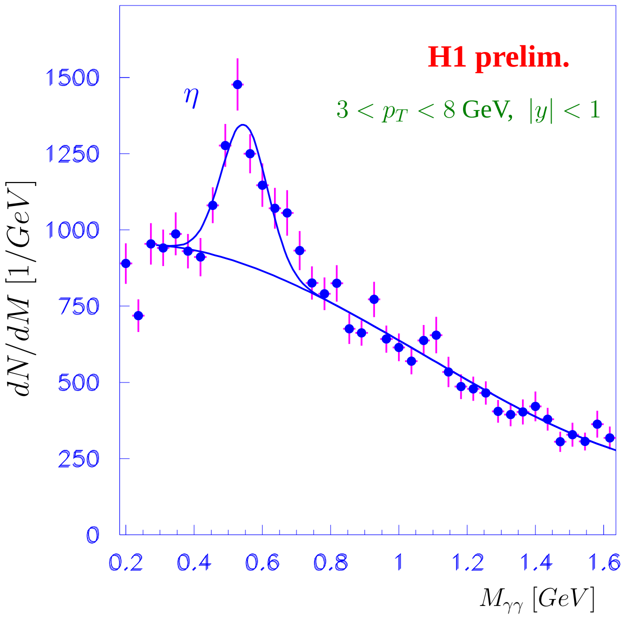


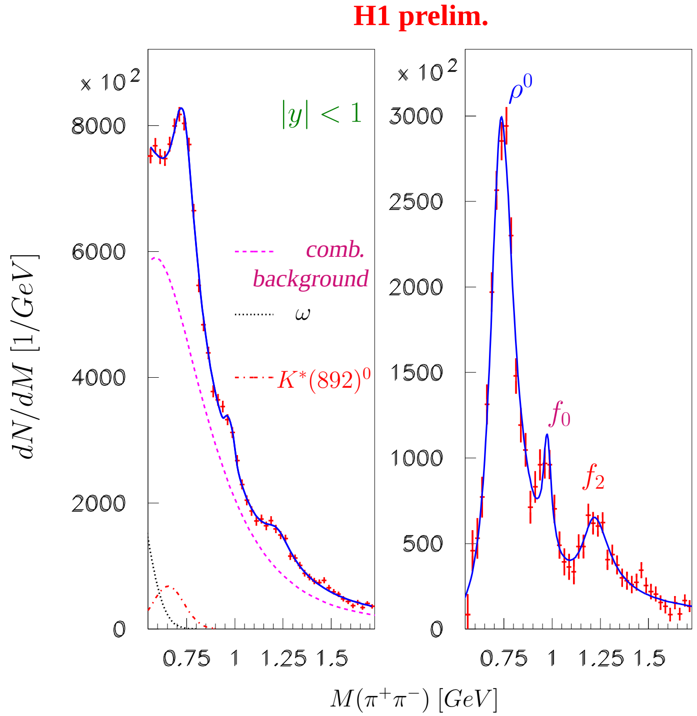


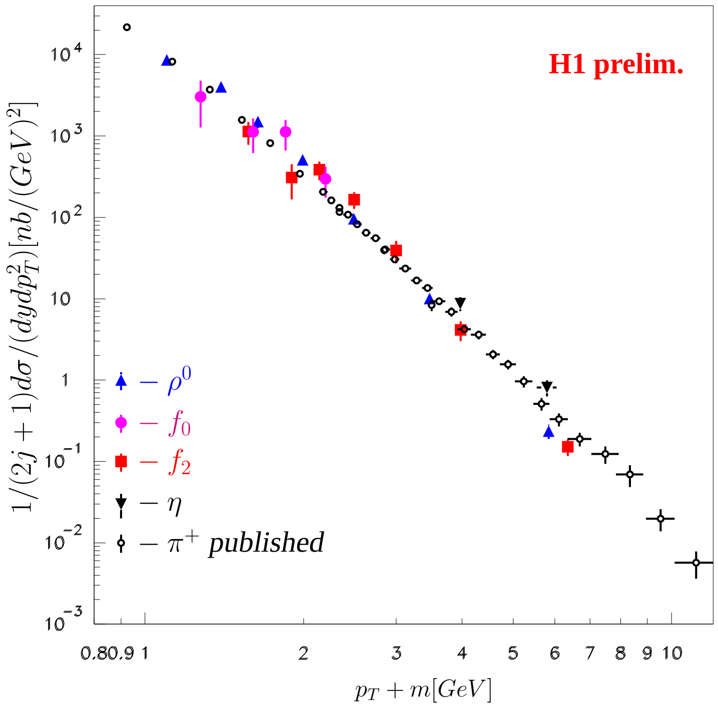


HERA II collecting data

Light mesons in $M(\gamma\gamma)$ and $M(\pi^+\pi^-)$







Inclusive photoproduction of
η, ρ^0, $f_0(980)$ **and** $f_2(1270)$ **at** $W \sim 210$ **GeV**

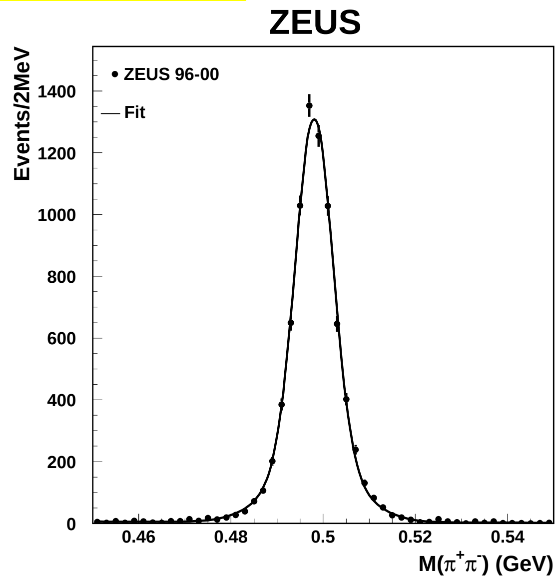
$\Longleftarrow$ **Similar behavior vs** $p_T + m$
of pions and heavier light mesons

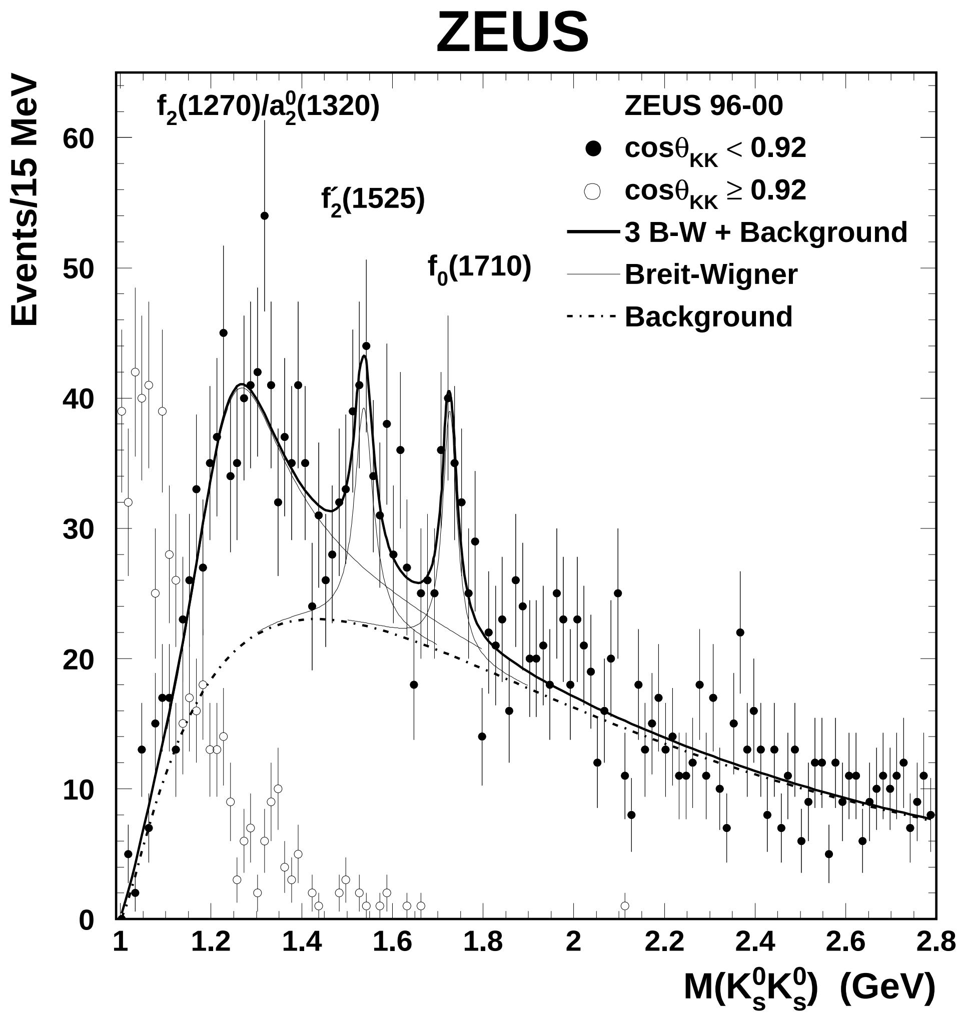
$\Longrightarrow$ **suggest similar production**
mechanism in q/g **fragmentation**

Light mesons in $M(K_s^0 K_s^0)$

$Q^2 \gtrsim 1\,\mathbf{GeV}^2$, $50 < W < 250\,\mathbf{GeV}$

K_s^0 are well identified using
the displaced secondary vertices $\Longrightarrow$





$\Longleftarrow$

threshold enhancement ($f_0(980)/a_0(980)$?)

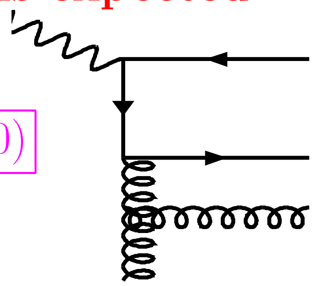
contribution from $f_2(1270)/a_2^0(1320)$

$f_2'(1525)$ **(fit agrees with PDF)**

$f_0(1710)$ **(narrower but agrees with PDF)**

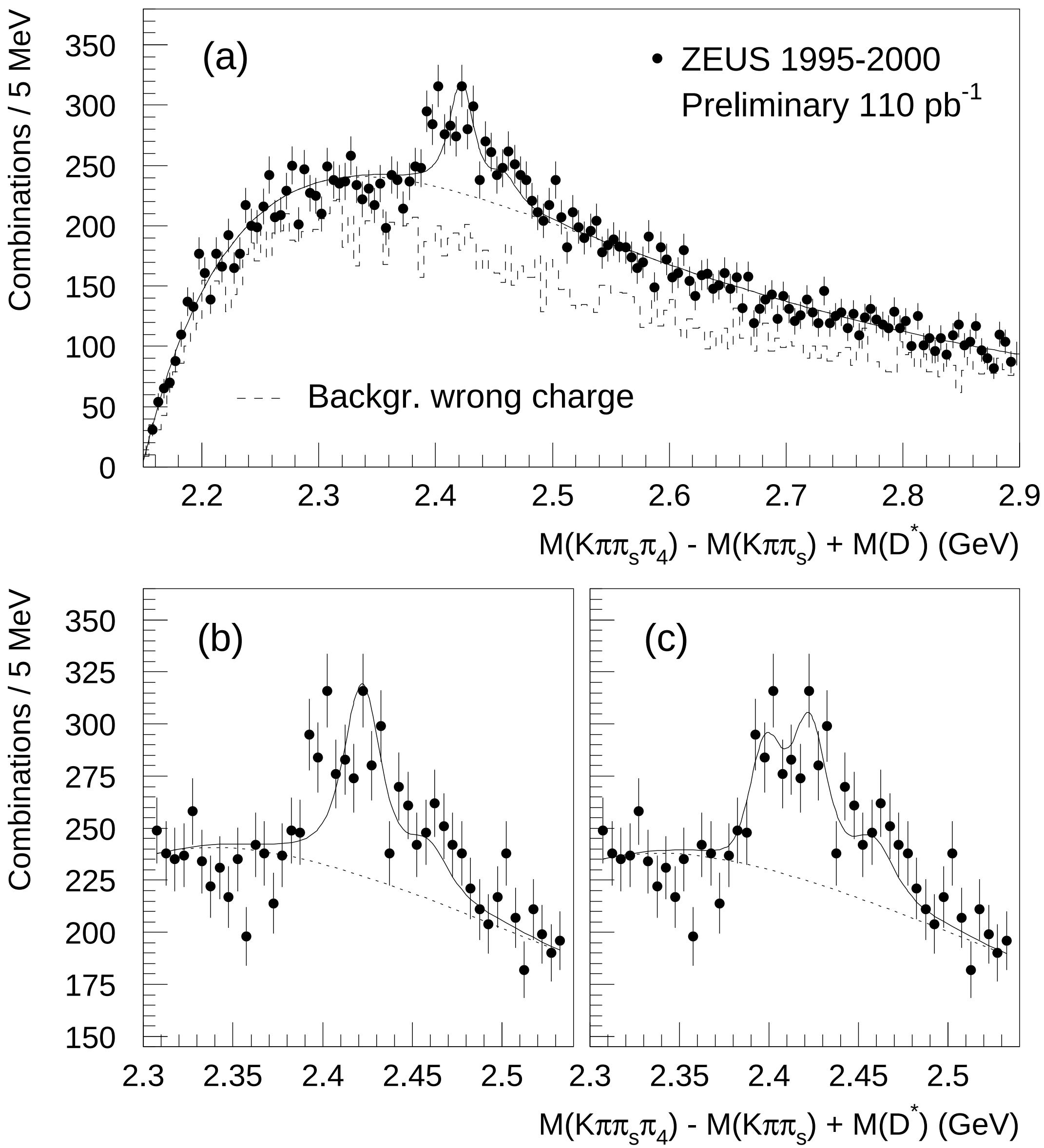
$M = 1726 \pm 7\,\mathbf{MeV}$, $\Gamma = 38^{+20}_{-14}\,\mathbf{MeV}$

produced in the region where sizeable initial state gluon radiation is expected



additional hint for large
gluonic component of $f_0(1710)$

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. :

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

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

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

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

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

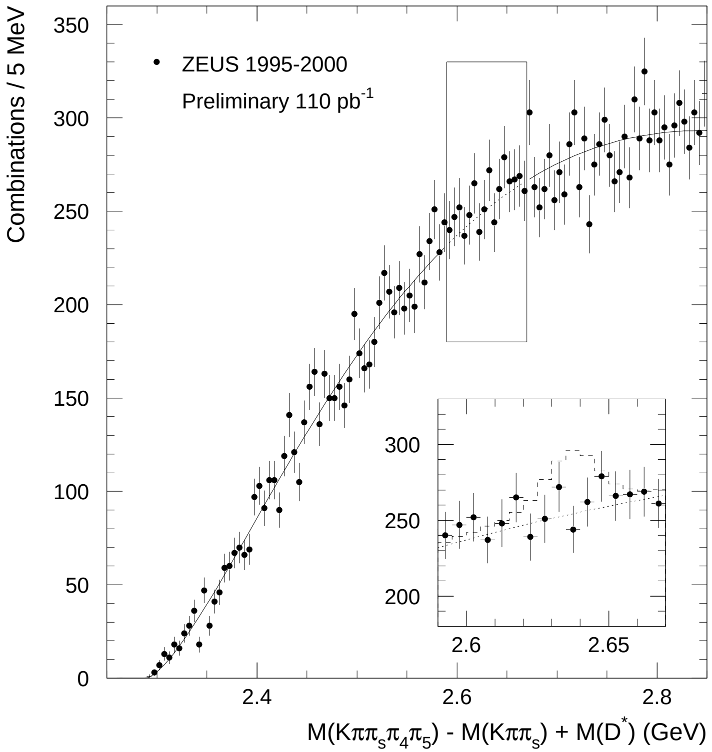
Additional narrow bump ?

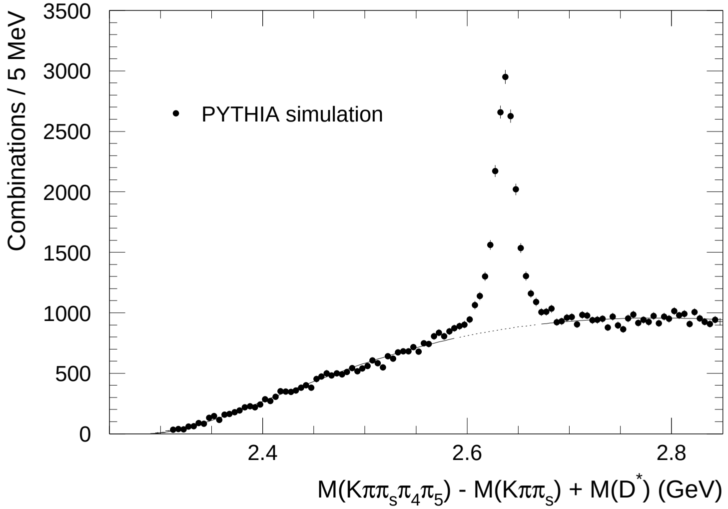
$N = 211 \pm 49$

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

New D meson ? Interference ?

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





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

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

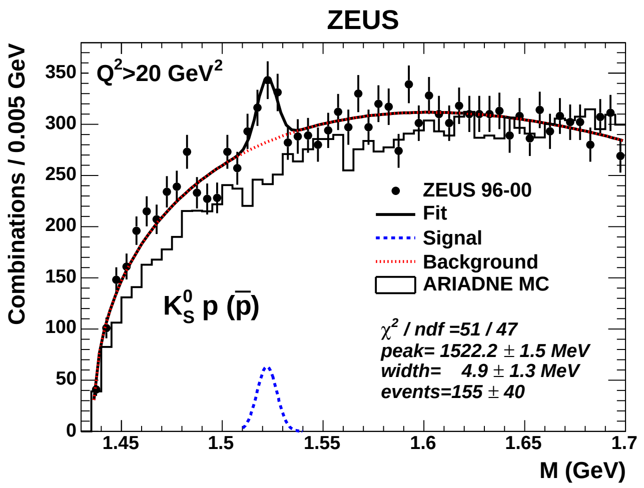
Using world average for $f(c \rightarrow D^{*+})$ **:**

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

(ZEUS prel.)

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

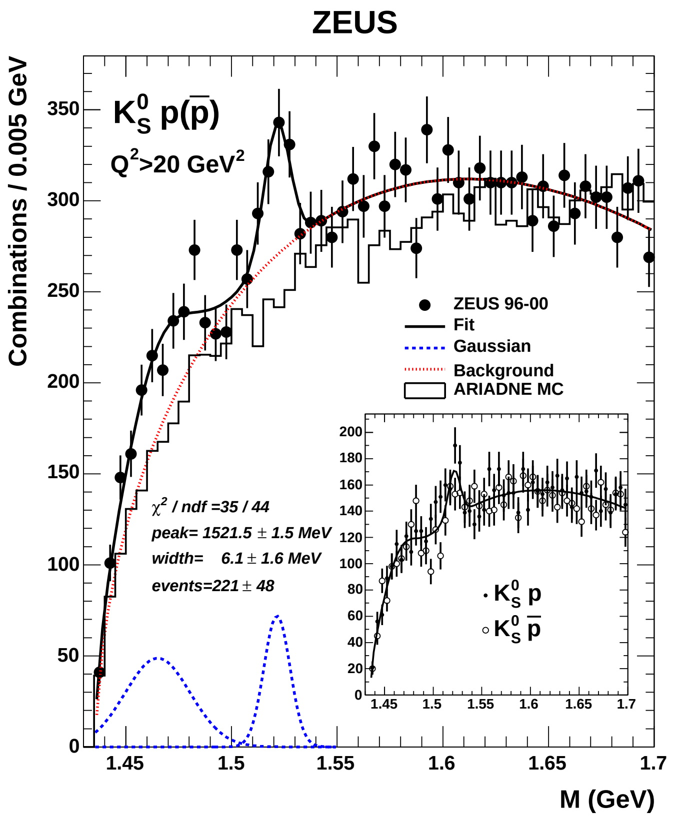
$M(K_s^0 p(\bar{p}))$ for $Q^2 > 20\,\mathbf{GeV}^2$



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

Fit with Gaussian + background (3 par.)

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



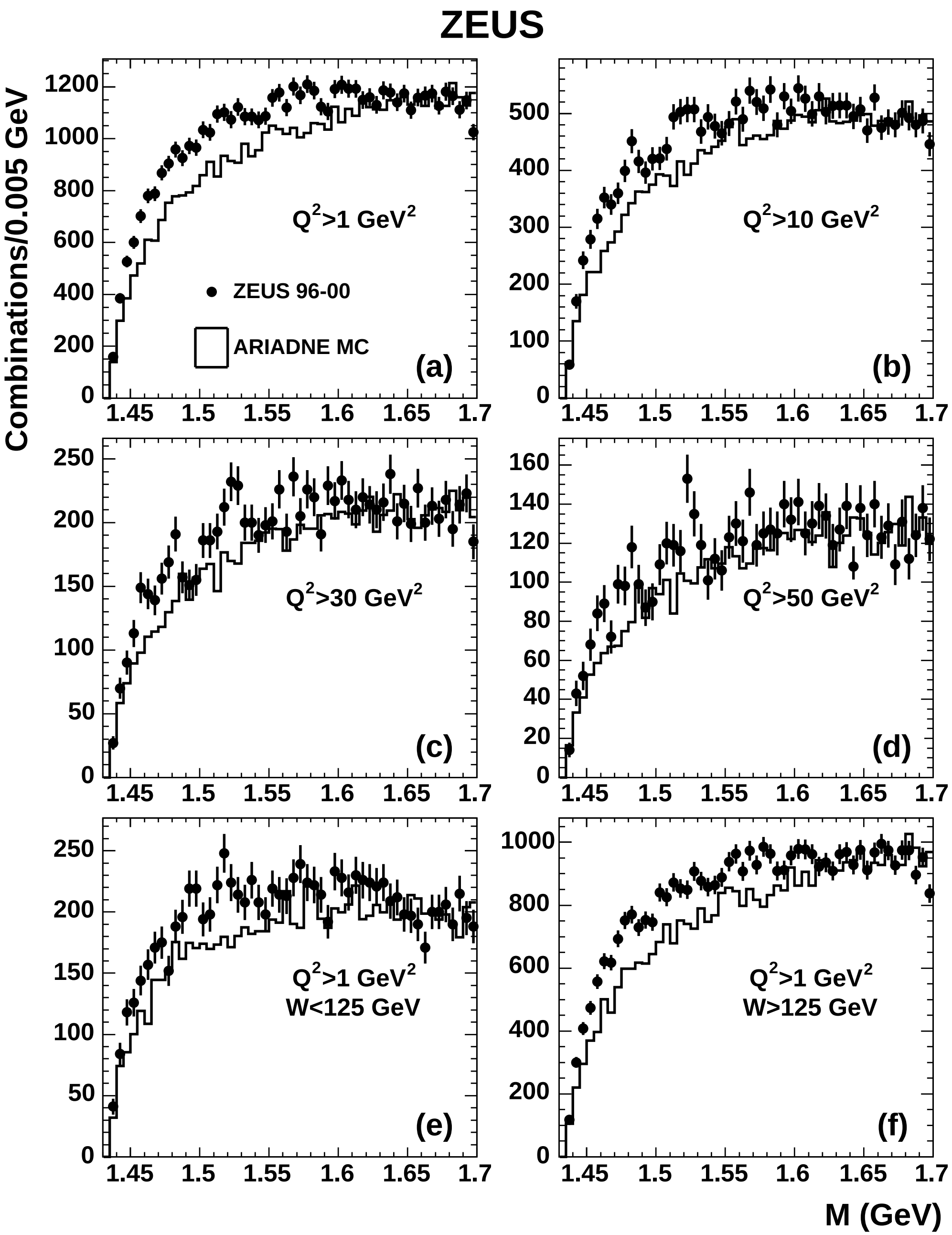
Fit with 2nd Gaussian for $(\Sigma\ ?)$ **bump around** $1465\,\mathbf{MeV}$

$N = 221 \pm 48$**,** $M = 1521.5 \pm 1.5\,\mathbf{MeV}$
width compatible with resolution
For BW: $\Gamma = 8 \pm 4$ **(stat.) MeV**

$\Longleftarrow$ **signal seen in both charges**

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

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



large background

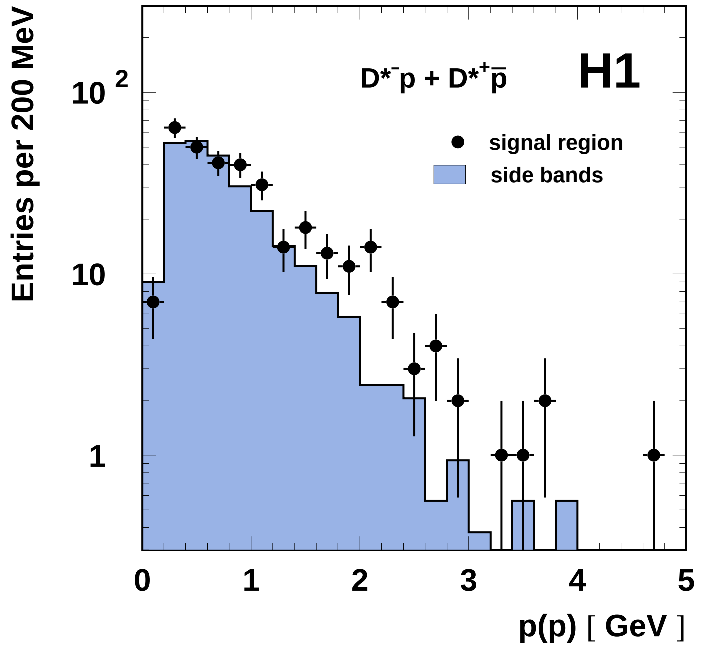
signal becomes visible for $Q^2 > 10\,\text{GeV}^2$

ARIADNE (JETSET) MC (normalized to data above $1.65\,\text{GeV}$) does not reproduce the shape.

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

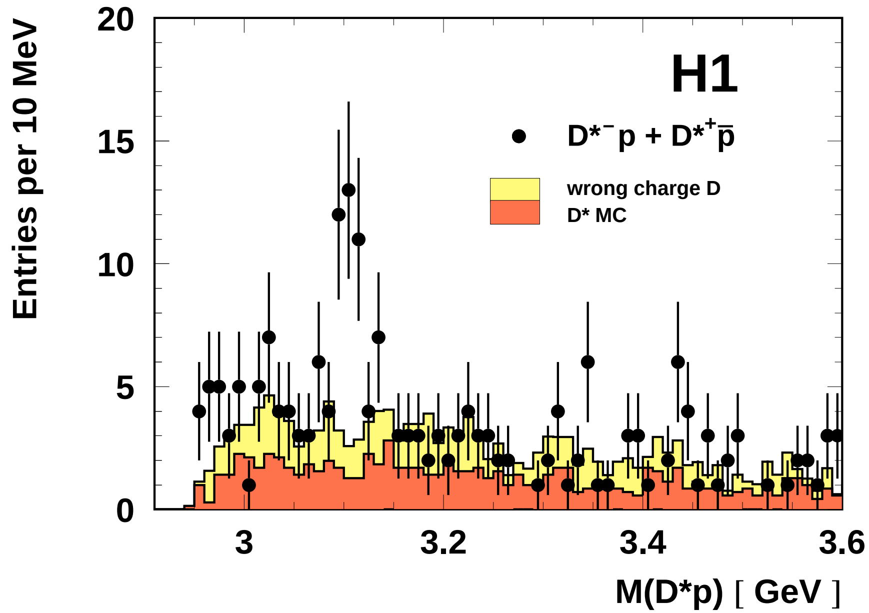
for $Q^2 > 1\,\text{GeV}^2$, signal is visible for $W < 125\,\text{GeV}$

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



particles taken as protons
w/o dE/dx requirements

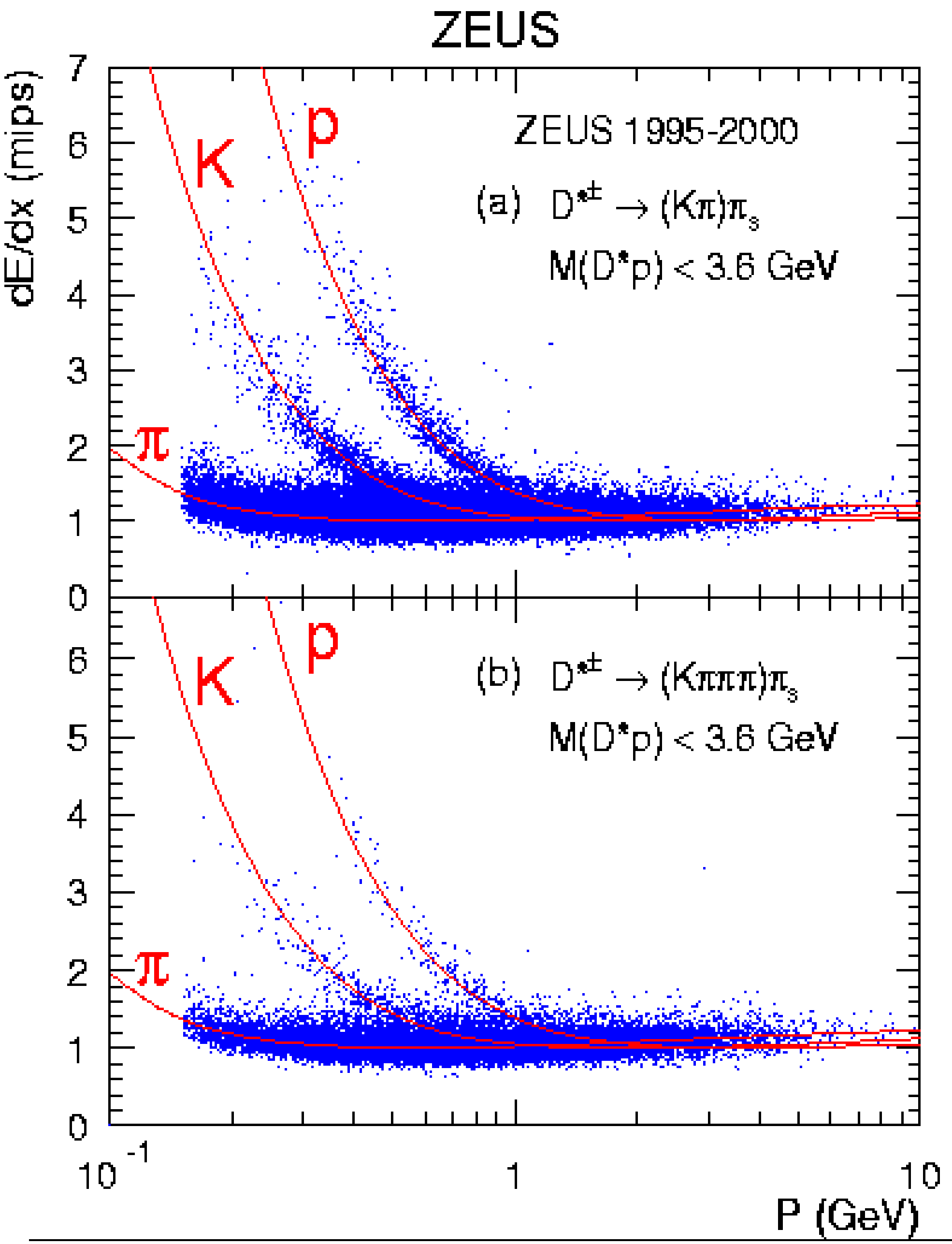
"protons" from signal region
$(3.085 < M(D^*p) < 3.115\,\mathbf{GeV})$
have harder momentum distribution
than "protons" from side bands



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

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

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



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

resolution $\sim 9\%$

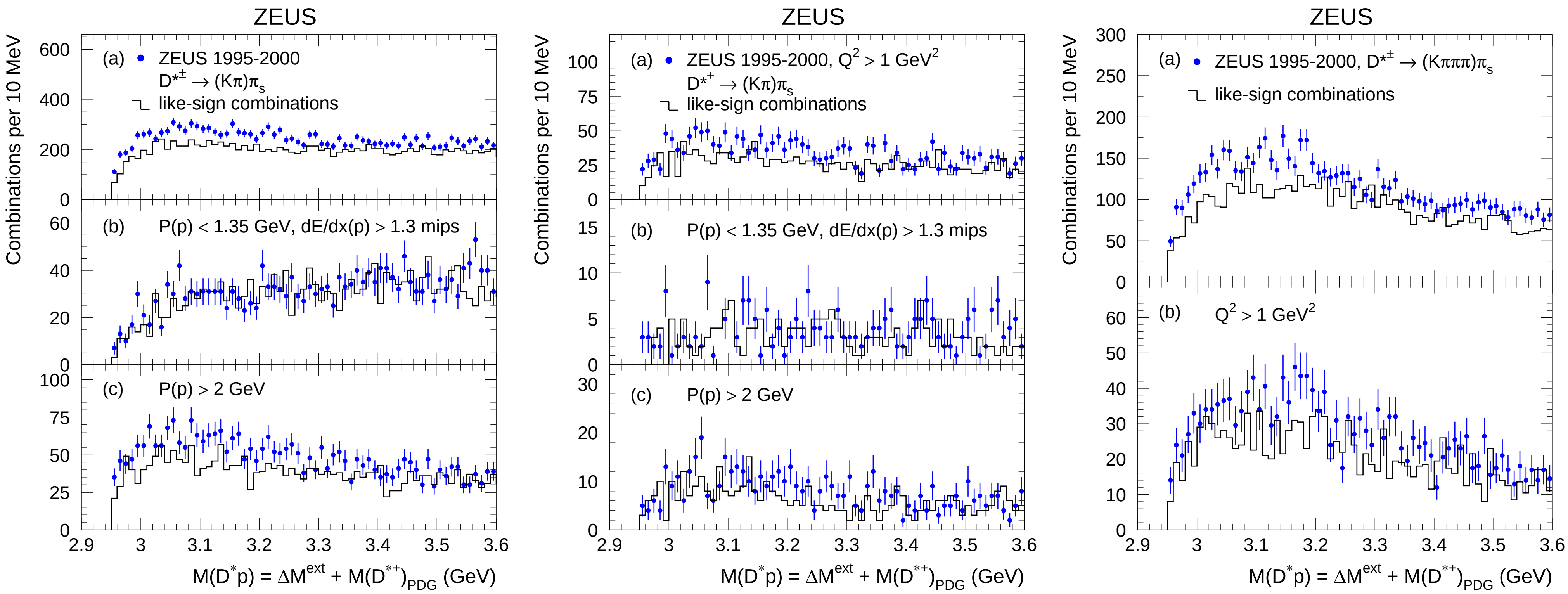
param. tuned using tagged $p(\bar{p})$ from Λ^0 decays

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

$Prob(\chi^2) > 0.15$

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

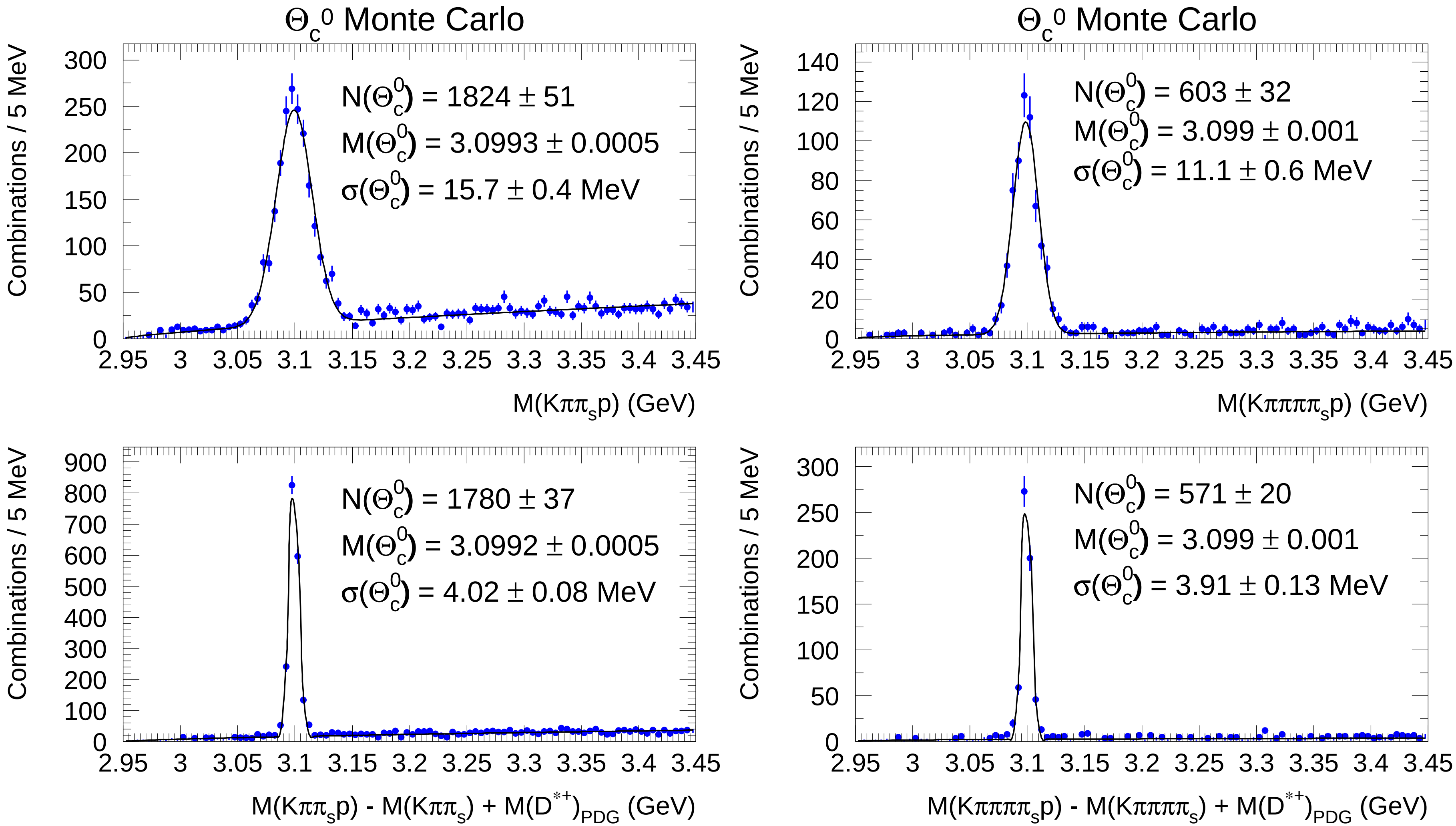
$M(D^*p)$, ZEUS



no signal in either distribution

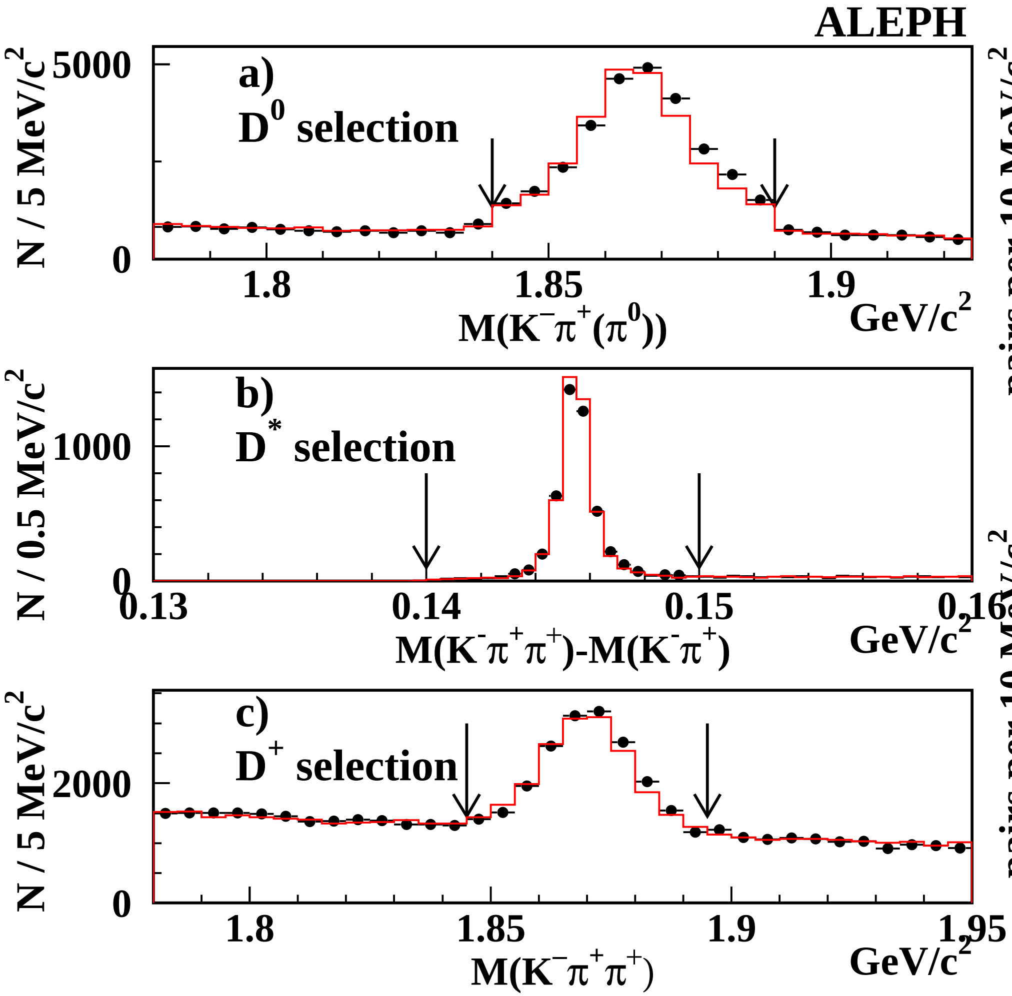
ZEUS Θ_c^0 MC and extended ΔM method

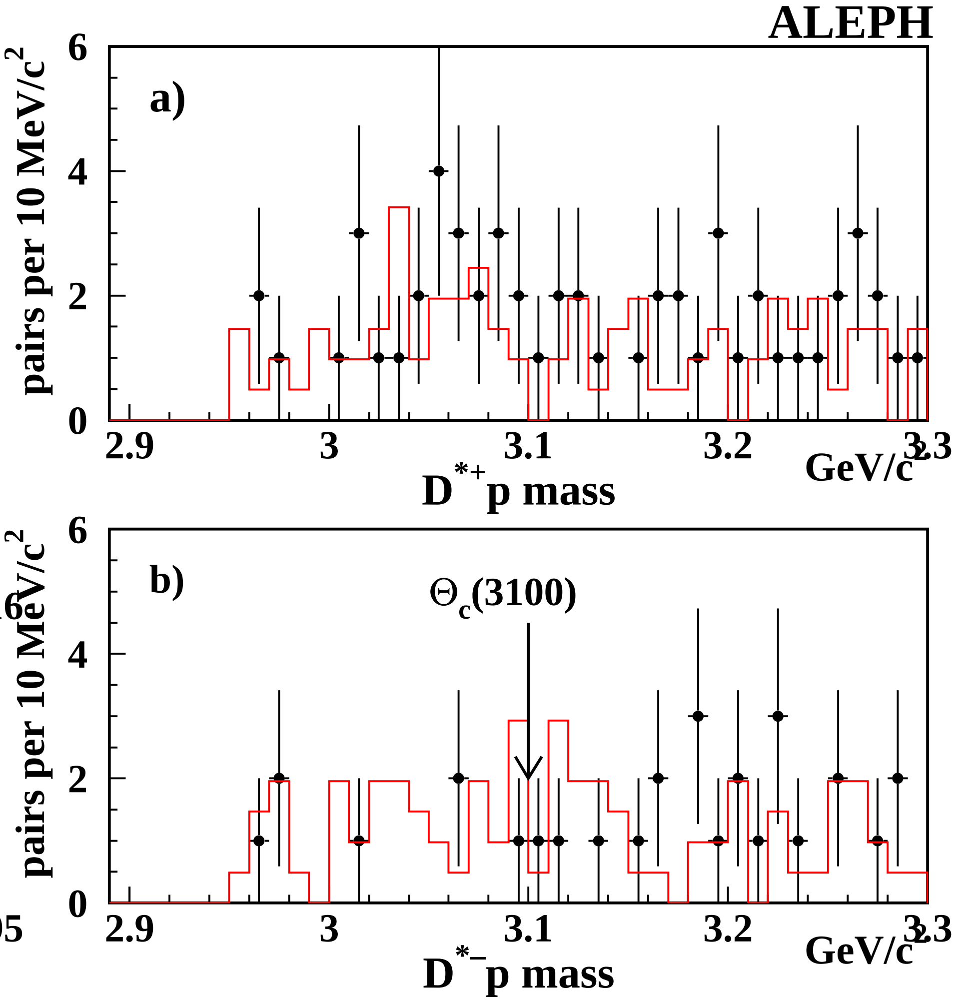
To prepare signal MC, Θ_c^0 was emulated by redefining mass, width and decay channel of $\Sigma_c^0(ddc)$



resolution is $\sim 4\,\text{MeV}$ (w.r.t. $\sim 7\,\text{MeV}$ in H1 analysis)

e^+e^- : ALEPH, Θ_c^0 in Z^0 decays ?

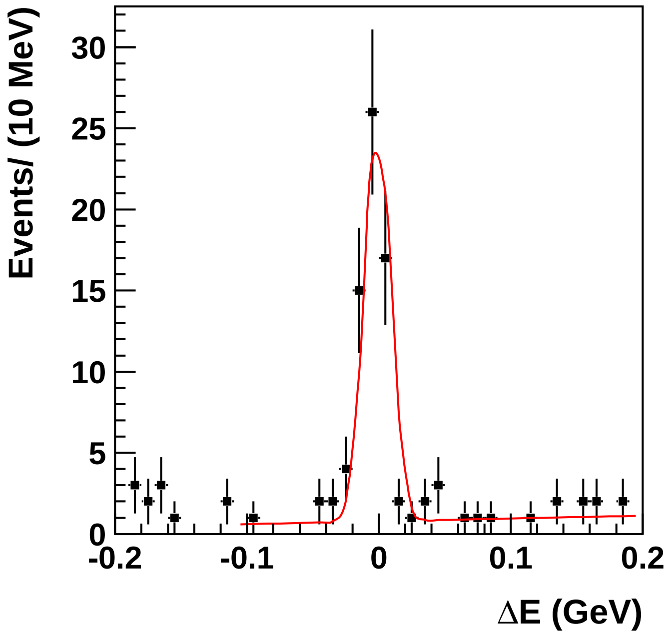




$N(D^{*\pm}) \sim 3500$ $\qquad$ $R(\Theta_c^0 \to D^* p / D^*) < 0.31\,\%$ (95%**C.L.)**

dE/dx **for** $p(\bar{p})$ **identification** $\qquad$ **for** ± 20 **MeV window**

e^+e^- : BELLE, Θ_c^0 in B^0 decays ?

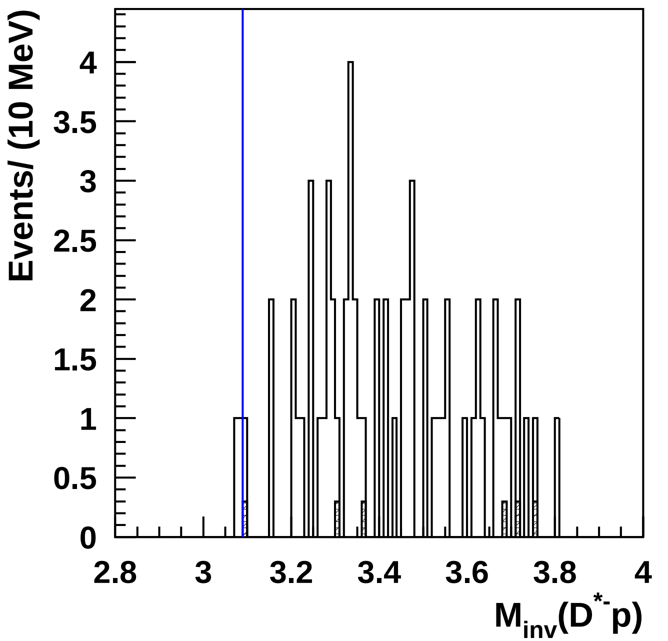


dE/dx, **ToF and Čerenkov for particle identification**

B identification : $\Delta E = (\sum_i E_i) - E_{beam}$

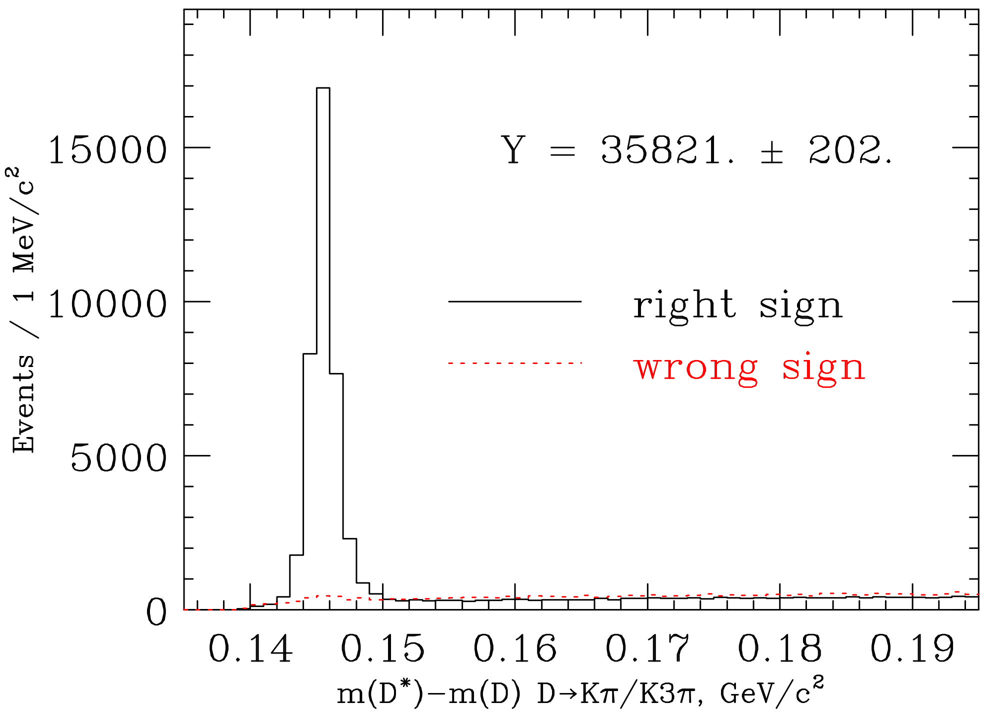
for $M_{bc} = \sqrt{E_{beam}^2 - (\sum_i \vec{p}_i)^2} > 5.27\,\mathbf{GeV}$

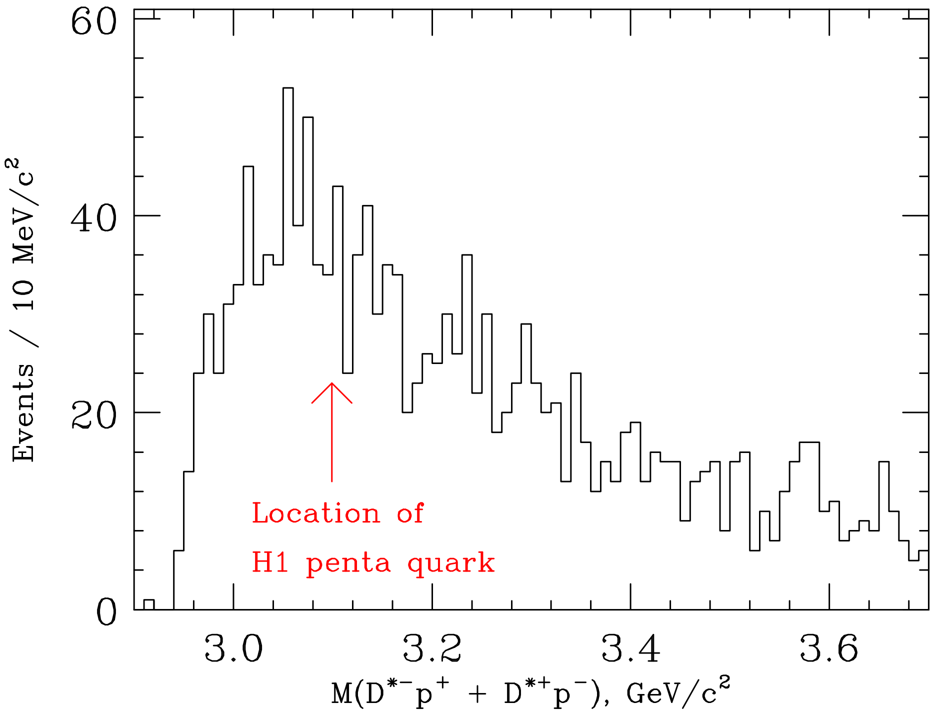
$N(B^0 \to D^{*-} p\bar{p}\pi^+) = 60 \pm 8$



$\frac{\mathcal{B}(B^0 \to \Theta_c^0 \bar{p}\pi^+) \times \mathcal{B}(\Theta_c^0 \to D^{*-}p)}{\mathcal{B}(B^0 \to D^{*-}p\bar{p}\pi^+)} < 11\%$ **(**90% **C.L.)**

γA : FOCUS, Θ_c^0 in dedicated charm experiment ?



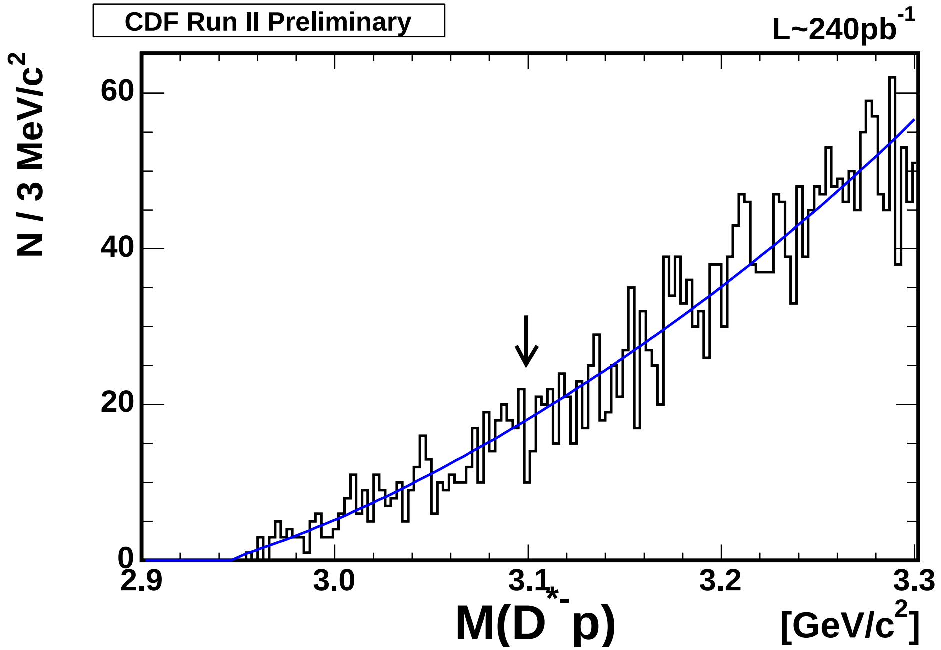


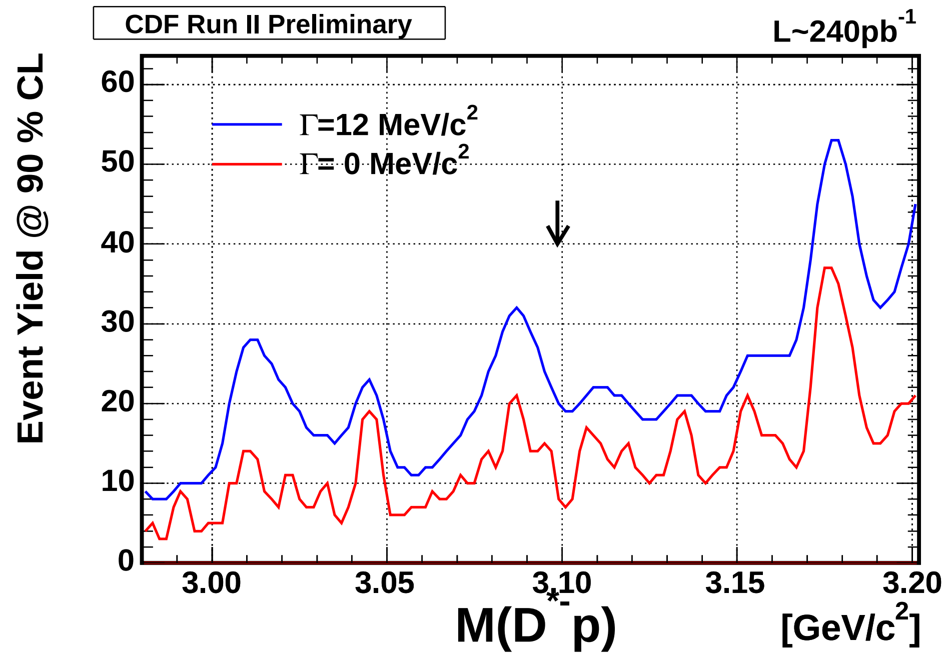
$N(D^{*\pm}) = 35821 \pm 202$

Čerenkov for $p(\bar{p})$ identification

no evidence for charm pentaquark

$p\bar{p}$: CDF, Θ_c^0 in high energy experiment ?





$\approx 500000\, D^{*\pm}$ **in the full sample**

dE/dx **and ToF**

for $p(\bar{p})$ **identification**

$\Longleftarrow$ **no signal**

In the window (3099.0 ± 17.4) **MeV**

$N(\Theta_c^0 \to D^{*-}p) < 21$ **for** $\Gamma = 0$ **MeV**

$N(\Theta_c^0 \to D^{*-}p) < 32$ **for** $\Gamma = 12$ **MeV**

while $N(D_1^0, D_2^{*0} \to D^{*+}\pi^-) \approx 10000$