Charm hadronisation

in γp collisions with ZEUS at HERA

Leonid Gladilin

(DESY / Moscow University / Weizmann Institute)

DIS 2003

April 23 - 27, 2003, St. Petersburg, Russia

O U T L I N E :

Charm hadronisation issues

Photoproduction of $D_s^{\pm}, D^{\pm}, \Lambda_c^{\pm}, D^0$ and $D^{*\pm}$

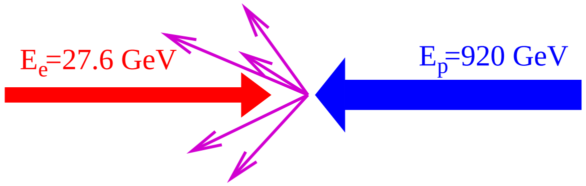
Measurement of fragmentation ratios : $R_{u/d}, \gamma_s$ and $P_{\rm v}$

Measurement of fragmentation fractions : $f(c \to D)$

Measurement of fragmentation function ($D^{*\pm}$)

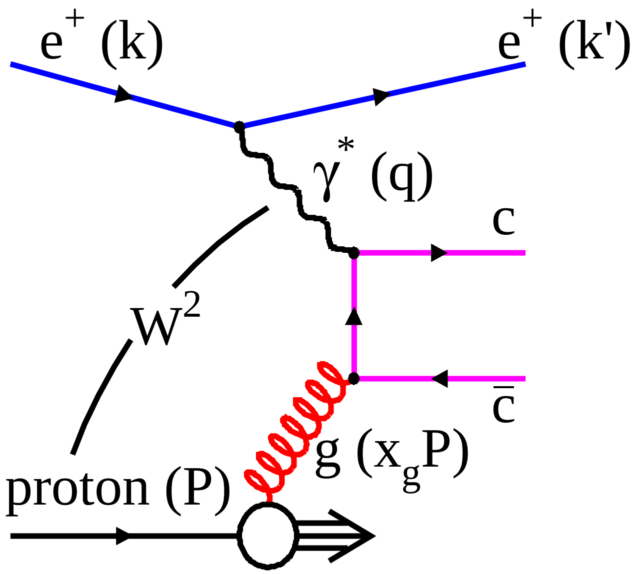
Summary

Charm production at HERA



1992-1997 $E_p = 820\,\mathbf{GeV}$ $\sqrt{s} = 300\,\mathbf{GeV}$

1998-2000 $E_p = 920\,\mathbf{GeV}$ $\sqrt{s} = 318\,\mathbf{GeV}$



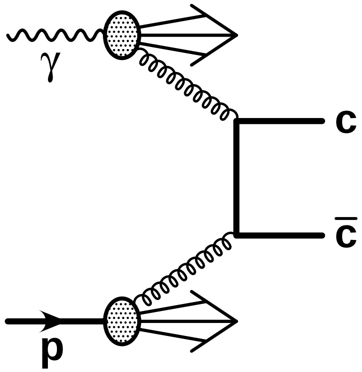
$$s = (P + k)^2$$

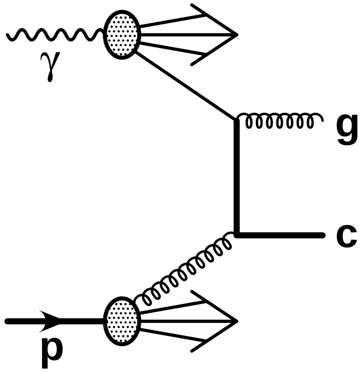
$$Q^2 = -q^2 = -(k - k')^2$$

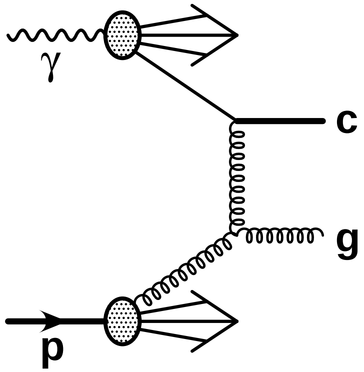
Photoproduction $Q^2 \simeq 0\,GeV^2$

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

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







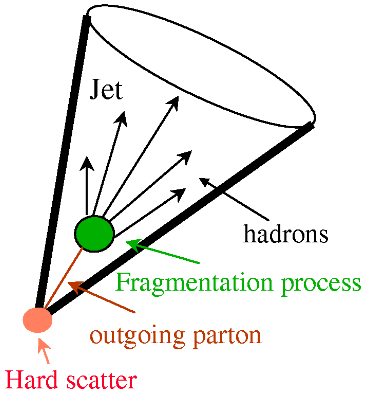
At parton level

pQCD is expected

to work !

$c \Longrightarrow D$?

Charm hadronisation issues



Important to study

charm hadronisation to find :

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

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

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

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

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

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

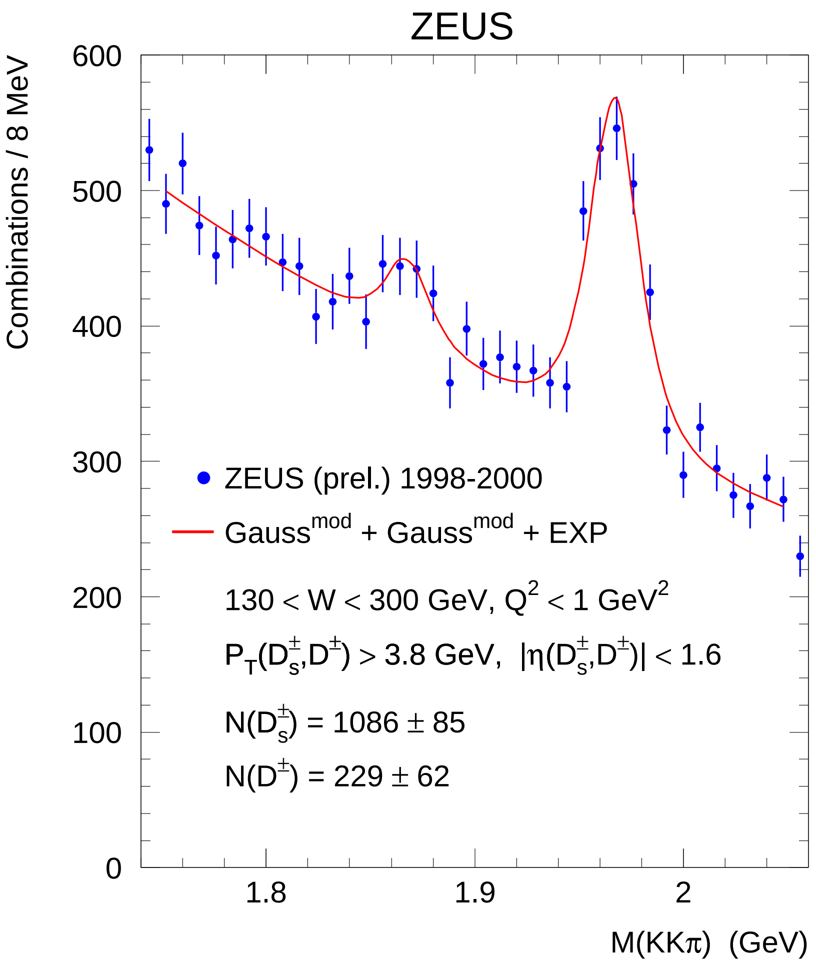
$D_s^\pm \to \phi\pi^\pm \to K^+K^-\pi^\pm$ in photoproduction

to measure charm hadronisation ratios and fractions

reconstruct 4 ground states ($D_s^\pm, D^\pm, \Lambda_c^\pm, D^0$) and $D^{*\pm}$

in the same kinematic region : $130 < W < 300\,\mathrm{GeV},\ Q^2 < 1\,\mathrm{GeV}^2$

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



$M(K^+K^-)$: $\pm 8\,\mathrm{MeV}$ around $M(\phi)_{\mathrm{PDG02}}$

$$\mathrm{Gauss}^{\mathrm{mod}} \propto e^{-0.5\cdot x^{1+\frac{1}{1+0.5\cdot x}}},$$

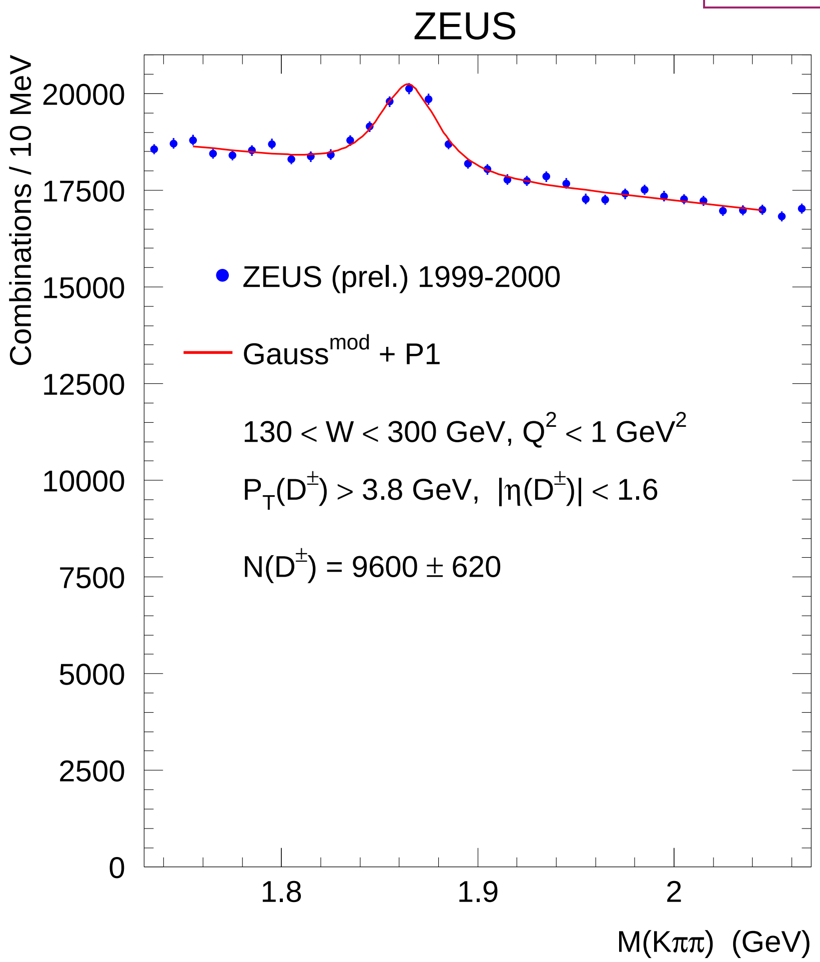
$$x = \left|\frac{M-M_0}{\sigma}\right|$$

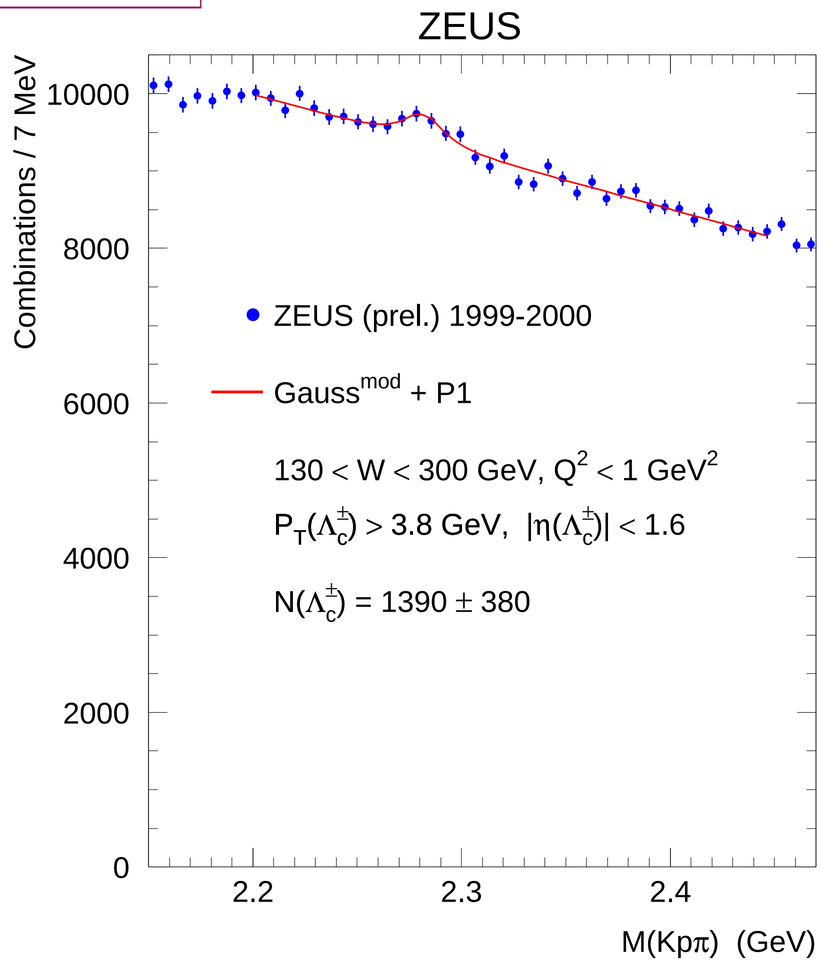
$$\boxed{\mathcal{L}_{int} = 79\,\mathrm{pb}^{-1}}$$

$$\boxed{N(D_s^\pm) = 1086 \pm 85}$$

$D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ and $\Lambda_c^{\pm} \to K^{\mp}p^{\pm}\pi^{\pm}$

$\mathcal{L}_{int} = 65.5\,\mathrm{pb}^{-1}$





no lifetime tagging (pre-MVD data)

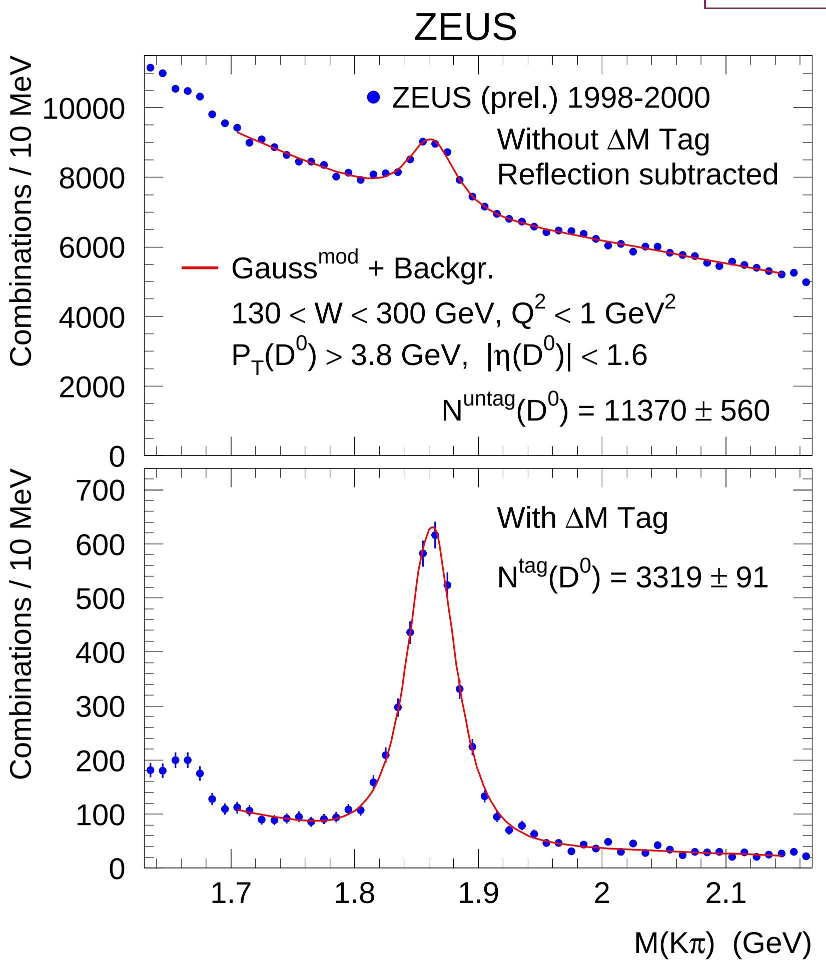
no dE/dx selection (high-P_T range)

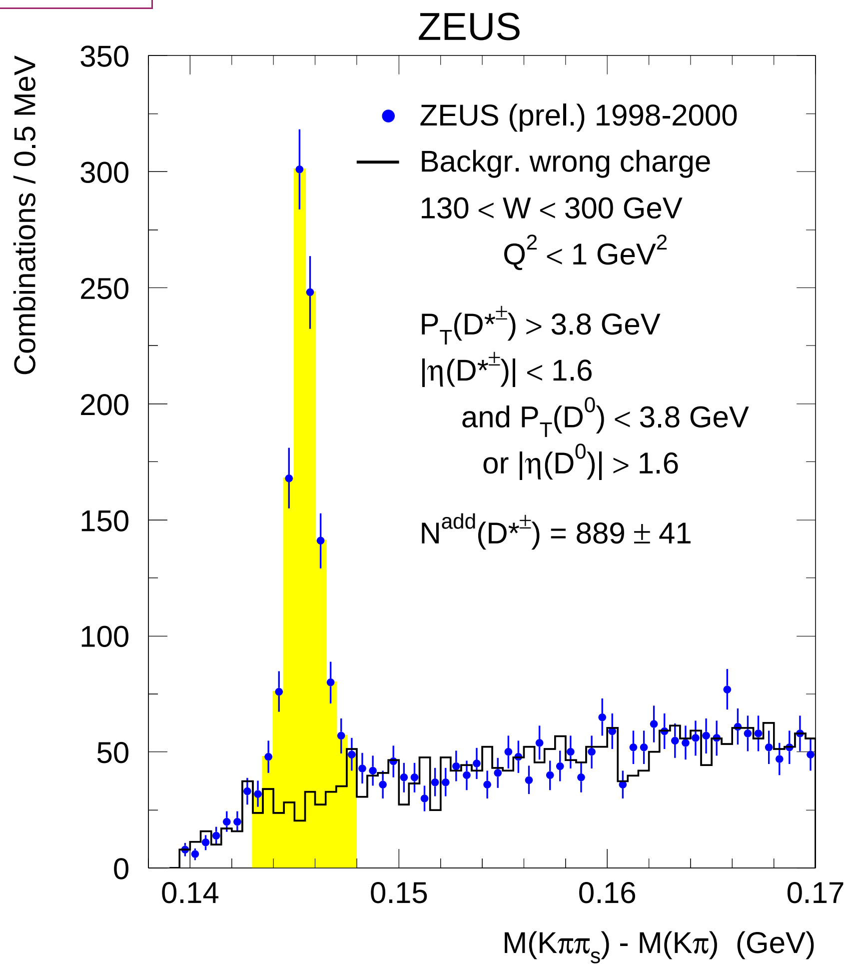
$N(D^{\pm}) = 9600 \pm 620$

$N(\Lambda_c^{\pm}) = 1390 \pm 380$

$D^0 \to K^{\mp}\pi^{\pm}$ and $D^{*\pm} \to D^0\pi_s^{\pm} \to (K^{\mp}\pi^{\pm})\pi_s^{\pm}$

$\boxed{\mathcal{L}_{int} = 79\,\mathrm{pb}^{-1}}$





$\boxed{N^{\mathrm{untag}}(D^0) = 11370 \pm 560}$

“additional” $D^{*\pm}$ signal

$\boxed{N^{\mathrm{tag}}(D^0) = 3319 \pm 91}$

$\boxed{N^{\mathrm{add}}(D^{*\pm}) = 889 \pm 41}$

$N^{\mathrm{tag}}(D^0) = N(D^{*\pm}\text{ with }D^0\text{ in kin. range})$

Branchings and cross sections

PDG02 branchings :

$BR = B_{D^{*+}\to D^0\pi^+} = (67.7 \pm 0.5)\,\%$

$B_{D^0\to K^-\pi^+} = (3.80 \pm 0.09)\,\%, \quad B_{D^+\to K^-\pi^+\pi^+} = (9.1 \pm 0.6)\,\%$

$B_{\Lambda_c^+\to K^- p^+\pi^+} = (5.0 \pm 1.3)\,\%$

$B_{D_s^+\to \phi\pi^+} = (3.6 \pm 0.9)\,\%, \quad B_{\phi\to K^-K^+} = (49.2^{+0.6}_{-0.7})\,\%$

$\boxed{\text{branching uncertainties are irrelevant for comparisons}}$

Kinematic region :

$130 < W < 300\,\mathrm{GeV}$ and $Q^2 < 1\,\mathrm{GeV}^2$

$P_T(D, \Lambda_c) > 3.8\,\mathrm{GeV}$ and $|\eta(D, \Lambda_c)| < 1.6$

Measured cross sections :

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

small beauty contributions are subtracted with Monte Carlo

$\boxed{\text{common uncertainties are canceled in ratio and fraction calculations}}$

$R_{u/d}$ measurement

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

$$= \frac{\sigma(D^0)-\sigma(D^{*\pm})\times BR}{\sigma(D^{\pm})+\sigma(D^{*\pm})\times BR} = \frac{\sigma^{\mathrm{untag}}(D^0)}{\sigma(D^{\pm})+\sigma^{\mathrm{tag}}(D^0)}$$

$$\boxed{R_{u/d} = 1.014 \pm 0.068\,(stat)^{+0.024}_{-0.031}\,(syst)}\quad \text{(ZEUS prel.)}$$

H1 prel. (DIS) : $R_{u/d} = 1.26 \pm 0.20 \pm 0.11 \pm 0.04\,(theory)$

ALEPH : $R_{u/d} = 1.02 \pm 0.12$

OPAL : $R_{u/d} = 1.19 \pm 0.36$

DELPHI : $R_{u/d} = 0.963 \pm 0.051 \pm 0.054$

u and d quarks are produced equally in charm fragmentation

Equivalent phase space treatment for D and D^* mesons

To subtract D^* contributions to D cross sections:

$$\sigma(D^{*\pm}\,\text{with}\,D^0\,\text{in kin. range}) = \sigma^{\text{tag}}(D^0)/BR$$

To calculate $\sigma(D^{*\pm})$ cross sections:

$$\sigma(D^{*\pm}\,\text{with}\,D^{*\pm}\,\text{in kin. range}) = \sigma^{\text{tag}}(D^0)/BR + \sigma^{\text{add}}(D^{*\pm})$$

Direct (not from D^*) D^+ and D^0 cross sections :

$$\sigma^{dir}(D^{\pm}) = \sigma(D^{\pm}) - (1 - BR) \times \sigma^{\text{tag}}(D^0)/BR$$

$$\sigma^{dir}(D^0) = \sigma^{\text{untag}}(D^0) - \sigma^{\text{tag}}(D^0)/BR$$

$\sigma(D^{*0}) = \sigma(D^{*+})$ is assumed in $\sigma^{dir}(D^0)$

Such phase space treatment allows measurement of fragmentation ratios and fractions directly in the considered $P_T(D, \Lambda_c)$ and $\eta(D, \Lambda_c)$ range

γ_s measurement

$$\gamma_s = \frac{2\,c\bar{s}}{c\bar{d}+c\bar{u}} = \frac{2\,\sigma(D_s^\pm)}{\sigma^{dir}(D^\pm)+\sigma^{dir}(D^0)+2\,\sigma(D^{*\pm})}$$

$$= \frac{2\,\sigma(D_s^\pm)}{\sigma(D^\pm)-\sigma^{\rm tag}(D^0)\times(1-BR)/BR+\sigma^{\rm untag}(D^0)-\sigma^{\rm tag}(D^0)/BR+2\,\sigma^{\rm tag}(D^0)/BR+2\,\sigma^{\rm add}(D^{*\pm})}$$

$$= \frac{2\,\sigma(D_s^\pm)}{\sigma(D^\pm)+\sigma^{\rm untag}(D^0)+\sigma^{\rm tag}(D^0)+2\,\sigma^{\rm add}(D^{*\pm})}$$

$$\boxed{\gamma_s = 0.266 \pm 0.023\,(stat)^{+0.014}_{-0.012}\,(syst)}$$ (ZEUS prel.)

ZEUS 96-97 (published) : $\gamma_s = 0.27 \pm 0.04^{+0.02}_{-0.03}$ (from $D^{*\pm}$ and $D_s^\pm$)

H1 prel. (DIS) : $\gamma_s = 0.36 \pm 0.10 \pm 0.01 \pm 0.08\,(theory)$

Combined e^+e^- value : $\gamma_s = 0.26 \pm 0.03$

s-quark production suppressed by factor $3-4$ in c-fragmentation

perfect agreement with other measurements

$P_{\rm v}$ measurement

$$P_{\rm v} = \frac{V}{V+PS} = \frac{\sigma(D^*)}{\sigma(D^*)+\sigma^{dir}(D)}$$

For charged ($c\bar{d}$) D mesons (no assumptions) :

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

$\boxed{P_{\rm v}^{d} = 0.557 \pm 0.023\,(stat)^{+0.009}_{-0.006}\,(syst)}$ (ZEUS prel.)

H1 prel. (DIS) : $0.693 \pm 0.045 \pm 0.004 \pm 0.009\,(theory)$, ALEPH : 0.595 ± 0.045

For sum of charged and neutral D mesons (assuming $\sigma(D^{*0}) = \sigma(D^{*+})$) :

$\boxed{P_{\rm v} = 0.554 \pm 0.019\,(stat)^{+0.008}_{-0.004}\,(syst)}$ (ZEUS prel.)

H1 prel. (DIS) : $0.613 \pm 0.061 \pm 0.033 \pm 0.008\,(theory)$, OPAL : 0.57 ± 0.05

DELPHI : $0.620 \pm 0.014 \pm 0.014$

For $D^{*\pm}$ and D^0 (assuming $\sigma(D^{*0}) = \sigma(D^{*+})$) :

$\boxed{P_{\rm v}^{d/u} = 0.551 \pm 0.027(stat)^{+0.014}_{-0.006}(syst)}$ (ZEUS prel.)

(ZEUS EPS01 paper : $0.546 \pm 0.045 \pm 0.028$) $\Longleftarrow$ superseded

$\boxed{P_{\rm v} \neq 0.75 \quad \Longrightarrow \quad \text{naive spin counting does not work for charm}}$

Sum of charm hadron cross sections

Sum of measured cross sections :

$$\sum_{\rm meas}\sigma(D) = \sigma^{dir}(D^{\pm}) + \sigma^{dir}(D^{0}) + 2\sigma(D^{*\pm}) + \sigma(D_s^{\pm}) + \sigma(\Lambda_c^{\pm})$$

($\sigma(D_s^{*\pm})$ and $\sigma(\Sigma_c)$ are counted in inclusive $\sigma(D_s^{\pm})$ and $\sigma(\Lambda_c^{\pm})$ cross sections)

Two charm-strange baryons are missed : $\Xi_c^{0,\pm}$ and Ω_c^0

Their rates can be estimated from non-charm Ξ and Ω rates to be $14 \pm 5\%$ of $\Lambda_c^{\pm}$ rate. Then :

$$\sum_{\rm all}\sigma(D) = \sigma^{dir}(D^{\pm}) + \sigma^{dir}(D^{0}) + 2\sigma(D^{*\pm}) + \sigma(D_s^{\pm}) + \sigma(\Lambda_c^{\pm}) \times 1.14$$

Now we can calculate fragmentation fractions as :

$$f(c \to D^{+}) = (\sigma(D^{\pm}) + \sigma^{\rm add}(D^{*\pm}) * (1 - BR)) / \sum_{\rm all}\sigma(D)$$

$$f(c \to D^{0}) = (\sigma^{\rm untag}(D^{0}) + \sigma^{\rm tag}(D^{0}) + \sigma^{\rm add}(D^{*\pm}) * (1 + BR)) / \sum_{\rm all}\sigma(D)$$

$$f(c \to D_s^{+}) = \sigma(D_s^{\pm}) / \sum_{\rm all}\sigma(D)$$

$$f(c \to \Lambda_c^{+}) = \sigma(\Lambda_c^{\pm}) / \sum_{\rm all}\sigma(D)$$

$$f(c \to D^{*+}) = (\sigma^{\rm tag}(D^{0}) / BR + \sigma^{\rm add}(D^{*\pm})) / \sum_{\rm all}\sigma(D)$$

Charm fragmentation fractions

ZEUS prel. (γp) $P_T(D,\Lambda_c) > 3.8\,\mathrm{GeV}$, $\lvert\eta(D,\Lambda_c)\rvert < 1.6$	Combined e^+e^- data	H1 prel. (DIS)
$\boxed{f(c \to D^+) = 0.249 \pm 0.014^{+0.004}_{-0.008}}$	0.232 ± 0.010	$0.202 \pm 0.020^{+0.045}_{-0.033}{}^{+0.029}_{-0.021}$
$\boxed{f(c \to D^0) = 0.557 \pm 0.019^{+0.005}_{-0.013}}$	0.549 ± 0.023	$0.658 \pm 0.054^{+0.117}_{-0.142}{}^{+0.086}_{-0.048}$
$\boxed{f(c \to D_s^+) = 0.107 \pm 0.009 \pm 0.005}$	0.101 ± 0.009	$0.156 \pm 0.043^{+0.036}_{-0.035}{}^{+0.050}_{-0.046}$
$\boxed{f(c \to \Lambda_c^+) = 0.076 \pm 0.020^{+0.017}_{-0.001}}$	0.076 ± 0.007	
$\boxed{f(c \to D^{*+}) = 0.223 \pm 0.009^{+0.003}_{-0.005}}$	0.235 ± 0.007	$0.263 \pm 0.019^{+0.056}_{-0.042}{}^{+0.031}_{-0.022}$

charm fragmentation fractions are universal

Predictions for extrapolation factors

factors for extrapolation outside of $P_T(D,\Lambda_c)$ and $\eta(D,\Lambda_c)$ range :

	Peterson (PYTHIA)	Bowler (PYTHIA)	Cluster model (HERWIG)
$R_{u/d}$	$0.99^{+0.02}_{-0.00}$	$0.99^{+0.02}_{-0.00}$	$1.00^{+0.01}_{-0.00}$
γ_s	$1.04^{+0.04}_{-0.07}$	$1.00^{+0.02}_{-0.00}$	$1.18^{+0.07}_{-0.05}$
$P_{\rm v}^{d}$	$1.00^{+0.02}_{-0.03}$	$0.97^{+0.01}_{-0.00}$	$0.96^{+0.02}_{-0.01}$
$P_{\rm v}$	$1.00^{+0.01}_{-0.03}$	$0.97^{+0.00}_{-0.01}$	$0.96^{+0.02}_{-0.01}$
$P_{\rm v}^{d/u}$	$1.01^{+0.01}_{-0.04}$	$0.97^{+0.00}_{-0.02}$	0.96 ± 0.01
$f(c \to D^+)$	$1.00^{+0.02}_{-0.01}$	1.02 ± 0.01	$0.99^{+0.01}_{-0.03}$
$f(c \to D^0)$	0.99 ± 0.01	0.98 ± 0.01	$0.96^{+0.00}_{-0.02}$
$f(c \to D_s^+)$	$1.03^{+0.04}_{-0.05}$	$1.00^{+0.05}_{-0.03}$	$1.15^{+0.06}_{-0.05}$
$f(c \to \Lambda_c^+)$	$1.01^{+0.03}_{-0.05}$	$1.08^{+0.03}_{-0.02}$	$\boxed{1.46^{+0.03}_{-0.09}}$
$f(c \to D^{*+})$	$1.00^{+0.02}_{-0.03}$	$0.96^{+0.00}_{-0.02}$	$0.93^{+0.01}_{-0.02}$

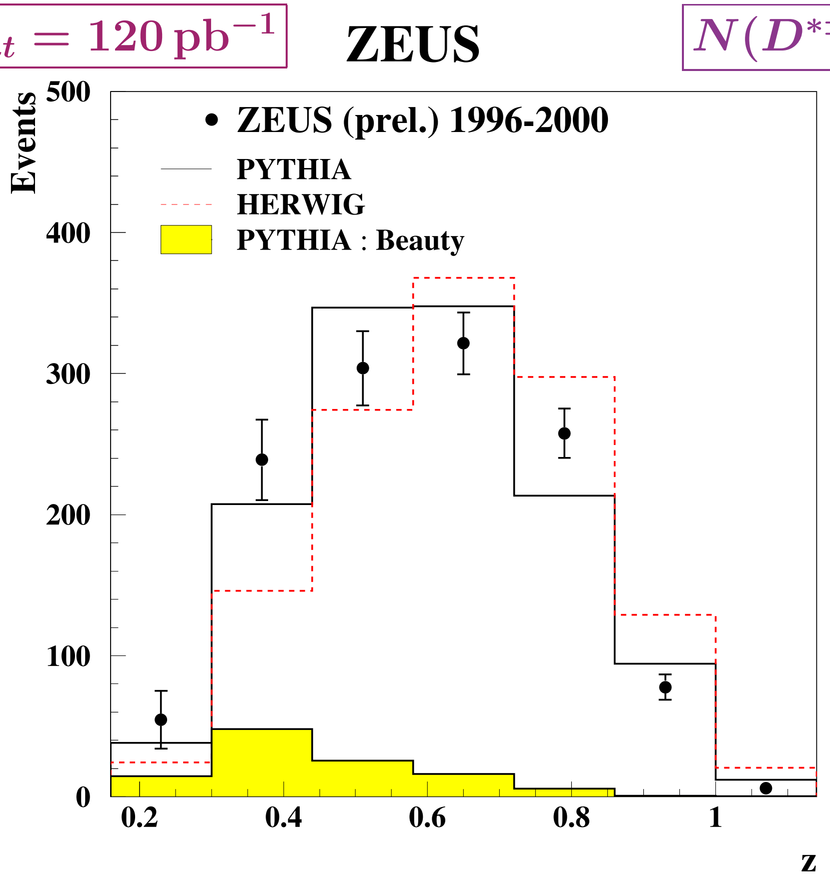
large extrapolation factors are not expected

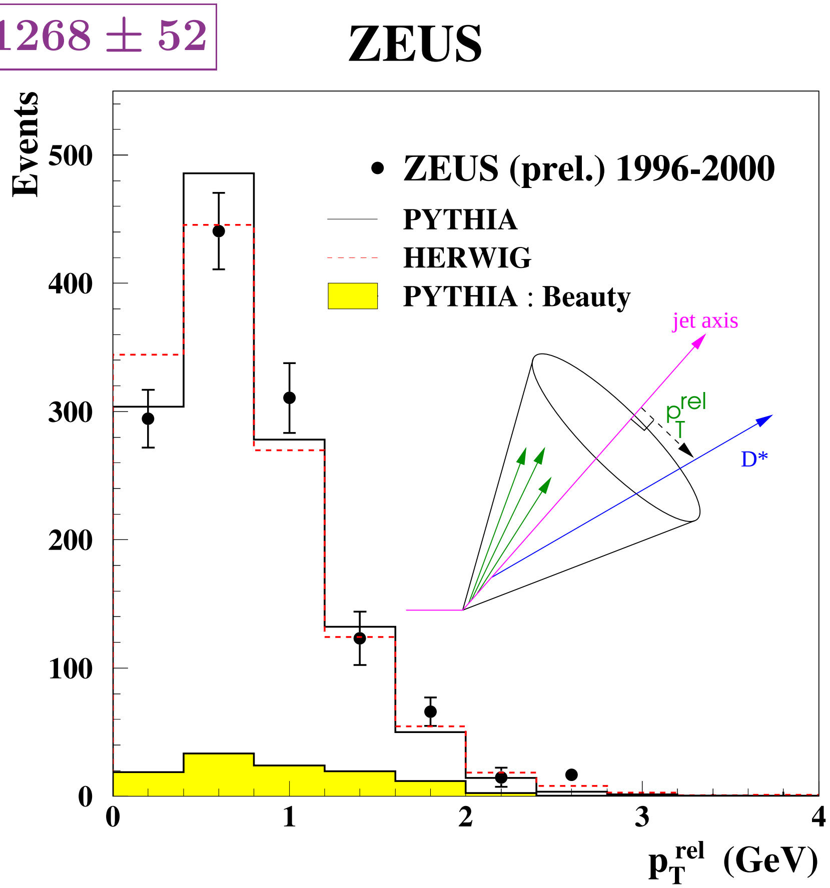
Measurement of charm fragmentation function ($D^{*\pm}$)

$130 < W < 280\,\mathrm{GeV}$, $Q^2 < 1\,\mathrm{GeV}^2$, $P_T(D^{*\pm}) > 2\,\mathrm{GeV}$, $|\eta(D^{*\pm})| < 1.5$

$D^{*\pm}$ belongs to a jet (k_T) with $E_T^{\mathrm{jet}} > 9\,\mathrm{GeV}$ and $|\eta^{\mathrm{jet}}| < 2.4$

$\boxed{\mathcal{L}_{int} = 120\,\mathrm{pb}^{-1}}$ $\boxed{N(D^{*\pm}) = 1268 \pm 52}$



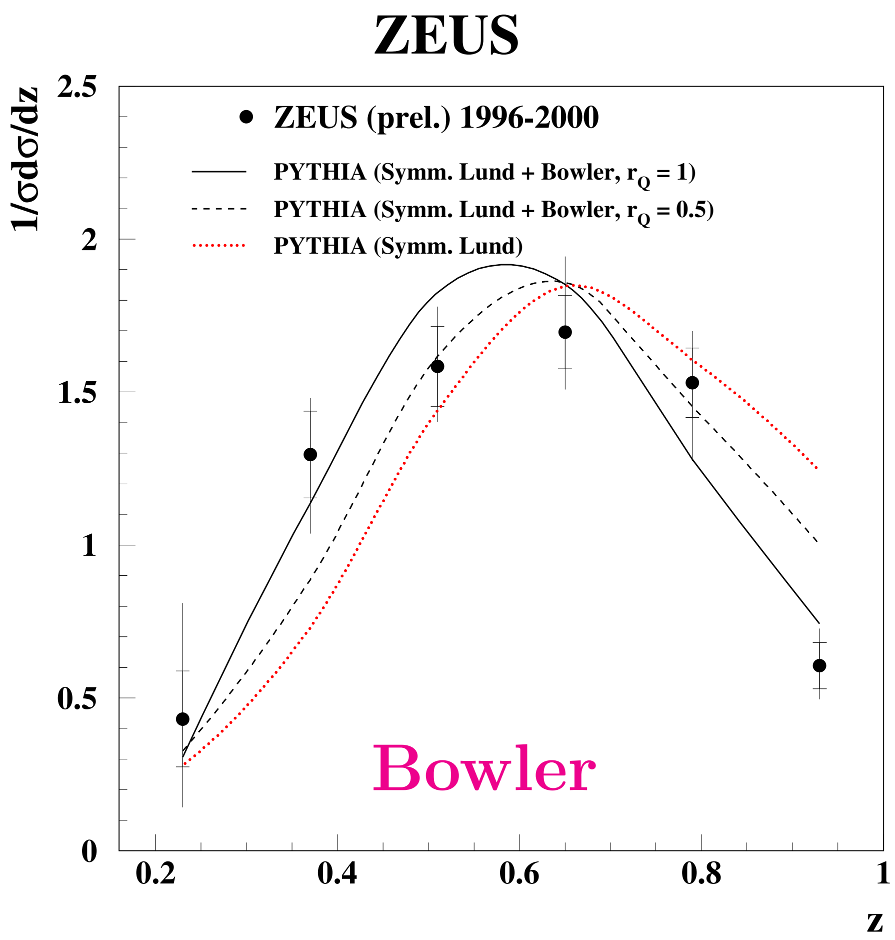


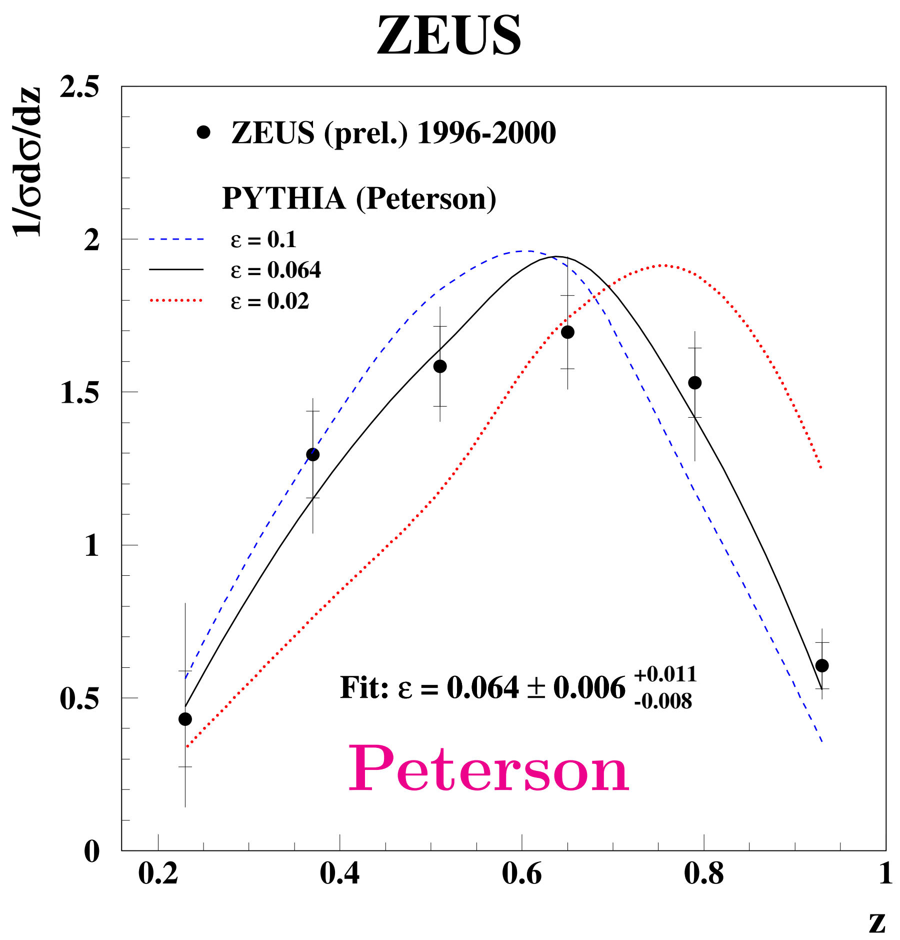
$$z = (E + p_{||})^{D^*} / (E + p_{||})^{\mathrm{jet}} \equiv (E + p_{||})^{D^*} / 2\,E^{\mathrm{jet}}$$

PYTHIA (Symm. Lund + Bowler) agrees with data

HERWIG (Cluster model) is too hard

Charm fragmentation function in γp collisions at HERA





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

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

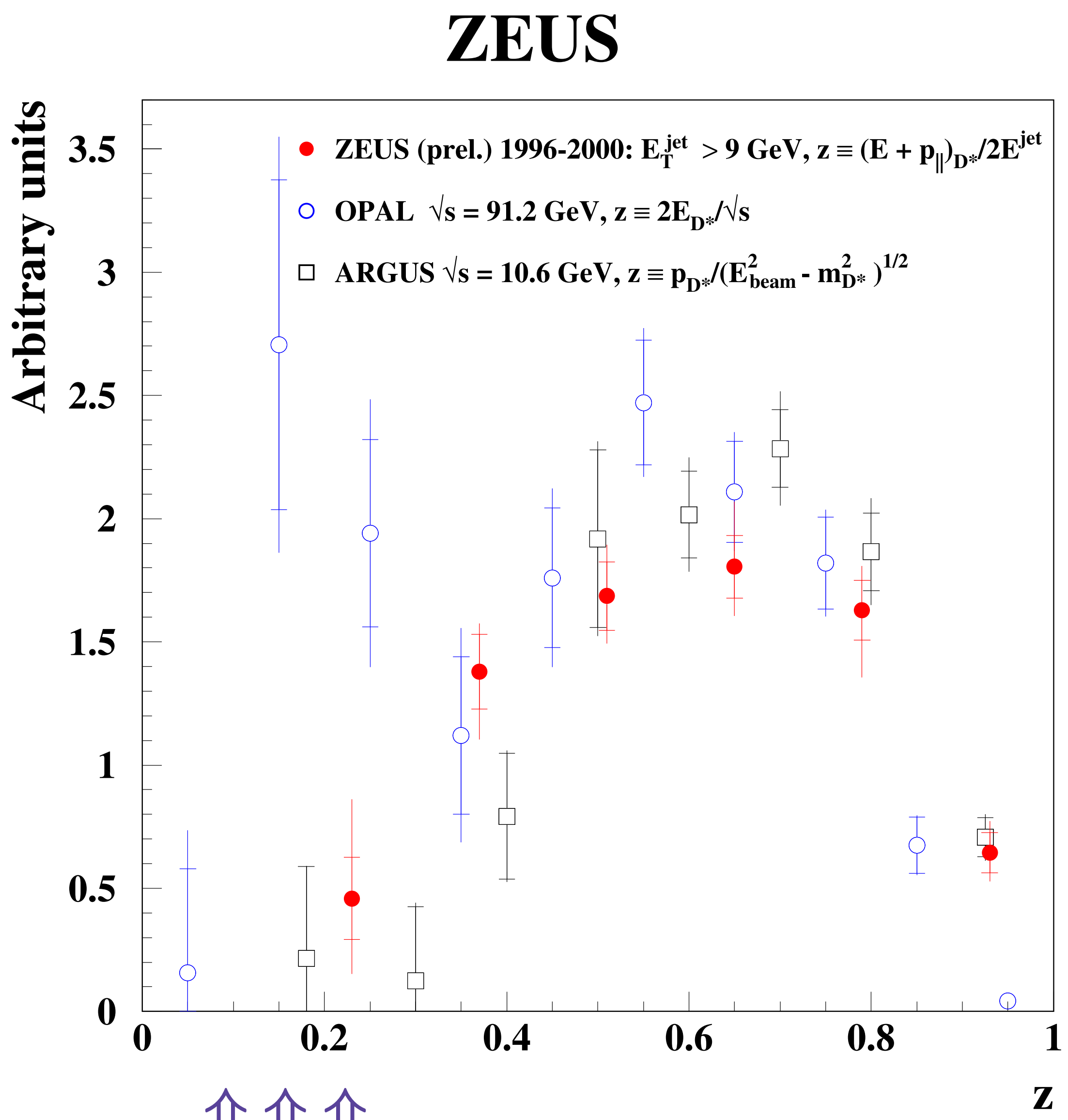
$r_Q = 1$ (default) is preferable

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

$\epsilon = 0.05$ (PYTHIA default)

Nason, Oleari $\Longrightarrow$ $\epsilon = 0.053$ (LL fit to ARGUS data)

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



different

z definitions

qualitative

agreement

⇑ ⇑ ⇑

no gluon-splitting component in ZEUS and ARGUS data

Summary

measurement of charm fragmentation ratios :

u and d quarks are produced equally in charm fragmentation

s-quark production suppressed by factor $3-4$ in c-fragmentation

$P_{\mathrm{v}} \neq 0.75 \quad \Longrightarrow$ naive spin counting does not work for charm

measurement of charm fragmentation fractions :

charm fragmentation fractions measured in $e^{\pm}p$ and $e^{+}e^{-}$ collisions
are in reasonable agreement

measurement of charm fragmentation function $(D^{*\pm})$:

PYTHIA with Bowler and Peterson fragmentation functions
provide good description; $\epsilon = 0.064 \pm 0.006^{+0.011}_{-0.008}$ (ZEUS prel.)

this leading-logarithm Monte Carlo fit to ZEUS data
agrees with LL fit to ARGUS data performed by Nason and Oleari

all above supports universality of charm fragmentation

it is valid to use charm fragmentation parameters measured
in $e^{+}e^{-}$ annihilations to describe D−production in $e^{\pm}p$ collisions

HERA provides own charm hadronisation

measurements with competitive precision