Experimental results on heavy quark fragmentation

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O U T L I N E :

Introduction

b fragmentation functions

b fragmentation branchings

b fragmentation ratios

c fragmentation in e^+e^-

c fragmentation at HERA

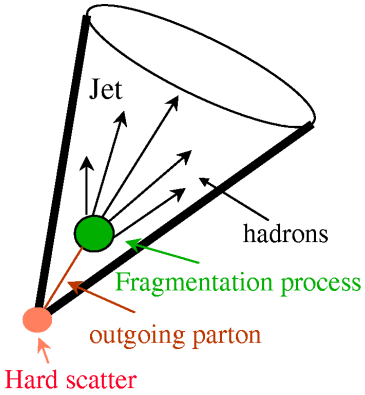
Summary

B A C K U P :

estimates of extrapolation factors

fragm. branchings for excited D mesons

Heavy Quark fragmentation issues



Important to measure

HQ fragmentation to find :

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

2) **What are the relative fragm. branchings (FB's) of B/D-hadrons ?**
   $f(c \to D) = \frac{N(D)}{N(c)} = \frac{\sigma(D)}{\sum_{\text{all}} \sigma(D)}$

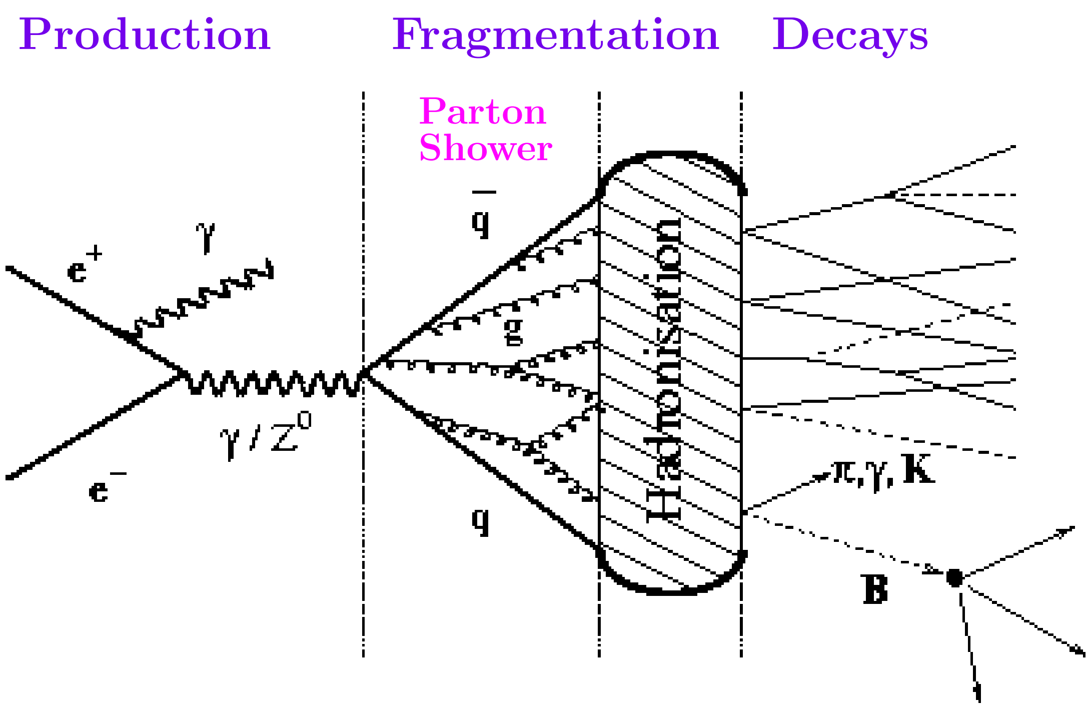
   a) **Are u and d quarks produced equally ?** $R_{u/d} = \frac{c\bar{u}}{c\bar{d}}$

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

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

3) **Are these functions, branchings and ratios universal ?**
   compare results in e^+e^- annihilations with those at HERA

Heavy Quark fragmentation in e^+e^- annihilations



HQ fragmentation is hard

harder for larger m_Q

e.g., for Peterson param.:

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

$$\epsilon(b) \sim \frac{m_c^2}{m_b^2}\epsilon(c) \sim 0.1\epsilon(c)$$

pQCD is applicable to "initial" Q-fragmentation: LO, NLO, LL, NLL, ...

anyhow, some parameterisation is needed for the non-perturbative (NP) rest

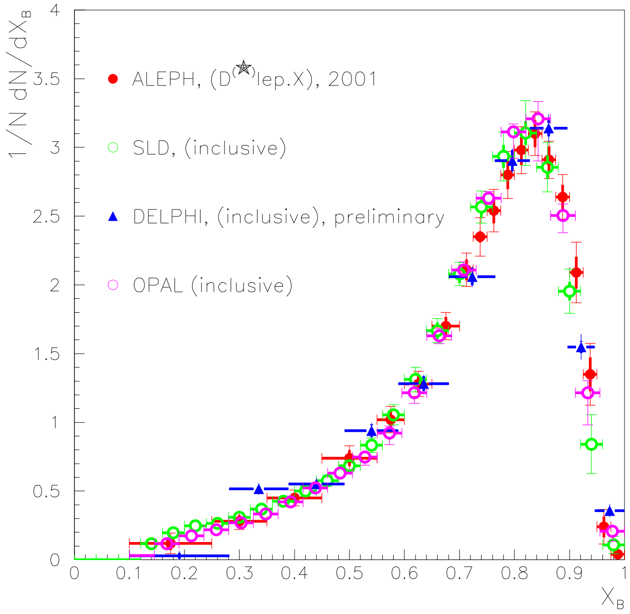
the NP parameterisation is strongly dependent from the perturbative core

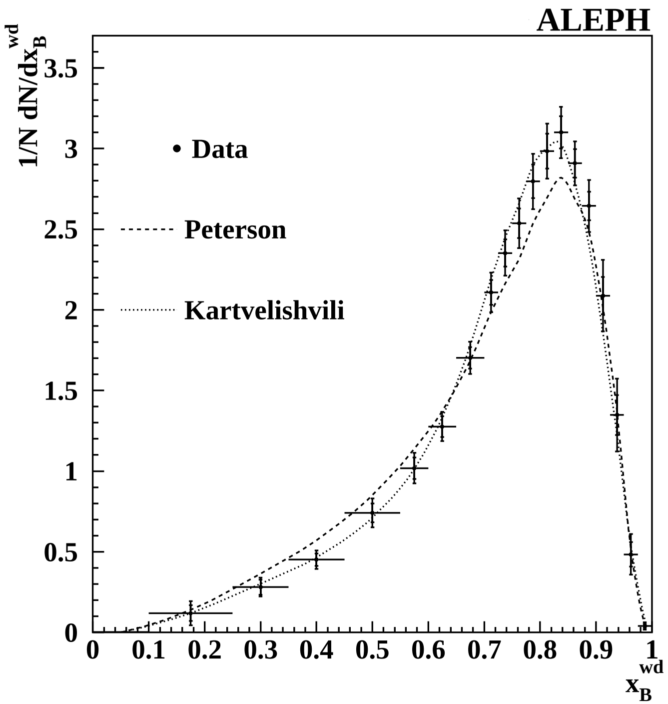
(it is wrong to use MC fragmentation for NLO w/o full retuning the fragm. parameters)

the NP parameterisation can include some decays

FB's are expected to be independent from the perturbative core

b fragmentation function, FF with LL MC





measured at LEP and SLD
from sec. vertices or s/l decays (ALEPH)

in terms of the scaled energy: $x \equiv E_{\rm hadron}/E_{\rm beam}$
for weakly decaying B hadrons

$< x >= 0.7193 \pm 0.0016^{+0.0038}_{-0.0033}$ **(OPAL)**

FF with LL Monte Carlo

Bowler, $\frac{1}{z^{1+bm_\perp^2}}(1-z)^a \exp(\frac{-bm_\perp^2}{z})$**, and**

Lund symmetric, $\frac{1}{z}(1-z)^a \exp(\frac{-bm_\perp^2}{z})$**, are**
in good agreement with data (2 parameters)

Kartvelishvili et al., $z^\alpha(1-z)$ **, is o.k. with 1 parameter**

Collins-Spiller, $(\frac{1-z}{z}+\frac{(2-z)\epsilon}{1-z})(1+z^2)(1-\frac{1}{z}-\frac{\epsilon}{1-z})^{-2}$ **, and**
Peterson are too broad (1 par.)

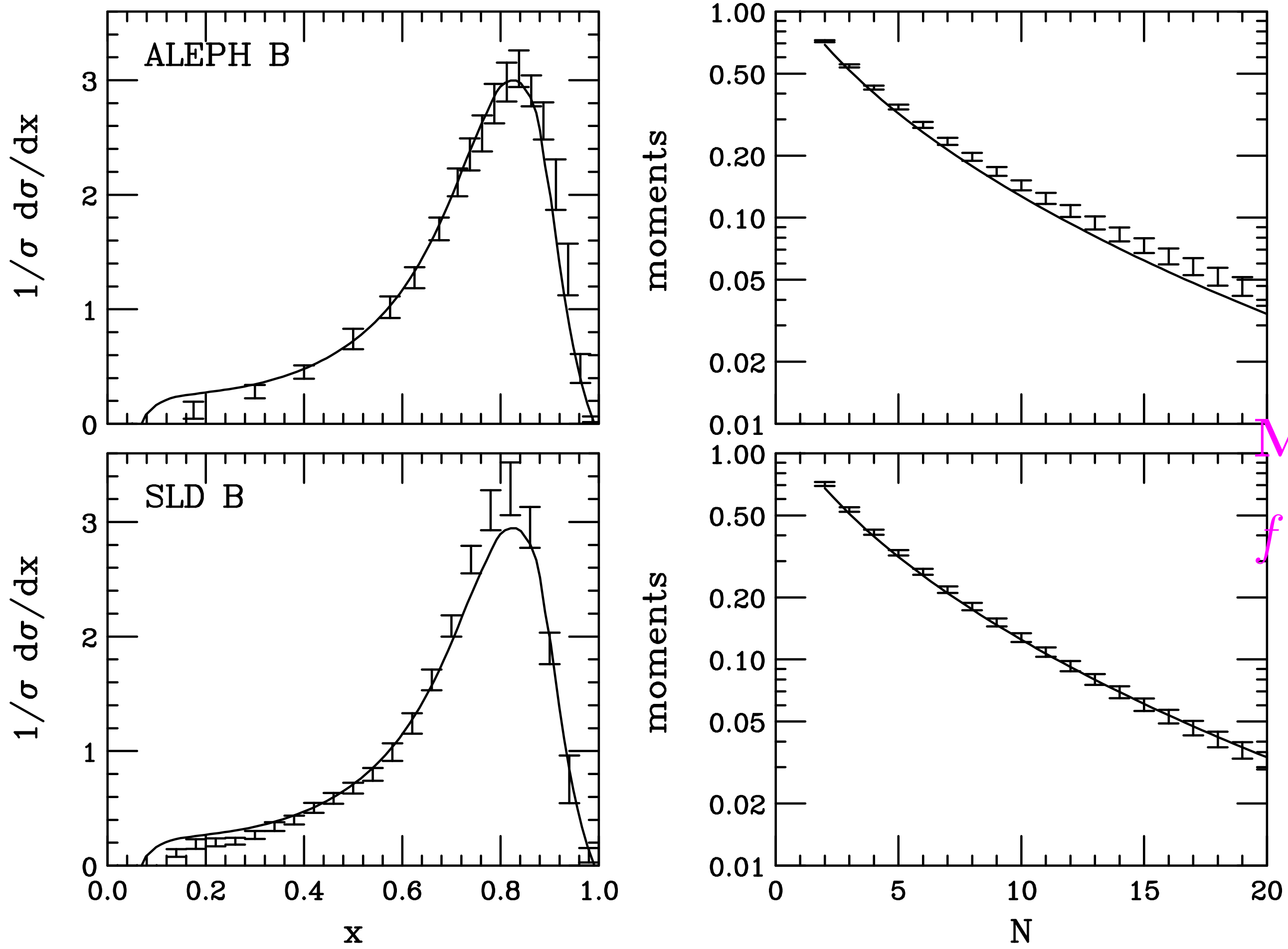
$$z \equiv (E+p_{||})_{\rm hadron}/(E+p)_{\rm quark}$$

HERWIG cluster model disfavoured

(what about MC@NLO ?)

b FF with NLO+NLL+Sudakov pQCD

Cacciari, Nason, Oleari



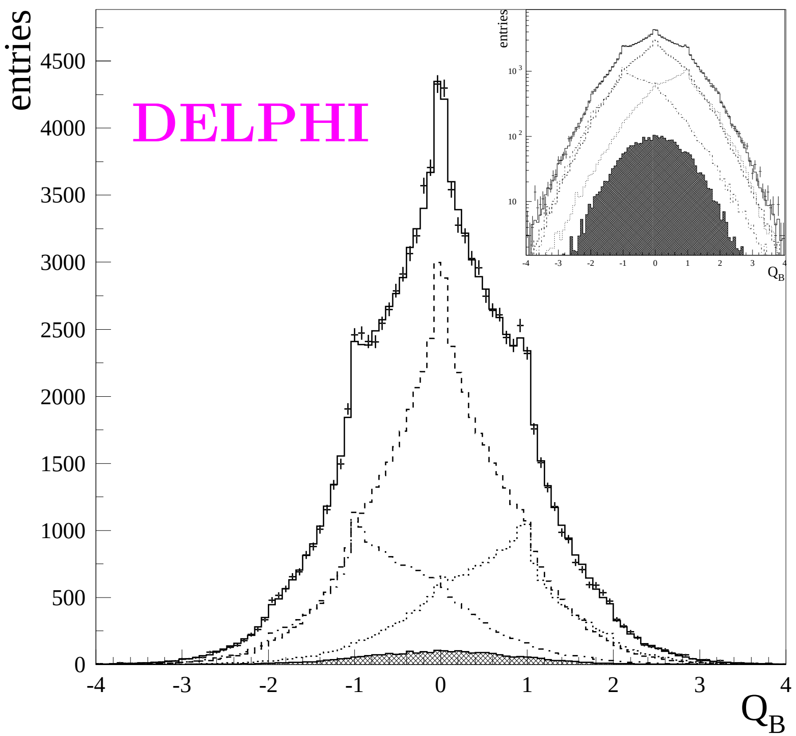
Mellin transform:

$f(N) \equiv \int_0^1 x^{N-1} f(x) dx$

$D_{NP}(x) \propto (1-x)^a x^b$ **(Colangelo-Nason)**

provides reasonable description with $a = 24 \pm 2$, $b = 1.5 \pm 0.2$

b fragmentation branchings



fit of the secondary vertex charge:

$f^+ = (42.09 \pm 0.82 \pm 0.89)\%$

using $f(b \to \Xi_b^-) = (1.1 \pm 0.5)\%$
from LEP measurements of $\Xi_b^- \to \Xi^- l^- \bar{\nu}_l X$
and neglecting Ω_b^-

$f_u = (40.99 \pm 0.82 \pm 1.11)\%$

HFAG from $B_s^0 \to D_s^- l^+ \nu_l X$**,** $\Lambda_b^0 \to \Lambda_c^+ l^- \bar{\nu}_l X$**,** $\Xi_b^- \to \Xi^- l^- \bar{\nu}_l X$
using $f_u = f_d$ **and** $f_u + f_d + f_s + f_{\rm baryon} = 1$ **:**

$f_u = f_d = (40.3 \pm 1.1)\%$

$f_s = (8.8 \pm 2.1)\%$

$f_{\rm baryon} = (10.7 \pm 1.8)\%$

using time-integrated mixing probabilities (f_d **and** f_s**)** $\Longrightarrow$

$f_u = f_d = (39.7 \pm 1.1)\%$

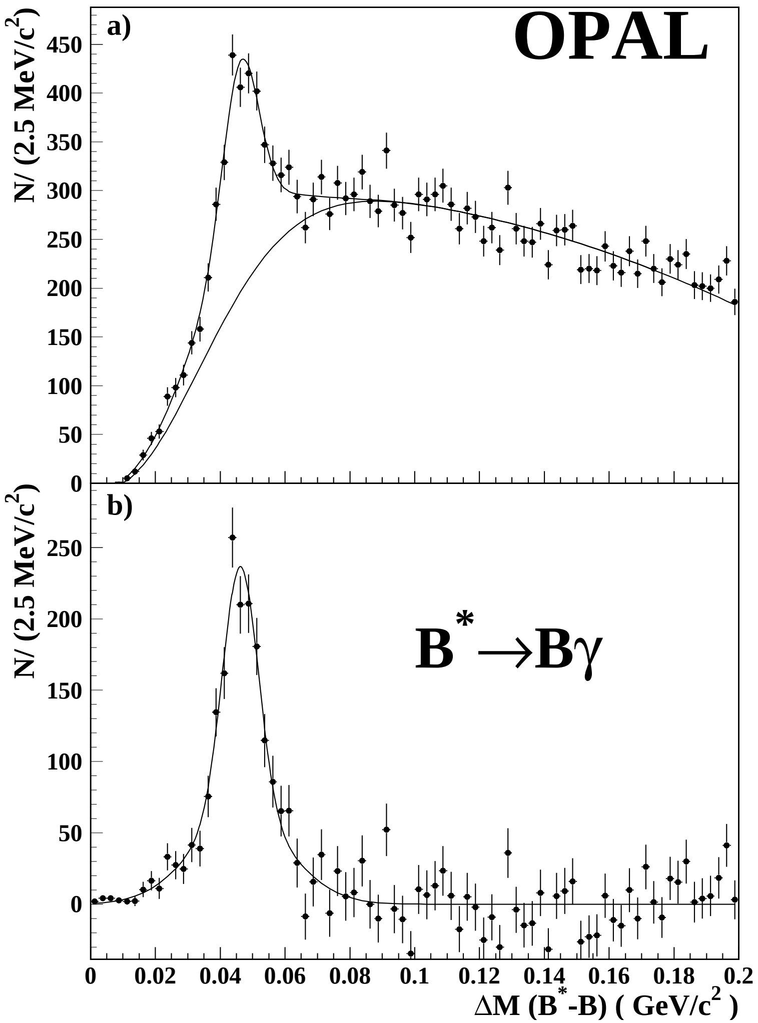
$f_s = (10.7 \pm 1.1)\%$

$f_{\rm baryon} = (9.9 \pm 1.7)\%$

b fragmentation ratios

a) $R_{u/d} = f_u/f_d \equiv 1$ **by construction (agrees with DELPHI's f_u measurement)**

b) $\gamma_s = \frac{2f_s}{f_u+f_d} = 0.27 \pm 0.03$ B_s **production suppressed by factor** ≈ 3.7



c) P_{v}

$B^* \to B\gamma$

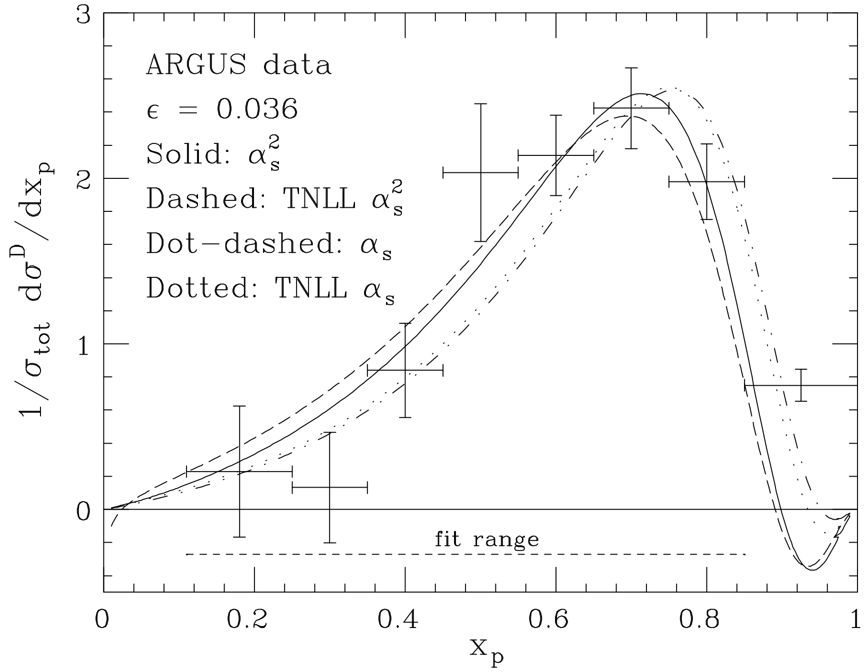
$P_{\mathrm{v}} = \sigma(B^*)/\sigma(B)$

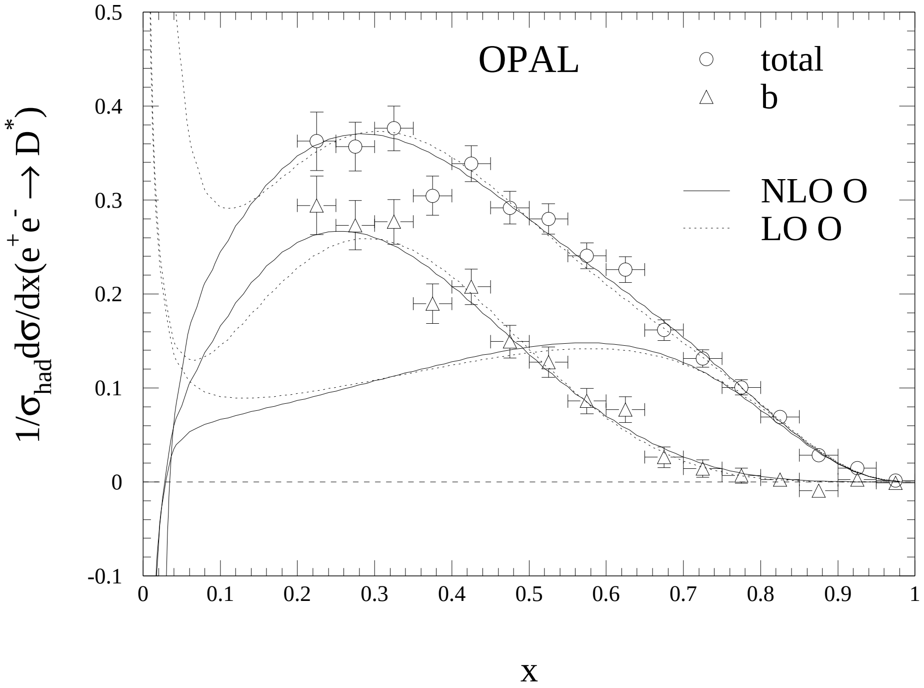
OPAL, ALEPH, DELPHI, L3 :

$P_{\mathrm{v}} = 0.75 \pm 0.04$

agrees with spin counting

c fragmentation function, NLO with Peterson FF





Fixed-order approach (NLO fits of P. Nason and C. Oleari) :

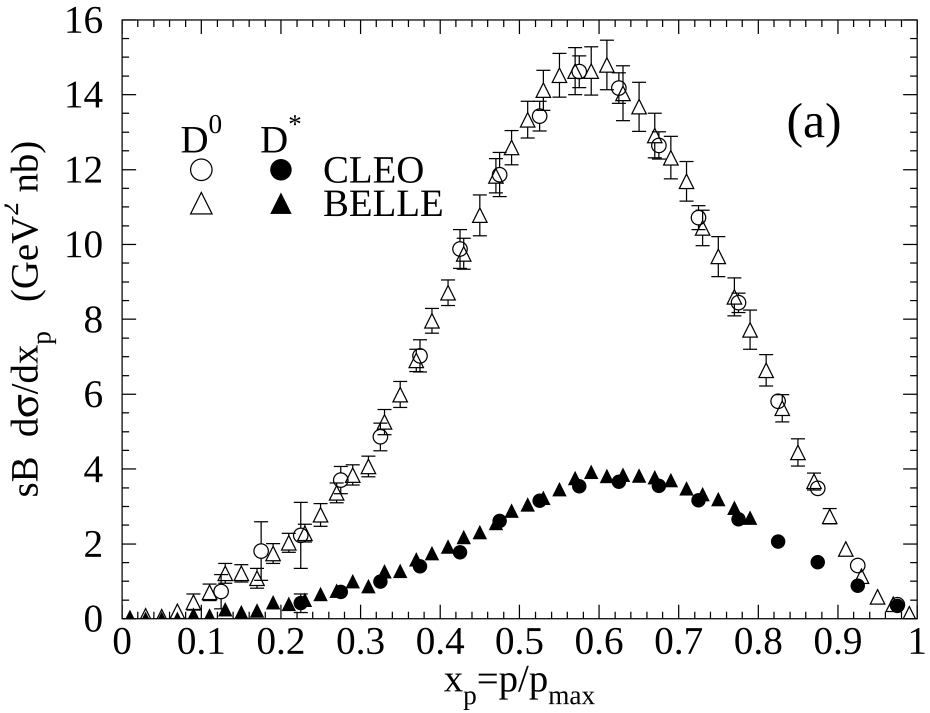
$\epsilon(D^*, D_s) = 0.035$ **ARGUS data** $\Leftarrow$ **Recommended !**

Resummed approach (LEP I data fit):

Kniehl et al. $\epsilon(D^*) = 0.116$

(fit results depend from the perturbative core)

c fragmentation function with LL MC



FF (Belle, D^{*+}) with LL Monte Carlo

Bowler : $\chi^2/NDF = 541.8/55$

Lund : $\chi^2/NDF = 965.6/55$

Kartvelishvili : $\chi^2/NDF = 1271.1/54$

Collins-Spiller : $\chi^2/NDF = 1540.7/54$

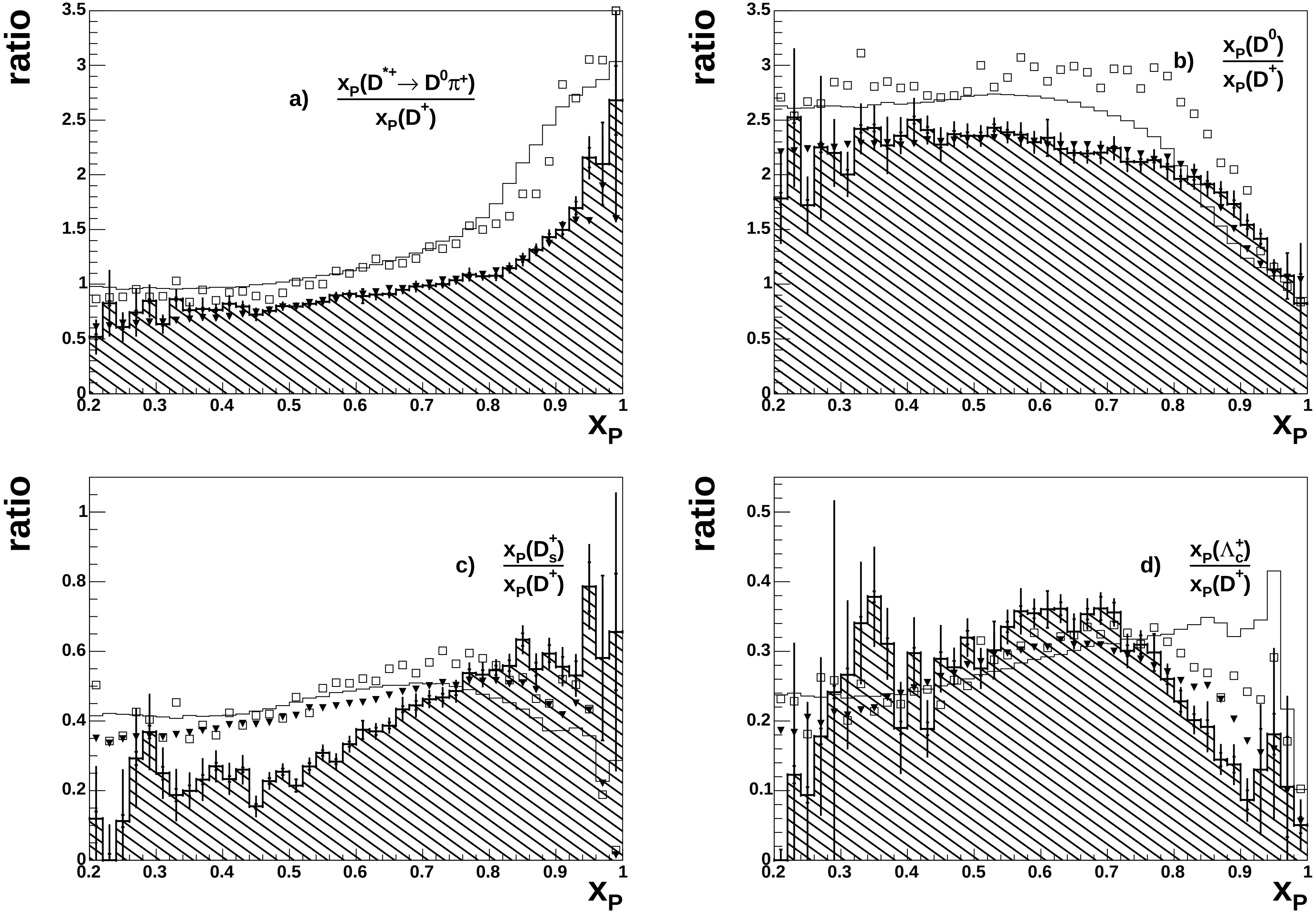
Peterson : $\chi^2/NDF = 3003.0/54$

Recent precise measurements from CLEO and Belle

$< x_p >= 0.611 \pm 0.007 \pm 0.004$ **(CLEO, D^{*+})**

Qualitatively, the same picture as for b FF with LL MC

differential fragmentation ratios (Belle)



o.k.

fails

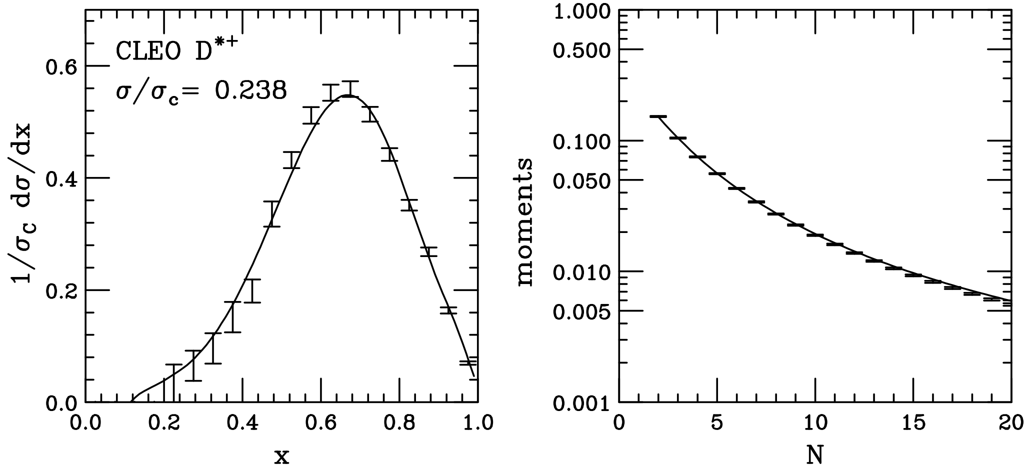
hatched histograms: data

full triangles: tuned Bowler with PARP(13)=0.59 (P_{v})

c FF with NLO+NLL+Sudakov pQCD

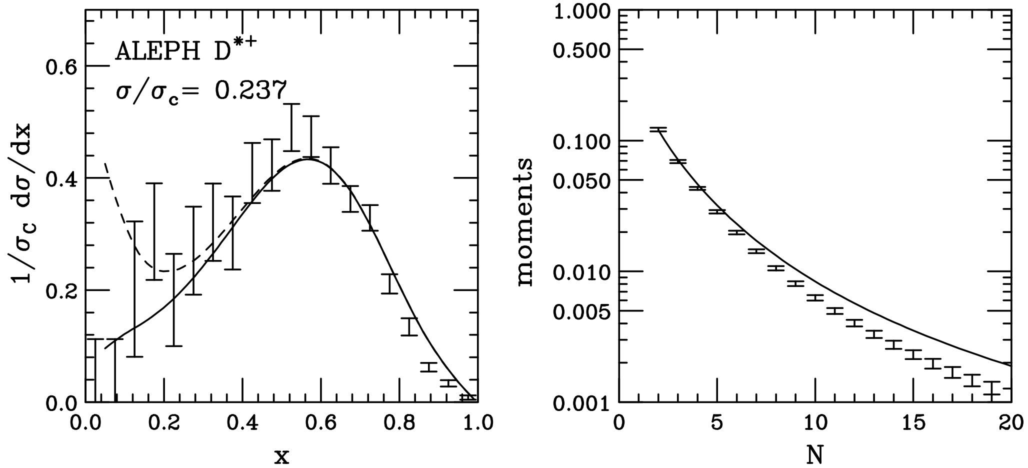
Cacciari, Nason, Oleari

$$D_{NP}(x) \propto \frac{1}{1+c}[\delta(1-x) + cN_{a,b}^{-1}(1-x)^a x^b]$$



CLEO, Belle described with

$a = 1.8 \pm 0.2$, $b = 11.3 \pm 0.6$, $c = 2.46 \pm 0.07$



above fit does not describe ALEPH

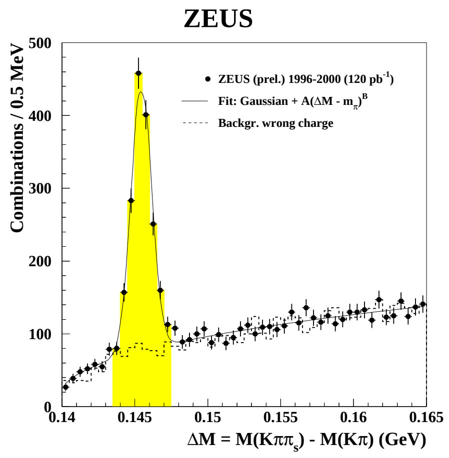
fit to ALEPH yields

$a = 2.4 \pm 1.2$, $b = 13.9 \pm 5.7$, $c = 5.9 \pm 1.7$

the difference for D^{*+} hadroproduction up to 20%

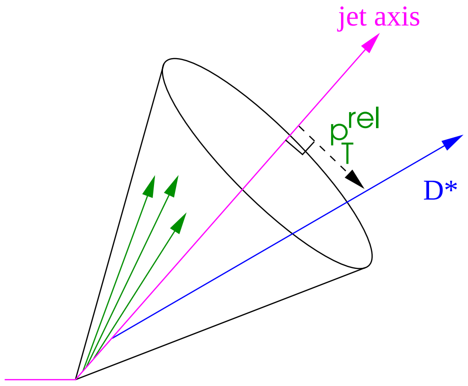
experimental info on fragmentation in hadroproduction ?

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



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

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



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: $Q^2 < 1\,\mathbf{GeV}^2$, $P_T(D^{*\pm}) > 2\,\mathbf{GeV}$, $E_T^{\rm jet} > 9\,\mathbf{GeV}$

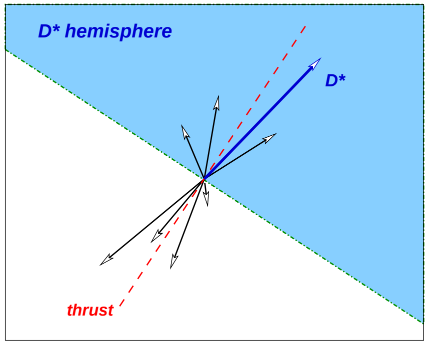
$$z = (E + p_{||})^{D^*}/(E + p_{||})^{\rm jet} \equiv (E + p_{||})^{D^*}/2\,E^{\rm jet}$$

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

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

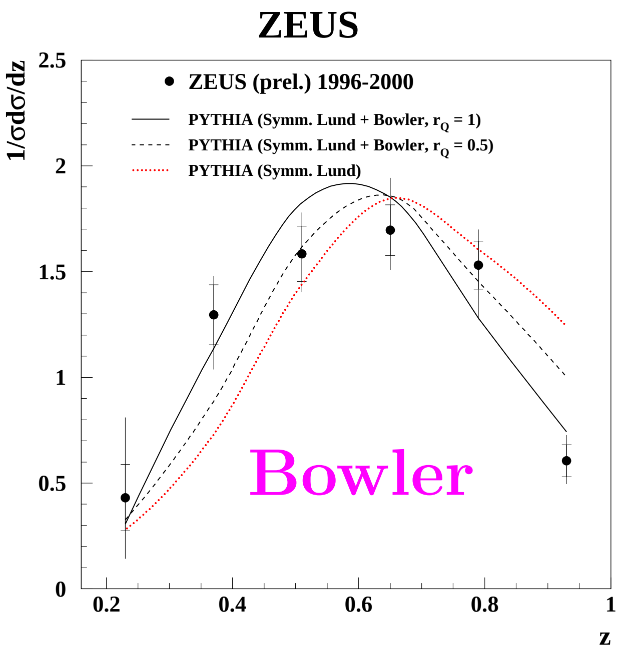
3) H1, hemisphere method:

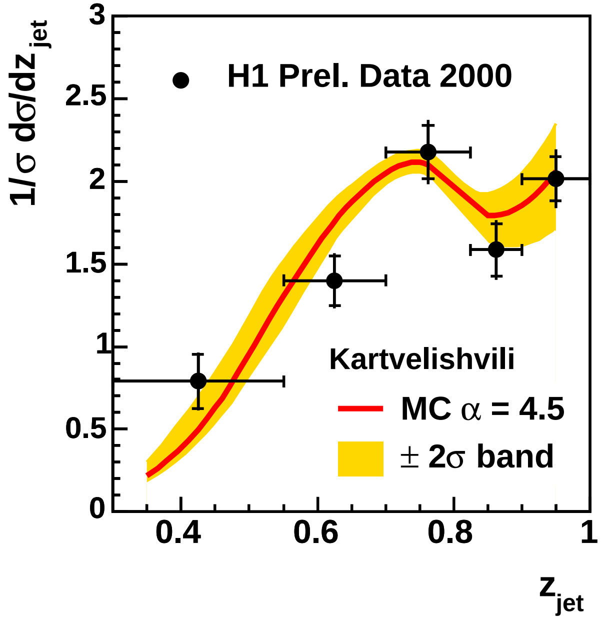
$$z_{\rm hem} = (E + p_{||})^{D^*}/\sum_{\rm hem}(E + p) \ \ \textbf{in}\ \gamma^* p$$

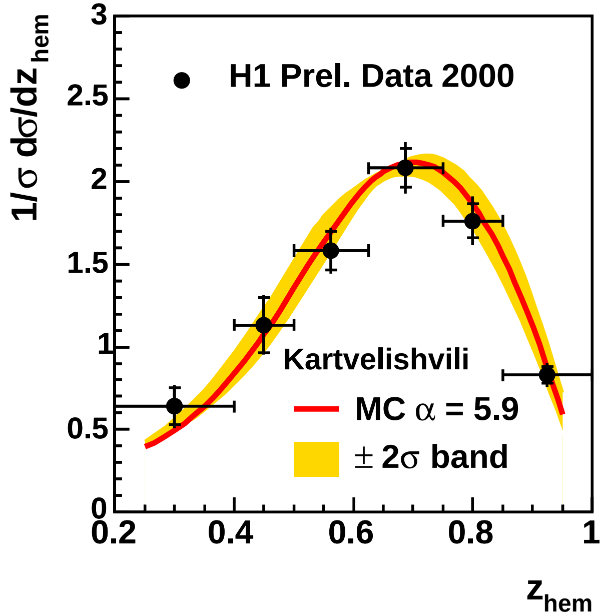


Bowler and Kartvelishvili parameterizations

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







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

$r_Q = 1$ **(default) is preferable**

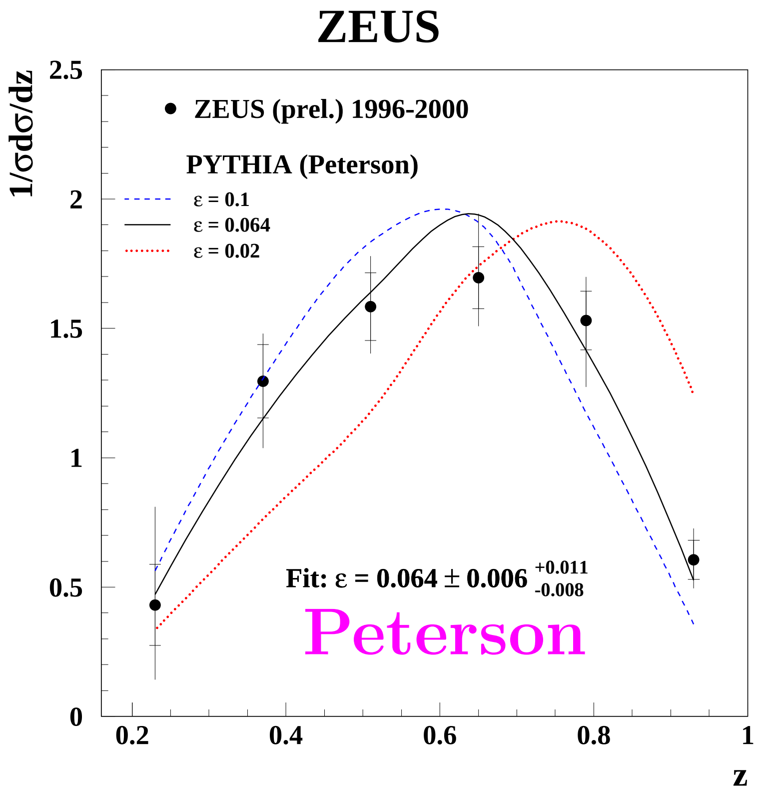
$$f(z) \propto z^{\alpha}(1-z)$$

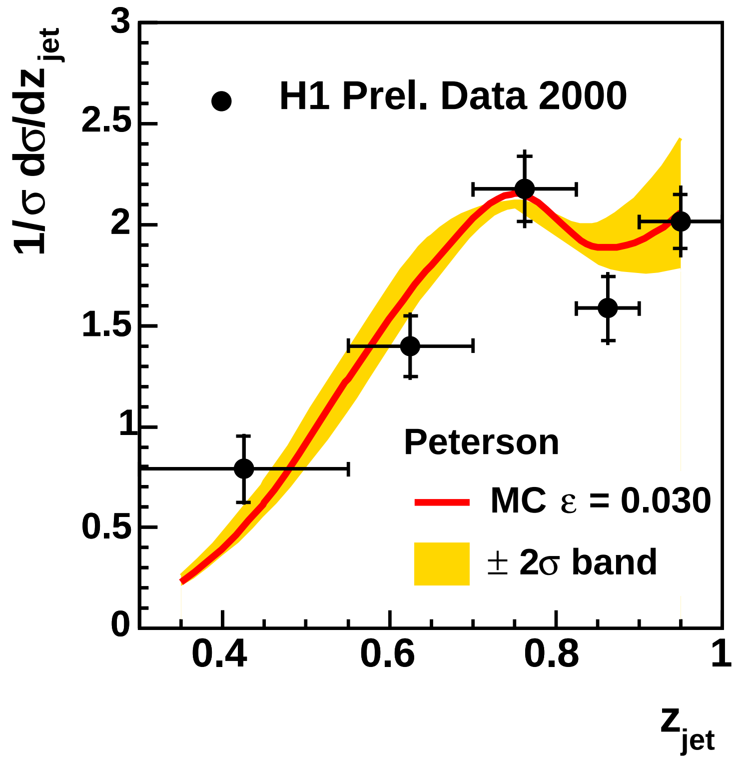
$\alpha = 4.5 \pm 0.5$ **(H1 jet method)**

$\alpha = 5.9^{+0.9}_{-0.6}$ **(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)**

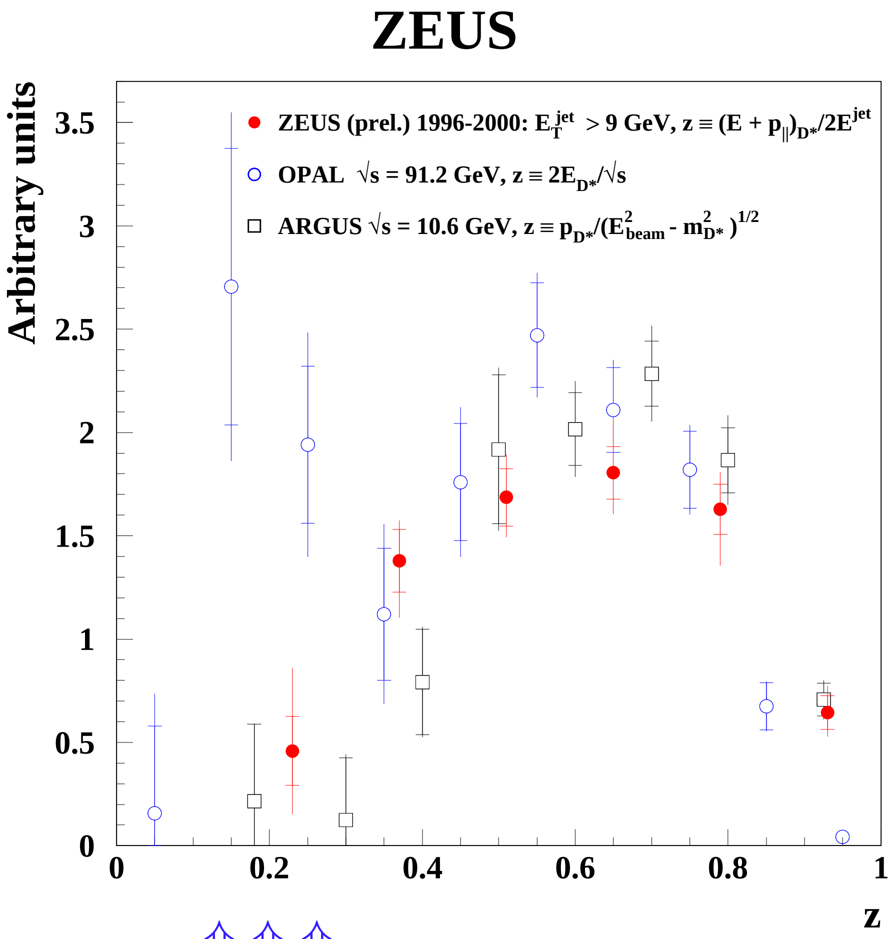
$\epsilon = 0.018 \pm 0.004$ **(hem. method)**

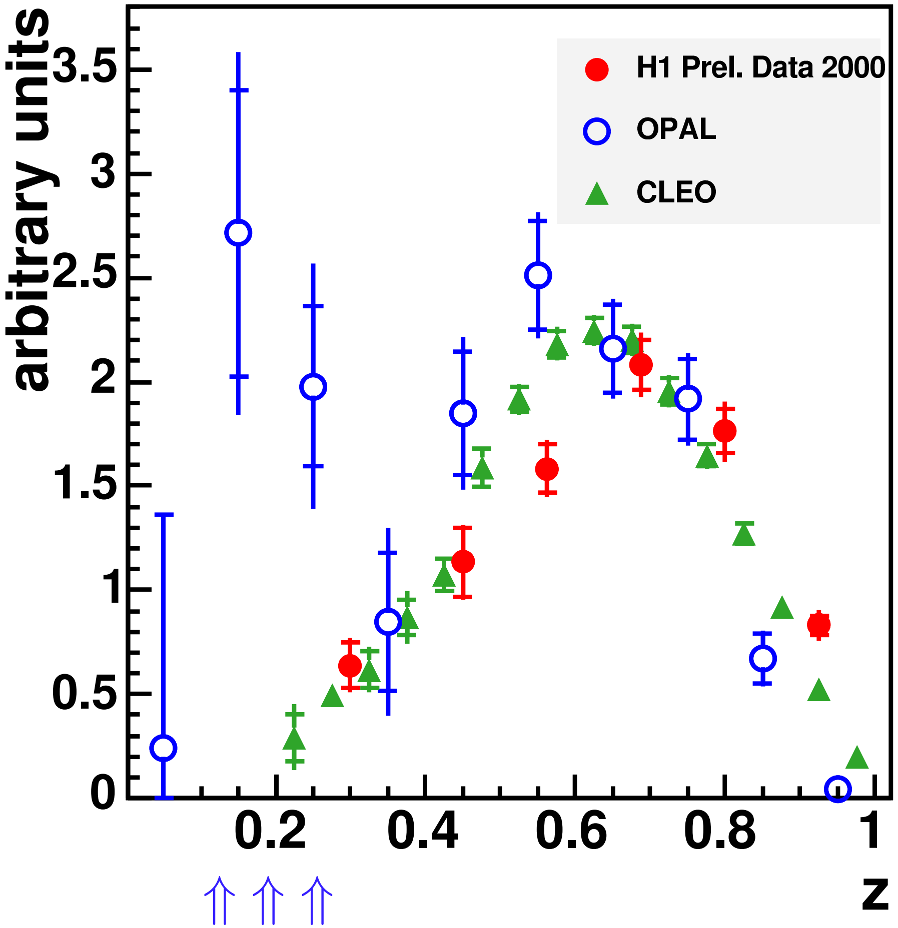
$0.014 < \epsilon < 0.036$ **(H1 prel.)**

corrected for D^{**} decays

NLO fits are expected

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





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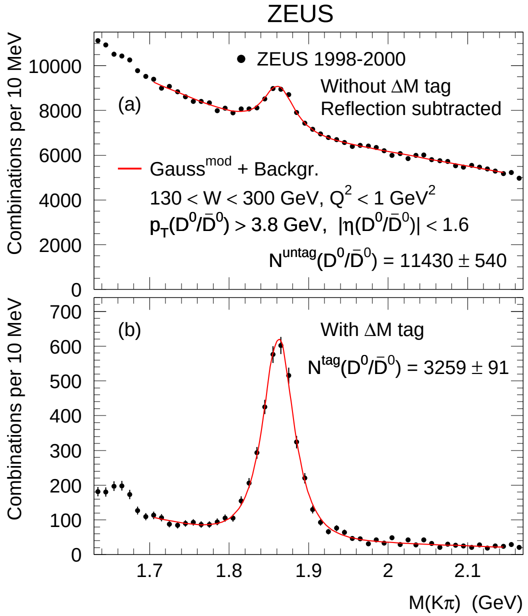
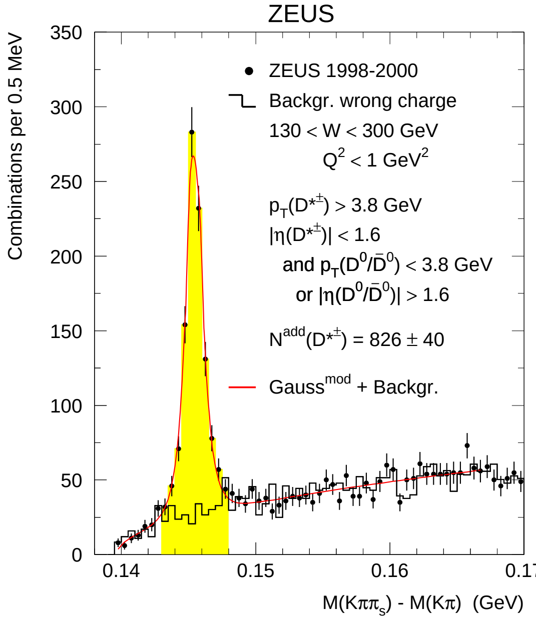
no gluon-splitting component in low-energy data

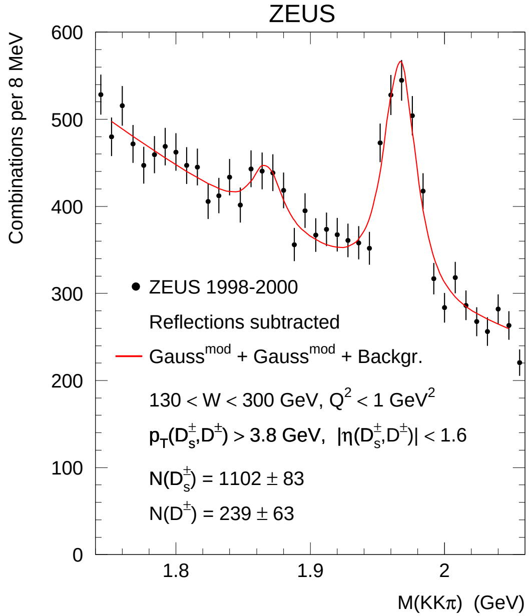
different z definitions

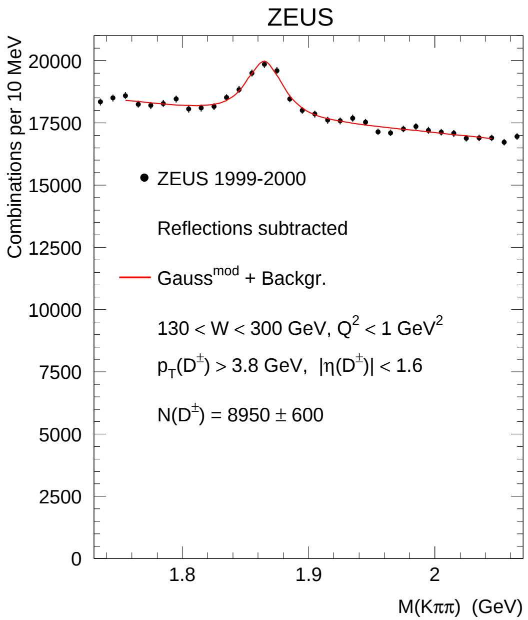
qualitative agreement

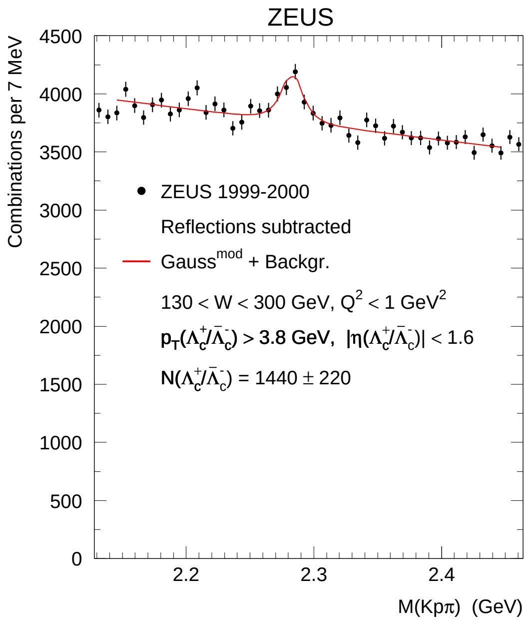
Measurement of c-fragmentation ratios and branchings $D^{*\pm}$ and c ground states: D^0, $D_s^\pm$, $D^\pm$ and $\Lambda_c^\pm$











Kinematic range of ZEUS γp analysis:

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

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

"Measured" x-sections:

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

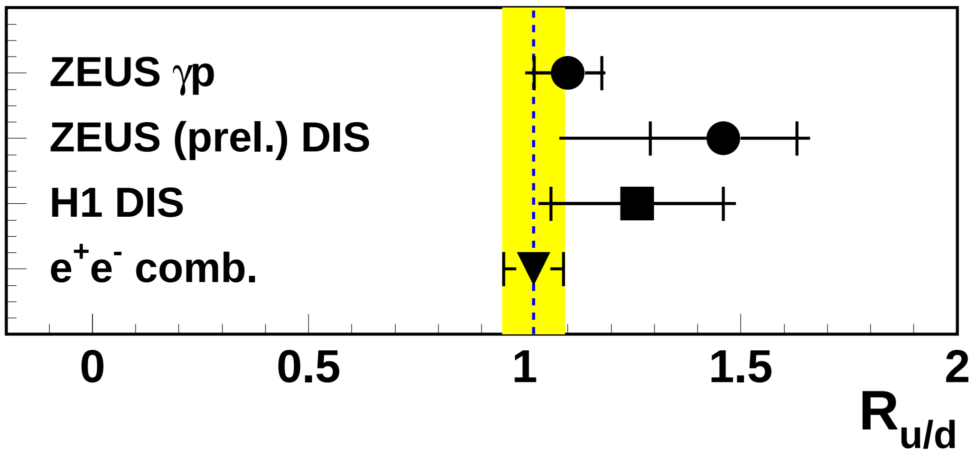
$\sigma(D_s^\pm),\ \sigma(D^\pm),\ \sigma(\Lambda_c^\pm)$

$R_{u/d}$ 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

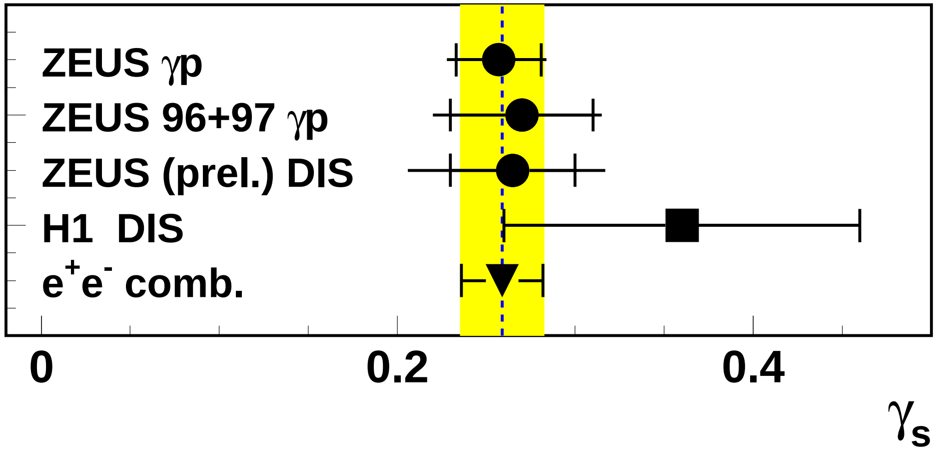
u and d quarks are produced equally in charm fragmentation

more precise measurement in DIS ?

γ_s measurement

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

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

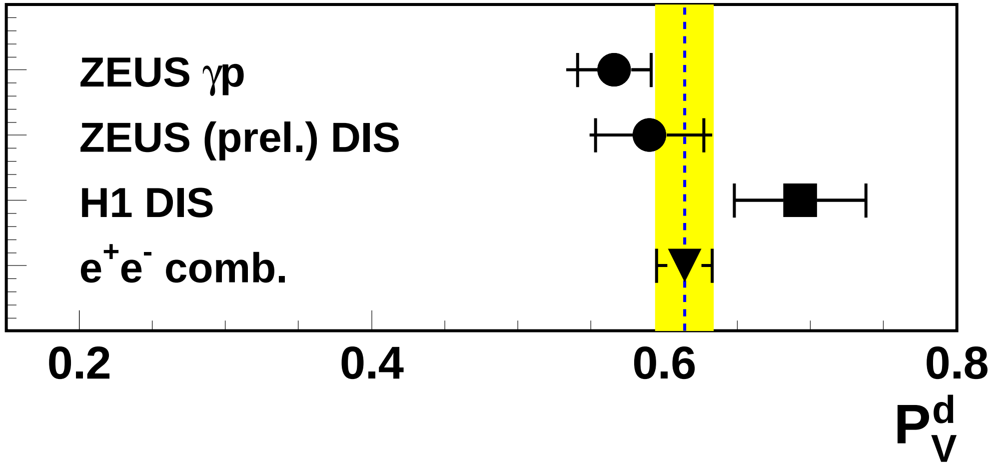
D_s production suppressed by factor ≈ 3.9 in c-fragmentation

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^-

(recent precise Belle results: $P_{\rm v}^d = 0.564$)

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

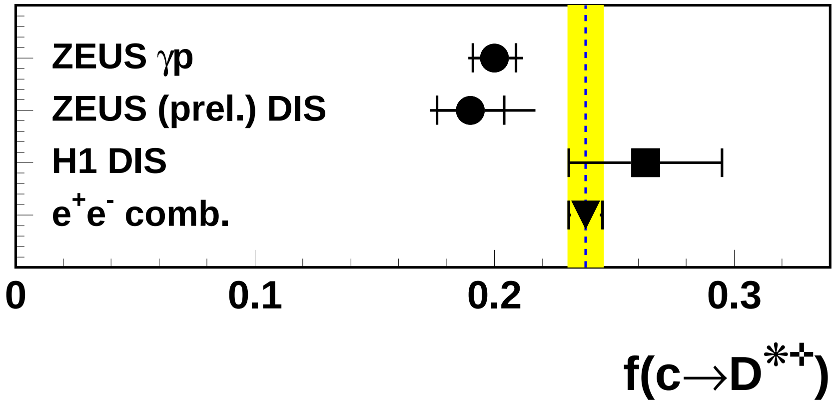
challenge for fragmentation models:

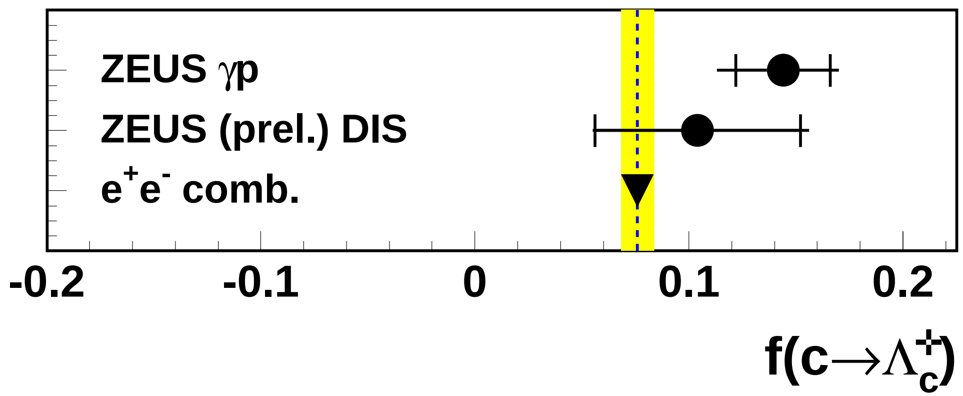
thermodynamics and string fragmentation predict $2/3$

BKL predicts ≈ 0.6 **for** e^+e^- **where only fragmentation diagrams contribute**
for ZEUS γp **kinematic range, BKL prediction is** ≈ 0.66

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

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 branchings

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

Summary

Measurements of HQ fragmentation

- **test pQCD calculations**
- **provide non-perturbative input**

LL Monte Carlo with Bowler FF is generally able to describe b/c fragmentation

fails for $x_p(D_s^+)/x_p(D^+)$ and $x_p(\Lambda_c^+)/x_p(D^+)$

**NLO/NLL pQCD calculations are compatible
with high-precision FF measurements**

sizeable difference between fits to CLEO+Belle and ALEPH data observed

measurements of b/c fragmentation ratios suggest

u **and** d **quarks are produced equally in HQ fragmentation**

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

$P_{\rm v}(b) = 0.75 \quad \Longrightarrow$ **naive spin counting works for beauty**

$P_{\rm v}(c) \neq 0.75 \quad \Longrightarrow$ **naive spin counting does not work for charm. Why ?**

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

Estimates of extrapolation factors

factors which correct the ZEUS ratios and branchings measured in the accepted $P_T(D, \Lambda_c)$ and $\eta(D, \Lambda_c)$ region to the full phase space

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

large extrapolation factors are not expected

Fragmentation branchings 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 ?