# Charm Fragmentation at HERA

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for H1 and ZEUS collaborations

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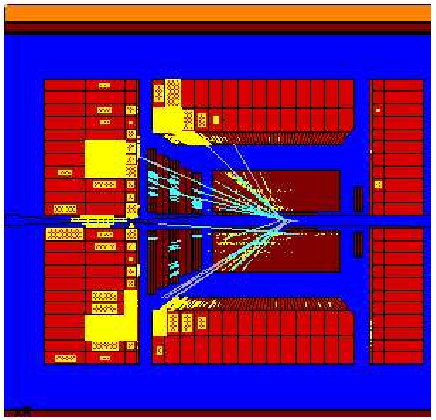
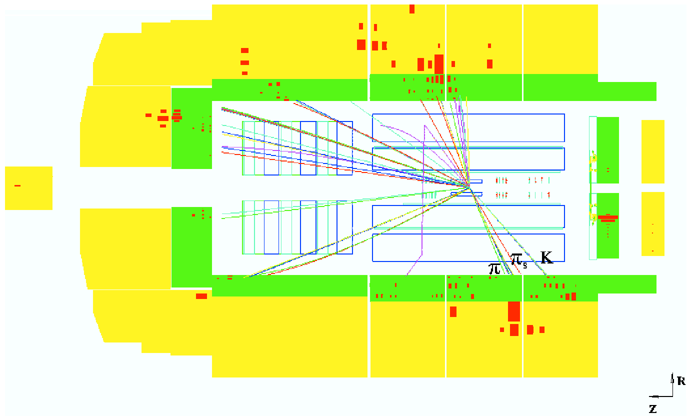




# Introduction - Hadronization of heavy quarks

Exclusive production of a charmed hadron:

$$\sigma(p) = \int dz dp_{part} \sigma(p_{part}) D_H^{part}(z) \delta(p - z p_{part})$$

- $\sigma(p_{part})$ - perturbative part (calculable) part=$q$,$\overline{q}$,$g$
- $D_H^{part}(z)$ - fragmentation function (contains nonperturbative part)

**Is $D_H^{part}(z)$ universal?**

$\longrightarrow$ what are the probabilities for quark to hadronize into various hadrons?

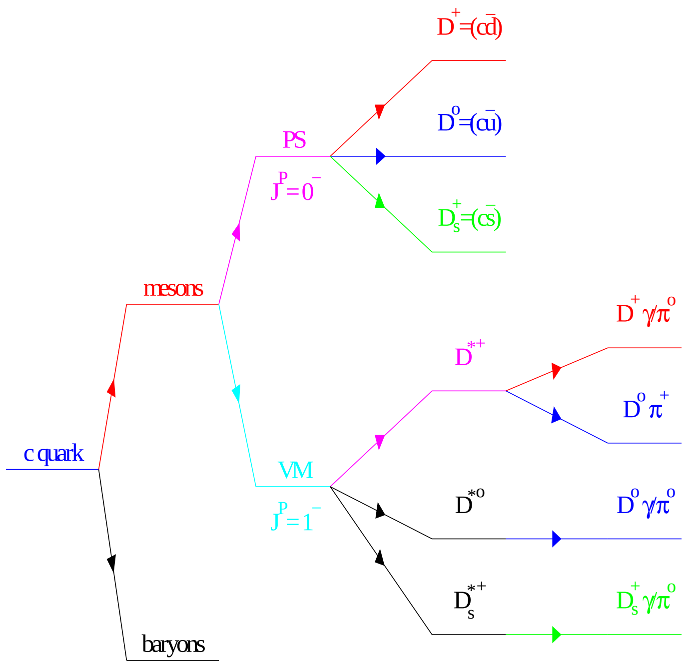
$\longrightarrow$ what part of the quark's momentum is carried by the heavy hadron?

O($10^3$) charmed events available at HERA !

# Fragmentation fractions and fragmentation ratios

**Into which hadrons does the charm quark hadronize?**

- Fragmentation fractions (total cross sections used):
  - $f(c \to \mathrm{H}) = \frac{\sigma(H)^{tot}}{\sigma(c)_{tot}}$
- Fragmentation ratios (direct cross sections used):
  - $\mathrm{R}_{u/d} = \frac{\sigma(c\bar{u})^{dir}_{S} + \sigma(c\bar{u})^{dir}_{V}}{\sigma(c\bar{d})^{dir}_{S} + \sigma(c\bar{d})^{dir}_{V}}$
  - $\mathrm{P}^{d}_{V} = \frac{\sigma(c\bar{d})^{dir}_{V}}{\sigma(c\bar{d})^{dir}_{S} + \sigma(c\bar{d})^{dir}_{V}}$
  - $\mathrm{P}^{u+d}_{V} = \frac{\sigma(c\bar{d})^{dir}_{V} + \sigma(c\bar{u})^{dir}_{V}}{\sigma(c\bar{d})^{dir}_{S} + \sigma(c\bar{d})^{dir}_{V} + \sigma(c\bar{u})^{dir}_{S} + \sigma(c\bar{u})^{dir}_{V}}$
  - $\gamma_S = 2\frac{\sigma(c\bar{s})^{dir}_{S} + \sigma(c\bar{s})^{dir}_{V}}{\sigma(c\bar{u})^{dir}_{S} + \sigma(c\bar{u})^{dir}_{V} + \sigma(c\bar{d})^{dir}_{S} + \sigma(c\bar{d})^{dir}_{V}}$

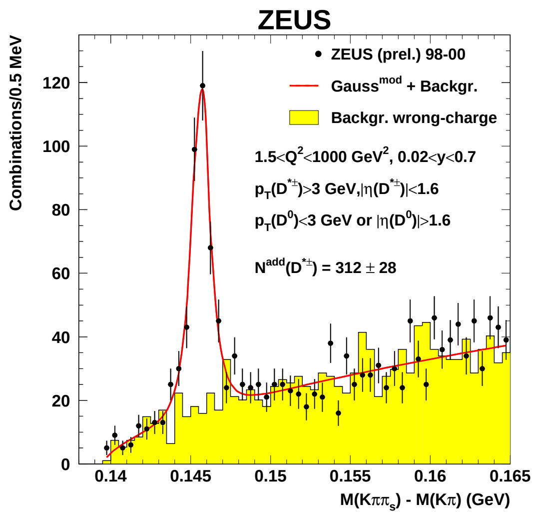


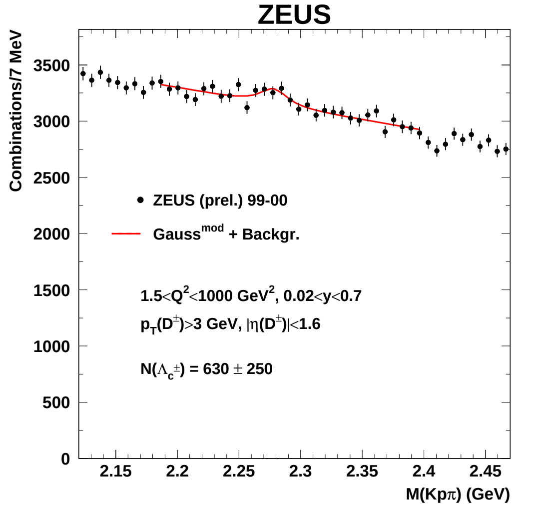
# FF and FR of $D^+$, $D^0$, $D_s^+$, $D^*$ and $\Lambda_c$ - ZEUS

Tracks from Central Tracking Detector used:

- $D^0 \rightarrow K\pi$ with $\pi_S$ from $D^*$ : $\sigma^{tag}(D^0)$
- $D^0 \rightarrow K\pi$ without $\pi_S$ from $D^*$ : $\sigma^{untag}(D^0)$
- $D^{*\pm} \rightarrow D^0\pi_S \rightarrow K\pi\pi_s$ without vis. $D^0$: $\sigma^{add}(D^{*\pm})$
- $D^\pm \rightarrow K\pi\pi$: $\sigma(D^\pm)$
- $D_S^\pm \rightarrow \phi\pi \rightarrow KK\pi$: $\sigma(D_S^\pm)$
- $\Lambda_c^\pm \rightarrow Kp\pi$: $\sigma(\Lambda_c^\pm)$

reflections subtracted, then signal + background shape fitted to invariant mass distribution



# FF and FR: visible range and procedure - ZEUS

**DIS**

$1.5 < \mathrm{Q}^2 < 1000\ \mathrm{GeV}^2$

$0.02 < \mathrm{y} < 0.7$

$\mathrm{p_T}(\mathrm{D}, \Lambda) > 3\ \mathrm{GeV}$

$|\eta(\mathrm{D}, \Lambda)| < 1.6$

$\mathrm{L} = 82\ \mathrm{pb}^{-1}$

**photoproduction**

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

$130 < \mathrm{W} < 300\ \mathrm{GeV}$

$\mathrm{p_T}(\mathrm{D}, \Lambda) > 3.8\mathrm{GeV}$

$|\eta(\mathrm{D}, \Lambda)| < 1.6$

$\mathrm{L} = 79\ \mathrm{pb}^{-1}$

- Visible charm cross section used for determination of fragmentation fractions:

$$\sigma_{\mathrm{c}} = \sigma(D^+) + \sigma^{untag}(D^0) + \sigma^{tag}(D^0) + \sigma^{add}(D^{*+})(1 + R_{u/d}) + \sigma(D_S^+) + \sigma(\Lambda_c^+) \times 1.14$$

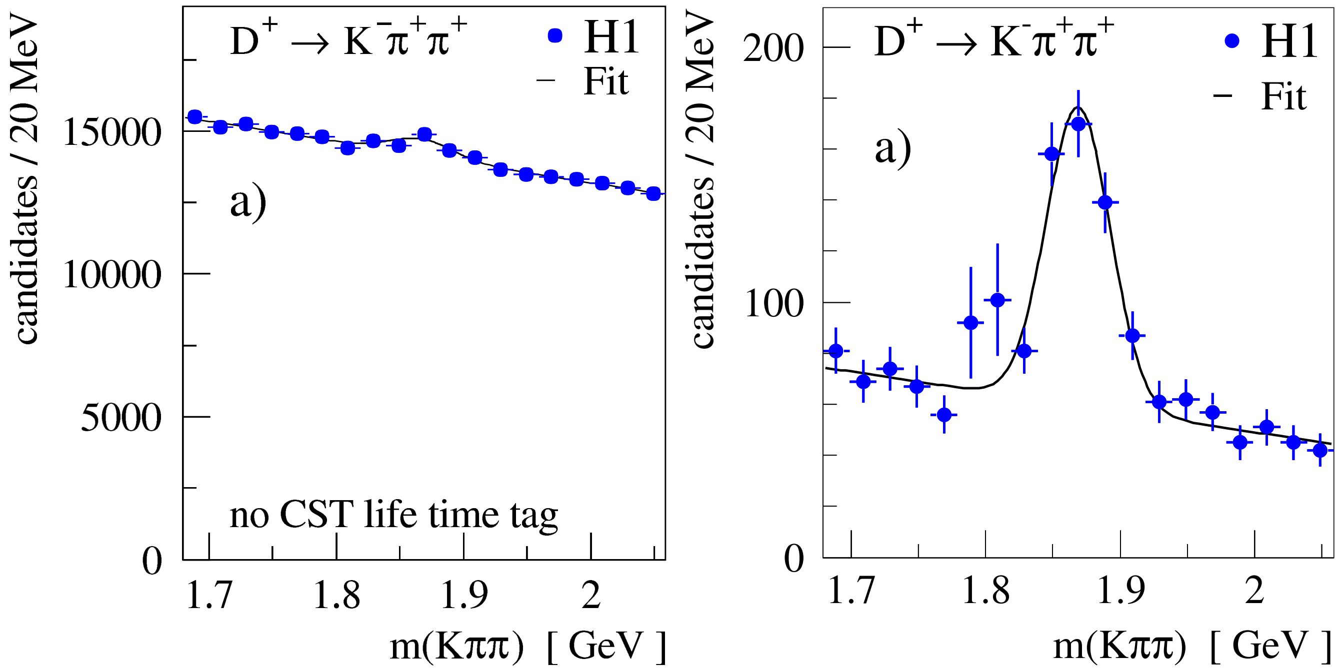
(use world average ratios for $\Xi/\Lambda$ and $\Omega/\Lambda$, this gives factor $1.14$)

- Fragmentation ratios calculated from visible cross sections of measured charmed hadrons!

# FF and FR of $D^+$, $D^0$, $D_s^+$, $D^*$ - H1

▷ Charm tagging: reconstruction of secondary vertex with the central silicon tracker

▷ signal to background ratio can be improved significantly by a cut on the decay length significance ($S_l = l/\sigma_l$)



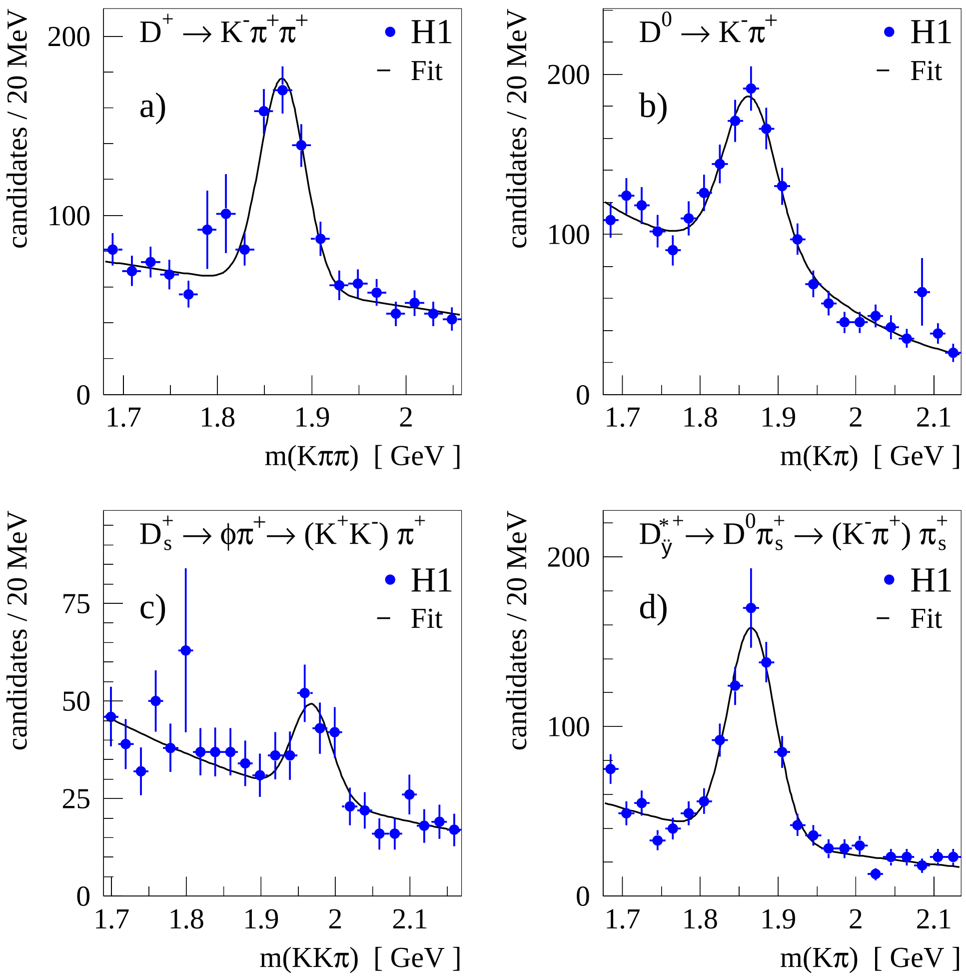
# D Meson Signals - H1

- **Kinematic region:**
  $2 < Q^2 < 100$ GeV$^2$
  $0.05 < y < 0.7$
  $p_t(D) > 2.5$ GeV
  $|\eta(D)| < 1.5$
  $\mathrm{L} = 47\ \mathrm{pb}^{-1}$

- Invariant mass spectra fitted:
  Gaussian + background

- Visible cross-sections were determined

[Eur.Phys.J.C38:447-459,2005]



# Determination of FF and FR - H1

- Leading Order + Parton Shower MC used (AROMA $2.2$):
  - $\longrightarrow$ to extrapolate to full phase space
  - $\longrightarrow$ to predict total cross section for charm production
- fragmentation fractions are calculated from extrapolated (predicted) cross sections
- fragmentation ratios are calculated from fragmentation fractions

Both experiments: assume $\sigma(D^{*+}) = \sigma(D^{*0})$, $\sigma(D^{*+}) = \sigma(D^{*-})$, $\sigma(D^{+}) = \sigma(D^{-})$

# Results: $\mathrm{R}_{u/d}$ and $\gamma_S$

H1:

$$\mathrm{R}_{u/d} = \frac{f(c\to D^0) - f(c\to D^{*+})BR(D^{*+}\to D^0\pi)}{f(c\to D^+) + f(c\to D^{*+})BR(D^{*+}\to D^0\pi)}$$

ZEUS:

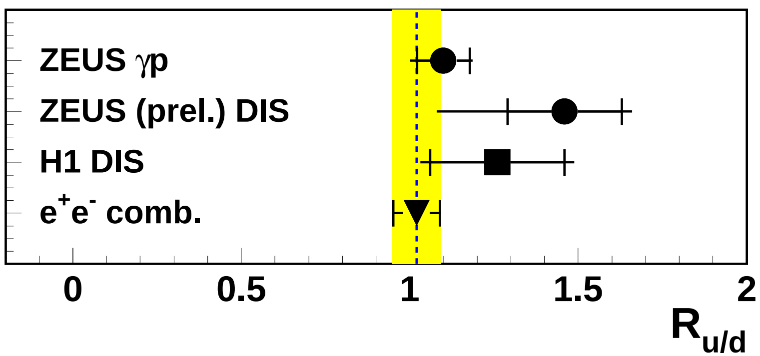
$$\mathrm{R}_{u/d} = \frac{\sigma^{untag}(D^0)}{\sigma(D^{\pm}) + \sigma^{tag}(D^0)}$$

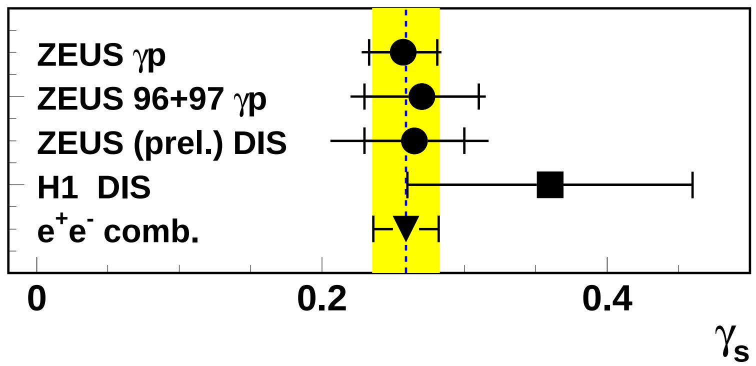
H1:

$$\gamma_{u/d} = \frac{2f(c\to D_S^+)}{f(c\to D^+) + f(c\to D^0)}$$

ZEUS:

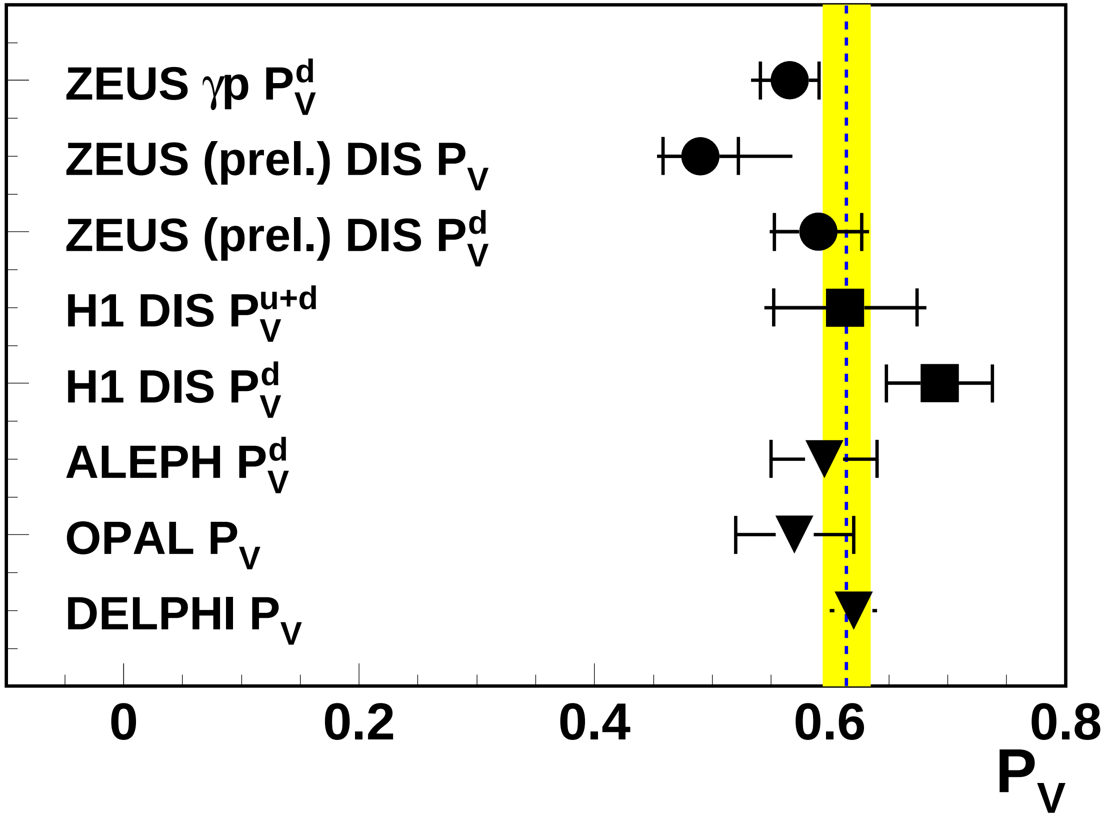
$$\gamma_{u/d} = \frac{2\sigma(D_S^{\pm})}{\sigma(D^{\pm}) + \sigma^{tag}(D^0) + \sigma^{untag}(D^0) + 2\sigma^{add}(D^{*\pm})}$$




In agreement with each other, expectation and world average.

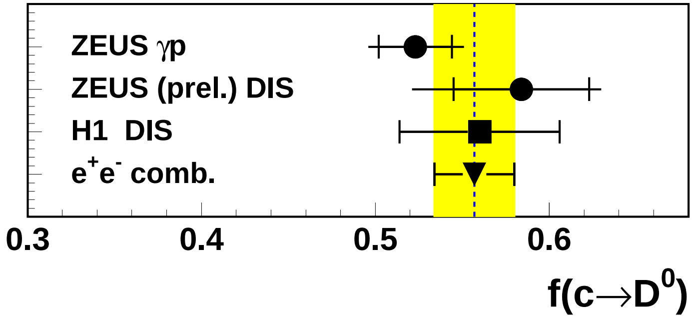
# Results: $P_V$ and $P_V^d$

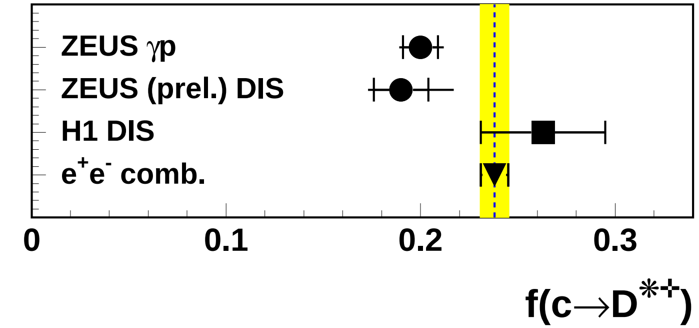


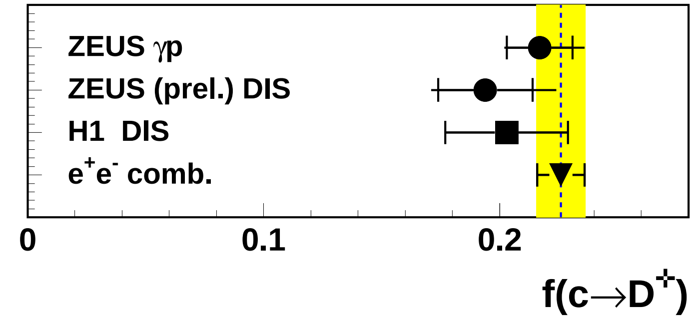

→ Naive spin counting does not work ($P_V \neq 3/4$)

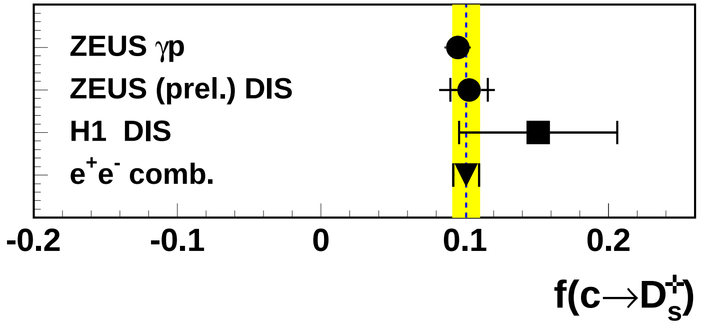
→ In agreement with world average

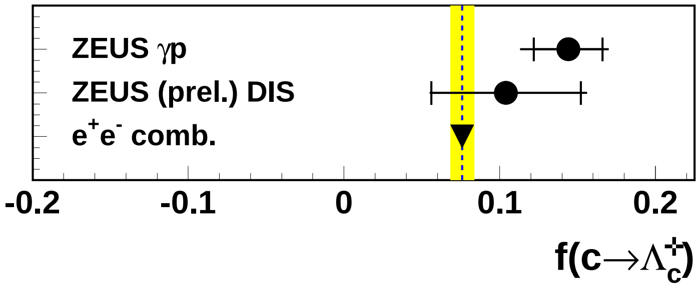
# Results: Fragmentation fractions




All fragmentation fractions are in agreement with world average and support assumption of universality

# Structure of Charm jets in DIS - H1

$$\sigma(p) = \int dz dp_{part} \sigma(p_{part}) D_H^{part}(z) \delta(p - z p_{part})$$

⇒ arbitrary division between $\sigma(p_{part})$ and $D_H^{part}(z)$

⇒ usually evolution down to $m_c$ put in $\sigma(p_{part})$ , understood?

⇒ structure of charm jets studied

! gluon emmision off heavy quark influenced by $m_c$

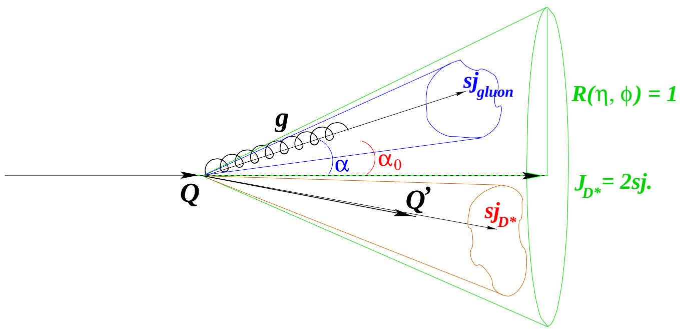
! QCD predicts for small $\alpha$:

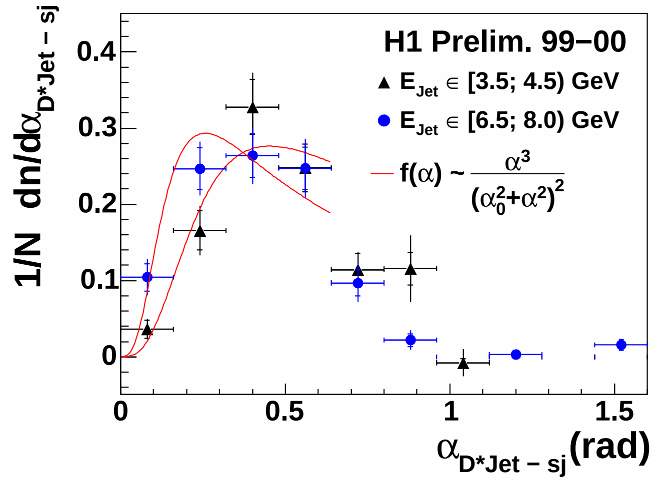
$$\frac{d^2\sigma_{Q \to Q+g}}{d\alpha} \approx K \frac{\alpha^3}{(\alpha^2 + \alpha_0^2)^2},$$
$$\alpha_0 = M_Q / E_Q$$

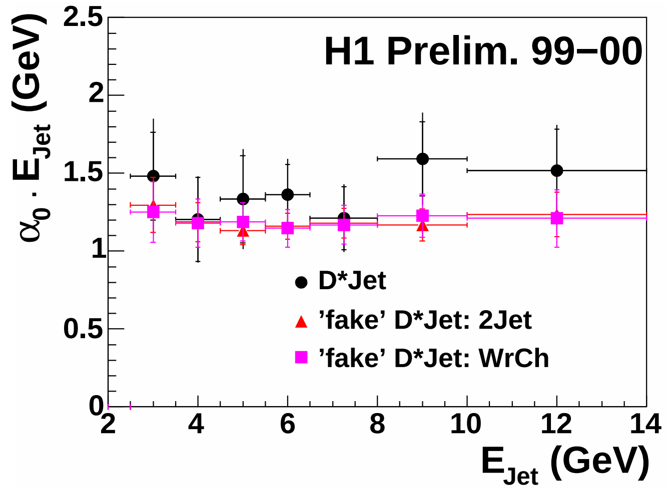
! $\alpha < \alpha_0$ - dead cone

- Charm events tagged by $D^*$ in the DIS region:
  - $2 < Q^2 < 100$ GeV$^2$
  - $0.05 < y_e < 0.7$
  - $p_t(D^*) > 1.5$ GeV
  - $|\eta(D^*)| < 1.5$
- Jets found using $k_T$ in lab:
  - $p_{t\ jet} > 1.5$ GeV
  - $|\eta_{jet}| < 1.5$

# Structure of Charm jets II.




- jet algorithm rerun till exactly two subjets are found
- study angle $\alpha$ between the charm jet axis and non-charm subjet

▷ distribution in agreement with pQCD formula, fit with $\alpha_0$ as a free parameter

▷ from pQCD formula expect $\alpha_0 E_{jet}$ independent of jet energy

Data consistent with pQCD prediction, difference to light jets statistically not significant

# Study of Fragmentation Function - H1

Fragmentation function describes the energy transfer from quark to a given meson.

## *$e^+e^-$ collisions*

- ▷ natural choice $$z = \frac{E_{D^*}}{\sqrt{s}/2} = \frac{E_{D^*}}{E_{beam}}$$
- ▷ assuming LO processes - direct measurement of non perturbative fragmentation function

## *ep collisions*

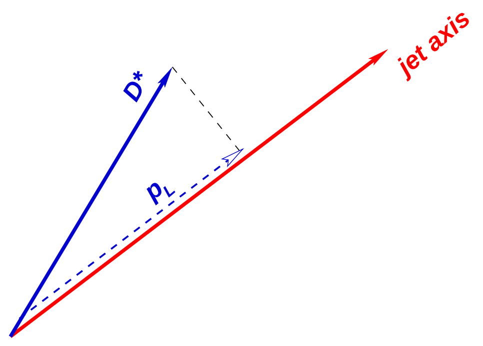
- ▷ choice of z observable not so obvious
- ▷ differences: IPS contribution,
  different kinematics

# The Experimental Methods

## *Jet Method* :

▷ the energy of $c$-quark is approximated by the energy of the reconstructed $D^*$ jet

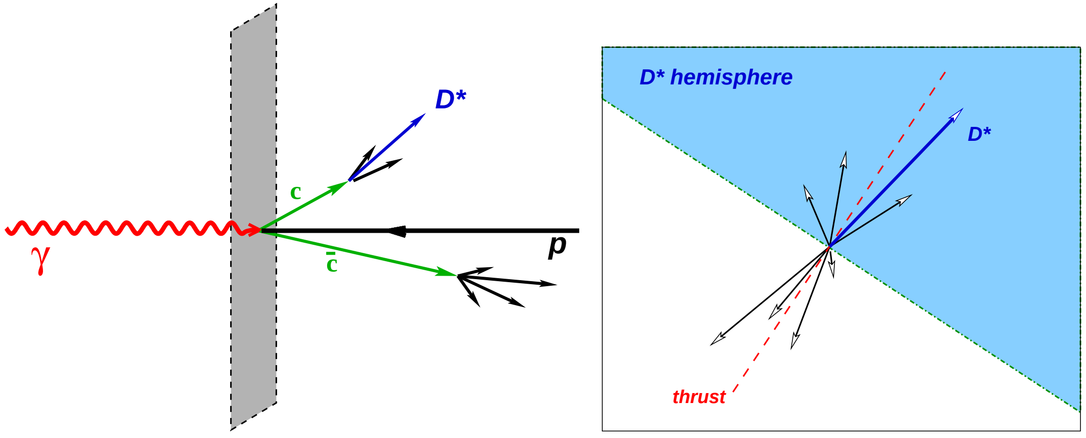
$$z_{\rm jet} = \frac{(E+p_L)_{D^*}}{(E+p)_{\rm jet}}$$




## *Hemisphere Method* :

▷ in $\gamma p$-frame the $c\bar{c}$ pair is balanced in $p_t$ $\Longrightarrow$ possibility to divide event into two hemispheres

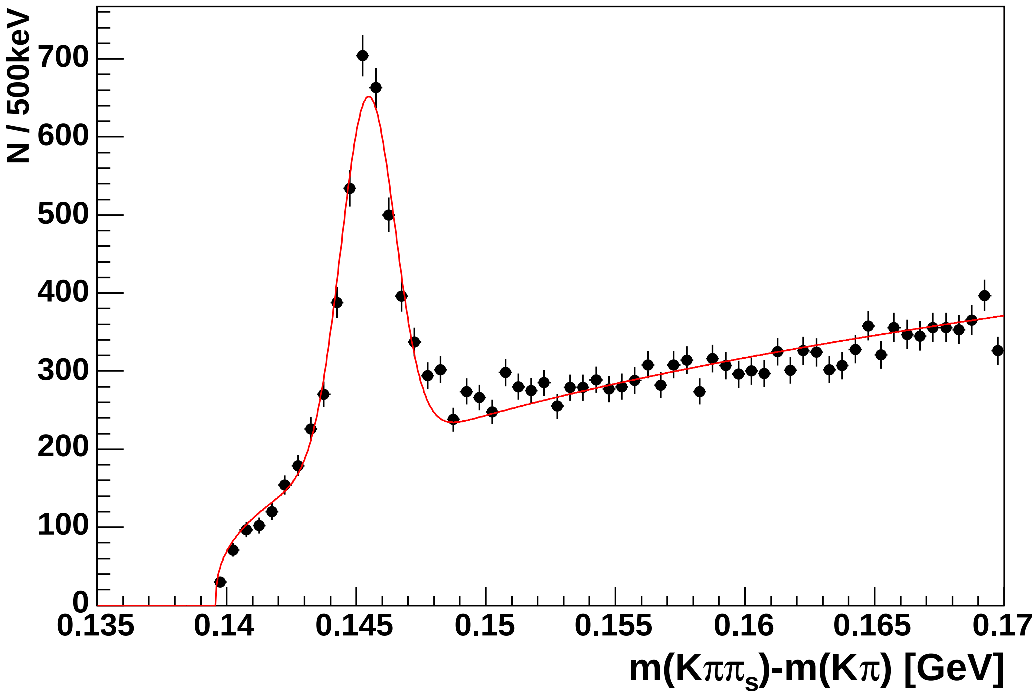
$$z_{\rm hem} = \frac{(E+p_L)_{D^*}}{\sum_{\rm hem}(E+p)}$$



# $D^*$ Tagging

**Golden channel:**

$$D^{*\mp} \rightarrow D^0\pi_s^{\mp} \rightarrow K^{\pm}\pi^{\mp}\pi_s^{\mp}$$




## Kinematic cuts:

$2 < Q^2 < 100$ GeV$^2$

$0.05 < y_e < 0.7$

$p_t(D^*) > 1.5$ GeV

$|\eta(D^*)| < 1.5$

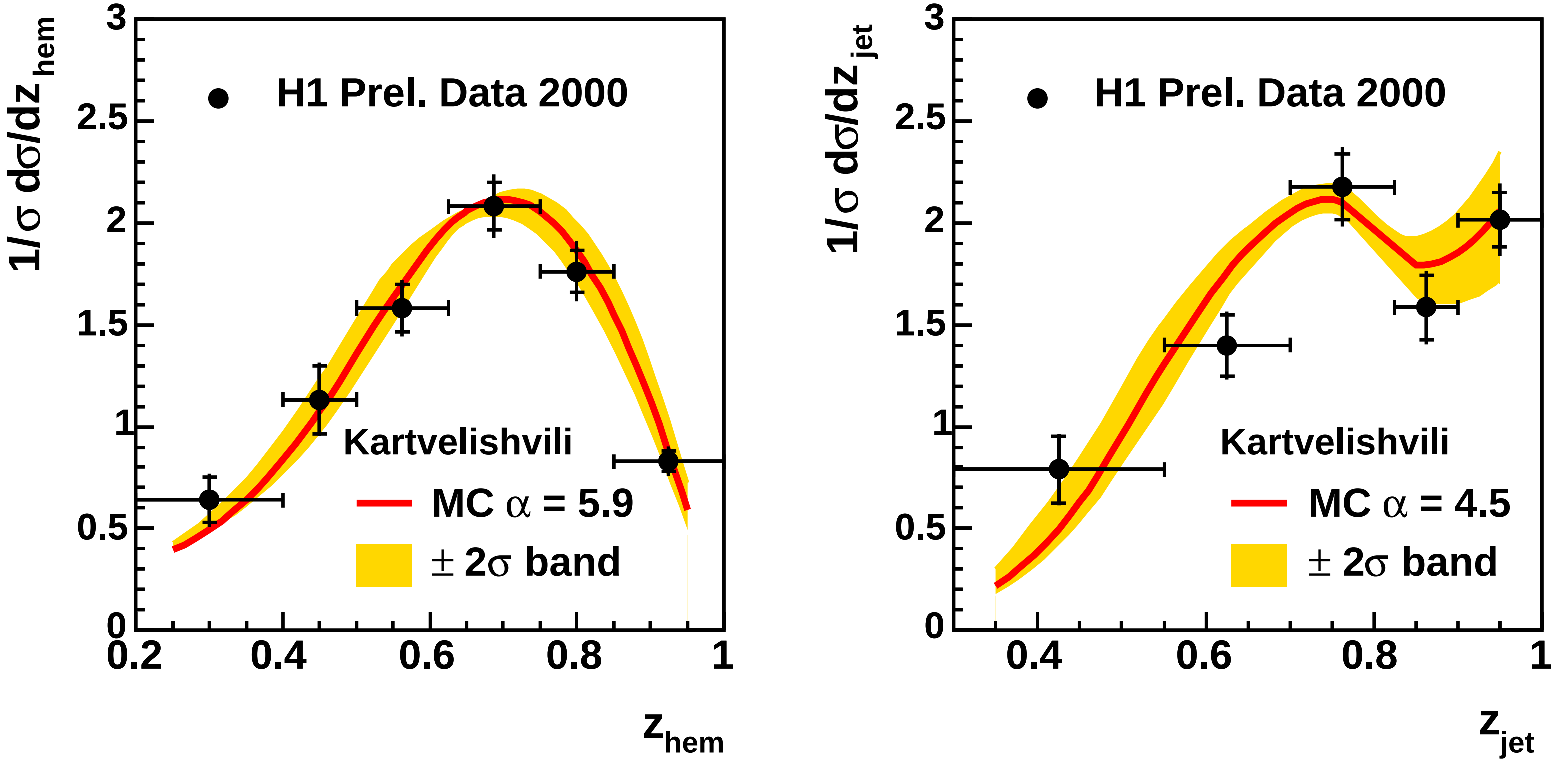
## Jet method:

▷ $D^*$ treated as stable meson

▷ massive $k_t$-cluster jet algorithm applied in $\gamma p$ frame

# Measured z-distributions with Kartvelishvili parametrization

*RAPGAP/PYTHIA+Kartvelishvili :* $f(z) \sim z^{\alpha}(1-z)$




Visible Range: (In addition to cuts on previous page.)

$\eta_{\mathrm{part},\gamma p} > 0.$ $\qquad$ $p_t(D^*\mathrm{jet}) > 3$ GeV

$z > 0.2$ $\qquad$ $z > 0.3$

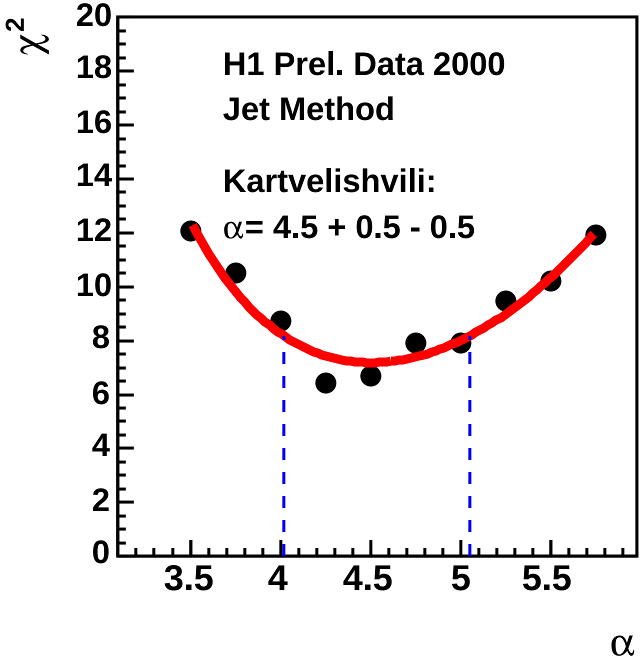
# Extraction of Fragmentation Parameter

▷ Fragmentation parameters extracted for RAPGAP 3.1 MC (direct +resolved)/ PYTHIA 6.2 with excited D-states (ALEPH tune)

▷ for fragmentation used: $a.)$ Peterson parametrization
$b.)$ Kartvelishvili parametrization

**Extraction procedure:**

▷ MC-files generated for various frag. parameters: best parameter value obtained (correlated systematic errors taken into account) using $\chi^2$



# Summary of the Fragmentation Function Results

▷ Kartvelishvili and Peterson parametrizations provide equally good descriptions of the data

▷ hemisphere method appears to give harder fragmentation function than the jet method

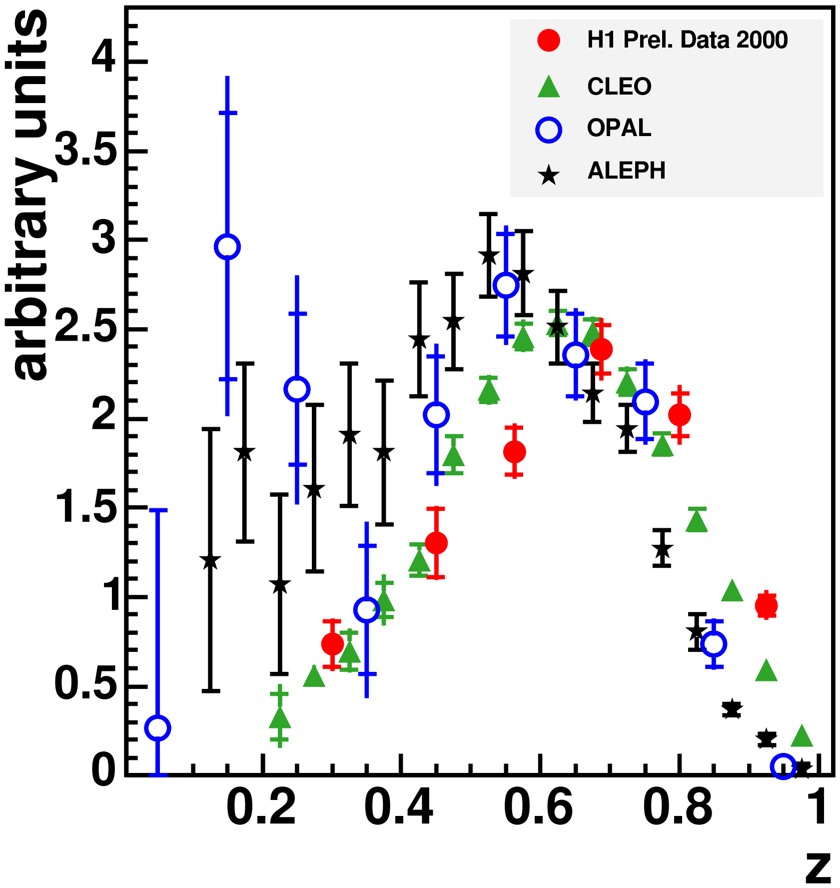
H1 Prel. Data 2000 + RAPGAP/PYTHIA

| parametrization | | Hemisphere method | Jet method |
|---|---|---|---|
| Peterson | $\varepsilon$ | $0.018^{+0.004}_{-0.004}$ | $0.030^{+0.006}_{-0.005}$ |
| Kartvelishvili | $\alpha$ | $5.9^{+0.7}_{-0.6}$ | $4.5^{+0.5}_{-0.5}$ |

▷ difference ($< 3\sigma$) between hemisphere and jet method result may indicate imperfect MC description of hadronic final state in charm events

$\Rightarrow$ $0.014 < \epsilon < 0.036$ $4.0 < \alpha < 6.8$

# Comparison with $e^+e^-$ Experiments




**H1** hemisphere method
$\langle\sqrt{\hat{s}}\rangle \approx 10$ GeV,
$z = \frac{(E+p_L)_{D^*}}{\sum_{hem}(E+p)}$

**CLEO** $\sqrt{s} \approx 10$ GeV,
$z = p_{D^*}/p_{max}$

**OPAL** $\sqrt{s} = 91.2$ GeV,
$z = 2E_{D^*}/\sqrt{s}$

**ALEPH** $\sqrt{s} = 91.2$ GeV,
$z = 2E_{D^*}/\sqrt{s}$

▷ although different observable definitions, spectra similar in shape

# Conclusions

- Inclusive cross sections of $D^+$, $D^0$, $D_s^+$, $D^*$ and $\Lambda_c$ were measured in DIS and photoproduction
- Extracted fragmentation ratios and fractions support assumption of universality
- Structure of charm jets in DIS is well described by pQCD and LO+PS MC
- Fragmentation function of charm to $D^*$ was measured in DIS, allows comparison with $e^+e^-$