Study of Charm Fragmentation at H1

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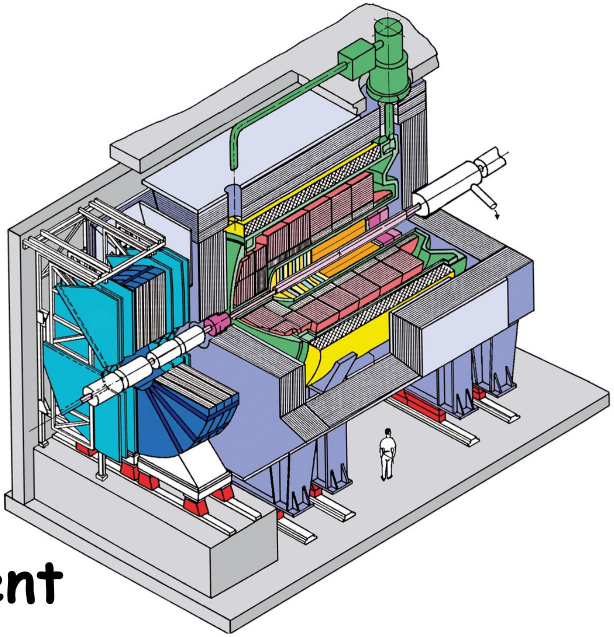


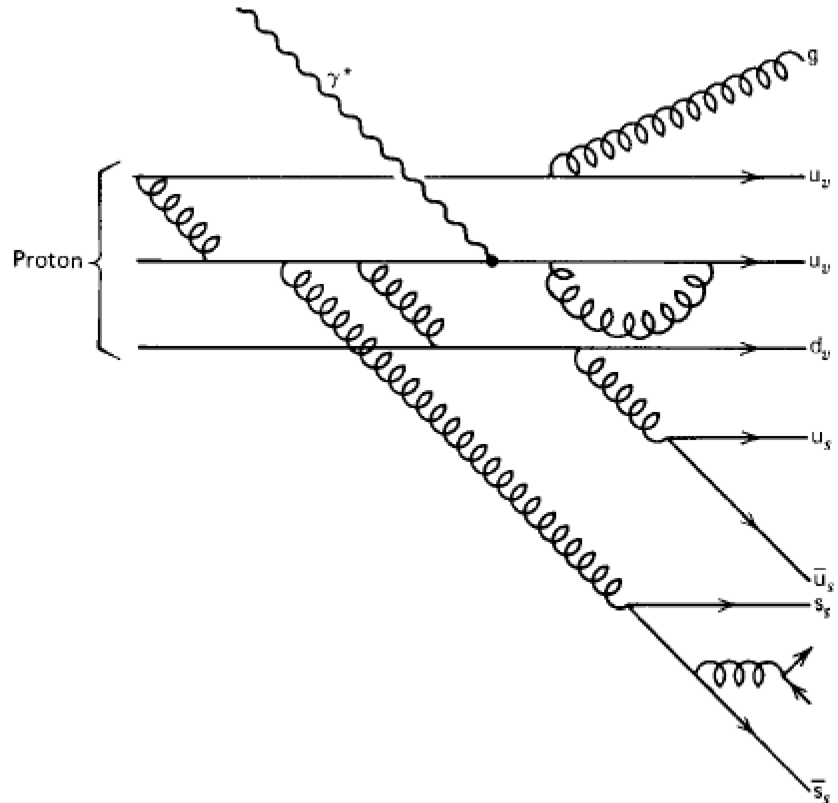
- Introduction
- Observable definitions & measurement
- Extraction of fragmentation parameters

Introduction I.

$$L_{\mathrm{QCD}} = -\frac{1}{4} F^{(a)}_{\mu\nu} F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q \gamma^\mu (D_\mu)_{ij} \psi^j_q - \sum_q m_q \overline{\psi}^i_q \psi_{qi} ,$$

$$F^{(a)}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu ,$$

$$(D_\mu)_{ij} = \delta_{ij} \partial_\mu + i g_s \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu ,$$



QCD: language problem

- It speaks about partons
- We see hadrons all around

Introduction II.

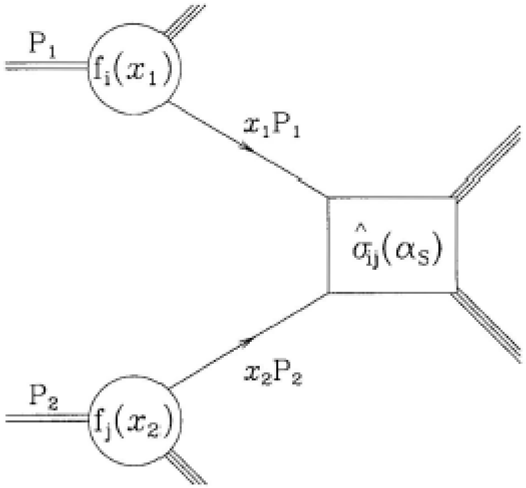
- **Our picture of particle production at high energies:**

$$\sigma_H = \sum_i \sum_k f_{i/p}(x, \mu_{\rm f}) \otimes \hat{\sigma}_{i\gamma \to kX}(\alpha_{\rm s}(\mu_{\rm r}), \mu_{\rm r}, \mu_{\rm f}) \otimes D_k^H(z, \mu_{\rm f})$$

Parton Density Function — **Hard Scattering (perturbative)** — **Fragmentation Function**

Three ingredients needed to describe high energy hadronic collision:

- parton density functions (from experiment)
- matrix element (calculable in pQCD)
- fragmentation functions (from experiment)

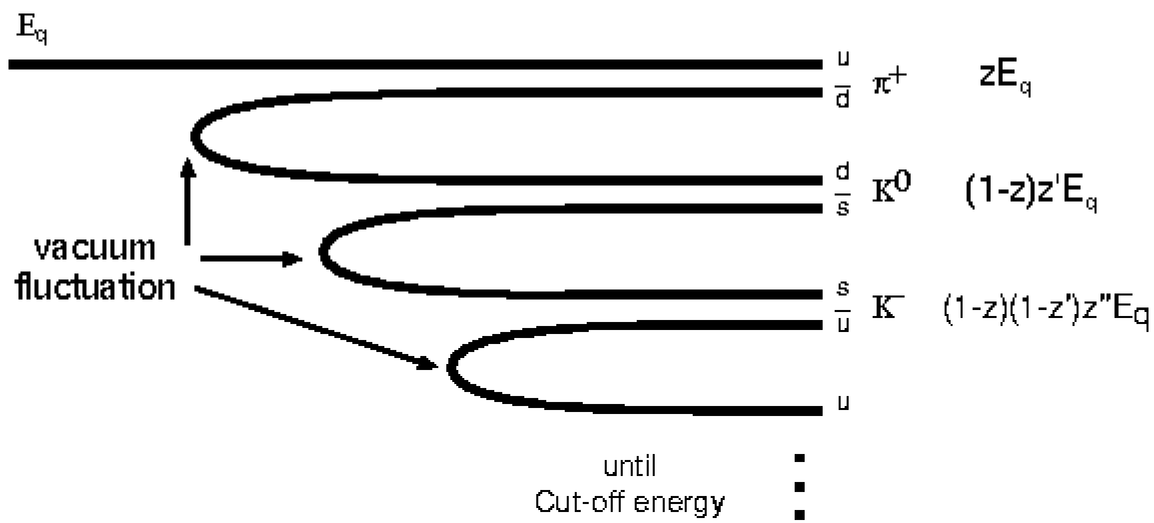


How to describe fragmentation 1.

Independent fragmentation:

Model of Feynman and Field:

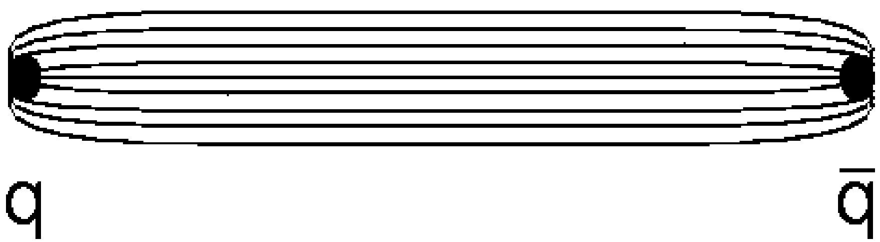
- each quark fragments independently
- there are many quark-antiquark pairs in the vacuum
- quark picks antiquark from vacuum, forming a hadron
- whole process continues until cut-off energy
- fraction of original quark energy carried by hadron is described by an arbitrary function, tuned to data



How to describe fragmentation 2.

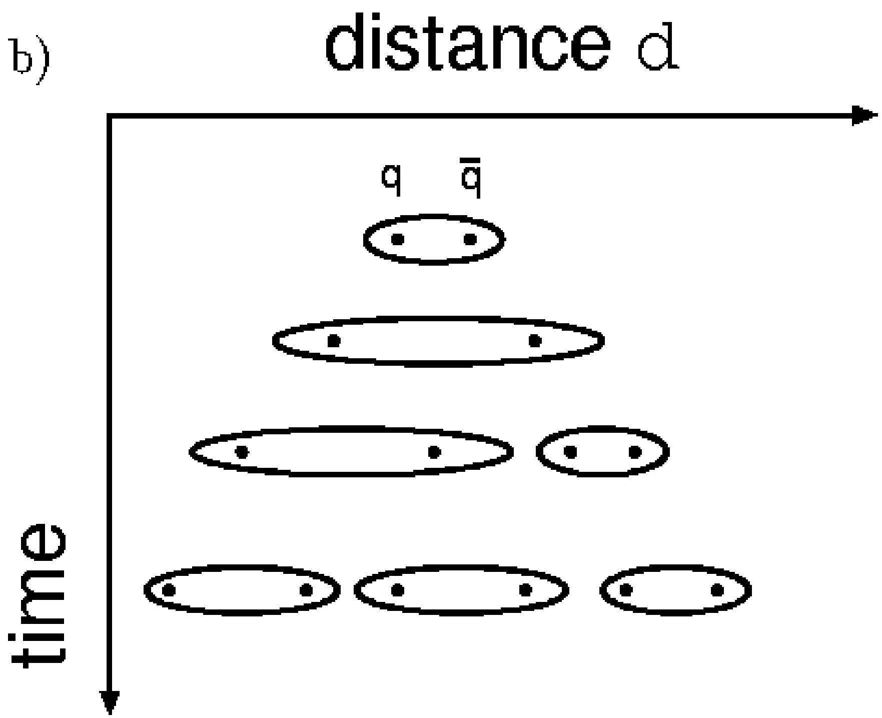
Lund string model:

a)



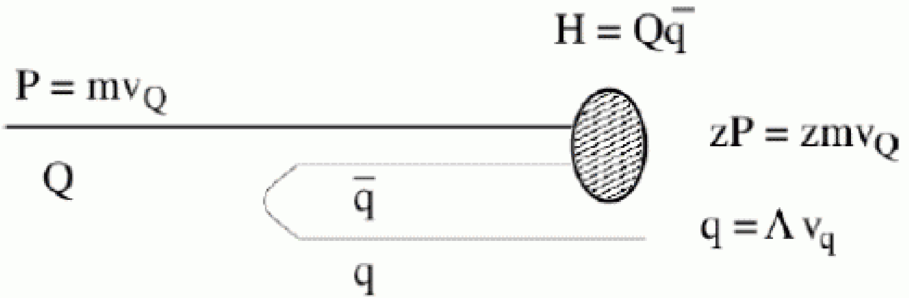
- Strong colour field between quark and antiquark forms a string
- at some point the string breaks
- small string pieces form hadrons
- the function describing string breaking tuned to data

b)



Fragmentation functions for light and heavy quarks 1

Fragmentation of heavy quarks should be different compared to light quarks (Bjorken, Suzuki, ~1977):



The heavy quark has momentum $P = mv_Q$, the light quarks have momentum $q = \Lambda v_q$, with Λ a hadronic mass scale

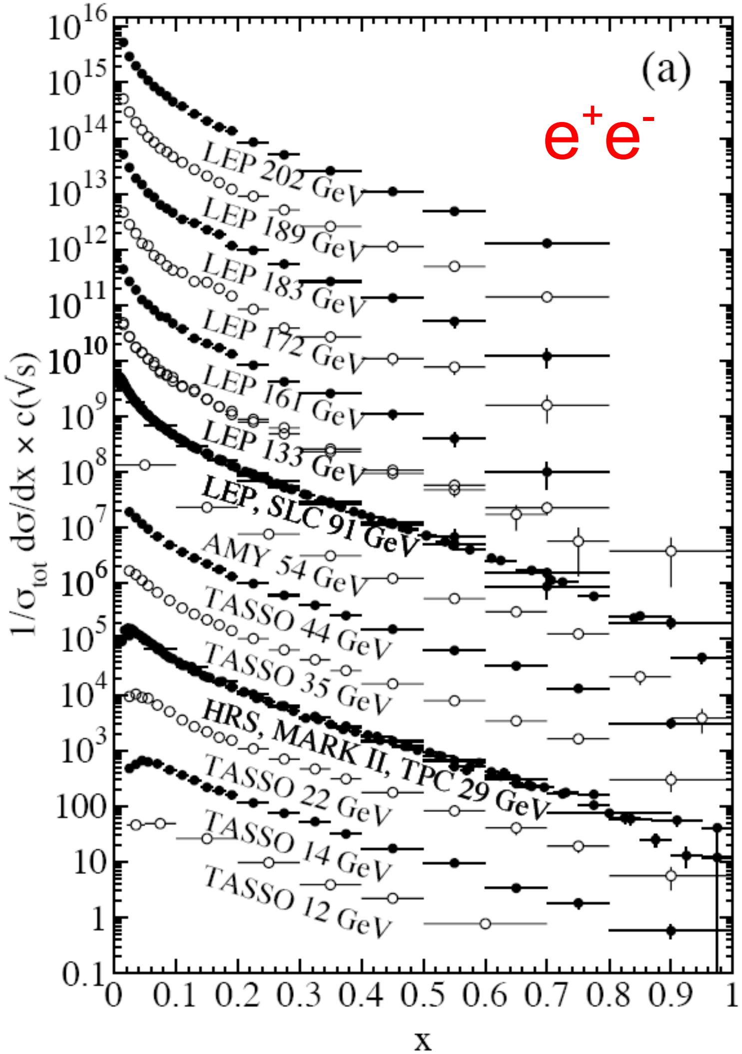
For the binding we need $v_Q \simeq v_q = v$. We have then

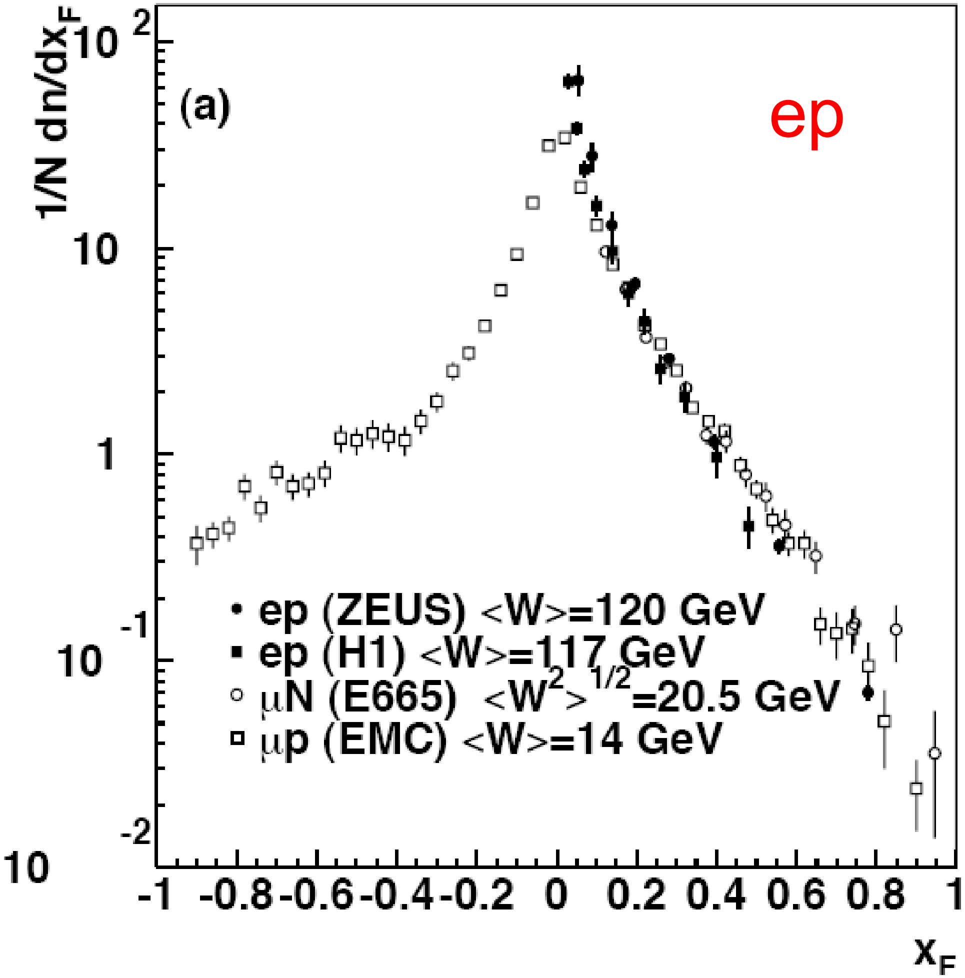
$$P = zP + q \qquad mv = zmv + \Lambda v$$

and therefore

$$\langle z \rangle \simeq 1 - \frac{\Lambda}{m}$$

Fragmentation functions for light and heavy quarks 2

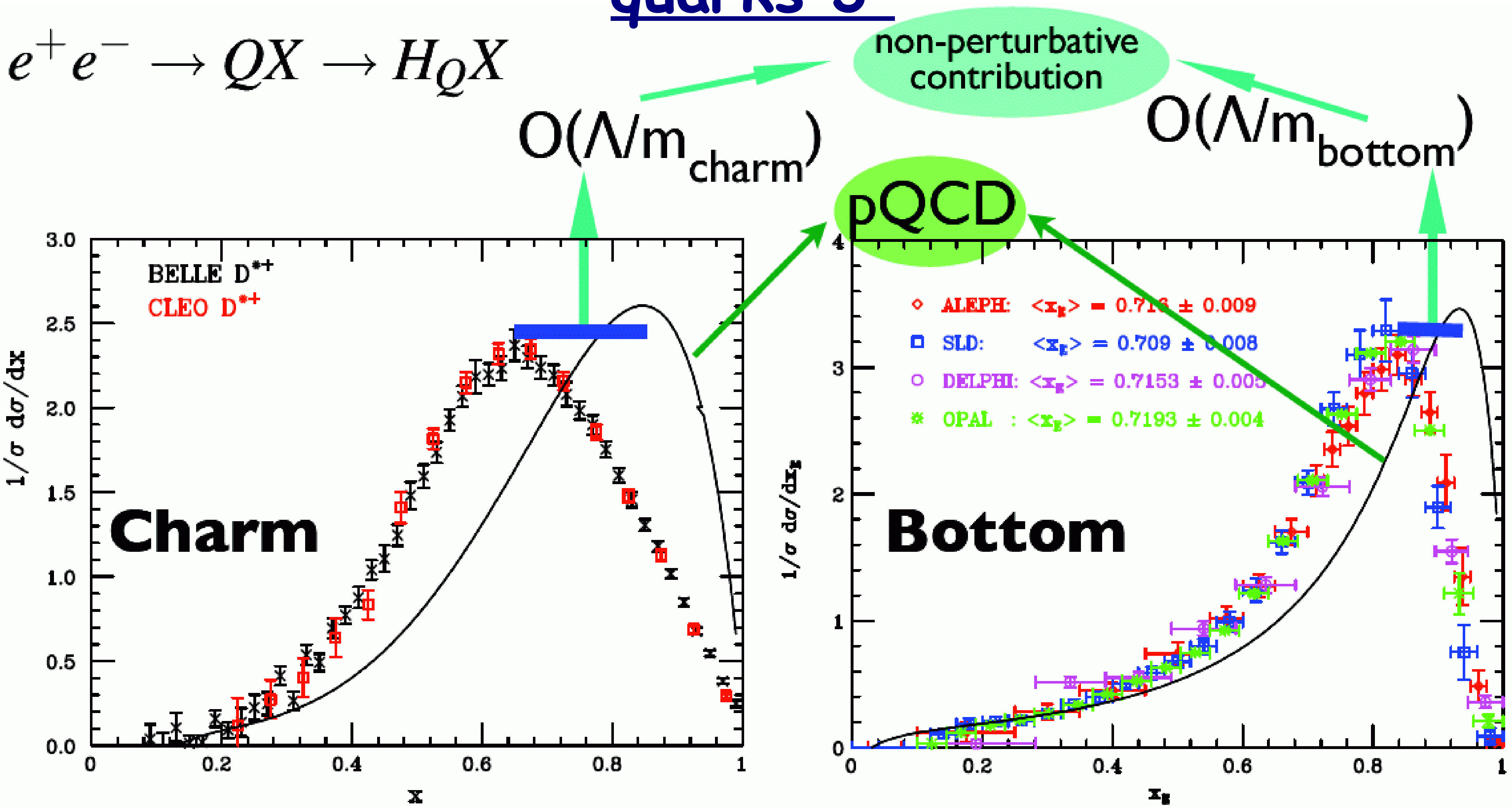




Most of light hadrons carry a small fraction of original parton momentum ...

Fragmentation functions for light and heavy quarks 3

$$e^+e^- \to QX \to H_Q X$$



Spectrum of heavy hadrons is rather hard ...

Fragmentation functions for light and heavy quarks 4

Peterson et al.: $D_{\mathrm{Q}}^{\mathrm{H}}(z) \propto \frac{1}{z[1-(1/z)-\varepsilon/(1-z)]^2}$

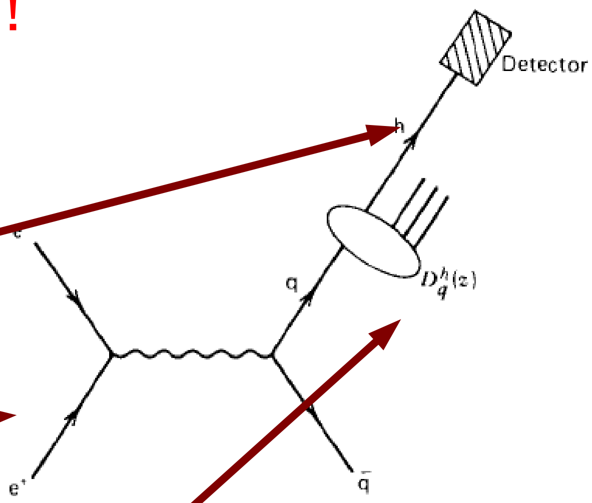
Kartvelishvili et al.: $D_{\mathrm{Q}}^{\mathrm{H}}(z) \propto z^{\alpha}(1-z)$

All models use fragmentation functions tuned to e+e- data!

$\Rightarrow$ **interesting to check, how well this approach works in ep**

Fragmentation - a bit of terminology

Terminology in the field is very confusing!

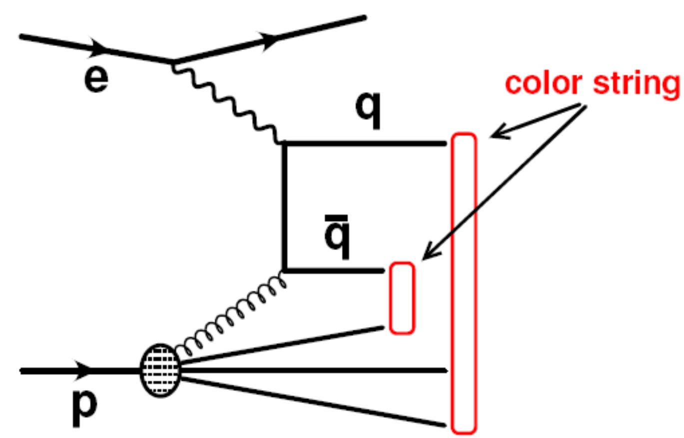


In e^+e^- two things are called 'fragmentation function':

1. differential cross section of heavy hadron as a function of the scaling variable z:

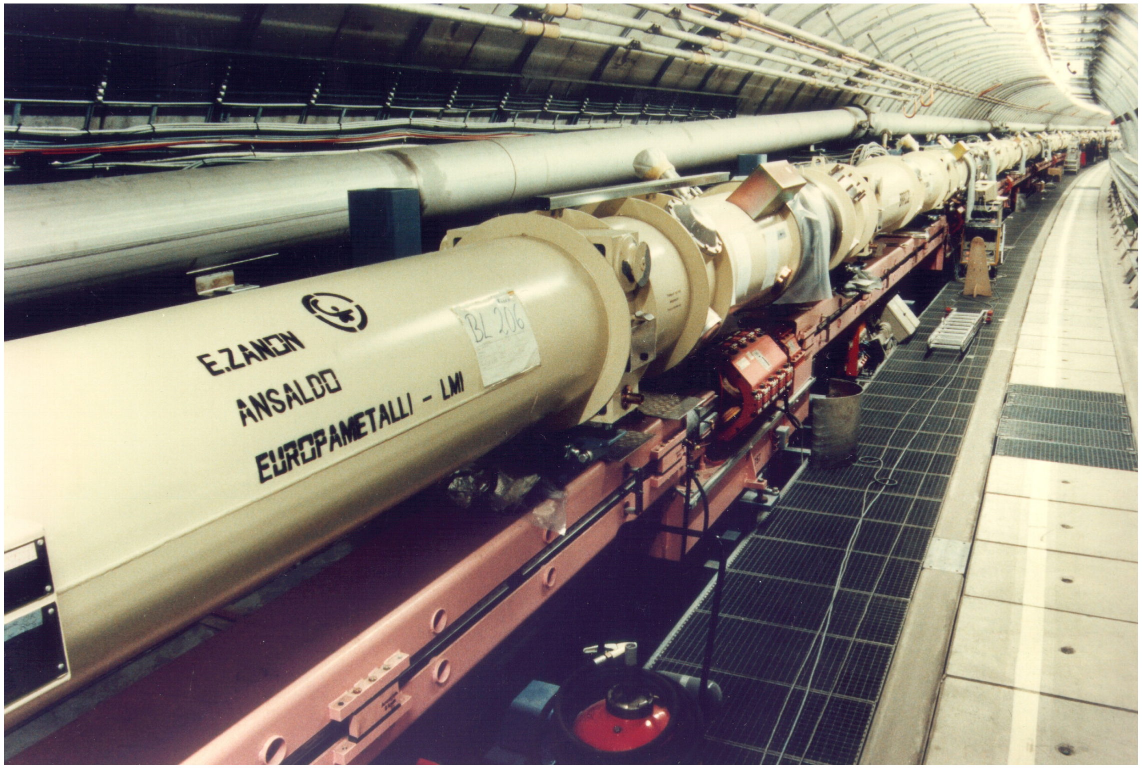
$$Z = E_h / E_{beam}$$

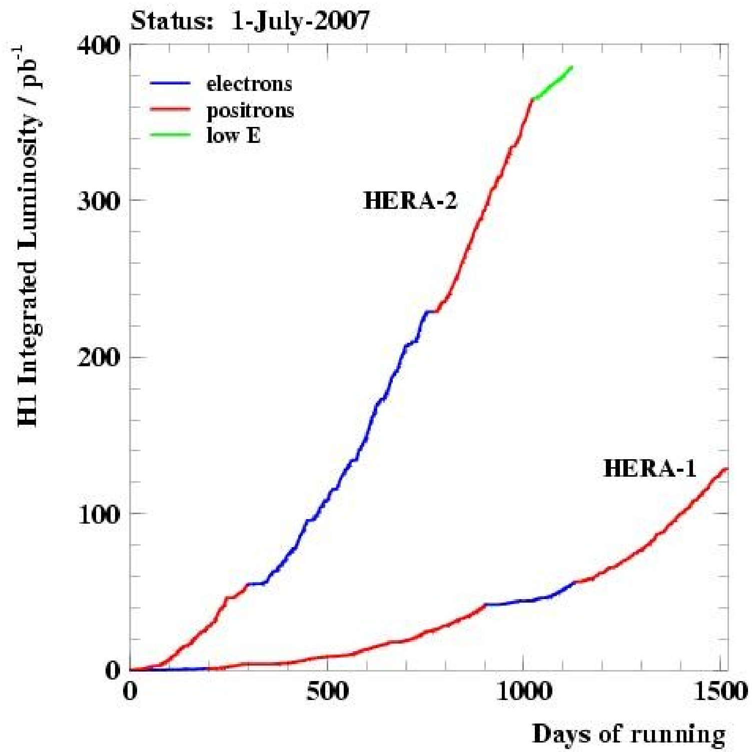
2. a function that is used (in a given model) to describe momentum transfer from parton to hadron

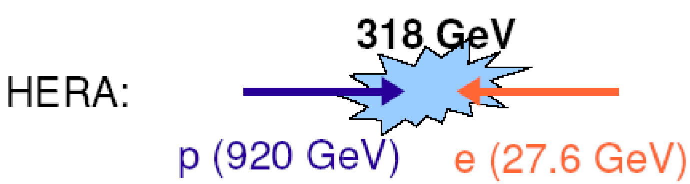


When I speak about FF, I always mean the function used (in a given model) to describe the transition from partons to hadrons

ep physics at HERA collider







HERA I+II data:

Luminosity≈0.5 fb^{-1}

Fragmentation in e^+e^- and ep

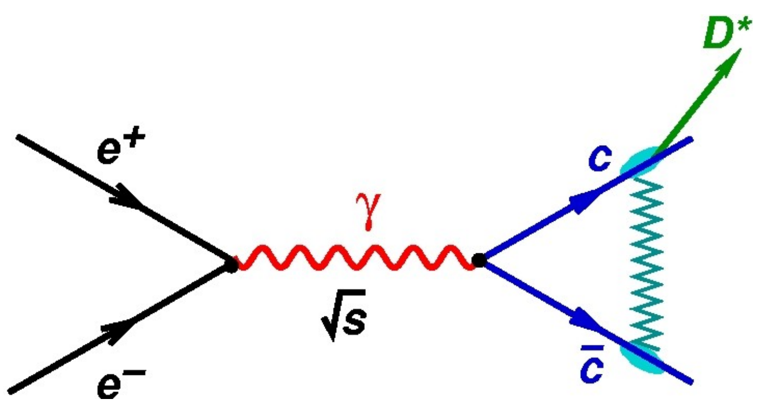
e+e- collisions

- natural choice:

  $z = E_{D^*}/(\frac{1}{2}\sqrt{s}) = E_{D^*}/E_{BEAM}$

- in LO approximation $E_{BEAM} = E_c$

  ==> z corresponds to direct measurement of FF



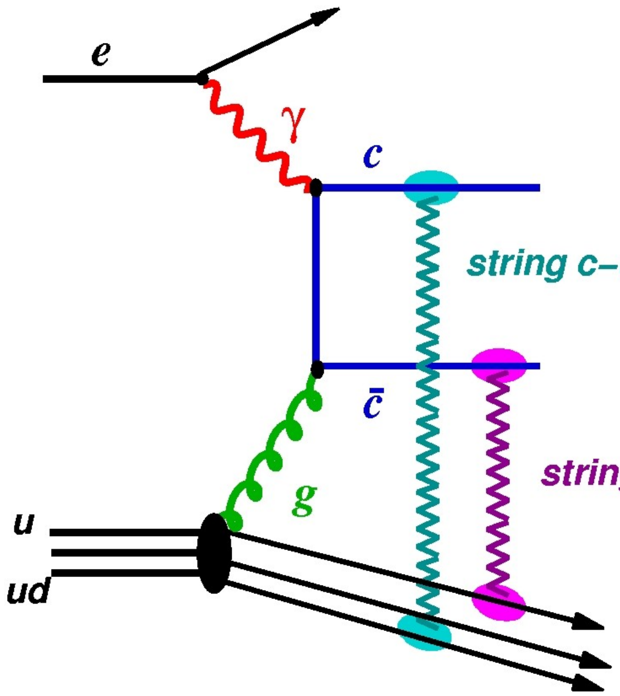
ep collisions

- √s of hard subprocess unknown

  ==> choice of observable not obvious

- differences: presence of IPS

  different color flow



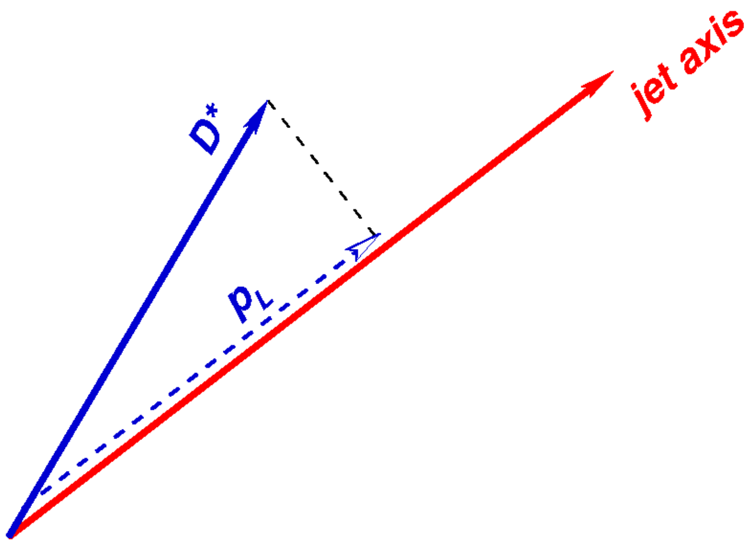
Observables for ep: Jet observable

Jet method:

- momentum of c-quark approximated by momentum of rec. D^*-jet

$$z_{\text{jet}} = \frac{(E+p_{\text{L}})_{D^*}}{(E+p)_{\text{jet}}}$$

- $k_\perp$-clus jet algorithm applied in γp-frame ($E_{\text{t}}(D^* jet) > 3$ GeV)



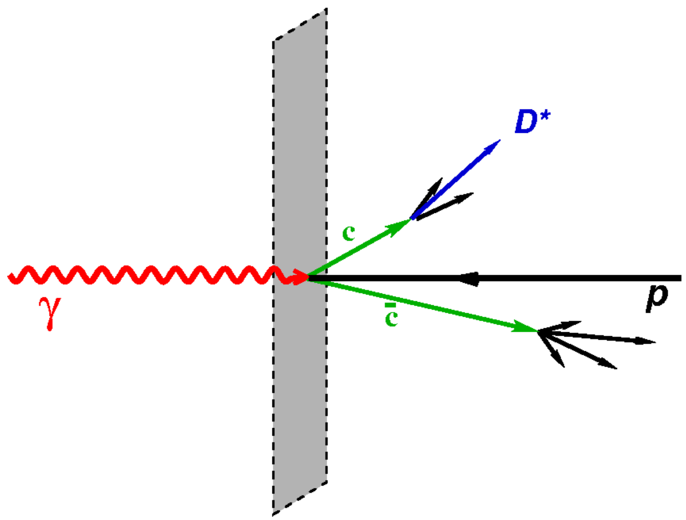
Observables for ep: Hemisphere observable

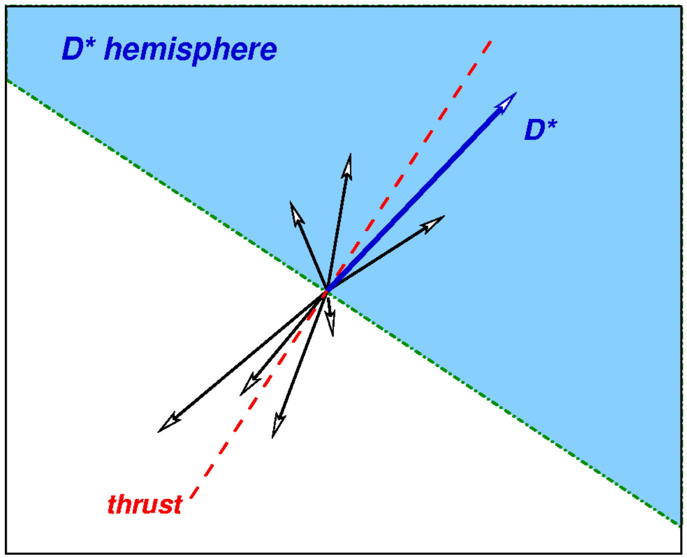
Hemisphere method:

- ▷ momentum of c-quark approximated by momentum of rec. D^*-hemisphere

$$z_{\text{hem}} = \frac{(E+p_{\text{L}})_{D^*}}{\sum_{\text{hem}}(E+p)_i}$$

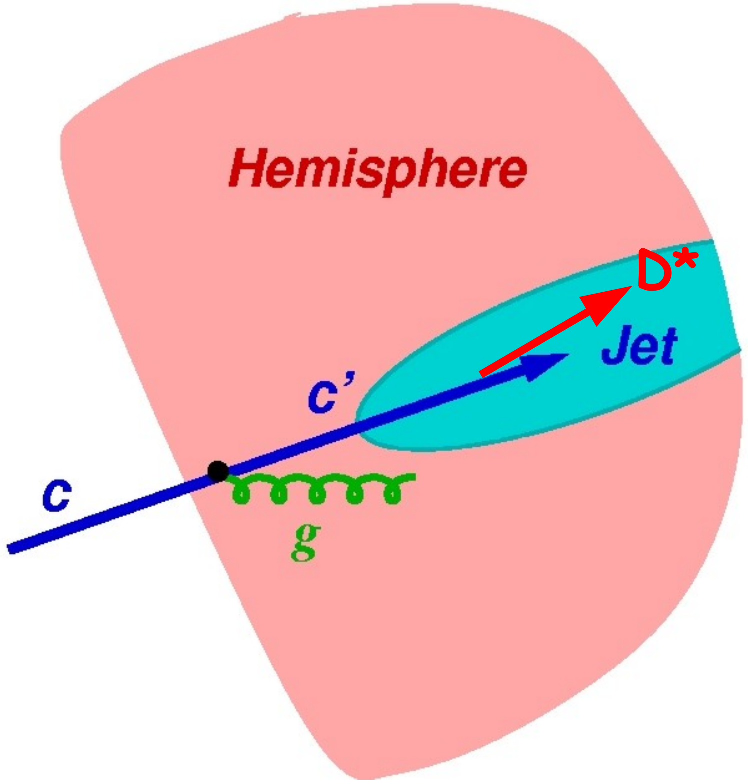
- ▷ $\eta(\text{part}) > 0$ for p-remnant suppression
- ▷ thrust axis in plane perpendicular to γ used for hemisphere division





Comparison of Observables

Hemisphere Method:



- Sums more gluon radiation than jet method
- May have different sensitivity to the hadronization process

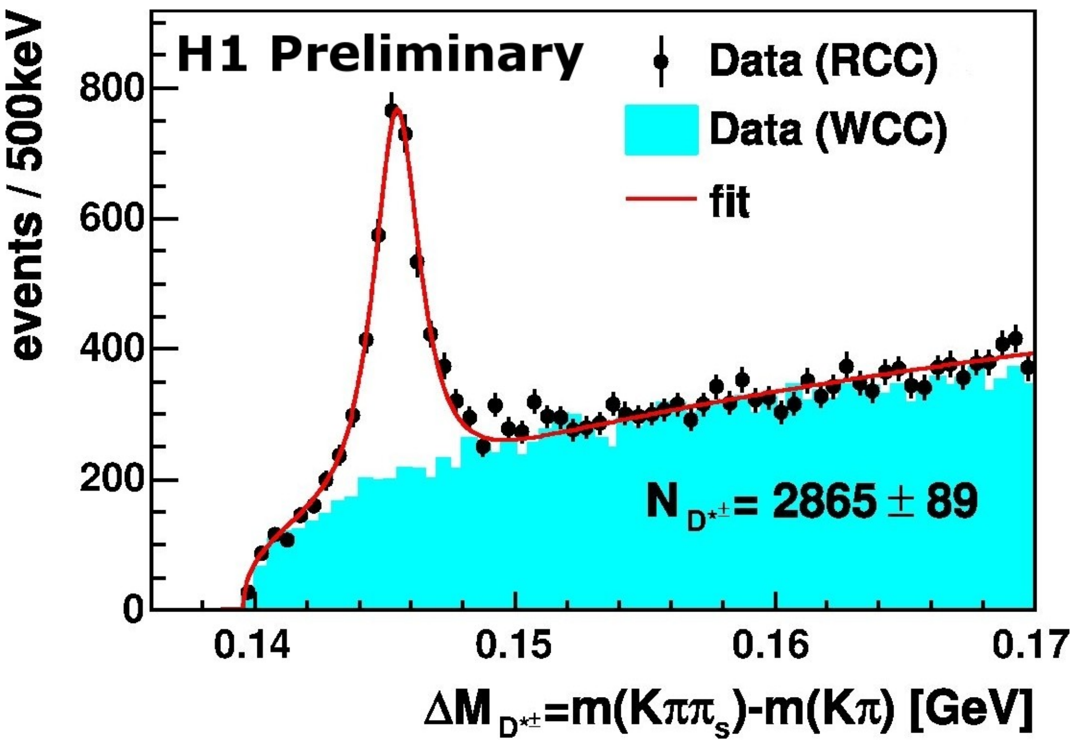
Interesting to measure both $d\sigma/z_{hem}$ and $d\sigma/z_{jet}$ because:

- Allows to test understanding of parton radiation
- Both distributions should look differently, but extracted non-pert. FF should be the same if model is perfect

Event Selection

Golden channel: $D^* \to D^0\pi_s \to K\pi\pi_s$

- 99+2000 data (47 pb^{-1})
- DIS cuts:
  - $2 < Q^2 < 100$ GeV^2
  - $0.05 < y_e < 0.7$
- D* cuts:
  - $|\eta(D^*)| < 1.5$
  - $1.5 < P_T(D^*) < 15$ GeV
  - !
- Jet cut:
  - E_T(D*jet)>3GeV
  - !
- after E_T jet cut
  - N(D*)≈1500



Charm tagging - D*

Golden channel:

$D^* \to D^0 \pi_s \to K\pi\pi_s$

Mass of D* very close to the mass of D^0:

- m(D*)=2.010 GeV
- m(D*)-m(D^0) = 145.5 MeV
- ($m_{\pi+-}$ = 139.6 MeV)

=> D^0 and pion are almost at rest!

Plotting m(Kππ) - m(Kπ)!

- trick used since 70'ties , for example at SPEAR (√s=6.8 GeV)
- (Feldman et al., Phys Rev Lett 38(1977)1313)

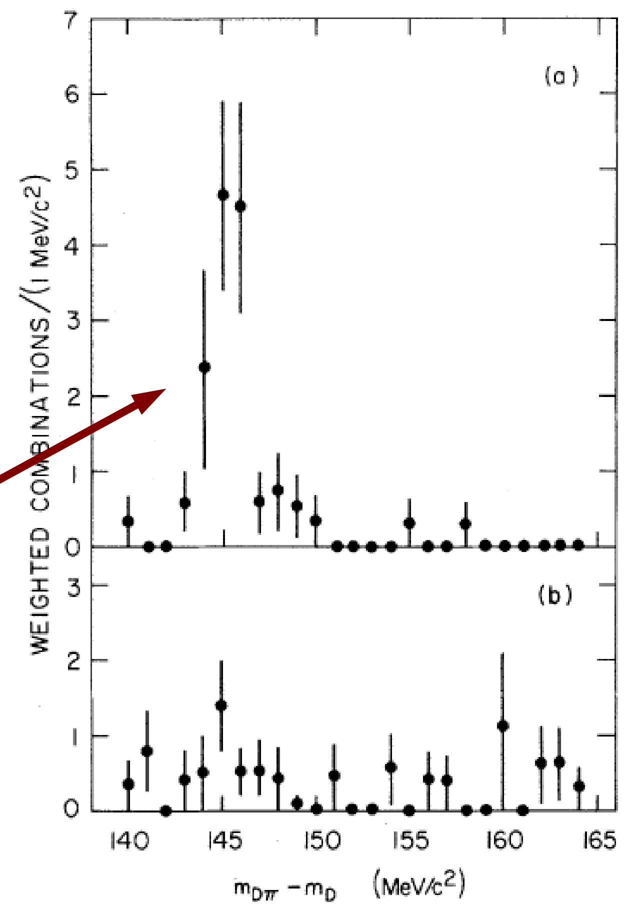
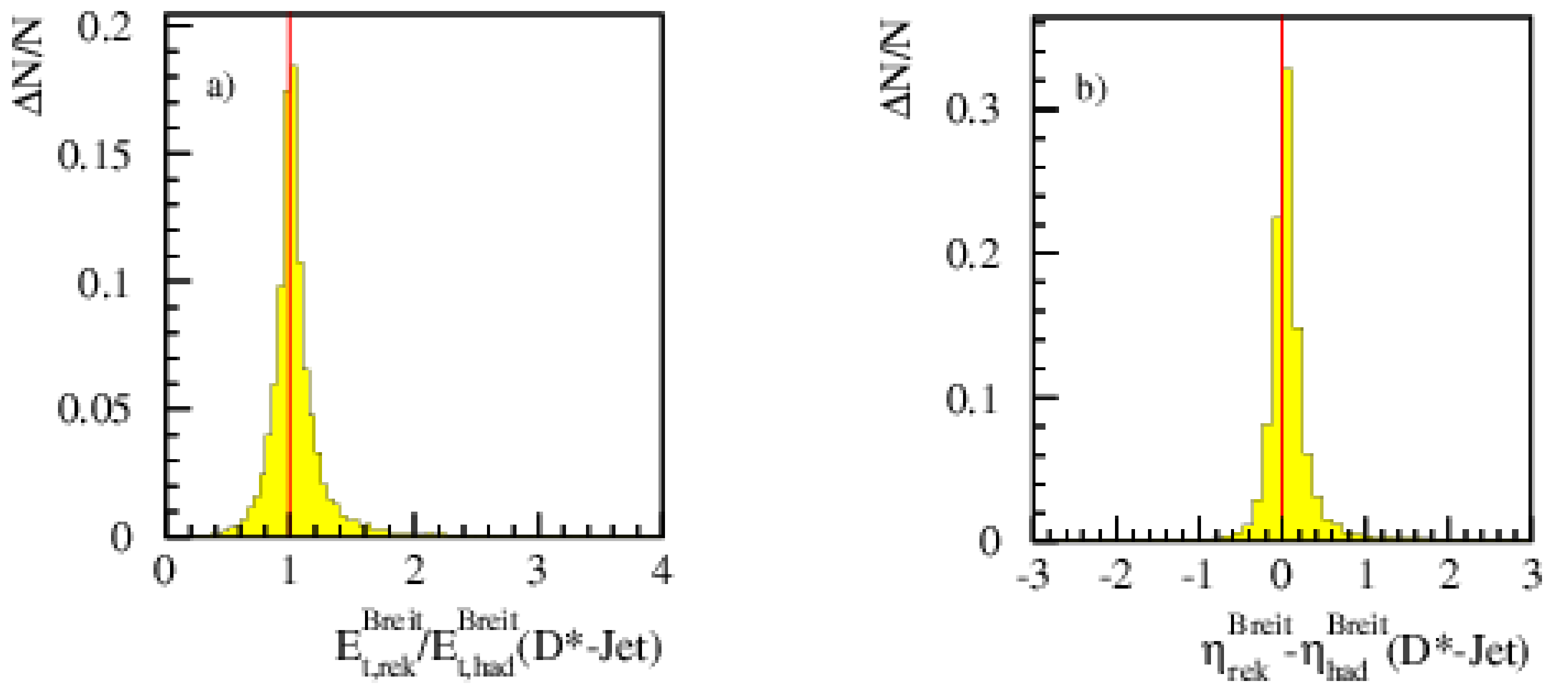


FIG. 2. Weighted $D\pi$–D mass difference spectra for (a) $D^0\pi^+$ and $\overline{D}^0\pi^-$ (i.e., $K^{\mp}\pi^{\pm}\pi^{\pm}$) combinations and (b) $\overline{D}^0\pi^+$ and $D^0\pi^-$ (i.e., $K^{\mp}\pi^{\pm}\pi^{\mp}$) combinations.

Finding D* jets



- **Jet cut:**

  E_T(D*jet)>3GeV

Hmmmm...

Modified jet finder:

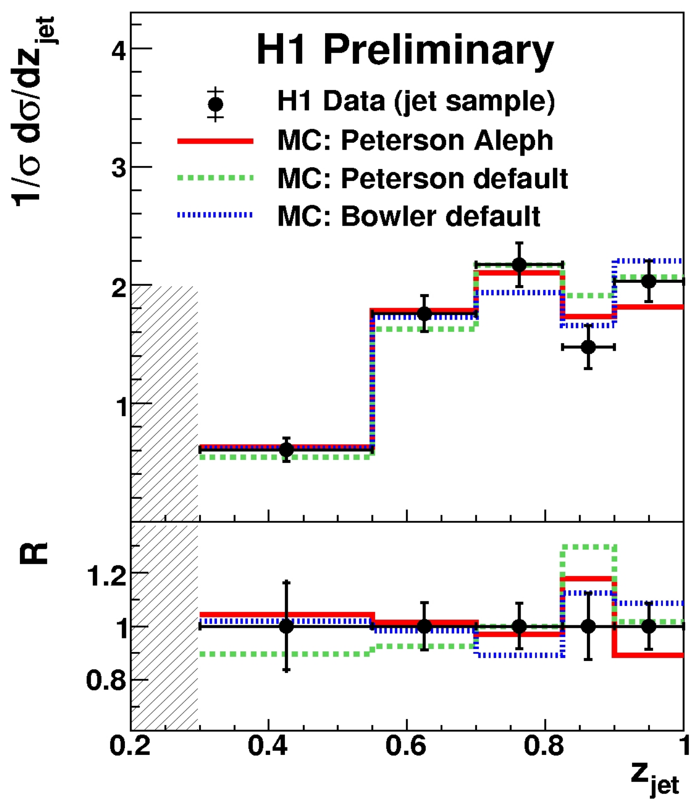
- inclusive kT algorithm
- treating D*=K as one particle
- quite a good correlation with 'truth' down to low ET

Correction Procedure

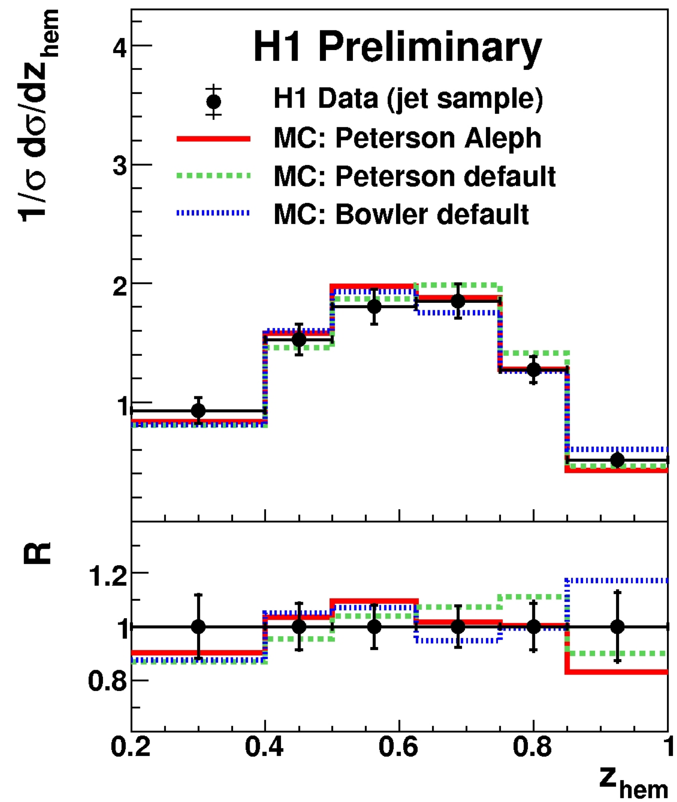
- **Subtraction of the beauty contribution to D* production**
  - using bb RAPGAP MC prediction (fraction below 2%)
- **Correcting for detector effects**
  - regularized unfolding procedure applied, migrations from one bin into another one taken into account by detector response matrix
- **QED radiative corrections**
  - calculated by RAPGAP/HERACLES

Frag. Observable Distributions

Jet method



Hemisphere method



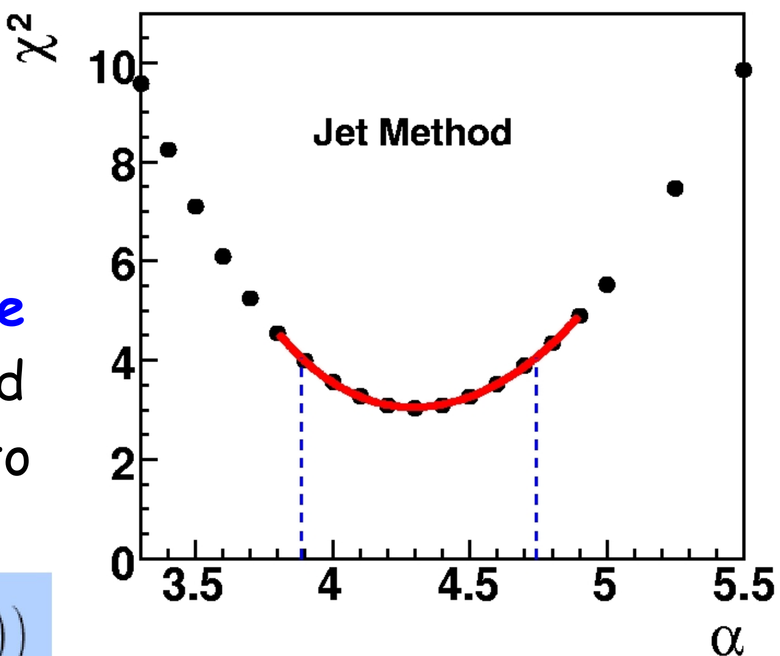
- Reasonable (but not optimal) description of the data by models

FF Extraction Procedure

Non-pert. Frag. function defined only within given theoretical model:

- LO+PS Monte Carlo models RAPGAP and CASCADE with Lund string fragmentation model as implemented in PYTHIA (default setting, Aleph setting)
- NLO calculations (HVQDIS)
- Fitted parametrizations of non-pert. FF: Kartvelishvili, Peterson
- optimal parameters and confidence limits obtained from χ^2 (correlated statistical and sys. errors taken into account)

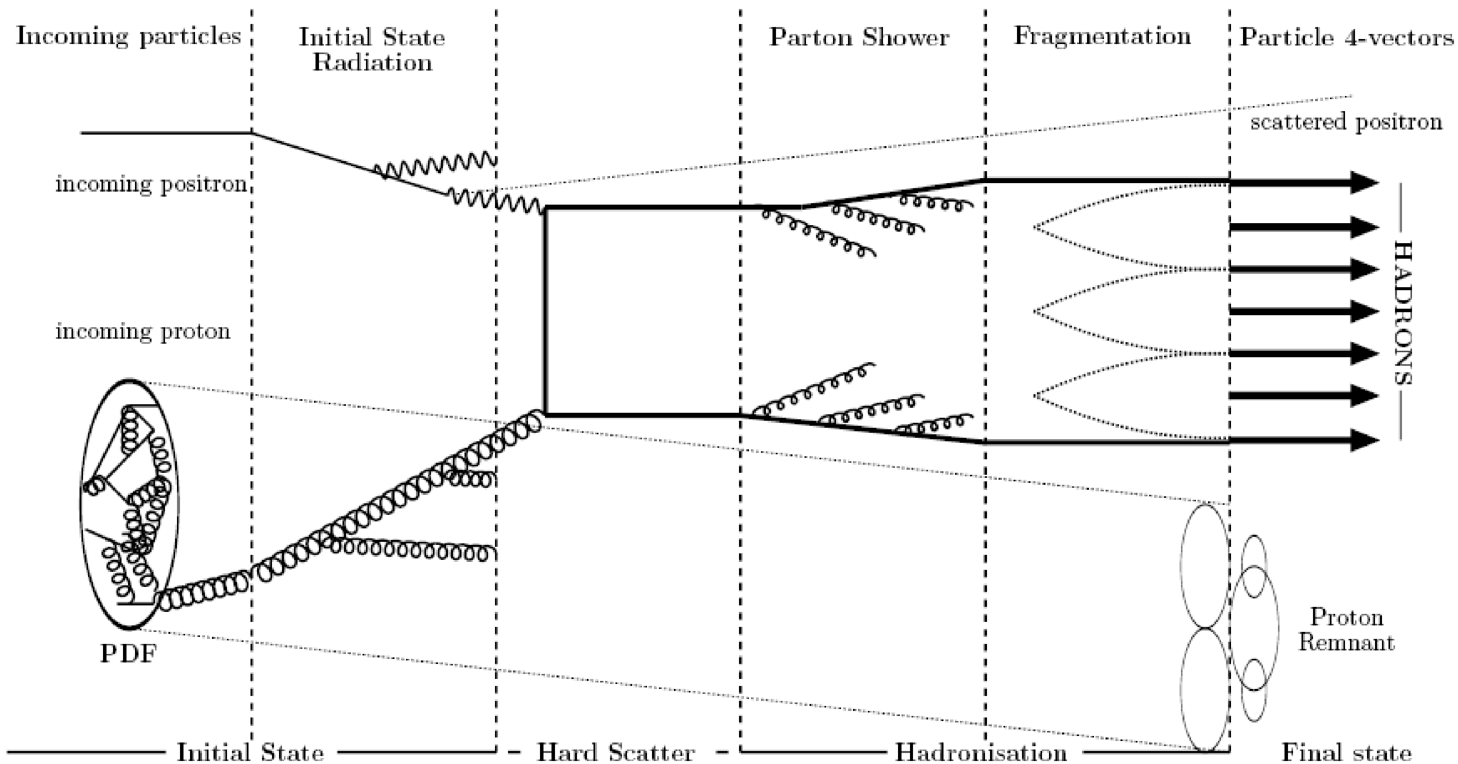
$$\chi^2(\varepsilon) = (z - z^{MC}(\varepsilon))^T V^{-1} (z - z^{MC}(\varepsilon))$$



QCD Models I. (Rapgap, Cascade)

Both models:

- Leading order matrix element
- parton shower (approximating higher orders in α_s)
- Lund String fragmentation
- A lot (really a lot :-( ) of free parameters



RAPGAP:

- using DGLAP parton density functions and parton showers
- (in philosophy very similar to PYTHIA)

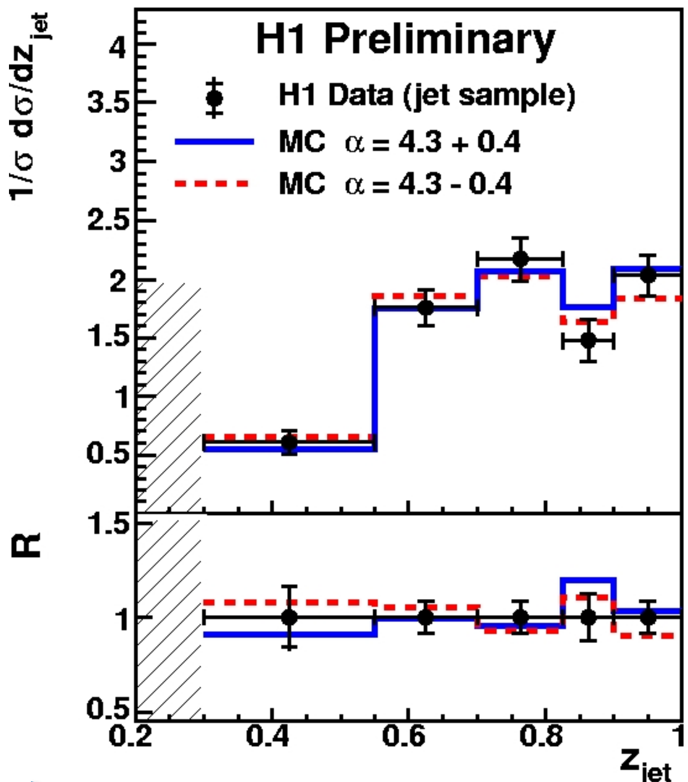
CASCADE:

- using CCFM parton density functions and parton showers
- Off-mass-shell LO matrix element
- Unintegrated parton density function

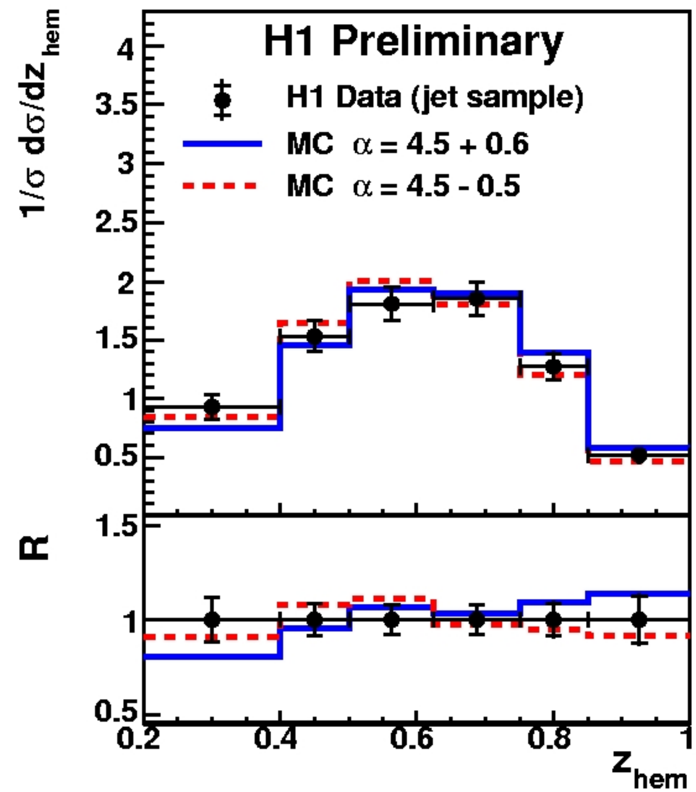
Extracted FF Plots - MC

Rapgap with Aleph setting & Kartvelishvili parametrization:

Jet method



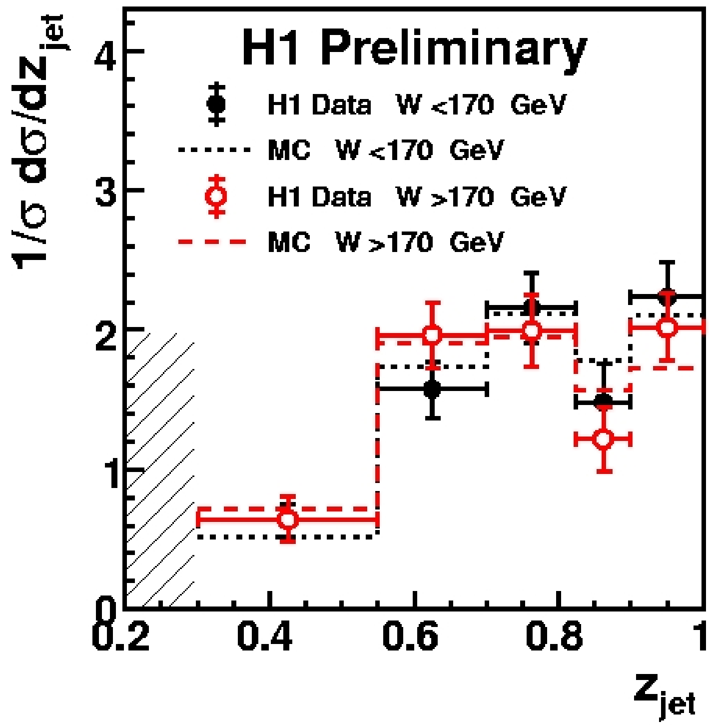
Hemisphere method



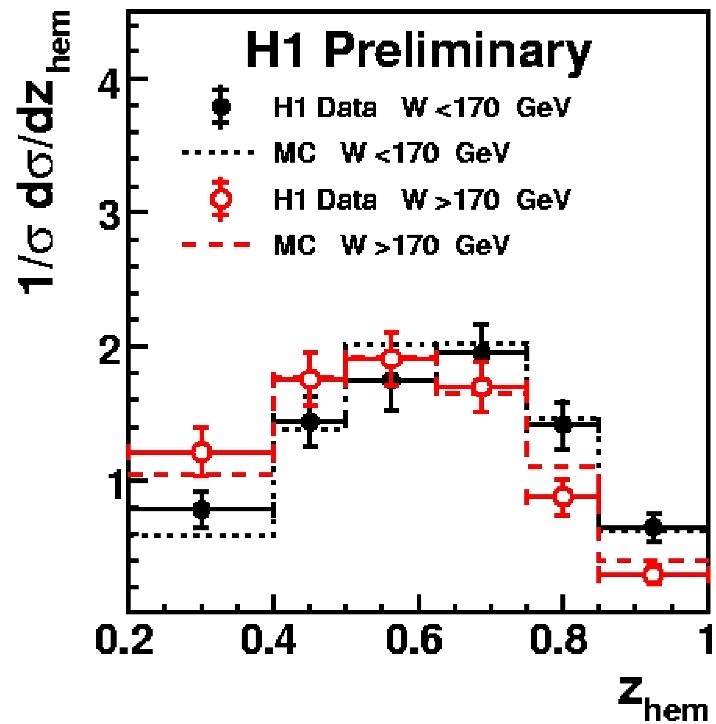
- both methods (hemisphere and jet) agree well with each other within errors
- <u>Extracted FF parameter depends on all other free parameters of the model !</u> (f.e. α= 4.5 for Aleph setting, α =3.3 for default Pythia setting)

Observables as a function of W

Jet method



Hemisphere method

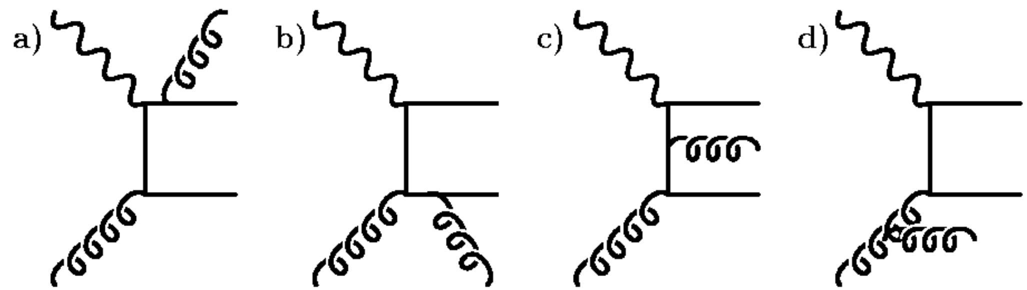


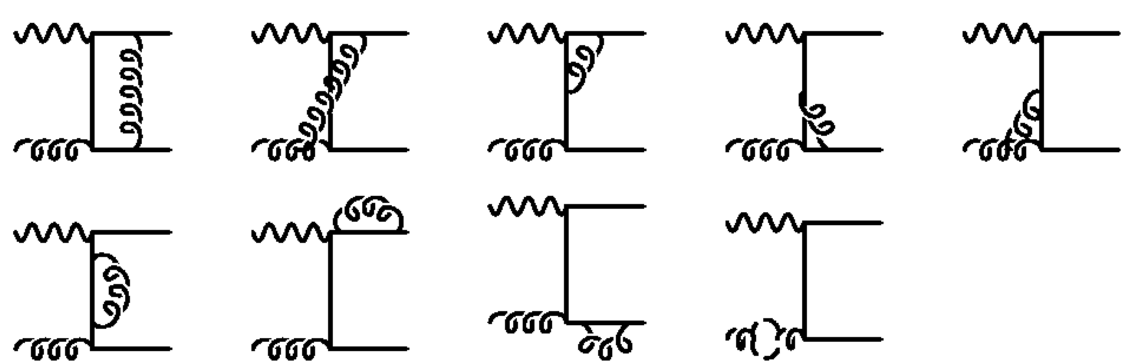
- z as function of γp cms energy -W
  - MC follows the trend in data
  - z_{hem} includes more gluon radiation than z_{jet} --> scale dependence more pronounced

QCD Models II. (HVQDIS)

HVQDIS:

- full NLO calculation
- not really an event generator (rather a calculation with numerical integration using Monte Carlo method)
- negative event weights
- fixed (3) number of flavours
- results are a configurations of partons





"hand made" fragmentation:

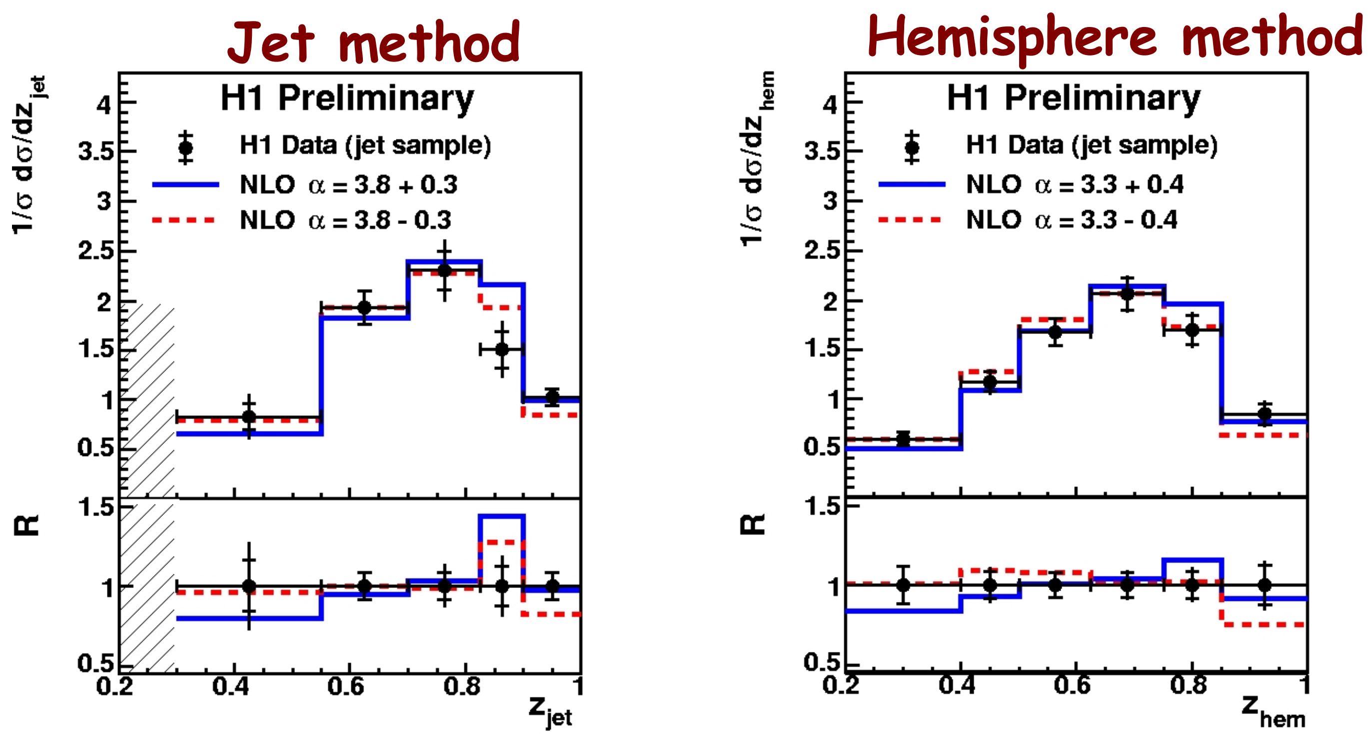
- c-quarks fragmented in **γ**p frame
- $p_L(D^*)$ generated according to given
- parametrization (D* put on mass shell)

Extracted FF Plots - HVQDIS

HVQDIS: massive NLO calculation

(m_c=1.5 GeV, $\mu_r=\mu_f=\sqrt{(Q^2+4m_c^2)}$, proton PDF= CTEQ5F3)

- **data corrected to parton level** & compared with NLO partonic cross-sections (c-quark fragmented independently in γ*p-rest frame)



- **Peterson fails to describe the data**
- **Reasonable description in case of Kartvelishvili**

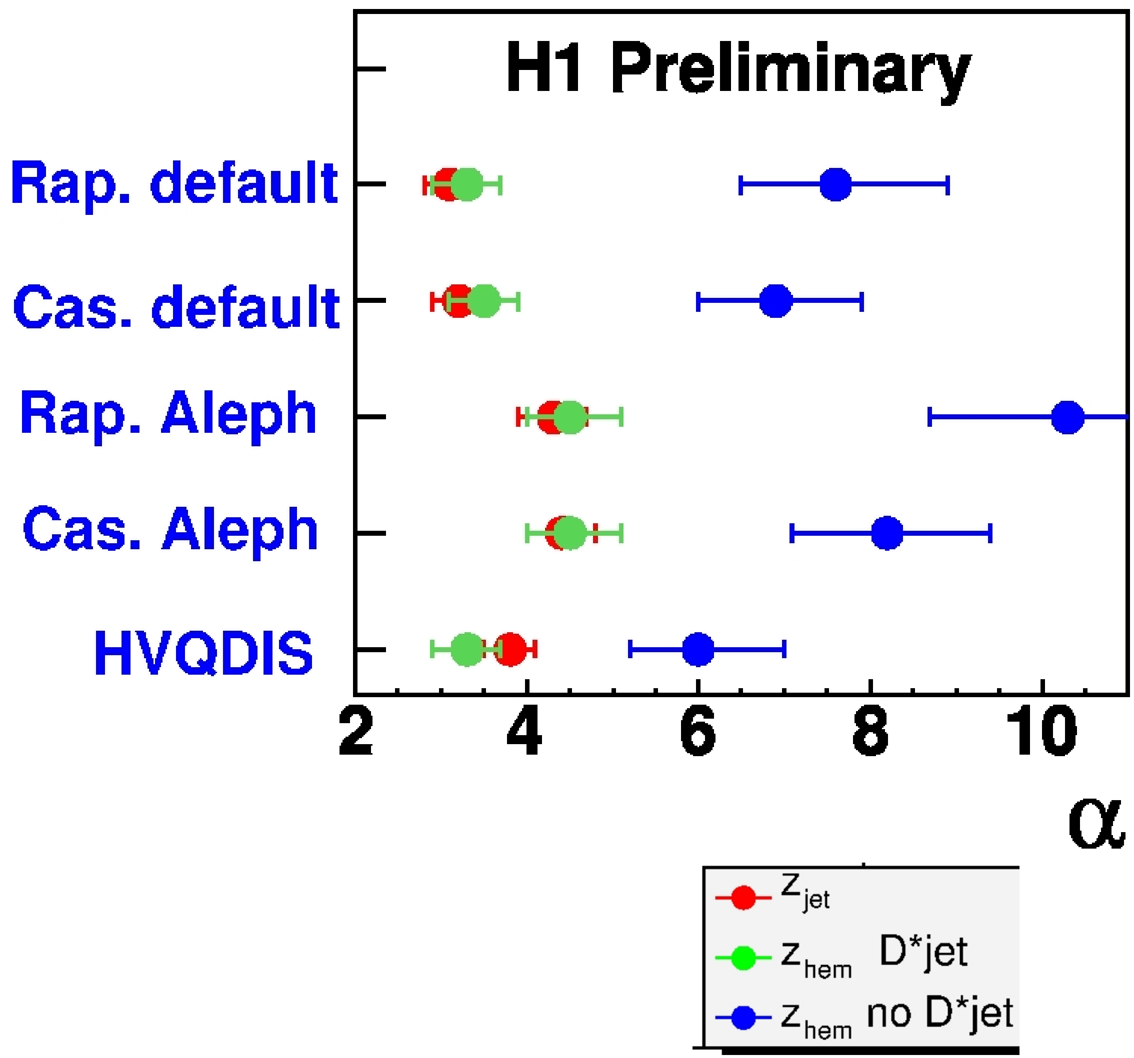
FF Parameter Fit Results (Summary)

- It is possible to tune the models so that they describe the data very well
- extracted Peterson parameter value is in agreement with the ε parameter in the Aleph tuned steering (ε=0.04)

--> Confirms charm fragmentation universality between e^+e^- and ep, if hard scale is involved !

- And what are the blue points ???

Kartvelishvili



Investigating the Threshold Region I.

Hemisphere method does not need any "hard" object to be present:

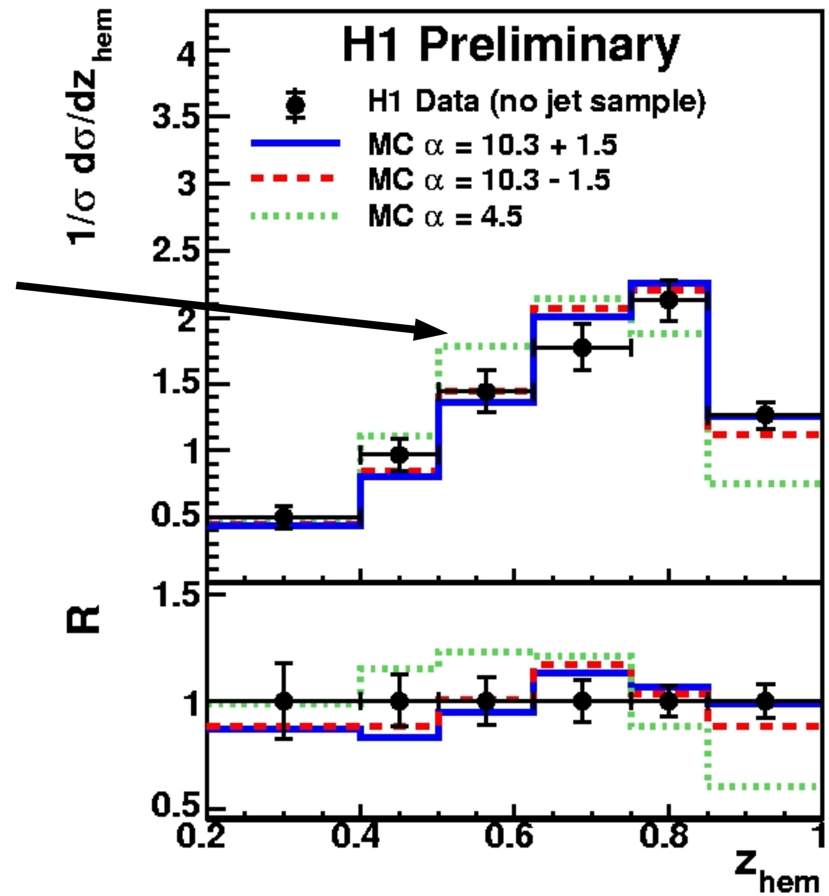
- events not fulfilling hard scale cut E_T(D*jet)>3GeV
- ~1300 D* events, approximately half of our D* statistics
- a big fraction of total charm cross section (efficiency is small at low P_T)

=> interesting kinematic region!

Investigating the Threshold Region II.

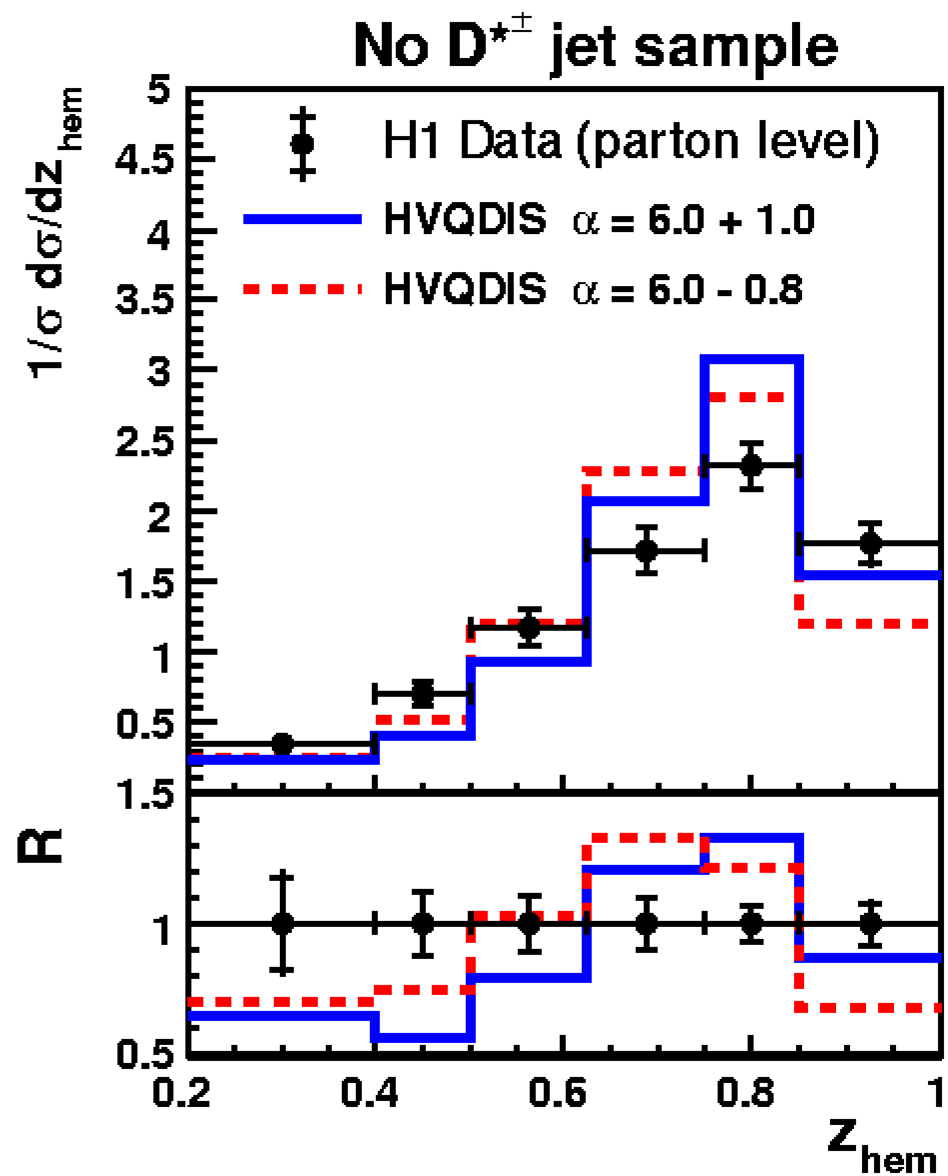
- extracted FF almost 4σ far from the FF extracted from the nominal sample (**spectrum much harder!)**
- **discrepancy due to improper description of underlying physics close to the charm production threshold in QCD models**
- NLO (HVQDIS) completely fails to describe the data
- (χ^2_{MIN}/N_{df} ≈40/4)

Rapgap with Aleph tune and Kartvelishvili FF:



Investigating the Threshold Region III.

- NLO (HVQDIS) completely fails to describe the data
- (χ^2_{MIN}/N_{df} ≈40/4)

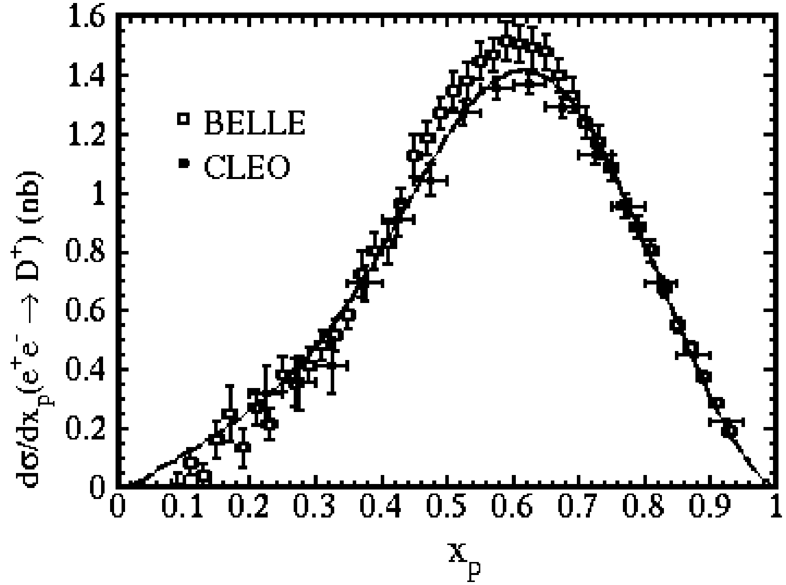


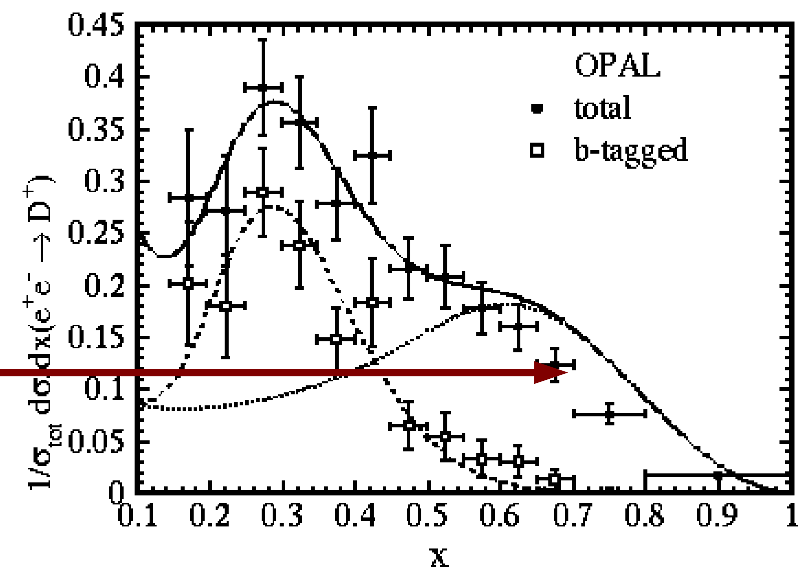
Global fits of FF's

Several groups:
- trying to do „global fits „ of fragmentation functions to various data
- similar to the global fits of parton density functions by MRST (MSTW) and CTEQ

Example:
- B. Kniehl at al (2008): global fit of several precision e+e- experiments:
- description of low energy experiments (Belle, Cleo, √s~10 GeV) very good
- problem to describe high energy data (LEP, √s~100GeV)

Global fit dominated by low s experiments, there FF seems to be significantly harder that at high √s





Conclusions I

- **charm fragmentation studied with ep data at H1 experiment:**
  - two different observable definitions (z_{jet} & z_{hem}) used
  - reasonable description of data by QCD models
- **FF parameters extracted for LO+PS MC models and NLO, using Peterson and Kartvelishvili parametrizations:**
  - both FF observables lead to consistent parameter values
  - ep FF parameters consistent with e^+e^- FF parameters
    --> **FF universality!**
- **Investigating threshold region with z_{hem}:**
  - Needs different FF then basic sample
  - NLO (HVQDIS) fails completely
- **We don't get a consistent picture of charm fragmentation over full phase space**

Conclusions II

Need more input from both theory and experiment!

Backup slides

RAPGAP with PYTHIA		hemisphere observable	jet observable
parameter settings	fragmentation function	(χ^2/n.d.f.)	(χ^2/n.d.f.)
Aleph	Peterson $\varepsilon = 0.04$	6.0/5	4.3/4
default	Peterson $\varepsilon = 0.05$	6.1/5	6.0/4
default	Bowler $a = 0.3, b = 0.58$	5.6/5	3.5/4

Data compared with default MC models