Study of Charm Fragmentation at H1

Juraj Braciník
(in collaboration with Zuzana Rúriková and Günter Grindhammer)
University of Birmingham
for H1 Collaboration

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- Introduction
- Observable definitions & measurement
- Extraction of fragmentation parameters
\[ L_{\text{QCD}} = -\frac{1}{4} F^{(a)}_{\mu\nu} F^{(a)\mu\nu} + i \sum_q \bar{\psi}_q \gamma^\mu (D_\mu)_{ij} \psi^j_q \]
\[ - \sum_q m_q \bar{\psi}_q^i \psi_q^i , \]
\[ F^{(a)}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu , \]
\[ (D_\mu)_{ij} = \delta_{ij} \partial_\mu + i g_s \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu , \]

**QCD: language problem**
- It speaks about partons
- We see hadrons all around
Introduction II.

Our picture of particle production at high energies:

\[
\sigma_H = \sum_i \sum_k f_{i/p}(x, \mu_f) \otimes \hat{\sigma}_{i\gamma \rightarrow kX}(\alpha_s(\mu_R), \mu_R, \mu_f) \otimes D_k^H(z, \mu_f)
\]

Three ingredients needed to describe high energy hadronic collision:

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

\[ E_q, \quad \frac{d}{d} \pi^+, \quad zE_q \]
\[ \frac{d}{d} \pi^0, \quad (1-z)z'E_q \]
\[ \frac{s}{d} \pi^-, \quad (1-z)(1-z')z''E_q \]

until Cut-off energy

\[ \frac{d}{d} \pi^+, \quad zE_q \]
\[ \frac{d}{d} \pi^0, \quad (1-z)z'E_q \]
\[ \frac{s}{d} \pi^-, \quad (1-z)(1-z')z''E_q \]
How to describe fragmentation 2.

**Lund string model:**

- 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
Fragmentation functions for light and heavy quarks

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

\[ P = m v_Q \]
\[ Q = H = Q \bar{q} \]
\[ zP = zm v_Q \]
\[ q = \Lambda v_q \]

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

\[ P = zP + q \]
\[ mv = zm v + \Lambda v \]

and therefore

\[ \langle z \rangle \simeq 1 - \frac{\Lambda}{m} \]
Most of light hadrons carry a small fraction of original parton momentum...
Fragmentation functions for light and heavy quarks

\[ e^+ e^- \rightarrow QX \rightarrow H_{QX} \]

O(\Lambda/m_{charm})

O(\Lambda/m_{bottom})

pQCD

Spectrum of heavy hadrons is rather hard ...

Juraj Bracinik
Bham Particle physics seminar, 18/2/2009
**Fragmentation functions for light and heavy quarks**

Peterson et al.: \[ D^H_Q(z) \propto \frac{1}{z[1 - (1/z) - \varepsilon/(1 - z)]^2} \]

Kartvelishvili et al.: \[ D^H_Q(z) \propto z^\alpha (1 - z) \]

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

⇒ 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 $z$:

   $Z = \frac{E_h}{E_{\text{beam}}}$

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:
  \[ z = \frac{E_{D^*}}{\sqrt{s}/2} = \frac{E_{D^*}}{E_{\text{BEAM}}} \]

- In LO approximation $E_{\text{BEAM}} = E_c$
  \[ \Rightarrow z \text{ corresponds to direct measurement of FF} \]

**$ep$ collisions**

- $\sqrt{s}$ of hard subprocess unknown
  \[ \Rightarrow \text{choice of observable not obvious} \]

- 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

\[
Z_{\text{jet}} = \frac{(E+p_L)_{D^*}}{(E+p)_{\text{jet}}}
\]

- $k_\perp$-clus jet algorithm applied in $\gamma p$-frame ($E_t(D^* \text{jet}) > 3 \text{ GeV}$)
**Observables for ep: Hemisphere observable**

**Hemisphere method:**

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

\[
Z_{\text{hem}} = \frac{(E+p_L)_{D^*}}{\sum_{\text{hem}} (E+p)_i}
\]

- **\(\eta(\text{part}) > 0\) for \(p\)-remnant suppression**
- **thrust axis in plane perpendicular to \(\gamma\) 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 $d\sigma/z_{\text{hem}}$ and $d\sigma/z_{\text{jet}}$ 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: \( D^* \rightarrow D^0 \pi_s \rightarrow K\pi\pi_s \)

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

\[ \Delta M_{D^*} = m(K\pi\pi_s) - m(K\pi) \] [GeV]

\[ N_{D^*} = 2865 \pm 89 \]
Charm tagging - D*

Golden channel:
D* → D⁰π → Kππ

Mass of D* very close to the mass of D⁰:
- m(D*)=2.010 GeV
- m(D*)-m(D⁰) = 145.5 MeV
- (m_π⁺⁻ = 139.6 MeV)

=> D⁰ 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 Dπ-D mass difference spectra for
(a) D⁰π⁺ and D₀π⁻ (i.e., K⁺π⁺π⁻) combinations and
(b) D⁰π⁺ and D⁰π⁻ (i.e., K⁺π⁺π⁻) combinations.
**Finding D* jets**

**Jet cut:**
\[ E_T(D^* \text{jet}) > 3 \text{GeV} \]

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

Hmmmmm...
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** $\chi^2$ (correlated statistical and sys. errors taken into account)

\[
\chi^2(\varepsilon) = (Z - Z^{MC}(\varepsilon))^T V^{-1} (Z - Z^{MC}(\varepsilon))
\]
Both models:
- Leading order matrix element
- parton shower (approximating higher orders in $\alpha_s$)
- 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

- Extracted FF parameter depends on all other free parameters of the model! (f.e. $\alpha = 4.5$ for Aleph setting, $\alpha = 3.3$ for default Pythia setting)
Observables as a function of $W$

Jet method

H1 Preliminary

$1/\sigma \, d\sigma/dz_{\text{jet}}$

$z_{\text{jet}}$

$z$ as function of $\gamma p$ cms energy -$W$

$MC$ follows the trend in data

$z_{\text{hem}}$ includes more gluon radiation than $z_{\text{jet}}$ --> scale dependence more pronounced

Hemisphere method

H1 Preliminary

$1/\sigma \, d\sigma/dz_{\text{hem}}$

$z_{\text{hem}}$
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 γp frame
- $p_L(D^*)$ generated according to given parametrization ($D^*$ put on mass shell)
Extracted FF Plots - HVQDIS

HVQDIS: massive NLO calculation

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

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

- Peterson fails to describe the data
- Reasonable description in case of Kartvelishvili
It is possible to tune the models so that they describe the data very well.

Extracted Peterson parameter value is in agreement with the $\varepsilon$ parameter in the Aleph tuned steering ($\varepsilon=0.04$).

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

And what are the blue points ???

**FF Parameter Fit Results (Summary)**

Kartvelishvili

**H1 Preliminary**

- Rap. default
- Cas. default
- Rap. Aleph
- Cas. Aleph
- HVQDIS

\[ \alpha \]

- $z_{\text{jet}}$
- $z_{\text{hem}}$ D*$\text{jet}$
- $z_{\text{hem}}$ no D*$\text{jet}$
Investigating the Threshold Region I.

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

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

$\Rightarrow$ interesting kinematic region!
Investigating the Threshold Region II.

- extracted FF almost 4\sigma 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

\[ \chi^2_{\text{MIN}} / N_{\text{df}} \approx 40/4 \]
Investigating the Threshold Region III.

NLO (HVQDIS) completely fails to describe the data

$(\chi^2_{\text{MIN}} / N_{\text{df}} \approx 40/4)$
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, $\sqrt{s} \sim 10$ GeV) very good
  - problem to describe high energy data (LEP, $\sqrt{s} \sim 100$ GeV)

Global fit dominated by low s experiments, there FF seems to be significantly harder that at high $\sqrt{s}$
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
### Data compared with default MC models

<table>
<thead>
<tr>
<th>Parameter settings</th>
<th>Fragmentation function</th>
<th>Hemisphere observable $(\chi^2/\text{n.d.f.})$</th>
<th>Jet observable $(\chi^2/\text{n.d.f.})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aleph</td>
<td>Peterson $\varepsilon = 0.04$</td>
<td>6.0/5</td>
<td>4.3/4</td>
</tr>
<tr>
<td>default</td>
<td>Peterson $\varepsilon = 0.05$</td>
<td>6.1/5</td>
<td>6.0/4</td>
</tr>
<tr>
<td>default</td>
<td>Bowler $a = 0.3, b = 0.58$</td>
<td>5.6/5</td>
<td>3.5/4</td>
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</tbody>
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