Hadron multiplicities and fragmentation functions from COMPASS

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Baryons 2013 – 24-28 June 2013

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Outline

- Fragmentation functions (FF)
- FFs from hadron production in lepton DIS
- Measurements at COMPASS
- Latest results
Fragmentation functions

- FFs describe the collinear transition of a parton $i$ into a massless hadron $h$ carrying momentum fraction $z$

$$D^h_i(z)$$

They give the mean no. of hadrons $h$ created in the hadronisation of $p_i$

- Important any time a hadron is emitted in a high energy collision
  - heavy ion studies of QGP
  - flavour separation of polarised parton distributions
  - extraction of polarised gluon density
  - key role in single spin asymmetries, transversity etc.

- Hadronisation lies at the long/short distance “border”: important in its own right!
Properties of FFs

- Universal (if factorisation theorems hold!)
  ⇒ determinable from global fits on different observables

- Depend on energy fraction of the parton $i$ transferred to the hadron $h$:
  \[ z = \frac{E_h}{E_i} \] (in lepton DIS $E_i = \nu = E' - E_{\text{beam}}$)

- Scale evolution equations (like for PDFs)
  \[
  \frac{d}{d \ln \mu^2} D^h_q(z, \mu^2) = \left[ P_{qq'} \otimes D^h_{q'}(z, \mu^2) + P_{qg} \otimes D^h_g(z, \mu^2) \right] \quad \text{(NLO)}
  \]

  $P_{ij}$ calculable “perturbatively” but very singular at small $z$ ($< 0.05...0.1$)

- Energy conservation sum rule (not very useful...):
  \[
  \sum_h \int_0^1 dz \, z \, D^h_i(z, \mu^2) = 1
  \]
Access to FFs (not in this talk)

$e^+e^- \text{ annihilation into hadrons}$

- Precise data from LEP
  (+ prel. res. from BELLE and BABAR)
- Sole non-perturbative object intervening
  - Narrow scale coverage (low sensitivity to $D_g$)
  - Access to singlet combination only

$$D_\Sigma = D_u + D_\bar{u} + D_d + D_\bar{d} + D_s + D_\bar{s} + \ldots$$

**pp and p\bar{p} collisions**
(Data from SPS, RHIC, Fermi Lab.)

- Direct gluon contributions (dominant)
  - Larger theoretical uncertainties
  - Strong dependence on PDFs
FFs from SIDIS

SIDIS = Semi inclusive deeply inelastic scattering:

\[ \ell N \rightarrow \ell' h(X) \]

**Data**
- without hadron identification
  - Fermi Lab. (E665)
  - CERN (EMC)
  - HERA (ZEUS,H1)
- with hadron identification
  - HERA (HERMES)
  - CERN (COMPASS) (preliminary)

**PROS**
- Allows flavour/charge separation
- Larger \( z \)
- Better scale coverage ("low" \( Q^2 \)) \( \Rightarrow D_g \)
- Relevant for spin physics kinematics

**CONS**
- dependence on PDFs
- non-perturbative corrections at low \( Q^2 \)?
The strange quark helicity density $\Delta s$

Strangeness contribution to long. spin:

$$\Delta S = \int dx \left[ \Delta s(x) + \Delta \bar{s}(x) \right]$$

From **inclusive** measurements:

$$\Delta S = -0.08 \pm 0.01_{\text{stat.}} \pm 0.02_{\text{syst.}}$$

- $\Gamma_1 = \int g_1(x)$
- SU(3) flavour symmetry + axial charges of baryons (from $\beta$ decay meas.)

From **SIDIS**:

$$\Delta S = -0.02 \pm 0.02_{\text{stat.}} \pm 0.02_{\text{syst.}}$$

- Fragmentation functions $D^h_q$?
- Strong dependence on the ratio:
  $$R_{\text{SF}} = D_{\bar{s}}^{K^+} / D_{u}^{K^+}$$

(DSS – Phys. Rev. D 75, 114010 (2007))
Hadron production in SIDIS

Observables: **Hadron Multiplicities**

\[
M^h(x, Q^2, z) \equiv \frac{dN^h}{dz} = \frac{\sum_q e_q^2 \left[ q(x, Q^2) D_q^h(z, Q^2) + \bar{q}(x, Q^2) D_{\bar{q}}^h(z, Q^2) \right]}{\sum_q e_q^2 \left[ q(x, Q^2) + \bar{q}(x, Q^2) \right]}
\] (at LO)

- Unpolarised PDFs for u and d are well known
- And \( s(x) \)? Not well known... ⇒ could be extracted at the same time
- Binning in \( Q^2, x, z \) needed ⇒ high statistics required!
- Flavour separation ⇒ particle identification required!
Latest HERMES data

- Data on deuteron and proton target
- \(\pi\) and \(K\) multiplicities
- Kinematics:
  - \(\langle Q^2 \rangle \approx 2.5\) GeV\(^2\)
  - \(\langle W^2 \rangle \approx 10\) GeV\(^2\)
  - \(0.023 < x_{Bj} < 0.6\)

\[\begin{array}{c}
\text{Multiplicity} \\
\text{z} \\
\end{array}\]

\[\begin{array}{c}
\text{Proton} \\
\text{Deuteron} \\
\end{array}\]
The COMPASS experiment at CERN

230 physicists
25 institutes
11 countries
COMPASS spectrometer

60m long

E/HCAL1

SM1

Polarised Target

160/200 GeV μ beam

E/HCAL2

SM2

Hodoscopes

Muon Wall 1

Muon Wall 2, MWPC

MWPC, Gems, Scifi, W45

Straws, Gems

Scifi, Silicon

Micromegas, DC, Scifi
Multisciplicity measurement

\[ M = \frac{N^h}{N_{\text{DIS}} \Delta z} \]

**Event selection**
- Only “inclusive triggers”
- \( Q^2 > 1 \text{ GeV}^2 \)
- \( 0.1 < y < 0.9 \) (\( y = v/E_{\text{beam}} \))

**Hadron track selection**
- \( 0.2 < z < 0.85 \) (implies \( x_F > 0 \): current fragmentation)
- \( X/X_0 < 15 \) to eliminate \( \mu \)'s

**“Acceptance” correction**
- Simulate DIS events with some generator (LEPTO) \( \Rightarrow M_{\text{gen}}^{\text{MC}} \)
- Simulate the detector response and do the same analysis as for real data \( \Rightarrow M_{\text{rec}}^{\text{MC}} \)
- Correction factor for geom. acceptance and reconstruction efficiency: \( a = M_{\text{rec}}^{\text{MC}} / M_{\text{gen}}^{\text{MC}} \)
- Correct real data:
  \[ M_{\text{cor}} = \frac{M_{\text{raw}}}{a} \]
Multidimensional binning

- Good for global fits, best with relevant variables \((x_{Bj}, Q^2, z)\)

\[
M^h(x, Q^2, z) = \frac{\sum_q e^2_q \left[ q(x, Q^2) D^h_q(z, Q^2) + \bar{q}(x, Q^2) D^h_{\bar{q}}(z, Q^2) \right]}{\sum_q e^2_q \left[ q(x, Q^2) + \bar{q}(x, Q^2) \right]} \quad \text{(LO)}
\]

- Necessary for acceptance correction:
  minimises dependence on event generator

- We choose \(x_{Bj}, y (= v/E_{\text{beam}}), z\):

\[
E_h = z v = z y E_{\text{beam}}
\]

fixed \(y\) and \(z\) \(\Rightarrow\) hadron momentum well defined in each bin

\(\Rightarrow\) mom. distr. in ev. gen. is not important
Particle identification

RICH detector ⇒ hadron identification in SIDIS

RICH characterisation

- Use pure samples of π, K and p from:
  - $K^0 \rightarrow \pi^+ \pi^-$
  - $\phi \rightarrow K^+ K^-$
  - $\Lambda \rightarrow \pi^- p$ ($\bar{\Lambda} \rightarrow \pi^+ \bar{p}$)

- Measure identif./misidentif. prob. matrix:

\[
\begin{pmatrix}
I_{\pi} \\
I_{K} \\
I_{p}
\end{pmatrix} = 
\begin{pmatrix}
  P_{\pi \rightarrow \pi} & P_{K \rightarrow \pi} & P_{p \rightarrow \pi} \\
  P_{\pi \rightarrow K} & P_{K \rightarrow K} & P_{p \rightarrow K} \\
  P_{\pi \rightarrow p} & P_{K \rightarrow p} & P_{p \rightarrow p}
\end{pmatrix} 
\begin{pmatrix}
T_{\pi} \\
T_{K} \\
T_{p}
\end{pmatrix} = P
\]

- Unfold data:

\[
\vec{T} = P^{-1} \vec{I}
\]
Recent results

- From 2006 $^6$LiD data
- Both unidentified and identified hadrons ($\pi$ and $K$)
- 3 dim. binning in $x_{Bj}$, $y$ and $z$
- Kinematics:
  - $0.004 < x_{Bj} < 0.7$
  - $0.1 < y < 0.7$
  - $5\ \text{GeV} \lesssim W \lesssim 15\ \text{GeV}$
  - $1\ \text{GeV}^2 \lesssim \langle Q^2 \rangle \lesssim 30\ \text{GeV}^2$
  - $0.2 < z < 0.85$
Multiplicities: Unidentified Hadrons

COMPASS Preliminary

\( h^+ \)

\( h^- \)
Multiplicities: Pions

COMPASS Preliminary

\[ \begin{array}{c}
\pi^+ \\
\pi^-
\end{array} \]

COMPASS Preliminary

27/6/2013 Luigi Capozza – Baryons 2013 17/23
Multiplicities: Kaons

COMPASS Preliminary

\( K^+ \)
\( K^- \)
Kaon multiplicity sum: \( K^+ + K^- \)

For a deuteron target (using proton PDFs):

- \( Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \)
- \( S(x) = s(x) + \bar{s}(x) \) (\( s(x) = \bar{s}(x) \))
- \( D_Q = 4D_{\text{fav}} + 6D_{\text{unf}} \)
- \( D_{\text{str}} = D_s + D_{\bar{s}} \)

\[
M^{K^+} + M^{K^-} = \frac{Q(x)D_Q + 2S(x)D_{\text{str}}}{5Q(x) + 2S(x)} \quad \text{(LO)}
\]

Speculations

- \( S(x)/Q(x) \) changes with \( x \)
- \( \Rightarrow D_{\text{str}} \) is small?

- Negative \( \Delta S \)?
- Or no sensitivity on strangeness?
- What about the \( Q^2 \)-dependence?
- Other effects:
  - NLO contributions?
  - Diffractive production?

\( \Rightarrow \) no visible \( x \) dependence!
Summary

Fragmentation functions
- Universal non-perturbative objects
- Relevant for all high energy processes with hadrons in the final state
- Measurable in semi-inclusive DIS through hadron multiplicities

Measurement of hadron multiplicities
- New published results from HERMES
- Preliminary results from COMPASS
  - Broad kinematical ranges
  - Multidimensional binning
  - Identified pions and kaons
Backup slides
Extraction of $\Delta S$

**Inclusive measurements**

From longitudinal double-polarisation asymmetry:

\[
A = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \Rightarrow g_1(x, Q^2)
\]

\[
\Gamma_1 = \int_0^1 dx \, g_1(x) = \frac{1}{2} \sum_q e_q^2 \int_0^1 dx \, (\Delta q(x) + \Delta \bar{q}(x))
\]

\[
\equiv \Delta Q
\]

**Isospin symmetry:**

\[
\Gamma^N_1 = \frac{1}{2} (\Gamma_1^p + \Gamma_1^n) = \frac{1}{36} [5\Delta U + 5\Delta D + 2\Delta S]
\]

**SIDIS measurements**

\[
A^h(x, z) = \frac{\sigma_h^{\uparrow\uparrow} - \sigma_h^{\uparrow\downarrow}}{\sigma_h^{\uparrow\uparrow} + \sigma_h^{\uparrow\downarrow}} \quad (\text{LO}) \quad \Rightarrow \quad \frac{\sum_q e_q^2 \left( \Delta q(x) D_q^h(z) + \Delta \bar{q}(x) D_{\bar{q}}^h(z) \right)}{\sum_q e_q^2 \left( q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z) \right)}
\]

\[
\Rightarrow \Delta s(x), \Delta \bar{s}(x)
\]

\[
\Delta S = \int dx \left[ \Delta s(x) + \Delta \bar{s}(x) \right]
\]

With $\Gamma^N_1$, SU(3) and axial couplings from baryon $\beta$ decays:

\[
\Delta Q_8 = \Delta U + \Delta D - 2\Delta S = 3F - D = 0.585 \pm 0.025
\]

\[
\Delta S = 3\Gamma^N_1 - \frac{5}{12}\Delta Q_8
\]
Global fits

- Assume functional form for FFs, typically:

\[ D_i^h(z, \mu^2) = A z^\alpha (1 - z)^\beta \left( 1 + \gamma (1 - z)^\delta \right) \]

where parameters \( A, \alpha, \beta, \gamma, \delta \) depend on the scale \( \mu^2 \)

- Fit on data available from all or some of the observables

- Several fits on the market, e.g.