Hadron multiplicities and fragmentation functions from COMPASS

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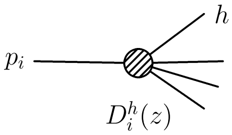
Outline

- 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



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!)
  $\Rightarrow$ determinable from global fits on different observables
- Depend on energy fraction of the parton i transferred to the hadron h:

$$z = \frac{E_h}{E_i} \quad \text{(in lepton DIS } E_i = \nu = E' - E_{\text{beam}}\text{)}$$

- Scale evolution equations (like for PDFs)

$$\frac{d}{d\ln\mu^2} D_q^h(z,\mu^2) = \left[P_{qq'} \otimes D_{q'}^h(z,\mu^2) + P_{qg} \otimes D_g^h(z,\mu^2) \right] \quad \text{(NLO)}$$

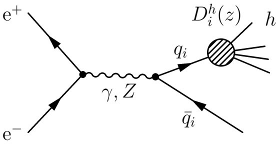
  P_{ij} calculable “perturbatively” but very singular at small z ($< 0.05...0.1$)
- Energy conservation sum rule (not very useful...):

$$\sum_h \int_0^1 dz\, z\, D_i^h(z,\mu^2) = 1$$

Access to FFs (not in this talk)

e^+e^- annihilation into hadrons

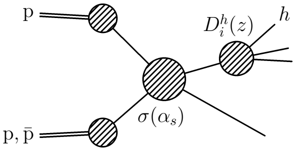
- **+** Precise data from LEP
  (+ prel. res. from BELLE and BABAR)
- **+** Sole non-perturbative object intervening
- **−** Narrow scale coverage (low sensitivity to D_g)
- **−** Access to singlet combination only



$$D_\Sigma = D_\mathrm{u} + D_{\bar{\mathrm{u}}} + D_\mathrm{d} + D_{\bar{\mathrm{d}}} + D_\mathrm{s} + D_{\bar{\mathrm{s}}} + \ldots$$

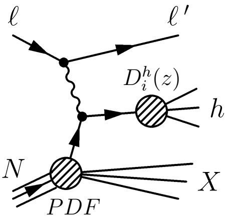
pp and $\mathrm{p\bar{p}}$ collisions
(Data from SPS, RHIC, Fermi Lab.)

- **+** Direct gluon contributions (dominant)
- **−** Larger theoretical uncertainties
- **−** Strong dependence on PDFs



FFs from SIDIS

SIDIS = Semi inclusive deeply inelastic scattering: $\boxed{\ell N \to \ell' h (X)}$



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 Δs

Strangeness contribution to long. spin:

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

From inclusive measurements:

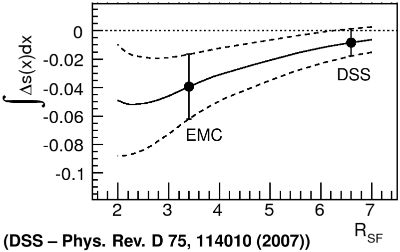
$$\Delta S = -0.08 \pm 0.01_{\text{stat.}} \pm 0.02_{\text{syst.}}$$

- $\Gamma_1 = \int g_1(x)$
- SU(3) flavour symmetry + axial charges of baryons (from β decay meas.)
- SU(3) breaking?
  (see e.g. S. D. Bass and A. W. Thomas,
  Phys. Lett. B684 (2010) 216)

From SIDIS:

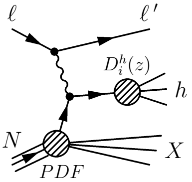
$$\Delta S = -0.02 \pm 0.02_{\text{stat.}} \pm 0.02_{\text{syst.}}$$

- Fragmentation functions D_q^h?
- Strong dependence on the ratio: $R_{SF} = D_{\bar{s}}^{K^+} / D_u^{K^+}$



(DSS – Phys. Rev. D 75, 114010 (2007))

Hadron production in SIDIS



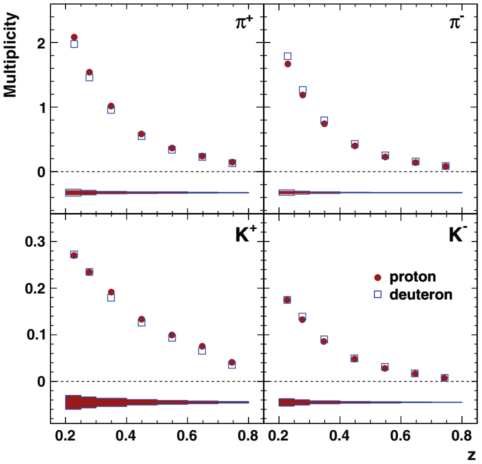
Observables: **Hadron Multiplicities**

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

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

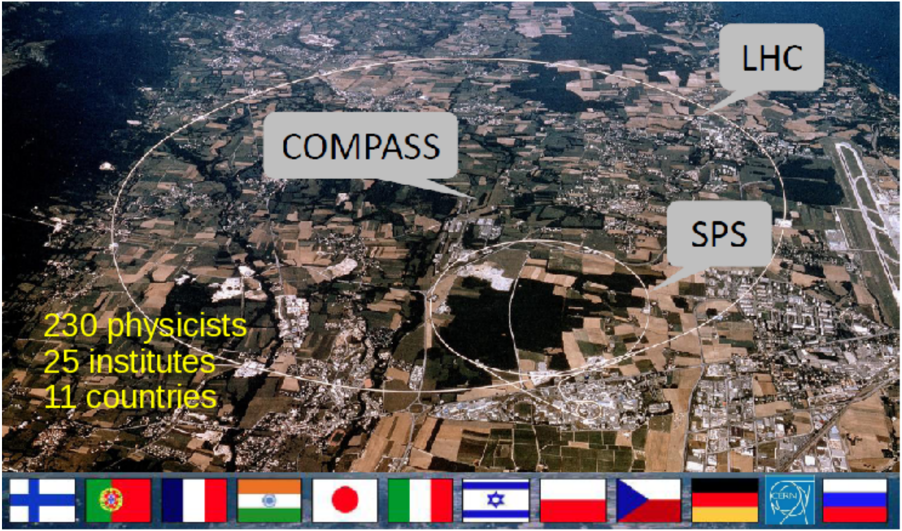
Latest HERMES data

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

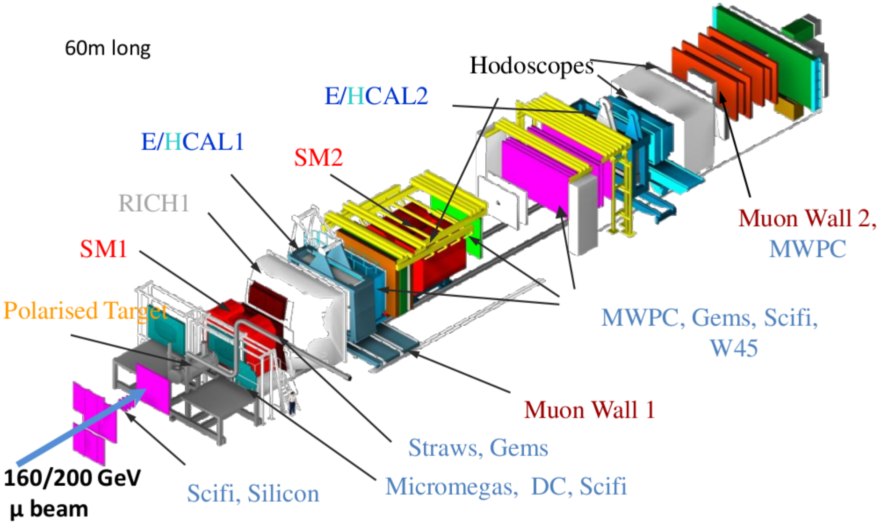


Phys.Rev.D 87 (2013), 074029

The COMPASS experiment at CERN



COMPASS spectrometer



Multiplicity measurement

$$M = \frac{N^h}{N_{\mathrm{DIS}}\,\Delta z}$$

Event selection

- Only "inclusive triggers"
- $Q^2 > 1$ GeV^2
- $0.1 < y < 0.9$ ($y = \nu/E_{\mathrm{beam}}$)

Hadron track selection

- $0.2 < z < 0.85$ (implies $x_F > 0$: current fragmentation)
- $X/X_0 < 15$ to eliminate μ's

"Acceptance" correction

- Simulate DIS events with some generator (LEPTO) $\Rightarrow M^{\mathrm{MC}}_{\mathrm{gen}}$
- Simulate the detector response and do the same analysis as for real data $\Rightarrow M^{\mathrm{MC}}_{\mathrm{rec}}$
- Correction factor for geom. acceptance and reconstruction efficiency: $a = M^{\mathrm{MC}}_{\mathrm{rec}}/M^{\mathrm{MC}}_{\mathrm{gen}}$
- Correct real data:

$$M_{\mathrm{cor}} = \frac{M_{\mathrm{raw}}}{a}$$

Multidimensional binning

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

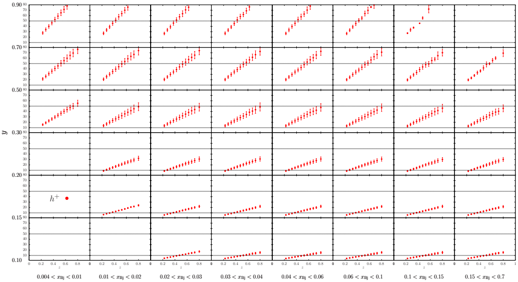
$$M^h(x,Q^2,z) = \frac{\sum_q e_q^2\left[q(x,Q^2)D_q^h(z,Q^2) + \bar{q}(x,Q^2)D_{\bar{q}}^h(z,Q^2)\right]}{\sum_q e_q^2\left[q(x,Q^2)+\bar{q}(x,Q^2)\right]} \quad \text{(LO)}$$

- Necessary for acceptance correction:
  minimises dependence on event generator

- We choose x_{Bj}, $y\ (=\nu/E_{\mathrm{beam}})$, z:

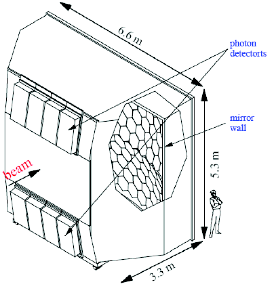
$$E_h = z\nu = zyE_{\mathrm{beam}}$$

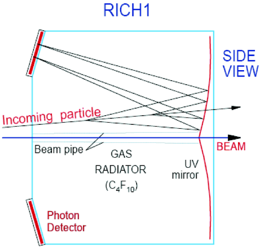
fixed y and z $\Rightarrow$ hadron momentum
well defined in each bin
$\Rightarrow$ mom. distr. in ev. gen.
is not important

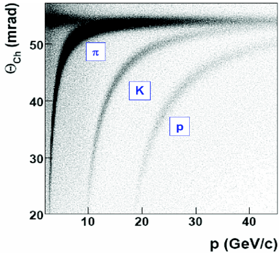


Particle identification

RICH detector ⇒ hadron identification in SIDIS







RICH characterisation

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

- Measure identif./misidentif. prob. matrix:

$$\begin{pmatrix} I_\pi \\ I_K \\ I_p \end{pmatrix} = \underbrace{\begin{pmatrix} P^{\pi\to\pi} & P^{K\to\pi} & P^{p\to\pi} \\ P^{\pi\to K} & P^{K\to K} & P^{p\to K} \\ P^{\pi\to p} & P^{K\to p} & P^{p\to p} \end{pmatrix}}_{=P} \begin{pmatrix} T_\pi \\ T_K \\ T_p \end{pmatrix}$$

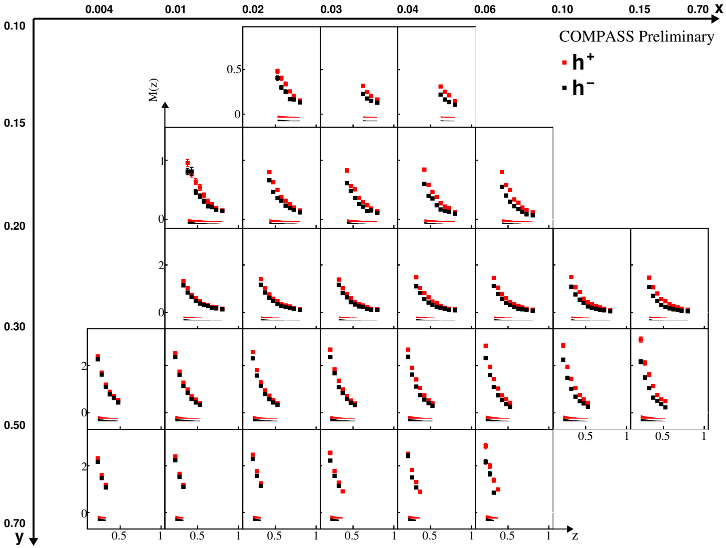
- Unfold data:

$$\boxed{\vec{T} = P^{-1}\vec{I}}$$

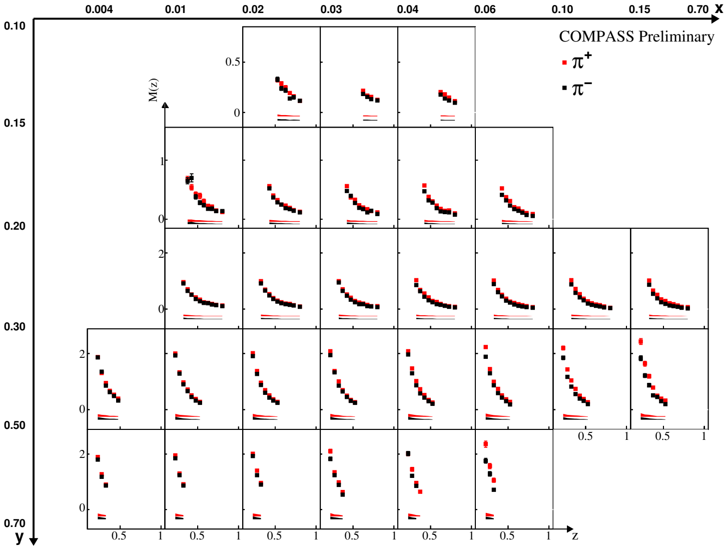
Recent results

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

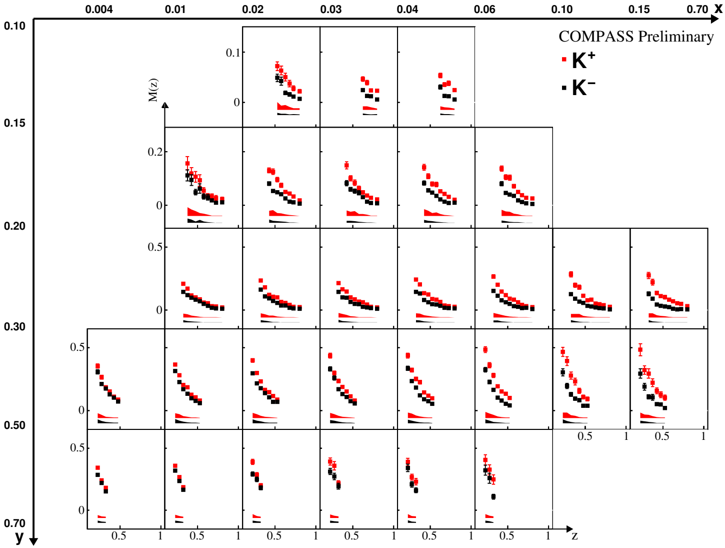
Multiplicities: Unidentified Hadrons



Multiplicities: Pions



Multiplicities: Kaons

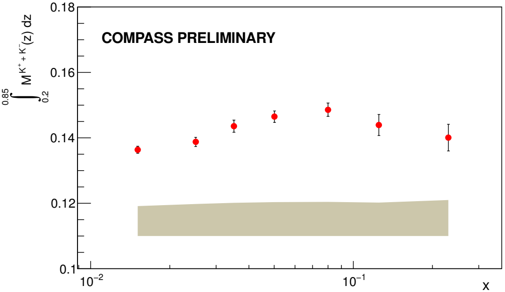


Kaon multiplicity sum: $K^+ + K^-$

For a deuteron target (using proton PDFs):

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

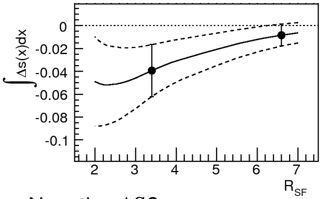
$$M^{K^+} + M^{K^-} = \frac{Q(x)D_Q + 2S(x)D_{str}}{5Q(x) + 2S(x)} \quad \text{(LO)}$$



$\Rightarrow$ **no visible x dependence!**

Speculations

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



- Negative ΔS?
- Or no sensitivity on strangeness?
- What about the Q^2-dependence?
- Other effects:
  NLO contributions?
  diffractive production?

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 ΔS

Inclusive measurements

From longitudinal double-polarisation asymmetry:

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

$$\Gamma_1 = \int_0^1 dx\, g_1(x) = \frac{1}{2}\sum_q e_q^2 \underbrace{\int_0^1 dx\ (\Delta q(x) + \Delta\bar{q}(x))}_{\equiv \Delta Q}$$

Isospin symmetry:

$$\Gamma_1^N \equiv \frac{1}{2}\left(\Gamma_1^{\mathrm{p}} + \Gamma_1^{\mathrm{n}}\right) = \frac{1}{36}\left[5\Delta\mathrm{U} + 5\Delta\mathrm{D} + 2\Delta\mathrm{S}\right]$$

With Γ_1^N, SU(3) and axial couplings from baryon β decays:

$$\begin{aligned} \Delta Q_8 &= \Delta\mathrm{U} + \Delta\mathrm{D} - 2\Delta\mathrm{S} \\ &= 3F - D = 0.585 \pm 0.025 \end{aligned}$$

$$\boxed{\Delta\mathrm{S} = 3\Gamma_1^N - \frac{5}{12}\Delta Q_8}$$

SIDIS measurements

$$A^h(x,z) = \frac{\sigma_h^{\uparrow\uparrow} - \sigma_h^{\uparrow\downarrow}}{\sigma_h^{\uparrow\uparrow} + \sigma_h^{\uparrow\downarrow}} \overset{\text{(LO)}}{=} \frac{\sum_q e_q^2 \left(\Delta q(x) D_q^h(z) + \Delta\bar{q}(x) D_{\bar{q}}^h(z)\right)}{\sum_q e_q^2 \left(q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)\right)} \Rightarrow \boxed{\Delta\mathrm{s}(x),\ \Delta\bar{\mathrm{s}}(x)}$$

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

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, α, β, γ, δ depend on the scale μ^2
- Fit on data available from all or some of the observables
- Several fits on the market, e.g.
  - KRE – Phys. Rev. D 62, 054001 (2000)
  - AKK – Nucl. Phys. B 803, 42 (2008)
  - HKNS – Phys. Rev. D 75, 094009 (2007)
  - DSS – Phys. Rev. D 75, 114010 (2007)