Final COMPASS Results on Hadrons, Pions and Kaons Multiplicities

M. Stolarski
LIP

On behalf of the COMPASS Collaboration

4-IV-2017
Outline

1. COMPASS @ CERN
2. Motivation
3. Multiplicity Extraction
3. Results
COMPASS Spectrometer 2006

- **COLLABORATION**
  - about 210 physicists
  - 27 institutes

- **DETECTOR**
  - two stage spectrometer
  - 60 m length
  - about 350 detector planes

- **TARGET**
  - \(^6\)LiD target
  - 3 cells (120 cm total length)

- **BEAM**
  - \(\mu^+\) at 160 GeV/c

- **FEATURES**
  - angular acceptance: \(\pm 180\) mrad
  - track reconstruction:
    - \(p > 0.5\) GeV/c
  - identification \(h, e, \mu\): calorimeters and muon filters
  - identification: \(\pi, K, p\) (RICH)
    - \(p > 2, 9, 18\) GeV/c respectively
Motivation

- Fragmentation functions (FF, $D^h_q$) describe parton fragmentation into hadrons.
- FF are needed in analyses which deal with a hadron(s) in the final state.
- In Leading Order QCD, $D^h_q$ describes probability density for a quark of flavour $q$ to fragment into hadron of type $h$.
- The cleanest way to access FFs is in $e^+e^-$ annihilation. However,
  - only sensitive to the sum of $q + \bar{q}$ fragmentation.
  - flavour separation possibilities are limited.
- In the SIDIS data, FF are convoluted with PDFs. However,
  - possibility to separate fragmentation from $q$ and $\bar{q}$.
  - full flavour separation possible.
- By studying $pp$ collisions with a high $p_T$ hadrons, access to gluon fragmentation functions.
- SIDIS data are crucial to understand quark fragmentation process.
Hadron multiplicities are defined as number of observed hadrons in a number of DIS events

\[ \frac{dM^h(x,z,Q^2)}{dz} = \frac{d^3\sigma^h(x,z,Q^2)/dx dQ^2 dz}{d^2\sigma^{DIS}(x,Q^2)/dx dQ^2} \]

Experimentally measured hadron multiplicities need to be corrected for various effects e.g.

- spectrometer acceptance & reconstruction program efficiency
- RICH efficiency & purity (for π and K)
- radiative corrections
- diffractive vector meson production
- ...
Results

Multiplicities of $\pi$ on Iso-Scalar Target

- COMPASS extracted $\pi^{\pm}$ multiplicities
- Results published in PLB 764 (2017) 001
- Some preliminary data were used in DSS+ fit.
- COMPASS performed LO fit, using HKNS FF programme
- Results agrees with world FFs.

As expected $D_{fav} > D_{unf}$
The $\pi$ Multiplicity Sum

- For iso-scalar target:

\[
\frac{dM_{\pi^+}}{dz} + \frac{M_{\pi^-}}{dz} = D_{\text{fav}} + D_{\text{unf}} - \frac{2S}{5Q^2 + 2S} (D_{\text{fav}} - D_{\text{unf}}) \approx D_{\text{fav}} + D_{\text{unf}}
\]

- $Q = u + \bar{u} + d + \bar{d}$; $S = s + \bar{s}$
- $D_{\text{fav}} = D_q^h$ where $q$ is valence quark of $h$
- $D_{\text{unf}} = D_q^h$ where $q$ is NOT valence quark of $h$
- $D(Q^2, z) \rightarrow$ obtained multiplicity sum is effectively independent of $x$
- in fixed target experiment $x$ and $Q^2$ are correlated, but $Q^2$ dependence of $z$ integrated FF is weak

- $\mathcal{M}_{\pi^+} + \mathcal{M}_{\pi^-} = \int_{0.2}^{0.85} \frac{dM_{\pi^+}}{dz} + \frac{dM_{\pi^-}}{dz} \, dz \text{ vs. } x \text{ should be almost flat}$

![Graphs](image_url)
The $\pi^+ / \pi^-$ Multiplicity Ratio

- The ratio of $\pi^+ / \pi^-$ or $(h^+ / h^-)$ is interesting to study due to significant cancellation of experimental systematic errors.
- Here, a good agreement between HERMES and COMPASS is seen.
- Difference between HERMES and JLab likely explained by different $W$.
- As previously there is a good agreement between COMPASS and EMC data for unidentified hadrons.

![Graph showing $\pi^+ / \pi^-$ and $h^+ / h^-$ ratios with data points from COMPASS, HERMES, and JLab E00-108 and EMC.]
Results

Multiplicities of Kaons on Iso-Scalar Target

- COMPASS extracted
  Kaon multiplicities
- More than 620 data points
- Recently published in
  PLB 767 (2017) 133
Kaon Multiplicity Sum and Ratio

For the iso-scalar target:

\[ 5\left( \frac{dM^+}{dz} + \frac{dM^-}{dz} \right) \approx D_Q^K + S/Q D_S^K \approx 4D_{\text{fav}}^K + 6D_{\text{unf}}^K + S/Q D_S^K \]

There are large differences observed between COMPASS and HERMES

- shape of the distribution at low \( x \)
- the value of \( M^+ + M^- \) at high \( x \rightarrow \int D_Q \)
- \( M^+ / M^- \) multiplicity ratio (which agrees for \( \pi \) case)
Kaon Multiplicity Ratio at High $z$

NEW!

- COMPASS measured kaon multiplicity ratio at high $z$
- High $z$ region is free from kaons coming from decays of diffractive production of $\phi$
- Why ratio?
  - radiative corrections largely cancel
  - a lot of experimental systematic uncertainties also cancels
  - DIS sample is not needed
- It was possible to extend studies for all 2006 data and also semi-inclusive triggers
  → Statistics was increased four fold w.r.t. published data
Motivation - Physics

- There are $e^+e^-$ measurements of multiplicities up to $z = 0.98$
- So far region $z > 0.85$ was not investigated in SIDIS
- In LO pQCD + independent fragmentation and proton target

$$\frac{dM_{K^+}^+}{dz} / \frac{dM_{K^-}}{dz} = \frac{4uD_{fav} + (4\bar{u} + d + \bar{d} + s)D_{unf} + \bar{s}D_{str}}{4\bar{u}D_{fav} + (4u + d + \bar{d} + s)D_{unf} + sD_{str}}$$

- So far all the studies show that $D_{unf} \approx 0$ for $z \approx 0.5$, Thus for data with $z > 0.75$, one can neglect it.

$$\frac{dM_{K^+}^+}{dz} / \frac{dM_{K^-}}{dz} < \frac{u}{\bar{u}}$$

$$\frac{dM_{K^+}^+}{dz} / \frac{dM_{K^-}}{dz} < \frac{u+d}{\bar{u}+d}, \text{ for deuteron target}$$
Motivation - Physics cont.

- Typical ratio $\frac{u+d}{u+d}$ at $Q^2 = 1.6$ (GeV/c)$^2$ and $x = 0.03$
  - $2.15$ MSTW08 LO, $2.05$ MRST04L
  - $1.90 \pm 0.10$ NNPDF3.0L, $2.35 \pm 0.20$ NNPDF2.3
  - $2.12 - 2.38$ NLO

- Note that in NLO, the limit can be broken ($\sim \frac{\alpha_S}{2\pi}$) as cross section formula is more complex

- In Lund string model the kaon multiplicity ratio (almost) fulfils the limit

![Graph](image.png)
Analysis

- We try to keep all the cuts as in the published kaon paper but,
  - $z$ range was extended above 0.85
  - stricter cuts on $K/\pi$ separation were applied
  - improved method of acceptance corrections was used
  - 4 times more data was used than in PLB 764 (2017) 133

- Here we concentrate in region of $x < 0.05$
  - $\langle x \rangle = 0.03$
  - $\langle Q^2 \rangle = 1.6(\text{GeV}/c)^2$
  - 40000 $K^+$ and $K^-$ analysed for $z > 0.75$
Results

COMPASS PRELIMINARY
isoscalar target
\langle x \rangle = 0.03, \langle Q^2 \rangle = 1.6 \text{ (GeV/c)}^2

not allowed in LO QCD (MSTW08L)

NO z unfolding, which would further increase the ratio
Observe clear discrepancy between LO QCD expectation and data
This discrepancy is even larger than presented in figure because of the $z$ smearing
Obtained result may mean that universality of FFs does not hold and/or factorisation is broken
Further calculations are welcome, also at higher orders

\[
\frac{dk^{+}}{dz} - \frac{dk^{-}}{dz} + \frac{dK_{0}}{dz} = 1.6 \text{ (GeV/c)}^2 
\]

COMPASS PRELIMINARY isoscalar target
\(\langle x \rangle = 0.03, \langle Q^2 \rangle = 0.03\) not allowed in LO QCD (MSTW08L)

COMPASS
LUND MC
LO DSS fit
An “hybrid method” was used consisting of
- smearing matrix \( z_{\text{generated}} \) vs \( z_{\text{reconstructed}} \) from MC
- functional form assumed for the \( K^+, K^- \) yields: \( \alpha \exp(-\beta z)(1 - z)^\gamma \)

As expected unfolding procedure further increases the ratio \( K^+/K^- \)

However, for \( z < 0.95 \) the unfolding impact is not that dramatic

### Diagram

**COMPASS PRELIMINARY**

**isoscalar target**

\( \langle x \rangle = 0.03, \langle Q^2 \rangle = 1.6 \text{ (GeV/c)}^2 \)

**unfolded ratio**
Strong dependence of the kaon multiplicity ratio on $\nu = E - E'$ is observed in certain $z$ bins.

In NLO QCD fits it should be difficult to describe COMPASS high $z$ and low $y$ data points of the published paper, PLB 767 (2017) 133.

Note that HERMES has lower $\nu$ than COMPASS.
COMPASS recently published final multiplicities for $h^\pm$, $\pi^\pm$ and $K^\pm$ from DIS on an iso-scalar target

- **PLB 764 (2017) 001, PLB 767 (2017) 133**
- Large sample of precise data vs ($x, y, z$) covering a wide kinematical range, constitute an important input for future FF global analyses

Preliminary results for the kaon multiplicity ratio $K^+/K^-$ at high $z$ were shown

- results are inconsistent with prediction of (N)LO pQCD
- they may indicate that factorisation and/or universality of FF is broken
- hints of the problem can already be noticed in the published data
- more calculations needed, possibly also at higher orders