COMPASS Results on Pion, Kaon and Unidentified Hadrons Multiplicities from SIDIS on Proton Target

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On behalf of the COMPASS Collaboration

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COMPASS Spectrometer 2016

COLLABORATION
- about 210 physicists
- 27 institutes

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

BEAM & TARGET
- \( \mu^\pm \) at 160 GeV/c
- Liquid H target, 250 cm

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(s), $D^h_q$) describe parton fragmentation into hadrons.
- In Leading Order pQCD, $D^h_q$ describes probability density for a quark of flavour $q$ to fragment into a 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, $\mu^\pm + p(d) \rightarrow \mu^{\pm'} + h + X$
  - possibility to separate fragmentation from $q$ and $\bar{q}$,
  - full flavour separation possible.
- FF are convoluted with PDFs.
- By studying $pp$ collisions with high $p_T$ hadrons, access to gluon fragmentation functions.
- SIDIS data are crucial to understand quark fragmentation process.
Multiplicity Measurement

- Fragmentation studies in SIDIS can be done using hadron multiplicity data
- Hadron multiplicities are defined as number of observed hadrons per DIS event
  \[
  \frac{dM^h(x,z,Q^2)}{dz} = \frac{d^3\sigma^h(x,z,Q^2)/dx dQ^2 dz}{d^2\sigma^{DIS}(x,Q^2)/dx dQ^2}
  \]
- Experimentally measured hadron multiplicities need to be corrected for e.g.
  - spectrometer acceptance and reconstruction program efficiency
  - RICH efficiency and purity (for $\pi$ and $K$)
  - QED radiative effects
  - diffractive vector meson production
- COMPASS already published several articles based on isoscalar target data
  - PLB 764 (2017) 001
  - PLB 767 (2017) 133
  - PRD 97 (2018) 032006
  - PLB 786 (2018) 390
  - PLB 807 (2020) 135600
- Today, preliminary results from the proton target are presented
Correction due to radiative effects is a multiplicative factor to the multiplicity itself, and can be large, especially at low $x$ and high $y$.

The DJANGOH programme is used for RC simulations.

It was tested against COMPASS data and the TERAD program.

As an example of the comparison, charged tracks transverse momentum squared w.r.t. $\mu$, $\mu'$ and $\gamma^*$ directions are shown below.
COMPASS was always showing results with and without our estimate for RC.

Thus, new RC results can be easily implemented to older COMPASS multiplicity papers.

Note: according to our present knowledge the data from PLB 764 (2017) 001 ($\pi^\pm$, $h^\pm$) need correction sometimes above 10%.
Data Selection and Kinematic Distributions

- DIS selection:
  - Reconstructed $\mu$ and $\mu'$,
  - $Q^2 > 1$ (GeV/c)$^2$, $W > 5$ GeV/c$^2$,
  - $0.1 < y < 0.7$, fraction of beam energy carried by virtual gamma

- Hadron cuts:
  - $0.2 < z < 0.85$, fraction of the virtual photon energy carried by a hadron
  - $12$ GeV/c < $p$ < $40$ GeV/c, $\theta < 0.12$, $|dy/dz| < 0.08$, PID cuts

- Analysis is performed in 9 bins of Bjorken $x$, 5 bins of $y$ and 12 bins of $z$

- Total sample: unidentified hadrons: 1.7M, $\pi$: 1.3M, K: 280k
Multiplicities of Unidentified Hadrons

COMPASS proton data preliminary

- $h^+$
- $h^-$

$x<0.01$

$0.10<y<0.15$

$0.01<x<0.02$

$0.02<x<0.03$

$0.03<x<0.04$

$0.04<x<0.06$

$0.06<x<0.10$

$0.10<x<0.14$

$0.14<x<0.18$

$x>0.18$

$0.15<y<0.20$

$0.20<y<0.30$

$0.30<y<0.50$

$0.50<y<0.70$

$z/d$ $h$ $M$ $d$

$y<0.10$

$0.10<y<0.2$

$0.2<y<0.3$

$0.3<y<0.4$

$0.4<y<0.5$

$0.5<y<0.6$

$0.6<y<0.7$

$0.7<y<0.8$

$0.8<y<1.0$

$z/0.2$ $0.4$ $0.6$ $0.8$ $z/0.4$ $0.6$ $0.8$ $z/0.8$ $0.2$ $0.4$ $0.6$ $0.8$ $z/2$ $0.4$ $0.6$ $0.8$ $z/4$ $0.4$ $0.6$ $0.8$ $z/8$ $0.2$ $0.4$ $0.6$ $0.8$ $z/16$ $0.2$ $0.4$ $0.6$ $0.8$ $z/32$ $0.2$ $0.4$ $0.6$ $0.8$ $z/64$ $0.2$ $0.4$ $0.6$ $0.8$ $z/128$ $0.2$ $0.4$ $0.6$ $0.8$
Multiplicities of $\pi^+$

COMPASS proton data
preliminary

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Multiplicities of $\pi^-$

COMPASS proton data preliminary

- $0.50 < y < 0.70, \alpha = 1.2$
- $0.30 < y < 0.50, \alpha = 0.9$
- $0.20 < y < 0.30, \alpha = 0.6$
- $0.15 < y < 0.20, \alpha = 0.3$
- $0.10 < y < 0.15, \alpha = 0.0$

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Multiplicities of $K^+$

COMPASS proton data preliminary

- $0.50 < y < 0.70, \alpha = 0.4$
- $0.30 < y < 0.50, \alpha = 0.3$
- $0.20 < y < 0.30, \alpha = 0.2$
- $0.15 < y < 0.20, \alpha = 0.1$
- $0.10 < y < 0.15, \alpha = 0.0$

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DIS 2024, Grenoble
Multiplicities of $K^-$

COMPASS proton data preliminary

- $0.50 < y < 0.70, \alpha = 0.4$
- $0.30 < y < 0.50, \alpha = 0.3$
- $0.20 < y < 0.30, \alpha = 0.2$
- $0.15 < y < 0.20, \alpha = 0.1$
- $0.10 < y < 0.15, \alpha = 0.0$

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Sum of Pion Multiplicities

- Let $D_{\text{fav},(\text{unf})} = D^h_q$ where $q$ is (not) the valence quark of $h$
- For proton and isoscalar targets in LO pQCD:
  \[ \frac{dM^+_{\pi}}{dz} + \frac{M^-_{\pi}}{dz} \approx D_{\text{fav}} + D_{\text{unf}}, \] i.e. results are expected to be very similar
- $D(Q^2, z)$ obtained from multiplicity sum is effectively independent of $x$
- $M^+_{\pi} + M^-_{\pi} = \int_{0.2}^{0.85} (\frac{dM^+_{\pi}}{dz} + \frac{dM^-_{\pi}}{dz}) dz$
Sum of Kaon Multiplicities

- Contrary to pion case, here $D_s^{K^-}, D_s^{K^+}$ are dominant, larger than e.g. $D_u^{K^+}$
- Since there are not too many $s, \bar{s}$ at high $x$, we should see some turn-on effect related to the increased density of strange quark PDFs at lower $x$
- Perhaps $x$ values accessed by COMPASS is too low to assure low density of $s, \bar{s}$

\[ \mathcal{M}^{K^+} + \mathcal{M}^{K^-} = \int_{0.2}^{0.85} \left( \frac{dM^{K^+}}{dz} + \frac{dM^{K^-}}{dz} \right) dz \]
In the multiplicity ratio a lot experimental and theoretical uncertainties cancel

In LO pQCD one can calculate a lower limit for the ratio

\[ R_K(x, Q^2, z) = \frac{dM_{K^-}(x, Q^2, z)/dz}{dM_{K^+}(x, Q^2, z)/dz} > \frac{\bar{u} + \bar{d}}{u + d} \]

\[ R_p(x, Q^2, z) = \frac{dM_{\bar{p}}(x, Q^2, z)/dz}{dM_p(x, Q^2, z)/dz} > \frac{\bar{u} + \bar{d}}{u + d} \]

The lower limits predicted by LO pQCD for \( R_K \) and \( R_p \) are the same

Actual value of \( R_K \) is expected to be 10-15% higher than \( R_p \) because of large \( D_{str} \)

\( R_\pi \) suffers from large contamination of decay products of diffractive \( \rho^0 \)
$R_K$ and $R_p$ from Isoscalar Target

- Results published PLB 786 (2018) 390 and PLB 807 (2020) 135600
- At high $z$, $R_K$ and $R_p$ are found below lower limits expected from pQCD in (N)LO
- Kaon results presented for $x < 0.05$
- Effect more pronounced for $\bar{p}/p$ and starts at lower $z$
Summary

- SIDIS data are crucial for understanding quark fragmentation into hadrons
- COMPASS already published several papers based on isoscalar data analysis
- Today, results for $h^\pm$, $\pi^\pm$, $K^\pm$ multiplicities on proton target were shown
- Impact of Radiative Correction is larger than originally anticipated in early isoscalar data analyses
- Analysis is considered as finished - paper is in preparation