COMPASS legacy results concerning longitudinal spin structure of the nucleon

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**COMPASS**

Common Muon Proton Apparatus for Structure and Spectroscopy

Main task: study of hadron structure and spectroscopy

Data taking since 2002

Participants:
- \(~240\) scientists
- 28 institutions from 12 countries

LHC

COMPASS

SPS

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COMPASS legacy results

HADRON’17, 24-29 Sept.
C0mmon Muon and Proton Apparatus for Structure and Spectroscopy

TARGET:

120 cm total length
2 or 3 cells, oppositely polarised material: $^6$LiD or NH$_3$

polarisation: about 50% or 90%

2.5 T solenoid field

Polarised BEAM: about 80%

$\mu^+$ at 160 (200) GeV/c

FEATURES

angular acceptance: $\pm 180$ mrad

track reconstruction: $p > 0.5$ GeV/c

$h, e, \mu$ identification: calorimeters and muon filters

$\pi, K, p$ identification (RICH);

$p > 2, 9, 18$ GeV/c, respectively

DETECTOR

two stage spectrometer

60 m length

about 350 detector planes

COMPASS spectrometer for muon run, NIMA 577 (2007) 455
Nucleon spin structure in DIS: $\mu + N \rightarrow \mu' + X$

Definitions of DIS variables...

- $Q^2 = -q^2$ \quad $\gamma^*$ virtuality
- $x = Q^2/(2Pq)$ \quad Bjorken variable
- $y = Pq/(Pk)$ \quad relative $\gamma^*$ energy
- $W = P + q$ \quad $\gamma^*$-N cms energy

...and of the $\gamma^*$-N asymmetry (e.g. for $\gamma^*$-p):

$A_1(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$

Specifications:

- $\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2Mq^4} \frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpolarised DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}$, $q(x, Q^2) \rightarrow g_{1,2}$, $\Delta q(x, Q^2)$
- $q = q^+ + q^-$, $\Delta q = q^+ - q^-$, but...
- ...anomalous gluon contribution to $g_1(x, Q^2)$
- ...$g_2(x, Q^2)$ has no interpretation in terms of partons.

slide from B. Badelek, “Low x 2017”
Results on $A_1(x)$ and $g_1(x)$ at the measured values of $Q^2$

- Good agreement of new COMPASS $A_1(x)$ and $g_1(x)$ with world data
- $g_1^p(x)$ clearly positive at lowest measured $x$; $g_1^d(x)$ compatible with zero
The asymmetry $A_p^1$ as a function of $Q^2$ in bins of $x$

In none of the $x$ bins, a significant $Q^2$ dependence is observed.
World data on $g_1^p$ and $g_1^d$, $Q^2 > 1$ (GeV/c)^2

Continuous line: COMPASS NLO QCD fit to the world data, $W^2 > 10$ (GeV/c^2)^2
Dashed line: extrapolation to $W^2 < 10$ (GeV/c^2)^2


Data little sensitive to $\Delta g$
Flavour separation using SIDIS data

SIDIS permits to separate $q$ and $\bar{q}$ distributions, in LO:

\[ A_1^h = \frac{\sum_q e_q^2 \Delta q(x) \int D_q^h(z)dz}{\sum_q e_q^2 q(x) \int D_q^h(z)dz} \]

COMPASS: measured on both proton and deuteron targets for $\pi^+$, $\pi^-$, $K^+$, $K^-$

COMPASS: LO DSS FFs and LO unpolarised MRST assumed

NLO parametrisation of DSSV describes the data well

\[ \Delta S = \int_0^1 (\Delta s(x) + \Delta \bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.02 \] from DIS + SU(3), while from SIDIS it is compatible with zero but depends upon chosen FFs

Most critical:

\[ R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz} \]


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Most critical:

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Direct measurements of $\Delta g(x)$

Direct measurements via the cross section asymmetry for the photon-gluon fusion (PGF) with subsequent fragmentation into $c\bar{c}$ (LO, NLO) or $q\bar{q}$ (high $p_T$ hadron pair (LO)): $A_{\gamma N}^{PGF} \approx \langle a_{LL}^{PGF} \rangle \frac{\Delta g}{g}$

COMPASS, EPJC 77 (2017) 209

COMPASS from SIDIS on $d$ for any $(p_T)_h$ and at LO:
$\Delta g/g = 0.113 \pm 0.038\,(\text{stat.}) \pm 0.036\,(\text{syst.})$ at $\langle Q^2 \rangle \approx 3\,(\text{GeV}/c)^2$, $\langle x_g \rangle \approx 0.1$

clearly positive gluon polarisation!
Fragmentation functions (FFs, $D_{qh}^h$)

- FFs describe parton fragmentation into hadrons
- FFs are needed in analysis which deals with a hadron(s) in the final state
- In Leading Order QCD, $D_{qh}^h$ 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 SIDIS data, FFs 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
Multiplicity measurement

- Hadron multiplicities are defined as number of observed hadrons in a number of DIS events, in LO

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

where \( z \) is a fraction of the virtual photon energy carried by a hadron

- Experimentally measured hadron multiplicities need to be corrected for various effects, e.g.
  - spectrometer acceptance and reconstruction program efficiency
  - RICH efficiency and purity (for \( \pi \) and \( K \))
  - radiative corrections
  - diffractive vector meson production
Multiplicities of $\pi^{\pm}$ on isoscalar target

- Results published in PLB 764 (2017) 001
- Some preliminary data were used in DSS+ fit
- COMPASS performed LO fit, using HKNS FF program
- Results agree with world FFs. As expected $D_{fav} > D_{unf}$
The $\pi$ multiplicity sum

For iso-scalar target:

$$\frac{dM^{\pi^+}}{dz} + \frac{dM^{\pi^-}}{dz} = D_{fav} + D_{unf} - \frac{2S}{5Q+2S}(D_{fav} - D_{unf}) \approx D_{fav} + D_{unf}$$

- $Q = u + \bar{u} + d + \bar{d}; S = s + \bar{s}$
- $D_{fav} = D_{q}^h$ where $q$ is a valence quark of $h$
- $D_{unf} = D_{\bar{q}}^h$ where $q$ is NOT a 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

$$M^{\pi^+} + M^{\pi^-} = \int_{0.2}^{0.85} \left( \frac{dM^{\pi^+}}{dz} + \frac{dM^{\pi^-}}{dz} \right) dz \text{ vs. } x \text{ should be almost flat}$$
The $\pi^+ / \pi^-$ multiplicity ratio

- Significant cancellation of experimental systematic errors
- A good agreement between HERMES and COMPASS
- Difference between HERMES and JLab likely explained by different $W$
- A good agreement between COMPASS and EMC data for unidentified hadrons
Multiplicities of $K^\pm$ on isoscalar target

- More than 620 data points
- Results published in PLB 767 (2017) 133
Kaon multiplicity sum and ratio

For iso-scalar target:

\[ 5\left(\frac{dM^{K^+}}{dz} + \frac{dM^{K^-}}{dz}\right) \approx D^K_Q + S/Q D^K_S \approx 4D^K_{fav} + 6D^K_{unf} + S/Q D^K_S \]

There are large differences observed between COMPASS and HERMES:

- shape of the distribution at low \( x \)
- the value of \( M^{K^+} + M^{K^-} \) at high \( x \) \( \rightarrow \int D_Q \)
- \( M^{K^+} / M^{K^-} \) multiplicity ratio (while agrees for \( \pi \) case)
Kaon multiplicity ratio at high $z$: physics motivation

- 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 QCD + independent fragmentation and proton target

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

So far, all the studies show that $D_{unf} \approx 0$ for $z \approx 0.5$

$\Rightarrow$ for data with $z > 0.75$, one can neglect it

$$\frac{dM_{K^+}}{dz} \frac{dz}{dM_{K^-}} = \frac{4uD_{fav} + \bar{s}D_{str}}{4\bar{u}D_{fav} + sD_{str}}$$, or

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

- For isoscalar target:

$$\frac{dM_{K^+}}{dz} \frac{dz}{dM_{K^-}} < \frac{u+d}{\bar{u}+d}$$
Kaon multiplicity ratio at high $z$: physics motivation

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

- Note, that in NLO the cross section formula is more complex ($\sim \alpha_S/2\pi$)

- In Lund string model the kaon multiplicity ratio goes (almost) in the LO QCD allowed region

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Kaon multiplicity ratio at high $z$ from COMPASS

• High $z$ region is free from kaons coming from decays of diffractively produced $\phi$

• Why ratio?
  ▶ radiative corrections largely cancel
  ▶ experimental systematic uncertainties are also mostly canceled out
  ▶ DIS sample is not needed

• COMPASS can and DID measure kaon multiplicity ratio at high $z$
Kaon multiplicity ratio at high $z$ from COMPASS 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 767 (2017) 133

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

- 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 indicate that factorisation and/or universality of FF does not hold in the studied region
- Further calculations are welcome, also at higher orders

No $z$ unfolding, which would further increase the ratio
Kaon multiplicity ratio at high $z$ from COMPASS

$z$ unfolded kaon multiplicity ratio

- A “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: $\alpha e^{-\beta z} (1 - z)^\gamma$

- As expected, unfolding procedure further increases the ratio $K^+/K^-$
- However, for $z < 0.95$ the unfolding impact is not that dramatic

![Graph showing the unfolded kaon multiplicity ratio](image)
Summary

DIS gave and is giving fundamental contributions to the study of the nucleon structure. The COMPASS contribution is remarkable:

- **Structure functions** $g_1^d$ and $g_1^p$ (PLB 753 (2016) 18, and PLB 769 (2017) 034)
- **Helicity PDFs** (PLB 693 (2010) 227, and EPJC 77 (2017) 209)
- $h^\pm$, $\pi^\pm$, and $K^\pm$ multiplicities from DIS on an isoscalar target
  - Large sample of precise data vs. $(x, y, z)$ covering a wide kinematical range, constitute an important input for future FF global analysis
  - PLB 764 (2017) 001, and PLB 767 (2017) 133
- **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 does not hold in the studied region
  - Hints of the problem can already be noticed in the published data
  - More calculations are needed, possibly also at higher orders