Studying nucleon partonic structure with the COMPASS unpolarised Drell-Yan programme

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Outline

• COMPASS facility at CERN
• Nucleon Tomography at COMPASS
• Experimental Set-up
• Kinematics and Acceptance
• Physics Run in 2015
• Reachable Physics from COMPASS-DY
• Feasibility for COMPASS (beyond 2020)
• Reachable Physics from Future COMPASS-DY
• Summary
Drell-Yan experiment at COMPASS

- **2014**: DY Pilot Run (without target polarisation)
  17 days of stable data taking
- **2015**: DY Physics Run (1st year)
  4 months of stable data taking
- **2016-2017**: DVCS Run
- **2018**: DY Physics Run (2nd year)
COMPASS facility at CERN

**COMPASS**

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

- Fixed target experiment at the end of M2 SPS beam line
- Nearly 220 physicists from 13 countries and 24 institutions
Beam:
- Polarized lepton beam: $\mu^+$, $\mu^-$ 50-280 GeV/c
- Hadron beam: $\pi^+$, $\pi^-$, $K^+$, $K^-$, $p$

Target:
- Polarized proton and deuteron target
- Liquid hydrogen target
- Nuclear targets

Powerful tracking system: 350 planes
PID: $\mu$-Walls, Calorimeters, RICH

Various Combinations of Beam & Target

Target Region
Large Angle Spectrometer (LAS)
Small Angle Spectrometer (SAS)

ECAL & HCAL
GEM, SciFi
MicroMega, DC, straw
MWPC, GEM, SciFi
MW1
MW2

SM1
SM2

RICH

Beam:

COMPASS facility at CERN
Nucleon Tomography

Wigner Distributions

\[ W(x, \vec{b}_\perp, \vec{k}_\perp) \]

\[ \int d\vec{b}_\perp \int d\vec{k}_\perp \]

Momentum tomography

\[ f(x, \vec{k}_\perp) \]

\[ \int d\vec{k}_\perp \]

Spatial tomography

\[ H(x, \vec{b}_\perp) \]

\[ \int d\vec{b}_\perp \int dx \]

Longitudinal momentum density

\[ f(x) \]

\[ \int dx \]

Spatial density

\[ F(\vec{b}_\perp) \]

Form Factors

Transverse Momentum Dependent distribution functions

TMDs

GPDs

Generalized Parton Distributions

PDFs

1D

3D

5D

Wigner Distributions

Spatial density

Form Factors
Nucleon Tomography at COMPASS

Wigner Distributions

\[ W(x, \vec{b}_\perp, \vec{k}_\perp) \]

\[ \int d\vec{b}_\perp \]

\[ \int d\vec{k}_\perp \]

Momentum tomography

Spatial tomography

5D

3D

\[ f(x, \vec{k}_\perp) \]

\[ H(x, \vec{b}_\perp) \]

SIDIS

Drell-Yan

TMDs

GPDs

DVCS

COMPASS I (2002-2011)

- Longitudinally polarised DIS and SIDIS
- Transversely polarised SIDIS
- Hadron spectroscopy
- Pion polarisability

COMPASS II (2012-2018)

- DVCS
- Transversely polarised Drell-Yan
- Hadron spectroscopy

This talk (unpol. DY)

Next talk (pol. DY)
COMPASS for Drell-Yan setup

**Beam**
- 190 GeV/c $\pi^-$
- Intensity: $10^8 \pi^-$/s

**Magnet**
- Solenoid: 2.5 T
- Dipole: 0.5 T

**Polarized NH$_3$ targets**
- Dilution factor: 0.22
- Polarization: > 90%

**Hadron Absorber**
- Large Stopping Power for hadrons
- Small Multiple Scattering for leptons
- Radiation Shielding

**Stainless Stell Alumina (Al$_2$O$_3$)**
+ Surrounded by concrete on each side

**Vertex Detector**

**Nuclear Targets**
(Unpolarised)
Kinematics and Acceptance

- The COMPASS acceptance covers the **valence quark region**
- \(<P_T> \sim 1\text{GeV} – TMDs induced effects expected to be dominant with respect to the higher QCD corrections**
The COMPASS acceptance covers the **valence quark region**

\(<P_T> \sim 1\text{GeV} – \text{TMDs induced effects expected to be dominant with respect to the higher QCD corrections}\)

### Kinematics and Acceptance


**u-quark Sivers from SIDIS**

\(-x f_T^{(1)} u(x)\)  

\(Q^2=25\text{ GeV}^2\)

- **Generated**
- **Accepted**

**Large detector acceptance (~40%)**
Typical acceptance of the DY experiments performed so far was 4-6% (NA10, NA50, E615)

Large detector acceptance (~40%)
Drell-Yan – Physics run in 2015

Beam
- 190 GeV/c $\pi^-$
- Intensity: $10^8 \pi^-/s$

Polarized NH$_3$ targets

Vertex Detector

Hadron Absorber

Al

W beam plug

Z-coordinate of vertex distribution for $\mu^+\mu^-$ pairs

Blue(filled): Events used for analysis

COMPASS ongoing analysis
Drell-Yan 2015 data (~30%)
$4 < M_{\mu\mu}/(\text{GeV}/c^2) < 9$
Drell-Yan – Physics run in 2015

Polarized NH₃ targets

COMPASS ongoing analysis
Drell-Yan NH₃ 2015 data (~30%)

Blue(filled):
Events used for analysis

W beam plug

COMPASS ongoing analysis
Drell-Yan W 2015 data (~30%)
Polarized NH₃ targets

- **Intermediate Mass Region**  \( (2 < M_{\mu\mu} < 2.5 \text{ GeV}/c^2) \)
  - High DY cross section
  - Open-charm
  - Combinatorial background

- **J/ψ Region**  \( (2.5 < M_{\mu\mu} < 4 \text{ GeV}/c^2) \)
  - J/ψ dominant

- **High Mass Region**  \( (4 < M_{\mu\mu} < 9 \text{ GeV}/c^2) \)
  - Clean DY signal (Negligible background)
  - Low cross section
Reachable Physics from Current COMPASS-DY

**Beam:** $\pi^-$

**Target:** NH$_3$(polarised/unpolarised), Al, W

**Observable physics process:**
- (final state : 2mu): $J/\psi$, DY, ($\psi'$), $\Upsilon$, (open-charm)
- (3mu): open-beauty
- (4mu): double $J/\psi$

**Observables and physics:**

- Angular distributions from polarised NH$_3$ target:
  - Sivers functions of valence quarks in proton (DY)

- from unpolarised NH$_3$, Al, W:
  - Boer-Mulders functions of valence quarks in proton (DY)
  - Lam-Tung violation (DY)
  - Higher Twist & Pion DA (DY at large $x_1$)

- A-dependence of $x_1$, $x_F$ distributions (DY, $J/\psi$):
  - Quark energy loss in the cold nuclear matters

- Absolute production cross sections (DY, $J/\psi$, (double $J/\psi$)):
  - pion PDF
  - $J/\psi$ production mechanism

- $\Upsilon$ and open-beauty production

(Blue) Physics from unpolarised nucleon
Reachable Physics from Current COMPASS-DY

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**Target:** NH$_3$(polarised/unpolarised), Al, W  
**Observable physics process:**  
(final state : 2mu): $J/\psi$, DY, ($\psi'$), $\Upsilon$, (open-charm)  
(3mu): open-beauty  
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Absolute production cross sections (DY, $J/\psi$, (double $J/\psi$)):
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$\Upsilon$ and open-beauty production

A-dependence of $P_T$ distributions (DY, $J/\psi$):
- EMC effect
- $J/\psi$ formation

Next page
Drell-Yan decay angular distributions

Collins-Soper frame

$\theta$ and $\phi$ are the decay polar and azimuthal angles of the $\mu^+$ in the dilepton rest-frame.

\[
\frac{d\sigma}{d\Omega} \propto (1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi) \\
\propto (W_T (1 + \cos^2 \theta) + W_L (1 - \cos^2 \theta) + W_\Delta \sin 2\theta \cos \phi + W_\Delta \sin^2 \theta \cos 2\phi)
\]

$q\bar{q}$ annihilation parton model:

$O(\alpha_s^0) \quad \lambda = 1, \mu = \nu = 0; \quad W_T = 1, W_L = 0$

Lam-Tung relation (1978): test of QCD effect

Collinear pQCD: $O(\alpha_s^1), \quad W_L = 2W_\Delta; \quad 1 - \lambda - 2\nu = 0$
Violation of Lam-Tung Relation (1)

CERN NA10

\[ \pi^- + W \ 140 \text{ GeV} \quad \pi^- + W \ 194 \text{ GeV} \quad \pi^- + W \ 286 \text{ GeV} \]

\[ P_T[\text{GeV}] \]

LT relation was violated at large \( p_T \)

1 - \( \lambda \) - 2\( \nu \) = 0
Violation of Lam-Tung Relation (2)

**FNAL E615**

252-GeV $\pi^- + W$

$\cos 2\phi$ modulation at large $p_T$

$1 - \lambda - 2\nu = 0$
Spin-orbit correlation of transversely polarized noncollinear partons inside an unpolarized hadron

\[ h_1^\perp = \]  

- Boer-Mulders Function \( h_1^\perp \): a correlation between quark's \( k_T \) and transverse spin \( S_T \) in an unpolarized hadron

- \( h_1^\perp \) can lead to an azimuthal dependence with \( \frac{\nu}{2} \propto h_1^\perp(N)\bar{h}_1^\perp(\pi) \)

\[ h_1^\perp(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x), \]

\[ \nu = 16k_1 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}, \quad k_1 = C_{H1} C_{H2}/2 \]

\[ \kappa = \frac{\nu}{2} \to 0 \text{ for large } |k_T| \]

Consistency of factorization in term of TMDs
Projected Uncertainties

- 30% of 2015 data
- $\pi^-$ beam, NH$_3$ target
- $4 \leq M_{\mu\mu} \leq 9$ GeV/c$^2$

**Sivers**

- COMPASS Drell-Yan NH$_3$ 2015 data (~30%)
- Estimated uncertainties (ongoing analysis)
- $4 < M_{\mu\mu}$(GeV/c$^2$) < 9

**Boer-Mulders**

- COMPASS Drell-Yan NH$_3$ 2015 data (~30%)
- Estimated uncertainties (ongoing analysis)
- $4 < M_{\mu\mu}$(GeV/c$^2$) < 9

**Pretzelosity**

- COMPASS Drell-Yan NH$_3$ 2015 data (~30%)
- Estimated uncertainties (ongoing analysis)
- $4 < M_{\mu\mu}$(GeV/c$^2$) < 9

**Transversity**

- COMPASS Drell-Yan NH$_3$ 2015 data (~30%)
- Estimated uncertainties (ongoing analysis)
- $4 < M_{\mu\mu}$(GeV/c$^2$) < 9

Proton BM extracted from SIDIS or pp/pd DY

- Measurement of $A_T \propto h_{1,\pi}^{q} \otimes h_{1,p}^{q}$
- Proton BM
- (Model dependent)
Feasibility for COMPASS (beyond 2020)

First ideas: submitted to European Strategy Preparatory Group, 2012

- Hadron Spectroscopy: 280 GeV, \(\pi, K, \bar{p}\) separation
- GPD \(E\): Measurements with a polarised target
- SIDIS: 100 GeV, transversely polarised \(p\) and \(d\) targets
- Drell-Yan: Transversely polarised \(d\) and \(p\) targets, Unpolarised \(p\), \(d\) targets, Nuclear targets (EMC effect), \(\pi, K, \bar{p}\) separation

Dedicated workshop before proposal:

[Link to workshop information]

Mar. 2016
Unseparated $\pi/K/\bar{p}$ beams and beam PID

Fraction of particles in the positive or negative M2-Hadron-beam at COMPASS target

Beam PID by CEDAR (Cerenkov Differential Counters with Achromatic Ring Focus)

http://www.staff.uni-mainz.de/jasinsk/index.htm
# Possibility of RF Separated $\pi/K/\bar{p}$ Beam?

First and very preliminary thoughts, guided by:
- recent studies for P326
- CKM studies by J.Doornbos/TRIUMF, e.g. http://trshare.triumf.ca/~trjd/rfbeam.ps.gz

E.g. a system with two cavities:

\[
DF = 2p \left( \frac{L}{c} \right) (b_1^{-1} - b_2^{-1}) \quad \text{with} \quad b_1^{-1} - b_2^{-1} = \frac{(m_1^2 - m_2^2)}{2p^2}
\]

## Table: Particle Characteristics

<table>
<thead>
<tr>
<th>Particle type</th>
<th>From CKM beam</th>
<th>Antiproton beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum (GeV/c)</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Momentum spread (%)</td>
<td>±1</td>
<td>±2</td>
</tr>
<tr>
<td>Angular emittance $H,V$ (mrad)</td>
<td>±3.5, ±2.5</td>
<td>±3.5, ±2.5</td>
</tr>
<tr>
<td>Solid angle ($\mu$sterad)</td>
<td>10-12$\pi$</td>
<td>10-12$\pi$</td>
</tr>
<tr>
<td>% wanted particles lost on dump</td>
<td>37</td>
<td>20</td>
</tr>
</tbody>
</table>

Kaon and Anti-Proton Flux possibly reaching $10^7 p./s$
Reachable Physics from **Future COMPASS-DY**

**Beam:** $\pi^-, K^-, \bar{p}$

**Target:** polarised NH$_3$, $^6$LiD

unpolarised Long-LH$_2$, Long-LD$_2$, Nuclear targets

**(Blue) Physics from unpolarised nucleon**

**Observables and physics:**

Angular distributions

- with $\pi^-$ beam and trans. polarised $^6$LiD target
  - flavor separation of Sivers

- with $\bar{p}$ beams and trans. polarised NH3 target
  - Model independent extraction of the proton Sivers- and Boer-Mulders

  ↓

- with $\pi^- / K^-$ beams
  - Boer-Mulders quark distributions for Pions and Kaons

with $K$ beam (and long-LH$_2$ target)

- Nucleon strange quark structure
- Kaon PDFs

with $\pi^- / K^- / \bar{p}$ beams

- Differentiating the origin of Lam-Tung violation
- $\pi / K / \bar{p}$ Distribution Amplitude

with Long-LD$_2$ and nuclear targets

- EMC effect

- with lower momentum $\pi^-$ beam
  - Exclusive production near $x_F \rightarrow 1$
    (DY, J/ψ): GPD and pion DA
Reachable Physics from **Future COMPASS-DY**

**Beam:** $\pi^−, K^−, \bar{p}$  
**Target:** polarised NH$_3$, $^6$LiD  
unpolarised Long-LH$_2$, Long-LD$_2$, Nuclear targets

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**Observables and physics:**

**Angular distributions**

- with $\pi^−$ beam and trans. polarised $^6$LiD target  
  - flavor separation of Sivers

- with $\bar{p}$ beams and trans. polarised NH3 target  
  - Model independent extraction of the proton Sivers- and Boer-Mulders

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  - $\pi/ K/ \bar{p}$ Distribution Amplitude

- with Long-LD$_2$ and nuclear targets  
  - EMC effect

- with lower momentum $\pi^−$ beam  
  - Exclusive production near $x_F \to 1$  
  (DY, J/ψ): GPD and pion DA
Model independent extraction of the proton BM function

Boer-Mulders from $\bar{p}p$ DY

$$A_U^{\cos 2\varphi} \propto h_{1,\bar{p}}^{\perp q} \otimes h_{1,p}^{\perp q}$$
beam BM target BM

DY from anti-proton beam and (polarised) proton target can be used to achieve a model independent extraction of the proton (Sivers-) and Boer-Mulders quark distributions.

After extracting the proton BM

DY from pion/Kaon beams and LH$_2$ target
$\rightarrow$ pion/Kaon BM
Summary

- COMPASS collaboration at CERN have performed a series of Drell-Yan experiments using a high-intensity $\pi^-$ beam with momentum 190-GeV/c impinging on a transversely polarised NH$_3$ target and unpolarised Al and W targets in 2015. A second year of data taking will be performed in 2018.
  - The experiment provides a greatly improved statistics for the unpolarised Drell-Yan and J/$\psi$ measurements w.r.t. past experiments.

- We hope it will have a continuation as well in future (beyond 2020)
  - DY program with Improved CEDAR/RF-separated beam and LH$_2$/LD$_2$/nuclear targets will bring unique opportunities to address many important unresolved issues in understanding the flavor and TMD structures of proton, antiproton, pion, kaon and nuclei.