Meson and proton structure in the new QCD facility at the M2 beam line at CERN

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on behalf of COMPASS++/AMBER working team
Motivations

**Pion**
- $M_\pi \sim 140\text{MeV}$
- Spin 0
- 2 light valence quarks
- 2 TMD PDFs at LT

**Kaon**
- $M_K \sim 490\text{MeV}$
- Spin 0
- 1 light and 1 “heavy” valence quarks
- 2 TMD PDFs at LT

**Proton**
- $M_p \sim 940\text{MeV}$
- Spin 1/2
- 3 light valence quarks
- 8 TMD PDFs at LT

3 QCD objects, different structures, different properties, understanding differences and similarities teaches us about QCD
Almost all what we know about pion structure

Example with three fits:

- Large uncertainties or not even at all
- Not enough data to directly constrain all PDFs → use of: momentum sum rules, constituent quark model...
- Sea no direct constraints

More data is needed, with better control of uncertainties, and full error treatment.

How to access the sea

**DIS with di-jet and leading neutron**

\[ F_2^{LN}(x_L = 0.73) / \Gamma_N, \Gamma_N = 0.13 \]

- **Wide \( x \) coverage**
- Estimation of pion flux introduces a strong model dependence

**Drell-Yan NA3**

Badier et al., Z. Phys. C18, 1983

- Limited statistics:
  - 4.7k \( \pi^- \)-event (shown)
  - 1.7k \( \pi^+ \)-event
- Heavy nuclear target (Pt)
Pion Sea-Valence separation in Drell-Yan

With $\pi^+$ and $\pi^-$ beam with an isoscalar target:

\[
\begin{align*}
\sigma(\pi^+ d) &\propto \frac{4}{9} [u^\pi \cdot (\bar{u}_s^P + \bar{d}_s^P)] + \frac{4}{9} [\bar{u}_s^\pi \cdot (u^P + d^P)] + \frac{1}{9} [\bar{d}_s^\pi \cdot (d^P + u^P)] + \frac{1}{9} [d_s^\pi \cdot (\bar{d}_s^P + \bar{u}_s^P)] \\
\sigma(\pi^- d) &\propto \frac{4}{9} [u_s^\pi \cdot (\bar{u}_s^P + \bar{d}_s^P)] + \frac{4}{9} [\bar{u}_s^\pi \cdot (u^P + d^P)] + \frac{1}{9} [\bar{d}_s^\pi \cdot (d^P + u^P)] + \frac{1}{9} [d_s^\pi \cdot (\bar{d}_s^P + \bar{u}_s^P)]
\end{align*}
\]

- Assumption:
  - Charge conjugation and SU(2)$_f$ for valence:
    \[u_v^\pi^+ = \bar{u}_v^\pi^- = \bar{d}_v^\pi^+ = d_v^\pi^+\]
  - Charge conjugation and SU(3)$_f$ for sea:
    \[u_s^\pi^+ = \bar{u}_s^\pi^- = u_s^\pi^- = \bar{u}_s^\pi^+ = \bar{d}_s^\pi^+ = d_s^\pi^+ = \bar{d}_s^\pi^- = d_s^\pi^- = s_s^\pi^+ = s_s^\pi^- = \bar{s}_s^\pi^+ = \bar{s}_s^\pi^-
\]

- Two linear combination
  - Only valence sensitive:
    \[\Sigma_v^{\pi D} = -\sigma^{\pi^+ D} + \sigma^{\pi^- D} \propto \frac{1}{3} u_v^\pi (u_v^P + d_v^P)\]
  - Sea sensitive
    \[\Sigma_s^{\pi D} = 4\sigma^{\pi^+ D} - \sigma^{\pi^- D}\]
Opportunity at the CERN M2 beamline

High energy and intensity pion beams

Example @ 190 GeV:

\[ I_{\pi^-} \sim I_{\text{beam}} = 7.0 \times 10^7 / \text{s} \]

\[ I_{\pi^+} \sim 25\% \ I_{\text{beam}} = 1.7 \times 10^7 / \text{s} \]

COMPASS-like apparatus

Large acceptance: \( 8\text{mrad} < \theta < 160\text{mrad} \)

Segmented Carbon target:
Expected accuracy compared to NA3 result

- Collect at least a **factor 10 more statistics** than presently available
- Aim at the first precise direct measurement of the pion sea contribution

\[ \Sigma_{val} = \sigma_{\pi^-} - \sigma_{\pi^+} \]: only valence-valence
\[ \Sigma_{sea} = 4\sigma_{\pi^+} - \sigma_{\pi^-} \]: no valence-valence
Renewed interest in pion structure

- Agreement restored between DSE and fit to data at NLL
- First extraction of PDFs with Hera data (DIS with leading neutron)
- Foreseen measurement of Tagged DIS at JLab and at EIC

Aim for direct data in the circled area and check the method for Tagged DIS
## Pion induced Drell-Yan statistics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target type</th>
<th>Beam energy (GeV)</th>
<th>Beam type</th>
<th>Beam intensity (part/sec)</th>
<th>DY mass (GeV/c²)</th>
<th>DY events</th>
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<td>E615</td>
<td>20cm W</td>
<td>252</td>
<td>π⁺</td>
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<td></td>
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<td>π⁻</td>
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<td>4.1 – 8.5</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>π⁻</td>
<td>3.0 × 10⁷</td>
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<td>121</td>
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<tr>
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<td>6cm Pt</td>
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<td>π⁻</td>
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<tr>
<td>COMPASS 2015</td>
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<td>π⁻</td>
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<td>4.3 – 8.5</td>
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<td>COMPASS 2018</td>
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<td>100cm C</td>
<td>190</td>
<td>π⁺</td>
<td>1.7 × 10⁷</td>
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<td>190</td>
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<td></td>
<td></td>
<td></td>
<td>3.8 – 8.5</td>
<td>9,000</td>
</tr>
</tbody>
</table>

Also 100 of thousands of J/ψ available for free
Parallel measurements with an additional nuclear target

Energy loss:
- Multiple scattering of incoming quark in large nuclei
- No energy loss in the final state

→ Comparison between DY and $J/\psi$ complementary information

Flavour dependent EMC effect: Meson induced Drell-Yan process tags flavours

Using two $\pi$ beam charges and two targets, one can add constraints on the EMC flavour dependence
What do we know about kaon structure?

Sole measurement from NA3
J. Badier et al., PLB93 354 (1984)
- Limited statistics: 700 events with $K^-$
- Sensitivity to SU(3)$_f$ breaking
- Mostly only model predictions

Interesting observation: At hadronic scale gluons carry only 5% of K’s momentum vs $\sim$30% in $\pi$
- Scarce data on $u$-valence
- No measurements on gluons
- No measurements on sea quarks

How to improve the situation?

C. Chen et al., PRD 93 074021, 2016
Unique opportunities with RF separated beam

- Enriched $K$ and $\bar{p}$ beams ($\sim 3 \times 10^7$/s)
- Expected energies: $\sim 80 (110)$ GeV for $K(\bar{p})$
  - Small cross-section in HM
  - Lepton pairs emitted at large angles

Necessity to rethink the concept of DY absorber:
- Tracking with magnetic field
- Good resolution for vertexing
- Capability to collect $e^+e^-$ DY pairs

*R&D necessary*
More data points and more precise compared to NA3

Discriminating power between models

1 year with $2 \times 10^7$ s$^{-1}$ 100 GeV $K^-$ beam

$\pi$ taken simultaneously

Unique and Promising
Projections for valence/sea separation for Kaons

- **First measurement of sea in kaons**
- Requires an additional year with $K^+$ beam to complement the former $K^-$ data
- Assuming the intensity for $K^+$ and $K^-$: $2 \times 10^7 \text{ s}^{-1}$

Gluon contribution addressed by prompt photon production → see Barbara Badelek
So far, I talked only about mesons but what about the nucleon?

At LO QCD, the nucleon can be decomposed into 8 twist-2 TMD PDFs.

Using a transversally polarised target, one can access in SIDIS as well as in Drell-Yan:

- Sivers
- Transversity
- Pretzelosity
Synergy DY vs SIDIS

<table>
<thead>
<tr>
<th>DY:</th>
<th>SIDIS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{UU}^{\cos(2\phi)}$</td>
<td>$A_{UU}^{\cos(2\phi_h)}$</td>
</tr>
<tr>
<td>$A_{UT}^{\sin(\phi_S)}$</td>
<td>$A_{UU}^{\sin(\phi_h-\phi_S)}$</td>
</tr>
<tr>
<td>$A_{UT}^{\sin(2\phi-\phi_S)}$</td>
<td>$A_{UT}^{\sin(\phi_h+\phi_S)}$</td>
</tr>
<tr>
<td>$A_{UT}^{\sin(2\phi+\phi_S)}$</td>
<td>$A_{UT}^{\sin(3\phi_h-\phi_S)}$</td>
</tr>
<tr>
<td>$h_{1,h}^{1,q}$</td>
<td>$h_{1,p}^{1,q}$</td>
</tr>
<tr>
<td>$f_{1,T,p}^{1,q}$</td>
<td>$f_{1,T,p}^{1,q}$</td>
</tr>
<tr>
<td>$h_{1,p}^{1,q}$</td>
<td>$h_{1,p}^{1,q}$</td>
</tr>
<tr>
<td>$h_{1,T,p}^{1,q}$</td>
<td>$h_{1,T,p}^{1,q}$</td>
</tr>
</tbody>
</table>

TMD PDFs are universal but

final state interaction (SIDIS) vs. initial state interaction (DY)

→ Sign flip for naive T-odd TMD PDFs

Crucial test of TMD framework in QCD addressed by COMPASS

We propose to address the question again with:

→ Anti-proton beam and polarised target
→ Extra constraints on proton Boer-Mulders function
Recent evidence in terms of QCD: radiative effects describe well data at large $q_T$

J.-C. Peng et al. PLB 758, 384 (2016)
M. Lambertsen and W. Vogelsang PRD93, 114013 (2016)

- Boer Mulders expected at low $q_T \rightarrow$ fixed target regime
- To single out Boer Mulders effects very precise data are necessary
Anti-proton beam: Synergy DY and SIDIS

Additional insight with $\bar{p}$ on Boer Mulders (private exchange with Andreas Metz)
- Transversity modulation less affected by QCD effects
- Smooth matching between TMD approach and QCD

$\rightarrow$ Extract transversity from SIDIS $A_{UT}^{\sin(\phi_h + \phi_S)} \propto h_{1,h}^q \otimes H_{1q}^\perp$ measurements

- Use DY measured $A^{\sin(2\phi - \phi_S)} \propto h_{1,h}^\perp \otimes h_{1,p}^q$ and SIDIS transversity knowledge

Obtain Boer-Mulders $h_{1,q}^\perp$ for proton and meson with antiproton and meson beams

Complementary to SIDIS, where Cahn effects can be difficult to disentangle from Boer-Mulders effects
Anti-proton with a RF separated beam

Possibility to study valence proton TMD PDFs in a model free way

- cross-sections for $\bar{p}$ induced-DY at 120 GeV $\sim \pi^-$ induced-DY at 190 GeV
- Combined statistics from $\mu^+\mu^-$ and $e^+e^-$ channels $\sim$ 2 years of COMPASS-II data taking
- With active absorber: better acceptance in $\theta_{CS}$

<table>
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<th>Beam type</th>
<th>Beam intensity (part/sec)</th>
<th>Beam energy (GeV)</th>
<th>DY mass (GeV/c^2)</th>
<th>DY events $\mu^+\mu^-$</th>
<th>DY events $e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>This exp.</td>
<td>110cm NH$_3$</td>
<td>$\bar{p}$</td>
<td>$3.5 \times 10^7$</td>
<td>100</td>
<td>4.0 – 8.5</td>
<td>28,000</td>
<td>21,000</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120</td>
<td>4.0 – 8.5</td>
<td>40,000</td>
<td>27,300</td>
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<td></td>
<td></td>
<td>140</td>
<td>4.0 – 8.5</td>
<td>52,000</td>
<td>32,500</td>
</tr>
</tbody>
</table>
A new QCD facility

- Letter of Intent
  arXiv:1808.00848
  DY, Spectroscopy, muon-p elastics scattering, ...

- A web page

- Can register to stay informed

New ideas and collaborators are welcome
Proposal in preparation to be submitted this year
Near term future: Current beams

- **Precise** determination of **pion structure** and valuable inputs for nuclear effects (nPDFs, EMC, $J/\psi$, ...)

Long term future: RF-separated beams

- **Unprecedented** studies of **Kaon structure**
- **Unique** opportunity to study **proton valence TMD PDFs** in a model free way

Many other valuables measurements described in the LoI for both short and long term future

→ see also Barbara Badelek, Sergey Gevorkyan and Christian Dreisbach
Background less than 4% in $4.3 < M_{\mu\mu}/(\text{GeV}) < 8.5$
LS = long shutdown of CERN accelerators
Parallel studies

Energy loss:
- Multiple scattering of incoming quark in large nuclei
- No energy loss in the final state
→ Fixed target regime especially suited
→ Comparison between DY and $J/\psi$ complementary information

Flavour dependent EMC effect:
Iso-vector $\rho^0$ mean field generated in $N \neq Z$ nuclei can modify nucleon’s $u$ and $d$ PDF differently
- NA3 $\pi$ on Pt favours flavour dependence
- Omega $\pi$ on W not conclusive
→ Meson induced Drell-Yan process tags flavours
### Kaon induced Drell-Yan statistics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target type</th>
<th>Beam type</th>
<th>Beam intensity (part/sec)</th>
<th>Beam energy (GeV)</th>
<th>DY mass (GeV/c^2)</th>
<th>DY events</th>
<th>DY events</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>µ^+ µ^-</td>
<td>e^+ e^-</td>
</tr>
<tr>
<td>NA3</td>
<td>6 cm Pt</td>
<td>K^-</td>
<td></td>
<td>200</td>
<td>4.2 – 8.5</td>
<td>700</td>
<td>0</td>
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<tr>
<td>K^-</td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td>4.0 – 8.5</td>
<td>25,000</td>
<td>13,700</td>
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<td>This exp.</td>
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<td></td>
<td>2.1 × 10^7</td>
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<td></td>
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<tr>
<td>K^-</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>4.0 – 8.5</td>
<td>40,000</td>
<td>17,700</td>
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<tr>
<td>K^+</td>
<td></td>
<td></td>
<td></td>
<td>120</td>
<td>4.0 – 8.5</td>
<td>54,000</td>
<td>20,700</td>
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<tr>
<td>K^+</td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td>4.0 – 8.5</td>
<td>2,800</td>
<td>1,300</td>
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<td></td>
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<td></td>
<td>100</td>
<td>4.0 – 8.5</td>
<td>5,200</td>
<td>2,000</td>
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<td>120</td>
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<td>4.0 – 8.5</td>
<td>95,500</td>
<td>36,000</td>
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<td>120</td>
<td>4.0 – 8.5</td>
<td>123,600</td>
<td>39,800</td>
</tr>
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</table>

Achievable statistics of the new experiment, assuming 2 × 140 days of data taking with equal time sharing between the two beam charges. For comparison, the collected statistics from NA3 is also shown.
## Requirements per topic

<table>
<thead>
<tr>
<th>Program</th>
<th>Beam Energy [GeV]</th>
<th>Beam Intensity [/s]</th>
<th>Trigger Rate [kHz]</th>
<th>Beam Type</th>
<th>Target</th>
<th>Hardware Additions</th>
<th>R</th>
<th>C</th>
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<td>Proton radius</td>
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<td>$\mu^\pm$</td>
<td>high-pr. H2</td>
<td>active TPC, SciFi trigger, silicon veto</td>
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<td>GPD E</td>
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<td>10</td>
<td>$\mu^\pm$</td>
<td>NH3↑</td>
<td>recoil silicon, modified PT magnet</td>
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<td>Anti-matter</td>
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<td>$5 \cdot 10^5$</td>
<td>25</td>
<td>$p$</td>
<td>LH2, LHe</td>
<td>recoil TOF</td>
<td>×</td>
<td>×</td>
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<td>Spectroscopy $\bar{p}$</td>
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<td>$5 \cdot 10^7$</td>
<td>25</td>
<td>$\bar{p}$</td>
<td>LH2</td>
<td>target spectrometer: tracking, calorimetry</td>
<td>×</td>
<td>×</td>
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<td>Drell-Yan conv</td>
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<td>$6.8 \cdot 10^7$</td>
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<td>$\pi^\pm$</td>
<td>C/W</td>
<td>vertex detector</td>
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<td>Drell-Yan RF</td>
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<td>$10^8$</td>
<td>25-50</td>
<td>$K^\pm$, $\bar{p}$</td>
<td>NH3↑, C/W</td>
<td>&quot;active absorber&quot;, vertex detector</td>
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<tr>
<td>Primakoff</td>
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<td>$5 \cdot 10^6$</td>
<td>&gt; 10</td>
<td>$K^-$</td>
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<td>$K^+$</td>
<td>LH2</td>
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<td>$3.7 \cdot 10^6$</td>
<td>25</td>
<td>$K^-$</td>
<td>LH2</td>
<td>recoil TOF</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

Requirements for the future programs at the M2 beam line after 2021. **Standard muon beams** are in blue, **standard hadron beams** in orange, and **RF-separated hadron beams** in red. The common baseline is the COMPASS-II setup without RICH-1. “R” refers to RICH-1 and if possible RICH-0, “C” to CEDARs.