Drell-Yan cross-section measurement at COMPASS

Vincent Andrieux
on behalf of the COMPASS Collaboration

University of Illinois at Urbana-Champaign

25th International Spin Symposium
24th-30th September 2023
Durham (North Carolina)
Pion structure

In principle the simplest hadron and yet still pretty unknown structure

\[ \pi^- + p \rightarrow X + \ell^- + \ell^+ \]

\[ \rightarrow \text{valence contribution} \]

\[ \pi^- + p \rightarrow X + \gamma^* \]

\[ \rightarrow \text{sullivan process} \]

\[ \gamma^* \rightarrow \ell^- + \ell^+ \]

\[ \rightarrow \text{prompt photon} \]

Renew of interest with foreseen measurements at AMBER, JLab and EIC ... 

COMPASS can already contribute
COMPASS Collaboration at CERN

~ 200 physicists from 25 institutions from 13 countries

 Beam line:
- High intensity hadron beam: ~70 MHz
- High energy: 190 GeV
- Negative hadron beam composition:
  - **97% pions**
  - 2% kaons
  - 1% anti proton
Apparatus: Two-stage spectrometer

Key elements:
- Versatile target area configuration
- 2 triggering systems
- 2 spectrometers in 1 for a wide coverage: 8 mrad $\theta < 160$ mrad $\rightarrow -0.2 < x_F < 0.9$
- 2 Muon filters
- $\sim 400$ tracking planes

Variable definitions:
- $M^2 = (p_{\mu^+} + p_{\mu^-})^2$
- $q_L^*$: Photon long. momentum in $\pi$-N rest frame
- $x_F = \frac{2q_L^*}{\sqrt{s}}$
- $x_{\pi/N} = \frac{1}{2} \left( \sqrt{x_F^2 + 4 \frac{M^2}{s}} \pm x_F \right)$
Light nuclei from spin average polarised target: mixture of NH$_3$ & LHe:

molar fraction of nucleons:

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>He</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15.7%</td>
<td>11.1%</td>
<td>73.2%</td>
</tr>
</tbody>
</table>

~ ±2% in the accessible region

Target will be denoted NH$_3$-He in the following

Two nuclear targets: intermediate and large A: Al & W

Nuclear modification PDF for $u$-quark from nNNPDF3.0
Several channels contribute to inclusive dimuon final state production:

- Combinatorial background
- Open-Charm production in low mass
- Resonances: $J/\psi$ and $\psi'$
- Drell-Yan in high mass

Statistical separation based on the different kinematic dependence with various Monte-Carlo samples and the combinatorial background distribution assessed from like-sign pairs in real data ($2\sqrt{N^{++}N^{--}}$): “Cocktail fit”

**Collected pairs in the region of interest 4.3 GeV/$c^2$ to 8.5 GeV/$c^2$:**

- NH$_3$-He: 36 000
- Al: 6 000
- W: 43 000
Long way to cross-section measurement

Recorded number of dimuons

Drell-Yan cross section

1. Process purity > 90% for $M/(\text{GeV}/c^2) > 4.3, 4.9$ and $5.5$ in NH$_3$-He, Al and W
2. Acceptance: between 1 and 20 
3. Luminosity
4. Trigger system normalisation
5. ...
First high statistics measurement with light material

Red line/shaded area: statistical / total (stat. and syst.) uncertainties

Dominated by statistical uncertainty

Vincent Andrieux (UIUC) Durham (N.C.) September-2023
Unique inputs to extract π TMD PDF with minimum nuclear effects

Systematics uncertainty at the level of statistical precision
Wide kinematic coverage
Red line/shaded area: statistical / total (stat. and syst.) uncertainties
Dominated by systematic uncertainty
Drell-Yan cross section on $W$ and comparison to E615

$\sqrt{\tau} = M/\sqrt{s}$

- **New results since 30 years**
- Similar kinematic coverage as E615
- Better statistics, similar total systematics except for the low mass region
Drell-Yan cross section on $W$ and comparison to NA10

- Wider kinematic coverage
- Worse accuracy in statistics as well as in systematics

\[ \sqrt{\tau} = \frac{M}{\sqrt{s}} \]
Flavour dependent EMC effect:
Unlike DIS, $\pi$-induced Drell-Yan process tags the quark flavour
nCTEQ15: unconstrained flavour dependence
EPS09: no flavour dependence

N>Z in gold isoscalar data

PRC 83 (2010) 042201
Flavour dependence of \( R_{\pi A}^{DY}(x_N) = \frac{A_2 d\sigma_{\pi A}^{DY}}{A_1 d\sigma_{\pi A}^{DY}} \)

- Ratio of integrated DY cross section per nucleon in all but \( x_N \) variable
- Covering the domain of EMC effect and end of anti-shadowing
- General trend as expected...
- ... Currently limited by systematics except possibly for Al/(NH\(_3\)-He)
Parton energy loss and Cronin effects

Parton crossing nuclear medium, looses energy due to multiple scattering and gluon emission

Signatures:
- Gain of transverse momentum: $q_T$ Broadening
- Loss of longitudinal momentum: Suppression at large $x_F$
Drell-Yan nuclear modification factor \( R_{\pi A}^{DY} = \frac{A_2 d\sigma_{\pi A}^{DY}}{A_1 d\sigma_{\pi A_2}^{DY}} \) vs \( q_T \)

- Ratio of integrated DY cross section per nucleon in all but \( q_T \) variable
- Measurements are in agreement with effective effects encoded in nPDF
- Currently limited by systematics except possibly for Al/(NH₃-He)
Drell-Yan nuclear modification factor $R(A_1/A_2)$ in $x_F$ for various $q_T$ bins

Steeper slope in $x_F$ at large $q_T$ mainly in $W/(\text{NH}_3\text{-He})$ and $\text{Al}/(\text{NH}_3\text{-He})$

Soon in bins of $x_N$ to disentangle from anti-shadowing and EMC effects
⇒ COMPASS has released a wealth of preliminary Drell-Yan cross sections
⇒ High statistics measurement is available on a light target
⇒ Systematics uncertainties are at the same order of magnitude as E615

Perspective:
Finalisation of Drell-Yan cross-section measurements in the coming months expected
**How to probe the meson structure?**

### Physics Motivation

The concept of a composite nucleon structure may be traced back to 1933 with the discovery of the anomalous magnetic moment of the proton [1]. This was explicitly formulated by Fermi and Marshall in a 1947 paper [2] that noted experimental evidence pointed to the nucleon existing approximately 20% of the time in a virtual meson-nucleon state. The virtual meson "cloud" of the nucleon plays an important role in the understanding of the nucleon-nucleon interaction and the pion cloud in particular has always been considered critical to understanding the nucleon’s long-range structure.

At shorter ranges, the role of mesons in electron-nucleon deep inelastic scattering (DIS) have also been investigated. In 1972 Sullivan [3] suggested that some fraction of the nucleon’s anti-quark sea distribution may be associated with this pion content of the nucleon. For many decades these and numerous other theories that describe and/or utilize the meson cloud of the nucleon have advanced significantly (see [4, 5, 6] for some review). From partially conserved axial current to the success of chiral quark models, it is considered known that the nucleon has an associated meson cloud. In very stark contrast to the substantial body of theory associated with the meson cloud, however, experimental results remain few and far between. In a 1983 paper, Thomas commented that "...it is rather disturbing that no one has yet provided direct experimental evidence of a pion component in the nucleon" [7].

Even with results becoming available from Drell-Yan experiments at Fermilab, W production at RHIC, and diassociate DIS at HERA and COMPASS, all discussed below, the "disturbing" situation is not yet been substantially improved.

### π⁻-induced Drell-Yan measurements:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target type</th>
<th>Beam energy (GeV)</th>
<th>DY mass (GeV/c²)</th>
<th>DY events</th>
<th>Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA3</td>
<td>30cm H₂</td>
<td>200</td>
<td>4.10 – 8.50</td>
<td>121</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6cm Pt</td>
<td>200</td>
<td>4.20 – 8.50</td>
<td>4,961</td>
<td>12.6%</td>
</tr>
<tr>
<td>NA10</td>
<td>120cm D₂</td>
<td>286</td>
<td>4.2 – 8.5</td>
<td>7,800</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>140</td>
<td>4.35 – 8.5</td>
<td>3,200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>286</td>
<td>4.2 – 8.5</td>
<td>49,600</td>
<td></td>
<td>6.5%</td>
</tr>
<tr>
<td></td>
<td>12cm W</td>
<td>194</td>
<td>4.07 – 15.19</td>
<td>155,000</td>
<td>(inc. Υ)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>140</td>
<td>4.35 – 8.5</td>
<td>29,300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E615</td>
<td>20cm W</td>
<td>252</td>
<td>30,000</td>
<td>16%</td>
</tr>
</tbody>
</table>
Situation for the other experiments

- NA10: Estimated to be negligible and no correction
- E615: Evaluation with MC technique and subtraction