Pion structure measurement at a new QCD facility at SPS

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New QCD facility
Mini workshop
June 21st
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
Motivations

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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 is the most unknown contribution

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**

\[ F_2^{LN(3)}(x_t = 0.73)/\Gamma_p, \Gamma_{\pi} = 0.13 \]

**Drell-Yan NA3**

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

- Limited statistics: 4.7k \( \pi^- \)-event (shown) and 1.7k \( \pi^+ \)-event
- Heavy nuclear target (Pt)

- Wide \( x \) coverage
- Estimation of pion flux introduce a strong model dependence
High intensities available
Almost pure $\pi^-$ beam
Reasonable contribution of $\pi^+$ for positive beam
COMPASS-like spectrometer for initial simulation studies

- **Large acceptance:** $8 \text{ mrad} < \theta < 160 \text{ mrad}$

- **4x larger than previous Drell-Yan experiment**

- **Hadron absorber + nuclear targets**
Choice of target

- Isoscalar for sea-valence separation
- Minimize nuclear effect: Carbon
- Embedded in an absorber for high intensity
- Segmented with vertex tagging for flux and resolution
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

\[
\Sigma_{\text{val}} = \sigma_{\pi^-}^\text{C} - \sigma_{\pi^+}^\text{C} : \text{only valence-valence}
\]

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

- Recent reanalysis at NLL
- Agreement restored between DSE and data
- Sea and gluon from GRS
- First MC global QCD analysis ("model dependence")
- Hera data included
- Clear impact on sea and gluon distribution

Direct data would constrain the circled area and check the method.
Forseen meson structure measurements

Tagged DIS at JLab

- Same approach as H1 and Zeus:
  
- Test of pion cloud
- Caveat: Model dependence from the unknown pion flux

Provide complementary data at large $x$
Same process is also foreseen for the future EIC to reach very low $x$
## 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>
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Also 100 of thousands of $J/\psi$ available for free
Using two $\pi$ beam charges and two targets, one can add constraints on the EMC flavour dependence

**Should play a significant role in nPDFs uncertainties and EMC effect**
Outlook

With current beams:

- **Precise** direct determination of pion structure
- Valuable measurements of nuclear effects (nPDFs, EMC, ...)
- Large sample of $J/\psi$ available

CERN is a unique place with high energy pion beams ($\pi^+$ and $\pi^-$), where those measurements can be performed.
BACKUP
How to access meson structure

Drell-Yan:

- 90’s: NA3, NA10, E615
- 10’s: COMPASS-II
- 20’s: New Experiment

Prompt photon production:

- 90’s NA24, W70
- 20’s New experiment

DIS with leading N:

- 90’s: H1, ZEUS
- 10’s: JLAB TDIS
- 30’s: EIC

The concept of a composite nucleon structure may be tracked as far back as 1933 to the discovery of the anomalous magnetic moment of the proton [1]. This was explicitly formulated by Fermi and Marshall who noted in a 1947 paper [2] that 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 an ion component in the nucleon” [7]. Even with results becoming available from Drell-Yan experiments at Fermilab, W production at RHIC, and diffractive DIS at HERA and COMPASS, all discussed below, the “disturbing” situation is not yet been substantially improved.

Figure 1: Feynman diagram for electron scattering from the pion cloud of the nucleon N, with the initial nucleon at rest (the Sullivan process).

The 12 GeV upgrade of JLab presents new opportunities to study the mesonic structure of the nucleon. One such technique is to measure the contribution to electron Deep Inelastic Scattering (DIS) of the meson cloud of a nucleon target, as pointed out by Sullivan [3] (Fig. 1). This so-called Sullivan process was shown to persist even at large $Q^2$ scales. An immediate consequence of the Sullivan process is that the nucleon parton distributions contain a component which can be attributed to the meson cloud. This...
Pion Structure Function: $F_\pi(x_1)$

Simultaneous fit of NA3 $\pi^+$, $\pi^-$ and p at 200 GeV Drell-Yan data, using CDHS nucleon PDF set.


Left: Curve scaled with $K_{factor} = 2.3$; Right: Data point corrected by $K_{factor}$

Discrepancy by 20% between E615 and NA3/NA10

Recent reanalysis at NLL
Agreement restored between DSE and data
Only valence quark distributions are fitted
Sea and gluon from GRS
Target choice and sea-valence separation

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

$$\sigma(\pi^+ d) \propto \frac{4}{9} [u^{\pi} \cdot (\bar{u}_s^p + d_s^p)] + \frac{4}{9} [\bar{u}_s^{\pi} \cdot (u^p + d^p)] + \frac{1}{9} [\bar{d}_s^{\pi} \cdot (d^p + u^p)] + \frac{1}{9} [d_s^{\pi} \cdot (\bar{d}_s^p + \bar{u}_s^p)]$$

$$\sigma(\pi^- d) \propto \frac{4}{9} [u_s^{\pi} \cdot (\bar{u}_s^p + d_s^p)] + \frac{4}{9} [\bar{u}_s^{\pi} \cdot (u^p + d^p)] + \frac{1}{9} [\bar{d}_s^{\pi} \cdot (d^p + u^p)] + \frac{1}{9} [d_s^{\pi} \cdot (\bar{d}_s^p + \bar{u}_s^p)]$$

- 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:
    $$u_s^{\pi^+} = \bar{u}_s^{\pi^-} = u_s^{\pi^-} = \bar{u}_s^{\pi^+} = d_s^{\pi^+} = \bar{d}_s^{\pi^+} = d_s^{\pi^-} = \bar{d}_s^{\pi^-} = s_s^{\pi^+} = s_s^{\pi^-} = \bar{s}_s^{\pi^+} = \bar{s}_s^{\pi^-}$$
  - Two linear combination
    - Only valence sensitive: $\Sigma_v^{\pi D} = -\sigma_v^{\pi^+ D} + \sigma_v^{\pi^- D} \propto \frac{1}{3} u_v^{\pi} (u_v^p + d_v^p)$
    - Sea sensitive: $\Sigma_s^{\pi D} = 4\sigma_s^{\pi^+ D} - \sigma_s^{\pi^- D}$
Requirements for pion case

- **EHN2**
  - Roof shielding to reduce sky-shining and satisfy RP
  - Good CEDARs (upgrade happening for 2018 run)

- **Beam line**
  - Beam momentum 190 GeV
  - Higher intensity: \(2 \times 10^8\) particles per second
  - Differential absorber (2m polyethylene) if does not degrade too much beam parallelism

Increasing the intensity (at least \(1.4 \times 10^8\) total flux) should guarantee the projected uncertainties within a year
### 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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</thead>
<tbody>
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<td>100</td>
<td>$\mu^\pm$</td>
<td>high-pr. H2</td>
<td>active TPC, SciFi trigger, silicon veto</td>
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<td>$10^7$</td>
<td>10</td>
<td>$\mu^\pm$</td>
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<td>25</td>
<td>$\rho$</td>
<td>LH2, LHe</td>
<td>recoil TOF</td>
<td>×</td>
<td></td>
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<tr>
<td>Spectroscopy $\bar{\tau}$</td>
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<td>$5 \cdot 10^7$</td>
<td>25</td>
<td>$\bar{\tau}$</td>
<td>LH2</td>
<td>target spectrometer: tracking, calorimetry</td>
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<tr>
<td>Drell-Yan conv</td>
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<td>$6.8 \cdot 10^7$</td>
<td>25</td>
<td>$\pi^\pm$</td>
<td>C/W</td>
<td>vertex detector</td>
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<td>$10^8$</td>
<td>25-50</td>
<td>$K^\pm, \bar{\tau}$</td>
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<td>&quot;active absorber&quot;, vertex detector</td>
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<td>LH2</td>
<td>recoil TOF</td>
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</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.
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