Probing the pion’s parton structure with AMBER (Phase-1 experiments)

Stephane Platchkov, Apr. 27, 2021
(On behalf of the AMBER collaboration)
Physics potential of AMBER – Phase 1 (“DY” = Dimuon production)

- Three main advantages of CERN + COMPASS:
  - 1) mesons beams (Amber phase-1: pions, later: kaons)
  - 2) both positive and negative – very important!
  - 3) Large and uniform acceptance spectrometer

  Only place in the world!

- Three main physics goals of AMBER phase-1:
  - 1) Separate valence and sea pion PDFs
  - 2) Access gluon distribution in the pion using $J/\psi$ and $\psi'$ production
  - 3) Study the flavor dependence of the nuclear mean field

  Fall 2020: official approval by SPSC!
Goal #1:
Separate valence and sea contributions in the pion
Properties of the lightest mesons (pion and kaon)

- Light meson properties
  - How the (simplest) light mesons compare to the nucleon?

<table>
<thead>
<tr>
<th>M (MeV)</th>
<th>938</th>
<th>135</th>
<th>493</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rch (fm)</td>
<td>0.841(2)</td>
<td>0.659(4)</td>
<td>0.560(31)</td>
</tr>
</tbody>
</table>

- Help understanding the emergence of hadron masses
  - Higgs mechanism can’t explain hadron masses
  - EHM: explain the heavy nucleon and the light pion

- Meson PDFs: Important input

S. Platchkov

EHM-V, April 2021
Present status of pion PDFs (global fits ≃ experiment)

Valence: must be checked and improved. Sea and gluons: nearly unknown.

Chang, Peng, SP, Sawada. PRD 102, 054024 (2020).
Pion PDFs (very recent progress…)


First multidimensional global fit by JAM21 (March 2021)

First pion glue lattice QCD calculation (April 2021)
Pion sea/valence: the only available results (NA3, 1983)

- Only measurement: NA3 ($\pi^- / \pi^+$ on a $^{195}$Pt target)
  - $\pi^-$: 200 GeV (4.7k)
  - $\pi^+$: 200 GeV (1.7k)
  - Insufficient statistics!

- Requirements for a new measurement
  - Beams of $\pi^-$ and $\pi^+$
  - Good control of $\sigma$(abs) normalization
  - Statistics: $\gtrsim$ order of magnitude!

The available $\pi^+$ statistics will be increased to $\gtrsim 20$ 000
### Drell-Yan: available data and expected statistics

**Table 7:** Statistics collected by earlier experiments (top rows), compared with the achievable statistics of the proposed experiment (bottom rows), in 213 days ($\pi^+$ beam) + 67 days ($\pi^-$ beam).

<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/c^2)</th>
<th>DY events</th>
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</thead>
<tbody>
<tr>
<td>E615</td>
<td>20 cm W</td>
<td>252</td>
<td>$\pi^-$</td>
<td>$17.6 \times 10^7$</td>
<td>4.05 – 8.55</td>
<td>5000</td>
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<td></td>
<td></td>
<td></td>
<td>$\pi^+$</td>
<td>$18.6 \times 10^7$</td>
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<td>30000</td>
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<tr>
<td>NA3</td>
<td>30 cm H₂</td>
<td>200</td>
<td>$\pi^-$</td>
<td>$2.0 \times 10^7$</td>
<td>4.1 – 8.5</td>
<td>40</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$\pi^+$</td>
<td>$3.0 \times 10^7$</td>
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<td>121</td>
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<tr>
<td></td>
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<td>200</td>
<td>$\pi^+$</td>
<td>$2.0 \times 10^7$</td>
<td>4.2 – 8.5</td>
<td>1767</td>
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<td></td>
<td></td>
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<td>$\pi^-$</td>
<td>$3.0 \times 10^7$</td>
<td></td>
<td>4961</td>
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<tr>
<td>NA10</td>
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<td>286</td>
<td>$\pi^-$</td>
<td>$65 \times 10^7$</td>
<td>4.2 – 8.5</td>
<td>7800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>140</td>
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<td>4.35 – 8.5</td>
<td>3200</td>
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<td>12 cm W</td>
<td>286</td>
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<td>4.2 – 8.5</td>
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<td>194</td>
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<td>140</td>
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<td>4.35 – 8.5</td>
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<td>COMPASS 2015</td>
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<td>This exp</td>
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<td>12 cm W</td>
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<td>$\pi^+$</td>
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<td>4.3 – 8.5</td>
<td>8300</td>
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<td>4.0 – 8.5</td>
<td>11700</td>
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<td>190</td>
<td></td>
<td>$\pi^-$</td>
<td>$1.6 \times 10^7$</td>
<td>4.3 – 8.5</td>
<td>24100</td>
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<td></td>
<td>4.0 – 8.5</td>
<td>32100</td>
</tr>
</tbody>
</table>

**Amber advantages**

- $^{12}$C (3 x 25 cm) target
- - control reinteraction

**Improvement in statistics:**

- $\pi^-$: x 19
- $\pi^+$: x 18
Expected results, emphasizing valence/sea separation

\[
D_{\text{sea}} = 4D^+ D
\]

\[
D_{\text{val}} = D^+ + D
\]

no valence

only valence

COMPASS resolution

20% sea

10% sea

AMBER resolution
Goal #2: 
Access the gluons in the pion using charmonium production
Charmonium production: pros and cons

- Extremely attractive observable, linked to the gluon distribution
  - J/ψ has large cross sections: factor of 30-50 larger than Drell-Yan
  - AMBER will measure $x_F$, $p_T$, $\lambda$ distributions with huge statistics (> 1 M events)
  - Fixed target energies: production is dominated by 2 --> 1 process
  - AMBER@CERN: simultaneous measurements of ($\pi^+$ and p) and $\pi^-$
  - No new FT data since two decades!

- However!
  - The J/ψ production mechanism is not well known
  - Fixed-target energies: $p_T \leq M(J/\psi)$; for LHC $p_T >> M(J/\psi)$;
    - Additional effects may contribute
π + ¹²C cross section for two PDF “global” fits (CEM at LO)


Strong dependence on the pion PDF parametrization!
GRV(1992) vs JAM(2018) pion PDFs

The two global fits provide different PDFs: valence, gluon, sea

S. Platchkov
NLO CEM calculation for a $H_2$ target (NA3)

- NLO CEM calculation for $J/\psi$ cross section
  - pion beam, $E = 200$ GeV
  - Target = Hydrogen

- 4 different pion PDFs:
  - SMRS, GRV, xFitter, JAM

Result: very different magnitudes of the $q\bar{q}$ and $gg$ contributions
Polarization

- $J/\psi$ is a $1^-\bar{1}$ particle; its third component is $J_z = 0, +1, -1$.
  - $\alpha = +1$ : 100% transverse polarization ($J_z = \pm 1$)
  - $\alpha = 0$ : unpolarized
  - $\alpha = -1$ : 100% longitudinal polarization ($J_z = 0$)

- Polarization is a fundamental observable
  - angular momentum, chirality, parity conservations preserve the properties of the $J/\psi$: from production to the $2\mu$ decay
  - Nature wants to help us, for $q\bar{q}$: $\alpha \simeq +1$, but for $gg$: $\alpha \simeq -1$
  - Key variable for understanding the bound state formation

\[
\frac{d\sigma}{d(\cos \theta)} \propto 1 + \alpha \cos^2 \theta,
\]
Polarization: expected results

(Cheung and Vogt, priv. comm.)

- ICEM xF-dependent predictions
  - with minimal model-dependence
    \[ \lambda_{qg}^{CS} \approx +0.4 \text{ for } q\bar{q} \]
    \[ \lambda_{qg}^{CS} \approx -0.6 \text{ for } gg \]
  - The difference between the two predictions results from the different amount of \( q\bar{q} \) and \( gg \) contributions as a function of \( x_F \).

The polarization value as a function of \( x_F \) is sensitive to the shape differences between \( gg \) and \( q\bar{q} \) contributions to the cross section.
Multidimensional analysis of both cross section and dilepton decay angles should provide constraint on the $g g$ and $q \bar{q}$ fractions.
## Estimated J/ψ statistics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target type</th>
<th>Beam energy (GeV)</th>
<th>Beam type</th>
<th>J/ψ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA3 [75]</td>
<td>Pt</td>
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<td>π⁻</td>
<td>6010000</td>
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<td></td>
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<td>280</td>
<td>π⁻</td>
<td>5110000</td>
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<td></td>
<td></td>
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<td>π⁺</td>
<td>1310000</td>
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<td></td>
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<td></td>
<td>π⁻</td>
<td>1050000</td>
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<td>E789 [127,128]</td>
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<td>800</td>
<td>p</td>
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<td>E866 [129]</td>
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<td>800</td>
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<tr>
<td></td>
<td>Fe</td>
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<tr>
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<td>Cu</td>
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<td>p</td>
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<td>d</td>
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<tr>
<td>HERA-B [132]</td>
<td>C</td>
<td>920</td>
<td>p</td>
<td>152000</td>
</tr>
</tbody>
</table>

### Comments

Cross sections not published, only plots available

- $x_F$ and $p_T$ cross sections available

- Only ratios of cross sections available

- Only A-dependent studies of total cross sections

$x_F$ and $p_T$ cross sections available

- Only A-dependent studies of total cross sections

### Estimations based on Compass preliminary numbers

Largest statistics ever (between 0.5M and 1.8 events/target/beam)
**ψ’ production**

**Pros**
- No feed-down contributions. Consequences:
  - $q\bar{q}$ and $gg$ contributions could reach their maximum polarization values
- Measure: $x_F$ and $p_T$ distributions + polarization
- AMBER could provide the largest $ψ'$ data set ever.

**Cons**
- Lower cross section (~1/7) smaller BR (~1/8):
- Ratio $(ψ’/J/ψ) ≈ 0.018$

Requirements: Good mass resolution ($≤ 100$ MeV) – need vertex detectors and/or dedicated runs without absorber (AMBER II)
ψ’ production – expected statistics

- AMBER – 6 complementary measurements!

<table>
<thead>
<tr>
<th>Target</th>
<th>Energy</th>
<th>Beam</th>
<th>Nb of ψ’</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹²C</td>
<td>190 GeV</td>
<td>π⁺</td>
<td>21 600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>π⁻</td>
<td>32 400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p</td>
<td>27 000</td>
</tr>
<tr>
<td>¹⁸⁴W</td>
<td></td>
<td>π⁺</td>
<td>9 000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>π⁻</td>
<td>12 600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p</td>
<td>12 600</td>
</tr>
</tbody>
</table>

Improved statistics on two targets and with three different beams

Gribushin et al., PRD 53,4723 (1996)

E672 experiment

E = 515 GeV
Goal #3:
Flavor dependence of the EMC effect
“Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.”

How can AMBER contribute (“for free”)?
**Flavor-dependence of the EMC effect**

- **Cloët, Benz and Thomas (2009):**
  - Use nuclear matter within a covariant Nambu–Jona-Lasinio model
  - Compute the flavour-dependence of the nuclear PDFs
    - “...for $N\neq Z$ nuclei, the $u$ and $d$ quarks have distinct nuclear modifications.”

- Isovector-vector mean-field force
  - Appears in nuclei with $N \neq Z$
  - $u$ quarks feel additional attraction,
    - $d$ quarks feel additional repulsion

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Can be accessed ONLY through parity-violating DIS (JLAB) or with AMBER@CERN
AMBER – expected results

\[ \frac{\sigma_{W}^{\pi^+}}{\sigma_{W}^{\pi^-}} \]

\[ \frac{\sigma_{W}^{\pi^-} - \sigma_{W}^{\pi^+}}{\sigma_{C}^{\pi^-} - \sigma_{C}^{\pi^+}} \]

LO vs NLO

\[ \sigma_{W}^{\pi^+} / \sigma_{W}^{\pi^-} \]

LO/NLO: minimal effect

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Summary

◆ Map out the pion parton structure at large $x$, $x > 0.1$
  - 1) DY data: separate valence and sea distributions in the pion
  - 2) $J/\psi$ and $\psi'$ data: study pion-induced production – infer pion valence and gluon distributions
    - AMBER@CERN is unique for these meson PDFs measurements

◆ Nuclear dependence at large $x$
  - Improve our knowledge of the EMC effect – first look at the flavor dependence of the nuclear mean field
    - AMBER@CERN is unique for this nuclear stricture measurement

These three fundamental measurements will be achieved using the same data set