Pion TMDs analysis at COMPASS and AMBER
an impact study through MAP framework
Filippo Delcarro

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[Outline]

● COMPASS DY program
● Impact study for pion TMDs on COMPASS pseudodata using MAP framework
● Future possibilities for meson structure at AMBER
[TMDs in nucleons]

TMD PDF

\( h_A \)

\( q \)

\( x \)

TMD PDF

\( h_B \)

\( \bar{q} \)

\( \gamma^* \)

Drell-Yan

SIDIS

TMD FF

lepton

photon (q)

parton

remnants

proton

\( k_T \)

\( P_h \)

\( P_{hT} \)

e\(^+\)e\(^-\) annihilation

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[pion TMDs]

pion TMD PDF

\[ \begin{align*}
\pi & \rightarrow q \bar{q} \\
\pi & \rightarrow \gamma^* \\
h_A & \rightarrow X \\
TMD PDF
\end{align*} \]

Drell-Yan

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[COMPASS setup for DY]

**Measured process:**

- $H_\pi(P_\pi)$
- $q(k_\pi)$
- $\gamma^*(q)$
- $\mu^-(l)$
- $X$

**Beam:**
- 190 GeV $h^-$ beam
- purity 97% $\pi^-$
- intensity $\sim$70 MHz

**Key elements:**
- 2 x 55cm $\text{NH}_3$ polarised target
- Al and W target (beam plug)
- 2.4m long $h$ absorber
- $\sim$300 tracking planes

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COMPASS setup for DY

Target

\textbf{W} \textbf{Al} \textbf{NH}_3

190 \text{ GeV} \textbf{e}^- \text{beam}

\begin{itemize}
  \item \textbf{NH}_3
  \item \textbf{Al}
  \item \textbf{W}
\end{itemize}

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Kinematic coverage

SIDIS on transv. pol. proton $\mu + p^\uparrow \rightarrow \mu' + h + X$

Pion-induced transv. pol. Drell-Yan $\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$

PLB 770 (2017) 138

PRL 119 (2017) 112002

COMPASS 2007, 2010

COMPASS 2015, 2018

Similar $x$ and $Q^2$ range $\rightarrow$ minimisation of $Q^2$ evolution effects between the two processes

Unique conditions to test TMD universality

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[DY COMPASS measurements: kinematics]

I. $1 < \mu \mu < 2 \text{ GeV}/c^2$  Low Mass
   large background contamination

II. $2 < \mu \mu < 2.5 \text{ GeV}/c^2$  Intermediate Mass
    High DY cross section
    low DY signal/background ratio

III. $2.5 < \mu \mu < 4.3 \text{ GeV}/c^2$  Charmonia Mass
     $J/\psi$ physics

IV. $4.3 < \mu \mu < 8.5 \text{ GeV}/c^2$  High Mass
    beyond $J/\psi$ and $\psi'$ peak
    valence quark region
    but...low DY cross-section

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[DY analysis cuts]

- \( 4.3 < M_{\mu\mu} < 8.5 \text{ GeV}/c^2 \)
- Drell-Yan purity: 96%
- Probing \( x_N \sim 0.17 \): up quark dominance
- \( q_T > 0.4 \text{ GeV} \) for angular resolution,
- but low cross-section
DY cross section at COMPASS

First new results in the last 30 years

Similar kinematic coverage as E615, better statistics, similar systematics

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(V. Andrieux, SPIN 2023)
Pion TMDs from Drell-Yan

DY PROCESS

\[ h_A(p_A) + h_B(p_B) \rightarrow \gamma^*(q) + X \rightarrow \ell^+(l) + \ell^-(l') + X \]

unpolarized cross section

STRUCTURE FUNCTIONS

\[ F^{1}_{UU}, F^{2}_{UU} \]

CROSS SECTION

\[ \frac{d\sigma^{DY}}{dq_t|dydQ} \approx \frac{16\pi^2\alpha^2}{9Q^3} |q_T|F^{1}_{UU}(x_A, x_B, q_T, Q) \]
pion TMDs from Drell-Yan

\( \frac{d\sigma^{DY}}{d|q_T|dydQ} \propto \int d|b_T| |b_T| J_0(|q_T|b_T) \hat{f}_1^a (x_A, b_T^2; \mu, \zeta_A) \hat{f}_{1p}^\bar{a} (x_B, b_T^2; \mu, \zeta_B) \)

taken from MAP collaboration global extraction at N^3LL

MAP22Pion [2206.07598]
Non-perturbative part

$$f^{\pi}_{1NP}(x, b_T^2; \zeta) = e^{-g_1(x) \frac{b_T^2}{4}} \left[ \frac{\zeta}{Q_0} \right]^{g_K(b_T^2)/2}$$

$$= e^{-g_1(x) \frac{b_T^2}{4}} \left[ \frac{\zeta}{Q_0} \right]^{-g_2(b_T^2)/4}$$

evolution kernel

$$b_*(|b_T|, b_{\text{min}}, b_{\text{max}}) = b_{\text{max}} \left( \frac{1-e^{-|b_T|^2/b_{\text{min}}^2}}{1-e^{-|b_T|^2/b_{\text{max}}^2}} \right)^{1/4}$$

$$b_{\text{min}} = 2e^{-\gamma_E}/\mu_f \quad b_{\text{max}} = 2e^{-\gamma_E} \text{GeV}^{-1}$$
Impact study: DY predictions on COMPASS space

COMPASS kinematics

CMP predictions (used as pseudodata)

MAP22 pion TMDs

Uncertainties
stat. from experimental analysis
syst: W 15% AI 10% NH^3 10%

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Impact study: exploratory fit of pion TMDs

IMPACT STUDY

MAP NANGAPARBAT [2210.01733]

200 replicas

\[ \frac{d^2 \sigma}{dQ dq_T} \text{[pbGeV}^{-2}] \]

CMP
[Impact study: exploratory fit of pion TMDs]

IMPACT STUDY

MAP NANGAPARBAT [2210.01733]

NO replicas

\[ \frac{d^2\sigma}{dQdq_{T}} \text{[pbGeV}^{-2}] \]
Impact study: exploratory fit of pion TMDs

MAP
NANGAPARBAT
[2210.01733]

200 replicas

\[ \frac{d^2\sigma}{dq_0 dq_T} \text{[pbGeV}^{-2}\text{]} \]

E615

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[Exploratory fit of pion TMDs: results]

\textbf{E615+E537} $\chi^2_0$: 1.55
\textbf{...+ C22} $\chi^2_0$ W: 1.62
\textbf{...+ C22} $\chi^2_0$ Al: 1.75

Hint of smaller uncertainties in pion TMD PDF with the inclusion of COMPASS results

209 data points
Future of meson structure: AMBER physics program

- In EHN2 (former COMPASS) experimental hall
- Availability of both hadron and muon beams
- Positive and negative beam available, and in wide range of energies (~ 60 - 250 GeV/c)
- Re-use of large aperture dipole magnets and some of the most recent COMPASS detectors
- Improved particle identification and tracking through implementations of new detectors and update of existing ones
### AMBER planned physics program

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**Phase I**  
2023 -> 2029

**Phase II**  
Beyond 2029

**MESON STRUCTURE AT AMBER**
[knowledge of pion structure]

Current limits:
- Mostly heavy target
  - nuclear effects
- Some did not publish cross-sections
- Some did not measure with both beam charges
  - no sea/valence separation

AMBER improvements
- High energy and intensity pion beams
  - Example @ 190 GeV/c^2
    - \( \text{I}_\pi^- \sim I_{\text{beam}} = 7.0 \times 10^7 / s \)
    - \( \text{I}_\pi^+ \sim 25\% \ I_{\text{beam}} = 1.7 \times 10^7 / s \)
- COMPASS-like apparatus
- Segmented Carbon target
  \( \Rightarrow \pi^+ \) and \( \pi^- \) beam on C and W target

Improved PDF flavour separation

- Aim at the first precise direct measurement of the pion sea contribution

\[ \sum_{\text{sea}} / \sum_{\text{val}} \]

\[ 4.3 < M/(\text{GeV}/c) < 8.5 \]

from proposal Amber Phase I
CERN-SPSC-2019-022 ; SPSC-P-360
Summary

COMPASS is a unique framework to study TMD PDFs universality and evolution.

Pion TMDs extractions are now based on a limited number of data, COMPASS new dataset could help to better understand them.

AMBER planned physics program will give us new tools to look at meson structure through pions and kaons processes.