Hadron production from $\mu-d$ scattering at $\sqrt{s} = 17$ GeV at Compass

$\mu^+d \rightarrow \mu^+h^\pm X$

Astrid Morréale
The QCD Proton Picture
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*Spin physics has open a box full of questions about matter, and it has also laid the groundwork to a plethora of scientific advancements: from the medical field, to astronomy research.*
The SIDIS Reaction
How can we access polarized parton information?

\[ \sigma \]

\[ p \]

\[ p_T \]

\[ \gamma^* \]

\[ \text{Center of mass} \]

\[ \eta = 0 \]

\[ \text{neg. } \eta \text{ pos. } \eta \]

\[ \text{Factorization Theorem} \]

\[ f_i \]

\[ \text{hadron} \]

\[ X \]

\[ FF^h \]

\[ h \]
How can we access polarized parton information?

\[
A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \sum_{i=q,\bar{q},g} \Delta f_\gamma \otimes \Delta f_i \otimes \Delta \hat{\sigma} \otimes FF_{h/i}
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\]

\[
A_{LL} = \frac{1}{FP_{\text{beam}}P_{\text{target}}} \frac{N_{++} - N_{+-}}{N_{++} + N_{+-}}
\]

(N) Number of events
(F) Dilution Factor
(P) Polarization in beam or target
How can we access polarized parton information?

Spin Asymmetries give us access to polarized parton densities.
In a NLO pQCD framework, factorization is employed to separate long and short distance elements:

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What motivates the Measurement of an Unpol Cross-section?
1. Measure the unpolarized differential Cross Section to confirm that the pQCD framework is applicable to data.

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→ The pQCD unpolarized cross section
Cross-Sections compared to pQCD

\( \pi^0 \) Cross-Sections at \( \eta_{cm} = 0 \)

Experiment vs Theory

\( \rightarrow \sqrt{s}=200 \text{ GeV (RHIC) Agreement} \)

$\pi^0$ Cross-Sections at $\eta_{cm} = 0$

Experiment vs Theory

$\Rightarrow \sqrt{s}=200$ GeV (RHIC) Agreement
$\Rightarrow \sqrt{s}=52.8$ GeV (ISR) Agreement

Cross-Sections compared to pQCD

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- $\sqrt{s}=200$ GeV (RHIC) Agreement
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- $\sqrt{s}=38.8$ GeV (E706) Disagreement

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Disagreement at lower center of mass energies
Observed in p+p data

→ Work needed to understand lower energies?

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What about SIDIS: \( \mu+d \rightarrow \mu'hX \)
Unpolarized Cross sections: The Measurement

\[
\int \frac{1}{2\pi p_T} \cdot \frac{d^2\sigma}{dp_T dy} \Rightarrow \frac{1}{L} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2N}{dp_T dy} \Rightarrow \frac{1}{2\pi p_T} \int L dt \epsilon_{Acc} \Delta p_T \Delta \eta
\]

\[\int L dt \rightarrow \text{Integrated luminosity: 142.4 pb}^1\]

\[N_{h\pm}(p_T) \rightarrow \text{Number of hadrons.}\]

\[\epsilon_{Acc} \rightarrow \text{Detector's geometrical acceptance, reconstruction algorithm, detection efficiencies.}\]

\[\Delta p_T \rightarrow \text{Bin width (250 MeV)}\]

\[\Delta \eta \rightarrow \text{Rapidity width (w.r.t. to theory calculation)}\]
The experiment:

COMPASS @CERN (Prevelsin):

COMMON APPARATUS FOR MUON SPECTROSCOPY:

Tertiary beam of positive muons produced in the M2 beamline at the CERN SPS.
→ Spill cycle every 16.8 seconds (Flat top extraction 4.8 seconds)

→ Polarized $\mu$ scattering off deuterons in a polarized 6 LiD solid-state target.

→ Beam energy is $E_\mu = 160$ GeV $\rightarrow$ lepton-nucleon c.m.s. energy of $\sqrt{S} \approx 18$ GeV.

→ Average beam polarization: $P_\mu \approx 80\%$.

→ About $F_d \approx 50\%$ (“dilution factor”) of the nucleon can be polarized, with an average polarization of $P_d \approx 50\%$. 
\[ \eta_{cm} = -\log(\tan(\theta/2)) - 0.5\log(2P_{\text{beam}}/M_p) \]

Low \( \theta \rightarrow \text{Forward} \ \eta_{cm} \). High \( \theta \rightarrow \text{Central} \ \eta_{cm} \). (Hard Scattering)
The kinematic cuts:
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- $\theta$ (Scattering angle): 20 - 120 mrad
  - translates to $-0.1 < \eta_{cm} < 1.7$
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- $p_T > 1$ GeV/c
Accurate Apparatus description (GEANT).

→ MC used only for extraction of acceptance.
Raw Hadron Yields

![Graph showing the number of particles versus $p_T$ (GeV/c) for $h^-$.

- COMPASS - 30% of 2004
- $\mu^+ + d \rightarrow \mu^+ + h^- + X$
- $\sqrt{s} = 17.4$ GeV
- $Q^2 < 0.1$ (GeV/c)$^2$, $-0.1 < \eta < 1.7$]
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High statistics Measurement

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30/11/2010
Cross-sections of $h^\pm$

$\mu^+d \rightarrow \mu^+ h^\pm X$ : Cross-sections.

- 2004 $\mu^+ - d$ Data.

First SIDIS cross-sections compared to NLO pQCD

30/11/2010
Cross-sections $h^-$ and $h^+$

NLO pQCD curves by W. Vogelsang (DSS FF, CTEQ6M5)

$\frac{1}{2\pi p_T} \frac{d\sigma}{dp_T}$ (pbarn (GeV/c)^2)

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$\Delta \sigma$:
- systematic uncertainty
- statistical uncertainty

additional 10% normalization uncertainty

Compatibility with NLO pQCD.
Cross-sections of $h^\pm$ and ratio $h^-/h^+$

More up quarks in the final state: Conservation of charge.

The measurement indicates that the calculated ratio does not agree with expt. FF?

→ Flat as a function of $p_T$

→ Disagreement observed with calculation.

→ Sensitive to Fragmentation functions.
Low $p_T^2$ production and high $Q^2$.

Cross section is calculated in $z$ bins: linear fit described by $< p_T^2 (Q^2, x_Bj, z, \pm)>$

The turn over description of hadron production from an exponential to a power like description can give insights about partonic behavior.

Would like to verify the pQCD description of hadron production rates at low $Q^2$ and high $Q^2$ (production rates are about an order of magnitude higher for low $Q^2$).

\[
\frac{d^{4}\sigma_{\mu N \rightarrow \mu' h X}}{d x_{B} d Q^2 d z d p_{T}^2} \approx \sum_{i} \frac{2\pi \alpha^2 e_i^2}{Q^4} f_i(x_{Bj}) D_{q}(z)[1 + (1 - y)^2] \frac{1}{\pi \langle p_{T}^2 \rangle} e^{-p_{T}^2 / \langle p_{T}^2 \rangle}
\]

Simple dependence on \(z^2\)

\[
\langle p_{T}^2 \rangle = \langle p_{\perp}^2 \rangle + z^2 \langle k_{\perp}^2 \rangle
\]

Dependence revisited (i.e A. Bacchetta):

\[
\langle p_{T}^2 \rangle = z^{\alpha}(1 - z)^{\beta} \langle p_{\perp}^2 \rangle + z^2 \langle k_{\perp}^2 \rangle
\]

The average intrinsic transverse momentum squared of partons \(< k_{\perp}^2 >\) is extracted from fits of the z-dependence of \(< p_{T}^2 >\).
$< k_{\perp}^2 >$ Extraction

$< p_T^2 >$ : measured $z$ dependence, in two intervals $Q^2$, $x_{Bj}$

$\rightarrow h^+$ (Red), $h^-$ (Blue)

$Z$ dependent fit (blue and red lines above) describe the data well.
Conclusions

- First SI cross-sections measured and released → pQCD in agreement.
- Ratio of $h^-/h^+$ is flat as a function of $p_T$.
- Benchmark to test the sum over flavors NLO pQCD framework at $\sqrt{s}=17.4$ GeV
- High statistics: Separate the forward and central $\eta_{cml\text{physics}}$. → Upcoming Publication
- $A_{LL}(p_T)$ will provide an additional precise measurement of $\Delta G(x)$ → will follow soon.
- High $Q^2$: The $p_T^2$ spectra of charged hadrons are measured and fitted with a Gaussian function at low values of $p_T^2$.
- $<k_{\bot}^2>$ is extracted from $z$-dependence fits of $<p_T^2>$
- Dependence on $Q^2$, $X_{bj}$ is also explored → Upcoming publication.
Thank You for Listening
The NLO pQCD parametrizations

NLO Calculations by
B. Jaeger, M. Stratmann, V. Wogelsang

→ pi0 production prediction: difficult to compare at the time.

→ The updated calculations for charged hadron production at Compass' full kinematics have been performed by V. Wogelsang

→ Radiative contributions calculation, however small, has been calculated by A. Afanasiev.

Fig. 2. Unpolarized and polarized $p_T$-differential single-inclusive cross sections at LO (dashed) and NLO (solid) for the photoproduction of neutral pions, $\mu d \rightarrow \mu' \pi^0 X$ at $\sqrt{S} = 18$ GeV, integrated over the angular acceptance of Compass. The lower panel shows the ratios of NLO to LO contributions ($K$-factor)
→ Low $Q^2$ (<0.1GeV/c) and high $p_T$.
→ NLO Calculation exists for Compass Kinematics.
→ This process has an advantage of higher production rates of hadrons than in (DIS) electro-production.
→ The selected hadron $H$ is at high $p_T$ (>1GeV/c): large momentum transfer, $p_T$ sets the scale.
NLO pQCD: Quasi Real Photo-production of high $p_T$ hadrons

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→ **Direct Processes** contribute with different sign ($\gamma g$, $\gamma q$)

Partonic contributions to the production of high $p_T$ hadrons at low $Q^2$ (<0.5GeV$^2$) in lepton nucleon scattering. c.m. = 18 GeV
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→ Resolved processes contribute with the same sign for a positive $\Delta G$ ($q g, q q, g q, g g$)

Partonic contributions to the production of high $p_T$ hadrons at low $Q^2$ (<0.5GeV$^2$) in lepton nucleon scattering. c.m= 18 GeV
RESULTS

Radiative corrections:

→ Current values are below 1% for all p_T <3 and Y<=0.70.

→ highest contribution occurs at y=0.8 and pT>3 ~1.8%

Refer to September invited talk meeting on the extraction method.
RESULTS

$\frac{1}{2\pi p_T} \frac{d\sigma}{dp_T}$ (pbarn (GeV/c)^2)

COMPASS - 30% of 2004
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$\sqrt{s} = 17.4$ GeV
$Q^2 < 0.1$ (GeV/c)^2, $-0.1 < \eta < 1.7$

- systematic uncertainty
- statistical uncertainty

additional 10% normalization uncertainty

$p_T$ (GeV/c)
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\begin{align*}
\Delta \sigma & \approx 0.015 \\
& \pm 0.005 \text{ (statistical uncertainty)} \\
& \pm 0.002 \text{ (systematic uncertainty)} \\
& \text{additional 10% normalization uncertainty}
\end{align*}

NLO pQCD curves by
W. Vogelsang (DSS FF, CTEQ6M5)
- \( \mu = p_T / 2 \)
- \( \mu = p_T \)
- \( \mu = 2 p_T \)

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\end{align*}
Max $\gamma$ and min $\gamma$ correspond to minimal and maximal saturation of the polarized photon densities.


→ Additional ongoing effort by A. Afanasiev to produce a parametrization that takes into account higher twist effects.
→ We expect to make available the comparisons between these Models with compass measurements soon.
Luminosity

→ Luminosity is measured using the beam scalers spill by spill.

→ Each spill corresponds to the beam delivered by SPS.
  - Every 16.8 seconds (Flattop duration of 4.8 seconds).

→ Detector effects which affect the total beam rate are accounted for: Acquisition, veto (beam halo) deadtimes.

For the data sample of interest the luminosity has been determined within 10% accuracy.
→ Evaluate the spill rates as seen by the beam scaler as a function of time.
→ Only events within the flattop are considered (red line)
The compass veto system prevents a large fraction of beam halo tracks from contaminating the trigger sample.

During high veto signal times no triggers are taken (this includes good events)

→ The “dead time” effect is taken into account in the Luminosity calculation.
→ Ratio of the rates as measured with the random triggers and scalers is dependent on the beam intensity

→ The observed dispersion of the ratio as a consequence of the intensity dependence is accounted for in the systematic uncertainty (~5%)
The transverse connections $p_T$, $k_\perp$, $p_\perp$
The fitted $<k_{\perp}^2>$ and $<p_{\perp}^2>$ may depend on $Q^2$ and $x_{Bj}$.
And they do, see next figures:

$<k_{\perp}^2>$ dependence on $Q^2$

- Clear rise of $<k_{\perp}^2>$ with $Q^2$
- $h^{-}$ have lower $<k_{\perp}^2>$ than $h^{+}$