Cold nuclear matter effects from charmonium measurements

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on behalf of the COMPASS and AMBER collaborations

“Revealing emergent mass through studies of hadron spectra and structure”
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Motivation

Ultra-relativistic heavy ion collisions: Quark Gluon Plasma (QGP)

One of the signatures for the QGP:
• J/$\psi$ suppression in central collisions
  \(\text{(Matsui & Satz, PLB 178(1986)416)}\)

But: J/$\psi$ suppression also occurs in pA collisions, which provide a needed baseline to interpret the suppression in QGP.

J/$\psi$ production in light systems allows to measure cold nuclear matter effects:
– parton energy loss
– nuclear absorption
– Cronin effect ($p_T$ broadening)
– nPDF

A useful observable to study this is the nuclear modification factor:

\[
R_{hA} = \frac{dN^J/\psi_{hA}}{\langle N_{coll} \rangle dN^J/\psi_{hh}}
\]

If no nuclear effects: $R_{hA} = 1$
Nuclear shadowing and parton energy loss

Different phenomena observed. At low $x$, driven by partons multiple scattering.

Try to encode it all in process-independent nPDFs

Partons may also lose energy via soft gluon emissions when crossing the cold nuclear matter

Different hard processes allow to study the energy loss effect:
- Drell-Yan $\rightarrow$ initial state radiation
- $J/\psi$ production $\rightarrow$ initial and final state radiation, interference

(from N. Armesto, 2006)
Some $J/\psi$ measurements from past experiments

From F. Arléo and S. Peigné, PRL 109 (2012) 122301

Coherent parton energy loss (---) seems able to explain the $J/\psi$ suppression in heavy nucleus compared to lighter nucleus.
**Nuclear modification factor in COMPASS**

COMPASS: 190 GeV $\pi^-$ beam on fixed target (W or Al). $\sqrt{s}=18.9$ GeV

In COMPASS we measure **inclusive $J/\psi$ production**:

$$\pi^- A \rightarrow J/\psi \, X \rightarrow \mu^+ \mu^- \, X$$

$R_{\pi A} (x_F, p_T)_{W/Al}$ is defined as the ratio of $J/\psi$ production cross sections (per nucleon) between W and Al targets, in a given $(x_F, p_T)$ bin.

In the center-of-mass of the hadrons collision (*),

$$x_F = \frac{2 \, p^*_L}{\sqrt{s}}$$

$p_L$ and $p_T$: longitudinal and transverse momentum of the dimuon.
π⁻ beam
190 GeV/c, I ~ 10⁸/second

Measurements done with the "Drell-Yan set-up"
In 2015 and 2018.

Two dimuon triggers based on hodoscope pairs:
- “2 muons in LAS” (LL);
- “1 muon in LAS and 1 muon in SAS” (LO).

- NH3 polarized target
- Aluminium target
- Tungsten target
Data selection

- All data recorded in 2018
- Muon pairs of opposite charge
- Dimuon trigger fired (LL or LO)
- $1.5 < M < 8.5 \text{ GeV/c}^2$
- $0 < x_F < 0.9$
- $p_T < 4 \text{ GeV/c}$
- Vertices inside one of targets:
  - $-73.5 < Z_{vtx} < -66.5 \text{ cm} \ (\text{Al})$
  - $-30 < Z_{vtx} < -20 \text{ cm} \ (\text{W})$
- ~80K J/ψ in Al and ~600K J/ψ in W

Full Monte Carlo simulation of all relevant physics processes, and propagation in the spectrometer (pythia 8 + GEANT4):
- J/ψ
- ψ(2S)
- Drell-Yan
- Open charm
- and combinatorial background estimated from real data like-sign muon pairs.
Analysis done in bins ($x_F$, $p_T$): dimuon mass
**Analysis done in bins ($x_F$, $p_T$): dimuon mass**

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$p_T$ (GeV/c)</th>
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<tr>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>0.1</td>
<td>0.5</td>
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<tr>
<td>0.2</td>
<td>1.0</td>
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<tr>
<td>0.3</td>
<td>1.5</td>
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<td>0.4</td>
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<td>0.5</td>
<td>2.5</td>
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<tr>
<td>0.6</td>
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<tr>
<td>0.7</td>
<td>3.5</td>
</tr>
<tr>
<td>0.8</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**Legend:**
- COMPASS preliminary
- LasOuter
- W
- Al

The graph shows histograms of dimuon mass distributions for different bins of $x_F$ and $p_T$. Each bin is color-coded and labeled with the corresponding $x_F$ and $p_T$ values.
Reconstructed MC physics components and combinatorial background from real data are used to fit the dimuon mass spectra, in each of the $(x_F, p_T)$ bins, separately per trigger and per target.

Example:
W target, LL trigger
$0.1 < x_F < 0.2$, in bins of $p_T$

Cocktail fits done in the mass range
$2.1 < M < 8.5$ GeV/$c^2$
Monte Carlo to real data comparison

Example: W target, LL trigger, $\mu^+$

Good description, once all MC physics components (in the proportions given by cocktail fit) and combinatorial background from real data (RD) are taken into account.
J/ψ acceptance

The acceptance – including smearing effects and detector and trigger efficiencies – is obtained in $(x_F, p_T)$ bins, separately per trigger and per target.

LL trigger

LO trigger
$R_{\pi A}$ as a function of $x_F$, in bins of $p_T$

Error bars show the statistical uncertainty.

Systematic uncertainty estimated: <10%

Suppression towards high $x_F$, more prominent at low $p_T$. This 2D analysis provides additional insight, not possible from past experiments (cf. 1D results from NA3).
$R_{\pi A}$ as a function of $p_T$, in bins of $x_F$.

Error bars show the statistical uncertainty.

Systematic uncertainty estimated: <10%

Suppression at low $p_T$, more prominent at large $x_F$. 
\( R_{\pi A} \) as a function of \( x_F \)

COMPASS Preliminary
\( \pi^- A \rightarrow J/\psi X \rightarrow \mu^+\mu^- X \)
\( \sqrt{s} = 18.9 \text{ GeV} \)

- \( p_T < 3 \text{ GeV/c} \)

Error bars show the statistical uncertainty.
Systematic uncertainty estimated: <10%

\( R_{\pi A} \) as a function of \( p_T \)

COMPASS Preliminary
\( \pi^- A \rightarrow J/\psi X \rightarrow \mu^+\mu^- X \)
\( \sqrt{s} = 18.9 \text{ GeV} \)

- \( 0.1 < x_F < 0.5 \)

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Comparing COMPASS result

To a model of energy loss, with transport coefficient $q_o$ by F. Arléo and S. Peigné, JHEP 03 (2013) 122.

Comparing COMPASS result

Using a model of energy loss, with transport coefficient $q_o$, by F. Arléo and S. Peigné, as in JHEP 03 (2013) 122.

COMPASS preliminary

$\pi^- A \rightarrow J/\psi X \rightarrow \mu^+ \mu^- X$
$\sqrt{s} = 18.9$ GeV
$p_T < 3$ GeV/c

F. Arléo, private communication, preliminary

$x_F$ definition used by Arléo:

$$x_F = x_F(E) = \frac{E}{E_p} - \frac{p_{T}}{E_p} \frac{M^2}{s}$$

In the center-of-mass frame of the $\pi N$ collision

$E$: energy of the $J/\psi$

$E_p$: energy of the pion beam

$M$: transverse mass

COMPASS Preliminary

$R_{W/AI}$

$\pi^- A \rightarrow J/\psi X \rightarrow \mu^+ \mu^- X$

$p_T < 3$ GeV/c
Still to come from COMPASS

✔ These nuclear modification factor results from COMPASS are very recent and still preliminary.

✔ Comparison to models of coherent parton energy loss is ongoing.

✔ An analysis of the $J/\psi <p_T^2>$ from W and Al targets is ongoing, which should allow comparison to models of nuclear $p_T$-broadening.

✔ $J/\psi$ absolute cross section in Al and W targets should follow soon.

✔ An analysis on the $J/\psi$ polarization from W and NH3 targets is also ongoing.

✔ The nuclear modification factor from the Drell-Yan process, and Drell-Yan cross-section should also be released soon.
What else can we learn from quarkonium measurements?

Pion-induced $J/\psi$ production: access to the **pion structure**…

… provided we understand and manage to distinguish experimentally its production mechanisms (namely $q\bar{q}$ annihilation and $gg$ fusion)
The AMBER/NA66 experiment had phase-I measurements approved at CERN in December 2020 (→ proposal)

Several topics related to the emergence of hadron mass:
- Hadron charge radii
- Hadron spectroscopy
- Hadron structure

Setup similar to COMPASS with added/upgraded detectors and target region

π± and K± beam particles 190 GeV/c
Pion structure studies at AMBER

Most direct way to access pion structure: Drell-Yan process

Sea/Valence separation (at Leading Order), by using the two pion beam charges:

\[
\frac{\Sigma_{\text{sea}}}{\Sigma_{\text{valence}}} = \frac{4\sigma^{+C} - \sigma^{-C}}{-\sigma^{+C} + \sigma^{-C}}
\]

LO: only sea-val and val-sea terms

LO: only val-val terms

(Model dependent) access to the gluon distribution in the pion

\[ J/\psi \text{ production} \]
J/Ψ: access to gluon content in the pion

- Large statistics on J/ψ production at dimuon channel:
  \[ \pi^\pm C \rightarrow J/\psi X \rightarrow \mu^+\mu^- X \]
- Inclusive: due to the hadron absorber, we cannot distinguish prompt production from the rest
- Expected significant feed-down: ψ(2S), χ_{c1}, χ_{c2}
- In the low-\(p_T\) regime
- Dominant contribution from 2→1 processes
- Use the polarization, \(x_F\) and \(p_T\) dependences to distinguish production mechanisms...

AMBER phase-II: RF-separated kaon beams for access to kaon structure

The RF-separation technique allows to improve the kaon purity in a hadron beam. But:

– kaon intensity limited to $5 \times 10^5$/second (as opposed to $2 \times 10^7$ assumed in AMBER LoI)

• **Drell-Yan process**: not enough statistics

• **Charmonium measurements**: possible!
  The lower Intensity might allow for open spectrometer
AMBER phase-II: RF-separated kaon beams

J/ψ and access to valence and glue

- Beam intensity $10^5$ kaons/second
- $\sim 10 \, 000$ J/ψ events for each beam
- Model-dependent access to the gluon distribution in kaons
- J/ψ production cross section (LO):

$$\sigma(K^-) - \sigma(K^+) \propto \bar{u}_v^K u^K_v$$

JAM18 “pion” PDFs, PRL 121, 152001 (2018)
Higher charmonium states at AMBER

With RF-separated kaon beams:
- much lower beam intensity
- open spectrometer measurements become possible
  - Much better mass resolution, allowing to distinguish $J/\psi$ and $\psi(2S)$

$\psi(2S)$:

Cleaner than $J/\psi$, since no feed-down from $\chi_c$ states.

Its polarization is a stronger discriminant than $J/\psi$ between $qq$ and $gg$ mechanisms

But: relatively low statistics
First measurements of the $J/\psi$ nuclear modification factor from COMPASS. $R_{\pi A} (x_F, p_T)|_{W/Al}$ is seen to decrease for higher $x_F$ and lower $p_T$. 

The measured $J/\psi$ suppression is in qualitative agreement with past experiments, and with the coherent parton energy loss assumption.

Many more results expected soon.

The AMBER new experiment at CERN focuses on the studies of meson structure: pion and kaon.

A new generation of charmonium measurements at intermediate energies are proposed:

– understand production mechanisms;
– access to valence and gluon content in the pion and kaon.
SPARES
The double differential $J/\psi$ cross section:

$$\frac{d^2\sigma^{\pi^- A}}{dx_F dp_{\perp}} J/\psi = \frac{N_{\text{events}}^{J/\psi}(x_F, p_{\perp})}{\varepsilon^A \cdot \text{BR} \cdot \Delta x_F \cdot \Delta p_{\perp} \cdot L}$$

$\varepsilon^A$: acceptance for target A

$\text{BR}$: branching ratio $J/\psi \to \mu\mu$

$L$: integrated luminosity

The integrated luminosity:

$$L = \Phi^0 \alpha^A L_{\text{eff}}^A \rho^A \frac{N_A}{M_A}$$

$\Phi^0$: integrated beam flux

$\alpha^A$: beam attenuation at entry of target A

$L_{\text{eff}}^A$: effective target length

$\rho^A$: density of target A

$N_A$: Avogadro number

$M_A$: molar mass of target A

The effective target length, taking into account the beam attenuation inside the target:

$$L_{\text{eff}}^i = \frac{\lambda_{\text{int}}}{\rho} \left[ 1 - \exp\left(\frac{-\rho L}{\lambda_{\text{int}}}\right) \right]$$

$R_{\pi^- A}^{J/\psi}(W/Al) = \frac{N_{W}^{J/\psi}(x_F, p_{\perp})}{\epsilon_W \cdot \alpha_W \cdot L_{\text{eff}}^W \cdot \rho_W} / \frac{N_{Al}^{J/\psi}(x_F, p_{\perp})}{\epsilon_{Al} \cdot \alpha_{Al} \cdot L_{\text{eff}}^{Al} \cdot \rho_{Al}}$
**J/ψ production and model interpretation on the mechanisms of production**


Using global fit extracted pion and nucleon PDFs (GRS and CT10)

Daniele Binosi, at this workshop

Using pion structure predictions from the continuum approach