CHARMONIUM MEASUREMENTS WITH AMBER – A TOOL FOR ACCESSING THE MESON PDFS

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ON BEHALF OF THE COMPASS++/AMBER COLLABORATION

(WITH INPUT FROM W.-C. CHANG, J.-C. PENG, T. SAWADA, P. FACCIOLI)
Contrary to nucleon, the meson structure is nearly unknown

- Meson structure
  - What is the behavior of the kaon and pion PDFs vs the PDFs in the nucleon?
  - The s quark in the kaon is heavier: Are kaon and pion gluon PDFs identical?

- Understand the hadron mass budget
  - Higgs mechanism can’t explain hadron masses
  - Need to explain the “heavy” nucleon and the “massless” pion

- My talk: charmonium production could prove a powerful tool for accessing the π/K PDFs
AMBER EXPERIMENT – PROPOSED SETUP

- Run 3: 2022 – 2024
  - positive beam: pions (25%), protons (74%)
  - negative beam: pions (97%), kaons (2%)

- Run 4 (with RF): > 2026
  - negative kaons (~50%), pions (~50%)
  - positive kaons
  - antiprotons

Only place in the world with pion and (kaon, antiproton) beams!
DIMUON STUDIES IN COMPASS++/AMBER

- Run 3: 2022 – 2024
  - E = 190 GeV, positive and negative hadron beams
  - light (\(^{12}\)C) and heavy (\(^{184}\)W) targets
  - Simultaneous measurements: \(\pi^+\) and p, and also \(\pi^-\)

- Run 4:
  - strongly relies on RF separated beams
  - E < 100 GeV, positive and negative beams
  - New, highest-ever statistics measurements with \(K^+, K^-\), antiprotons …

Note that: Drell-Yan and charmonium data are collected in parallel
CHARMONIUM WITH AMBER

- Advantages of (our) FT energies: 100 – 200 GeV
  - J/ψ has large cross sections – factor of 30-40 larger than Drell-Yan at 190 GeV
  - Fixed-target energies: production is dominated by 2 -> 1 processes
  - Can measure $x_F$, $p_T$, $\lambda$ distributions with unprecedented statistics (> 1 M events)
  - Collect also $\psi'$ data, together with J/ψ

- Present status of FT measurements
  - Meson FT data come from CERN and Fermilab experiments: mostly 80’s, 90’s
  - No new FT data since nearly two decades – contrary to charmonium collider data
CHARMONIUM WITH AMBER

- Difficulties – and impetus for deeper studies
  - Model dependence: the production mechanism is not well known. A long history...
  - Mainly two production models: CEM and NRQCD. At FT energies, both models have $q\bar{q}$ and $gg$ as dominant contributions to the cross section
  - $p_T \leq M(J/\psi)$: complementary to LHC, where $p_T \gg M(J/\psi)$

- Huge potential interest
  - Add meson-induced FT data to charmonium production studies at colliders
  - Access quark/gluon PDFs of pion and kaon
  - Access gluon PDFs in nuclei…
J/\psi PRODUCTION MECHANISMS

- Color Evaporation Model (CEM)
  - Simple cross section for producing $Q\bar{Q}$ pairs. Ignores quantum numbers.
  - Considerable phenomenological success

- Recent improvements: Improved CEM (ICEM) (Cheung and Vogt, PRD98, 2018)
  - Includes $p_T$ dependence, ICEM + $k_T$ factorization => cross sections, $x_F$ and $p_T$ dependence, polarization, etc…

- NRQCD (Bodwin, Braaten, Lepage): rigorous consequence of QCD
  - Long-Distance Matrix Elements (LDME): probability of the $cc$ pair to evolve into a quarkonium state. LDME: conjectured to be universal, ….
DO WE UNDERSTAND THE J/ψ PRODUCTION?

- Two models at NLO: CEM and NRQCD

![Graphs showing J/ψ production cross sections at 800 and 120 GeV.](image)

Qualitatively similar, but quantitatively different results

(R. Vogt, 2000)
Could $J/\psi$ data be used to infer meson PDFs?
The two global fits lead to different PDFs: valence, gluon, sea.
ICEM PREDICTIONS – $X_F$ DEPENDENCE

ICEM: Cheung and Vogt, PRD98,114029 (2018) and priv. comm.
POLARIZATION

- \( J/\psi \) is a \( 1^-^- \) 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 \( q\bar{q}: \alpha \approx +1 \), but for \( gg: \alpha \approx -1 \)
  - Key variable for understanding the bound state formation

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

- ICEM xF-dependent predictions
  - with minimal model-dependence
    \[ \lambda_{q}^{CS} \approx +0.4 \text{ for } q\bar{q} \]
    \[ \lambda_{g}^{CS} \approx -0.6 \text{ for } gg \]
  - 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 ALSO 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 $gg$ and $q\bar{q}$ fractions.
## ESTIMATED $J/\psi$ STATISTICS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target type</th>
<th>Beam energy (GeV)</th>
<th>Beam type</th>
<th>$J/\psi$ events</th>
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<td>p</td>
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<td>HERA-B [132]</td>
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<td>920</td>
<td>p</td>
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</tr>
</tbody>
</table>

## Comments

Cross sections not published, only plots available

$\xi_F$ and $p_T$ cross sections available

Only ratios of cross sections available

Only $A$-dependent studies of total cross sections

$\xi_F$ and $p_T$ cross sections available

Estimations based on Compass preliminary numbers
ψ' PRODUCTION

- **Advantages**
  - No feed-down contributions. Consequences:
    - straight forward test of production models, no dilution.
    - $q\bar{q}$ and $gg$ contributions could reach their maximum polarization values
  - $x_F$ and $p_T$ dependences could be measured altogether with the polarization
  - AMBER could provide the largest ψ’ data set ever.

- **Requirements**
  - Good mass resolution (≤ 100 MeV) to separate $J/\psi$ and ψ’ – vertex detectors
  - Alternative: dedicated run for charmonium studies without absorber – much improved resolution, but significantly lower statistics.
**ψ’ PRODUCTION – EXPECTED STATISTICS**

- From previous measurements (e.g. HERA-B, 2007)
  - \( R (\psi'/J/\psi) \approx 0.018 \) (used to estimate nb of \( \psi' \))

<table>
<thead>
<tr>
<th>Target</th>
<th>Energy</th>
<th>Beam</th>
<th>Nb of ( \psi' )</th>
</tr>
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<td>(^{12}\text{C})</td>
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<td>(\pi^+)</td>
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<td></td>
<td></td>
<td>(\pi^-)</td>
<td>32 400</td>
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<tr>
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<td></td>
<td>(p)</td>
<td>27 000</td>
</tr>
<tr>
<td>(^{184}\text{W})</td>
<td></td>
<td>(\pi^+)</td>
<td>9 000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\pi^-)</td>
<td>12 600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(p)</td>
<td>12 600</td>
</tr>
</tbody>
</table>

An order of magnitude better than previous experiments!
RUN4++ : RF SEPARATED BEAMS – HIGH-INTENSITY

- Studies underway at CERN for RUN4 (2026++)
- Some assumptions:
  - L = 450 m, f = 3.9 GHz, beam spot within 1.5 mm
  - Reasonable primary target efficiency, 80% wanted particles pass dump
  - Number of primary protons: 100 - 400x10^{11} ppp on the production target
  - Energy limitation: ≲ 100 GeV

Large improvement in kaon and antiproton intensities ( > x 20- 40 !)
**PROTON AND ANTIPROTON-INDUCED J/Ψ PRODUCTION**

- $p(\bar{p}) + p$ charmonium cross sections

\[
\bar{p}(\bar{u}\bar{u}\bar{d}) + p(uud) \propto gg + [\bar{u}_v u_v + d_v d_v] + [\bar{u}_v u_s + \bar{d}_v d_s] + [\bar{u}_s u_v + \bar{d}_s d_v] + \text{sea} - \text{sea terms}
\]

\[
p(uud) + p(uud) \propto gg + [-\ldots -] + [\bar{u}_s u_v + \bar{d}_s d_v] + [u_v \bar{u}_s + d_v \bar{d}_s] + \text{sea} - \text{sea terms}
\]

- Difference of the $\bar{p}$ and $p$-induced cross sections:

\[
\sigma(\bar{p}) - \sigma(p) \propto [\bar{u}_v u_v + d_v d_v]
\]

- Note that the proton PDFs are very well known.

The cross section difference could serve as a benchmark for the $J/\psi$ production mechanism.
proton beam on a Pt target
no valence-valence quark term

antiproton beam
with valence-valence quark term

The (largest) valence-valence term is only present in antiproton-induced production
J/ψ – MODEL-INDEPENDENT ACCESS TO THE KAON VALENCE PDF!

- Production cross section for $K^+$ and $K^-$

\[
K^-(u\bar{s}) + p(uud) \propto gg + \left[ \bar{u}_v^K u^p_v + \bar{u}_s^K u^p_s + s^K_s s^p_s \right] + \left[ \bar{u}_v^K u^p_s + u^K_s \bar{u}_s^p + s^K_s s^p_s + s^K_s s^p_s \right]
\]

\[
K^+(u\bar{s}) + p(uud) \propto gg + \left[ \bar{u}_v^K u^p_v + \bar{u}_s^K u^p_s + s^K_s s^p_s \right] + \left[ \bar{u}_v^K u^p_s + u^K_s \bar{u}_s^p + s^K_s s^p_s + s^K_s s^p_s \right]
\]

- The cross section difference isolates the val-val term:

\[
\sigma(K^-) - \sigma(K^+) \propto \bar{u}_v^K u^p_v
\]

- Can be compared with the kaon valence PDF determined using Drell-Yan

- For $E < 100$ GeV, the $q\bar{q}$ contribution is dominant
KAON-INDUCED J/ψ PRODUCTION – CEM AT 100 GEV

LO CEM calculations

identical val-sea and sea-sea contributions
identical gg contributions

K⁻ – K⁺ difference provides alternative (to DY) way to access the kaon valence PDF
DSE: at the hadronic scale gluons carry
5% of the momentum of the kaon BUT
30% of the momentum of the pion!

700 DY events only. But the number of J/ψ events is much larger ….
J/Ψ DATA ON THE KAON: STATISTICS

NA3 K^-/π^- J/ψ RATIO

AMBER: nb of expected K (*using LoI DY conditions – with RF)

<table>
<thead>
<tr>
<th>Expt</th>
<th>Tgt</th>
<th>E(GeV)</th>
<th>Beam</th>
<th>Nb of J/ψ</th>
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<td>WA39</td>
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<tr>
<td>AMBER</td>
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<tr>
<td></td>
<td>12C</td>
<td>100</td>
<td>π^+</td>
<td>≳ 300 000</td>
</tr>
</tbody>
</table>

J/ψ production K/π ratio brings essential newl information
SUMMARY FOR J/ψ MEASUREMENTS WITH AMBER

- J/ψ data with π+ and π− beams (Run 3)
  - J/ψ and ψ’ measurements with high statistics
  - Allow for multidimensional analysis of cross section and polarization data
  - Goal: understand production mechanism and infer meson PDFs
    - AMBER is unique for such measurements; no direct competition

- J/ψ data with K−, K+ and antiproton beams (Run 4 and RF separation)
  - J/ψ and ψ’ data: extensive comparison K− and K+; possibly p and p̅ data
  - Goal: constrain production mechanism + determine K valence and gluon structure
    - Motivating extensions with kaon and antiproton beams; no direct competition