Charm Production in E866/FNAL & PHENIX

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For E866/NuSea & the PHENIX Collaboration

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- Gluon shadowing & energy loss in nuclei
- $J/\Psi$ production mechanisms & absorption
- Cronin effect ($p_T$ broadening)
- PHENIX measurements and charm in d-Au
- Summary
Physics Issues in heavy-quark production in nuclei - Shadowing

- **Shadowing** of gluons → depletion of the small x gluons
- Very low momentum fraction partons have large size, overlap with neighbors, and fuse to thus enhancing higher population at higher momenta at the expense of lower momenta
- Or, coherent scattering resulting in destructive interference for coherence lengths longer than the typical intra-nucleon distance

**Graphical Data**

- **Drell-Yan**
  - E866 R(W/Be)
  - E772 R(W/D)

- **Plots**
  - Ratio (W/Be)
  - R_g^A(x, Q^2)
  - E866 (mid-rapidity)
  - NA50
Nuclear Dependence of charm in E866

FNAL E866/NuSea

\[ \sigma_A = \sigma_N \times A^\alpha \]

Donald Isenhower, Mike Sadler, Rusty Towell, Josh Willis Abilene Christian
Don Geesaman, Sheldon Kaufman, Bryon Mueller ANL
Chuck Brown, Bill Cooper FNAL
Gus Petitt, Xiao-chun He, Bill Lee Georgia State
Dan Kaplan IIT
Tom Carey, Gerry Garvey, Mike Leitch, Pat McGaughey, Joel Moss, Jen-Chieh Peng, Paul Reimer, Walt Sondheim LANL
Mike Beddo, Ting Chang, Vassili Papavassiliou, Jason Webb New Mexico St.
Paul Stankus, Glenn Young ORNL
Carl Gagliardi, Bob Tribble, Eric Hawker, Maxim Vasiliev Texas A & M
Don Koetke Valparaiso

- J/Ψ and Ψ’ similar at large x_F where they both correspond to a c\overline{c} traversing the nucleus
- but Ψ’ absorbed more strongly than J/Ψ near mid-rapidity (x_F ~ 0) where the resonances are beginning to be hadronized in nucleus
- open charm not suppressed (at x_F ~ 0)
Scaling of J/Ψ Suppression?

- Shadowing and initial-state gluon energy loss thought to be main reasons for increasing suppression at larger $x_F$
- But this effect does not scale with $x_2$ as expected for shadowing between E866 at 800 GeV & NA3 at 200 GeV
- Although does scale with $x_F$ which would be expected for energy loss
- Remains a puzzle…

$\sigma_A = \sigma_N \ast A^\alpha$

E866 - PRL 84, 3256 (2000)
& NA3 - PRL84(2000),3258
Gluon Shadowing – Largely Unknown

Gluon shadowing for $J/\Psi$’s in PHENIX $\mu$ acceptance; large uncertainty:

- *Eskola*... : ~ 0.8 vrs *Kopeliovich*... : ~ 0.4
- Must be measured
**J/Ψ at fixed target: Absorption at mid-rapidity**

- Significant nuclear dependence of cross section is observed
- Power law parameterization $\sigma = \sigma_N \cdot A^\alpha$
  - $\alpha = 0.92$ (E772, PRL 66 (1991) 133) (limited $p_T$ acceptance bias)
  - $\alpha = 0.919 \pm 0.015$ (NA38, PLB 444 (1998)516)
  - $\alpha = 0.954 \pm 0.003$ (E866 @ $x_F=0$. PRL 84 (2000),3258)
  - $\alpha = 0.934 \pm 0.014$ (NA50, QM2001)
- Absorption model parameterization
  - $\sigma = 6.2$ mb (NA38/50/51) to 4.4 mb (NA50, QM2002)
- Small difference in $\alpha$ between J/Ψ and Ψ(2S) (E866)
  - $\alpha_{J/Ψ} - \alpha_{Ψ(2S)} \sim 0.02-0.03$ @ $x_F = 0$
Energy loss of gluons in nuclei

Energy loss of incident parton shifts effective $x_F$ and produces nuclear suppression which increases with $x_F$

Color-dipole model
Kopeliovich, Tarasov, Hufner

1. $c\bar{c}$ absorption
2. dynamic calc. of gluon shadowing
3. anti-shadowing from Eskola
4. energy loss
5. Decay of $\chi \rightarrow J/\Psi$ (base calculation is for $\chi$)

\[ \sigma_A = \sigma_N * A^\alpha \]
\( P_T \) Broadening at 800 GeV

\[ 800 \text{ GeV/c } p + A \rightarrow J/\Psi \text{ or } \Psi' \]

\( E866/\text{NuSea}, \sigma_A = \sigma_N \times A^\alpha \)

\( -0.1 < x_F < 0.3 \quad 0.2 < x_F < 0.7 \)

\( 0.3 < x_F < 0.93 \quad \text{NA3 (200 GeV/c)} \)

\( \alpha(p_T) \) shape is independent of \( x_F \) & same for NA3 at a lower energy (curves are \( \alpha(p_T) = A \times (1 + 0.06 p_T + 0.011 p_T^2) \) with \( A \) slightly different for each)
Systematics of $P_T$ Broadening

\[ \Delta \langle p_T^2 \rangle = C \ast [(A/2)^{1/3} - 1] \]

\[ \Delta \langle p_T^2 \rangle = C \ast [(A/2)^{1/3} - 1] \]

\[ C = 0.027 \]

\[ C = 0.077^{+0.003}_{-0.001} + (8.18^{+1.21}_{-1.03})e^{-A/E^2} \]

\[ C = 0.030 \]
E866 - J/Ψ Nuclear dependence even for Deuterium/Hydrogen

Nuclear dependence in deuterium seems to follow the systematics of larger nuclei, but with an effective $A$ smaller than two.

From fits to E866/NuSea $p + $ Be, Fe, W data:

\[
\alpha(x_F) = A \times (1 - 0.052x_F - 0.034x_F^2)
\]

\[
\alpha(p_T) = A \times (1 + 0.06p_T + 0.011p_T^2)
\]
Feeding of \( J/\Psi \)'s from Decay of Higher Mass Resonances

**E705 @ 300 GeV/c, PRL 70, 383 (1993)**

- Large fraction of \( J/\Psi \)'s are not produced directly

| \( \chi_{1,2} \rightarrow J/\Psi \) | 30% | 37% |
| \( \Psi' \rightarrow J/\Psi \) | 5.5% | 7.6% |

### Nuclear dependence of parent resonance, e.g. \( \chi_c \) is probably different than that of the \( J/\Psi \)

- e.g. in proton production \( \sim30\% \) of \( J/\Psi \)'s will have effectively stronger absorption because they were actually more strongly absorbed (larger size) \( \chi_c \)'s while in the nucleus

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<th>M(GeV)</th>
<th>R(Fm)</th>
<th>BE (MeV)</th>
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<tr>
<td>( J/\Psi )</td>
<td>3.1</td>
<td>.45</td>
<td>(~640)</td>
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<tr>
<td>( \Psi' )</td>
<td>3.7</td>
<td>.88</td>
<td>(~52)</td>
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<tr>
<td>( \chi_c )</td>
<td>3.5</td>
<td>.70</td>
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Open Charm Nuclear Dependence: $x_F$ Dependence?

- Open charm has little or no nuclear dependence
  \[ \alpha = 1.00 \pm 0.05 \] (E769 250GeV $\pi + A$)
  \[ \alpha = 0.92 \pm 0.06 \] (WA82 340GeV $\pi + A$)
  \[ \alpha = 1.02 \pm 0.03 \pm 0.02 \] (E789 800GeV $p + A$)
- This is consistent with there being little nuclear shadowing in the $x$ region probed by the fixed target charm experiments.
- Significant nuclear suppression is reported in large $x_F$ region (WA78, $\alpha = 0.81 \pm 0.05$). This could be due to nuclear shadowing in small $x$ (large $x_F$), but this is not well understood.
- At RHIC, we can probe $x$ values much smaller than for fixed target and may observe nuclear shadowing effect in charm production.

E769 250 GeV $\pi^\pm$ PRL 70,722 (1993)

WA82 340 GeV $\pi$
PRB 28,453 (1992)

**Fig. 4.** Dependence of the parameter $\alpha$ on $P_T$ and $x_F$ for $D^+$ and $D^0$.

**WA866/NuSea, $\sigma = \sigma_n \cdot A^0$**

**α**

**Fig. 4.** The parameter $\alpha$ for charm production as measured in this $\pm 1\sigma$ interval.
2 Muon Trackers = 2x3 stations
2 Muon Identifiers = 2x5 planes

South Arm:
Began operations in 2001-2002 run.

North Arm:
Installed in 2002.

Acceptance: $1.2 < |\eta| < 2.4$
$\Delta \Phi = 2\pi$
Muon minimum momentum ~ 2 GeV/c
First $J/\Psi \rightarrow \mu^+\mu^-$'s at RHIC

- 36 counts from South muon arm in 2001-2002 run as shown at Quark Matter last July (now 66 with tuned pattern recognition and analysis)
- Quark Matter cross section consistent with lower energy measurements extrapolated to RHIC energy by various theoretical models

![Graph showing dimuon invariant mass distribution](image)

![Graph showing cross section as a function of energy](image)

$\sigma \sim 150$ MeV

More recent analysis - 4/17/03

~ 66 counts
Electron Measurement in PHENIX

- High resolution tracking and momentum measurement from Drift chamber.
- Good electron identification from Ring Imaging Cherenkov detector (RICH) and Electromagnetic Calorimeter (EMCal).
- High performance Level-1/Level-2 trigger

Measure electron between $|\eta| \leq 0.35$ and $\text{mom} \geq 0.2 \text{GeV}$
$J/\Psi \rightarrow \text{ee in pp @ 200 GeV}$

$|y| < 0.35 \quad N_{J/\Psi} = 24 \pm 6 \pm 4 \text{ (sys)}$

$Bd\sigma/dy = 61.8 \pm 9.8 \text{ (stat)} \pm 9.4 \text{ (sys)} \pm 6.4 \text{ (abs)} \text{ nb}$
PHENIX data agrees with the color evaporation model prediction at $\sqrt{s}=200$ GeV.

$\sigma (p+p \rightarrow J/\Psi X) = 3.98 \pm 0.62 \text{ (stat.)} \pm 0.56 \text{ (sys)} \pm 0.41 \text{ (abs)} \ \mu b$

- PHENIX data agrees with the color evaporation model prediction at $\sqrt{s}=200$ GeV
Both PHENIX Muon Arms Operational in Present d-Au Run
200 GeV d+Au

South Arm operating at optimal level after extensive repair work during the shutdown before the d+Au run
- less than 1/3 of d+Au data in this analysis
- trigger and other efficiencies still under study

Number of J/Ψ’s expected from the $\int L \sim 2.7 \text{ nb}^{-1}$ d-Au run (w/o shadowing)
- ~ 1000/arm for $\mu^+\mu^-$
- ~ 400 for $e^+e^-$

p-p run (just completed) may give ~ 300/arm J/Ψ’s
North PHENIX Muon Arm

200 GeV d+Au

- opposite-sign pairs
- same-sign pair bkgd

~ 356 J/Ψ’s
3.11 ± .01 GeV
σ = 145 ± 11 MeV

d+Au run is 1st for North Muon arm
- mass resolution already close to optimal even without final alignment constants
- this analysis from less than 1/3 of the d+Au data
- efficiencies, especially for the trigger, still largely unknown for this quick analysis

Comparison of North and South J/Ψ yields not instructive at this stage since we are only beginning to study efficiency issues which could have large effects and the data samples are not identical
J/ψ→e⁺e⁻ Signal in d-Au Collision

- With online calibration, we observed J/ψ→e⁺e⁻ signal.
- The width of J/ψ is expected to be 60 MeV after good calibration.
- We expect to get a few hundred J/ψ→e⁺e⁻ from the 2003 d-Au run.
Expected PHENIX d–Au Statistics
& Vogt CEM with only shadowing

FAKE data points to illustrate statistical power of d-Au data just taken
(there will be additional systematic uncertainties)
FAKE data points to illustrate statistical power of d-Au data just taken (there will be additional systematic uncertainties)

(also impact parameter dependence)
PHENIX Silicon Vertex Upgrade

A schematic cut-away mechanical drawing of the proposed vertex detector (from Hytec).

Physics Highlights:
- gluon shadowing & spin in the nucleon
- J/Ψ suppression & contrast to open-charm
- beauty
- heavy-quark energy loss

The pt distribution of muons that decay within 1cm of the collision vertex.

The reconstructed Z-vertex distribution for the J/ψ from B decays (solid line) and the prompt J/ψ (dashed line).
**Summary**

$J/\Psi$ suppression has a rich variation with kinematic variables, i.e. $x_F$ and $p_T$:
- gluon shadowing, absorption, parton energy-loss and $p_T$ broadening all important
- $J/\Psi$ is complicated by feed-down from higher mass resonances
- open-charm has no nuclear dependence at mid-rapidity (but this doesn’t shed any light on shadowing at small $x$)
- Understanding $J/\Psi$ suppression for normal nuclear matter is critical if the $J/\Psi$ is to be used as a probe for hot high-density matter (QGP) in heavy-ion collisions
- At RHIC the effect of shadowing is very uncertain with predictions that vary by large factors. So it is quite important to measure shadowing
New results from the PHENIX muon and electron arms for d-Au collisions are beginning to come out from this years data and should shed light on the question of shadowing for gluons, as well as provide a baseline for high-luminosity Au-Au measurements in the next RHIC run.

Comparison of North and South J/Ψ yields not instructive at this stage since we are only beginning to study efficiency issues which could have large effects and the data samples are not identical.
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<td>Vanderbilt University, Nashville, TN</td>
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*as of July 2002
Backup slides
Acceptance in $p_T$ is considerably narrowed at low $x_F$
Use MC acceptance & $d\sigma/dp_T$ consistent with our data to correct for incomplete coverage
This also is why E772 (which had stronger narrowing of $p_T$ at small $x_F$) $J/\Psi$’s got $\alpha \sim 0.92$
Parton Energy Loss in Nuclei for Drell-Yan – Kopeliovich Model

Shadowing when coherence length, 
\[ l_{\text{coherence}} \approx \frac{1}{2m_N x_2} \]
is larger than nucleon separation

- From E772 & E866 Drell-Yan data
- With separation of shadowing & \( dE/dz \) via Mass dependence
- In the color-dipole model:
  \( dE/dz \approx -2.7 \pm 0.4 \pm 0.5 \) GeV/fm
  
  PRC 65, 025203 (2002)
Process Dependence of Shadowing?

- Ordinary shadowing is process independent and is a “property” of the structure function in a nucleus

H \text{open-charm}

In the color-dipole model suppression at large $x_F$ (small $x_2$) is much stronger for the J/Ψ than for open-charm
- but here much of the “shadowing” is “higher-twist final-state c\overline{c}bar interactions”


Jorg Raufeisen (private comm.)
- Gluon shadowing in the color-dipole model for Au
- here only the higher-twist shadowing causes the difference between open and closed charm
- (anti-shadowing from Eskola - ad hoc)
- also see, PRD 67, 054008 (2003)

PHENIX will look for this in d-Au measurements by comparisons of rapidity dependence of suppression between open- and closed-charm.
We can not discriminate between scenarios, given our present statistical accuracy

200A GeV Au-Au J/Ψ → ee

PHENIX

Binary scaling

4.4 mb absorption

7.1 mb absorption