Charm production in high-energy p+A & A+A collisions

1. Cold nuclear matter effects from SPS to RHIC
2. Charm in heavy ion collisions

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Motivation

- Charm as a probe of the QGP
  - J/ψ suppression: golden signature of the QGP
  - Charmonia as thermometer
  - Open charm
    - Heavy quark energy loss in medium
    - Reference for charmonium suppression
- Cold nuclear matter effects important for interpretation of HI measurements
  - Nuclear PDFs, initial state parton energy loss, final state absorption ($\sigma_{\text{abs}}$), etc.
1. Cold nuclear matter effects from SPS to RHIC
Charm production at E866...

• Fixed target p-A collisions at 800 GeV
• Broad rapidity coverage

\[ \sigma_{pA} = \sigma_{pp} A^\alpha \]

Mid-rapidity \((y<0.5)\):
• \(J/\psi\) strongly absorbed
• No nuclear effects on open charm
→ At mid-rapidity, final state effects dominate the changes to the per-nucleon cross sections (and kinematics)

Forward rapidity:
• Strong reduction of the \(J/\psi\) and open charm per-nucleon production cross sections
→ Strong indication of initial state effects
  – Nuclear modification of PDFs?
  – Initial state gluon energy loss?
...at SPS and HERA-B...

- **NA3, NA50, E866, HERA-B**
  - (200, 400/450, 800, 920 GeV)
- Similar J/ψ trend as E866 in p-A:
  - Changes with J/ψ rapidity & collision energy
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  – Prediction for 158 GeV shown as black dotted line
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  → Different physics at forward rapidity than just nuclear absorption?
    • But similar trend also observed for open charm, ergo initial state effects...?

• Non-trivial cocktail of initial and final state effects
• Collider with $\sqrt{s} = 200$ GeV
  p+p, d+Au (+heavy ions)

• $J/\psi$ in d+Au central vs. peripheral shows significant increase of
  "absorption" at forward rapidity
  – As seen by E866, NA3, ...
  $\rightarrow$ energy loss as well?

...and at RHIC?
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  $\rightarrow$ energy loss as well?
  – If so, should also affect open charm
  – Existing data of non-photonic leptons from semi-leptonic open charm decays
    have large uncertainties, but indicate the same trend
  – Should be seen in new data (Run 8)
    analysis is ongoing
2. Charm in heavy ion collisions
NA60: open charm in In-In

• NA60 measured dimuon continuum in In-In collisions at the SPS at 158 GeV
• With vertexing able to distinguish non-prompt from prompt dimuons in the intermediate mass region (1.16–2.56 GeV)
• Non-prompt:
  – From simultaneous semi-leptonic decays of charmed mesons
  – Two times larger charm cross section than the world average (based on fully reconstructed D → π K decays)
  – Open charm in p-p needed
RHIC: open charm in Au+Au

- PHENIX & STAR have measured non-photonic single electrons in p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- STAR measures 2× larger open charm cross section than PHENIX both in p+p and Au+Au (cancels in $R_{AA}$)
- Both measure high $p_T$ suppression of electrons from semi-leptonic open charm (& beauty?) decays
- Significant elliptic flow
  → Final state effect: strong coupling of heavy quarks to the medium
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• Where does beauty become important?
• $b/(c+b)$ measured via e-h correlations in p+p
• PHENIX has measured dielectrons in p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

• p+p:
  – IMR shape in excellent agreement with PYTHIA
  – Total charm and beauty cross section:
    $\sigma_{cc} = 544 \pm 39\text{ (stat)} \pm 142\text{ (syst)} \pm 200\text{ (model)} \mu$b
    $\sigma_{bb} = 3.9 \pm 2.5\text{ (stat)} +^{3.2}_{-2}\text{ (syst)} \mu$b
  – In very good agreement with PHENIX result from non-photonic single electrons:
    $\sigma_{cc} = 567 \pm 57\text{ (stat)} \pm 193\text{ (syst)} \mu$b

• Au+Au:
  – IMR in apparent agreement with PYTHIA scaled to total cross section of $\sigma_{cc} = 567 \mu b \times N_{coll}$
  – But we know that open charm is heavily modified
  – Toy model: randomized correlation of c and cbar is much softer
  – Would leave room for thermal photons from qqbar
  – We know they should be there, because PHENIX has measured thermal photons at very low mass from qg Compton scattering and NA60 (SPS) has seen them
PHENIX: open charm in dielectrons

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Summary

• Cold Nuclear Matter Effects
  – Charm production in p-A collisions at forward rapidity seems to probe initial state effects (similar behavior of closed and open charm)
  – Mid-rapidity different for open and closed charm
→ shows non-trivial cocktail of initial and final state effects

• Charm in heavy ion collisions
  – Single electrons from semi-leptonic open charm decays suppressed at high $p_T$ in Au+Au collisions at RHIC (+ significant elliptic flow)
→ attributed to heavy quark energy loss in the hot and dense medium
  – Dielectrons in IMR from correlated open charm decays in Au+Au collision consistent with no modification in shape with respect to p+p
→ a fortunate cancelation of modified open charm + thermal radiation from qqbar annihilation?
Outlook

RHIC II
- Will provide increased luminosities to study rare processes with higher statistics
- Detector upgrades in PHENIX and STAR will enable vertexing and improved beauty/charm separation
- Will hopefully resolve factor 2 difference in charm cross section measurements by PHENIX and STAR

The LHC
- Higher $\sqrt{s}$ $\rightarrow$ even higher production rates of rare processes
- Will allow quantitative measurements of the $\Upsilon$ family
- ALICE will measure hadronic decays of $D$ mesons
- CMS will measure beauty through displaced $J/\psi$ over large $y$ range
- Open and closed charm and beauty measurements ($J/\psi$, $\psi'$, $\chi_c$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and $\chi_b$) will allow us to perform a more systematic study of heavy flavor production and suppression than ever before...
References

- PHENIX, “Enhanced production of direct photons in Au+Au collision sat $\sqrt{s_{NN}} = 200$GeV” (2008), arXiv:0804.4168
Backup
PHENIX Open Charm ($\mu^\pm$)

**Graphical Content:**
- Plot showing $d+Au$ (0-88%) data with distributions of $E \cdot d^2\sigma/dp^3$ [mb GeV$^{-2}$/cm$^2$] versus $p_T$ [GeV/c].
- Legend includes:
  - $(e^+e^-)/2$
  - Non-photonic
  - Systematic error
  - PHENIX pp fit

**Additional Information:**
- $R_{dAu}(\text{Prompt } \mu^\pm)$
- South: $\mu^-$
- North: $\mu^+$
- $1.4 < | \eta | < 1.8$
- Systematic Error Bars
PHENIX Open Charm ($e^\pm$)
STAR Open Charm ($e^{±}$)
PHENIX Thermal Photons

\begin{align*}
\text{Au+Au (MB) } 1.0 < p_T < 1.5 \text{ GeV/c} \\
\text{cocktail components} \\
\text{black: } f_{\text{dir}}(m) \\
\text{red: } f_{\mu}(m) \\
\text{green: } f_{\eta}(m) \\
\text{blue: } (1-r)f_{\mu}(m) + rf_{\text{dir}}(m) \\
\text{green dot: } \pi \\
\text{blue line: } \eta \\
\text{yellow star: } \omega \\
\text{black circle: } \gamma' \\
\text{red triangle: } \gamma \\
\end{align*}

\begin{align*}
r &= 0.128 \pm 0.015 \\
\chi^2/\text{NDF} &= 13.8/10
\end{align*}

\begin{align*}
E^2N/dp^2 (\text{GeV}^2 \cdot \text{cm}^{-2}) \text{ or } E^3N/dp^3 (\text{mb GeV}^2 \cdot \text{cm}^{-2})
\end{align*}
PHENIX J/ψ

![Graph showing $R_{dAu}$ versus Rapidity with ±11% Global Scale Uncertainty](image)

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