Measurement of the open charm cross-section in 200 GeV Cu+Cu collisions using STAR @ RHIC

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Physics motivations

**Charm:**
- is primarily produced by gluon fusion
  - little contribution from gluon splitting (see talk by A. Mischke and poster by X. Dong).
- is sensitive to early stage of the collision (quark produced at $\tau \sim \hbar / 2m_\phi c^2 \sim 0.1 \text{ fm/c}$)
- has an undisturbed mass
- large uncertainty in pQCD
  - $\alpha_s$ large
  - gluon PDF undetermined
  
  for $P_T < M_c$
  
  $\rightarrow$ the cross-section is little constrained by theory

\[ NLO: \quad 301^{+1000}_{-210} \text{\mu b} \]

R. Vogt  hep/ph 0709.2531
Charm production is a hard process: expect binary scaling.
Data so far supports this ⇒ d+Au to Au+Au.
What about Cu+Cu?
Open charm measurements
via semileptonic decays
Electrons and Muons….

Measured by STAR and PHENIX

c → e⁺ + X

c → μ⁺ + X

D⁰ → e⁺ + X (6.87%)

D⁰ → μ⁺ + X

Straightforward using detectors with e⁻ PID

(TPC, EMC and TOF)

Background is difficult to assess (photonic)

Limited to higher \( P_T \)

e⁻ does not reflect full D kinematics

Muon from heavy quark semileptonic decay

Electron from heavy quark semileptonic decay
**Charm Cross-Section to Date**

Non photonic electrons, Muons and D mesons

- **Precise measurements at low** $P_T$ **are important**
- **$e^-$ are weakly correlated to heavy quarks** (fraction coming from both D and B)
- Need direct measurements

Cross-section measurements so far:

<table>
<thead>
<tr>
<th></th>
<th>p+p</th>
<th>Au+Au (MinBias)</th>
<th>d+Au</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STAR</strong></td>
<td>driven by D mesons</td>
<td>1.26 ± 0.09 ± 0.23</td>
<td>1.4 ± 0.2 ± 0.4</td>
</tr>
<tr>
<td><strong>PHENIX</strong></td>
<td>from electrons</td>
<td>0.567 ± 0.057 ± 0.224</td>
<td>0.622 ± 0.057 ± 0.160</td>
</tr>
</tbody>
</table>

What about Cu+Cu?
Open charm measurements via hadronic decays
Direct reconstruction

- Hadronic decay channels ($D_0 \rightarrow Kp$ (B.R.: 3.8%))

- $c \rightarrow e^+ + \text{anything}$
- $c \rightarrow \mu^+ + \text{anything}$
- $D^0 \rightarrow e^+ + \text{anything}$
- $D^0 \rightarrow \mu^+ + \text{anything}$

**muon** from heavy quark semileptonic decay
**electron** from heavy quark semileptonic decay
**hadronic** “Direct” $D^0$ reconstruction (event mixing technique)

$D^0$ hadronic decay reconstructed in minimum bias collision (unique @ RHIC)

↑ Direct measurement, covers large fraction of the cross-section
↓ Large combinatorial background
↓ High precision vertexing is needed
Direct $D^0$ reconstruction in STAR

- Pions and Kaons are selected using the TPC
- Combine “same event” pairs $\Rightarrow$ signal+background
- Combine pairs coming from different events $\Rightarrow$ background ("mixed events" or "track rotating")
- After subtraction $\Rightarrow$ signal

\[ M_{K\pi} (\text{GeV}/c^2) \]
Cu+Cu collisions @ 200 GeV

- 28 Million events used
- All the statistics available
- Cu+Cu « minimum bias » (RHIC run V)
  - After track rotating or mixed event subtraction: residual background
  - Low S/B ratio:
    \[
    \frac{S}{B} \approx \frac{1}{600}
    \]
    \[
    \frac{S}{\sqrt{S + B}} \approx 4
    \]
  - Measurement only possible because of large S (~ 150 000)
  - Large STAR acceptance!
  → Challenging measurement
D^0 Mass in agreement with the PDG
\((M_{D^0} = 1864.84 \pm 0.17 \text{ MeV/c}^2)\)

<table>
<thead>
<tr>
<th>(p_T) (GeV/c)</th>
<th>Mass (GeV/c^2)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-1.2</td>
<td>1.864 ± 0.005</td>
<td>8.4 ± 8.7</td>
</tr>
<tr>
<td>1.2-2.0</td>
<td>1.864 ± 0.005</td>
<td>8.3 ± 13</td>
</tr>
<tr>
<td>2.0-3.3</td>
<td>1.850 ± 0.015</td>
<td>12 ± 18</td>
</tr>
</tbody>
</table>
After corrections:

Fit using an Exponential or a Boltzmann function → same results (within stat. errors).

\[
\frac{1}{2\pi p_T} \frac{d^2N}{dp_T} = 0.18 \pm 0.035
\]
Extraction of the cross-section

\[ \sigma_{NN}^{\text{NN}} = \frac{dN_{Cu+Cu}^{D^0}}{dy} \times \frac{\sigma_{pp}^{\text{inel}}}{N_{bin}^{Cu+Cu}} \times f(R) \]

\[ dN_{D^0} / dy = 0.18 + / - 0.035 \text{ (stat.)} \]

Number of binary collisions (Glauber)

Inelastic cross-section in p+p (UA5)

Conversion to full rapidity (Pythia)

Ratio obtained from e+e- collisions

\[ \Rightarrow \sigma_{NN}^{\text{NN}} = 1.30 \pm 0.25 \text{ (stat.) mb} \]
d \sigma/dy in STAR...

Scaling with the number of binary collisions from d+Au to Au+Au **confirmed in Cu+Cu.**

Accurate background subtraction is **crucial**

**Systematic study** is ongoing
Summary

Today:

- The charm cross-section was measured in Cu+Cu @ 200 GeV; \( \sigma_{c\bar{c}}^{NN} = 1.30 \pm 0.25 \text{ mb} \)
- A direct measurement in Cu-Cu is consistent with a scaling of the cross-section with \( N_{\text{bin}} \) (at low pT).
- Theory: large uncertainty in pQCD calculations and data points are needed.

In the Future:

- STAR low material runs
- use of SSD/SVT and eventually the HFT upgrade (2010-2012)
  will allow:
    - precise measurements of the charm cross-section
    - direct topological measurements of charm and of its anisotropy parameter \( V_2, R_{AA}, R_{CP} \)
    - isolation of the bottom contributions
Outlook

- Low material run (without the SVT/SSD)
  → low radiation length in run VIII
  → reduce the photonic background

- Reconstructing the secondary vertex with SVT/SSD in Au+Au (run VII)

- « Upgrade » for RHIC2
  and especially
  The future STAR Heavy Flavor Tracker

→ Direct and topological measurements of charm and precise $V_2$

See the HFT poster
by Jan Kapitan
(for the STAR HFT collaboration)
Backup
The charm cross-section

$$\sigma_Q(S, m^2) = \sum_{i,j} dx_1 dx_2 \hat{\sigma}_{ij}(x_1x_2S, m^2; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) F_{i/A}(x_1, \mu_F) F_{i/B}(x_2, \mu_F) + O\left(\frac{\Lambda}{m}\right)^p$$

Hard scattering  Parton Distribution Functions (PDF)  Corrections

Calculation:

NLO QCD + resummations

minimal & properly extracted NP fragm.

Simulation (MC) of decay

$p p \rightarrow pQCD \rightarrow Q \rightarrow NP\text{ fragm.} \rightarrow H_Q \rightarrow \text{decay} \rightarrow e$

For predicting total cross sections one can stop here

NLO: $301^{+1000}_{-210} \mu b$

R. Vogt  hep/ph 0709.2531

FONLL: $256^{+400}_{-146} \mu b$

M. Cacciari et al., PRL 95 (2005) 122001


Experiment:

$pQCD + \text{PDF}$  Fragmentation Functions

$$\frac{d\sigma_H}{dp_T} = \frac{d\sigma_Q}{dp_T} \otimes D_{np}$$

Measured (differential) cross section

NLO (+NLL) calculation

non-perturbative fragmentation (usually extracted from e+e- data)
Cross-section – How well is the calculation constrained?

- Energy
- Charm quark mass ($m_c$)
- Scales
  - $m_R$: fragmentation scale
  - $m_F$: factorization scale
  - $a_s$: strong coupling
- PDF used
- Fragmentation Functions (FF) non perturbative inserted in a perturbative calculation

Example:

FONLL: 
$$\mu_F = \mu_R = \mu = \sqrt{p_T^2 + m_c^2}, m_c = 1.2\text{GeV}/c^2$$

PYTHIA: CTEQ5M1, MSEL=1

NLO: MRST 
$$\mu = 2m_c, m_c = 1.2\text{GeV}/c^2$$

How to compare measurements to calculations?

Using QCD (and pQCD):
- Heavy flavor cross-section can be correctly predicted
- Differential cross-section (as function of momentum, rapidity or energy…), requires « adding a minimal, self-consistent and universal set of non-perturbative input parameters »

Matteo Cacciari
ISMD 2007

To make an accurate comparison, one should:
- Use dedicated theoretical tools (FONLL and now NNLO)
- Use adequate parameters (mass, renormalization and factorization scales, coupling), Partons Distribution Functions (PDF) and Fragmentation Functions (FF).
- Minimize extrapolations and deconvolutions between measurements and theory

→ If and only if all those conditions are satisfied, a good agreement between measurements and calculations can be reached

→ In real life, the error band is large and data points are needed...

pur - Feb. 2008
- Spectra shapes are the same. STAR and PHENIX are seeing the same scaling with Nbin.

- The value of the cross-section is not the same (factor 2 to 3)

- STAR and PHENIX are both above FONLL predictions…

→ Disagreement but let’s look at the $R_{AA}$...
$R_{AA}$: (e$^-$) from d+Au to Au+Au central

$R_{AA}$ in agreement between STAR and PHENIX
→ Is there a normalization issue?

Dead cone effect not observed ... (non photonic e$^-$)