Heavy flavor systematics from PHENIX

Craig Ogilvie, Iowa State University
On behalf of the PHENIX Collaboration

• Complexity of interpreting data from HI collisions
  • Use systematics: spectra, elliptic flow,…
  • Present d+Au, Cu+Cu, excitation function,…
• Which leads to the complexity of interpreting d+Au…
Complexity of d(p)+A collisions

- **Nuclear structure functions**
  - Shadowing, saturation at low-x
  - Anti-shadowing at moderate, high-x
- **Initial state scattering**
  - Often modeled as increase in effective kT
  - Likely largest impact at RHIC where spectra are softer
- **Possible collective effects**
  - Barbara Jacak’s talk on Wed
- **Final state energy-loss, absorption,** ....
- **Centrality classification**
CNM I: d+Au heavy-flavor at 200 GeV

- Non-photonic e, from heavy-flavor decays


Significant enhancement at moderate $p_T$

$d+Au$ @ $\sqrt{s_{NN}} = 200$ GeV

a) 0-20%

b) 60-88%
CNM II: d+Au heavy-flavor at 200 GeV

- Non-photonic e, from heavy-flavor decays
  Enhancement present in min-bias
  Effect not caused by challenges of centrality definition

CNM IV: Forward, backward $\mu$ from HF decay

Forward rapidity suppressed
Likely shadowing at low-$x$ in Au

Backward rapidity enhanced
anti-shadowing at higher $x$ in Au?
or increase in $<k_T>$ due to initial scattering?

cogilvie@iastate.edu

Sep 27, 2013
CNM III: Identified hadron spectra in dA


Cronin peak: proton $\sim >$ HF$_e$
Why?
CNM II: d+Au heavy-flavor at 200 GeV


Does $<k_T>$ increase have larger impact when p+p spectrum is soft?

spectra = convolution of scattering + fragmentation

Or recombination effects in hadronization?

Or collective? Or...

Opportunity for theory impact
Example with $\pi^0 R_{dA}$

- $\pi^0$ calc from I. Vitev
- Reasonable reproduction of $\pi^0$
  - Nuclear structure function
  - Cronin
    - Large initial state multiple-scattering
  - Final state $E_{\text{loss}}$
- Need calculations for heavy-flavor $R_{dA}$

Vitev et al., PRD 74 (2006)

Sep 27, 2013
J/ψ CNM

EPS09 nuclear structure functions plus breakup
Reasonable reproduction, misses centrality dependence

BUT, charm is enhanced at moderate $p_T$ (non-photonic electrons $R_{dA}>1$)

1) Do these calculations reproduce open charm $R_{dA}>1$?
2) If not, then more effective suppression needed for J/ψ
Normalize $J/\psi$ by HF?

$J/\psi$ at mid-$y$ suppressed @ low-\(pt\)

Charm is enhanced at moderate \(pt\)
(non-photonic electrons \(R_{dA}>1\))

Alternative: use dA HF spectra as baseline?

- $J/\psi$
- \(HF\) electron
- Question, what axis? \(p_T\)?
Connect d+Au to A+A

1) Enhancement in d+Au + energy-loss $\Rightarrow$ suppression in A+A
2) Models must attempt to reproduce both d+A and A+A


Min-bias collisions
One method to organize results

Common suppression pattern when normalized by square of $R_{dA}$

Does this take into account impact of initial state increase of $\langle k_T \rangle$?


Matt Durham

cogilvie@iastate.edu
Intermediate Cu+Cu: links d+A and Au+Au

Peripheral Cu+Cu (yellow) Enhancement ~ central d+Au (blue)
d+Au to Cu+Cu to Au+Au

Interplay of two effects
CNM increases yield, competes with energy-loss suppression
d+Au to Cu+Cu to Au+Au

Higher $p_T$

CNM increases yield, stronger energy-loss suppression
Cu+Cu heavy-flavor, forward rapidity

Large uncertainties: Forward $y$ in central d+Au ~ peripheral Cu+Cu
Additional lever arm: beam energy

\( \pi^0 \quad \text{Phys. Rev. Lett. 109, 152301 (2012)} \)

charged hadrons from Au+Au

\[ R_{AA} \]

\begin{align*}
\text{AuAu, Most central, 0-10\%} \\
Vitev Calculation \\
\bullet \ s = 39 \text{ GeV} \\
\square \ s = 62.4 \text{ GeV} \\
\triangle \ s = 200 \text{ GeV} \\
\end{align*}

\[ p_T \text{ [GeV/c]} \]

Dominant energy-loss at high \( \sqrt{s} \)
Transitions to stronger Cronin effect at lower \( \sqrt{s} \)

Sep 27, 2013
Need $R_{dA}$ at lower-beam energy

- Not in current RHIC running plan :(  
  - How does $R_{dA}$ change from 200 GeV to 62 GeV  
  - Three beam energies (62, 200 GeV, LHC) constrains interplay of structure function, initial state scattering

- $R_{dA}$ calculations at 62 GeV
  - $\pi$ $R_{dA}$ $\sim$ 2 at 62 GeV  
  - $\pi$ $R_{dA}$ $\sim$ 1.2 at 200 GeV

Non-photonic electrons Au+Au 62 GeV

Lower beam energy changes interplay of two effects
  Stronger CNM competing with weaker energy-loss
Forthcoming PHENIX publication
  spectra with smaller systematics
  comparison with p+p, R_{AA} etc.
If your model reproduces 200 GeV and 2.76 TeV heavy flavor R_{AA}
  Final call for 62 GeV HF R_{AA} prediction

Sep 27, 2013
HF $v_2$ at lower beam energy

HF flow is $> 0$ at 62 GeV, but uncertainties large
$V_2$ 2\textsuperscript{nd} constraint on e-loss Au+Au 200 GeV

- Low-pt Charm $v_2$, extent of thermalization of HF
- Challenge for theory to reproduce both $R_{AA}$, $v_2$

Many calculations, theory updates past few years
One example, P.B. Gossiaux SQM 2013

Elastic + radiative LPM

Elastic + radiative energy loss
With running coupling $\alpha$

Sep 27, 2013
Is $\delta p_T/p_T$ what we should be plotting for HF?

Suggestion in spirit of workshop,
This is being worked on for HF, but no results available yet
VTX Upgrade @ PHENIX

Two layers of silicon pixel detectors
Two layers of silicon strip detectors
Four layers in endcaps
Tracks extrapolate back to collision vertex
Displaced vertices $\Rightarrow$ charm (D), beauty (B)
Requires $\sim$ 50 $\mu$m precision

Installed 2010-12
VTX p+p results

DCA data are fit by expected DCA shapes of

- Signal components: \( c \rightarrow e \) and \( b \rightarrow e \) (right column)
- Background components (left column)

charm/bottom assumes
PYTHIA spectra

\[ \frac{b}{b+c} = 0.22 \pm 0.06 \]

Fit range:
\[ 0.2 < |DCA| < 1.5 \text{ (mm)} \]
VTX p+p results

FONLL consistent with $b/(b+c)$ data

PHENIX Preliminary

FONLL, $y = 0$
Physics Goal

Energy-loss heavy-flavor $\Rightarrow$ understand nature of sQGP

- Progress on understanding many details
- If a model reproduces a broad range of data
  - Can we infer any characteristics of QGP?
- Either direct via a parameter of model
  - Diffusion parameter
- Or run same dynamical model in a “box”, e.g. radiation + collision $E_{\text{loss}}$
  - Infer effective transport parameters
- Which characteristics of sQGP are accessible this way and can we communicate this to our fellow physicists?
- Maybe too many unsettled aspects yet
Summary

- Complexity of interpreting d+Au
  - Levers: centrality, A, y, $\sqrt{s}$, change impact of
    - Structure function, initial state scattering, e-loss,...
  - HF $R_{dA}$ enhancement up to factor of 1.5
    - Call for model calculations
    - Is dAu HF a better baseline for $R_{AA}$ HF and dAu J/$\psi$ production??

- Complexity of interpreting data from HI collisions
  - Cu+Cu HF yields smoothly connects dAu to Au+Au
    - Competition between enhancement + suppression
    - Change this competition
      - Au+Au HF data @ 62 GeV, need dAu running at 62 GeV
Backup slides
### X-ranges

<table>
<thead>
<tr>
<th></th>
<th>SPS Pb+Pb 17 GeV</th>
<th>RHIC Au+Au 200 GeV</th>
<th>LHC Pb+Pb 5.5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-cbar</td>
<td>$X \sim 10^{-1}$</td>
<td>$X \sim 10^{-2}$</td>
<td>$X \sim 10^{-3}$ to $10^{-4}$</td>
</tr>
</tbody>
</table>

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Eskola et al. JHEP 0904 (2009) 065
$R_{AA}$ of heavy-flavor: from RHIC to LHC

Note to Craig add citations
• $e$ and $\mu$ baseline measurements in central and forward rapidity
• Consistent with FONLL upper limit
Charm production at 62 GeV reproduced by FONLL
pp: pQCD calculations vs data

HF-lepton $p_T$-differential cross section

200 GeV

2.76 TeV

7 TeV

 PHENIX, PRC84 (2011) 044905
N. Apadula (WWND2013)

ALICE, PRL 109 (2012) 112301

ALICE, PRD86 (2012) 112007
ATLAS, PLB707 (2012) 438

- HF-decay electrons and muons at central and forward $y$
- FONLL: “b > c” for $p_T > 4$ (5) GeV/c at RHIC (LHC)
Open heavy flavor data

LHC fit, RHIC extrapolation parameter-free

Constrained by LHC pion fit

April 17th, 2013

Alessandro Buzzatti – LBNL
Less bound charmonia in dAu collisions

All three systems consistent within uncertainties

arXiv:1305.5516
Less bound charmonia in dAu collisions

ψ' suppression stronger than J/ψ for more central dAu collisions

Stronger effective breakup cross-section?

arXiv:1305.5516
Photon in dA