Scientific Opportunities in pA & dA Collisions

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- gluon saturation & shadowing
  - small-x suppression
- cold nuclear matter (CNM) effects
  - on J/ψ & heavy quarks
- parton energy loss
- baseline for AA collisions
- RHIC-II rates & reach
- contrasting with LHC

![Diagram showing R_{dAu} for 200 GeV d+Au collisions](image)

![Graph comparing BRAHMS and PHENIX data](image)
Cold Nuclear Matter (CNM) Effects
Gluon Shadowing and Saturation

Phenomenological fit to DIS & Drell-Yan data
Leading twist gluon shadowing
Coherence approach and many others
Amount of gluon shadowing differs by up to a factor of three between diff models!

Saturation or Color Glass Condensate (CGC)
• At low-x there are so many gluons that 2→1 diagrams become important and deplete low-x region
• Nuclear amplification: \( x_A G(x_A) = A^{1/3} x_p G(x_p) \), i.e. gluon density is ~6x higher in Gold than the nucleon
Hadrons at forward rapidity (small-\(x\))

- Increasing suppression at forward rapidity w.r.t. binary scaling
- Limiting fragmentation seen in comparison to lower energy measurements
- Many physics issues to consider - shadowing, gluon saturation, initial-state parton energy loss, Sudakov suppression?

1/12/2007
But do forward $\pi^0$'s really probe small $x$?


However, they also show that if one measures two forward hadrons ($\pi^0$'s) then one CAN pin down $x_2$ to small values.
Mono-jets from the CGC picture

p+p: Di-jet

d+Au: Mono-jet?

Dilute parton system (deuteron)

Dense gluon field (Au)

$P_T$ is balanced by many gluons

Kharzeev, Levin, McLerran give physics picture (NPA748, 627)

Color glass condensate predicts that the back-to-back correlation from p+p should be suppressed
$\pi^0 + h^\pm$ Correlations in dAu Collisions

The back-to-back correlation peak is smaller in dAu compared to pp, qualitatively consistent with the mono-jet picture from the CGC or coherent scattering (Vitev, Qiu) models. But is the reduction really significant given the large background?

$\pi^0 \langle \eta \rangle = 4$
and $h^\pm p_T > 0.5$ GeV/c

"S" is area of the coincident peak
Cold Nuclear Matter Effects for $J/\psi$
Absorption & Energy Loss

$J/\psi$ suppression is a puzzle with possible contributions from shadowing & from:

Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)

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

800 GeV p-A (FNAL)
PRL 84, 3256 (2000); PRL 72, 2542 (1994)

open charm: no A-dep at mid-rapidity

shadowing, dE/dx, and/or intrinsic charm

Hadronized $J/\psi$?
FNAL E906 (120 GeV) or JPARC (50 GeV)
quark energy loss in nuclei

At 800 GeV, the nuclear dependence of Drell-Yan on nuclear targets could not unambiguously separate shadowing and dE/dx effects at low x

- E866 data are consistent with no energy loss (using EKS shadowing)
- or with Kopeliovich shadowing, Johnson et al. find 2.2 GeV/fm from the same data
- for 120 or 50 GeV p-A Drell-Yan x > 0.1 & only quark dE/dx remains (no shadowing)
- also stronger, dE/dx ~ 1/s

Important for understanding of RHIC data

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Heavy quarks at forward rapidity & small-$x$

- $J/\psi$ suppression does not scale like shadowing with $x_2$
- Apparent scaling with $x_F$ is similar to limiting fragmentation in hadron production
  - or (large) initial-state gluon energy loss could also explain this $x_F$ scaling

Prompt muons from open charm & beauty also suppressed at forward rapidity
J/ψ suppression in AA collisions & CNM baseline
(CNM = Cold Nuclear Matter)

Cold nuclear matter baseline poorly constrained by present d+Au J/ψ
data so far - an example of the importance of d+Au for A+A studies
Detector Upgrades - enabling our physics goals

**PHENIX Nosecone Calorimeter (NCC)**
- forward $\gamma$ & $\pi^0$
- $\chi_c \rightarrow J/\psi \gamma$

**STAR Forward Meson Spectrometer**
- forward $\pi^0$ (also PHENIX MPC’s)

**PHENIX Forward Vertex Detector**
- $B \rightarrow J/\psi X$
- robust D & B with reduced bkgd.
- improved bkgd. & mass resolution for quarkonia & dimuons

**STAR Forward Tracker Upgrade**
- charge sign for W’s
- help other forward physics as well??

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![Graphs and diagrams related to detector upgrades.](image-url)
Contrasting small-x physics at RHIC-II and the LHC

At RHIC/RHIC-II measurements explore the onset of shadowing or saturation, while at the LHC most measurements will be deep into the saturation region

- exploring the onset at RHIC-II will be key to understanding saturation and complimentary to those at the LHC
- quarkonia annual rates similar at RHIC-II and LHC

From the LHC pA Workshop (May 2005):
- p+A at the LHC is still officially an upgrade
- First year that LHC might run p+Pb: 2010
- Possible “target” luminosity: $10^{29}$ cm$^{-2}$s$^{-1}$ (RHIC-II: $2\times10^{30}$ cm$^{-2}$s$^{-1}$ avg)
- N-N CM not at lab $y=0$ ($\Delta y=-0.46$ for 8.8 TeV p+A)
- Has to share 1-month/yr with HI running - difficult to build a systematic program
Goals for the Future

Accurate data from multiple probes to allow quantitative analysis & isolation of gluon saturation from other effects (parton energy loss, coherence effects causing shadowing, Sudakov suppression)

Quarkonia:
- **higher luminosity** (RHIC-II) to enable precision for rare probes (J/ψ, ψ', ϒ)
- lower backgrounds via detached vertices (vertex detector upgrades)
- **better onia mass resolution** to isolate states (J/ψ from ψ'; ϒ family)
- ψ' where there is no feed down - the physics is cleaner
- ϒ where x probed is larger than J/ψ (x ~ m_Q/√s)
- and χ_C → J/ψ γ (forward calorimeters)

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

R. Vogt, NRQCD calculations

All J/ψ’s
Goals for the Future continued

**Open-heavy:**
- explicit identification of open heavy semi-leptonic decays via detached vertices
  - lower backgrounds, smaller systematic uncertainties
- explicit isolation of beauty via $B \rightarrow J/\psi X$
- explicit $D \rightarrow K \pi$ (at central rapidity with STAR upgrades, but don't know about forward??)
- high precision comparison of open and hidden heavy to isolate physics

Separation of $B \rightarrow J/\psi X$ from prompt $J/\psi$ via detached vertex

$D \rightarrow K \pi$ in $dAu$ at central rapidity from STAR
Goals for the Future continued

**Lepton pairs** (Drell-Yan) with reduced $\pi, K$ decay & open charm backgrounds (vertex upgrades)

$\pi^0$ & $\gamma$ at large rapidity to probe saturation at small $x$ (forward calorimeters)

**2-particle correlations** and search for mono-jets (forward calorimeters)
Summary - p+A and d+A Opportunities

Is gluon saturation the source of forward-y (small-x) suppression?

Azimuthal Correlations
W = 200 GeV
η_1 = 3.8, η_2 = 0, central
p_1 = 1.5 GeV, p_2 = 0.2 - 1.5 GeV
Proton - Proton
Deuteron - Gold

Forward hadron suppression. Are there mono-jets?

Contrasting open-heavy with J/ψ & light hadrons; separating B’s from D’s

CNM dE/dx? Source of the nucleon sea?

R dvAu

200 GeV d+Au → J/ψ

R. Vogt, nucl-th/0507027

PHENIX PRL 96, 012304 (2006)

0 mb Low x_2 ~ 0.003 (shadowing region)

3 mb

Summary - p+A and d+A Opportunities
Extra Slides
A few rates for RHIC-II

Substantial increase in rates of rare processes at RHIC-II
• $J/\psi$ yields still smaller than the 1.5M at FNAL E866/NuSea but quite good for a collider!

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi$</th>
<th>$\psi'$</th>
<th>$\Upsilon$</th>
<th>$\chi_C$</th>
<th>$B \rightarrow J/\psi X$</th>
<th>$D$</th>
<th>$B$</th>
<th>$\pi^0$</th>
<th>Direct $\gamma$</th>
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<tbody>
<tr>
<td>Run-3</td>
<td>~900</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RHIC-I</td>
<td>13k</td>
<td>230</td>
<td>40</td>
<td>1.4k</td>
<td>350</td>
<td>38M</td>
<td>440k</td>
<td>8.2k</td>
<td>1k</td>
</tr>
<tr>
<td>RHIC-II</td>
<td>200k</td>
<td>3.6k</td>
<td>650</td>
<td>22k</td>
<td>5.5k</td>
<td>600M</td>
<td>7M</td>
<td>130k</td>
<td>17k</td>
</tr>
</tbody>
</table>

• Est. yields in one PHENIX forward spectrometer in a 10-week d+Au run
• use RHIC-II at 62 nb$^{-1}$/week; RHIC-I at 3.9 nb$^{-1}$/week luminosities
• compared to ~0.27 nb$^{-1}$/week in Run-3
• with the PHENIX Forward Vertex and Nose Cone Calorimeter upgrades

Rates for STAR FMS double $\pi^0$ coincidence ~100k in 10-week RHIC-II d+Au run
Cold Nuclear Matter Effects
Gluon Shadowing

- Phenomenological fit to Deep-Inelastic Scattering & Drell-Yan data
- Leading twist gluon shadowing
- Coherence approach, and many others
Amount of gluon shadowing differs by up to a factor of three between diff models!

EKS, NP A696, 729 (2001)


Armesto & Salgado, hep-ph/0308248
Cold Nuclear Matter Effects
Gluon Saturation & the Color Glass Condensate (CGC)

At low-\(x\) gluon density becomes very large & a non-linear evolution regime with \(2 \rightarrow 1\) gluon processes sets in at saturation scale \(Q_s\)

- CGC is an effective theory for that regime
- Nuclear amplification: \(x_A G(x_A) = A^{1/3} x_p G(x_p)\), i.e. gluon density is \(~6\)x higher in Gold than the nucleon
  - gives “shadowing”

More saturation at Lower \(x\)
\(y \sim \log(1/x)\)
Lower \(x \rightarrow\) forward rapidity

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Cold Nuclear Matter for $J/\psi$
Transverse Momentum Broadening

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

Initial-state gluon multiple scattering causes $p_T$ broadening (or Cronin effect)

PHENIX 200 GeV results show $p_T$ broadening comparable to that at lower energy ($\sqrt{s}=39$ GeV in E866/NuSea)
Alternative picture for forward charm suppression in dAu
Vitev, Goldman, Johnson, Qiu - hep-ph/0605200

cg & cq dominate inclusive D production

final-state coherence effects
- simultaneous interaction with more than one nucleon ($x_N < 1/2 r_0 m_N$)
- equivalent to shift in effective $x$

initial-state inelastic radiative energy loss necessary to reproduce data
- large dE/dx - average parton loses 10% of its energy!
Another urgent d+Au question:
\( v_2 \) and the hydro limit--Glauber vs Color Glass Condensate

Hirano et al, PLB 636, 299

CGC: Treats the nucleus as a saturated gluon field
Effects initial eccentricity of the overlap zone

- Do we have Glauber matter distribution + perfect liquid, or Color Glass Condensate distribution + viscous matter?
- Understanding the initial state is crucial to understand what we are seeing in the final state
Double parton correlations

CDF, PRL 79, 584

PRL 88, 031801

Measuring Double-Parton Distributions in Nucleons at Proton-Nucleus Colliders

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(Received 11 June 2001; published 2 January 2002)

We predict a strong enhancement of multijet production in proton-nucleus collisions at collider energies, as compared to a naive expectation of a cross section \( \propto A \). The study of the process would allow one to measure, for the first time, the double-parton distribution functions in a nucleon in a model-independent way and hence to study both the longitudinal and the transverse correlations of partons.

\( A \)-dependence of 4-jet yields in p+A collisions can be used to measure \( x_1 - x_2 \) momentum correlations within the proton.

• This would require pA, not dA collisions!
Annual yields at RHIC II & LHC are similar from RHIC-II White Paper.

RHIC-II:
- AuAu 12 weeks

LHC HI:
- PbPb $10^6$ sec (500 $\mu$b$^{-1}$)

from RHIC-II White Paper.
RHIC-II & LHC rate comparisons (RHIC: 12 weeks of AuAu; LHC: 1 month of PbPb). From RHIC-II White paper,

<table>
<thead>
<tr>
<th>Signal</th>
<th>RHIC-II</th>
<th>LHC Heavy Ions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PHENIX</td>
<td></td>
</tr>
<tr>
<td>J/$\psi$ → ee</td>
<td>55k</td>
<td>&lt;0.35</td>
</tr>
<tr>
<td>J/$\psi$ → μμ</td>
<td>470k</td>
<td>1.2-2.4</td>
</tr>
<tr>
<td>ψ' → ee</td>
<td>990</td>
<td>&lt;0.35</td>
</tr>
<tr>
<td>ψ' → μμ</td>
<td>8.5k</td>
<td>1.2-2.4</td>
</tr>
<tr>
<td>χ_c → eeγ</td>
<td>3.6k</td>
<td>&lt;0.35</td>
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<tr>
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</tr>
<tr>
<td>γ → ee</td>
<td>200</td>
<td>&lt;0.35</td>
</tr>
<tr>
<td>γ → μμ</td>
<td>500</td>
<td>1.2-2.4</td>
</tr>
<tr>
<td>B → J/$\psi$ → ee</td>
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<tr>
<td>B → J/$\psi$ → μμ</td>
<td>3k</td>
<td>1.2-2.4</td>
</tr>
<tr>
<td>D → Kπ</td>
<td>?</td>
<td>30k</td>
</tr>
</tbody>
</table>

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Proton Structure: By What Process Is the Sea Created?

- **Meson Cloud in the nucleon**
  - Sullivan process in DIS
  - \(|p > = |p_0 > + \alpha |N\pi > + \beta |\Delta \pi > + \ldots\)

- **Chiral Models**
  - Interaction between Goldstone Bosons and valence quarks
  - \(|u > \rightarrow |d\pi > + \bar{q}\) and \(|d > \rightarrow |u\pi > + \bar{q}\)

Perturbative sea apparently dilutes meson cloud effects at large-x.