PHENIX highlights

- Introduction to PHENIX
- Hard physics and QCD at RHIC
- Jets as probes of the hot, dense medium
- J/Ψ and open charm at RHIC
- Some insights on collective flow

PHENIX Collaboration
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PHENIX goals & requirements

- Probe early stage of collisions, when QGP exists
  - Use short wavelength & EM (penetrating) probes
    (high $p_T$, high production $Q^2$, low $\sigma$)
  - Study heavy quarks (mass sets a scale other than $T$)
  - Measure radiation from plasma: $\gamma, \gamma^*$ (rare & large backgrounds)
- Sample the hadrons to see collision dynamics
  - Collective effects, thermalization, freeze-out
- Requirements
  - High rate capability, sensitive triggers
  - Excellent particle ID
- Tradeoff
  - Give up acceptance for granularity, rate, PID, trigger
PHENIX at RHIC

2 Central spectrometers

2 Forward spectrometers

3 Global detectors
Hard physics: start with p+p collisions

π^0 well described by pQCD and usual fragmentation functions

\[ f_{a/N}(x, Q^2) \text{ Parton distribution functions} \]

\[ D_{h/a}(z, Q^2) \text{ Fragmentation functions} \]

To generalize for nuclei:

\[ f_{a/N}(x_a, Q^2, r) \rightarrow f_{a/N}(x_a, Q^2) \cdot S_{a/A}(x_a, r) \cdot t_A(r) \]

Nuclear modification to structure function (shadowing, saturation, etc.)

Nuclear thickness function
Direct photons in p+p

• Direct $\gamma$ produced in initial hard $q+g\rightarrow q+\gamma$ Compton

• Penetrating probe - not suppressed (unless gluon saturation).

• Use measured $\pi^0 (\eta)$ spectra in Monte Carlo to calculate decay $\gamma$ spectra

• Compare to measured inclusive $\gamma$ spectra to search for excess $\gamma$

• $\gamma_{\text{Meas}}/\gamma_{\text{Decay}} > 1$ implies direct $\gamma$ excess; in p+p agrees with NLO pQCD
pQCD in Au+Au? direct photons

[pQCD x N_{coll}]/[\gamma_{background}] Vogelsang/CTEQ6

([pQCD x N_{coll}]/[\gamma_{background} x N_{coll}])

[w/ the real \pi suppression]

[if there were no \pi suppression]

Au+Au 200 GeV/A: 10% most central collisions

Preliminary
Nuclear medium modifies initial state

- Probe response of cold nuclear matter with increased number of collisions.
  - d+Au: Cronin Effect ($R_{dA} > 1$): Multiple Collisions broaden $p_T$ spectrum

- Initial state multiple soft or semi-hard scattering $k_T$ broadening

Cronin effect for baryons $> \text{mesons}$

But shouldn’t initial state scattering and fragmentation factorize?!
Cronin effect persists to 8 GeV/c $p_T$

Pion identification to high $p_T$

Determine extent of Cronin effect

$$R_{CP} \sim 1 \text{ for } p_T > 7 \text{ GeV/c}$$
Direct Evidence of High (parton) Density Matter

High $p_T$ suppression of $\pi^0$

- Strong suppression of high $p_T$ hadrons unique at RHIC
- d+Au is control measurement – no hot, dense medium
- Direct evidence for matter at extreme density in Au+Au
Compare centrality dependence to control

- Dramatically different and opposite centrality evolution of AuAu experiment from dAu control.
- Jet suppression is clearly a final state effect.

\[ R_{AA} = \frac{\text{Yield}_{AuAu}}{\langle N_{\text{binary}} \rangle_{AuAu}} \frac{\langle N_{binary} \rangle_{dAu}}{\text{Yield}_{pp}} \]
How much suppression in 62 GeV Au+Au?

- Suppression at $p_T \sim 7$ GeV/c similar to @ 200 GeV at $p_T \sim 4$ GeV/c
- Cronin enhancement apparently larger
π⁰ R_{AA} \sqrt{s} \ \text{Systematics: Predictions}

Cronin↑ and parton energy loss↓ at lower \sqrt{s}

Reasonable agreement with 62.4 GeV result

larger Cronin effect gluon dN/dy = 850 (rather than 1100)

NB systematic errors in p+p reference are large.
Color Glass Condensate?

- Suppression at low $x_{Au}$ (shadowing, saturation?)
- Enhancement at high $x_{Au}$ (Cronin, anti-shadowing, magnitude not understood…)
- $J/\psi$ behaves similar to other mesons
Let’s look more closely at the jets

Trigger:
- hadron with $p_T > 2.5$ GeV/c
- Identify as baryon or meson

*Biased, low energy, high $z$ jets!

Plot $\Delta\phi$ of associated partners
Fit jet widths &
Count associated lower $p_T$ particles for each trigger
→ “conditional yield”

Near side yield: number of jet associated particles from same jet in specified $p_T$ bin
Away side yield: jet fragments from opposing jet
Subtract the underlying event

includes ALL triggers (even those with no associated particles in the event)

\[ \frac{1}{N_{\text{trig}}} \frac{dN}{d\Delta \phi} \]

combinatorial background large in Au+Au! Small in p+p

Underlying event is big! Collective flow causes another correlation in them:

\[ B(1+2v_2(p_T^{\text{trig}})v_2(p_T^{\text{assoc}})\cos(2\Delta \phi)) \]

Can treat as 2 Gaussians
pp and dAu correlation functions

Fixed correlation: both $p_T^{trigg}$ and $p_T^{assoc}$ are in the same range

Assorted correlation: $p_T^{trigg}$ and $p_T^{assoc}$ are different

For $p_T < 1.5$:
- p+p
- $h^{+-}$ correl.

For $2.2 < p_T < 6.0$:
- Near angle peak

For $d+Au$:
- $\pi^{\pm}$: $5 < p_T < 16$ GeV/c
- assoc. with $h^{+-}$

Fit = const + Gauss(0)+Gauss($\pm\pi$)
These widths in p+p, d+Au, and Au+Au can be related to the standard jet correlation parameters $<|j_{Ty}|>$ and $<|k_{Ty}|>$. The near-side width is independent of centrality. The away-side width increases with centrality.
Medium effect: single particles are different!
Baryon excess continues to 5 GeV/c

\[
\frac{(h^+ + h^-)}{2} \quad \pi^0
\]

**Central**

**Peripheral**
The baryons scale with $N_{\text{coll}}$!

But observed enhancement can be explained by recombination of thermal quarks from an expanding quark gluon plasma. *NOT Jet-like!*

Expected interaction with the medium

Fragmentation:

\[ z \equiv \frac{p_{\text{hadron}}}{p_{\text{parton}}} \]

Hard scattering happens early
affected by initial state nucleus

Hard partons traverse the
interesting stuff

Energy loss by induced gluon
radiation

Modification of fragmentation
outside the medium??

→ recombination with
medium partons

radiated gluons nearby!
2 particle correlations

Select particles with $p_T=2.5-4.0\text{GeV/c}$

Identify them as mesons or baryons via Time-of-flight

Find second particle with $p_T=1.7-2.5\text{GeV/c}$

Plot distribution of the pair opening angles
Analysis in PHENIX

- Large multiplicity of charged particles
  --solution: find jets in a statistical manner using angular correlations of particles.
  Mixed events give combinatorial background.

- $2 \times 90$ degree acceptance in phi and $|\eta|<0.35$
  --solution: correct for azimuthal acceptance, but not for $\eta$ acceptance.

- Elliptic flow correlations
  --solution:
  use published strength values and subtract.

- Integrate partner yield over $55^\circ$
intermediate $p_T$ baryons ARE from jets

jet partner equally likely for trigger baryons & mesons

Same side: slight decrease with centrality for baryons

Larger partner probability than pp, dAu

Away side: partner rate as in p+p confirms jet source of baryons!

“disappearance” of away-side jet for both baryons and mesons
What’s going on?

Thermal quark recombination

Radiated gluons are collinear (inside jet cone)

Dilutes jet partner yield

Increases partner yield

Meson trigger

Fries, Bass & Mueller
nucl-th/0407102
Jet partner distribution on trigger side

Corrected to full jet yield
Partner spectrum flatter, indicates jet source
Partners soften in most central collisions

Fragmentation fn. modified!
Baryon formation is not outside medium

- formation time from hadron size, $R_h$ and mass, $m_h$
  
  In laboratory frame: $\tau_f \sim R_h \left( \frac{E_h}{m_h} \right)$
  
  consider 2.5 GeV pT hadrons
  
  $\tau_{f,\pi} \sim 9-18$ fm/c ($R_h \sim 0.5-1$ fm); $\tau_{f,p} \sim 2.7$ fm/c ($R_h \sim 1$ fm)

So, could expect hard-soft recombination (C.M. Ko)

Partner spectrum
Hwa & Yang
nucl-th/0407081

Soft-hard recomb. can also explain baryon Cronin effect!
Turn to $J/\psi - d+Au$ first

- Low and med $x_{Au}$: small variations
- Small shadowing centrality depend.

- High $x_{Au}$ has a steeply rising shape
  - Strong anti-shadowing but weak shadowing?
$P_T$ broadening observed in both the low and high $x$ part of the $J/\psi$ spectra.

Very similar $p_T$ enhancement as observed at lower energies.

\[ \sigma_{dA} = \sigma_{pp} \left(2 \times 197\right)^\alpha \]
J/ψ in Au + Au

Does colored medium screen c+cbar?

We don’t know yet!


But we will!

Run 4:1. 5 B Min Bias events (241 \( \mu b^{-1} \))
Partial data set here

\[ J/\psi \rightarrow e^+e^- \]
Open charm

Measure charm $\sigma$ via semi-leptonic decay to $e^+$ & $e^-$

$\pi^0$, $\eta$, photon conversions are measured and subtracted

fit $p+p$ data to get the baseline for $d+Au$ and $Au+Au.$
d+Au data vs centrality

The curves are the p+p fit, binary scaled.
Curves are the p+p fit, scaled by the number of binary collisions

NB: these data mainly at $p_T \leq 2$ GeV/c
Charm in Au+Au

Charm yield scales with Ncoll

\[ dN/dy = A \left( N_{\text{coll}} \right)^\alpha \]

Integrated \( 0.8 < p_t < 4.0 \) (GeV/c)

\[ 0.906 < \alpha < 1.042 \]

First hints that charm may flow
Some insights into collective flow

Min Bias 62.4A GeV Au+Au

$v_2$ magnitude and mass ordering similar to 200 GeV
Centrality dependence also same as 200 GeV

$v_2$ saturates at RHIC: implies soft EOS?
thermalization and freezeout:
200 GeV $v_2$ & spectra vs. hydrodynamic models

Proton $p$ & Pion $\pi^-$

Hydro models:
- Teaney (w/ & w/o RQMD)
- Hirano (3d)
- Kolb
- Huovinen (w/ & w/o QGP)
Conclusions

- Form high density, high energy density matter at RHIC. 
  \( \varepsilon \sim 15 \text{ GeV/fm}^3 \gg \varepsilon_{\text{crit}} \) \( \frac{dN_g}{dy} \sim 1000 \)

- Collective flows (v2, spectra) show matter behaves as \( \sim \) perfect fluid. Pressure, thermalization early. \( \sigma_{\text{int}} \) large.
  quantitative comparisons with hydro \( \rightarrow \) hadronization & final state interactions affect observables

- Jet fragmentation is modified by the medium.
  Au+Au jets richer in soft hadrons than p+p or d+Au;
  effect of induced radiation?
  baryon yield increased with volume: soft-hard recomb?
  away side jet into fixed angular range suppressed

- Deconfinement evidence not yet in hand; \( T_{\text{init}} \) ?
  Circumstantial evidence for QGP is present.
## Current knowledge on properties

- **Extract from models, constrain by data**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy loss $&lt;dE/dz&gt;$ (GeV/fm)</td>
<td>7-10</td>
<td>0.5 in cold matter</td>
</tr>
<tr>
<td>Energy density (GeV/fm$^3$)</td>
<td>14-20</td>
<td>&gt;5.5 from $E_T$ data</td>
</tr>
<tr>
<td>$dN$(gluon)/dy</td>
<td>~1000</td>
<td>From energy loss + hydro</td>
</tr>
<tr>
<td>$T$ (MeV)</td>
<td>380-400</td>
<td>Experimentally unknown as yet</td>
</tr>
<tr>
<td>Equilibration time $\tau_0$ (fm/c)</td>
<td>0.6</td>
<td>From hydro initial condition; cascade agrees</td>
</tr>
<tr>
<td>Opacity (L/mean free path)</td>
<td>3.5</td>
<td>Based on energy loss theory</td>
</tr>
</tbody>
</table>

*Equation of state?* Saturation of $v_2$ → soft  
*Early degrees of freedom?* Success of recombination → partonic  
*Deconfinement?* $\sigma$ of resonances at high $T$? Conductivity?
Cross section fits into expected energy dependence

Thermalization? Hydro-models score board

| Source average |

<table>
<thead>
<tr>
<th></th>
<th>QGP+mixed+RG</th>
<th>mixed+RG</th>
<th>RG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Teaney</td>
<td>Hirano</td>
<td>Kolb</td>
</tr>
<tr>
<td>latent heat (GeV/fm³)</td>
<td>0.8</td>
<td>1.7</td>
<td>1.15</td>
</tr>
<tr>
<td>init. $\epsilon_{\text{max}}$ (GeV/fm³)</td>
<td>16.7</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>init. $\langle \epsilon \rangle$ (GeV/fm³)</td>
<td>11.0</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>$\tau_0$ fm/c</td>
<td>1.0</td>
<td>0.6</td>
<td>0.6</td>
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<tr>
<td>hadronic stage</td>
<td>RQMD</td>
<td>partial chemical equil.</td>
<td>partial chemical equil.</td>
</tr>
<tr>
<td>proton v2</td>
<td>yes</td>
<td>$&lt; 0.7$ GeV/c</td>
<td>$&lt; 0.7$ GeV/c</td>
</tr>
<tr>
<td>pion v2</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>proton spectra</td>
<td>yes</td>
<td>overpredict</td>
<td>overpredict</td>
</tr>
<tr>
<td>pion spectra</td>
<td>yes</td>
<td>$&lt; 1$ GeV/c</td>
<td>$&lt; 1$ GeV/c</td>
</tr>
<tr>
<td>HBT</td>
<td>Not available</td>
<td>No</td>
<td>Not available</td>
</tr>
</tbody>
</table>

- **hadronic + QGP hydro reproduces features of v2($p_T$) of π, K, p**

- **require early thermalization ($\tau_{\text{therm}} < 1\text{fm/c}$) + high $\epsilon_{\text{init}} > 10$ GeV/fm³**

- **most fail to get v2 and spectra simultaneously**
η Analysis

Photon cuts:
- low energy threshold
- $|\text{TOF}|$
- $\chi^2$ (photon-like cluster)
- fiducial cut
Asymmetry cut < 0.5
Yields (shown in arbitrary units) as a function of $p_T$

- Yields in 3 centrality selections
  - 0-20%, 20-60%, 60-92%
- Corrected for acceptance, efficiency, and branching ratio
- Absolute normalization still being finalized (to present $\eta/\pi^0$)
- Errors dominated by uncertainty in peak extraction (point-to-point systematic error)

PHENIX Preliminary
Nuclear Modification Factor for $\eta$ (compared to $\pi^0$)

$$R_{CP} = \frac{\text{Yield}_{\text{central}} / \langle N_{\text{binary}} \rangle_{\text{central}}}{\text{Yield}_{\text{peripheral}} / \langle N_{\text{binary}} \rangle_{\text{peripheral}}}$$

PHENIX Preliminary
Compare p+p and d+Au to PYTHIA

p+p agree well

Hwa & Yang: hard-soft recombination can reproduce Cronin effect

d+Au
Compare to charged hadrons

- Charged hadrons from ISR used for p+p reference.
  \( \pi^0 \) yield is divided by \((\text{charged reference})/1.6\)

- Discrepancy between charged hadron and \( \pi^0 \) not surprising due to expected p, pbar contribution.

Particle ID is essential!
**J/ψ d+Au x-Dependence II**

Not universal versus $x_2$ : shadowing is not the whole story

\[ \sigma_{dA} = \sigma_{pp} (2 \times 197)^{\alpha} \]

\[ X_F = X_d - X_{Au} \]

E866: PRL 84, 3256 (2000)
Physics of the quark gluon plasma?

- Want to know
  
  *pressure, viscosity, energy gradients, equation of state, thermalization time & extent*
  
  determine from collective behavior
  
  *radiation rate, collision frequency, conductivity, opacity, Debye screening length?*
  
  use interaction of fast q, g probes with medium

- Expected interactions with QGP
  
  Energy loss by induced gluon bremsstrahlung
  
  Modified fragmentation functions
Hydro. expansion at low $p_T$ + jet quenching at high $p_T$. 

Coalesce (recombine) boosted quarks $\rightarrow$ hadrons enhances mid $p_T$ hadrons baryons especially

$T_{\text{eff}} = 350$ MeV

R. Fries, et al

pQCD spectrum shifted by 2.2 GeV

Are extras from the (soft) underlying event?
Phase space filled with partons: coalesce into hadrons

- Use lowest Fock state, i.e. valence quarks

- ReCo of hadrons: convolution of Wigner functions

\[ \frac{dN_M}{d^3P} = \sum_{a,b} \int \frac{d^3R}{(2\pi)^3} \int \frac{d^3q}{(2\pi)^3} W_{ab}(R - \frac{r}{2}, \frac{P}{2}, -q; R + \frac{r}{2}, \frac{P}{2}, +q)\Phi_M(r, q) \]

\[ W_{ab}(1;2) = w_a(1)w_b(2) \]

- Where does ReCo win?

Exponential: \[ w \sim Ae^{-p_T/T} \]

\[ N_{\text{frag}} = w \otimes D \sim Ae^{-p_T/(zT)} \langle D \rangle \]

\[ N_{\text{reco}} = w \otimes \Phi \otimes w \sim A^2e^{-p_T/T} \]

Power law: \[ w \sim p_T^{-\alpha} \]

\[ N_{\text{frag}} \sim P_T^{-\alpha} \]

\[ N_{\text{reco}} \sim P_T^{-2\alpha} \]
Coalescence Model results

- Particle ratios and spectra OK
- Intermediate $p_T$ hadrons from coalescence of flowing partons
  NOT from jets, so no jet-like associated particles
What do we still want to know?

- Quantitative information on medium modification of jet fragmentation

- Where does the energy radiated by fast partons go?
  Many soft gluons – no (per observed multiplicity)
  A few semi-hard gluons? … could be

- How is the lost energy propagated in the medium?
  Infer energy, color transport properties of QGP
  basic plasma physics!
  Is the lost energy thermalized in the medium?
<table>
<thead>
<tr>
<th>$B$ (fm)</th>
<th>$N_{\text{part}}$</th>
<th>$R/R+F_{\pi}$</th>
<th>$R/R+F_{p}$</th>
<th>Partner yield $\pi$</th>
<th>Partner yield $p$</th>
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</thead>
<tbody>
<tr>
<td>12</td>
<td>24</td>
<td>0.45</td>
<td>0.95</td>
<td>$0.027 \pm 0.0047$</td>
<td>$0.0014 \pm 0.0007$</td>
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<tr>
<td>7.5</td>
<td>156</td>
<td>0.65</td>
<td>0.97</td>
<td>$0.0172 \pm 0.0030$</td>
<td>$0.0008 \pm 0.0004$</td>
</tr>
<tr>
<td>0</td>
<td>390</td>
<td>0.8</td>
<td>0.98</td>
<td>$0.0098 \pm 0.04017$</td>
<td>$0.0005 \pm 0.0003$</td>
</tr>
</tbody>
</table>
$k_T, j_T$ at RHIC from p+p Data

Statistical Errors Only

$\sigma_N$ [rad]

$\sigma_F$ [rad]

$\sqrt{s}=200$ GeV

near-side away-side

$\sigma_{near}$ $\sigma_{far}$
Does Cronin enhancement saturate?

- A different approach:
- Intrinsic momentum broadening in the excited projectile proton:
  \[ \langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + C \cdot h_{pA}(b) . \]
- \( h_{pA} \): average number of collisions:
  \[ h_{pA}(b) = \begin{cases} 
  \nu_A(b) - 1 & \nu_A(b) < \nu_m \\
  \nu_m - 1 & \text{otherwise}
  \end{cases} . \]


jet fragmentation and $\perp$ momentum

$$\langle k_{\perp}^2 \rangle = \langle k_{\perp}^2 \rangle_{\text{vac}} + \langle k_{\perp}^2 \rangle_{\text{IS nucl}} + \langle k_{\perp}^2 \rangle_{\text{FS nucl}}$$

$\langle |j_{\perp y}| \rangle$ = mean transverse momentum of the hadron with respect to the jet axis (in the plane $\perp$ to beam axis)

$$\langle |j_{\perp y}| \rangle = \frac{1}{\sqrt{\pi}} \sqrt{\langle j_{\perp}^2 \rangle} = \langle p_{\perp} \rangle \sin \frac{\sigma_N}{\sqrt{\pi}}$$

$$\langle |k_{\perp y}| \rangle = \frac{1}{\sqrt{\pi}} \sqrt{\langle k_{\perp}^2 \rangle} = \langle p_{\perp} \rangle \cos \left( \frac{\sigma_N}{\sqrt{\pi}} \right) \sqrt{\frac{1}{2} \tan^2 \left( \sqrt{\frac{2}{\pi}} \sigma_F \right) - \tan^2 \left( \frac{\sigma_N}{\sqrt{\pi}} \right)}$$
\( \sigma_N, \sigma_F, \langle |j_{Ty}| \rangle, \langle |k_{Ty}| \rangle \) relations

Inspired by Feynman, Field, Fox and Tannenbaum we derived the equation

\[
\langle z_{trigg} \rangle \langle |k_{Ty}| \rangle = \frac{\langle p_T \rangle}{\sqrt{2} x_h} \sqrt{\frac{\sin^2 \frac{2}{\pi} \sigma_F - (1 + x_h^2) \sin^2 \frac{\sigma_N}{\sqrt{\pi}}}{\sqrt{\pi}}}
\]

\[x_h = \frac{p_{T,assoc}}{p_{T,trigg}}\]

\[z_{trigg} = \frac{p_{T,trigg}}{p_{T,jet}}\]

Knowing \( \sigma_N \) and \( \sigma_F \) it is straightforward to extract \( \langle |j_{Ty}| \rangle \) and \( \langle z_{trigg} \rangle \langle |k_{Ty}| \rangle \)
from jet correlations in pp at $\sqrt{s} = 200\text{GeV}$

PHENIX preliminary

$\langle |j_{Ty}| \rangle = 367 \pm 15 \text{ MeV/c}$

$\langle z \rangle \langle |k_{Ty}| \rangle = 660 \pm 50 \text{ MeV/c}$

$\langle |k_{Ty}| \rangle = 920 \pm 100 \text{ MeV/c}$
Comparison to outside world

PHENIX preliminary

Add the legend – experiment names

Larger markers and legends
did something new happen at RHIC?

- Study collision dynamics (via final state)
  - Equilibrium?
    - hadron spectra, yields
  - Collective behavior
    - i.e. pressure and expansion?
      - elliptic, radial flow

- Probe the early (hot) phase
  - Particles created early, predictable quantity, interact *differently* in QGP vs. hadron matter
  - *fast quarks/gluons, J/Ψ, D mesons*
  - thermal radiation

[Diagram of QGP and vacuum]