Recent Results from the PHENIX-Experiment on p+p, Au+Au and d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

Christian Klein-Bösing
IKP Münster
for the PHENIX Collaboration

Nuclear Physics
Spring Meeting 2004
Köln, March 8th
Recent Results on Hard Probes with the PHENIX-Experiment in Au+Au and d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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Particle Production at High $p_T$

- **General**
  - *Hard* processes: Parton collisions with large $Q^2$ ("Jets")
  - Factorization:
    - Parton Distr. $\otimes$ pQCD $\otimes$ FF

- **p+p**
  - Fragmentation into QCD-vacuum

- **Au+Au**
  - Early reaction-phase
  - Probe for a later hot and dense phase

- **Medium influences:**
  - "Jet"-like correlations
  - Particle ratios
  - Particle yields
Particle Production at High $p_T$

- **General**
  - *Hard* processes: Parton collisions with large $Q^2$ ("Jets")
  - Factorization:
    - Parton Distr. $\otimes$ pQCD $\otimes$ FF

- **p+p**
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- **Au+Au**
  - Early reaction-phase
  - Probe for a later hot and dense phase

- **Quantifying medium influence:**
  \[ d^2 \]
Nuclear Modification Factor

- Glauber model:
  - AA/dA incoherent superposition of NN
  \[ \sigma_{AB}^{\text{hard}} \approx \int d^2 b \sigma_{NN}^{\text{hard}} T_{AB}(b) \]

- Comparison with scaled NN
  - \( R_{AA} \approx 1 \) (for \( p_T > 2 \text{ GeV} \))?
  - Deviation \( \Rightarrow \) medium effects?
Known Effects N→A

- Multiple soft scattering
  - Broadens $p_T$ spectrum
  - Cronin Effect
- Change of the nuclear structure function / PDF
  - Shadowing ($R_{AA} < 1$)
  - Anti-shadowing ($R_{AA} > 1$)
  - Color Glass Condensate ??

Cronin-Effect observed in p+A experiments:
Phenix @ RHIC

- **Central Arms**
  - $|\eta| < 0.35$
  - Calorimetry (PbSc PbGI)
  - Tracking (PC, DC)
  - PID (RICH, TOF)

- **North and South Arms**
  - Muon PID and Tracking

- **Global**
  - Trigger (BBC)
  - Centrality (BBC, ZDC)
Au+Au @ $\sqrt{s_{NN}} = 200$ GeV at Midrapidity

PRL 91,072301 (2003) + high $p_T$ triggered data

nucl-ex/0310005
The Reference

- Good agreement with NLO pQCD
- Sensitive to choice of fragmentation function $D(g \rightarrow \pi)$
- Basis for comparisons in the nuclear modification factor

Poster S. Bathe (HK 14.14)
Peripheral Au+Au Compared to Scaled p+p

consistent with $N_{\text{coll}}$ scaling
Central Au+Au Compared to Scaled p+p

factor 5 suppression
One Possible Explanation

- **Jet quenching**
  - Hard scattered partons lose energy via gluon-bremsstrahlung
  - Depends on color charge density
  - Depends on traversed distance in medium (\(\rightarrow\)correlations)

- **Theoretical models**
  - Good quantitativ description within **energy loss** scenario

**Comparison to model calculations with and without parton energy loss:**

*Au+Au at \(\sqrt{s_{NN}} = 200 \text{ GeV}\)*

- With parton energy loss
  - Levai
  - Vitev
  - Wang

- Without parton energy loss
  - Wang
But...

Effects of cold nuclear matter ("initial state") at $\sqrt{s_{NN}} = 200$ GeV unknown

Suppression already in d+Au... ...or not?

d+Au needed as reference case:
No produced medium...
The Control Experiment I

\textbf{d+Au @ PHENIX}

- No suppression in d+Au collisions @ $\sqrt{s_{_{NN}}}$ = 200 GeV
  \begin{itemize}
  \item PRL 91, 0723903 (2003)
  \item Similar results from STAR, PHOBOS, BRAHMS
  \end{itemize}

⇒ Initial state effects excluded
d+Au Spectra at Midrapidity

Poster H. Büsching (HK 14.13)

PHENIX preliminary
Centrality Dependence at Midrapidity

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

80-92%

$R_{AA}$

charged hadrons
neutral pions

PHENIX

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

60-88%

$R_{dA}$

PHENIX preliminary
Centrality Dependence at Midrapidity

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

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

50-60%

40-60%
Centrality Dependence at Midrapidity

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

$R_{\text{AA}}$

charged hadrons
neutral pions

PHENIX

20-30%

$p_T$ (GeV/c)

0

1

2

0

5

10

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

$R_{\text{dA}}$

PHENIX preliminary

20-40%

$p_T$ (GeV/c)

0

2

4

6

8

10
Centrality Dependence at Midrapidity

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

$0-10\%$

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

$0-20\%$

PHENIX preliminary
Centrality Dependence

- Examine nuclear modification at fixed $p_T$
  - Enhancement in central $d+Au$
  - Suppression in central $Au+Au$
  - Deviation from scaled $pp$ vanishes in peripheral collisions

$\Rightarrow$ Strong medium effects in central $Au+Au$ overcome initial Cronin enhancement
Any Control in Au+Au?

- Strong Final State Interactions should not influence hard electromagnetic probes (in Situ control)
- Photons:
  - Also produced in initial hard scatterings, but no fragmentation
  - Additional production via Bremsstrahlung (and possibly thermal production in QGP)
Search for Direct Photons

- Inclusive Photon spectra dominated by decay $\gamma$
- Corrected for:
  - Hadronic contamination
  - Conversion
  - Efficiency
- Determination of background $\gamma$ needed
  - Mainly from $\pi^0, \eta$
  - Measured $\pi^0, m_T$-scaling else
  - Decay in simulation
\( \gamma/\pi^0 \) in p+p

- Comparison to expectation from decays with the \( \gamma/\pi \) double Ratio
  - Many systematics cancel
  - Excess above one indicates photon excess

![Graph showing the ratio \( \gamma/\pi^0 \) as a function of \( p_T \) with measured and expected background data points.](image)
Result in p+p

Consistent with pQCD with large uncertainties
Control II
Direct Photons in Au+Au

Expectation p+p pQCD:

\[ 1 + \frac{N_{coll} \times \gamma_{pQCD}}{\gamma_{bckgd}(\pi^0_{AuAu})} \]

\[ 1 + \frac{N_{coll} \times \gamma_{pQCD}}{\gamma_{bckgd}(N_{coll} \times \pi^0_{pp})} \]
Control II
Direct Photons in Au+Au

Expectation $p+p$ pQCD:

$$1 + \frac{N_{coll} \times \gamma_{pQCD}}{\gamma_{bckgd}(\pi_0^{0})}$$
Control II
Direct Photons in Au+Au

Expectation p+p pQCD:

$$1 + \frac{N_{\text{coll}} \times \gamma_{pQCD}}{\gamma_{\text{bckgd}}(\pi_0^{AuAu})}$$
Control II
Direct Photons in Au+Au

Expectation p+p pQCD:

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Control II
Direct Photons in Au+Au

Expectation \( p+p \) pQCD:

\[
1 + \frac{N_{\text{coll}} \times \gamma_{\text{pQCD}}}{\gamma_{\text{bckgd}}(\pi^0_{\text{AuAu}})}
\]
Control II
Direct Photons in Au+Au

Expectation $p+p$ pQCD:
$$1 + \frac{N_{\text{coll}}}{\gamma_{\text{bckgd}}(\pi^0_{\text{AuAu}})} \times \gamma_{\text{pQCD}}$$

First measurement of direct photons at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
Conclusion

- Observation: Suppression of high $p_T$ $\pi^0$'s and charged hadrons in central Au+Au
  - Suggests medium induced energy loss

- Enhancement/absence of suppression at midrapidity in d+Au
  - As expected from Cronin effect
  - Rules out initial state effects for observed suppression in Au+Au

- Established baseline for the effects of cold nuclear medium at $\sqrt{s_{NN}} = 200$ GeV

- First measurement of direct photons at $\sqrt{s_{NN}} = 200$ GeV
  - Agreement with (scaled) pQCD calculation
  - No suppression of Photons in Au+Au
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<td>Vanderbilt University, Nashville, TN</td>
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*as of January 2004
Backup Slides
Corrections

- Geometrical acceptance
- Detector effects
  - Multiplicity
  - Energy- / position resolution
- Analysis cuts
  - Asymmetrie
  - PID
  - Bad modules

Efficiency:
From embedding of simulated $\pi^0$ into real events
π⁰'s @ PHENIX

- **Reconstruction π⁰→2γ**
  - All pair combinations
  - Invariant mass
    \[ m_{\text{inv}} = \sqrt{2E_1E_2 (1- \cos \theta)} \approx 135 \text{ MeV} \]
  - Combinatorial background:
    - "Mixed events"
    - \( \gamma_1 \) from current event \( \gamma_2 \) from old event

- **Corrections**
  - Acceptance
  - Efficiency
Charged Particles @ PHENIX

- Tracking in west arm
  - Momentum reconstruction with BBC, PC1 and DC
- Background rejection
  - Matching PC2 and PC3 hits
  - Remaining background:
    - Conversions and decays
    - Determined and subtracted statistically
- Corrections
  - Acceptance, decay in flight
  - Efficiency
$\pi^0$ Peaks

$2 \text{ GeV} \leq p_T < 2.5 \text{ GeV}$

$134\,939 \pm 3184 \, \pi^0$ from

26 M minimum bias events (PbGl)
Signal/Background

- $\pi^0$ analysis limited by statistics
  - Further improvement with high $p_T$ photon triggers
- Charged particle analysis limited by background:
  - $\delta p/p = 0.7\% \oplus 1.1\% p$ (GeV/c)
  - Background from conversion electrons hardly separable from charged $\pi$
h/π Ratios

- **Expectation (pp, e+e-):**
  - h/π ≈ 1.6
- **Only the case in peripheral collisions and above 5GeV**
- **Identified Hadrons**
  - Anomalous p/π
  - Data suggests baryon vs. meson effect (from λ,p vs φ,π)
  - Talks: F. Matathias
- **Approaches**
  - E.g. recombination of quarks in a thermal phase
Recombination

- Two competing processes for hadron production
  - Jet fragmentation
  - Recombination of 3 quarks or a quark/anti-quark pair in a densely populated phase space

- Fries et al.:
  - In case of thermalized partons fragmentation wins over recombination only above 5 GeV/c
  - Explains $p/\pi$ ratio
  - “Such a phase may be appropriately called a QGP”

Fries, et al, nucl-th/0301087
also, Greco, Ko, Levai, nucl-th/0301093
\( \eta \) in Au+Au
d+Au Centrality Dependence

- Centrality Selection with BBC-South
  - Au going side
  - $3 < |\eta| < 3.9$
  - Charge sum $\Rightarrow$ multiplicity
- $N_{\text{coll}}$ from Glauber model

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<tr>
<th>Centrality</th>
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<tr>
<td>0-20%</td>
<td>$15.0 \pm 1.0$</td>
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<tr>
<td>20-40%</td>
<td>$10.4 \pm 0.7$</td>
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<tr>
<td>40-60%</td>
<td>$6.9 \pm 0.6$</td>
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<tr>
<td>60-88%</td>
<td>$3.2 \pm 0.3$</td>
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</table>
Centrality Dependence $\pi^0$

- Examine nuclear modification at fixed $p_T$
  - Enhancement in central d+Au
  - Suppression in central Au+Au
  - Deviation from scaled pp vanishes in peripheral collisions

⇒ Strong medium effects in central Au+Au overcome initial state Cronin enhancement
Theory Comparison

- **Prediction from pQCD**
  - Tuned to pp \( \langle k_T^2 \rangle \ldots \)
  - Good qualitativ agreement with expectation from Cronin enhancement
  - Further improvement with inclusion of shadowing

- **Prediction from saturation models**
  - Fails, no suppression in central d+Au at midrapidity
  - Different rapidity regions?
Does the Enhancement Vanish at High $p_T$??

- $R_{CP}$
  - Compares Yields in central and peripheral scaled by $N_{coll}$
  - Many systematics cancel

- Different parts of PHENIX measure different $p_T$ ranges of $\pi$

- Enhancement in central vanishes at high $p_T$