Highlights from PHENIX

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Introduction

Highlights selected from recent PHENIX results

- Beam Energy scan 7.7 – 200 GeV
- Direct photon emission in AuAu
- Dilepton continuum in AuAu
- Charm and Bottom energy loss in AuAu
- Strongly coupled matter in small systems (pA, dA, \(^3\)HeA)

Summary and Outlook
The PHENIX Experiment

Central Arms
\(|\eta| < 0.35\)
\(e^\pm, \gamma, \pi, K, p\)

Muon Arms
\(1.2 < |\eta| < 2.2\)
\(\mu\)

BBC
\(3.1 < |\eta| < 3.9\)
\(\gamma\)

Vertex tracker (FVTX)
\(1 < \eta < 3\)
\(h^\pm\)

Vertex tracker (VTX)
\(|\eta| < 1.2\)
\(h^\pm\)
The PHENIX Experiment

Central Arms
$|\eta| < 0.35$
$e^\pm, \gamma, \pi K p$

Muon Arms
$1.2 < |\eta| < 2.2$
$\mu$

Since QM2014
17 new papers on arXiv
16 published papers

At QM2015
36 poster presentations
15 contributed talks
PHENIX Results after 15 Years of Operation

Highlights based on:

Advanced analysis techniques:
Example b/c separation

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<th>energy (GeV)</th>
<th>U+U</th>
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Vertex tracking:
FVTX-VTX

Results from detector upgrades

HBD

PHENIX

Stony Brook University
Schematic View of Space-Time Evolution

Collision
Initial state?
CGC?

Rapid equilibration
How?
Glasma?
Role of B-field?

Anisotropically expanding sQGG
Properties?
T, \eta/s, \hat{q}, D, \ldots \, ?

Hadronization to freeze-out
Coalescence?
Chiral symmetry?

PHENIX highlights:

- Heavy flavor energy loss
- Dilepton continuum
- Strongly coupled matter in small systems
- Direct photon emission

\[ \tau < 1 \text{ fm/c} \]
\[ \tau \geq 10 \text{ fm/c} \]
Beam Energy Scan

Comprehensive surveys of multiple observables as function of beam energy

- **HBT Radii:**

- **$N_{ch}, E_T$:**

- **$Net N_{ch}$ cumulants**

**Monotonic change of baryo-chemical potential at constant freeze-out temperature**

\[ T_f = 162 \pm 5 \text{ MeV} \]
Thermal Radiation from Hot & Dense Matter

Black Body Radiation
- Real or virtual photons
- Spectrum and yield sensitive to temperature
  Avg. inv. slope $\propto T$, Yield $\propto T^3$
- Space-time evolution of matter
  collective motion $\rightarrow$ Doppler shift
  $\rightarrow$ anisotropy

Microscopic view of thermal radiation
QGP: $g \leftrightarrow q \leftrightarrow q$ hadron gas: $\pi \leftrightarrow \pi \leftrightarrow \rho \leftrightarrow \gamma$
photons $\rightarrow$ low mass lepton pairs

High yield $\rightarrow$ high T $\rightarrow$ early emission
Large Doppler shift $\rightarrow$ late emission

Need realistic model simulation for rates and space-time evolution for quantitative comparison with data
Direct Photon Emission from 200 GeV Au+Au


Large direct photon excess

yield $\propto N_{\text{part}}^{1.38 \pm 0.3 \pm 0.07}$ with inv. slope $T \sim 240$ MeV
Anisotropic Emission of Direct Photons


Anisotropic emission of direct photon with large $v_2$ and $v_3$
Many model calculations and consideration*:

- More traditional, large contribution from hadron gas
  - Thermal rate in QGP & HG, with hydro (viscous/non viscous) or blastwave evolution
  - Microscopic transport (PHSD)

- New early contributions
  - Non-equilibrium effects (glasma, etc.)
  - Enhanced thermal emission in large B-fields
  - Modified formation time and initial conditions

- New effects at phase boundary
  - Extended emission
  - Emission at hadronization

*list not complete
Low Mass $e^+e^-$ Pair Emission

- PHENIX run 2004 data show large low mass dilepton excess
  - factor of ~5 in min.bias collisions
  - Small signal-to-background (S/B) ratio ~ 1:500

- Much larger than expected from theoretical models
- Recent STAR results shows smaller (factor ~1.8) enhancement

- PHENIX Hadron Blind Detector (HBD) upgrade designed to improve S/B and to study $e^+e^-$ continuum more precisely
- HBD data taken in 2010 now fully analyzed:
  - Active rejection of conversion and Dalitz pairs (close pairs)
  - Improved hadron rejection
  - Neural networks to optimize cuts

- Quantitative understanding of background
- Results verified by 2nd analysis using different techniques


*STAR: Phys.Lett. 113 022301 (2014)*

*PHENIX: arXiv 1509.04667 (2015)*
Low Mass $e^+e^-$ Enhancement in 200 GeV Au+Au


- Moderate enhancement for $300 < m < 750$ MeV factor*
  - min.bias $2.3 \pm 0.4 \pm 0.4 \pm 0.2$
  - central $3.2 \pm 1.0 \pm 0.7 \pm 0.2$

- Smaller than previous result
- Consistent with STAR data
- Consistent with $\rho$ broadening

*binary scaled PYTHIA for c/b
Energy Loss of Open Heavy Flavor

Discovery of large suppression and elliptic flow of single electrons from heavy flavor decays

Data implies charm AND bottom lose energy
Use distance of closest approach (DCA) to unfold charm and bottom contribution

Electron $DCA_T$

- **Prompt components**
  - Dalitz ($\pi, \eta \rightarrow e^+e^-\gamma$)
  - $J/\psi \rightarrow e^+e^-$
- **Non-prompt components**
  - Conversions $\gamma \rightarrow e^+e^-$ after ~75% rejected by 2nd hit in VTX
  - $K_s^0, K^{\pm} \rightarrow e^\nu\pi$
- **Mis-reconstructed component**
  - Hadrons identified as electrons
  - Wrong VTX hit association
Silicon Vertex Tracker (VTX) since 2011

Use distance of closest approach (DCA) to unfold charm and bottom contribution

**Electron DCA$_T$**

- **Prompt components**
  - Dalitz ($\pi, \eta \rightarrow e^+e^+\gamma$)
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- **Non-prompt components**
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- **Mis-reconstructed component**
  - Hadrons identified as electrons
  - Wrong VTX hit association

**Open heavy flavor**

Unfolding Charm and Bottom Spectra

DCA for B, D decays depends on momentum distribution which is not a priori known

**Input:**

Heavy flavor electron data $x$:

\[
\frac{1}{N_{\text{evt}}} \frac{dN_{\text{enhf}}}{dp_T}
\]

$DCA_T(p_T)$

**Variables:**

$c, b$ hadron yields $\theta$:

\[
\frac{d\theta_c}{dp_T} \quad \frac{d\theta_b}{dp_T}
\]

$\pi(\theta)$ suppress discontinuities deviations from $\theta_{\text{prior}}$

**Likelihood**

$P(x|\theta)$

Sample $\theta_c, \theta_b$

Markov Chain MC

**Output:**

Probability for $\theta$ given $x$:

\[
p(\theta|x) = \frac{P(x|\theta)\pi(\theta)}{P(x)}
\]

Yields in $4\pi$ for min. bias Au+Au at 200 GeV

\begin{align*}
&\text{Au+Au MB } \sqrt{s_{NN}} = 200 \text{ GeV} \\
&\text{PHENIX 2011}
\end{align*}

\[ \frac{d^2 N}{dz^2 p_T} \text{ [GeV/c]}^{-2} \]

<table>
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<th>$D^\pm$, $B^0$, $B_S$, $A_b$</th>
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\[ \text{Data/fit} \]

$|y|<1$

Au+Au at $\sqrt{s_{NN}} = 200$ GeV
Charm and Bottom $R_{AA}$

Fraction of electrons from bottom

$$F = \frac{b \rightarrow e}{b \rightarrow e + c \rightarrow e}$$

Single electron $R_{AA}$ for bottom and charm

$F_{AuAu} > F_{pp}$

$F_{AuAu} \sim F_{pp}$

Mapped $p_T$ dependence separately for charm and bottom suppression

Data provides new constraints on theoretical description of b & c energy loss

Comparison to Theoretical Models

QGP in Small Systems

- CMS discovery of collective phenomena “the ridge” in p+p and p+Pb
- Use versatility RHIC for a set of controlled experiment
  - Engineer initial state geometry through collision system

Phys. Rev. Lett. 113, 112301 (2014), figure courtesy of B. Schenke

Initial State Hot Spots
Glauber with nucleons

Hydrodynamics

Collectivity in Final State

Sensitivity to initial conditions and early time evolution


PHENIX data with high multiplicity trigger
Flow in Small Systems at $\sqrt{s_{NN}} = 200$ GeV


Top 5% in centrality

$v_2^{^3\text{HeAu}} \geq v_2^{\text{dAu}} > v_2^{\text{pAu}}$

Collective motion: Large anisotropy $v_2$ in p+Au, d+Au, and v2, v3 $^3$He-Au
Empirical Scaling Behavior

A+A collisions show scaling: \[ \frac{v_n}{\epsilon_n N_{\text{part}}^{1/3}} \]


Empirical scaling of $v_2$ works well for small collision systems

For $v_3$ scaling does not work for small collision systems
Comparison to Model Predictions

SONIC Glauber + hydro + hadron cascade
super SONIC + pre-equilibrium
IPGlasma + hydrodynamic
AMPT parton + hadron cascade

\[ \text{predicts } v_n \]

\[ 3\text{He}(d)+A \uparrow v_n, \text{p}+A \downarrow v_n \]

under predicts \( v_n \) at high \( p_T \)

Sensitivity to initial conditions
and early time evolution

AMPT: arXiv:1501.06880
SONIC: arXiv:1502.04745
Jet Measurements in d+Au

- Jet reconstruction in p+p and d+Au
  - $12 < p_T < 50$ GeV/s

- $R_{dA} \sim 1$ for min.bias d+Au

- $R_{dA}$ shows strong centrality dependence
  - For central collisions jets are suppressed
  - For peripheral collisions jets are enhanced

No evidence for final state effects in jet measurements in d+Au
Strong suppression of $\psi(2S)$ at backward rapidity in $p+Au$

50% suppression of double ratio to $J/\psi$ in min.bias collisions

Evidence for final state effect in charmonium production in $p+Au$
Summary and Outlook

- Large yield and large anisotropy ($v_2, v_3$) of direct photons
  - Challenges understanding of sources, rates and space-time evolution
- Final results on low mass dielectron continuum
  - Moderate enhancement consistent with broadening of $\rho$ in medium
- Separate charm and bottom both are suppressed at high $p_T$
  - New constraints for theoretical models
- Strongly coupled matter created in central $pA, dA, ^3HeA$
  - New sensitive to initial state and early collision dynamics
  - No indication for jet energy loss
  - Evidence for final state effects in charmonium

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Outlook beyond QM2015

- Many ongoing analysis
- High statistics data sets $Au+Au$ 2014, $p+p$ 2015
- Final run in 2016: high statistics $Au+Au$ and $d+Au$ energy scan
Science case endorsed through Department of Energy review
First constitutional collaboration meeting December 10-12, 2015 at Rutgers University, New Jersey, USA
Backup
Systematic Uncertainties on \( v_n \)

\[
\sigma_{v_n}^2 = \left( \frac{R_\gamma}{R_\gamma - 1} \right)^2 \times \sigma_{v_n}^{inc} + \left( \frac{1}{R_\gamma - 1} \right)^2 \times \sigma_{v_n}^{dec} + \left( \frac{v_n^{dec} - v_n^{inc}}{R_\gamma - 1} \right)^2 \times \sigma_{R_\gamma}^2 + \sigma_{EP}^2
\]

- Revisited systematic uncertainty calculation based on discussions with ALICE
- Non-linear dependence of uncertainty on \( R_\gamma \)
  - Asymmetric uncertainties
- Model probability distributions with MC

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<th>40-60%</th>
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<td>( \pi^0 ) ( v_2 ) (sys)</td>
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<td>2%</td>
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<td>( \eta, \omega ) ( v_2 ) (sys)</td>
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<td>( v_n^{dec} ) decay photon</td>
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Model Dependence of Heavy Flavor

Mass spectra

1/\Delta N dN/dm_{ee} [GeV/c^2] in PHENIX acceptance

p+p \ s= 200 \ GeV
|y| < 0.35
p_T > 0.2 \ GeV/c
Comparison to previous PHENIX analysis

- Hadron contamination: was 30%, now 5% in MB
- Signal sensitivity: a factor of $\sim 3.5$ improvement in 0.15-0.75 GeV/c²
- Pair cuts: now stronger pair cuts fully remove detector correlations
- Flow: now included in the shape of the mixed BG
- e-h pairs: now subtracted
- Jets: opposite jets component now explicitly subtracted
- Background subtraction: all correlated components calculated and subtracted on absolute terms
Dilepton Enhancement

TABLE IX: The enhancement factor, defined as the ratio between the measured yield and the expected yield for $0.15 < m_{ee} < 0.75$ GeV/$c^2$, for different centrality bins. The meaning of the errors is defined in the text.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Enhancement (±stat ±syst ±model)</th>
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<td>00-10 %</td>
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<td>10-20 %</td>
<td>3.2 ± 0.4 ± 0.1 ± 0.6</td>
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<td>20-40 %</td>
<td>1.4 ± 1.3 ± 0.02 ± 0.3</td>
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<tr>
<td>40-60 %</td>
<td>0.8 ± 0.3 ± 0.03 ± 0.2</td>
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<tr>
<td>60-92 %</td>
<td>1.5 ± 0.3 ± 0.001 ± 0.3</td>
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<tr>
<td>Min. Bias</td>
<td>4.7 ± 0.4 ± 1.5 ± 0.9</td>
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</table>

TABLE VIII. Enhancement factors, defined as the ratio of measured over expected dilepton yield in the mass region $m_{ee} = 0.30-0.76$ GeV/$c^2$, for the five centrality bins and for MB. The enhancement factors are quoted separately for the two cases where the correlated yield from $c\bar{c}$ decays is calculated with PYTHIA or MC@NLO. The ±model uncertainties represent the cocktail systematic uncertainties.

<table>
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<tr>
<th>Centrality</th>
<th>Enhancement factor ±stat ±syst ±model</th>
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<td>MC@NLO $c\bar{c}$</td>
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<tr>
<td>MB</td>
<td>1.7 ± 0.3 ± 0.3 ± 0.2</td>
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<tr>
<td>0%-10%</td>
<td>2.3 ± 0.7 ± 0.5 ± 0.2</td>
</tr>
<tr>
<td>10%-20%</td>
<td>1.3 ± 0.4 ± 0.5 ± 0.2</td>
</tr>
<tr>
<td>20%-40%</td>
<td>1.4 ± 0.2 ± 0.3 ± 0.2</td>
</tr>
<tr>
<td>40%-60%</td>
<td>1.2 ± 0.2 ± 0.3 ± 0.2</td>
</tr>
<tr>
<td>60%-92%</td>
<td>1.0 ± 0.1 ± 0.2 ± 0.2</td>
</tr>
</tbody>
</table>
Testing Possible Baryon Enhancement II

- Including above enhancement causes an increase in the bottom electron fraction.
- Within systematic uncertainties of the measurement.
- Not included as an additional uncertainty.
Small Systems

![Graph showing $V_2/\varepsilon_2$ vs. $p_T$ for different systems: p+Au 200GeV 0-5%, d+Au 200GeV 0-5%, $^3$He+Au 200GeV 0-5%, and SONIC p+Au, d+Au, $^3$He+Au. The graph includes data from PRL 114, 192301 and arXiv:1507.06273, and is preliminary.]