Dielectron measurements by PHENIX

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Huge enhancement was observed in Au+Au collisions
Well described by models with $\rho$ broadening

**CERES**

PbAu 158 AGeV

**NA60**

Large hadron contamination
~30% in the most central bin

**PHENIX**
Analysis of 2010 AuAu data

1. HBD
2. Electron identification
3. Background subtraction
4. Cocktail
5. Results

Almost all the materials are taken from arxiv: 1509.04667
Hadron Blind Detector (HBD) was installed in 2009
- Cherenkov detector using GEMs with CsI photocathode and CF₄ in a windowless configuration
- Cherenkov light is formed only by electrons
- Detector operated in reverse bias mode to repel the ionization charge from dE/dx
- Additional hadron rejection
Dalitz/conversion rejector

- $\pi^0$ Dalitz decays and $\gamma$ conversions are major background sources in dielectron measurements
- $e^+e^-$ pairs from $\pi^0$ Dalitz decays and $\gamma$ conversions can be identified by their small opening angle
- Preserve the opening angle by creating a magnetic field free region around the beam pipe
We did our best not only with the new detector, HBD.

We maximized the performance of other detectors, too.
  - Exploit the timing information of PbSc and TOF-E for additional hadron rejection.
  - Improve the RICH ring reconstruction algorithm to reduce the ring sharing problem.
Timing information

○ PbSc
  □ 3/4 of acceptance
  □ Resolution ~450 ps

○ TOFE
  □ ~1/8 of acceptance
  □ Resolution ~150 ps
RICH algorithm

- Parallel tracks point to the same ring in RICH
- Hadron tracks can steal fired PMTs from electron tracks in the old algorithm
- New algorithm forbids a ring to be associated with multiple tracks
- Associate only with signal electron candidates

arxiv:1509.04667
Neural network

- NNs are trained and monitored by simulations
- The detector responses in data are well reproduced by MC based on GEANT
Summary of eID flow

1. Reject obvious hadrons (EMCal+RICH+TOF)
2. Erase RICH PMTs of uninteresting electrons
   a. identified conversion
   b. electrons with $p_T<0.2$ GeV/c
   c. HBD double hits ($N_{N_d}$)
3. Reject remaining background electrons
   a. hadrons ($N_{N_h}$)
   b. $\gamma$ conversions in detector materials ($N_{N_e}$)

arxiv:1509.04667
1. Reject obvious hadrons (EMCal+RICH+TOF)
2. Erase RICH PMTs of uninteresting electrons
   a. identified conversion
      ● Hadron contamination less than 5% is achieved for all centralities
      ● Hadron contamination was 30% in the most central bin in the 2004 data analysis
      ● Small hadron contamination is critical to keep the background sources under control
Background subtraction strategy

- Why don’t we use “like-sign method”?
  - Signal = Unlike-sign ($e^+e^-$) - Like-sign ($e^+e^+$ or $e^-e^-$)
  - Substantial acceptance difference between unlike-sign and like-sign
  - We have charge asymmetric background sources
    - $e$-$h$ pairs (discussed later)
  - We also have signal pairs from $bb$ in like-sign spectra

- Component-by-component subtraction
  - Each source is evaluated separately using simulations for the shape and data for the absolute normalization
  - Our background description is validated using like-sign spectra
Background pairs in 2004 analysis

Background = combinatorial BG + correlated BG

Mixed event technique

Jet pairs

Cross pairs
Background pairs in 2010 analysis

Background = combinatorial BG + correlated BG

Mixed event technique with flow modulation

Jet pairs

Cross pairs

e-h pairs (residual detector correlation)
Cross pairs and jet pairs

○ Cross pairs
  □ $\pi^0 \rightarrow e\gamma, \pi^0 \rightarrow \gamma\gamma, \eta \rightarrow e\gamma, \eta \rightarrow \gamma\gamma$
  □ Exodus passed through GEANT
  □ Absolute normalization using $dN/dy$ of $\pi^0$ and $\eta$

○ Jet pairs
  □ PYTHIA passed through GEANT
  □ Absolute normalization
  □ $R_{AA}$ and $I_{AA}$ from PHENIX measurements are taken into account
Background pairs in 2010 analysis

Background = combinatorial BG + correlated BG

Mixed event technique with flow modulation

Jet pairs

Cross pairs

e-h pairs (residual detector correlation)
- e-h pairs

- RICH spherical mirror causes hit sharing of parallel tracks
- Simulated and statistically subtracted
- Absolute normalization using dN/dy of $\pi^0$ and $\eta$

Charge asymmetric unlike other background sources
Background pairs in 2010 analysis

Background = combinatorial BG + correlated BG

Mixed event technique with flow modulation

Jet pairs

Cross pairs

e-h pairs (residual detector correlation)
Combinatorial BG and flow

○ In heavy ion collisions, any electrons in a same event are correlated through a reaction plane
○ How can we implement this effect into mixed events?
  □ Reaction plane binning method
    ○ Mix the events with similar reaction plane angles
    ○ Limited by reaction plane resolution
  □ Weighting method
    ○ Apply the following weight pair-by-pair (next slide)
      □ $1 + 2v_2^2v_2^2 \cos(2\Delta\varphi)$
    ○ Estimate the single electron $v_2$ using our own data

Tested with ToyMC
Weighting method

- **Azimuthal distribution of a particle**

\[
P(\phi - \Psi) = \epsilon(\phi) \left( 1 + 2v_2 \cos 2(\phi - \Psi) \right)
\]

- **\(\Delta\phi\) distribution of any two particles in the same event**

\[
P_{FG}(\Delta\phi) = \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} d\Psi \int_{\phi_1 - \phi_2 = \Delta\phi} d\phi_1 d\phi_2 P(\phi_1 - \Psi) P(\phi_2 - \Psi)
\]

\[
= \left( \int_{-\pi}^{\pi} d\phi_1 \epsilon(\phi_1) \epsilon(\phi_1 + \Delta\phi) \right) \times \left( 1 + 2v_2 v_2 \cos 2\Delta\phi \right)
\]

- **\(\Delta\phi\) distribution of any two particles in the mixed event**

\[
P_{MIX}(\Delta\phi) = \int_{-\pi}^{\pi} d\phi_1 \epsilon(\phi_1) \epsilon(\phi_1 + \Delta\phi)
\]

- **Weighting factor:**

\[
w(\Delta\phi) = 1 + 2v_2 v_2 \cos 2\Delta\phi
\]
Like-sign mixed event normalization

- \( FG_{++} = CP_{++} + Jet_{++} + EH_{++} + BB_{++} + nf_{++}MIX_{++} \)
- \( FG_{--} = CP_{--} + Jet_{--} + EH_{--} + BB_{--} + nf_{--}MIX_{--} \)
- All correlated components are absolutely normalized
- Like-sign mixed BG is normalized to residual yields in the pair opening angle region where the correlated backgrounds are smallest
Understanding of BG

Good description of like-sign spectra

arxiv:1509.04667
Unlike-sign mixed event normalization

○ How do we calculate $n_f_{+-}$ from $n_f_{++}$ and $n_f_{--}$?
  □ $CB_{+-} = 2 \sqrt{(CB_{++} CB_{--})}$ from PRC81(2010)034911
  □ We generate mixed events such that $MIX_{+-} = 2\sqrt{(MIX_{++} MIX_{--})}$ is satisfied
  □ $n_f_{+-} = \sqrt{(n_f_{++} n_f_{--})}$ where $n_f = CB/MIX$

○ The $CB_{+-} = 2 \sqrt{(CB_{++} CB_{--})}$ can be violated by:
  □ Pair cuts: it was already noticed in 2004 analysis
  □ Flow + non-uniform acceptance: Newly found
  □ We introduce the same violation effects into mixed BG, so $n_f_{+-} = \sqrt{(n_f_{++} n_f_{--})}$ still holds true.
\[ CB_{+-} = 2 \sqrt{(CB_{++} \ CB_{--})} \]

- Proof in PRC 81, 034911 (2010)
  - e^+e^- are always produced in pairs
  - N pairs are produced in a given event
  - Out of N pairs, only a fraction, \( \varepsilon_p \), is fully reconstructed.
  - Of the remaining pairs, one leg is reconstructed with a probability, \( \varepsilon_+ \) or \( \varepsilon_- \).

- Using these variables and the properties of binomial and multinomial distributions, you get the following:

\[
\begin{align*}
\langle BG_{+-} \rangle &= \frac{\varepsilon_p + \varepsilon_+(1 - \varepsilon_p)}{2} \left[ \varepsilon_p + \varepsilon_-(1 - \varepsilon_p) \right] \left( \langle N^2 \rangle - \langle N \rangle \right) \\
\langle BG_{++} \rangle &= \frac{1}{2} \left[ \varepsilon_p + \varepsilon_+(1 - \varepsilon_p) \right]^2 \left( \langle N^2 \rangle - \langle N \rangle \right) \\
\langle BG_{--} \rangle &= \frac{1}{2} \left[ \varepsilon_p + \varepsilon_-(1 - \varepsilon_p) \right]^2 \left( \langle N^2 \rangle - \langle N \rangle \right) \\
\langle BG_{+-} \rangle &= 2 \sqrt{\langle BG_{++} \rangle \langle BG_{--} \rangle}
\end{align*}
\]

BG is CB in their notation.
\[ CB_{+-} \neq 2 \sqrt{(CB_{++} \cdot CB_{--})} \]

○ So far, we are using constant average efficiencies, \((\varepsilon_p, \varepsilon_+, \varepsilon_-)\)

○ However, the average efficiencies depend on reaction plane \(\psi\)
  □ Efficiency itself does not depend on the reaction plane, but the average does:
  \[
  \varepsilon_{p/+-/(\psi)} = \int d\phi \varepsilon_{p/+-/(\phi)}(1 + 2v_2 \cos(\phi - \psi))
  \]

□ So, the equations in the previous page hold only at fixed reaction plane angle

○ If you take average over reaction plane angles,

\[
\left[ \int d\psi A(\psi)B(\psi) \right]^2 \leq \int d\psi A(\psi)^2 \cdot \int d\psi B(\psi)^2 \Rightarrow CB_{+-} \leq 2 \sqrt{CB_{++} \cdot CB_{--}}
\]
Efficiency correction

- Measured spectra are corrected into “ideal PHENIX acceptance”

\[
\frac{dN}{dm_{ee}} = \frac{1}{N_{evt}} \frac{N(m_{ee})}{\Delta m_{ee}} \frac{1}{\epsilon_{total}^{pair}}
\]

\[
\epsilon_{total}^{pair} = \epsilon_{eID}^{pair} \cdot \epsilon_{live}^{pair} \cdot \epsilon_{ghost}^{pair} \cdot \epsilon_{mult}^{pair}
\]

- Special care was taken to ensure that the detector responses are very well reproduced in the MC simulations
## Systematic uncertainties (MB)

<table>
<thead>
<tr>
<th>Component</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>eID + occupancy</td>
<td>± 4%</td>
</tr>
<tr>
<td>Acceptance (time variation)</td>
<td>± 8%</td>
</tr>
<tr>
<td>Acceptance (data vs MC)</td>
<td>± 4%</td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>± 25% (@ 0.6 GeV/c²)</td>
</tr>
<tr>
<td>Residual yield (0-0.08 GeV/c²)</td>
<td>- 5% (@ 0.08 GeV/c²)</td>
</tr>
<tr>
<td>Residual yield (1-5 GeV/c²)</td>
<td>- 15% (@ 1 GeV/c²)</td>
</tr>
</tbody>
</table>
Dielectron and Dalitz decays of mesons simulated with EXODUS

- $\pi^0$
  - parameterized with modified Hagedorn function
  - Normalized in $m_{ee}<0.1$ GeV/$c^2$ and $p_T/m_{ee} > 5$ with $\eta$ and $\gamma$ contributions

- Other mesons
  - $m_T$ scaling + meson/$\pi^0$ ratio at high $p_T$

Semileptonic decays of open heavy flavor ($c,b$) simulated with PYTHIA and MC@NLO

- 2004 analysis used only PYTHIA
- The cross sections are determined using IMR of dielectron spectra in d+Au collisions
cc̅ dominant

bb̅ dominant

d+Au

PRC 91 (2015) 014907
HF cross sections

- Fit the MC calculations to the measured dielectron spectra in \((m, p_T)\) planes
  - PYTHIA
  - MC@NLO
- Measured \(b\bar{b}\) cross section
  - \(d\sigma/dy = 1.36 \pm 0.32 \pm 0.44 \mu\text{b}\)
  - Less model dependent due to its heavy mass
- Huge model dependence of \(c\bar{c}\) cross section

<table>
<thead>
<tr>
<th>d(\sigma_{cc}/dy)</th>
<th>PYTHIA</th>
<th>MC@NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>106 (\pm 9 \pm 33 \mu\text{b})</td>
<td>287 (\pm 29 \pm 100 \mu\text{b})</td>
<td></td>
</tr>
</tbody>
</table>
PYTHIA and MC@NLO

- They have different shapes of dielectron spectra
  - Single charm $p_T$ distributions are different
  - Opening angle distributions are also different

Figures provided by D. Sharma
p+p and d+Au are giving consistent results (N_{coll} scaling)
Understanding of the $c\bar{c}$ contribution is more crucial in Au+Au collisions

- Other cocktail sources scale with $N_{\text{part}}$
- $c\bar{c}/b\bar{b}$ scale with $N_{\text{coll}}$
MB spectra

- Huge enhancement in 2004 analysis is not confirmed
- Consistent with STAR results

<table>
<thead>
<tr>
<th>0.3-0.76 GeV/c²</th>
<th>PYTHIA</th>
<th>MC@NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhancement factor</td>
<td>2.3 ±0.4 ±0.4 ±0.2</td>
<td>1.7 ±0.3 ±0.3 ±0.2</td>
</tr>
</tbody>
</table>
Centrality dependence

Enhancement grows towards the most central bin
**p_T dependence**

Enhancement is distributed over all p_T range
Data points are well described by the model including the broadening of the $\rho$ spectral function.
Comparison to Rapp’s calculation

Model predicts the scaling of dielectron excess with $N_{\text{part}}^{1.45}$.
Differences from 2004 analysis

- **Hadron contamination**
  - was 30%, now 5% in the most central bin
- **Signal sensitivity at LMR**
  - a factor of 3.5 better in the new data
- **Pair cuts**
  - 2004 analysis was using loose pair cuts leaving some residual correlations in the final spectra
- **Flow in mixed BG**
  - It was not included in 2004 analysis
- **e-h pairs**
  - Not subtracted in 2004 analysis
- **Jets**
  - Opposite side jet was not subtracted
- **Background normalization**
  - correlated BG components are normalized by fits
Two extreme scenarios

- $c\bar{c}$ correlation remains the same in Au+Au as in $p+p/p+A$
- $c\bar{c}$ totally decorrelated
  - There is room for QGP radiation
PHENIX has installed VTX detectors
- DCA$_T$ resolution $\sim 75\mu$m @ $\sim 1$ GeV/c
- Useful to discriminate the prompt contributions from open heavy flavor decays

Single electron results in Au+Au collisions were presented at QM2015

J/ψ peak in p+p collisions is clearly seen and presented at QM2015
Summary

- Huge enhancement observed in 2004 data is not confirmed by the new analysis
- The new results are consistent with STAR results
- All the data from SPS 40 AGeV upto RHIC 200 GeV is consistently described by $\rho$ broadening, produced by the scattering of the $\rho$ off the baryons in the medium
- Understanding of open charm contributions is crucial for a precise definition the “excess”
Backup
Cross checks

○ Independent analysis was done to provide a cross-check
○ Key differences are:
  □ Different HBD reconstruction algorithm
  □ eID with 1D cuts
  □ Normalization of background components by simultaneous fit to the like-sign spectra
○ Features
  □ Hadron contamination: 15%
  □ Signal sensitivity @ LMR ~0.5 compared to the main analysis
arxiv:1509.04667