Low-$p_T$ $e^+e^-$ pair production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV at STAR

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Dilepton – penetrating probe of hot, dense medium

- Do not suffer strong interactions
- Bring direct information of the medium created in heavy-ion collisions

- Consistent with an in-medium broadened $\rho$ model calculation \[ \text{[R. Rapp, PRC 63 (2001) 054907]} \]
- Indicate longer medium lifetime in central \text{UU@193GeV and AuAu@200GeV collisions.}

**STAR, PRL 113 (2014) 022301**

**Reduction in dN/dM measured in heavy-ion collisions**

**Theory lifetime:**
- 200 GeV
- 193 GeV
- 62.4 GeV
- 39 GeV
- 27 GeV
- 19.6 GeV
- 17.3 GeV

```
<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Rapp: broadened $\rho$ +QGP</th>
<th>PHSD: broadened $\rho$ +QGP</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 GeV</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>193 GeV</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>62.4 GeV</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>39 GeV</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>27 GeV</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>19.6 GeV</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>17.3 GeV</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
```

**Ratio to Cocktail**

Input: $p_T>0.2$ GeV/c, $|\eta|<1, |y_e|<1$

**STAR preliminary**
Dileptons from photon interactions

PHENIX, PLB 679 (2009) 321

- Large quasi-real photon flux $\propto Z^2$
- Photon interactions
  - Photon-nuclear interaction (vector mesons) $\propto Z^2$
  - Photon-photon interaction (dilepton...) $\propto Z^4$
  - Distinctly peaked at low $p_T$
- Conventionally only studied in ultraperipheral collisions (UPCs)

$E \rightarrow Z_1 e$ $\rightarrow Z_2 e$
$\gamma \rightarrow V(\rho, \omega, \phi, J/\psi)$
$e^- + e^+$
Photon interactions only happens in UPCs? – Anomalous J/ψ enhancement

Significant enhancement at low $p_T$ in peripheral collisions

- Cannot be explained by hadronic production accompanied with the cold and hot medium effects
- Could be qualitatively explained by coherent photonuclear production mechanism [W. M. Zha et al., PRC 97 (2018) 044910]
The STAR detector

- Midrapidity coverage: $|\eta|<1$, $0 < \varphi < 2\pi$

- TPC: Tracking + PID ($dE/dx$)
- TOF: PID ($1/\beta$)

**Diagram:**

- Time Projection Chamber
- Time Of Flight

**Graph:**

- Au + Au $s_{NN} = 200$ GeV

- (a) Neutral pions and kaons
- (b) Electrons and protons

10/02/18  Shuai Yang, Hard Probes 2018
Low-\(p_T\) e\(^+\)e\(^-\) invariant mass spectra in peripheral heavy-ion collisions

\[dN/dM = \begin{cases} \times 10^{-2} & 60-80\% \\ \times 10^{-4} & 40-60\% \\ 10-40\% \end{cases} \]

- Significant enhancement with respect to the cocktail in 60-80% Au+Au and U+U collisions

<table>
<thead>
<tr>
<th>Mass (GeV/c(^2))</th>
<th>Au+Au</th>
<th>U+U</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4 - 0.76</td>
<td>12.4 ± 0.7 ± 2.0 ± 3.7</td>
<td>17.1 ± 1.0 ± 2.4 ± 5.1</td>
</tr>
<tr>
<td>0.76 - 1.2</td>
<td>3.9 ± 0.3 ± 0.6 ± 0.8</td>
<td>4.6 ± 0.4 ± 0.5 ± 0.9</td>
</tr>
<tr>
<td>1.2 - 2.6</td>
<td>12.6 ± 1.2 ± 1.7 ± 1.9</td>
<td>13.8 ± 1.9 ± 1.5 ± 2.1</td>
</tr>
</tbody>
</table>

- Enhancement factor (data/cocktail) decreases from peripheral to central collisions
p_T spectra in 60-80% collisions

- Excess concentrate below p_T ≈ 0.15 GeV/c
- Data are consistent with hadronic expectation when p_T > 0.15 GeV/c
Excess spectra in $p_T < 0.15$ GeV/c

- Can not be explained by an in-medium broadened $\rho$ model
- Compared to hadronic production, observed excess yield exhibits a much weaker centrality dependence
- Need additional source(s)

**Figure:**
- Graphs (a) and (b) show data for different centrality bins and $p_T$ ranges.
- Graph (c) illustrates the integrated cocktail yield in the 0.76-1.2 GeV/c range.

**References:**
- STAR, PRL 121 (2018) 132301
- R. Rapp, PRC 63 (2001) 054907

**Legend:**
- Data - Cocktail
- Au+Au 200 GeV
- $p_T < 0.15$ GeV/c
- U+U 193 GeV
- $p_T > 0.2$ GeV/c, $|y^e_l| < 1$, $|y^\pi_l| < 1$
- Hot_Med (broadened $\rho + $ QGP)
- Centrality: 60-80%
- Centrality: 40-60%
- 70-80% 60-70% 40-60%
- Solid: Au+Au 200 GeV
- Open: U+U 193 GeV
- $\Delta$ 0.4-0.76 GeV/c²
- $\ast$ 0.76-1.2 GeV/c²
- $\diamond$ 1.2-2.6 GeV/c²

**Note:**
- Excess spectra in $p_T < 0.15$ GeV/c.
- Data compared to hadronic production.
- Need additional source(s) for excess yield explanation.
Few tips of photon interaction model calculations

- **Equivalent Photon Approximation (EPA) method**
  - Photon is treated as real
  - Weizsäcker–Williams method to estimate photon flux

- **Model by Zha et al.** [W. M. Zha et al., PLB 781 (2018) 182]
  - Considers the charge distribution in nucleus for photon flux estimation
  - Takes into account dilepton production within the geometrical radius of the nucleus

- **STARlight** [S. R. Klein, PRC 97 (2018) 054903]
  - Ignores dilepton production within the geometrical radius of the nucleus
Compared to photon interaction models

The observed excess can be qualitatively described by photon-photon interaction model calculations

- Zha et al.: $\chi^2$/NDF = 19/15 in 60-80% collisions
- STARlight: $\chi^2$/NDF = 32/15 (underestimate) in 60-80% collisions

Photoproduced vector mesons’ contributions can be negligible

Enhancement in U+U collisions is larger than that in Au+Au collisions, which is in line with STARlight prediction
$p_T^2$ distributions in 60-80% collisions

- Models fail to describe $p_T^2$ distributions

- Employ $\sqrt{\langle p_T^2 \rangle}$ (characterizes $p_T$ broadening) to quantify the discrepancy between data and models

- $\sqrt{\langle p_T^2 \rangle}$ has invariant mass and collision species dependence

- $\sqrt{\langle p_T^2 \rangle}$ from data are $\sim 6.1\sigma$, $3.3\sigma$, and $1.8\sigma$ above models for three mass regions
  - Suggestive of possible other origins of $p_T$ broadening, e.g. magnetic field trapped in QGP
To account for the effect of the time-dependent magnetic field on average, the model assumes that all the $e^+e^-$ pairs traverse 1 fm through a magnetic field of $10^{14}$ T **perpendicular to the beam line**

- The net effect of this approach is close to $\int eB(t)cdt = eB\tau$
- $eB\tau \approx 30$ MeV/c, the extreme pair $p_T$ increase: $2eB\tau \approx 60$ MeV/c
$p_T^2$ distributions in 60-80% collisions

- Calculated $p_T^2$ spectra with EM effects can describe the data much better than the same model without incorporating EM effects.
  - The broaden level is measurable
  - May indicate the existence of strong magnetic field trapped in QGP

- Advantage of this measurement to probe possible residual magnetic field
  - $e^+e^-$ pairs are produced in initial stage and only participate in electromagnetic interaction
  - Pair $p_T$ peaks at 30-40 MeV/c, which is comparable to eBL ($\approx 30$ MeV/c)
  - The $e^+e^- p_T^2$ spectrum measurements in UPCs can serve as a baseline for the low-$p_T$ enhancement study in hadronic heavy-ion collisions.
A plausible explanation for the collision species dependence of $\sqrt{<p_T^2>}$

calculations are based on: S. Chatterjee and P. Tribedy, PRC 92, 011902 (2015)

Initial magnetic fields (t=0) at the center of the participant zone

- Peripheral U+U has larger charge number but more spread-out compared to Au+Au
  - Larger cross section
  - Smaller $\sqrt{<p_T^2>}$

10/02/18 Shuai Yang, Hard Probes 2018
Isobaric collisions in 2018

- $^{96}_{44}\text{Ru}$ vs. $^{96}_{40}\text{Zr}$
  - Charge differs by 10%, everything else is almost the same
  - Huge statistics: 3.1B vs. 1.5B (goal) minimum-bias events
  - Rapidly (daily) switching between Zr and Ru: minimize systematic uncertainty

Based on W. M. Zha et al., PLB 781 (2018) 182

- 60-80% Au+Au vs. 47-75% Ru+Ru
  - Similar hadronic contribution
  - Different yields from two photon interactions

- Statistics
  - 60-80% Au+Au: ~180M
  - 47-75% Ru+Ru (Zr+Zr): ~840M

- Yield ratio in 0.4-0.76 GeV/c$^2$
  - Au : Ru : Zr ≈ 8.11 : 1.46 : 1
  - Difference between Ru+Ru and Zr+Zr: 3.7σ
  - Help to verify and constrain the possible trapped magnetic field
Summary

- A significant $e^+e^-$ enhancement w.r.t. cocktail is observed at very low $p_T$
  - Entirely happens below $p_T \approx 0.15$ GeV/c
  - Can be qualitatively explained by photon-photon interaction mechanism
  - $\sqrt{<p_T^2>}$ from data are larger than that from model calculations -> May indicate the existence of strong magnetic field trapped in QGP
  - The isobaric data could further constrain the photon interactions and the strong magnetic field in hadronic heavy-ion collisions
Backup
Excess spectra are corrected for the STAR acceptance

Different initial conditions by changing energy density (species + $\sqrt{S_{NN}}$)  
Acceptance-corrected excess mass spectra from SPS to top RHIC energies are well described by an in-medium broadened $\rho$ model calculation
Anomalous low-$p_T$ $J/\psi$ enhancement in hadronic heavy-ion collisions

Qualitatively described by photon-nuclear interactions in peripheral collisions
- N+N scenario overestimates while S+S scenario underestimates data in semi-central collisions.
- Different scenarios predict different centrality dependence → measurements in central collisions are important
- N+S and S+N scenarios have weak centrality dependence in peripheral and semi-central collisions
Excess yield ratios of U+U over Au+Au

Table 1. The ratios of observed excess yields in U+U collisions over those in Au+Au collisions for three different mass regions in three different centrality bins. The error listed in this table includes statistical error only.

<table>
<thead>
<tr>
<th>Mass Region (GeV/c^2)</th>
<th>70-80%</th>
<th>60-70%</th>
<th>40-60%</th>
</tr>
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<tbody>
<tr>
<td>0.4-0.76</td>
<td>1.42 ± 0.13</td>
<td>1.54 ± 0.23</td>
<td>1.24 ± 0.35</td>
</tr>
<tr>
<td>0.76-1.2</td>
<td>1.02 ± 0.18</td>
<td>1.49 ± 0.35</td>
<td>2.12 ± 0.96</td>
</tr>
<tr>
<td>1.2-2.6</td>
<td>0.92 ± 0.20</td>
<td>1.43 ± 0.39</td>
<td>0.97 ± 0.61</td>
</tr>
</tbody>
</table>

- STARlight predicts that the excess yields from photon-photon interactions in U+U collisions are ~40% larger than those in Au+Au collisions
Spatial distribution of photon collisions

Example of $e^+e^-$ pair spatial distribution, 50-60% Au+Au collisions

Conductivities of the medium
$b=8$fm, $\tau=0.4$fm, $\sigma=5.8$MeV, $\sigma_{\chi}=1.5$MeV

G. Inghirami et al., arXiv: 1609.03042,
Chirality workshop

Z. Xu, BNL seminar (8/28/2018)
Strength of the magnetic field

G. Inghirami et al., EPJC 76, 659 (2016)

M. Asakawa et al., PRC 81 (2010) 064912