Low-$p_T$ $e^+e^-$ pair production in Au+Au collisions and exclusive $J/\psi$ production in d+Au collisions at STAR

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The hadronic cocktail can describe the data for $p_T > 0.15\text{GeV/c}$ in all three mass regions.

The observed excess is found to concentrate below $p_T \approx 0.15\text{GeV/c}$.

Equivalent Photon Approximation (EPA):
In a specific phase space, EM fields can be quantized as a flux of quasi-real photons.
\[ \gamma \gamma \rightarrow e^+ e^- : \text{Ultra-Peripheral vs. Peripheral} \]

- Leading order QED calculation of \( \gamma \gamma \rightarrow e^+ e^- \) describes both spectra (\( \pm 1\sigma \))
- STAR observes 4.8\( \sigma \) difference between UPC and 60-80% Au+Au collisions
- Proposed as a probe of trapped magnetic field or Coulomb scattering in QGP
- Di-electron measurement at the centrality of 80-100% can serve as a bridge between HIC and UPC \( \gamma \gamma \rightarrow e^+ e^- \) process

<table>
<thead>
<tr>
<th>( \sqrt{\langle p_T^2 \rangle} ) (MeV/c)</th>
<th>UPC Au+Au</th>
<th>60-80% Au+Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>38.1 ± 0.9</td>
<td>50.9 ± 2.5</td>
</tr>
<tr>
<td>QED</td>
<td>37.6</td>
<td>48.5</td>
</tr>
</tbody>
</table>

STAR, ArXiv: 1910.12400
The Solenoid Tracker At RHIC (STAR)

- Excellent electron identification capability with the information from TPC and TOF
- High electron purity (95% in $n\sigma_e$ non-overlapping area) sample with STAR PID
Mass Distribution in Low-$p_T$

- First di-electron measurement at the centrality of 80-100% at STAR
- Significant enhanced di-electron yield compared to hadronic cocktail
- No vector meson is observed → forbidden for real photons with helicity ± 1
- Observed excess is concentrated below 0.2 GeV/c in 80-100% compared to the cocktail.
- Similar $p_T$ distribution of $e^+e^-$ pairs to those of Au+Au at $\sqrt{s_{NN}} = 200$ GeV/c 60-80% centrality.
  - Indication of $\gamma\gamma \rightarrow e^+e^-$ production.
**cos(4Δφ) Modulations**

- Lorentz contraction of EM fields →
  Quasi-real photons should be **linearly** polarized ($\vec{E} \perp \vec{B} \perp \vec{k}$)

- Recently realized, there are $\cos(4\Delta\phi)$ modulations in polarized $\gamma\gamma \rightarrow e^+e^-$ [1]

  ![Data - Cocktail](Image)

  **Table:**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>$\chi^2/ndf$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>62.5 ± 5.3</td>
<td>8.9/8</td>
</tr>
<tr>
<td>$-A_{4\Delta\phi}$ (%)</td>
<td>20.8 ± 11.8</td>
<td></td>
</tr>
</tbody>
</table>


- Indication of $\cos(4\Delta\phi)$ modulations in linearly polarized $\gamma\gamma \rightarrow e^+e^-$ process with a significance of $2\sigma$
  (systematics needs to be studied)

  ✓ More statistics is needed to confirm the trend
Photoproduction of $J/\psi$

- Cross section of $J/\psi$ meson in photoproduction, with a **hard scale** imposed by its mass, is sensitive to the gluon density at the LO

$$\frac{d\sigma}{dt}(\gamma^* p \rightarrow \psi p) = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \frac{\alpha_s(Q^2)^2}{Q^8} \left[x g(x, Q^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right)$$

- It's a powerful probe to study the gluon density and its distributions inside nucleons and nucleus, physics applications:

  ✓ Gluon spatial distributions
  ✓ Gluon shadowing effects
  ✓ ...
Photoproduction of $J/\psi$

- $J/\psi \rightarrow e^+ e^-$ pair are reconstructed using TPC for $|\gamma| < 1.0$
- Zero Degree Calorimeter (ZDC) was used to detect neutrons from deuteron breakup, providing additional info about the physics process

- $Au + d \rightarrow J/\psi + Au' + X$
  - $X = d'$ (coherent) or $X = d'$, $d' \rightarrow p' + n'$ (coherent + Coulomb)
  - $X = p' + n'$ (elastic nucleon)
  - $X = p' + X$ or $n' + X$ (nucleon dissoc.)
Photoproduction of $J/\psi$

- Clear signal, roughly 300 $J/\psi$ are reconstructed
- The UPC trigger used in analysis is unbiased with respect to the ZDC
- Au-going side has no neutron, stay intact!
Photoproduction of $J/\psi$

- Total data – no selections on final-state of the deuteron breakups
- $n$-tagged data = total data $\oplus$ requirement of neutron at d-going ZDC
- The data is at $x_p \sim 0.01$ at STAR
  - $x_p$ : longitudinal momentum fraction of the proton carried by the color-neutral “pomeron”

The data, despite large uncertainty,
- Coherent: Hulthen and AV18 describes the data equally well. Expected to be dominant at low t
- Incoherent: Qs/Shape fluctuation is found to describe the data better.

ZDC n-tagged data: incoherent only at small t
Separate coherent and incoherent process is extremely interesting but challenging, will be significantly improved at the EIC
Summary

- First di-electron measurement at the centrality of 80-100% at $\sqrt{s_{NN}} = 54.4$ GeV at STAR
  ✓ Indication of $\gamma\gamma \rightarrow e^+e^-$ process

- Indication of $\cos(4\Delta\phi)$ modulations in linearly polarized $\gamma\gamma \rightarrow e^+e^-$ process, but more precise measurement is needed to improve the significance

- First measurement of $J/\psi$ meson in photoproduction off deuteron in UPC
  ✓ Data is well described by theoretical calculations using Hulthen/AV18 wave function for the coherent contribution along with incoherent contributions calculated using Qs/shape fluctuations

- Data with ZDC neutron tagging indicates incoherent contribution at low $t$
Summary

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Thanks for Your Attention
Backup
Au+Au $\sqrt{s_{NN}} = 54.4$ GeV

Centrality: 80-100%

$0 < p_T < 0.15$ GeV/c

STAR PRELIMINARY
Mass Distribution in Low-$p_T$

- A smooth $e^+e^-$ invariant mass distribution
- $\gamma\gamma \rightarrow e^+e^-$: no vector meson production forbidden for real photons with helicity $\pm 1$ (i.e. 0 is forbidden)
Photoproduction of $J/\psi$

- Total data – no selections on final-state of the deuteron breakups, only $J/\psi$ at mid-rapidity with no other activity
- $n$-tagged data = total data + requirement of neutron at d-going ZDC
- Total fit has three components:
  - Coherent contribution, assuming an exponential function
  - Elastic nucleon (H1 proton data as shape)
  - Nucleon dissociative (H1 proton data as shape)


Only statistical uncertainty is shown, green band is 1σ fit err
What to look forward?

1. More statistics in this case \textit{absolutely helps} (a lot), esp at low $t$.

2. Higher energy $\|\$ lower $x$ $\|$ forward rapidity $\rightarrow$ sensitive to gluonic structure!
• The left plot is, in every momentum bin, the pure hadron samples (π/K/p) mean $n\sigma_e$ distribution. We can found, for the electron mean $n\sigma_e$, it have overlap region with other hadron samples. For example, red circle is the electron and kaon $n\sigma_e$ overlap range.

◆ In $n\sigma_e$ overlap range, it is hard to identify electron. So in this range, the electron purity is lower than non-overlap range.