Photoproduction in Ultra Peripheral Relativistic Heavy Ion Collisions with STAR

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Ultra Peripheral Collisions – nuclei miss each other and interact via long range fields

Strong electromagnetic fields from heavy ions
- Weizsacker-Williams: a field of almost-real photons
  - Virtuality $Q^2 < (h/R_A)^2$

Photon $E_{\text{max}} \sim \gamma h/R_A$
- 3 GeV with gold at RHIC
- 80 GeV with Lead at the LHC

Photon flux $\sim Z^2$
- Higher intensity with heavy ions, higher probability of multi-photon interactions

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Photonuclear and $\gamma\gamma$ Interactions

- **Photonuclear interactions**
  - $\gamma$-Pomeran/meson can be coherent
  - Coupling: $A^{4/3}$ (surface) to $A^2$ (volume)

- **$\gamma\gamma$ interactions**
  - QED process – proposed as luminosity monitor
  - Strong coupling and multiple interactions
    - $Z^2\alpha \sim 0.6$ with gold/lead
    - Multi photon reactions
    - Mutual Coulomb excitation - event tag
    - Factorize as function of impact parameter

- Required $b > 2R_A$
  - No hadronic interactions
  - $<b> \sim 20$-60 fm at RHIC

$$\sigma = \int d^2b P_{2GDR}(b)P_{\rho^0}(b)$$
Photoproduction Physics

- Gluon structure function
  - $\gamma A \rightarrow J/\Psi$, cc(bar), dijets, etc
    - $\sigma_{J/\Psi} \sim g^2(x)$
    - $\sigma_{QQ, dijets} \sim g(x)$

- Meson spectroscopy
  - $\rho, \omega, \phi$, excited states, etc

- Fundamental tests of Quantum Mechanics
  - Interference between non overlapping particles

- Diffractive phenomenon
  - Elastic and inelastic processes, spin dependence

- New physics
  - Glueballs, odderon, etc
STAR Detector

Central Trigger Barrel (CTB)

Time-Projection Chamber (TPC)

Zero-Degree Calorimeters (ZDC)

Magnetic Field: 0.5 T
Signatures & Triggering

**Signatures:**
- Coherent production dominates
- $p_T \leq 2h/RA \approx 60 \text{ MeV/c}$
- Low multiplicity events with vertex
- Events with nuclear breakup accompanied by forward neutrons

**Triggers:**
- “Minimum bias”
  - Low multiplicity
  - Neutrons in both ZDCs
- “Topography”
  - Low multiplicity events
  - Coincidence of North and South
  - Top and Bottom veto cosmics
Coherently produced events

- Exclusive $\rho^0$ accompanied by mutual Coulomb excitation
- $p_T < 150$ MeV/c
- Acceptance corrected

Fit function:

- Relativistic Breit-Wigner for $\rho^0$ signal
- Mass independent direct $\pi^+\pi^-$ production amplitude
- Söding term for the interference of the two:

$$\frac{d\sigma}{dM_{\pi\pi}} = \left| A \frac{\sqrt{M_{\pi\pi} M_{\rho}} \Gamma_{\rho}}{M_{\pi\pi}^2 - M_{\rho}^2 + i M_{\rho} \Gamma_{\rho}} + B \right|^2.$$
Goncalves & Machado (EPJ C29, 2003)
- QCD color dipole approach
- Nuclear effects and parton saturation phenomena

Frankfurt, Strikman & Zhalov (PRC67 034901, 2003)
- Generalized vector dominance (VDM)
- QCD – Gribov-Glauber approach

Klein & Nystrand (PR C60 014903, 1999)
- VDM
- Classical mechanical approach for scattering

Coherent and Incoherent Production of $\rho$

- Access to the coherent and incoherent form factor
  - Double exponential fit function
- Incoherent production – nucleon form factor
  - $b_N = 8.8 \pm 1.0 \text{ GeV}^{-2}$
- Coherent production
  - $b_{Au} = 388.4 \pm 24.8 \text{ GeV}^{-2}$
  - Data sensitive to hadronic radius of gold
    - $b_{Au} \sim R_A^2$
- $\sigma(\text{incoh})/\sigma(\text{coh}) \sim 0.29 \pm 0.03$

$$\frac{d\sigma}{dt} = a \exp(-b_{Au} \cdot t) + c \exp(-b_N \cdot t)$$

Non resonant pion production

Ratio of non-resonant to resonant pion production

\[
\frac{d\sigma}{dM_{\pi\pi}} = \left| A \frac{\sqrt{M_{\pi\pi}M_{\rho}\Gamma_\rho}}{M_{\pi\pi}^2 - M_{\rho}^2 + iM_{\rho}\Gamma_\rho} + B \right|^2.
\]

|B/A| - ratio of non-resonant to resonant \(\pi^+\pi^-\) production

- 200 GeV: |B/A| = 0.84 ± 0.11 GeV\(^{-1/2}\)
- 130 GeV: |B/A| = 0.81 ± 0.28 GeV\(^{-1/2}\)
- No angular dependence or rapidity dependence
- In agreement with previous HERA experiments
  - EPJ C2 247 (1998)

S-channel Helicity

- **S-channel helicity conservation**
  - Produced vector meson retains helicity of the initial photon

\[
\frac{1}{\sigma} \frac{d\sigma}{d\cos(\Theta_h) d\Phi_h} = \frac{3}{4\pi} \left[ \frac{1}{2} (1 - r_{00}^{04}) + \frac{1}{2} (3r_{00}^{04} - 1) \cos^2(\Theta_h) \right] \\
- \sqrt{2}\text{Re}[r_{10}^{04}] \sin(2\Theta_h) \cos(\Phi_h) - r_{1-1}^{04} \sin^2(\Theta_h) \cos(2\Phi_h)
\]

- \(\Theta\) is angle between polar angle between the beam direction and the direction of the \(\pi^+\)
- \(\Phi\) is angle between \(\rho\) decay and production plane

- Spin density elements close to zero – s-channel helicity conservation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>STAR</th>
<th>ZEUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r_{00}^{04})</td>
<td>(-0.03 \pm 0.03_{\text{stat.}} \pm 0.06_{\text{syst.}})</td>
<td>(0.01 \pm 0.01_{\text{stat.}} \pm 0.02_{\text{syst.}})</td>
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<td>(\text{Re}[r_{10}^{04}])</td>
<td></td>
<td>(0.01 \pm 0.01_{\text{stat.}} \pm 0.01_{\text{syst.}})</td>
</tr>
<tr>
<td>(r_{1-1}^{04})</td>
<td>(-0.01 \pm 0.03_{\text{stat.}} \pm 0.05_{\text{syst.}})</td>
<td>(-0.01 \pm 0.01_{\text{stat.}} \pm 0.01_{\text{syst.}})</td>
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</table>

- The fit function describes different states: non-flip, single and double flip and their combination

- Not able to measure interference between non flip and single flip due to production plane ambiguity

Several data sets:
- AuAu $\sqrt{s}=62$ GeV  In progress
- AuAu $\sqrt{s}=130$ GeV  PRL89 272302 (2002)
- AuAu $\sqrt{s}=200$ GeV  PRC77 34910 (2008)
- dAu $\sqrt{s}=200$ GeV  In progress

Production cross section with mutual Coulomb excitation as a function of ion gamma
Solid line – simulation based on Klein & Nystranand
Asymmetric collision

- The photon is almost always emitted by the gold nucleus, avoiding the two-fold ambiguity.

Two fit functions

- Single exponential
- Fit function based on the Glauber prediction from Eisenberg et al, NP B104, 61 1976

Downturn at low $t$, not enough energy for the $d$ dissociation

- Similar behavior observed by SLAC experiment at 4.3 GeV Eisenberg et al, NP B104, 61 1976

Red – incoherent production
Blue – coherent production
Impossible to distinguish source of $\gamma$ and target

- Interference
- Entangled final state $\pi\pi$ wave function

$\rho, \omega, \phi, J/\psi$ are $J^{PC} = 1^- -$

- $\sigma \sim |A_{1(b,y)} - A_{2(b,-y)}e^{ipcdotb}|^2$ where $b$ is impact parameter
- Suppression at low $p_T < h/<b>$

Different triggers provide access to different median impact parameter

- Topology data: median $b \approx 46$ fm
- Minimum bias: median $b \approx 18$ fm (extends interference effects to larger $p_T$)

Photon energy dependence of the $\rho$ production amplitudes leads to the decrease of the interference at large rapidities
Measured level of interference at 87 ±5 (stat.) ±8 (syst.)% from the expected level (arXiv:0812.1063)
Photoproduction of $\pi^+\pi^-\pi^+\pi^-$

- Expected to be largely through a radially excited $\rho$
  - Could be $\rho(1450)$ and/or $\rho(1700)$
- Peaks at low $p_T$ due to the coherent production
- Mass spectra similar to $\gamma p$ collisions
- Studies of the substructure showed low mass pion pairs accompanied by $\rho(770)$
Compared with two models

- EPA (equivalent photon approach)
  - Treats $\gamma$ as real photon
- QED – lowest order QED calculation based on GDR only with correction for higher states Hencken PR C69 054902 (2004)

New calculation by Baltz PRL 100, 062302 (2007)
- Realistic phenomenological treatment of nuclear breakup
**J/ψ Production at RHIC**

**Trigger**
- $e^+e^-$ pair + 1 nucleus breakup

**Signal:** 12 events

**Cross section at expected level, big errors**

**PHENIX, nucl-ex/0601001**

**J. Pinfold, Wkshp. on HE Photon Collisions at the LHC**

334 exclusive $\mu^+\mu^-$ events

Paper draft in collaboration
J/ψ sensitive to gluon distribution in the nucleus

- \( \sigma \sim g(x,Q^2)^2 \)
  - \( X \sim \text{few } 10^{-4} \) for J/ψ at LHC
  - \( X \sim \text{few } 10^{-2} \) for J/ψ at RHIC

Clear shadowing effect

- Several factor difference in cross section at LHC

Black \( \rightarrow \) Impulse Approx.

Red \( \rightarrow \) gluon diffractive density

Blue \( \rightarrow \) H1 Gluon density

Why UPC is interesting at LHC

- Maximum mass given by the coherence production conditions:
  \[ M_{\text{max}} = \gamma \frac{\hbar}{R_{\text{nucleus}}} \]
- Mass of accessible final states increase from 2-3 GeV to 100 GeV

<table>
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<tr>
<th>Final State</th>
<th>Acceptance</th>
<th>Rate/10^6 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho^0 \rightarrow \pi^+\pi^- )</td>
<td>central barrel</td>
<td>2 \times 10^8</td>
</tr>
<tr>
<td>( J/\psi \rightarrow e^+e^- )</td>
<td>central barrel</td>
<td>1.50 \times 10^5</td>
</tr>
<tr>
<td>( \Upsilon(1S) \rightarrow e^+e^- )</td>
<td>central barrel</td>
<td>400 – 1400</td>
</tr>
<tr>
<td>( e^+e^-, M &gt; 1.5 \text{ GeV/c}^2 )</td>
<td>central barrel, ( p_T &gt; 0.15 \text{ GeV/c} )</td>
<td>7 \times 10^5</td>
</tr>
<tr>
<td>( e^+e^-, M &gt; 1.5 \text{ GeV/c}^2 )</td>
<td>central barrel, ( p_T &gt; 3 \text{ GeV/c} )</td>
<td>1.4 \times 10^4</td>
</tr>
<tr>
<td>( \mu^+\mu^-, M &gt; 1.5 \text{ GeV/c}^2 )</td>
<td>muon spectrometer, ( p_T &gt; 1 \text{ GeV/c} )</td>
<td>6 \times 10^4</td>
</tr>
</tbody>
</table>

Yields in PbPb UPC collisions in ALICE acceptance
Alice collaboration JP G 32 1295
Program at LHC

- CMS, ALICE, ATLAS, FP420, TOTEM & other forward detectors planned programs
- “Yellow Book” gives physics case
- Gluon structure Functions at low-x
  - Nuclear gluon distributions can be measured by studying photo-production of heavy quarks
    - \( \sigma_{J/\psi} \sim g^2(x) \)
    - \( \sigma_{QQ, dijets} \sim g(x) \)
- The ‘black disc’ regime of QCD
- Search for exotica/new physics
  - \( \gamma\gamma \rightarrow \) Higgs, Magnetic monopoles, etc.
- Diffractive phenomenon
  - Roman pots useful for pp
Plans at LHC

- **J/ψ, ψ’, Y in lepton channel**
  - CMS, ATLAS, Alice
    - $\gamma + A \rightarrow J/\Psi + A$
      - *expected prod rate ~ $1 \times 10^7$/ year
    - $\gamma + A \rightarrow Y + A$
      - *expected prod rate ~ $1 \times 10^5$/ year

- **Photonuclear production of heavy quarks**
  - $\gamma + g \rightarrow cc$

- **Di-jets**
  - ATLAS
    - Photonuclear jet production; photon+parton $\rightarrow$ jet+jet; e.g. $\gamma + g \rightarrow q + q$

- **Triggering is challenging**
  - ZDC signal may help reduce background; not always available at Level 0
Hadron collider is unique tool to study photoproduction reaction

- At RHIC STAR & Phenix have studied several topics
  - Published new measurement of $\rho^0$ production cross section at $\sqrt{s}=200$ GeV
    - Good agreement with theoretical predictions
  - Paper about interference effect has been submitted to the PRL and is likely being published

- Ongoing analysis
  - dAu at 200 GeV and AuAu at 62 GeV data sets are currently analyzed
  - Resonant production of $\pi\pi\pi\pi$ at $\sqrt{s}=200$ GeV
    - At very advanced stage, manuscript is being prepared
Several new detector are being commissioned right now
- Central Trigger Barrel is being replaced by the TOF system
  - Improved triggering performance
- New data acquisition system
  - Readout at 1kHz with low dead time

- Roman pots system has been installed
  - Dedicated three day run this year
    - Phase I – elastic scattering and particle production in Double Pomeron Exchange (DPE)
    - Phase II - increased data set for elastic scattering and particle production in DPE

RHIC is a good place to study diffractive and electromagnetic processes in heavy ion collisions
Physics Outlook

- New DAQ 1000 system should increase available statistic by factor 10
  - Studies of J/Ψ, etc
    - Gluon shadowing
  - Substructure in 4 pion state
  - Meson spectroscopy: ρ*, ρ⁰, ψ, ω, φ, etc
- Roman pots system
  - Elastic and inelastic diffractive processes and spin dependence
  - Exotic