Ultra-peripheral Collisions at STAR
Janet Seger (for the STAR Collaboration)
Creighton University
Ultra-peripheral Collisions

- Large impact parameter \((b > R_1 + R_2) \rightarrow\) no nuclear overlap \(\rightarrow\) no “collision” \(\rightarrow\) electromagnetic interactions dominate

- Relativistic heavy ions are intense source of quasi-real photons
  - \(Q \sim 1/R \sim 0.06\) GeV (Au) or 0.28 GeV (p)
  - Photon flux \(~ Z^2\) from each nucleus
  - Experimentally: very low multiplicity events with small momentum transfer, rapidity gaps

- Photoproduction in \(\gamma p\) and \(\gamma A\) interactions
- QED processes in \(\gamma\gamma\) interactions

\[b > R_1 + R_2\]
Photoproduction of vector mesons

- Has been extensively studied at HERA, RHIC, LHC
- Factorize into
  - photon emission
  - interactions with nuclear target
- Allows one to probe the nucleus via QCD to learn about shadowing, saturation effects, nPDFs
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• Coherent interaction: Photon interacts with entire nucleus
  • Nucleus generally remains intact
  • Small momentum transfer: $p_T \sim \hbar/R_A \sim 15$ MeV
  • Max photon energy $\sim \gamma \hbar/R_A \sim 3$ GeV at RHIC
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• Incoherent interaction: Photon can interact with individual nucleons
  • Nucleus generally breaks
  • Momentum transfer is bigger: \( p_T \sim \hbar/R_A \sim 100 \text{ MeV} \)
  • Max photon energy \( \sim \gamma \hbar/R_A \sim 20 \text{ GeV} \) at RHIC

Heavy Vector Mesons: $J/\psi$

\[
\frac{d\sigma}{dt}^{\gamma^* A \rightarrow J/\psi A} \propto (x G_A(x, Q^2))^2
\]

- 2-gluon exchange at the lowest order
- Probe of gluon distribution function
- For vector mesons:

\[
x \sim \frac{m_{J/\psi} e^{-y}}{\sqrt{s}} \quad Q^2 = \frac{M_{J/\psi}^2}{4}
\]

- Measurements at different rapidities sample different values of $x$
The STAR detector

• Central tracking and particle identification, forward counters and neutron detection
• Time Projection Chamber: tracking and identification in $|\eta| < 1$
• Time-Of-Flight: multiplicity trigger, identification and pile-up track removal
• Barrel ElectroMagnetic Calorimeter: topology trigger and pile-up track removal
• Beam-Beam Counters: scintillator counters in $2.1 < |\eta| < 5.2$, forward veto
• Zero Degree Calorimeters: detection of very forward neutrons, $|\eta| > 6.6$
UPC trigger at STAR

Trigger requires:

• Back-to-back hits in BEMC
• Limited activity in TOF
• Veto from both BBCs
• Signal in both ZDCs (xnxn)
  • Energy deposition within 1/4 to 4 beam-energy neutrons
  • Full efficiency for single neutrons
J/ψ candidates observed in e⁺e⁻ decay channel

200 GeV Au+Au data from 2014 run at STAR

Selection criteria:
• Vertex with exactly two tracks of opposite sign
• |y| < 1
• $p_T < 0.17$ GeV/c

Like-sign background is minimal
Non-negligible background from e⁺e⁻ continuum is parametrized with empirical formula

$$f_{\gamma\gamma \rightarrow e^+e^-} = (m - c_1)e^{\lambda(m-c_1)^2} + c_2m^3$$

• Effective convolution of $\gamma\gamma \rightarrow e^+e^-$ cross section and detector effects
Transverse momentum of J/ψ candidates

• Select candidates within J/ψ mass peak
• Distribution is mostly well reproduced by the template from STARLIGHT for different contributions
  • $e^+e^-$ normalized using mass fit
  • Discrepancy in region $0.2 \text{ GeV/c} < p_T < 0.4 \text{ GeV/c}$
Separate incoherent from coherent

• Plot as a function of $\log_{10}(p_T^2)$

• Parametrize the incoherent contribution at high $p_T$ (well above coherent peak)

$$f_{incoherent} = A \cdot e^{-bp_T^2}$$

• Extrapolate to lower $p_T$ and subtract to get coherent sample
Diffractive dip seen in coherent $d^2\sigma/dtdy$

- After background subtraction
- $t \approx -p_T^2$

Model comparisons:
- **STARLIGHT**: Klein, Nystrand, CPC 212 (2017) 258-268
  - Vector meson dominance
  - Glauber approach
  - Includes photon $p_T$
  - Dipole approach with IPsat amplitude
  - Scaled to XnXn using STARLIGHT
  - Hot spot model for nucleons, dipole approach
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Slope below first diffractive minimum is consistent with the Glauber approach in **STARLIGHT**
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Diffractive dip around $|t| \approx 0.02$ GeV$^2$ is correctly predicted by the dipole **MS** and **CCK** models.
Coherent $\rho$ photoproduction

- High statistics 200 GeV Au+Au dataset
- Like-sign background has been subtracted
- Incoherent fit to dipole form factor at high $t$, extrapolated to lower $t$ and subtracted to reveal coherent signal
- Diffractive dips evident
- Fourier-Bessel transform of $d\sigma/dt$ gives nuclear density profile

\[ Au + Au \rightarrow \rho + Au + Au + XnXn, \quad \sqrt{s_{NN}}=200 \text{ GeV} \]

\[ F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_Tp_TJ_0(bp_T)\sqrt{\frac{d\sigma}{dt}} \]

Shadowing changes effective shape of nucleus

- Photon fluctuates to $q\bar{q}$ dipole, scatters off nucleus to emerge as $\rho$
- Smaller mass $\rightarrow$ larger dipole $\rightarrow$ interacts on the front of the nucleus
  - “black disk”
- Higher mass $\rightarrow$ smaller dipole $\rightarrow$ penetrates further, sees internal nucleons
  - Woods-Saxon distribution

\[
\sigma_c = \int d^3 \vec{k} |\Sigma_i A_i \exp(ik \cdot \vec{x}_i)|^2
\]

- Do we see a difference in shape for different dipole size (mass)?
Data selection and mass binning

- Exactly 2 tracks from a common vertex
- $|Z_{vtx}| < 50$ cm
- $|y_{\pi\pi}| > 0.04$ (removes cosmic rays)
- Each track has $> 25$ space points
- $0.62 \text{ GeV/c}^2 < M_{\pi\pi} < 0.95 \text{ GeV/c}^2$
- Divide into three mass bins of ~ equal statistic

$Au + Au \rightarrow \rho + Au + Au + XnXn$, $\sqrt{s_{NN}}=200$ GeV

PoS(DIS2018)047
Subtract like-sign and incoherent backgrounds

Red: like-sign background
Blue: opposite sign pairs
Subtract like-sign and incoherent backgrounds

Red: like-sign background
Blue: opposite sign pairs

After subtraction of like-sign background
Fit with dipole form factor

\[ \frac{dN}{dt} = \frac{A/Q_0^2}{(1+t/Q_0^2)^2} \]

PoS(DIS2018)047
$d\sigma/dt$ for Coherent $\rho$ mesons

- After subtraction of incoherent contribution
- Normalized to same number of events/$M_{\pi\pi}$ bin
- Depth of diffractive dip varies with mass

$Au + Au \rightarrow \rho + Au + Au + XnXn$, $\sqrt{s_{NN}}=200$ GeV

*STAR Preliminary*

Low Mass
Medium Mass
High Mass
Transform to $F(b)$

$$F(b) \propto \frac{1}{2\pi} \int_0^{\sqrt{t_{\text{max}}}} d\sqrt{t_{\text{max}}} p_T p_T J_0(b p_T) \sqrt{\frac{d\sigma_c}{dt}}$$

- Use $t_{\text{max}} = 0.006$ GeV$^2$ for baseline
  - Below first dip
  - Vary as systematic

- Effects of shadowing would be to broaden the distribution
  - In the black disk limit, $F(b)$ would be constant
  - Expect lower-mass to be broader, flatter
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$Au + Au \rightarrow \rho + Au + Au + XnXn, \sqrt{s_{NN}}=200 \text{ GeV}$

Preliminary
Windowing effect from choosing $t_{\text{max}}$

$$F(b) \propto \frac{1}{2\pi} \int_0^{t_{\text{max}}} dp_T p_T J_0(b p_T) \sqrt{\frac{d\sigma_c}{dt}}$$

- Choice of $t_{\text{max}}$ affects the shape, particularly at $b = 0$ fm
- Does not change the general trend that lower-mass $\rightarrow$ wider distribution
STARLIGHT, for comparison

- No shadowing effects included

STARLIGHT variation with $M_{\pi\pi}$

Low mass
Medium mass
High mass

STARLIGHT

$F(b)$

1.1*Low Mass
1.05*Medium Mass
High Mass

$p_T^2$ (GeV$^2$)

b (fm)
Conclusions

• STAR has a high statistics sample of coherently produced \( \rho \) mesons
  • Allows clear observation of diffractive dips
  • Shape of \( d\sigma/dt \) sensitive to distribution of interaction sites
  • \( M_{\pi\pi} \) serves as a proxy for dipole size
  • Pilot study shows shape difference with mass (dipole size)
    • Systematic effects due to choice of \( t_{\text{max}} \)

• Diffractive structure also seen in lower-statistics sample of coherently produced \( J/\psi \)
  • Location of diffractive dip in \( d\sigma/dt \) consistent with dipole models
  • Slope of \( d\sigma/dt \) at low \( t \) reproduced by Glauber model