Excess of $J/\psi$ yield at very low $p_T$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV with STAR

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J/ψ production modification in hadronic A+A collisions

- Hot medium effects:
  - Color Screening
    - “Smoking gun” signature for QGP
  - Regeneration
    - Recombination of charm quarks

- Cold Nuclear Matter effects:
  - PDF modification in nucleus
  - Initial-state energy loss
  - Cronin effect
  - ……..

The interplay of these effects can explain the results from SPS to LHC!
Introduction to photon interactions in A+A

- Studied in detail for Ultra-Peripheral Collisions (UPC)
  - UPC conditions: $b > 2R_A$, no hadronic interactions

- This large flux of quasi-real photons makes a hadron collider also a photon collider!

- Photon-nucleus interactions:
  - Coherent: emitted photon interacts with the entire target nucleus.
  - Incoherent: emitted photon interacts with nucleon or parton individually.
Features of coherent photon-nucleus interaction

- **Coherently:**
  - ✓ Both nuclei remain intact
  - ✓ Photon/Pomeron wavelength \( \frac{h}{p} > R_A \)
  - ✓ \( p_T < \frac{h}{R_A} \) \( \sim \) 30 MeV/c for heavy ions
  - ✓ Strong couplings \( (Z\alpha_{EM} \sim 0.6) \) \( \rightarrow \) large cross sections

- **Interference:**
  - ✓ Two indistinguishable processes (photon from \( A_1 \) or \( A_2 \))
  - ✓ Vector meson \( \rightarrow \) opposite signs in amplitude
  - ✓ Significant destructive interference for \( p_T << 1/b \)

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Excess of J/ψ production at very low p_T with ALICE

- Significant enhancement of J/ψ yield observed in p_T interval 0 – 0.3 GeV/c for peripheral collisions (50 – 90%).
- Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!
- Origin from coherent photon-nucleus interactions?

Measurement of J/ψ yield at very low p_T in hadronic collisions (U+U and Au+Au):
- Enhancement of J/ψ yield at very low p_T?
- If so, what are the properties and origin of the excess?
  - p_T, centrality and system size dependence of the excess; t distribution.
STAR detector

- **Large acceptance:**
  \[ |\eta| < 1, \ 0 < \phi < 2\pi \]

- **Time Projection Chamber (TPC)** – tracking, particle identification, momentum

- **Time of Flight detector (TOF)** – particle identification

- **Barrel ElectroMagnetic Calorimeter (BEMC)** – electron identification, triggering
Electron Identification

$1/\beta$ distribution for electrons and hadrons from TOF

Normalized $dE/dx (n\sigma_e)$ distribution before and after TOF cuts

$p/E$ distribution for electrons and hadrons from BEMC

J/ψ signal

Centrality: 40 – 80%

The signal is extracted by subtracting the mixed event background from the unlike-sign pairs.

Good signal over background ratio!

STAR Preliminary

Signal: 102
Background: 11
S/B: 8.9
Significance: 9.6σ
J/ψ invariant yield in Au+Au and U+U Collisions

- Significant enhancement of J/ψ yield observed at $p_T$ interval 0 – 0.2 GeV/c for peripheral collisions (40 – 80 %).
- The yield of J/ψ at very low $p_T$ in Au+Au is similar to that in U+U within uncertainties.

Function to describe hadronic production:

$$\frac{d^2N}{p_T dp_T} = a \times \frac{1}{(1 + b^2 p_T^2)^n}$$
J/ψ yield at very low $p_T$ versus centrality

- Low $p_T$ J/ψ from hadronic production is expected to increase dramatically with $N_{\text{part}}$.
- No significant centrality dependence of the excess yield!
- No significant difference between Au+Au and U+U collisions.
J/ψ dN/dt distribution for Au+Au 40-80%

Similar structure to that in UPC case!
Indication of interference!

- Interference shape from calculation for UPC case
  - PRL 84 2330 (2000)

- Similar slope parameter!
  - Slope from STARLIGHT prediction in UPC case
    - $-196 \text{ (GeV/c)}^{-2}$
  - Slope w/o the first point: $199 \pm 31 \text{(GeV/c)}^{-2}$
    - $\chi^2/NDF = 1.7/2$
  - Slope w/ the first point: $164 \pm 24 \text{(GeV/c)}^{-2}$
    - $\chi^2/NDF = 5.9/3$

ρ₀ cross-section as a function of the momentum transfer squared ($t \approx p_T^2$) from STAR UPC measurements.

- The slope from the exponential fit reflects the size and shape of target.
The scaled rapidity and $p_T$ distributions follow a universal trend.

$pp$ baseline at very low $p_T$ is interpolated from the world-wide experimental data.

$J/\psi$ $p+p$ baseline extraction from world-wide data

J/ψ \( R_{AA} \) for Au+Au and U+U collisions

\[ R_{AA} \sim 20 \text{ in } 60 – 80\% \text{ centrality at } p_T \text{ interval } 0 – 0.1 \text{ GeV/c} \]

\[ R_{AA} \sim 4 \text{ for } 40 – 60\% \text{ centrality at } p_T \text{ interval } 0 – 0.1 \text{ GeV/c} \]
Summary

- Significant excess of J/$\psi$ yield at $p_T$ interval 0 – 0.2 GeV/c is observed for peripheral collisions (40 – 80%).

- The excess trend shows no significant centrality dependence (30 – 80%) within uncertainties, which is beyond the expectation from hadronic production.

- The properties of the excess are consistent with the physical picture of coherent photon-nucleus interactions.
  - Similar $dN/dt$ distribution to that in UPC case.
  - Indication of interference at $p_T$ interval 0 – 0.03 GeV/c.
  - The extracted nuclear form factor slope is consistent with nucleus size.
Discussion and outlook

- Challenges for theoretical calculations in hadronic peripheral collisions:
  - How do the broken nucleus satisfy the condition of coherence?
  - No significant dependence of production on impact parameter?
    - The coherent cross section increases dramatically with decreasing impact parameter in UPC collisions.
    - Cancellation of photon flux in the overlapping region of colliding nuclei for hadronic peripheral collisions.
  - How large is incoherent contribution?
  - Can the products of coherent photon-nucleus interactions serve as a probe to test the cold and hot medium effects?

- Future experimental measurements:
  - More differential measurements for J/ψ.
  - The excess of other vector meson (ρ, ω, φ, Y ...) in hadronic collisions?
  - The excess of photon-photon process (π⁰, η, η’, f₂(1270), a₂(1320), π⁺+π⁻, e⁺+e⁻, μ⁺+μ⁻ ...)?