Excess of J/ψ 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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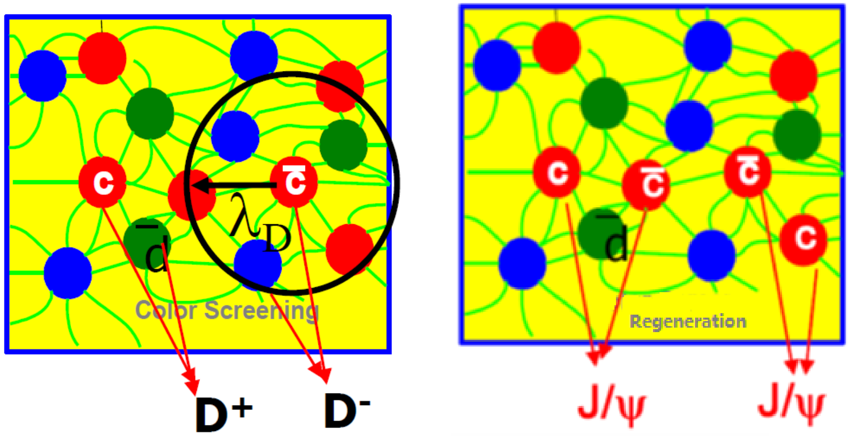
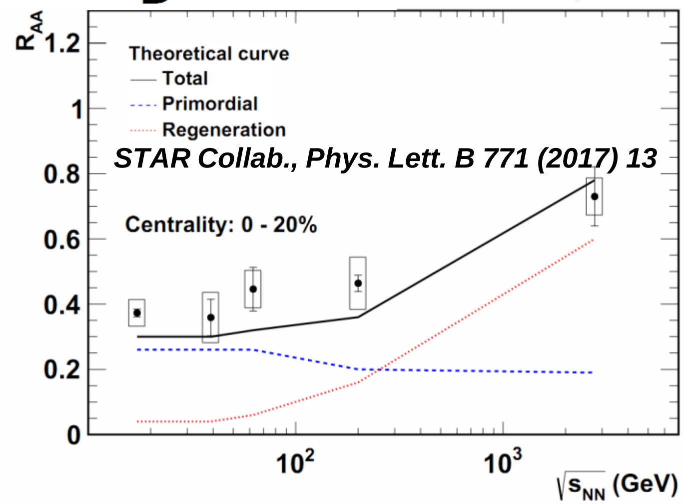
W. Zha etal., arXiv: 1705.01460

J/ψ production and modification in hadronic A+A collisions

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





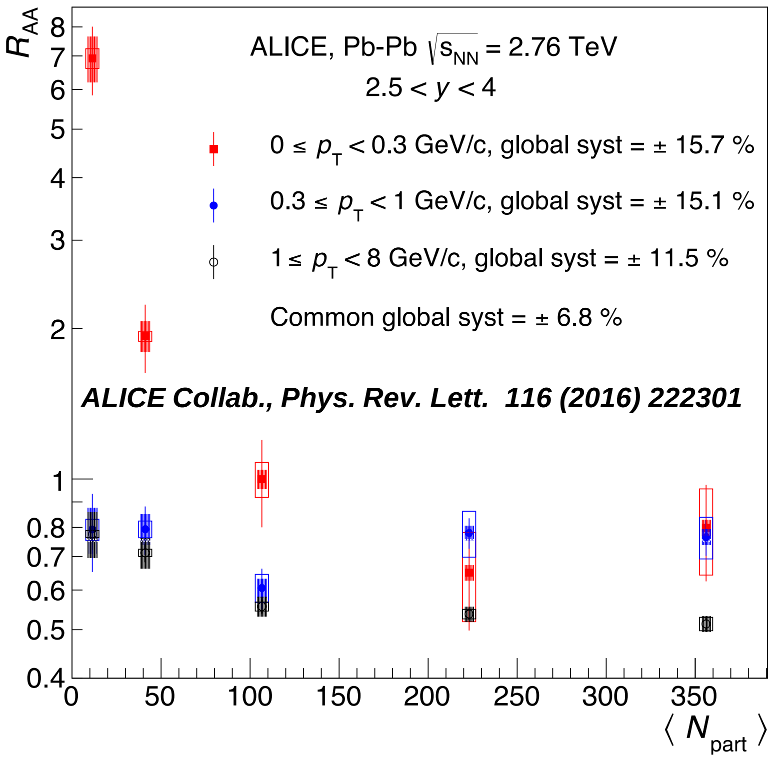
X. Zhao etal., Phys. Rev. C 82 {2010} 064905

- Cold Nuclear Matter effects:
  - ✓PDF modification in nucleus
  - ✓Initial state energy loss
  - ✓Cronin effect
  - ✓Nuclear absorption
- Final state effect:
  - ✓Dissociation by co-mover

$$R_{AA} = \frac{1}{T_{AA}} \frac{d^2N_{AA}/(2\pi p_T dp_T dy)}{d^2\sigma_{pp}/(2\pi p_T dp_T dy)}$$

The interplay of these effects can explain the results from SPS to LHC!

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

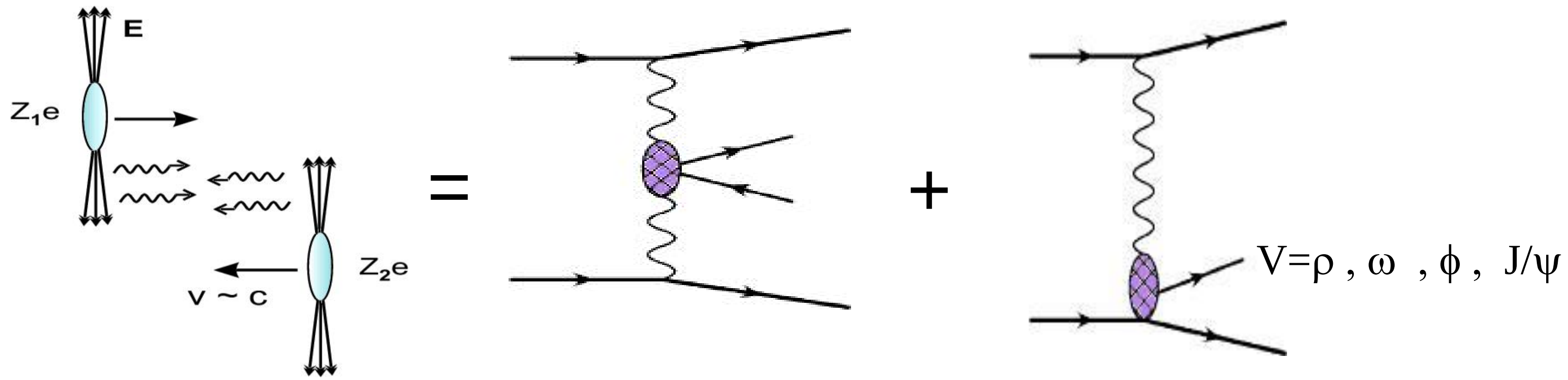


- ✓ Significant enhancement of J/ψ yield observed in p_T interval 0 – 0.3 GeV/c for peripheral collisions (50 – 90%).
- ✓ Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!
- ✓ Originate from coherent photon-nucleus interactions?

- ➢ 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 the origin of the excess?
    - ➢ p_T, centrality and system size dependence of the excess; t distribution.

Introduction to photon interactions in A+A

C.A. Bertulani etal., Ann. Rev. Nucl. Part. Sci 55 (2005) 271



Electromagnetic interaction

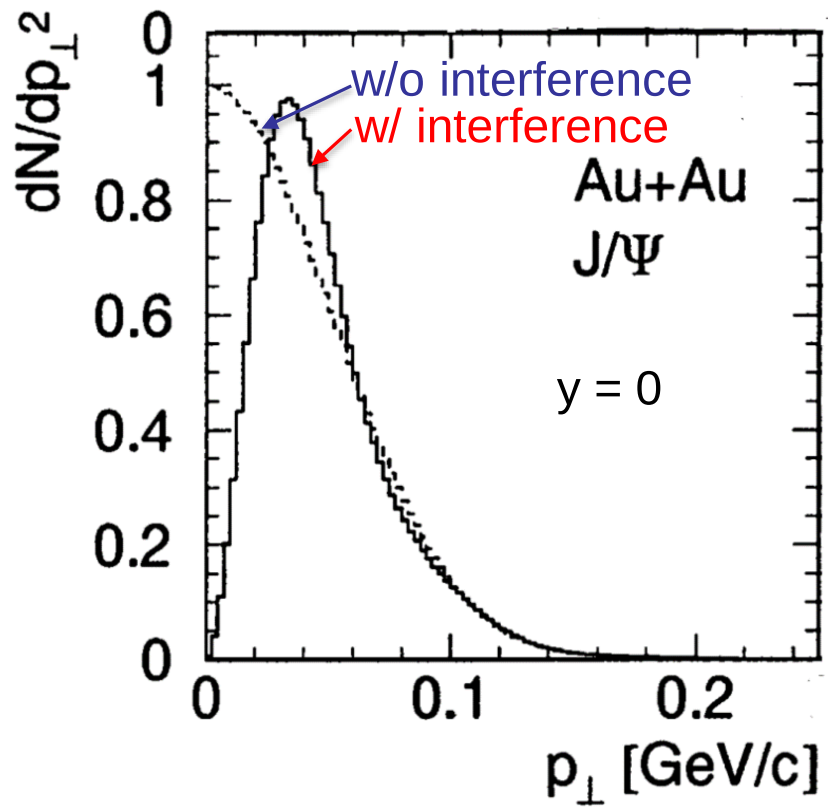
Photon-photon interactions

Photon-nucleus interactions

- The 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

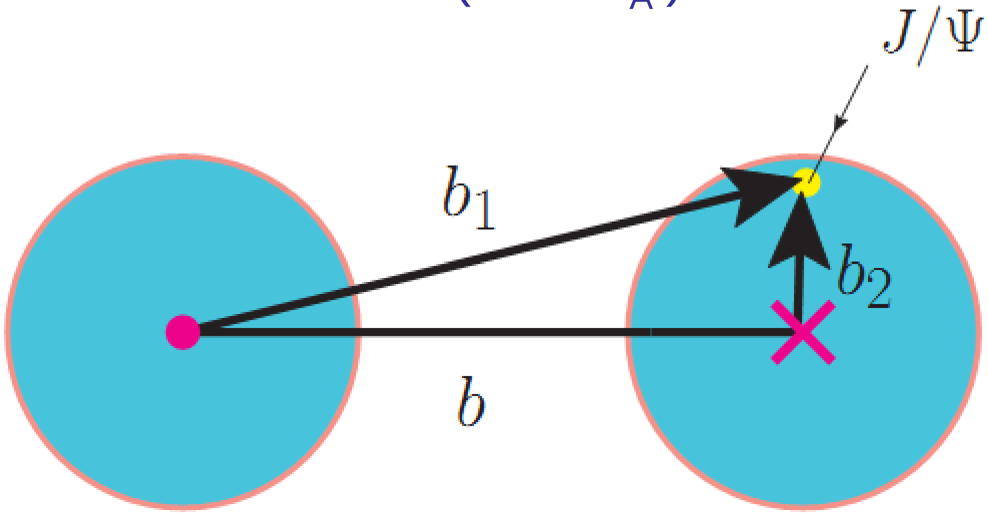
- Coherently:
  - ✓ Both nuclei remain intact
  - ✓ Photon/Pomeron wavelength $\lambda = \frac{h}{p} > R_A$ (nucleus radius)
  - ✓ $p_T < h/R_A$ ~30 MeV/c for heavy ions
  - ✓ Strong couplings ($Z\alpha_{EM}$ ~ 0.6) → large cross sections
- Interference:
  - ✓ Two indistinguishable processes (photon from A_1 or A_2)
  - ✓ Vector meson → opposite signs in amplitude of production
  - ✓ Significant destructive interference for p_T << 1/<b>



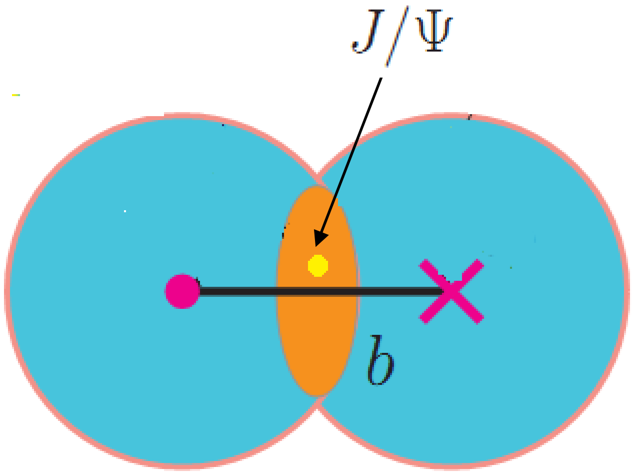
S.R. Klein and J. Nystrand, Phys. Rev. Lett. 84 (2000) 2330

J/ψ hadronic production versus photoproduction

- J/ψ can be produced via strong and electromagnetic interactions.
- The strong interactions can obscure the electromagnetic interactions
- Study the electromagnetic process in Ultra-Peripheral Collisions (UPC)
  - ✓ UPC conditions ($b > 2R_A$): no hadronic interactions

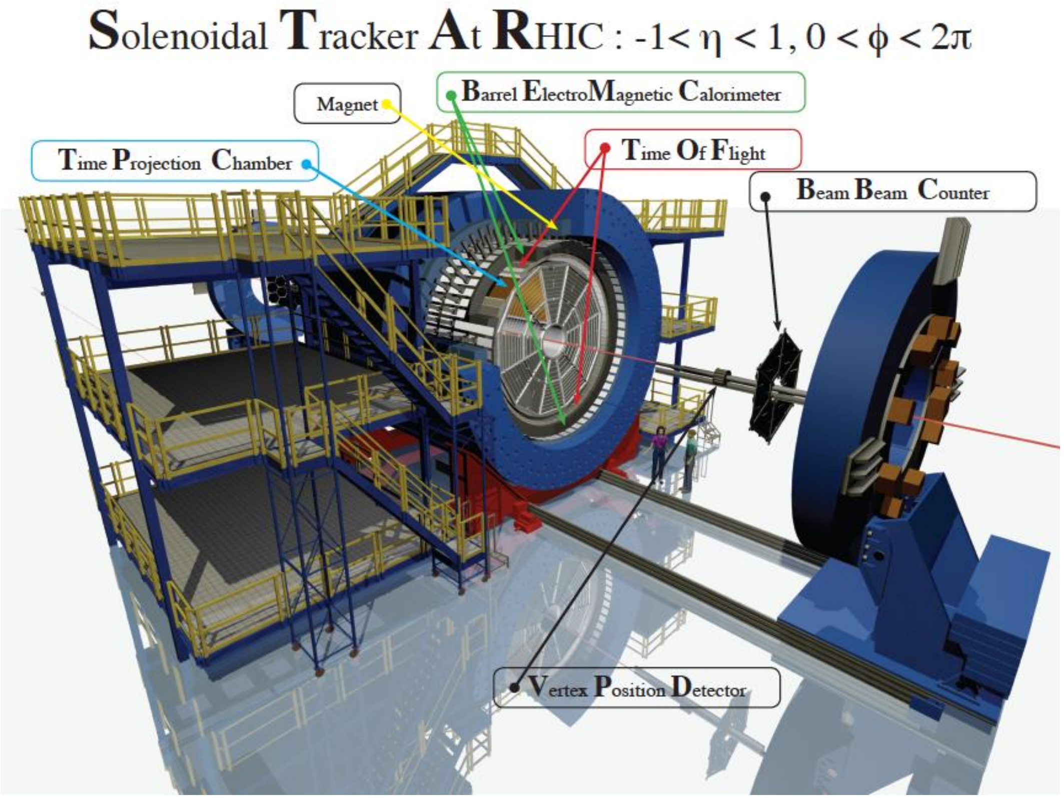


UPC collisions:
J/ψ photoproduction



Hadronic collisions:
J/ψ hadronic production and modification

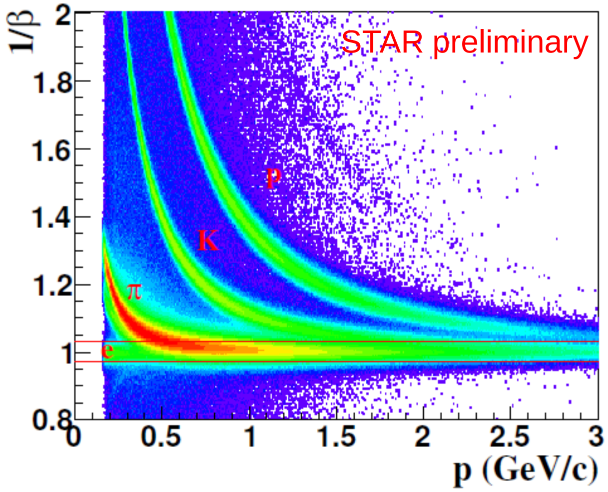
The STAR detector



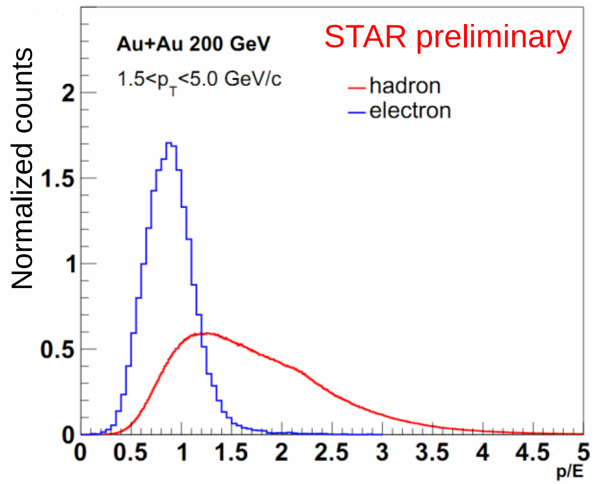
- **Large acceptance:**
  $|\eta| < 1$, $0 < \phi < 2\pi$
- **Time Projection Chamber**
  (TPC) – tracking, particle identification, momentum
- **Time of Flight detector**
  (TOF) – particle identification
- **Barrel ElectroMagnetic Calorimeter**
  (BEMC) – electron identification, triggering

Electron identification

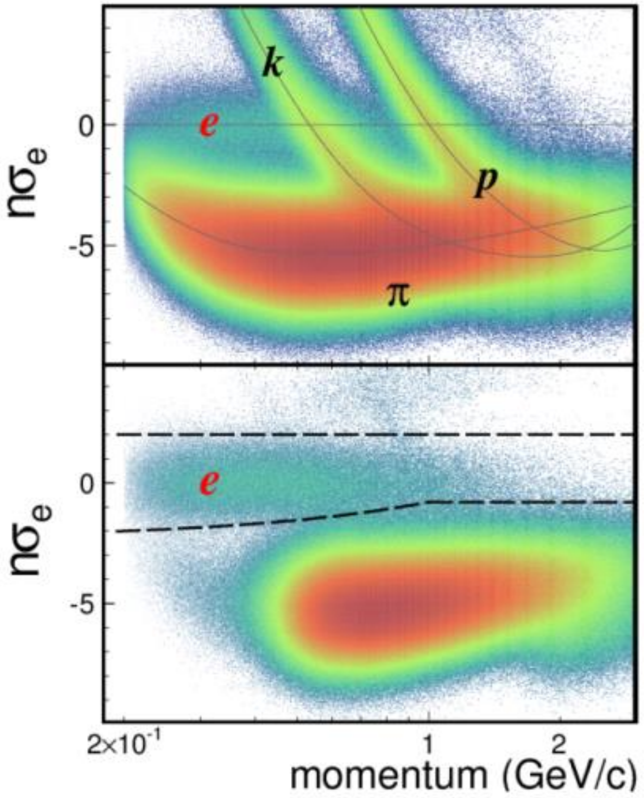
1/β distribution for electrons and hadrons from TOF



p/E distribution for electrons and hadrons from BEMC

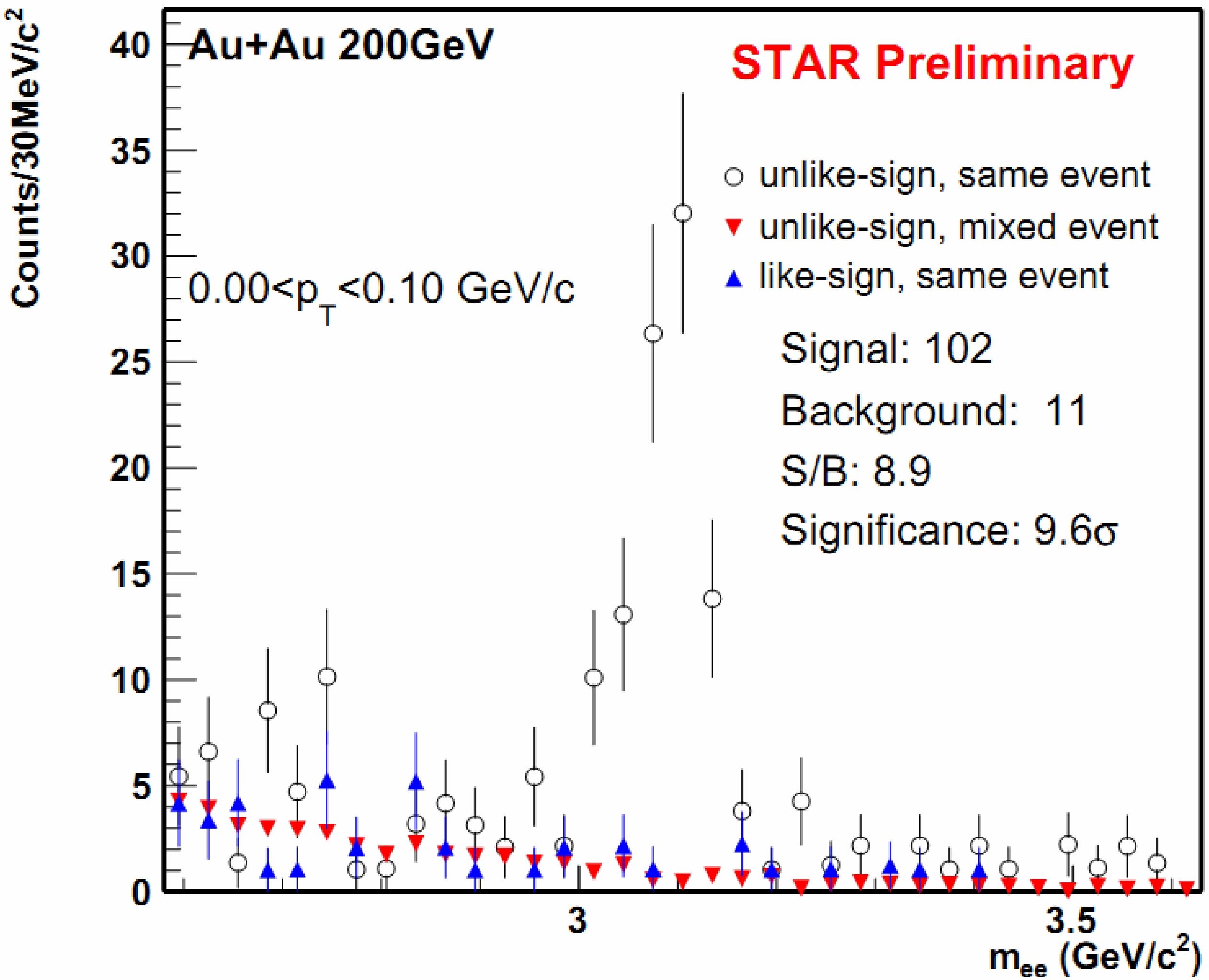


Normalized dE/dx ($n\sigma_e$) distribution before and after TOF cuts



STAR Collab., Phys. Rev. C 92 (2015) 24912

J/ψ signal

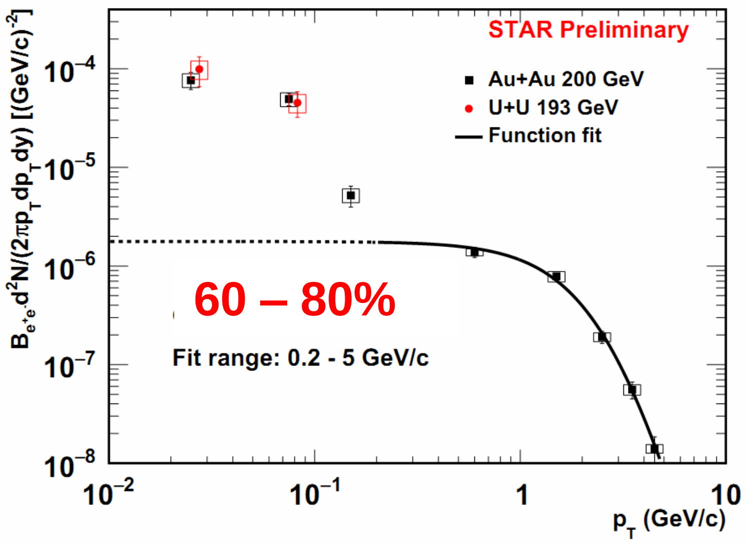


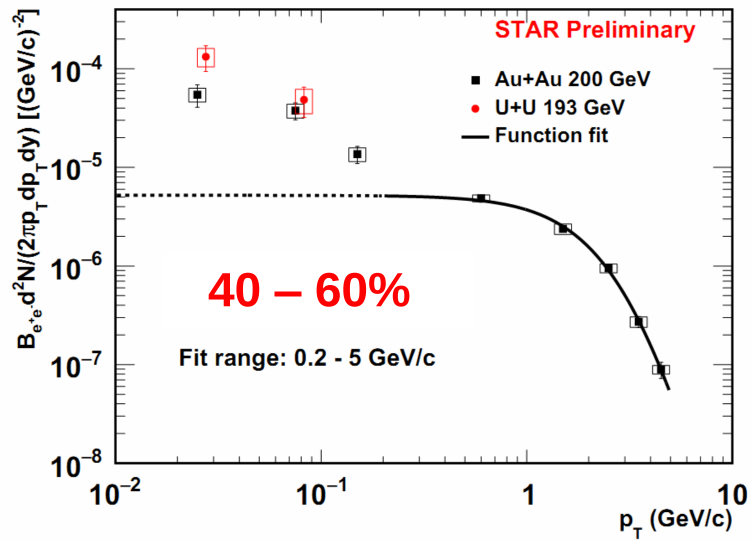
Centrality: 40 – 80%

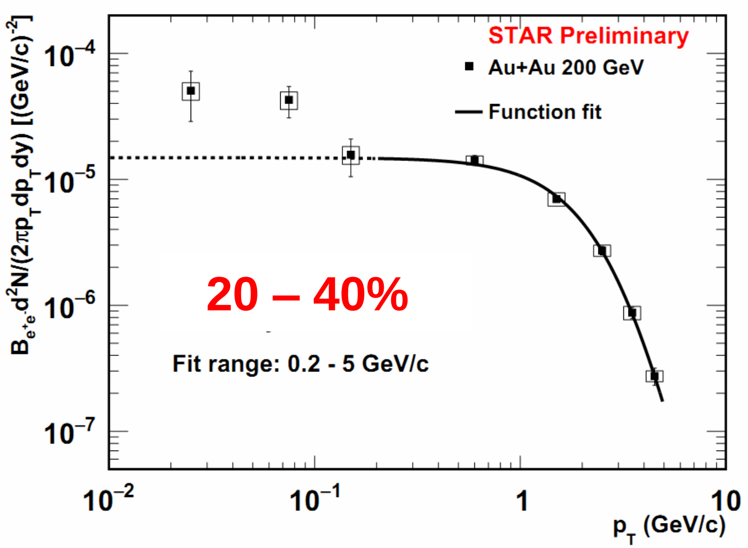
The signal is extracted by subtracting the mixed event background from the unlike-sign pairs.

Good signal over background ratio!

J/ψ invariant yield in Au+Au and U+U collisions





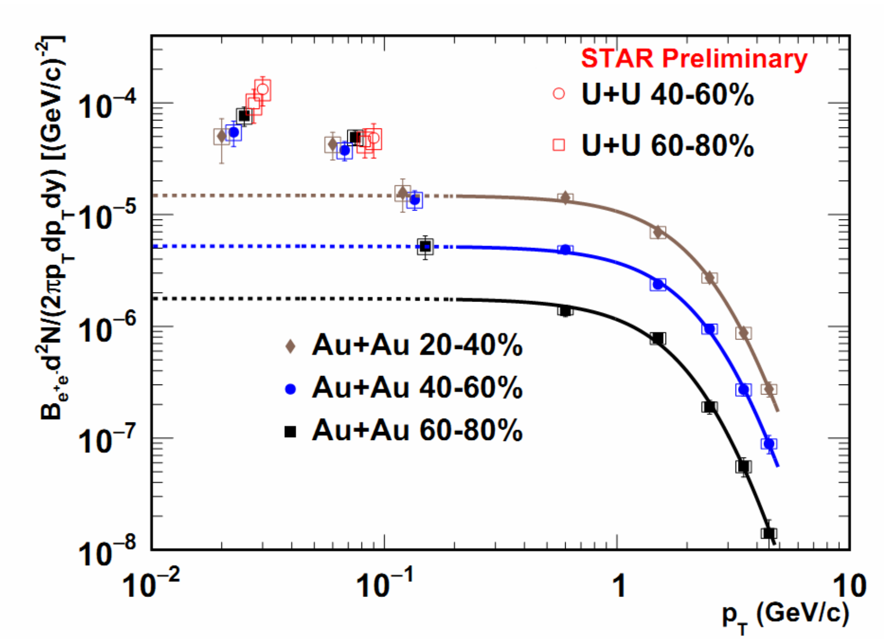


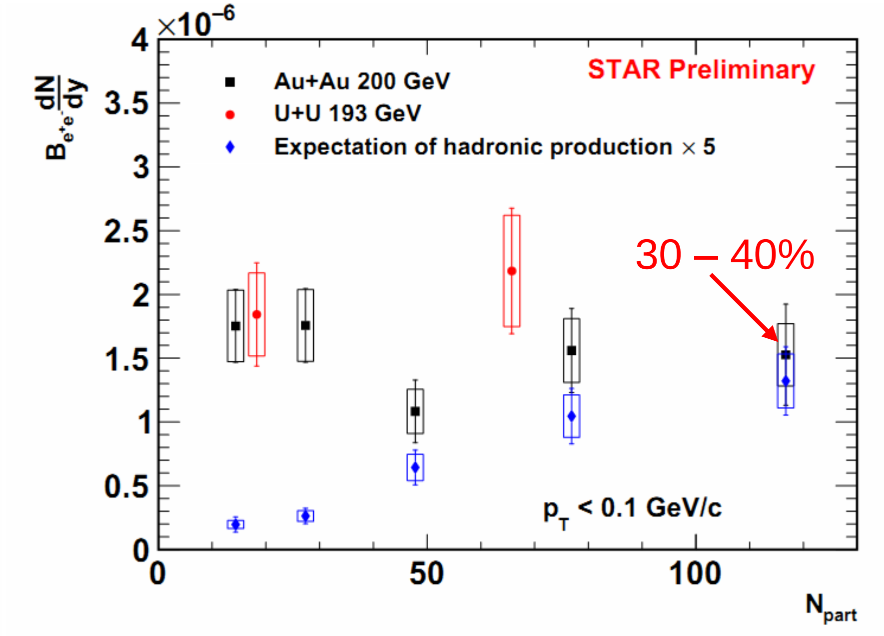
Function to describe hadronic production:

$$\frac{d^2N}{p_T dp_T} = a \times \frac{1}{(1 + b^2 p_T^2)^n}$$

- 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.

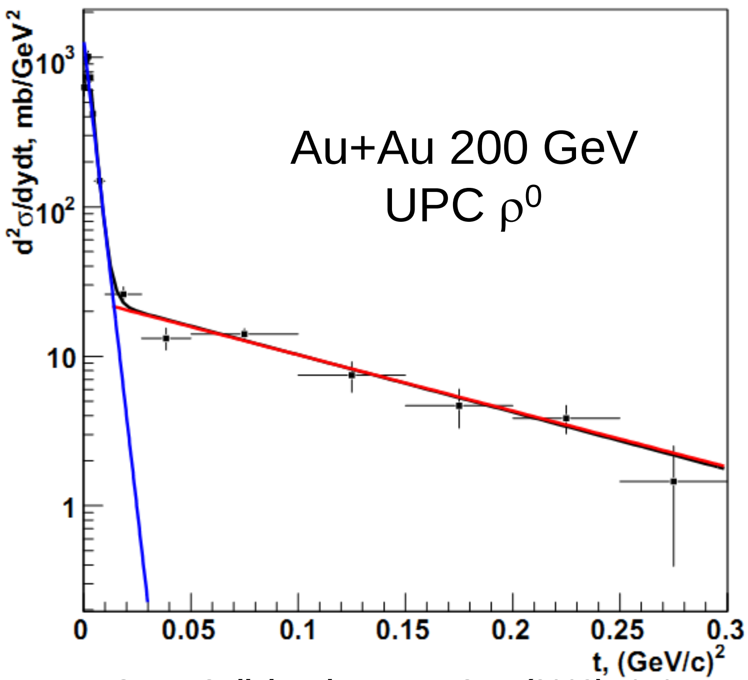
J/ψ yield at very low p_T versus centrality





- ✓ No significant centrality dependence of the excess yield!
  - ✓ Low p_T J/ψ from hadronic production is expected to increase dramatically with N_{part}.
- ✓ No significant difference between Au+Au and U+U collisions.

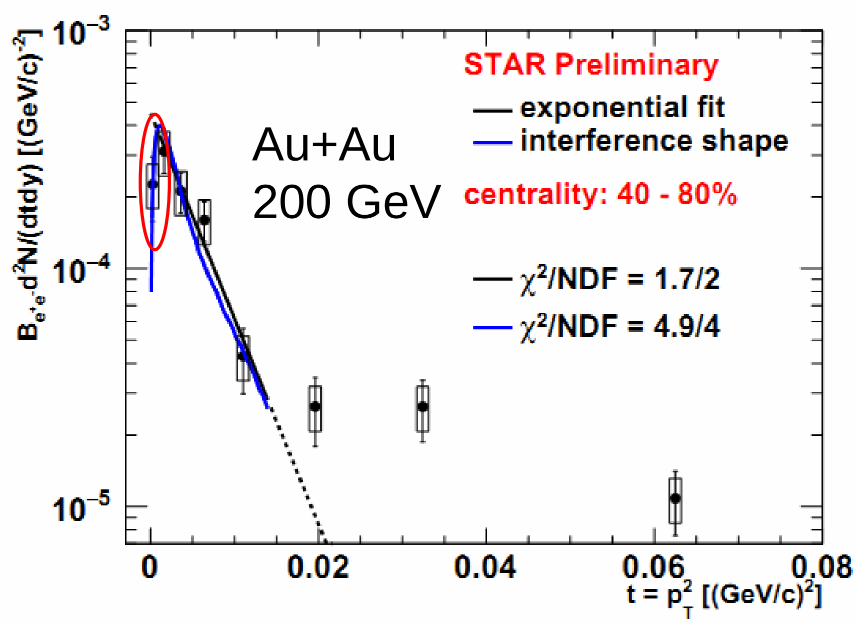
J/ψ dN/dt distribution for 40-80% Au+Au collisions



STAR Collab., Phys. Rev. C 77 (2008) 4910

ρ^0 cross-section as a function of the momentum transfer squared ($t \approx p_T^2$) from STAR UPC measurements.

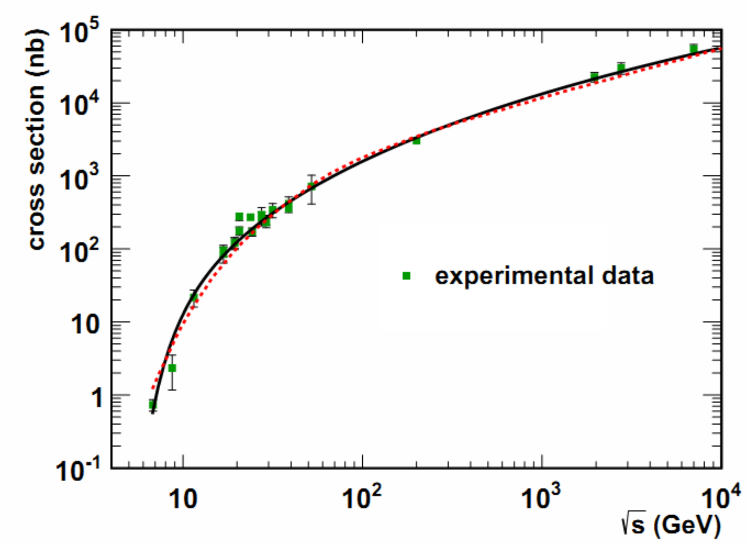
- The slope from the exponential fit reflects the density profile of the target.

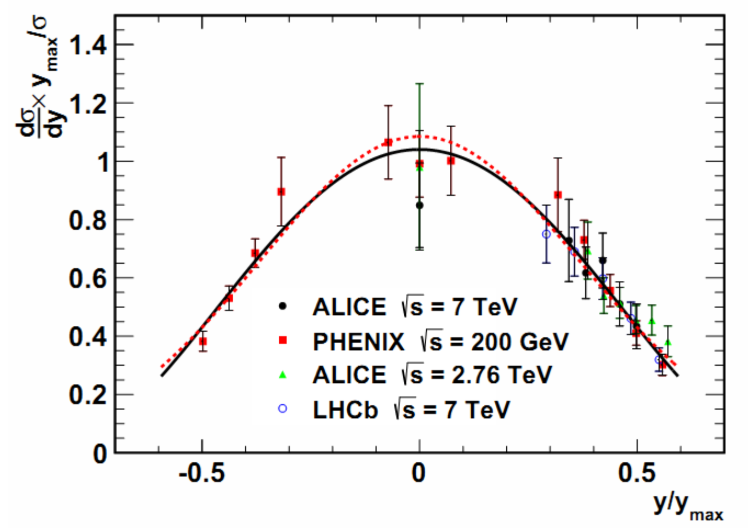


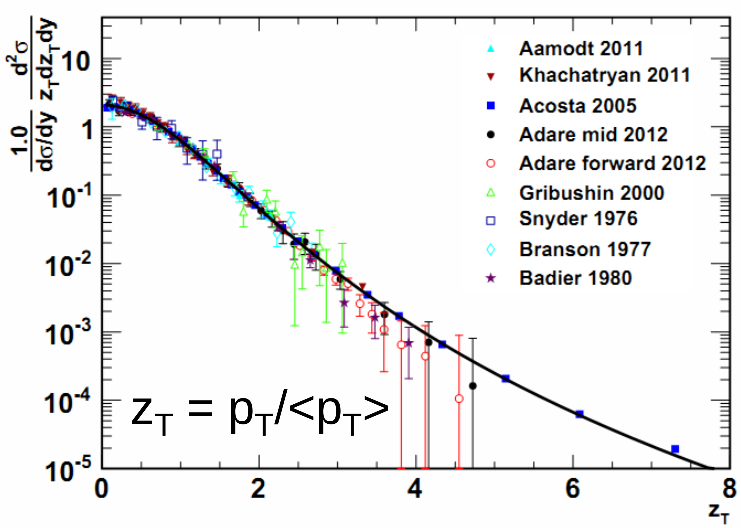
- ✓ Similar structure to that in UPC case!
- ✓ Indication of interference!
  - ✓ Interference shape from calculation for UPC case

    S.R. Klein and J. Nystrand, Phys. Rev. Lett. 84 (2000) 2330
- ✓ Similar slope parameter!
  - ✓ Slope from STARLIGHT prediction in UPC case – 196 (GeV/c)$^{-2}$
  - ✓ Slope w/o the first point: 199 $\pm$ 31(GeV/c)$^{-2}$ χ^2/NDF = 1.7/2
  - ✓ Slope with the first point: 164 $\pm$ 24(GeV/c)$^{-2}$ χ^2/NDF = 5.9/3

J/ψ p+p baseline extraction from world-wide data



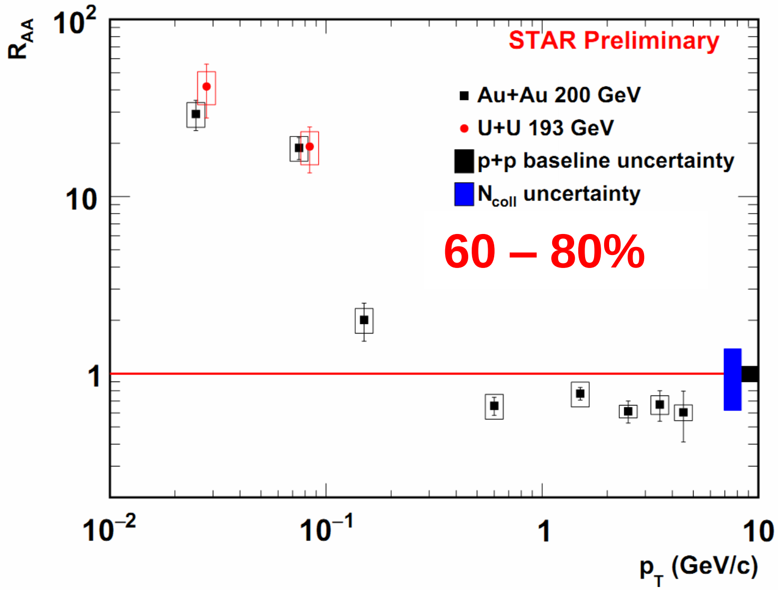


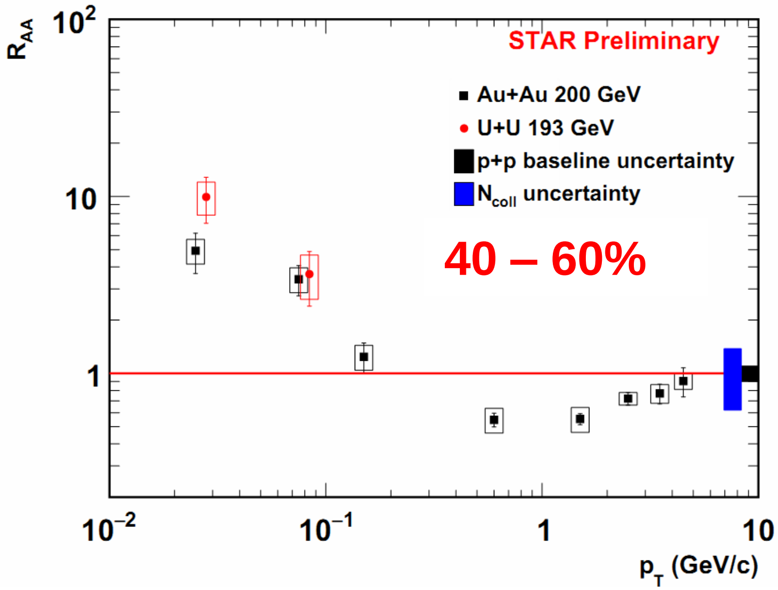


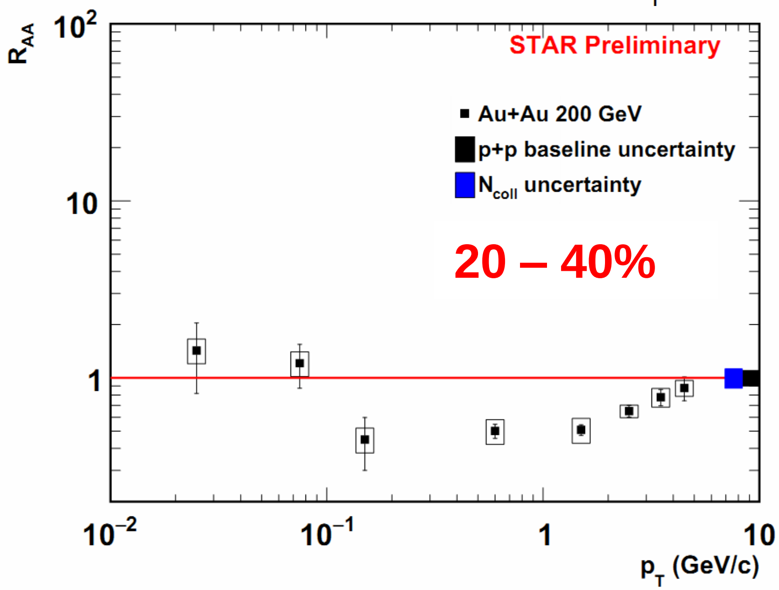
W. Zha etal., Phys. Rev. C93 (2016) 024919

- ✓ The scaled rapidity and p_T distributions follow a universal trend.
- ✓ p+p baseline at very low p_T is interpolated from the world-wide experimental data.

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

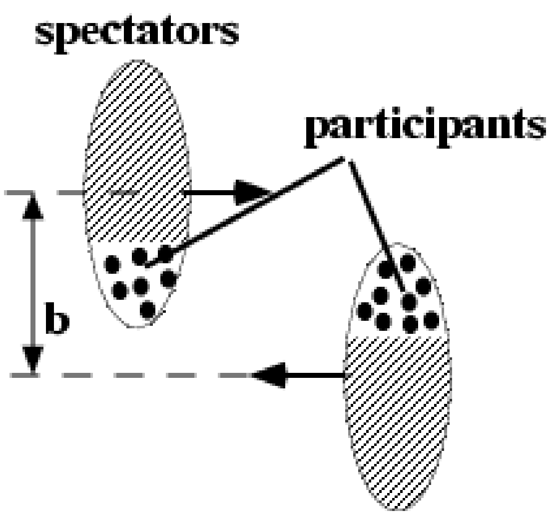






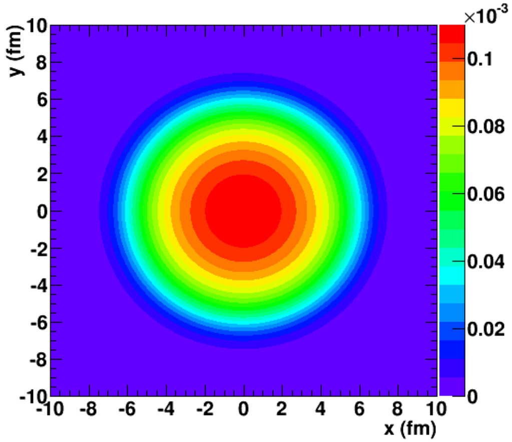
- R_{AA} ~ 20 in 60 – 80% centrality at p_T interval 0 – 0.1 GeV/c
- R_{AA} ~ 4 for 40 – 60% centrality at p_T interval 0 – 0.1 GeV/c

Model for J/ψ photoproduction in hadronic collisions



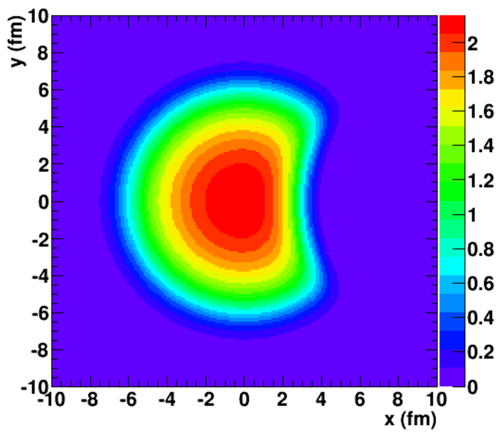
W. Zha etal., arXiv: 1705.01460

Photon emitter and target



nucleus

OR



spectator

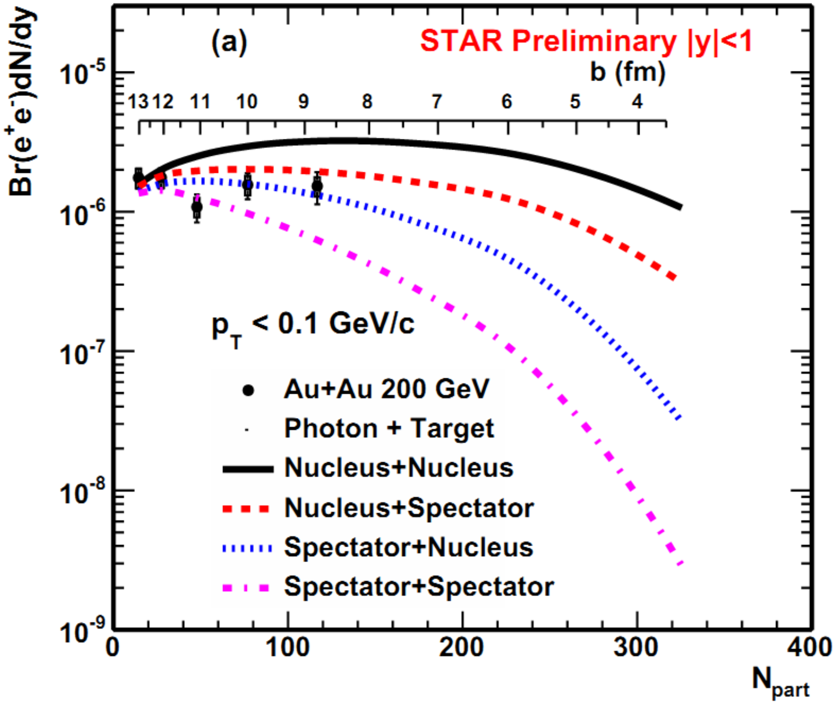
The density profile of spectators is from optical Glauber calculations!

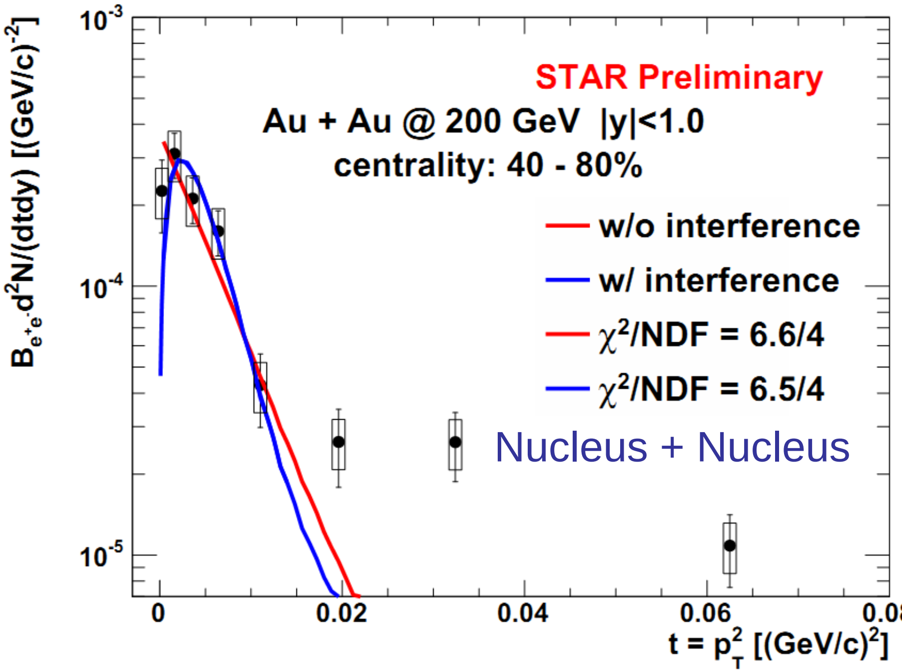
Photon emitter	Target	
Nucleus	Nucleus	(1)
Nucleus	Spectator	(2)
Spectator	Nucleus	(3)
Spectator	Spectator	(4)

Incoherent contribution, cold nuclear and hot medium effects are not included in the calculations!

Model calculations with different scenarios

W. Zha etal., arXiv: 1705.01460



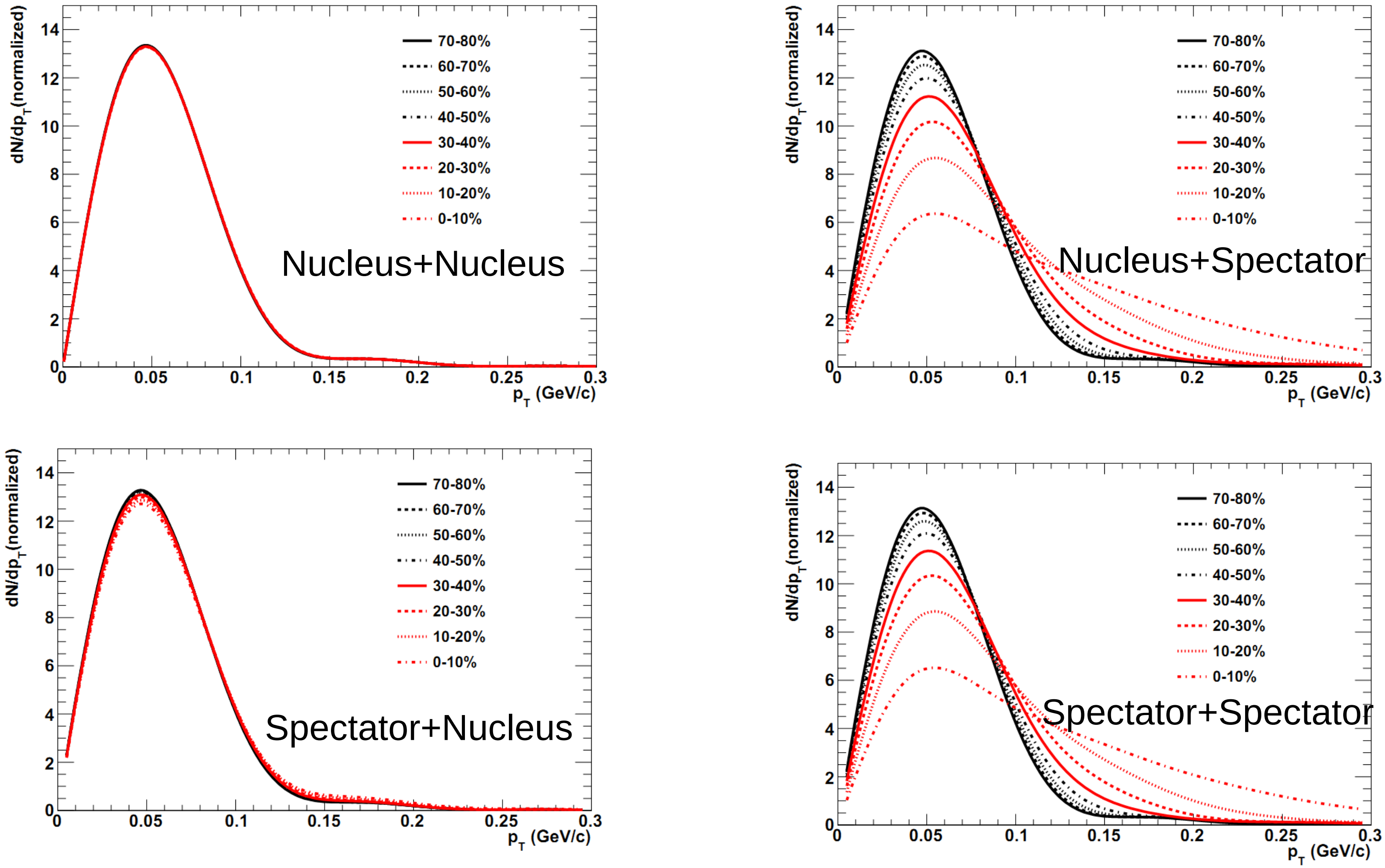


- ✓ All four scenarios describe data well in peripheral collisions (60-80%)!
- ✓ Different scenarios have different trends toward central collisions!
  - ✓ The data favor “Nucleus + Spectator” and “Spectator + Nucleus”.
  - ✓ To distinguish the different scenarios, measurements in central collisions are needed!
- ✓ Calculations based on the “Nucleus + Nucleus” scenario describe the t distribution!
  - ✓ The differences between different scenarios in t distributions are negligible in 40-80% centrality class.

Summary

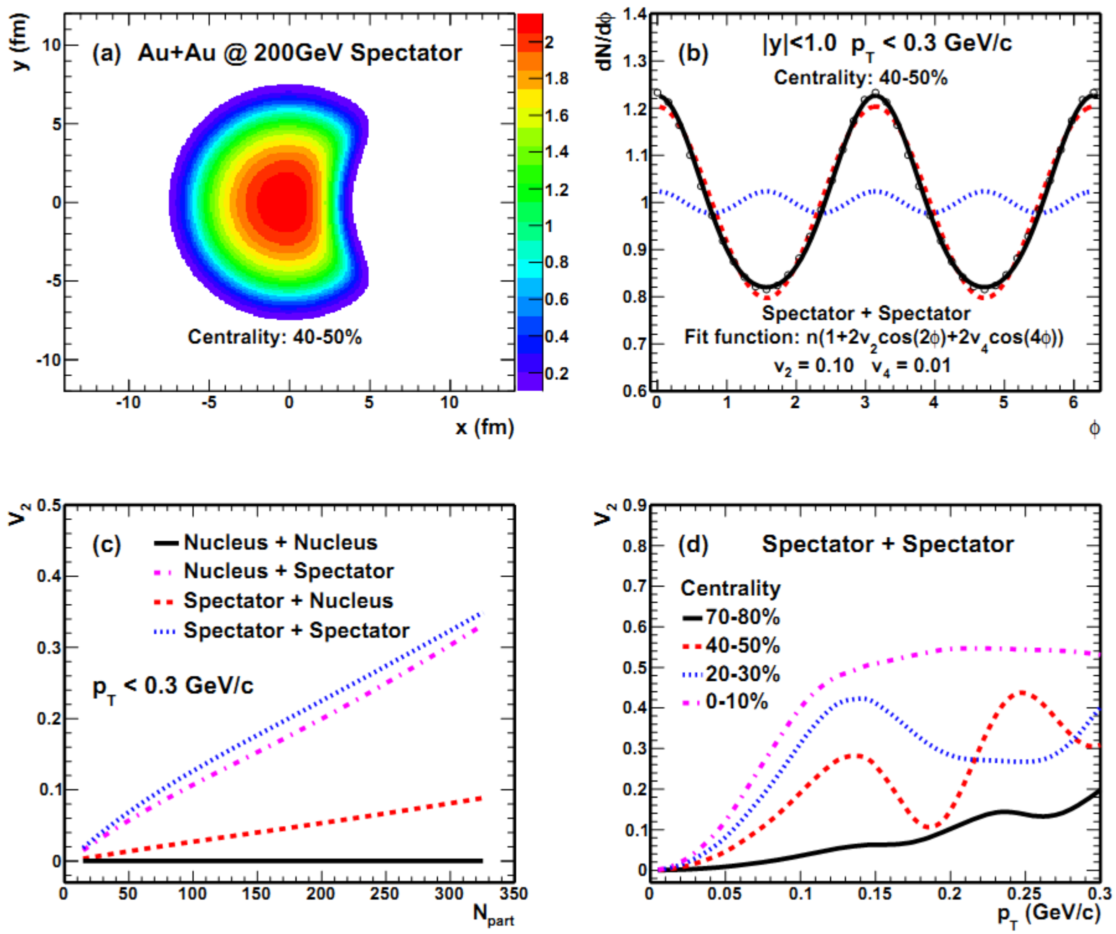
- Significant excess of J/ψ yield at p_T interval 0 – 0.2 GeV/c is observed in peripheral Au+Au and U+U collisions (40 – 80%).
- The excess has no significant centrality dependence (40 – 80%) within uncertainties, which is different from the expectation from hadronic production.
- The properties of the excess are consistent with 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.
- A theoretical calculation based on coherent photoproduction scenario can qualitatively describe the excess.

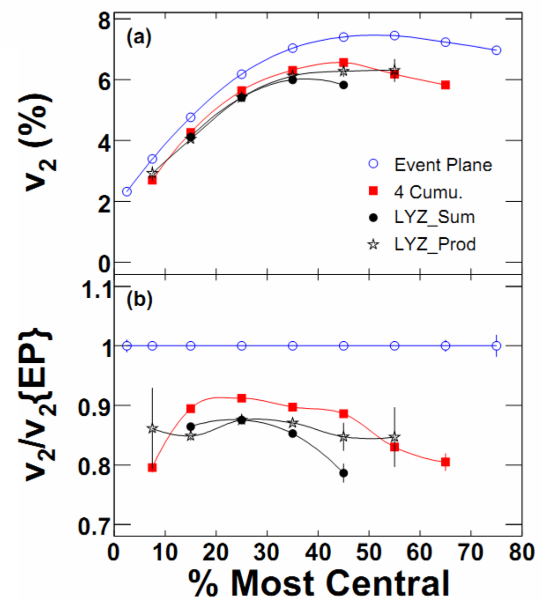
Future directions: more differentially ----p_T shape with different scenarios



- ✓ The p_T shape is very sensitive to the target!
- ✓ If the target is spectator, the p_T shape has significant centrality dependence!

Production versus ϕ (relative to reaction plane)

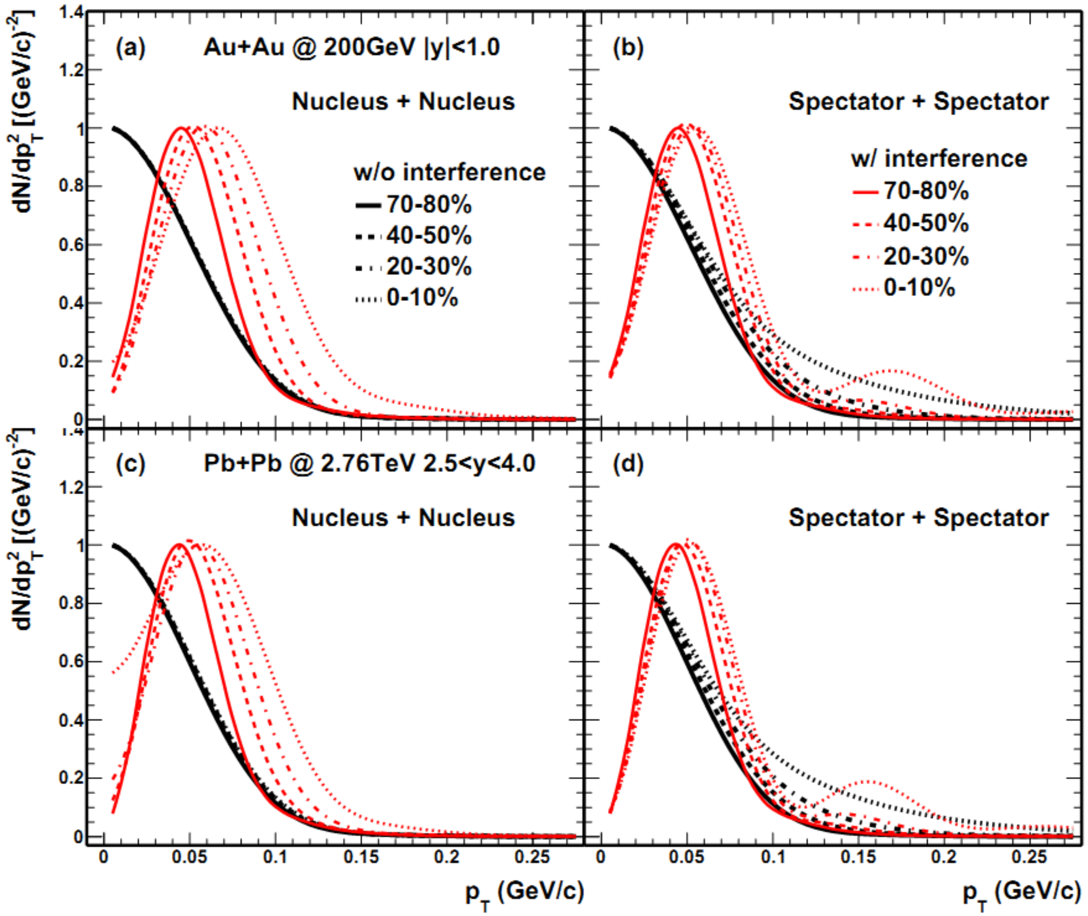




Phys. Rev. C 77 (2008) 54901

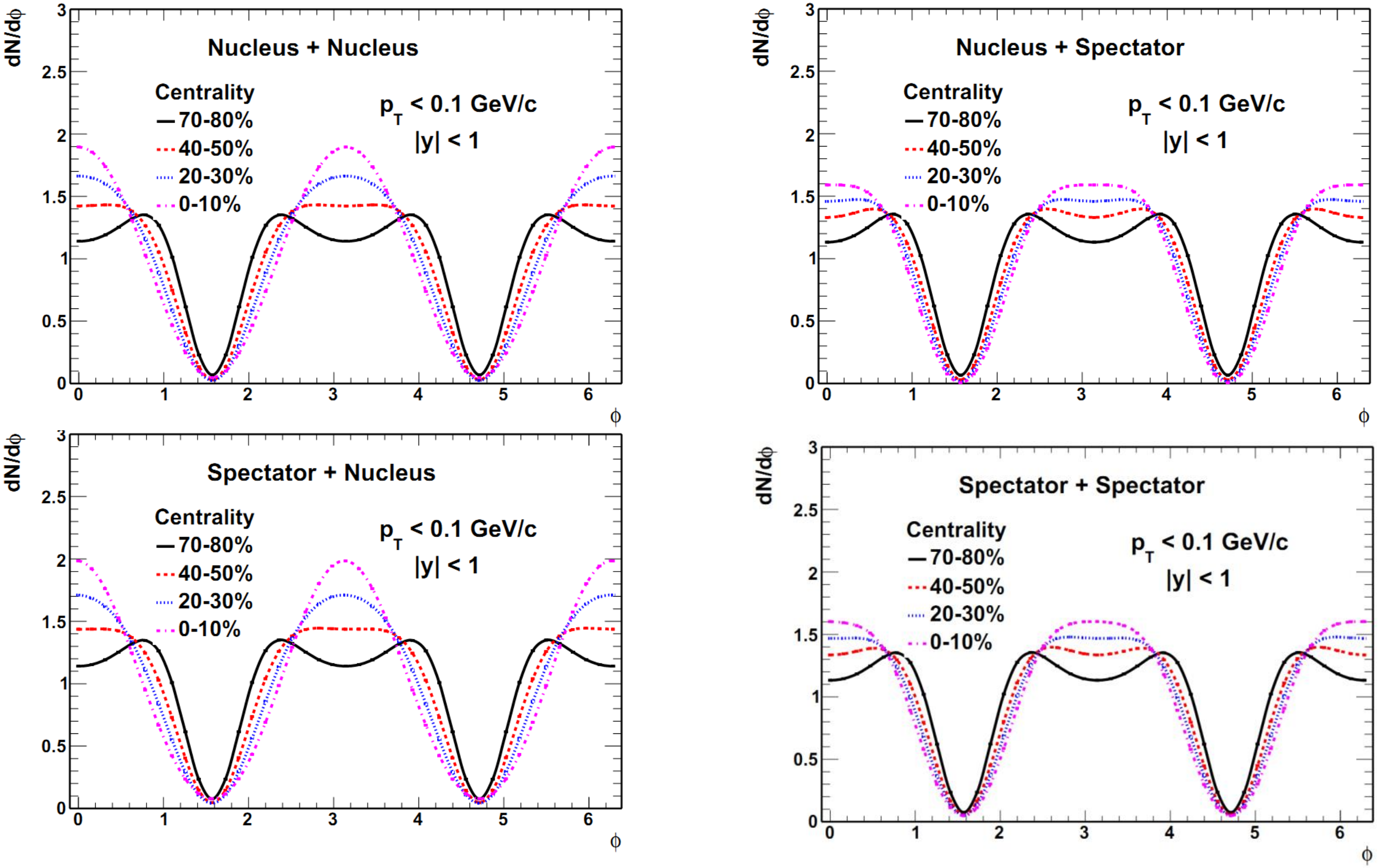
- ✓ Sensitive to the target!
- ✓ Large v_2 and sizeable v_4 will be observed if the target is spectator!
- ✓ V_2 increase dramatically toward central collisions!
- ✓ Probe of initial geometry of the overlap region!

p_T shape with interference



- ✓ Dramatically change the p_T spectra!
- ✓ Different interference pattern in different centrality!
- ✓ The effect is relative small with spectator coupling!

ϕ distribution with interference



- ✓ Dramatically change ϕ distribution!
- ✓ Sensitive to the target!

Discussion

The excess: more sensitive to the color screening?

J/ψ production & modification	Hadronic production	Photoproduction
B-hadron decay	Yes	No
Feed-down from χ_c and $\psi(2s)$	Yes	Only from $\psi(2s)$
Color screening	Yes	Maybe?
Regeneration	Yes	No

Photoproduction	In UPC	In hadronic collisions
Impact parameter dependence	No	Yes
Event plane dependence	No	Yes
Test the medium	No	Maybe?

- Perspectives:
  - ✓ Measurements in more central collisions
  - ✓ p_T shape and event plane dependence: is the target nucleus or spectator?
  - ✓ photon-photon process (π^0, η, η', $f_2(1270)$, $a_2(1320)$, $\pi^+ + \pi^-$, $e^+ + e^-$, $\mu^+ + \mu^-$…): is the photon emitter spectator or nucleus?