



Measurements and calculations of very low p_T J/ψ yield at RHIC STAR

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Collaboration

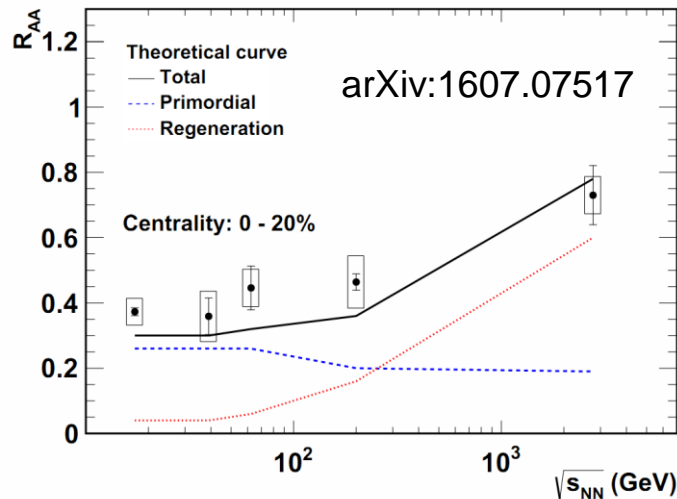
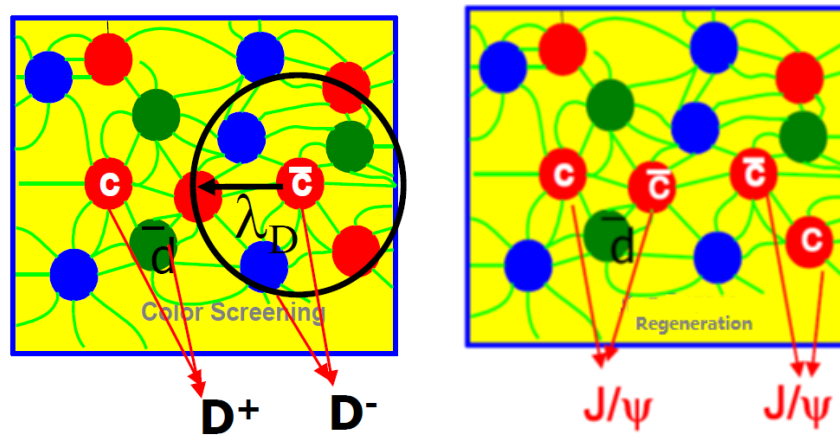
University of Science and Technology of
China

FCPPL Quarkonium Production Workshop,
30 March 2017, Peking University



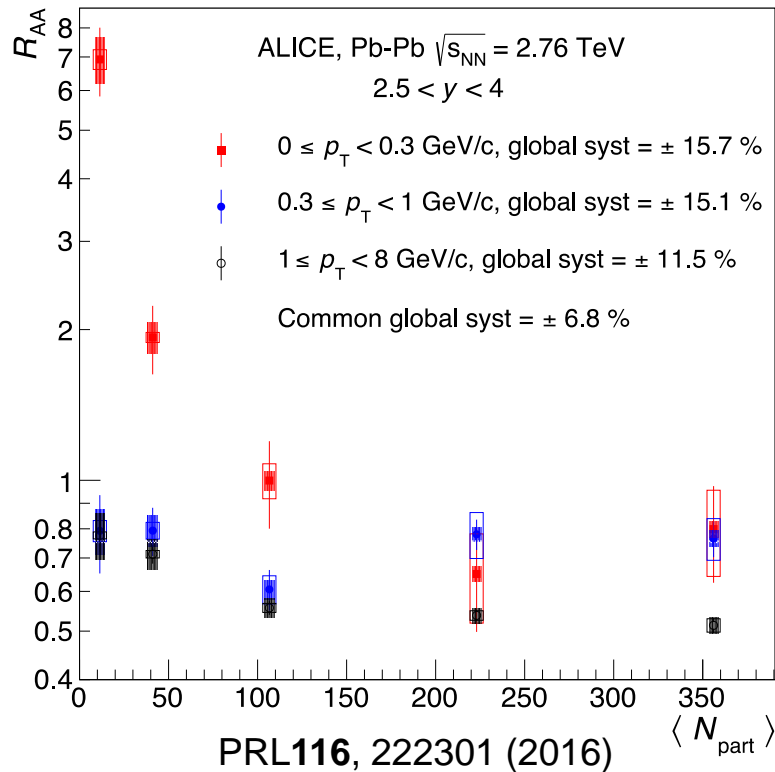
J/ψ production and modification in hadronic A+A collisions

- 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
 - ✓ Nuclear absorption
- Final state effect:
 - ✓ Dissociation by co-mover



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

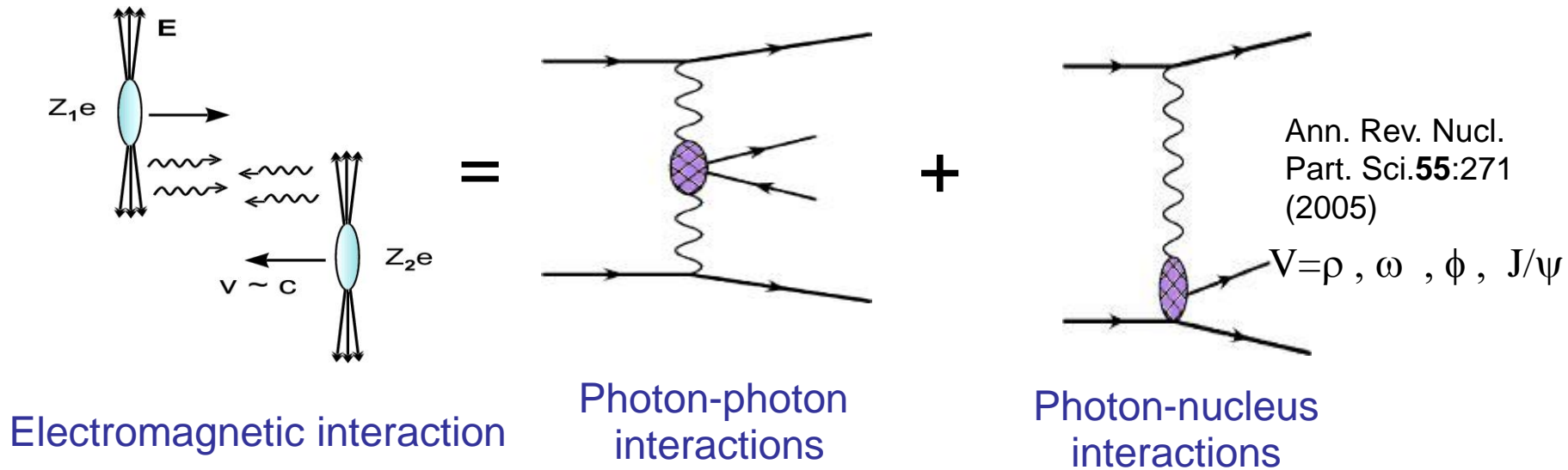
Excess of J/ψ production at very low p_T with ALICE



- ✓ 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!
- ✓ 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.

Introduction to photon interactions in A+A



- 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.

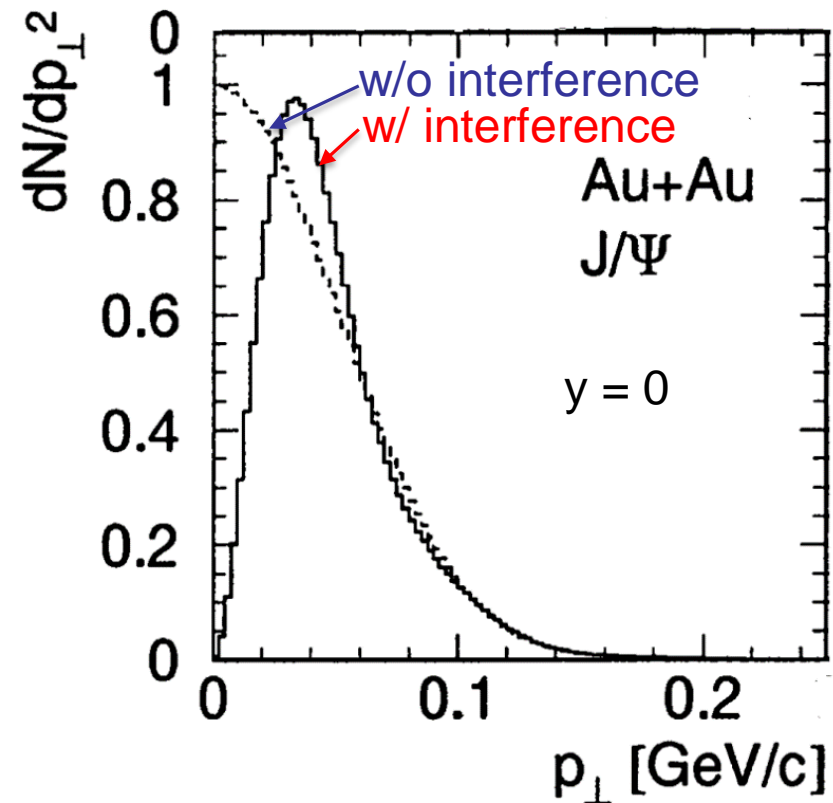
Features of coherent photon-nucleus interaction

- Coherently:

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

- Interference:

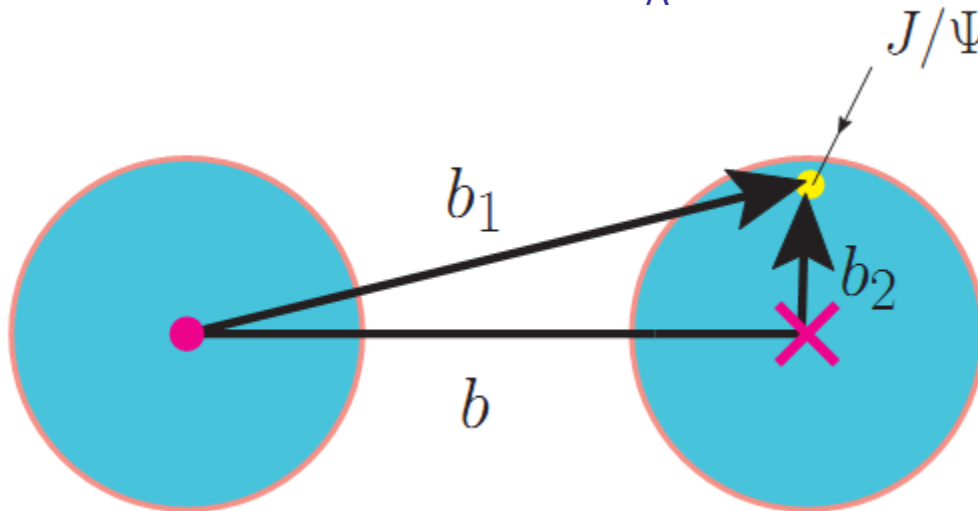
- ✓ Two indistinguishable processes (photon from A_1 or A_2)
- ✓ Vector meson \rightarrow opposite signs in amplitude
- ✓ Significant destructive interference for $p_T \ll 1/\langle b \rangle$



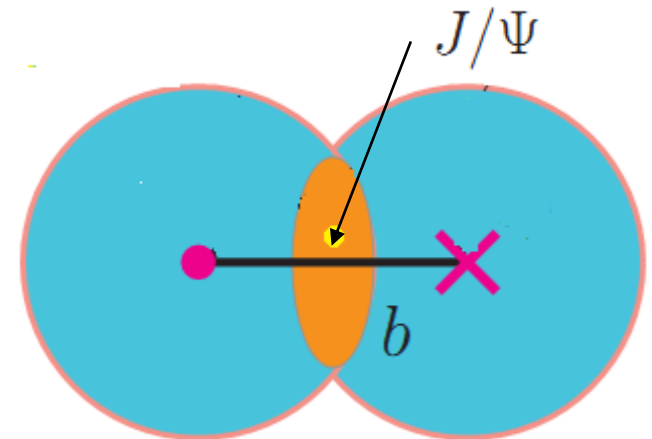
PRL **84** 2330 (2000)

J/ψ hadronic production and photoproduction

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



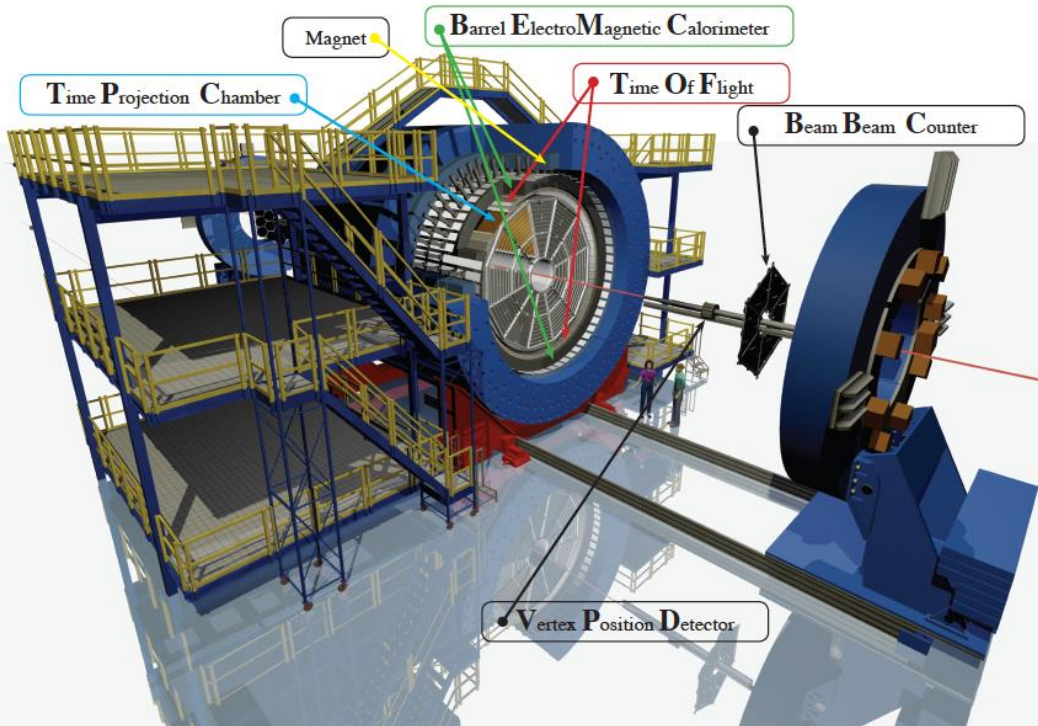
UPC collisions:
 J/ψ photoproduction



hadronic collisions:
 J/ψ hadronic production
and modification

STAR detector

Solenoidal **T**racker **A**t **R**HIC : $-1 < \eta < 1, 0 < \phi < 2\pi$



➤ Large acceptance:

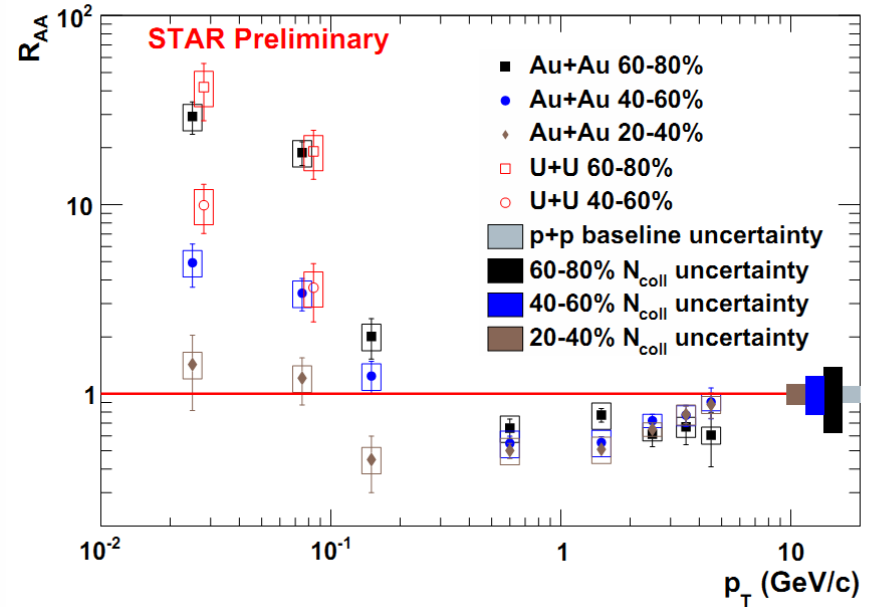
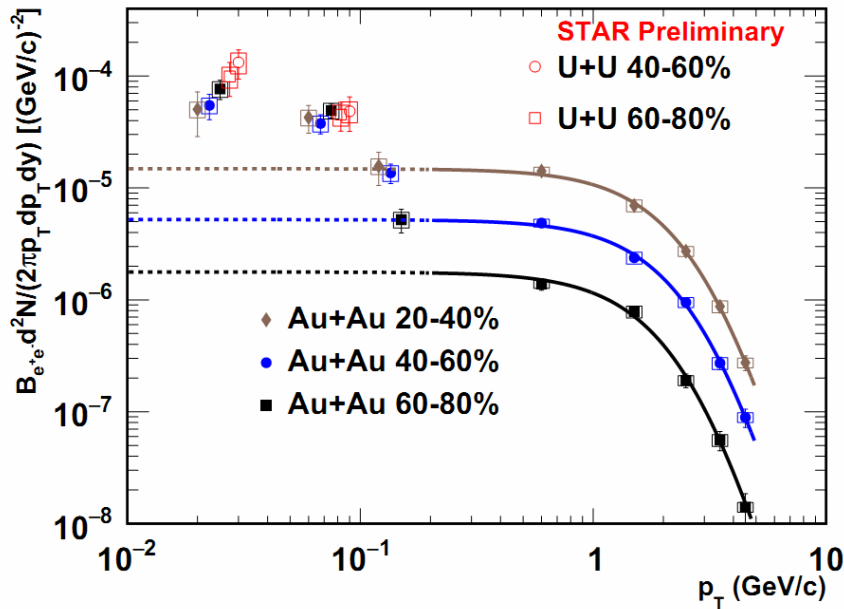
$$|\eta| < 1, 0 < \phi < 2\pi$$

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

➤ Time of Flight detector (TOF) – particle identification

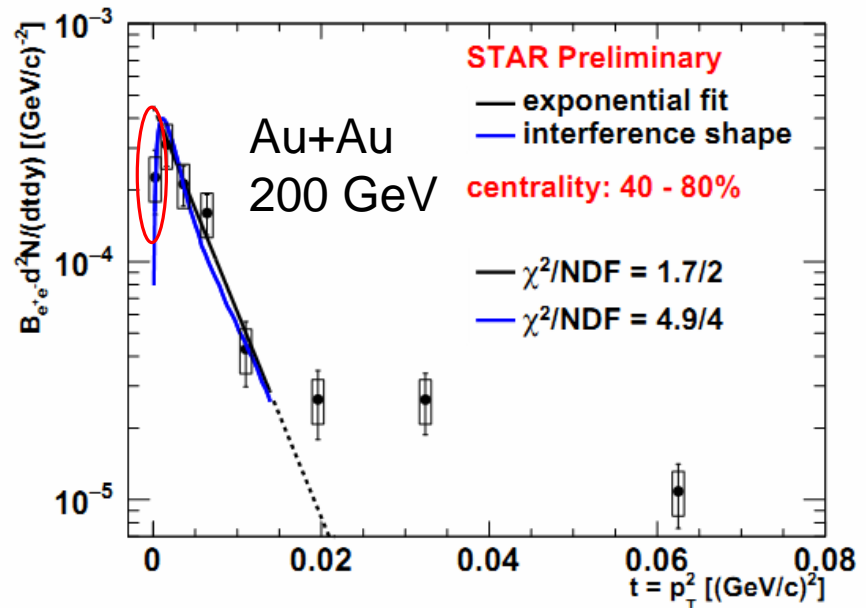
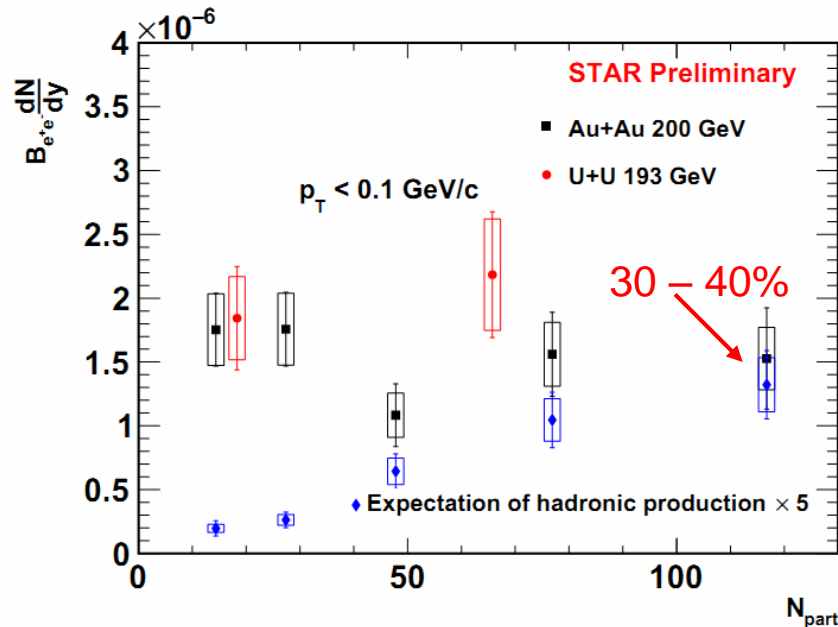
➤ Barrel Electromagnetic Calorimeter (BEMC) – electron identification, triggering

J/ψ production and modification at very low p_T



- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions (40 – 80 %)!
 - ✓ No significant difference between Au+Au and U+U collisions.

The excess yield and dN/dt distribution



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

- ✓ 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 (GeV/c)⁻²
 - ✓ Slope w/o the first point: 199 ± 31 (GeV/c)⁻²
 $\chi^2/NDF = 1.7/2$
 - ✓ Slope w/ the first point: 164 ± 24 (GeV/c)⁻²
 $\chi^2/NDF = 5.9/3$

The calculation of the coherent production

$$\sigma(AA \rightarrow AAV) = \int dk \frac{dN_\gamma(k)}{dk} \sigma(\gamma A \rightarrow VA) = \int_0^\infty dk \frac{dN_\gamma(k)}{dk} \int_{t_{min}}^\infty dt \left. \frac{d\sigma(\gamma A \rightarrow VA)}{dt} \right|_{t=0} |F(t)|^2$$

$$\frac{d^3 N_\gamma(k, r)}{dk d^2 r} = \frac{Z^2 \alpha x^2}{\pi^2 k r^2} K_1^2(x) \quad \frac{d\sigma(\gamma A \rightarrow J/\psi A; t=0)}{dt} = \frac{\alpha_{em} \sigma_{tot}^2(J/\psi A)}{4 f_{J/\psi}^2}$$

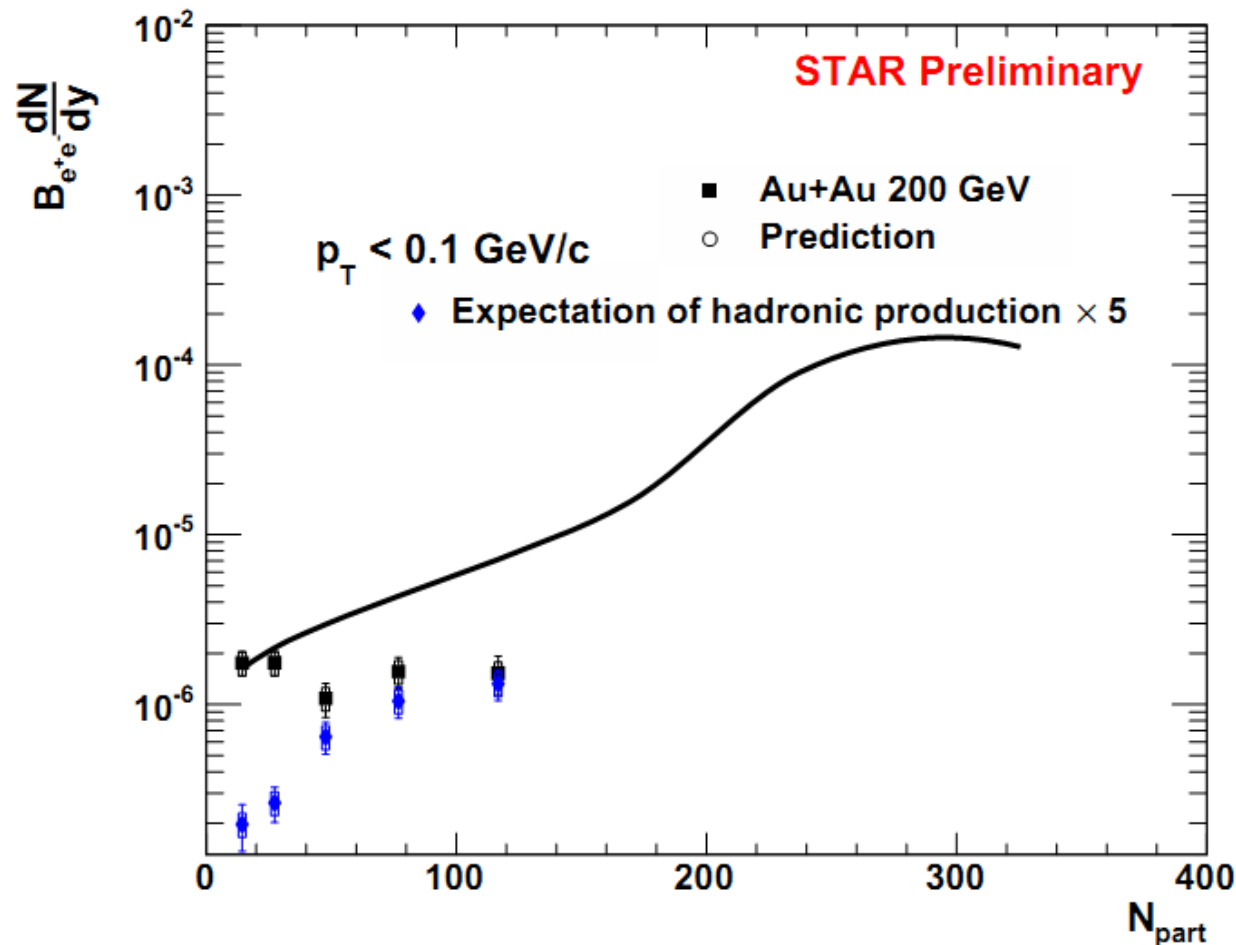
$$\sigma_{tot}^{CM}(J/\psi A) = \int d^2 \mathbf{r} (1 - \exp(-\sigma_{tot}(J/\psi p) T_A(\mathbf{r})))$$

$$\sigma_{tot}^2(J/\psi p) = 16\pi \frac{d\sigma(J/\psi p \rightarrow J/\psi p; t=0)}{dt}$$

$$\frac{d\sigma(J/\psi p \rightarrow J/\psi p; t=0)}{dt} = \frac{f_{J/\psi}^2}{4\pi \alpha_{em}} \frac{d\sigma(\gamma p \rightarrow J/\psi p; t=0)}{dt}$$

$$\frac{d\sigma(\gamma p \rightarrow J/\psi p; t=0)}{dt} = b_{J/\psi} X_{J/\psi} W_{\gamma p}^{\epsilon_{J/\psi}}$$

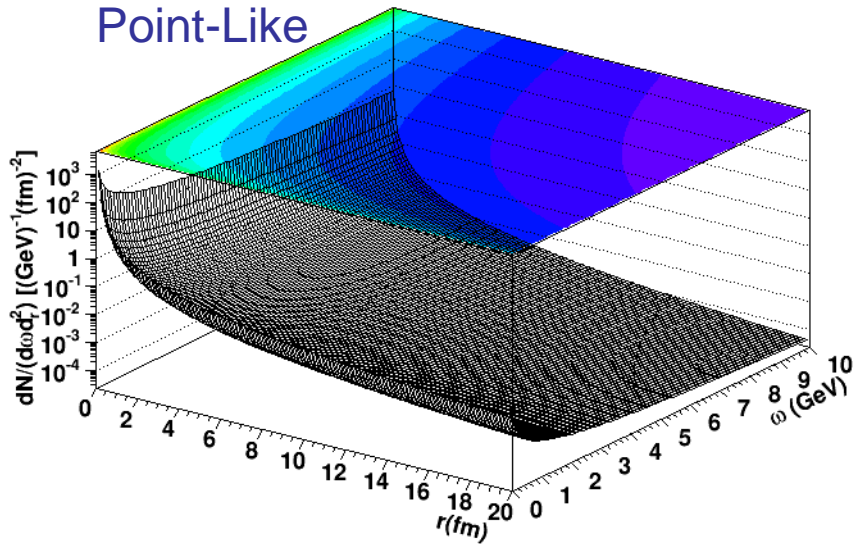
Comparison with data



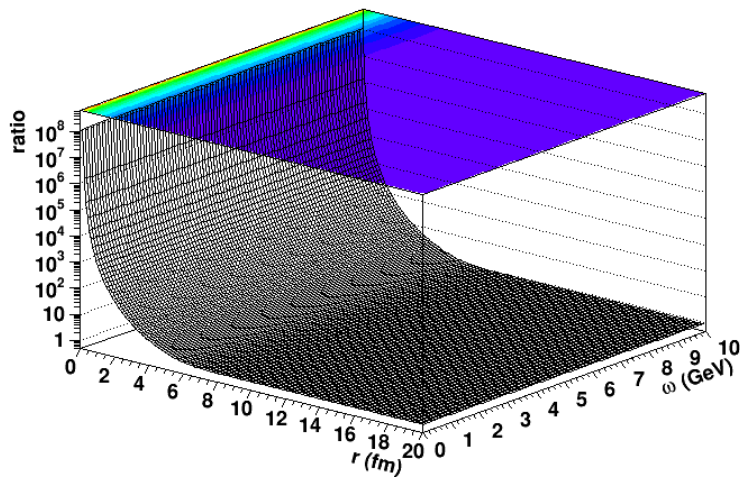
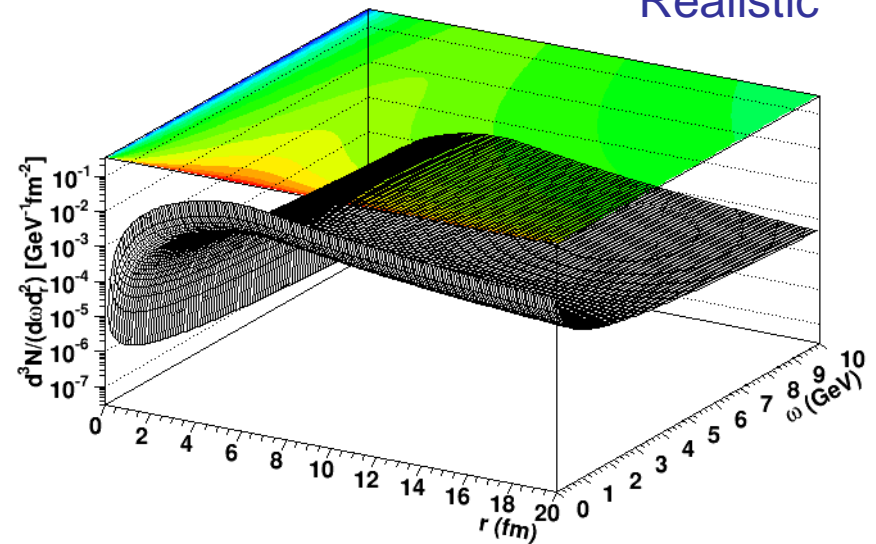
- ✓ Describe the data very well at very peripheral collisions (60-80%)!
- ✓ Overestimate at semi-central collisions!
- ✓ The charge density distribution?

Photon flux induced by Au

Point-Like

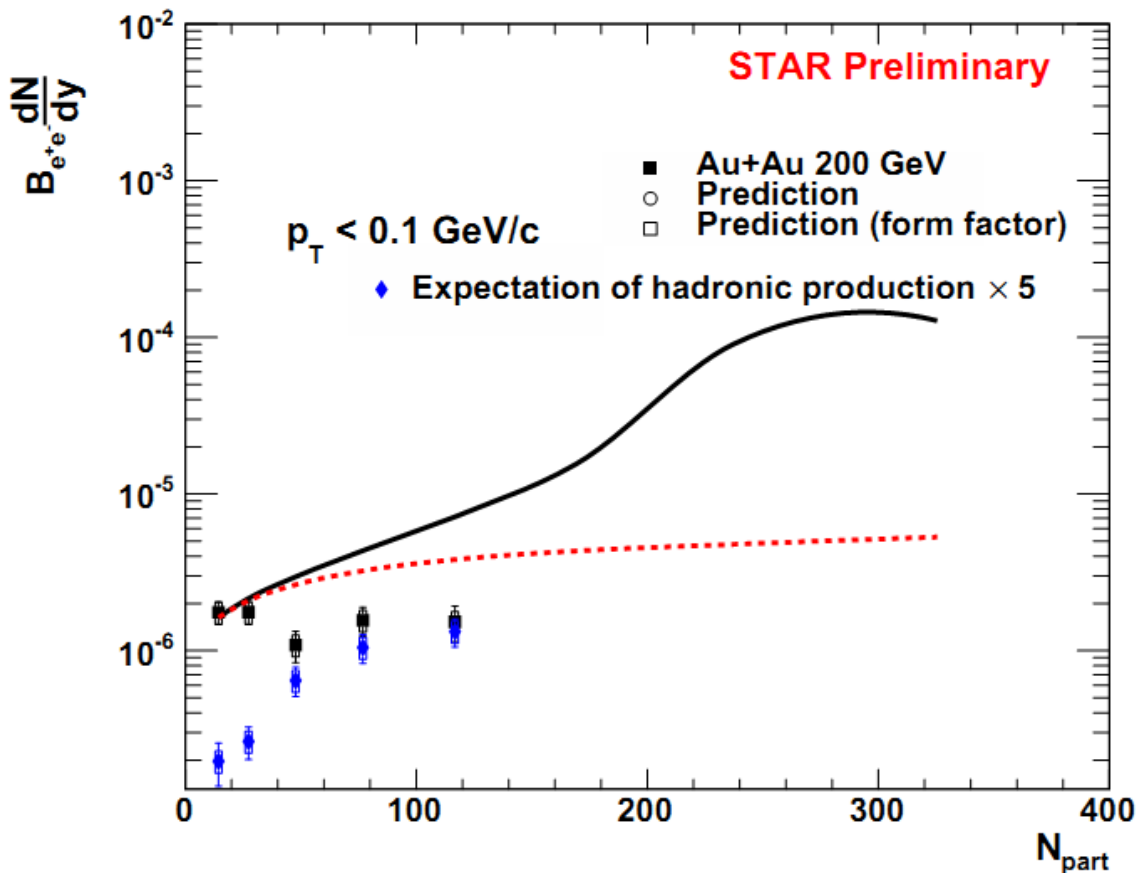


Realistic



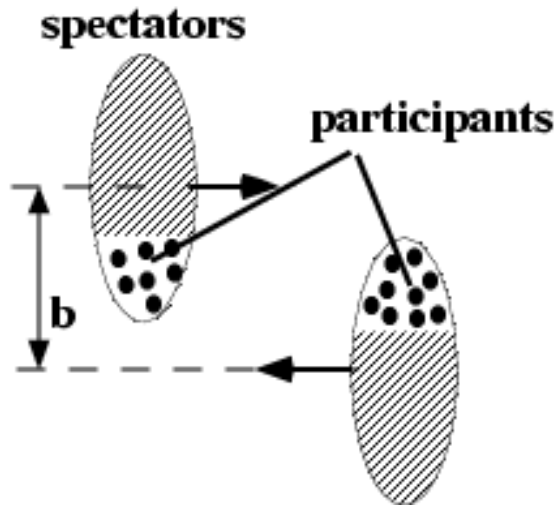
Collision system : Au+Au 200 GeV
The same magnitude outside the nucleus.
Big difference inside the nucleus!

Calculations with nuclear form factor

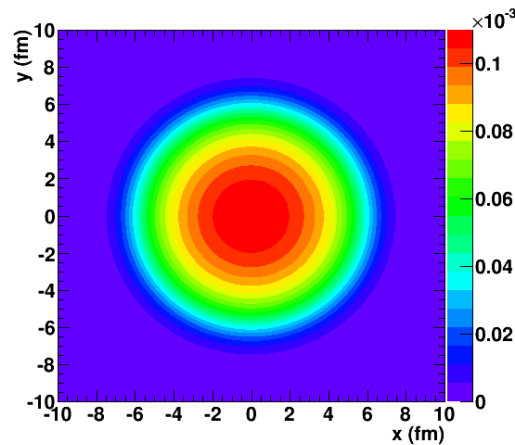


- ✓ Describe the data very well at very peripheral collisions (60-80%)!
- ✓ Still overestimate at semi-central collisions!
- ✓ Cancellation of photon flux or target in the overlapping region?

Different scenarios for calculations

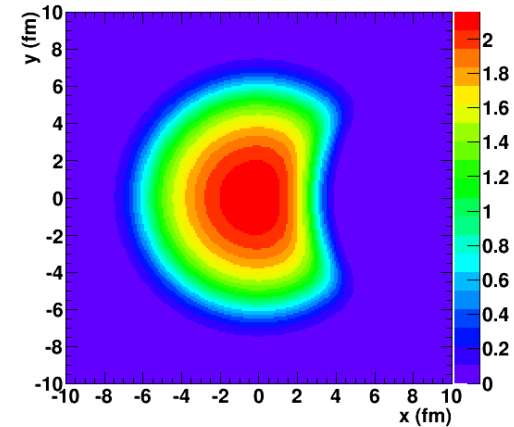


Photon emitter and target



nucleus

OR



spectator

The shape of spectator is from optical Glauber calculations!

Photon emitter

Nucleus

Nucleus

Spectator

Spectator

Target

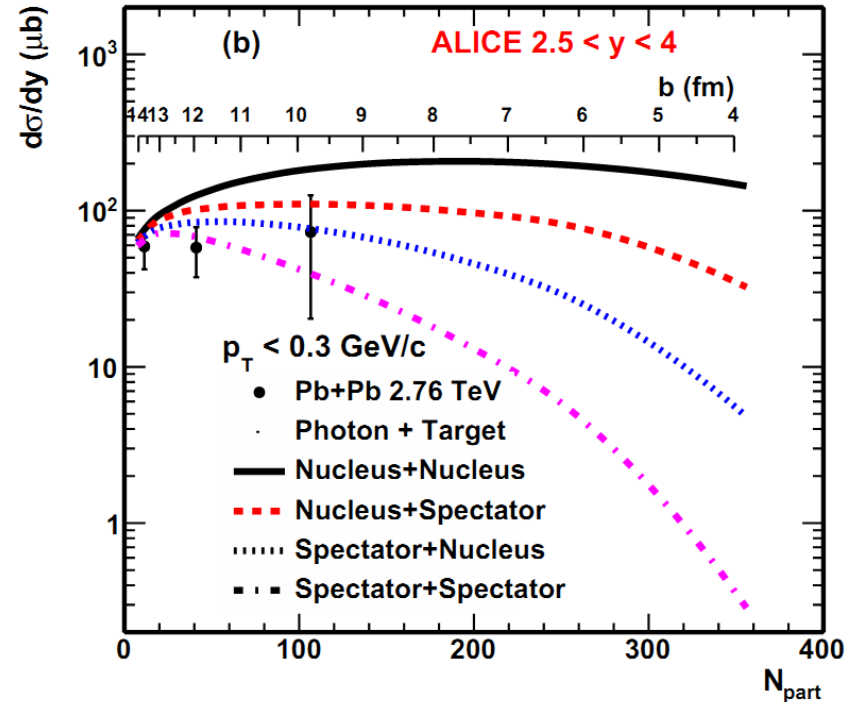
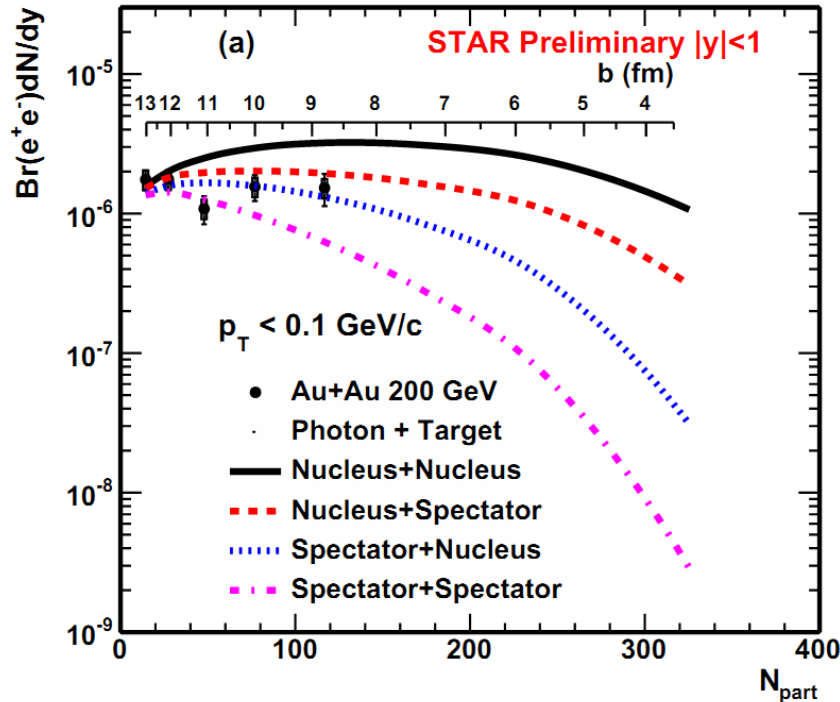
Nucleus (1)

Spectator (2)

Nucleus (3)

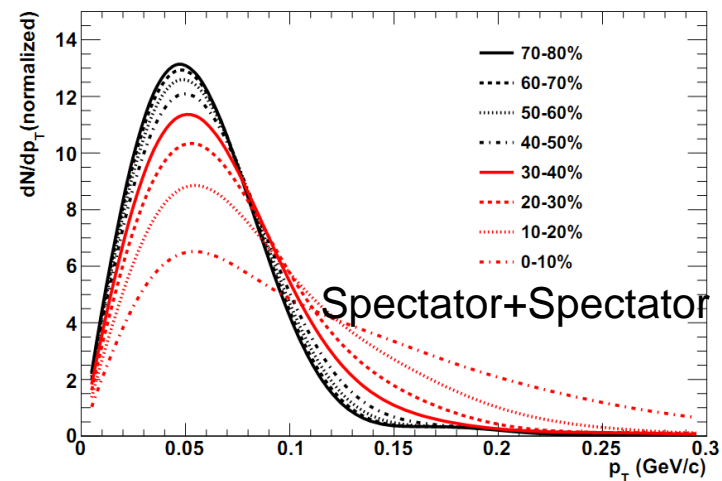
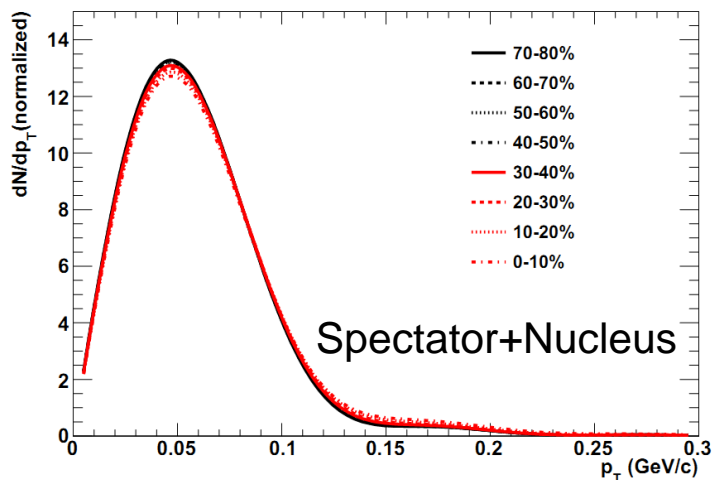
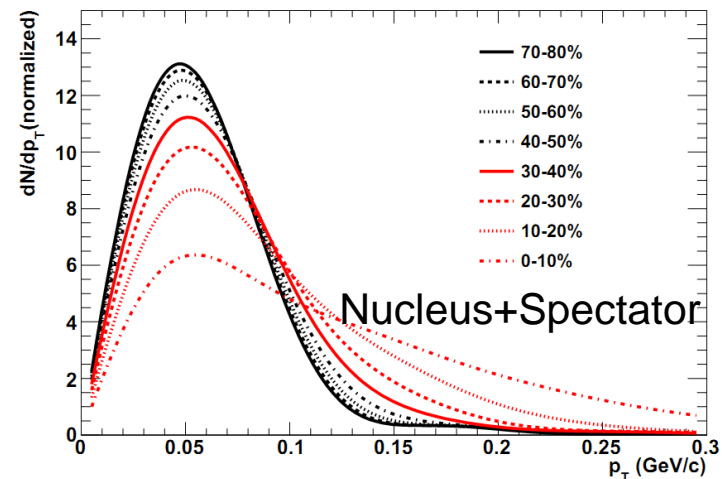
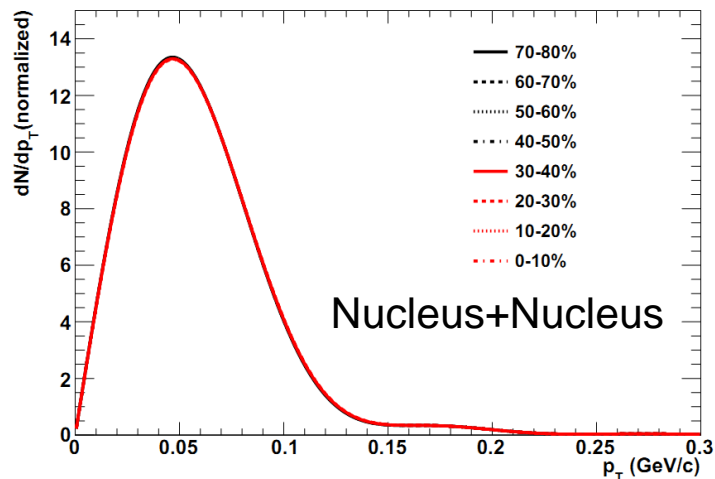
Spectator (4)

Calculations with different scenarios



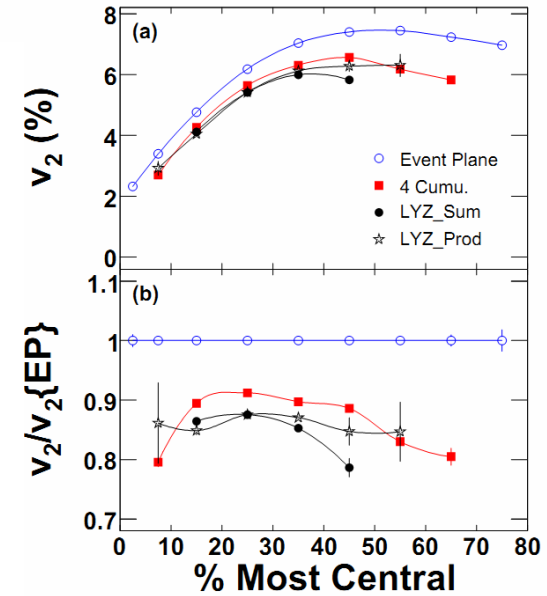
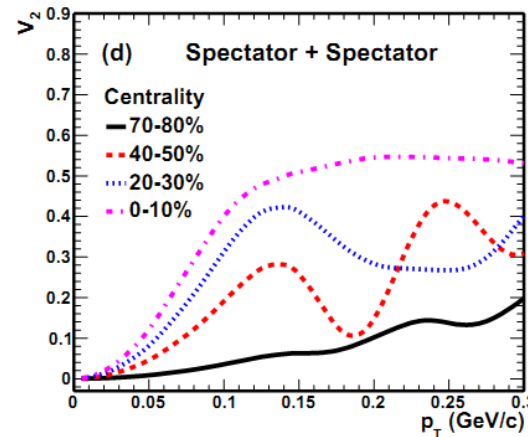
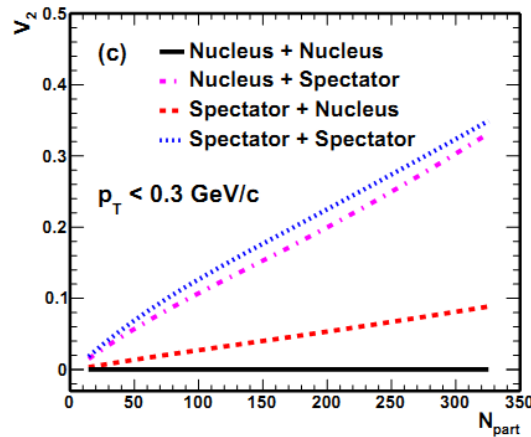
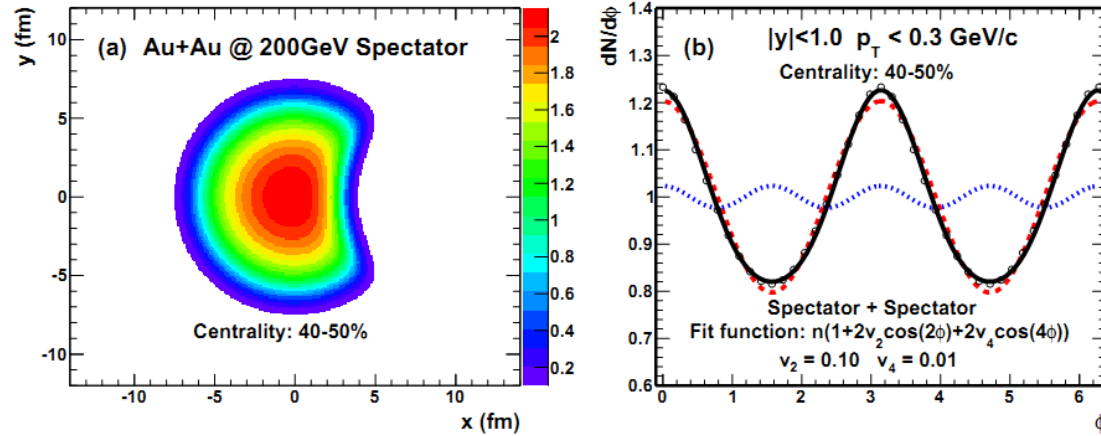
- ✓ Different scenarios have different trend toward central collisions!
- ✓ Spectator+Spectator: under predict the data in semi-central collisions.
- ✓ To distinguish the different scenarios, measurements at central collisions are needed!
- ✓ Cold Nuclear and hot medium effects are not included in the calculation.

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!

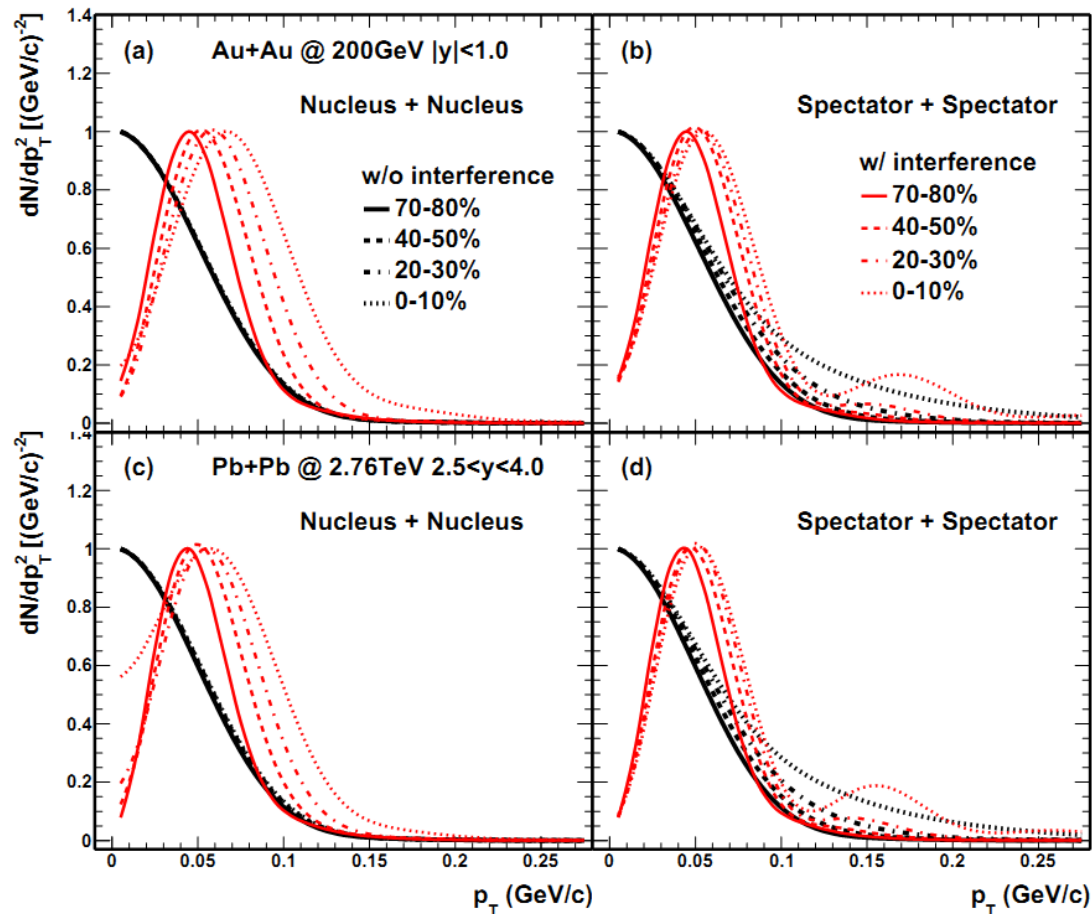
Production versus ϕ (relative to reaction plane)



Phys. Rev. C 77 (2008) 54901

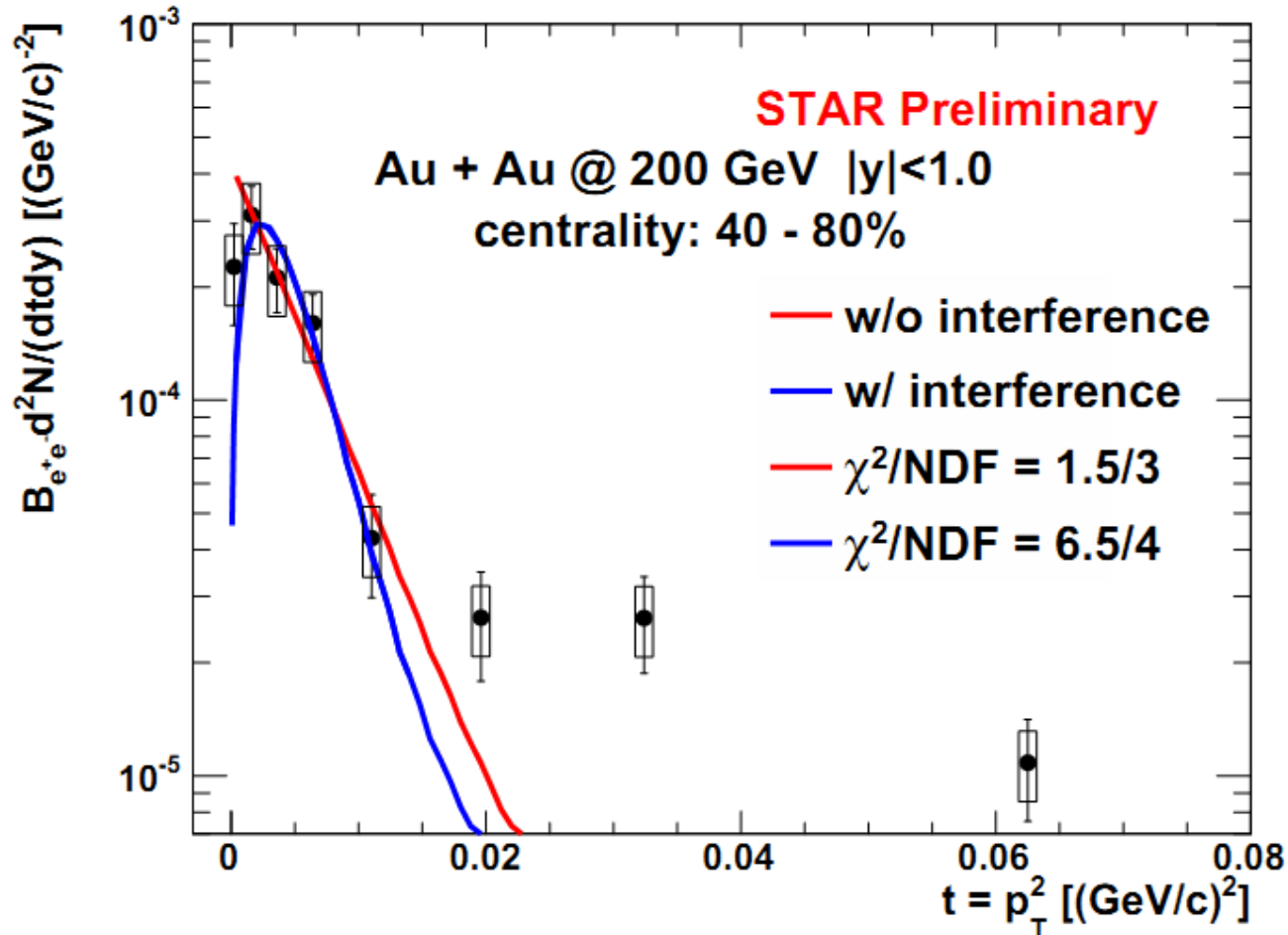
- ✓ Sensitive to the target!
- ✓ Large v_2 and sizeable v_4 will be observed if the target is spectator!
- ✓ V_2 increase dramatically toward central collisions!
- ✓ Probe of initial geometry of the overlap region!

p_T shape with interference



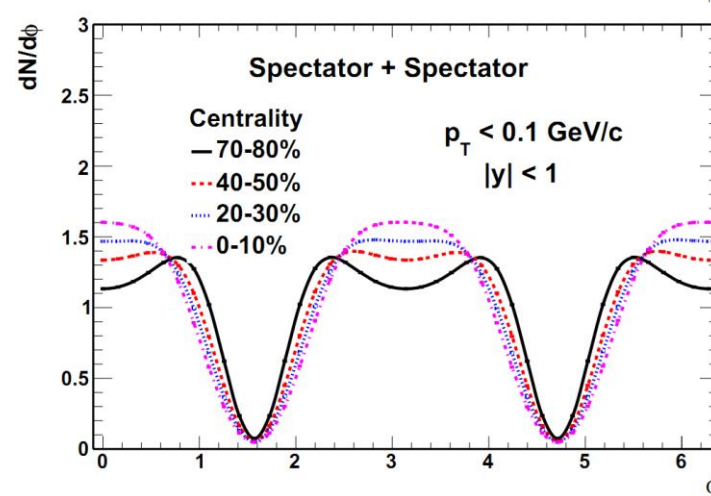
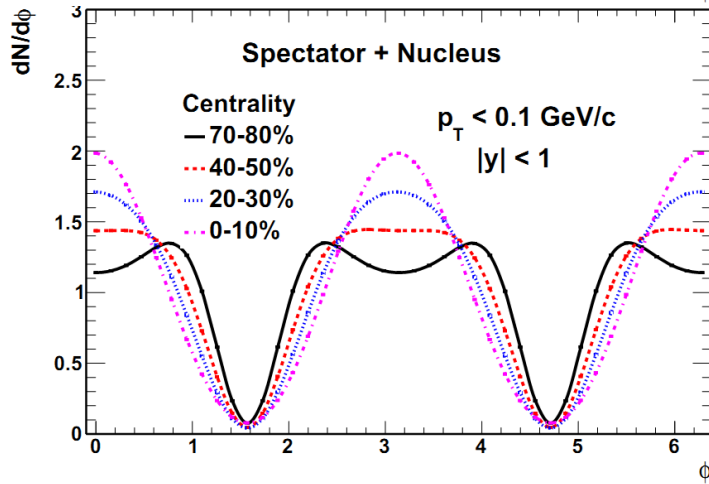
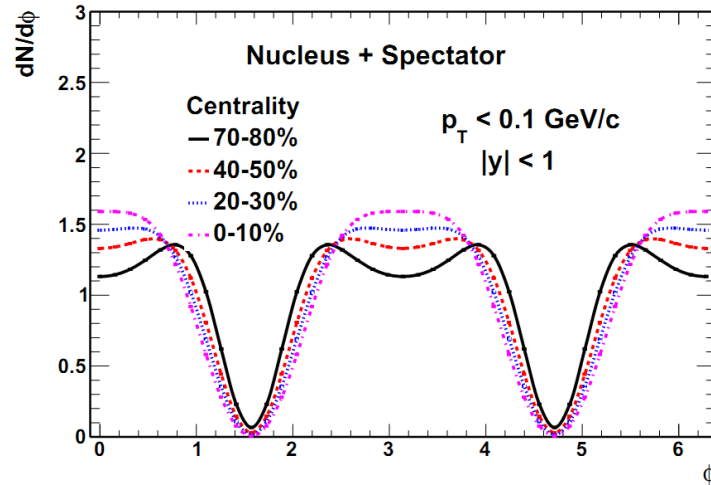
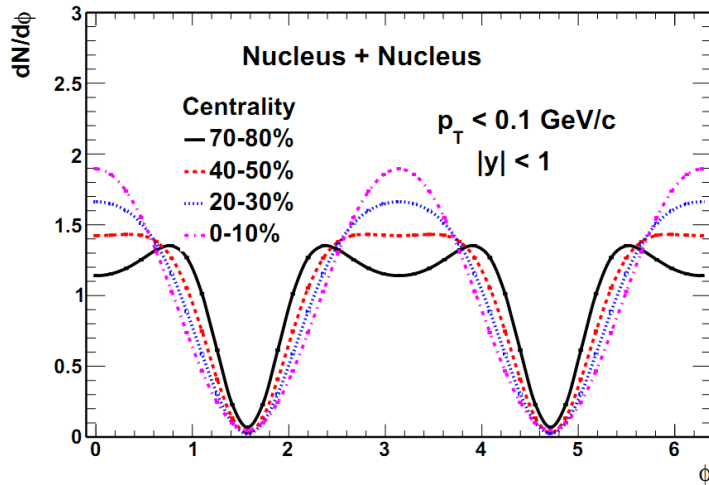
- ✓ Dramatically change the p_T spectra!
- ✓ Different interference pattern in different centrality!
- ✓ The effect is relative small with spectator coupling!

t distribution



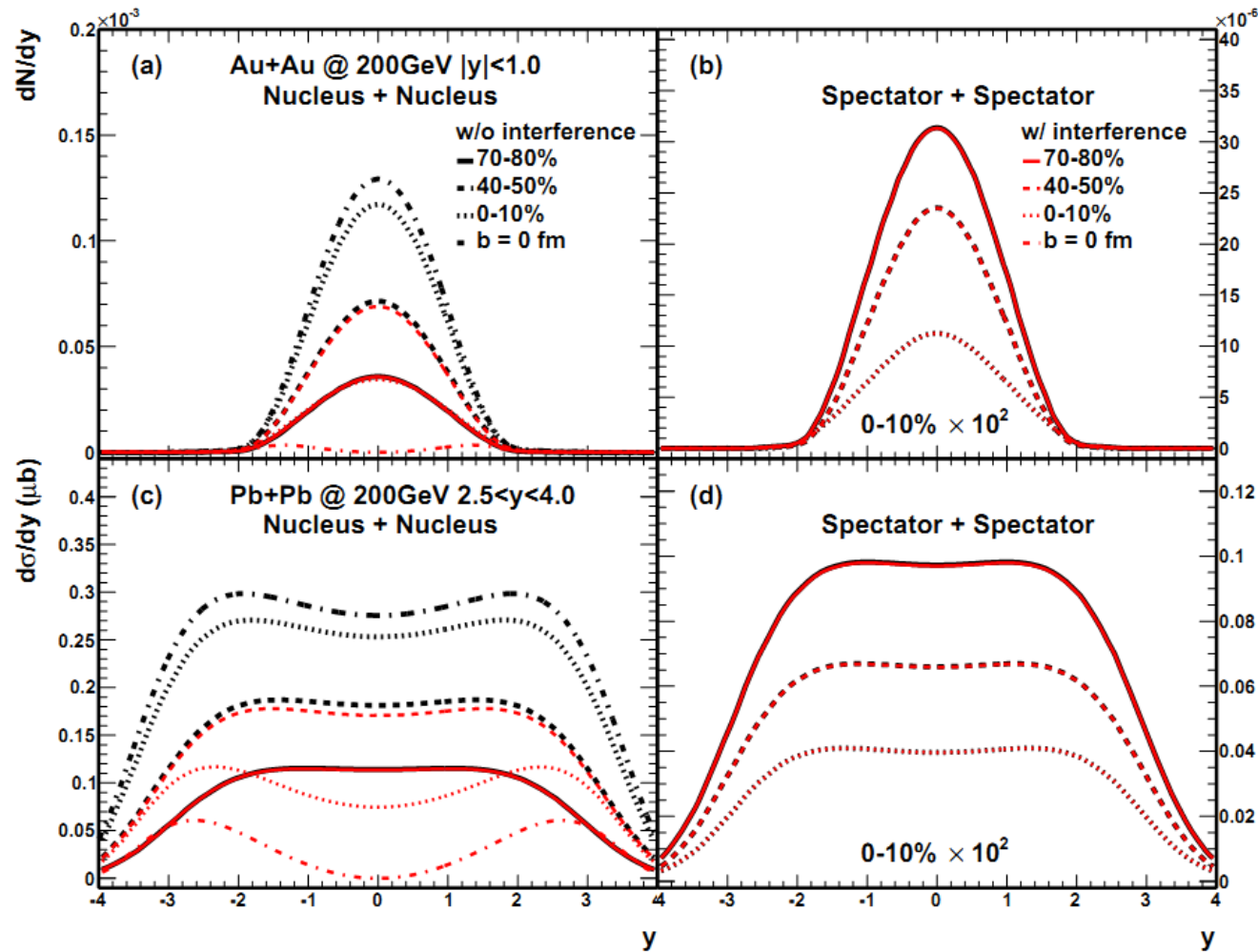
✓ Describe the data reasonably well

ϕ distribution with interference



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

Rapidity distribution with interference



- ✓ Dramatically change the rapidity distribution with nucleus coupling!
- ✓ Stay unaffected with spectator coupling!

Summary

- Significant excess of J/ψ 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.
- Theoretical calculations describe the data of peripheral collisions (60 – 80%)
 - ✓ Different scenarios have different trend toward central collisions!
 - ✓ Semi-central and central collisions: Nucleus+ Nucleus => overestimate
Spectator+Spectator => underestimate
 - ✓ p_T and ϕ distribution: sensitive to the target
 - ✓ The interference effect plays an important role for the production

Discussion

Hadronic produced J/ψ :

B-hadron decay

Feed-down from χ_c (18%) and $\psi(2s)$ (10%)

Color Screening

Regeneration

J/ψ from photoproduction:

No B-hadron decay

No feed-down from χ_c (18%)

Color Screening

Negligible regeneration

More sensitive to the color
screening of direct produced J/ψ ?

Photoproduction in UPC:

Very clean

Impact parameter and ϕ dependence ---
NO!

Photoproduction in hadronic collisions:

Not clean

Impact parameter and ϕ dependence ---
YES!

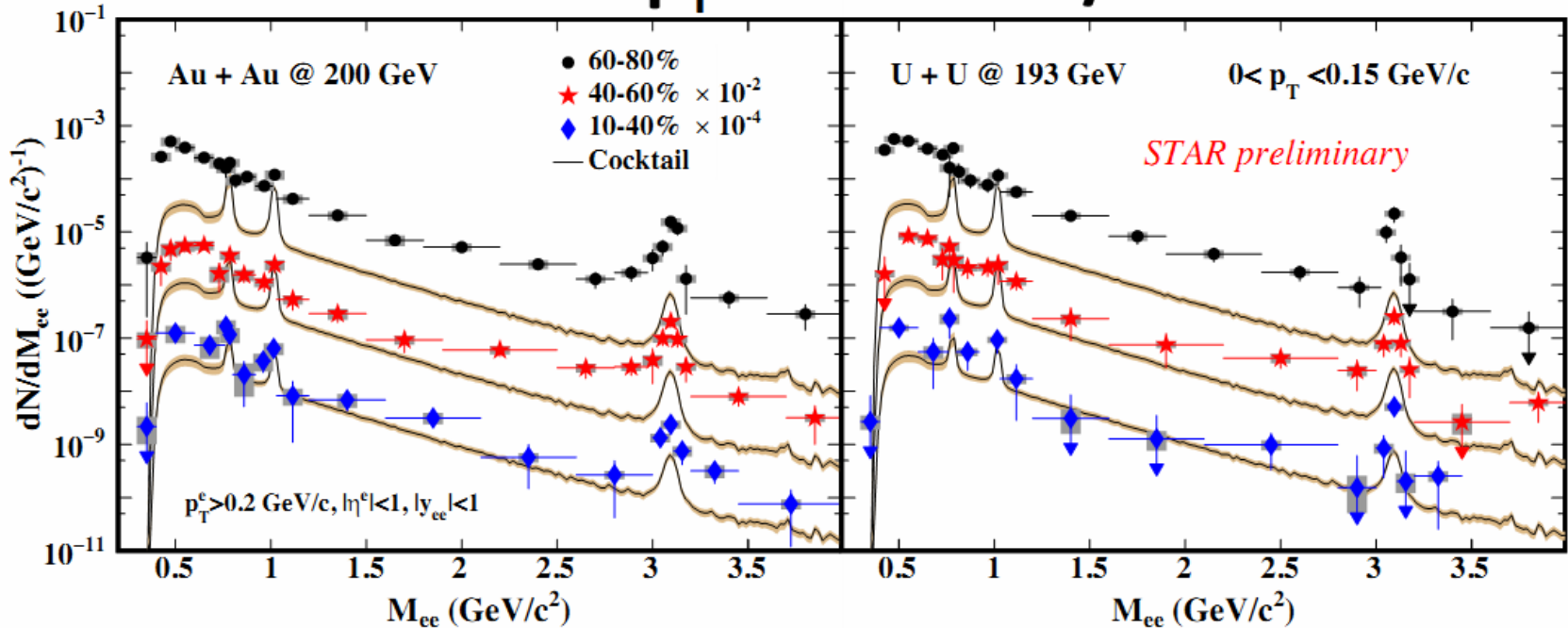
Test the medium?

➤ Perspectives:

- ✓ Measurements in more central collisions
- ✓ p_T shape and ϕ measurement: the target is nucleus or spectator?
- ✓ photon-photon process ($\pi^0, \eta, \eta', f_2(1270), a_2(1320), \pi^+\pi^-, e^+e^-, \mu^+\mu^- \dots$): test the photon emitter (spectator or nucleus)
- ✓ Incoherent contribution?
- ✓ Cold Nuclear Matter and hot medium effects?

Measurements beyond J/ψ

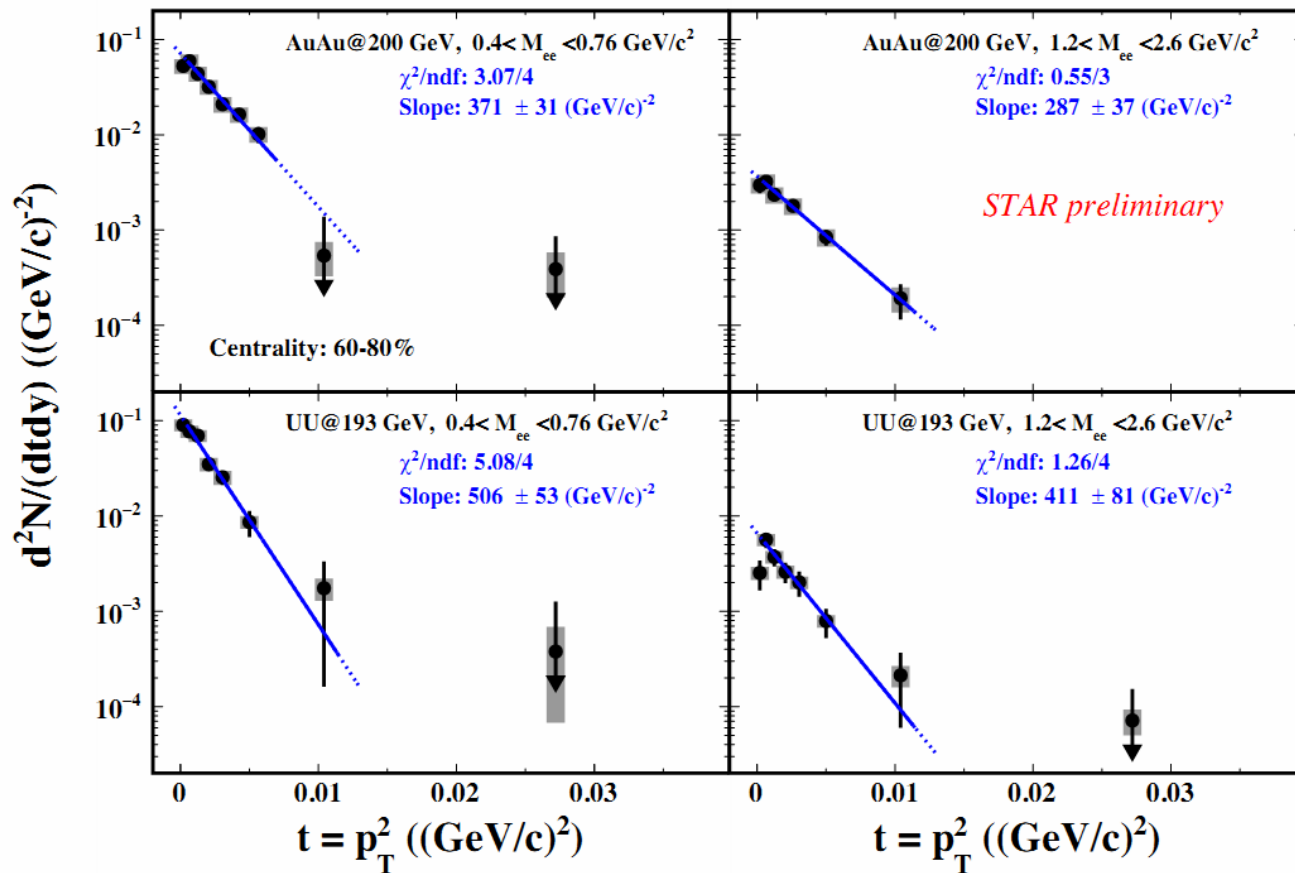
$0 < p_T < 0.15 \text{ GeV}/c$



Analysis done by Shuai Yang

- ✓ Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range.
- ✓ The observation of coherent photon – photon interactions!
- ✓ Where is the ρ^0 peak?

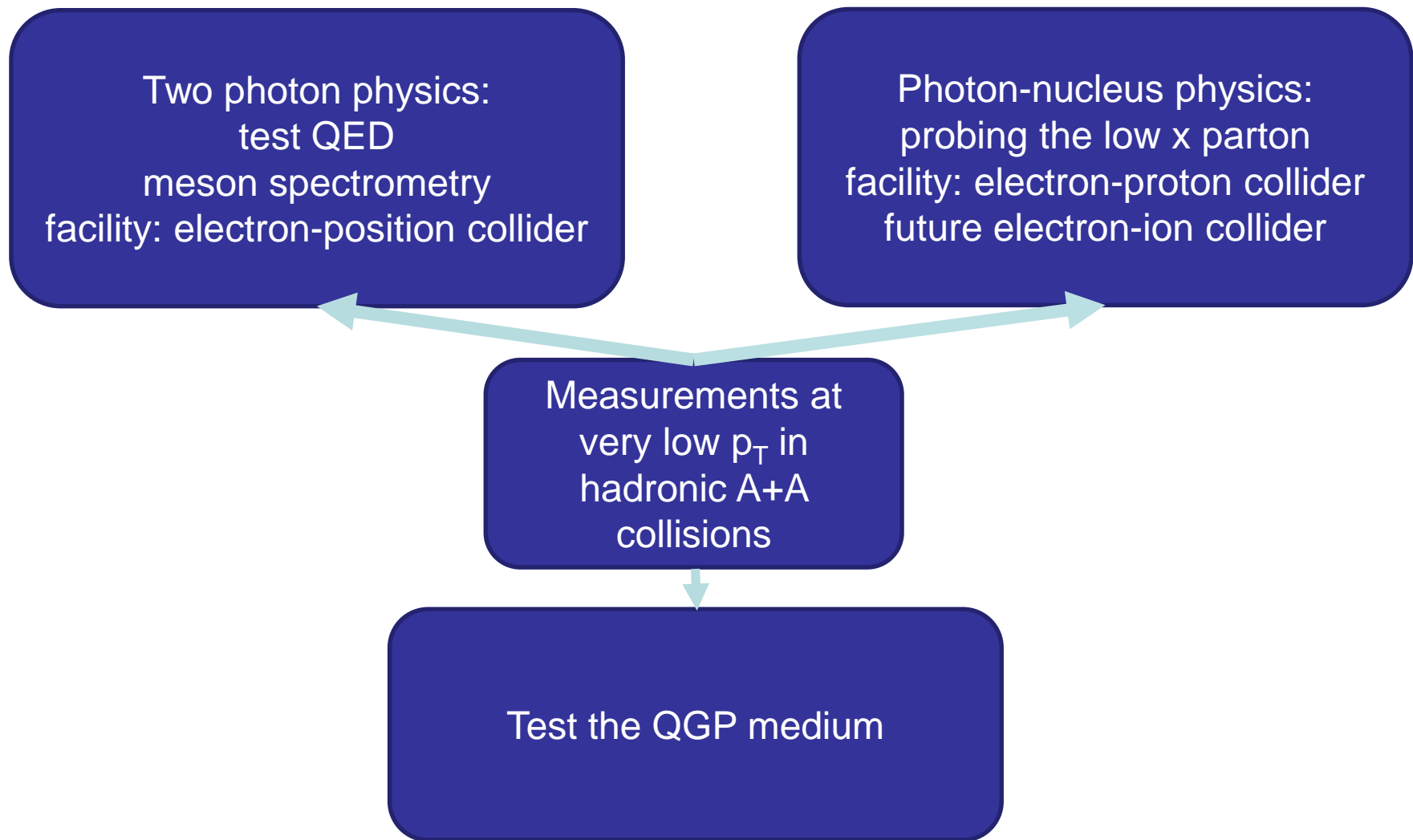
t distribution for dielectron



Analysis done by Shuai Yang

- ✓ Unexpected small slope parameter?
- ✓ More theoretical efforts!

Outlook



Back-up

- Heavy nuclei carry strong electric and magnetic fields
 - Fields are perpendicular -> treat as nearly-real virtual photons
 - $E_{\text{max}} = \gamma hc/b$
 - Photonuclear interactions
 - Two-photon interactions
- Visible when $b > \sim 2R_A$, so there are no hadronic interactions;

Energy	AuAu RHIC	pp RHIC	PbPb LHC	pp LHC
Photon energy (target frame)	0.6 TeV	~ 12 TeV	500 TeV	$\sim 5,000$ TeV
CM Energy $W_{\gamma\gamma}$	24 GeV	~ 80 GeV	700 GeV	~ 3000 GeV
Max $\gamma\gamma$ Energy	6 GeV	~ 100 GeV	200 GeV	~ 1400 GeV

Phyiscis of UPC

- The energy frontier for electromagnetic probes
 - Maximum CM energy $W_{\gamma p} \sim 3 \text{ TeV}$ for pp at the LHC
 - ~ 10 times higher in energy than HERA
 - Probe parton distributions in proton and heavy-ions down to
 - Bjorken- x down to a few 10^{-6} at moderate Q^2
- Electromagnetic probes have $\alpha_{\text{EM}} \sim 1/137$, so are less affected by multiple interactions than hadronic interactions
 - “Precision” measurements,
 - Exclusive interactions
- Two-photon physics & couplings at the energy frontier
 - New particle searches (axions), $\gamma\gamma \rightarrow W^+W^-$, etc.

Photon production of vector meson

- Process has large cross-sections
- Produced via colorless 'Pomeron exchange'
 - Require ≥ 2 gluon exchange for color neutrality
 - Gluon ladder
- Light meson production usually treated via vector meson dominance model
 - ρ , direct $\pi^+\pi^-$, ω , ρ' observed at RHIC
- Heavy meson production treated with pQCD
 - J/ψ , ψ' , $Y(1S)$, $Y(2S)$, and $Y(3S)$ seen at LHC
- Rapidity maps into photon energy
 - $k = M_V/2 \exp(\pm y)$
 - Twofold ambiguity – which nucleus emitted the photon?
 - Cross-section is convolution of bi-directional photon flux with $\sigma(\gamma A)$
 - Photon flux is understood to $< 10\%$

