Measurements and calculations of very low p_T J/ψ yield in A+A collisions

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Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks

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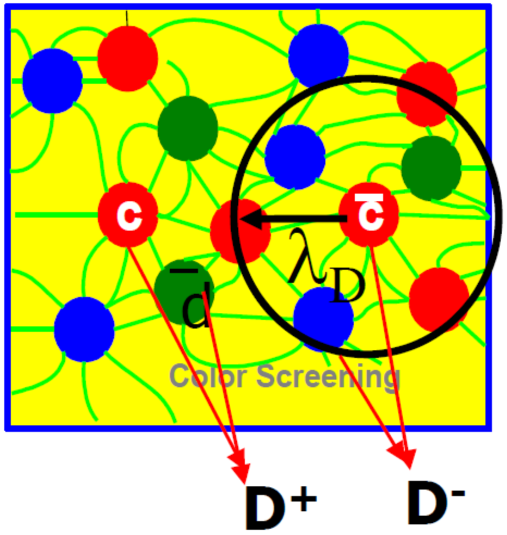
J/ψ as a sensitive probe of QGP

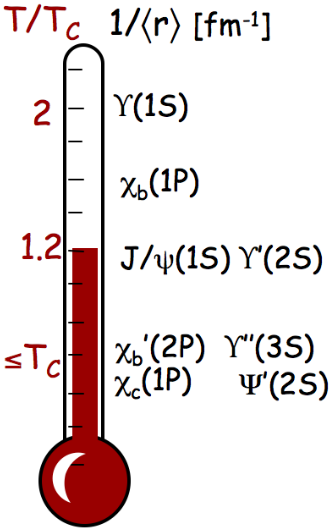
- Color Screening: the quark-antiquark potential is color-screened by surrounding partons -> dissociation
  - A smoking gun signature for QGP formation

  T. Matsui and H. Satz, PLB 178 (1986) 416



- Thermometer: different quarkonia states of different binding energies dissociate at different temperatures -> sequential melting

  A. Mocsy EPJC61 (2009) 705



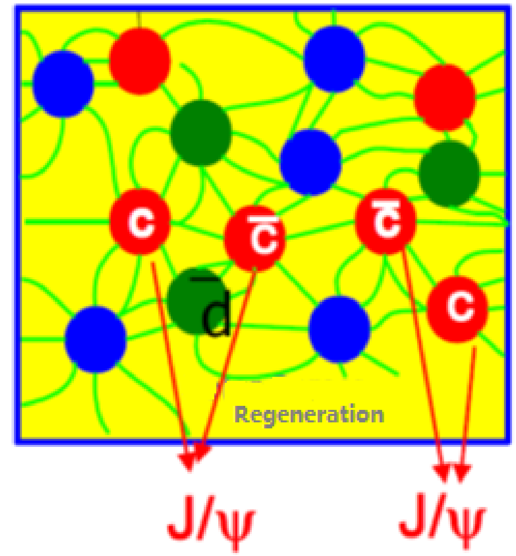
Not that simple --- other effects

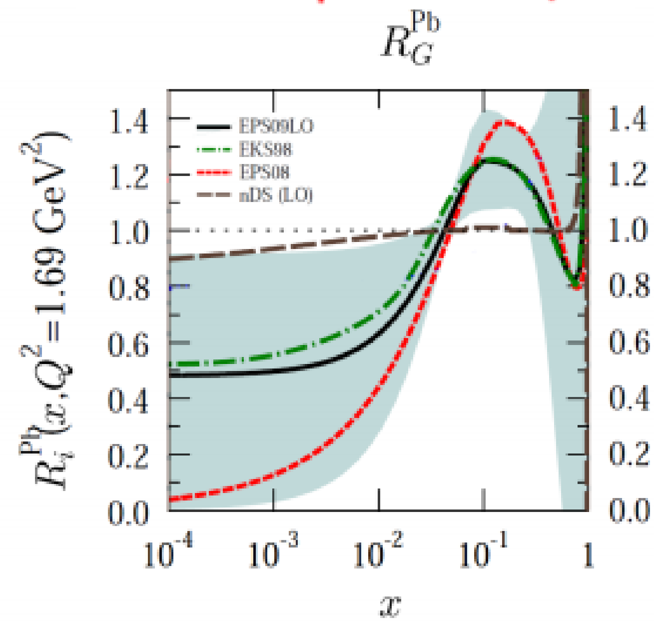
- Hot medium effects:
  - ✓ Regeneration
    -Recombination of charm quarks

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

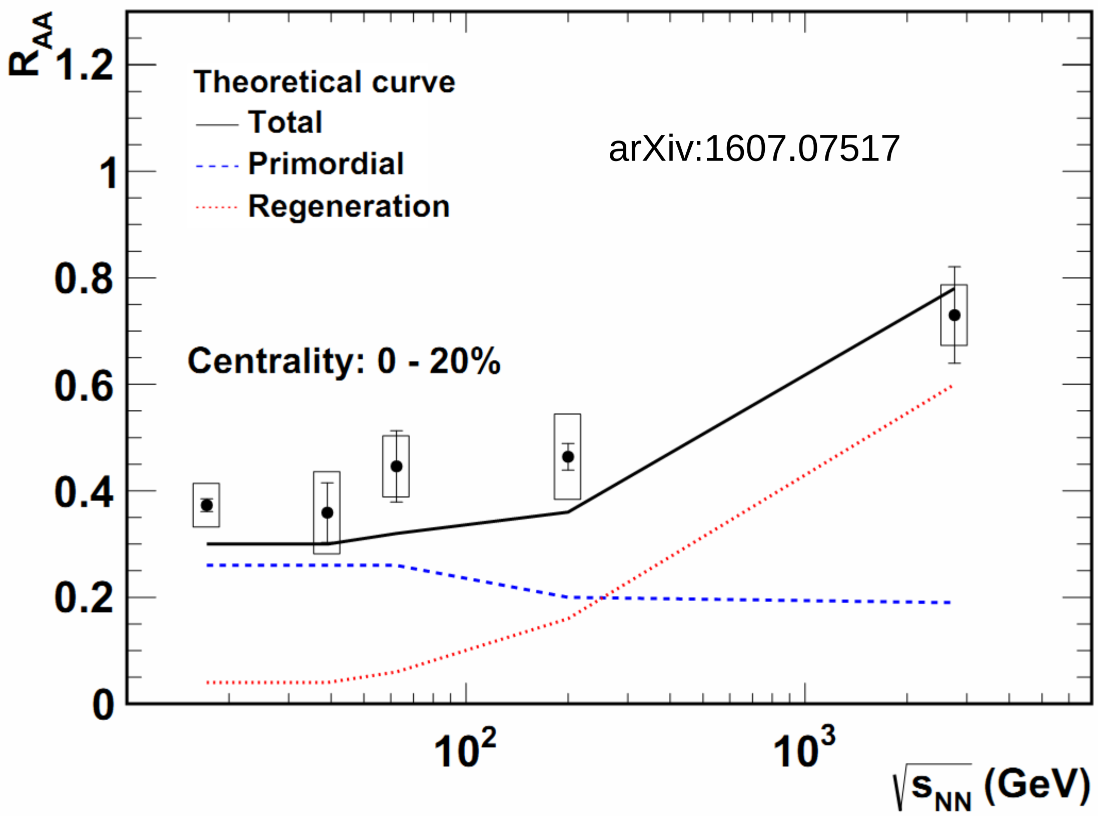
- Final state effect:
  - ✓Dissociation by co-mover

- Feed down contribution:
  - ✓ χ_c, ψ(2s), B-hadron …



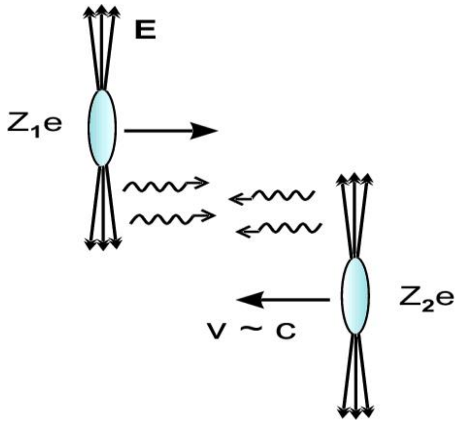


"Dissociation + Regeneration" picture



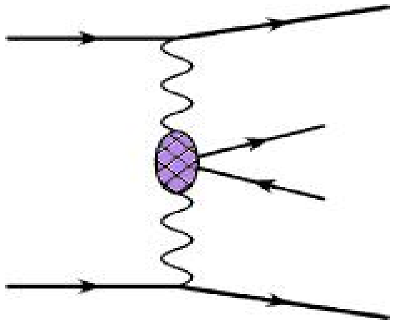
The interplay of these effects can explain the results from SPS to LHC!

Photon interactions in A+A



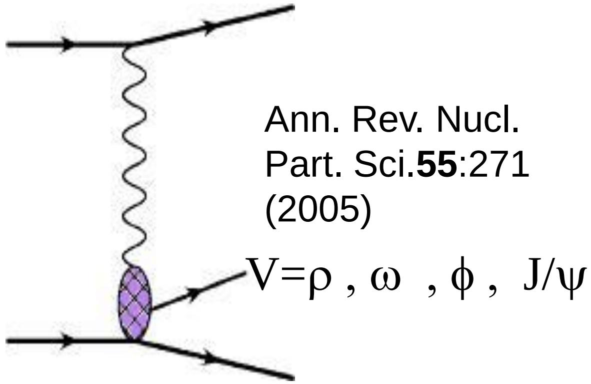
Electromagnetic interaction

=



Photon-photon interactions

+

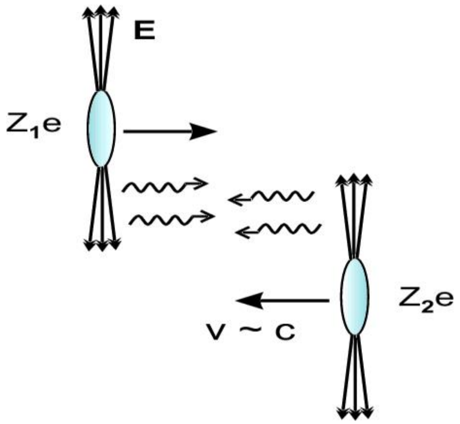


Photon-nucleus interactions

Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

- 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.
  - Studied in detail for Ultra-Peripheral Collisions.

Quasi-real photons --- Equivalent photon approximation



Coherent limitation: $Q^2 \leq 1/R^2$ => quasi-real !

Photon four momentum: $q^u = (\omega,\ \overrightarrow{q_T}, \omega/v)$

$$Q^2 = \frac{\omega^2}{\gamma^2} + q_T^2$$

$$\omega \leq \omega_{max} \sim \frac{\gamma}{R}$$

$$q_T \leq 1/R$$

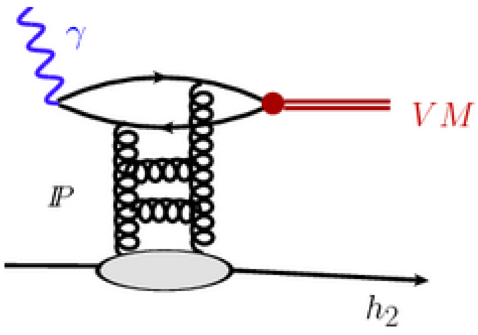
Energy	AuAu RHIC	pp RHIC	PbPb LHC	pp LHC
Photon energy (target frame)	0.6 TeV	~12 TeV	500 TeV	~5,000 TeV
CM Energy $W_{\gamma p}$	24 GeV	~80 GeV	700 GeV	~3000 GeV
Max $\gamma\gamma$ Energy	6 GeV	~100 GeV	200 GeV	~1400 GeV

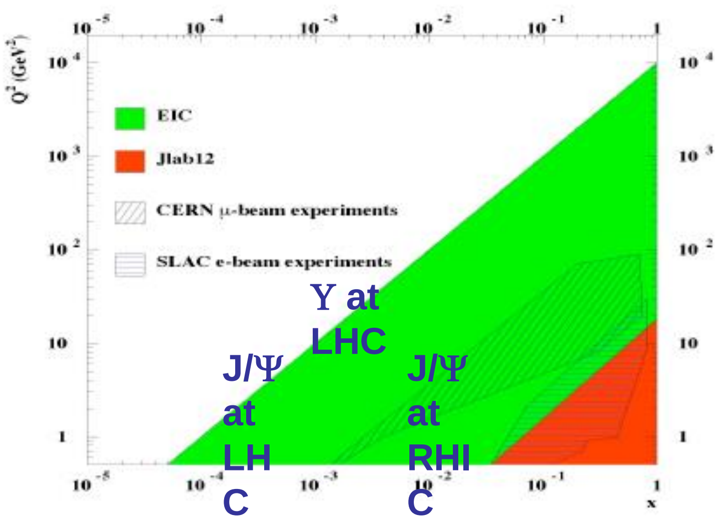
$$\frac{d^3 N_\gamma(\omega, k_\perp)}{d\omega d^2 k_\perp} = \frac{\alpha_{em}^2 Z^2 F^2(\vec{k}) k_\perp^2}{\pi^2 (k_\perp^2 + \omega^2/\gamma^2)^2}.$$

Weizsäcker-Williams virtual photon spectrum

Vector meson photon-production

- Vector meson production:
  - ✓ chargeless 'Pomeron exchange'
  - ✓ Light meson production usually treated via vector meson dominance model:
    ρ, direct $\pi^+\pi^-$, ω….
  - ✓ Heavy meson production treated with pQCD:
    J/ψ, ψ', Υ(1S), Υ(2S), Υ(3S)…





- Sensitive to the gluon distribution:

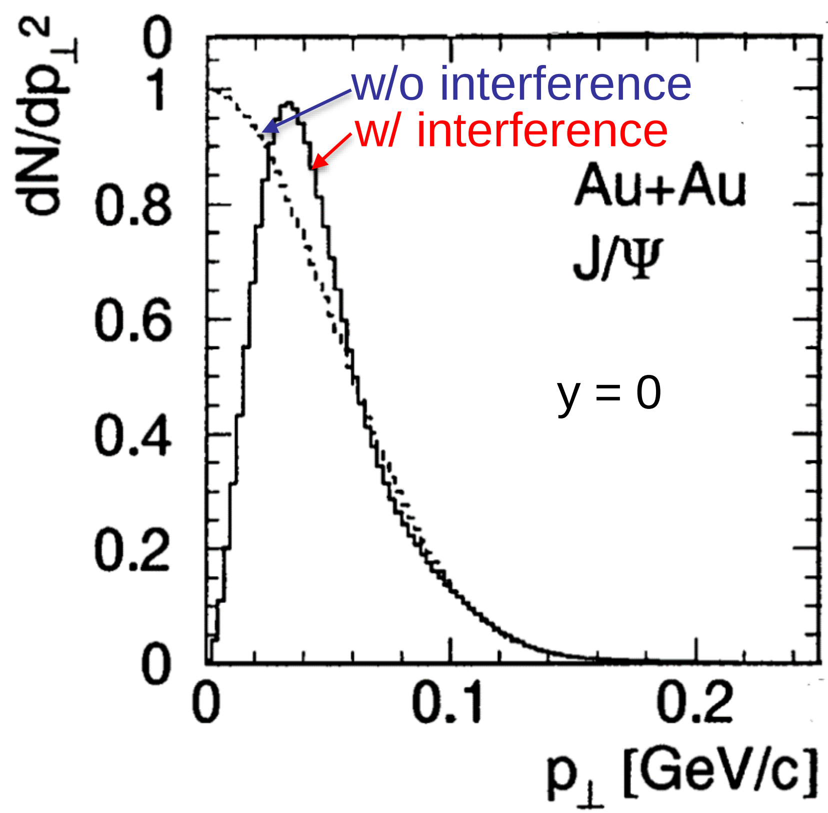
$$\left.\frac{d\sigma(\gamma A \to VA)}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xG_A(x,Q^2)\right]^2$$

$$x = \frac{M_V e^{\pm y}}{\sqrt{s}} \quad Q^2 = M_V^2/4$$

RHIC y=0: $x \sim 0.01$
LHC y=0: $x \sim 0.001$

Features of coherent produced J/ψs

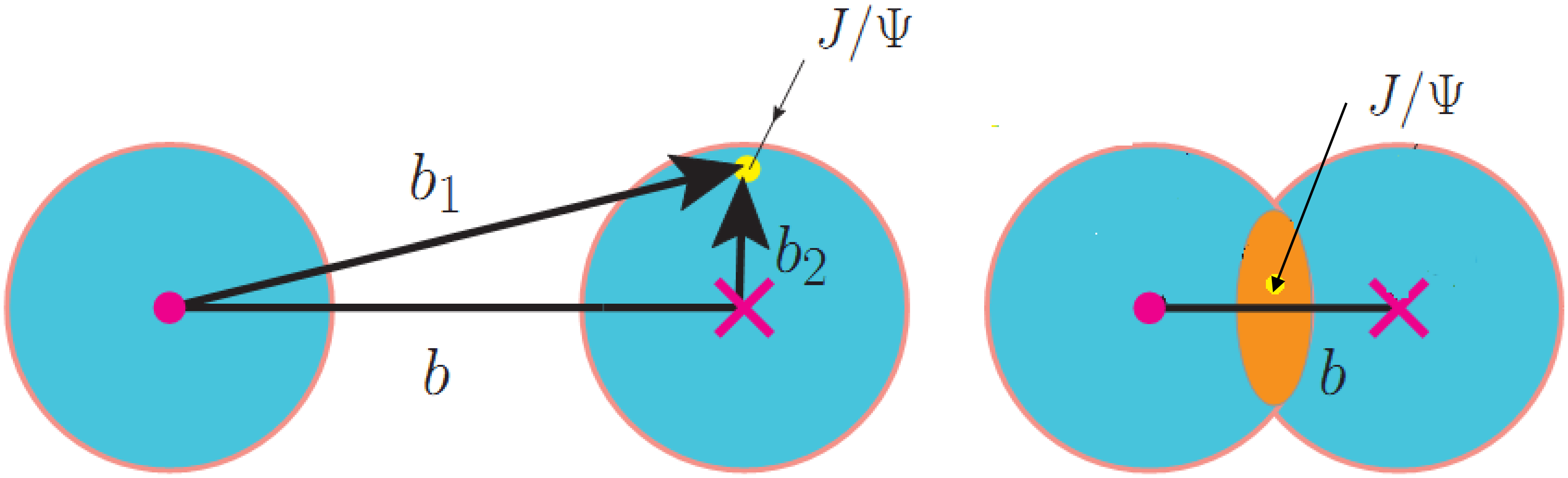
- Coherently:
  - ✓ Both nuclei remain intact
  - ✓ Photon/Pomeron wavelength $\lambda = \frac{h}{p} > R_A$
  - ✓ $p_T < h/R_A$ ~30 MeV/c for heavy ions
  - ✓ Strong couplings ($Z\alpha_{EM}$ ~ 0.6) → large cross sections
- Interference:
  - ✓ Two indistinguishable processes (photon from A_1 or A_2)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



PRL **84** 2330 (2000)

J/ψ hadronic production and photoproduction

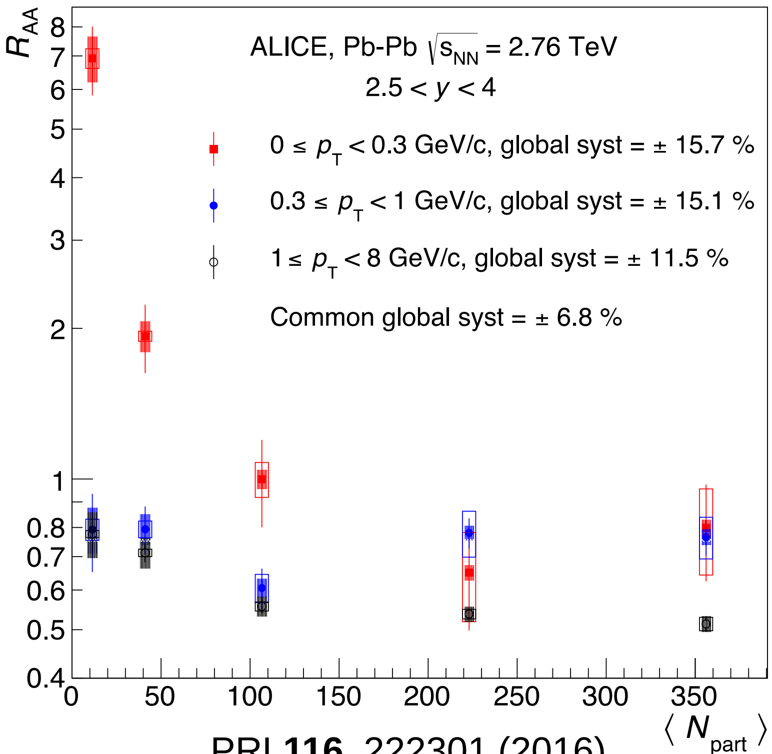
- The J/ψ can be produced via photoproduction
- Conventionally, only in Ultra-Peripheral Collisions (UPC)
  - ✓ UPC conditions: $b > 2R_A$, no hadronic interactions
  - ✓ Both nuclei stay intact
- The strong interactions in hadronic collisions would break the nuclei, destroy the coherent condition



UPC collisions:
J/ψ photoproduction

hadronic collisions:
J/ψ hadronic production and modification

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

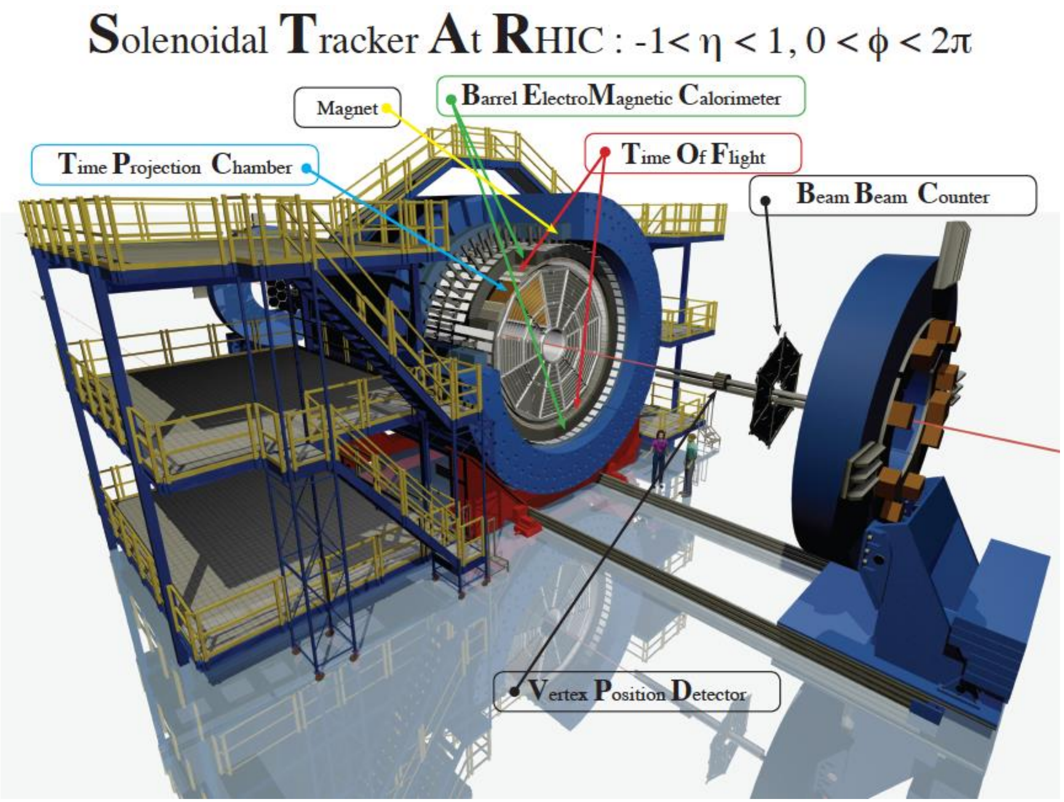


PRL**116**, 222301 (2016)

- ✓ 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?

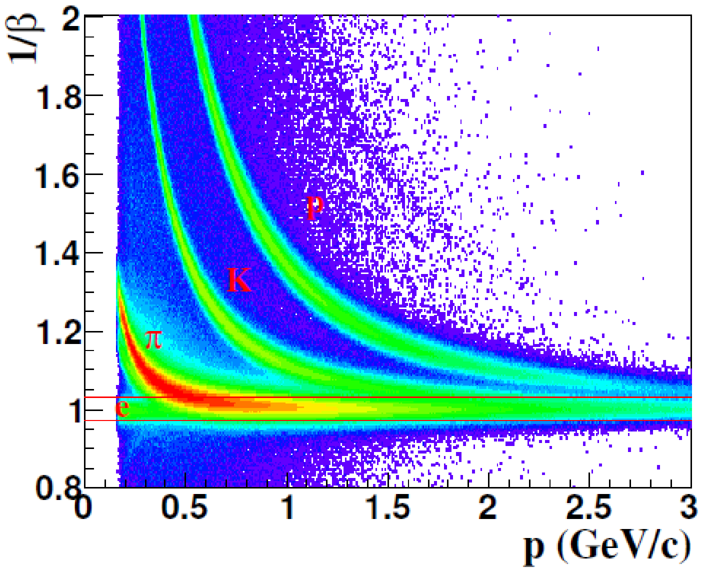
- Measurement of J/ψ yield at very low p_T in hadronic collisions (U+U and Au+Au):
  - Enhancement of J/ψ yield at very low p_T?
  - If so, what are the properties and origin of the excess?
    - p_T ,centrality and system size dependence of the excess; t distribution.

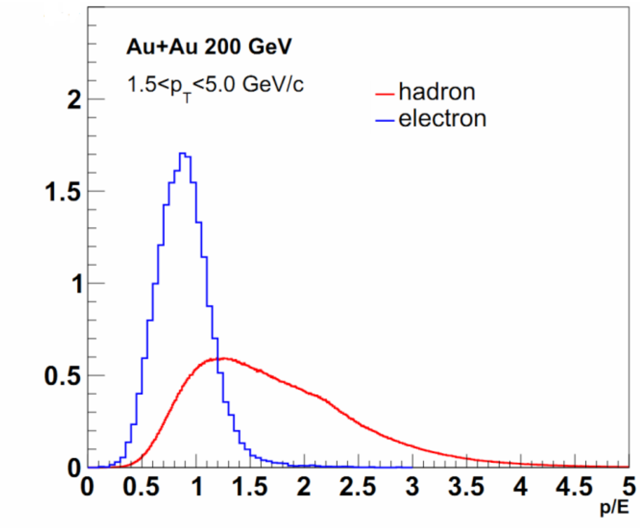
STAR detector

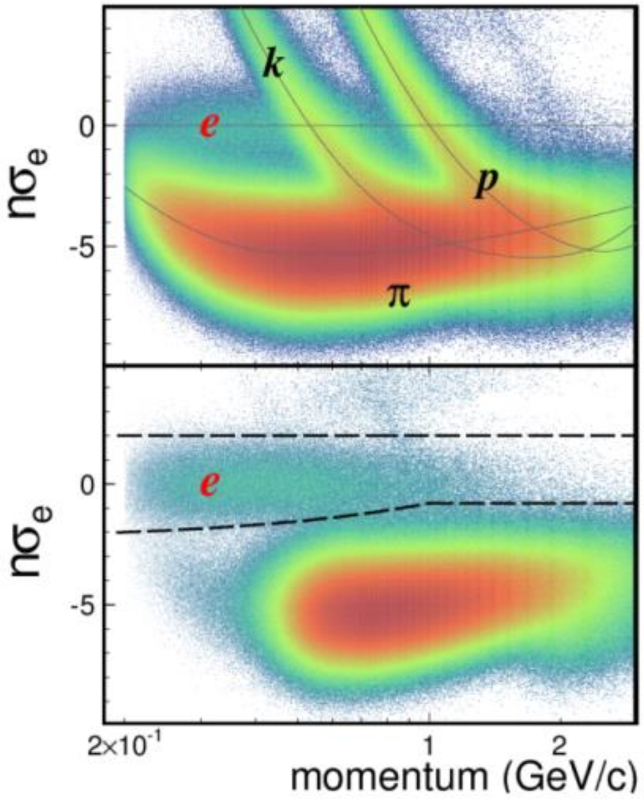


- **Large acceptance:**
  $|\eta| < 1,\ 0 < \phi < 2\pi$
- **Time Projection Chamber**
  (TPC) – tracking, particle identification, momentum
- **Time of Flight detector**
  (TOF) – particle identification
- **Barrel ElectroMagnetic Calorimeter**
  (BEMC) – electron identification, triggering

Electron Identification

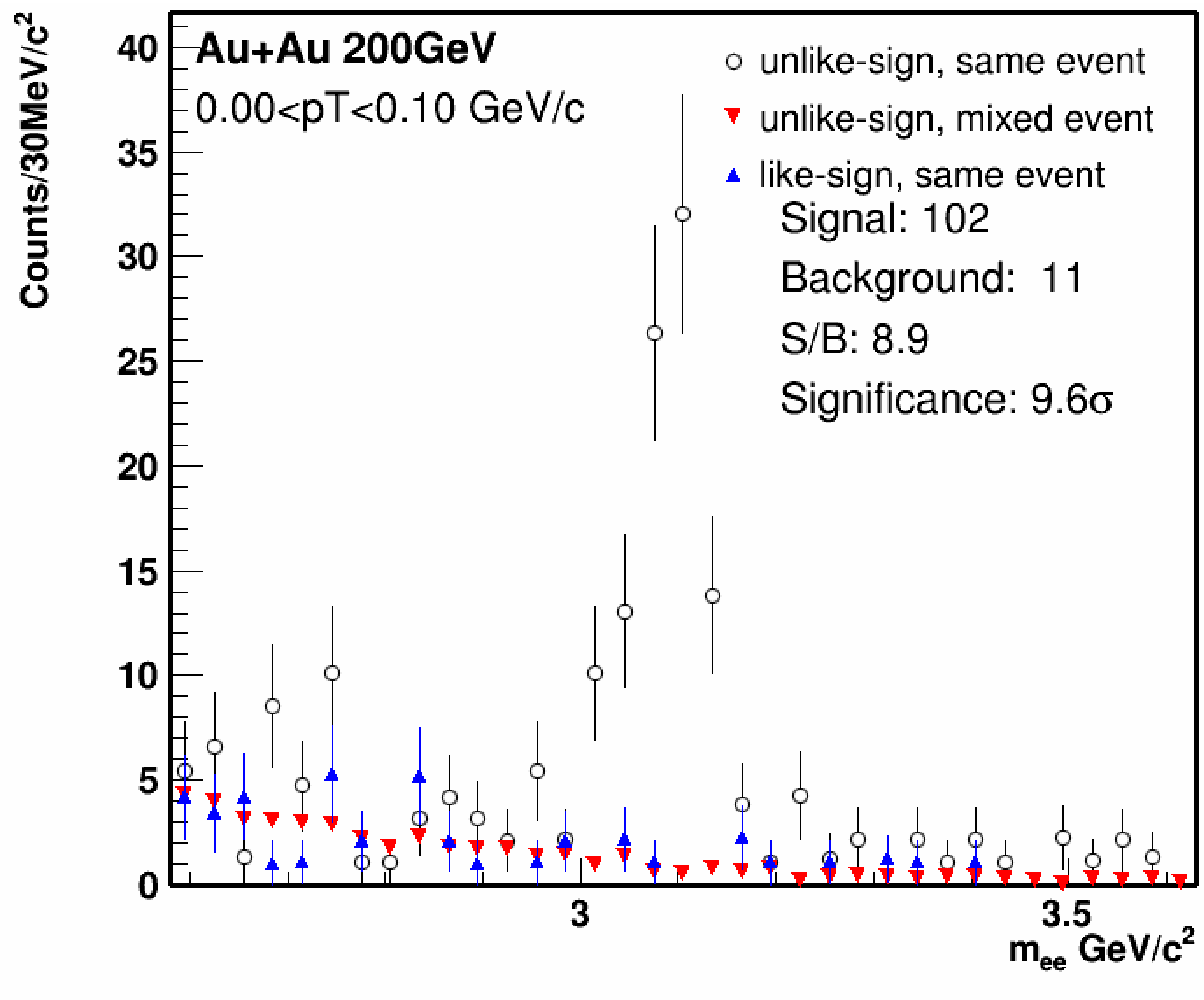






$n\sigma_e$: Normalized dE/dx

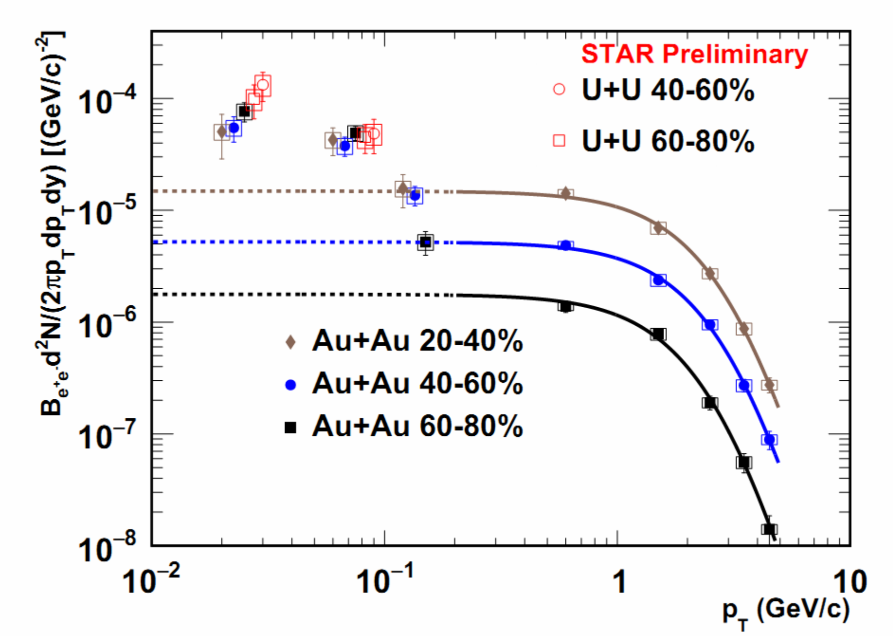
J/ψ signal

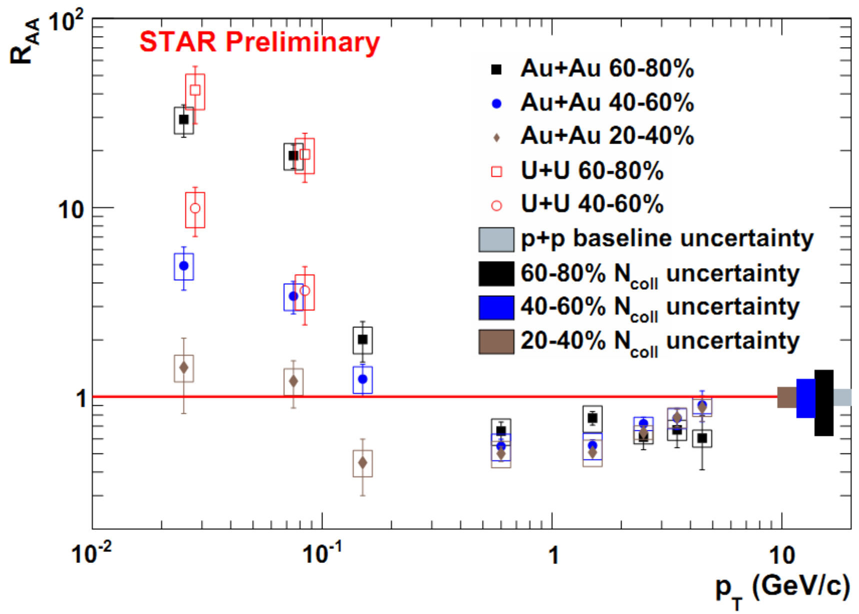


Centrality: 40- 80%

Good signal over background ratio!

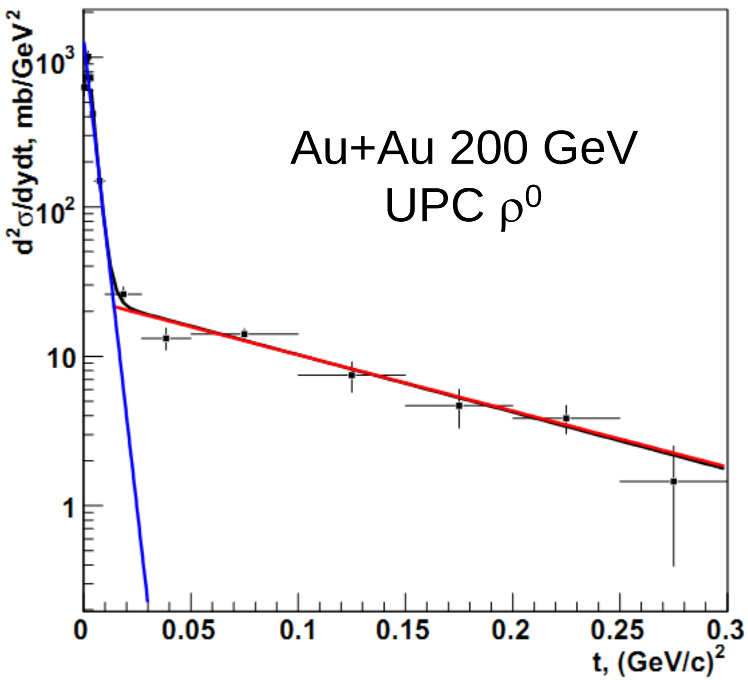
J/ψ production and modification at very low p_T





- ➢ 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.

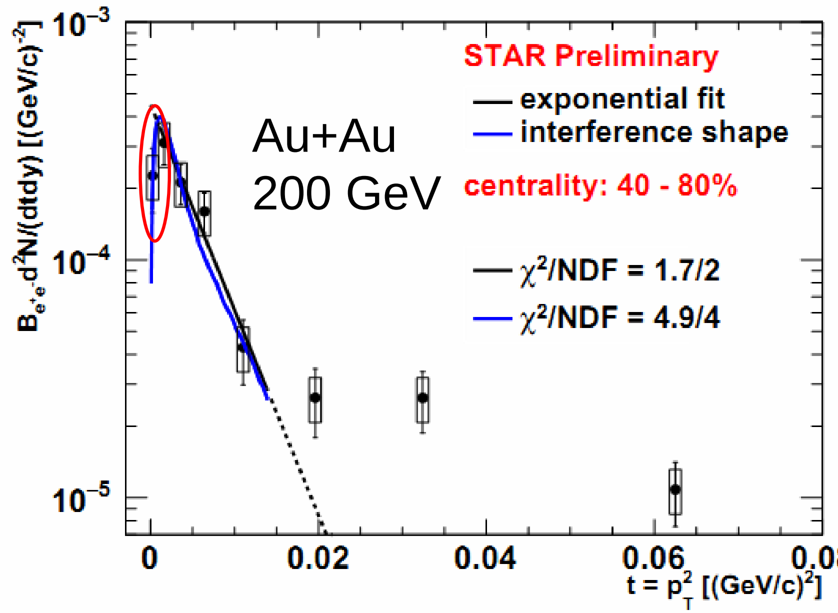
J/ψ dN/dt distribution for Au+Au 40-80%



Phys. Rev. C **77** 4910 (2008)

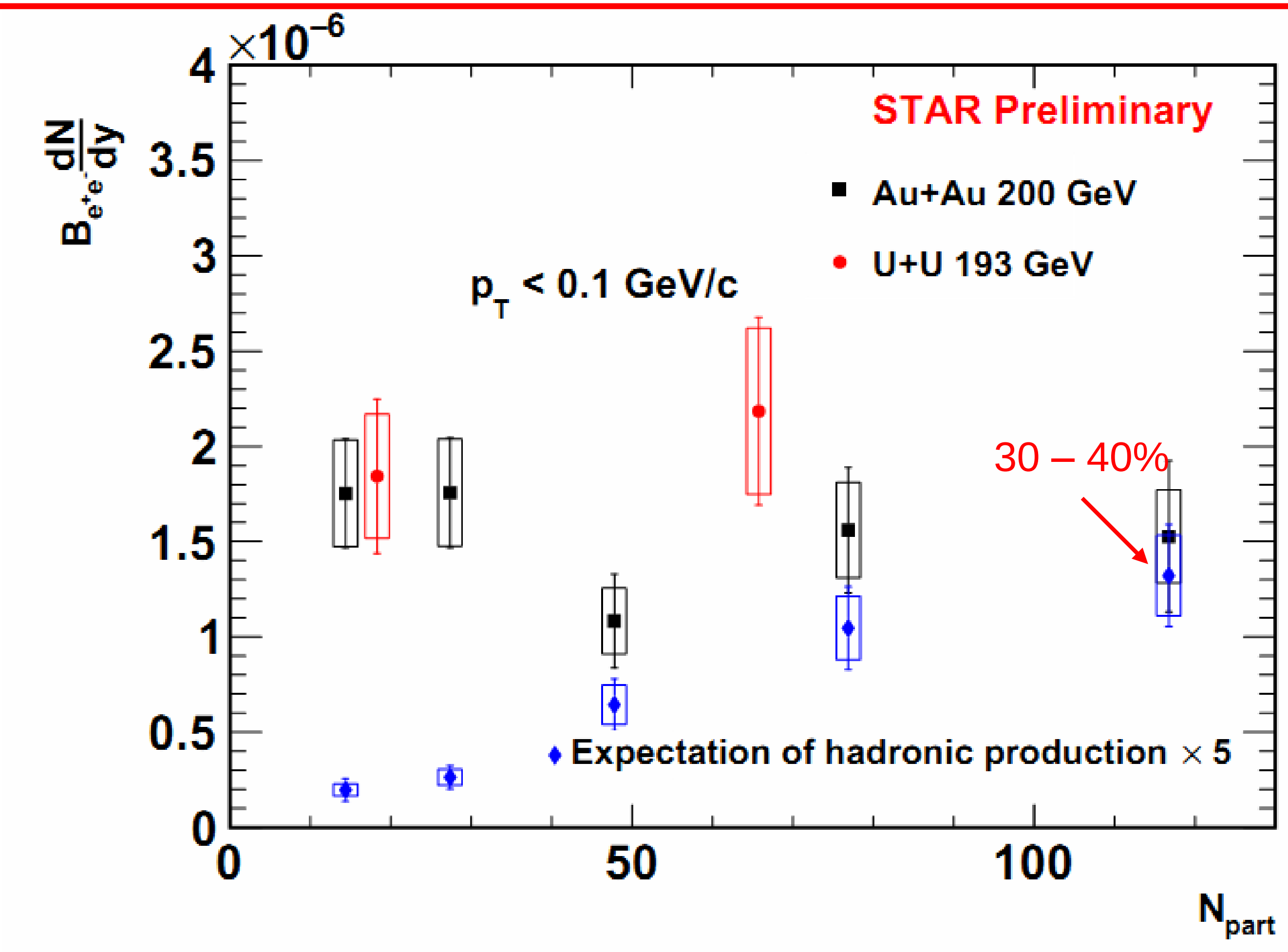
ρ^0 cross-section as a function of the momentum transfer squared ($t \approx p_T^2$) from STAR UPC measurements.

- The slope from the exponential fit reflects the size and shape of target.



- ✓ 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 $\pm$ 31(GeV/c)$^{-2}$ χ^2/NDF = 1.7/2
  - ✓ Slope w/ the first point: 164 $\pm$ 24(GeV/c)$^{-2}$ χ^2/NDF = 5.9/3

The excess yield



✓ Low p_T J/ψ from hadronic production is expected to increase dramatically with N_{part}.

✓ No significant centrality dependence of the excess yield!

Photoproduction of J/ψ in hadronic A+A

- View photons as "partons" being present in fast moving ions

- J/ψ coherent production in hadronic A+A:
  - "Photon distribution function" induced by ions?
  - Equivalent Photon Approximation
  - Microscope cross sections?
  - J/ψ cross section in γ+p convoluted with Glauber
  - Possible disruption by the hadronic collisions?
  - Shadowing?
  - Possible hot medium effects?

The calculation of the coherent production

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

$$\frac{d^3 N_\gamma(k,r)}{dk d^2 r} = \frac{Z^2 \alpha x^2}{\pi^2 k r^2} K_1^2(x)$$

$$\frac{\mathrm{d}\sigma\left(\gamma A \to J/\psi A; t=0\right)}{\mathrm{d}t} = \frac{\alpha_{em} \sigma_{tot}^2 (J/\psi A)}{4 f_{J/\psi}^2}$$

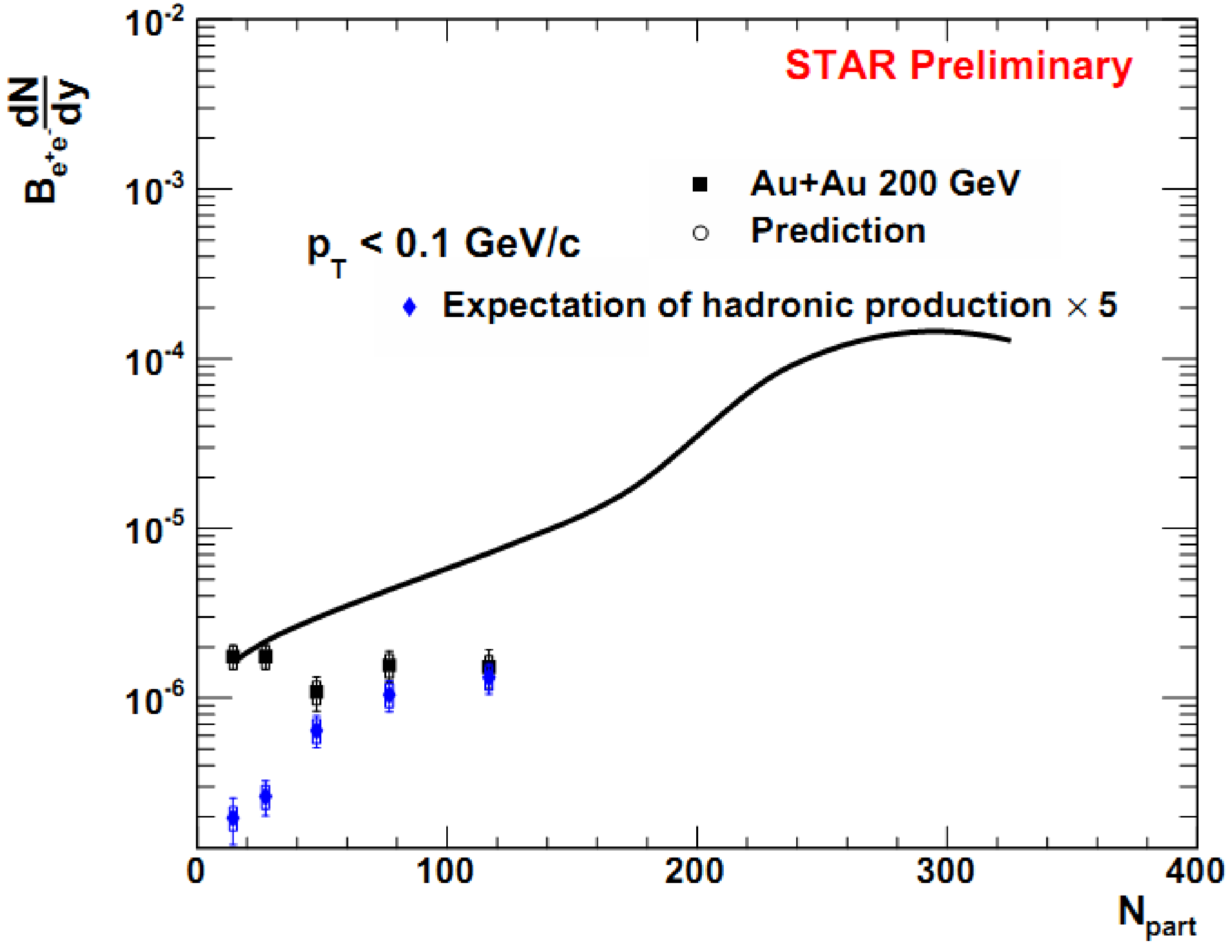
$$\sigma_{tot}^{CM}\left(J/\psi A\right) = \int \mathrm{d}^2\mathbf{r}\left(1 - \exp\left(-\sigma_{tot}\left(J/\psi p\right) T_A\left(\mathbf{r}\right)\right)\right)$$

$$\sigma_{tot}^2\left(J/\psi p\right) = 16\pi \frac{\mathrm{d}\sigma\left(J/\psi p \to J/\psi p; t=0\right)}{\mathrm{d}t}$$

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

$$\frac{\mathrm{d}\sigma\left(\gamma p \to J/\psi p; t=0\right)}{\mathrm{d}t} = b_{J/\psi} X_{J/\psi} W_{\gamma p}^{\epsilon_{J/\psi}}$$

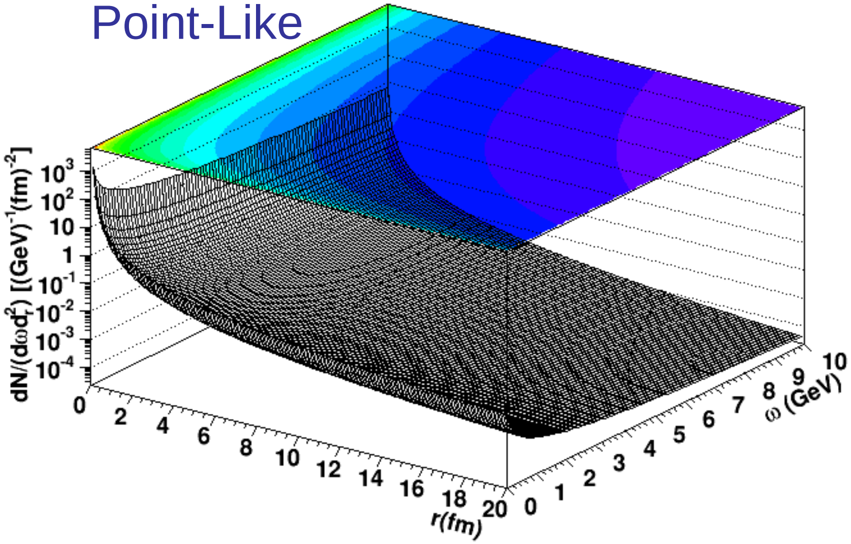
Comparison with data



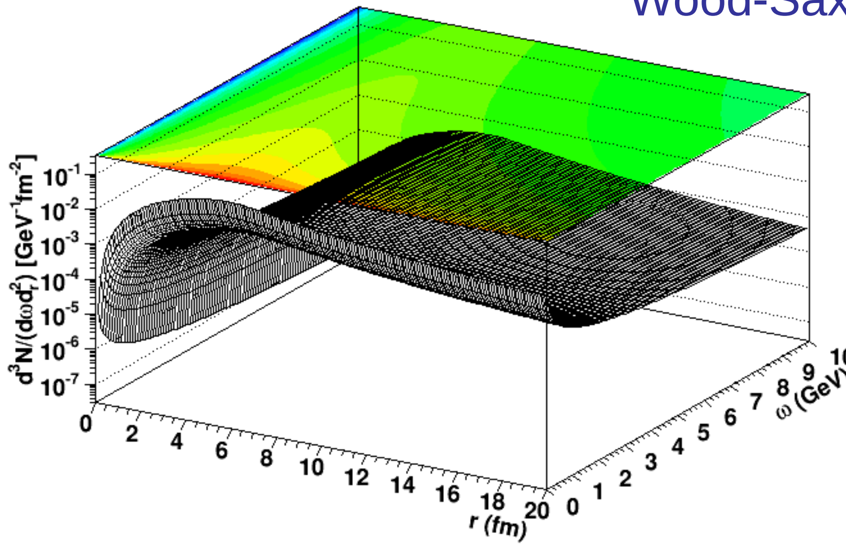
- ✓ Describe the data very well at very peripheral collisions (60-80%)!
- ✓ Overestimate at semi-central collisions!
- ✓ The charge density distribution?

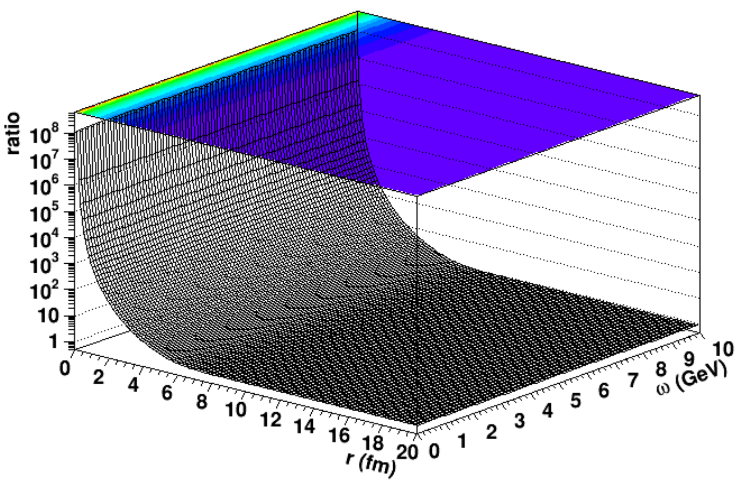
Photon flux induced by Au

Point-Like



Wood-Saxon



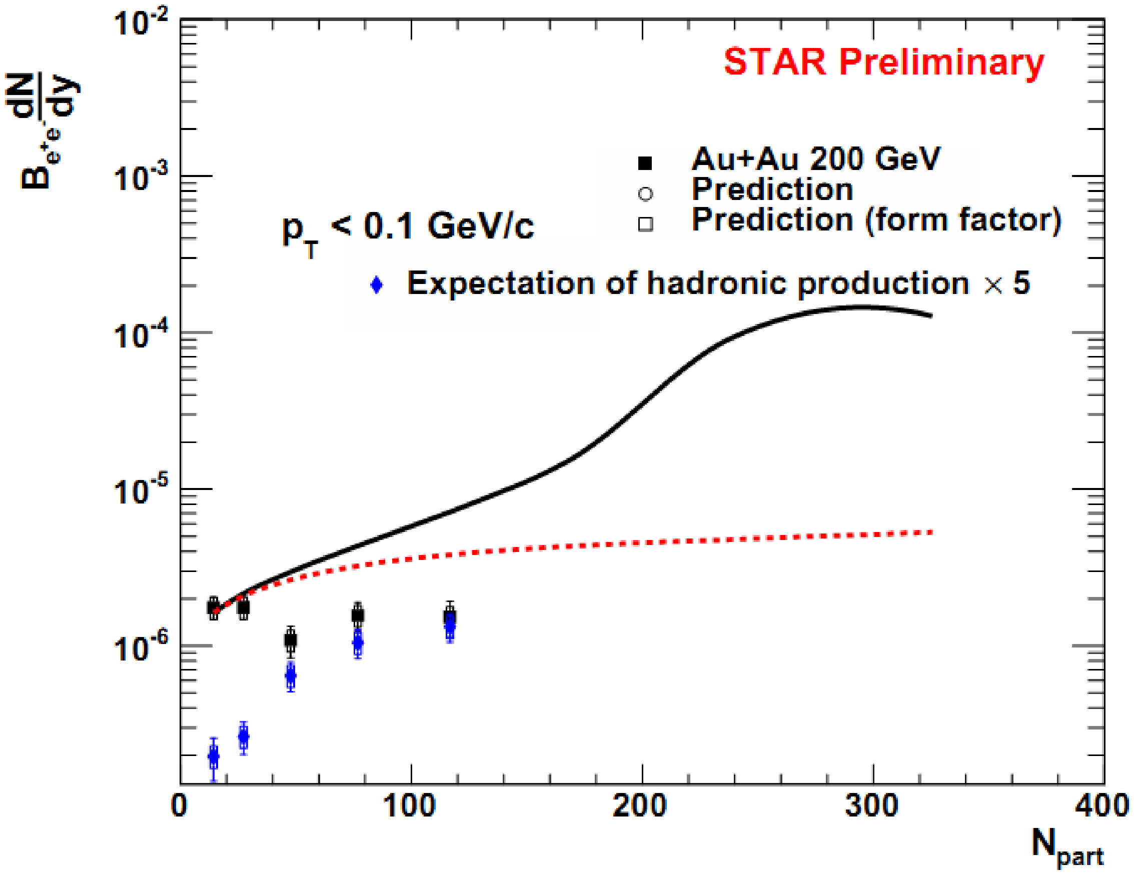


Collision system : Au+Au 200 GeV

The same magnitude outside the nucleus.

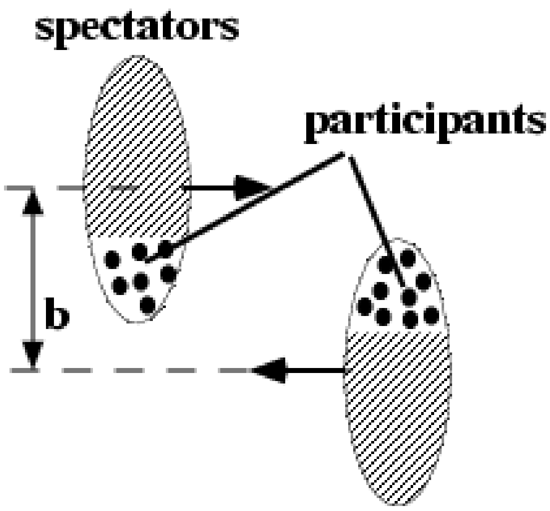
Big difference inside the nucleus!

Calculations with nuclear form factor

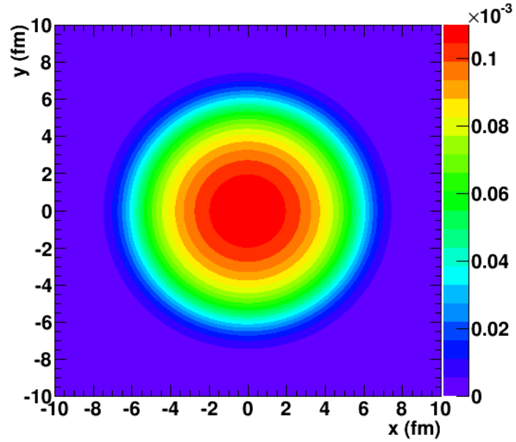


- ✓ Describe the data very well at very peripheral collisions (60-80%)!
- ✓ Still overestimate at semi-central collisions!
- ✓ Cancellation of photon flux or target in the overlapping region?

Different scenarios for calculations

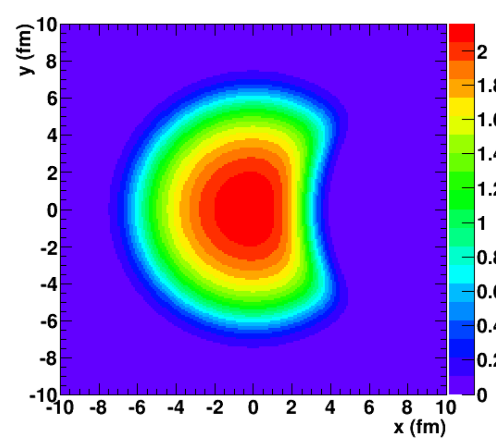


Photon emitter and target



nucleus

OR



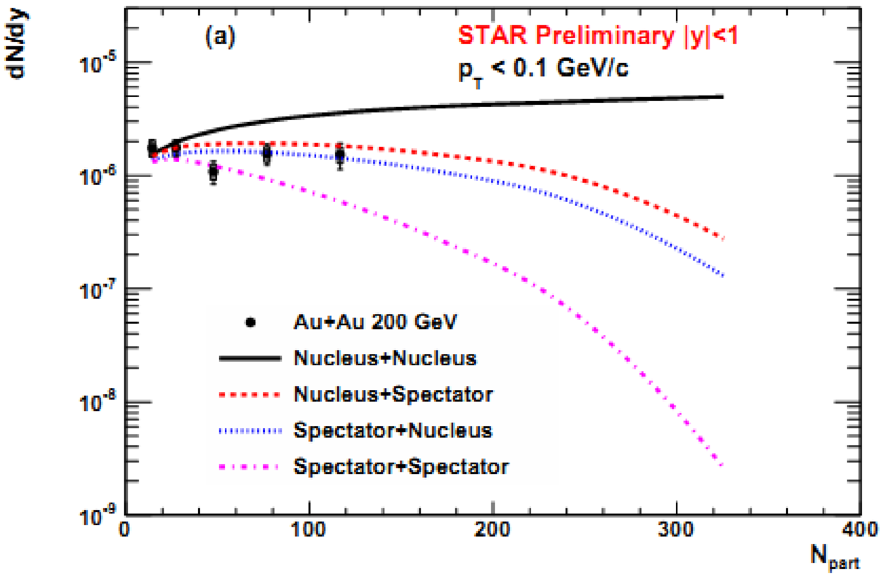
spectator

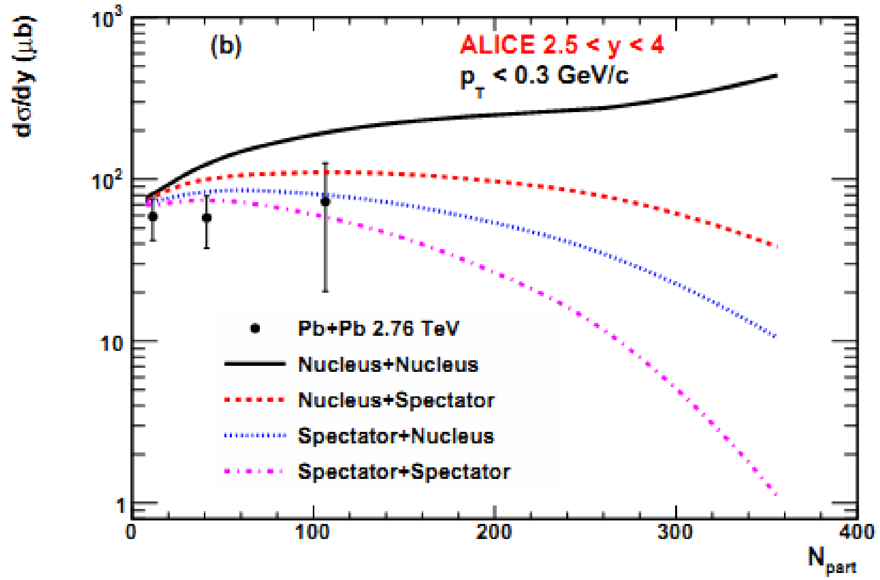
The shape of spectator is from optical Glauber calculations!

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

Spectator + Spectator: no hadronic collisions, still “UPC” like!

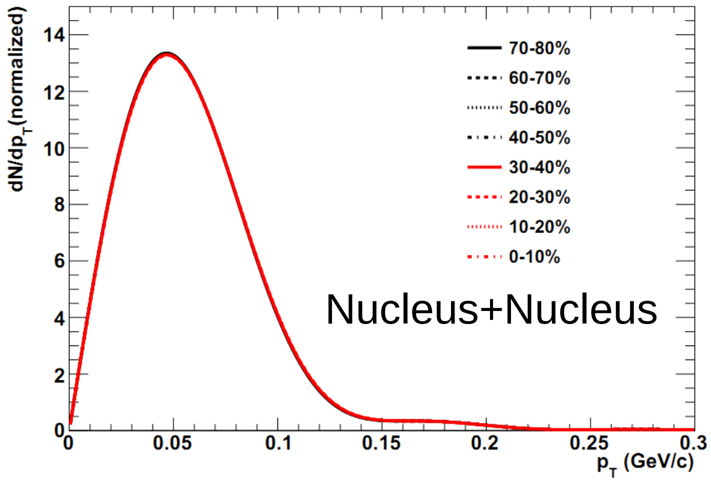
Calculations with different scenarios

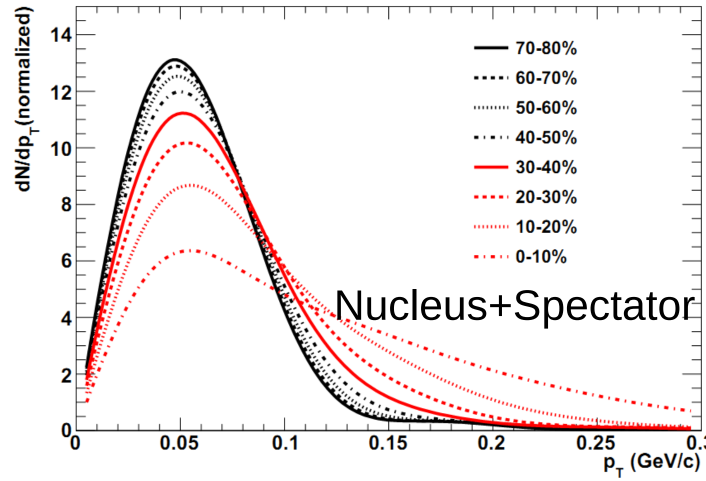


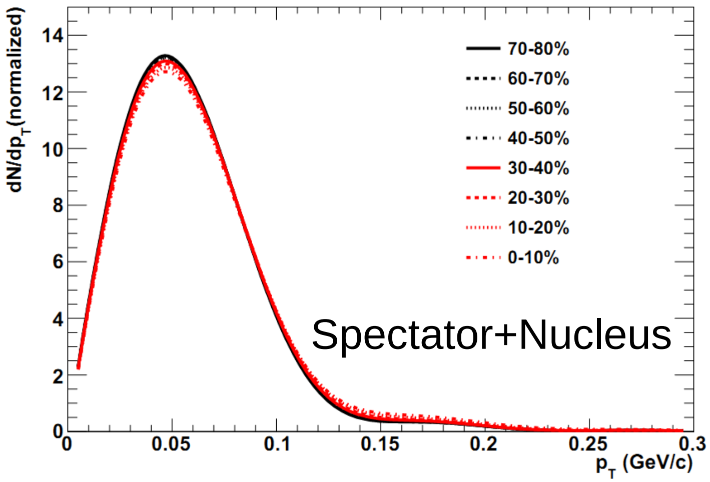


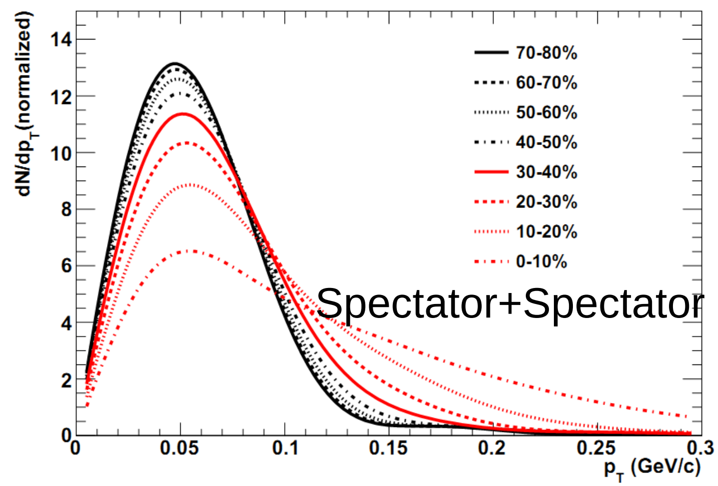
- ✓ Different scenarios have different trend toward central collisions!
- ✓ Spectator+Spectator: under predict the data in semi-central collisions.
- ✓ To distinguish the different scenarios, measurements at central collisions are needed!
- ✓ Cold Nuclear and hot medium effects are not included in the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

p_T shape with different scenarios





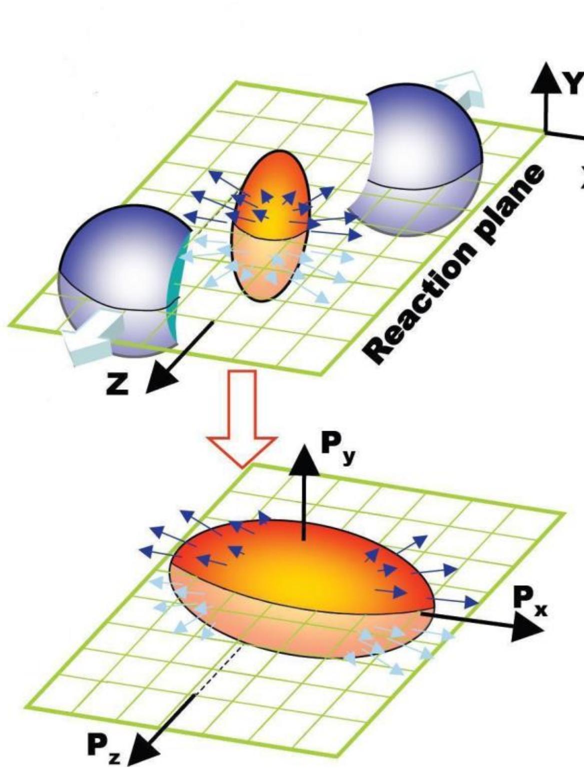


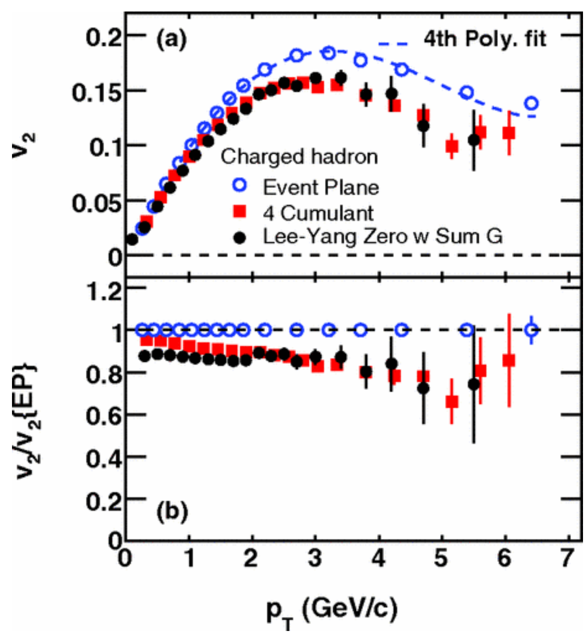


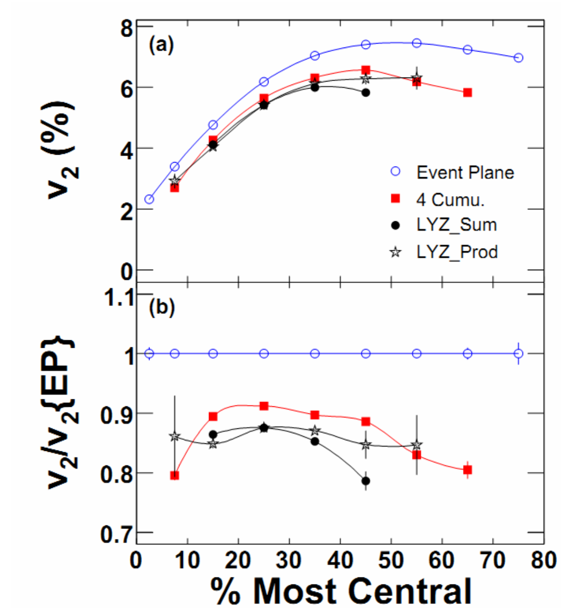
- ✓ The p_T shape is very sensitive to the target!
- ✓ If the target is spectator, the p_T shape has significant centrality dependence!

Reaction plane in hadronic collisions

- In UPC, no special direction can be determined.
- Reaction plane can be extracted by the copious produced tracks in hadronic collisions.







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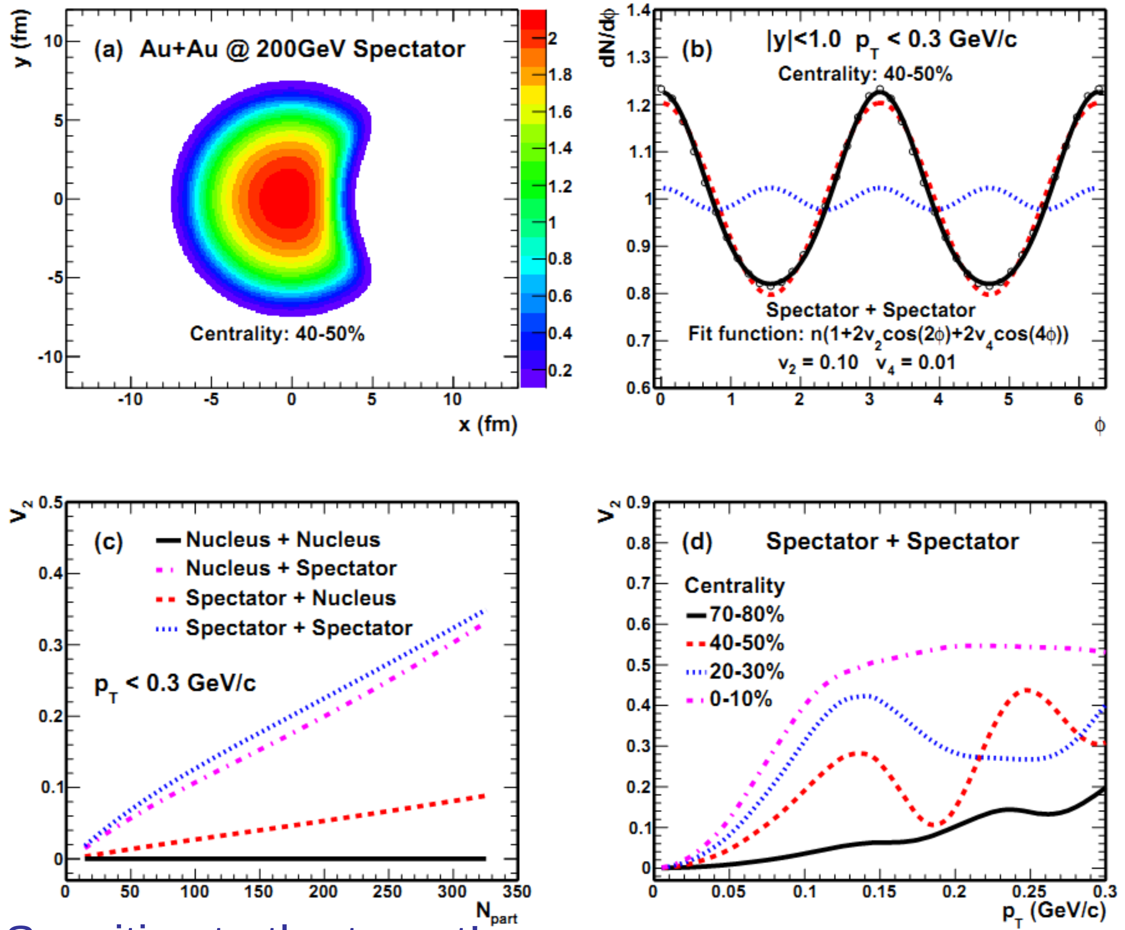
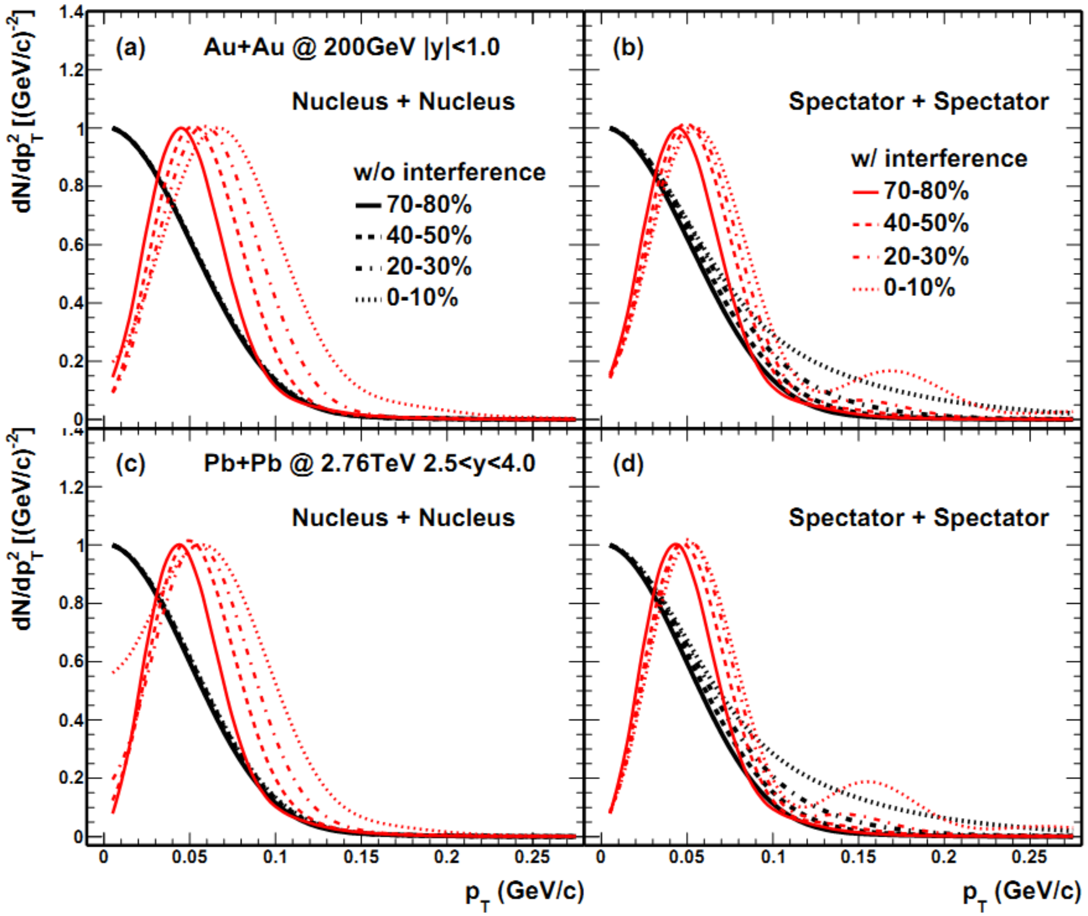
The elliptic flow vanishes at low pT and central collisions!

Production versus ϕ (relative to reaction plane)



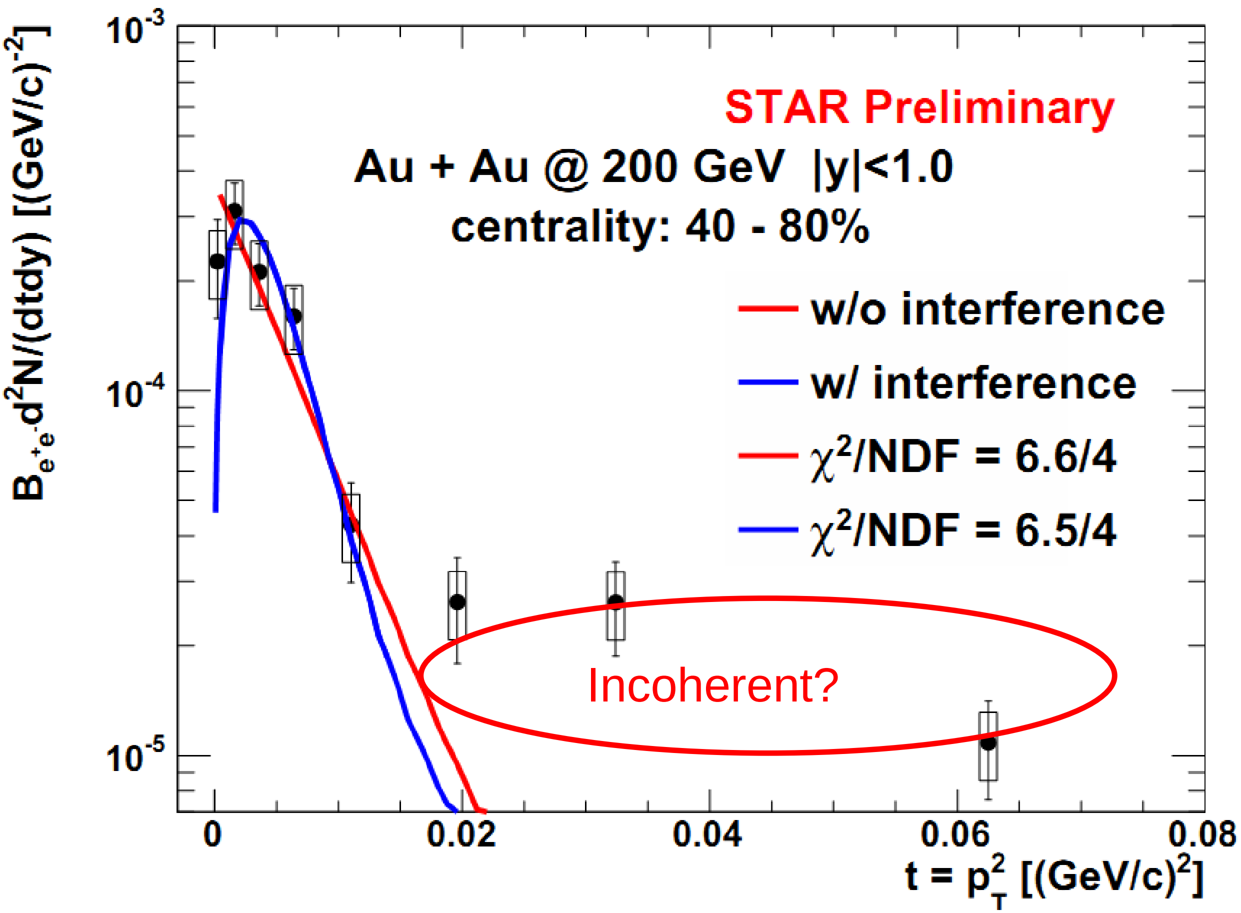
- ✓ Sensitive to the target!
- ✓ Large v_2 and sizeable v_4 will be observed if the target is spectator!
- ✓ V_2 increase dramatically toward central collisions!
- ✓ Probe of initial geometry of the overlap region!

p_T shape with interference



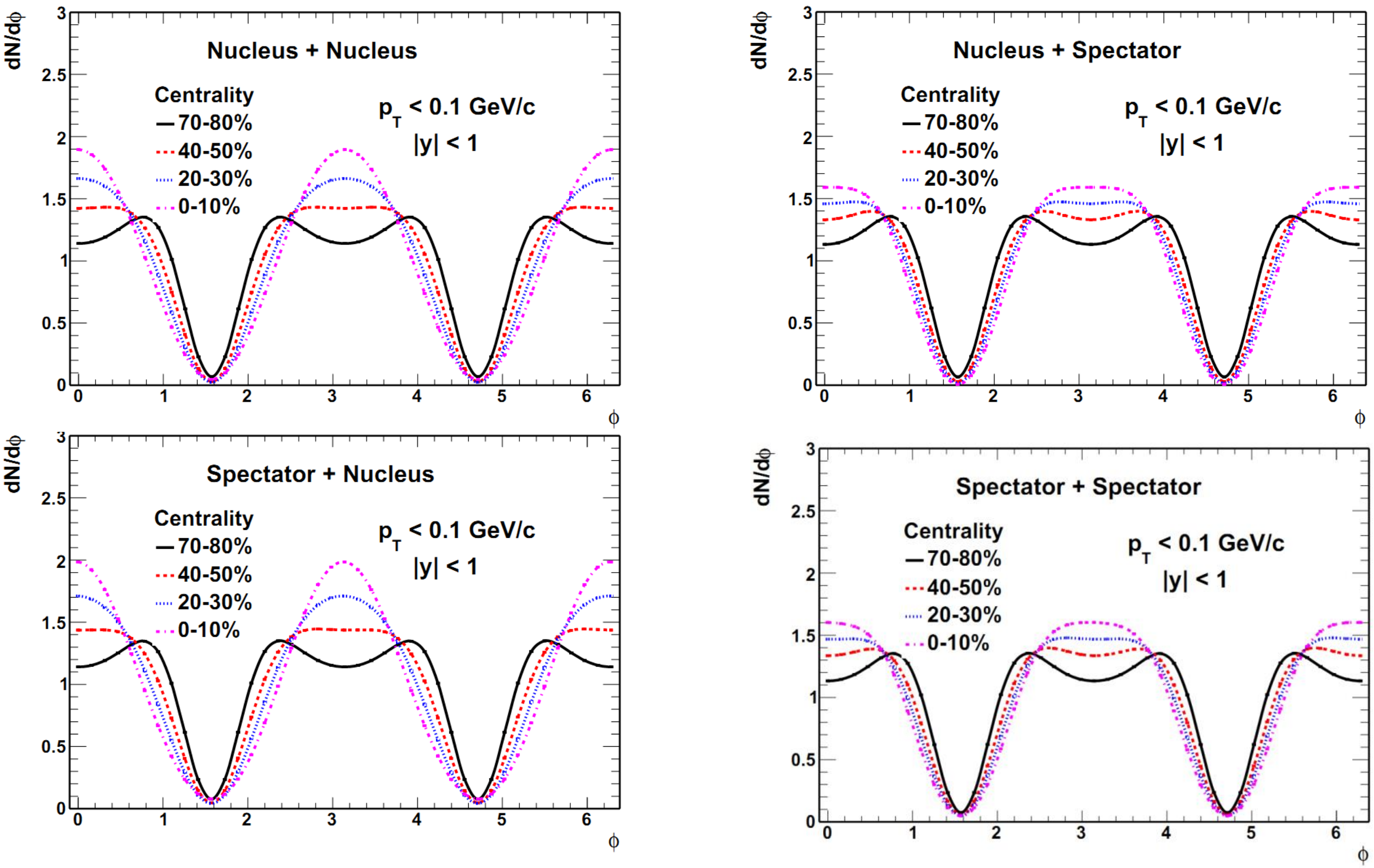
- ✓ Dramatically change the p_T spectra!
- ✓ Different interference pattern in different centrality!
- ✓ The effect is relative small with spectator coupling!

t distribution



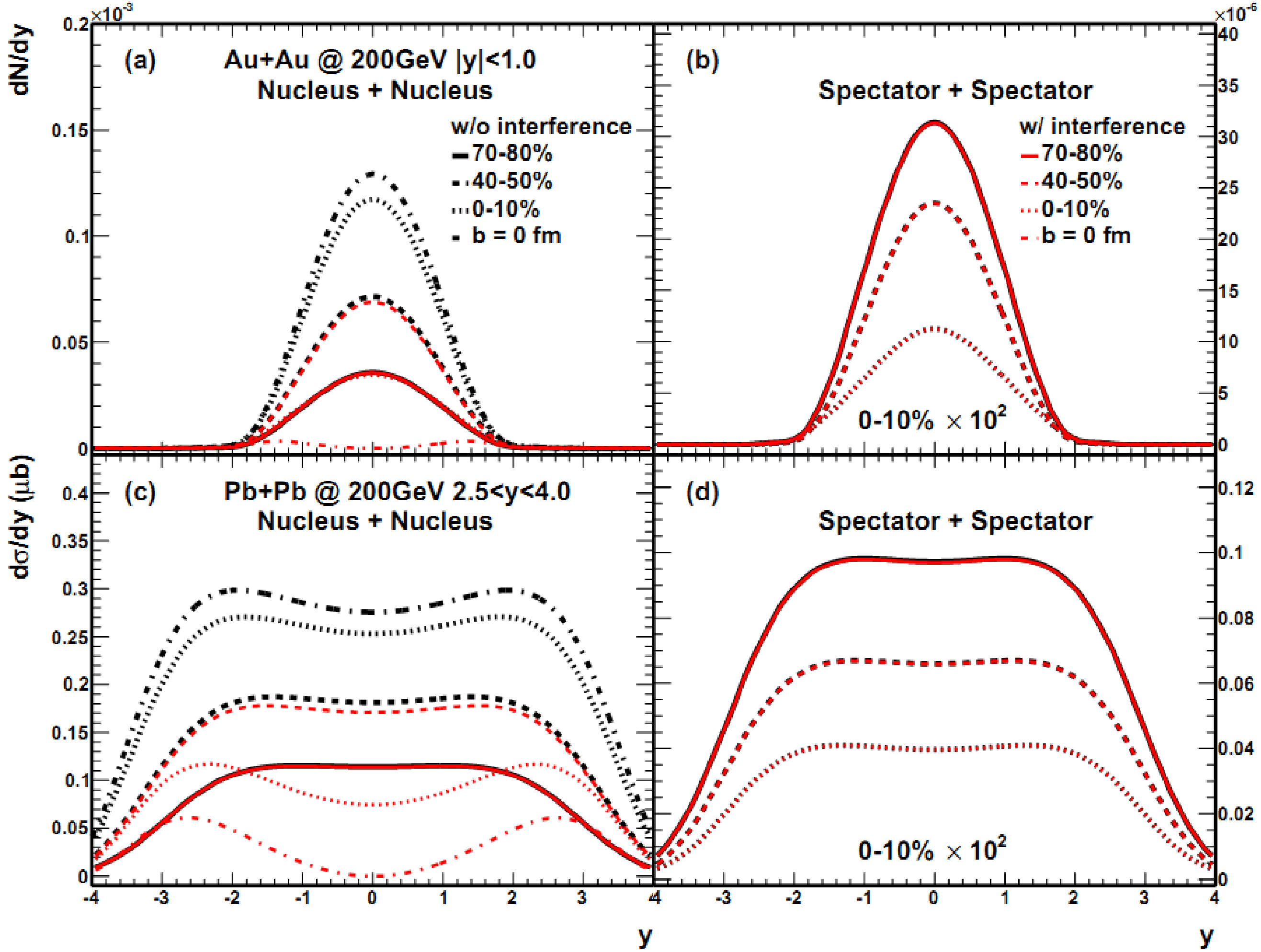
✓ Both scenarios describe the data reasonably well!

ϕ distribution with interference



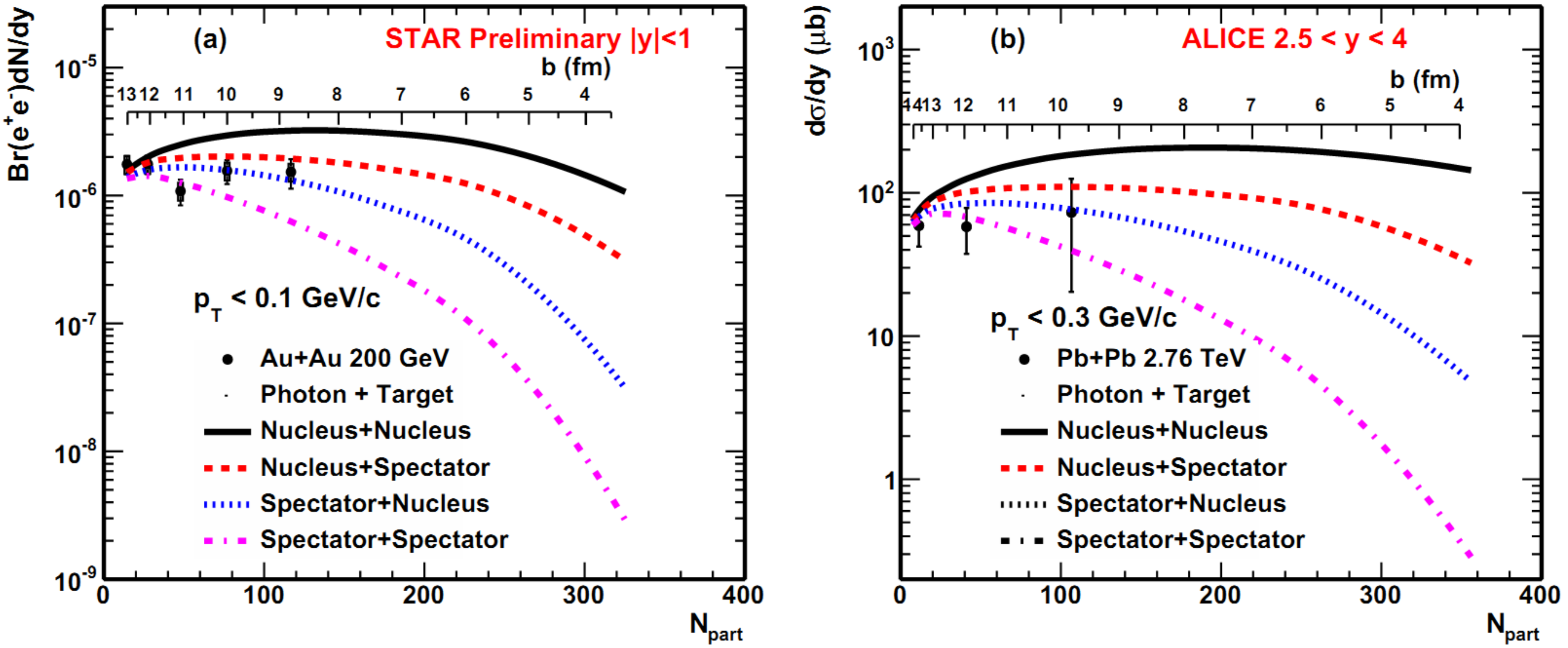
- ✓ Dramatically change ϕ distribution!
- ✓ Sensitive to the target!

Rapidity distribution with interference



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

Cross section with interference



✓ The cross section with nucleus coupling is decreased in central collisions!

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?

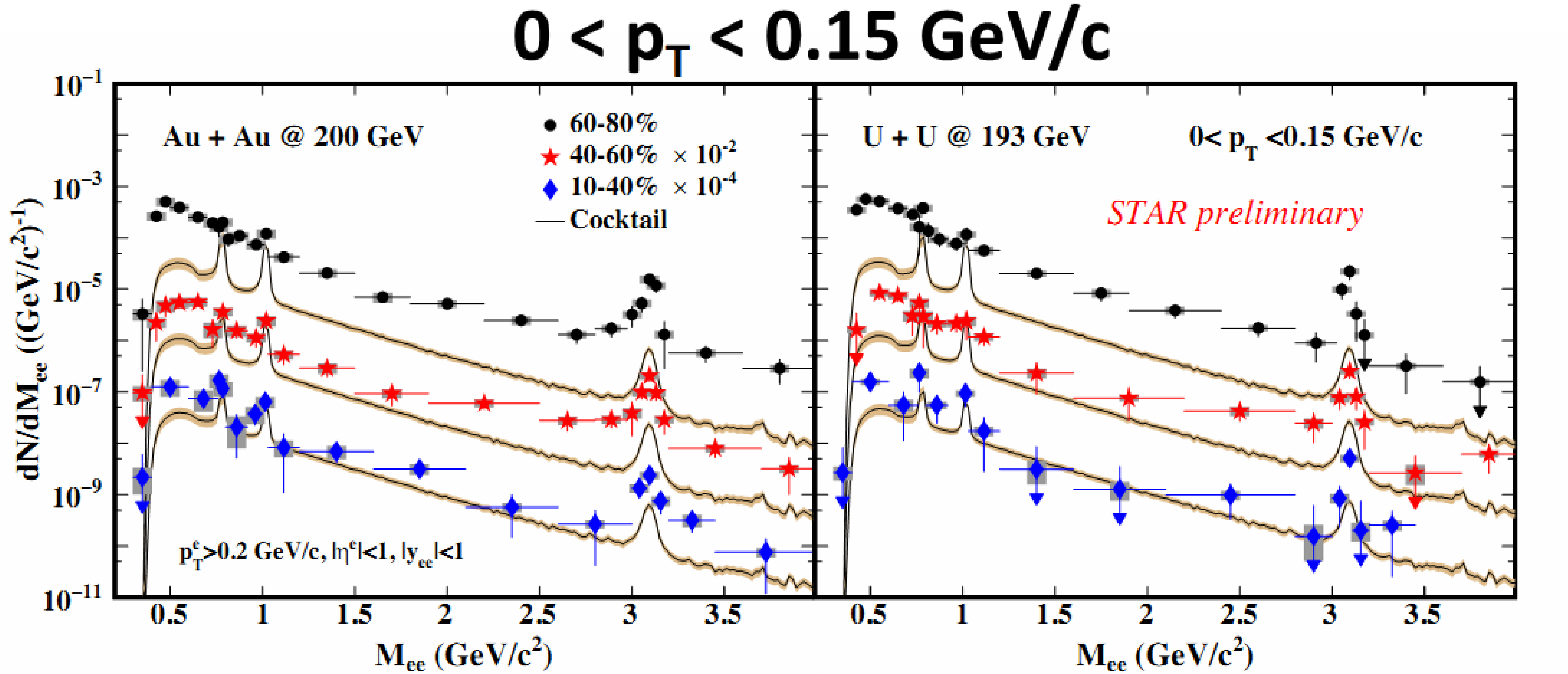
Photoproduction in UPC:
Very clean
Impact parameter and ϕ dependence --- NO!

Photoproduction in hadronic collisions:
Not clean
Impact parameter and ϕ dependence --- YES!
Test the medium?

➢ Perspectives:

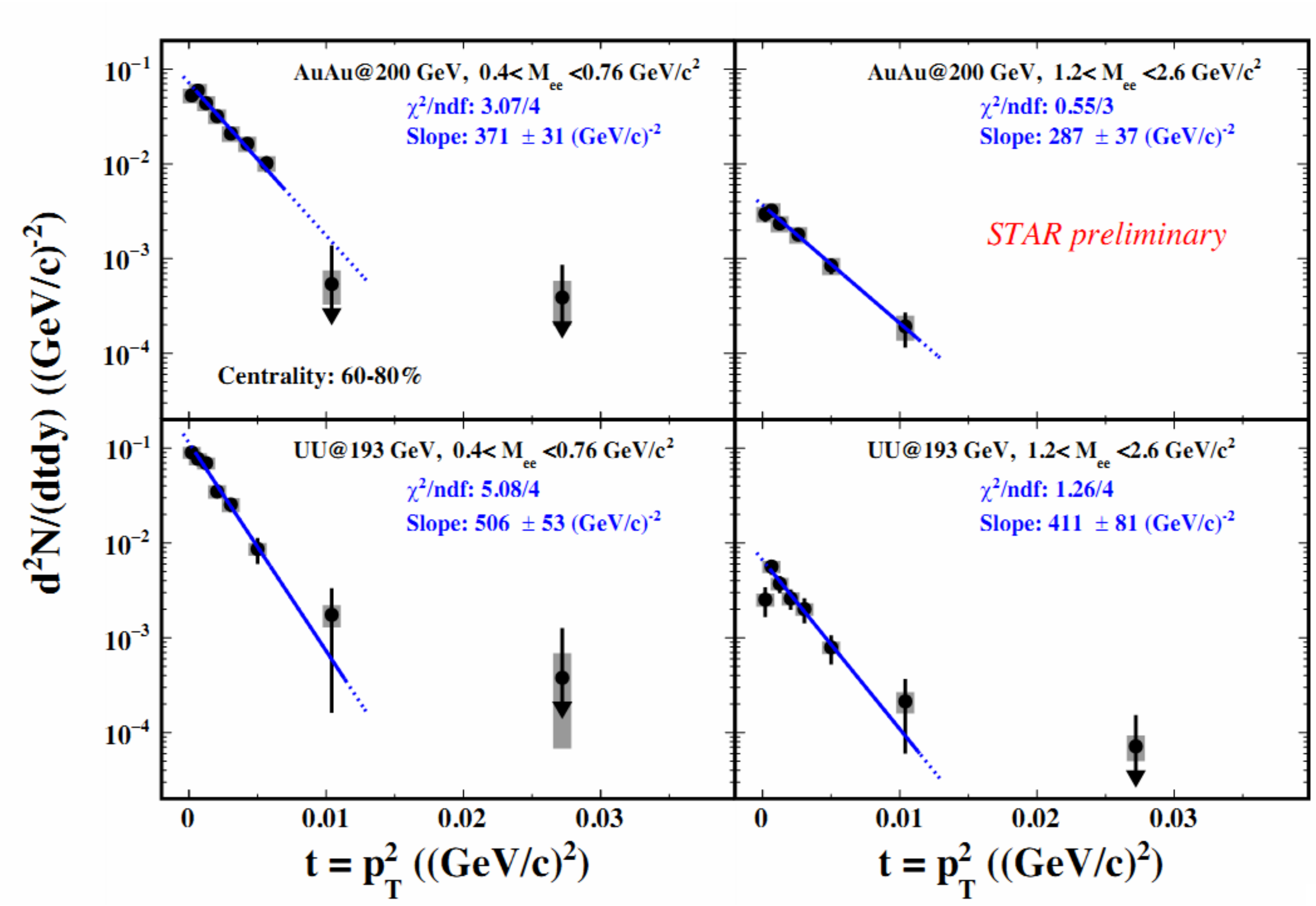
- ✓ Measurements in more central collisions
- ✓ p_T shape and ϕ measurement: the target is nucleus or spectator?
- ✓ photon-photon process (π^0, η, η', $f_2(1270)$, $a_2(1320)$, $\pi^+ + \pi^-$, $e^+ + e^-$, $\mu^+ + \mu^-$…): test the photon emitter (spectator or nucleus)
- ✓ Incoherent contribution?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

Measurements beyond J/ψ



- ✓ 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!
- ✓ To test the photon emitter (Nucleus or Spectator?)

t distribution for dielectron



✓ The size of photon interaction range?

Outlook

Two photon physics:
test QED
meson spectrometry
facility: electron-position collider

Photon-nucleus physics:
probing the low x parton
facility: electron-proton collider
future electron-ion collider

Measurements at very low p_T in hadronic A+A collisions

Test the QGP medium