Workshop on AMPT for Relativistic Heavy Ion Collisions (AMPT2017)

Department of Physics, Sichuan University, Chengdu, China 2017/07/25-27

Coherent J/ψ photoproduction in hadronic heavy-ion collisions

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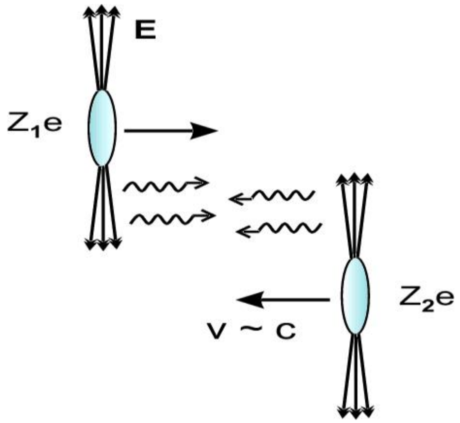
https://arxiv.org/pdf/1705.01460.pdf

National Natural Science Foundation of China

Photon interactions in heavy-ion collisions



Electromagnetic interaction

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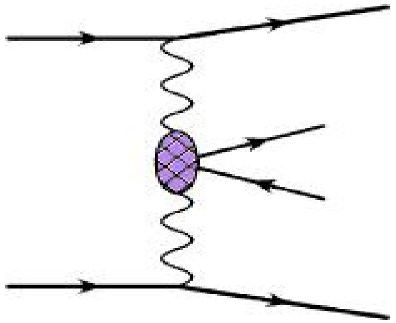
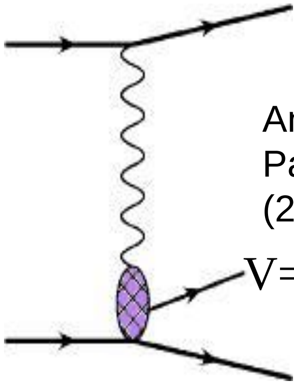


Photon-photon interactions

+



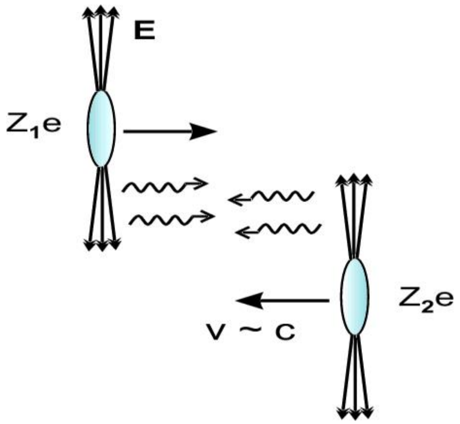
Photon-nucleus interactions

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

$V = \rho, \omega, \phi, J/\psi$

- 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.

Quasi-real photons --- Equivalent photon approximation



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

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

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

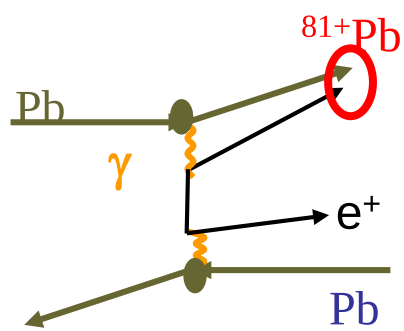
$$\omega \leq \omega_{max} \sim \frac{\gamma}{R}$$

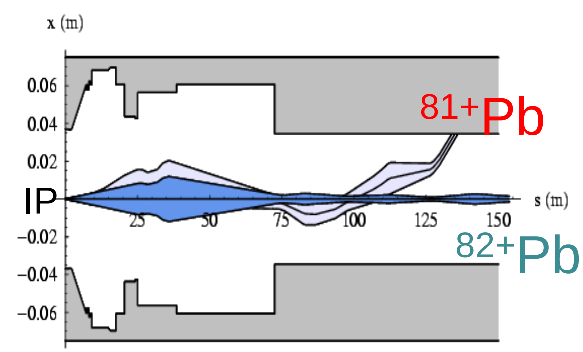
$$q_T \leq 1/R$$

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

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

The flux of photon is large!
The LHC luminosity is limited by the beam loss induced by photon-photon and photon-nucleus interactions.





σ[PbPb($\gamma\gamma$) -> (Pbe$^-$) Pb e$^+$] ~ 280 b @ LHC

SK [NIM, 2000], J. Jowett et al., IPAC 2016

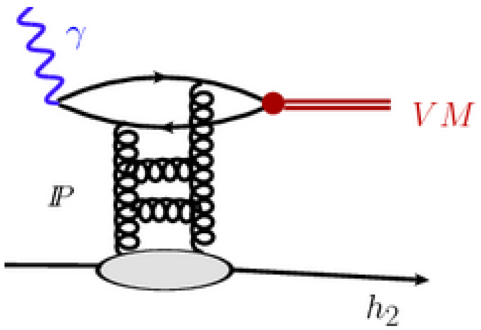
Vector meson photon-production

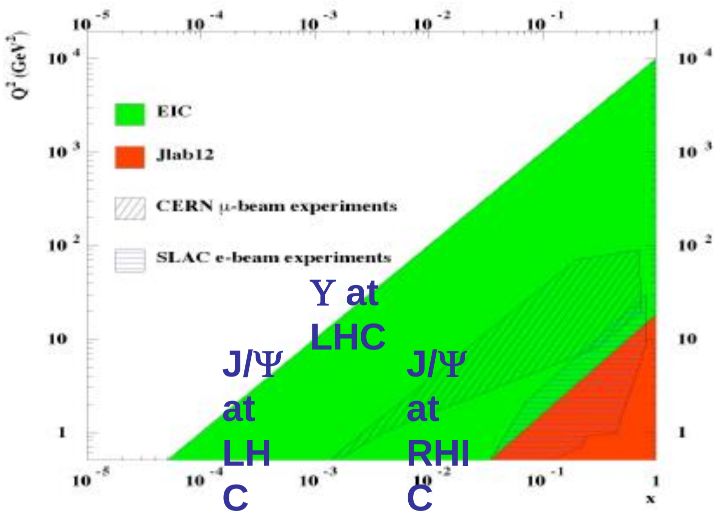
- Vector meson production:
  - ✓ chargeless ‘Pomeron exchange’
  - ✓ Light meson production usually treated via vector meson dominance model:
    ρ, direct $\pi^+\pi^-$, ω….
  - ✓ Heavy meson production treated with pQCD:
    J/ψ, ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$…

- Sensitive to the gluon distribution:

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

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

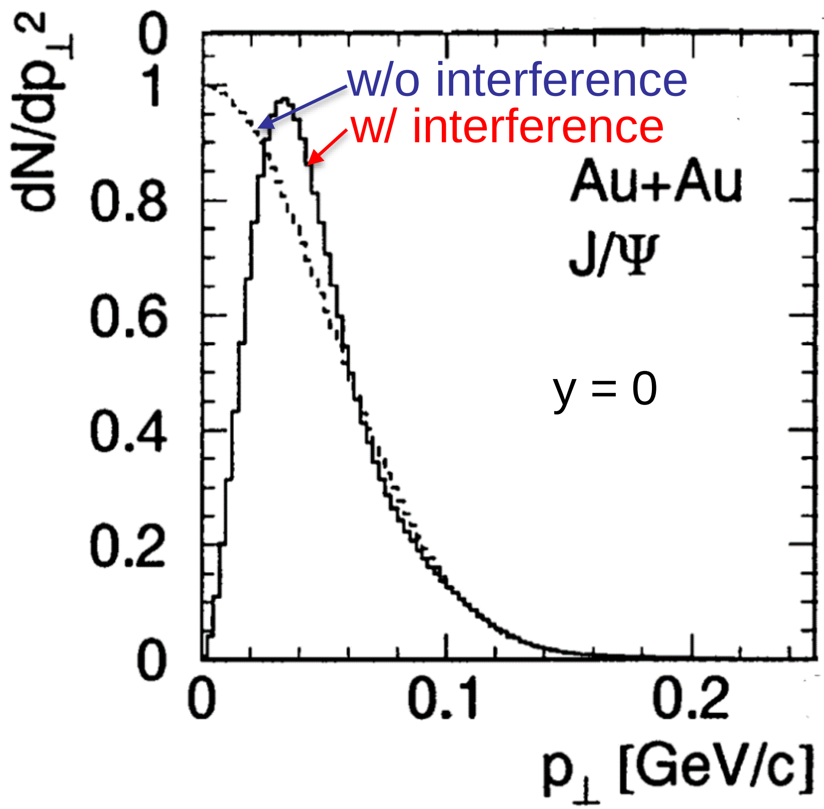




RHIC y=0: $x \sim 0.01$
LHC y=0: $x \sim 0.001$

Features of coherent photon-nucleus interaction

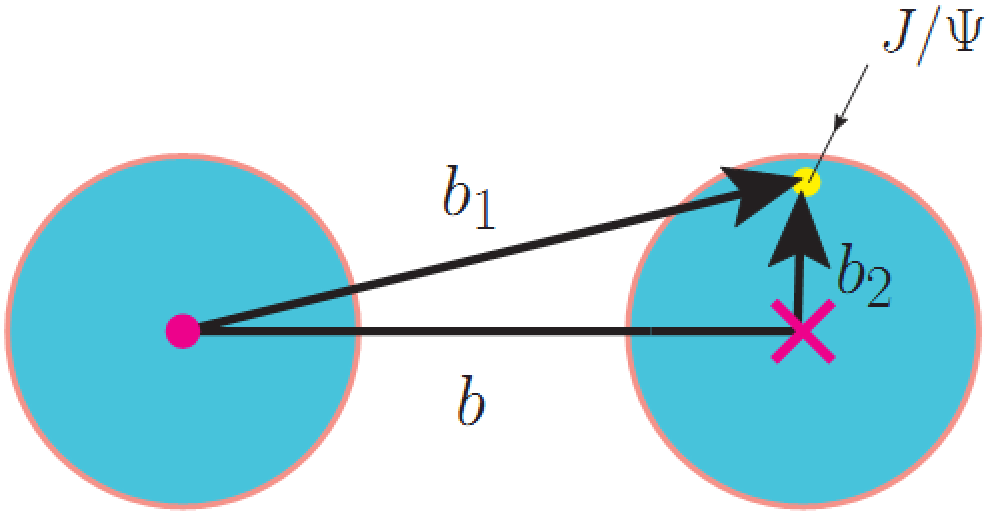
- Coherently:
  - ✓ Both nuclei remain intact
  - ✓ Photon/Pomeron wavelength $\lambda = \frac{h}{p} > R_A$
  - ✓ $p_T < h/R_A$ ~30 MeV/c for heavy ions
  - ✓ Strong couplings ($Z\alpha_{EM}$ ~ 0.6) → large cross sections
- Interference:
  - ✓ Two indistinguishable processes (photon from A_1 or A_2)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



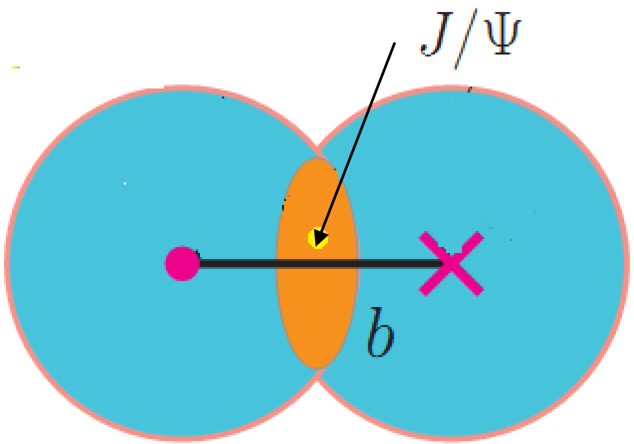
PRL **84** 2330 (2000)

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

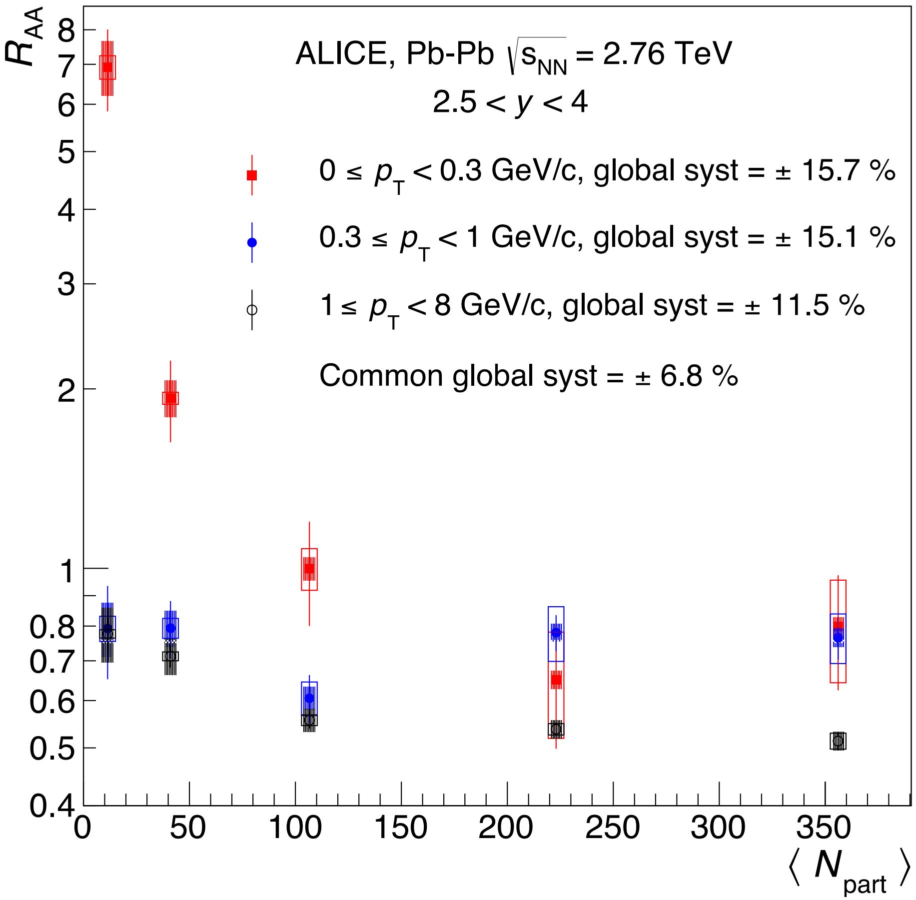


UPC collisions:
J/ψ photoproduction



hadronic collisions:
J/ψ hadronic production
and modification

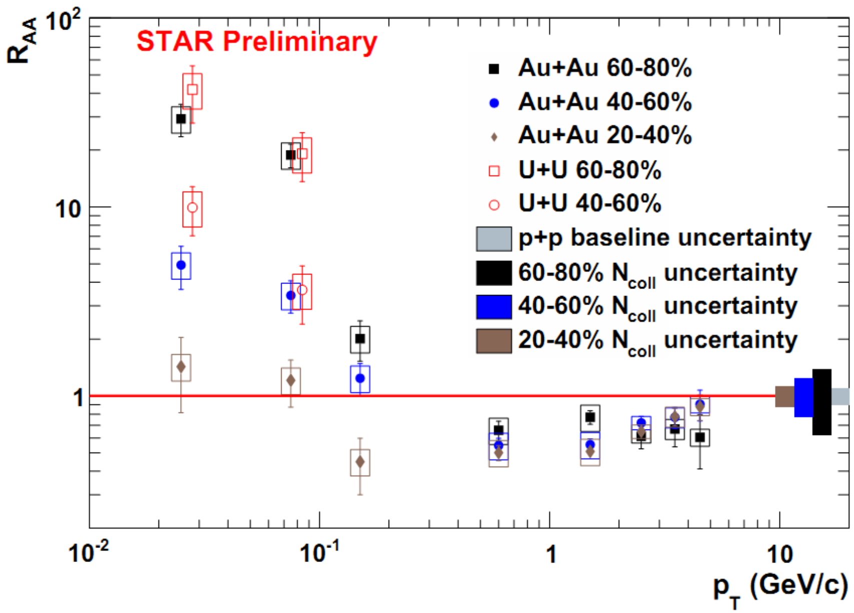
Excess of J/ψ production at very low p_T with ALICE

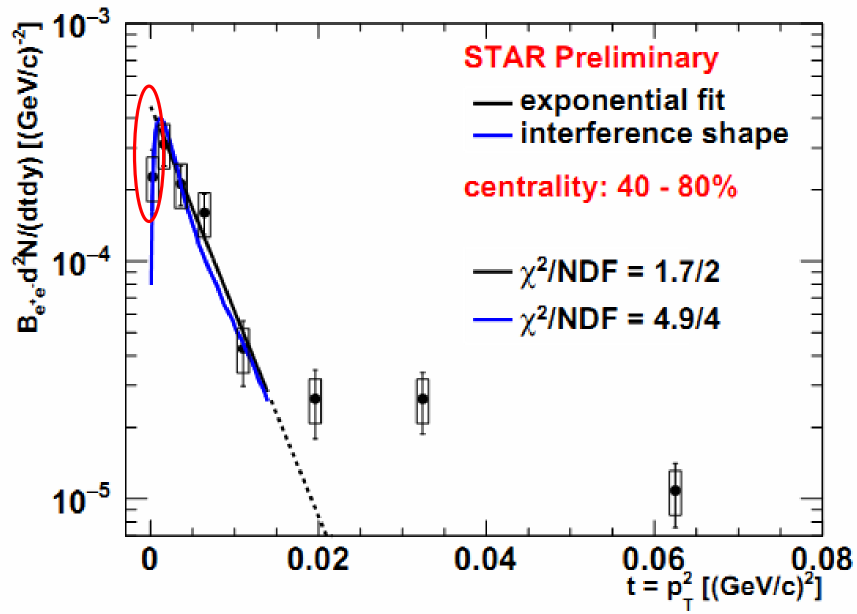


PRL**116**, 222301 (2016)

- ✓ 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?

The observations at STAR

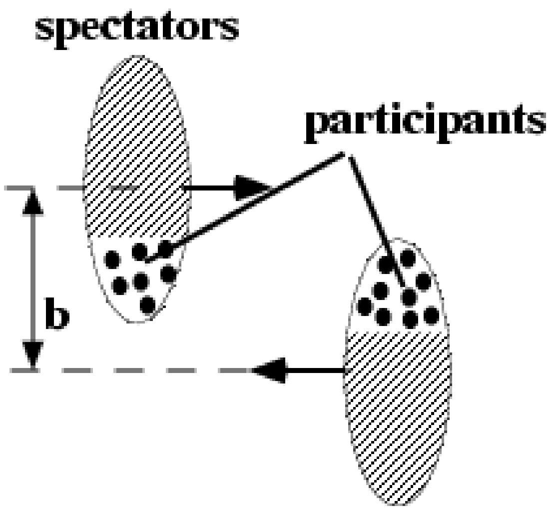




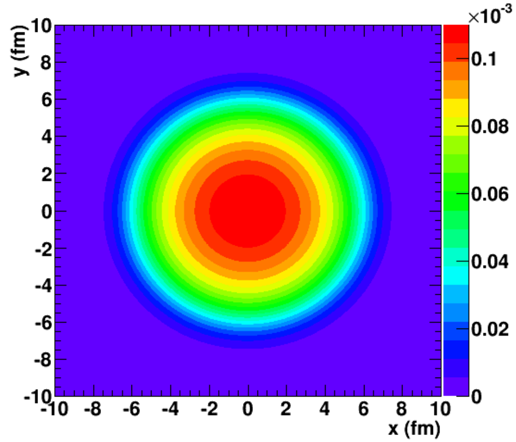
Wangmei Zha @ HP2016

- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.1 GeV/c for peripheral collisions (40 – 80 %)!
- t distribution is consistent with the coherent production picture!
  - ✓ Similar slope parameter!
    - ✓ Slope from STARLIGHT prediction in UPC case – 196 $(GeV/c)^{-2}$
    - ✓ Slope w/o the first point: 199 ± 31$(GeV/c)^{-2}$ χ^2/NDF = 1.7/2
  - ✓ Indication of interference!
    - ✓ Interference shape from calculation for UPC case PRL **84** 2330 (2000)

Different scenarios for calculations

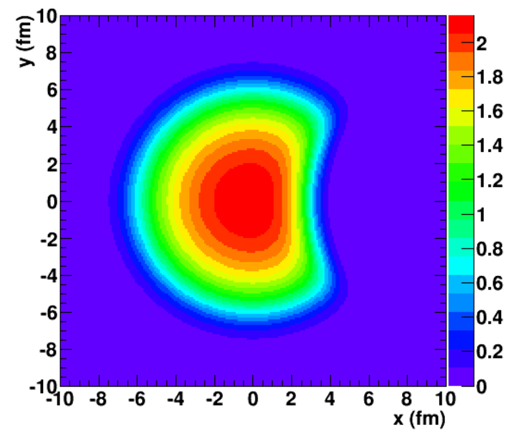


Photon emitter and target



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)

The calculation of the coherent production

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

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

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

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

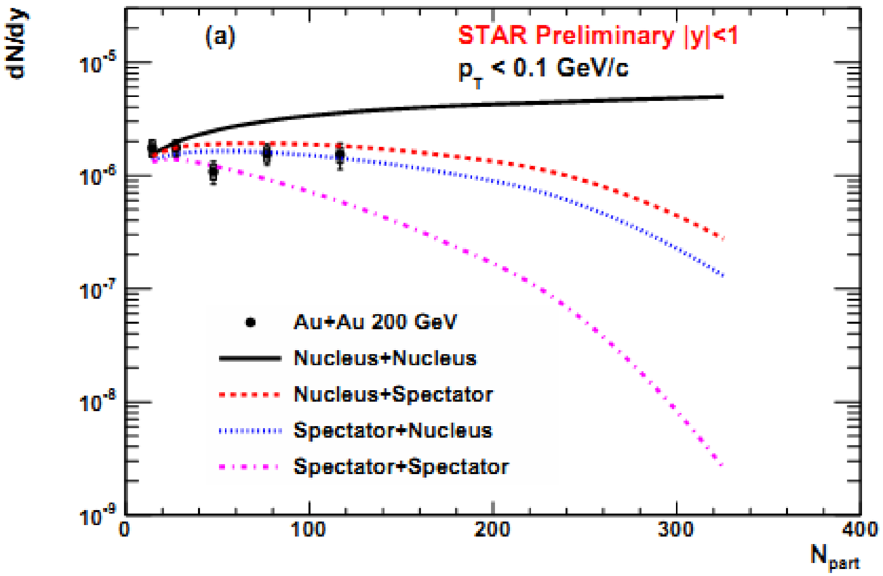
$$\sigma_{tot}^2\left(J/\psi p\right) = 16\pi \frac{\mathrm{d}\sigma\left(J/\psi p \rightarrow J/\psi p; t=0\right)}{\mathrm{d}t}$$

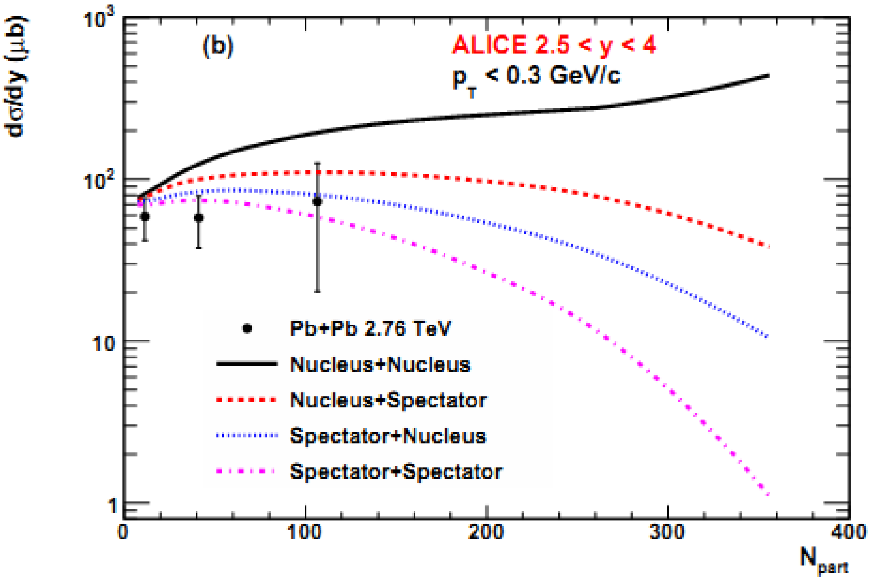
arxiv1705.01460

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

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

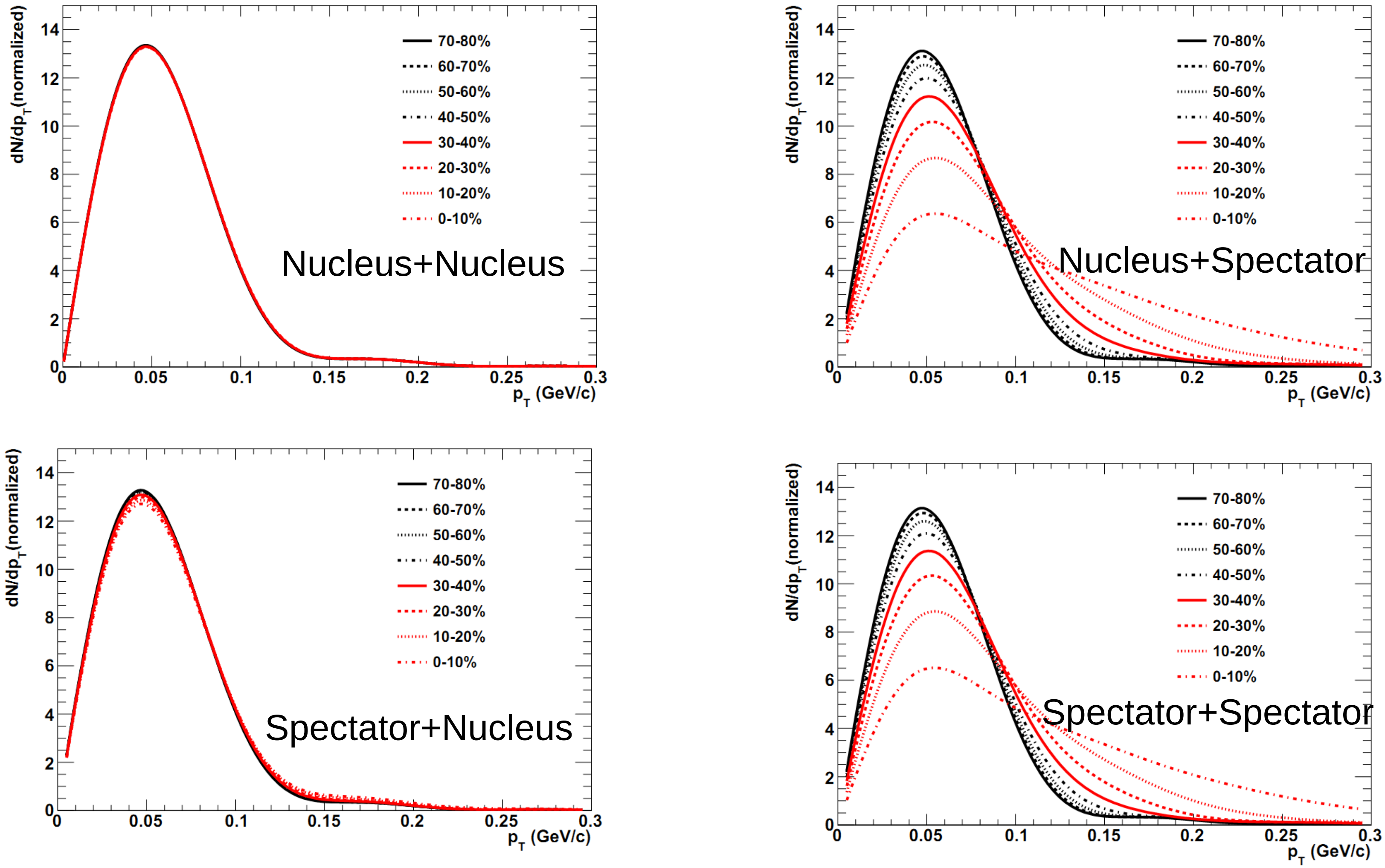
Calculations with different scenarios





- ✓ 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.

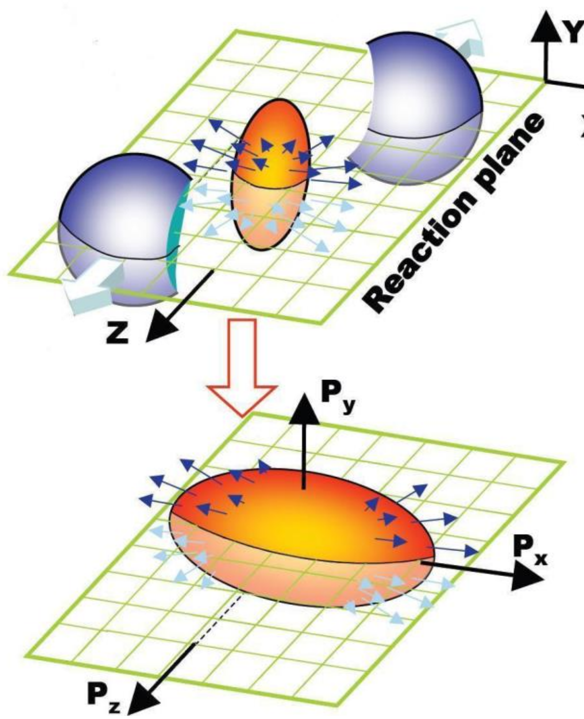
p_T shape with different scenarios

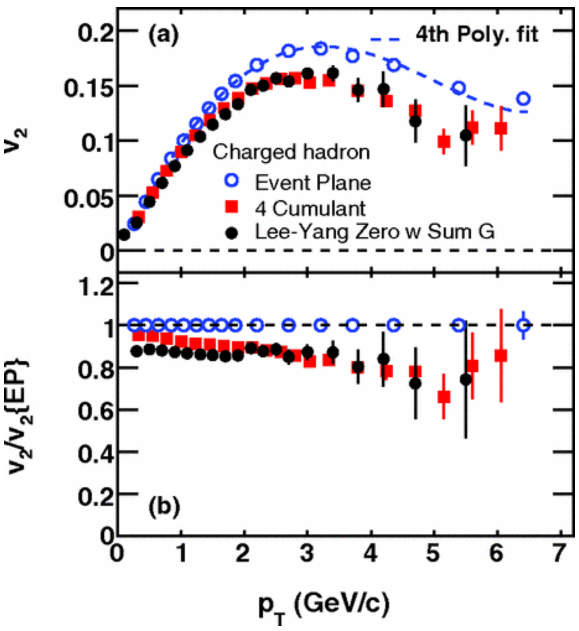


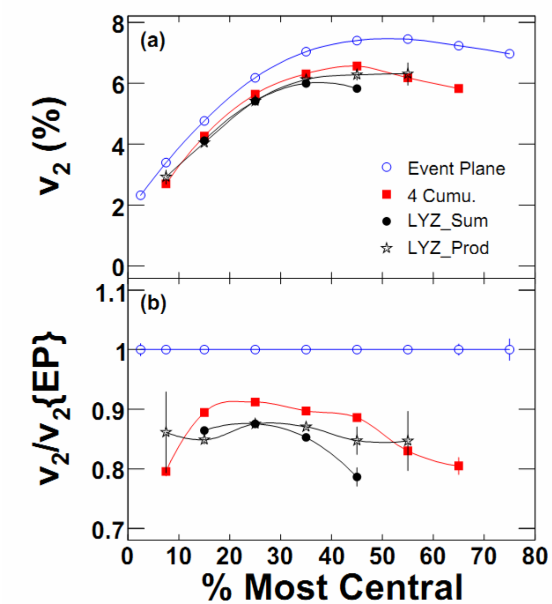
- ✓ The p_T shape is very sensitive to the target!
- ✓ If the target is spectator, the p_T shape has significant centrality dependence!

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.



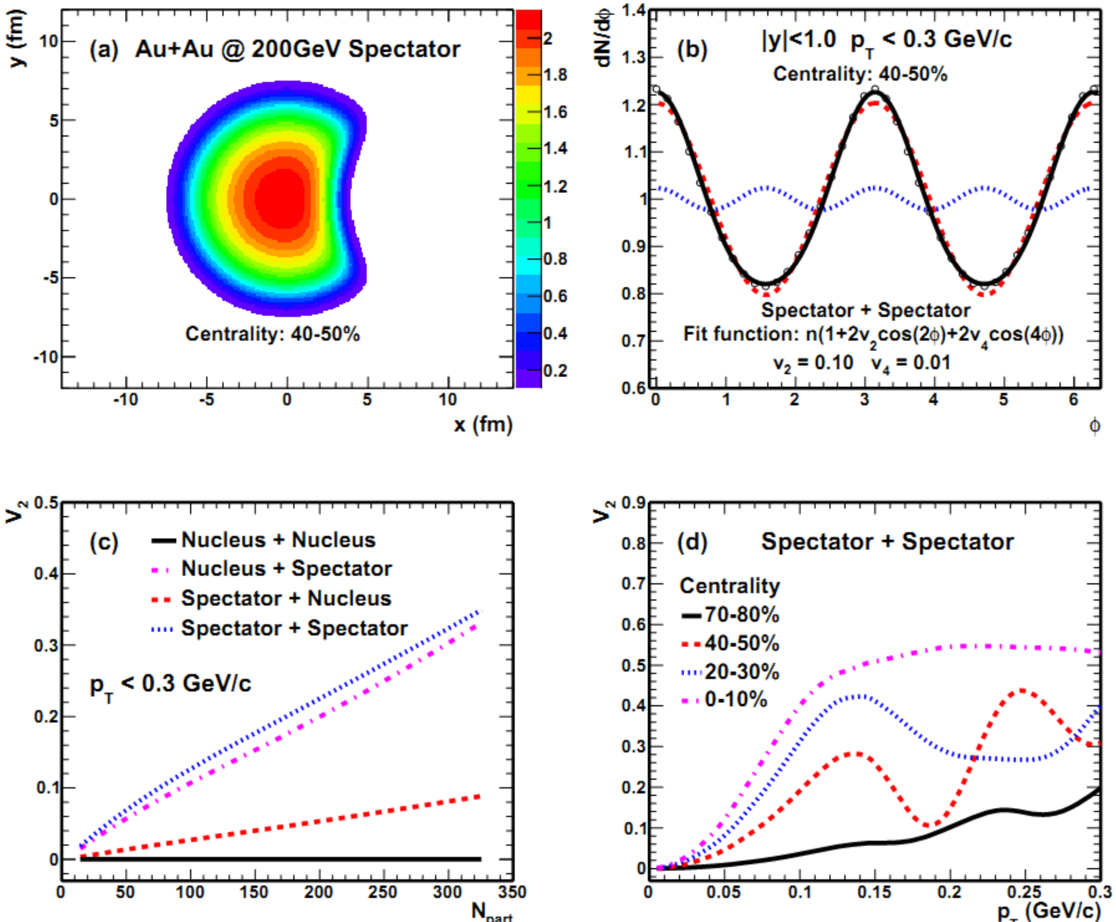




Phys. Rev. C **77** (2008) 54901

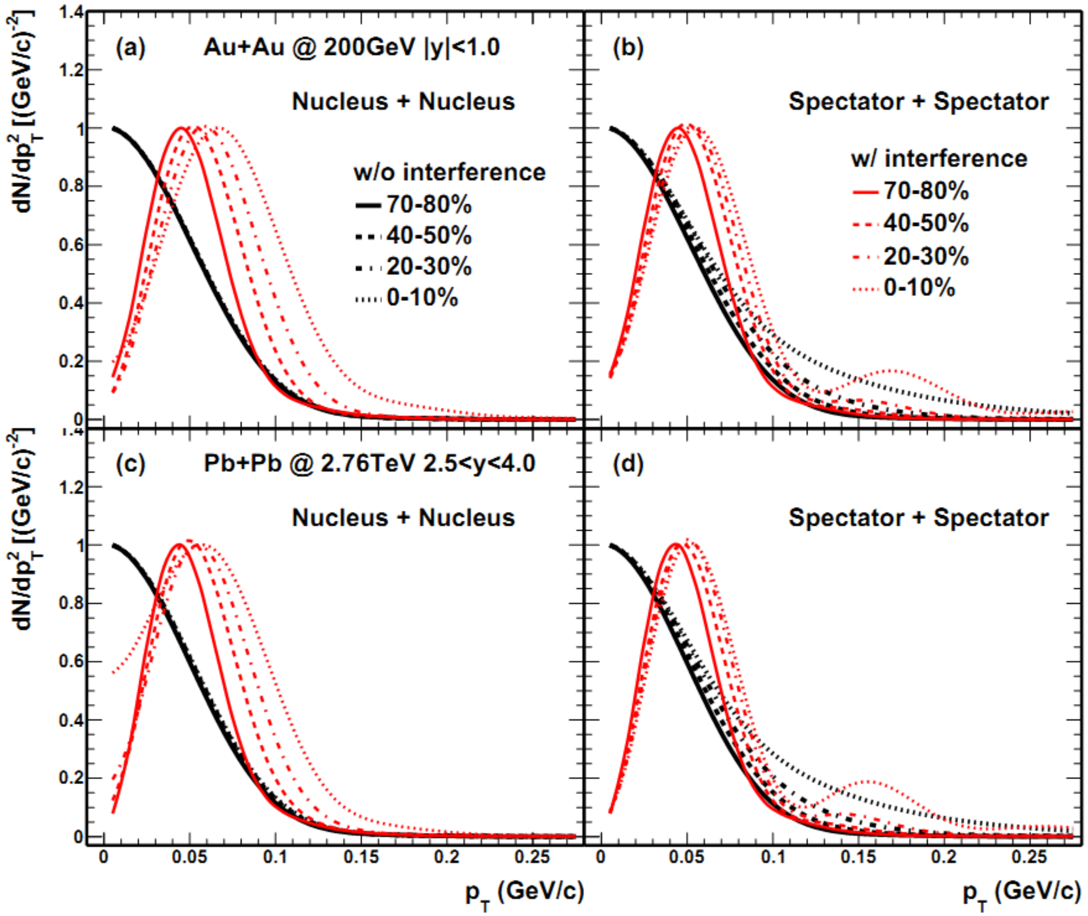
The elliptic flow vanishes at low p_T and central collisions!

Production versus ϕ (relative to reaction plane)



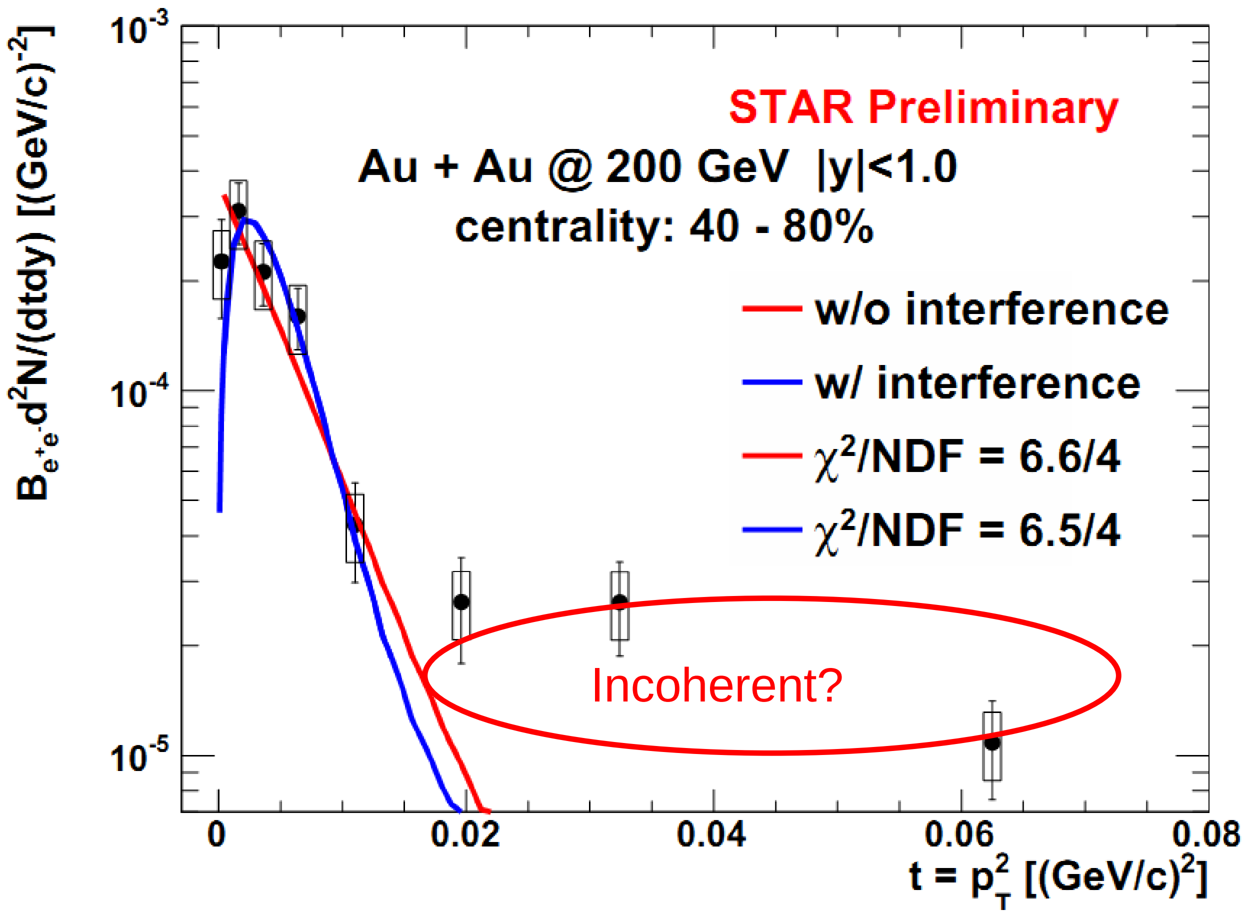
- ✓ Sensitive to the target!
- ✓ Large v_2 and sizeable v_4 will be observed if the target is spectator!
- ✓ V_2 increase dramatically toward central collisions!
- ✓ Probe of initial geometry of the overlap region!

p_T shape with interference



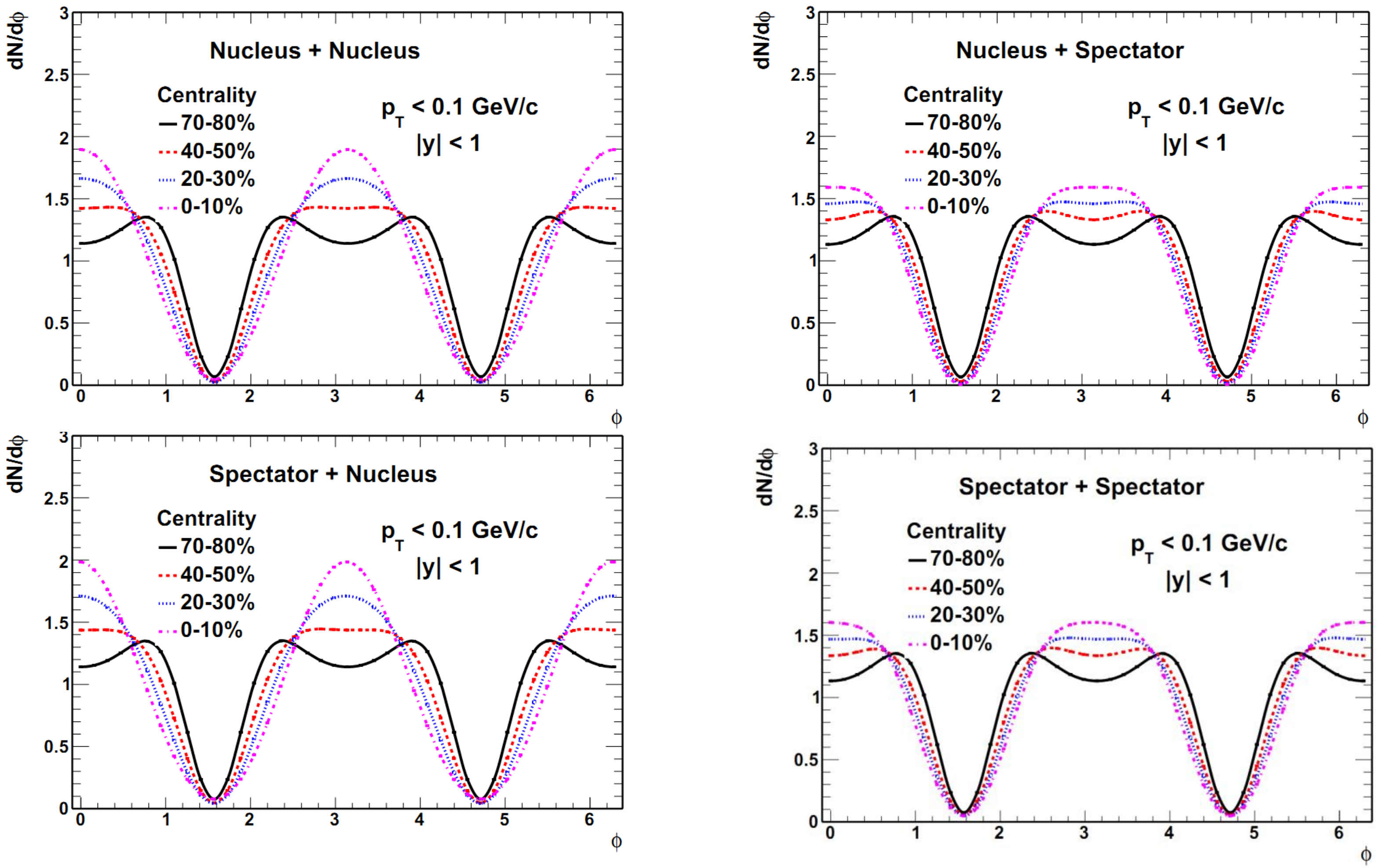
- ✓ Dramatically change the p_T spectra!
- ✓ Different interference pattern in different centrality!
- ✓ The effect is relative small with spectator coupling!

t distribution



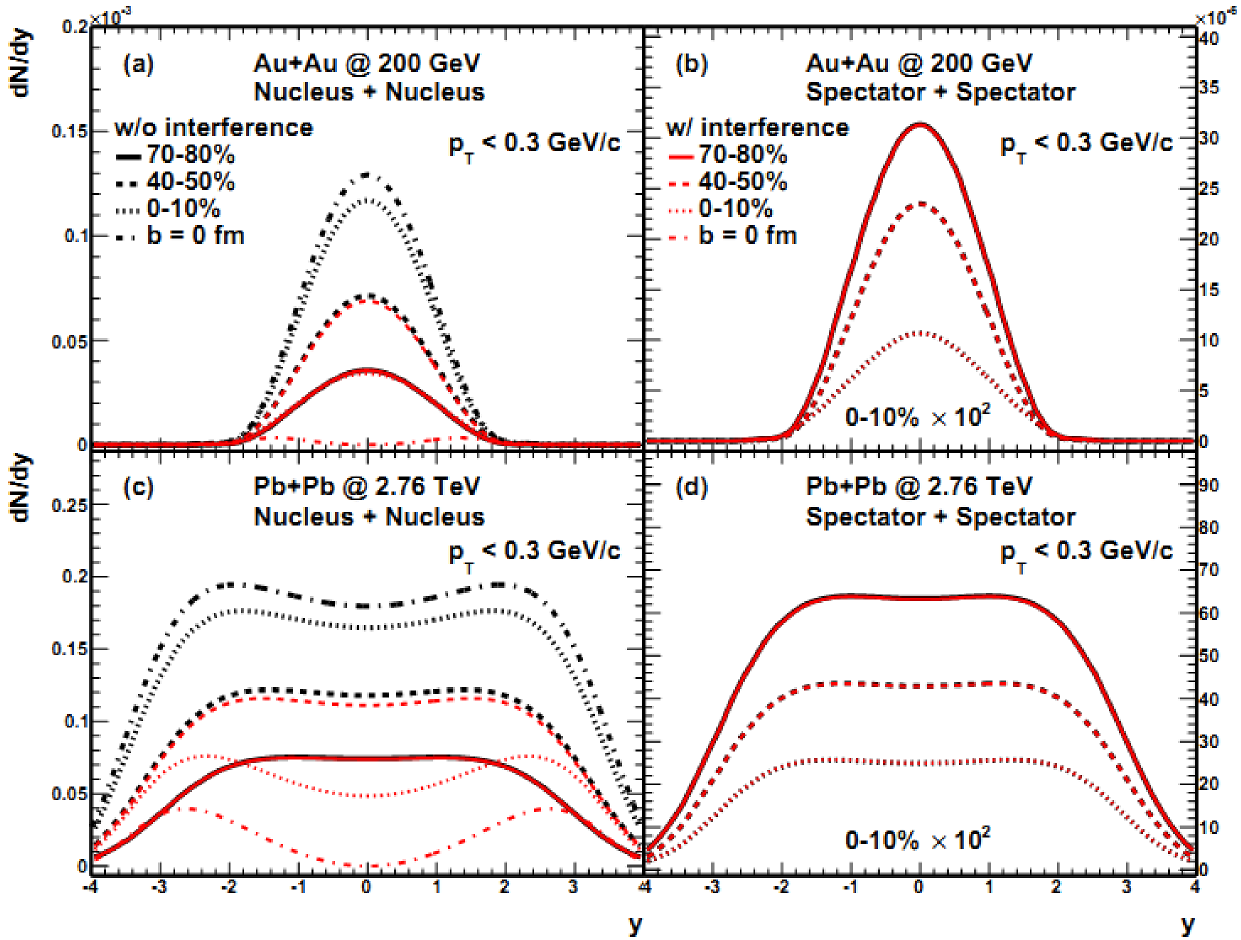
✓ Both scenarios describe the data reasonably well!

ϕ distribution with interference



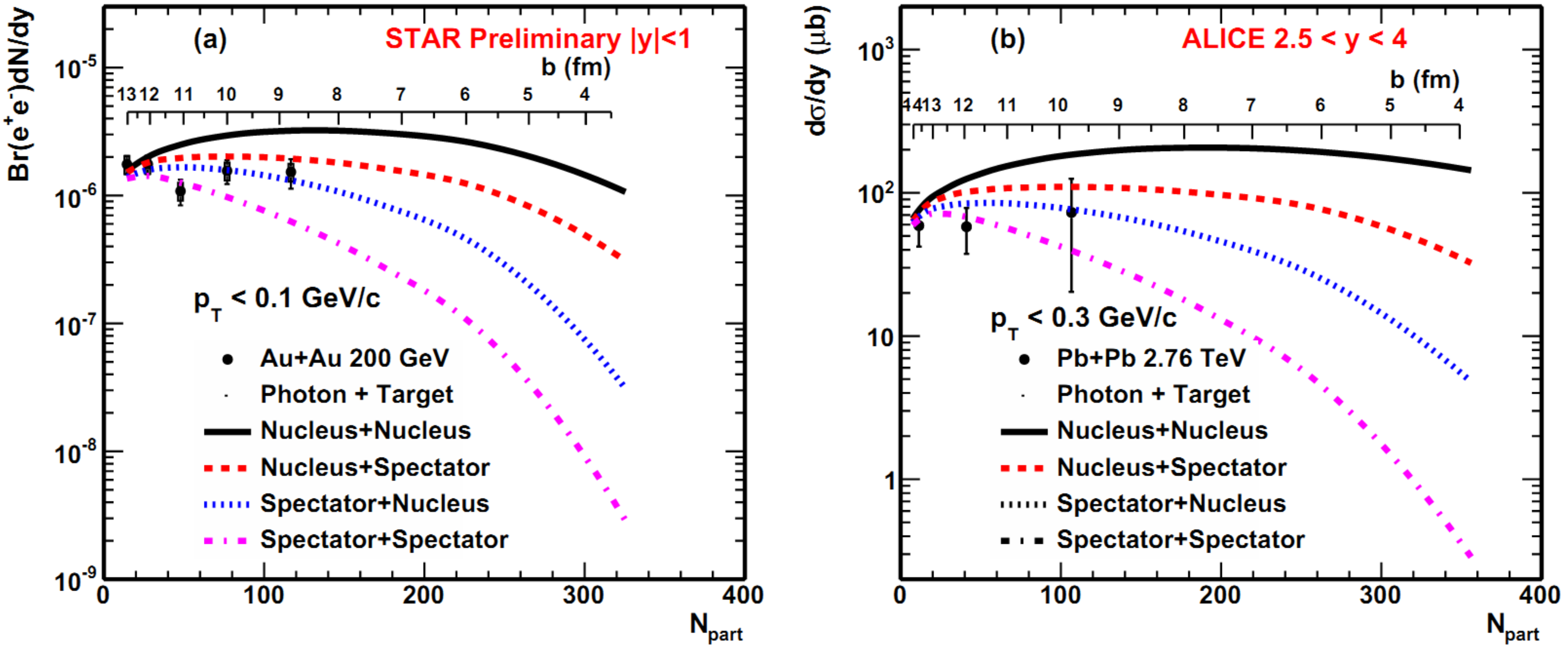
✓ Dramatically change ϕ distribution!

Rapidity distribution with interference



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

Cross section with interference



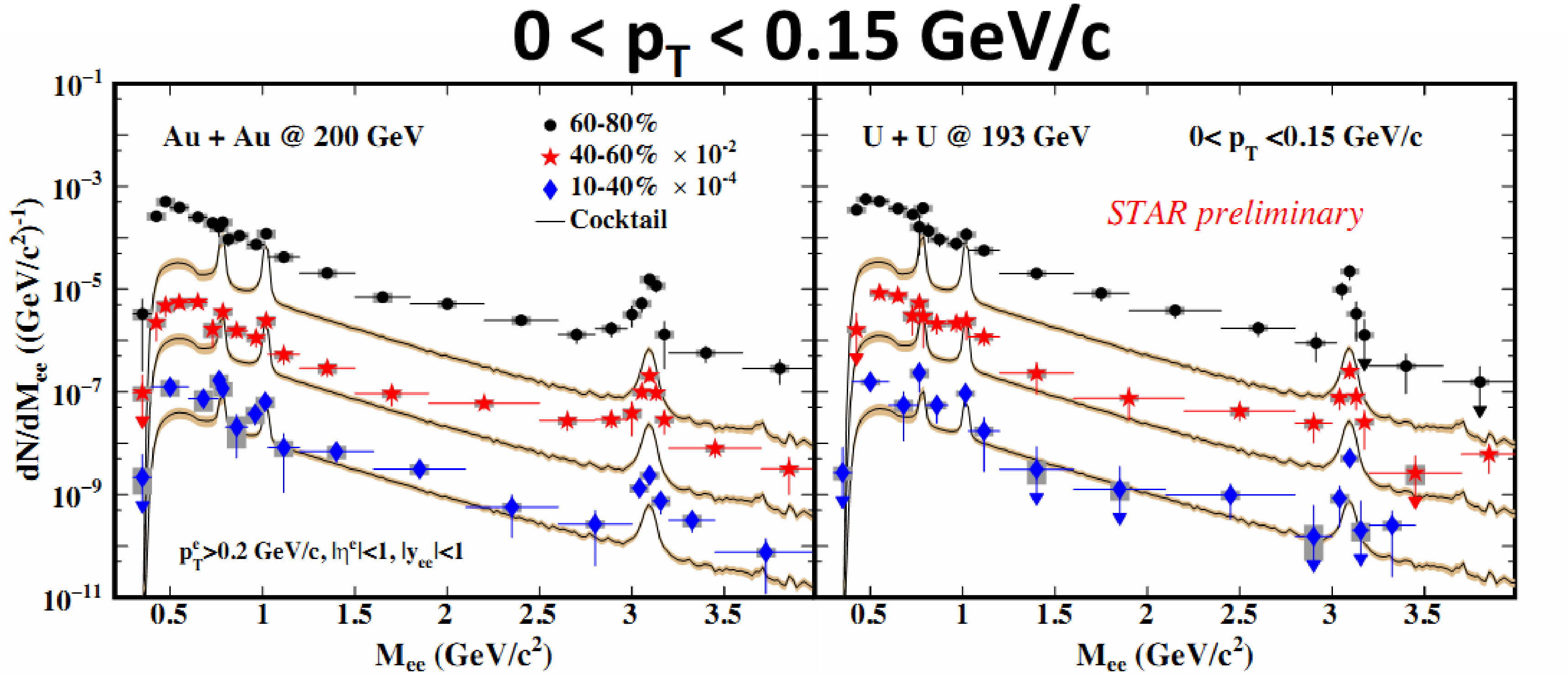
- ✓ The cross section with nucleus coupling is decreased in central collisions!

Summary

- 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.

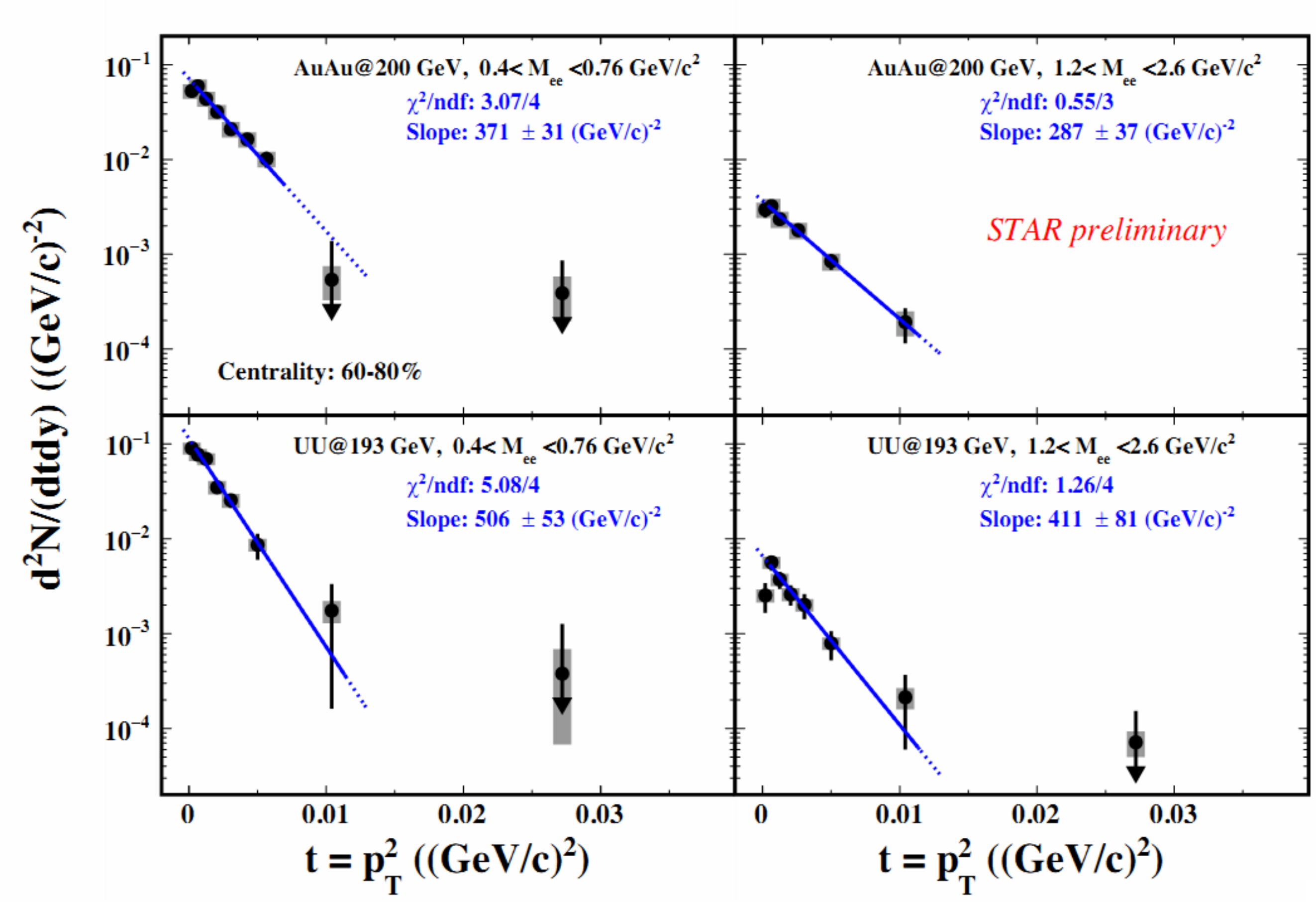
- Theoretical calculations describe the data of peripheral collisions (60 – 80%)
  - ✓ Different scenarios have different trend toward central collisions!
  - ✓ Semi-central and central collisions: Nucleus+ Nucleus => overestimate Spectator+Spectator => underestimate
  - ✓ p_T and ϕ distribution: sensitive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

Measurements beyond J/ψ



- ✓ Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range.
- ✓ ρ^0 peak?
- ✓ 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?

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? Measure magnetic field?

- 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?

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
(Using AMPT?)

Thank you!

Back-up

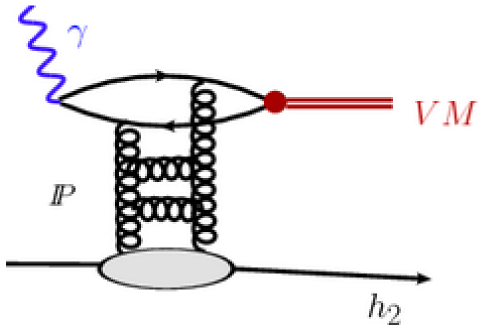
- Heavy nuclei carry strong electric and magnetic fields
  - Fields are perpendicular -> treat as nearly-real virtual photons
    - $E_{max} = \gamma hc/b$
  - Photonuclear interactions
  - Two-photon interactions
- Visible when $b > \sim 2R_A$, so there are no hadronic interactions;

Energy	AuAu RHIC	pp RHIC	PbPb LHC	pp LHC
Photon energy (target frame)	0.6 TeV	~12 TeV	500 TeV	~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

Physcis of UPC

- The energy frontier for electromagnetic probes
  - Maximum CM energy $W_{\gamma p}$ ~ 3 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 α_{EM} ~ 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', Υ(1S), Υ(2S), and Υ(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%