Coherent photoproduction in hadronic heavy-ion collisions

Wangmei Zha

University of Science and Technology of China

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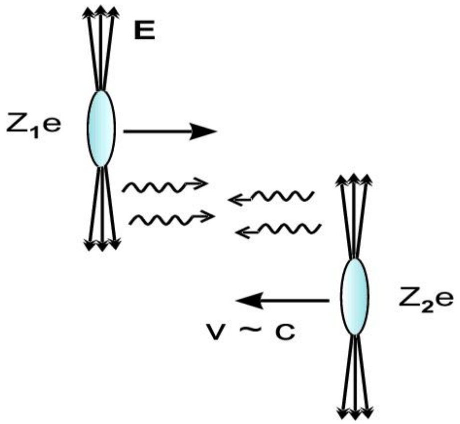
https://arxiv.org/pdf/1705.01460.pdf
and paper in preparation

Coherent photons as “partons” in heavy-ion collisions



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

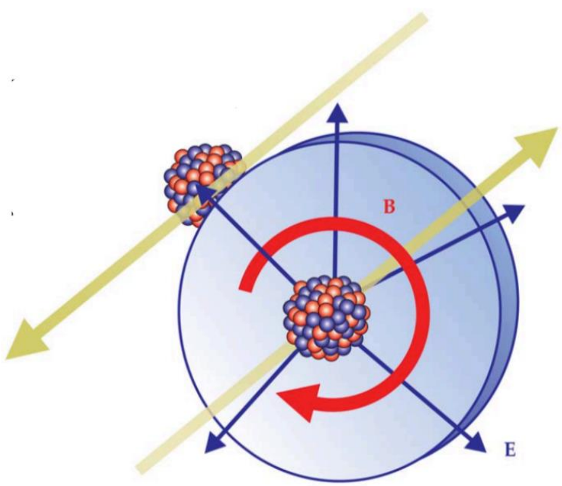
Photon four momentum: $q^u = (\omega,\ \vec{q}_T, \omega/v)$

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

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

$$q_T \leq 1/R$$

- View photons as “partons” being present in fast moving ions!



The extent of photons swarming about the ions:

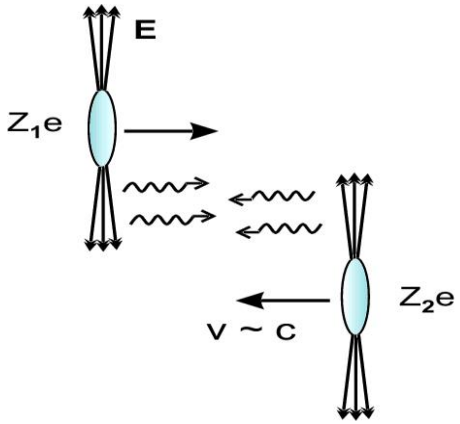
The radius of nuclear matter R_{Nuc} ~ 6.3 fm (Au)

$R_{photons}$ >> R_{Nuc}

Take the photoproduction of ρ (Au+Au 200 GeV)in ultra-peripheral collisions (UPCs) as example: $<R_{producton}>$ ~ 40 fm

- Every heavy-ion collider also serves as a photon collider!

Coherent photon interactions in heavy-ion collisions



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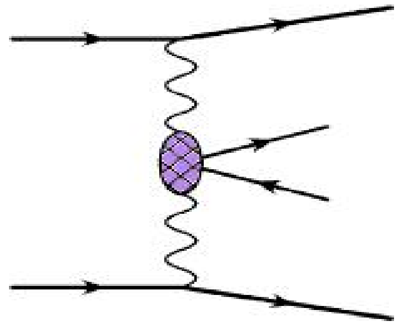

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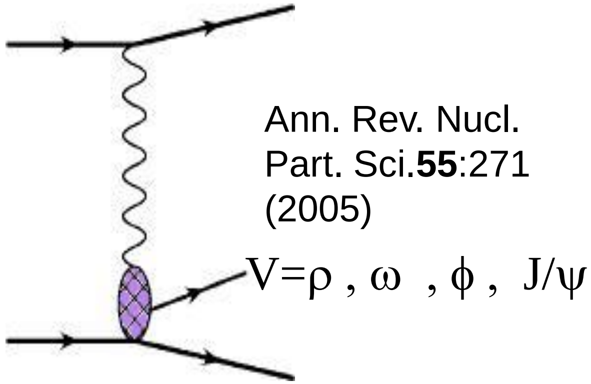


Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

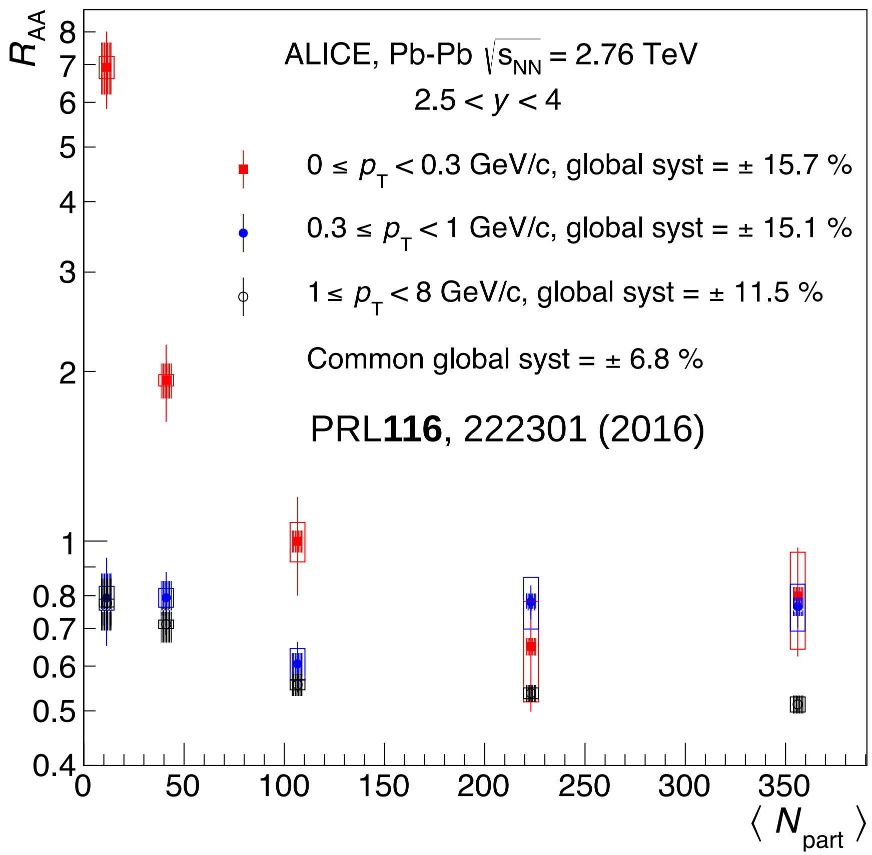
Electromagnetic interaction

Photon-photon interactions

Photon-nucleus interactions

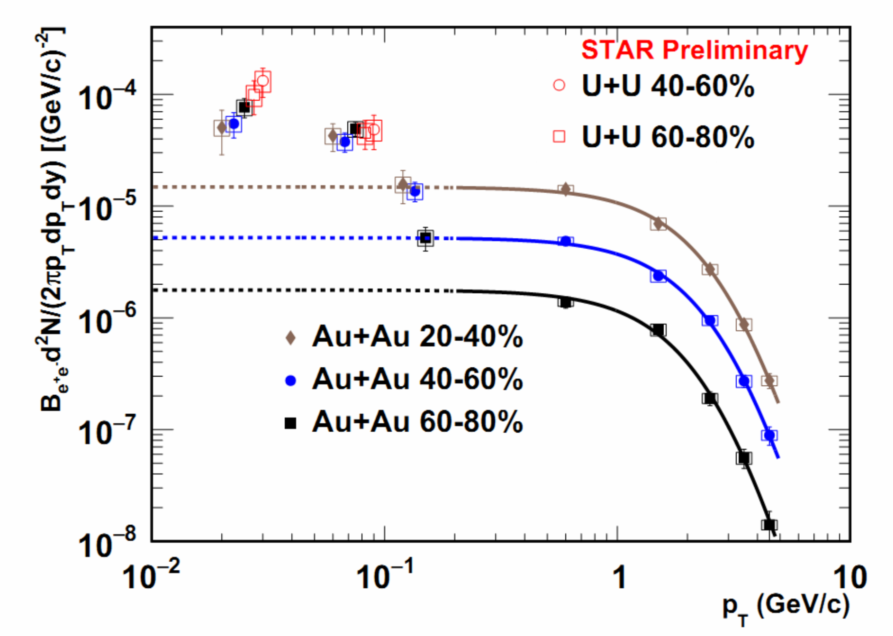
- Conventionally, only expected in UPCs
  - ✓ UPC conditions: $b > 2R_A$, no hadronic interactions, both nuclei stay intact with only product at extreme low p_T
- Can this coherent process also exist in hadronic heavy-ion collisions?
- In hadronic collisions, the violent strong interactions would break the nuclei, destroy the coherent condition!

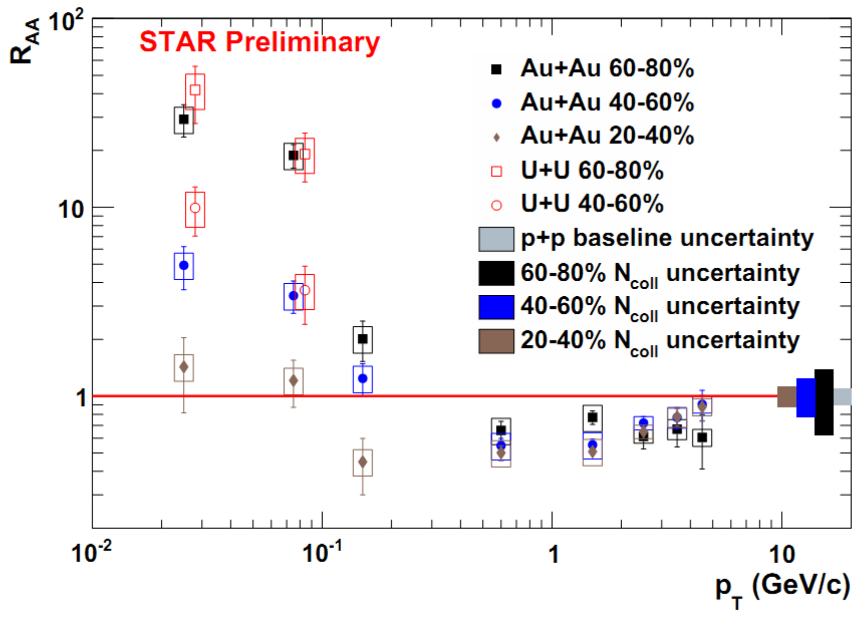
Excess of J/ψ production at very low p_T with ALICE



- 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?

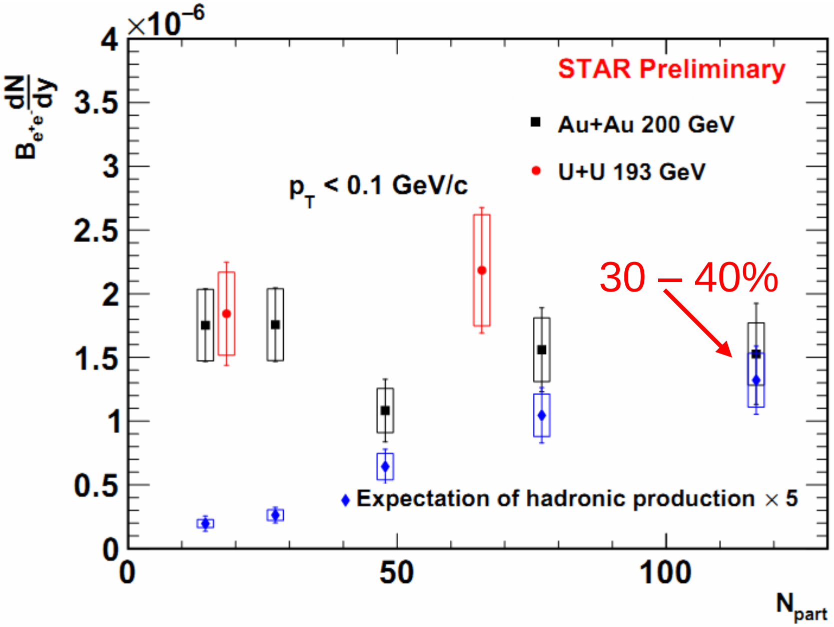
The measurements at STAR

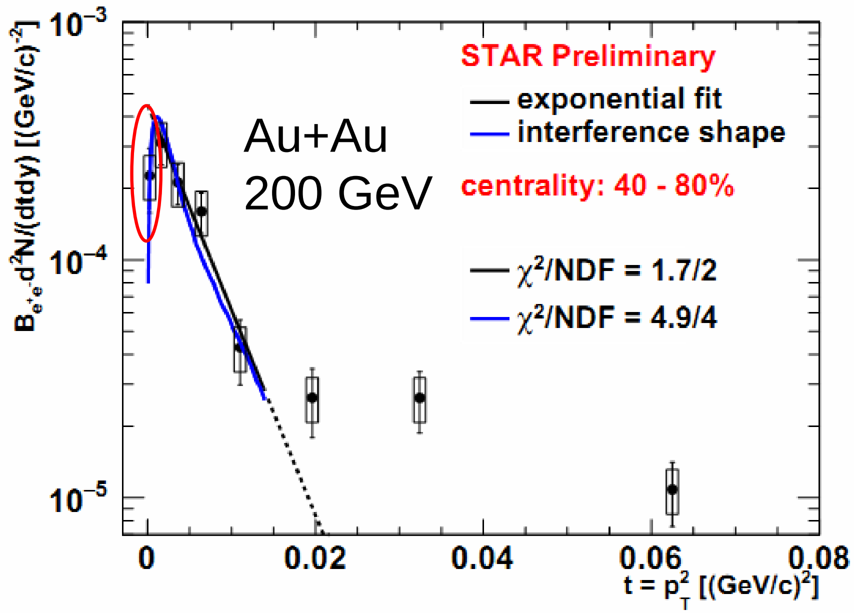




- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions (40 – 80 %)!
- No significant difference between Au+Au and U+U collisions.

The excess yield and dN/dt distribution





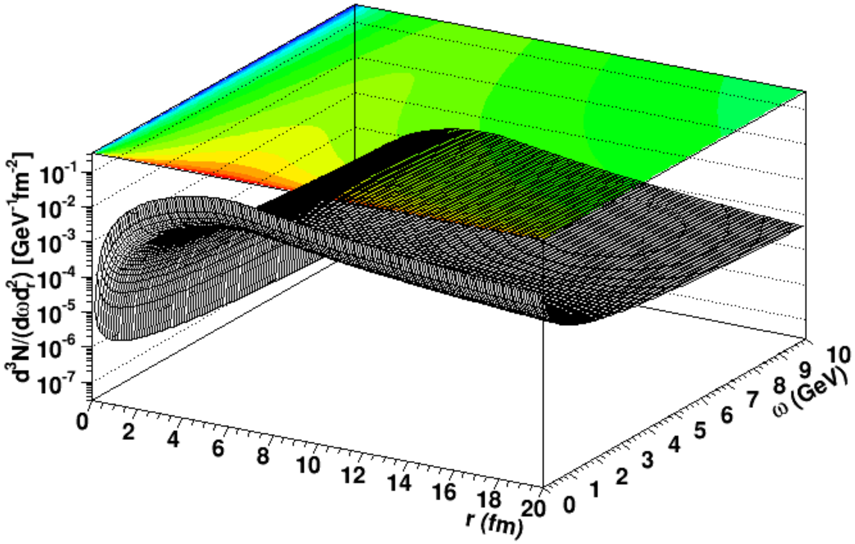
- Low p_T J/ψ from hadronic production is expected to increase dramatically with N_{part}.
- No significant centrality dependence of the excess yield!

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

Calculation strategy

Photon PDF:

equivalent photon approximation



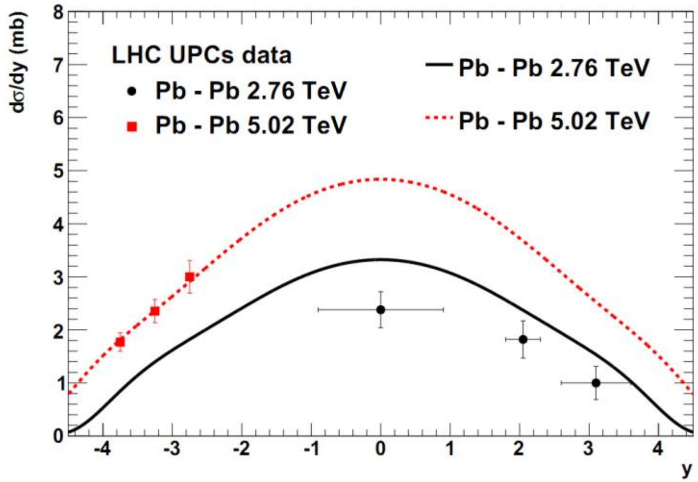
Au+Au 200 GeV

γ + A cross section:

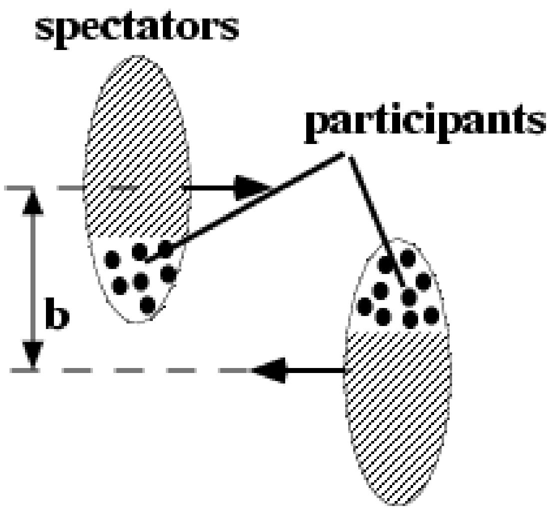
γ + p as input

Vector Meson Dominance

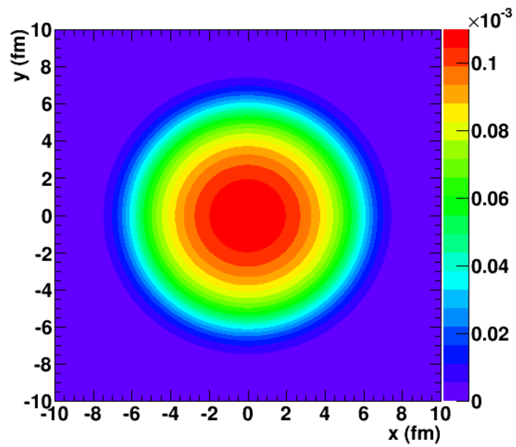
Glauber



Scenarios for calculations

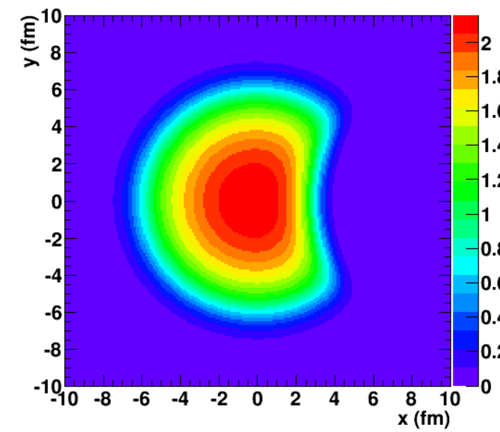


Photon emitter and target



nucleus

OR

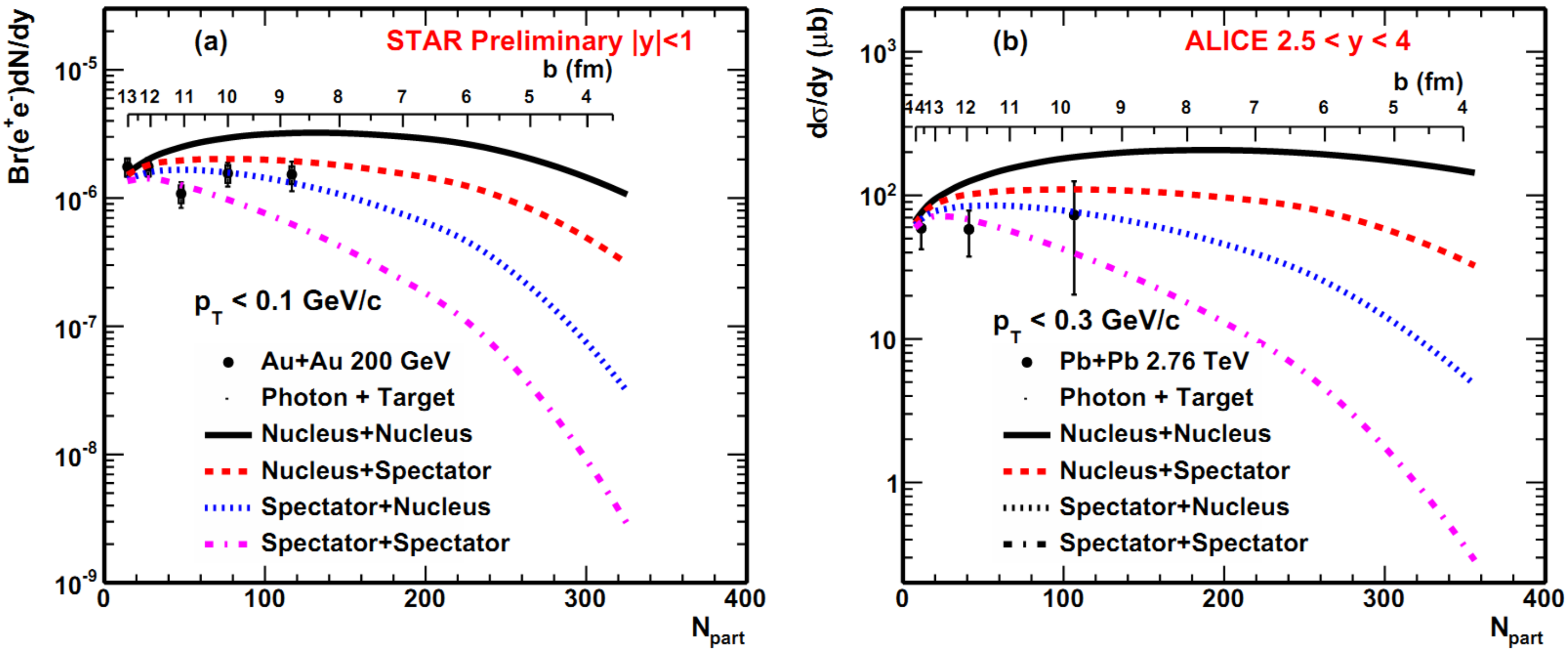


spectator

The shape of spectator is from optical Glauber calculations!

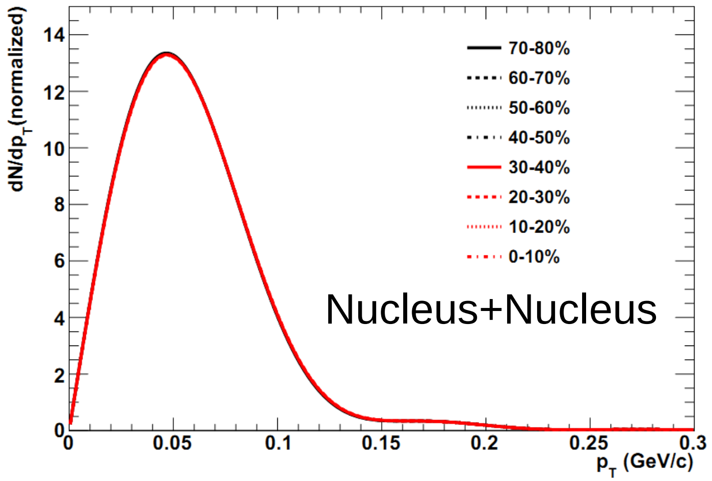
Photon emitter	Target	
Nucleus	Nucleus	(1)
Nucleus	Spectator	(2)
Spectator	Nucleus	(3)
Spectator	Spectator	(4)

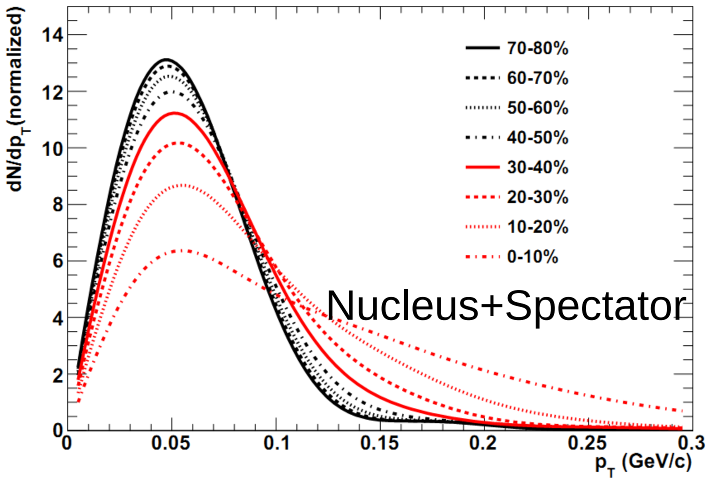
Calculations with different scenarios

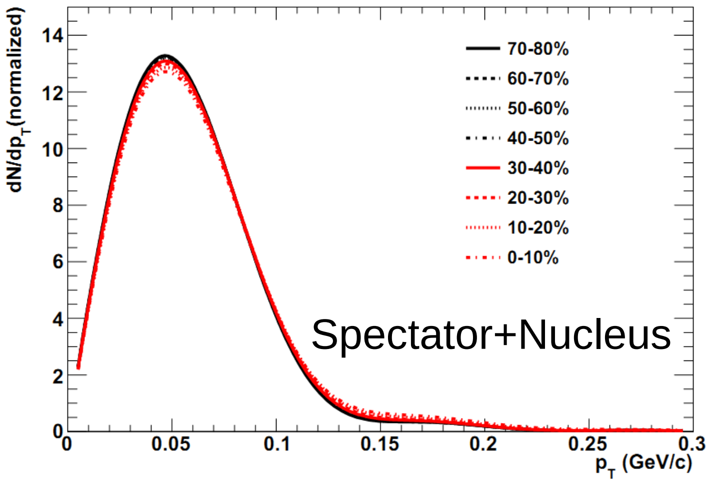


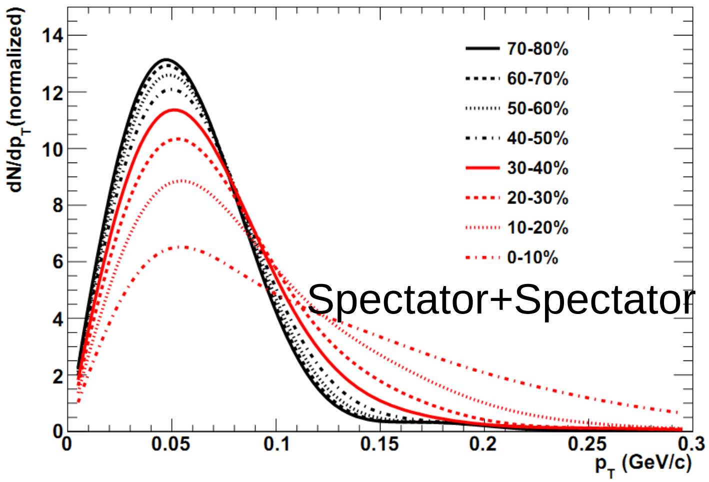
- Different scenarios have different trend toward central collisions!
- Spectator+Spectator: under predict the data in semi-central collisions.
- To distinguish the different scenarios, measurements at central collisions are needed!

p_T shape with different scenarios



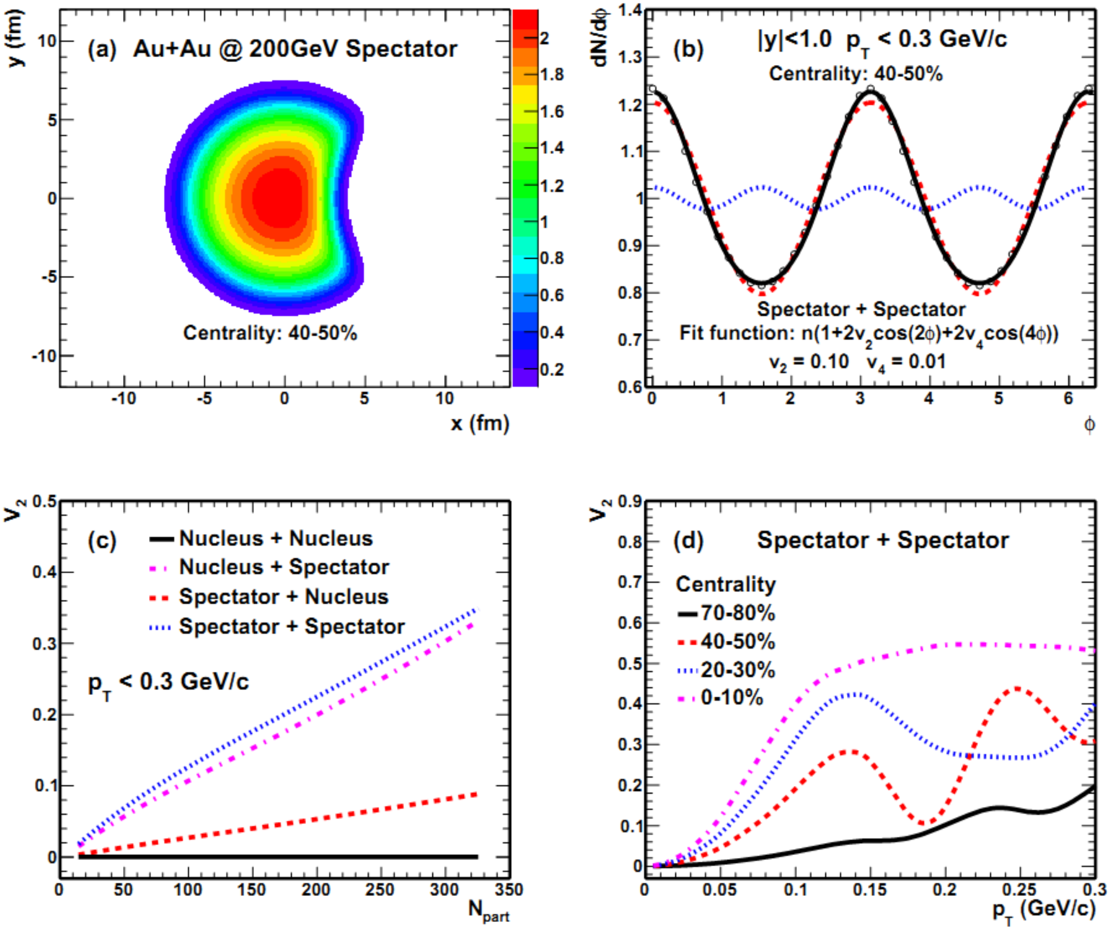


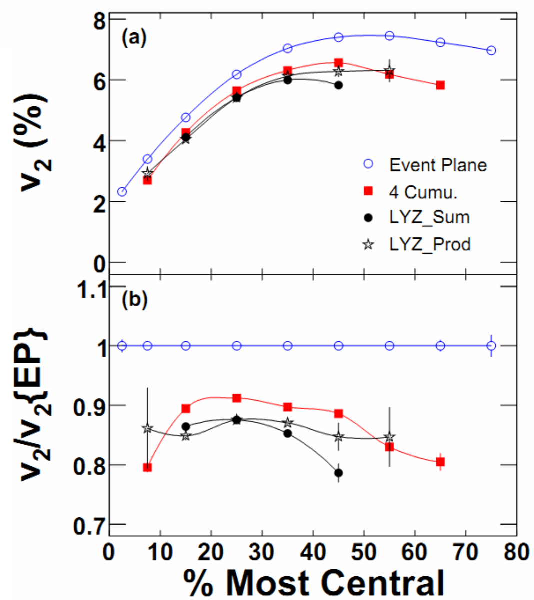




- The p_T shape is very sensitive to the target!
- If the target is spectator, the p_T shape has significant centrality dependence!

Production versus ϕ (relative to reaction plane)

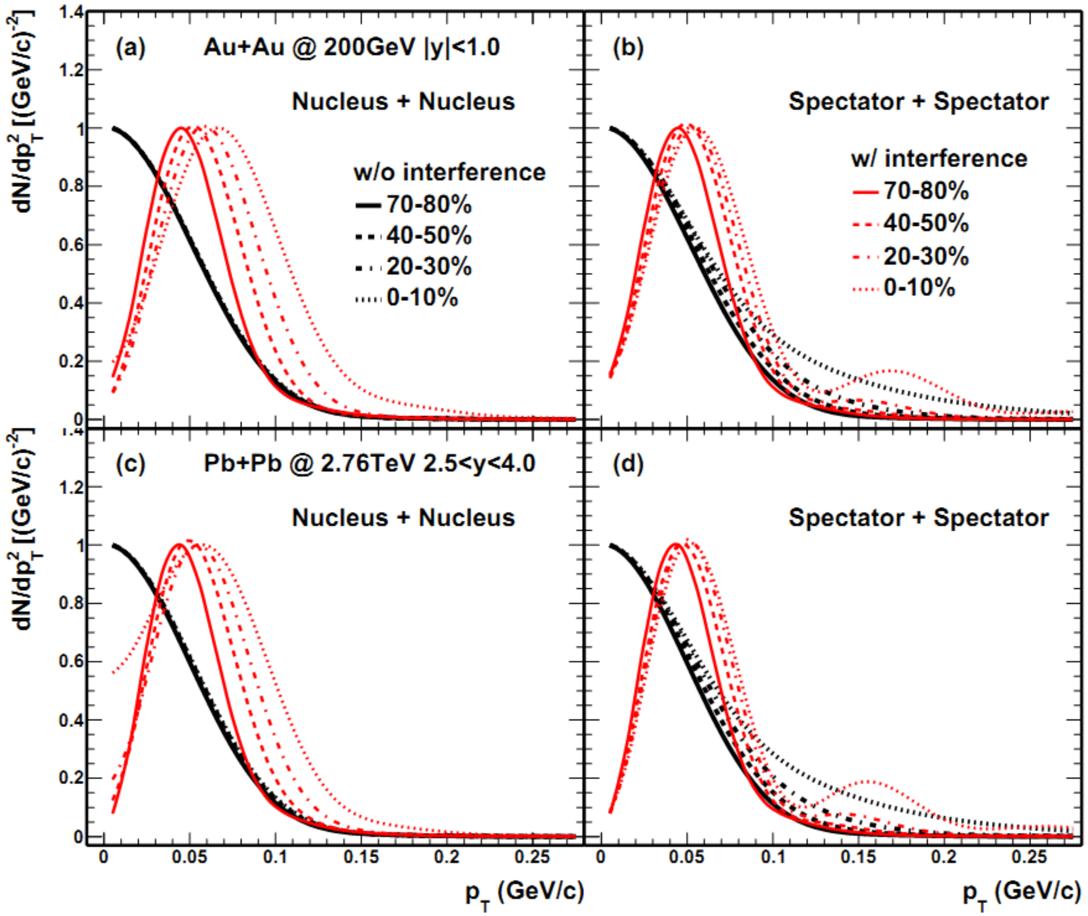




Phys. Rev. C 77 (2008) 54901

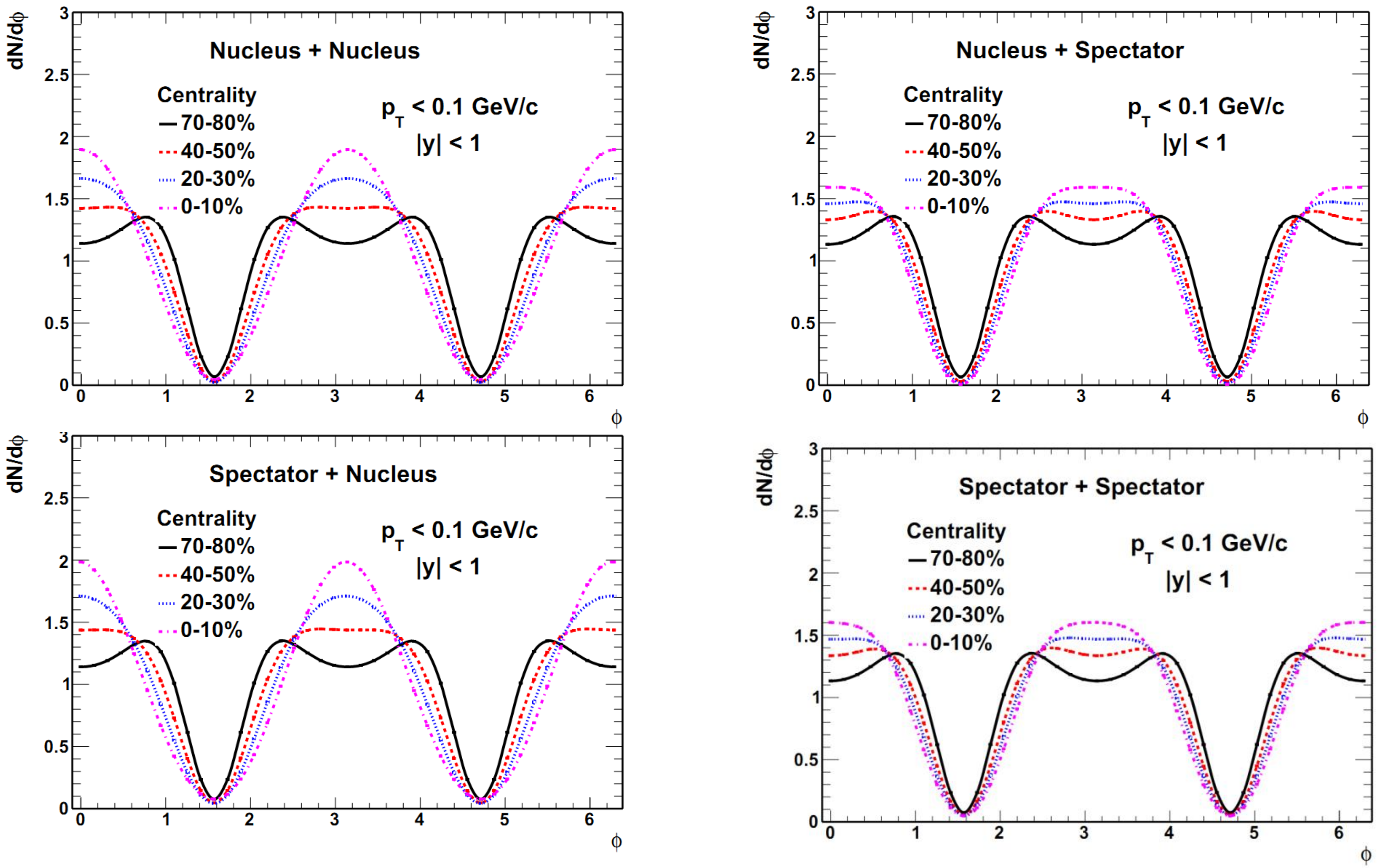
- Sensitive to the target!
- Large v_2 and sizeable v_4 will be observed if the target is spectator!
- V_2 increase dramatically toward central collisions!
- Probe of initial geometry of the overlap region!

p_T shape with interference



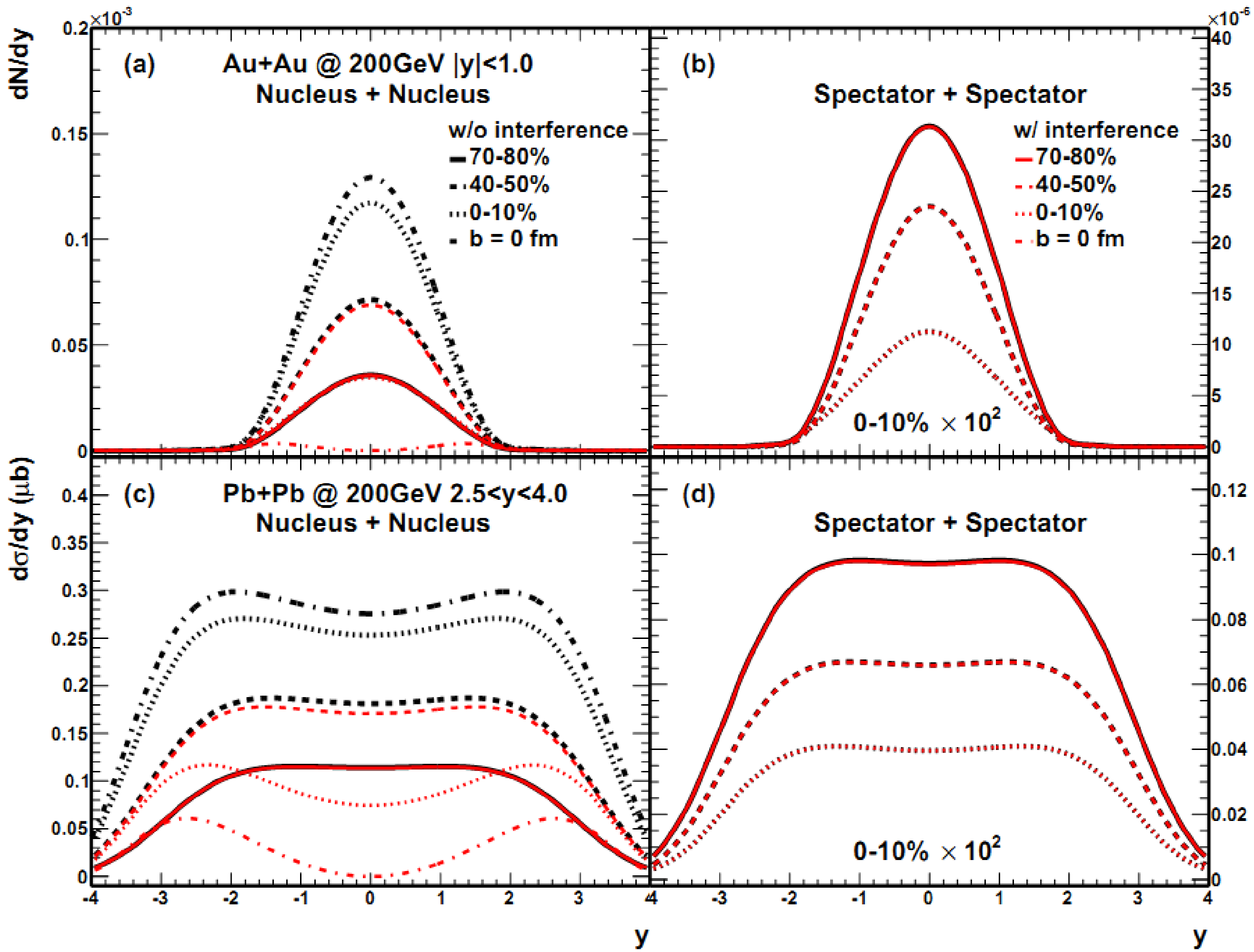
- Dramatically change the p_T spectra!
- Different interference pattern in different centrality!
- The effect is relative small with spectator coupling!

ϕ distribution with interference



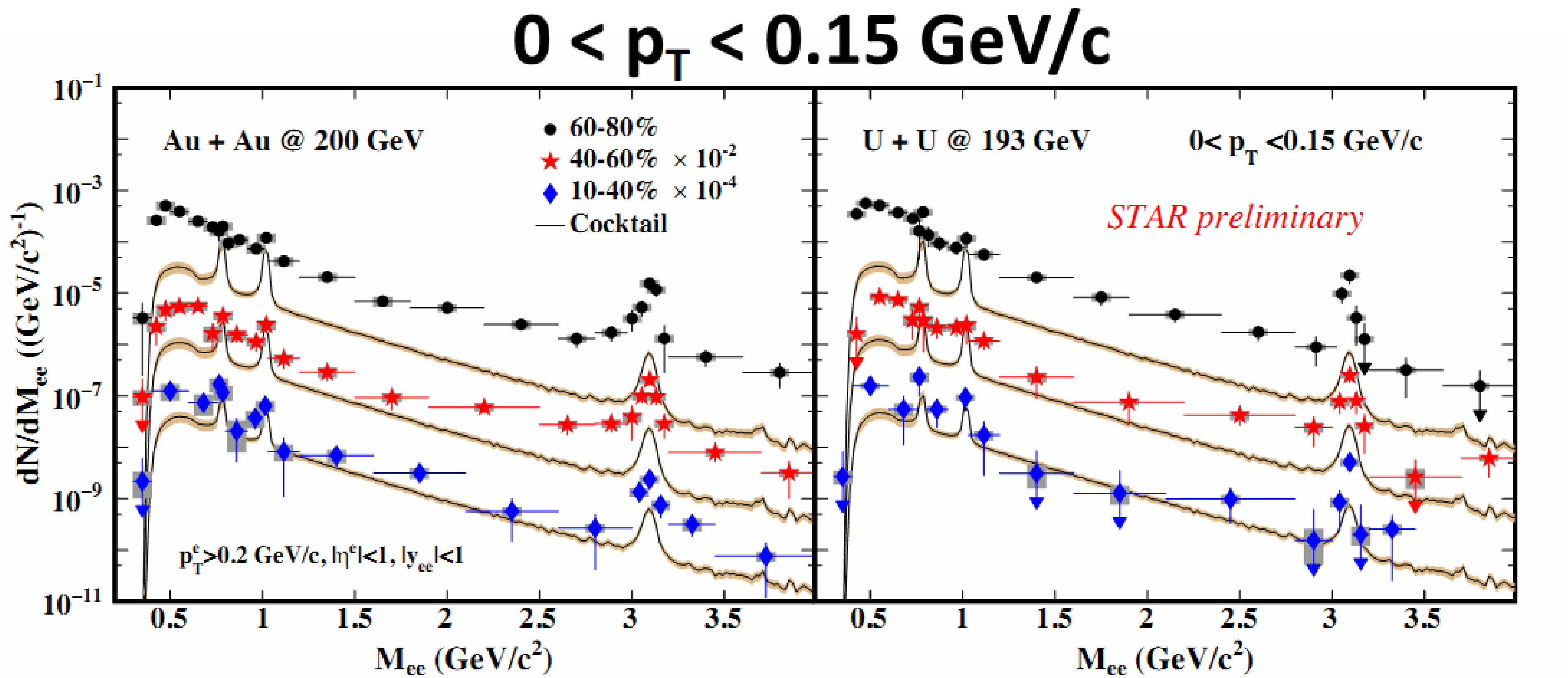
- Dramatically change ϕ distribution!
- Sensitive to the target!

Rapidity distribution with interference



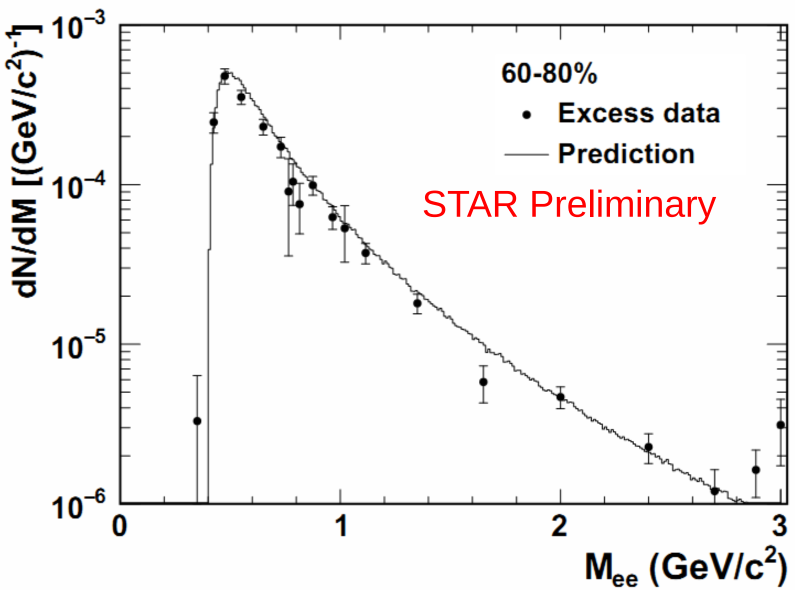
- Dramatically change the rapidity distribution with nucleus coupling!
- Stay unaffected with spectator coupling!

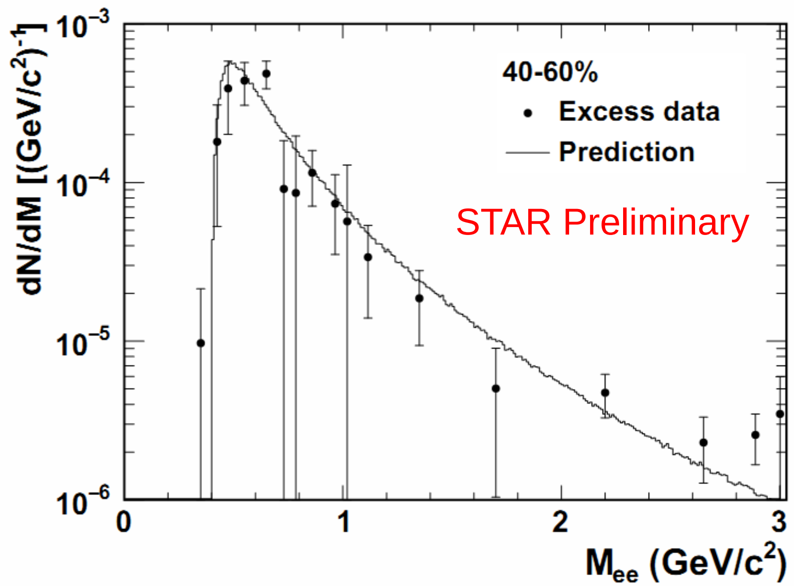
Hint of coherent photon-photon process?

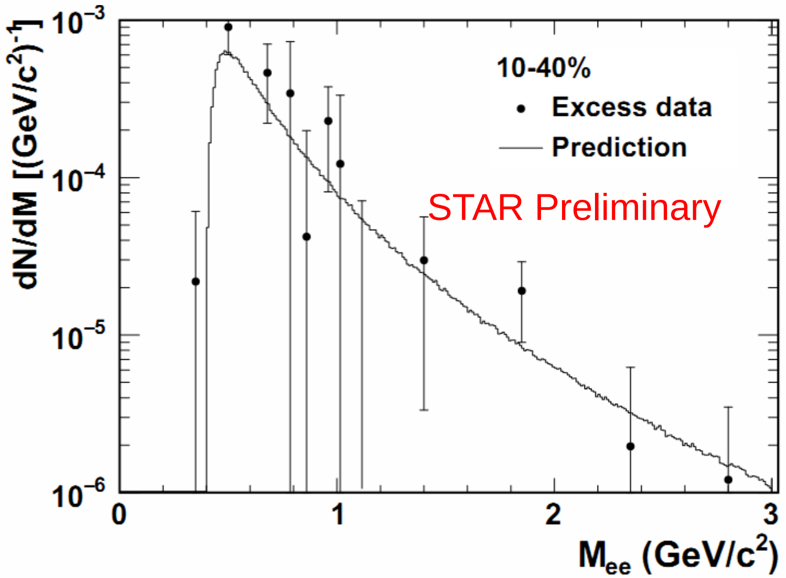


- Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range!
- Can the excess be described by the coherent photon-photon process?

Calculations for the excess



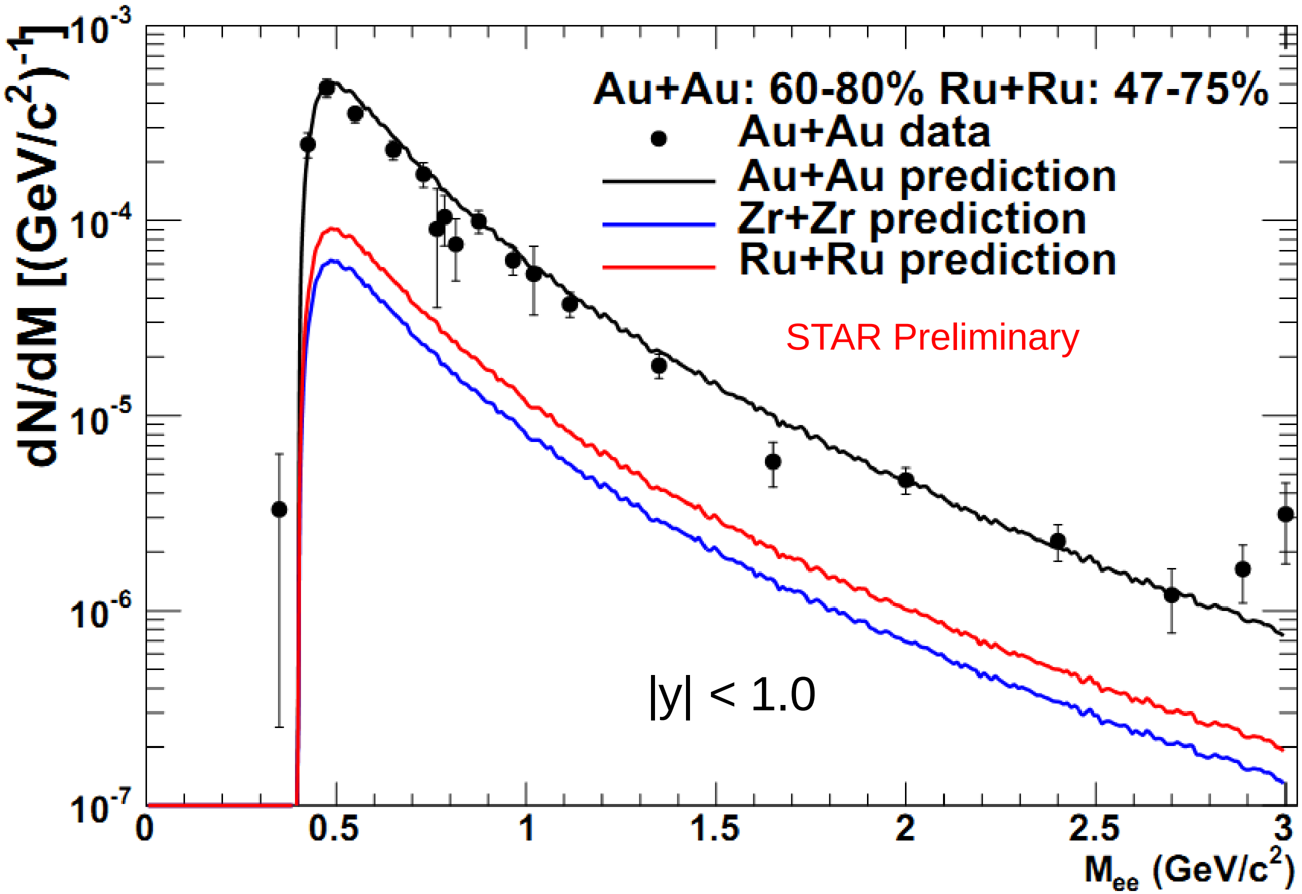




Describe the data reasonability well!

Nucleus coupling for photon emitter

Predictions for isobar collisions



Au: Ru: Zr ≈ 7.3 : 1.5 :1

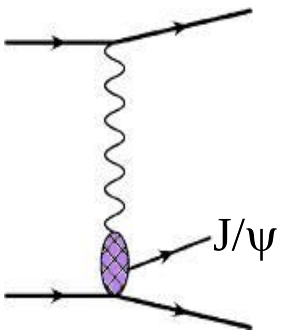
Au+Au (0-80%) 700M
Zr+Zr (0-75%) 1.2B
Ru+Ru (0-75%) 1.2B

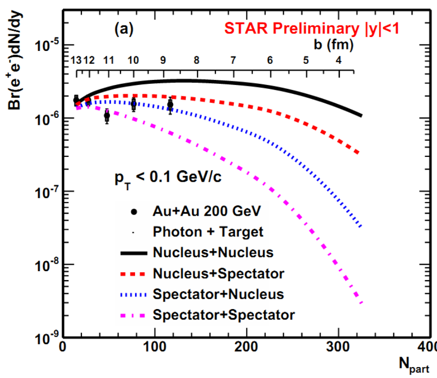
Au and Ru: 17.8σ
Au and Zr: 19.3σ
Ru and Zr: 3.7σ

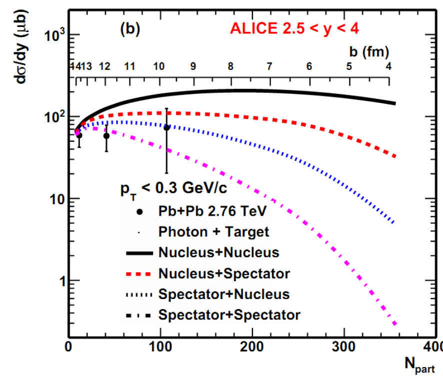
Test initial magnetic field!

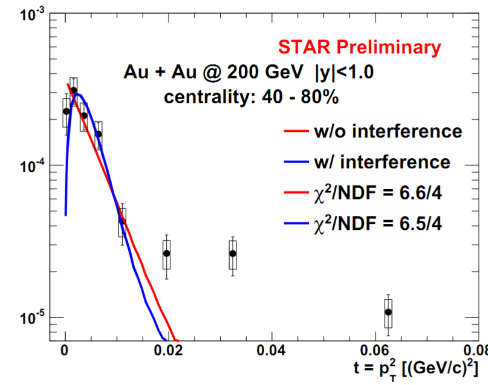
Summary

- Excess of J/ψ at very low p_T!
  - ✓Consistent with coherent photonuclear production!

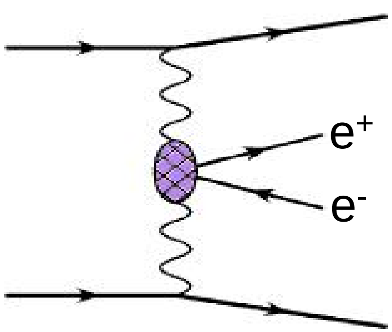


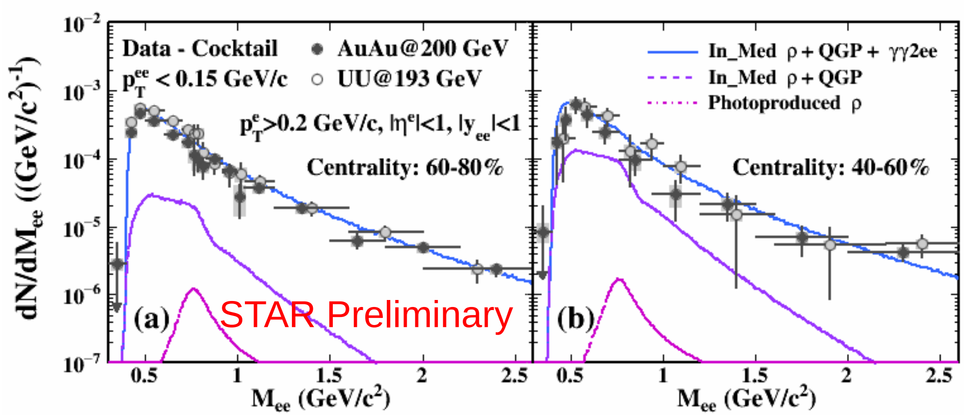






- Excess of dielectron at very low p_T!
  - ✓Consistent with coherent photon-photon production!





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>~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), $\gamma\gamma \to W^+W^-$, etc.

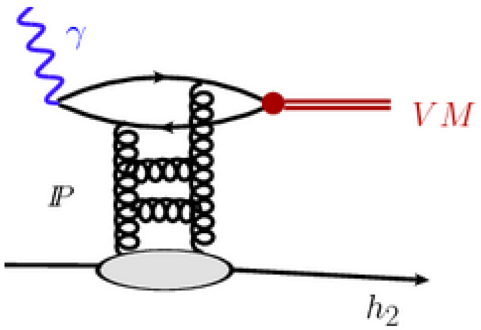
Vector meson photon-production

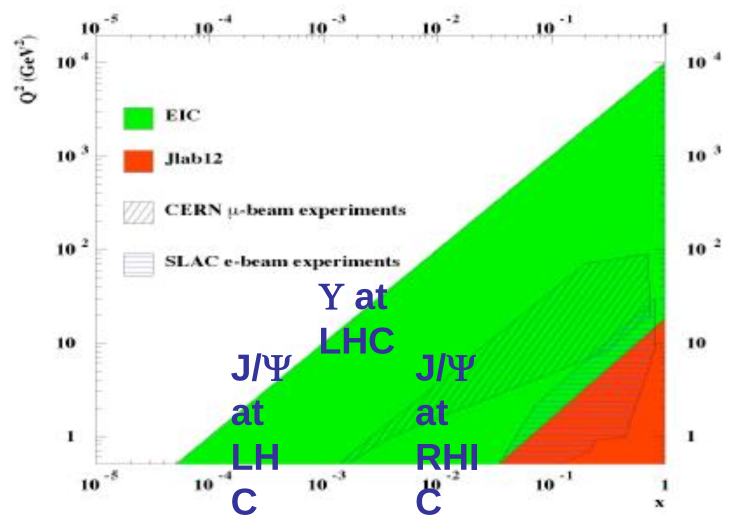
- Vector meson production:
  - ✓ chargeless ‘Pomeron exchange’
  - ✓ Light meson production usually treated via vector meson dominance model:
    ρ, direct $\pi^+\pi^-$, ω….
  - ✓ Heavy meson production treated with pQCD:
    J/ψ, ψ’, Υ(1S), Υ(2S), Υ(3S)…

- Sensitive to the gluon distribution:

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

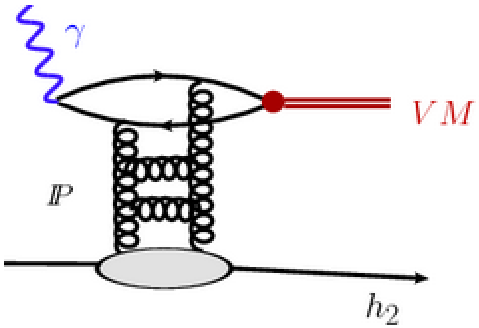
$$x = \frac{M_V e^{\pm y}}{\sqrt{s}} \quad Q^2 = M_V^2/4$$





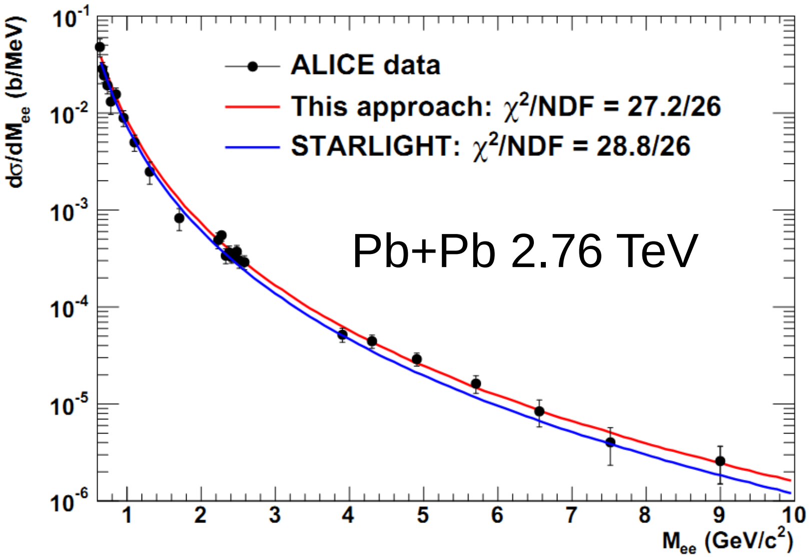
RHIC y=0: $x \sim 0.01$
LHC y=0: $x \sim 0.001$

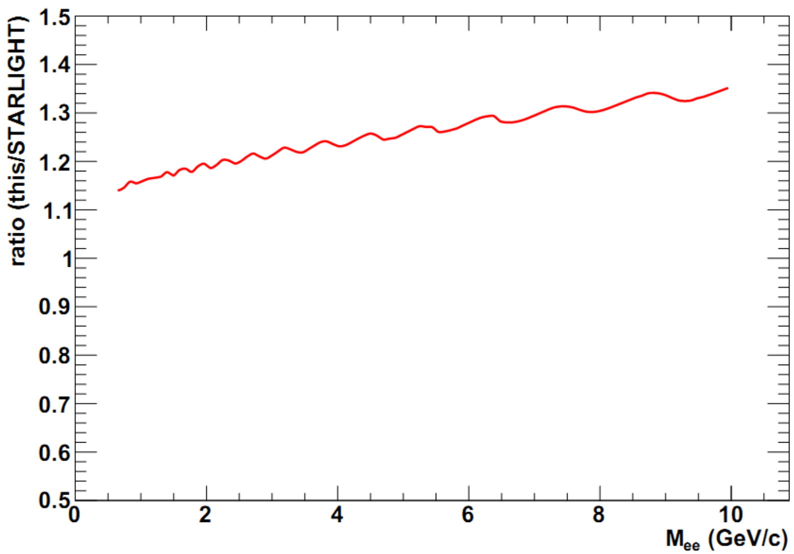
Photon production of vector meson



- 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%

Consistency check – ALICE UPC data

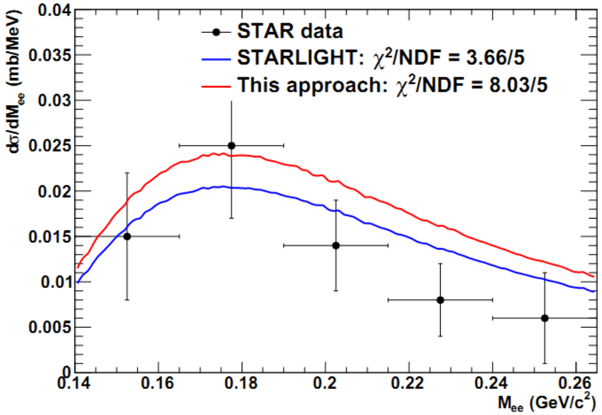




ALICE: preliminary + EPJC73 (2013) 2617

- ✓ Both approaches can reasonably describe the data.
- ✓ Our approach is about 10-40% higher than that of STARLIGHT.
- ✓ The Difference grows with pair mass, due to more production contribution at small impact parameters for heavier pair mass.

Consistency check – STAR UPC data



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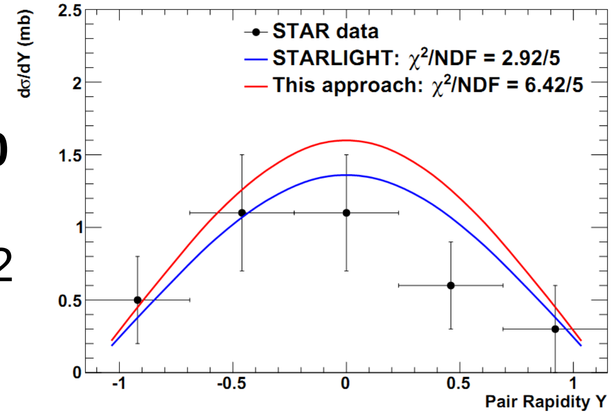
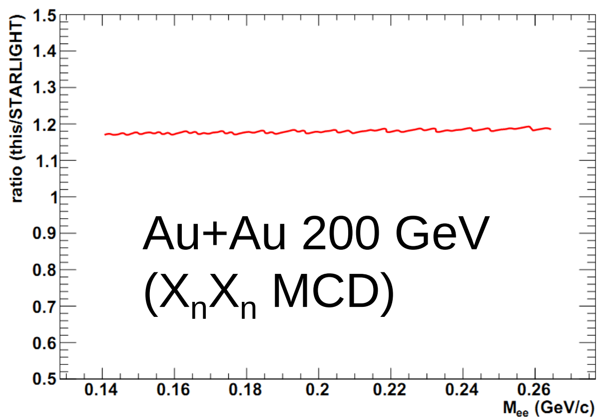
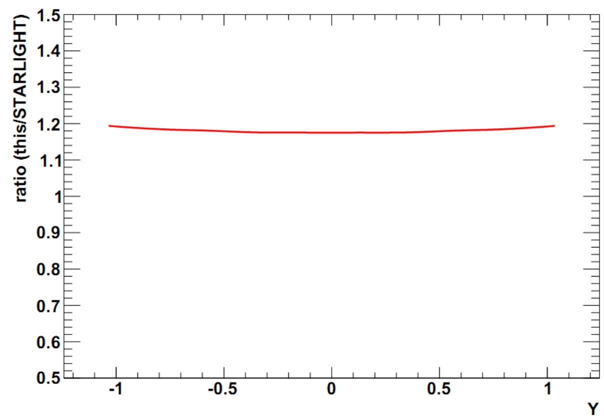






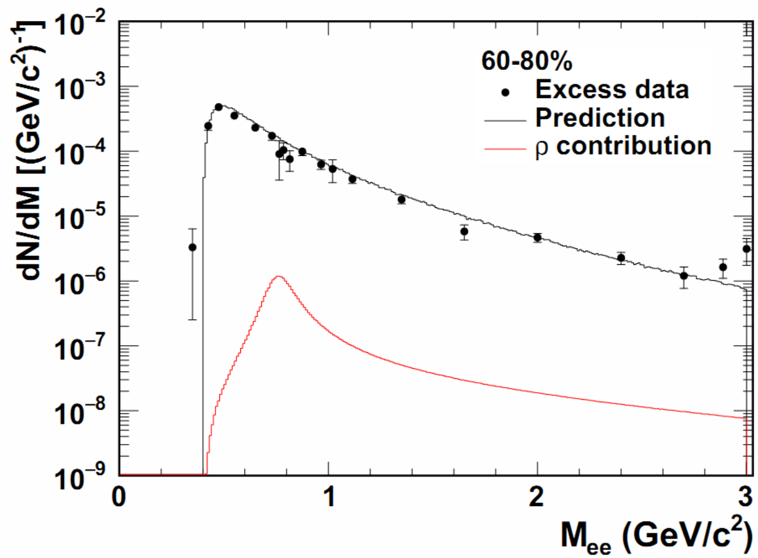
- ✓ Both approaches can reasonably describe the data.

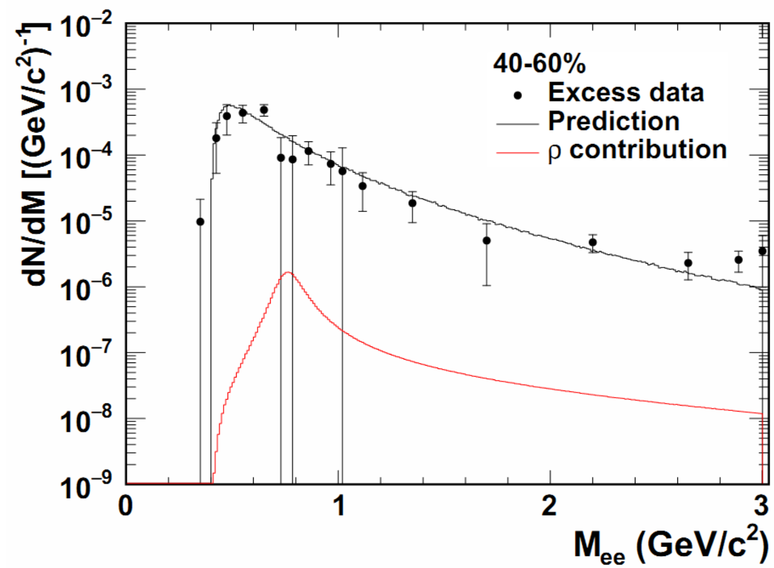
MCD probability:

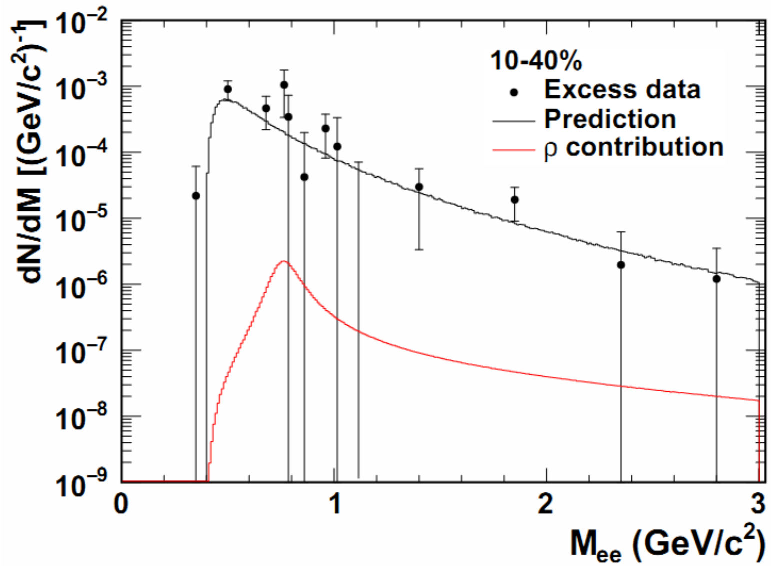
$$P^1_{Xn}(b) = \int_{E_{\min}}^{E_{\max}} dk \frac{d^3 n_\gamma}{d^2 b dk} \sigma_{\gamma A \to A^*}(k)$$

$$P_{Xn}(b) = 1 - \exp\left[-P^1_{Xn}(b)\right]$$

ρ contributions?

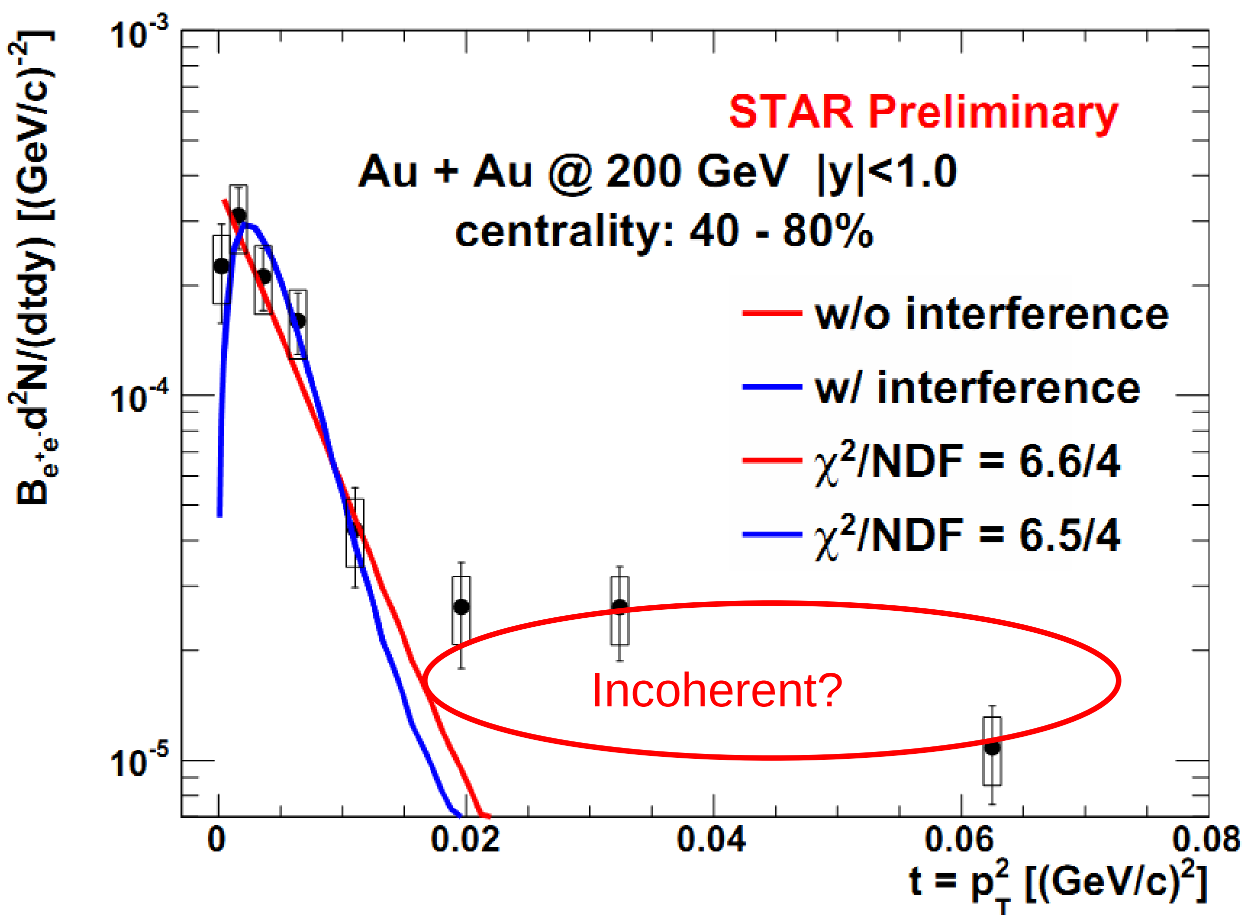






ρ contribution from 1-photon interactions is negligible!

t distribution



✓ Both scenarios describe the data reasonably well!

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?

Input for Glauber calculation

The spatial distribution --- Woods-Saxon form

Zr: A=96 Z=40
Ru: A=96 Z=44

$$\rho(r,\theta) = \frac{\rho_0}{1 + \exp\{[r - R_0 - \beta_2 R_0 Y_2^0(\theta)]/a\}}$$

Ru ($R_0 = 5.085$ fm) Zr ($R_0 = 5.02$ fm)

empirical formula for R_0

$$R_0 = 1.16A^{\frac{1}{3}}\left(1 - 1.16A^{-\frac{2}{3}}\right)$$

For Zr and Ru: R_0= 5.018 fm

$\rho_0 = 0.16 \ \text{fm}^{-3}$ $a \approx 0.46 \ \text{fm}$

$\beta_2^{\text{Ru}} = 0.158$ $\beta_2^{\text{Zr}} = 0.08$

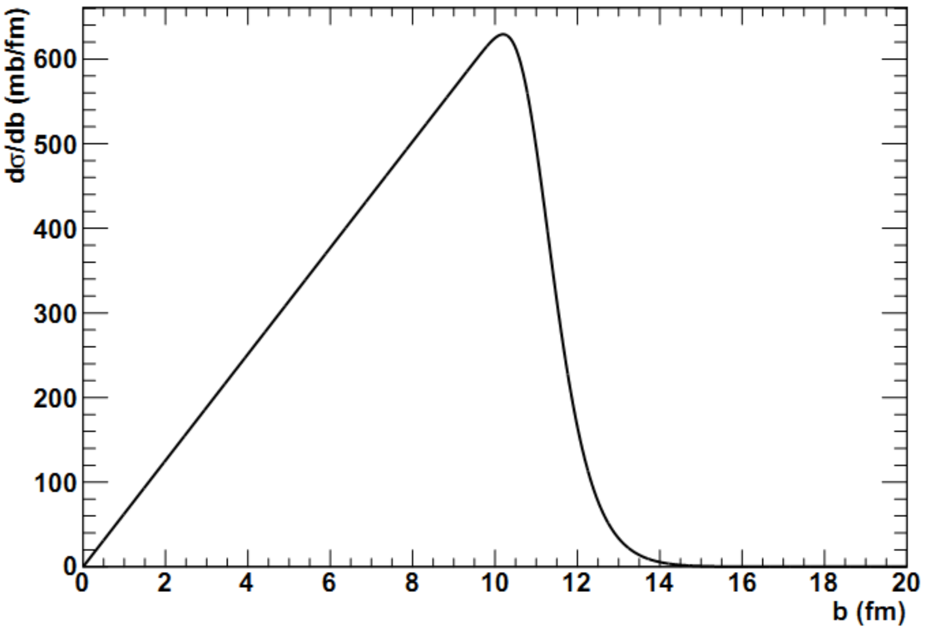
Atom. Data Nucl. Data Tabl. 107, 1 (2016)

For simplicity, use the same parameter set for Zr and Ru and assume $\beta_2 = 0$:

R_0= 5.018 fm $a \approx 0.46 \ \text{fm}$ $\rho_0 = 0.16 \ \text{fm}^{-3}$

Centrality determination --- optical Glauber

Collision energy: 200 GeV $\sigma_{pp} = 42\,mb$



Centrality (%)	b (fm)	Centrality (%)	b (fm)
0-5	<2.58	45-50	8.14
5-10	3.64	50-55	8.54
10-15	4.46	55-60	8.92
15-20	5.15	60-65	9.28
20-25	5.76	65-70	9.63
25-30	6.31	70-75	9.97
30-35	6.81	75-80	10.30
35-40	7.28	80-85	10.64
40-45	7.72	85-90	11.02

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