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

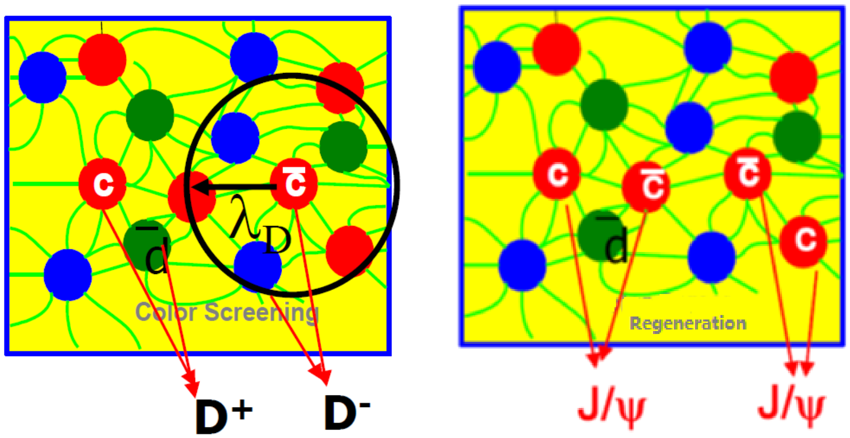
Wangmei Zha for the STAR Collaboration

University of Science and Technology of China

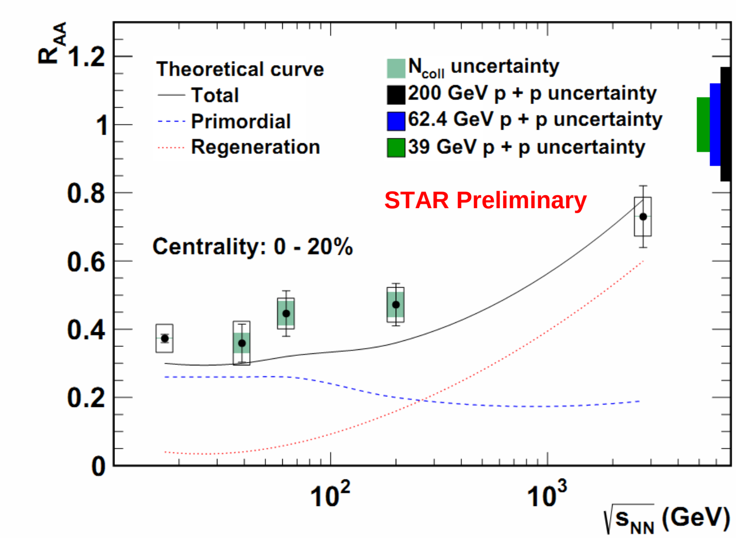
National Natural Science Foundation of China

J/ψ production modification in hadronic A+A collisions

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



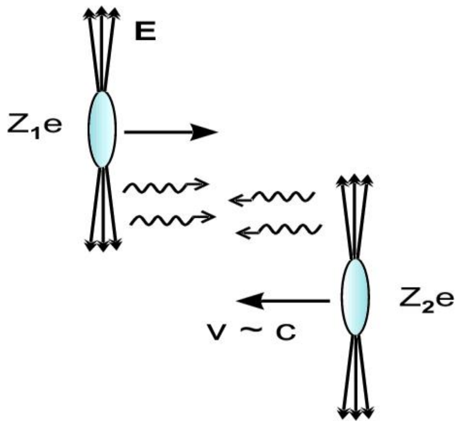
- Cold Nuclear Matter effects:
  - ✓PDF modification in nucleus
  - ✓Initial state energy loss
  - ✓Cronin effect
  - ✓……..



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

Introduction to photon interactions in A+A

- Studied in detail for Ultra-Peripheral Collisions (UPC)
  - ✓ UPC conditions: $b > 2R_A$, no hadronic interactions



UPC A+A interaction

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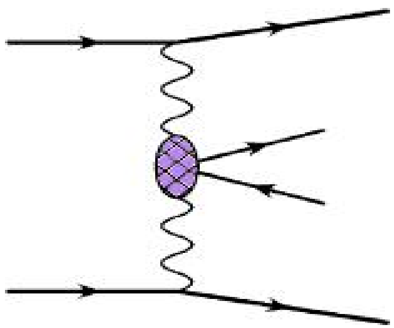

Photon-photon interactions

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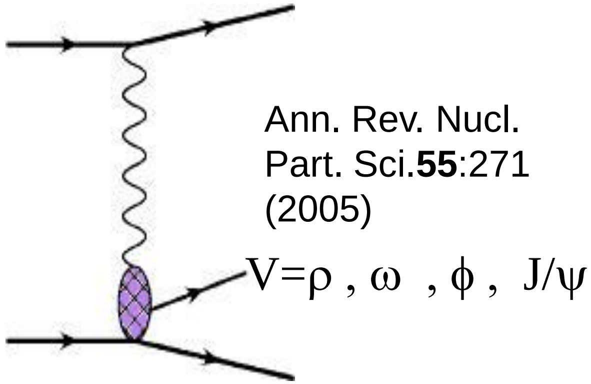


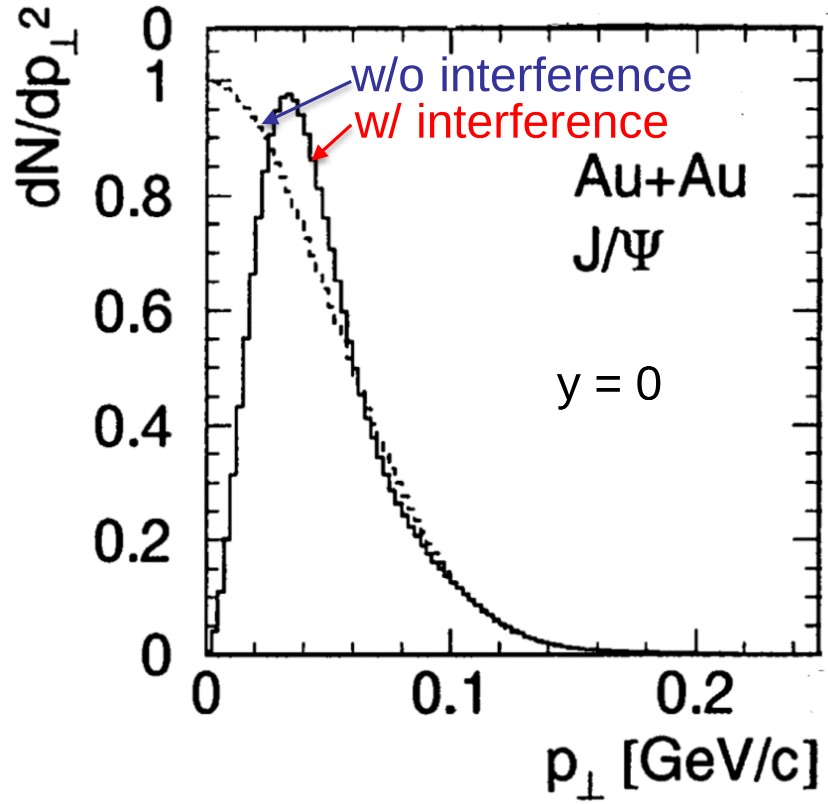
Photon-nucleus interactions

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.

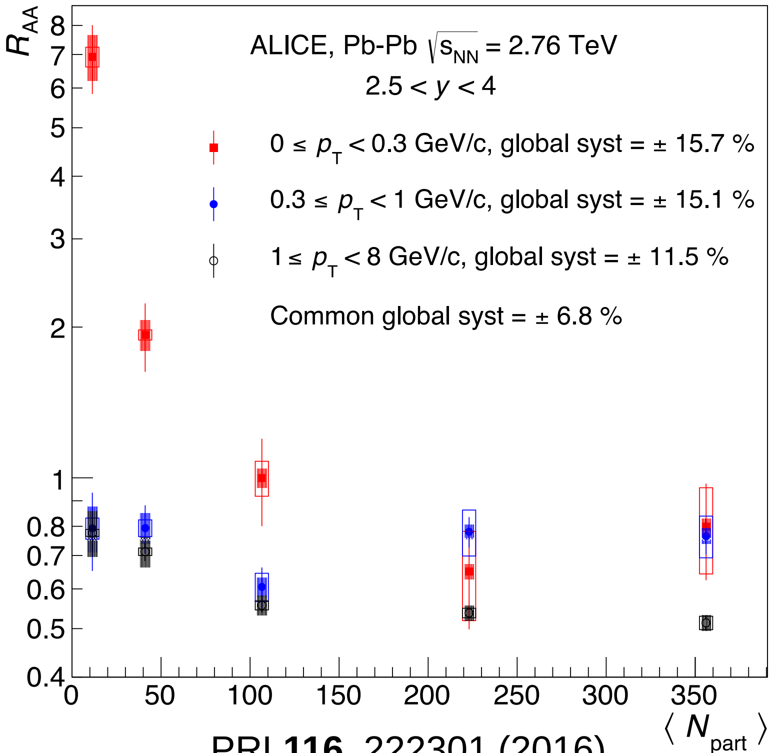
Features of coherent photon-nucleus interaction

- 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)

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

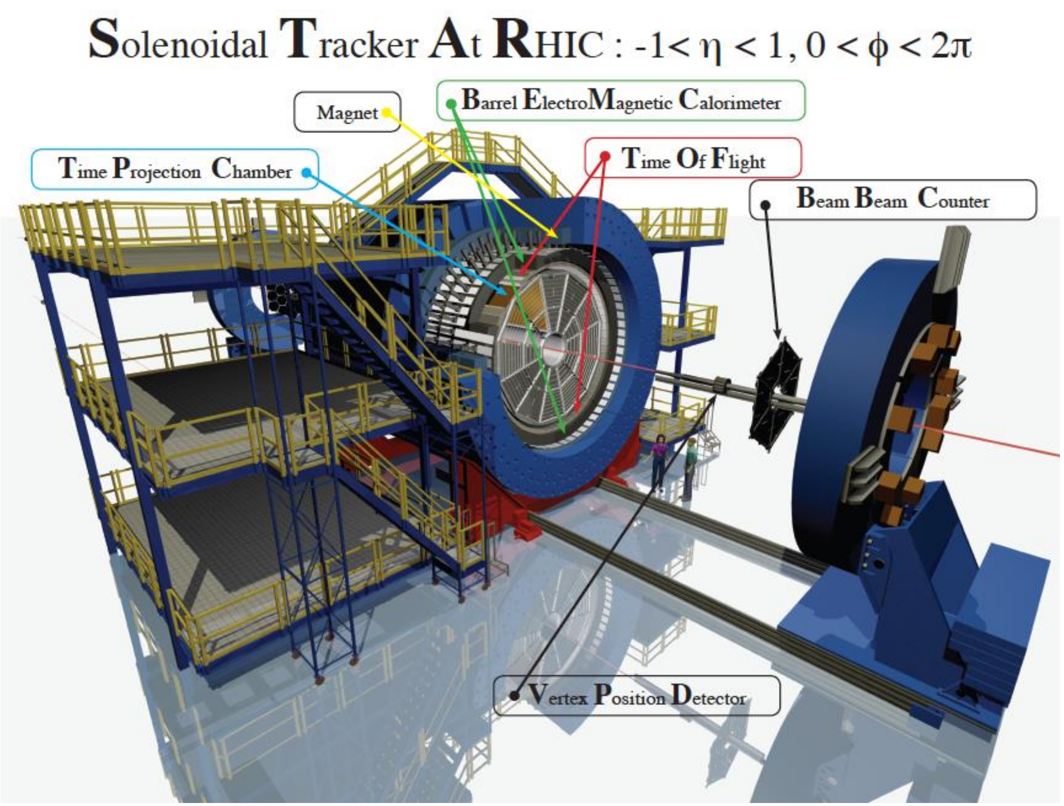


PRL**116**, 222301 (2016)

- ✓ 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.

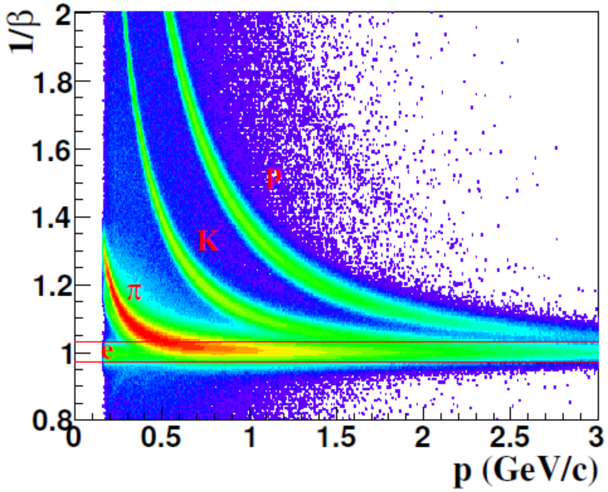
STAR detector



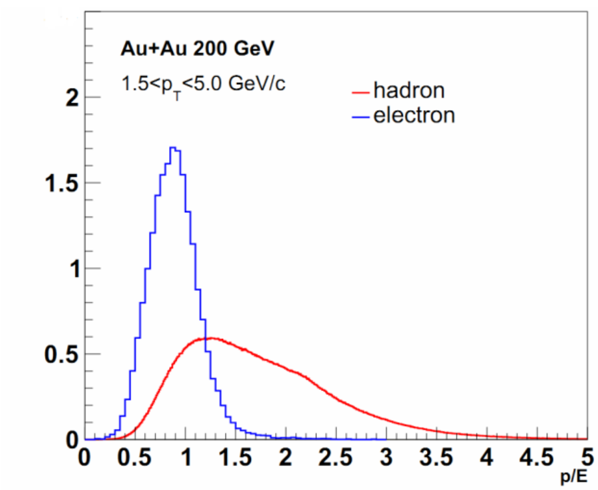
- Large acceptance:
  $|\eta| < 1,\ 0 < \phi < 2\pi$
- Time Projection Chamber
  (TPC) – tracking, particle identification, momentum
- Time of Flight detector
  (TOF) – particle identification
- Barrel ElectroMagnetic Calorimeter
  (BEMC) – electron identification, triggering

Electron Identification

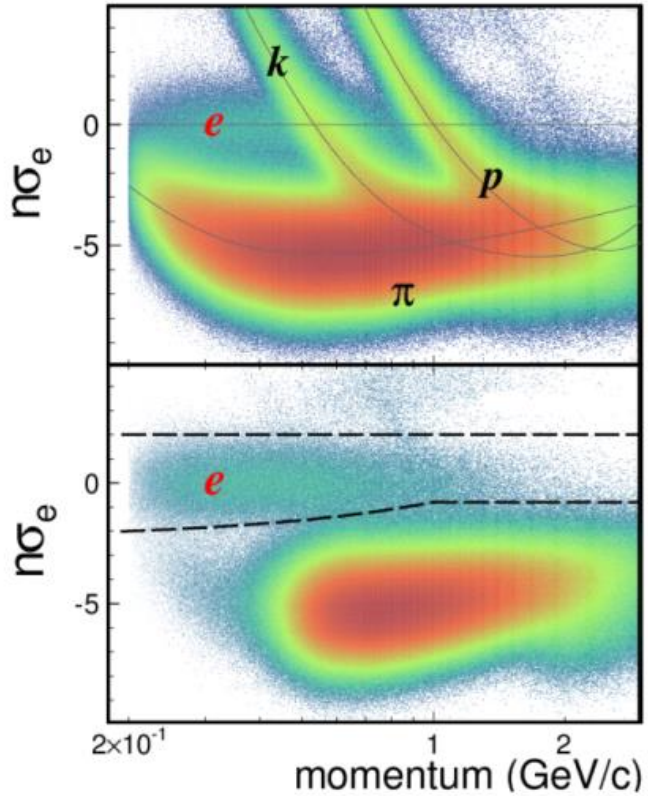
1/β distribution for electrons and hadrons from TOF



p/E distribution for electrons and hadrons from BEMC

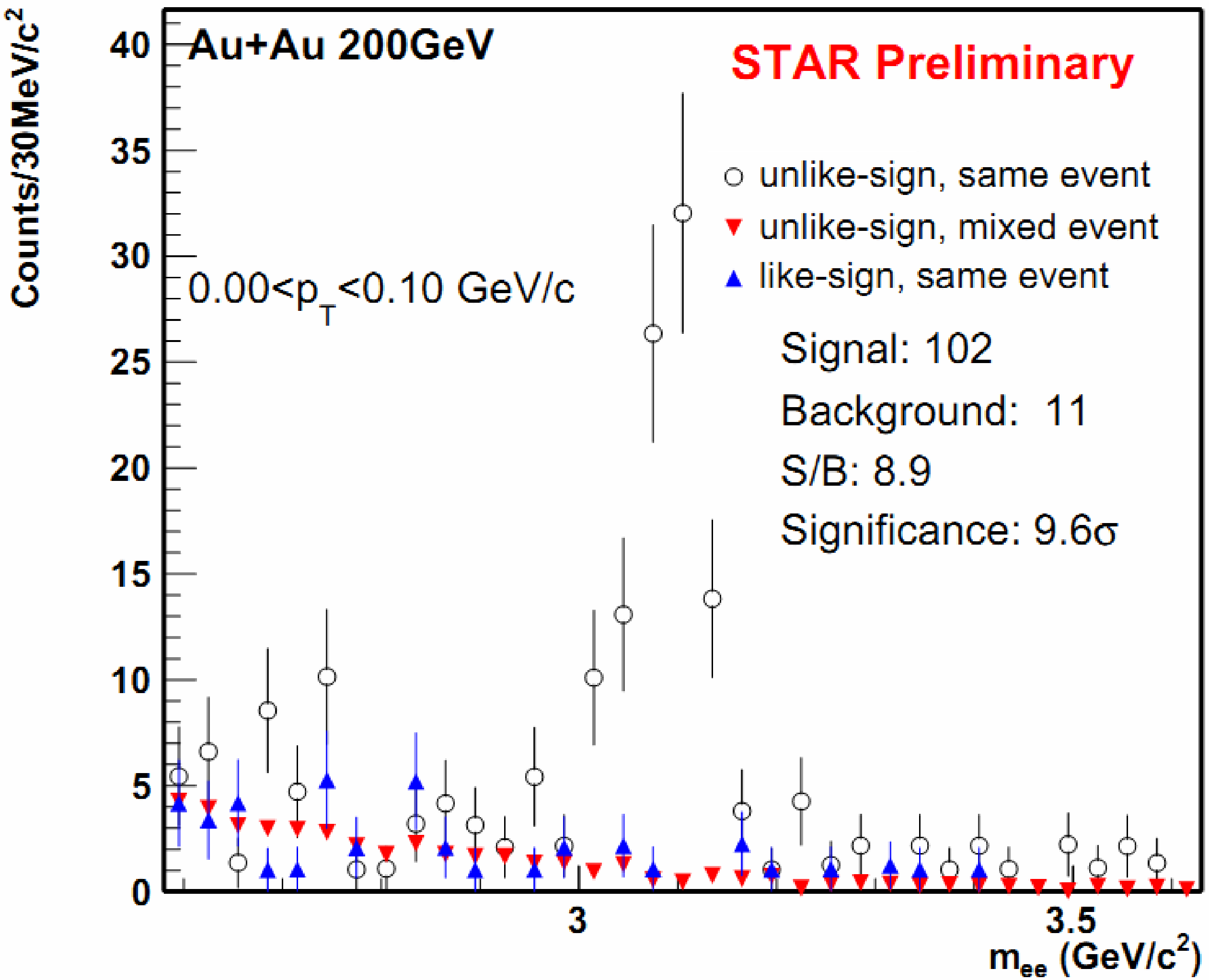


Normalized dE/dx ($n\sigma_e$) distribution before and after TOF cuts



Phys. Rev. C**92** (2015) 24912

J/ψ signal

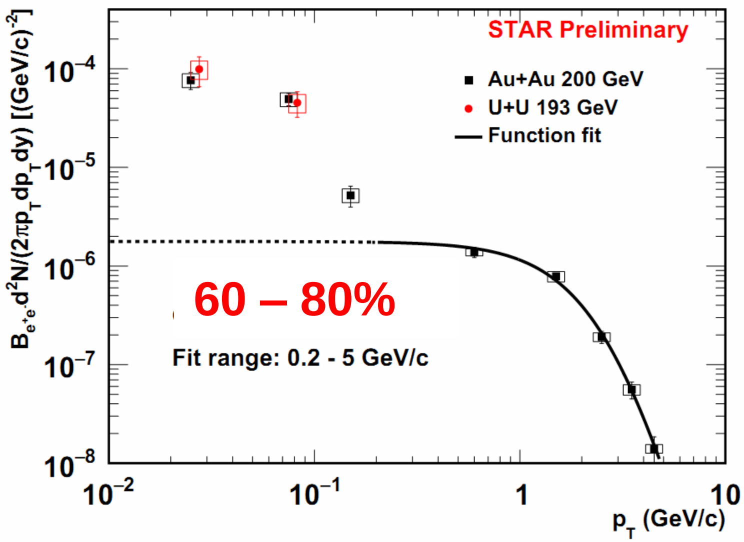


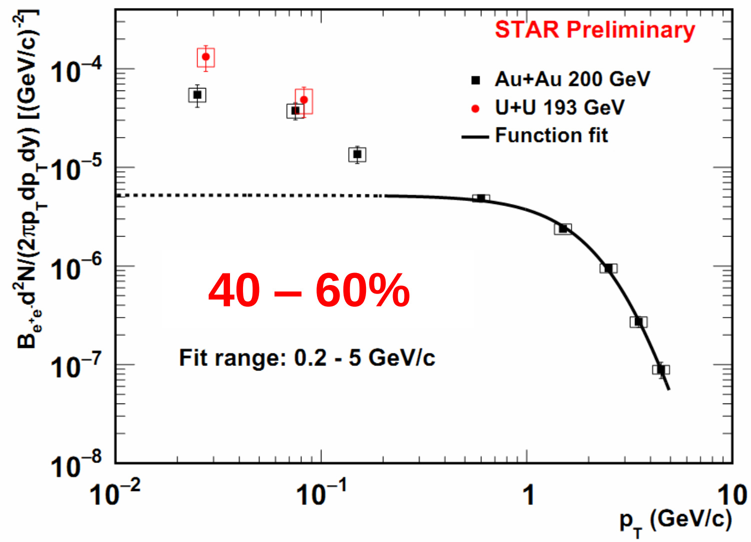
Centrality: 40 – 80%

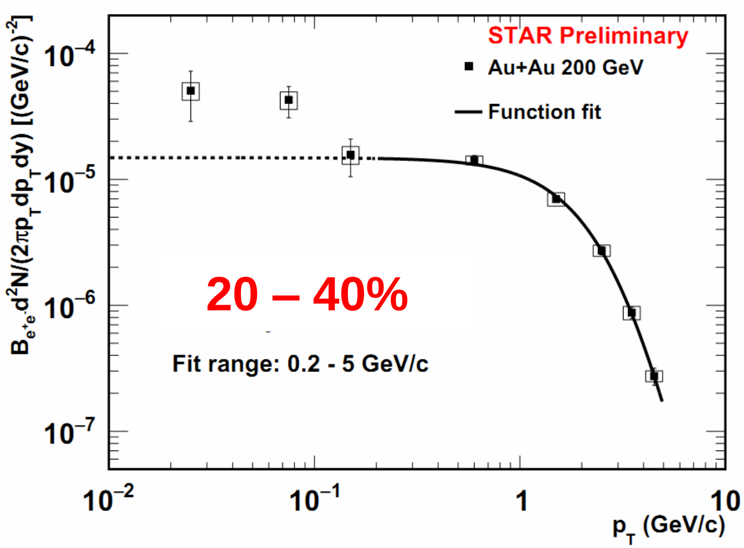
The signal is extracted by subtracting the mixed event background from the unlike-sign pairs.

Good signal over background ratio!

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





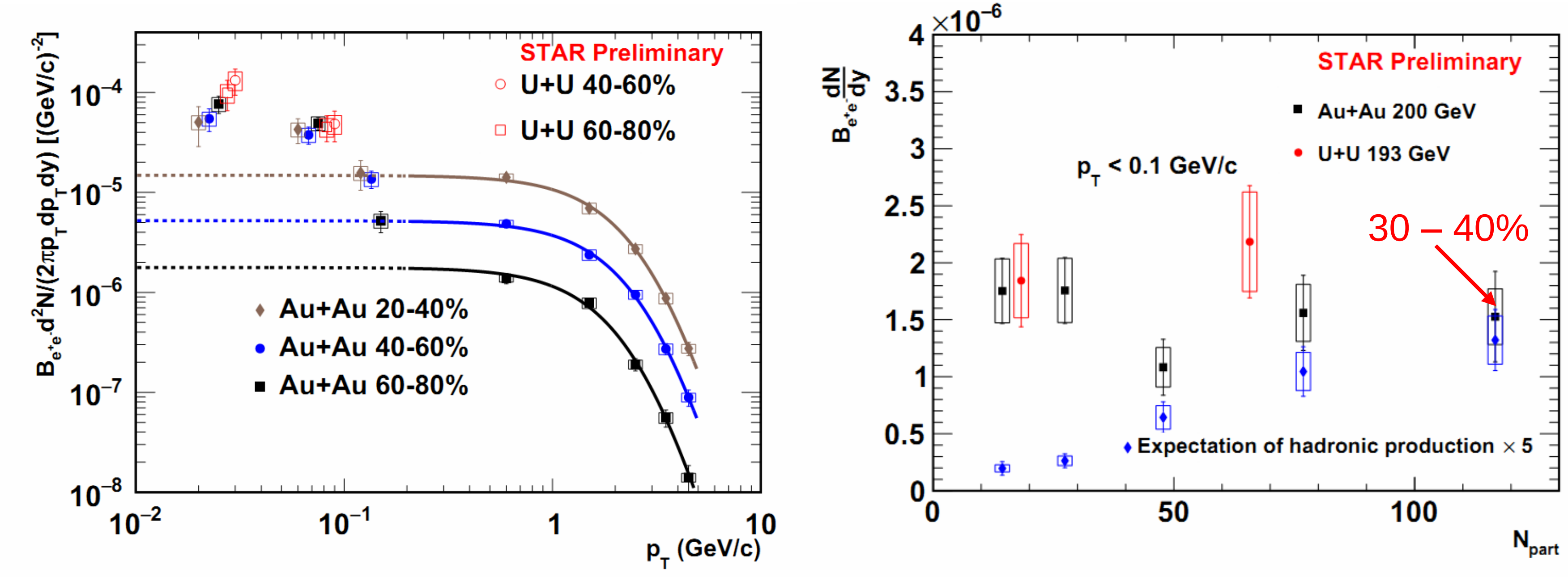


Function to describe hadronic production:

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

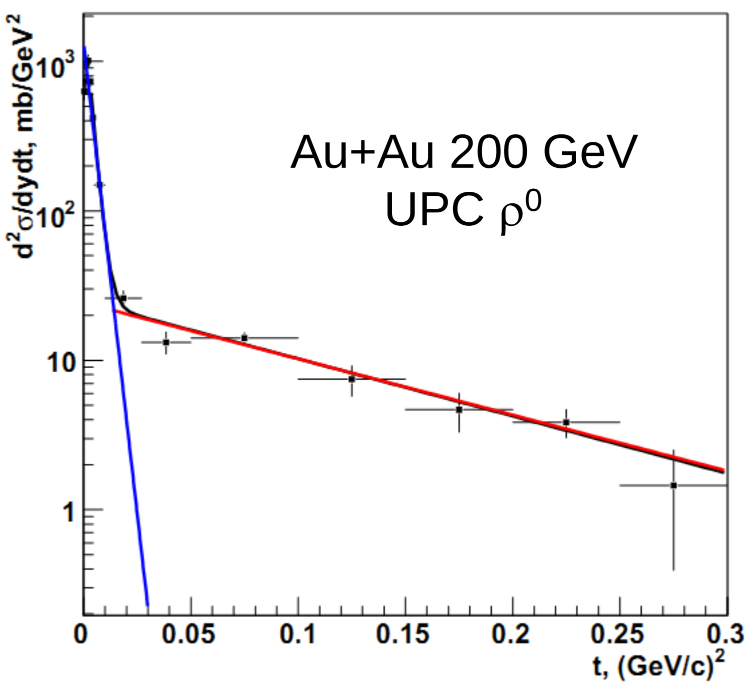
- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions (40 – 80 %)!
- The yield of J/ψ at very low p_T in Au+Au is similar to that in U+U within uncertainties.

J/ψ yield at very low p_T versus centrality



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

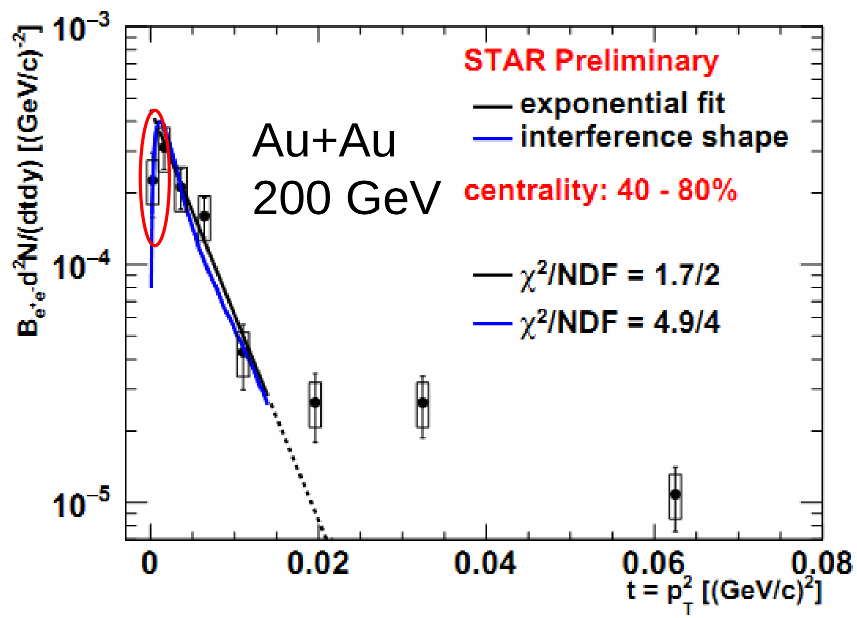
J/ψ dN/dt distribution for Au+Au 40-80%



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

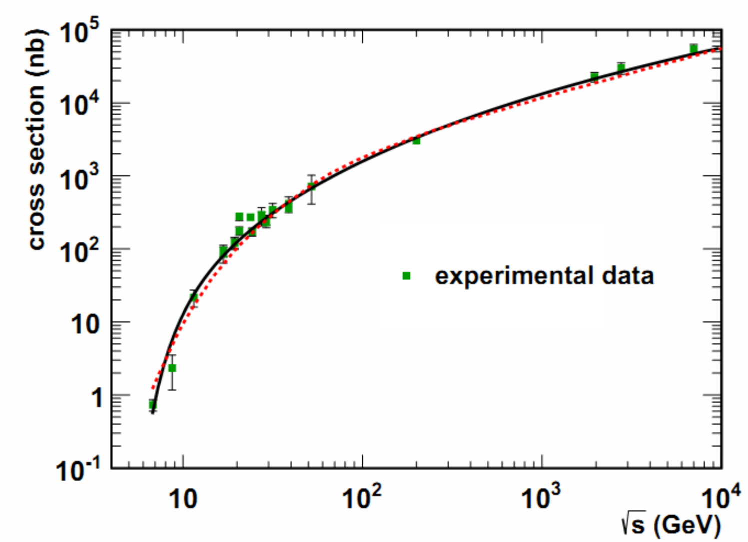
ρ^0 cross-section as a function of the momentum transfer squared ($t \approx p_T^2$) from STAR UPC measurements.

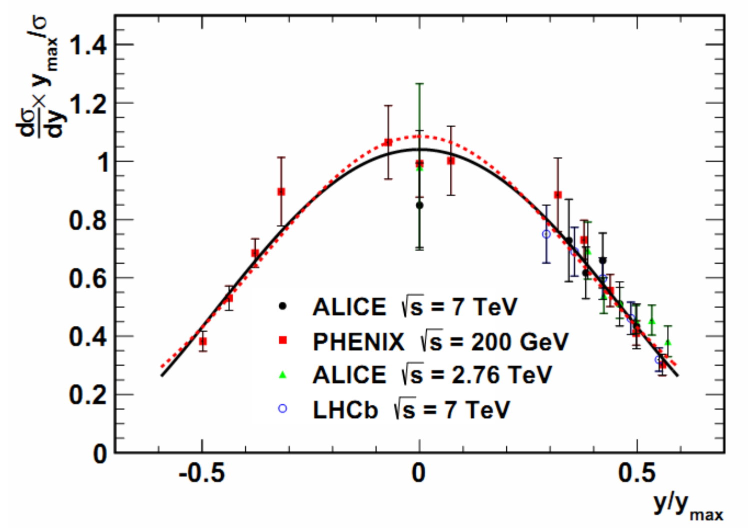
- The slope from the exponential fit reflects the size and shape of target.

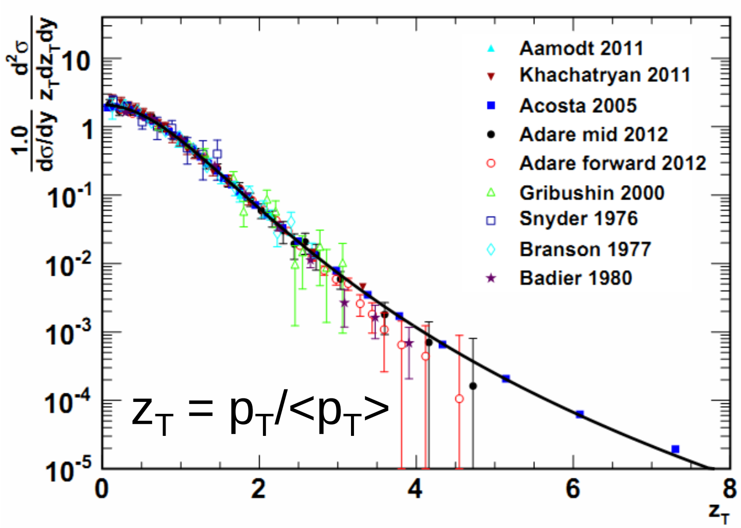


- ✓ Similar structure to that in UPC case!
- ✓ Indication of interference!
  - ✓ Interference shape from calculation for UPC case PRL **84** 2330 (2000)
- ✓ Similar slope parameter!
  - ✓ Slope from STARLIGHT prediction in UPC case – 196 (GeV/c)$^{-2}$
  - ✓ Slope w/o the first point: 199 $\pm$ 31(GeV/c)$^{-2}$ χ^2/NDF = 1.7/2
  - ✓ Slope w/ the first point: 164 $\pm$ 24(GeV/c)$^{-2}$ χ^2/NDF = 5.9/3

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



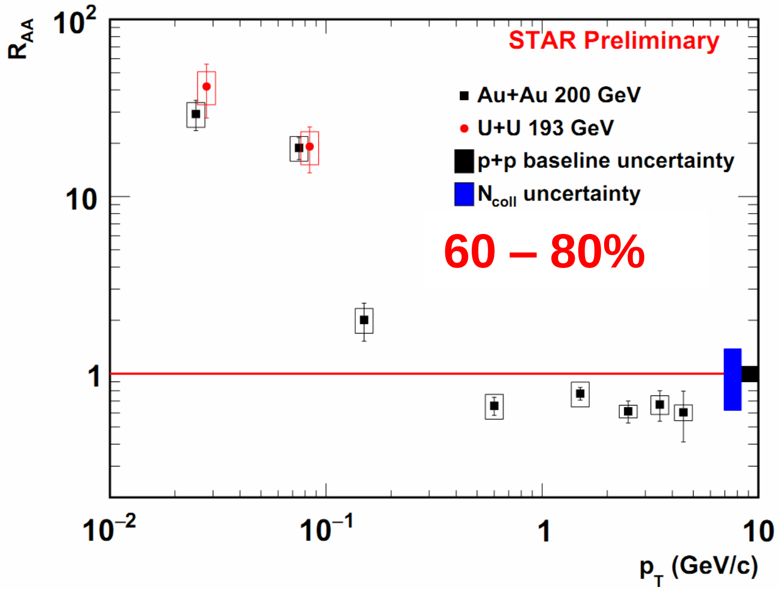


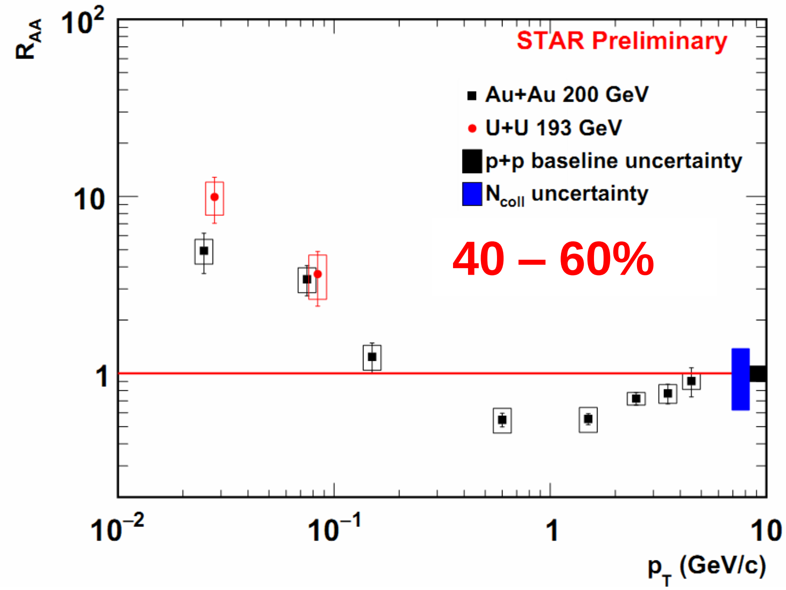


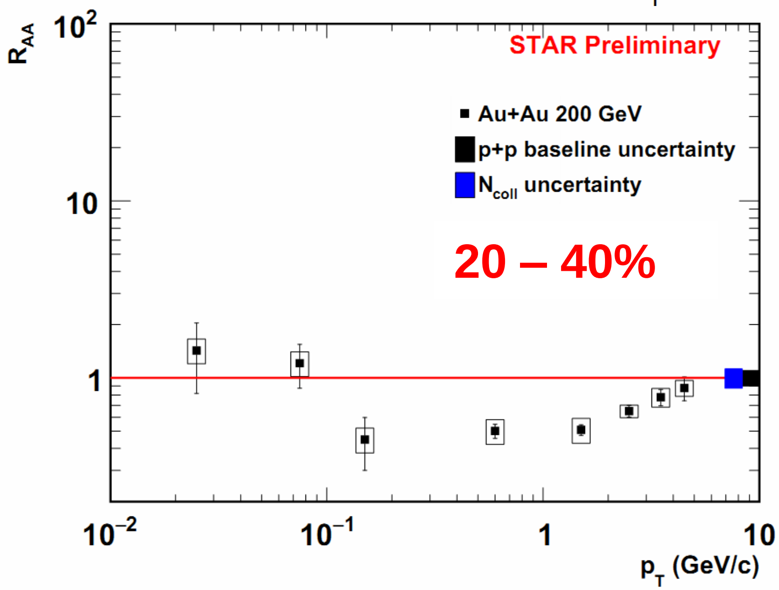
Phys. Rev. C**93**, 024919 (2016)

- ✓ The scaled rapidity and p_T distributions follow a universal trend.
- ✓ pp 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



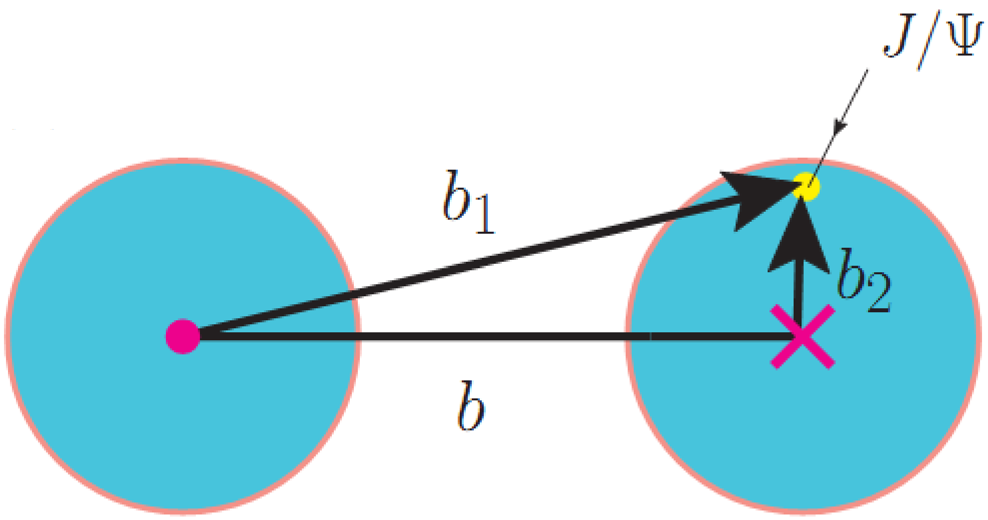




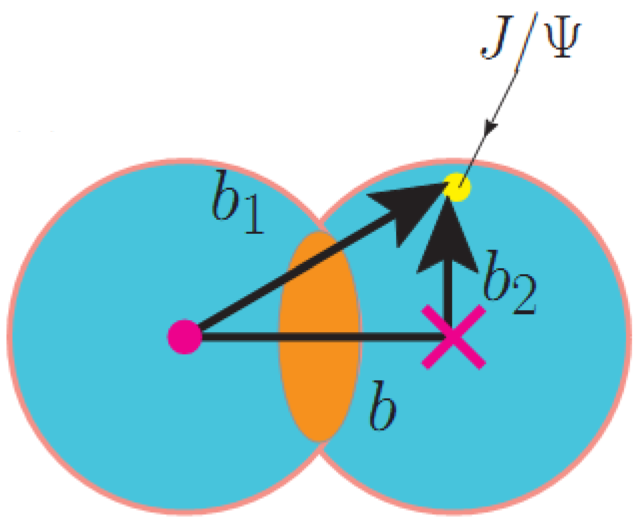
- R_{AA} ~ 20 in 60 – 80% centrality at p_T interval 0 – 0.1 GeV/c
- R_{AA} ~ 4 for 40 – 60% centrality at p_T interval 0 – 0.1 GeV/c

The calculation strategy for coherent production

$$\sigma(AA \to AAV) = \int dk \frac{dN_\gamma(k)}{dk} \sigma(\gamma A \to VA)$$

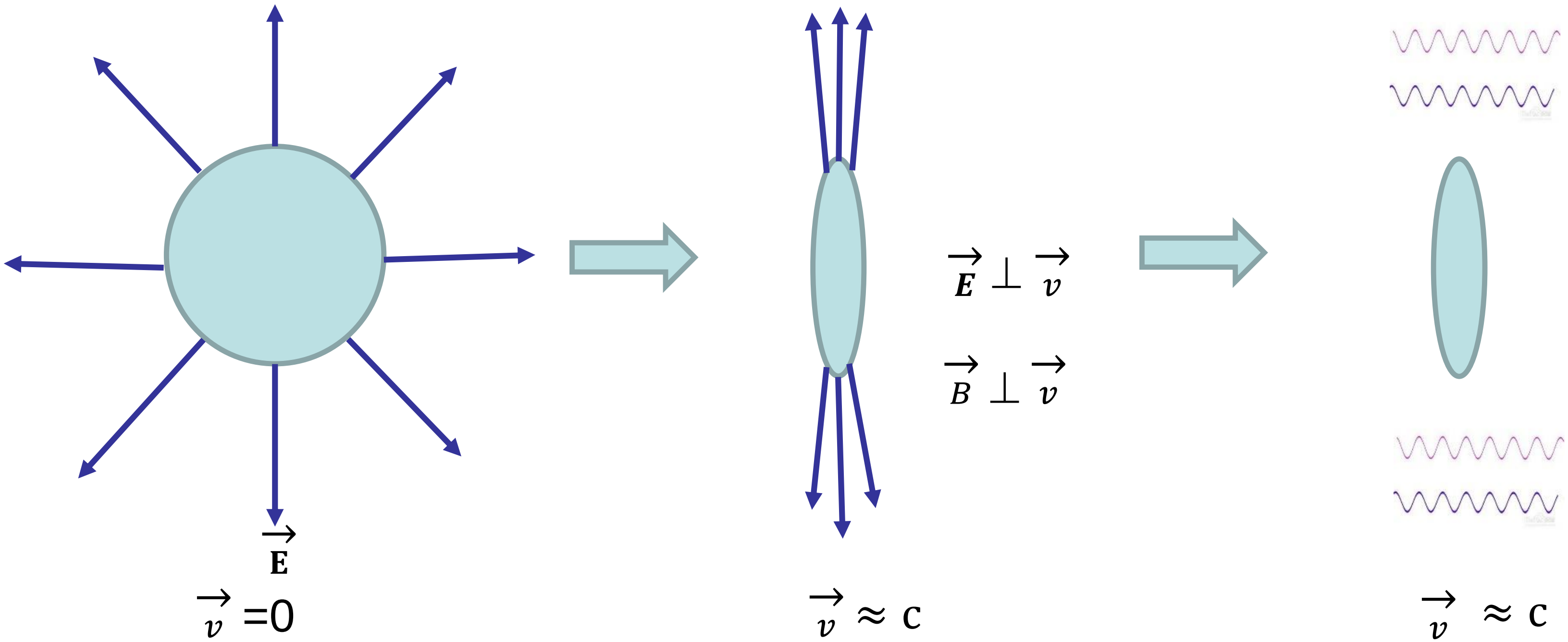


Utra-Peripheral Collisions



Semi-Peripheral Collisions

Equivalent Photon Approximation



$$\frac{d^3N_\gamma}{dkd^2r} = \frac{1}{\pi k}|E_\perp(k,r)|^2 = \frac{4Z^2\alpha_{QED}}{k}\left|\int \frac{d^2q_\perp}{(2\pi)^2} q_\perp \frac{F(q_\perp^2 + (\frac{k}{\gamma})^2)}{q_\perp^2 + (\frac{k}{\gamma})^2} e^{iq_\perp r}\right|^2$$

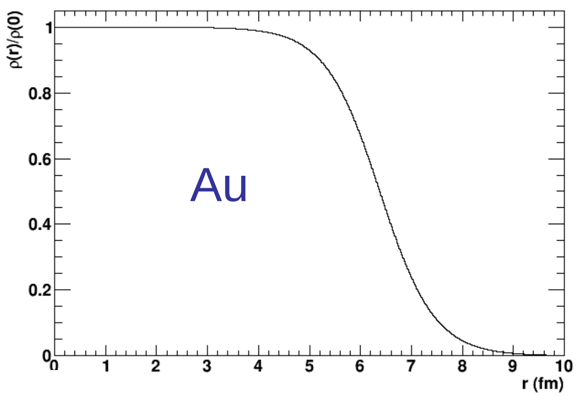
Point like: $F(q^2) = 1$ $\quad \frac{d^3N_\gamma}{dkd^2r} = \frac{Z^2\alpha_{QED}k}{\pi^2\gamma^2} K_1^2(\frac{kr}{\gamma})$

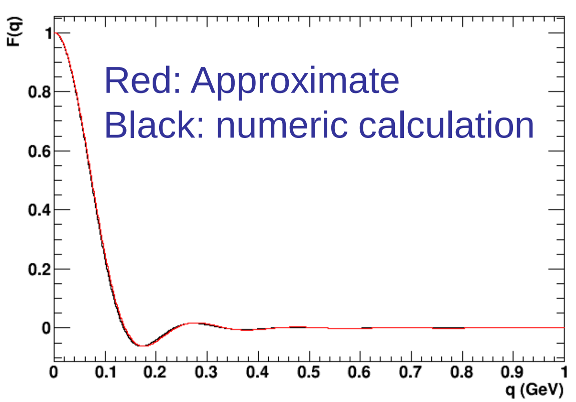
The calculation of nuclear form factor

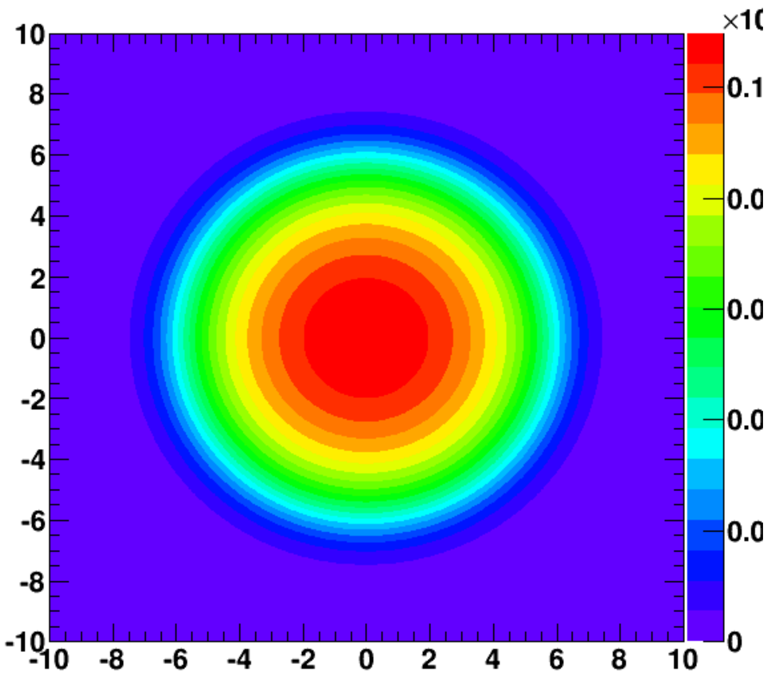
$$F(\vec{q}) = \int \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d\vec{r}$$

Two fermi distribution:
No analytical results

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-c}{a}\right)}$$





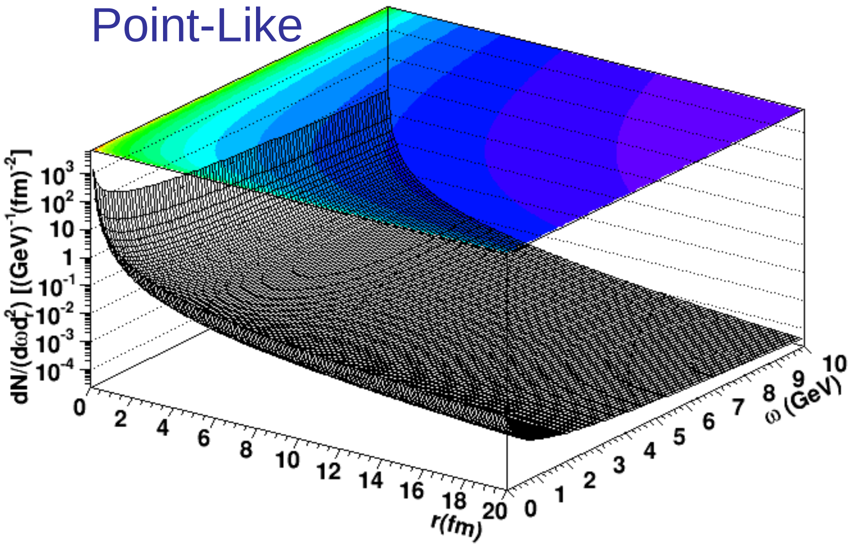


Approximate results:

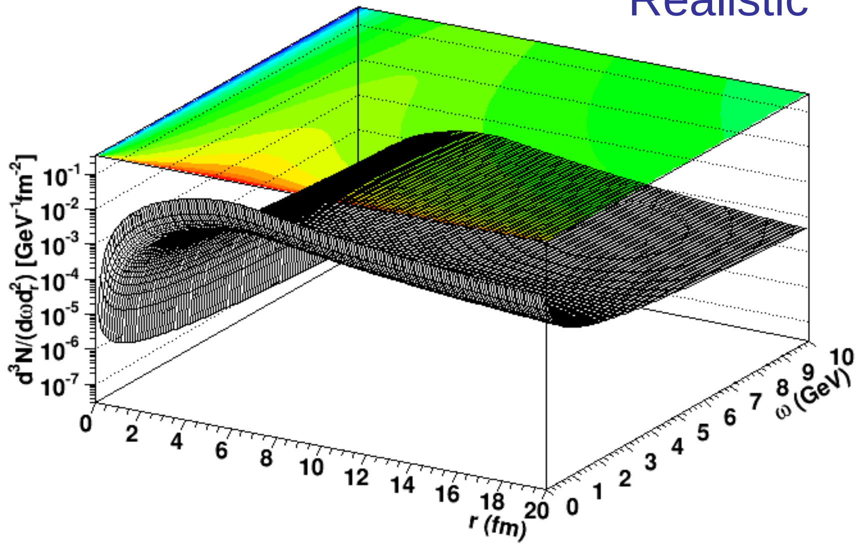
$$F(q = \sqrt{|t|}) = \frac{4\pi\rho_0}{Aq^3}\left[\sin(qR_a) - qR_a\cos(qR_A)\right]\left[\frac{1}{1+a^2q^2}\right]$$

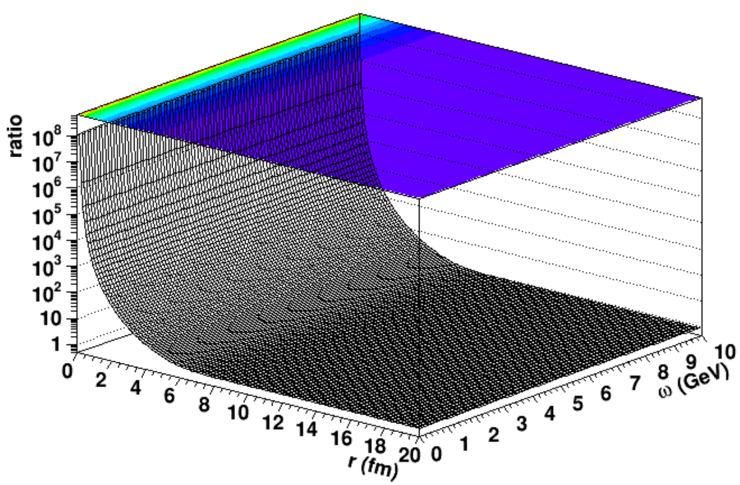
Photon flux induced by Au

Point-Like



Realistic

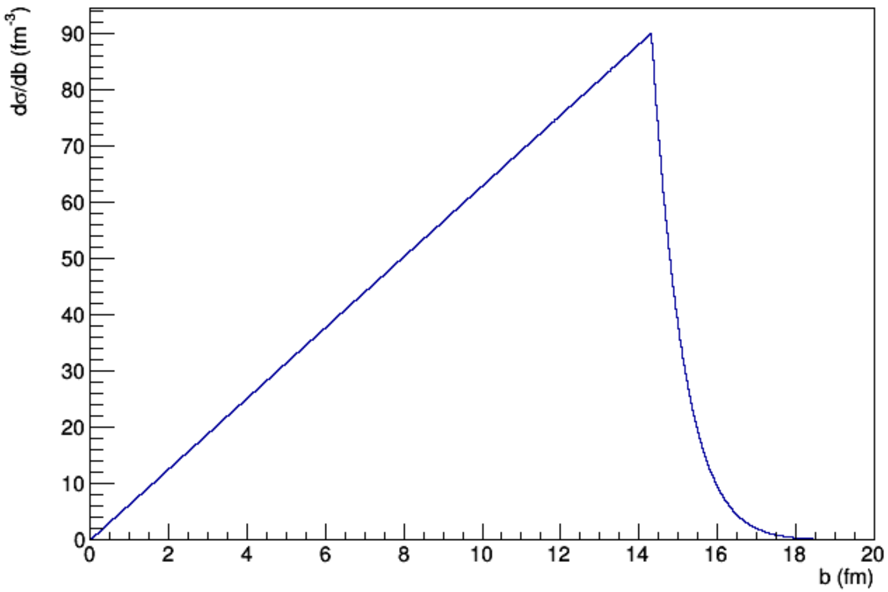


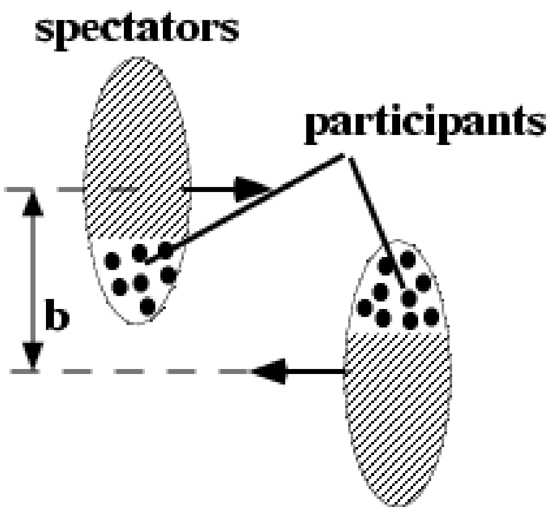


Collision system : Au+Au 200 GeV
The same magnitude outside the nucleus.
Big difference inside the nucleus!

Centrality definition by Glauber model

Optical Glauber calculation:





Centrality (%)	b (fm)	<b> (fm)
0-10	0 – 4.765	3.188
10-20	4.765 – 6.735	5.725
20-30	6.735 – 8.245	7.424
30-40	8.245 – 9.525	8.802
40-50	9.525 – 10.645	10.00
50-60	10.645 – 11.655	11.082
60-70	11.655 – 12.605	12.084
70-80	12.605 – 13.475	13.042

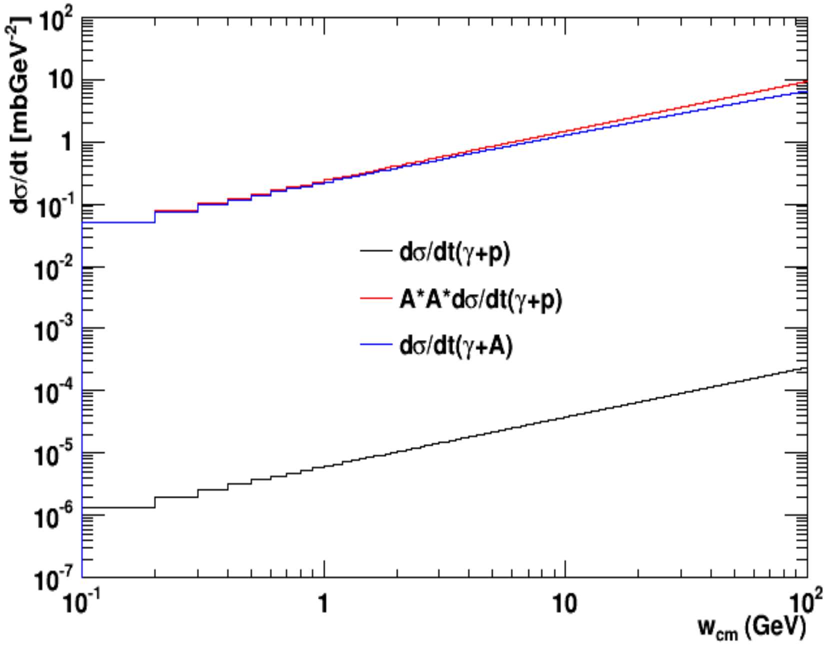
Au+Au geometry cross section:

Glauber: 7125.4 mb

Experiment: 6840 mb

Determination of γ+A cross section

$$\sigma(\gamma A \to VA) = \int_{t_{min}}^{\infty} dt \frac{d\sigma(\gamma A \to VA)}{dt}\Big|_{t=0} |F(t)|^2$$



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

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

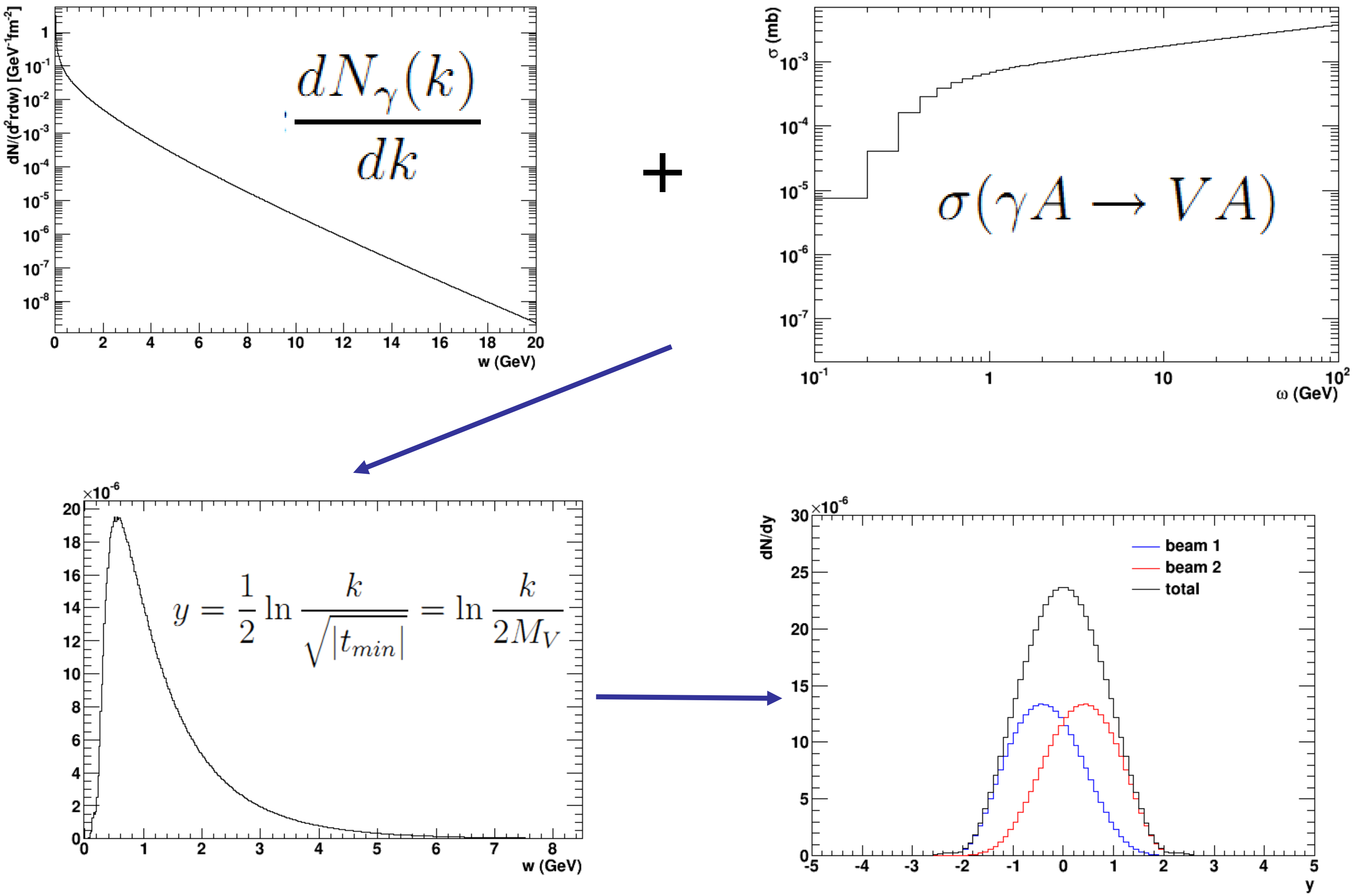
$$\sigma_{tot}^2\left(J/\psi p\right) = 16\pi \frac{\mathrm{d}\sigma\left(J/\psi p \to J/\psi p; t=0\right)}{\mathrm{d}t}$$

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

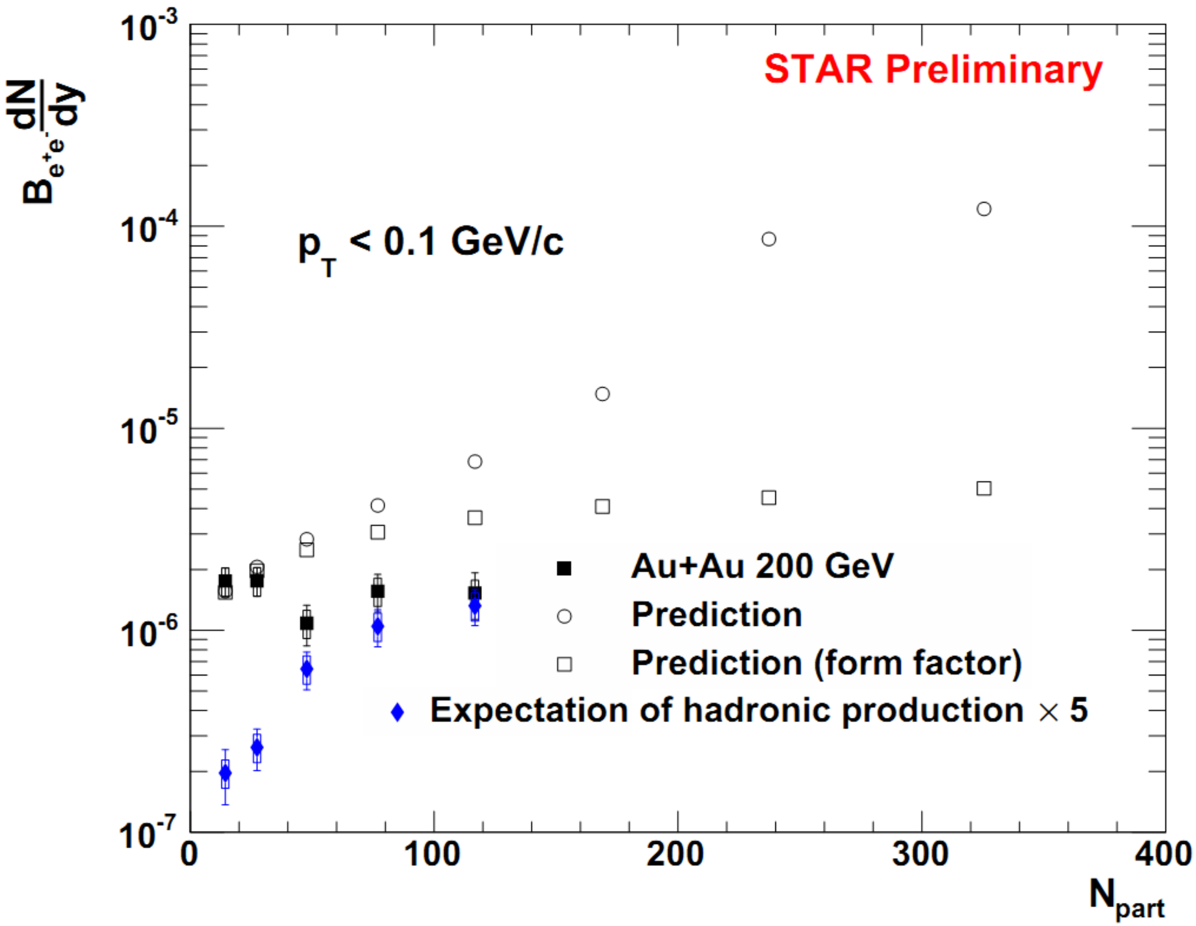
$$\frac{\mathrm{d}\sigma\left(\gamma p \to J/\psi p; t=0\right)}{\mathrm{d}t} = b_{J/\psi} X_{J/\psi} W_{\gamma p}^{\epsilon_{J/\psi}}$$

The parameters of γ+p cross section are determined from low energy fixed target photon beams and ep collisions at HERA.

Cross section at b = 13.042 fm



Comparison with data



- ✓ Describe the data very well at very peripheral collisions (60-80%)!
- ✓ Overestimate at semi-central collisions!
- ✓ Indication of spectator-spectator interactions?

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%) , while overestimate the cross section at semi-central collisions.
  - ✓ Indication of spectator-spectator interactions

Discussion and outlook

- Challenges for theoretical calculations in hadronic peripheral collisions:
  - How do the broken nucleus satisfy the condition of coherence?
  - No significant dependence of production on impact parameter?
    - The coherent cross section increases dramatically with decreasing impact parameter in the calculations.
    - Cancellation of photon flux in the overlapping region of colliding nuclei for hadronic peripheral collisions.
  - How large is incoherent contribution?
  - Can the products of coherent photon-nucleus interactions serve as a probe to test the cold and hot medium effects?

- Future experimental measurements:
  - More differential measurements for J/ψ.
  - The excess of other vector meson (ρ, ω, ϕ, Υ ...) in hadronic collisions?
  - The excess of photon-photon process (π^0,η, η', $f_2(1270)$, $a_2(1320)$, $\pi^+ + \pi^-$, $e^+ + e^-$, $\mu^+ + \mu^-$…)?