The 35th Winter Workshop on Nuclear Dynamics (WWND 2019)
6-12 January 2019, Beaver Creek

STAR

Measurements of low-p_T e^+e^- pairs and J/ψ in heavy-ion collisions at STAR

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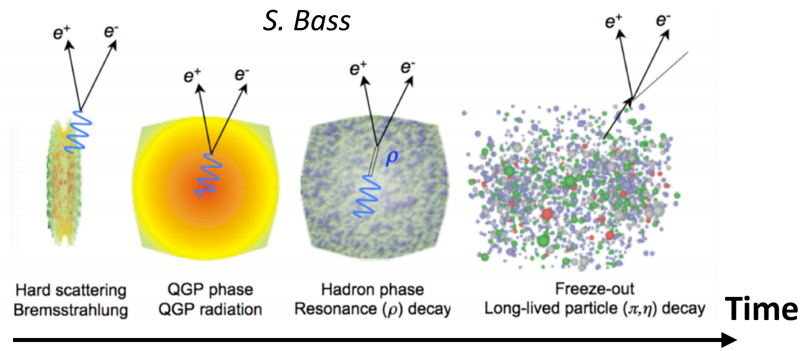
BROOKHAVEN NATIONAL LABORATORY

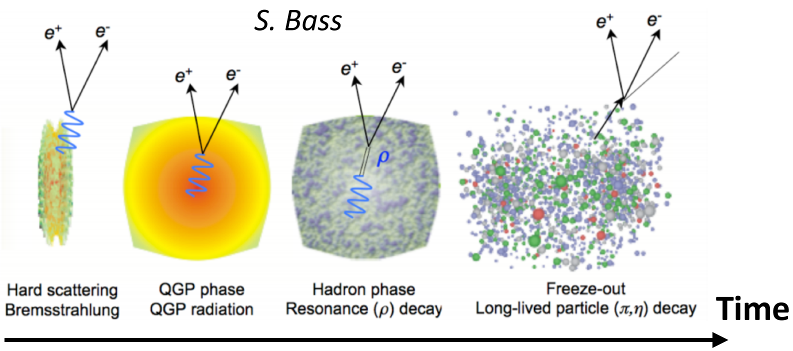
U.S. DEPARTMENT OF ENERGY | Office of Science

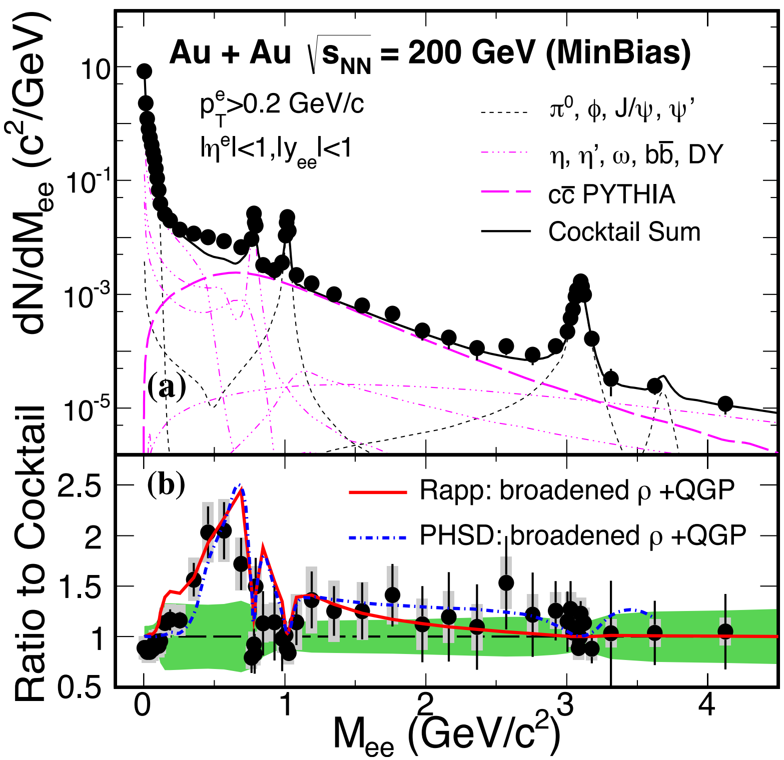
Dileptons - electromagnetic probe



- Penetrating probe
- Direct information about the medium created in heavy-ion collisions

Dileptons - electromagnetic probe

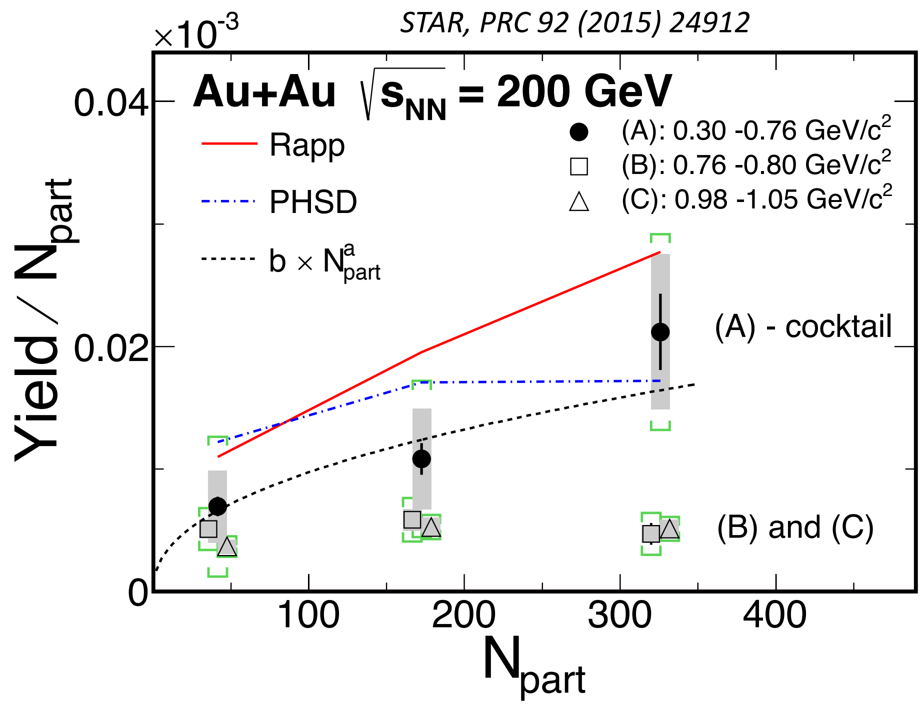




STAR, PRL 113 (2014) 022301

- Penetrating probe
- Direct information about the medium created in heavy-ion collisions

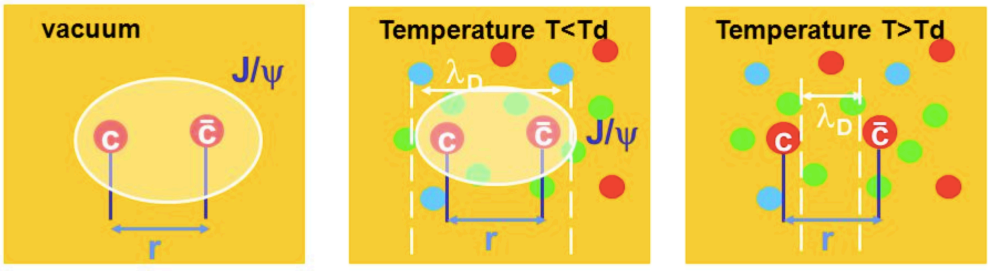
STAR, PRC 92 (2015) 24912



- Consistent with in-medium broadened ρ model calculation *[R. Rapp, PRC 63 (2001) 054907]*
- $\propto N_{part}^{1.44\pm0.1}$, sensitive to hot medium dynamics

Quarkonia - heavy flavor probe

- Color-screening in QGP: the quark-antiquark binding potential is screened by the color charges of the surrounding light quarks and gluons -> *dissociation*
  - J/ψ suppression was proposed a direct proof of QGP formation *[T. Matsui and H. Satz, PLB 178 (1986) 416]*



$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

Quarkonia - heavy flavor probe

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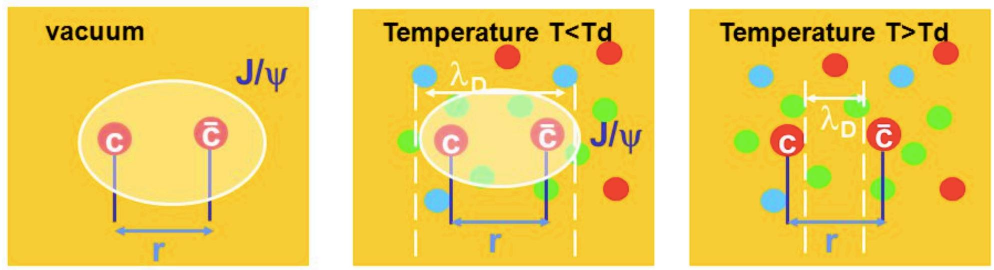
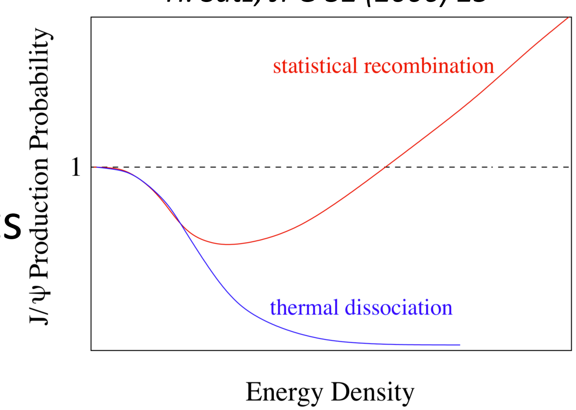
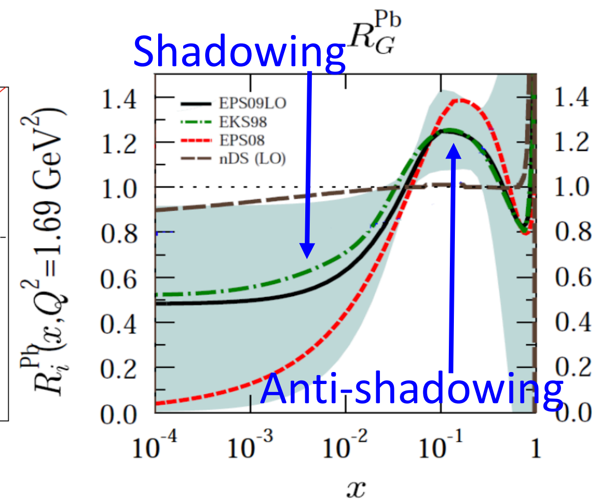


$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

- Other effects
  - Hot medium effects
    - ✓ regeneration, …
  - Cold nuclear matter effects
    - ✓ nPDF, …
  - Feed-down

H. Satz, JPG 32 (2006) 25

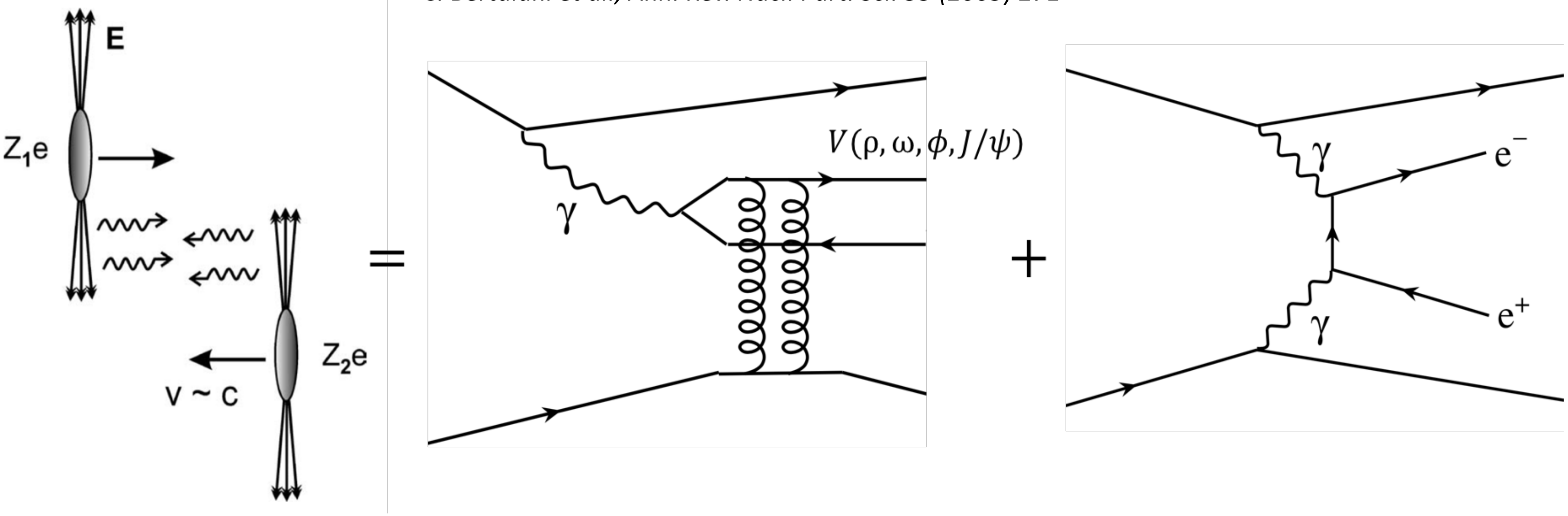




Ferreiro et al., PRC 81 (2010) 064911

Photon interactions

C. Bertulani et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 271



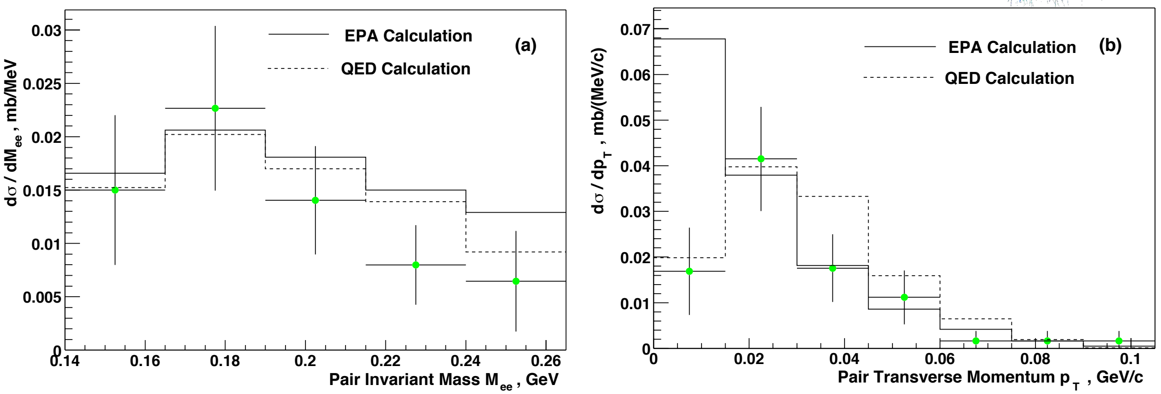
- Large quasi-real photon flux $\propto Z^2$
- Photon interactions
  - Photon-photon interaction (dilepton…) $\propto Z^4$
  - Photonuclear interaction (vector mesons) $\propto Z^2$
    - ✓Coherent & Incoherent
- Conventionally only studied in UPC ($b>2R_A$)

Features of photon interactions

STAR, PRC 70 (2004) 031902

➢ Two-photon interaction

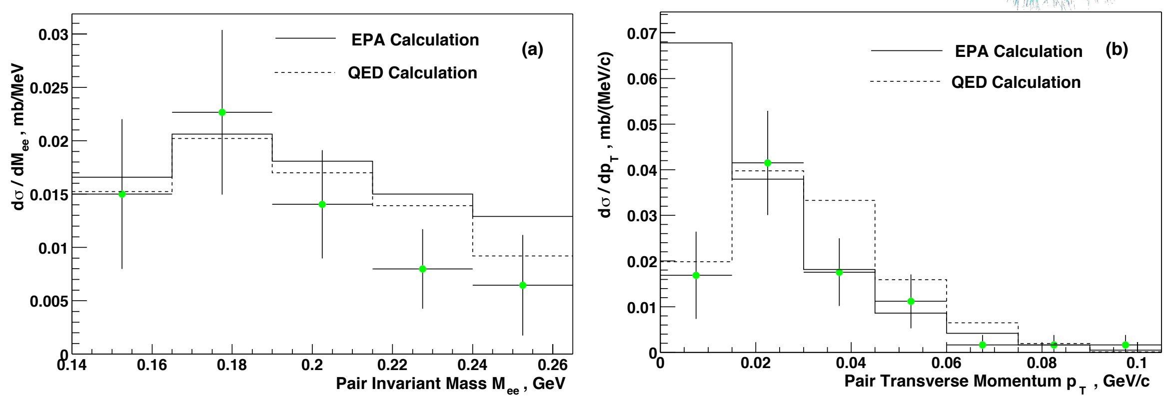
- Continuous mass spectrum
- Concentrated at low p_T

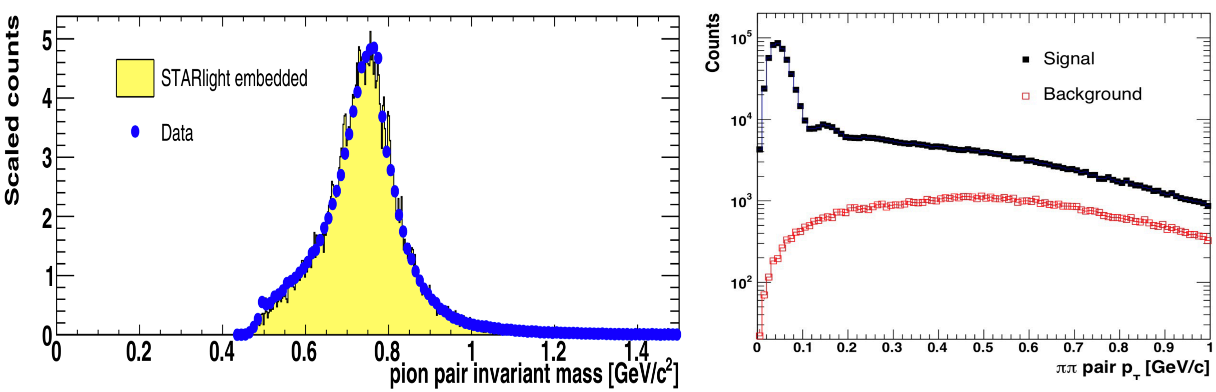


Features of photon interactions

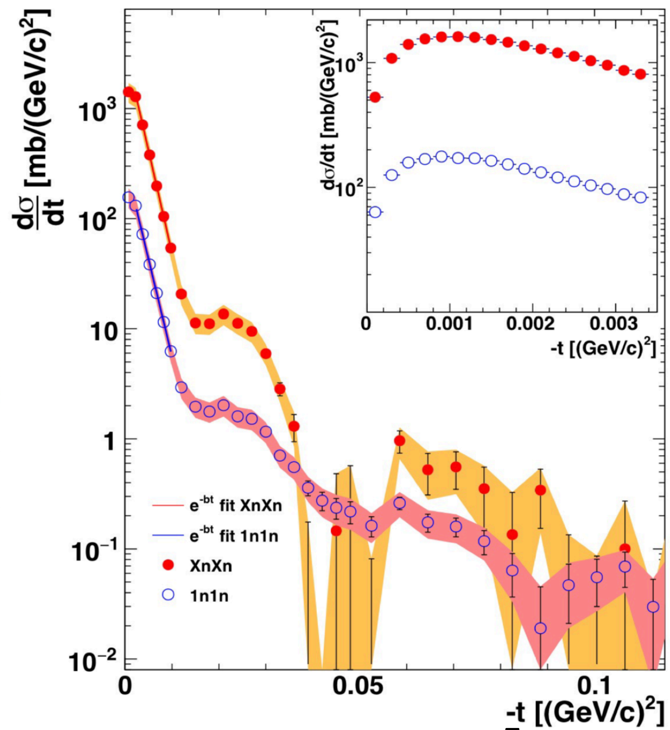
- **Two-photon interaction**
  - Continuous mass spectrum
  - Concentrated at low p_T
- **Coherent photonuclear interaction**
  - Vector meson production
  - Concentrated at low p_T
  - Interference structure ($p_T \ll 1/b$)

STAR, PRC 70 (2004) 031902



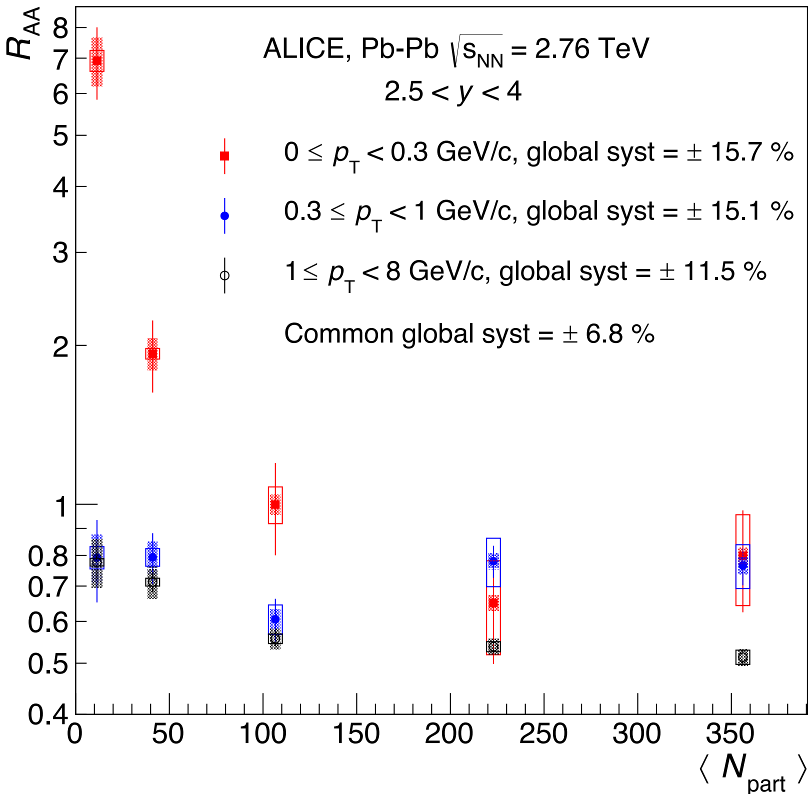


STAR, PRC 96 (2017) 54904



Anomalous J/ψ enhancement at LHC

ALICE, PRL 116 (2016) 222301



- ➢ Significant enhancement at low p_T in peripheral Pb+Pb collisions

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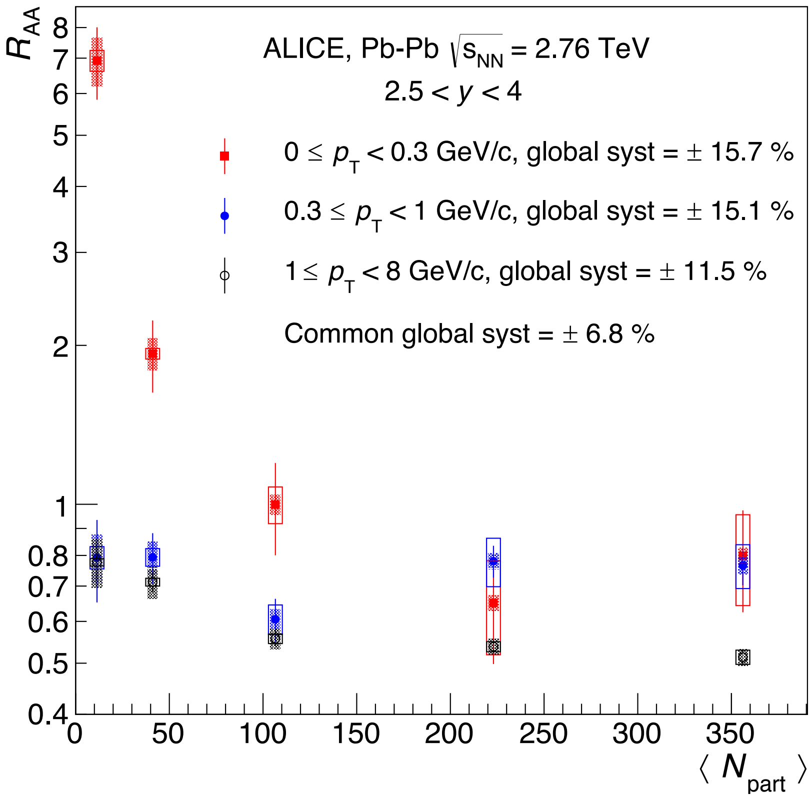
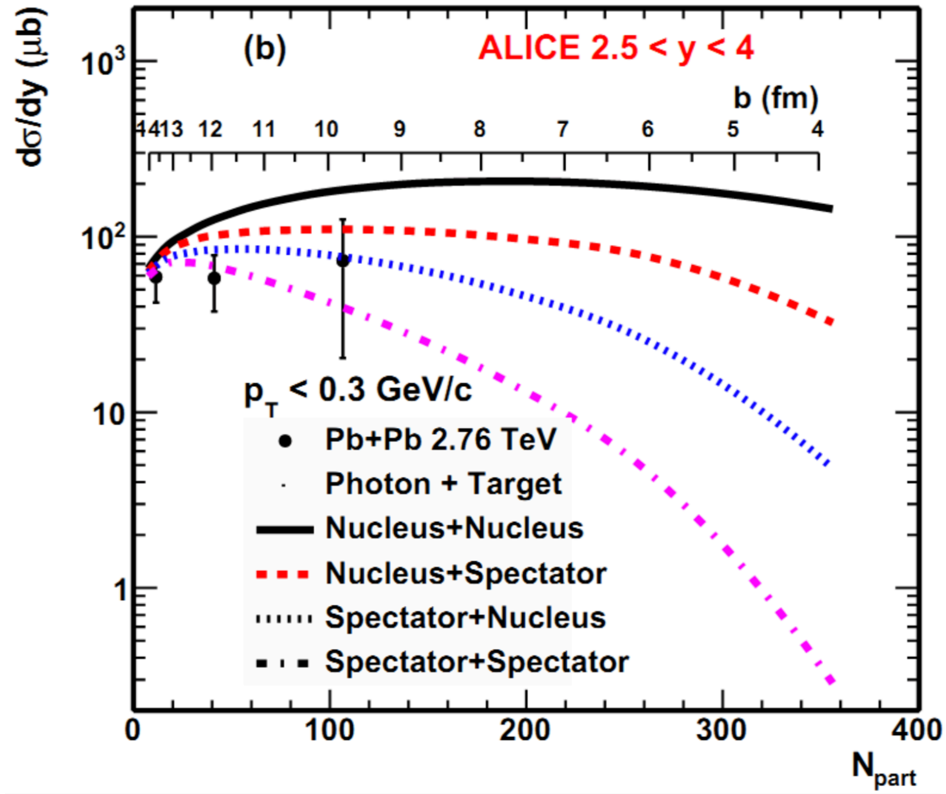


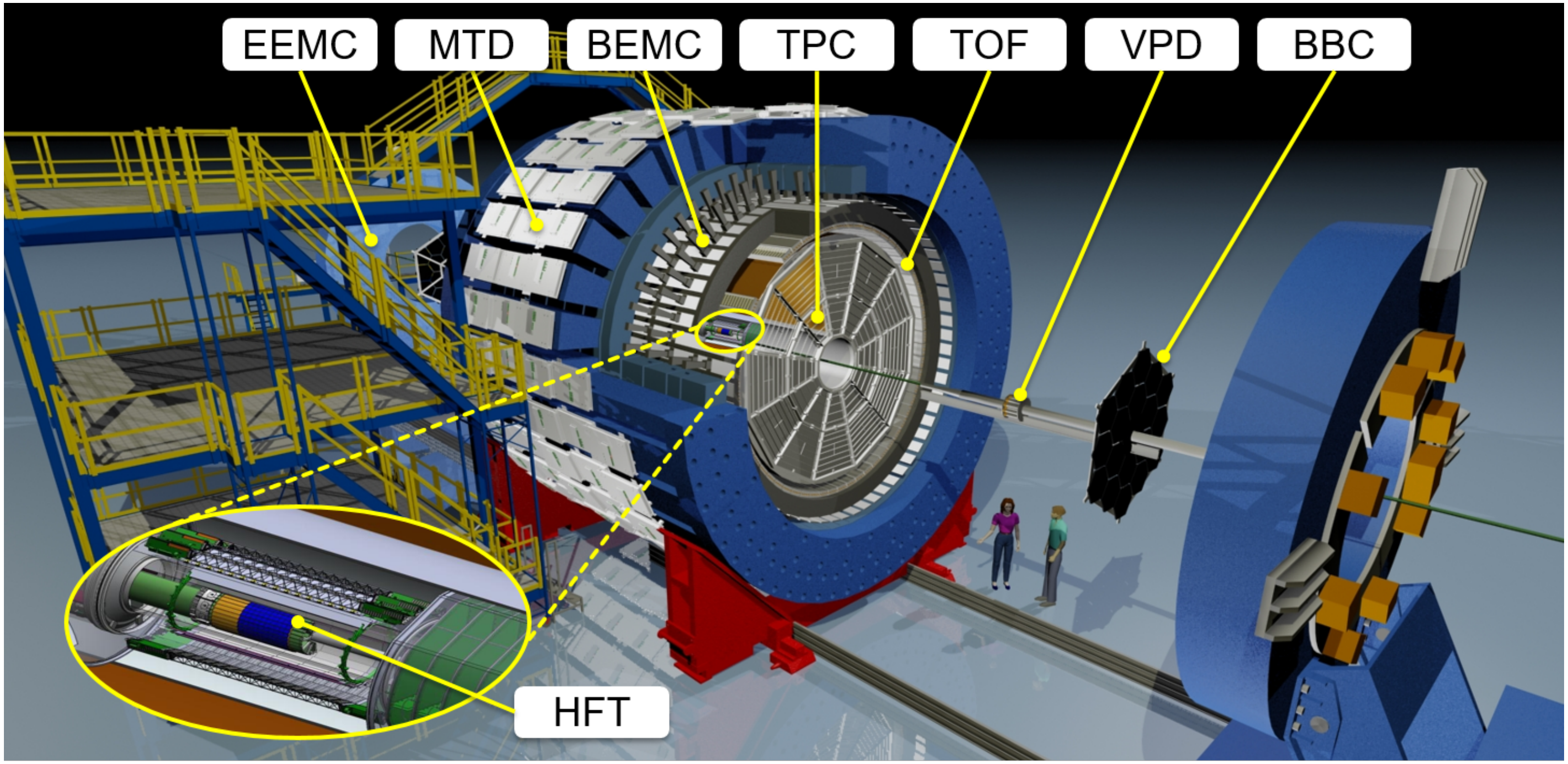
W. Zha et al., PRC 97 (2018) 044910



- Significant enhancement at low p_T in peripheral Pb+Pb collisions
- Qualitatively explained by coherent photonuclear production mechanism

The STAR detector

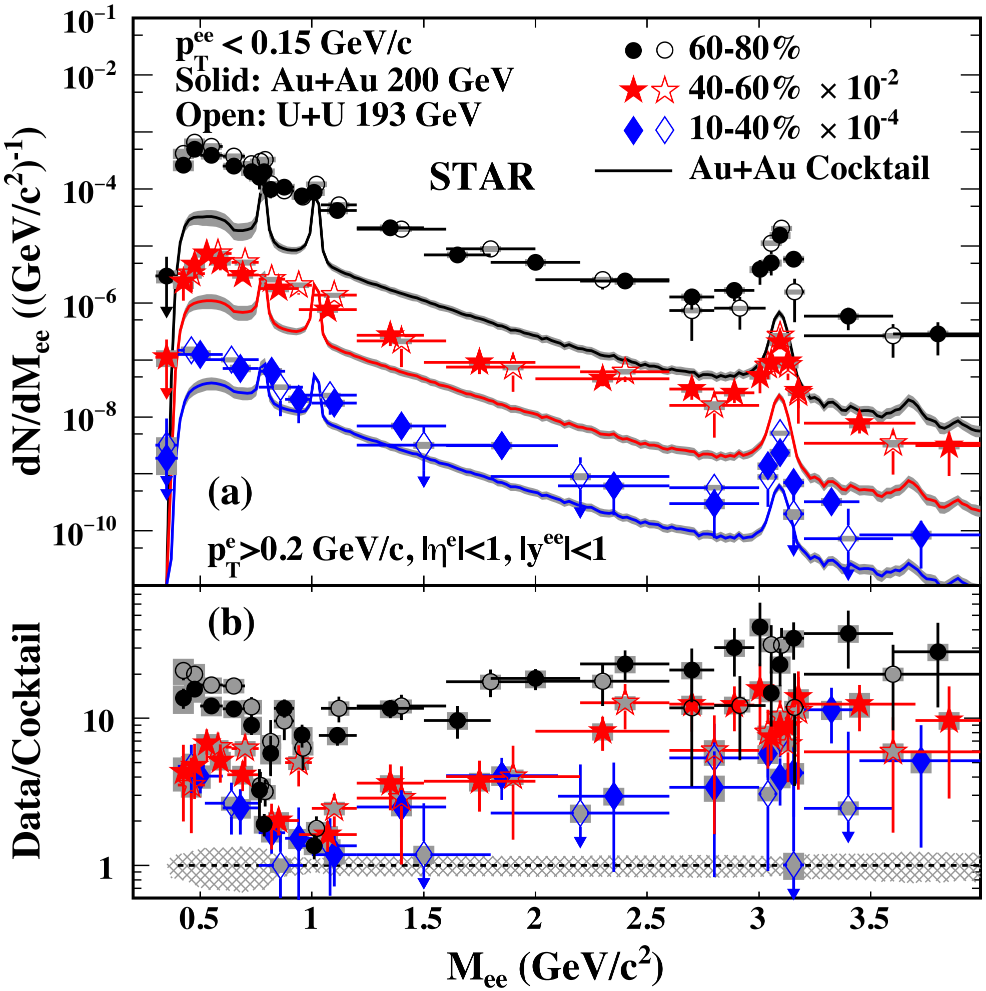
- Midrapidity, large acceptance: $|\eta|<1$, $0<\phi<2\pi$



- Time Projection Chamber: tracking, momenta, and energy loss
- Time-Of-Flight: velocity
- Barrel Electromagnetic Calorimeter: trigger on and identify high-p_T electrons

Low-p_T e^+e^- invariant mass spectra

STAR, PRL 121 (2018) 132301



- Significant enhancement with respect to the cocktail for p_T < 0.15 GeV/c in 60-80% Au+Au and U+U collisions

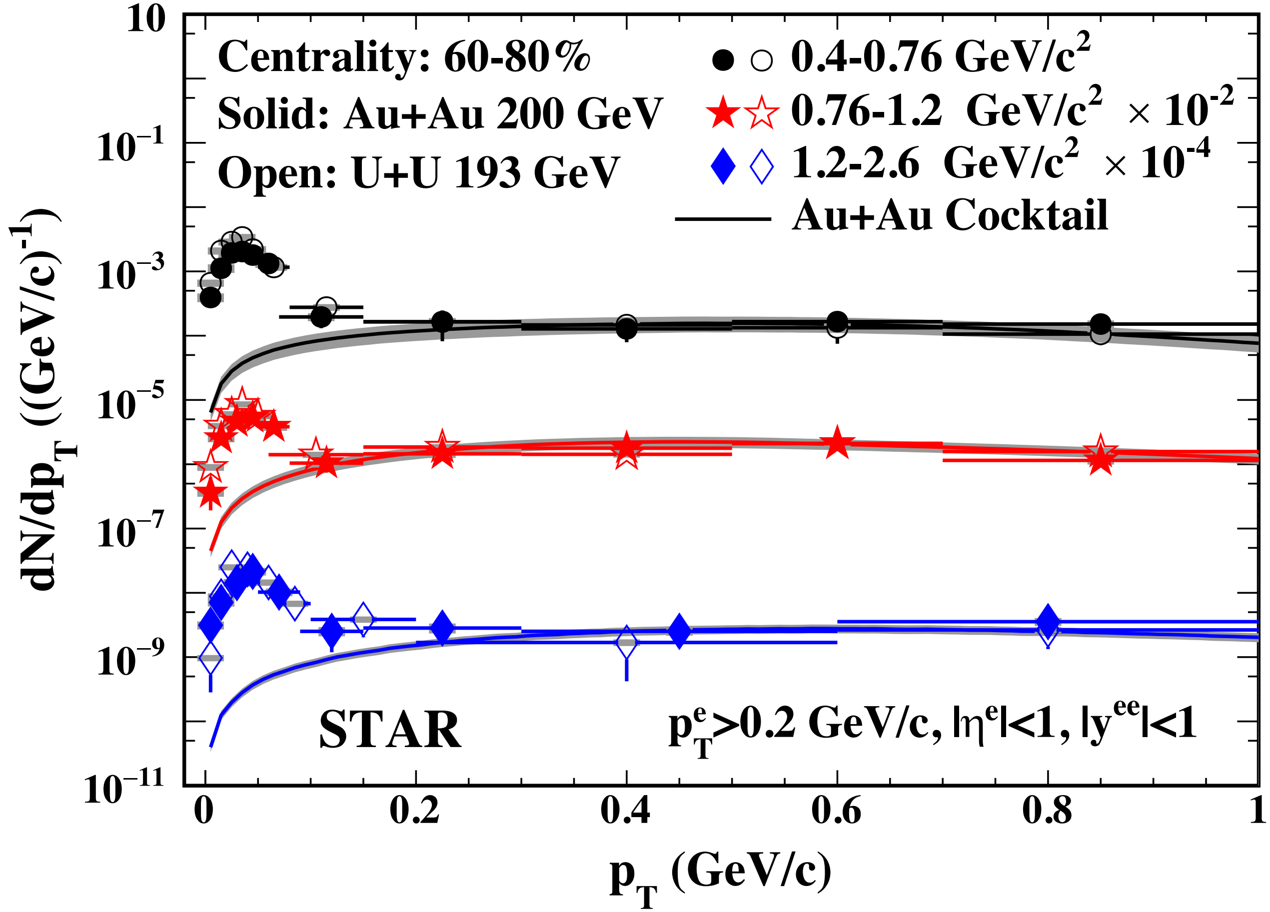
Ratio of data/cocktail

Mass (GeV/c^2)	Au+Au	U+U
0.4 - 0.76	$12.4 \pm 0.7 \pm 2.0 \pm 3.7$	$17.1 \pm 1.0 \pm 2.4 \pm 5.1$
0.76 - 1.2	$3.9 \pm 0.3 \pm 0.6 \pm 0.8$	$4.6 \pm 0.4 \pm 0.5 \pm 0.9$
1.2 - 2.6	$12.6 \pm 1.2 \pm 1.7 \pm 1.9$	$13.8 \pm 1.9 \pm 1.5 \pm 2.1$

- Enhancement factor (data/cocktail) decreases from peripheral to central collisions

p_T spectra in 60-80% collisions

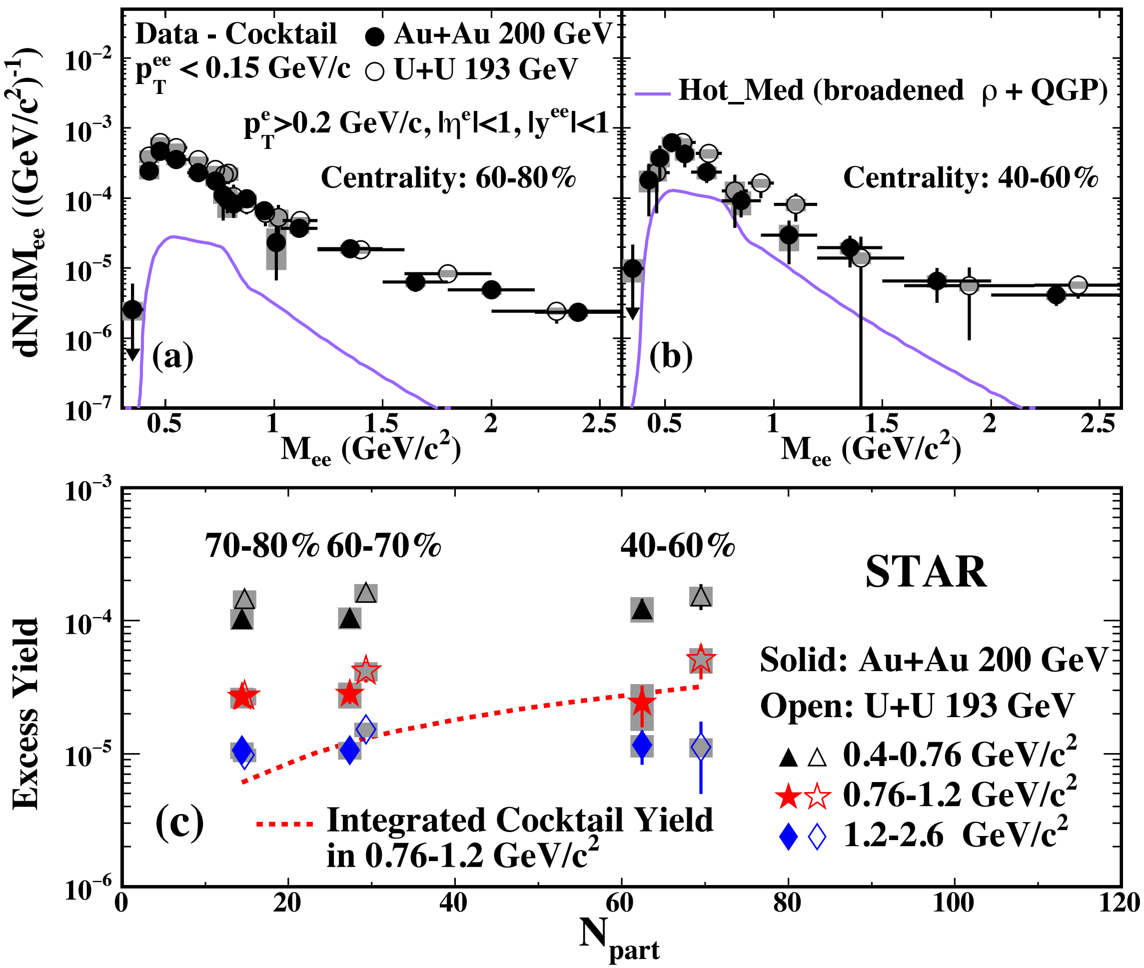
STAR, PRL 121 (2018) 132301



- Excess concentrated below $p_T \approx 0.15$ GeV/c
- Data are consistent with hadronic cocktail for $p_T > 0.15$ GeV/c

Origin of the low-p_T enhancement

STAR, PRL 121 (2018) 132301
R. Rapp, PRC 63 (2001) 054907



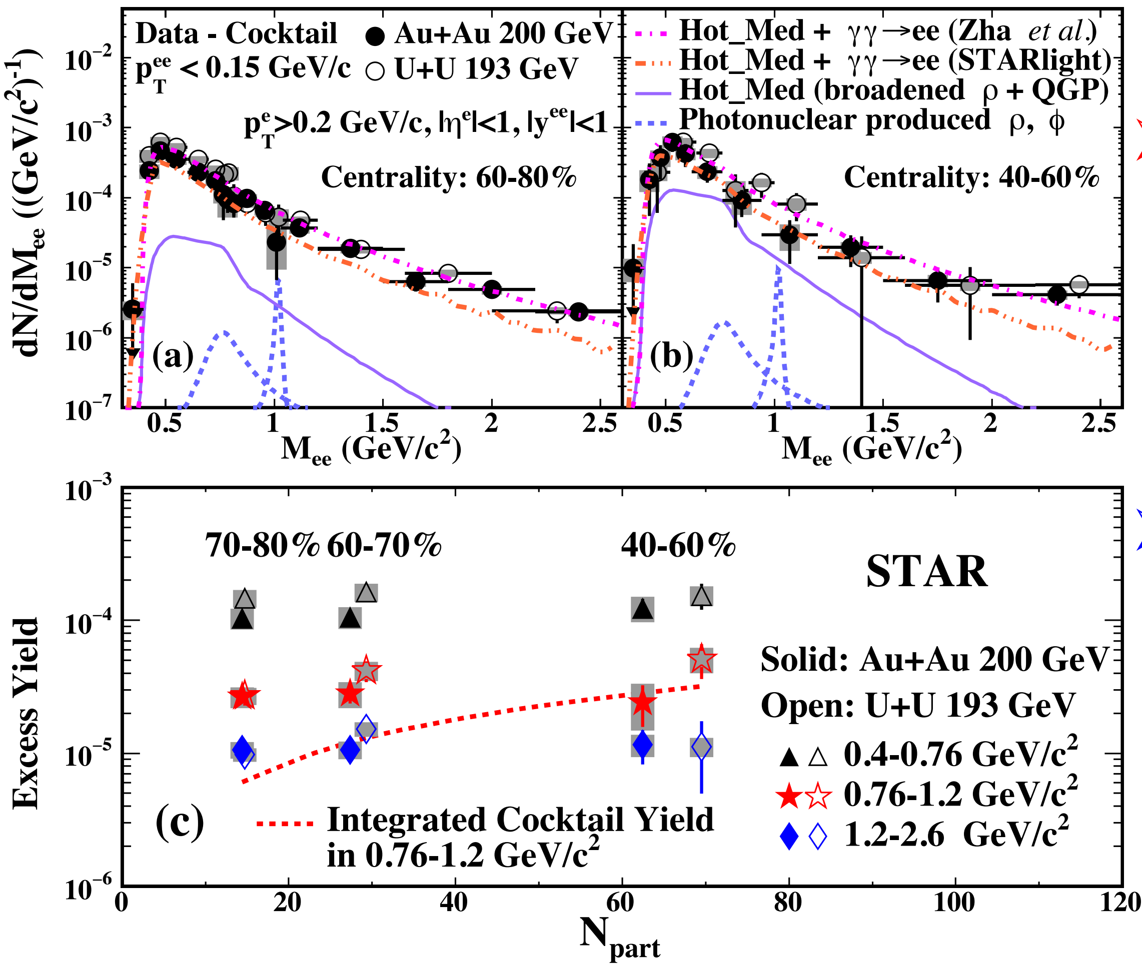
- Can not be explained by in-medium broadened ρ model
- Compared to hadronic production, excess yield exhibits a much weaker centrality dependence
- Need additional source(s)

Models of two-photon interaction

- Equivalent Photon Approximation (EPA) method
  - Photon is treated as real
  - Weizsäcker–Williams method to estimate photon flux
  - No impact parameter dependence of p_T spectrum for the dilepton from initial photon-photon interaction
- Models based on EPA method
  - Model by Zha *et al.* *[W. Zha et al., PLB 781 (2018) 182]*
    - ✓ Use Woods-Saxon charge distribution in nucleus for photon flux estimation
    - ✓ Consider dilepton production insides nucleus
  - STARlight *[S. Klein, PRC 97 (2018) 054903]*
    - ✓ Ignore dilepton production insides nucleus
  - STARlight with next-to-leading order correction and hot medium effects - Coulomb scattering *[S. Klein et al., arxiv: 1811.05519]*
- Model based on external classical field approach *[M. Vidovic et al., PRC 47 (1993) 2308]*
  - Model by Zha *et al.* *[W. Zha et al., arxiv: 1812.02820]*
    - ✓ Consider impact parameter dependence of p_T spectrum for the dilepton from initial photon-photon interaction

Origin of the low-p_T enhancement

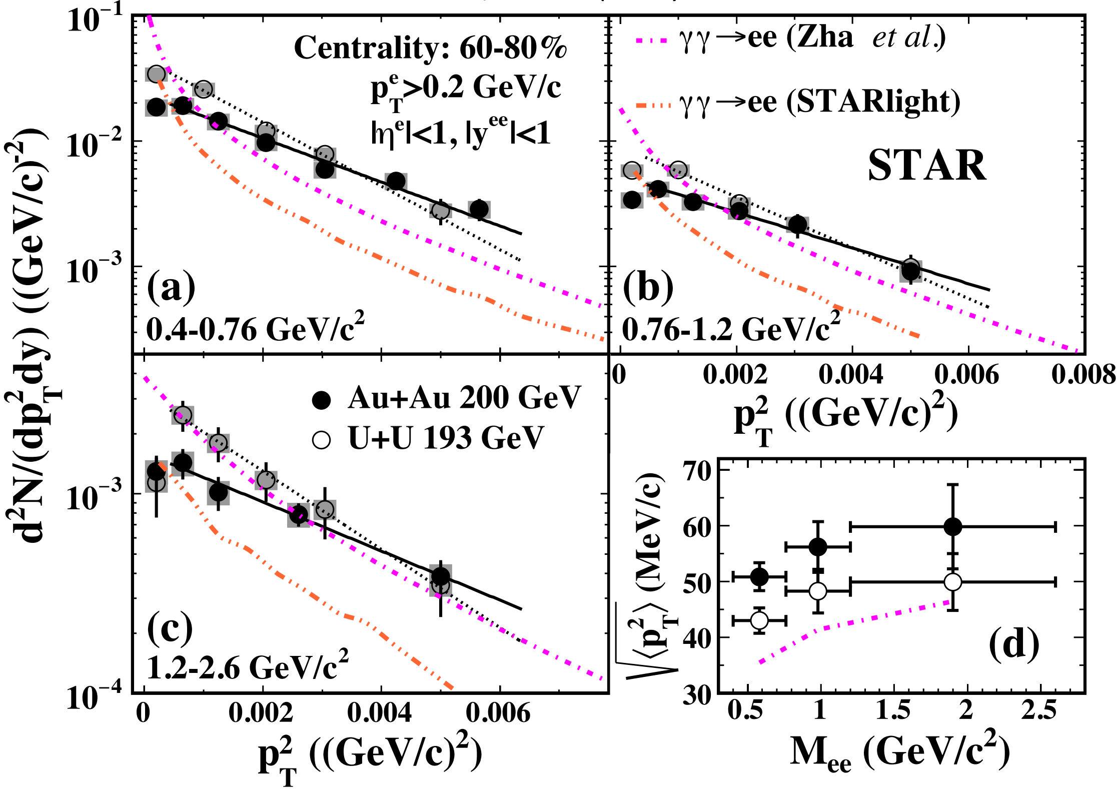
STAR, PRL 121 (2018) 132301
R. Rapp, PRC 63 (2001) 054907
W. Zha et al., PRC 97 (2018) 044910 , PLB 781 (2018) 182
S. Klein, PRC 97 (2018) 054903



- Qualitatively described by models including two-photon interaction
  - Data from 60-80% collisions favors model by Zha *et al.*
- Negligible contributions from photoproduced vector mesons

p_T^2 distributions in 60-80% collisions

STAR, PRL 121 (2018) 132301
W. Zha et al., PLB 781 (2018) 182
S. Klein, PRC 97 (2018) 054903



- Models fail to describe p_T^2 distributions
- Employ $\sqrt{< p_T^2 >}$ to quantify the discrepancy between data and models
  - Mass and collision species dependence
  - Data are systematically higher than models

p_T^2 distributions in 60-80% collisions

STAR, PRL 121 (2018) 132301
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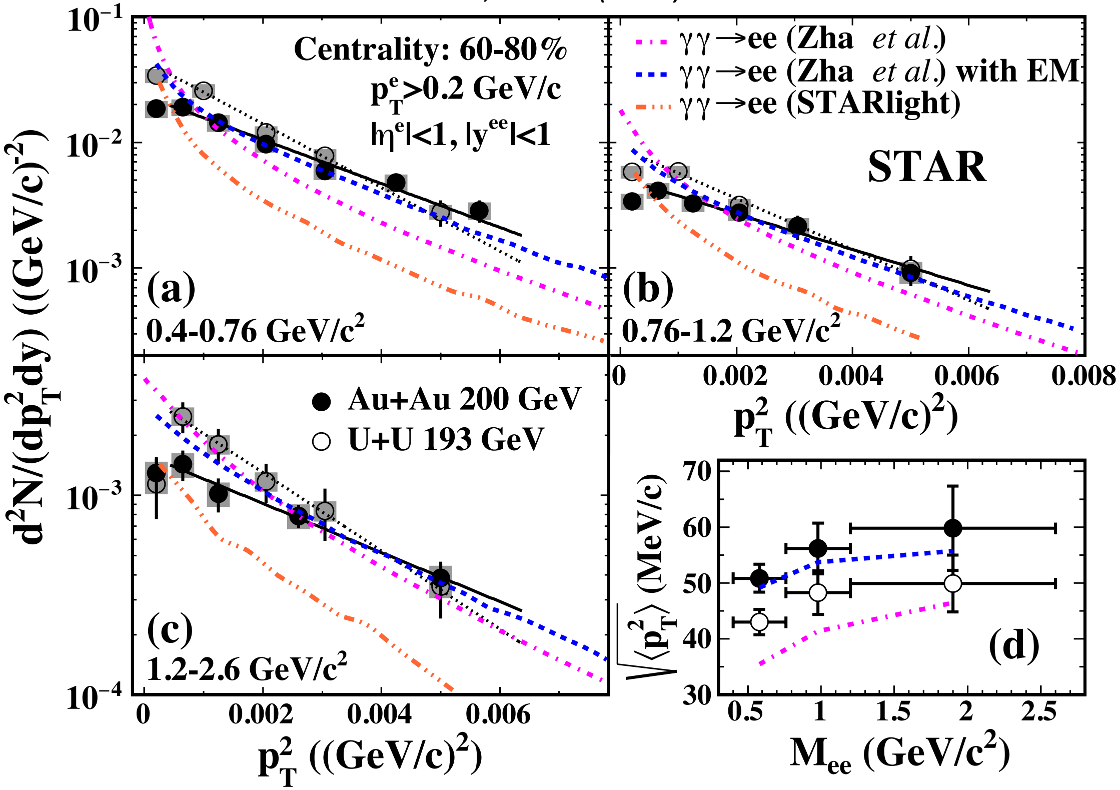
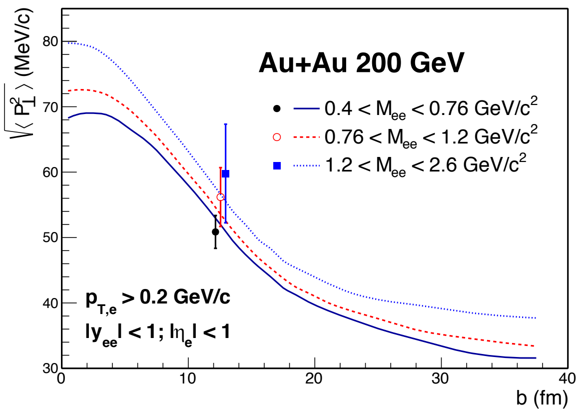


- Models fail to describe p_T^2 distributions
- Employ $\sqrt{< p_T^2 >}$ to quantify the discrepancy between data and models
  - Mass and collision species dependence
  - Data are systematically higher than models
- Model of Zha describes data when including effects of magnetic field on the produced pairs
  - Indication the existence of strong magnetic field trapped in QGP?

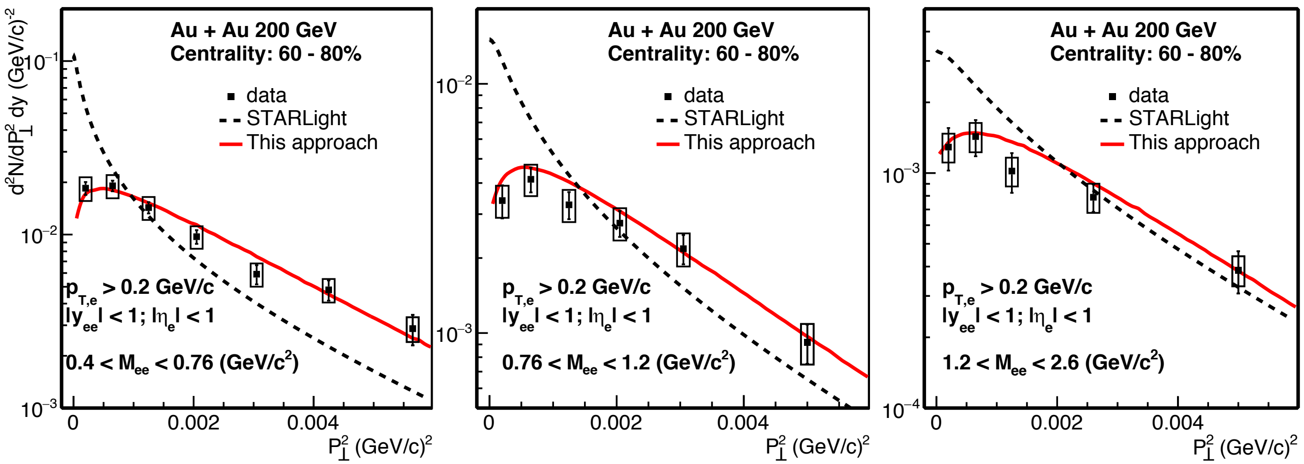
Impact parameter dependence of initial two-photon interaction *[W. Zha et al., arxiv: 1812.02820]*

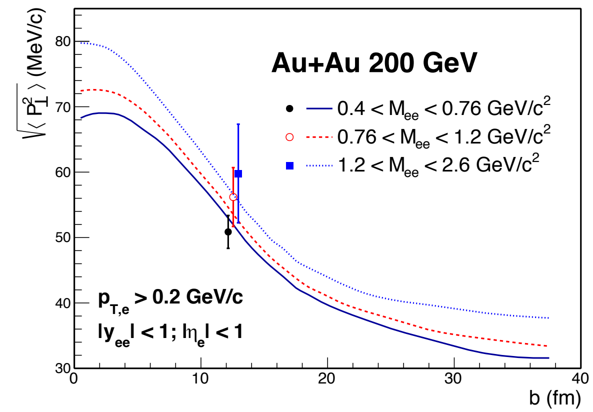


STAR, PRL 121 (2018) 132301

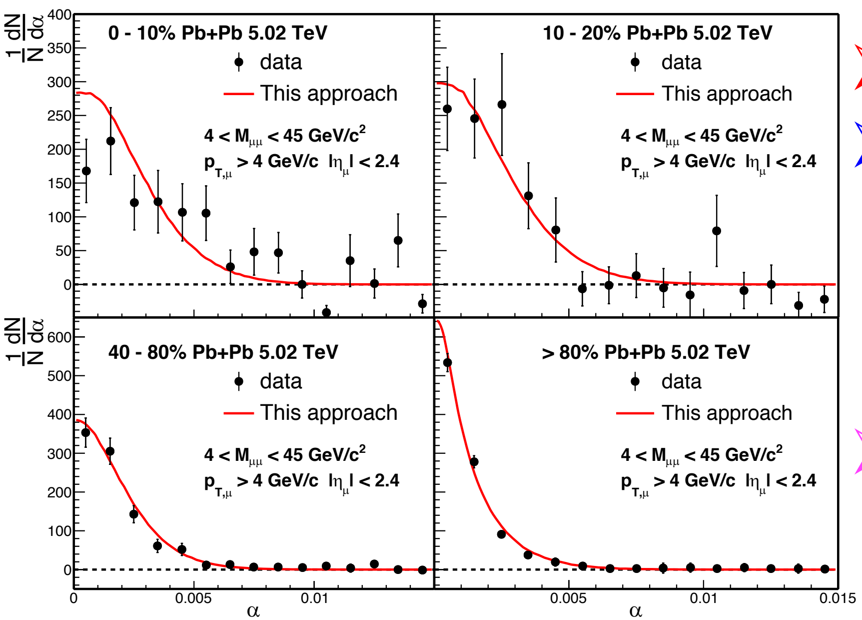
- Strong impact parameter dependence

Impact parameter dependence of initial two-photon interaction *[W. Zha et al., arxiv: 1812.02820]*



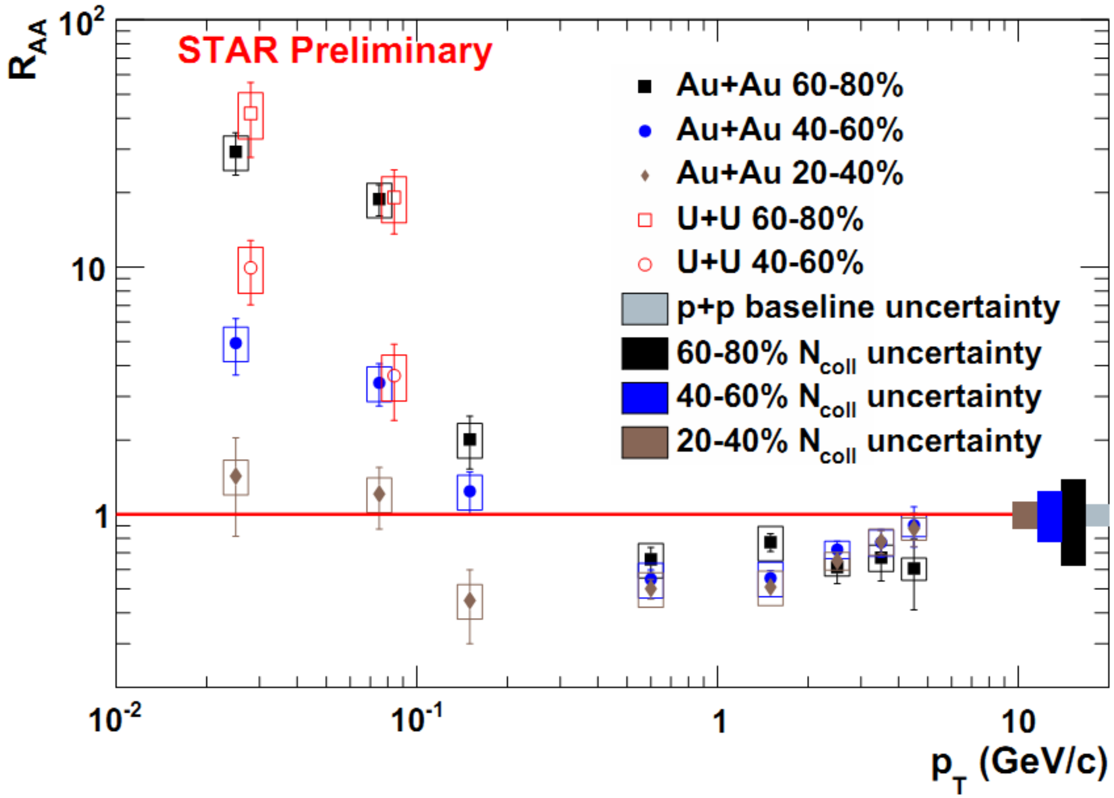


STAR, PRL 121 (2018) 132301
ATLAS, PRL 121 (2018) 212301



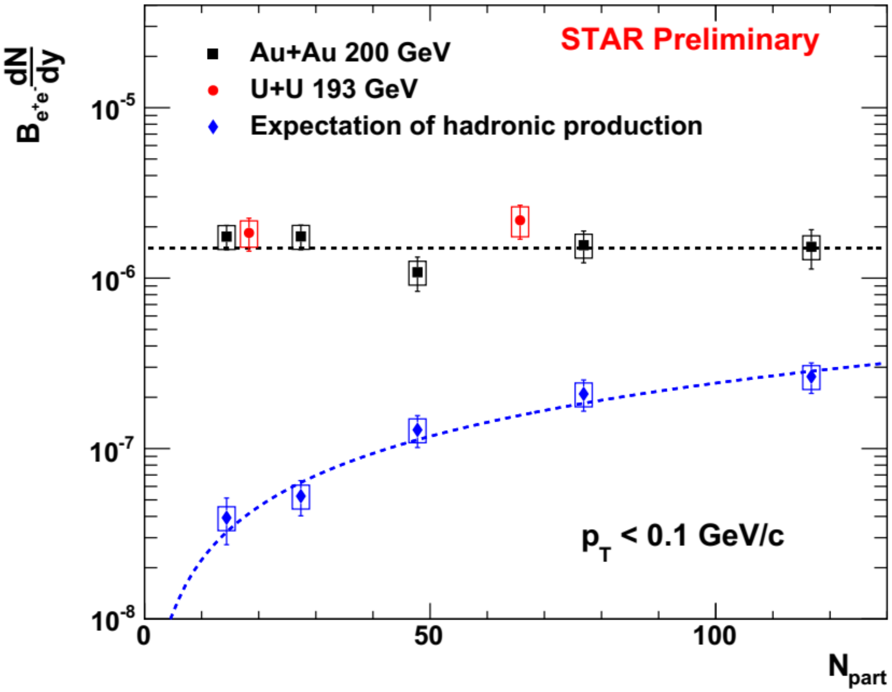
- **Strong impact parameter dependence**
- **Can describe STAR and ATLAS data simultaneously**
  - ATLAS data can also be qualitatively described by EPA model incorporating Coulomb scattering *[S. Klein et al., arxiv: 1811.05519]*
- **Critical for the study of possible hot medium effects**

Low-p_T J/ψ at STAR



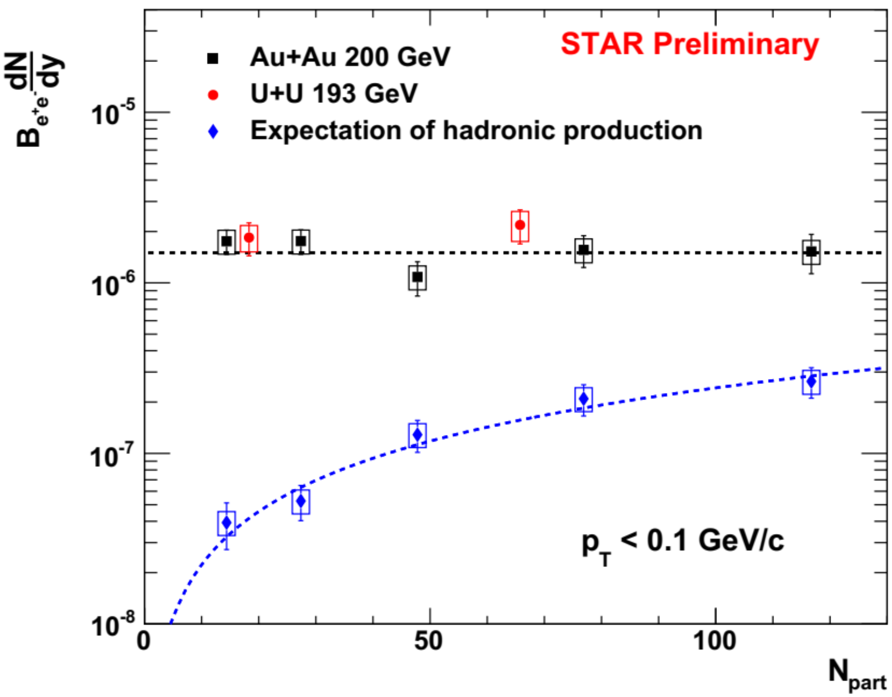
- Significant enhancement at low p_T (< 0.1 GeV/c) in 40-80% collisions
- No significant difference between Au+Au and U+U collisions

Excess yields of low-p_T J/ψ

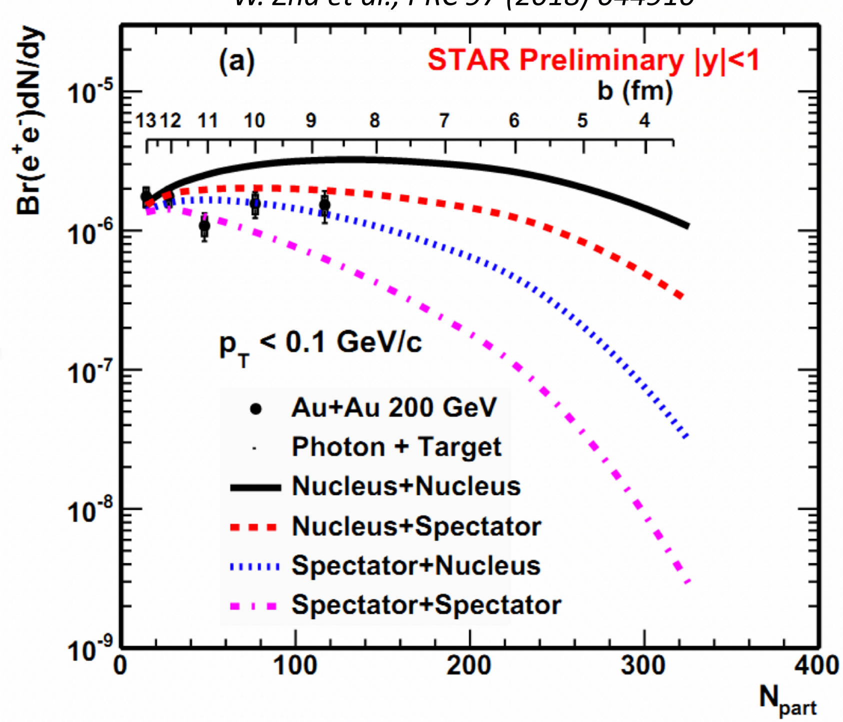


- **No significant centrality dependence of the excess yield**
  - Yield of low-p_T J/ψ from hadronic production is expected to increase dramatically with N_{part}

Excess yields of low-p_T J/ψ

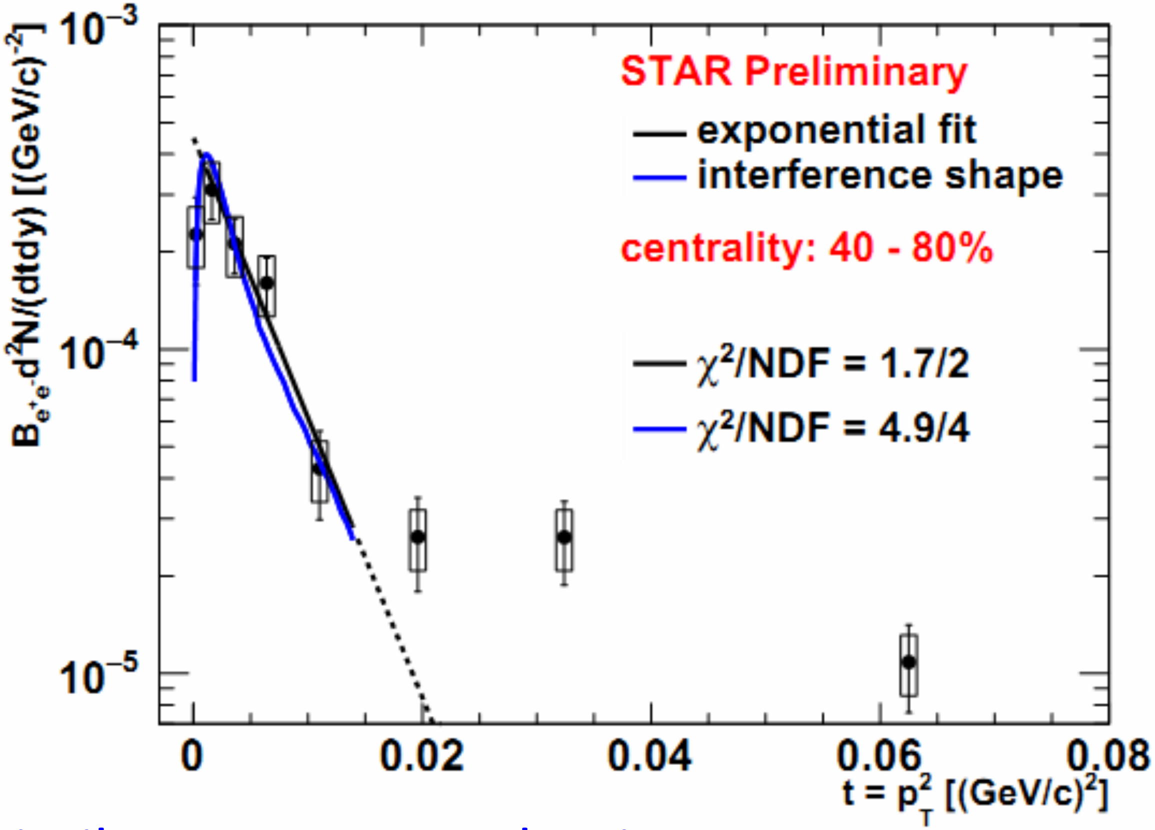


W. Zha et al., PRC 97 (2018) 044910



- No significant centrality dependence of the excess yield
  - Yield of low-p_T J/ψ from hadronic production is expected to increase dramatically with N_{part}
- Qualitatively described by photonuclear interaction
  - N+S and S+N scenarios can describe the data reasonably well
    - ✓ Measurements in central collisions are critical

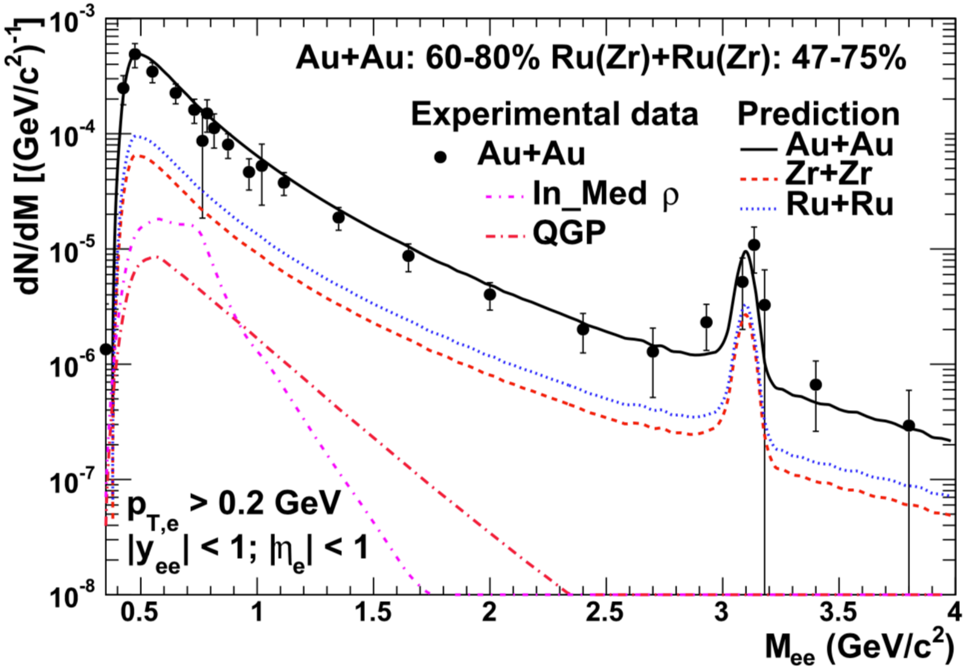
t distribution of J/ψ



- Similar structure to that in UPCs
  - Indication of interference *[S. Klein, PRL 84 (2000) 2330]*
  - Similar slope parameter for exponential fit
    - ✓ Slope = 196 (GeV/c)$^{-2}$ in UPC case
    - ✓ Slope = 199 $\pm$ 31 (GeV/c)$^{-2}$ (w/o the first point) in 40-80% collisions

Isobaric collisions

- ${}^{96}_{44}$Ru+${}^{96}_{44}$Ru vs. ${}^{96}_{40}$Zr+${}^{96}_{40}$Zr
  - Charge differs by 10%, everything else is almost the same
  - Large statistics taken by STAR in 2018: 3.1B vs. 1.5B (goal) minimum-bias events
  - Rapid (daily) switching between Ru and Zr: minimize systematic uncertainty

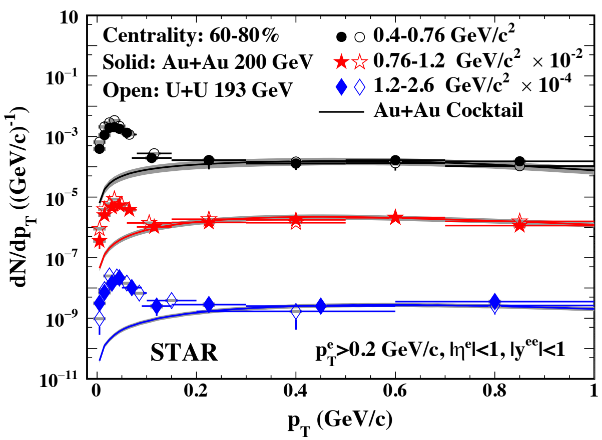


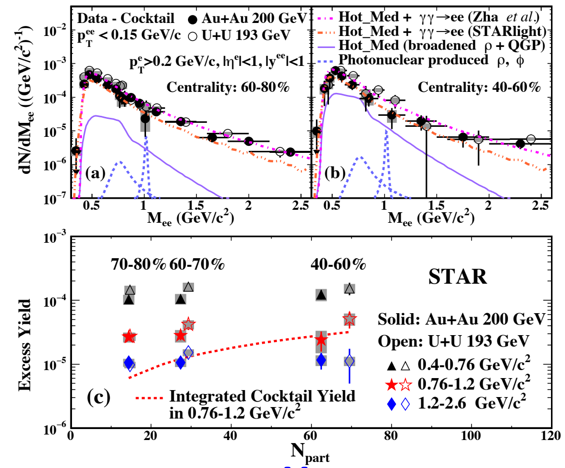
W. Zha et al., PLB 789 (2019) 238
STAR, PRL 121 (2018) 132301

- Further constrain the photon interactions and their possible impacts on emerging phenomena in heavy-ion collisions

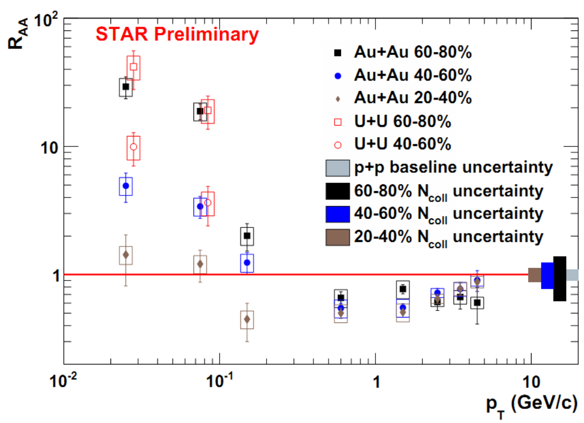
Summary

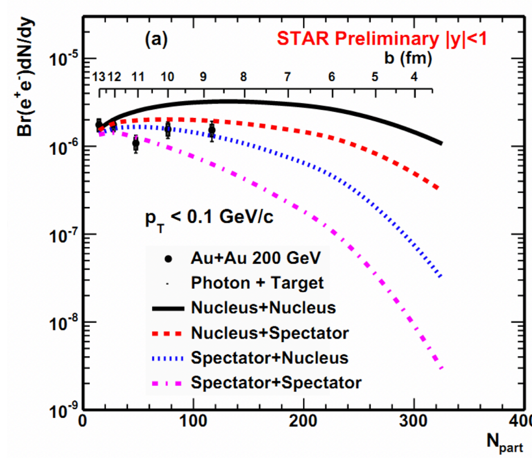
➢ Low-p_T e^+e^- pair production in heavy-ion collisions

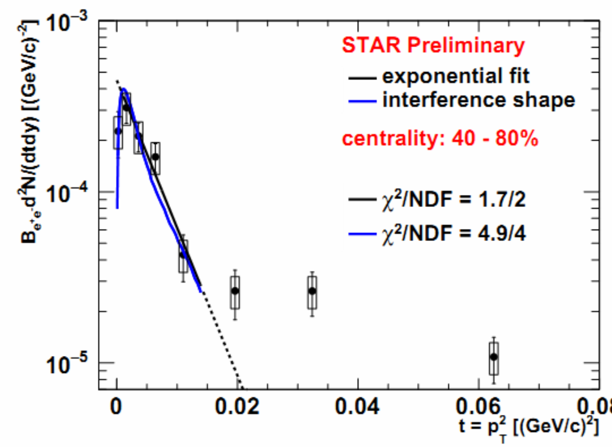




➢ Low-p_T J/ψ production in heavy-ion collisions



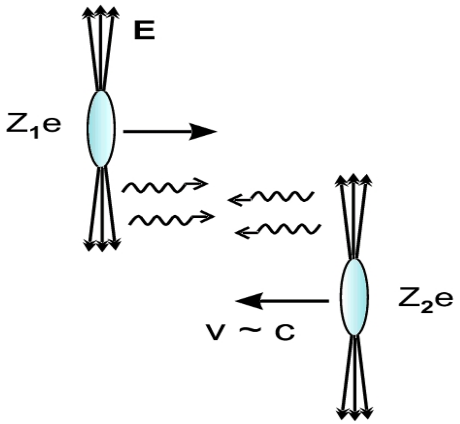




➢ Explore photon interactions in isobaric collisions

Backup

Coherent photons as "partons" in heavy-ion collisions

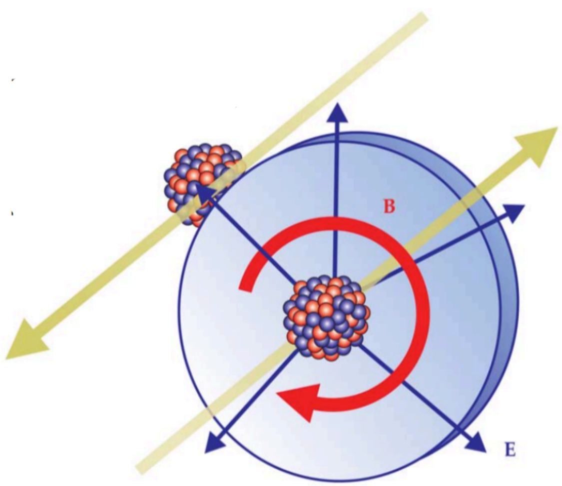


Coherent limitation: $Q^2 \leq 1/R^2$ => quasi-real !

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

$$Q^2 = \frac{\omega^2}{\gamma^2} + q_T^2$$
$$\omega \leq \omega_{max} \sim \frac{\gamma}{R}$$
$$q_T \leq 1/R$$

- View photons as "partons" being present with fast moving ions!



Physics Today **70**, 10, 40 (2017)

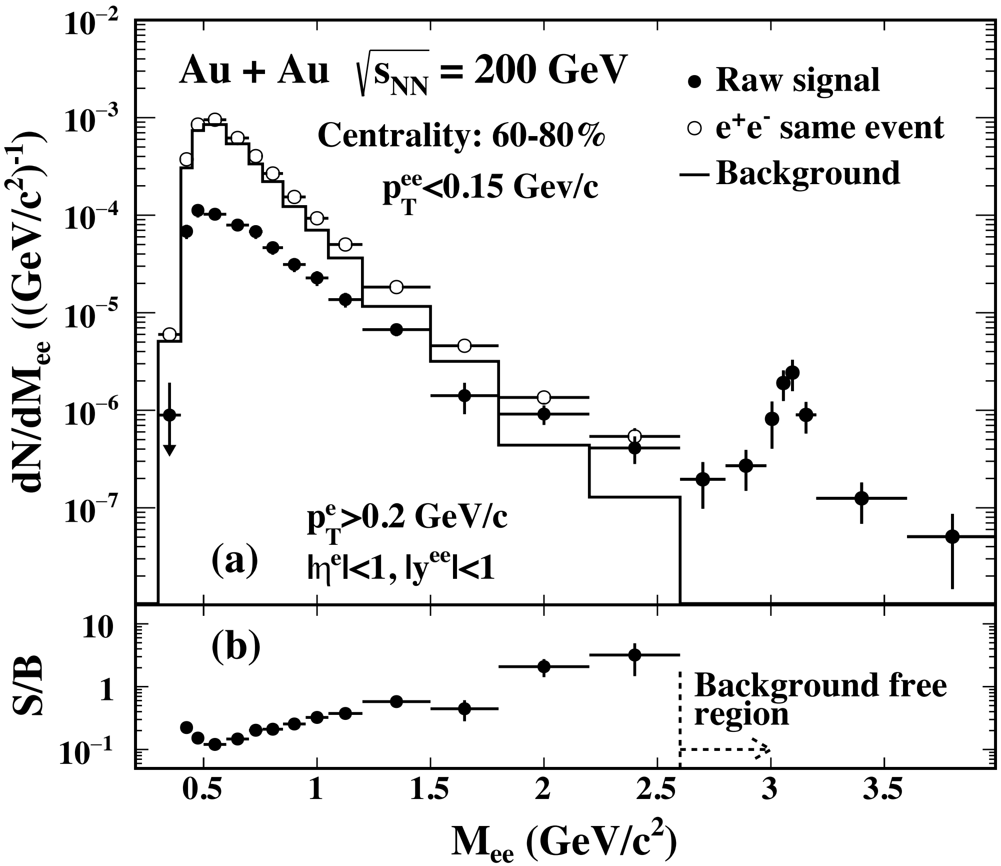
The extent of photons swarming about the ions:

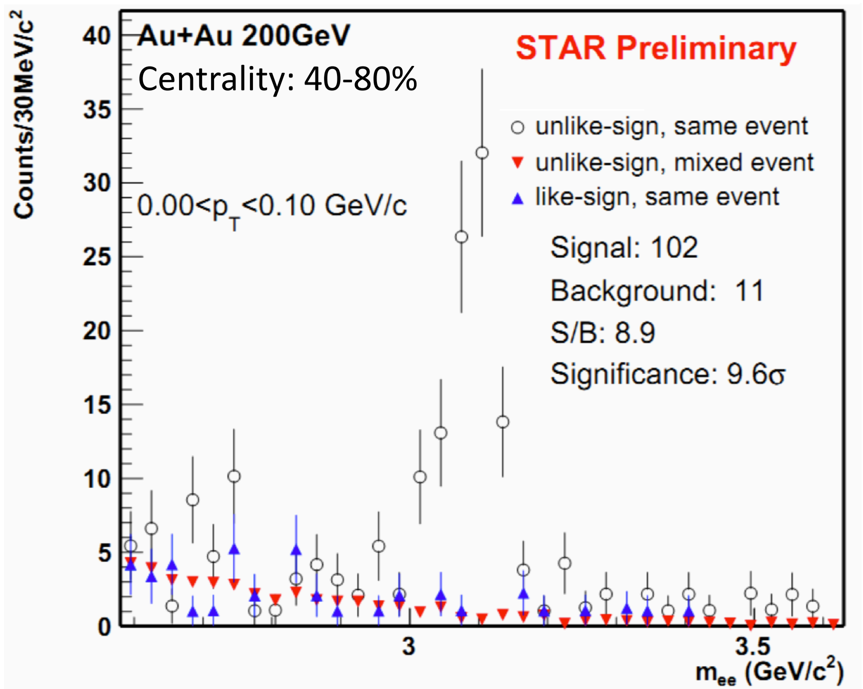
The radius of nuclear matter R_{Nuc} ~ 6.3 fm (Au)

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

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

Raw e^+e^- and J/ψ signal at low p_T





Model calculation with impact parameter dependence

$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int d^2b\int\frac{dw_1}{w_1}\frac{dw_2}{w_2}\frac{d^2k_{1\perp}}{(2\pi)^2}\frac{d^2k_{2\perp}}{(2\pi)^2}\frac{d^2q_{\perp}}{(2\pi)^2}$$
$$\times\frac{F(-k_1^2)}{k_1^2}\frac{F(-k_2^2)}{k_2^2}\frac{F^*(-k_1'^2)}{k_1'^2}\frac{F^*(-k_2'^2)}{k_2'^2}\boxed{e^{-i\vec{b}\cdot\vec{q}_\perp}} \qquad (2)$$
$$\times\left[(\vec{k}_{1\perp}\cdot\vec{k}_{2\perp})(\vec{k}'_{1\perp}\cdot\vec{k}'_{2\perp})\sigma_s(w_1,w_2)\right.$$
$$\left.+(\vec{k}_{1\perp}\times\vec{k}_{2\perp})(\vec{k}'_{1\perp}\times\vec{k}'_{2\perp})\sigma_{ps}(w_1,w_2)\right]$$

where the four momenta of photons are

$$k_1 = (w_1, k_{1\perp}, \frac{w_1}{v}), k_2 = (w_2, P_\perp - k_{1\perp}, \frac{w_2}{v})$$
$$w_1 = \frac{1}{2}(P_0 + vP_z), w_2 = \frac{1}{2}(P_0 - vP_z)$$
$$k_{2\perp} = P_\perp - k_{1\perp}, q_\perp = k_{1\perp} - k'_{1\perp} \qquad (3)$$
$$k'_1 = (w_1, k_{1\perp} - q_\perp, w_1/v)$$
$$k'_2 = (w_2, k_{2\perp} - q_\perp, w_2/v)$$

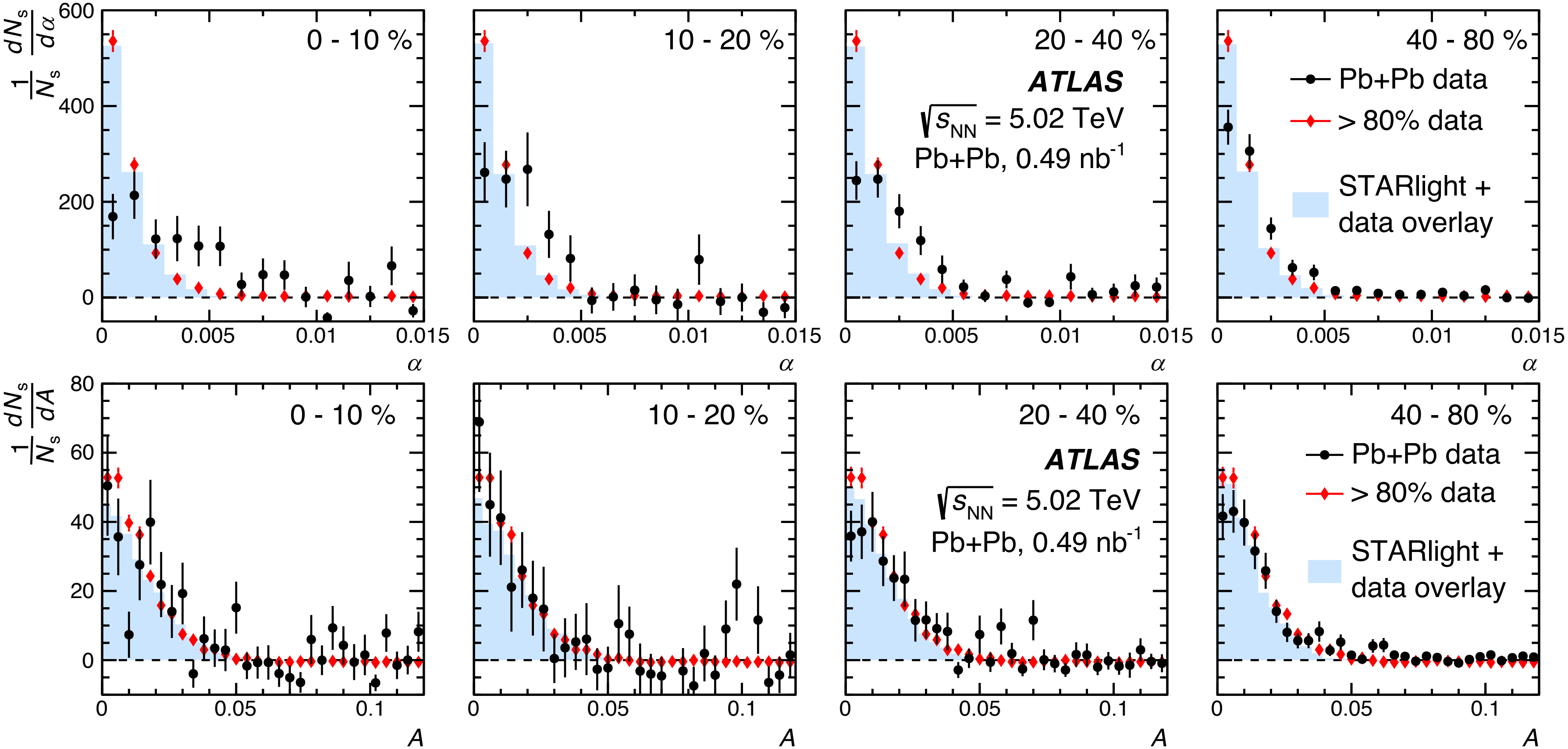
Integration over b →

$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int\frac{dw_1}{w_1}\frac{dw_2}{w_2}\frac{d^2k_{1\perp}}{(2\pi)^2}\frac{d^2k_{2\perp}}{(2\pi)^2}\left|\frac{F(-k_1^2)}{k_1^2}\right|^2$$
$$\times\left|\frac{F(-k_2^2)}{k_2^2}\right|^2 k_{1\perp}^2 k_{2\perp}^2\sigma(w_1,w_2) \qquad (6)$$

- EPA expression commonly used in traditional photon-photon models

W. Zha et al., arxiv: 1812.02820

Dimuon pairs from two-photon interaction at ATLAS

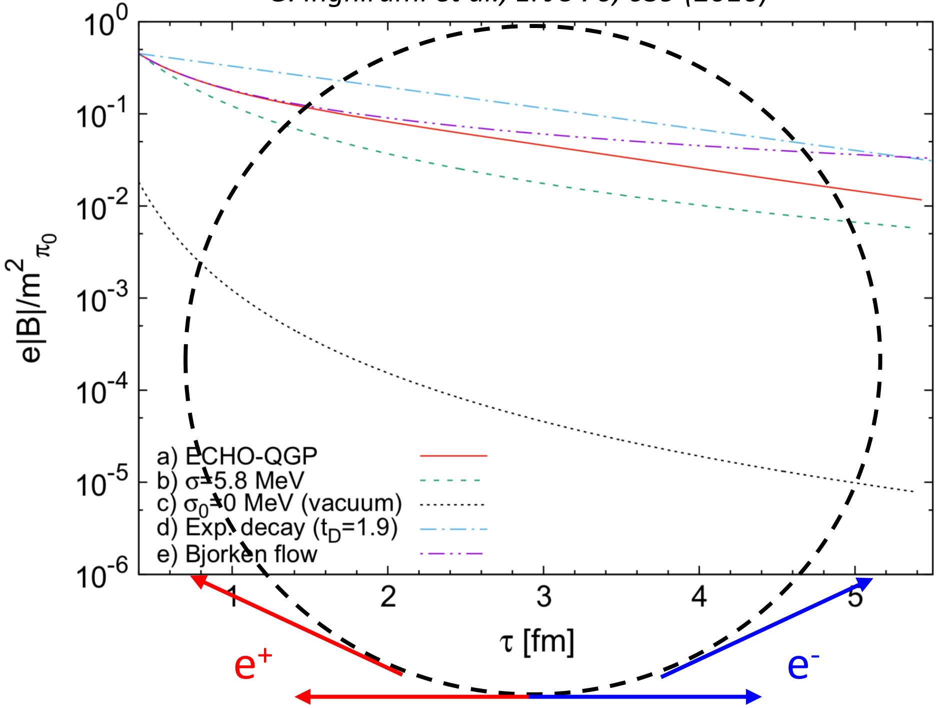


$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \quad A \equiv \left|\frac{p_T^+ - p_T^-}{p_T^+ + p_T^-}\right|$$

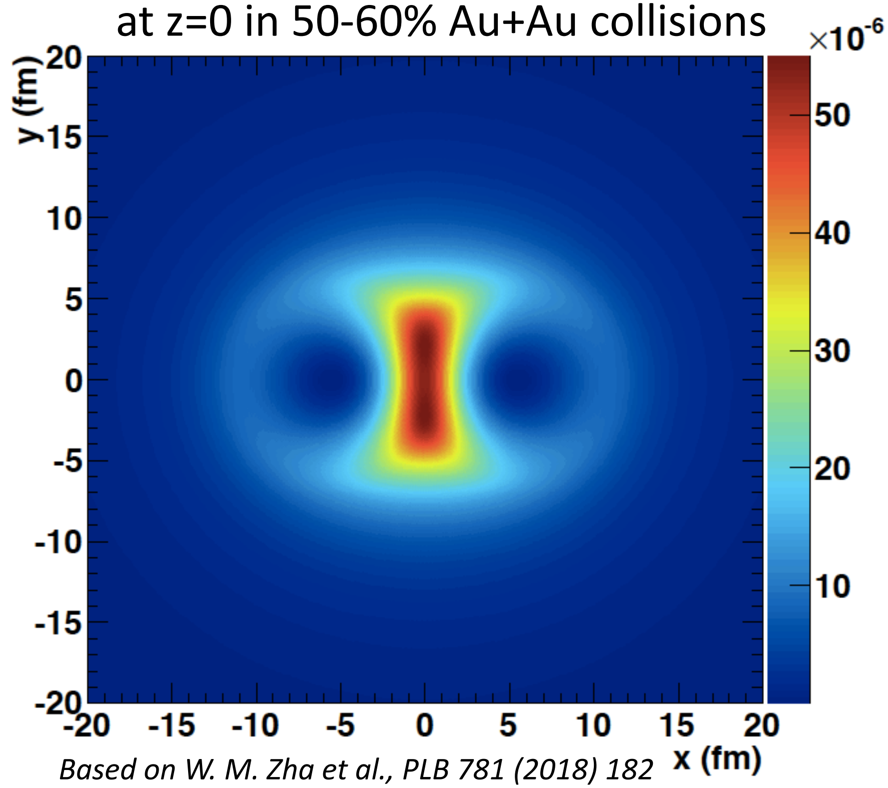
- Use >80% collisions as baseline
- Indication of Coulomb scattering? *[S. Klein et al., arxiv: 1811.05519]*

Sensitivity to residual magnetic field?

G. Inghirami et al., EPJC 76, 659 (2016)



Example of e^+e^- spatial distributions at z=0 in 50-60% Au+Au collisions



Based on W. M. Zha et al., PLB 781 (2018) 182

- To account for the effect of the time-dependent magnetic field on average, the model assumes that all the e^+e^- pairs traverse 1 fm through a magnetic field of 10^{14} T perpendicular to the beam line
  - The net effect of this approach is close to $\int eB(t)cdt = e\bar{B}L$
  - $e\bar{B}L \approx$ 30 MeV/c, the extreme pair p_T increase: $2e\bar{B}L \approx$ 60 MeV/c