Low-p_T e^+e^- pair production in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV and U+U collisions at $\sqrt{s_{NN}}$= 193 GeV at STAR

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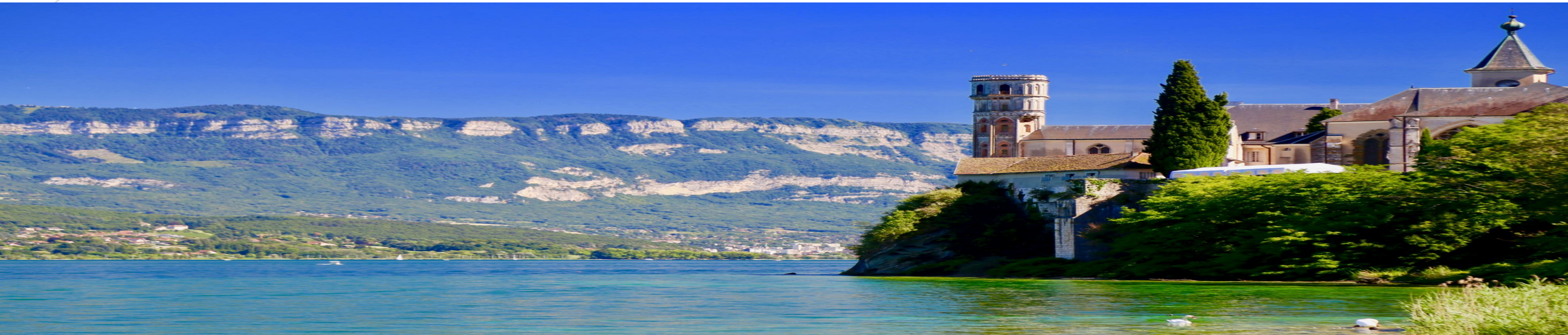
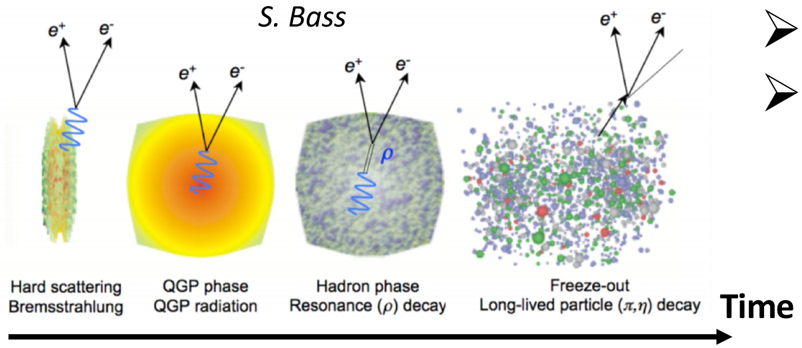
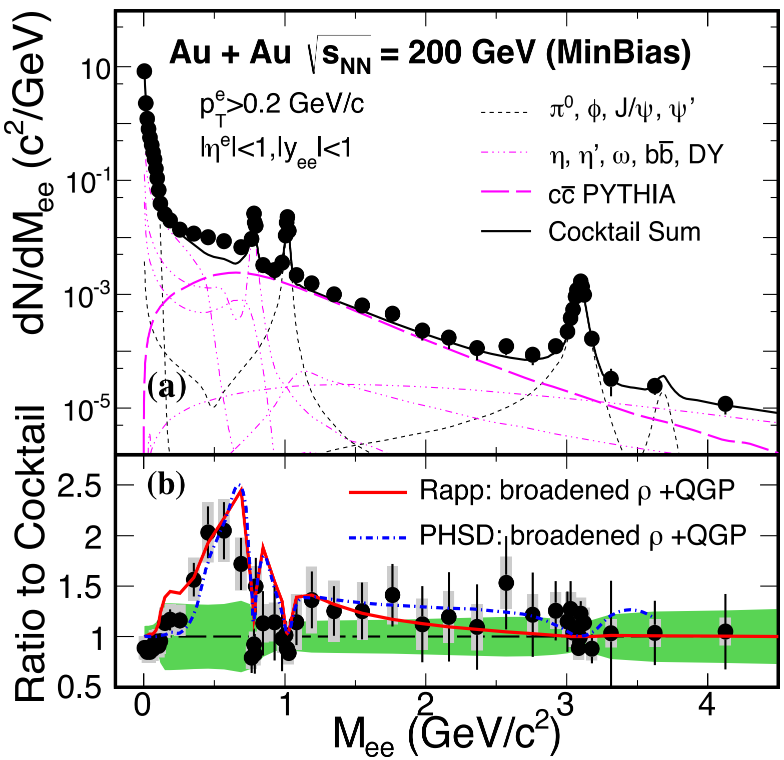


Dilepton – penetrating probe of hot, dense medium

S. Bass

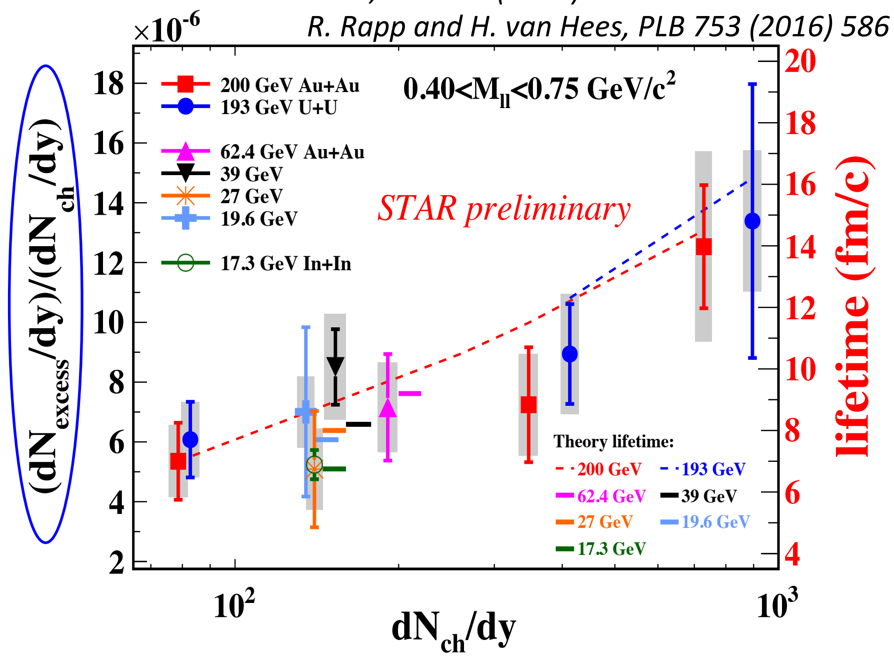


- Do not suffer strong interactions
- Bring direct information of the medium created in heavy-ion collisions



STAR, PRL 113 (2014) 022301

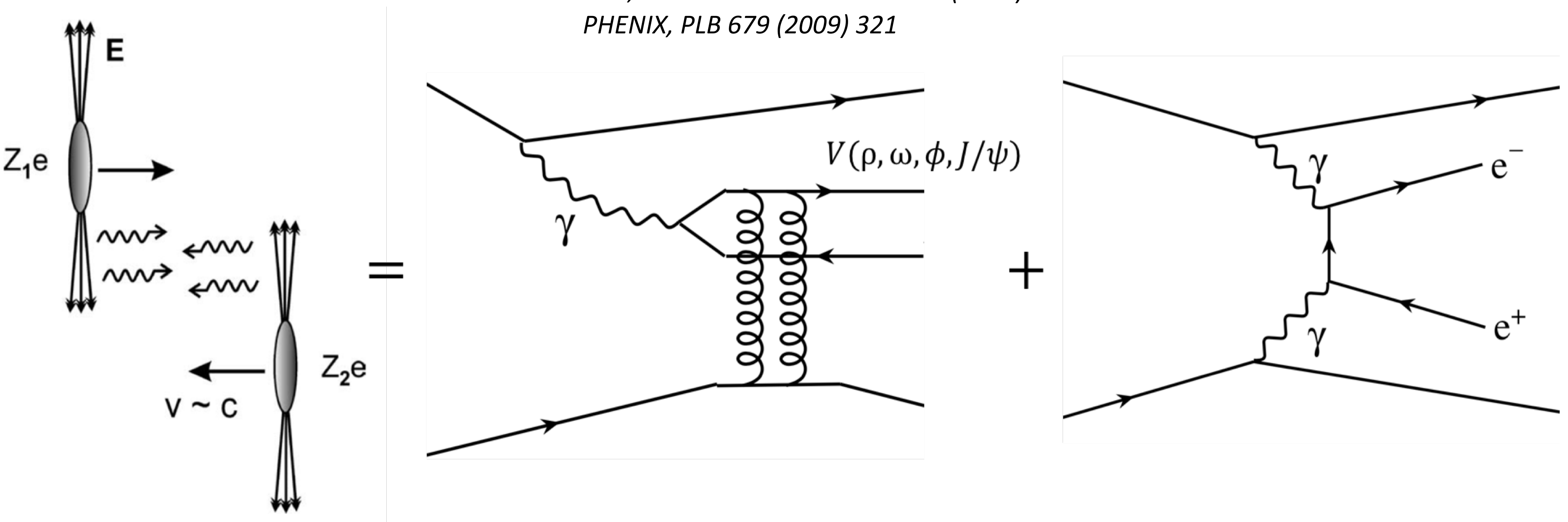
NA60, EPJ C 59 (2009) 607
STAR, PLB 750 (2015) 64
R. Rapp and H. van Hees, PLB 753 (2016) 586



- Consistent with an in-medium broadened ρ model calculation *[R. Rapp, PRC 63 (2001) 054907]*
- Indicate longer medium lifetime in central UU@193GeV and AuAu@200GeV collisions.

Dileptons from photon interactions

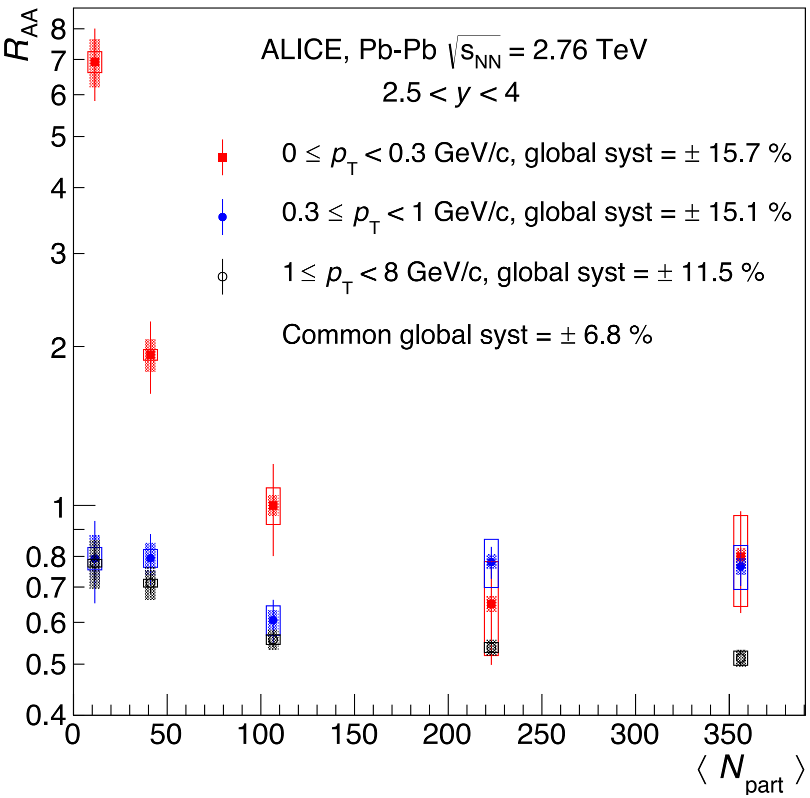
C. A. Bertulani et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 271
PHENIX, PLB 679 (2009) 321

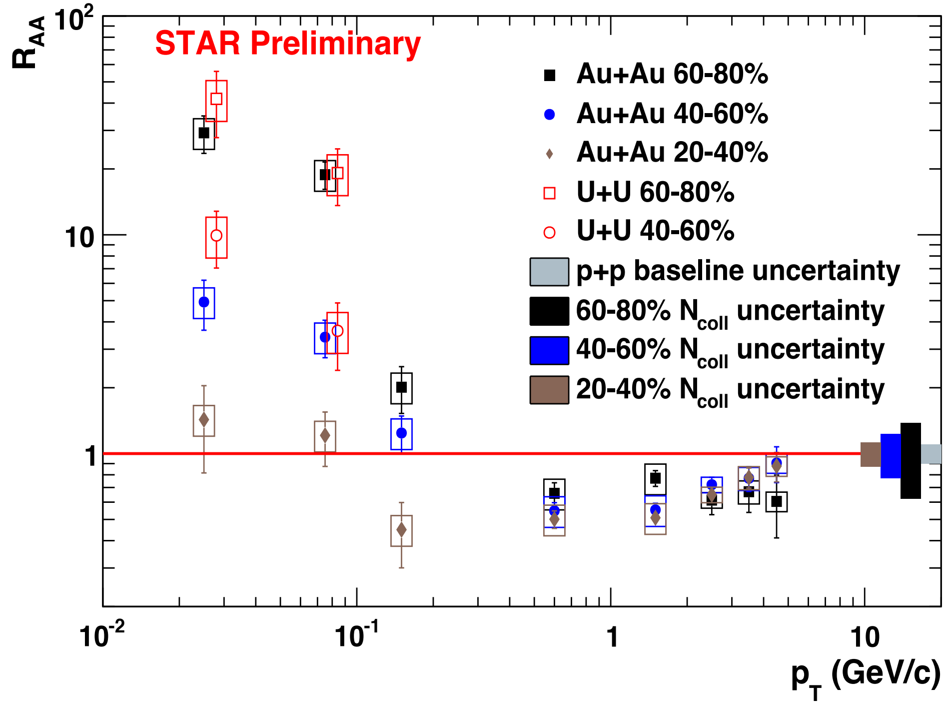


- Large quasi-real photon flux $\propto Z^2$
- Photon interactions
  - Photon-nuclear interaction (vector mesons) $\propto Z^2$
  - Photon-photon interaction (dilepton…) $\propto Z^4$
  - Distinctly peaked at low p_T
- Conventionally only studied in ultraperipheral collisions (UPCs)

Photon interactions only happens in UPCs? – Anomalous J/ψ enhancement

ALICE, PRL 116 (2016) 222301

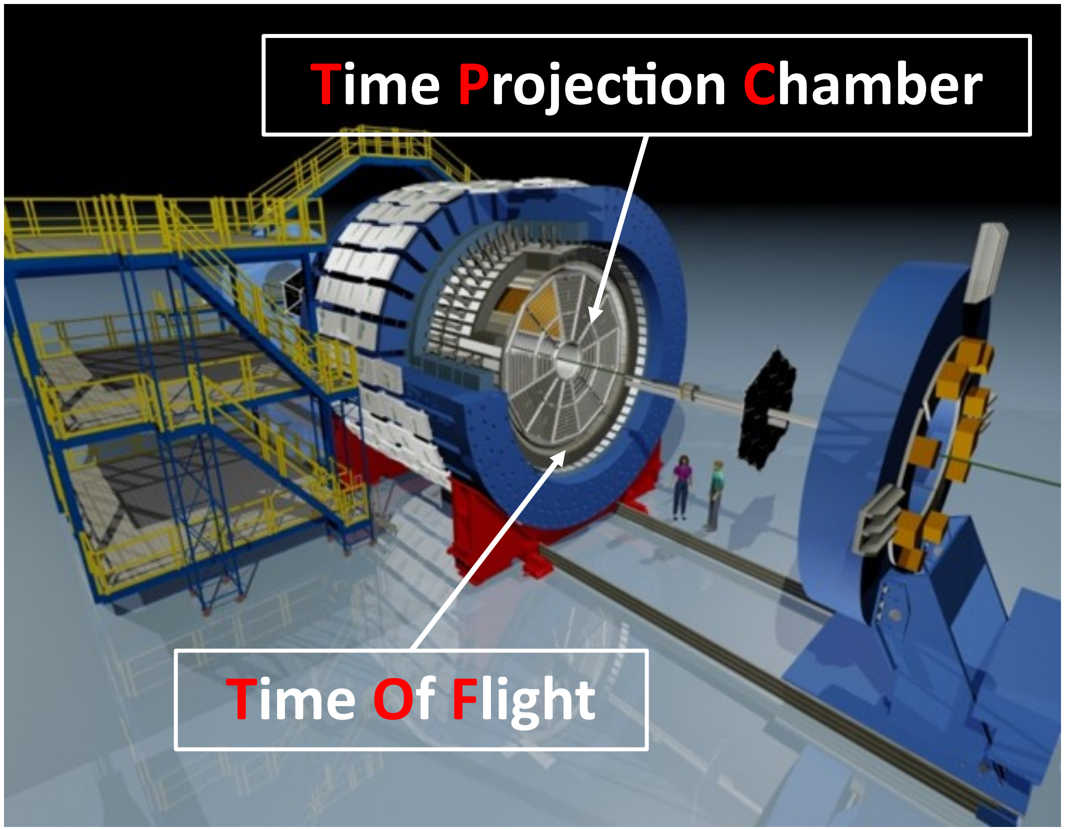


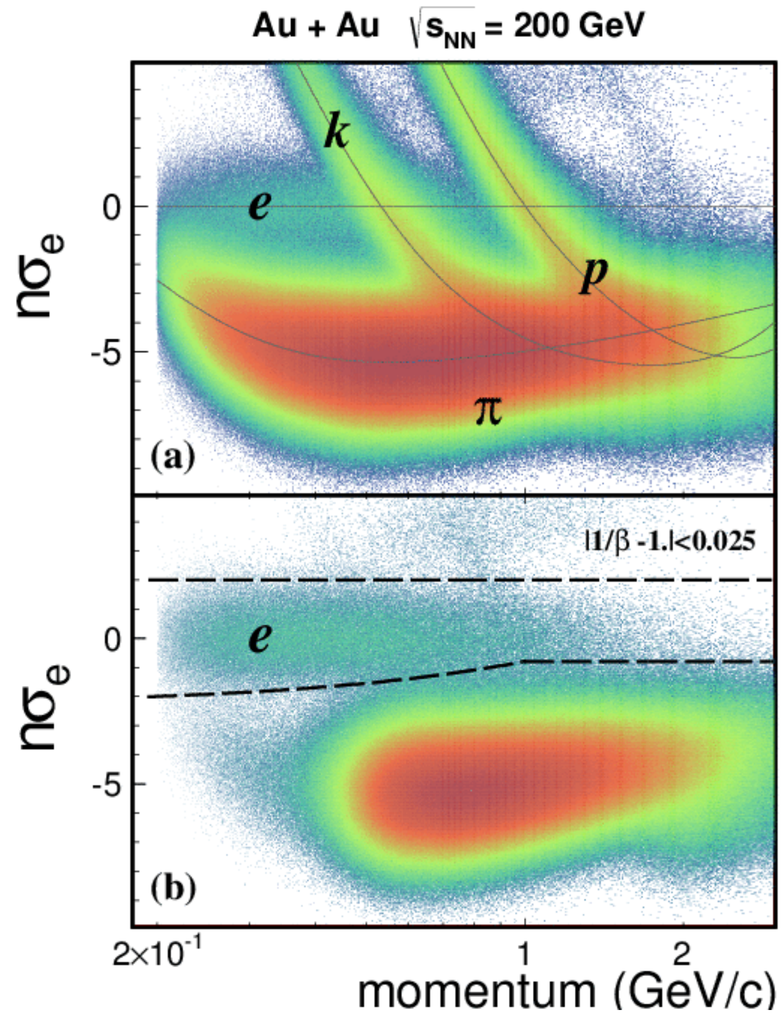


- Significant enhancement at low p_T in peripheral collisions
  - Cannot be explained by hadronic production accompanied with the cold and hot medium effects
  - Could be qualitatively explained by coherent photonuclear production mechanism *[W. M. Zha et al., PRC 97 (2018) 044910]*

The STAR detector

- Midrapidity coverage: $|\eta|<1$, $0 < \varphi < 2\pi$

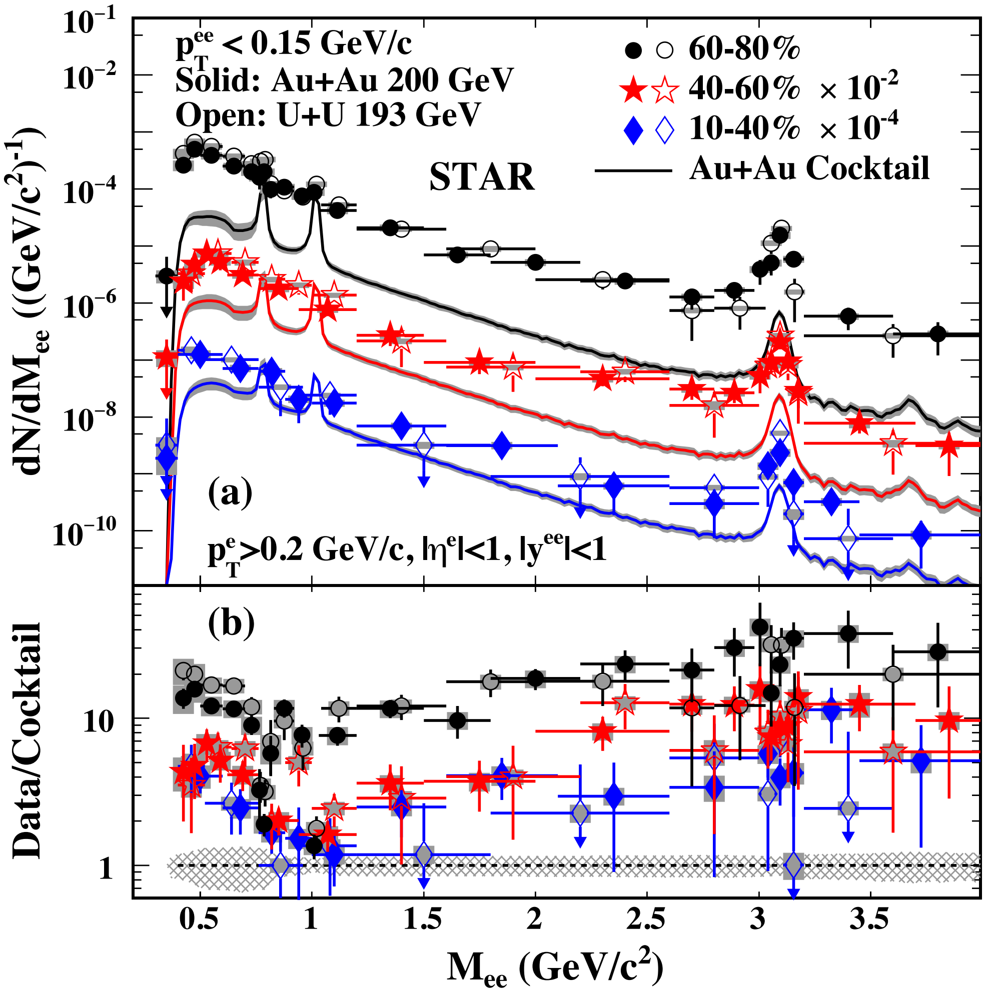




- TPC: Tracking + PID (dE/dx)
- TOF: PID ($1/\beta$)

Low-p_T e^+e^- invariant mass spectra in peripheral heavy-ion collisions

STAR, PRL 121 (2018) 132301



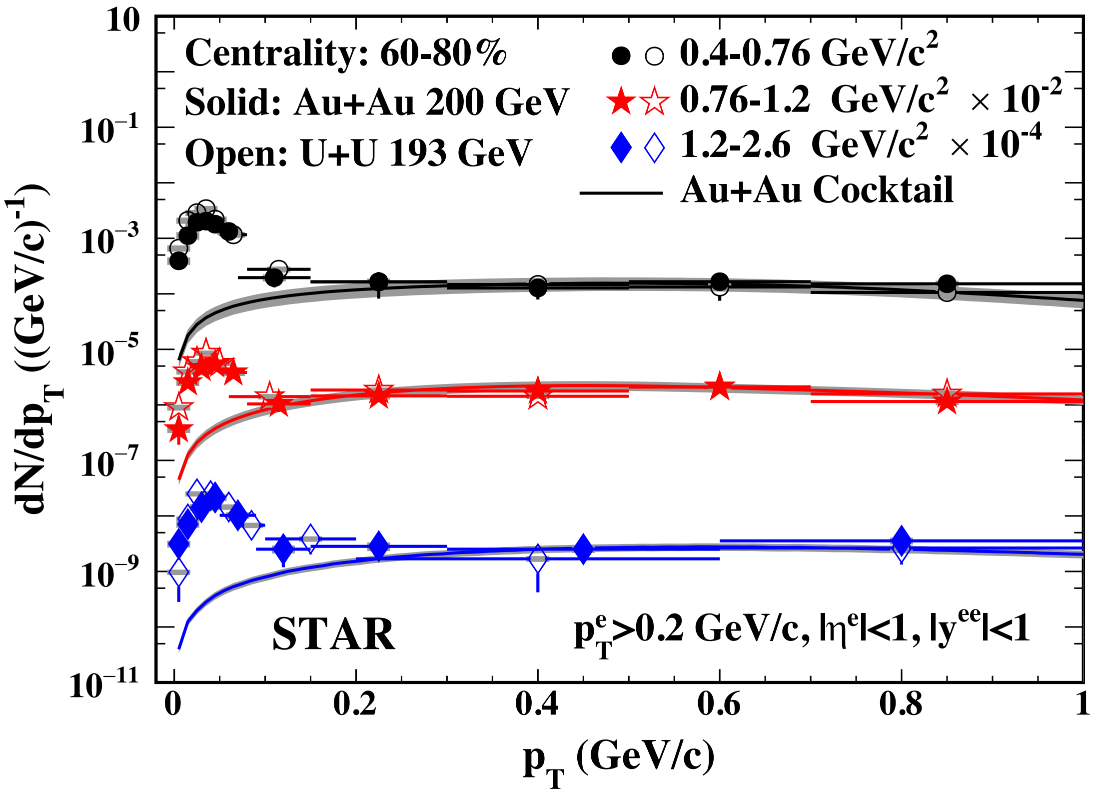
- Significant enhancement with respect to the cocktail in 60-80% Au+Au and U+U collisions

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	$12.6 \pm 1.2 \pm 1.7 \pm 1.9$	$13.8 \pm 1.9 \pm 1.5 \pm 2.1$

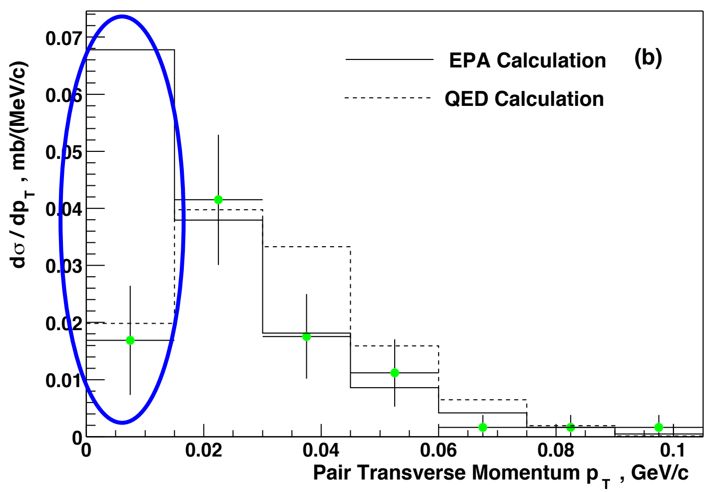
- Enhancement factor (data/cocktail) decreases from peripheral to central collisions

p_T spectra in 60-80% collisions

STAR, PRL 121 (2018) 132301



STAR, PRC 70 (2004) 031902

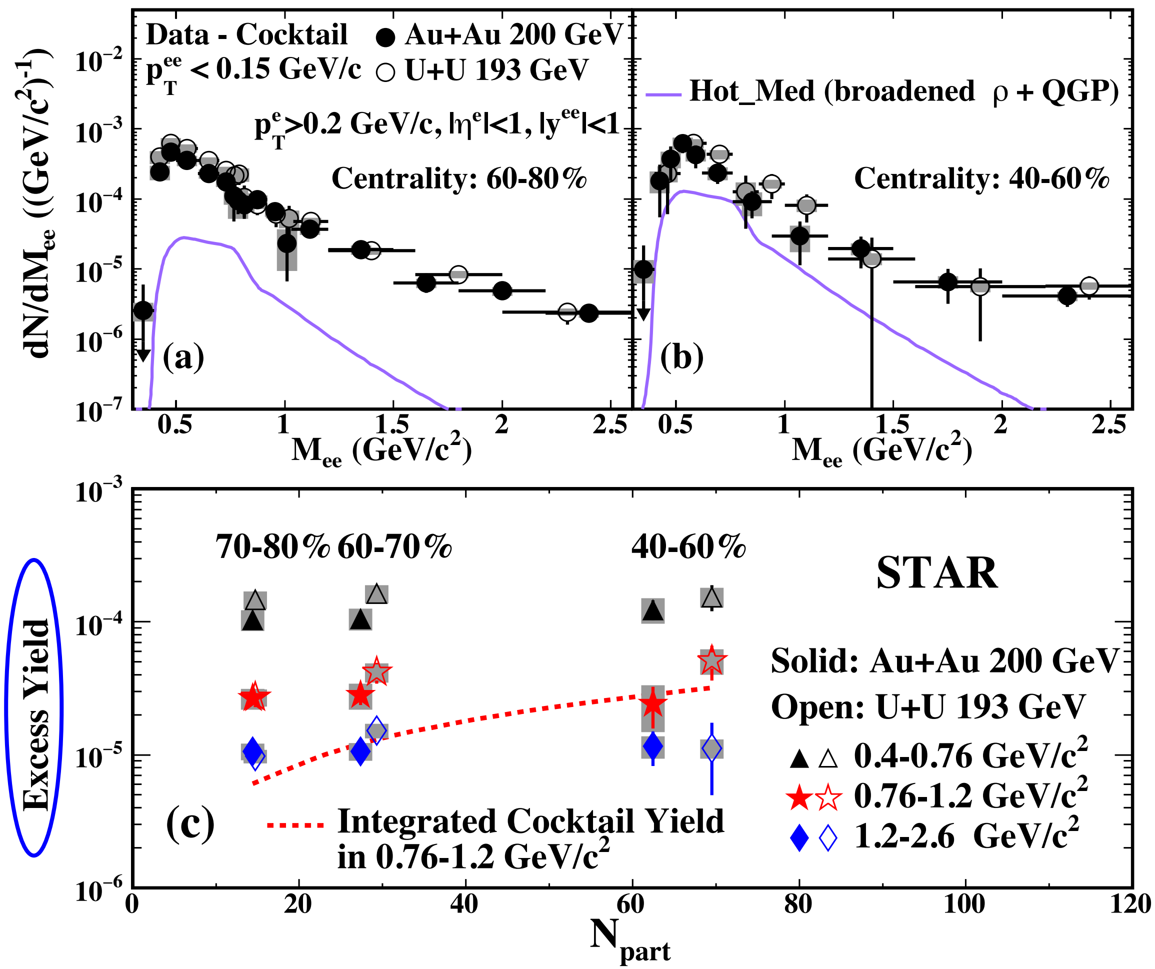


Two-photon interactions in UPCs

- Excess concentrate below $p_T \approx 0.15$ GeV/c
- Data are consistent with hadronic expectation when $p_T > 0.15$ GeV/c

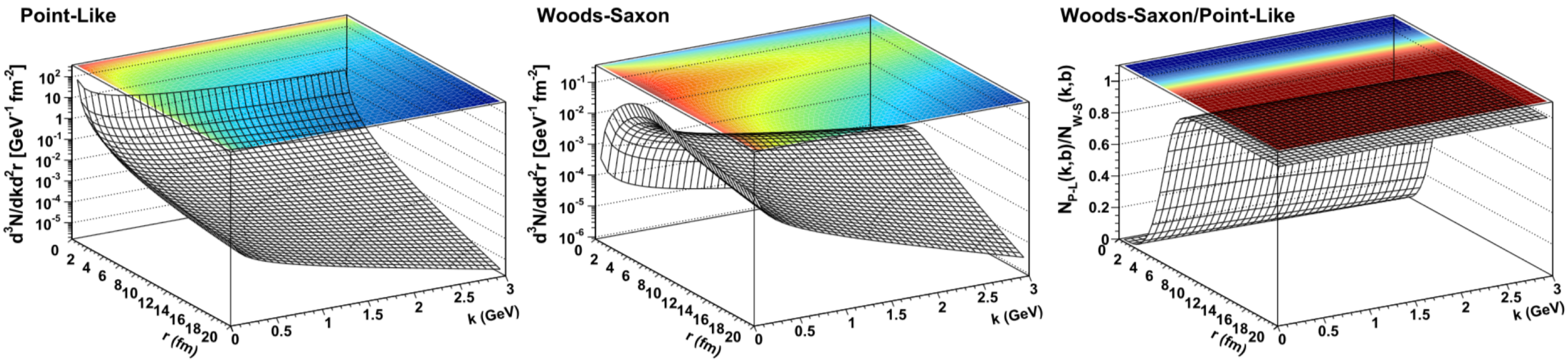
Excess spectra in $p_T < 0.15$ GeV/c

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



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

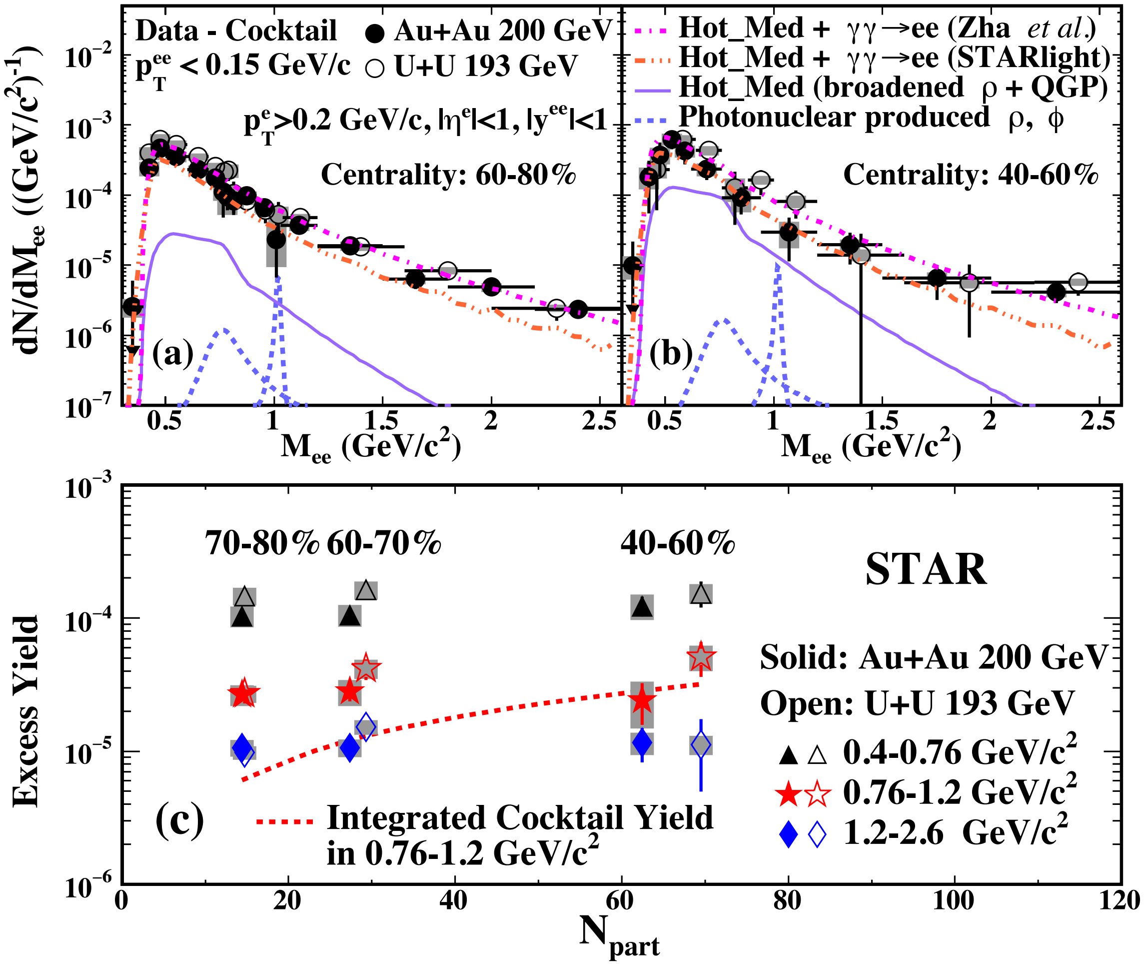
Few tips of photon interaction model calculations



- Equivalent Photon Approximation (EPA) method
  - Photon is treated as real
  - Weizsäcker–Williams method to estimate photon flux
- Model by *Zha et al.* *[W. M. Zha et al., PLB 781 (2018) 182]*
  - Considers the charge distribution in nucleus for photon flux estimation
  - Takes into account dilepton production within the geometrical radius of the nucleus
- STARlight *[S. R. Klein, PRC 97 (2018) 054903]*
  - Ignores dilepton production within the geometrical radius of the nucleus

Compared to photon interaction models

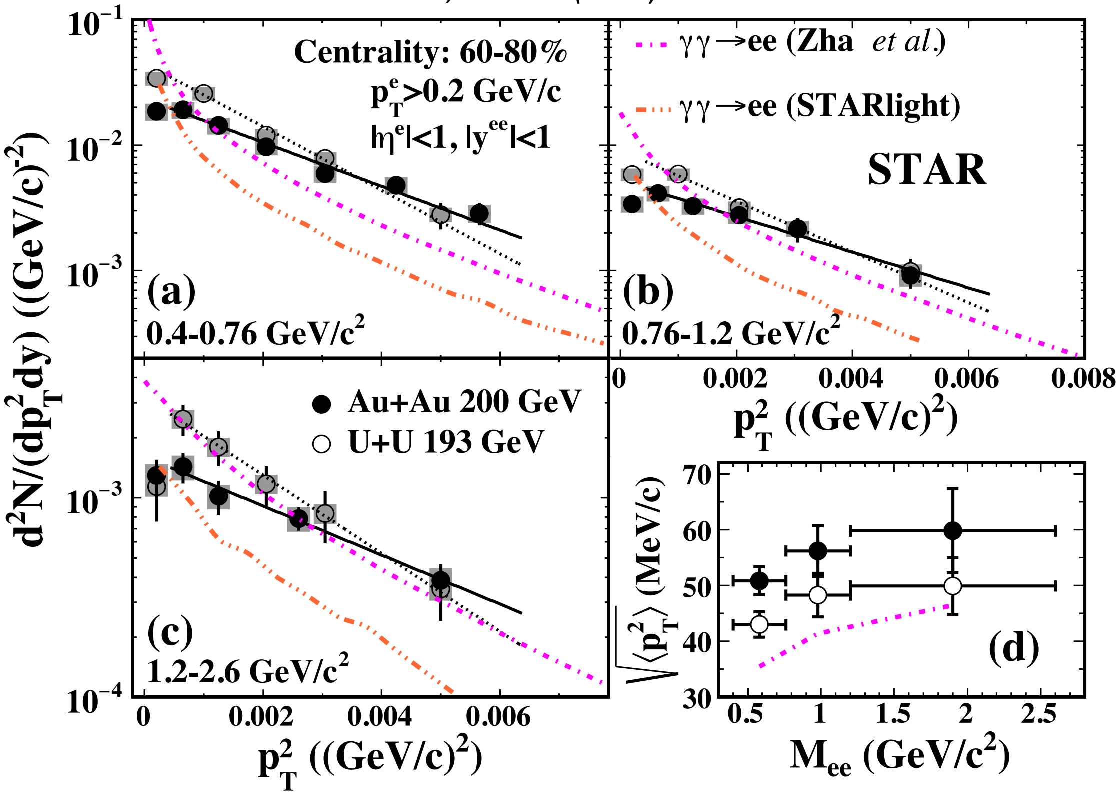
STAR, PRL 121 (2018) 132301
W. M. Zha et al., PLB 781 (2018) 182
S. R. Klein, PRC 97 (2018) 054903



- The observed excess can be qualitatively described by photon-photon interaction model calculations
  - Zha *et al.*: χ^2/NDF = 19/15 in 60-80% collisions
  - STARlight: χ^2/NDF = 32/15 (underestimate) in 60-80% collisions
- Photoproduced vector mesons' contributions can be negligible
- Enhancement in U+U collisions is larger than that in Au+Au collisions, which is in line with STARlight prediction

p_T^2 distributions in 60-80% collisions

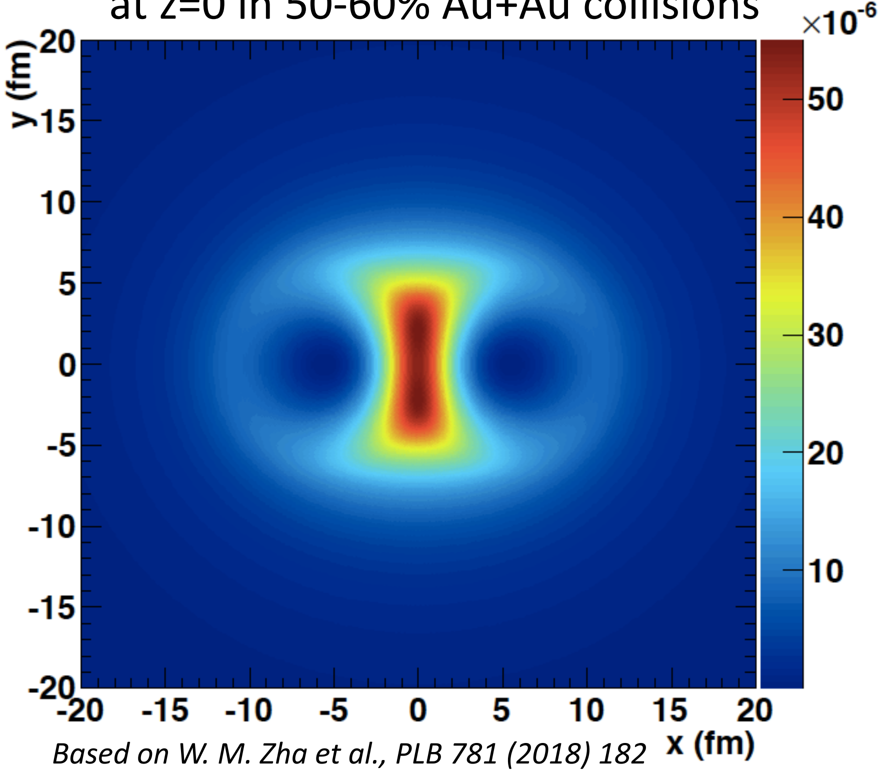
STAR, PRL 121 (2018) 132301



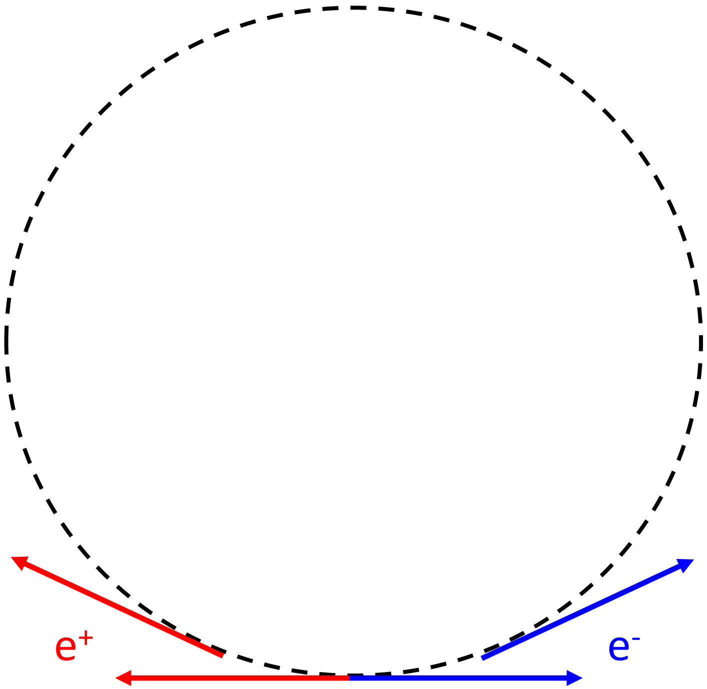
- Models fail to describe p_T^2 distributions
- Employ $\sqrt{< p_T^2 >}$ (characterizes p_T broadening) to quantify the discrepancy between data and models
- $\sqrt{< p_T^2 >}$ has invariant mass and collision species dependence
- $\sqrt{< p_T^2 >}$ from data are ~6.1σ, 3.3σ, and 1.8σ above models for three mass regions
  - Suggestive of possible other origins of p_T broadening, e.g. magnetic field trapped in QGP

Sensitivity to residual magnetic field

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



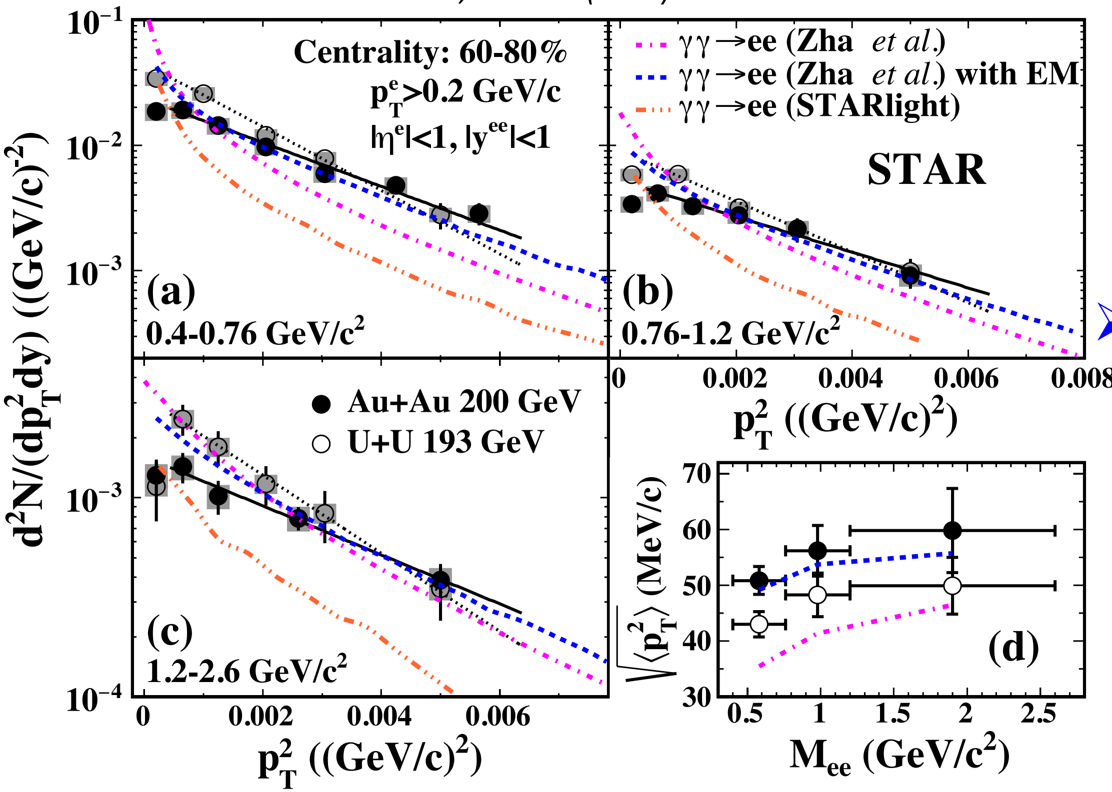
Based on W. M. Zha et al., PLB 781 (2018) 182



- 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

p_T^2 distributions in 60-80% collisions

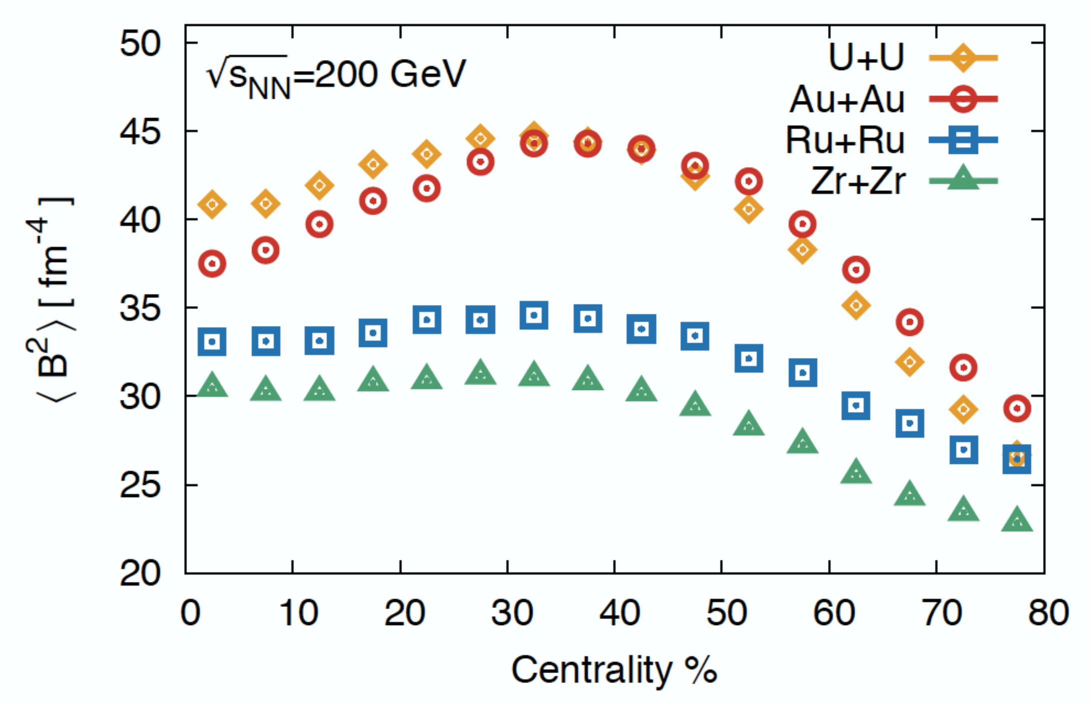
STAR, PRL 121 (2018) 132301



- Calculated p_T^2 spectra with EM effects can describe the data much better than the same model without incorporating EM effects.
  - The broaden level is measurable
  - May indicate the existence of strong magnetic field trapped in QGP
- Advantage of this measurement to probe possible residual magnetic field
  - e^+e^- pairs are produced in initial stage and only participate in electromagnectic interaction
  - Pair p_T peaks at 30-40 MeV/c, which is comparable to eBL (≈ 30 MeV/c)
  - The e^+e^- p_T^2 spectrum measurements in UPCs can serve as a baseline for the low-p_T enhancement study in hadronic heavy-ion collisions.

A plausible explanation for the collision species dependence of $\sqrt{< p_T^2 >}$

calculations are based on: S. Chatterjee and P. Tribedy, PRC 92, 011902 (2015)



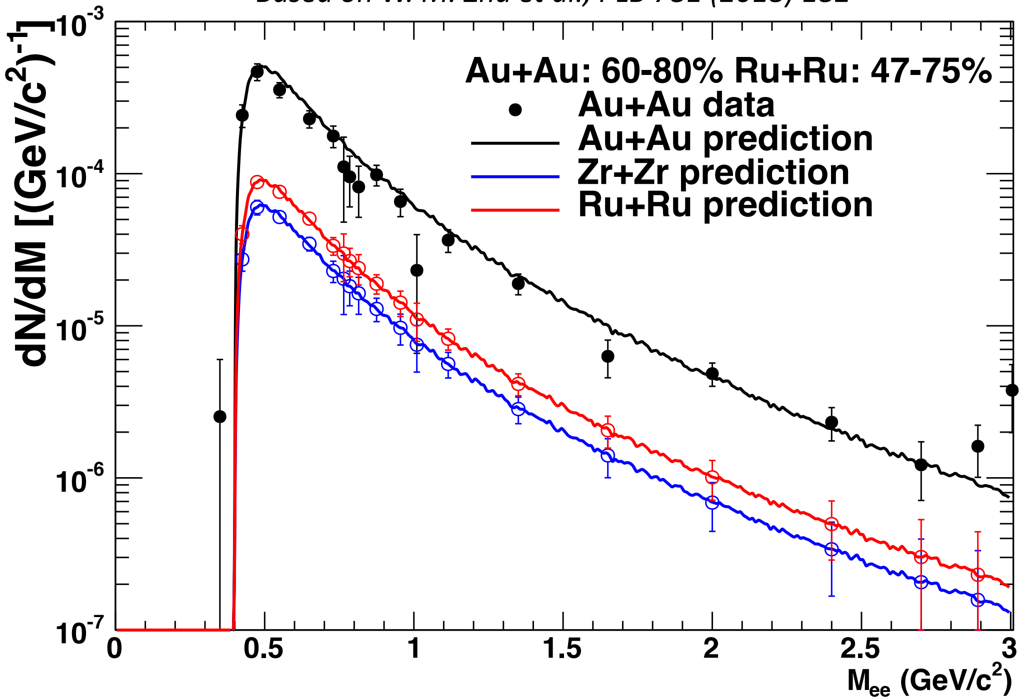
Initial magnetic fields (t=0) at the center of the participant zone

- Peripheral U+U has larger charge number but more spread-out compared to Au+Au
  - Lager cross section
  - Smaller $\sqrt{< p_T^2 >}$

Isobaric collisions in 2018

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

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



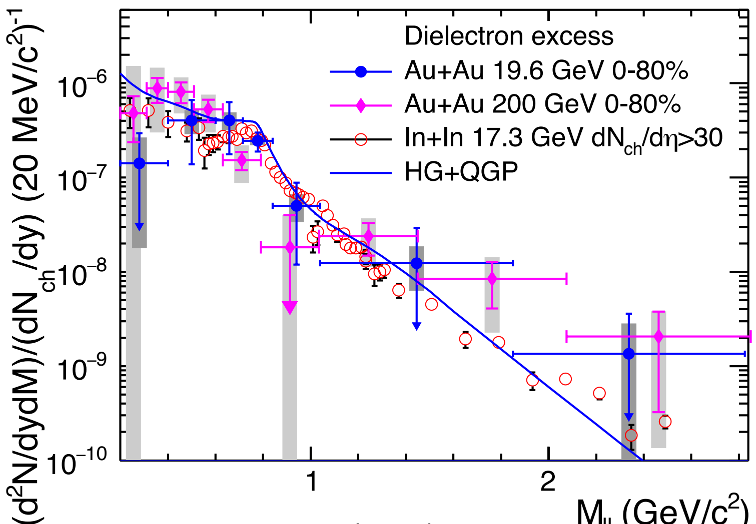
- 60-80% Au+Au vs. 47-75% Ru+Ru
  - Similar hadronic contribution
  - Different yields from two photon interactions
- Statistics
  - 60-80% Au+Au: ~180M
  - 47-75% Ru+Ru (Zr+Zr): ~840M
- Yield ratio in 0.4-0.76 GeV/c^2
  - Au : Ru : Zr ≈ 8.11 : 1.46 : 1
  - Difference between Ru+Ru and Zr+Zr: 3.7**σ**
  - Help to verify and constrain the possible trapped magnetic field

Summary

- A significant e^+e^- enhancement w.r.t. cocktail is observed at very low p_T
  - Entirely happens below $p_T \approx 0.15$ GeV/c
  - Can be qualitatively explained by photon-photon interaction mechanism
  - $\sqrt{< p_T^2 >}$ from data are larger than that from model calculations -> May indicate the existence of strong magnetic field trapped in QGP
  - The isobaric data could further constrain the photon interactions and the strong magnetic field in hadronic heavy-ion collisions

Backup

Excess spectra are corrected for the STAR acceptance



STAR, PLB 750 (2015) 64
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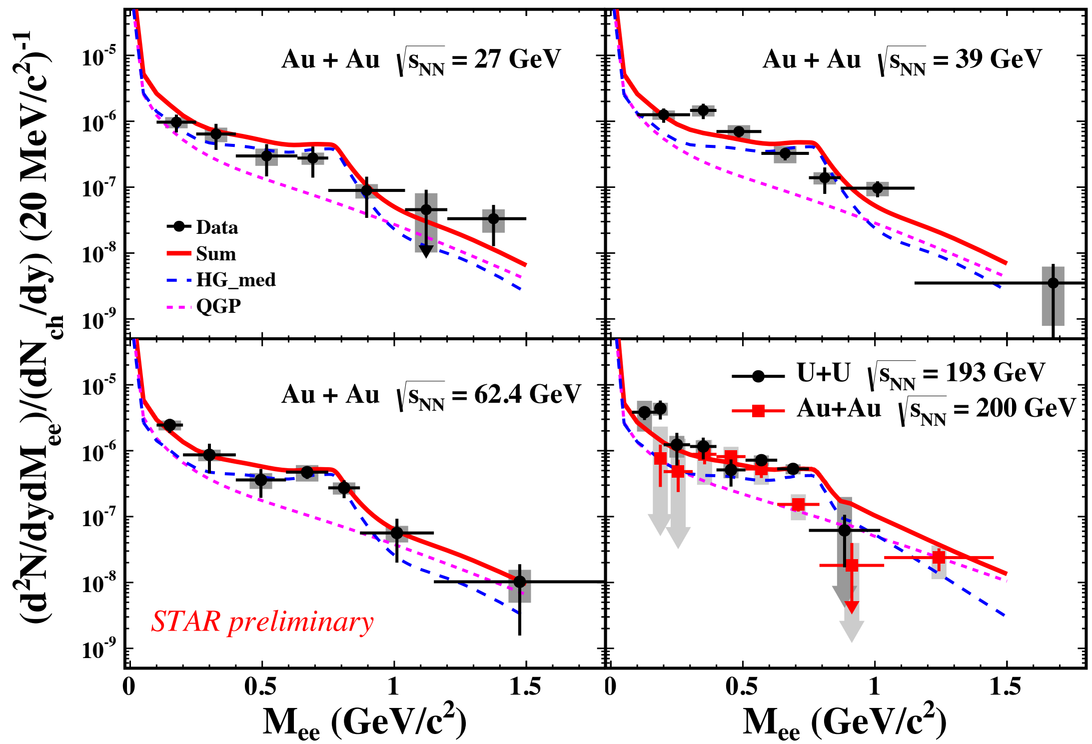
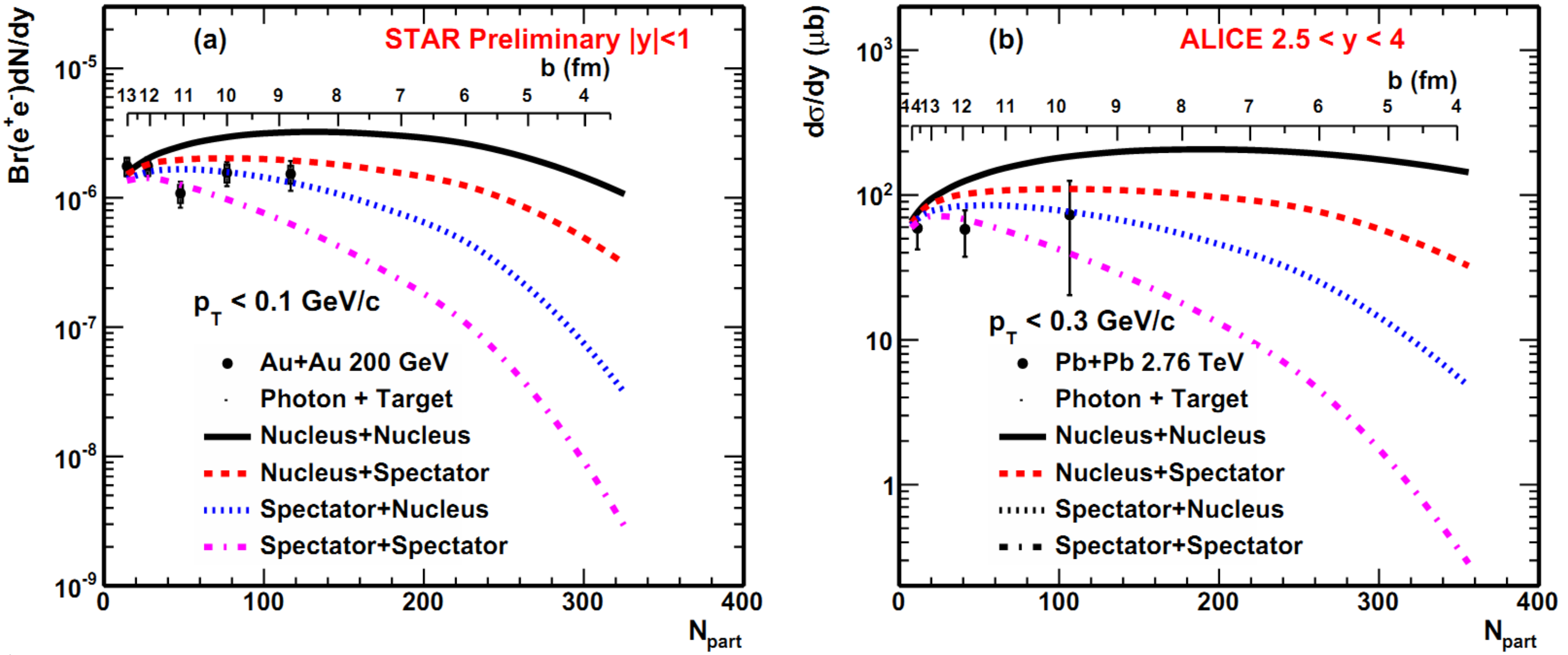
R. Rapp, PRC 63 (2001) 054907



- Different initial conditions by changing energy density (species + $\sqrt{s_{NN}}$)
- Acceptance-corrected excess mass spectra from SPS to top RHIC energies are well described by an in-medium broadened ρ model calculation

Anomalous low-p_T J/ψ enhancement in hadronic heavy-ion collisions

W. M. Zha et al., PRC 97 (2018) 044910
ALICE, PRL 116 (2016) 222301



- Qualitatively described by photon-nuclear interactions in peripheral collisions
  - N+N scenario overestimates while S+S scenario underestimates data in semi-central collisions.
  - Different scenarios predict different centrality dependence –> measurements in central collisions are important
  - N+S and S+N scenarios have weak centrality dependence in peripheral and semi-central collisions

Excess yield ratios of U+U over Au+Au

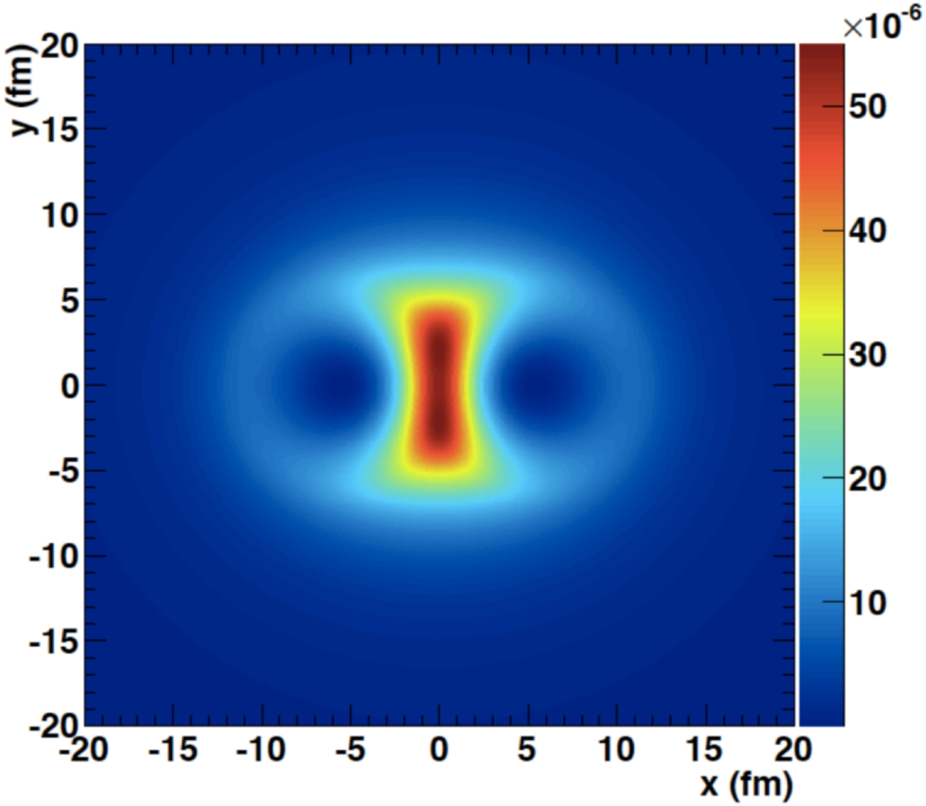
Table 1. The ratios of observed excess yields in U+U collisions over those in Au+Au collisions for three different mass regions in three different centrality bins. The error listed in this table includes statistical error only.

	70-80%	60-70%	40-60%
0.4-0.76 (GeV/c^2)	1.42 ± 0.13	1.54 ± 0.23	1.24 ± 0.35
0.76-1.2 (GeV/c^2)	1.02 ± 0.18	1.49 ± 0.35	2.12 ± 0.96
1.2-2.6 (GeV/c^2)	0.92 ± 0.20	1.43 ± 0.39	0.97 ± 0.61

- STARlight predicts that the excess yields from photon-photon interactions in U+U collisions are ~40% larger than those in Au+Au collisions

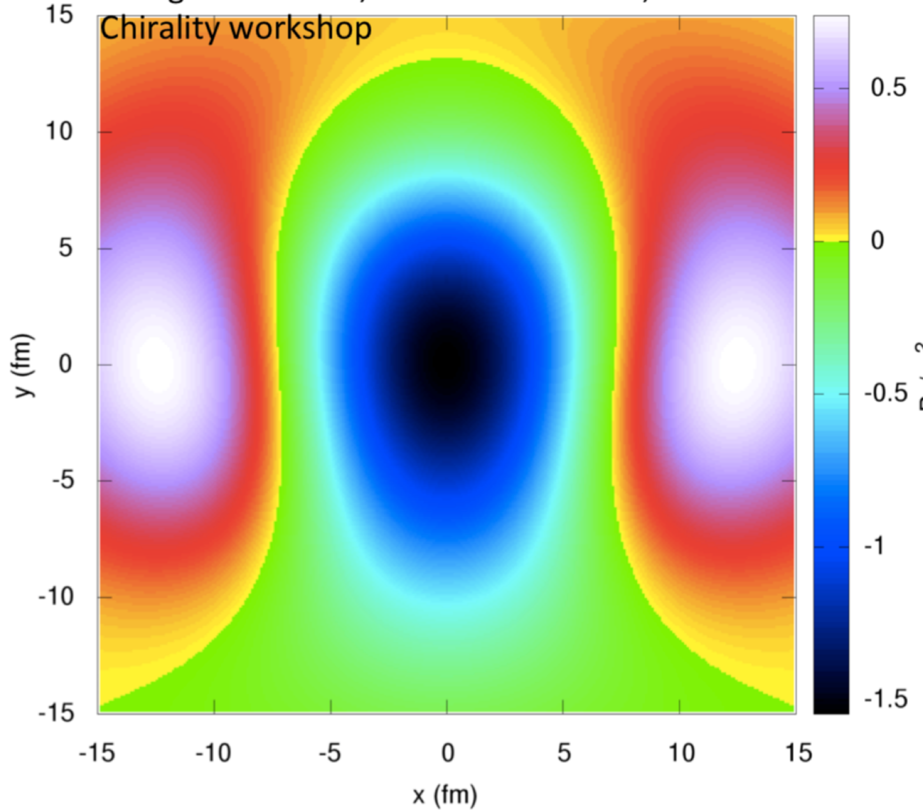
Spatial distribution of photon collisions

Example of e^+e^- pair spatial distribution, 50-60% Au+Au collisions



Conductivities of the medium
b=8fm, τ=0.4fm, σ= 5:8MeV, σ_χ= 1.5MeV

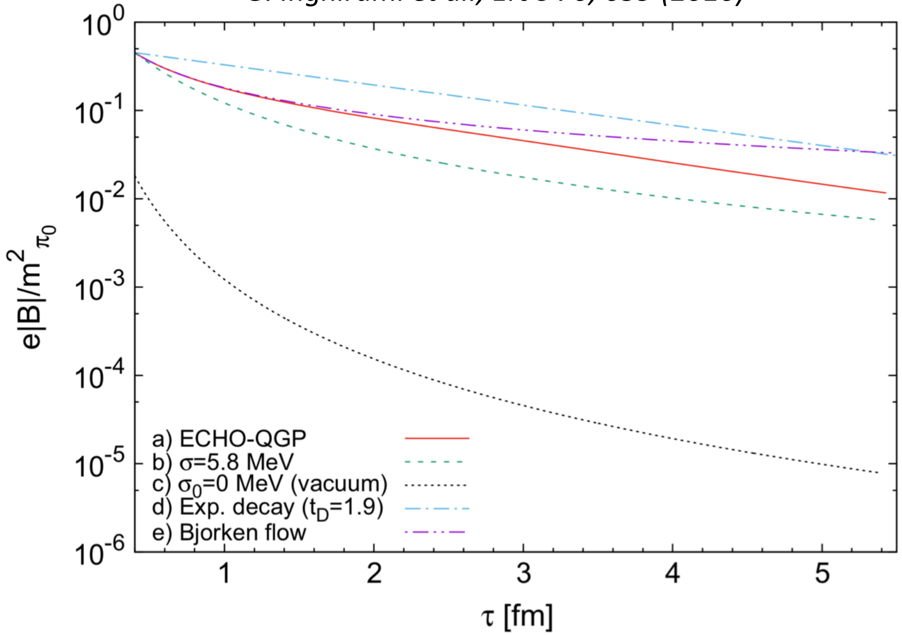
G. Inghirami et al., arXiv: 1609.03042, Chirality workshop



Z. Xu, BNL seminar (8/28/2018)

Strength of the magnetic field

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



M. Asakawa et al., PRC 81 (2010) 064912