Characterization of Extremely Strong Electromagnetic Field Produced in Heavy-Ion Collisions

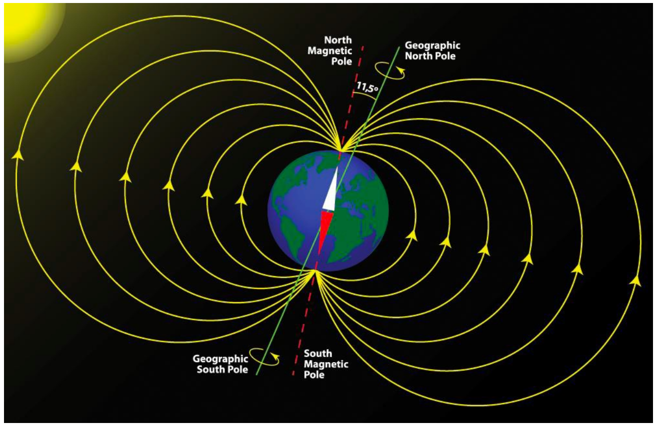
唐泽波

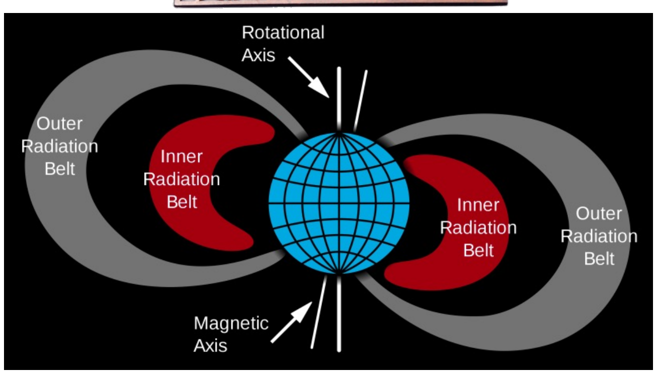
物理学院近代物理系,
核探测与核电子学国家重点实验室,
中国科学技术大学

合作者：查王妹，许长补，阮丽娟，杨帅，J. Brandenburg
杨驰，刘圳，周健，李子阳，沈凯峰等

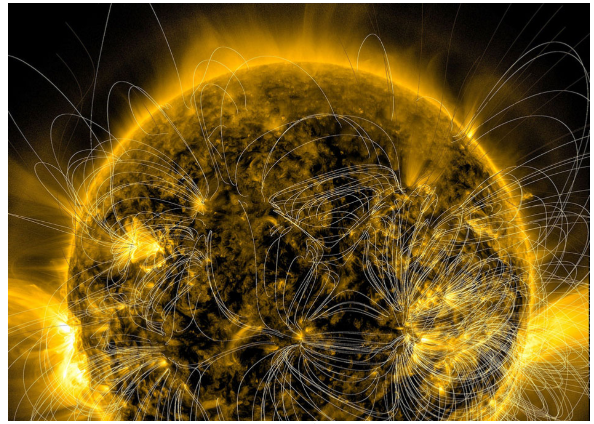
Magnetic Field in Nature

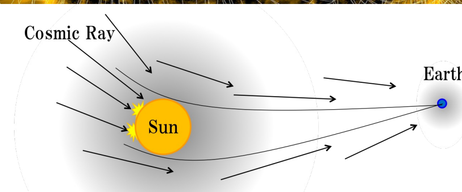
Earth, $O(10^{-5}$ T)



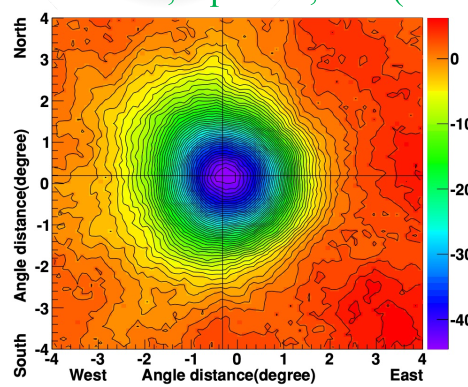


Sun, $O(10^{-4}$ T)

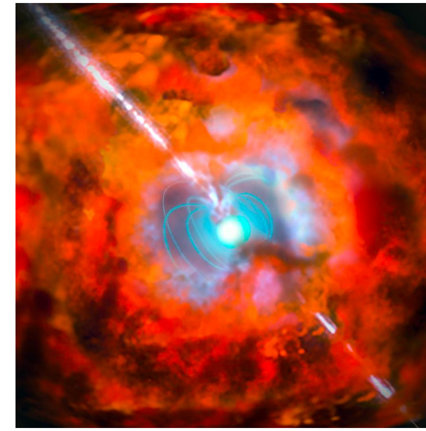




ARGO-YBJ, ApJ 729, 113 (2011)

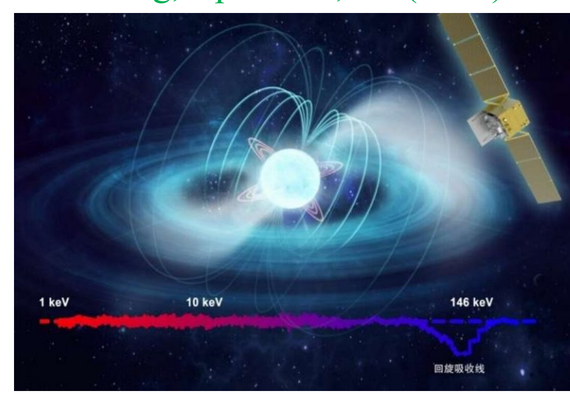


Magnetar, $O(10^{9-11}$ T)

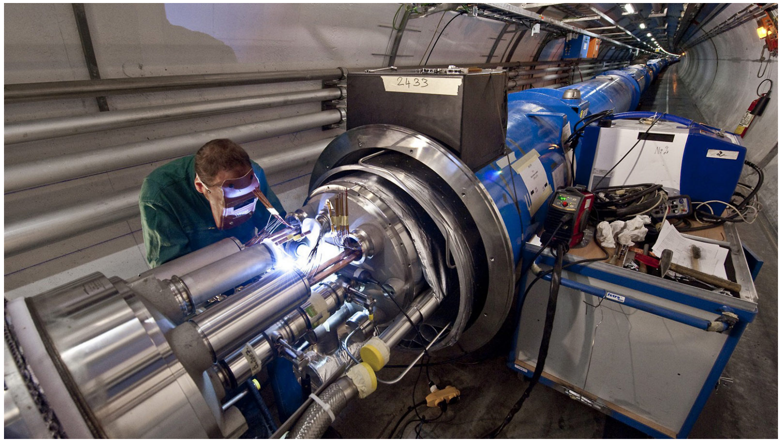


Record!!

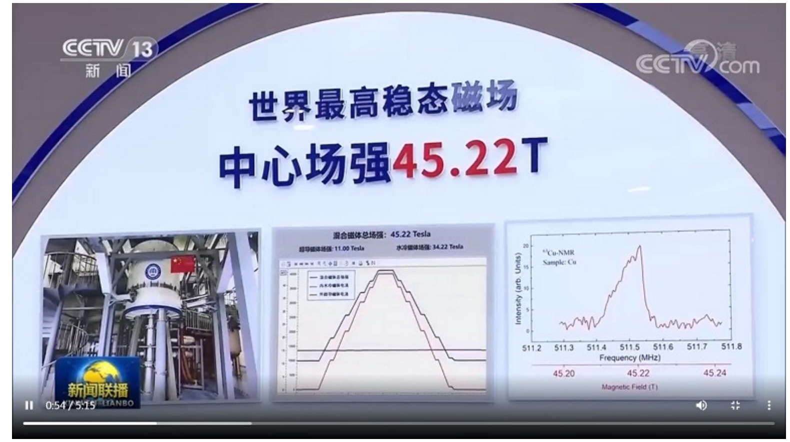
L. Kong, ApJL 933, L3 (2022)



Man-made Strong Magnetic Field



LHC dipole, 8.36 T



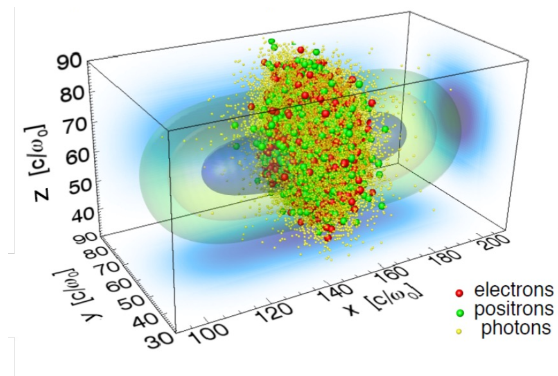
Steady High Magnetic Field Facility

Pulsed Magnet

100 T, 15 ms

Pulsed Magnet

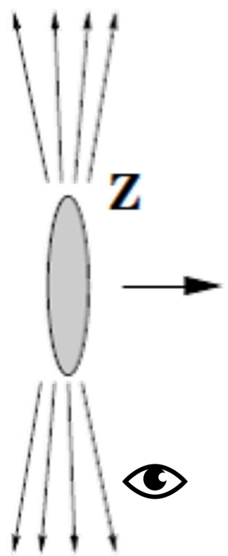
1200 T, 0.1 ms



High Power Laser

O(10^{10} T), O(10 fs)

EM Filed of Fast Moving Charge

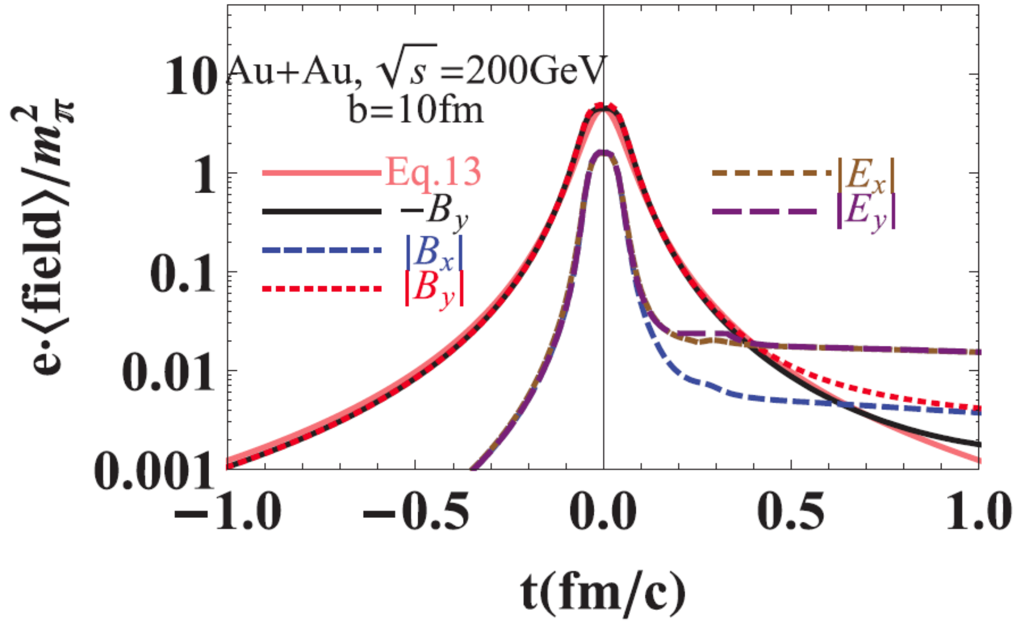


- Fast moving charge generates strong EM filed, especially for heavy ions

$$B \sim \frac{1}{4\pi}\frac{\gamma Z e\beta r}{[\gamma^2(z-\beta t)^2+r^2]^{3/2}} \sim O(10^{14-16}\,T)$$

in lab. frame

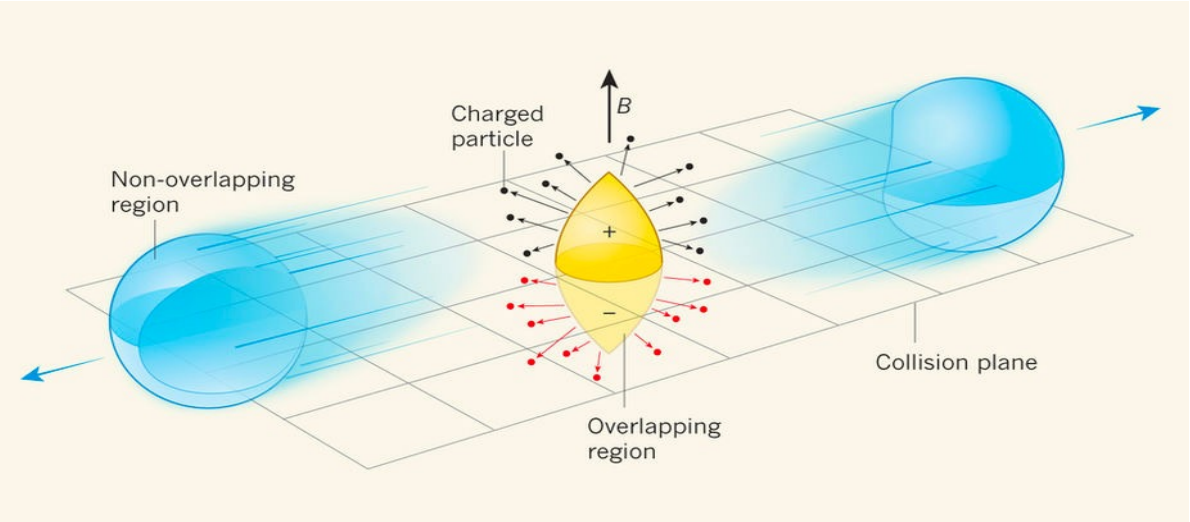
- Strong in a limited space
  O(10) fm
- Decay very fast with time
  O(R/γ) fm/c



How to probe it? Getting close!

W. Deng, X. Huang, PRC85, 044902 (2012)

Relativistic Heavy Ion Collisions



When two heavy ion collides, the strong fields are close enough

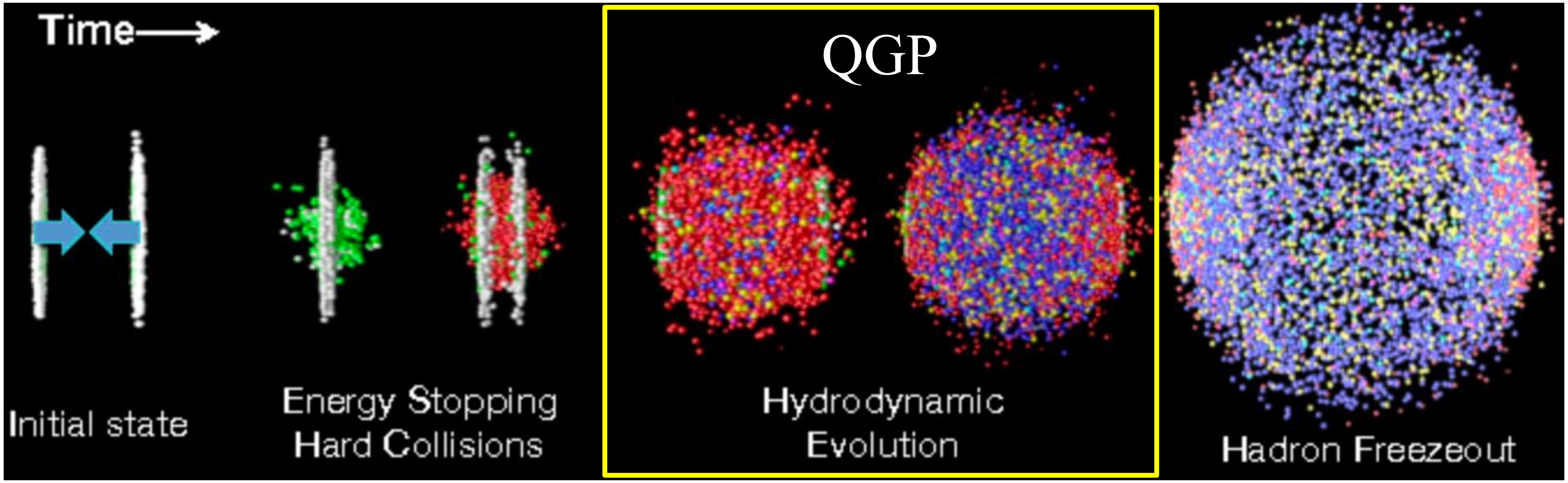
b>2R: Ultra-peripheral collisions (UPC)

EM interactions only, clean

b<2R: Heavy ion collisions with nuclear overlaps

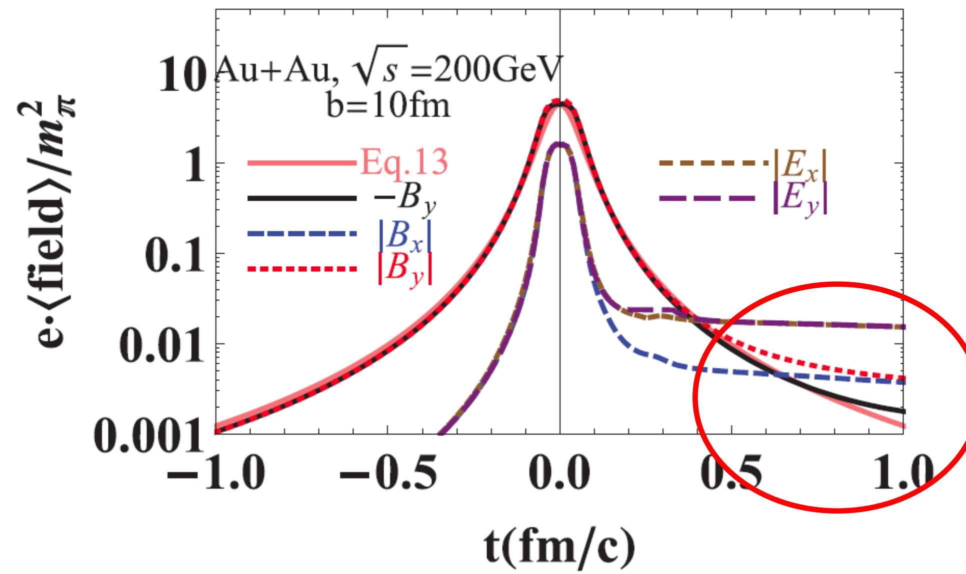
EM and hadronic interactions (EM + quark gluon plasma?)

Evolution of Heavy Ion Collisions

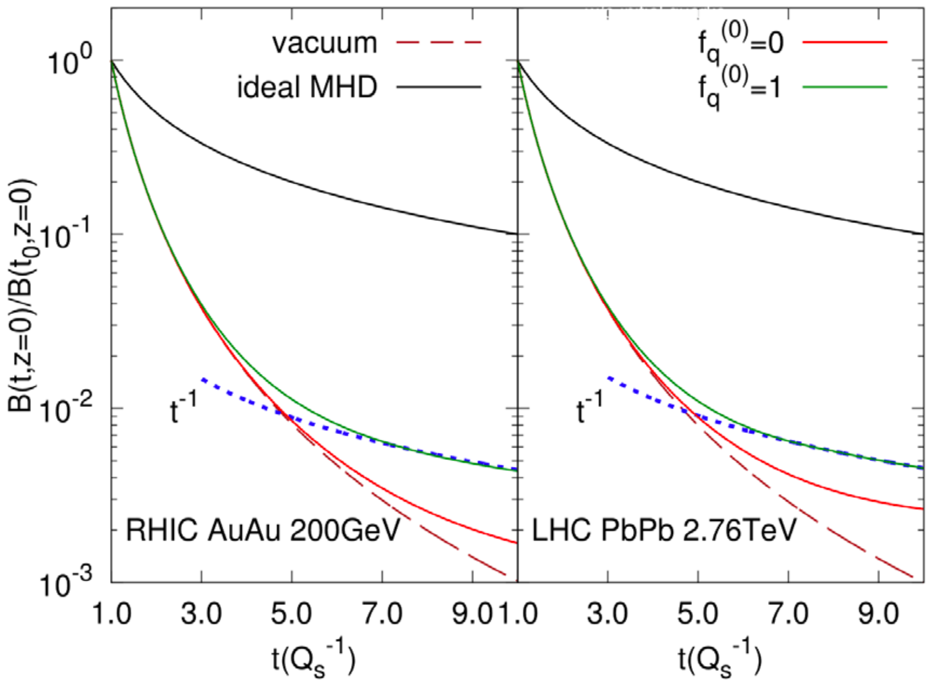


Relativistic heavy ion collision experiences a pre-equilibrium stage before forming QGP ~1 fm/c

The EM filed decreases by many orders of magnitude when the QGP is formed



EM Induction in QGP



L. Yan, X. Huang, arXiv:2104.00831

FIG. 1 Evolution of magnetic field at z = 0 for the AuAu collisions at RHIC (left) and PbPb collisions at the LHC (right), relative to its initial strength at $t=t_0$. In comparison to the decay of magnetic field in vacuum (brown dashed lines), effects due to the QGP medium with initial quarks (red solid lines) and without initial quarks (green solid lines) are obvious. The expected t^{-1} decay from ideal magnetohadrodynamics (MHD) is plotted as the black solid lines and blue dotted lines.

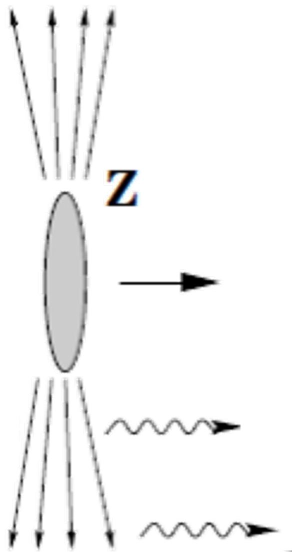
If QPG is conduct, it may slow down the decay of the EM field via EM induction (Faraday effect)

QGP with Strong EM Field

- Chiral magnetic effect
  - Deconfinement + chiral symmetry + B field
- Chiral separation effect, chiral magnetic wave, chiral electric separation effect
- The QCD phase diagram in strong magnetic fields
  - EPJA topical collection (24 articles)
- Transition of bound states in strong magnetic fields
- EM-induced directed flow
- Hall effect
- …

See Xu-guang Huang's TDLI/INPAC seminar

How to Probe the Strong EM Field?



- The Lorentz contracted EM field can be expressed in terms of equivalent photon flux *E. Fermi, Z. Phys. 29, 315 (1924)*

$$E \perp B \perp z, E = B$$

C. Weizsacker, ZP88, 612 (1934)
E. Williams, PR45, 729 (1934)

Photon energy: Fourier transform

$$\omega \le \omega_{max} \sim \gamma/R$$

$$\omega_{max} \sim 3\ GeV\ \text{@RHIC}$$

$$\sim 80\ GeV\ \text{@LHC}$$

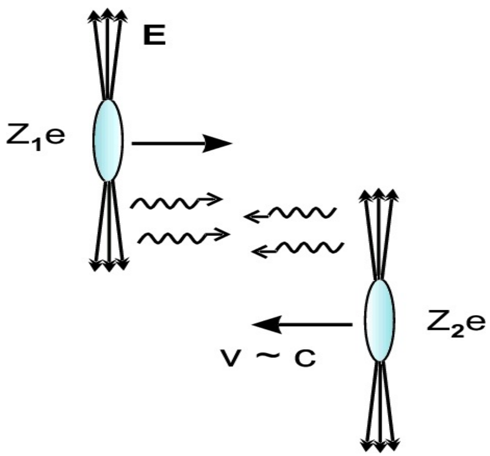
Photon flux: Poynting vector

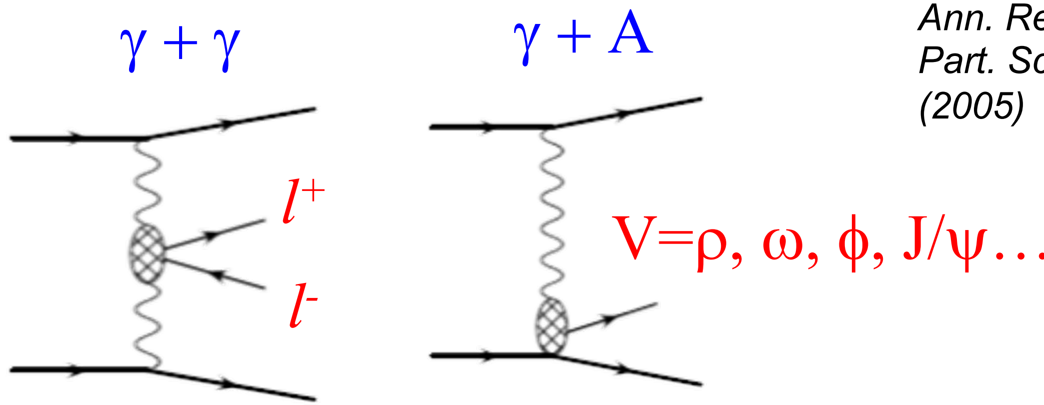
$$n \propto Z^2$$

The qusi-real photons carry the information of the EM field

Hadron collider + photon collider

Photon Interactions in HIC



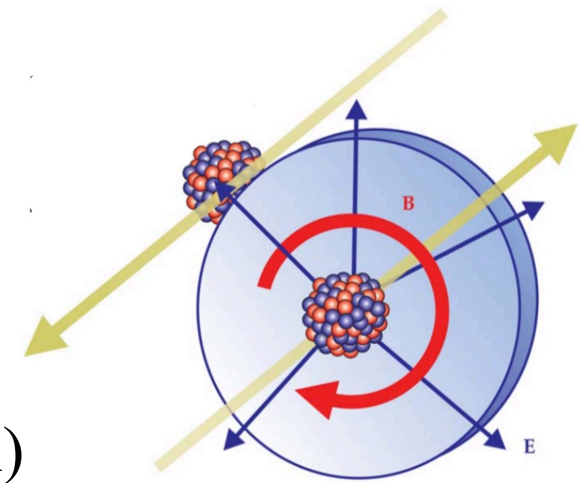


Ann. Rev. Nucl. Part. Sci. ***55***:*271 (2005)*

Breit-Wheeler process

Traditionally studied in UPC

- The radius of nuclear matter $R_A << R_\gamma$
- $<R_\rho>$ ~ 40 *fm* in Au+Au @ 200 GeV

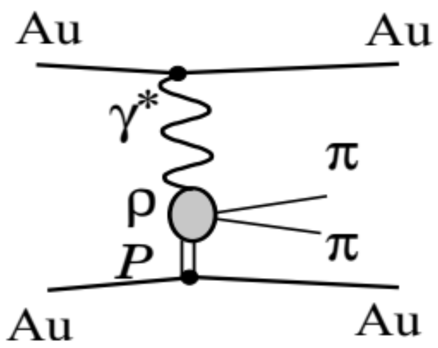


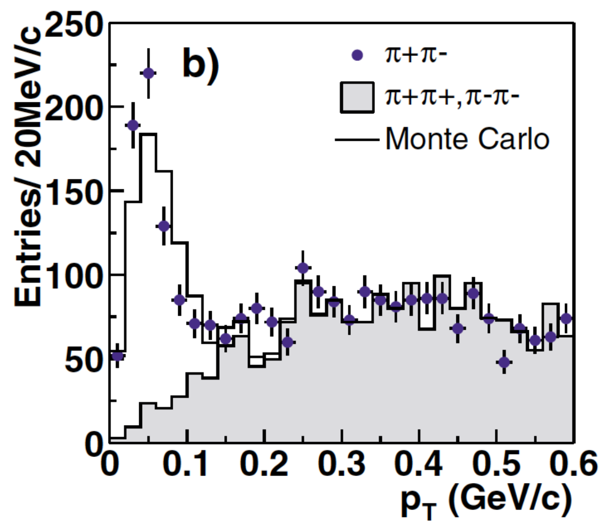
Physics Today 70, 10, 40 (2017)

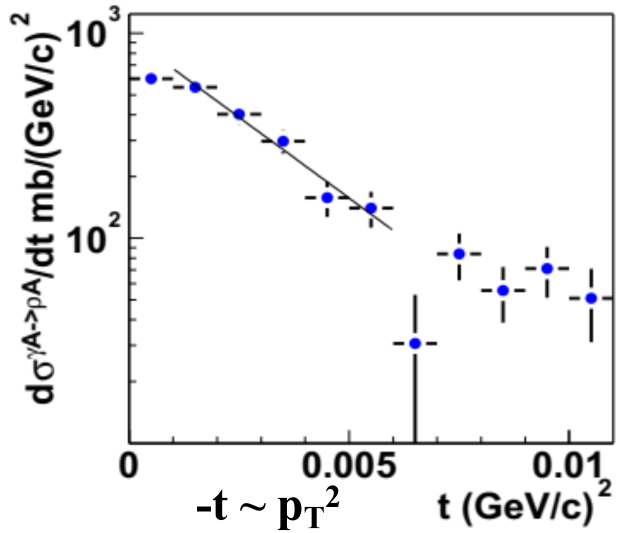
Theoretical description

- Equivalent Photon Approximation (EPA)
  - Point-like charge distribution
  - Cares only the field outside of the nuclei

Vector Meson Photoproduction



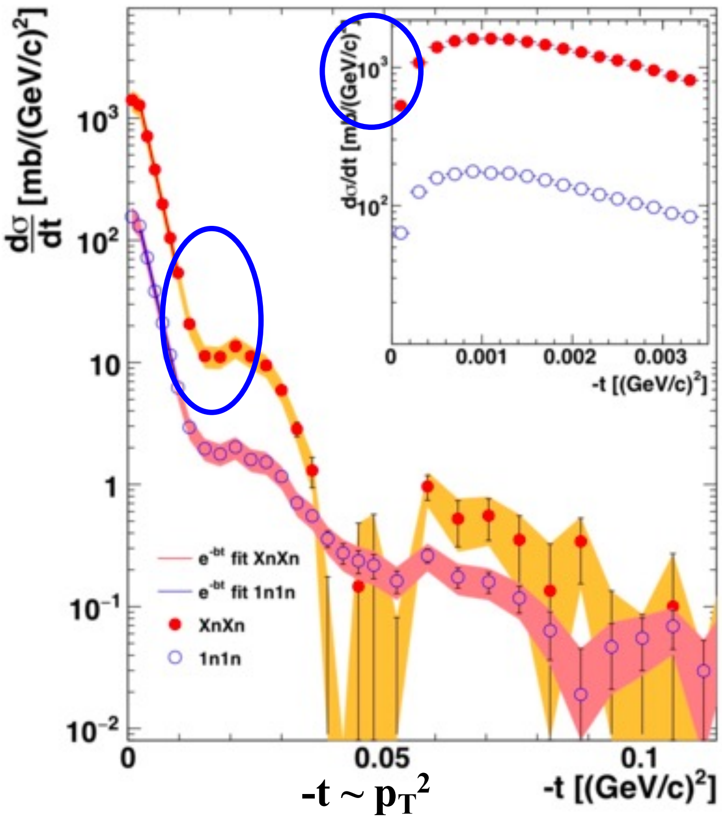




STAR, PRL89, 272302 (2002)

- Colorless "Pomeron" exchange
- Dominantly produced at very-low p_T (p_T<~ 0.1 GeV/c)
- *t* slope reflects nucleus form factor (radius)

Vector Meson Photoproduction



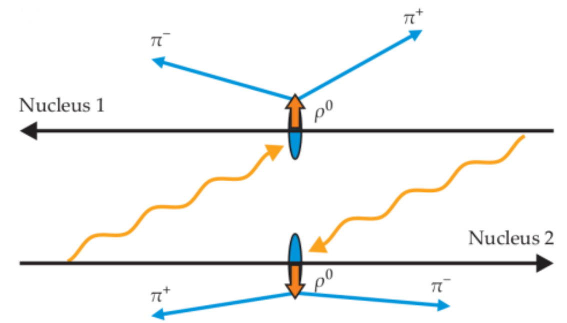
-t ~ p_T^2

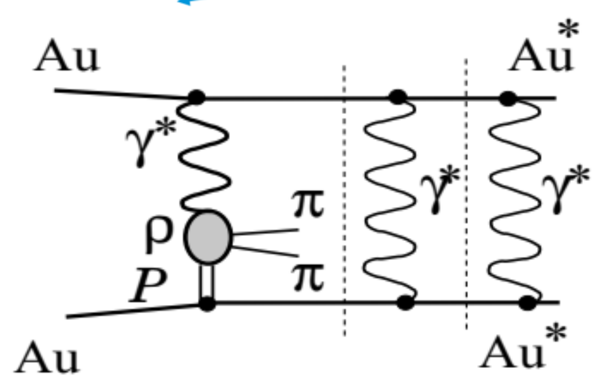
STAR, PRC96, 054904 (2017)

t distribution tells more

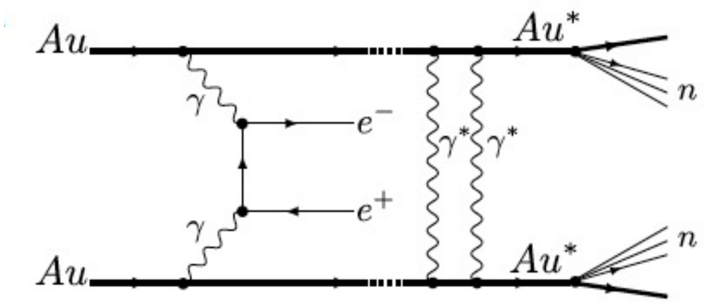
- Diffraction
- Destructive interference

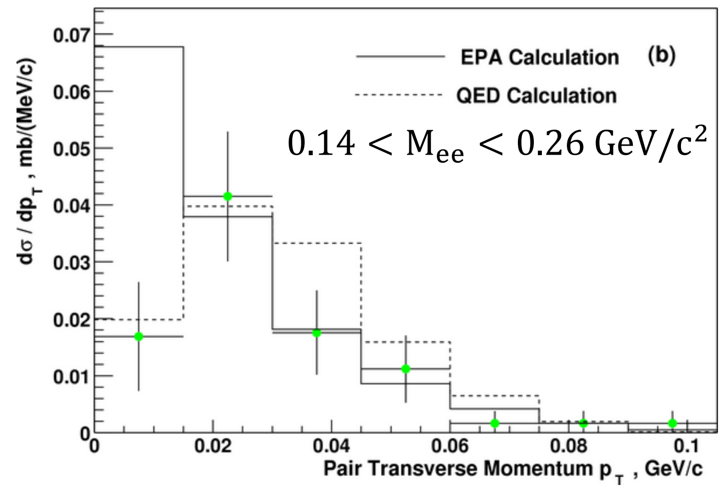
Double-slit experiment at Fermi scale





Photon-photon Interaction in UPC

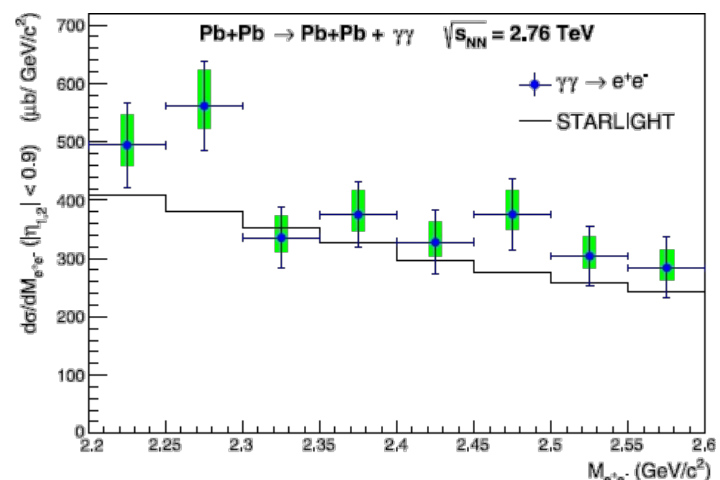




STAR, PRC70, 031902 (2004)

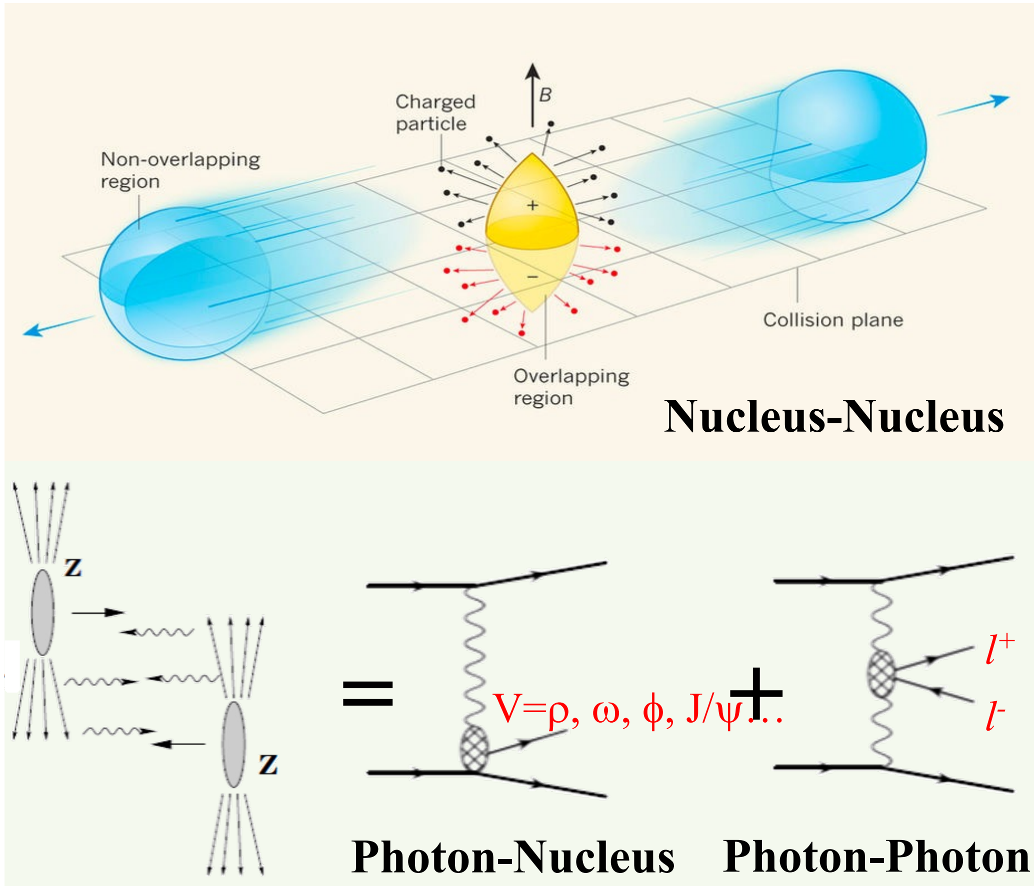
- Very low-p_T dilepton pairs observed in UPC

- Consistent with QED calculations



ALICE, EPJC73, 2617 (2013)

Photoproduction in HIC w/ Nucl. Overlap



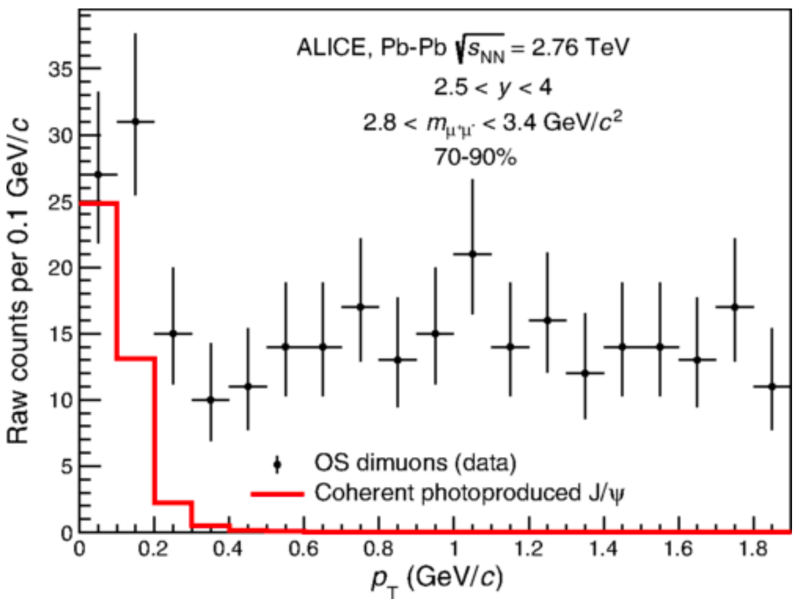
- Probe EM field at much smaller distance
  - Spatial distribution of the field
  - Charge and gluon distribution of nuclei
- QGP could be produced

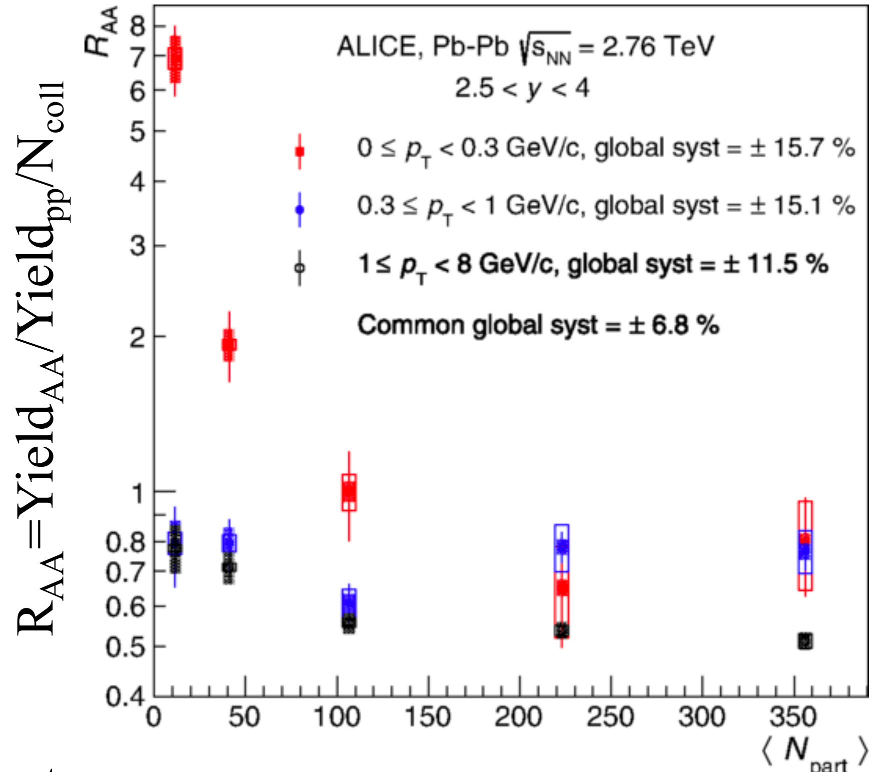
  Novel probes of QGP
  - Produced early
  - Almost at rest in QGP
  - Clear signature
    - Distinct peak at low p_T

Can it happen?

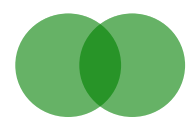
Very-low-p_T J/ψ Enhancement at ALICE

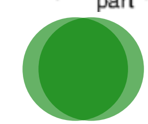
ALICE, PRL116, 222301 (2016)





ALICE observed strong enhancement of J/ψ at very low-p_T in peri. collisions

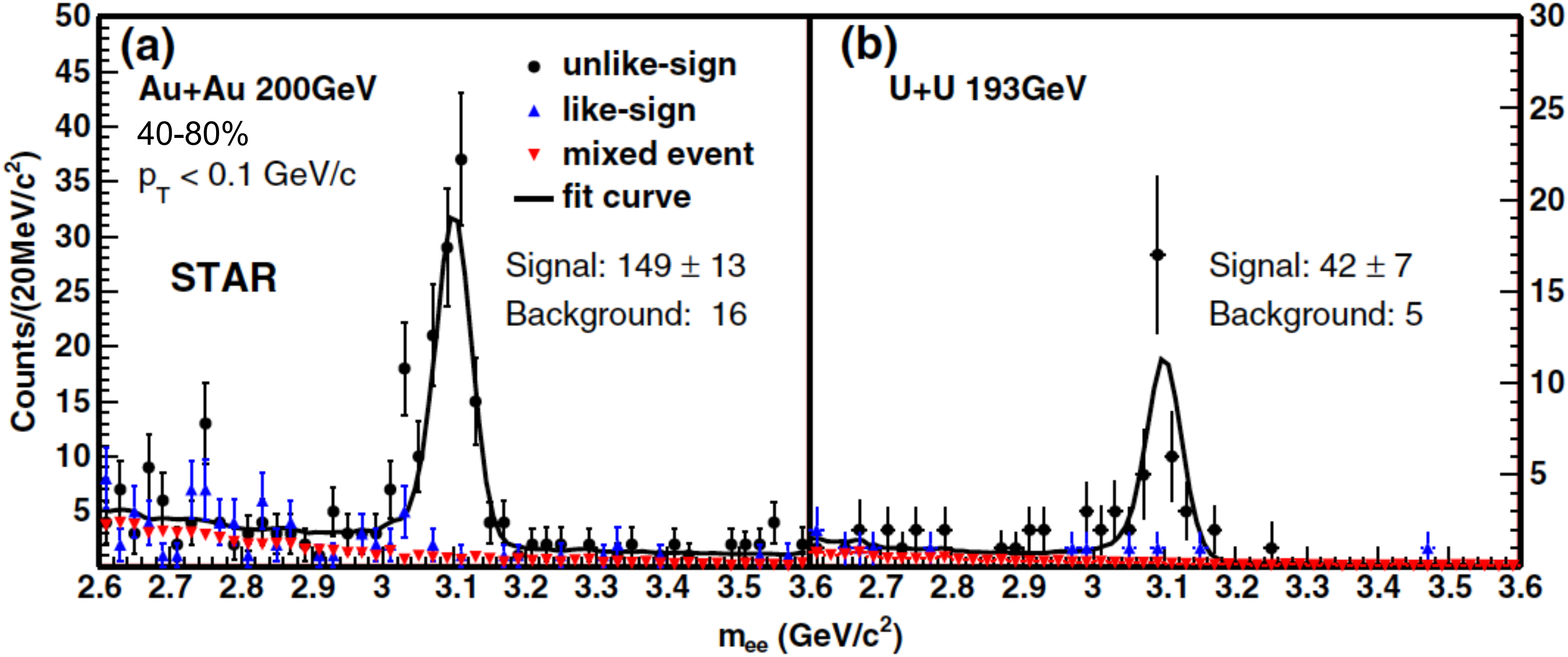




Originate from coherent photoproduction in non-UPC?

Very-low-p_T J/ψ Signal at STAR

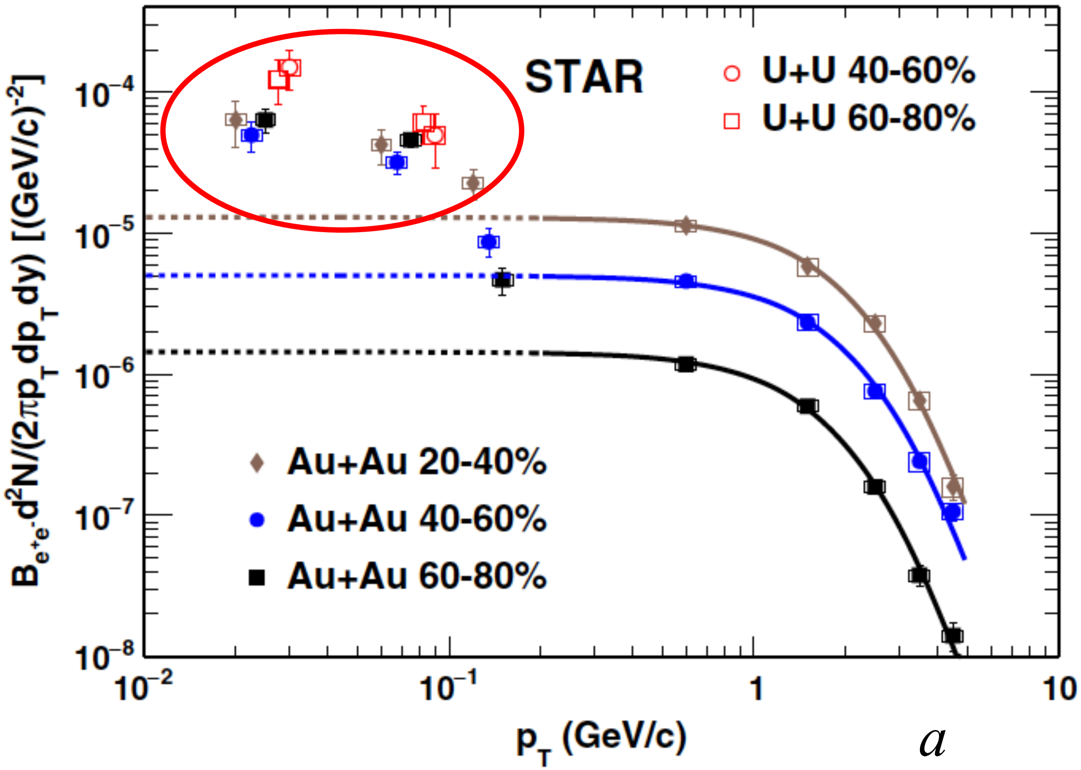
STAR, PRL123, 132302 (2019)



Clear J/ψ signal at p_T<0.1 GeV/c in (semi-)peripheral Au+Au and U+U collisions at STAR

Very-low-p_T J/ψ Enhancement at STAR

STAR, PRL123, 132302 (2019)

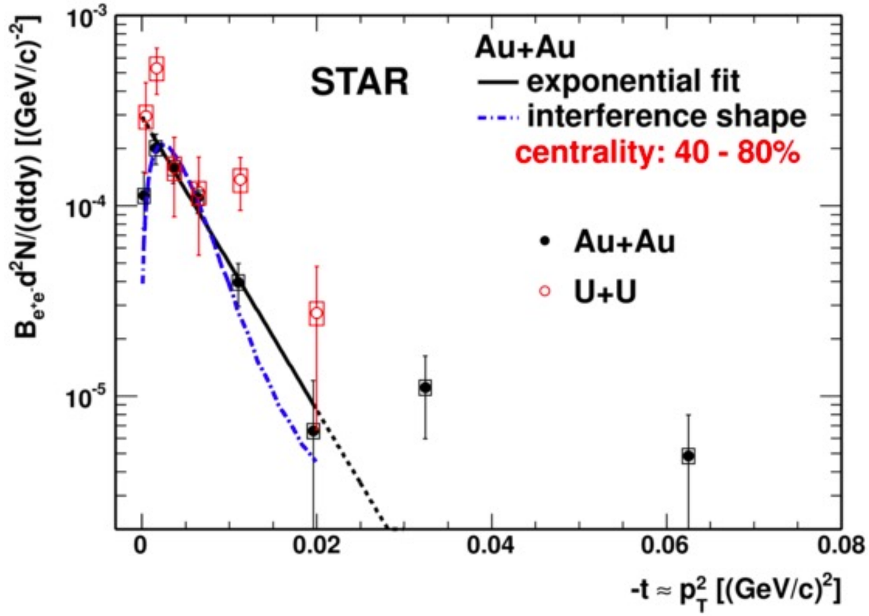


Fit function (empirical): $$\frac{a}{\left(1+b^2 p_T^2\right)^n}$$

Significant enhancement of J/ψ yield at low p_T in both Au+Au and U+U collisions

Momentum Transfer Squared Distribution

STAR, PRL123, 132302 (2019)



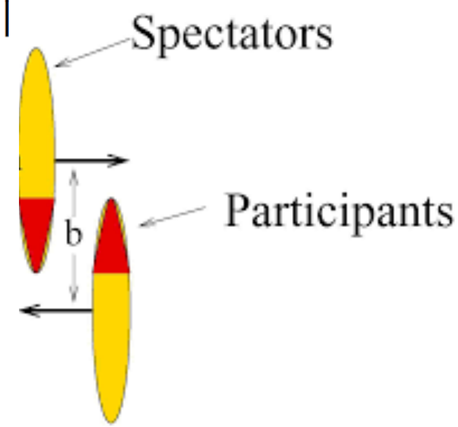
- First *-t* distribution of J/ψ production at low p_T in non-UPC
- Slope = 177 ± 22 $(GeV/c)^{-2}$ consistent with expected from coherent photoproduction for an Au nucleus (199 $(GeV/c)^{-2}$)
- The drop at the lowest bin may be an indication of interference $\chi^2/ndf = 4.8/4$

Modeling Coh. J/ψ Photo-prod. in Non-UPC

$$\sigma(AA \rightarrow AAJ/\psi) = \int d\omega_\gamma \frac{dN_\gamma(\omega_\gamma)}{d\omega_\gamma} \sigma(\gamma A \rightarrow J/\psi A)$$

Photon flux:

$$\frac{d^3N_\gamma(\omega_\gamma, \vec{x}_\perp)}{d\omega_\gamma d\vec{x}_\perp} = \frac{4Z^2\alpha}{\omega_\gamma} \left| \int \frac{d^2\vec{k}_{\gamma\perp}}{(2\pi)^2} \vec{k}_{\gamma\perp} \frac{F_\gamma(\vec{k}_\gamma)}{|\vec{k}_\gamma|^2} e^{i\vec{x}_\perp \cdot \vec{k}_{\gamma\perp}} \right|^2$$



EM form factor ← Woods-Saxon distribution

From entire nucleus or spectator?

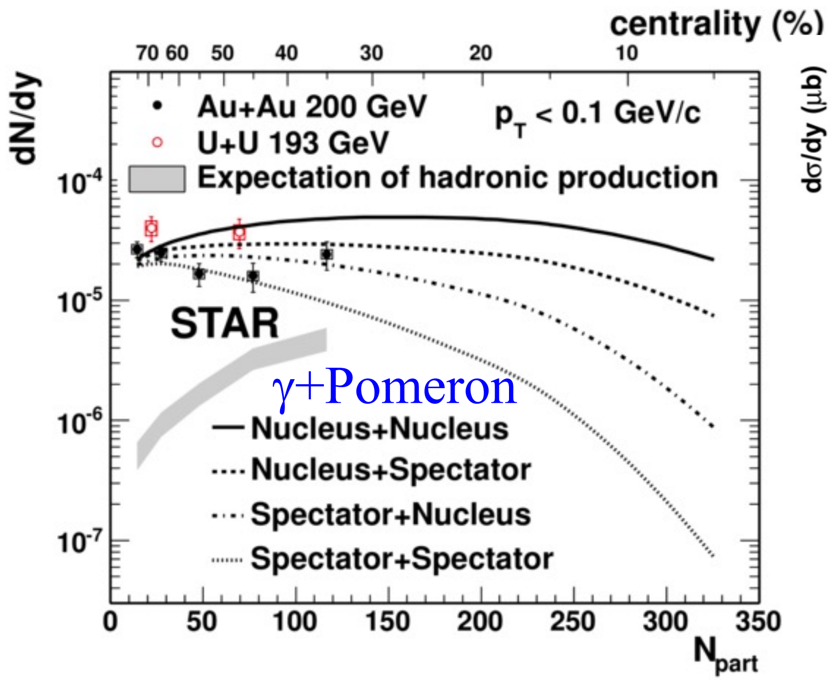
Photon-nucleus scattering:

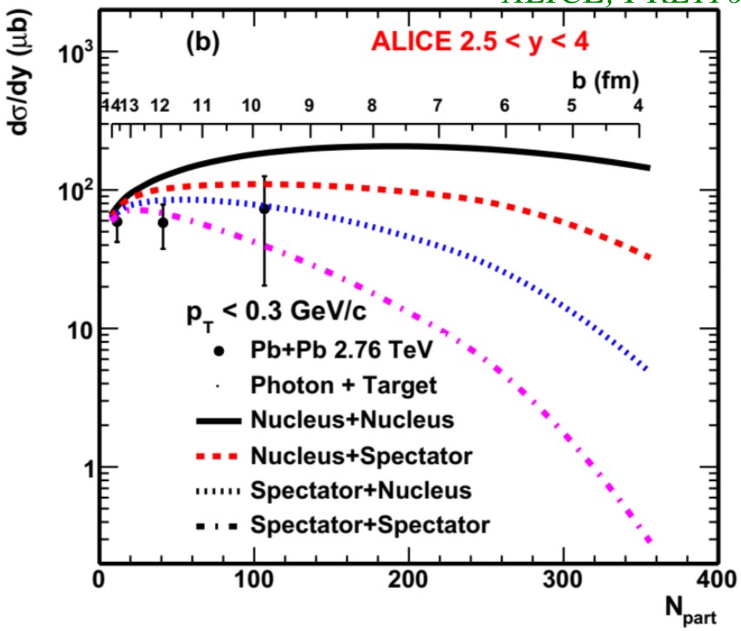
$$\sigma(\gamma A \rightarrow J/\psi A) = \left. \frac{d\sigma(\gamma A \rightarrow J/\psi A)}{dt} \right|_{t=0} \times \int |F_P(\vec{k}_P)|^2 d^2\vec{k}_{P\perp}$$

Form factor for Pomeron ← Nuclear density distribution

From entire nucleus or spectator?

Data vs. Model





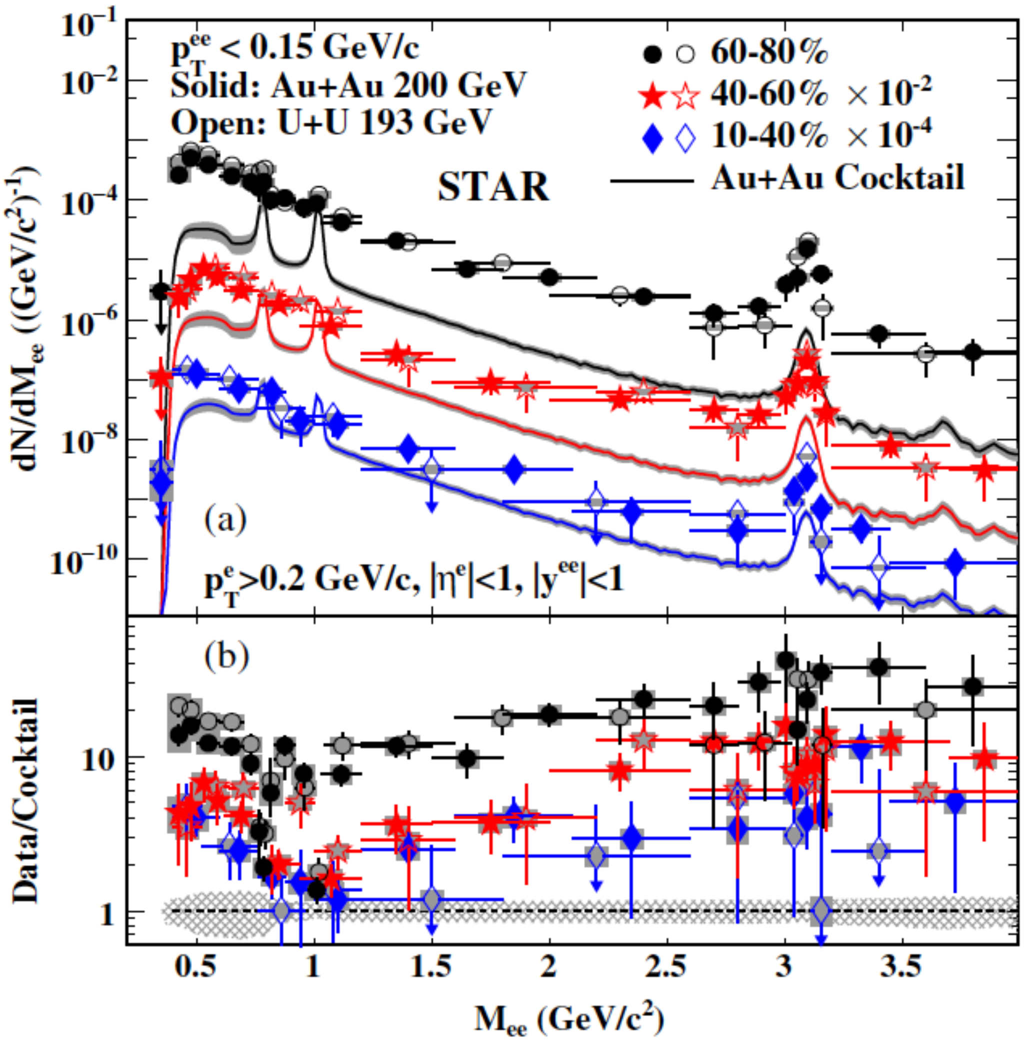
STAR, PRL123, 132302 (2019)
ALICE, PRL116, 222301 (2016)

W. Zha, L. Ruan, ZBT*, Z. Xu, S. Yang, PRC99, 061901(R) (2019)*
W. Zha, …, ZBT, …, PRC97, 044910 (2018)*

- No significant centrality dependence for very-low-p_T J/ψ yield
- Model calculations with all scenarios describe data at *b~2R*
- "Nucleus+Spectator" and "Spectator+Nucleus" seem favored
- Pushing to central collisions is experimentally very challenging

Very-low-p_T ee Enhancement at STAR

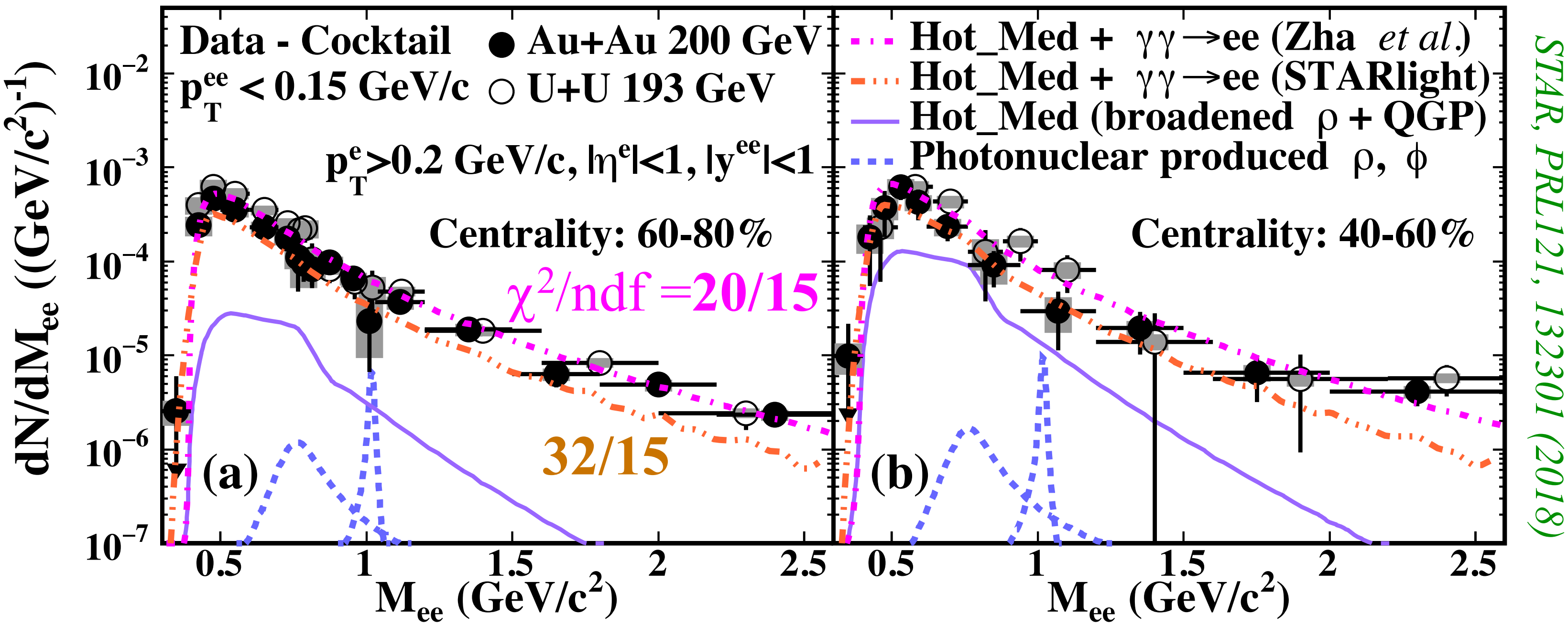
STAR, PRL121, 132301 (2018)



Significant enhancement of dilepton yield at p_T<0.15 GeV/c in (semi-)peripheral Au+Au and U+U collisions

Enhancement factor increases from semi-central to peripheral collisions

Excess Yield vs. Invariant Mass



Well described by theoretical calculations

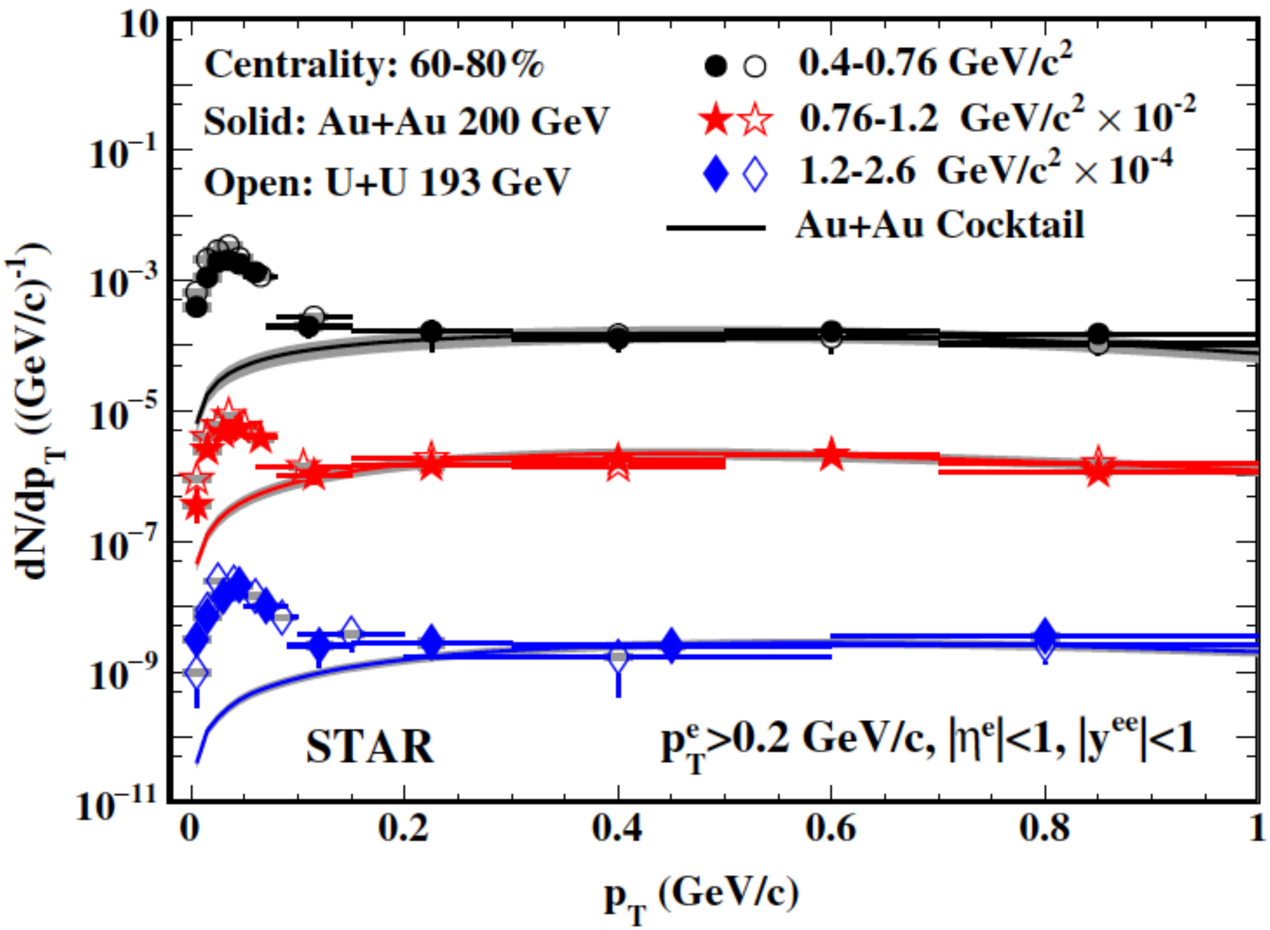
STARlight: point-like charge, ignore x_T<R *S. Klein, PRC97, 054903 (2018)*

Zha et al.: Woods-Saxon, entire nucleus as emitter

W. Zha, L. Ruan, ZBT, Z. Xu and S. Yang, PLB 781, 182 (2018)*

Very-low-p_T dilepton dominantly produced by γγ in peri. collisions

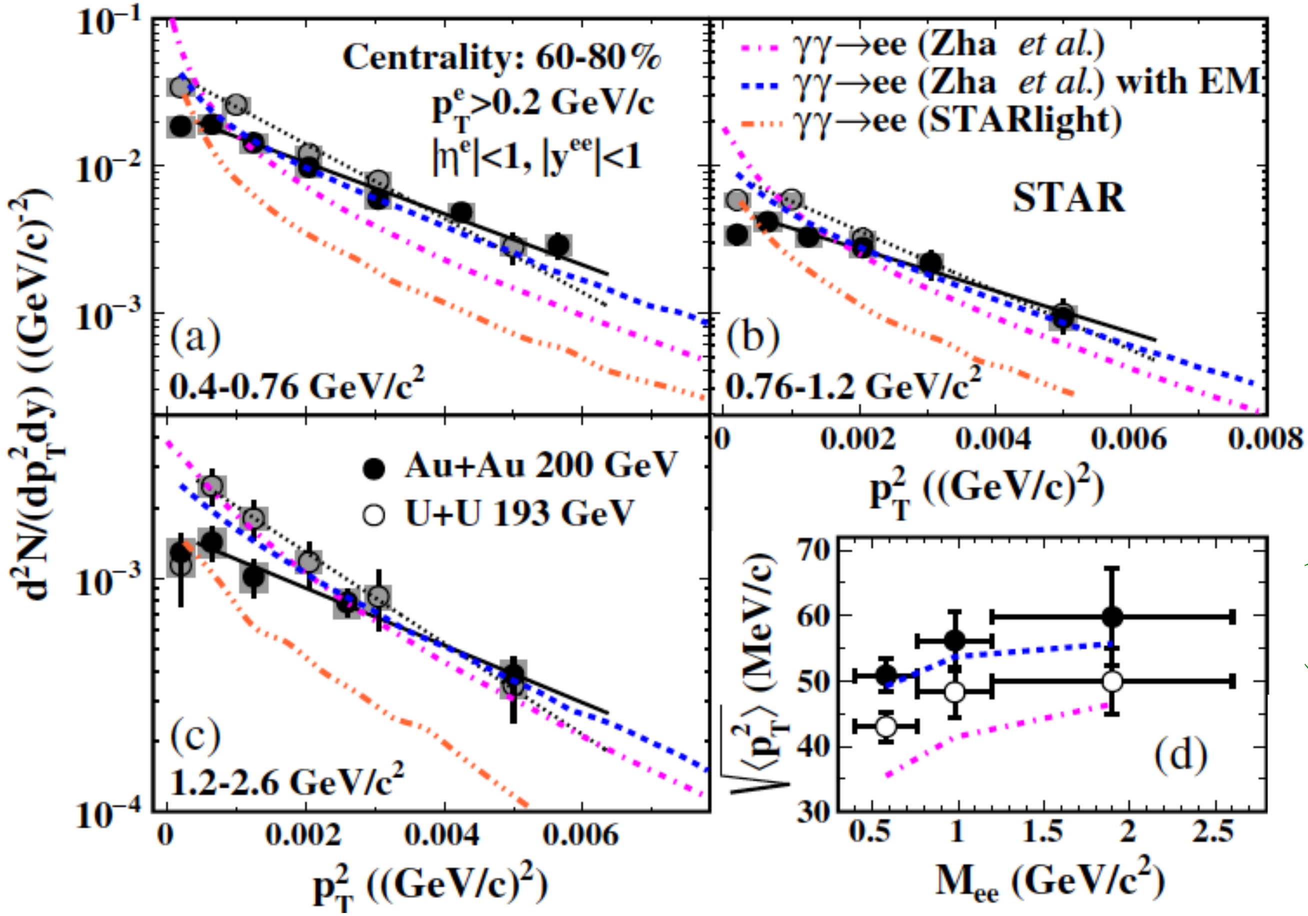
ee p_T Distribution



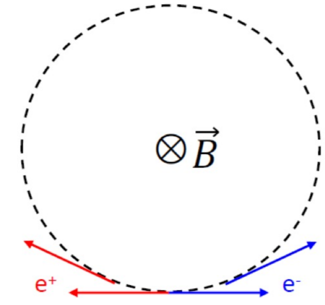
STAR, PRL121, 132301 (2018)

- Excesses dominate at p_T<~0.15 GeV/c
- Consistent with hadronic cocktail above 0.2 GeV/c

Transverse Momentum Broadening



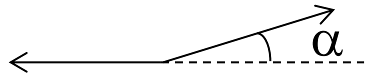
STAR, PRL121, 132301 (2018)



p_T^2 in data broader than in both models

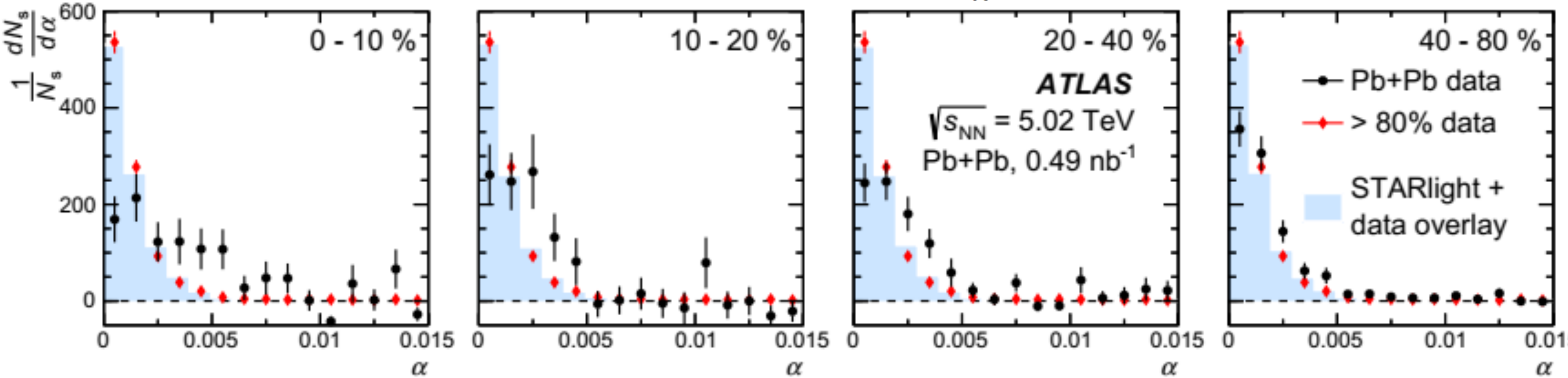
Deflection by magnetic field trapped in QGP?

Acoplanarity of Very-low-p_T Di-muon

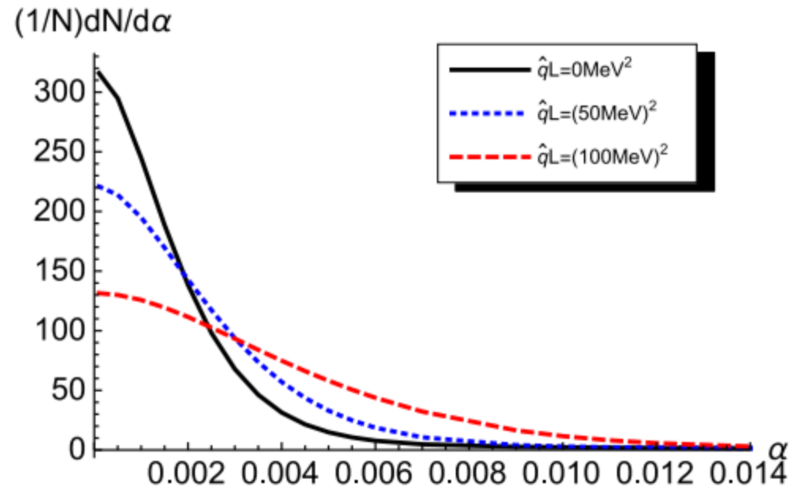


$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

ATLAS, PRL121, 212301 (2018)

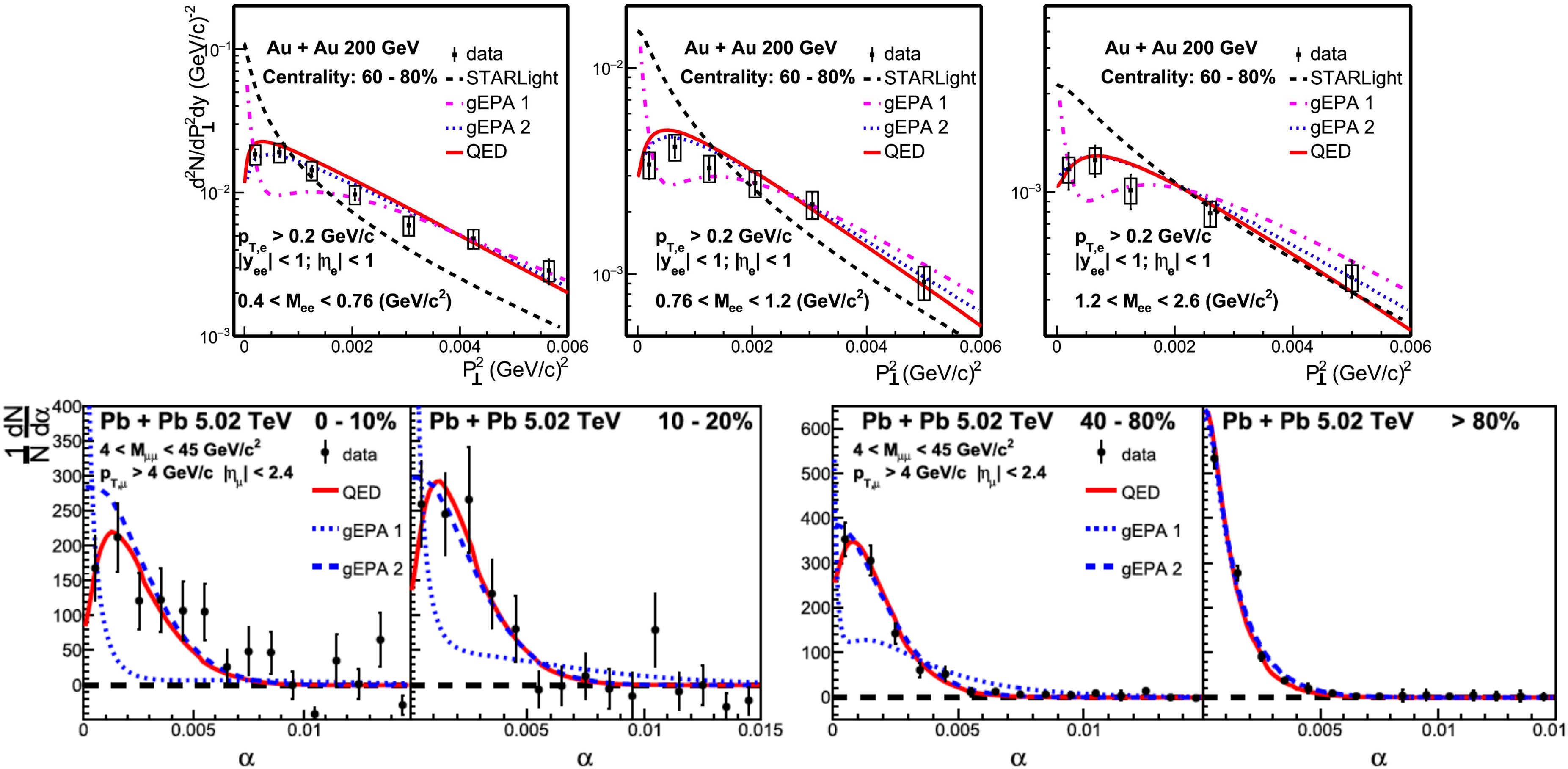


- Acoplanarity increases towards central collisions
- Possible QGP effects
  ➔QED multiple scattering?



S.R. Klein et al, PRL122 (2019) 132301

Model with *b* dependence



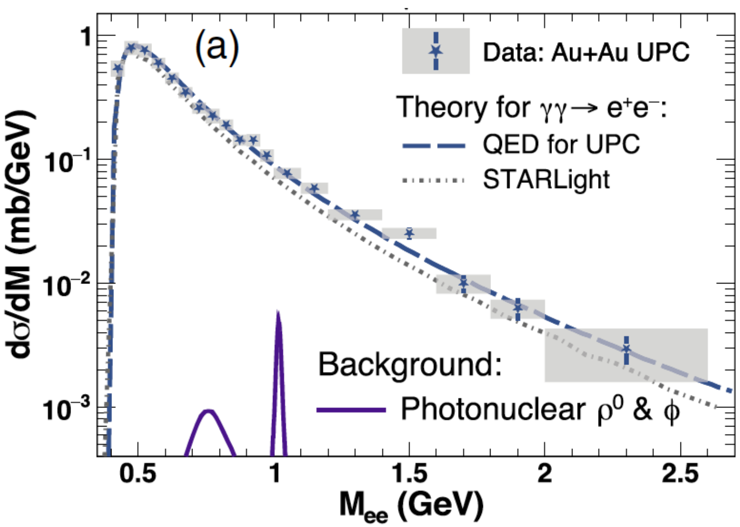
Introducing impact parameter (*b*) dependent explains both observations

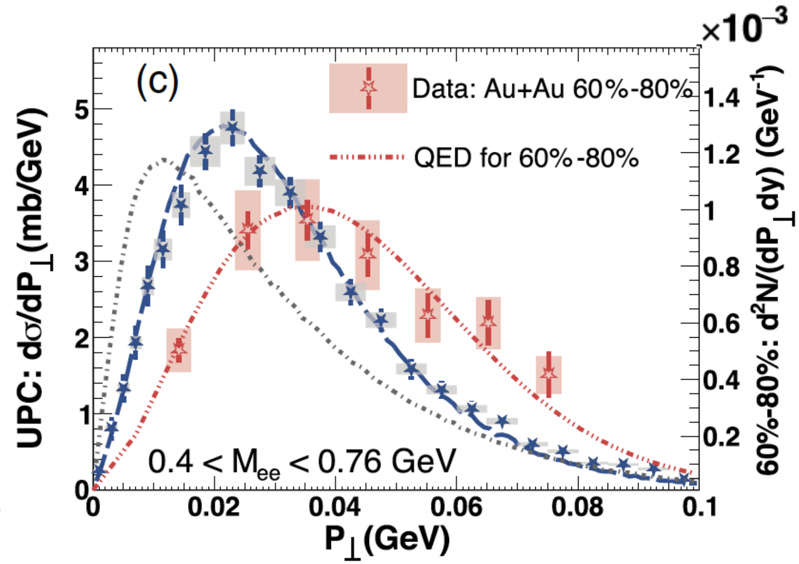
W. Zha, J. Brandenburg, ZBT and Z. Xu, PLB 800, 135089 (2020)*

No QGP effects needed with current uncertainties

Change Impact Parameter

STAR: Au+Au at $\sqrt{s_{NN}}$ = 200 GeV, $|y^{ee}| < 1$, $P_\perp < 0.1$ GeV, $P_T^e > 0.2$ GeV, $|\eta^e| < 1$





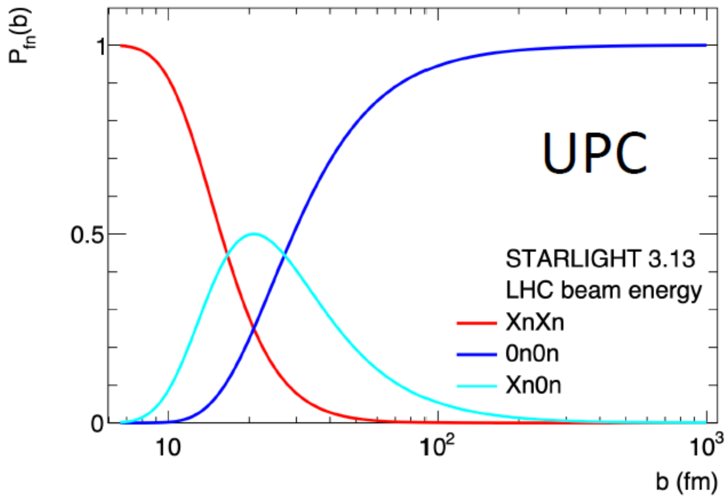
STAR, PRL127, 052302 (2021) *W. Zha, J. Brandenburg, ZBT and Z. Xu*, PLB 800, 135089 (2020)*

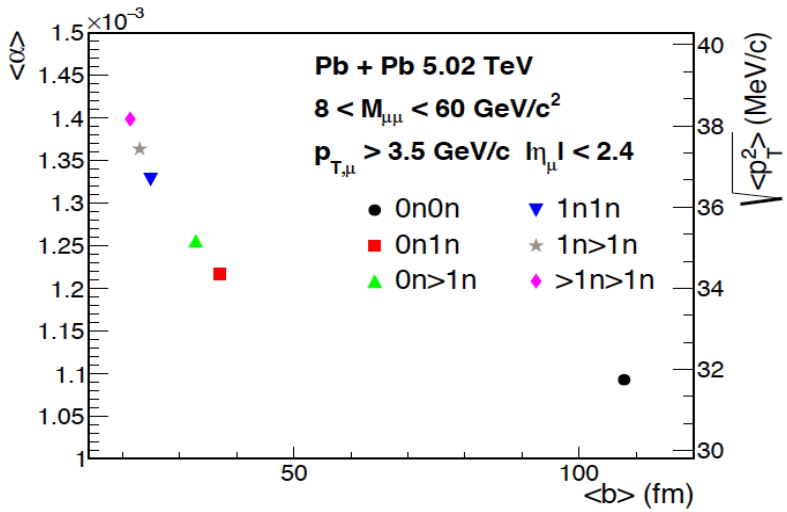
Narrower p_T distribution in UPC than peripheral collisions

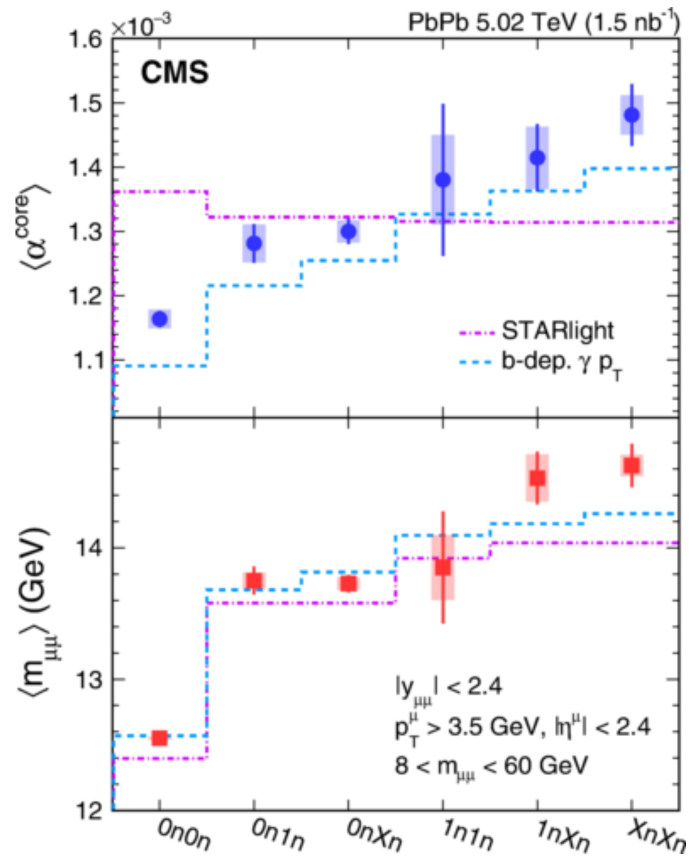
Systematically described by the EPA-QED with *b* dependence

Control *b* with Neutron Multiplicity

- Initial-state broadening confirmed



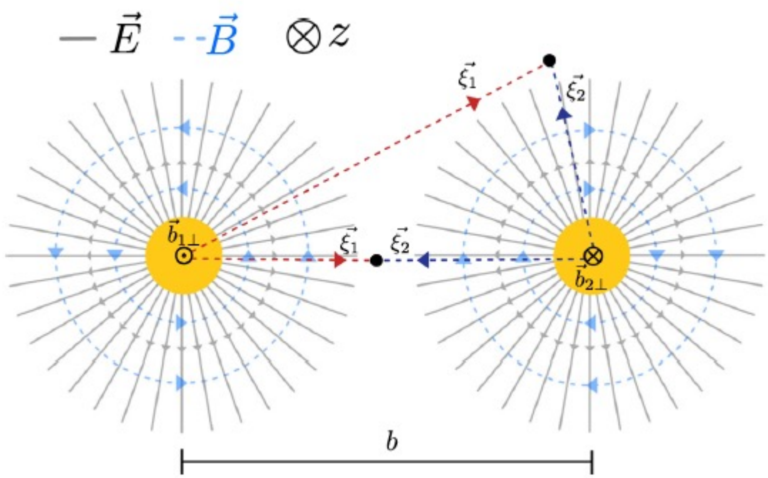


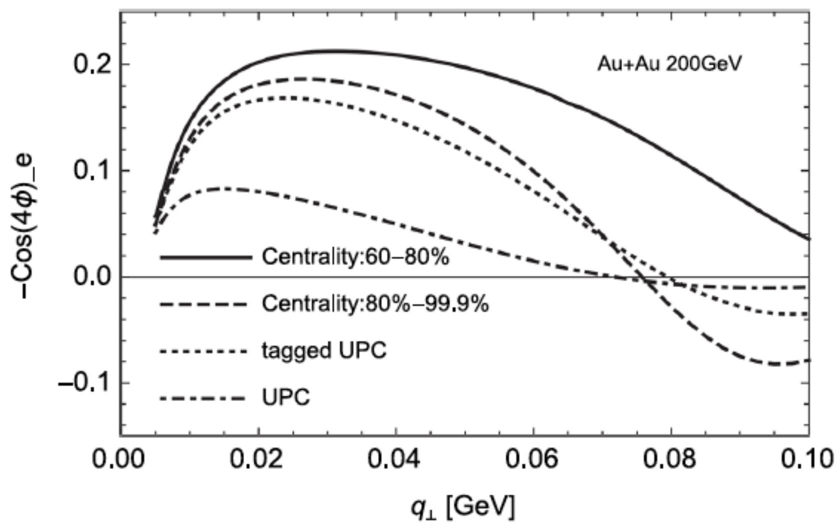


J. Brandenburg, …,ZBT, …, W. Zha, arXiv:2006.07365*

CMS, PRL127, 122001 (2021)

Polarization





$$\phi = \phi_e - \phi_{ee}$$

Photons from the highly Lorentz contracted EM filed are linearly polarized in the transverse plane

Polarization vectors coincide with the positions and thus transverse momenta

Spin interference effect in QED predicts cos4ϕ modulation

Cos4ϕ Modulation

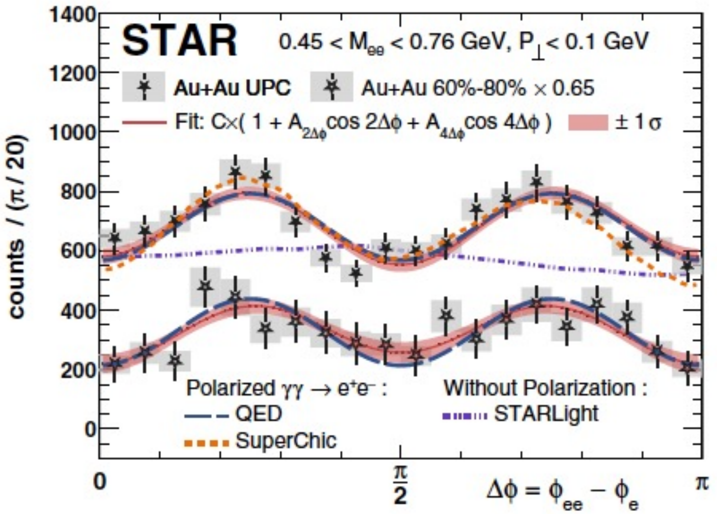


FIG. 4. The $\Delta\phi = \phi_{ee} - \phi_e$ distribution from UPCs and 60%–80% central collisions for $M_{ee} > 0.45$ GeV with calculations from QED [47], STARLight [43], and from the publicly available SUPERCHIC3 code [8].

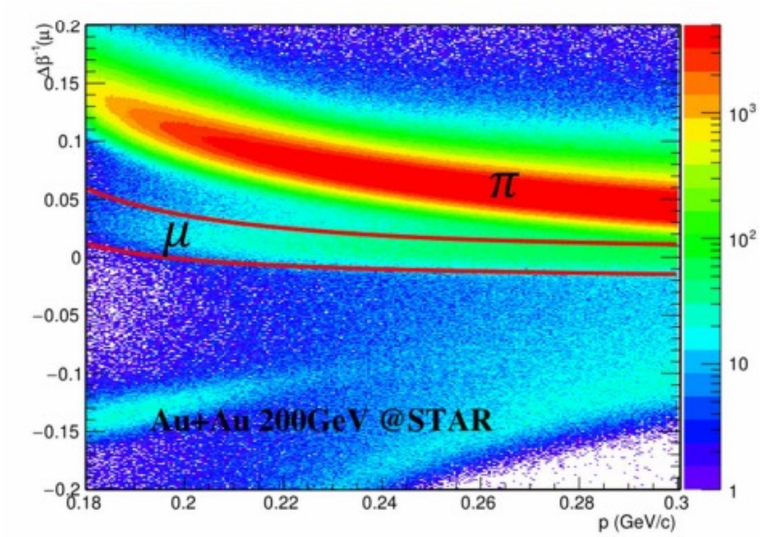
	Ultraperipheral				Peripheral	
	Measured	QED	SC	SL	Measured	QED
$\lvert A_{4\Delta\phi}\rvert$ (%)	16.8 ± 2.5	16.5	19	0	27 ± 6	34.5
$\lvert A_{2\Delta\phi}\rvert$ (%)	2.0 ± 2.4	0	5	5	6 ± 6	0

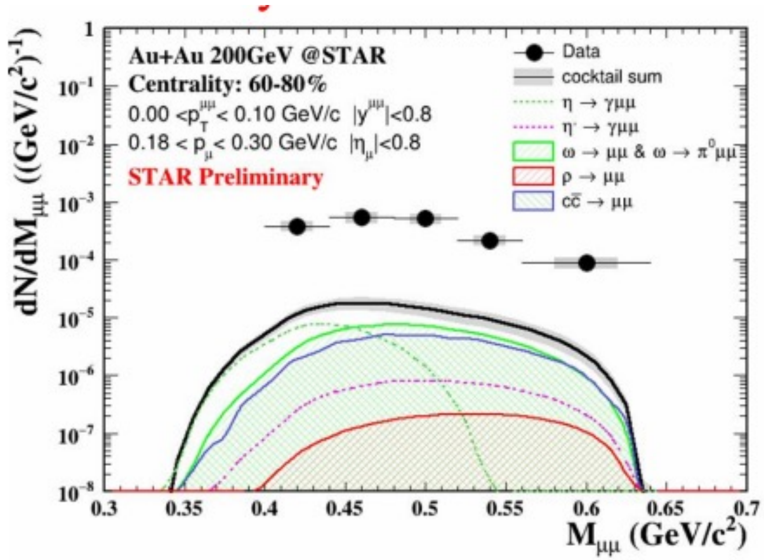
STAR, PRL127, 052302 (2021)

- Cos4ϕ modulation predicted by QED is observed
- Larger modulation with smaller impact parameter
- QED also predicts cos2ϕ modulation for dimuon ($\sim m_l^2/p_T^2$)

Di-muon at STAR

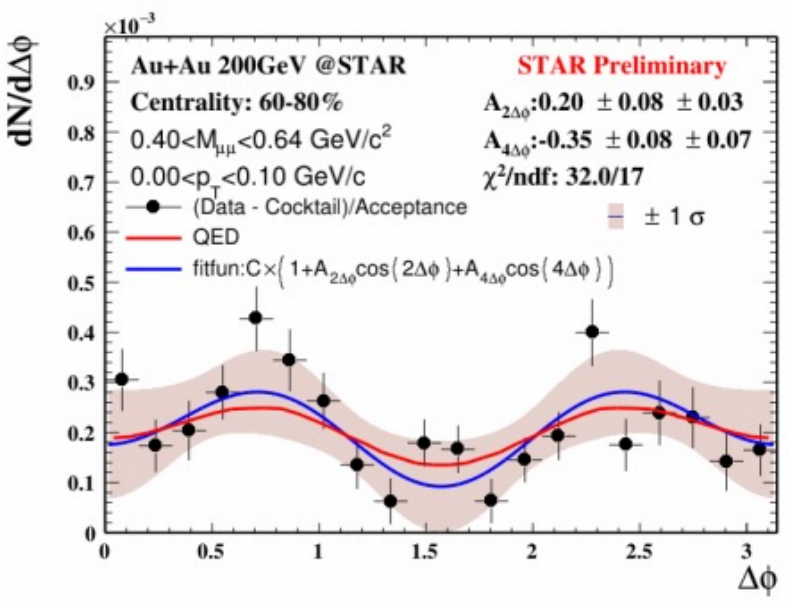
J. Zhou, SQM2021





- Muon identified at low p_T with excellent Time-of-Flight
- Allows the measurement of dimuon in the low mass region
- Clear signals at very low p_T in peripheral Au+Au collisions

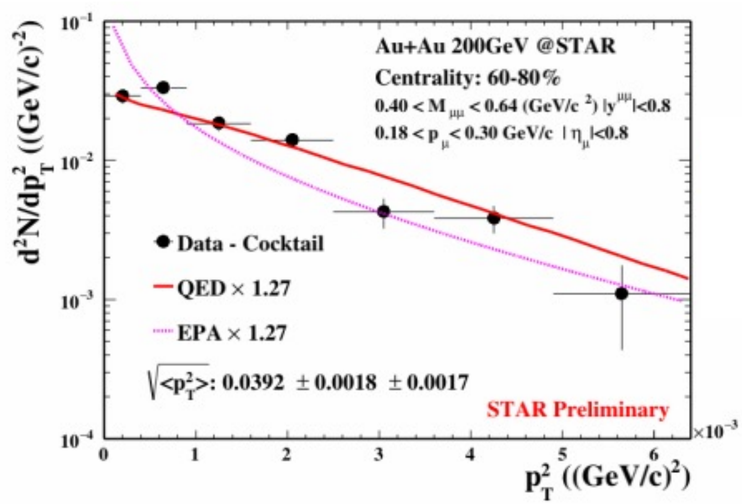
Modulations of Dimuon



		Measurement	QED
$A_{4\Delta\phi}$	μμ	**35 ± 8± 7**	**22**
	ee	27 ± 6	34.5
$A_{2\Delta\phi}$	μμ	**20 ± 8± 3**	**13**
	ee	6 ± 6	0

- Confirmation of cos4ϕ modulation (3.3 σ)
- First indication of cos2ϕ modulation (2.3 σ)
- All the results consistent with QED calculations

p_T Broadening



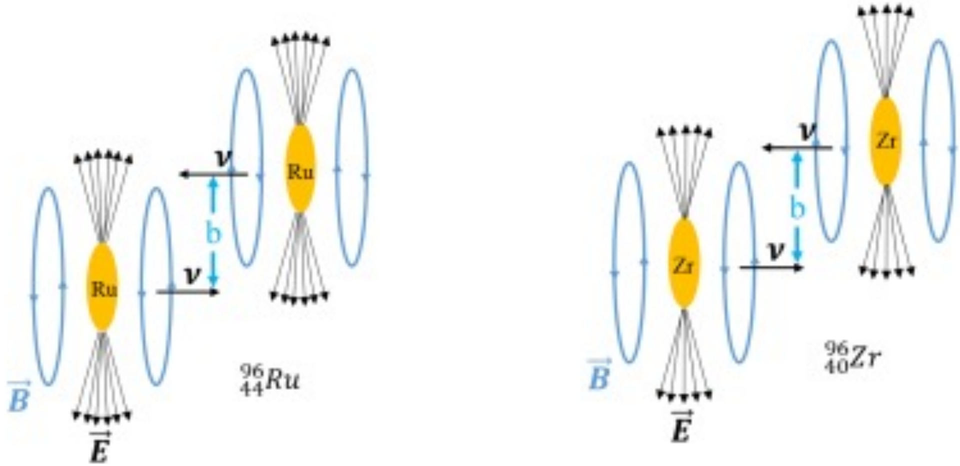
	Mass GeV/c^2	$\sqrt{\langle p_T^2 \rangle}$ MeV/c	QED
μμ	**0.40-0.64**	**39.2 ± 1.8± 1.7**	**42.3**
ee	0.45-0.76	50.9 ± 2.5	48.5

Results from both channels are consistent with QED calculations

No additional broadening is observed

Precision to be improved for the search for QGP effect

Charge Dependence?



STAR took high statistics isobaric collisions data in 2018, dedicated for the search for chiral magnetic effect (CME)

A is the same but Z differs by 10%
➔Magnetic field should differ by ~20% and others are the same

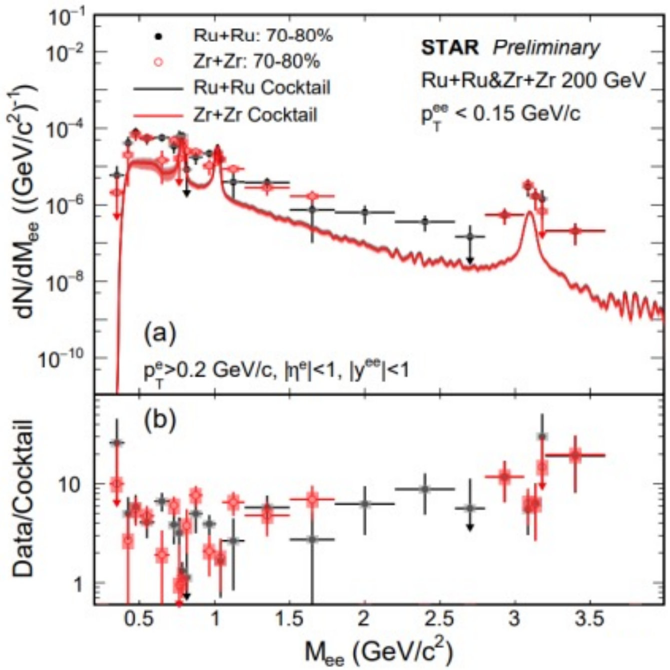
Blind analyses show no difference of all the CME observables

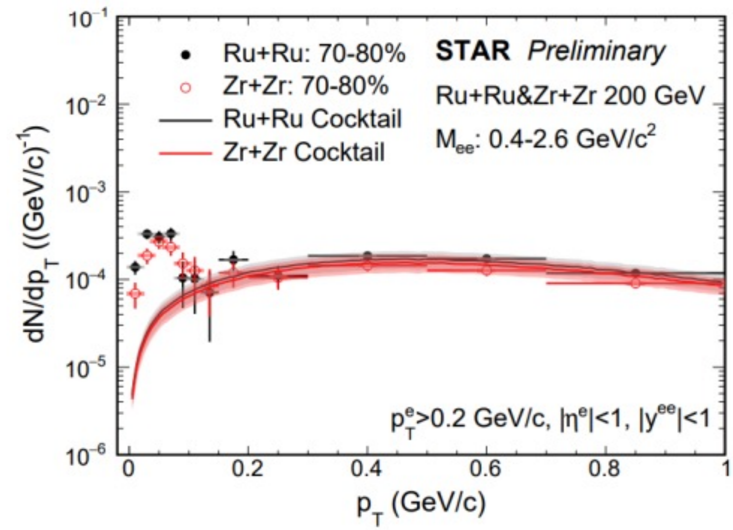
STAR, PRC104, 014901 (2022)

Is there really difference of the field?

Mass and p_T Spectra

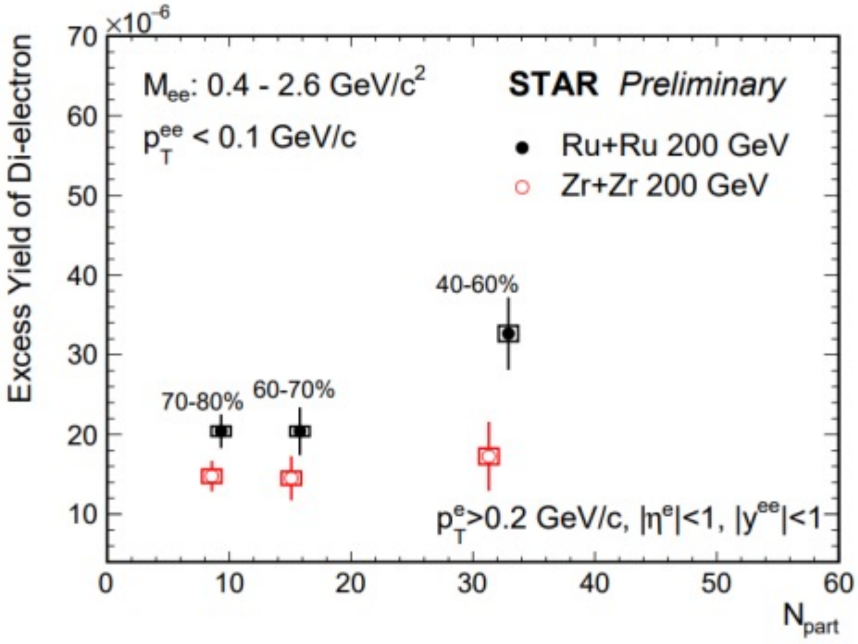
K. Shen, SQM2021

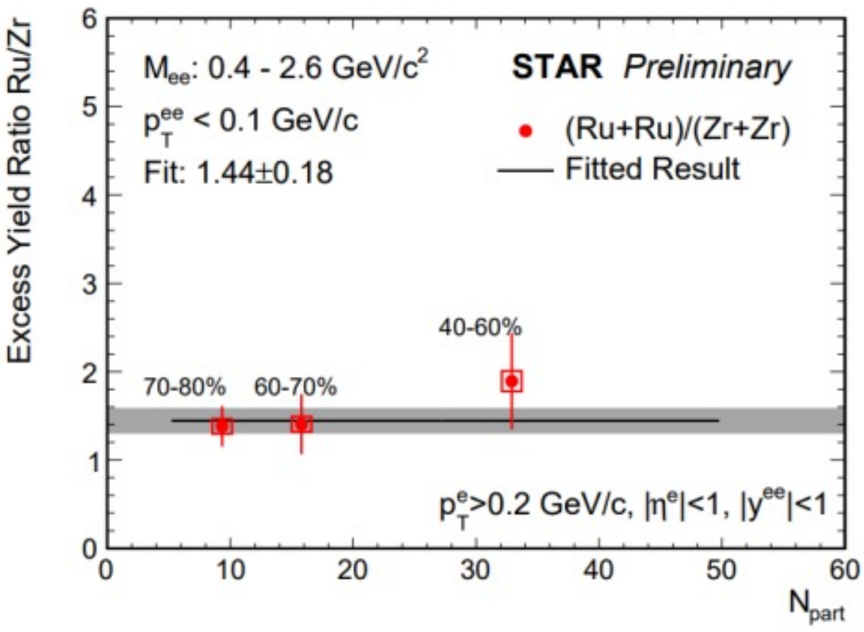




Excess yield of di-electron observed at low-p_T in both collisions systems

Difference of Excess Yield

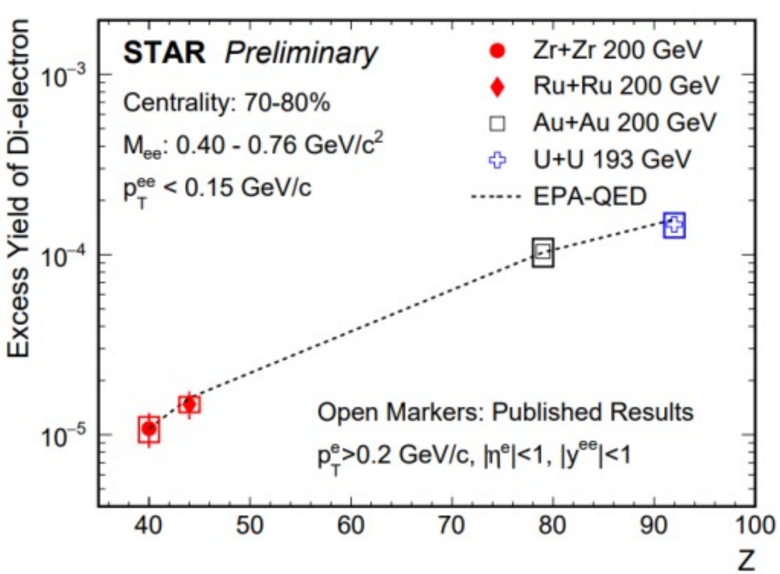


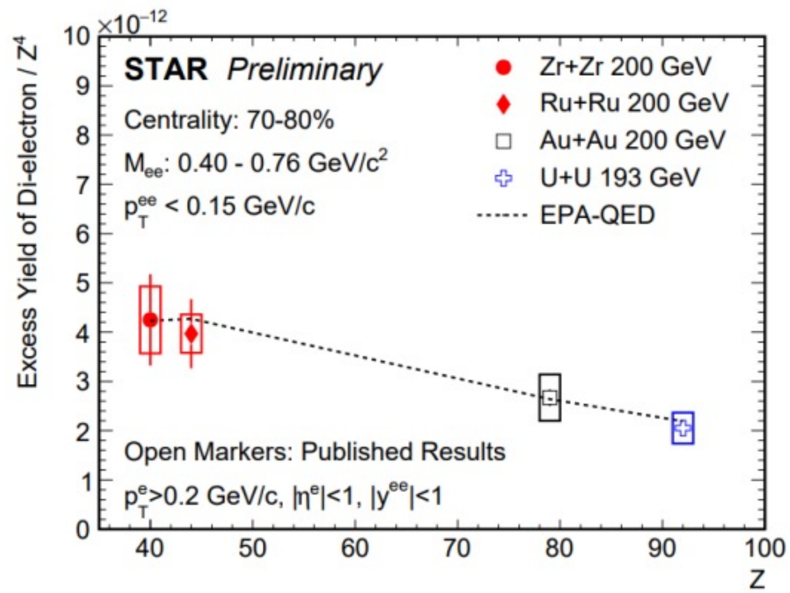


Excess yield in Ru+Ru systematically higher than in Zr+Zr

A ratio of $1.44 \pm 0.18 \sim Z^4$

Charge Dependence of Yield



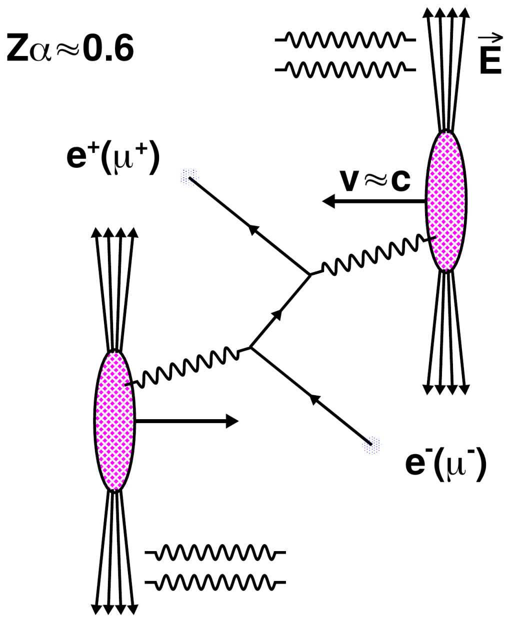


Excess yield increase significantly with Z

Z^4-scaled yield decrease with Z, likely originating from *b* dependence

Consistently described by EPA-QED calculations

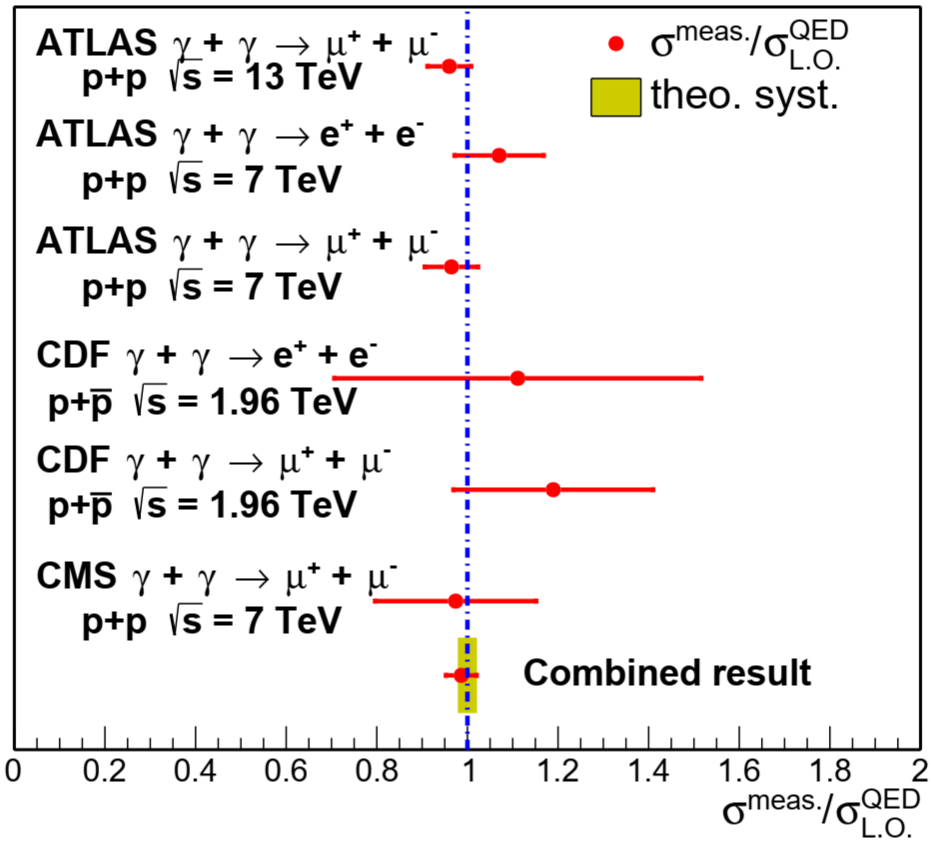
Higher Order Effect in Strong EM Field



Zα~1/137 in p+p but ~0.6 in A+A

Any higher order effects in A+A?

Cross Section in p+p

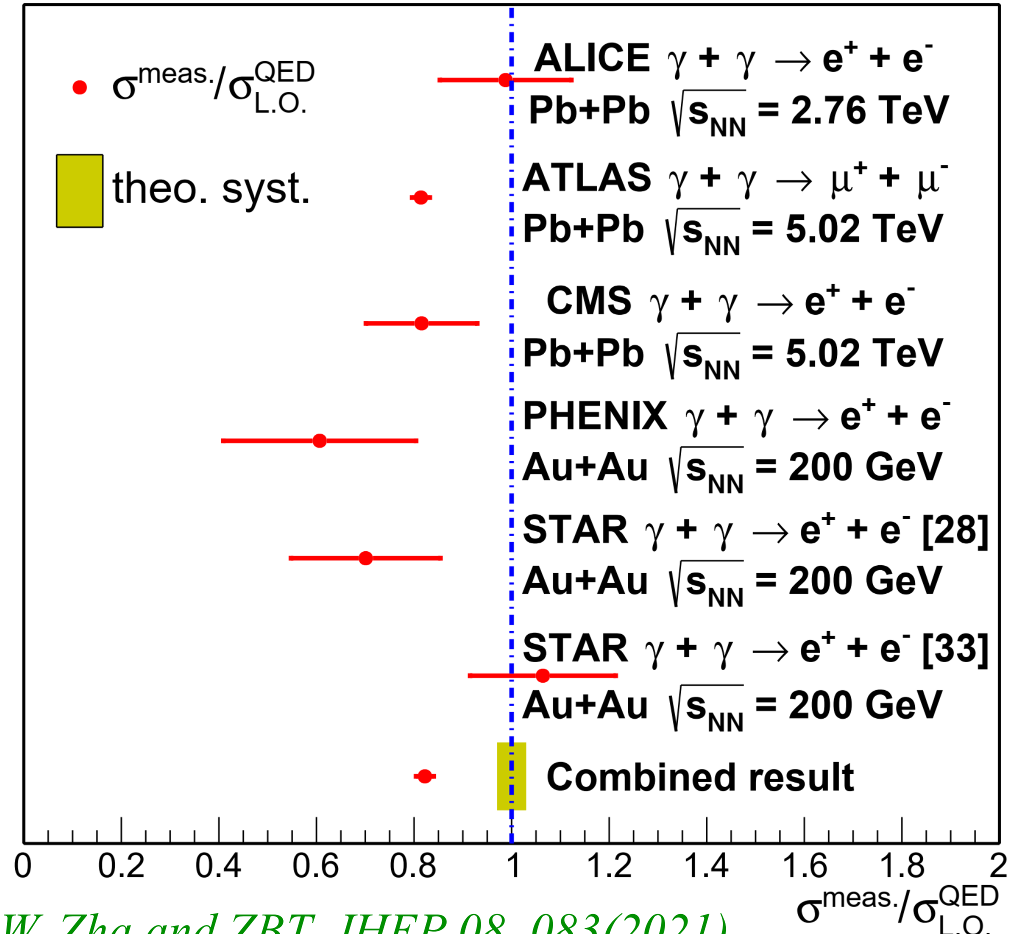


CDF, PRL102,242001 (2009)
CDF,PRL98, 112001 (2007)
ATLAS,PLB749, 242 (2015)
ATLAS, PLB777, 303 (2018)
CMS, JHEP11, 080 (2012)

W. Zha and ZBT, JHEP 08, 083(2021)

Consistent with lowest QED calculations

Cross Section in A+A

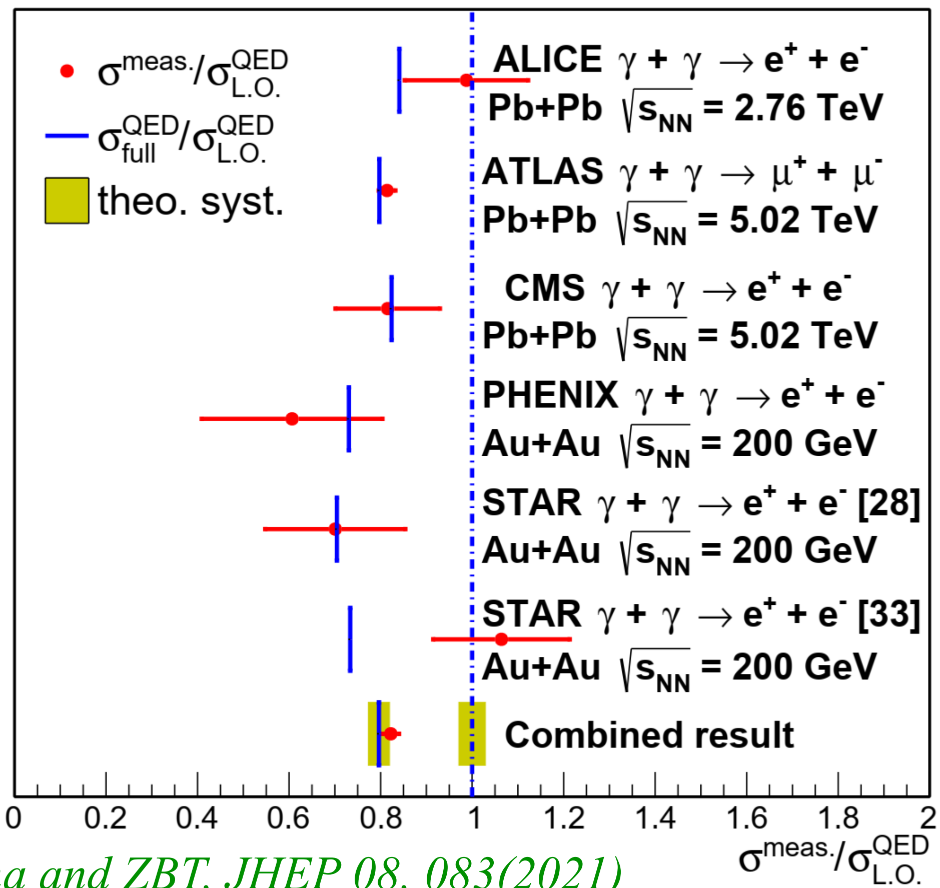


W. Zha and ZBT, JHEP 08, 083(2021)

STAR, PRC70, 031902 (2004)
STAR, PRL127, 052302 (2021)
PHENIX, PLB679, 321 (2009)
ALICE, EPJC73, 2617 (2013)
CMS, PLB797, 134826 (2019)
ATLAS , PRC104, 024906 (2021)

5.2 σ lower than the Lowest order QED calculations !

Cross Section in A+A

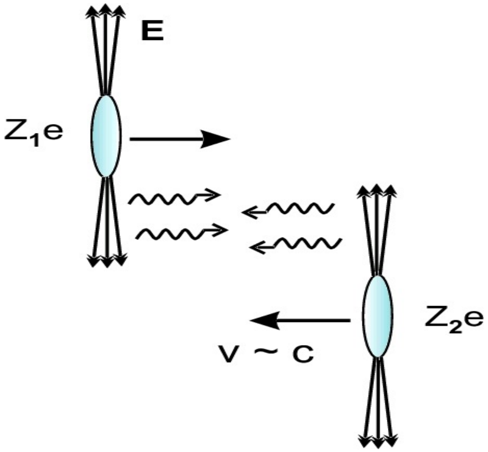


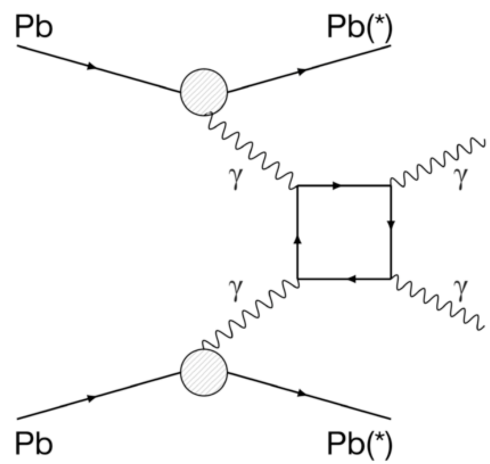
W. Zha and ZBT, JHEP 08, 083(2021)

STAR, PRC70, 031902 (2004)
STAR, PRL127, 052302 (2021)
PHENIX, PLB679, 321 (2009)
ALICE, EPJC73, 2617 (2013)
CMS, PLB797, 134826 (2019)
ATLAS , PRC104, 024906 (2021)

Consistent with higher order QED calculations !

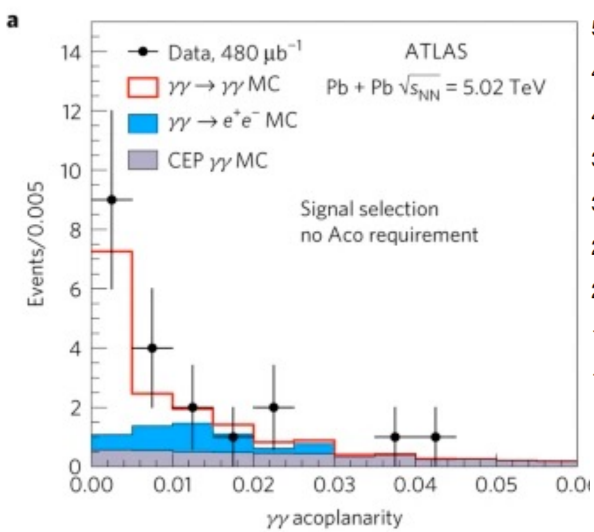
Light-by-Light Scattering



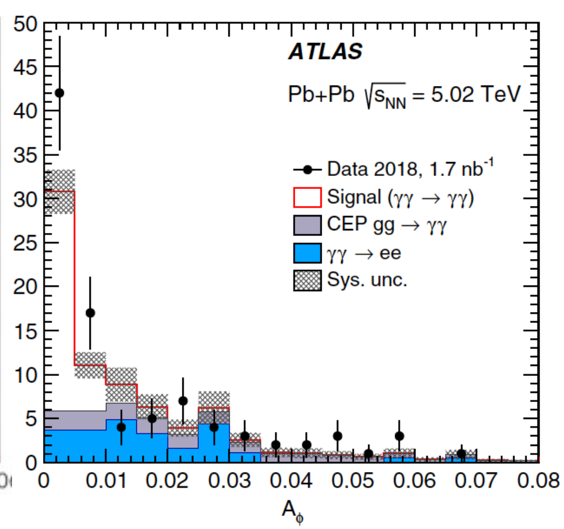


Light-by-light elastic scattering observed by ATLAS

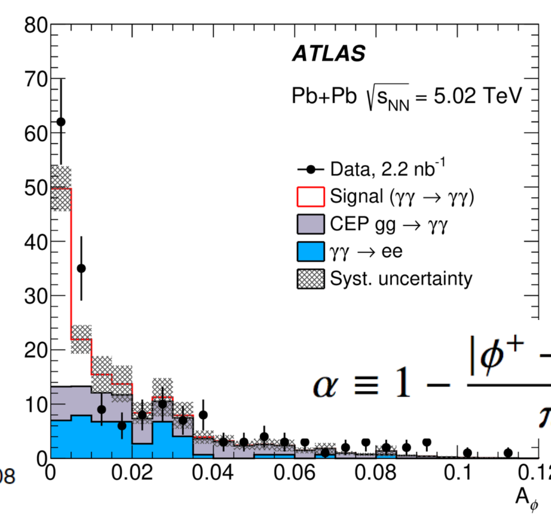
Nat. Phys. 13, 852 (2017)



PRL123, 052001 (2019)



JHEP03, 243 (2021)

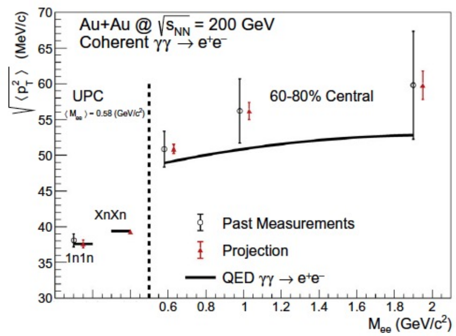


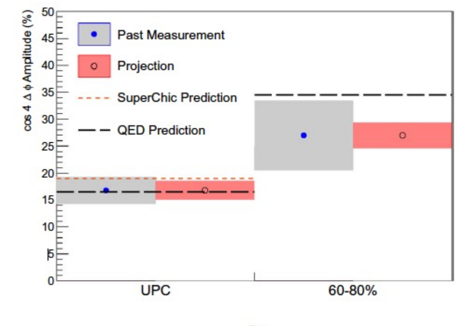
$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

Other Opportunities

- EM probe of QGP

QGP effect, if exists, may broaden p_T and wash out ϕ modulations





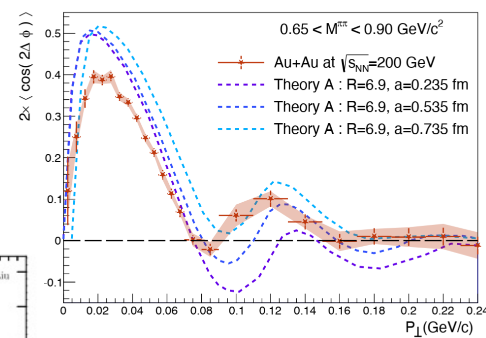
- Probe nuclear charge and gluon distribution

    Charge radius

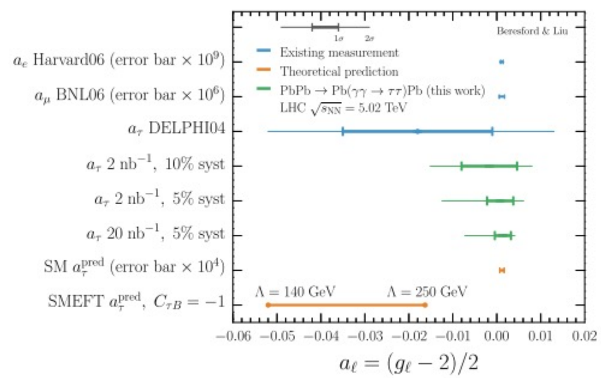
    Neutron skin

    …

Eic(C) physics



- tau g-2 measurements



L. Beresford and J. Liu, PRD102, 113008(2020)

- Search for Axion-like particles, dark photons etc

S. Knapen et al., PRL118, 171801 (2017)

Summary

Strong electromagnetic field generated in heavy ion collisions provides a unique laboratory to study QED and QCD

We conduced systematic experiments, as well as phonomenological works, to study the properties of the strong EM field

All observed features consistent with EPA-QED calculations, which is developed in the last half decade (good reference)

It can also be used to search for new physics BSM

Experiments:

- STAR Preliminary results
- STAR, arXiv:2204.01625, submitted Science Advances
- CMS, PRL127, 122001 (2021)
- STAR, PRL127, 052302 (2021)
- STAR, PRL123, 132302 (2019)
- STAR, PRL121, 132301 (2018)

Phenomenology:

- CPC46, 074103 (2022)
- JHEP08, 083 (2021)
- PRD103, 033007 (2021)
- arXiv:2006.07365
- PLB800, 135089 (2020)
- CPC43, 061403 (2019)
- PLB789, 238 (2019)
- PRC99, 061901 (2019)
- PLB781, 182 (2018)
- PRC97, 044910 (2018)

Thanks!