Experimental results on magnetic fields in ultra-peripheral heavy-ion collisions

[1] JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).
[2] W. Zha, JDB, Z. Tang, and Z. Xu, Physics Letters B **800**, 135089 (2020).
[3] STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).
[4] STAR Collaboration, Phys. Rev. Lett. **121**, 132301 (2018).
[5] JDB, W. Li, et al., arXiv:2006.07365 [hep-ph, physics:nucl-th] (2020).

James [Daniel] Brandenburg, Goldhaber Fellow,
Brookhaven National Laboratory / CFNS Stony Brook

Chirality, Vorticity, and Magnetic Fields in Heavy-Ion Collisions, 2021
Stony Brook University, CFNS

BROOKHAVEN
NATIONAL LABORATORY

Center for Frontiers
in Nuclear Science

1 – Introduction

- QCD in Strong fields
- Pair production from strong fields

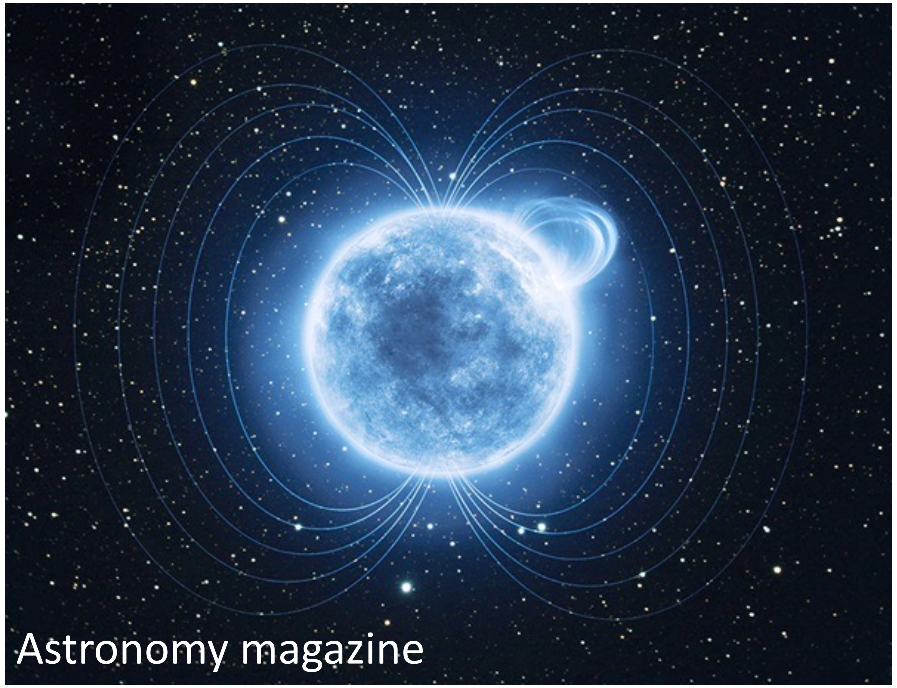
2 – Initial EM Fields

- Phenomenology of two photon interactions
- Experimental Catalysts
- “Mapping” the spatial extent of magnetic fields in heavy-ion collisions

3 – EM Fields in Medium

- Origin of coherent field
- Medium Interaction
- Future opportunities

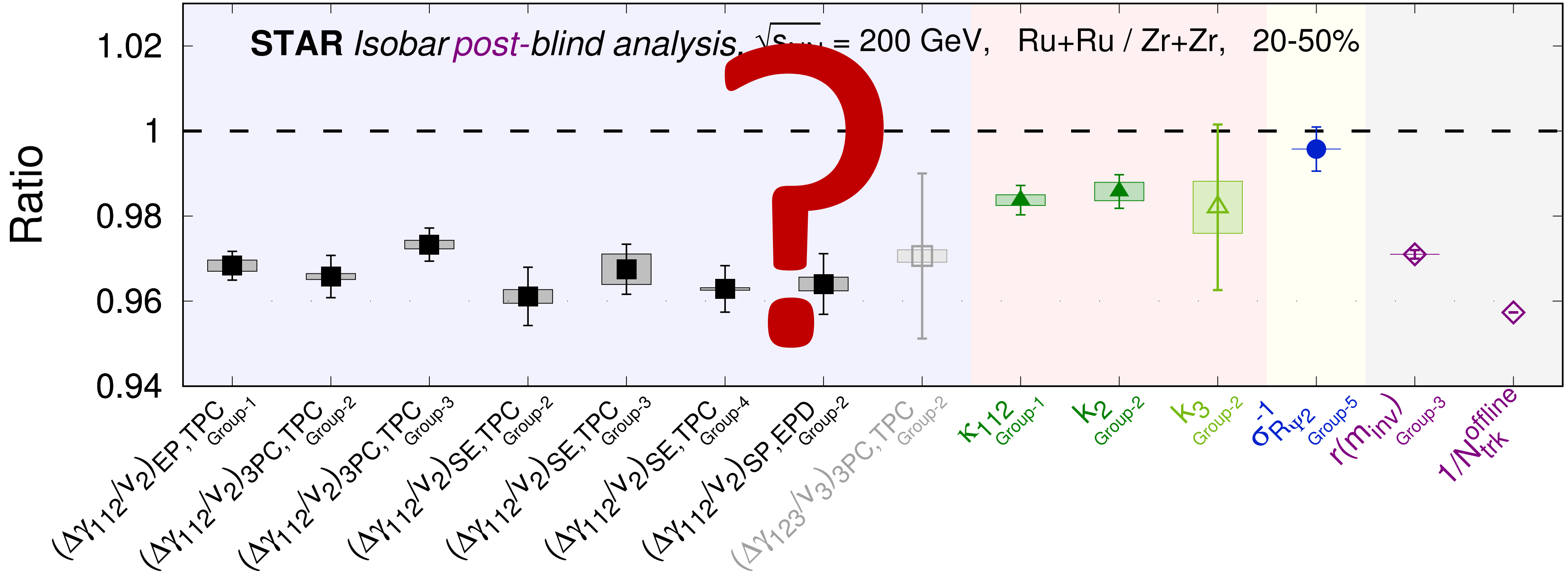
Open Questions: QCD in Strong Magnetic Fields


Astronomy magazine

- Potential effects on evolution of the early universe and effects on strong (QCD) processes [1]
- Strong magnetic fields inside dense neutron stars may lead to non-trivial QCD phenomena [1]
- In heavy-ion collisions, coexistence of strong fields + nontrivial topological structure of the QGP -> chiral anomaly [2, 3]
- How does an external magnetic field effect the QCD phase diagram & existence / location of critical point? [4,5]

[1] Bali, G. S. *et al. J. High Energ. Phys.* **2012**, 44 (2012).
[2] Fukushima, K., Kharzeev, D. E. & Warringa, H. J. *Phys. Rev. D* **78**, 074033 (2008).
[3] Kharzeev, D. E., Liao, J., Voloshin, S. A. & Wang, G. *Progress in Particle and Nuclear Physics* **88**, 1–28 (2016).
[4] D’Elia, M., Mukherjee, S. & Sanfilippo, F. *Phys. Rev. D* **82**, 051501 (2010).
[5] Bali, G. S. *et al. J. High Energ. Phys.* **2012**, 44 (2012).

Open Questions: QCD in Strong Magnetic Fields



Can we provide **experimental** constraints on the magnetic field in heavy-ion collisions?

STAR Collaboration, et al., arXiv:2109.00131 [hep-ex, physics:hep-ph, physics:nucl-ex, physics:nucl-th] (2021).

Pair Production in Strong Fields

- In 1951, Julian Schwinger developed quintessential form of e^+e^- pair production in QED
- Schwinger: Vacuum breaks down above a critical field (E_C):

$$E_C = \frac{m^2 c^3}{e\hbar} \simeq 1.3 \times 10^{16} \text{ V/cm}$$

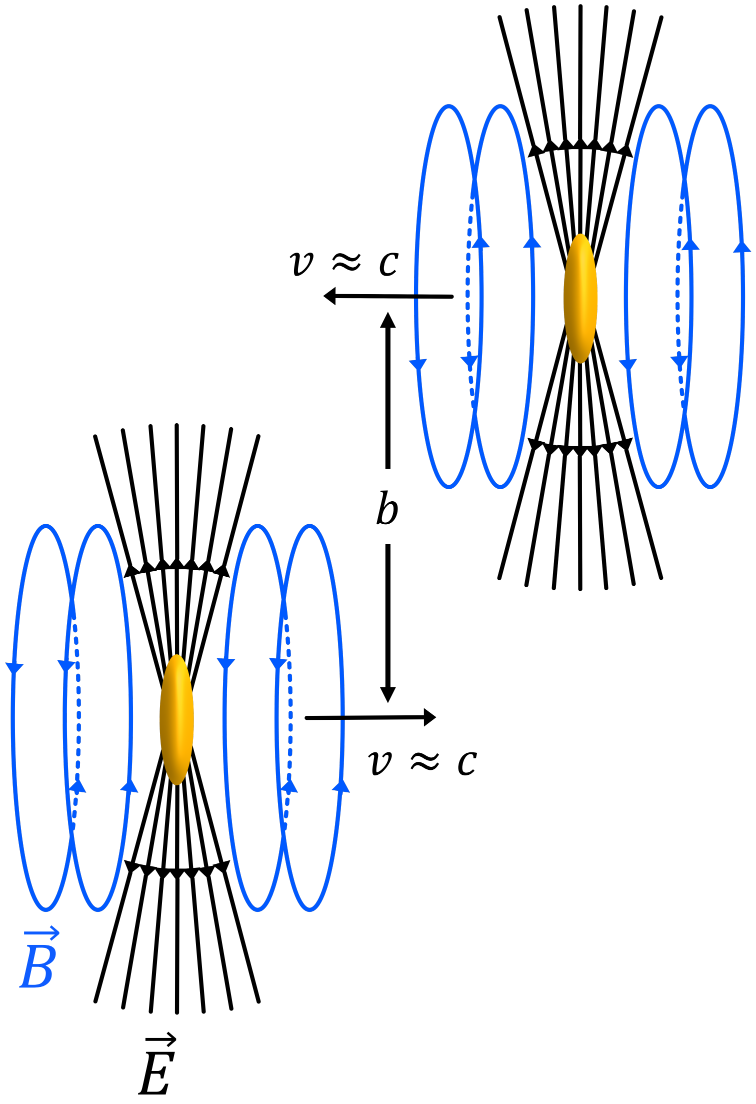
- In heavy-ion collisions:

$$E_{max} = \frac{Ze\gamma}{b^2} \approx 5\times10^{16} - 10^{18} \text{ V/cm}$$

  - But very short lifetime – not constant

M. Vidović, M. Greiner, C. Best, and G. Soff, Phys. Rev. C **47**, 2308 (1993).

Two Photon Interactions



Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field

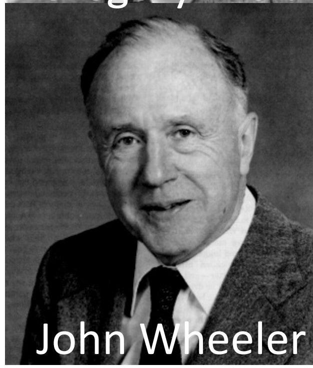
EM overlap time: $\Delta t = {}^{b}/_{\gamma v} < 10^{23}$ s (RHIC)

- ▻Fields must be treated in terms of quanta
- ▻Equivalent photon approximation: Fermi, Williams, and Weizäcker

$\gamma\gamma \rightarrow l^{+}l^{-}$: Breit-Wheeler Process

- One photon from the field of each nucleus interacts
- Second order process in α
- $Z\alpha \approx 1$ → High photon density with highly charged nuclei
- Conventionally studied in ultra-peripheral collisions


Gregory Breit


John Wheeler

Part 2: Initial EM Fields

Phenomenology of $\gamma\gamma \rightarrow l^+ l^-$ in HICs

1. External Field Approximation
    - Nuclei are not deflected, maintain straight-line velocity
    - Field results from entire charge distribution

Start from the electromagnetic 4-potential in the Lorentz gauge:

$$A_1^\mu(k_1, b_\tau) = -2\pi(Z_1 e) e^{ik_1^\tau b_\tau} \delta(k_1^\nu u_{1\nu}) \frac{F_1(-k_1^\rho k_{1\rho})}{k_1^\sigma k_{1\sigma}} u_1^\mu,$$

$$A_2^\mu(k_2, b_\tau = 0) = -2\pi(Z_2 e) \delta(k_2^\nu u_{2\nu}) \frac{F_2(-k_2^\rho k_{2\rho})}{k_2^\sigma k_{2\sigma}} u_2^\mu.$$

With photon momenta $k_{1,2}$ and nuclei velocities $u_{1,2} = \gamma(1, 0, 0, \pm v),$

M. Vidović, et al., Phys. Rev. C **47**, 2308 (1993).

Phenomenology of $\gamma\gamma \rightarrow l^+ l^-$ in HICs

1. External Field Approximation
   - Nuclei are not deflected, maintain straight-line velocity
   - Field results from entire charge distribution

Start from the electromagnetic 4-potential in the Lorentz gauge:

$$A_1^\mu(k_1, b_\tau) = -2\pi(Z_1 e)e^{ik_1^\tau b}\boxed{\delta(k_1^\nu u_{1\nu})}\frac{F_1(-k_1^\rho k_{1\rho})}{k_1^\sigma k_{1\sigma}}u_1^\mu,$$

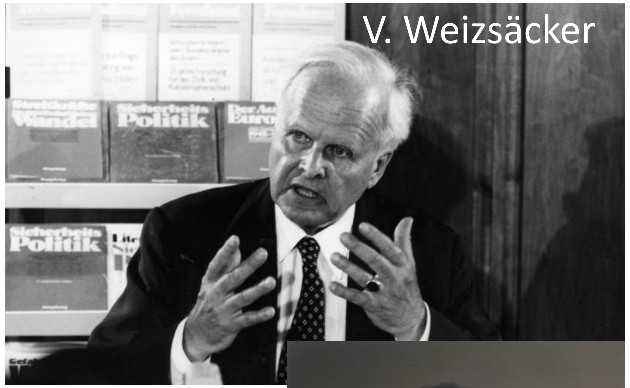
$$A_2^\mu(k_2, b_\tau = 0) = -2\pi(Z_2 e)\boxed{\delta(k_2^\nu u_{2\nu})}\frac{F_2(-k_2^\rho k_{2\rho})}{k_2^\sigma k_{2\sigma}}u_2^\mu.$$

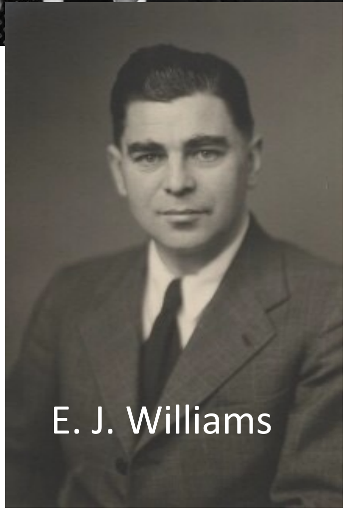
With photon momenta $k_{1,2}$ and nuclei velocities $u_{1,2} = \gamma(1, 0, 0, \pm v),$

Straight line trajectory assumption → quasi-real photons, very different from $e^+ + e^-$ collider where large deflection can take place

M. Vidović, et al., Phys. Rev. C **47**, 2308 (1993).

Phenomenology of $\gamma\gamma \rightarrow l^+l^-$ in HICs


V. Weizsäcker


E. J. Williams

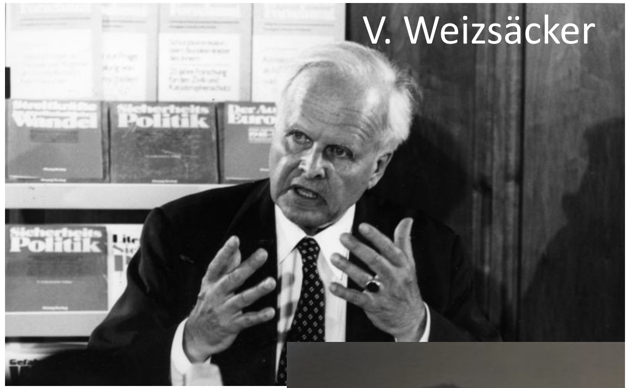
1. External Field Approximation
   - Nuclei are not deflected, maintain straight-line velocity
   - Field results from entire charge distribution
2. Equivalent Photon Approximation (EPA)
   - Photon number density related to time-averaged energy-flux

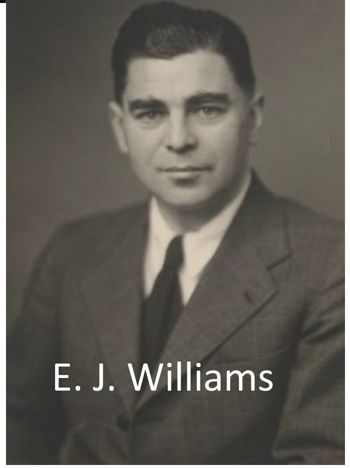
$$n(\omega; b_\perp) = \frac{1}{\pi\omega} |E_\perp(\omega, b_\perp)|^2$$

$$= \frac{4Z^2\alpha_{em}}{\omega} \times \left| \int \frac{d^2k_\perp}{(2\pi)^2} k_\perp \frac{F\left(k_\perp + {\omega^2}/{\gamma^2}\right)}{k_\perp + {\omega^2}/{\gamma^2}} e^{-ib_\perp \cdot k_\perp} \right|^2$$

M. Vidović, et al., Phys. Rev. C **47**, 2308 (1993).

Phenomenology of $\gamma\gamma \rightarrow l^+ l^-$ in HICs





1. External Field Approximation
   - Nuclei are not deflected, maintain straight-line velocity
   - Field results from entire charge distribution
2. Equivalent Photon Approximation (EPA)
   - Photon number density related to time-averaged energy-flux

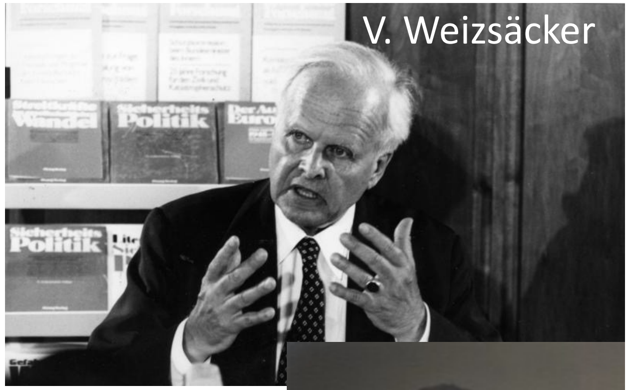
$$n(\omega; b_\perp) = \frac{1}{\pi\omega} |E_\perp(\omega, b_\perp)|^2$$

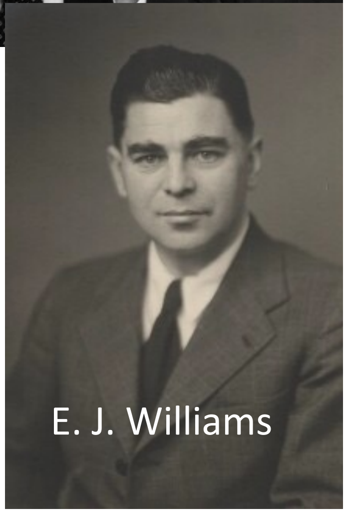
$$= \frac{4Z^2\alpha_{em}}{\omega} \times \left| \int \frac{d^2 k_\perp}{(2\pi)^2} k_\perp \frac{F\left(k_\perp + \omega^2/\gamma^2\right)}{k_\perp + \omega^2/\gamma^2} e^{-i b_\perp \cdot k_\perp} \right|^2$$

Inherently connected to the field's lifetime → more on field lifetime later

M. Vidović, et al., Phys. Rev. C **47**, 2308 (1993).

Phenomenology of $\gamma\gamma \rightarrow l^+l^-$ in HICs


V. Weizsäcker


E. J. Williams

1. External Field Approximation
   - Nuclei are not deflected, maintain straight-line velocity
   - Field results from entire charge distribution
2. Equivalent Photon Approximation (EPA)
   - Photon number density related to time-averaged energy-flux

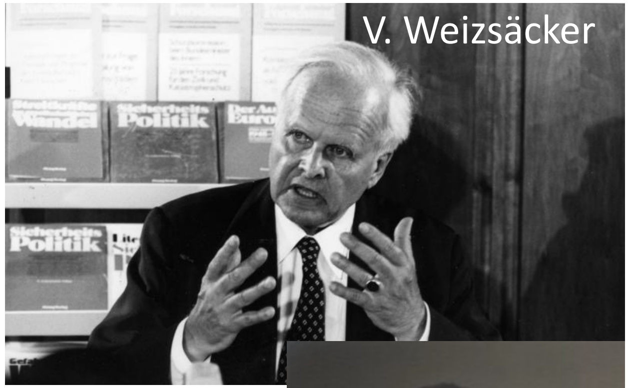
$$n(\omega; b_\perp) = \frac{1}{\pi\omega} \boxed{|E_\perp(\omega, b_\perp)|^2}$$

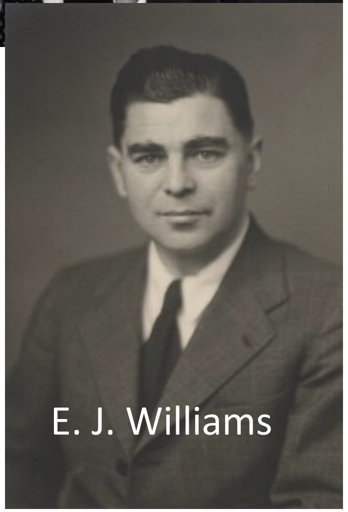
$$= \frac{4Z^2\alpha_{em}}{\omega} \times \left| \int \frac{d^2k_\perp}{(2\pi)^2} k_\perp \frac{F\left(k_\perp + \omega^2/\gamma^2\right)}{k_\perp + \omega^2/\gamma^2} e^{-ib_\perp \cdot k_\perp} \right|^2$$

Connection to electric field → magnetic field cannot separate pair in vacuum

M. Vidović, et al., Phys. Rev. C **47**, 2308 (1993).

Phenomenology of $\gamma\gamma \to l^+ l^-$ in HICs





1. External Field Approximation
   - Nuclei are not deflected, maintain straight-line velocity
   - Field results from entire charge distribution
2. Equivalent Photon Approximation (EPA)
   - Photon number density related to time-averaged energy-flux

$$n(\omega; b_\perp) = \frac{1}{\pi\omega} |E_\perp(\omega, b_\perp)|^2$$

$$= \frac{4Z^2\alpha_{em}}{\omega} \times \left| \int \frac{d^2k_\perp}{(2\pi)^2} k_\perp \frac{F\left(k_\perp + {\omega^2}/{\gamma^2}\right)}{k_\perp + {\omega^2}/{\gamma^2}} e^{-ib_\perp \cdot k_\perp} \right|^2$$

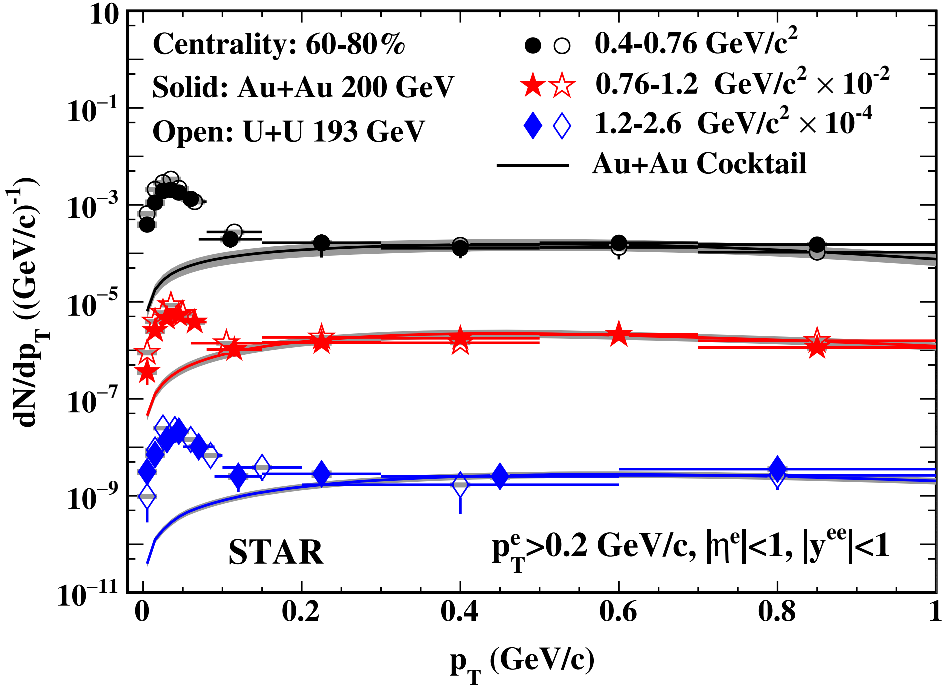
Basic phenomenology in place for > 20 years, so what is new?

M. Vidović, et al., Phys. Rev. C **47**, 2308 (1993).

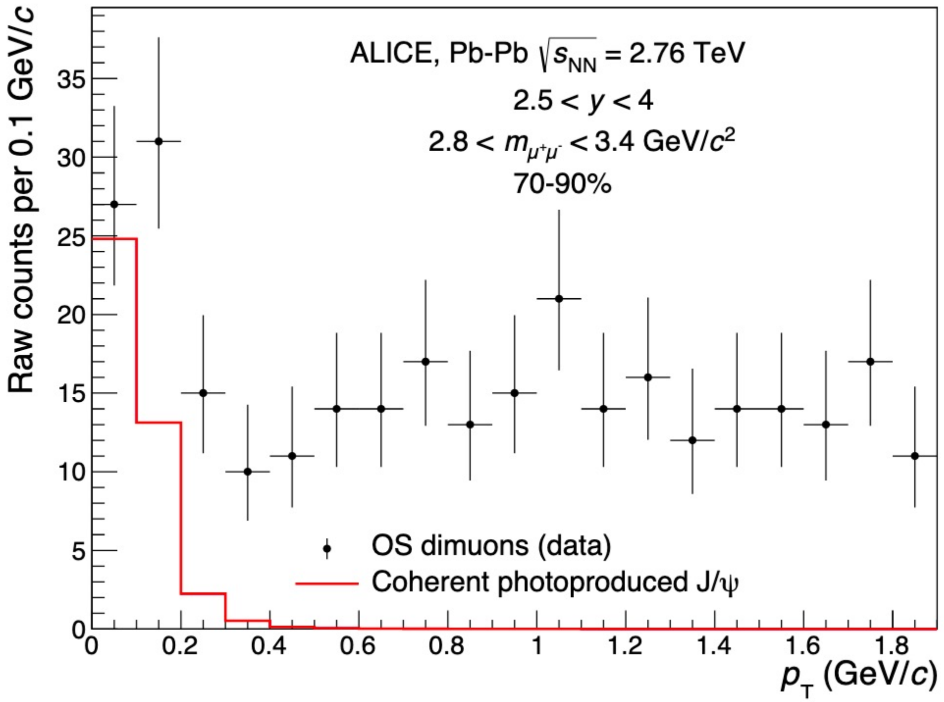
Photo-Processes in **Hadronic Collisions**

$\gamma\gamma \rightarrow l^+l^-$ in 60 – 80% Central

$\gamma\mathbb{P} \rightarrow J/\psi$ in 70 – 90% Central



STAR Collaboration, PRL.121(13), 132301 (2018).



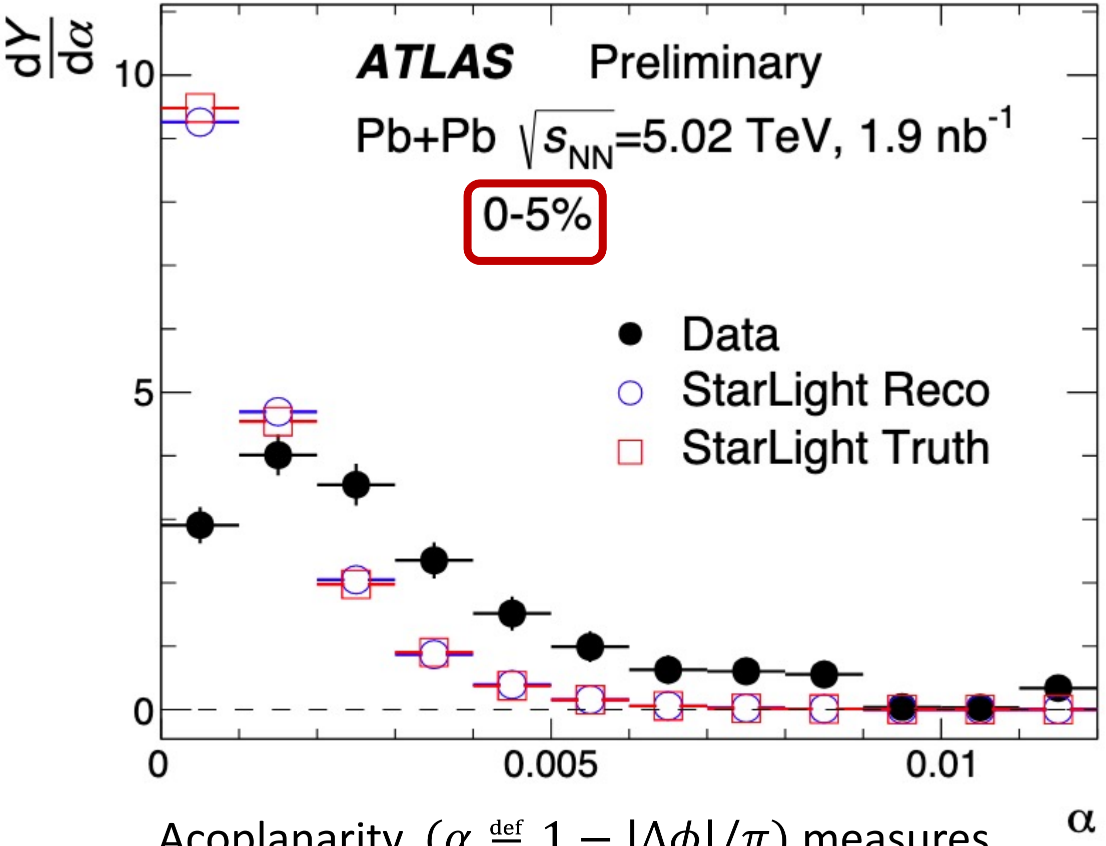
J. Adam *et al.* (ALICE Collaboration) Phys. Rev. Lett. 116, 222301

- Significant excess yields at low transverse momentum
  - Very small photon p_T from coherent EM field
- Clear signature of photon mediated processes, even in hadronic collisions

Photon-Photon processes in **Central Collisions**

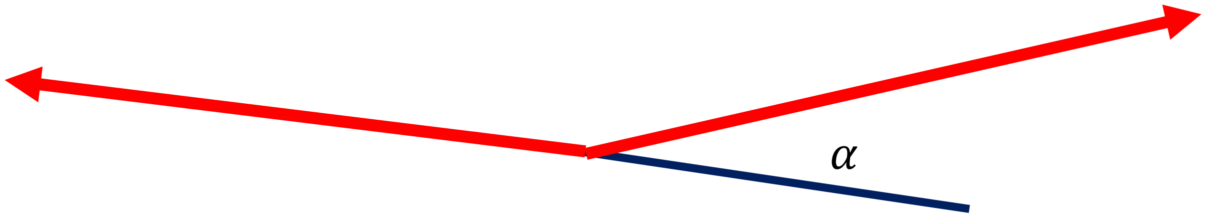
- ATLAS: able to measure $\gamma\gamma \rightarrow \mu^+\mu^-$ even in central collisions

ATLAS-CONF-2019-051



Acoplanarity, ($\alpha \overset{\text{def}}{=} 1 - |\Delta\phi|/\pi$) measures how back-to-back is the pair

- Stringent test of impact parameter dependence in $b \rightarrow 0$ fm collisions
- Significant broadening of α in central collisions compared to STARLight

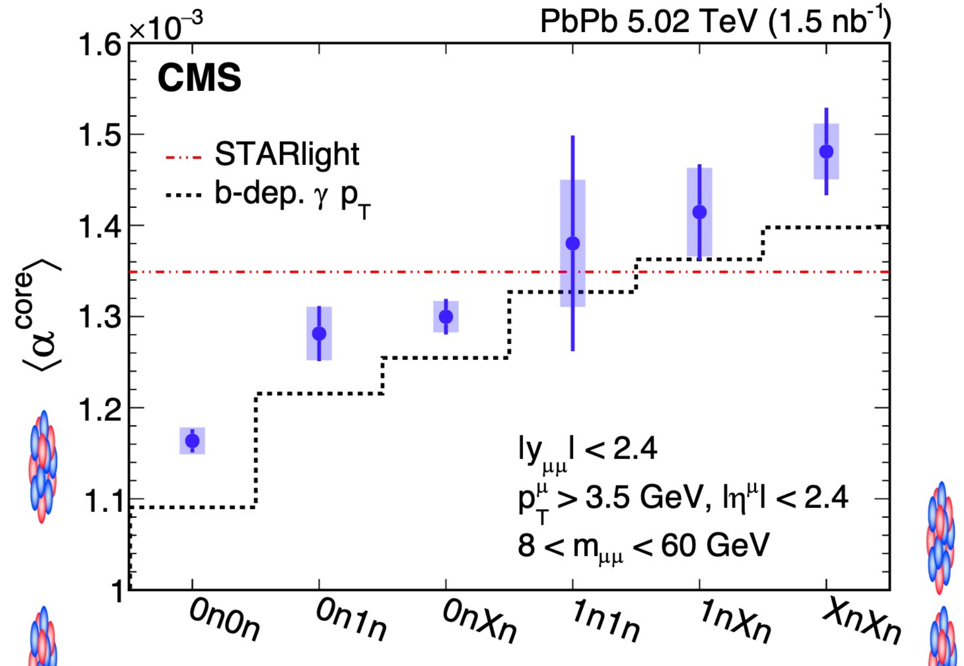


What is the source of this broadening?

ATLAS, Phys. Rev. Lett. 121, 212301 (2018)

Testing **Impact Parameter Dependence**

Creative new ways to test **impact parameter dependence** of photons in UPC



CMS: arXiv:2011.05239

Other unique measurements from STAR, ATLAS, ALICE …

Use neutron spectra to access impact parameter dependence

Neutron Spectra in UPC ⇔ Glauber in HICs

- Strong impact parameter dependence

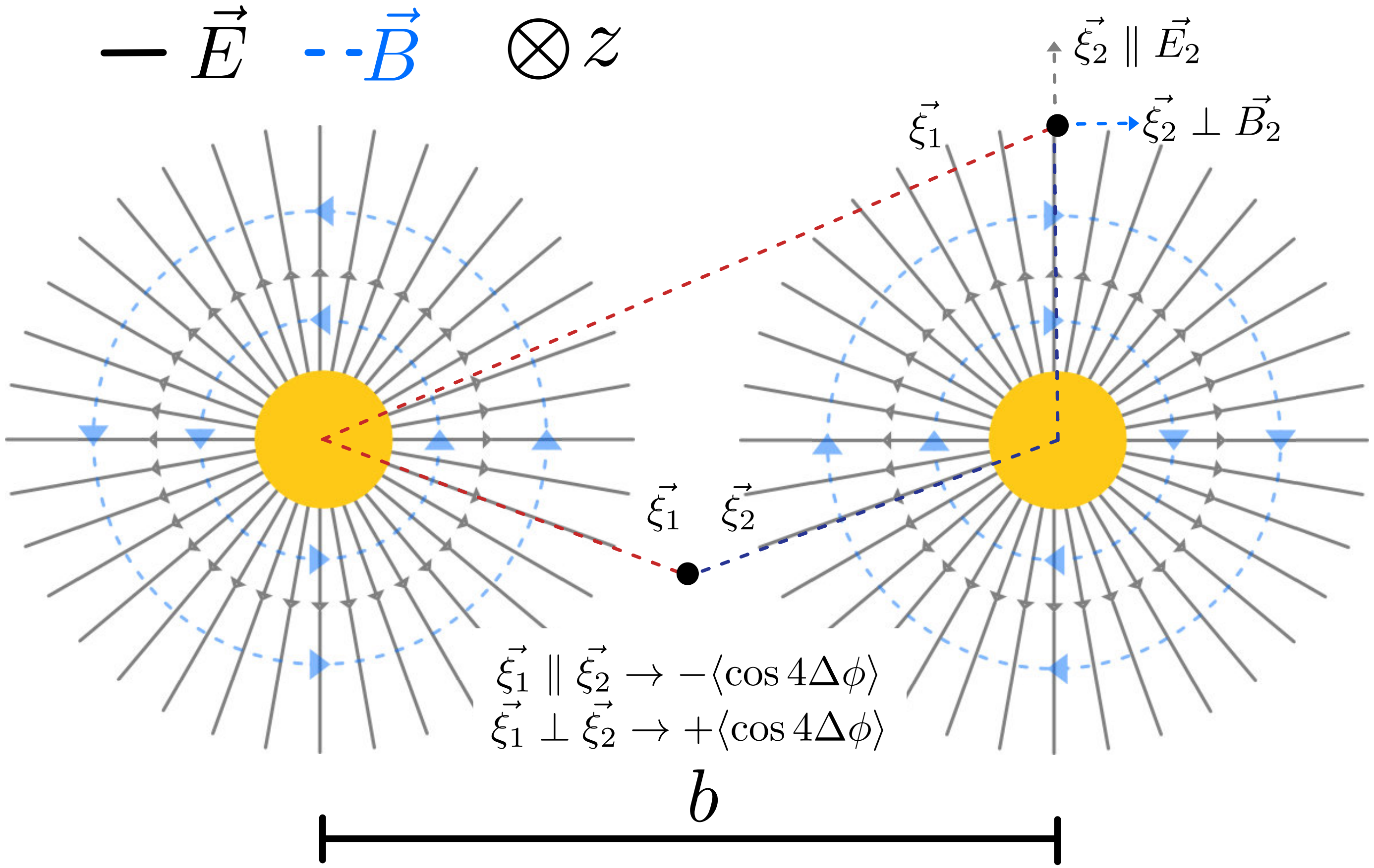
→ Traditional EPA fails to describe data

→ Trend agrees with full QED calculations & calculations via Wigner functions

What do we learn?

→ **Photon momenta results from field geometry**

Photon Polarization

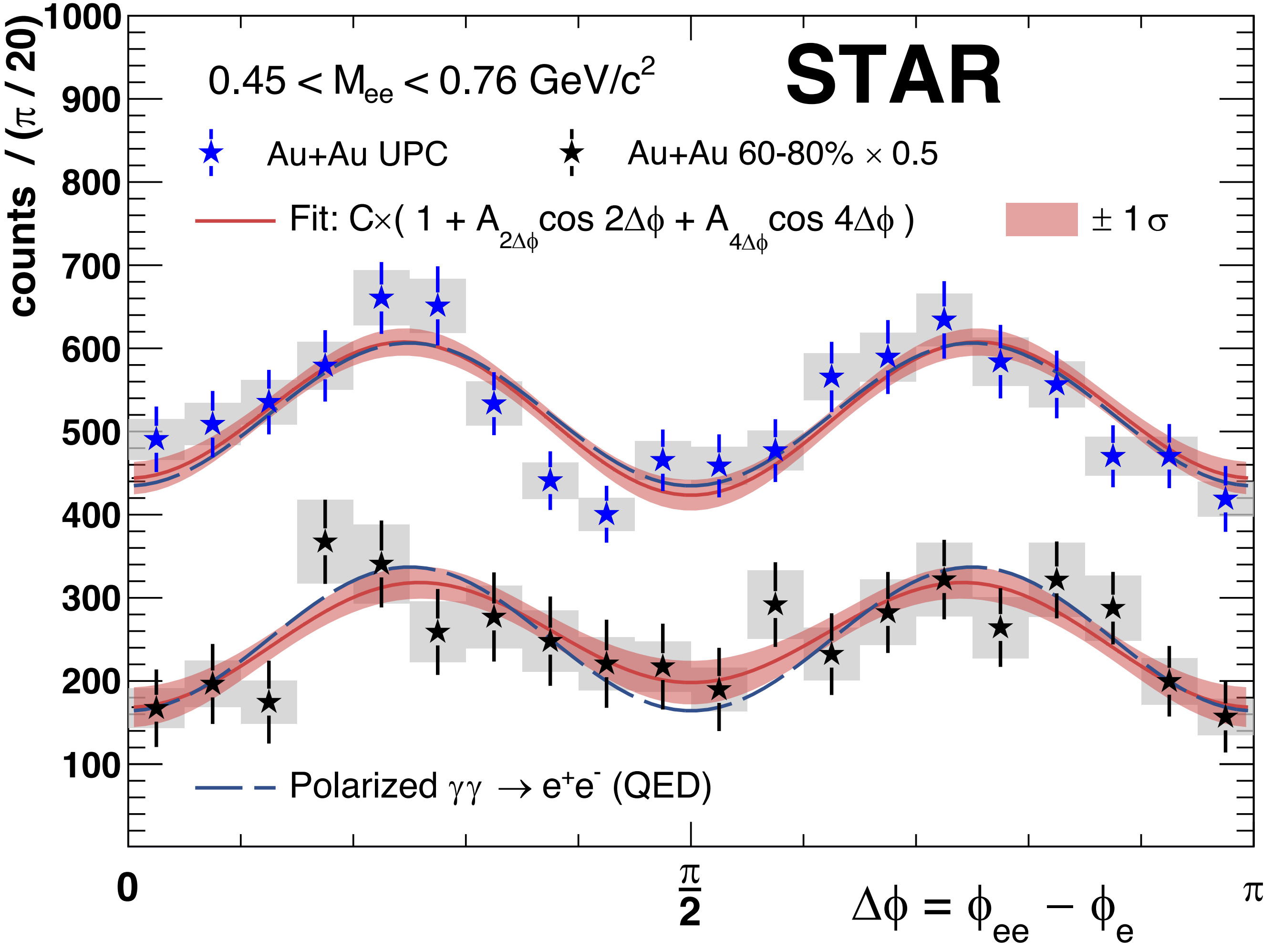


Photon Polarization:

- Polarization vector is defined by the semi-classical EM fields
- Experimental signature of polarization: $\cos 4\phi$ modulation
- Final $\cos 4\phi$ modulation depends precisely on the field strength and extent in space

[1] JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).

Photon Polarization



C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
Li, C., Zhou, J. & Zhou, Y. Phys. Rev. D 101, 034015 (2020).

Photon Polarization:

- Polarization vector is defined by the semi-classical EM fields
- Experimental signature of polarization: cos 4ϕ modulation
- Final cos 4ϕ modulation depends precisely on the field strength and extent in space

Vacuum polarization effect, first laboratory evidence for vacuum birefringence

STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).
JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).
Phys. Rev. D 90, 045025
Thesis J Toll, ProQuest.https://search.proquest.com/docview/301990593/

Rigorous Theoretical Descriptions

- QED calculations from Feynman diagrams
  - W. Zha, JDB, et al., PLB **800**, 135089 (2020).
  - C. Li, J. Zhou, and Y. Zhou, *PL*B **795**, 576 (2019).
  - C. Li, J. Zhou, and Y. Zhou, Phys. Rev. D **101**, 034015 (2020).
- Calculations using photon Wigner function
  - S. R. Klein, et. al, PRL. 122, (2019), 132301
  - M. Kłusek-Gawenda, et al., PLB **814**, 136114 (2021).
- Classical field approximation
  - R. Wang, S. Pu, and Q. Wang, Phys. Rev. D **104**, 056011 (2021).
- Exact results from stochastic plane waves
  - T. Adamo, A. Ilderton, and A. J. MacLeod, arXiv:2110.02567 (2021).

$$
\begin{aligned}
\frac{d\sigma}{d^3k_1 d^3k_2} \approx\ & \frac{1}{32(2\pi)^6}\frac{1}{E_{k1}E_{k2}}\int d^2\mathbf{b}_T d^2\mathbf{b}_{1T} d^2\mathbf{b}_{2T}\int d^4p_1 d^4p_2 \\
& \times\delta^{(2)}\left(\mathbf{b}_T-\mathbf{b}_{1T}+\mathbf{b}_{2T}\right)(2\pi)^4\delta^{(4)}\left(p_1+p_2-k_1-k_2\right) \\
& \times\int\frac{d^2\mathbf{P}_{(1+1')T}}{(2\pi)^2}\frac{d^2\mathbf{P}_{(2+2')T}}{(2\pi)^2}\frac{1}{v\sqrt{E_{P1}E_{P2}E_{P1'}E_{P2'}}} \\
& \times G^2\left[(P_1'^z-P_{A1}^z)^2\right]\phi_T(\mathbf{P}_{1T})\phi_T(\mathbf{P}_{2T})\phi_T^*(\mathbf{P}'_{1T})\phi_T^*(\mathbf{P}'_{2T}) \\
& \times\mathcal{S}_{\sigma\mu}(p_1,\mathbf{b}_{1T})\mathcal{S}_{\rho\nu}(p_2,\mathbf{b}_{2T}) \\
& \times L^{\mu\nu;\sigma\rho}\left(p_1,p_2;p_1-P_1+P_1',p_2-P_2+P_2';k_1,k_2\right),
\end{aligned}
$$

Key Characteristics:

- Photon momentum (and therefore e^+e^- momentum) determined by EM field distribution – can be used to "map" the field
- Photons are quasi-real with linear polarization – sensitivity to relative polarization angle

Procedure for Mapping Field with $\gamma\gamma \rightarrow l^+l^-$

1. Measure $\mathrm{d}\sigma/dP_\perp$ from $\gamma\gamma \rightarrow l^+l^-$ interactions
2. Compute the QED prediction for various EM field input
3. Find all QED field configurations that fall within $\pm 1\sigma$ of experimental uncertainties

- QED calculation input are the four-potentials of two colliding fields

$$A_1^\mu(k_1, b_\tau) = -2\pi(Z_1 e)e^{ik_1^\tau b_\tau}\delta(k_1^\nu u_{1\nu})\frac{F_1(-k_1^\rho k_{1\rho})}{k_1^\sigma k_{1\sigma}}u_1^\mu,$$

$$A_2^\mu(k_2, b_\tau = 0) = -2\pi(Z_2 e)\delta(k_2^\nu u_{2\nu})\frac{F_2(-k_2^\rho k_{2\rho})}{k_2^\sigma k_{2\sigma}}u_2^\mu.$$

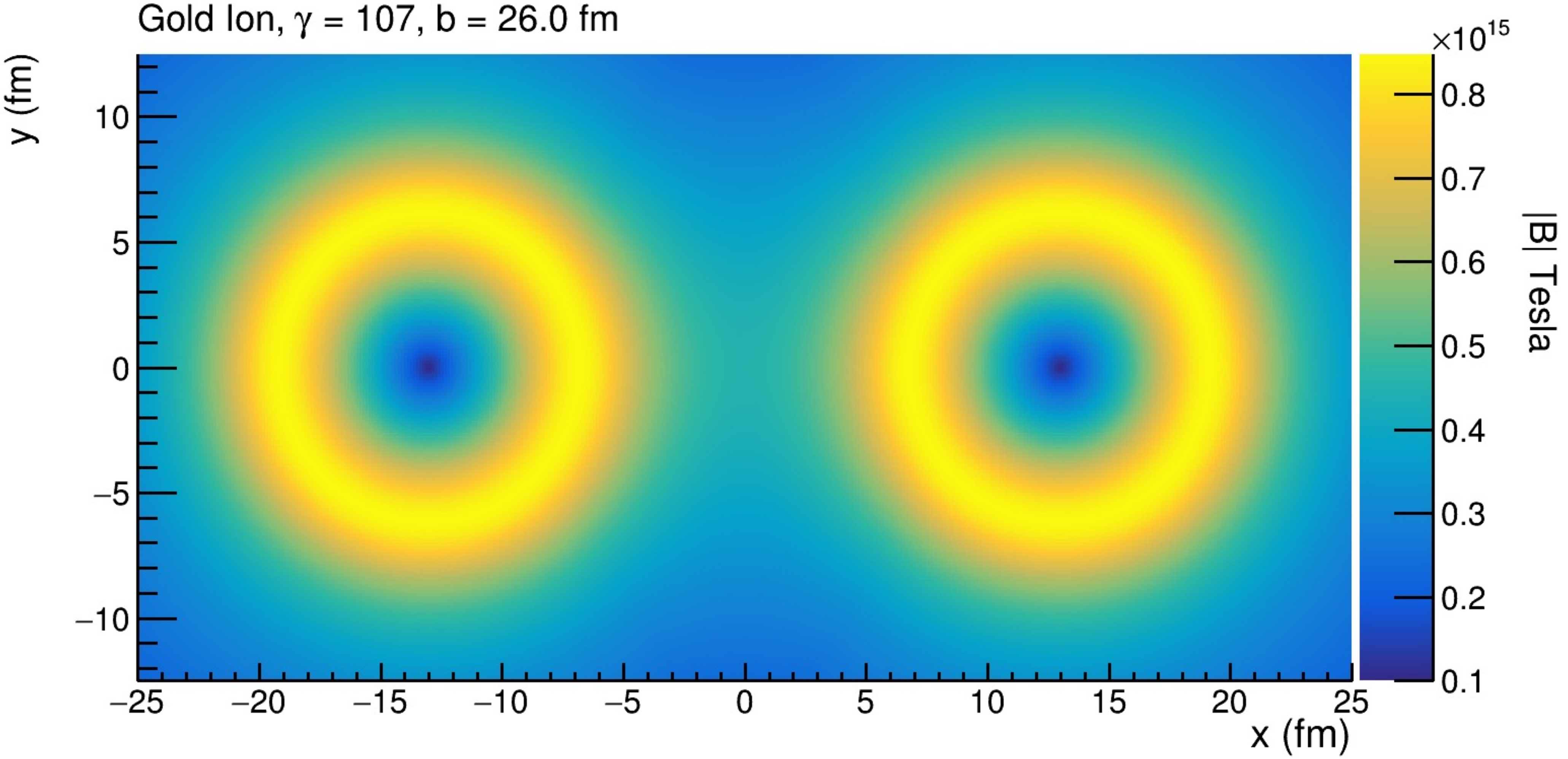
→ Only the electromagnetic form factor(FF) and photon kinematics are “free” parameters

→ Numerically compute FF from Woods-Saxon density, vary R and a

[1] JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).

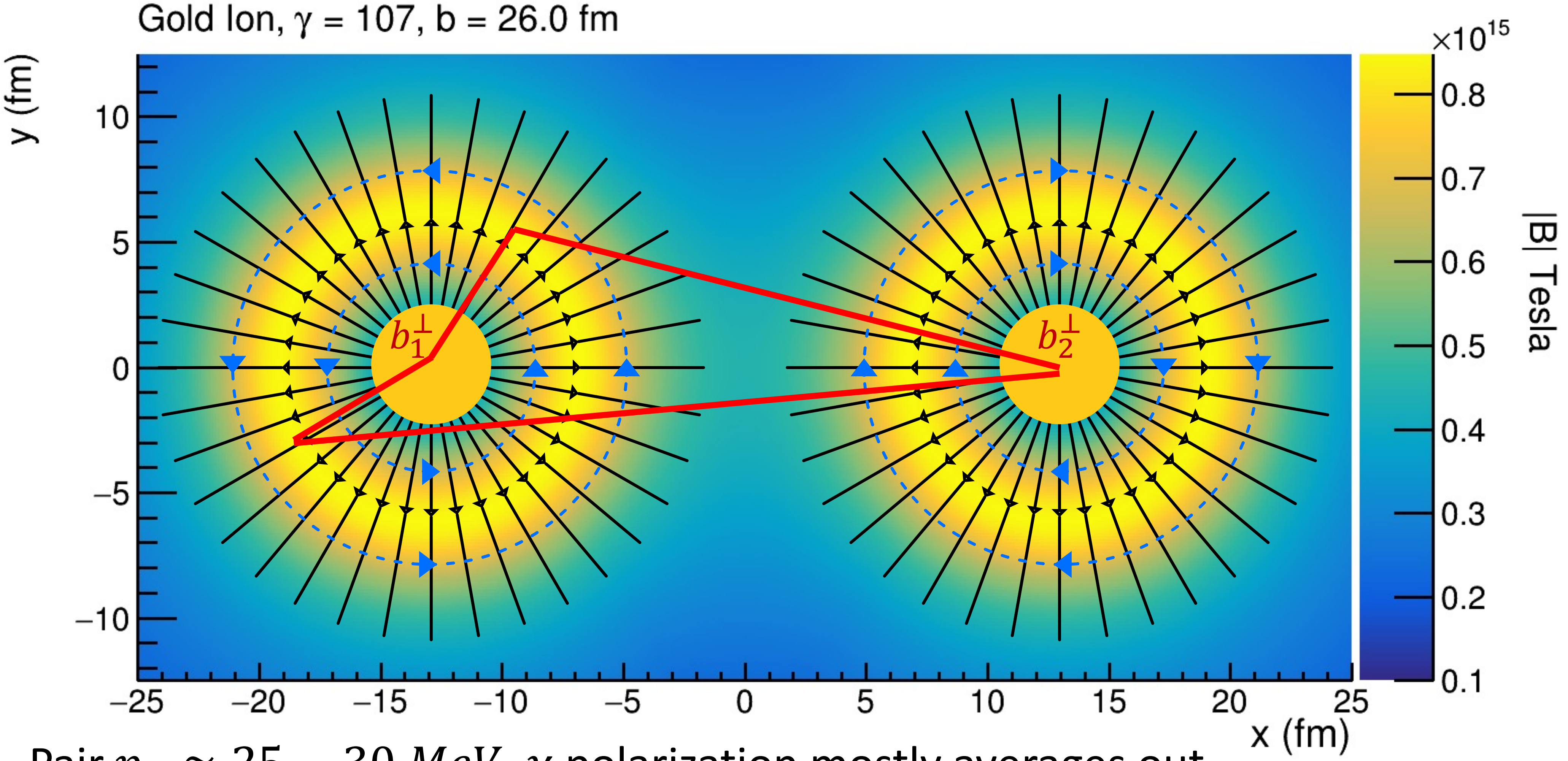
Field distribution from QED

Photon density is $\propto |E|^2, |\mathrm{B}|^2$



Field distribution from QED

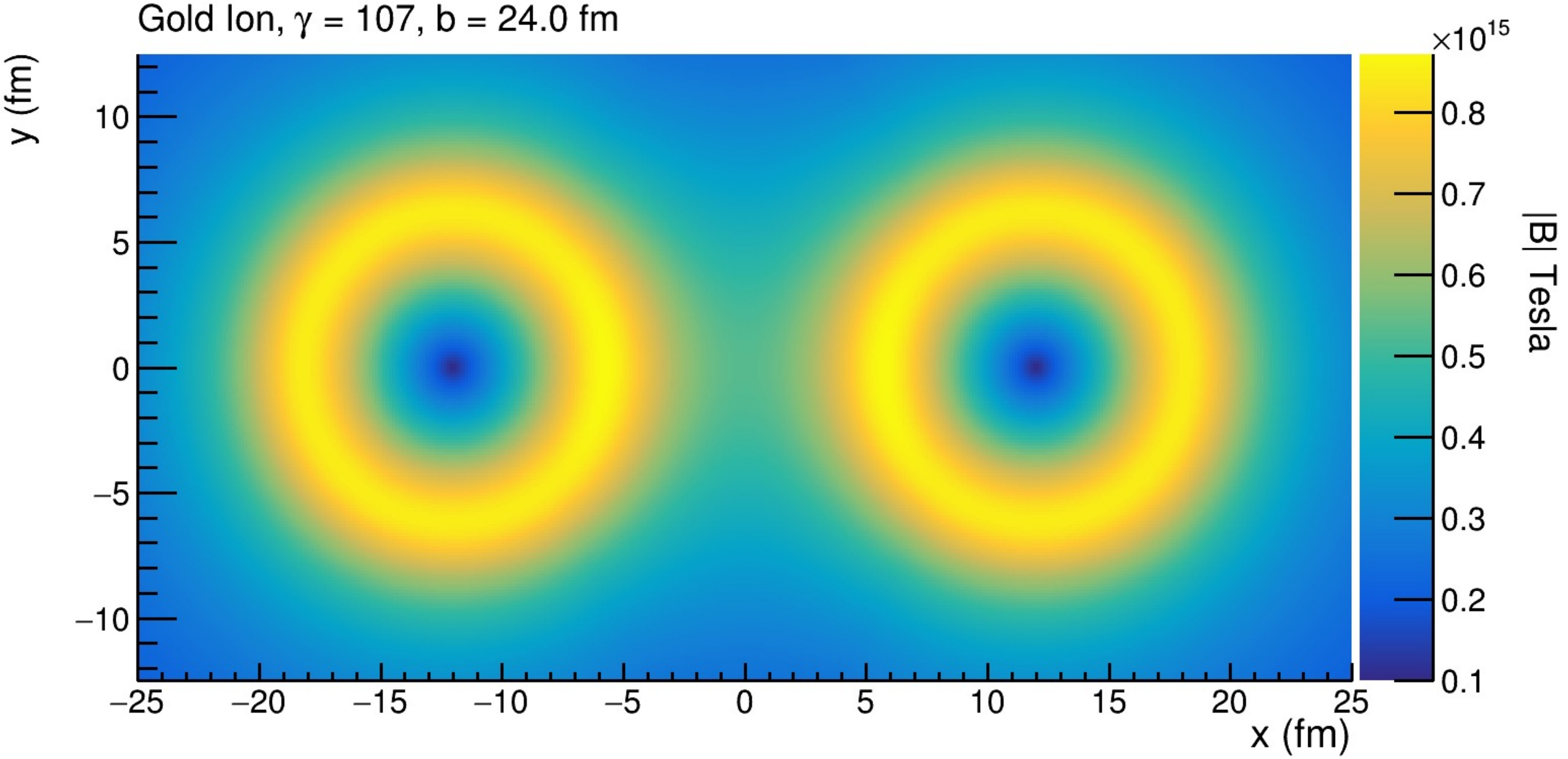
Photon density is $\propto |E|^2, |\mathrm{B}|^2$



Pair $p_\perp \approx 25 - 30\ MeV, \gamma$ polarization mostly averages out

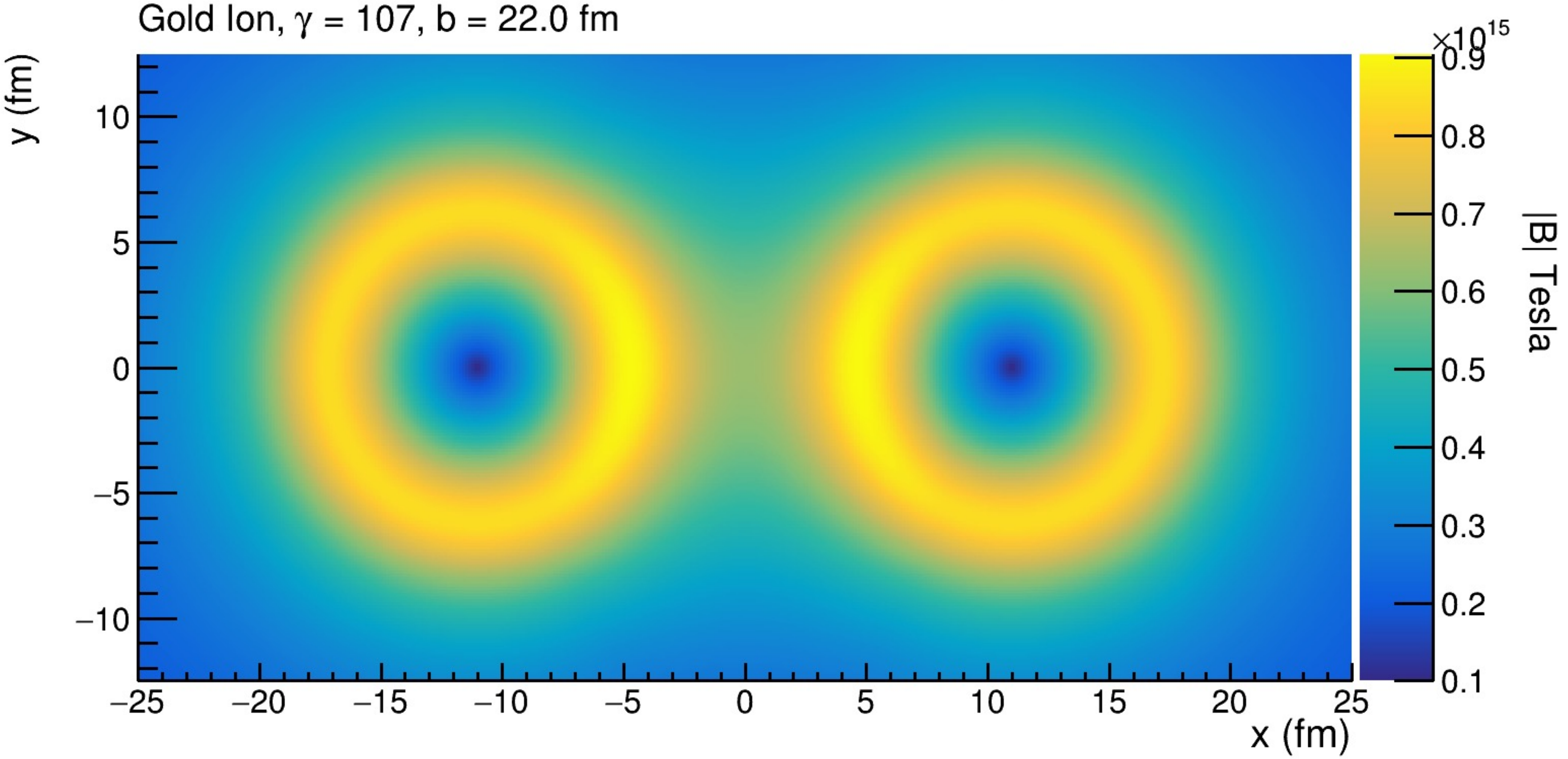
Field distribution from QED

Photon density is $\propto |E|^2, |\mathrm{B}|^2$



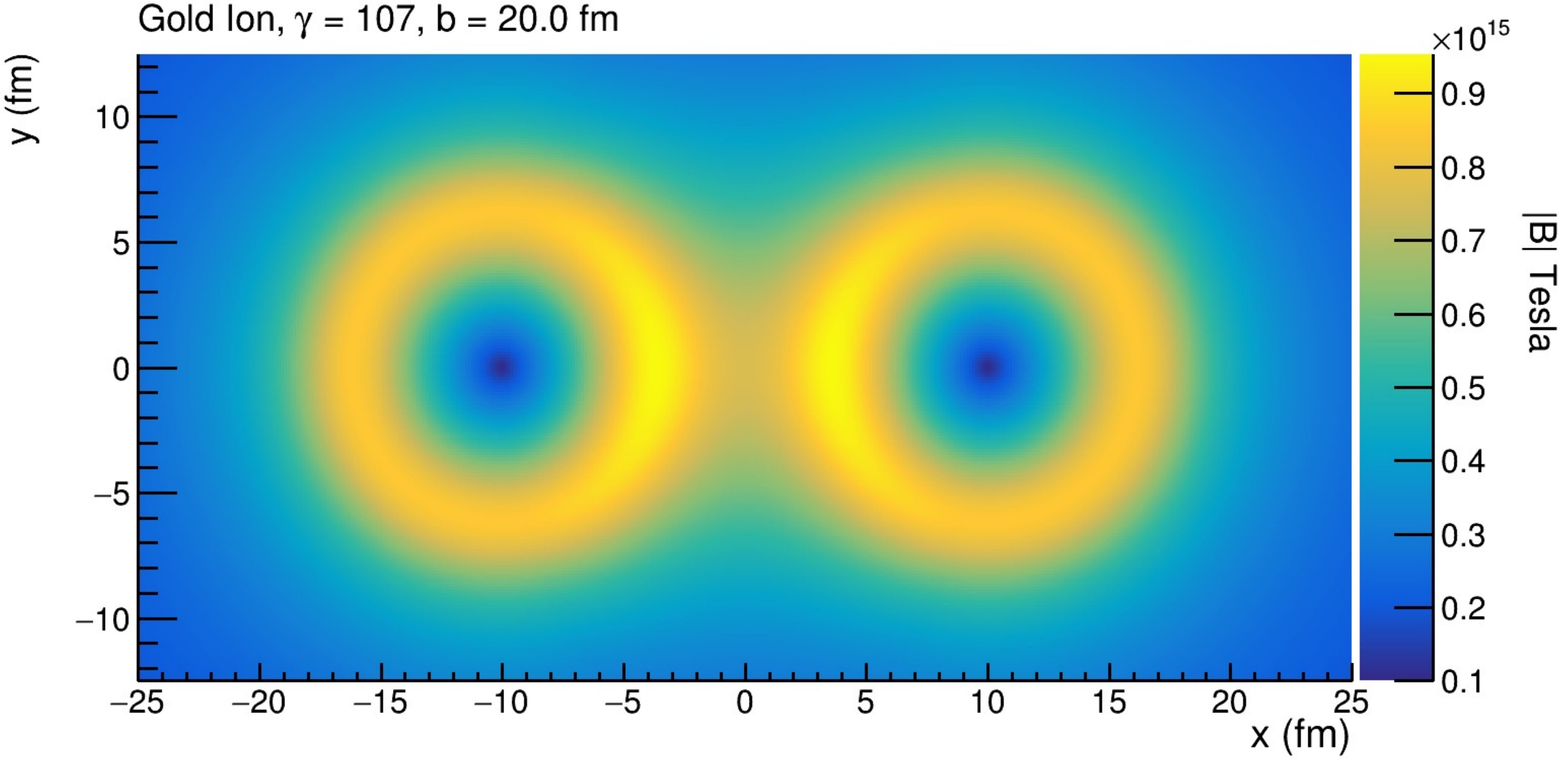
Field distribution from QED

Photon density is $\propto |E|^2, |\mathrm{B}|^2$



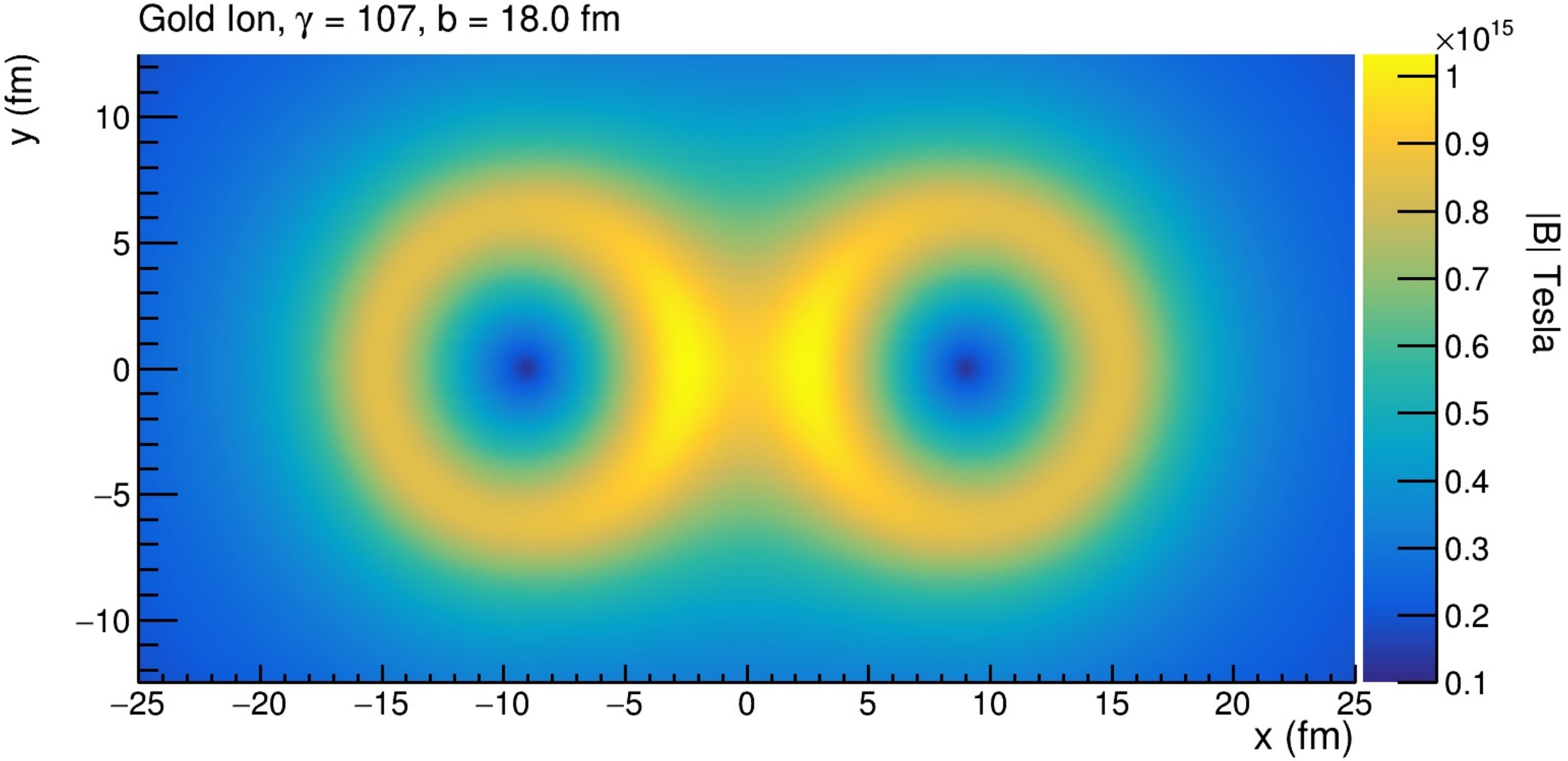
Field distribution from QED

Photon density is $\propto |E|^2, |\mathrm{B}|^2$



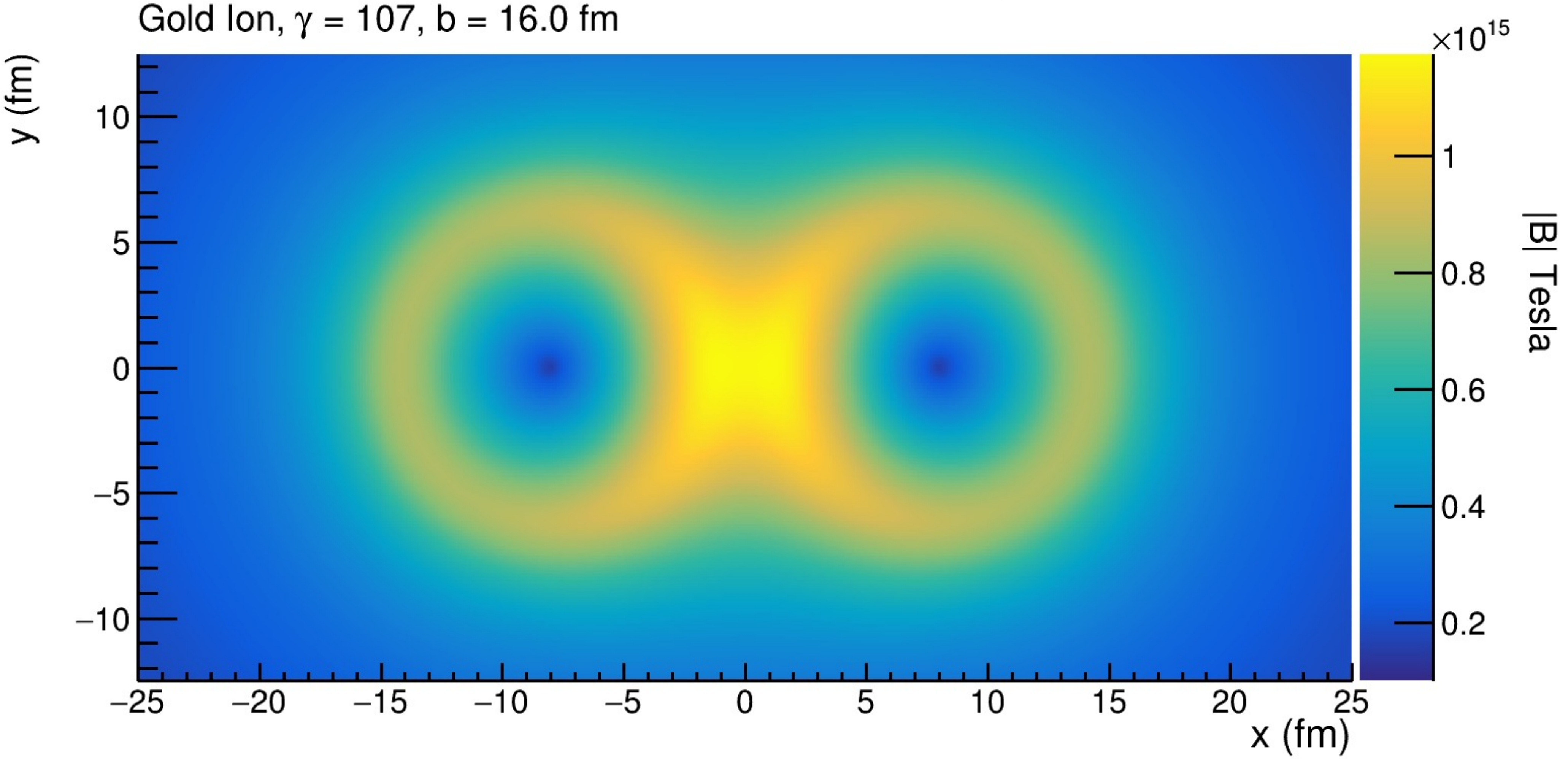
Field distribution from QED

Photon density is $\propto |E|^2, |B|^2$



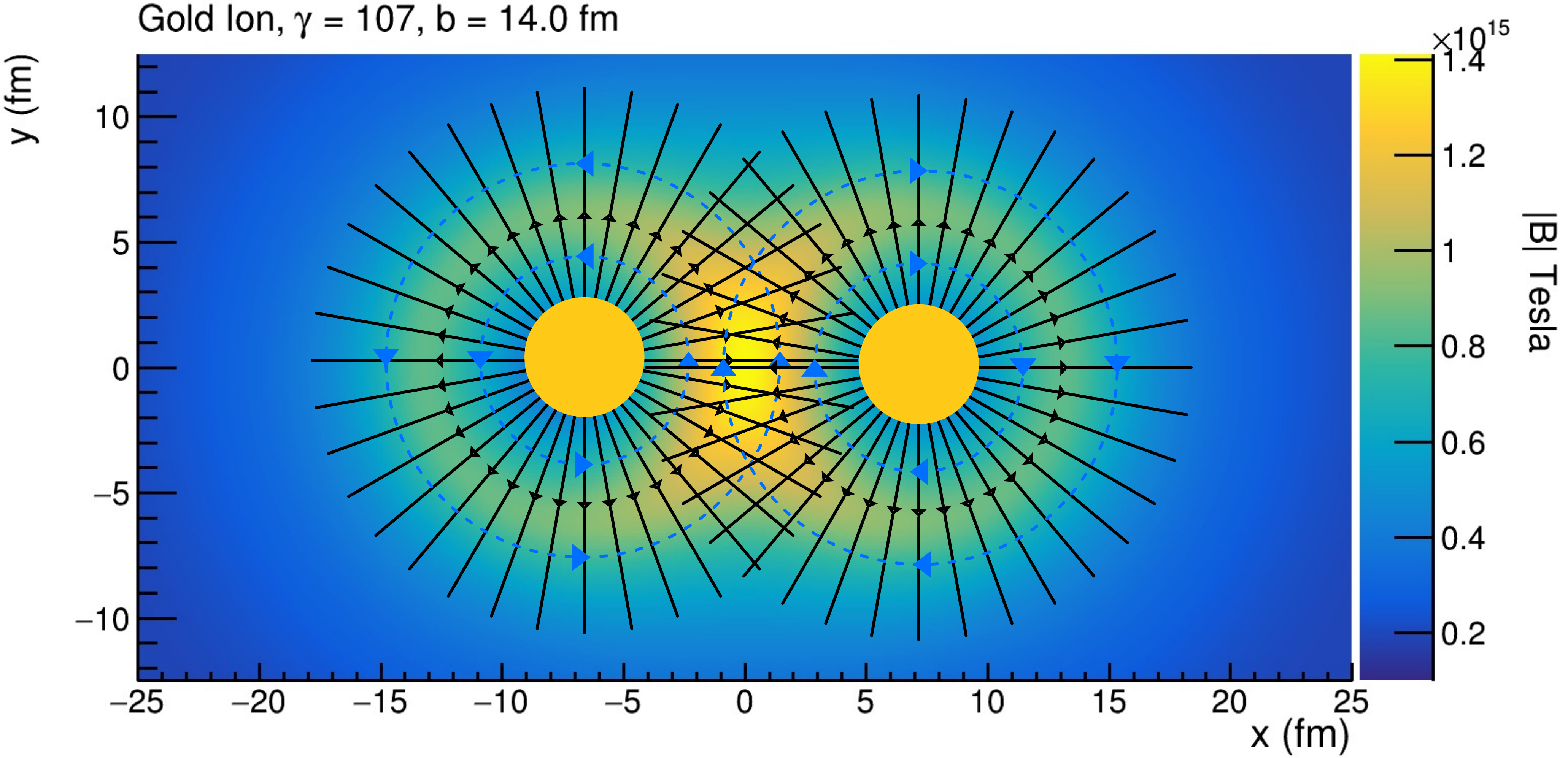
Field distribution from QED

Photon density is $\propto |E|^2, |\mathrm{B}|^2$



Field distribution from QED

Photon density is $\propto |E|^2, |\mathrm{B}|^2$

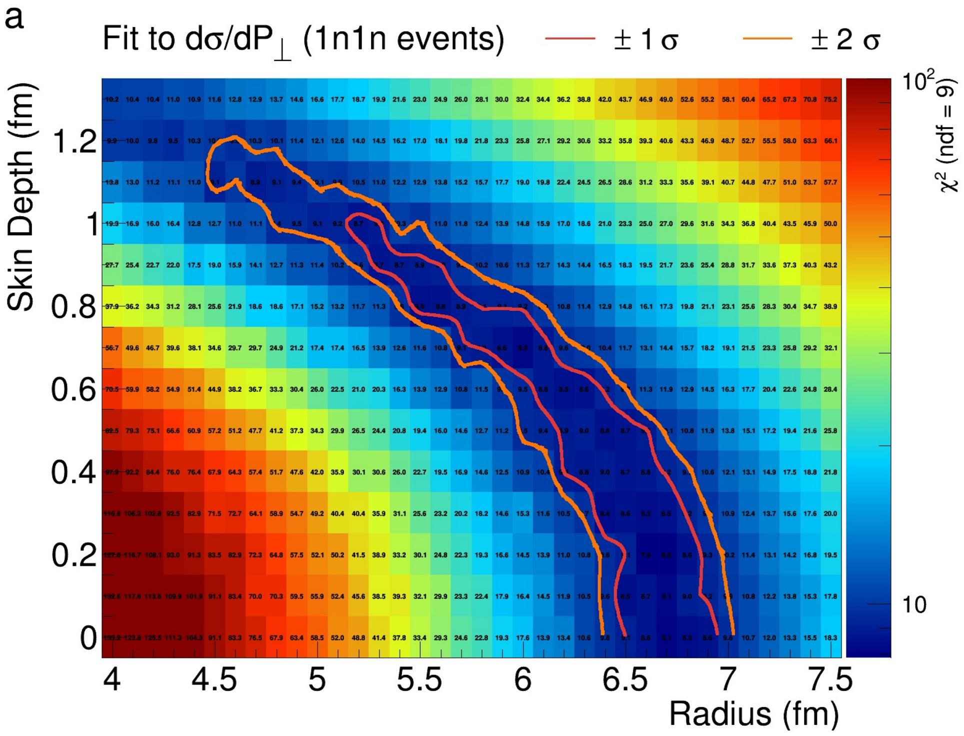


Pair $p_{\perp} \approx 40\ MeV$, γ polarization : mostly (anti)parallel → $-\cos 4\Delta\phi$

Mapping of EM Field Distribution

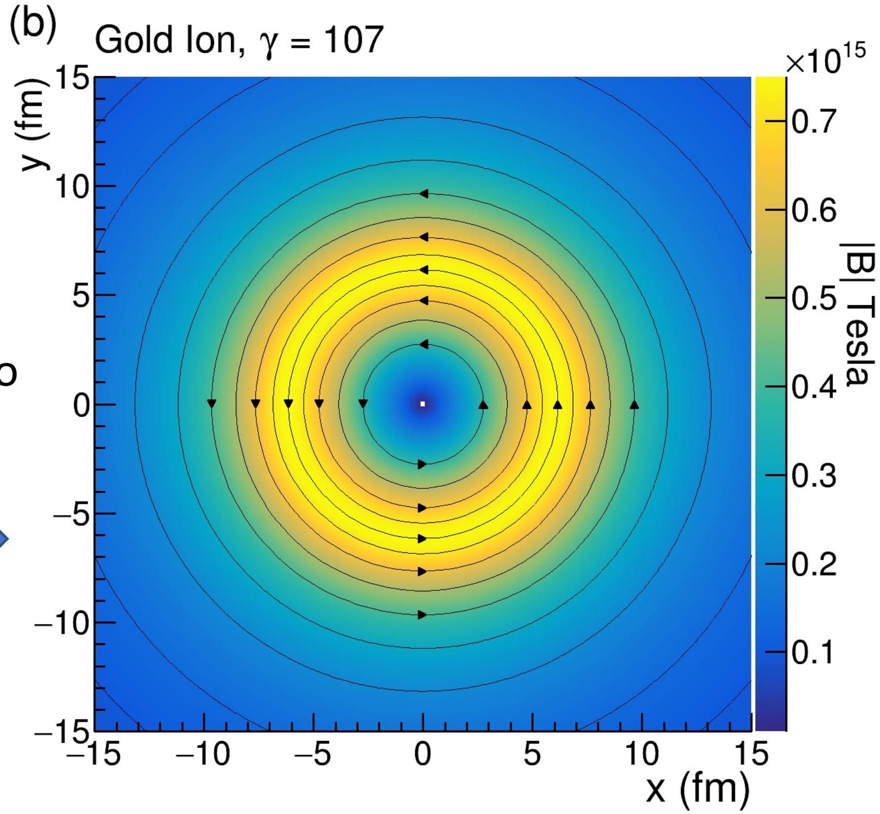
STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).
JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).

Precision transverse momentum + polarization = constrain field spatial extent



Assumptions:

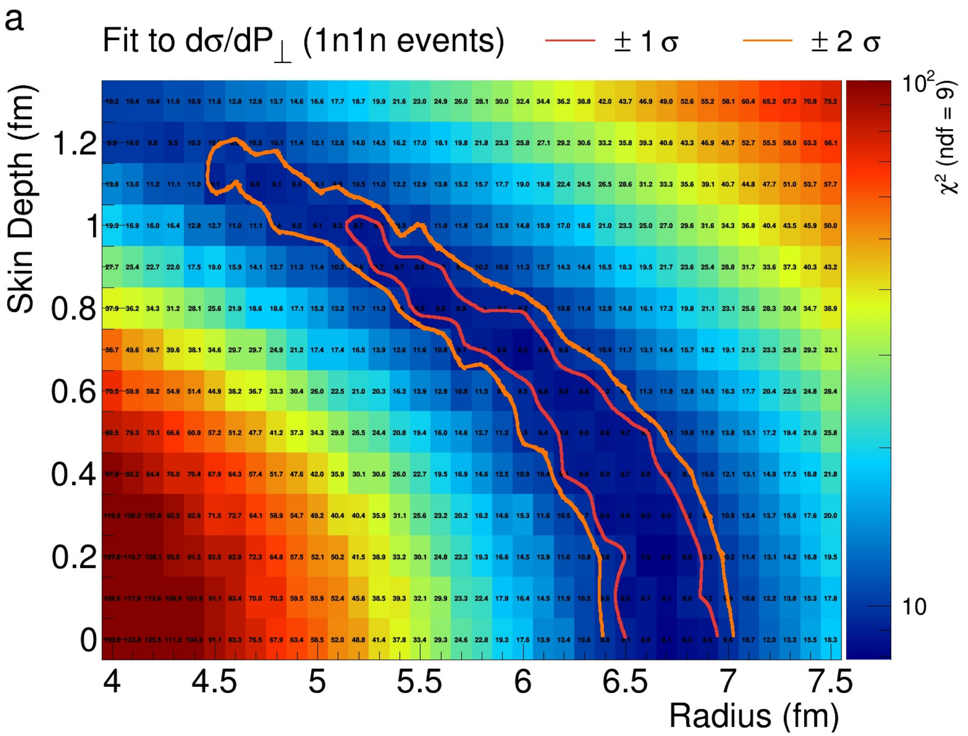
1) Continuous Woods-Saxons distribution
2) Individual field of two ions are identical

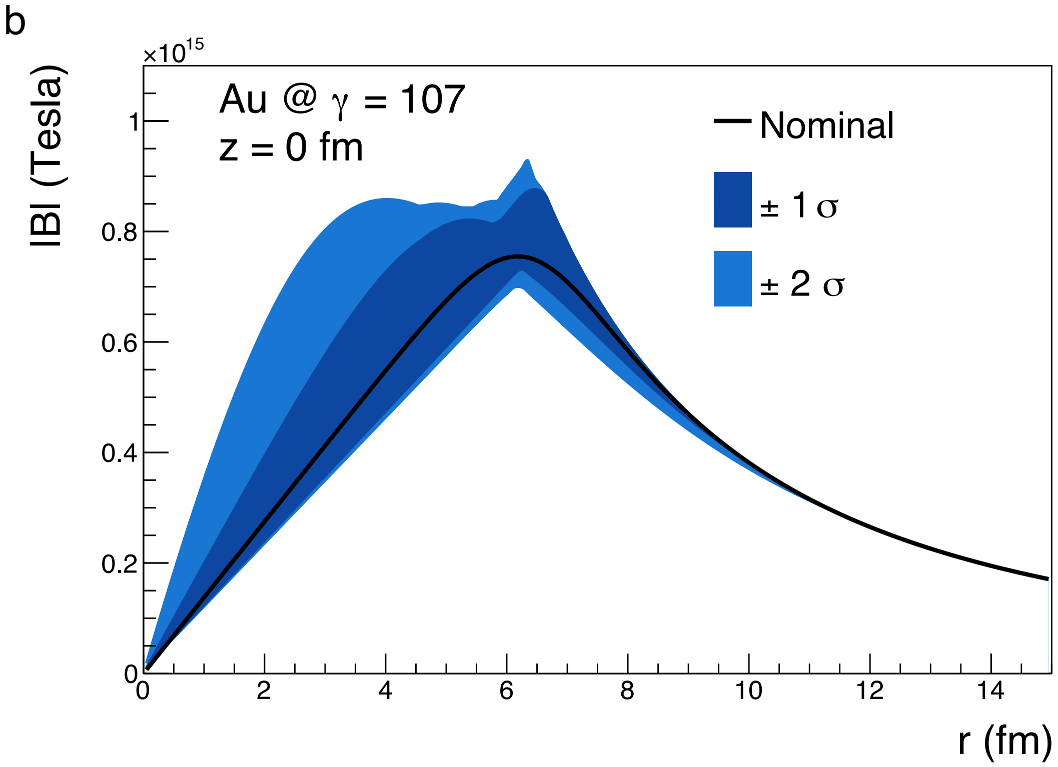


Mapping of EM Field Distribution

STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021).
JDB, W. Zha, and Z. Xu, Eur. Phys. J. A **57**, 299 (2021).

Precision transverse momentum + polarization = constrain field spatial extent





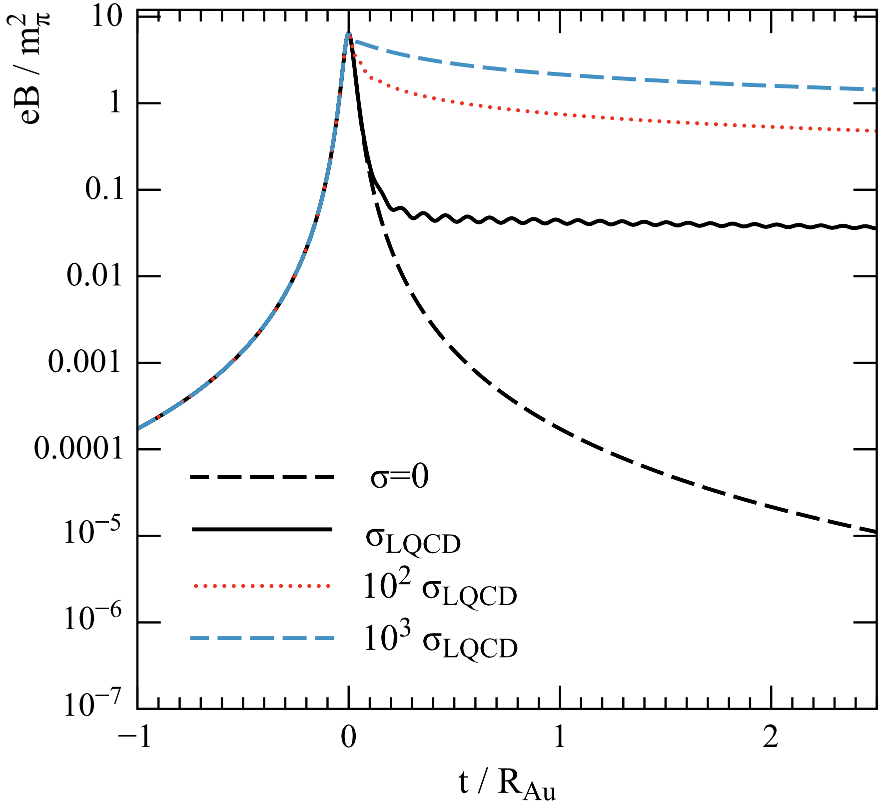
- Much stronger field possible at small distances
  - More measurements needed to constrain event-by-event fluctuations of EM fields
- **Novel input for magnetic-field driven phenomena**

Part 3: EM Fields in Medium

[1] Skokov, V. V., Illarionov, A. Yu. & Toneev, V. D. *Int. J. Mod. Phys. A* **24**, 5925–5932 (2009).
[2] A. Bzdak and V. Skokov,, Physics Letters B **710**, 171 (2012).

Searching for Medium Effects

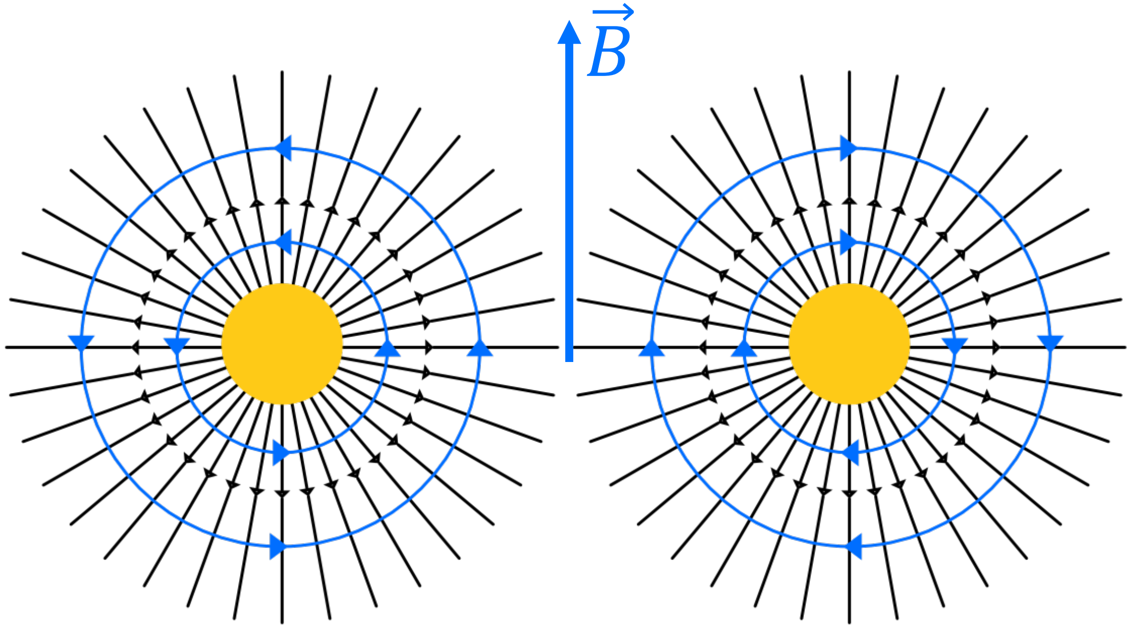
L. McLerran, V. Skokov, Nuclear Physics A 929 (2014) 184–190



- Question:
  - Electrically conductive QGP → “trap” the field
- Possible Effect:
  - Increased pair production
  - Lorentz-force bending of e^+/e^-

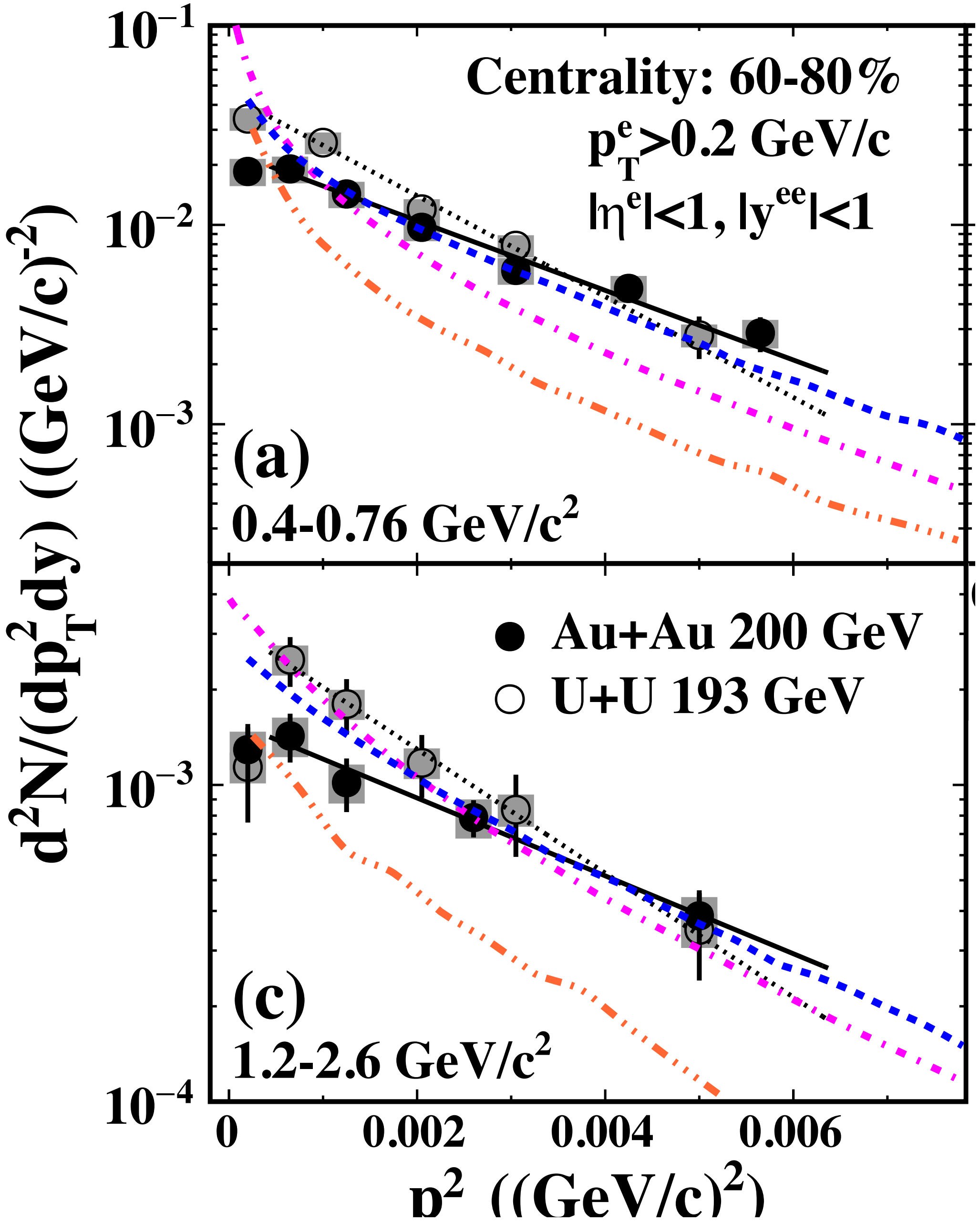
Long-lived Magnetic Field?

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$



<u>Assumptions:</u>

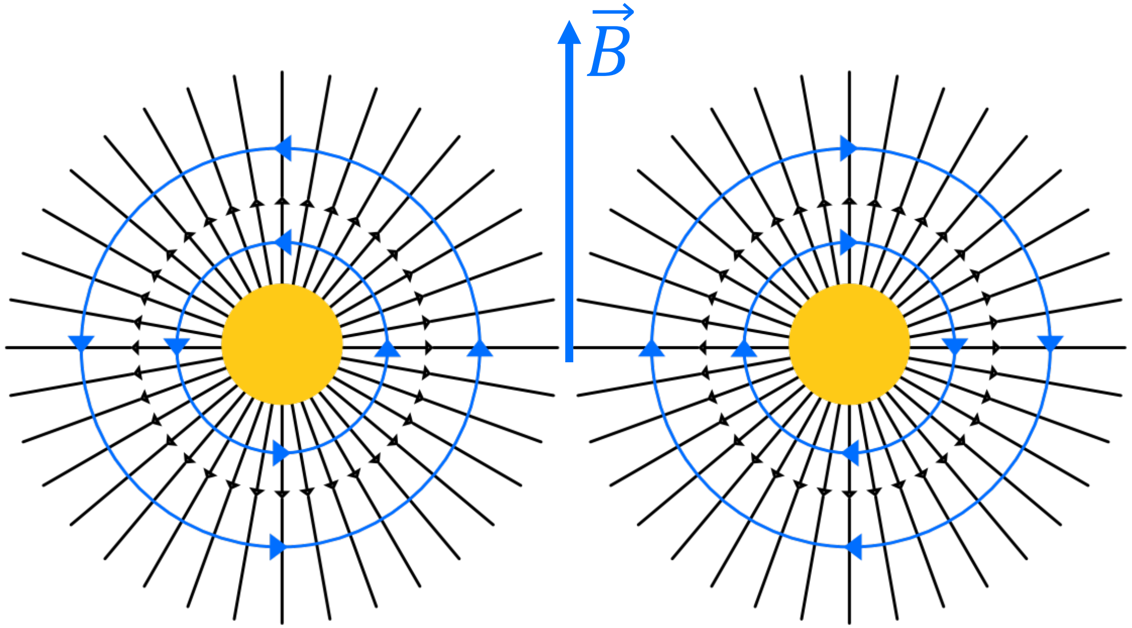
1. **Used STARLight $P_\perp$ Spectra as baseline**
2. All $e^{\pm}$ travers 1 fm through $|B| \approx 10^{14}$T ($eBL \approx 30$ MeV/c)

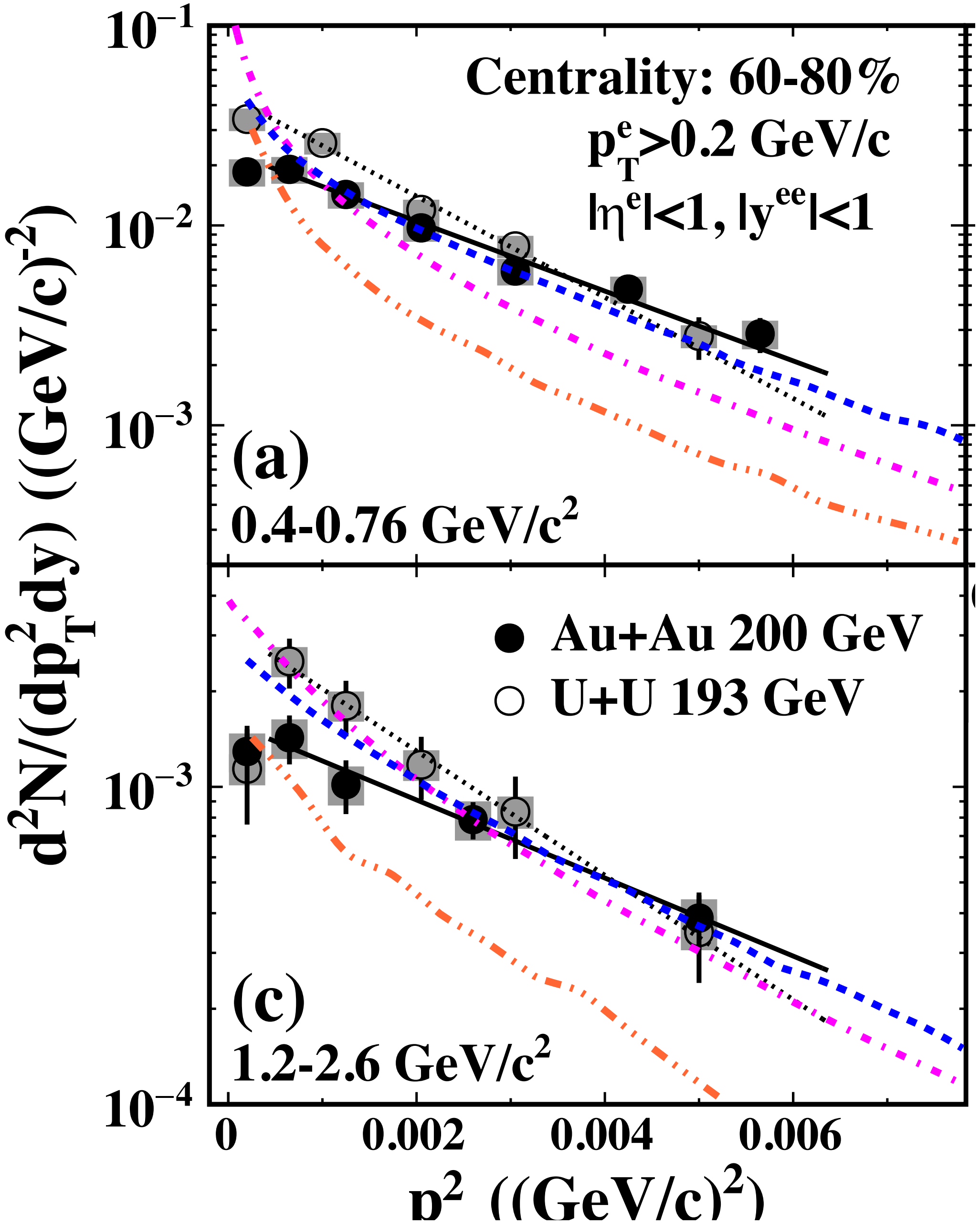


STAR Collaboration, Phys. Rev. Lett. **121**, 132301 (2018).

Long-lived Magnetic Field?

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$





STAR Collaboration, Phys. Rev. Lett. **121**, 132301 (2018).

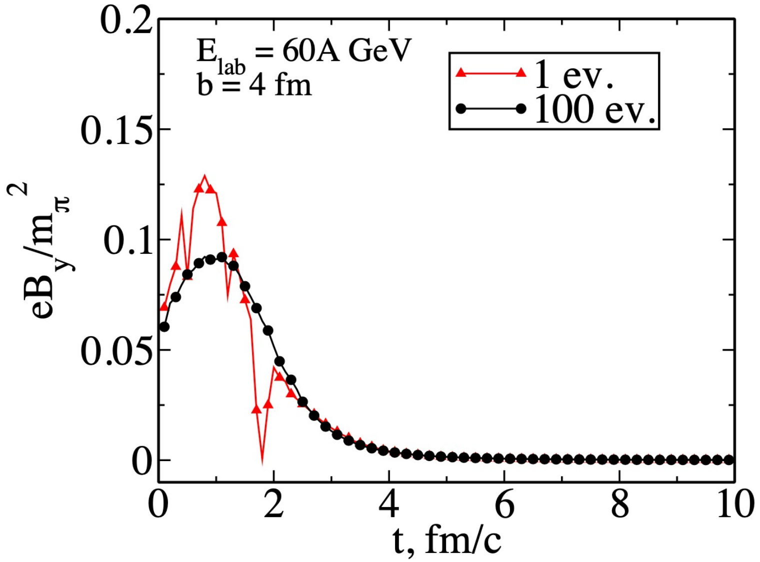
Distinguishing Characteristics:

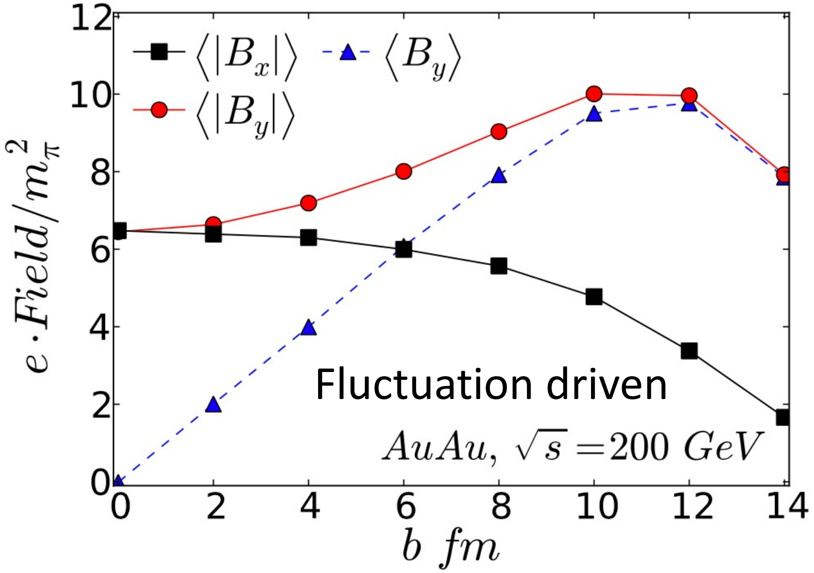
- Effect should increase with rapidity difference between leptons
- Effect should saturate for separation > 3 units of rapidity

S. Klein, A.H. Mueller, B.W. Xiao, F. Yuan, Phys. Rev. D 102(9), 094013 (2020).

[1] Skokov, V. V., Illarionov, A. Yu. & Toneev, V. D. *Int. J. Mod. Phys. A* **24**, 5925–5932 (2009).
[2] A. Bzdak and V. Skokov,, Physics Letters B **710**, 171 (2012).

Searching for Medium Effects





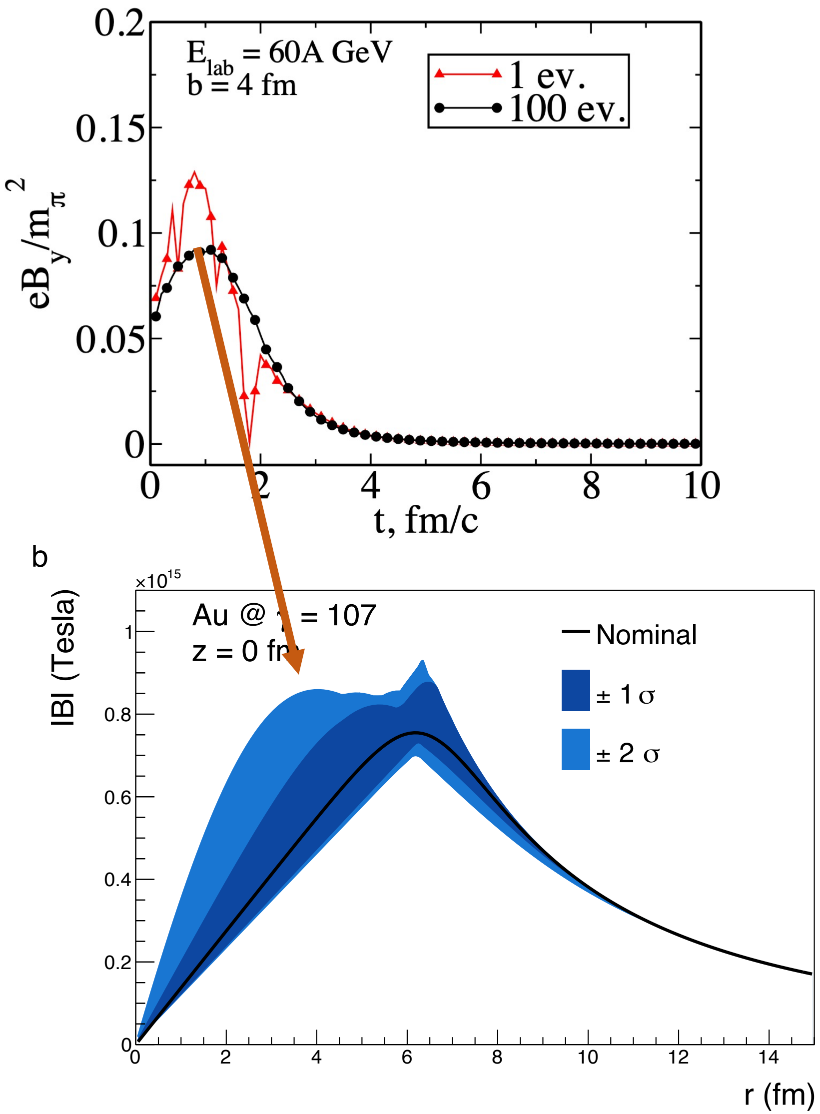
Fluctuation driven

- Question:
  - Field at low-x and effect of event-by-event fluctuations

- Possible Effect:
  - Modified $P_\perp$ and α distribution
  - Modification of relative photon-photon polarization angle
    → Modified $\cos 4\phi$ modulation

[1] Skokov, V. V., Illarionov, A. Yu. & Toneev, V. D. *Int. J. Mod. Phys. A* **24**, 5925–5932 (2009).
[2] A. Bzdak and V. Skokov,, Physics Letters B **710**, 171 (2012).

Event-by-event Fluctuations + Interactions

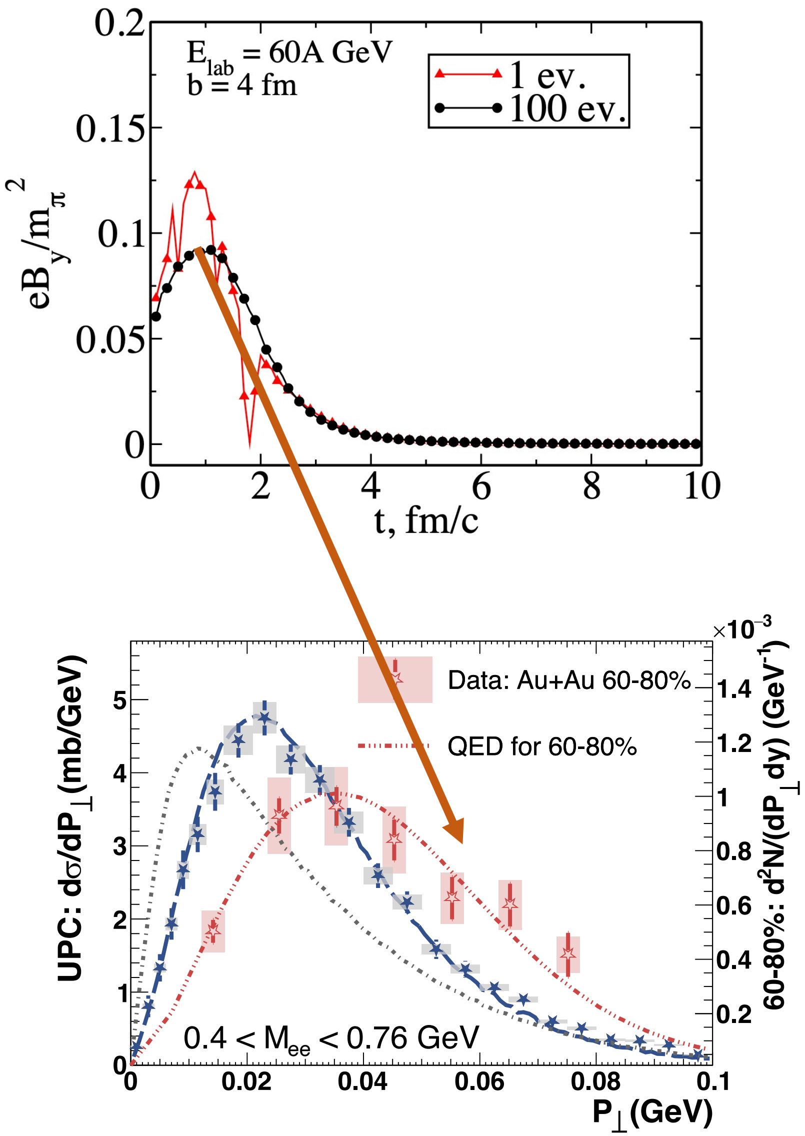


- Significantly stronger field possible at small radial distances (based on current data)
- Fluctuating nucleon positions effect field inside nucleus
- OR Long-lived magnetic field → Lorentz-force bending of pairs
- High precision data from STAR 2023-25
- What to look for:
  - Field at small distance→ large $P_\perp$ and α
  - Look for modification of $d\sigma/dP_\perp$ shape

[1] Skokov, V. V., Illarionov, A. Yu. & Toneev, V. D. *Int. J. Mod. Phys. A* **24**, 5925–5932 (2009).

[2] A. Bzdak and V. Skokov,, Physics Letters B **710**, 171 (2012).

Event-by-event Fluctuations + Interactions



- Significantly stronger field possible at small radial distances (based on current data)
- Fluctuating nucleon positions effect field inside nucleus
- OR Long-lived magnetic field
  → Lorentz-force bending of pairs
- High precision data from STAR 2023-25
- What to look for:
  - Field at small distance→ large $P_\perp$ and α
  - Look for modification of $d\sigma/dP_\perp$ shape

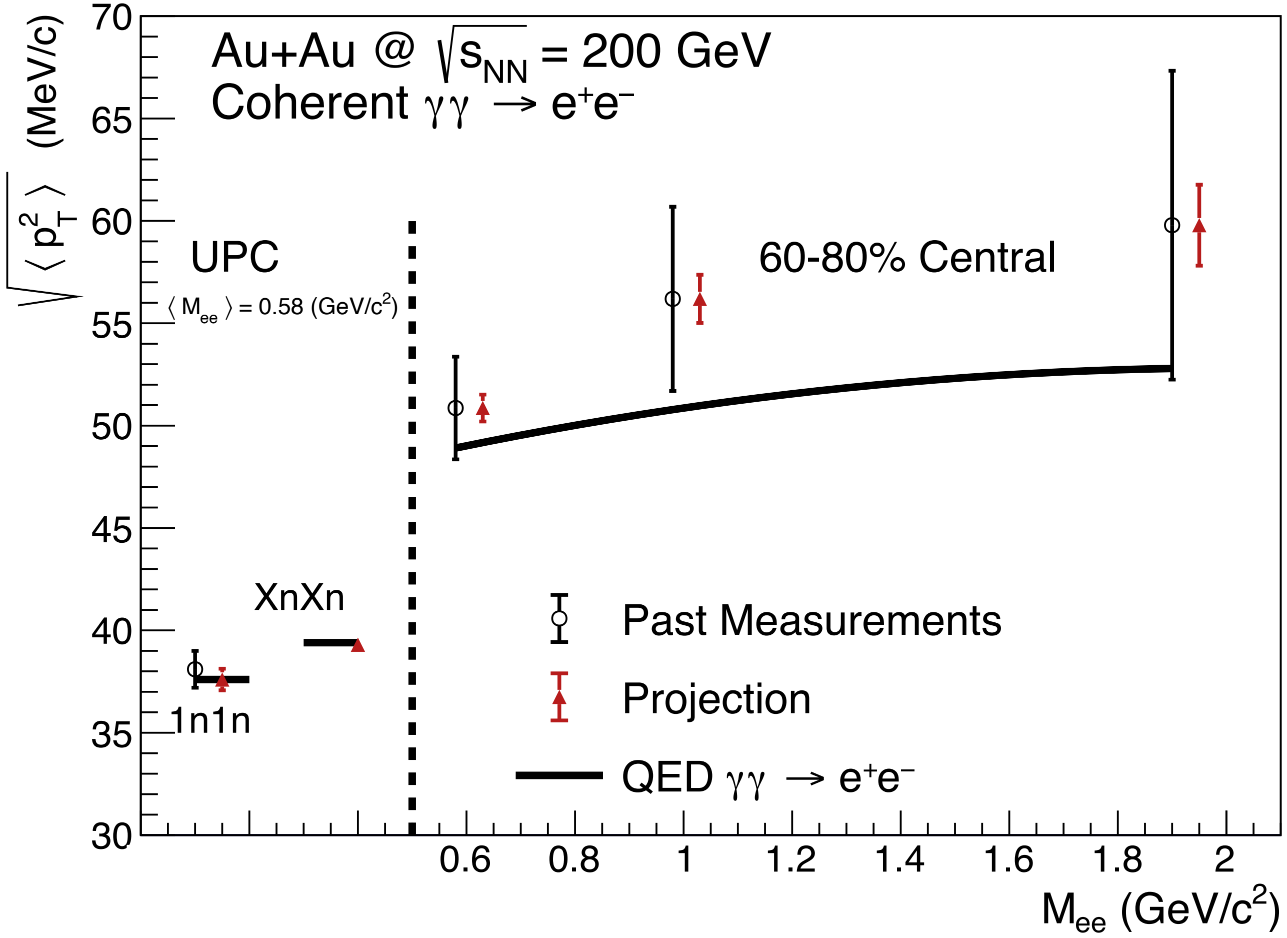
Hint of modification in $60 - 80\%$ central collisions:

Additional 14 ± 4 (stat.)± 4 (syst.) MeV/c broadening

[1] Skokov, V. V., Illarionov, A. Yu. & Toneev, V. D. *Int. J. Mod. Phys. A* **24**, 5925–5932 (2009).

[2] A. Bzdak and V. Skokov,, Physics Letters B **710**, 171 (2012).

Projections for STAR 2023-25

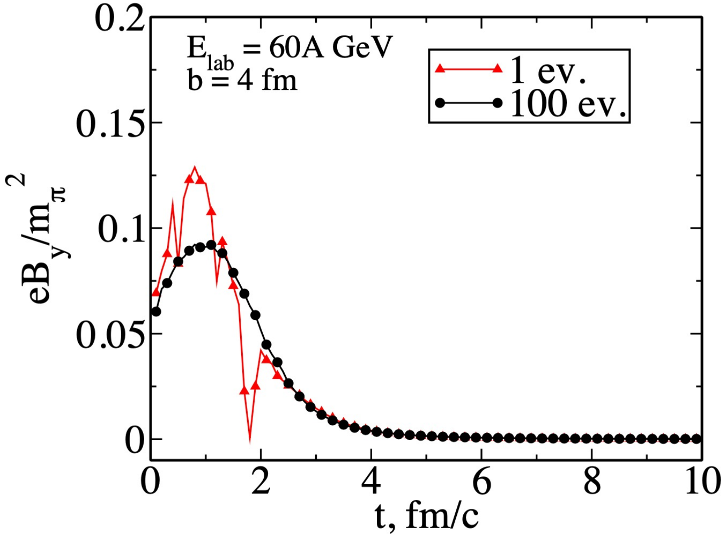


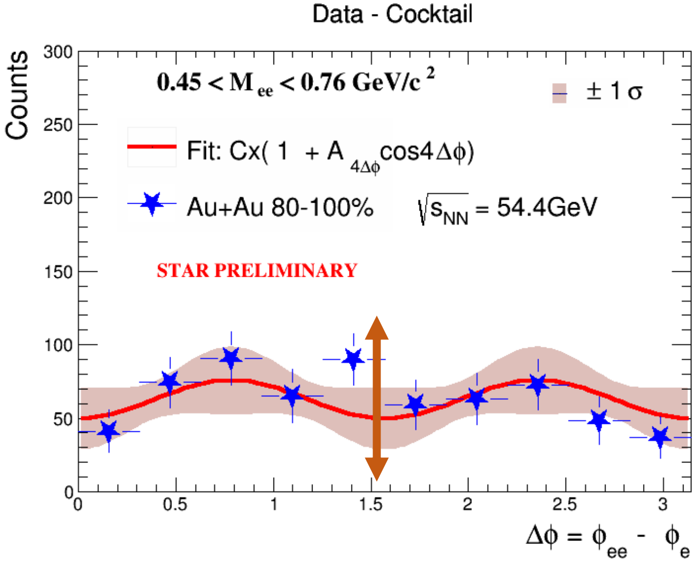
- STAR's Beam Use Request now approved through 2025
- High statistics (10-20B) Au+Au at $\sqrt{s_{NN}} = 200$ GeV
- Potential sensitivity to observe modification in $\sqrt{\langle P_T^2 \rangle}$

SN0755 : The STAR Beam Use Request for Run-21, Run-22 and Data Taking in 2023-25 | The STAR Experiment, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0755.

SN0773 : The STAR Beam Use Request for Run-22 and Data Taking in 2023-25 | The STAR Experiment, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0773.

Event-by-event Fluctuations + Interactions



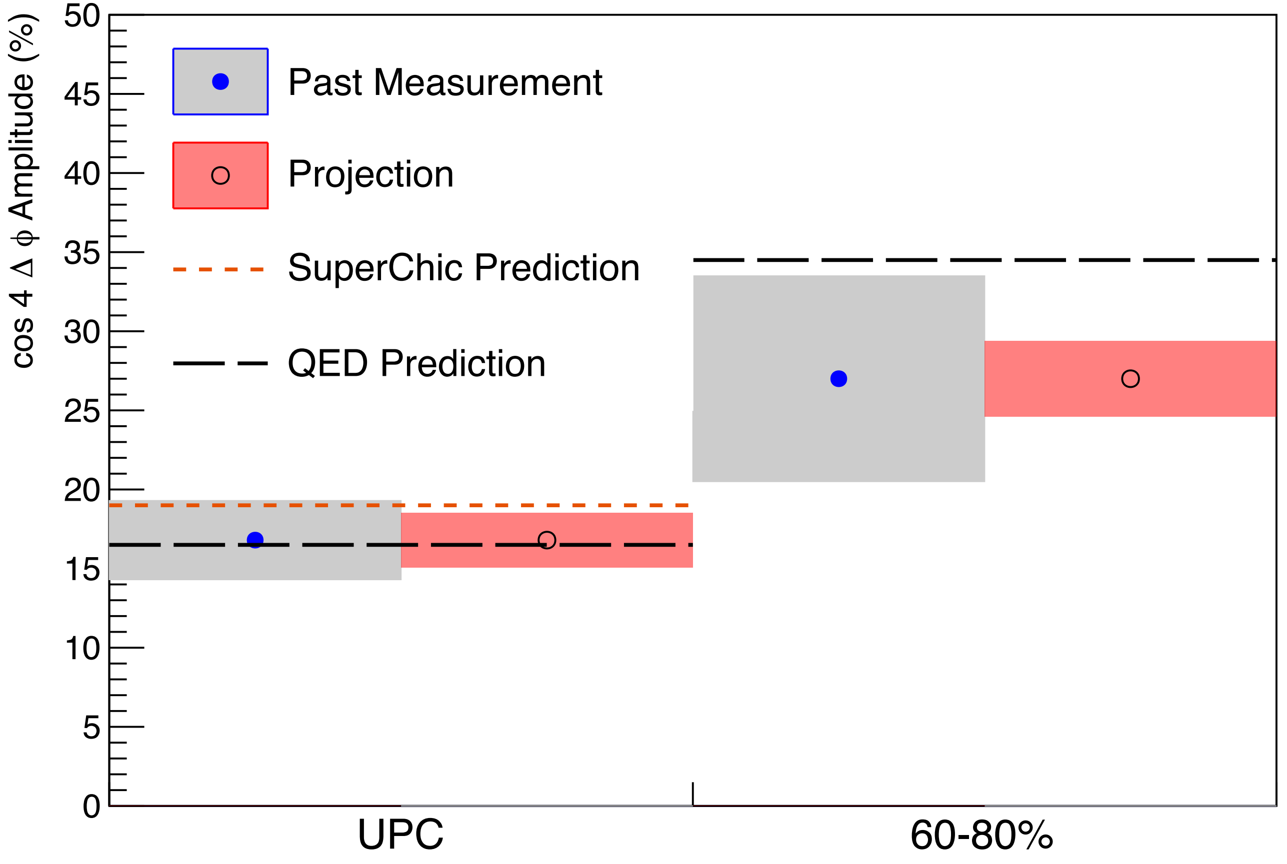


- Fluctuating nucleon positions effect field inside nucleus
- Long-lived magnetic field
  → Lorentz-force bending of pairs
- High precision data from STAR 2023-25
- What to look for:
  - Modification of $\Delta\phi$ distribution (relative photon-photon polarization angle)

In the mean time, measurement in BES-II datasets:
Xiaofeng Wang, Initial Stages 2021 :
https://indico.cern.ch/event/854124/contributions/4135471/

[1] Skokov, V. V., Illarionov, A. Yu. & Toneev, V. D. *Int. J. Mod. Phys. A* **24**, 5925–5932 (2009).
[2] A. Bzdak and V. Skokov,, Physics Letters B **710**, 171 (2012).

Projections for STAR 2023-25

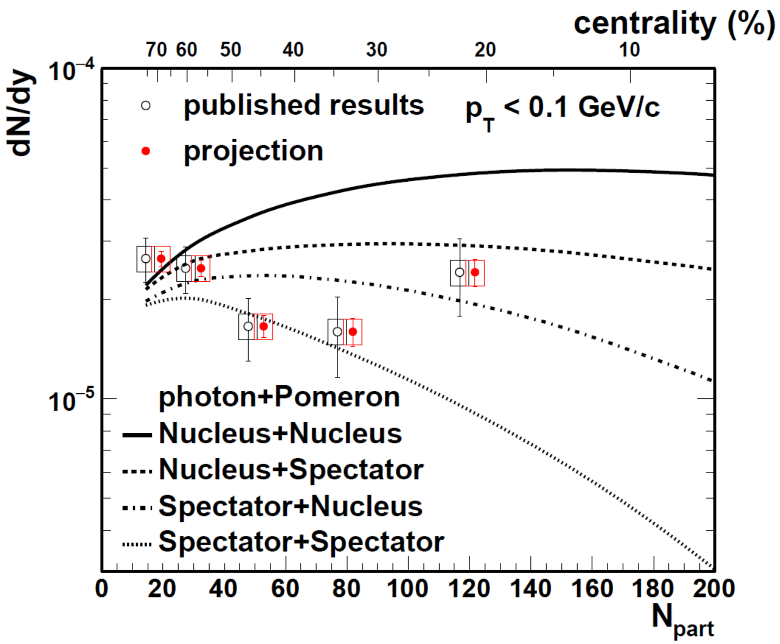


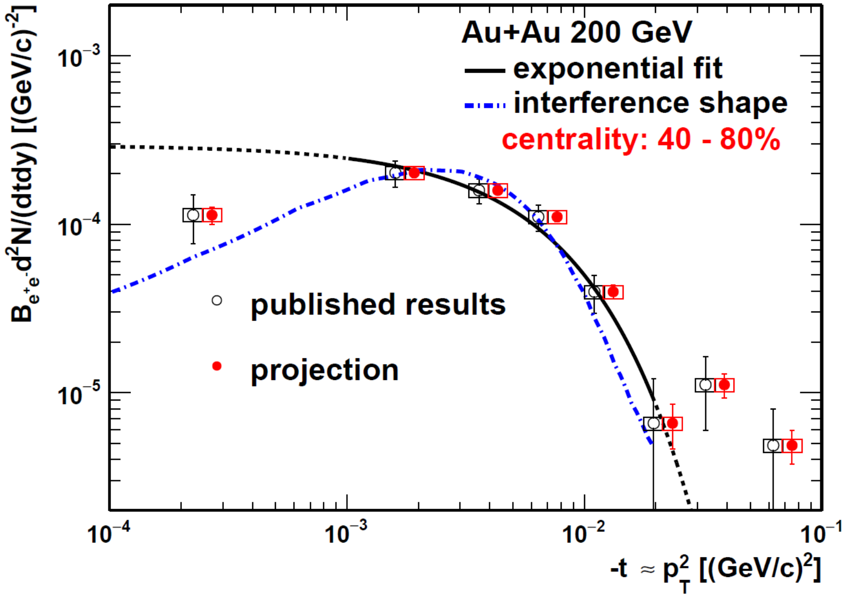
- STAR's Beam Use Request now approved through 2025
- High statistics (10-20B) Au+Au at $\sqrt{s_{NN}} = 200$ GeV
- Potential sensitivity to observe modification in $\sqrt{\langle P_T^2 \rangle}$

SN0755 : The STAR Beam Use Request for Run-21, Run-22 and Data Taking in 2023-25 | The STAR Experiment, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0755.
SN0773 : The STAR Beam Use Request for Run-22 and Data Taking in 2023-25 | The STAR Experiment, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0773.

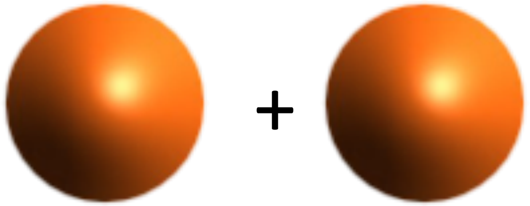
Origin of the coherent EM Field?

Question: What is coherently interaction?

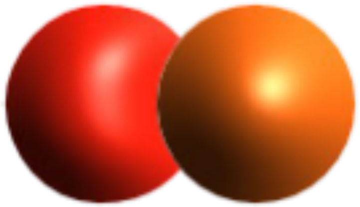




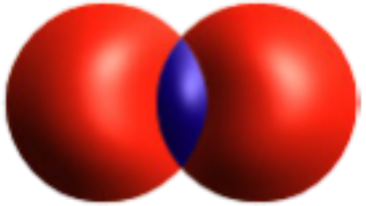
Nucleus + Nucleus



Spectator + Nucleus



Spectator + Spectator



- STAR Measurements of $J/\psi \rightarrow l^+l^-$ in peripheral collisions already indicate interference
- Distinguish coherent emitter: photo-Nuclear interactions in peripheral events

SN0755 : The STAR Beam Use Request for Run-21, Run-22 and Data Taking in 2023-25 | The STAR Experiment, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0755.

SN0773 : The STAR Beam Use Request for Run-22 and Data Taking in 2023-25 | The STAR Experiment, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0773.

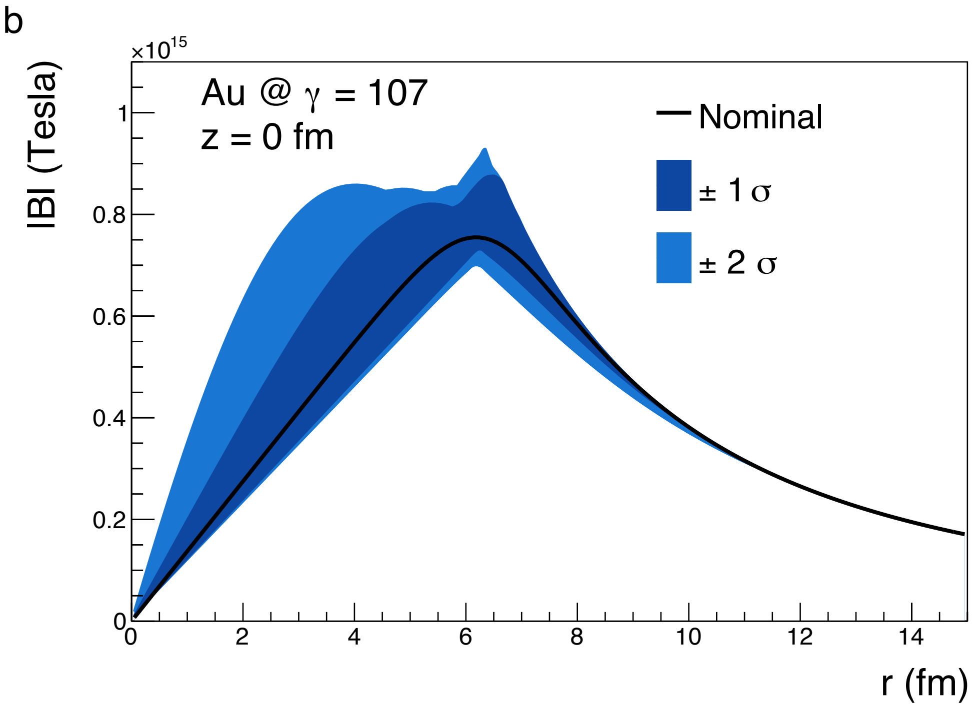
STAR Collaboration et al., PRL **123**, 132302 (2019).

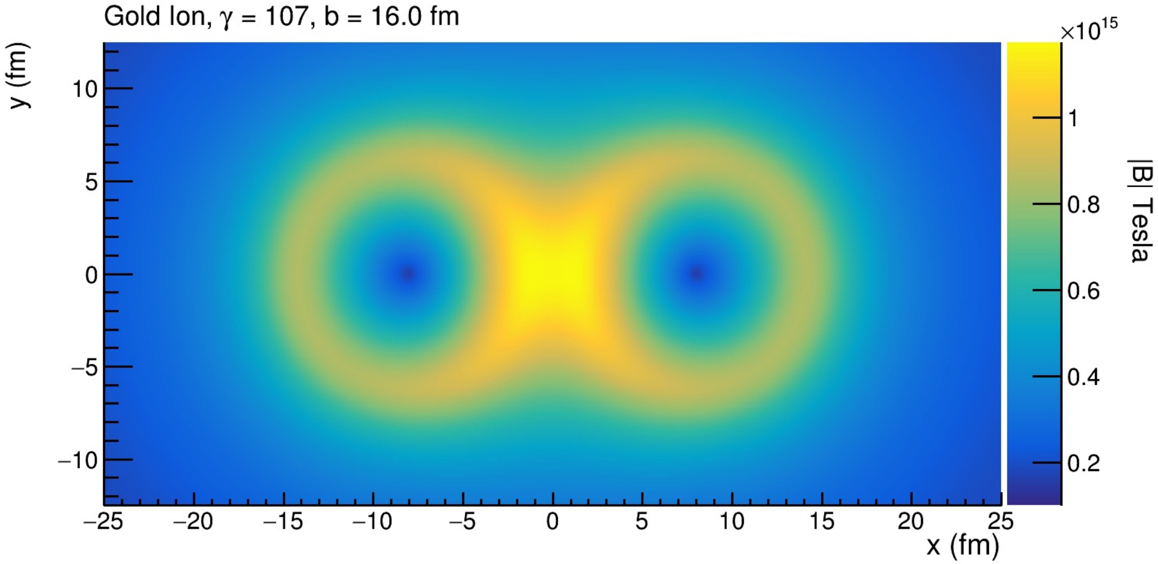
Conclusions

- First **experimental** constraints on **magnetic field** produced in HICs
- Still many open questions:
    - Event-by-event fluctuations
    - Field at low-x
    - Lorentz-force bending
    - Source of coherent field
- Exciting opportunities available:
    - LHC and RHIC between now – 2025

Many thanks to coauthors:

Zhangbu Xu and Wangmei Zha and others





Backup

What have we learned from recent experiments?

Several common assumptions in EPA implementations (past decades)

- Assumption: Photon mediated processes are only relevant for UPC $(b > 2R)$

→ **Photo-induced processes even in CENTRAL heavy-ion collisions**

→ **Test impact parameter dependence in collisions with precise b**

- Assumption: Photon momentum ∝ photon virtuality, with virtuality $q^2 \approx {}^{1}/_{R^2}$ [2,3]
  - Photon $k_\perp$ and pair $p_\perp$ independent of impact parameter
  - Photon's are predominantly longitudinally polarized

→ **Strong impact parameter dependence of pair $p_\perp$ even in UPC->Not medium effect**

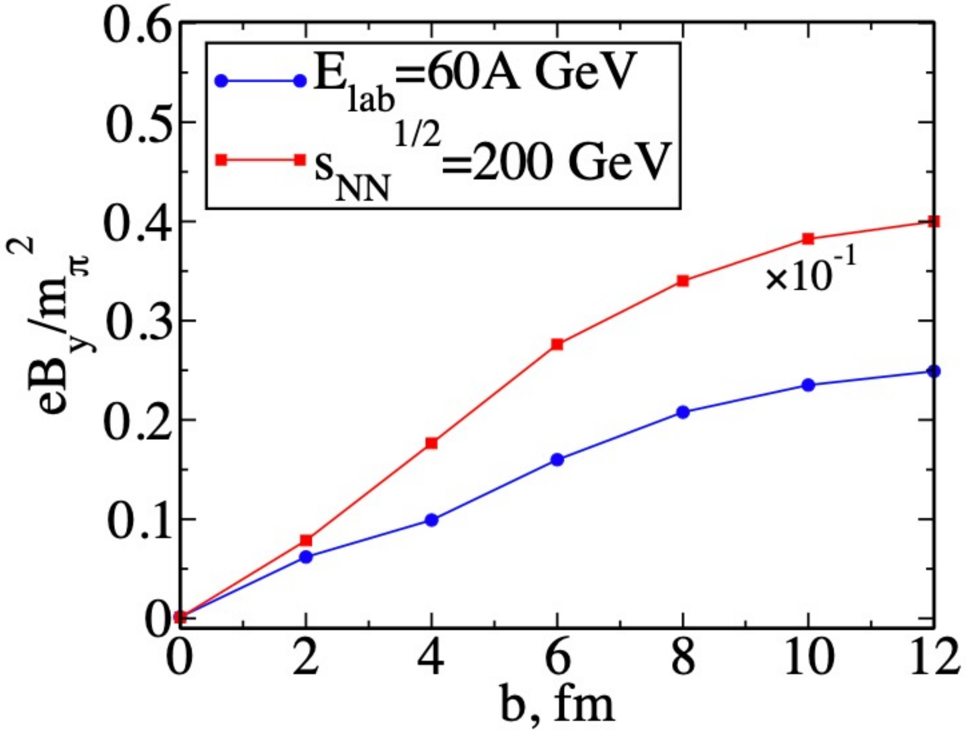
→ **Photons are linearly polarized in transverse plane**

[1] A. J. Baltz, G. Baur, et al., Physics Reports **458**, 1 (2008).
[2] ATLAS Collaboration et al. Phys. Rev. Lett. 123, 052001 (2019).
[3] Annu. Rev. Nucl. Part. Sci. 2005.55:271-310

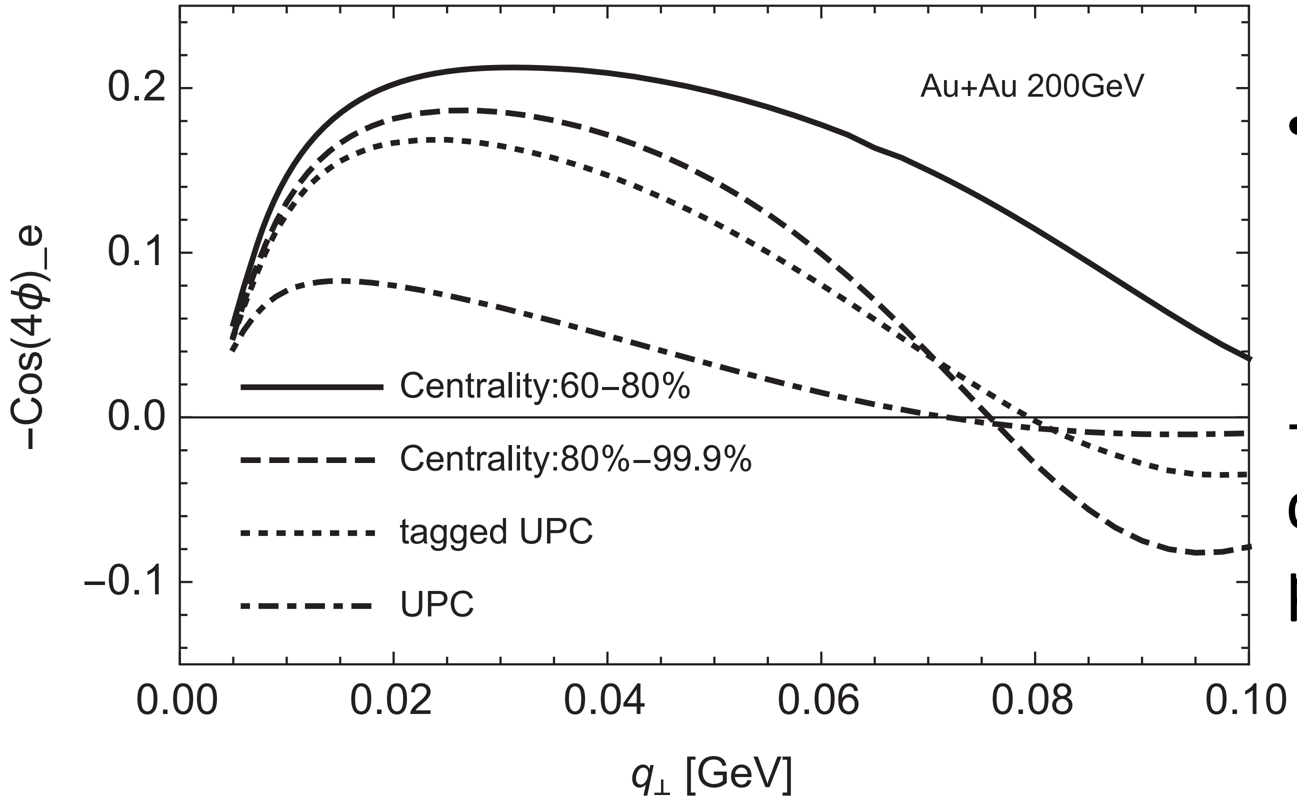
The Magnetic Field in Heavy Ion Collisions

$$e\vec{E}(t,\vec{x}) = \alpha_{\mathrm{EM}} \sum_n \frac{1-v_n^2}{R_n^3(1-[\vec{R}_n \times \vec{v}_n]^2/R_n^2)^{3/2}} \vec{R}_n,$$

$$e\vec{B}(t,\vec{x}) = \alpha_{\mathrm{EM}} \sum_n \frac{1-v_n^2}{R_n^3(1-[\vec{R}_n \times \vec{v}_n]^2/R_n^2)^{3/2}} \vec{v}_n \times \vec{R}_n,$$



Mapping Magnetic field with Polarization Effects



- Quantum interference leads to structure in $\cos 4\Delta\phi$ vs. $P_{\perp}$

→ Very sensitive to the field distribution due to relative photon-photon polarization angle

STAR has statistical precision for this measurement in Au+Au and U+U collisions

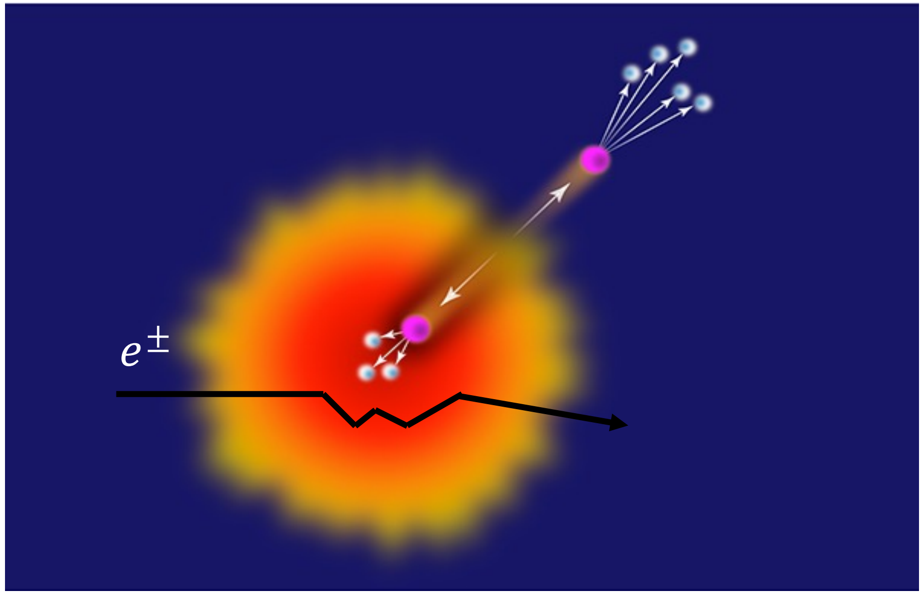
→ Requirement: differential measurement of $\langle\, cos\ 4\phi\, \rangle$

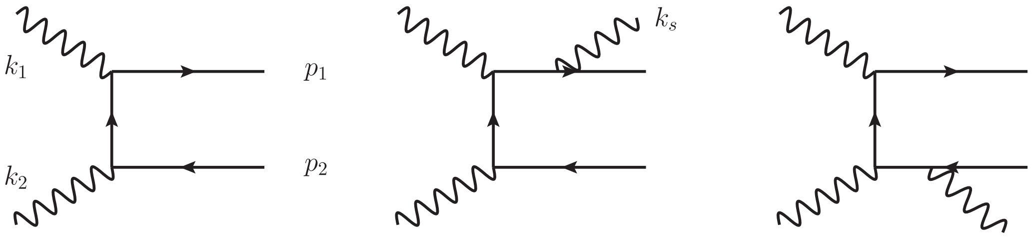
→ U+U is especially interesting, due to deformation

Coulomb Scattering through QGP

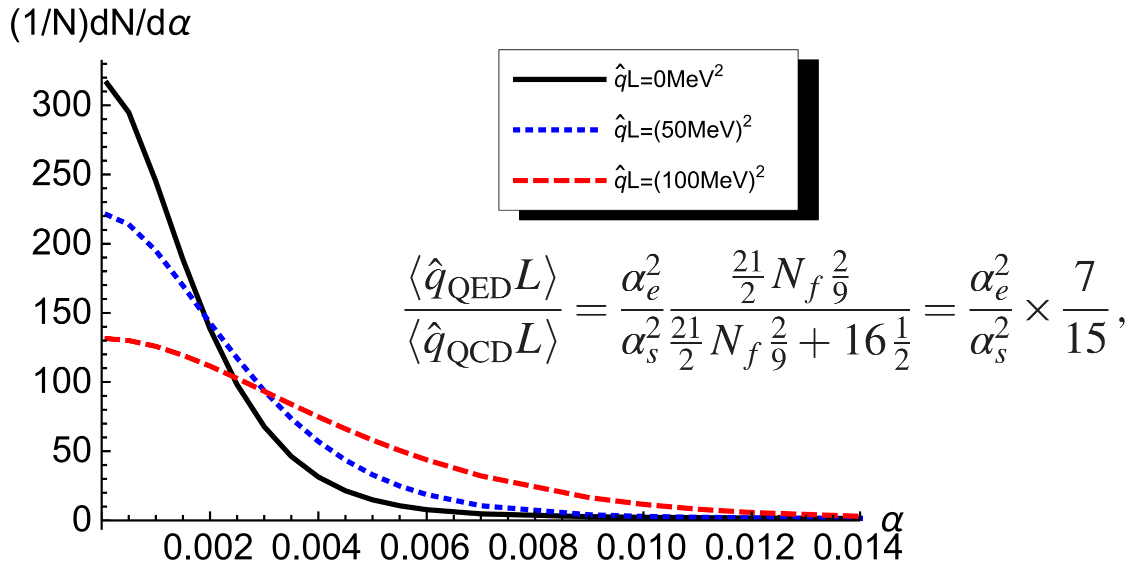
[1] S. R. Klein, et. al, Phys. Rev. Lett. 122, (2019), 132301
[2] ATLAS Phys. Rev. Lett. 121 (2018) , 212301

- Charged particles may scatter off charge centers in QGP, modifying primordial pair $P_\perp$?





(a) (b) (c)



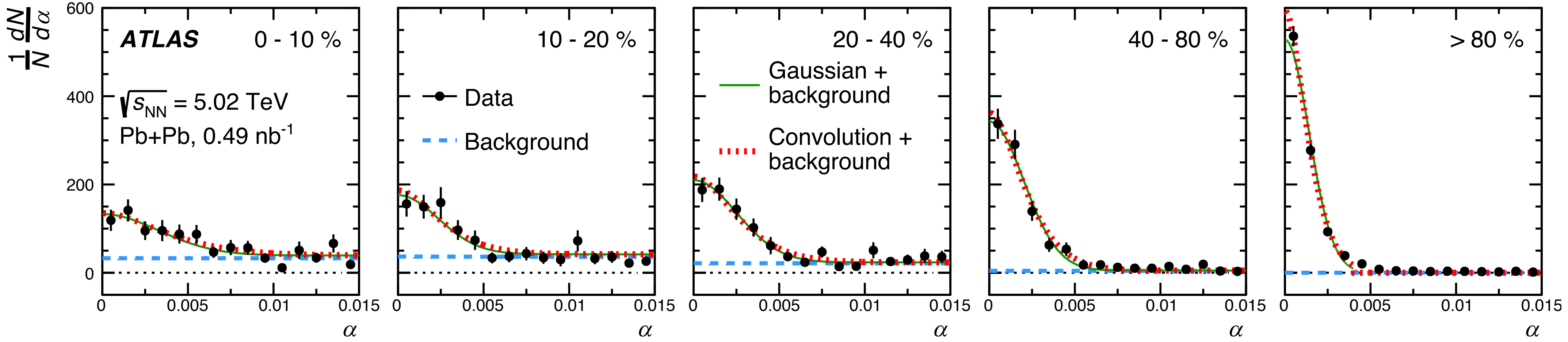
$$\frac{\langle \hat{q}_{\rm QED} L\rangle}{\langle \hat{q}_{\rm QCD} L\rangle} = \frac{\alpha_e^2}{\alpha_s^2}\frac{\frac{21}{2}N_f\frac{2}{9}}{\frac{21}{2}N_f\frac{2}{9}+16\frac{1}{2}} = \frac{\alpha_e^2}{\alpha_s^2}\times\frac{7}{15},$$

Assumptions:

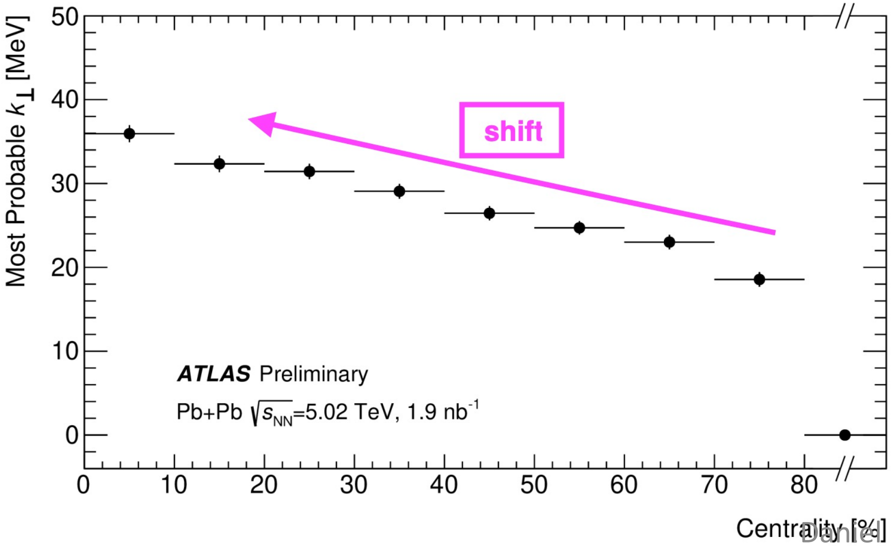
1. <u>STARLight as **baseline**</u>
2. Daughters traverse medium

ATLAS: $\gamma\gamma \to \mu^+\mu^-$ at $b = 0$ fm

Central ⟷ **Ultra-Peripheral**



Broad ⟷ **Narrow**



Momentum “kick” from Coulombic multiple scattering off QGP?

ATLAS Collaboration, Phys. Rev. Lett. 121, 212301 (2018)