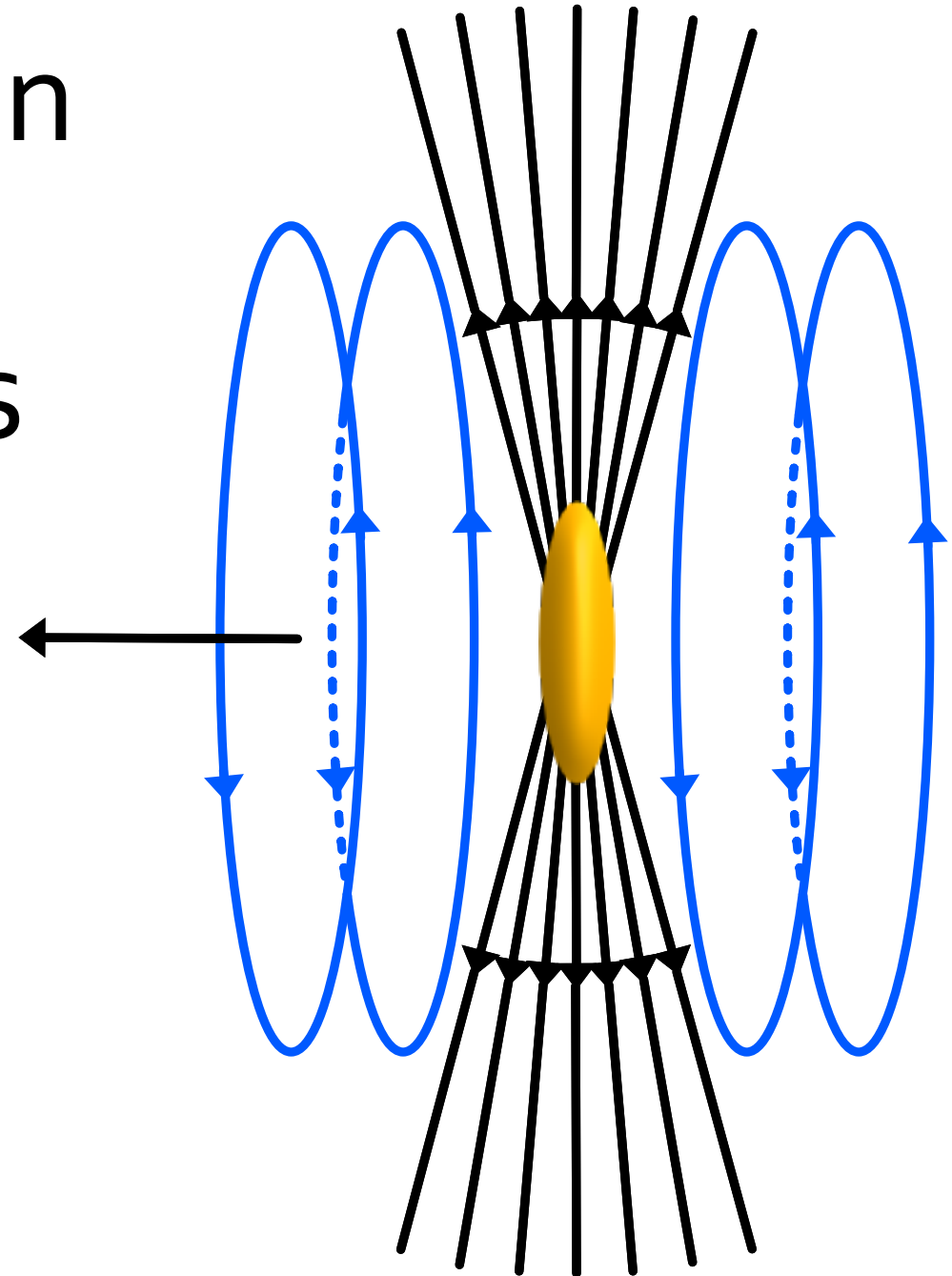# Effects of Strong Fields in Ultra-Peripheral and Peripheral A+A collisions

Daniel Brandenburg

Brookhaven National Lab(CFNS) : Goldhaber Fellow

RHIC & AGS Users' Meeting 2020

October 22nd, 2020 (via ZOOM)

BROOKHAVEN NATIONAL LABORATORY

Center for Frontiers in Nuclear Science

Motivation for Directly Measuring the Magnetic Field

Predicted emergent magnetohydrodynamical phenomena of Quantum Chromodynamics

o Manifestations require ultra-strong magnetic fields

o E.g. **Chiral Magnetic Effect**

o <u>Major goal of RHIC heavy-ion program</u>

  o Dedicated Isobar run in 2018

Dima Kharzeev's Quark Matter 2019 talk:

DK, L.McLerran, H.Warringa NPA'o

Chiro-genesis in Heavy Ion Collisions

Image: D. Leinweber

Absent in Maxwell theory!

$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Coefficient is fixed by the chiral anomaly, no corrections

K.Fukushima, DK, H.Warringa, "Chiral magnetic effect" PRD'08
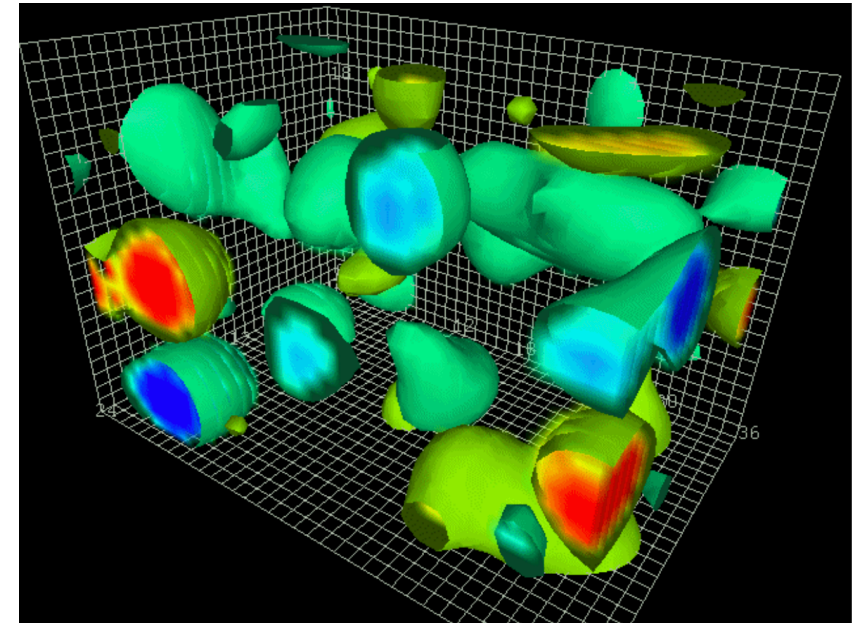
5

NEED TO KNOW THE MAGNETIC FIELD FOR QUANTITATIVE STUDIES

Ultra-Relativistic Heavy-Ion Collisions

Ultra-relativistic charged nuclei produce <u>highly Lorentz contracted electromagnetic field</u>

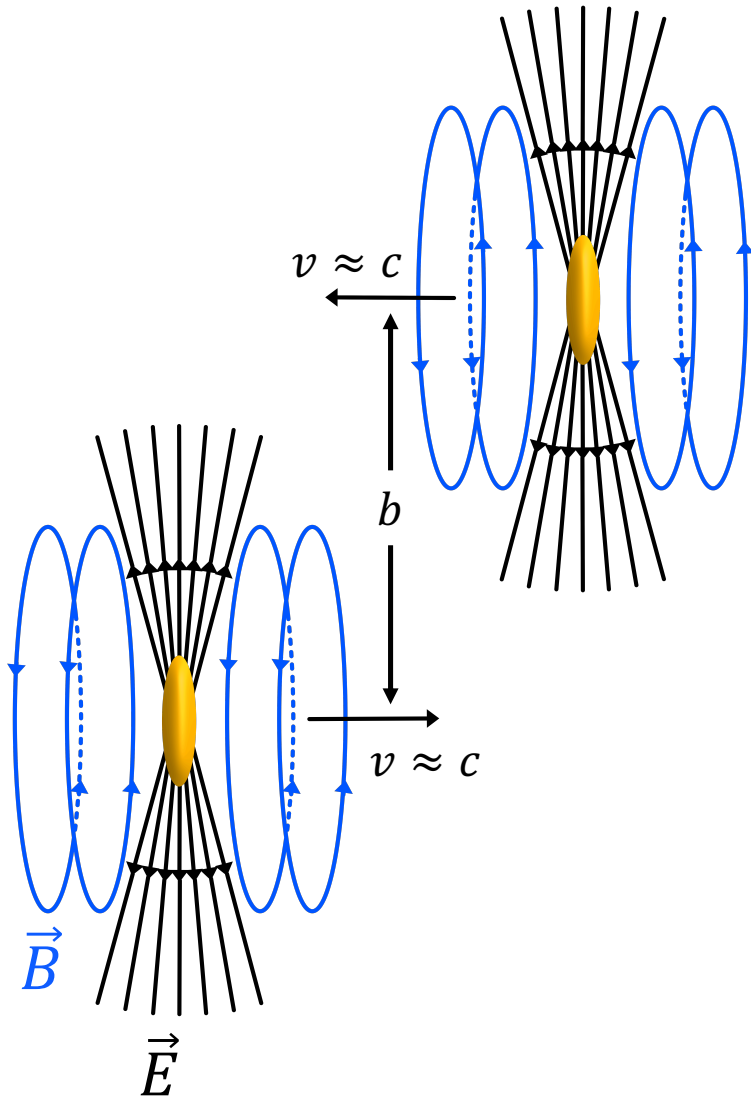$Z\alpha \approx 1 \rightarrow$ High photon density

Ultra-strong electric and magnetic fields:

$\rightarrow$ Expected magnetic field strength $\vec{\mathbf{B}} \approx \mathbf{10^{14} - 10^{16}\,T}$

Skokov, V., et. al. *Int. J. Mod. Phys. A* 24 (2009): 5925–32

Study unique features of QED under extreme conditions

$v \approx c$

b
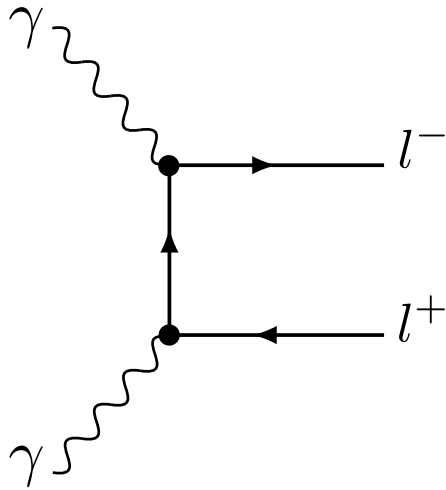
$v \approx c$

$\vec{B}$

$\vec{E}$

Photon-Photon fusion (Breit-Wheeler Process)

Weizsäcker, C. F. v. *Zeitschrift für Physik* 88 (1934): 612

Weizäcker-Williams *Equivalent Photon Approximation* (EPA)

→ In a specific phase space, <u>transverse</u> EM fields can be quantized as a flux of **real photons**

Photon number density related to field strength (Poynting Vector)

$$n \propto \vec{S} = \frac{1}{\mu_0}\, \vec{E} \times \vec{B} \approx \left|\vec{E}\right|^2 \approx \left|\vec{B}\right|^2$$

Photon-photon fusion into lepton anti-lepton pair
Characterized by l^+l^- pair with very small p_T

Traditional EPA calculations (e.g. STARLight[1]) have predicted cross section correctly for decades
→ **so what is new**?

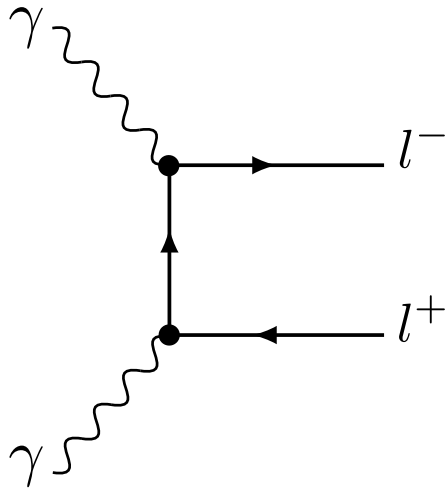[1] S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258

Photon-Photon fusion (Breit-Wheeler Process)

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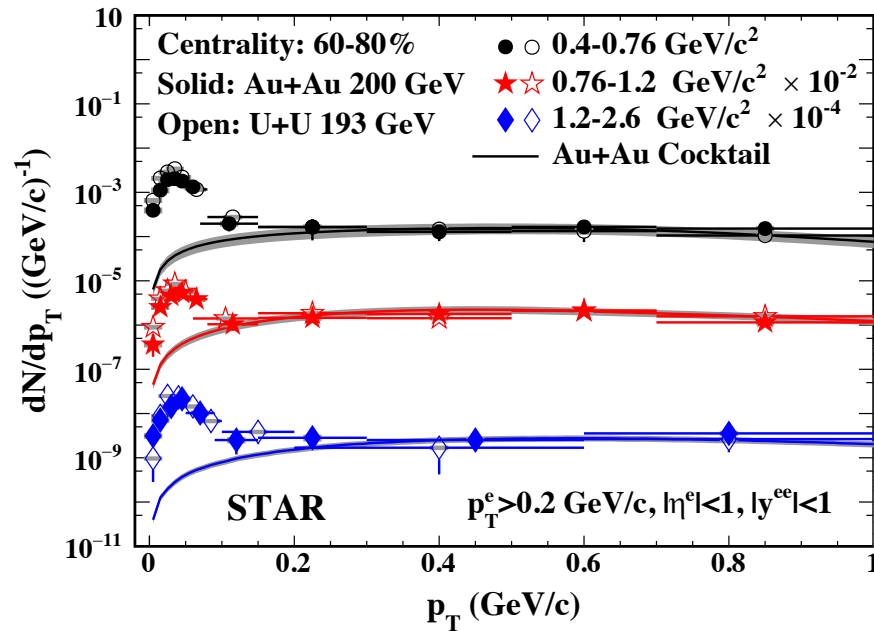**Characterized by l^+l^- pair with very small p_T**

What's new?
1. Pair p_T shows impact parameter dependence
    → Sensitivity to the field mapping
2. Azimuthal angle correlation in daughter leptons
    → Quantum position-momentum correlations

Use these to experimentally constrain the initial EM fields
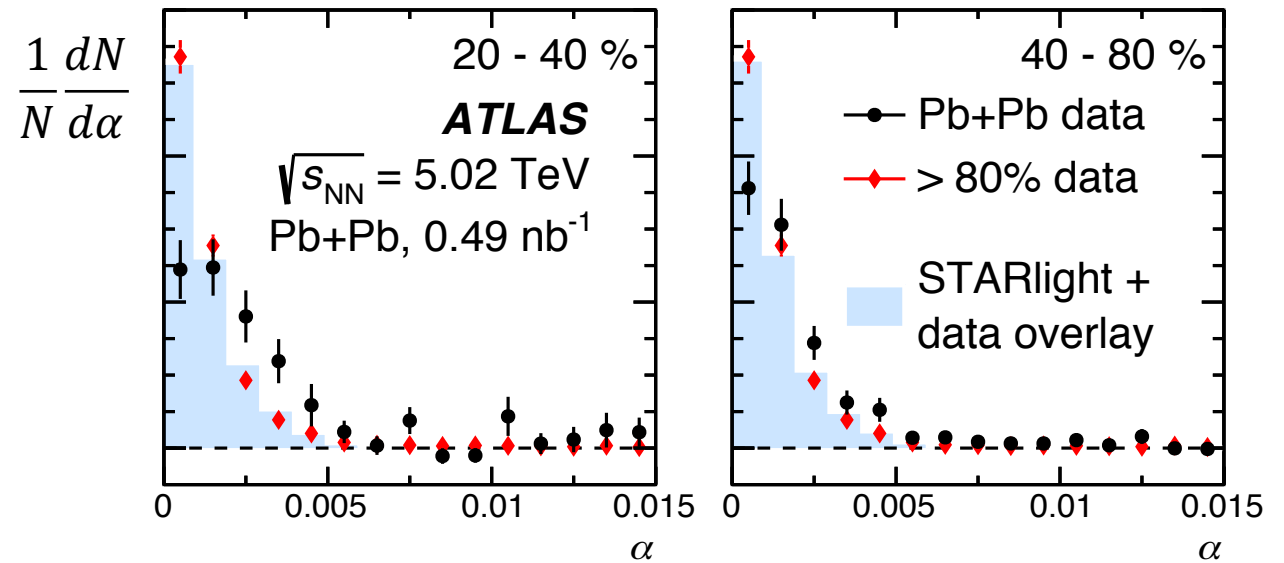
Surprising result in Peripheral Collisions

STAR Measurement of e^+e^- at low p_T

Centrality: 60-80%
Solid: Au+Au 200 GeV
Open: U+U 193 GeV

● ○ 0.4-0.76 GeV/c^2
★☆ 0.76-1.2 GeV/c^2 × 10^{-2}
◆◇ 1.2-2.6 GeV/c^2 × 10^{-4}
— Au+Au Cocktail

STAR

$p_T^e > 0.2$ GeV/c, $|\eta^e| < 1$, $|y^{ee}| < 1$

ATLAS Measurement of $\mu^+\mu^-$ at small acoplanarity

$$\frac{1}{N}\frac{dN}{d\alpha}$$

20 - 40 %

ATLAS
$\sqrt{s_{NN}} = 5.02$ TeV
Pb+Pb, 0.49 nb^{-1}

40 - 80 %

● Pb+Pb data
♦ > 80% data

STARlight + data overlay

Strong excess at low p_T over hadronic cocktail observed in peripheral collisions

Pairs with small acolanarity (proxy to pair p_T) observed in peripheral collisions

$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi} \propto \frac{p_T}{M}$$

[1] STAR, Phys. Rev. Lett. 121 (2018) 132301

[2] ATLAS, Phys. Rev. Lett. 121, 212301 (2018)

→Photon-photon fusion even in peripheral collisions with hadronic overlap?

Surprising result in Peripheral Collisions

**STAR Measurement of e^+e^- at low p_T**

ATLAS Measurement of $\mu^+\mu^-$ at small acoplanarity

$$\frac{1}{N}\frac{dN}{d\alpha}$$
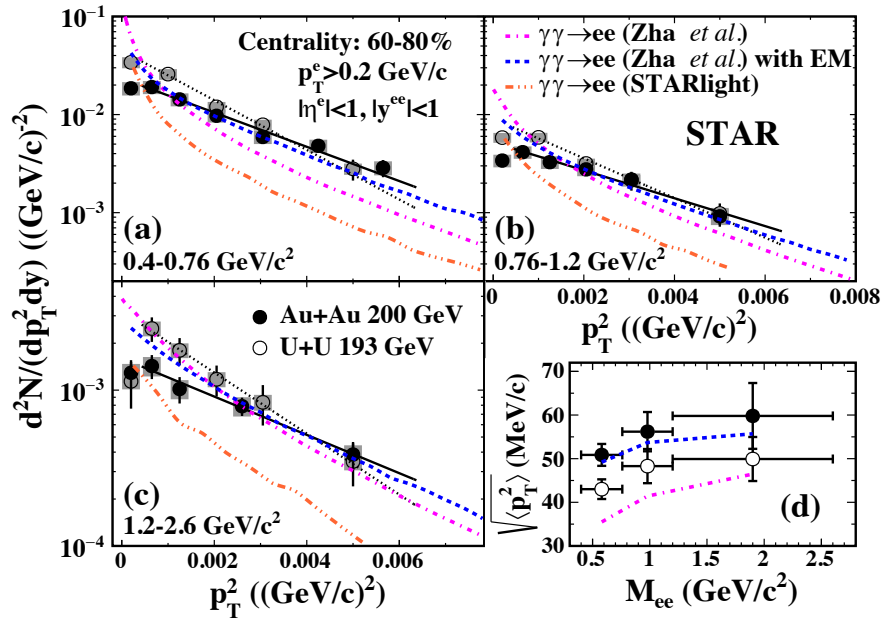
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$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi} \propto \frac{p_T}{M}$$

→Photon-photon fusion even in peripheral collisions with hadronic overlap?

Traditional EPA calculation cannot describe p_T or α distribution
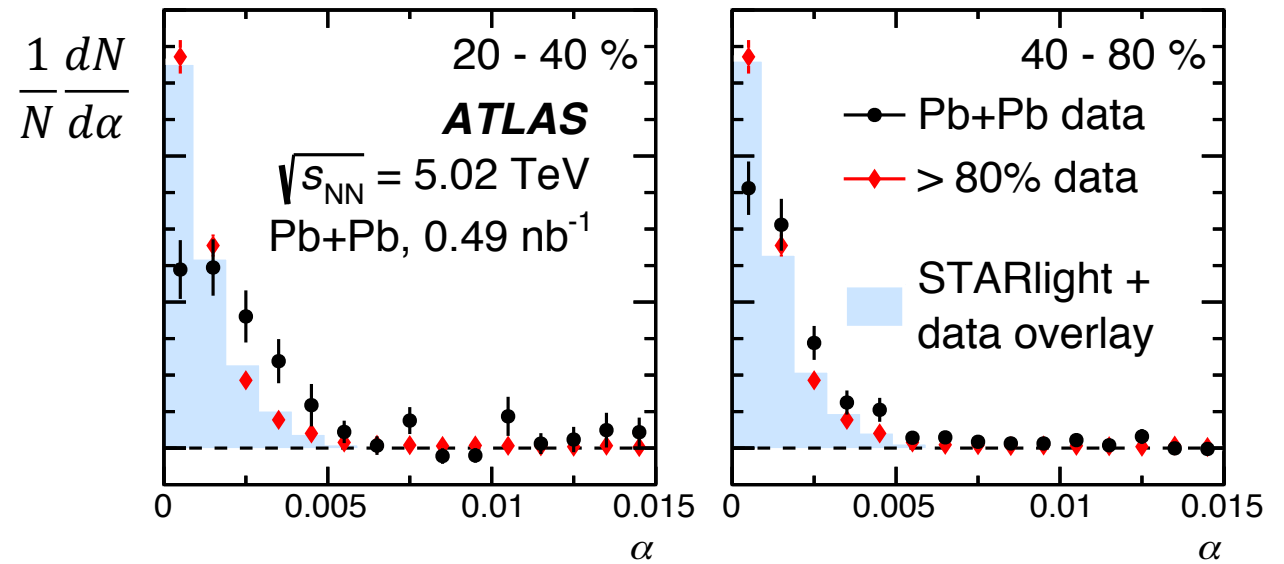
Is the broadening due to final state, medium effects?

- Idea: Extremely small $P_\perp \rightarrow$ easily deflected by relatively small perturbations

- Two proposals from different groups:

1. Lorentz-Force bending due to long-lived magnetic field   [1] STAR, Phys. Rev. Lett. 121 (2018) 132301

2. Coulomb scattering through QGP medium   [2] S. R. Klein, et. al, Phys. Rev. Lett. 122, (2019), 132301
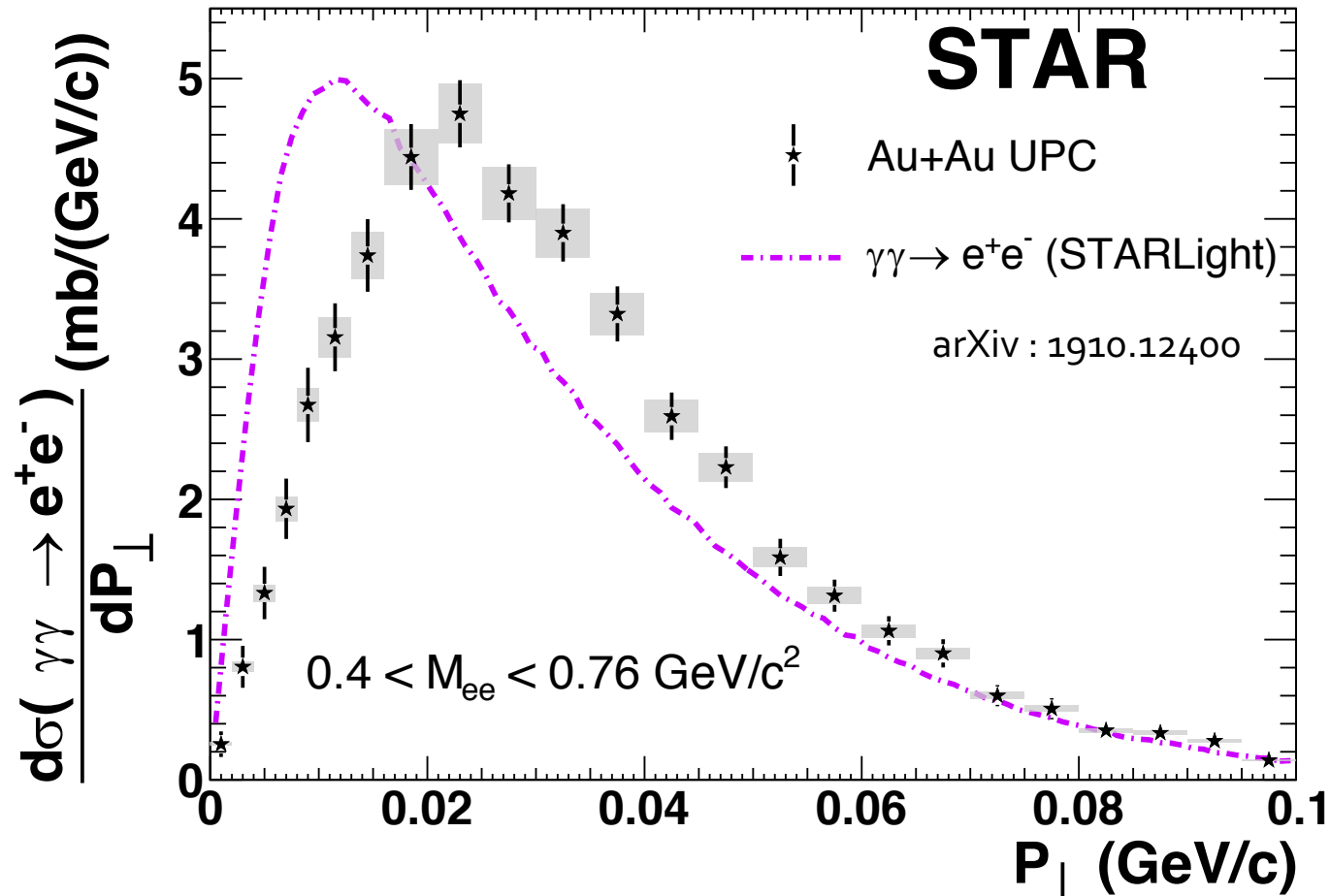   [3] ATLAS, Phys. Rev. Lett. 121 (2018) , 212301

$\sigma = 0$

σ_{LQCD}

$10^2 \, \sigma_{LQCD}$

$10^3 \, \sigma_{LQCD}$

vacuum

eB / m_π^2

t / R_{Au}
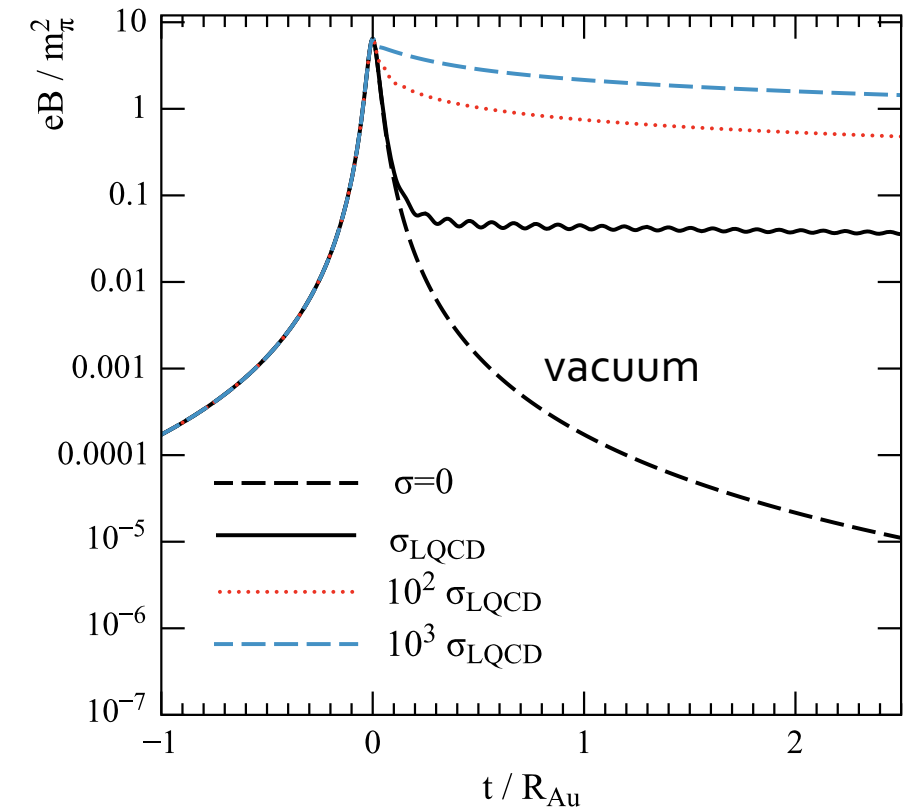
L. McLerran, V. Skokov, Nuclear Physics A 929 (2014) 184–190

Equivalent Photon Approximation

- Traditional Equivalent Photon Approximation (EPA) has been used to describe cross section successfully ($\sim \pm 30\%$ level) for years

✓ Take impact parameter (b) into account for photon flux

✗ BUT, treats photons as plane waves with $\vec{k} = k\hat{z}$

  - In this treatment photon p_T must result from virtuality
  $\rightarrow$ **No b-dependence on kinematics (p_T, α, etc)**

- Until recently there was no data to test the validity of these assumptions
  - E.g. past ATLAS UPC measurements agree with STARLight but resolution effects are significant, obscure the physics
  - Past STAR measurements – insufficient statistical precision

[1] S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258

$d\sigma(\gamma\gamma \rightarrow e^+e^-)/dP_\perp$

STAR

$\star$ Au+Au UPC

$-\cdot-\cdot-$ $\gamma\gamma \rightarrow e^+e^-$ (STARLight)

arXiv : 1910.12400

$0.4 < M_{ee} < 0.76$ GeV/c^2

QED and STARLight are scaled to match measured $\sigma(\gamma\gamma \rightarrow e^+e^-)$

STARLight: S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258
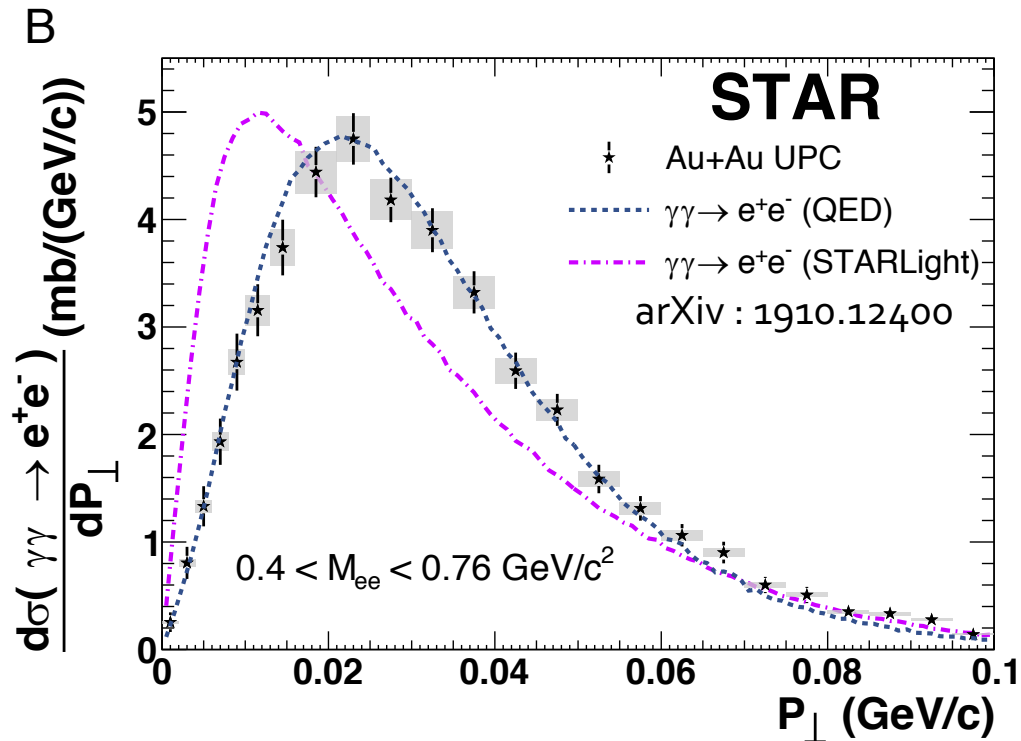QED : W. Zha, J.D.B., Z. Tang, Z. Xu arXiv:1812.02820 [nucl-th]

- STAR's excellent p_T resolution → directly measure pair p_T
- High precision data – **test various theory predictions/assumptions**

- STARLight predicts significantly lower $\langle P_\perp \rangle$ than seen in data

- Is the increased $P_\perp$ observed due to significant virtuality?
- Let's look at how the calculation is done in the lowest order QED case

Pair p_T and impact parameter

B

STAR

Au+Au UPC

$\gamma\gamma \to e^+e^-$ (QED)

$\gamma\gamma \to e^+e^-$ (STARLight)

arXiv : 1910.12400

$0.4 < M_{ee} < 0.76$ GeV/c^2

Impact Parameter Dependence

	gEPA 1	gEPA 2	QED	Mass Range
	— (magenta)	— (blue)	— (red solid)	$0.4 < M_{ee} < 0.76$ GeV/c^2
			— (red dashed)	$0.76 < M_{ee} < 1.2$ GeV/c^2
			— (red dotted)	$1.2 < M_{ee} < 2.6$ GeV/c^2

Au+Au 200 GeV

$p_{T,e} > 0.2$ GeV/c

$|y_{ee}| < 1; |\eta_e| < 1$

Zha, W., Brandenburg, J. D., Tang, Z. & Xu, Z. Phys. Lett. B 800, 135089 (2020).

QED (and gEPA parameterization) describe data
Larger $\langle P_\perp \rangle$ from impact parameter dependence
not a result of significant photon virtuality
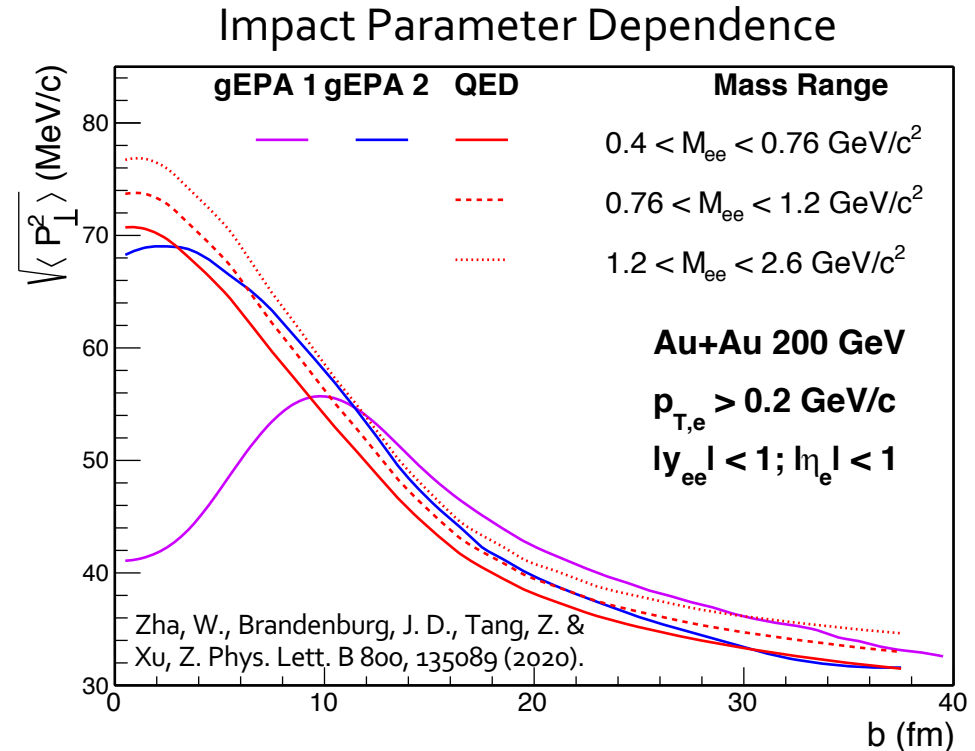
Note: gEPA1 vs. gEPA2 : gEPA2 includes phase term to approximate full QED result

○ QED calculation predicts impact parameter dependence → **dependence on the overlapping field strengths. Can the QED describe the peripheral data?**
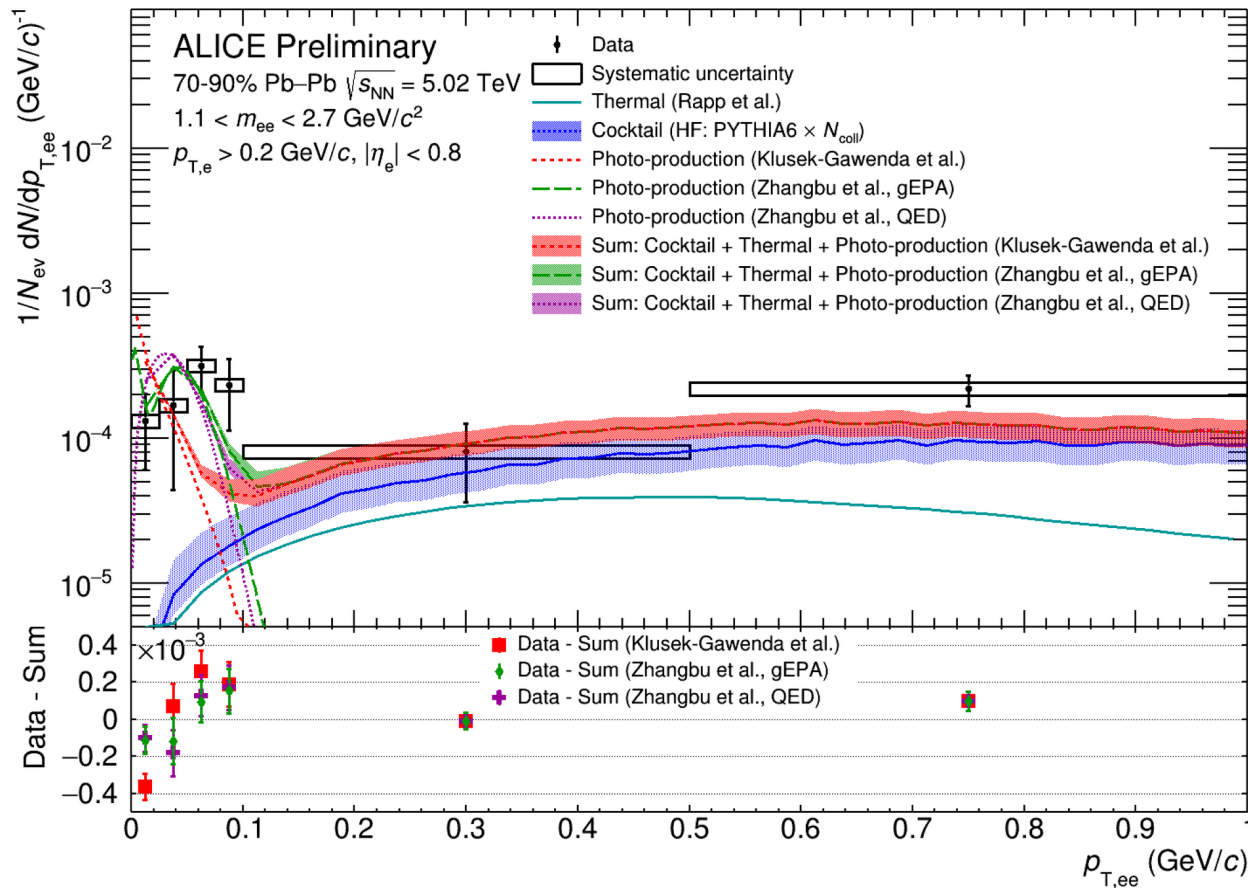
QED Calculation & Peripheral Data

Physics Letters B 800 (2020) 135089
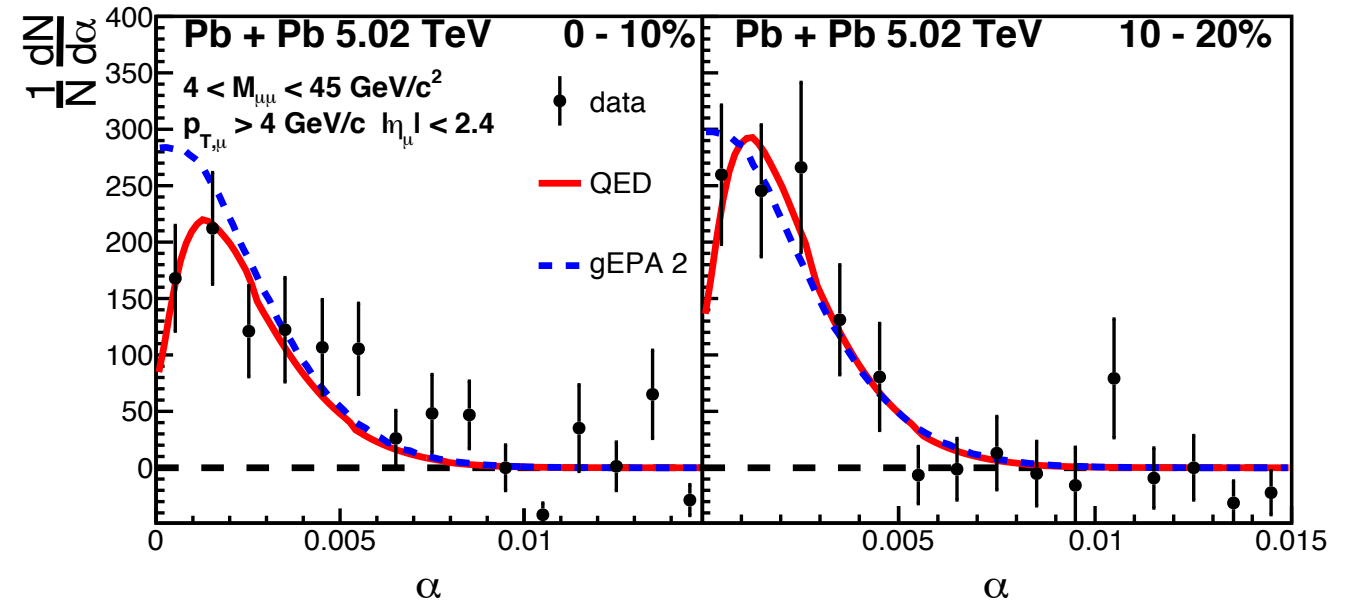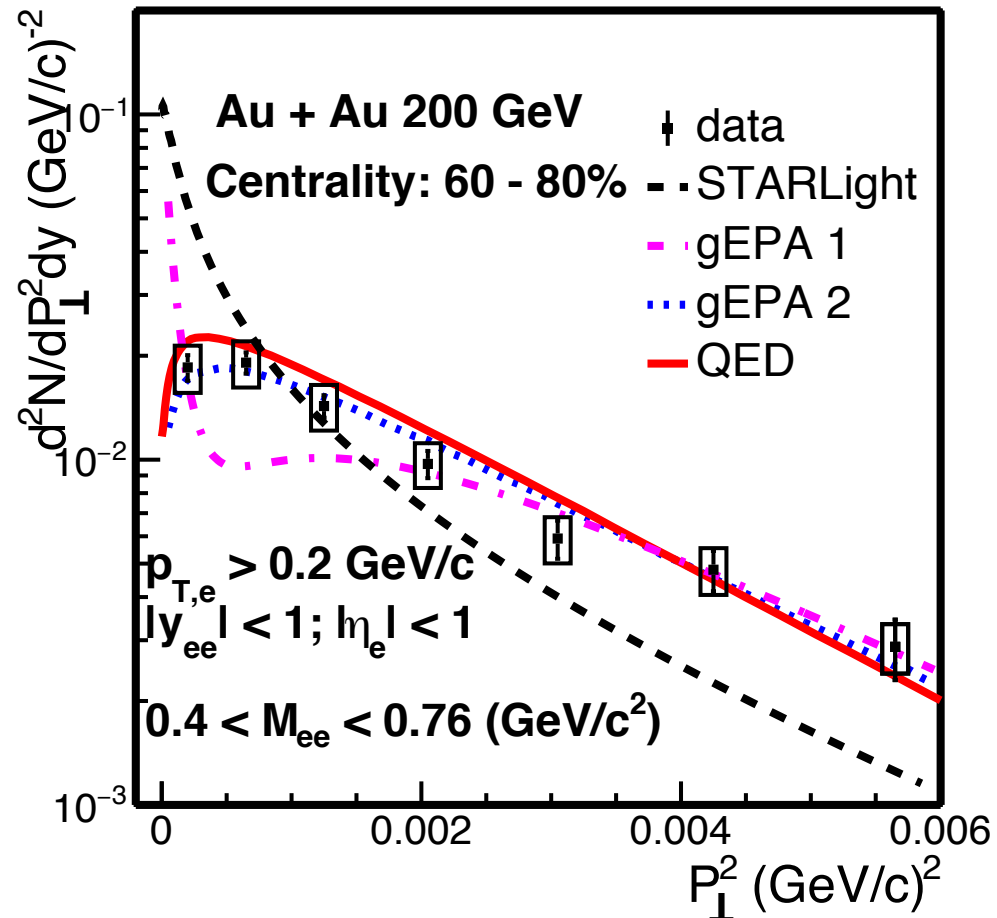
- Peripheral data from both STAR and ATLAS are well described by QED calculation
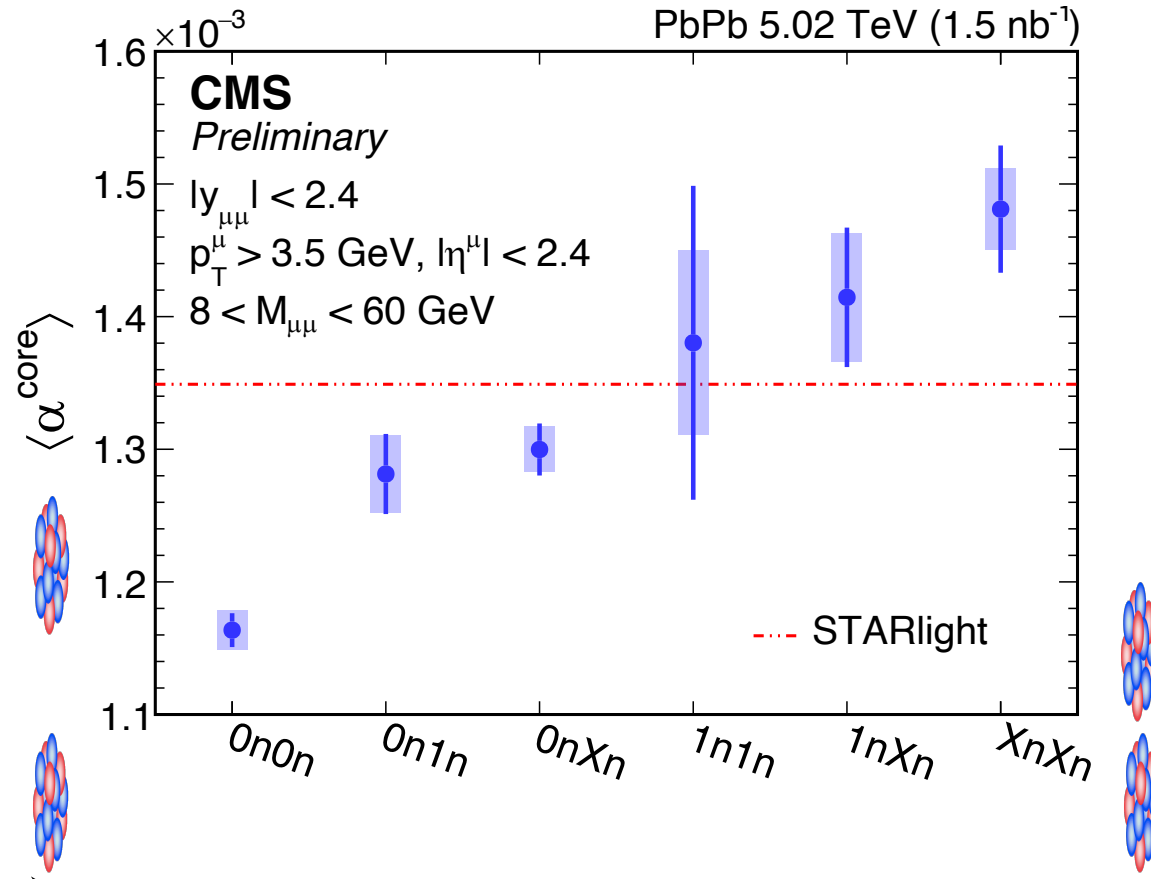
- ATLAS has newer high precision data

QED Calculation & Peripheral Data

ALICE Preliminary from QM19

- Similar measurement by ALICE in $70 - 90\%$ central collisions
- Low statistics $\rightarrow p_T$ distribution favors QED calculation over traditional EPA

QED Calculation & CMS UPC Data

PbPb 5.02 TeV (1.5 nb^{-1})

$\times 10^{-3}$

CMS *Preliminary*

$|y_{\mu\mu}| < 2.4$

$p_T^\mu > 3.5$ GeV, $|\eta^\mu| < 2.4$

$8 < M_{\mu\mu} < 60$ GeV

$\langle \alpha^{core} \rangle$

$0n0n$ $0n1n$ $0nX_n$ $1n1n$ $1nX_n$ X_nX_n

--- STARlight

Shuai Yang, CMS Preliminary from HP2020

- CMS measured α for various impact parameter ranges by tagging the neutron emission

- Acoplanarity shows impact parameter dependence in UPC – purely initial state effect

- QED calculation also describes this data well,

  see arxiv:2006.07365

$\gamma\gamma \to e^+e^-$: UPC vs. Peripheral

[1] STAR, Phys. Rev. Lett. 121 (2018) 132301
[2] S. R. Klein, et. al, Phys. Rev. Lett. 122, (2019), 132301
[3] ATLAS Phys. Rev. Lett. 121 (2018) , 212301
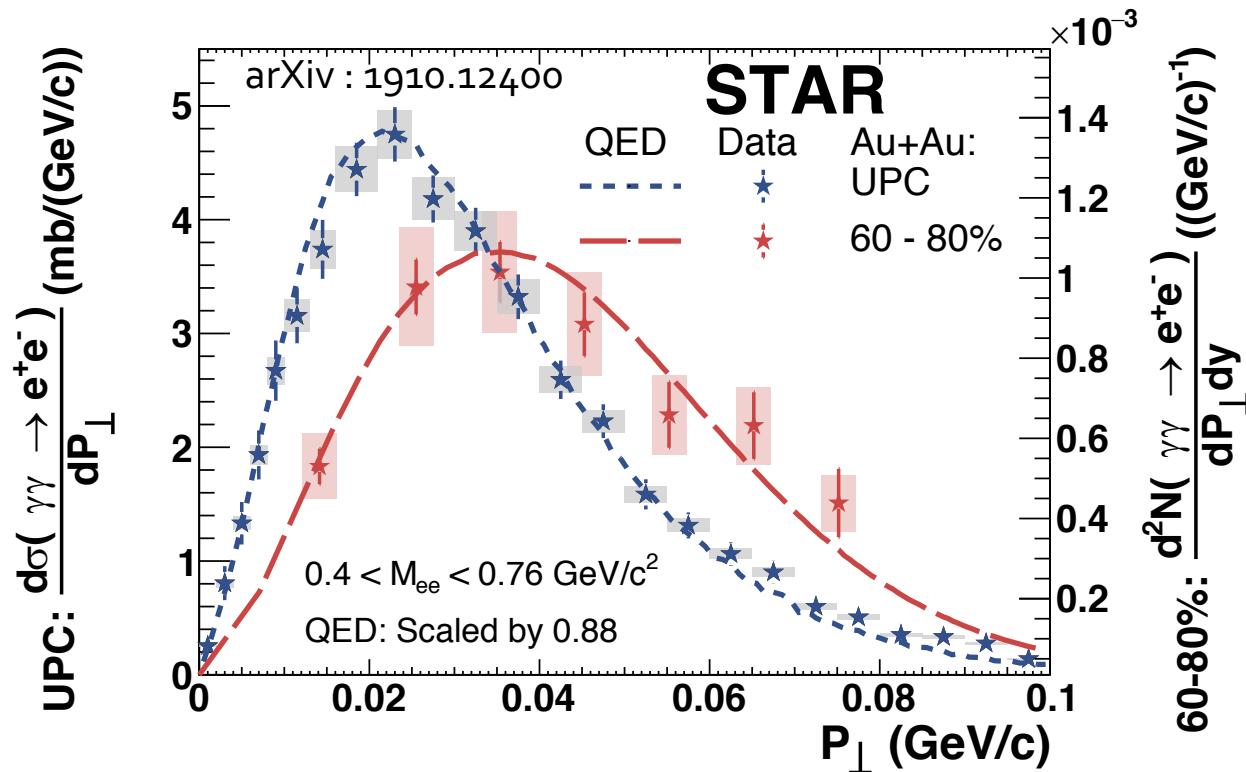
Characterize difference in spectra via $\sqrt{\langle P_\perp^2 \rangle}$

$\sqrt{\langle P_\perp^2 \rangle}$ (MeV/c)	UPC Au+Au	60-80% Au+Au
Measured	38.1 ± 0.9	50.9 ± 2.5
QED	37.6	48.5
b range (fm)	≈ 20	$\approx 11.5 - 13.5$

o Leading order QED calculation of $\gamma\gamma \to e^+e^-$ describes both spectra ($\pm 1\sigma$)

o Best fit for spectra in 60-80% collisions found for QED shape plus
14 $\pm$ 4 (stat.)$\pm$4 (syst.) MeV/c broadening

o Proposed as a probe of trapped magnetic field or Coulomb scattering in QGP [1-3]

**QED describes p_T spectra in terms of the initial fields!**
Maybe there is still room for final state effects – test with new ATLAS results (QM19)

Connection to the <u>Initial</u> Magnetic Field

Magnetic field strength and spatial distribution:

- Impact parameter dependence of $P_\perp$

- Amplitude of azimuthal angular modulation

QED calculations for Breit-Wheeler ($\gamma\gamma \rightarrow e^+e^-$) process that use the field map (to the right) describe data $\pm 1\sigma$


Gold Ion, $\gamma = 107$

arXiv : 1910.12400
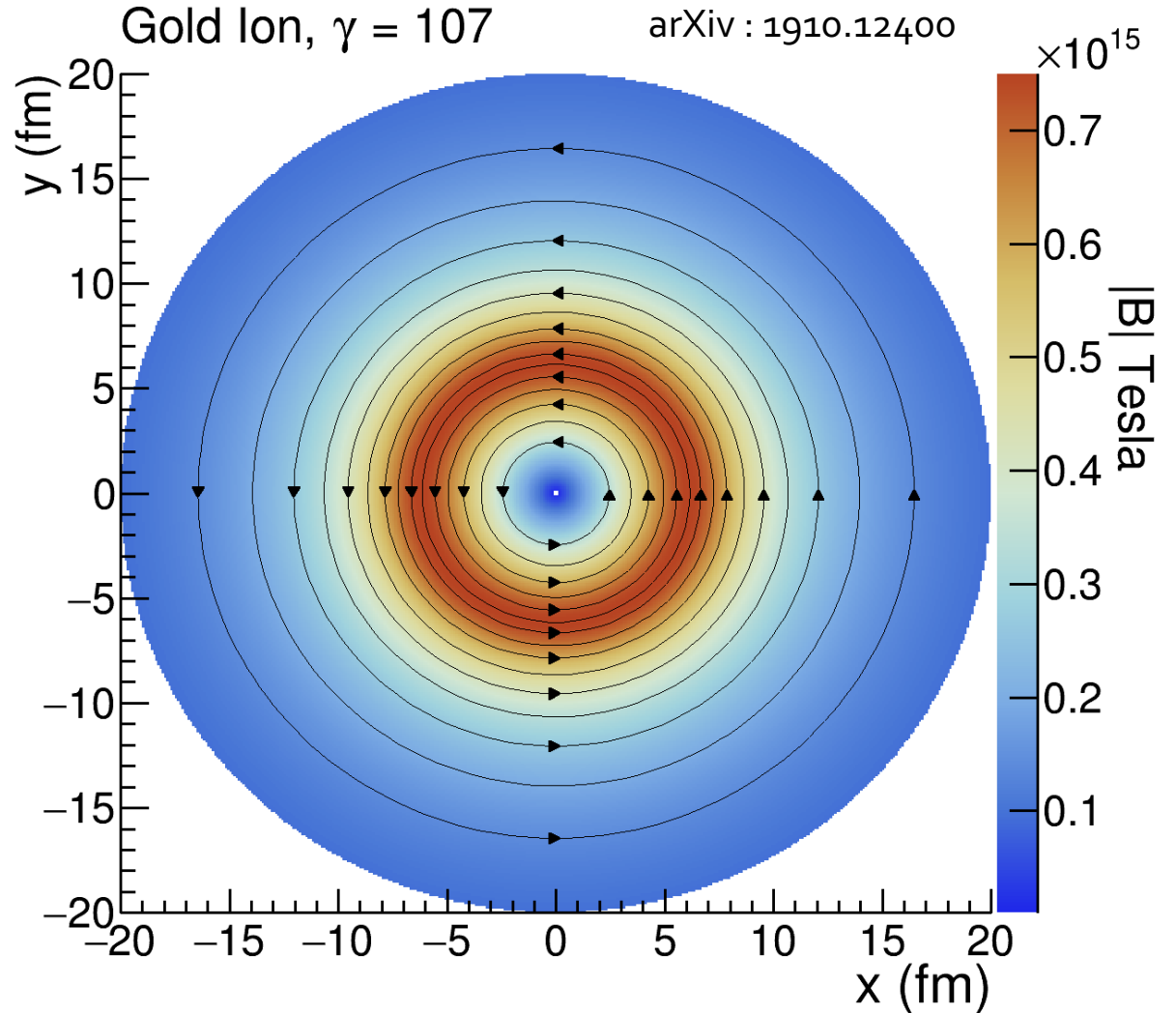
Peak value for single ion: $|B| \approx 0.8 \times 10^{15}$ Tesla $\approx 10,000\times$ stronger than Magnetars
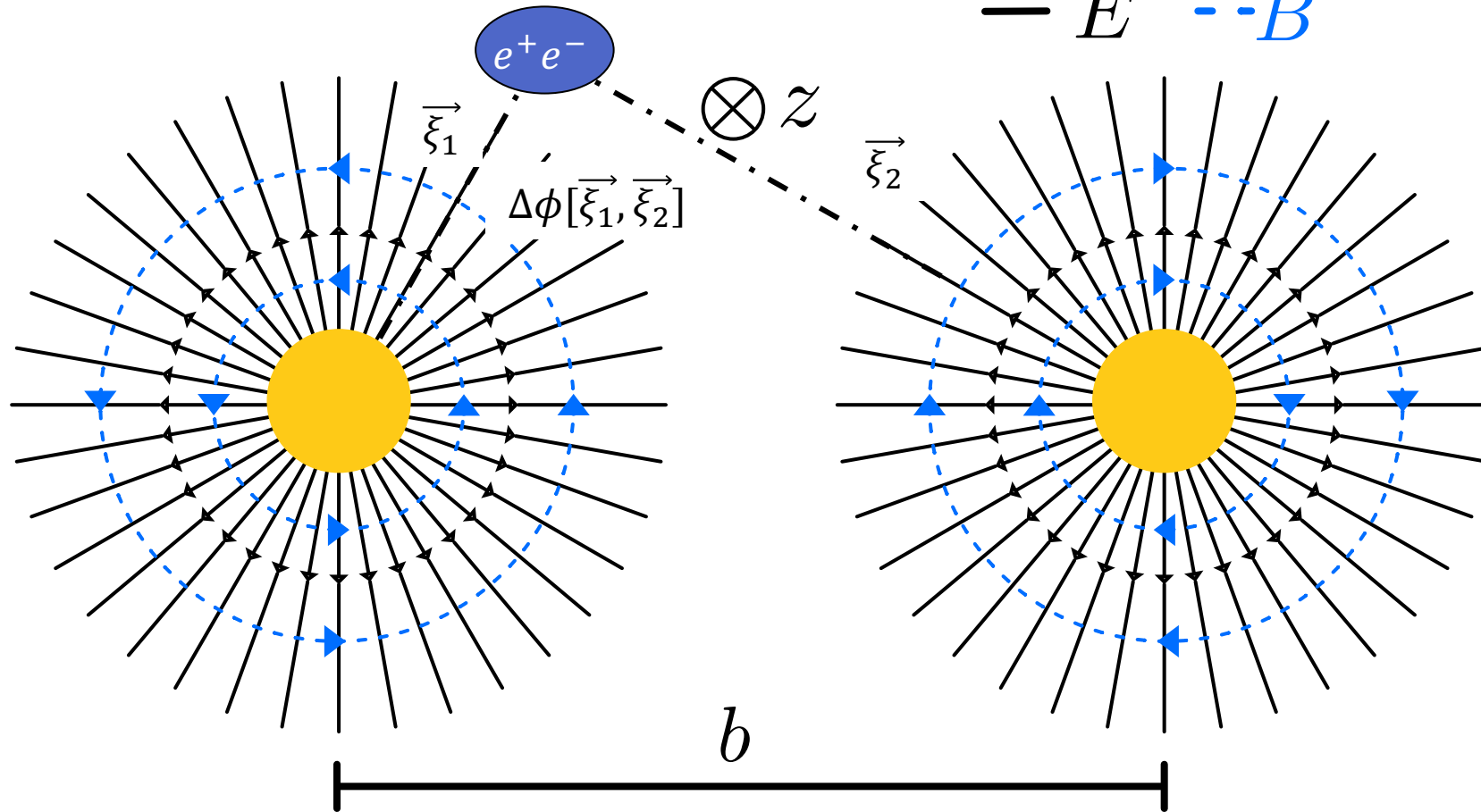
Transverse linearly polarized photons

- Lorentz contraction of EM fields → Quasi-real photons should be linearly polarized in transverse plane ($\vec{E} \perp \vec{B} \perp \vec{k}$)

$$— \vec{E} \quad \text{- -} \vec{B}$$

- Polarization vector : aligned radially with the "emitting" source

- Well defined in the photon position eigenstates

- In general event average, washes out polarization effects, since $\vec{b}$ is random
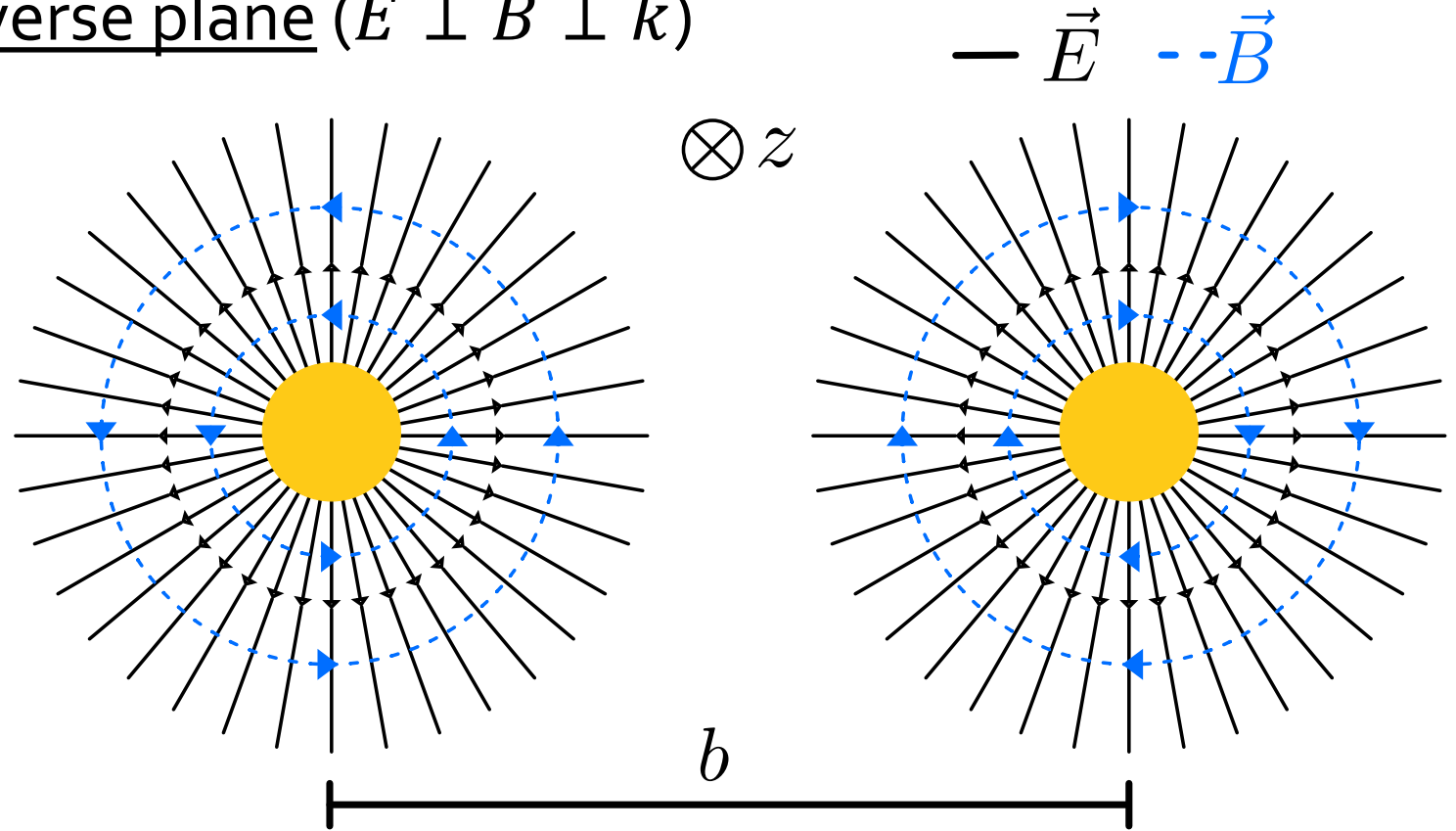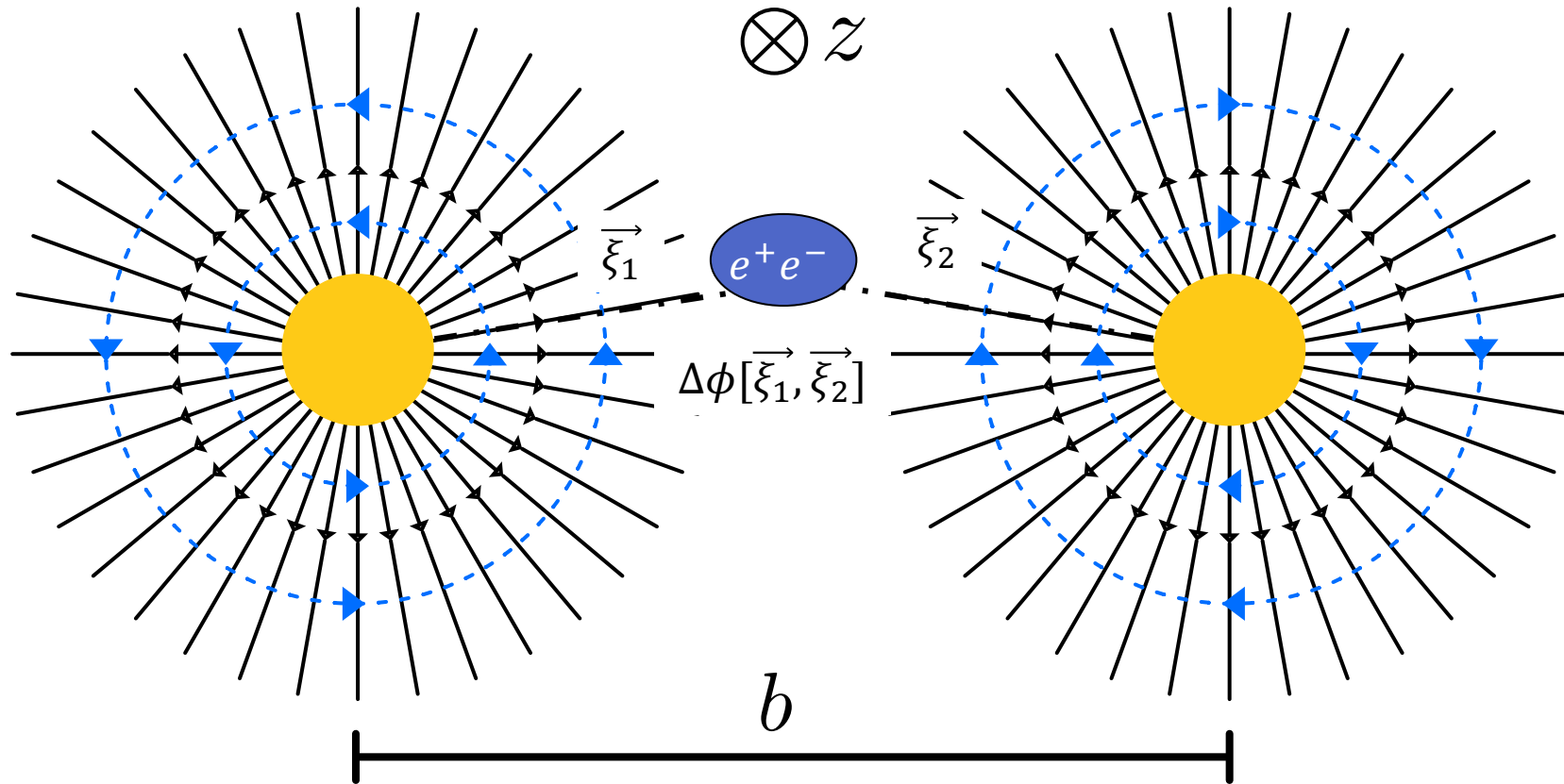
$$\otimes z$$

$$b$$

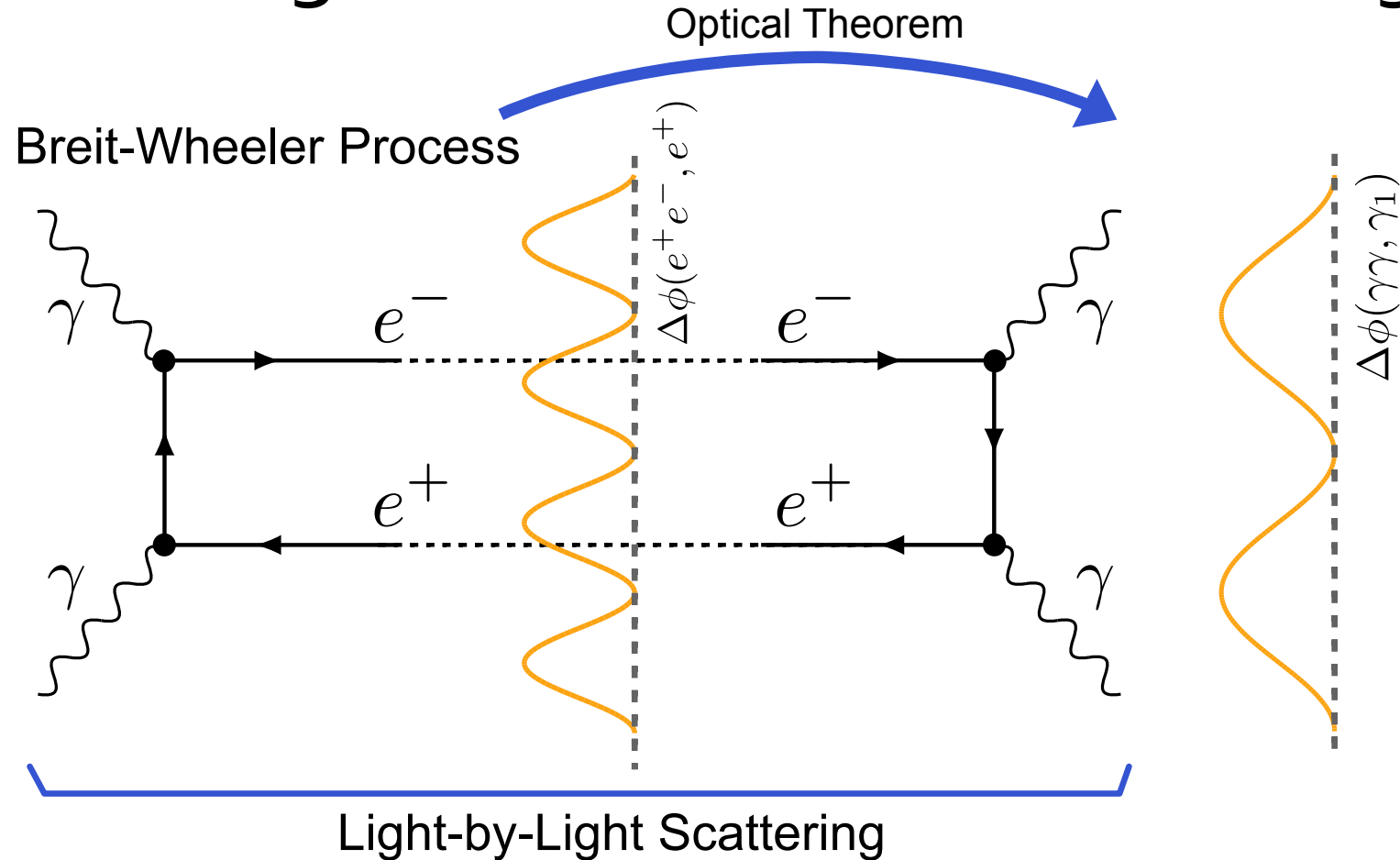# Transverse linearly polarized photons

- Angle between photon polarizations depends on location of produced pair

Transverse linearly polarized photons

$$\longrightarrow \vec{E} \quad \text{-}\text{-}\vec{B}$$

$\otimes z$

$\vec{\xi_1}$

$e^+ e^-$

$\vec{\xi_2}$

$\Delta\phi[\vec{\xi_1}, \vec{\xi_2}]$

b

- Angle between photon polarizations depends on location of produced pair

Experimental Signature of Vacuum Birefringence

Recently realized, $\Delta\sigma = \sigma_\parallel - \sigma_\perp \neq 0$ leads to a **$\cos(4\Delta\phi)$ modulation** in polarized $\gamma\gamma \to e^+e^-$ [1]

The corresponding vacuum LbyL scattering[2] displays a **$\cos(2\Delta\phi)$ modulation**

[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)

[2] Harland-Lang, L. A., Khoze, V. A. & Ryskin, M. G. Eur. Phys. J. C 79, 39 (2019).

$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+]$$

Birefringence of the QED Vacuum

[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
QED calculation: Li, C., Zhou, J. & Zhou, Y. Phys. Rev. D 101, 034015 (2020).

Polarized $\gamma\gamma \to e^+e^-$ leads to $\cos 4\Delta\phi$ modulations due to quantum space-momentum correlations[1]

$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)]$$
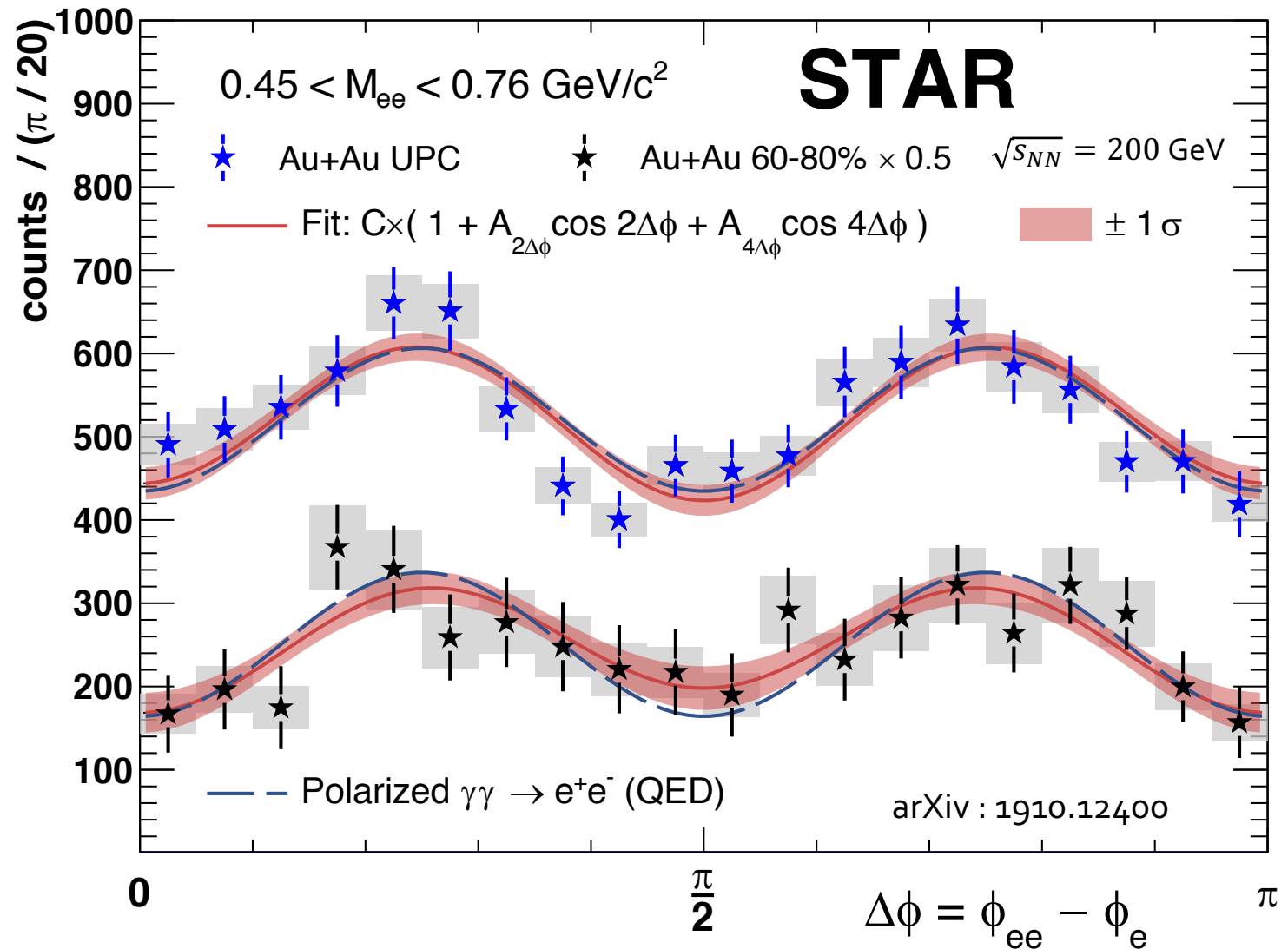$$\approx \Delta\phi[(e^+ + e^-), e^+]$$

Ultra-Peripheral

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	16.8 ± 2.5	16.5	$18.8 / 16$

Peripheral (60−80%)

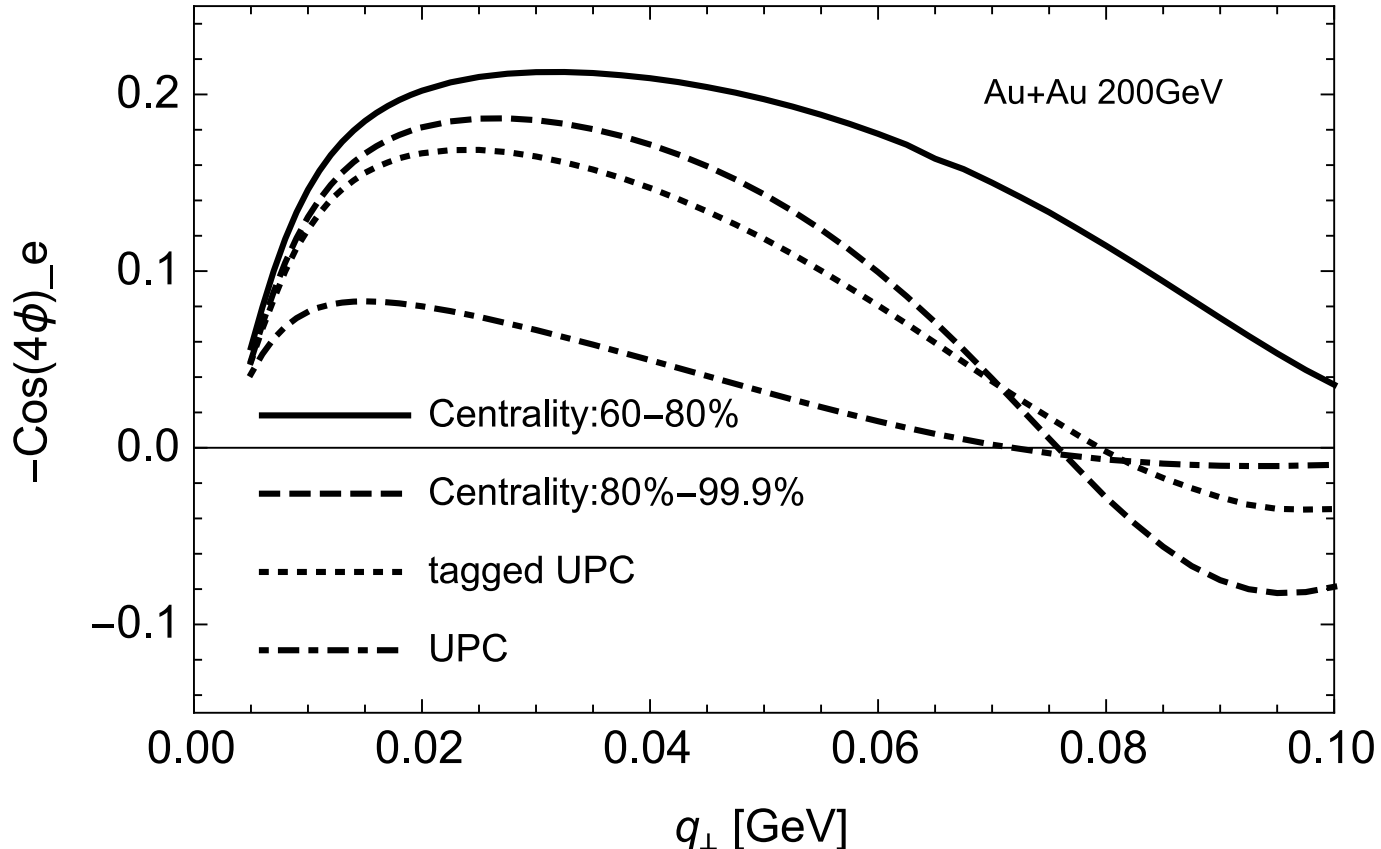| Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	27 ± 6	34.5	$10.2 / 17$

→ **First Earth-based observation** (6.7σ level) of vacuum birefringence

Connection to the <u>Initial</u> Magnetic Field

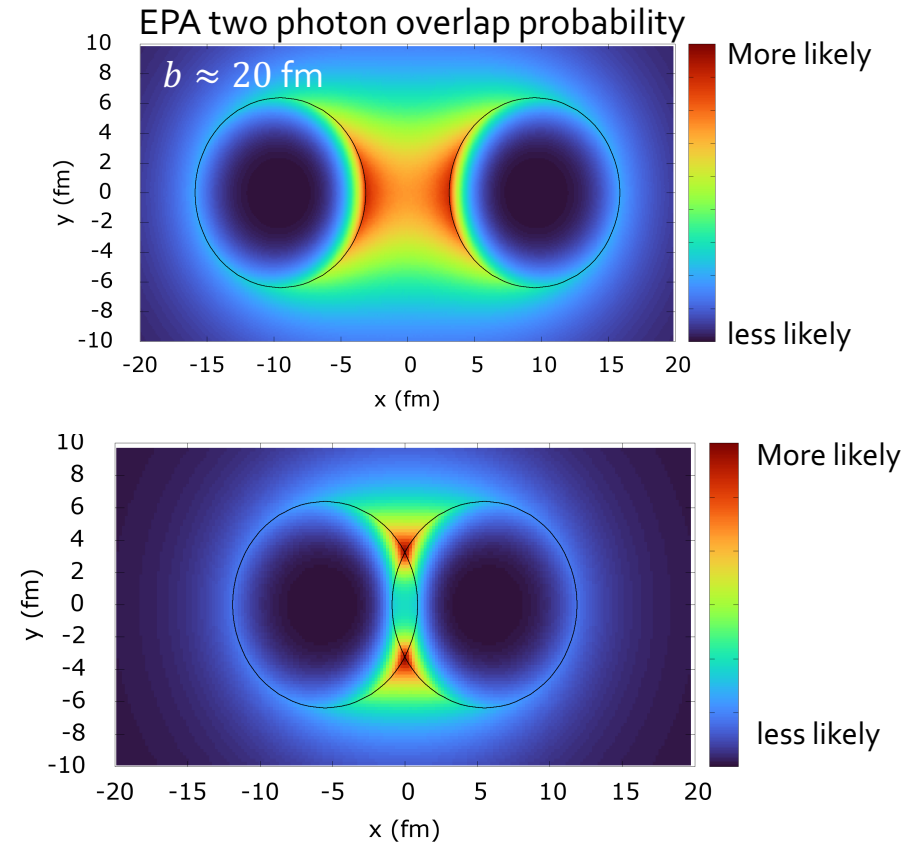**Magnetic field strength and spatial distribution:**

Li, C., Zhou, J. & Zhou, Y. Phys. Rev. D 101, 034015 (2020).

- Illustration to show that $\Delta\phi[\vec{\xi}_1, \vec{\xi}_2]$ changes with b

EPA two photon overlap probability

$b \approx 20$ fm

- Amplitude of $\cos 4\Delta\phi$ modulation is quite sensitive to field distribution

Caveat: These do not include $\sigma^{\gamma\gamma \to l^+ l^-}$, integrated over kinematics, only meant as illustration

Summary

1. Many recent exciting developments in photo-processes

2. Experimental & theoretical advances
   → connection to initial EM field strength & distribution

3. First Earth-based evidence of vacuum birefringence :
   - Observed by STAR (6.7σ) via angular modulations in linear polarized $\gamma\gamma \rightarrow e^+e^-$ process

4. Experimental evidence that HIC produce the strongest magnetic fields in the Universe $\approx 10^{15}$ Tesla - <u>over an extensive spatial distribution</u>

A lot more work needed to further constrain magnetic field topology and to test for possible medium effects – Exciting opportunities lie ahead
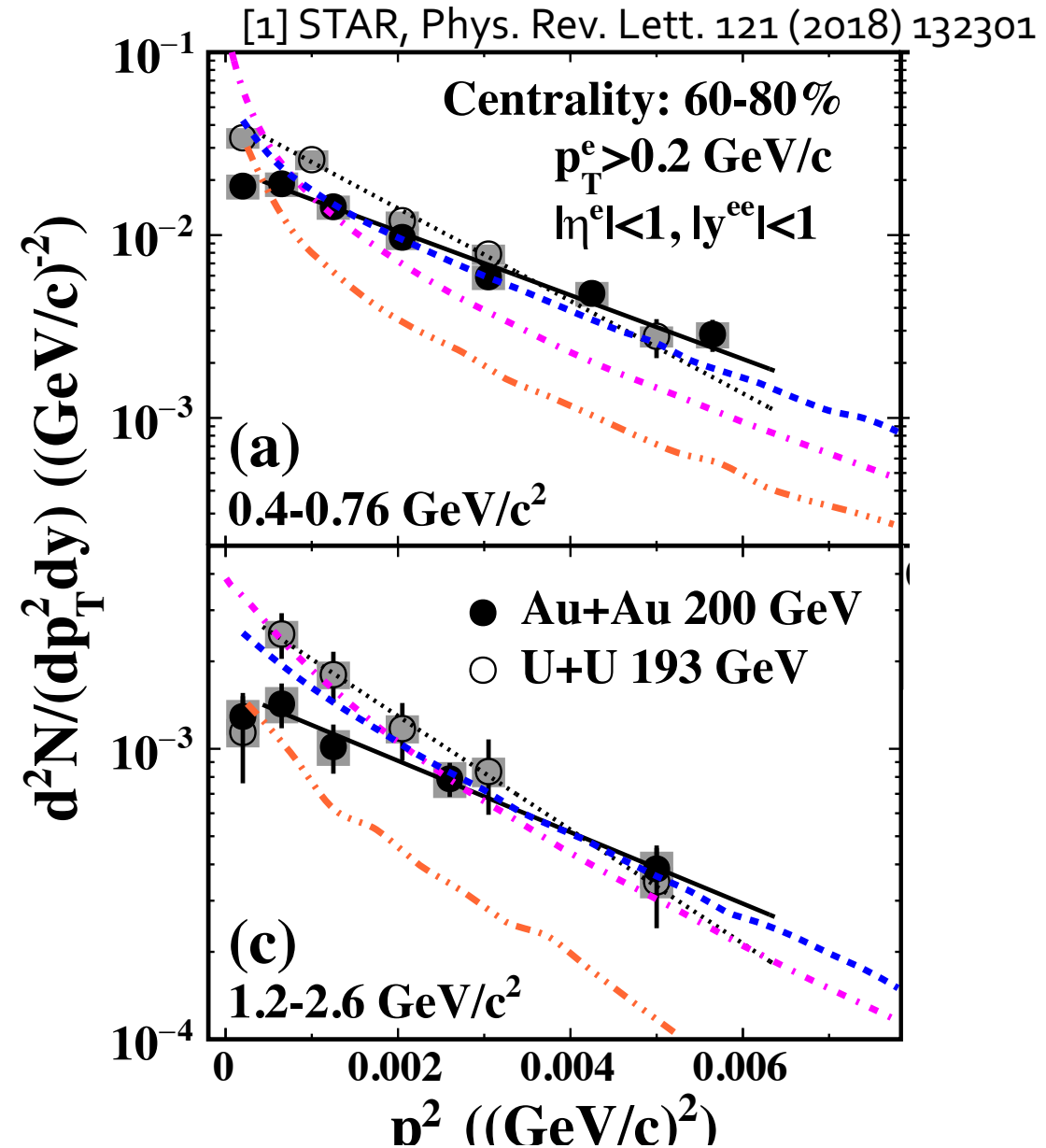
Additional Slides

Long-lived Magnetic Field?

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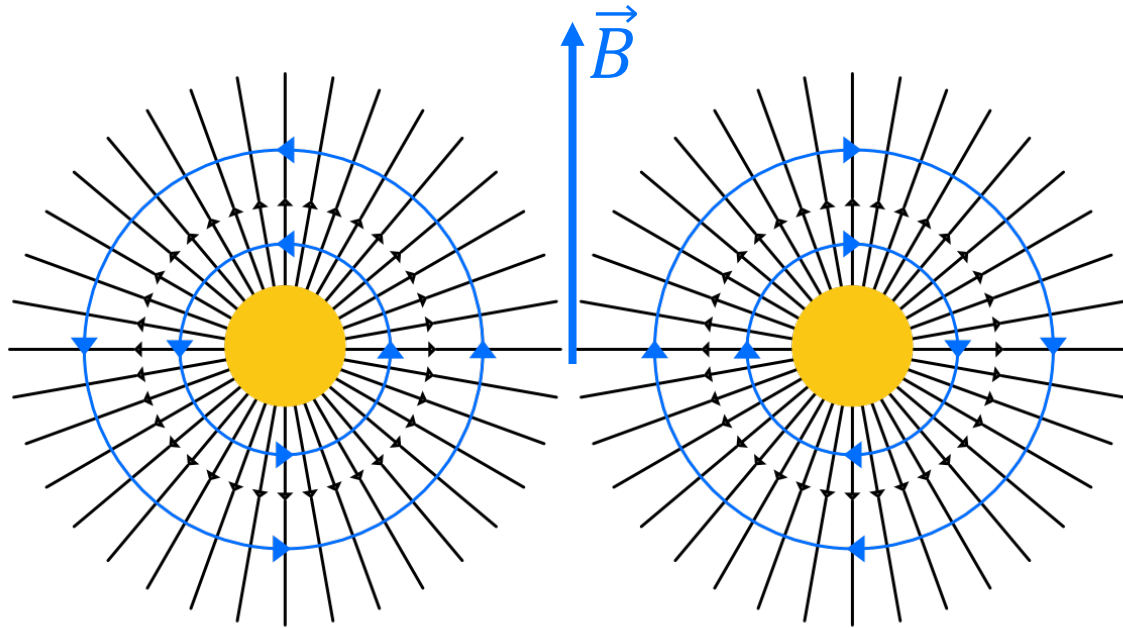
Assumptions:

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

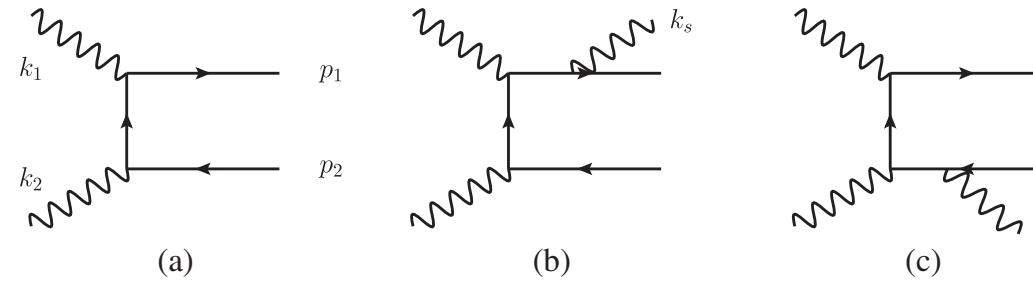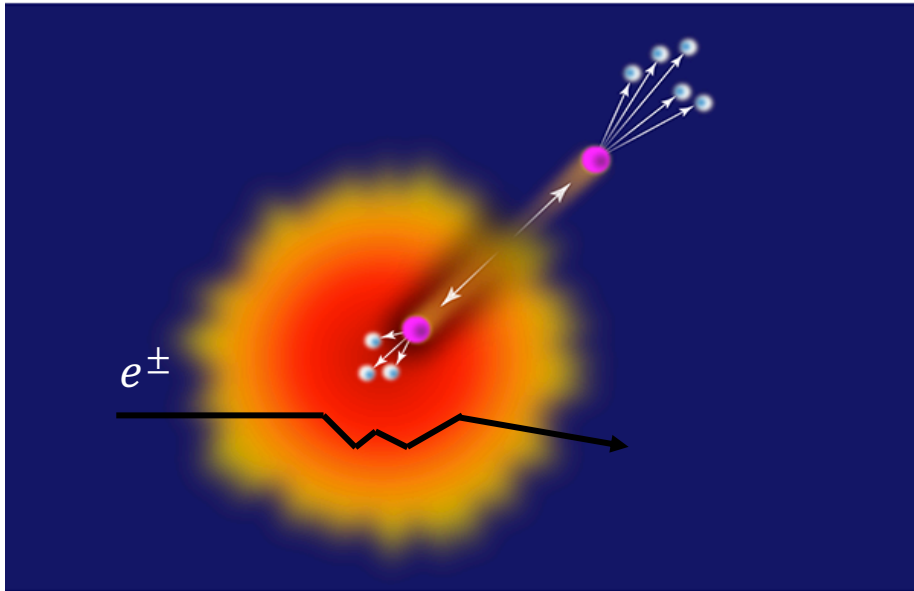Centrality: 60-80%
$p^e_T > 0.2$ GeV/c
$|\eta^e| < 1, |y^{ee}| < 1$

(a) 0.4-0.76 GeV/c^2

● Au+Au 200 GeV
○ U+U 193 GeV

(c) 1.2-2.6 GeV/c^2

$\mathbf{d^2N/(dp^2_T dy)}$ ((GeV/c)^2)

p^2 ((GeV/c)^2)

Coulomb Scattering through QGP

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

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

Assumptions:
1. Primordial distribution given by STARLight
2. Daughters traverse medium
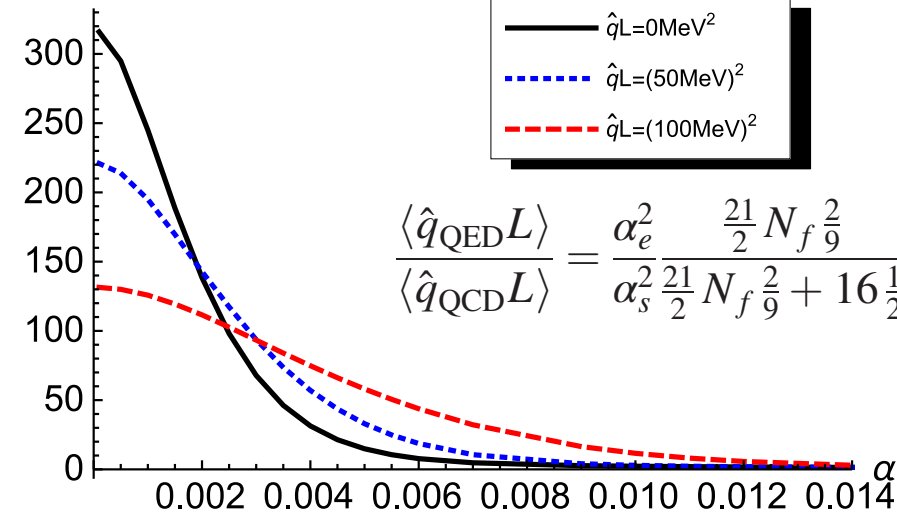
QED Calculations & CMS Acoplanarity

PbPb 5.02 TeV (1.5 nb⁻¹)

CMS
Preliminary
$|y_{\mu\mu}| < 2.4$
$p_T^\mu > 3.5$ GeV, $|\eta^\mu| < 2.4$
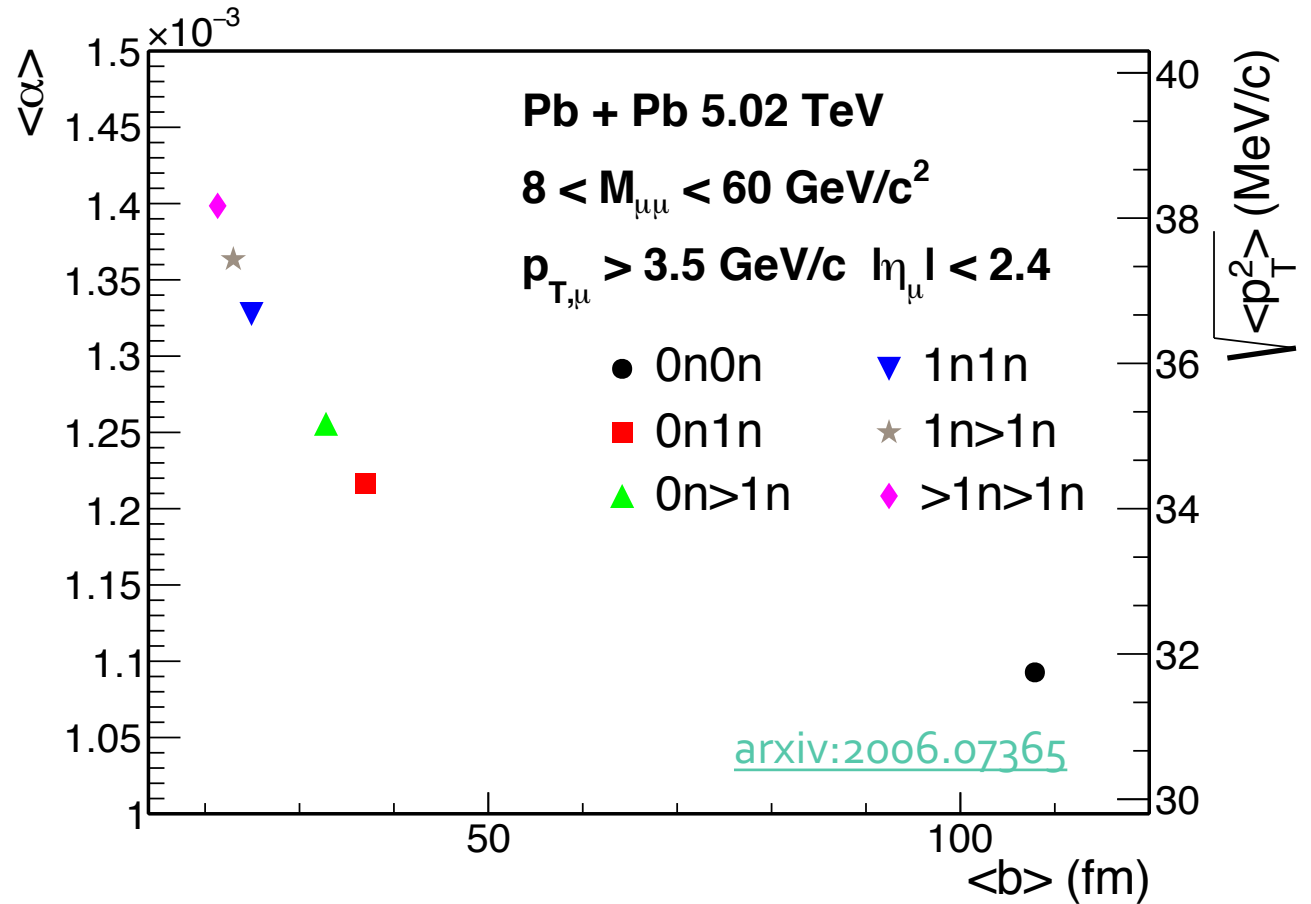$8 < M_{\mu\mu} < 60$ GeV

$\langle \alpha^{core} \rangle$

0n0n 0n1n 0nXn 1n1n 1nXn XnXn

--- STARlight

$\langle \alpha \rangle$ — $\sqrt{\langle p_T^2 \rangle}$ (MeV/c)

Pb + Pb 5.02 TeV

$8 < M_{\mu\mu} < 60$ GeV/c²

$p_{T,\mu} > 3.5$ GeV/c $|\eta_\mu| < 2.4$

● 0n0n   ▼ 1n1n
■ 0n1n   ★ 1n>1n
▲ 0n>1n   ◆ >1n>1n

arxiv:2006.07365

$\langle b \rangle$ (fm)
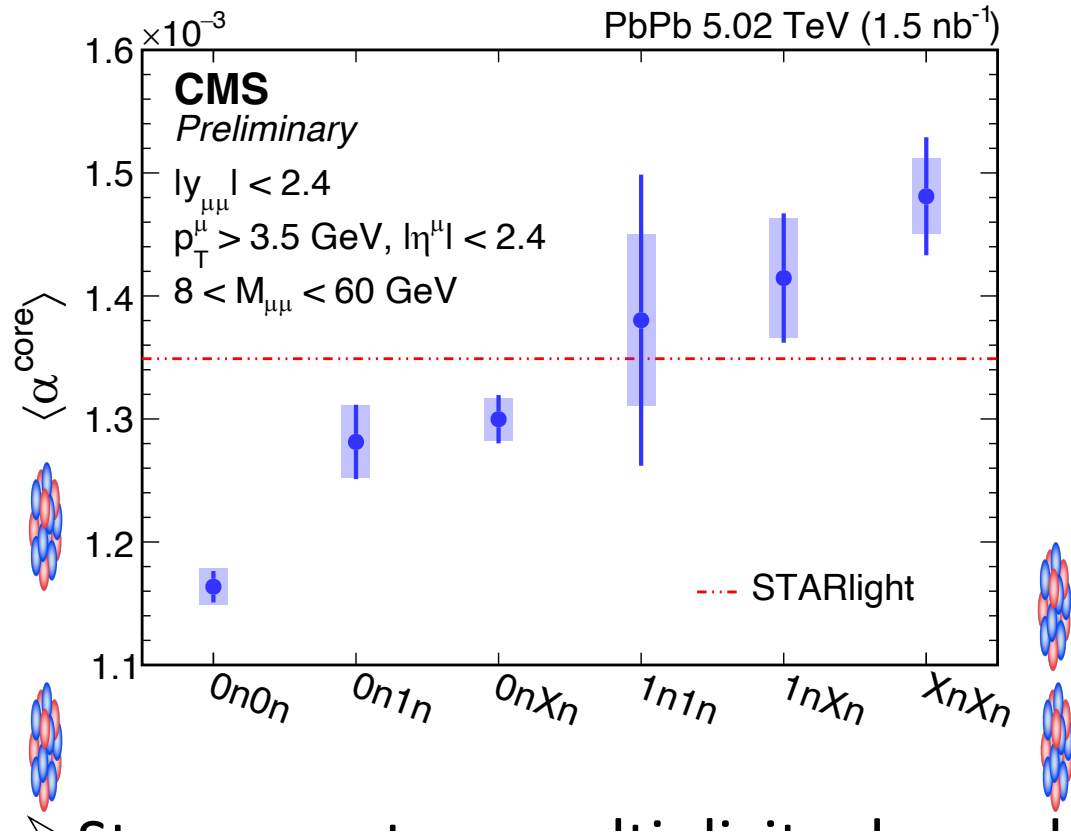
Determine neutron multiplicity

CMS *Preliminary* PbPb 5.02 TeV (a)

ZDC$_{Minus}$ (a.u.) vs ZDC$_{Plus}$ (a.u.)

CMS *Preliminary* PbPb 5.02 TeV (c)

Entries vs ZDC$_{Minus}$ (a.u.)

- 1n
- 2n
- 3n

UPC

STARLIGHT 3.13
LHC beam energy
- XnXn
- 0n0n
- Xn0n

$P_{fn}(b)$ vs b (fm)

STARLIGHT only provides a few neutron emission scenarios
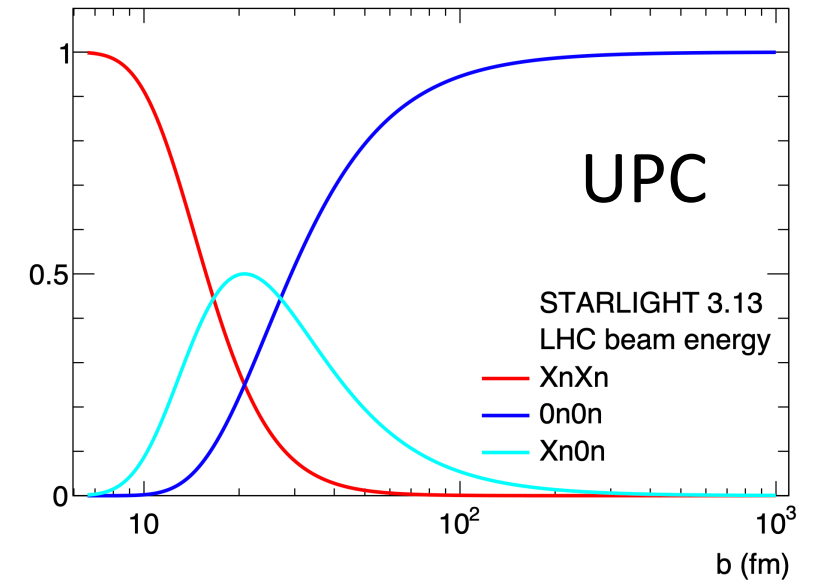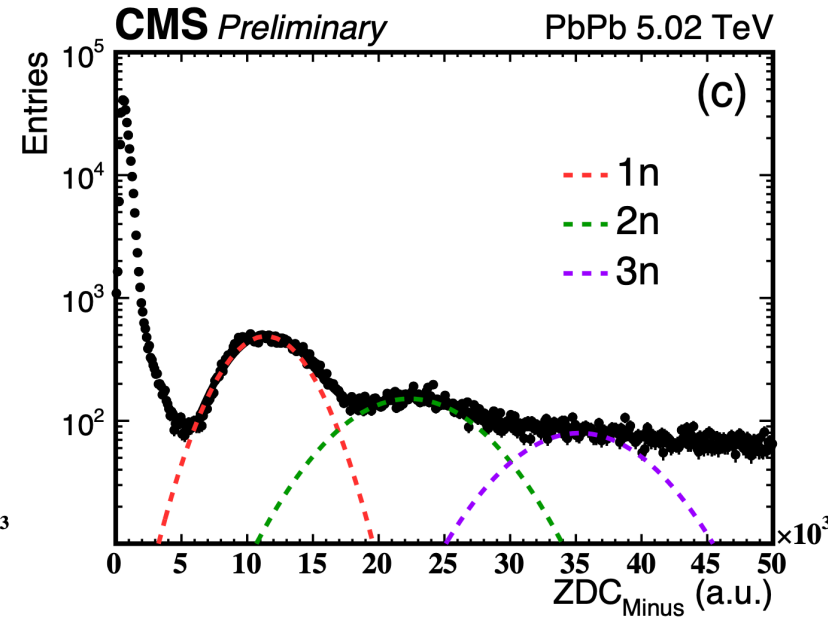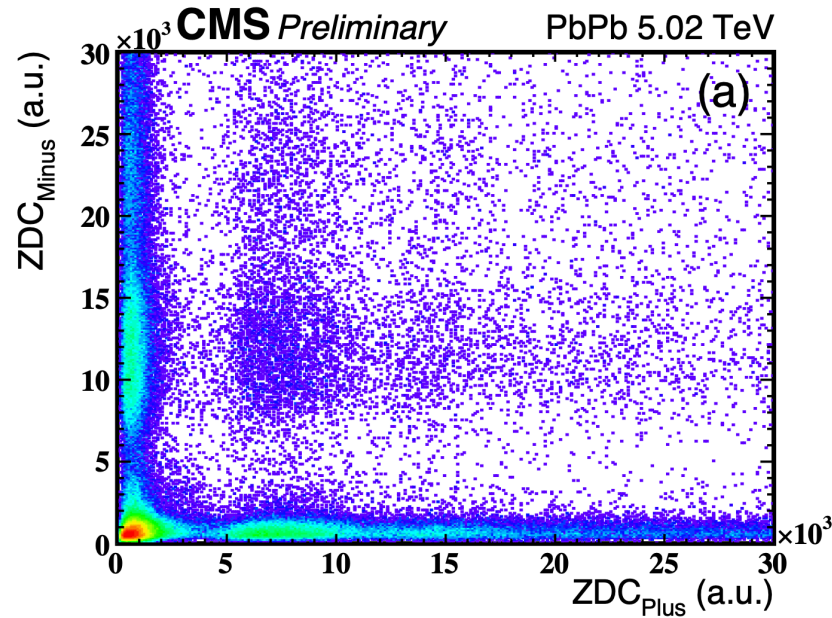
➤ Straight cut to disentangle neutrons

• 0n0n, 0n1n, 0nXn, 1n1n, 1nXn, XnXn (X≥2)

➤ Fit to estimate purity

• 0n and Xn: ~100%

• 1n: ~93-95%

Leading order $\gamma\gamma \rightarrow \mu^+\mu^-$
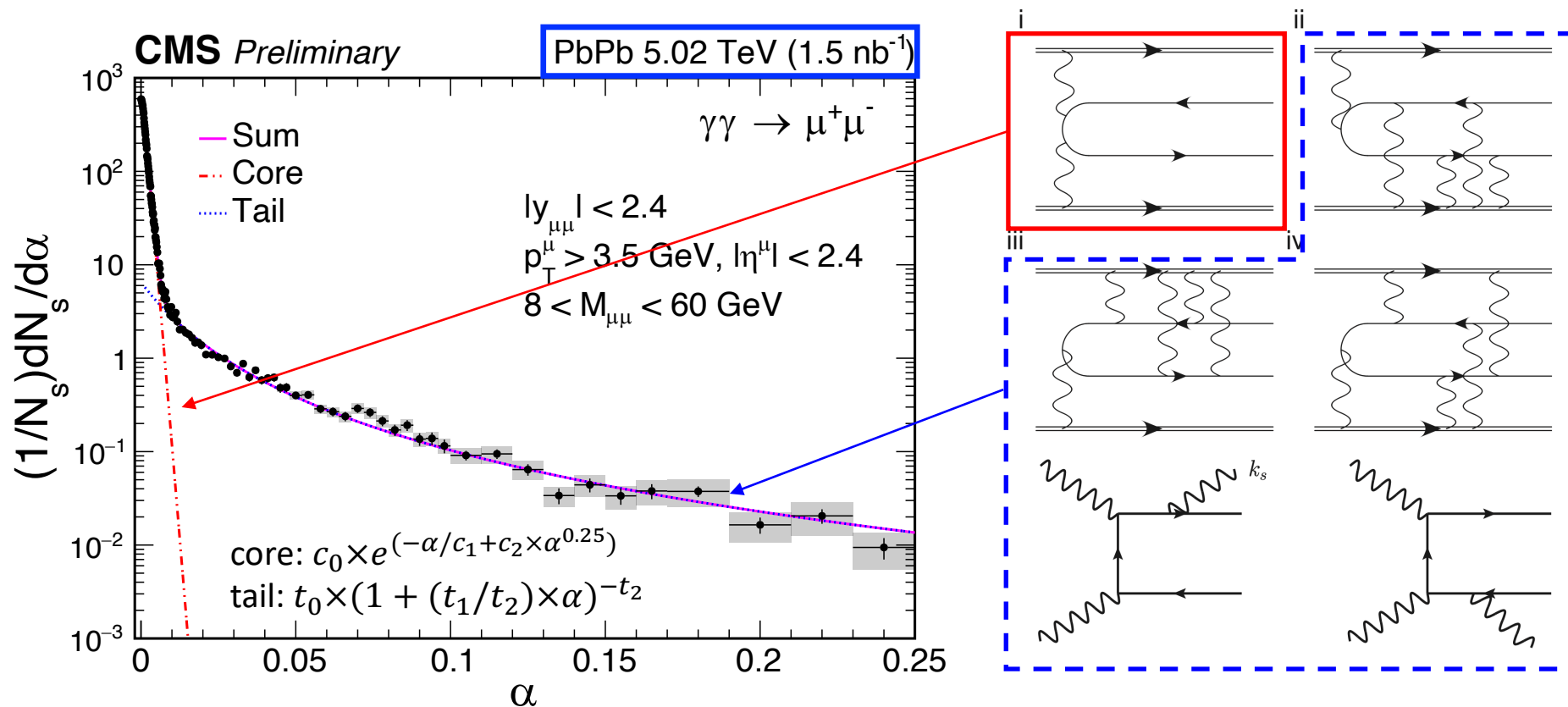

CMS *Preliminary*   PbPb 5.02 TeV (1.5 nb^{-1})

$\gamma\gamma \rightarrow \mu^+\mu^-$

- Sum
- Core
- Tail

$|y_{\mu\mu}| < 2.4$
$p_T^\mu > 3.5$ GeV, $|\eta^\mu| < 2.4$
$8 < M_{\mu\mu} < 60$ GeV

core: $c_0 \times e^{(-\alpha/c_1 + c_2 \times \alpha^{0.25})}$
tail: $t_0 \times (1 + (t_1/t_2) \times \alpha)^{-t_2}$

➤ Decouple α spectrum:

- Data: $\langle \alpha^{core} \rangle = (1227 \pm 7 \text{ (stat.)} \pm 8 \text{ (syst.)}) \times 10^{-6}$
- STARlight: 1348×10^{-6}

Total $\gamma\gamma \rightarrow e^+ e^-$ cross-section in STAR Acceptance

arXiv : 1910.12400

STAR

- ⊦ Au+Au UPC
- - - $\gamma\gamma \rightarrow$ e⁺e⁻ (QED)
- ⋯ $\gamma\gamma \rightarrow$ e⁺e⁻ (gEPA)
- -⋅-⋅ $\gamma\gamma \rightarrow$ e⁺e⁻ (STARLight)

Scale Uncertainty : ± 13%

$P_\perp^e > 0.2$ GeV/c & |η^{el}| < 1.0

|y^{ee}| < 1.0 & $P_\perp$ < 0.1 GeV/c
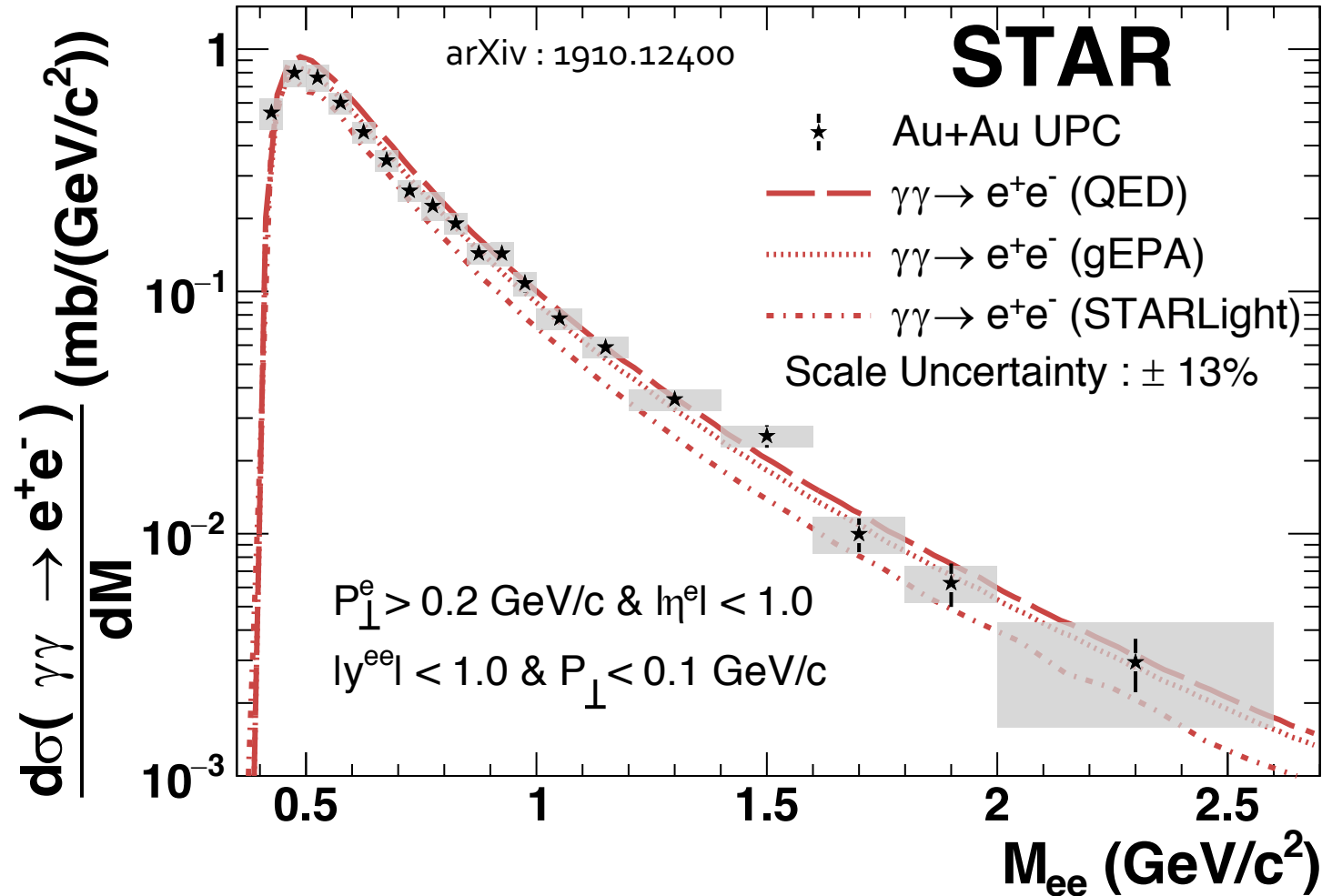
Pure QED 2 → 2 scattering :
$$d\sigma/dM \propto E^{-4} \approx M^{-4}$$

No vector meson production
→ Forbidden for real photons with helicity ±1 (i.e. 0 is forbidden)

$\sigma(\gamma\gamma \rightarrow e^+ e^-)$ **in STAR Acceptance:**

Data : 0.261±0.004 (stat.) ± 0.013 (sys.) ± 0.034 (scale) mb

STARLight	gEPA	QED
0.22 mb	0.26 mb	0.29 mb

Measurement of total cross section agrees with theory calculations at ±1σ level

STARLight: S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258
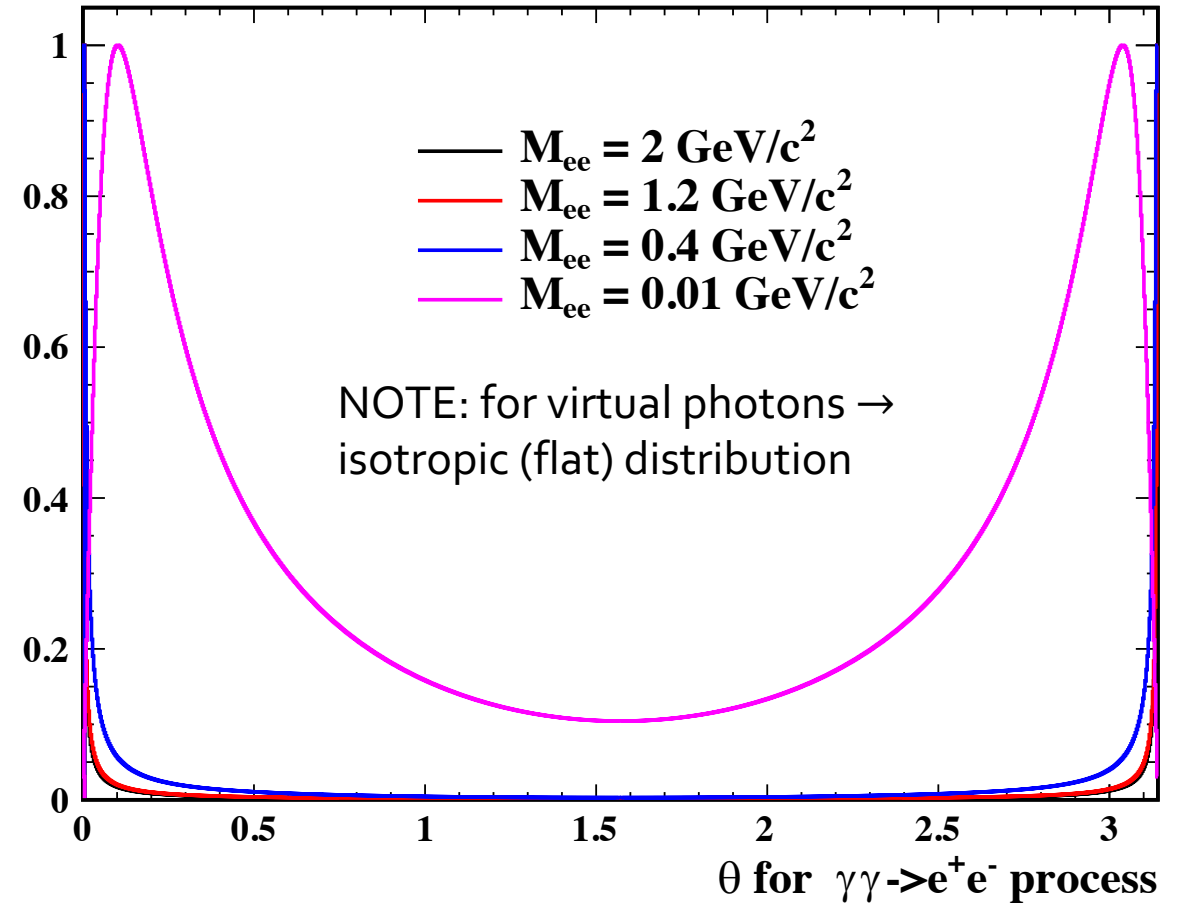gEPA & QED : W. Zha, J.D.B., Z. Tang, Z. Xu arXiv:1812.02820 [nucl-th]

$d\sigma(\gamma\gamma \to e^+e^-)/dcos\,\theta'$

$\gamma\gamma \to e^+e^-$: Individual e^+/e^- preferentially aligned along beam axis [1]:

$$G(\theta) = 2 + 4\left(1 - \frac{4m^2}{W^2}\right)\frac{\left(1 - \frac{4m^2}{W^2}\right)\sin^2\theta\cos^2\theta + \frac{4m^2}{W^2}}{\left(1 - \left(1 - \frac{4m^2}{W^2}\right)\cos^2\theta\right)^2}$$

o Highly virtual photon interactions should have an <u>isotropic distribution</u>

o Measure θ', the angle between the e^+ and the beam axis in the pair rest frame.

NOTE: for virtual photons → isotropic (flat) distribution

Legend:
— M_{ee} = 2 GeV/c^2
— M_{ee} = 1.2 GeV/c^2
— M_{ee} = 0.4 GeV/c^2
— M_{ee} = 0.01 GeV/c^2

θ for $\gamma\gamma$->e$^+$e$^-$ process

[1] S. Brodsky, T. Kinoshita and H. Terazawa, Phys. Rev. **D4**, 1532 (1971)
STARLight: S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258

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o Highly virtual photon interactions should have an <u>isotropic distribution</u>

o Measure θ', the angle between the e^+ and the beam axis in the pair rest frame.

⇒**Data are fully consistent with $G(\theta)$ distribution expected for $\gamma\gamma \to e^+e^-$**

⇒**Measurably distinct from isotropic distribution**
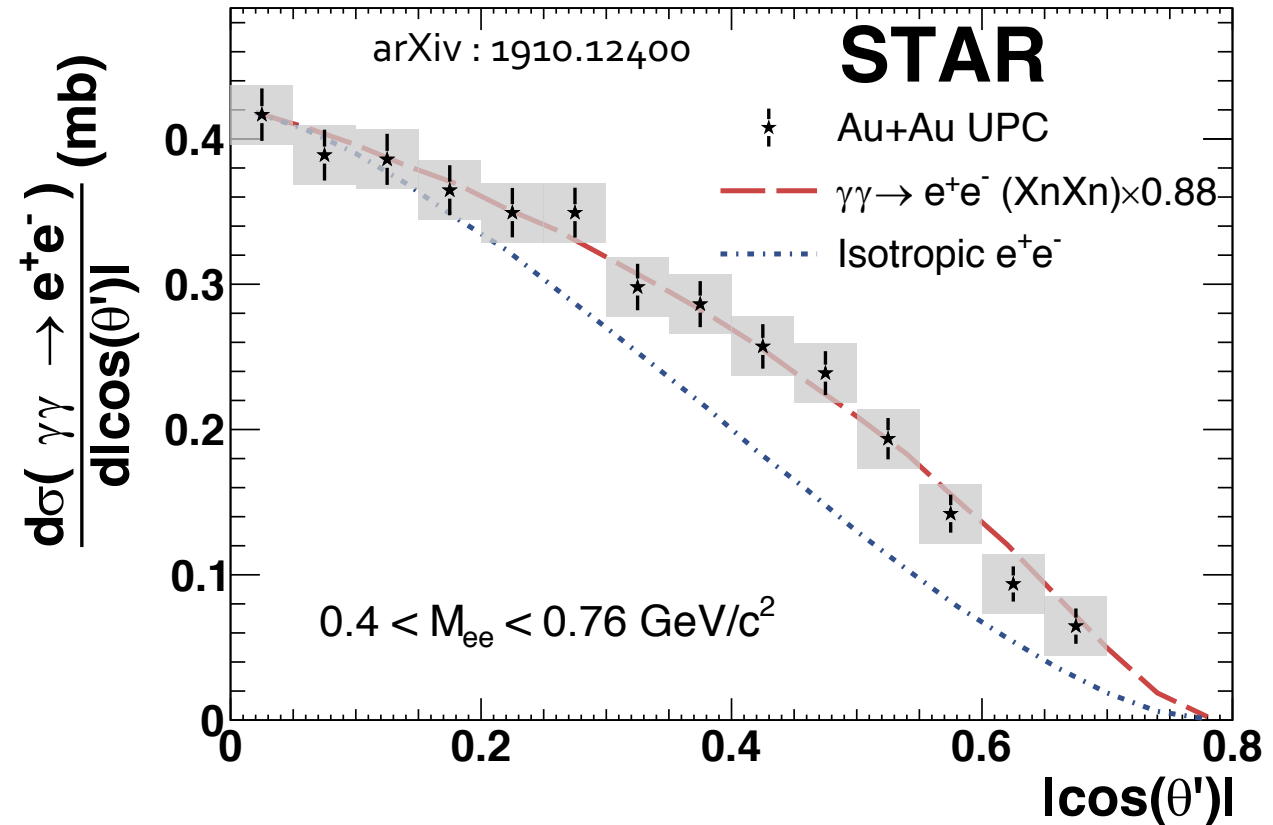
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STARLight: S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258

Outline of this talk

1. Introduction and Motivation
    o Motivation for direct measurement of electromagnetic fields
    o The extreme EM fields in heavy-ion collisions

2. Heavy ion collisions → QED under extreme conditions
    * Surprising results in peripheral heavy-ion collisions
    * Breit-Wheeler pair production & vacuum birefringence

3. A tool for precision mapping of the electromagnetic fields

4. Conclusions