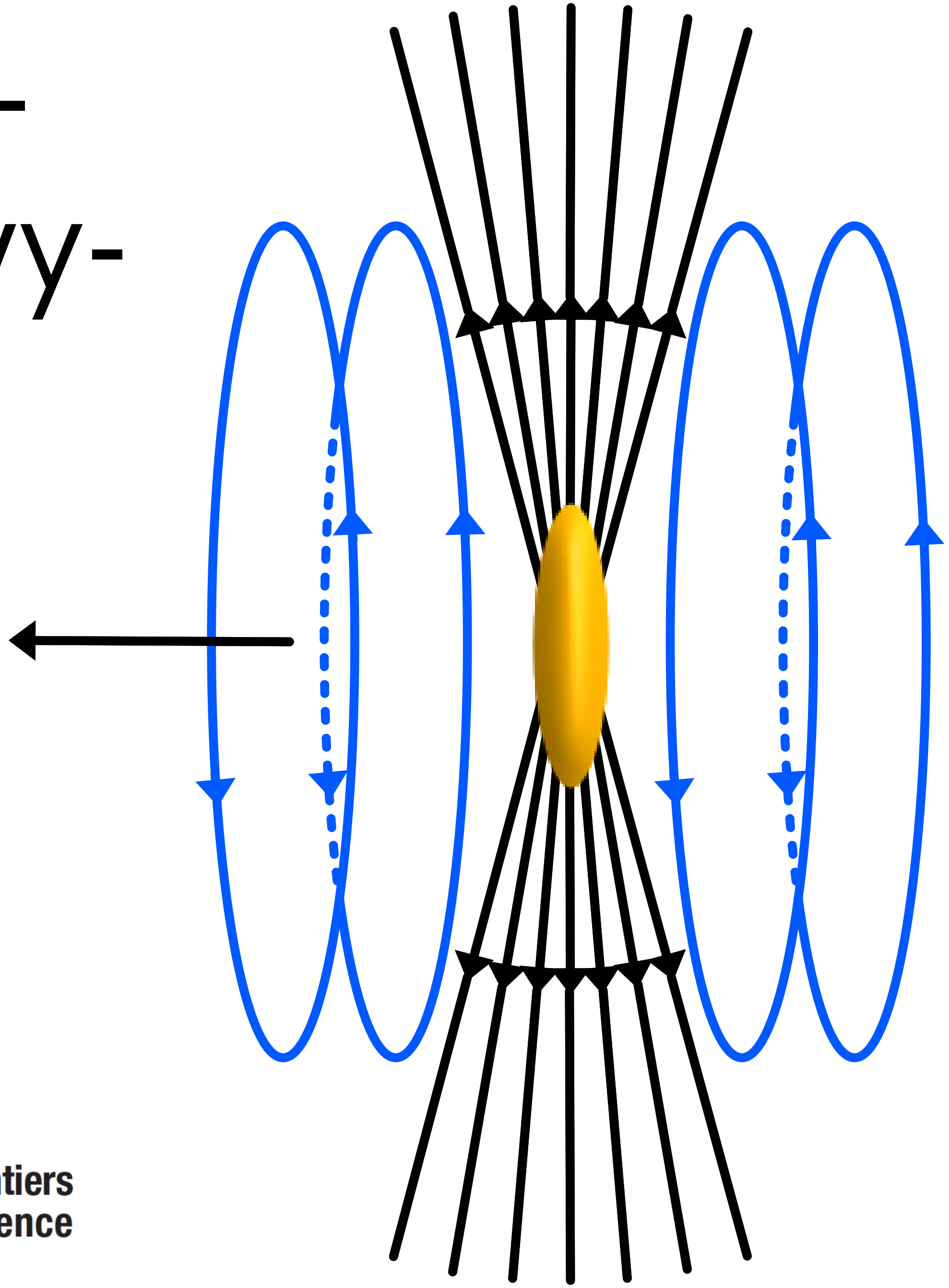
Observation of the Breit-Wheeler Process in Heavy-Ion Collisions

Daniel Brandenburg
BNL(CFNS) / SDU

115th Seminar : High Energy Nuclear Physics in China
July 30th, 2020 (via ZOOM)



Outline of this talk

1. Quantum Electrodynamics
    - Introduction & some history
    - Ultra-peripheral Heavy Ion collisions → QED under extreme conditions
    - Breit-Wheeler Pair Production & Vacuum birefringence

2. A tool for studying Quantum Chromodynamics
    - Mapping the initial Magnetic field
    - Final state/Medium effects?

3. Conclusions

Fundamental Interactions : light & matter

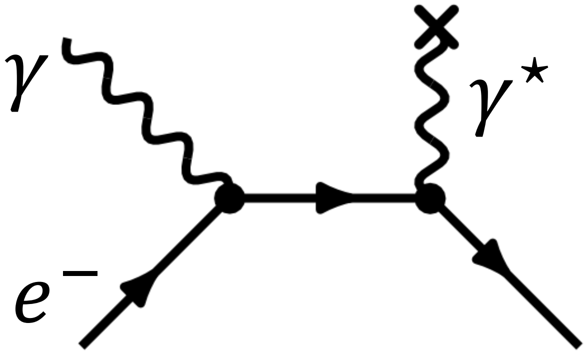
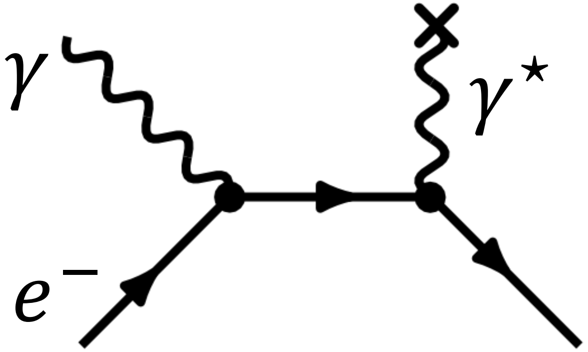


Photo Electric Effect
1887 *Hertz, Ann Phys (Leipzig) 31, 983*

Based on slide by O. Pike

Fundamental Interactions : light & matter



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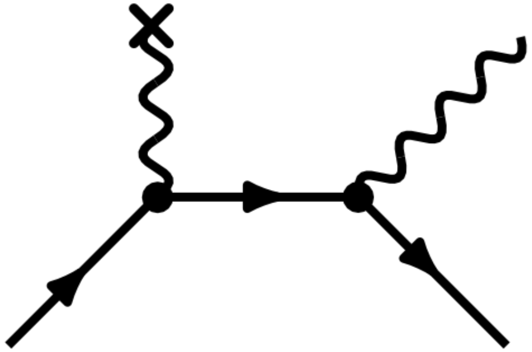
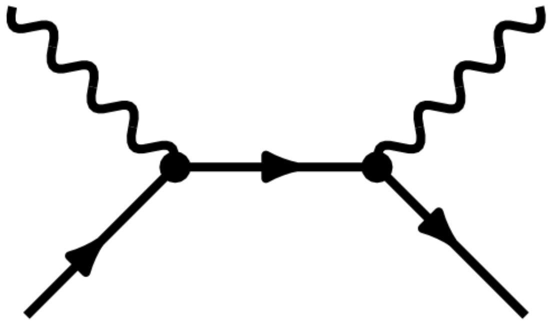
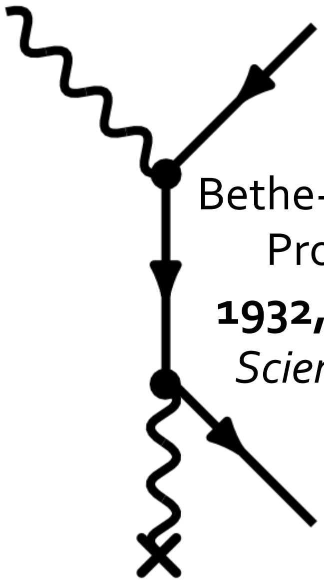


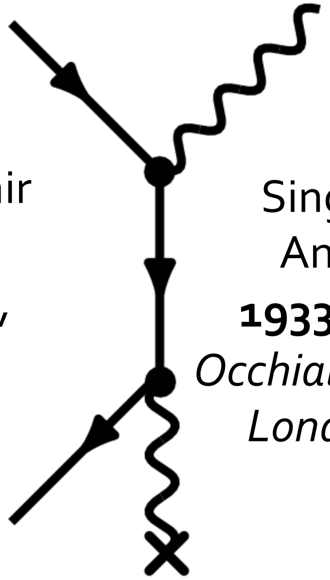
Bremsstrahlung
1895 *Röntgen, Ann Phys (Leipzig) 300, 1*



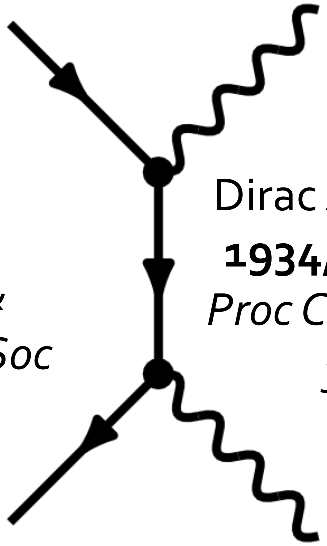
Compton Scattering
1906 *Thomson, Conduction of Electricity through Gases*



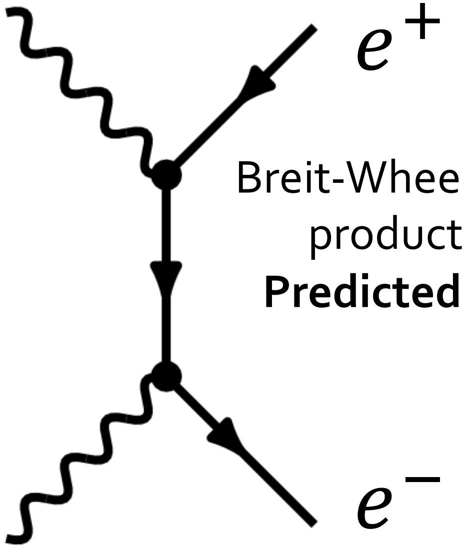
Bethe-Heitler Pair Production
1932, *Anderson, Science 76,238*



Single Photon Annihilation
1933, *Blackett & Occhialini, Proc R Soc Lond A 139, 699*



Dirac Annihilation
1934, *Klemperer, Proc Camb Phil Soc 30, 347*

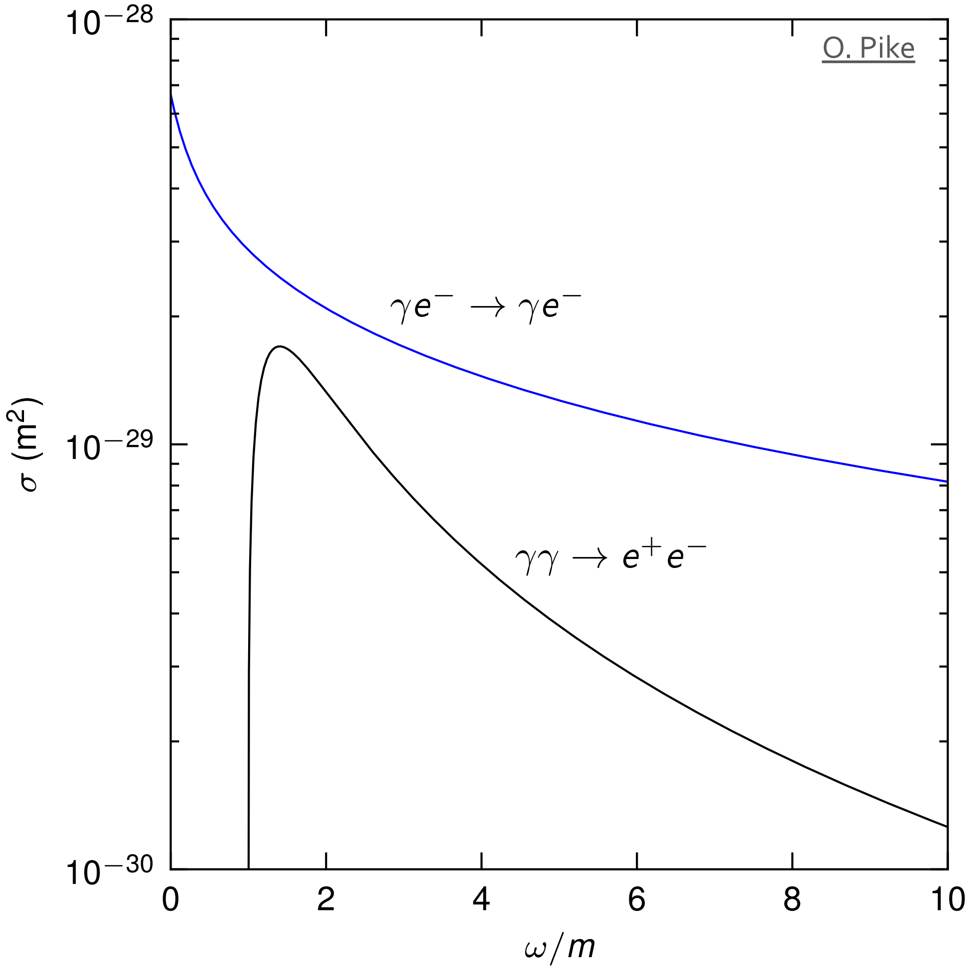


Breit-Wheeler pair production
Predicted 1934

Based on slide by O. Pike

Breit-Wheeler Process, why so *elusive?*

Breit-Wheeler and Klein-Nishina cross-sections



Breit-Wheeler Pair Production Cross Section $\sigma_{\gamma\gamma}$:

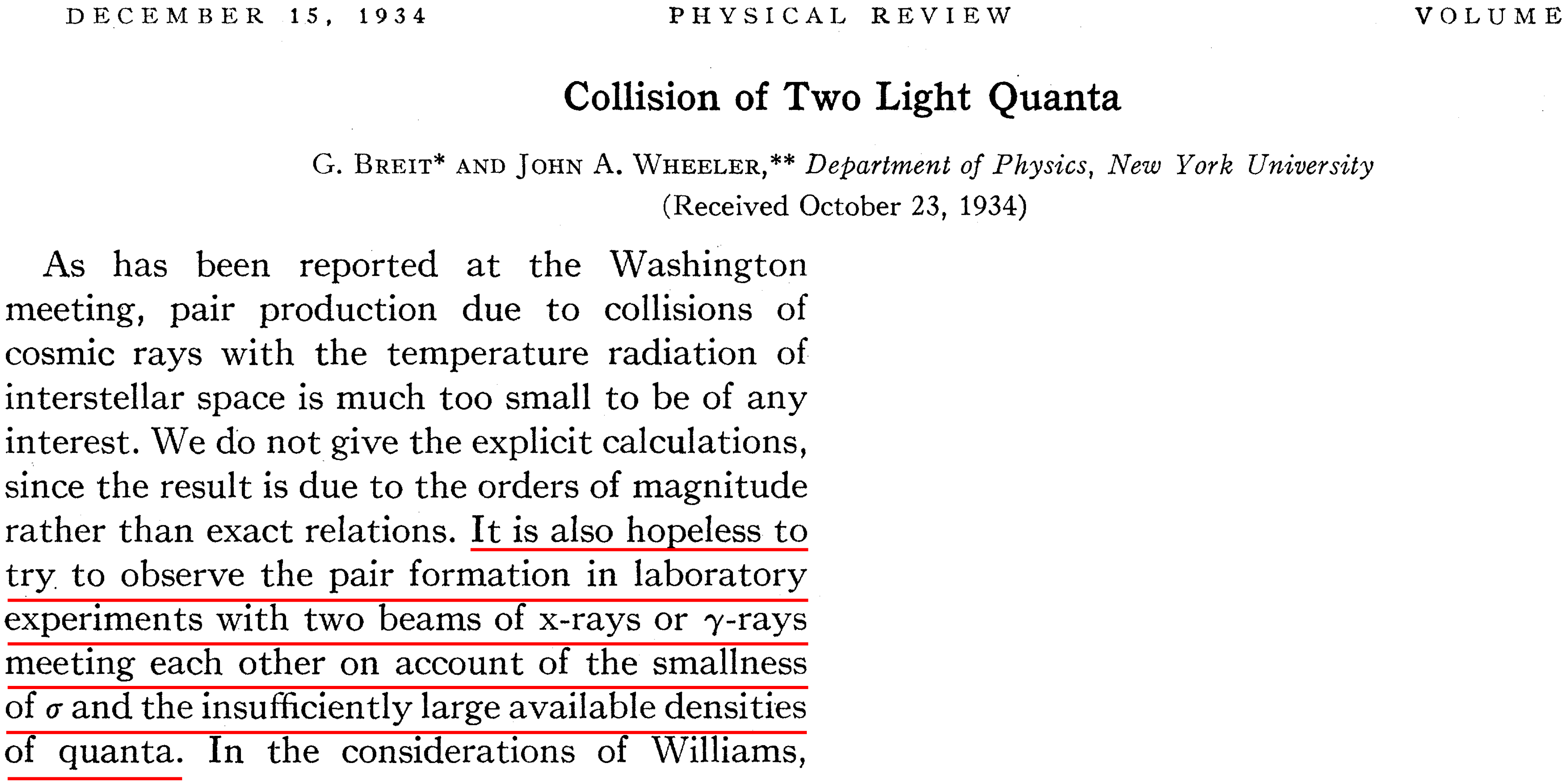
$$\sigma_{\gamma\gamma} = \pi r_0^2 \left(\frac{m}{\omega}\right)^2 \left\{ \left[2\left(1+\left(\frac{m}{\omega}\right)^2\right) - \left(\frac{m}{\omega}\right)^4\right] \cosh^{-1}\frac{\omega}{m} - \left(1+\left(\frac{m}{\omega}\right)^2\right)\sqrt{1-\left(\frac{m}{\omega}\right)^2} \right\}$$

- Same peak cross section as Compton scattering and Dirac annihilation
- Cross section, $\sigma_{\gamma\gamma}$ peaks at 10^{-29}m²
- Creating matter from massless state, remember : $E = mc^2$
  - center of mass energy must be $W \geq 2m_e$

Breit and Wheeler, *Phys Rev* **46,** 1087 (1934)
Jauch and Rohrlich, *The Theory of Photons and Electrons* (1959)

Breit-Wheeler Process, why so *elusive?*

- Already in 1934 Breit and Wheeler knew it was hard, maybe impossible?



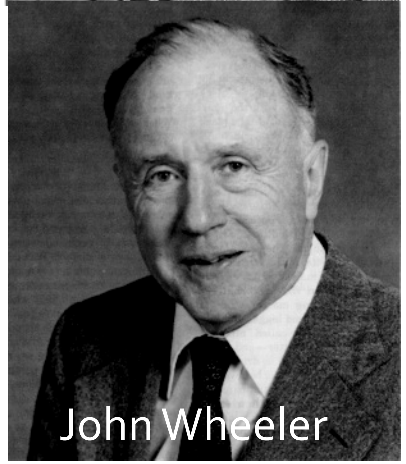
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME

Collision of Two Light Quanta

G. BREIT* AND JOHN A. WHEELER,** *Department of Physics, New York University*
(Received October 23, 1934)

As has been reported at the Washington meeting, pair production due to collisions of cosmic rays with the temperature radiation of interstellar space is much too small to be of any interest. We do not give the explicit calculations, since the result is due to the orders of magnitude rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams,

Gregory Breit



John Wheeler

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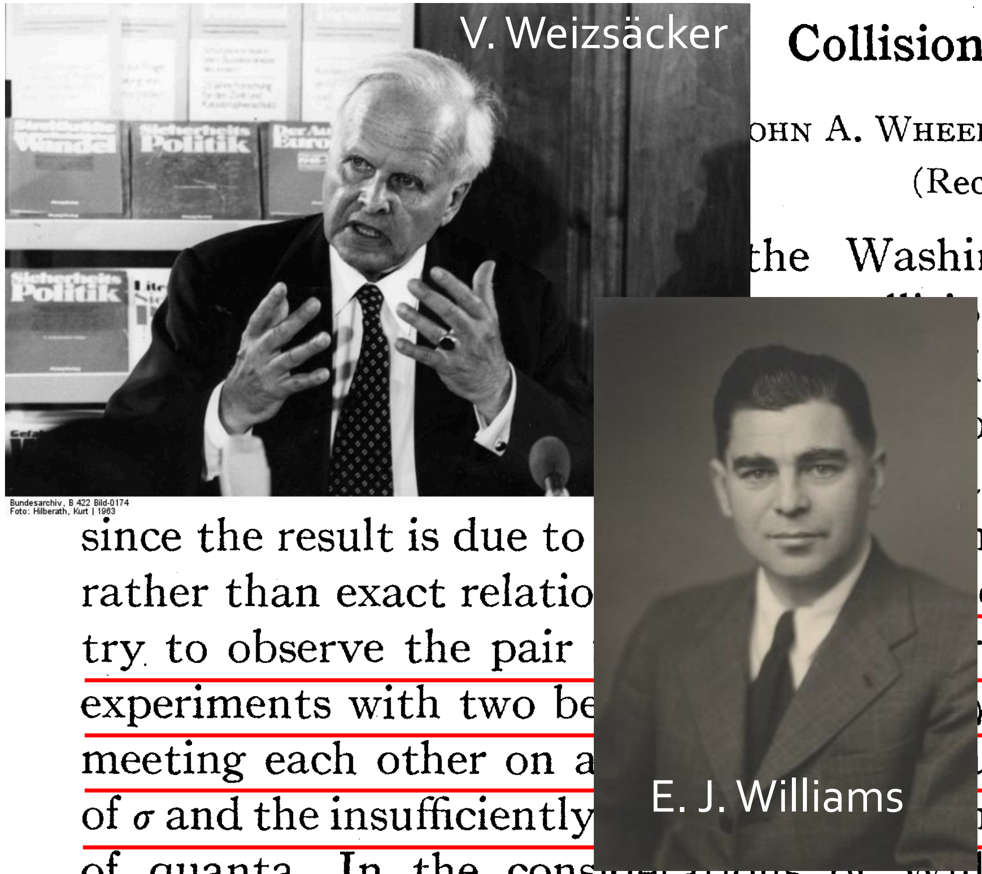
V. Weizsäcker

E. J. Williams

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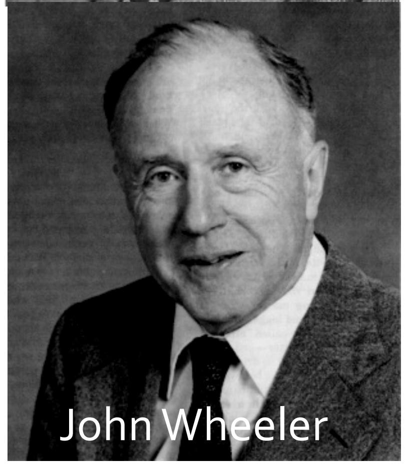
- Or maybe not impossible!

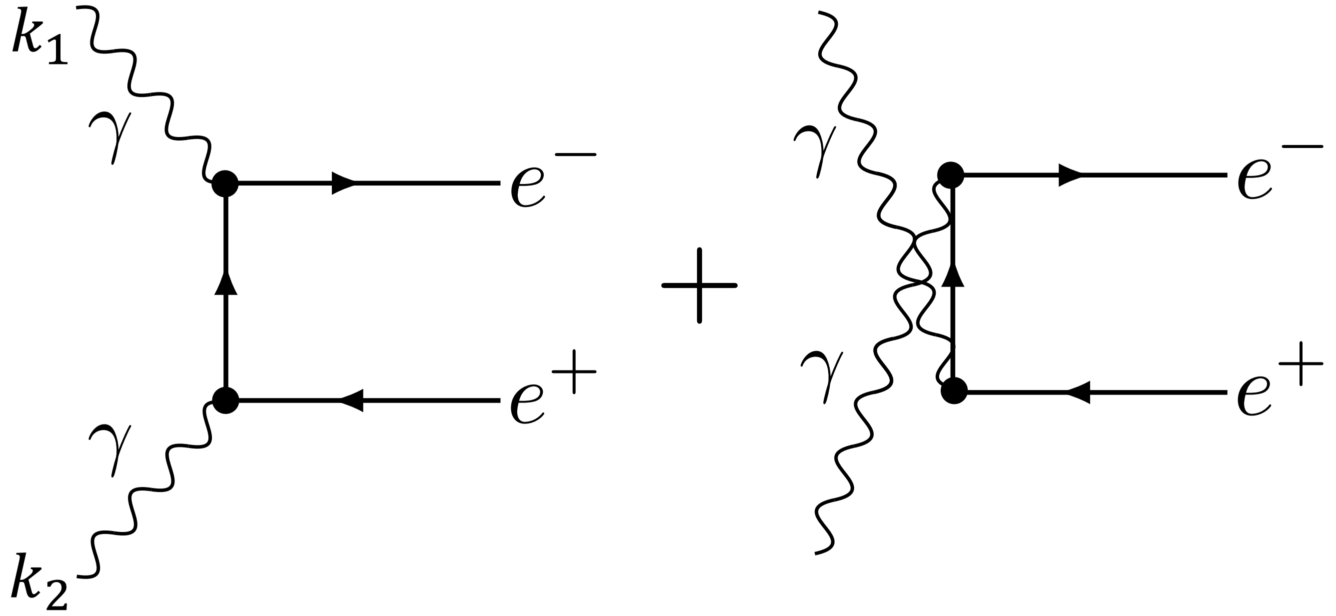
of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number of nucleii available in unit volume of ordinary materials, increases the effect to observable amounts. Analyzing the field of the nucleus into quanta by a procedure similar to that of v. Weizsäcker,[4] he finds that if one quantum *hν*

E. J. Williams Phys. Rev. **45**, 729 (1934)
K. F. Weizsacker, Z. Physik , 612 (1934)


Gregory Breit


John Wheeler

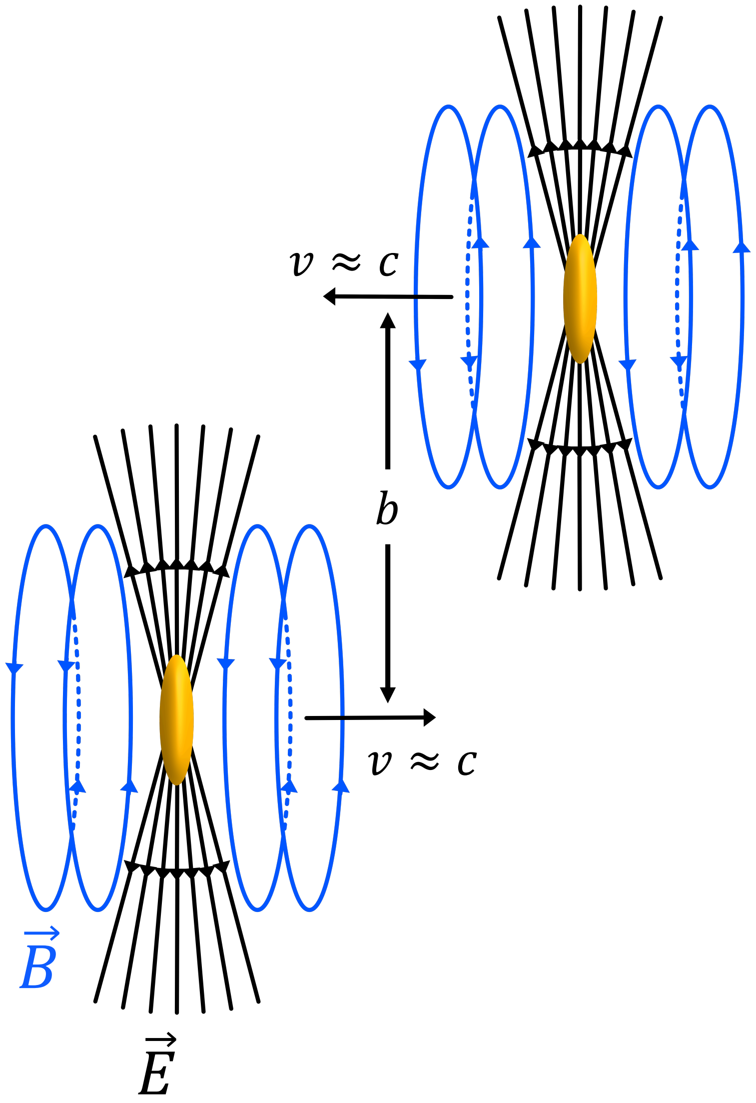
The Breit-Wheeler ($\gamma\gamma \rightarrow e^+e^-$) Process



- Breit-Wheeler process is by definition the lowest-order process
- Two Feynman diagrams contribute at lowest-order
- Specifically note:

$$P_\perp = k_{1\perp} + k_{2\perp}$$

Ultra-Peripheral Heavy Ion Collisions



Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field

Weizäcker-Williams *Equivalent Photon Approximation* (EPA):
→ In a specific phase space, transverse EM fields can be quantized as a flux of **real photons**

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

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

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

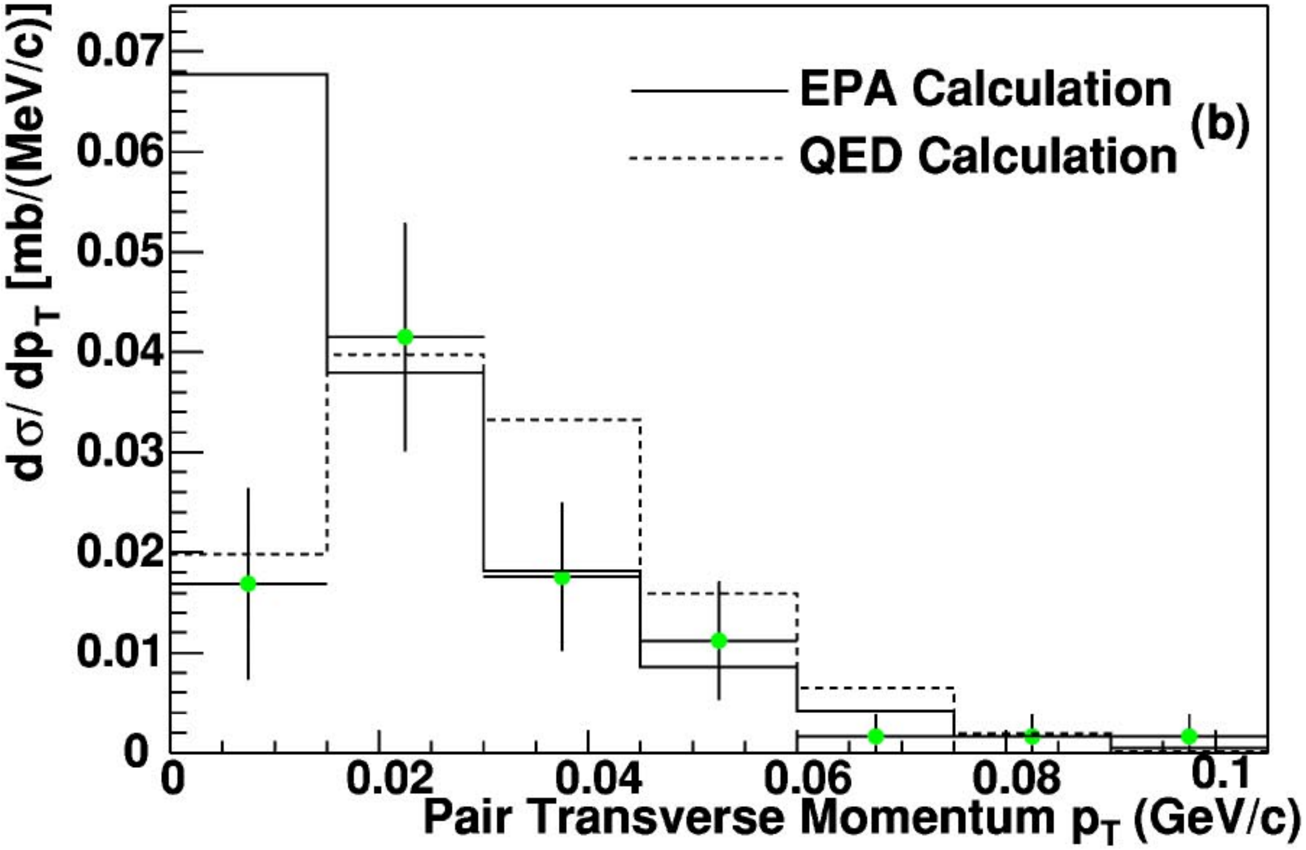
Ultra-strong electric and magnetic fields:

→ 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

Test QED under extreme conditions

STAR 2004 : $d\sigma(\gamma\gamma \rightarrow e^+e^-)/dP_\perp$



Actually, STAR tried to measured $\gamma\gamma \rightarrow e^+e^-$ before, in 2004

Low statistics measurement

(only 52 e^+e^- pairs)

Unable to definitively determine process

In that paper and subsequent papers from community, assume that difference between EPA and QED (near $P_\perp \approx 0$) **results from significant photon virtuality**

STAR Collaboration, et al. *Physical Review C*, vol. 70, no. 3, Sept. 2004, p. 031902. *APS*, doi:10.1103/PhysRevC.70.031902.

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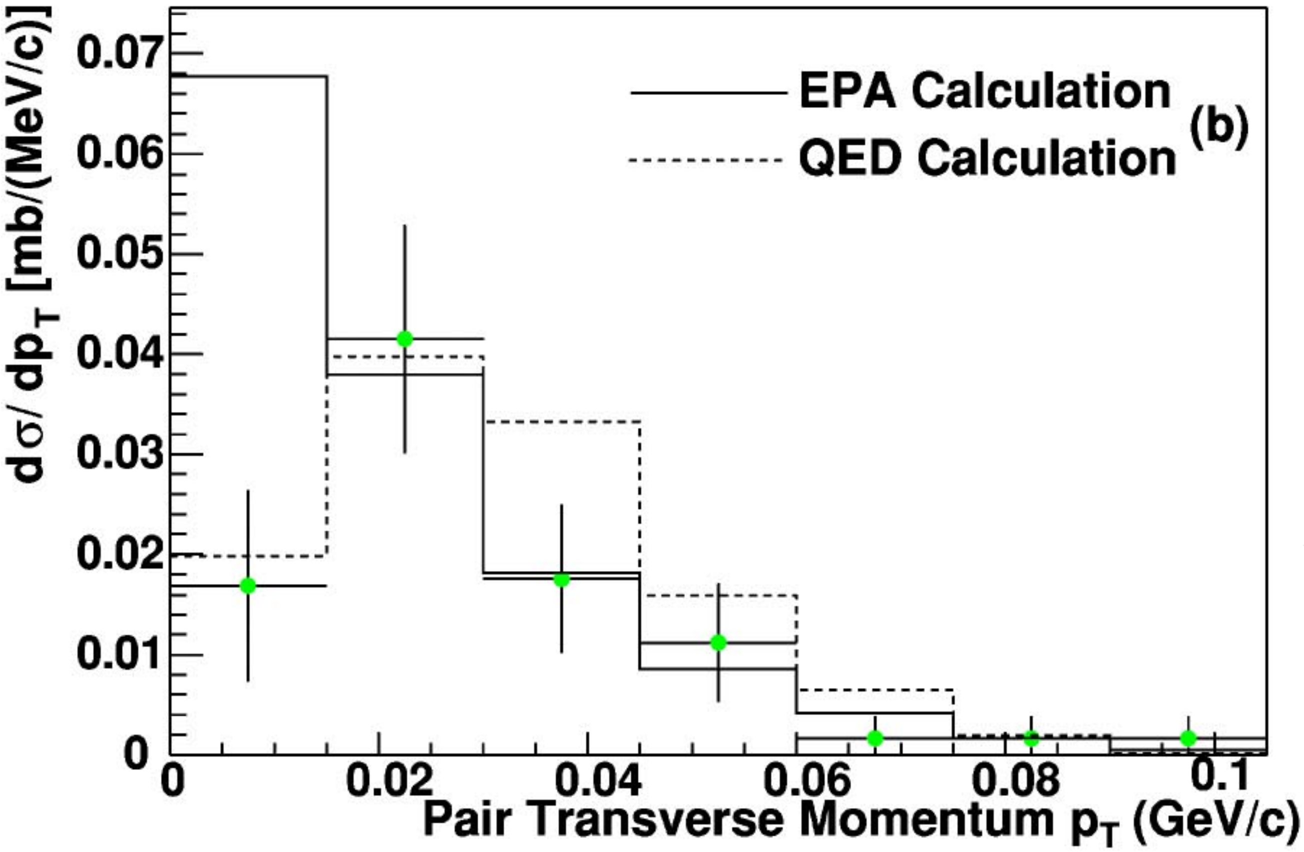
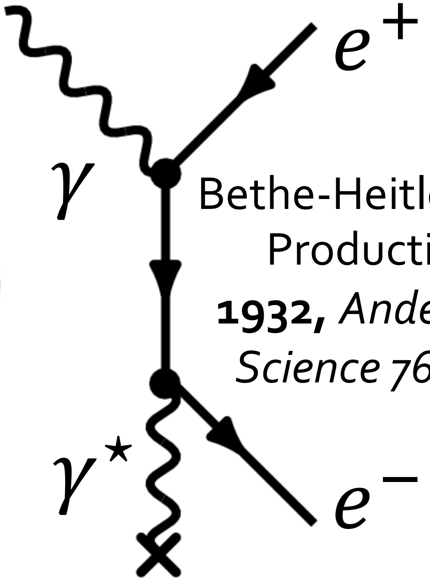


STAR Collaboration, et al. *Physical Review C*, vol. 70, no. 3, Sept. 2004, p. 031902. *APS*, doi:10.1103/PhysRevC.70.031902.

Other experiments have also investigated the $\gamma\gamma \rightarrow e^+e^-$ in UPCs before.

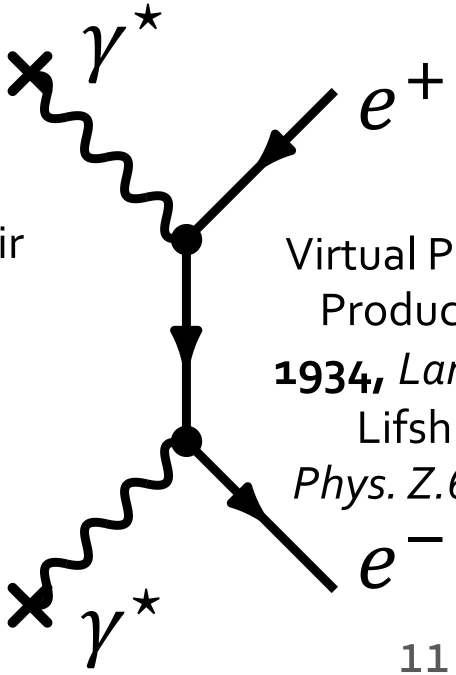
Problem:

Cross section alone cannot distinguish Breit-Wheeler Process from background from virtual photons



Bethe-Heitler Pair Production

1932, *Anderson, Science 76,238*



Virtual Photon Production

1934, *Landau &* Lifshitz *Phys. Z.6, 244*

A Novel Approach for the Breit-Wheeler Process

→ **Perform a precision measurement of the differential cross sections**

1. Photon Energy Spectrum
    - Transverse Momentum distribution
    - Invariant mass distribution
    - Impact parameter dependence
2. Angular Distribution
    - Distinctive polar angle distribution
    - Azimuthal modulations predicted for real photon (transversely polarized)

General density matrix for the two-photon system:

$$\rho^{a,a'} = \begin{pmatrix} \rho^{++} & \rho^{+0} & \rho^{+-} \\ \rho^{+0} & \rho^{00} & \rho^{+0} \\ \rho^{+-} & \rho^{+0} & \rho^{++} \end{pmatrix}$$

Spin 1 Photon helicity a = $(-, 0, +)$

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Helicity 0 : Forbidden for real photon

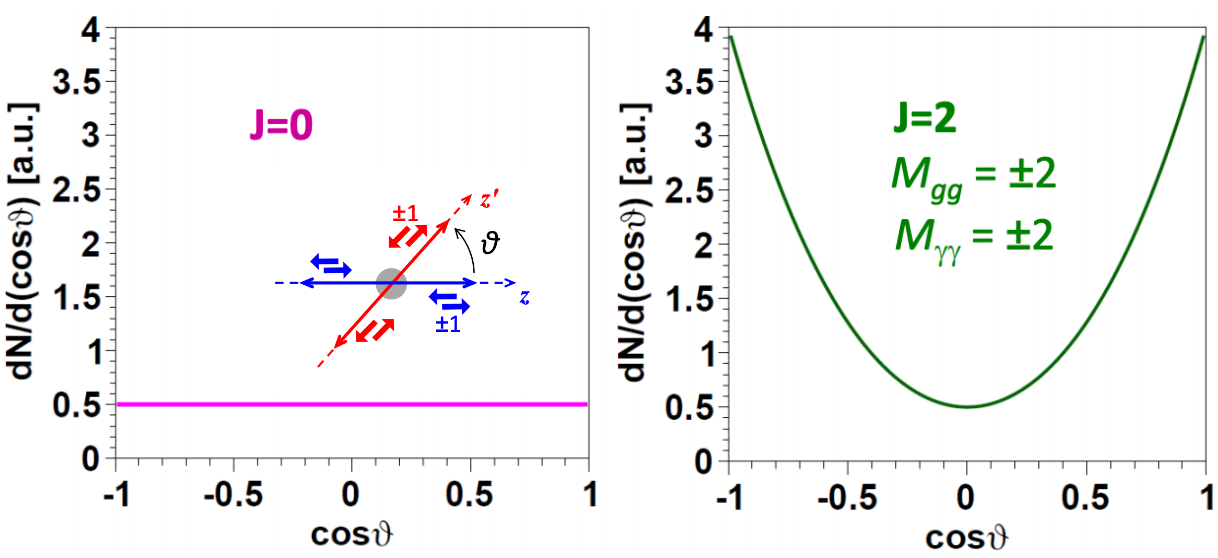
Real photon: Allowed J^P states: $2^{\pm}, 0^{\pm}$

A Novel Approach for the Breit-Wheeler Process

→ **Perform a precision measurement of the differential cross sections**

Angular distribution allows identification of quantum numbers - e.g. Higgs Boson

SM Higgs boson



Pietro Faccioli,
https://indico.cern.ch/event/246009/attachments/422282/586290/CERN_23_4_2013_no_animations.pdf

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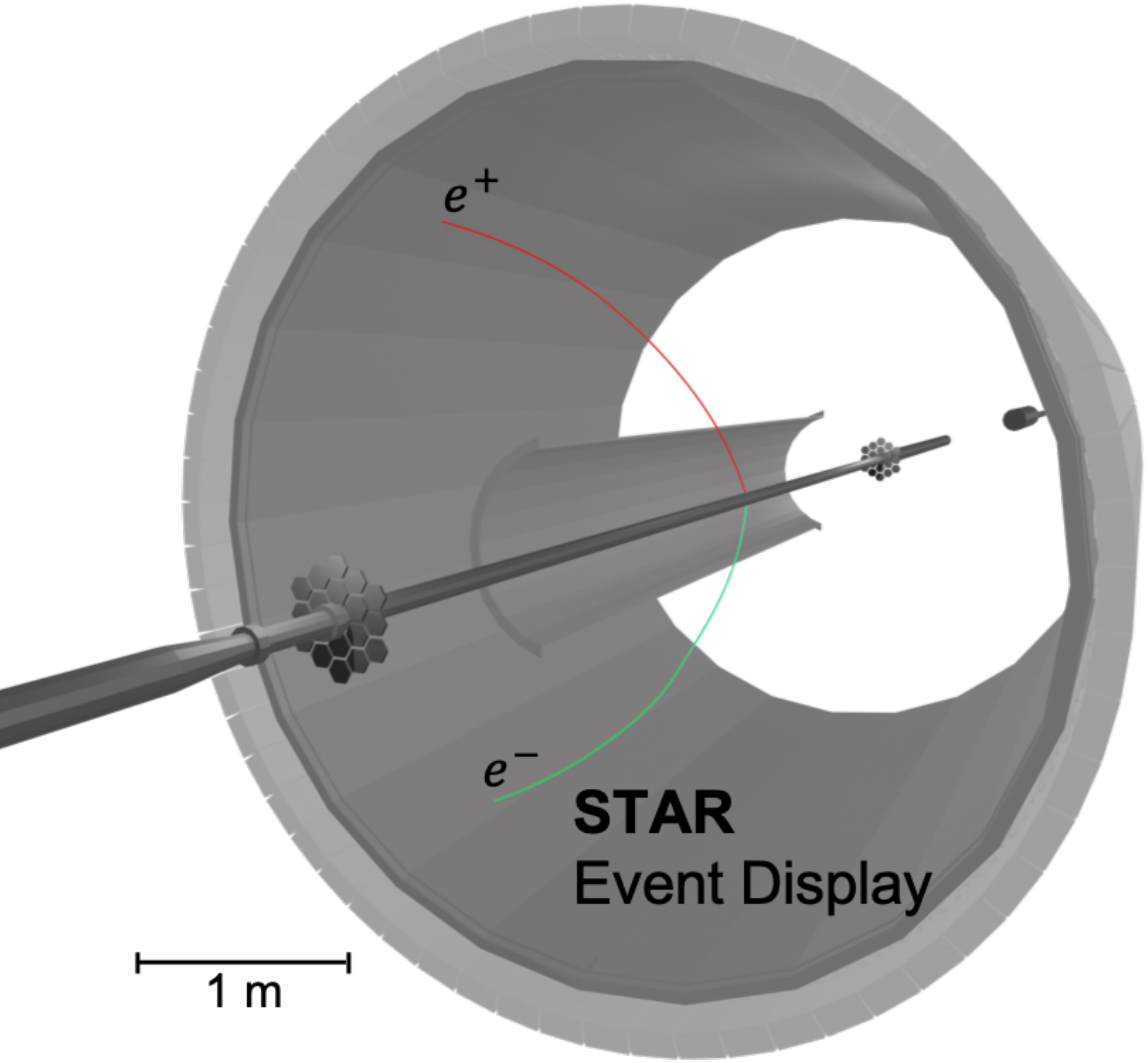
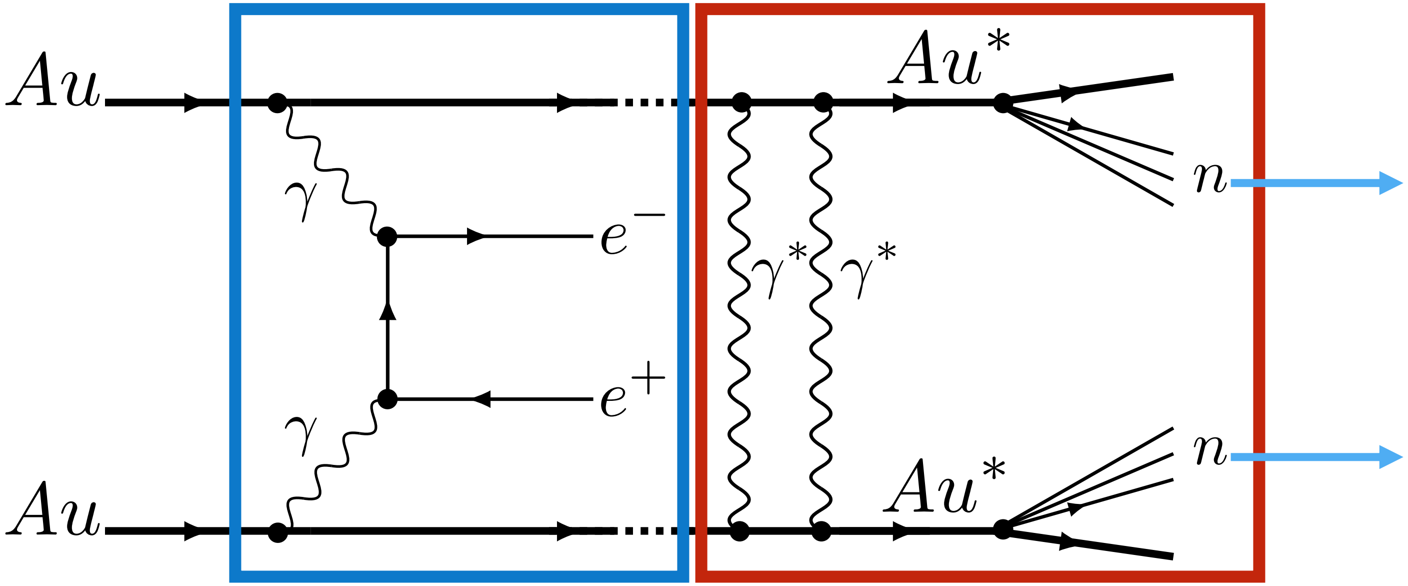
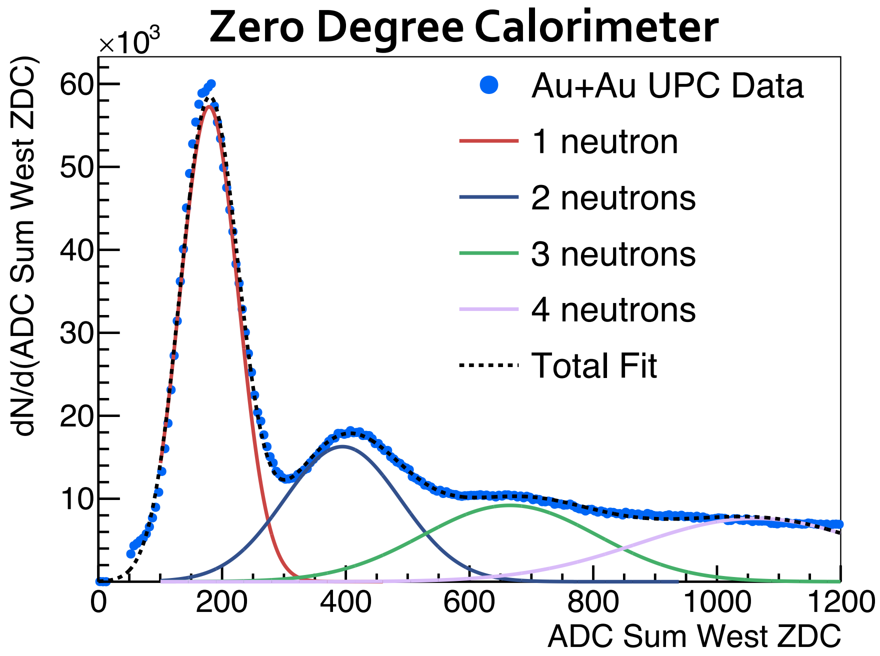
Signatures of the Breit-Wheeler Process



1. Exclusive e^+e^- pair production
2. Photon helicity +/-1 only
   - Smooth invariant mass spectra (No vector mesons)
   - Individual e^+e^- preferentially aligned along beam direction
3. Energy Spectrum:
   - Production peaked at very low $P_\perp$ (pair transverse momentum)
   - Impact parameter dependence on $P_\perp$
4. Photon transverse polarization & spatial distribution

$\gamma\gamma \to e^+e^-$ Process in UPCs





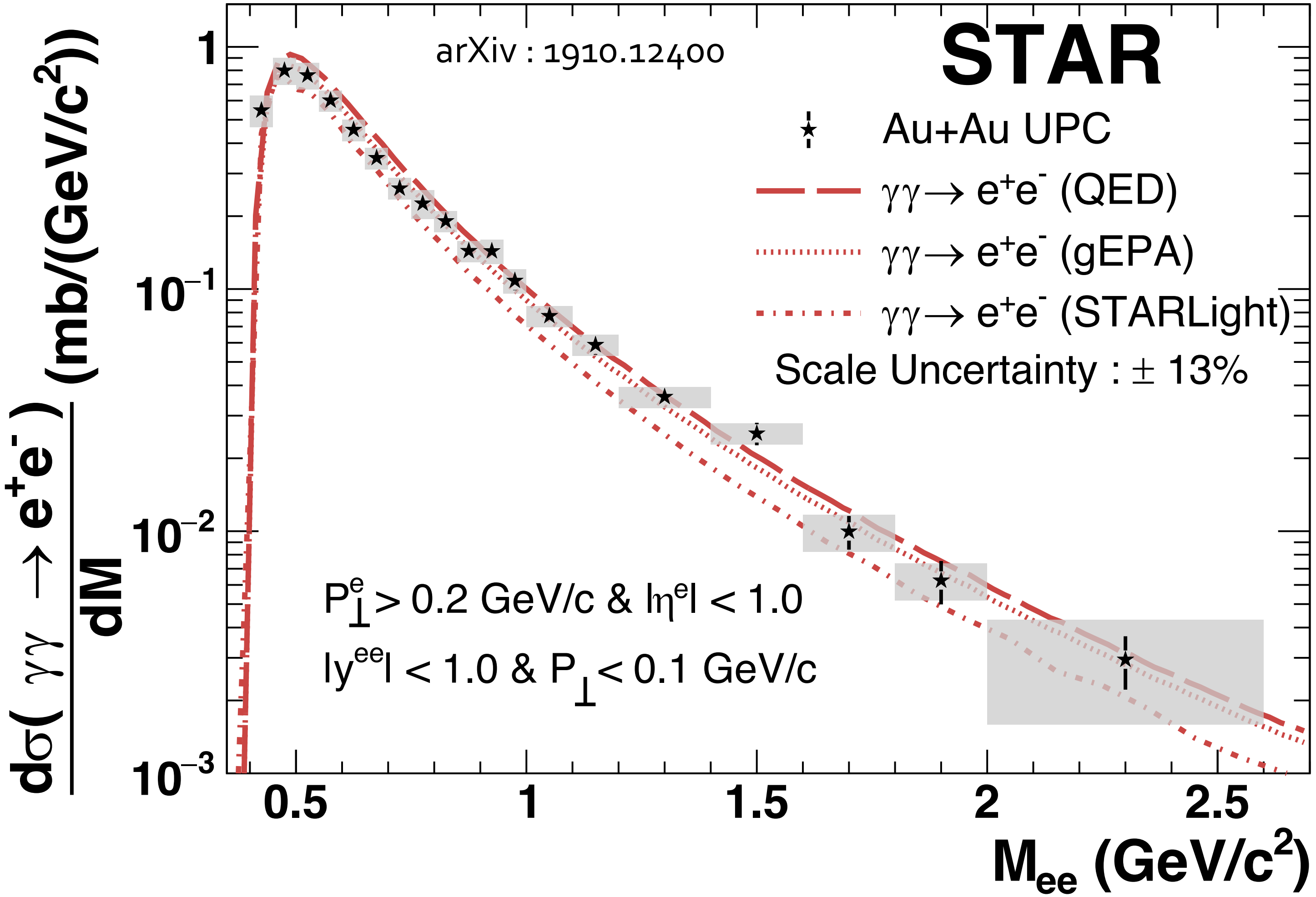
Breit-Wheeler $\gamma\gamma \to e^+e^-$ pair production process

Mutual Coulomb excitation and nuclear dissociation

- **Provides efficient trigger condition**

→Provides high statistics sample (>6,000 e^+e^- pairs) for multi-differential analysis

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



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]

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

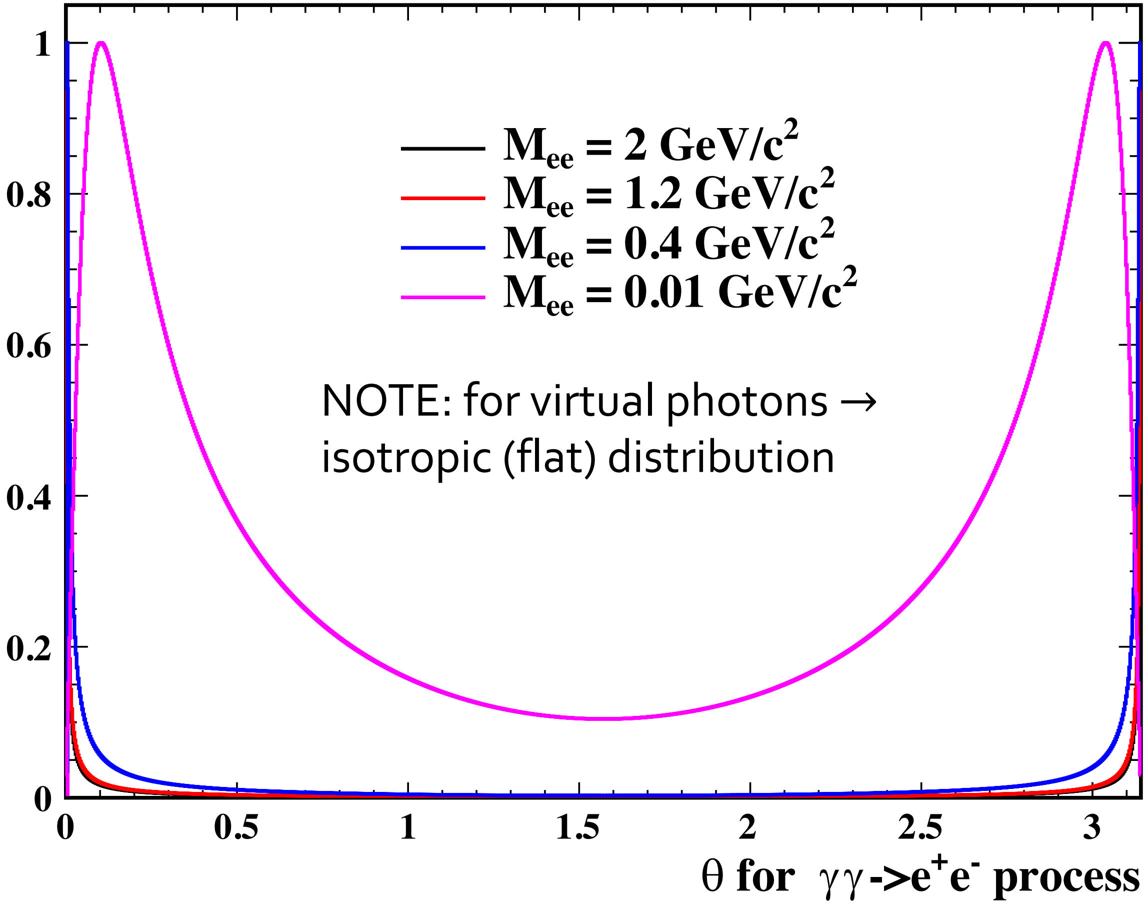
Measurement of total cross section agrees with theory calculations at $\pm 1\sigma$ level

$d\sigma(\gamma\gamma \rightarrow e^+e^-)/d\cos\theta'$

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

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

- ○ Highly virtual photon interactions should have an isotropic distribution
- ○ Measure θ', the angle between the e^+ and the beam axis in the pair rest frame.



NOTE: for virtual photons → isotropic (flat) distribution

[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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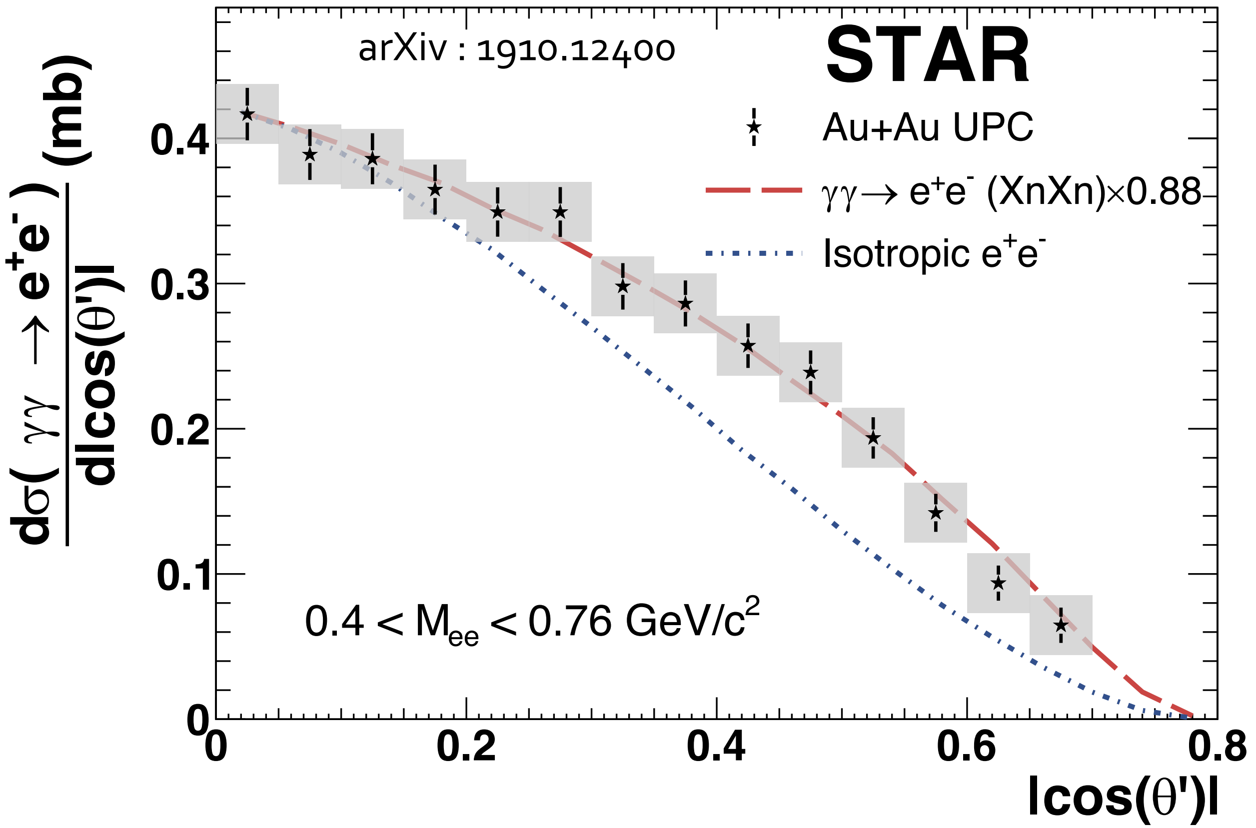
- Highly virtual photon interactions should have an isotropic distribution
- Measure θ', the angle between the e^+ and the beam axis in the pair rest frame.

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

⇒Measurably distinct from isotropic distribution



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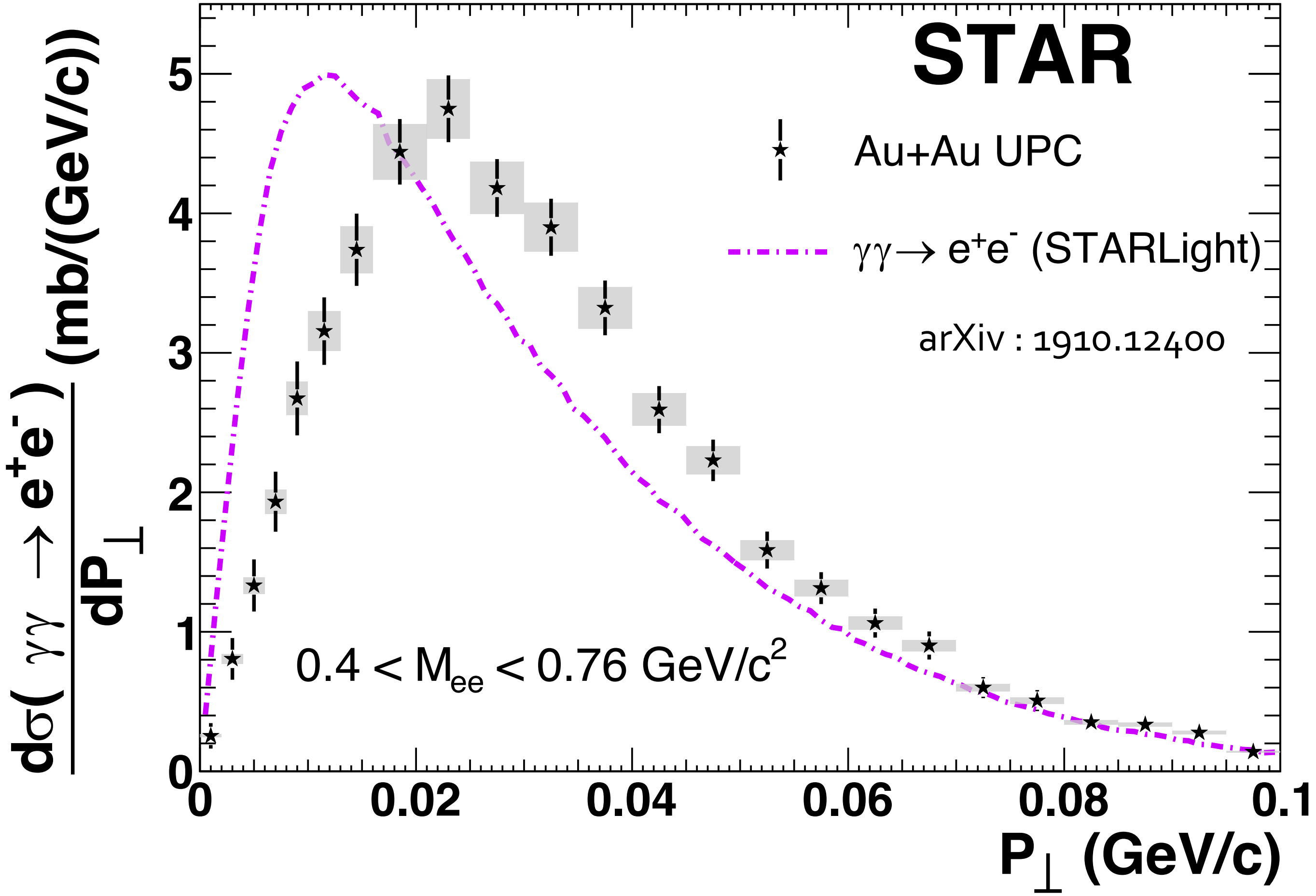
$d\sigma(\gamma\gamma \rightarrow e^+e^-)/dP_\perp$

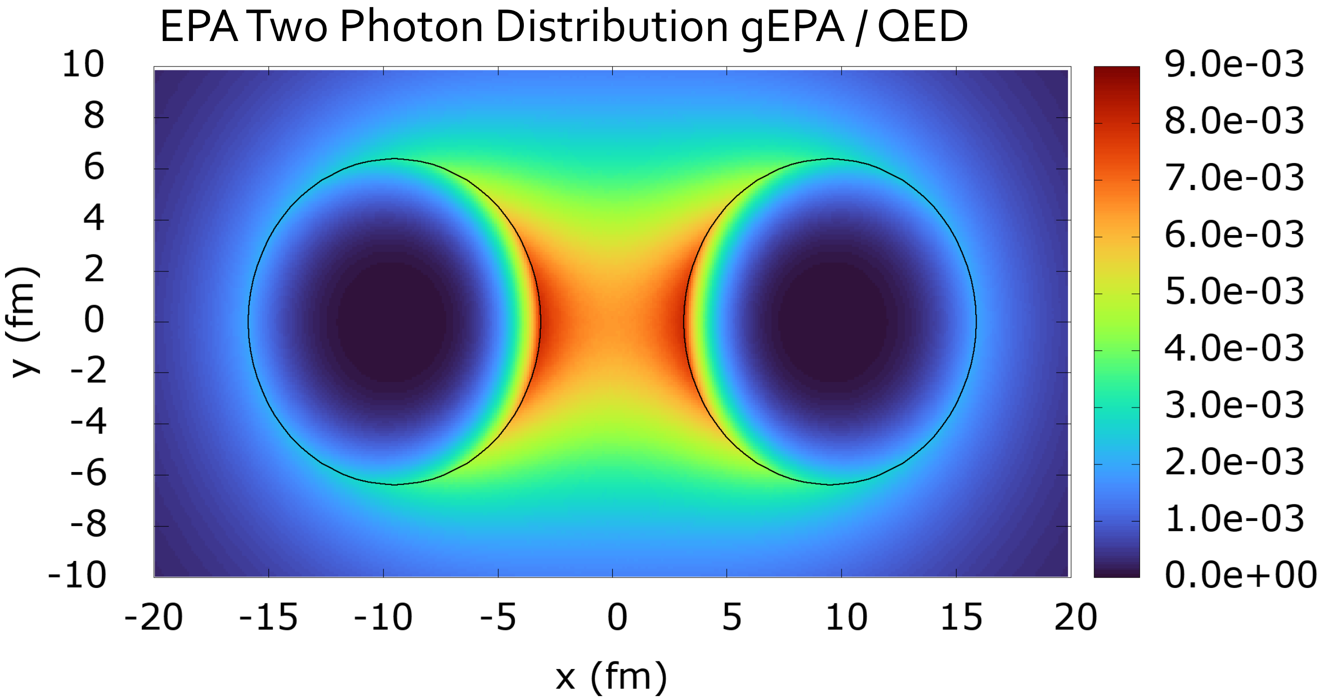


QED and STARLight are scaled to match measured $\sigma(\gamma\gamma \rightarrow e^+e^-)$

- High precision data – test theory predictions
- 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

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]

Calculating Cross Section for $\gamma\gamma \rightarrow e^+e^-$ Process



Two-photon density
(arb. norm.)

Equivalent Photon Approximation, photon density (single ion):

$$n(\omega; b) = \frac{1}{\pi\omega}|S_\perp(b,\omega)| \approx \frac{1}{\pi\omega}|E_\perp(b,\omega)|^2 \approx \frac{1}{\pi\omega}|B_\perp(b,\omega)|^2$$

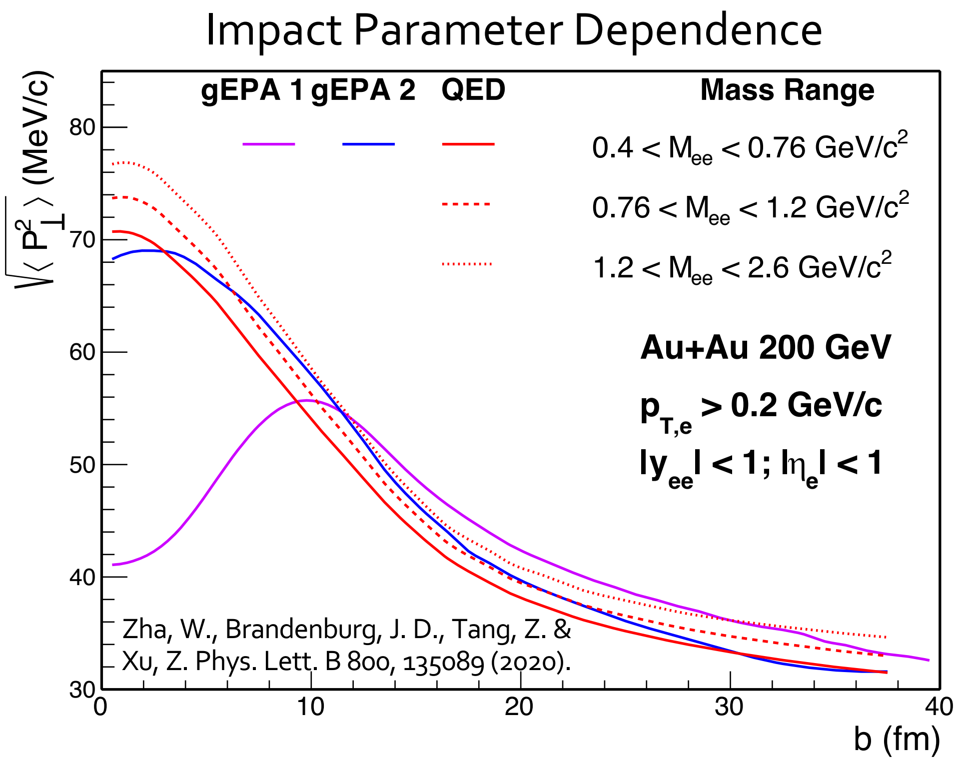
$$= \frac{4Z^2\alpha}{\omega}\left|\int \frac{d^2k_\perp}{(2\pi)^2} k_\perp \frac{F(k_\perp^2+\omega^2/\gamma^2)}{k_\perp^2+\omega^2/\gamma^2} e^{-i\,b\cdot k_\perp}\right|^2$$

Woods-Saxson
Au ion, $R = 6.38$ fm
$b = 19$ fm

Generalized EPA & QED Calculations:

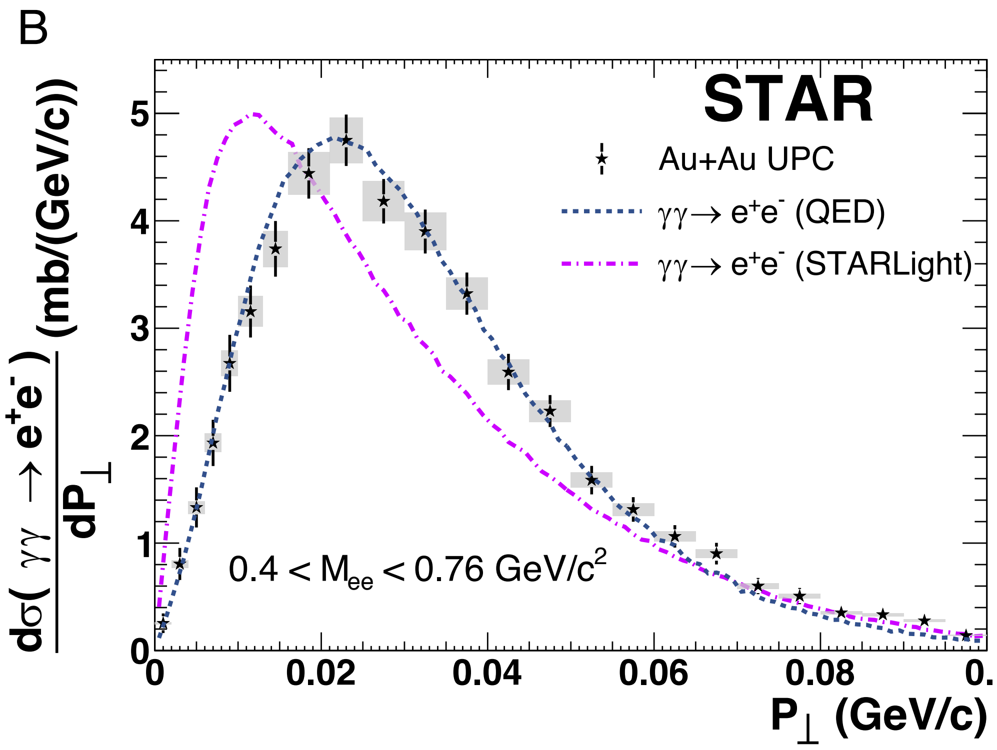
- Use Woods-Saxson Form Factor for nuclear charge distribution
- Include production inside nucleus – absorption effects found to be negligible
- **Predict impact parameter dependent $P_\perp$ distribution**

Photon virtuality and differential cross section



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

Note: gEPA1 vs. gEPA2 : gEPA2 includes phase term to approximate full QED result



QED (and gEPA parameterization) describe data
Larger $\langle P_\perp \rangle$ from impact parameter dependence
no evidence for significant photon virtuality

- Still only models, can we experimentally investigate impact parameter dependence :

→**Compare UPC vs. same process in peripheral collisions**

Classical Electromagnetism

- Maxwell's equations are linear
  - ➢ Superposition principle holds

$$\mathcal{L}_{classical} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right)$$

$$\vec{D} = \frac{\partial \mathcal{L}_{classical}}{\partial \vec{E}}$$

$$\vec{H} = -\frac{\partial \mathcal{L}_{classical}}{\partial \vec{B}}$$

⇒

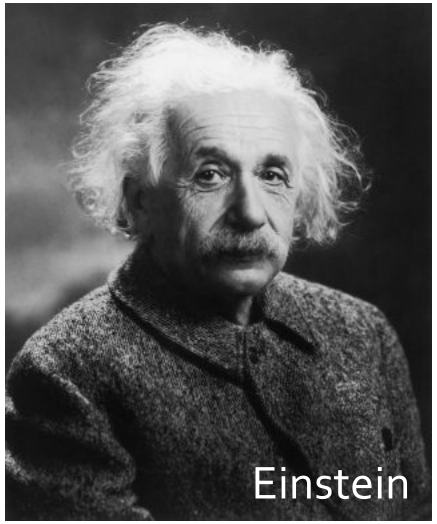
$$\vec{D} = \epsilon_0 \vec{E}$$

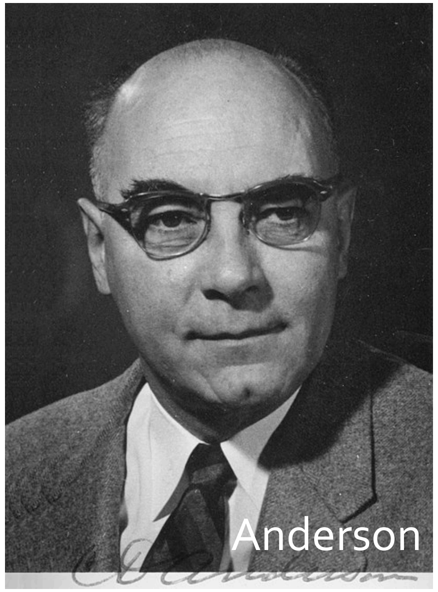
$$\vec{H} = \frac{1}{\mu_0}\vec{B}$$

→ Unique speed of light in vacuum:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 299792458 \text{ m/s}$$

Quantum Electrodynamics


Einstein


Anderson

Three important discoveries that <u>alter the classical picture</u>:

- Einstein's energy-mass equivalence: $E = mc^2$
- Uncertainty principle: $\Delta E \Delta t \geq \hbar/2$
- Existence of positron : Dirac predicts negative electron energy states (1928), Anderson discovered positron in 1932

Quantum Electrodynamics

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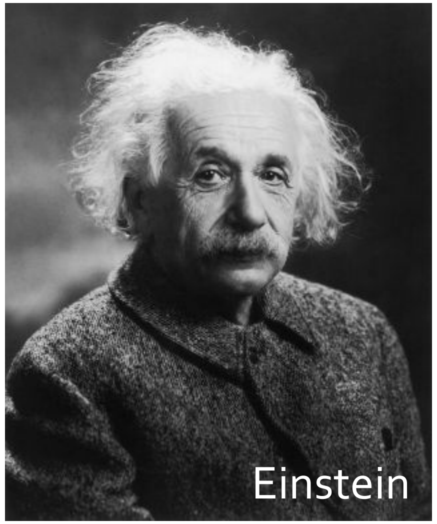
→ Vacuum fluctuations

- 1936: Euler & Heisenberg present modified Lagrangian

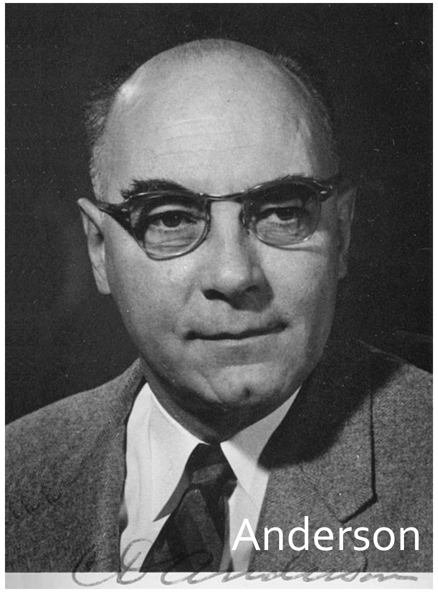
$$\mathcal{L}_{EH} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c} \cdot \vec{B}\right)\right] + \cdots$$

- Non-linear → Super-position principle broken!

NB: in 1951 Shwinger derived the Lagrangian within QED



Einstein

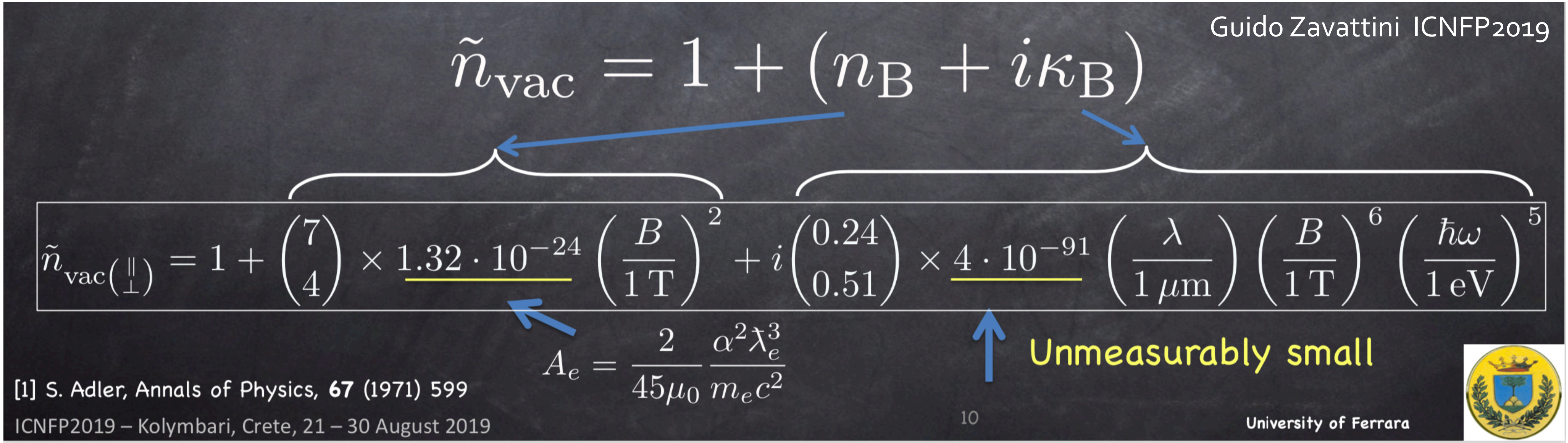


Anderson

Vacuum Magnetic Birefringence

$c = \frac{1}{\sqrt{\epsilon\mu}}$ BUT $\epsilon_{\parallel} \neq \epsilon_{\perp}$ and $\mu_{\parallel} \neq \mu_{\perp}$

Light behaves as if it is traveling through a medium with an index of refraction $n_{vac} \neq 1$



Guido Zavattini ICNFP2019

$$\tilde{n}_{\mathrm{vac}} = 1 + (n_{\mathrm{B}} + i\kappa_{\mathrm{B}})$$

$$\boxed{\tilde{n}_{\mathrm{vac}\left({\parallel \atop \perp}\right)} = 1 + \overbrace{\begin{pmatrix}7\\4\end{pmatrix} \times \underline{1.32 \cdot 10^{-24}} \left(\frac{B}{1\,\mathrm{T}}\right)^{2}} + i\overbrace{\begin{pmatrix}0.24\\0.51\end{pmatrix} \times \underline{4 \cdot 10^{-91}} \left(\frac{\lambda}{1\,\mu\mathrm{m}}\right)\left(\frac{B}{1\,\mathrm{T}}\right)^{6}\left(\frac{\hbar\omega}{1\,\mathrm{eV}}\right)^{5}}}$$

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2 \bar{\lambda}_e^3}{m_e c^2}$$

Unmeasurably small

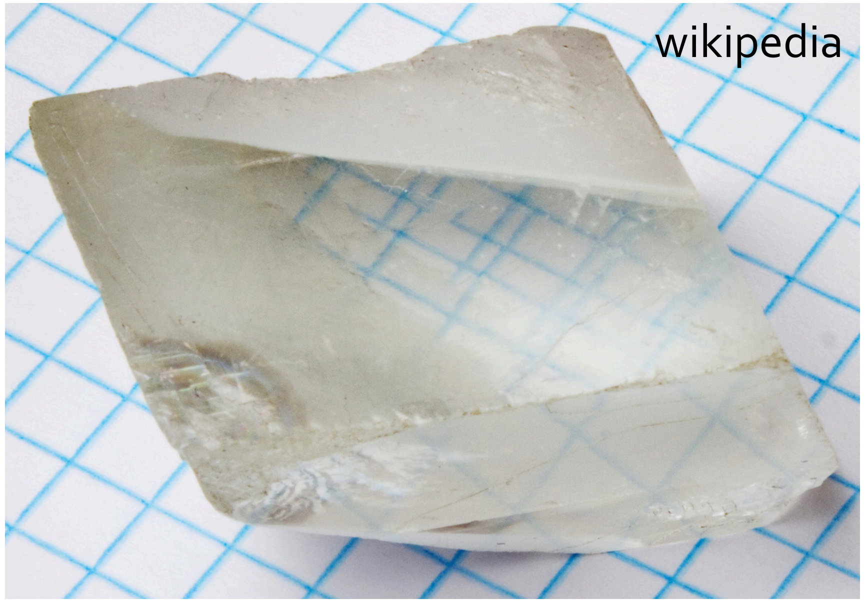
[1] S. Adler, Annals of Physics, **67** (1971) 599

ICNFP2019 – Kolymbari, Crete, 21 – 30 August 2019

10

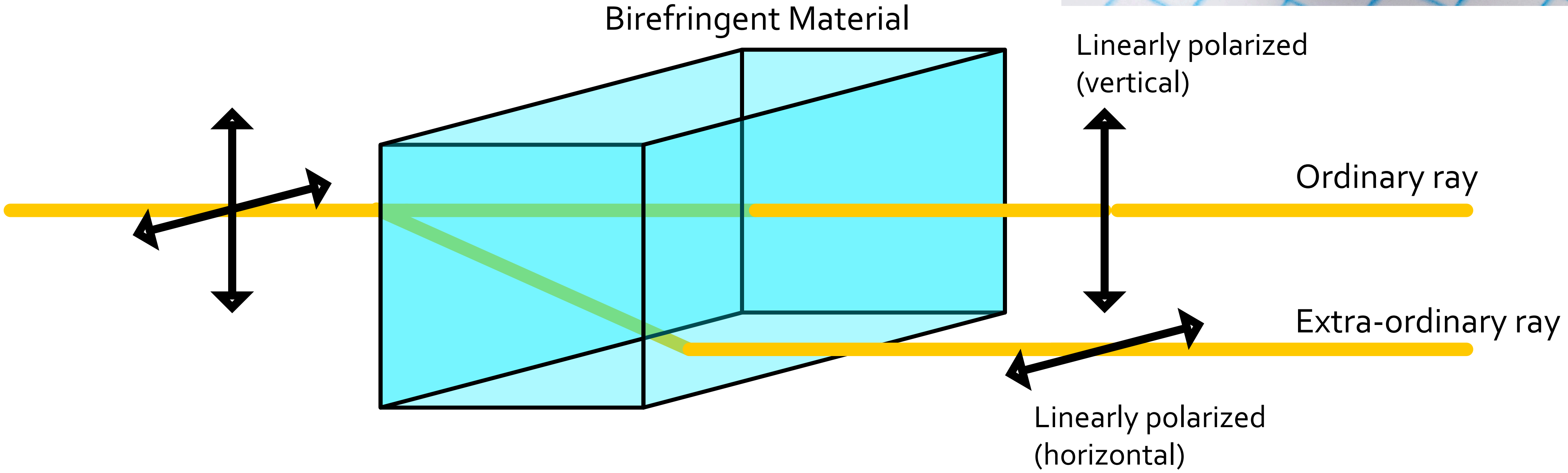
University of Ferrara

Optical Birefringence


wikipedia

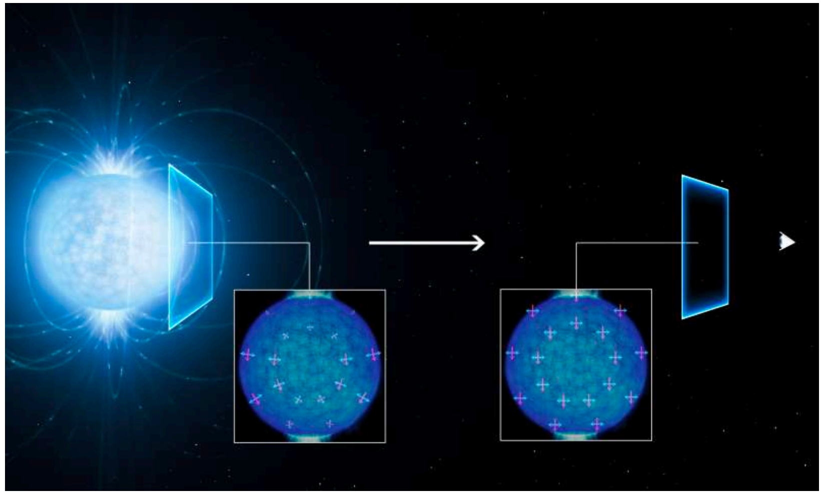
Birefringent material: Different index of refraction for light polarized parallel ($n_{\parallel}$) vs. perpendicular ($n_{\perp}$) to material's ordinary axis

→ **splitting of wave function when $\boldsymbol{\Delta n = n_{\parallel} - n_{\perp} \neq 0}$**

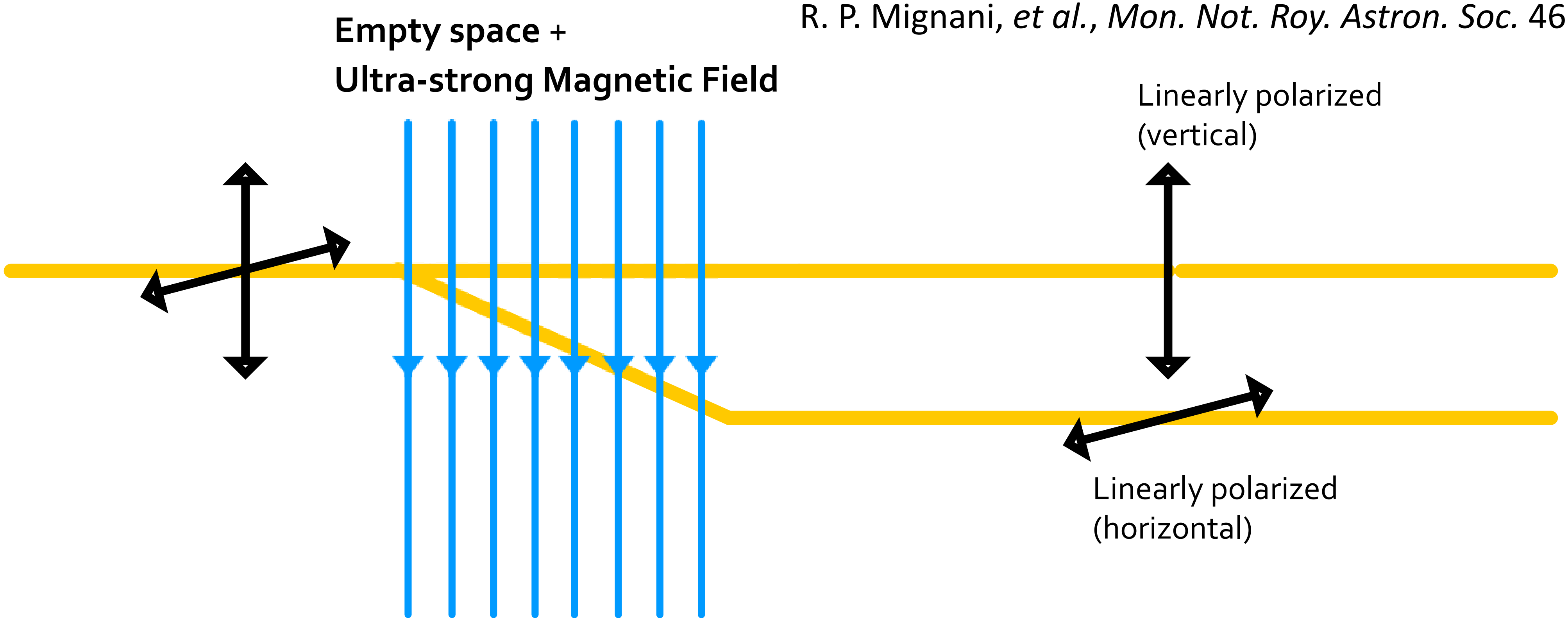


Vacuum Birefringence

Vacuum birefringence : Predicted in 1936 by Heisenberg & Euler. Index of refraction for γ interaction with $\vec{B}$ field depends on relative polarization angle i.e. $\boldsymbol{\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0}$



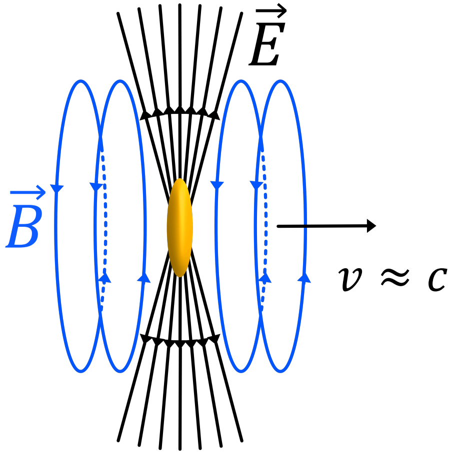
R. P. Mignani, *et al.*, *Mon. Not. Roy. Astron. Soc.* 465 (2017), 492



Birefringence of the QED Vacuum

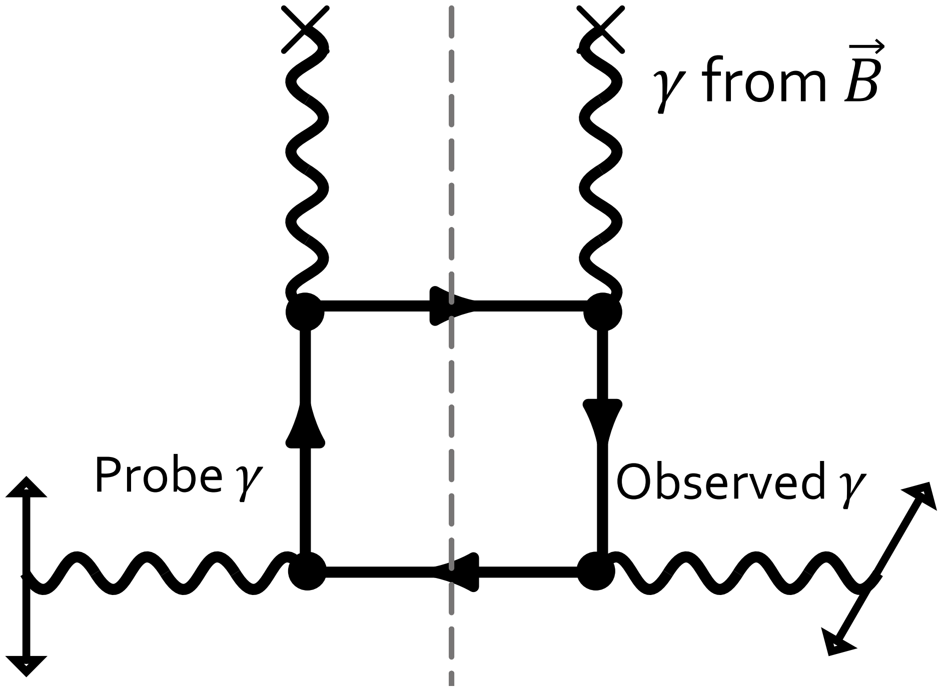
Vacuum birefringence : Predicted in 1936 by Heisenberg & Euler. Index of refraction for γ interaction with $\vec{B}$ field depends on relative polarization angle i.e. $\boldsymbol{\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0}$

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



Can we observe vacuum birefringence in ultra-peripheral collisions?

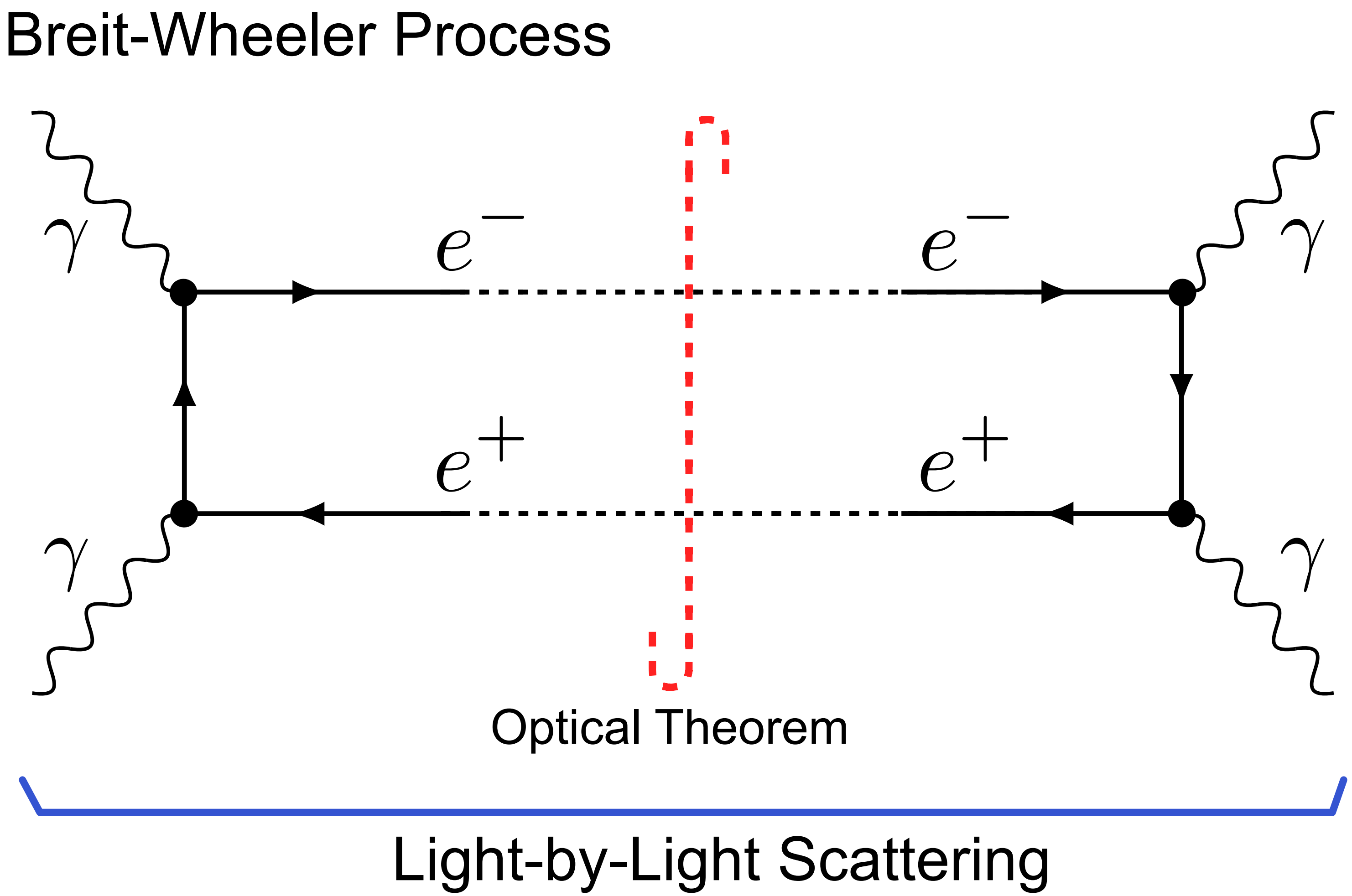
Feynman Diagram for Vacuum Birefringence



$Real(n)$ = transmission process $\gamma\gamma \rightarrow \gamma\gamma$
$Imag(n)$ = absorption process $\gamma\gamma \rightarrow e^{+}e^{-}$ (diagram cut)

S. Bragin, et. al., *Phys. Rev. Lett.* 119 (2017), 250403
R. P. Mignani, *et al.*, *Mon. Not. Roy. Astron. Soc.* 465 (2017), 492

Breit-Wheeler Process and Light-by-Light Scattering



The Breit-Wheeler process and Light-by-Light scattering are intimately connected

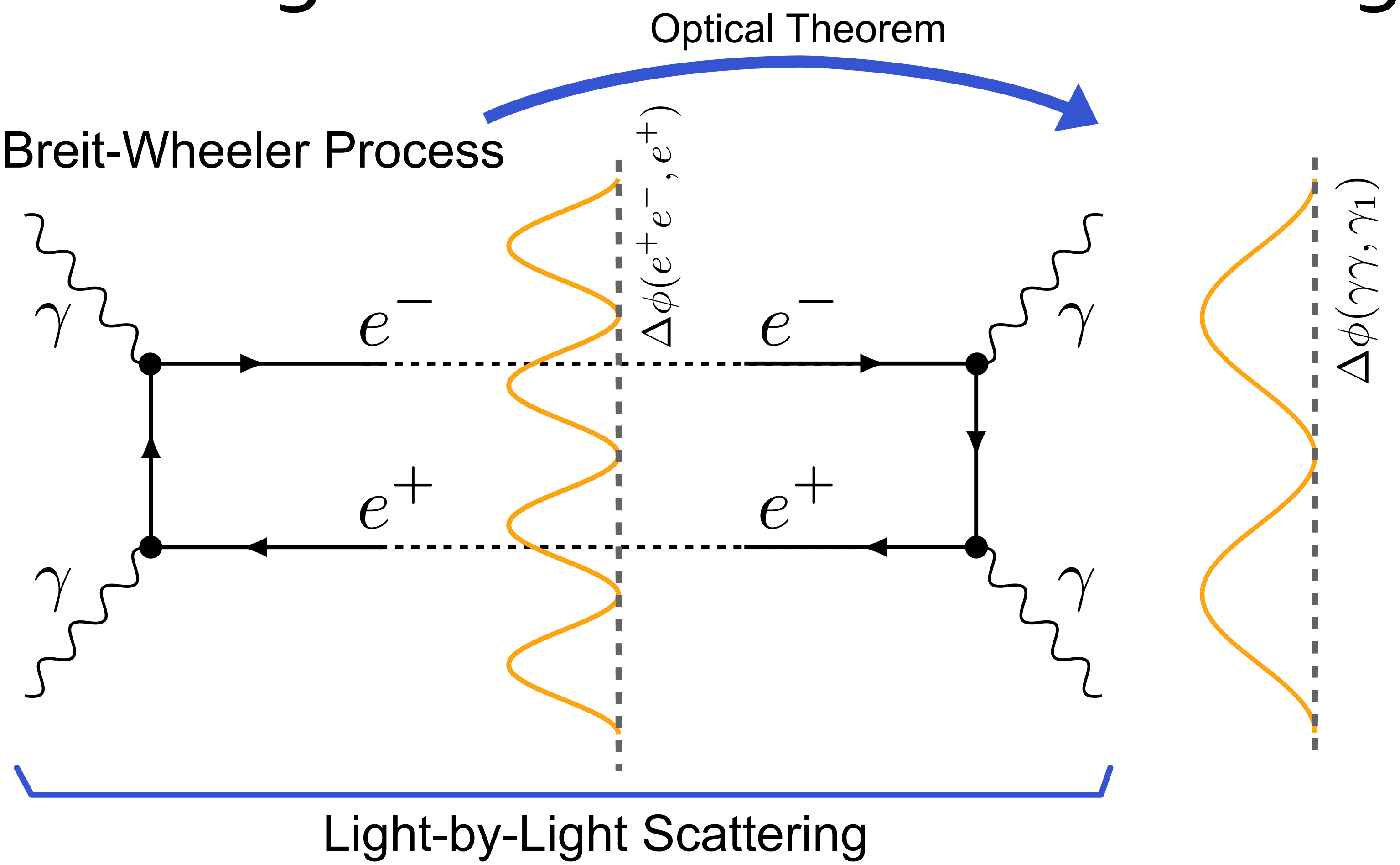
According to the optical theorem[1] the Breit-Wheeler process is the imaginary part of the forward scattering amplitude

In QED formalism, the Breit-Wheeler process is the imaginary part of the propagator – i.e. when the e^+e^- masses are real.

Light-by-Light recently observed by ATLAS [2] and CMS collaborations

[1] Budnev, V. M., Ginzburg, I. F., Meledin, G. V. & Serbo, V. G. Physics Reports 15, 181–282 (1975).
[2] ATLAS Collaboration et al. Phys. Rev. Lett. 123, 052001 (2019).

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 = vacuum birefringence**

[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).

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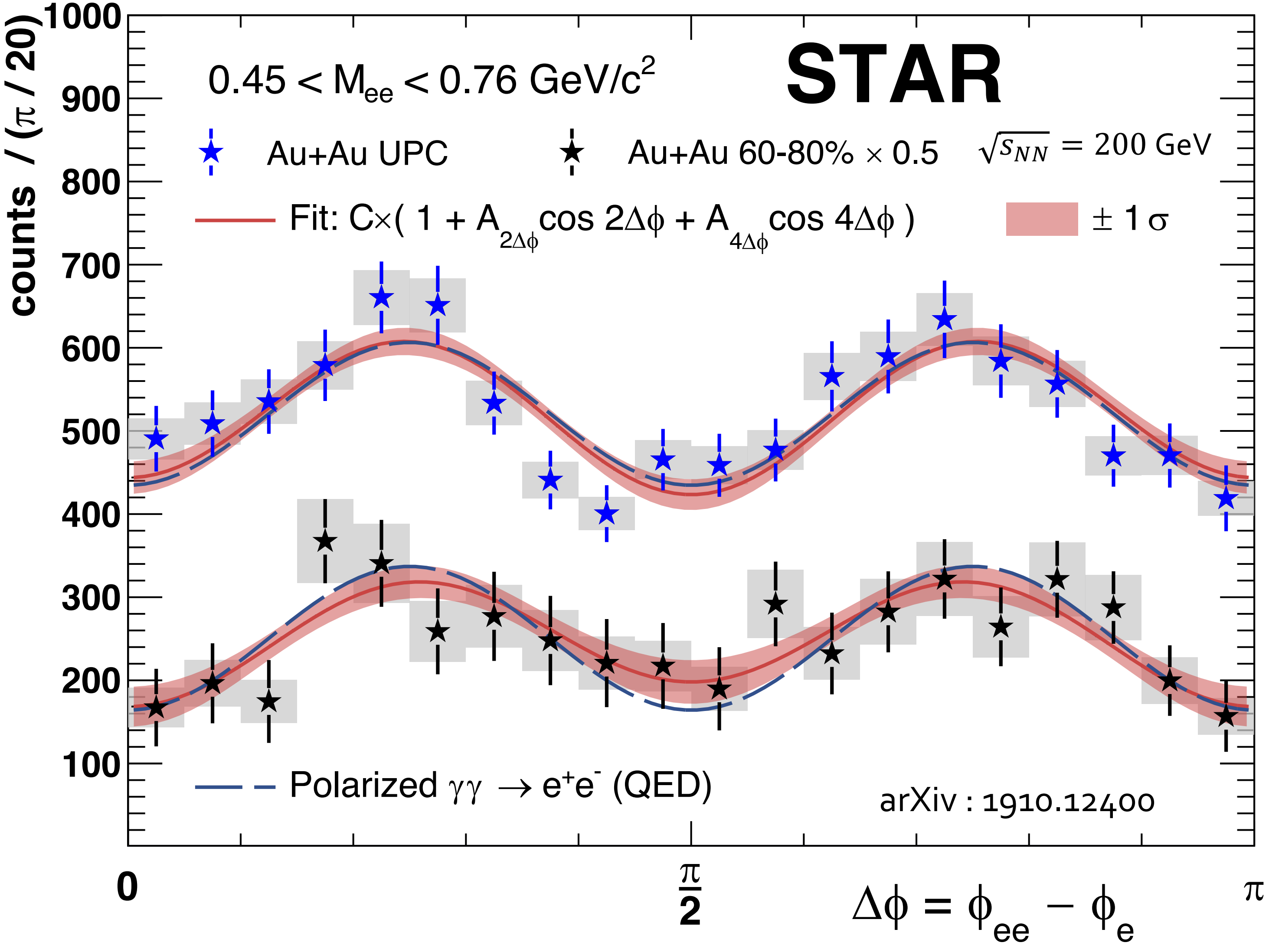
$$\Delta\phi = \Delta\phi[(e^{+} + e^{-}), (e^{+} - e^{-})]$$
$$\approx \Delta\phi[(e^{+} + e^{-}), e^{+}]$$

Ultra-Peripheral

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

Peripheral (60−80%)

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



Birefringence of the QED Vacuum

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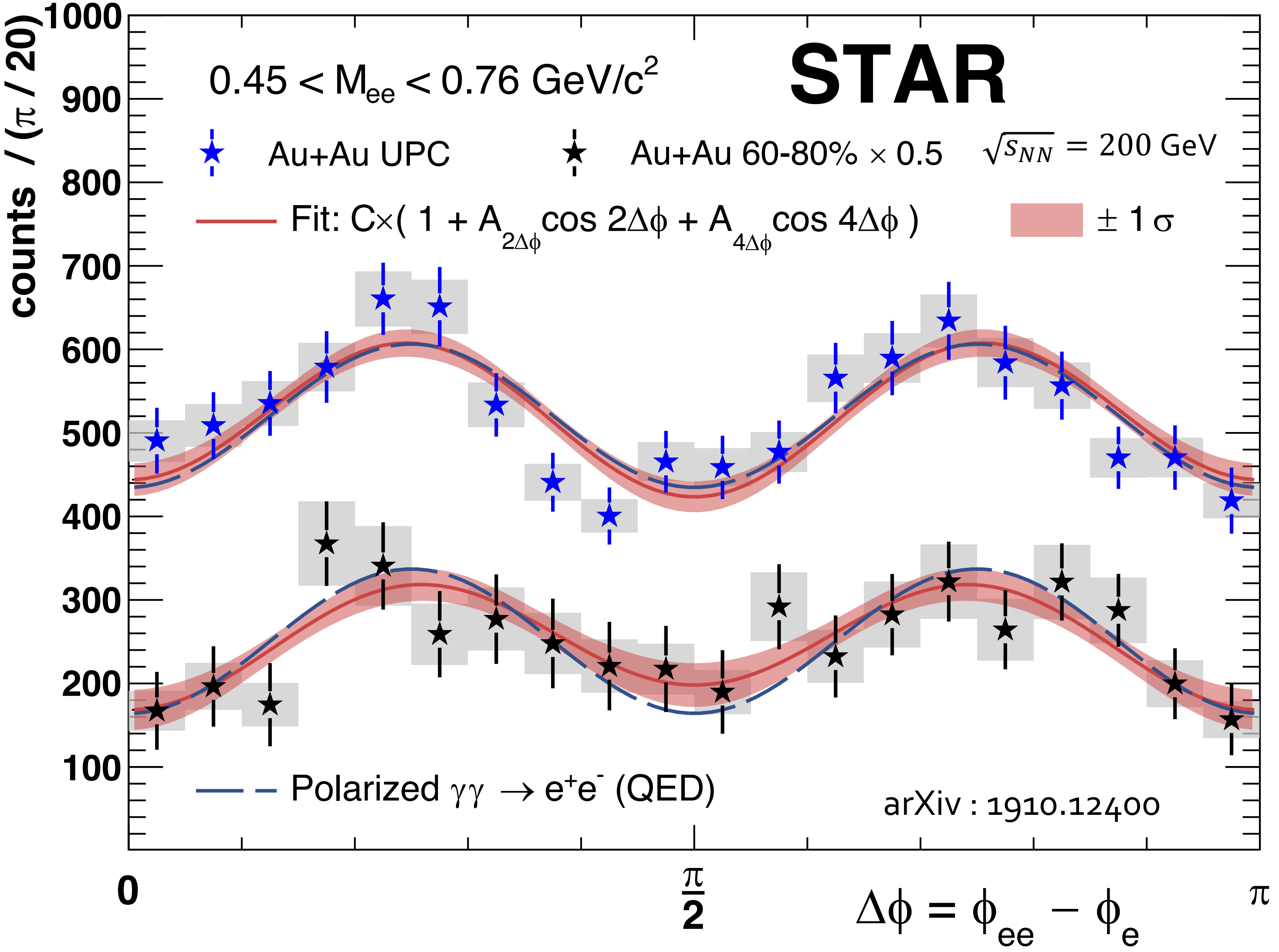


→ **<u>First Earth-based observation</u> (6.7σ level) of vacuum birefringence**

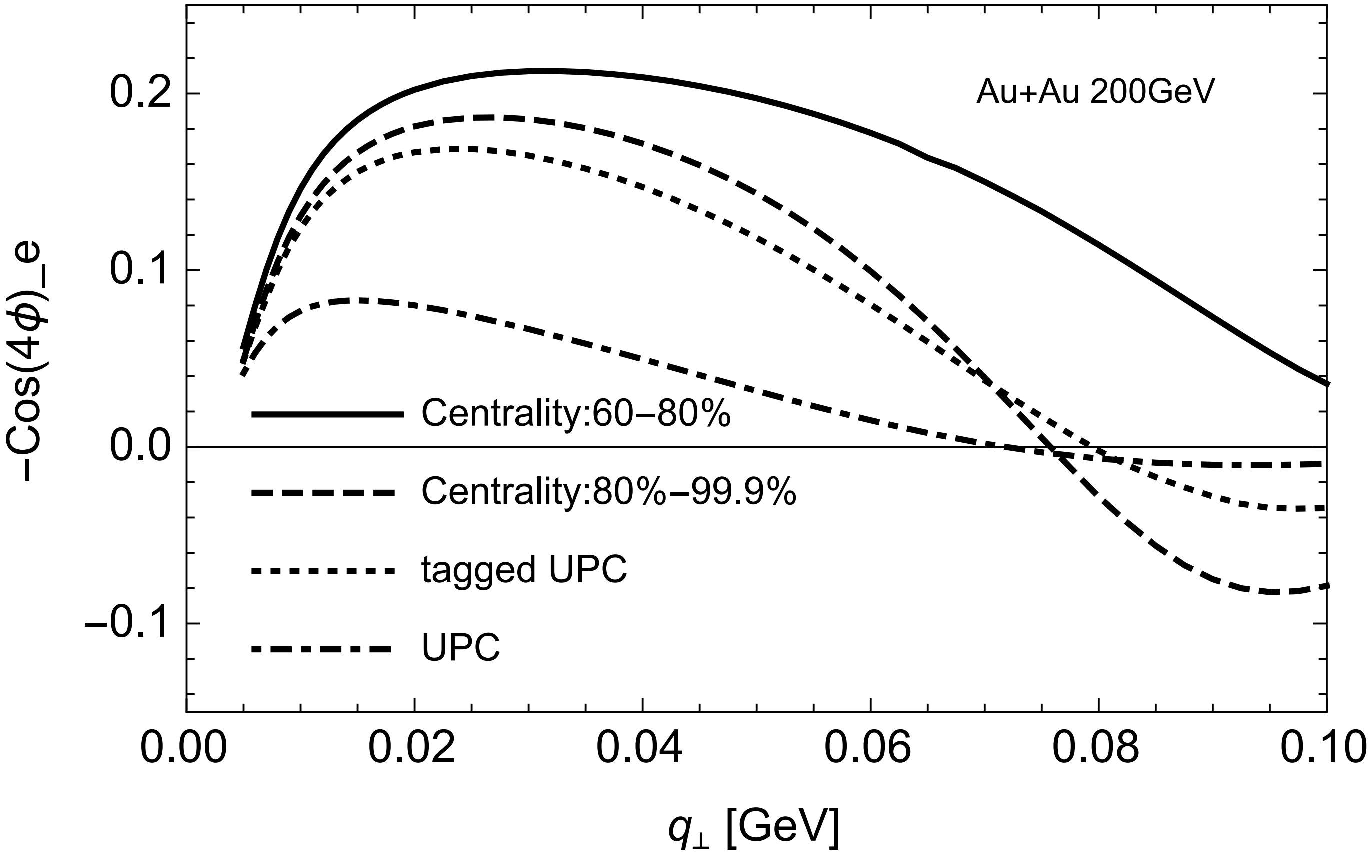
Connection to the Initial Magnetic Field

Magnetic field strength and spatial distribution:

- Impact parameter dependence of $P_\perp$
- Amplitude of $\cos 4\Delta\phi$ modulation

QED calculations for Breit-Wheeler ($\gamma\gamma \rightarrow e^{+}e^{-}$) process and vacuum birefringence (good agreement with all data) use this field density:

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



Peak value for single ion: $|B| \approx 0.7 \times 10^{15}$ Tesla $\approx 10{,}000\times$ stronger than Magnetars

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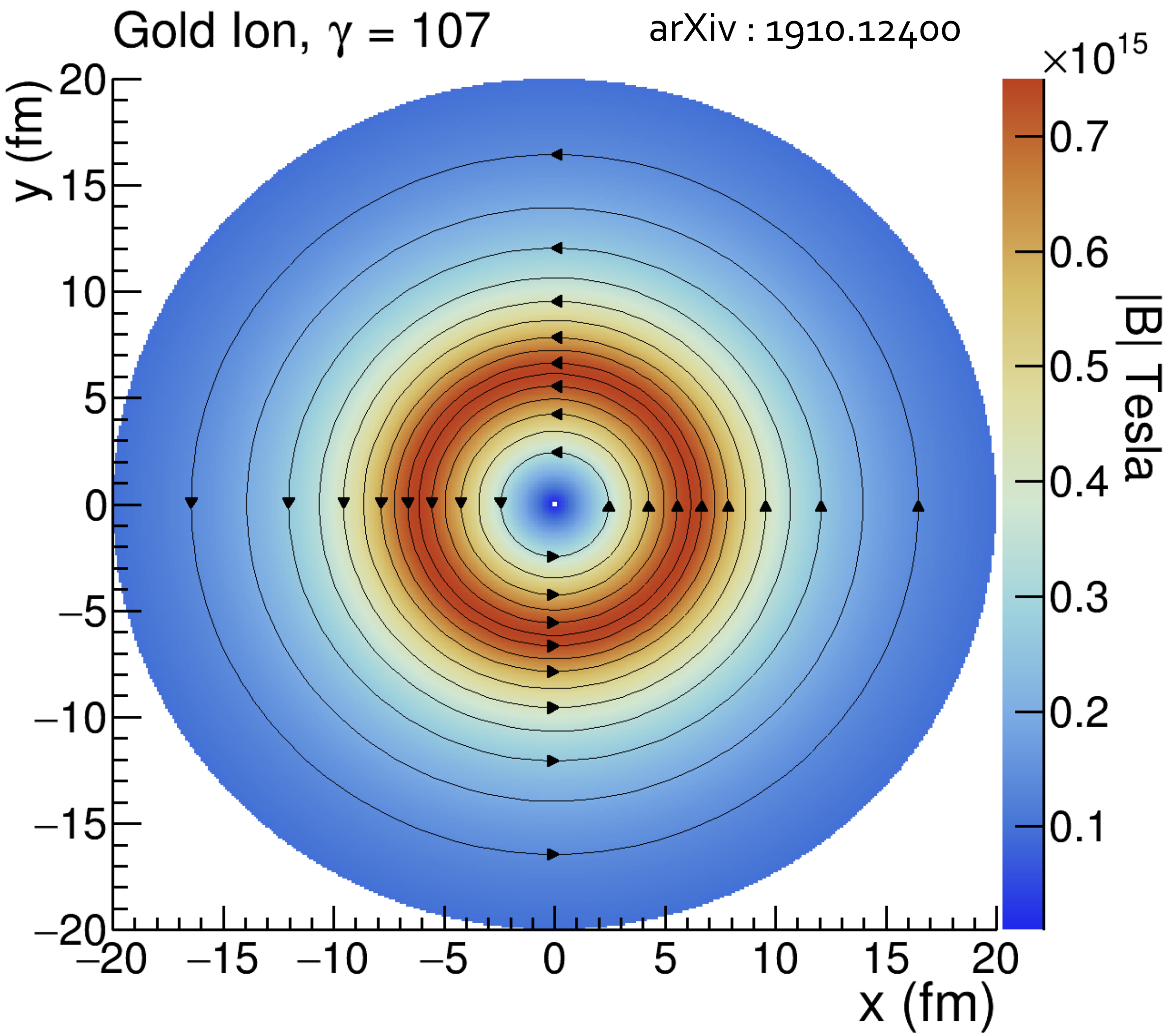

Peak value for single ion: $|B| \approx 0.8 \times 10^{15}$ Tesla $\approx$ 10,000× stronger than Magnetars

Connection to the Initial Magnetic Field

Magnetic field strength and spatial distribution:

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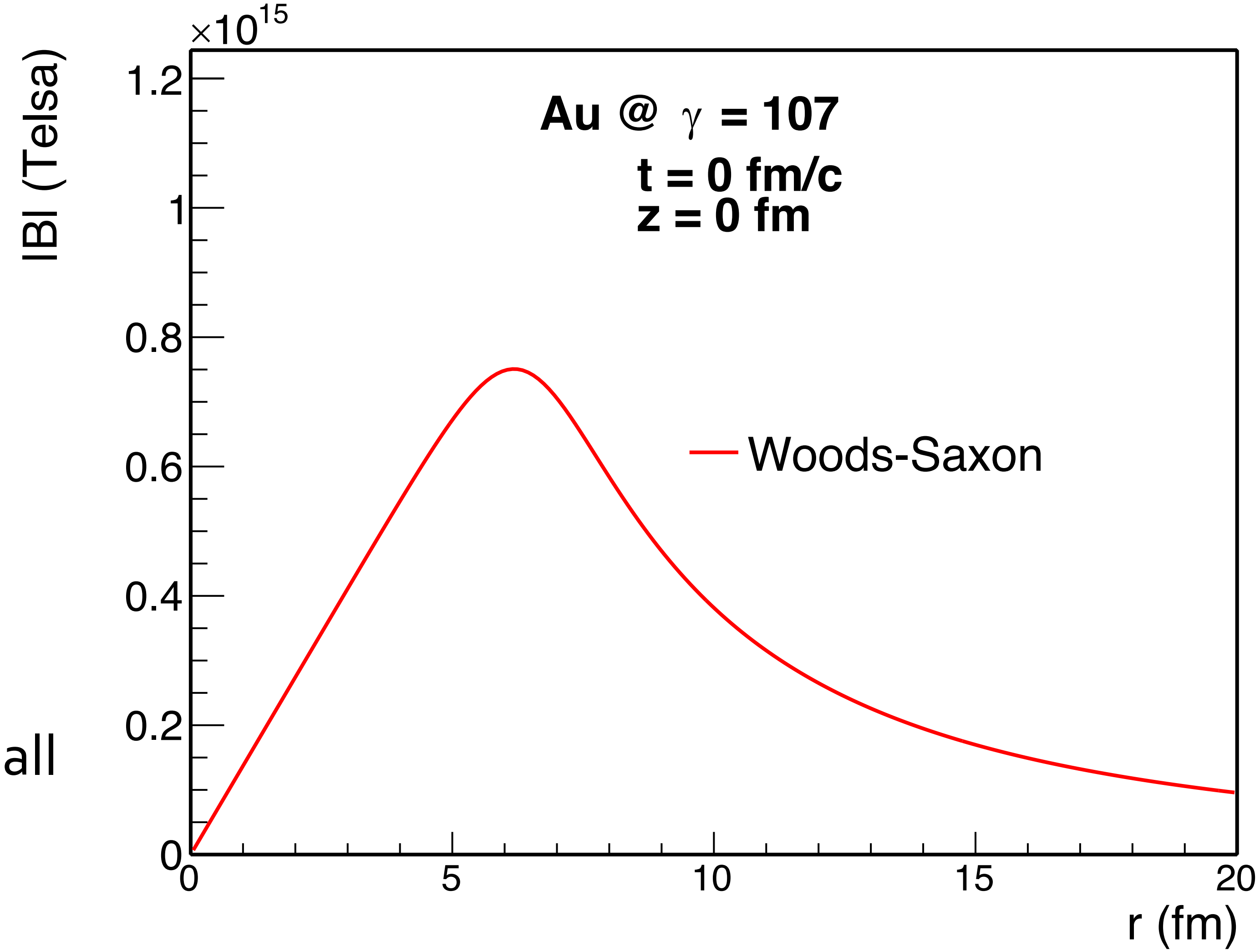


Peak value for single ion: $|B| \approx 0.8 \times 10^{15}$ Tesla $\approx$ 10,000× stronger than Magnetars

Applications for studying QCD

DK, L.McLerran, H.Warringa NPA‘o

Predicted emergent magnetohydrodynamical phenomena of Quantum Chromodynamics

- Manifestations require ultra-strong magnetic fields
- E.g. **Chiral Magnetic Effect**
- Major goal of RHIC heavy-ion program
  - Dedicated Isobar run in 2018

Chiro-genesis in Heavy Ion Collisions

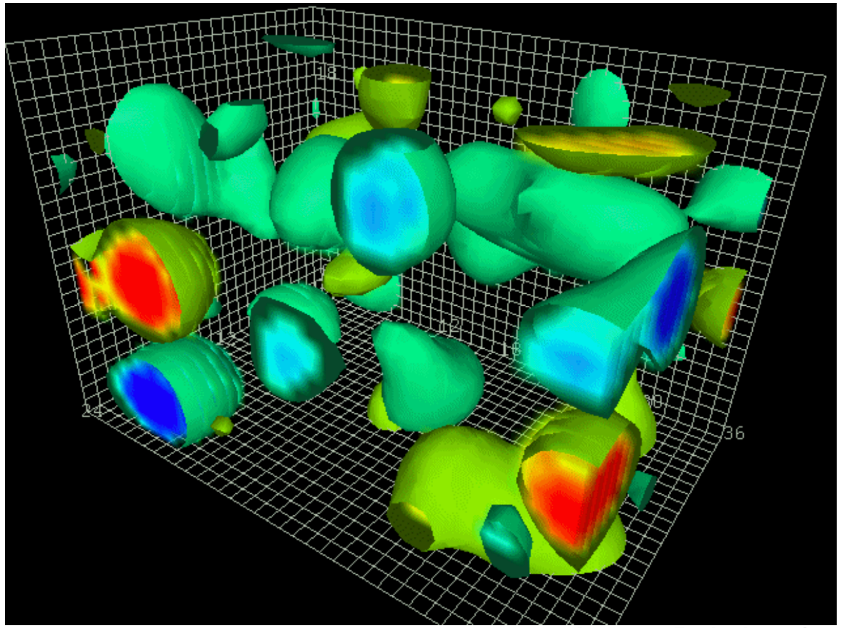


Image: D. Leinweber

<u>Dima Kharzeev’s Quark Matter 2019 talk:</u>

Absent in Maxwell theory!

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

Coefficient is fixed by the chiral anomaly, no corrections

5

K.Fukushima, DK, H.Warringa, “Chiral magnetic effect” PRD’08

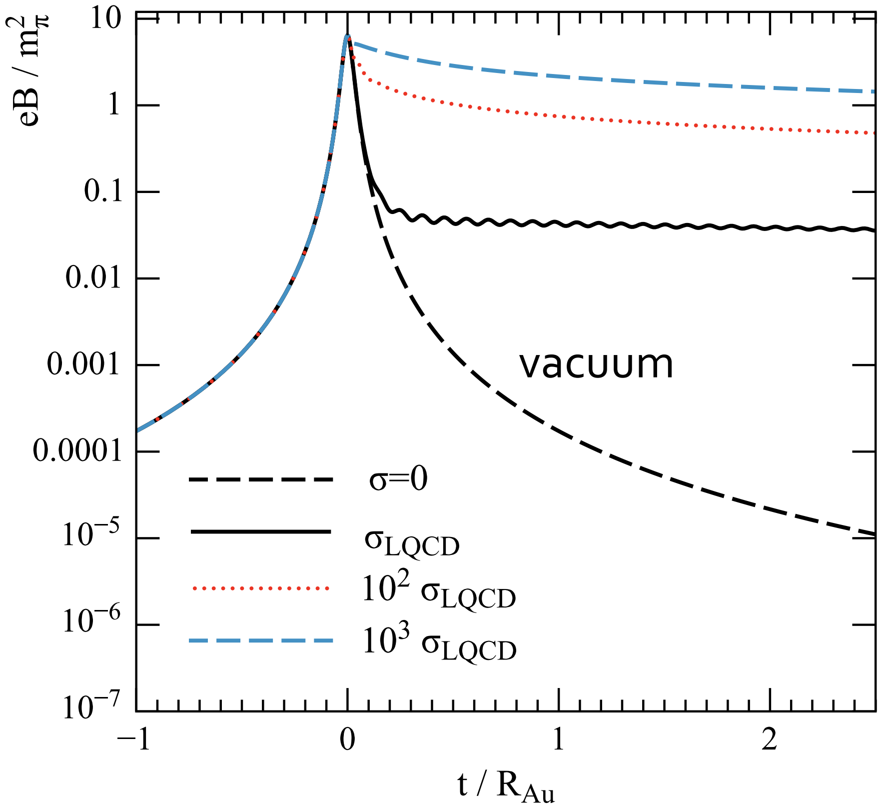
NEED TO KNOW THE MAGNETIC FIELD FOR QUANTITATIVE STUDIES

What can we learn about final state, medium effects?

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

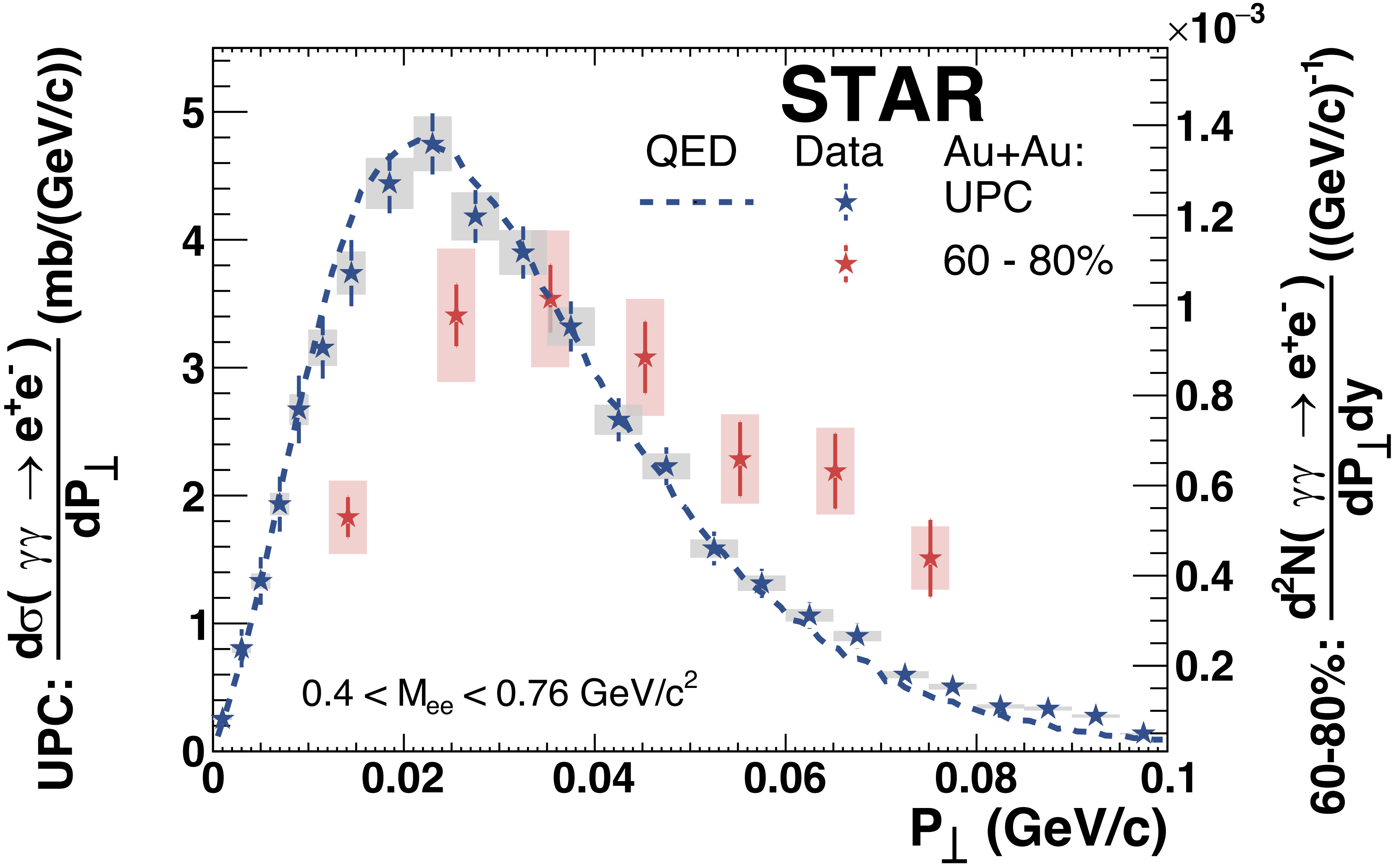
- Two proposals from different groups:

1. Lorentz-Force bending due to long-lived magnetic field
2. Coulomb scattering through QGP medium



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

UPC vs. Peripheral



In UPC we can measure the quasi-exclusive $\gamma\gamma \rightarrow e^+e^-$ process.

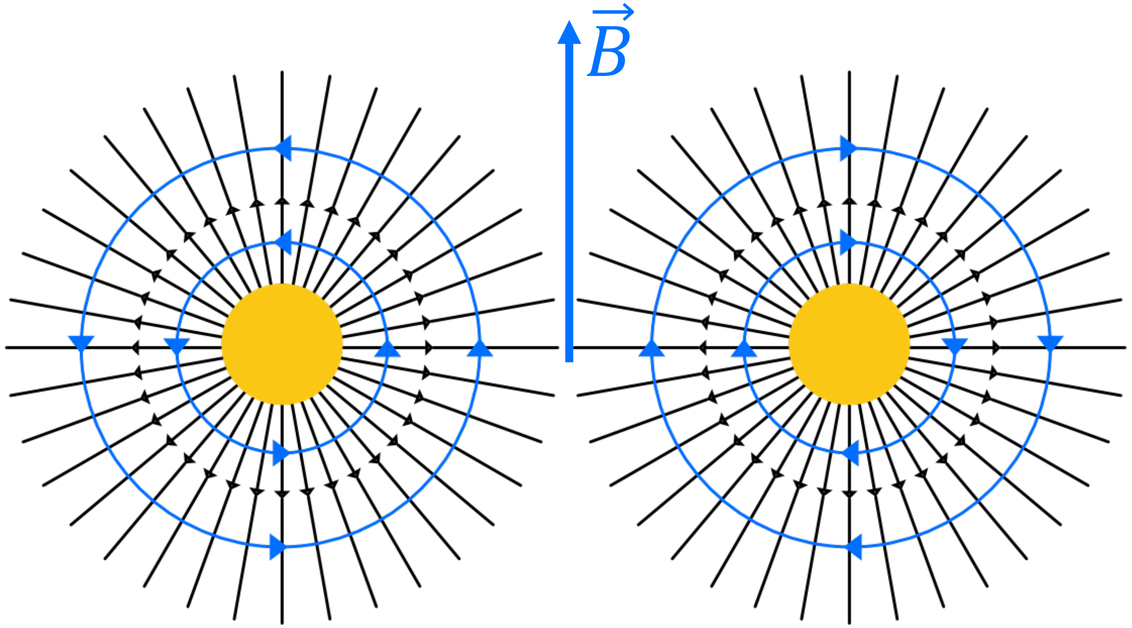
In peripheral collisions we can statistically isolate the spectra from the $\gamma\gamma \rightarrow e^+e^-$ process.

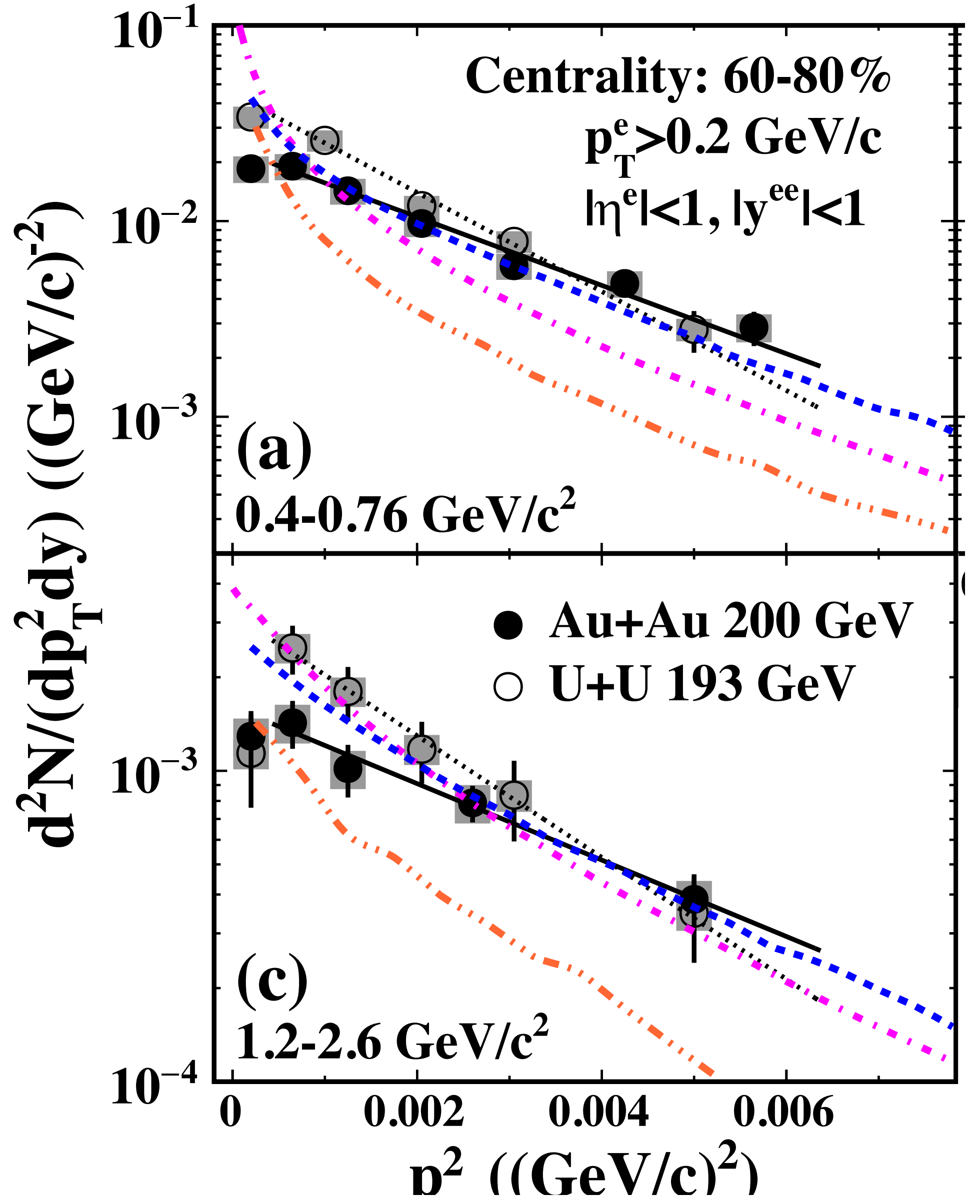
STAR Collaboration, J. Adam, *et al.*, *Phys. Rev. Lett.* 121, 132301 (2018).

Spectra from peripheral collisions is significantly broader than spectra from UPC, possible medium effect?

Long-lived Magnetic Field?

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





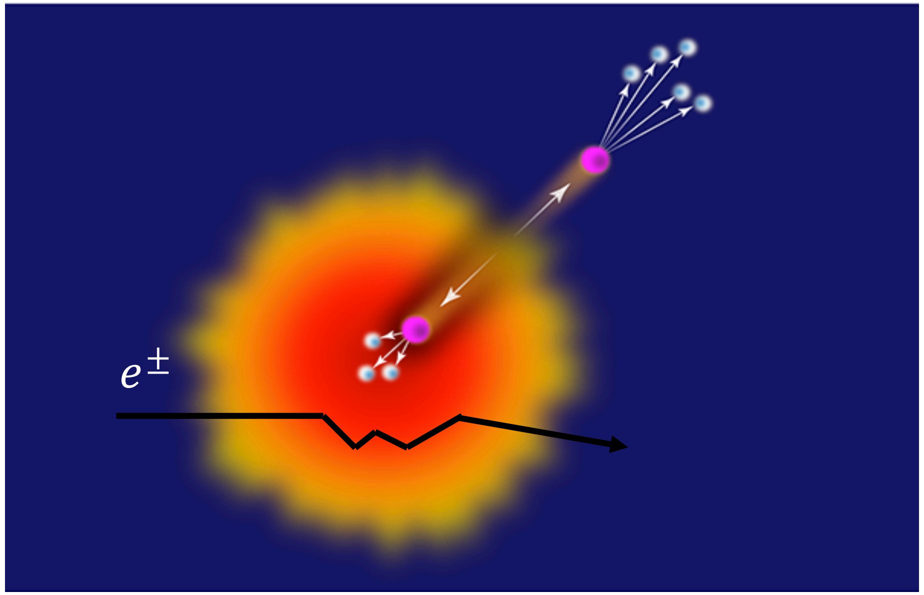
<u>Assumptions:</u>

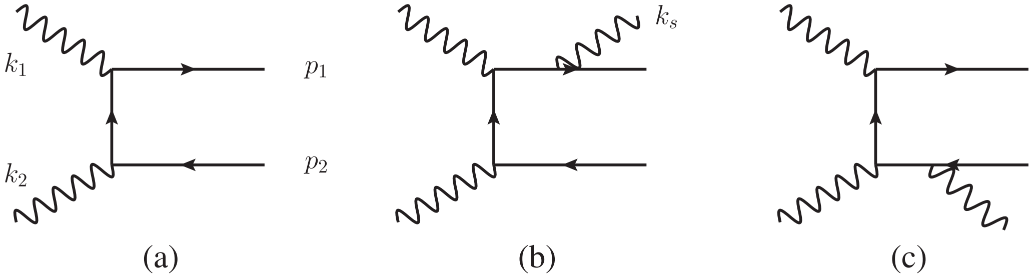
1. Used STARLight $P_\perp$ Spectra
2. All $e^{\pm}$ travers 1fm through $|B| \approx 10^{14}$T ($eBL \approx 30$ MeV/c)

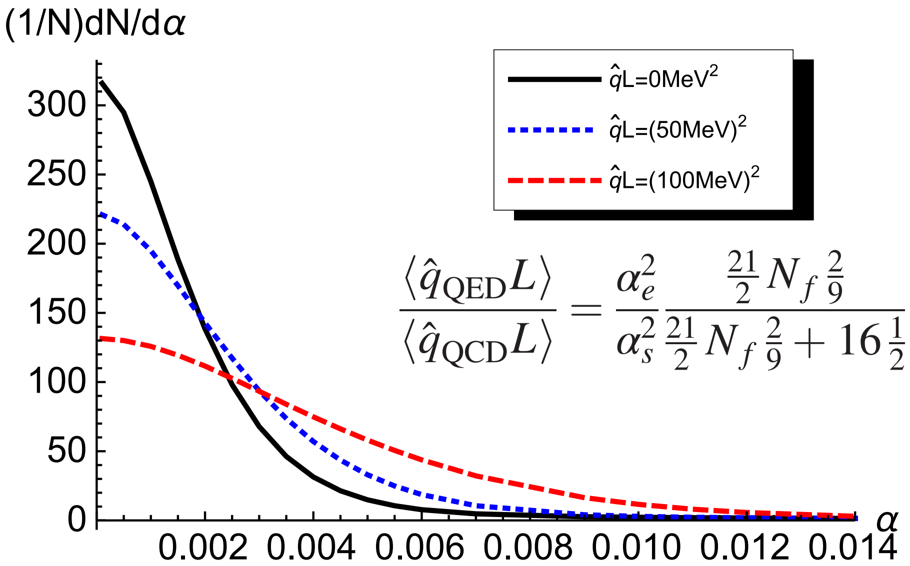
Coulomb Scattering through QGP

[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 $P_{\perp}$?







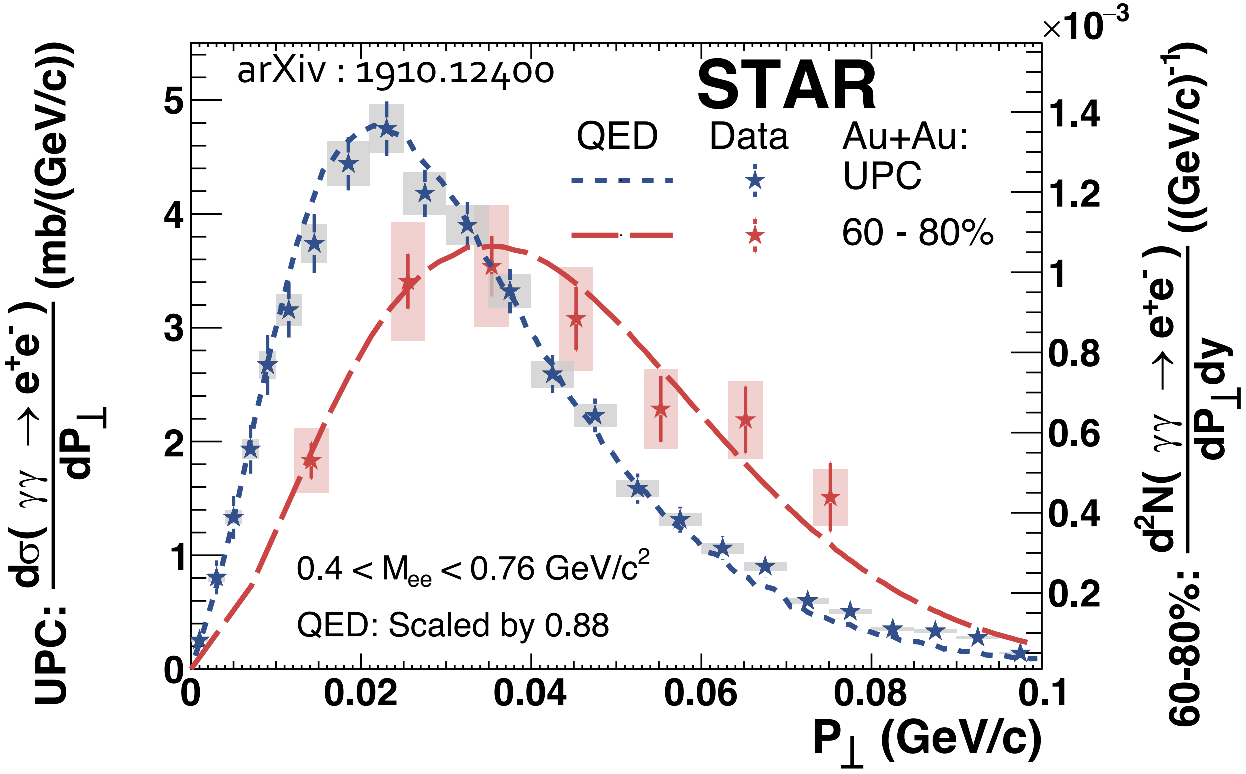
$$\frac{\langle \hat{q}_{\mathrm{QED}} L \rangle}{\langle \hat{q}_{\mathrm{QCD}} L \rangle} = \frac{\alpha_e^2}{\alpha_s^2} \frac{\frac{21}{2} N_f \frac{2}{9}}{\frac{21}{2} N_f \frac{2}{9} + 16 \frac{1}{2}} = \frac{\alpha_e^2}{\alpha_s^2} \times \frac{7}{15},$$

Assumptions:

1. Primordial distribution given by STARLight
2. Daughters traverse medium

$\gamma\gamma \to e^+e^-$: 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	$\approx 11.5 - 13.5$

- ○ Leading order QED calculation of $\gamma\gamma \to e^+e^-$ describes both spectra ($\pm 1\sigma$)
- ○ Best fit for spectra in 60-80% collisions found for QED shape plus 14 ± 4 (stat.)± 4 (syst.) MeV/c broadening
- ○ Proposed as a probe of trapped magnetic field or Coulomb scattering in QGP [1-3]

We have not yet compared QED calculation to the new, high precision data from ATLAS (from Quark Matter 2019)

Summary

1. Observation of the Breit-Wheeler process in HICs
2. **First Earth-based observation of Vacuum Birefringence :**

   Observed (6.7σ) via angular modulations in linear polarized $\gamma\gamma \rightarrow e^+e^-$ process
3. First 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

Fundamental Interactions : light & matter

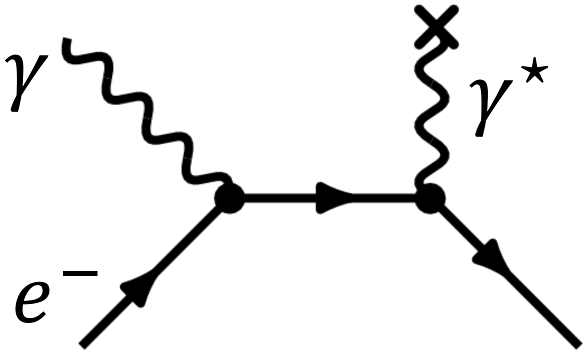
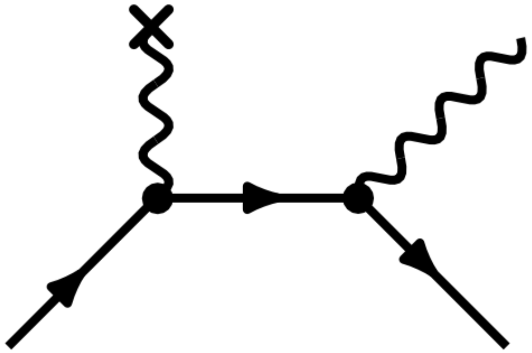
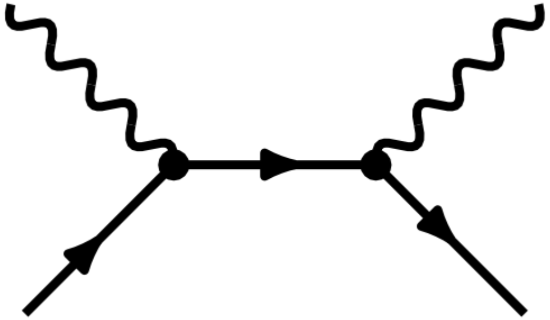


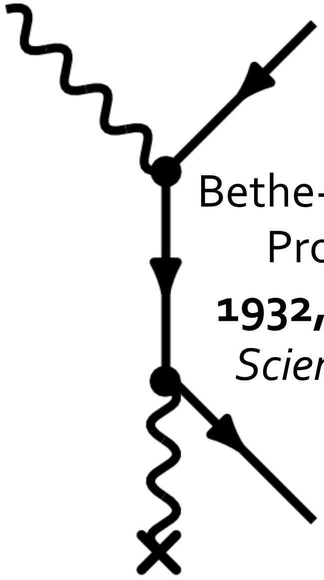
Photo Electric Effect
1887 *Hertz, Ann Phys (Leipzig) 31, 983*



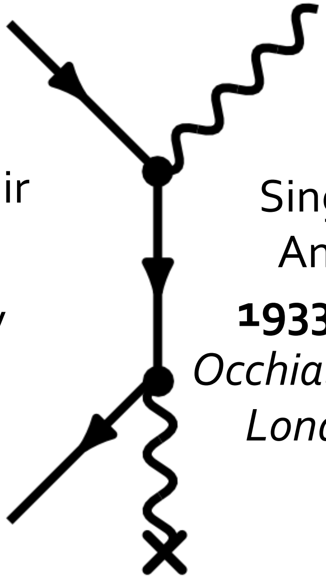
Bremsstrahlung
1895 *Röntgen, Ann Phys (Leipzig) 300, 1*



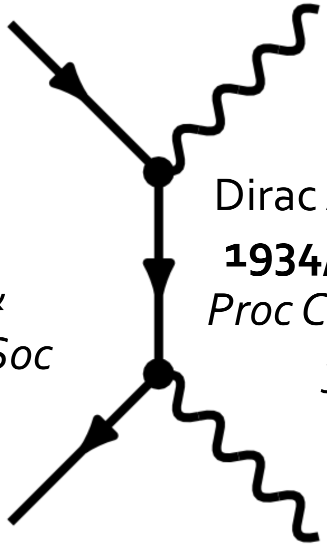
Compton Scattering
1906 *Thomson, Conduction of Electricity through Gases*



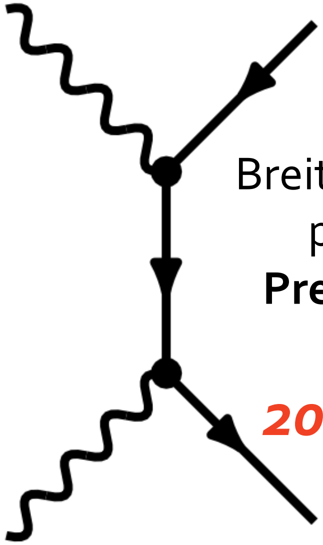
Bethe-Heitler Pair Production
1932, *Anderson, Science 76,238*



Single Photon Annihilation
1933, *Blackett & Occhialini, Proc R Soc Lond A 139, 699*



Dirac Annihilation
1934, *Klemperer, Proc Camb Phil Soc 30, 347*



Breit-Wheeler pair production
Predicted 1934

2019, STAR

Based on slide by O. Pike

Thank You

Additional Slides

External Field Approach

W. Zha, JDB, Z. Tang, Z. Xu arXiv:1812.02820

Derive impact parameter dependence using external field approach

- Based on work from M. Vidovi´c et al., Phys. Rev. C 47, 2308 (1993).

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

$$A_2^\mu(k_2,0) = -2\pi(Z_2 e)e^{ik_2^\tau b_\tau}\delta(k_2^\nu u_{2\nu})\frac{F_2(-k_2^\rho k_{2\rho})}{k_2^\sigma k_{2\sigma}}u_2^\mu.$$

$$\longrightarrow$$

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

- Term relating impact parameter (b) and transverse momentum $q_\perp$
- Integrating out the b dependence gives the standard EPA result used in literature (STARLight + other)

F. Krauss, M. Greiner, and G. Soff, Progress in Particle and Nuclear Physics 39, 503 (1997).

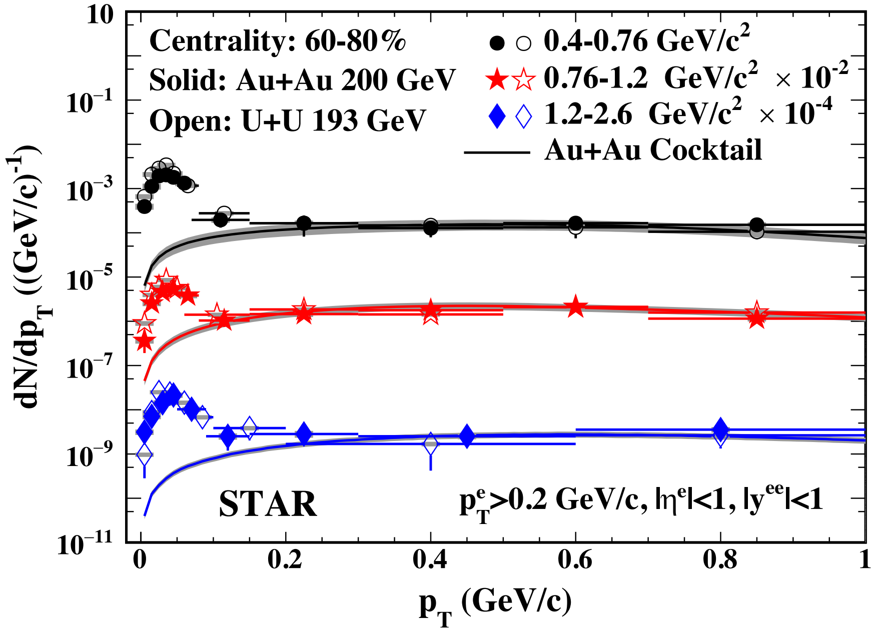
- Pair p_T is sensitive to initial field strength function of (b)

$$\int_0^\infty db$$

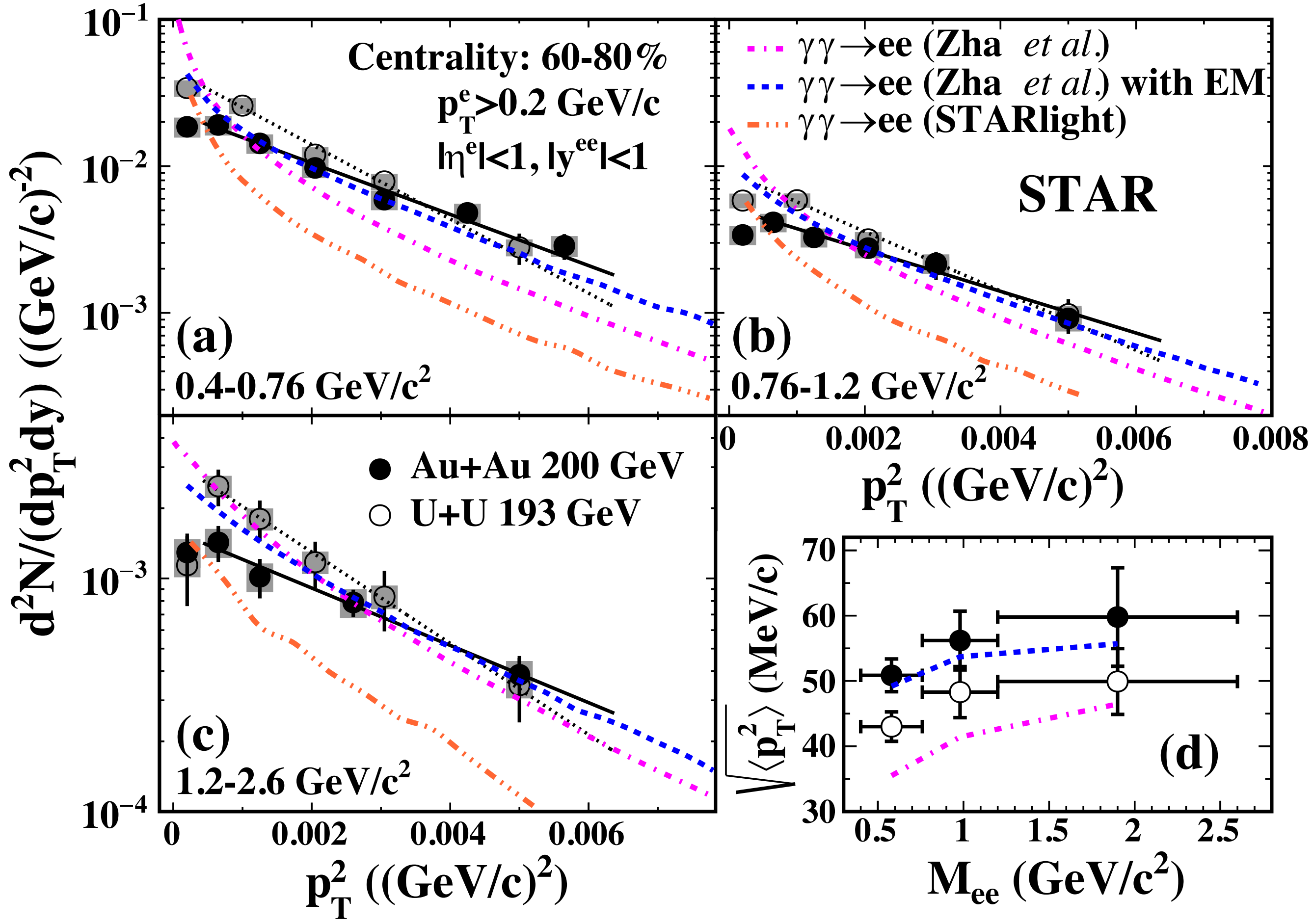
Famous EPA result

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

STAR Measurements of $\gamma\gamma \rightarrow e^+e^-$ in Peripheral Collisions



Phys. Rev. Lett. 121, 132301 (2018)



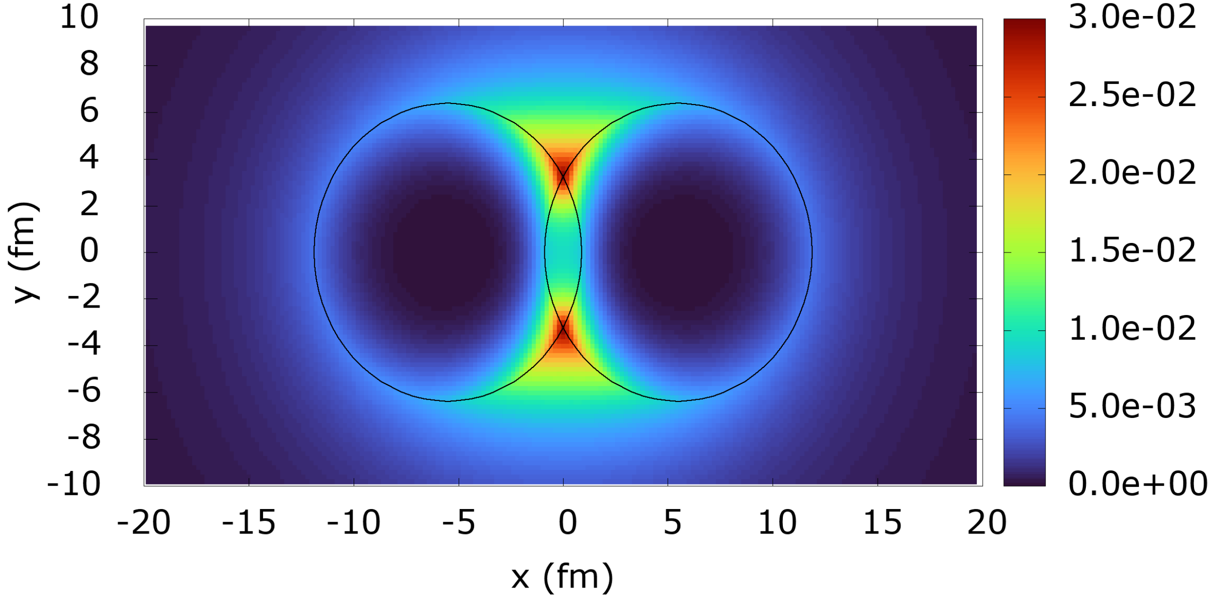
Strong excess at low p_T over hadronic cocktail

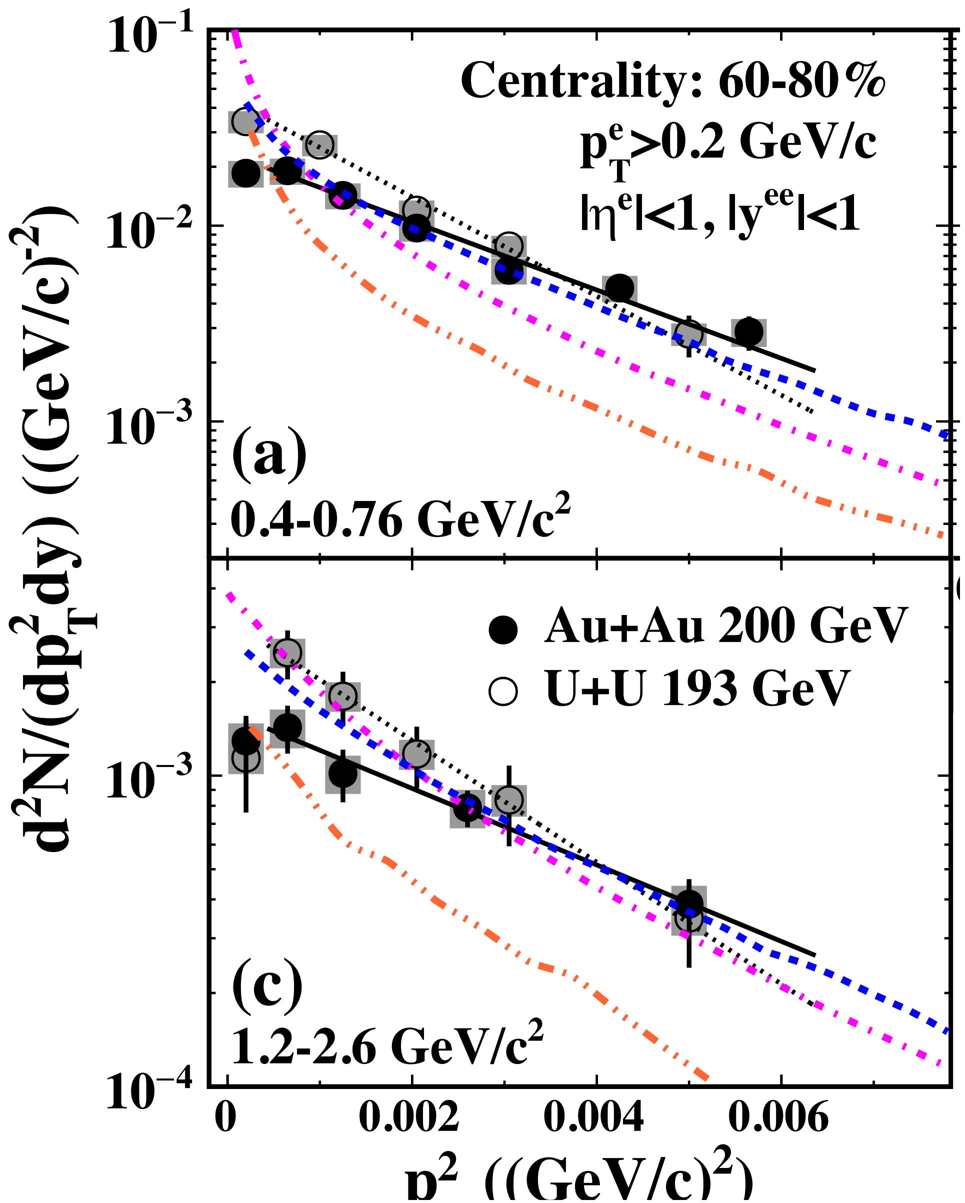
STAR Measurements:
$p_T^e > 0.2$ GeV/c
$0.4 < m_{ee} < 2.6$ GeV/c^2

- $P_\perp^2$ slope significantly broader in peripheral A+A than STARLight predicts.
- Compare with additional effect from trapped EM field in conducting QGP

Long-lived Magnetic Field?

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





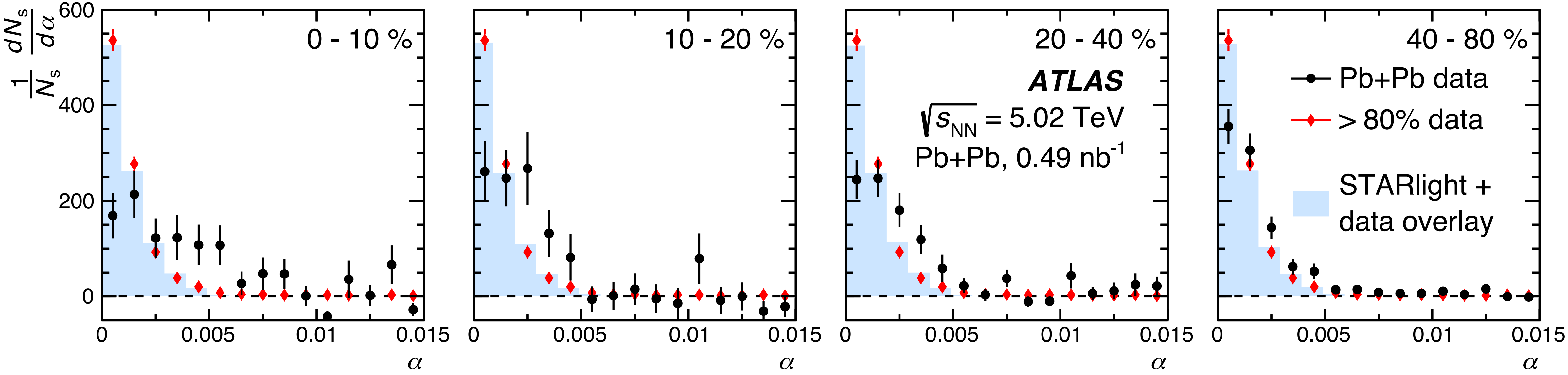
<u>Assumptions:</u>

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

ATLAS Measurement of $\gamma\gamma \rightarrow \mu^{+}\mu^{-}$

arXiv:1806.08708

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



- ATLAS recently measured forward $\mu^{+}\mu^{-}$ pairs
- Poor momentum resolution, better angular resolution

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

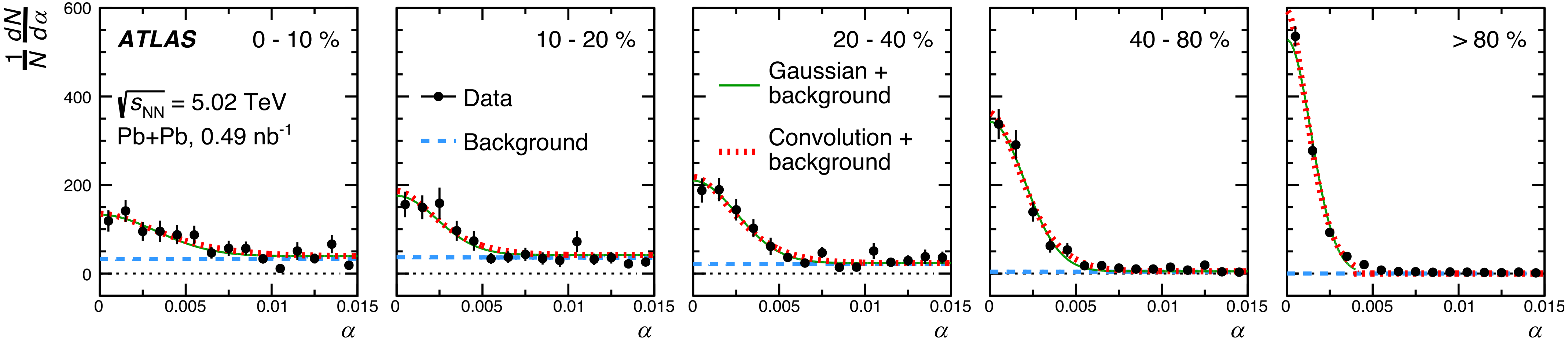
ATLAS Measurements:
$p_T^{\mu} > 4$ GeV/c
$4 < m_{\mu\mu} < 45$ GeV/c^2

- Significant broadening observed in central collisions w.r.t > 80 % data

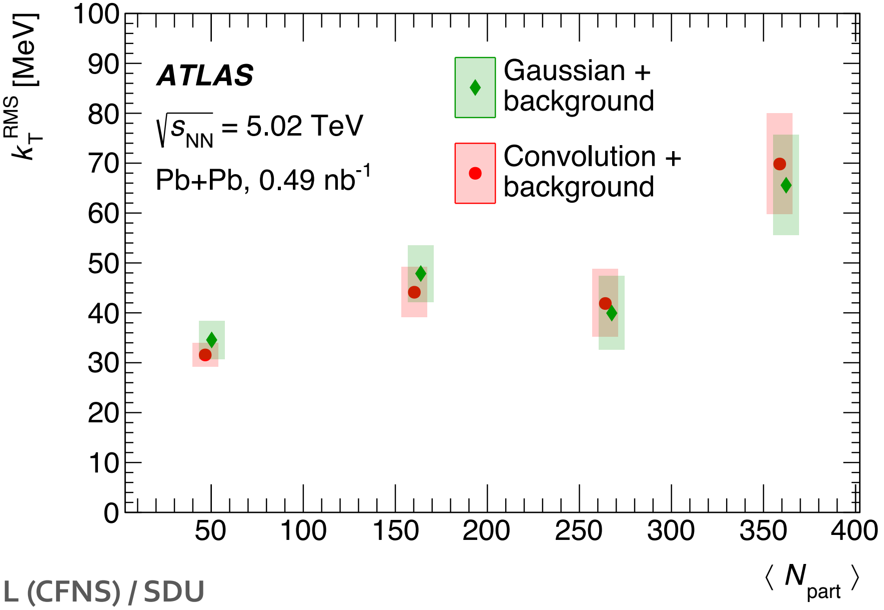
Motivation From STAR and ATLAS

arXiv:1806.08708

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



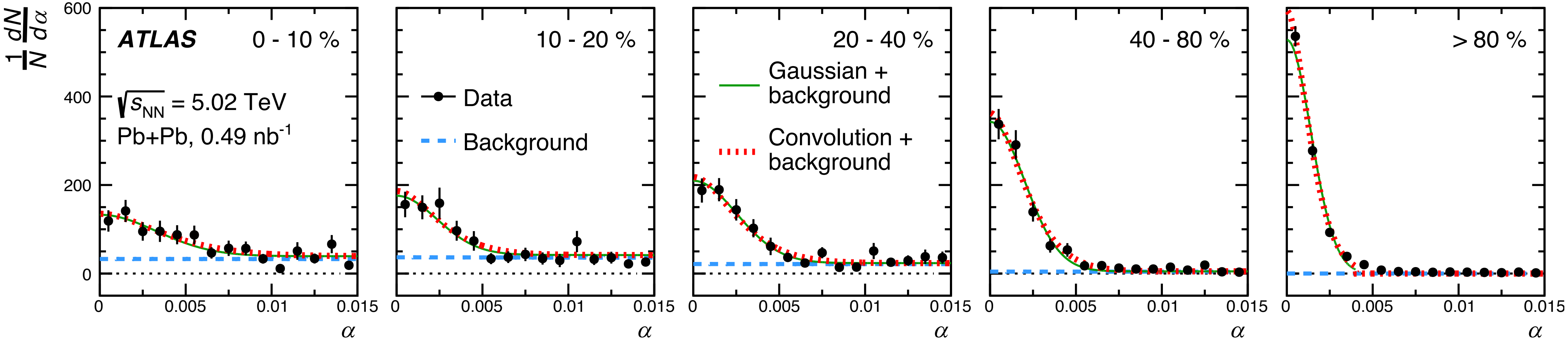
- Describe the broadening in terms of UPC curve + kick from Coulombic multiple scattering (in QGP)
- Fits to data: $k_T^{RMS} \approx 40 - 50$ MeV
- No significant centrality dependence, maybe a hint in last bin
- Very different kinematics range than STAR dielectrons, $\vec{B}$ field / coulomb scattering may not be mutually exclusive descriptions



Motivation From STAR and ATLAS

arXiv:1806.08708

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



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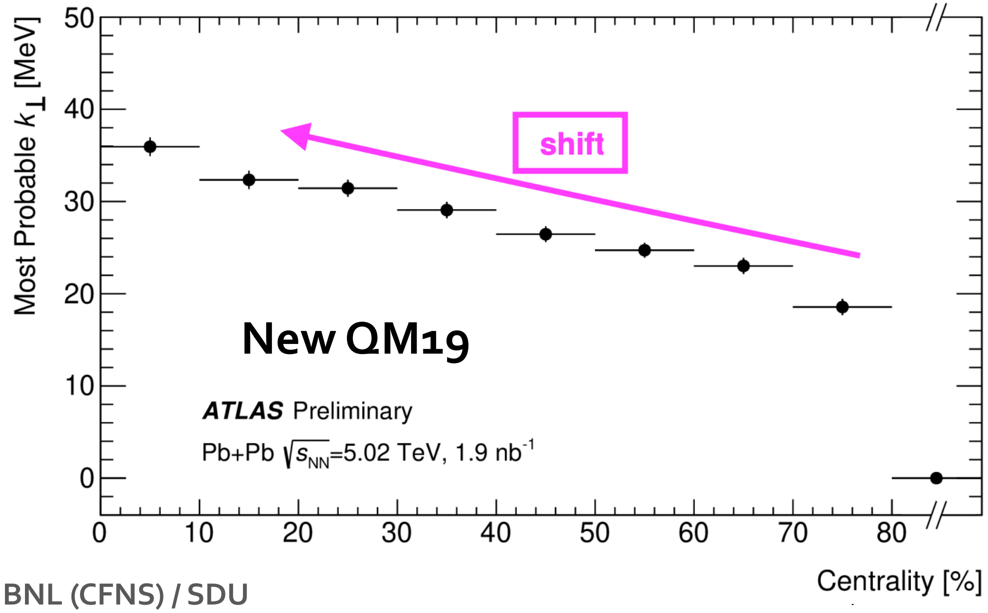
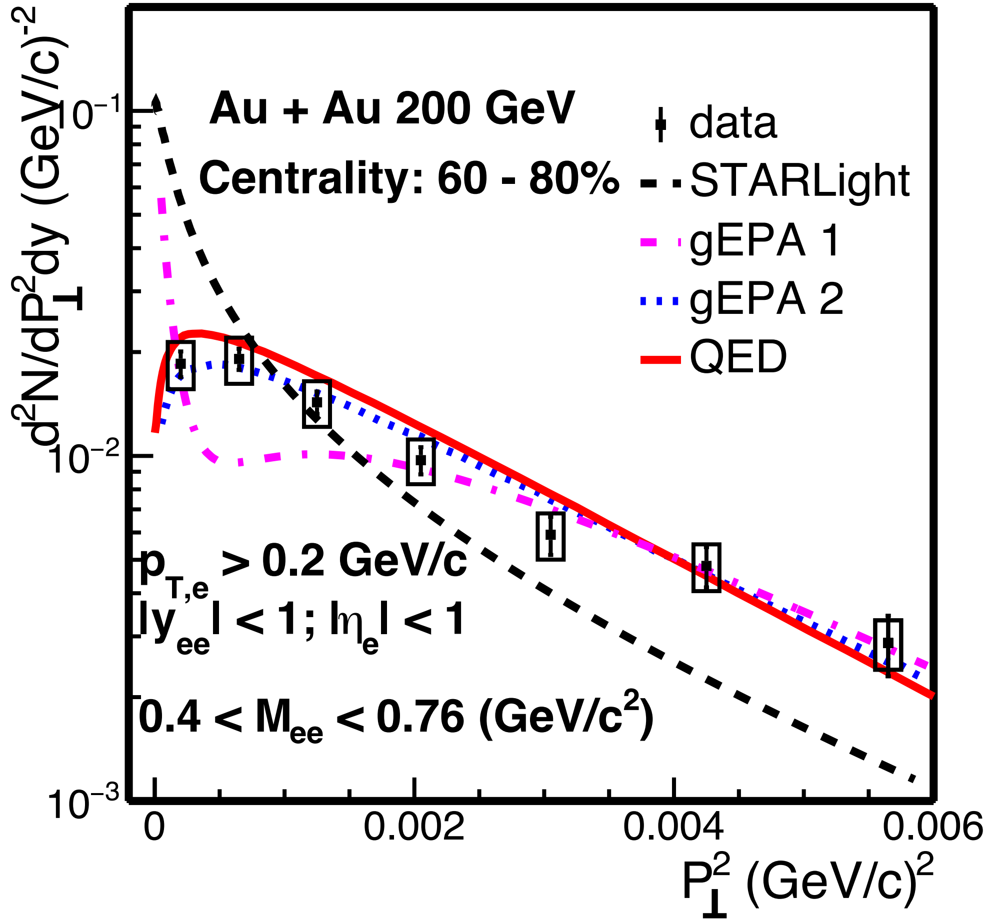
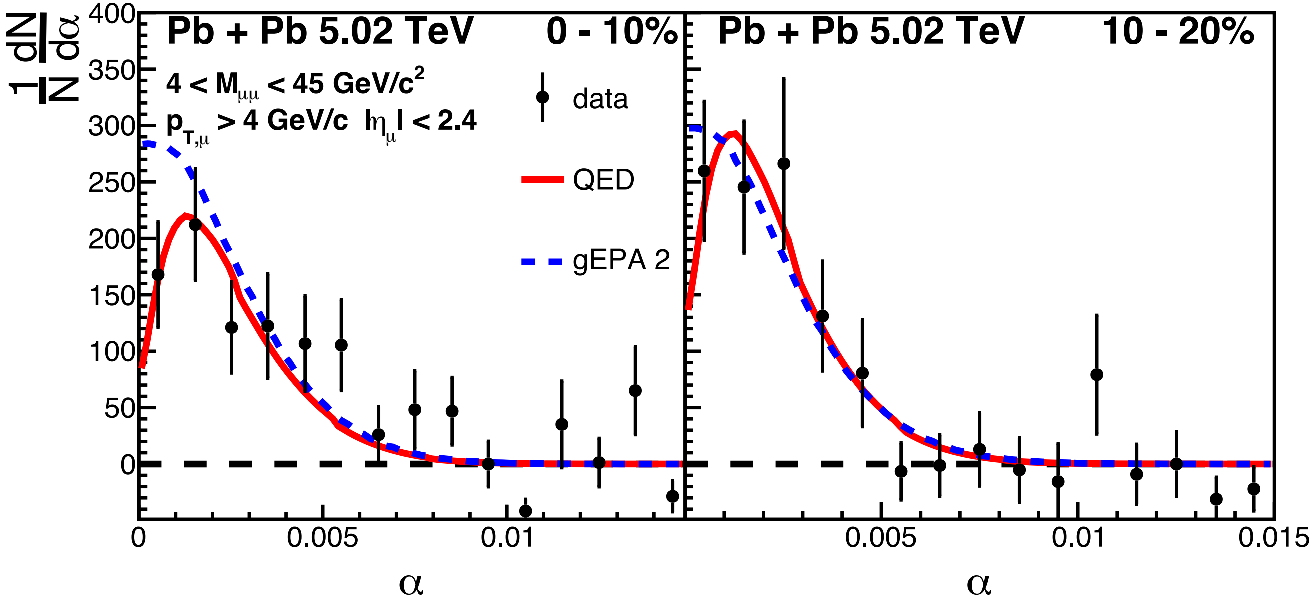


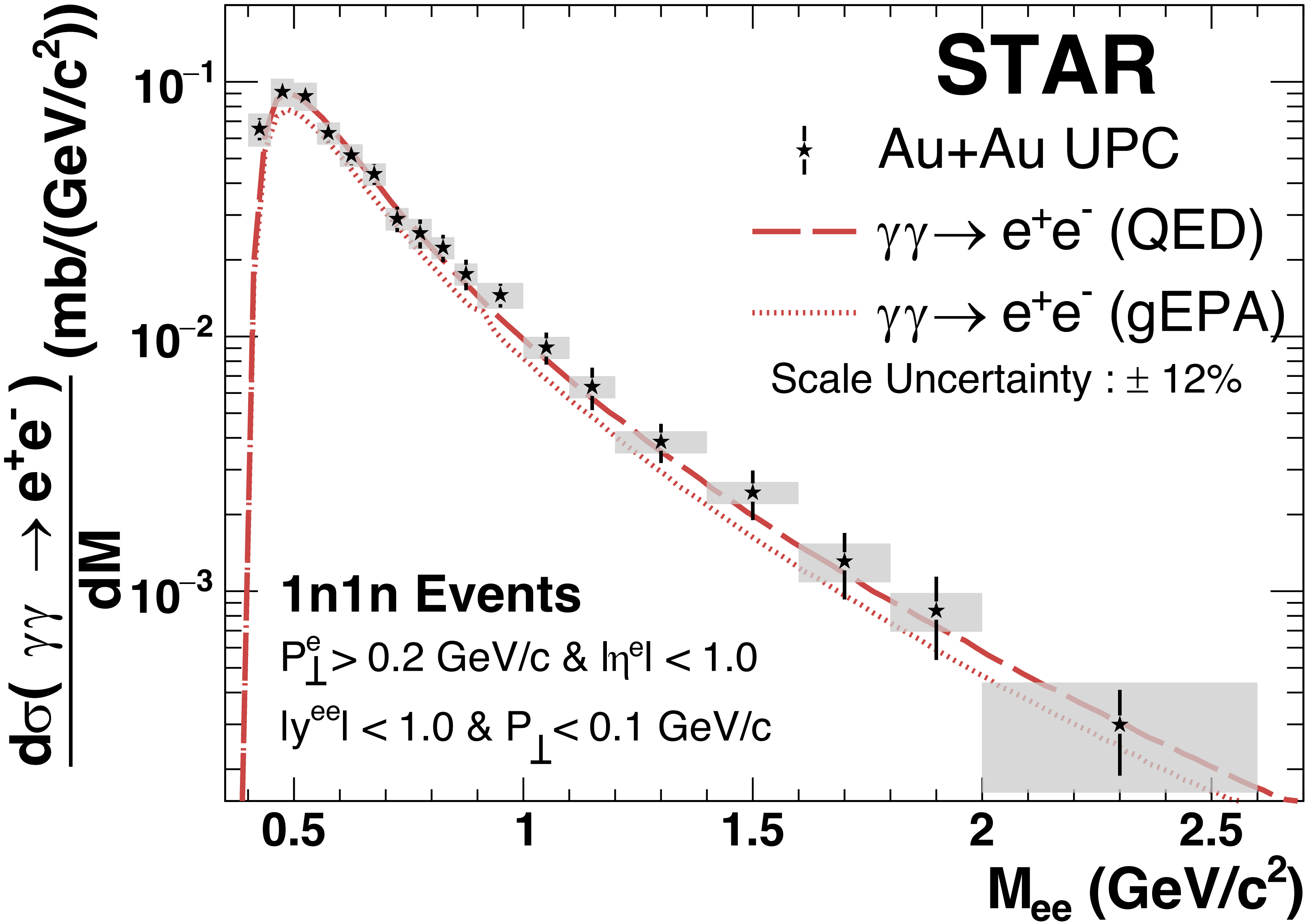
Peripheral Data





- Peripheral data from both STAR and ATLAS are well described by QED calculation
- → No need for final state effects?

$d\sigma/dM$ for events with 1n1n events



1n1n: events with 1 neutron in each ZDC

e^+e^- Identification

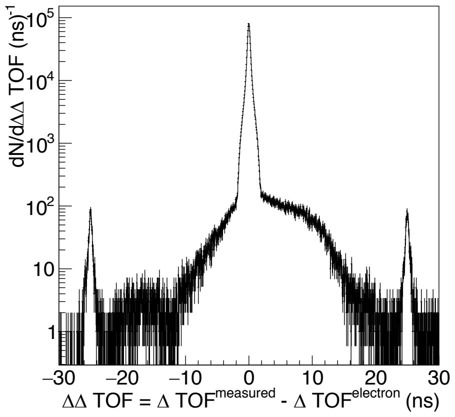
- No hits in VPD and only 2 tracks: No TOF start time
- Use TOF without a start time (to), use relative time difference between tracks

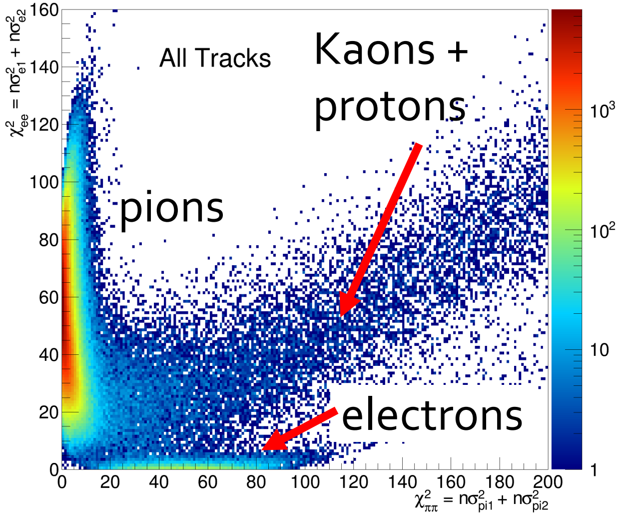
$$\Delta\, TOF = t_1 - t_2$$

$$t^{exp} = \frac{L}{c}\sqrt{\left(1 + \frac{m^2}{p^2}\right)}$$

$$\Delta\, TOF^{exp} = t_1^{exp} - t_2^{exp}$$

$$\Delta\, \Delta TOF = \Delta TOF - \Delta TOF^{exp}$$



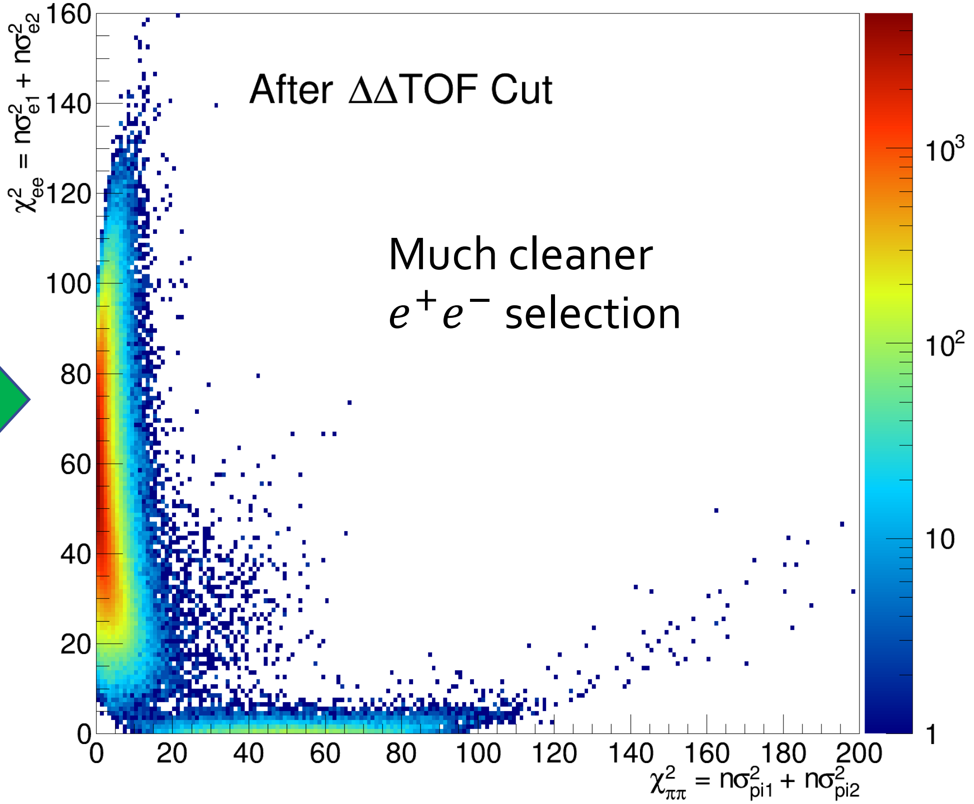


Run 10 Au+Au

$$\chi^2_{ee} = n\sigma^2_{e1} + n\sigma^2_{e2}$$

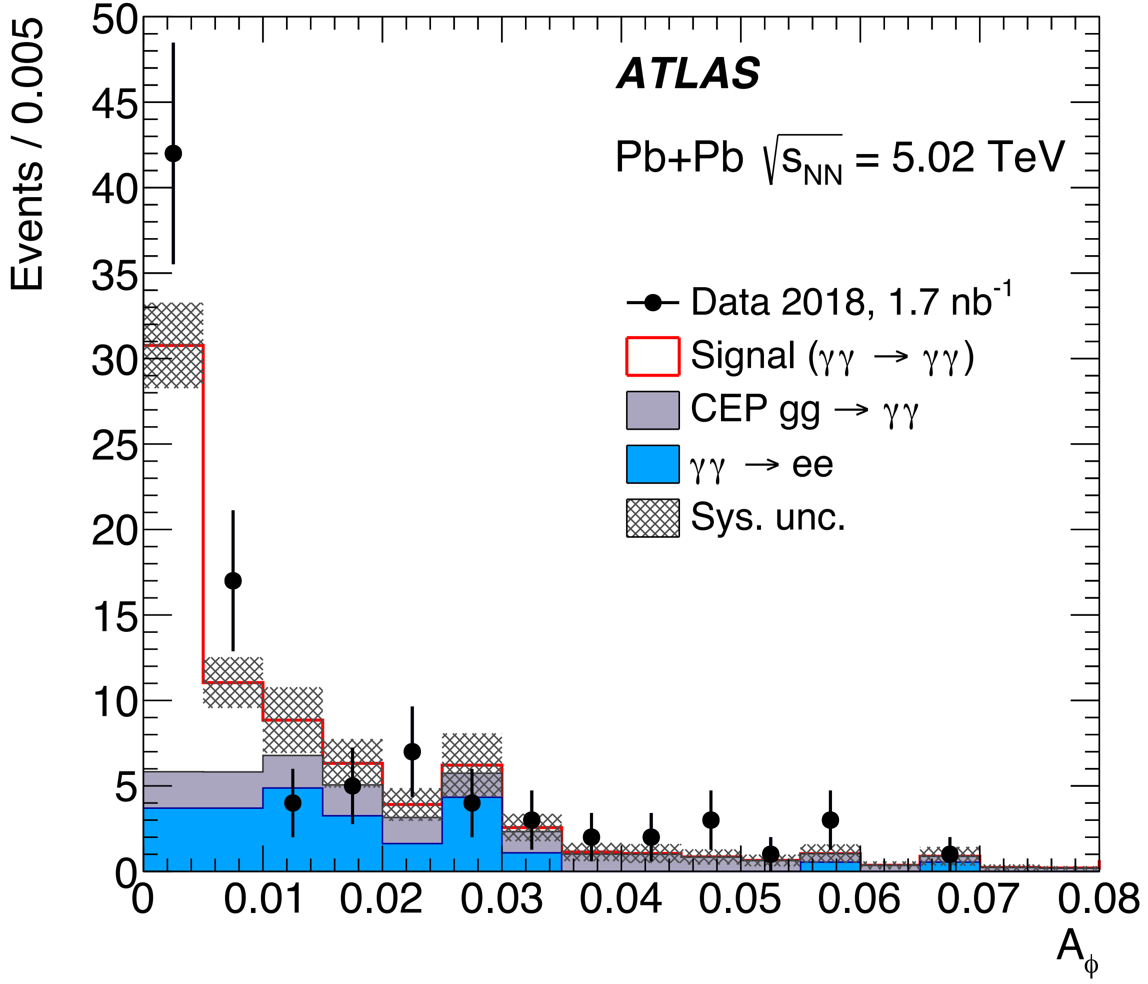
$$\chi^2_{\pi\pi} = n\sigma^2_{\pi 1} + n\sigma^2_{\pi 2}$$

i.e. pair PID using dE/dx

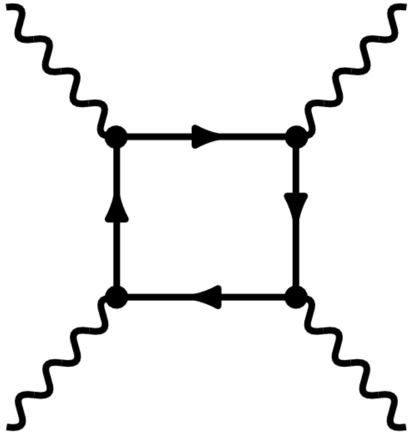


Run 10 Au+Au

Example : Light-by-Light Scattering



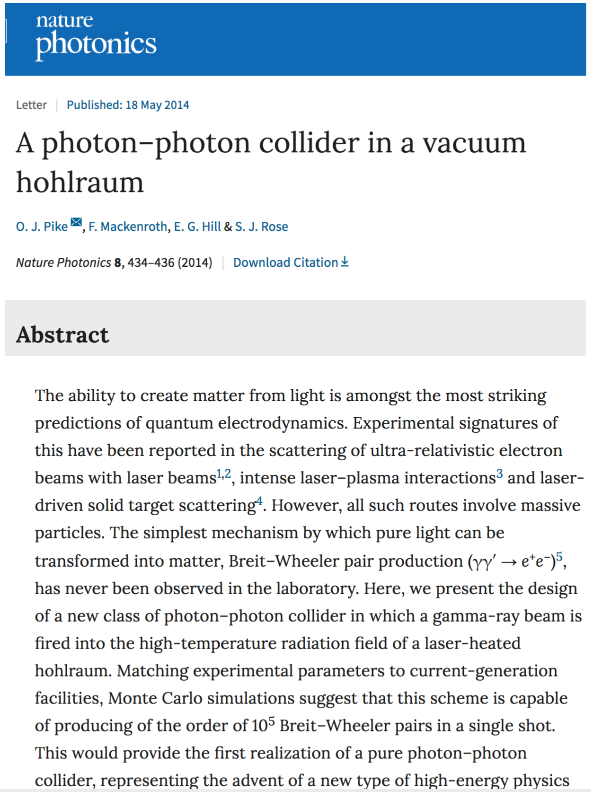
ATLAS Observed Light-by-Light Scattering in UPCs:



- Purely quantum mechanical process (α_{em}^4)
- Light-by-Light scattering involves real photons by definition

ATLAS, *Nature Physics* 13 (2017), 852

Motivation outside HIC / HEP



nature photonics

Letter | Published: 18 May 2014

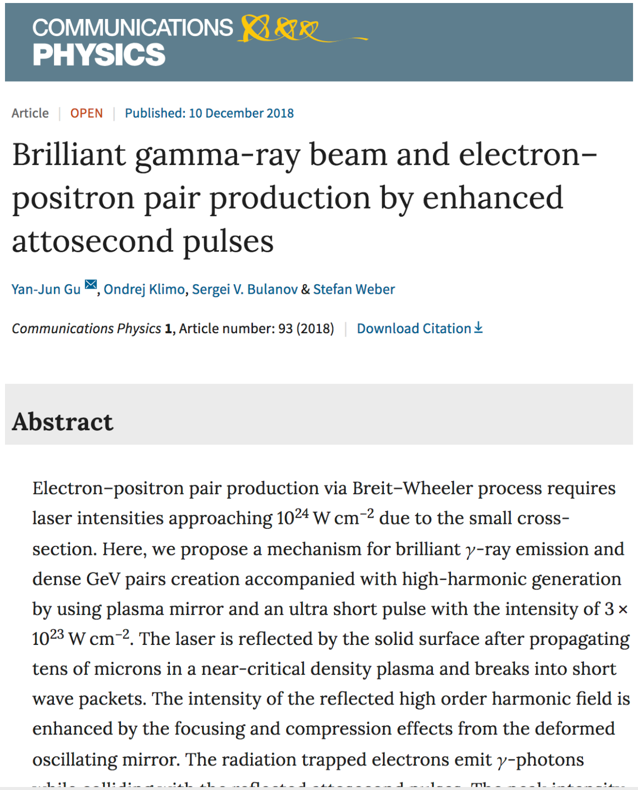
A photon–photon collider in a vacuum hohlraum

O. J. Pike, F. Mackenroth, E. G. Hill & S. J. Rose

Nature Photonics **8**, 434–436 (2014) | Download Citation

Abstract

The ability to create matter from light is amongst the most striking predictions of quantum electrodynamics. Experimental signatures of this have been reported in the scattering of ultra-relativistic electron beams with laser beams[1,2], intense laser–plasma interactions[3] and laser-driven solid target scattering[4]. However, all such routes involve massive particles. The simplest mechanism by which pure light can be transformed into matter, Breit–Wheeler pair production ($\gamma\gamma' \rightarrow e^+e^-$)[5], has never been observed in the laboratory. Here, we present the design of a new class of photon–photon collider in which a gamma-ray beam is fired into the high-temperature radiation field of a laser-heated hohlraum. Matching experimental parameters to current-generation facilities, Monte Carlo simulations suggest that this scheme is capable of producing of the order of 10^5 Breit–Wheeler pairs in a single shot. This would provide the first realization of a pure photon–photon collider, representing the advent of a new type of high-energy physics



COMMUNICATIONS PHYSICS

Article | OPEN | Published: 10 December 2018

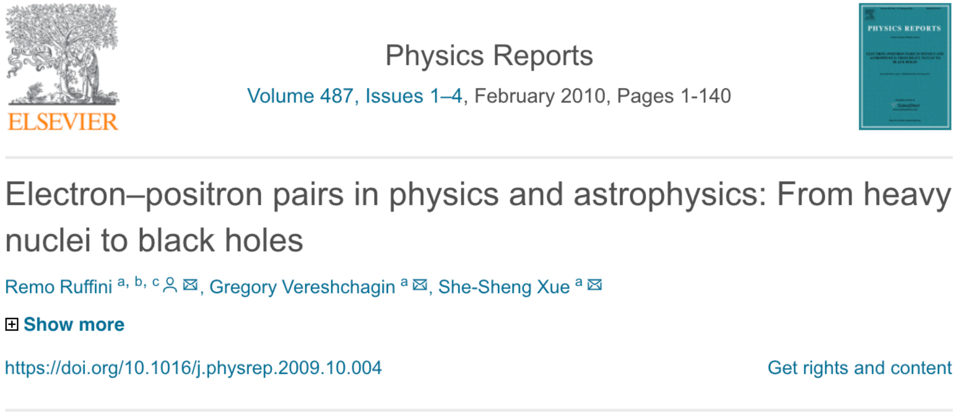
Brilliant gamma-ray beam and electron–positron pair production by enhanced attosecond pulses

Yan-Jun Gu, Ondrej Klimo, Sergei V. Bulanov & Stefan Weber

Communications Physics **1**, Article number: 93 (2018) | Download Citation

Abstract

Electron–positron pair production via Breit–Wheeler process requires laser intensities approaching 10^{24} W cm^{-2} due to the small cross-section. Here, we propose a mechanism for brilliant γ-ray emission and dense GeV pairs creation accompanied with high-harmonic generation by using plasma mirror and an ultra short pulse with the intensity of 3 × 10^{23} W cm^{-2}. The laser is reflected by the solid surface after propagating tens of microns in a near-critical density plasma and breaks into short wave packets. The intensity of the reflected high order harmonic field is enhanced by the focusing and compression effects from the deformed oscillating mirror. The radiation trapped electrons emit γ-photons



ELSEVIER

Physics Reports

Volume 487, Issues 1–4, February 2010, Pages 1-140

Electron–positron pairs in physics and astrophysics: From heavy nuclei to black holes

Remo Ruffini [a, b, c], Gregory Vereshchagin [a], She-Sheng Xue [a]

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https://doi.org/10.1016/j.physrep.2009.10.004

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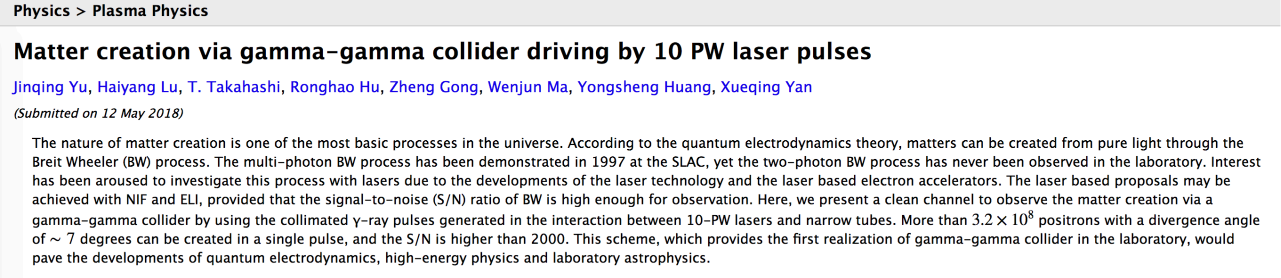


Physics > Plasma Physics

Matter creation via gamma-gamma collider driving by 10 PW laser pulses

Jinqing Yu, Haiyang Lu, T. Takahashi, Ronghao Hu, Zheng Gong, Wenjun Ma, Yongsheng Huang, Xueqing Yan

(Submitted on 12 May 2018)

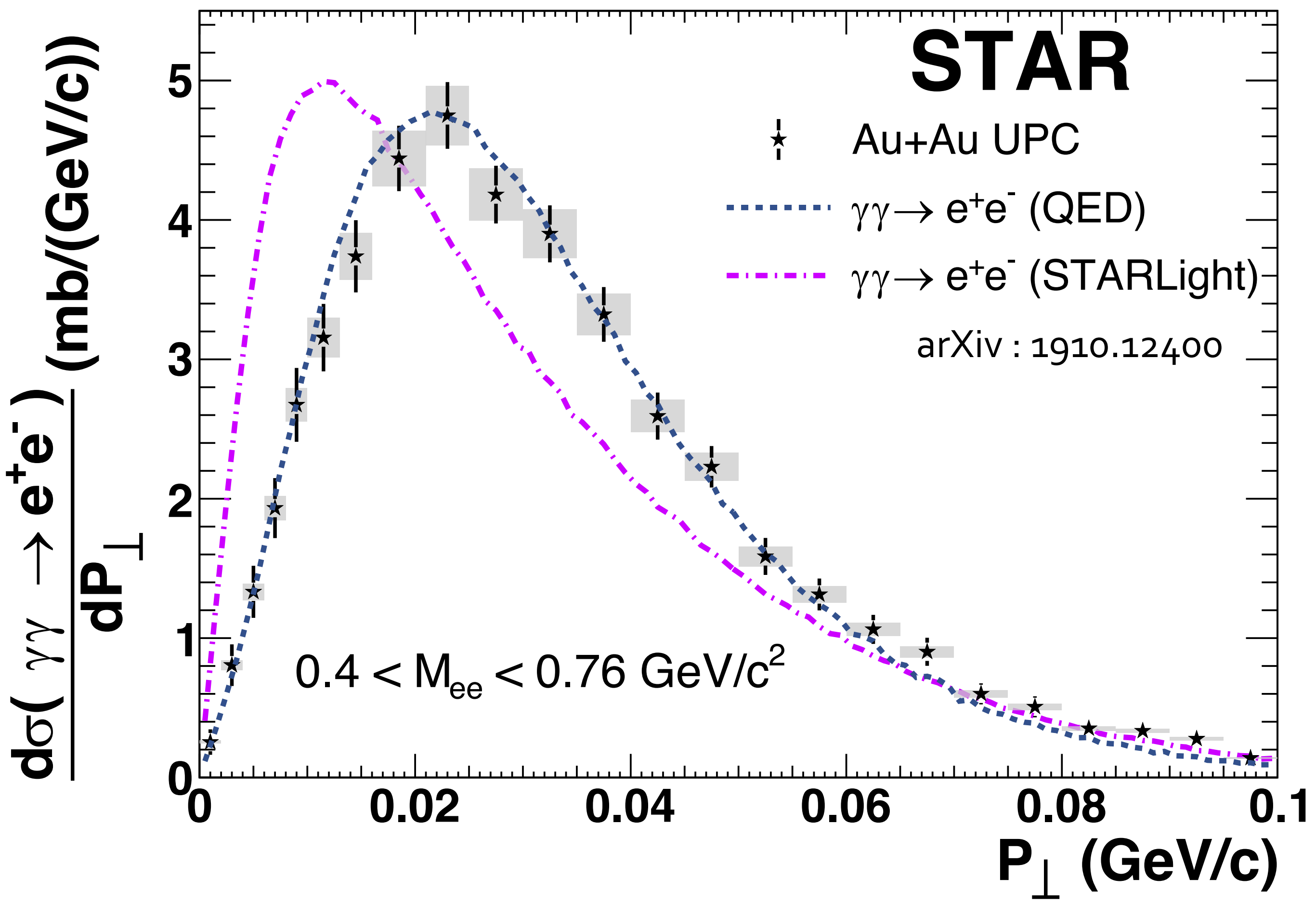
The nature of matter creation is one of the most basic processes in the universe. According to the quantum electrodynamics theory, matters can be created from pure light through the Breit Wheeler (BW) process. The multi-photon BW process has been demonstrated in 1997 at the SLAC, yet the two-photon BW process has never been observed in the laboratory. Interest has been aroused to investigate this process with lasers due to the developments of the laser technology and the laser based electron accelerators. The laser based proposals may be achieved with NIF and ELI, provided that the signal-to-noise (S/N) ratio of BW is high enough for observation. Here, we present a clean channel to observe the matter creation via a gamma-gamma collider by using the collimated γ-ray pulses generated in the interaction between 10-PW lasers and narrow tubes. More than 3.2×10^8 positrons with a divergence angle of ~ 7 degrees can be created in a single pulse, and the S/N is higher than 2000. This scheme, which provides the first realization of gamma-gamma collider in the laboratory, would pave the developments of quantum electrodynamics, high-energy physics and laboratory astrophysics.

Breit-Wheeler process has never been (definitely)achieved

Impact on photonics, laser physics, plasma physics, study of QED under extreme conditions

Just demonstrating Breit-Wheeler process is a very important result

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



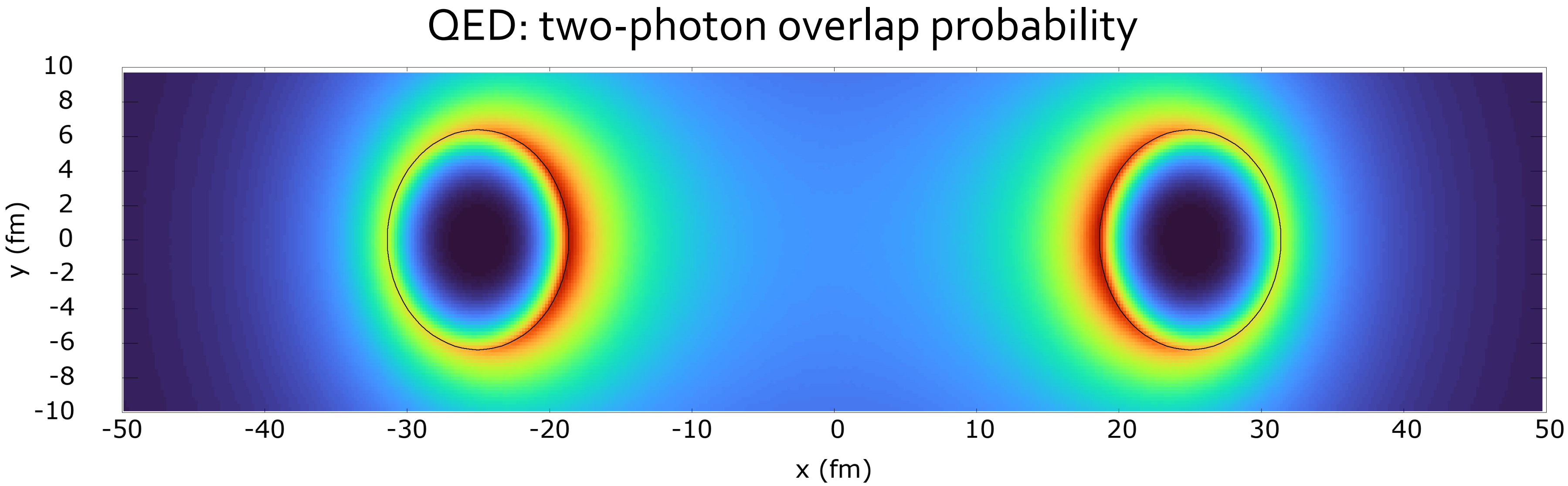
QED and STARLight are scaled to match measured $\sigma(\gamma\gamma \rightarrow e^+e^-)$

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]

- Cross-section peaks at low $P_\perp$, as expected for quasi-real photon collisions
- **Data are well described by leading order QED calculation ($\gamma\gamma \rightarrow e^+e^-$)**
- STARLight predicts significantly lower $\langle P_\perp \rangle$ than seen in data

Connection to the Initial Magnetic Field

- OK but how sensitive are these measurements to the **peak** field?
- How sensitive to the geometry of the fields?



- Most $\gamma\gamma$ interactions in region where field from one ion is maximum

$$n_1 \times n_2 \propto |B_1|^2 \times |B_2|^2 \approx \left|B_{1,peak}\right|^2 \times const$$ (at large impact parameters)

Connection to the Initial Magnetic Field

- At large impact parameters

$$n_1 \times n_2 \propto |B_1|^2 \times |B_2|^2 \approx \left|B_{1,peak}\right|^2 \times const$$

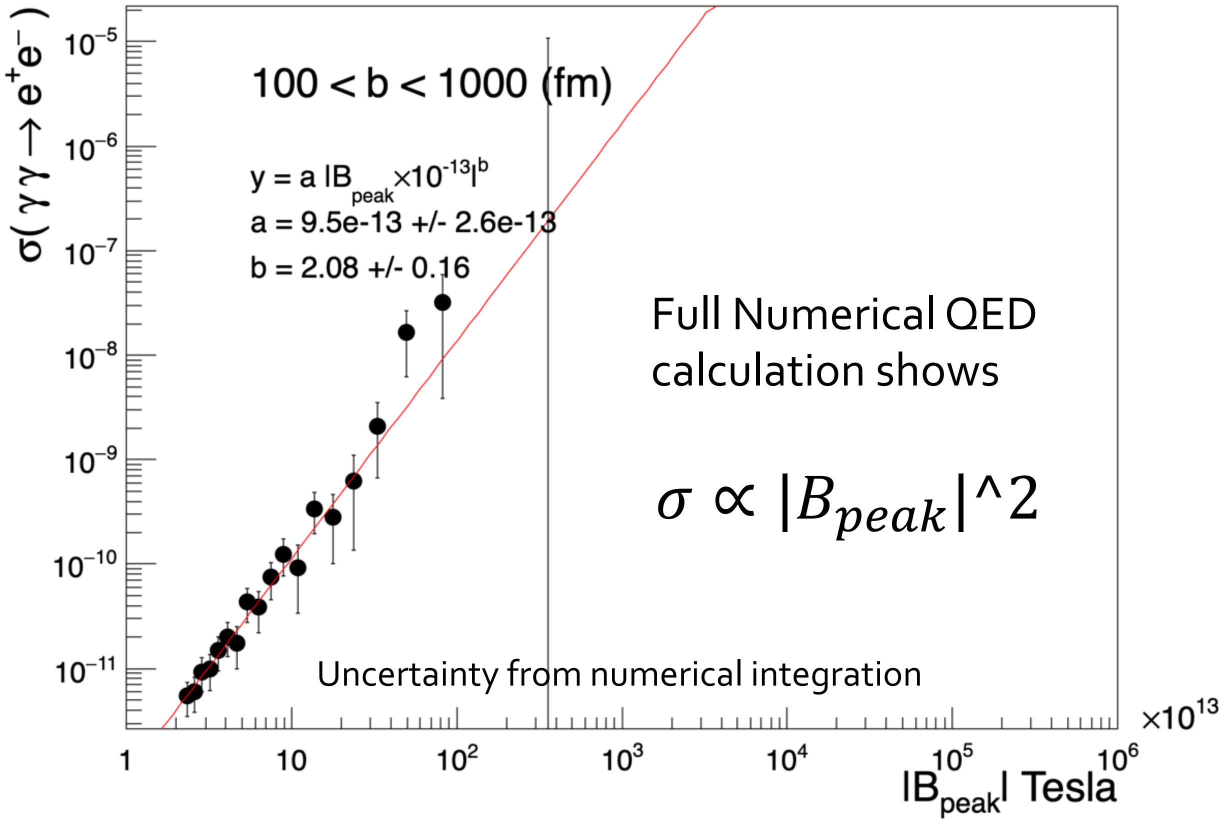
Numerical QED calculation using arbitrary Four-Potential as input

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

$$A_2^\mu(k_2, 0) = -2\pi(Z_2 e) e^{ik_2^\tau b_\tau} \delta(k_2^\nu u_{2\nu}) \frac{F_2(-k_2^\rho k_{2\rho})}{k_2^\sigma k_{2\sigma}} u_2^\mu.$$

Assumptions:

- ○ Spherically symmetric
- ○ Woods-Saxon charge distribution



Full Numerical QED calculation shows

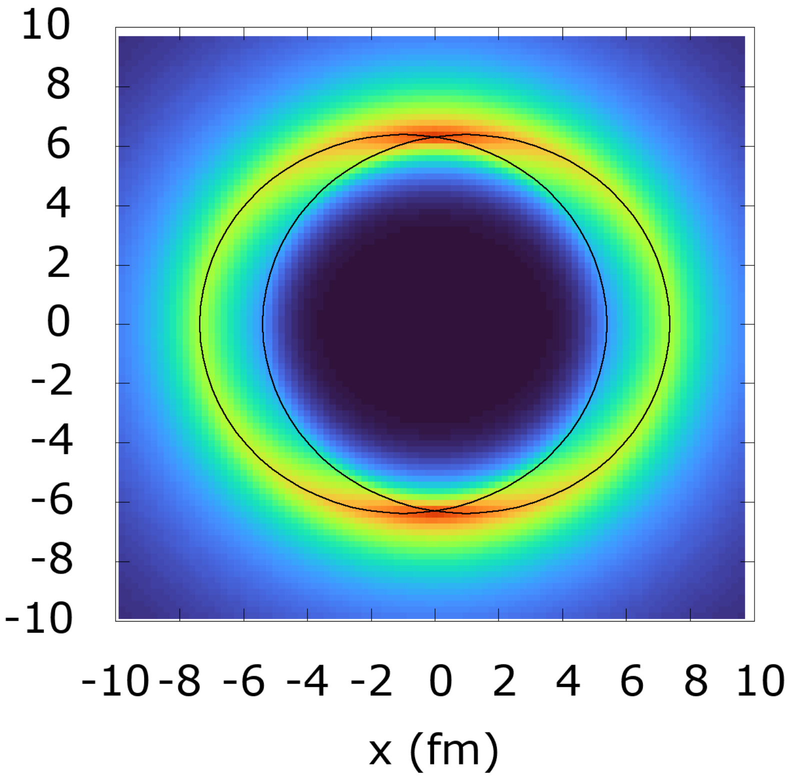
$$\sigma \propto |B_{peak}|\text{^}2$$

Uncertainty from numerical integration

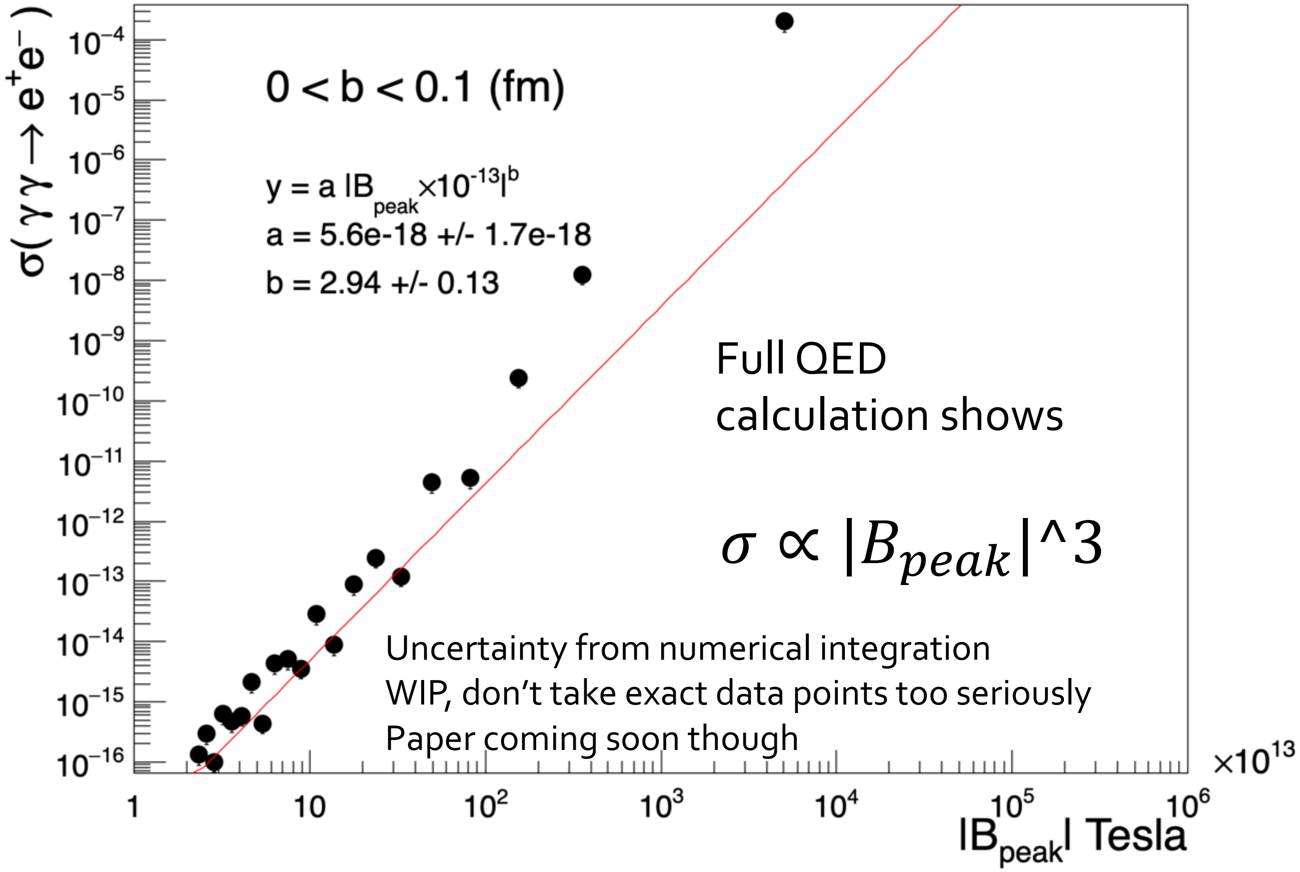
Connection to the Initial Magnetic Field

- At impact parameter $b \approx 0$

$$n_1 \times n_2 \propto |B_1|^2 \times |B_2|^2 \approx \left|B_{1,peak}\right|^2 \times \left|B_{2,peak}\right|^2 \approx \left|B_{peak}\right|^4$$



Most $\gamma\gamma$ interactions take place in region where **both** fields are maximal



Full QED calculation shows

$$\sigma \propto |B_{peak}|\hat{}3$$

Uncertainty from numerical integration
WIP, don't take exact data points too seriously
Paper coming soon though