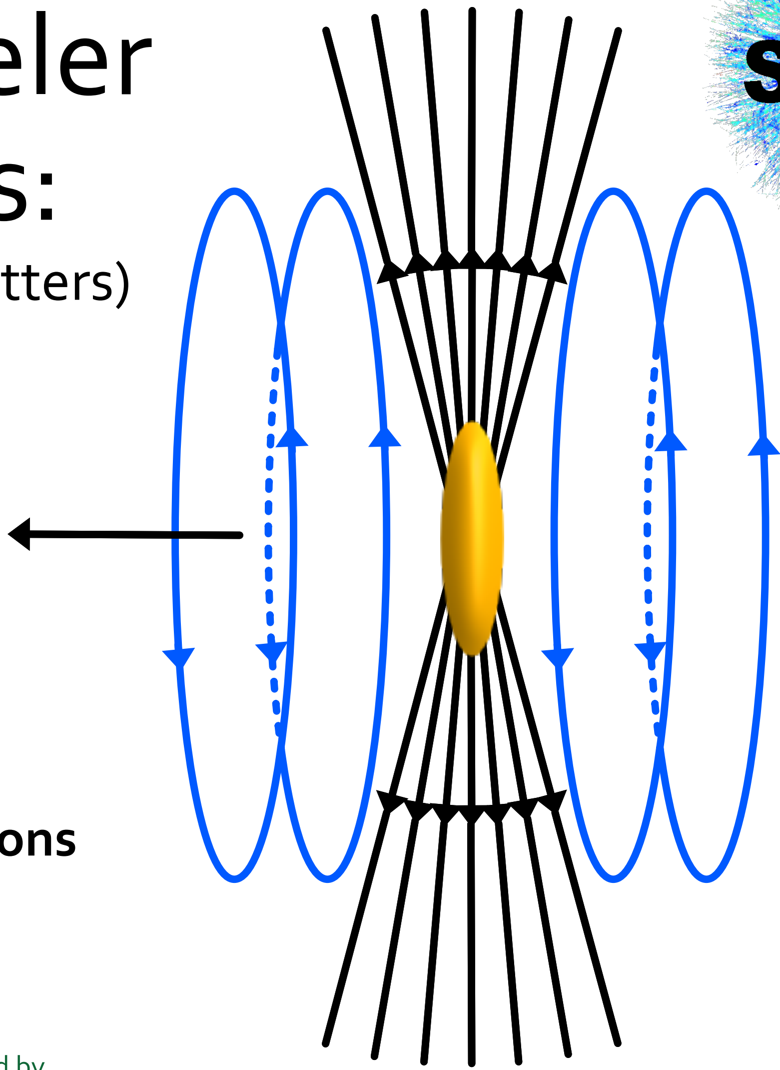
Observation of the Breit-Wheeler Process in Heavy-Ion Collisions:

based on arXiv : 1910.12400 (accepted by Physical Review Letters)



James Daniel Brandenburg (for the STAR Collaboration)

Brookhaven National Laboratory /

Center for Frontiers in Nuclear Science

LPHYS`21 : **29th annual International Laser Physics Workshop**

Seminar 9: Extreme Light Technologies, Science, and Applications

July 12th, 2021 (online)

BROOKHAVEN NATIONAL LABORATORY

Center for Frontiers in Nuclear Science

In part supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Outline of this talk

1. Quantum Electrodynamics
   - Introduction & some history
   - Ultra-peripheral Heavy Ion collisions → QED under extreme conditions
2. Observation of the Breit-Wheeler Pair Production process
   1. Energy spectrum
   2. Anisotropic effects in polarized $\gamma\gamma \rightarrow e^+e^-$ process
3. Summary

Fundamental Interactions : light & matter

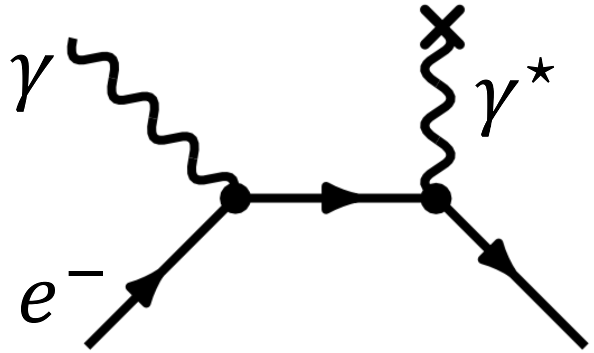
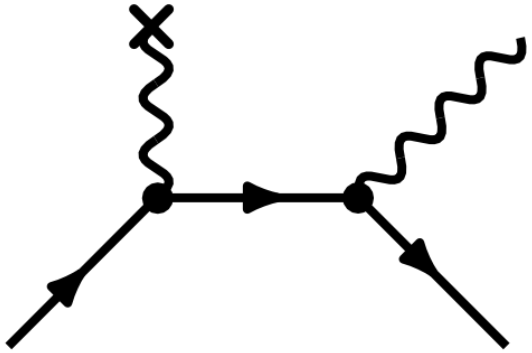
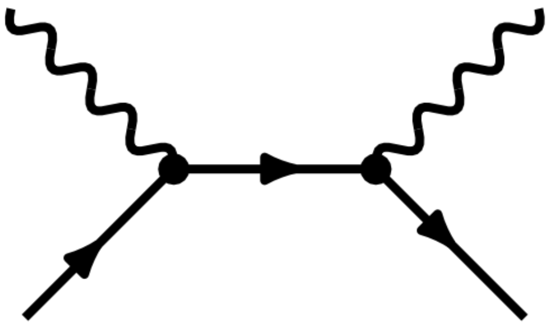


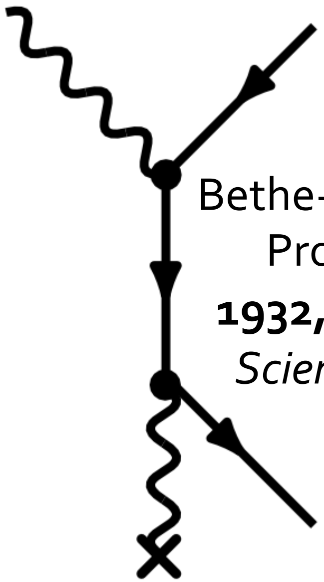
Photo Electric Effect
1887 *Hertz, Ann Phys (Leipzig) 31, 983*



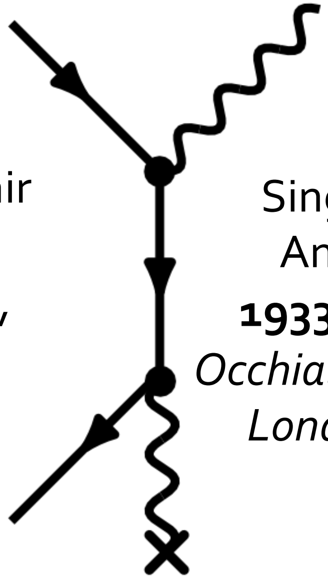
Bremsstrahlung
1895 *Röntgen, Ann Phys (Leipzig) 300, 1*



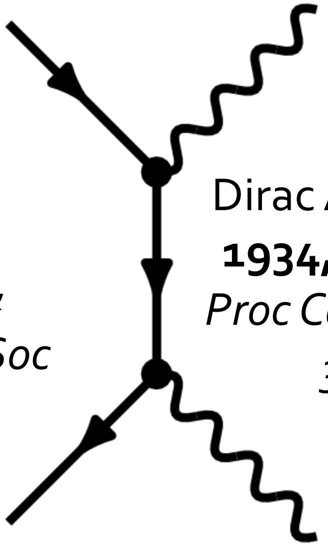
Compton Scattering
1906 *Thomson, Conduction of Electricity through Gases*



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



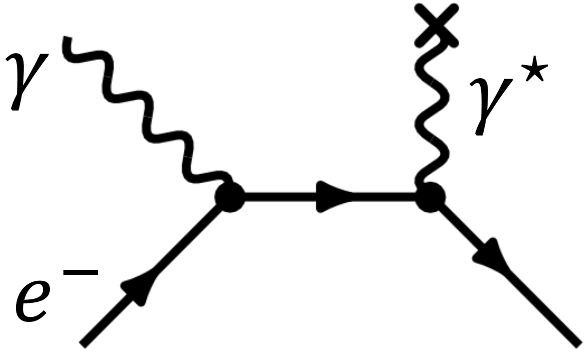
Single Photon Annihilation
1933, *Blackett & Occhialini, Proc R Soc Lond A 139, 699*



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

Fundamental Interactions : light & matter

STAR



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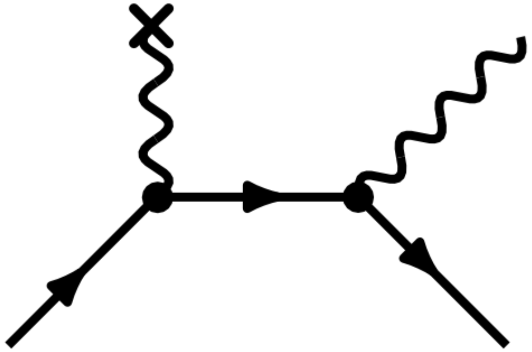

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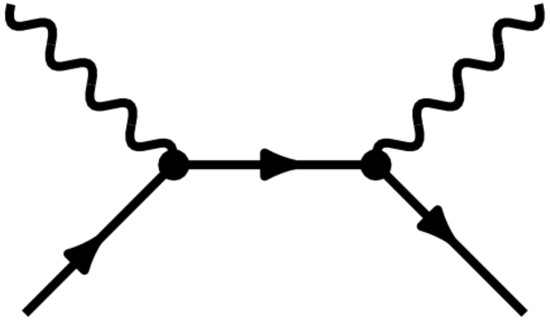

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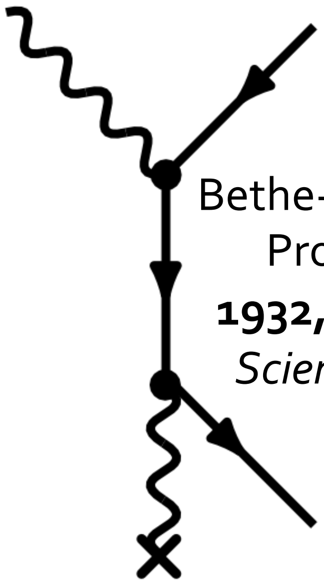

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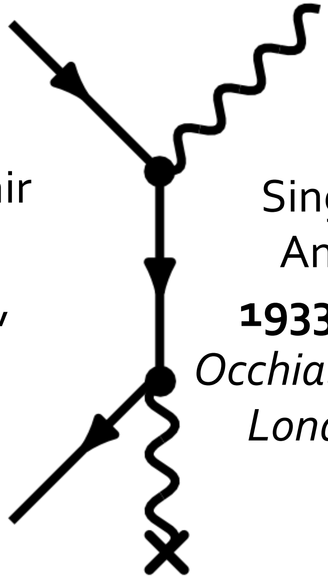

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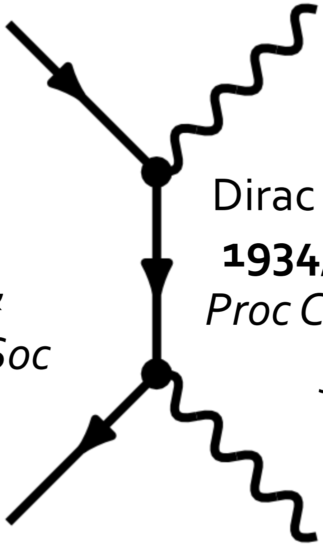

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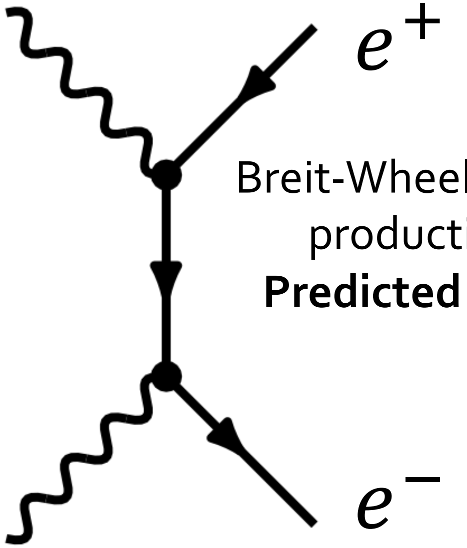
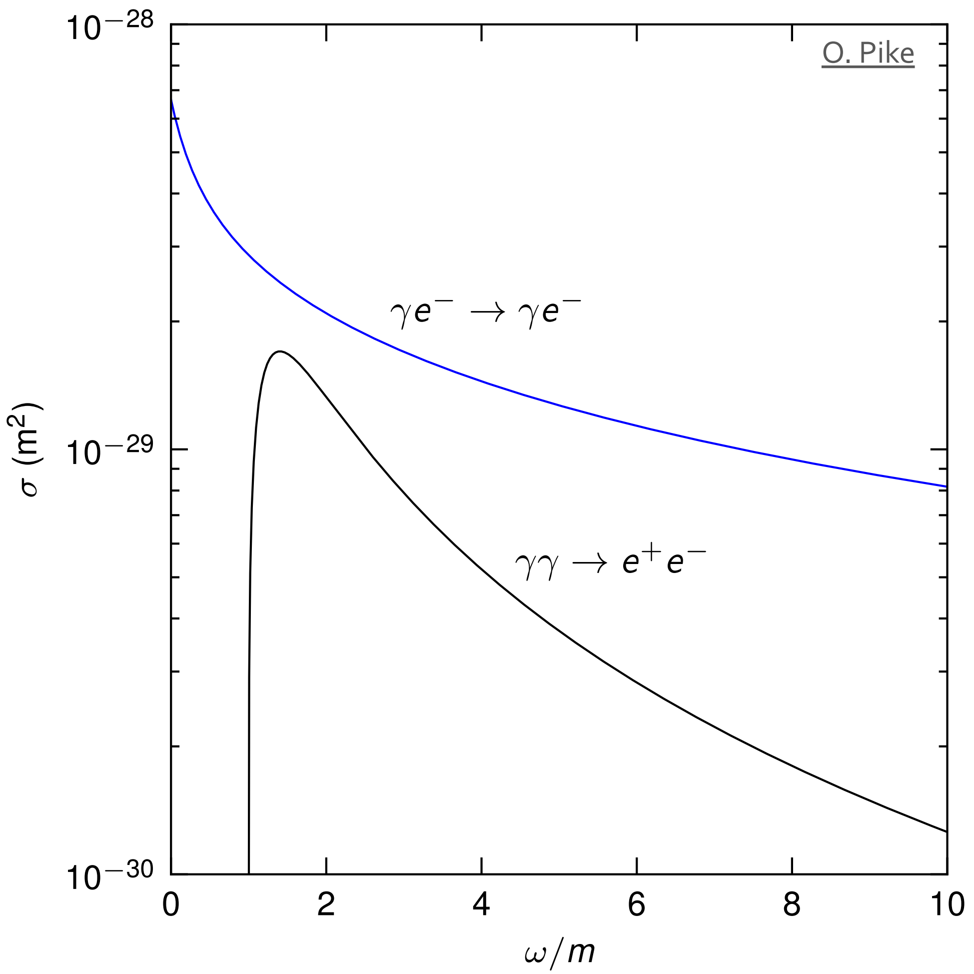


Breit-Wheeler pair production
Predicted 1934

Breit-Wheeler Process, why so *elusive?*

STAR

Breit-Wheeler and Klein-Nishina cross-sections



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

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

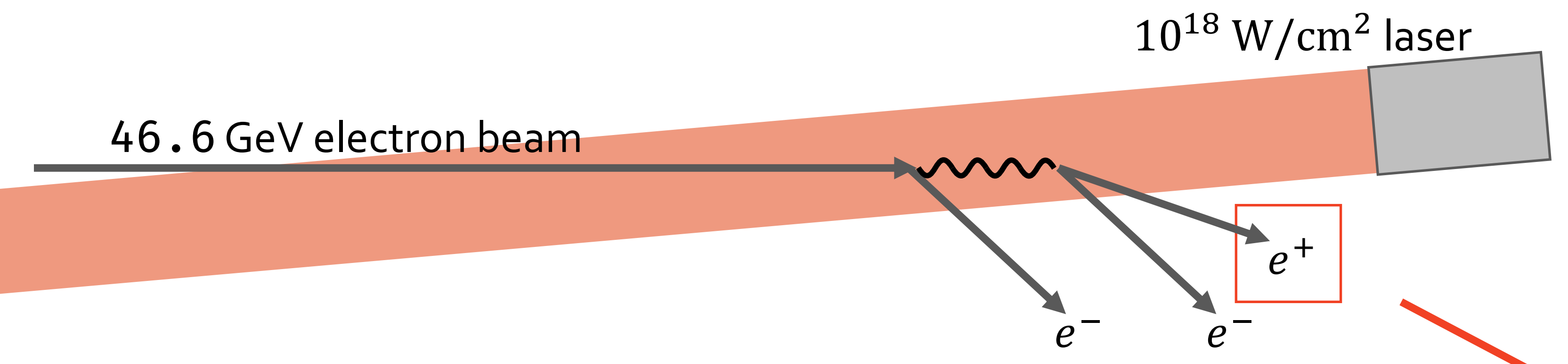
- Same peak cross section as Compton scattering and Dirac annihilation
- Cross section, $\sigma_{\gamma\gamma}$ peaks at 10^{-29}m²
- Creating matter from massless state, remember : $E = mc^2$
  - center of mass energy must be $W \geq 2m_e$

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

Progress Towards the Breit-Wheeler Process

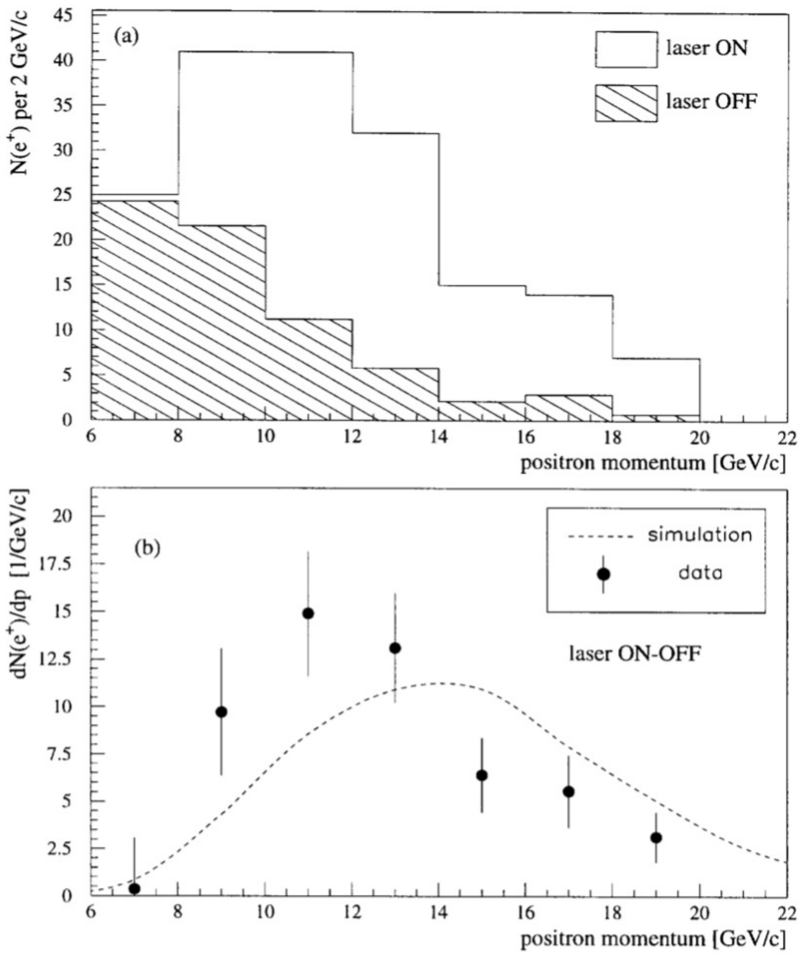
SLAC E−144 Experiment

- Non-linear Breit-Wheeler Process: $\gamma + n\gamma_0 \rightarrow e^+e^-$
  - Two step process: Compton backscattering
  - Energy threshold requires $n > 4$ with $\langle n \rangle = 6.44$



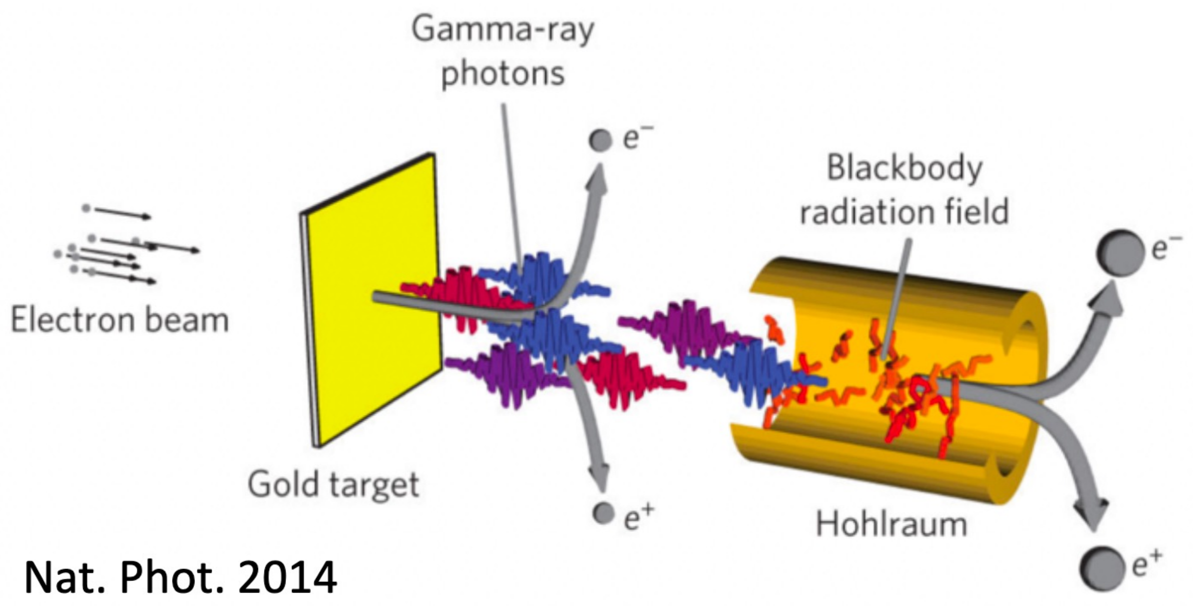
→No pair measurements
→No angular measurements

Excess of ~100 positrons detected in 20,000 shots



Burke et al., PRL79, 1626 (1997)
Hu & Müller, PRL107, 090402 (2010)

Photon Scattering with Ultra-Strong Lasers



Nat. Phot. 2014

Due to advances in laser technology and experimental designs, the achievability of the linear Breit-Wheeler process with ultra-strong lasers is nearing realization.

$>$ **$\mathbf{100\ MeV}$ $\boldsymbol{\gamma}$-rays** from high energy electron beam

+

$>$ **keV X-ray field** inside an NIF hohlraum

$=$ **$\mathbf{10,000}$ pairs / shot**

Setup capable of achieving energy threshold:

$$\sqrt{E_{\gamma 1} E_{\gamma 2}} > m_e c^2$$

Many Laser-based experimental concepts for achieving the Breit-Wheeler process
Cannot cover them all

Breit-Wheeler Process, why so *elusive?*

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

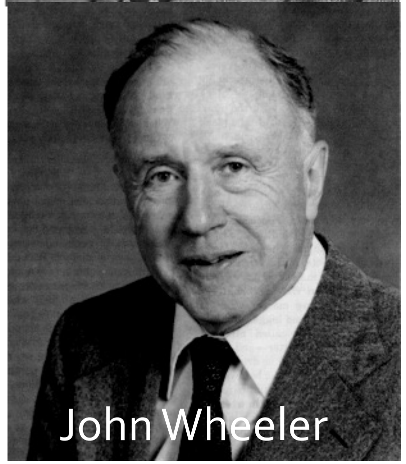
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME

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,



Breit-Wheeler Process, why so *elusive?*

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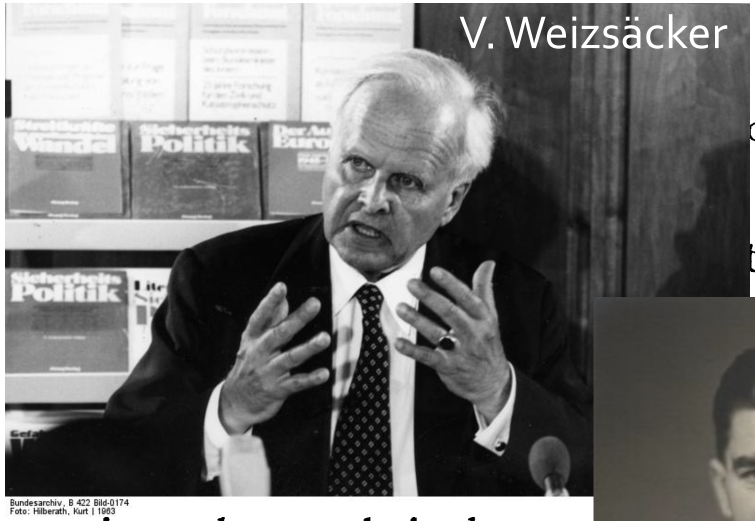

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try to observe the pair … atory
experiments with two be… -rays
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of σ and the insufficiently … sities
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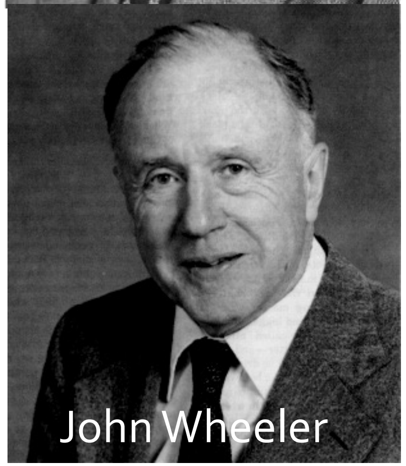
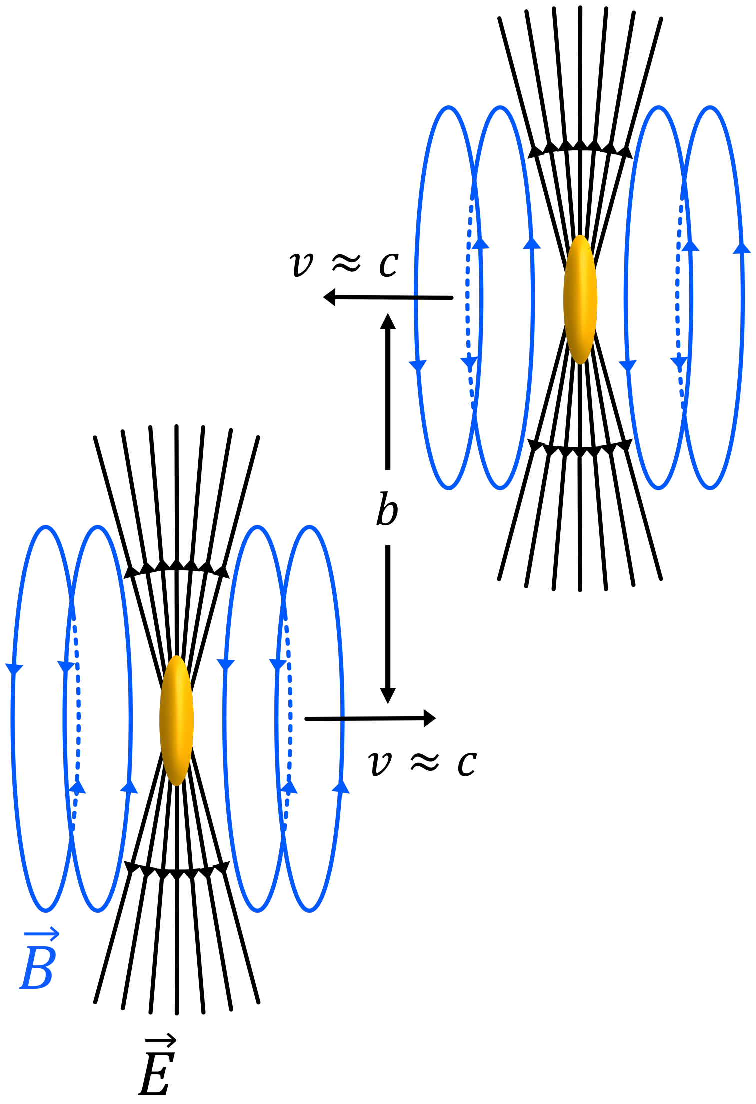
- Or maybe not impossible!

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)



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 **quasi-real photons**

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

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

$Z\alpha \approx 1$ → High photon density
Ultra-strong electric and magnetic fields:
→ Expected magnetic field strength $\vec{\mathbf{B}} \approx \mathbf{10^{14} - 10^{16}}$ **T**

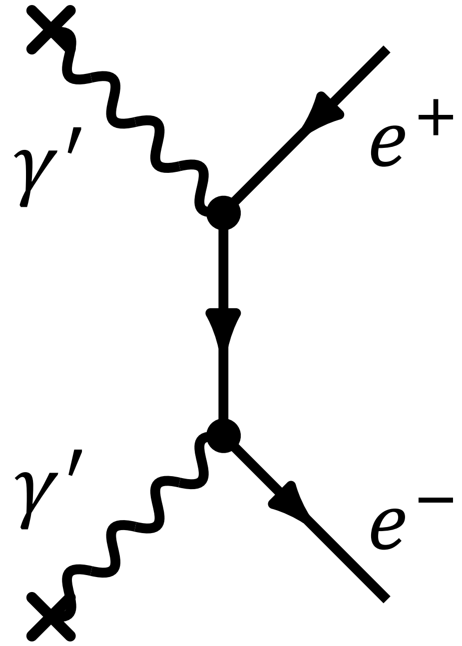
Skokov, V., et. al. *Int. J. Mod. Phys. A* 24 (2009): 5925–32

Test QED under extreme conditions[1]

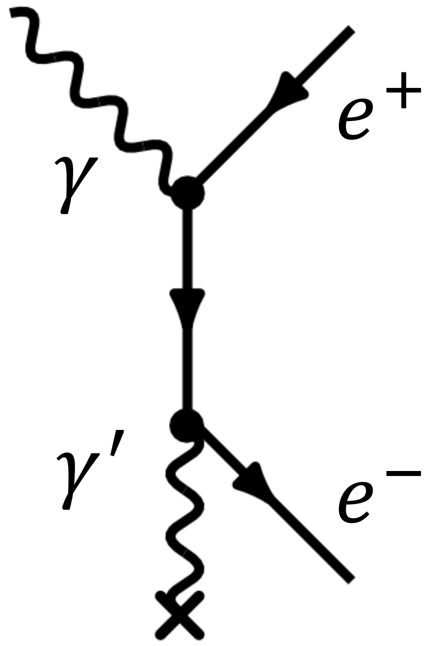
K. Hattori and K. Itakura, *Photon and Dilepton Spectra from Nonlinear QED Effects in Supercritical Magnetic Fields Induced by Heavy-Ion Collisions*, Nuclear and Particle Physics Proceedings **276–278**, 313 (2016).

The Central Challenge

Similar to the laser experiments, **central challenge is to precisely distinguish pair production mechanism**



Virtual photon scattering
1934, *Landau* & Lifshitz
Phys. Z.6, 244



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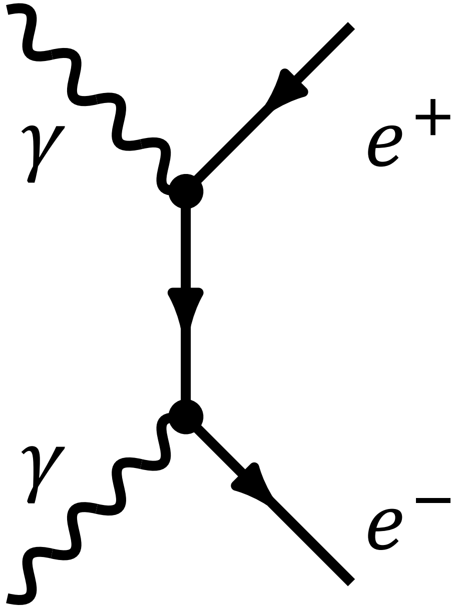

Breit-Wheeler pair production
Predicted 1934

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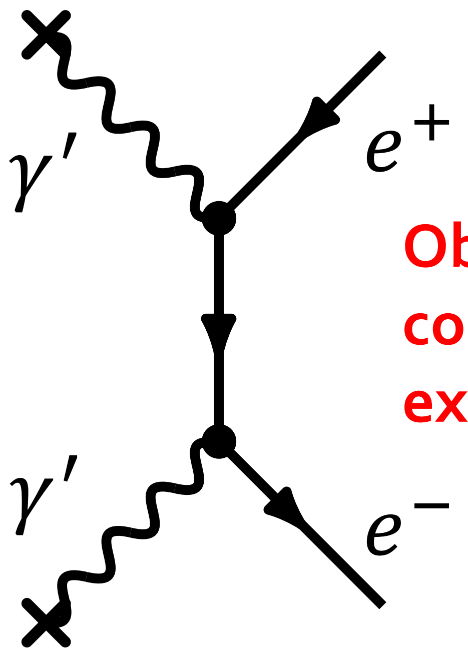

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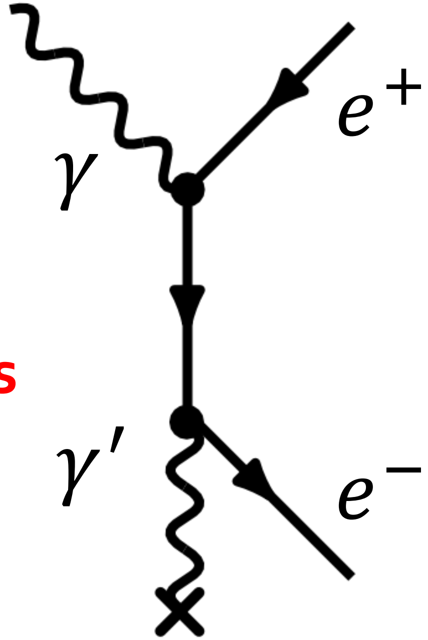
1934, *Landau* & Lifshitz
Phys. Z.6, 244

Observed in collider experiments



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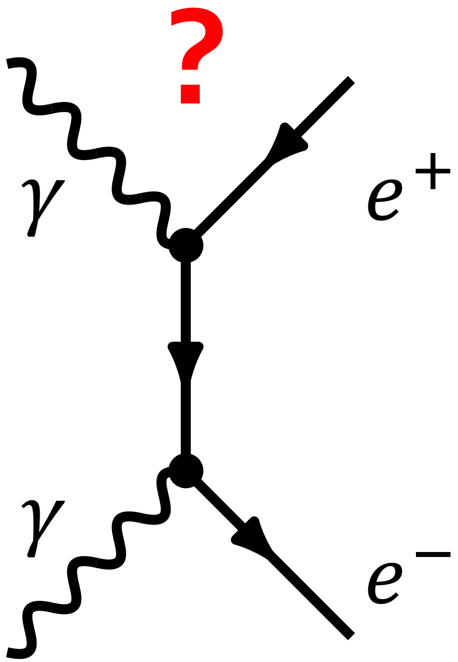
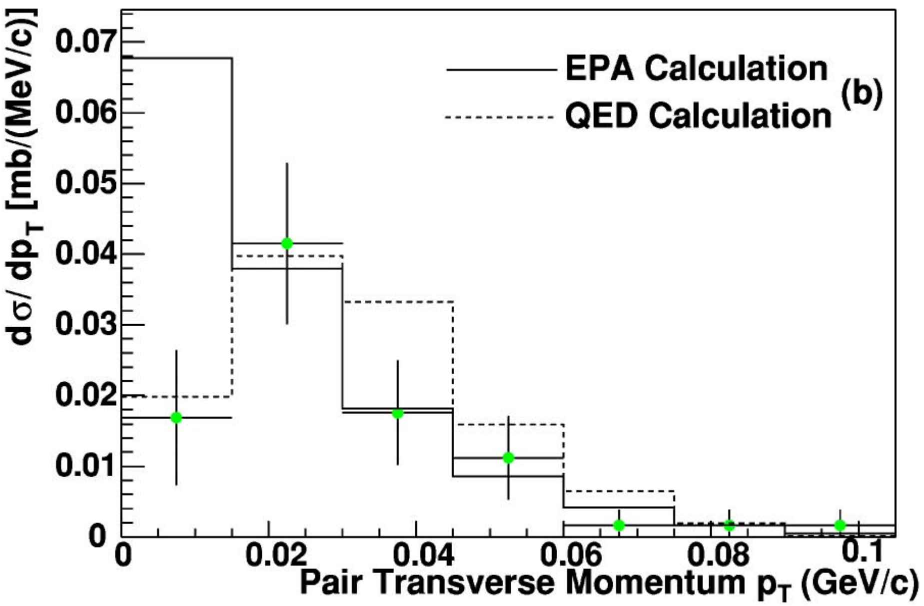


Breit-Wheeler pair production
Predicted 1934

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



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

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**

Higher order processes may reduce cross section by ~20%

→ Unable to definitively determine process

By 2005, review paper (with nearly 500 citations) states:

These photons are almost real, with virtuality $-q^2 < (\hbar/R_A)^2$. Except for the production of e^+e^- pairs, the photons can usually be treated as real photons.

Annu. Rev. Nucl. Part. Sci. 2005.55:271-310

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

Helicity 0 : Forbidden for real photon

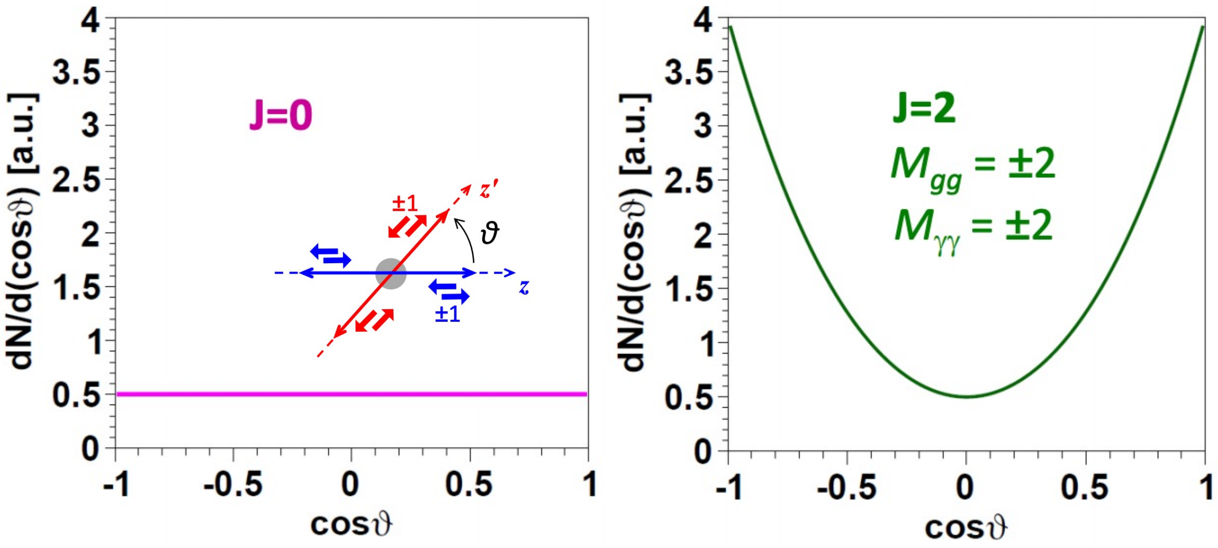
Real photon: Allowed J^P states: $2^{\pm}, 0^{\pm}$

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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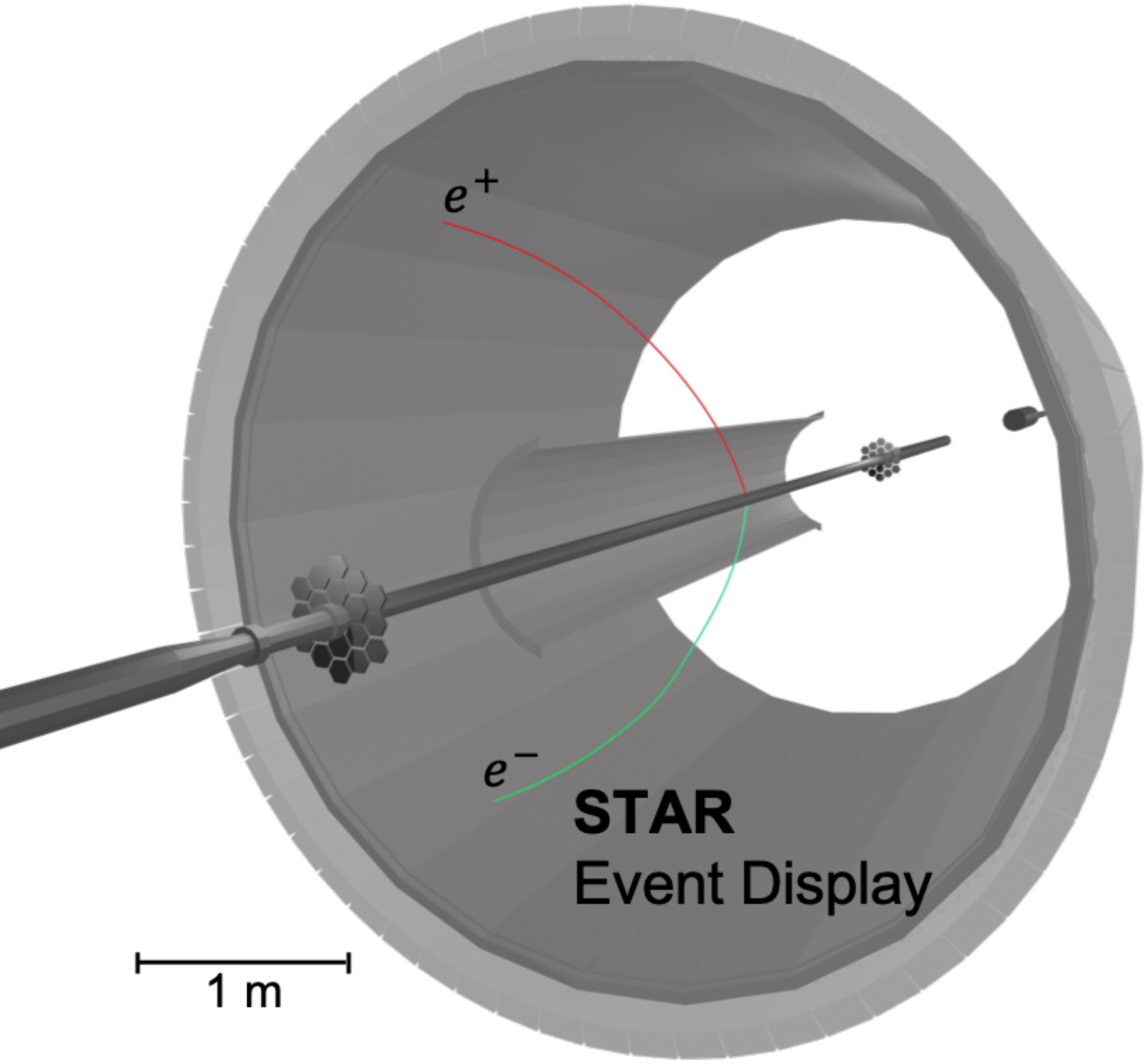
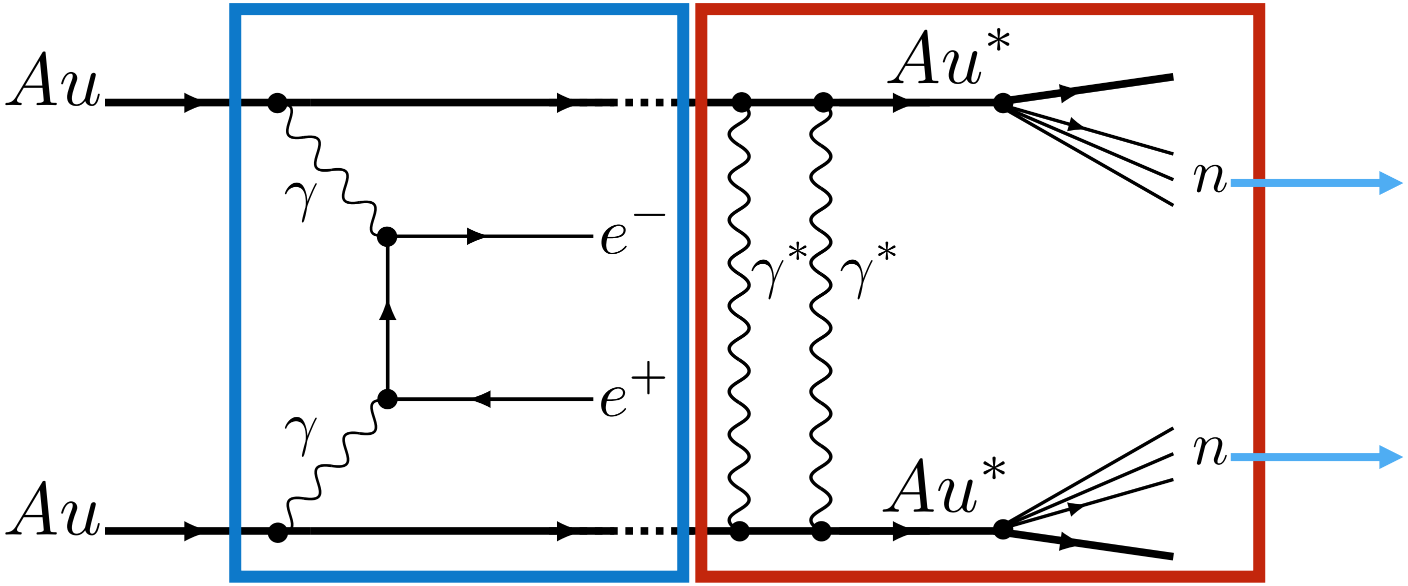
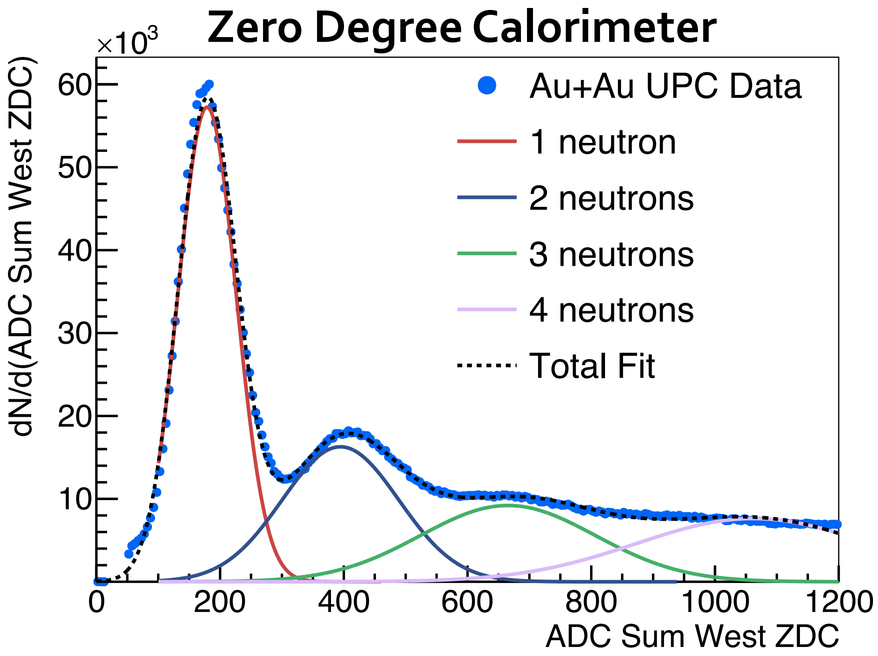
Signatures of the Breit-Wheeler Process



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





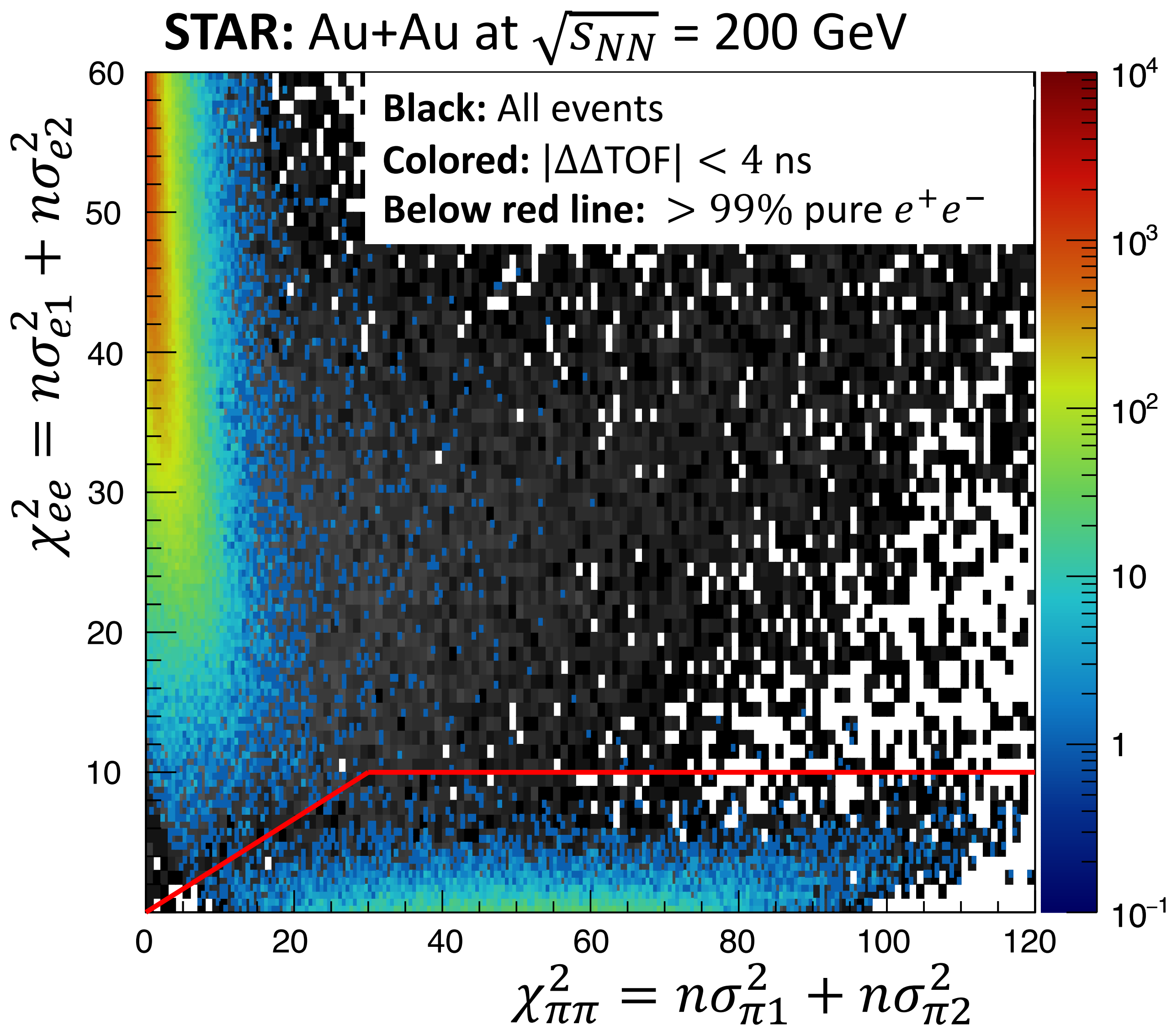
Breit-Wheeler $\gamma\gamma \to e^+e^-$ pair production process

Mutual Coulomb excitation and nuclear dissociation

- **Provides efficient trigger condition**

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

High Purity electron(positron) Identification

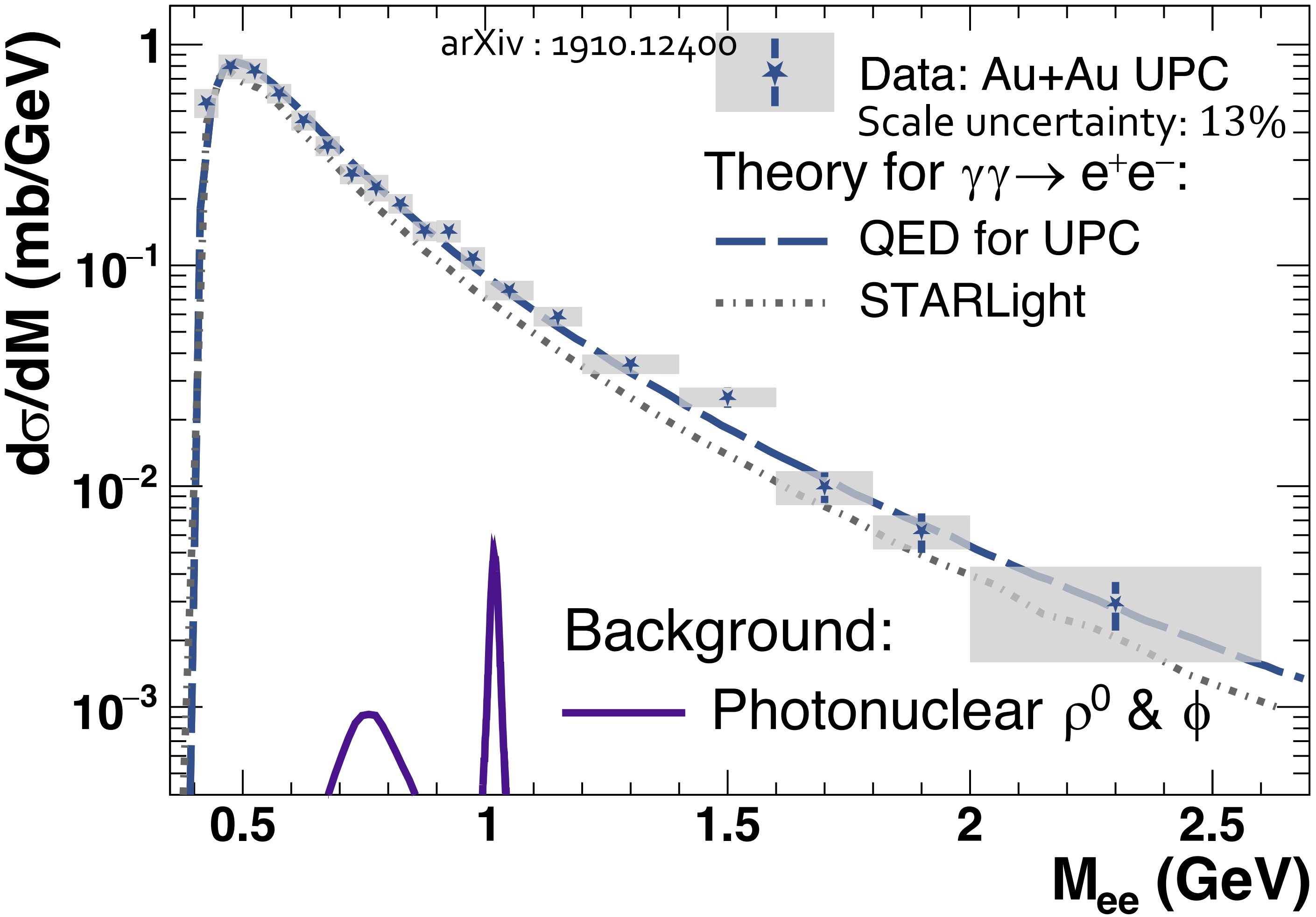


Combination of two STAR detectors allows e^+e^- pairs to be identified with $> 99\%$ purity

Crucial, since photo-nuclear production of $\pi^+\pi^-$ pairs are dominate contribution to UPC events

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

STAR: $Au + Au$ at $\sqrt{s_{NN}} = 200$ GeV



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)

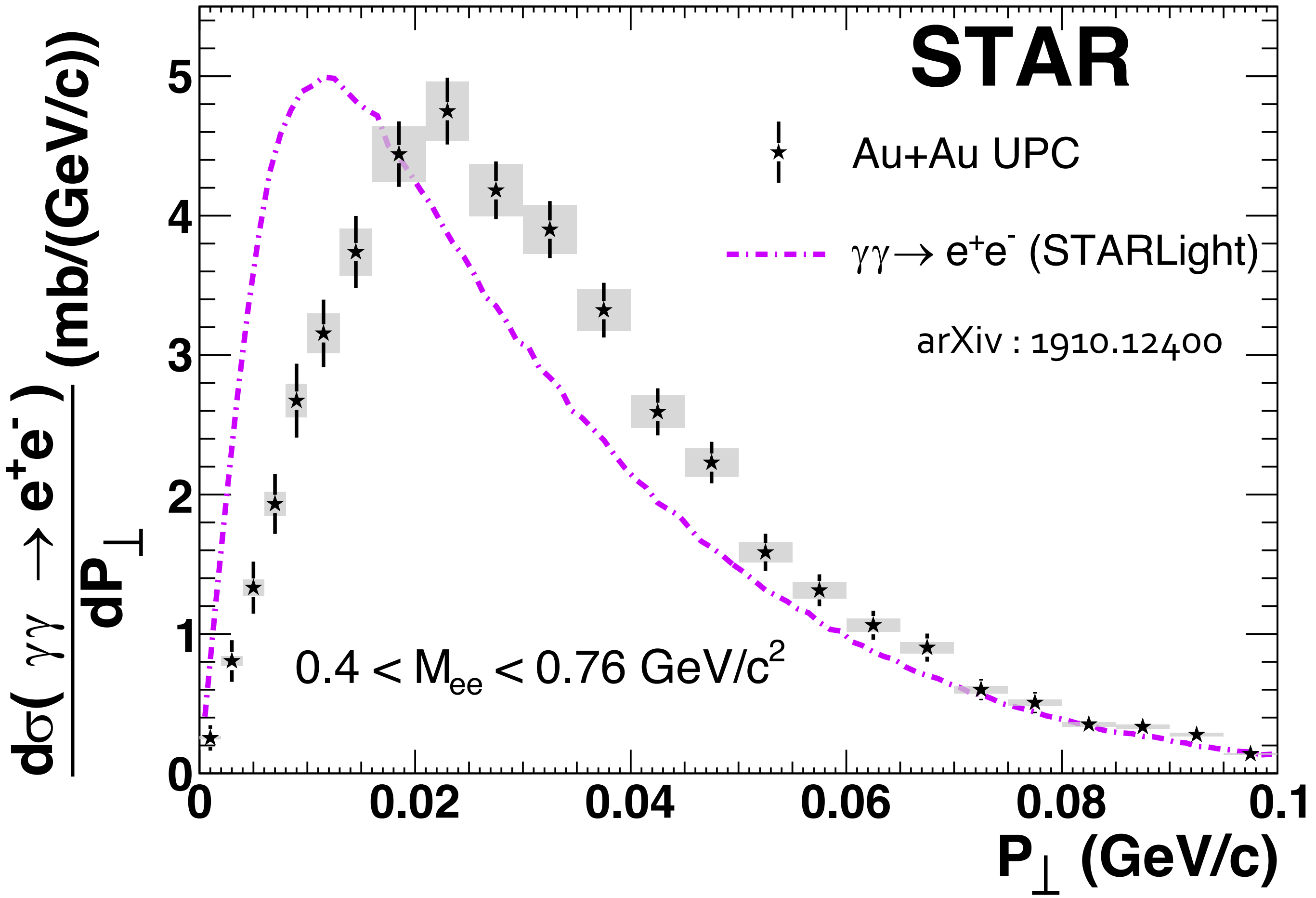
$\sigma(\gamma\gamma \rightarrow e^+e^-)$ in STAR Acceptance:

Data : 0.261$\pm$0.004 (stat.) $\pm$ 0.013 (sys.) $\pm$ 0.034 (scale) mb

STARLight	gEPA	QED
0.220 mb	0.260 mb	0.260 mb

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

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

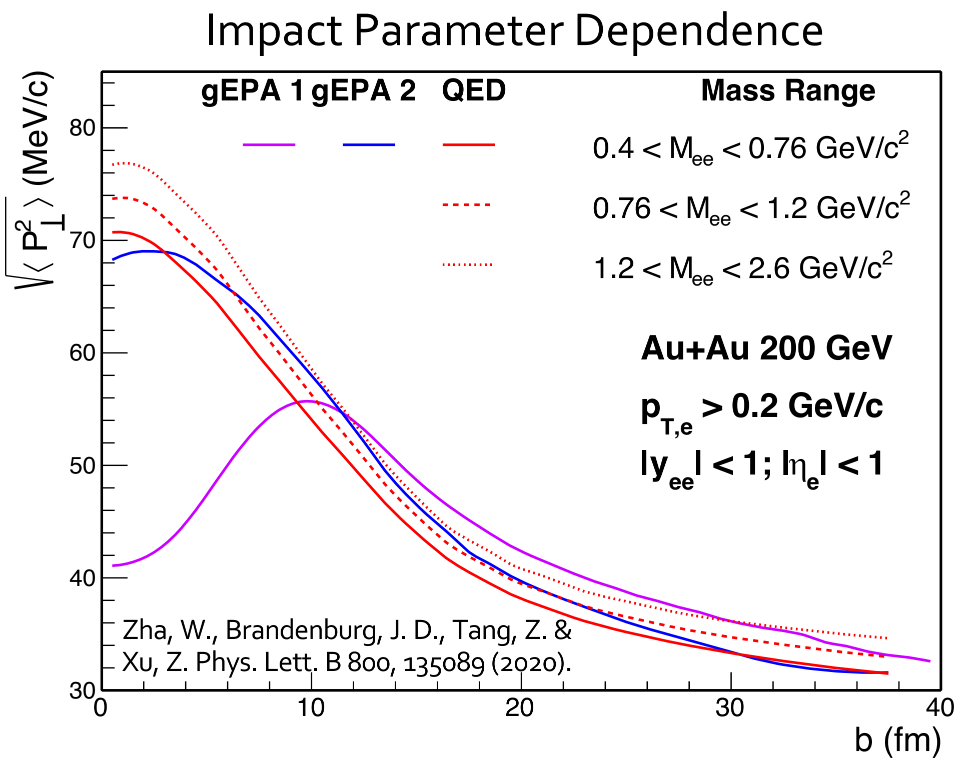


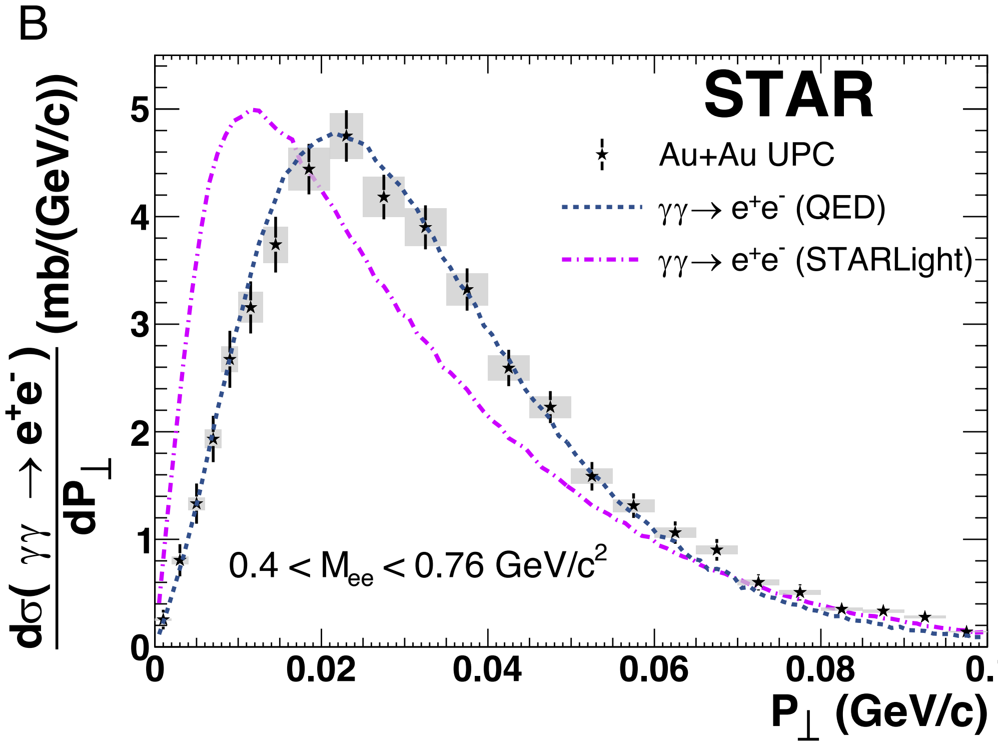
STARLight is scaled to match measured $\sigma(\gamma\gamma \to e^+e^-)$

STARLight: S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258

- First high precision measurement of differential cross section – **stringent test of theory predictions**
- STARLight predicts significantly lower $\langle P_\perp \rangle$ than seen in data
- Is the increased $P_\perp$ observed due to significant photon virtuality?
- Let's look at how the calculation is done in the lowest order QED case

Photon virtuality and differential cross section





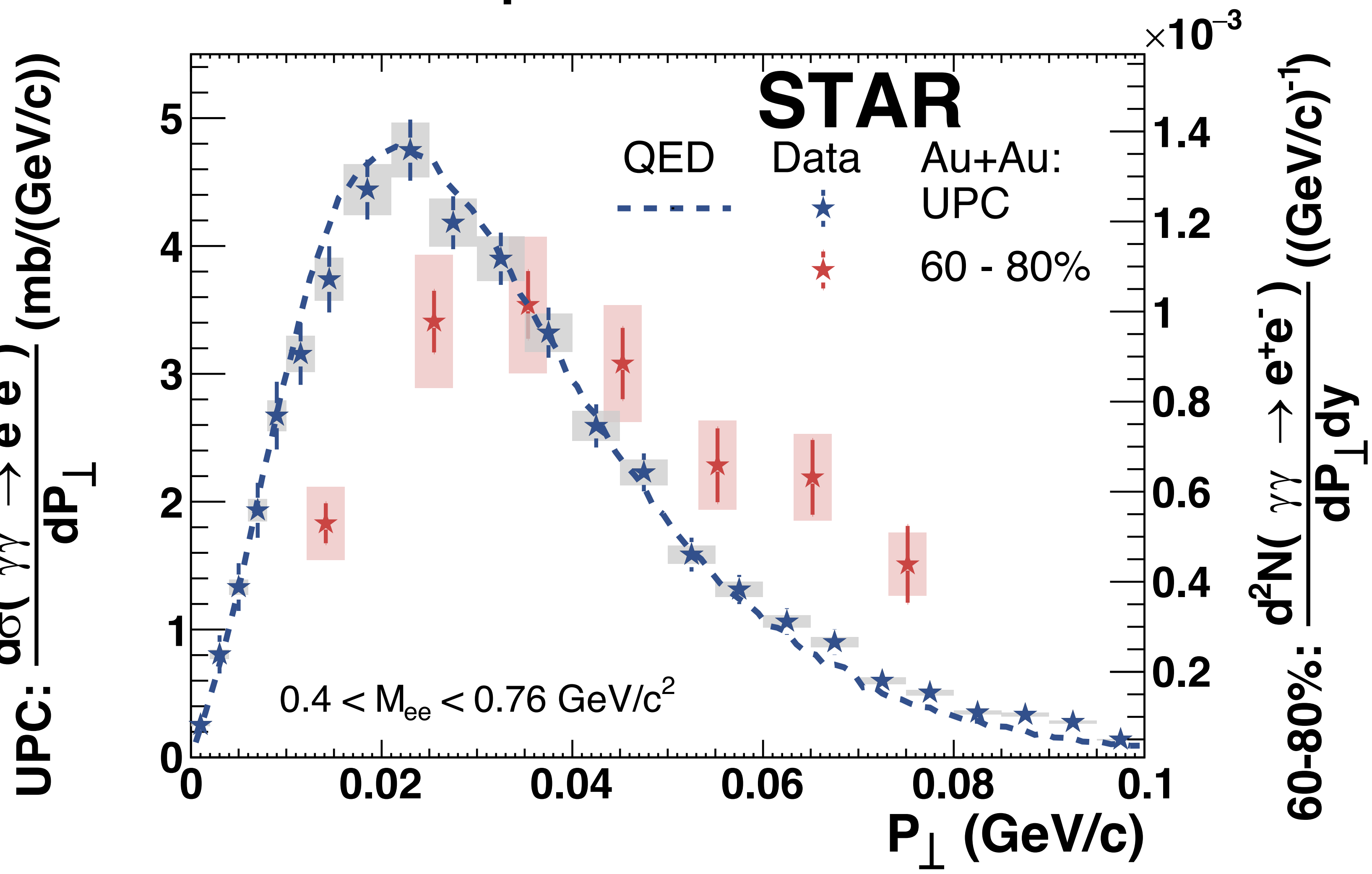
Note: gEPA1 vs. gEPA2 : gEPA2 includes phase term to approximate full QED result

- 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 at a different $\langle b \rangle$ (mean impact parameter)**

UPC vs. Peripheral



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

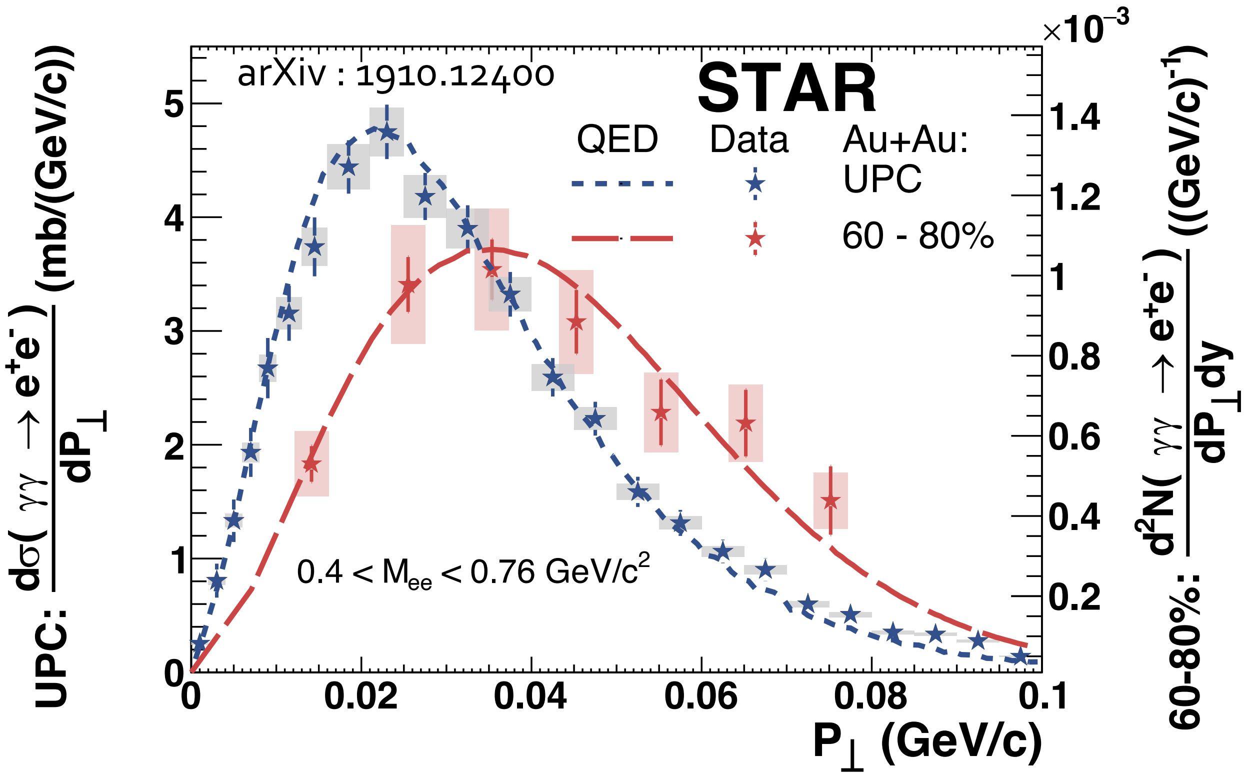
In peripheral collisions we can statistically isolate the spectra from the $\gamma\gamma \rightarrow e^+e^-$ process.

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

Spectrum from peripheral collisions is significantly broader than spectrum from UPC, possible medium effect?

$\gamma\gamma \to e^+e^-$: 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



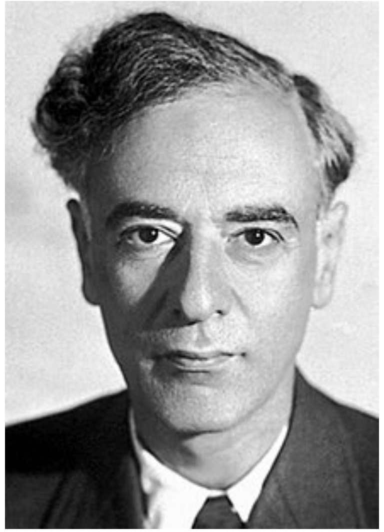
Characterize difference in spectra via $\sqrt{\langle P_\perp^2 \rangle}$

$\sqrt{\langle P_\perp^2 \rangle}$ (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 spectrum in $60 - 80\%$ collisions found for QED shape plus 14 ± 4 (stat.)± 4 (syst.) MeV/c broadening

- Additional broadening has been proposed as a precision probe of medium interactions: due to trapped magnetic field or Coulomb scattering in QGP [1-3]
- Future measurements may provide needed precision
- Impact parameter dependence recently confirmed by CMS arxiv:2011.05239

Unique signature of the Breit-Wheeler process



Lev Landau

Evgenni Lifshitz

What has been shown so far → already enough to demonstrate that colliding photons **are real** with respect to $e^{+}e^{-}$ pair production <u>for the first time</u>

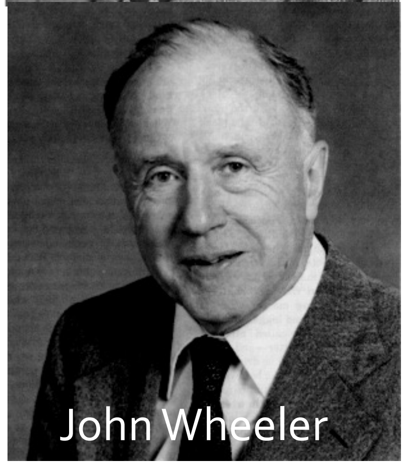
- Both Breit + Wheeler and Landau + Lifshitz studied the theory of photon + photon collisions in the early 30s
- Both BW and LL predicted (their) process in high-energy heavy-ion collisions

<u>Real photons</u> are transversely polarized

Breit & Wheeler predict photon polarization dependence : $d\sigma_{\perp} \neq d\sigma_{\parallel}$

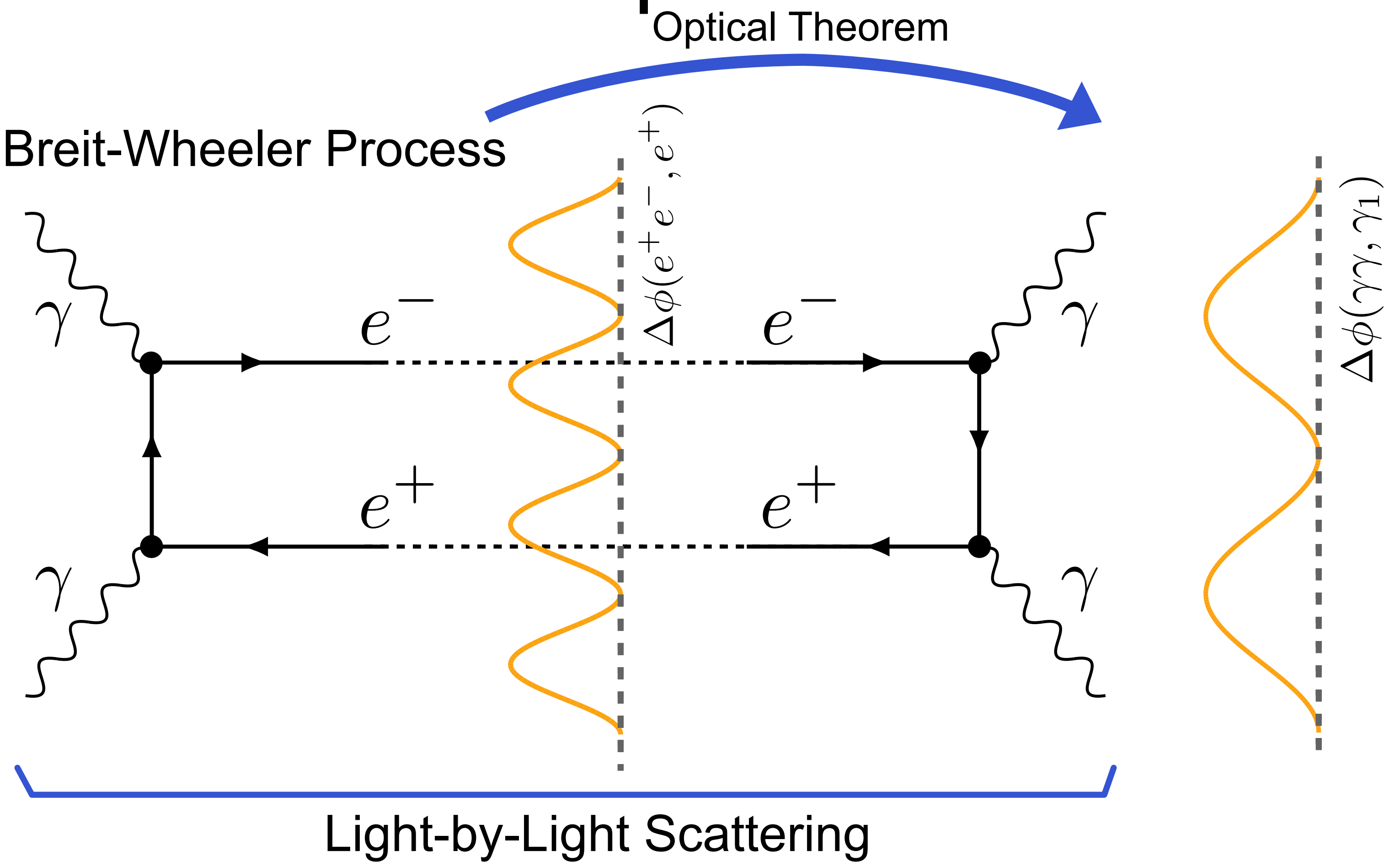
However, Experimentally accessing polarization information is extremely challenging

Gregory Breit



John Wheeler

Experimental Anisotropic Polarization Effect



Recently realized, photon polarization leads to a $\cos(4\Delta\phi)$ **modulation** in polarized $\gamma\gamma \to e^+e^-$ [1]

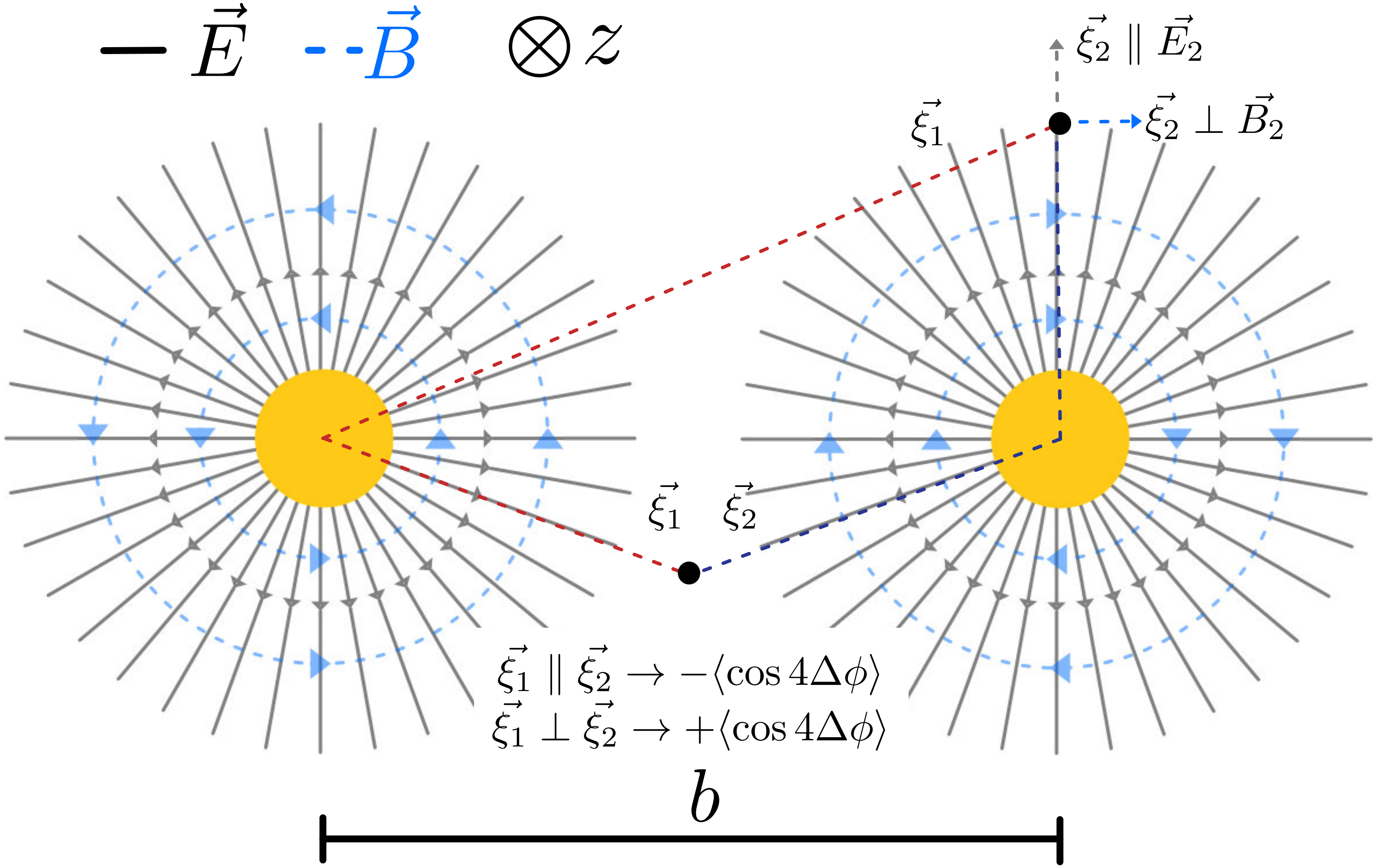
The corresponding vacuum LbyL scattering[2] displays a $\cos(2\Delta\phi)$ **modulation**

[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).

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

First $\gamma\gamma$ polarization sensitive measurement



- Polarization vector : aligned radially with the "emitting" source
- Well defined in the photon position eigenstates
- Well defined in terms of electric and magnetic field directions

Anisotropic Polarization Effect

Probe photon with polarization vector $\overrightarrow{\xi_1}$ takes two different transverse paths depending on $\Delta\phi$ – the angle between $\overrightarrow{\xi_1}$ and $\overrightarrow{\xi_2}$ $(\overrightarrow{B_2})$

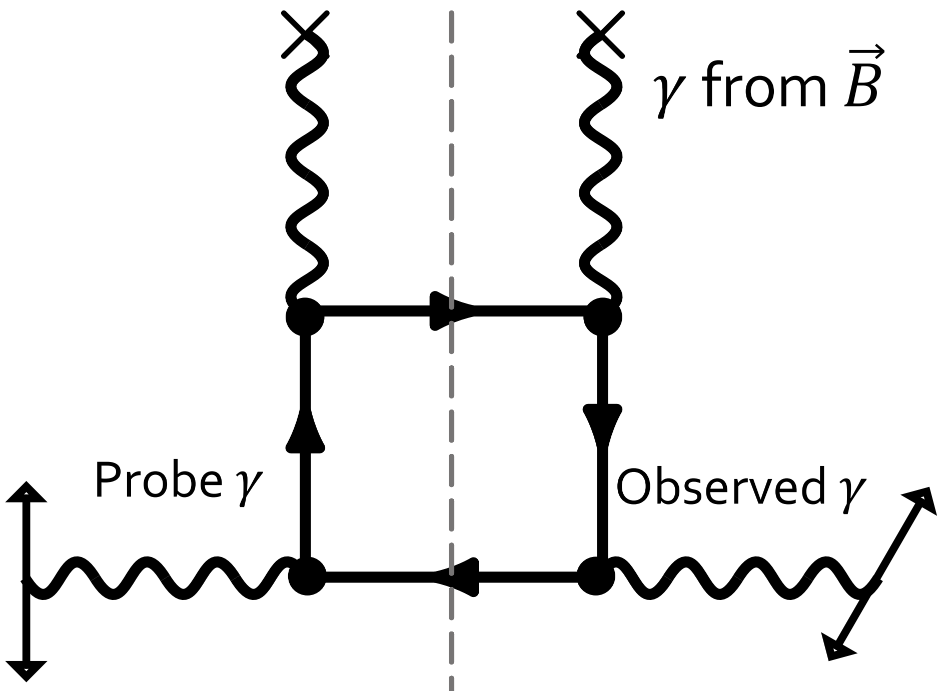
Two photon system: $0^{\pm}, 2^{\pm}$

Upon decay into spin $1/2$ fermions, spin is encoded into orbital angular momentum

1. $\overrightarrow{\xi_1} \perp \overrightarrow{B_2}\ (\overrightarrow{\xi_1} \parallel \overrightarrow{\xi_2}) \rightarrow -\langle\cos 4\Delta\phi\rangle$
2. $\overrightarrow{\xi_1} \parallel \overrightarrow{B_2}\ (\overrightarrow{\xi_1} \perp \overrightarrow{\xi_2}) \rightarrow +\langle\cos 4\Delta\phi\rangle$

Recently realized that measurement of e^+e^- angular distributions are sensitive to polarization through **quantum space-momentum correlations**

Feynman Diagram



$Real(n)$ = 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

Linearly polarized photon collisions

[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).

Recently realized, $\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0$ leads to **$\cos(n\Delta\phi)$ modulations** in polarized $\gamma\gamma \rightarrow e^+e^-$ [1]

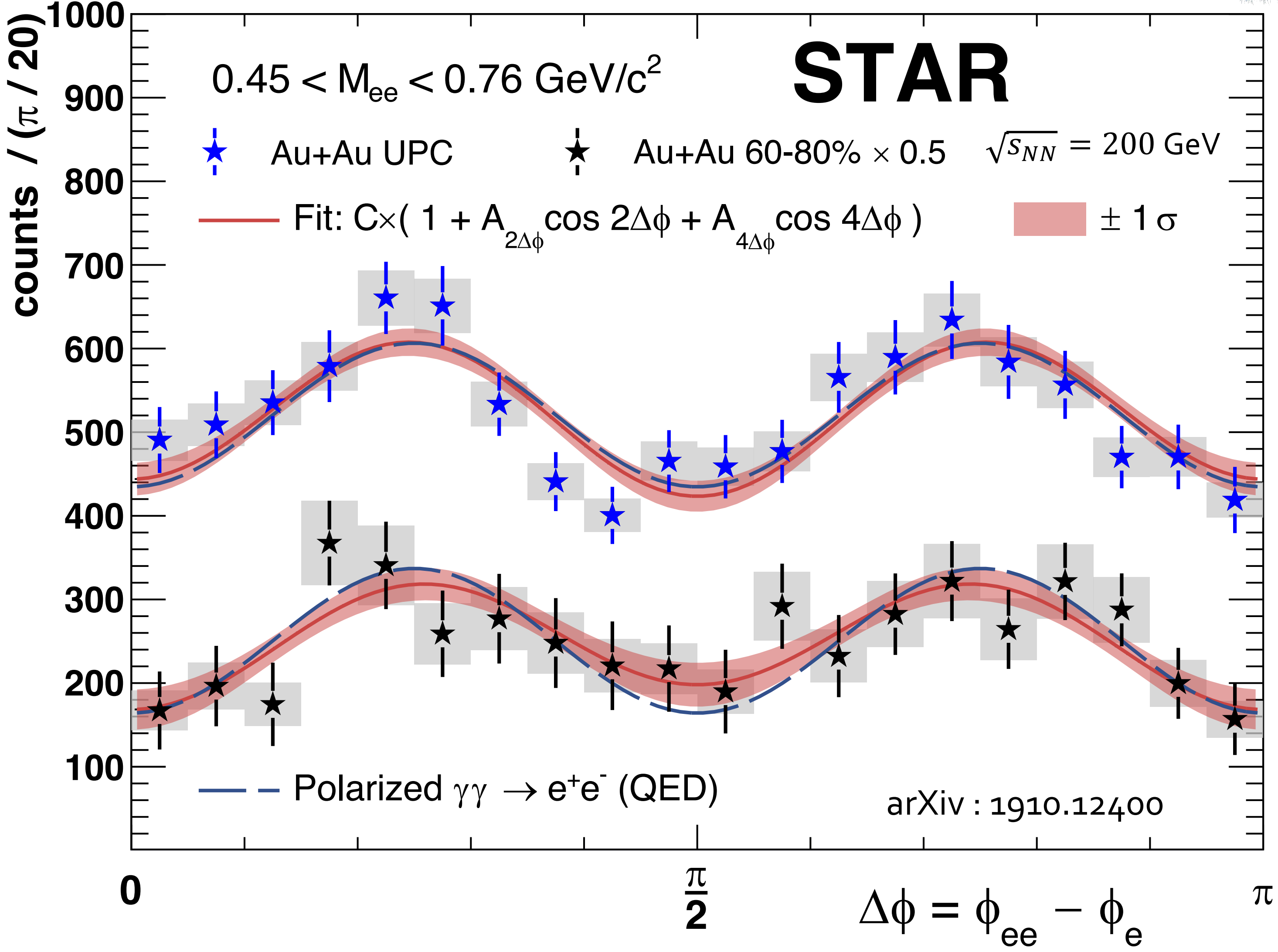
$$\Delta\phi = \Delta\phi[(e^+ + e^-),(e^+ - e^-)] \approx \Delta\phi[(e^+ + e^-), e^+]$$

Ultra-Peripheral

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



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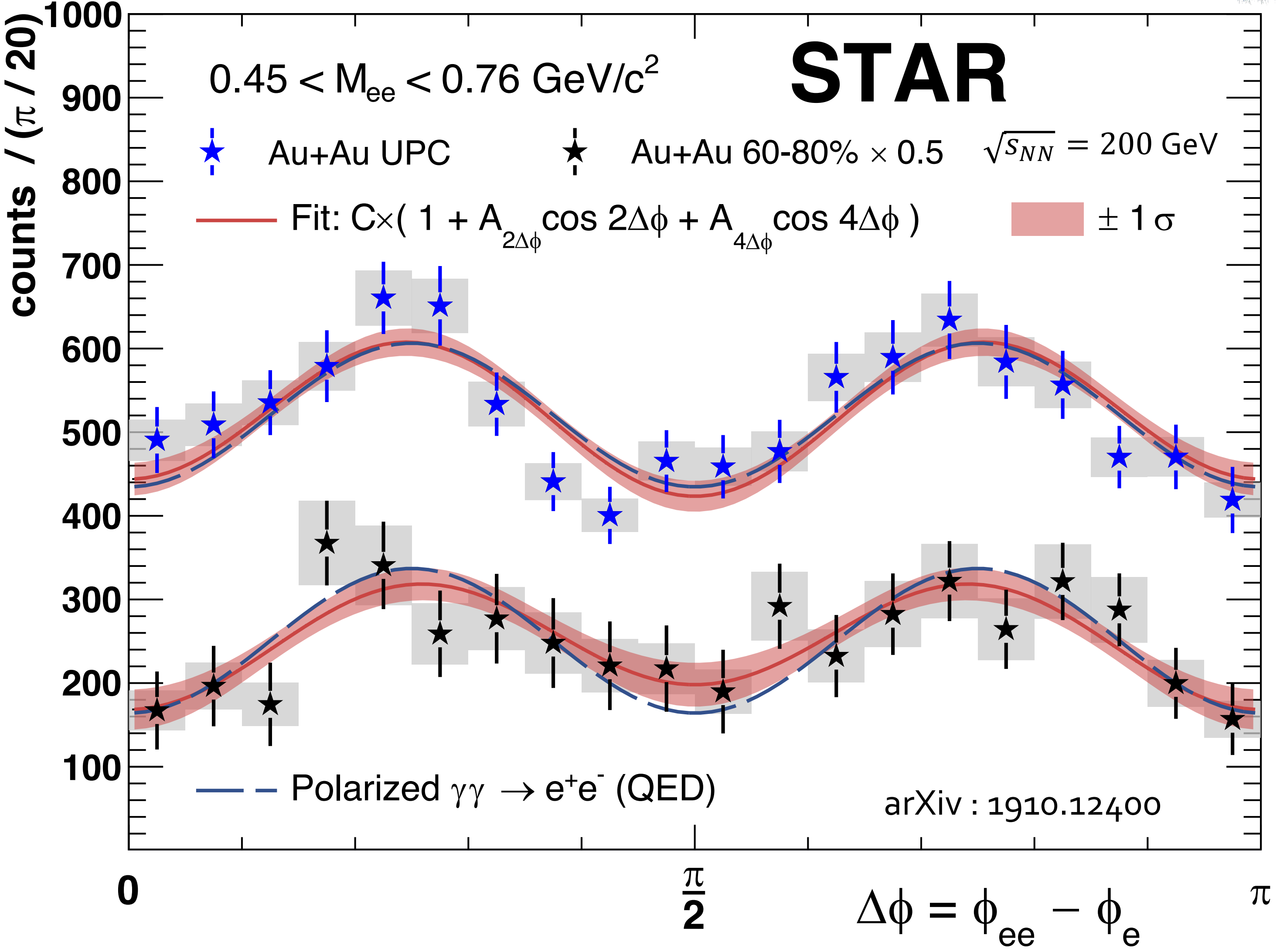
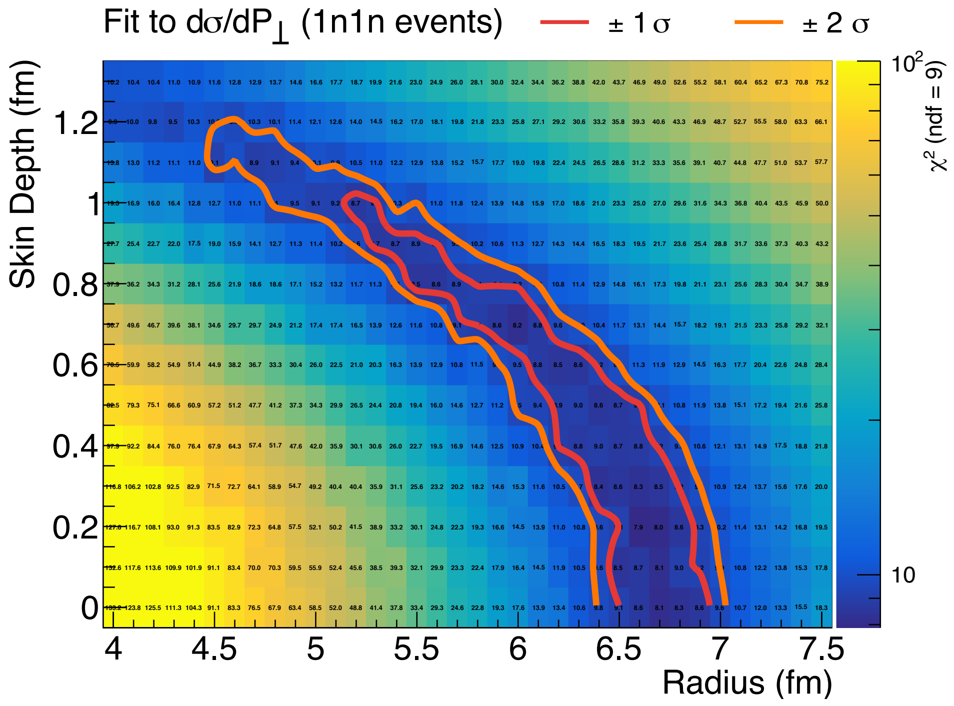


→ **<u>First Earth-based observation</u> (6.7σ level) of anisotropic photon polarization effect**

First Experimental Measurement of Magnetic Field in HICs

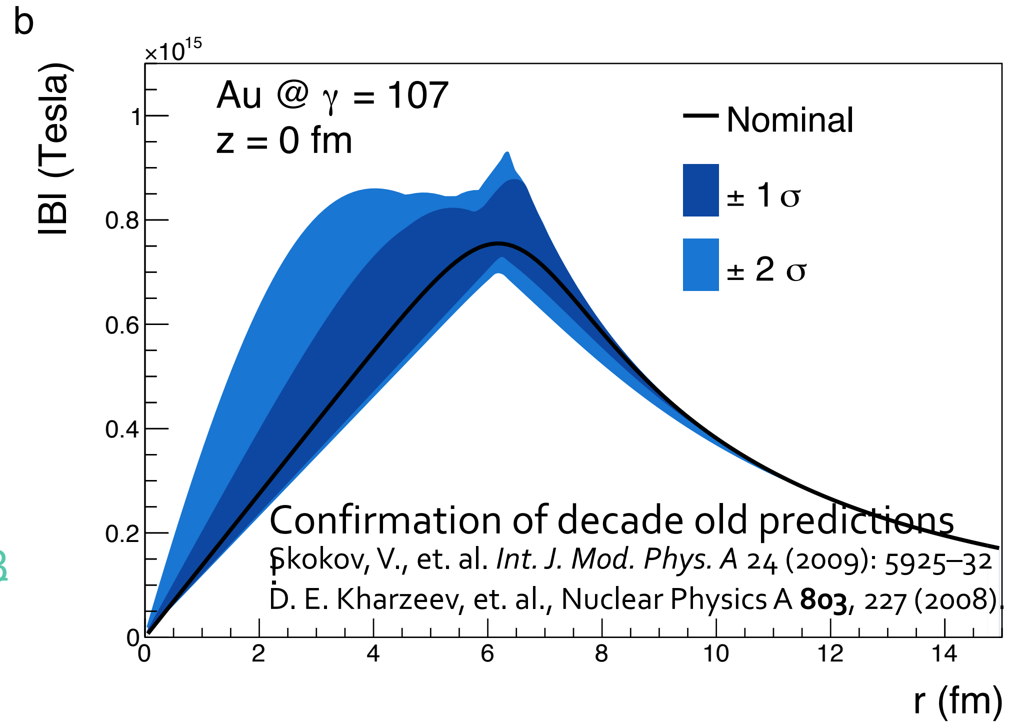
Sensitive to magnetic field strength and spatial distribution:

- Impact parameter dependence of $P_\perp$
- Amplitude of $\cos 4\Delta\phi$ modulation
  - (photon polarization provides connection to magnetic field)



Data & QED comparison

See: [JDB, W. Zha, Z. Xu, arxiv:2103.16623]() for details



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

Fundamental Interactions : light & matter

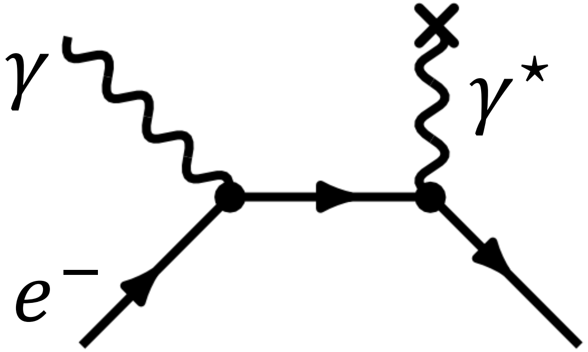
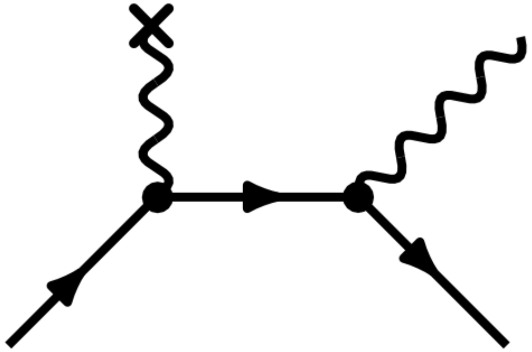
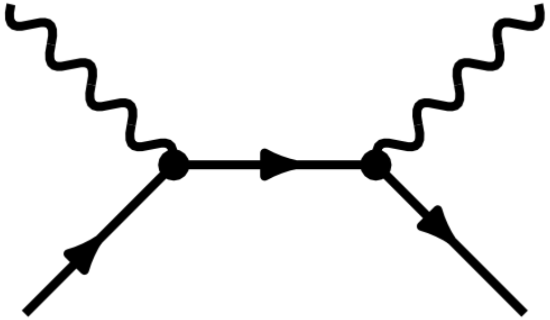


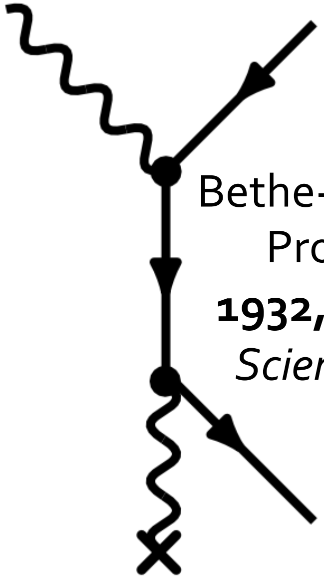
Photo Electric Effect
1887 *Hertz, Ann Phys (Leipzig) 31, 983*



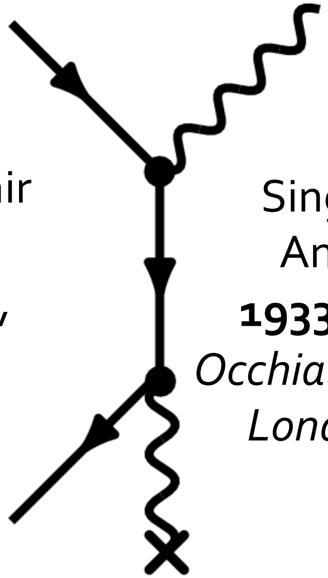
Bremsstrahlung
1895 *Röntgen, Ann Phys (Leipzig) 300, 1*



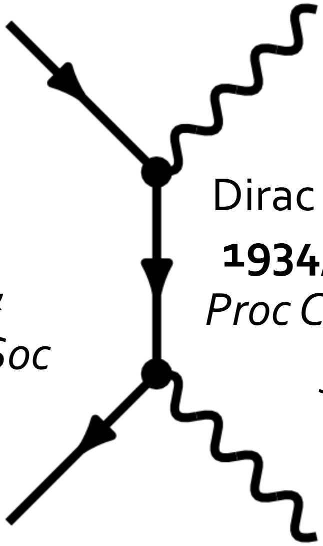
Compton Scattering
1906 *Thomson, Conduction of Electricity through Gases*



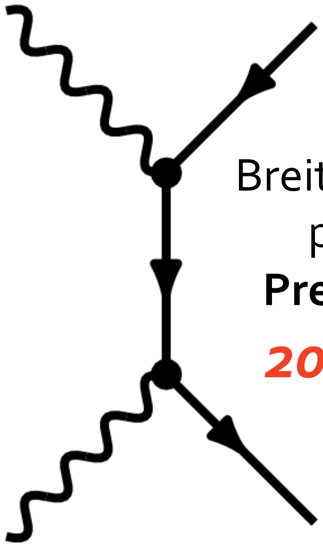
Bethe-Heitler Pair Production
1932, *Anderson, Science 76,238*



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
2021, STAR

Summary

1. Observation of the Breit-Wheeler process in HICs
2. **First Earth-based observation of anisotropic photon polarization effect :**

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

3. Novel experimental measurements sensitive to EM field strength and distribution in space.

   → First experimental measurement that HIC produce the strongest magnetic fields in the Universe $\approx 10^{15}$ Tesla

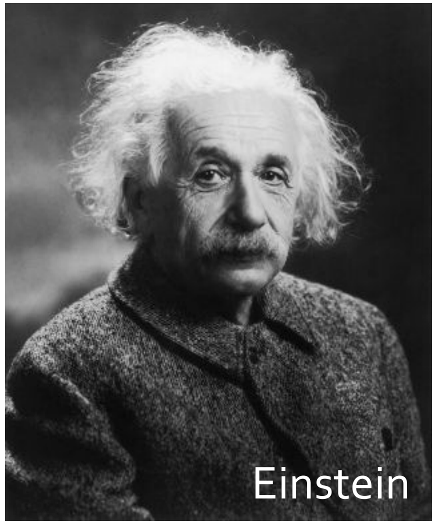
More work needed to constrain magnetic field topology, to test for possible medium effects, explore QED in the strong field regime – Exciting opportunities lie ahead

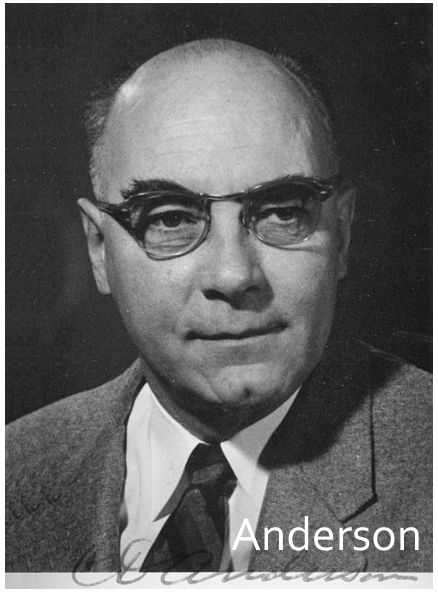
Thank You

Quantum Electrodynamics

Three important discoveries that alter the classical picture:

- 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





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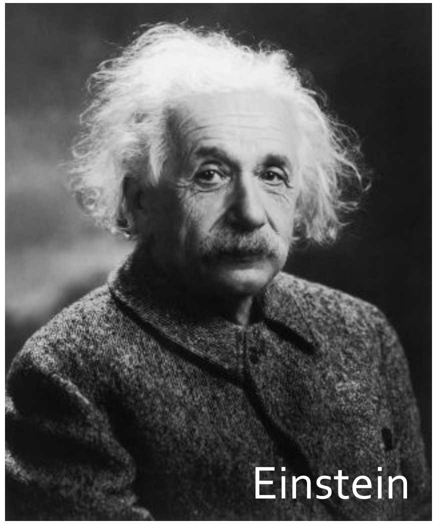
→ Vacuum fluctuations

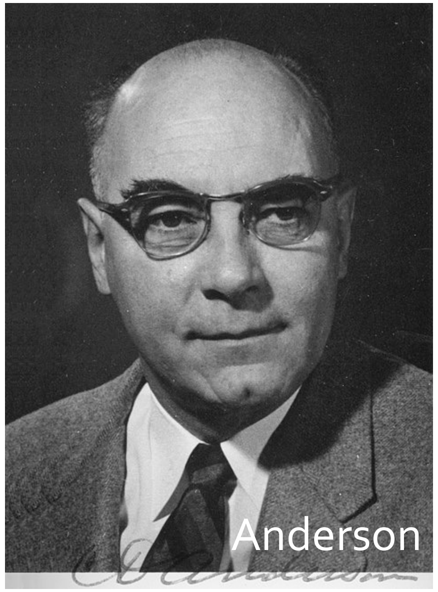
- 1936: Euler & Heisenberg present modified Lagrangian

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

- Non-linear → Super-position principle broken!
  - → **light-by-light scattering possible**

NB: in 1951 Shwinger derived the Lagrangian within QED



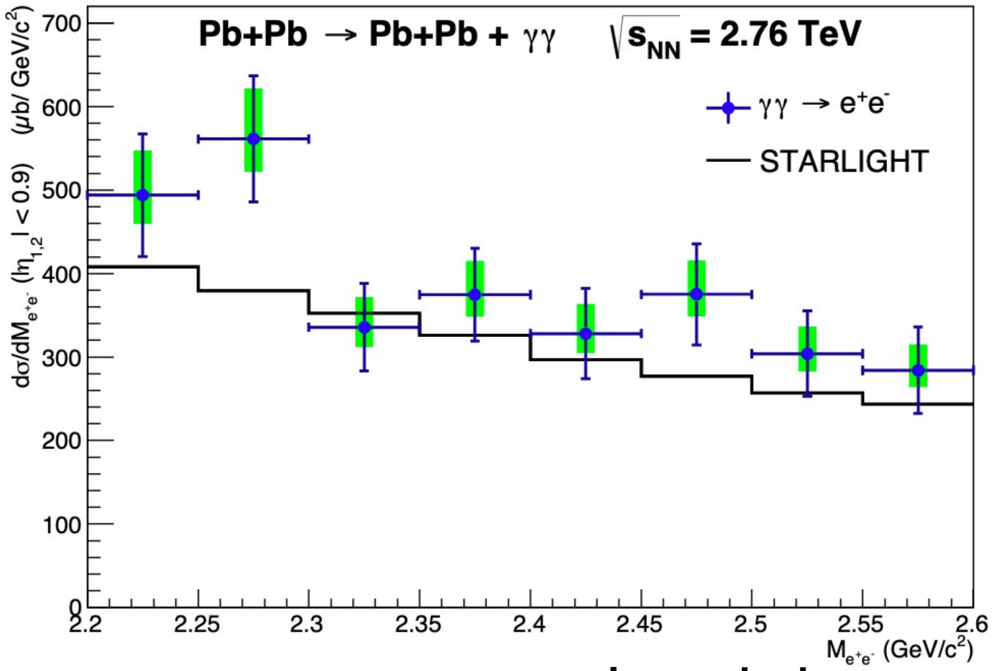


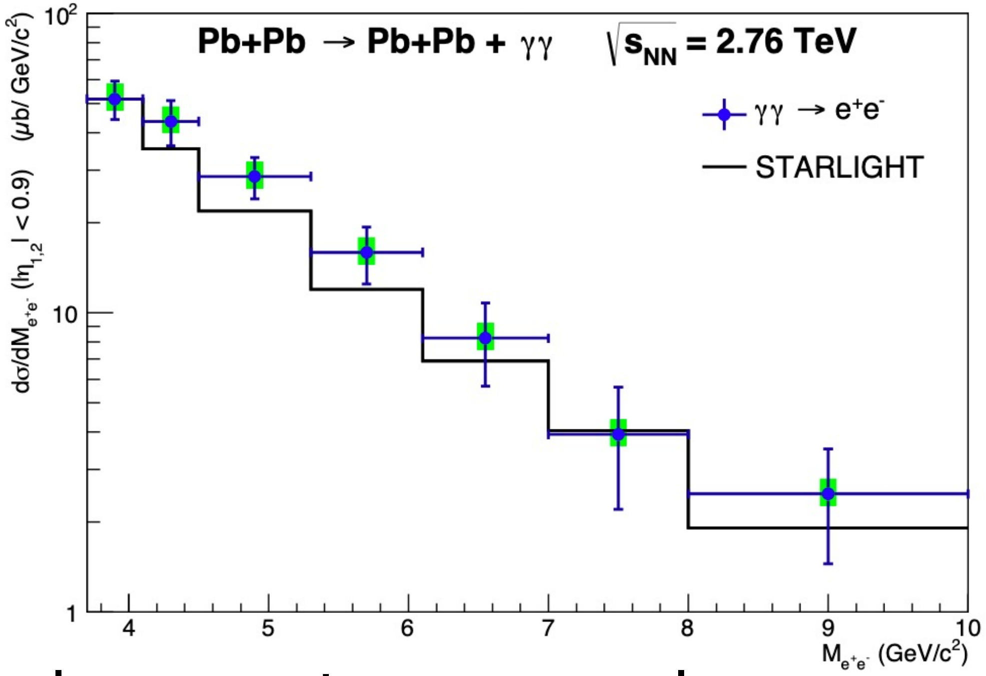
Measurements at the LHC

The ALICE Collaboration., Abbas, E., Abelev, B. *et al. Eur. Phys. J. C* **73,** 2617 (2013).
https://doi.org/10.1140/epjc/s10052-013-2617-1

- Measurements of total production cross section at LHC

  → Note: Must reject vector-meson (J/ψ)mass region





Large experimental and theoretical uncertainty on total cross section

<u>Cross section measurement alone cannot distinguish process</u>

Some Jargon

Various models and theoretical predictions

- **EPA** = Equivalent photon approximation
- **STARLight** = Specific EPA implementation used for comparison to heavy-ion experiment for ~20 years
  - Includes some strong (but common) assumptions on photon wave function and kinematics – specifically on spatial dependencies
  - Specifically, integrate over all impact parameters
- **Generalized EPA (gEPA)** = EPA implementation with explicit spatial (impact parameter) dependence
  - Equivalent to STARLight EPA when integrated over all space
- **QED** = lowest order calculation of Breit-Wheeler process

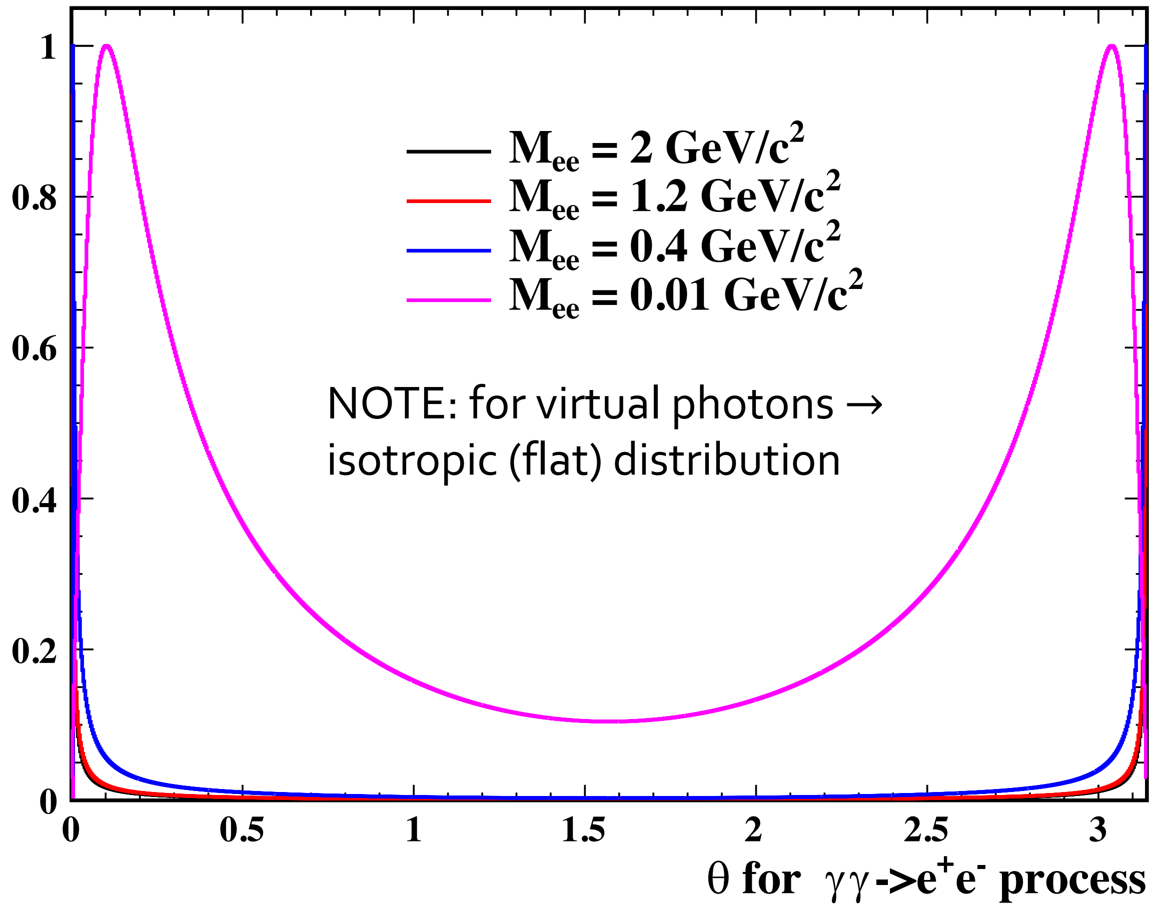
- All predict approximately the same total cross section (few percent)
- Drastically different prediction for pair p_T and correlation between e^+, e^-

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

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

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

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



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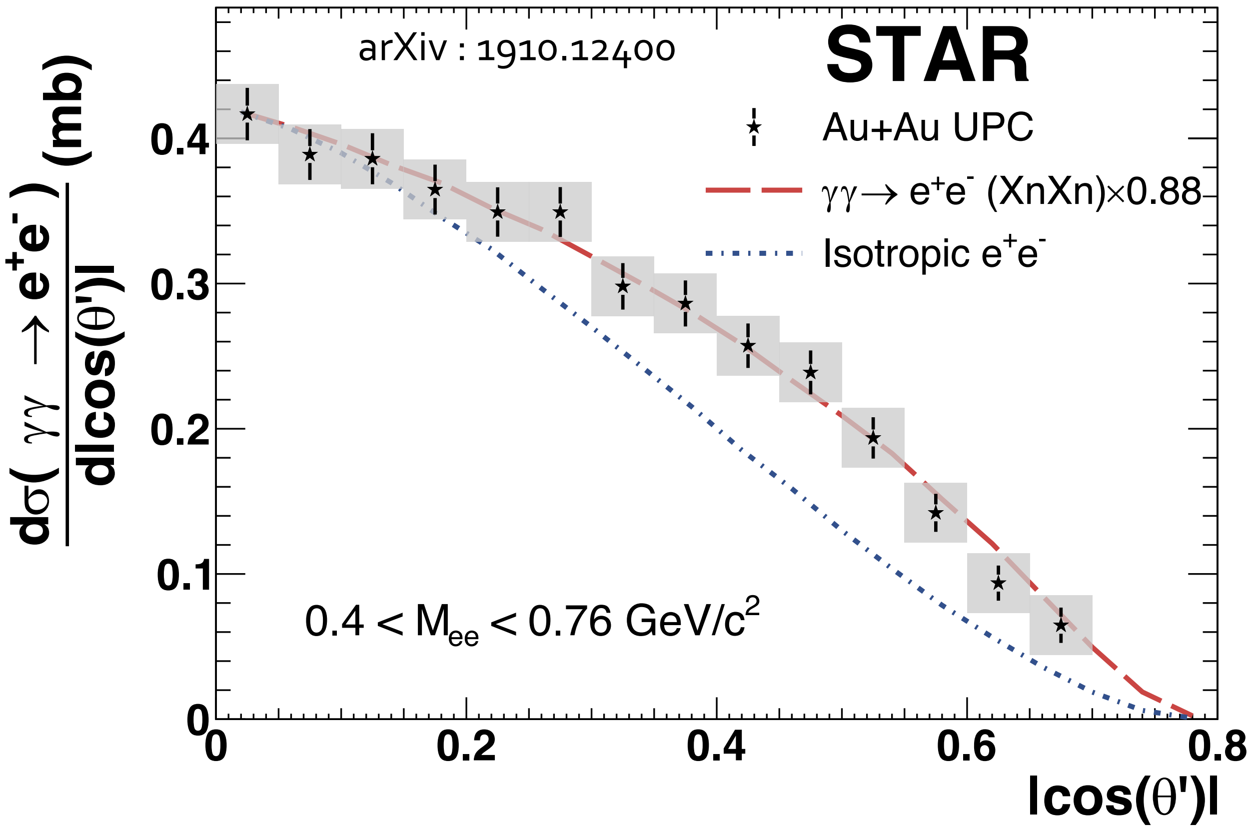
- Highly virtual photon interactions should have an isotropic distribution
- Measure θ', the angle between the e^+ and the beam axis in the pair rest frame.

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

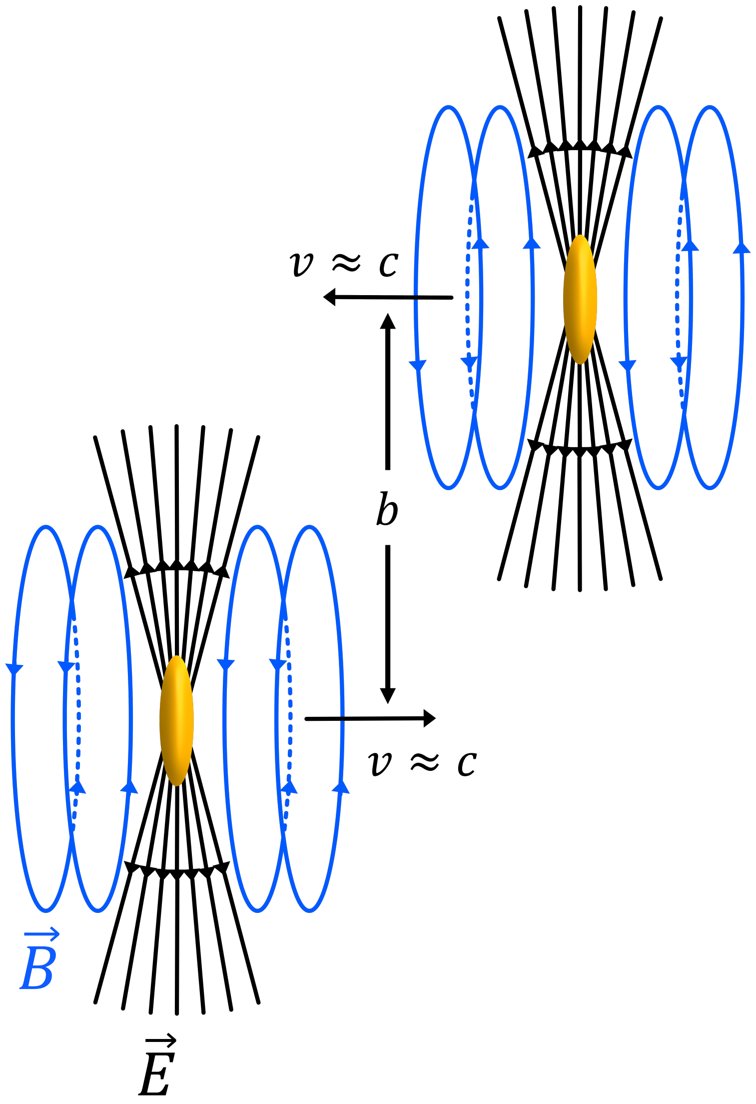
⇒**Measurably distinct from isotropic distribution**



[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

STARLight EPA calculation

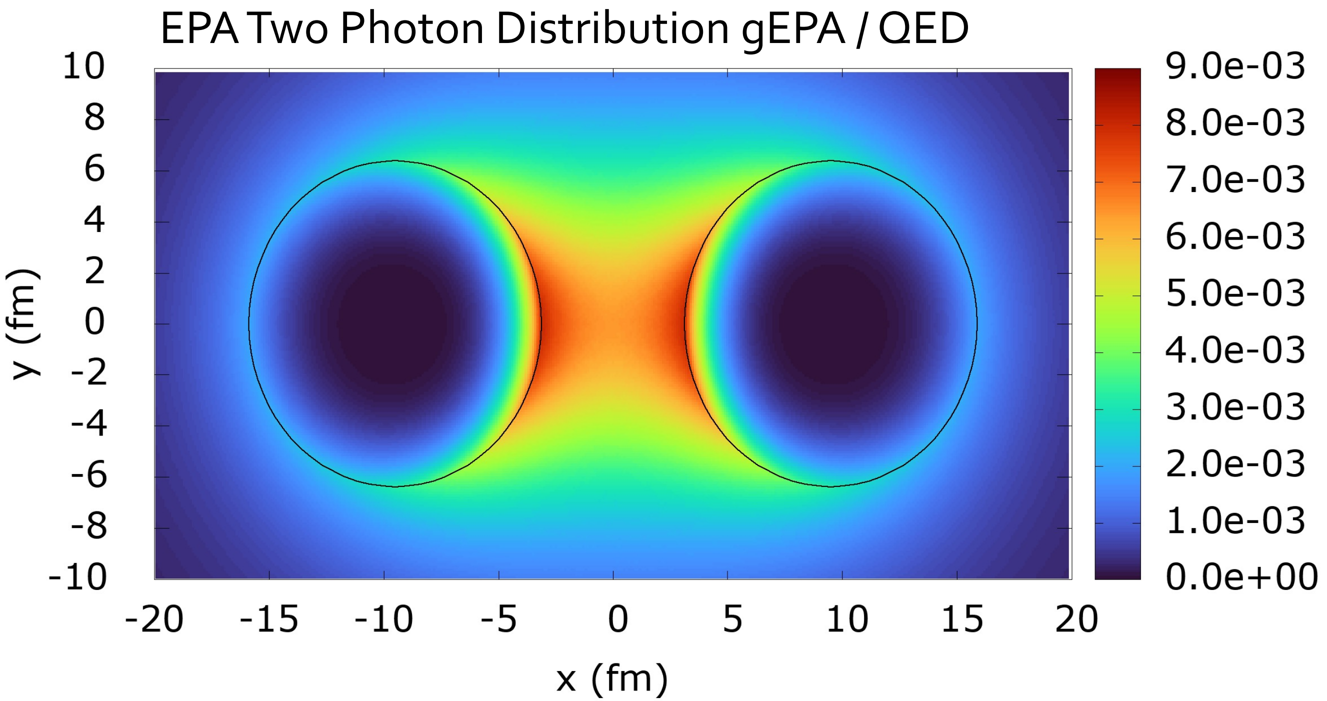


Core assumptions in STARLight, SuperChic, and other similar EPA codes

- The impact parameter is conjugate to pair p_T, uncertainty principle → must integrate over all $b > 2R$
- Use point charge source
- No production within nucleus

- STARLight manually applies polar angle correlations, no azimuthal correlations

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



Two-photon density (arb. norm.)

Equivalent Photon Approximation, photon density (single ion):

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

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

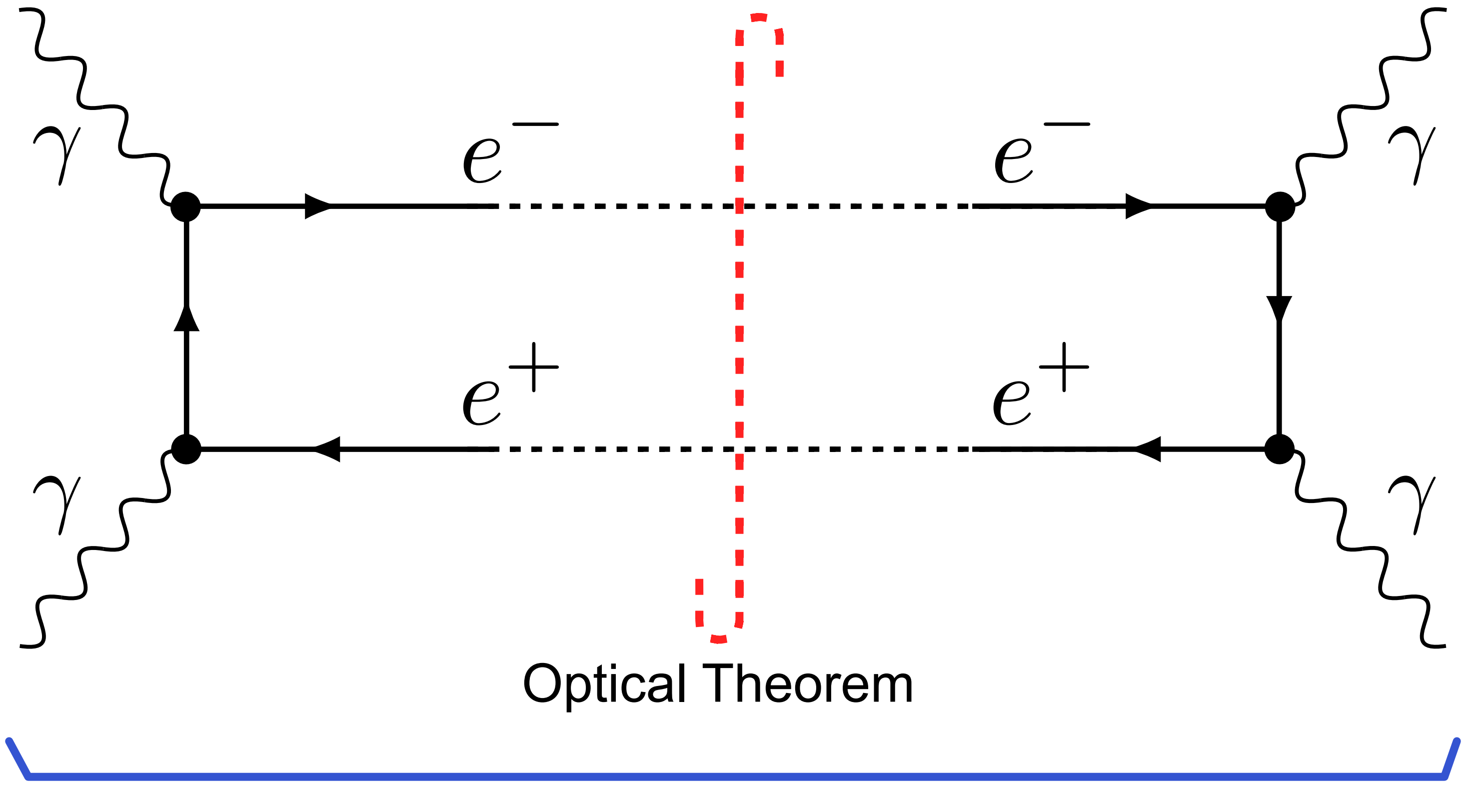
Woods-Saxon
Au ion, $R = 6.38$ fm
$b = 19$ fm

Generalized EPA & QED Calculations:

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

Breit-Wheeler Process and Light-by-Light Scattering

Breit-Wheeler Process



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

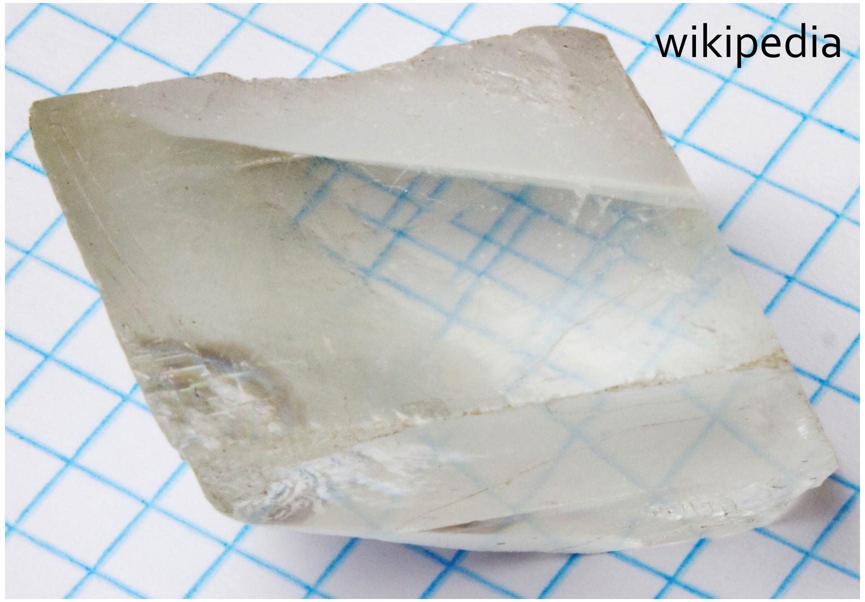
[1] Budnev, V. M., Ginzburg, I. F., Meledin, G. V. & Serbo, V. G. Physics Reports 15, 181–282 (1975).
[2] ATLAS Collaboration et al. Phys. Rev. Lett. 123, 052001 (2019).

Looking to the Future

- Implications for non-perturbative QED?

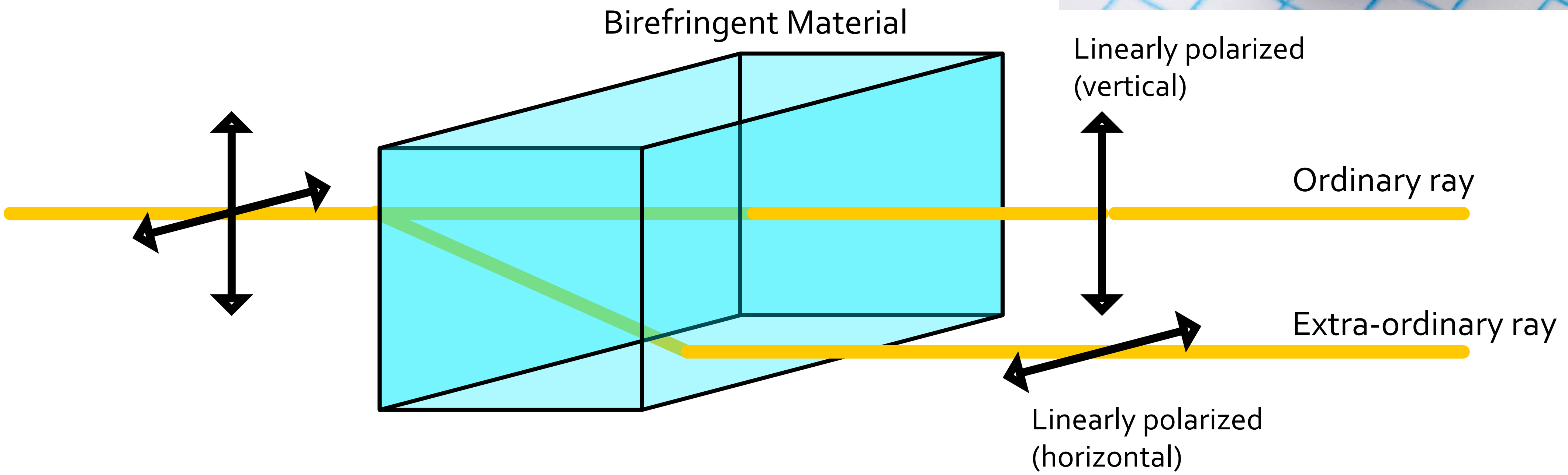
1. Implications for vacuum birefringence?
2. Schwinger pair production in heavy ion collisions?

Optical Birefringence



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 $\Delta n = n_{\parallel} - n_{\perp} \neq 0$**



Classical Electromagnetism

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

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

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

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

$$\Rightarrow$$

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

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

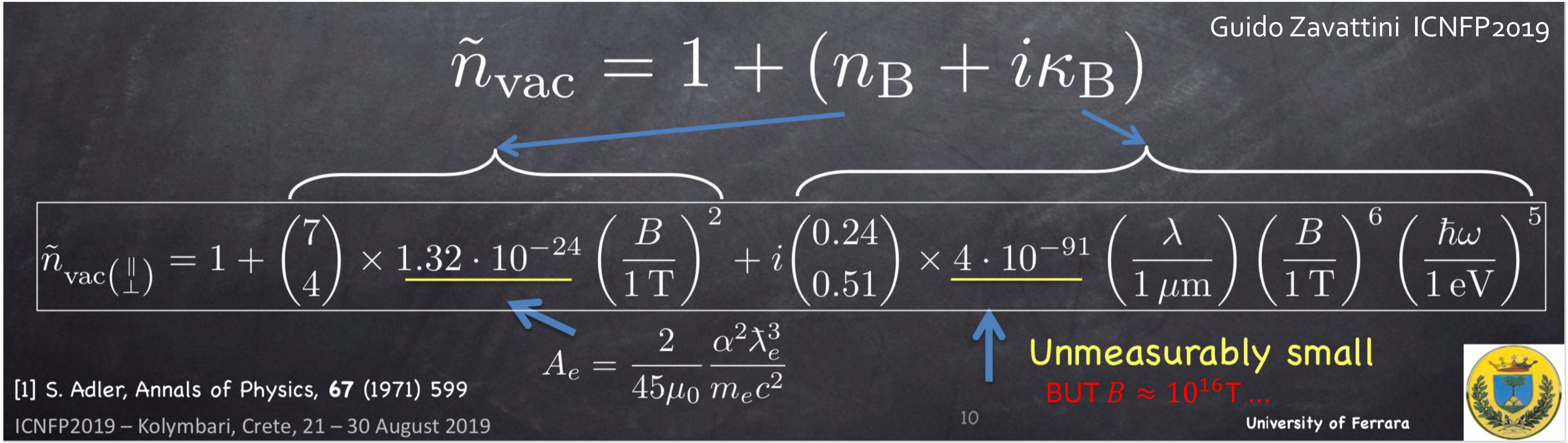
→ Unique speed of light in vacuum:

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

Vacuum Magnetic Birefringence

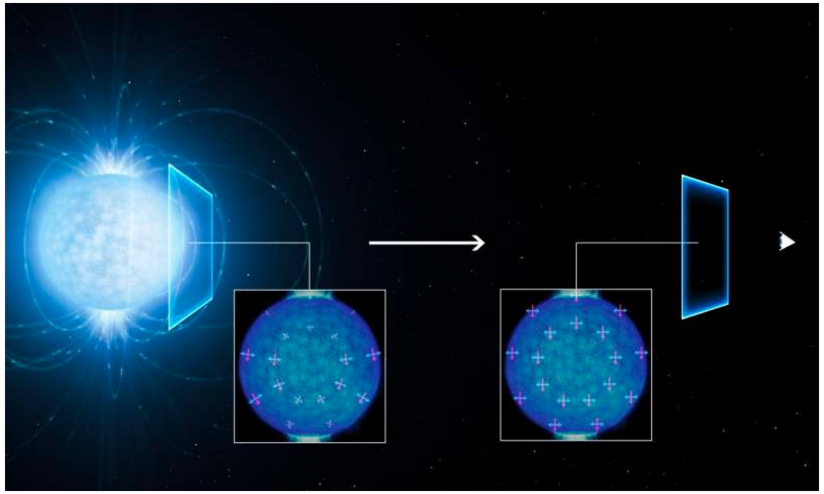
$c = \frac{1}{\sqrt{\epsilon\mu}}$ BUT $\epsilon_{\parallel} \neq \epsilon_{\perp}$ and $\mu_{\parallel} \neq \mu_{\perp}$

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



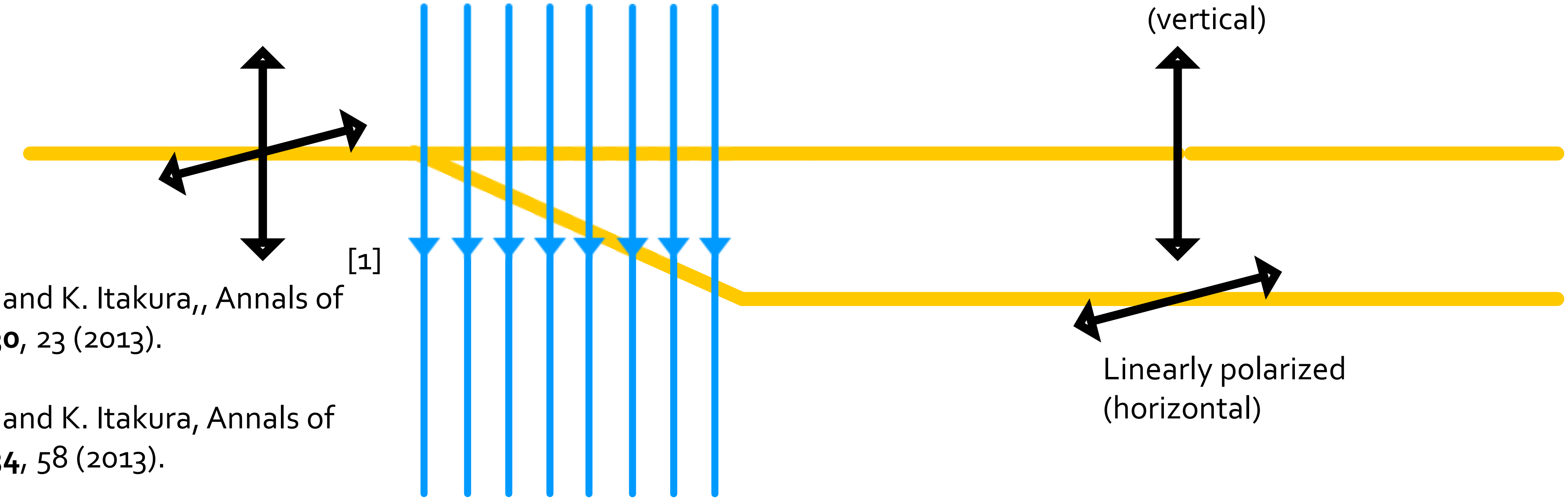
Vacuum Birefringence

Vacuum birefringence : Predicted in 1936 by Heisenberg & Euler. Index of refraction for γ interaction with $\vec{B}$ field <u>depends on relative polarization angle wrt B-field direction</u>



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

Empty space +
Ultra-strong Magnetic Field



K. Hattori and K. Itakura,, Annals of Physics **330**, 23 (2013).
[1]
K. Hattori and K. Itakura, Annals of Physics **334**, 58 (2013).

Implications for vacuum birefringence

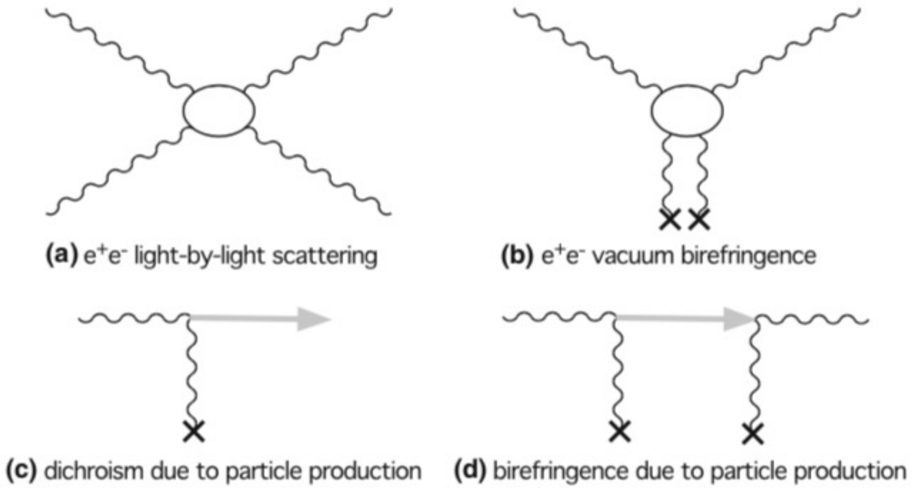
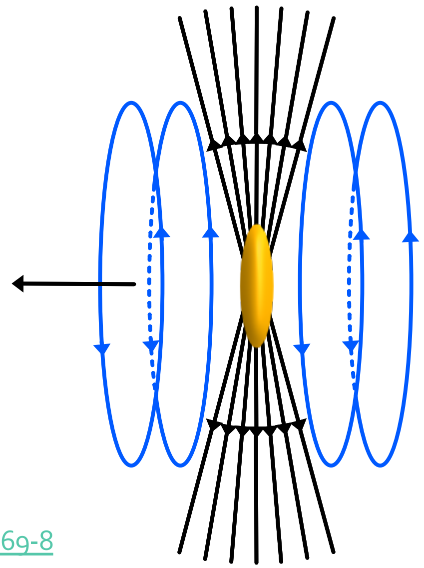


Fig. 1 Lowest order elementary processes leading to magnetic birefringence and dichroism

F. D. Valle, A. Ejlli, et al., *Eur. Phys. J. C* **76,** 24 (2016). https://doi.org/10.1140/epjc/s10052-015-3869-8



First observation of light experiencing transverse anisotropy wrt. B-field.

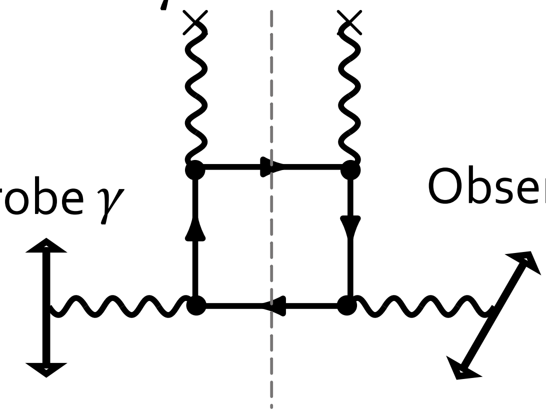
In HICs, EM-field strength:

$B_{max} \approx 10^{15}$ T $\gg B_c \approx 10^9$ T

Fields are well above critical field strengths, but act over very short time:

$$\Delta t \approx \frac{b}{\gamma v} \approx 10^{-23} \text{ s}$$

Cannot be considered a static classical field



Unlike the normal theoretical picture, in this case:
both photons are real and soft ($k_\perp \approx 30$ MeV/c)
and <u>all photons are manifestations of strong EM fields</u>

However, currently there are no evidence of higher-order effects – looking forward to input from more theoretical investigations.

Hattori, K., Taya, H. & Yoshida, S . *J. High Energ. Phys.* **2021,** 93 (2021). https://doi.org/10.1007/JHEP01(2021)093

The Schwinger Production Mechanism

- Schwinger mechanism is a non-perturbative QED effect
- In HICs the $E_{max} \approx 5\times10^{16}$ V/cm $\gg E_c \approx 10^{16}$V/cm
  - Observation of Breit-Wheeler process → lowest order process, currently no evidence of higher-order effects

Possible to investigate Schwinger mechanism experimentally in HICs?

- Precise measurements at lower beam energy – where the fields vary more slowly → more closely resemble a classical field
- Effect of long-lived EM-fields due to (conductive) QGP is formation
- Need additional theory input for expectation from higher order effects – with specific attention to our experimental conditions

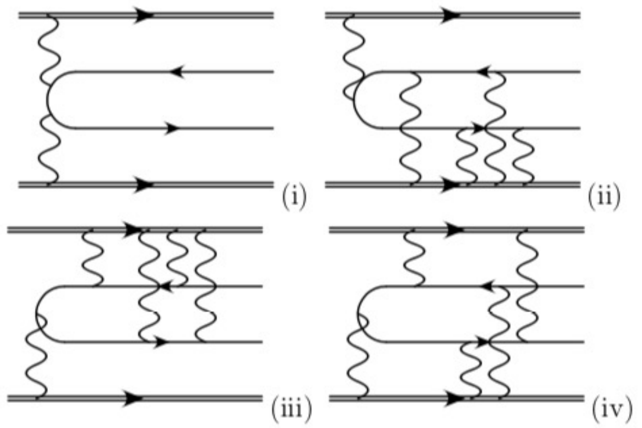


Fig. 3. e^+e^- pair production is classified by the number of photons attached to each ion. We distinguish for classes (i) $n = n' = 1$ (ii) $n = 1$, $n' > 1$ (iii) $n > 1$, $n' = 1$ and (iv) $n > 1$, $n' > 1$.

Some authors have predicted that higher order processes should be present due to $Z\alpha \approx 1$

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