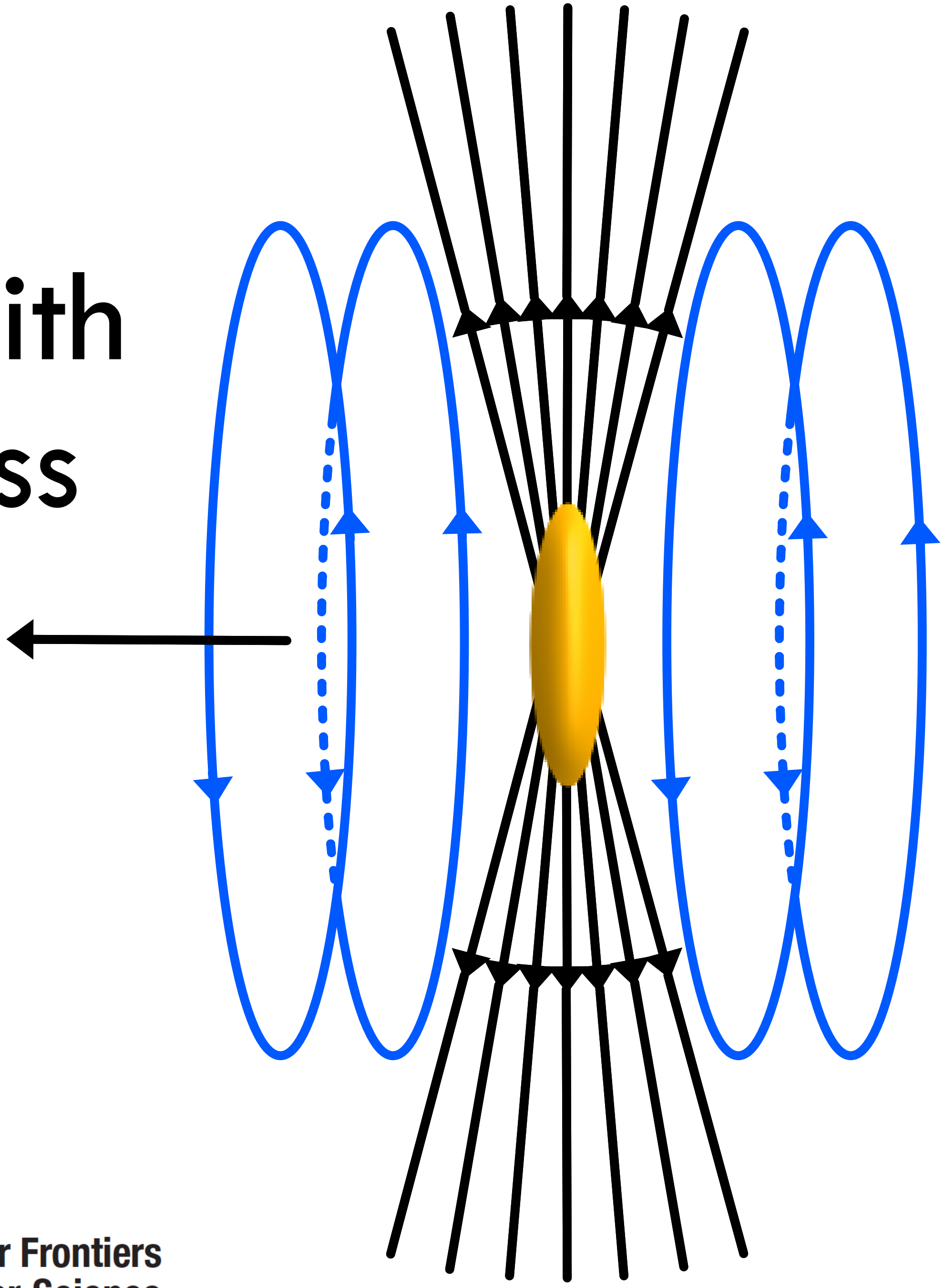
Probing Extreme Electromagnetic Fields with the Breit-Wheeler Process

Daniel Brandenburg for the **STAR Collaboration**

(Shandong University & BNL/CFNS)



March 3, 2020

36th Winter Workshop on Nuclear Dynamics

Puerto Vallarta, Mexico

BROOKHAVEN NATIONAL LABORATORY

SHANDONG UNIVERSITY 1901

Center for Frontiers in Nuclear Science

Outline of this Talk

1. Intro: What is the Breit-Wheeler Process?
2. Results from STAR Collaboration
3. Vacuum Birefringence in Extreme Magnetic Fields
4. The Magnetic Field in Heavy Ion Collisions
    1. Measuring the "Initial" $(\tau = 0)$ Magnetic Field
    2. Evidence for Long-lived Magnetic Field or Medium Effects?
5. Conclusions

Fundamental Interactions : light & matter

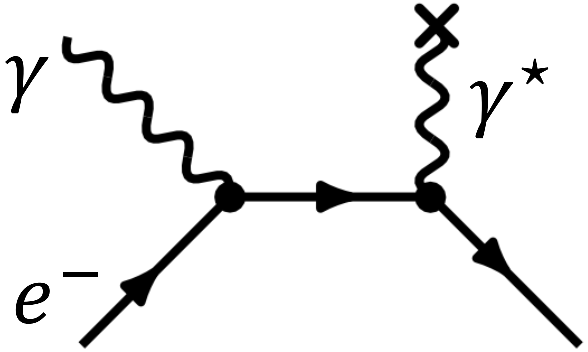
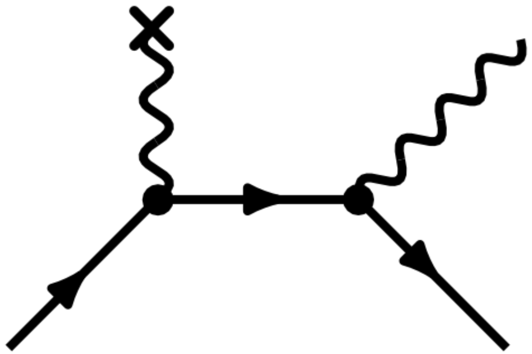
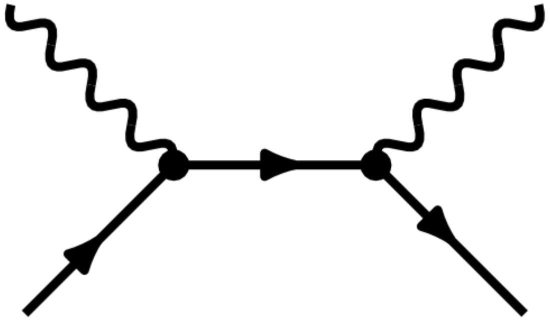


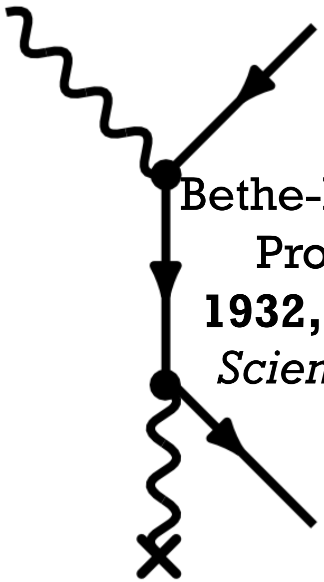
Photo Electric Effect
1887 *Hertz, Ann Phys (Leipzig) 31, 983*



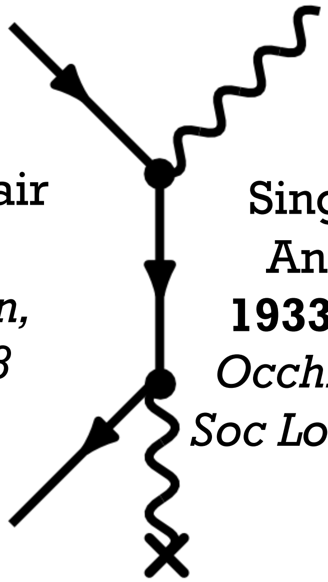
Bremsstrahlung
1895 *Röntgen, Ann Phys (Leipzig) 300, 1*



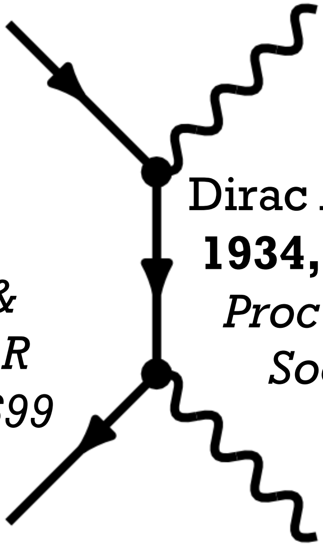
Compton Scattering
1906 *Thomson, Conduction of Electricity through Gases*



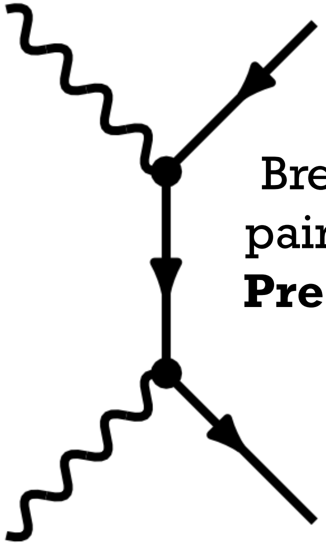
Bethe-Heitler Pair Production
1932, *Anderson, Science 76,238*



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

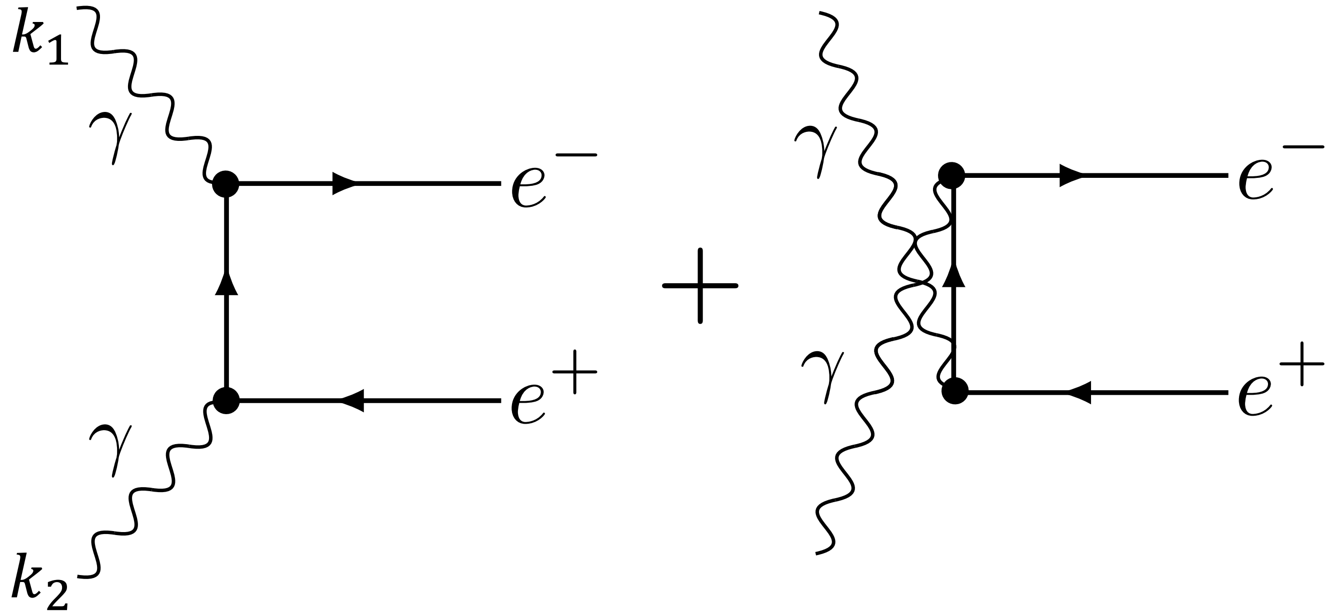


Dirac Annihilation
1934, *Klemperer, Proc Camb Phil Soc 30, 347*



Breit-Wheeler pair production
Predicted 1934

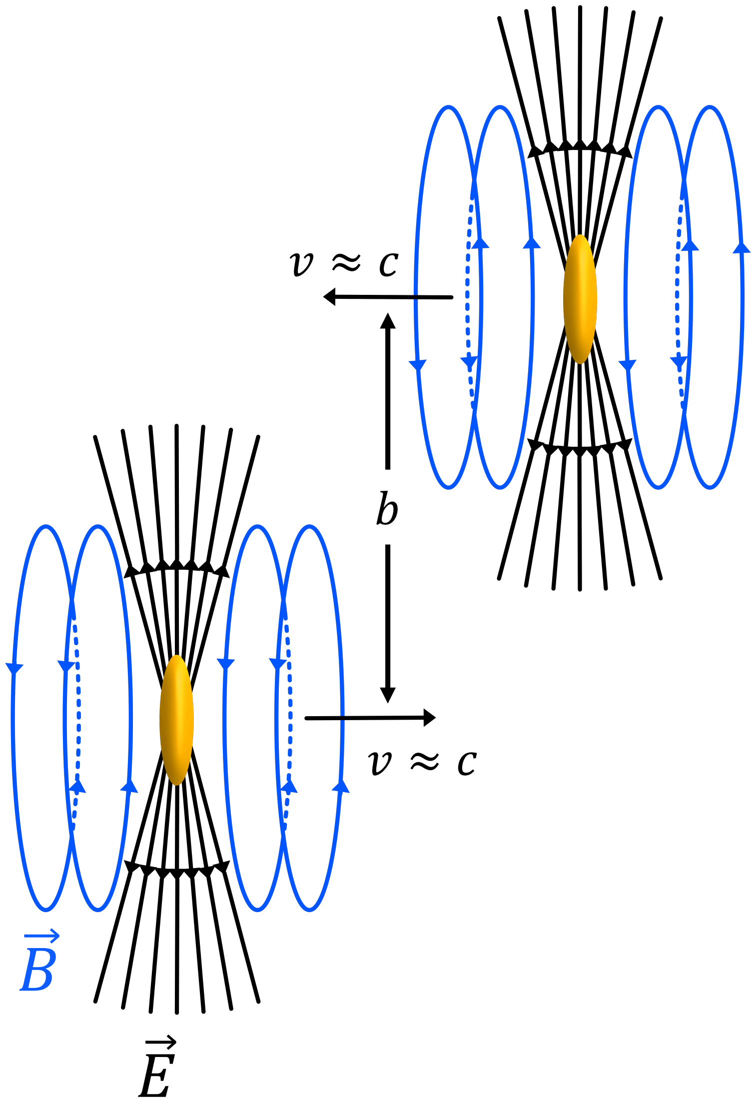
The Breit-Wheeler Process : $\gamma\gamma \rightarrow e^+e^-$



- Breit-Wheeler process is by definition the lowest-order, tree level process
- Two diagrams contribute at lowest-order
- t-channel process, 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

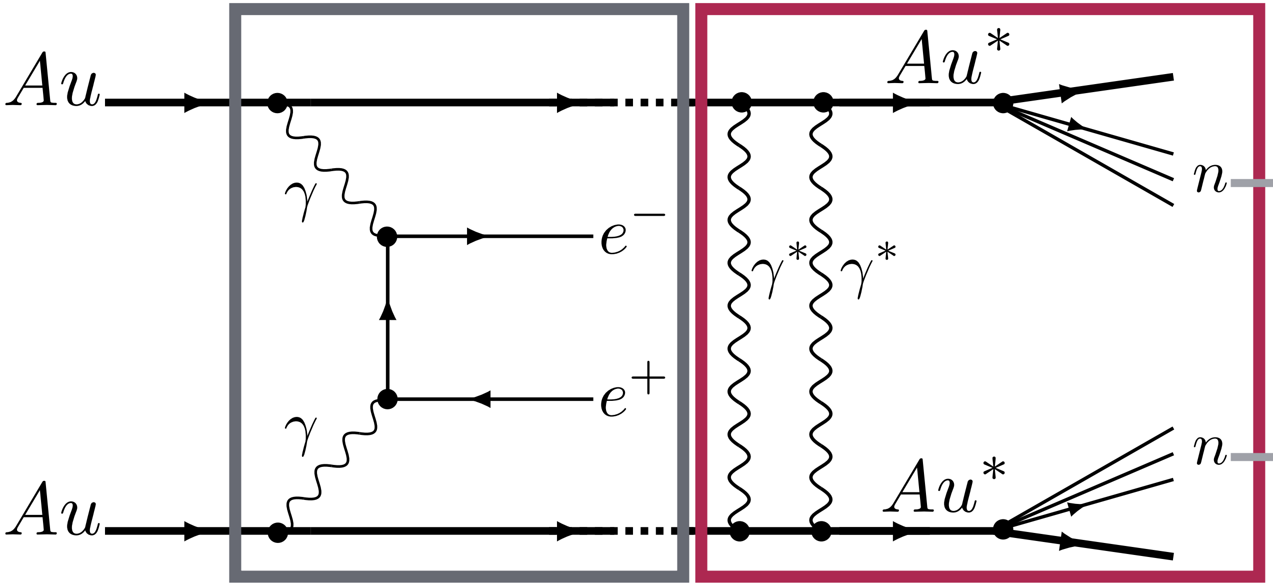
Weizäcker-Williams *Equivalent Photon Approximation* (EPA):
→ In a specific phase space, transverse EM fields can be quantized as a flux of **real photons** Weizsäcker, C. F. v. *Zeitschrift für Physik* 88 (1934): 612

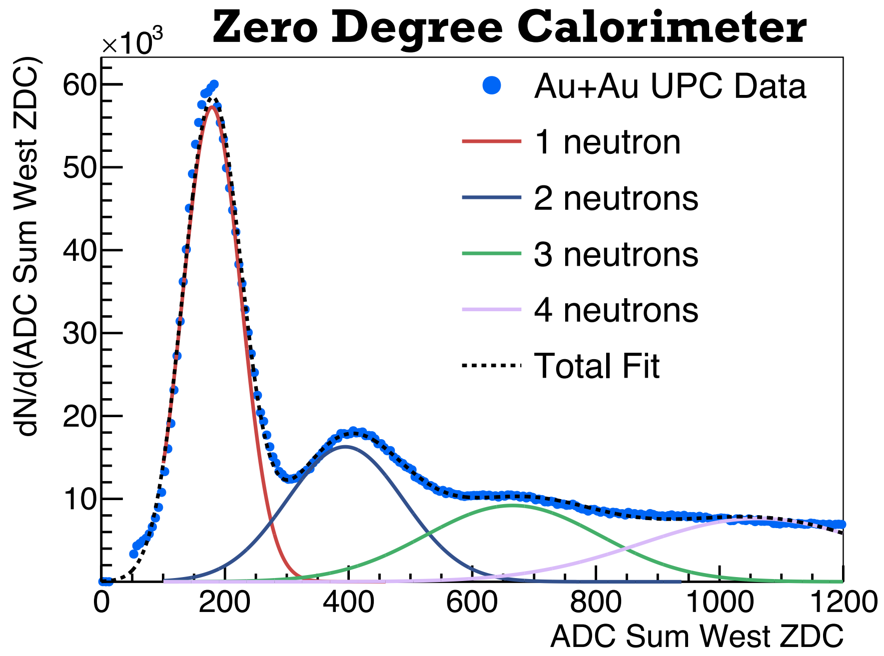
$$n \propto \vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B} \approx |\vec{E}|^2 \approx |\vec{B}|^2$$

$Z\alpha \approx 1$ → 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

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





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

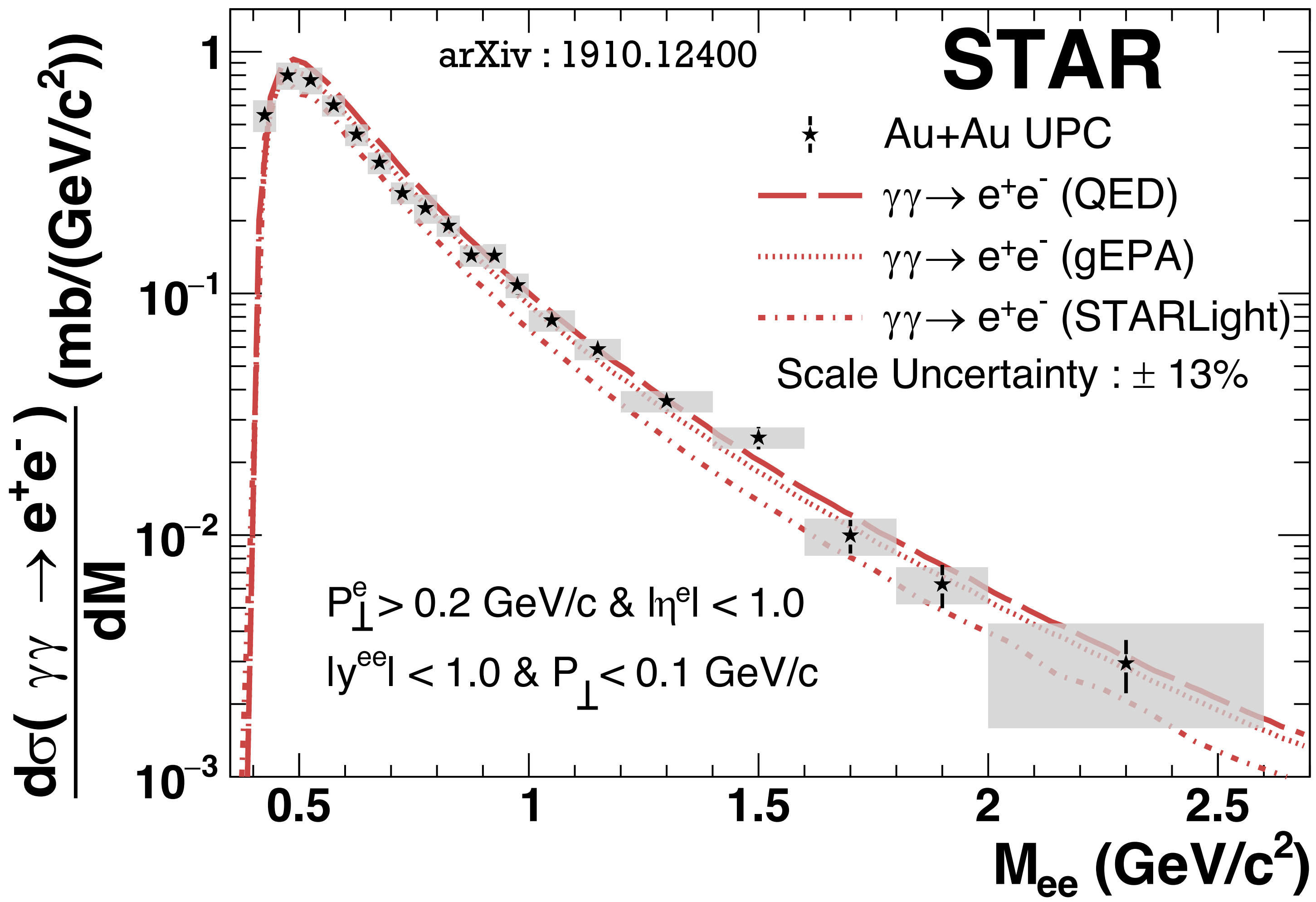
Mutual Coulomb excitation and nuclear dissociation

- **Provides efficient trigger condition**

→Provides high statistics sample (>6,000 e^+e^- pairs from data collected in 2010)

→ Allows 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$\pm$0.004 (stat.) $\pm$ 0.013 (sys.) $\pm$ 0.034 (scale) mb

STARLight	gEPA	QED
0.22 mb	0.26 mb	0.29 mb

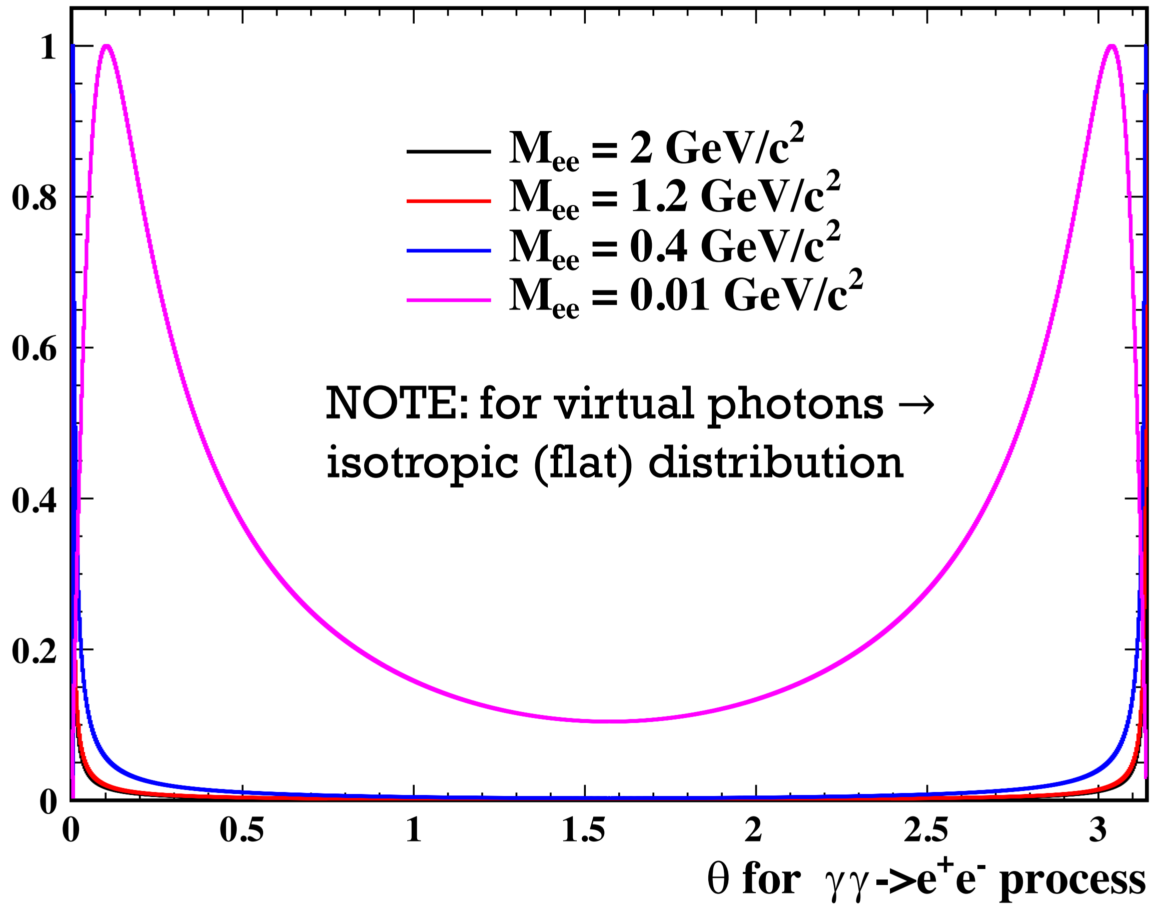
Measurement of total cross section agrees with theory calculations at $\pm 1\sigma$ level

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

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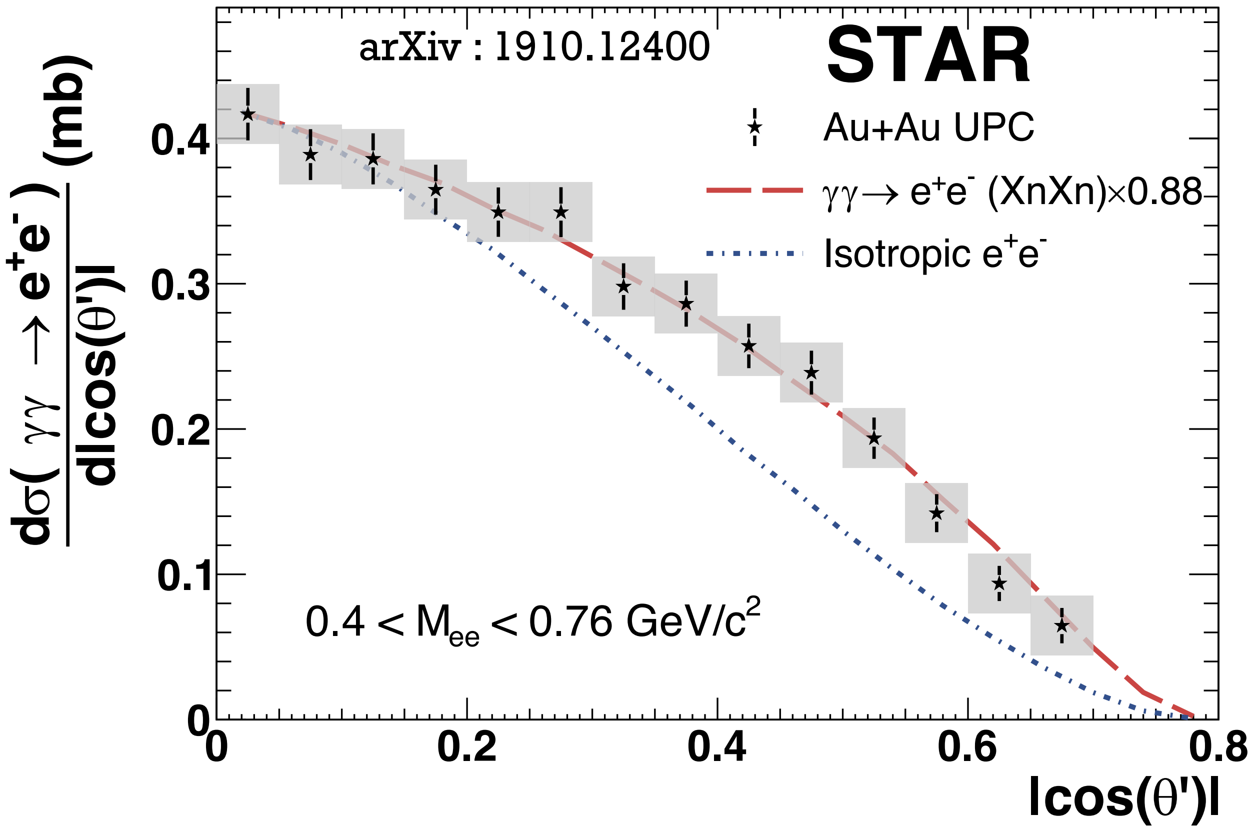
- Highly virtual photon interactions should have an <u>isotropic distribution</u>
- Measure θ', the angle between the e^+ and the beam axis in the pair rest frame.

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

⇒ **Measurably distinct from isotropic distribution**



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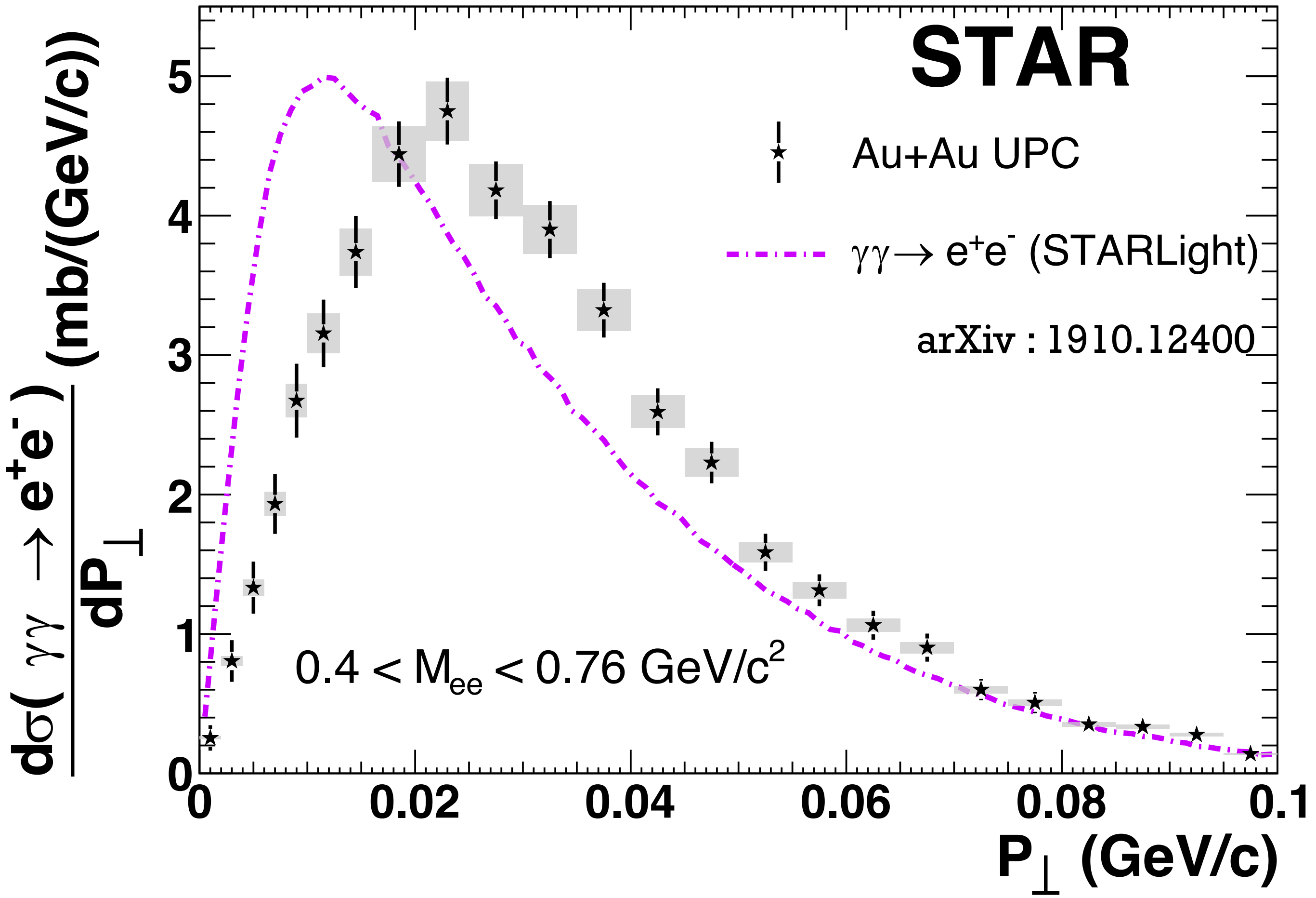
$d\sigma(\gamma\gamma \to e^+e^-)/dP_\perp$

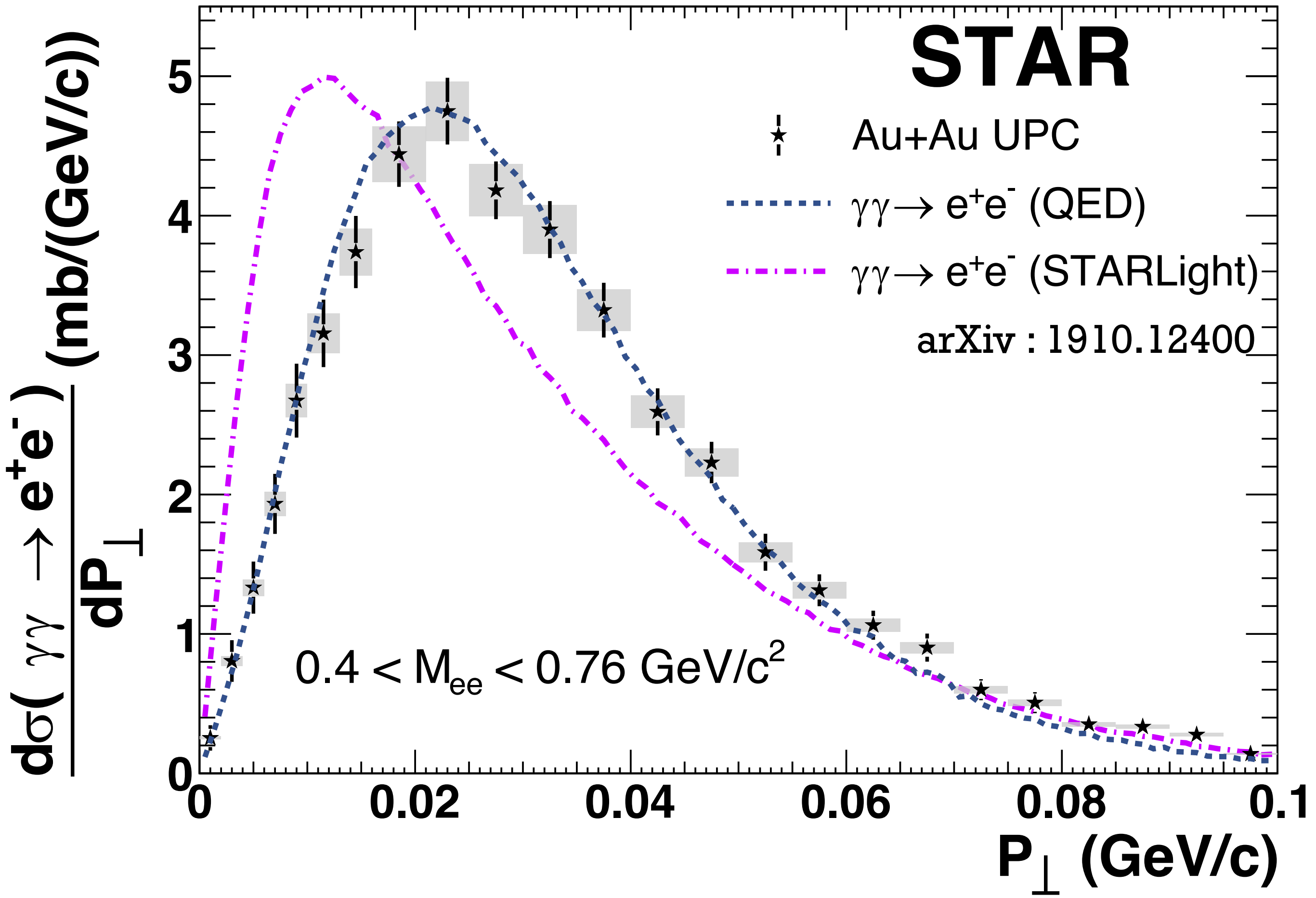


QED and STARLight are scaled to match measured $\sigma(\gamma\gamma \to e^+e^-)$

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]

- High precision data – test theory predictions
- STARLight predicts significantly lower $\langle P_\perp \rangle$ than seen in data

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



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QED : W. Zha, J.D.B., Z. Tang, Z. Xu arXiv:1812.02820 [nucl-th]

- **Data are well described by leading order QED calculation ($\gamma\gamma \rightarrow e^+e^-$) with quasi-real photons**
- STARLight predicts significantly lower $\langle P_\perp \rangle$ than seen in data
  - STARLight calculations do not have centrality dependent $P_\perp$ distribution
- Experimentally investigate impact parameter dependence :

→**Compare UPC vs. peripheral collisions (come back to later)**

Classical Electromagnetism

- Maxwell's equations are linear
  - <u>Superposition principle holds</u>

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

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

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

⇒

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

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

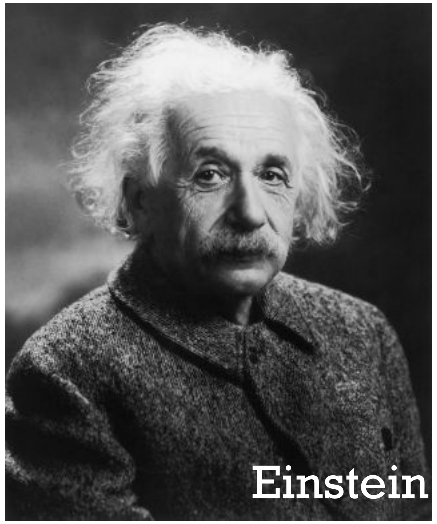
→ Unique speed of light in vacuum:

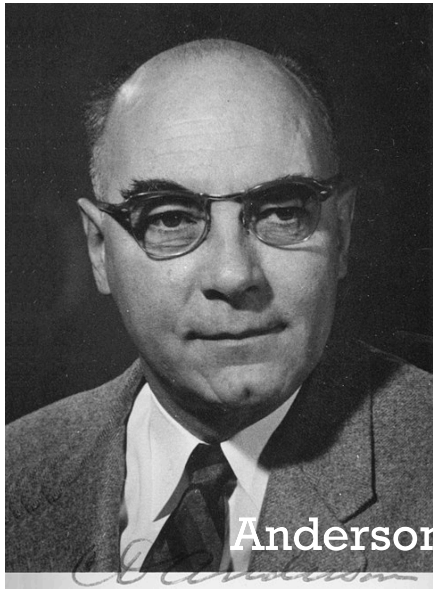
$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 299792458\ \mathrm{m/s}$$

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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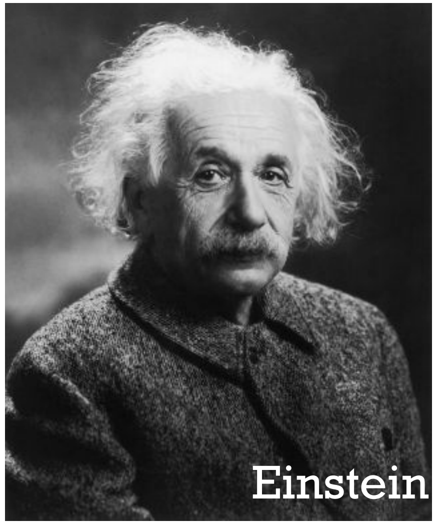
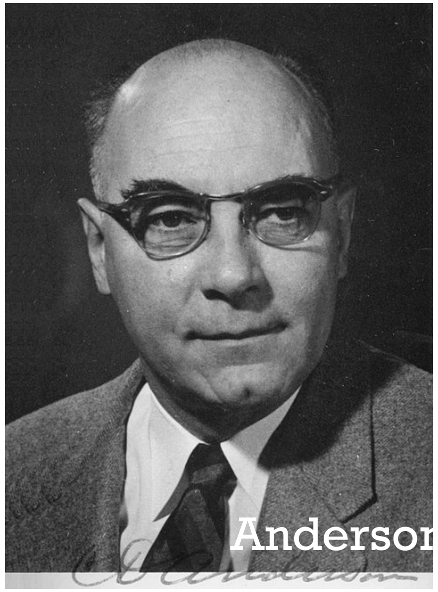




→ Vacuum fluctuations

- 1936: Euler & Heisenberg present modified Lagrangian

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

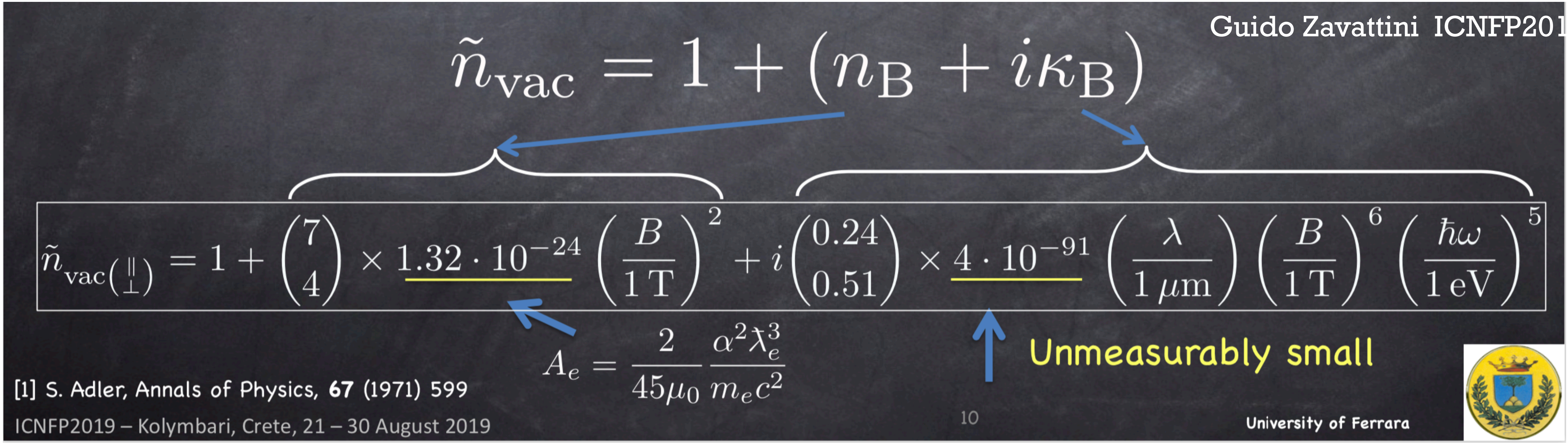
- **Non-linear** → Super-position principle is broken!

NB: in 1951 Shwinger derived the Lagrangian within QED formalism

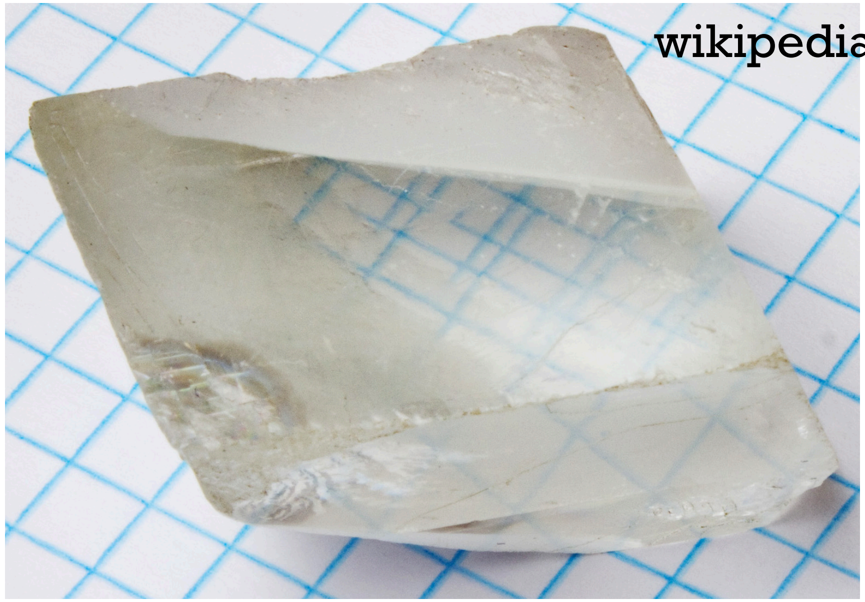
Vacuum Magnetic Birefringence

$c = \frac{1}{\sqrt{\epsilon\mu}}$ **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 $n_{vac} \neq 1$

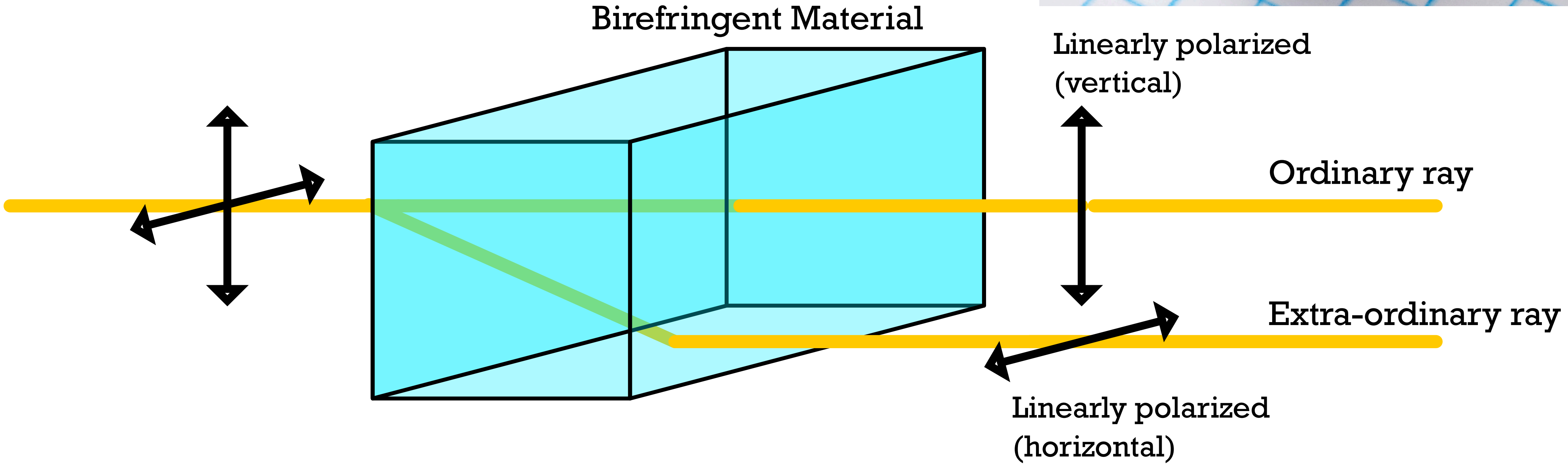


Optical Birefringence



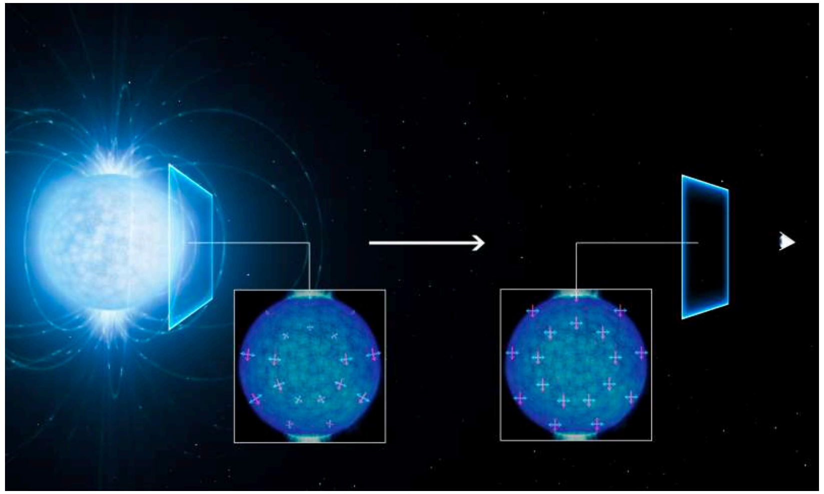
Birefringent material: Different index of refraction for light polarized parallel ($n_{\parallel}$) vs. perpendicular ($n_{\perp}$) to material's ordinary axis

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



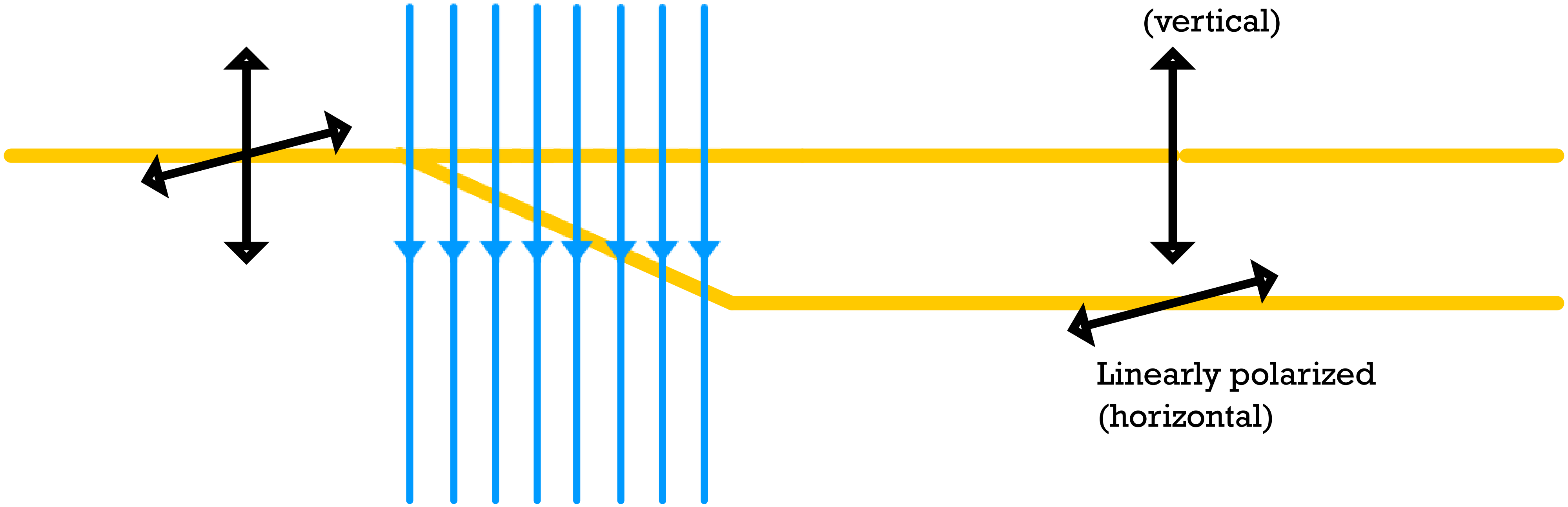
Vacuum Birefringence

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



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

Empty space +
Ultra-strong Magnetic Field



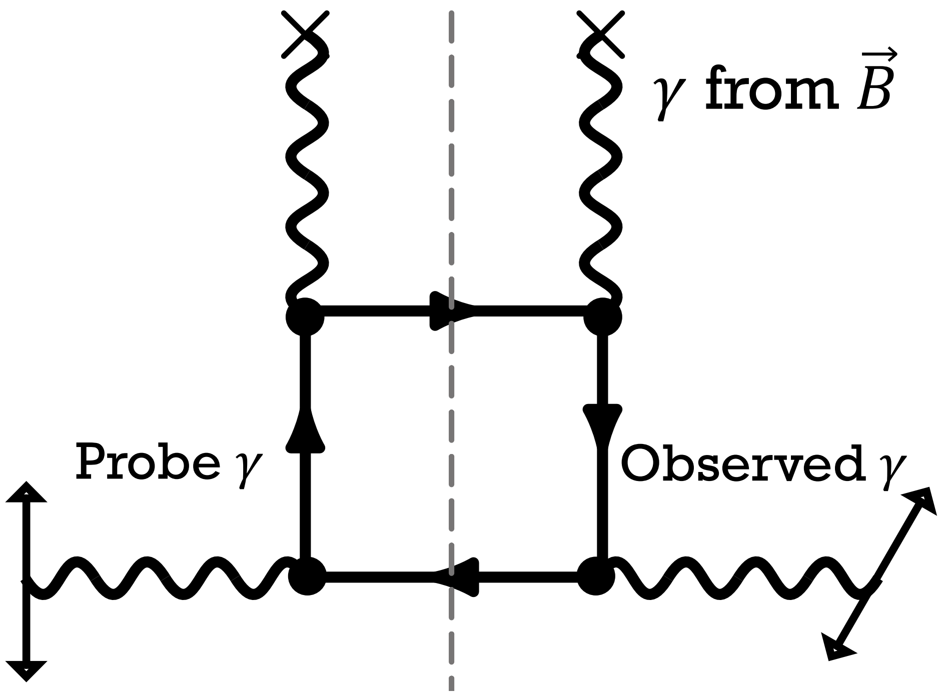
Birefringence of the QED Vacuum

Vacuum birefringence : Index of refraction for γ interaction with $\vec{B}$ field <u>depends on relative polarization angle</u> i.e. $\boldsymbol{\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp} \neq 0}$

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

Recently realized that a consequence of $\sigma_{\parallel} - \sigma_{\perp} \neq 0$ in $\gamma\gamma \rightarrow e^{+}e^{-}$ collisions is a $cos(4\Delta\phi)$ modulation[3] between the pair momentum and the daughter momentum.

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)

Can we observe vacuum birefringence in ultra-peripheral collisions?

[1]S. Bragin, et. al., *Phys. Rev. Lett.* 119 (2017), 250403
[2]R. P. Mignani, *et al.*, *Mon. Not. Roy. Astron. Soc.* 465 (2017), 492
[3] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)

Birefringence of the QED Vacuum

[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
QED calculation: arxiv : 1911.00237

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]

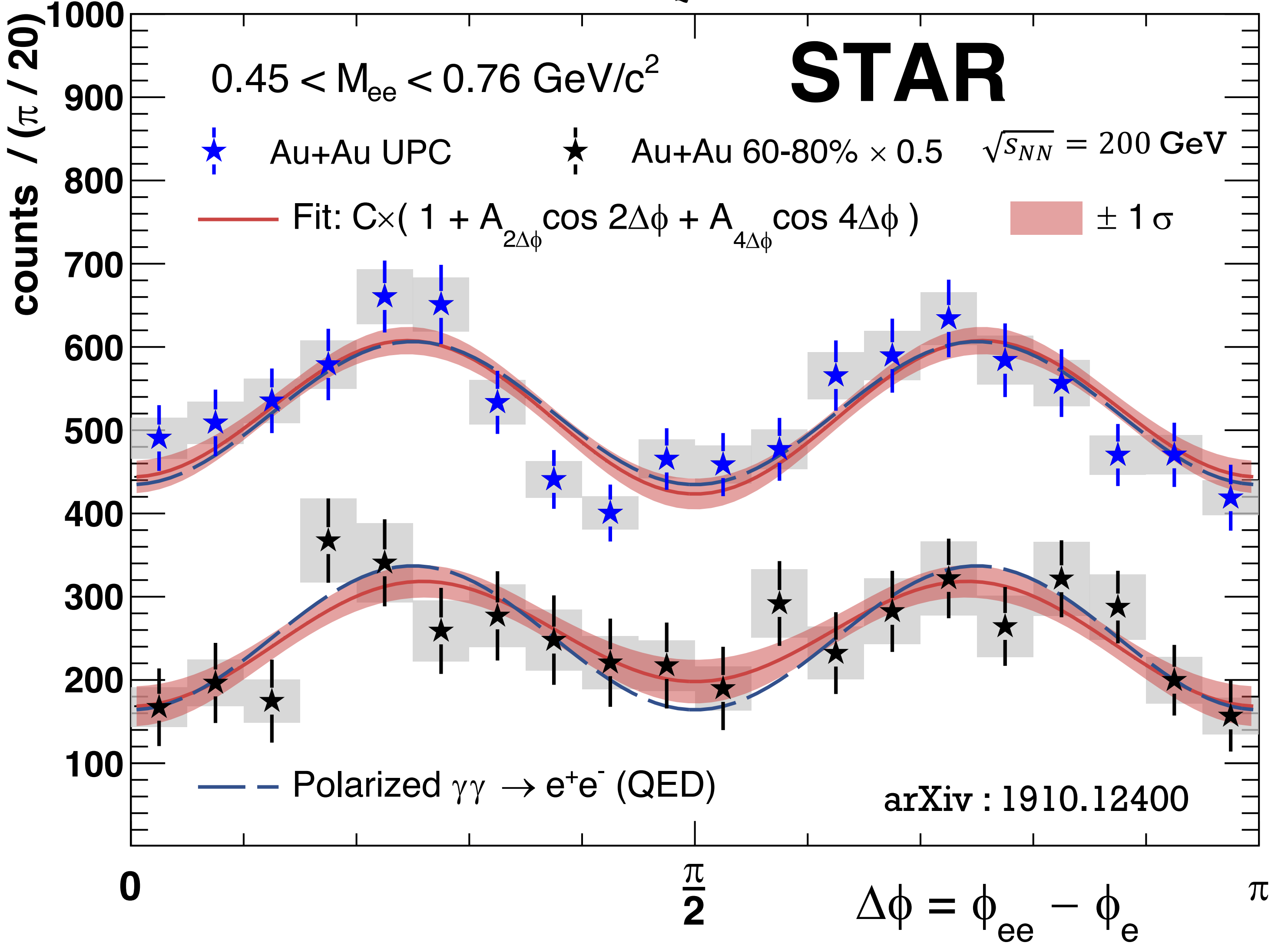
$$\Delta\phi = \Delta\phi[(e^{+} + e^{-}), (e^{+} - e^{-})]$$
$$\approx \Delta\phi[(e^{+} + e^{-}), e^{+}]$$

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

Ultra-Peripheral

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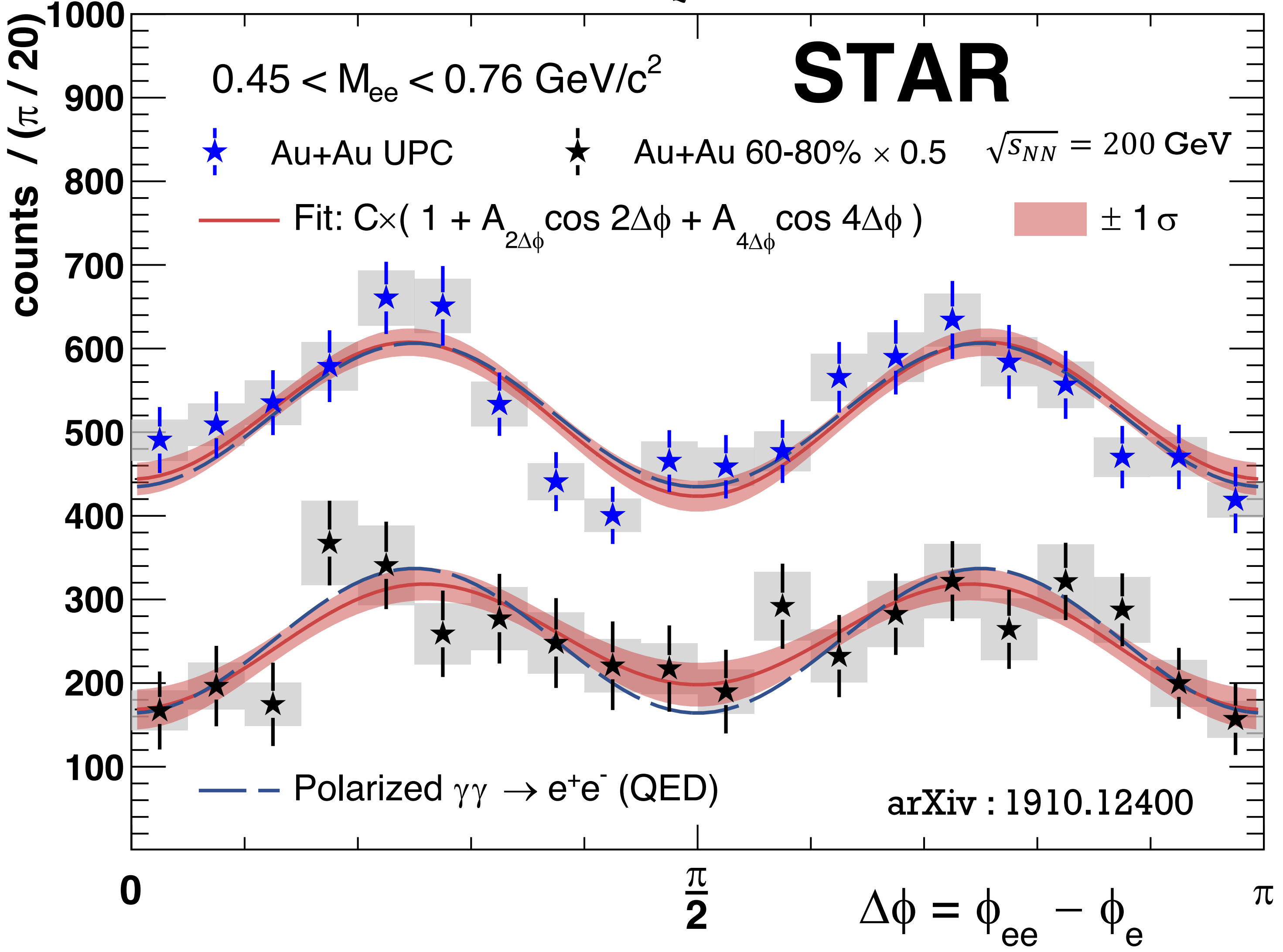


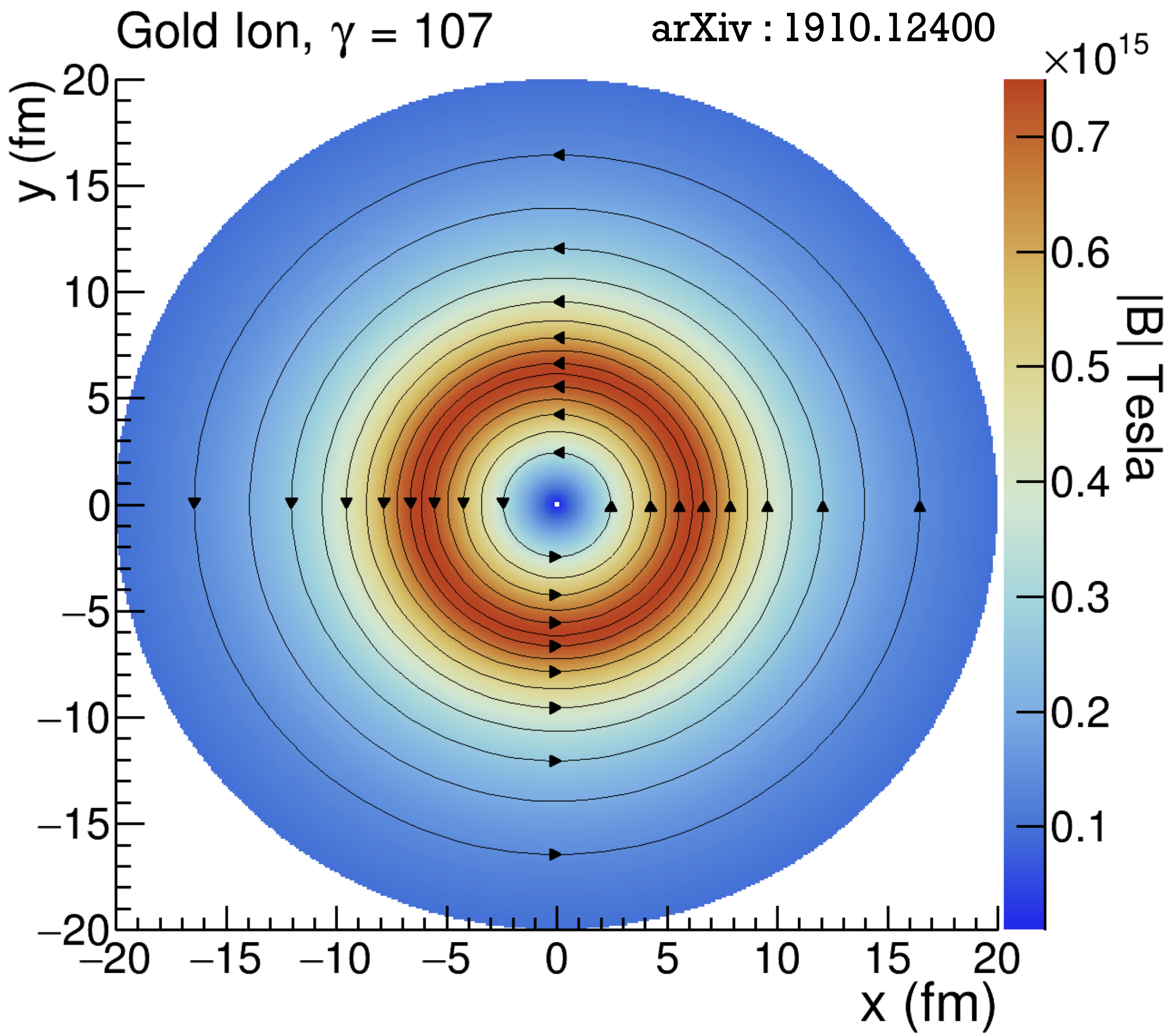
→ **<u>First Earth-based observation</u> (6.7σ level) of vacuum birefringence**

Connection to the Initial Magnetic Field

Two direct "connections" to the $\vec{B}$ field

1. Total $\gamma\gamma \to e^+e^-$ cross section
2. Strength of the vacuum birefringence phenomena

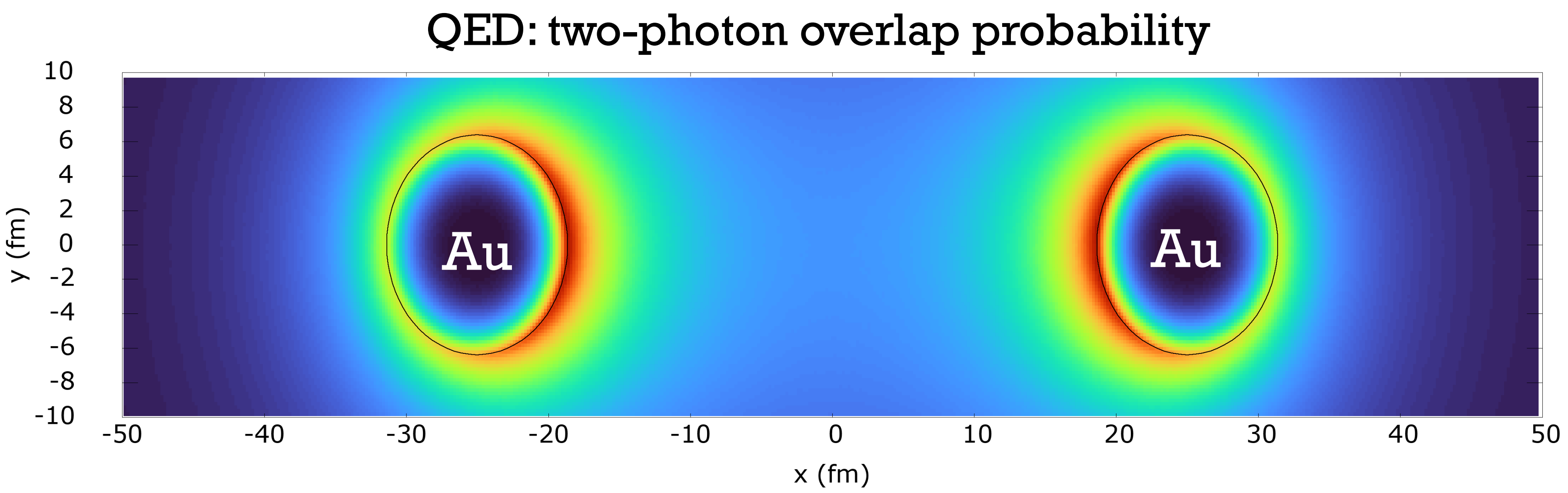
This field density is used in the QED calculations for Breit-Wheeler ($\gamma\gamma \to e^+e^-$) process and vacuum birefringence that achieve good agreement with all data.



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

Connection to the Initial Magnetic Field

- 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

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

Mapping the Initial Magnetic Field Strength

- At large impact parameters

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

Zha, W., Brandenburg, J. D., Tang, Z. & Xu, Z. Phys. Lett. B800, 135089 (2020).

Numerical QED calculation using arbitrary Four-Potential as input

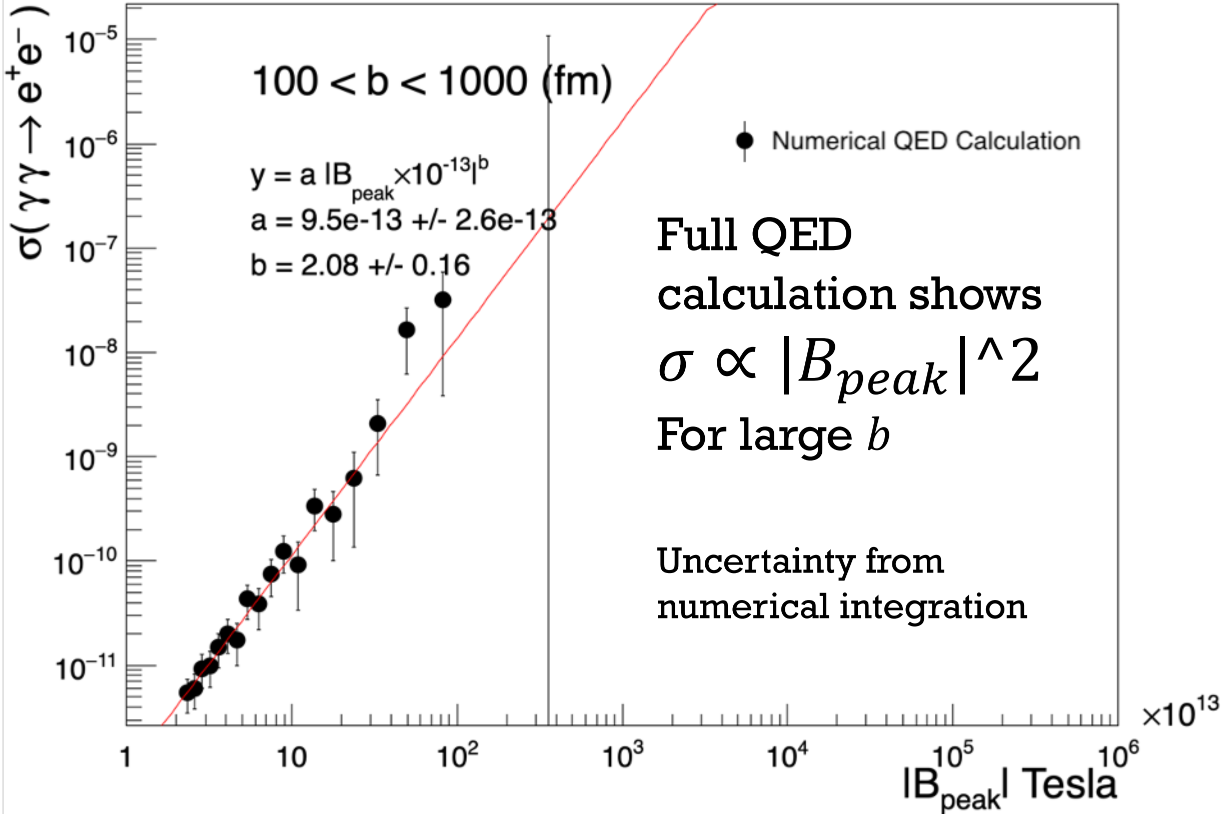
$$A_1^\mu(k_1, b) = -2\pi(Z_1 e)e^{ik_1^\tau b_\tau}\delta(k_1^\nu u_{1\nu})\frac{F_1(-k_1^\rho k_{1\rho})}{k_1^\sigma k_{1\sigma}}u_1^\mu,$$

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

Note: Z and γ are fixed, the only free parameter is the Form-Factor (i.e. configuration of charges)

Assumptions:

- Spherically symmetric
- Woods-Saxon charge distribution



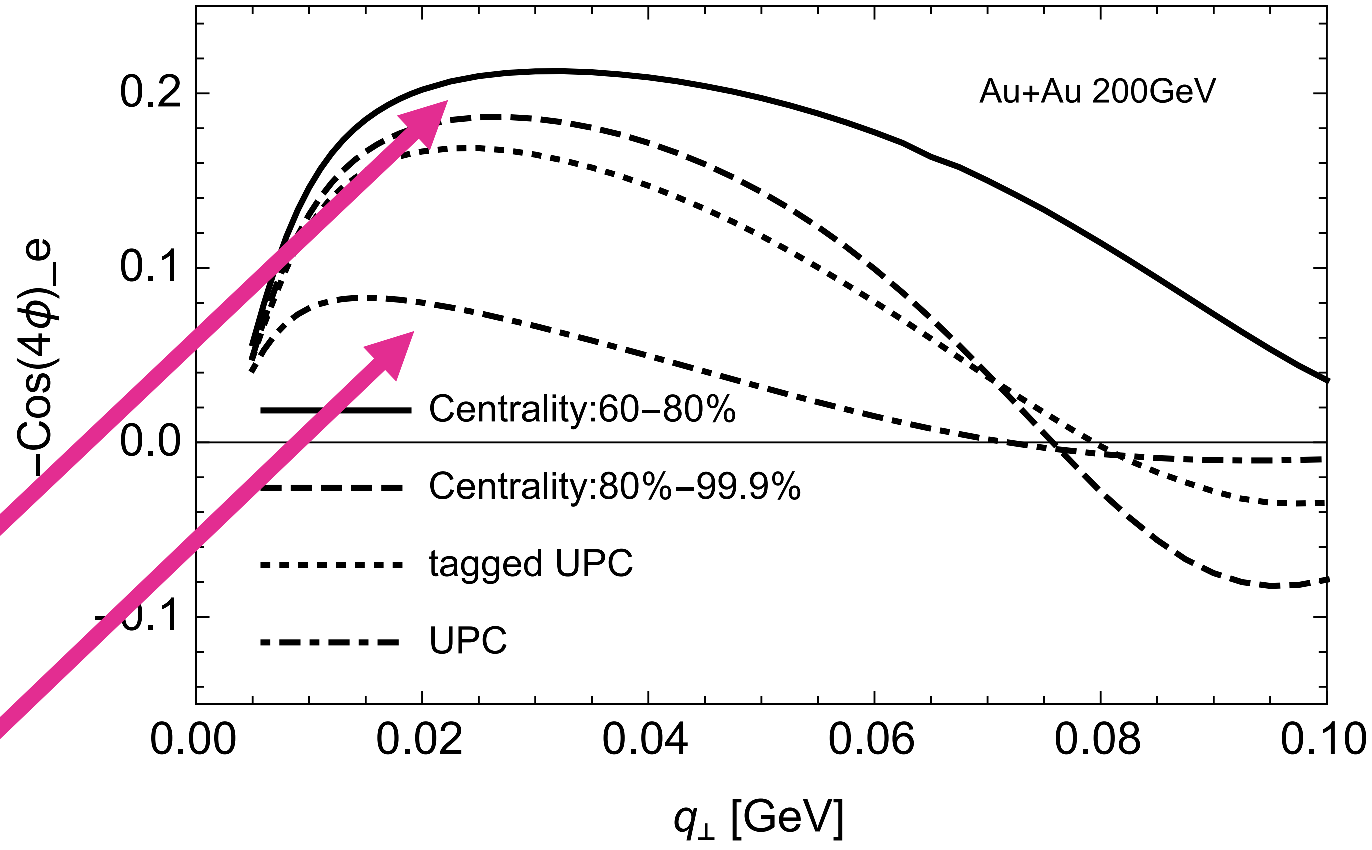
Full QED calculation shows $\sigma \propto |B_{peak}|^2$ For large b

Uncertainty from numerical integration

Mapping the Initial Magnetic Field Strength

- The $\cos(4\Delta\phi)$ modulation caused by vacuum birefringence depends on:
  - Field Strength
  - Field geometry (photon polarization orientations)

- Larger modulation for small impact parameters
- Smaller modulation for large impact parameters



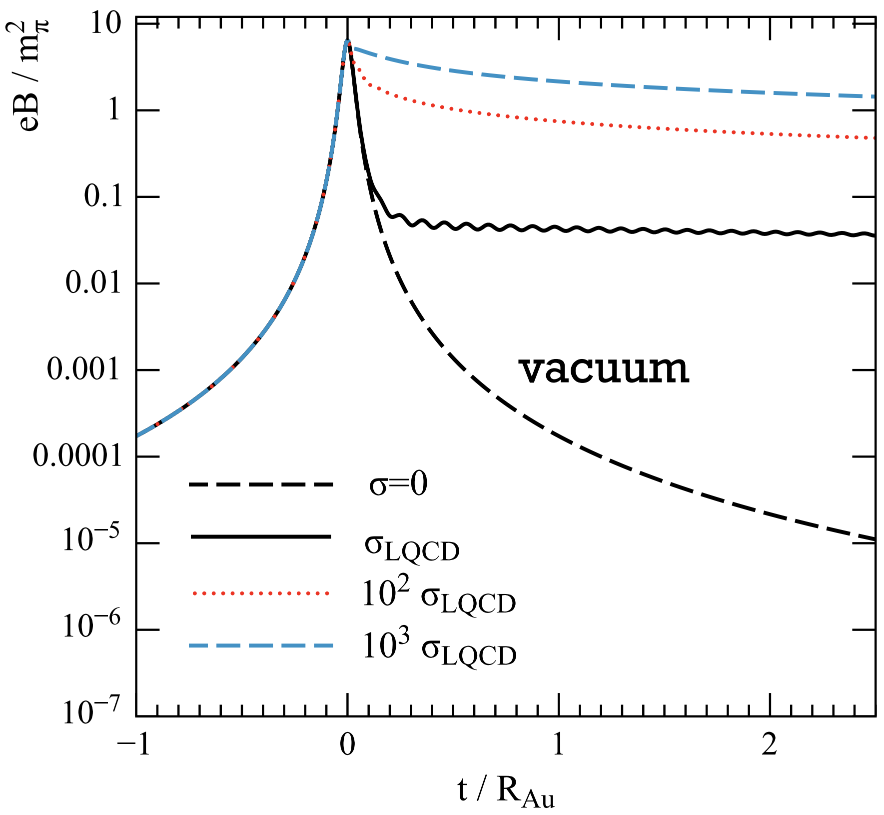
⇒ STAR's neutron "tagged" UPC Measurement agrees with theory prediction. To map the field, need more measurements at various b etc.

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[1]
2. Coulomb scattering through QGP medium [2,3]

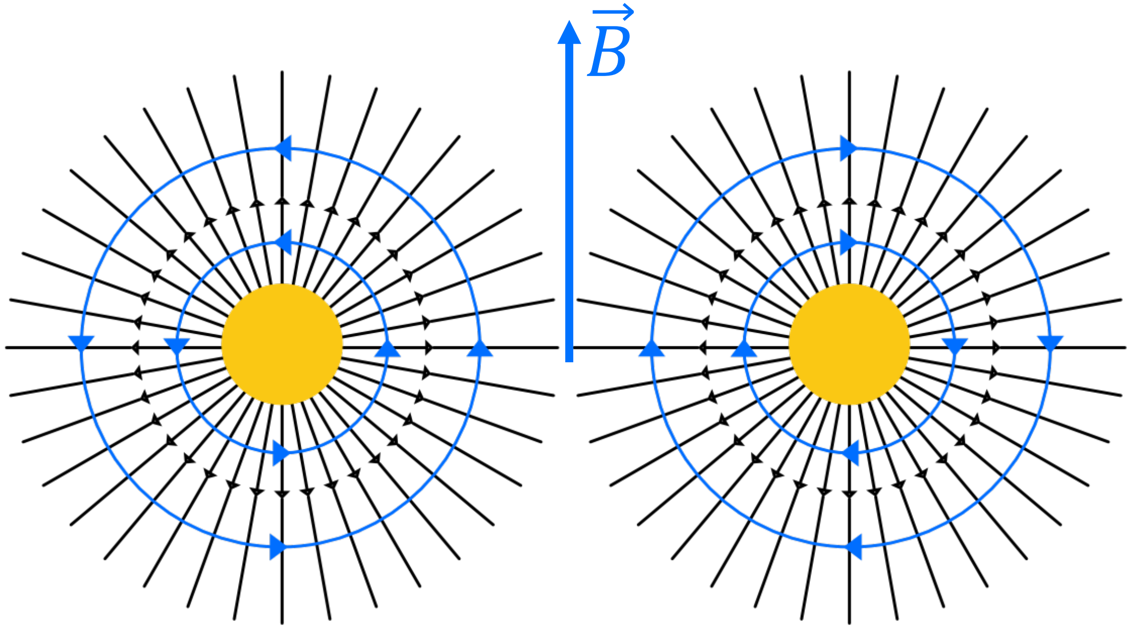


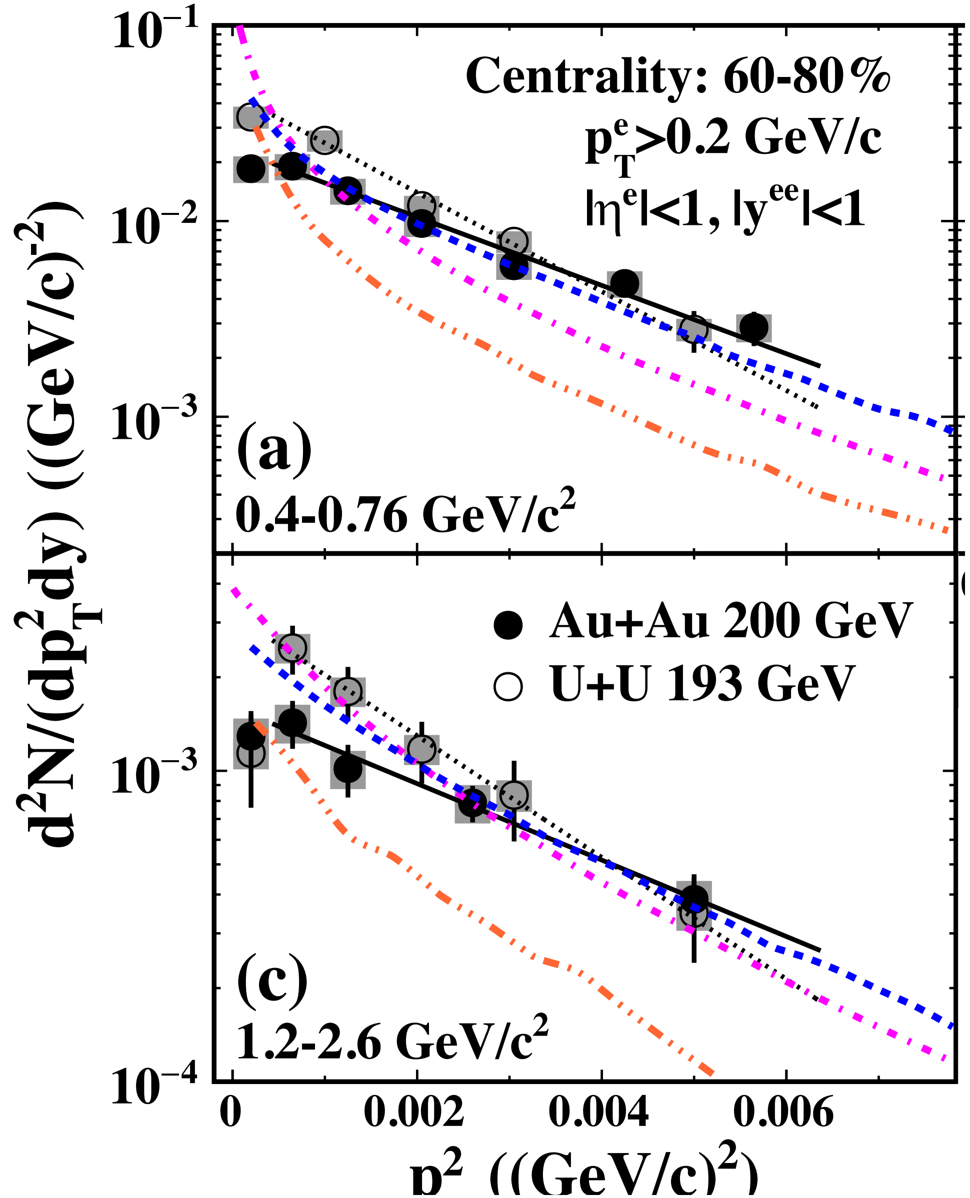
L. McLerran, V. Skokov, Nuclear Physics A 929 (2014) 184–190

[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

Long-lived Magnetic Field?

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



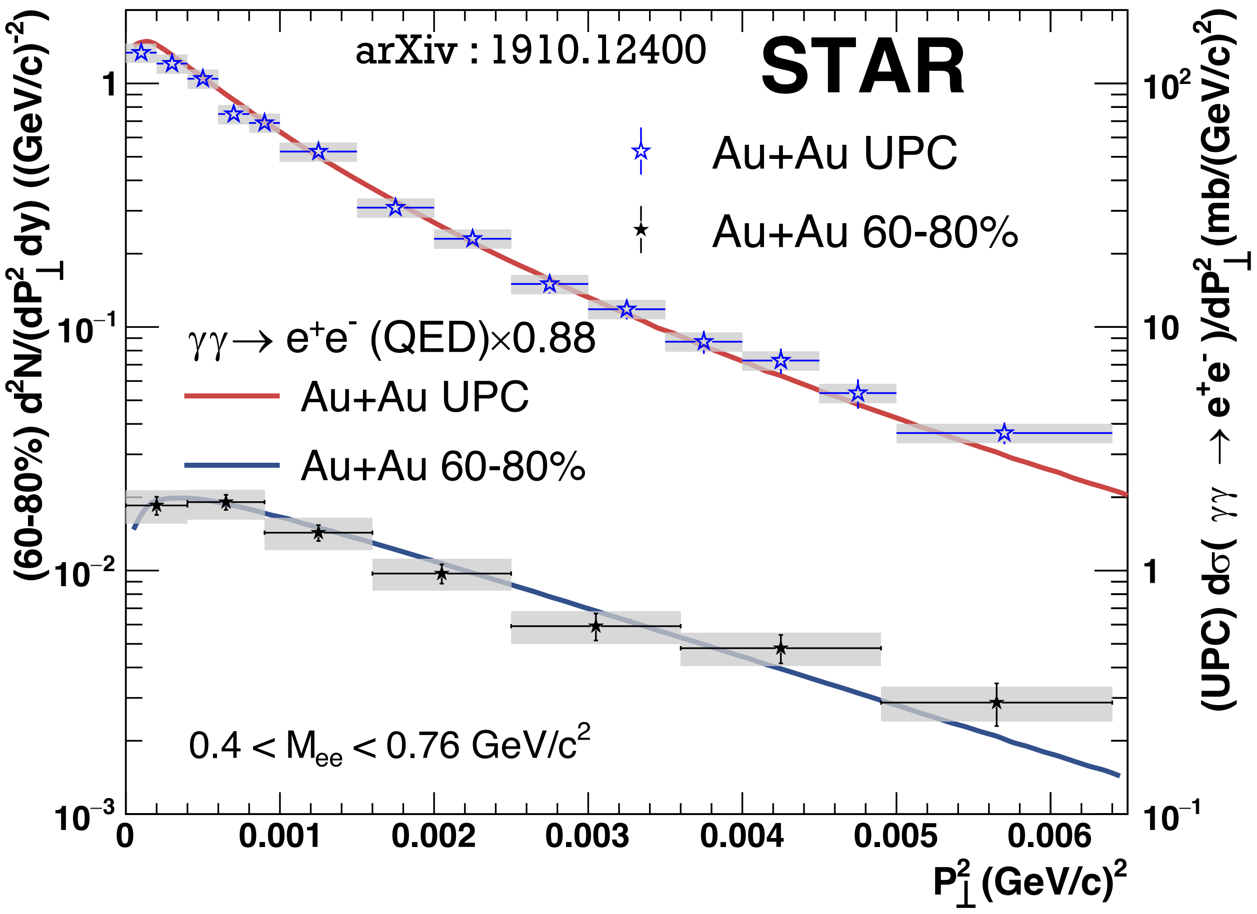


<u>Assumptions:</u>

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

$\gamma\gamma \rightarrow e^+e^-$: 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 $\gamma\gamma \rightarrow e^+e^-$ 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
- Due to additional final-state effects?
- Better statistics + higher precision is needed for a definitive conclusion

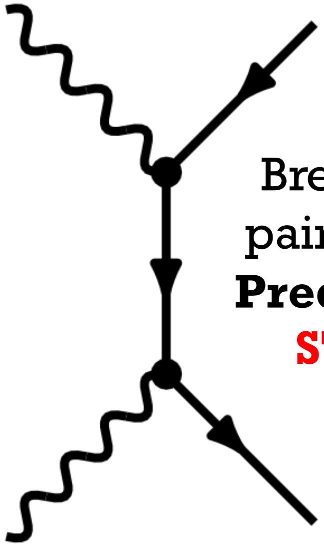
We have not yet compared QED calculation to the new, high precision data from ATLAS (from Quark Matter 2019) – should provide more insight

Summary & Conclusions

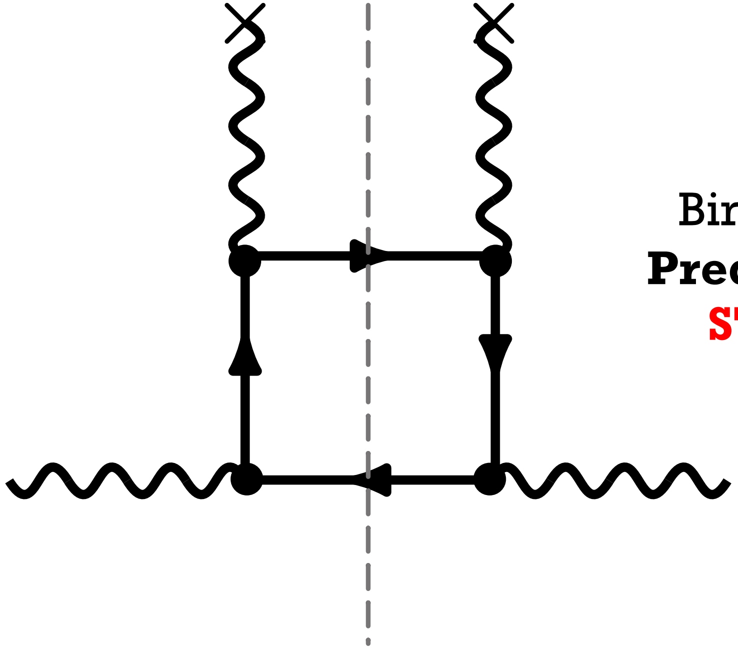
1. Measurements of exclusive $\gamma\gamma \rightarrow e^{+}e^{-}$ process
2. Experimental demonstration that the $\sqrt{\langle P_{\perp}^{2} \rangle}$ spectra from $\gamma\gamma \rightarrow l^{+}l^{-}$ **depends on impact parameter** (4.8σ observation)
3. **First Earth-based observation of Vacuum Birefringence :**
   Observed (6.7σ) via angular modulations in linear polarized $\gamma\gamma \rightarrow e^{+}e^{-}$ process

- Breit-Wheeler process in HICs (UPC and in hadronic collisions) provides a **new precision tool** for studying the magnetic field in Heavy-Ion Collisions
  - More data will help mapping the initial field strength in detail
  - Higher precision data needed to conclusively determine if there are medium effects

Thank you



Breit-Wheeler
pair production
Predicted 1934,
STAR 2019

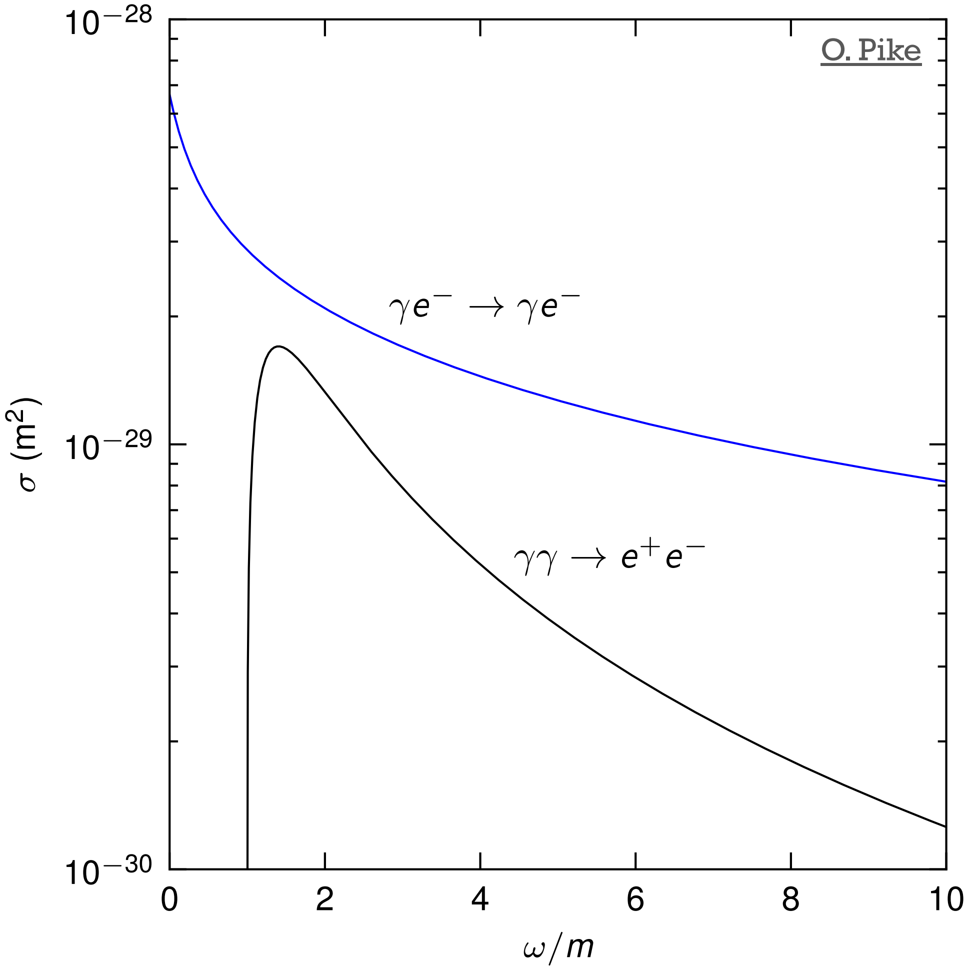


Vacuum
Birefringence
Predicted 1936,
STAR 2019

Extra Slides

Breit-Wheeler Process, why so *elusive*?

Breit-Wheeler and Klein-Nishina cross-sections



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

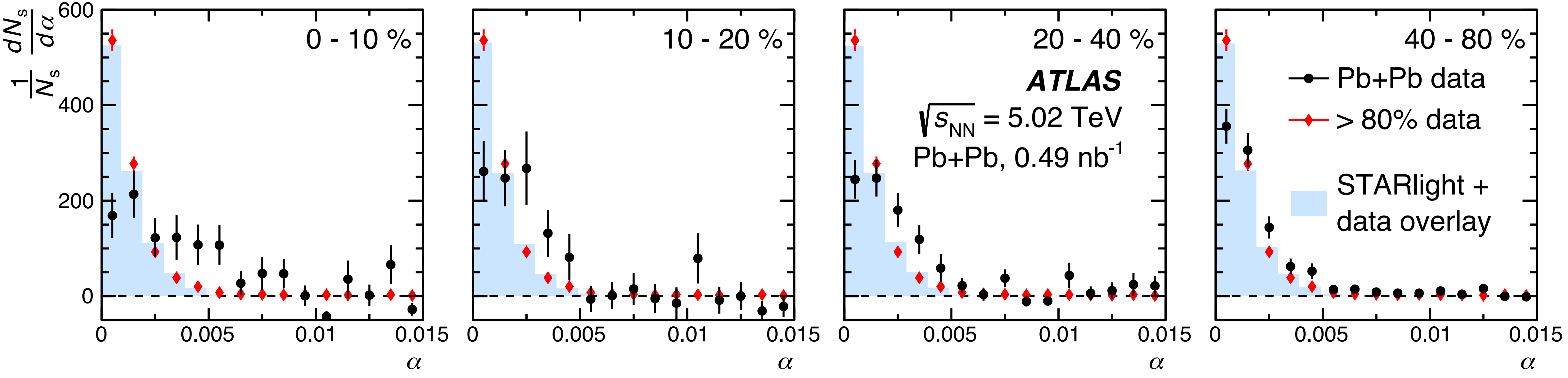
Breit-Wheeler Pair Production Cross Section $\sigma_{\gamma\gamma}$:

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

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

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

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

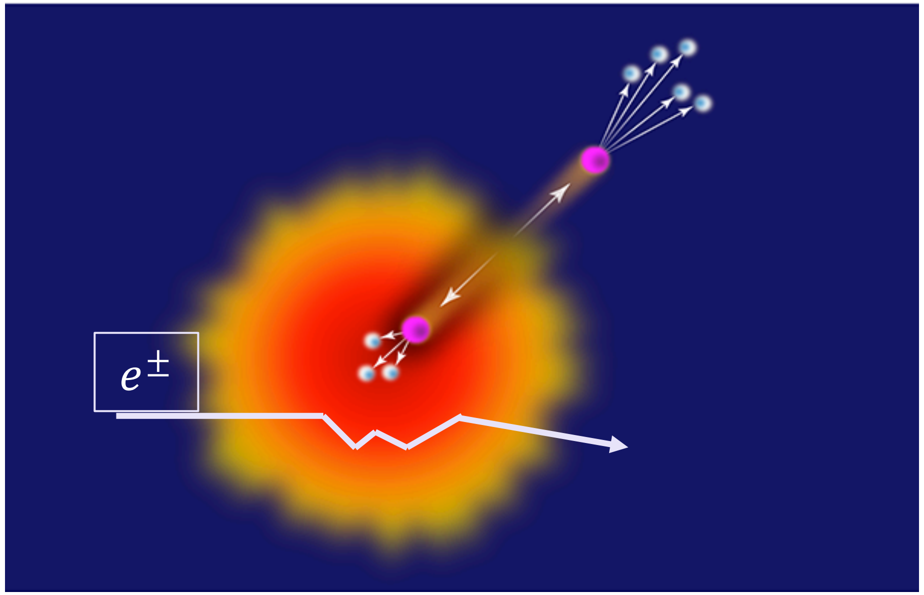
ATLAS Measurements:
$p_T^\mu > 4$ GeV/c
$4 < m_{\mu\mu} < 45$ GeV/c^2

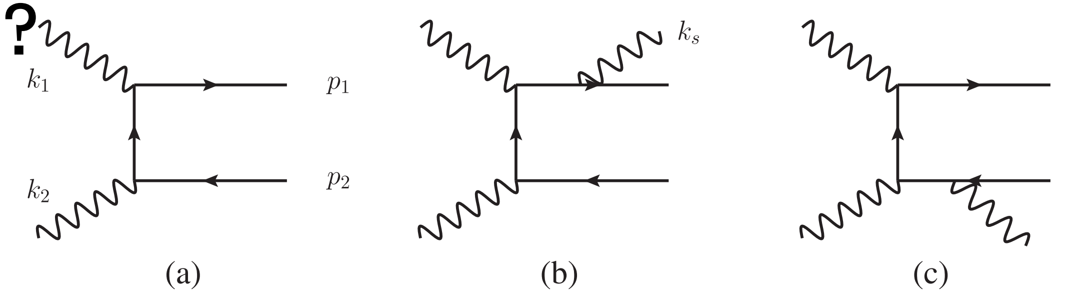
- Significant broadening observed in central collisions w.r.t > 80 % data

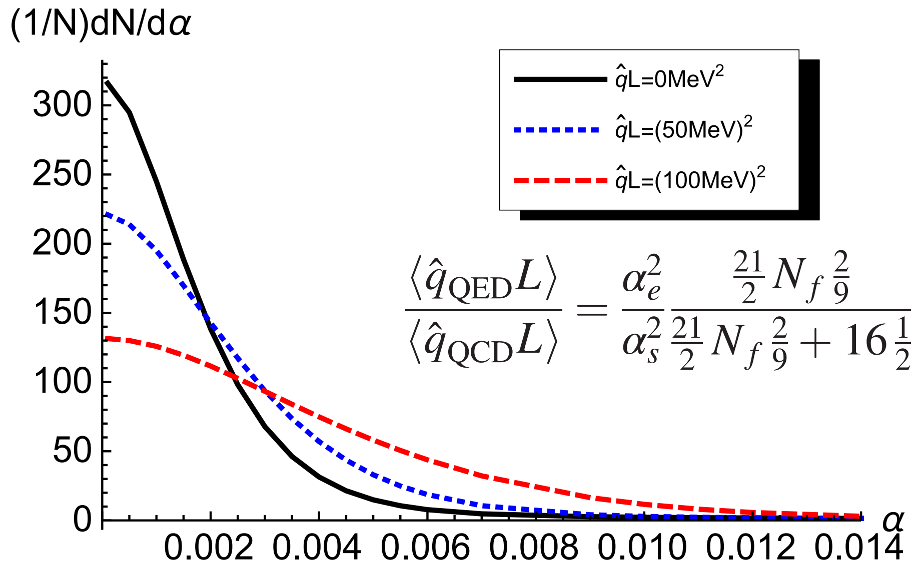
[1] S. R. Klein, et. al, Phys. Rev. Lett. 122, (2019), 132301
[2] ATLAS Phys. Rev. Lett. 121 (2018) , 212301

Coulomb Scattering through QGP

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







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

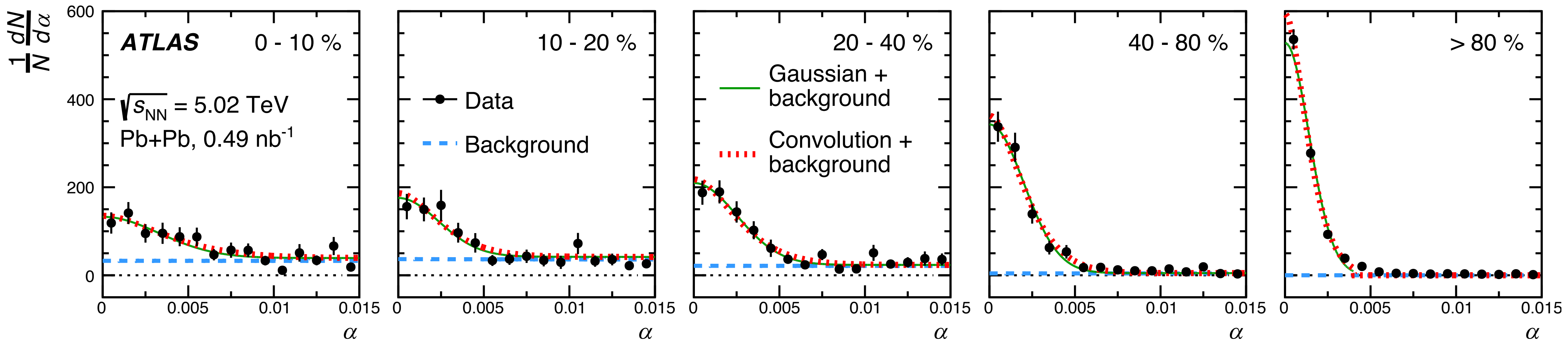
Assumptions:

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

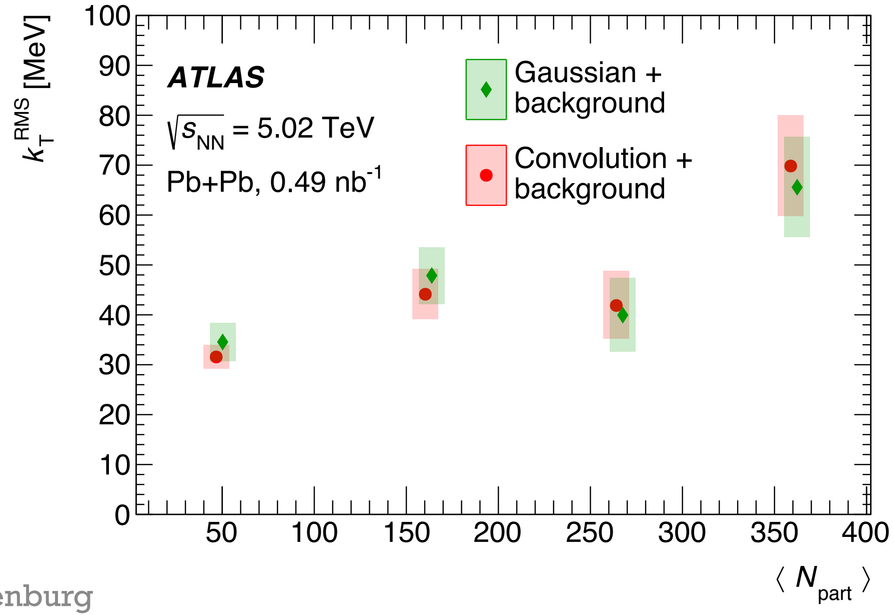
Motivation From STAR and ATLAS

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



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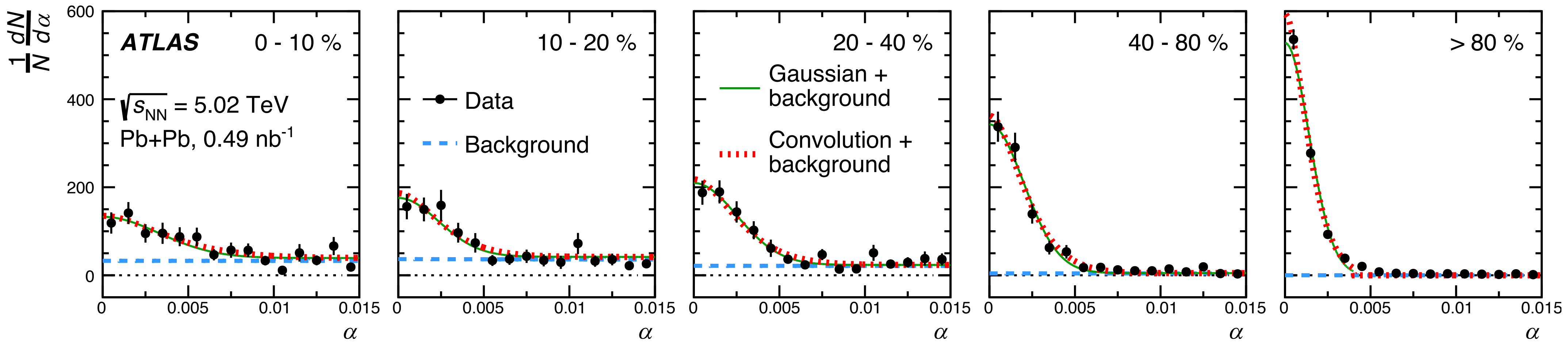

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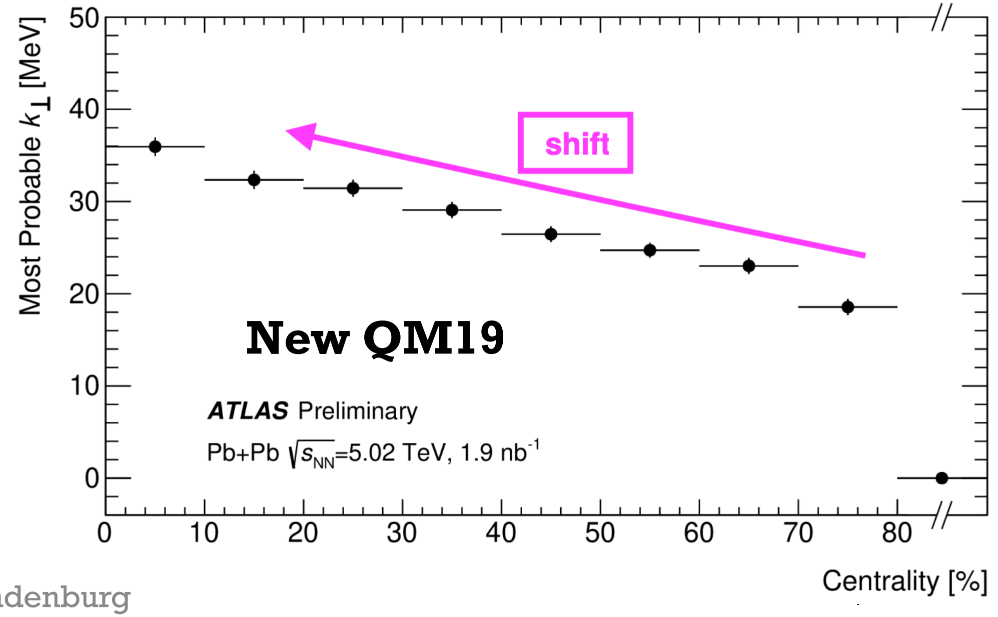
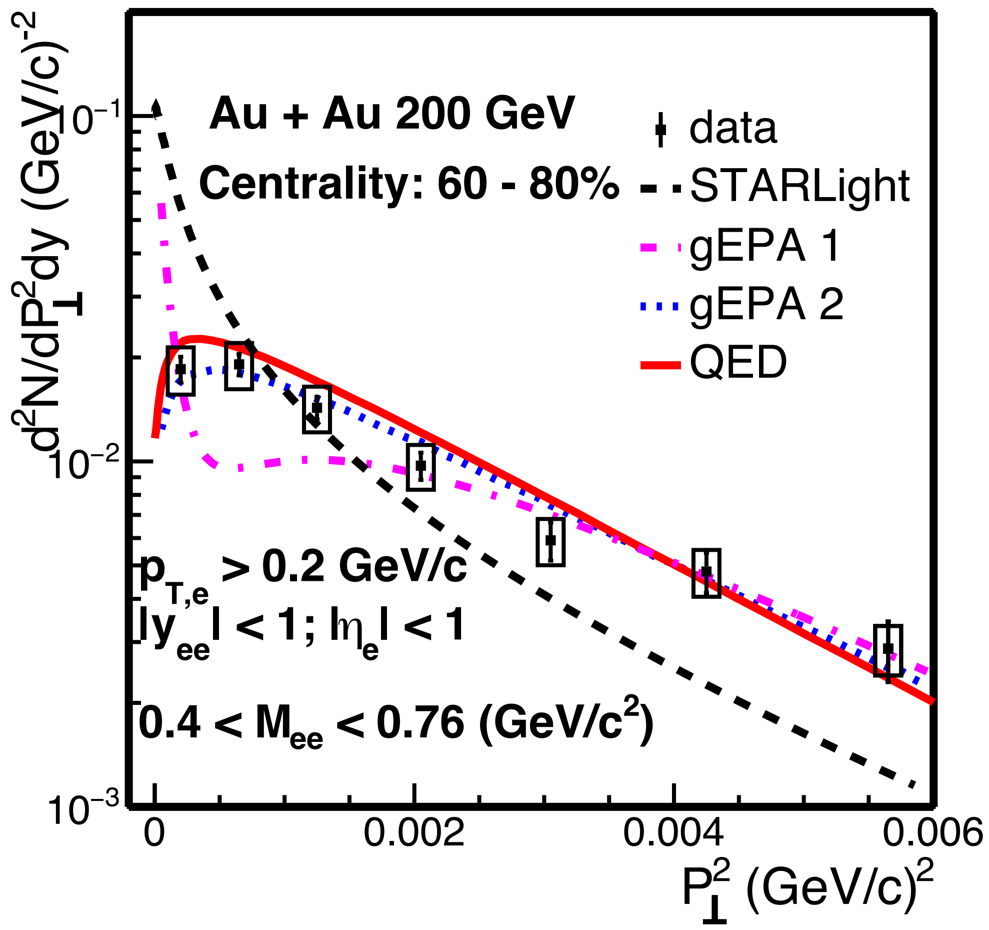
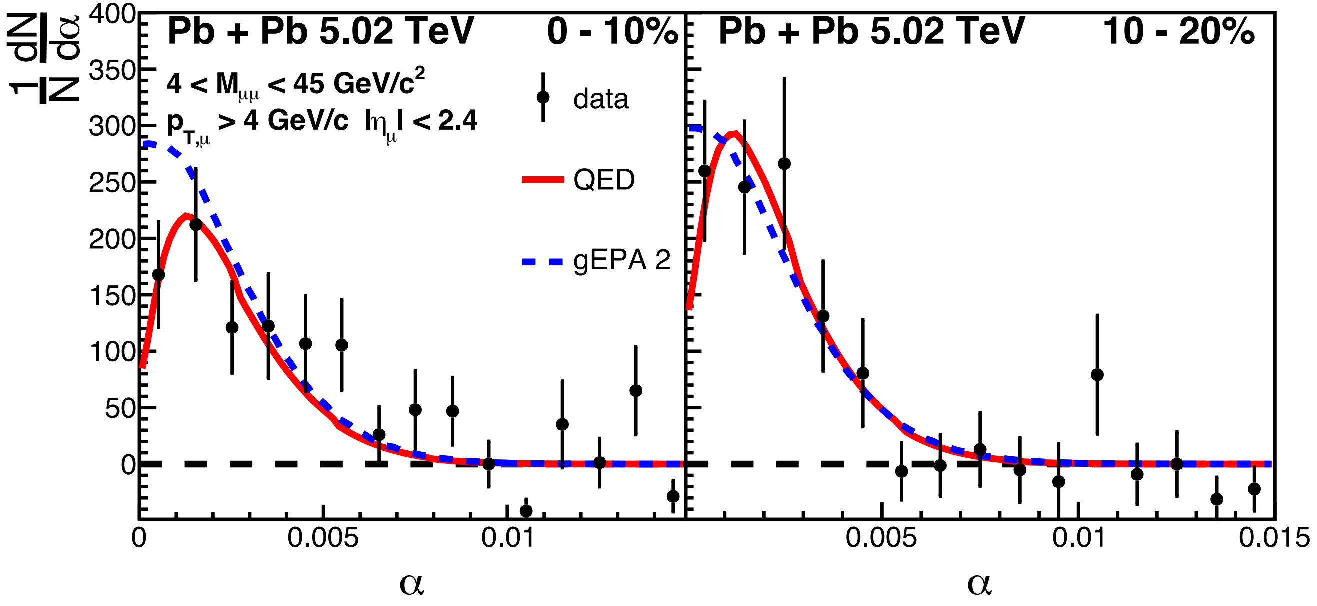


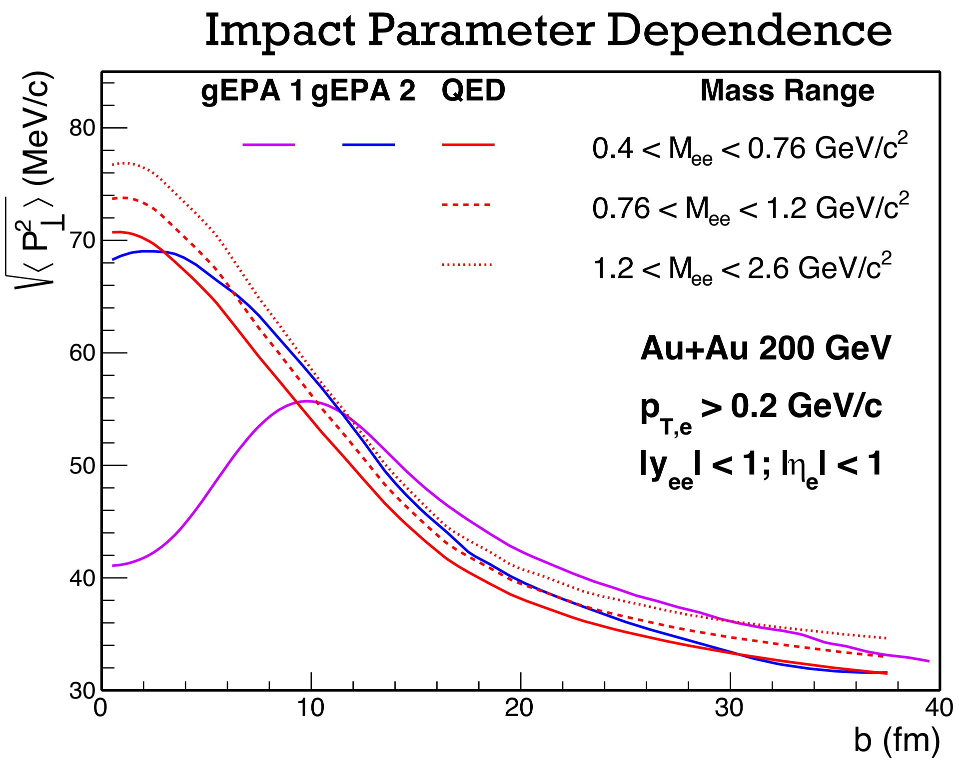
Peripheral Data

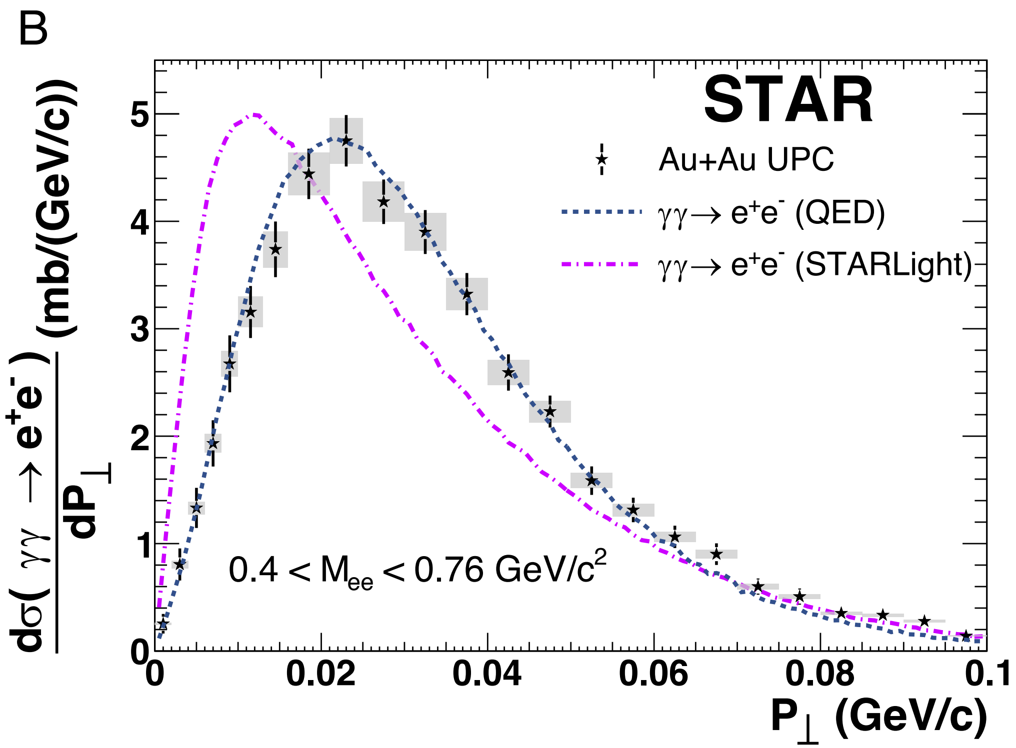




- Peripheral data from both STAR and ATLAS are well described by QED calculation
- → No need for final state effects?

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 in peripheral collisions**

Application : Mapping the Magnetic Field

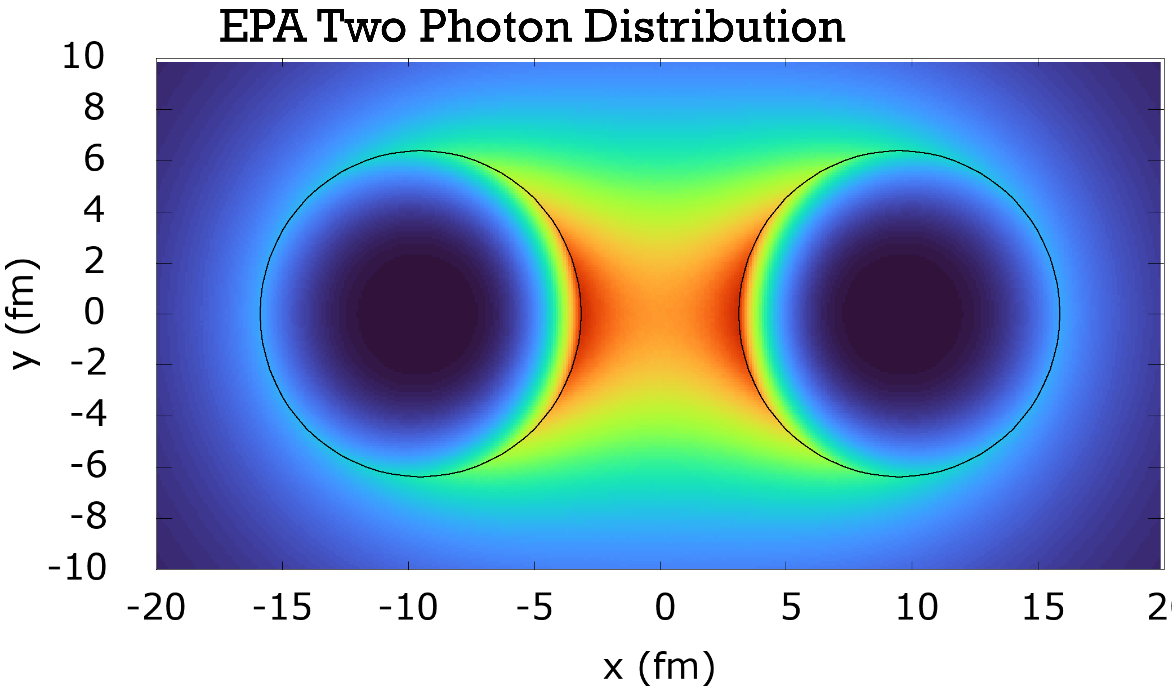
The colliding photons in the $\gamma\gamma \rightarrow e^+e^-$ process originate from the Lorentz-contracted Electromagnetic fields

photon density is related to energy flux of the electromagnetic fields

$$n \propto \vec{S} = \frac{1}{\mu_0}\ \vec{E}\times\vec{B}$$

For highly Lorentz contracted fields

$|E| \approx |B|$ with $\vec{E} \perp \vec{B}$ and $\vec{S} \propto |E|^2 \approx |B|^2$



Two-photon density (arb. norm.)

Uniformly Charged Sphere

Au ion, $R = 6.38$ fm

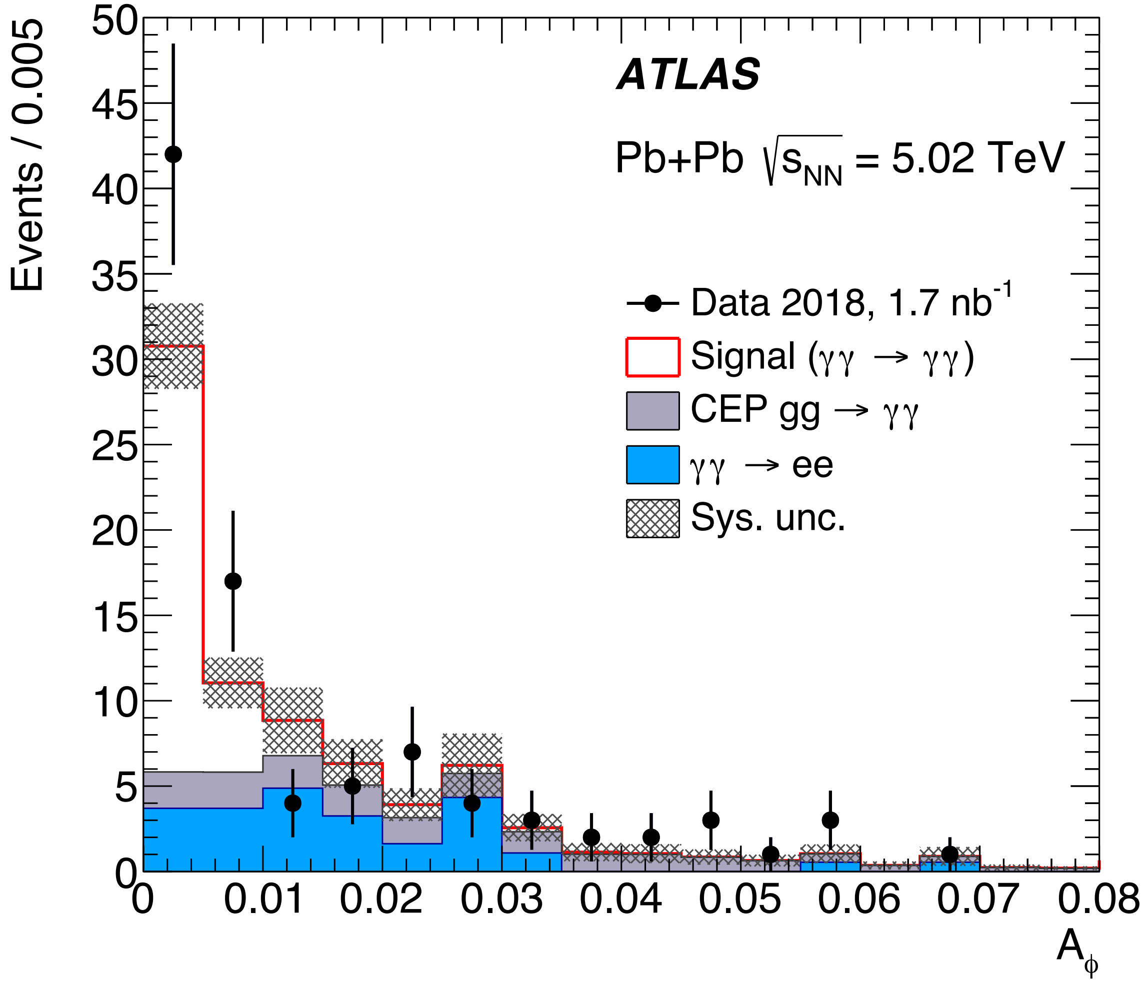
$b = 19$ fm

Equivalent Photon Approximation, photon density (single ion):

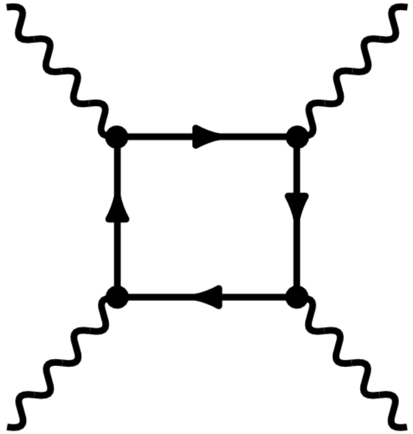
$$n(\omega; b) = \frac{1}{\pi\omega}|E_\perp(b,\omega)|^2 = \frac{1}{\pi\omega}|B_\perp(b,\omega)|^2 = \frac{4Z^2\alpha}{\omega}\left|\int \frac{d^2k_\perp}{(2\pi)^2} k_\perp \frac{F(k_\perp^2 + \omega^2/\gamma^2)}{k_\perp^2 + \omega^2/\gamma^2} e^{-i\, b\cdot k_\perp}\right|^2$$

[1] M. Vidović, *et al.*, *Phys. Rev. C* 47, 2308 (1993).
[2] C. F. v. Weizsäcker, *Z. Phys.* 88, 612 (1934).

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

Breit-Wheeler Process, why so *elusive*?

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

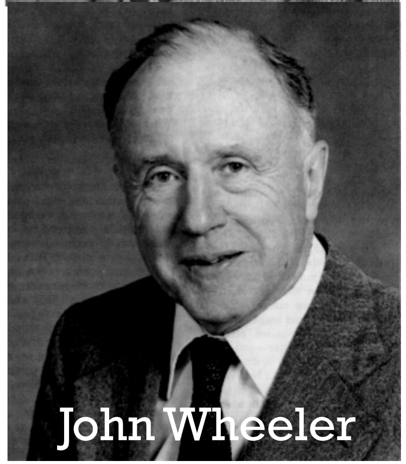
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME

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,



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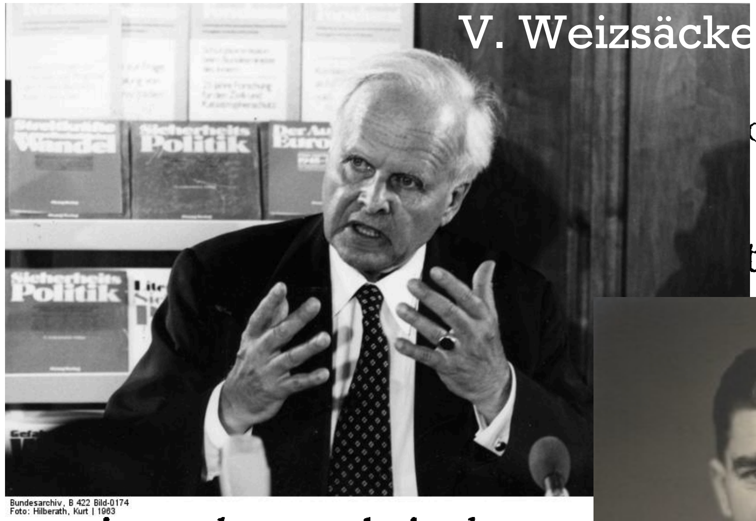

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meeting each other on a ... llness
of σ and the insufficiently ... sities
of quanta. In the considerations of Williams,

- 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 $h\nu$

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