Search for experimental observables sensitive to higher order QED

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X. Li et al., PLB 847 (2023) 138314

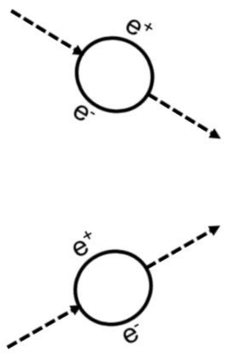
(Credit: Augusto / Adobe Stock)

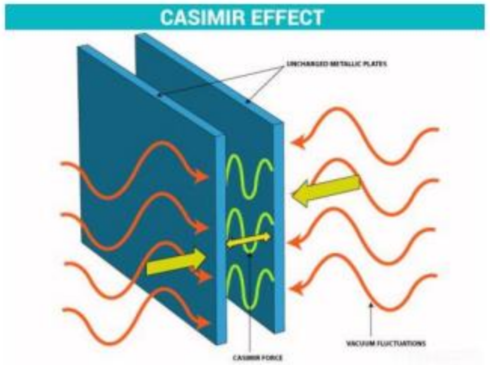
Outline

- QED vacuum “bubble”
- Vacuum pair production and vector meson photoproduction
- Vacuum is polarized
- “Invisible” higher order effect
- Observable candidates sensitive to higher order effect
- Summary

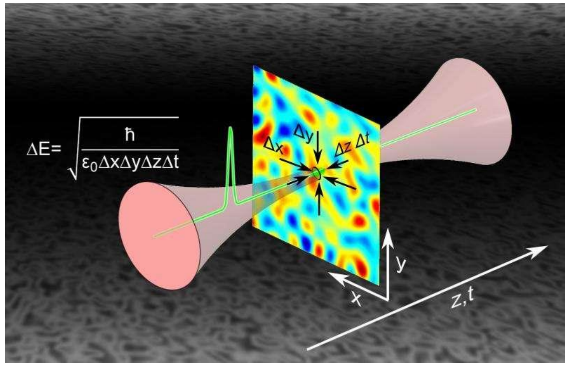
QED vacuum structure - Seeing is believing

- According to QFT, the vacuum contains short-lived pairs — vacuum bubbles.





H.B.G. Casimir Indag.Math. 10 (1948) 261-263



The vacuum is actually pretty "crowded".

The hadronic structure of a photon?

But how to see the structure?
— Extremely strong EM field !
— interaction with nuclei

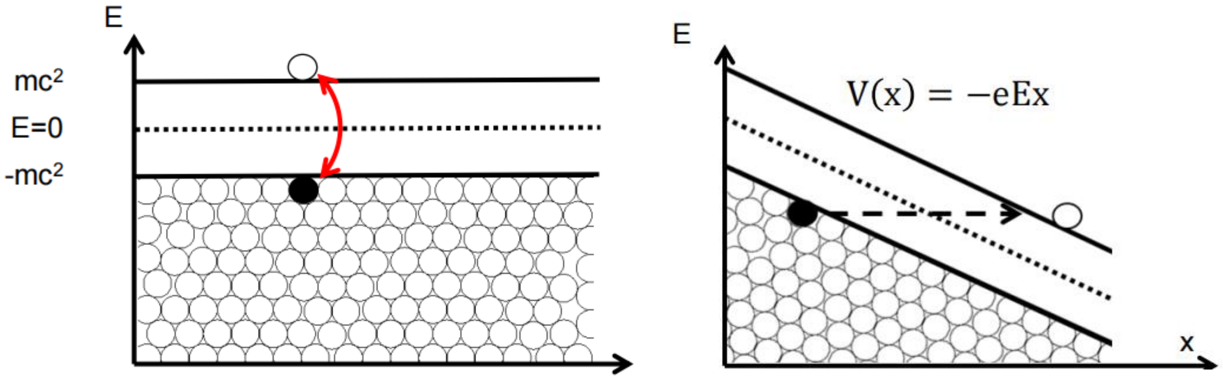
- The Schwinger Mechanism

Virtual pair "lifetime" $\Delta t = \hbar/2mc^2$.
Virtual pair "size" $\Delta l = 2\hbar/mc$.

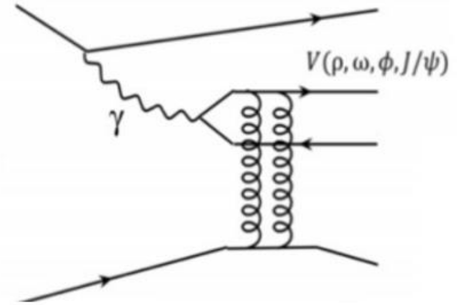
$eE_c\Delta l = 2mc^2$

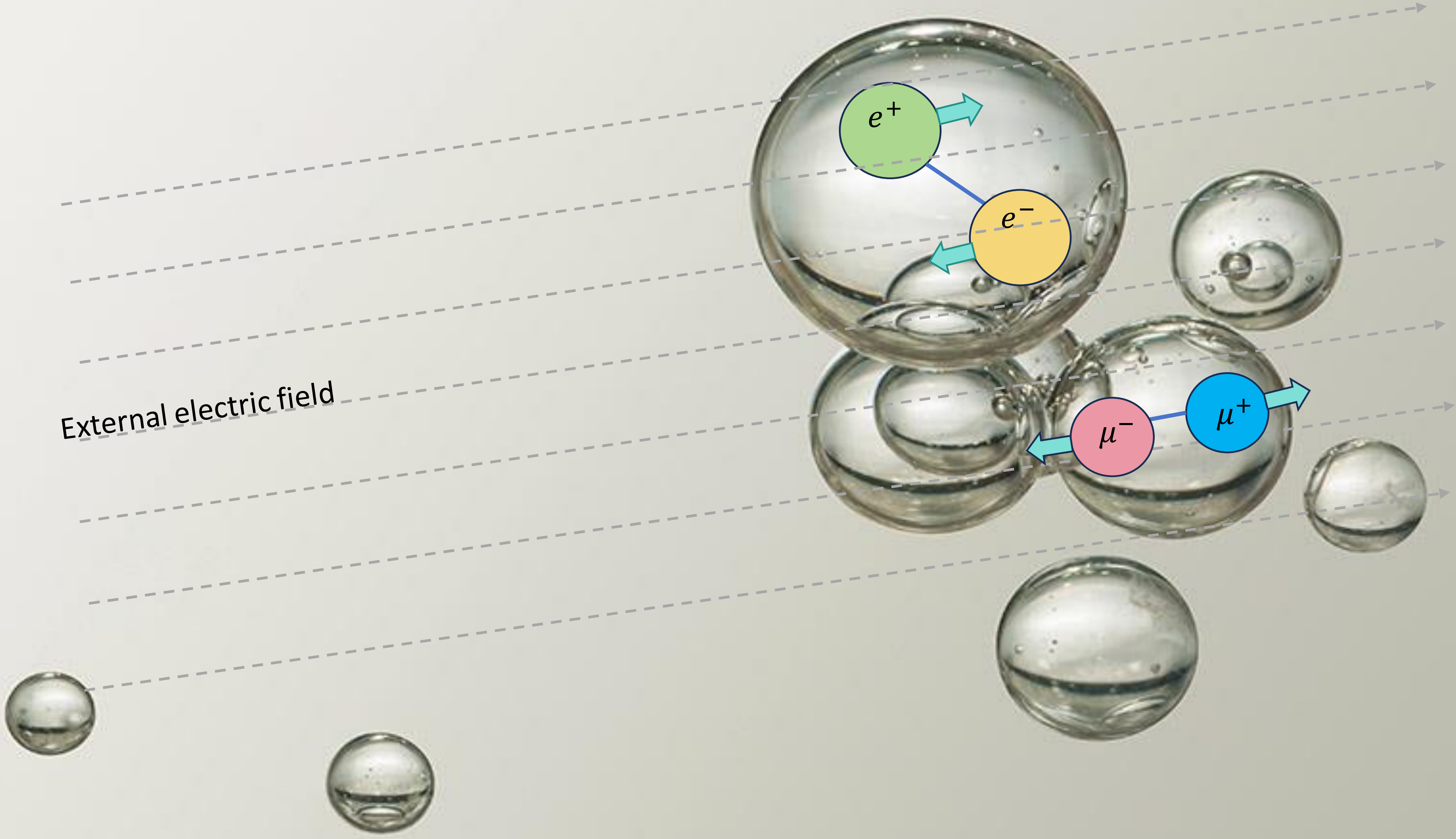
$E_c = 1.3 \times 10^{16}\ V/cm$

- Vacuum pair production



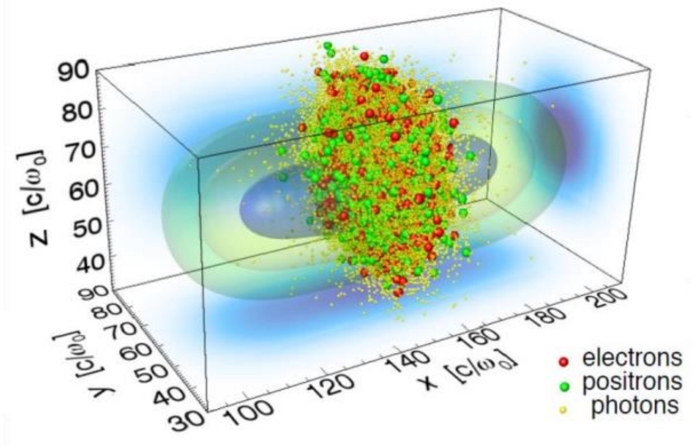
- Scattering off a nucleus




e^+
e^-
External electric field
μ^-
μ^+

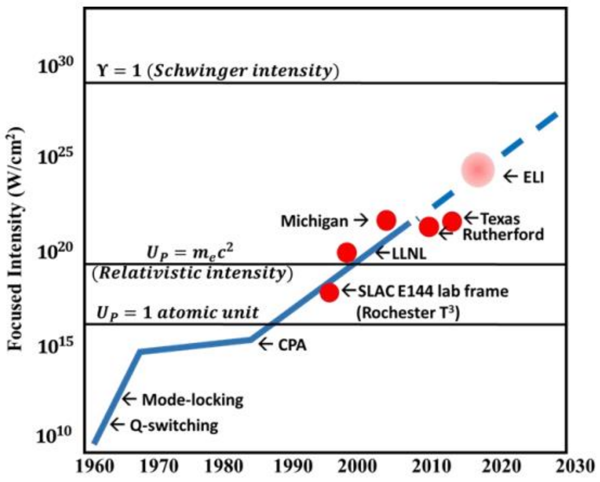
EM field and photoproduction

- Colliding laser beams in laboratory

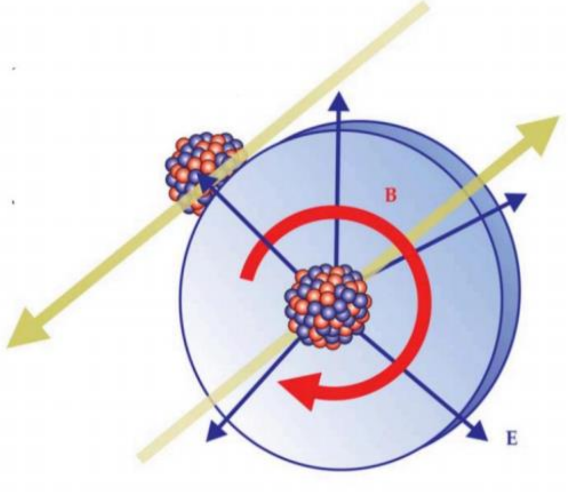


$$E_c = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16} V/cm$$

$$I_c = \frac{E_c^2}{4\pi} = 2.2 \times 10^{29} W/cm^2$$



- Extremely strong electromagnetic field in relativistic heavy ion collisions



At RHIC b=15 fm:

$$E_{Max} = 5.3 \times 10^{16} V/cm$$
$$I_{Max} = 9 \times 10^{29} W/cm^2$$

At LHC b=15 fm:

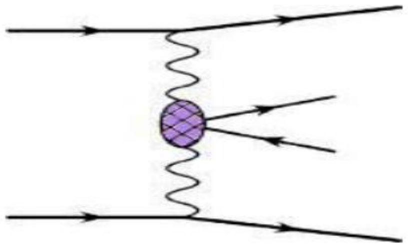
$$E_{Max} = 1.4 \times 10^{18} V/cm$$
$$I_{Max} = 2.4 \times 10^{31} W/cm^2$$

Four momentum vector of photon:

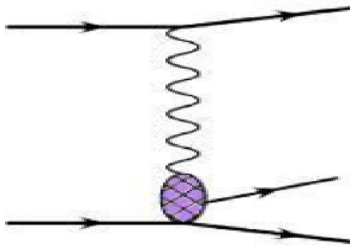
$q^\mu = (\omega, q_T, \omega/v)$

Quasi-real: $\frac{\omega^2}{\gamma^2} + q_T^2 \sim 0$

Photon-photon fusion



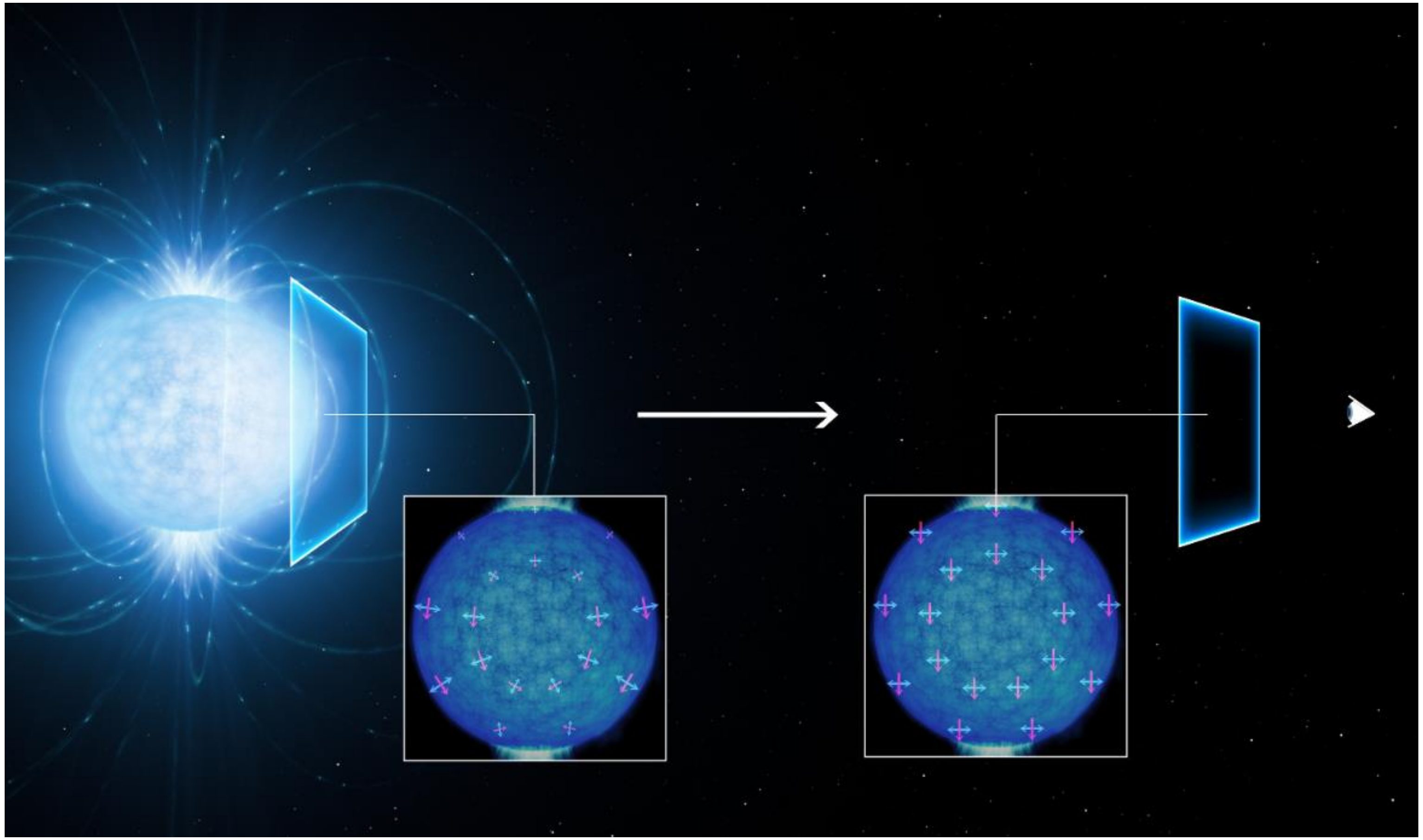
Photon-gluon fusion

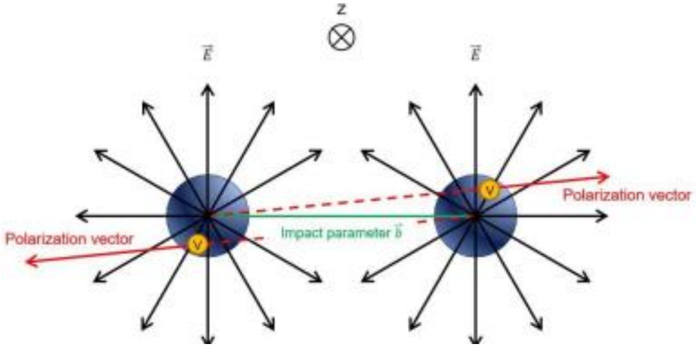


Physics Today 70(10) (2017) 40

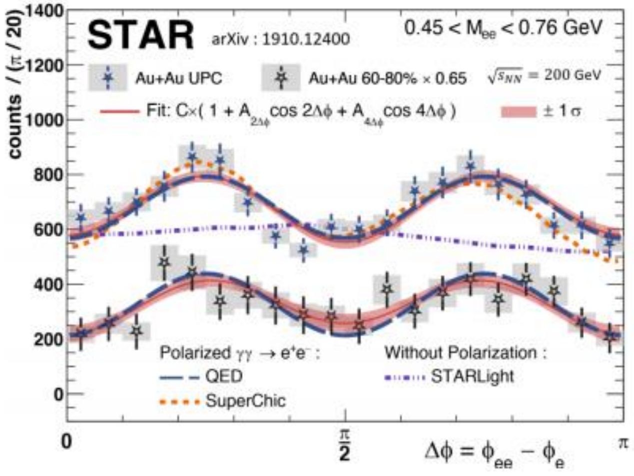
Vacuum is polarized!

- highly magnetised vacuum — a prism for the propagation of light





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

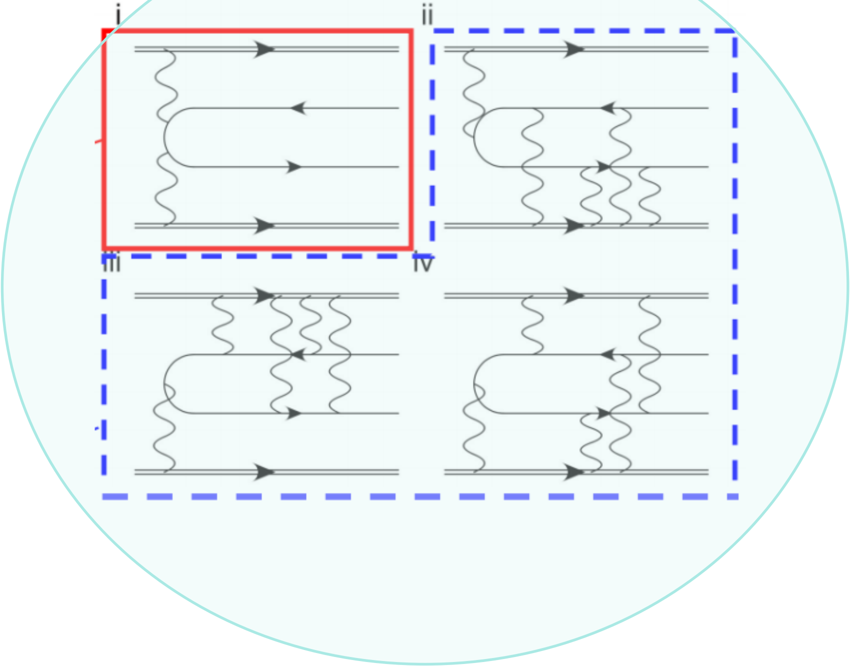


STAR Collaboration, PRL127 (2021) 052302

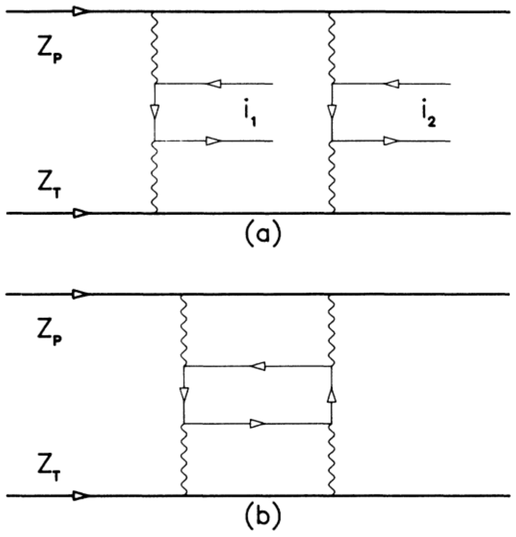
credit: ESO/L. Calçada.

“Invisible” higher order effect

Initial production:
Multi-photon

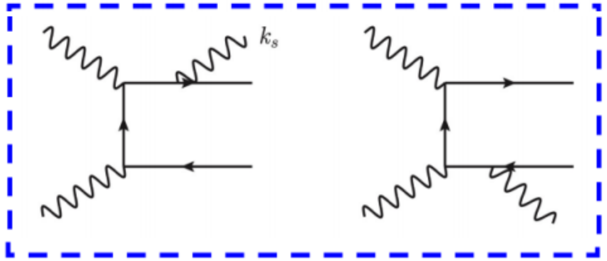


Multi-pairs



G. Baur, Phys. Rev. A 42, 5736 (1990)

Final state:
Photon radiation



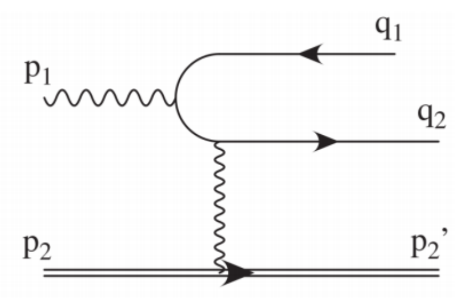
S.R. Klein, et al., Phys. Rev. D 102, 094013 (2020)

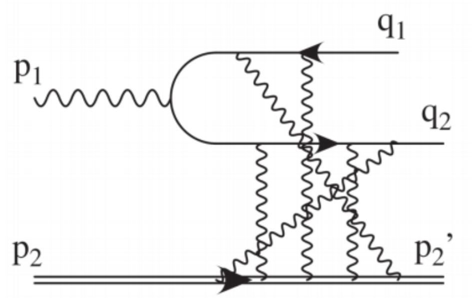
At RHIC and LHC $Z\alpha$ ~ 0.6 —— nonperturbative

Multi-photons contribute to “pull” one virtual pair onto the mass shell

"Invisible" higher order effect

- At RHIC and LHC $Z\alpha \sim 0.6$ —— nonperturbative





$$\sigma_{\rm BH} = \frac{28}{9}\frac{\alpha^3 Z^2}{m^2}\left(\log\frac{2\omega}{m} - \frac{109}{42}\right) \qquad \sigma = \frac{28}{9}\frac{\alpha^3 Z^2}{m^2}\left(\log\frac{2\omega}{m} - \frac{109}{42} - f(Z\alpha)\right)$$

$$f(Z\alpha) = \gamma_{\rm E} + Re\,\Psi(1 + iZ\alpha) = (Z\alpha)^2 \sum_{n=1}^{\infty} \frac{1}{n(n^2 + (Z\alpha)^2)}$$

H. A. Bethe, W. Heitler, Proc. Roy. Soc. Lond. A 146 (1934) 83
H.A. Bethe, L.C. Maximon, Phys. Rev. 93 (1954) 768

Sommerfeld-Manue type solution

Same results with the standard Feynman diagram approach.

Sizable negative correction!

In April 1990 a workshop took place in Brookhaven with the title 'Can RHIC be used to test QED?' [98]. We think that after about 17 years the answer to this question is 'no'. However, many theorists were motivated to deal with this

G. Baur, K. Hencken and D. Trautmann Phys. Rep. 453, 1 (2007)

to this question is 'no'" [26]. The present results indicate that the answer may turn out to be "yes."

A. J. Baltz, Phys. Rev. Lett. 100 (2008) 062302

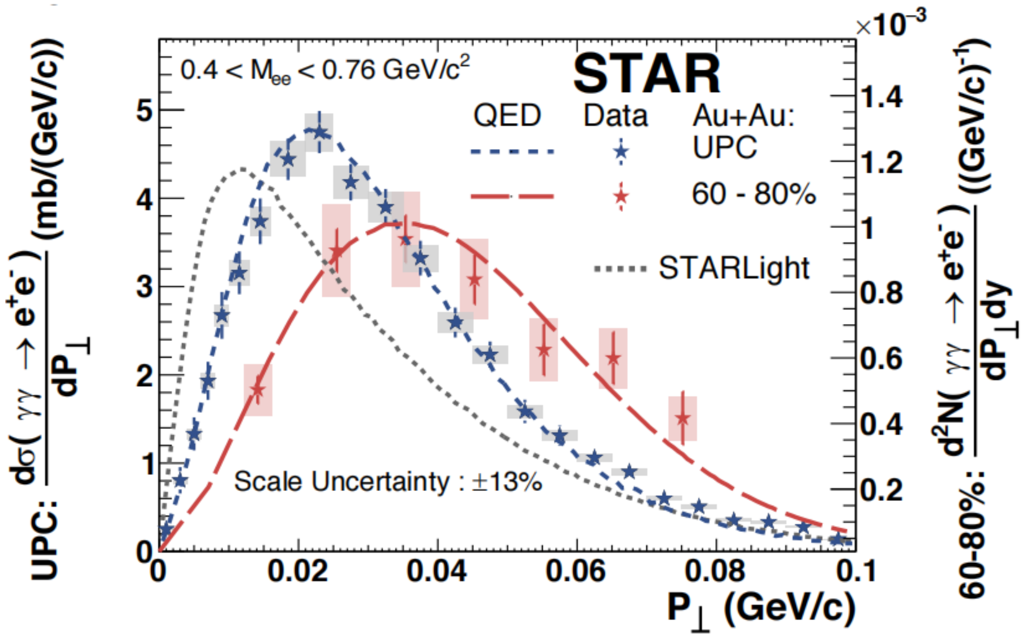
Life time of virtual pair > $10^5 \times$ duration time of strong field

Still perturbative…

"Invisible" higher order effect

Still well described by the lowest order calculation?

A.J. Baltz, et al., Phys. Rep. 458 (2008) 1
S.R. Klein, Phys. Rev. C 97 (5) (2018) 054903
M. Aaboud, et al., ATLAS Collaboration, Phys. Rev. Lett. 121 (21) (2018) 212301
J. Adam, et al., STAR Collaboration, Phys. Rev. Lett. 121 (13) (2018) 132301
The ATLAS collaboration, ATLAS Collaboration, ATLAS-CONF-2019-051
S. Lehner, ALICE Collaboration, arXiv:1909.02508 [nucl-ex]
S. Klein, A.H. Mueller, B.W. Xiao, F. Yuan, Phys. Rev. Lett. 122 (13) (2019) 132301



Multi-pair production?

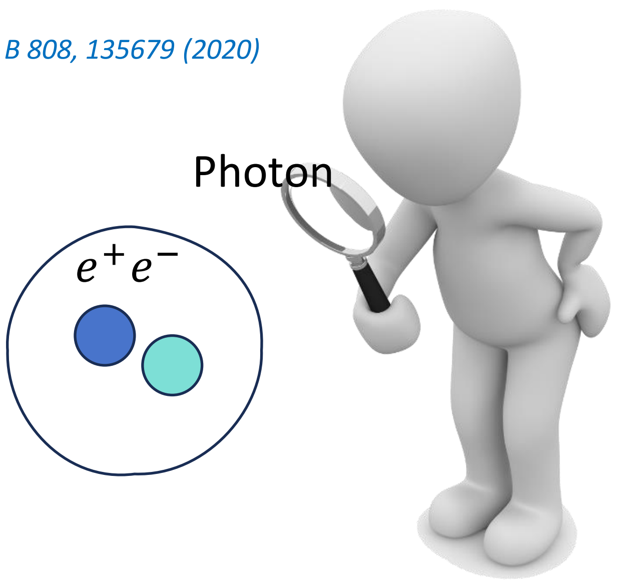
lowest order perturbation theory may violate unitarity

G. Baur, Phys. Rev. A 42, 5736 (1990)
M. J. Rhoades-Brown and J. Weneser, Phys. Rev. A 44, 330 (1991)

Coulomb effects cancel exactly

behave as a neutral object (point like approx.)

Z.-h. Sun, et al., Phys. Lett. B 808, 135679 (2020)



Theoretical setup for pair production

Straight line approximation

$$A_\mu^{(1,2)}(q) = -2\pi Z e \mu_\mu^{(1,2)} \delta(q\mu^{(1,2)}) \frac{f(q^2)}{q^2} \exp(\pm \mathrm{iqb}/2)$$

The matrix element

$$\begin{aligned}\hat{M} = &-ie^2 \int \frac{d^4 q_1}{(2\pi)^4} A\!\!\!/^{(1)}(q_1) \frac{p\!\!\!/_- - q\!\!\!/_1 + m}{(p_- - q_1)^2 - m^2} A\!\!\!/^{(2)}(p_+ + p_- - q_1) \\ &- ie^2 \int \frac{d^4 q_1}{(2\pi)^4} A\!\!\!/^{(2)}(p_+ + p_- - q_1) \frac{q\!\!\!/_1 - p\!\!\!/_+ + m}{(q_1 - p_+)^2 - m^2} A\!\!\!/^{(1)}(q_1) \\ = &-i(\frac{Ze^2}{2\pi})^2 \frac{1}{2\beta} \int d^2 q_{1\perp} \frac{1}{q_1^2} \frac{1}{(p_+ + p_- - q_1)^2} \exp(\mathrm{i} q_{1\perp} \mathrm{b}) \\ &\{ \frac{\psi\!\!\!/^{(1)}(p\!\!\!/_- - q\!\!\!/_1 + m)\psi\!\!\!/^{(2)}}{[(p_- - q_1)^2 - m^2]} + \frac{\psi\!\!\!/^{(2)}(q\!\!\!/_1 - p\!\!\!/_+ + m)\psi\!\!\!/^{(1)}}{[(q_1 - p_+)^2 - m^2]} \},\end{aligned}$$

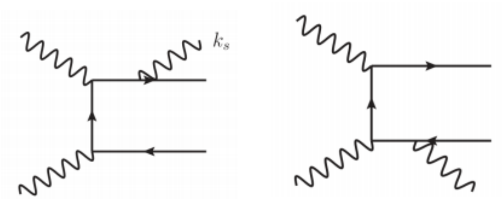
$$P(p_+, p_-, b) = \sum_s |M|^2$$

Higher order introduced

$$F(k) = \int d^2 r_\perp \exp(-\mathrm{i} k r_\perp) \{\exp[-\mathrm{i}\chi(\mathrm{r}_\perp)] - 1\} \qquad \chi(r_\perp) = \int_{-\infty}^{+\infty} dz V(r_\perp, z)$$

$$F(k) = \int d^2 r_\perp \exp(-\mathrm{i} k r_\perp)[\exp(-2\mathrm{i} z\alpha \ln r_\perp) - 1] \quad V(r_\perp, z) = -Z\alpha/\sqrt{r_\perp^2 + z^2}$$

Another type of higher order: soft photon radiation



$$\int \frac{d^2 r_\perp}{(2\pi)^2} e^{i r_\perp \cdot q_\perp} e^{-S(Q, r_\perp)} \int d^2 q'_\perp e^{i r_\perp \cdot q'_\perp} d\sigma_0(q'_\perp, \ldots)$$

$$S(Q, r_\perp) = \begin{cases} \frac{\alpha_e}{2\pi} \ln^2 \frac{Q^2}{\mu_r^2}, & \mu_r > m_\mu \\ \frac{\alpha_e}{2\pi} \ln \frac{Q^2}{m_\mu^2} \left[\ln \frac{Q^2}{\mu_r^2} + \ln \frac{m_\mu^2}{\mu_r^2} \right], & \mu_r < m_\mu \end{cases}$$

Bowen Xiao et al., Phys. Rev. Lett. 122 (2019) 132301

optical Glauber model: no hadronic interaction, neutron Skin

$$m_H(b) = \int d^2 r_\perp T_A(r_\perp - b)\{1 - \exp[-\sigma_{\mathrm{NN}} \mathrm{T_A}(\mathrm{r}_\perp)]\}$$

$$\rho_N(r) = \frac{Z}{A}\rho_p(r) + \frac{N}{A}\rho_n(r) \qquad P_H(b) = \exp[-\mathrm{m_H(b)}]$$

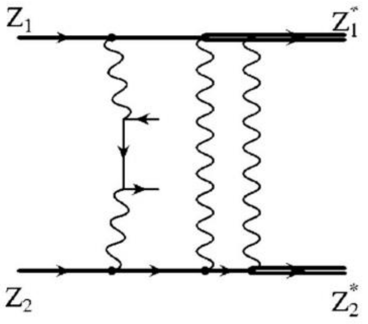
Mutual Coulomb Dissociation

$$m_{Xn}(b) = \int dk n(b, E) \sigma_{\gamma A \to A^*}(E)$$

$$P_{0n}(b) = e^{-m_{Xn}(b)}$$

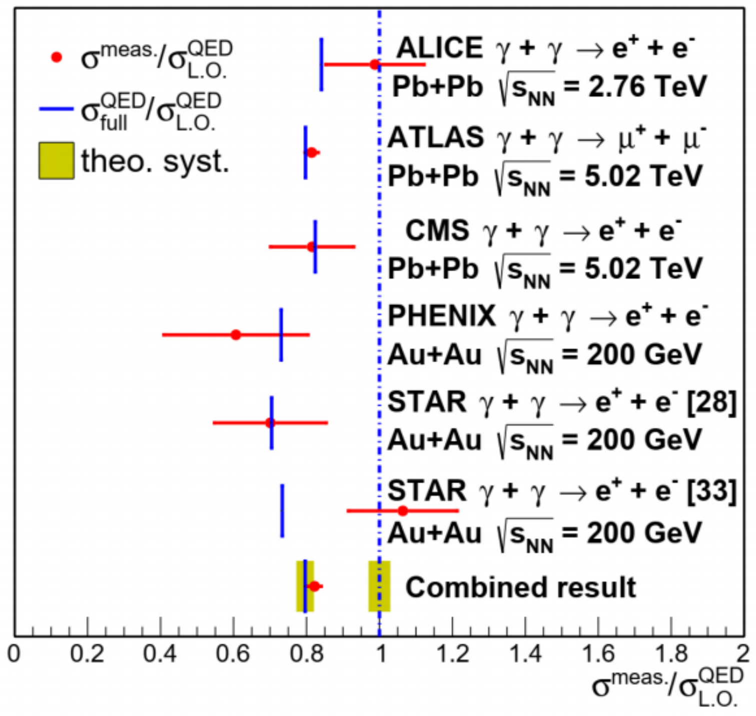
$$P_{XnXn}(b) = (1.0 - e^{-m_{Xn}(b)})^2,$$

$$P_{0nXn}(b) = 2(1.0 - e^{-m_{Xn}(b)}) e^{-m_{Xn}(b)}$$



A meaningful step on a long journey

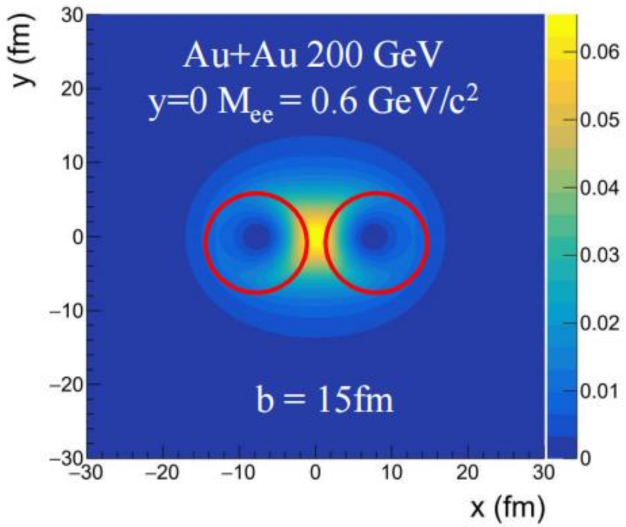
5.2 σ deviation from the lowest QED



STAR, Phys. Rev. C 70 (2004) 031902.
STAR, STAR, Phys. Rev. Lett. 127 (2021) 052302
PHENIX, Phys. Lett. B 679 (2009) 321.
ALICE, Eur. Phys. J. C 73 (2013) 2617.
CMS, Phys. Lett. B 797 (2019) 134826.
ATLAS , arXiv (2020) [2011.12211]

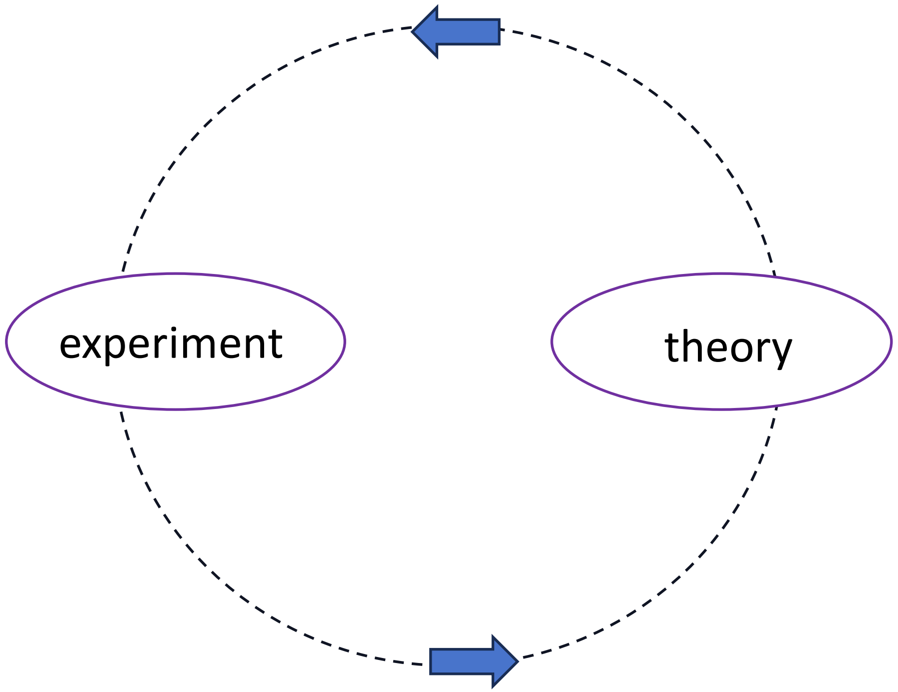
Point-like approximation
Photon flux in STARlight

$$n(\omega, r_\perp) = \frac{Z^2\alpha}{\pi^2 \omega r_\perp^2} x^2 K_1^2(x), x = \omega r_\perp/\gamma$$



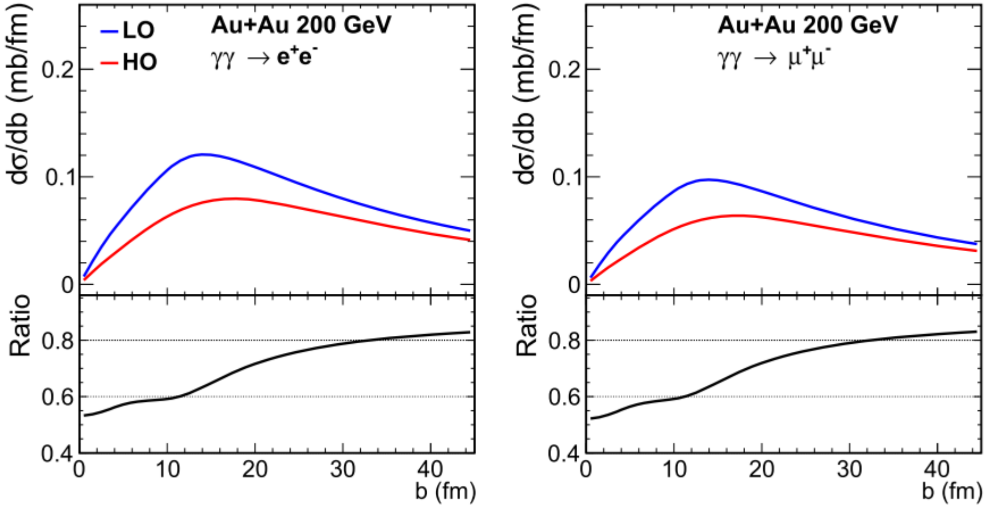
Missing production within nuclei
compensate with higher order effect

More experimental precise measurements
More theoretical investigation

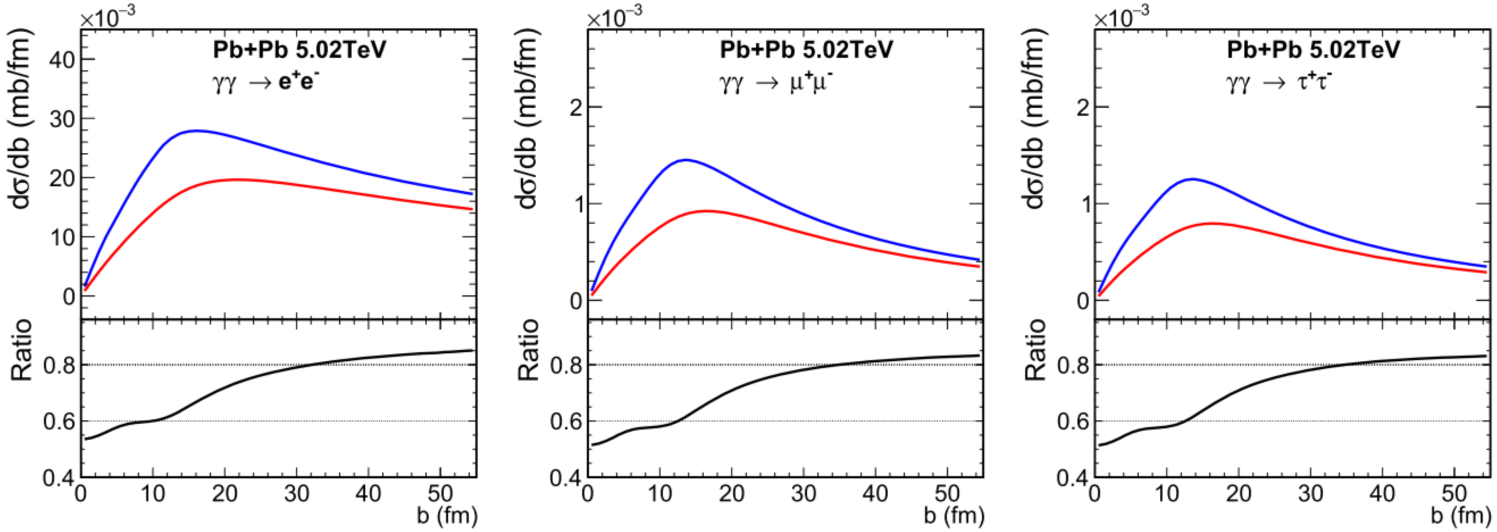


In search of sensitive observables

Differential cross-section:



(a) $\gamma\gamma \rightarrow e^+e^-$ in Au+Au $\sqrt{s_{NN}} = 200$ GeV (b) $\gamma\gamma \rightarrow \mu^+\mu^-$ in Au+Au $\sqrt{s_{NN}} = 200$ GeV



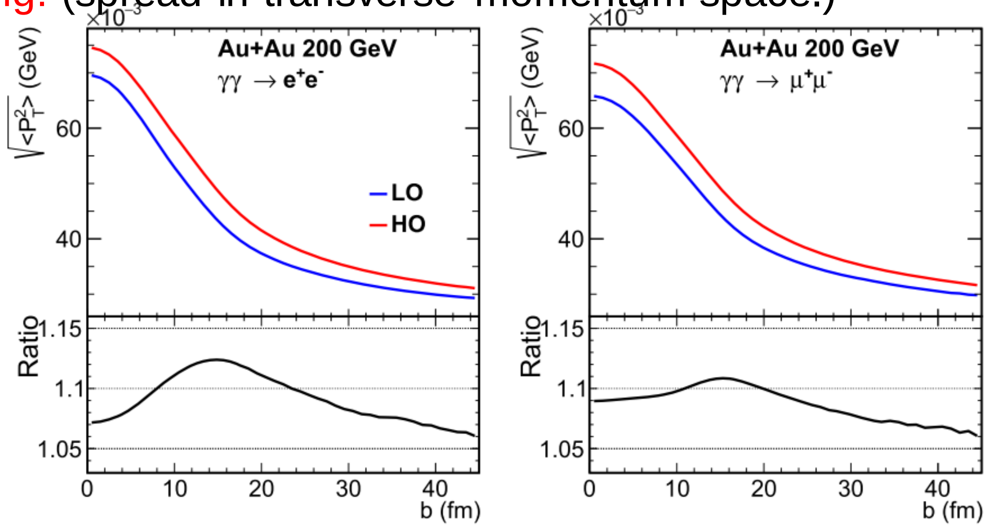
(c) $\gamma\gamma \rightarrow e^+e^-$ in Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV (d) $\gamma\gamma \rightarrow \mu^+\mu^-$ in Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV (e) $\gamma\gamma \rightarrow \tau^+\tau^-$ in Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV

- Evaluate the higher order (HO) effects differentially.
- Qualify the sensitivity by calculating the ratio of higher order results to lowest order results.
- Prediction for e, μ, τ pairs production in RHIC and LHC energies.

The intensification of the electromagnetic field towards small impact parameters.

In search of sensitive observables

P_T broadening: (spread in transverse momentum space.)



(a) $\gamma\gamma \to e^+e^-$ in Au+Au $\sqrt{s_{NN}}$ = 200 GeV (b) $\gamma\gamma \to \mu^+\mu^-$ in Au+Au $\sqrt{s_{NN}}$ = 200 GeV

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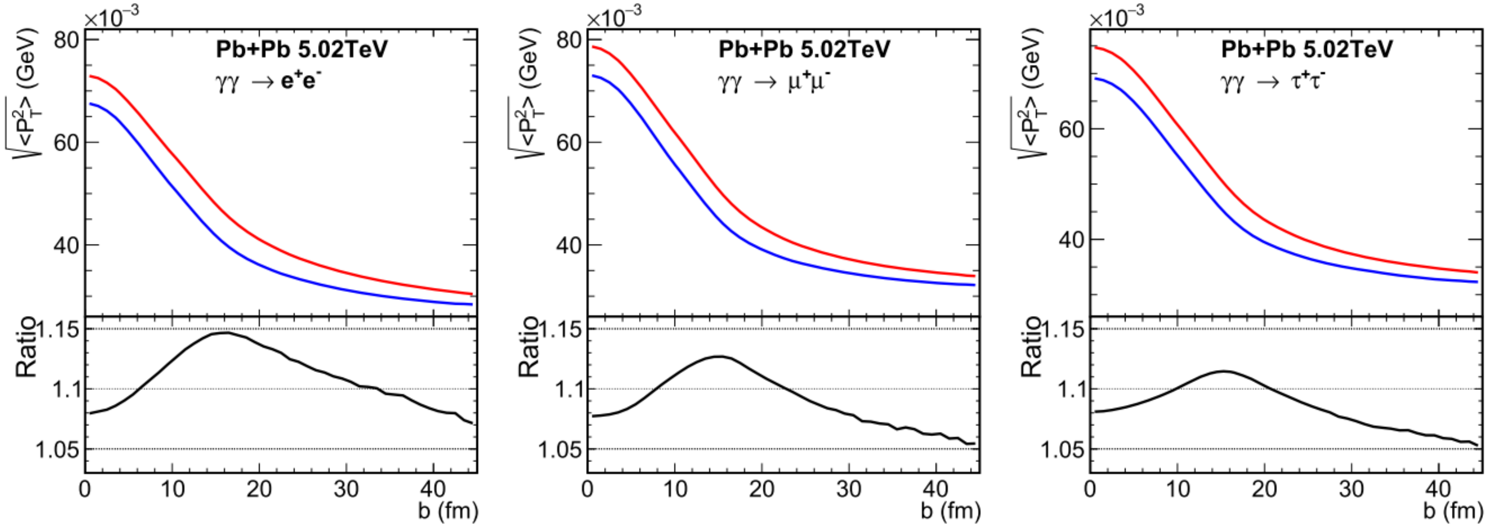
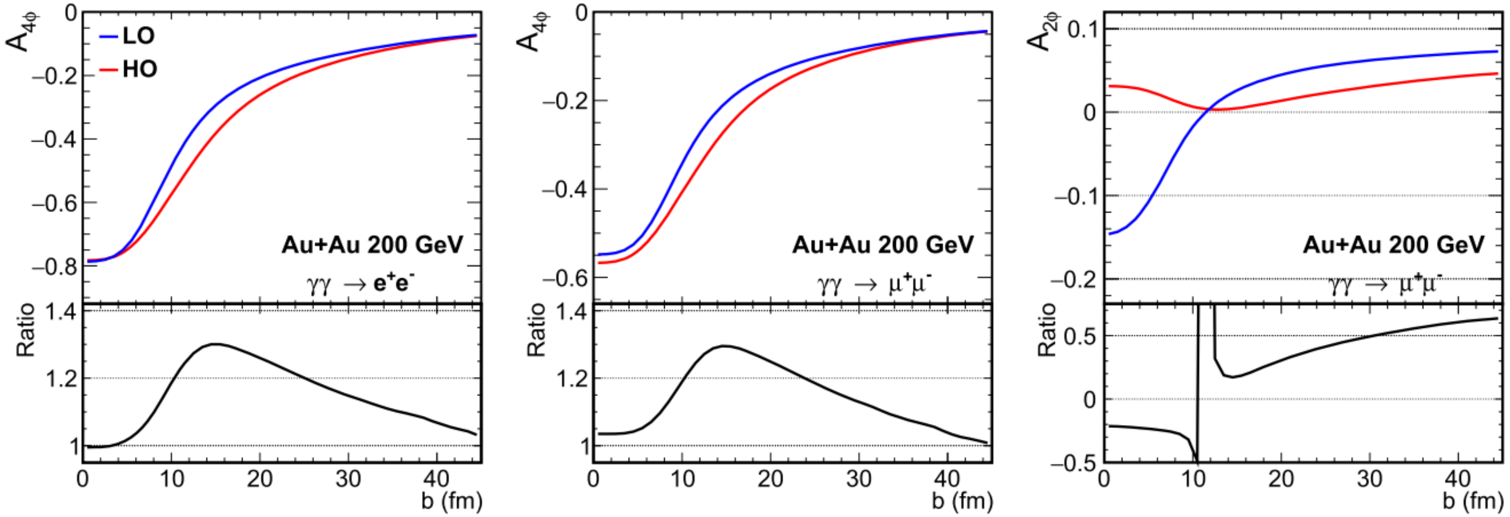


(c) $\gamma\gamma \to e^+e^-$ in Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV (d) $\gamma\gamma \to \mu^+\mu^-$ in Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV (e) $\gamma\gamma \to \tau^+\tau^-$ in Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV

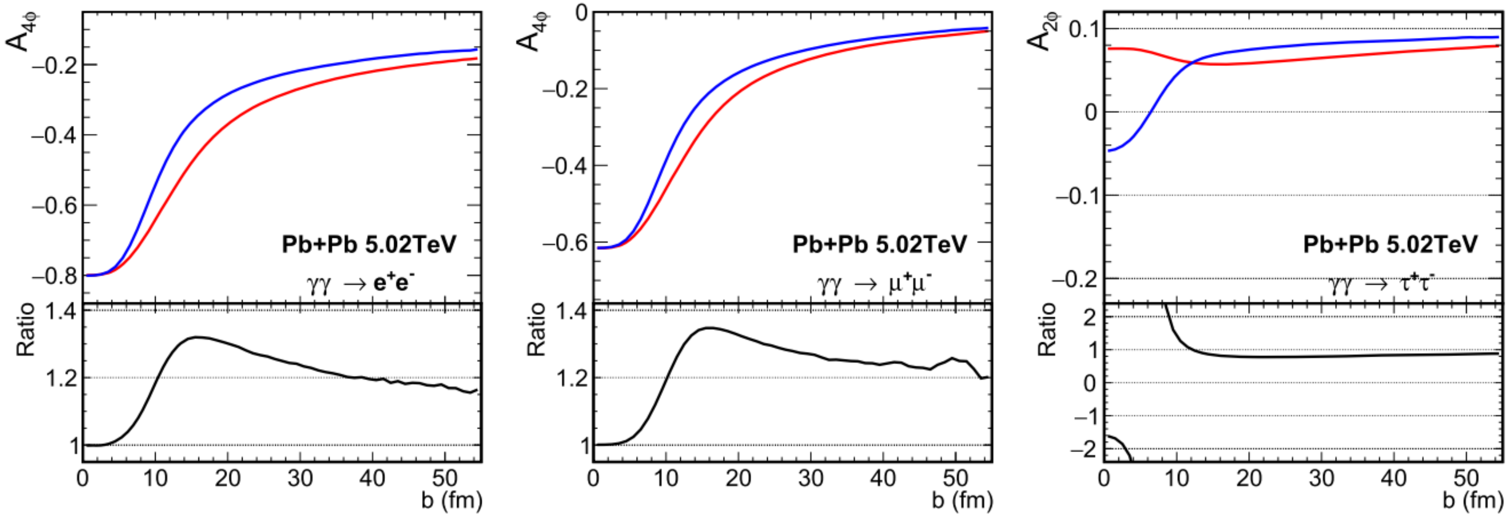
A prominent peak structure near 15 fm.
Around 2 times radius of nuclei.

In search of sensitive observables

Amplitude of cos2ϕ and cos4ϕ modulation:



(a) $A_{4\phi}$ for $\gamma\gamma \to e^+e^-$ in Au+Au 200 GeV (b) $A_{4\phi}$ for $\gamma\gamma \to \mu^+\mu^-$ in Au+Au 200 GeV (c) $A_{2\phi}$ for $\gamma\gamma \to \mu^+\mu^-$ in Au+Au 200 GeV



(d) $A_{4\phi}$ for $\gamma\gamma \to e^+e^-$ in Pb+Pb 5.02 TeV (e) $A_{4\phi}$ for $\gamma\gamma \to \mu^+\mu^-$ in Pb+Pb 5.02 TeV (f) $A_{2\phi}$ for $\gamma\gamma \to \tau^+\tau^-$ in Pb+Pb 5.02 TeV

A distinct flip for $A_{2\phi}$

$$A_{2\phi} \propto \frac{4m^2 \Delta P_T^2}{(m^2 + \Delta P_T^2)^2} \sim \frac{4m^2}{\Delta P_T^2} \quad \text{for } \Delta P_T^2 \gg m,$$

$$A_{4\phi} \propto \frac{-2\Delta P_T^4}{(m^2 + \Delta P_T^2)^2} \sim -2\left(1 - \frac{m^2}{\Delta P_T^2}\right) \quad \text{for } \Delta P_T^2 \gg m.$$

$$\Delta \vec{P}_T \equiv \vec{p}_{1T} - \vec{p}_{2T}$$

C. Li, J. Zhou, Y.-J. Zhou, Phys. Lett. B 795 (2019) 576–5

A prominent peak structure near 15 fm.
Around 2 times radius of nuclei for $A_{4\phi}$.

Summary

- Evaluate the sensitivity of the differential cross section and two luminosity independent observables to the higher order QED effects.

On a long journey to reach a definitive conclusion…

Make it clear where we are…

Try to tell where we would go…

BACK UP

Fiducial cuts implemented in the calculation.

Process and beam energy		p_{Tl} (GeV/c)	η_l	P_{Tll} (GeV/c)	Y_{ll}	M_{ll} (GeV)
$\gamma\gamma \to e^+e^-(\mu^+\mu^-)$	Au+Au $\sqrt{s_{NN}} = 200$ GeV	$(0.2, +\infty)$	$(-1.0, 1.0)$	$(0, 0.3)$	$(-1.0, 1.0)$	$(0.4, 2.6)$
$\gamma\gamma \to e^+e^-$	Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV	$(0.5, +\infty)$	$(-1.0, 1.0)$	$(0, 0.3)$	$(-1.0, 1.0)$	$(1.0, 2.8)$
$\gamma\gamma \to \mu^+\mu^-(\tau^+\tau^-)$	Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV	$(4.0, +\infty)$	$(-2.4, 2.4)$	$(0, 0.3)$	$(-2.4, 2.4)$	$(8.0, 100.0)$