$\gamma\gamma$ FUSION IN HEAVY-ION COLLISIONS

Mariola Kłusek-Gawenda

Outline:

- Equivalent Photon Approximation
- $\gamma\gamma \to \ell^+\ell^-$
- $\gamma\gamma \to q\bar{q}$
- $\gamma\gamma \to M$
- $\gamma\gamma \to \gamma\gamma$

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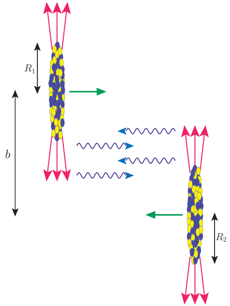
HEAVY-ION COLLISIONS

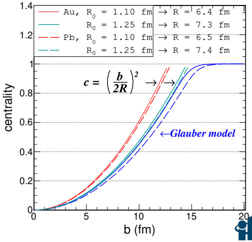


The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.
Electromagnetism is a long-range force, so electromagnetic interactions occur even at relatively large ion-ion separations.

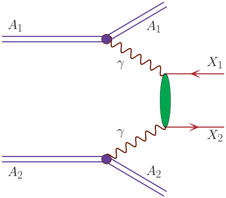
Photon energy: $\omega = \frac{\gamma}{b}$

Virtuality: $Q^2 = \frac{1}{R^2}$

1. Collision energy:
   - low energy processes: $\sqrt{s_{NN}} < 10$ MeV/nucleon;
   - intermediate energies: $\sqrt{s_{NN}} = (10 - 100)$ MeV/nucleon;
   - relativistic energies: $\sqrt{s_{NN}} = (0.1 - 100)$ GeV/nucleon;
   - ultrarelativistic energies: $\sqrt{s_{NN}} > 100$ GeV/nucleon;
2. Centrality vs. impact parameter:
   - central collisions: b $\approx$ (0 fm $+\triangle b$);
   - semi-central collisions: b $\approx$ (5 — 10) fm;
   - semi-peripheral collisions: b $\approx$ (10 — 12) fm;
   - peripheral collisions: b $\approx$ (12 fm $-(R_1 + R_2)$);
   - ultraperipheral collisions: b $> (R_1 + R_2)$.



HEAVY-ION COLLISIONS



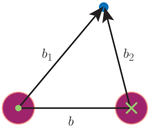
Cross section

$$\sigma_{A_1A_2\to A_1A_2X_1X_2} = \int \sigma_{\gamma\gamma\to X_1X_2}(\omega_1,\omega_2)\mathrm{d}\omega_1\,\mathrm{d}\omega_2\; n(\omega_1)n(\omega_2) \to \ldots n(\omega) = \int_{R_{min}}^{\infty} 2\pi b\mathrm{d}b\, N(\omega,b)\ldots$$

$$= \int \sigma_{\gamma\gamma\to X_1X_2}(W_{\gamma\gamma}) N(\omega_1,\mathbf{b_1})\, N(\omega_2,\mathbf{b_2})\, \frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}Y_{X_1X_2}\,\mathrm{d}\overline{b}_x\,\mathrm{d}\overline{b}_y\,\mathrm{d}^2b$$

$$= \int \frac{\mathrm{d}\sigma_{\gamma\gamma\to X_1X_2}(W_{\gamma\gamma})}{\mathrm{d}\cos\theta} N(\omega_1,\mathbf{b_1})\, N(\omega_2,\mathbf{b_2})\, \frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}Y_{X_1X_2}\,\mathrm{d}\overline{b}_x\,\mathrm{d}\overline{b}_y\,\mathrm{d}^2b$$

$$\times \frac{\mathrm{d}\cos\theta}{\mathrm{d}y_{X_1}\,\mathrm{d}y_{X_2}\,\mathrm{d}p_t} \times dy_{X_1}\,dy_{X_2}\,dp_t$$



EQUIVALENT PHOTON FLUX VS. FORM FACTOR

$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2}$$

$$\times \left| \int d\chi\, \chi^2 \frac{F\left(\frac{\chi^2 + u^2}{b^2}\right)}{\chi^2 + u^2} J_1(\chi) \right|^2$$

$$\beta = \frac{p}{E},\ \gamma = \frac{1}{\sqrt{1-\beta^2}},\ u = \frac{\omega b}{\gamma \beta},\ \chi = k_\perp b$$

- point-like $F\left(\mathbf{q}^2\right) = 1$

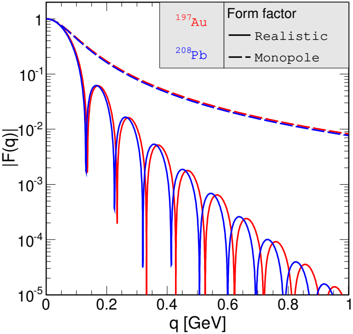
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times u^2 \left[K_1^2(u) + \frac{1}{\gamma^2} K_0^2(u)\right]$$

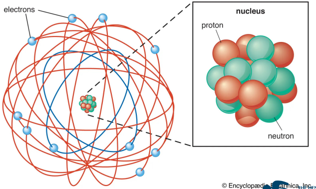
- monopole $F\left(\mathbf{q}^2\right) = \frac{\Lambda^2}{\Lambda^2 + |\mathbf{q}|^2}$

$$\sqrt{\langle r^2 \rangle} = \sqrt{\frac{6}{\Lambda^2}} = 1 \text{ fm } A^{1/3}$$

- realistic

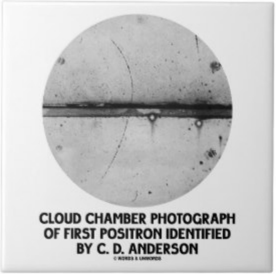
$$F\left(\mathbf{q}^2\right) = \frac{4\pi}{|\mathbf{q}|} \int \rho(r) \sin(|\mathbf{q}|\, r)\, r dr$$





HISTORY OF TWO-PHOTON PHYSICS

❶ Carl David Anderson (1905-1991) was an American physicist. He is best known for his discovery of the **positron** in 1932, an achievement for which he received the 1936 Nobel Prize in Physics, and of the muon in 1936.



❹ 1970 - production of e^+e^- pairs was discovered in collisions of virtual photons at the e^+e^- - storage ring VEPP-2 in Novosibirsk

❷ L.D. Landau and E.M. Lifschitz, *Production of electrons and positrons by a collision of two particles*, Phys.Z.Sowjetunion 6 (1934) 244.
$\sigma(A_1A_2 \rightarrow A_1A_2e^+e^-)$ in the leading logarithmic approximation

❸ H. Bethe and W. Heitler, *On the Stopping of fast particles and on the creation of positive electrons*, Proc.Roy.Soc.Lond. **A146** (1934) 83
$\gamma A \rightarrow e^+e^-A$

Theoretical papers devoted to the $\gamma\gamma$ fusion are concerned with:

- methods for extracting information on the $\gamma\gamma \rightarrow h$ transition from exp. data
- effects connected with the production of leptons
- search for new physics

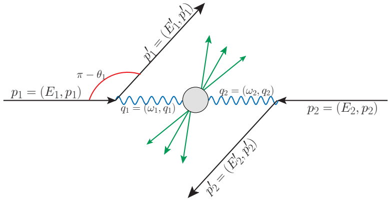
EQUIVALENT PHOTON APPROXIMATION

$s = (p_1 + p_2)^2 = 2m_e^2 + 2E_1E_2 - 2\boldsymbol{p_1}\cdot\boldsymbol{p_2}$
$\hat{s} = (q_1 + q_2)^2 = M_X^2$
$q_i = (p_i - p_i')^2$

IN THE C.M. FRAME OF e^+e^-:

$\boldsymbol{p_1} = \boldsymbol{p_2} = \boldsymbol{p}$ and $E_1 = E_2 = E$

$s = 2m_e^2 + 2p^2 + 2E^2 = 4E^2$
$\omega_1 = E - E_1' = \frac{1}{2}(\omega + p)$
$\omega_2 = E - E_2' = \frac{1}{2}(\omega - p)$
$\hat{s} = 4\omega_1\omega_2$



$e^+e^- \to e^+e^- X$

$$\frac{\mathrm{d}^4\sigma(e^+e^- \to e^+e^-\mathbf{X}; s)}{\mathrm{d}E_1'\mathrm{d}\Omega_1'\mathrm{d}E_2'\mathrm{d}\Omega_2'} = \left(\frac{\alpha_{em}}{8\pi^2}\right)^2 \frac{1}{q_1^2 q_2^2}\frac{E_1'}{E_1}\frac{E_2'}{E_2}\rho_1^{\mu\mu'}\rho_2^{\nu\nu'}W_{\mu\nu\mu'\nu'}$$

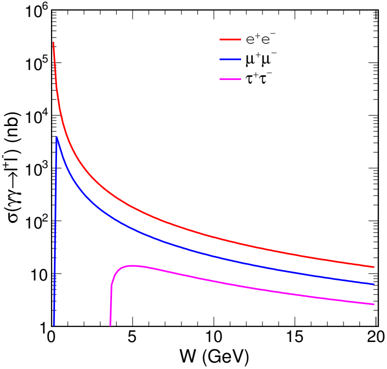
$\mathrm{d}\Omega_i = \sin^2\theta_i\,\mathrm{d}\theta_i\mathrm{d}\phi_i$

- ✗ $\rho_i^{\alpha\beta}$ - the electron density matrix
- ✗ $W_{\mu\nu\mu'\nu'}$ - the amplitude for forward elastic $\gamma\gamma$ scattering

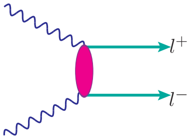
Ignoring the dependence of the amplitude $\rho_i^{\alpha\beta}$ on the azimuthal angle:

$$\frac{\mathrm{d}^2\sigma(e^+e^- \to e^+e^-\mathbf{X}; s)}{\mathrm{d}\omega_1\mathrm{d}\omega_2} = n(\omega_1)n(\omega_2)\sigma(\gamma\gamma \to \mathbf{X}; W^2)$$

PHOTON+PHOTON → 2 LEPTONS



- m_e = 0.511 MeV
- m_μ = 105.658 MeV
- m_τ = 1776.84 MeV



- $W_{\gamma\gamma} > 2m_\ell$

$$\sigma_{\gamma\gamma\to\ell^+\ell^-}\left(W_{\gamma\gamma}\right) = \frac{4\pi\alpha_{em}^2}{W_{\gamma\gamma}^2}\left\{2\ln\left[\frac{W_{\gamma\gamma}}{2m_\ell}\left(1+\sqrt{1-\frac{4m_\ell^2}{W_{\gamma\gamma}^2}}\right)\right]\right.$$

$$\left.\times\left(1+\frac{4m_\ell^2 W_{\gamma\gamma}^2-8m_\ell^4}{W_{\gamma\gamma}^4}\right)-\sqrt{1-\frac{4m_\ell^2}{W_{\gamma\gamma}^2}}\left(1+\frac{4m_\ell^2}{W_{\gamma\gamma}^2}\right)\right\}$$

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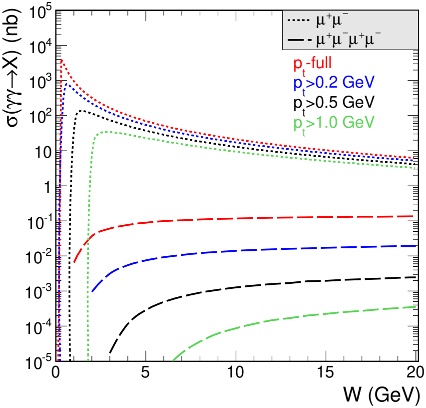
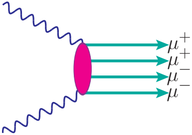
PHOTON+PHOTON → 4 LEPTONS

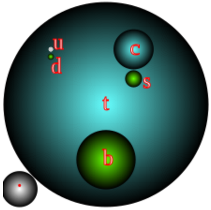




KATIE - it is an event generator that is specially designed to deal with initial states that have an explicit transverse momentum dependence, but can also deal with on-shell initial states. KATIE is a parton-level generator for hadron scattering, but requires only a few adjustments to deal with photon scattering.

QUARKS PRODUCTION

- $Q/\bar{Q}$ - heavy-quark/-antiquark
  - $m_c = 1.5$ GeV
  - $m_b = 4.75$ GeV
- $q/\bar{q}$ - light-quark/-antiquark
  - $m_u = 0.3$ GeV
  - $m_d = 0.3$ GeV
  - $m_s = 0.5$ GeV
- In contrast to dimuon production, the $Q\bar{Q}$ state cannot be directly observed because of the quark confinement

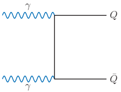


Current quark masses for all six flavors in comparison, as balls of proportional volumes.
en.wikipedia.org

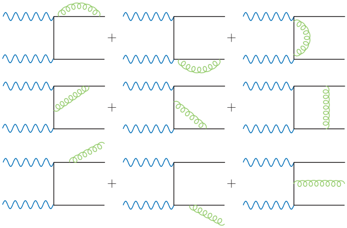
❶ $2 \to 2$ process (Born amplitude)

$$\sigma_{\gamma\gamma\to Q\bar{Q}}\left(W_{\gamma\gamma}\right) = N_c e_Q^4 \frac{4\pi\alpha_{em}^2}{W_{\gamma\gamma}^2}\left\{2\ln\left[\frac{W_{\gamma\gamma}}{2m_Q}\left(1+\sqrt{1-\frac{4m_Q^2}{W_{\gamma\gamma}^2}}\right)\right]\right.$$

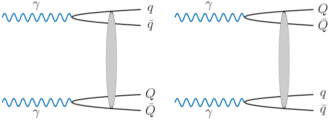
$$\times\left.\left(1+\frac{4m_Q^2W_{\gamma\gamma}^2-8m_Q^4}{W_{\gamma\gamma}^4}\right)-\sqrt{1-\frac{4m_Q^2}{W_{\gamma\gamma}^2}}\left(1+\frac{4m_Q^2}{W_{\gamma\gamma}^2}\right)\right\}$$



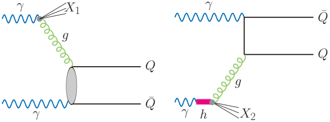
❷ LO QCD corrections

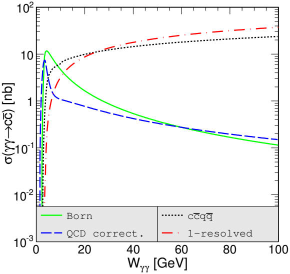


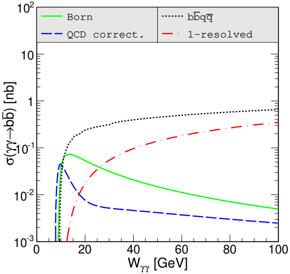
❸ $Q\bar{Q}q\bar{q}$ production



❹ single-resolved mechanism







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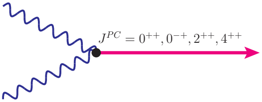
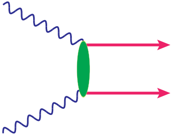
MESON PRODUCTION

Quantum numbers:

Meson = $q\bar{q}$

- S - spin
- L - the orbital angular momentum
- J - the total angular momentum; $J = |L - S|$ to $J = |L + S|$,
- P - parity; $P = (-1)^{L+1}$
- C - parity; $|q\bar{q}\rangle = |\bar{q}q\rangle \to C = +1$, $|q\bar{q}\rangle = -|\bar{q}q\rangle \to C = -1$





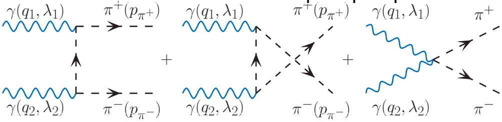
✓ scalar
✓ pseudoscalar
✓ tensor
✓ 4-spin meson

✓ scalar
✓ pseudoscalar
✓ vector
✓ tensor
✓ 4-spin meson

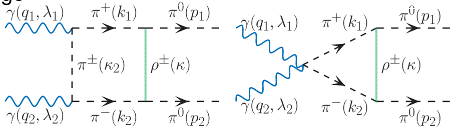
PION-PAIR PRODUCTION

The quark structure of the pion.
en.wikipedia.org

- the Born term matrix elements for non-resonant pion pair production



- $\rho^\pm$ meson exchange



Continuum

$$\mathcal{M}(\lambda_1, \lambda_2) = \mathcal{M}^t(\lambda_1, \lambda_2) + \mathcal{M}^u(\lambda_1, \lambda_2) + \mathcal{M}^c(\lambda_1, \lambda_2)$$

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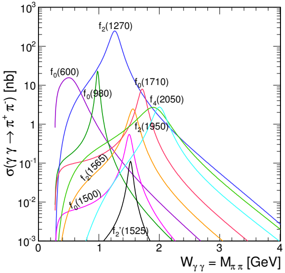
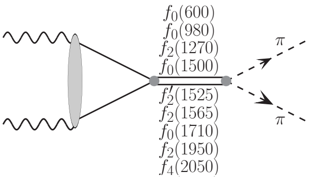
s-channel $\gamma\gamma \rightarrow$resonances

❷





$$\Gamma_R(W_{\gamma\gamma}) = \Gamma_R \frac{\sqrt{\frac{W_{\gamma\gamma}^2}{4} - m_\pi^2}}{\sqrt{\frac{m_R^2}{4} - m_\pi^2}} F^J\left(W_{\gamma\gamma}, R\right) F^J\left(W_{\gamma\gamma}, R\right)$$

- the Blatt-Weisskopf form factor

$$\mathcal{M}\left(\lambda_1, \lambda_2\right) = \frac{\sqrt{64\pi^2 W_{\gamma\gamma}^2 \times 8\pi(2J+1)\left(\frac{m_R}{W_{\gamma\gamma}}\right)^2 \Gamma_R \Gamma_R\left(W_{\gamma\gamma}\right) Br(R\rightarrow\gamma\gamma) Br\left(R\rightarrow\pi^{+/0}\pi^{-/0}\right)}}{W_{\gamma\gamma}^2 - m_R^2 + i m_R \Gamma_R\left(W_{\gamma\gamma}\right)} e^{i\varphi_R}$$

$$\times\sqrt{2}\delta_{\lambda_1,\lambda_2} \left\{ \begin{array}{l} Y_0^0(\theta,\phi); \text{for } f_0 \\ Y_2^2(\theta,\phi); \text{for } f_2(1270),\ f_2'(1525),\ f_2(1950) \\ Y_2^0(\theta,\phi); \text{for } f_2(1565) \\ Y_4^0(\theta,\phi); \text{for } f_4(2050) \end{array} \right\} \exp\left(\frac{-\left(W_{\gamma\gamma} - m_R\right)^2}{\Lambda_R^2}\right)$$

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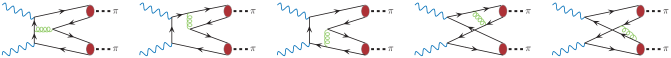
pQCD mechanisms

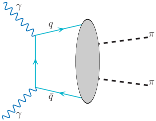
❸ Brodsky-Lepage perturbative mechanism



$$\mathcal{M}(\lambda_1,\lambda_2) = \int_0^1 dx \int_0^1 dy\, \phi_\pi\left(x,\mu_x^2\right) T_H^{\lambda_1\lambda_2}\left(x,y,\mu^2\right) \phi_\pi\left(y,\mu_y^2\right) F^{pQCD}(s)$$

- ✓ x, y - fractional momentum of hadron carrying by q or $\bar{q}$
- ✓ ϕ_π - parton distribution amplitude
- ✓ $\mu_{x/y} = \min\left(x/y, 1 - x/y\right)\sqrt{s(1-z^2)}$
- ✓ $T_H^{\lambda_1\lambda_2}\left(x,y,\mu^2\right)$ - a hard-scattering amplitude
- ✓ $F^{pQCD}(s)$ - form factor

❹ Handbag mechanism

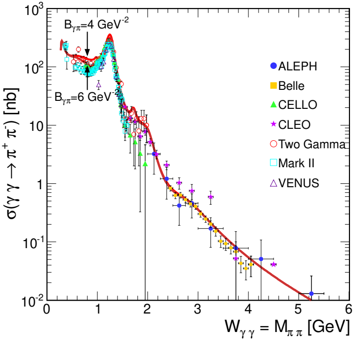


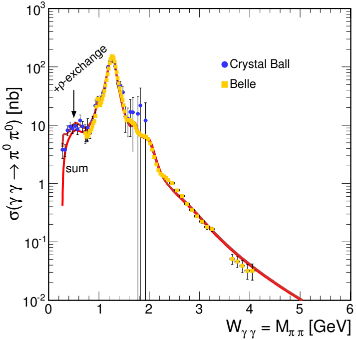
$$\mathcal{A}_{+-} = \mathcal{A}_{-+} = -4\pi\alpha_{em}\frac{s^2}{tu}R_{2\pi}(s)$$

☞ M. Diehl, P. Kroll and C. Vogt, "The Handbag contribution to $\gamma\gamma \to \pi\pi$ and KK ", *Phys. Lett.* **B532** (2002) 99;

☞ M. Diehl and P. Kroll, "Two-photon annihilation into octet meson pairs: Symmetry relations in the handbag approach ", *Phys. Lett.* **B683** (2010) 165.

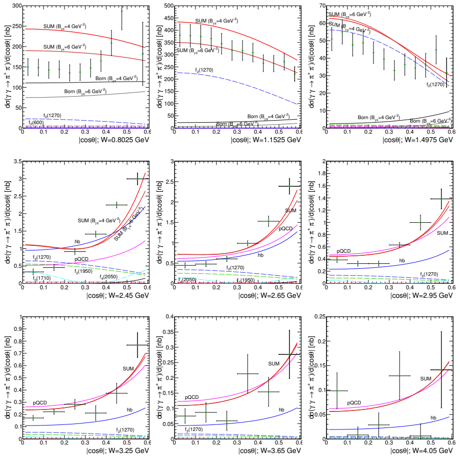
TOTAL CROSS SECTION FOR THE $\gamma\gamma \to \pi\pi$

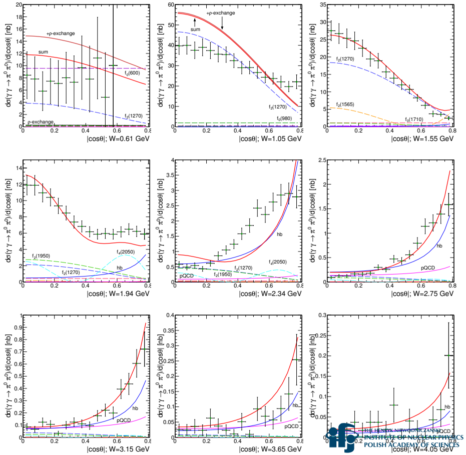




- M. K-G and A. Szczurek, "$\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy ion collisions ",
  Phys.Rev. **C87** (2013) 054908

ANGULAR DISTRIBUTIONS FOR THE $\gamma\gamma \to \pi\pi$





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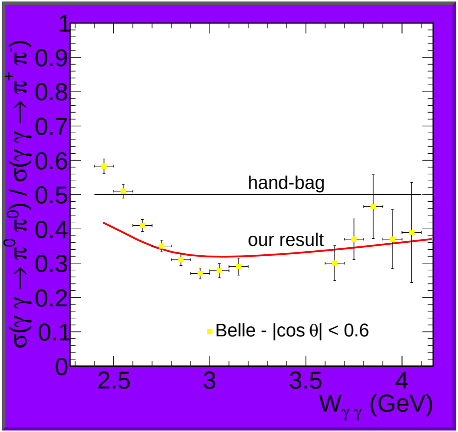
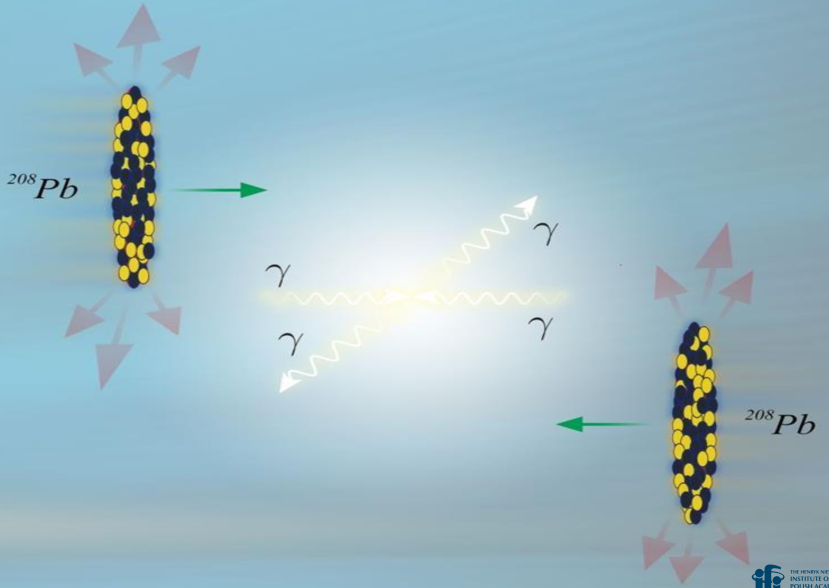


Our results prove that the correct description of the high-energy cross section requires to take into account both

- the Brodsky-Lepage and
- handbag mechanisms.

The black solid line represents only the handbag model result, which is independent of θ and is constant (= $\frac{1}{2}$).

LIGHT-BY-LIGHT SCATTERING

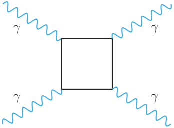


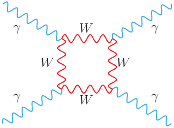
LIGHT-BY-LIGHT SCATTERING

- Maxwell classical theory
  - ✓ light doesn't interact with each other
- Quantum theory
  - ✓ interaction of photons through quantum fluctuations

- $\sigma(\gamma\gamma \to \gamma\gamma) \propto \alpha_{em}^4 \simeq \left(\frac{1}{137}\right)^4$ → very small
- Photon beams
  - ✗ High-power lasers
    - ➢ K. Homma, K. Matsuura, K. Nakajima, PTEP 2016 (2016) 013C01 *Testing helicity-dependent $\gamma\gamma \to \gamma\gamma$ scattering in the region of MeV*
  - ✔ Ultrarelativistic heavy-ion collision
    - Cross section $\propto Z^4$; Pb-Pb collisions $\Rightarrow 82^4 \approx 45 \times 10^6$
    - Quasi-real photons

Boxes **WELL-KNOWN**

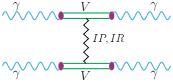


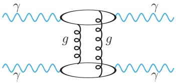


Fermionic boxes (LO QED) — FormCalc. W Box — LoopTools.

$$|\mathcal{M}_{\gamma\gamma\to\gamma\gamma}|^2 = \alpha_{em}^4 f(\hat{t}, \hat{u}, \hat{s})$$

VDM-Regge **WE ADD** **2-gluon exch.**





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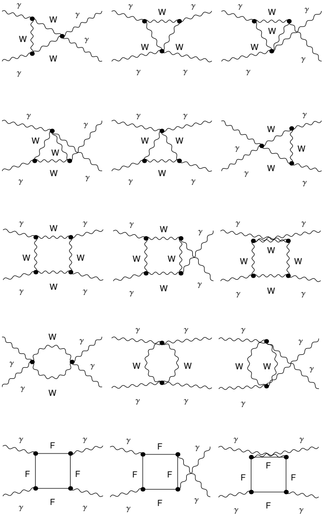
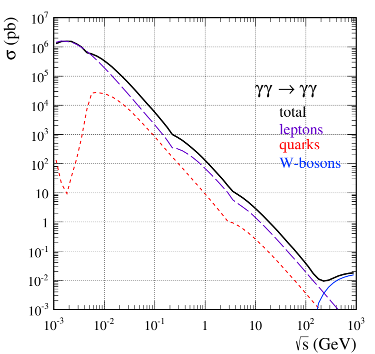
BOXES $\gamma\gamma \to \gamma\gamma$



Fermionic box LO QED - `FormCalc`.

The one-loop W box diagram - `LoopTools`.



- Jikia et al. (1993)
- Bern et al. (2001)
- Bardin et al. (2009)

Bern et al. consider QCD and QED corrections (two-loop Feynman diagrams) to the one-loop fermionic contributions in the ultrarelativistic limit ($\hat{s}, |\hat{t}|, |\hat{u}| \gg m_f^2$). The corrections are quite small numerically.

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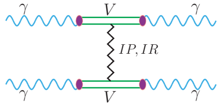
VDM-REGGE CONTRIBUTION



$$\mathcal{A}_{\gamma\gamma\to\gamma\gamma}(s,t) = \sum_i^3 \sum_j^3 C^2_{\gamma\to V_i} \mathcal{A}_{V_iV_j\to V_iV_j} C^2_{\gamma\to V_j}$$

$$\approx \left(\sum_{i=1}^3 C^2_{\gamma\to V_i}\right) \mathcal{A}_{VV\to VV}(s,t) \left(\sum_{j=1}^3 C^2_{\gamma\to V_j}\right)$$

$i, j = \rho, \omega, \phi$

$$\mathcal{A}_{VV\to VV}(s,t) = \mathcal{A}(s,t) \exp\left(\frac{B}{2} t\right)$$

$$\mathcal{A}(s,t) \approx s\left((1+i)\, C_{\mathbf{R}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{R}}(t)-1} + i\, C_{\mathbf{P}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{P}}(t)-1}\right)$$

- $C^2_{\gamma\to V_i} = \frac{e}{f_{V_i}}$
- $C_{\mathbf{P}}$, $C_{\mathbf{R}}$ - Donnachie-Landshoff
- $\alpha_{\mathbf{R}}(t)$, $\alpha_{\mathbf{P}}(t)$ - trajectories

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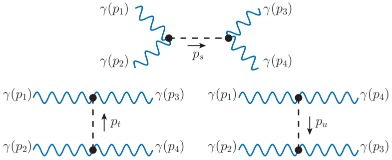
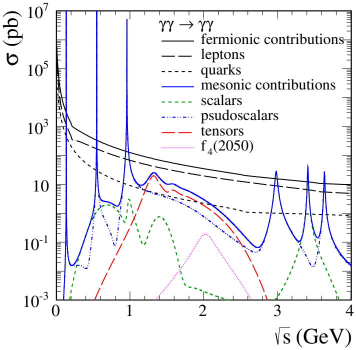
MESON EXCHANGE





$f_0(500)$	π^0	$f_2(1270)$	
$f_0(980)$	η	$a_2(1320)$	
$a_0(980)$	$\eta'(958)$	$f_2'(1525)$	$f_4(2050)$
$f_0(1370)$	$\eta_c(1S)$	$f_2(1565)$	
$\chi_{c0}(1P)$	$\eta_c(2S)$	$a_2(1700)$	

$s-$channel diagrams (leading to peaks at $\sqrt{s} \cong m_M$)

$t-$ and $u-$channels (leading to broad continua)

☞ P. Lebiedowicz and A. Szczurek, "The role of meson exchanges in light-by-light scattering", *Phys. Lett.* **B772** (2017) 330

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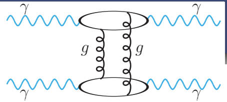
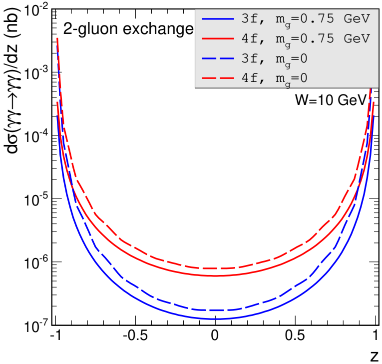
2-GLUON EXCHANGE

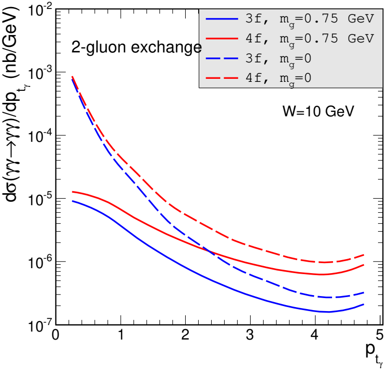


16 diagrams ⇒

$z = \cos\theta$; θ - scattering ∢

$p_{t_\gamma} = p\sin\theta$





3f = u ,d, s

4f = u, d, s, c

$m_u \simeq 0.15$ GeV
$m_d \simeq 0.15$ GeV
$m_s \simeq 0.30$ GeV
$m_c \simeq 1.50$ GeV

Significant effect of c quark inclusion at $z \approx 0$ (large p_{t_γ}) - interference

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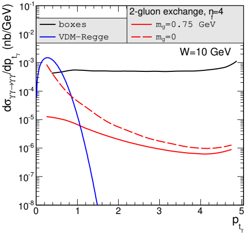
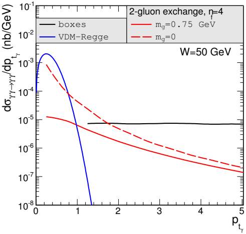
EXPERIMENTAL IDENTIFICATION OF PROCESSES?

- ✔ boxes
- ✔ VDM-Regge
- ✔ 2-gluon exchange

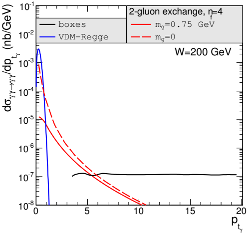
W = 10 GeV



W = 50 GeV



W = 200 GeV



$\gamma - \gamma$ Collider? | the International e^+e^- Linear Collider or the Compact Linear Collider

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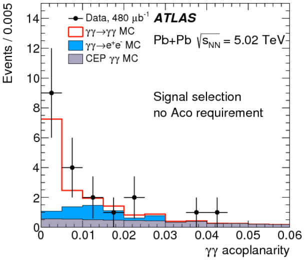
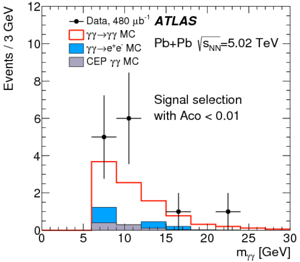
AA→AA$\gamma\gamma$ - ATLAS RESULTS

➢ ATLAS Collaboration (M. Aaboud et al.),
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC,
Nature Phys. **13** (2017) 852
Phys. Rev. Lett. **123** (2019)* 052001





- ✗ $p_{t_\gamma} > 3$ GeV
- ✗ $|\eta_\gamma| < 2.4$
- ✗ $M_{\gamma\gamma} > 6$ GeV
- ✗ $p_{t_{\gamma\gamma}} < 2$ GeV
- ✗ Aco < 0.01

- ✔ $\gamma\gamma \to \gamma\gamma$ - Our results
- ✔ background:
  - ✔ $\gamma\gamma \to e^+e^-$
  - ✔ $gg \to \gamma\gamma$
  - ✔ $\gamma\gamma \to q\bar{q}$
- ✔ 13 events
  59 events (2019)*

ATLAS ⇒ σ = 70 ± 20(stat.)±17(syst.) nb

(2019)* ⇒ σ = 78 ± 13(stat.)±7(syst.)±3(lumi.) nb

Our result ⇒ σ = 51 ± 0.02 nb

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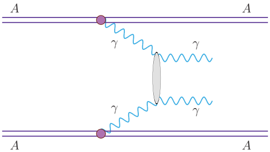
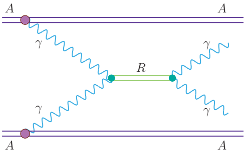
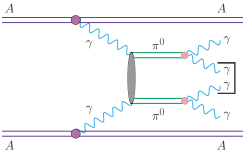
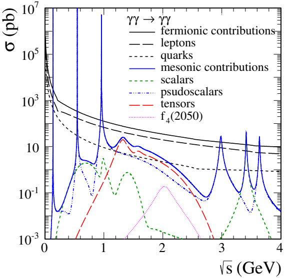
AA→AAγγ FOR $M_{\gamma\gamma} < 5$ GEV ?

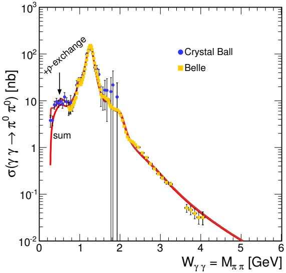
CONTINUUM **RESONANCES** **BACKGROUND**











- P. Lebiedowicz, A. Szczurek, *Phys. Lett.* ***B772*** *(2017) 330*, The role of meson exchanges in light-by-light scattering
- M. K-G, A. Szczurek, *Phys. Rev.* ***C87*** *(2013) 054908*; $\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy-ion collisions

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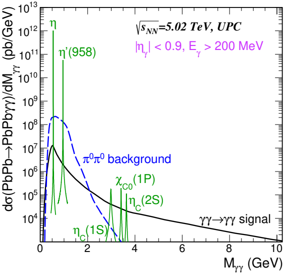
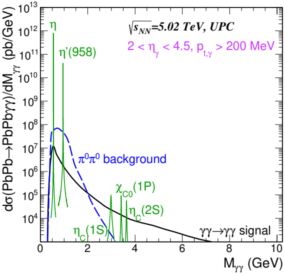
UPC OF AA...

ALICE cuts

- ✔ boxes
- ✔ bkg
- ✔ mesons

LHCb cuts





Total nuclear cross section [nb]

Energy	$W_{\gamma\gamma}$ = (0 – 2) GeV		$W_{\gamma\gamma} > 2$ GeV	
Fiducial region	ALICE	LHCb	ALICE	LHCb
Boxes	4 890	3 818	146	79
$\pi^0\pi^0$ bkg	135 300	40 866	46	24
η	722 573	568 499		
$\eta'(958)$	54 241	40 482		
$\eta_c(1S)$			9	5
$\chi_{c0}(1P)$			4	2
$\eta_c(2S)$			2	1

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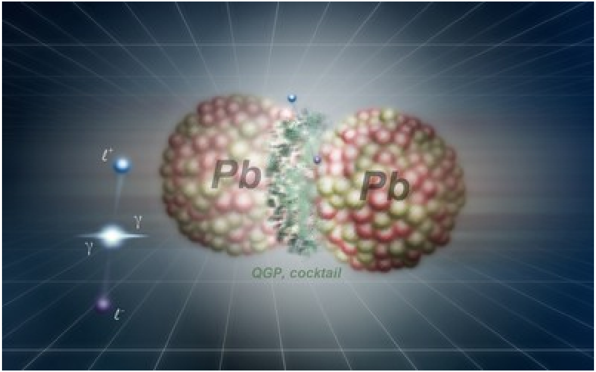
SEMICENTRAL HEAVY-ION COLLISIONS



- From ultraperipheral to semicentral collisions $\rightarrow$ dilepton sources
  - $\gamma\gamma$ fusion mechanism
- Invariant mass
  - SPS (NA60 data)
  - RHIC (STAR data)
  - LHC (ALICE data)
- Low-P_T dilepton spectra
  - RHIC (STAR data)
  - LHC (ALICE data)
- Acoplanarity
  - LHC (ATLAS data)

DIELECTRON INVARIANT-MASS SPECTRA - RHIC

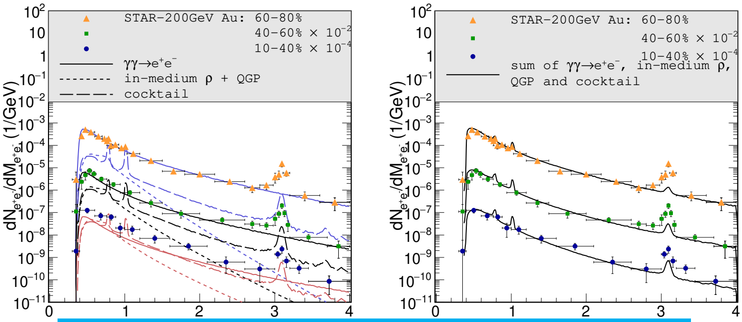
$p_t > 0.2$ GeV,

$|\eta_e| < 1$

$|y_{e^+e^-}| < 1$

- ✔ $\gamma\gamma$-fusion
- ✔ thermal radiation
- ✔ hadronic cocktail

3 centrality classes



The coherent emission dominates for the two peripheral samples

and is comparable to the cocktail and thermal radiation yields in semi-central collisions.

EPA in the impact parameter space - the pair transverse momentum $P_T^{\ell^+\ell^-}$ is neglected

$$\sigma_{A_1 A_2 \to A_1 A_2 \ell^+\ell^-} = \int N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2})\, \delta^{(2)}(\mathbf{b} - \mathbf{b}_1 - \mathbf{b}_2) \int d^2\mathbf{b}_1 d^2\mathbf{b}_2 d^2\mathbf{b}\, dy_{\ell^+} dy_{\ell^-} dp_{t,\ell}^2 \frac{d\sigma(\gamma\gamma \to \ell^+\ell^-;\hat{s})}{d(-\hat{t})}$$

➪ **k_t-factorization**

$$\frac{dN_{ll}}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int \frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2} d^2\boldsymbol{q}_{1t} d^2\boldsymbol{q}_{2t} \frac{dN(\omega_1, q_{1t}^2)}{d^2\boldsymbol{q}_{1t}} \frac{dN(\omega_2, q_{2t}^2)}{d^2\boldsymbol{q}_{2t}} \delta^{(2)}(\boldsymbol{q}_{1t} + \boldsymbol{q}_{2t} - \mathbf{P}_T^{\ell^+\ell^-})\hat{\sigma}(\gamma\gamma \to \ell^+\ell^-)\Big|_{\mathrm{cuts}},$$

➪ **Exact calculation**

$$\frac{d\sigma[\mathcal{C}]}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int \frac{d^2\boldsymbol{Q}}{2\pi} w(Q; b_{\max}, b_{\min}) \int \frac{d^2\boldsymbol{q}_1}{\pi}\frac{d^2\boldsymbol{q}_2}{\pi} \delta^{(2)}(\mathbf{P}_T^{\ell^+\ell^-} - \mathbf{q}_1 - \boldsymbol{q}_2) \int \frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2}$$

$$\times\ E_i\left(\omega_1, \boldsymbol{q}_1 + \frac{\boldsymbol{Q}}{2}\right) E_j^*\left(\omega_1, \boldsymbol{q}_1 - \frac{\boldsymbol{Q}}{2}\right) E_k\left(\omega_2, \boldsymbol{q}_2 - \frac{\boldsymbol{Q}}{2}\right) E_l^*\left(\omega_2, \boldsymbol{q}_2 + \frac{\boldsymbol{Q}}{2}\right) \frac{1}{2\hat{s}} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger}\, d\Phi(\ell^+\ell^-).$$

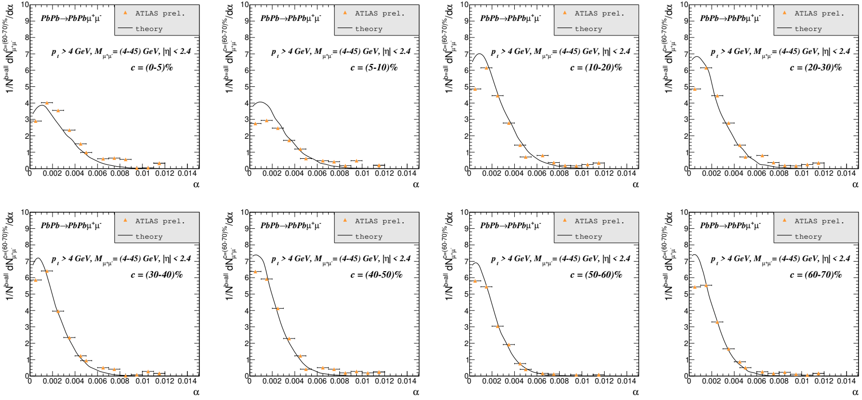
The factorization formula is written in terms of the Wigner function:

$$N_{ij}(\omega, \mathbf{b}, \mathbf{q}) = \int \frac{d^2\mathbf{Q}}{(2\pi)^2} \exp[-i\mathbf{bQ}]\, E_i\left(\omega, \mathbf{q} + \frac{\mathbf{Q}}{2}\right) E_j^*\left(\omega, \mathbf{q} - \frac{\mathbf{Q}}{2}\right) = \int d^2\mathbf{s}\, \exp[i\mathbf{qs}]\, E_i\left(\omega, \mathbf{b} + \frac{\mathbf{s}}{2}\right) E_j^*\left(\omega, \mathbf{b} - \frac{bs}{2}\right),$$

$$N(\omega, \mathbf{q}) = \delta_{ij} \int d^2\mathbf{b}\, N_{ij}(\omega, \mathbf{b}, \mathbf{q}) = \delta_{ij}\, E_i(\omega, \mathbf{q}) E_j^*(\omega, \mathbf{q}) = \left|\boldsymbol{E}(\omega, \mathbf{q})\right|^2,$$

$$N(\omega, \mathbf{b}) = \delta_{ij} \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} N_{ij}(\omega, \mathbf{b}, \mathbf{q}) = \delta_{ij}\, E_i(\omega, \mathbf{b}) E_j^*(\omega, \mathbf{b}) = \left|\mathbf{E}(\omega, \mathbf{b})\right|^2.$$

ACOPLANARITY - ATLAS DATA



A successful description of ATLAS data by $\gamma\gamma$-fusion alone

A correct normalization and shape of the distributions

$p_t > 4$ GeV,

$M_{\mu^+\mu^-}$ =(4-45) GeV,

$|\eta_\mu| < 2.4$

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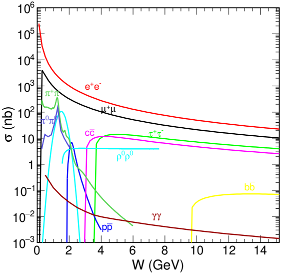
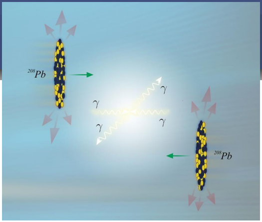
Conclusion

$\gamma\gamma \rightarrow X_1 X_2$

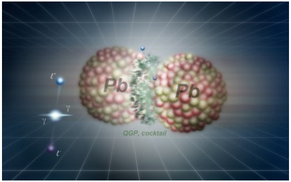


- EPA in the impact parameter space
- Ultraperipheral & semicentral heavy-ion collisions
- Multidimensional integrals $\rightarrow$ differential cross section
- Description of experimental data for UPC and semicentral events
- Predictions focused on experimental acceptance
- Collaboration - theoreticians and experimenters

Thank you



Photon collisions: Photonic billiards might be the newest game!, EurekAlert!
Ultraperipheral collisions of lead nuclei at the LHC accelerator can lead to elastic collisions of photons with photons.



Creation without contact in the collisions of lead and gold nuclei, EurekAlert!
Semicentral or central collisions of lead nuclei in the LHC produce QGP and a cocktail with contributions of other particles. Simultaneously, clouds of photons surrounding the nuclei collide, resulting in the creation of $\ell^+\ell^-$ pairs within the plasma and cocktail, and in the space around the nuclei.

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences