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New development in the light-by-light scattering phenomenology

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Linearity of light

"The rays of light neither mutually color each other, nor mutually illuminate each other, nor mutually impede each other in any way (...) This is just like one physical motion's not impeding another."

Johannes Kepler,
Ad Vitellionem Paralipomena, Quibus Astronomiae Pars Optica Traditur, 1604

Differential equations of an electromagnetic wave in vacuum:

$$\frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = 0 \qquad \frac{1}{c^2}\frac{\partial^2 \mathbf{B}}{\partial t^2} - \nabla^2 \mathbf{B} = 0$$

The linearity of Maxwell's equations expresses the principle of superposition - the absence of interaction between electromagnetic waves

Light-by-Light Scattering

$$\gamma\gamma \rightarrow \gamma\gamma$$

O. Halpern, *Scattering processes produced by electrons in negative energy states.*, Physical Review 44:10 855-85, 1933.

- In the limit of weak e-m fields:

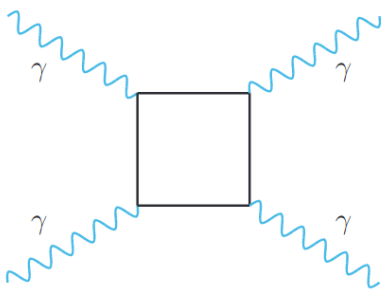
$$\sigma \sim \alpha^4 \lambda_e^8 \left(\frac{\omega}{c}\right)^6$$

H. Euler, B. Kockel, *Über die Streuung von Licht an Licht nach der Diracschen Theorie*, 1935*

- For visible light:

$$\sigma \approx 10^{-76}\text{cm}^2 = 10^{-52}\text{b} = 10^{-43}\text{nb}$$

* "The experimental test of the deviation from the Maxwell theory is difficult since the noteworthy effects are extraordinarily small."



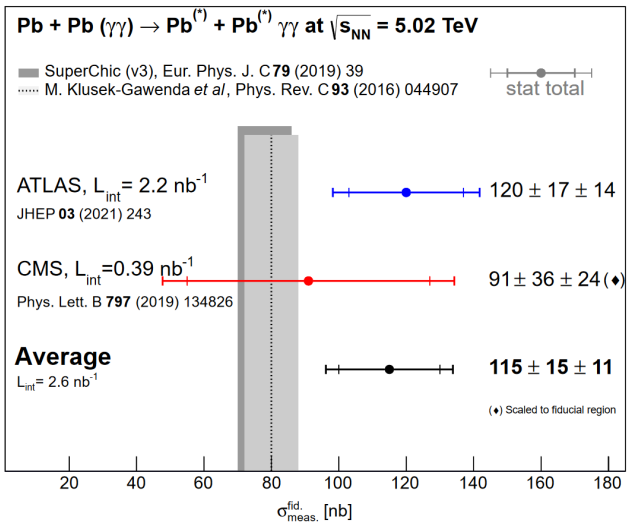
Feynman diagram of the fermionic box.

- W. Heisenberg, H. Euler, *Folgerungen aus der Diracschen Theorie des Positrons*, 1936

Highlights of experiments

Year	Experiment	$p_{t,min}^{\gamma}$ [GeV]	$M_{\gamma\gamma,min}$ [GeV]	$\sigma_{tot.}^{exp.}$ [nb]	$\sigma_{tot.}^{theo.}$ [nb]
2017	ATLAS	3	6	70 ± 29	51 ± 5
2018	CMS	2	5	120 ± 55	103 ± 10
2019	ATLAS	2.5	5	120 ± 22	80 ± 8

Total cross-section for light-by-light scattering in collisions with energy $\sqrt{s_{NN}} = 5.02$ TeV, in range of photon rapidity $|y| < 2.4$.



The average light-by-light scattering cross-section value along with the individual cross-section measurements at 5.02 TeV by ATLAS and CMS.

Current experiments have a high minimum threshold for transverse momentum of photon and diphoton mass:
$p_t > 2$ GeV
$M_{\gamma\gamma} > 5$ GeV

G. K. Krintiras, I. Grabowska-Bold, M. Kłusek-Gawenda, É. Chapon, R. Chudasama and R. Granier de Cassagnac *Light-by-light scattering cross-section measurements at LHC.* arXiv:2204.02845, 2022.

CMS latest results

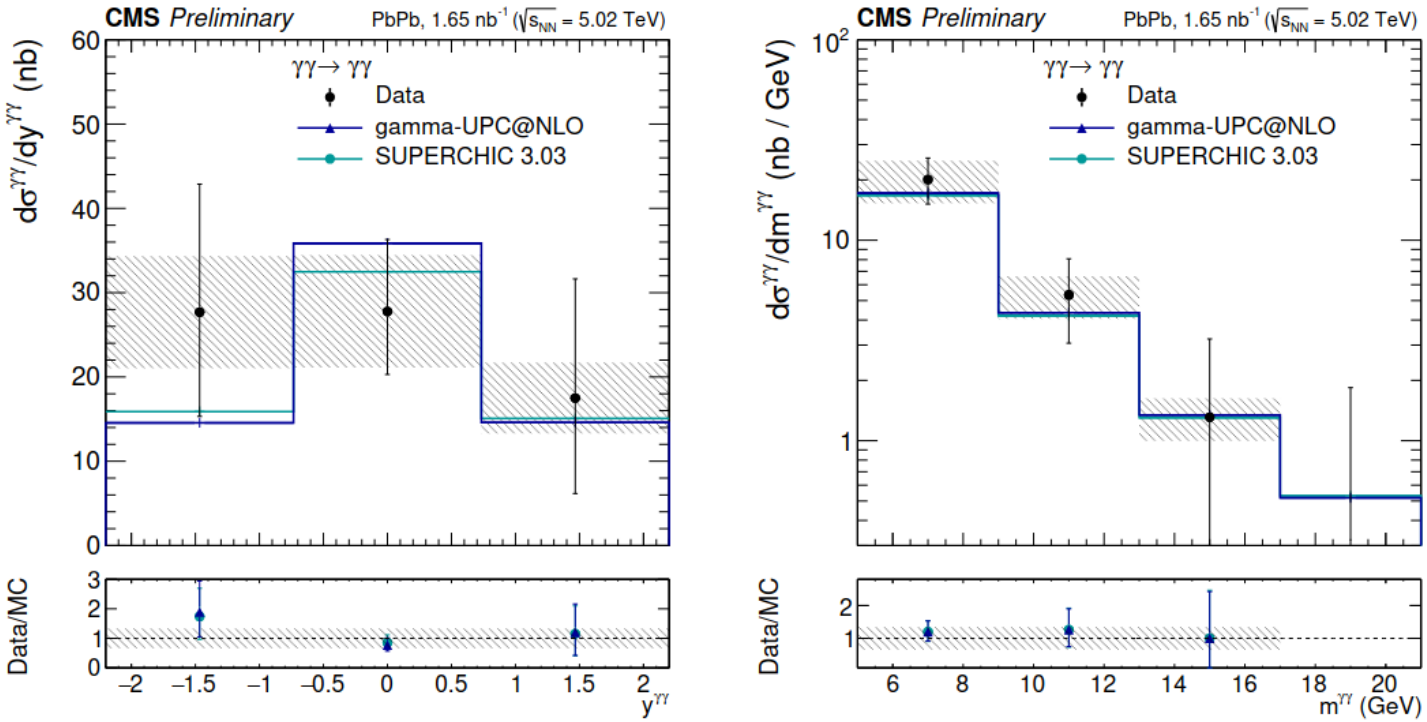
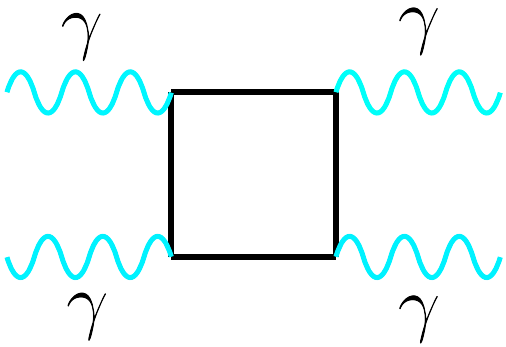


Figure 7: Differential exclusive diphoton cross sections in the fiducial phase space of Table 1 as a function of diphoton rapidity (left) and invariant mass (right) measured in data (black dots) compared with SUPERCHIC, and gamma-UPC@NLO predictions. Vertical bars (boxes) indicate statistical (systematic) uncertainties.

CMS Collaboration *Measurement of light-by-light scattering and the Breit-Wheeler process, and search for axion-like particles in ultraperipheral PbPb collisions at* $\sqrt{s_{NN}} = 5.02$ *TeV*, J. High Energ. Phys. 2025, 6 (2025).

Light-by-light scattering - the elementary cross section



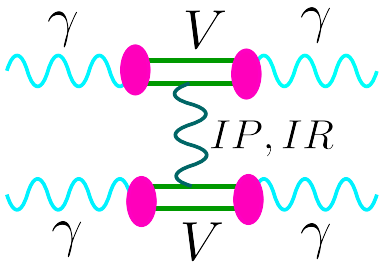
Fermionic box

- Fermionic box is the main mechanism of light-by-light scattering.
- Box diagram represents the fluctuation of photons to fermion-antifermion pair. Interaction between leptons are calculated within QED theorem, and between quarks within both QED and QCD.
- We used the FormCalc and LoopTools libraries based on Mathematica software to calculate the elementary cross sections distribution as a function of $W_{\gamma\gamma}$ and $z = \cos\theta$.

- The elementary cross section is calculated for unpolarised photons - 5 independent photon helicity combinations of the amplitudes was added up with weights resulting from symmetry.

$$\sum_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} \left|\mathcal{A}^{\gamma\gamma\to\gamma\gamma}_{\lambda_1\lambda_2\to\lambda_3\lambda_4}\right|^2 = 2\left|\mathcal{A}^{fermions}_{++++}\right|^2 + 2\left|\mathcal{A}^{fermions}_{+--+}\right|^2 + 2\left|\mathcal{A}^{fermions}_{+-+-}\right|^2 + 2\left|\mathcal{A}^{fermions}_{++--}\right|^2 + 8\left|\mathcal{A}^{fermions}_{+--++}\right|^2 .$$

Elementary cross section - VDM-Regge & mesonic resonances

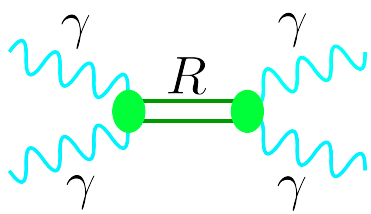


Vector Meson Dominance model involves fluctuations of photons to the light mesons like ρ, ω, ϕ.

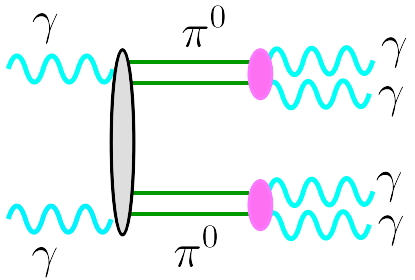
M. Kłusek-Gawenda, P. Lebiedowicz, A. Szczurek, *Light-by-light scattering in ultraperipheral Pb-Pb collisions at energies available at the CERN Large Hadron Collider,* Phys. Rev. C **93**, 044907, 2016.

Main contribution to the $\gamma\gamma \to \gamma\gamma$ process from mesonic resonances in the low mass region coming from pseudoscalars: π, η and η'.

P. Lebiedowicz, A. Szczurek, *The role of meson exchanges in light-by-light scattering,* Physics Letters B, **772**:330-335, 2017.

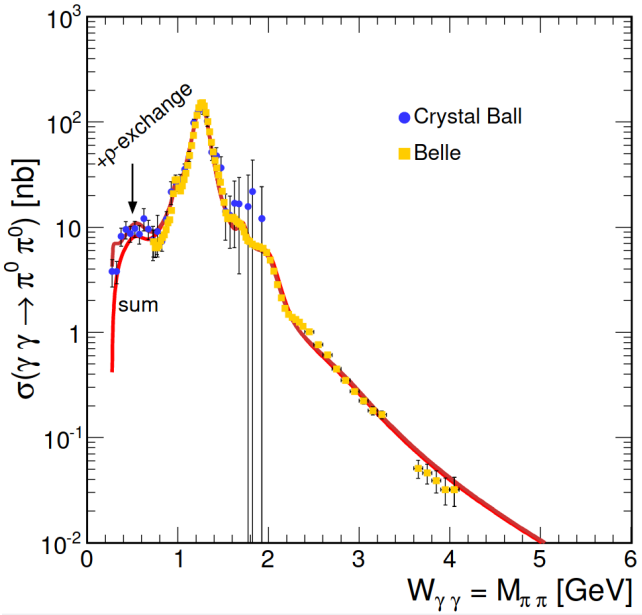


Light-by-light scattering background



- Main difficulties of light-by-light measurement in low p_t region is two pion production.
- Two pions can decay to four photons, in many cases only two photons reach the detector.
- Previous research and new analysis can help reduce the impact of background on experimental results.

M. Kłusek-Gawenda, A. Szczurek, $\pi^+\pi^-$ *and* $\pi^0\pi^0$ *pair production in photon-photon and in ultraperipheral ultrarelativistic heavy-ion collisions*, Phys. Rev. C **87** (2013) 054908.



Elementary cross section for $\gamma\gamma \to \pi^0\pi^0$ for $|\cos\theta| < 0.8$.

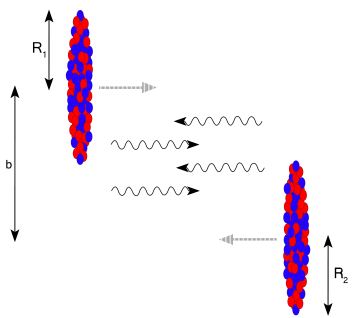
Equivalent Photon Approximation

- Nuclear cross section:

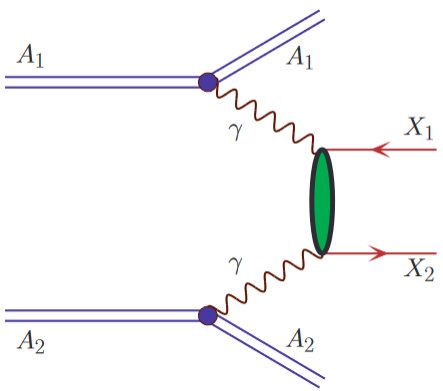
$$\sigma_{A_1A_2\to A_1A_2X_1X_2} = \int \frac{\mathrm{d}\sigma_{\gamma\gamma\to X_1X_2}(W_{\gamma\gamma})}{\mathrm{d}\cos\theta} \times N(\omega_1, b_1)N(\omega_2, b_2)S^2_{abs}(b)$$
$$\times \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{X_1X_2} d\bar{b}_x d\bar{b}_y d^2b \times \frac{\mathrm{d}\cos\theta}{dy_{X_1} dy_{X_2} dp_t} \times dy_{X_1} dy_{X_2} dp_t$$

- Photon flux:

$$N(\omega, b) = \frac{Z^2\alpha_{em}}{\pi^2\beta^2}\frac{1}{\omega b^2} \times \left| \int d\chi\ \chi^2 \frac{F(\frac{\chi^2+u^2}{b^2})}{\chi^2+u^2} J_1(\chi) \right|^2 \qquad u = \frac{\omega b}{\gamma\beta} \qquad \chi = k_\perp b$$



Collision geometry.

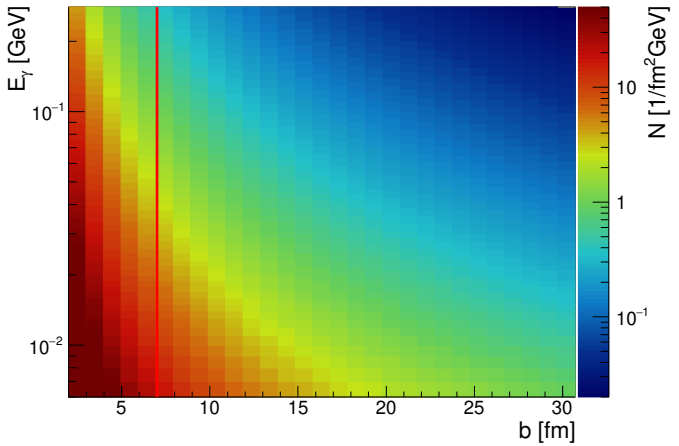


Photon fusion.

Elastic form factor and photon flux

- Point like:

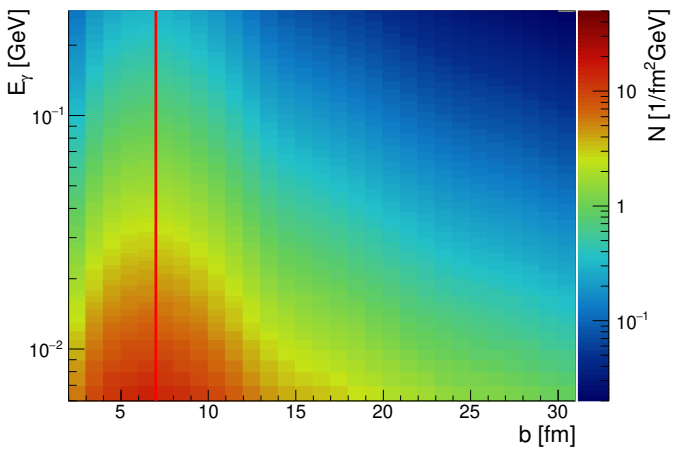
$$F(q^2) = 1$$



Point-like model

- Realistic (Fermi charge distribution):

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



Realistic model

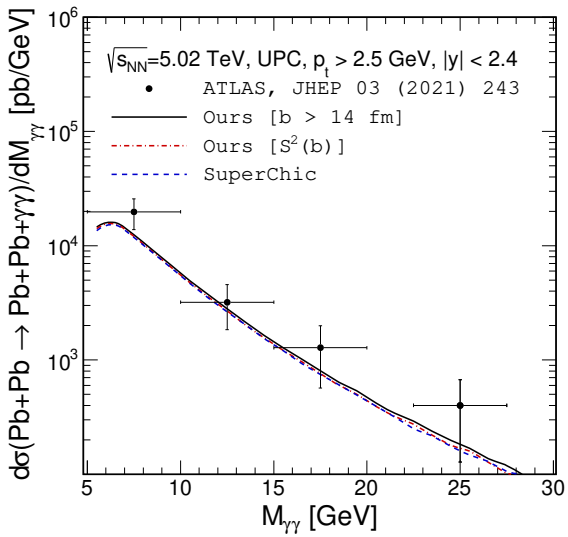
Survival factor

- Sharp edge of nucleus:

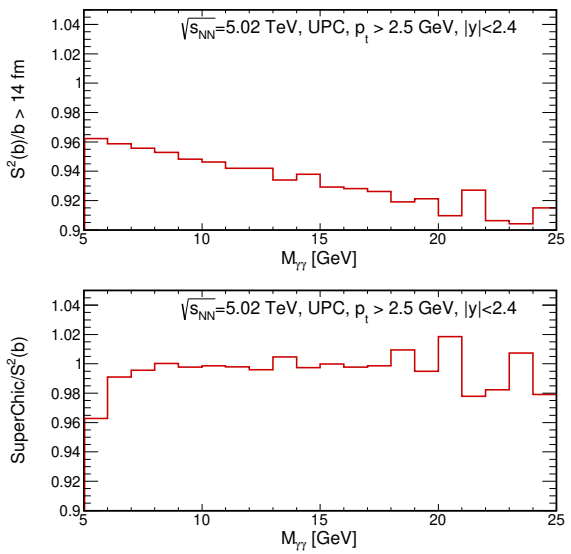
$$b_{min} = R_{A_1} + R_{A_2} \approx 14 \text{ fm}$$

- Smooth edge of nucleus:

$$S^2_{abs}(b) = exp\left(-\sigma_{NN}\int d^2\rho\, T_A(\vec{\rho}-\vec{b})\, T_A(\rho)\right), \quad T_A(\vec{\rho}) = \int \rho_A(\vec{r})\, dz$$



Differential cross section as function of diphoton invariant mass.



Ratios between different theoretical approaches.

ATLAS experiment

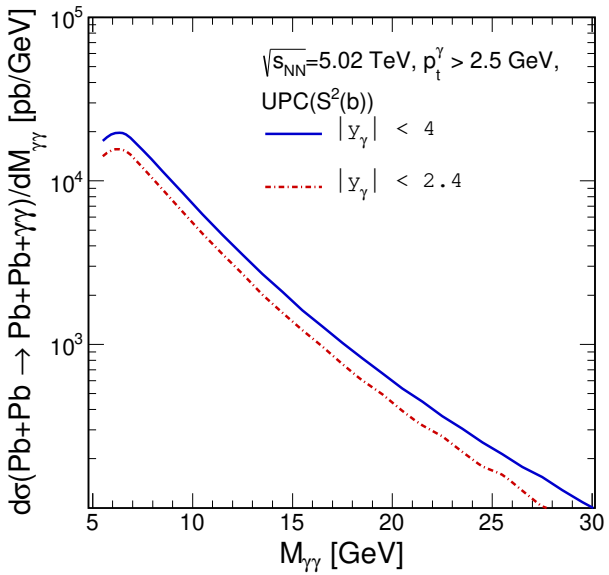
Kinematical cuts for future ATLAS measurement:

$$\begin{aligned} |y_\gamma| &< 4 \\ p_t^\gamma &> 2.5 \text{ GeV} \end{aligned}$$

The ATLAS collaboration, *Expected tracking and related performance with the updated ATLAS Inner Tracker layout at the High-Luminosity LHC*, ATL-PHYS-PUB-2021-024.

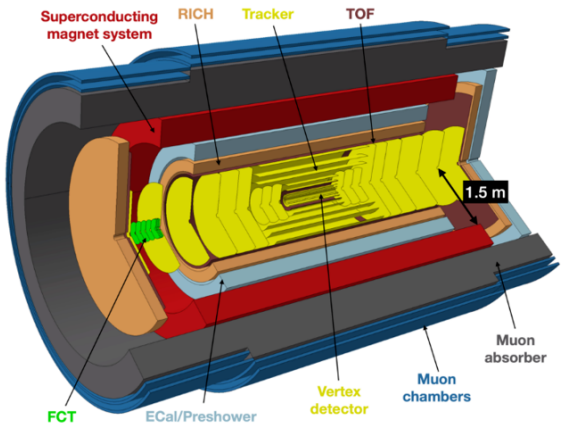
$\lvert y_\gamma \rvert <$	$\sigma_{tot.}^{theo.}$ [nb]	$\sigma_{tot.}^{exp.}$ [nb]
2.4	80 ± 8	120 ± 22
4	100 ± 10	planned

Total cross section for light-by-light scattering in collisions with energy $\sqrt{s_{NN}} = 5.02$ TeV, in range of photon transverse momentum $p_t^\gamma < 2.5$ GeV and diphoton invariant mass $M_{\gamma\gamma} > 5$ GeV; y_γ is a rapidity of measured single photon.



Differential cross section as function of diphoton invariant mass for future and recent ATLAS measurement.

ALICE 3



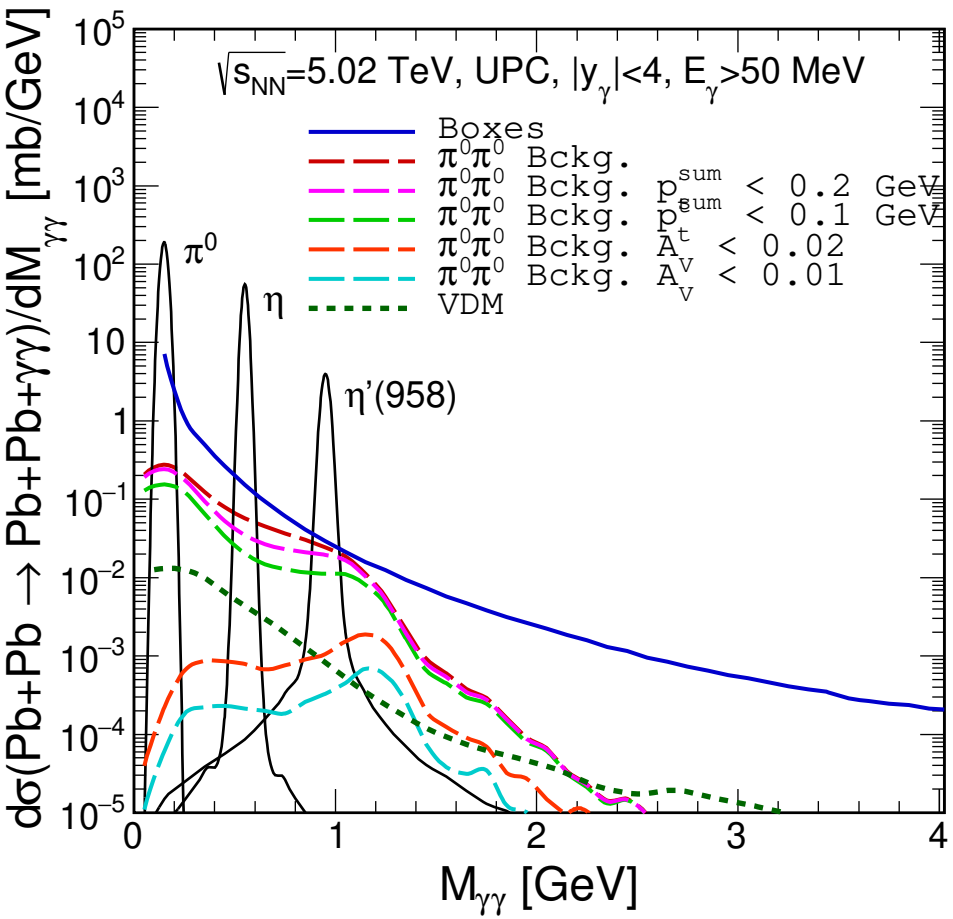
ALICE 3 - a next-generation heavy-ion detector for the LHC Runs 5-6.

$p_{t,min}[GeV]$	$p_{t,max}$ [GeV]	y_{min}	y_{max}
0.001	0.1	3	5
0.2	50	-1.6	4

Assumed kinematic limits in ALICE 3 experiment for photon measurement.

L. Musa, W. Riegler, *Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC*, arXiv:2211.02491, 2022.

UPC Results for ALICE 3

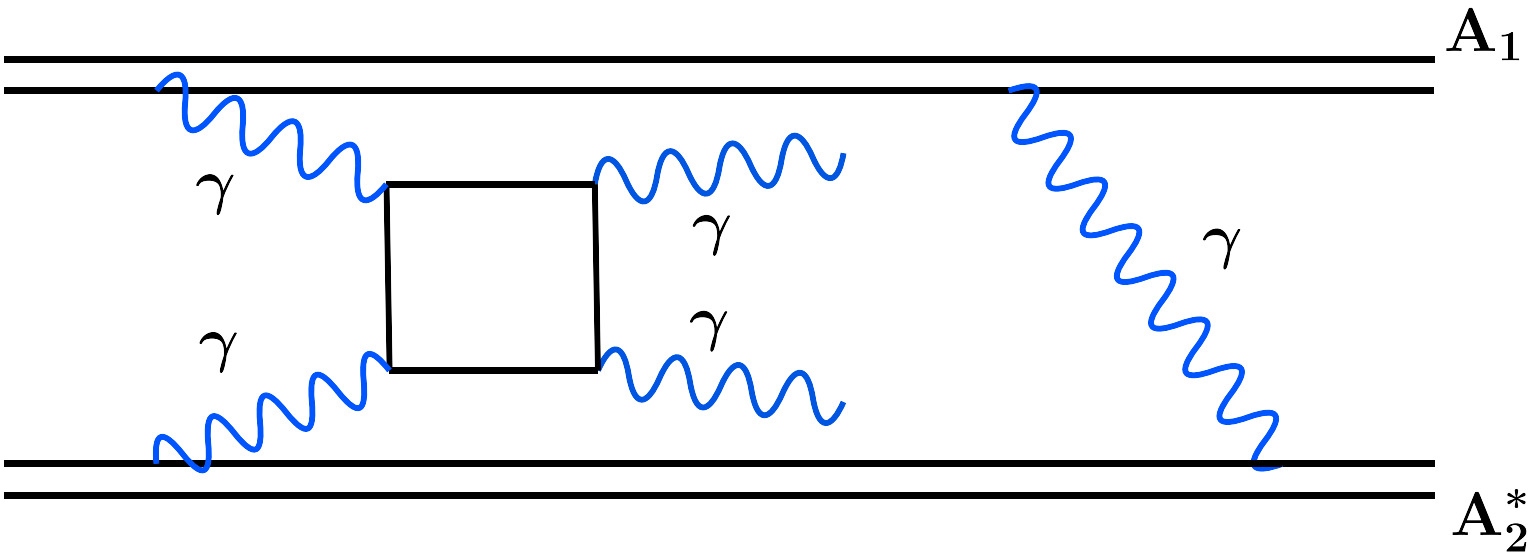


Differential cross section as function of diphoton invariant mass for future ALICE 3 experiment.

Vector asymmetry is defined as $A_v = |\vec{p}_{t,1} - \vec{p}_{t,2}|/|\vec{p}_{t,1} + \vec{p}_{t,2}|$

Photoproduction with nucleus break-up

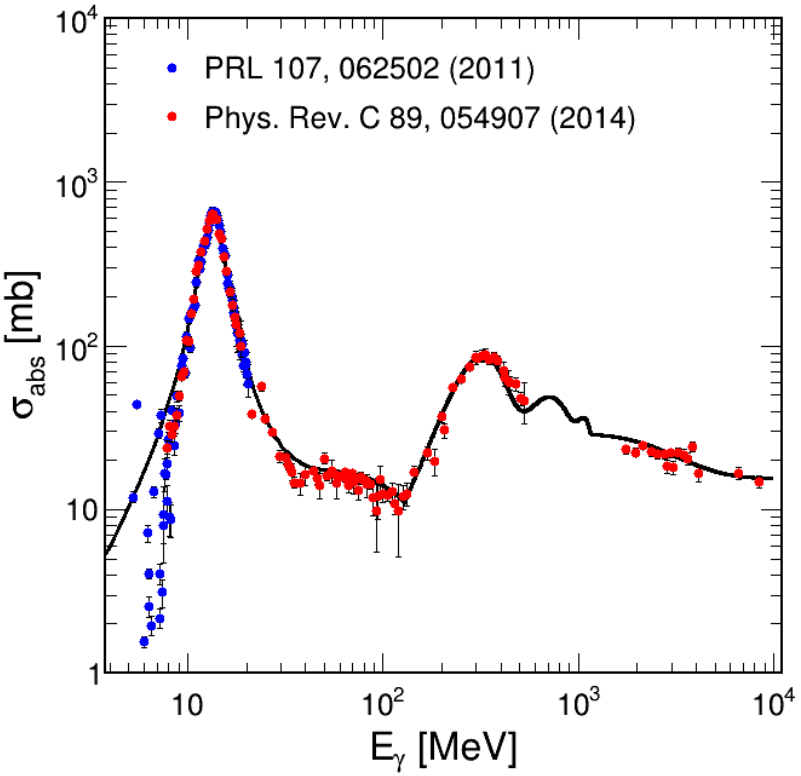
- The neutron measurement can be linked up with simultaneous observation of different processes like $\gamma\gamma \to \gamma\gamma$ scattering.
- Neutrons emitted from longitudinal boosted nucleus can be measured by Zero Degree Calorimeter.



Visualization of the process of light-by-light scattering with simultaneous photon absorption.

Photoproduction with nucleus break-up

$$\sigma_{\mathbf{PbPb\to AA+\gamma\gamma+kn+jn}} = \int \frac{\mathbf{d}\sigma_{\gamma\gamma\to\gamma\gamma}(\mathbf{W}_{\gamma\gamma})}{\mathbf{dz}} \mathbf{S^2(b)} \mathbf{P^c(b)} \mathbf{N}(\omega_1, \mathbf{b_1}) \mathbf{N}(\omega_2, \mathbf{b_2}) \times d^2 b d\bar{b}_x d\bar{b}_y \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{\gamma\gamma} dz \ .$$



Photoabsorption cross section for ^{208}Pb.

$$m(b) = \int d\omega N(\omega, b) \sigma_{abs}(\omega),$$

ATLAS ZDCs can measure the nuclear break-up with categories:

- nuclear break-up:

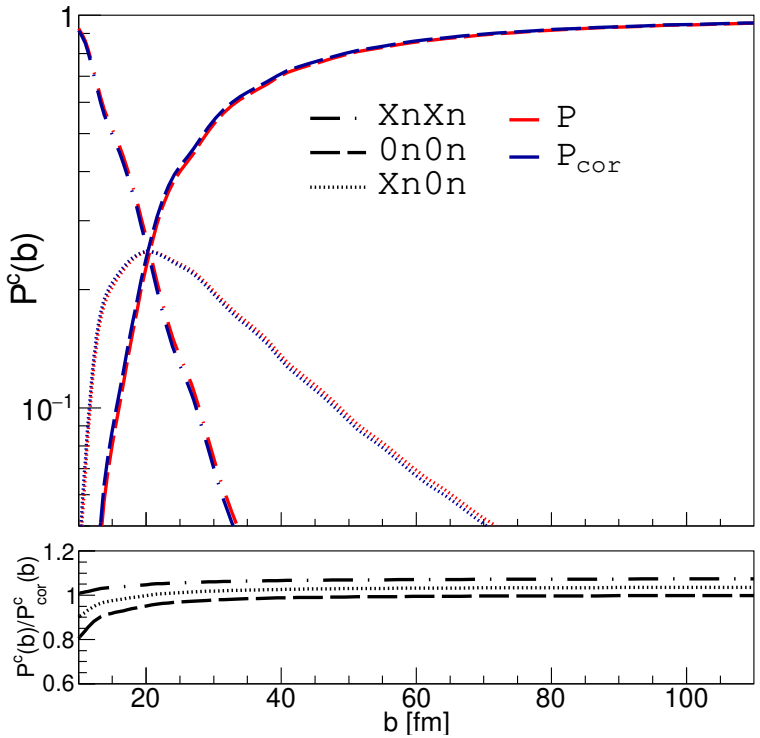
$$P^{Xn}(b) = 1 - \exp[-m(b)];$$

- no nuclear break-up:

$$P^{0n}(b) = \exp[-m(b)].$$

Photoproduction with nucleus break-up

$$\sigma_{\mathbf{PbPb\to AA+\gamma\gamma+kn+jn}} = \int \frac{\mathbf{d}\sigma_{\gamma\gamma\to\gamma\gamma}(\mathbf{W}_{\gamma\gamma})}{\mathbf{dz}} \mathbf{S^2(b)P^c(b)N}(\omega_1,\mathbf{b_1})\mathbf{N}(\omega_2,\mathbf{b_2}) \times d^2b d\bar{b}_x d\bar{b}_y \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{\gamma\gamma} dz \ .$$



Probability of nuclear break-up categories.

- nuclear break-up:

$$P^{Xn}(b) = 1 - \exp[-m(b)];$$

- no nuclear break-up:

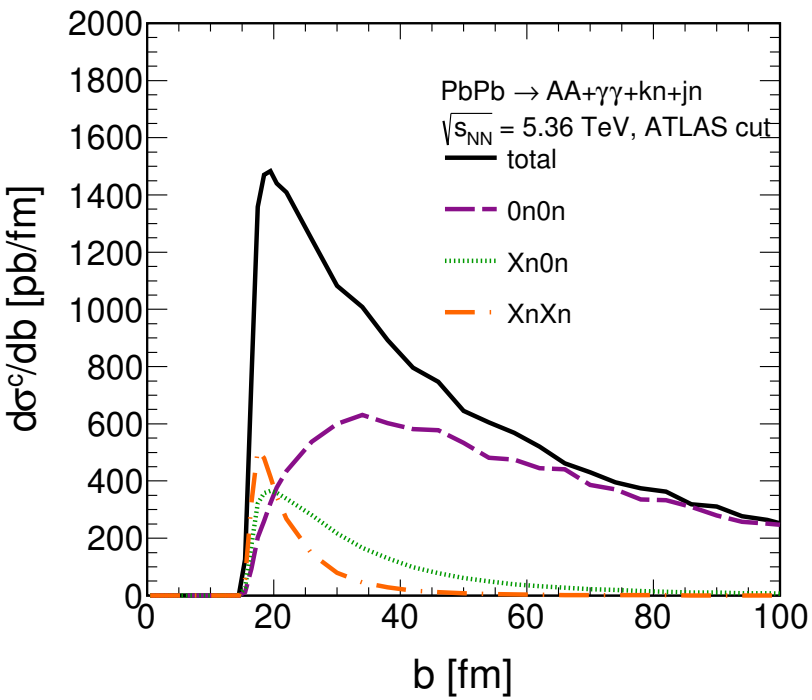
$$P^{0n}(b) = \exp[-m(b)].$$

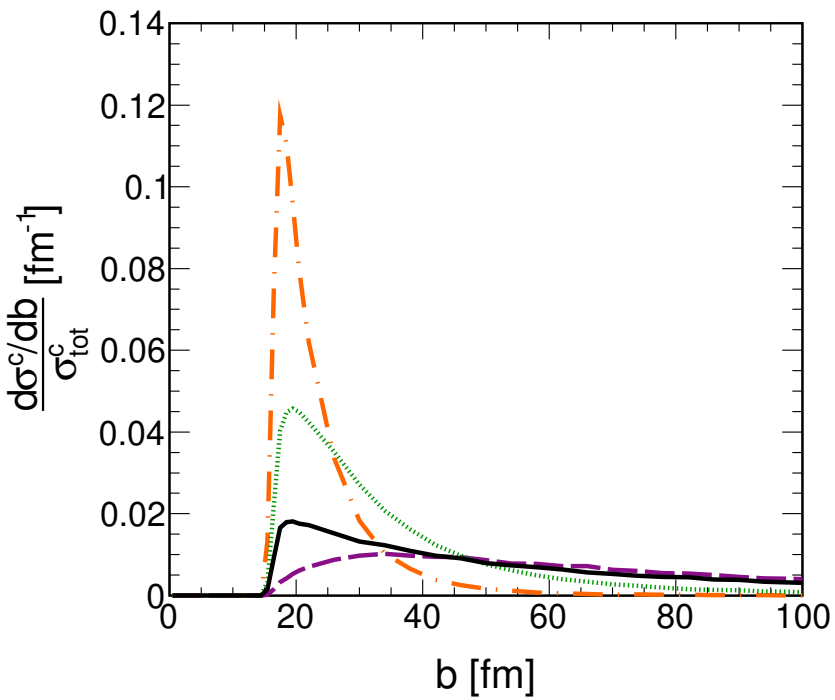
$$P^{XnXn}(b) = \left(P^{Xn}(b)\right)^2,$$
$$P^{0n0n}(b) = \left(P^{0n}(b)\right)^2,$$
$$P^{Xn0n}(b) = P^{Xn}(b)P^{0n}(b).$$

Photoproduction with nucleus break-up

	σ_{total}	$0n0n$	$XnXn$	$Xn0n + 0nXn$
σ [nb]	81.886	61.679	4.261	15.963
σ/σ_{total} [%]		75.30	5.20	9.50

Cross section light-by-light scattering in $Pb + Pb$ UPC and different neutron categories. Here $\sqrt{s_{NN}} = 5.36$ TeV.





Impact parameter distribution of cross section for different categories.

Photoproduction with nucleus break-up

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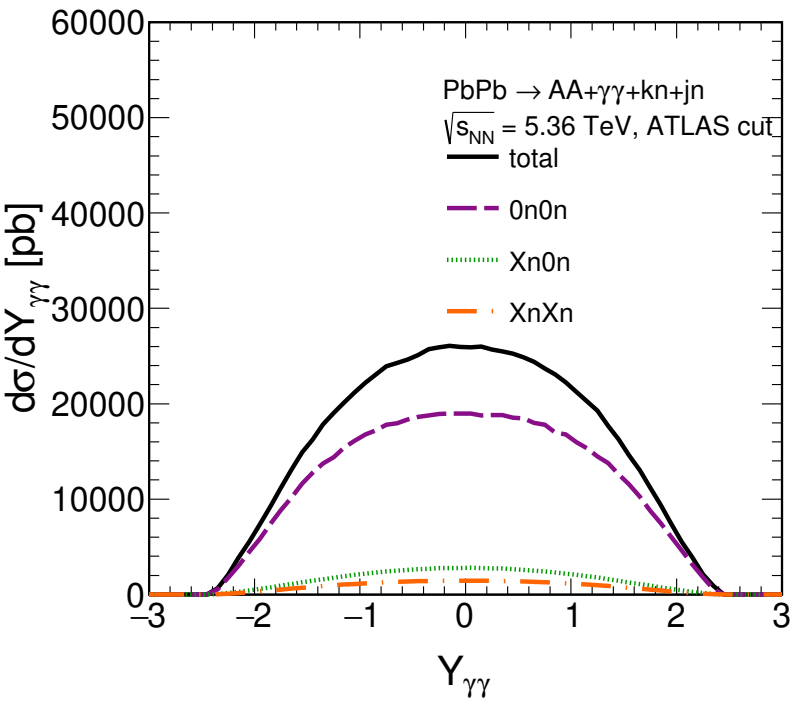

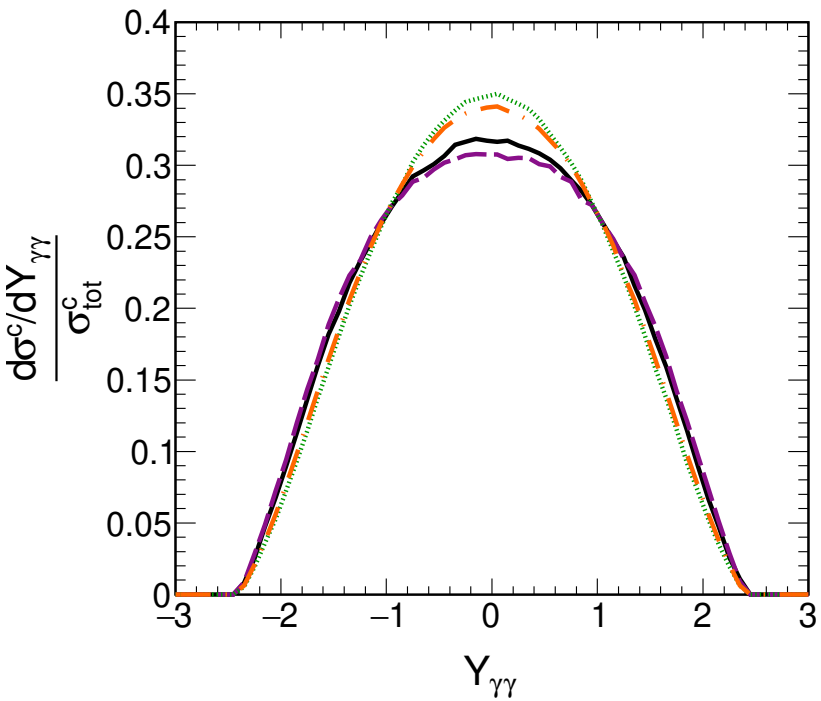

Rapidity distribution of cross section for different categories.

Summary

- Light-by-light scattering is a fundamental prediction of QED.
- Ultrarelativistic, ultraperipheral collisions of heavy ions allow observations of photon-induced processes hitherto not accessible.
- Future experiments will improve statistics and extend the kinematic ranges of measurements, allowing theoretical predictions to be tested.
- Neutrons emitted in the UPCs can be measure alongside the photons from light-by-light scattering providing information about distance of occurred collision.
- Most of light-by-light scattering events occur without simultaneous nuclear break-up.

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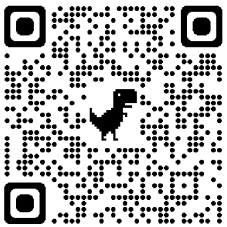
Summary



P. Jucha, M. Kłusek-Gawenda, A. Szczurek, *Light-by-light scattering in ultraperipheral collisions of heavy ions at two future detectors*, Physical Reviev D 109, 014004, 2024.

P. Jucha, M. Klusek-Gawenda, A. Szczurek, M. Ciemala, K. Mazurek, *Neutron emission from the photon-induced reactions in ultraperipheral ultrarelativistic heavy-ion collisions*, Physical Reviev C 111, 034901, 2025.

P. Jucha, M. Kłusek-Gawenda, A. Szczurek, *Neutron emission associated with $\gamma\gamma \to \gamma\gamma$ scattering in ultraperipheral collisions of heavy ions at the LHC*, Phys. Rev. D 112, L051501, 2025.

P. Jucha, K. Mazurek, A. Szczurek, K. Pysz, *New UPC results at the LHC - modeling the proton and neutron emission in photon-induced nuclear processes*, arXiv:2508.20791, 2025. - during review