INSTYTUT FIZYKI JĄDROWEJ
IM. HENRYKA NIEWODNICZAŃSKIEGO
POLSKIEJ AKADEMII NAUK

The future of experimental measurements of light-by-light scattering

Paweł Jucha
pawel.jucha@ifj.edu.pl

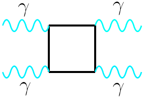
Mariola Kłusek-Gawenda, Antoni Szczurek

New Trends in High-Energy and Low-x Physics
2nd September 2024

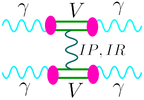
Topics list

- Light-by-Light scattering
  - Brief history
  - Elementary cross section
- Equivalent Photon Approximation
- Experimental predictions
  - ATLAS
  - Forward Calorimeter (FoCal) ALICE
  - ALICE 3
- Quest for VDM
- Pomeron-Pomeron

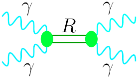
Light-by-light scattering



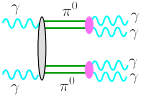
Fermionic box



VDM-Regge



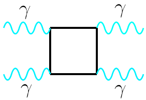
Mesonic resonances

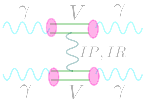


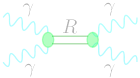
Background - 2π production

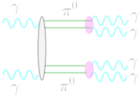
- Light-by-light scattering is a process where two photons interact with each other.
- O. Halpern in 1933 proposed mechanism of interaction between two light quanta via virtual electron-positron pair
- First calculation of light-by-light scattering cross section was conducted by H. Euler, B. Kockel.

Light-by-light scattering - elementary cross section





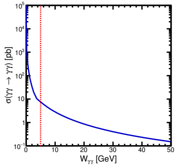




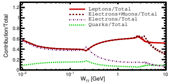
Fermionic box

- Fermionic box is the main mechanism of light-by-light scattering.
- The elementary cross section is calculated for unpolarised photons - 5 independent photon helicity combinations of the amplitudes was added up with with weights resulting from symmetry.

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

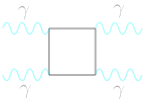


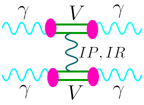
Elementary cross section of the light-by-light scattering box mechanism as distribution of energy.



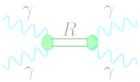
Ratio of different box mechanism components to the total cross section.

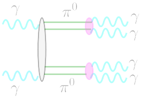
Light-by-light scattering - elementary cross section





VDM-Regge

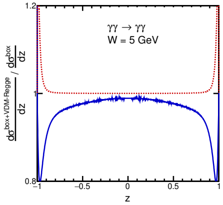




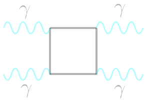
- Vector Meson Dominance model involves oscillations of photons to the light mesons like ρ, ω, ϕ.
- Interactions of this mesons are described by amplitude from the Regge theorem:

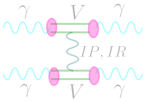
$$\mathcal{A}_{\gamma\gamma\to\gamma\gamma}(s,t) \approx \left(\sum_{i=1}^{3} C^{2}_{\gamma\to V_i}\right) \mathcal{A}(s,t) exp\left(\frac{B}{2}t\right) \left(\sum_{j=1}^{3} C^{2}_{\gamma\to V_j}\right) .$$

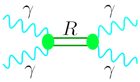
- The sum of amplitudes from box and VDM mechanisms must be added coherently.



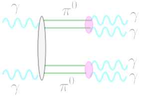
The ratio of the coherent and incoherent sum of the box and VDM-Regge contributions divided by the cross section for the box contribution.







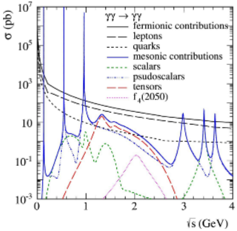
Mesonic resonances



- 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'.
- Mesonic resonance amplitudes was calculated via relativistic Breit-Wigner formula:

$$\mathcal{M}_{\gamma\gamma\to R\to\gamma\gamma}(\lambda_1,\lambda_2) = \frac{\sqrt{64\pi^2 W^2_{\gamma\gamma}\Gamma^2_R Br^2(R\to\gamma\gamma)}}{\hat{s} - m_R^2 - i m_R \Gamma_R} \times \frac{1}{\sqrt{2\pi}}\delta_{\lambda_1-\lambda_2},$$

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

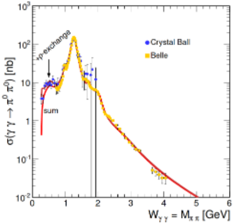


Elementary cross section for different $\gamma\gamma \to \gamma\gamma$ processes.

Light-by-light scattering background

2π production

- 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.



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

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. C87 (2013) 054908.

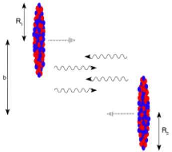
Equivalent Photon Approximation

- Nuclear cross section:

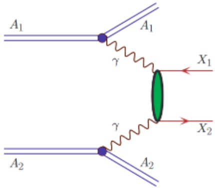
$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \int \frac{\mathrm{d}\sigma_{\gamma\gamma \to X_1 X_2}(W_{\gamma\gamma})}{\mathrm{d}\ \cos\theta} \times N(\omega_1, b_1) N(\omega_2, b_2) S^2_{abs}(b)$$
$$\times \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{X_1 X_2} d\overline{b}_x d\overline{b}_y d^2 b \times \frac{\mathrm{d}\ \cos\theta}{dy_{X_1} dy_{X_2} dp_t} \times dy_{X_1} dy_{X_2} dp_t$$

- 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.

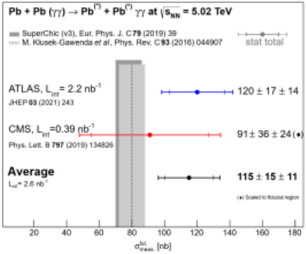


Photon fusion.

Experimental results

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 $|y| < 2.4$; $p_{t,min}^{\gamma}$ is a minimal measured value of photon transverse momentum of single photon, $M_{\gamma\gamma,min}$ is a diphoton invariant mass.



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 invariant mass:
$p_t^{\gamma} > 2$ GeV
$M_{\gamma\gamma} > 5$ GeV

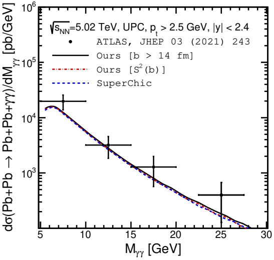
G. K. Krintiras, I. Grabowska-Bold, M. Kłusek-Gawenda, É. Chapon, R. Chudasama and R. Granier de Cassagnac, *Light-by-light scattering cross-section measurements at LHC.* arXiv:2204.02845, 2022.

- Sharp edge of nucleus:

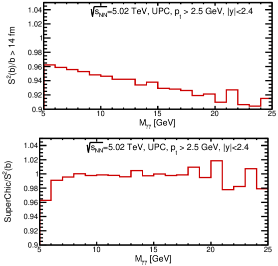
$$b_{min} = R_{A_1} + R_{A_2} \approx 14 \text{ fm}$$

- Smooth edge of nucleus:

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



Differential cross section as function of diphoton invariant mass.



Ratios between different theoretical approaches.

Results for ATLAS expreriment

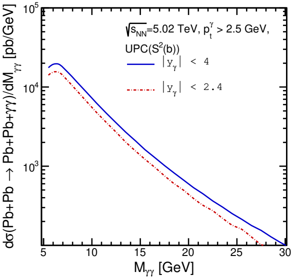
Kinematical cuts for new ATLAS measurement:

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

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	77.084 ± 0.005	120 ± 22
4	100.444 ± 0.027	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.

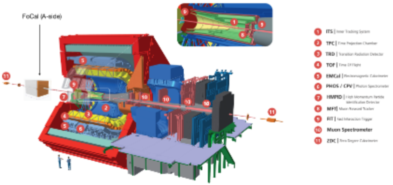


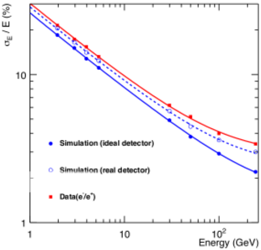
Differential cross section as function of diphoton invariant mass for future and recent ATLAS measurement.

Forward Calorimeter (FoCal) ALICE

- Acceptance:
  $3.4 < y_\gamma < 5.8$
  $p_t^\gamma > 200$ MeV
- Position resolution:
  $\sigma_x = \sigma_y = 1$ mm
- Energy resolution:

$$\frac{\sigma_E}{E} = \frac{28.5\%}{\sqrt{E(GeV)}} + \frac{6.3\%}{E(GeV)} + 2.95\%$$

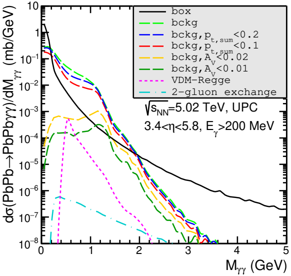


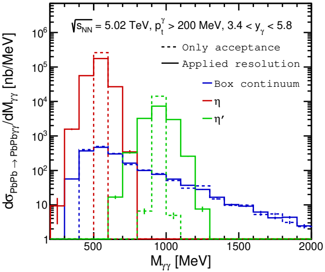


A.P. de Haas et al. (ALICE Collaboration), *The FoCal prototype — an extremely fine-grained electromagnetic calorimeter using CMOS pixel sensors*, JINST 13 P01014, 2018.

C. Loizides, *The Forward Calorimeter project in ALICE*, EF06 meeting 2020, https://indico.fnal.gov/event/44126/contributions/191953/attachments/132434/162766/20200805_focal_snowmass.pdf

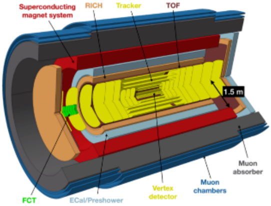
Forward Calorimeter (FoCal) ALICE





Invariant mass distribution for the nuclear process. Predictions are made for the future FoCal acceptance $E_{t,\gamma} > 200$ MeV and $3.4 < y_\gamma < 5.8$.

Results of combined theoretical results for light-by-light scattering and Monte Carlo simulation of energy and position resolution for diphoton invariant mass for FoCal detector.



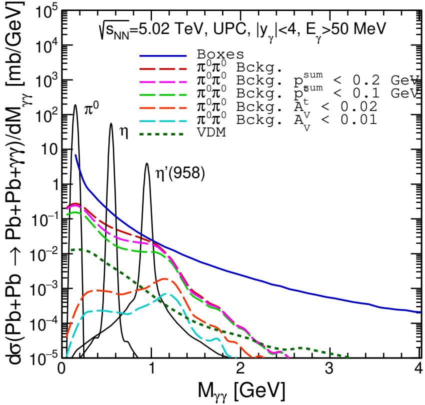
ALICE 3 - a next-generation heavy-ion detector for the LHC Runs 5-6.

$p_{t,min}[GeV]$	$p_{t,max}$ [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.

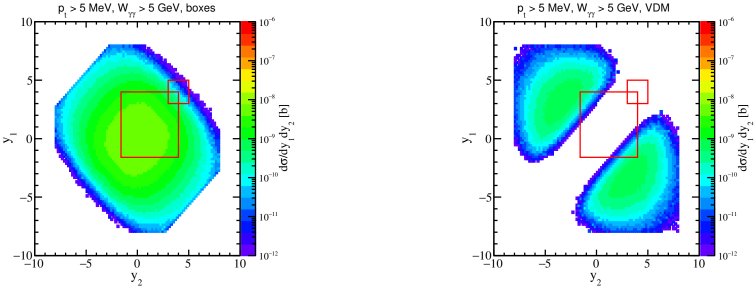
L. Musa, W. Riegler, *Letter of intent for ALICE 3: A next generation heavy-ion experiment at the LHC*, arXiv:2211.02491, 2022.

ALICE 3 results



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

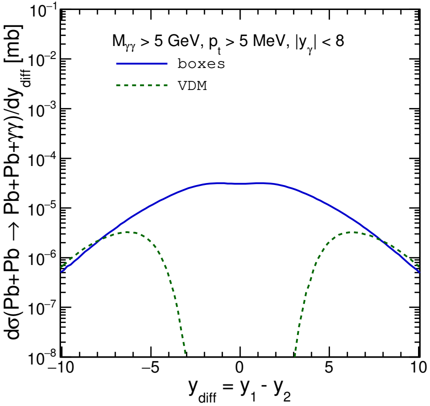
The differential cross-section for the VDM-Regge process in UPC, Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.



The red frames mark the acceptance range of the ALICE 3 detectors.

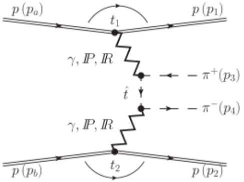
Wide rapidity range is key to the experimental observation of VDM.

Quest for VDM-Regge



Introduction of the new variable: difference of photons rapidity.

Pomeron-Pomeron interaction



P. Lebiedowicz, O. Nachtmann, A. Szczurek, Extracting the Pomeron-Pomeron-$f_2(1270)$ coupling in the $pp \to pp\pi^+\pi^-$ reaction through the angular distribution of the pions, Physical Reviev D **101**, 034008 (2020).

Naively, one can assume that:

$$\sigma = \int \frac{d\sigma(M_{\pi\pi}, \cos\theta)}{d\,\cos\theta} f_{\mathbb{P}/p}(\omega_1) f_{\mathbb{P}/p}(\omega_2)$$

$$\frac{M_{\gamma\gamma}}{2} d\omega_1 d\omega_2 dY_{\pi\pi} dM_{\pi\pi} \frac{d\,\cos\theta}{dy_1 dy_2 dp_t} dy_1 dy_2 dp_t$$

However, consider that:

- for photons $t_1 \approx 0$, $t_2 \approx 0$. For pomerons $t_1 \neq 0$, $t_2 \neq 0$ and $t_1 \neq t_2$;
- one should use the $2 \to 4$ kinematics;
- also assumption that $p_{t,1} = p_{t,2}$ may be too optimistic.

Summary

- Light-by-light scattering is a fundamental prediction of QED.
- Ultrarelativistic, ultraperipheral collisions of heavy ions allow observations of photon-photon processes hitherto not accessible.
- Light-by-light scattering not only provides evidence of the quantum nature of the electromagnetic interaction, but is also a tool to test the limits of theoretical models, and it provides a basis for the exploration of so-called "New Physics".
- Future experiments such as ATLAS, FoCal and ALICE 3 will improve statistics and extend the kinematic ranges of measurements, allowing theoretical predictions to be tested

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.

Speaker acknowledges financial support provided by the Polish National Agency for Academic Exchange NAWA under the Programme STER– Internationalisation of doctoral schools, Project no. PPI/STE/2020/1/00020

Krakow School of Interdisciplinary PhD Studies