# **Possibilities of light-by-light scattering** measurement in FoCal detector

**mgr inż. Paweł Jucha**

Institute of Nuclear Physics
Polish Academy of Sciences

XXX Cracow Epiphany Conference
11.01.2024

# 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:

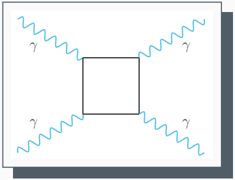
$$\sigma \sim (\frac{e^2}{mc^2})^4 (\frac{\hbar}{mc})^2 \cdot \frac{1}{\lambda^2}$$

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."




Fermionic box.

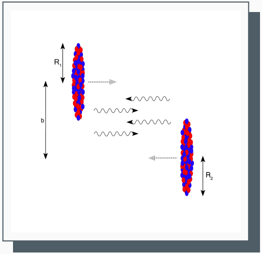
# Equivalent Photon Approximation

- Nuclear cross section:

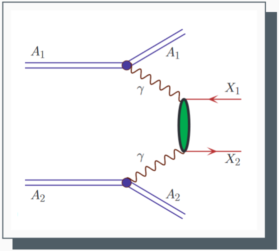
$$\sigma_{A_1A_2\to A_1A_2X_1X_2} = \int \frac{d\sigma_{\gamma\gamma\to X_1X_2}(W_{\gamma\gamma})}{d\cos\theta} \times N(\omega_1,b_1)N(\omega_2,b_2)S^2_{abs}(b)$$
$$\times \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{X_1X_2} d\bar{b}_x d\bar{b}_y d^2b \times \frac{d\cos\theta}{dy_{X_1}dy_{X_2}dp_t}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

- 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.

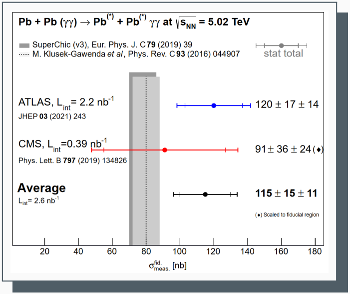



Photon fusion.

# Highlights of experiments

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

Total cross section for light-by-light scattering in collisions with energy $\sqrt{s_{NN}}$ = 5.02 TeV, in range of photon rapidity $|y| < 2.4$; $p^{\gamma}_{t,min}$ 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:
$p^{\gamma}_t > 2$ 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.

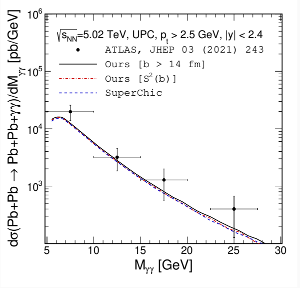
# Results for ATLAS expreriment

- Sharp edge of nucleus:

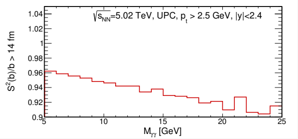
$$b_{min} = R_{A_1} + R_{A_2} \approx 14 \text{ fm}$$

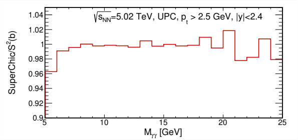
- Smooth edge of nucleus:

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




Differential cross section as function of diphoton invariant mass.




Ratios between different theoretical approaches.

# Results for ATLAS expriment

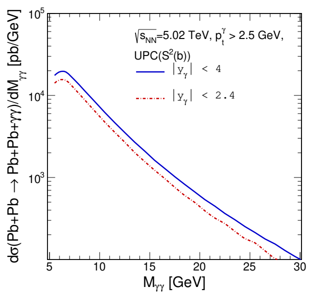
Kinematical cuts for new ATLAS measurement:

$$|y_\gamma| < 4$$
$$p_t^\gamma > 2.5 \text{ GeV}$$

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.

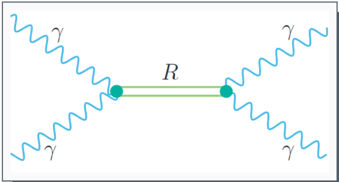
| $\|y_\gamma\| <$ | $\sigma_{tot.}^{theo.}$ [nb] | $\sigma_{tot.}^{exp.}$ [nb] |
|---|---|---|
| 2.4 | $77.084 \pm 0.005$ | $120 \pm 22$ |
| 4 | $100.444 \pm 0.027$ | planned |

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; $y_\gamma$ is a rapidity of measured single photon.



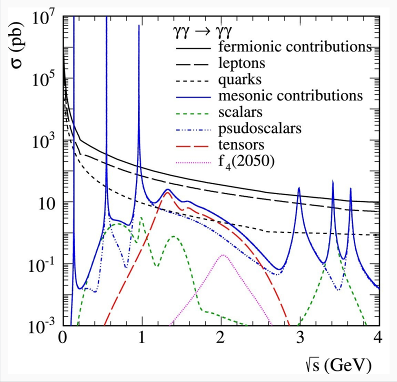

Differential cross section as function of diphoton invariant mass for future and recent ATLAS measurement.

# Resonances



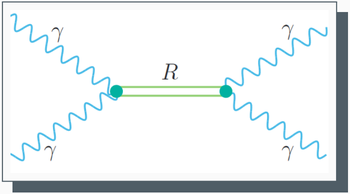

Mesonic resonance.

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.

# Resonances - elementary cross section




Mesonic resonance.

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

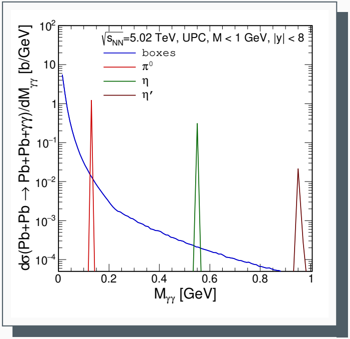
$$\frac{d\sigma_{\gamma\gamma\to R\to\gamma\gamma}(W_{\gamma\gamma})}{d\cos\theta} = \frac{1}{32\pi W_{\gamma\gamma}^2}\frac{1}{4}\sum_{\lambda_1,\lambda_2}\left|\mathcal{M}_{\gamma\gamma\to R\to\gamma\gamma}(\lambda_1,\lambda_2)\right|^2$$

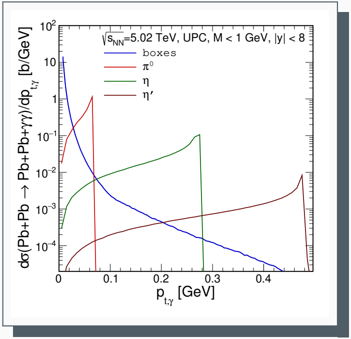
$$\mathcal{M}_{\gamma\gamma\to R\to\gamma\gamma}(\lambda_1,\lambda_2) = \frac{\sqrt{64\pi^2 W_{\gamma\gamma}^2 \Gamma_R^2 Br^2(R\to\gamma\gamma)}}{\hat{s} - m_R^2 - i m_R \Gamma_R} \times \frac{1}{\sqrt{2\pi}}\delta_{\lambda_1-\lambda_2}$$

Relativistic Breit–Wigner distribution

# Resonances - nuclear cross section

The distributions of nuclear cross section as function of diphoton invariant mass and single photon transverse momentum for fermionic loops and resonances.

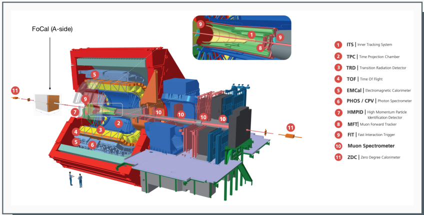


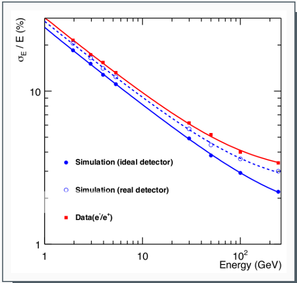



# FoCal

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

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

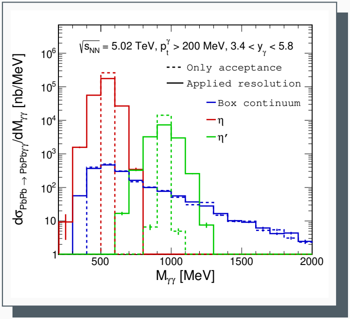


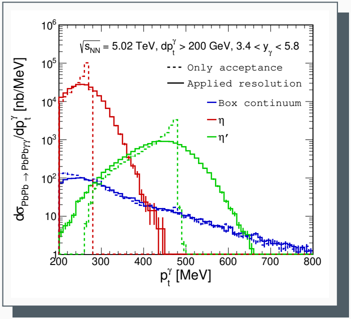




A.P. de Haas et al. (ALICE Collaboration), *The FoCal prototype — an extremely fine-grained electromagnetic calorimeter using CMOS pixel sensors*, JINST 13 P01014, 2018.

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`

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



# 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" (axions, dark photons).
- Future experiments such as FoCal and ATLAS will improve statistics and extend the kinematic ranges of measurements, allowing theoretical predictions to be tested

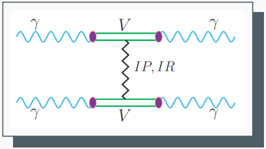
P. Jucha, M. Kłusek-Gawenda, A. Szczurek, *Light-by-light scattering in ultraperipheral collisions of heavy ions at two future detectors*, Physical Reviev D 109, 014004, 2024.

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

BACKUP

# VDM-Regge - elementary cross section




M. Klusek-Gawenda, P. Lebiedowicz, A. Szczurek
*Light-by-light scattering in ultraperipheral PbPb collisions at the Large Hadron Collider,*
Phys. Rev. C, 93:4, 2016.

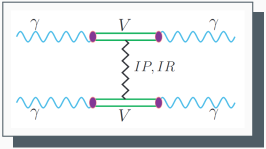
VDM-Regge: Fluctuation of $\gamma$ into virtual $\rho$, $\omega$, $\phi$.

$$\frac{d\sigma_{\gamma\gamma\to\gamma\gamma}}{d\Omega} = \frac{1}{64\pi^2 s}\overline{|\mathcal{A}_{\gamma\gamma\to\gamma\gamma}|}^2$$

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

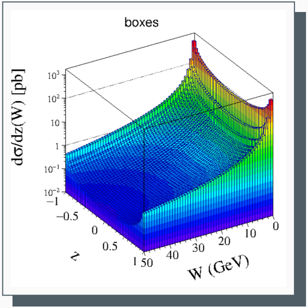
$$\mathcal{A}(s,t) \approx s\left((1+i)C_R\left(\frac{s}{s_0}\right)^{\alpha_R(t)-1} + iC_P\left(\frac{s}{s_0}\right)^{\alpha_P(t)-1}\right),$$

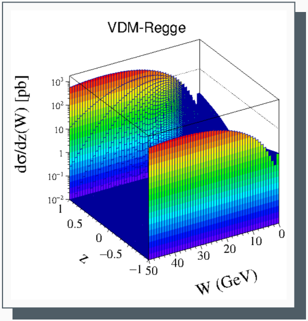
# VDM-Regge - elementary cross section




M. Klusek-Gawenda, P. Lebiedowicz, A. Szczurek
*Light-by-light scattering in ultraperipheral PbPb collisions at the Large Hadron Collider,*
Phys. Rev. C, 93:4, 2016.

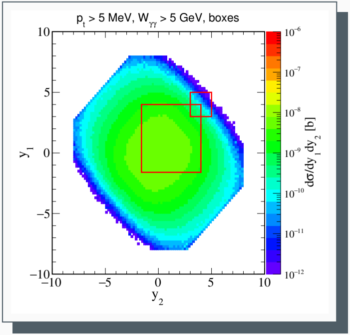
VDM-Regge: Fluctuation of $\gamma$ into virtual $\rho$, $\omega$, $\phi$.

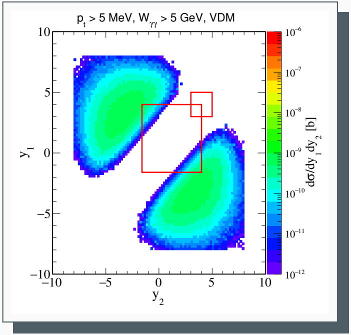


# VDM-Regge - nuclear cross section

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

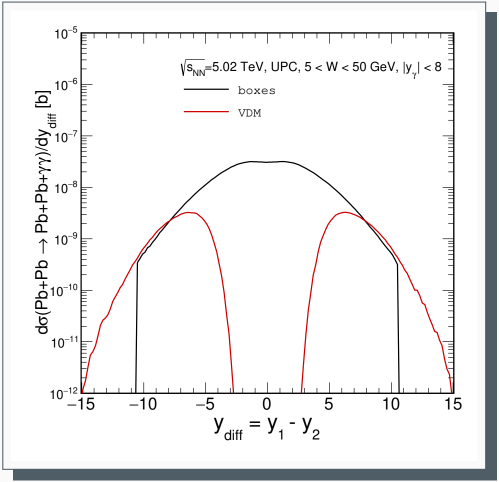



The red frames mark the acceptance range of the ALICE 3 detectors.

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

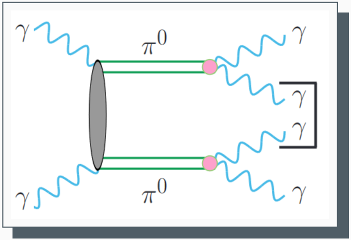
# VDM-Regge - nuclear cross section




Introduction of the new variable: difference of photons rapidity.

# Two pions creation - elementary cross section

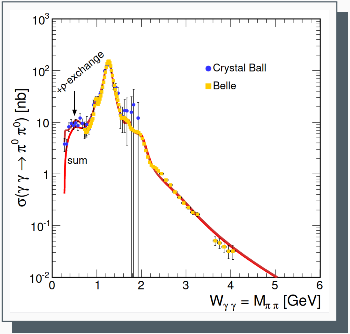
$$\frac{d\sigma_{\gamma\gamma\to\pi^0\pi^0}(W_{\gamma\gamma})}{d\cos\theta} = \frac{\sqrt{\frac{W_{\gamma\gamma}^2}{4} - m_\pi^2}}{\frac{W_{\gamma\gamma}}{2}} \frac{4\pi}{4\times 64\pi^2 W_{\gamma\gamma}^2} \sum_{\lambda_1,\lambda_2} |\mathcal{M}_{\gamma\gamma\to\pi^0\pi^0}(\lambda_1,\lambda_2)|^2$$



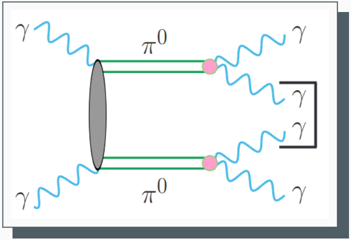

Two pion production.

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;

# Two pions creation - elementary cross section



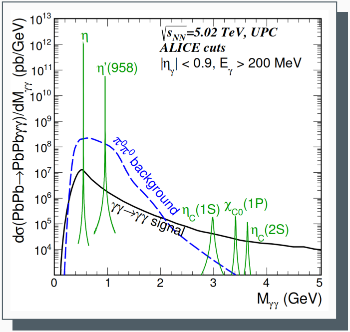

Elementary cross section for $\gamma\gamma \to \pi^0\pi^0$ for $|\cos\theta| < 0.8$.



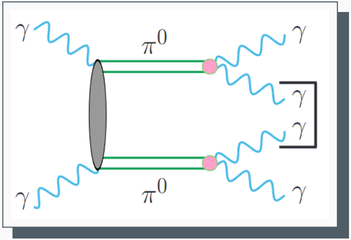

Two pion production.

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;

# Two pions creation - nuclear cross section



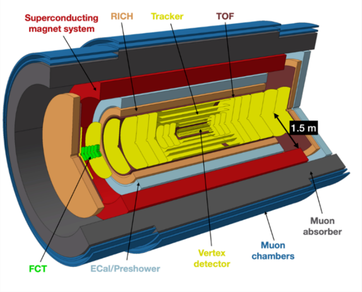

Differential cross section as a function of invariant diphoton mass within the ALICE fiducial region.




Two pion production.


M. Kłusek-Gawenda, R. McNulty, R. Schicker, and A. Szczurek. *Light-by-light scattering in ultraperipheral heavy-ion collisions at low diphoton masses,*
Phys. Rev. D, 99(9):093013, 2019.

# ALICE 3



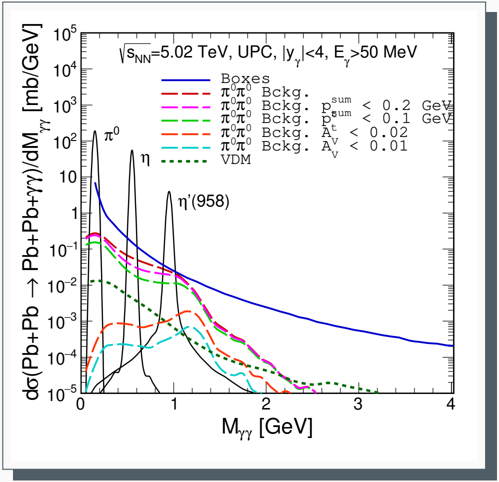

ALICE 3 - a next-generation heavy-ion detector for the LHC Runs 5-6.

| $p_{t,min}$ [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.

# ALICE 3 results




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