# The Role of Mesons in Light-by-Light Scattering

at Low Transverse Momentum

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# Light-by-Light Scattering

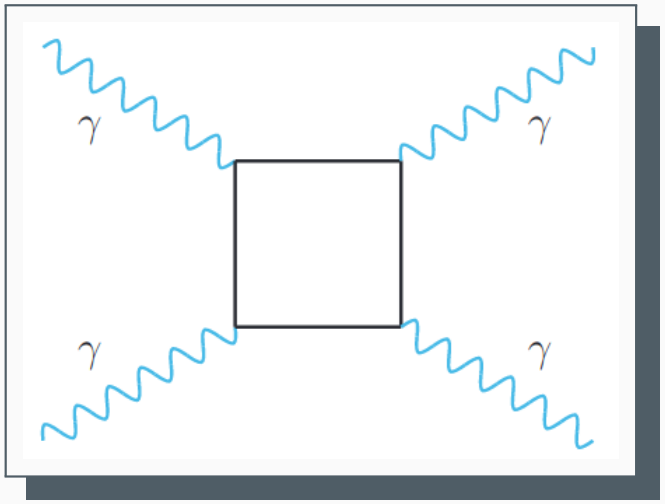
$$\gamma\gamma \to \gamma\gamma$$

- In the limit of weak electromagnetic fields:

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

- For visible light:

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




Fermionic box.

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

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

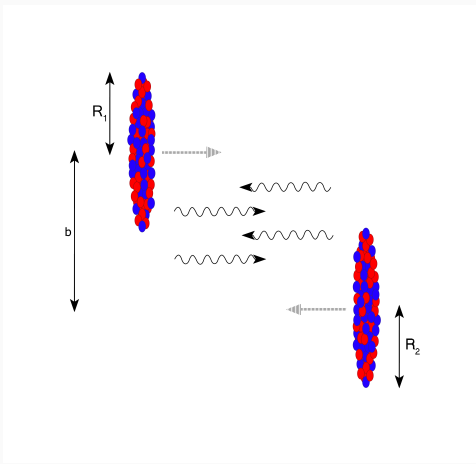
# Equivalent Photon Approximation

- Nuclear cross-section:

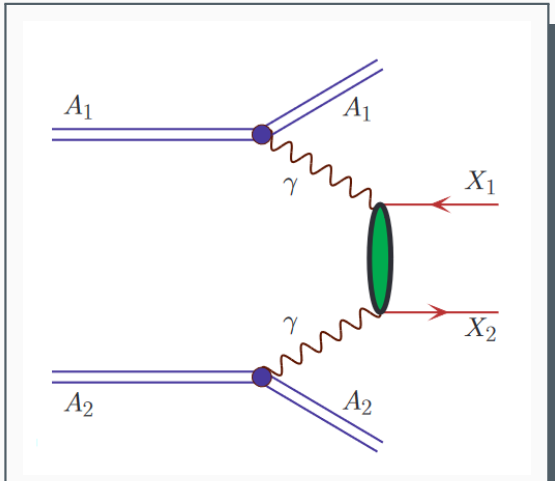
$$\sigma_{A_1A_2\to A_1A_2X_1X_2} = \int \frac{d\sigma_{\gamma\gamma\to X_1X_2}(W_{\gamma\gamma})}{d\cos\theta} \times N(\omega_1,b_1)N(\omega_2,b_2)S^2_{abs}(b)$$
$$\times \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{X_1X_2} d\bar{b}_x d\bar{b}_y d^2b \times \frac{d\cos\theta}{dy_{X_1}dy_{X_2}dp_t}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

- Photon flux:

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




Collision geometry.

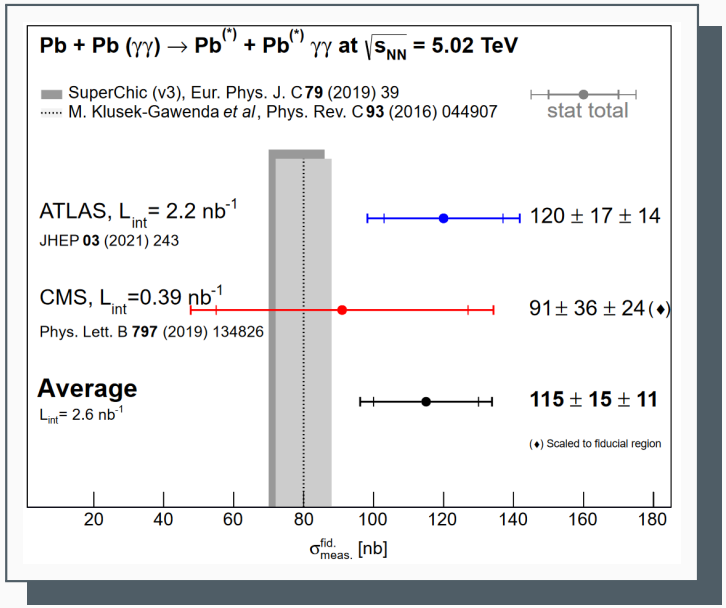



Photon fusion.

# 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 | $120 \pm 22$ | $80 \pm 8$ |

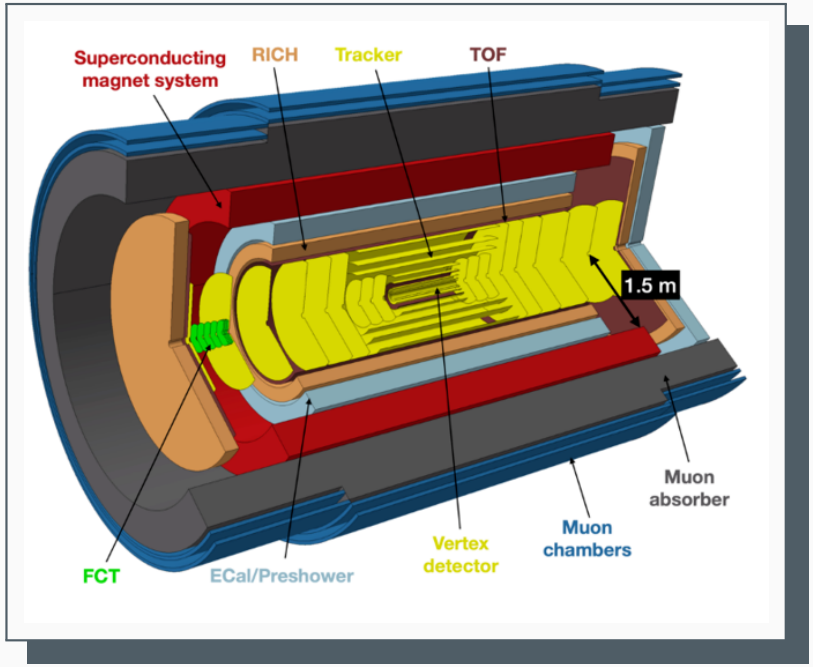
Total cross-section for light-by-light scattering in collisions with energy $\sqrt{s_{NN}}$ = 5.02 TeV, in range of photon rapidity $|y| < 2.4$; $p^{\gamma}_{t,min}$ is a minimal measured value of photon transverse momentum of single photon, $M_{\gamma\gamma,min}$ is a di-photon mass.




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

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

# ALICE 3



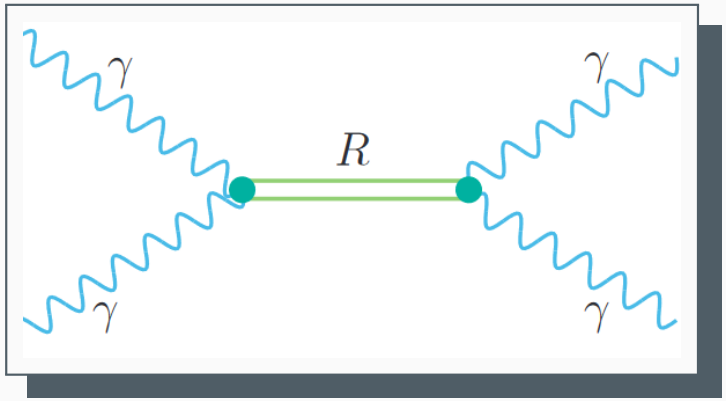

ALICE 3 - a next-generation heavy-ion detector for the LHC Runs 5-6.

| $p_{t,min}$ [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.

# Resonances - elementary cross-section




Mesonic resonance.

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

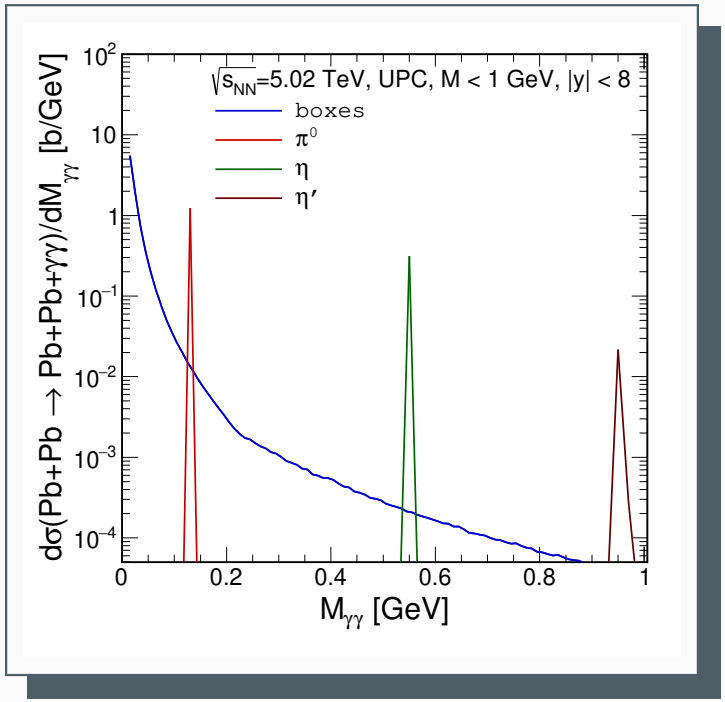
$$\mathcal{M}_{\gamma\gamma\to R\to\gamma\gamma}(\lambda_1,\lambda_2) = \frac{\sqrt{64\pi^2 W_{\gamma\gamma}^2\Gamma_R^2 Br^2(R\to\gamma\gamma)}}{\hat{s}-m_R^2-im_R\Gamma_R}\times\frac{1}{\sqrt{2\pi}}\delta_{\lambda_1-\lambda_2}$$

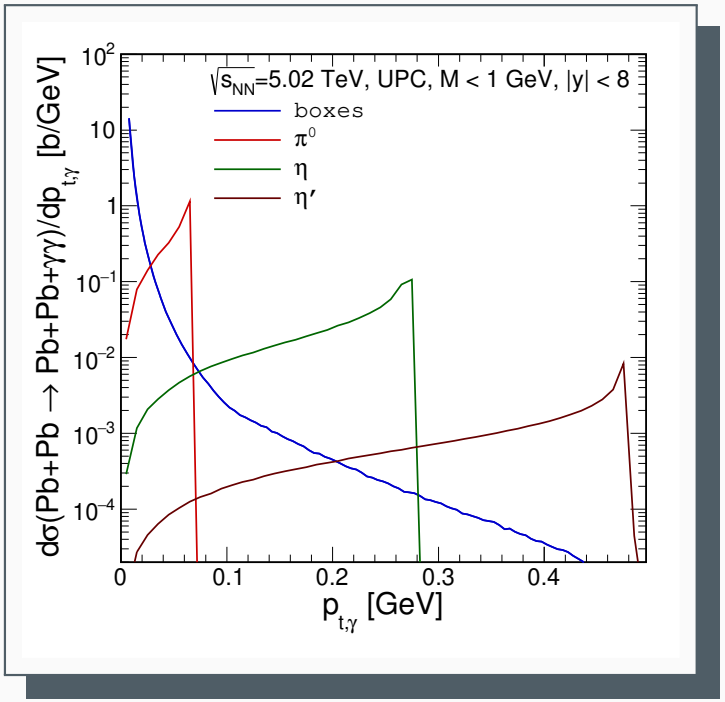

P. Lebiedowicz, A. Szczurek, *The role of meson exchanges in light-by-light scattering,* Physics Letters B, 772:330-335, 2017.

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.

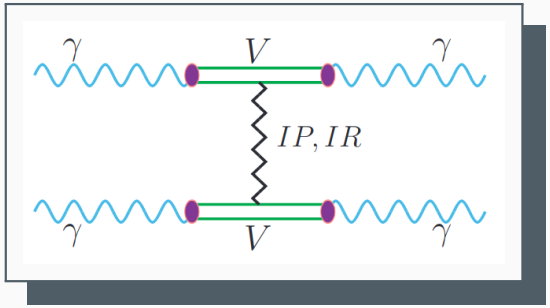
# Resonances - nuclear cross-section

The distributions of nuclear cross-section as a function of di-photon mass and transverse momentum for fermionic loops and resonances.



# 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.

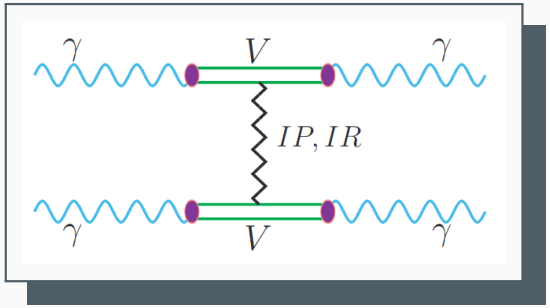
VDM-Regge: Fluctuation of $\gamma$ into virtual $\rho, \omega, \phi$.

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

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

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

# VDM-Regge - elementary cross-section

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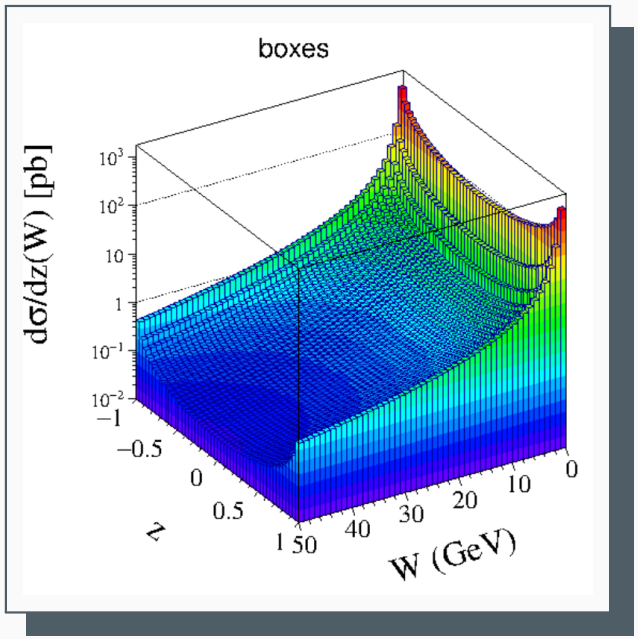
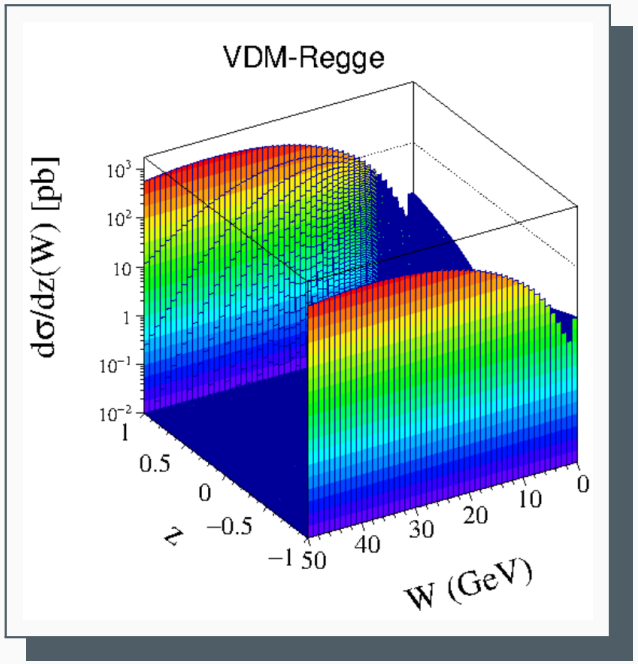
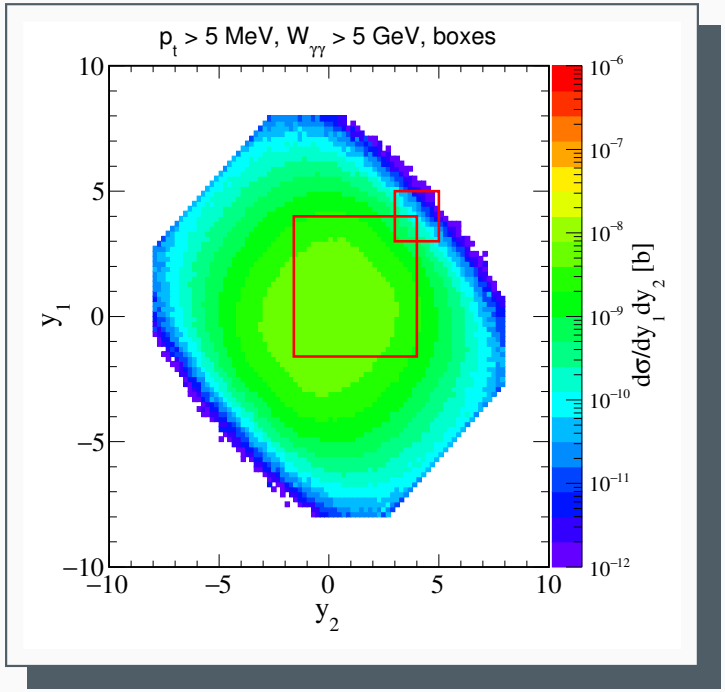
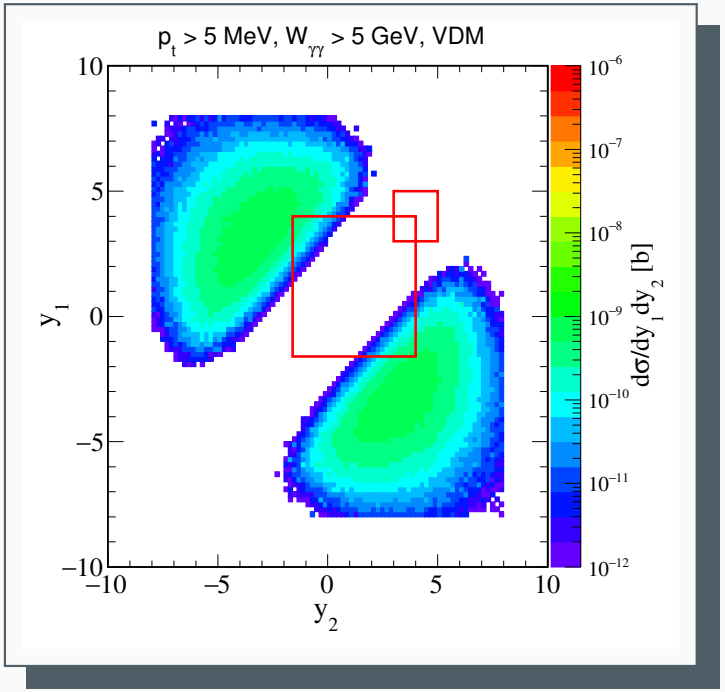


# VDM-Regge - nuclear cross-section

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

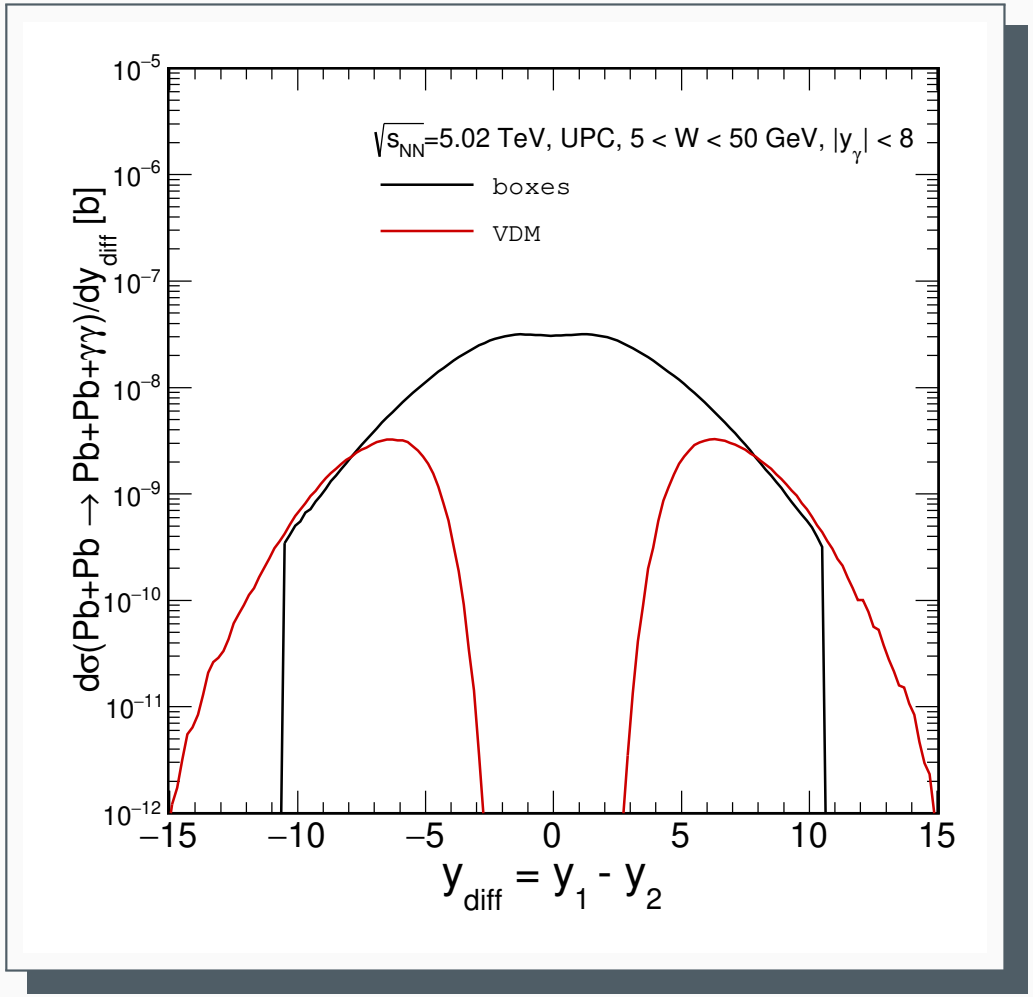



The red frames mark the acceptance range of the ALICE 3 detectors.

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

# VDM-Regge - nuclear cross-section



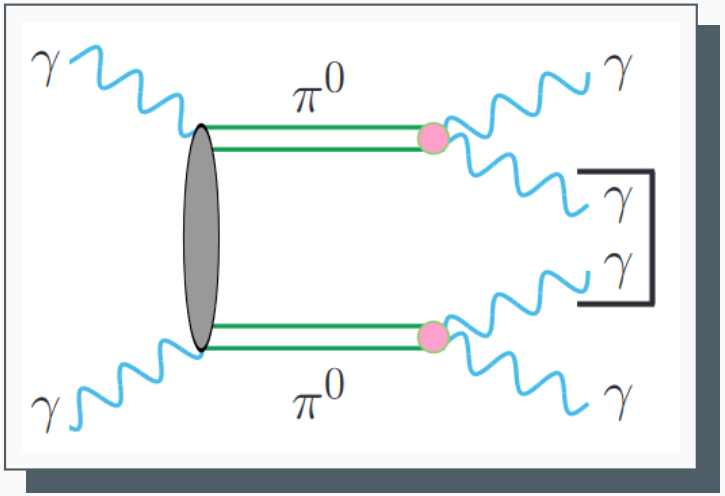

Introduction of the new variable: difference of photons rapidity.

# Two pions creation - elementary cross-section

$$\frac{d\sigma_{\gamma\gamma\to\pi^0\pi^0}(W_{\gamma\gamma})}{d\cos\theta} =$$

$$\frac{\sqrt{\frac{W_{\gamma\gamma}^2}{4} - m_\pi^2}}{\frac{W_{\gamma\gamma}}{2}} \frac{4\pi}{4 \times 64\pi^2 W_{\gamma\gamma}^2}$$

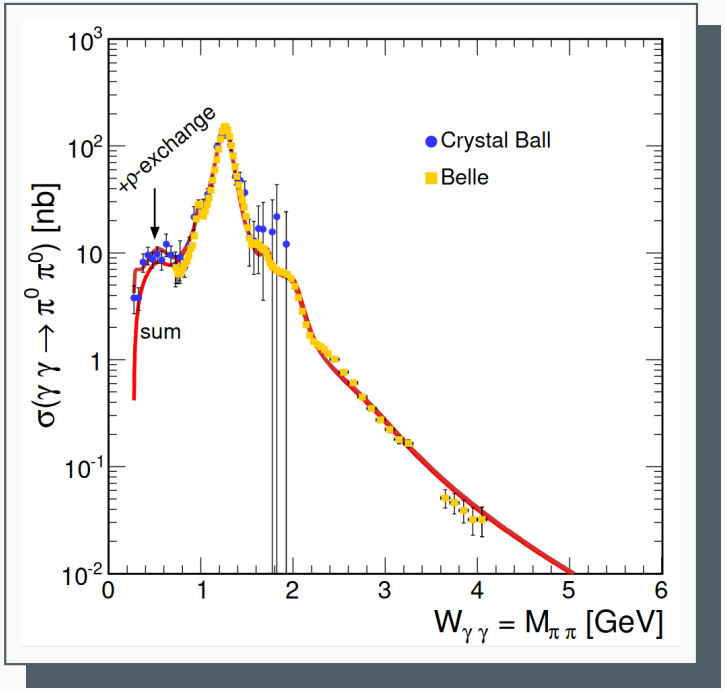
$$\sum_{\lambda_1,\lambda_2} |\mathcal{M}_{\gamma\gamma\to\pi^0\pi^0}(\lambda_1,\lambda_2)|^2$$



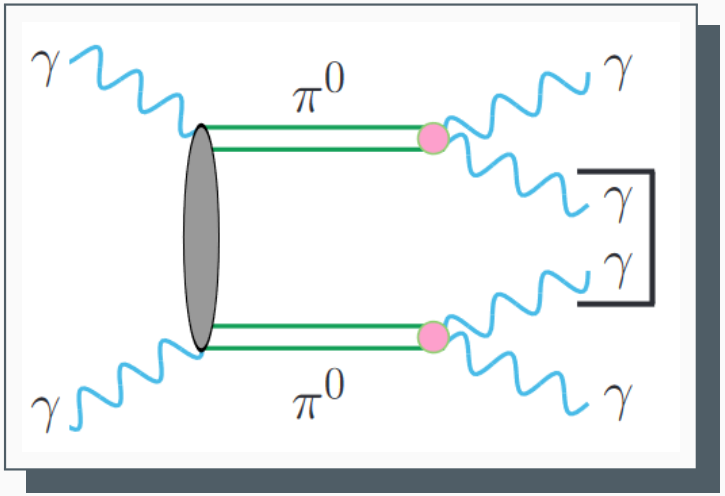

Two pion production.

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 $|\cos\theta| < 0.8$.

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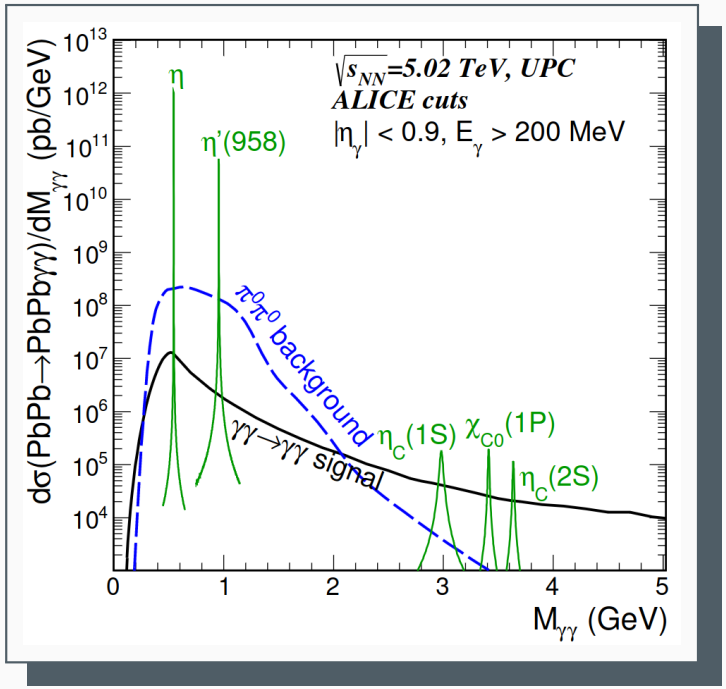
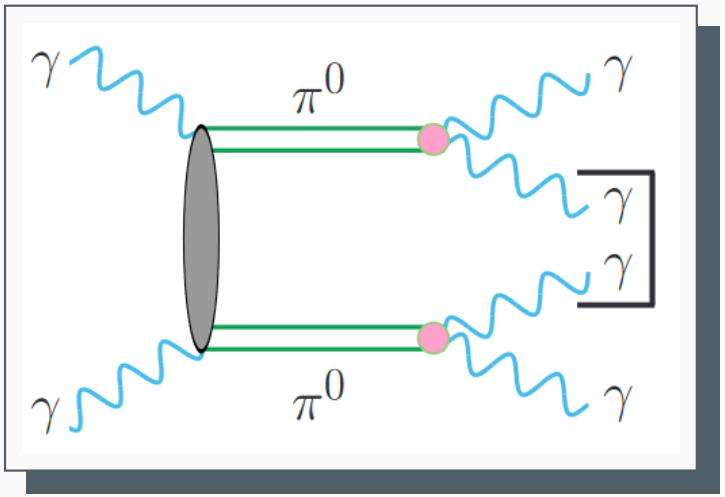
# Two pions creation - nuclear cross-section




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

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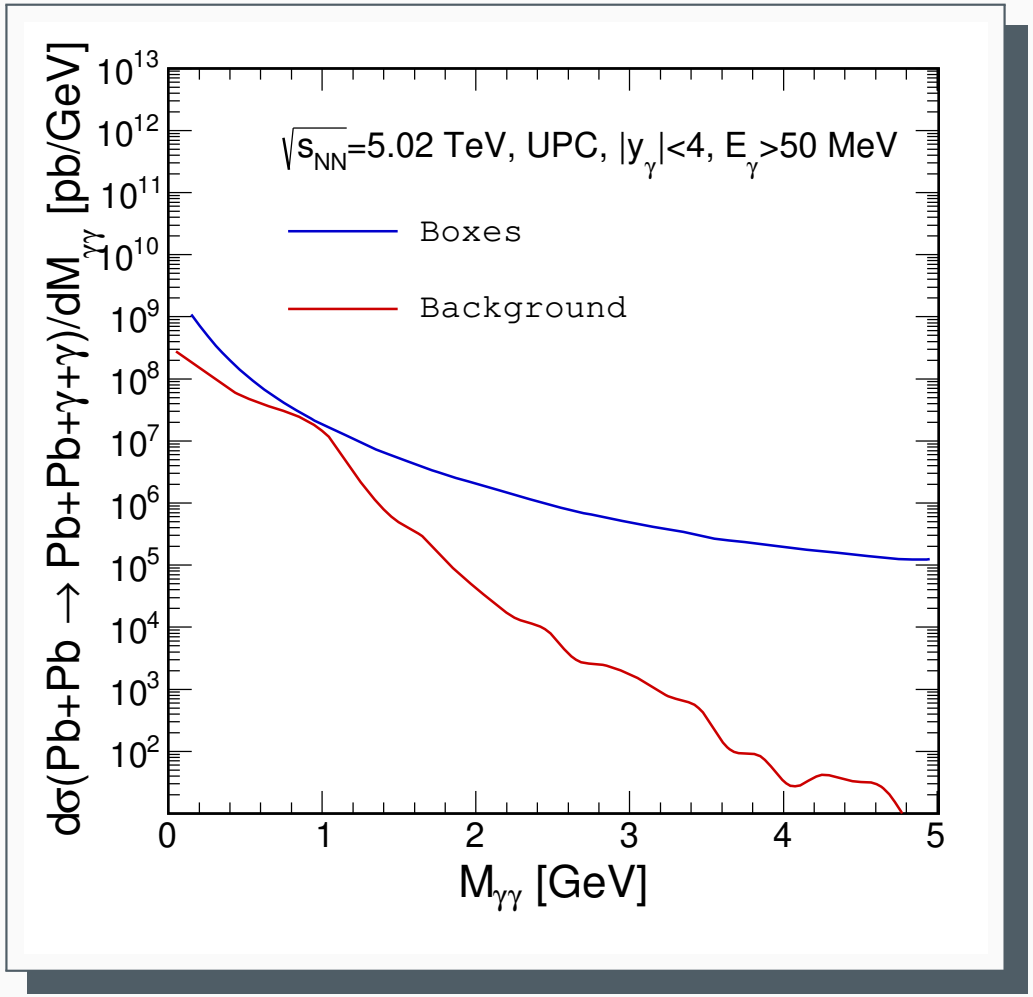
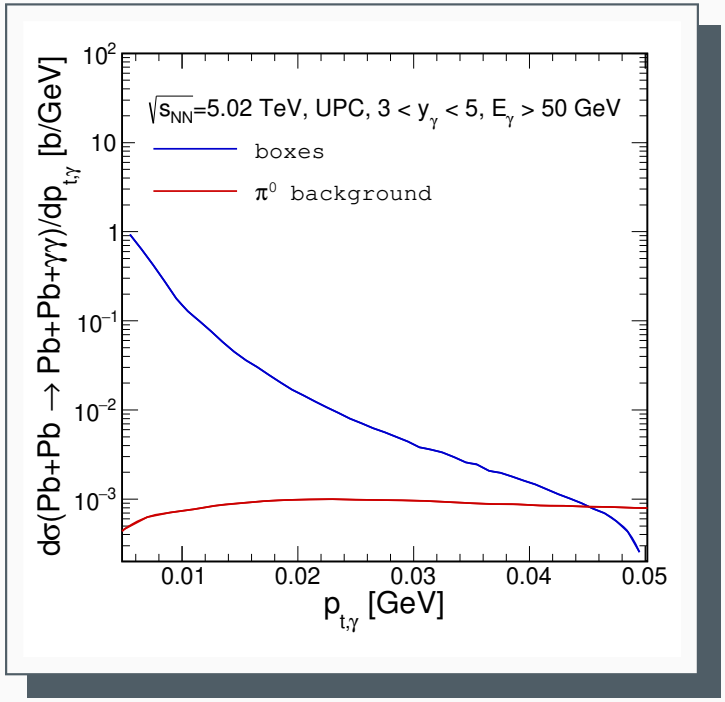
Phys. Rev. D, 99(9):093013, 2019.

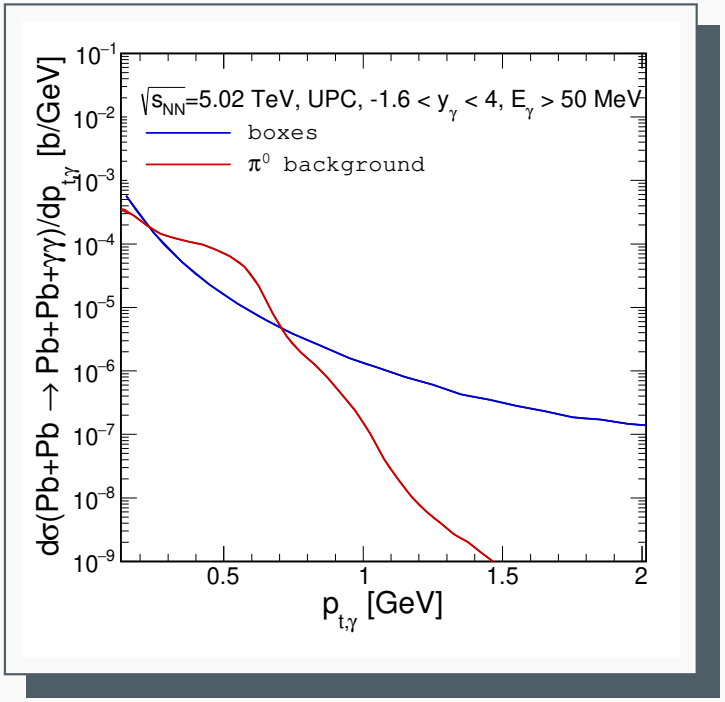
# Results for ALICE 3




New calculation of background for ALICE 3 experiment.

# Results for ALICE 3




Additional cut for $|\vec{p_{t,1}} + \vec{p_{t,2}}|$ will reduce background.

# Future & Summary

Next steps:

- Light-by-light scattering in direct photon measurement
- Nucleus excitation

Summary:

- Light-by-light scattering was a key prediction of QED.
- Ultrarelativistic, ultraperipheral collisions of heavy ions allow observations of processes unmeasurable by any other experiment.
- The issue of light-by-light scattering is important because of the exploration of the limits of theoretical models and the search for "New Physics".
- The role of meson in light-by-light scattering still waits for experimental confirmation.