Excited QCD 2016

Light-by-light scattering in ultraperipheral heavy-ion collisions at the LHC

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Contents

PHOTON-PHOTON SCATTERING

- In classical Maxwell theory photons/waves/wave packets do not interact
- In quantal theory interaction via quantal fluctuations
- So far only inelastic processes (with virtual, quasi real photons) were studied (mostly in e^+e^- or some in nucleus-nucleus UPCs.
  - $\gamma\gamma \to$ hadrons
  - $\gamma\gamma \to l^+l^-$
  - $\gamma\gamma \to M\bar{M}$
  - $\gamma\gamma \to$ dijets
  - total $\gamma\gamma$ cross section
- For elastic $\gamma\gamma \to \gamma\gamma$ scattering the main mechanism are intermediate boxes.

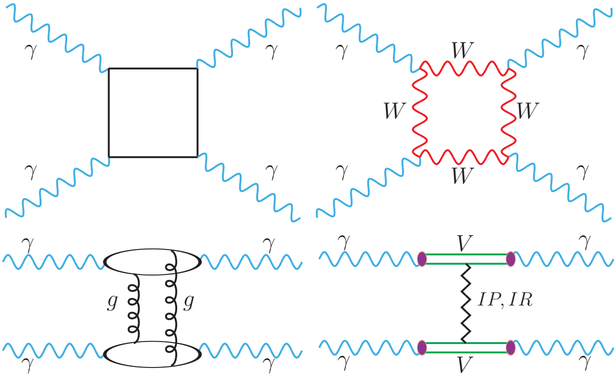
PHOTON-PHOTON ELASTIC SCATTERING

- There were (still are) plans to construct high-energy photon-photon collider(s) at linear e^+e^- colliders (double back Compton scattering), but this seems to be still a remote future.
- In the region of MeV energies – high-power lasers were discussed recently: K. Homma, K. Matsuura, K. Nakajima, arXiv:1505.03630.
- At (present) the LHC (high energy) two options a priori possible
  - $pp \to pp\gamma\gamma$ or $pp \to \gamma\gamma X$
  - $AA \to AA\gamma\gamma$
- For proton-proton collisions a serious background of KMR mechanism in elastic-elastic case at low photon-photon energies. At high energies:
  (a) P. Lebiedowicz, R. Pasechnik, A. Szczurek, Nucl. Phys. **B881** (2014) 288.
  (b) S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys. Rev. **D89** (2014) 114004.

PHOTON-PHOTON ELASTIC SCATTERING

- Exotic effects are possible. Like technipion at 750 GeV (new signal observed by ATLAS and CMS).
- In Pb-Pb UPC the reaction is enhanced by $Z_1^2 Z_2^2$ factor (naive). A first estimate: D. d'Enterria, G. da Silveira, Phys. Rev. Lett. **111** (2013) 080405, erratum in preparation.
- This presentation will be based on our recent analysis: M. Kłusek-Gawenda, P. Lebiedowicz and A. Szczurek, arXiv:1601.07001.

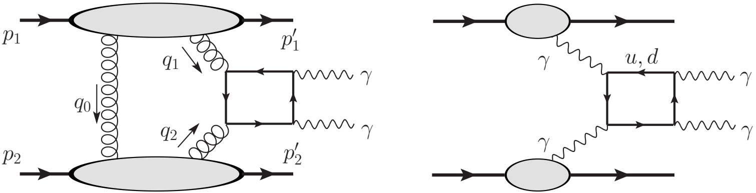
Photon-photon elastic scattering



Upper mechanisms well known.
The mechanisms below were not considered.

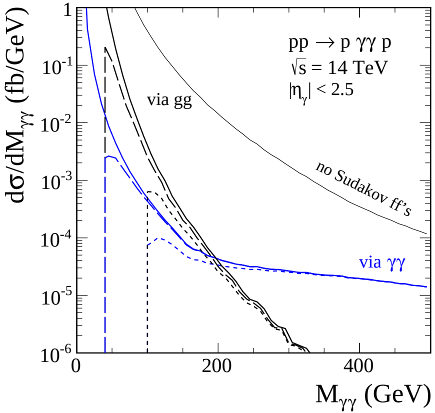
EXCLUSIVE $pp \to pp\gamma\gamma$

Two mechanisms of the exclusive production:



The QCD mechanism disturbs to see the QED mechanism

Exclusive $pp \to pp\gamma\gamma$



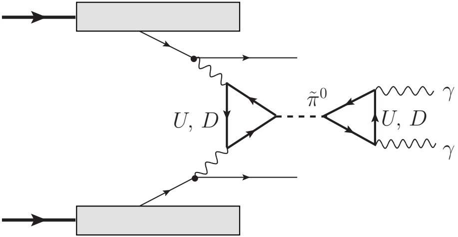
At low energy diffractive mechanism dominates

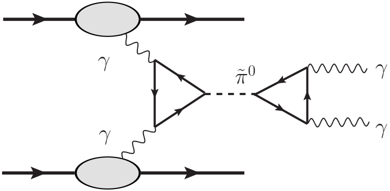
At high energy the $\gamma\gamma$ rescattering dominates

Potential place to look for effects beyond Standard Model

Search for neutral technipions

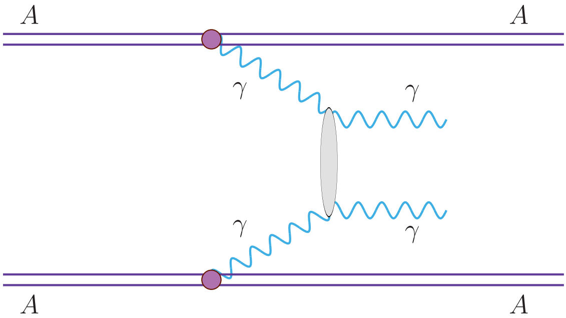
In a chirally symmetric technicolor model:





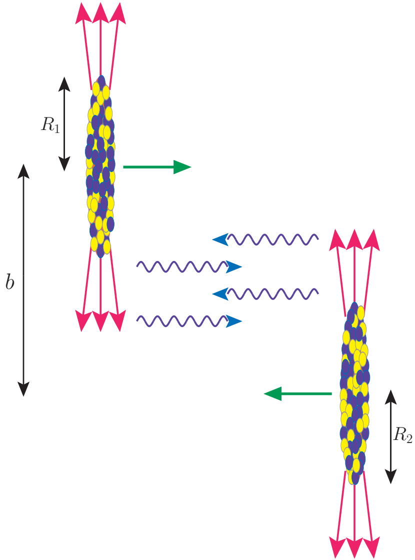
Both exclusive and inclusive case is interesting.
Recently ATLAS and CMS observed an interesting signal at $M_{\gamma\gamma}$ = 750 GeV

$AA \to AA\gamma\gamma$



Let us consider ultraperipheral collisions.

EQUIVALENT PHOTON APPROXIMATION

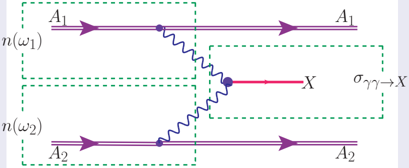


The strong electromagnetic field
is a source of photons
that induce electromagnetic
reactions in ion-ion
collisions.

ULTRAPERIHERAL COLLISIONS

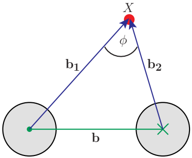
$$b > R_{min} = R_1 + R_2$$

Nuclear cross section



$$n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b \, N(\omega, b)$$

$$\begin{aligned}
\sigma_{A_1A_2\to A_1A_2X} &= \int \mathrm{d}\omega_1 \, \mathrm{d}\omega_2 \, n(\omega_1) n(\omega_2) \sigma_{\gamma\gamma\to X}(\omega_1, \omega_2) \\
&= \ldots \\
&= \int N(\omega_1, \mathbf{b_1}) \, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \\
&\times \; \sigma_{\gamma\gamma\to X}\left(\sqrt{s_{\gamma\gamma}}\right) \\
&\times \; 2\pi b \mathrm{d}b \, \mathrm{d}\overline{b}_x \, \mathrm{d}\overline{b}_y \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_X
\end{aligned}$$



Elementary cross section

The differential cross section for the elementary $\gamma\gamma \to \gamma\gamma$ subprocess can be calculated as:

$$\frac{d\sigma_{\gamma\gamma\to\gamma\gamma}}{dt} = \frac{1}{16\pi s^2}\overline{|\mathcal{A}_{\gamma\gamma\to\gamma\gamma}|^2} \tag{1}$$

or

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

In the most general case, including virtualities of initial photons, the amplitude can be written as: $\mathcal{A} = \mathcal{A}_{TT} + \mathcal{A}_{TL} + \mathcal{A}_{LT} + \mathcal{A}_{LL}$ where $\mathcal{A}_{TL} \propto \sqrt{Q_2^2}$, $\mathcal{A}_{LT} \propto \sqrt{Q_1^2}$, $\mathcal{A}_{LL} \propto \sqrt{Q_1^2 Q_2^2}$. Since in UPC's $Q_1^2, Q_2^2 \approx 0$ (nuclear form factors kill large virtualities) the other terms can be safely neglected and $\mathcal{A} \approx \mathcal{A}_{TT}$.

ELEMENTARY CROSS SECTION, FERMION BOXES

Leading-order QED fermion box diagram cross section is well known.

$$\overline{|\mathcal{M}_{\gamma\gamma\to\gamma\gamma}|^2} = \alpha_{em}^4 f(\hat{t},\hat{u},\hat{s}) \; . \qquad (3)$$

Inclusion of W boxes can be calculated with Loop Tools.
Our result was confronted with that by Jikia et al. (1993), Bern et al. (2001) and Bardin et al. (2009).
Bern et al. considered both the 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,

ELEMENTARY CROSS SECTION, VDM-REGGE COMPONENT

The t-channel amplitude for the VDM-Regge contribution:

$$\mathcal{A}_{\gamma\gamma\to\gamma\gamma}(s,t) \approx \left(\sum_{i=1}^{3} C^2_{\gamma\to V_i}\right) \mathcal{A}\,(s,t) \exp\left(\frac{B}{2}t\right) \left(\sum_{j=1}^{3} C^2_{\gamma\to V_j}\right) \,, \quad (4)$$

where $i,j = \rho,\omega,\phi$. The amplitude for $V_iV_j \to V_iV_j$ elastic scattering is parametrized in the Regge approach (similar as for $\gamma\gamma \to \rho^0\rho^0$)

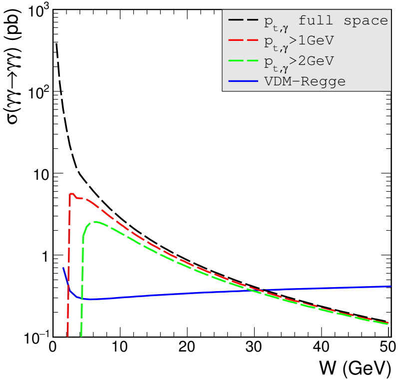
$$\mathcal{A}\,(s,t) \approx s \left((1+i)\,C_{\mathbf{R}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{R}}(t)-1} + iC_{\mathbf{P}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{P}}(t)-1} \right) . \quad (5)$$

The interaction parameters are the same as for the $\pi^0 p$ interaction:

$$\mathcal{A}_{\pi^0 p}(s,t) = \frac{1}{2}\left(\mathcal{A}_{\pi^+ p}(s,t) + \mathcal{A}_{\pi^- p}(s,t)\right) . \quad (6)$$

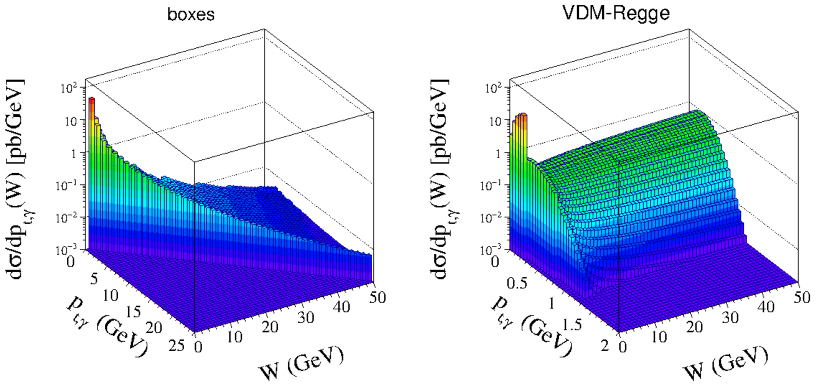
$$\sigma^{tot}_{\pi p}(s) = \frac{1}{s} Im \mathcal{A}_{\pi p}(s,t=0) . \quad (7)$$

ELEMENTARY CROSS SECTION

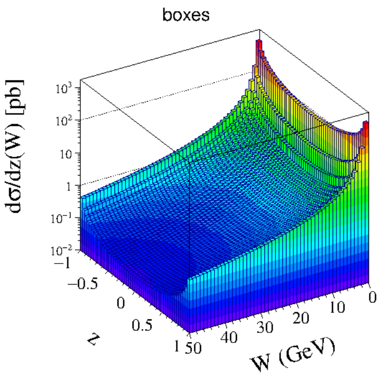


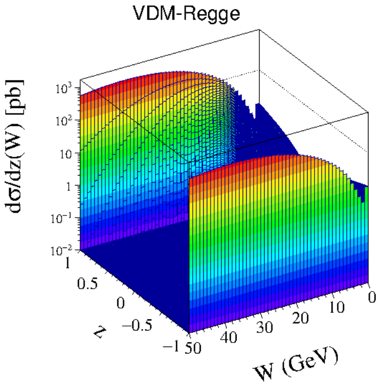
At large W a small lower cut on photon transverse momenta is not important.

Elementary cross section



Elementary cross section





Hard and soft, respectively

NUCLEAR CROSS SECTION

In our b-space EPA:

$$\sigma_{A_1A_2\to A_1A_2\gamma\gamma}\left(\sqrt{s_{A_1A_2}}\right) = \int \sigma_{\gamma\gamma\to\gamma\gamma}\left(\sqrt{s_{\gamma\gamma}}\right) N(\omega_1,\mathbf{b_1})\, N(\omega_2,\mathbf{b_2})\, S^2_{abs}(\mathbf{b}$$
$$\times\ 2\pi b \mathrm{d}b\, \mathrm{d}\overline{b}_x\, \mathrm{d}\overline{b}_y\, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma}\, \mathrm{d}Y_{\gamma\gamma}\ , \qquad ($$

where $N(\omega_i,\mathbf{b_i})$ are photon fluxes

$$Y_{\gamma\gamma} = \frac{1}{2}\left(y_{\gamma_1}+y_{\gamma_2}\right) \qquad (9)$$

is a rapidity of the outgoing $\gamma\gamma$ system.

$$W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}\ , \qquad (10)$$

where $\omega_{1/2} = W_{\gamma\gamma}/2\exp(\pm Y_{\gamma\gamma})$. The quantities $\overline{b}_x$, $\overline{b}_y$ are the components of the vector $\overline{\mathbf{b}} = (\mathbf{b_1}+\mathbf{b_2})/2$

$$\mathbf{b_1} = \left[\overline{b}_x + \frac{b}{2}, \overline{b}_y\right]\ , \qquad \mathbf{b_2} = \left[\overline{b}_x - \frac{b}{2}, \overline{b}_y\right]\ . \qquad (11)$$

NUCLEAR CROSS SECTION

If one wishes to impose some cuts on produced photons a more complicated calculations are required. Then we introduce new kinematical variables of photons in the $\gamma\gamma$ center-of-mass system:

$$E^*_{\gamma_i} = p^*_{\gamma_i} = \frac{W_{\gamma\gamma}}{2} \,, \tag{13}$$

$$z = \cos\theta^* = \sqrt{1 - \left(\frac{p_{t,\gamma}}{p^*_{\gamma_i}}\right)^2} \,, \tag{14}$$

$$p^*_{z,\gamma_i} = \pm z p^*_{\gamma_i} \,, \tag{15}$$

$$y^*_{\gamma_i} = \frac{1}{2} \ln \frac{E^*_{\gamma_i} + p^*_{z,\gamma_i}}{E^*_{\gamma_i} - p^*_{z,\gamma_i}} \tag{16}$$

and in overall AA center of mass system (laboratory system):

$$y_{\gamma_i} = Y_{\gamma\gamma} + y^*_{\gamma_i} \,, \tag{17}$$

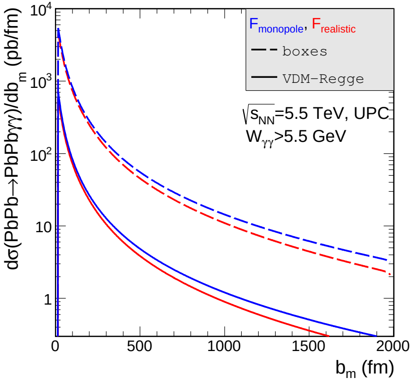
$$p_{z,\gamma_i} = p_{t,\gamma} \sinh(y_{\gamma_i}) \,, \tag{18}$$

$$E \;=\; \sqrt{p^2 \; + p^2} \tag{19}$$

AA→AA$\gamma\gamma$ - form factor

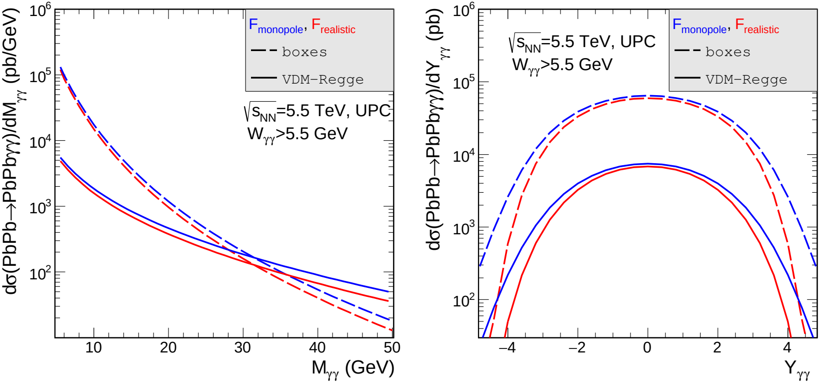
$N\left(\omega_{1/2}, \mathbf{b}_{1/2}\right)$ depends on the electromagnetic form factor

- realistic
- monopole



$AA \to AA\gamma\gamma$ - FORM FACTOR

- realistic
- monopole

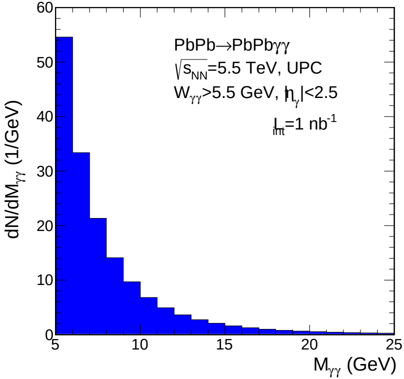


AA→AA$\gamma\gamma$ - INTEGRATED CROSS SECTION

cuts	boxes $F_{realistic}$	boxes $F_{monopole}$	VDM-Regge $F_{realistic}$	VDM-Regge $F_{monopole}$
$W_{\gamma\gamma} > 5$ GeV	306	349	19	22
$W_{\gamma\gamma} > 5$ GeV, $p_{t,\gamma} > 2$ GeV	159	182	7E-9	8E-9
$E_\gamma > 3$ GeV	16 692	18 400	13	14
$E_\gamma > 5$ GeV	4 800	5 450	4	6
$E_\gamma > 3$ GeV, $\|y_\gamma\| < 2.5$	183	210	7E-2	8E-2
$E_\gamma > 5$ GeV, $\|y_\gamma\| < 2.5$	54	61	3E-4	6E-4
$p_{t,\gamma} > 0.9$ GeV, $\|y_\gamma\| < 0.7$ (ALICE cuts)	107			
$p_{t,\gamma} > 5.5$ GeV, $\|y_\gamma\| < 2.5$ (CMS cuts)	10			
$\sqrt{s}$ = 39 TeV, $W_{\gamma\gamma} > 5$ GeV	6169		882	
$\sqrt{s}$ = 39 TeV, $E_\gamma > 3$ GeV	4.696 mb		574	

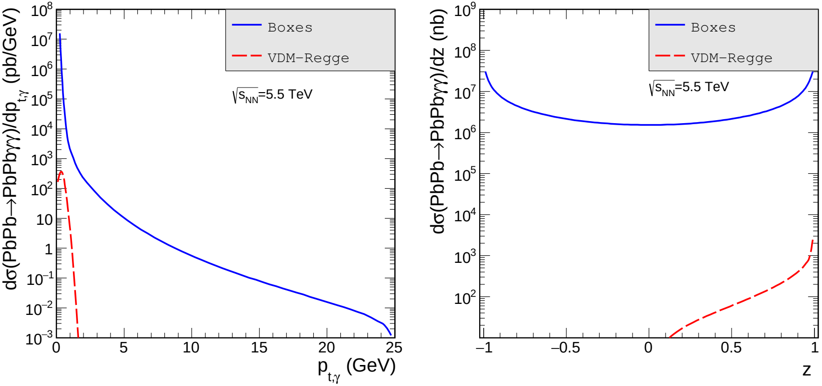
TABLICA: Integrated cross sections in *nb* for exclusive diphoton production processes with both photons measured, for $\sqrt{s_{NN}} = 5.5$ TeV (LHC) and $\sqrt{s_{NN}} = 39$ TeV (FCC). Impact-parameter EPA.

AA→AA$\gamma\gamma$ - NUMBER OF COUNTS

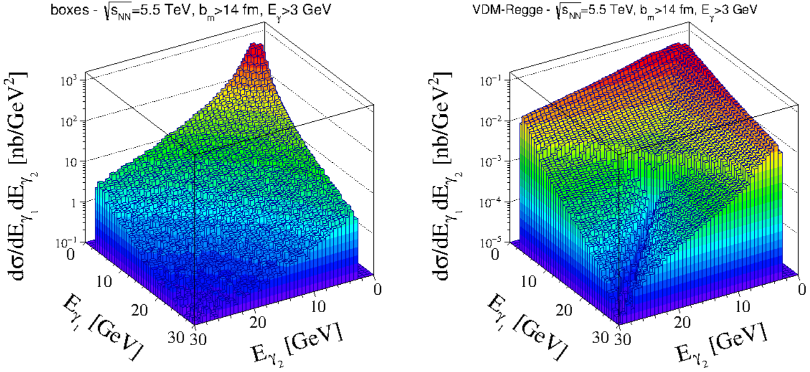


For L_{int} = 10 nb^{-1} a few counts per GeV – measurable quantity

$AA \to AA\gamma\gamma$ - DISTRIBUTIONS

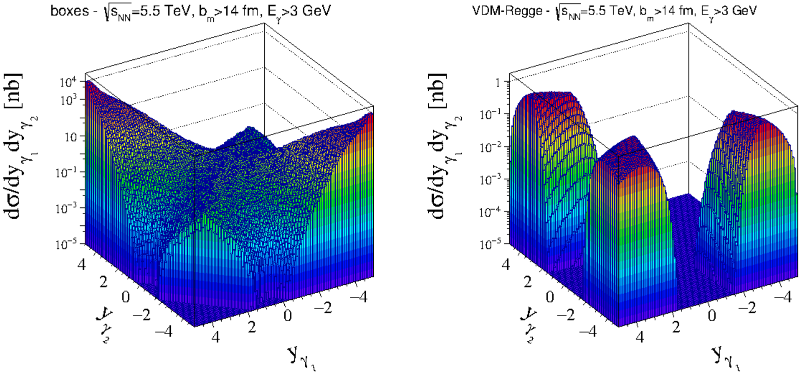


AA→AA$\gamma\gamma$ - DISTRIBUTIONS



Cross section strongly depends on the photon energy cuts

AA→AA$\gamma\gamma$ - DISTRIBUTIONS

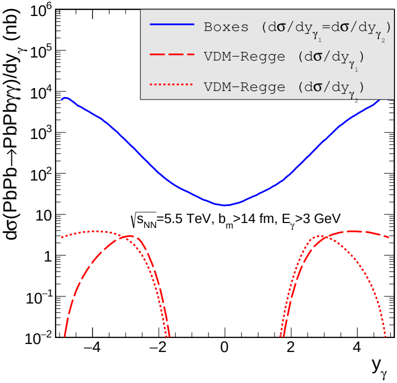


Simple patern in photon-photon frame.

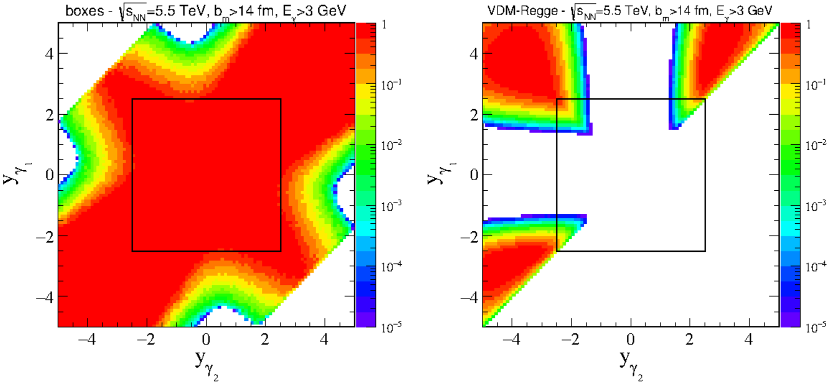
Complicated pattern in the LAB system

One can judge about a measurement.

AA→AA$\gamma\gamma$ - PHOTON RAPIDITY



AA→AA$\gamma\gamma$ - RAPIDITY CORRELATIONS



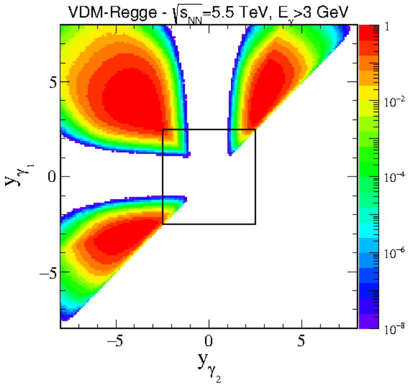
At midrapidity boxes dominate

The soft mechanism at large rapidities

Can it be measured with ZDC ?

AA→AA$\gamma\gamma$ - RAPIDITY CORRELATIONS

In the extended rapidity range:



May be difficult to measure

CONCLUSIONS

- Detailed analysis of the $\gamma\gamma \to \gamma\gamma$ (quasi)elastic scattering in nucleus-nucleus collisions at the LHC
- Two subprocesses included:
  - Box contributions (known for some time)
  - Soft VDM Regge contribution (new, for a first time)
- Calculation done in the impact parameter EPA.
  Possibility of exclusion break-up of nuclei.
- Compare to literature we make an extension following kinematics of photons in the LAB frame.
- Measurable cross sections obtained.
- Very interesting pattern in kinematical variables of photons.
- The two subprocesses almost separate in the phase space.
- Experimental possibilities not completely clear.
  It is a matter of a trigger. At ALICE only at run 3.
  FCC – may be, if planned in advance.

CONCLUSIONS

- Multiple Coulomb excitations associated with $\gamma\gamma$ production may cause additional excitation of one or both nuclei to the giant resonance region (can be calculated)
  Reference: M. Kłusek-Gawenda, M. Ciemała, W. Schäfer and A. Szczurek
  ”Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions”
  Phys. Rev. **C89** (2014) 054907

Thank You

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Thank You