EXCITED QCD 2016

LIGHT-BY-LIGHT SCATTERING
IN ULTRAPERIPHERAL HEAVY-ION COLLISIONS
AT THE LHC

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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).

- $\gamma\gamma \rightarrow \text{hadrons}$
- $\gamma\gamma \rightarrow l^+l^-$
- $\gamma\gamma \rightarrow M\bar{M}$
- $\gamma\gamma \rightarrow \text{dijets}$
- total $\gamma\gamma$ cross section

For elastic $\gamma\gamma \rightarrow \gamma\gamma$ 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
  - $pp \rightarrow pp\gamma\gamma$ or $pp \rightarrow \gamma\gamma X$
  - $AA \rightarrow AA\gamma\gamma$
- For proton-proton collisions a serious background of KMR mechanism in elastic-elastic case at low photon-photon energies.
  - At high energies:
Exotic effects are possible. Like technipion at 750 GeV (new signal observed by ATLAS and CMS).


This presentation will be based on our recent analysis: M. Kłusek-Gawenda, P. Lebiedowicz and A. Szczurek, arXiv:1601.07001.
Upper mechanisms well known.
The mechanisms below were not considered.
Two mechanisms of the exclusive production:

The QCD mechanism disturbs to see the QED mechanism
**At low energy diffractive mechanism dominates**

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

**Potential place to look for effects beyond Standard Model**

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**PHOTON-PHOTON SCATTERING**

**EXCLUSIVE $pp \rightarrow pp\gamma\gamma$**

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**A. Szczurek (INP PAS Kraków)**

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**Excited QCD 2016**
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.
Let us consider ultraperipheral collisions.
The strong electromagnetic field is a source of photons that induce electromagnetic reactions in ion-ion collisions.

\[ b > R_{\text{min}} = R_1 + R_2 \]
**Nuclear Cross Section**

\[
n(\omega) = \int_{R_{\text{min}}}^{\infty} 2\pi b db \ N(\omega, b)
\]

\[
\sigma_{A_1 A_2 \rightarrow A_1 A_2 X} = \int d\omega_1 \ d\omega_2 \ n(\omega_1) n(\omega_2) \sigma_{\gamma \gamma \rightarrow X}(\omega_1, \omega_2)
\]

\[
= \ldots
\]

\[
= \int N(\omega_1, b_1) \ N(\omega_2, b_2) S_{\text{abs}}^2(b)
\]

\[
\times \ \sigma_{\gamma \gamma \rightarrow X} \left( \sqrt{s_{\gamma \gamma}} \right)
\]

\[
\times \ 2\pi b db d\bar{b}_x \ d\bar{b}_y \ \frac{W_{\gamma \gamma}}{2} \ dW_{\gamma \gamma} \ dY_X
\]
The differential cross section for the elementary $\gamma\gamma \to \gamma\gamma$ subprocess can be calculated as:

$$\frac{d\sigma_{\gamma\gamma\to\gamma\gamma}}{dt} = \frac{1}{16\pi s^2} |A_{\gamma\gamma\to\gamma\gamma}|^2$$ (1)

or

$$\frac{d\sigma_{\gamma\gamma\to\gamma\gamma}}{d\Omega} = \frac{1}{64\pi^2 s} |A_{\gamma\gamma\to\gamma\gamma}|^2.$$ (2)

In the most general case, including virtualities of initial photons, the amplitude can be written as: $A = A_{TT} + A_{TL} + A_{LT} + A_{LL}$ where $A_{TL} \propto \sqrt{Q_2^2}$, $A_{LT} \propto \sqrt{Q_1^2}$, $A_{LL} \propto \sqrt{Q_1^2 Q_2^2}$. 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 $A \approx A_{TT}$. 

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**Elementary cross section, fermion boxes**

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

\[
|M_{\gamma\gamma\to\gamma\gamma}|^2 = \alpha_{em}^4 f(\hat{t}, \hat{u}, \hat{s}).
\]  \hspace{1cm} (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:

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

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

$$A(s, t) \approx s \left( (1 + i) C_R \left( \frac{s}{s_0} \right)^{\alpha_R(t)-1} + i C_P \left( \frac{s}{s_0} \right)^{\alpha_P(t)-1} \right) . \quad (5)$$

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

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

$$\sigma_{\pi p}^{tot}(s) = \frac{1}{s} \text{Im} A_{\pi p}(s, t = 0) . \quad (7)$$
At large $W$ a small lower cut on photon transverse momenta is not important.
Elementary Cross Section

boxes

VDM-Regge
Elementary cross section

Hard and soft, respectively
**Nuclear cross section**

In our b-space EPA:

\[
\sigma_{A_1 A_2 \rightarrow A_1 A_2 \gamma \gamma} \left( \sqrt{S_{A_1 A_2}} \right) = \int \sigma_{\gamma \gamma \rightarrow \gamma \gamma} \left( \sqrt{S_{\gamma \gamma}} \right) N(\omega_1, b_1) N(\omega_2, b_2) S_{abs}^2 (b) \times 2 \pi b db d\bar{b}_x d\bar{b}_y \frac{W_{\gamma \gamma}}{2} dW_{\gamma \gamma} dY_{\gamma \gamma},
\]

where \(N(\omega_i, b_i)\) are photon fluxes

\[
Y_{\gamma \gamma} = \frac{1}{2} (y_{\gamma 1} + y_{\gamma 2})
\]

is a rapidity of the outgoing \(\gamma \gamma\) system.

\[
W_{\gamma \gamma} = \sqrt{4\omega_1 \omega_2},
\]

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

\[
b_1 = \left[ \bar{b}_x + \frac{b}{2}, \bar{b}_y \right], \quad b_2 = \left[ \bar{b}_x - \frac{b}{2}, \bar{b}_y \right].
\]
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:

$$E_{\gamma_i}^* = p_{\gamma_i}^* = \frac{W_{\gamma\gamma}}{2},$$  \hspace{1cm} (13)

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

$$p_{z,\gamma_i}^* = \pm z p_{\gamma_i}^*,$$  \hspace{1cm} (15)

$$y_{\gamma_i}^* = \frac{1}{2} \ln \frac{E_{\gamma_i}^* + p_{z,\gamma_i}^*}{E_{\gamma_i}^* - p_{z,\gamma_i}^*},$$  \hspace{1cm} (16)

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

$$y_{\gamma_i} = Y_{\gamma\gamma} + y_{\gamma_i}^*,$$  \hspace{1cm} (17)

$$p_{z,\gamma_i} = p_{t,\gamma} \sinh(y_{\gamma_i}),$$  \hspace{1cm} (18)

$$E_{\gamma_i} = \sqrt{p_{\gamma_i}^2 + m_{\gamma}^2}.$$  \hspace{1cm} (19)
\( N(\omega_{1/2}, b_{1/2}) \) depends on the electromagnetic form factor

- realistic
- monopole
AA\rightarrow AA\gamma\gamma - FORM FACTOR

- realistic
- monopole
### EPA - $\gamma \gamma$ FUSION

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

<table>
<thead>
<tr>
<th>cuts</th>
<th>boxes</th>
<th>VDM-Regge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_{\text{realistic}}$</td>
<td>$F_{\text{monopole}}$</td>
</tr>
<tr>
<td>$W_{\gamma \gamma} &gt; 5$ GeV</td>
<td>306</td>
<td>349</td>
</tr>
<tr>
<td>$W_{\gamma \gamma} &gt; 5$ GeV, $p_{t,\gamma} &gt; 2$ GeV</td>
<td>159</td>
<td>182</td>
</tr>
<tr>
<td>$E_{\gamma} &gt; 3$ GeV</td>
<td>16 692</td>
<td>18 400</td>
</tr>
<tr>
<td>$E_{\gamma} &gt; 5$ GeV</td>
<td>4 800</td>
<td>5 450</td>
</tr>
<tr>
<td>$E_{\gamma} &gt; 3$ GeV, $</td>
<td>y_{\gamma}</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$E_{\gamma} &gt; 5$ GeV, $</td>
<td>y_{\gamma}</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$p_{t,\gamma} &gt; 0.9$ GeV, $</td>
<td>y_{\gamma}</td>
<td>&lt; 0.7$ (ALICE cuts)</td>
</tr>
<tr>
<td>$p_{t,\gamma} &gt; 5.5$ GeV, $</td>
<td>y_{\gamma}</td>
<td>&lt; 2.5$ (CMS cuts)</td>
</tr>
<tr>
<td>$\sqrt{s} = 39$ TeV, $W_{\gamma \gamma} &gt; 5$ GeV</td>
<td>6169</td>
<td></td>
</tr>
<tr>
<td>$\sqrt{s} = 39$ TeV, $E_{\gamma} &gt; 3$ GeV</td>
<td>4.696 mb</td>
<td></td>
</tr>
</tbody>
</table>

**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.
For $L_{int} = 10 \text{ nb}^{-1}$ a few counts per GeV – measurable quantity
\[ \Gamma_{\gamma\gamma} \rightarrow DD \]

\[ \Gamma_{\gamma\gamma} \rightarrow DD \]

\[ \frac{d\sigma}{dp_{t\gamma}} \]

\[ d\sigma_{\text{PbPb} \rightarrow \text{PbPb}\gamma\gamma} / dz \]

\[ \sqrt{s_{NN}} = 5.5 \text{ TeV} \]

**Boxes**

**VDM-Regge**

\[ A. \text{ Szczyrek (INP PAS Kraków)} \]

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Cross section strongly depends on the photon energy cuts
Simple pattern in photon-photon frame.
Complicated pattern in the LAB system
One can judge about a measurement.
$\gamma \gamma$ Fusion

$AA \rightarrow AA \gamma \gamma$ - Photon Rapidity

$$\frac{d\sigma}{dy_{\gamma}} \text{(PbPb)} \rightarrow \sigma \approx 10^{-5} \text{ (nb)}$$

$\sqrt{s_{NN}} = 5.5 \text{ TeV}, b > 14 \text{ fm}, E_\gamma > 3 \text{ GeV}$
AA → AAγγ - RAPIDITY CORRELATIONS

At midrapidity boxes dominate
The soft mechanism at large rapidities
Can it be measured with ZDC?

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In the extended rapidity range:

May be difficult to measure
Conclusions

- Detailed analysis of the $\gamma\gamma \rightarrow \gamma\gamma$ (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 the 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.
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. Klusek-Gawenda, M. Ciemała, W. Schäfer and A. Szczurek
"Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions"
CONCLUSIONS

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Thank You