Polish Workshop on Relativisitic HI Collisions

New vistas in ultraperipheral heavy ion collisions

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UPC OF HEAVY IONS

Two types of proceses:

- (a) $\gamma\gamma$ fusion
- (b) photon-fluctuation rescattering in the second nucleus

Examples of processes considered so far:

- $AA \to AAe^+e^-$ (EXP) or $AA \to AA\mu^+\mu^-$
- $AA \to AA\rho^0$ (EXP) or $AA \to AAJ/\psi$ (EXP)
- $AA \to AA\pi^0, \eta, \eta', f_2(1270)$, etc
- $AA \to AA\pi^+\pi^-$ (EXP) or $AA \to AA\pi^0\pi^0$
- $AA \to AAjetjet$
- $AA \to AAQ\bar{Q}$
- $AA \to AA\rho^0\rho^0$

  $\gamma\gamma$ or double scattering
- $AA \to AA\gamma\gamma$ (EXP)
- $AA \to AAe^+e^-e^+e^-$

Contents of this talk

1. $\gamma\gamma \to \gamma\gamma$ scattering
   - Box contributions
   - A new soft mechanism
2. $pp \to pp\gamma\gamma$ (short)
3. $AA \to AA\gamma\gamma$
   - Equivalent photon approximation
   - $\gamma\gamma \to \gamma\gamma$
   - form factor
4. Nuclear results
   - Realistic and monopole form factor
   - Integrated cross sections
   - Differential distributions
   - Experimental possibilities
5. $\gamma\gamma \to \gamma\gamma$, two-gluon exchange mechanism
   - $AA \to AA\gamma\gamma$
   - $pp \to pp\gamma\gamma$ (short)
6. $AA \to AAe^+e^-e^+e^-$ double scattering mechanism
7. Conclusions

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.

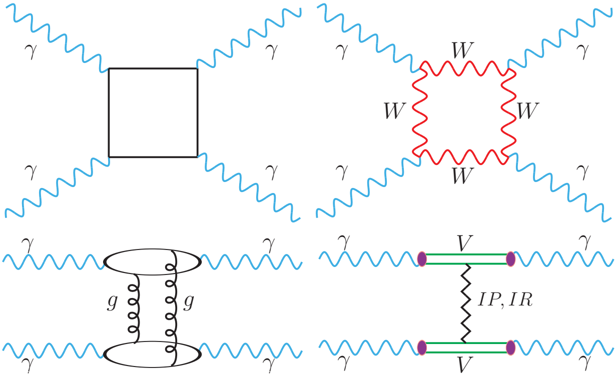
PHOTON-PHOTON ELASTIC SCATTERING

- 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

- 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 and erratum 2016.
- This presentation will be based on our recent studies:
  M. Kłusek-Gawenda, P. Lebiedowicz and A. Szczurek, arXiv:1601.07001, Phys. Rev. **C93** (2016) 044907, (box+VDM Regge)
  M. Kłusek-Gawenda, W. Schäfer and A. Szczurek, arXiv:1606.01058, Phys. Lett. **B761** (2016) 221. (two-gluon exchange)

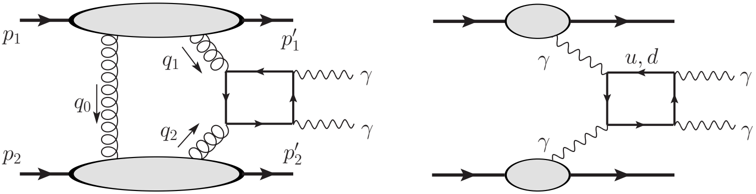
PHOTON-PHOTON ELASTIC SCATTERING



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

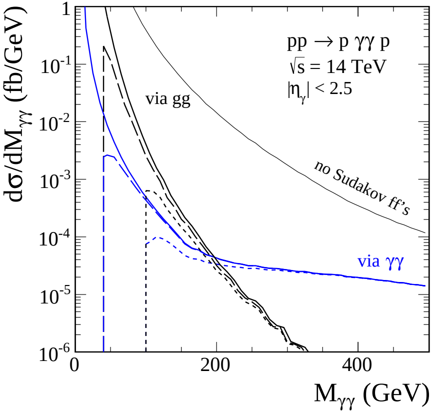
EXCLUSIVE $pp \to pp\gamma\gamma$

Two mechanisms of the exclusive production:



The QCD mechanism disturbs to see the QED mechanism

EXCLUSIVE $pp \to pp\gamma\gamma$

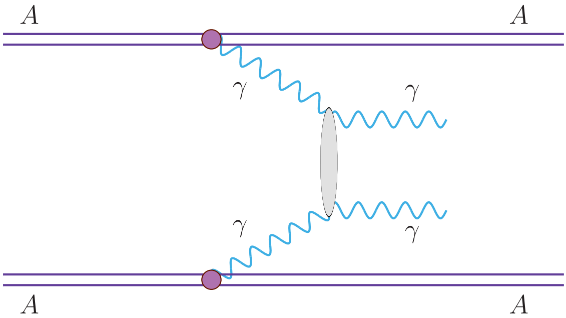


At low energy diffractive mechanism dominates

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

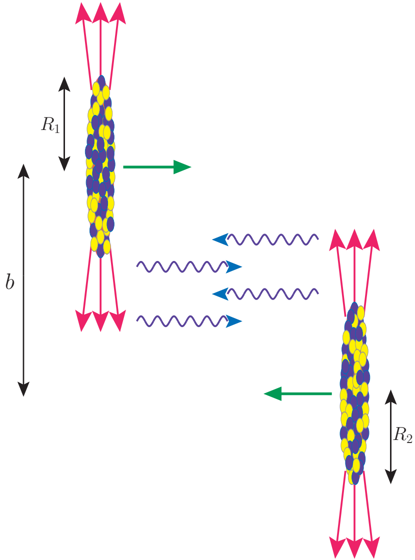
Potential place to look for effects beyond Standard Model

$AA \to AA\gamma\gamma$



Let us consider ultraperipheral collisions.

Equivalent photon approximation

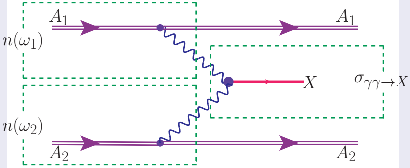


The strong electromagnetic field
is a source of photons
that induce electromagnetic reactions in ion-ion collisions.

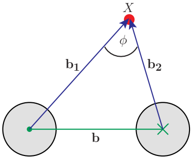
UltraPeriheral Collisions

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

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 situation is more complicated (transverse and longitudinal photons). This was not considered so far.

ELEMENTARY CROSS SECTION, FERMION BOXES

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

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

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:

$$\begin{aligned} \mathcal{A}_{\gamma\gamma\to\gamma\gamma}(s,t) &= \sum_i^3 \sum_j^3 C^2_{\gamma\to V_i} \mathcal{A}_{V_i V_j \to V_i V_j} C^2_{\gamma\to V_j} \\ &\approx \left(\sum_{i=1}^3 C^2_{\gamma\to V_i} \right) \mathcal{A}_{VV\to VV}(s,t) \left(\sum_{j=1}^3 C^2_{\gamma\to V_j} \right) , \quad (4) \end{aligned}$$

where $i, j = \rho, \omega, \phi$ and

$$\mathcal{A}_{VV\to VV} = \mathcal{A}(s,t) \exp\left(\frac{B}{2} t\right) \quad (5)$$

The amplitude for $V_i V_j \to V_i V_j$ elastic scattering is parametrized in the Regge approach (similar as for $\gamma\gamma \to \rho^0 \rho^0$)

Elementary cross section

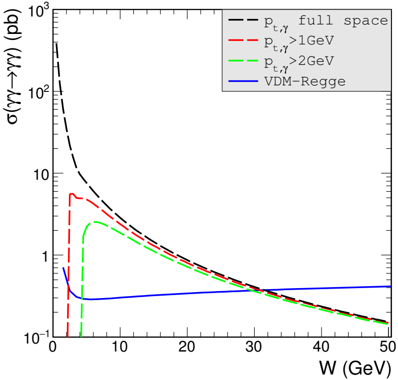
$$\mathcal{A}(s,t) \approx s \left((1+i)\, C_{\mathbf{R}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{R}}(t)-1} + i C_{\mathbf{P}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{P}}(t)-1} \right) . \quad (6)$$

The interaction parameters are the same as for the $\pi^0\pi^0$ interaction.
The latter obtained from NN and πN total cross sections assuming Regge factorization.
For example:

$$\mathcal{A}_{\pi^0 p}(s,t) = \frac{1}{2}\left(\mathcal{A}_{\pi^+ p}(s,t) + \mathcal{A}_{\pi^- p}(s,t)\right) . \quad (7)$$

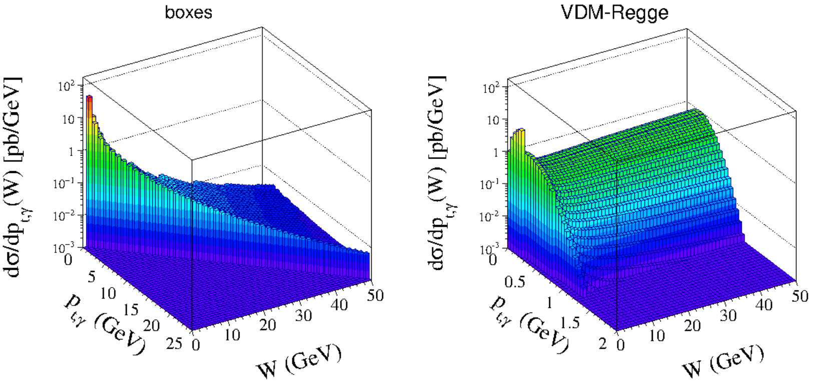
$$\sigma^{tot}_{\pi^\pm p}(s) = \frac{1}{s} Im \mathcal{A}_{\pi^\pm p}(s, t=0) . \quad (8)$$

ELEMENTARY CROSS SECTION

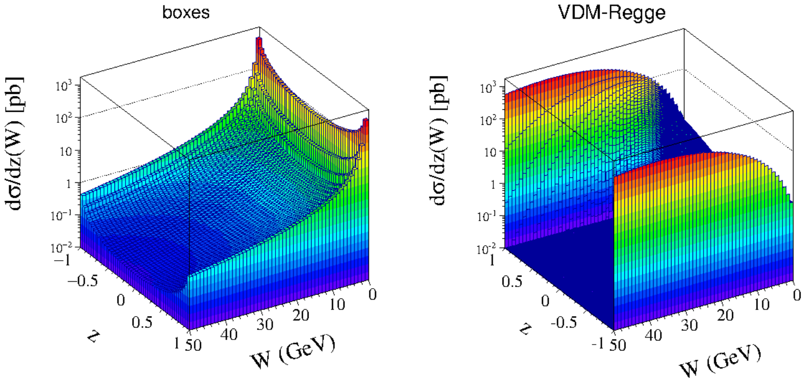


At large W a small lower cut on photon transverse momenta is not important.

Elementary cross section



Elementary cross section



Hard and soft, respectively

NUCLEAR CROSS SECTION

In our b-space EPA:

$$\sigma_{A_1A_2\to A_1A_2\gamma\gamma}\left(\sqrt{s_{A_1A_2}}\right) = \int \sigma_{\gamma\gamma\to\gamma\gamma}\left(\sqrt{s_{\gamma\gamma}}\right) N\left(\omega_1,\mathbf{b_1}\right) N\left(\omega_2,\mathbf{b_2}\right) S^2_{abs}\left(\mathbf{b}\right.$$
$$\times \quad 2\pi b \mathrm{d}b \, \mathrm{d}\overline{b}_x \, \mathrm{d}\overline{b}_y \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_{\gamma\gamma} \,, \quad (9$$

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

$$Y_{\gamma\gamma} = \frac{1}{2}\left(y_{\gamma_1} + y_{\gamma_2}\right) \quad (10)$$

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

$$W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}\,, \quad (11)$$

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 $\overline{\mathbf{b}} = (\mathbf{b_1} + \mathbf{b_2})/2$

$$\mathbf{b_1} = \left[\overline{b}_x + \frac{b}{2}, \overline{b}_y\right] \,, \qquad \mathbf{b_2} = \left[\overline{b}_x - \frac{b}{2}, \overline{b}_y\right] \,. \quad (12)$$

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:

$$E^*_{\gamma_i} = p^*_{\gamma_i} = \frac{W_{\gamma\gamma}}{2} , \quad (14)$$

$$z = \cos\theta^* = \sqrt{1 - \left(\frac{p_{t,\gamma}}{p^*_{\gamma_i}}\right)^2} , \quad (15)$$

$$p^*_{z,\gamma_i} = \pm z p^*_{\gamma_i} , \quad (16)$$

$$y^*_{\gamma_i} = \frac{1}{2} \ln \frac{E^*_{\gamma_i} + p^*_{z,\gamma_i}}{E^*_{\gamma_i} - p^*_{z,\gamma_i}} \quad (17)$$

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

$$y_{\gamma_i} = Y_{\gamma\gamma} + y^*_{\gamma_i} , \quad (18)$$

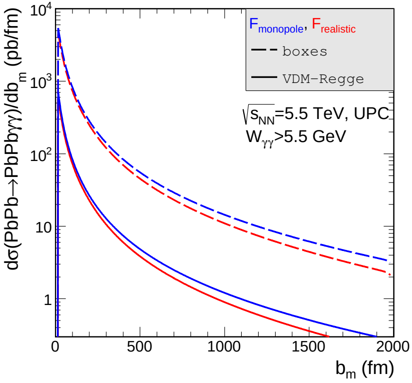
$$p_{z,\gamma_i} = p_{t,\gamma} \sinh(y_{\gamma_i}) , \quad (19)$$

$$E \quad = \quad \sqrt{p^2 \quad + p^2} \quad (20)$$

AA→AA$\gamma\gamma$ - FORM FACTOR

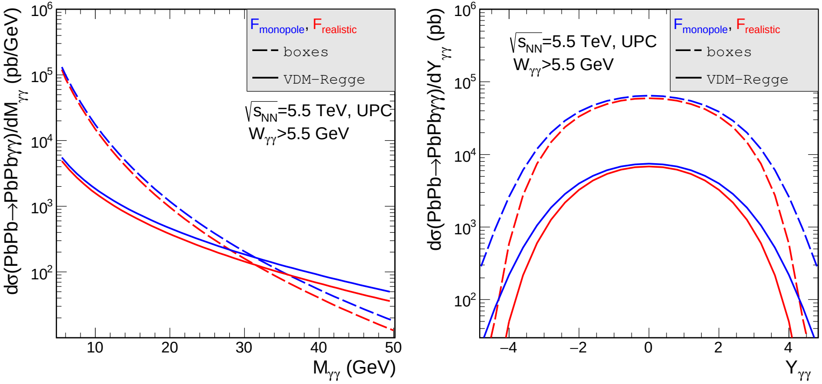
$N\left(\omega_{1/2}, \mathbf{b_{1/2}}\right)$ depends on the electromagnetic form factor

- realistic
- monopole



AA→AA$\gamma\gamma$ - FORM FACTOR

- realistic
- monopole

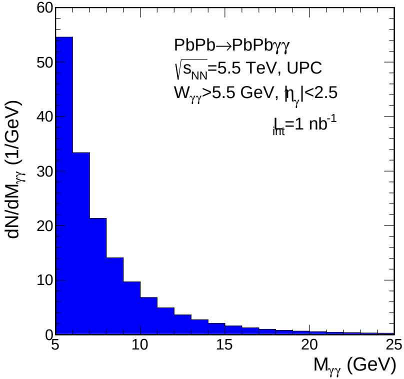


AA→AA$\gamma\gamma$ - INTEGRATED CROSS SECTION

cuts	boxes $F_{realistic}$	boxes $F_{monopole}$	VDM-Regge $F_{realistic}$	VDM-Regge $F_{monopole}$
$W_{\gamma\gamma} > 5$ GeV	306	349	31	36
$W_{\gamma\gamma} > 5$ GeV, $p_{t,\gamma} > 2$ GeV	159	182	7E-9	8E-9
$E_{\gamma} > 3$ GeV	16 692	18 400	17	18
$E_{\gamma} > 5$ GeV	4 800	5 450	9	611
$E_{\gamma} > 3$ GeV, $\lvert y_{\gamma}\rvert < 2.5$	183	210	8E-2	9E-2
$E_{\gamma} > 5$ GeV, $\lvert y_{\gamma}\rvert < 2.5$	54	61	4E-4	7E-4
$p_{t,\gamma} > 0.9$ GeV, $\lvert y_{\gamma}\rvert < 0.7$ (ALICE cuts)	107			
$p_{t,\gamma} > 5.5$ GeV, $\lvert y_{\gamma}\rvert < 2.5$ (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	

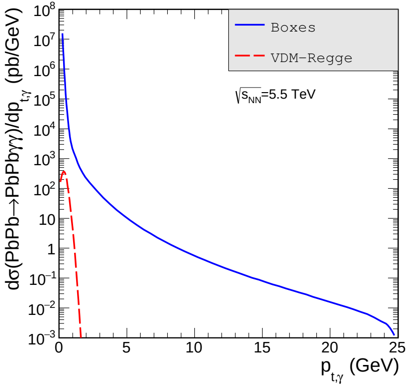
TABLICA: Integrated cross sections in *nb* for exclusive diphoton production processes with both photons measured, for $\sqrt{s_{NN}} = 5.5$ TeV (LHC) and $\sqrt{s_{NN}} = 39$ TeV (FCC). Impact-parameter EPA.

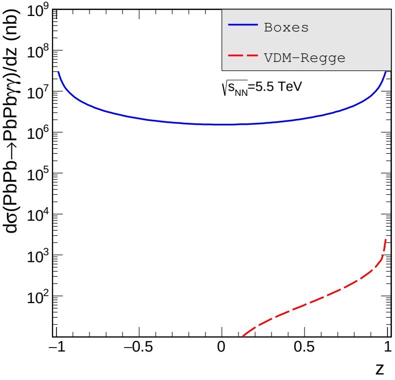
AA→AA$\gamma\gamma$ - NUMBER OF COUNTS



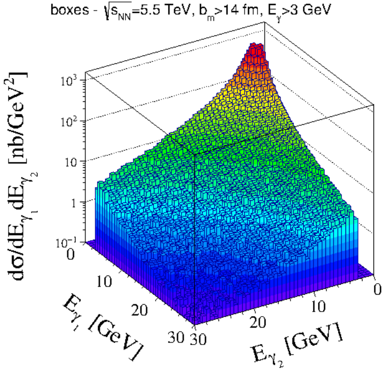
For L_{int} = 1 nb^{-1} a few counts per GeV – measurable quantity

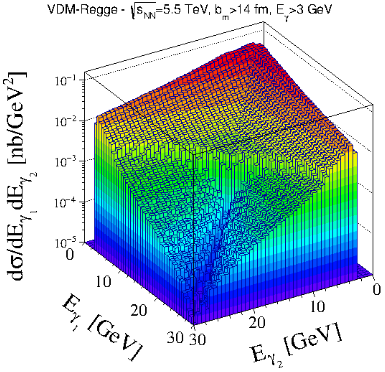
AA→AA$\gamma\gamma$ - DISTRIBUTIONS





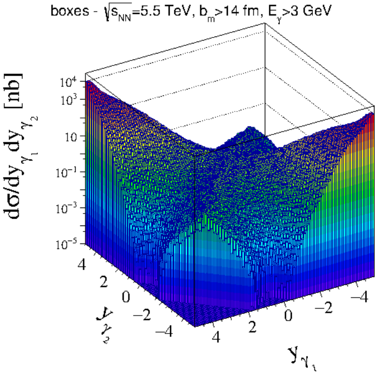
AA→AA$\gamma\gamma$ - DISTRIBUTIONS

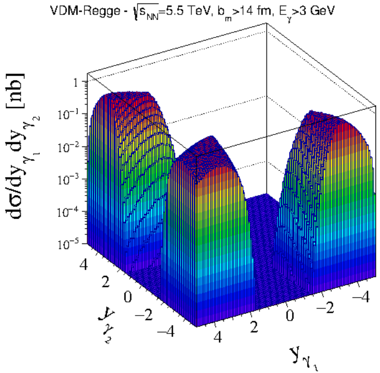




Cross section strongly depends on the photon energy cuts

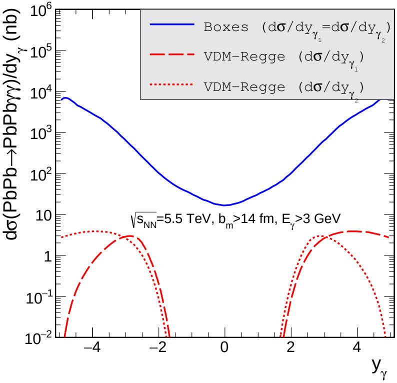
AA→AA$\gamma\gamma$ - DISTRIBUTIONS



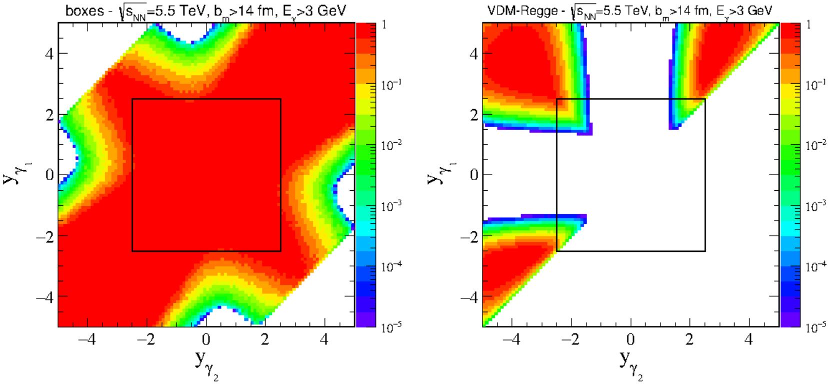


Simple patern in photon-photon frame.
Complicated pattern in the LAB system
One can judge about a measurement.

AA→AA$\gamma\gamma$ - PHOTON RAPIDITY



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



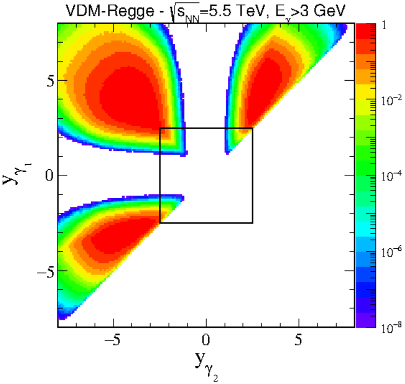
At midrapidity boxes dominate

The soft mechanism at large rapidities

Can it be measured with ZDC ?

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

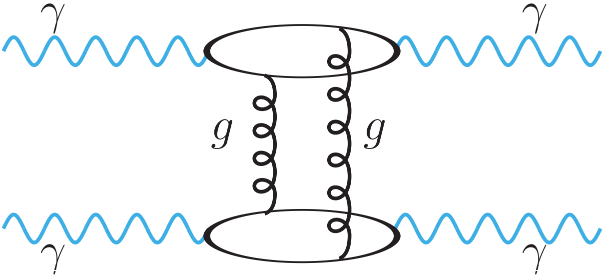
In the extended rapidity range:



May be difficult to measure.

$\gamma\gamma \to \gamma\gamma$, two-gluon exchange

Let us consider (with M.Kłusek-Gawenda and W.Schäfer):



Not yet considered in the context of elastic scattering.
Exact calculation very difficult (three loops)
Here we consider high-energy approximation.

$\gamma\gamma \to \gamma\gamma$, TWO-GLUON EXCHANGE

The altogether 16 diagrams result in the amplitude, which can be cast into the impact-factor representation:

$$A(\gamma_{\lambda_1}\gamma_{\lambda_2} \to \gamma_{\lambda_3}\gamma_{\lambda_4}; s, t)$$

$$= i\, s \sum_{f,f'} \int d^2\boldsymbol{\kappa}\, \frac{\mathcal{J}^{(f)}(\gamma_{\lambda_1}\to\gamma_{\lambda_3};\boldsymbol{\kappa},\boldsymbol{q})\, \mathcal{J}^{(f')}(\gamma_{\lambda_2}\to\gamma_{\lambda_4};-\boldsymbol{\kappa},-\boldsymbol{q})}{[(\boldsymbol{\kappa}+\boldsymbol{q}/2)^2+\mu_G^2][(\boldsymbol{\kappa}-\boldsymbol{q}/2)^2+\mu_G^2]}\, .$$

Here $\boldsymbol{q}$ is the transverse momentum transfer, $t \approx -\boldsymbol{q}^2$, and μ_G is a gluon mass parameter. We parametrize the loop momentum such that gluons carry transverse momenta $\boldsymbol{q}/2 \pm \boldsymbol{\kappa}$ Notice, that the amplitude is finite at $\mu_G \to 0$, because the impact factors $\mathcal{J}$ vanish for $\boldsymbol{\kappa} \to \pm\boldsymbol{q}/2$.

$\gamma\gamma \to \gamma\gamma$, TWO-GLUON EXCHANGE

The amplitude is normalized such, that differential cross section is given by

$$\frac{d\sigma(\gamma\gamma \to \gamma\gamma; s)}{dt} = \frac{1}{16\pi s^2}\frac{1}{4}\sum_{\lambda_i}\left|A(\gamma_{\lambda_1}\gamma_{\lambda_2} \to \gamma_{\lambda_3}\gamma_{\lambda_4}; s, t)\right|^2 . \qquad (21)$$

At small t, within the diffraction cone, the cross section is dominated by the s-channel helicity conserving amplitude. In this case, the explicit form of the impact factor is

$$\mathcal{J}^{(f)}(\gamma_\lambda \to \gamma_\tau; \boldsymbol{\kappa}, \boldsymbol{q}) = \sqrt{N_c^2 - 1}\,\frac{e_f^2 \alpha_{\rm em}\alpha_S}{2\pi^2}\int_0^1 dz \int \frac{d^2\boldsymbol{k}}{\boldsymbol{k}^2 + m_f^2} \times \Big(\delta_{\lambda\tau} I(T,T) + \delta_{\lambda,-\tau} I(T,T')\Big) , \qquad (22)$$

where $N_c = 3$ is the number of colors, e_f is the charge of the quark of flavour f. Quark and antiquark share the large lightcone momentum of the incoming photon in fractions $z, 1-z$, respectively. The transverse momenta entering the outgoing $Q\bar{Q}\gamma$-vertex are $\boldsymbol{k} + z\boldsymbol{q}$ and

$\gamma\gamma \to \gamma\gamma$ TWO-GLUON EXCHANGE

The spin-momentum structure of the quark-loop is encoded in the function $I(T,T)$ (Ivanov-Nikolaev-Schäfer 2006) Indices T,T refer to the transverse polarizations of photons. The s-channel-helicity conserving piece $I(T,T)$ and the helicity-flip piece $I(T,T')$, read explicitly:

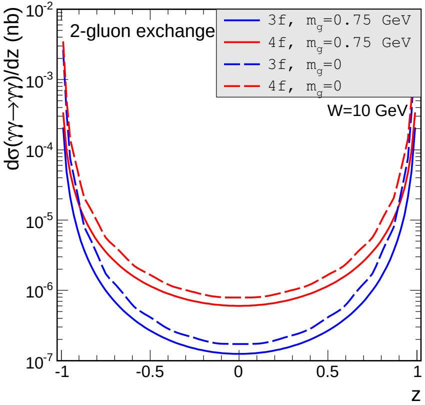
$$\begin{aligned} I(T,T) &= m_f^2\,\Phi_2 + \Big[z^2 + (1-z)^2\Big](\boldsymbol{k}\,\boldsymbol{\Phi}_1) \\ I(T,T') &= 2z(1-z)\Big((\boldsymbol{\Phi}_1\boldsymbol{n})(\boldsymbol{k}\boldsymbol{n}) - [\boldsymbol{\Phi}_1,\boldsymbol{n}][\boldsymbol{k},\boldsymbol{n}]\Big)\,. \end{aligned} \quad (23)$$

Here, $\boldsymbol{n} = \boldsymbol{q}/|\boldsymbol{q}|$, and $[\boldsymbol{a},\boldsymbol{b}] = a_x b_y - a_y b_x$. Here $\boldsymbol{\Phi}_1, \Phi_2$ are shorthand notations for the momentum structures, corresponding to the four relevant Feynman diagrams:

$$\Phi_2 = -\frac{1}{(\boldsymbol{l}+\boldsymbol{\kappa})^2 + m_f^2} - \frac{1}{(\boldsymbol{l}-\boldsymbol{\kappa})^2 + m_f^2} + \frac{1}{(\boldsymbol{l}+\boldsymbol{q}/2)^2 + m_f^2} + \frac{1}{(\boldsymbol{l}-\boldsymbol{q}/2)^2 + m_f^2}$$

$$\boldsymbol{\Phi}_1 = -\frac{\boldsymbol{l}+\boldsymbol{\kappa}}{(\boldsymbol{l}+\boldsymbol{\kappa})^2 + m_f^2} - \frac{\boldsymbol{l}-\boldsymbol{\kappa}}{(\boldsymbol{l}-\boldsymbol{\kappa})^2 + m_f^2} + \frac{\boldsymbol{l}+\boldsymbol{q}/2}{(\boldsymbol{l}+\boldsymbol{q}/2)^2 + m_f^2} + \frac{\boldsymbol{l}-\boldsymbol{q}/2}{(\boldsymbol{l}-\boldsymbol{q}/2)^2 + m_f^2}\,, \quad (2$$

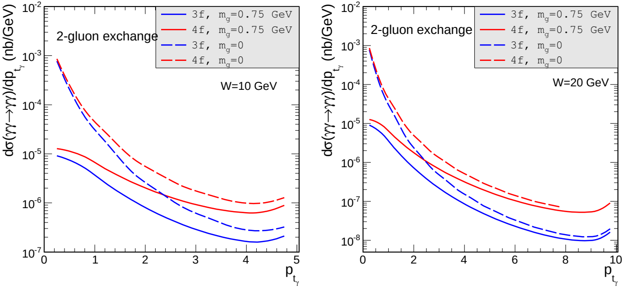
Two-gluon exchange mechanism, first results



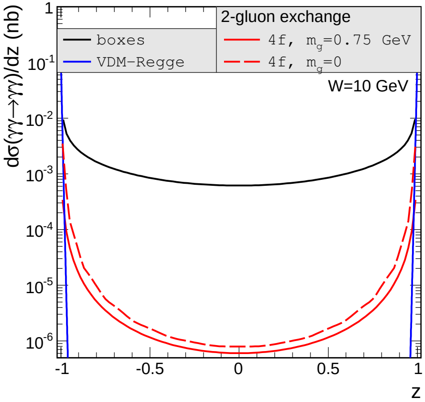
Huge effect of including charm at $z \approx 0$

– interference effect

Two-gluon exchange mechanism, number of flavours

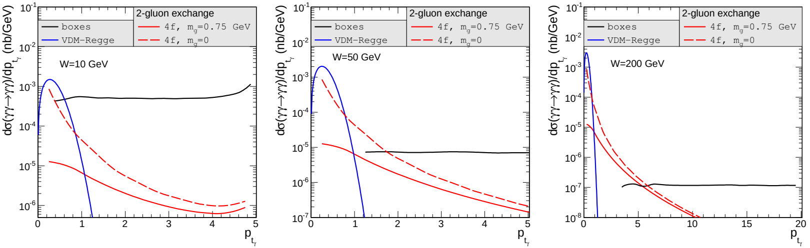


Two-gluon exchange vs box mechanisms vs VDM-Regge



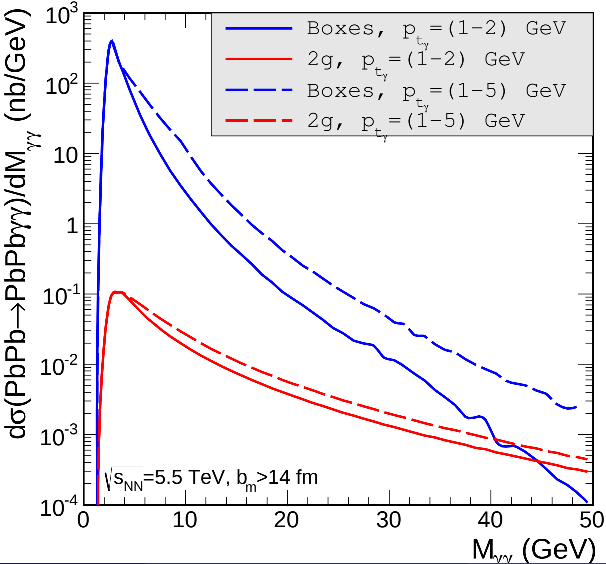
At low energies dominance of the box contributions

Two-gluon exchange vs box mechanisms vs VDM-Regge

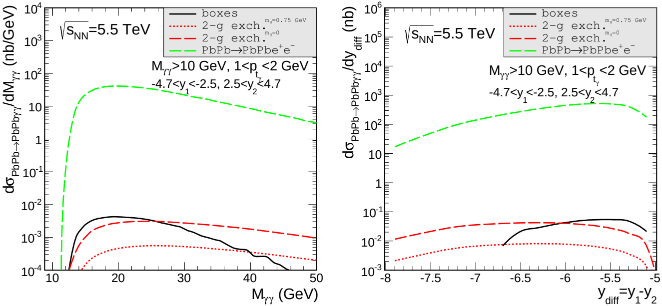


At linear collider with double back Compton scattering could probably verify.

$AA \to AA\gamma\gamma$ with 2g exchange

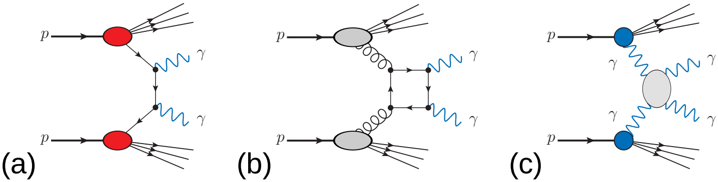


$AA \to AA\gamma\gamma$, 2G EXCHANGE VS OTHER MECHANISMS



RYSUNEK: Distribution in invariant mass of photons and in rapidity distance between the two photons for $M_{\gamma\gamma} > 10$ GeV, 1 GeV $< p_{t_\gamma} <$ 2 GeV and $-4.7 < y_1 < -2.5$, $2.5 < y_2 < 4.7$. In addition, we show (top dashed, green line) a similar distribution for $AA \to AAe^+e^-$.

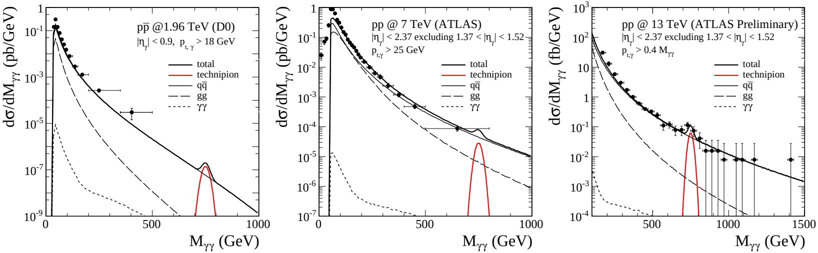
$pp \to \gamma\gamma$



RYSUNEK: Mechanisms of $\gamma\gamma$ pair production in proton-proton collisions.

$\gamma\gamma \to \gamma\gamma$ contribution small.

$pp \to \gamma\gamma$



Lebiedowicz, Łuszczak, Pasechnik, Szczurek, arXiv:1604.0203
Phys. Rev. **D94** (2016) 015023.

$pp \to pp\gamma\gamma$

The cross section of $\gamma\gamma$ production via $\gamma\gamma$ fusion in *pp* collisions can be calculated in the parton model in (equivalent photon approximation) as

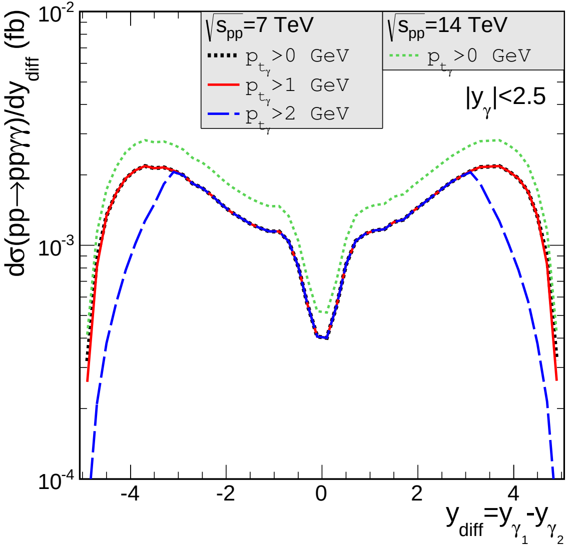
$$\frac{d\sigma}{dy_3 dy_4 d^2p_{t,\gamma}} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{ij} x_1 \gamma^{(i)}(x_1, \mu_F^2) x_2 \gamma^{(j)}(x_2, \mu_F^2) \overline{|\mathcal{M}_{\gamma\gamma\to\gamma\gamma}|^2} \,. \tag{26}$$

i,j = elastic, inelastic

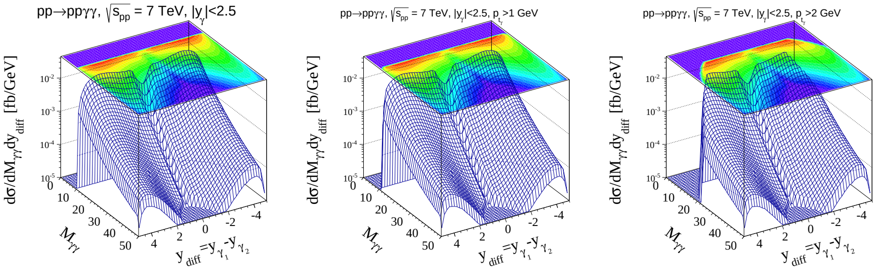
In practical calculations for elastic fluxes we shall use parametrization proposed by Drees-Zeppenfeld.

Only elastic-elastic contributions with forward protons considered here.

$pp \to pp\gamma\gamma$, FIRST RESULTS



$pp \to pp\gamma\gamma$, FIRST RESULTS



$W > 10$ GeV, experimental range of (pseudo)rapidities.

increasing cut on photon transverse momentum

A COMMENT ON BFKL RESUMMATION

- So far we have made calculations within two-gluon exchange approximation.
- At high energies a (BFKL) resummation may be needed (ladder exchange).
- In LL BFKL formulae depend on $z = \frac{N_c \alpha_s}{\pi} ln\left(\frac{s}{s_0}\right)$
- The choice of s_0 is pretty arbitrary which means that it is difficult to make any reliable predictions.
- NLL predictions would be necessary (not yet available).

First experimental results

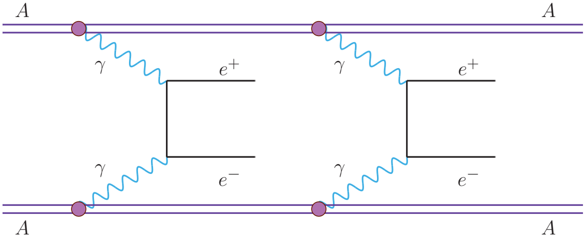
Recently ATLAS presented first results:
ATLAS-CONF-2016-111, 26th September 2016
"Light-by-light scattering ..."

In their measurement:
$\sqrt{s_{NN}}$ = 5.02 GeV, $E_T > 3$ GeV, $|\eta| < 2.4$
In addition:
$p_{t,\gamma\gamma} < 2$ GeV, Aco < 0.01

ATLAS obtained: 70 $\pm$ 20 (stat) $\pm$ 17 (syst.) nb
our predictions: 49 $\pm$ 10 nb

Consistent with our predictions !!!

$AA \to AAe^+e^-e^+e^-$



RYSUNEK: Double-scattering mechanism for $e^+e^-e^+e^-$ production in ultrarelativistic UPC of heavy ions.

M. Kłusek-Gawenda and A. Szczurek, arXiv:1607.05095, in print in Phys. Lett. **B**.

$AA \to AAe^+e^-$

$$\sigma_{A_1A_2\to A_1A_2e^+e^-}\left(\sqrt{s_{A_1A_2}}\right) = \int \sigma_{\gamma\gamma\to e^+e^-}\left(W_{\gamma\gamma}\right) N\left(\omega_1,\mathbf{b_1}\right) N\left(\omega_2,\mathbf{b_2}\right) S^2_{abs}$$
$$\times \quad 2\pi b \mathrm{d}b \, \mathrm{d}\overline{b}_x \, \mathrm{d}\overline{b}_y \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_{e^+e^-} \; ,$$

where $N(\omega_i,\mathbf{b_i})$ are photon fluxes, $W_{\gamma\gamma} = M_{e^+e^-}$ and $Y_{e^+e^-} = \left(y_{e^+} + y_{e^-}\right)/2$ is a invariant mass and a rapidity of the outgoing e^+e^- system, respectively. Energy of photons is expressed through $\omega_{1/2} = W_{\gamma\gamma}/2\exp(\pm Y_{e^+e^-})$. $\mathbf{b_1}$ and $\mathbf{b_2}$ are impact parameters of the photon-photon collision point with respect to parent nuclei 1 and 2, respectively, and $\mathbf{b} = \mathbf{b_1} - \mathbf{b_2}$ is the standard impact parameter for the A_1A_2 collision. The quantities $\overline{b}_x$ and $\overline{b}_y$ are the components of the $(\mathbf{b_1} + \mathbf{b_2})/\mathbf{2}$: $\overline{b}_x = (b_{1x} + b_{2x})/2$ and $\overline{b}_y = (b_{1y} + b_{2y})/2$.

$AA \to AAe^+e^-$

The five-fold integration is performed numerically. In both cases the integrated cross section can be then written formally as

$$\sigma_{A_1A_2 \to A_1A_2e^+e^-} = \int P_{\gamma\gamma \to e^+e^-}(b)\, \mathrm{d}^2b \; . \qquad (28)$$

Here $P_{\gamma\gamma \to e^+e^-}(b)$ has an interpretation of a probability to produce a single e^+e^- pair in the collision at the impact parameter b. This formula is not very useful for practical calculation of double scattering. If the calculation is done naively $P_{\gamma\gamma \to e^+e^-}(b)$ can be larger than 1 in the region of low impact parameter. Then a unitarization procedure is needed (Serbo et al.).

DOUBLE SCATTERING

If one wishes to impose some cuts on produced electron or positron or to have distribution in some kinematical variables of individual particles, more complicated calculations are required (Klusek-Gawenda-Szczurek). To have detailed information about rapidities of individual electrons an extra integration over a kinematical variable describing angular distribution for the $\gamma\gamma \to e^+e^-$ subprocess is required and the total $\sigma_{\gamma\gamma\to e^+e^-}$ cross section has to be replaced by differential cross section. Then the formula above can be written more differentially as:

$$\frac{d\sigma_{A_1A_2\to A_1A_2e^+e^-}}{dy_+dy_-dp_t} = \int \frac{\mathrm{d}P_{\gamma\gamma\to e^+e^-}(b;y_+,y_-,p_t)}{dy_+dy_-dp_t}\,\mathrm{d}^2b\,. \tag{29}$$

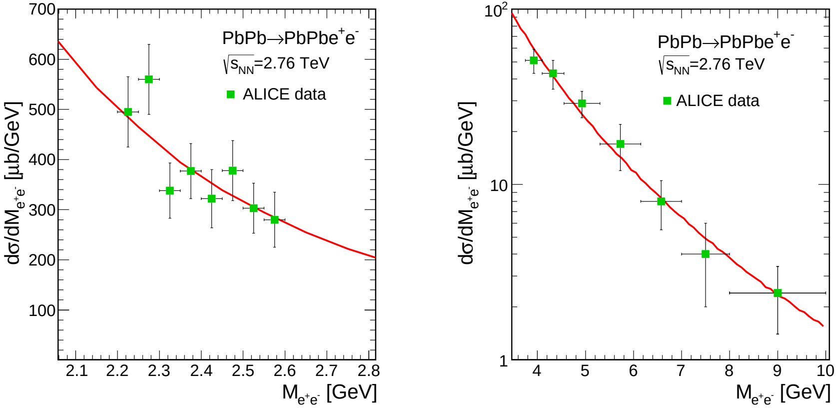
DOUBLE SCATTERING

The cross section for double scattering can be then written as:

$$\frac{d\sigma_{AA\to AAe^+e^-e^+e^-}}{dy_1 dy_2 dy_3 dy_4} = \frac{1}{2}\int \left(\frac{dP_{\gamma\gamma\to e^+e^-}(b, y_1, y_2; p_t > p_{t,cut})}{dy_1 dy_2} \times \frac{dP_{\gamma\gamma\to e^+e^-}(b, y_3, y_4; p_t > p_{t,cut})}{dy_3 dy_4} \right) \times 2\pi b \, db \, . \tag{30}$$

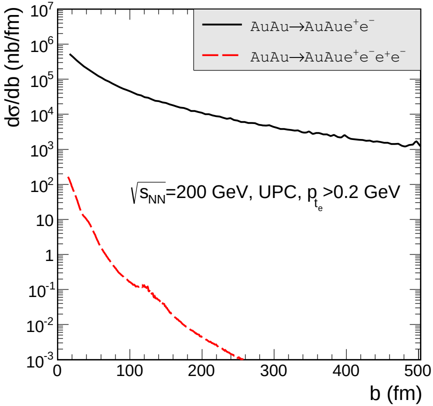
The combinatorial factor $1/2$ takes into account identity of the two pairs.
In our calculations here we use both realistic fluxes of photons calculated with charge form factors of a nucleus, being Fourier transform of realistic charge distributions or a more simplified formula is used.

Results for one-pair production



Rysunek: Invariant mass distributions of dielectrons in UPC of heavy ions calculated within our approach together with the recent ALICE data.

FIRST RESULTS FOR DOUBLE SCATTERING



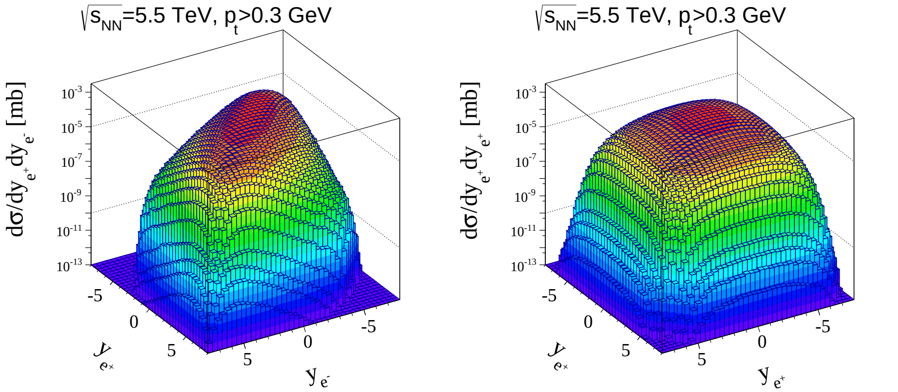
RYSUNEK: Differential cross section as a function of impact parameter. The upper line denotes result for the AuAu→AuAue^+e^- reaction and the lower line shows result for the AuAu→AuAu$e^+e^-e^+e^-$ reaction.

FIRST RESULTS FOR DOUBLE SCATTERING

TABLICA: Nuclear cross section for $PbPb \to PbPbe^+e^-e^+e^-$ at $\sqrt{s_{NN}} = 5.5$ TeV for different cuts specified in the table.

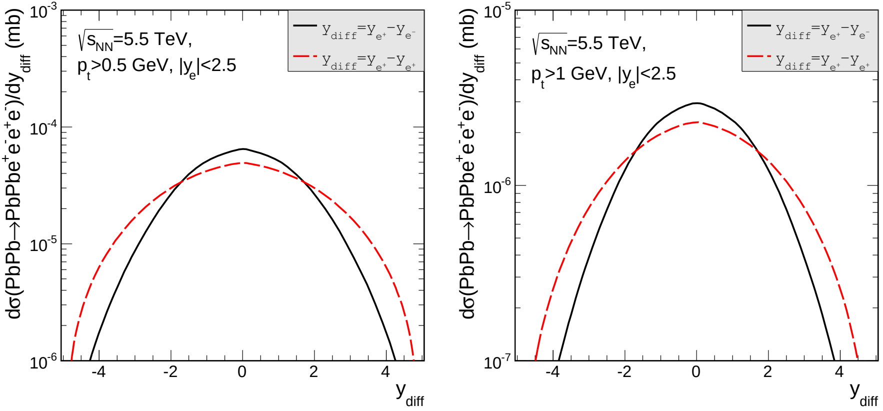
cut set	σ_{UPC}	N_{events} for L=1 nb^{-1}
$p_{t_e} > 0.2$ GeV	52.525 μb	52 525
$p_{t_e} > 0.2$ GeV, $\|y_e\| < 2.5$	10.636 μb	10 636
$p_{t_e} > 0.2$ GeV, $\|y_e\| < 1$	0.649 μb	649
$p_{t_e} > 0.3$ GeV, $\|y_e\| < 4.9$	7.447 μb	7 447
$p_{t_e} > 0.3$ GeV, $\|y_e\| < 2.5$	2.052 μb	2 052
$p_{t_e} > 0.5$ GeV, $\|y_e\| < 4.9$	0.704 μb	704
$p_{t_e} > 0.5$ GeV, $\|y_e\| < 2.5$	0.235 μb	235
$p_{t_e} > 1$ GeV	25.2 nb	25
$p_{t_e} > 1$ GeV, $\|y_e\| < 4.9$	22.6 nb	23
$p_{t_e} > 1$ GeV, $\|y_e\| < 2.5$	9.8 nb	10
$p_{t_e} > 1$ GeV, $\|y_e\| < 1$	0.6 nb	1

FIRST RESULTS FOR DOUBLE SCATTERING



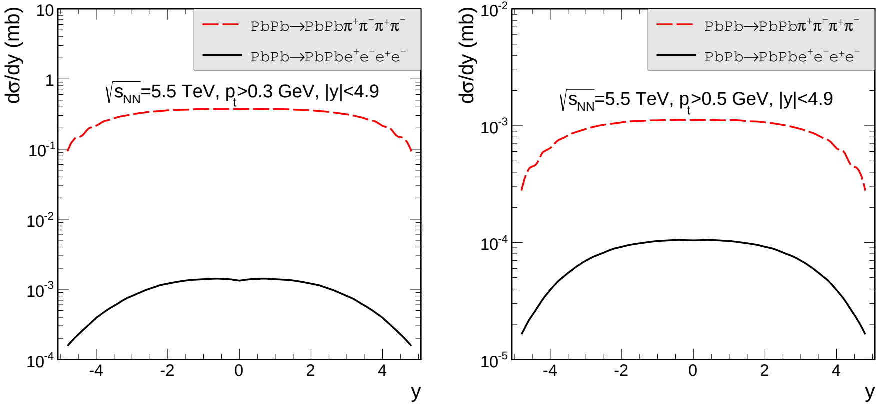
RYSUNEK: Two-dimensional distribution in rapidities of the opposite-sign leptons from the same collision (left panel) and for the same-sign leptons (right panel). The cross section for the $e^+e^-e^+e^-$ production is calculated for lead-lead UPC at $\sqrt{s_{NN}} = 5.5$ TeV and $p_t > 0.3$ GeV.

First results for double scattering



Rysunek: Distributions in rapidity difference between the opposite-sign electrons (solid line) and between the same-sign electrons (or positrons) (dashed line) for two different lower cuts on lepton transverse momenta: 0.5 GeV (left panel) and 1.0 GeV (right panel). This calculation is for

FIRST RESULTS FOR DOUBLE SCATTTERING



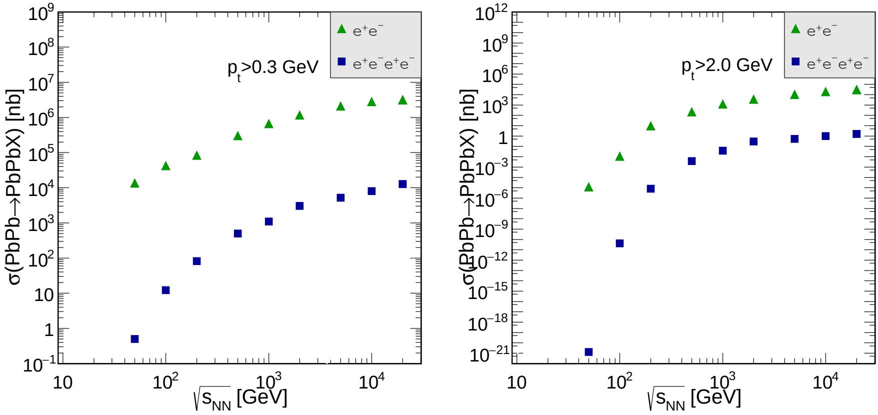
RYSUNEK: Rapidity distribution of electron/positron (solid line) and charged pion (dashed line) for lead-lead collisions at the LHC ($\sqrt{s_{NN}} = 5.5$ TeV). The left panel for $p_t > 0.3$ GeV and the right panel for $p_t > 0.5$ GeV.

BACKGROUND

TABLICA: Nuclear cross section for the $PbPb \to PbPb\pi^+\pi^-\pi^+\pi^-$ and $PbPb \to PbPbe^+e^-e^+e^-$ reactions at $\sqrt{s_{NN}} = 5.5$ TeV with $|y| < 4.9$ and for different cuts on transverse momenta of pions or electrons.

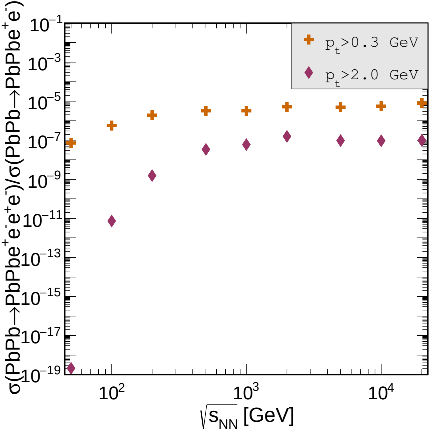
Reaction	$p_{t,min}$ = 0.3 GeV	$p_{t,min}$ = 0.5 GeV
$PbPb \to PbPb\pi^+\pi^-\pi^+\pi^-$	2.954 mb	8.862 μb
$PbPb \to PbPbe^+e^-e^+e^-$	7.447 μb	0.704 μb

ENERGY DEPENDENCE OF THE CROSS SECTIONS



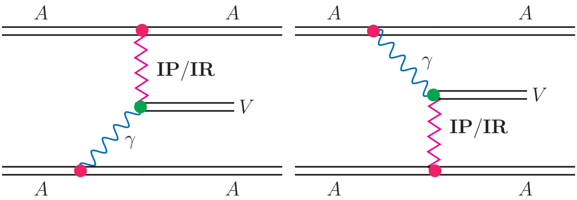
RYSUNEK: Energy dependence of the cross sections for e^+e^- and $e^+e^-e^+e^-$ production. The left panel for $p_t > 0.3$ GeV and the right panel for $p_t > 2$ GeV.

ENERGY DEPENDENCE OF THE CROSS SECTIONS



RYSUNEK: Energy dependence of the ratio of the cross sections for e^+e^- and $e^+e^-e^+e^-$ production for $p_t > 0.3$ GeV and for $p_t > 2$ GeV.

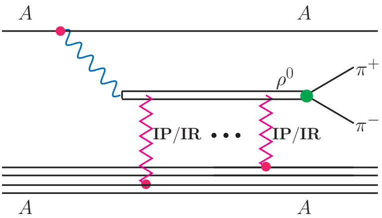
UPC and semicentral photoproduction of J/ψ



RYSUNEK: Mechanism of photoproduction of J/ψ mesons.

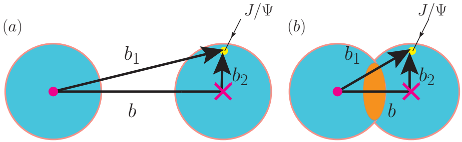
M. Kłusek-Gawenda and A. Szczurek, " Photoproduction of J/ψ mesons in peripheral and semicentral heavy ion collisions", Phys. Rev. **C93** (2016) 044912.

MULTIPLE SCATTERING



RYSUNEK: Multiple scattering of hadronic excitation or color dipole in the second nucleus.

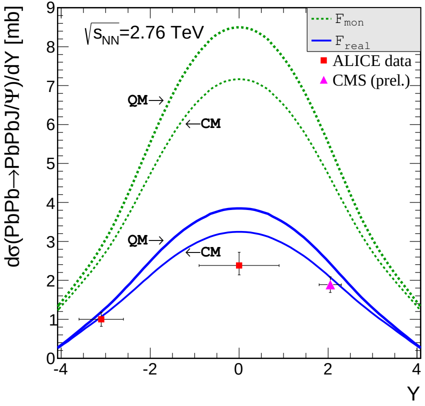
SEMICENTRAL PHOTOPRODUCTION OF J/ψ



RYSUNEK: From ultraperipheral to semicentral collisions.

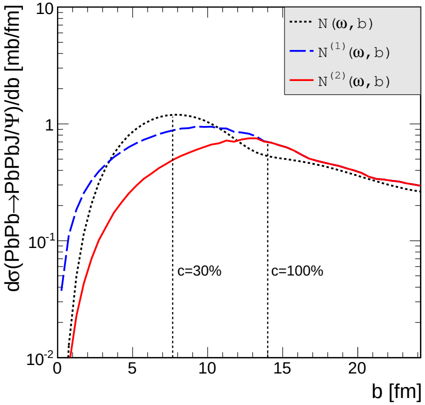
ALICE observed enhancement of J/ψ
for very low transverse momenta for semi-central collisions
What it is ???

ULTRAPERIPHERAL PRODUCTION OF J/ψ



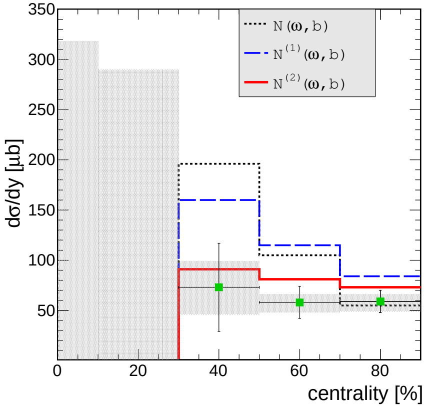
RYSUNEK: Result for UPCs together with experimental data.

SEMICENTRAL PHOTOPRODUCTION OF J/ψ



RYSUNEK: Impact parameter dependence of the cross section.

SEMICENTRAL PHOTOPRODUCTION OF J/ψ



RYSUNEK: Centrality dependence of the cross section.

L. Massacrier et al. (ALICE Collaboration), arXiv:1510.08315 [nucl-ex].

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.
- Both CMS and ATLAS will study this (we are in contact)
  It is a matter of a trigger. At ALICE only at run 3.
  FCC – may be, if planned in advance.

CONCLUSIONS, VERY RECENT RESULTS

- Amplitude for two-gluon exchange has been derived for the first time (relatively simple formula).
- Cross section for $\gamma\gamma \to \gamma\gamma$ was calculated (z and p_t distributions)
- Helicity-conserving contribution dominates. Helicity-flip contributions are very small even at large p_t.
- There is a window where two-gluon exchange wins with both boxes and VDM-Regge contribution.
- Future linear colliders ? (long-term perspective).
- $AA \to AA\gamma\gamma$? (statistics)
- $pp \to pp\gamma\gamma$? (statistics, pile ups)
- BFKL effects would increase the cross section. LO $\to$ NLO

Conclusions for $AA \to AAe^+e^-e^+e^-$

- Good description of single pair production.
- First predictions have been presented for double scattering.
- Measureable cross sections with luminosity of 1 nb^{-1} even with experimental cuts.
- The distribution between azimuthal angles of the same-sign and opposite-sign electrons is very interesting.
- Single scattering contribution has to be evaluate and compared to double scattering mechanism.

CONCLUSIONS, SEMICENTRAL

- Photoproduction of J/ψ survives even in semi-central collisions and may modify nuclear modification factor.
- This could be important also for other processes:
  - e^+e^-, $\mu^+\mu^+$
  - D meson production
- Such processes could influence some conclusions about QGP !

CONCLUSIONS, OUTLOOK

- 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