EPS 2017

$\gamma\gamma \to \gamma\gamma$*scattering*
IN ULTRARELATIVISTIC UPC

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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
- For elastic $\gamma\gamma \to \gamma\gamma$ scattering the main mechanism are intermediate boxes.

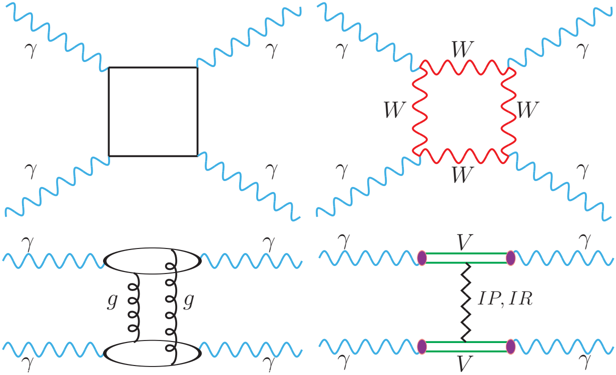
PHOTON-PHOTON ELASTIC SCATTERING

- 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.
  wrong by a factor of about 8.
  erratum was written.
- This presentation will be based on our recent analysis:
  M. Kłusek-Gawenda, P. Lebiedowicz and A. Szczurek,
  arXiv:1601.07001, Phys. Rev. **C93** (2016) 044907.
- M. Kłusek-Gawenda, W. Schäfer and A. Szczurek, "Two-gluon exchange contribution to elastic $\gamma\gamma \to \gamma\gamma$ scattering and production of two-photons in ultraperipheral ultrarelativistic heavy ion and proton-proton collisions", Phys. Lett. **B761** (2016) 399.

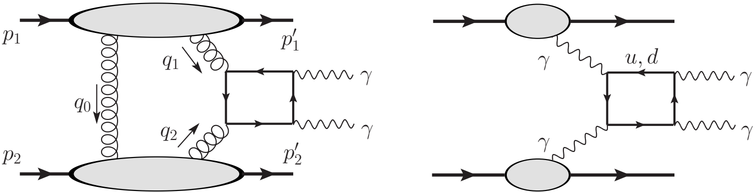
PHOTON-PHOTON ELASTIC SCATTERING



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

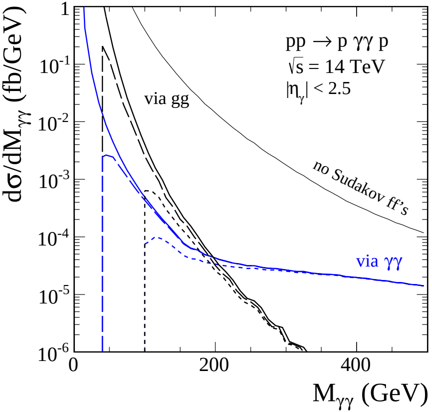
EXCLUSIVE $pp \to pp\gamma\gamma$

Two mechanisms of the exclusive production:



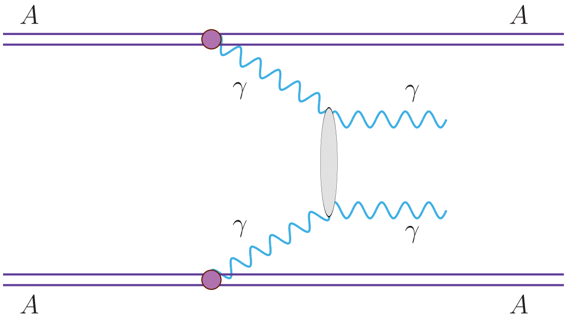
The QCD mechanism disturbs to see the QED mechanism

EXCLUSIVE $pp \rightarrow pp\gamma\gamma$



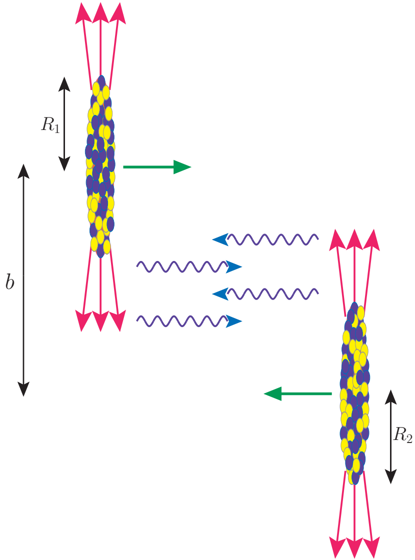
At low energy diffractive mechanism dominates
At high energy the $\gamma\gamma$ rescattering dominates
Potential place to look for effects beyond Standard Model

$AA \to AA\gamma\gamma$



Let us consider ultraperipheral collisions.

EQUIVALENT PHOTON APPROXIMATION

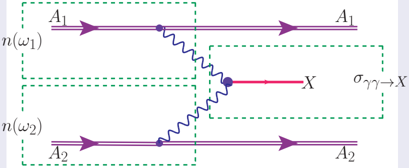


The strong electromagnetic field
is a source of photons
that induce electromagnetic reactions in ion-ion collisions.

ULTRAPERIHERAL COLLISIONS

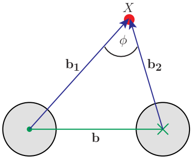
$$b > R_{min} = R_1 + R_2$$

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

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

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:

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

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

ELEMENTARY CROSS SECTION

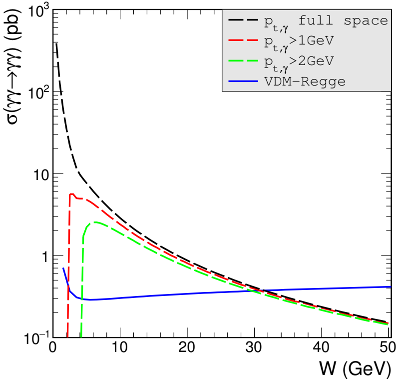
$$\mathcal{A}(s,t) \approx s \left((1+i)\, C_{\mathbf{R}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{R}}(t)-1} + i C_{\mathbf{P}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbf{P}}(t)-1} \right) . \qquad (6)$$

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:

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

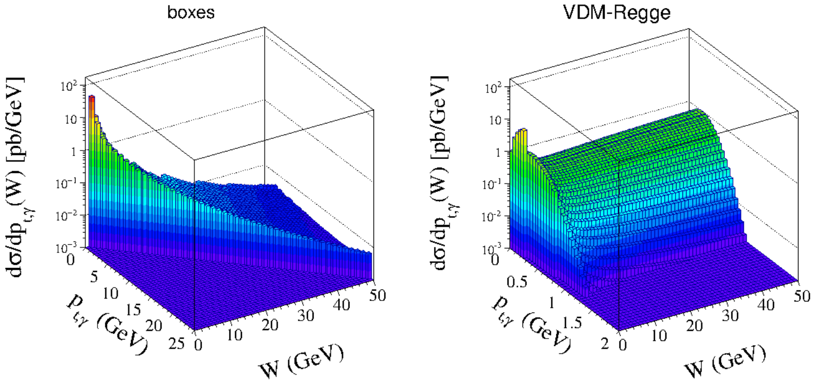
$$\sigma^{tot}_{\pi^\pm p}(s) = \frac{1}{s} Im \mathcal{A}_{\pi^\pm p}(s,t=0) . \qquad (8)$$

Elementary cross section

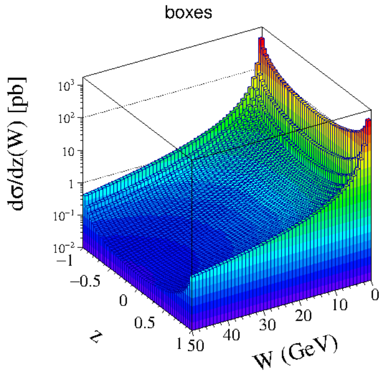


At large W a small lower cut on photon transverse momenta is not important.

Elementary cross section



ELEMENTARY CROSS SECTION



Hard and soft, respectively

NUCLEAR CROSS SECTION

In our b-space EPA:

$$\sigma_{A_1A_2\to A_1A_2\gamma\gamma}\left(\sqrt{s_{A_1A_2}}\right) = \int \sigma_{\gamma\gamma\to\gamma\gamma}\left(\sqrt{s_{\gamma\gamma}}\right) N\left(\omega_1, \mathbf{b_1}\right) N\left(\omega_2, \mathbf{b_2}\right) S^2_{abs}\left(\mathbf{b}\right.$$

$$\times \quad 2\pi b \mathrm{d}b \, \mathrm{d}\overline{b}_x \, \mathrm{d}\overline{b}_y \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_{\gamma\gamma} \; , \qquad (9$$

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

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

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

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

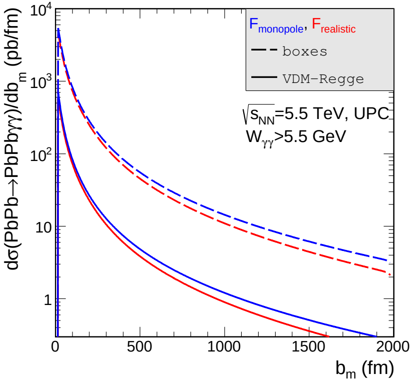
where $\omega_{1/2} = W_{\gamma\gamma}/2 \exp(\pm Y_{\gamma\gamma})$. The quantities $\overline{b}_x, \overline{b}_y$ are the components of the vector $\overline{\mathbf{b}} = (\mathbf{b_1} + \mathbf{b_2})/2$

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

AA→AA$\gamma\gamma$ - FORM FACTOR

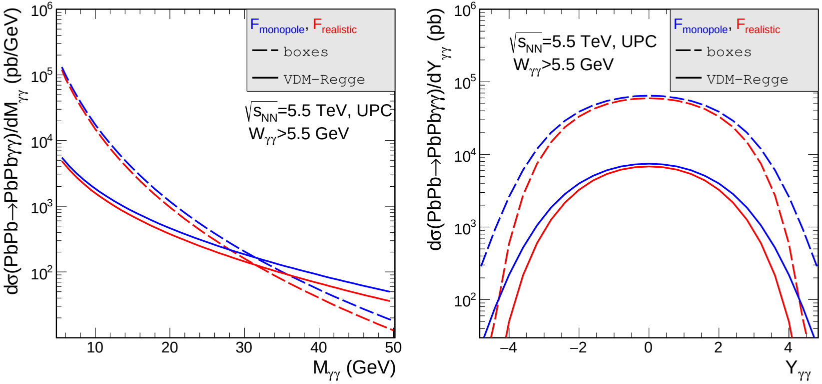
$N\left(\omega_{1/2}, \mathbf{b_{1/2}}\right)$ depends on the electromagnetic form factor

- realistic
- monopole



AA→AA$\gamma\gamma$ - FORM FACTOR

- realistic
- monopole

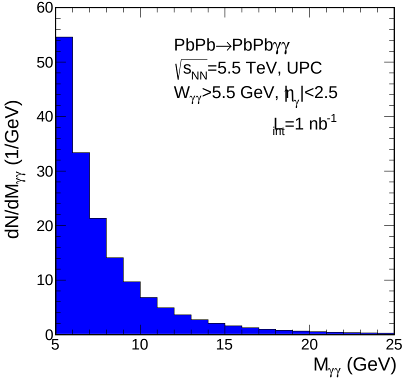


AA→AA$\gamma\gamma$ - INTEGRATED CROSS SECTION

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	

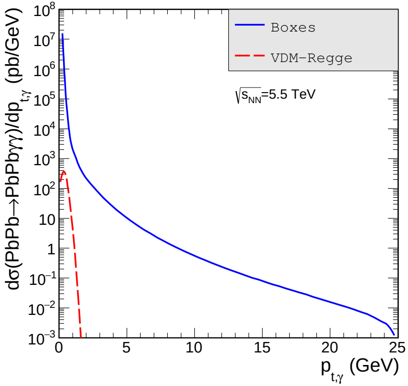
TABLICA: Integrated cross sections in *nb* for exclusive diphoton production processes with both photons measured, for $\sqrt{s_{NN}} = 5.5$ TeV (LHC) and $\sqrt{s_{NN}} = 39$ TeV (FCC). Impact-parameter EPA.

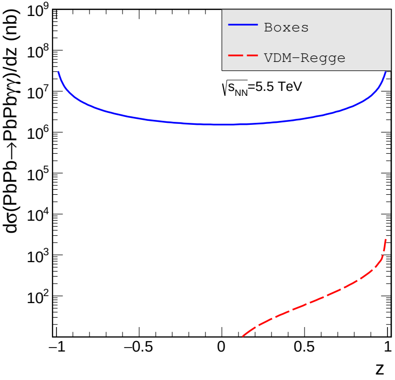
AA→AA$\gamma\gamma$ - NUMBER OF COUNTS



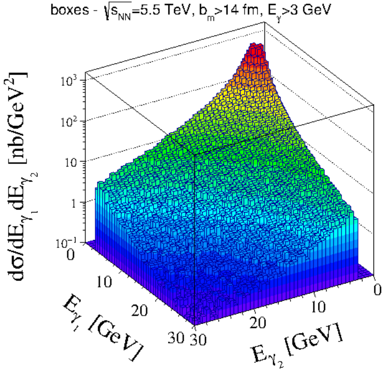
For L_{int} = 1 nb^{-1} a few counts per GeV – measurable quantity

AA→AA$\gamma\gamma$ - DISTRIBUTIONS



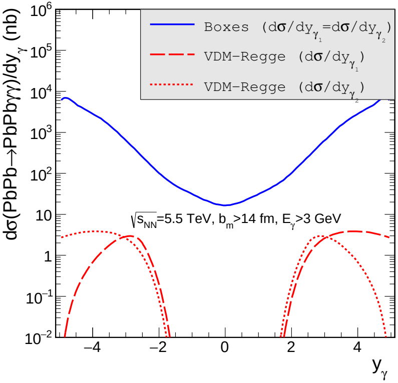


AA→AA$\gamma\gamma$ - DISTRIBUTIONS

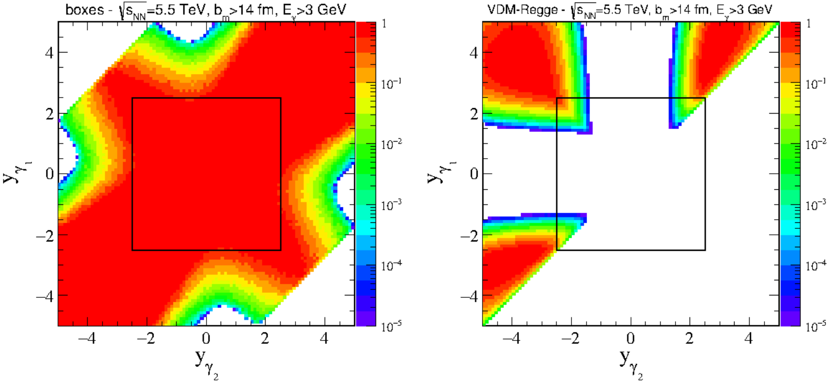


Cross section strongly depends on the photon energy cuts

AA→AA$\gamma\gamma$ - PHOTON RAPIDITY



$AA \to AA\gamma\gamma$ - RAPIDITY CORRELATIONS



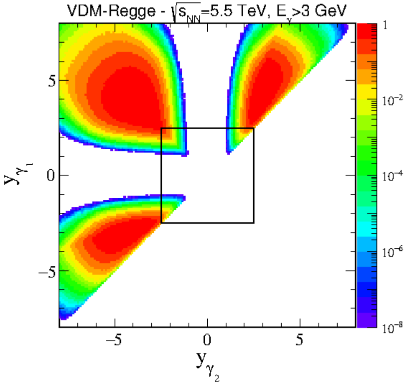
At midrapidity boxes dominate

The soft mechanism at large rapidities

Can it be measured with ZDC ?

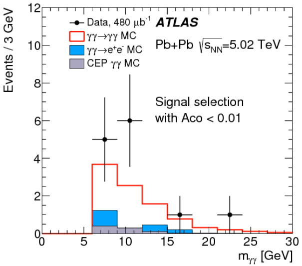
AA→AA$\gamma\gamma$ - RAPIDITY CORRELATIONS

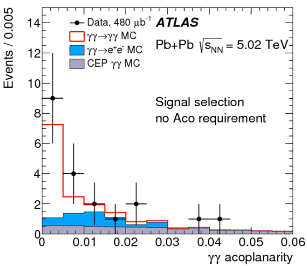
In the extended rapidity range:



May be difficult to measure.

ATLAS RESULTS





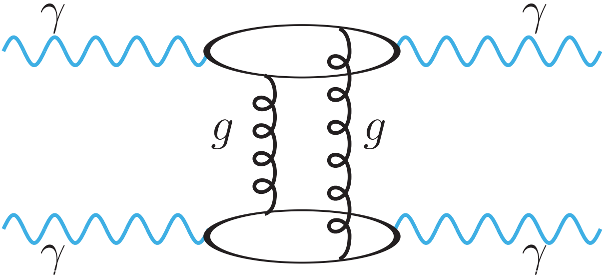
Our results were used for the ATLAS conditions

Only 13 events

Agreement with our predictions

$\gamma\gamma \to \gamma\gamma$, 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 $\boldsymbol{q}/2 \pm \boldsymbol{\kappa}$.

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

$$\frac{d\sigma(\gamma\gamma \to \gamma\gamma; s)}{dt} = \frac{1}{16\pi s^2} \frac{1}{4} \sum_{\lambda_i} \Big| A(\gamma_{\lambda_1}\gamma_{\lambda_2} \to \gamma_{\lambda_3}\gamma_{\lambda_4}; s, t) \Big|^2 . \qquad (14)$$

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

$$\mathcal{J}^{(f)}(\gamma_\lambda \to \gamma_\tau; \boldsymbol{\kappa}, \boldsymbol{q}) = \sqrt{N_c^2 - 1}\, \frac{e_f^2 \alpha_{\rm em} \alpha_S}{2\pi^2} \int_0^1 dz \int \frac{d^2\boldsymbol{k}}{\boldsymbol{k}^2 + m_f^2} \times \Big(\delta_{\lambda\tau} I(T, T) + \delta_{\lambda,-\tau} I(T, T') \Big) , \qquad (15)$$

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:

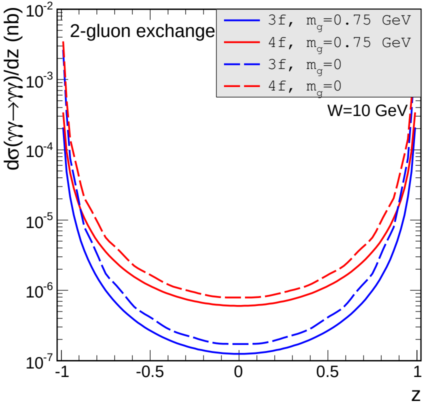
$$\begin{aligned} I(T,T) &= m_f^2\,\Phi_2 + \Big[z^2 + (1-z)^2\Big](\boldsymbol{k}\boldsymbol{\Phi}_1) \\ I(T,T') &= 2z(1-z)\Big((\boldsymbol{\Phi}_1\boldsymbol{n})(\boldsymbol{k}\boldsymbol{n}) - [\boldsymbol{\Phi}_1,\boldsymbol{n}][\boldsymbol{k},\boldsymbol{n}]\Big)\,. \end{aligned} \tag{16}$$

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:

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

$$\boldsymbol{\Phi}_1 = -\frac{\boldsymbol{l}+\boldsymbol{\kappa}}{(\boldsymbol{l}+\boldsymbol{\kappa})^2+m_f^2} - \frac{\boldsymbol{l}-\boldsymbol{\kappa}}{(\boldsymbol{l}-\boldsymbol{\kappa})^2+m_f^2} + \frac{\boldsymbol{l}+\boldsymbol{q}/2}{(\boldsymbol{l}+\boldsymbol{q}/2)^2+m_f^2} + \frac{\boldsymbol{l}-\boldsymbol{q}/2}{(\boldsymbol{l}-\boldsymbol{q}/2)^2+m_f^2}\,, \quad (1$$

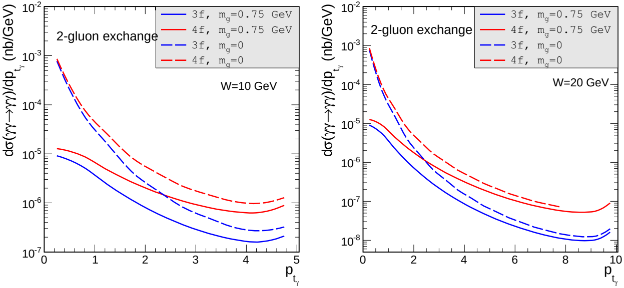
TWO-GLUON EXCHANGE MECHANISM, FIRST RESULTS



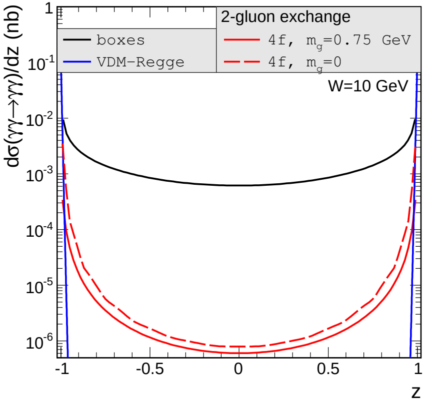
Huge effect of including charm at $z \approx 0$

– interference effect

Two-gluon exchange mechanism, number of flavours

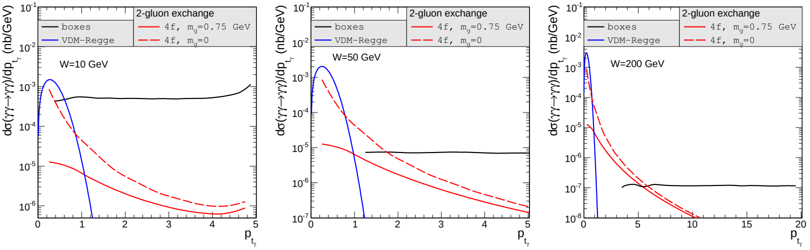


Two-gluon exchange vs box mechanisms vs VDM-Regge



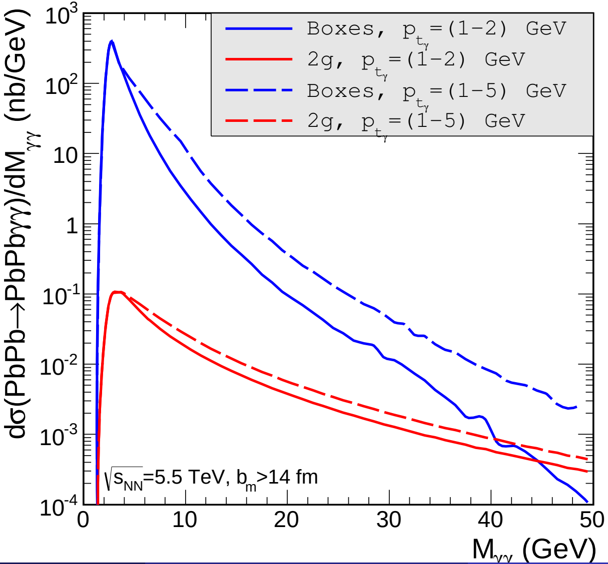
At low energies dominance of the box contributions

TWO-GLUON EXCHANGE VS BOX MECHANISMS VS VDM-REGGE



At linear collider with double back Compton scattering could be probably verified.

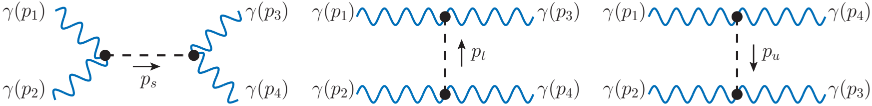
$AA \to AA\gamma\gamma$ with 2g exchange



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).

MESON-EXCHANGE MECHANISMS



RYSUNEK: Diagrams for light-by-light scattering via a time-like (s-channel) and a space-like (t-channel and u-channel) meson exchanges.

P. Lebiedowicz and A. Szczurek, "The role of meson exchanges in light-by-light scattering", arXiv:1705.06535, in print in Phys. Lett. B.

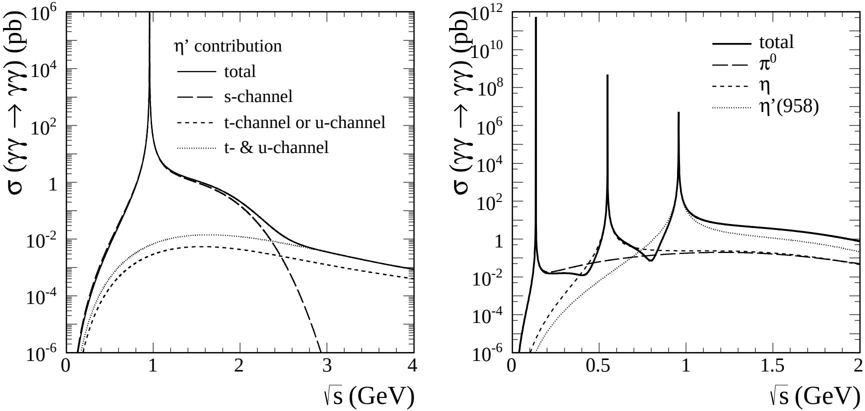
AMPLITUDES

The amplitude for the meson-exchange reaction:

$$\mathcal{M}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} = \sum_{M_{PS}=\pi^0,\eta,\eta'(958),\eta_c(1S),\eta_c(2S)} \mathcal{M}^{(M_{PS})}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} + \sum_{M_S=f_0(500),f_0(980),a_0(980),f_0(1370),\chi_{c0}(1P)} \mathcal{M}^{(M_S)}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} + \sum_{M_T=f_2(1270),a_0(1320),f_2'(1525)} \mathcal{M}^{(M_T)}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} . \tag{19}$$

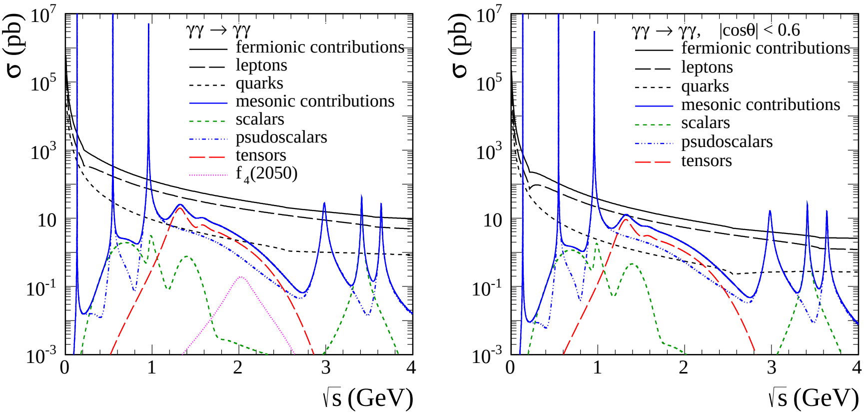
The contribution of axial-vector mesons vanishes for on-shell photons due to the Landau-Yang theorem.

RESULTS



RYSUNEK: Energy dependence of the pseudoscalar meson contributions to the $\gamma\gamma \to \gamma\gamma$ scattering.

RESULTS



RYSUNEK: Energy dependence of the meson exchange contributions compared with the fermion-box ones. Results integrated over full z-range (left) and for $|z| < 0.6$ (right).

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