THE 24TH LOW-X MEETING

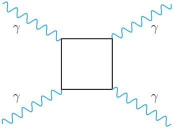
DIPHOTON PRODUCTION IN LEAD-LEAD (AND PROTON-PROTON) UPC

Mariola Kłusek-Gawenda

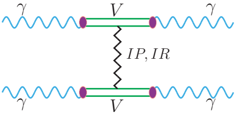
Institute of Nuclear Physics PAS Kraków

POLSKA AKADEMIA NAUK

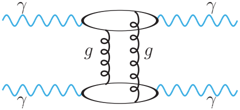
1. $\gamma\gamma \to \gamma\gamma$ scattering
   - box mechanism



   - VDM-Regge



   - 2-g exchange



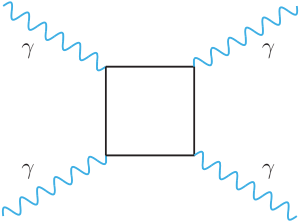
2. $AA \to AA\gamma\gamma$
3. $pp \to pp\gamma\gamma$
4. Conclusions

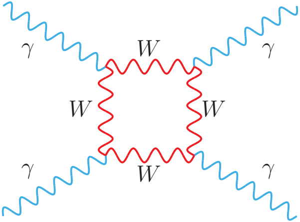
REFERENCES

1. M. K-G, P. Lebiedowicz and A. Szczurek,
   Light-by-light scattering in ultraperipheral Pb-Pb collisions at energies available at the CERN Large Hadron Collider,
   Phys.Rev. **C93** (2016) 044907
2. M. K-G, 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,
   arXiv:1606.01058 [hep-ph]

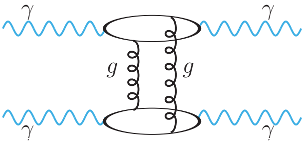
PHOTON-PHOTON ELASTIC SCATTERING

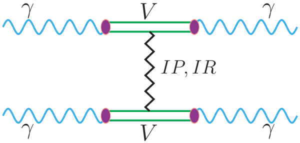
WELL KNOWN





NEW





BOXES

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

or

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

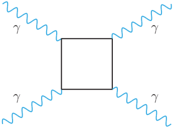
Including virtualities of initial photons

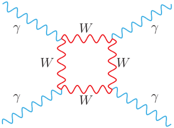
$$\mathcal{A} = \mathcal{A}_{TT} + \mathcal{A}_{TL} + \mathcal{A}_{LT} + \mathcal{A}_{LL}$$

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

$$\mathcal{A} \approx \mathcal{A}_{TT}\ .$$

BOXES





LO QED fermion box diagram cross section is well known (calculated with `FormCalc`).

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

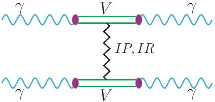
Inclusion of W boxes can be calculated with the `LoopTools`.

Our result was confronted with that by

- Jikia et al. (1993),
- Bern et al. (2001)
- 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.

VDM-REGGE COMPONENT



$$\mathcal{A}_{\gamma\gamma\to\gamma\gamma}(s,t) = \sum_i^3 \sum_j^3 C^2_{\gamma\to V_i} \mathcal{A}_{V_iV_j\to V_iV_j} C^2_{\gamma\to V_j}$$

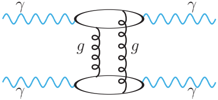
$$\approx \left(\sum_{i=1}^3 C^2_{\gamma\to V_i}\right) \mathcal{A}_{VV\to VV}(s,t) \left(\sum_{j=1}^3 C^2_{\gamma\to V_j}\right)$$

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

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

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

TWO-GLUON EXCHANGE

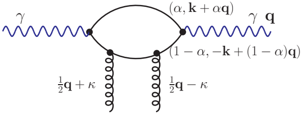


The altogether 16 diagrams result in the amplitude, which can be cast into the impact-factor representation:

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

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

- $\boldsymbol{q}$ - the transverse momentum transfer $t \approx -\boldsymbol{q}^2$
- m_G - 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 $\boldsymbol{\kappa} \to \pm\boldsymbol{q}/2$.

TWO-GLUON EXCHANGE

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

The explicit form of the impact factor:

$$\begin{aligned}\mathcal{J}^{(f)}(\gamma_\lambda\to\gamma_\tau;\boldsymbol{\kappa},\boldsymbol{q}) \quad &= \quad \sqrt{N_c^2-1}\;\frac{e_f^2\alpha_{\rm em}}{2\pi^2}\int_0^1 d\alpha\int\frac{d^2\boldsymbol{k}}{\boldsymbol{k}^2+m_f^2}\alpha_S(\mu^2)\\ &\times \quad \Big\{\delta_{\lambda\tau}\Big(m_f^2\,\Phi_2+\Big[\alpha^2+(1-\alpha)^2\Big]\,(\boldsymbol{k}\boldsymbol{\Phi}_1)\Big)\\ &+ \quad \delta_{\lambda,-\tau}2\alpha(1-\alpha)\Big((\boldsymbol{\Phi}_1\boldsymbol{n})(\boldsymbol{k}\boldsymbol{n})-[\boldsymbol{\Phi}_1,\boldsymbol{n}][\boldsymbol{k},\boldsymbol{n}]\Big)\Big\}\end{aligned}$$

Quark and antiquark share the large lightcone momentum of the incoming photon in fractions $\alpha, 1-\alpha$ respectively.
The helicity conserving part is easily obtained, after due change of the final state wave function, from the one used in the $\gamma\gamma\to J/\psi J/\psi$ process.

Also the helicity-flip piece can be obtained from the $\gamma\to V$ impact factors for vector meson final states.

$\mathbf{\Phi}_1, \Phi_2$ - shorthand notations for the momentum structures, corresponding to the four relevant Feynman diagrams:

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

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

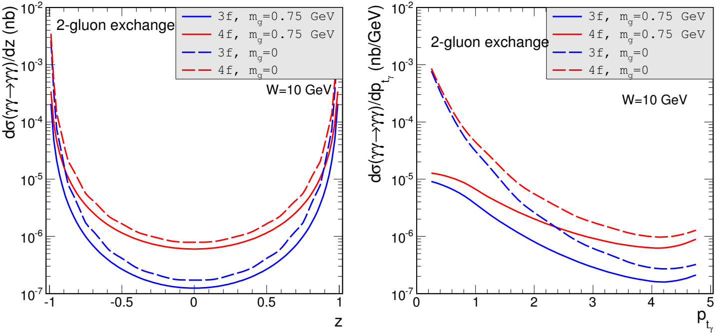
$$\boldsymbol{l} = \boldsymbol{k} + \left(\alpha - \frac{1}{2}\right)\boldsymbol{q}$$

The running scale of strong coupling constant for the evaluation of the two-gluon exchange cross section is taken as:

$$\mu^2 \;=\; \max\{\boldsymbol{\kappa}^2, \boldsymbol{k}^2 + m_Q^2, \boldsymbol{q}^2\} \,.$$

We freeze the running coupling in the infrared at a value of $\alpha_S \sim 0.8$.

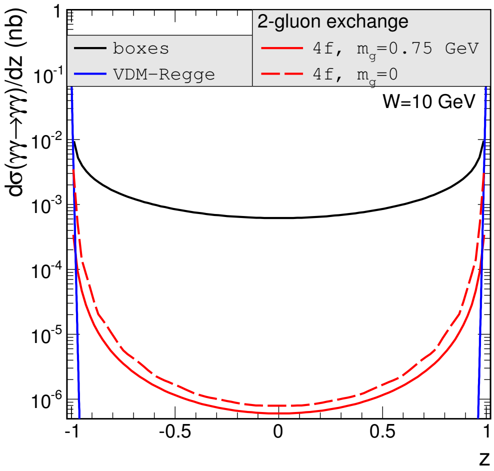
TWO-GLUON EXCHANGE MECHANISM, FIRST RESULTS



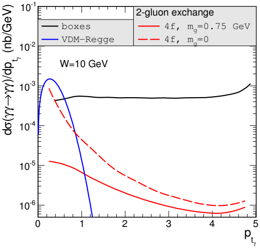
Huge effect of including charm at $z \approx 0$ (large p_{t_γ})

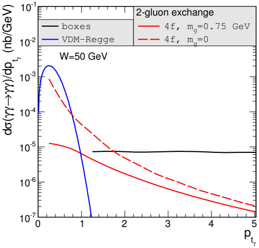
– interference effect

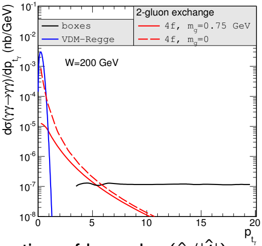
ELEMENTARY CROSS SECTION



ELEMENTARY CROSS SECTION



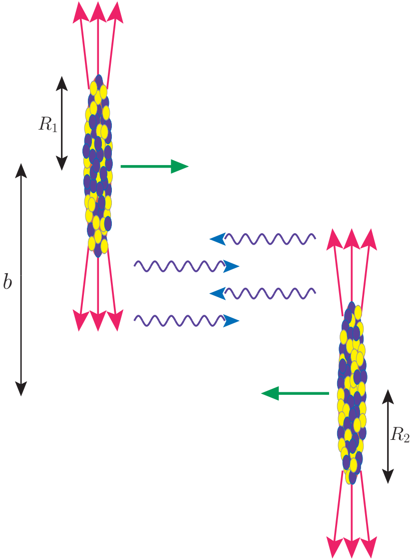




Future:

- theory - A BFKL resummation of large $\log(\hat{s}/|\hat{t}|)$ could lead to a substantial enhancement of the $\gamma\gamma \to \gamma\gamma$ elastic scattering
- experimentally - a $\gamma - \gamma$ collider (the International $e^+ e^-$ Linear Collider)

EQUIVALENT PHOTON APPROXIMATION

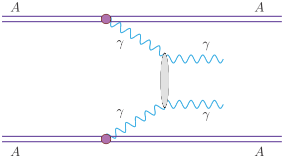


The strong electromagnetic field is a source of photons that induce electromagnetic reactions in ion-ion collisions.

ULTRAPERIHERAL COLLISIONS

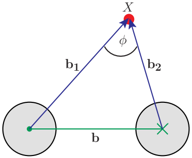
$$b > R_{min} = R_1 + R_2$$

NUCLEAR CROSS SECTION



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

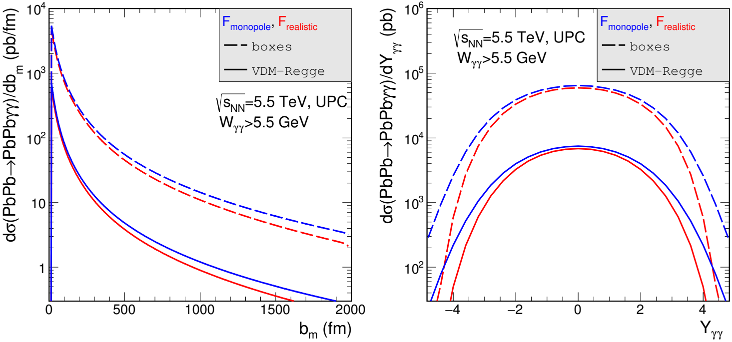
$$\begin{aligned}
\sigma_{A_1A_2\to A_1A_2X} &= \int \mathrm{d}\omega_1\, \mathrm{d}\omega_2\, n(\omega_1)\, n(\omega_2)\, \sigma_{\gamma\gamma\to X}(\omega_1, \omega_2) \\
&= \dots \\
&= \int N(\omega_1, \mathbf{b}_1)\, N(\omega_2, \mathbf{b}_2)\, S^2_{abs}(\mathbf{b}) \\
&\times\ \sigma_{\gamma\gamma\to X}\left(\sqrt{s_{\gamma\gamma}}\right) \\
&\times\ 2\pi b\,\mathrm{d}b\, \mathrm{d}\bar{b}_x\, \mathrm{d}\bar{b}_y\, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma}\, \mathrm{d}Y_X
\end{aligned}$$



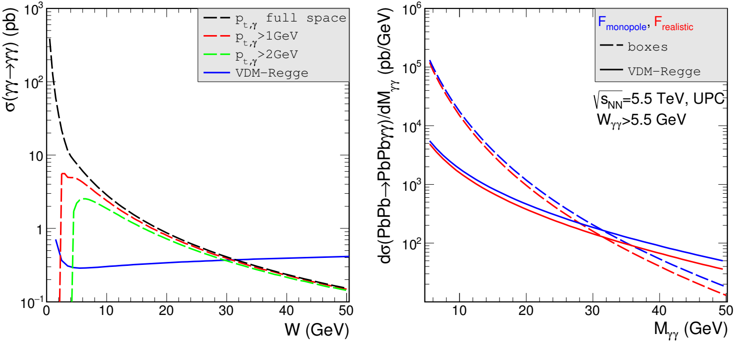
AA→AA$\gamma\gamma$ - FORM FACTOR

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

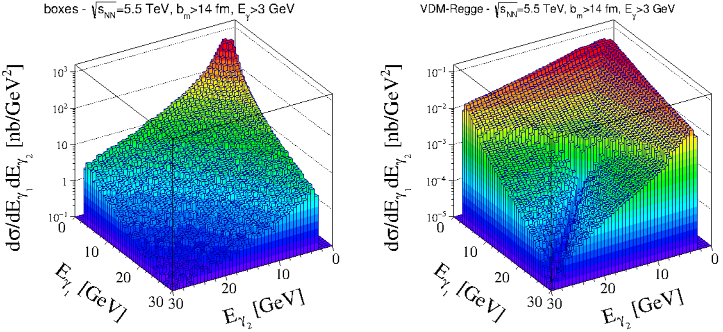
- realistic
- monopole



AA→AA$\gamma\gamma$

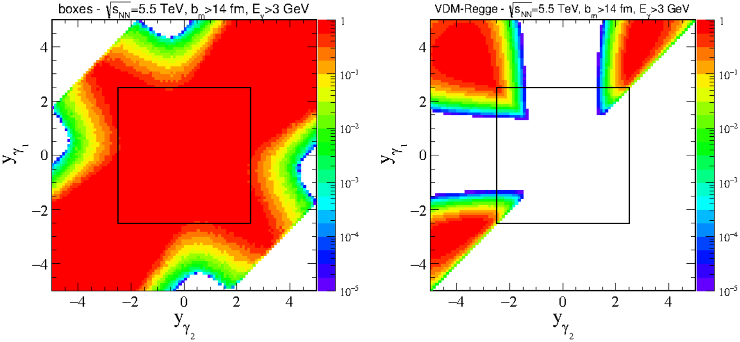


AA→AA$\gamma\gamma$ - DISTRIBUTIONS



Cross section strongly depends on the photon energy cuts

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



At midrapidity boxes dominate

The soft mechanism at large rapidities

Can it be measured with ZDC ?

May be difficult to measure.

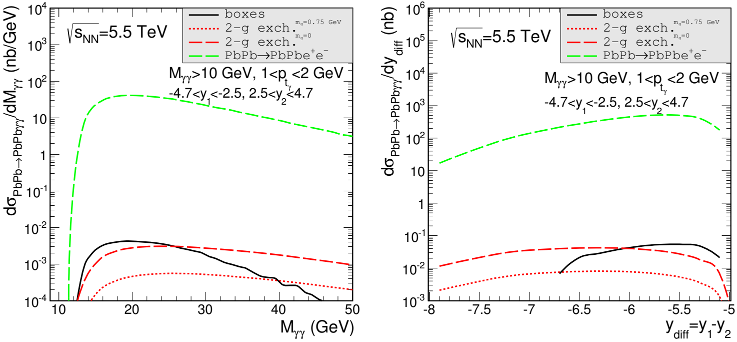
LOW-X 2016
MARIOLA K-G
PHOTON-PHOTON SCATTERING
BOXES
VDM-REGGE
2-GLUON EXCHANGE
NUCLEAR COLLISIONS
EPA - $\gamma\gamma$ FUSION
PROTON-PROTON COLLISIONS
CONSLUSIONS

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

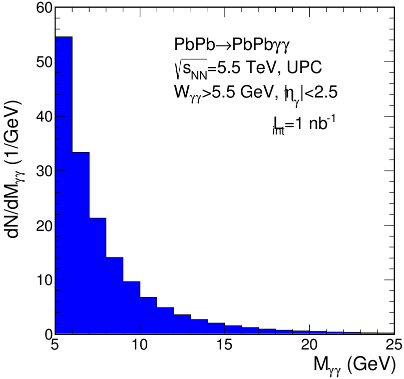
cuts	boxes		VDM-Regge	
	$F_{realistic}$	$F_{monopole}$	$F_{realistic}$	$F_{monopole}$
$W_{\gamma\gamma} > 5$ GeV	306	349	31	36
$W_{\gamma\gamma} > 5$ GeV, $p_{t,\gamma} > 2$ GeV	159	182	7E-9	8E-9
$E_{\gamma} > 3$ GeV	16 692	18 400	17	18
$E_{\gamma} > 5$ GeV	4 800	5 450	9	611
$E_{\gamma} > 3$ GeV, $\lvert y_{\gamma}\rvert < 2.5$	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	6 169		882	
$\sqrt{s}$ = 39 TeV, $E_{\gamma} > 3$ GeV	4 696 268		574	

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$\gamma\gamma$ (FCALS)



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



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

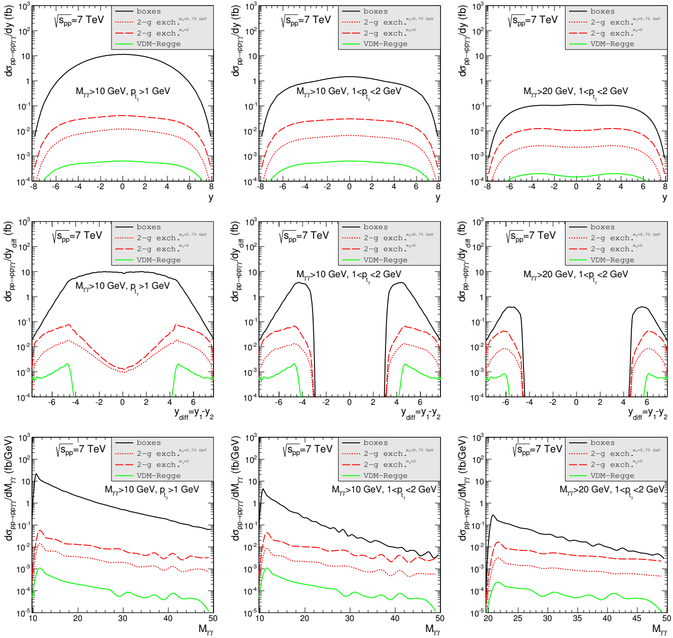
$pp \to pp\gamma\gamma$

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

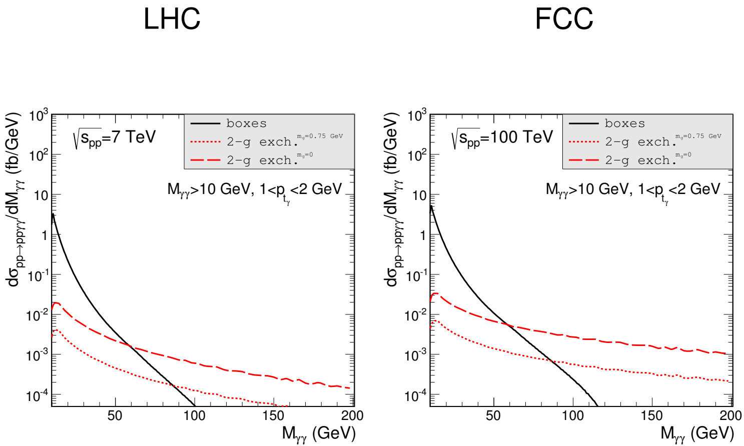
$$\frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} x_1\gamma^{(\mathrm{el})}(x_1) x_2\gamma^{(\mathrm{el})}(x_2) \overline{|\mathcal{M}_{\gamma\gamma\to\gamma\gamma}|^2} \, .$$

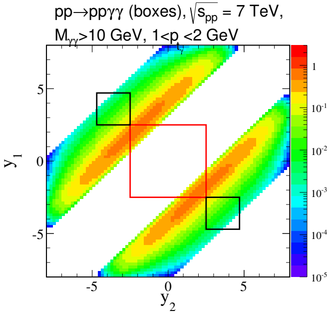
$$x_{1,2} = \frac{p_t}{\sqrt{s}}(\exp(\pm y_1) + \exp(\pm y_2))$$

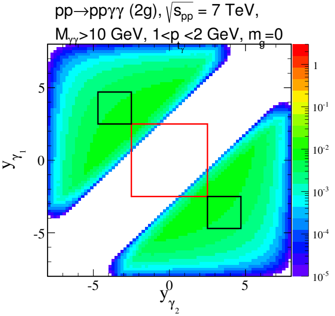
In practical calculations for elastic fluxes we shall use parametrization proposed by Drees-Zeppenfeld.
Only elastic-elastic contributions with forward protons considered here.

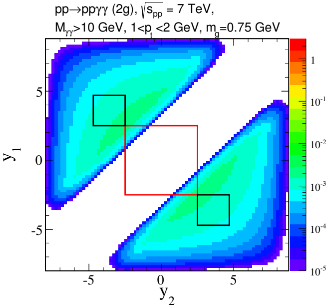

$\sqrt{s_{pp}}$=7 TeV
boxes
2-g exch. m_g=0.75 GeV
2-g exch. m_g=0
VDM-Regge
$M_{\gamma\gamma}$>10 GeV, p_{t_γ}>1 GeV
$M_{\gamma\gamma}$>10 GeV, 1<p_{t_γ}<2 GeV
$M_{\gamma\gamma}$>20 GeV, 1<p_{t_γ}<2 GeV
$d\sigma_{pp\to pp\gamma\gamma}/dy$ (fb)
$d\sigma_{pp\to pp\gamma\gamma}/dy_{diff}$ (fb)
$d\sigma_{pp\to pp\gamma\gamma}/dM_{\gamma\gamma}$ (fb/GeV)
y
$y_{diff}=y_1-y_2$
$M_{\gamma\gamma}$
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
-8
-6
-4
-2
0
2
4
6
8
10
20
25
30
35
40
45
50

$pp \to pp\gamma\gamma$

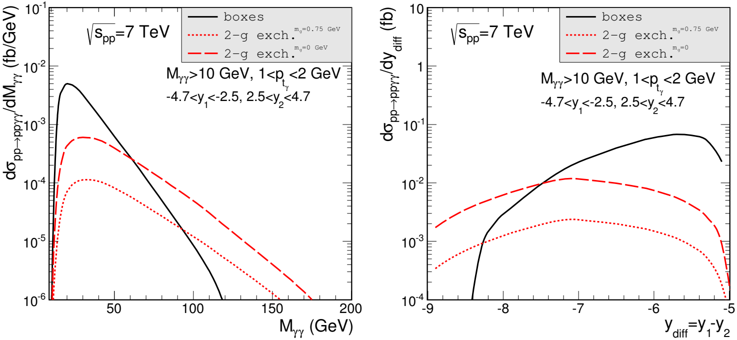



$pp \to pp\gamma\gamma$ (boxes), $\sqrt{s_{pp}}$ = 7 TeV,
$M_{\gamma\gamma}$>10 GeV, 1<p_{t_γ}<2 GeV
y_1
y_2
5
0
-5
-5
0
5
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}


$pp \to pp\gamma\gamma$ (2g), $\sqrt{s_{pp}}$ = 7 TeV,
$M_{\gamma\gamma}$>10 GeV, 1<p_{t_γ}<2 GeV, m_g=0
y_{γ_1}
y_{γ_2}
5
0
-5
-5
0
5
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}


$pp \to pp\gamma\gamma$ (2g), $\sqrt{s_{pp}}$ = 7 TeV,
$M_{\gamma\gamma}$>10 GeV, 1<p_t<2 GeV, m_g=0.75 GeV
y_1
y_2
5
0
-5
-5
0
5
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

$pp \to pp\gamma\gamma$



Limitation	Mechanism	$\sigma_{PbPb\to PbPb\gamma\gamma}$ [nb]	$\sigma_{pp\to pp\gamma\gamma}$ [fb]
$M_{\gamma\gamma} > 10$ GeV,	boxes	7.307	12.524
1 GeV $< p_{t_\gamma} <$ 2 GeV,	2g-exch. ($m_g = 0$)	1.234	0.317
$-8 < y_1 < 8$,	2g-exch. ($m_g = 0.75$ GeV)	0.260	0.067
$-8 < y_2 < 8$	$PbPb \to PbPbe^+e^-$	46 474.000	
$M_{\gamma\gamma} > 10$ GeV,	boxes	0.063	0.105
1 GeV $< p_{t_\gamma} <$ 2 GeV,	2g-exch. ($m_g = 0$)	0.092	0.027
$-4.7 < y_1 < -2.5$,	2g-exch. ($m_g = 0.75$ GeV)	0.017	0.005
$2.5 < y_1 < 4.7$	$PbPb \to PbPbe^+e^-$	763.000	

Integrated cross section for the $\gamma\gamma$ production in lead-lead and proton-proton collisions for LHC energy $\sqrt{s_{NN}} = 5.5$ TeV and $\sqrt{s_{pp}} = 7$ TeV.

CONCLUSIONS

- Detailed analysis of the $\gamma\gamma \to \gamma\gamma$ (quasi)elastic scattering in nucleus-nucleus and proton-proton collisions at the LHC
- 3 subprocesses included:
  - Box contributions (known for some time)
  - Soft VDM Regge contribution (new, for a 1^{st} time)
  - 2-gluon exchange contribution (NEW, for a 1^{st} 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.
- 3 subprocesses almost separate in the phase space.
- Both CMS and ATLAS will study this (we are in contact)

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).
- BFKL effects would increase the cross section.

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).

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

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