New theoretical results in ultrarelativistic ultraperipheral lead-lead collisions

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The 17th conference on Elastic and Diffractive scattering, EDS Blois 2017

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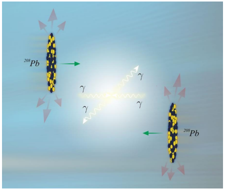

Photon physics in UPC

EPA

Double l^+l^- pair production

Photon-photon scattering

Proton-antiproton production

Conclusions

1. M. K-G, P. Lebiedowicz, A. Szczurek,
   Light-by-light scattering in ultraperipheral Pb-Pb collisions at energies available at the CERN Large Hadron Collide,
   Phys. Rev. **C93** (2016) 044907,
2. M. K-G, W. Schäfer, 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,
3. M. K-G, A. Szczurek,
   Double scattering production of two positron–electron pairs in ultraperipheral heavy-ion collisions,
   Phys. Lett. **B763** (2016) 416,
4. A. van Hameren, M. K-G, A. Szczurek,
   From the Single and double scattering production of four muons in ultraperipheral Pb-Pb collisions at the Large Hadron Collider,
   in preparation,
5. M. K-G, P. Lebiedowicz, O. Nachtmann, A. Szczurek,
   From the $\gamma\gamma \to p\bar{p}$ reaction to the production of $p\bar{p}$ pairs in ultraperipheral ultrarelativistic heavy-ion collisions at the LHC,
   in preparation.

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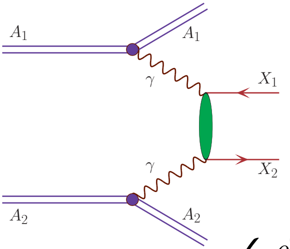
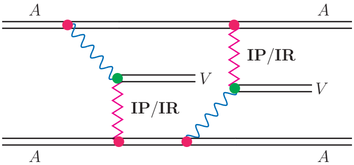
PHOTON PHYSICS IN UPC



vs. our predictions



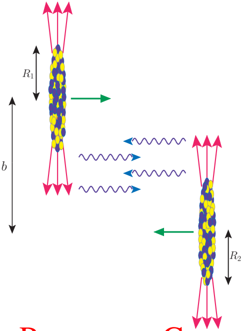
- ✓ ρ^0, J/ψ

- ✓ $\rho^0\rho^0$, $J/\psi J/\psi$
- ✓ $\pi^+\pi^-$, $\pi^0\pi^0$
- ✓ $c\bar{c}$, $b\bar{b}$
- ✓ e^+e^-, $\mu^+\mu^-$
- ✓ $\gamma\gamma$
- ✓ $p\bar{p}$

- ✓ $\pi^+\pi^-\pi^+\pi^-$
- ✓ $e^+e^-e^+e^-$
- ✓ $\mu^+\mu^-\mu^+\mu^-$

ALICE, ATLAS, CMS (^{208}Pb+^{208}Pb @ $\sqrt{s_{NN}} = 2.76, 3.5, 5.02, 5.5$ TeV)

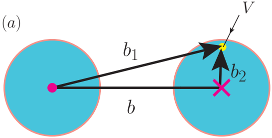
Equivalent Photon Approximation



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

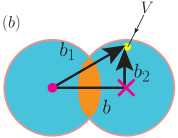
UltraPeriheral Collisions

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

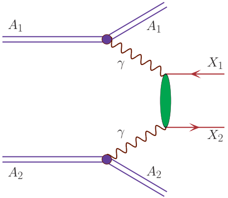


semi-CENTRAL Collisions

$$b \leq R_{min}$$



NUCLEAR CROSS SECTION



$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \dots$$

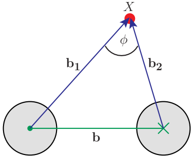
NAIVELY $\Rightarrow$ ...

$$= \int \mathrm{d}\omega_1 \, \mathrm{d}\omega_2 \, n(\omega_1) n(\omega_2) \times \sigma_{\gamma\gamma \to X_1 X_2}(\omega_1, \omega_2)$$

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

MORE CORRECTLY $\Rightarrow$ ...

$$= \int N(\omega_1, \mathbf{b_1}) \, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \times \sigma_{\gamma\gamma \to X_1 X_2}(W_{\gamma\gamma}) \times 2\pi b \mathrm{d}b \, \mathrm{d}\overline{b}_x \, \mathrm{d}\overline{b}_y \, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma} \, \mathrm{d}Y_{\gamma\gamma}$$



PHOTON FLUX & FORM FACTOR

✗ charge distribution in nucleus

$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times \left| \int \mathrm{d}\chi \, \chi^2 \frac{F\left(\frac{\chi^2 + u^2}{b^2}\right)}{\chi^2 + u^2} J_1(\chi) \right|^2$$

$$\beta = \frac{p}{E}, \gamma = \frac{1}{\sqrt{1-\beta^2}}, u = \frac{\omega b}{\gamma \beta}, \chi = k_\perp b$$

- point-like $F(\mathbf{q}^2) = 1$

$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times u^2 \left[K_1^2(u) + \frac{1}{\gamma^2} K_0^2(u) \right]$$

- monopole $F(\mathbf{q}^2) = \frac{\Lambda^2}{\Lambda^2 + |\mathbf{q}|^2}$

$$\sqrt{\langle r^2 \rangle} = \sqrt{\frac{6}{\Lambda^2}} = 1 \text{ fm } A^{1/3}$$

FORM FACTOR

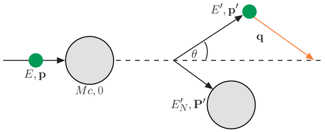


FIG. : Elastic scattering of electron-nucleus

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NEW THEORETICAL RESULTS IN UPC

γ PHYSICS IN UPC

EPA

THEORY

FORM FACTOR

DOUBLE l^+l^- PAIR PRODUCTION

PHOTON-PHOTON SCATTERING

PROTON-ANTIPROTON PRODUCTION

CONCLUSIONS

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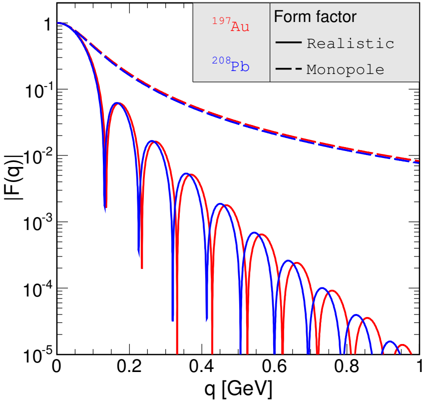
FORM FACTOR

- realistic charge distribution

$$F\left(\mathbf{q}^2\right) = \frac{4\pi}{|\mathbf{q}|} \int \rho\left(r\right) \sin\left(|\mathbf{q}|\, r\right) r \mathrm{d}r$$



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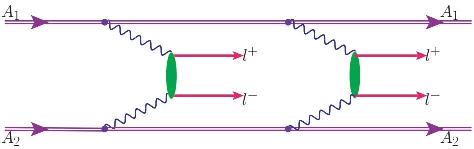
1. FOUR-LEPTON PRODUCTION



$$\sigma_{A_1A_2\to A_1A_2l^+l^-} = \int P_{\gamma\gamma\to l^+l^-}(b)\,\mathrm{d}^2b$$

$$\frac{\mathrm{d}\sigma_{A_1A_2\to A_1A_2l^+l^-}}{\mathrm{d}y_+\mathrm{d}y_-\mathrm{d}p_t} = \int \frac{\mathrm{d}P_{\gamma\gamma\to l^+l^-}(b;y_+,y_-,p_t)}{\mathrm{d}y_+\mathrm{d}y_-\mathrm{d}p_t}\mathrm{d}^2b$$

$$\frac{\mathrm{d}\sigma_{A_1A_2\to A_1A_2l_1^+l_2^-l_3^+l_4^-}}{\mathrm{d}y_1\mathrm{d}y_2\mathrm{d}y_3\mathrm{d}y_4} = \frac{1}{2}\int \frac{\mathrm{d}P_{\gamma\gamma\to l^+l^-}(b;y_1,y_2,p_{t,min})}{\mathrm{d}y_1\mathrm{d}y_2} \times \frac{\mathrm{d}P_{\gamma\gamma\to l^+l^-}(b;y_3,y_4,p_{t,min})}{\mathrm{d}y_3\mathrm{d}y_4}\,\mathrm{d}^2b$$

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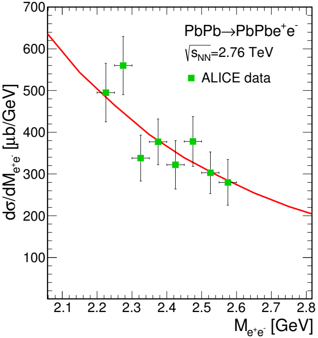
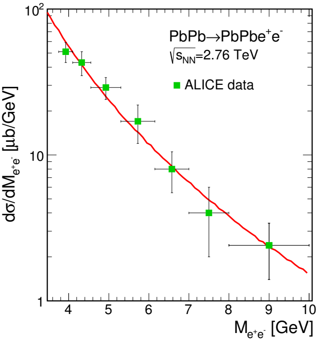
$AA \to AAe^+e^-$ - CALCULATIONS VS. DATA

- ALICE Collaboration (Abbas, E. et al.), *Charmonium and e^+e^- pair photoproduction at mid-rapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Eur. Phys. J. **C73** (2013) 2617

$2.2\ \text{GeV} < M_{ee} < 2.6\ \text{GeV}$ | $|y_e| < 0.9$ | $3.7\ \text{GeV} < M_{ee} < 10\ \text{GeV}$





Good description of single pair production ⇒ two l^+l^- pair production

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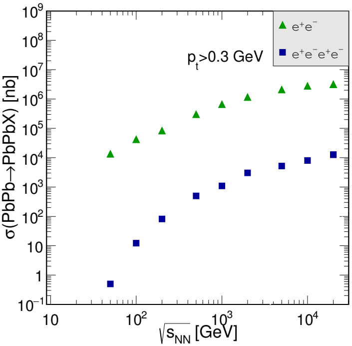
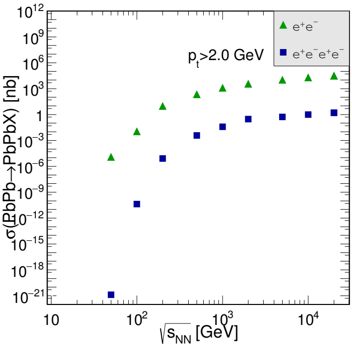
$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

$p_t > 0.3$ GeV



$p_t > 2.0$ GeV



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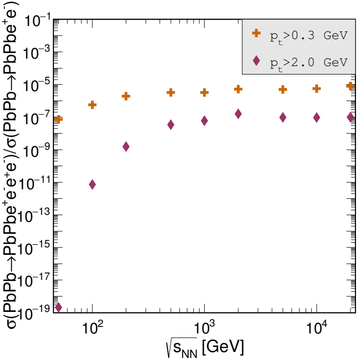
$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

$$\frac{\sigma_{AA\to AAe^+e^-e^+e^-}}{\sigma_{AA\to AAe^+e^-}}$$



Ratio depends on $\sqrt{s_{NN}}$ and $p_{t,min}$

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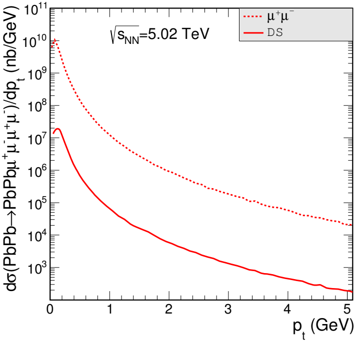
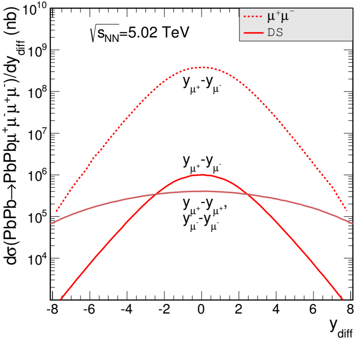
$AA \to AA\mu^+\mu^-$ & $AA \to AA\mu^+\mu^-\mu^+\mu^-$

$p_{t,\mu}$

y_{diff}





Similar like for electron-positron production: $\sigma_{\mu^+\mu^-} \simeq 1000 \times \sigma_{\mu^+\mu^-\mu^+\mu^-}$

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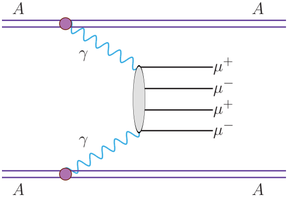
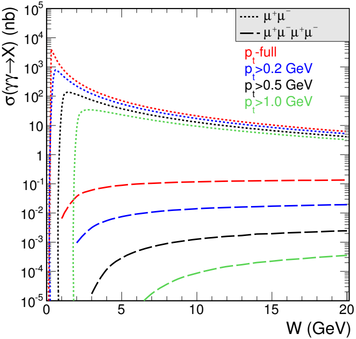
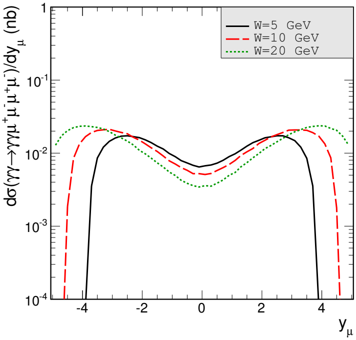
$\gamma\gamma \to \mu^+\mu^-\mu^+\mu^-$ - SINGLE SCATTERING

$\Uparrow$

A. van Hameren approach







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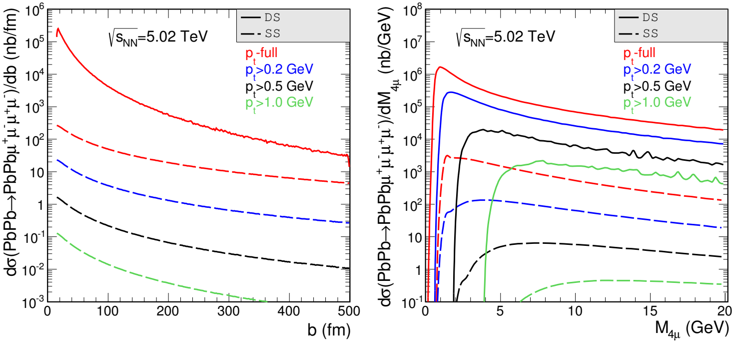
$AA \to AA\mu^+\mu^-\mu^+\mu^-$

impact parameter

$W_{\gamma\gamma} = M_{4\mu}$



↑ purely theoretical distribution

↑ DS "strongly" dominates

It is difficult to isolate range of SS domination

*DS - double-scattering mechanism
*SS - a NEW single-scattering mechanism

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NEW THEORETICAL RESULTS IN UPC

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DOUBLE l^+l^- PAIR PRODUCTION

PHOTON-PHOTON SCATTERING

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CONCLUSIONS

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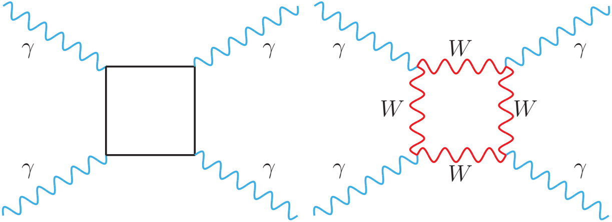
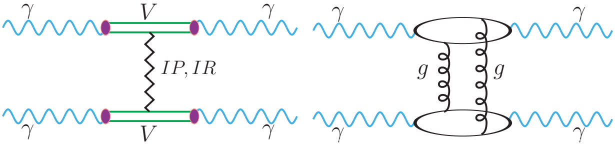
2. $\gamma - \gamma$ ELASTIC SCATTERING

WELL-KNOWN



WE ADD



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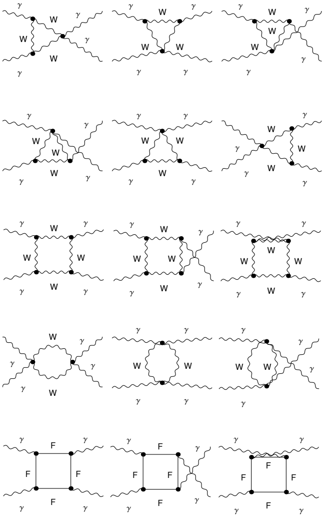
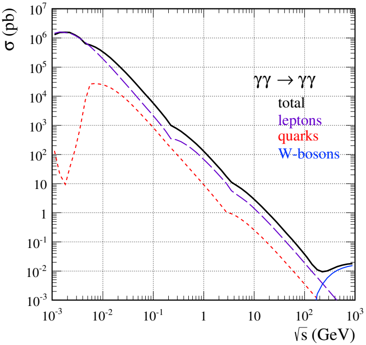
BOXES $\gamma\gamma \to \gamma\gamma$



Fermionic box LO QED - `FormCalc`.

The one-loop W box diagram - `LoopTools`.

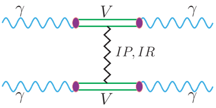


We have compared our results with:

- Jikia et al. (1993),
- Bern et al. (2001),
- Bardin et al. (2009).

Bern et al. consider 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 CONTRIBUTION



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

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

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

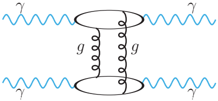
$$\mathcal{A}_{VV\to VV}(s,t) = \mathcal{A}(s,t)\exp\left(\frac{B}{2}t\right)$$

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

- $C^2_{\gamma\to V_i} = \frac{e}{f_{V_i}}$
- $C_{\mathbf{P}}$, $C_{\mathbf{R}}$ - Donnachie-Landshoff
- $\alpha_{\mathbf{R}}(t)$, $\alpha_{\mathbf{P}}(t)$ - trajectories

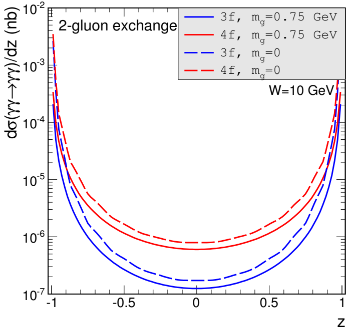
2-GLUON EXCHANGE

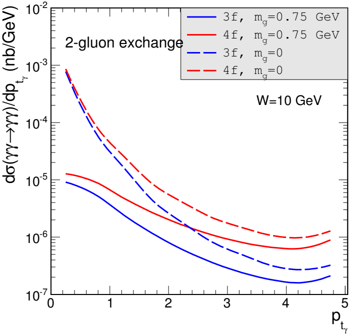
16 diagrams $\Rightarrow$



$z = \cos\theta$; θ - scattering $\sphericalangle$

$p_{t_\gamma} = p \sin\theta$





3f = u ,d, s

4f = u, d, s, c

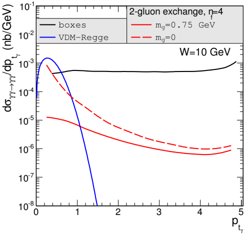
$m_u \simeq 0.15$ GeV
$m_d \simeq 0.15$ GeV
$m_s \simeq 0.30$ GeV
$m_c \simeq 1.50$ GeV

Significant effect of c quark inclusion at $z \approx 0$ (large p_{t_γ}) - interference

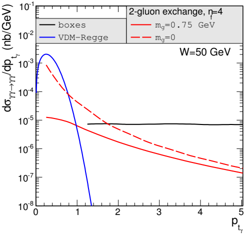
EXPERIMENTAL IDENTIFICATION OF PROCESSES?

- ✔ boxes
- ✔ VDM-Regge
- ✔ 2-gluon exchange

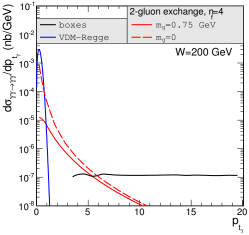
$W = 10$ GeV



$W = 50$ GeV

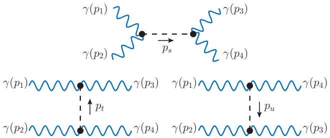


$W = 200$ GeV

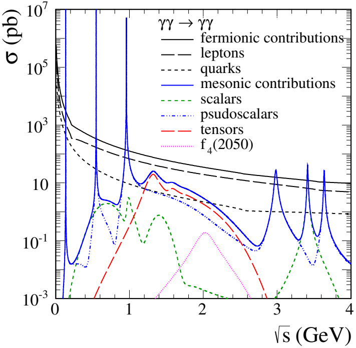


$\gamma - \gamma$ Collider (the International e^+e^- Linear Collider) ?

MESON EXCHANGE



π^0	$f_0(500)$	$f_2(1270)$	
η	$f_0(980)$	$a_2(1320)$	
$\eta'(958)$	$a_0(980)$	$f_2'(1525)$	$f_4(2050)$
$\eta_c(1S)$	$f_0(1370)$	$f_2(1565)$	
$\eta_c(2S)$	$\chi_{c0}(1P)$	$a_2(1700)$	



$s-$channel diagrams (leading to peaks at $\sqrt{s} \cong m_M$)

$t-$ and $u-$channels (leading to broad continua)

- P. Lebiedowicz, A. Szczurek,
  The role of meson exchanges in light-by-light scattering,
  arXiv:1705.06535 [hep-ph], Phys. Lett. B - in print

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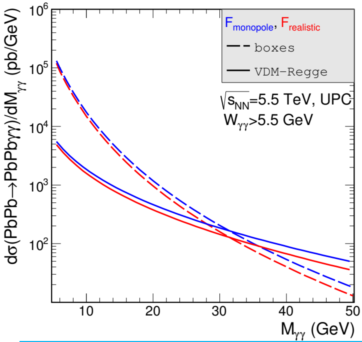
AA→AA$\gamma\gamma$ - FORM FACTOR

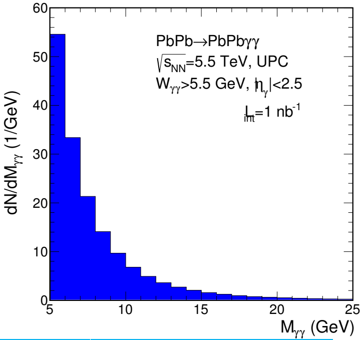
⇨ realistic

⇨ monopole

$W_{\gamma\gamma} = M_{\gamma\gamma}$

number of count





↑ VDM-Regge dominates for $W_{\gamma\gamma} > 30$ GeV

↑ several events / GeV

$\frac{\sigma_{monopole}}{\sigma_{realistic}} \nearrow$ for larger values of kinematic variables

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$AA \to AA\gamma\gamma$ - TOTAL CROSS SECTION [NB]

EXCLUSIVE PRODUCTION OF PHOTON PAIRS; UPC

at LHC ($\sqrt{s_{NN}} = 5.5$ TeV) and FCC ($\sqrt{s_{NN}} = 39$ TeV)

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	

$\Rightarrow$ $\sigma = 306$ nb

- D. d'Enterria and G. G. da Silveira, *Observing light-by-light scattering at the Large Hadron Collider*, Phys. Rev. Lett. 111 (2013) 080405 $\Rightarrow$ $\sigma = 35 \pm 7$ nb

  Erratum: Phys. Rev. Lett. 116 (2016) 129901 $\Rightarrow$ $\sigma = 370 \pm 70$ nb

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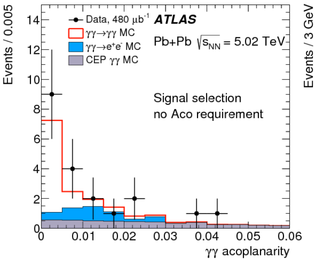
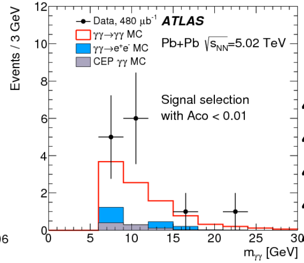
AA→AA$\gamma\gamma$ - THEORETICAL PREDICTIONS VS. EXPERIMENT

➢ ATLAS Collaboration (Aaboud, Morad et al.),
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC,
arXiv:1702.01625 [hep-ex], CERN-EP-2016-316





M. Guzik talk

✗ $p_{t_\gamma} > 3$ GeV
✗ $|\eta_\gamma| < 2.4$
✗ $M_{\gamma\gamma} > 6$ GeV
✗ $p_{t_{\gamma\gamma}} < 2$ GeV
✗ Aco < 0.01

✔ $\gamma\gamma \to \gamma\gamma$ - using our calculations

✔ background:
- ✔ $\gamma\gamma \to e^+e^-$
- ✔ $gg \to \gamma\gamma$
- ✔ $\gamma\gamma \to q\bar{q}$

✔ 13 events were observed

ATLAS ⇒ $\sigma = 70 \pm 20$(stat.)± 17(syst.) nb

from ours model ⇒ $\sigma = 49 \pm 10$ nb

PRL (2013)/(2016) ⇒ $\sigma = 45 \pm 9$ nb

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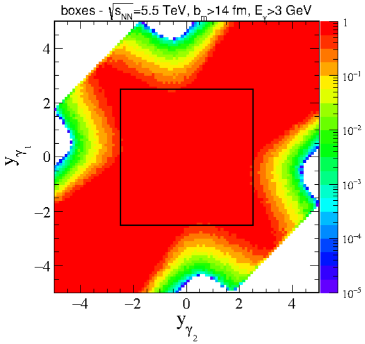
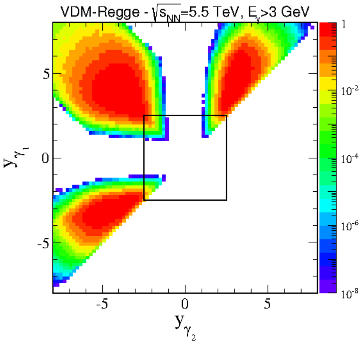
AA→AAγγ - correlation in rapidity

boxes



↑ dominates in midrapidity

VDM-Regge - t-channel



↑ larger y_γ

- ATLAS $|\eta| > 8.3$
- CMS $|\eta| > 8.5$

ZDC ?

VDM-Regge can be difficult to measure...

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AA→AA$\gamma\gamma$ - FCALs REGION

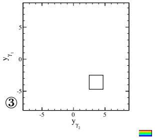
- ✔ boxes
- ✔ 2-gluon exchange
- ✔ background

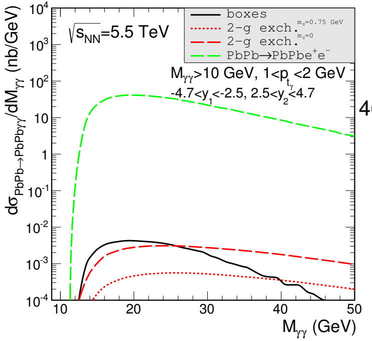
$W_{\gamma\gamma} = M_{\gamma\gamma}$

① $M_{\gamma\gamma} > 10$ GeV

② $p_{t_\gamma} = (1, 2)$ GeV

③ $y_{1/2} = (-8, 8)$





σ [nb]		σ [nb]
7.307	boxes	0.063
1.234	$m_g = 0$	0.092
0.260	$m_g = 0.75$ GeV	0.017
46 474.000	e^+e^-	763.000

Small probability to distinguish photons from electrons in FCALs.

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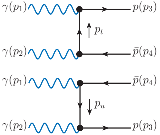
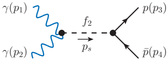
3. PROTON-ANTIPROTON PAIR PRODUCTION

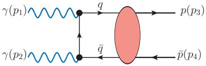
$$\gamma(p_1,\lambda_1) + \gamma(p_2,\lambda_2) \to p(p_3,\lambda_3) + \bar{p}(p_4,\lambda_4)$$



$$\mathcal{M}^{p-exchange}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} = (-i)\,\epsilon_{1\mu}(\lambda_1)\epsilon_{2\nu}(\lambda_2)$$
$$\times\,\bar{u}(p_3,\lambda_3)\Big(i\Gamma^{(\gamma pp)\,\mu}(p_3,p_t)\,\frac{i(\not{p}_t+m_p)}{t-m_p^2+i\epsilon}\,i\Gamma^{(\gamma pp)\,\nu}(p_t,-p_4)$$
$$+i\Gamma^{(\gamma pp)\,\nu}(p_3,p_u)\,\frac{i(\not{p}_u+m_p)}{u-m_p^2+i\epsilon}\,i\Gamma^{(\gamma pp)\,\mu}(p_u,-p_4)\Big)\,v(p_4,\lambda_4)$$



$$\mathcal{M}^{f_2(1270),f_2(1950)}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} = (-i)\,\epsilon_{1\mu}(\lambda_1)\,\epsilon_{2\nu}(\lambda_2)\,i\Gamma^{(f_2\gamma\gamma)\,\mu\nu\kappa\lambda}(p_1,p_2)\,i\Delta^{(f_2)}_{\kappa\lambda,\alpha\beta}(p_s)$$
$$\times\,\bar{u}(p_3,\lambda_3)i\Gamma^{(f_2 p\bar{p})\,\alpha\beta}(p_3,p_4)\,v(p_4,\lambda_4)$$



➢ M. Diehl, P. Kroll, and C. Vogt, *Two-photon annihilation into baryon anti-baryon pairs*, Eur. Phys. J. **C26** (2003) 567

Free parameters: off-shell form factors, the coupling constants.

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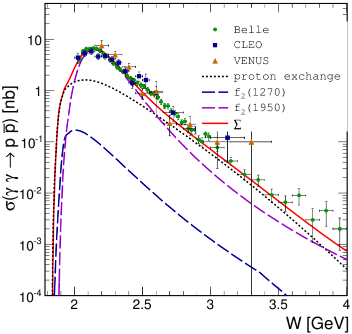
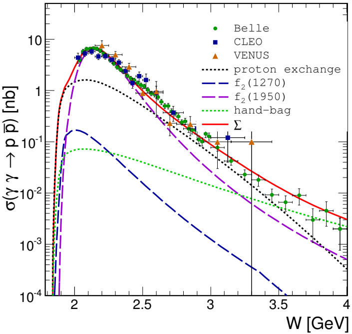
$\gamma\gamma \to p\bar{p}$ - RESULTS VS. DATA

$|\cos\theta| < 0.6$

$+$ hand-bag model





Good description of $\sigma(W)$ data $\Rightarrow \frac{d\sigma}{dz}$?

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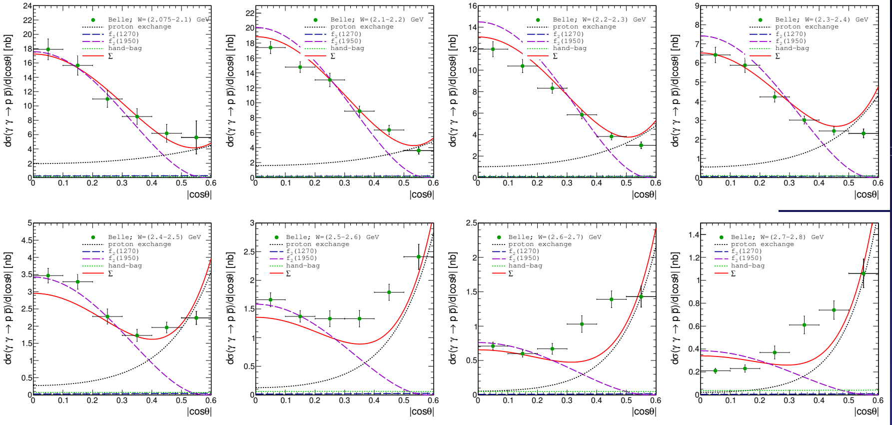
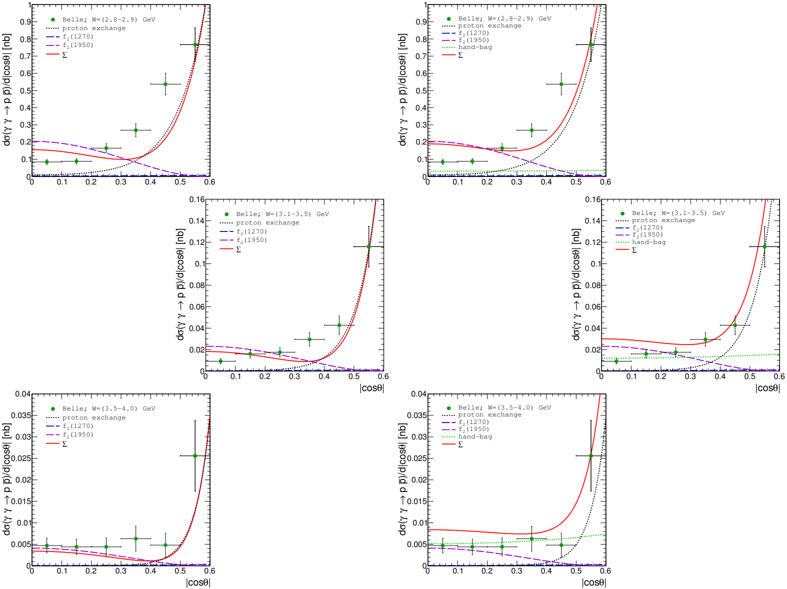
Angular distributions



without hand-bag

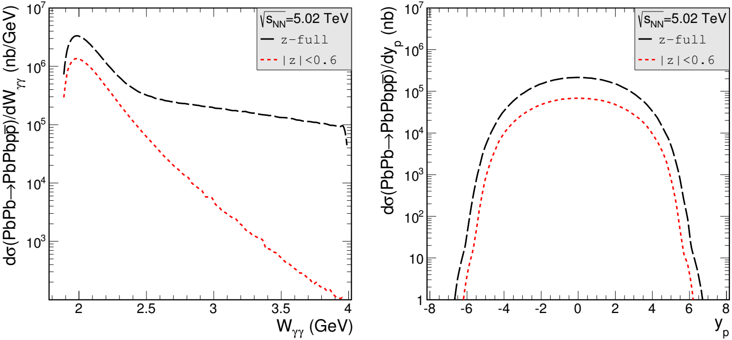
with hand-bag model



$AA \to AAp\bar{p}$ PRELIMINARY RESULTS

$W_{\gamma\gamma} = M_{p\bar{p}}$

y_p



Cross section $\sim$ mb

Can be studied by ALICE, ATLAS, CMS group?

CONCLUSIONS

- EPA in the impact parameter space
- Realistic charge distribution in the nucleus
- Calculations for ultrarelativistic heavy-ion collisions
- 4-leptons production
  - DS mechanism for $e^+e^-e^+e^-$ production: σ_{tot} very strongly depends on $p_{t,min}$ or y_e range
  - DS and (a new) SS mechanism for $\mu^+\mu^-\mu^+\mu^-$ production: it is difficult to isolate a region where SS dominates
  - $\sigma_{AA \to AA l^+ l^-} \cong 1000 \times \sigma_{AA \to AA l^+ l^- l^+ l^-}$
- Light-by-light scattering
  - 4 subprocesses (only boxes are important for experimental limitations for nuclear collisions)
  - we get measurable cross section
  - our predictions are compatible with ATLAS result
- Proton-antiproton production
  - 4 subprocesses (good agreement with Belle data)
  - Nuclear cross section $\sim$ mb

THANK YOU

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