Light-by-light scattering
- an ongoing challenge for theory (forward rapidity) and experiment (low invariant mass)

Mariola Kłusek-Gawenda

Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

✓ 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,

✓ 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*, Phys. Lett. **B761** (2016) 399,

✓ M. K-G, R. McNulty, R. Schicker and A. Szczurek, *Light-by-light scattering in ultraperipheral heavy-ion collisions at low diphoton masses*, Phys. Rev. **D99** (2019) 9, 093013,

✓ Z. Citron, M. K-G et al., *Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams*, CERN Yellow Rep. Monogr. 7 (2019) 1159-1410, Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC,

✓ G.K. Krintiras, I. Grabowska-Bold, M. K-G, É. Chapon, R. Chudasama, and R. Granier de Cassagnac, *Light-by-light scattering cross-section measurements at LHC*, arXiv:2204.02845 [hep-ph], $\eta_b(1S)$,

✓ FoCal.

Diffraction and Low-x

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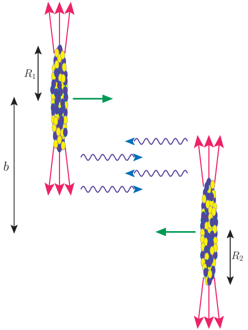
Equivalent Photon Approximation



The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.
Electromagnetism is a long-range force, so electromagnetic interactions occur even at relatively large ion-ion separations.

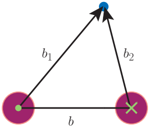
Photon energy: $\omega = \frac{\gamma}{b} \approx \gamma \times 15$ MeV

Virtuality: $Q^2 = \frac{1}{R^2} \approx 0.0008$ GeV^2

$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \int \sigma_{\gamma\gamma \to X_1 X_2}\left(W_{\gamma\gamma}\right) N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2})\, S^2_{abs}(\mathbf{b})\, \frac{W_{\gamma\gamma}}{2}\, \mathrm{d}W_{\gamma\gamma}\, \mathrm{d}Y_{X_1 X_2}\, \mathrm{d}\bar{b}_x\, \mathrm{d}\bar{b}_y\, \mathrm{d}^2 b$$

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

$$\times \frac{\mathrm{d}\cos\theta}{\mathrm{d}y_{X_1}\, \mathrm{d}y_{X_2}\, \mathrm{d}p_t} \times dy_{X_1}\, dy_{X_2}\, dp_t\ .$$



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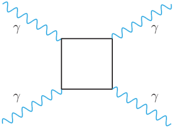
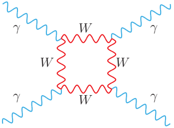
LIGHT-BY-LIGHT SCATTERING

Boxes | **WELL-KNOWN**



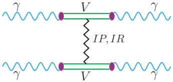


Fermionic boxes (LO QED) | *W* Box

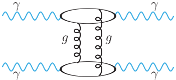
FormCalc. LoopTools.

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

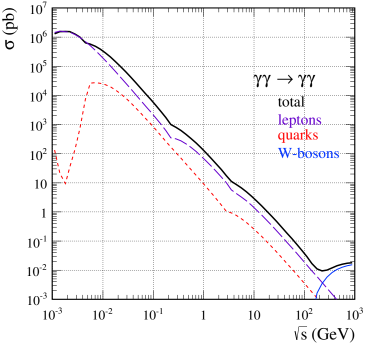
VDM-Regge | **WE ADD** | **2-gluon exch.**



fluctuation of γ
into virtual ρ, ω, ϕ



formally 3-loops



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.

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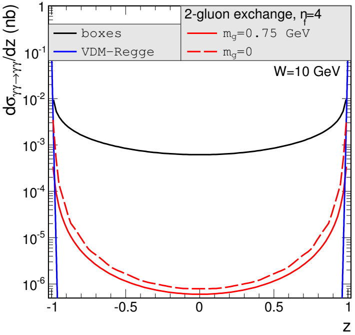
ELEMENTARY CROSS SECTION

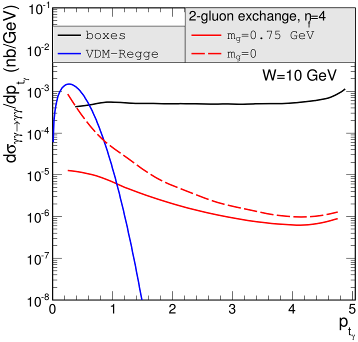
- ✔ boxes
- ✔ VDM-Regge
- ✔ 2-gluon exchange

$W = 10$ GeV

$z = \cos\theta$

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





$\theta = \frac{\pi}{2}$ - boxes , large z (low p_{t_γ}) - VDM-Regge.

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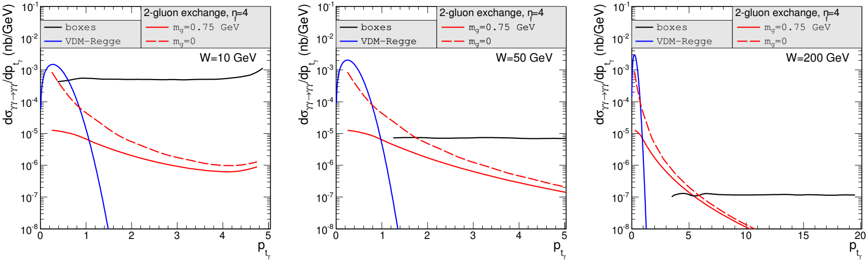
- ✔ Boxes
- ✔ VDM-Regge
- ✔ 2-gluon exchange

$W = 10$ GeV $W = 50$ GeV $W = 200$ GeV



EXPERIMENTAL IDENTIFICATION: e^+e^- Linear Collider ?

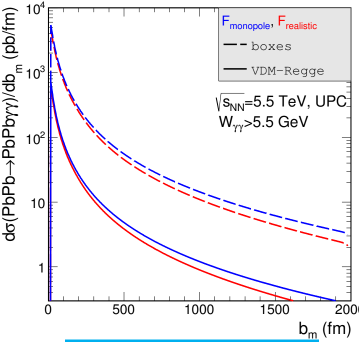
AA→AA$\gamma\gamma$ - FORM FACTOR

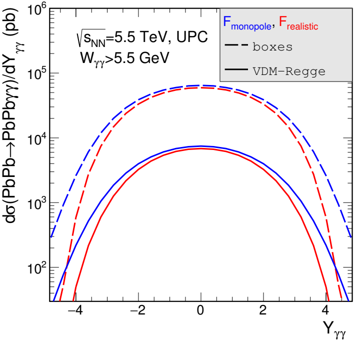
⇨ realistic

⇨ monopole

impact parameter

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





↑ theoretical distribution

$Y_{\gamma\gamma} \neq y_\gamma$

$\frac{\sigma_{monopole}}{\sigma_{realistic}}$ ↗ for larger value of kinematical variables

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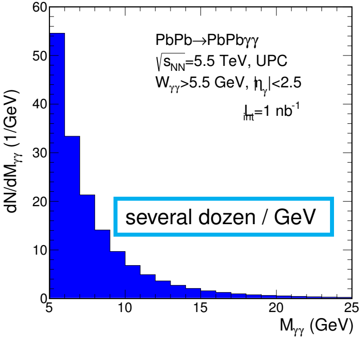
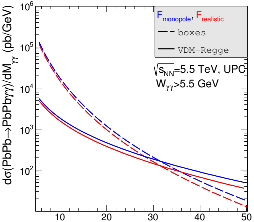


$W_{\gamma\gamma} = M_{\gamma\gamma}$



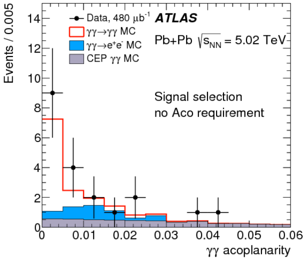
VDM-Regge dominates for $W_{\gamma\gamma} > 30$ GeV

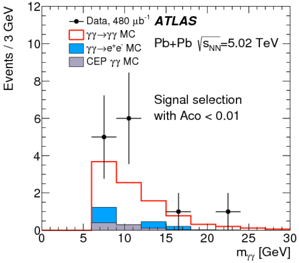
σ(PbPb→PbPb$\gamma\gamma$) [nb] @ LHC ($\sqrt{s_{NN}} = 5.5$ TeV)

	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
L	$E_\gamma > 3$ GeV	16 692	18 400	17	18
	$E_\gamma > 5$ GeV	4 800	5 450	9	611
H	$E_\gamma > 3$ GeV, $\|y_\gamma\| < 2.5$	183	210	8E-2	9E-2
	$E_\gamma > 5$ GeV, $\|y_\gamma\| < 2.5$	54	61	4E-4	7E-4
C	$p_{t,\gamma} > 0.9$ GeV, $\|y_\gamma\| < 0.7$ (ALICE cuts)	107			
	$p_{t,\gamma} > 5.5$ GeV, $\|y_\gamma\| < 2.5$ (CMS cuts)	10			

AA→AA$\gamma\gamma$ - ATLAS results

➢ ATLAS Collaboration (M. Aaboud et al.),
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC,
Nature Phys. **13** (2017) 852
Phys. Rev. Lett. **123** (2019) 052001





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

- ✔ $\gamma\gamma \to \gamma\gamma$ - Our results
- ✔ background:
  - ✔ $\gamma\gamma \to e^+e^-$
  - ✔ $gg \to \gamma\gamma$
  - ✔ $\gamma\gamma \to q\bar{q}$
- ✔ 13 events
  59 events (2019)*

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

(2019)* ⇒ $\sigma = 78 \pm 13$(stat.)± 7(syst.)± 3(lumi.) nb

Our result ⇒ $\sigma = 51 \pm 0.02$ nb

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$AA \to AA\gamma\gamma$ - CMS & ATLAS RESULTS - $M_{\gamma\gamma} > 5$ GEV

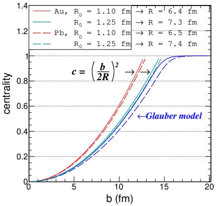
- CMS Coll., Phys. Lett. **B797** (2019) 134826
  - ✗ $E_{t_\gamma} > 2$ GeV
  - ✗ $|\eta_\gamma| < 2.4$
  - ✗ $M_{\gamma\gamma} > 5$ GeV
  - ✗ $p_{t_{\gamma\gamma}} < 1$ GeV
  - ✗ Aco < 0.01
- ATLAS Collaboration, JHEP 03 (2021) 243
  - ✗ $E_{t_\gamma} > 2.5$ GeV
  - ✗ $|\eta_\gamma| < 2.4$
  - ✗ $M_{\gamma\gamma} > 5$ GeV
  - ✗ $p_{t_{\gamma\gamma}} < 1$ GeV
  - ✗ Aco < 0.01

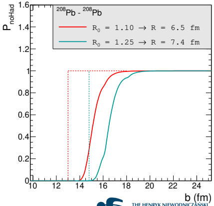
Experiment		Theory		
		Nuclear radius: $R = R_0 A^{\frac{1}{3}}$		Glauber model
Collaboration	σ nb	$\sigma(b = 13\text{fm})$	$\sigma(b = 14.8\text{fm})$	$\sigma(b = 20\text{fm})$
ATLAS (2018 data)	78 ± 13(stat.)± 7(syst.)	52	50	45
ATLAS (2015+2018)	120 ± 17(stat.)± 13(syst.)	82	80	71
CMS (2015)	120 ± 46(stat.)± 28(syst.)	105	103	92

UPC $\to b_{min} > 2\times$ R

14 FM $\to P_{NoHadronic}(\vec{b}) = exp(-\sigma_{NN} T_{AA}(\vec{b}))$

centrality [%]	100
nucleus and radius	b (fm)
Pb, $R = 6.5$ fm	13.0
Pb, $R = 7.4$ fm	14.8
Pb Pb, Glauber	20.0





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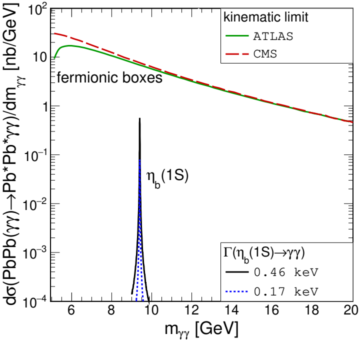
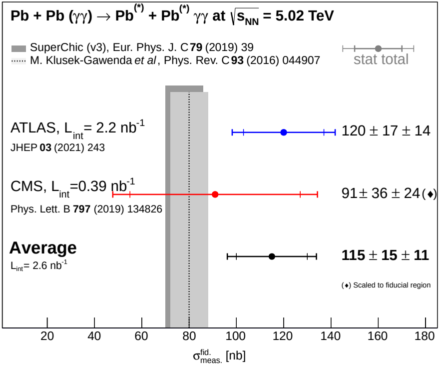
2022 RESULTS





This result paves the way for combining existing or forthcoming measurements using LHC heavy-ion collisions and provides an additional experimental input to the comparison with state-of-the-art predictions from quantum electrodynamics.

- The European Union's Horizon 2020 research and innovation program under the STRONG-2020,
  G. K. Krintiras, I. Grabowska-Bołd, M. Kłusek-Gawenda and É. Chapon R. Chudasama and R. Granier de Cassagnac,
  arXiv:2204.02845 [hep-ph];
  Light-by-light scattering cross-section measurements at LHC

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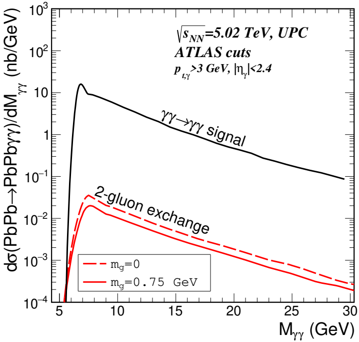
Higher order processes..?

$\gamma\gamma$ invariant mass

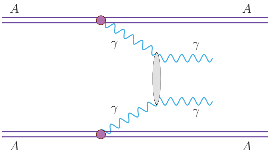


Coherent sum of both processes...?

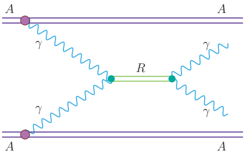
Pionic boxes...?

AA→AA$\gamma\gamma$ for $M_{\gamma\gamma} < 5$ GeV ?

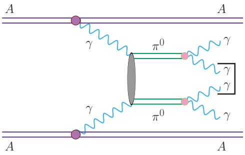
Continuum



Resonances



Background

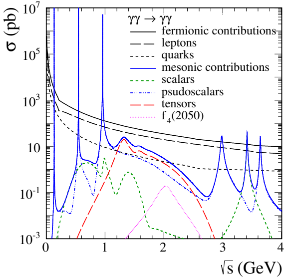


$f_0(500)$
$f_0(980)$
$a_0(980)$
$f_0(1370)$
$\chi_{c0}(1P)$

π^0
η
$\eta'(958)$
$\eta_c(1S)$
$\eta_c(2S)$

$f_2(1270)$
$a_2(1320)$
$f_2'(1525)$
$f_2(1565)$
$a_2(1700)$

$f_4(2050)$



- P. Lebiedowicz, A. Szczurek, The role of meson exchanges in light-by-light scattering, Phys. Lett. **B772** (2017) 330

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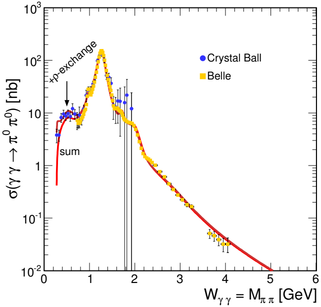
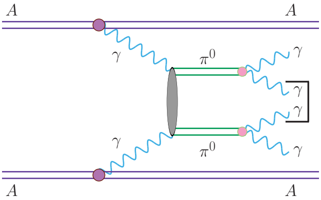
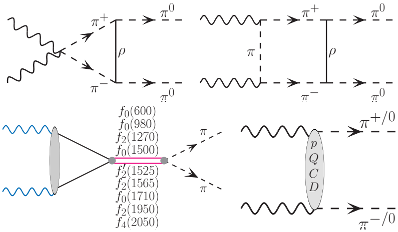
$M_{\gamma\gamma} < 5$ GeV $\Rightarrow$ PIONIC BACKGROUND

- M. K-G, A. Szczurek, $\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy-ion collisions, Phys. Rev. **C87** (2013) 054908
  - $W_{\gamma\gamma} \in (2m_\pi - 6)$ GeV
  - total cross section & angular distributions
  - $\gamma\gamma \to \pi^+\pi^-$ & $\pi^0\pi^0$





$\gamma\gamma \to \pi^0\pi^0$



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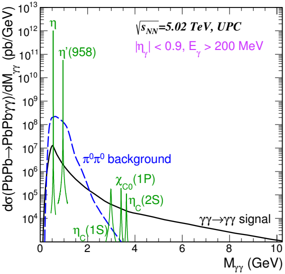
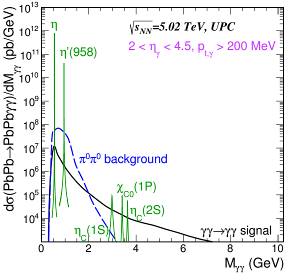
UPC OF AA...

ALICE cuts

- ✔ boxes
- ✔ bkg
- ✔ mesons

LHCb cuts





Total nuclear cross section [nb]

Energy	$W_{\gamma\gamma} = (0-2)$ GeV		$W_{\gamma\gamma} > 2$ GeV	
Fiducial region	ALICE	LHCb	ALICE	LHCb
Boxes	4 890	3 818	146	79
$\pi^0\pi^0$ bkg	135 300	40 866	46	24
η	722 573	568 499		
$\eta'(958)$	54 241	40 482		
$\eta_c(1S)$			9	5
$\chi_{c0}(1P)$			4	2
$\eta_c(2S)$			2	1

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EXPERIMENTAL CONDITION

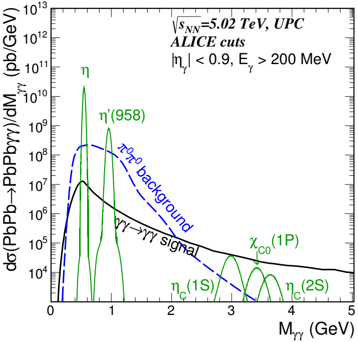
ENERGY RESOLUTION

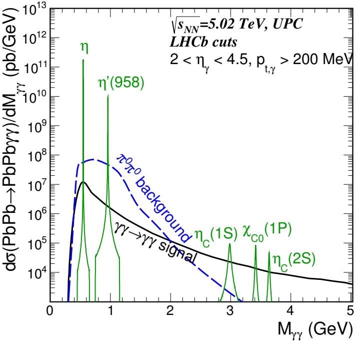
$$\frac{\sigma_{E_\gamma}}{E_\gamma} = 2\%$$

ALICE cuts

$$\frac{\sigma_{E_\gamma}}{E_\gamma} = \frac{0.085}{\sqrt{E_\gamma}} + \frac{0.003}{E_\gamma} + 0.008$$

LHCb cuts





The energy resolution modifies the resonance signal

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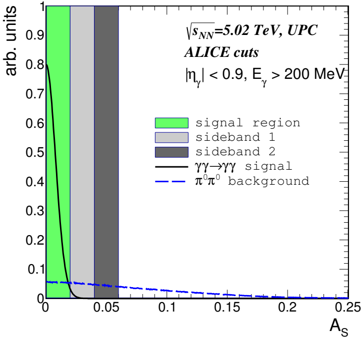
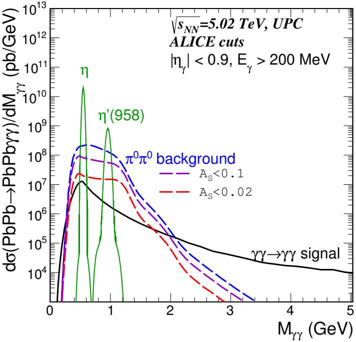
EXPERIMENTAL RESOLUTION & SCALAR ASYMMETRY

$$A_S = \left| \frac{|\vec{p}_T(1)| - |\vec{p}_T(2)|}{|\vec{p}_T(1)| + |\vec{p}_T(2)|} \right|$$

A_S

$M_{\gamma\gamma}$





80% of the signal events at $A_S < 0.02$

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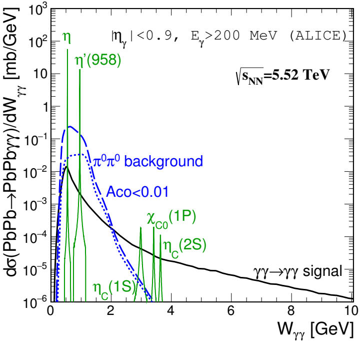
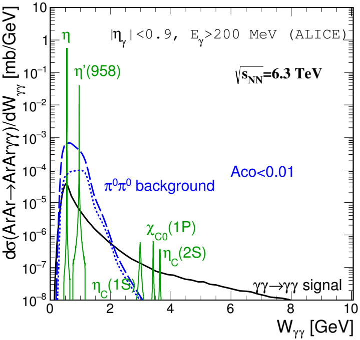
$AA \to AA\gamma\gamma$ @ MIDRAPIDITY

$^{208}Pb^{82+} + {}^{208}Pb^{82+}$



$^{40}Ar^{18+} + {}^{40}Ar^{18+}$



$$\sigma_{tot} \propto (Z_{Pb}/Z_{Ar})^4 \approx 430$$

$$\sqrt{s_{NN}} = \sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \sqrt{s_{pp}}$$

Run 5: $L_{\text{int}}^{\text{Ar}-\text{Ar}} = (3 - 8.8)$ pb $\to$ 1460–4280 signal events ($W_{\gamma\gamma} > 2$ GeV)

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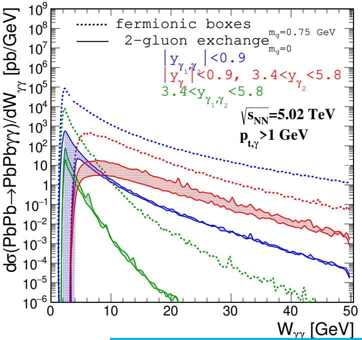
AA→AA$\gamma\gamma$ @ FORWARD REGION ?

✓ ALICE Collaboration,
Letter of Intent: A Forward Calorimeter (FoCal) in the ALICE experiment,
CERN-LHCC-2020-009

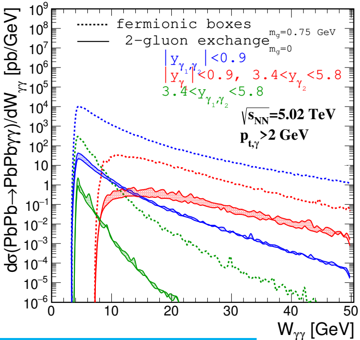
FOCAL $\rightarrow 3.4 < \eta < 5.8$

The forward electromagnetic and hadronic calorimeter is an upgrade to the ALICE experiment, to be installed during LS3 for data-taking in 2027–2029 at the LHC.

$p_{t,\gamma} > 1$ GeV



$p_{t,\gamma} > 2$ GeV



Boxes & 2-gluon exchange (with effective gluon mass)

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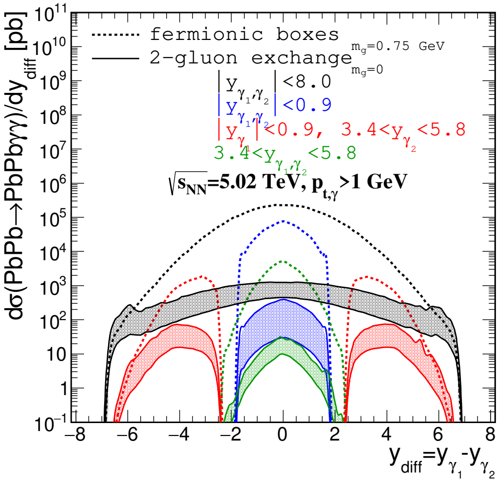
AA→AAγγ @ FORWARD REGION ?

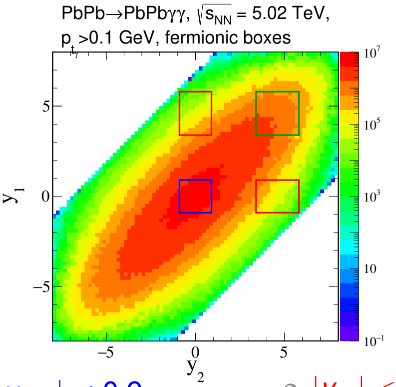
$y_{\gamma_1} - y_{\gamma_2}$



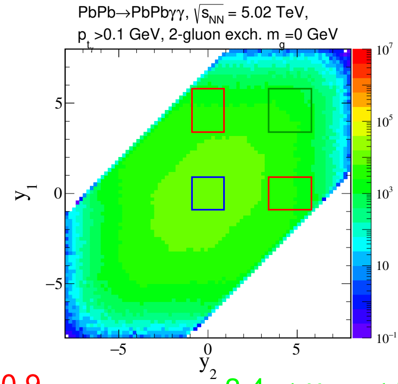
A smaller $p_{t,\gamma}$ is desirable

AA→AA$\gamma\gamma$ @ FORWARD REGION ?

fermionic boxes



2-gluon exchange



- $|y_{\gamma_{1,2}}| < 0.9$,
- $|y_{\gamma_1}| < 0.9$, $3.4 < y_{\gamma_2} < 5.8$
- $3.4 < y_{\gamma_{1,2}} < 5.8$

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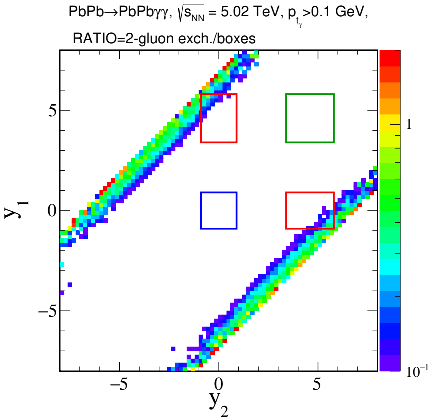
AA→AA$\gamma\gamma$ @ FORWARD REGION ?

RATIO = 2-gluon exchange / boxes



Promising results but need extended work.

CONCLUSION

- UPC of heavy-ion opens a possibility to measure or to test the $\gamma\gamma \to \gamma\gamma$ scattering:
  - mesons decay ($W_{\gamma\gamma} < 4$ GeV),
  - pionic background ($W_{\gamma\gamma} < 2$ GeV),
  - fermionic boxes ($W_{\gamma\gamma} > 2$ GeV),
  - VDM-Regge ($W_{\gamma\gamma} > 30$ GeV),
  - 2-gluon exchange ($W_{\gamma\gamma} > 30$ GeV);
- Measurable cross section;
- ATLAS/CMS have observed 13→59→80/14 events confirming LbL scattering in UPC;
- ALICE and LHCb could measure LbyL scattering for $W_{\gamma\gamma} > 2$ GeV in Pb-Pb and Ar-Ar collisions with very good statistic;
- Importance of η & η' for $W_{\gamma\gamma} < 2$ GeV;
- Collaboration - theoreticians and experimenters;
- Future - low p_t and forward rapidity region.

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