Ultraperipheral heavy-ion collisions in Run3 - verification of what we know or new physics?

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DPC-SMF

XVIII Mexican Workshop on Particles and Fields 2022
November 21st - 25th,
Puebla - México

- Equivalent Photon Approximation
- Light-by-light scattering
- Leptons production
- Electromagnetic excitation of nuclei and neutron evaporation

CLASSIFICATION

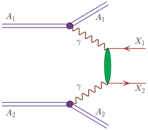
1. Collision energy:
   - low energy processes: $\sqrt{s_{NN}} < 10$ MeV/nucleon;
   - intermediate energies: $\sqrt{s_{NN}} = (10 - 100)$ MeV/nucleon;
   - relativistic energies: $\sqrt{s_{NN}} = (0.1 - 100)$ GeV/nucleon;
   - ultrarelativistic energies: $\sqrt{s_{NN}} > 100$ GeV/nucleon;

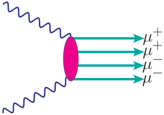
2. Centrality (for ^{208}Pb):
   - central collisions: b $\approx$ (0 fm $+\triangle b$);
   - semi-central collisions: b $\approx$ (5 $-$ 10) fm;
   - semi-peripheral collisions: b $\approx$ (10 $-$ 12) fm;
   - peripheral collisions: b $\approx$ (12 fm $-(R_1 + R_2)$);
   - ultraperiperal collisions: b $> (R_1 + R_2)$;

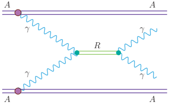
   where $R = R_0 A^{1/3}$.

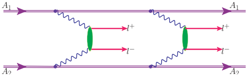
3. Type of production:

$\gamma\gamma$ fusion





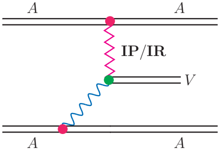


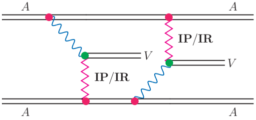


- ✓ $\rho^0\rho^0$, $J/\psi J/\psi$
- ✓ $\pi^+\pi^-$, $\pi^0\pi^0$
- ✓ $c\bar{c}$, $b\bar{b}$
- ✓ e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
- ✓ $\gamma\gamma$

- ✓ $p\bar{p}$
- ✓ $\pi^+\pi^-\pi^+\pi^-$
- ✓ $e^+e^-e^+e^-$
- ✓ $\mu^+\mu^-\mu^+\mu^-$

Photoproduction





- ✓ ρ^0, J/ψ
- ✓ $\rho^0\rho^0$, $J/\psi J/\psi$

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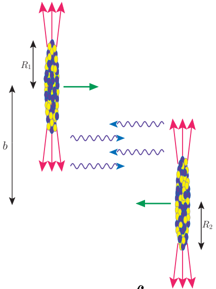
Equivalent Photon Approximation



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

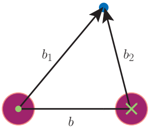
Virtuality: $Q^2 = \frac{1}{R^2} \approx 0.0008$ GeV^2

$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \int \sigma_{\gamma\gamma \to X_1 X_2}(\omega_1, \omega_2) \mathrm{d}\omega_1\, \mathrm{d}\omega_2\, n(\omega_1) n(\omega_2) \to \dots n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b\, N(\omega, b) \dots$$

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

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

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



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Equivalent Photon Flux vs. Form Factor

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

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

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

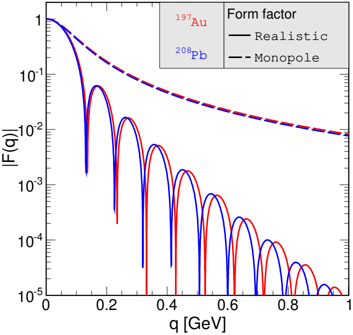
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times u^2 \left[K_1^2(u) + \frac{1}{\gamma^2} K_0^2(u) \right]$$

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

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

- realistic

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



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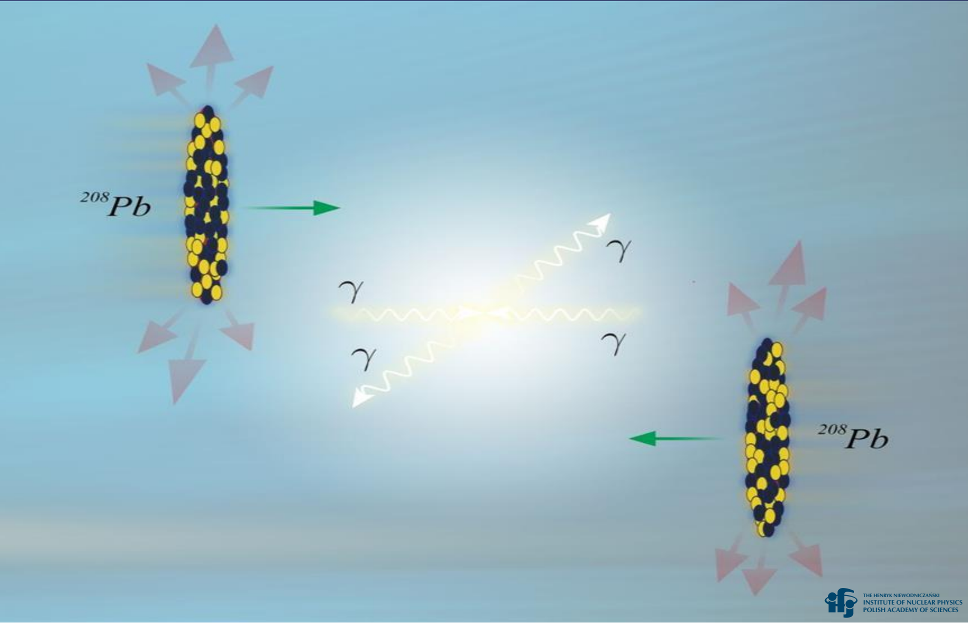
LIGHT-BY-LIGHT SCATTERING



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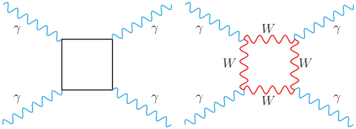
LIGHT-BY-LIGHT SCATTERING

- ❍ Maxwell classical theory
  - ✓ light doesn't interact with each other
- ❍ Quantum theory
  - ✓ interaction of photons through quantum fluctuations

- ● $\sigma(\gamma\gamma \to \gamma\gamma) \propto \alpha_{em}^4 \simeq \left(\frac{1}{137}\right)^4$ → very small
- ● Photon beams
  - ✗ High-power lasers
    - ➢ K. Homma, K. Matsuura, K. Nakajima, PTEP 2016 (2016) 013C01 *Testing helicity-dependent $\gamma\gamma \to \gamma\gamma$ scattering in the region of MeV*
  - ✔ Ultrarelativistic heavy-ion collision
    - ❍ Cross section $\propto Z^4$; Pb-Pb collisions ⇒ $82^4 \approx 45 \times 10^6$
    - ❍ Quasi-real photons

Boxes **WELL-KNOWN**

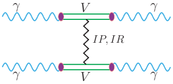


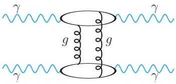
Fermionic boxes (LO QED) *W* Box

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.





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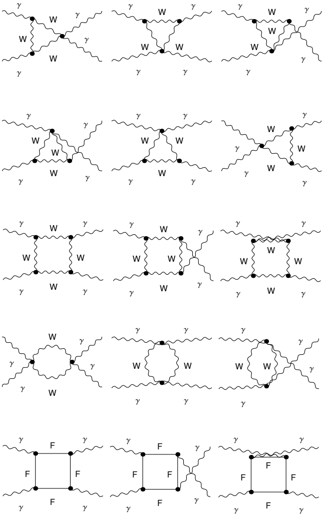
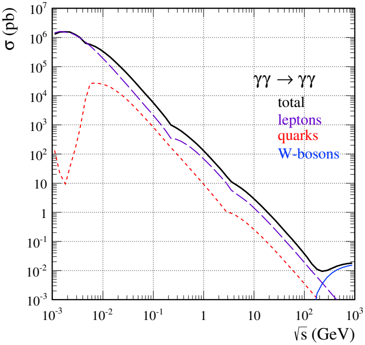
BOXES $\gamma\gamma \to \gamma\gamma$



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.

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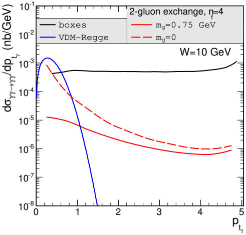
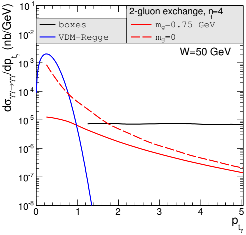
EXPERIMENTAL IDENTIFICATION OF PROCESSES

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

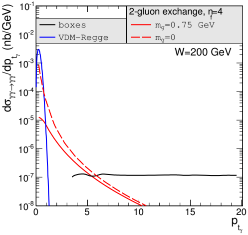
W = 10 GeV



W = 50 GeV



W = 200 GeV



γ-γ Collider?

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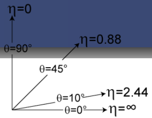
AA→AAγγ - form factor

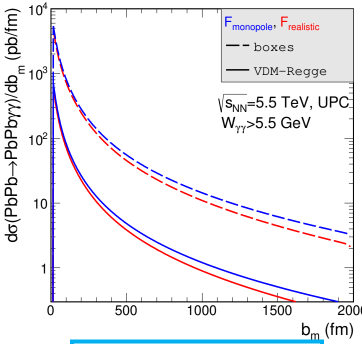


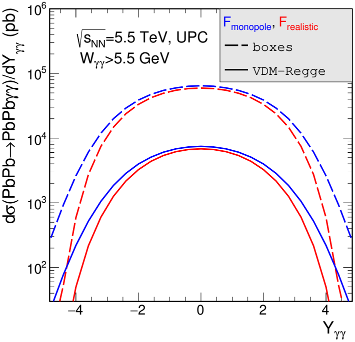
⇨ realistic

⇨ monopole

impact parameter

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

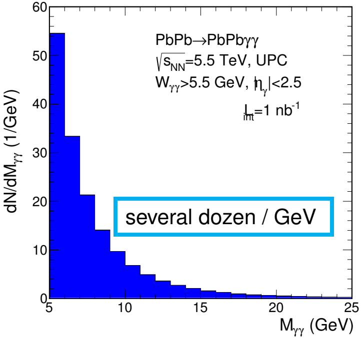




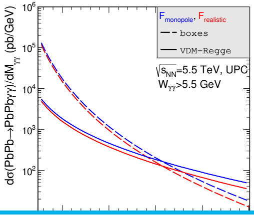
↑ theoretical distribution

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

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



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



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

σ(PbPb→PbPb$\gamma\gamma$) [nb] @ LHC ($\sqrt{s_{NN}}$ = 5.5 TeV) & FCC ($\sqrt{s_{NN}}$ = 39 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			
F	$W_{\gamma\gamma} > 5$ GeV	6 169		882	
C	$E_\gamma > 3$ GeV	4 696 268		574	
C					

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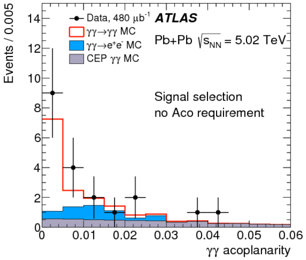
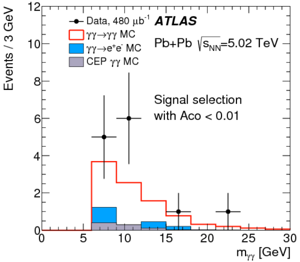
AA→AA$\gamma\gamma$ - ATLAS RESULTS

➢ 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 ⇒ σ = 70 ± 20(stat.)±17(syst.) nb

(2019)* ⇒ σ = 78 ± 13(stat.)±7(syst.)±3(lumi.) nb

Our result ⇒ σ = 51 ± 0.02 nb

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

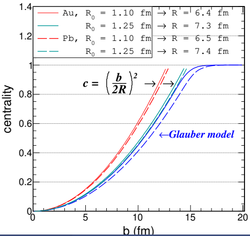
- CMS Coll., Phys. Lett. **B797** (2019) 134826
  - ✗ $E_{t_\gamma} > 2$ GeV
  - ✗ $|\eta_\gamma| < 2.4$
  - ✗ $M_{\gamma\gamma} > 5$ GeV
  - ✗ $p_{t_{\gamma\gamma}} < 1$ GeV
  - ✗ Aco < 0.01
- ATLAS Collaboration, JHEP **03** (2021) 243
  - ✗ $E_{t_\gamma} > 2.5$ GeV
  - ✗ $|\eta_\gamma| < 2.4$
  -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

SO FAR IT WAS 14 FM

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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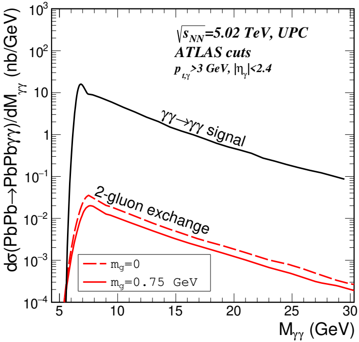
HIGHER ORDER PROCESSES..?

$\gamma\gamma$ invariant mass

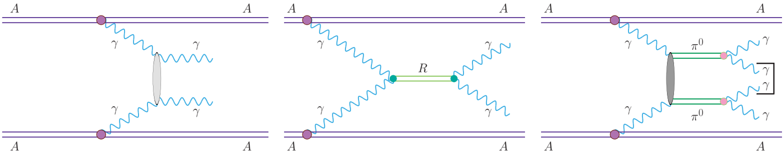


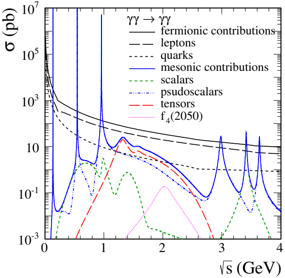
Coherent sum of both processes...?

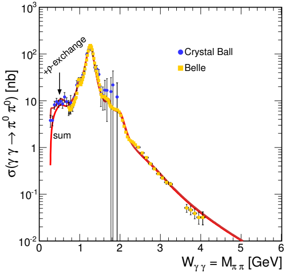
Pionic boxes...?

AA→AA$\gamma\gamma$ FOR $M_{\gamma\gamma} < 5$ GEV ?

CONTINUUM | **RESONANCES** | **BACKGROUND**







- P. Lebiedowicz, A. Szczurek, *Phys. Lett.* ***B772*** *(2017) 330*, The role of meson exchanges in light-by-light scattering
- M. K-G, A. Szczurek, *Phys. Rev.* ***C87*** *(2013) 054908*; $\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy-ion collisions

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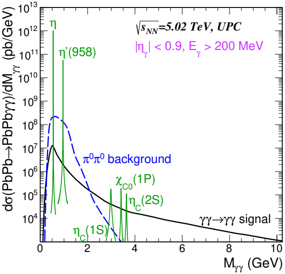
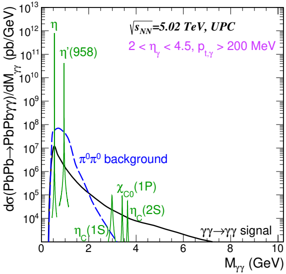
UPC OF AA...

- ✔ boxes
- ✔ bkg
- ✔ mesons

ALICE cuts



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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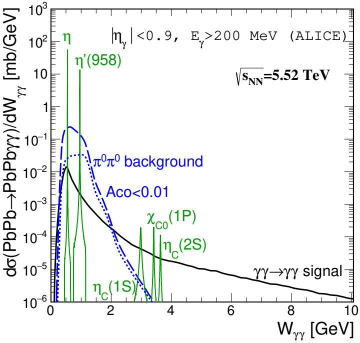
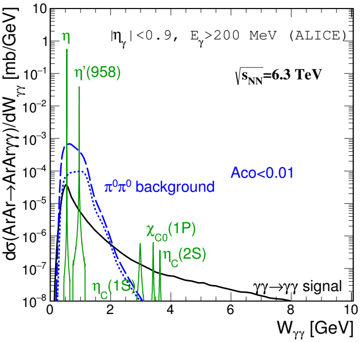
AA→AAγγ @ MIDRAPIDITY

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



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



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

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

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

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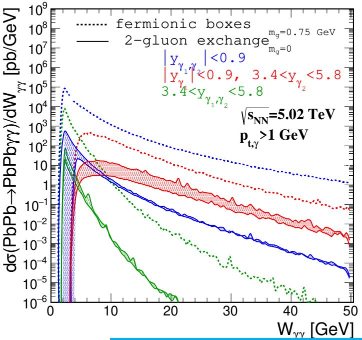
AA→AA$\gamma\gamma$ @ FORWARD REGION ?

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

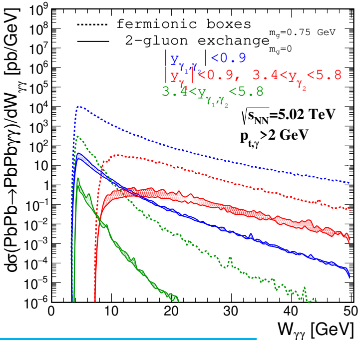
FoCal $\rightarrow 3.4 < \eta < 5.8$

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

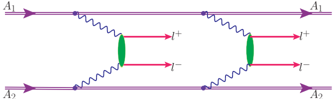


$p_{t,\gamma} > 2$ GeV



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

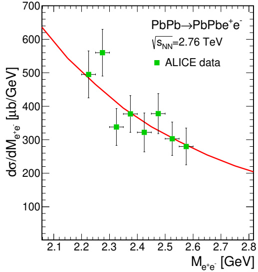
FOUR-LEPTON PRODUCTION

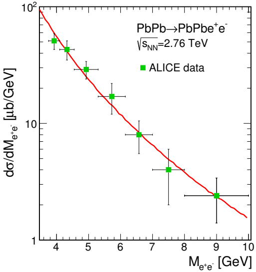


$$\frac{d\sigma_{A_1 A_2 \to A_1 A_2 (\ell^+\ell^-)(\ell^+\ell^-)}}{dy^I_{\ell+}\, dy^I_{\ell-}\, dy^{II}_{\ell+}\, dy^{II}_{\ell-}} = \frac{1}{2}\int \left(\frac{dP^I_{\gamma\gamma\to\ell^+\ell^-}\left(b, y^I_{\ell+}, y^I_{\ell-}; p_{t,\ell}\right)}{dy^I_{\ell+}\, dy^I_{\ell-}} \times \frac{dP^{II}_{\gamma\gamma\to\ell^+\ell^-}\left(b, y^{II}_{\ell+}, y^{II}_{\ell-}; p_{t,\ell}\right)}{dy^{II}_{\ell+}\, dy^{II}_{\ell-}} \right) \times 2\pi b\, db$$

$$P_{\gamma\gamma\to\ell^+\ell^-}(b; y_{\ell+}, y_{\ell-}, p_{t,\ell}) = \int N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \times \frac{d\sigma_{\gamma\gamma\to\ell_1\ell_2}\left(W_{\gamma\gamma}\right)}{d\cos\theta}\, d\bar{b}_x\, d\bar{b}_y\, \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, dY_{\ell_1\ell_2}$$

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





Good description of single pair production $\Rightarrow$ two e^+e^- pair production

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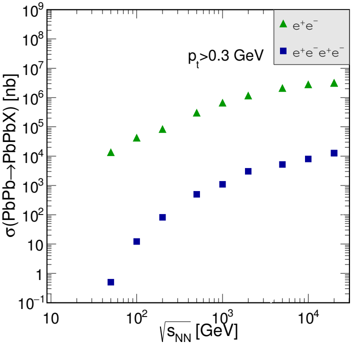
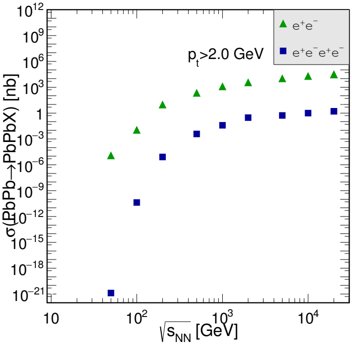
$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

Single e^+e^- pair production
vs.
double scattering production of two e^+e^- pairs

$p_t > 0.3$ GeV

$p_t > 2.0$ GeV





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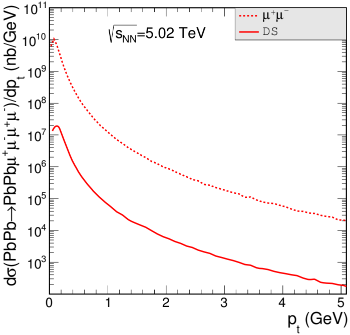
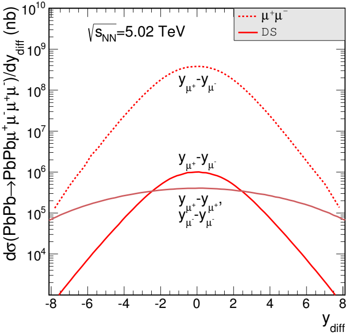
$AA \to AA\mu^+\mu^-$ & $AA \to AA\mu^+\mu^-\mu^+\mu^-$

Single $\mu^+\mu^-$ pair production
vs.
double scattering production of two $\mu^+\mu^-$ pairs

$p_{t,\mu}$



y_{diff}



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

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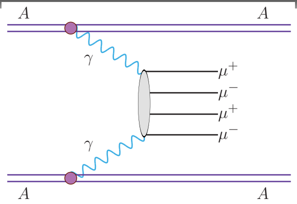
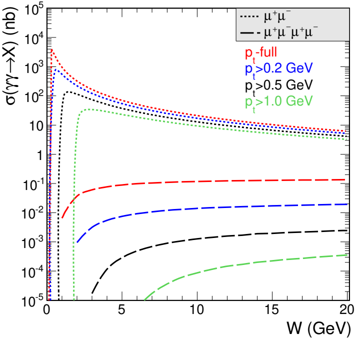
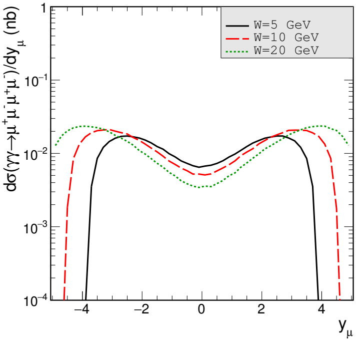
$\gamma\gamma \to \mu^+\mu^-\mu^+\mu^-$ - SINGLE SCATTERING



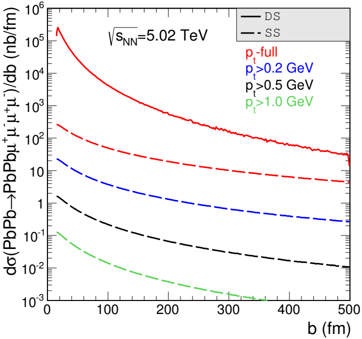
KATIE- an event generator that is specially designed to deal with initial states that have an explicit transverse momentum dependence but can also deal with on-shell initial states. KATIE is a parton-level generator for hadron scattering but requires only a few adjustments to deal with photon scattering.





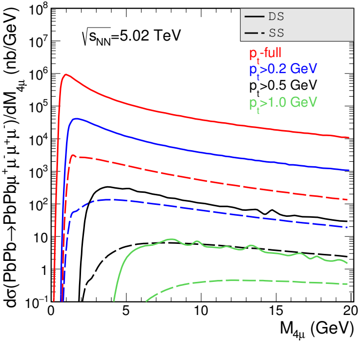
$AA \to AA\mu^+\mu^-\mu^+\mu^-$

impact parameter



↑ purely theoretical distribution

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



↑ DS dominates

It is difficult to isolate range of SS domination

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

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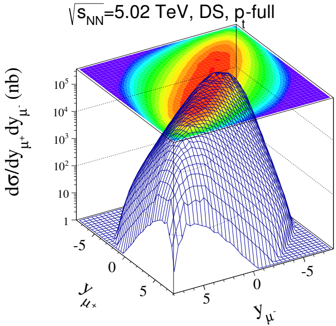
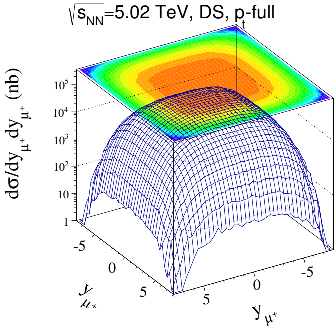
$AA \to AA\mu^+\mu^-\mu^+\mu^-$

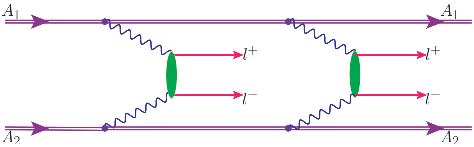
y_{μ^+}, y_{μ^-}



$y_{\mu^\pm}, y_{\mu^\pm}$



$p_{t,\mu^+} \simeq p_{t,\mu^-}$ $\Rightarrow$ construction of similar distributions by ALICE or CMS?



The number of counts for L_{int} = 1 nb^{-1}

(4μ), $\sqrt{s_{NN}}$ = 5.02 TeV		$(4e)$, $\sqrt{s_{NN}}$ = 5.5 TeV	
experimental cuts	N	experimental cuts	N
$\lvert y_i\rvert < 2.5$, $p_t > 0.5$ GeV	815	$\lvert y_i\rvert < 2.5$, $p_t > 0.5$ GeV	235
$\lvert y_i\rvert < 2.5$, $p_t > 1.0$ GeV	53	$\lvert y_i\rvert < 2.5$, $p_t > 1.0$ GeV	10
$\lvert y_i\rvert < 0.9$, $p_t > 0.5$ GeV	31	$\lvert y_i\rvert < 1.0$, $p_t > 0.2$ GeV	649
$\lvert y_i\rvert < 0.9$, $p_t > 1.0$ GeV	2	$\lvert y_i\rvert < 1.0$, $p_t > 1.0$ GeV	1
$\lvert y_i\rvert < 2.4$, $p_t > 4.0$ GeV	$\ll 1$		

CMS and ALICE $\Rightarrow p_{t,\mathrm{cut}}$ = 1 GeV   ALICE $\Rightarrow p_{t,\mathrm{cut}}$ = 0.2 GeV

ATLAS $\Rightarrow p_{t,\mathrm{cut}}$ = 4 GeV **Potential background**

$\downarrow \sqrt{s_{NN}}$ = 5.5 TeV, $|y| < 4.9$

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

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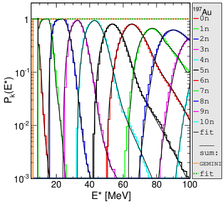
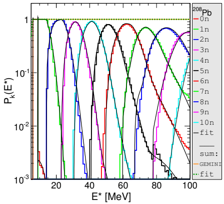
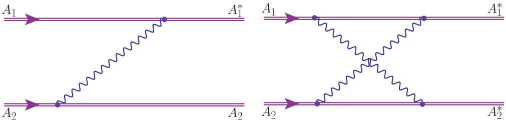
Electromagnetic excitation

$P_k(E*)$

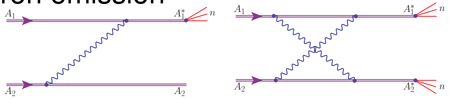




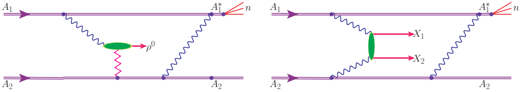
➤ Photon → nucleus excitation



✚ neutron emission

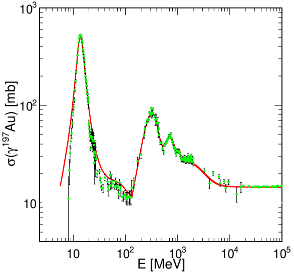


✚ particle production

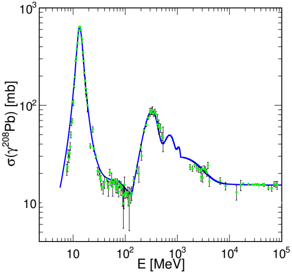


PHOTOABSORPTION

$\gamma\ ^{197}$Au

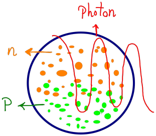


$\gamma\ ^{208}$Pb

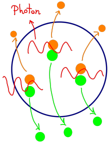


$$\sigma_{\gamma A} = \sigma_{\text{GDR}} + \sigma_{\text{QD}} + \sigma_{\text{nucleon res.}} + \sigma_{\text{nucleon cont.}}$$

❶ Giant Dipole Resonance
$E_\gamma < 40$ MeV

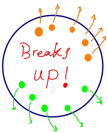


❷ quasi-deuteron contribution
$E_\gamma = (40 - 100)$ MeV



❸ nucleon resonances
$E_\gamma = (0.1 - 1)$ GeV

❹ break-up of nucleons
$E_\gamma > 1 - 8$ GeV



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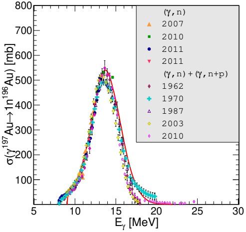
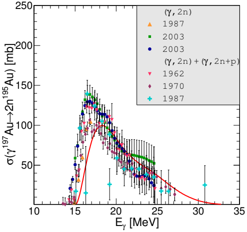
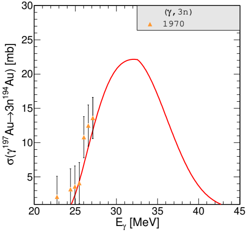
$\gamma\ ^{197}Au \to 1n\ ^{196}Au$



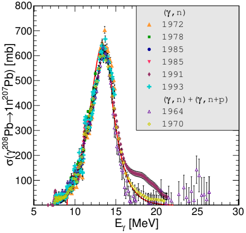
$\gamma\ ^{197}Au \to 2n\ ^{195}Au$



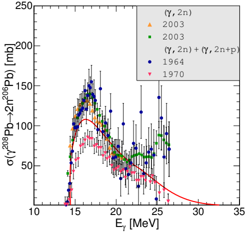
$\gamma\ ^{197}Au \to 3n\ ^{194}Au$



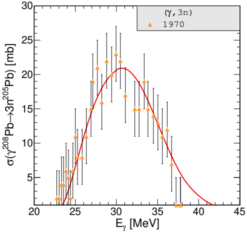
$\gamma\ ^{208}Pb \to 1n\ ^{207}Pb$



$\gamma\ ^{208}Pb \to 2n\ ^{206}Pb$



$\gamma\ ^{208}Pb \to 3n\ ^{205}Pb$



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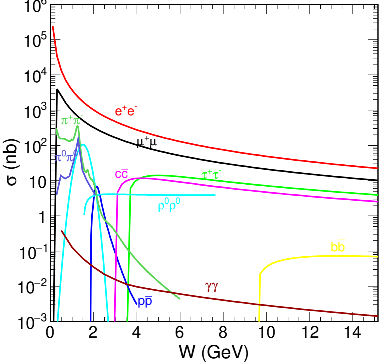
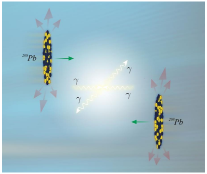
Conclusion

- EPA in the impact parameter space
- Fourier transform of the charge distribution
- Multidimensional integrals $\to$ differential cross section
- Description of experimental data for UPC
  - STAR - e^+e^-, $\pi^+\pi^-\pi^+\pi^-$
  - ATLAS - $\gamma\gamma$, $\mu^+\mu^-$
  - ALICE - e^+e^-, J/ψ
  - CMS - $\gamma\gamma$
- Predictions focused on experimental acceptance
  - $\mu^+\mu^-\mu^+\mu^-$ - single & double scattering
  - $e^+e^-e^+e^-$ - double scattering
  - $p\bar{p}$
  - $\pi^+\pi^-$ & $\pi^0\pi^0$
  - $\gamma\gamma$ for $M_{\gamma\gamma} < 5$ GeV
- Electromagnetic excitation
- Collaboration - theoreticians and experimenters
- Future:
  - greater precision
  - lower p_t

Thank you





Photon collisions: Photonic billiards might be the newest game!, EurekAlert!
Ultraperipheral collisions of lead nuclei at the LHC accelerator can lead to elastic collisions of photons with photons.

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