New Vistas in Ultraperipheral Heavy-Ion Collisions

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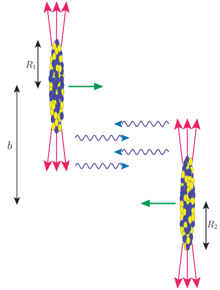

UltraPeripheralCollisions

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

1. M. Kłusek-Gawenda, W. Schäfer, A. Szczurek, *Centrality dependence of dilepton production via $\gamma\gamma$ processes from Wigner distributions of photons in nuclei*, Phys. Lett. **B814** (2021) 136114;
2. M. Dyndał, M. Kłusek-Gawenda, M. Schott, A. Szczurek, *Anomalous electromagnetic moments of τ lepton in $\gamma\gamma \to \tau^+\tau^-$ reaction in Pb+Pb collisions at the LHC*, Phys. Lett. **B809** (2020) 135682;
3. M. Kłusek-Gawenda, J. D. Tapia Takaki, *Exclusive Four-pion Photoproduction in Ultra-peripheral Heavy-ion Collisions at RHIC and LHC Energies*, Acta Phys. Polon. **B51** (2020) 1393-1404;
4. M. Kłusek-Gawenda, R. McNulty, R. Schicker, A. Szczurek, *Light-by-light scattering in ultraperipheral heavy-ion collisions at low diphoton masses*, Phys. Rev. **D99** (2019) 093013;
5. M. Kłusek-Gawenda, R. Rapp, W. Schäfer, A. Szczurek, *Dilepton Radiation in Heavy-Ion Collisions at Small Transverse Momentum*, Phys. Lett. **B790** (2019) 339–344;
6. A. van Hameren, M. Kłusek-Gawenda, A. Szczurek, *Single- and double-scattering production of four muons in ultraperipheral PbPb collisions at the Large Hadron Collider*, Phys. Lett. **B776** (2018) 84-90;
7. M. Kłusek-Gawenda, A. Szczurek, *Double scattering production of two positron–electron pairs in ultraperipheral heavy-ion collisions*, Phys. Lett. **B763** (2016) 416-421;
8. M. Kłusek-Gawenda, 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) 399-407;
9. M. Kłusek-Gawenda, P. Lebiedowicz, 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;
10. M. Kłusek-Gawenda, A. Szczurek, *Photoproduction of J/ψ mesons in peripheral and semicentral heavy ion collisions*, Phys. Rev. **C93** (2016) 044912.

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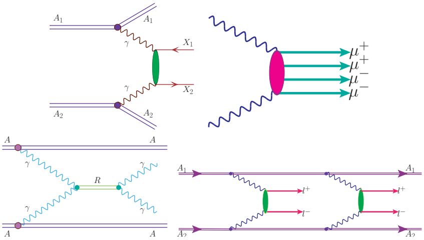
1. Collision energy:
   - low energy processes: $\sqrt{s_{NN}} < 10$ MeV/nucleon;
   - intermediate energies: $\sqrt{s_{NN}} = (10 - 100)$ MeV/nucleon;
   - relativistic energies: $\sqrt{s_{NN}} = (0.1 - 100)$ GeV/nucleon;
   - ultrarelativistic energies: $\sqrt{s_{NN}} > 100$ GeV/nucleon;

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:

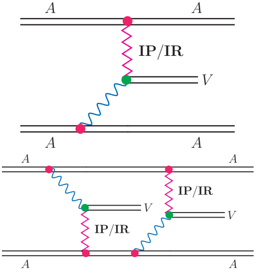
$\gamma\gamma$ fusion



- ✓ $\rho^0\rho^0$, $J/\psi J/\psi$
- ✓ $\pi^+\pi^-$, $\pi^0\pi^0$
- ✓ $c\bar{c}$, $b\bar{b}$
- ✓ 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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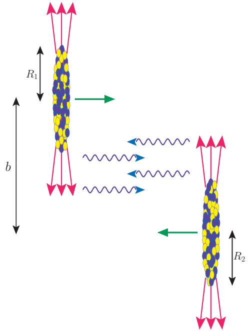
Equivalent Photon Approximation



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.

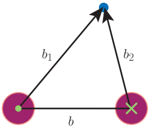
Photon energy: $\omega = \frac{\gamma}{b} \approx \gamma \times 15$ MeV

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

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

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

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



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

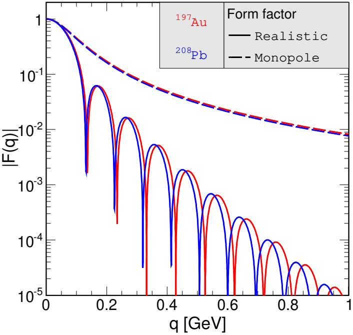
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{1}{\omega} \frac{1}{b^2} \times u^2 \left[K_1^2(u) + \frac{1}{\gamma^2} K_0^2(u) \right]$$

- 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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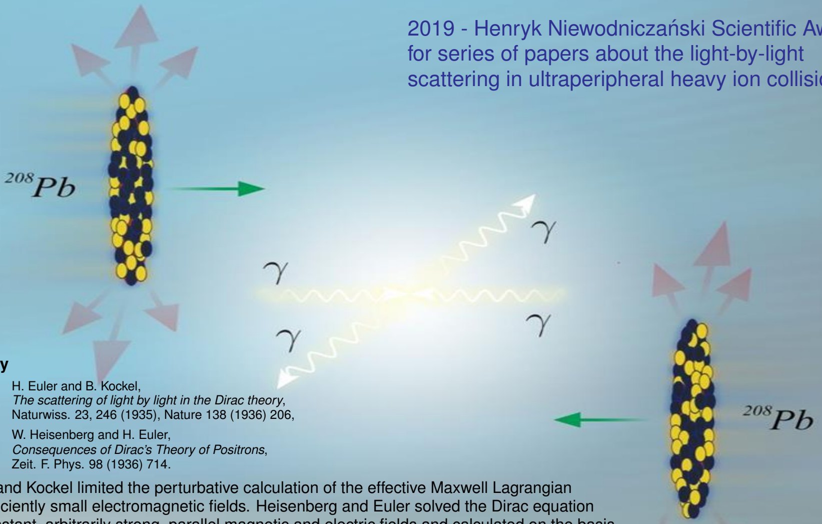
LIGHT-BY-LIGHT SCATTERING

2019 - Henryk Niewodniczański Scientific Award for series of papers about the light-by-light scattering in ultraperipheral heavy ion collisions



History

- H. Euler and B. Kockel,
  The scattering of light by light in the Dirac theory,
  Naturwiss. 23, 246 (1935), Nature 138 (1936) 206,
- W. Heisenberg and H. Euler,
  Consequences of Dirac's Theory of Positrons,
  Zeit. F. Phys. 98 (1936) 714.

Euler and Kockel limited the perturbative calculation of the effective Maxwell Lagrangian to sufficiently small electromagnetic fields. Heisenberg and Euler solved the Dirac equation for constant, arbitrarily strong, parallel magnetic and electric fields and calculated on the basis of this information the effective Maxwell Lagrangian.
This effective Maxwell (Euler-Heisenberg) Lagrangian for constant electromagnetic fields together with its weak-field limit, the EKH Lagrangian, represents a milestone in the history of quantum field theory.

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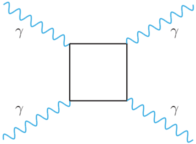
LIGHT-BY-LIGHT SCATTERING

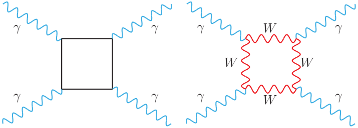
- ❍ Maxwell classical theory
  - ✓ light doesn't interact with each other
- ❍ Quantum theory
  - ✓ interaction of photons through quantum fluctuations



- $\sigma(\gamma\gamma \to \gamma\gamma) \propto \alpha_{em}^4$ → 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 $\propto Z^4$
    - ❍ Quasi-real photons

Boxes

WELL-KNOWN

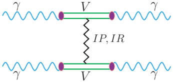


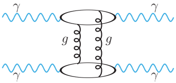
Fermionic boxes (LO QED) *W* Box

FormCalc. LoopTools.

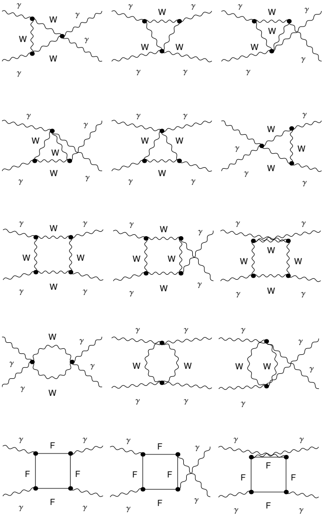
$$\overline{|\mathcal{M}_{\gamma\gamma\to\gamma\gamma}|^2} = \alpha_{em}^4 f(\hat{t}, \hat{u}, \hat{s})$$

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



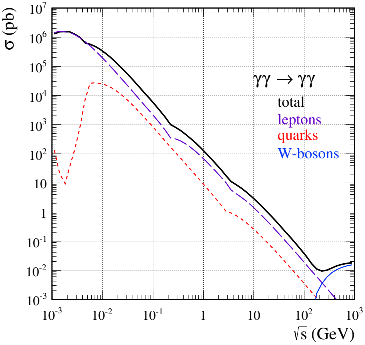


BOXES $\gamma\gamma \to \gamma\gamma$



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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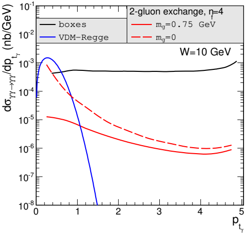
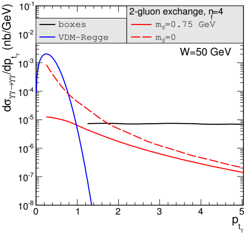
EXPERIMENTAL IDENTIFICATION OF PROCESSES

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

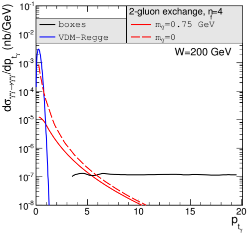
W = 10 GeV



W = 50 GeV



W = 200 GeV



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

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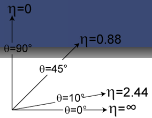
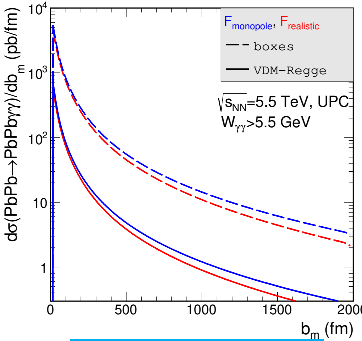
AA→AAγγ - form factor

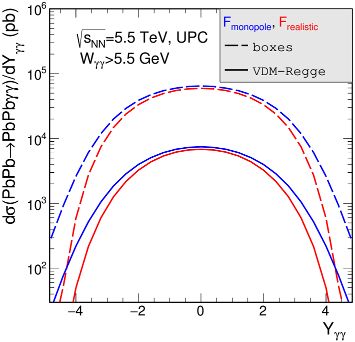


- ⇨ realistic
- ⇨ monopole

impact parameter

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





↑ theoretical distribution

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

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

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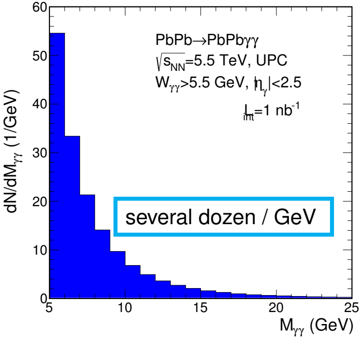
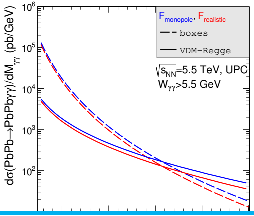


$W_{\gamma\gamma} = M_{\gamma\gamma}$



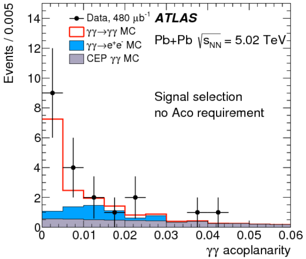
VDM-Regge dominates for $W_{\gamma\gamma} > 30$ GeV

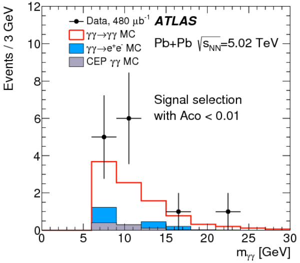
σ(PbPb→PbPb$\gamma\gamma$) [nb] @ LHC ($\sqrt{s_{NN}}$ = 5.5 TeV) & FCC ($\sqrt{s_{NN}}$ = 39 TeV)

	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, $\lvert y_\gamma \rvert < 2.5$	183	210	8E-2	9E-2
	$E_\gamma > 5$ GeV, $\lvert y_\gamma \rvert < 2.5$	54	61	4E-4	7E-4
C	$p_{t,\gamma} > 0.9$ 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			
F	$W_{\gamma\gamma} > 5$ GeV	6 169		882	
C	$E_\gamma > 3$ GeV	4 696 268		574	
C					

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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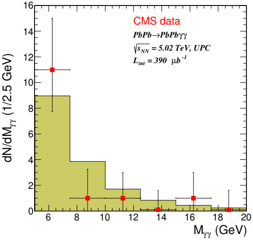
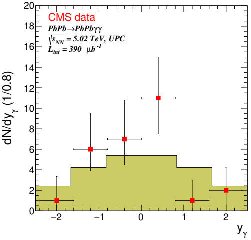
AA→AA$\gamma\gamma$ - CMS & ATLAS results - $M_{\gamma\gamma} > 5$ GeV

- CMS Collaboration, Phys. Lett. **B797** (2019) 134826

σ = 120 ± 46(stat.)±28(syst.) nb





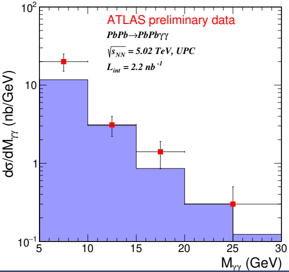
- ✗ $E_{t_\gamma} > 2$ GeV
- ✗ $|\eta_\gamma| < 2.4$
- ✗ $M_{\gamma\gamma} > 5$ GeV
- ✗ $p_{t_{\gamma\gamma}} < 1$ GeV
- ✗ Aco < 0.01
- ✔ 14 events

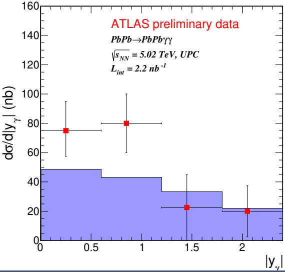
ours ⇒

σ = 103 ± 0.034 nb

- ATLAS Collaboration, JHEP 03 (2021) 243

σ = 120 ± 17(stat.)±13(syst.) nb



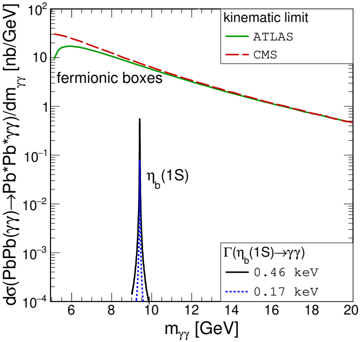


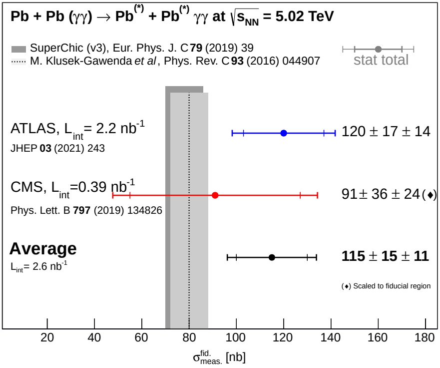
- ✗ $E_{t_\gamma} > 2.5$ GeV
- ✗ $|\eta_\gamma| < 2.4$
- ✗ $M_{\gamma\gamma} > 5$ GeV
- ✗ $p_{t_{\gamma\gamma}} < 1$ GeV
- ✗ Aco < 0.01
- ✔ 70 events(!!)

ours ⇒

σ = 80 ± 0.033 nb

2022 RESULTS





This result paves the way for combining existing or forthcoming measurements using LHC heavy-ion collisions and provides, within the studied phase space region, 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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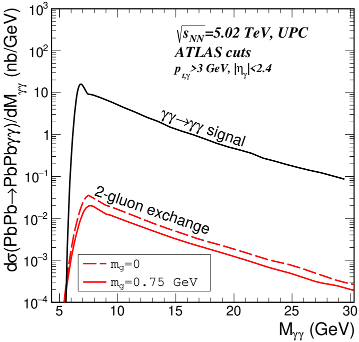
HIGHER ORDER PROCESSES..?

$\gamma\gamma$ invariant mass



Coherent sum of both processes...?

Pionic boxes...?

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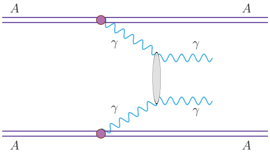
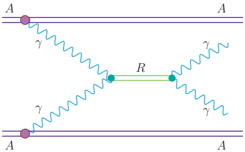
AA→AA$\gamma\gamma$ FOR $M_{\gamma\gamma} < 5$ GEV ?

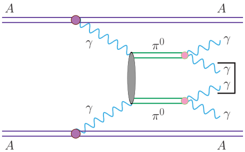
CONTINUUM

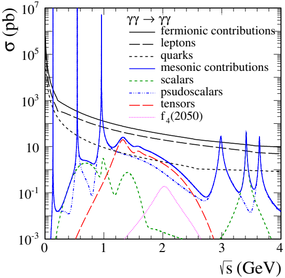


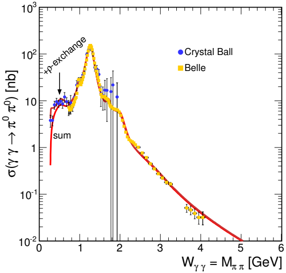
RESONANCES



BACKGROUND







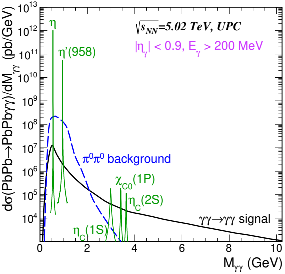
- P. Lebiedowicz, A. Szczurek, *Phys. Lett.* ***B772*** *(2017) 330*, The role of meson exchanges in light-by-light scattering
- M. K-G, A. Szczurek, *Phys. Rev.* ***C87*** *(2013) 054908*; $\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy-ion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

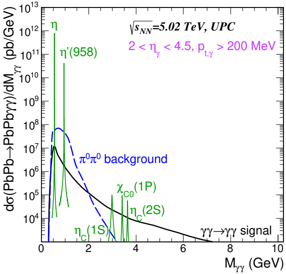
UPC OF AA...

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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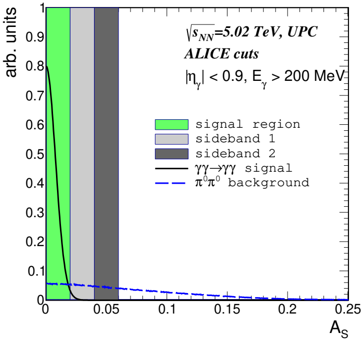
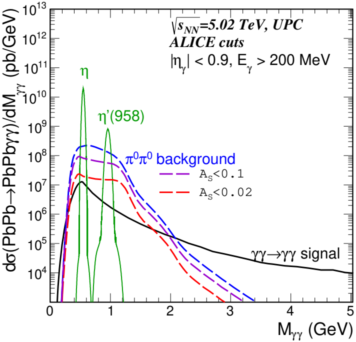
EXPERIMENTAL RESOLUTION & SCALAR ASYMMETRY & "UNWANTED" BKG

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

A_S



$M_{\gamma\gamma}$



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

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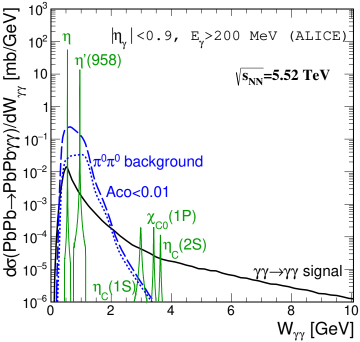
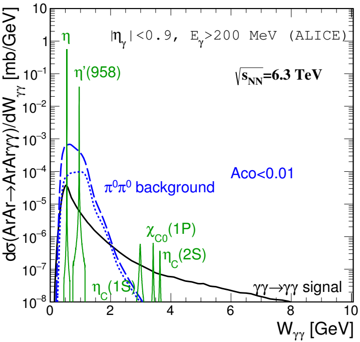
AA→AA$\gamma\gamma$ @ midrapidity

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



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



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

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

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

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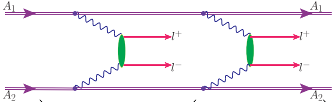
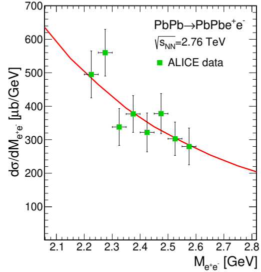
FOUR-LEPTON PRODUCTION

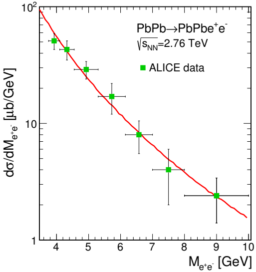


$$\frac{d\sigma_{A_1 A_2 \to A_1 A_2 (\ell^+\ell^-)(\ell^+\ell^-)}}{dy^I_{\ell+}\, dy^I_{\ell-}\, dy^{II}_{\ell+}\, dy^{II}_{\ell-}} = \frac{1}{2}\int \left(\frac{dP^I_{\gamma\gamma\to\ell^+\ell^-}\left(b, y^I_{\ell+}, y^I_{\ell-}; p_{t,\ell}\right)}{dy^I_{\ell+}\, dy^I_{\ell-}} \times \frac{dP^{II}_{\gamma\gamma\to\ell^+\ell^-}\left(b,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

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

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





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

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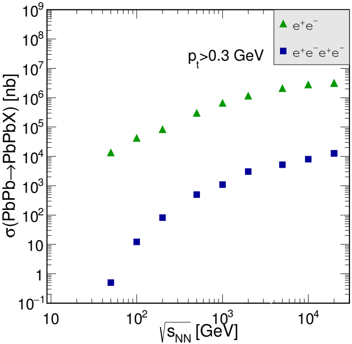
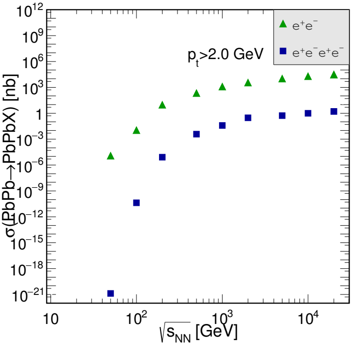
$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

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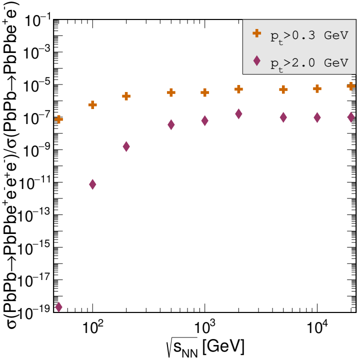
$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

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

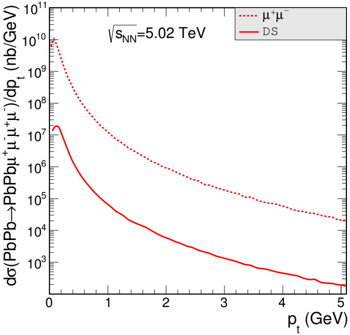


Ratio depends on $\sqrt{s_{NN}}$ and $p_{t,min}$

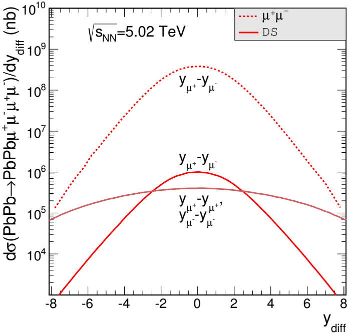
$AA \to AA\mu^+\mu^-$ & $AA \to AA\mu^+\mu^-\mu^+\mu^-$

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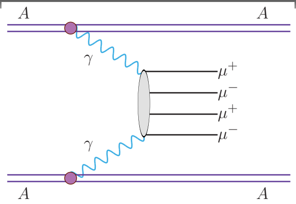
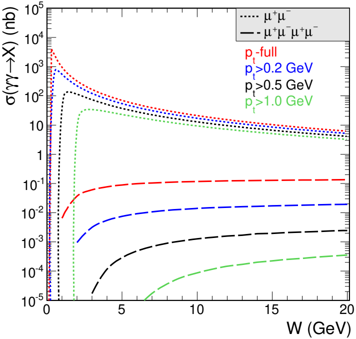
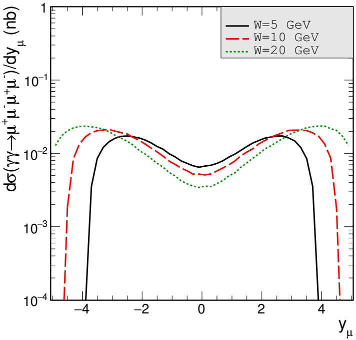
$\gamma\gamma \to \mu^+\mu^-\mu^+\mu^-$ - SINGLE SCATTERING

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.

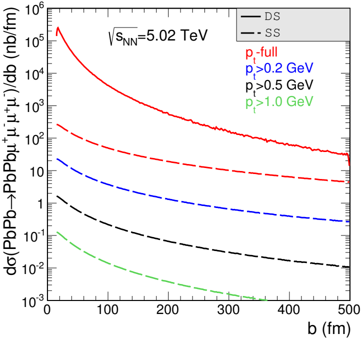






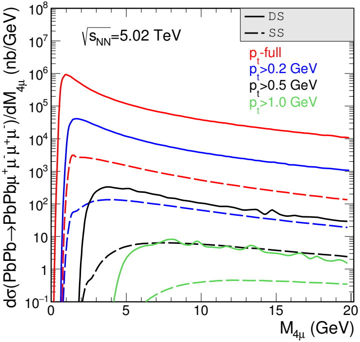
$AA \to AA\mu^+\mu^-\mu^+\mu^-$

impact parameter



↑ purely theoretical distribution

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

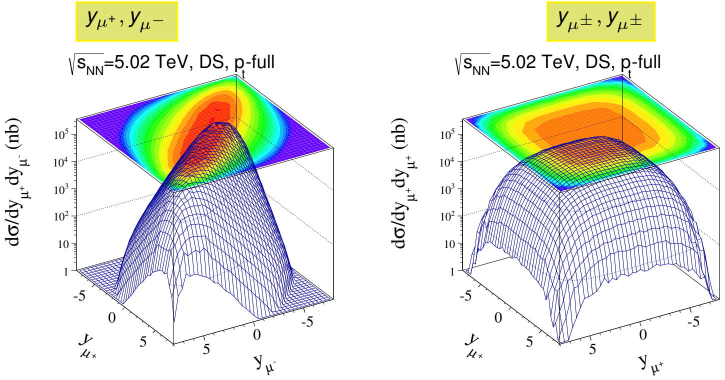


↑ DS dominates

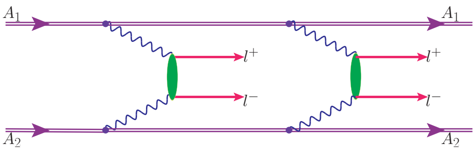
It is difficult to isolate range of SS domination

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

$AA \rightarrow AA\mu^+\mu^-\mu^+\mu^-$



$p_{t,\mu^+} \simeq p_{t,\mu^-} \Rightarrow$ 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	
experimental cuts	N
$\|y_i\| < 2.5$, $p_t > 0.5$ GeV	815
$\|y_i\| < 2.5$, $p_t > 1.0$ GeV	53
$\|y_i\| < 0.9$, $p_t > 0.5$ GeV	31
$\|y_i\| < 0.9$, $p_t > 1.0$ GeV	2
$\|y_i\| < 2.4$, $p_t > 4.0$ GeV	$\ll$1

$(4e)$, $\sqrt{s_{NN}}$ = 5.5 TeV	
experimental cuts	N
$\|y_i\| < 2.5$, $p_t > 0.5$ GeV	235
$\|y_i\| < 2.5$, $p_t > 1.0$ GeV	10
$\|y_i\| < 1.0$, $p_t > 0.2$ GeV	649
$\|y_i\| < 1.0$, $p_t > 1.0$ GeV	1

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

ALICE $\Rightarrow$ $p_{t,\text{cut}}$ = 0.2 GeV

ATLAS $\Rightarrow$ $p_{t,\text{cut}}$ = 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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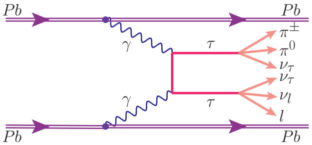
PRODUCTION OF $\tau^+\tau^-$

- UPC of heavy ions provide a very clean enviroment to study two-photon induced processes



- The presence of $\gamma\tau\tau$ vertex (twice) gives sensitivity to **anomalous** (a_τ) and **electric** (d_τ) moments
- So far the strongest experimental constraints on a_τ comes from DELPHI (LEP2) measurement on $e^+e^- \to e^+e^-\tau^+\tau^-$

$$-0.052 < a_\tau^{exp} < 0.013$$

- The theoretical Standard Model value is

$$a_\tau^{th} = 0.00117721 \pm 0.00000005$$

- Physics beyond the Standard Model (BSM):
  - lepton compositeness,
  - TeV-scale leptoquarks,
  - left-right symmetric models,
  - unparticle physics,
  - a_τ can be $\left(\frac{m_\tau}{m_\mu}\right)^2$ times more sensitive than a_μ
- Many interesting proposals how to improve experimental sensitivity on a_τ and d_τ using lepton beams

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Theoretical framework

- Nuclear cross section in UPC: $\sigma\left(PbPb \to PbPb\ell^+\ell^-; \sqrt{s_{AA}}\right) =$

$$\int \sigma\left(\gamma\gamma \to \ell^+\ell^-; W_{\gamma\gamma}\right) N(\omega_1, b_1) N(\omega_2, b_2) S^2_{abs}(\boldsymbol{b}) \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, dY_{\ell^+\ell^-}\, d\bar{b}_x\, d\bar{b}_y\, d^2b \qquad (1)$$

- Differential elementary cross section

$$\frac{\mathrm{d}\sigma(\gamma\gamma \to \ell^+\ell^-)}{\mathrm{d}\cos\theta} = \frac{2\pi}{64\pi^2 s} \frac{\boldsymbol{p_{out}}}{\boldsymbol{p_{in}}} \frac{1}{4} \sum_{\text{spin}} |\mathcal{M}|^2 \,. \qquad (2)$$

- The amplitude for the t- and u-channel

$$\mathcal{M} = (-i)\, \epsilon_{1\mu}\epsilon_{2\nu}\, \bar{u}(p_3) \Big(i\Gamma^{(\gamma\ell^+\ell^-)\,\mu}(p_3, p_t) \frac{i(\not{p}_t + m_\ell)}{t - m_\ell^2 + i\epsilon} i\Gamma^{(\gamma\ell^+\ell^-)\,\nu}(p_{t'} - p_4)$$
$$+ i\Gamma^{(\gamma\ell^+\ell^-)\,\nu}(p_3, p_u) \frac{i(\not{p}_u + m_l)}{u - m_\ell^2 + i\epsilon} i\Gamma^{(\gamma\ell^+\ell^-)\,\mu}(p_{u'} - p_4) \Big) v(p_4)\,. \qquad (3)$$

- Photon-lepton vertex function as a function of momentum transfer ($q = p' - p$)

$$i\Gamma_\mu^{(\gamma\ell^+\ell^-)}(p', p) = -ie \left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\ell} \sigma_{\mu\nu} q^\nu F_2(q^2) + \frac{i}{2m_\ell} \gamma^5 \sigma_{\mu\nu} q^\nu F_3(q^2) \right], \qquad (4)$$

➢ Dirac form factor

$F_1(0) = 1$

➢ Pauli form factor

$F_2(0) = a_\ell$

➢ electric dipole form factor

$F_3(0) = d_\ell \frac{2m_\ell}{e}$

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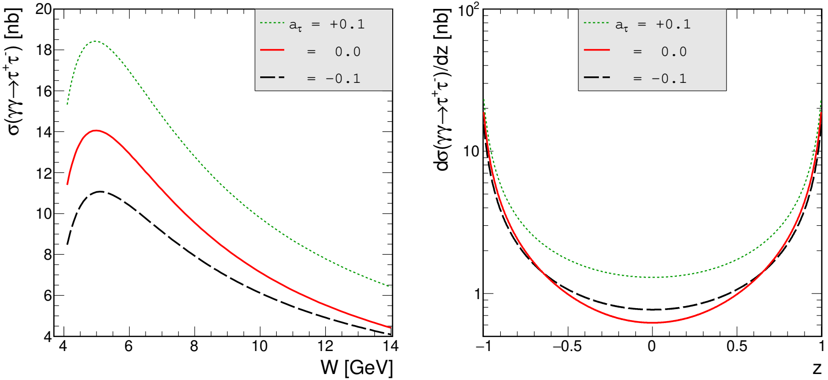
ELEMENTARY CROSS SECTION, a_τ DEPENDENCE

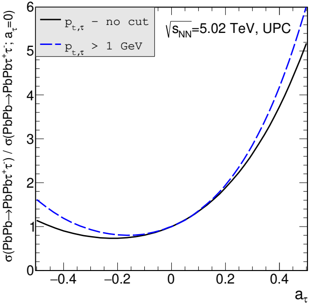


... as a function of energy

... as a function of $\cos\theta$ for W = 15 GeV

$\gamma\gamma \to \tau^+\tau^-$ STRONGLY DEPENDS ON a_τ

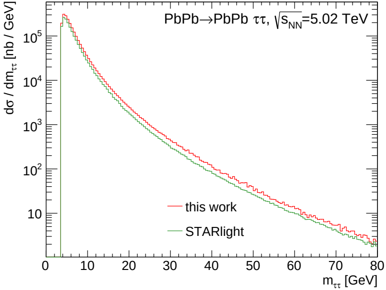
NUCLEAR CROSS SECTION, a_τ DEPENDENCE



Ratio of the total nuclear cross sections for Pb+Pb→Pb+Pb$\tau\tau$ production @ LHC as a function of a_τ, relative to SM (a_τ = 0).

FOR $|a_\tau| < 0.1$

RELATIVELY SMALL DEPENDENCE ON $p_{t,\tau}$



Comparison of SM results with STARLIGHT

DIFFERENCE ≈ 20%;

MODELING OF PHOTON FLUXES

AND ABSORPTION FACTOR

FIDUCIAL SELECTION AND τ DECAYS

- Tau is the heaviest lepton with a lifetime of 3×10^{-13} s
- Tau can decay into lighter leptons (electron or muon) or hadrons (mainly pions and kaons)
- Tau decay channels produce:
  - ➡ one charged particle (denoted as 1*ch*, or one-prong) $\approx$ 80%

    $$\tau \to \nu_\tau + \ell + \nu_\ell \; (\ell = e,\ \mu)$$

    $$\tau \to \nu_\tau + \pi^\pm + n\pi^0$$

  - ➡ three charged particles (denoted as 3*ch*, or three-prong) $\approx$ 20%

    $$\tau \to \nu_\tau + \pi^\pm + \pi^\mp + \pi^\pm + n\pi^0$$

Selection requirements of the $\gamma\gamma \to \tau^+\tau^-$ candidates events:

- ✓ at least one τ decays leptonically
- ✓ the leading lepton has $p_{t,e/\mu} > 4$ GeV & $|\eta| < 2.5$
- ✓ τ lepton pairs have low p_t → identification tools are not applicable → all charged-particle tracks from τ_{1ch} or τ_{3ch}: $p_T > 0.2$ GeV & $|\eta| < 2.5$
- ✓ condition on lepton-track system: $p_T^{\ell,ch} > 1$ GeV for $\tau_\ell\tau_{1ch}$ category to suppress e^+e^- & $\mu^+\mu^-$ bkg

SELECTION FOR ATLAS & CMS DETECTORS

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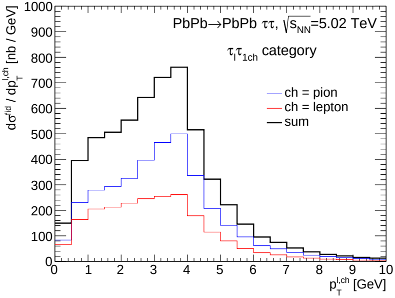
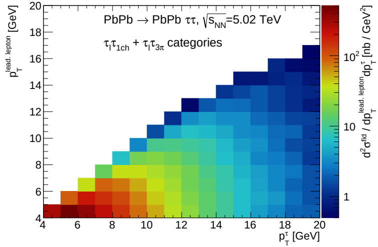
FIDUCIAL CROSS SECTION FOR SM SCENARIO



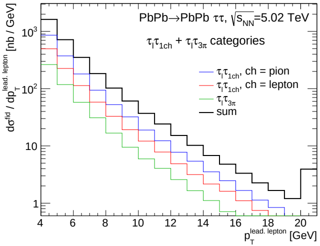
... as a function of $p_{\rm T}$ of the lepton+track system ($p_{\rm T}^{\ell\ ch}$) in the $\tau_\ell \tau_{1ch}$ category

$p_T^{\ell ch} > 1$ GEV (≈ 90% OF SIGNAL EVENTS)

TO SUPPRESS $\gamma\gamma \to \mu^+\mu^- / e^+e^-$ BKG

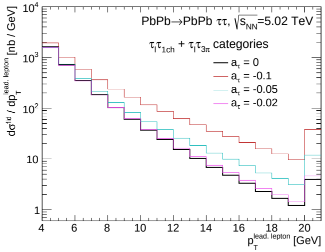


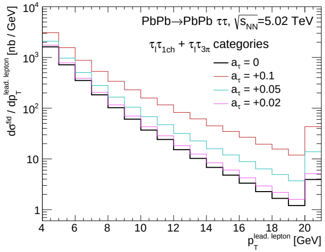
$p_{\rm T}^{\tau}$ & $p_{\rm T}^{lead.lepton}$ correlation



... as a function of $p_{\rm T}$ of the leading lepton for various event categories

FIDUCIAL CROSS SECTION FOR VARIOUS a_τ VALUES





.. as a function of p_T of the leading lepton for all event categories summed together

PREDICTIONS FOR CURRENT LHC PB+PB DATASET AND EXPECTED HL-LHC DATASET

a_τ value	σ_{fid} [nb]	Expected events (L_{int} = 2 nb^{-1}, C = 0.8)	Expected events (L_{int} = 20 nb^{-1}, C = 0.8)
−0.1	4770	7650	76 500
−0.05	3330	5350	53 500
−0.02	3060	4900	49 000
0 (SM)	3145	5050	50 500
+0.02	3445	5500	55 000
+0.05	4350	6950	69 500
+0.1	7225	11550	115 500

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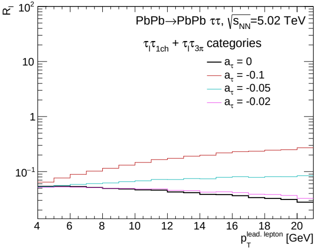
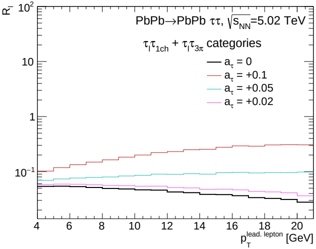
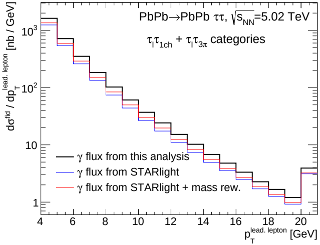
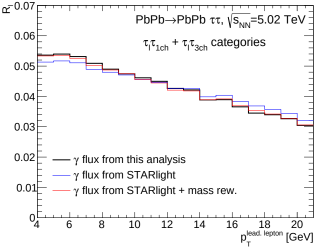
RATIO BETWEEN $\gamma\gamma \to \tau^+\tau^-$ AND $\gamma\gamma \to \ell^+\ell^-$





... as a function of p_{T} of the leading lepton for all event categories summed together





Fiducial cross section & Results with extra $m_{\ell\ell}$ shape reweighting

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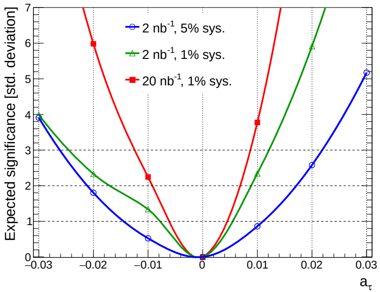
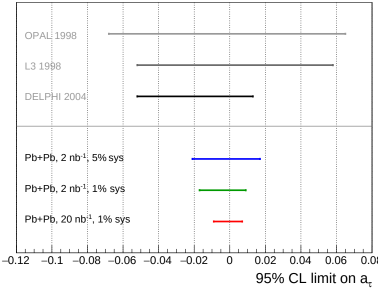
EXPECTED SIGNAL SIGNIFICANCE AS A FUNCTION OF a_τ

FOR VARIOUS ASSUMPTIONS ON PB+PB INTEGRATED LUMINOSITY AND TOTAL SYSTEMATIC UNCERTAINTY





Prediction (2020): $-0.021 < a_\tau^{expected} < 0.017$

CMS (2022): $-0.024 < a_\tau < 0.017$ (68% CL)

ATLAS (2022): $a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$ (95% CL)

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ELECTRIC DIPOLE MOMENT

EXPECTED

Including 95% CL sensitivity on $|d_\tau|$ and assuming $a_\tau = 0$:

- at the LHC with 5% systematic uncertainty

$$|d_\tau| < 6.3 \cdot 10^{-17}\ e \cdot \mathrm{cm}$$

- at the LHC with 1% systematic uncertainty

$$|d_\tau| < 4.4 \cdot 10^{-17}\ e \cdot \mathrm{cm}$$

- at HL-LHC with 1% systematic uncertainty

$$|d_\tau| < 3.5 \cdot 10^{-17}\ e \cdot \mathrm{cm}$$

The **CURRENT** best limits are measured by Belle experiment:

$$-2.2 < Re(d_\tau) < 4.5\ (10^{-17}\ e \cdot \mathrm{cm})$$

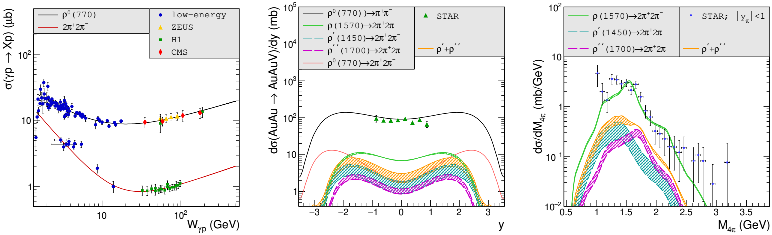
and

$$-2.5 < Im(d_\tau) < 0.8\ (10^{-17}\ e \cdot \mathrm{cm})$$

OUR RESULTS ON d_τ CAN BE THEREFORE COMPETITIVE WITH BELLE LIMITS

PHOTOPRODUCTION OF FOUR CHARGED PIONS

New H1 data!



Total cross section for $A_1 A_2 \to A_1 A_2 2\pi^+ 2\pi^-$ process.

Accelerator ($\sqrt{s_{NN}}$)	Experimental results	Theoretical results
RHIC (200 GeV)	2.4 ± 0.2(stat)± 0.8(syst) [mb]	$2.16 - 2.31$ [mb]
LHC (5.02 TeV)	-	$33.47 - 33.81$ [mb]

PROGRAM STYPENDIALNY IM. BEKKERA

THE MAIN SOURCE OF THE $4\pi^\pm$ PRODUCTION: THE EXCITED $\rho(1570)$ STATE

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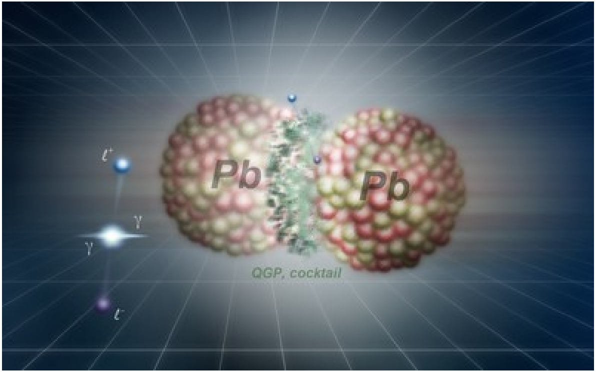
SEMICENTRAL HEAVY-ION COLLISIONS



- From ultraperipheral to semicentral collisions → dilepton sources
  - $\gamma\gamma$ fusion mechanism
- Invariant mass
  - SPS (NA60 data)
  - RHIC (STAR data)
  - LHC (ALICE data)
- Low-P_T dilepton spectra
  - RHIC (STAR data)
  - LHC (ALICE data)
- Acoplanarity
  - LHC (ATLAS data)

Dielectron invariant-mass spectra - RHIC

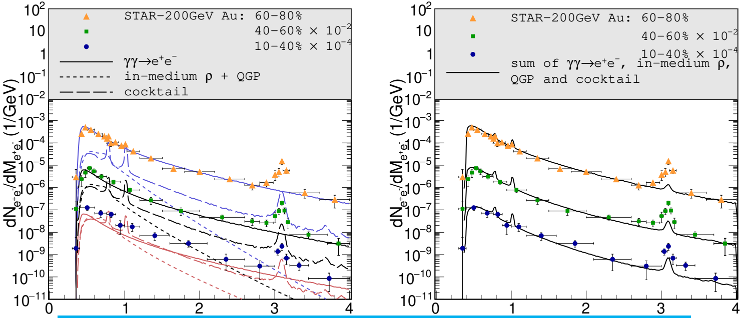
$p_t > 0.2$ GeV,

$|\eta_e| < 1$

$|y_{e^+e^-}| < 1$

- ✔ $\gamma\gamma$-fusion
- ✔ thermal radiation
- ✔ hadronic cocktail

3 centrality classes



The coherent emission dominates for the two peripheral samples

and is comparable to the cocktail and thermal radiation yields in semi-central collisions.

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EPA in the impact parameter space - the pair transverse momentum $P_T^{\ell^+\ell^-}$ is neglected

$$\sigma_{A_1 A_2 \to A_1 A_2 \ell^+\ell^-} = \int N(\omega_1, \mathbf{b_1}) N(\omega_2, \mathbf{b_2}) \delta^{(2)}(\mathbf{b} - \mathbf{b}_1 - \mathbf{b}_2) \int d^2\mathbf{b}_1 d^2\mathbf{b}_2 d^2\mathbf{b}\, dy_{\ell^+} dy_{\ell^-} dp_{t,\ell}^2 \frac{d\sigma(\gamma\gamma \to \ell^+\ell^-; \hat{s})}{d(-\hat{t})}$$

➩ k_t**-factorization**

$$\frac{dN_{ll}}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int \frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2} d^2\boldsymbol{q}_{1t} d^2\boldsymbol{q}_{2t} \frac{dN(\omega_1, q_{1t}^2)}{d^2\boldsymbol{q}_{1t}} \frac{dN(\omega_2, q_{2t}^2)}{d^2\boldsymbol{q}_{2t}} \delta^{(2)}(\boldsymbol{q}_{1t} + \boldsymbol{q}_{2t} - \mathbf{P}_T^{\ell^+\ell^-}) \hat{\sigma}(\gamma\gamma \to \ell^+\ell^-)\Big|_{\text{cuts}},$$

➩ **Exact calculation**

$$\frac{d\sigma[\mathcal{C}]}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int \frac{d^2\boldsymbol{Q}}{2\pi} w(Q; b_{\max}, b_{\min}) \int \frac{d^2\boldsymbol{q}_1}{\pi}\frac{d^2\boldsymbol{q}_2}{\pi} \delta^{(2)}(\mathbf{P}_T^{\ell^+\ell^-} - \mathbf{q}_1 - \boldsymbol{q}_2) \int \frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2}$$

$$\times\ E_i\left(\omega_1, \boldsymbol{q}_1 + \frac{\boldsymbol{Q}}{2}\right) E_j^*\left(\omega_1, \boldsymbol{q}_1 - \frac{\boldsymbol{Q}}{2}\right) E_k\left(\omega_2, \boldsymbol{q}_2 - \frac{\boldsymbol{Q}}{2}\right) E_l^*\left(\omega_2, \boldsymbol{q}_2 + \frac{\boldsymbol{Q}}{2}\right) \frac{1}{2\hat{s}} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger}\, d\Phi(\ell^+\ell^-).$$

The factorization formula is written in terms of the Wigner function:

$$N_{ij}(\omega, \mathbf{b}, \mathbf{q}) = \int \frac{d^2\mathbf{Q}}{(2\pi)^2} \exp[-i\mathbf{b}\mathbf{Q}] E_i\left(\omega, \mathbf{q} + \frac{\mathbf{Q}}{2}\right) E_j^*\left(\omega, \mathbf{q} - \frac{\mathbf{Q}}{2}\right) = \int d^2\mathbf{s} \exp[i\mathbf{q}\mathbf{s}] E_i\left(\omega, \mathbf{b} + \frac{\mathbf{s}}{2}\right) E_j^*\left(\omega, \mathbf{b} - \frac{bs}{2}\right),$$

$$N(\omega, \mathbf{q}) = \delta_{ij} \int d^2\mathbf{b}\, N_{ij}(\omega, \mathbf{b}, \mathbf{q}) = \delta_{ij} E_i(\omega, \mathbf{q}) E_j^*(\omega, \mathbf{q}) = \left|\boldsymbol{E}(\omega, \mathbf{q})\right|^2,$$

$$N(\omega, \mathbf{b}) = \delta_{ij} \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} N_{ij}(\omega, \mathbf{b}, \mathbf{q}) = \delta_{ij} E_i(\omega, \mathbf{b}) E_j^*(\omega, \mathbf{b}) = \left|\mathbf{E}(\omega, \mathbf{b})\right|^2.$$

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PAIR TRANSVERSE MOMENTUM - RHIC & LHC

$p_t > 0.2$ GeV,

$|\eta_e| < 1$

c=(60-80)%

$|y_{ee}| < 1$

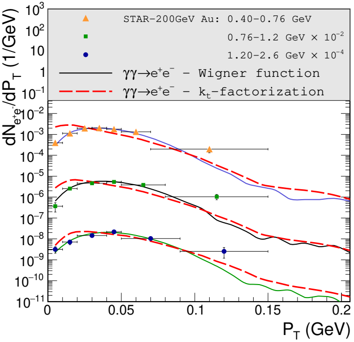
- - - - - - PLB**790** (2019) 339
vs.
—— PLB**814** (2021) 136114

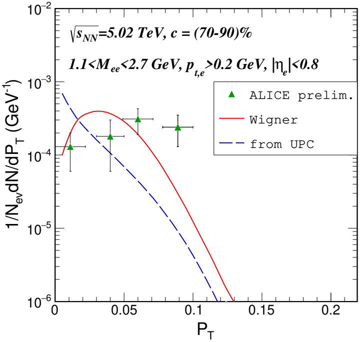
$p_t > 0.2$ GeV,

$|\eta_e| < 0.8$

c=(70-90)%

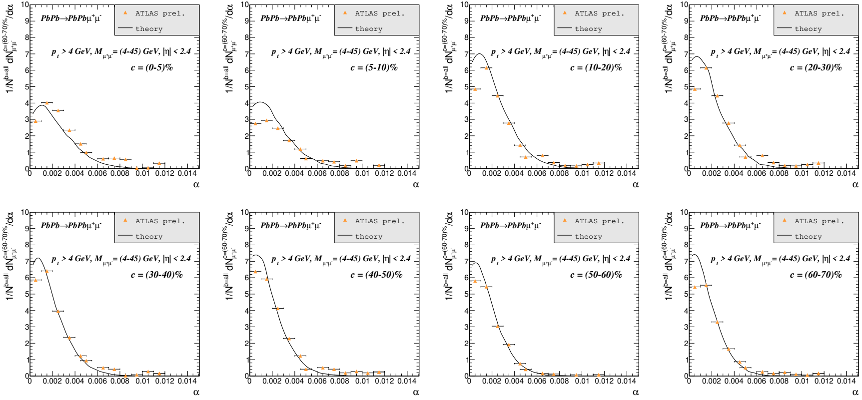
$M_{e^+e^-}$ =(1.1-2.7) GeV





Small correction to the STAR description & much better situation for LHC

ACOPLANARITY - ATLAS DATA



A successful description of ATLAS data by $\gamma\gamma$-fusion alone

A correct normalization and shape of the distributions

$p_t > 4$ GeV,

$M_{\mu^+\mu^-}$ =(4-45) GeV,

$|\eta_\mu| < 2.4$

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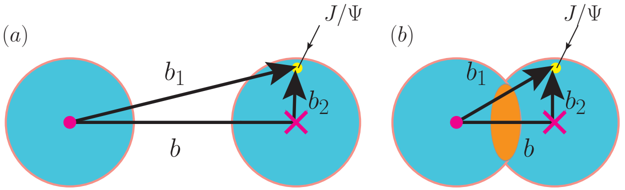
CHARMONIUM PHOTOPRODUCTION

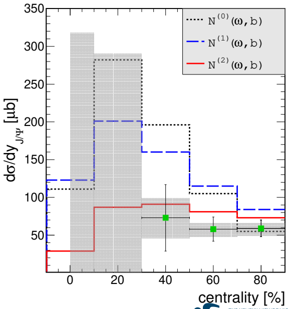


The inclusion of the absorption effect by modifying effective photon fluxes in the impact parameter space.

$$N^{(1)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|))}{\pi R_A^2} d^2 b_1$$

$$N^{(2)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|))(b_1 - R_A)}{\pi R_A^2} d^2 b_1$$

A successful description of ALICE data



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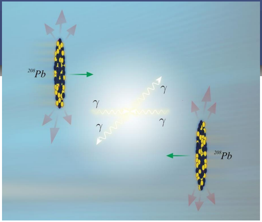
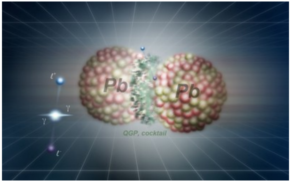
Conclusion

- EPA in the impact parameter space
- Ultraperipheral & semicentral heavy-ion collisions
- Fourier transform of the charge distribution
- Multidimensional integrals $\rightarrow$ differential cross section
- Description of experimental data for UPC and semicentral events
  - 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
- Study of a_τ in UPC
- Collaboration - theoreticians and experimenters
- Future - study of processes in low p_t (ALICE3)

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.



Creation without contact in the collisions of lead and gold nuclei, EurekAlert!
Semicentral or central collisions of lead nuclei in the LHC produce QGP and a cocktail with contributions of other particles. Simultaneously, clouds of photons surrounding the nuclei collide, resulting in the creation of $\ell^+\ell^-$ pairs within the plasma and cocktail, and in the space around the nuclei.

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