FROM UPC TO SEMI-CENTRAL HEAVY-ION COLLISIONS

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- ✓ 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,
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- ✓ M. K-G. Rapp, W. Schäfer, A. Szczurek, *Dilepton Radiation in Heavy-Ion Collisions at Small Transverse Momentum*, Phys. Lett. **B790** (2019) 339–344;
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- ✓ M. K-G, A. Szczurek, *Photoproduction of J/ψ mesons in peripheral and semicentral heavy ion collisions*, Phys. Rev. **C93** (2016) 044912.

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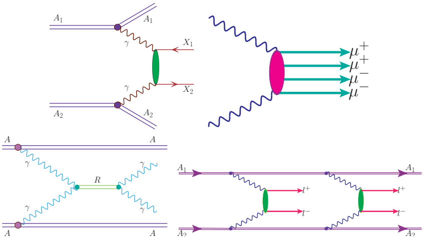
CLASSIFICATION

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 $-(R_1 + R_2)$);
   - ultraperipheral collisions: b $> (R_1 + R_2)$;

   where $R = R_0 A^{1/3}$.
3. Type of production:

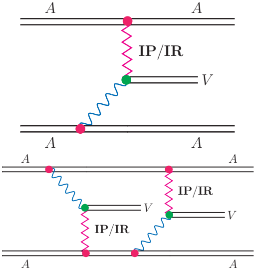
$\gamma\gamma$ fusion



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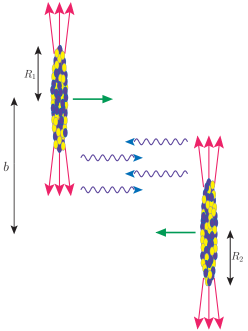
Equivalent Photon Approximation

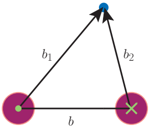


The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.
Electromagnetism is a long-range force, so electromagnetic interactions occur even at relatively large ion-ion separations.

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

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

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



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

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

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

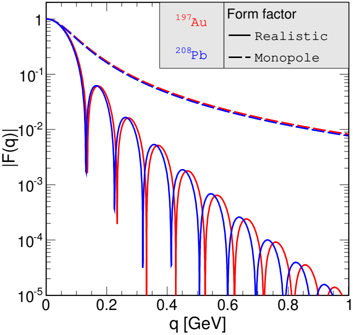
$$N(\omega, b) = \frac{Z^2\alpha_{em}}{\pi^2\beta^2}\frac{1}{\omega}\frac{1}{b^2} \times u^2 \left[K_1^2(u) + \frac{1}{\gamma^2}K_0^2(u)\right]$$

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

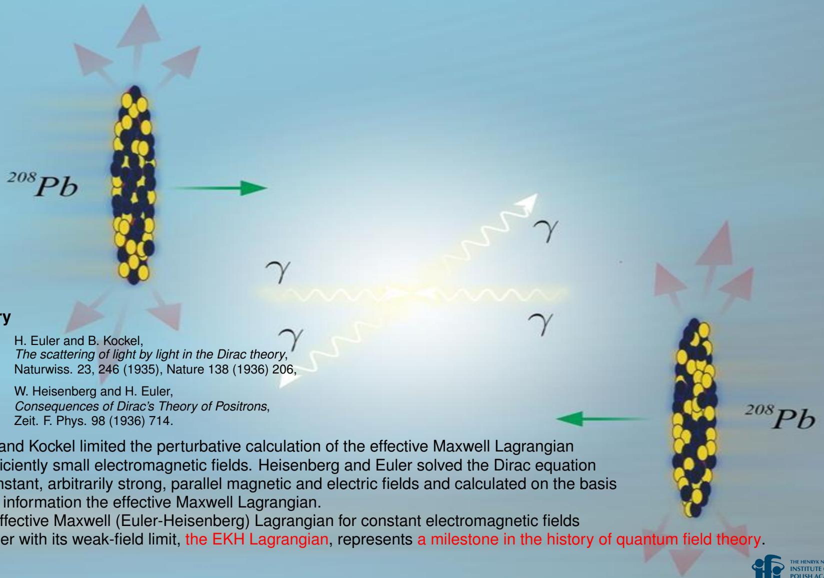
$$\sqrt{\langle r^2 \rangle} = \sqrt{\frac{6}{\Lambda^2}} = 1\ \text{fm}\ A^{1/3}$$

- realistic

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



LIGHT-BY-LIGHT SCATTERING



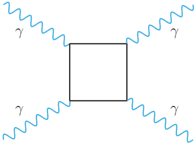
History

- 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.

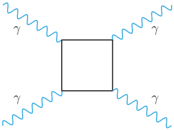
LIGHT-BY-LIGHT SCATTERING

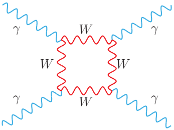
- ❍ Maxwell classical theory
  - ✓ light doesn't interact with each other
- ❍ Quantum theory
  - ✓ interaction of photons through quantum fluctuations



- $\sigma(\gamma\gamma \to \gamma\gamma) \propto \alpha_{em}^4$ → 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**

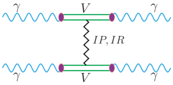


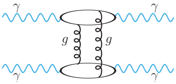


Fermionic boxes (LO QED) FormCalc. W Box LoopTools.

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

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





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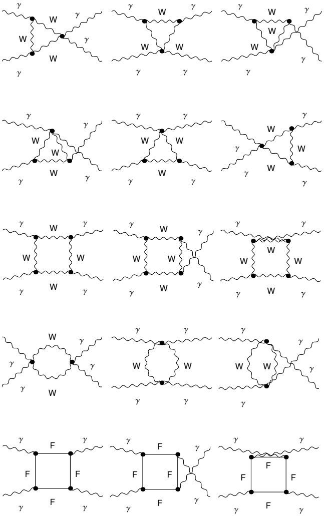
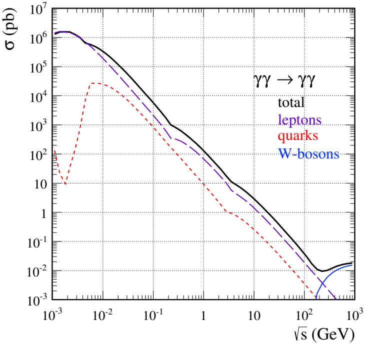
BOXES $\gamma\gamma \to \gamma\gamma$



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.

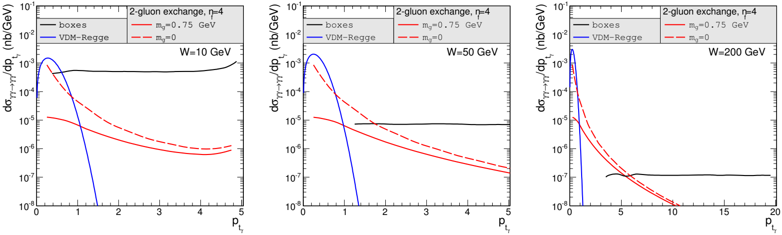
EXPERIMENTAL IDENTIFICATION OF PROCESSES

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

W = 10 GeV

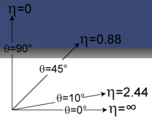
W = 50 GeV

W = 200 GeV



$\gamma - \gamma$ Collider?

$AA \to AA\gamma\gamma$ - FORM FACTOR

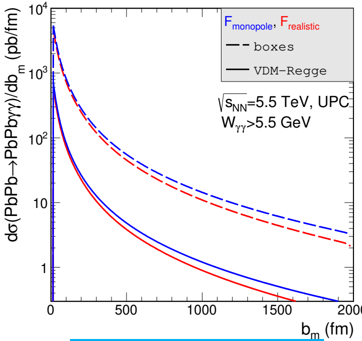


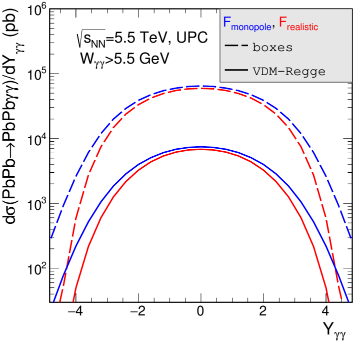
⇨ realistic

⇨ monopole

impact parameter

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





↑ theoretical distribution

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

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

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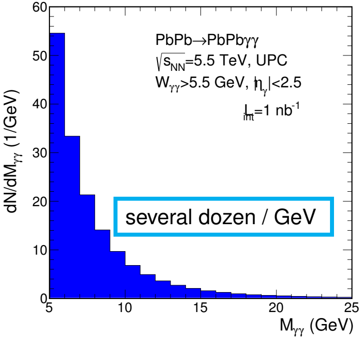
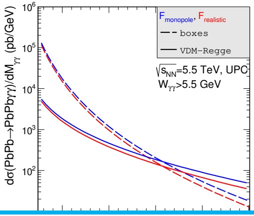


$W_{\gamma\gamma} = M_{\gamma\gamma}$



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					

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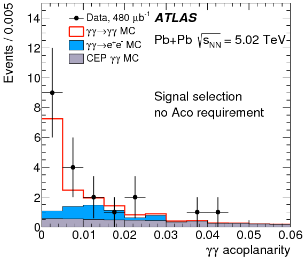
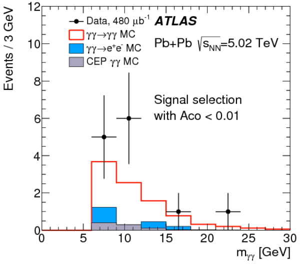
AA→AA$\gamma\gamma$ - ATLAS RESULTS

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

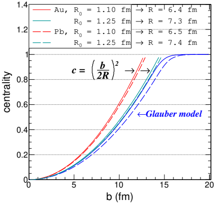
- CMS Coll., Phys. Lett. **B797** (2019) 134826
  - ✗ $E_{t_\gamma} > 2$ GeV
  - ✗ $|\eta_\gamma| < 2.4$
  - ✗ $M_{\gamma\gamma} > 5$ GeV
  - ✗ $p_{t_{\gamma\gamma}} < 1$ GeV
  - ✗ Aco < 0.01
- ATLAS Collaboration, JHEP 03 (2021) 243
  - ✗ $E_{t_\gamma} > 2.5$ GeV
  - ✗ $|\eta_\gamma| < 2.4$
  - ✗ $M_{\gamma\gamma}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

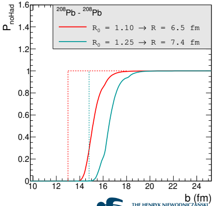
Experiment		Theory		
		Nuclear radius: $R = R_0 A^{\frac{1}{3}}$		Glauber model
Collaboration	σ nb	$\sigma(b = 13\text{fm})$	$\sigma(b = 14.8\text{fm})$	$\sigma(b = 20\text{fm})$
ATLAS (2018 data)	78 ± 13(stat.)± 7(syst.)	52	50	45
ATLAS (2015+2018)	120 ± 17(stat.)± 13(syst.)	82	80	71
CMS (2015)	120 ± 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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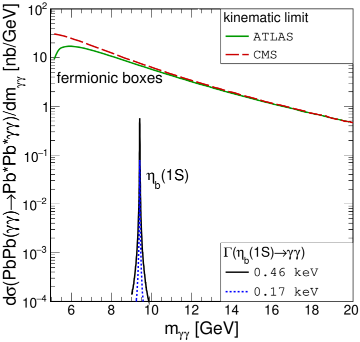
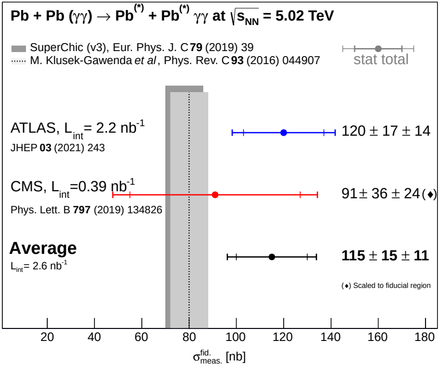
2022 results





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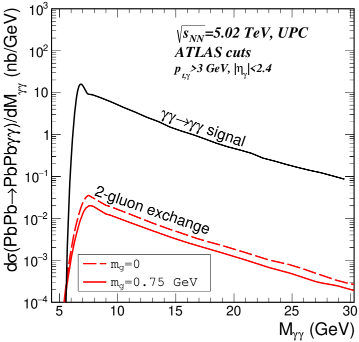
HIGHER ORDER PROCESSES..?

$\gamma\gamma$ invariant mass

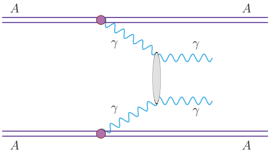


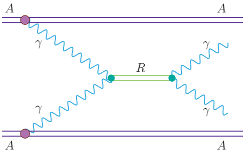
Coherent sum of both processes...?

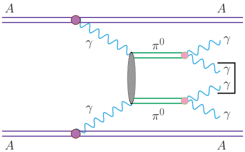
Pionic boxes...?

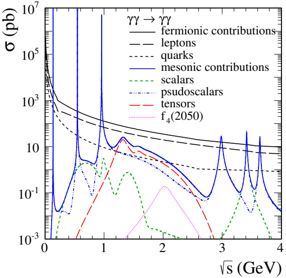
AA→AA$\gamma\gamma$ FOR $M_{\gamma\gamma} < 5$ GEV ?

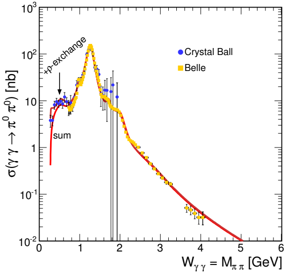
CONTINUUM **RESONANCES** **BACKGROUND**











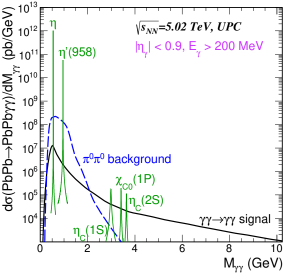
- P. Lebiedowicz, A. Szczurek,
  *Phys. Lett. **B772** (2017) 330*,
  The role of meson exchanges in light-by-light scattering
- M. K-G, A. Szczurek, *Phys. Rev. **C87** (2013) 054908*;
  $\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in ultraperipheral ultrarelativistic heavy-ion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

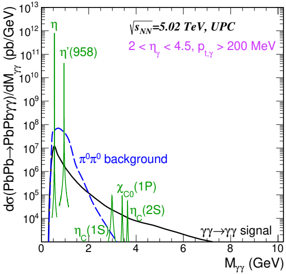
UPC OF AA...

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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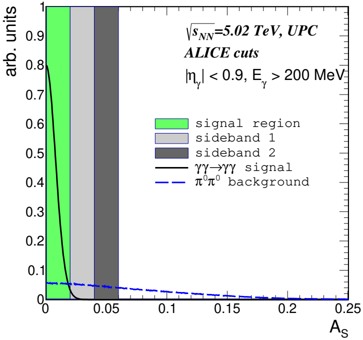
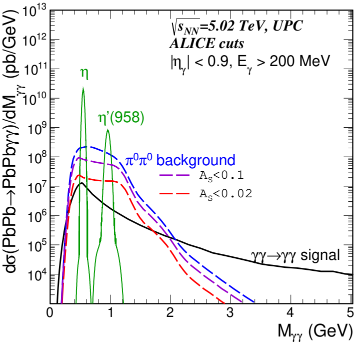
EXPERIMENTAL RESOLUTION & SCALAR ASYMMETRY & "UNWANTED" BKG

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

A_S



$M_{\gamma\gamma}$



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

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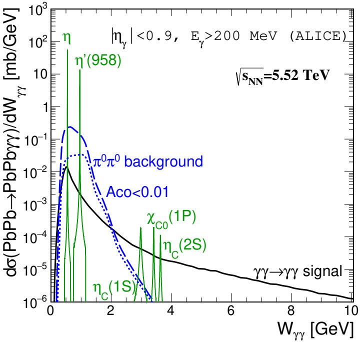
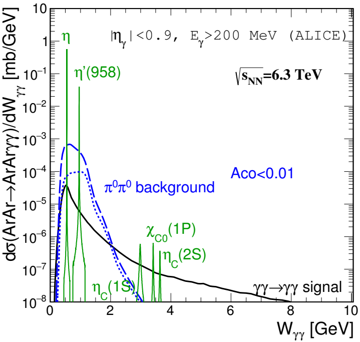
AA→AAγγ @ MIDRAPIDITY

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



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



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

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

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

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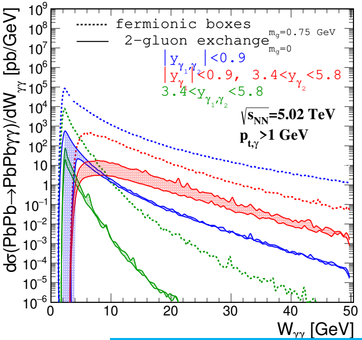
AA→AA$\gamma\gamma$ @ FORWARD REGION ?

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

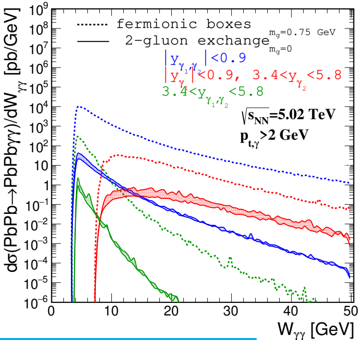
FoCAL $\rightarrow 3.4 < \eta < 5.8$

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



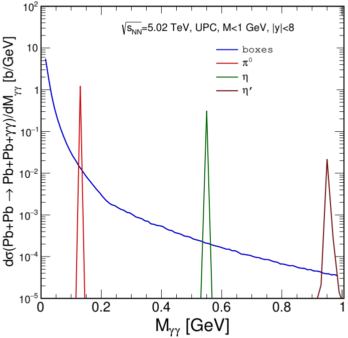
Boxes & 2-gluon exchange (with effective gluon mass)

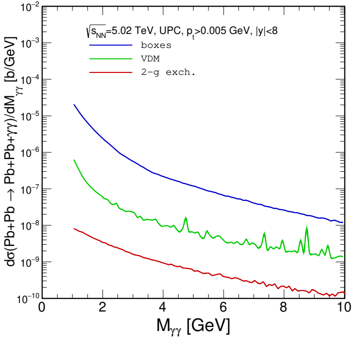
AA→AA$\gamma\gamma$ @ LOW p_t REGION ?

$p_{t,\gamma} > 5$ MeV

$M_{\gamma\gamma} < 1$ GeV

$M_{\gamma\gamma} > 1$ GeV





ALICE3 - new opportunities

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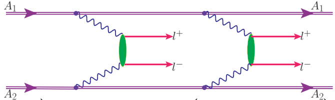
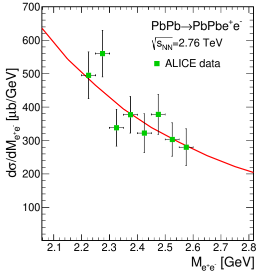
FOUR-LEPTON PRODUCTION

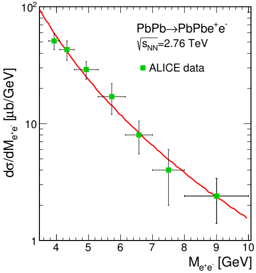


$$\frac{d\sigma_{A_1 A_2 \to A_1 A_2 (\ell^+\ell^-)(\ell^+\ell^-)}}{dy^{I}_{\ell^+} dy^{I}_{\ell^-} dy^{II}_{\ell^+} dy^{II}_{\ell^-}} = \frac{1}{2} \int \left(\frac{dP^{I}_{\gamma\gamma\to\ell^+\ell^-}\left(b, y^{I}_{\ell^+}, y^{I}_{\ell^-}; p_{t,\ell}\right)}{dy^{I}_{\ell^+} dy^{I}_{\ell^-}} \times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

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

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





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

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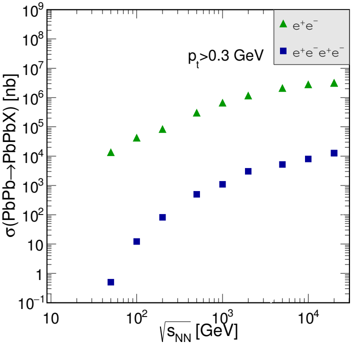
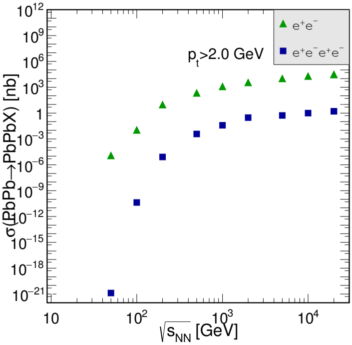
$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

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

$p_t > 0.3$ GeV

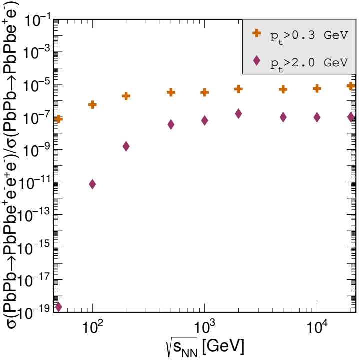


$p_t > 2.0$ GeV



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

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



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

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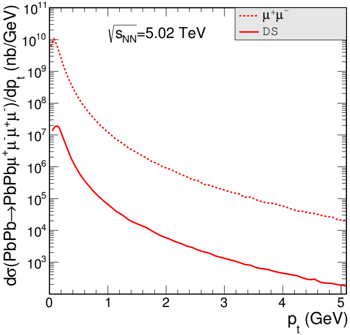
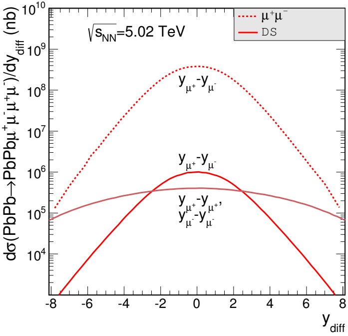
$AA \to AA\mu^+\mu^-$ & $AA \to AA\mu^+\mu^-\mu^+\mu^-$

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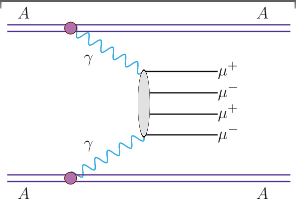
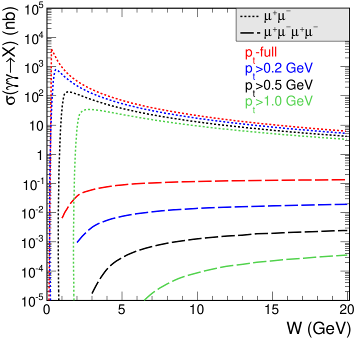
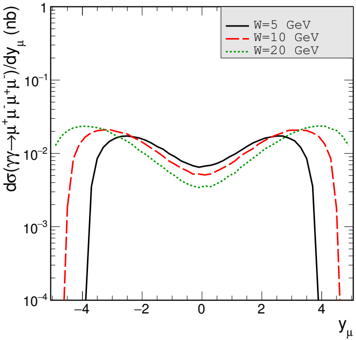
$\gamma\gamma \to \mu^+\mu^-\mu^+\mu^-$ - SINGLE SCATTERING

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.







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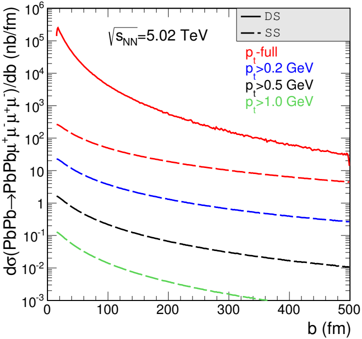
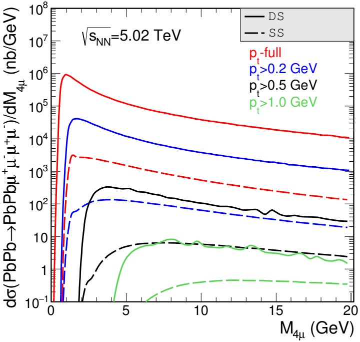
$AA \to AA\mu^+\mu^-\mu^+\mu^-$

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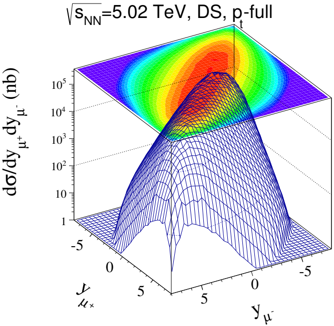
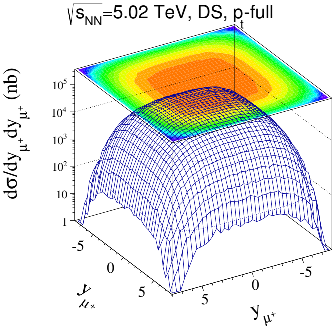
$AA \to AA\mu^+\mu^-\mu^+\mu^-$

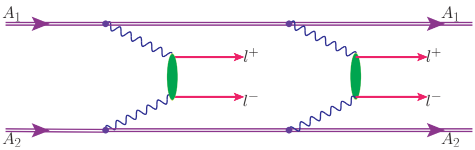
y_{μ^+}, y_{μ^-}



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



$p_{t,\mu^+} \simeq p_{t,\mu^-}$ $\Rightarrow$ 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

experimental cuts	N
$\lvert y_i \rvert < 2.5$, $p_t > 0.5$ GeV	815
$\lvert y_i \rvert < 2.5$, $p_t > 1.0$ GeV	53
$\lvert y_i \rvert < 0.9$, $p_t > 0.5$ GeV	31
$\lvert y_i \rvert < 0.9$, $p_t > 1.0$ GeV	2
$\lvert y_i \rvert < 2.4$, $p_t > 4.0$ GeV	$\ll$1

$(4e)$, $\sqrt{s_{NN}}$ = 5.5 TeV

experimental cuts	N
$\lvert y_i \rvert < 2.5$, $p_t > 0.5$ GeV	235
$\lvert y_i \rvert < 2.5$, $p_t > 1.0$ GeV	10
$\lvert y_i \rvert < 1.0$, $p_t > 0.2$ GeV	649
$\lvert y_i \rvert < 1.0$, $p_t > 1.0$ 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, $\lvert y \rvert < 4.9$

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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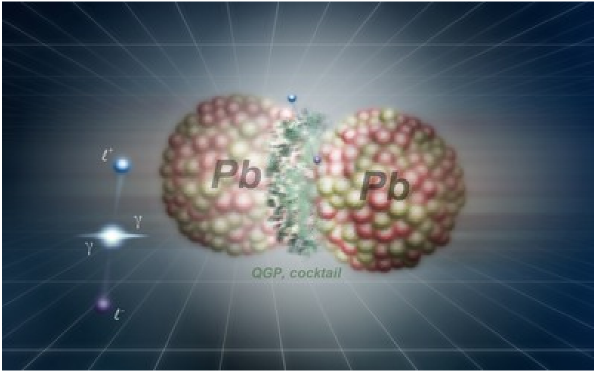
SEMICENTRAL HEAVY-ION COLLISIONS



- 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

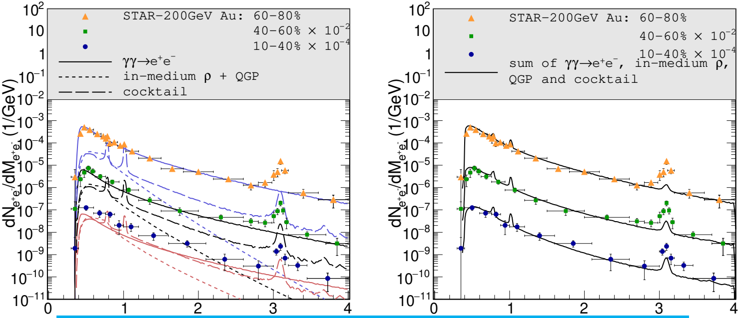
$p_t > 0.2$ GeV,

$|\eta_e| < 1$

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

- ✔ $\gamma\gamma$-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

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

- k_t**-factorization**

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

- **Exact calculation**

$$\frac{d\sigma[\mathcal{C}]}{d^2\mathbf{P}_T^{\ell^+\ell^-}} = \int \frac{d^2\boldsymbol{Q}}{2\pi} w(Q; b_{\max}, b_{\min}) \int \frac{d^2\boldsymbol{q}_1}{\pi} \frac{d^2\boldsymbol{q}_2}{\pi} \delta^{(2)}(\mathbf{P}_T^{\ell^+\ell^-} - \mathbf{q}_1 - \boldsymbol{q}_2) \int \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2}$$
$$\times \quad E_i\left(\omega_1, \boldsymbol{q}_1 + \frac{\boldsymbol{Q}}{2}\right) E_j^*\left(\omega_1, \boldsymbol{q}_1 - \frac{\boldsymbol{Q}}{2}\right) E_k\left(\omega_2, \boldsymbol{q}_2 - \frac{\boldsymbol{Q}}{2}\right) E_l^*\left(\omega_2, \boldsymbol{q}_2 + \frac{\boldsymbol{Q}}{2}\right) \frac{1}{2\hat{s}} \sum_{\lambda\bar{\lambda}} M_{ik}^{\lambda\bar{\lambda}} M_{jl}^{\lambda\bar{\lambda}\dagger}\, d\Phi(\ell^+\ell^-)\,.$$

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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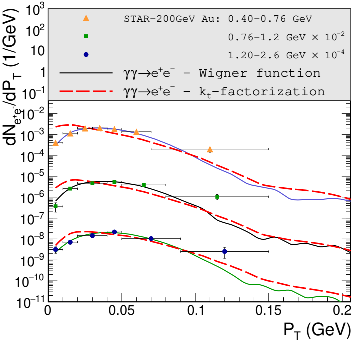
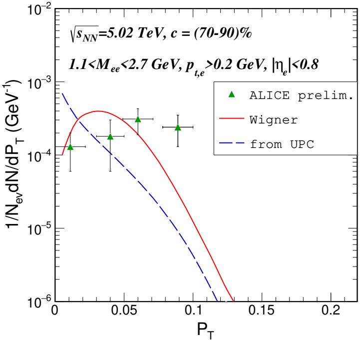
PAIR TRANSVERSE MOMENTUM - RHIC & LHC

RHIC		LHC
$p_t > 0.2$ GeV,	- - - - - - PL**B790** (2019) 339	$p_t > 0.2$ GeV,
$\vert\eta_e\vert < 1$	vs.	$\vert\eta_e\vert < 0.8$
c=(60-80)%	—— PL**B814** (2021) 136114	c=(70-90)%
$\vert y_{ee}\vert < 1$		$M_{e^+e^-}$ =(1.1-2.7) GeV





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

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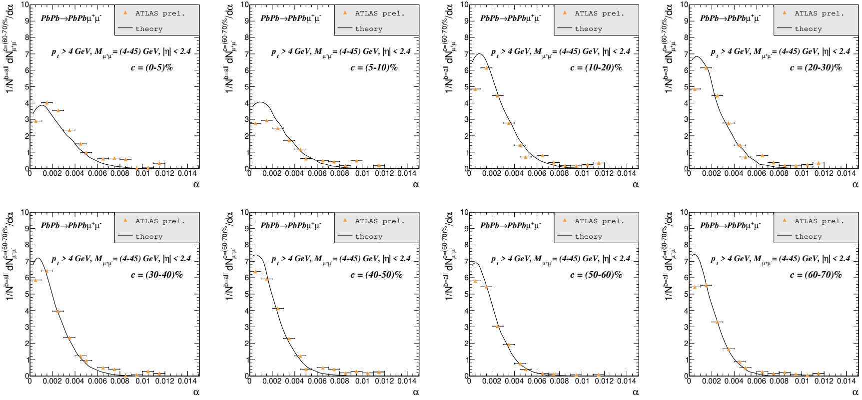
ACOPLANARITY - ATLAS DATA



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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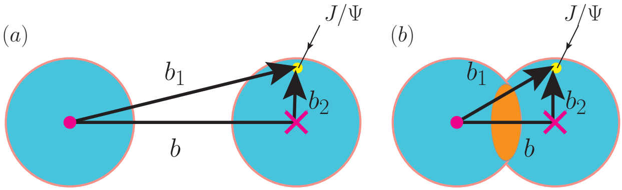
CHARMONIUM PHOTOPRODUCTION

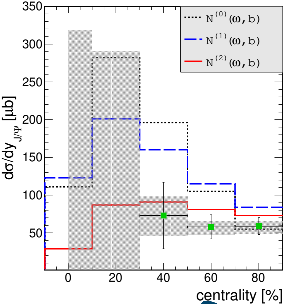


The inclusion of the absorption effect by modifying effective photon fluxes in the impact parameter space.

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

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

A successful description of ALICE data



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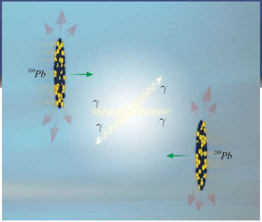
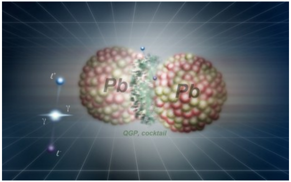
Conclusion

- 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
- 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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