Cracovian theoretical results for ultraperipheral heavy-ion collisions

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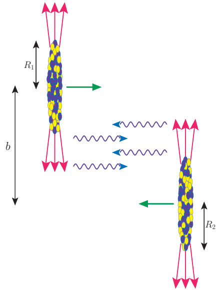
EPA

Photon-photon scattering

Four-lepton production

Proton-antiproton production

Conclusion



UltraPeripheralCollisions

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

1. M. K-G, P. Lebiedowicz, A. Szczurek, Light-by-light scattering in ultraperipheral Pb-Pb collisions at energies available at the CERN Large Hadron Collide, Phys. Rev. **C93** (2016) 044907,
2. M. K-G, W. Schäfer, A. Szczurek, Two-gluon exchange contribution to elastic $\gamma\gamma \to \gamma\gamma$ scattering and production of two-photons in ultraperipheral ultrarelativistic heavy ion and proton-proton collisions, Phys. Lett. **B761** (2016) 399,
3. M. K-G, A. Szczurek, Double scattering production of two positron–electron pairs in ultraperipheral heavy-ion collisions, Phys. Lett. **B763** (2016) 416,
4. A. van Hameren, M. K-G, A. Szczurek, From the Single- and double-scattering production of four muons in ultraperipheral PbPb collisions at the Large Hadron Collider, Phys. Lett. **B776** (2018) 84,
5. M. K-G, P. Lebiedowicz, O. Nachtmann, A. Szczurek, From the $\gamma\gamma \to p\bar{p}$ reaction to the production of $p\bar{p}$ pairs in ultraperipheral ultrarelativistic heavy-ion collisions at the LHC, Phys. Rev. **D96** (2017) 094029.

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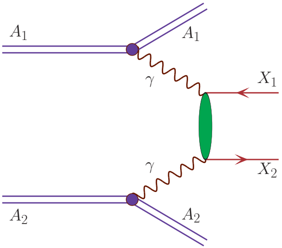
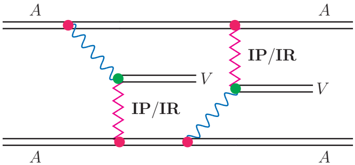
$\gamma\gamma$ fusion



Photoproduction

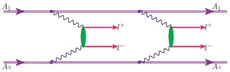


- ✓ ρ^0, J/ψ

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

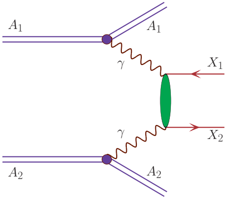
- ✓ $\pi^+\pi^-\pi^+\pi^-$

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



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

Nuclear Cross Section



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

NAIVELY $\Rightarrow$ ... $= \int \mathrm{d}\omega_1\, \mathrm{d}\omega_2\, n(\omega_1) n(\omega_2)$

$\times\ \sigma_{\gamma\gamma \to X_1 X_2}(\omega_1, \omega_2)$

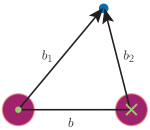
$$n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b\, N(\omega, b)$$

MORE

CORRECTLY $\Rightarrow$ ... $= \int N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b})$

$\times\ \sigma_{\gamma\gamma \to X_1 X_2}(W_{\gamma\gamma})$

$\times\ \mathrm{d}^2 b\, \mathrm{d}\bar{b}_x\, \mathrm{d}\bar{b}_y\, \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma}\, \mathrm{d}Y_{X_1 X_2}$



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Photon flux & Form factor

✗ charge distribution in nucleus

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

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

Form factor

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

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

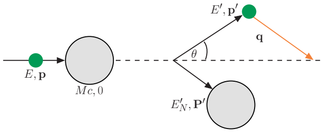

Fig.: Elastic scattering of electron-nucleus

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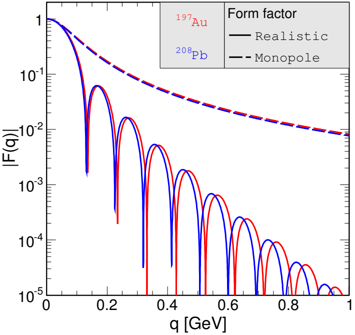
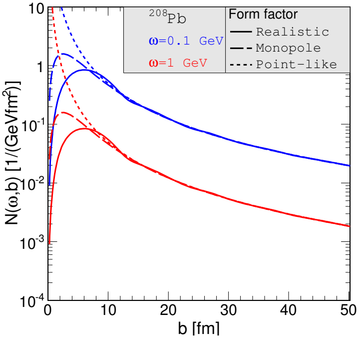
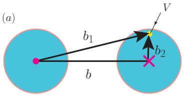
Form factor & Photon flux

- realistic charge distribution

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







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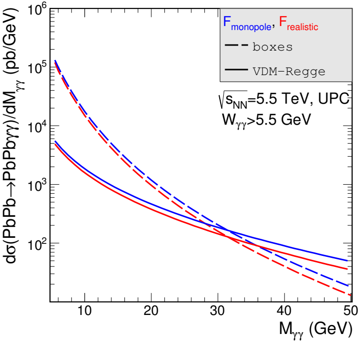
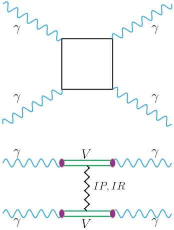
AA→AA$\gamma\gamma$ - FORM FACTOR

- ⇨ realistic
- ⇨ monopole



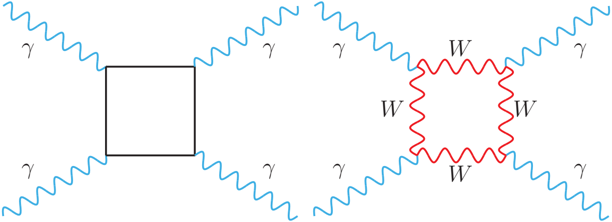


$\frac{\sigma_{monopole}}{\sigma_{realistic}}$ ↗ for larger values of kinematic variables

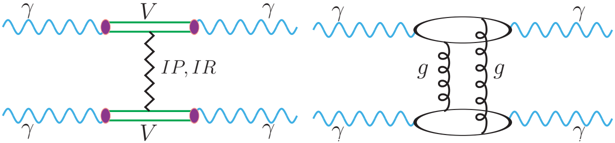
Cracovian theoretical results for UPC
EPA
$\gamma\gamma$ scattering
Four-lepton production
Electrons
Muons
Proton-antiproton production
Conclusion

$\gamma - \gamma$ ELASTIC SCATTERING

WELL-KNOWN



WE ADD



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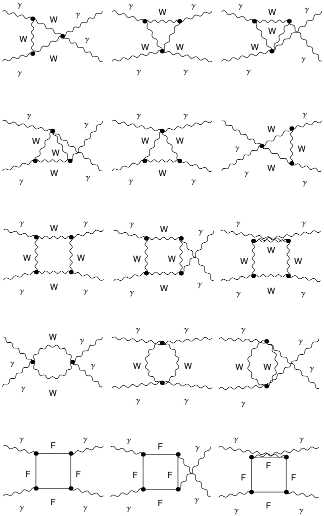
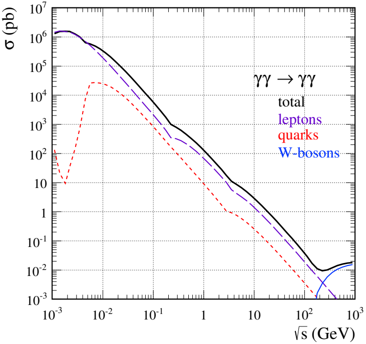
BOXES $\gamma\ \gamma \rightarrow \gamma\ \gamma$



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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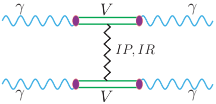
VDM-REGGE CONTRIBUTION



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

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

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

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

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

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

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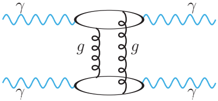
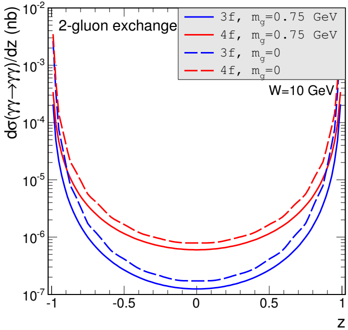
2-GLUON EXCHANGE

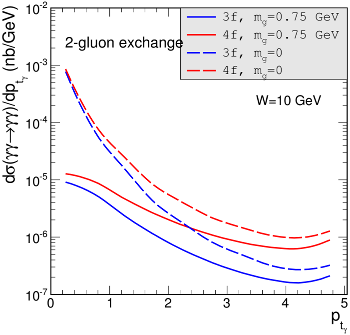
16 diagrams $\Rightarrow$



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

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





3f = u ,d, s

4f = u, d, s, c

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

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

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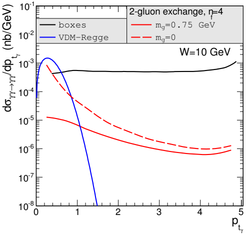
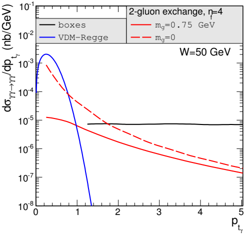
EXPERIMENTAL IDENTIFICATION OF PROCESSES?

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

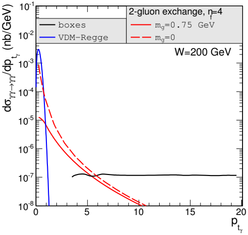
$W = 10$ GeV



$W = 50$ GeV



$W = 200$ GeV



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

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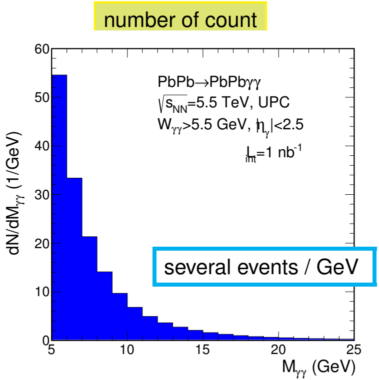
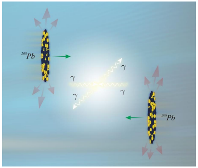


Photon collisions:
Photonic billiards might be the newest game!

www.eurekalert.org/pub_releases/2016-05/thni-pcp051916.php



$\sigma(PbPb \to PbPb\gamma\gamma)$ [nb] at LHC ($\sqrt{s_{NN}} = 5.5$ TeV) and 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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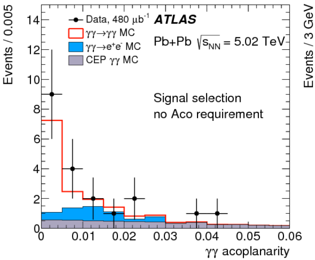
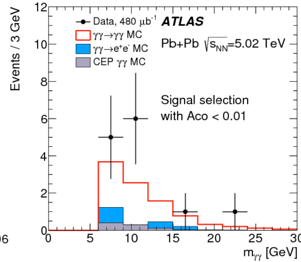
AA→AA$\gamma\gamma$ - THEORETICAL PREDICTIONS VS. EXPERIMENT

- 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





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

- ✔ $\gamma\gamma \to \gamma\gamma$ - using our calculations
- ✔ background:
  - ✔ $\gamma\gamma \to e^+e^-$
  - ✔ $gg \to \gamma\gamma$
  - ✔ $\gamma\gamma \to q\bar{q}$
- ✔ 13 events were observed

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

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

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

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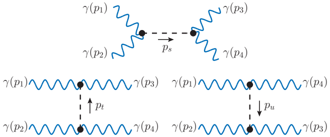
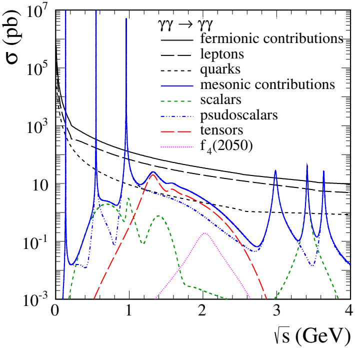
$M_{\gamma\gamma} < 5$ GeV $\Rightarrow$ Meson exchange





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

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

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

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

η & η' at UPC of AA...

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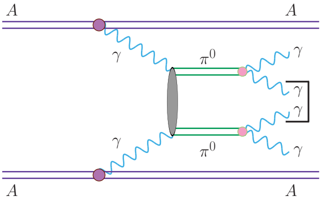
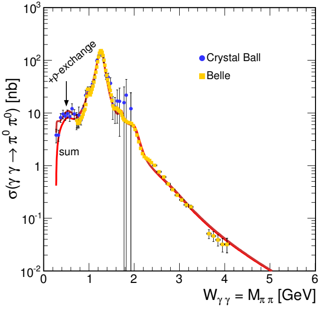
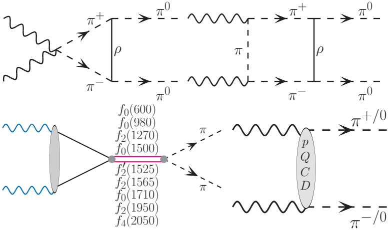
$M_{\gamma\gamma} < 5$ GeV $\Rightarrow \pi^0\pi^0$ Background

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



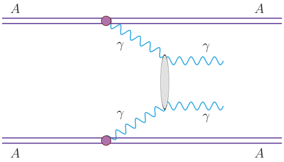
$\gamma\gamma \to \pi^0\pi^0$



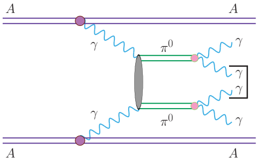


AA→AA$\gamma\gamma$ FOR $M_{\gamma\gamma} < 5$ GEV ? NEW

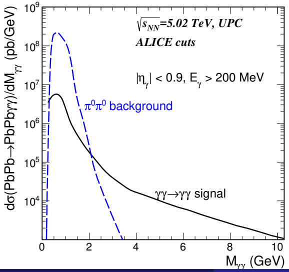
signal

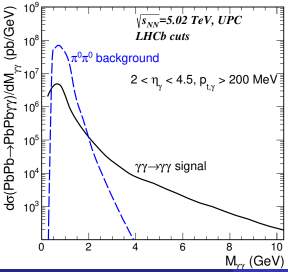


background



experiment	pseudorapidity range	other condition
ALICE	$-0.9 < \eta_\gamma < 0.9$	$E_\gamma > 200$ MeV
LHCb	$2.0 < \eta_\gamma < 4.5$	$p_{t,\gamma} > 200$ MeV





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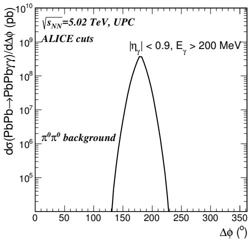
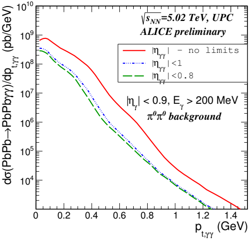
$$\Delta\phi = \phi_{\gamma_1} - \phi_{\gamma_2}$$

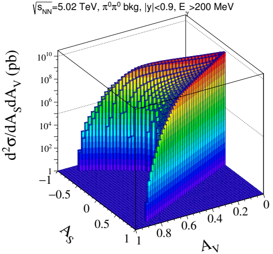


$$\vec{p}_{t,\gamma\gamma} = \vec{p}_{t,\gamma_1} + \vec{p}_{t,\gamma_2}$$

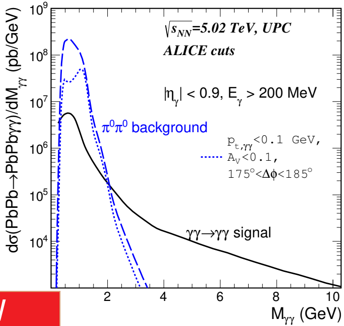


$$A_S = (|\vec{p_{t1}}| - |\vec{p_{t2}}|)/(|\vec{p_{t1}}| + |\vec{p_{t2}}|),$$

$$A_V = |\vec{p_{t1}} + \vec{p_{t2}}|/|\vec{p_{t1}} - \vec{p_{t2}}|$$



$$\Delta\phi \in (175 - 185)^o, |A_{S/V}| < 0.1, p_{t,\gamma\gamma} < 0.1 \text{ GeV}$$

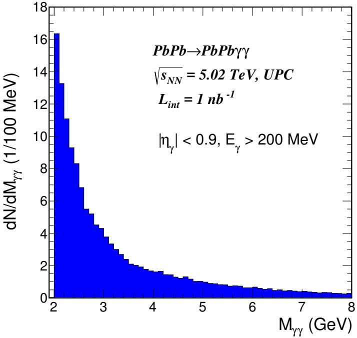


NEW

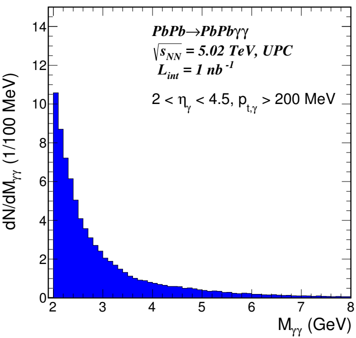
AA→AAγγ FOR $M_{\gamma\gamma} > 2$ GeV ?

Our Predictions

ALICE cuts



LHCb cuts



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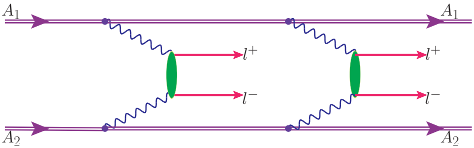
FOUR-LEPTON PRODUCTION



$$P_{AA\xrightarrow{\gamma\gamma}AAl^+l^-}(b; y_{l^+}, y_{l^-}, p_{t,l}) = \int N(\omega_1, \mathbf{b_1})\, N(\omega_2, \mathbf{b_2}) S^2_{abs}(\mathbf{b}) \times \frac{d\sigma_{\gamma\gamma\to l_1 l_2}(W_{\gamma\gamma})}{dz}\, d\overline{b}_x\, d\overline{b}_y\, \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, dY_{l_1 l_2}$$

$$\frac{d\sigma_{A_1A_2\to A_1A_2 l_1^+ l_2^- l_3^+ l_4^-}}{dy_{l^+}dy_{l^-}dp_{t,l}dy_{l^+}dy_{l^-}dp_{t,l}} = \frac{1}{2}\int \frac{dP^{I}_{AA\xrightarrow{\gamma\gamma}AAl^+l^-}(b; y_{l^+}, y_{l^-}, p_{t,l})}{dy_{l^+}dy_{l^-}dp_{t,l}} \times \frac{dP^{II}_{AA\xrightarrow{\gamma\gamma}AAl^+l^-}(b; y_{l^+}, y_{l^-}, p_{t,l})}{dy_{l^+}dy_{l^-}dp_{t,l}}\, d^2b$$

$$\sigma_{A_1A_2\to A_1A_2 l^+l^-} = \int \frac{dP_{AA\xrightarrow{\gamma\gamma}AAl^+l^-}(b; y_{l^+}, y_{l^-}, p_{t,l})}{dy_{l^+}dy_{l^-}dp_{t,l}}\, d^2b \times dy_{l^+}dy_{l^-}dp_{t,l}$$

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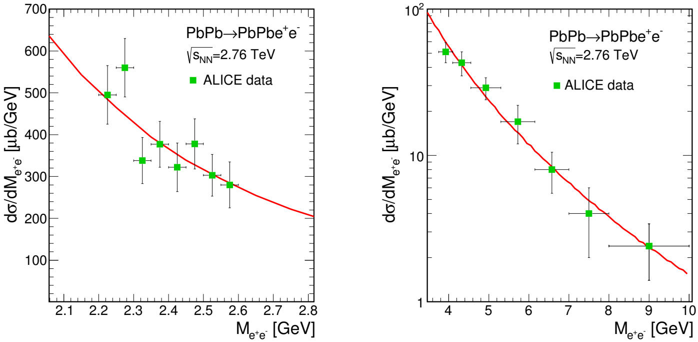
$AA \to AAe^+e^-$ - CALCULATIONS VS. DATA

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

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



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

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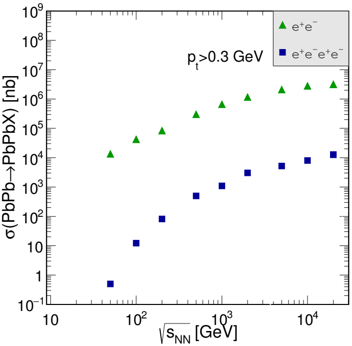
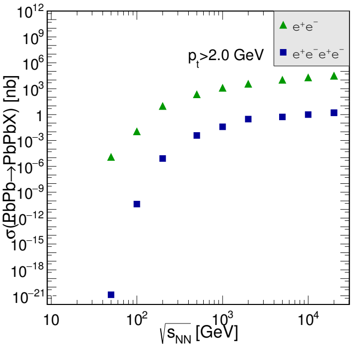
$AA \rightarrow AAe^+e^-$ & $AA \rightarrow AAe^+e^-e^+e^-$

$p_t > 0.3$ GeV

$p_t > 2.0$ GeV





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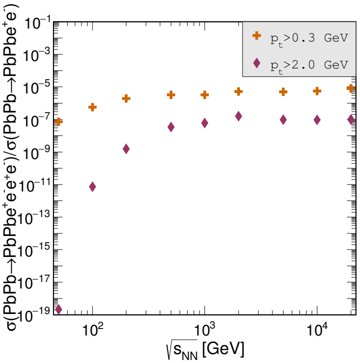
$AA \to AAe^+e^-$ & $AA \to AAe^+e^-e^+e^-$

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



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

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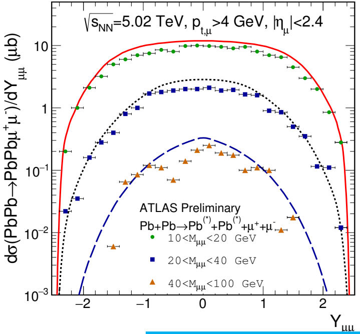
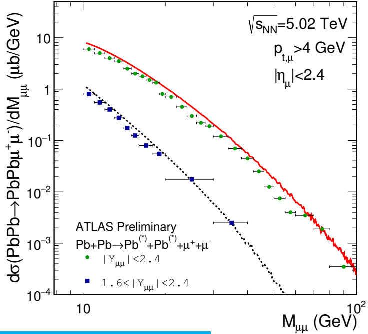
$AA \to AA\mu^+\mu^-$ - CALCULATIONS VS. DATA

- ATLAS Collaboration, *Measurement of high-mass dimuon pairs from ultraperipheral lead-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector at the LHC*, ATLAS-CONF-2016-025

$\frac{d\sigma}{dY_{\mu^+\mu^-}}$ $p_{t,\mu} > 4$ GeV, $|\eta_e| < 0.9$ $\frac{d\sigma}{dM_{\mu^+\mu^-}}$





"Overwriting" of single $\mu^+\mu^-$ pair production

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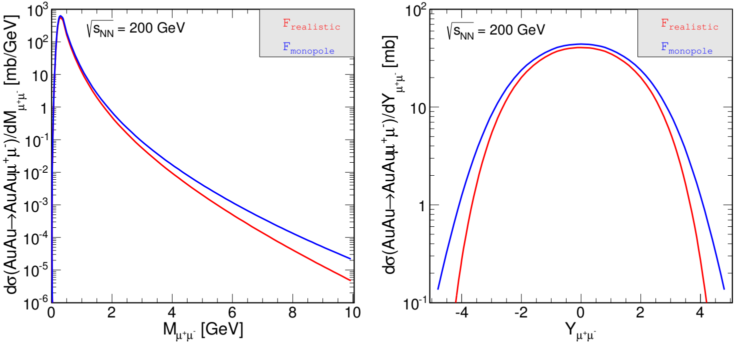
$AA \to AA\mu^+\mu^-$ - FORM FACTOR

⇨ realistic

⇨ monopole

$M_{\mu^+\mu^-}$

$Y_{\mu^+\mu^-}$



RHIC energy

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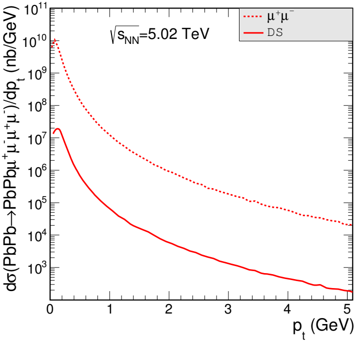
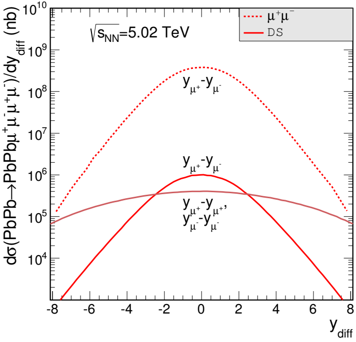
$AA \to AA\mu^+\mu^-$ & $AA \to AA\mu^+\mu^-\mu^+\mu^-$

$p_{t,\mu}$

y_{diff}

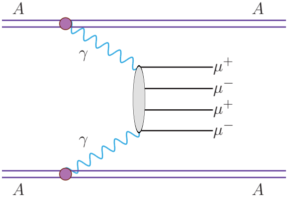


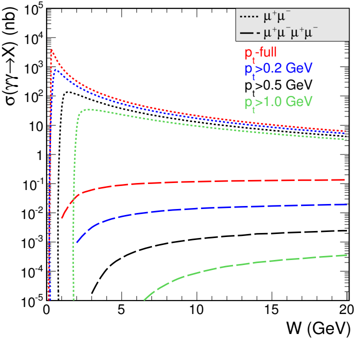


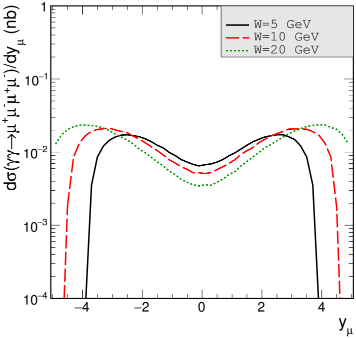
Similar like for electron-positron production: $\sigma_{\mu^+\mu^-} \simeq 1000 \times \sigma_{\mu^+\mu^-\mu^+\mu^-}$

$\gamma\gamma \to \mu^+\mu^-\mu^+\mu^-$ - 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.



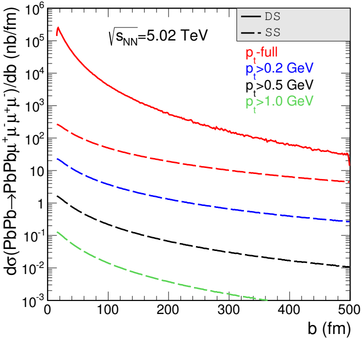


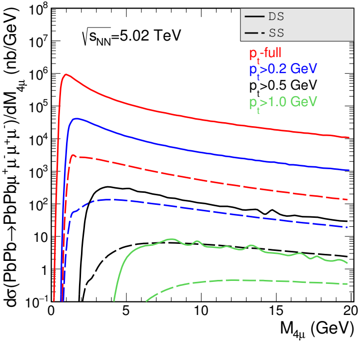


$AA \to AA\mu^+\mu^-\mu^+\mu^-$

impact parameter

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





↑ purely theoretical distribution

↑ 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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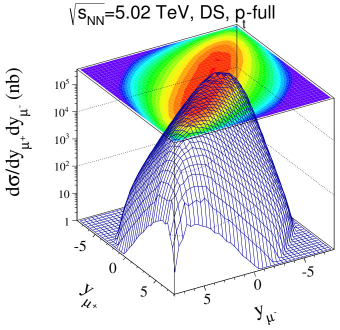
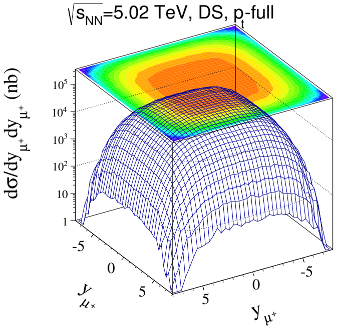
$AA \to AA\mu^+\mu^-\mu^+\mu^-$

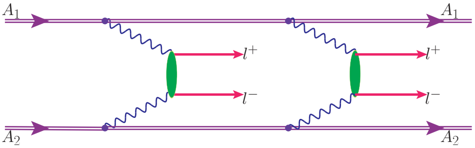
y_{μ^+}, y_{μ^-}



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



$p_{t,\mu^+} \simeq p_{t,\mu^-} \Rightarrow$ 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
$\|y_i\| < 2.5$, $p_t > 0.5$ GeV	815	$\|y_i\| < 2.5$, $p_t > 0.5$ GeV	235
$\|y_i\| < 2.5$, $p_t > 1.0$ GeV	53	$\|y_i\| < 2.5$, $p_t > 1.0$ GeV	10
$\|y_i\| < 0.9$, $p_t > 0.5$ GeV	31	$\|y_i\| < 1.0$, $p_t > 0.2$ GeV	649
$\|y_i\| < 0.9$, $p_t > 1.0$ GeV	2	$\|y_i\| < 1.0$, $p_t > 1.0$ GeV	1
$\|y_i\| < 2.4$, $p_t > 4.0$ GeV	$\ll 1$		

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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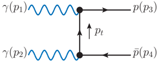
PROTON-ANTIPROTON PAIR PRODUCTION

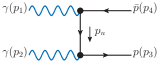
$$\gamma(p_1, \lambda_1) + \gamma(p_2, \lambda_2) \to p(p_3, \lambda_3) + \bar{p}(p_4, \lambda_4)$$

$$\mathcal{M}^{p-exchange}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} = (-i)\,\epsilon_{1\mu}(\lambda_1)\epsilon_{2\nu}(\lambda_2)$$

$$\times\bar{u}(p_3,\lambda_3)\Big(i\Gamma^{(\gamma pp)\,\mu}(p_3,p_t)\frac{i(\not{p}_t + m_p)}{t - m_p^2 + i\epsilon}i\Gamma^{(\gamma pp)\,\nu}(p_t,-p_4)$$

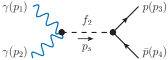
$$+i\Gamma^{(\gamma pp)\,\nu}(p_3,p_u)\frac{i(\not{p}_u + m_p)}{u - m_p^2 + i\epsilon}i\Gamma^{(\gamma pp)\,\mu}(p_u,-p_4)\Big)v(p_4,\lambda_4)$$

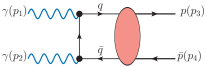




$$\mathcal{M}^{f_2(1270),f_2(1950)}_{\lambda_1\lambda_2\to\lambda_3\lambda_4} = (-i)\,\epsilon_{1\mu}(\lambda_1)\,\epsilon_{2\nu}(\lambda_2)\,i\Gamma^{(f_2\gamma\gamma)\,\mu\nu\kappa\lambda}(p_1,p_2)\,i\Delta^{(f_2)}_{\kappa\lambda,\alpha\beta}(p_s)$$

$$\times\bar{u}(p_3,\lambda_3)i\Gamma^{(f_2 p\bar{p})\,\alpha\beta}(p_3,p_4)\,v(p_4,\lambda_4)$$





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

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

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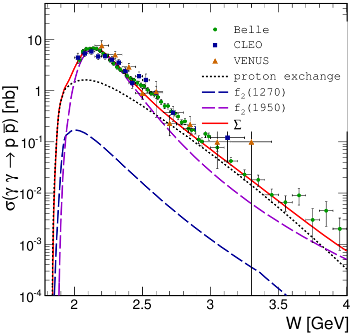
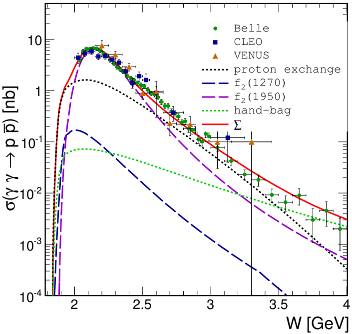
$\gamma\gamma \to p\bar{p}$ - RESULTS VS. DATA

$|\cos\theta| < 0.6$

$+$ hand-bag model





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

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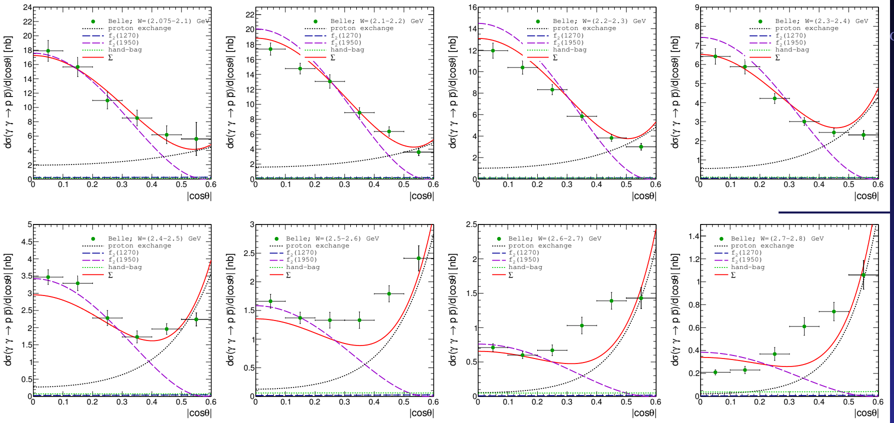
ANGULAR DISTRIBUTIONS

CRACOVIAN THEORETICAL RESULTS FOR UPC



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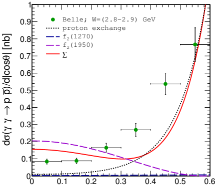
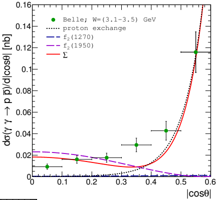
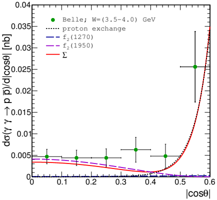
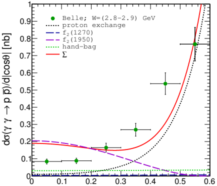
without hand-bag

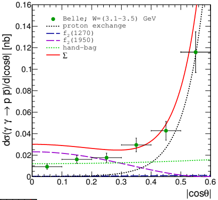


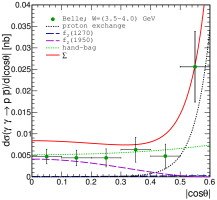




with hand-bag model







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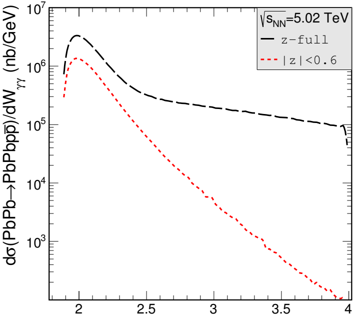
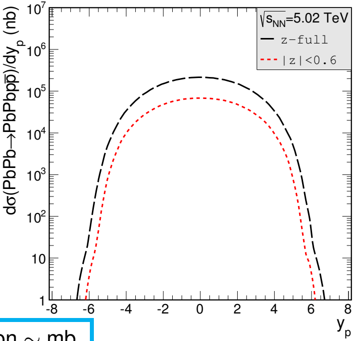
$AA \to AAp\bar{p}$ RESULTS

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

y_p





Cross section ∼ mb

Can be studied by ALICE, ATLAS, CMS group?

Experiment	Cuts	σ [μb]
ALICE	$p_{t,p} > 0.2$ GeV, $\lvert y_p \rvert < 0.9$	100
ATLAS	$p_{t,p} > 0.5$ GeV, $\lvert y_p \rvert < 2.5$	160
CMS	$p_{t,p} > 0.2$ GeV, $\lvert y_p \rvert < 2.5$	500
LHCb	$p_{t,p} > 0.2$ GeV, $2 < y_p < 4.5$	104

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Conclusion

- EPA in the impact parameter space
- $\gamma\gamma \to X_1 X_2 (X_3 X_4)$
- Realistic charge distribution
- Description of the ATLAS data for Pb Pb $\to$ Pb Pb $\gamma\gamma$ & for ALICE and ATLAS data for Pb Pb $\to$ Pb Pb $l^+ l^-$
- Pb Pb $\to$ Pb Pb $\mu^+\mu^-\mu^+\mu^- \Rightarrow \sigma_{SS}^{NEW} < \sigma_{DS}$
- Difficult to isolate a region where SS dominates
- $\sigma_{AA \to AA l^+ l^-} \cong 1000 \times \sigma_{AA \to AA l^+ l^- l^+ l^-}$
- The cross sections for four-lepton production strongly depend on the $p_{t,min}$ and y_l
- Light-by-light scattering in UPC for $M_{\gamma\gamma} < 5$ GeV - **new project**

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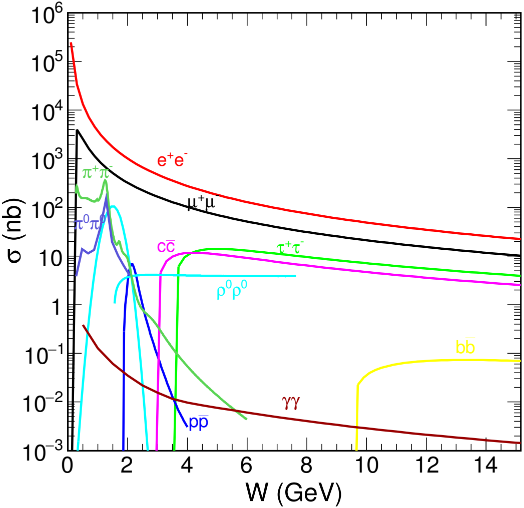
$\gamma\gamma \to X_1 X_2$ - REVIEW



Thank you

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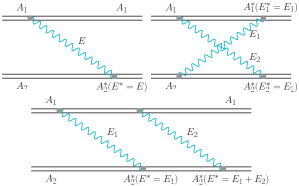
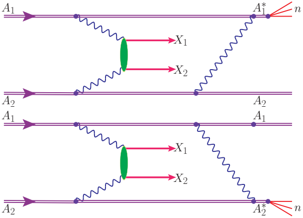
Backup Slides

○ Multiple Coulomb excitations

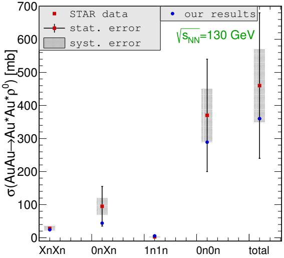


Ref.
M. Kłusek-Gawenda, M. Ciemała, W. Schäfer and A. Szczurek, Phys. Rev. **C89** (2014) 054907,
"Electromagnetic excitation of nuclei and neutron evaporation in ultrarelativistic ultraperipheral heavy ion collisions"

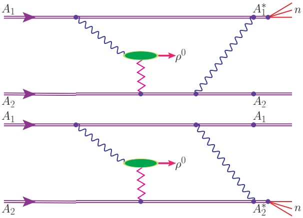
$$AA \to AA^*(kn)X_1X_2$$



ρ^0 production in heavy ion UPC with nuclear excitation



$$AA \to AA^*(kn)\rho^0$$



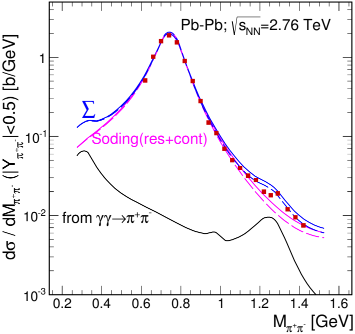
$$\mathcal{A}(m) = \mathcal{A}_{\mathcal{BW}} \frac{\sqrt{m m_{\rho^0} \Gamma_{\rho^0}(m)}}{m^2 - m_{\rho^0}^2 + i m_{\rho^0} \Gamma_{\rho^0}(m)} + \mathcal{B}_{\pi\pi}$$

running width: $\Gamma_{\rho^0}(m) = \Gamma_{\rho^0} \frac{m_{\rho^0}}{m} \left(\frac{m^2 - 4m_\pi^2}{m_{\rho^0}^2 - 4m_\pi^2} \right)^{3/2}$

Drell-Söding+$f_2(1270)$

colored solid lines - $\Gamma_{\rho^0} = 150.2$ MeV

colored dashed lines - $\Gamma_{\rho^0} = 140$ MeV



➢ ALICE Collaboration, *Coherent ρ^0 photoproduction in ultra-peripheral Pb-Pb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, JHEP 1509 (2015) 095

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