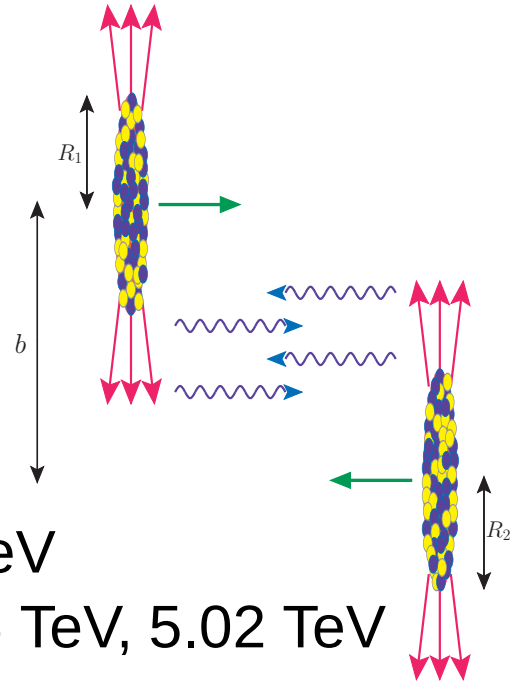
Diphoton elastic scattering in UPC at smaller $W_{\gamma\gamma}$

Antoni Szczurek & Mariola Kłusek-Gawenda

INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCE

ULTRAPERIPHERAL COLLISION OF HEAVY-ION

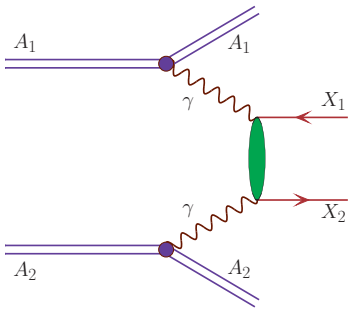


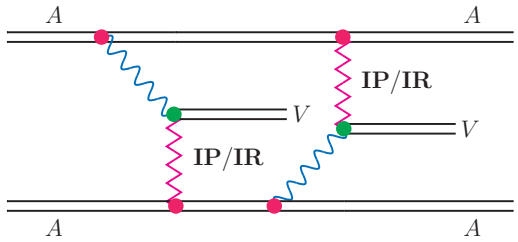
$$b > R_1 + R_2$$

Experimental results

- RHIC (1st collisions 2000):
  Au-Au @ $\sqrt{s_{NN}}$ = 130 GeV, 200 GeV
- LHC (2009) Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV, 5.02 TeV

- ✔ ρ^0
- ✔ $\pi^+\pi^-\pi^+\pi^-$
- ✔ e^+e^-
- ✔ $\mu^+\mu^-$
- ✔ J/ψ
- ✔ $\gamma\gamma$





Theoretical predictions

ρ^0
J/ψ
ψ'
$\Upsilon(1S)$

$\rho^0\rho^0$
$J/\psi J/\psi$
$\pi^+\pi^-$

$\pi^0\pi^0$
$c\bar{c}$
$b\bar{b}$

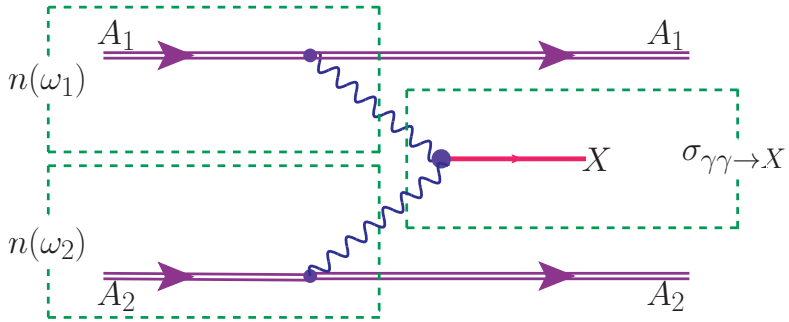
e^+e^-
$\mu^+\mu^-$
$\gamma\gamma$
$p\bar{p}$

$\pi^+\pi^-\pi^+\pi^-$
$e^+e^-e^+e^-$
$\mu^+\mu^-\mu^+\mu^-$

H
jets

Equivalent Photon Approximation

The strong electromagnetic field is a source of photons that can induce electromagnetic reactions in ion-ion collisions.



$$\sigma_{A_1A_2\to A_1A_2X_1X_2} = \int \mathrm{d}\omega_1\,\mathrm{d}\omega_2\, n(\omega_1)n(\omega_2)\sigma_{\gamma\gamma\to X_1X_2}(\omega_1,\omega_2)$$

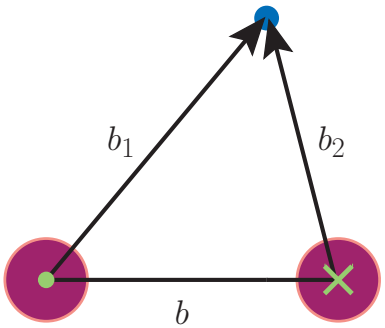
$$n(\omega) = \int_{R_{min}}^{\infty} 2\pi b\mathrm{d}b\, N(\omega,b)$$

IMPACT PARAMETER

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

$$\times\ \sigma_{\gamma\gamma\to X_1X_2}(W_{\gamma\gamma})$$

$$\times\ 2\pi b\mathrm{d}b\,\mathrm{d}\bar{b}_x\,\mathrm{d}\bar{b}_y\,\frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}Y_{X_1X_2}$$



Equivalent Photon Flux vs Form Factor

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

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

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

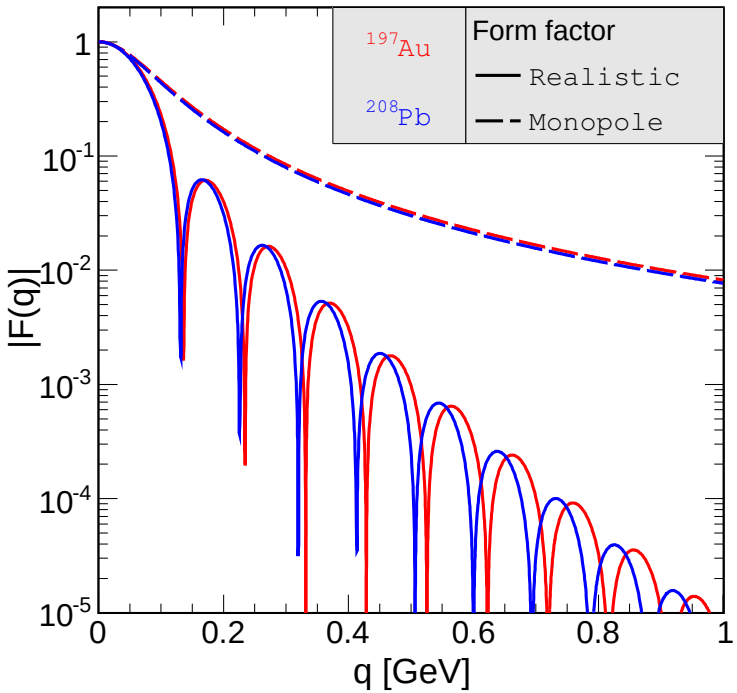
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{u^2}{\omega b^2} \left[K_1^2(u) + \frac{1}{\gamma^2} K_0^2(u) \right]$$

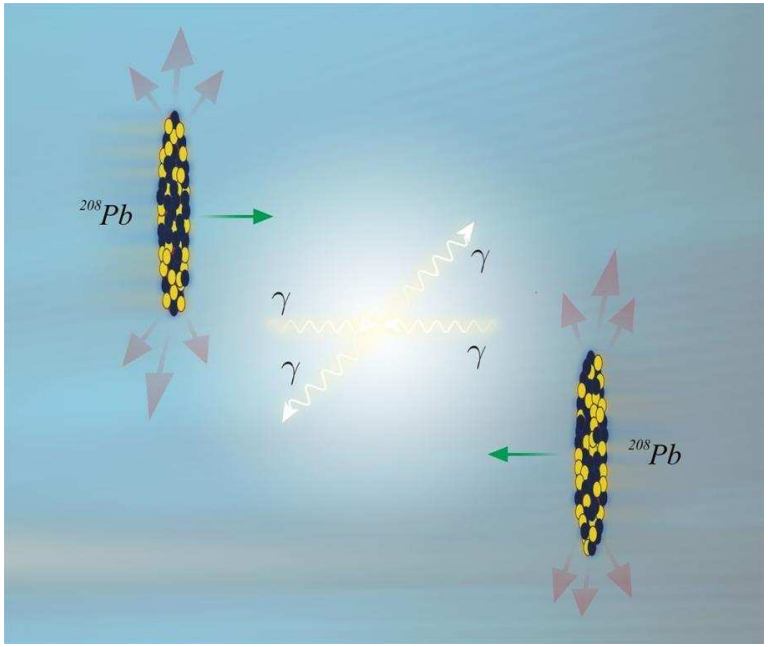
- monopole $F\left(\mathbf{q}^2\right) = \frac{\Lambda^2}{\Lambda^2 + |\mathbf{q}|^2}$

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

- realistic

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

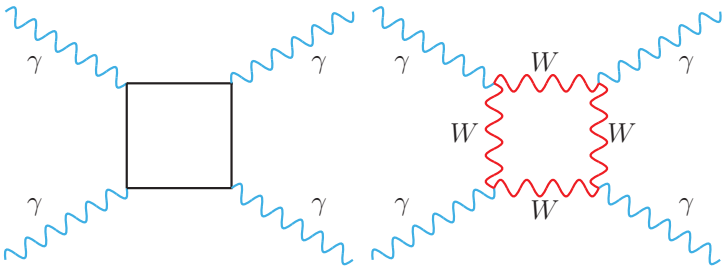




$$AA \rightarrow AA\gamma\gamma$$

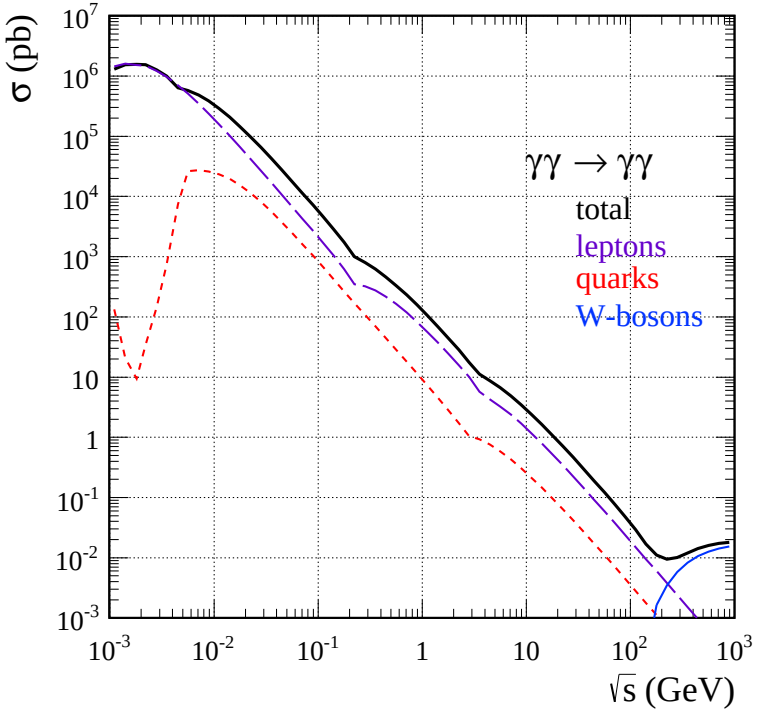
$\gamma\gamma$ Elastic Scattering

Boxes

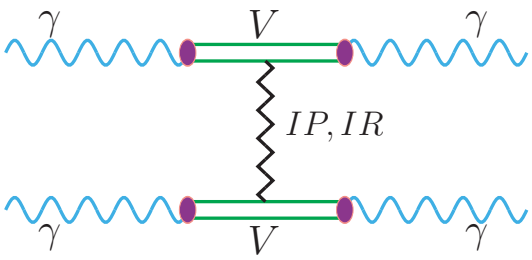


LO QED fermionic Box `FormCalc.`

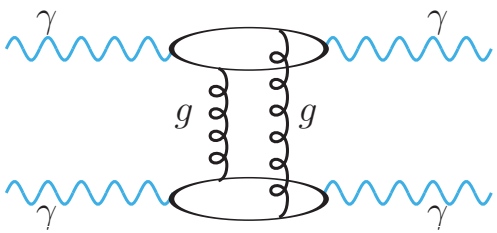
W Box `LoopTools.`



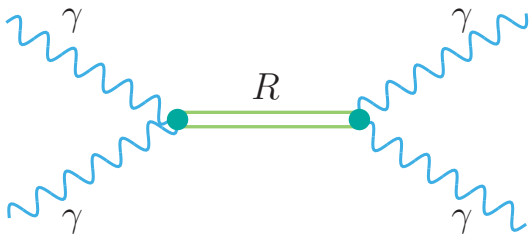
VDM-Regge



2-gluon exch.



Resonances



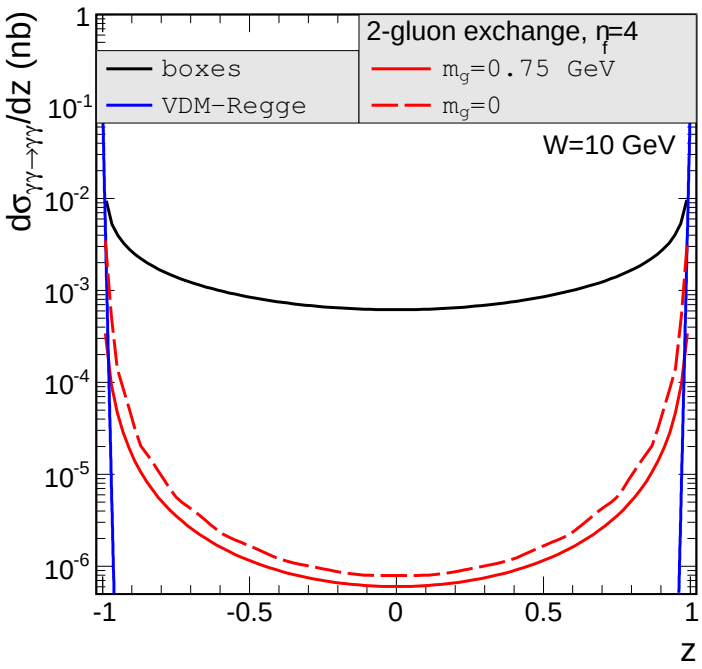
Elementary cross section

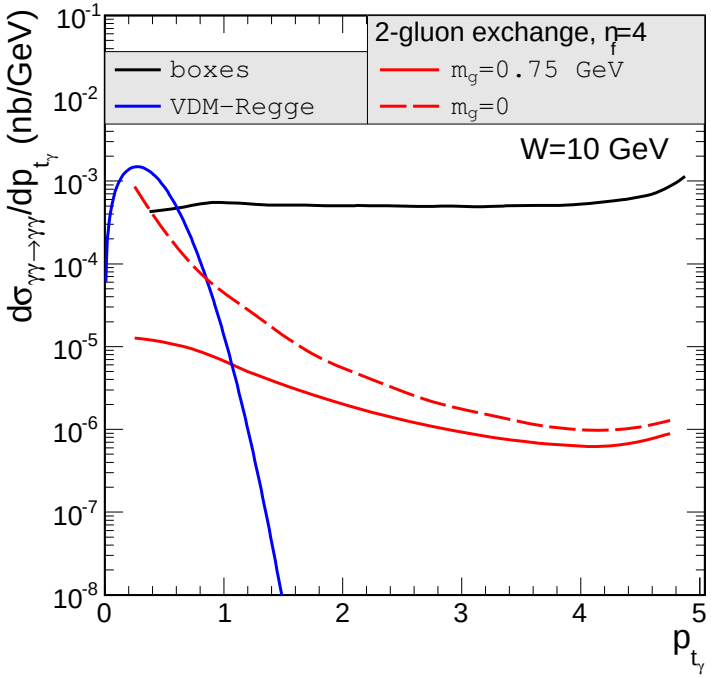
- ✔ boxes
- ✔ VDM-Regge
- ✔ 2-gluon exchange

$W = 10$ GeV

$z = \cos\theta$

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





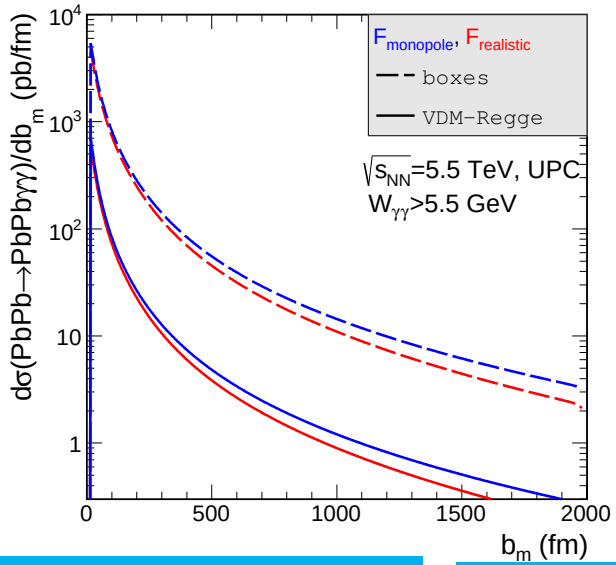
$\theta = \frac{\pi}{2}$ - boxes, large z (small p_{t_γ}) - VDM-Regge.

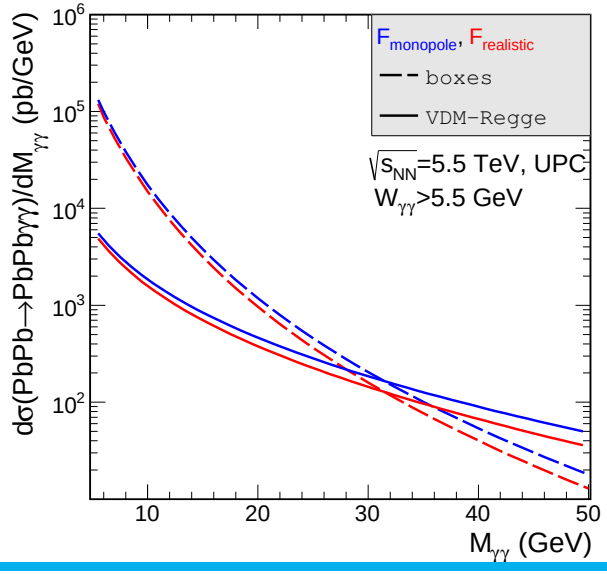
PBPB→PBPBγγ - FORM FACTOR

⇨ realistic

impact parameter ⇨ monopole

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





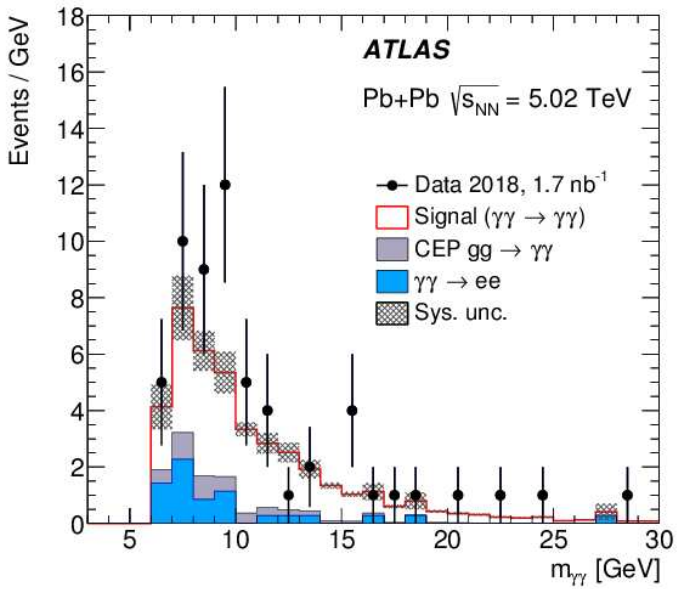
↑ theoretical distribution

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

cuts σ [nb] →	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
$E_\gamma > 3$ GeV	16 692	18 400	17	18
$E_\gamma > 5$ GeV	4 800	5 450	9	611
$E_\gamma > 3$ 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

$AA \to AA\gamma\gamma$ - ATLAS RESULT

➢ 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
Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector ATLAS Collaboration. CERN-EP-2019-051



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

✔ $\gamma\gamma \to \gamma\gamma$
✔ background
  ✔ $\gamma\gamma \to e^+e^-$
  ✔ $gg \to \gamma\gamma$
  ✔ $\gamma\gamma \to q\bar{q}$
✔ 13 events (2017)
59 events (2019)*

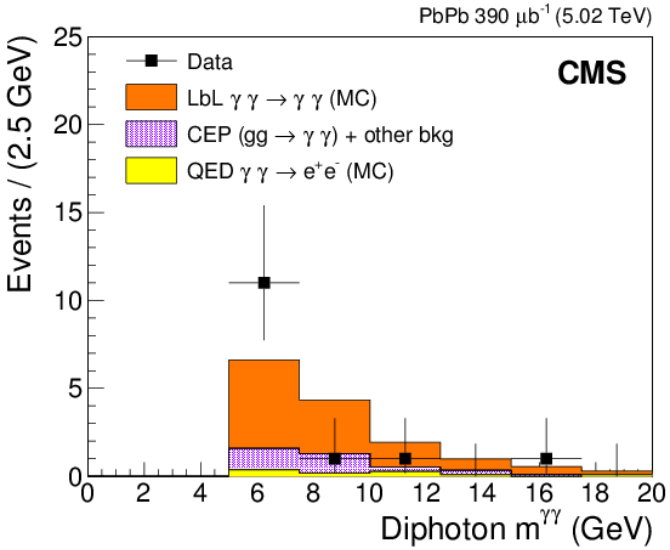
theory $\Rightarrow$ $\sigma = 51 \pm 0.02$ nb

ATLAS (2017) $\Rightarrow$ $\sigma = 70 \pm 20(\text{stat.}) \pm 17(\text{syst.})$ nb

(2019)* $\Rightarrow$ $\sigma = 78 \pm 13(\text{stat.}) \pm 7(\text{syst.}) \pm 3(\text{lumi.})$ nb

$AA \to AA\gamma\gamma$ - CMS RESULT

- CMS Collaboration (A. M. Sirunyan et al.),
  Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,
  arXiv:1810.04602 [hep-ex]



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

✔ 14 events

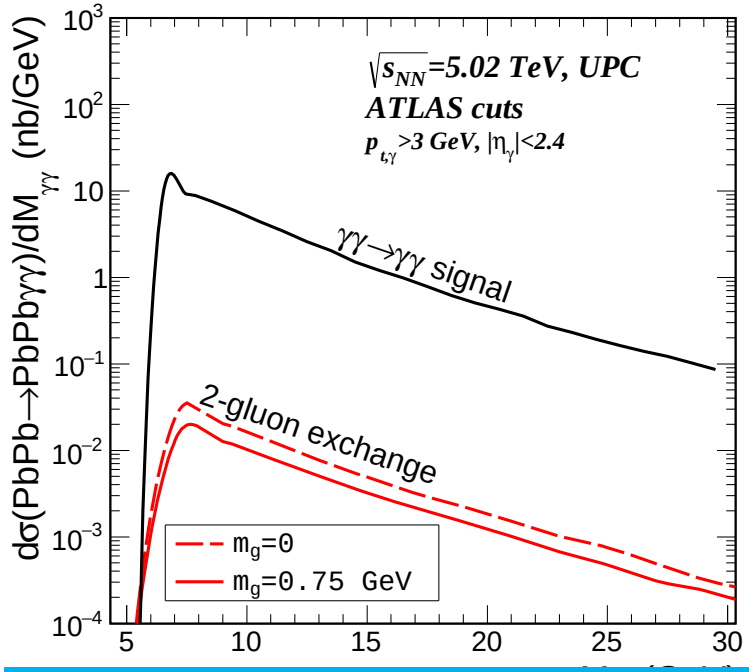
CMS $\Rightarrow$ $\sigma = 120 \pm 46(\text{stat.}) \pm 28(\text{syst.})$ nb

$\sigma = 138 \pm 14$ nb $\Leftarrow$ theory $\Rightarrow$ $\sigma = 103 \pm 0.034$ nb

point-like form factor &$n(\omega)$ **vs** realistic form factor &$N(\omega, b)$

HIGHER ORDER PROCESSES..?

$\gamma\gamma$ invariant mass



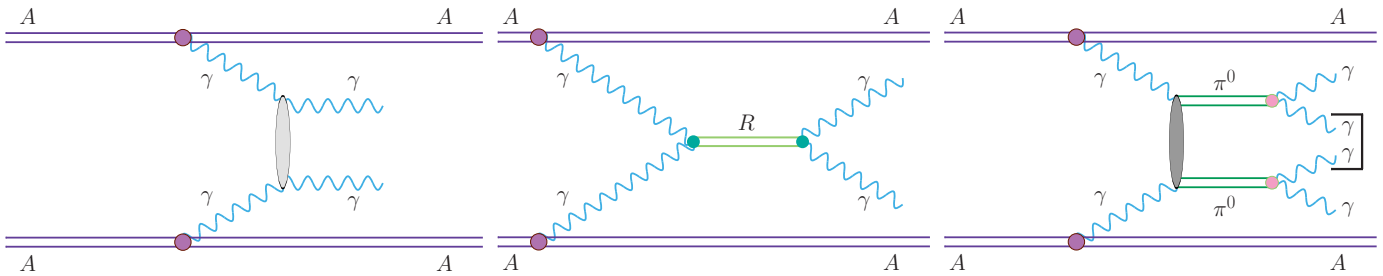
Coherent sum of both processes...?

Pionic boxes...?

$M_{\gamma\gamma} < 5$ GeV ??

$AA \to AA\gamma\gamma$ FOR $M_{\gamma\gamma} < 5$ GEV

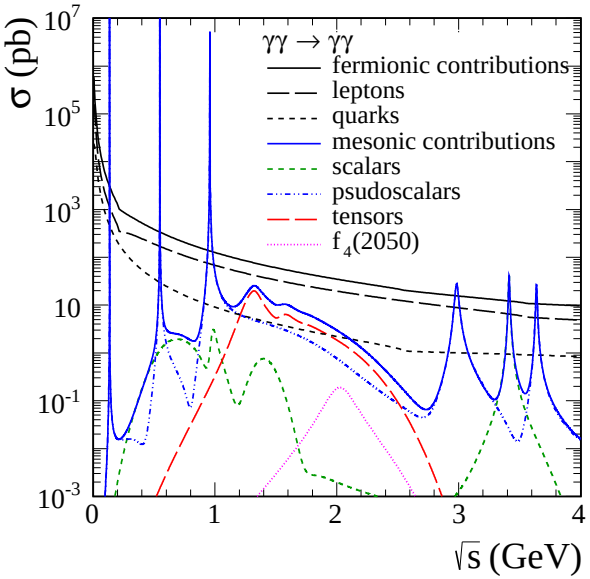
CONTINUUM **RESONANCES** **BACKGROUND**

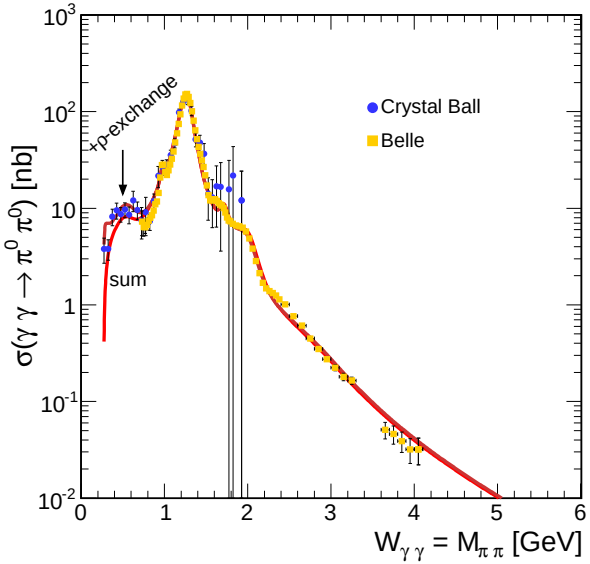


$\gamma\gamma \to \gamma\gamma$

$f_0(500)$
$f_0(980)$
$a_0(980)$
$f_0(1370)$
$\chi_{c0}(1P)$
$f_2(1270)$
$a_2(1320)$
$f_2'(1525)$
$f_2(1565)$
$a_2(1700)$

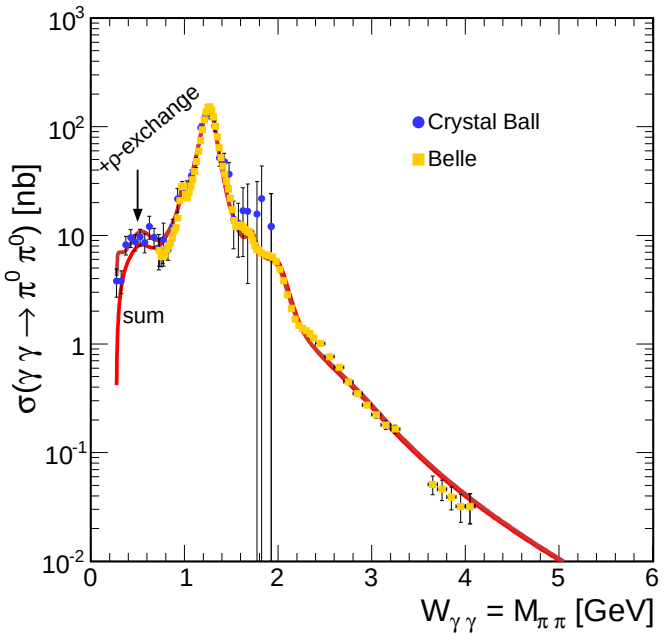
π^0
η
$\eta'(958)$
$\eta_c(1S)$
$\eta_c(2S)$
$f_4(2050)$

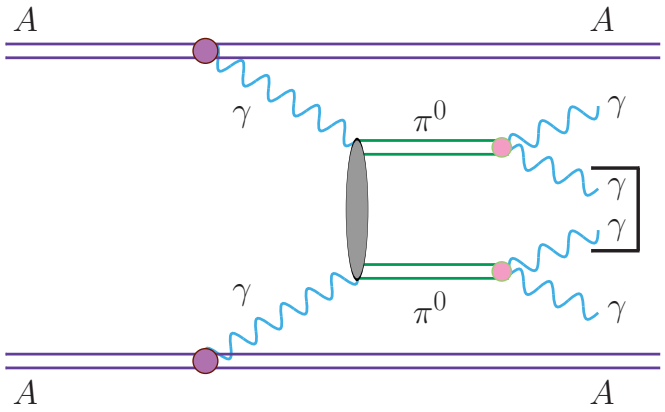




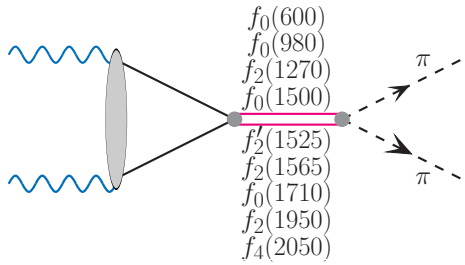
$M_{\gamma\gamma} < 5$ GeV $\Rightarrow$ PIONIC BACKGROUND

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





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



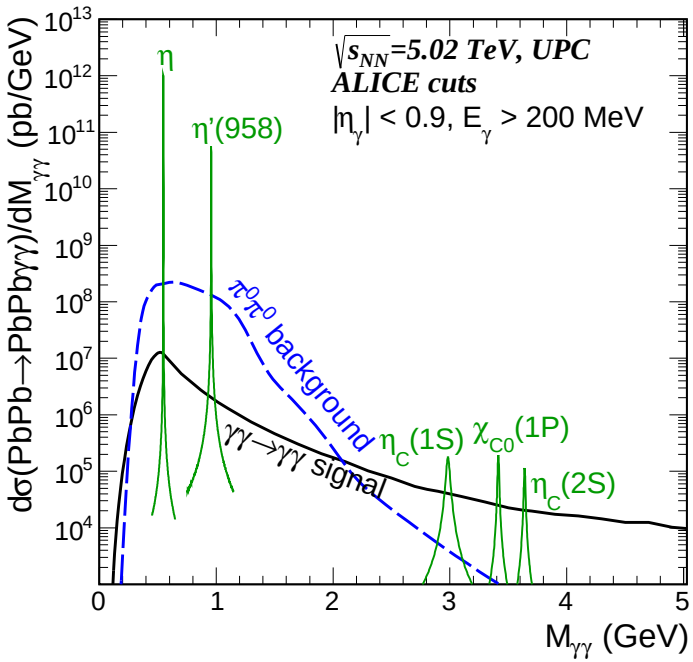
MESON EXCHANGE AT UPC

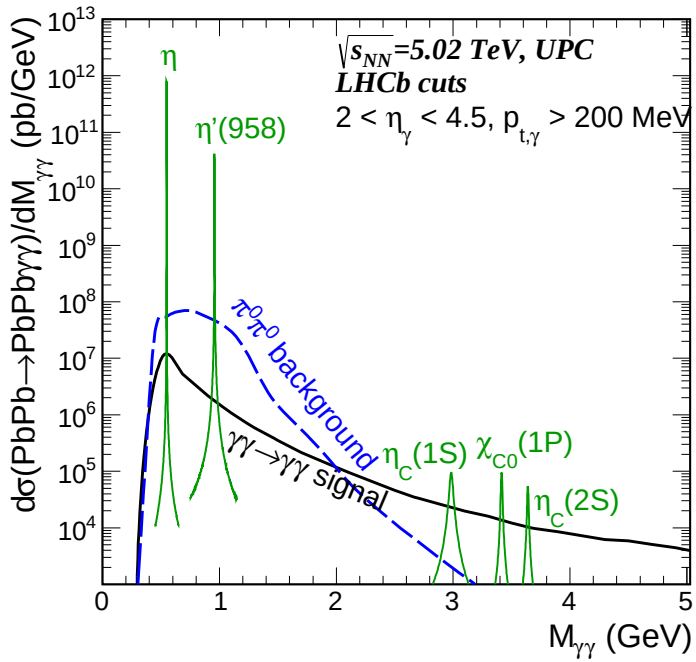
experiment	pseudorapidity range	other condition
ALICE	$-0.9 < \eta_\gamma < 0.9$	$E_\gamma > 200$ MeV
LHCb	$2.0 < \eta_\gamma < 4.5$	$p_{t,\gamma} > 200$ MeV

ALICE cuts

- ✔ boxes
- ✔ bkg
- ✔ mesons

LHCb cuts





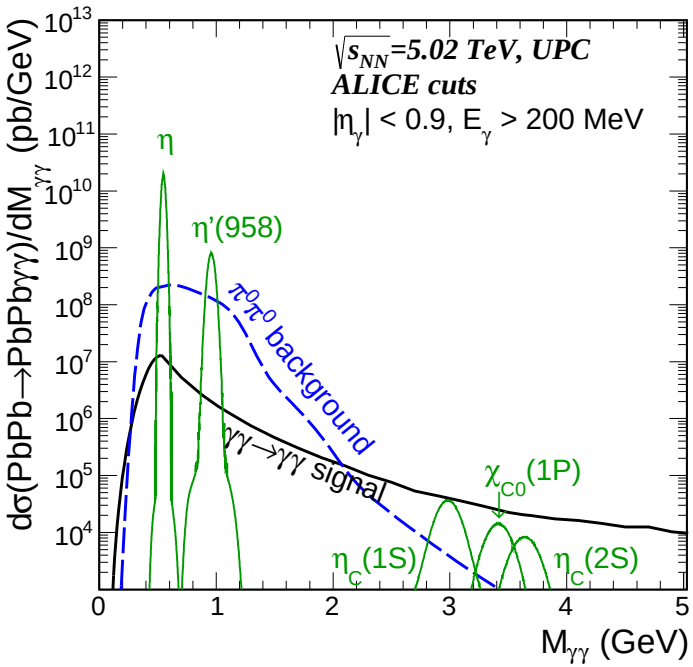
RESONANSE CONTRIBUTION & EXPERIMENTAL RESOLUTION

ENERGY RESOLUTION

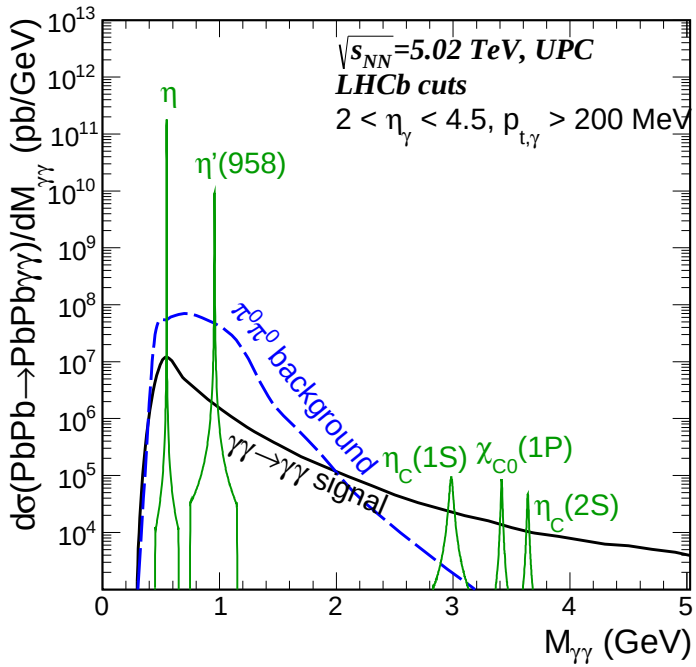
$$\frac{\sigma_{E_\gamma}}{E_\gamma} = 2\%$$

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

ALICE cuts



LHCb cuts



Energy resolution modifies resonant signals

PBPB $\to$ PBPB$\gamma\gamma$, $\sqrt{s_{NN}} = 5.02$ TEV

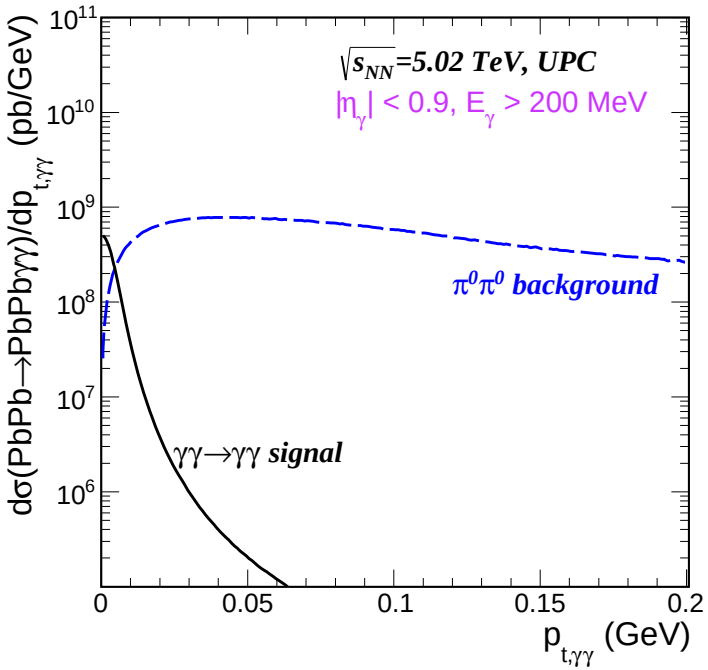
Total cross section [nb]

Energy	$W_{\gamma\gamma} = (0-2)$ GeV		$W_{\gamma\gamma} > 2$ GeV	
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

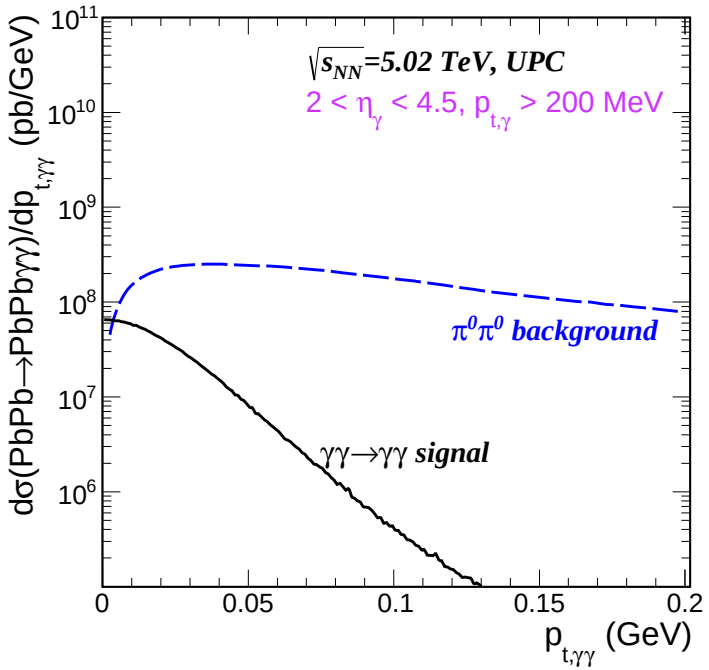
EXPERIMENTAL RESOLUTION & $p_{t,\gamma\gamma}$

$$p_{t,\gamma\gamma} = (|\vec{p_{t1}} + \vec{p_{t2}}|)$$

ALICE cuts



LHCb cuts

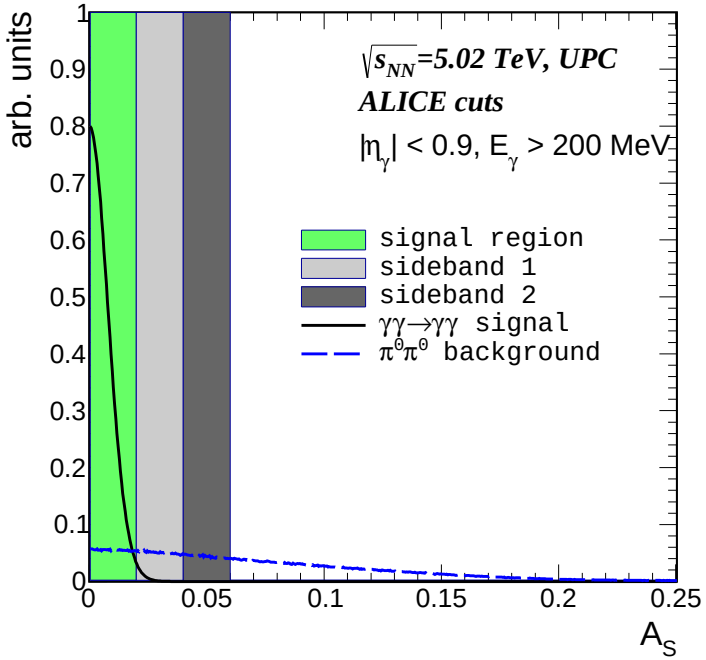


Very limited region where the signal overestimates the background

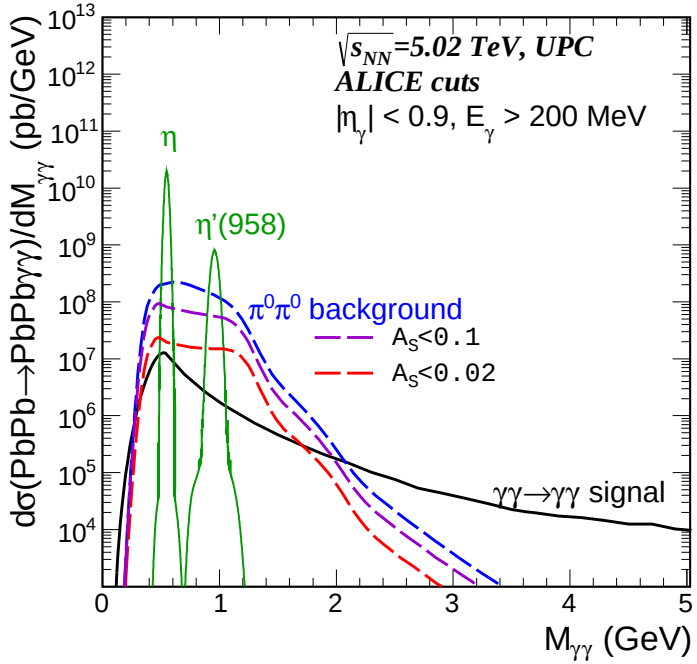
EXPERIMENTAL RESOLUTION & SCALAR & VECTOR ASYMMETRY

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

A_S



$M_{\gamma\gamma}$

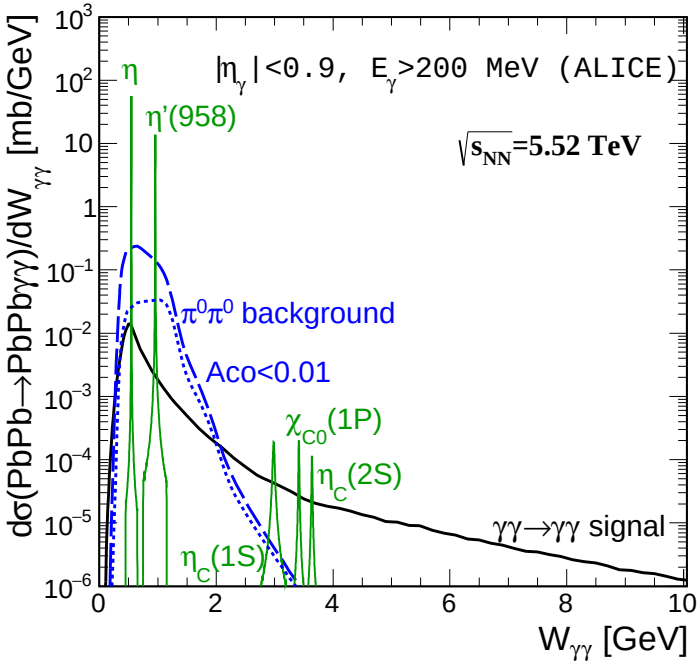


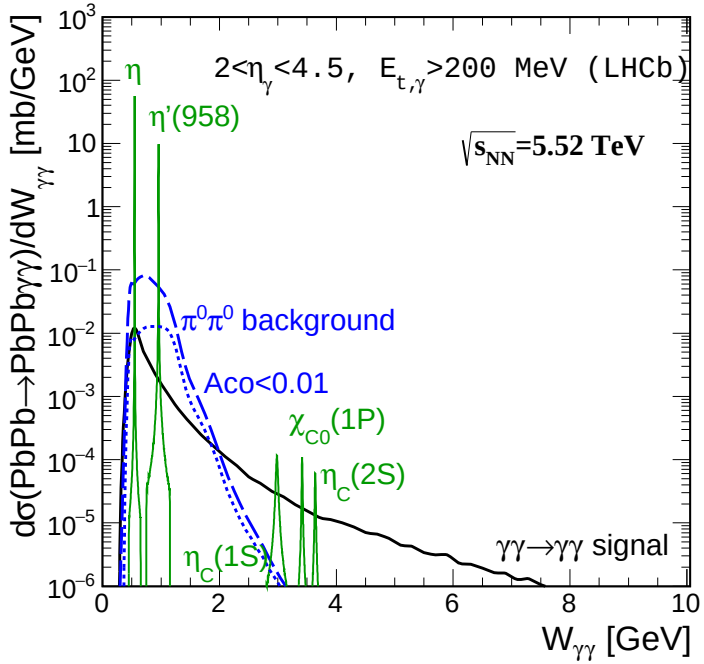
80% of the signal events at $A_S < 0.02$

$^{208}Pb^{82+} + {}^{208}Pb^{82+} \rightarrow {}^{208}Pb^{82+} + {}^{208}Pb^{82+}\gamma\gamma$

midrapidity

forward rapidity

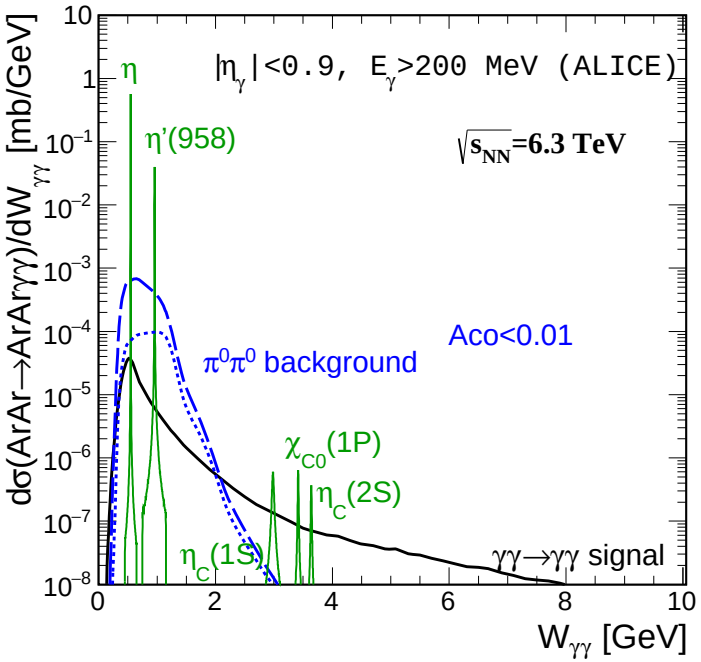




$$\sigma_{tot} \propto (Z_{Pb}/Z_{Ar})^4 \approx 430$$

$$^{40}\mathrm{AR}^{18+} + ^{40}\mathrm{AR}^{18+} \rightarrow ^{40}\mathrm{AR}^{18+} + ^{40}\mathrm{AR}^{18+}\gamma\gamma$$

midrapidity



Run 5: $L_{\mathrm{int}}^{\mathrm{Ar-Ar}} = (3 - 8.8)\ \mathrm{pb}^{-1}$

ALICE $\rightarrow W_{\gamma\gamma} > 2$ GeV $\rightarrow$ 1460 - 4280 events

CONCLUSION

- UPCs of heavy ions open a possibility to measure or to test the $\gamma\gamma \to \gamma\gamma$ scattering
- Different mechanisms:
  - boxes
  - VDM-Regge
  - 2-gluon exchange
  - meson decays
  - pionic background
- Theory predicts measurable cross sections
- ATLAS/CMS have observed 13→59/14 events confirming Light-by-Light scattering in UPC
- ALICE and LHCb could measure LbyL scattering for $W_{\gamma\gamma} > 2$ GeV in Pb-Pb and Ar-Ar collisions with very good statistics
- Importance of η & η'
- Next step → Missing contributions (?), interferences
  → Electromagnetic excitations ar

Thank you

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LBL IN UPC - THEORY

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