Low energy light-by-light scattering in heavy-ion UPC, a new possibility

Mariola Kłusek-Gawenda

- ✓ 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,
- ✓ M. K-G, W. Schäfer and 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,
- ✓ M. K-G, R. McNulty, R. Schicker and A. Szczurek,
  Light-by-light scattering in ultra-peripheral heavy-ion collisions at low diphoton masses,
  arXiv:1904.01243 $\to$ Phys. Rev. **D**,
- ✓ Z. Citron, M. K-G et al.,
  Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams,
  CERN-LPCC-2018-07, arXiv:1812.06772 [hep-ph]
  Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC.

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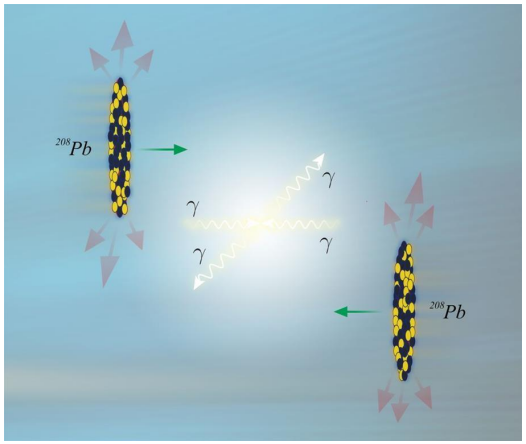
Equivalent Photon Approximation



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

$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2} = \int \mathrm{d}\omega_1 \, \mathrm{d}\omega_2 \, n(\omega_1) n(\omega_2) \sigma_{\gamma\gamma \to X_1 X_2}(\omega_1, \omega_2)$$

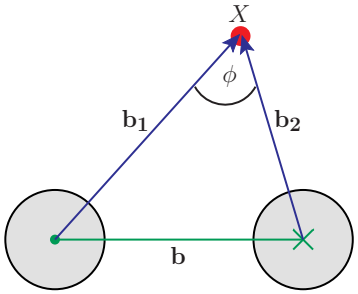
$$n(\omega) = \int_{R_{min}}^{\infty} 2\pi b \mathrm{d}b \, N(\omega, b)$$

MORE CORRECTLY $\Rightarrow$ ...

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

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

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



Equivalent Photon Flux vs Form Factor

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

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

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

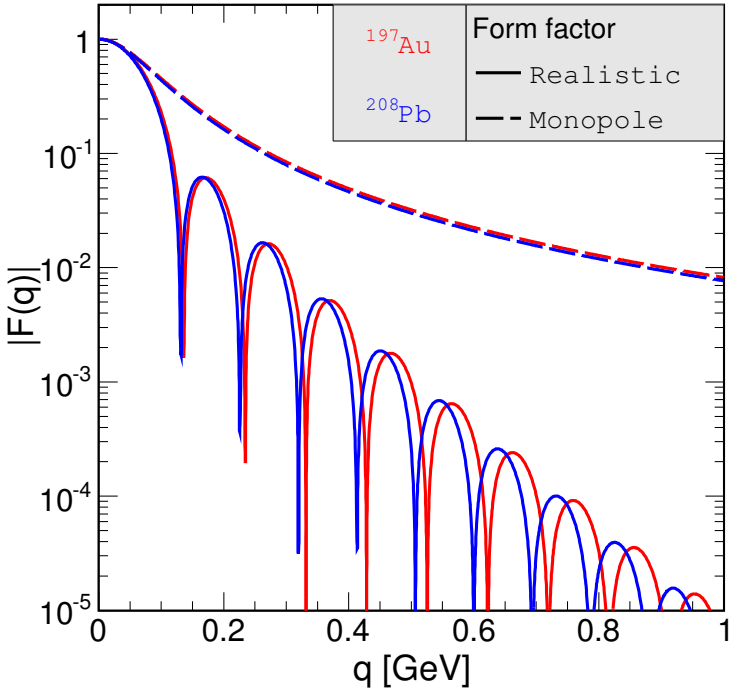
$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 \beta^2} \frac{u^2}{\omega b^2} \left[K_1^2(u) + \frac{1}{\gamma^2} K_0^2(u) \right]$$

- 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

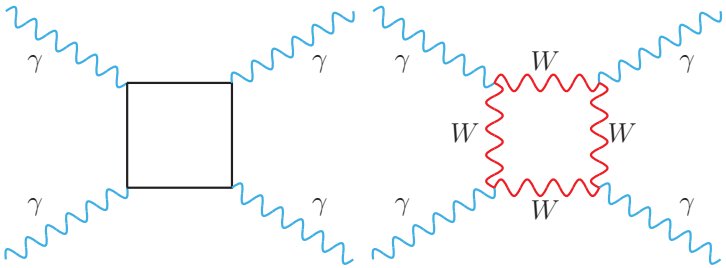
$$F(\mathbf{q}^2) = \frac{4\pi}{|\mathbf{q}|} \int \rho(r) \sin(|\mathbf{q}|\, r)\, r dr$$



$\gamma\gamma$ Elastic Scattering

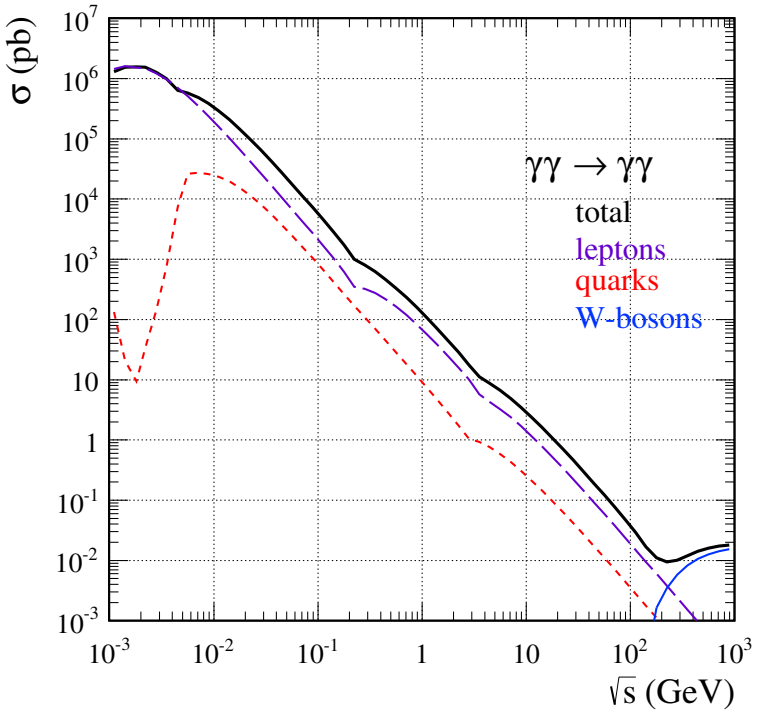
Well-known

Boxes



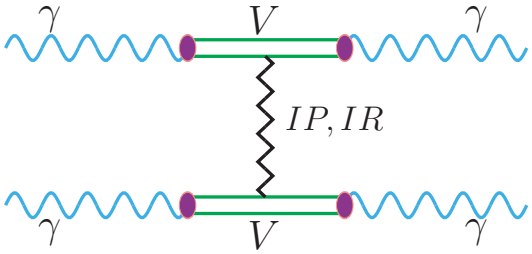
LO QED fermionic box — FormCalc.

W box — LoopTools.

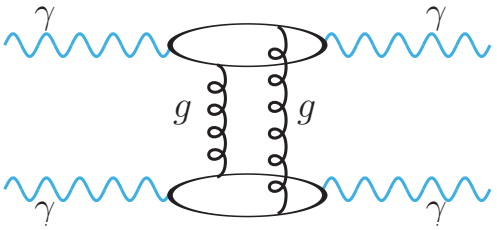


We add

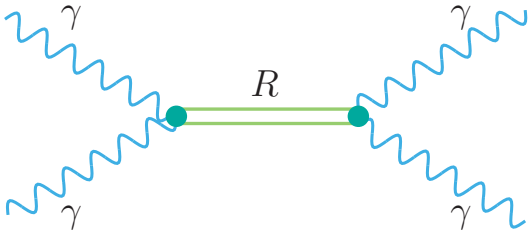
VDM-Regge



2-gluon exch.



Resonances



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NUCLEAR CROSS SECTION

σ(PbPb$\to$PbPb$\gamma\gamma$) [nb]

@ LHC ($\sqrt{s_{NN}} = 5.5$ TeV) & FCC ($\sqrt{s_{NN}} = 39$ TeV)

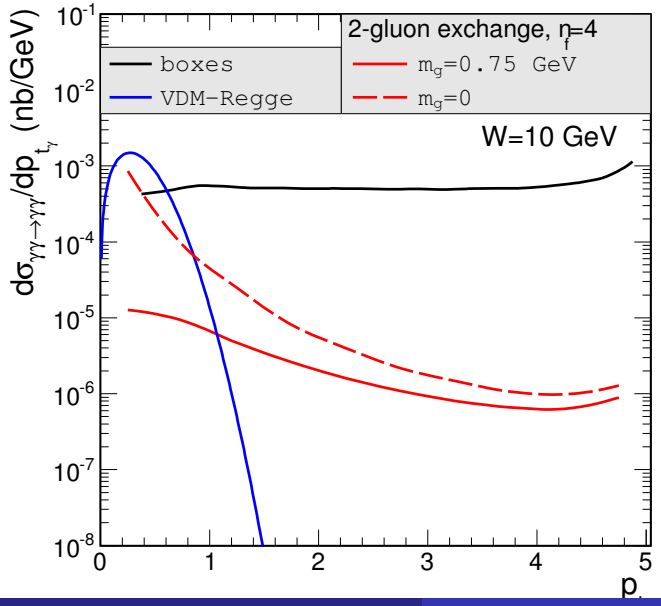
	cuts	Boxes $F_{realistic}$	Boxes $F_{monopole}$	VDM-Regge $F_{realistic}$	VDM-Regge $F_{monopole}$
LHC	$W_{\gamma\gamma} > 5$ GeV	306	349	31	36
	$W_{\gamma\gamma} > 5$ GeV, $p_{t,\gamma} > 2$ GeV	159	182	7E-9	8E-9
	$E_\gamma > 3$ GeV	16 692	18 400	17	18
	$E_\gamma > 5$ GeV	4 800	5 450	9	611
	$E_\gamma > 3$ 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
FCC	$W_{\gamma\gamma} > 5$ GeV	6 169		882	
	$E_\gamma > 3$ GeV	4 696 268		574	

- ✔ boxes
- ✔ VDM-Regge
- ✔ 2-gluon exch.

$W = 10$ GeV

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

small p_{t_γ} - VDM-Regge



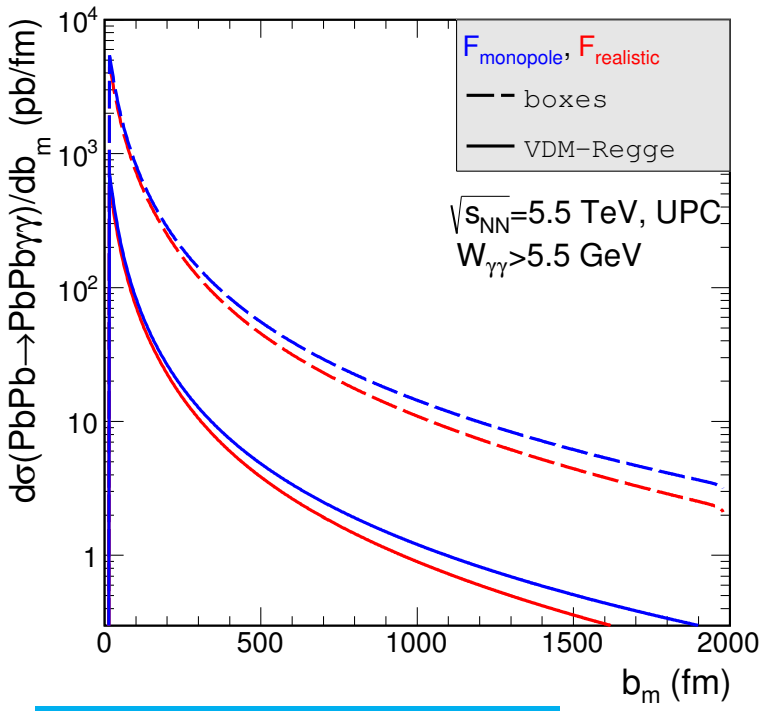
AA→AAγγ - FORM FACTOR

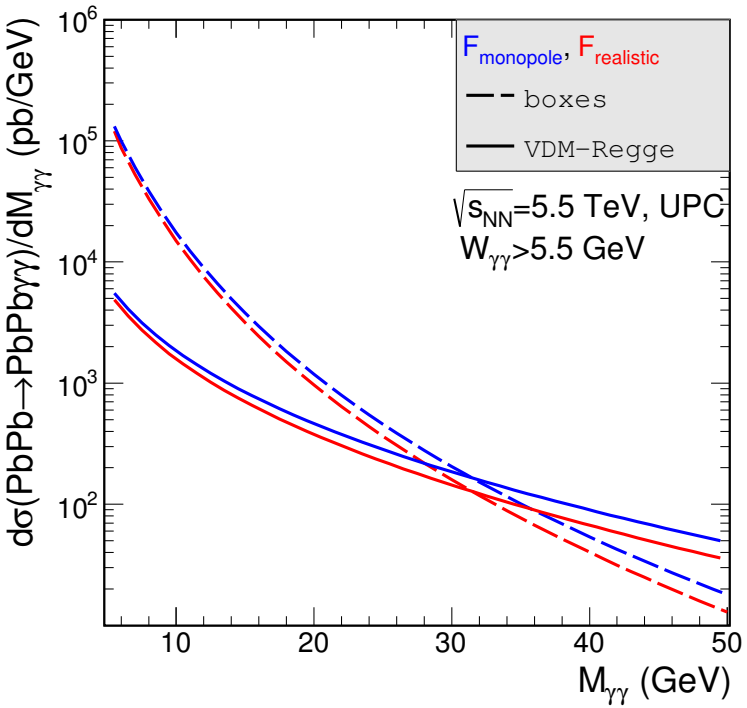
⇨ realistic

⇨ monopole

impact parameter

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





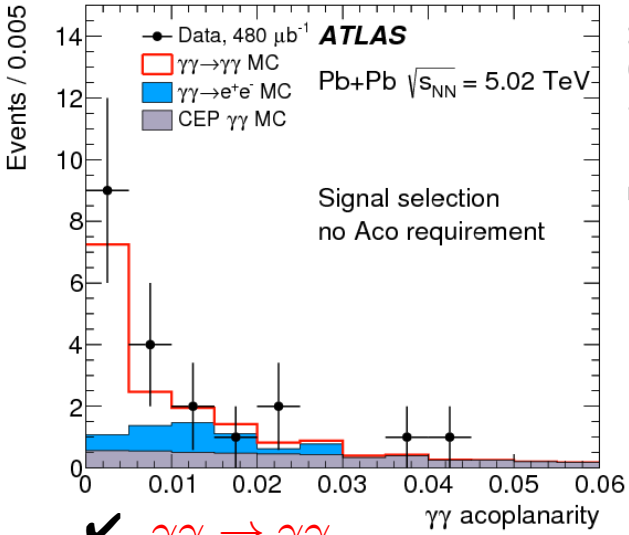
↑ theoretical distribution

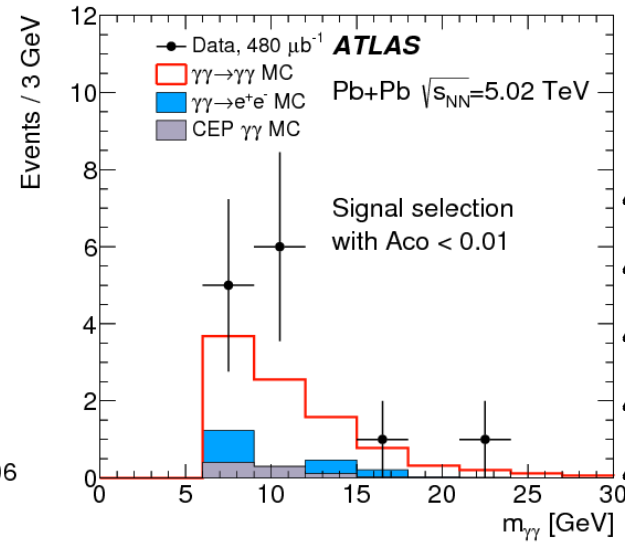
VDM-Regge dominates at $W_{\gamma\gamma} > 30$ GeV

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

AA→AAγγ - 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
Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector ATLAS Collaboration, ATLAS-CONF-2019-002*





✗ $p_{t_\gamma} > 3$ 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)*

*collected in Nov. 2018

ours ⇒ $\sigma = 49 \pm 10(5^*)$ nb / $\sigma = 51 \pm 0.02$ nb

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

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

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γγ → γγ
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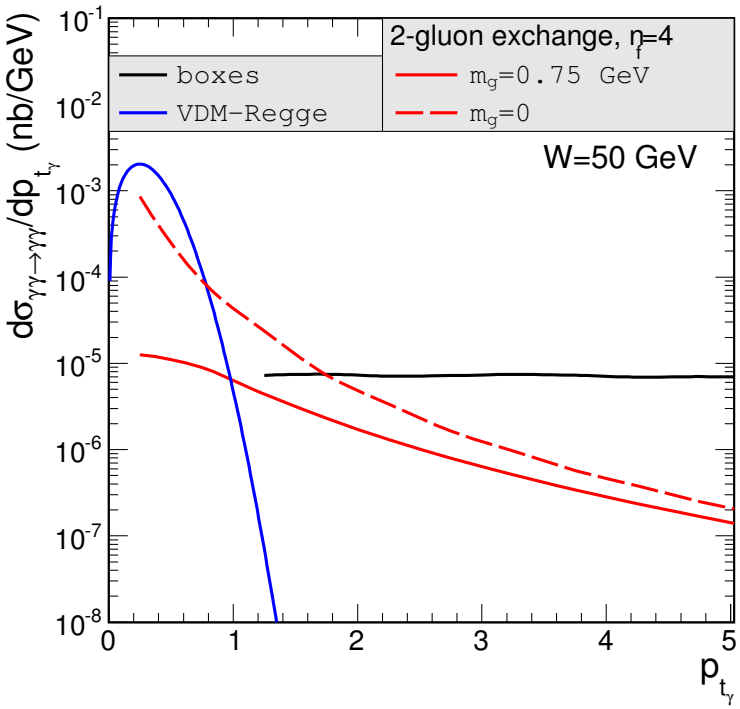
HIGHER ORDER PROCESSES..?

Elementary cross section

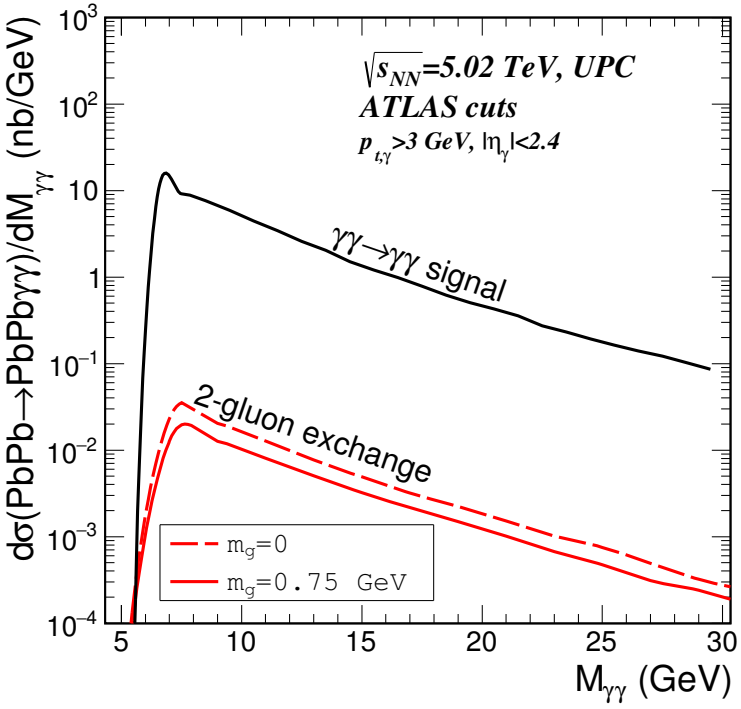
$p_{t_\gamma} = p \sin\theta$

$W = 50$ GeV



Nuclear cross section

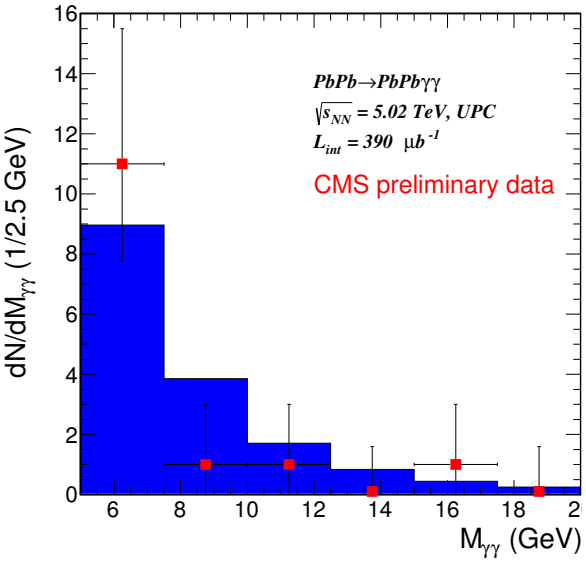
$W_{\gamma\gamma} = M_{\gamma\gamma}$

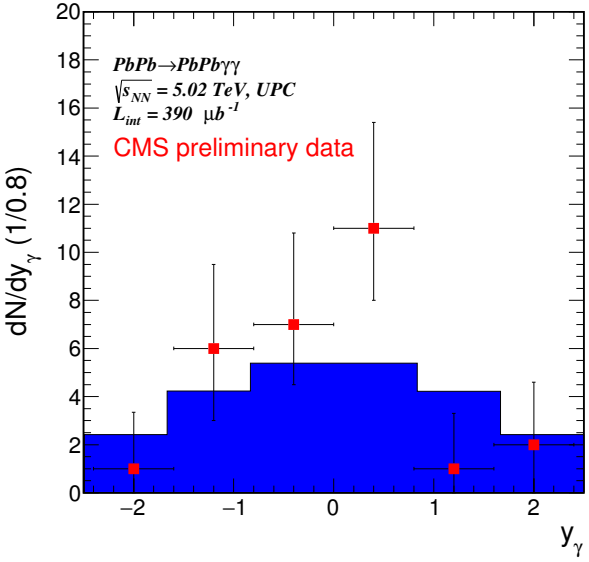


Coherent sum of boxes & 2-gluon exchange...

$AA \to AA\gamma\gamma$ - 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, CMS-FSQ-16-012





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

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

ours $\Rightarrow$ $\sigma = 103 \pm 0.034$ nb

✔ 14 events

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

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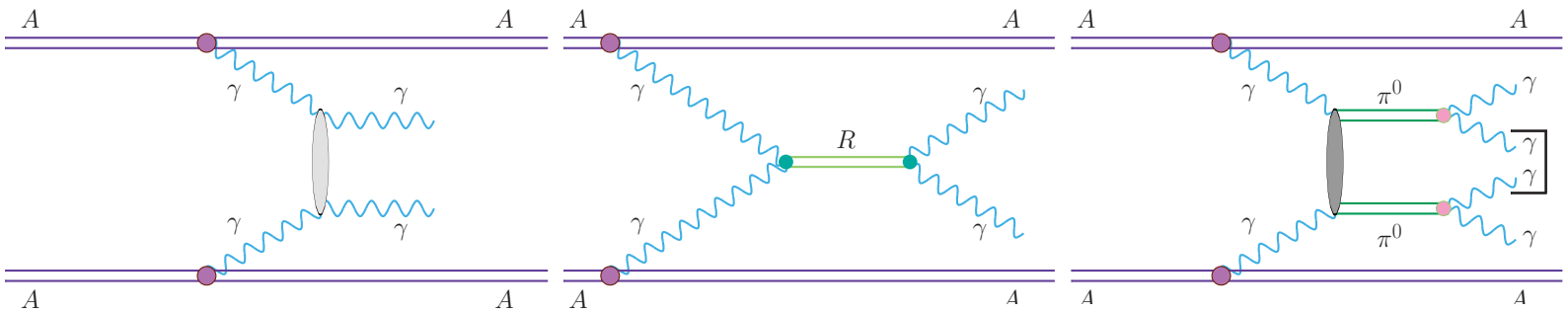
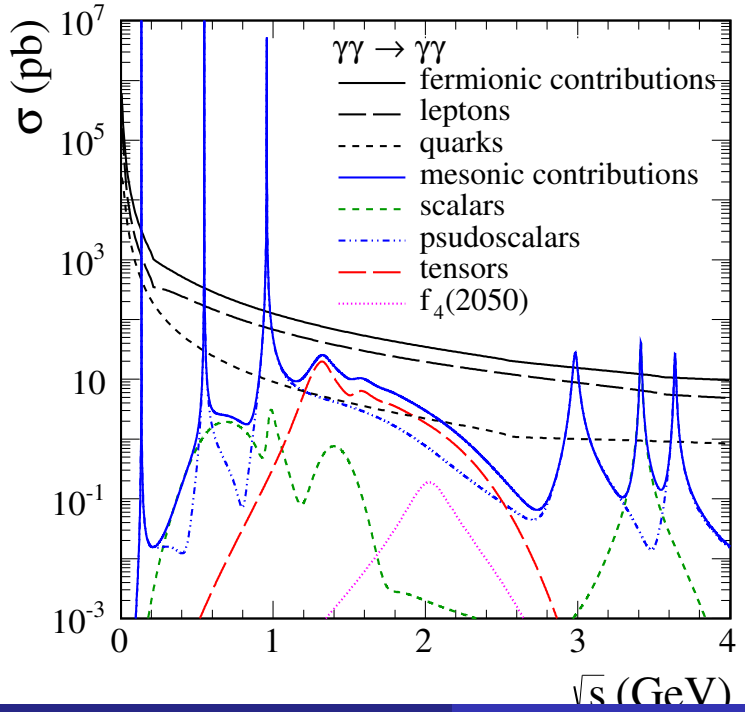
AA→AA$\gamma\gamma$ FOR $M_{\gamma\gamma} < 5$ GEV ? NEW

CONTINUUM **RESONANCES** **BACKGROUND**



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



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

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EPA
$\gamma\gamma \to \gamma\gamma$
NUCLEAR CROSS SECTION
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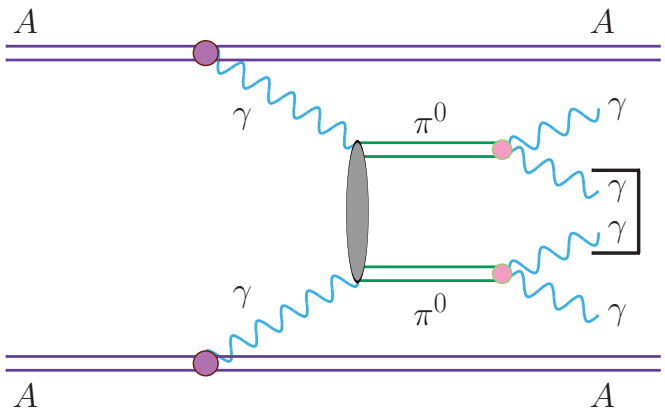
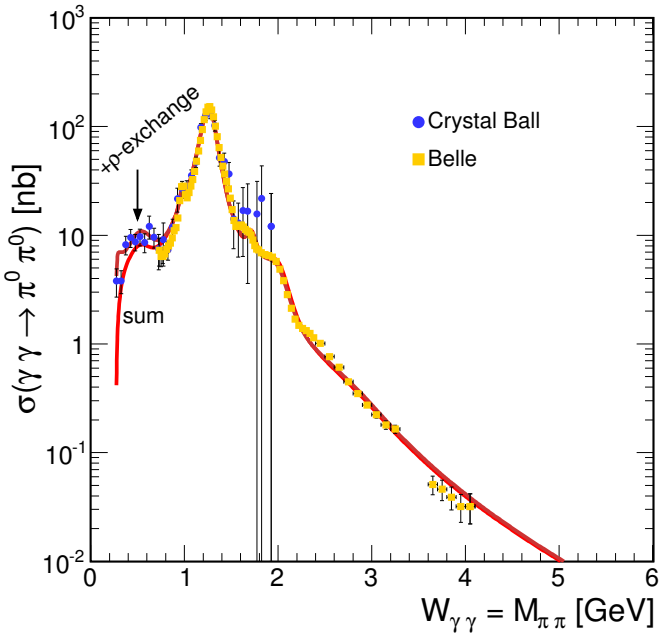
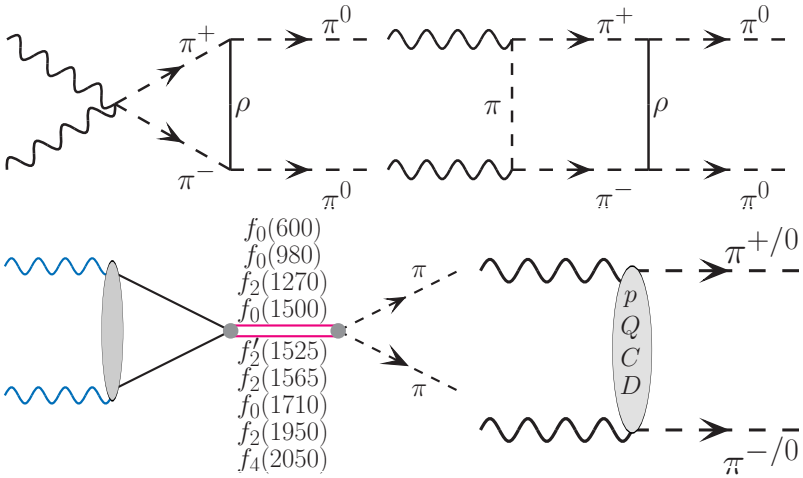
$M_{\gamma\gamma} < 5$ GeV $\Rightarrow$ PIONIC BACKGROUND

- 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
  - $\gamma\gamma \to \pi^+\pi^-$ & $\pi^0\pi^0$



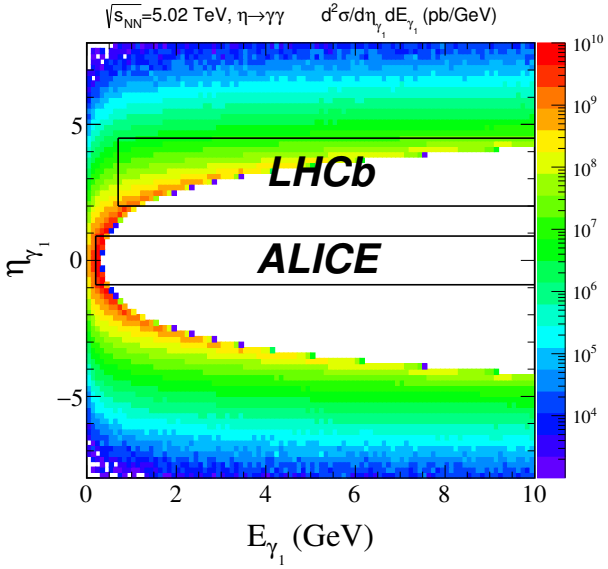


$\gamma\gamma \to \pi^0\pi^0$

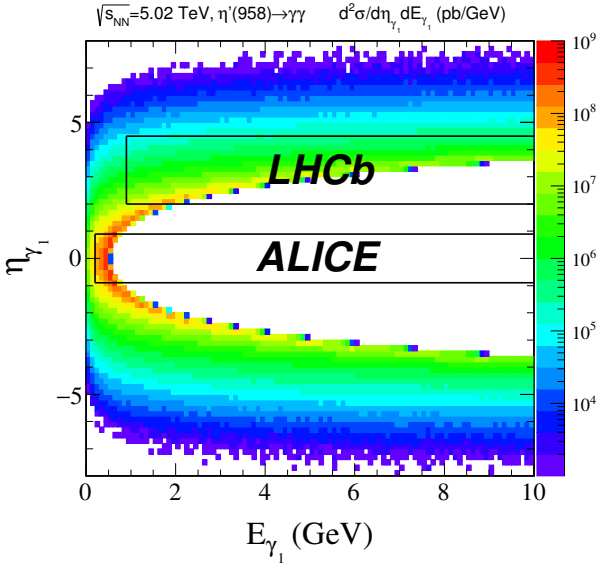


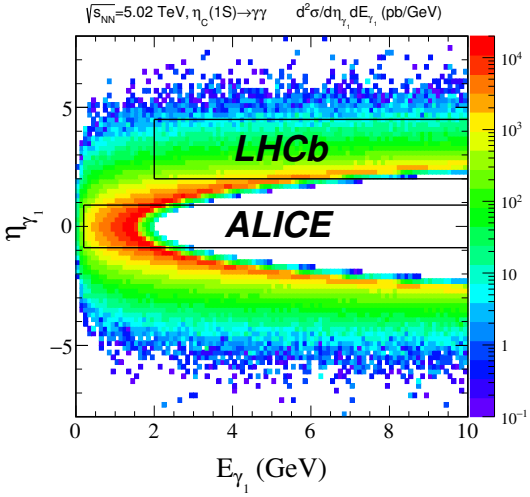
UPC of AA...?

η

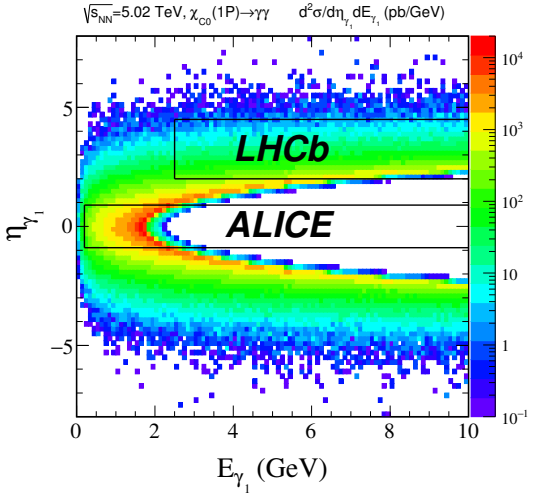


$\eta'(958)$

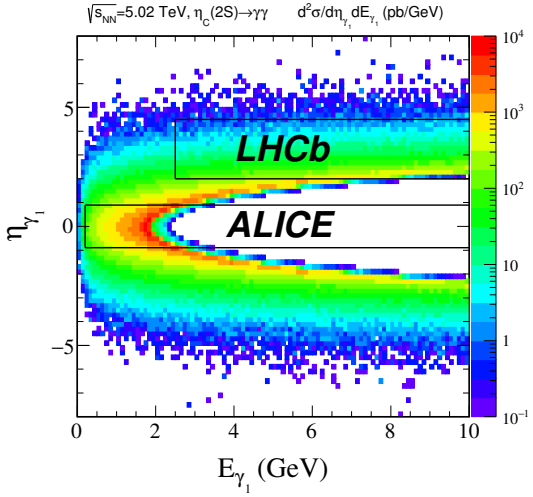




$\eta_c(1S)$



$\chi_{c0}(1P)$



$\eta_c(2S)$

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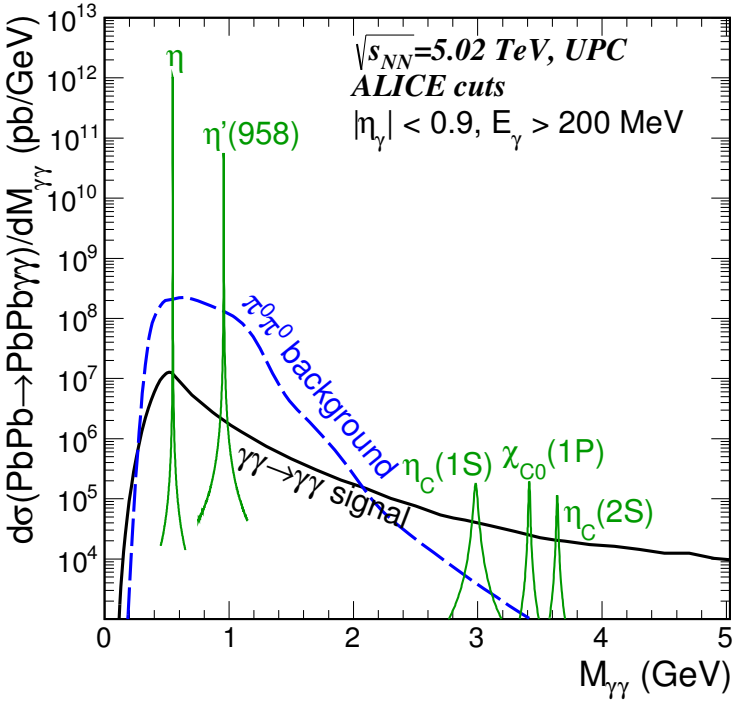
COMPARISON

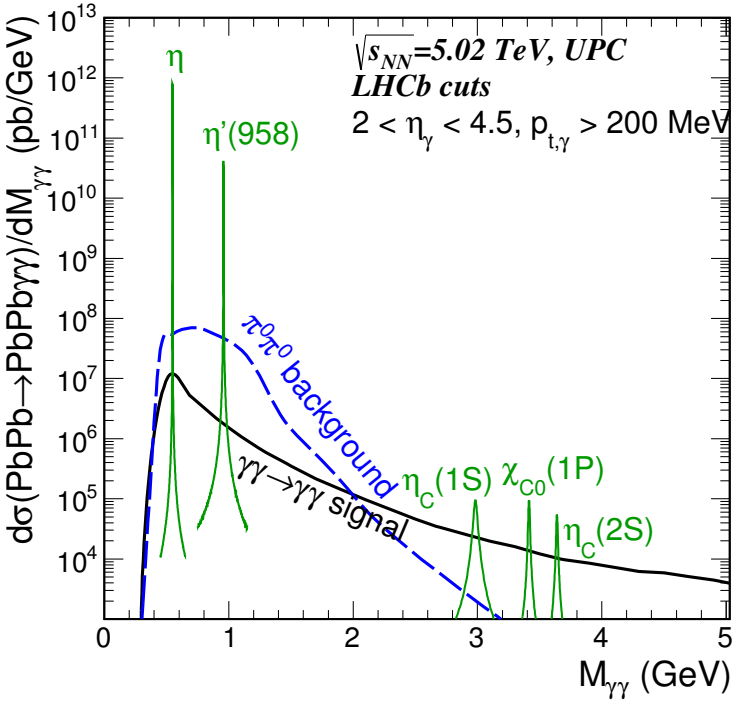
experiment	pseudorapidity range	other condition
ALICE	$-0.9 < \eta_\gamma < 0.9$	$E_\gamma > 200$ MeV
LHCb	$2.0 < \eta_\gamma < 4.5$	$p_{t,\gamma} > 200$ MeV

ALICE cuts

✔ boxes
✔ bkg
✔ mesons

LHCb cuts





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RESONANSE CONTRIBUTION & EXPERIMENTAL RESOLUTION

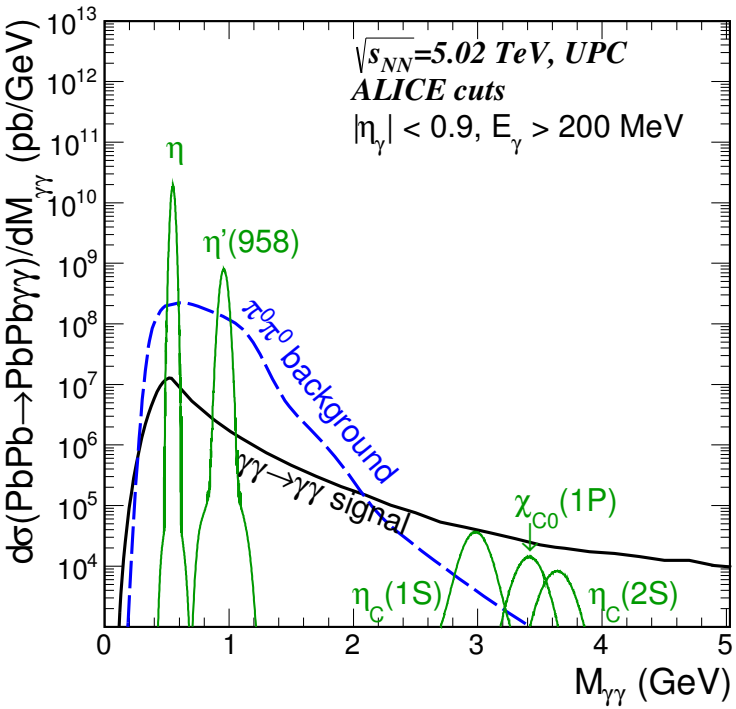
ENERGY RESOLUTION

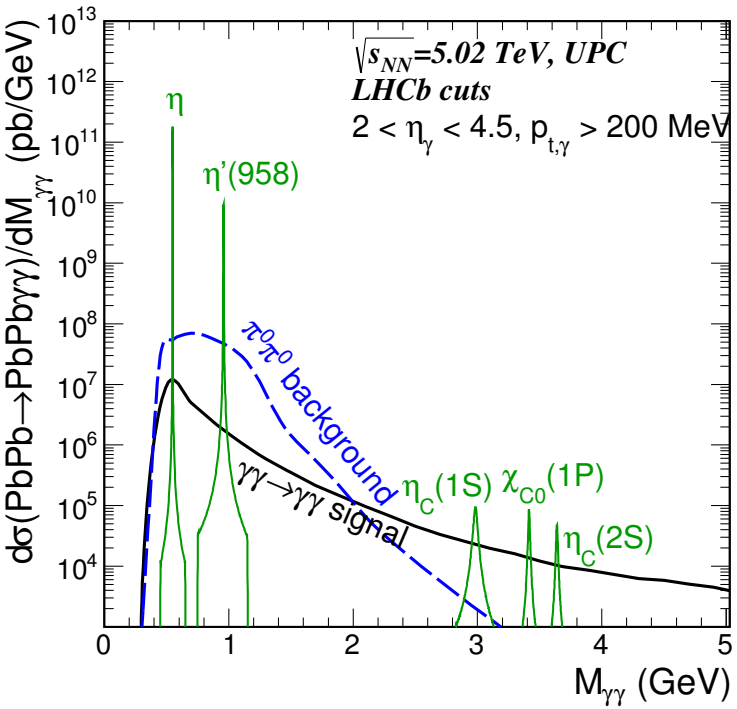
$$\frac{\sigma_{E_\gamma}}{E_\gamma} = 2\%$$

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

ALICE cuts

LHCb cuts





Energy resolution modifies resonant signals

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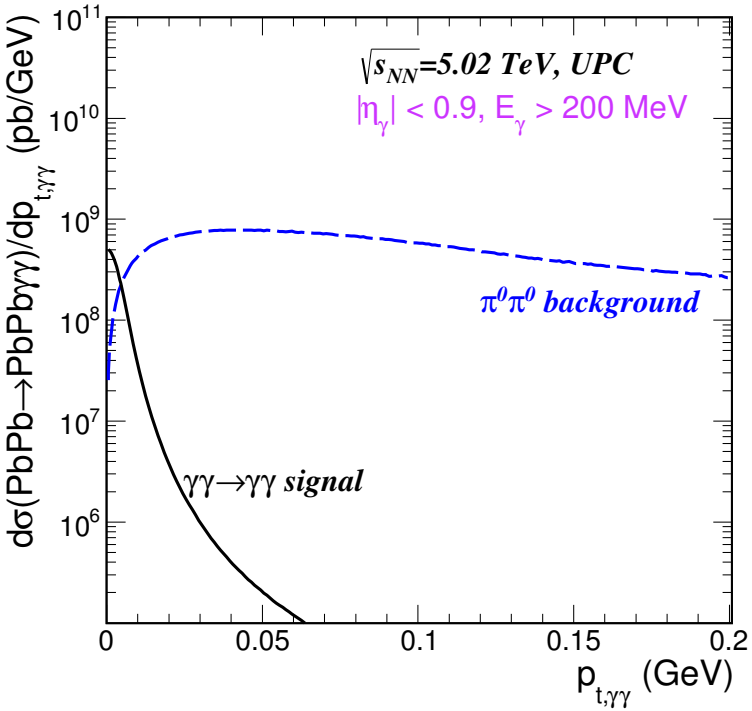
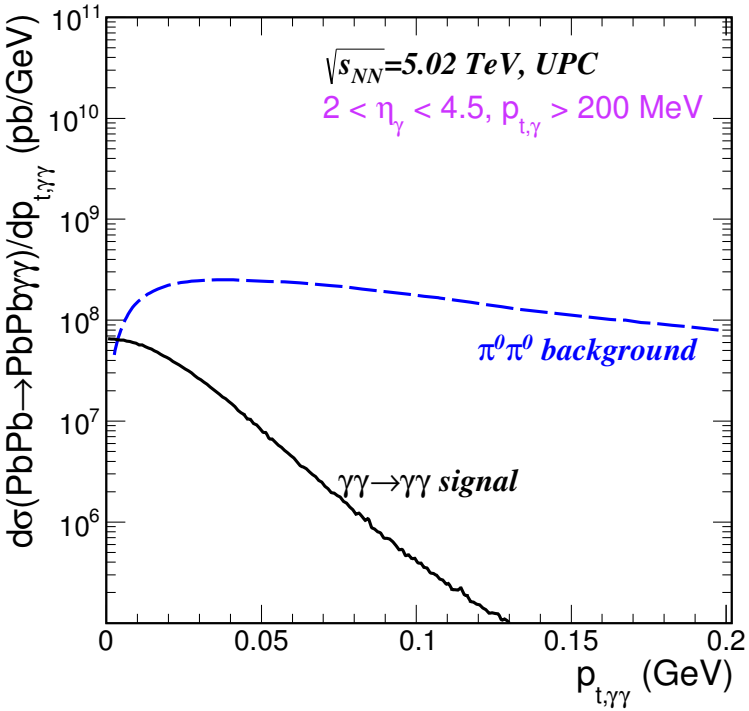
EXPERIMENTAL RESOLUTION & $p_{t,\gamma\gamma}$

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

ALICE cuts

LHCb cuts





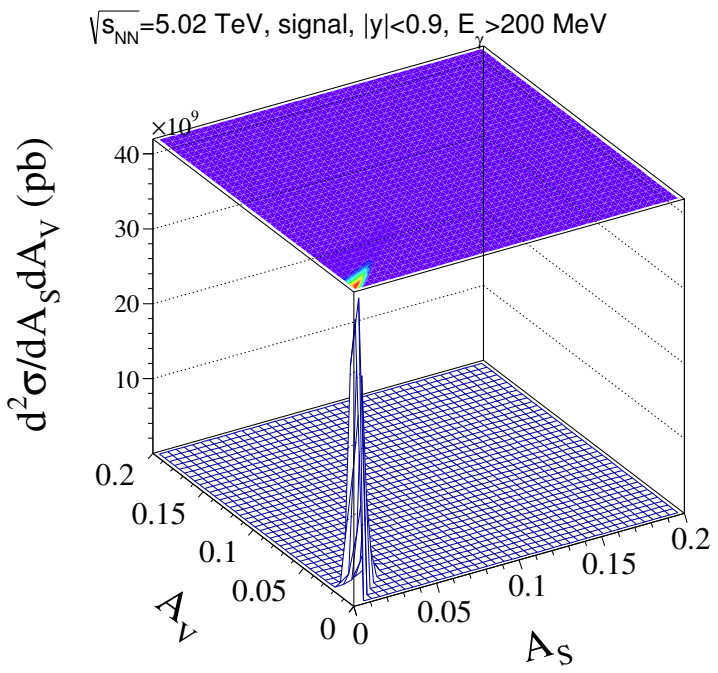
Very limited region where the signal overestimates the background

EXPERIMENTAL RESOLUTION & SCALAR & VECTOR ASYMMETRY

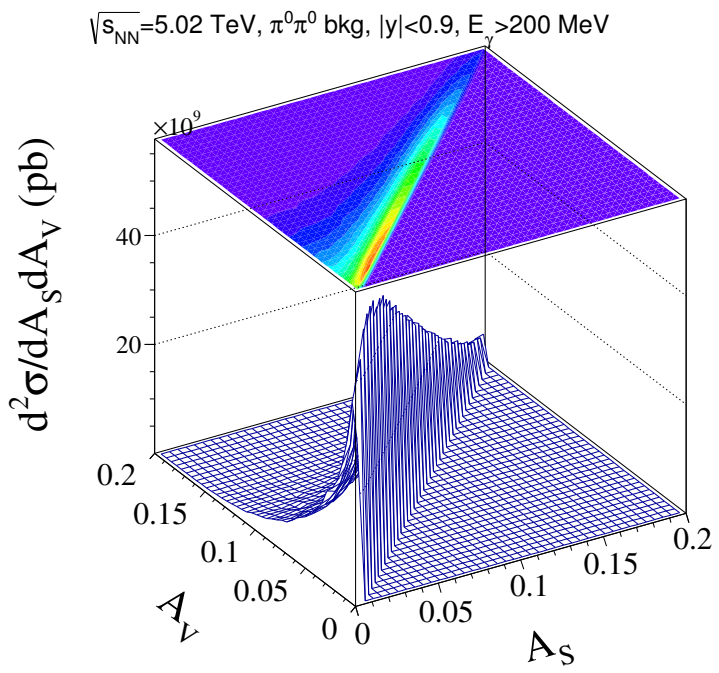
$$A_S = \left| \frac{|\vec{p}_T(1)| - |\vec{p}_T(2)|}{|\vec{p}_T(1)| + |\vec{p}_T(2)|} \right|$$

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

signal



background

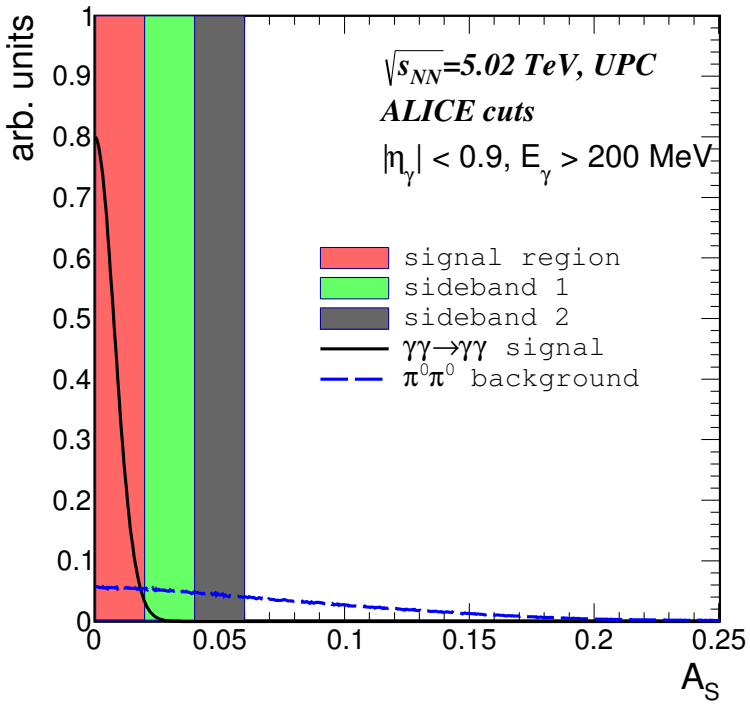


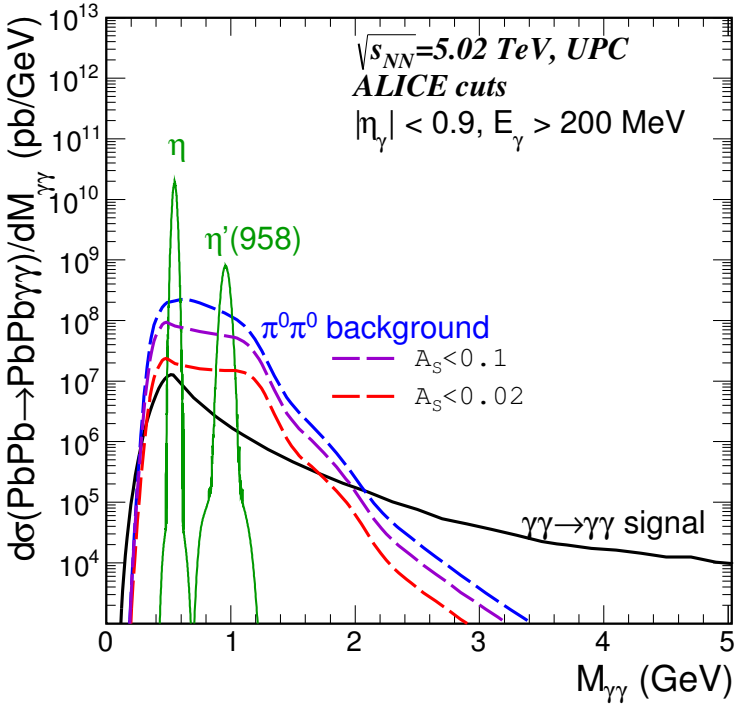
small A_S&A_V → background reduction

EXPERIMENTAL RESOLUTION & SCALAR ASYMMETRY

Scalar asymmetry

$M_{\gamma\gamma}$

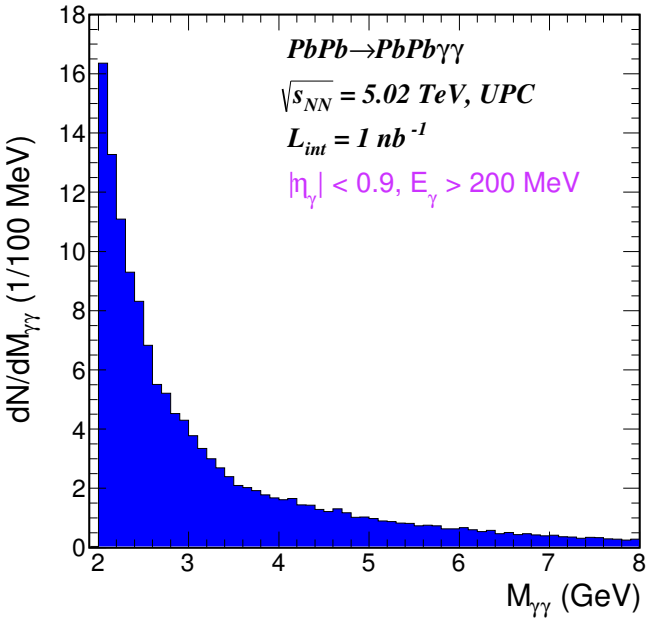




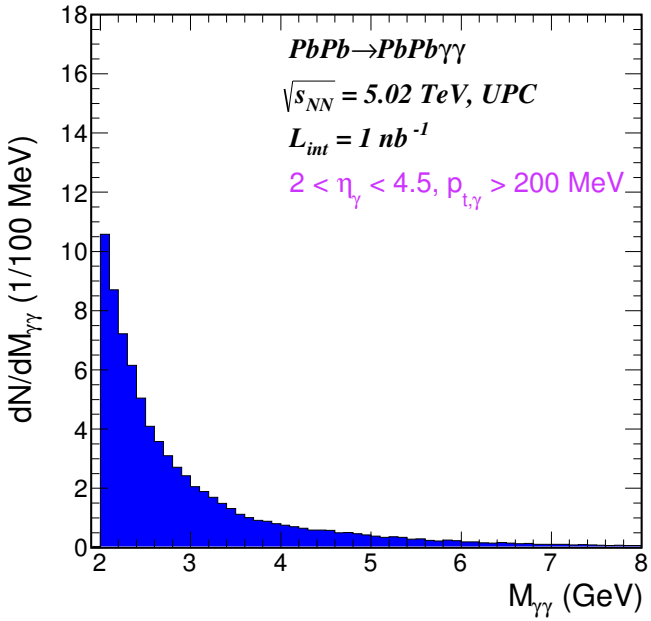
95% of the signal events at $A_S < 0.02$

Number of events, $L_{int} = 1$ nb

ALICE cuts



LHCb cuts

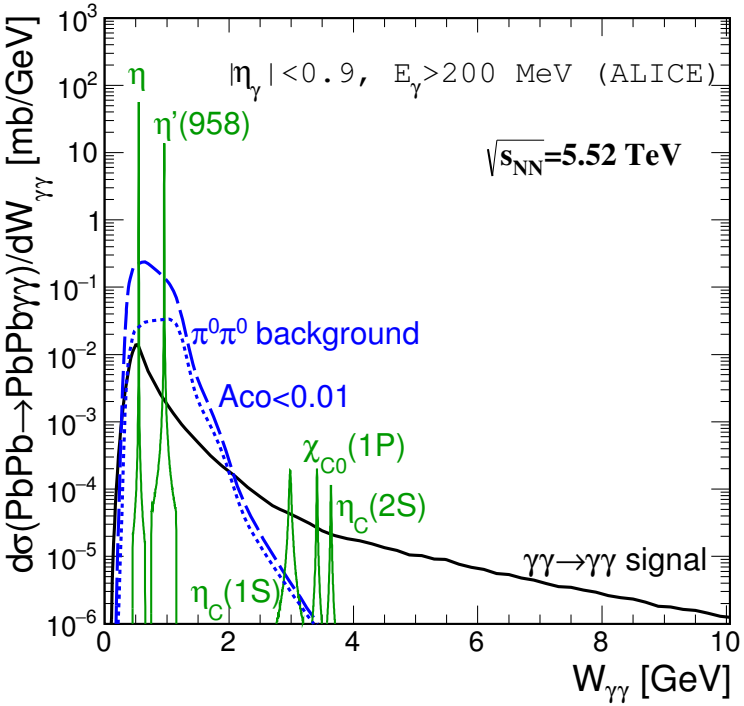


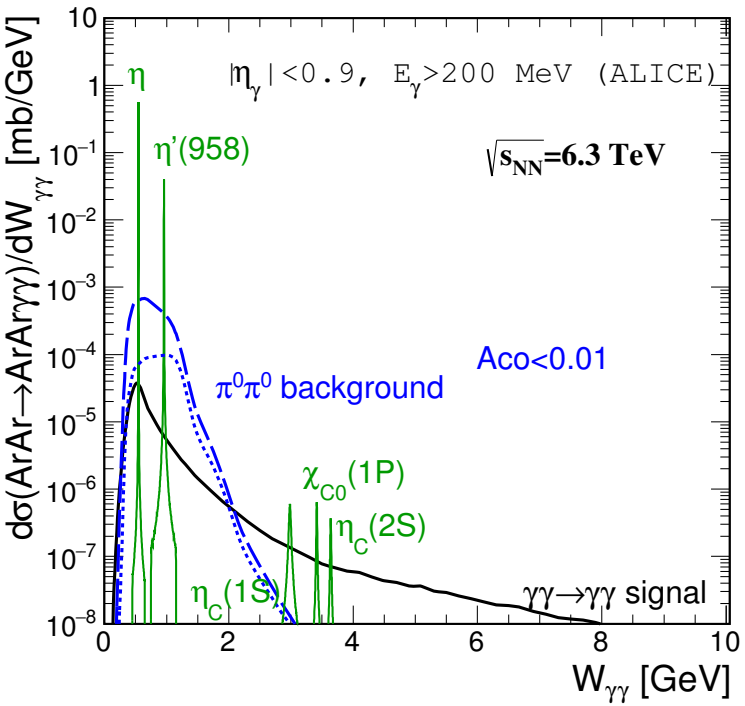
Energy	$W_{\gamma\gamma} = (0-2)$ GeV		$W_{\gamma\gamma} > 2$ GeV	
Region	ALICE	LHCb	ALICE	LHCb
boxes	4 890	3 818	146	79
$\pi^0\pi^0$ bkg	135 300	40 866	46	24
η	722 573	568 499		
$\eta'(958)$	54 241	40 482		
$\eta_c(1S)$			9	5
$\chi_{c0}(1P)$			4	2
$\eta_c(2S)$			2	1

AA→AAγγ @ MIDRAPIDITY

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

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



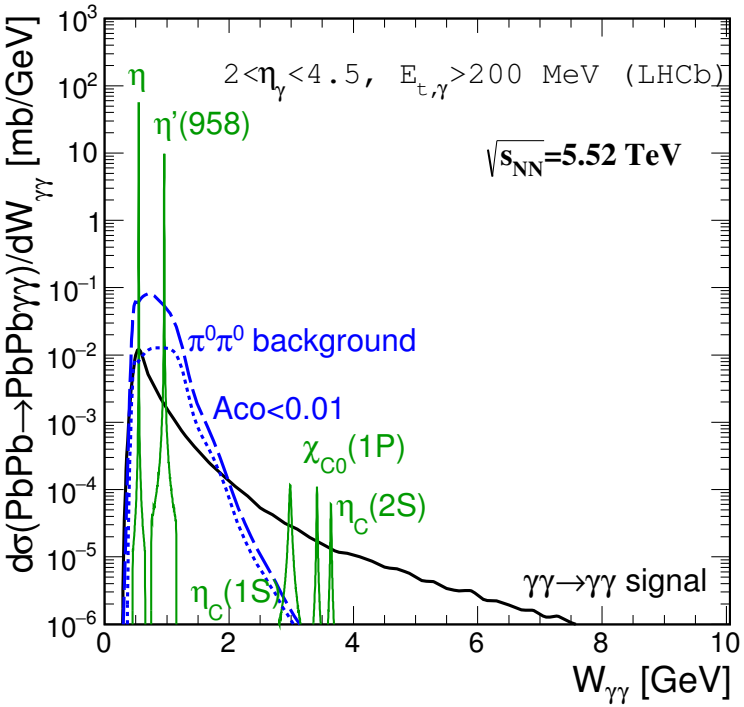


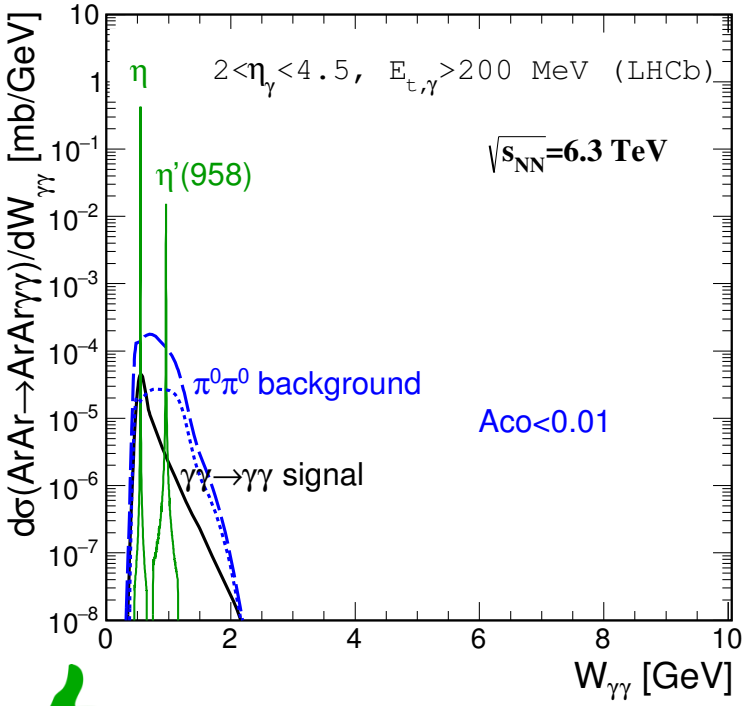
$$\sigma_{tot} \propto (Z_{Pb}/Z_{Ar})^4 \approx 430$$

$AA \to AA\gamma\gamma$ @ FORWARD RAPIDITY

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

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





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

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

LHCb $\to W_{\gamma\gamma} > 2$ GeV $\to$ 11 - 37 events (SIGNAL!)

CONCLUSION

- UPC of heavy ion opens a possibility to measure/ to test the $\gamma\gamma \to \gamma\gamma$ scattering
  - boxes
  - VDM-Regge
  - 2-gluon exchange
  - mesons decay
  - pionic background
- Measurable cross section
- ATLAS/CMS have observed 59/14 events confirming Light-by-Light scattering in UPC
- ALICE & LHCb could measure LbyL in Pb-Pb and Ar-Ar collisions with good statistic ($W_{\gamma\gamma} > 2$ GeV)
- Importance of η & η'
- Hopeful scalar/vector asymmetry
- Next step $\to$ Missing contribution (?)
  $\to$Electromagnetic excitation

Thank you

DIS2019
LIGHT-BY-LIGHT SCATTERING
EPA
$\gamma\gamma \to \gamma\gamma$
NUCLEAR CROSS SECTION
SIGNAL
RESONANCES
PIONIC BACKGROUND
COMPARISON
CONCLUSION

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