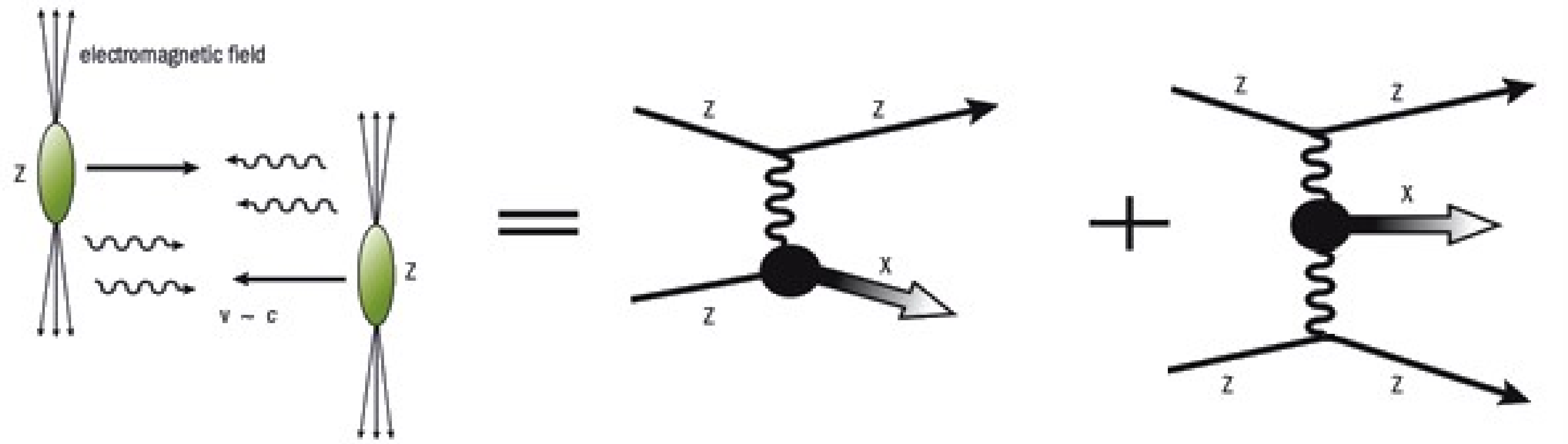
Ultraperipheral collisions at the LHC: short state-of-the-art

CMS Heavy-Ion Workshop

ECT* Trento, 30th May 2023

David d'Enterria (CERN)

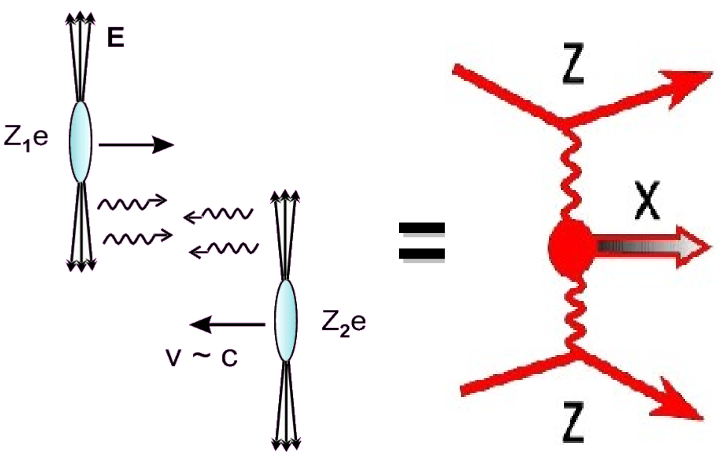


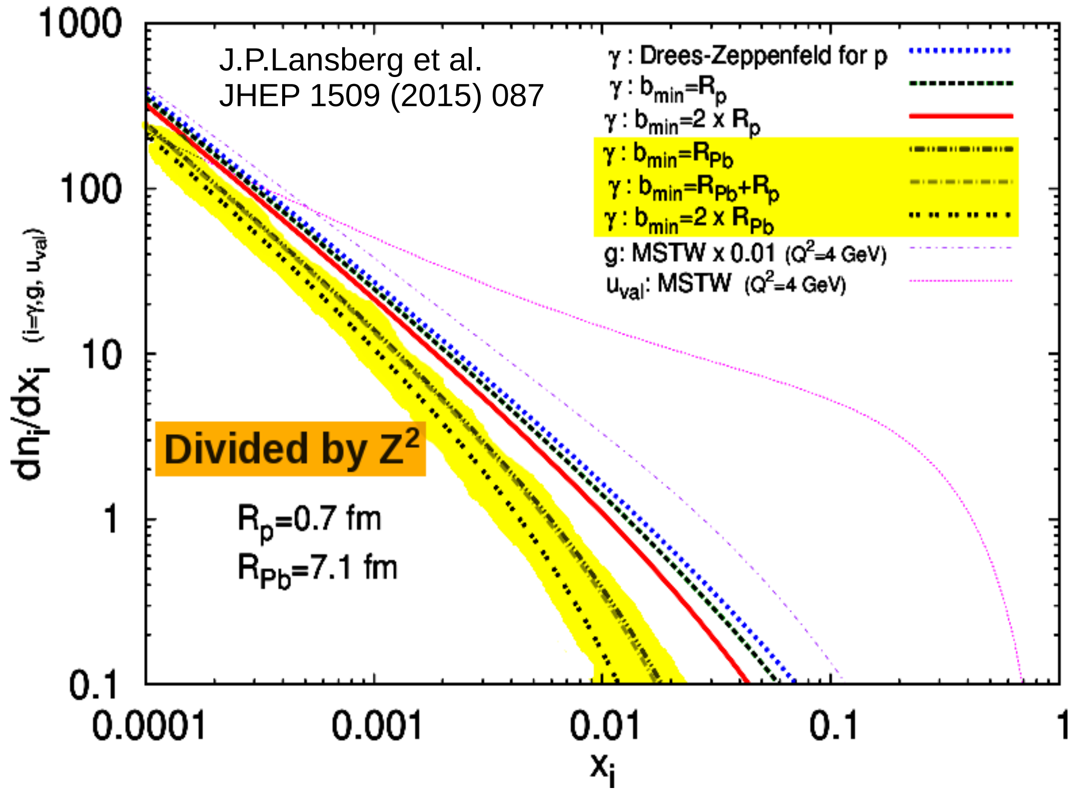
NB: Many plots obtained with gamma-UPC generator of γγ collisions:
https://arxiv.org/abs/2207.03012, JHEP 09 (2022) 248

Photon-photon collisions at the LHC

- Electromagnetic ultra-peripheral collisions (UPC): $b_{min} > R_A + R_B$
- HE ions generate huge EM fields from coherent action of Z=82 protons:

Weizsäcker-Williams (EPA) power-law photon flux:

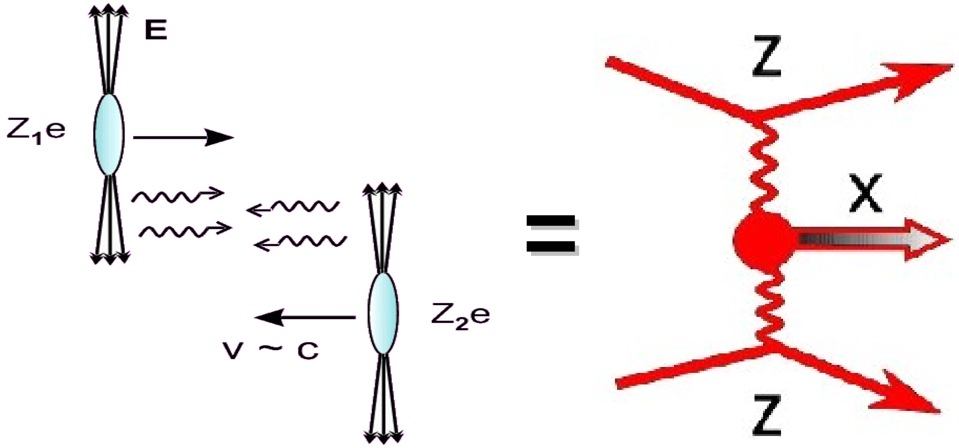




- Quasi-real γ (coherent emission): Q ~ 1/R ~ 0.06 GeV (Pb), 0.28 GeV (p)
- Maximum γ longitud. energies: $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 80 GeV (Pb), ~ 2.5 TeV (p)

Photon-photon collisions at the LHC

- Electromagnetic ultra-peripheral collisions (UPC): $b_{min} > R_A + R_B$
- HE ions generate huge EM fields from coherent action of Z=82 protons:



- Huge photon fluxes:
  $\sigma(\gamma\gamma) \sim Z^4$ (~$5\cdot 10^7$ for PbPb) times larger than p,$e^{\pm}$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

- Quasi-real γ (coherent emission): Q ~ 1/R ~ 0.06 GeV (Pb), 0.28 GeV (p)
- Maximum γ longitud. energies: $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 80 GeV (Pb), ~ 2.5 TeV (p)

System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$E_{beam1} + E_{beam2}$	γ_L	R_A	E_γ^{max}	$\sqrt{s_{\gamma\gamma}^{max}}$
Pb-Pb	5.52 TeV	5 nb^{-1}	2.76 + 2.76 TeV	2960	7.1 fm	80 GeV	160 GeV
p-Pb	8.8 TeV	1 pb^{-1}	7.0 + 2.76 TeV	7450, 2960	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV
p-p	14 TeV	150 fb^{-1}	7.0 + 7.0 TeV	7450	0.7 fm	2.45 TeV	4.5 TeV

▶ Single *X* = C-even (spin 0,2) resonances only (Landau-Yang + C symmetry)

How peripheral are Pb-Pb UPCs at the LHC?

- Average $|\vec{b}_1-\vec{b}_2|$ vs. $m_{\gamma\gamma}$:

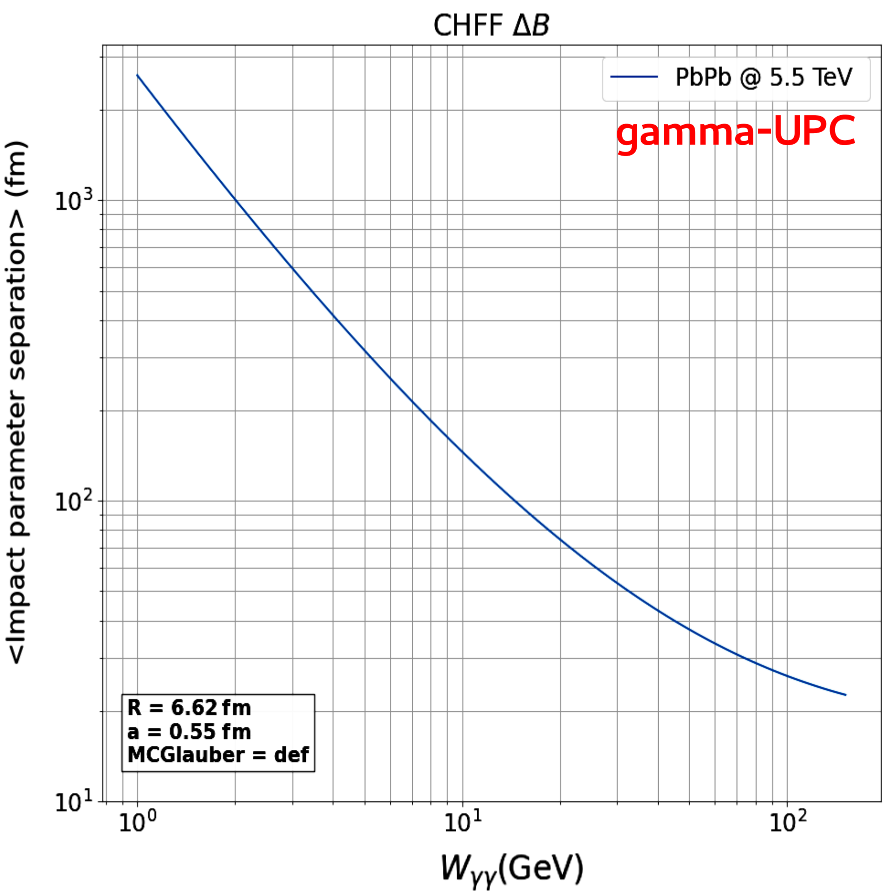
  $m_{\gamma\gamma}$<5 GeV: $\langle\Delta b\rangle$ >1000 fm

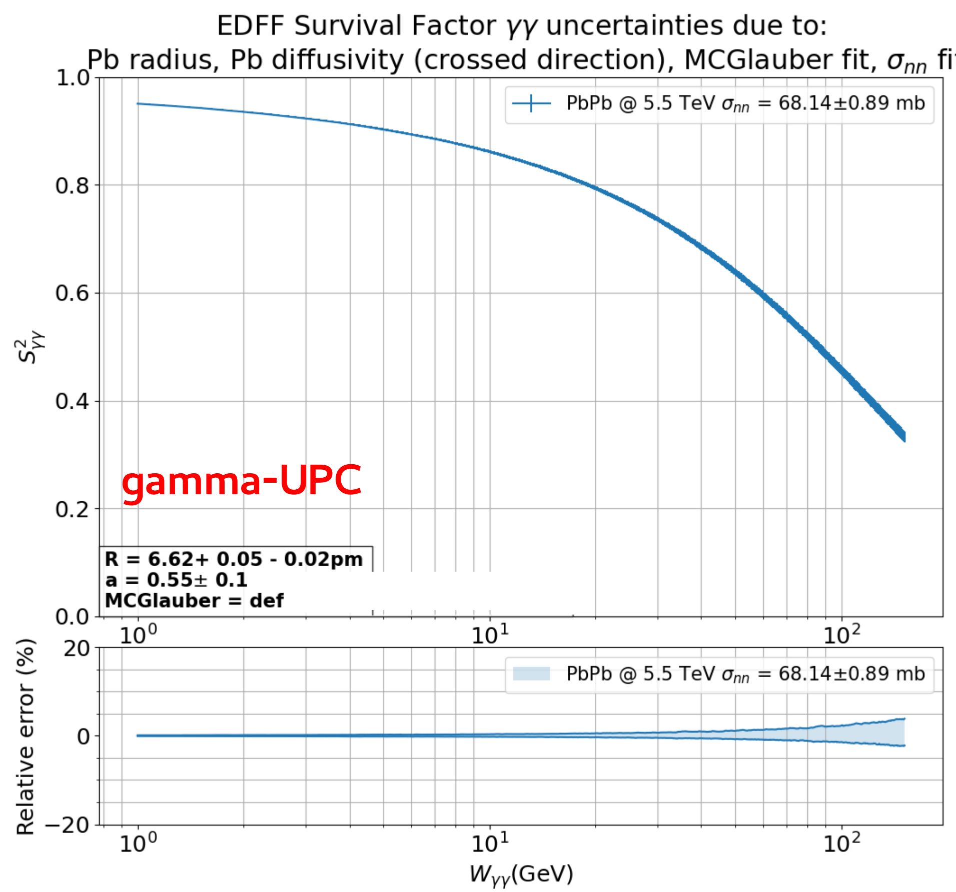
  $m_{\gamma\gamma}$>100 GeV: $\langle\Delta b\rangle$ ~20 fm

- Pb-Pb survival probab. vs. $m_{\gamma\gamma}$:

  $m_{\gamma\gamma}$<5 GeV: $\langle P_{\text{non-overlap}}\rangle$ >90%

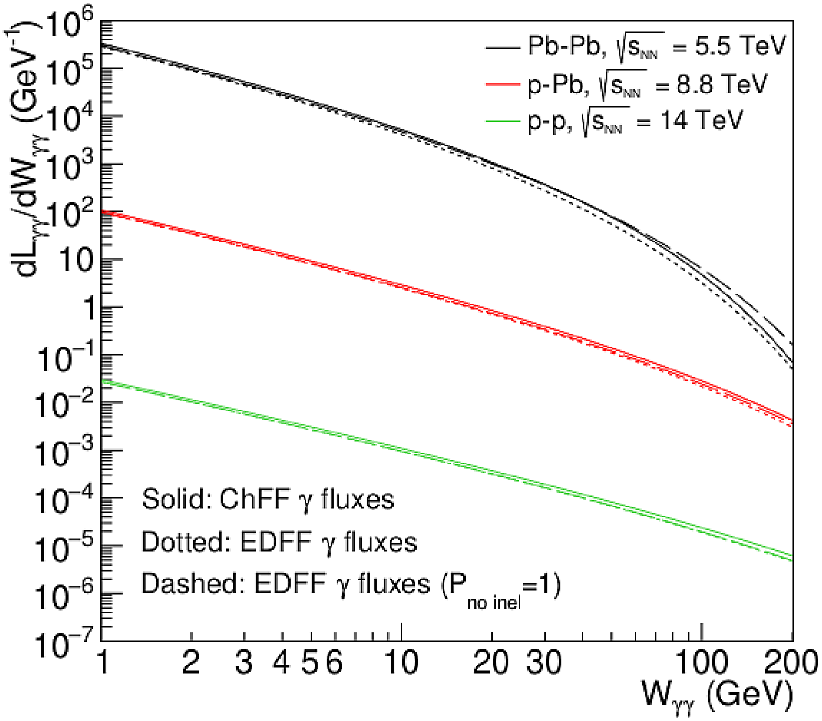
  $m_{\gamma\gamma}$>100 GeV: $\langle P_{\text{non-overlap}}\rangle$ <40%

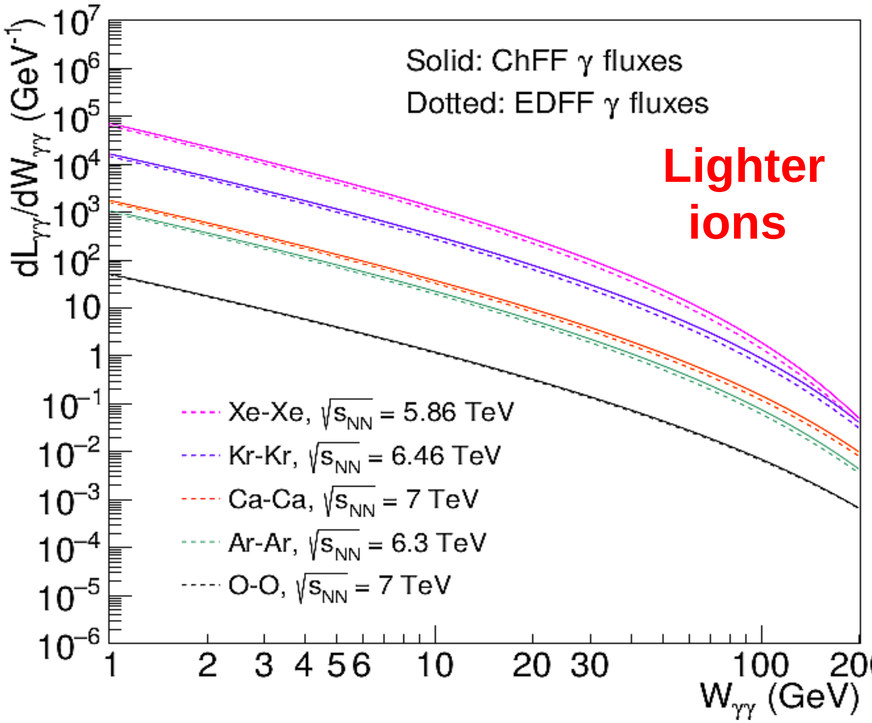




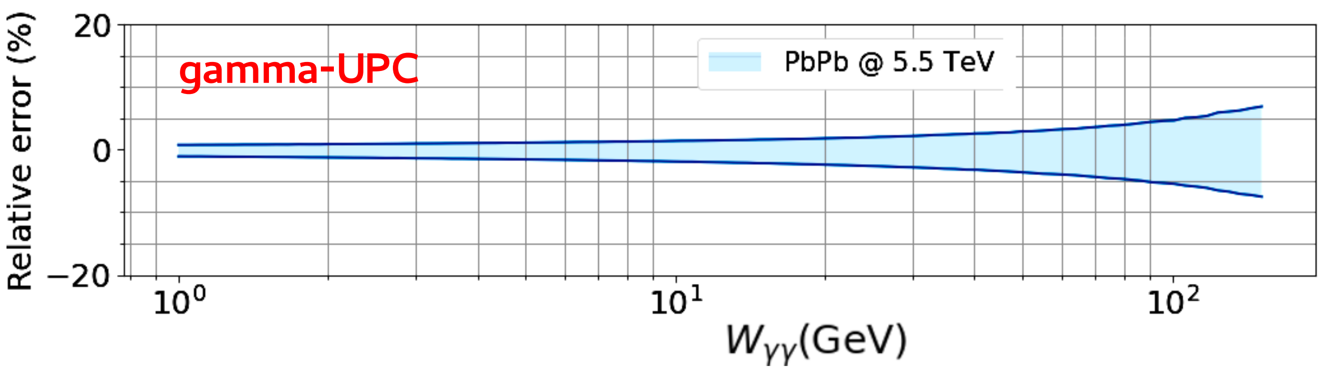
Effective γγ luminosities at the LHC

- Thanks to Z^4 boost, A-A γγ lumis (per collision) well above p-p ones:





- Elastic γγ luminosities uncertainties (PbPb): Low-mass: few %. High mass: ~10%



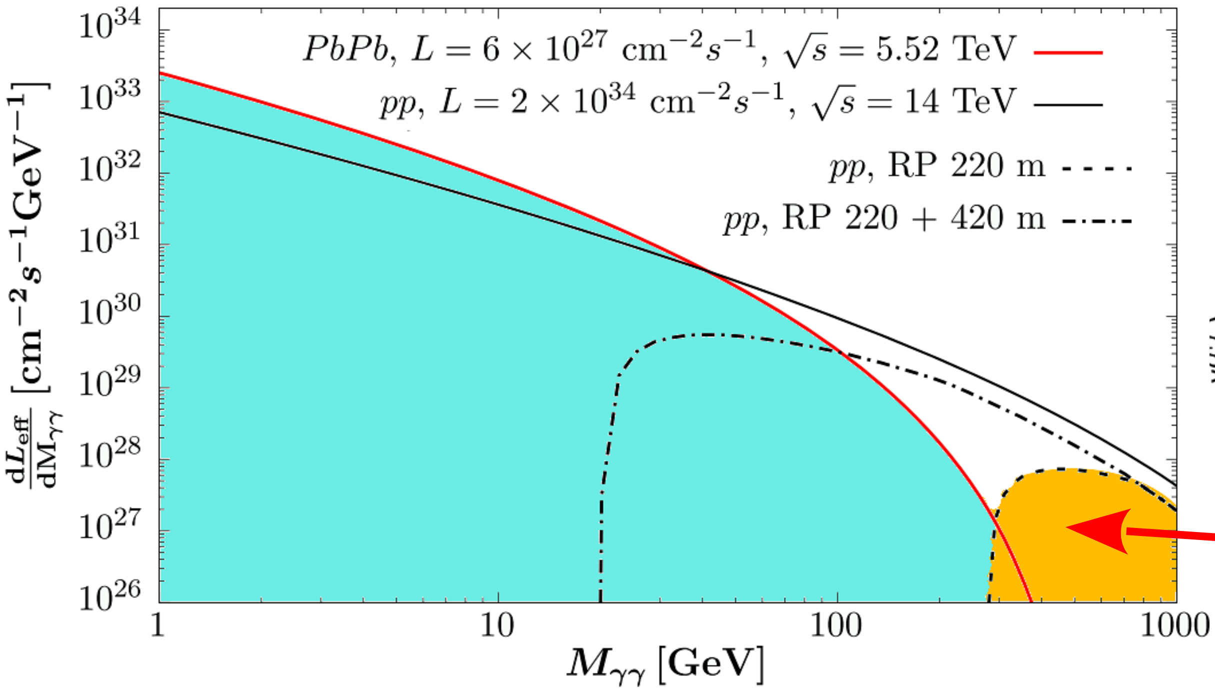
ChFF γ spectra

Glauber MC:

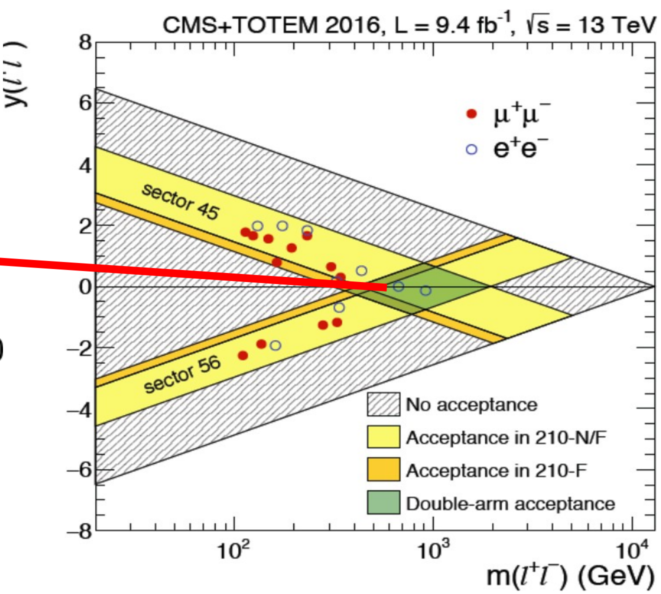
Variations of R,a,σ_{NN}

Effective γγ luminosities at the LHC

- Thanks to Z^4 boost, Pb-Pb γγ lumis (per collision) well above the p-p ones.
  - Up to $W_{\gamma\gamma}$ ~ 30 GeV, accounting for much larger p beam luminosity
  - Up to $W_{\gamma\gamma}$ ~ 300 GeV requiring double-arm p tagging at PPS (~220 m) (kinematic matching required to remove huge pp pileup):

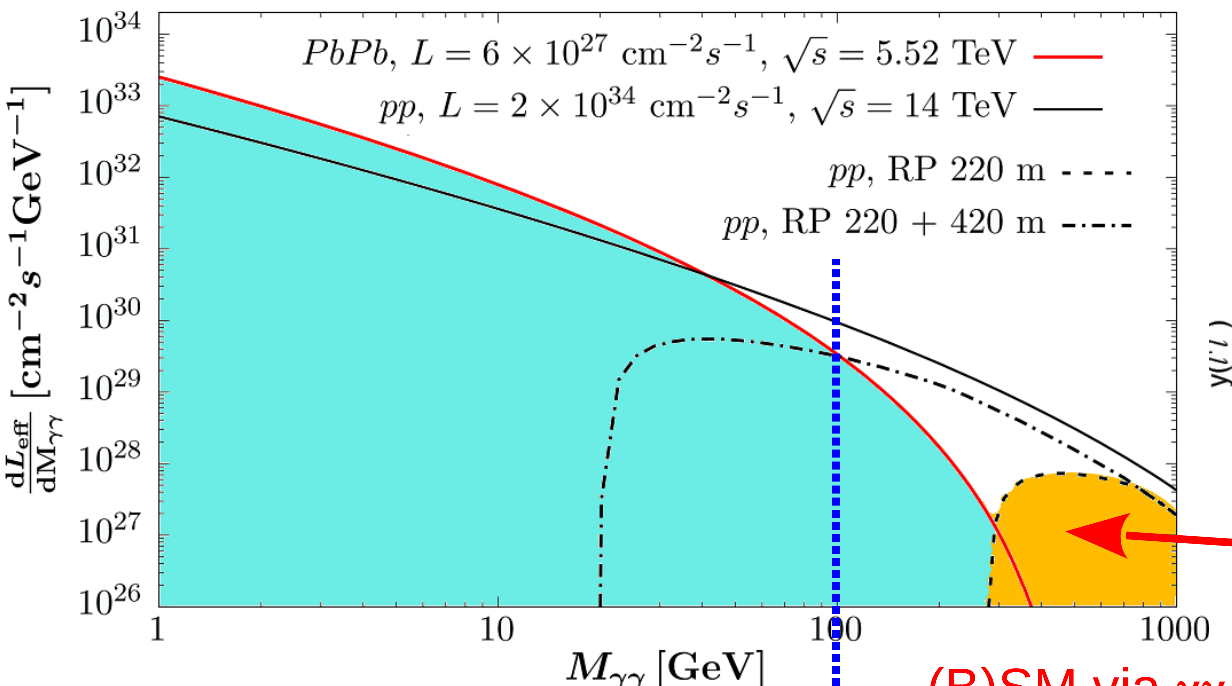


- PPS p-p acceptance vs. central mass & y

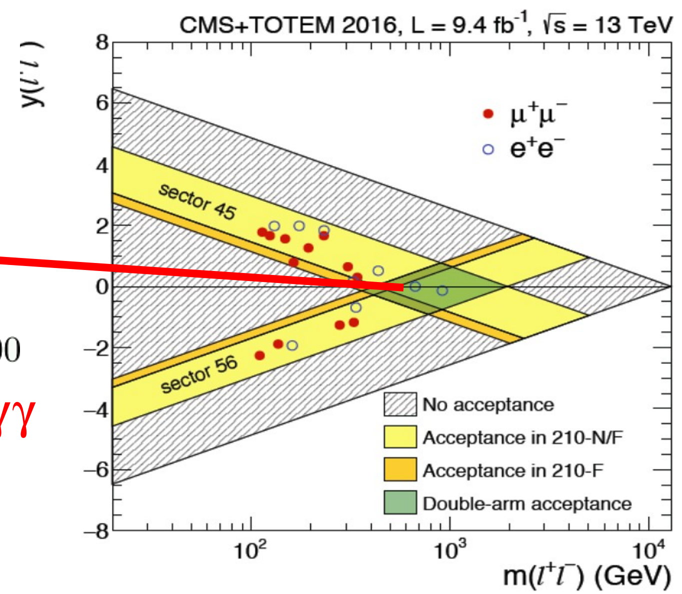


Effective γγ luminosities at the LHC

- Thanks to Z^4 boost, Pb-Pb γγ lumis (per collision) well above the p-p ones.
  – Up to $W_{\gamma\gamma}$ ~ 30 GeV, accounting for much larger p beam luminosity
  – Up to $W_{\gamma\gamma}$ ~ 300 GeV requiring double-arm p tagging at PPS (~220 m) (kinematic matching required to remove huge pp pileup):

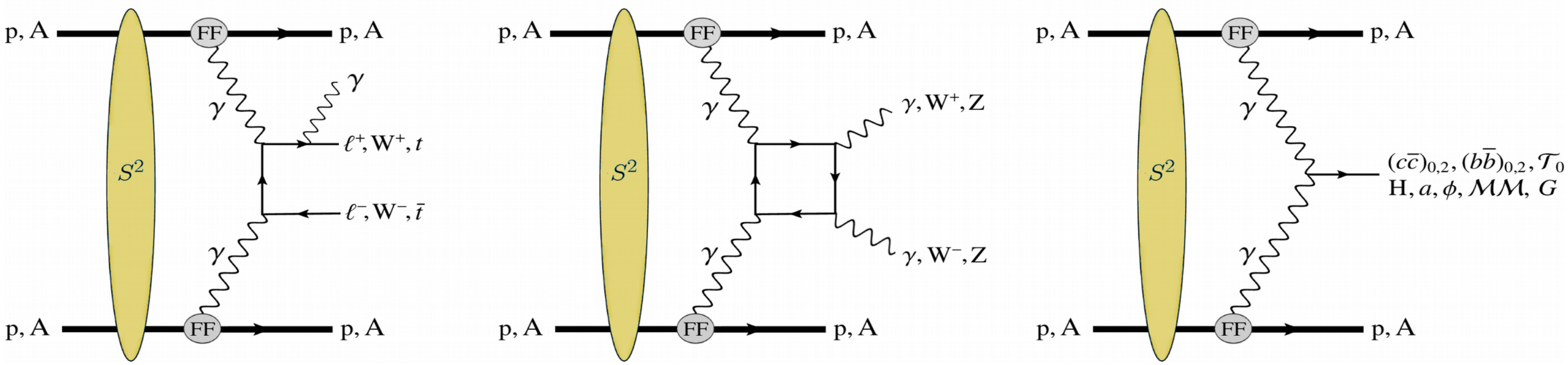


- PPS p-p acceptance vs. central mass & y



Rule of thumb: (B)SM via γγ in Pb-Pb ⇐ m_X~100 GeV ⇒ (B)SM via γγ in p-p with tagged p's

Rich & unique (B)SM γγ physics with UPCs at LHC

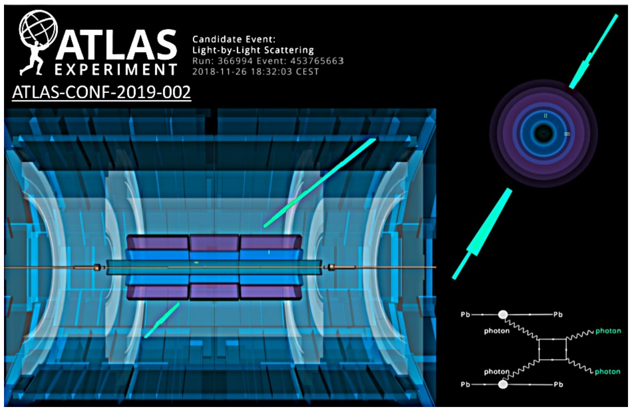


System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$E_{beam1} + E_{beam2}$	γ_L	R_A	E_γ^{max}	$\sqrt{s_{\gamma\gamma}^{max}}$
Pb-Pb	5.52 TeV	5 nb^{-1}	2.76 + 2.76 TeV	2960	7.1 fm	80 GeV	160 GeV
p-Pb	8.8 TeV	1 pb^{-1}	7.0 + 2.76 TeV	7450, 2960	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV
p-p	14 TeV	150 fb^{-1}	7.0 + 7.0 TeV	7450	0.7 fm	2.45 TeV	4.5 TeV

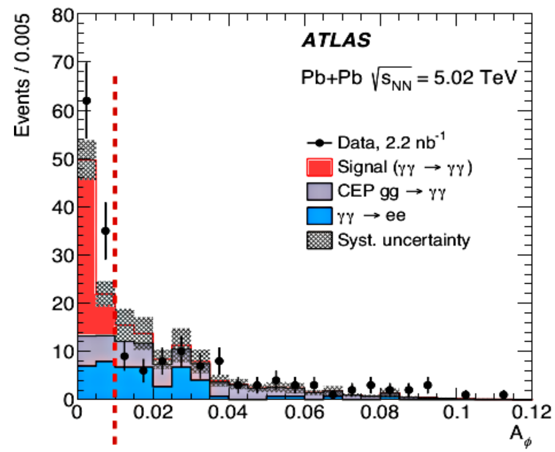
Process	Physics motivation
$\gamma\gamma \to e^+e^-, \mu^+\mu^-$	"Standard candles" for proton/nucleus γ fluxes, EPA calculations, and higher-order QED corrections
$\gamma\gamma \to \tau^+\tau^-$	Anomalous τ lepton e.m. moments [29–32]
$\gamma\gamma \to \gamma\gamma$	aQGC [25], ALPs [27], BI QED [28], noncommut. interactions [36], extra dims. [37],. . .
$\gamma\gamma \to \mathcal{T}_0$	Ditauonium properties (heaviest QED bound state) [38, 39]
$\gamma\gamma \to (c\bar{c})_{0,2}, (b\bar{b})_{0,2}$	Properties of scalar and tensor charmonia and bottomonia [40, 41]
$\gamma\gamma \to$ XYZ	Properties of spin-even XYZ heavy-quark exotic states [42]
$\gamma\gamma \to$ VM VM	(with VM = ρ, ω, ϕ, J/ψ, Υ): BFKL-Pomeron dynamics [43–46]
$\gamma\gamma \to W^+W^-$, ZZ, Zγ, $\cdots$	anomalous quartic gauge couplings [11, 26, 47, 48]
$\gamma\gamma \to$ H	Higgs-γ coupling, total H width [49, 50]
$\gamma\gamma \to$ HH	Higgs potential [51], quartic $\gamma\gamma$HH coupling
$\gamma\gamma \to t\bar{t}$	anomalous top-quark e.m. couplings [11, 49]
$\gamma\gamma \to \tilde{\ell}\tilde{\ell}, \tilde{\chi}^+\tilde{\chi}^-, H^{++}H^{--}$	SUSY pairs: slepton [11, 52, 53], chargino [11, 54], doubly-charged Higgs bosons [11, 55].
$\gamma\gamma \to a, \phi, \mathcal{MM}, G$	ALPs [27, 56], radions [57], monopoles [58–61], gravitons [62–64],. . .

Observation of $\gamma\gamma \to \gamma\gamma$ (PbPb, 5 TeV)

- Observation of light-by-light scattering in PbPb colls at 5 TeV (2.2 nb^{-1}):
  - – 2 photons (E_T>2.5 GeV, $|\eta|$<2.4, $m_{\gamma\gamma}$>5 GeV) with no hadronic activity over $|\eta|$<5
  - – Photon pair: p_T<1 GeV, Acoplanarity cut: $A\varphi$ < 0.01 to remove backgds.



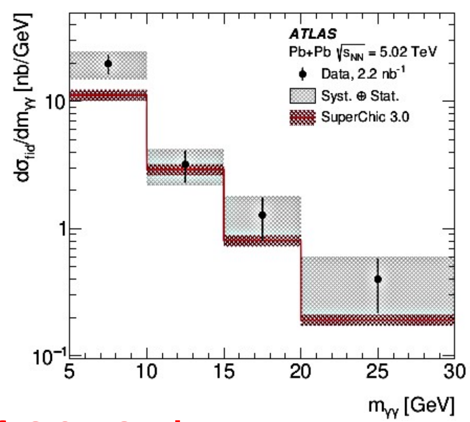
[ATLAS, PRL123 (2019) 052001]

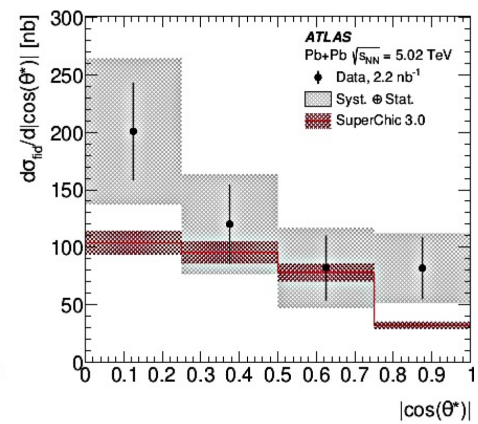


Observed: 97 evts
Expected: 45 signal
+ 27 backgd.

[ATLAS, arXiv:2008.05355]

- Combination of ATLAS (2015+2018) data, compared to LbL prediction:
  - – LbL observation: Signif. = 8.8σ
  - – Fiduc. x-section $\sigma(\gamma\gamma\to\gamma\gamma)$ = 120±22 nb is ~1.5 higher than theory (80±8 nb).
  - – Shape of differential distributions consistent with MC within uncertainties
  - – Control of (non)excl. backgds at low $m_{\gamma\gamma}$?

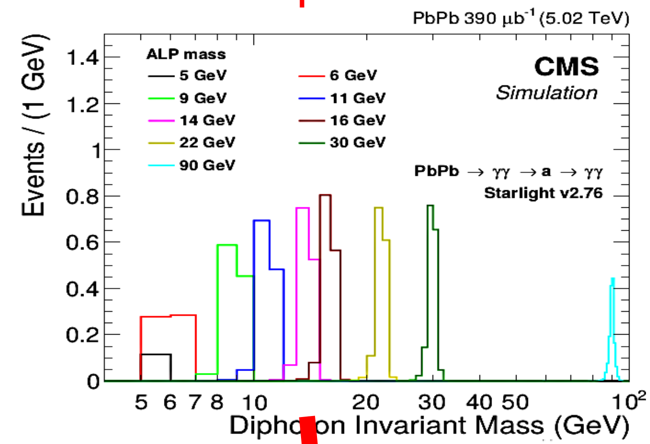


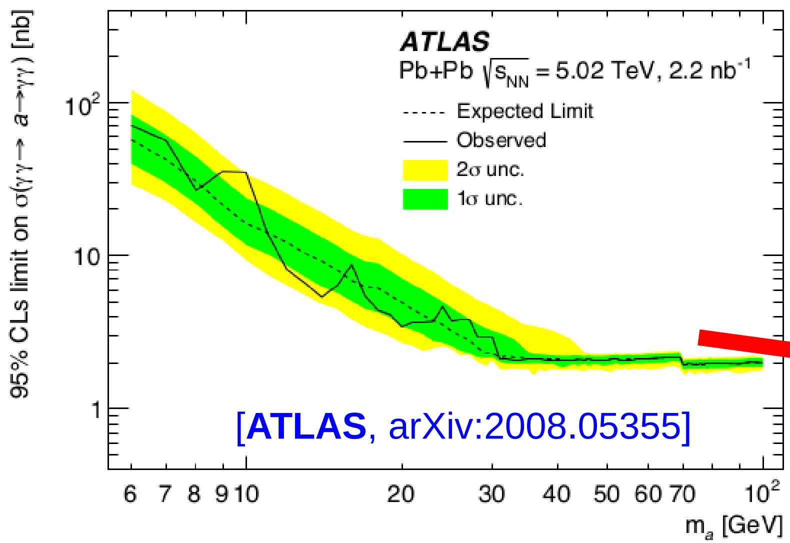


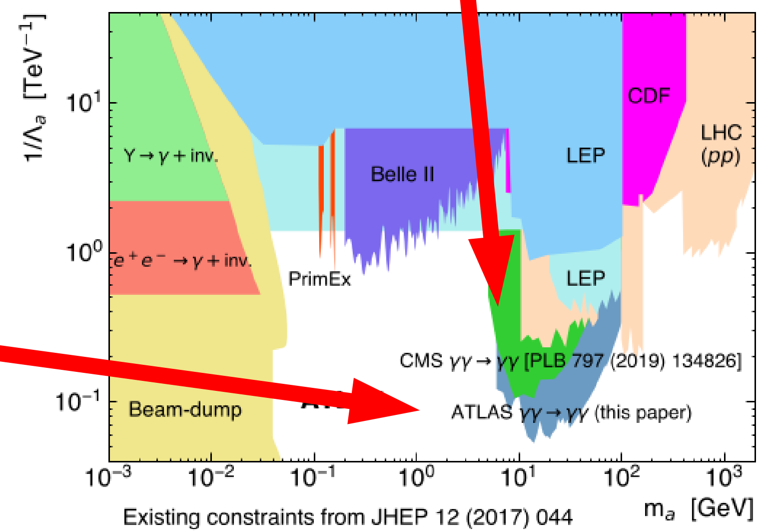
- Ongoing detailed CMS analysis of 2018 data.

ALPs searches via $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ (PbPb, 5 TeV)

- Recasting exclusive $\gamma\gamma$ measurement as ALP search on top of LbL continuum:
  - ALP model: $\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 - \frac{g_{a\gamma}}{4} a F^{\mu\nu}\tilde{F}_{\mu\nu}$
  - Limits on $\sigma_{\gamma\gamma\rightarrow a\rightarrow\gamma\gamma}$ extracted
    - Cast into limits on $a\gamma\gamma$ coupling ($1/\Lambda_a$) assuming BR($a\rightarrow\gamma\gamma$)=1 [CMS, PLB797 (2019) 134826]
    - Reco effic.: ~20% (6 GeV), ~45% (>40 GeV). ALP width dominated by exp. resolution.



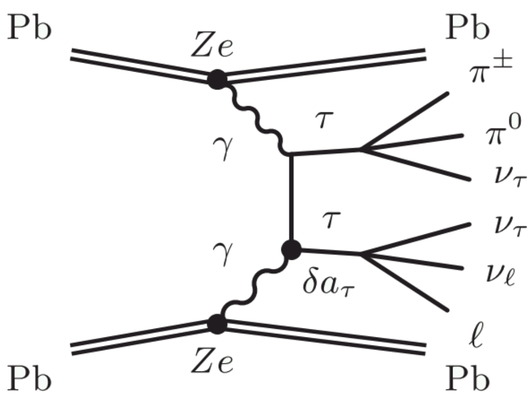




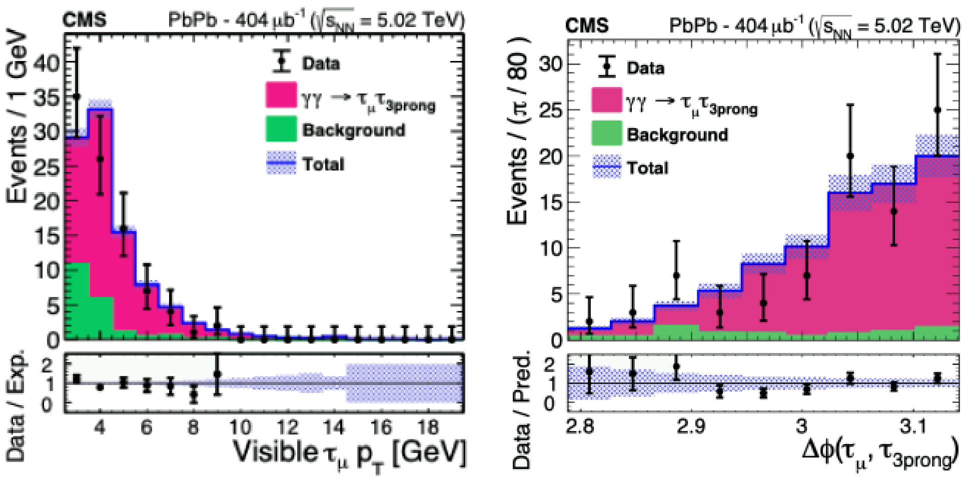
- Most stringent limits to date on ALPs over m_a = 5–100 GeV
- σ($\gamma\gamma\rightarrow a\rightarrow\gamma\gamma$) > 2–70 nb excluded at 95% C.L. over that mass interval.

Anomalous tau lepton $(g-2)_\tau$ via $\gamma\gamma \to \tau^+\tau^-$

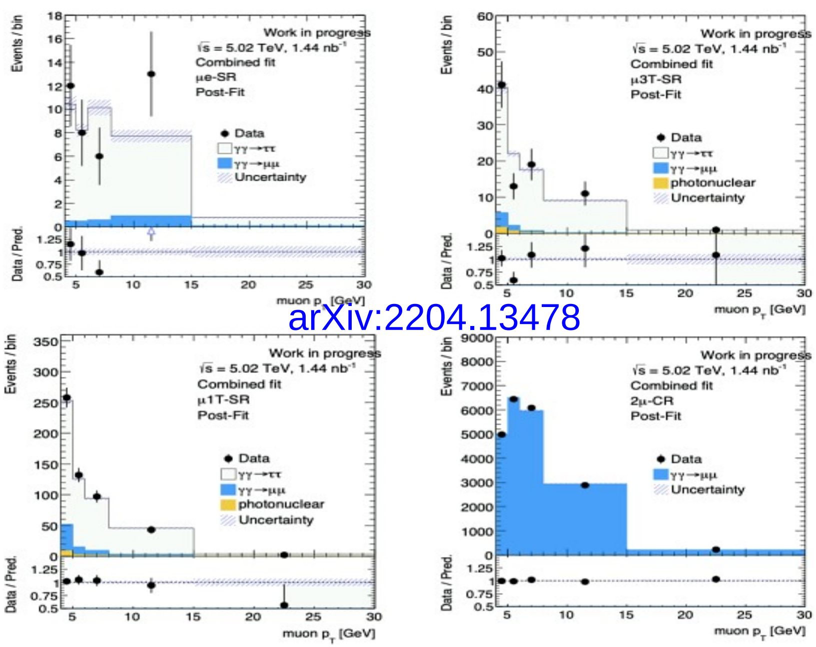
- Anomalous tau-lepton magnetic moment only mildly constrained from $\gamma\gamma \to \tau\tau$ studies at LEP times: $(g-2)_\tau = -0.05 - 0.03$



- Improved limits via UPCs at the LHC expected. First observation by ATLAS/CMS in various decay modes (1-prong, 3-prong, e-mu):



arXiv:2206.05192

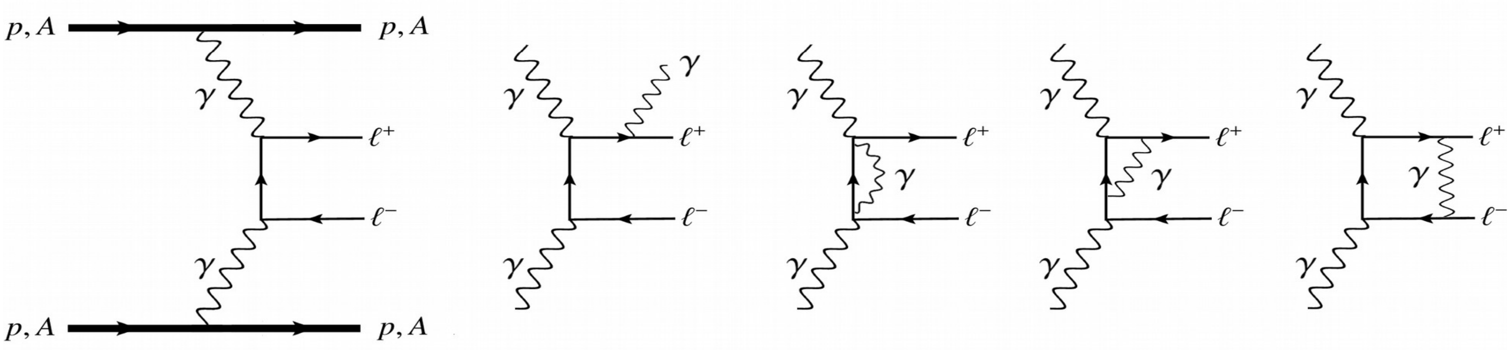


arXiv:2204.13478

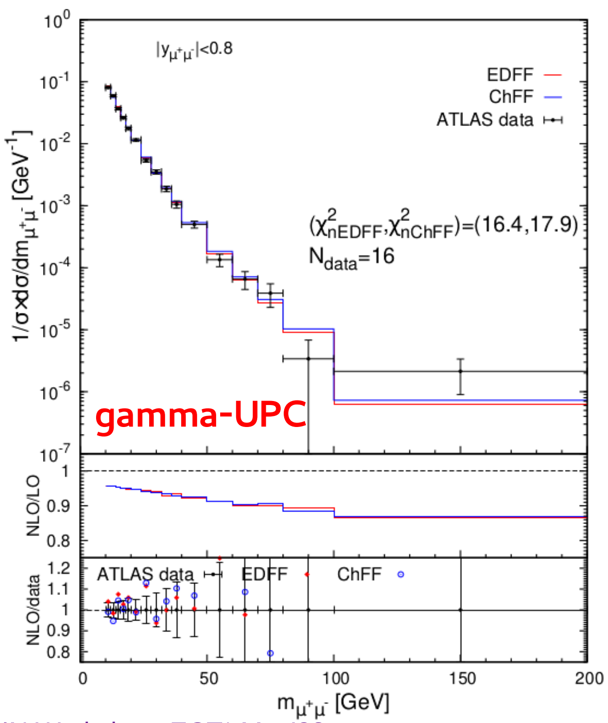
- Ongoing extended CMS studies with Run-2 PbPb (and pp) data

γγ collisions: NLO QED corrections

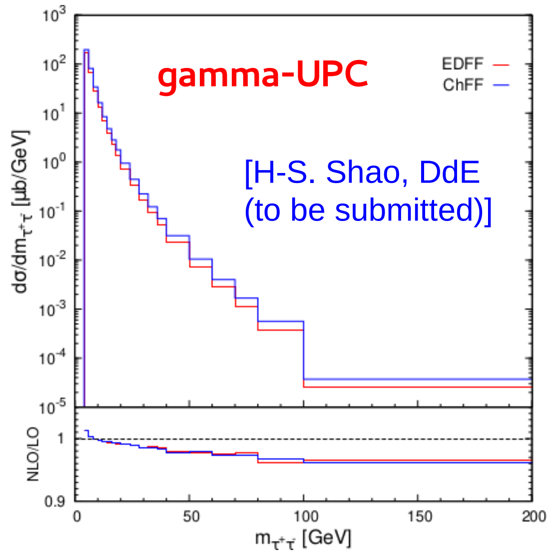
- All calculations so far included only LO diagrams (plus FSR emission in some cases)...

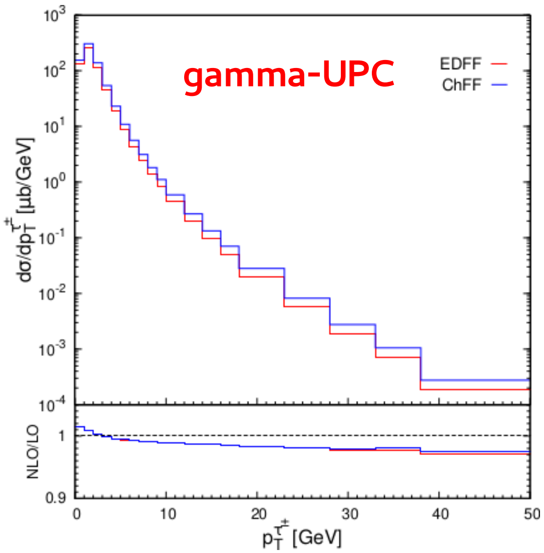


- Impact of virtual & real NLO QED corrections on exclusive dilepton production:



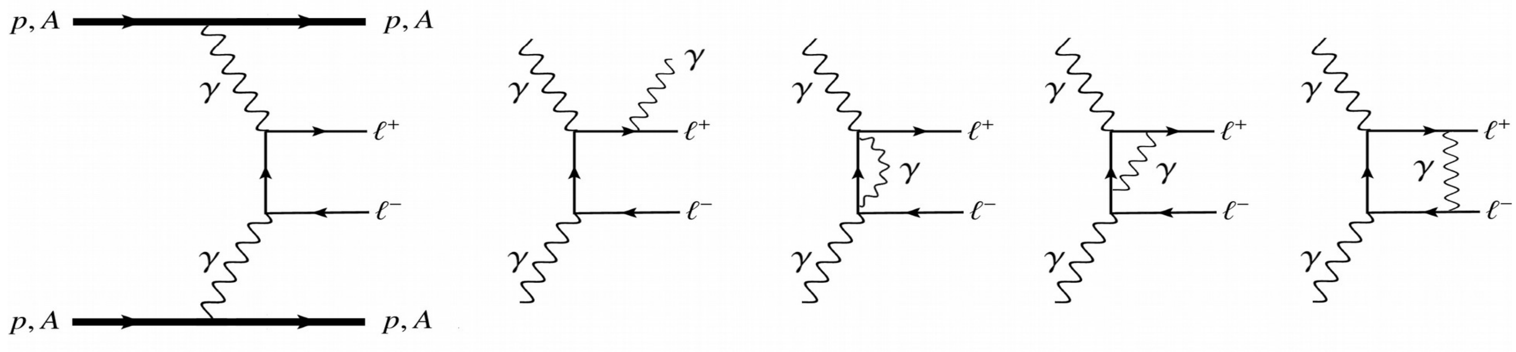
Dimuon: x-section reduced by up to ~10% at high mass
Ditau: x-section increases/decreases by few % at low/high masses: Relevant for accurate (g-2) extractions!



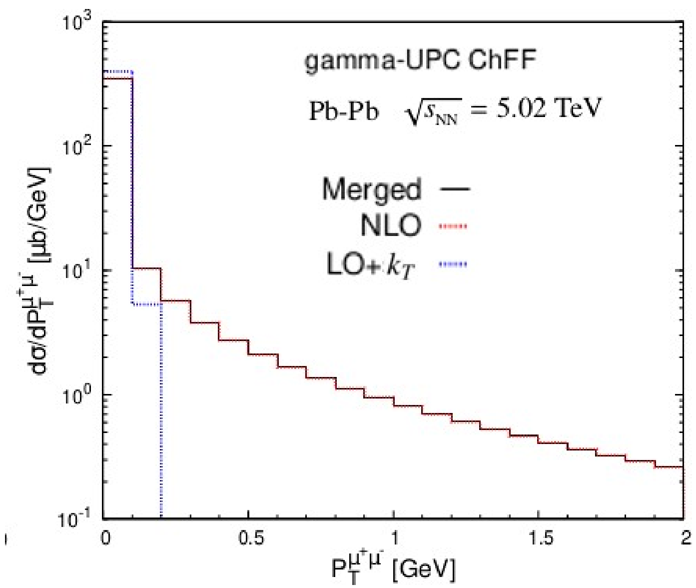


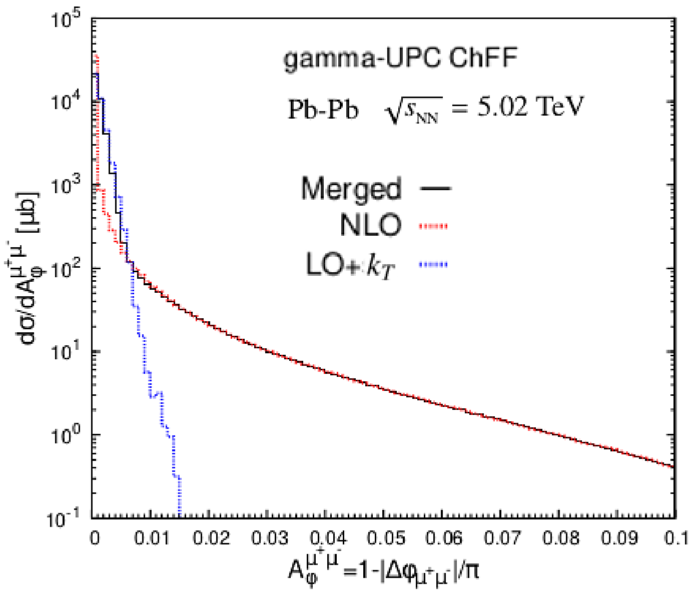
γγ collisions: NLO QED corrections

- All calculations so far included only LO diagrams (plus FSR emission in some cases)...



- Impact of virtual & real NLO QED corrections on exclusive dilepton p_T(pair), Aco(pair):





[H-S. Shao, DdE (to be submitted)]

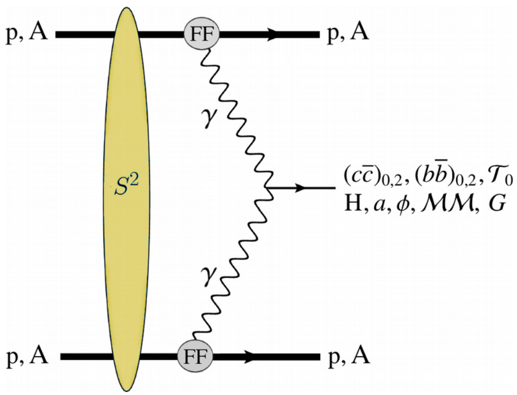
NLO corrections increase the p_T(pair), Aco(pair) tails:

Relevant for non-exclusive backgd removal when applyings cuts on both variables!

γγ collisions at LHC: Other x-sections

- C-even SM resonances (9 states m~3–10 GeV, plus Higgs):

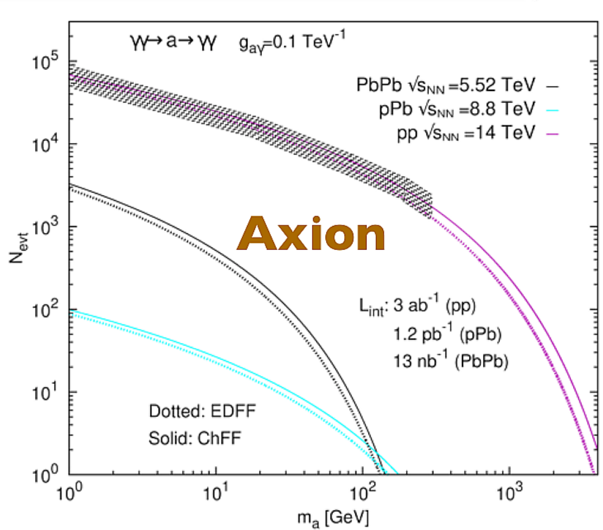
Colliding system	Form factor	gamma-UPC $\sigma(\gamma\gamma \to X)$ $\eta_c(1S)$	$\eta_c(2S)$	χ_{c0}	χ_{c2}	$\eta_b(1S)$	$\eta_b(2S)$	χ_{b0}	χ_{b2}	$\mathcal{T}_0$	H
p-p, 14 TeV	pointlike	61 pb	13 pb	17 pb	19 pb	110 fb	44 fb	29 fb	8.9 fb	0.12 fb	0.17 fb
	EDFF ($S^2_{\gamma\gamma}$ = 1)	51 pb	11 pb	14 pb	15 pb	88 fb	35 fb	23 fb	7.1 fb	0.10 fb	0.12 fb
	EDFF	50 pb	11 pb	14 pb	15 pb	86 fb	35 fb	23 fb	7.0 fb	0.10 fb	0.11 fb
	ChFF	56 pb	12 pb	15 pb	17 pb	99 fb	40 fb	26 fb	8.0 fb	0.11 fb	0.14 fb
p-Pb, 8.8 TeV	EDFF	0.16 μb	33 nb	43 nb	46 nb	0.23 nb	92 pb	60 pb	18 pb	0.31 pb	0.11 pb
	ChFF	0.18 μb	38 nb	49 nb	53 nb	0.27 nb	106 pb	70 pb	21 pb	0.35 pb	0.14 pb
O-O, 7 TeV	EDFF	76 nb	16 nb	21 nb	23 nb	0.10 nb	42 pb	28 pb	8.5 pb	0.15 pb	31 fb
	ChFF	82 nb	17 nb	22 nb	24 nb	0.11 fb	44 pb	29 pb	9.0 pb	0.16 pb	32 fb
Ca-Ca, 7 TeV	EDFF	2.5 μb	0.50 μb	0.63 μb	0.70 μb	3.1 nb	1.2 nb	0.81 nb	0.25 nb	4.6 pb	0.48 pb
	ChFF	2.7 μb	0.58 μb	0.74 μb	0.81 μb	3.5 nb	1.4 nb	0.91 nb	0.29 nb	5.2 pb	0.62 pb
Ar-Ar, 6.3 TeV	EDFF	1.5 μb	0.31 μb	0.40 μb	0.42 μb	1.8 nb	0.73 nb	0.48 nb	0.15 nb	2.9 pb	0.25 pb
	ChFF	1.6 μb	0.34 μb	0.44 μb	0.49 μb	2.1 nb	0.83 nb	0.55 nb	0.17 nb	3.1 pb	0.31 pb
Kr-Kr, 6.46 TeV	EDFF	22 μb	4.4 μb	5.9 μb	6.3 μb	25 nb	10 nb	6.7 nb	1.9 nb	41 pb	2.5 pb
	ChFF	25 μb	5.1 μb	6.4 μb	7.0 μb	31 nb	12 nb	7.9 nb	2.3 nb	46 pb	3.4 pb
Xe-Xe, 5.86 TeV	EDFF	89 μb	18 μb	24 μb	26 μb	98 nb	38 nb	26 nb	7.7 nb	0.16 nb	4.8 pb
	ChFF	101 μb	21 μb	27 μb	29 μb	116 nb	46 nb	31 nb	9.2 nb	0.19 nb	6.2 pb
Pb-Pb, 5.52 TeV	EDFF	0.39 mb	79 μb	0.10 mb	0.11 mb	0.40 μb	0.15 μb	0.10 μb	31 nb	0.71 nb	9.3 pb
	ChFF	0.46 mb	95 μb	0.12 mb	0.13 mb	0.50 μb	0.19 μb	0.13 μb	38 nb	0.86 nb	13 pb

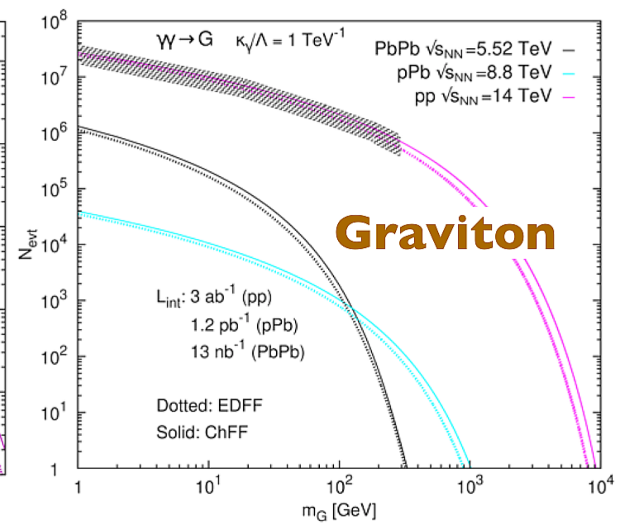


– Most low-mass resonances accessible in PbPb (pp without pileup) with low-p_T charged particle reco.

- C-even BSM resonances:

PbPb (pp with RPs) best limits below (above) $m_{\gamma\gamma}$~100 GeV





Summary

- Pb-Pb UPCs at the LHC provide the largest cross sections ever studied for $\gamma\gamma$ collisions over the $W_{\gamma\gamma}$ = 1 – 100 GeV:

  Unique (B)SM physics programme open for study!

- Many measurements carried out so far:
  - Exclusive dielectron & dimuon production (high-statistics samples).
  - Observation of light-by-light scattering
  - Best limits on low-mass axion-like particles (also gravitons)
  - Observation of exclusive ditau production: Best (g-2) for tau at reach
  - …

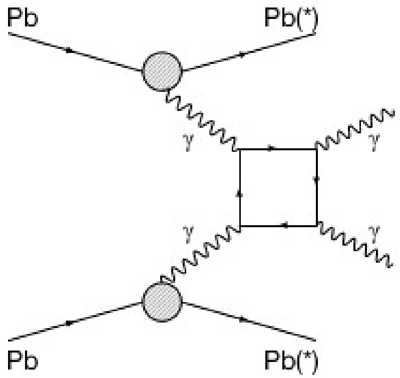
- Experimental studies reaching few % uncertainties.
  Theoretical calculations catching up in precision.
  NLO QED corrections relevant for precision studies!

- Many interesting photon-photon processes awaiting for measurement…
  (Use gamma-UPC, if you are interested in any new UPC analysis... ;-))

Backup slides

Observation of $\gamma\gamma \to \gamma\gamma$ (PbPb, 5 TeV)

ATLAS: JHEP 03 (2021) 243   CMS: Phys. Lett. B 797 (2019) 134826



Integrated fiducial cross-section:

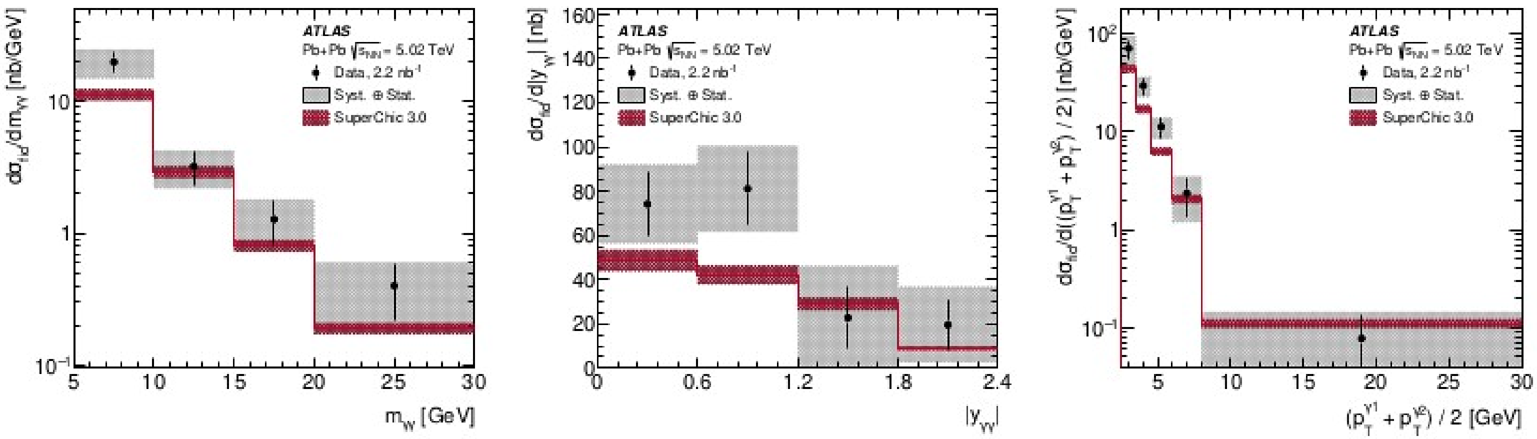
- Measurement:

$$\sigma_{fid} = 120 \pm 17(stat.) \pm 13(syst.) \pm 4(lumi.)\ \text{nb}$$

ATLAS data [15]	gamma-UPC σ			SuperChic σ
	EDFF	ChFF	average	
120 ± 22 nb	63 nb	76 nb	70 ± 7 nb	78 ± 8 nb

Differential cross-section:

- Uncertainties dominated by statistics



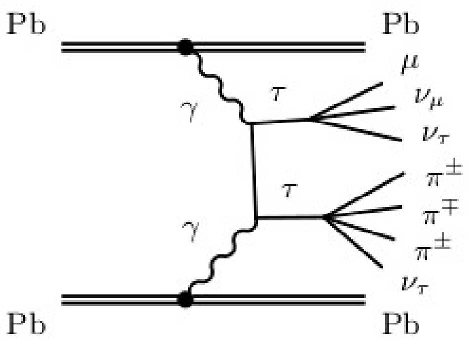
■ Do we really control all (non)exclusive backgrounds at low masses?

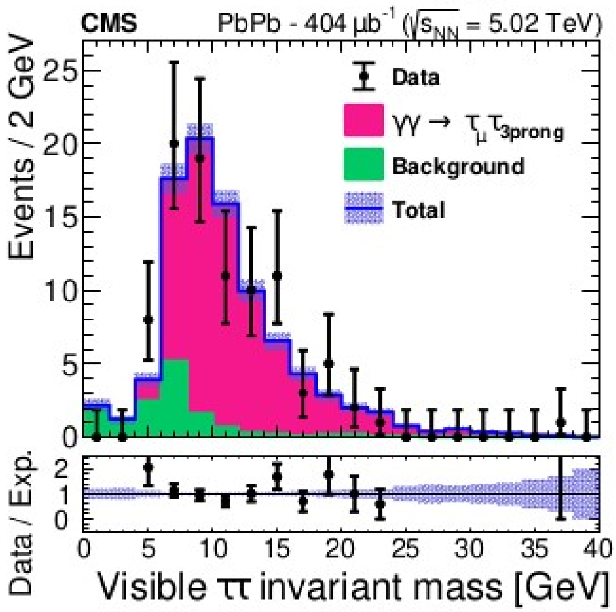
Observation of $\gamma\gamma \to \tau\tau$ (PbPb, 5 TeV)

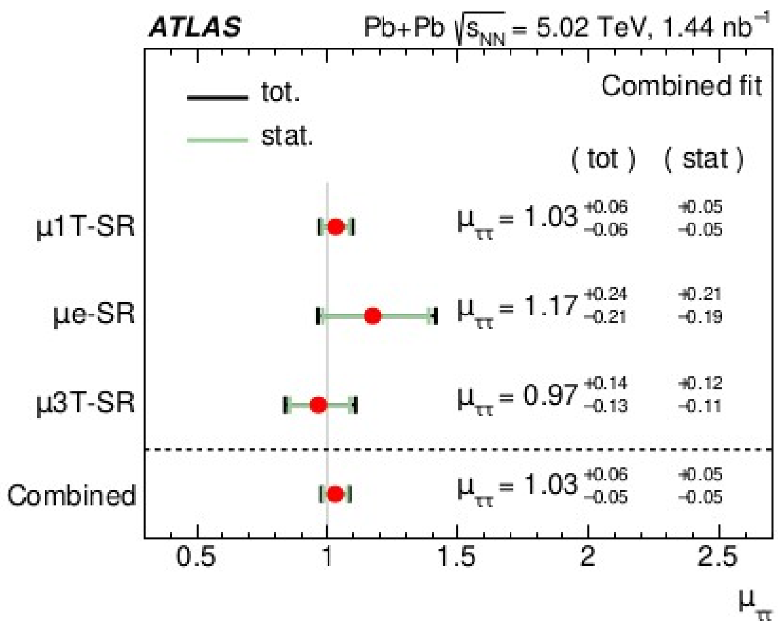
$\gamma\gamma \to \tau\tau$ production

ATLAS: CERN-EP-2022-079, CMS: CERN-EP-2022-098

- First observation of $\gamma\gamma \to \tau\tau$ production in hadron collisions by ATLAS and CMS.
- Targets μ+3prong (CMS) or μ+3prong, μ+1prong and μ+e (ATLAS) decays
- CMS: $\sigma_{fid} = 4.8 \pm 0.6(stat.) \pm 0.5(syst.)$ mb
- ATLAS: $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$

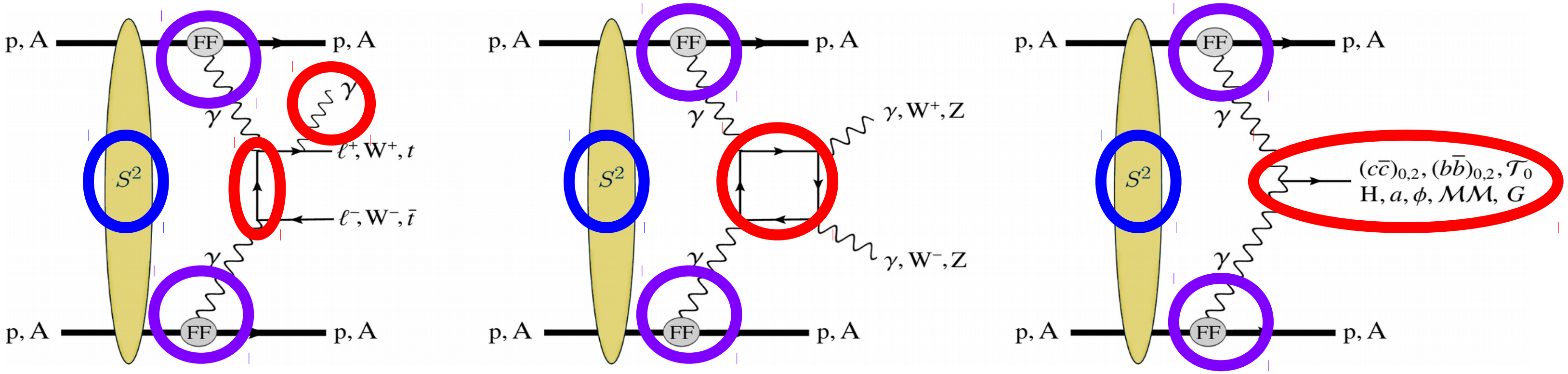






gamma-UPC γγ MC event generator

- So far existing MC event generators (StarLight, SuperChic, FPMC, UPCgen...) include only a few hard-coded γγ processes, QED/QCD LO only, no extra γ/gluon FSR, no generation of ("uninteresting") background processes,…
- gamma-UPC changes this significantly: Any arbitrary (B)SM, Quarkonia matrix elements with MG5@NLO & HelacOnia, N γ/gluon FSR out-of-the-box, extendable to NLO QED/EW, proton kinem. available, LHE output, 2 hadron form factors (γ fluxes) coded, p-p,p-A,A-A (for any A) UPCs,...



- gamma-UPC key ingredients:
  1) Matrix elements: MG5@NLO & HelacOnia (NLO QCD, plus γ/g FSR's)
  2) p,A form factors: Electric Dipole (EDFF) & Charge (ChFF) γ fluxes
  3) p,A survival probability: via Glauber-MC-based eikonal

γγ theoretical cross sections

- **Cross section:**

$$\sigma(\mathrm{A\ B} \xrightarrow{\gamma\gamma} \mathrm{A}\ X\ \mathrm{B}) = \int \frac{dE_{\gamma_1}}{E_{\gamma_1}} \frac{dE_{\gamma_2}}{E_{\gamma_2}} \frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} \sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$$

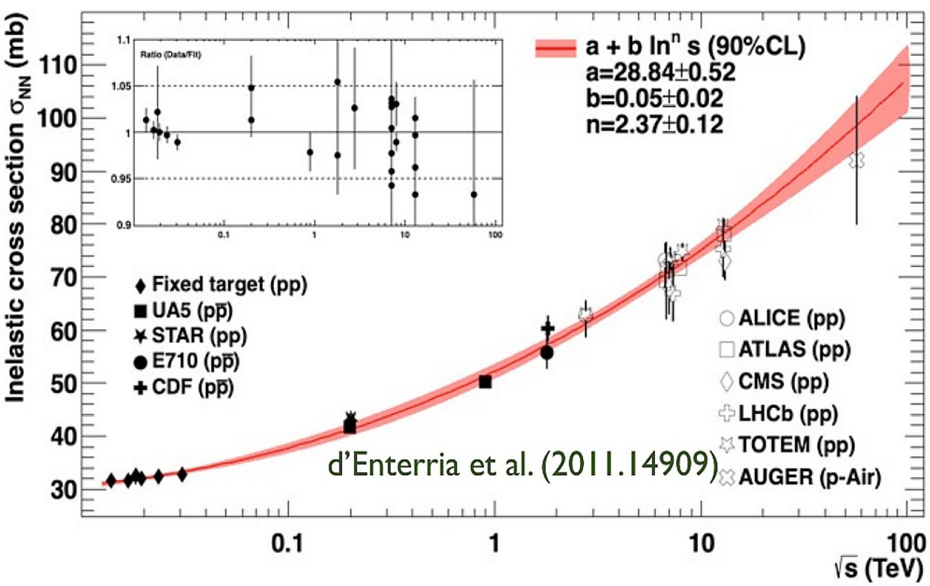
- **Effective two-photon luminosity:**

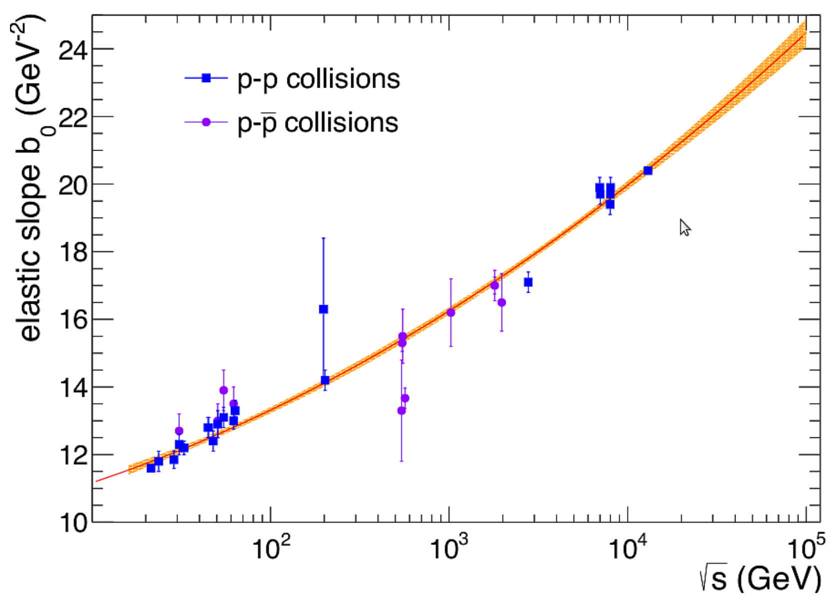
$$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, P_{\text{no inel}}\left(|\boldsymbol{b}_1 - \boldsymbol{b}_2|\right)\, N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1}, \boldsymbol{b}_1) N_{\gamma_2/\mathrm{Z}_2}(E_{\gamma_2}, \boldsymbol{b}_2) \times \theta(b_1 - \epsilon R_\mathrm{A})\theta(b_2 - \epsilon R_\mathrm{B})$$

- **No hadronic/inelastic interaction probability density:**

$$P_{\text{no inel}}(b) = \begin{cases} e^{-\sigma_{\text{inel}}^{\text{NN}} \cdot T_{\mathrm{AB}}(b)}, & \text{nucleus-nucleus} \\ e^{-\sigma_{\text{inel}}^{\text{NN}} \cdot T_{\mathrm{A}}(b)}, & \text{proton-nucleus} \\ \left|1 - \Gamma(s_{\text{NN}}, b)\right|^2, \quad \text{with}\ \ \Gamma(s_{\text{NN}}, b) \propto e^{-b^2/(2b_0)} & \text{p-p} \end{cases}$$

$T_{AB}(b)$ from (parametrized) Glauber MC





p,A form factors & γ fluxes: ChFF, EDFF

Electric dipole form factor (EDFF)

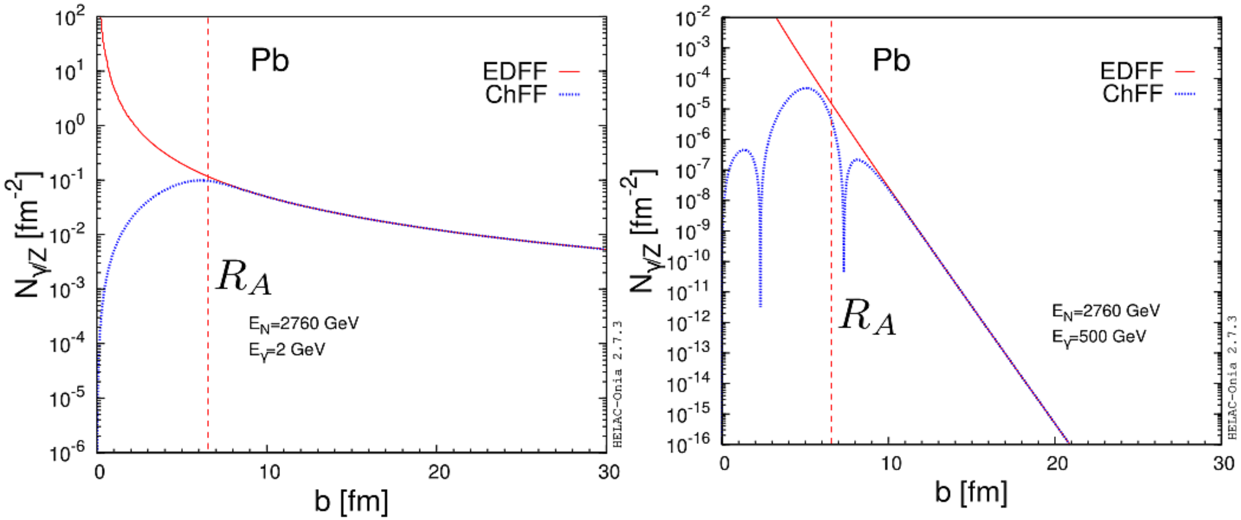
- Same as STARlight

$$N^{\mathrm{EDFF}}_{\gamma/\mathrm{Z}}(E_\gamma, b) = \frac{Z^2\alpha}{\pi^2}\frac{\xi^2}{b^2}\left[K_1^2(\xi) + \frac{1}{\gamma_\mathrm{L}^2}K_0^2(\xi)\right] \qquad \xi = \frac{E_\gamma b}{\gamma_\mathrm{L}}$$

Charge form factor (ChFF)

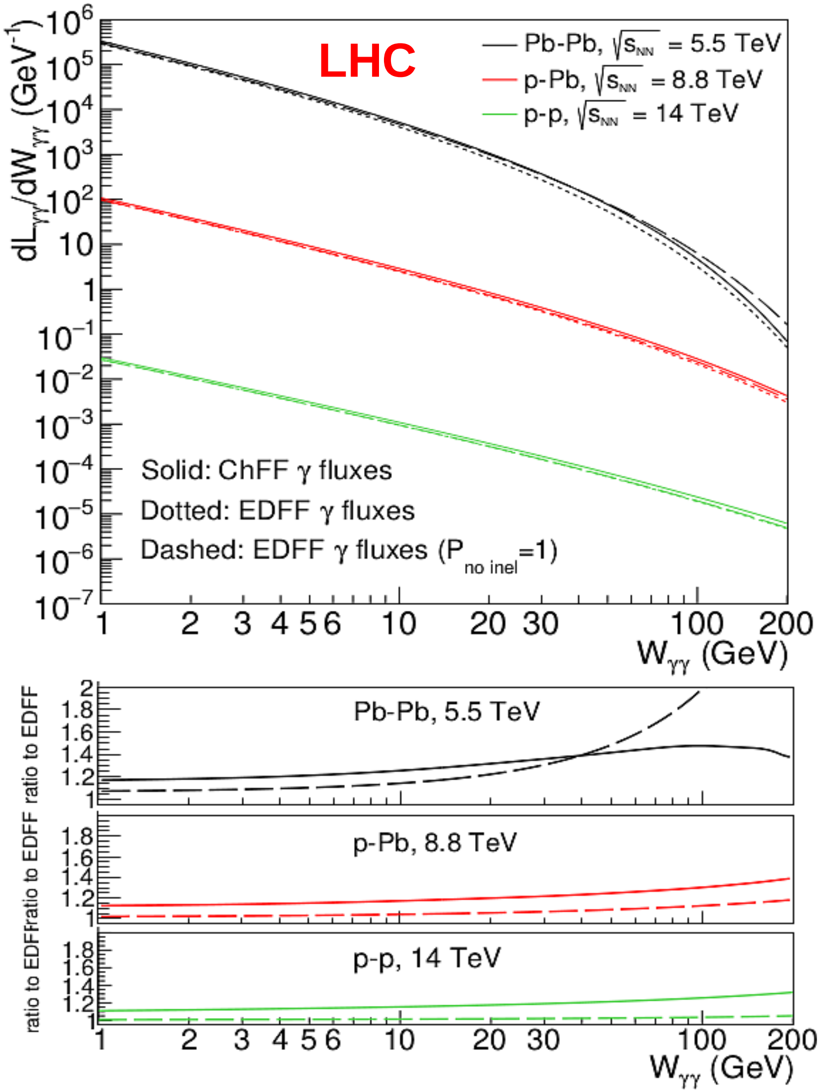
$$N^{\mathrm{ChFF}}_{\gamma/\mathrm{Z}}(E_\gamma, b) = \frac{Z^2\alpha}{\pi^2}\left|\int_0^{+\infty}\frac{dk_\perp k_\perp^2}{k_\perp^2 + E_\gamma^2/\gamma_\mathrm{L}^2}F_{\mathrm{ch,A}}\left(\sqrt{k_\perp^2 + E_\gamma^2/\gamma_\mathrm{L}^2}\right)J_1(bk_\perp)\right|^2$$

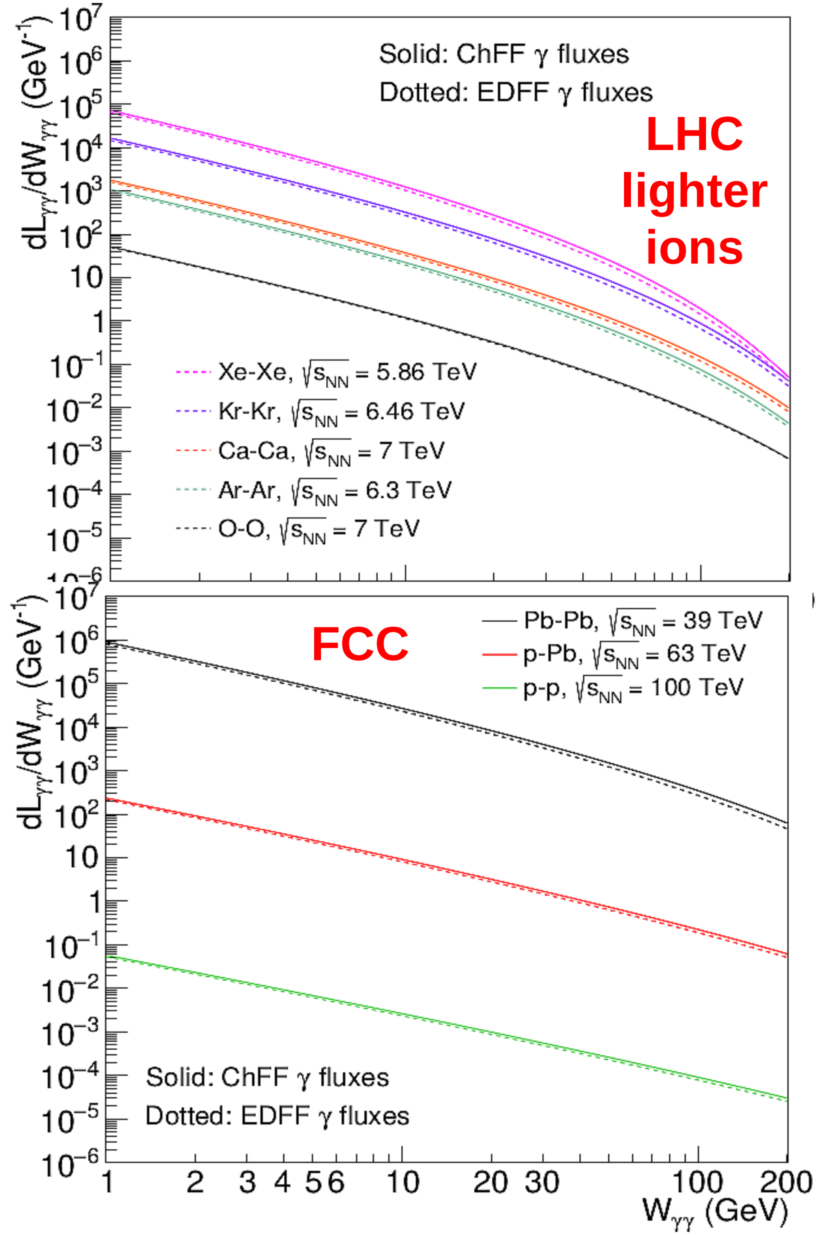
$$F_{\mathrm{ch,A}}(q) = \int \mathrm{d}^3\boldsymbol{r}e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\rho_\mathrm{A}(\boldsymbol{r}) = \frac{4\pi}{q}\int_0^{+\infty}\mathrm{d}r\rho_\mathrm{A}(r)r\sin(qr)$$



- Main difference comes from the $b < R_A$ regime
- EDFF photon number density is divergent at $b = 0$
  - Need a (arbitrary) cutoff when convoluting with ME

γγ effective luminosities





- ChFF/EDDF γ-fluxes differences (pp–PbPb):
  Low masses: ~7–15%. High masses: 20–50%

Existing γγ MC event generators

- So far dedicated MC event generators include only a few hard-coded γγ processes, QED/QCD LO only, no extra γ/gluon FSR, no generation of ("uninteresting") background processes,…

STARlight

Two-Photon Channels

Particle	Jetset ID
e^+e^- pair	11
$\mu^+\mu^-$ pair	13
$\tau^+\tau^-$ pair	15
$\tau^+\tau^-$ pair, polarized decay	10015*
ρ^0 pair	33
$a_2(1320)$ decayed by PYTHIA	115
η decayed by PYTHIA	221
$f_2(1270)$ decayed by PYTHIA	225
η' decayed by PYTHIA	331
$f_2(1525) \to K^+K^-(50\%), K^0\bar{K}^0(50\%)$	335
η_c decayed by PYTHIA	441
$f_0(980)$ decayed by PYTHIA	9010221

SuperChic

Two–photon collisions	
55	$W^+(\to \nu_l(8) + l^+(9)) + W^-(\to \overline{\nu}_l(10) + l^-(11))$
56	$e^+(6) + e^-(7)$
57	$\mu^+(6) + \mu^-(7)$
58	$\tau^+(6) + \tau^-(7)$
59	$\gamma(6) + \gamma(7)$
60	$H(5) \to b(6) + \overline{b}(6)$
68	$a(5) \to \gamma(6) + \gamma(7)$
69	$M(5) \to \gamma(6) + \gamma(7)$ (Dirac Coupling)
70	$M(5) \to \gamma(6) + \gamma(7)$ (βg Coupling)
71	$m(6) + \overline{m}(7)$ (Dirac Coupling)
72	$m(6) + \overline{m}(7)$ (βg Coupling)
73	$\tilde{\chi}^-(6)(\to \tilde{\chi}^1_0(8) + \mu^-(9) + \overline{\nu}_\mu(10)) + \tilde{\chi}^+(7)(\to \tilde{\chi}^1_0(11) + \mu^+(12) + \nu_\mu(13))$
74	$\tilde{\chi}^-(6)(\to \tilde{\chi}^1_0(8) + \overline{u}(9) + d(10)) + \tilde{\chi}^+(7)(\to \tilde{\chi}^1_0(11) + u(12) + \overline{d}(13))$
75	$\tilde{\chi}^-(6)(\to \tilde{\chi}^1_0(8) + \mu^-(9) + \overline{\nu}_\mu(10)) + \tilde{\chi}^+(7)(\to \tilde{\chi}^1_0(11) + u(12) + \overline{d}(13))$
76	$\tilde{l}^-(5))(\to \tilde{\chi}^1_0(8) + \mu^-(9)) + \tilde{l}^+(6)(\to \tilde{\chi}^1_0(10) + \mu^+(11))$
77	$\phi(5) \to \mu^+(6)\mu^-(7)$
78	$J/\psi(5) \to e^+(6)e^-(7)$
79	$\psi_{2S}(5) \to e^+(6)e^-(7)$

FPMC

IPROC	Description
16006	$\gamma\gamma \to ll$
16010	$\gamma\gamma \to W^+W^-$
16010	$\gamma\gamma \to W^+W^-$ beyond SM
16015	$\gamma\gamma \to ZZ$ beyond SM

only pp UPC

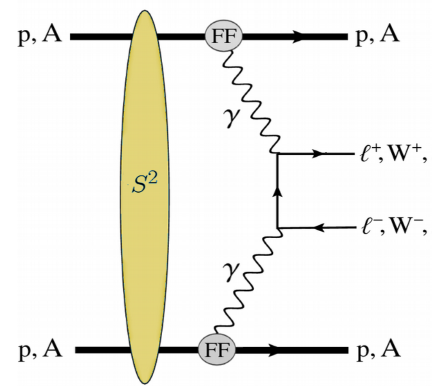
UPCgen

$$\gamma\gamma \to \ell^+\ell^-$$

γγ collisions at LHC: Examples x-sections

Double fermions (e.g. γγ→ ttbar):

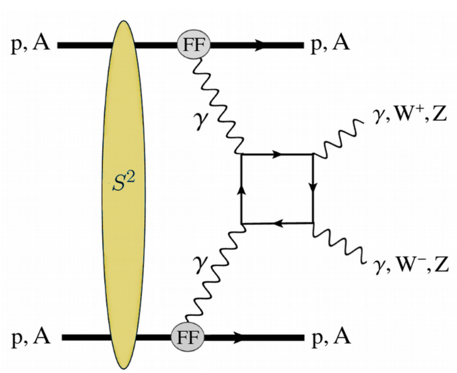
Process: $\gamma\gamma \to t\bar{t}$	gamma-UPC $\sigma_{\rm NLO}$		
Colliding system,	EDFF	ChFF	average
p-p at 14 TeV	$0.198^{+0.004}_{-0.003}$ fb	$0.287^{+0.005}_{-0.004}$ fb	$0.242^{+0.005}_{-0.004} \pm 0.045$ fb
p-Pb at 8.8 TeV	$36.5^{+0.8}_{-0.7}$ fb	$59.3^{+1.3}_{-1.1}$ fb	$48^{+1.0}_{-0.9} \pm 11$ fb
Pb-Pb at 5.52 TeV	$12.6^{+0.4}_{-0.3}$ fb	$18.8^{+0.5}_{-0.4}$ fb	$15.7^{+0.5}_{-0.4} \pm 3.1$ fb



- Quarkonia

Process: $\gamma\gamma \to J/\psi J/\psi$	gamma-UPC σ		
Colliding system, c.m. energy	EDFF	ChFF	average
p-p at 14 TeV	20^{+11}_{-6} fb	23^{+13}_{-7} fb	$22^{+12}_{-7} \pm 2$ fb
p-Pb at 8.8 TeV	55^{+30}_{-16} pb	64^{+35}_{-18} pb	$60^{+32}_{-17} \pm 4$ pb
Pb-Pb at 5.52 GeV	103^{+57}_{-29} nb	128^{+71}_{-36} nb	$115^{+64}_{-32} \pm 12$ nb

Double bosons (loop induced):



- Loop-induced rare processes in SM (BSM potential)

Process: $\gamma\gamma \to Z\gamma$	gamma-UPC σ		
Colliding system, c.m. energy	EDFF	ChFF	average
p-p at 14 TeV	36.2 ab	44.7 ab	40.5 ± 4.3 ab
p-Pb at 8.8 TeV	10.3 fb	15.6 fb	13.0 ± 2.6 fb
Pb-Pb at 5.52 TeV	109 fb	152 fb	130 ± 22 fb

Process: $\gamma\gamma \to ZZ$	gamma-UPC σ		
Colliding system, c.m. energy	EDFF	ChFF	average
p-p at 14 TeV	52.8 ab	78.4 ab	66 ± 13 ab
p-Pb at 8.8 TeV	12.3 fb	18.8 fb	15.5 ± 3.2 fb
Pb-Pb at 5.52 TeV	46.8 fb	63.2 fb	55 ± 8 fb

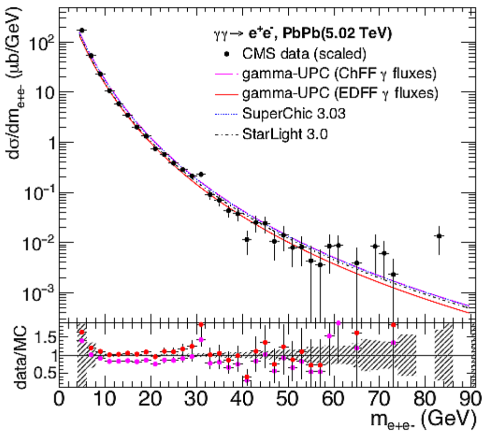
$$\mathcal{L} \supset \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}\left[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}\right]. \quad \sigma = \sigma_{\rm SM} + \left(\frac{c_{WWW}}{\Lambda^2} \times 1\ \mathrm{TeV}^2\right)\sigma_{WWW}$$

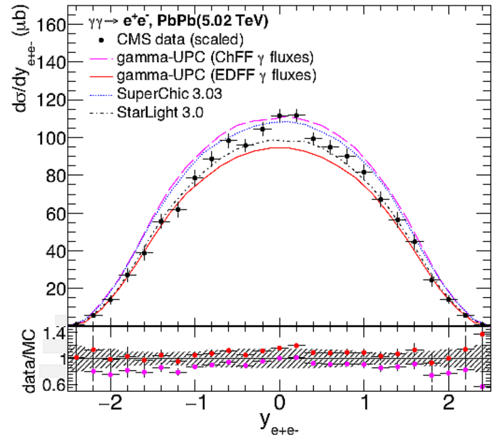
Process: $\gamma\gamma \to W^+W^-$	gamma-UPC average	
Colliding system, c.m. energy	$\sigma_{\rm SM}$	σ_{WWW}
p-p at 14 TeV	63 ± 11 fb	53 ± 8 ab
p-Pb at 8.8 TeV	26 ± 5 pb	28 ± 5 fb
Pb-Pb at 5.52 TeV	277 ± 44 pb	394 ± 64 fb

γγ collisions at LHC: Differential x-sections

- Breit-Wheeler process $\gamma\gamma \rightarrow e^+e^-$:

Process, system	Scaled CMS data [13]	gamma-UPC σ			STARLIGHT σ	SUPERCHIC σ
		EDFF	ChFF	average		
$\gamma\gamma \rightarrow e^+e^-$, Pb-Pb at 5.02 TeV	275 ± 55 μb	272 μb	326 μb	298 ± 28 μb	285 μb	318 μb

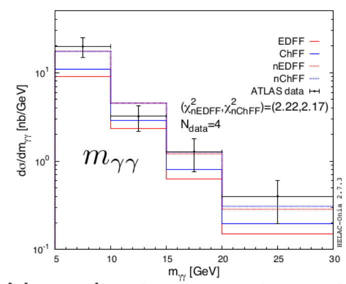


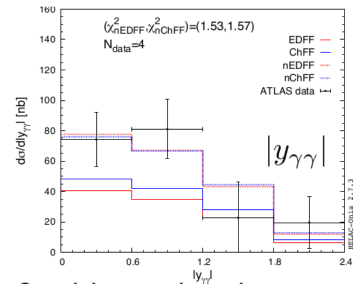


- Light-by-light scattering $\gamma\gamma \rightarrow \gamma\gamma$:

• Light-by-light scattering (loop-induced)

Process, system	ATLAS data [15]	gamma-UPC σ			SUPERCHIC σ
		EDFF	ChFF	average	
$\gamma\gamma \rightarrow \gamma\gamma$, Pb-Pb at 5.02 TeV	120 ± 22 nb	63 nb	76 nb	70 ± 7 nb	78 ± 8 nb

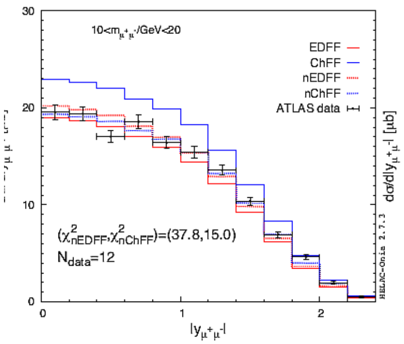


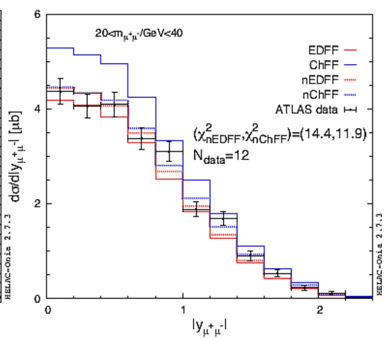


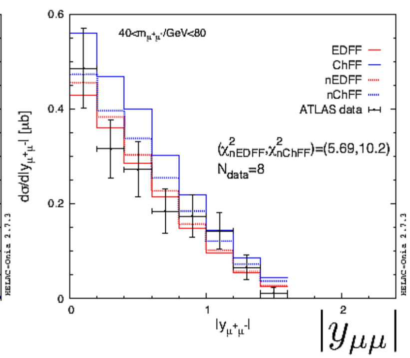
• Normalisation: experiment is 2 std. larger than theory

- Exclusive dimuons $\gamma\gamma \rightarrow \mu^+\mu^-$:

Process, system	ATLAS data [19]	gamma-UPC σ			STARLIGHT σ	SUPERCHIC σ
		EDFF	ChFF	average		
$\gamma\gamma \rightarrow \mu^+\mu^-$, Pb-Pb at 5.02 TeV	34.1 ± 0.8 μb	32.1 μb	40.4 μb	36.2 ± 4.2 μb	32.1 μb	38.9 μb







- Generic conclusions:

EDFF gamma-UPC~ Starlight
ChFF gamma-UPC~ SuperChic

Norm.: EDFF better than ChFF
Shape: ChFF better than EDFF

gamma-UPC outlook & summary

- gamma-UPC is a new versatile MC evt generator for any $\gamma\gamma$ process with protons & ions UPCs. Interfaced to MG5@NLO & HelacOnia.
- Ongoing/Future developments:
  - Non-zero photon k_T (working script upon request)
  - Protons kinematics for transport to & tagging at RPs spectrometers
  - Semi-exclusive photon-photon and W/Z-photon processes
  - NLO QED & EW corrections
  - UPCs for electron-proton & electron-ion collisions
  - …
- Download it, test it, use it (or ask us to produce the LHE files) for your favourite $\gamma\gamma$ exp./ph. studies!

http://cern.ch/hshao/gammaupc.html