gammaUPC: A new MC evt. generator for $\gamma\gamma$ processes in ultraperipheral p-p, p-A & A-A collisions

Diffraction & Low-x 2022

Corigliano Calabro, 28th Sept. 2022

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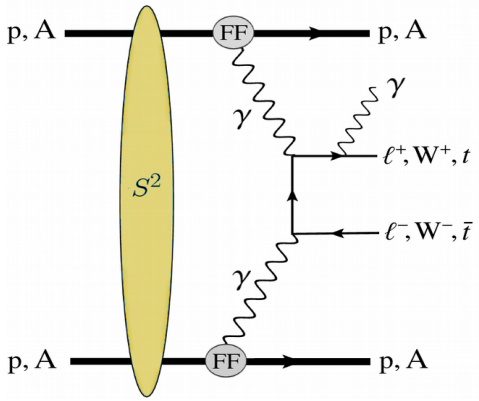
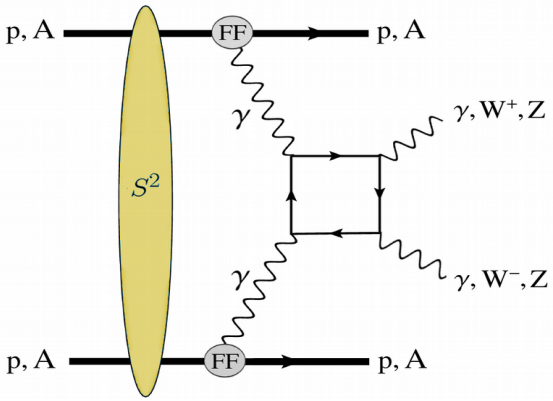
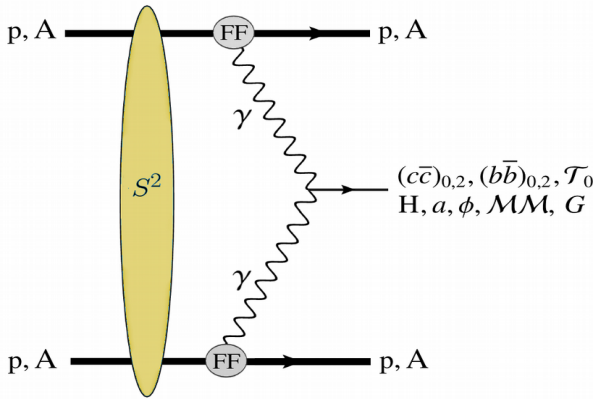
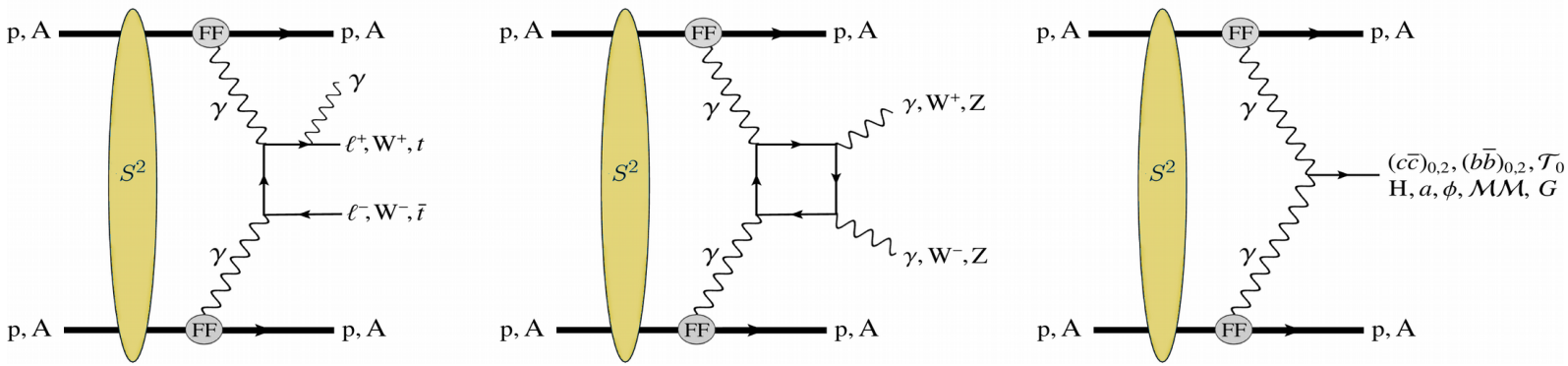






Details in: https://arxiv.org/abs/2207.03012 (JHEP, to appear)

Rich & unique (B)SM $\gamma\gamma$ physics with UPCs at LHC

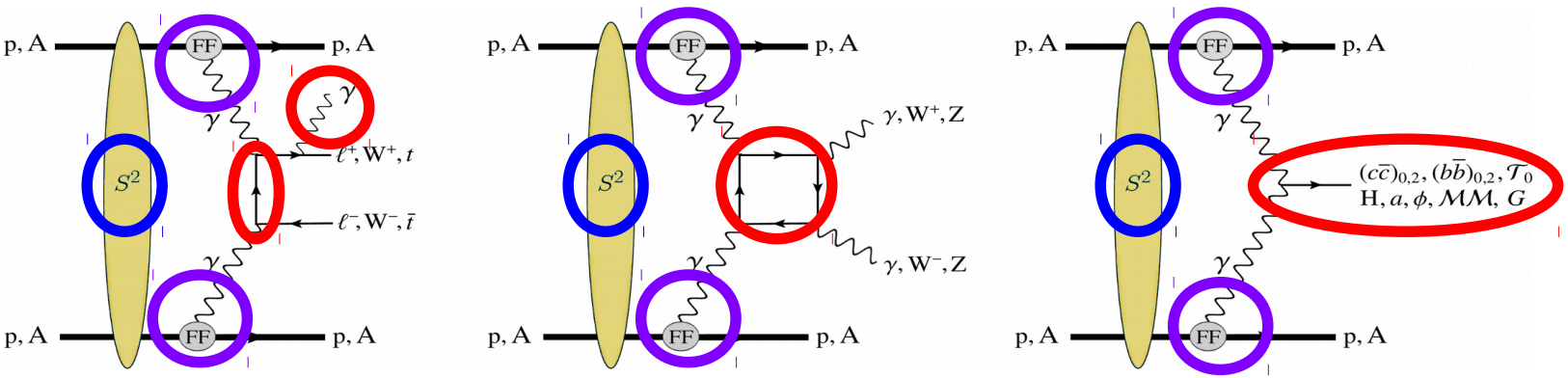


System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$E_{beam1} + E_{beam2}$	γ_L	R_A	E_γ^{max}	$\sqrt{s_{\gamma\gamma}^{max}}$
Pb-Pb	5.52 TeV	5 nb^{-1}	2.76 + 2.76 TeV	2960	7.1 fm	80 GeV	160 GeV
p-Pb	8.8 TeV	1 pb^{-1}	7.0 + 2.76 TeV	7450, 2960	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV
p-p	14 TeV	150 fb^{-1}	7.0 +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

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 cross sections & luminosities

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:

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

No hadronic/inelastic interaction probability density:

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

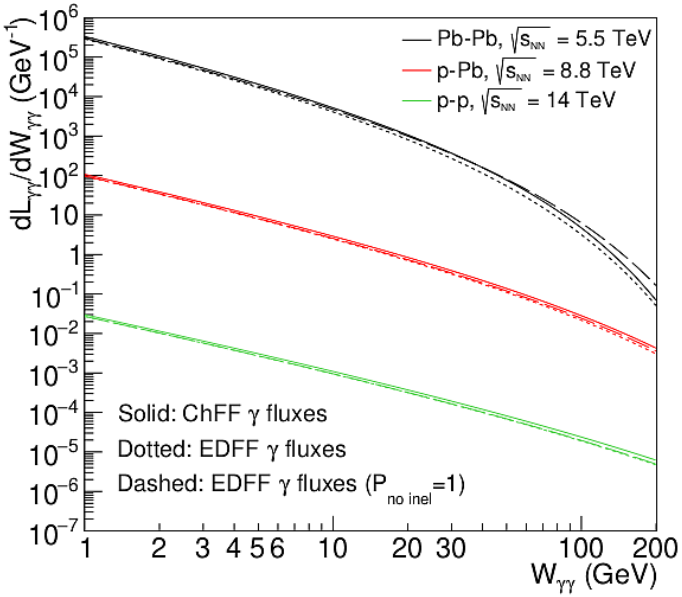
Electric dipole form factor (EDFF)

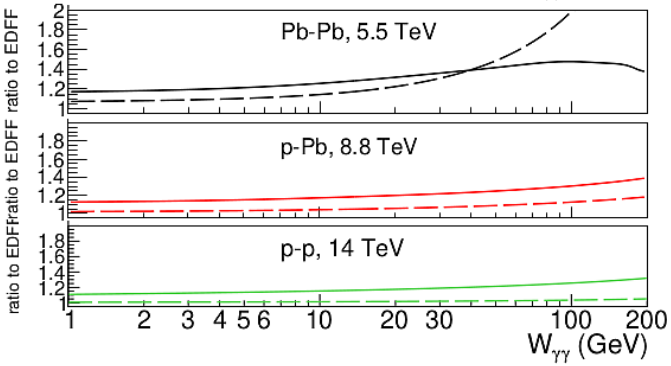
$$N^{\mathrm{EDFF}}_{\gamma/\mathrm{Z}}(E_\gamma, b) = \frac{Z^2\alpha}{\pi^2}\frac{\xi^2}{b^2}\left[K_1^2(\xi) + \frac{1}{\gamma_{\mathrm{L}}^2}K_0^2(\xi)\right] \qquad \xi = \frac{E_\gamma b}{\gamma_{\mathrm{L}}}$$

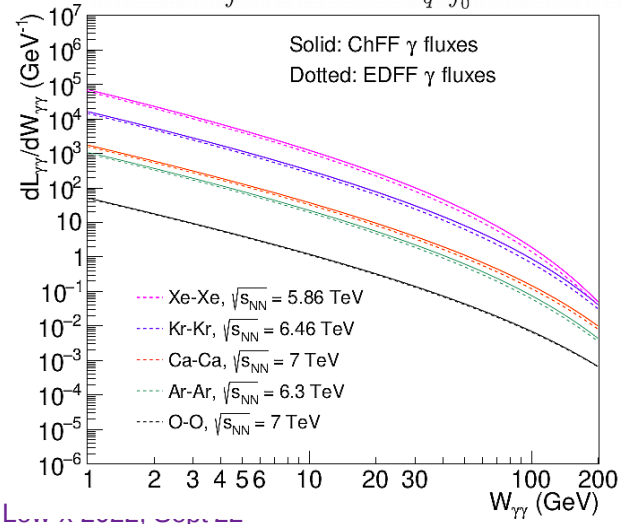
Charge form factor (ChFF)

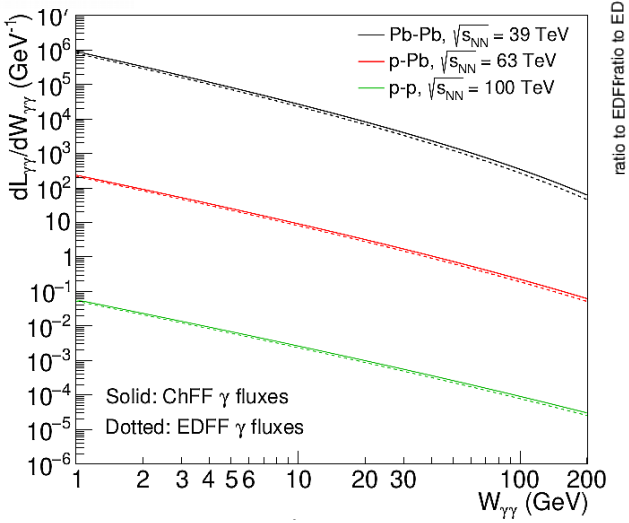
$$N^{\mathrm{ChFF}}_{\gamma/\mathrm{Z}}(E_\gamma, b) = \frac{Z^2\alpha}{\pi^2}\left|\int_0^{+\infty} \frac{dk_\perp k_\perp^2}{k_\perp^2 + E_\gamma^2/\gamma_{\mathrm{L}}^2} F_{\mathrm{ch,A}}\left(\sqrt{k_\perp^2 + E_\gamma^2/\gamma_{\mathrm{L}}^2}\right) J_1(bk_\perp)\right|^2$$

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





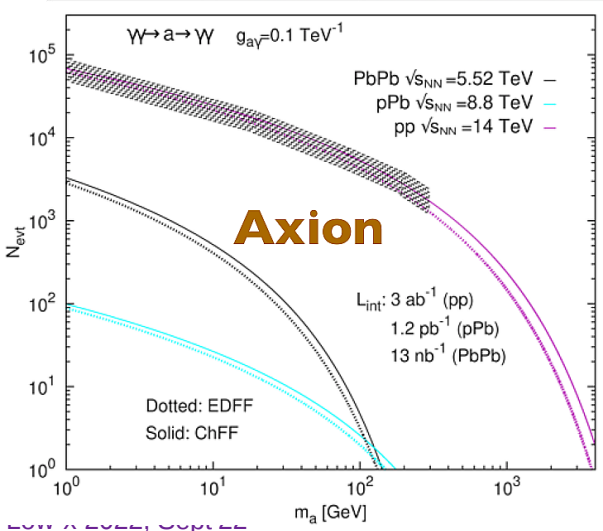


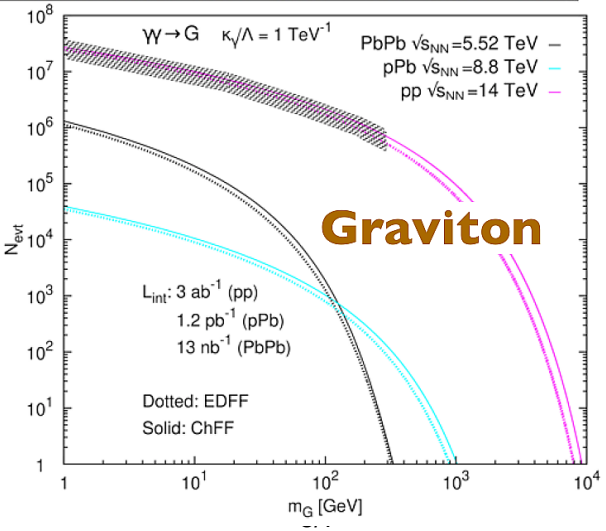


Many examples of γγ collision x-sections

C-even resonances:

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





Double fermions/bosons:

- Quarkonia

Process: $\gamma\gamma \to J/\psi J/\psi$ Colliding system, c.m. energy	gamma-UPC σ 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

Process: $\gamma\gamma \to t\bar{t}$ Colliding system,	gamma-UPC σ_{NLO} 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

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

Process: $\gamma\gamma \to Z\gamma$ Colliding system, c.m. energy	gamma-UPC σ 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: $\gamma\gamma \to ZZ$ Colliding system, c.m. energy	gamma-UPC σ 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

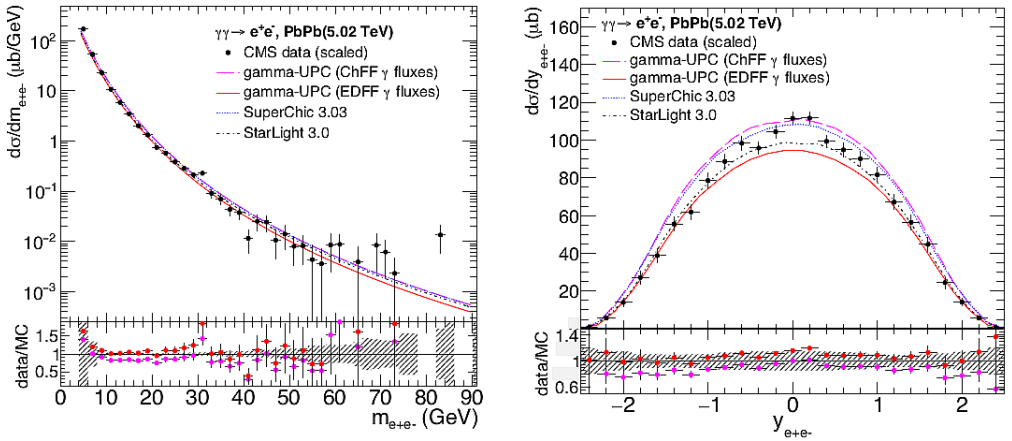
$$\mathcal{L} \supset \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}\left[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}\right], \quad \sigma = \sigma_{SM} + \left(\frac{c_{WWW}}{\Lambda^2} \times 1\ \mathrm{TeV}^2\right)\sigma_{WWW}$$

Process: $\gamma\gamma \to W^+W^-$ Colliding system, c.m. energy	gamma-UPC average σ_{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 collision differential x-sections

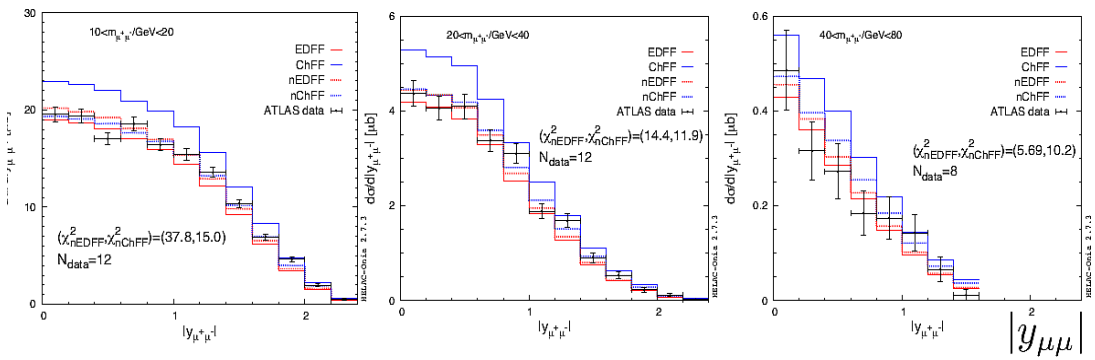
Breit-Wheeler process γγ → e+e-:

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



Exclusive dimuons γγ → μ+μ-:

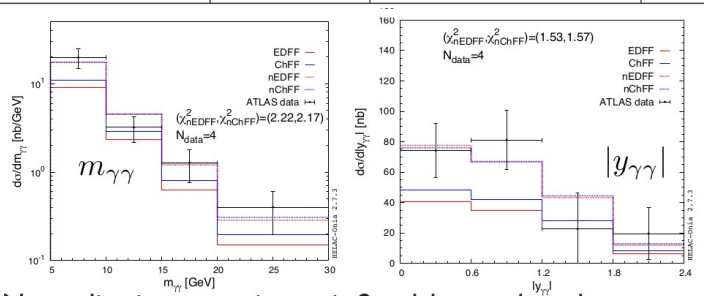
Process, system	ATLAS data [19]	gamma-UPC σ			Starlight σ	Superchic σ
		EDFF	ChFF	average		
$\gamma\gamma \to \mu^+\mu^-$, Pb-Pb at 5.02 TeV	34.1 ± 0.8 μb	32.1 μb	40.4 μb	36.2 ± 4.2 μb	32.1 μb	38.9 μb



Light-by-light scatt. γγ → γγ:

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

Process, system	ATLAS data [15]	gamma-UPC σ			Superchic σ
		EDFF	ChFF	average	
$\gamma\gamma \to \gamma\gamma$, 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

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 and EW corrections
  - UPCs for electron-proton or 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

Backup slides