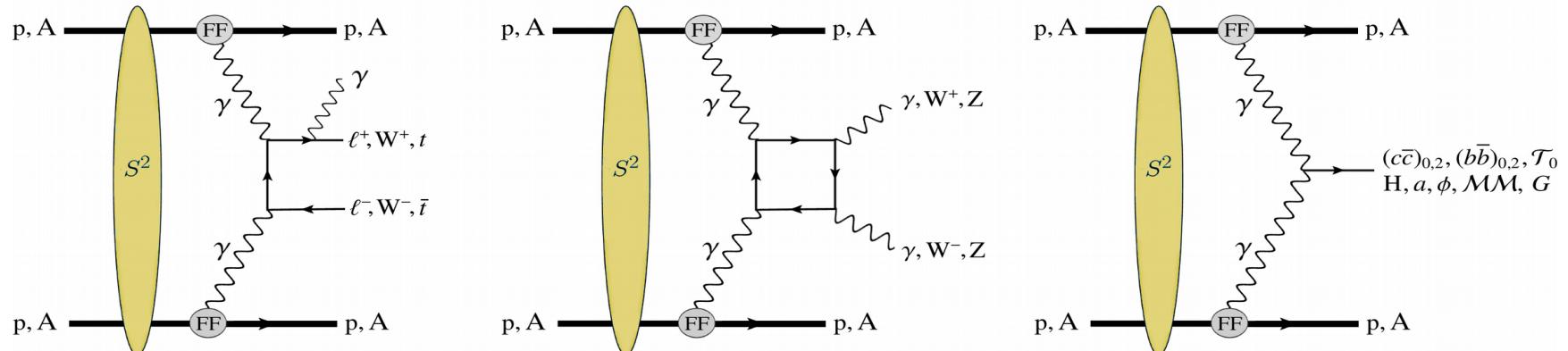


# gammaUPC: A new MC evt. generator for $\gamma\gamma$ processes in ultraperipheral p-p, p-A & A-A collisions

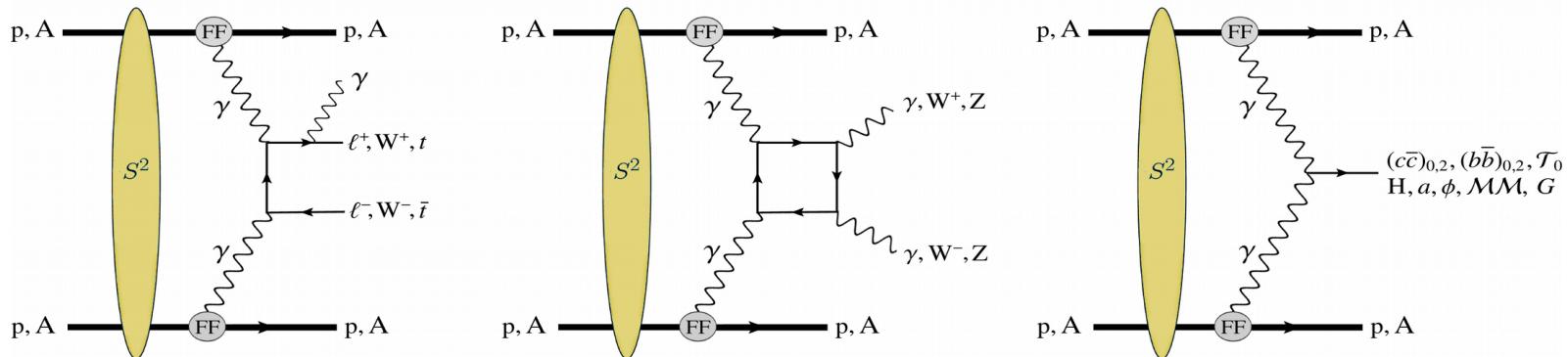
LHC forward physics WG meeting  
CERN, 24<sup>th</sup> Oct. 2022

David d'Enterria (CERN)  
Hua-Sheng Shao (LPTHE, Paris)



Details in: <https://arxiv.org/abs/2207.03012>, JHEP 09 (2022) 248

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



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

Process	Physics motivation
$\gamma\gamma \rightarrow e^+e^-, \mu^+\mu^-$	“Standard candles” for proton/nucleus $\gamma$ fluxes, EPA calculations, and higher-order QED corrections
$\gamma\gamma \rightarrow \tau^+\tau^-$	Anomalous $\tau$ lepton e.m. moments [29–32]
$\gamma\gamma \rightarrow \gamma\gamma$	aQGC [25], ALPs [27], BI QED [28], noncommut. interactions [36], extra dims. [37],...
$\gamma\gamma \rightarrow T_0$	Ditauonium properties (heaviest QED bound state) [38, 39]
$\gamma\gamma \rightarrow (c\bar{c})_{0,2}, (b\bar{b})_{0,2}$	Properties of scalar and tensor charmonia and bottomonia [40, 41]
$\gamma\gamma \rightarrow XYZ$	Properties of spin-even XYZ heavy-quark exotic states [42]
$\gamma\gamma \rightarrow VM VM$	(with $VM = \rho, \omega, \phi, J/\psi, \Upsilon$ ): BFKL-Pomeron dynamics [43–46]
$\gamma\gamma \rightarrow W^+W^-, ZZ, Z\gamma, \dots$	anomalous quartic gauge couplings [11, 26, 47, 48]
$\gamma\gamma \rightarrow H$	Higgs- $\gamma$ coupling, total H width [49, 50]
$\gamma\gamma \rightarrow HH$	Higgs potential [51], quartic $\gamma\gamma HH$ coupling
$\gamma\gamma \rightarrow t\bar{t}$	anomalous top-quark e.m. couplings [11, 49]
$\gamma\gamma \rightarrow \tilde{\ell}\tilde{\ell}, \tilde{\chi}^+\tilde{\chi}^-, H^{++}H^{--}$	SUSY pairs: slepton [11, 52, 53], chargino [11, 54], doubly-charged Higgs bosons [11, 55].
$\gamma\gamma \rightarrow a, \phi, MM, G$	ALPs [27, 56], radions [57], monopoles [58–61], gravitons [62–64],...

# Existing $\gamma\gamma$ MC event generators

- So far dedicated MC event generators include only a few hard-coded  $\gamma\gamma$  processes, QED/QCD LO only, no extra  $\gamma$ /gluon FSR, no generation of (“uninteresting”) background processes,...

## STARlight

Two-Photon Channels	
Particle	Jetset ID
e <sup>+</sup> e <sup>-</sup> pair	11
$\mu^+\mu^-$ pair	13
$\tau^+\tau^-$ pair	15
$\tau^+\tau^-$ pair, polarized decay	10015*
$\rho^0$ pair	33
a <sub>2</sub> (1320) decayed by PYTHIA	115
$\eta$ decayed by PYTHIA	221
f <sub>2</sub> (1270) decayed by PYTHIA	225
$\eta'$ decayed by PYTHIA	331
f <sub>2</sub> (1525) $\rightarrow K^+K^-$ (50%), K <sup>0</sup> $\bar{K}^0$ (50%)	335
$\eta_c$ decayed by PYTHIA	441
f <sub>0</sub> (980) decayed by PYTHIA	9010221

## SuperChic

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

## FPMC

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

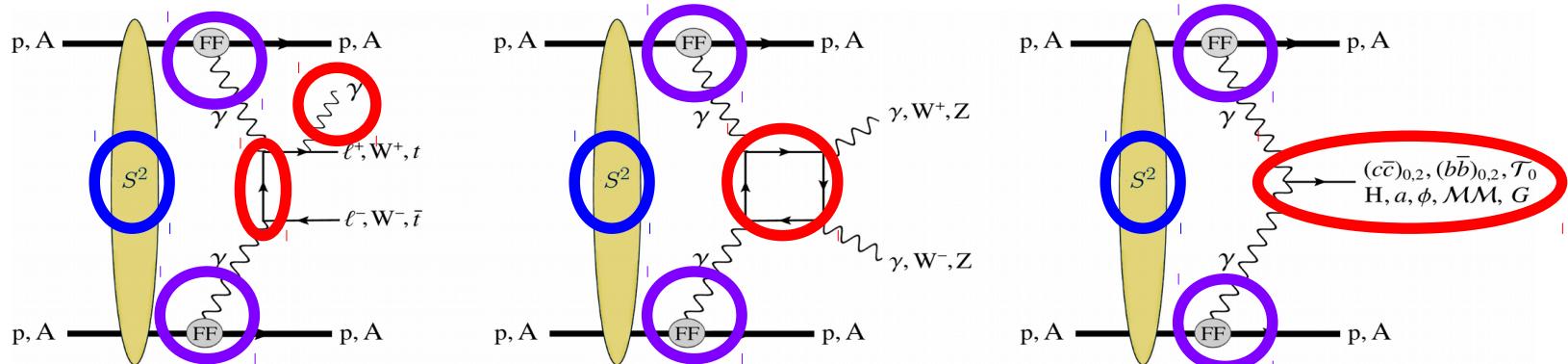
only  $p\bar{p}$  UPC

## UPCgen

$$\gamma\gamma \rightarrow \ell^+\ell^-$$

# gamma-UPC $\gamma\gamma$ MC event generator

- So far existing MC event generators (StarLight, SuperChic, FPMC, UPCgen...) include only a few hard-coded  $\gamma\gamma$  processes, QED/QCD LO only, no extra  $\gamma$ /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  $\gamma$ /gluon FSR out-of-the-box, extendable to NLO QED/EW, proton kinem. available, LHE output, 2 hadron form factors ( $\gamma$  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  $\gamma/g$  FSR's)
  - 2) p,A form factors: Electric Dipole (EDFF) & Charge (ChFF)  $\gamma$  fluxes
  - 3) p,A survival probability: via Glauber-MC-based eikonal

# $\gamma\gamma$ theoretical cross sections

## ■ Cross section:

$$\sigma(A B \xrightarrow{\gamma\gamma} A X B) = \int \frac{dE_{\gamma_1}}{E_{\gamma_1}} \frac{dE_{\gamma_2}}{E_{\gamma_2}} \frac{d^2 N_{\gamma_1/Z_1, \gamma_2/Z_2}^{(AB)}}{dE_{\gamma_1} dE_{\gamma_2}} \sigma_{\gamma\gamma \rightarrow X}(W_{\gamma\gamma})$$

## ■ Effective two-photon luminosity:

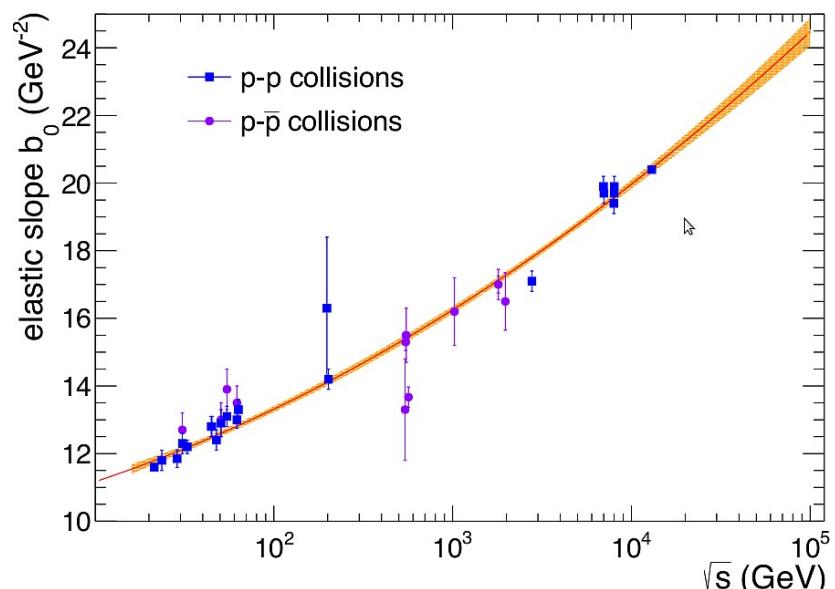
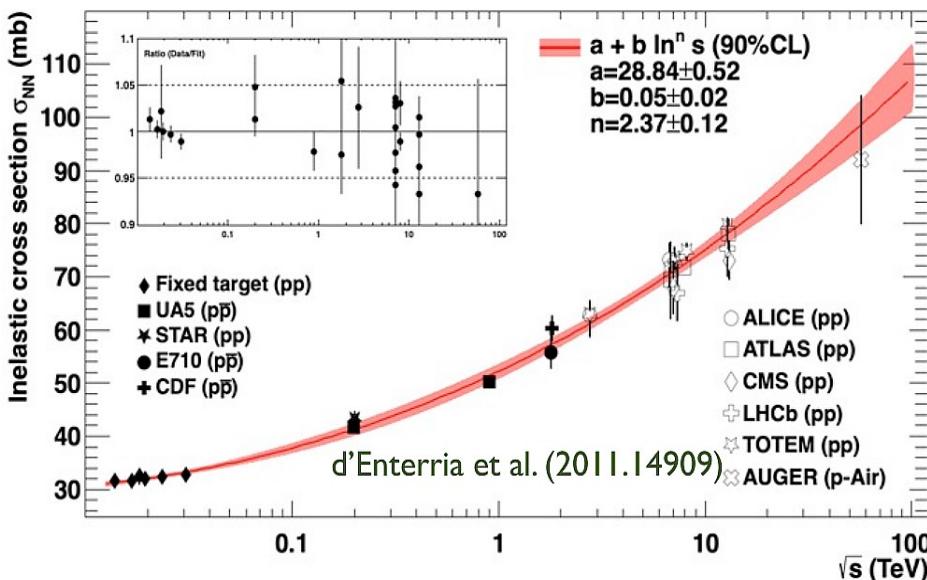
$$\frac{d^2 N_{\gamma_1/Z_1, \gamma_2/Z_2}^{(AB)}}{dE_{\gamma_1} dE_{\gamma_2}} = \int d^2 b_1 d^2 b_2 P_{\text{no inel}}(|b_1 - b_2|) N_{\gamma_1/Z_1}(E_{\gamma_1}, b_1) N_{\gamma_2/Z_2}(E_{\gamma_2}, b_2) \times \theta(b_1 - \epsilon R_A) \theta(b_2 - \epsilon R_B)$$

## ■ No hadronic/inelastic interaction probability density:

$$P_{\text{no inel}}(b) = \begin{cases} e^{-\sigma_{\text{inel}}^{\text{NN}} \cdot T_{AB}(b)}, \\ e^{-\sigma_{\text{inel}}^{\text{NN}} \cdot T_A(b)}, \\ |1 - \Gamma(s_{\text{NN}}, b)|^2, \text{ with } \Gamma(s_{\text{NN}}, b) \propto e^{-b^2/(2b_0)} \end{cases}$$

nucleus-nucleus  
proton-nucleus  
p-p

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



# p,A form factors & $\gamma$ fluxes: ChFF, EDFF

## ■ Electric dipole form factor (EDFF)

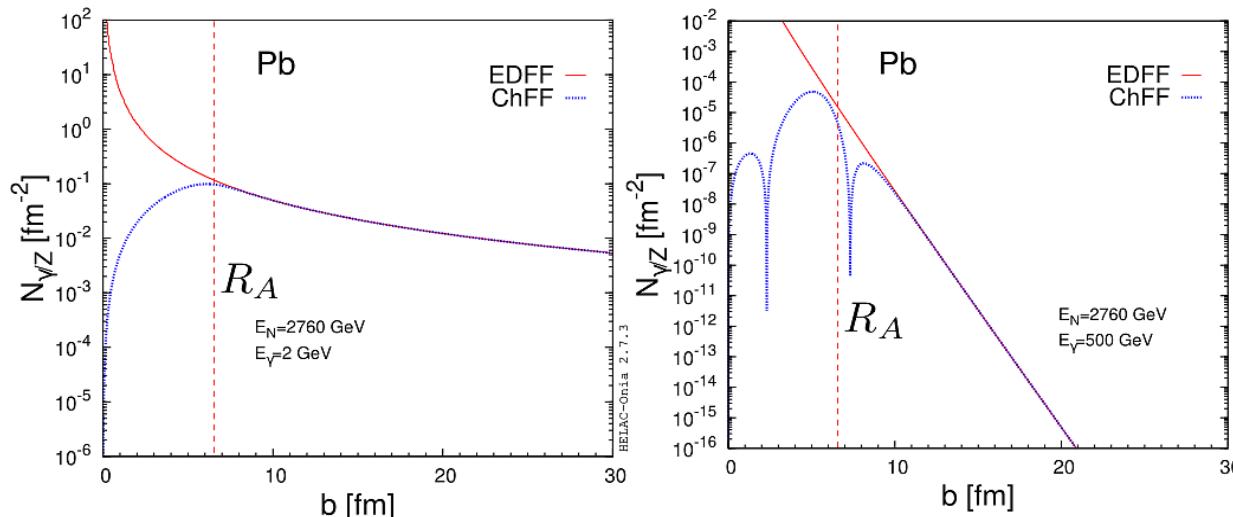
- Same as STARlight

$$N_{\gamma/Z}^{\text{EDFF}}(E_\gamma, b) = \frac{Z^2 \alpha}{\pi^2} \frac{\xi^2}{b^2} \left[ K_1^2(\xi) + \frac{1}{\gamma_L^2} K_0^2(\xi) \right] \quad \xi = \frac{E_\gamma b}{\gamma_L}$$

## ■ Charge form factor (ChFF)

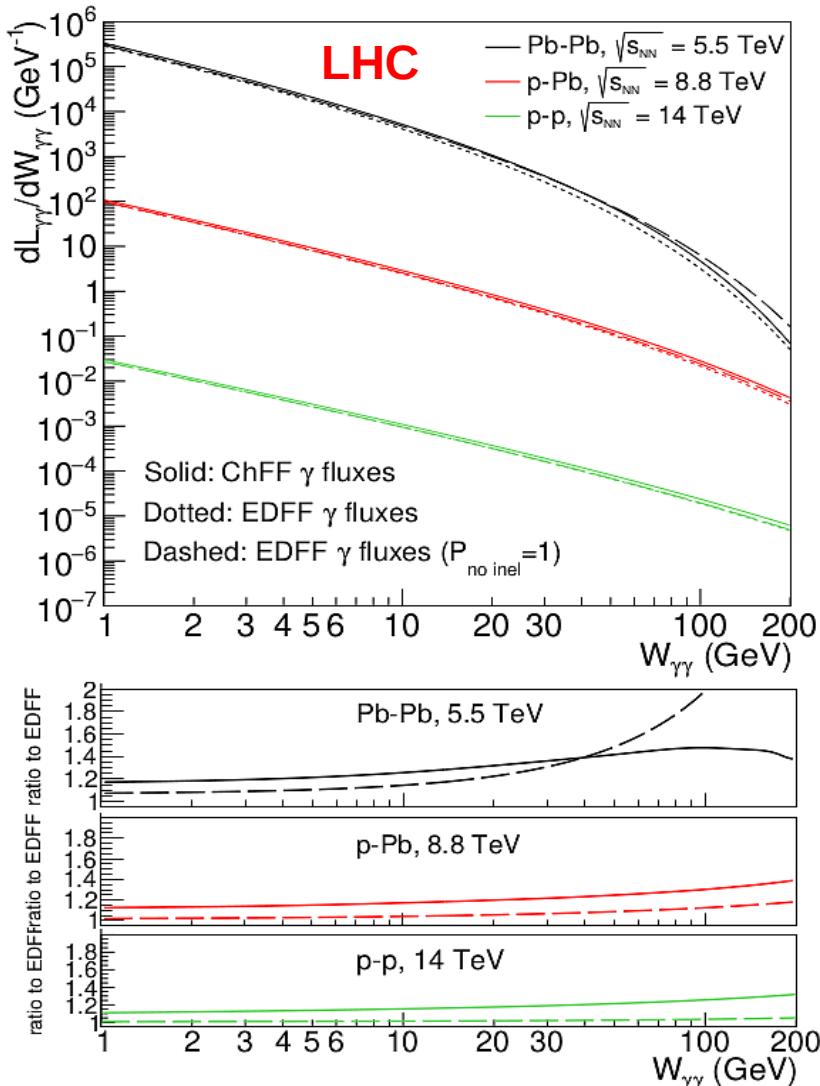
$$N_{\gamma/Z}^{\text{ChFF}}(E_\gamma, b) = \frac{Z^2 \alpha}{\pi^2} \left| \int_0^{+\infty} \frac{dk_\perp k_\perp^2}{k_\perp^2 + E_\gamma^2/\gamma_L^2} F_{\text{ch},A} \left( \sqrt{k_\perp^2 + E_\gamma^2/\gamma_L^2} \right) J_1(bk_\perp) \right|^2$$

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

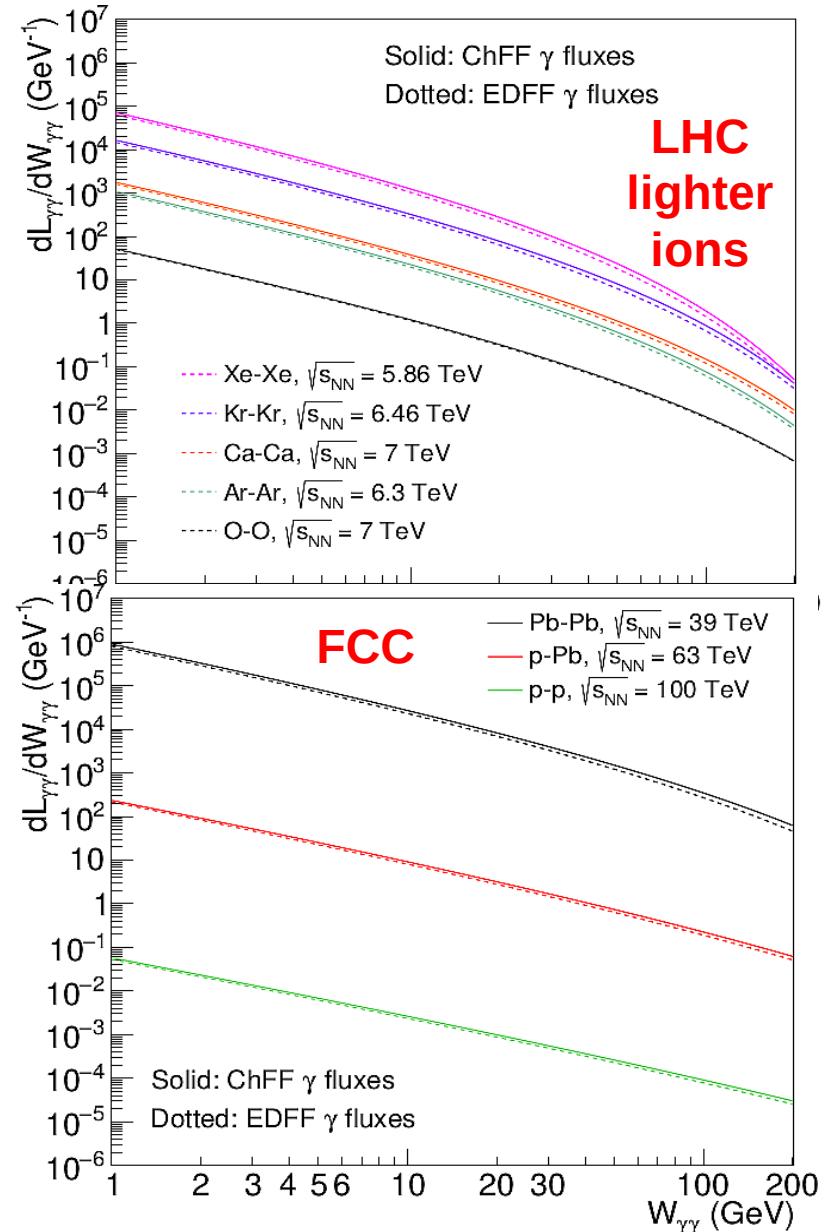


- Main difference comes from the  $b < R_A$  regime
- EDFF photon number density is divergent at  $b = 0$ 
  - Need a (arbitrary) cutoff when convoluting with ME

# $\gamma\gamma$ effective luminosities



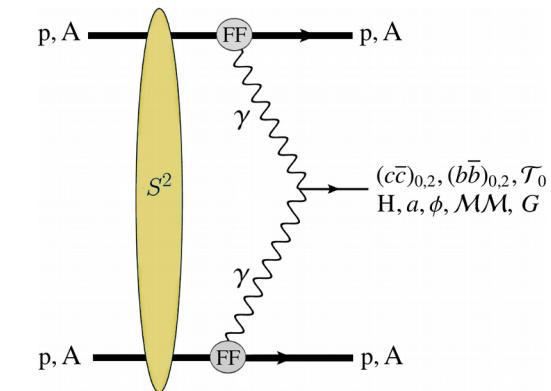
■ ChFF/EDDF  $\gamma$ -fluxes differences (pp–PbPb):  
Low masses: ~7–15%. High masses: 20–50%



# $\gamma\gamma$ collisions at LHC: Examples x-sections

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

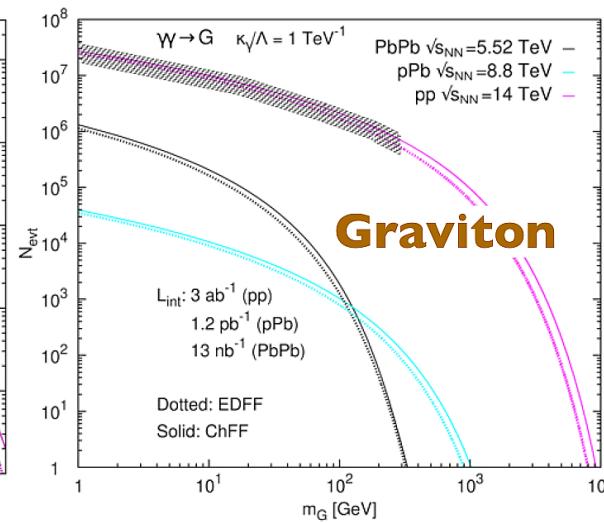
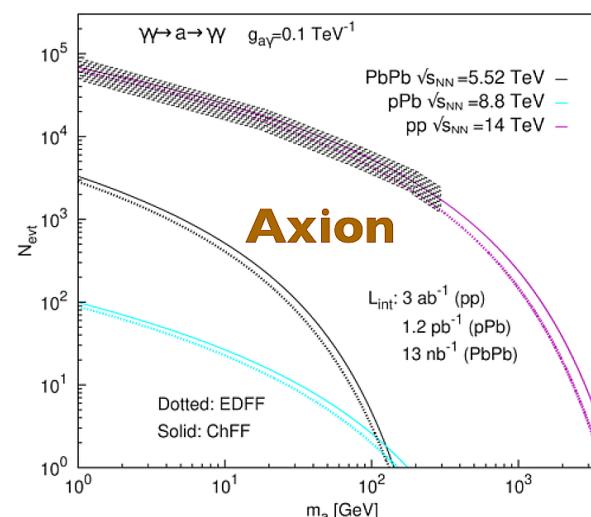
Colliding system	Form factor	gamma-UPC $\sigma(\gamma\gamma \rightarrow X)$									
		$\eta_c(1S)$	$\eta_c(2S)$	$\chi_{c0}$	$\chi_{c2}$	$\eta_b(1S)$	$\eta_b(2S)$	$\chi_{b0}$	$\chi_{b2}$	$\mathcal{T}_0$	H
p-p, 14 TeV	pointlike	61 pb	13 pb	17 pb	19 pb	110 fb	44 fb	29 fb	8.9 fb	0.12 fb	0.17 fb
	EDFF ( $S^2_{\gamma\gamma} = 1$ )	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 $\mu$ b	33 nb	43 nb	46 nb	0.23 nb	92 pb	60 pb	18 pb	0.31 pb	0.11 pb
	ChFF	0.18 $\mu$ b	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 $\mu$ b	0.50 $\mu$ b	0.63 $\mu$ b	0.70 $\mu$ b	3.1 nb	1.2 nb	0.81 nb	0.25 nb	4.6 pb	0.48 pb
	ChFF	2.7 $\mu$ b	0.58 $\mu$ b	0.74 $\mu$ b	0.81 $\mu$ b	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 $\mu$ b	0.31 $\mu$ b	0.40 $\mu$ b	0.42 $\mu$ b	1.8 nb	0.73 nb	0.48 nb	0.15 nb	2.9 pb	0.25 pb
	ChFF	1.6 $\mu$ b	0.34 $\mu$ b	0.44 $\mu$ b	0.49 $\mu$ b	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 $\mu$ b	4.4 $\mu$ b	5.9 $\mu$ b	6.3 $\mu$ b	25 nb	10 nb	6.7 nb	1.9 nb	41 pb	2.5 pb
	ChFF	25 $\mu$ b	5.1 $\mu$ b	6.4 $\mu$ b	7.0 $\mu$ b	31 nb	12 nb	7.9 nb	2.3 nb	46 pb	3.4 pb
Xe-Xe, 5.86 TeV	EDFF	89 $\mu$ b	18 $\mu$ b	24 $\mu$ b	26 $\mu$ b	98 nb	38 nb	26 nb	7.7 nb	0.16 nb	4.8 pb
	ChFF	101 $\mu$ b	21 $\mu$ b	27 $\mu$ b	29 $\mu$ b	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 $\mu$ b	0.10 mb	0.11 mb	0.40 $\mu$ b	0.15 $\mu$ b	0.10 $\mu$ b	31 nb	0.71 nb	9.3 pb
	ChFF	0.46 mb	95 $\mu$ b	0.12 mb	0.13 mb	0.50 $\mu$ b	0.19 $\mu$ b	0.13 $\mu$ b	38 nb	0.86 nb	13 pb



- Most low-mass resonances accessible in PbPb (pp without pileup) with low- $p_T$  charged particle reco.
- Higgs x-sections too low.

## ■ C-even BSM resonances:

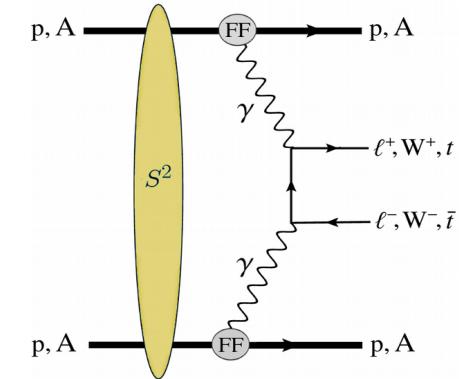
PbPb (pp with RPs) best limits below (above)  $m_{\gamma\gamma} \sim 100$  GeV



# $\gamma\gamma$ collisions at LHC: Examples x-sections

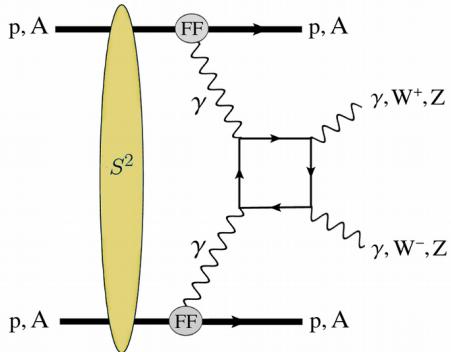
## ■ Double fermions (e.g. $\gamma\gamma \rightarrow t\bar{t}$ ):

Process: $\gamma\gamma \rightarrow t\bar{t}$	gamma-UPC $\sigma_{\text{NLO}}$		
	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



## • Quarkonia

## ■ Double bosons (loop induced):



Process: $\gamma\gamma \rightarrow J/\psi J/\psi$	gamma-UPC $\sigma$		
	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

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

Process: $\gamma\gamma \rightarrow Z\gamma$	gamma-UPC $\sigma$		
	EDFF	ChFF	average
p-p at 14 TeV	36.2 ab	44.7 ab	$40.5 \pm 4.3$ ab
p-Pb at 8.8 TeV	10.3 fb	15.6 fb	$13.0 \pm 2.6$ fb
Pb-Pb at 5.52 TeV	109 fb	152 fb	$130 \pm 22$ fb

Process: $\gamma\gamma \rightarrow ZZ$	gamma-UPC $\sigma$		
	EDFF	ChFF	average
p-p at 14 TeV	52.8 ab	78.4 ab	$66 \pm 13$ ab
p-Pb at 8.8 TeV	12.3 fb	18.8 fb	$15.5 \pm 3.2$ fb
Pb-Pb at 5.52 TeV	46.8 fb	63.2 fb	$55 \pm 8$ fb

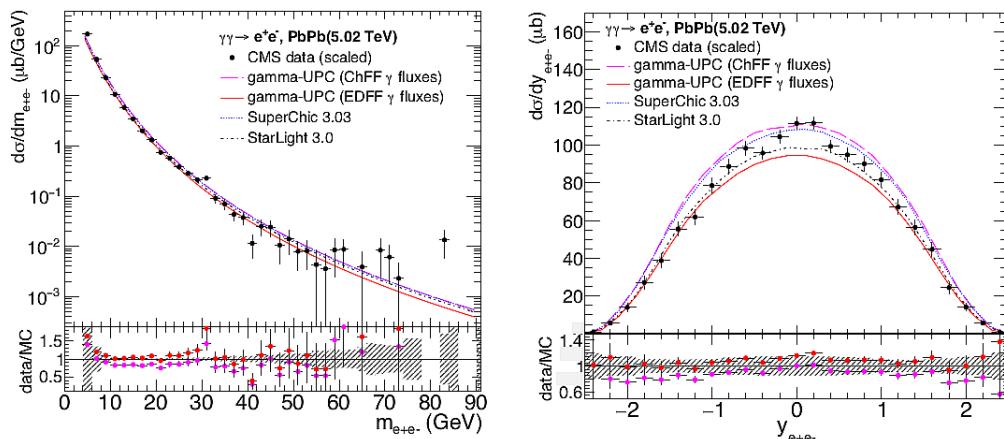
$$\mathcal{L} \supset \frac{c_{WWW}}{\Lambda^2} \text{Tr} [W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}] \quad \sigma = \sigma_{\text{SM}} + \left( \frac{c_{WWW}}{\Lambda^2} \times 1 \text{ TeV}^2 \right) \sigma_{WWW}$$

Process: $\gamma\gamma \rightarrow W^+W^-$	gamma-UPC average	
	$\sigma_{\text{SM}}$	$\sigma_{WWW}$
p-p at 14 TeV	$63 \pm 11$ fb	$53 \pm 8$ ab
p-Pb at 8.8 TeV	$26 \pm 5$ pb	$28 \pm 5$ fb
Pb-Pb at 5.52 TeV	$277 \pm 44$ pb	$394 \pm 64$ fb

# $\gamma\gamma$ collisions at LHC: Differential x-sections

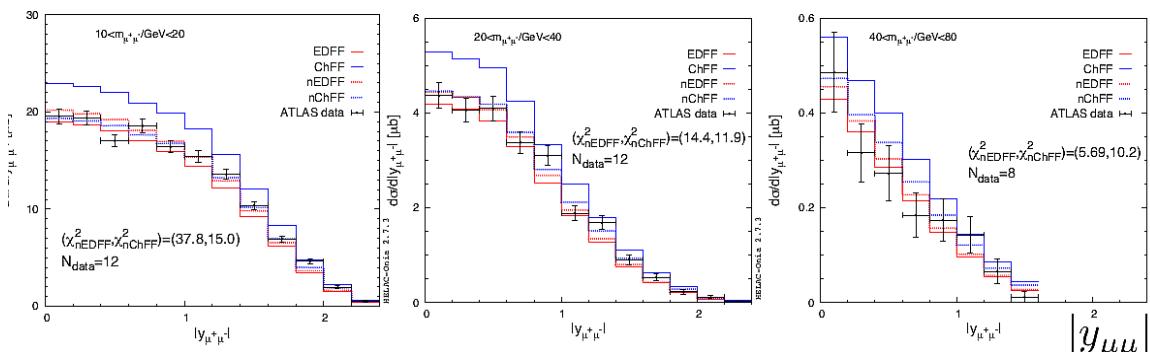
## ■ Breit-Wheeler process $\gamma\gamma \rightarrow e^+e^-$ :

Process, system	Scaled CMS data [13]	gamma-UPC $\sigma$	STARLIGHT $\sigma$	SUPERCHIC $\sigma$
$\gamma\gamma \rightarrow e^+e^-, \text{Pb-Pb at } 5.02 \text{ TeV}$	$275 \pm 55 \mu\text{b}$	EDFF ChFF average  272 $\mu\text{b}$ 326 $\mu\text{b}$ 298 $\pm 28 \mu\text{b}$	STARLIGHT $\sigma$  285 $\mu\text{b}$	SUPERCHIC $\sigma$  318 $\mu\text{b}$



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

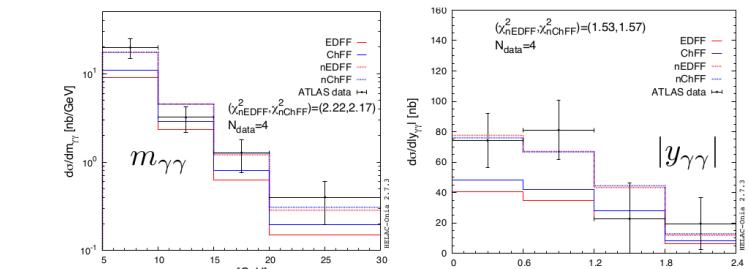
Process, system	ATLAS data [19]	gamma-UPC $\sigma$	STARLIGHT $\sigma$	SUPERCHIC $\sigma$
$\gamma\gamma \rightarrow \mu^+\mu^-, \text{Pb-Pb at } 5.02 \text{ TeV}$	$34.1 \pm 0.8 \mu\text{b}$	EDFF ChFF average  32.1 $\mu\text{b}$ 40.4 $\mu\text{b}$ 36.2 $\pm 4.2 \mu\text{b}$	STARLIGHT $\sigma$  32.1 $\mu\text{b}$	SUPERCHIC $\sigma$  38.9 $\mu\text{b}$



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

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

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



- 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 & 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>

# Backup slides