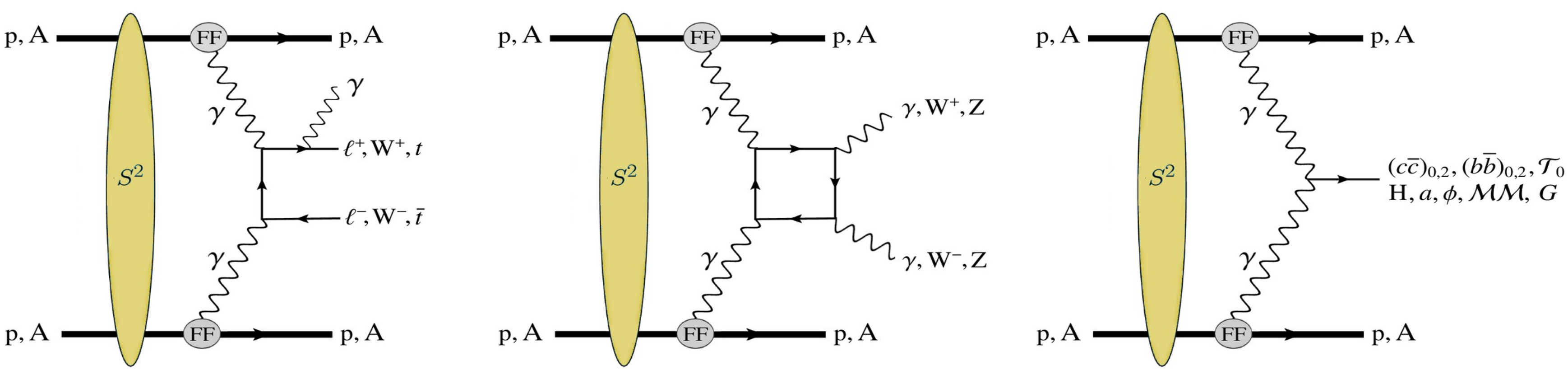
SM and BSM physics with photon-photon collisions at the LHC

DIS 2024

Grenoble, 11th April 2024

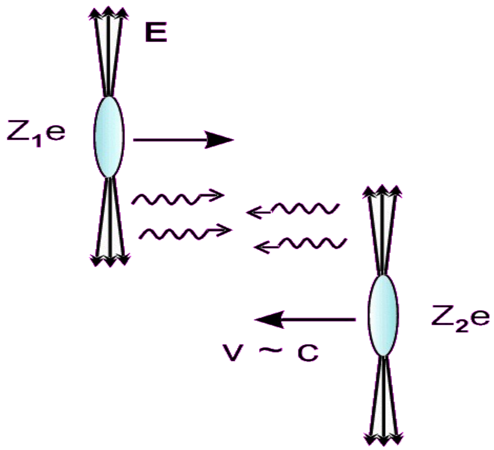
Nicolas Crépet (CERN)



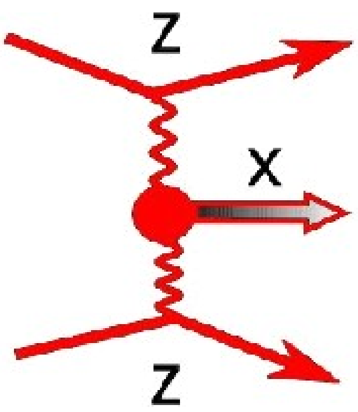
Work with **Hua-Sheng Shao** and **David d'Enterria**: https://arxiv.org/abs/2207.03012
[JHEP 09 (2022) 248]
+ additionnal paper to be published

LHC = a unique photon-photon collider

- Electromagnetic ultra-peripheral colls. (UPC): $b_{min} > R_A + R_B$, hadrons survive
- EM field = Weizsäcker-Williams (Equivalent Photon Approx.) photon flux:



=



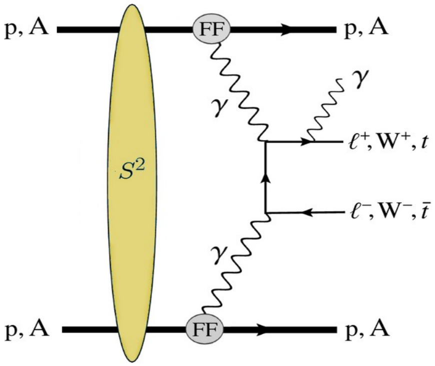
- Huge photon fluxes:
  $\sigma(\gamma\gamma) \sim Z^4$ (~$5\cdot10^7$ for PbPb) times larger than p,$e^\pm$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

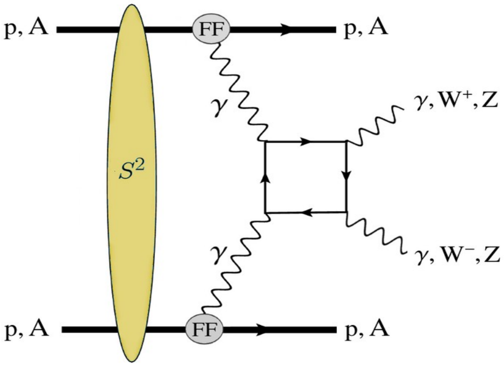
- Quasi-real γ (coherent emission): Q ~ 1/R ~ 0.03 GeV (Pb), 0.28 GeV (p)
- Max. (longitudinal) γ energies: $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 80 GeV (Pb), ~ 2.5 TeV (p)

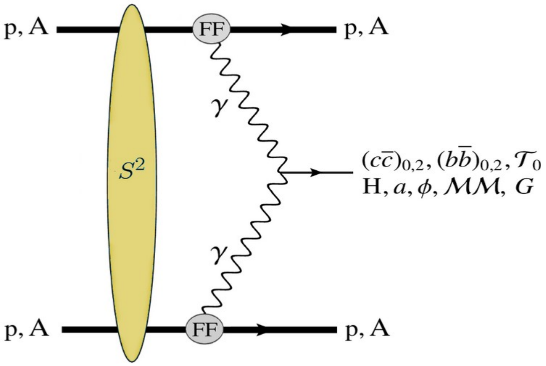
System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$E_{beam1} + E_{beam2}$	γ_L	R_A	E_γ^{max}	$\sqrt{s_{\gamma\gamma}^{max}}$
Pb-Pb	5.52 TeV	5 nb^{-1}	2.76 + 2.76 TeV	2960	7.1 fm	80 GeV	160 GeV
p-Pb	8.8 TeV	1 pb^{-1}	7.0 + 2.76 TeV	7450, 2960	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV
p-p	14 TeV	150 fb^{-1}	7.0 +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

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],...

Existing dedicated γγ MC event generators

- So far dedicated MC event generators include only hard-coded γγ processes, LO QED/QCD 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	$\tilde{\chi}^-(6)(\to \tilde{\chi}_0^1(8) + \mu^-(9) + \overline{\nu}_\mu(10)) + \tilde{\chi}^+(7)(\to \tilde{\chi}_0^1(11) + \mu^+(12) + \nu_\mu(13))$
74	$\tilde{\chi}^-(6)(\to \tilde{\chi}_0^1(8) + \overline{u}(9) + d(10)) + \tilde{\chi}^+(7)(\to \tilde{\chi}_0^1(11) + u(12) + \overline{d}(13))$
75	$\tilde{\chi}^-(6)(\to \tilde{\chi}_0^1(8) + \mu^-(9) + \overline{\nu}_\mu(10)) + \tilde{\chi}^+(7)(\to \tilde{\chi}_0^1(11) + u(12) + \overline{d}(13))$
76	$\tilde{l}^-(5))(\to \tilde{\chi}_0^1(8) + \mu^-(9)) + \tilde{l}^+(6)(\to \tilde{\chi}_0^1(10) + \mu^+(11))$
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 , LPAIR/CepGen

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

gamma-UPC γγ MC event generator

- gamma-UPC features:

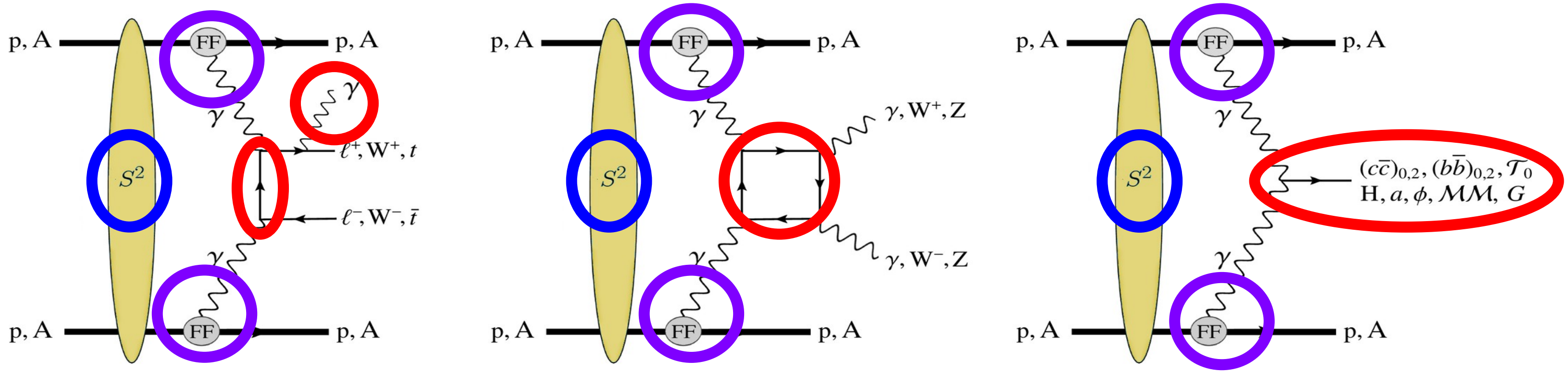
– Arbitrary (B)SM & QQbar matrix elements w/ MG5@NLO & HelacOnia

– N γ/gluon FSR out-of-the-box. Extendable to NLO QCD & EW

– LHE output: Shower+hadronization via PS (PY8, HERWIG,...)

– 2 different form factors (γ fluxes) coded. Glauber MC for the non-overlap

– Any colliding combination: p-p,p-A,A-A (for any A)



- gamma-UPC key properties:

1) Matrix elements: MG5@NLO, HelacOnia, custom (N γ/g FSR's, NLO QCD/EW)
2) p,A form factors: Charge (ChFF) (and Electric Dipole, EDFF) γ fluxes
3) p,A survival probability: Glauber-MC (and optical) based eikonal

Heavy-ion form factors & γ fluxes: ChFF, EDFF

Electric dipole form factor (EDFF)

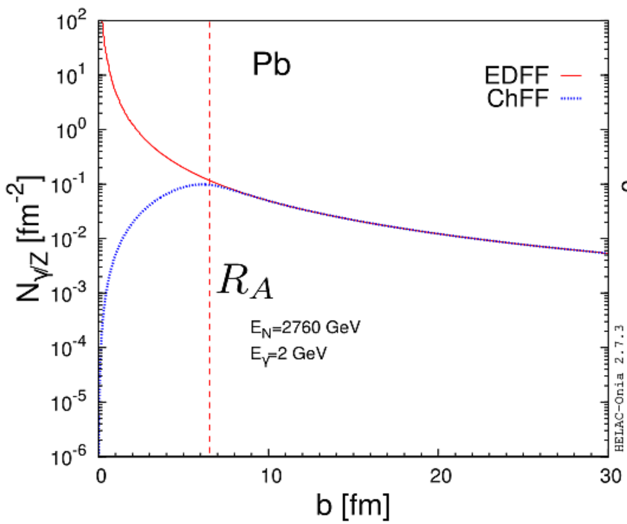
- Same as STARlight

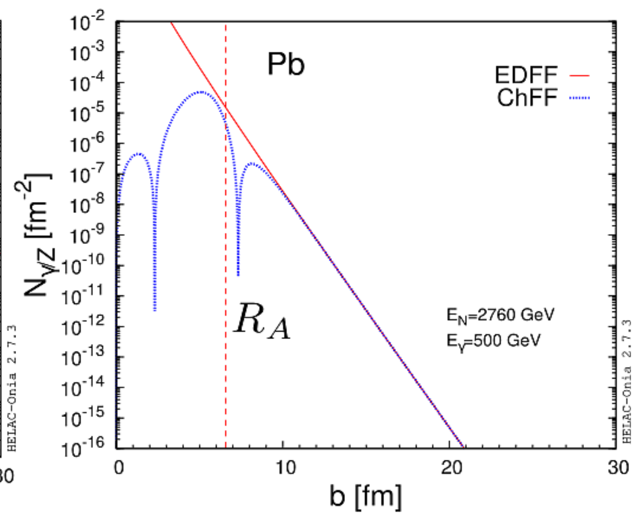
$$N^{\mathrm{EDFF}}_{\gamma/\mathrm{Z}}(E_\gamma, b) = \frac{Z^2\alpha}{\pi^2}\frac{\xi^2}{b^2}\left[K_1^2(\xi) + \frac{1}{\gamma_\mathrm{L}^2}K_0^2(\xi)\right] \qquad \xi = \frac{E_\gamma b}{\gamma_\mathrm{L}}$$

Charge form factor (ChFF)

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

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





- 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

ChFF is much more realistic: preferred.

Proton 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)**

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

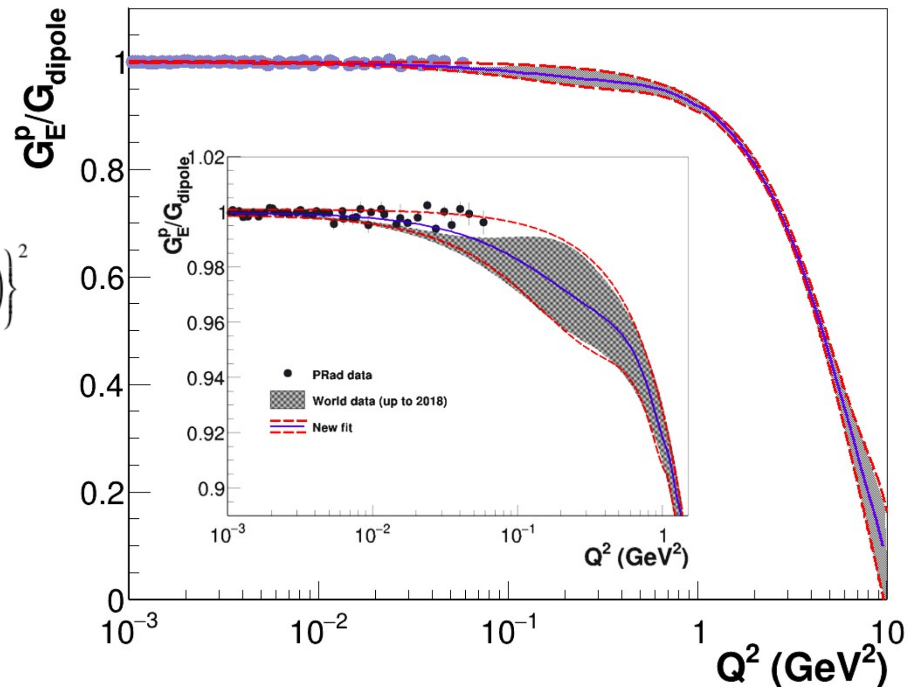
$$F_{\mathrm{ch,A}}(q) = \int \mathrm{d}^3\boldsymbol{r}e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\rho_\mathrm{A}(\boldsymbol{r}) = \frac{4\pi}{q}\int_0^{+\infty}\mathrm{d}r\,\rho_\mathrm{A}(r)r\sin(qr)$$

- Proton dipole form-factor:

$$F_{\mathrm{ch,p}}(q) = \frac{1}{\left(1 + q^2a_\mathrm{p}^2\right)^2} \qquad \text{with } a_\mathrm{p}^{-2} = Q_0^2 = 0.71\ \mathrm{GeV}^2$$

$$N^{\mathrm{ChFF}}_{\gamma/\mathrm{p}}(E_\gamma, b) = \frac{\alpha}{\pi^2}\frac{\xi^2}{b^2}\left\{\left[K_1(\xi) - \sqrt{1+\tilde{a}_\mathrm{p}^{-2}}K_1\left(\xi\sqrt{1+\tilde{a}_\mathrm{p}^{-2}}\right)\right] - \frac{\xi}{2\tilde{a}_\mathrm{p}^2}K_0\left(\xi\sqrt{1+\tilde{a}_\mathrm{p}^{-2}}\right)\right\}^2$$

- Updated proton elastic ChFF, from fit to latest A1+PRad e-p elastic data:



$\gamma\gamma$ EPA cross sections & survival probability

- **Cross section:**

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

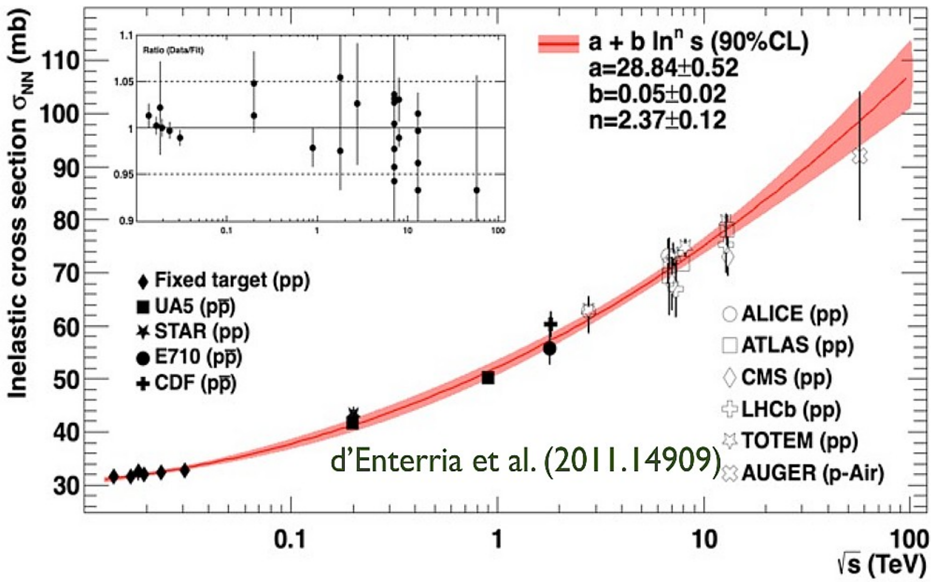
- **Effective two-photon luminosity:**

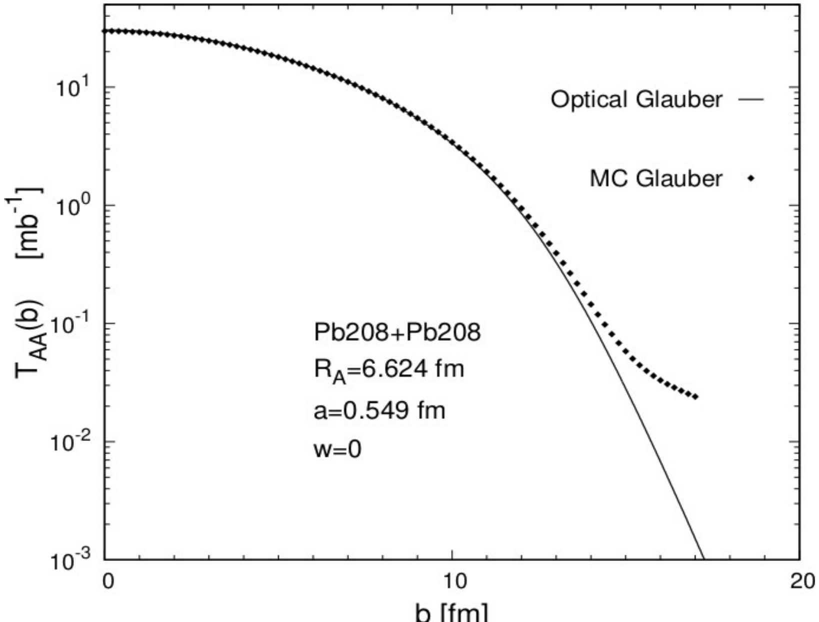
$$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1\mathrm{d}^2\boldsymbol{b}_2\, P_{\mathrm{no\,inel}}(|\boldsymbol{b}_1-\boldsymbol{b}_2|)\ N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1},\boldsymbol{b}_1)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

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

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

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





γγ EPA cross sections & survival probability

- **Cross section:**

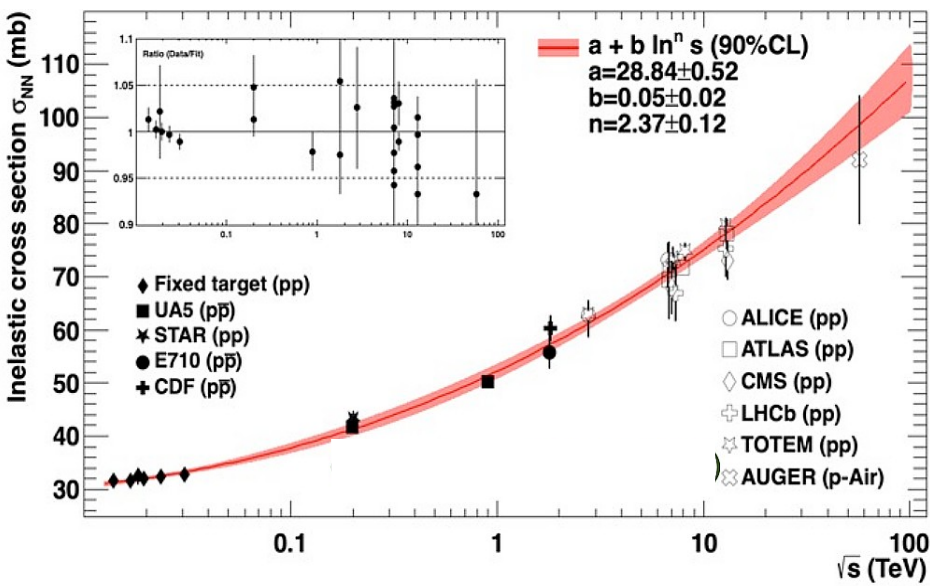
$$\sigma(\mathrm{A\ B} \xrightarrow{\gamma\gamma} \mathrm{A}\ X\ \mathrm{B}) = \int \frac{dE_{\gamma_1}}{E_{\gamma_1}} \frac{dE_{\gamma_2}}{E_{\gamma_2}} \frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} \sigma_{\gamma\gamma\to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

- **Effective two-photon luminosity:**

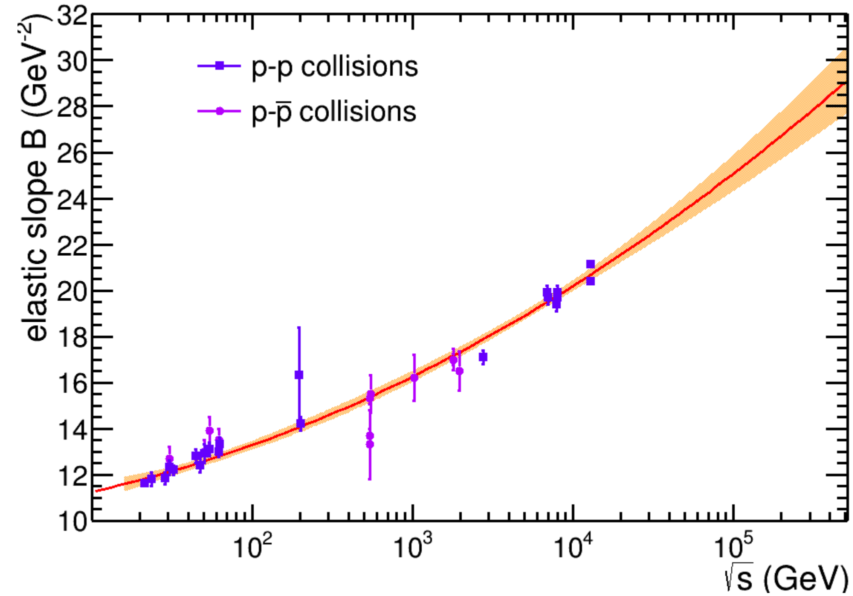
$$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, P_{\text{no inel}}(|\boldsymbol{b}_1 - \boldsymbol{b}_2|)\ N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1},\boldsymbol{b}_1)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

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

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



Parametrized proton elastic slope data:



How peripheral are Pb-Pb UPCs at the LHC?

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

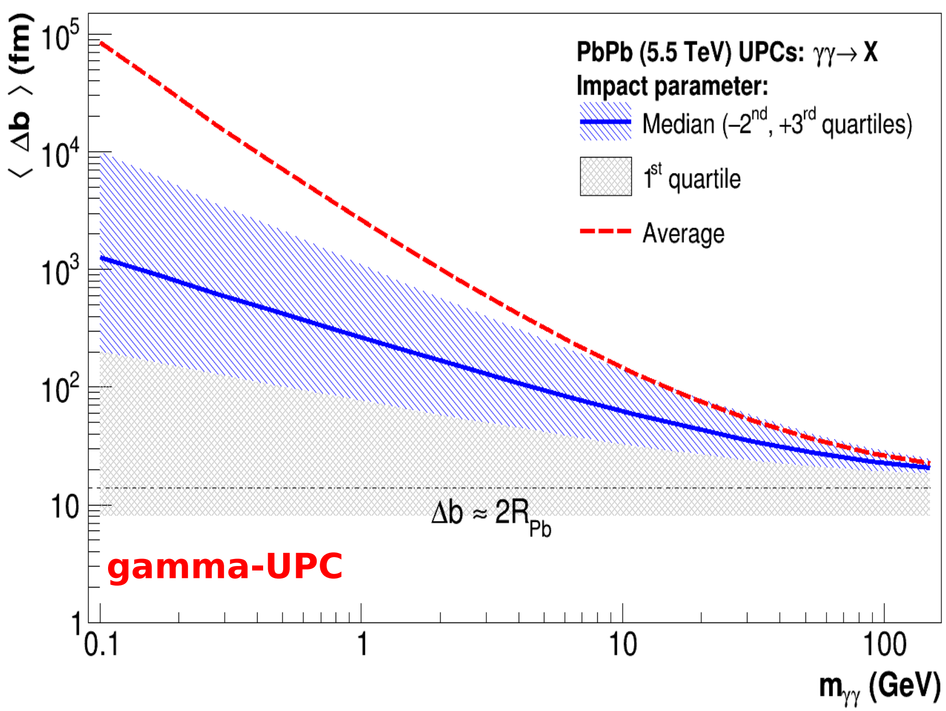
  $m_{\gamma\gamma} < 5$ GeV: $\langle \Delta b \rangle > 100$ fm

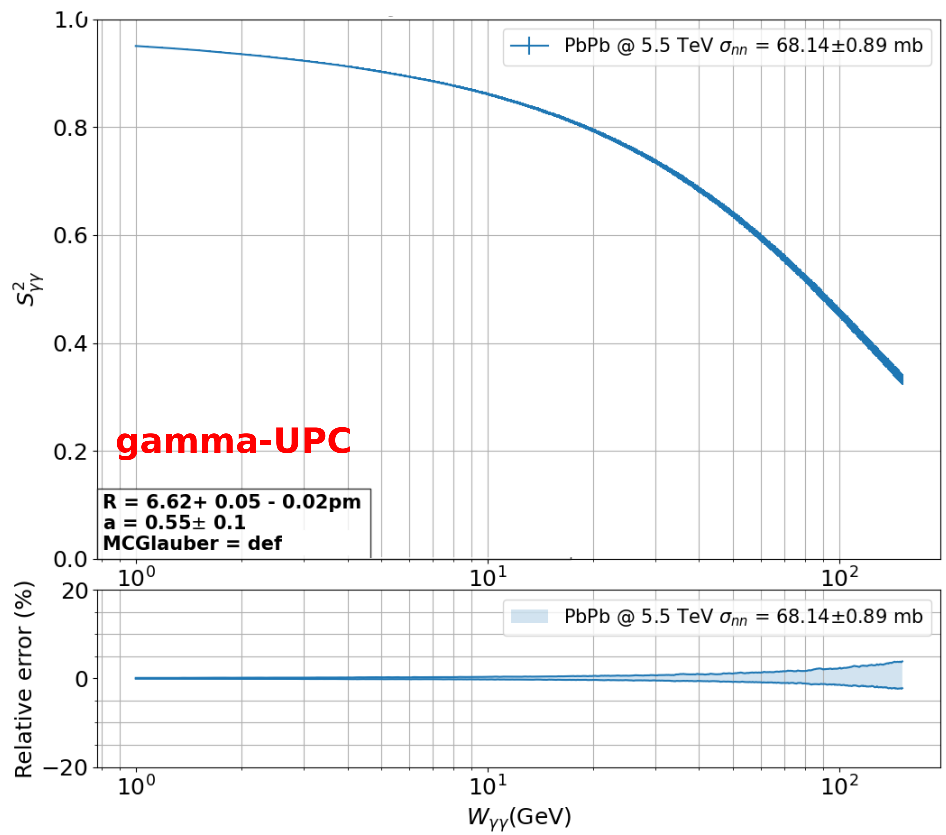
  $m_{\gamma\gamma} > 100$ GeV: $\langle \Delta b \rangle \sim 20$ fm

- 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: $\langle P_{\text{non-overlap}} \rangle < 40\%$





How peripheral are p-p UPCs at the LHC?

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

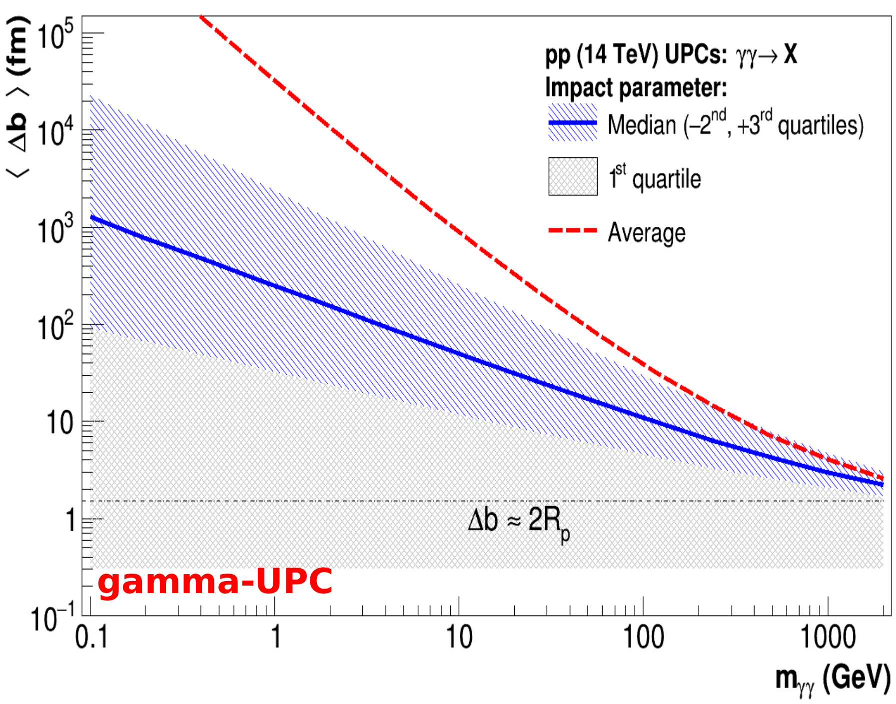
  $m_{\gamma\gamma} < 10$ GeV: $\langle \Delta b \rangle > 50$ fm

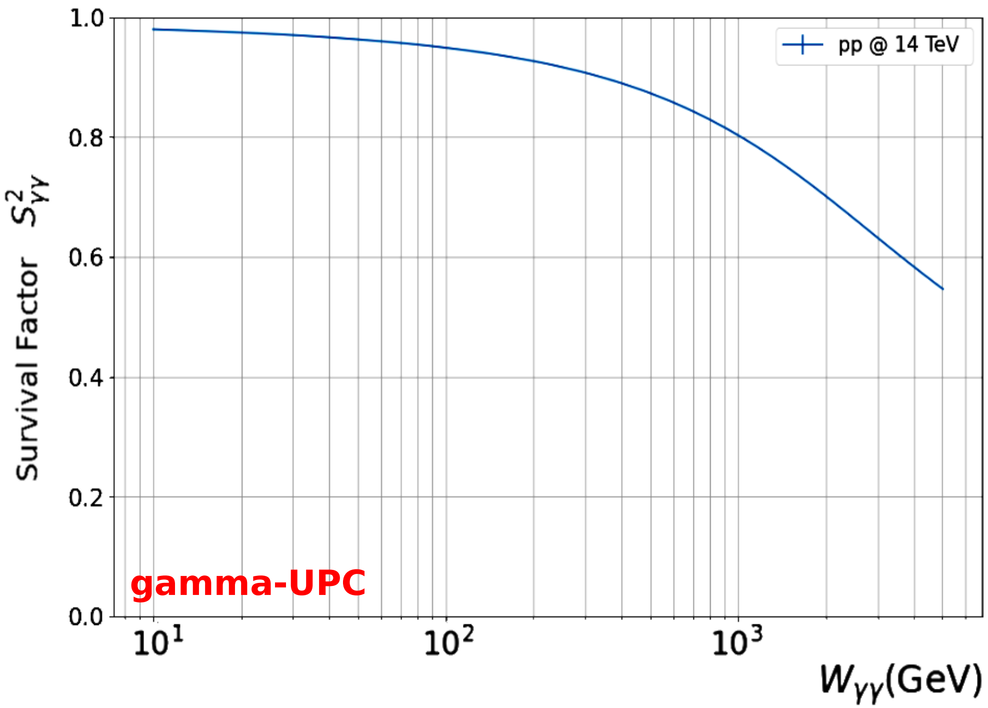
  $m_{\gamma\gamma} > 1$ TeV: $\langle \Delta b \rangle < 3$ fm

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

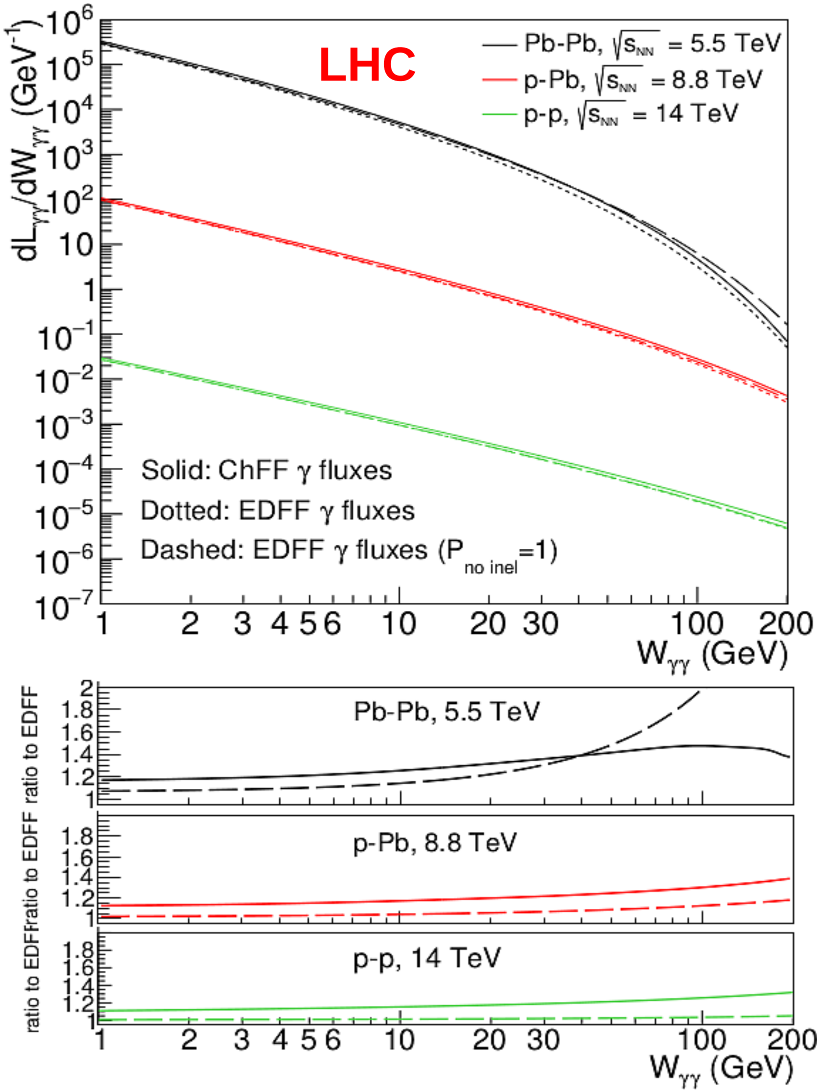
  $m_{\gamma\gamma} < 10$ GeV: $\langle P_{\text{non-overlap}} \rangle > 95\%$

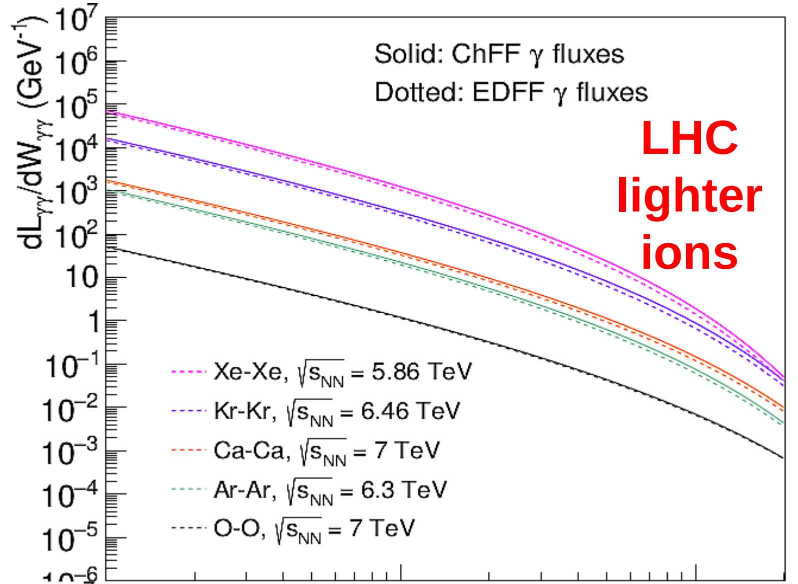
  $m_{\gamma\gamma} > 1$ TeV: $\langle P_{\text{non-overlap}} \rangle < 80\%$

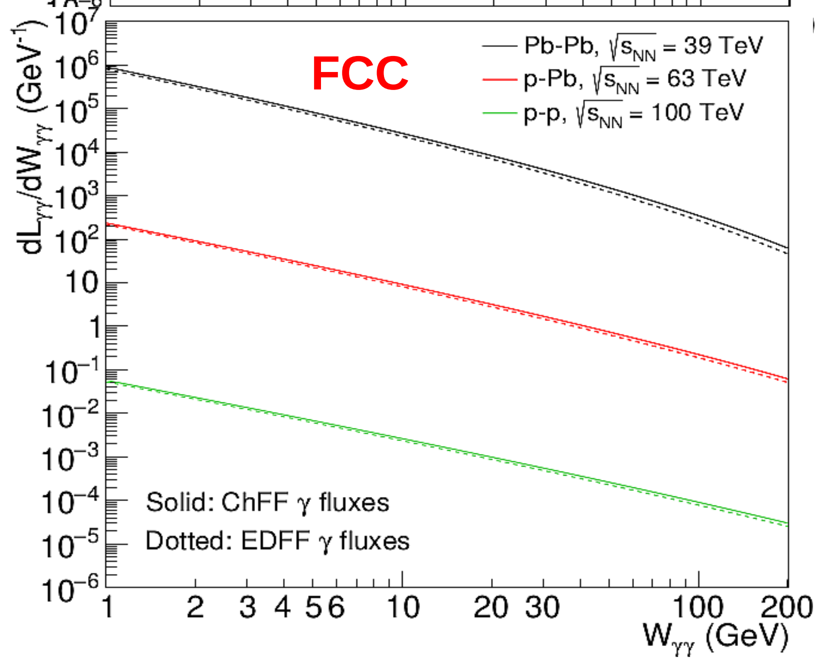




Effective γγ luminosities (LHC/FCC)



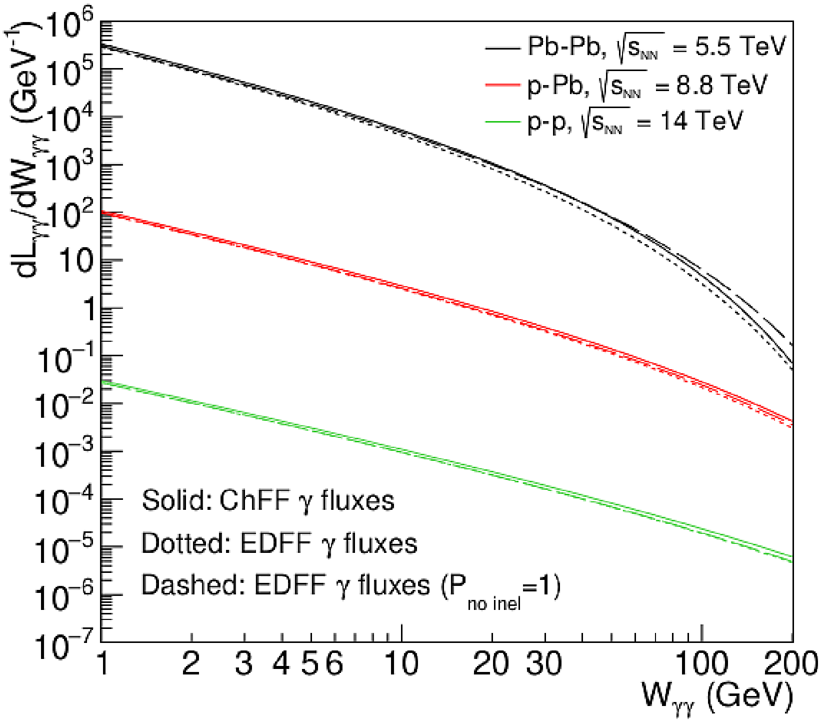


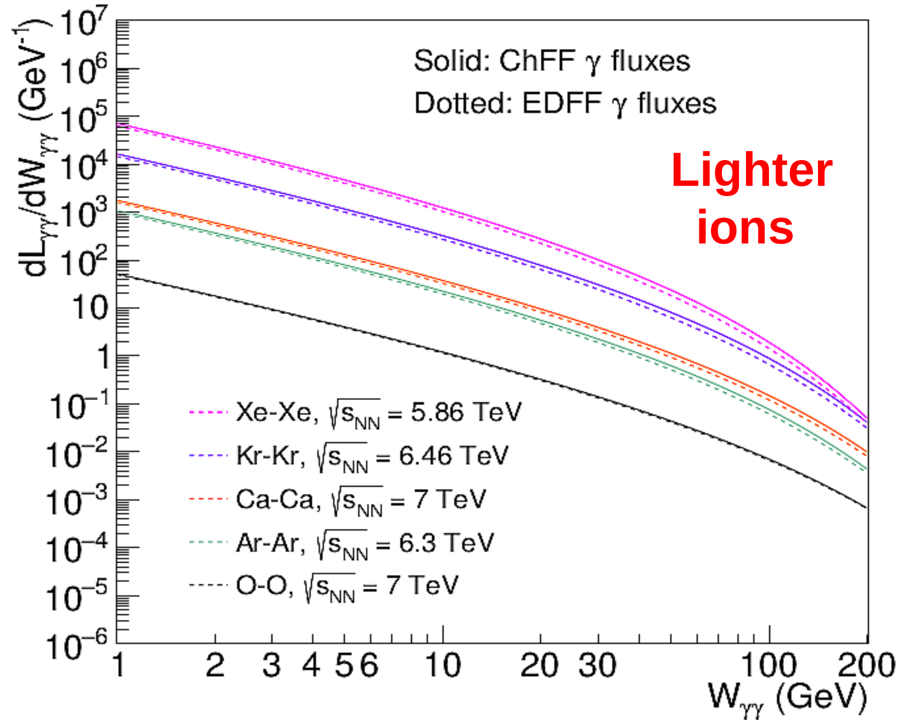


- ChFF/EDDF γ-fluxes differences (pp–PbPb): Low masses: 7–15%. High masses: 20–50%

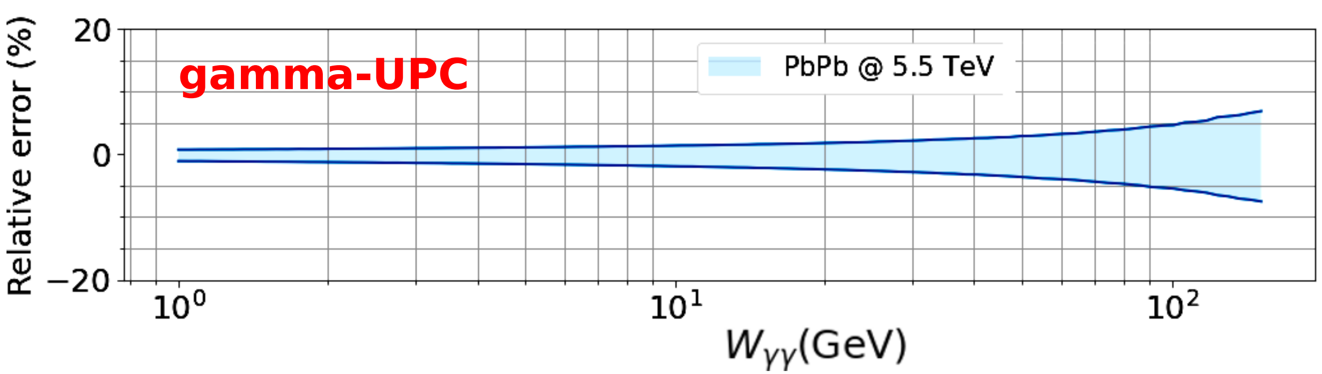
Effective γγ luminosities (LHC)

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





- ChFF γγ luminosity uncertainties (PbPb): Low-mass: few %. High mass: ~7%

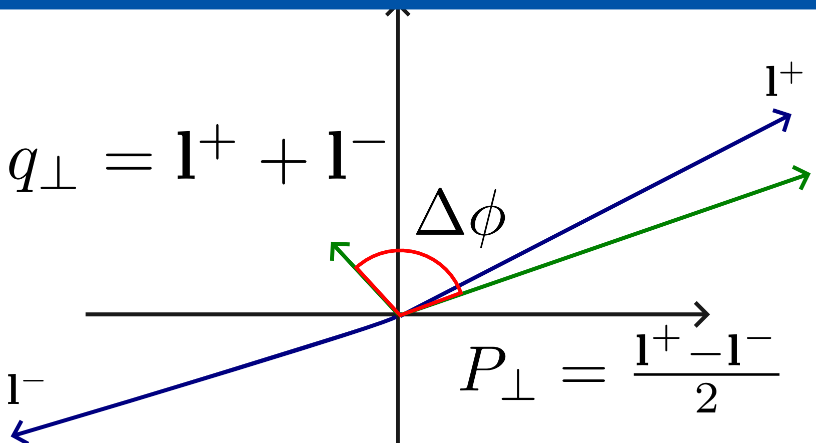


ChFF γ spectra
Glauber MC:
Variations of R,a,σ_{NN}

$\gamma\ \gamma \rightarrow l^+ l^-$ azimuthal modulation from lineary polarized γ fluxes

- MG5 expects colinear & unpolarized EPA photons. A dedicated python script is run on gammaUPC+MG5 LHE files to modify the $\gamma\ \gamma \rightarrow l^+ l^-$ initial and final state
- $\Delta\phi$ follows:

$$A + B\cos(2\Delta\phi) + C\cos(4\Delta\phi)$$



$$\mathcal{A} = \frac{(Q^2-2m^2)m^2+(Q^2-2P_\perp^2)P_\perp^2}{(m^2+P_\perp^2)^2} x_1 x_2 \int d^2k_{1\perp} d^2k_{2\perp} \delta^2(q_\perp - k_{1\perp} - k_{2\perp}) f_1^\gamma(x_1,k_{1\perp}^2) f_1^\gamma(x_2,k_{2\perp}^2)$$
$$+ \frac{m^4}{(m^2+P_\perp^2)^2} x_1 x_2 \int d^2k_{1\perp} d^2k_{2\perp} \delta^2(q_\perp - k_{1\perp} - k_{2\perp}) \left[2(\hat{k}_{1\perp}\cdot\hat{k}_{2\perp})^2 - 1\right] h_1^{\perp\gamma}(x_1,k_{1\perp}^2) h_1^{\perp\gamma}(x_2,k_{2\perp}^2)$$

$$\mathcal{B} = \frac{4m^2P_\perp^2}{(m^2+P_\perp^2)^2} x_1 x_2 \int d^2k_{1\perp} d^2k_{2\perp} \delta^2(q_\perp - k_{1\perp} - k_{2\perp})$$
$$\times \left\{ \left[2(\hat{k}_{2\perp}\cdot\hat{q}_\perp)^2 - 1\right] f_1^\gamma(x_1,k_{1\perp}^2) h_1^{\perp\gamma}(x_2,k_{2\perp}^2) + \left[2(\hat{k}_{1\perp}\cdot\hat{q}_\perp)^2 - 1\right] h_1^{\perp\gamma}(x_1,k_{1\perp}^2) f_1^\gamma(x_2,k_{2\perp}^2) \right\}$$

$$\mathcal{C} = \frac{-2P_\perp^4}{(m^2+P_\perp^2)^2} x_1 x_2 \int d^2k_{1\perp} d^2k_{2\perp} \delta^2(q_\perp - k_{1\perp} - k_{2\perp})$$
$$\times \left[2\left(2(\hat{k}_{2\perp}\cdot\hat{q}_\perp)(\hat{k}_{1\perp}\cdot\hat{q}_\perp) - \hat{k}_{1\perp}\cdot\hat{k}_{2\perp}\right)^2 - 1 \right] h_1^{\perp\gamma}(x_1,k_{1\perp}^2) h_1^{\perp\gamma}(x_2,k_{2\perp}^2)$$

Cong Li, Jian Zhou, and Ya-jin Zhou: arXiv.1903.10084

- Photon TMD:

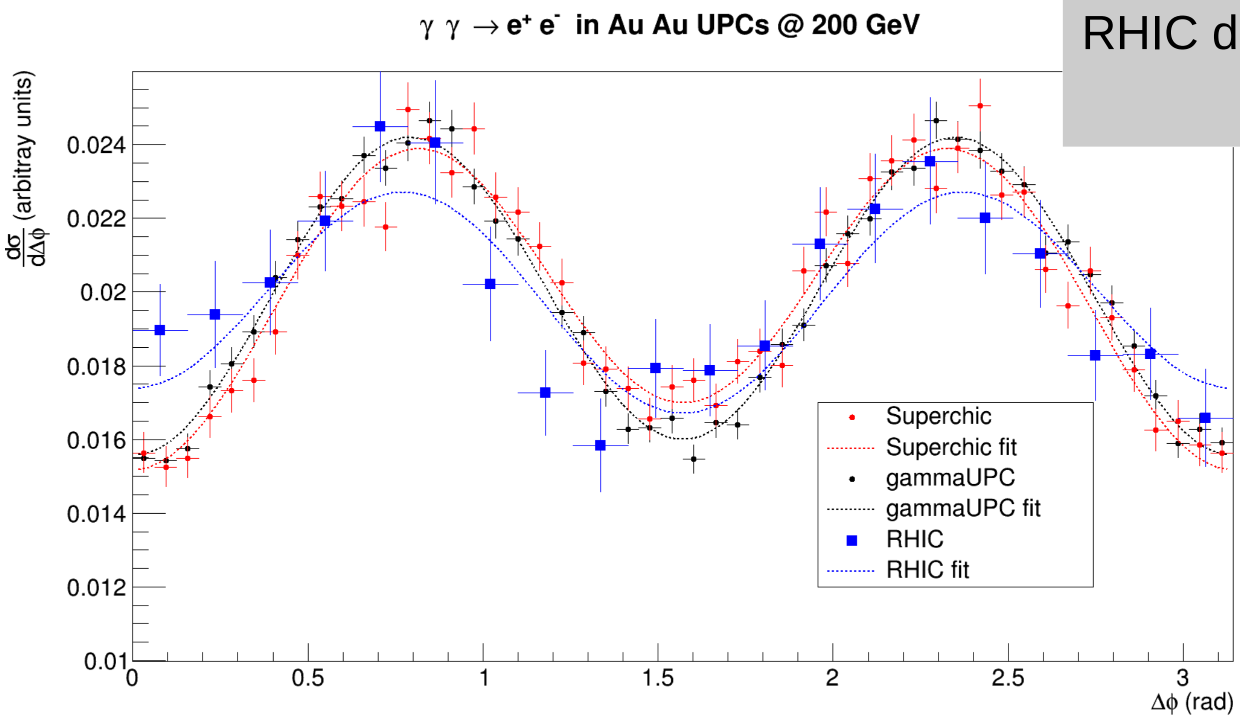
$$x f_1^\gamma(x,k_\perp^2) = x h_1^{\perp\gamma}(x,k_\perp^2) = \frac{Z^2\alpha_e}{\pi^2} k_\perp^2 \left[\frac{F(k_\perp^2 + x^2M_p^2)}{(k_\perp^2 + x^2M_p^2)}\right]^2$$

$\gamma\ \gamma \to l^+ l^-$ azimuthal modulation in Au-Au 200 GeV UPCs

- MG5 expects colinear & unpolarized EPA photons. A dedicated python script is run on gammaUPC+MG5 LHE files to modify the $\gamma\ \gamma \to l^+ l^-$ initial and final state
- Fitted $\Delta\phi$ distribution from gammaUPC, Superchic and RHIC data samples to:

$$A(1 + \frac{B}{A}\cos(2\Delta\phi) + \frac{C}{A}\cos(4\Delta\phi))$$

	B/A (%)	C/A (%)
gammaUPC	1.0 ± 0.5	21.7 ± 0.6
Superchic	4.5 ± 0.6	19.5 ± 0.6
RHIC data	2.0 ± 2.4	16.8 ± 2.5



$$p_T^{pair} < 0.1\text{GeV}$$

$$0.45 < m_{ee} < 0.76\text{GeV}$$

$$p_T^e > 0.2\text{GeV}$$

RHIC data: arXiv:1910.12400

Photon-photon collisions: Summary

- gamma-UPC is a new versatile code to generate any γγ process in UPCs with protons & ions. Interfaced to MG5@NLO & HelacOnia & custom codes.
- New developments:
  - Parametric uncertainties
  - Δϕ distribution modulation for lepton pairs

- Future developments:
  - Non-exclusive collisions possible
  - Semi-exclusive W/Z-γ processes
  - NLO EW corrections
  - UPCs for e-proton & e-ion collisions
  - …
- Download it, test it, use it (or ask us to produce the LHE files) for your favourite γγ EXP/PH studies!

https://hshao.web.cern.ch/hshao/