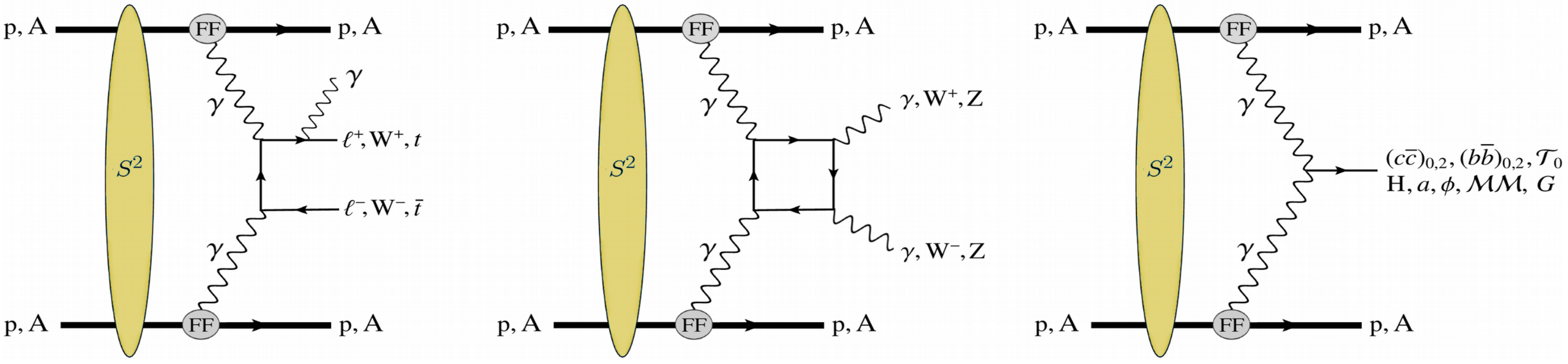
Photon-photon collisions with gamma-UPC

Workshop on the modeling of photon-induced processes

Durham, 6th June 2023

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

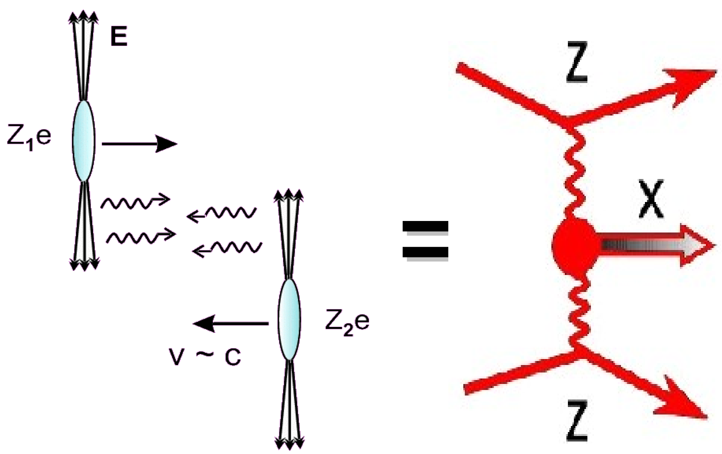


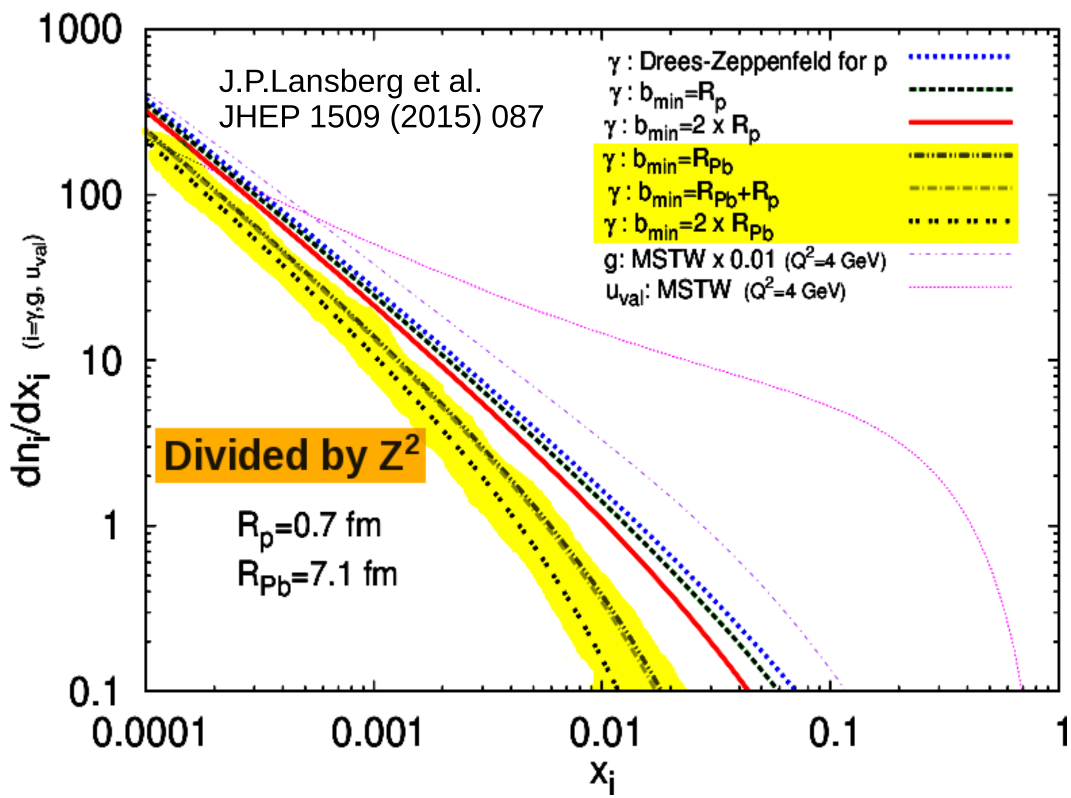
gamma-UPC: https://arxiv.org/abs/2207.03012 [JHEP 09 (2022) 248]

Plus: parametric uncertainties (with **N. Crepet**) & NLO-QED, to be submitted

Photon-photon collisions at the LHC

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

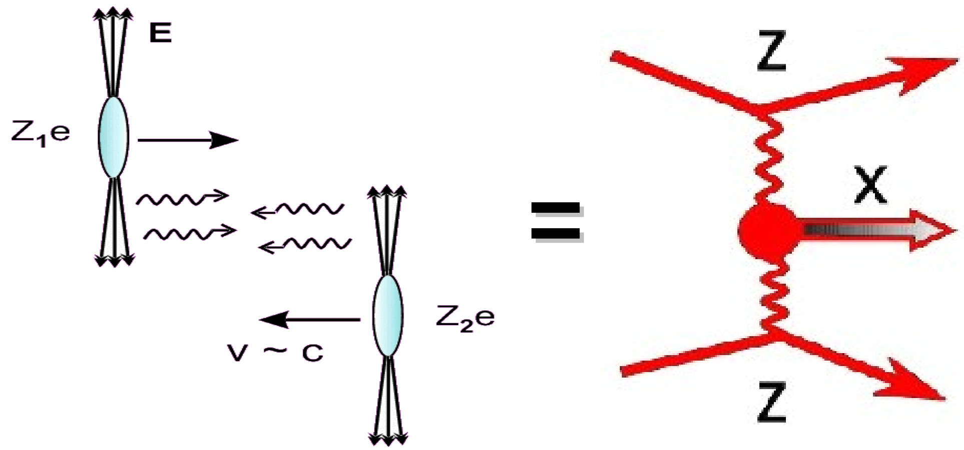




- Quasi-real γ (coherent emission): Q ~ 1/R ~ 0.06 GeV (Pb), 0.28 GeV (p)
- Maximum γ longitud. energies: $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 80 GeV (Pb), ~ 2.5 TeV (p)

Photon-photon collisions at the LHC

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



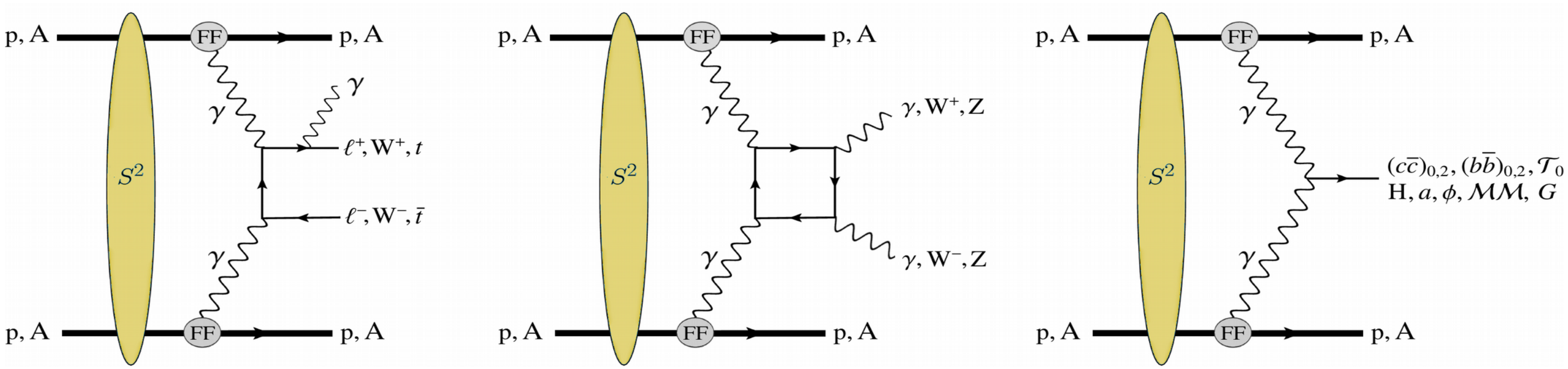
- Huge photon fluxes:
  $\sigma(\gamma\gamma) \sim Z^4$ (~$5\cdot10^7$ for PbPb)
  times larger than p,$e^{\pm}$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

- Quasi-real γ (coherent emission): Q ~ 1/R ~ 0.06 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)

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	$\tilde{\chi}^-(6)(\to \tilde{\chi}^1_0(8) + \mu^-(9) + \overline{\nu}_\mu(10)) + \tilde{\chi}^+(7)(\to \tilde{\chi}^1_0(11) + \mu^+(12) + \nu_\mu(13))$
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

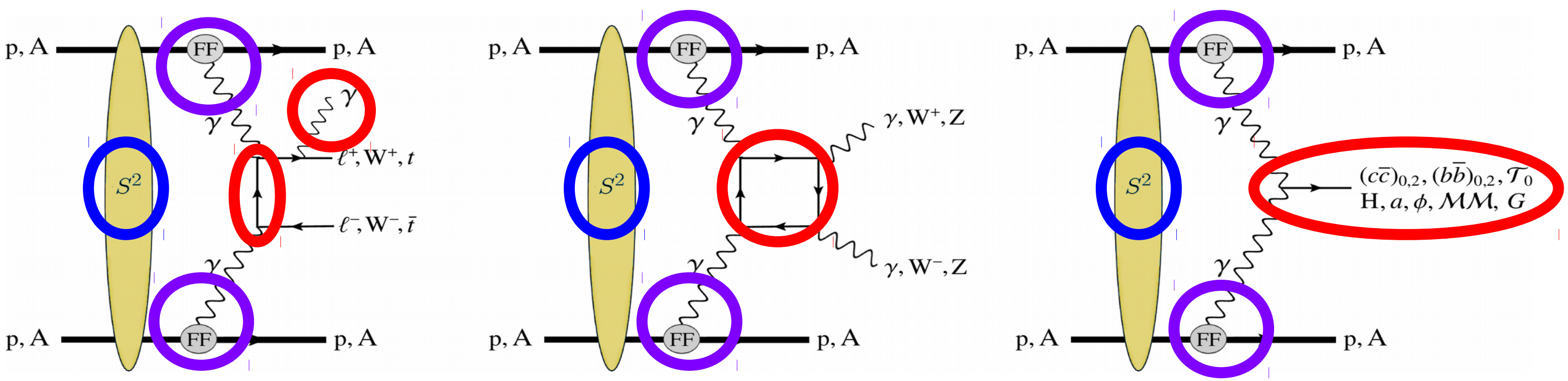
only pp UPC

UPCgen , LPAIR/CepGen

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

gamma-UPC γγ MC event generator

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



- gamma-UPC key properties:
  1) Matrix elements: MG5@NLO & HelacOnia (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

γγ EPA cross sections & survival probability

- **Cross section:**

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

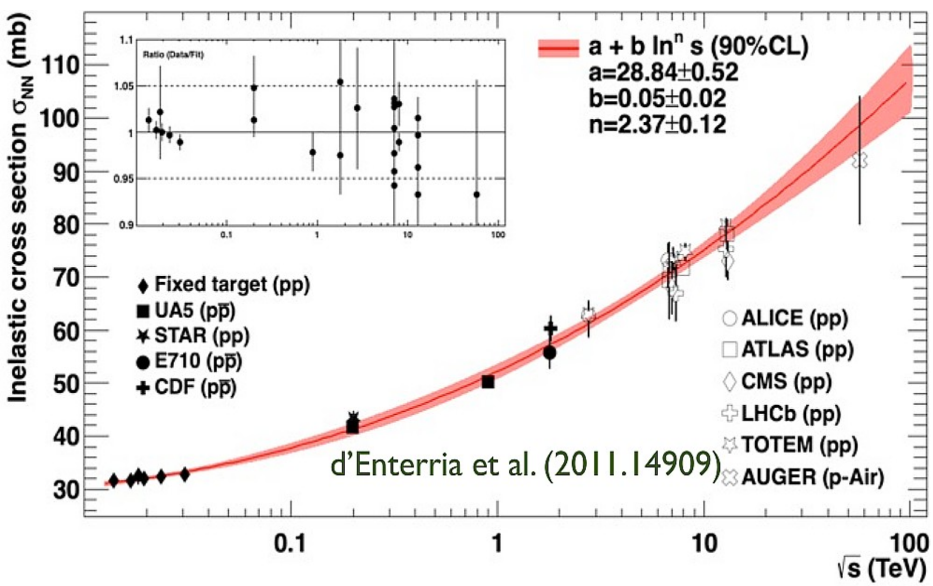
- **Effective two-photon luminosity:**

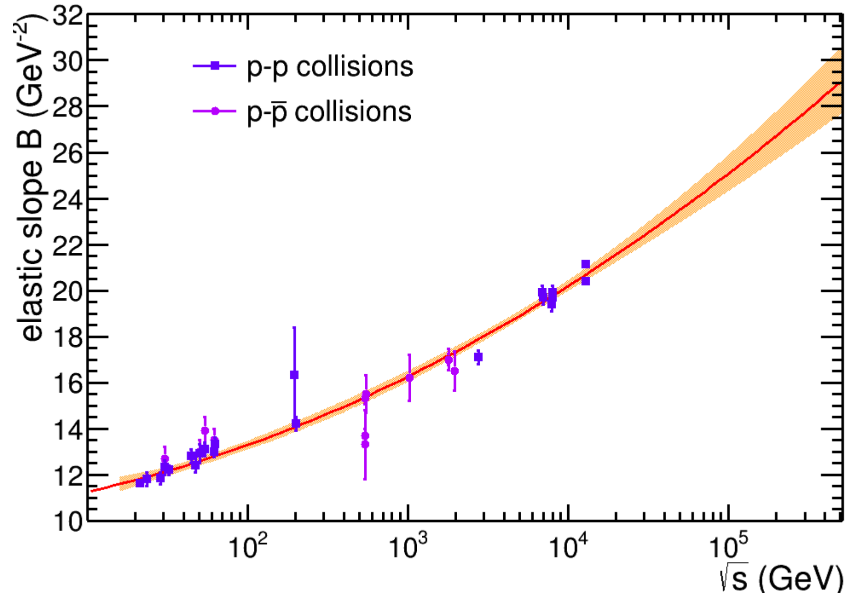
$$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, P_{\mathrm{no\,inel}}\left(|\boldsymbol{b}_1 - \boldsymbol{b}_2|\right)\; N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1},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

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

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

Parametrized proton elastic slope data:





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

- **Cross section:**

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

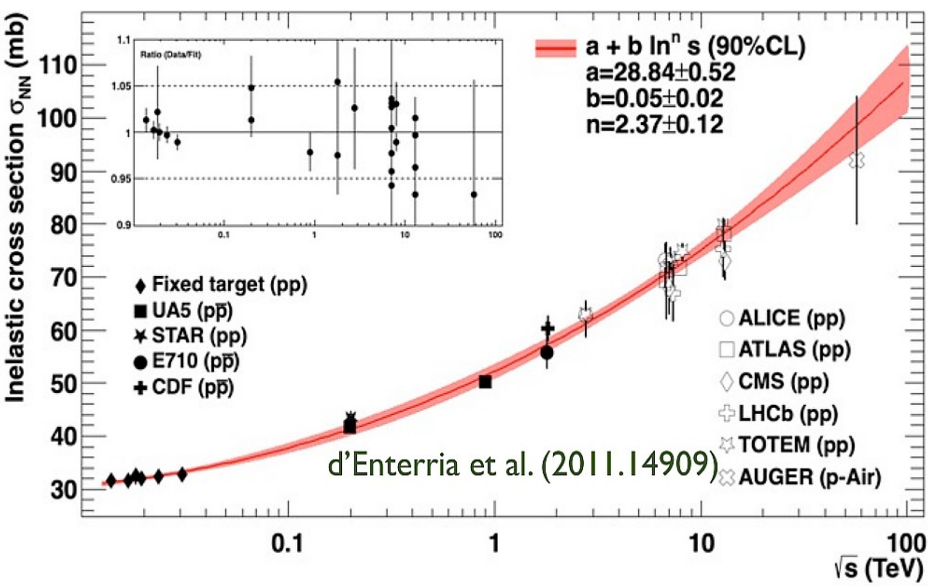
- **Effective two-photon luminosity:**

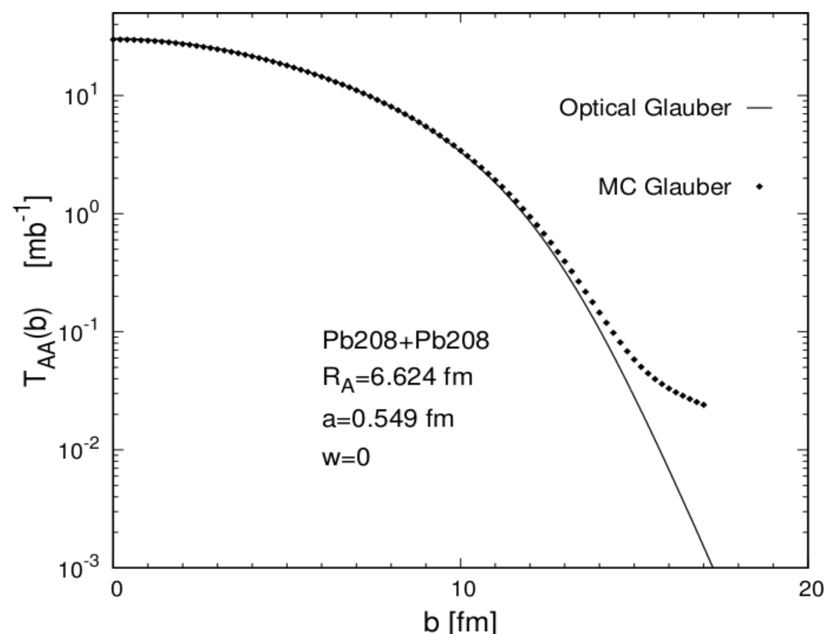
$$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, P_{\mathrm{no\,inel}}(|\boldsymbol{b}_1 - \boldsymbol{b}_2|)\ N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1},\boldsymbol{b}_1)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

- **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:





How peripheral are p-p UPCs at the LHC?

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

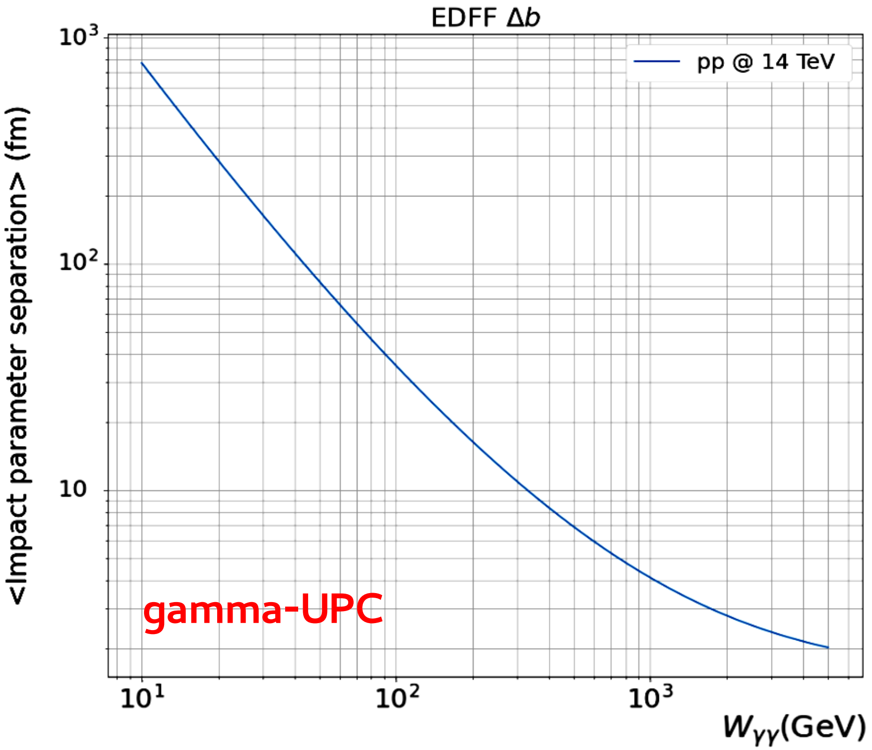
  $m_{\gamma\gamma}$<50 GeV: $\langle\Delta b\rangle$ >100 fm

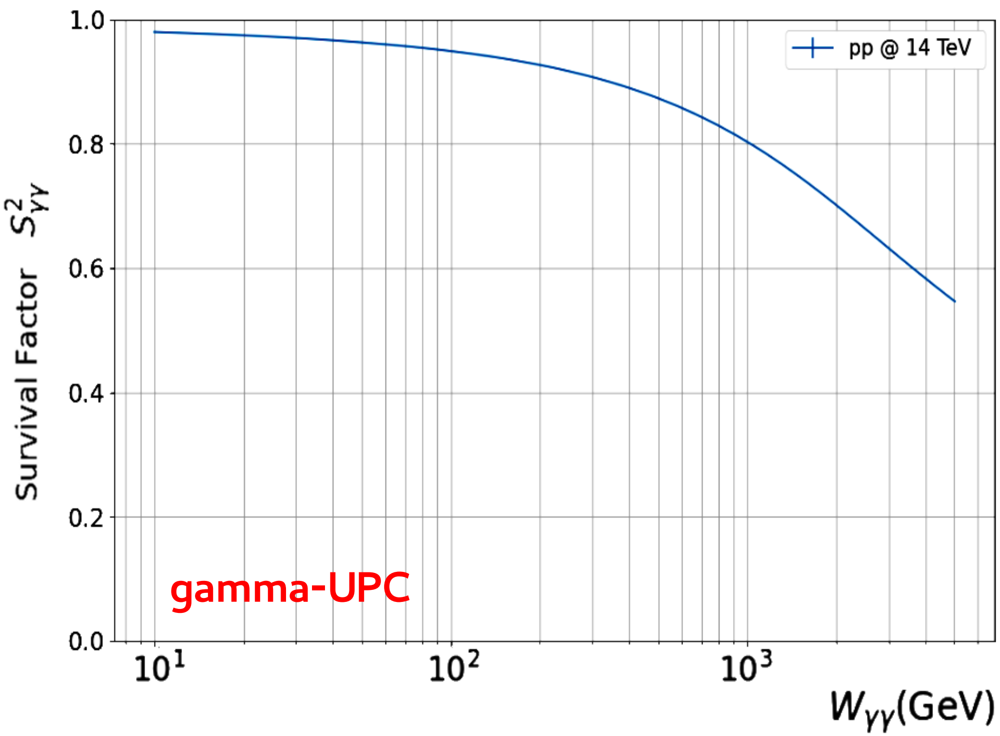
  $m_{\gamma\gamma}$>1 TeV: $\langle\Delta b\rangle$ < 4 fm

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

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

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





How peripheral are Pb-Pb UPCs at the LHC?

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

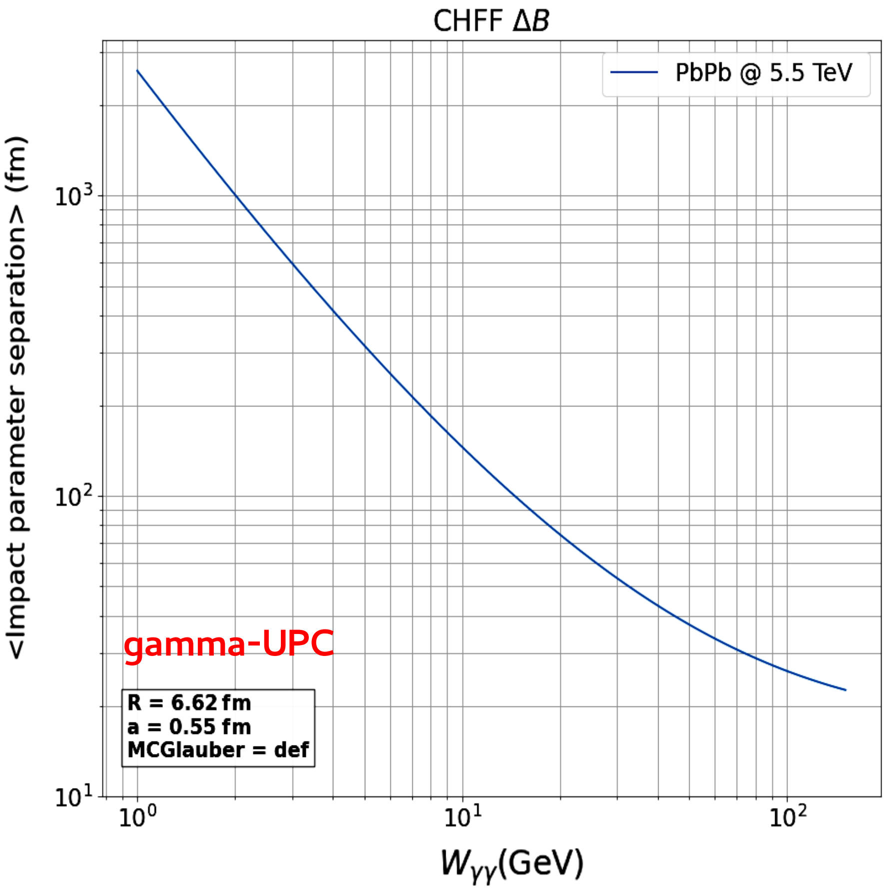
  $m_{\gamma\gamma}$<5 GeV: $\langle \Delta b \rangle$ >1000 fm

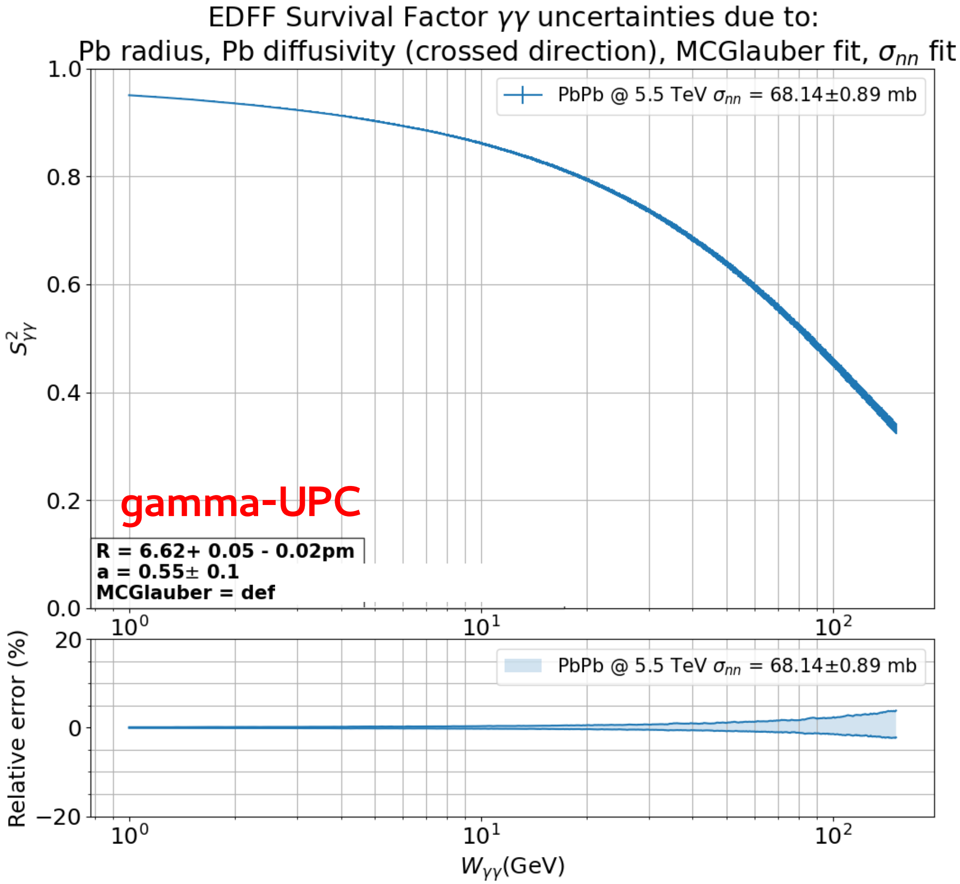
  $m_{\gamma\gamma}$>100 GeV: $\langle \Delta b \rangle$ ~20 fm

- 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%





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)**

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

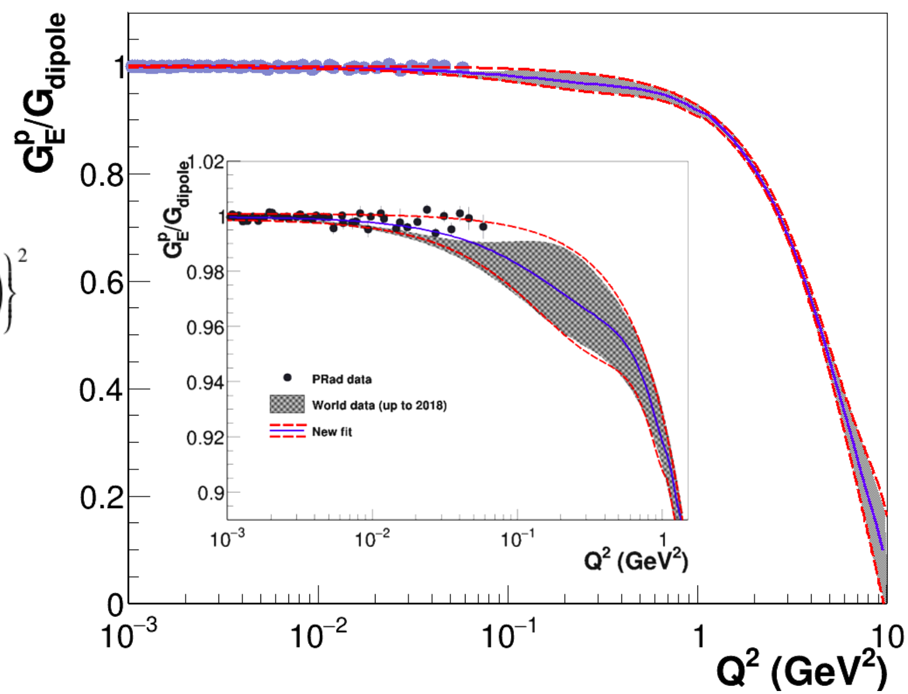
$$F_{\mathrm{ch,A}}(q) = \int \mathrm{d}^3\boldsymbol{r}e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\rho_\mathrm{A}(\boldsymbol{r}) = \frac{4\pi}{q}\int_0^{+\infty}\mathrm{d}r\rho_\mathrm{A}(r)r\sin(qr)$$

- 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 data:



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

Electric dipole form factor (EDFF)

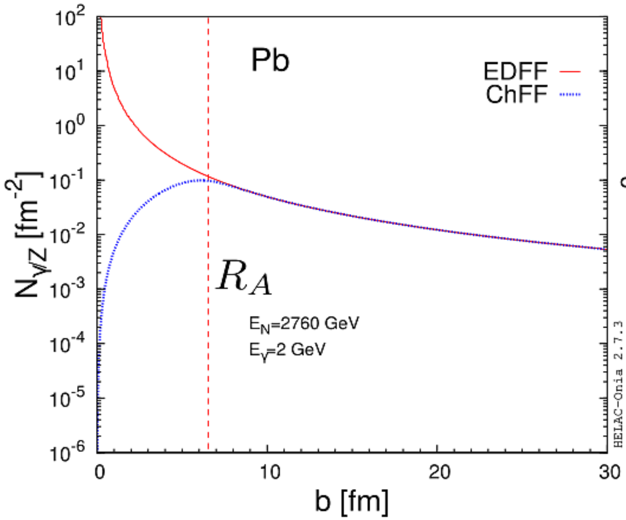
- Same as STARlight

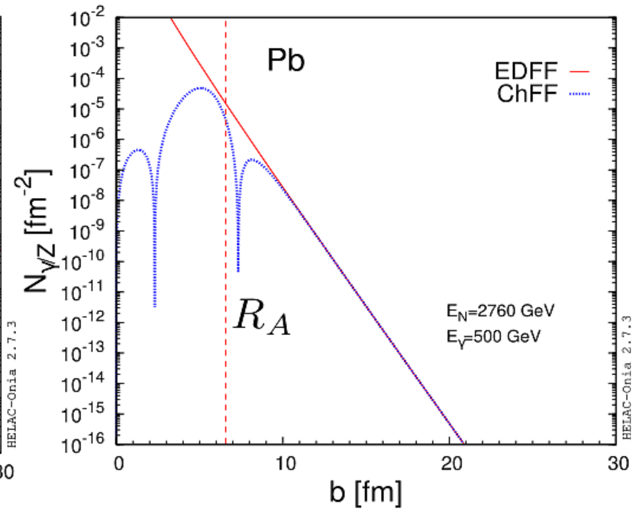
$$N^{\mathrm{EDFF}}_{\gamma/\mathrm{Z}}(E_\gamma, b) = \frac{Z^2\alpha}{\pi^2}\frac{\xi^2}{b^2}\left[K_1^2(\xi) + \frac{1}{\gamma_{\mathrm{L}}^2}K_0^2(\xi)\right] \qquad \xi = \frac{E_\gamma b}{\gamma_{\mathrm{L}}}$$

Charge form factor (ChFF)

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

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

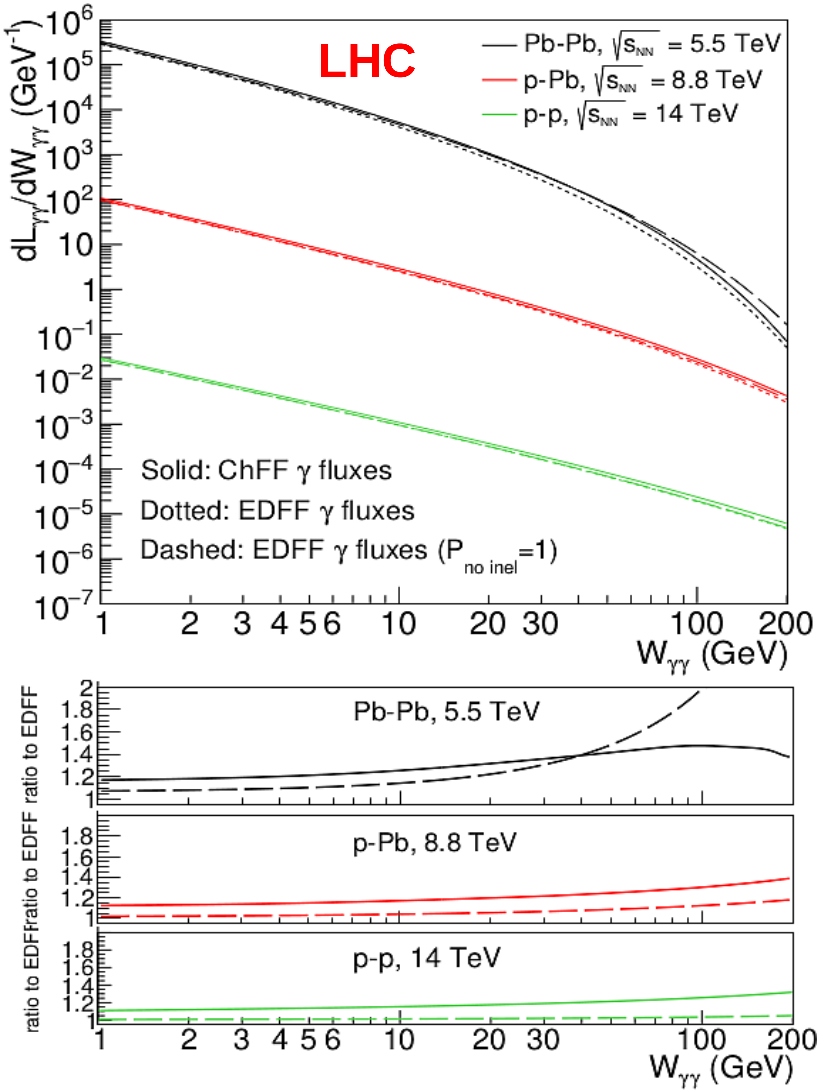


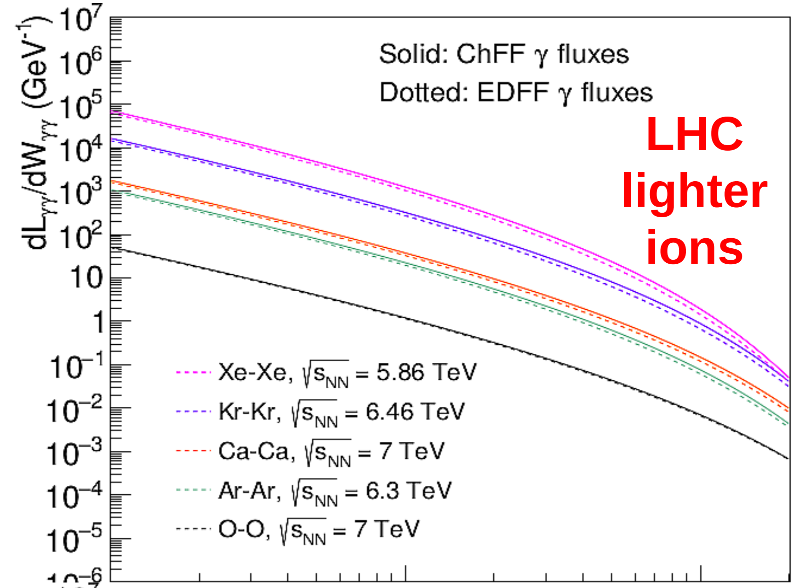


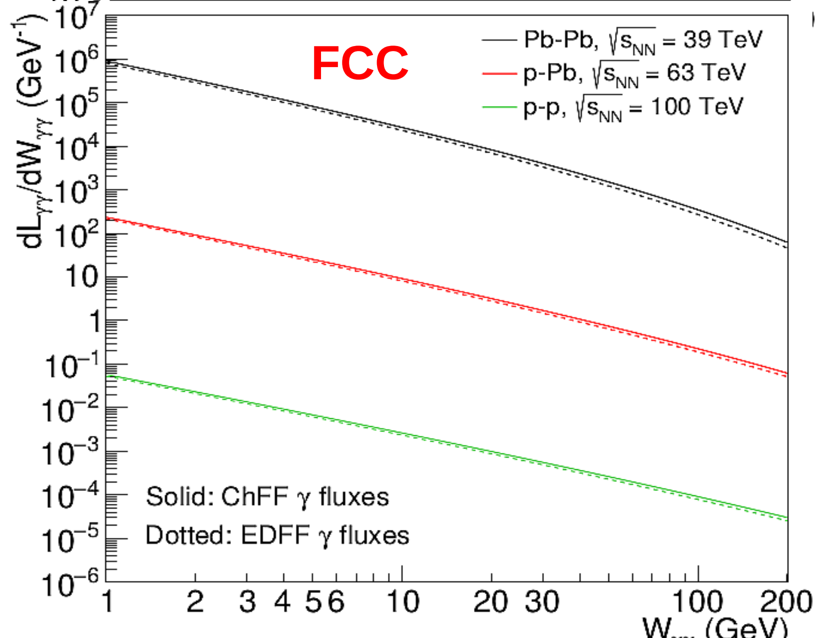
- Main difference comes from the $b < R_A$ regime
- EDFF photon number density is divergent at $b = 0$
  - Need a (arbitrary) cutoff when convoluting with ME

ChFF, much more realistic, preferred.

Effective γγ luminosities (LHC/FCC)



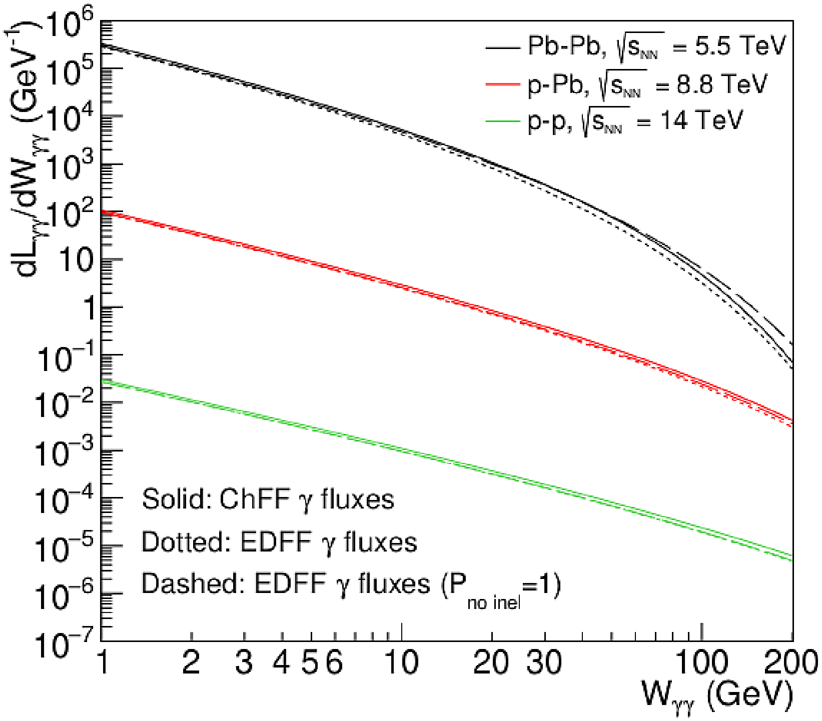


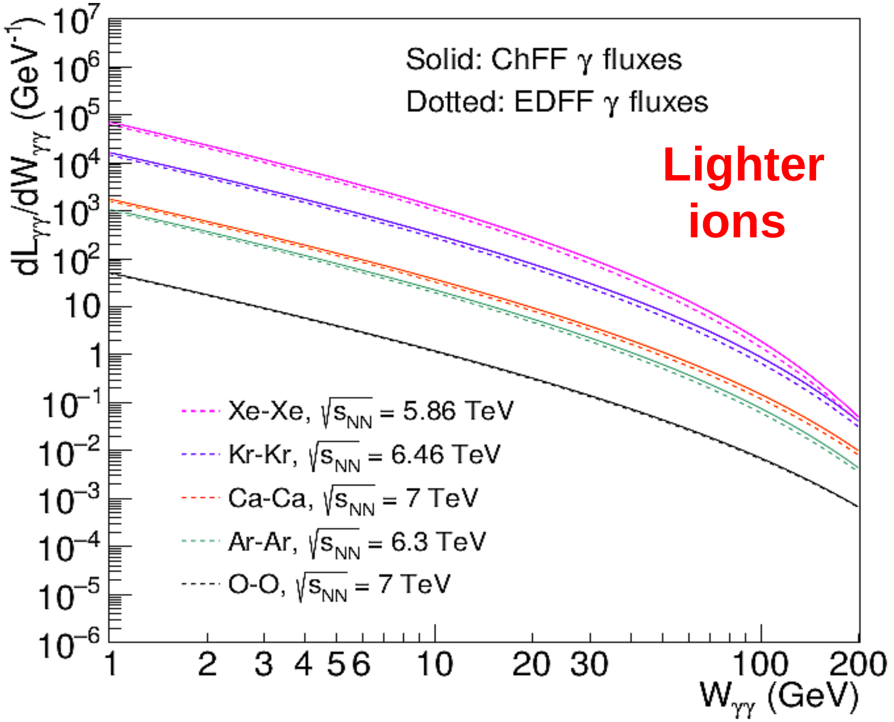


- ChFF/EDDF γ-fluxes differences (pp–PbPb):
  Low masses: ~7–15%. High masses: 20–50%

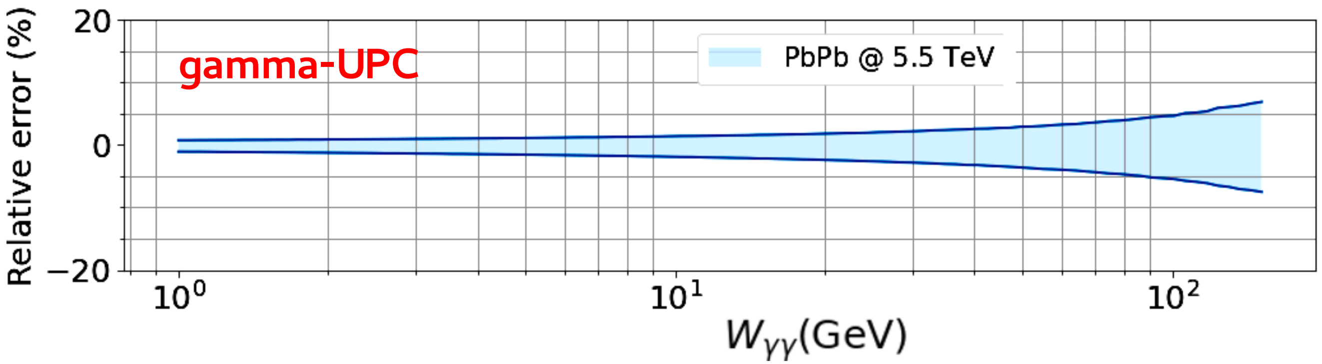
Effective γγ luminosities (LHC)

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





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



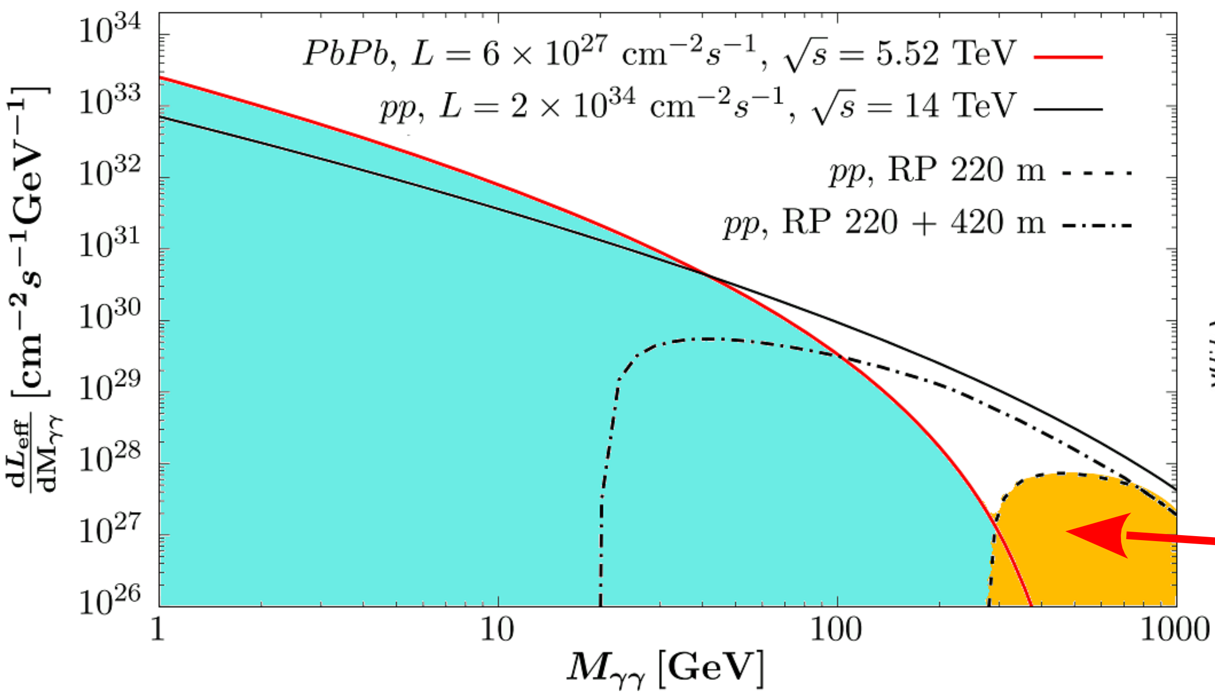
ChFF γ spectra

Glauber MC:

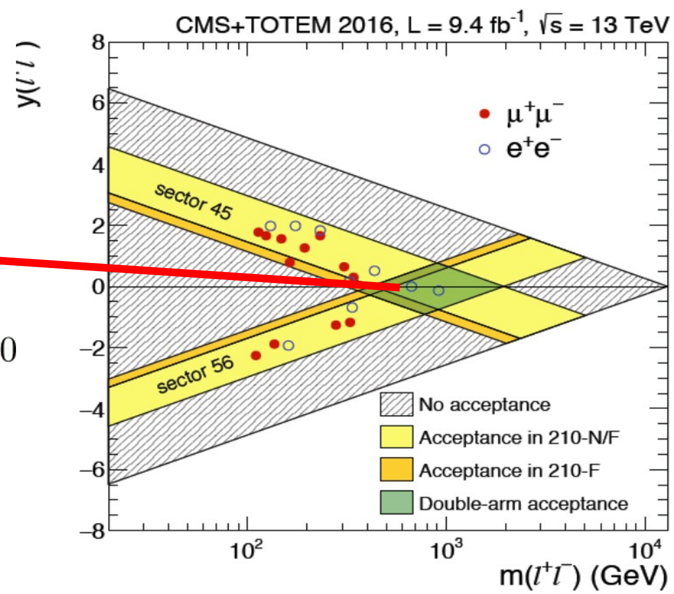
Variations of R,a,σ_{NN}

Effective γγ luminosities (LHC): pp vs. PbPb

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

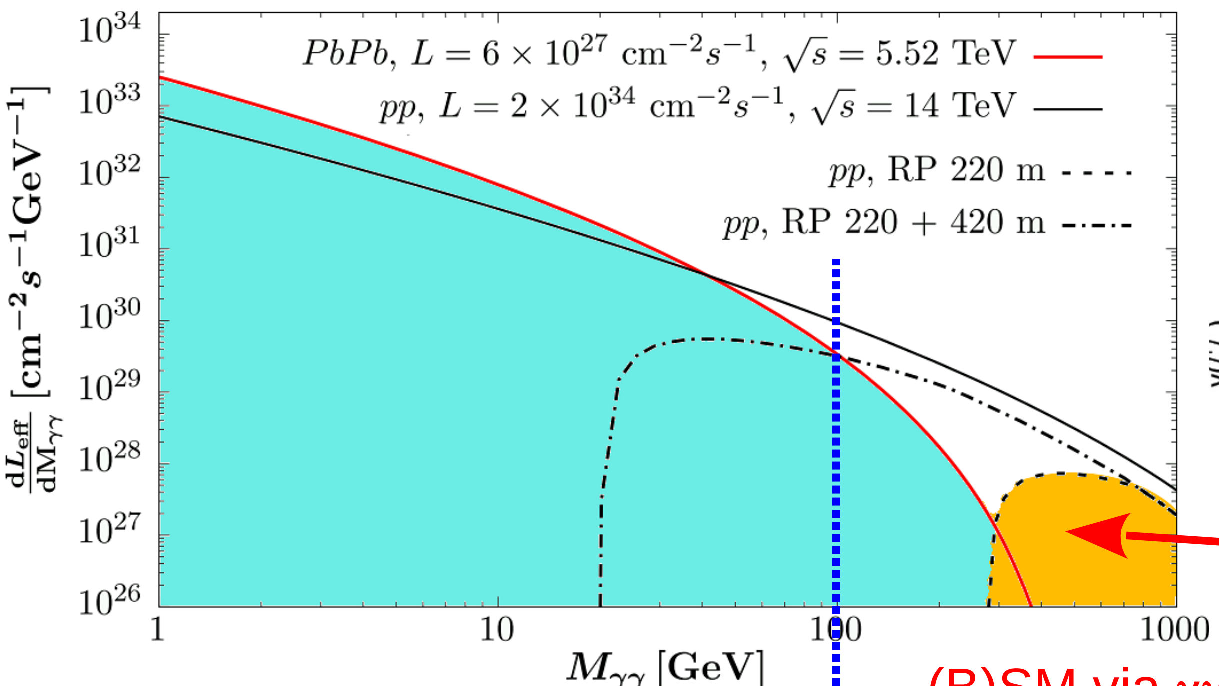


- PPS p-p acceptance vs. central mass & y

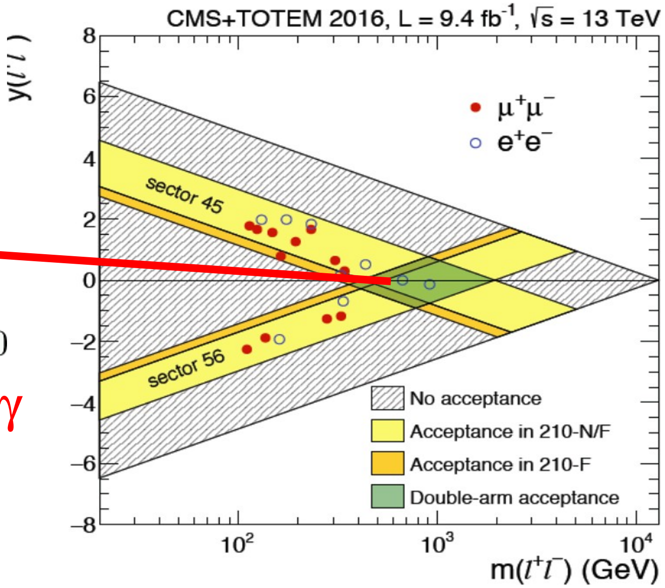


Effective γγ luminosities (LHC): pp vs. PbPb

- Thanks to Z^4 boost, Pb-Pb γγ lumis (per collision) well above the p-p ones.
  - Up to $W_{\gamma\gamma} \approx 30$ GeV, accounting for much larger p beam luminosity
  - Up to $W_{\gamma\gamma} \approx 300$ 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

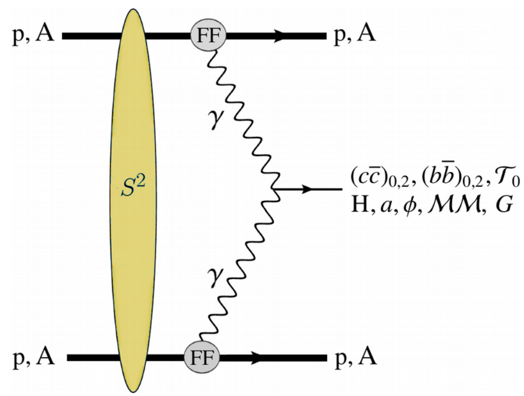


Rule of thumb: (B)SM via γγ in Pb-Pb ⇐ m_X~100 GeV ⇒ (B)SM via γγ in p-p with tagged p's

Example γγ cross sections (LHC)

- C-even SM resonances (9 states of 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

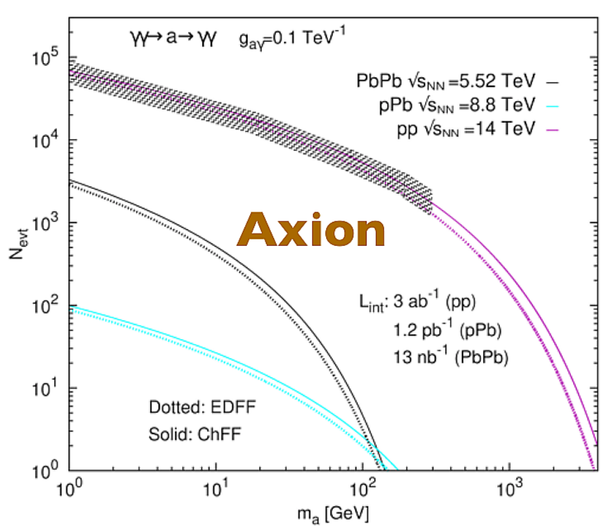


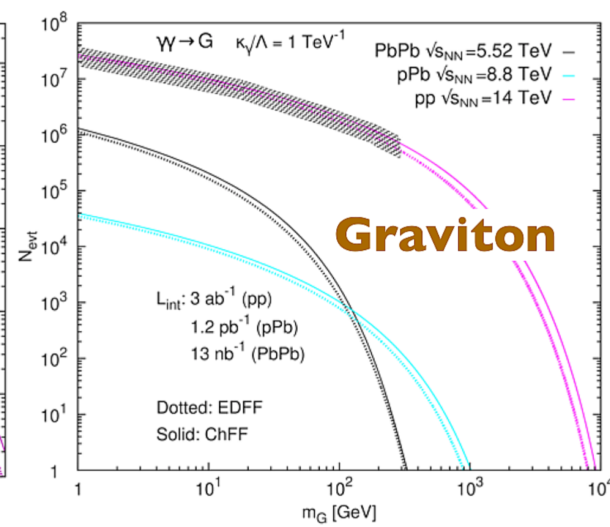
– Most low-mass resonances accessible in PbPb (pp without pileup) with low-p_T ch.part PID & γ reco.

– Higgs boson: no significance

- C-even **BSM** resonances:

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

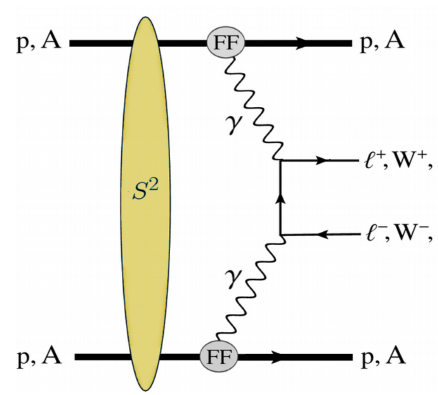




Example γγ cross sections (LHC)

- **Double fermions**, e.g. $\gamma\gamma\rightarrow$ ttbar (note **NLO** in QCD):

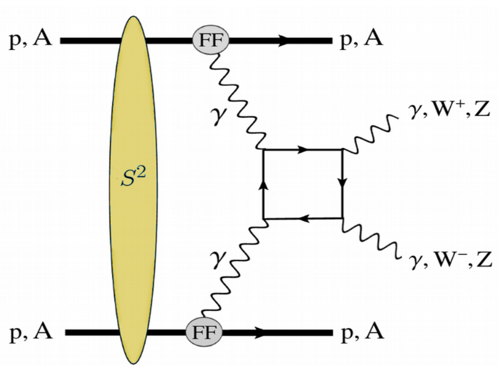
Process: $\gamma\gamma \rightarrow t\bar{t}$ Colliding system,	gamma-UPC $\sigma_{\rm NLO}$ EDFF	 ChFF	 average
p-p at 14 TeV	$0.198^{+0.004}_{-0.003}$ fb	$0.287^{+0.005}_{-0.004}$ fb	$0.242^{+0.005}_{-0.004} \pm 0.045$ fb
p-Pb at 8.8 TeV	$36.5^{+0.8}_{-0.7}$ fb	$59.3^{+1.3}_{-1.1}$ fb	$48^{+1.0}_{-0.9}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



- **Double quarkonia**:

Process: $\gamma\gamma \rightarrow J/\psi J/\psi$ 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

- **Double bosons** (loop induced):



Loop-induced rare processes in SM (BSM potential)

Process: $\gamma\gamma \rightarrow Z\gamma$ 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: $\gamma\gamma \rightarrow ZZ$ 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

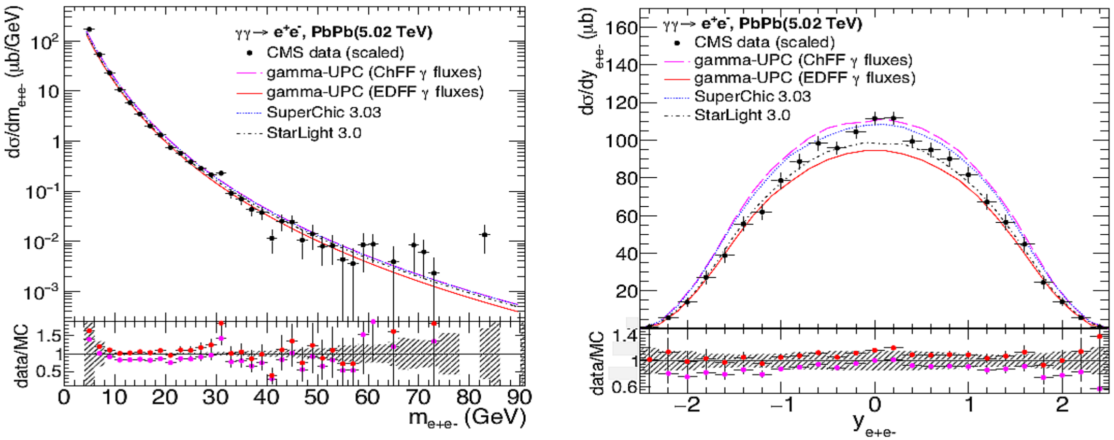
$$\mathcal{L} \supset \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}\left[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}\right]. \quad \sigma = \sigma_{\rm SM} + \left(\frac{c_{WWW}}{\Lambda^2}\times 1\,\mathrm{TeV}^2\right)\sigma_{WWW}$$

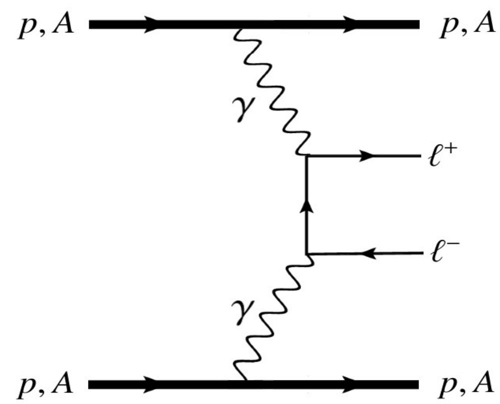
Process: $\gamma\gamma \rightarrow W^+W^-$ Colliding system, c.m. energy	gamma-UPC average $\sigma_{\rm SM}$	 σ_{WWW}
p-p at 14 TeV	63 ± 11 fb	53 ± 8 ab
p-Pb at 8.8 TeV	26 ± 5 pb	28 ± 5 fb
Pb-Pb at 5.52 TeV	277 ± 44 pb	394 ± 64 fb

Exclusive dileptons: Data vs. gamma-UPC

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

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





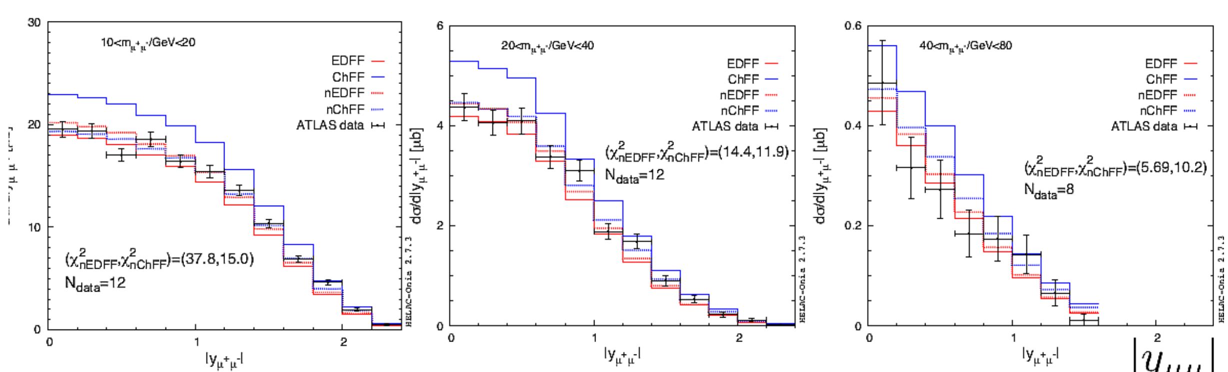
■ Generic conclusions:

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

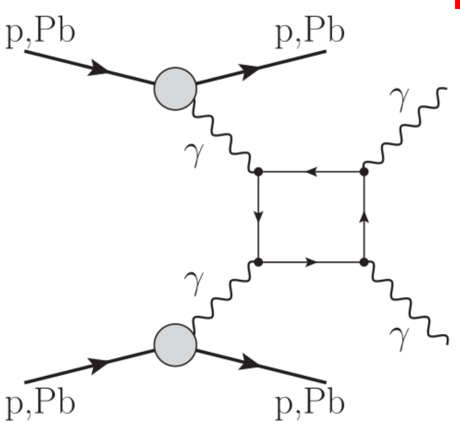
Norm.: EDFF better than ChFF
Shape: ChFF better than EDFF

■ Exclusive dimuons $\gamma\gamma \to \mu^+\mu^-$:

Process, system	ATLAS data [19]	gamma-UPC σ EDFF	gamma-UPC σ ChFF	gamma-UPC σ average	STARLIGHT σ	SUPERCHIC σ
$\gamma\gamma \to \mu^+\mu^-$, 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 scattering: Data vs. gamma-UPC



- LbL scattering $\gamma\gamma \rightarrow \gamma\gamma$ (1[st] proposed in PRL 111 (2013) 080405):

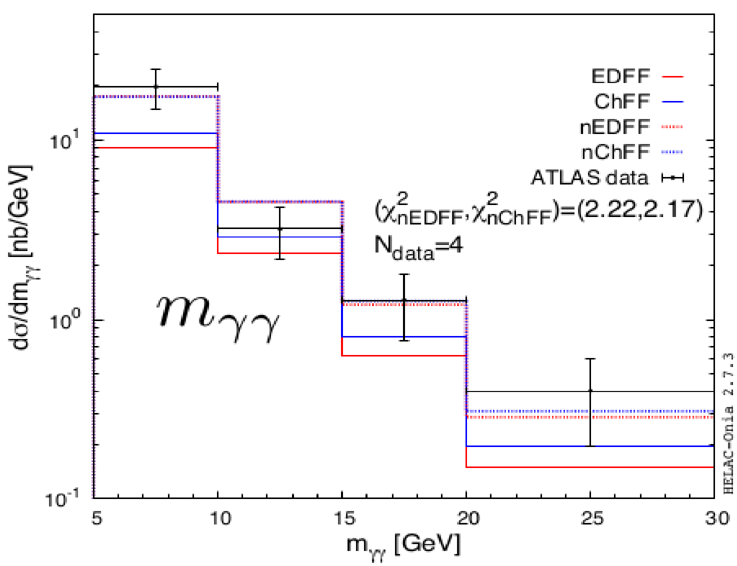
Integrated fiducial cross-section:

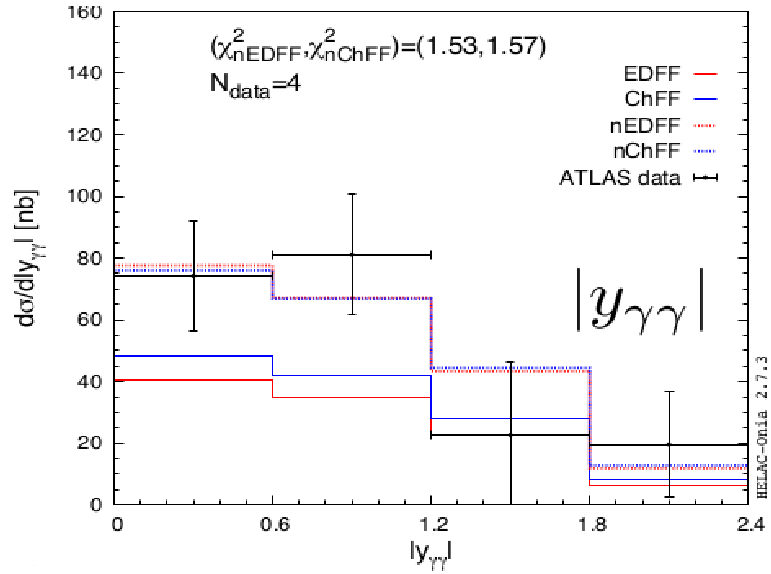
- Measurement:

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

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

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

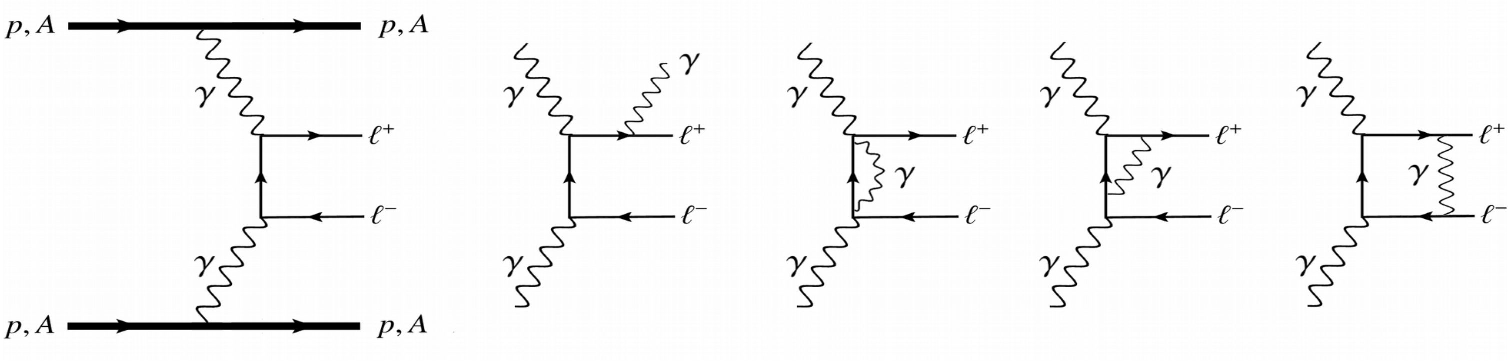




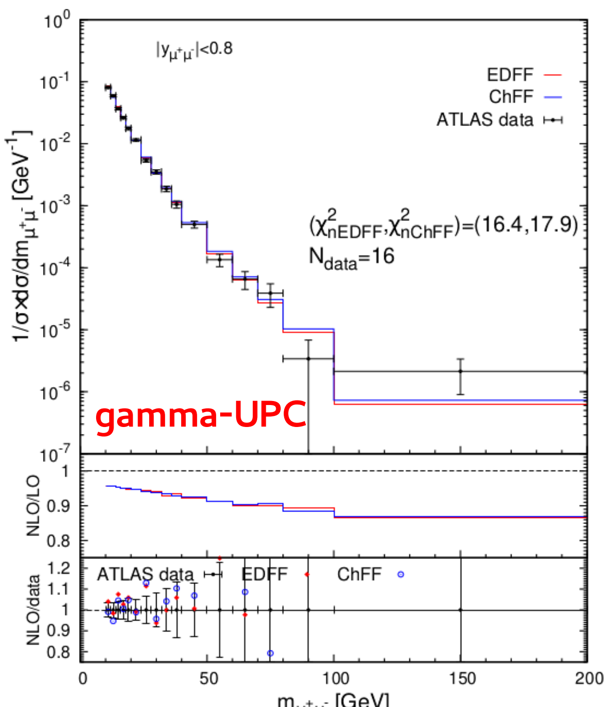
- Shape well reproduced except lowest mass: Data is 2σ larger than theory
- Do we really control all (non)exclusive backgrounds at low masses?

γγ collisions: NLO QED corrections

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

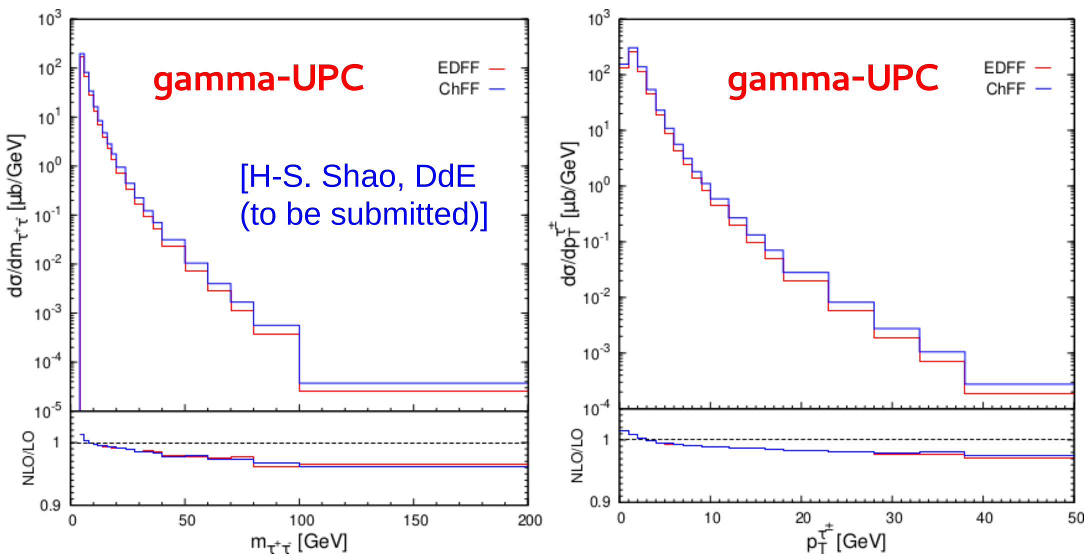


- Impact of virtual & real NLO QED corrections on exclusive dilepton production:



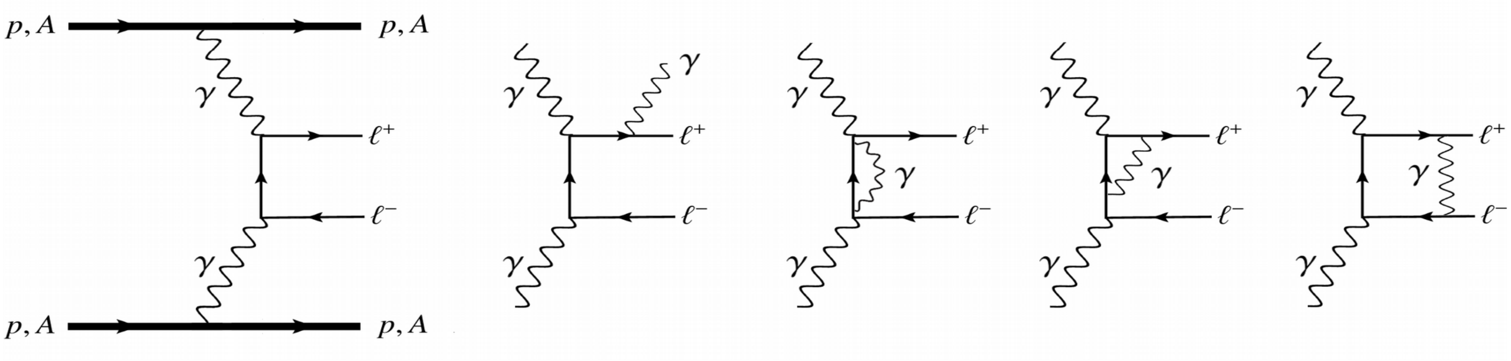
Dimuon: x-section reduced by up to ~10% at high mass

Ditau: x-section increases/decreases by few % at low/high masses: Relevant for accurate (g-2) extractions!

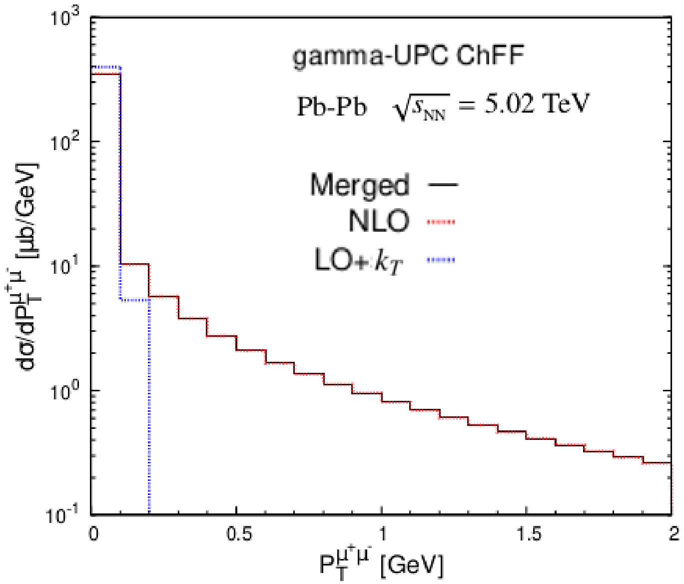


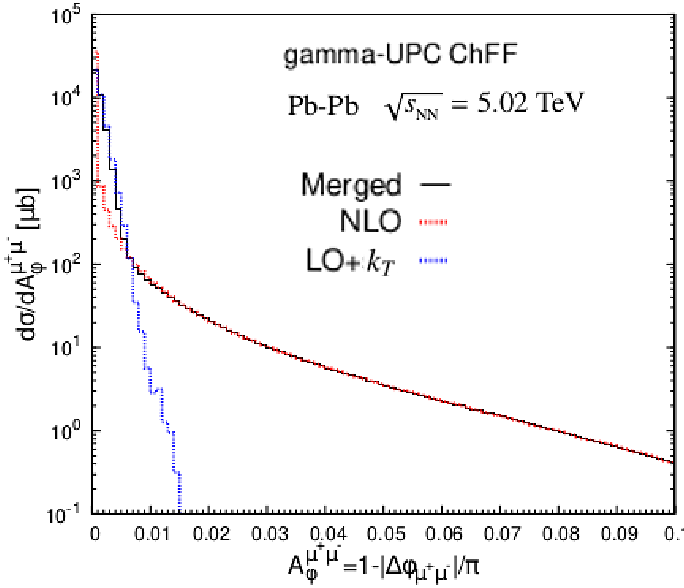
γγ collisions: NLO QED corrections

- 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):





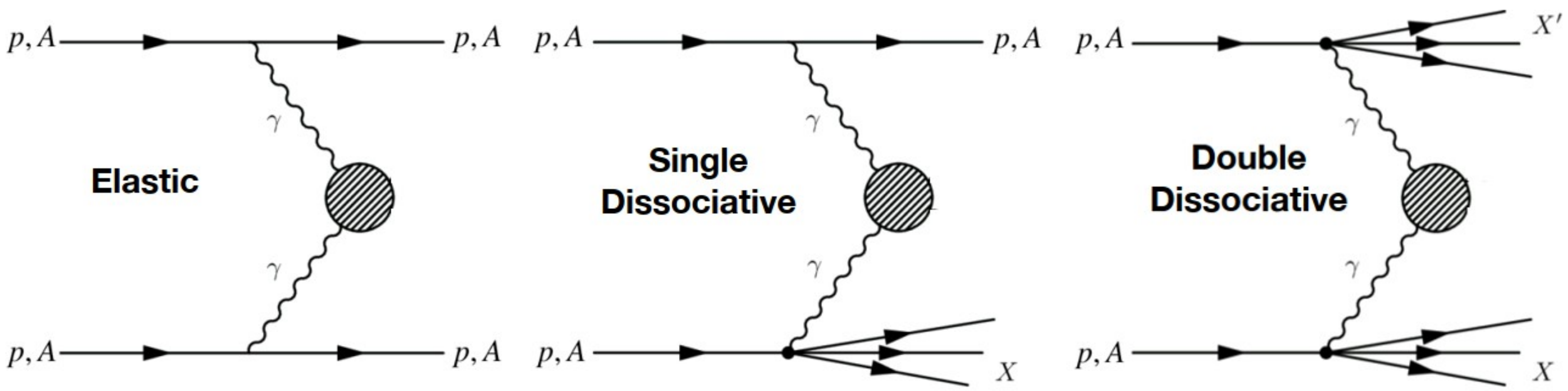
[H-S. Shao, DdE (to be submitted)]

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

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

γγ collisions: el.-el., inel-el., inel.-inel.

- Photons emitted coherently by p/A or incoherently by their constituent quarks/protons:



- gamma-UPC codes only the fully coherent γ flux. For heavy-ions, the most important, by far, x-sections: el-el : inel-el : inel-inel = Z^4 : Z^2 : Z = 1 : 1/6.7e3 : 1/45.e6 for PbPb

- For proton-proton collisions:

  - Cross section of 3 processes similar (depending on central system produced).
  - Incoherent photon flux available via γ PDF: LuxQED, MMHT2015qed, CT18lux, NNPDF31lux-QED.
  - Inel.-el: gamma-UPC+MG5 with ChFF (lpp2) + γ PDF (lpp1) in ppl. possible, but survival factor should be properly implemented.
  - Inel-inel: One can always run MG5-standalone with p beams selecting lux-type γ PDF

Questions from the organizers

- *What is the maintainability of gamma-UPC? Personpower?*

  gamma-UPC is maintained by H.-S. Shao. http://cern.ch/hshao/gammaupc.html
  Currently, H-S Shao, DdE, N.Crepet testing/extending it. More help welcome :)

- *Are there specific libraries/tools behind the choice of fortran?*

  No specific fortran libs, just choice of leading programmer

- *How do you see the code developing in the future?*

  Extended gradually to keep up state-of-the-art. Photoproduction (γ-p,A), inelastic first, then exclusive, could be added.

- *Did you consider the possibility of using LHAPDF?*

  LHAPDF already for γ PDF. Elastic γ fluxes in LHAPDF not enough for UPCs: one needs survival factor S^2

- *Any information about when MG 3.5.0 is coming out?*

  MG 3.5.0 contains only gamma-UPC v1.0, not latest additions.
  gamma-UPC is decoupled from MG. We'll provide gamma-UPC+MG5 3.X.Y

- *Currently only the elastic component is implemented, can you give more info about plans for modeling of the dissociative part?* (See previous slide)
- *What measurements would improve the modeling of the dissoc. component?*

  Events w/ low pileup & 1-,2-proton tag, & reduced |P-induced final state helpful

gamma-UPC outlook & summary

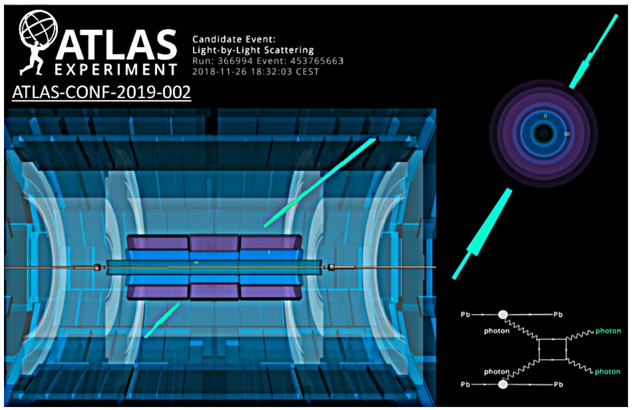
- UPCs at the LHC provide the largest x-sections ever studied for γγ colls. over $W_{\gamma\gamma}$= 1–2000 GeV: Unique (B)SM physics open for study. Increasing number of precise measurements.
- gamma-UPC is a new versatile code to generate any γγ process in UPCs with protons & ions. Interfaced to MG5@NLO & HelacOnia.
- Recent developments (v1.0 → v1.2 → v1.3, in preparation):
  - Photon k_T smearing (lhe_ktsmearing_UPC.py script run on LHE file)
  - Proton kinematics for transport to & tagging at RPs spectrometers
  - NLO QED corrections
  - Parametric uncertainties
  - Non-exclusive collisions possible
- Future developments:
  - Semi-exclusive W/Z-photon 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!

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

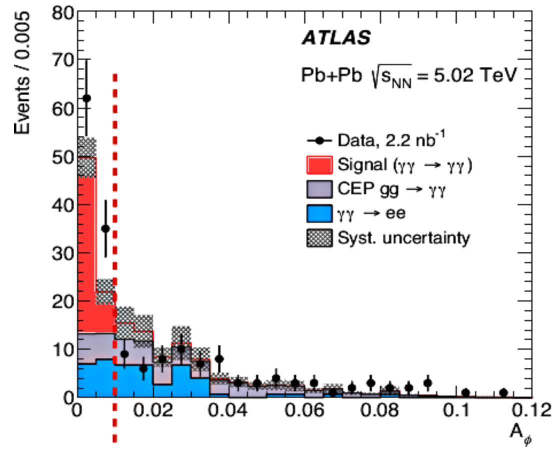
Backup slides

Observation of $\gamma\gamma \rightarrow \gamma\gamma$ (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]

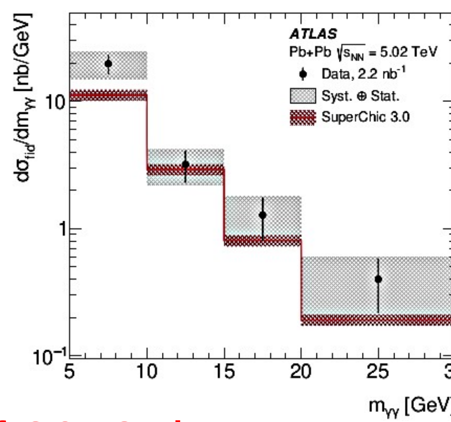


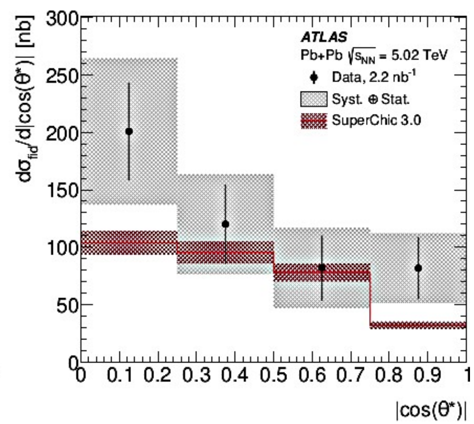
Observed: 97 evts
Expected: 45 signal
+ 27 backgd.

[ATLAS, arXiv:2008.05355]

- Combination of ATLAS (2015+2018) data, compared to LbL prediction:

  - LbL observation: Signif. = 8.8σ
  - Fiduc. x-section $\sigma(\gamma\gamma\rightarrow\gamma\gamma)$ = 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 $m_{\gamma\gamma}$?

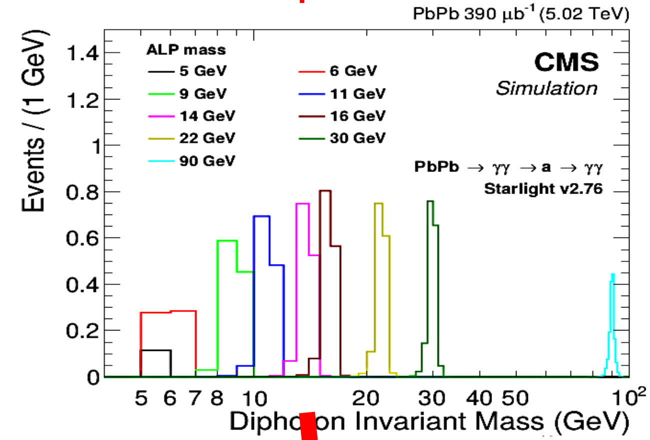


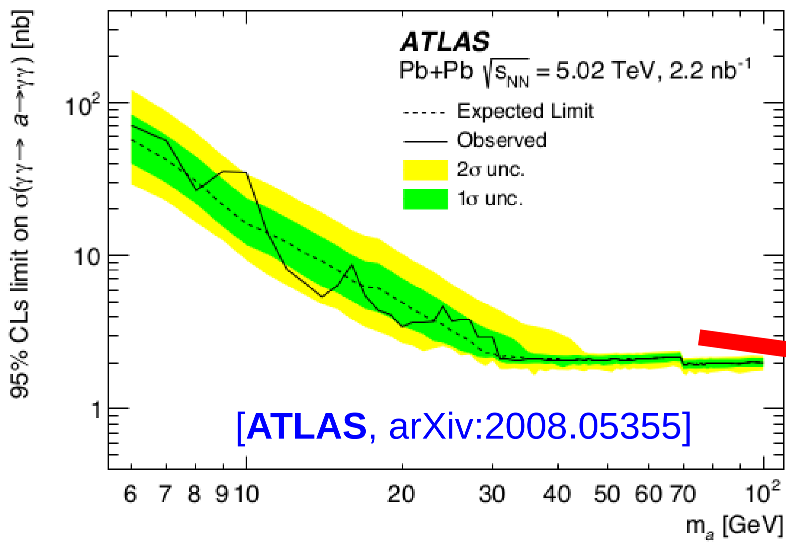


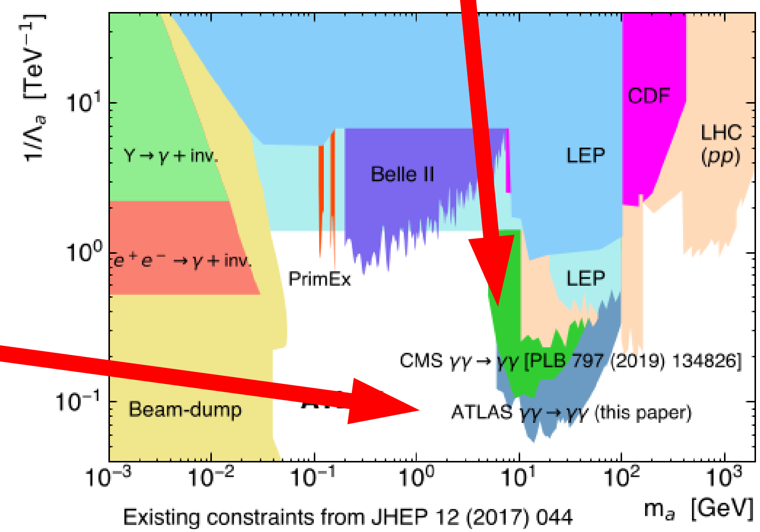
- Ongoing detailed CMS analysis of 2018 data.

ALPs searches via $\gamma\gamma \to a \to \gamma\gamma$ (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 $\sigma_{\gamma\gamma\to a\to\gamma\gamma}$ extracted
    - Cast into limits on $a\gamma\gamma$ coupling ($1/\Lambda_a$) assuming BR($a\to\gamma\gamma$)=1 [**CMS**, PLB797 (2019) 134826]
    - Reco effic.: ~20% (6 GeV), ~45% (>40 GeV). ALP width dominated by exp. resolution.



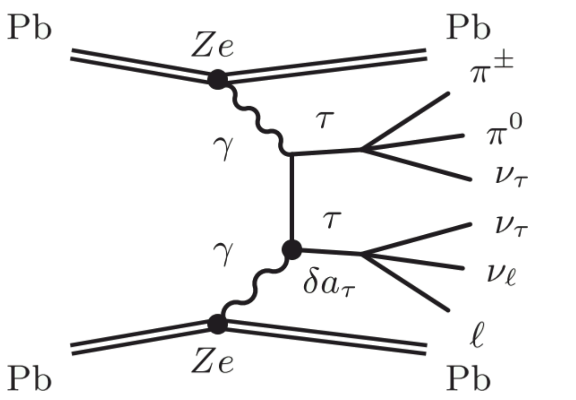




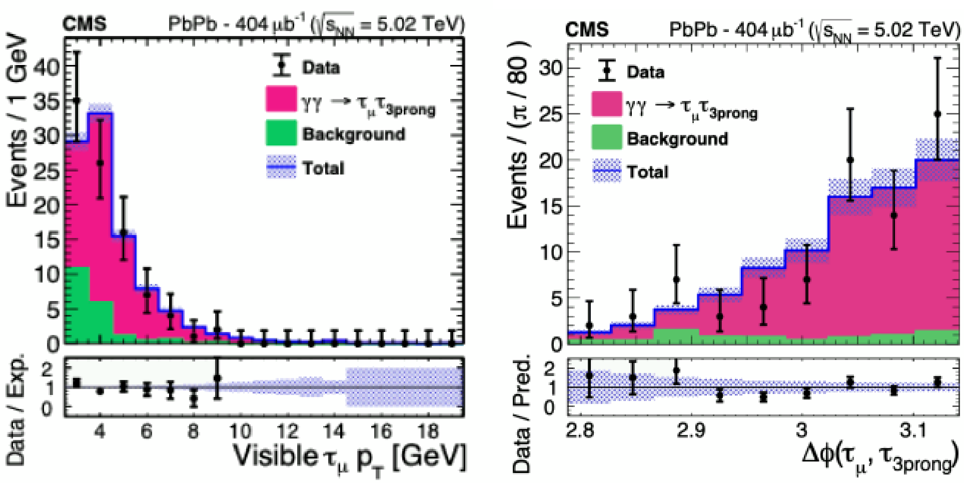
- Most stringent limits to date on ALPs over m_a = 5–100 GeV
- $\sigma(\gamma\gamma \to a \to \gamma\gamma)$ > 2–70 nb excluded at 95% C.L. over that mass interval.

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

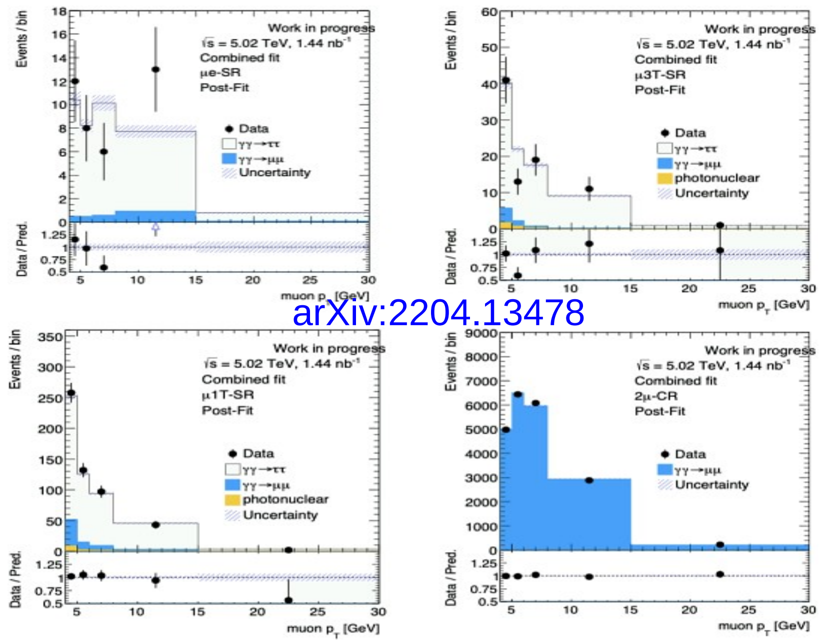
- Anomalous tau-lepton magnetic moment only mildly constrained from $\gamma\gamma \to \tau\tau$ studies at LEP times: $(g\text{–}2)_\tau$ = -0.05 – 0.03



- 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

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

$\gamma\gamma \rightarrow \tau\tau$ production

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

- First observation of $\gamma\gamma \rightarrow \tau\tau$ 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: $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$