Latest developments on γγ collisions modeling with gamma-UPC(*)

LHC Forward Physics Workshop

CERN, 13th December 2024

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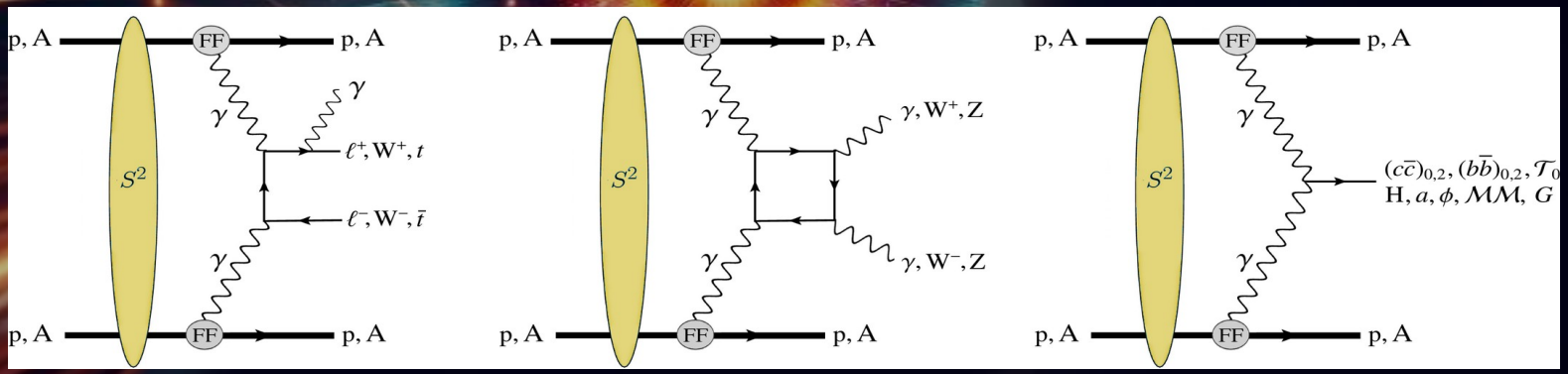
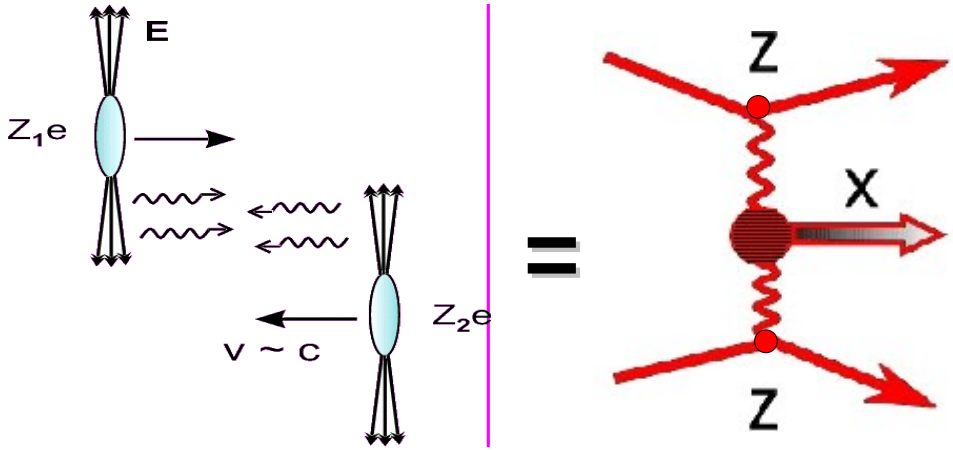


(*) H.-S. Shao & Dd'E: arXiv: 2407.13610 [hep-ph]
N. Crepet, H.-S. Shao, Dd'E: arXiv: 2407.13610 [hep-ph]

LHC = unique photon-photon collider

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



- Huge photon fluxes:
  $\sigma(\gamma\gamma) \approx Z^4$ ($\approx 5 \cdot 10^7$ 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): $Q \approx 1/R \approx 0.03$ GeV (Pb), 0.28 GeV (p)
- Max. (longitudinal) γ energies: $\omega < \omega_{max} \approx \frac{\gamma}{R} \approx 80$ GeV (Pb), 2.5 TeV (p)

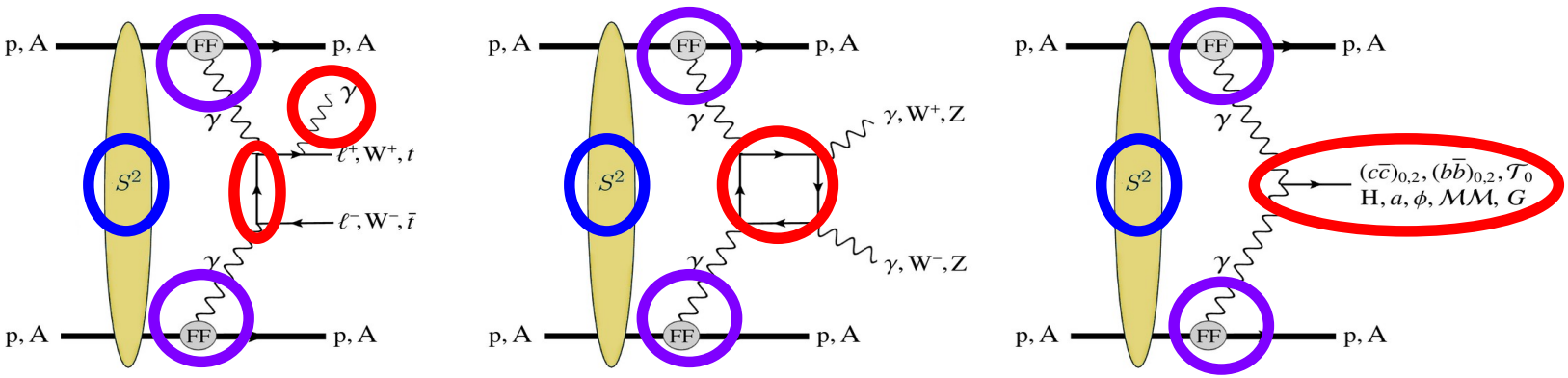
System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$E_{beam1} + E_{beam2}$	γ_L	R_A	E_γ^{max}	$\sqrt{s_{\gamma\gamma}^{max}}$
Pb-Pb	5.52 TeV	5 nb^{-1}	2.76 + 2.76 TeV	2960	7.1 fm	80 GeV	160 GeV
p-Pb	8.8 TeV	1 pb^{-1}	7.0 + 2.76 TeV	7450, 2960	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV
p-p	14 TeV	150 fb^{-1}	7.0 +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

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

- gamma-UPC features: [H.S.Shao/DdE, JHEP09(2022)248. http://cern.ch/hshao/gammaupc.html

  - Arbitrary (B)SM & $Q\bar{Q}$ matrix elements with MG5@NLO & HelacOnia
  - N γ/gluon FSR out-of-the-box. Extendable to NLO QCD & EW
  - LHE output: FSR+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 $T_{AA}(b)$ (and optical Glauber) eikonal

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

- gamma-UPC features: [H.S.Shao/DdE, JHEP09(2022)248. http://cern.ch/hshao/gammaupc.html

  - Arbitrary (B)SM & $Q\bar{Q}$ matrix elements with MG5@NLO & HelacOnia
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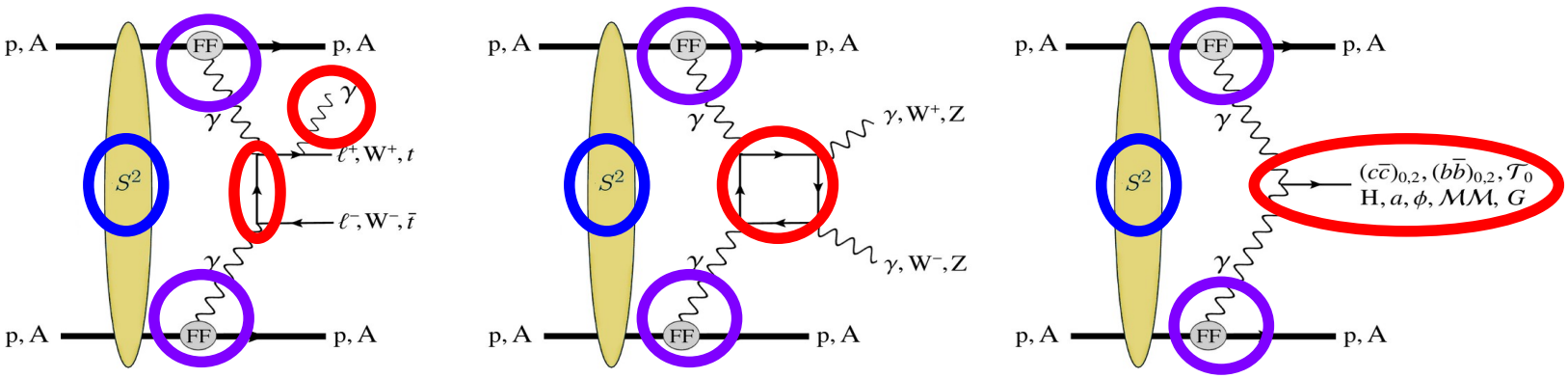


- gamma-UPC latest developments:

  4) ME: NLO QED corrections for $\gamma\gamma \to \mu^+\mu^-$, $\tau^+\tau^-$ (also before: $\gamma\gamma \to \gamma\gamma$ & $\gamma\gamma \to t\bar{t}$ at NLO)

  5) Improved proton γ flux at high Q^2. Inclusion of low Q^2 in γ fluxes (k_T smearing)

  6) Incorporation of mutual e.m. excitation of ions and XnYn fwd. neutron emission

Heavy-ion form factors & γ fluxes: ChFF vs. EDFF

Electric dipole form factor (EDFF)

- Same as STARlight

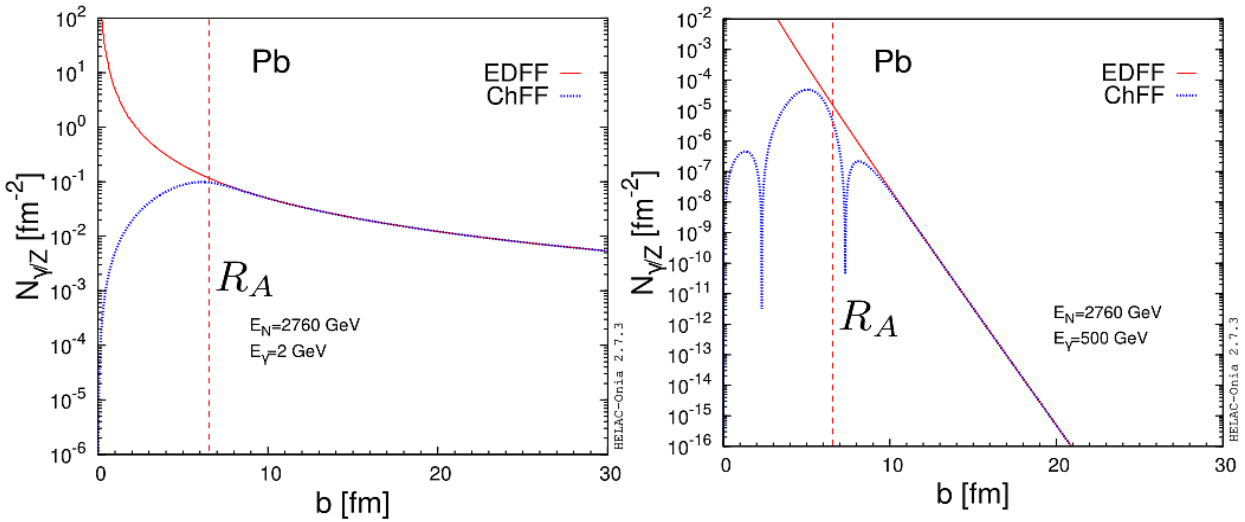
$$N_{\gamma/\mathrm{Z}}^{\mathrm{EDFF}}(E_\gamma, b) = \frac{Z^2\alpha}{\pi^2}\frac{\xi^2}{b^2}\left[K_1^2(\xi) + \frac{1}{\gamma_\mathrm{L}^2}K_0^2(\xi)\right] \qquad \xi = \frac{E_\gamma b}{\gamma_\mathrm{L}}$$

Charge form factor (ChFF) (same as *SuperChic*)

$$N_{\gamma/Z}^{\mathrm{ChFF}}(E_\gamma, k_\perp) = 2\pi k_\perp \frac{Z^2\alpha}{\pi^2}\left|\int_0^\infty \frac{\mathrm{d}bk_\perp^2}{k_\perp^2 + E_\gamma^2/\gamma_\mathrm{L}^2} F_{\mathrm{ch},A}\left(\sqrt{{k_\perp}^2 + E_\gamma^2/\gamma_\mathrm{L}^2}\right) J_1(bk_\perp)\right|^2 = \frac{2Z^2\alpha}{\pi}\frac{k_\perp^3}{\left(k_\perp^2 + E_\gamma^2/\gamma_\mathrm{L}^2\right)^2}\left[F_{\mathrm{ch},A}\left(\sqrt{k_\perp^2 + E_\gamma^2/\gamma_\mathrm{L}^2}\right)\right]^2.$$

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

$\rho_A(r)$ = *p,A matter density*



- 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 more realistic: preferred.

Proton form factors & γ fluxes: ChFF vs. EDFF

Electric dipole form factor (EDFF)

- Same as STARlight

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

Charge form factor (ChFF) (same as *SuperChic*)

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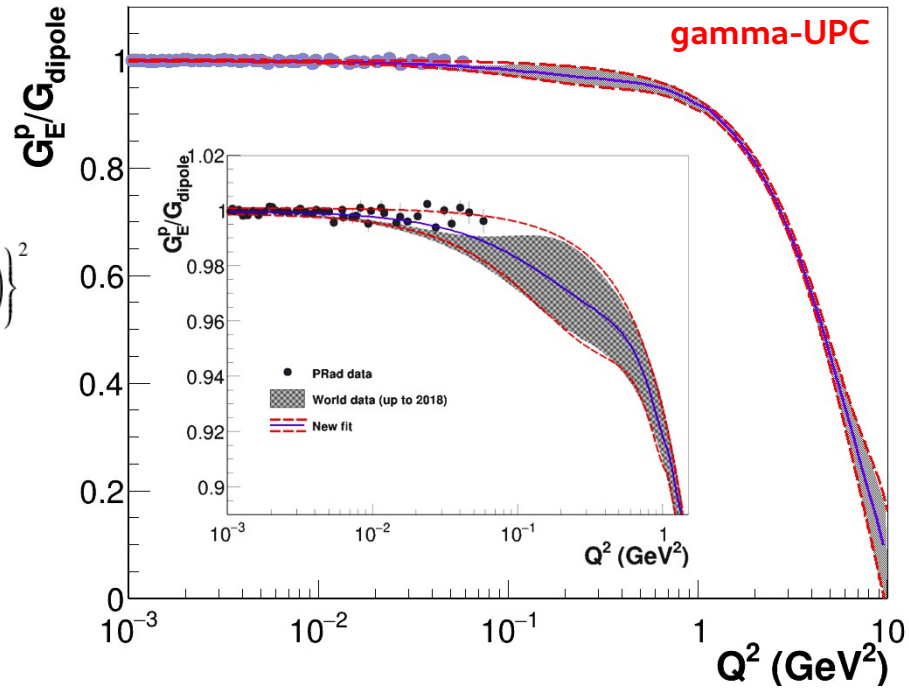
$\rho_A(r)$ = *p,A matter density*

Proton dipole form-factor:

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

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

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



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

- **Cross section:**

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

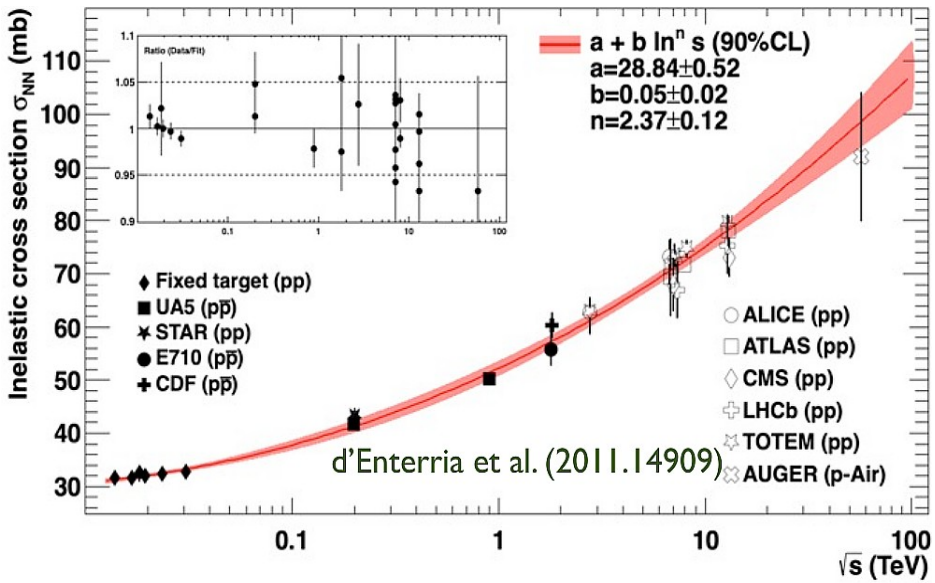
- **Effective two-photon luminosity:**

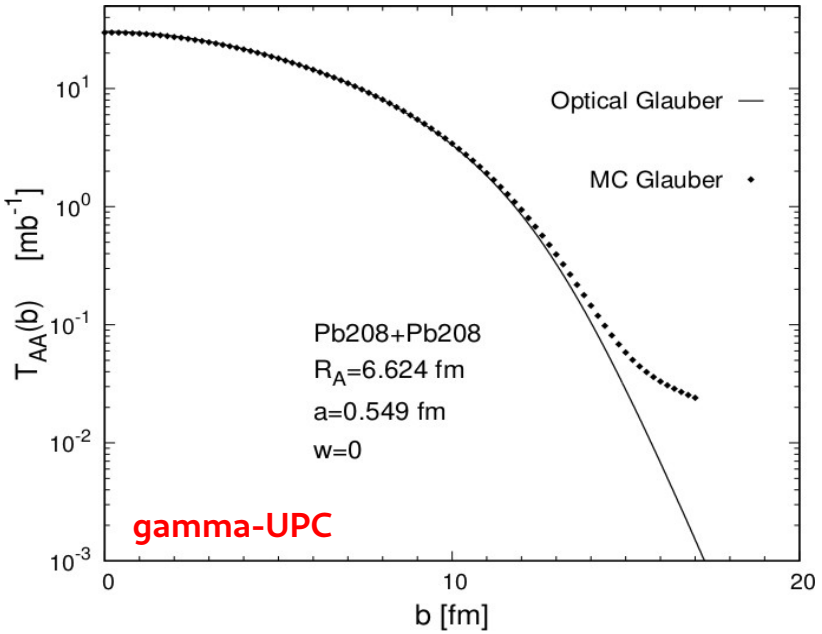
$$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, P_{\mathrm{no\,inel}}(\boldsymbol{b}_1,\boldsymbol{b}_2)\, N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1},\boldsymbol{b}_1) N_{\gamma_2/\mathrm{Z}_2}(E_{\gamma_2},\boldsymbol{b}_2)$$

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

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

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





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

- **Cross section:**

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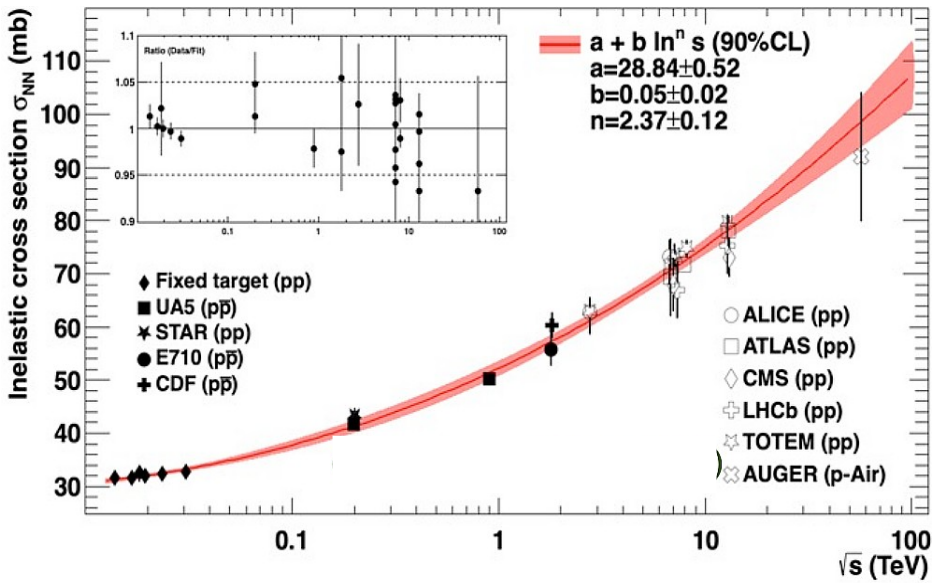
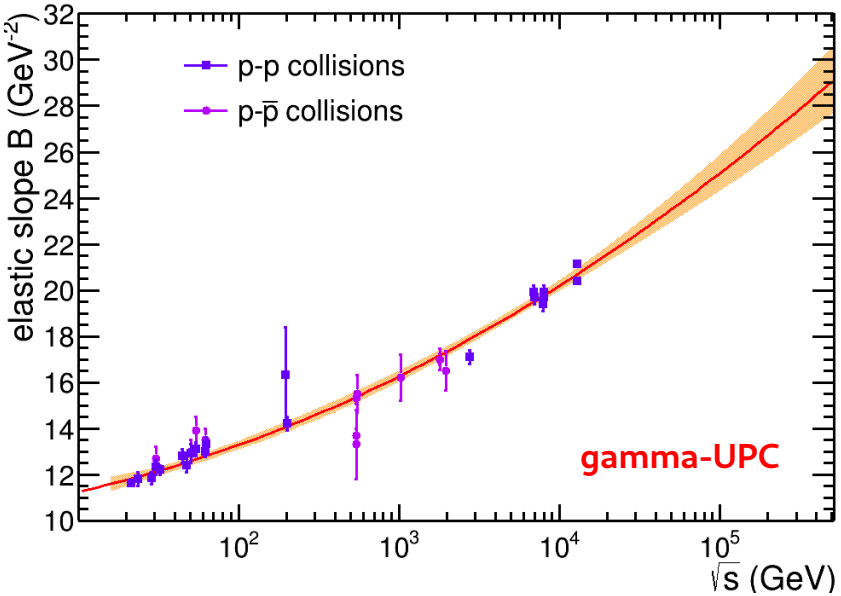
Parametrized proton elastic slope data:





How peripheral are Pb-Pb UPCs at the LHC?

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

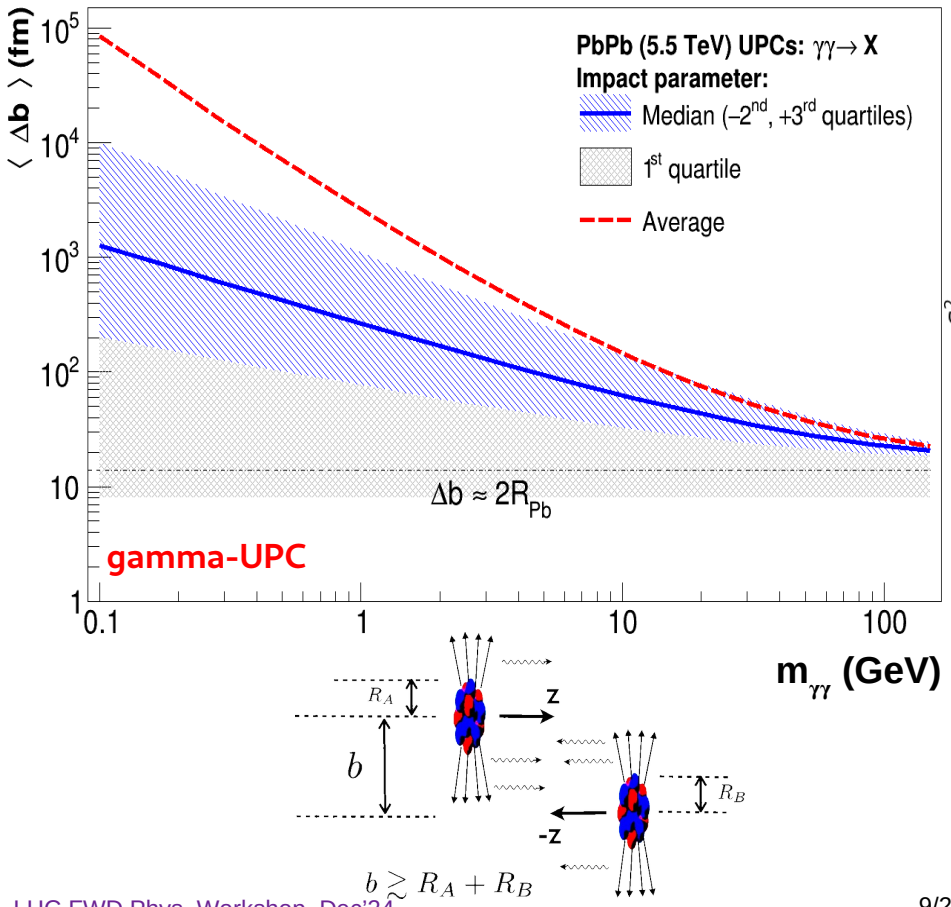
  $m_{\gamma\gamma}$ < 5 GeV: $\langle \Delta b \rangle$ > 100 fm

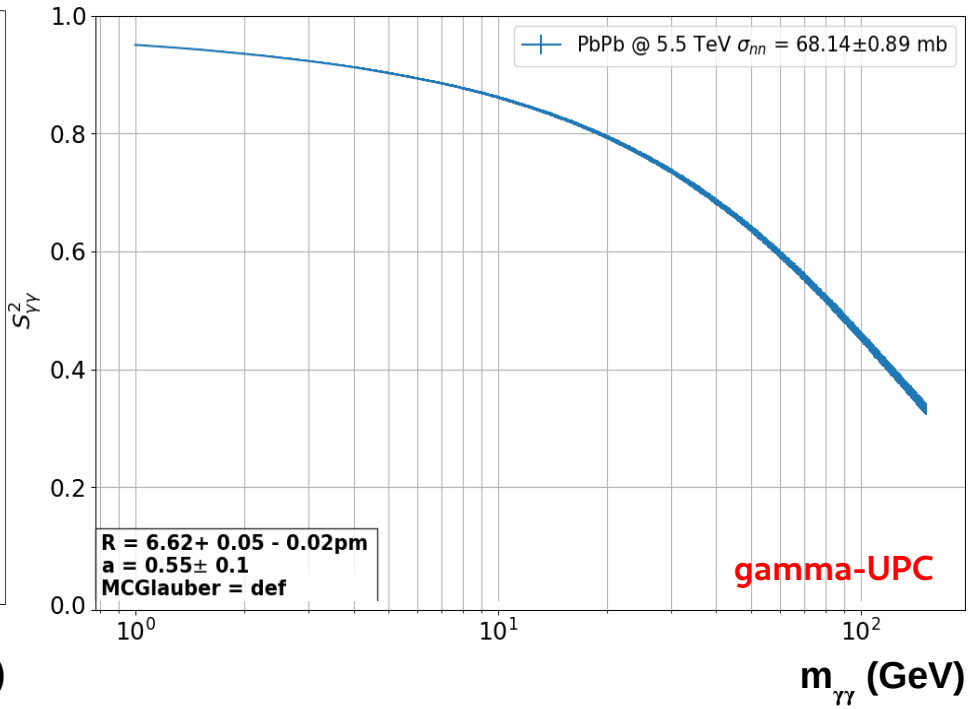
  $m_{\gamma\gamma}$ >100 GeV: $\langle \Delta b \rangle$ ~20 fm

- 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%





$$S^2_{\gamma\gamma} = \frac{\int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, P_{\text{no inel}}(\boldsymbol{b}_1,\boldsymbol{b}_2)\, N_{\gamma_1/Z_1}(E_{\gamma_1},\boldsymbol{b}_1) N_{\gamma_2/Z_2}(E_{\gamma_2},\boldsymbol{b}_2)}{\int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, N_{\gamma_1/Z_1}(E_{\gamma_1},\boldsymbol{b}_1) N_{\gamma_2/Z_2}(E_{\gamma_2},\boldsymbol{b}_2)}$$

How peripheral are p-p UPCs at the LHC?

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

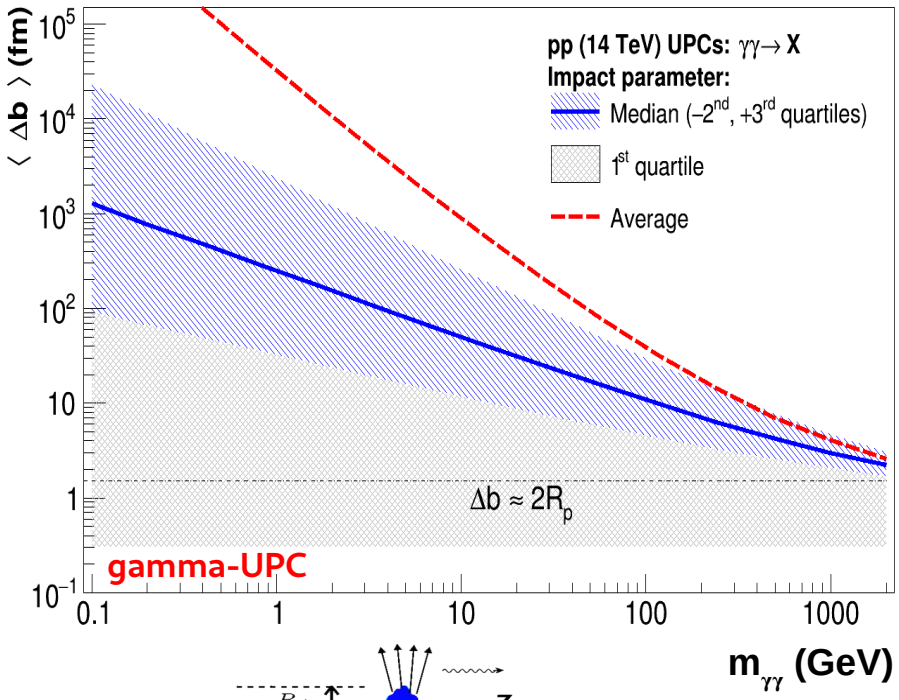
  $m_{\gamma\gamma} < 10$ GeV: $\langle \Delta b \rangle > 50$ fm

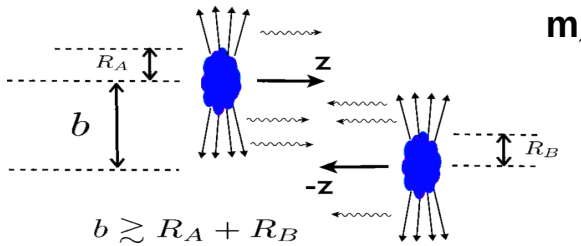
  $m_{\gamma\gamma} > 1$ TeV: $\langle \Delta b \rangle < 3$ fm

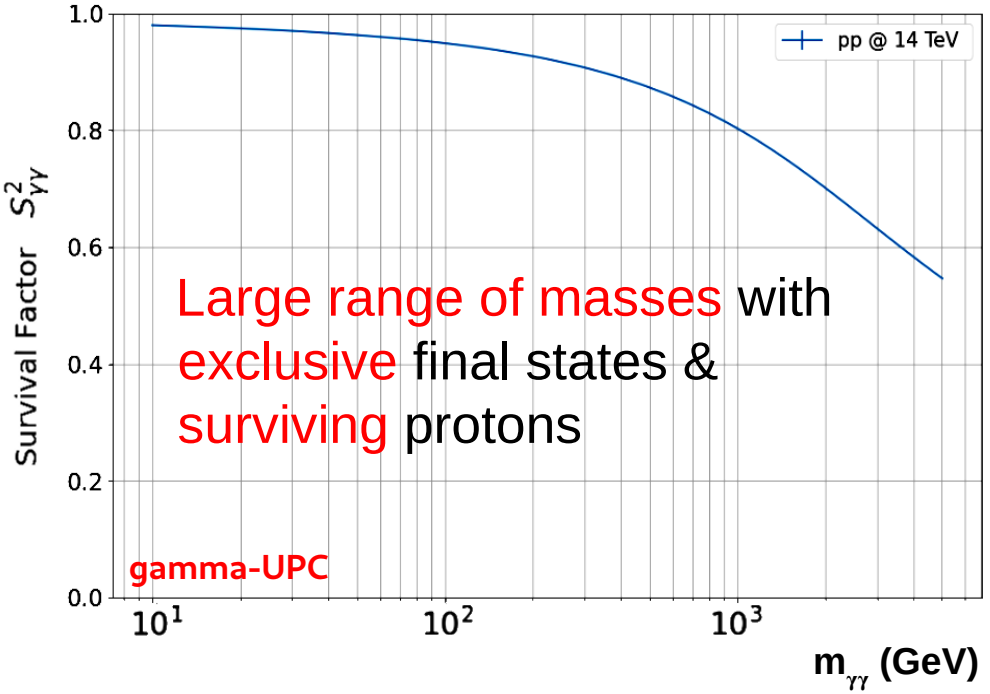
- p-p survival probab. vs. $m_{\gamma\gamma}$:

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

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







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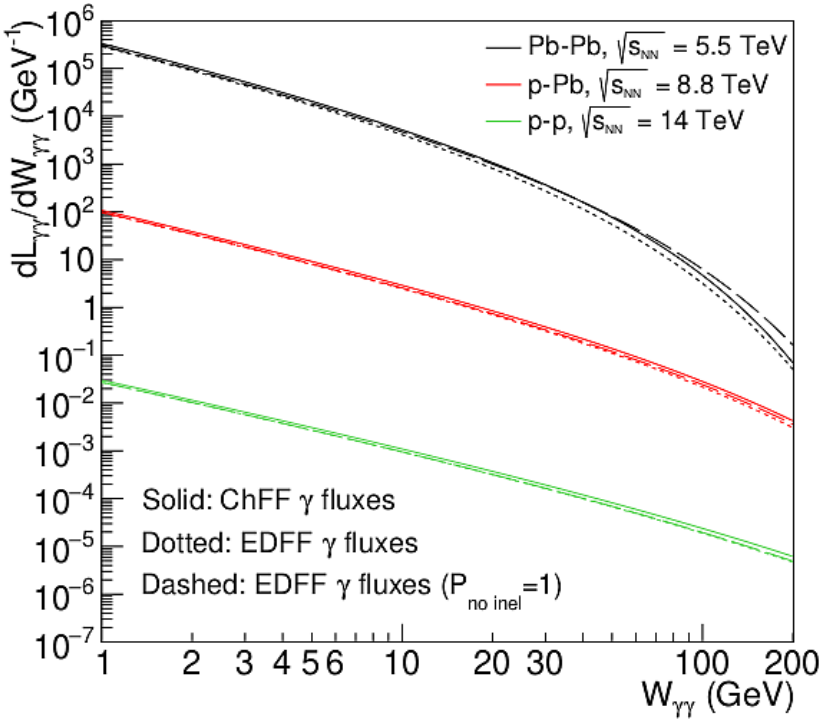
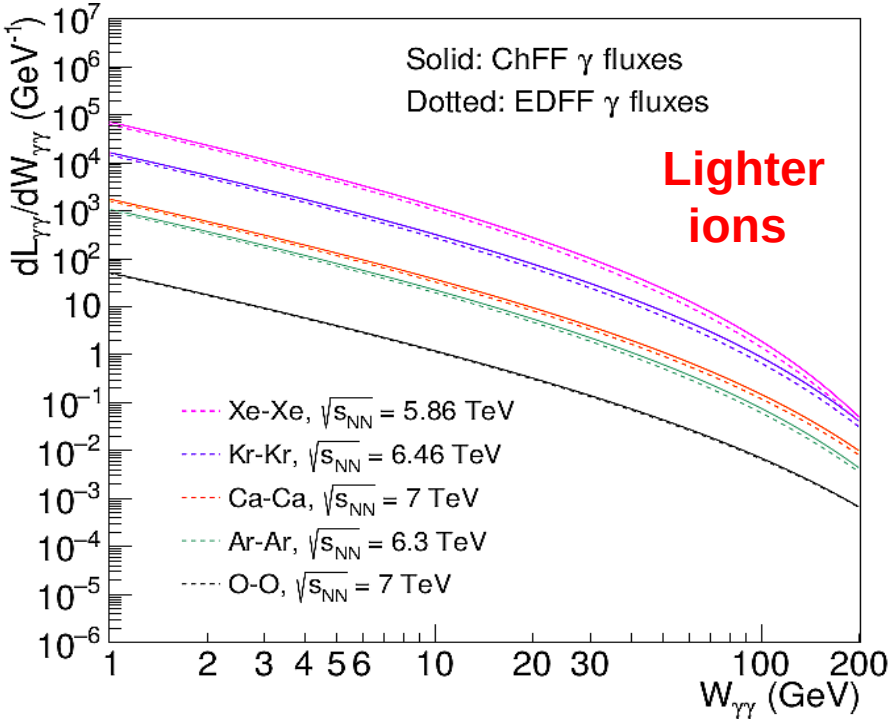
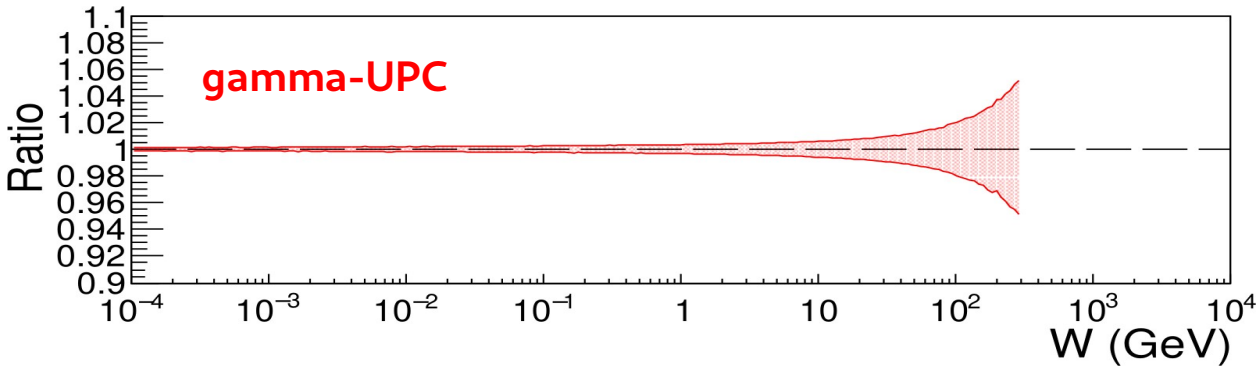
Effective $\gamma\gamma$ luminosities (p-p, p-A, A-A)

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





- ChFF $\gamma\gamma$ luminosity uncertainties (PbPb): Low-mass: <1%. High mass: ~5%



ChFF γ spectra.

Glauber MC:

Variations of R,a,σ_{NN}

Effective $\gamma\gamma$ luminosities (p-p, p-A, A-A)

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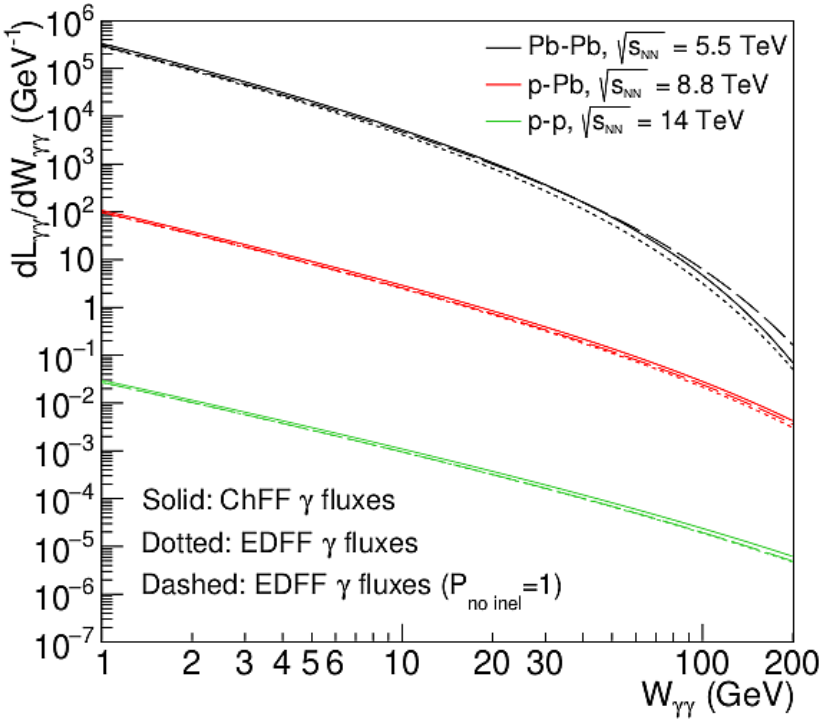
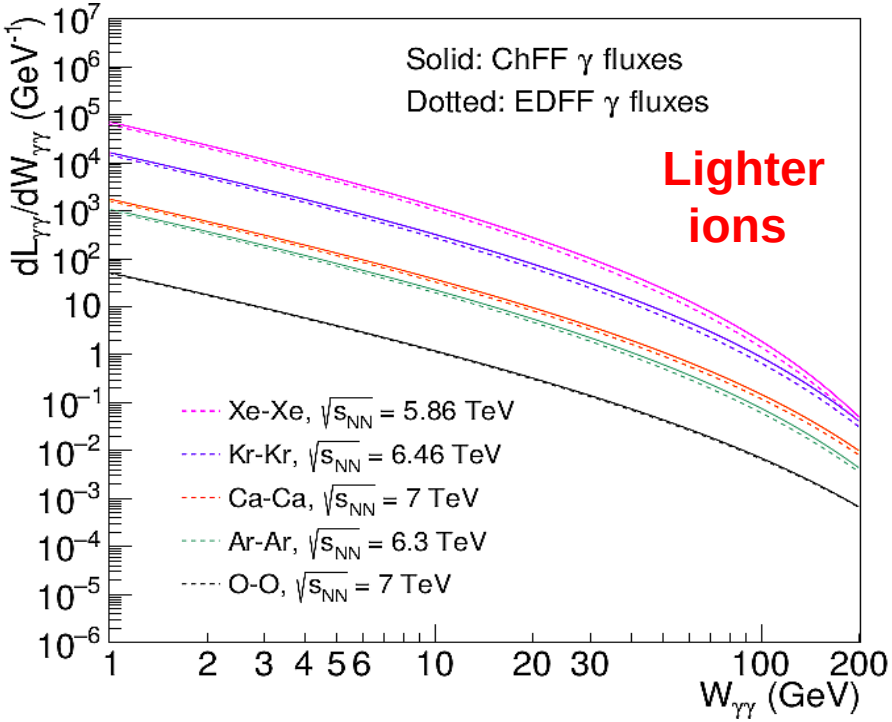
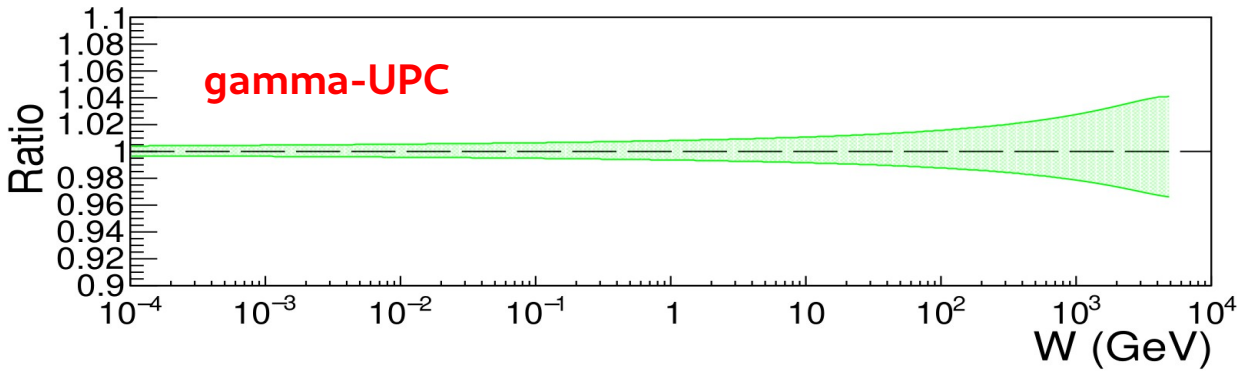




- ChFF $\gamma\gamma$ luminosity <u>uncertainties</u> (pp): Low-mass: <1%. High mass: ~4%

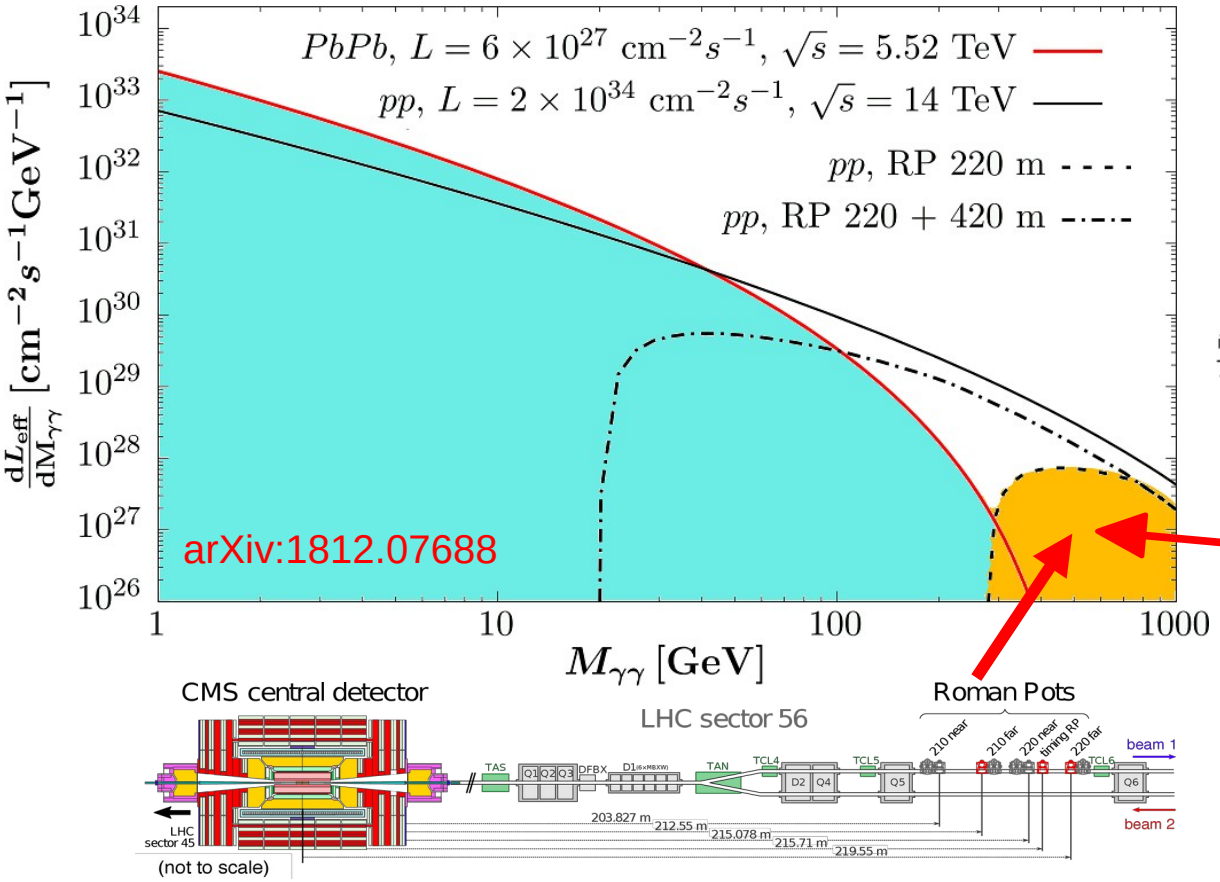


ChFF γ spectra.

Glauber MC:
Variations of elastic slope b_0

Effective γγ luminosities (LHC): pp vs. PbPb

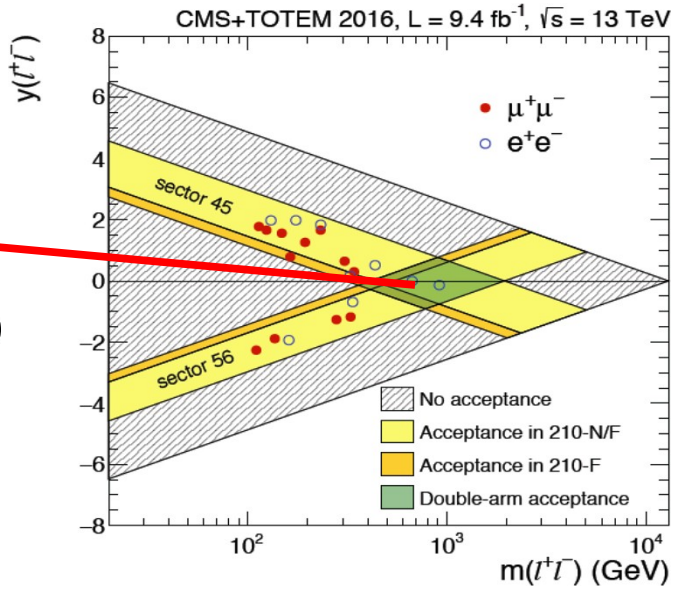
- PbPb feature $5 \cdot 10^7$ boost & no pileup, but pp has $\mathcal{O}(10^6)$ larger L_{int} & taggers:
  - PbPb "wins out" up to $W_{\gamma\gamma} \approx 50$ GeV.
  - pp w/ double-arm p tagging at PPS (~220 m) "wins out" for $W_{\gamma\gamma} \geq 300$ GeV (+ central-fwd kinematic matching required to remove huge pp pileup):



Proton kinematics: $t = (p_f - p_i)^2$

$$\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} \qquad M_X = \sqrt{s\xi_1\xi_2} \qquad y_X = \frac{1}{2}\log\left(\frac{\xi_1}{\xi_2}\right)$$

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



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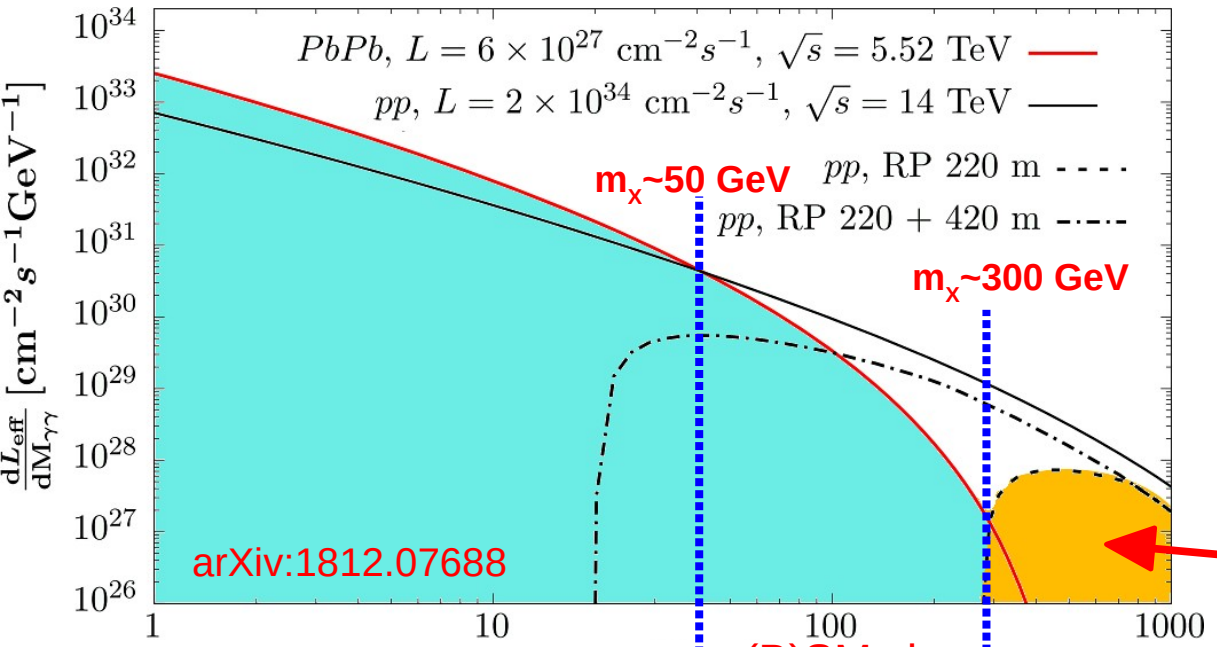
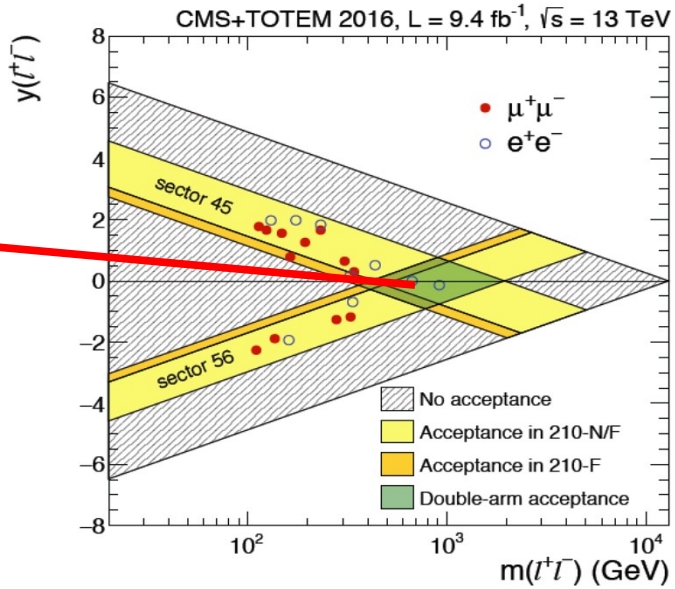


Proton kinematics: $t = (p_f - p_i)^2$

$$\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} \qquad M_X = \sqrt{s\xi_1\xi_2} \qquad y_X = \frac{1}{2}\log\left(\frac{\xi_1}{\xi_2}\right)$$

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



Rule of thumb:

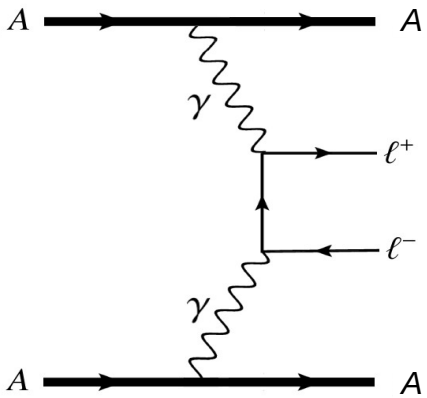
(B)SM via γγ in Pb-Pb

(B)SM via γγ in p-p: 1 tag, or Aco<1% & N^{vtx}_{tracks}=0

(B)SM via γγ in p-p with 2 tagged p's

Exclusive dileptons: $\gamma\gamma$ standard candle

- Breit-Wheeler process $\gamma\gamma \to e^+e^-$ is the simplest photon-fusion QED process:



- Analysis strategy:

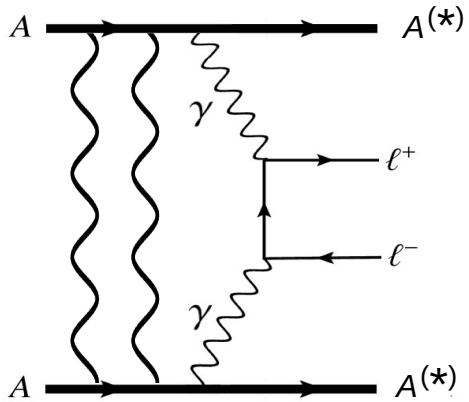
  Exclusive e^+e^- (zero extra activity)

  $m_{ee} > 5$ GeV (softest $e^{\pm}$ possible)

  $Aco_{\gamma\gamma} < 1\%$ (e^+e^- back-to-back)

Forward neutron emission in $\gamma\gamma \rightarrow e^+e^-$

- Breit-Wheeler process $\gamma\gamma \rightarrow e^+e^-$ is the simplest photon-fusion QED process:



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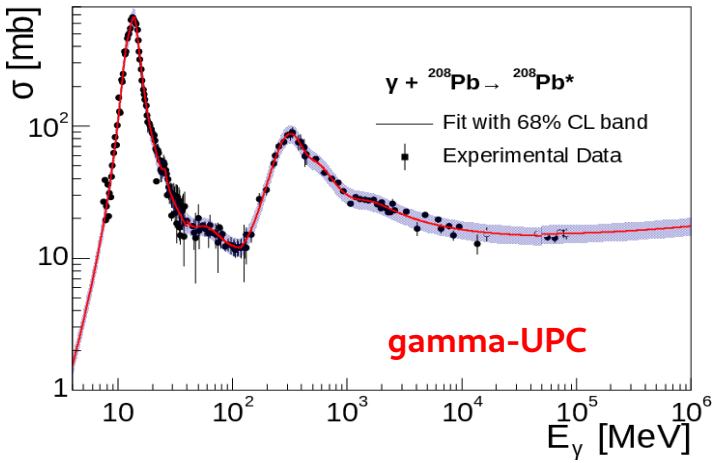
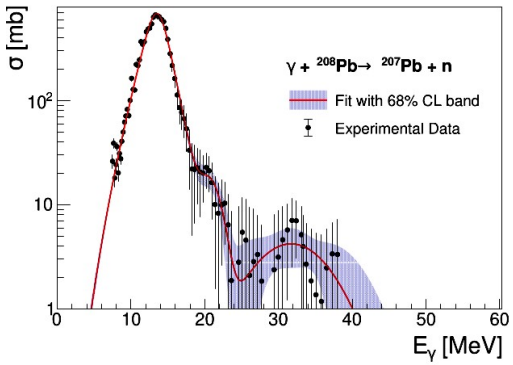
  $Aco_{\gamma\gamma} < 1\%$ (e^+e^- back-to-back)

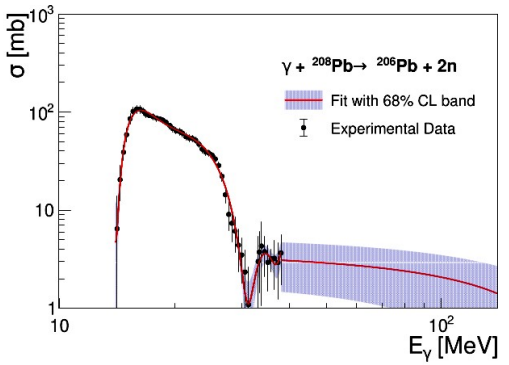
  ZDC neutron(s): XnXn (X=0,1,...)

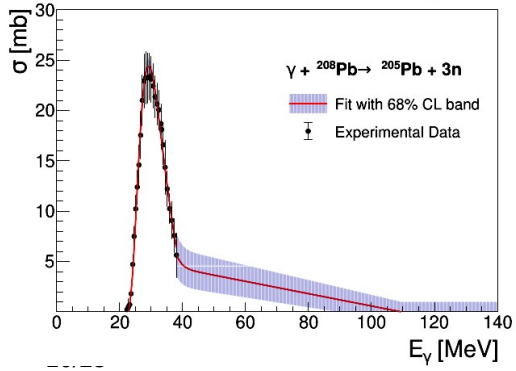
  ZDCs increasingly used to trigger on UPC events

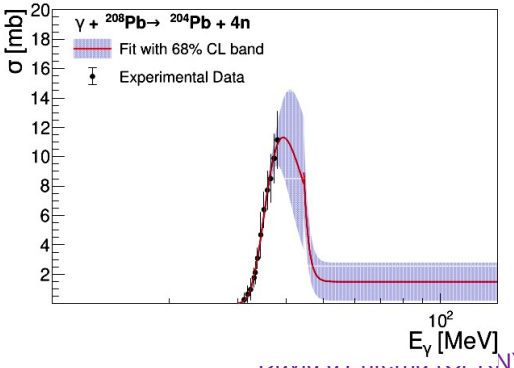
- Refitted the world-data of Pb photo-excitation plus emission of 1n, 2n, 3n, 4n, and Xn:











Forward neutron emission in $\gamma\gamma \rightarrow e^+e^-$

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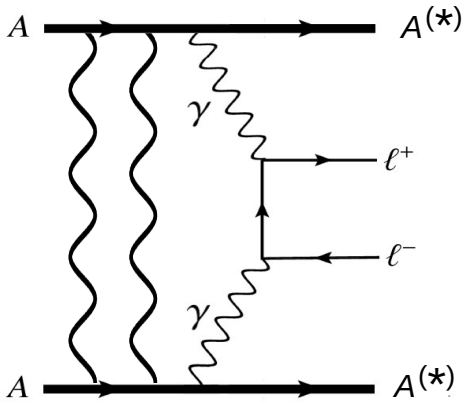

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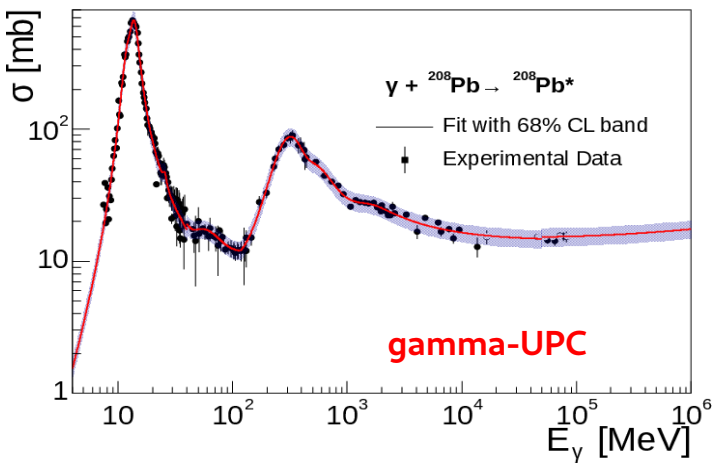
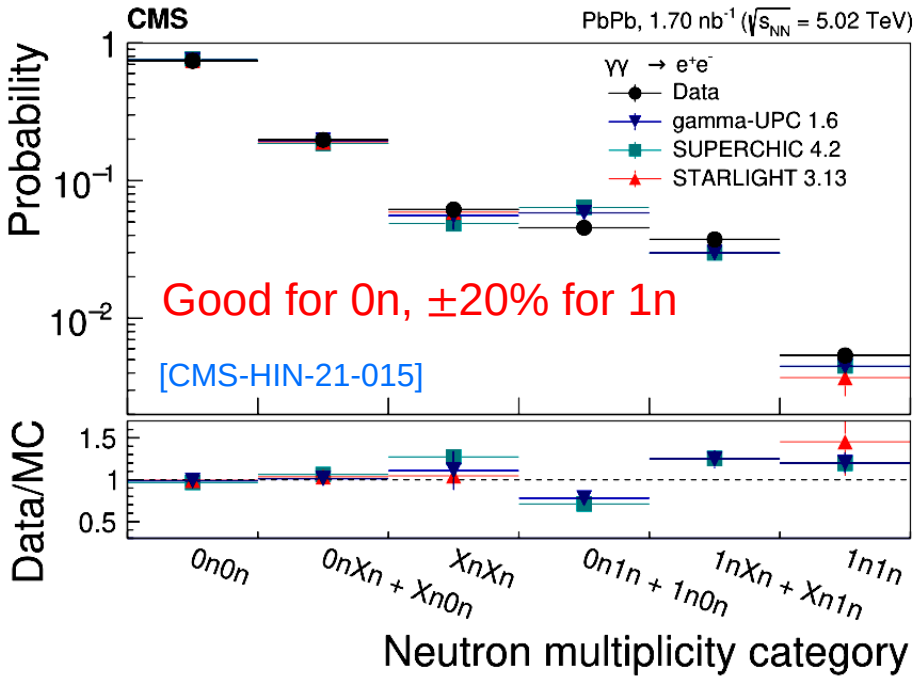
  $Aco_{\gamma\gamma}$<1% (e^+e^- back-to-back)

  ZDC neutron(s): XnXn (X=0,1,...)

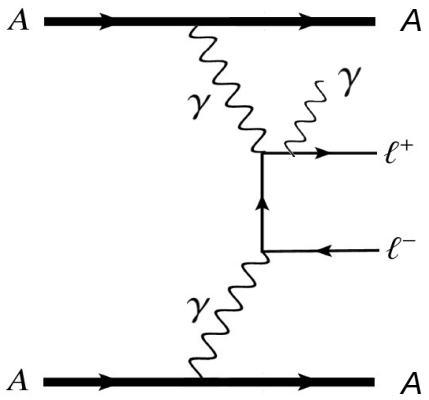
- Data-model agreement for the mutual e.m. Pb excitation and XnXn fwd neutron emission:





Exclusive dileptons: γγ standard candle

- Breit-Wheeler process $\gamma\gamma \to e^+e^-$ is the simplest photon-fusion QED process:



- Analysis strategy:

  Exclusive e^+e^- (zero extra activity)

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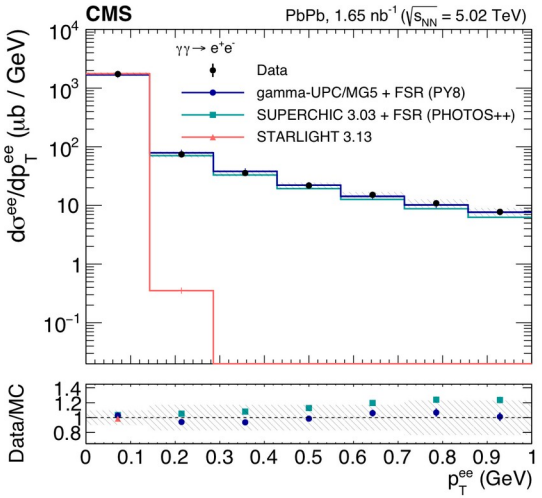
  $Aco_{\gamma\gamma} < 1\%$ (e^+e^- back-to-back)

[CMS-HIN-21-015]

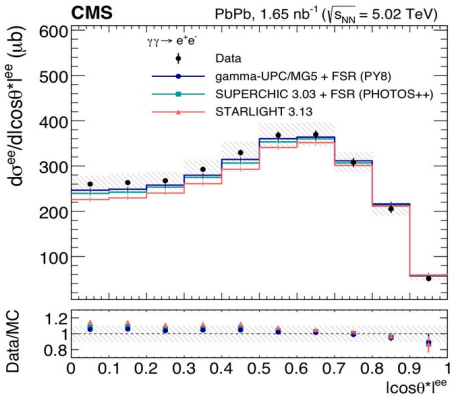


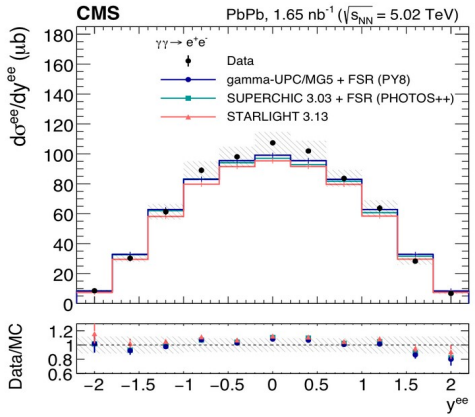
- Photon FSR needed to reproduce exp. data (acoplanarity, x-sections):

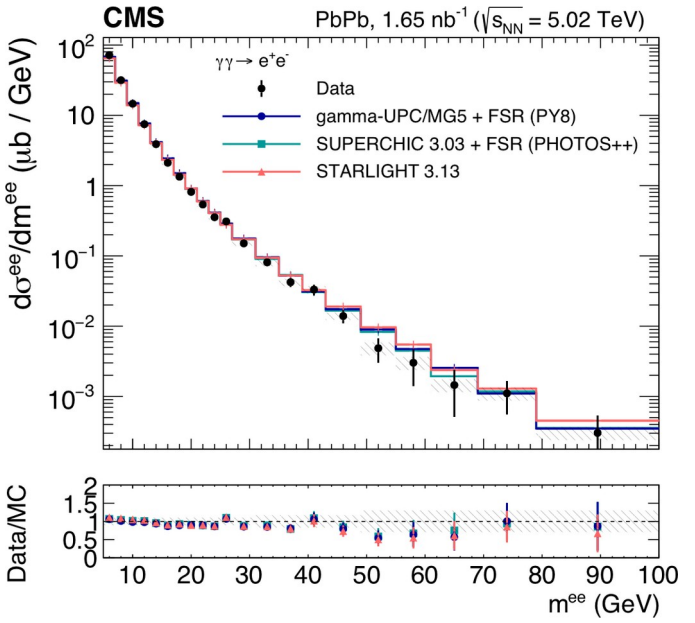
$$\sigma_{\text{fid}}(\gamma\gamma \to e^+e^-) = \frac{N^{ee,\text{data}}}{C^{ee}\mathcal{L}_{\text{int}}} = 271.5 \pm 1.9\,(\text{stat}) \pm 18.3\,(\text{syst})\ \mu\text{b}$$

$$\sigma_{\text{fid}}(\gamma\gamma \to e^+e^-) = 265\ \mu\text{b},\ \text{gamma-UPC/MG5} + \text{FSR}$$

$$\sigma_{\text{fid}}(\gamma\gamma \to e^+e^-) = 251\ \mu\text{b},\ \text{STARLIGHT 3.13}$$

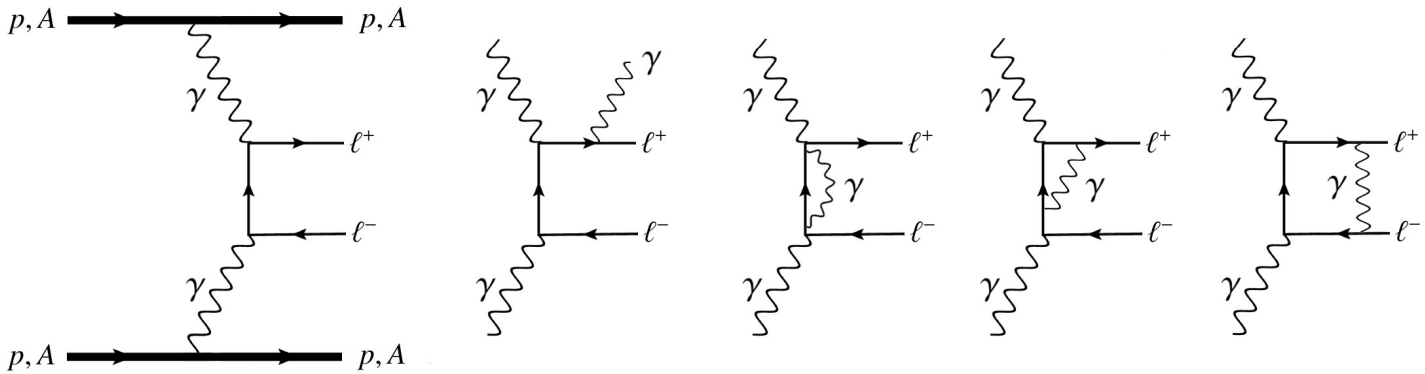




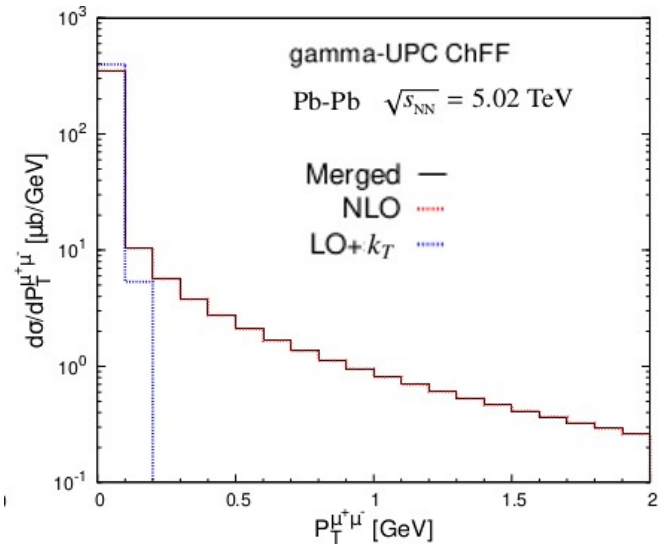


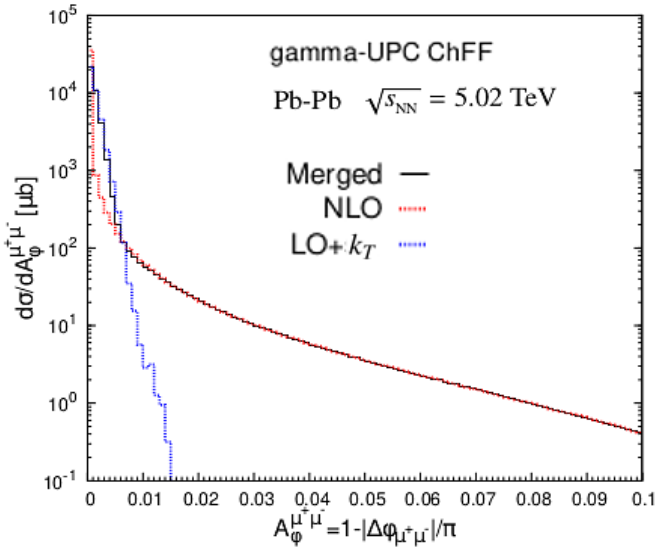
NLO QED corrections to $\gamma\gamma \to \ell^+\ell^-$

- All $\gamma\gamma$ MCs so far included only LO diags (plus FSR). Impact of NLO QED?



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



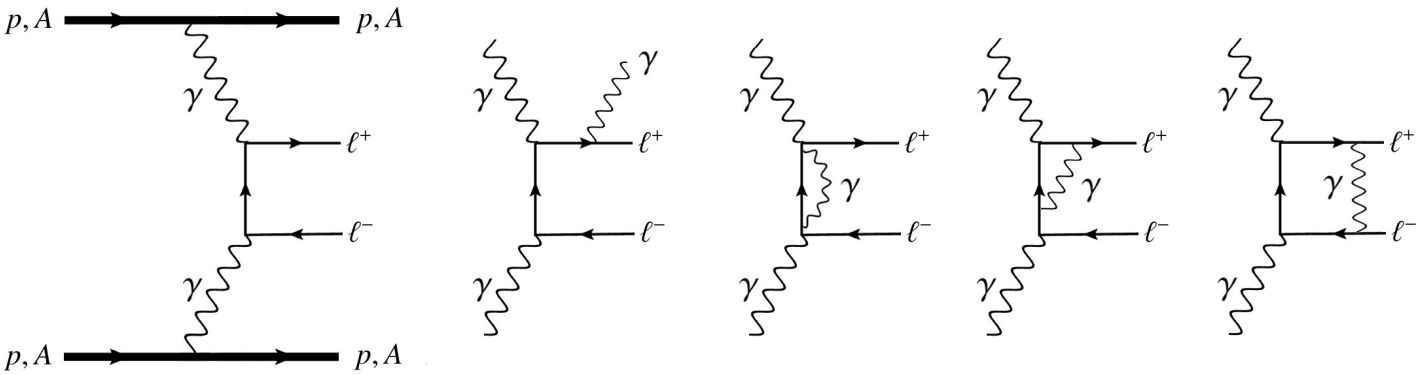


NLO corrections increase the p_T(pair), Aco(pair) tails:

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

NLO QED corrections to $\gamma\gamma \to \mu^+\mu^-$

- All $\gamma\gamma$ MCs so far included only LO diags (plus FSR). Impact of NLO QED:



- Addition of virtual & real NLO QED to $\gamma\gamma \to \mu^+\mu^-$:
  - Reduces fiducial total x-sections by 3.5–5%.
  - Modifies key diff. distributions: $Aco_{\gamma\gamma}$, $d\sigma/dp_T(\ell\ell)$
  - Improves data-model agreement. Key for precision SM studies:

$\gamma\gamma \to \mu^+\mu^-$ System, experiment	Measured σ^{data}	gamma-UPC σ^{LO} ChFF (EDFF)	gamma-UPC σ^{NLO} ChFF (EDFF)	ratio $\sigma^{\text{data}}/\sigma^{\text{NLO}}$ ChFF (EDFF)
p-p at 7 TeV, CMS [46]	$3.38^{+0.62}_{-0.59}$ pb	3.62 (3.20) pb	3.50 (3.10) pb	$0.97^{+0.18}_{-0.17}$ ($1.09^{+0.20}_{-0.19}$)
p-p at 7 TeV, ATLAS [30]	0.628 ± 0.038 pb	0.687 (0.59) pb	0.653 (0.56) pb	0.96 ± 0.06 (1.12 ± 0.07)
p-p at 13 TeV, ATLAS [47]	3.12 ± 0.16 pb	3.23 (2.88) pb	3.09 (2.76) pb	1.00 ± 0.05 (1.13 ± 0.06)
Pb-Pb at 5.02 TeV, ATLAS [49]	34.1 ± 0.8 μb	39.4 (31.5) μb	37.5 (30.0) μb	0.91 ± 0.02 (1.14 ± 0.03)

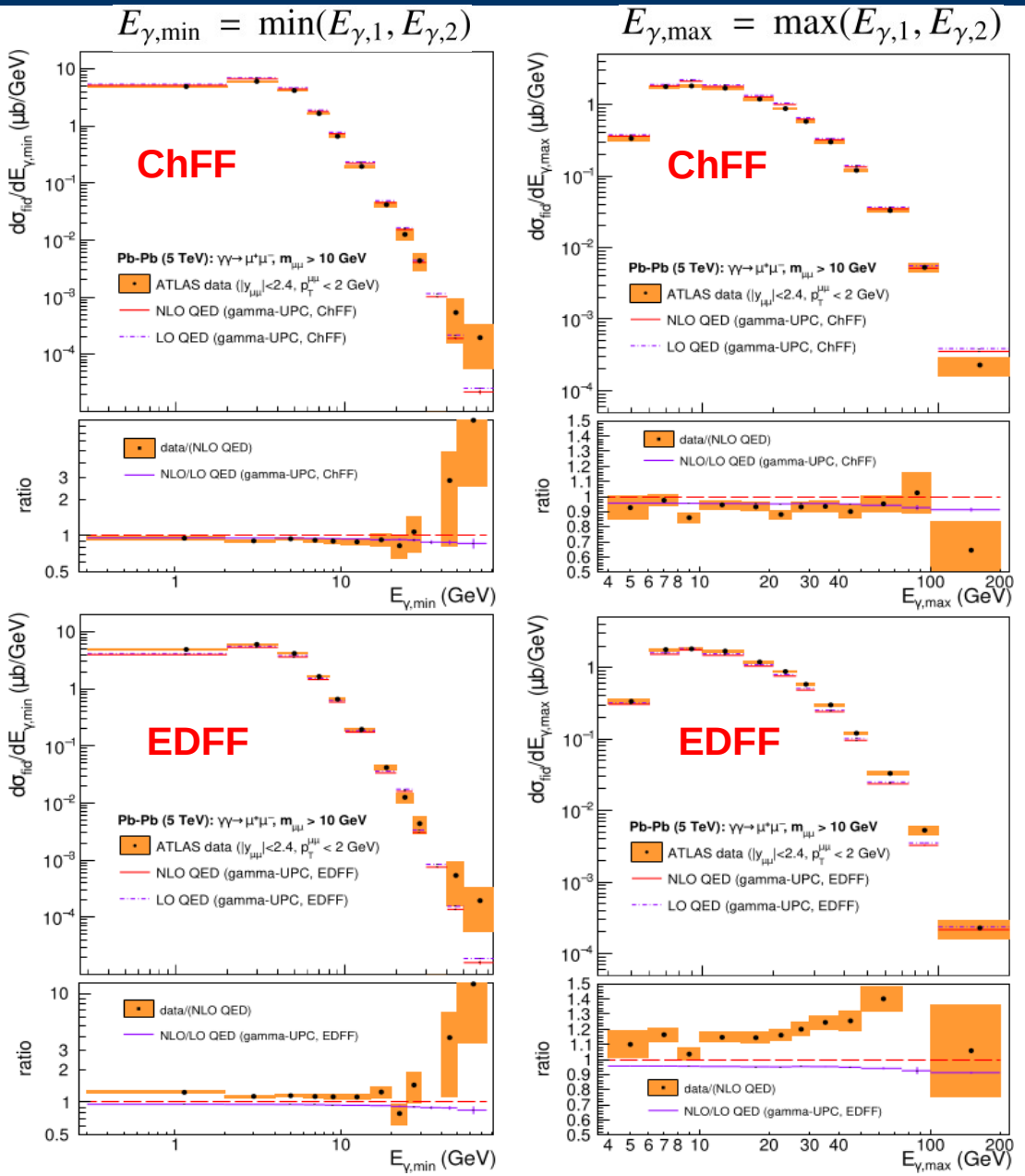
Photon flux constraints from $\gamma\gamma \rightarrow \mu^+\mu^-$

- Energies $E_{\gamma,1}$ and $E_{\gamma,2}$ of initial photons can be inferred from $\gamma\gamma \rightarrow \mu^+\mu^-$ final-state kinematics:

$$E_{\gamma,1} = (m_{\mu\mu}/2)\exp(+y_{\mu\mu})$$
$$E_{\gamma,2} = (m_{\mu\mu}/2)\exp(-y_{\mu\mu})$$

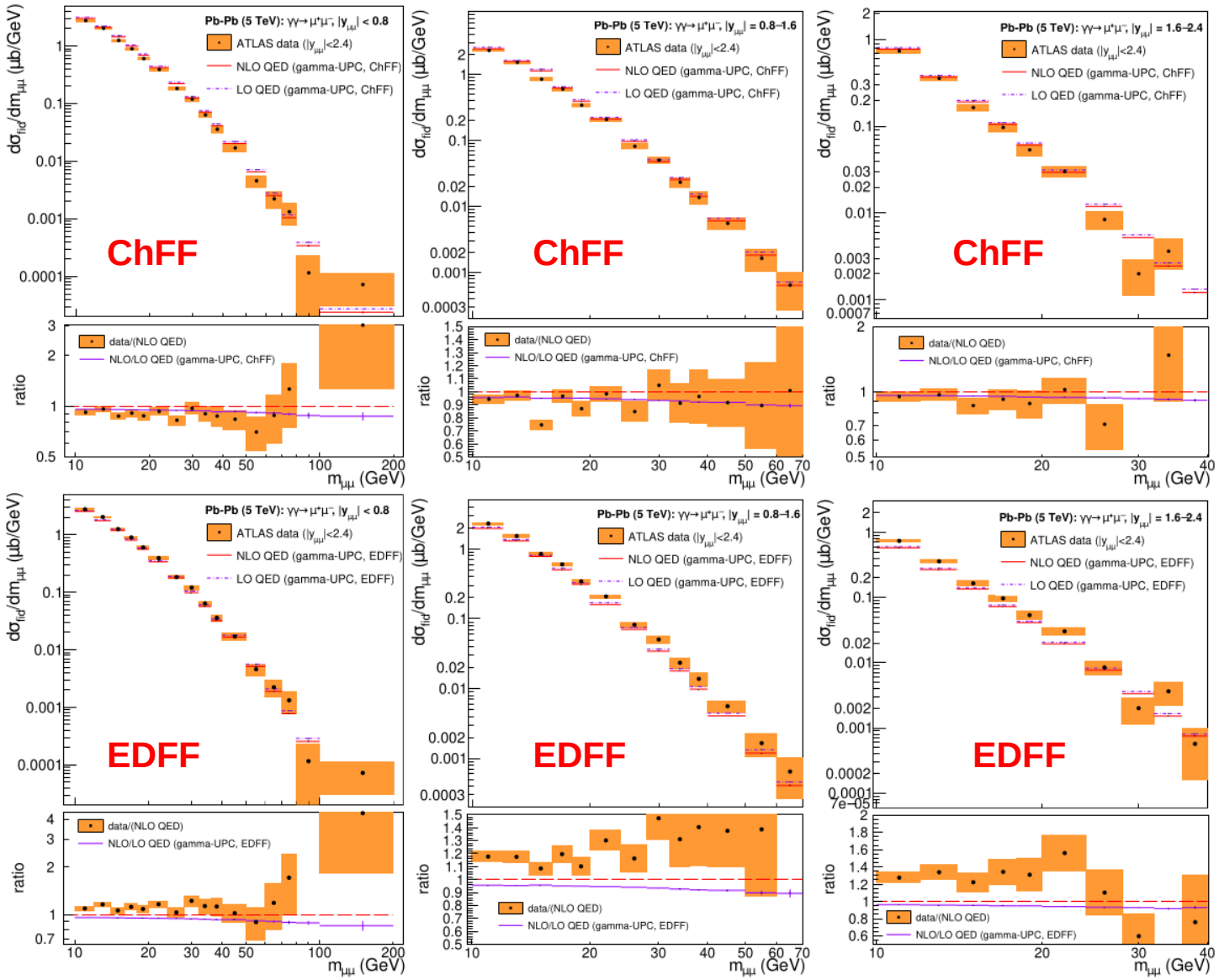
- NLO vs. ATLAS measurement of max. & min. photon E_γ spectra:

- ChFF reproduces norm. & shape
- EDFF undershoots spectra by ~10%, 30% at low, high E_γ



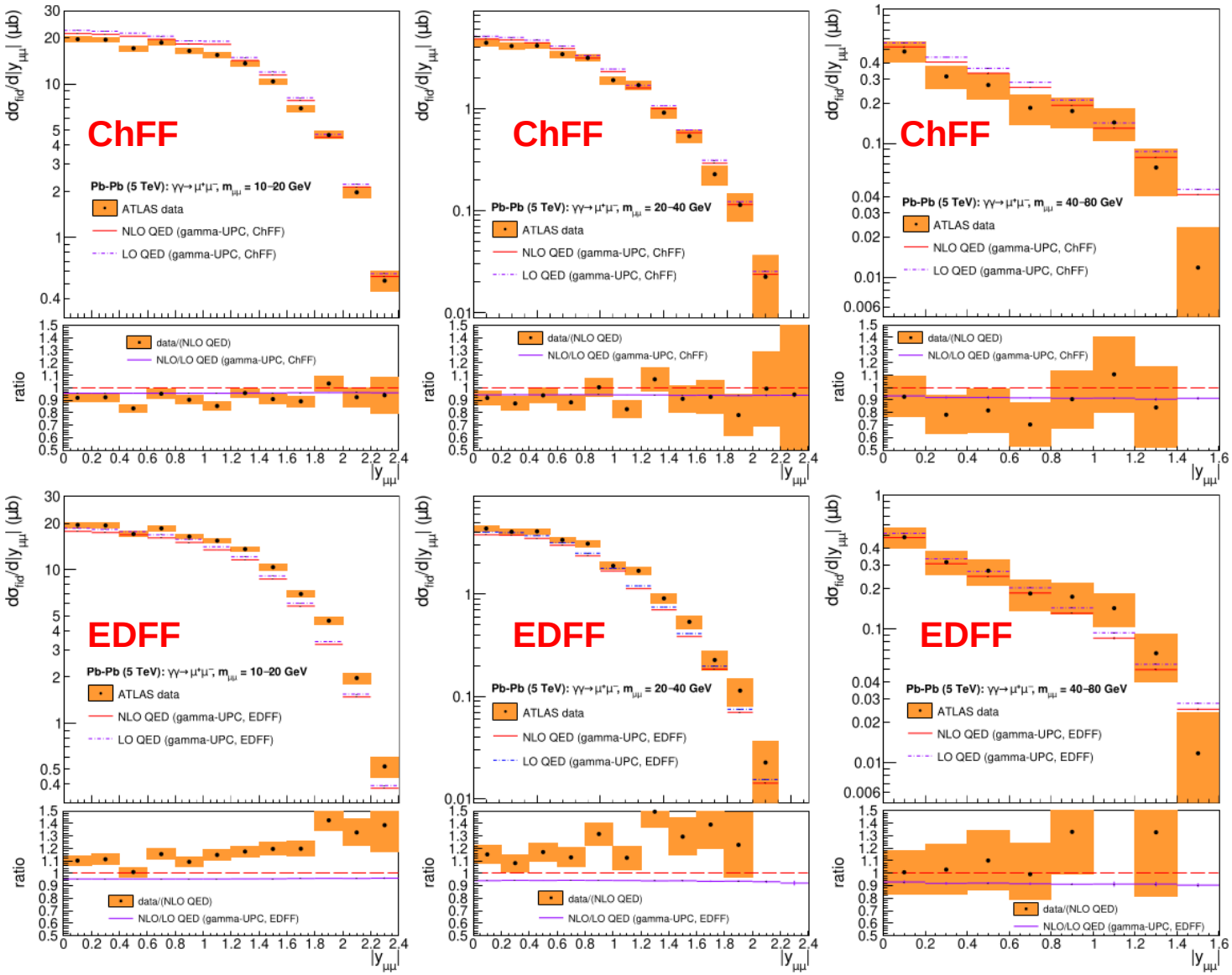
NLO QED vs $\gamma\gamma \rightarrow \mu^+\mu^-$ data (inv. mass)

- NLO+ChFF consistent with measured inv. mass norm. & shape
- NLO+EDFF undershoots inv. mass spectra by ~15-25%



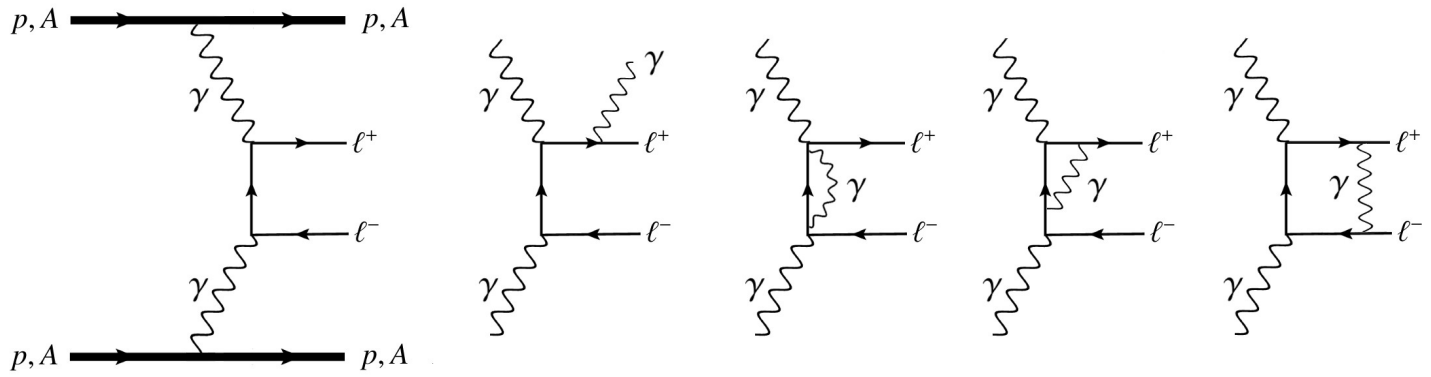
NLO QED vs $\gamma\gamma \rightarrow \mu^+\mu^-$ data (pair rapidity)

- NLO+ChFF consistent with measured pair rapidity norm. & shape
- NLO+EDFF undershoots pair rapidity spectra by ~15-25%



NLO QED corrections to $\gamma\gamma \to \tau^+\tau^-$

- All $\gamma\gamma$ MCs so far included only LO diags (plus FSR). Impact of NLO QED:

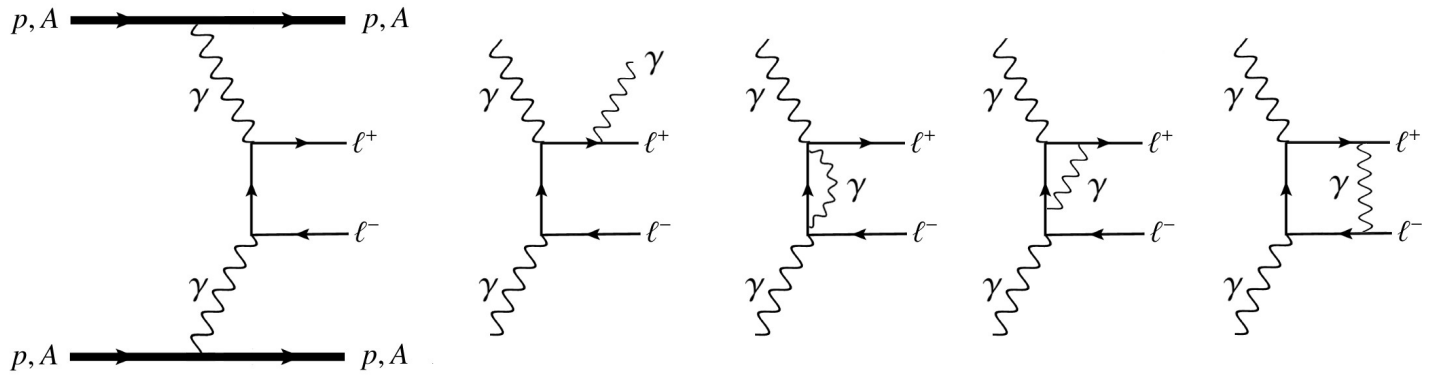


- Addition of virtual & real NLO QED to $\gamma\gamma \to \tau^+\tau^-$:
  - Modifies fiducial x-sections by +1% (incl), –0.5% (mid mass), –3.5% (high mass)
  - Modifies key diff. distributions: $A_{\gamma\gamma}$, $d\sigma/dp_T(\ell\ell)$
  - Eventually important for ultimate (g-2)τ extraction from data:

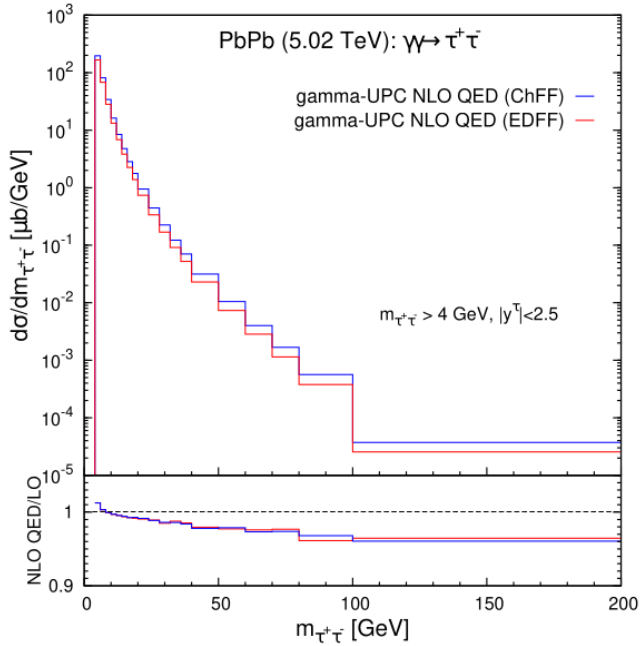
$\gamma\gamma \to \tau^+\tau^-$ Colliding system (kinematic cuts)	Measured σ^{data} (extrapolated)	gamma-UPC σ^{LO} ChFF (EDFF)	gamma-UPC σ^{NLO} ChFF (EDFF)	K factor $\sigma^{\text{NLO}}/\sigma^{\text{LO}}$
Pb-Pb at 5.02 TeV (inclusive)	580–850 μb	1060 (860) μb	1070 (870) μb	1.01
p-p at 13 TeV ($m_{\tau\tau} > 50$ GeV)	855^{+260}_{-215} fb	900 (730) fb	895 (725) fb	0.995
p-p at 13.6 TeV ($m_{\tau\tau} > 300$ GeV, $\lvert y^\tau\rvert < 2.5$)	–	1.35 (1.02) fb	1.31 (0.98) fb	0.965

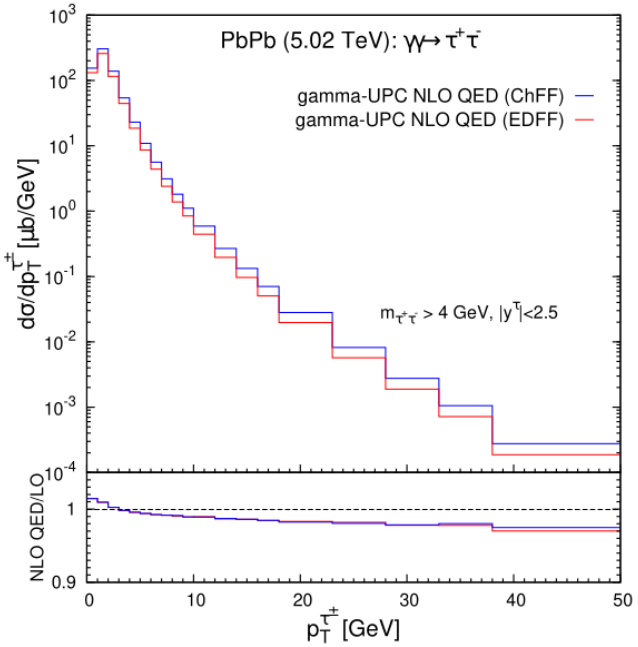
NLO QED corrections to $\gamma\gamma \to \tau^+\tau^-$ (PbPb UPCs)

- All $\gamma\gamma$ MCs so far included only LO diags (plus FSR). Impact of NLO QED:



- Impact of virtual & real NLO QED corrections on $d\sigma/dm(\tau\tau)$ and $d\sigma/p_T(\tau\tau)$:



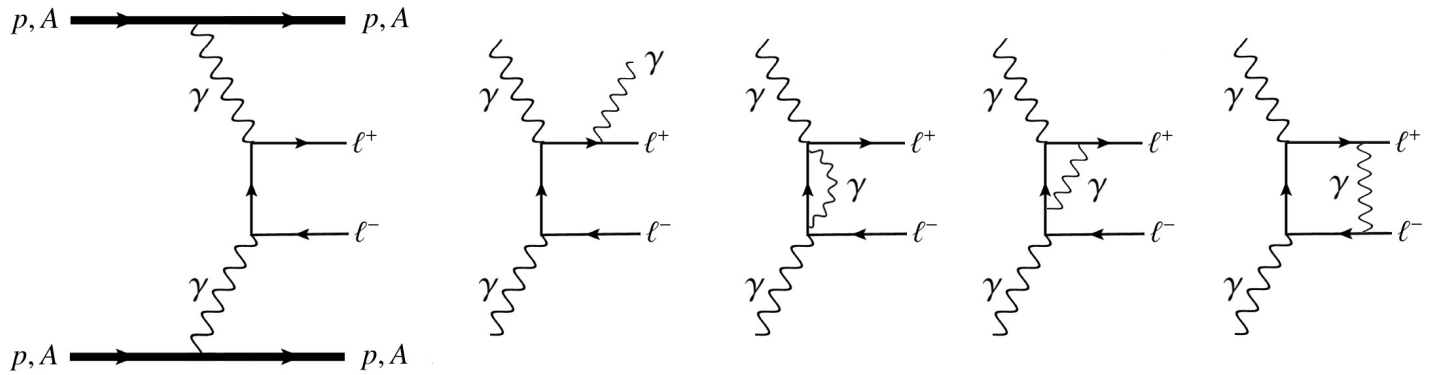


Differential x-sections increases/decreases by few % at low/high masses.

Relevant for accurate (g-2)τ extractions from PbPb UPCs

NLO QED corrections to $\gamma\gamma \rightarrow \tau^+\tau^-$ (p-p UPCs)

- All $\gamma\gamma$ MCs so far included only LO diags (plus FSR). Impact of NLO QED:



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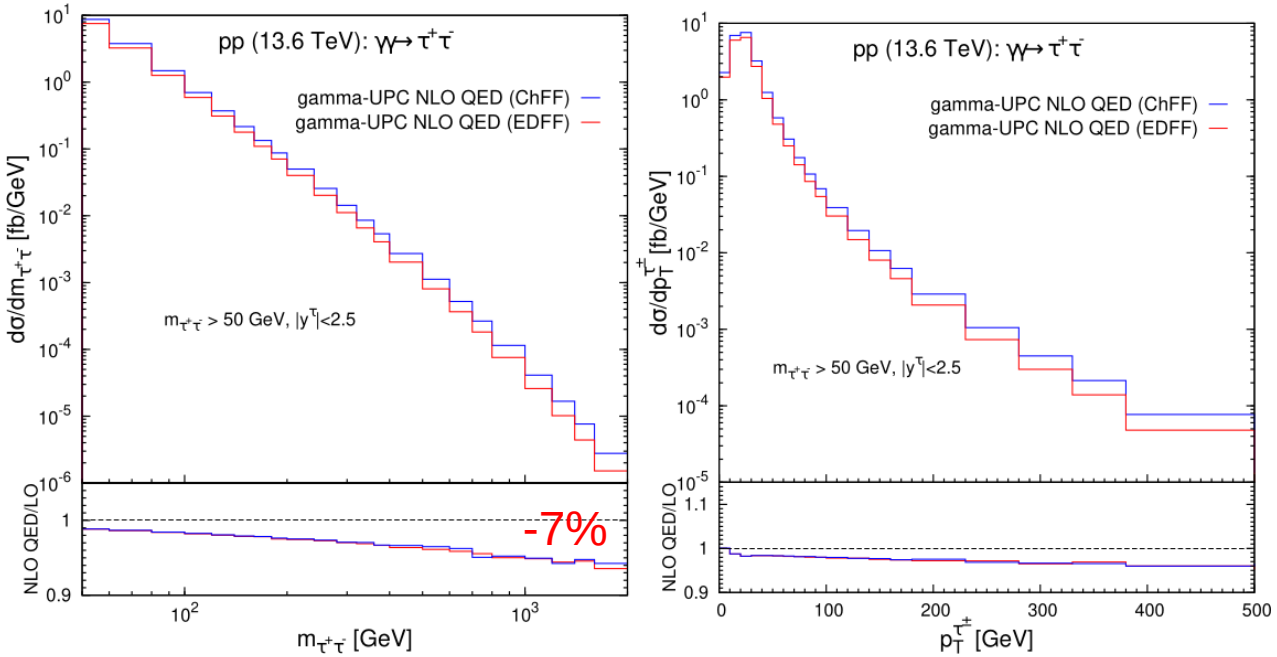
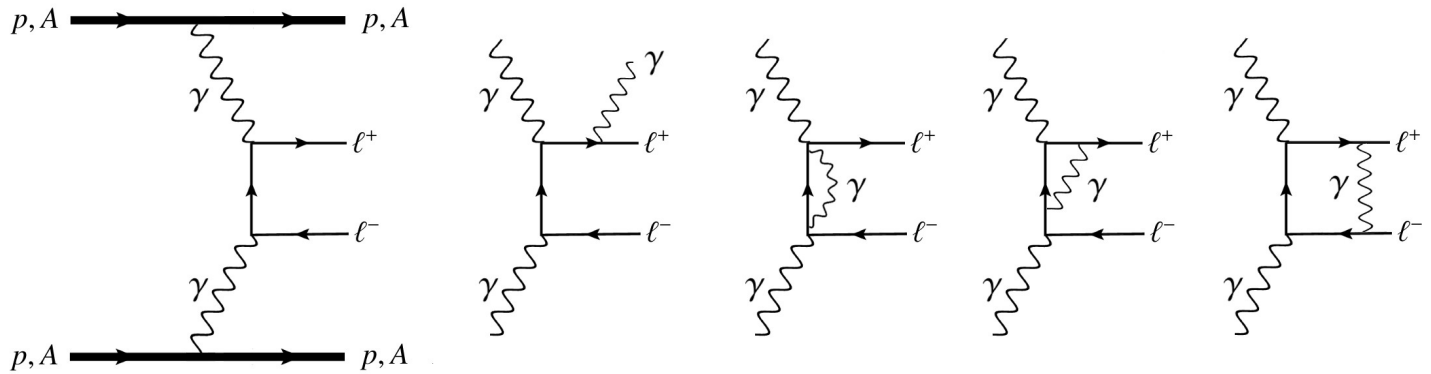


Differential x-sections decreases by few % at mid/high masses.

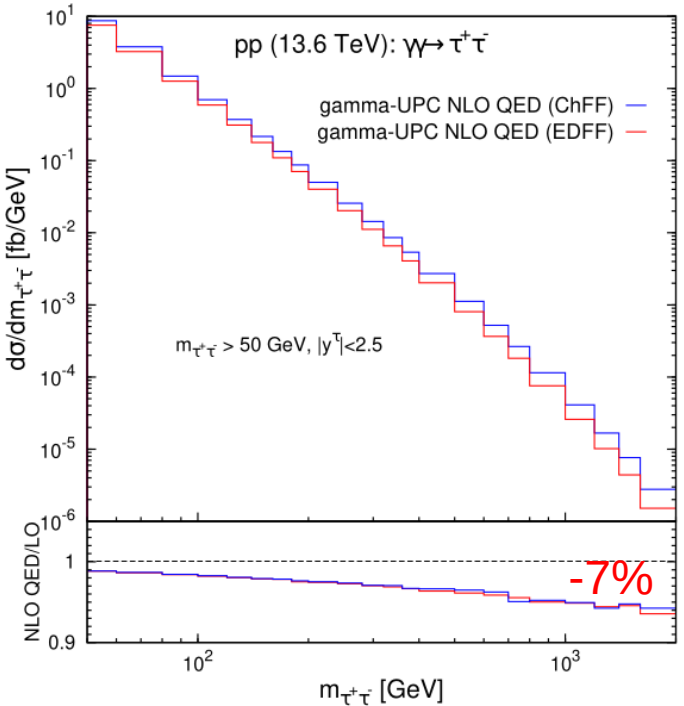
Relevant for accurate (g-2)τ extractions from pp UPCs

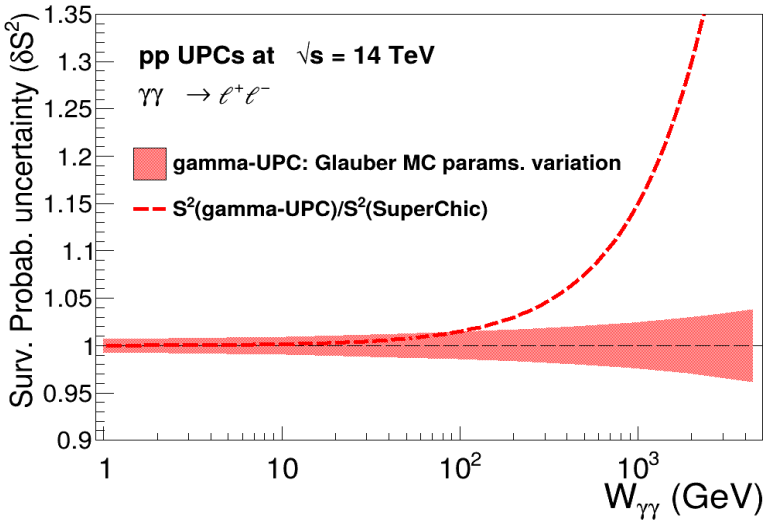
NLO QED corrections to $\gamma\gamma \to \tau^+\tau^-$ (p-p UPCs)

- All $\gamma\gamma$ MCs so far included only LO diags (plus FSR). Impact of NLO QED:



- Impact of virtual & real NLO QED corrections on $d\sigma/dm(\tau\tau)$ and $d\sigma/p_T(\tau\tau)$:





However, for $m(\tau\tau)$=0.3-2 TeV (proton tagging), the survival factor uncertainty is 4-25% !

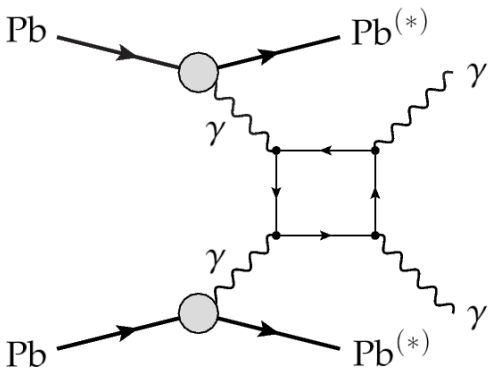
$\gamma\gamma$ collisions with gamma-UPC: Summary

- The LHC is a unique $\gamma\gamma$ collider, with the largest x-sections ever probed over masses $m_{\gamma\gamma} \approx 0.1$ GeV – 4 TeV
- Various complementary means to measure $\gamma\gamma$ processes:
  - PbPb UPCs: At low masses ($m_{\gamma\gamma} \approx 5$–$100$ GeV) with zero pileup
  - pp UPCs: At intermediate masses ($m_{\gamma\gamma} \approx 50$–$300$ GeV) with small N^{vtx}_{tracks}, Aco
  - pp UPCs: At high masses ($m_{\gamma\gamma} \approx 300$–$2500$ GeV) with protons tagged in PPS
- Increasing number of measurements performed:
  - Precise SM (few % uncert.) measurements: $\gamma\gamma \to e^+e^-$, $\gamma\gamma \to \mu^+\mu^-$ (constraints on photon fluxes, neutron emission probabilities,…)
  - First observations of rare SM processes: (g–2) tau, LbL,…
  - Competitive BSM limits: ALPs, massive gravitons, aQGC,...
- Improved theoretical predictions with $\mathcal{O}$(few %) uncertainties:
  - ChFF photon flux preferred. Controlled few % parametric uncertainties
  - NLO QED corrections modify $\gamma\gamma \to \ell^+\ell^-$ differential x-sections by few %
  - Proton survival probability has relatively larger uncertainties at high masses

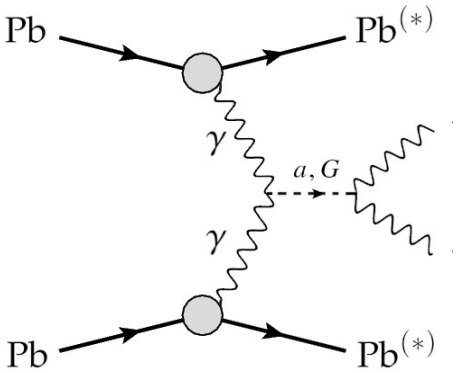
Backup slides

Photon-photon collisions @ LHC: Highlights

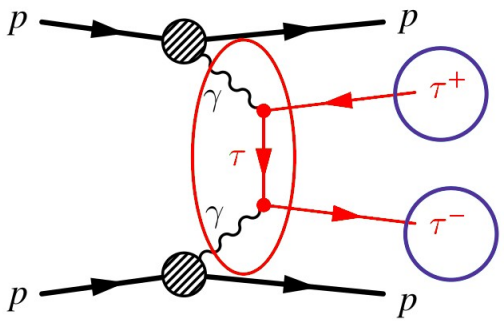
Observation of
light-by-light scattering

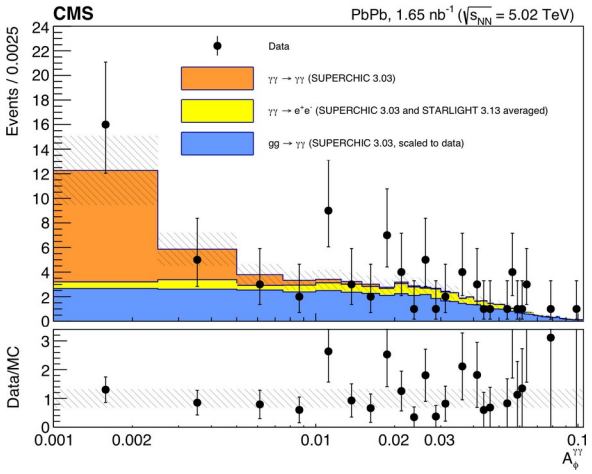


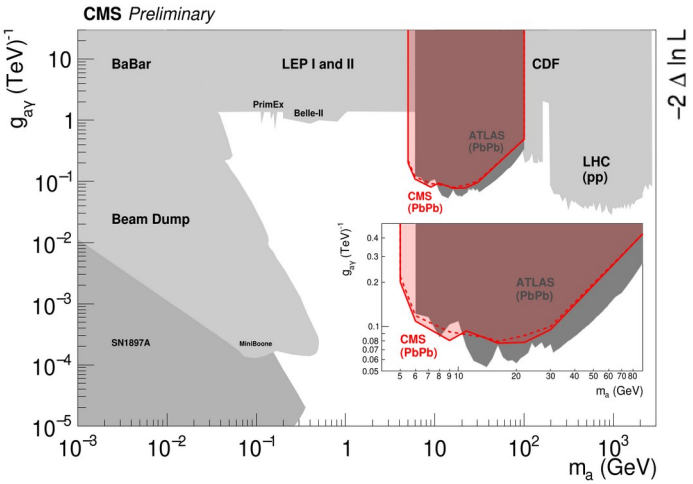
Competitive searches
for ALPs/gravitons

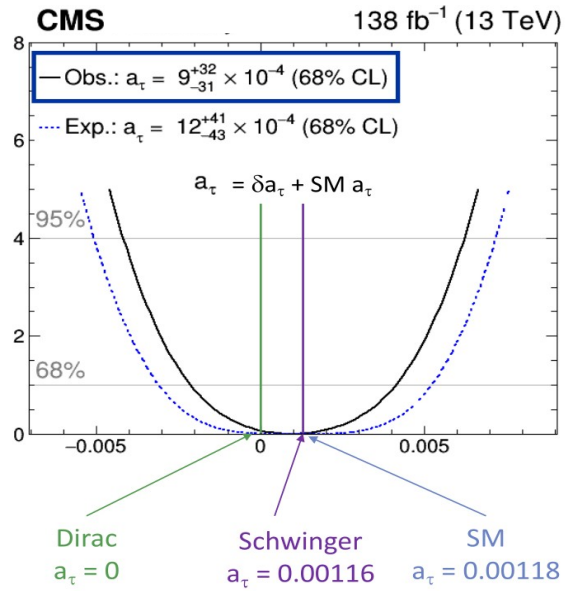


Best measurement
of tau (g–2)









$$\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 107 \pm 33\,(\text{stat}) \pm 20\,(\text{syst})\,\text{nb}$$

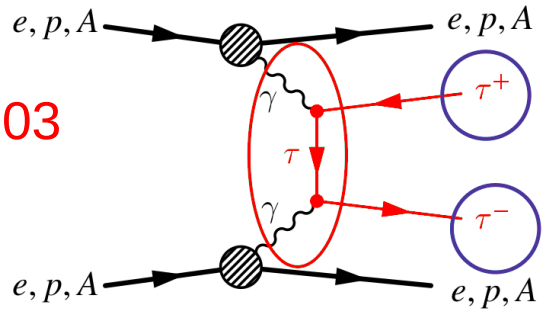
$$\sigma_{\text{NLO}}(\gamma\gamma \to \gamma\gamma) = 95.4 \pm 2.0\,\text{nb}$$

Best ALPs/Gravitons
limits ($g_{a\gamma}$>0.05 TeV^{-1})
over m_a = 5–10 GeV

$$a_\tau = 0.0009^{+0.0032}_{-0.0031}$$

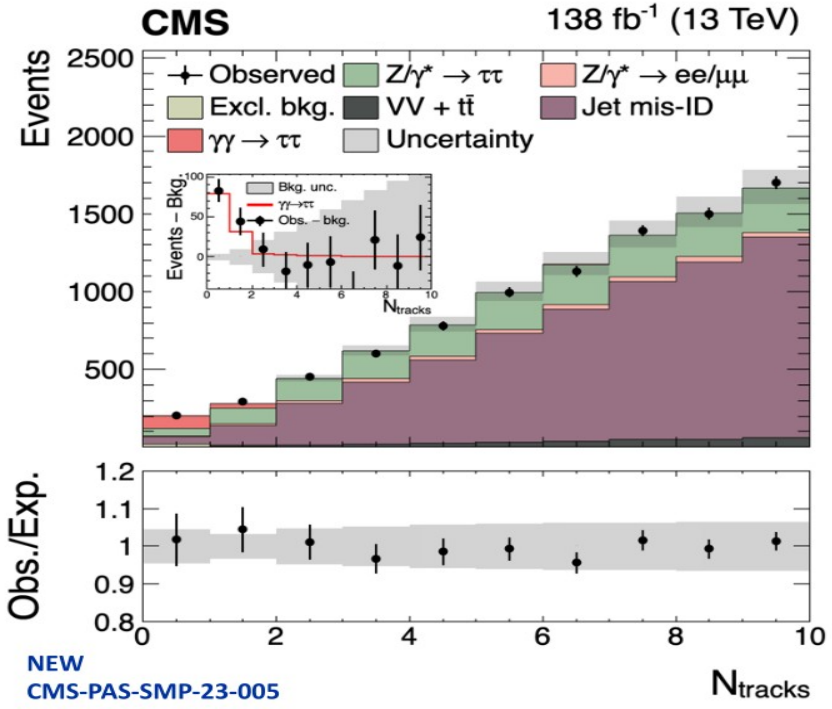
Anomalous tau lepton $(g-2)_\tau$ via $\gamma\gamma \to \tau^+\tau^-$

- Anomalous τ magnetic moment barely constrained from LEP $\gamma\gamma \to \tau\tau$ measurements: $(g-2)_\tau$ = -0.05 – 0.03

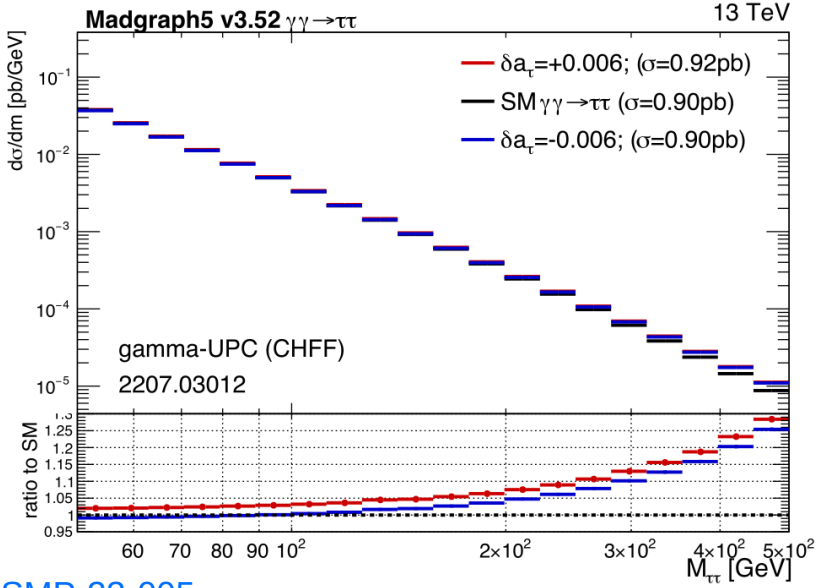


- 1st observation in PbPb UPCs by ATLAS/CMS in various decay modes (1-prong, 3-prong, e-mu).

1st observation in pp UPCs: N_{tracks}=0,1 at vtx & Aco<1% (back-to-back di-tau)



σ(γγ → ττ) vs. $m_{\tau\tau}$ within SMEFT-sim_general

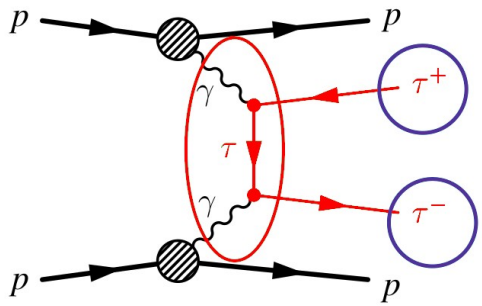


[CMS-SMP-23-005, arXiv:2406.03975]

- Cross section vs. visible ditau mass constrains (g-2) within EFT approach

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

- Anomalous τ magnetic moment barely constrained from LEP $\gamma\gamma \to \tau\tau$ measurements: $(g-2)_\tau$ = -0.05 – 0.03



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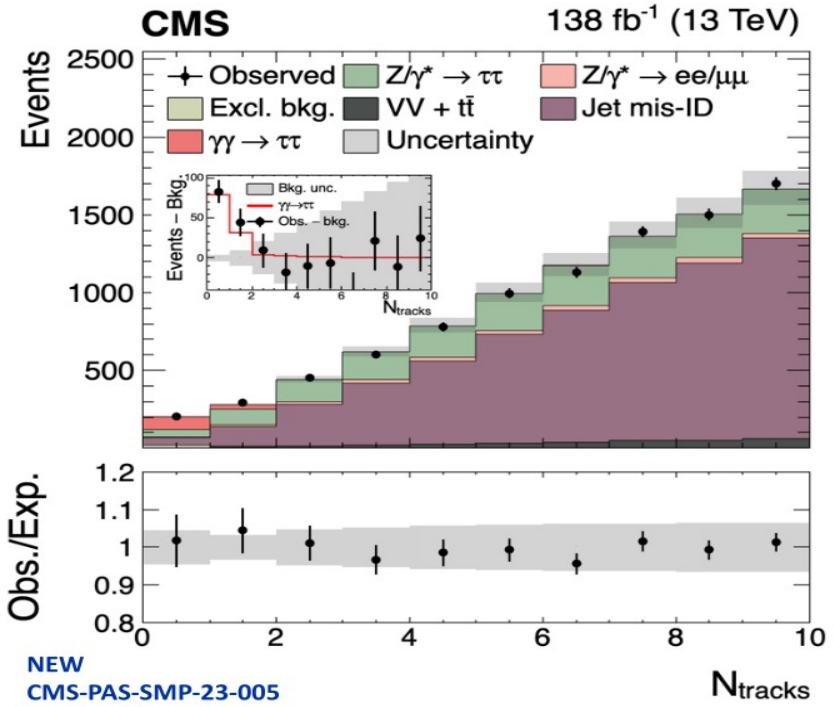
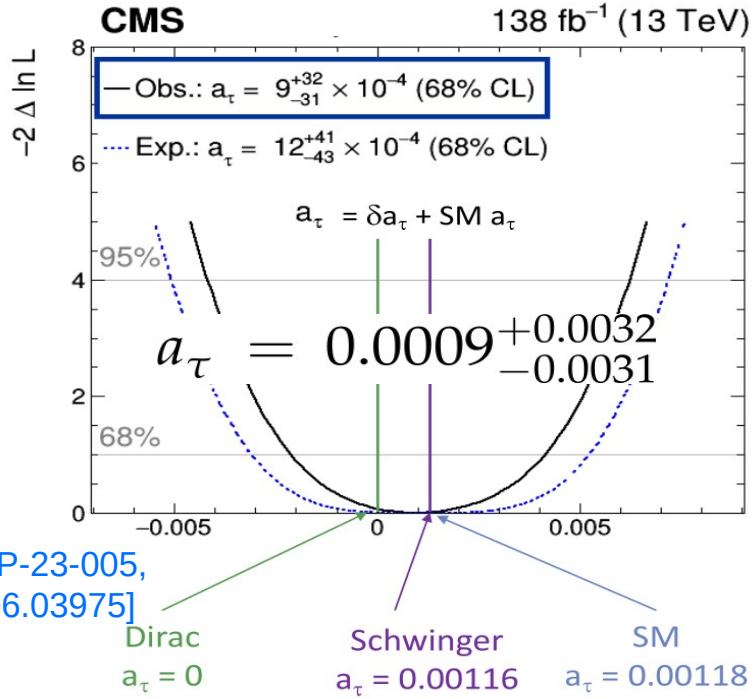




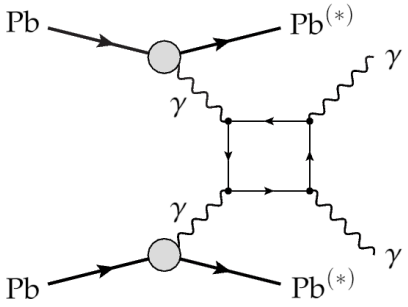
[CMS-SMP-23-005, arXiv:2406.03975]

- Most precise $(g-2)_\tau$ to date ($\times$10 LEP). Approaching NLO Schwinger term.

Observation of LbL scattering via $\gamma\gamma \to \gamma\gamma$

[CMS-HIN-21-015]

- Light-by-light scattering $\gamma\gamma \to \gamma\gamma$ in PbPb(5.02 TeV) UPCs:

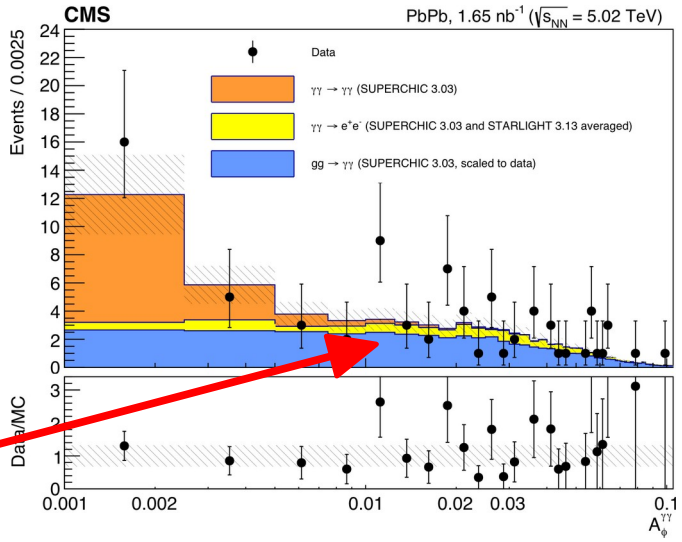


- Analysis strategy:

  Exclusive $\gamma\gamma$ (zero extra activ.)

  $m_{\gamma\gamma}$ > 5 GeV (softest γ possible)

  $Aco_{\gamma\gamma}$<1% ($\gamma\gamma$ back-to-back)



- Irreducible backgrounds:

  CEP $gg \to \gamma\gamma$: normalized to high-Aco tail.
  Mis'id $\gamma\gamma \to e^+e^-$: obtained from direct measurement

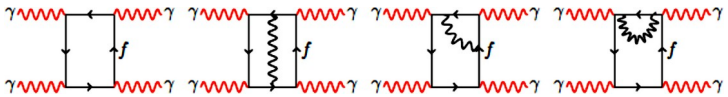
  Signal significance: 5.2σ

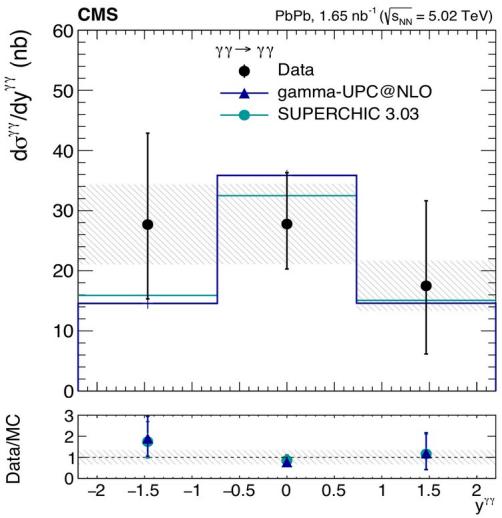
- Measured x-section agrees well with NLO QED+QCD:

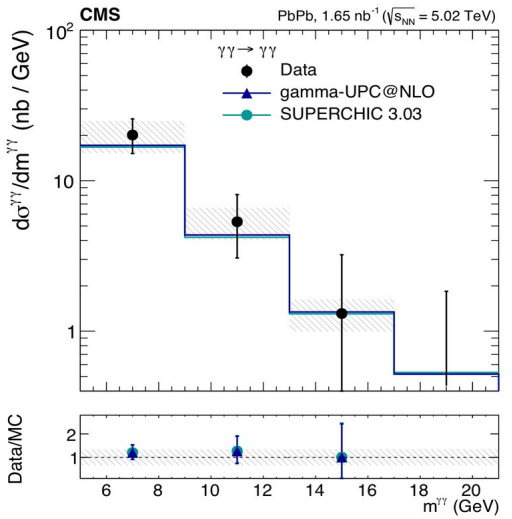
$$\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 107 \pm 33\,(\text{stat}) \pm 20\,(\text{syst})\,\text{nb}$$

$$\sigma_{\text{NLO}}(\gamma\gamma \to \gamma\gamma) = 95.4 \pm 2.0\,\text{nb}$$

K-factor NLO/LO ≈ few %



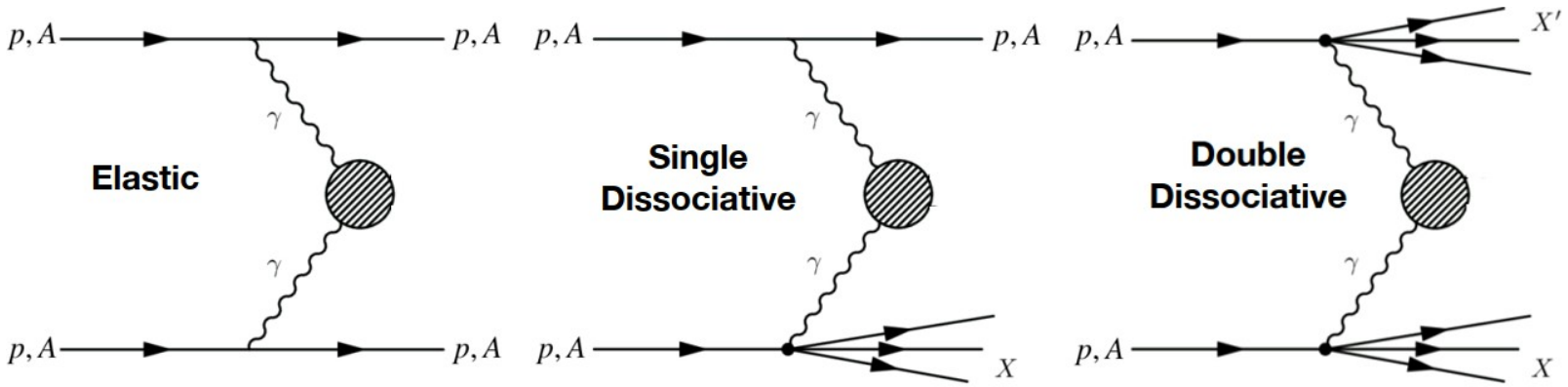




[NLO: A.A.H et al. JHEP 03 (2024) 121, PLB 851(2024) 138555]

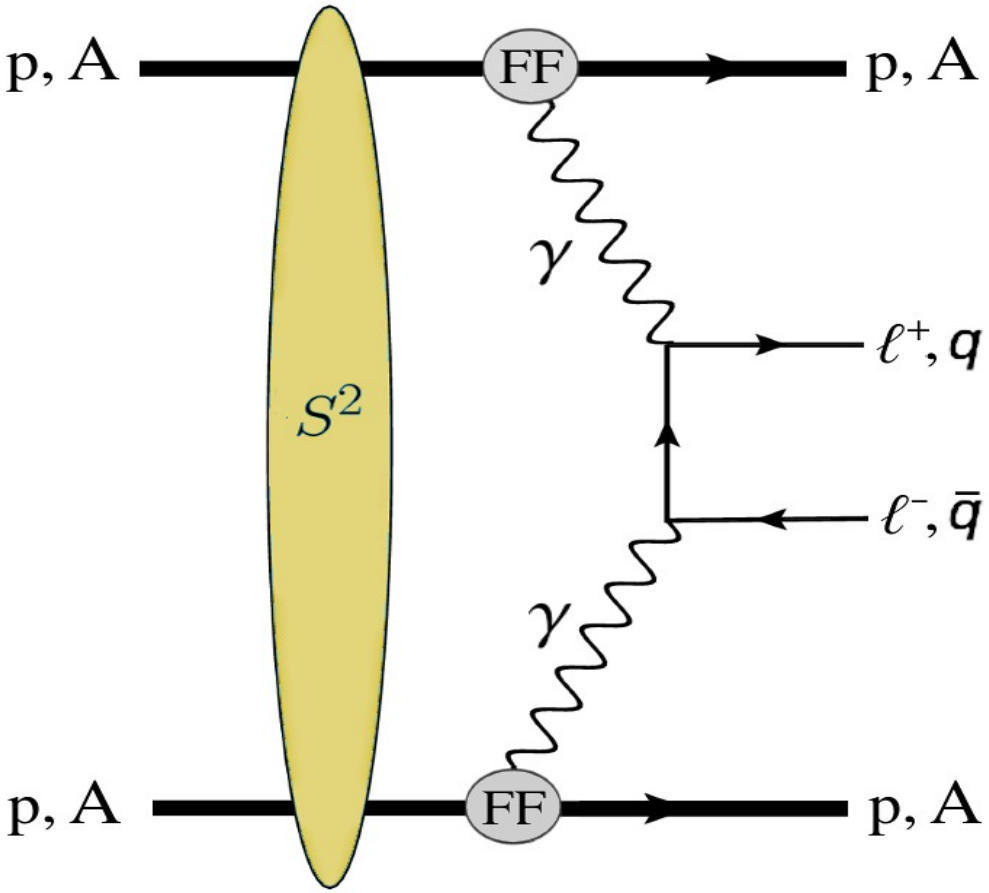
$\gamma\gamma$ collisions: elastic, inel-elastic, inel.-inel.

- 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

$\gamma\gamma \rightarrow X^+X^-$ processes at the LHC