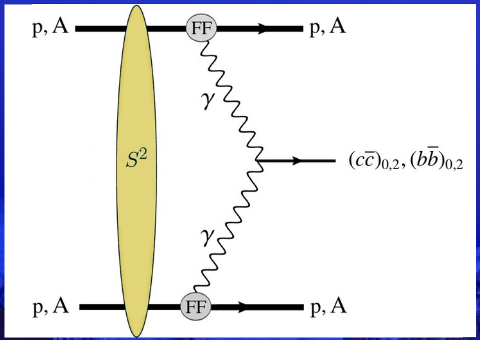
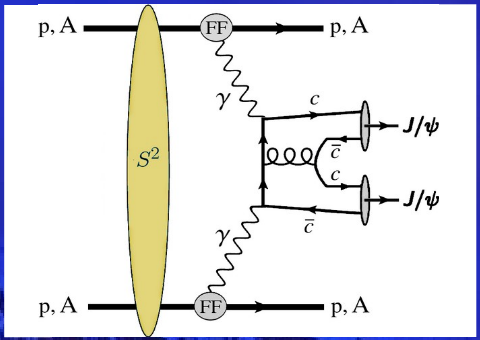




Exclusive quarkonium production in photon-photon collisions with gamma-UPC

Quarkonia As Tools

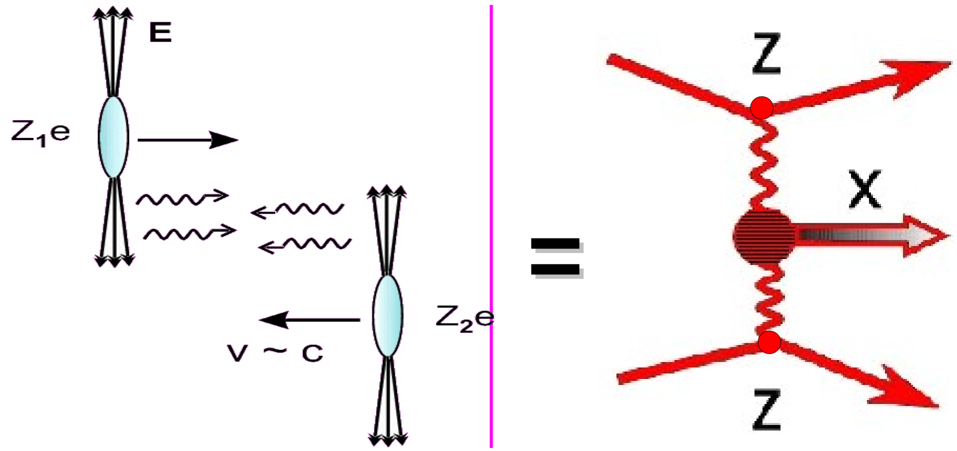
Aussois, Savoie, 10th Jan. 2025

David d'Enterria
(CERN)

Work w/ **Hua-Sheng Shao**: arxiv:2207.03012 [JHEP 09 (2022) 248]
(also DdE & K.Kang, to be submitted)

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:



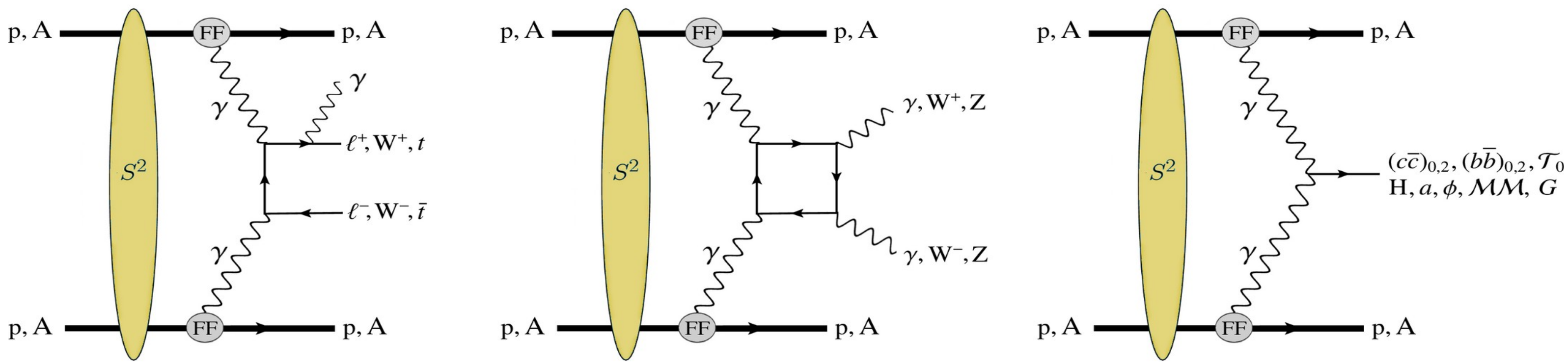
- Huge photon fluxes: $\sigma(\gamma\gamma) \approx Z^4$ ($\approx 5\cdot10^7$ for PbPb) times larger than p,$e^\pm$
- Beam-energy dependence: Photon-photon luminosities increase as $\propto \log^3(\sqrt{s})$

- 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)

Rich & unique (B)SM γγ physics with UPCs at LHC



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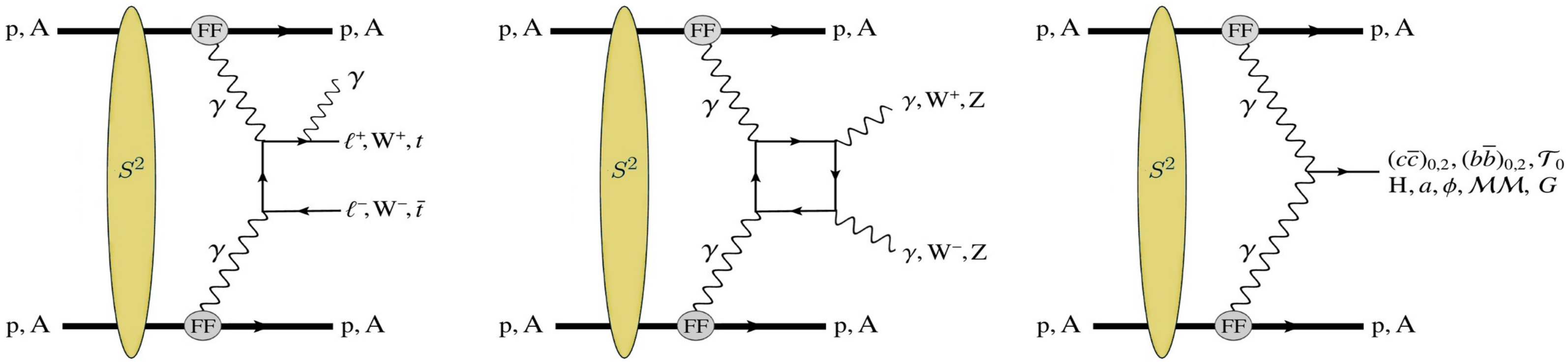
Process	Physics motivation
$\gamma\gamma \to e^+e^-, \mu^+\mu^-$	"Standard candles" for proton/nucleus γ fluxes, EPA calculations, and higher-order QED corrections
$\gamma\gamma \to \tau^+\tau^-$	Anomalous τ lepton e.m. moments [29–32]
$\gamma\gamma \to \gamma\gamma$	aQGC [25], ALPs [27], BI QED [28], 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],...

Rich & unique SM γγ physics with UPCs at LHC



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(this talk)

Dedicated $\gamma\gamma$ MC event generators (up to 2022)

- So far dedicated MC event generators include only hard-coded $\gamma\gamma$ processes, LO QED/QCD only, no extra γ/gluon FSR, few ("uninteresting") background processes generated,…

STARlight (~2000)

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 (~2010)

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 (~2010)

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

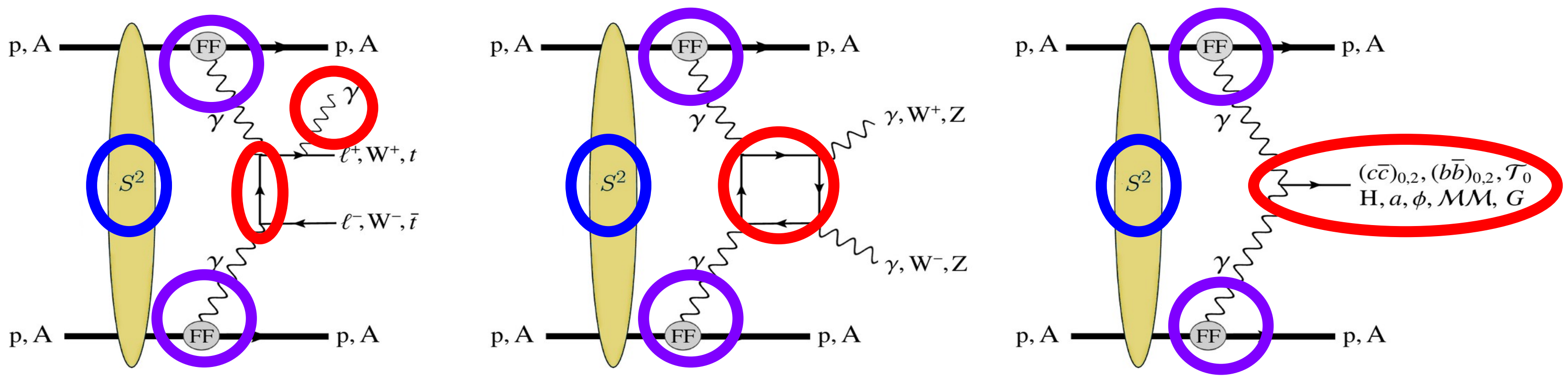
only pp UPC

UPCgen, LPAIR/CepGen (~2020)

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

gamma-UPC γγ 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

Heavy-ion γ fluxes: ChFF vs. EDFF

■ **Electric dipole form factor (EDFF)**

- Same as STARlight

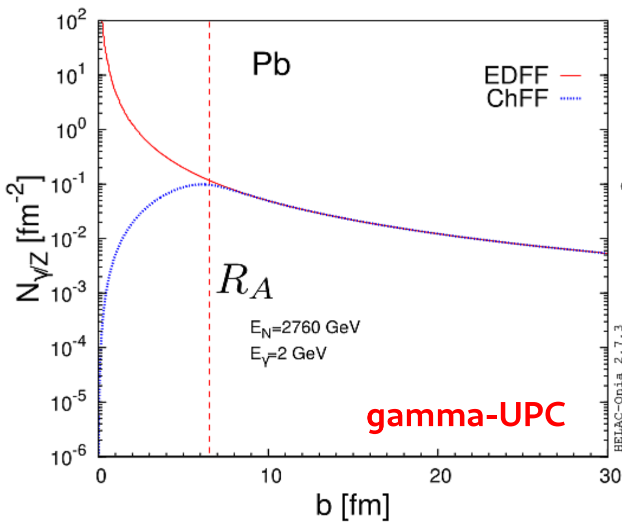
$$N^{\rm EDFF}_{\gamma/Z}(E_\gamma, b) = \frac{Z^2\alpha}{\pi^2}\frac{\xi^2}{b^2}\left[K_1^2(\xi) + \frac{1}{\gamma_L^2}K_0^2(\xi)\right] \qquad \xi = \frac{E_\gamma b}{\gamma_L}$$

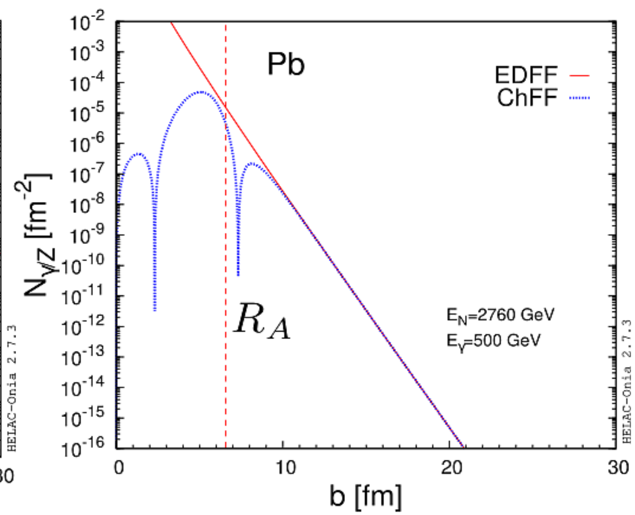
■ **Charge form factor (ChFF)** (same as SuperChic)

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

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

$\rho_A(r)$ = *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 & also agrees better with $\gamma\gamma\to\ell\ell$ UPC data at LHC.

Proton γ fluxes: ChFF vs. EDFF

- **Electric dipole form factor (EDFF)**
  - Same as STARlight

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

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

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

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

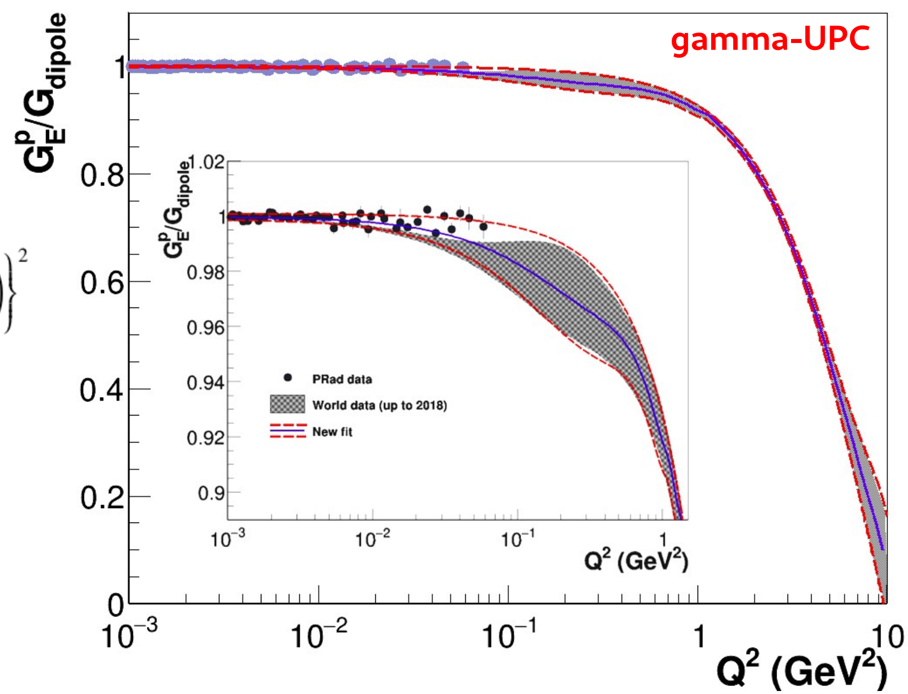
$\rho_A(r)$ = *p,A matter density*

- Proton dipole form-factor:

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

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

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



γγ EPA cross sections & A-A survival probability

- **Cross section:**

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

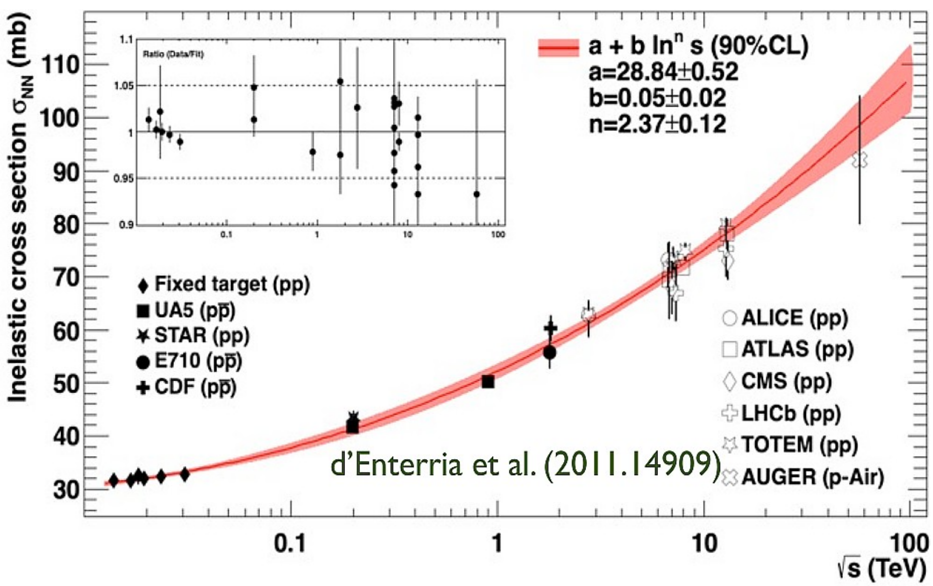
- **Effective two-photon luminosity:**

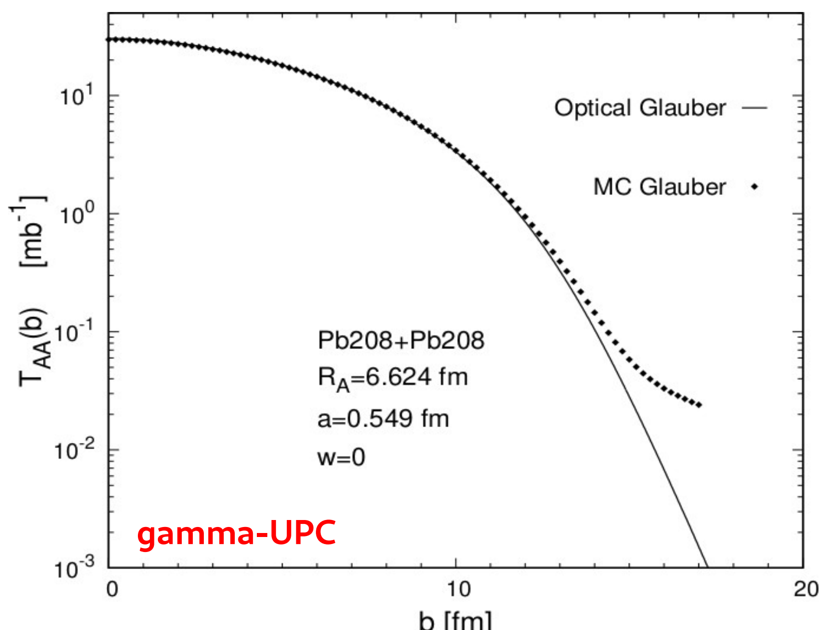
$$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, P_{\mathrm{no\,inel}}(\boldsymbol{b}_1,\boldsymbol{b}_2)\, N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1},\boldsymbol{b}_1)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

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

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

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





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

- **Cross section:**

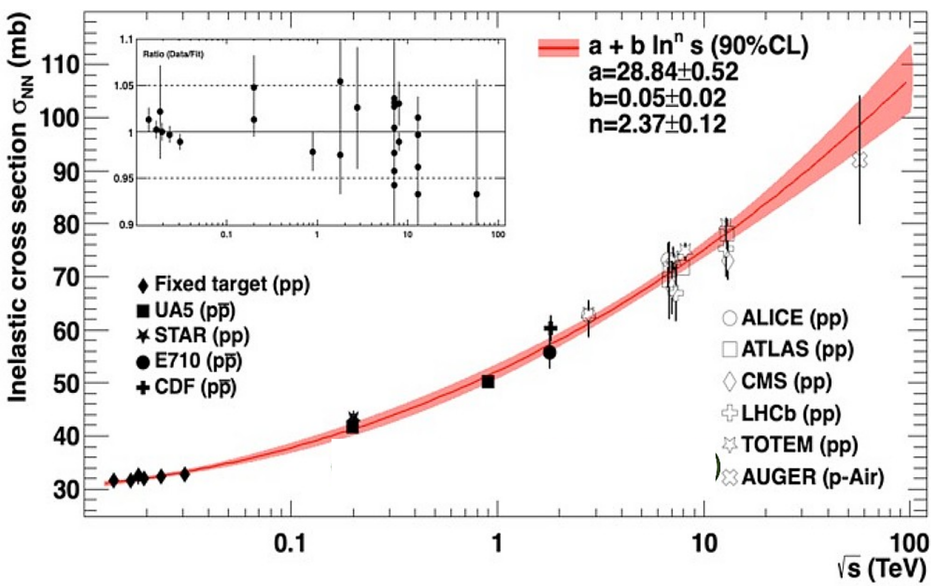
$$\sigma(\mathrm{A\ B} \xrightarrow{\gamma\gamma} \mathrm{A}\ X\ \mathrm{B}) = \int \frac{dE_{\gamma_1}}{E_{\gamma_1}} \frac{dE_{\gamma_2}}{E_{\gamma_2}} \frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} \sigma_{\gamma\gamma\to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

- **Effective two-photon luminosity:**

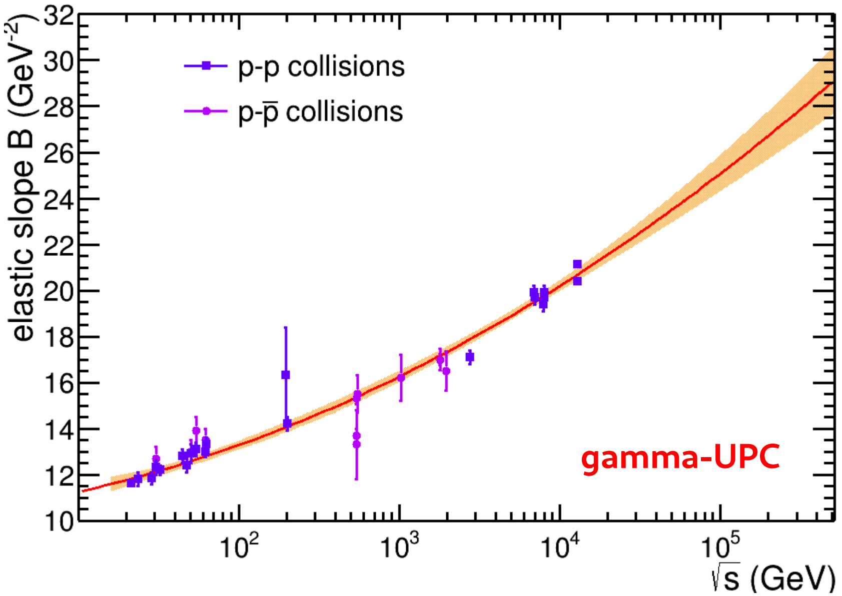
$$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, P_{\text{no inel}}(\boldsymbol{b}_1,\boldsymbol{b}_2)\, N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1},\boldsymbol{b}_1)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

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

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



Parametrized proton elastic slope data:



How peripheral are Pb-Pb UPCs at the LHC?

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

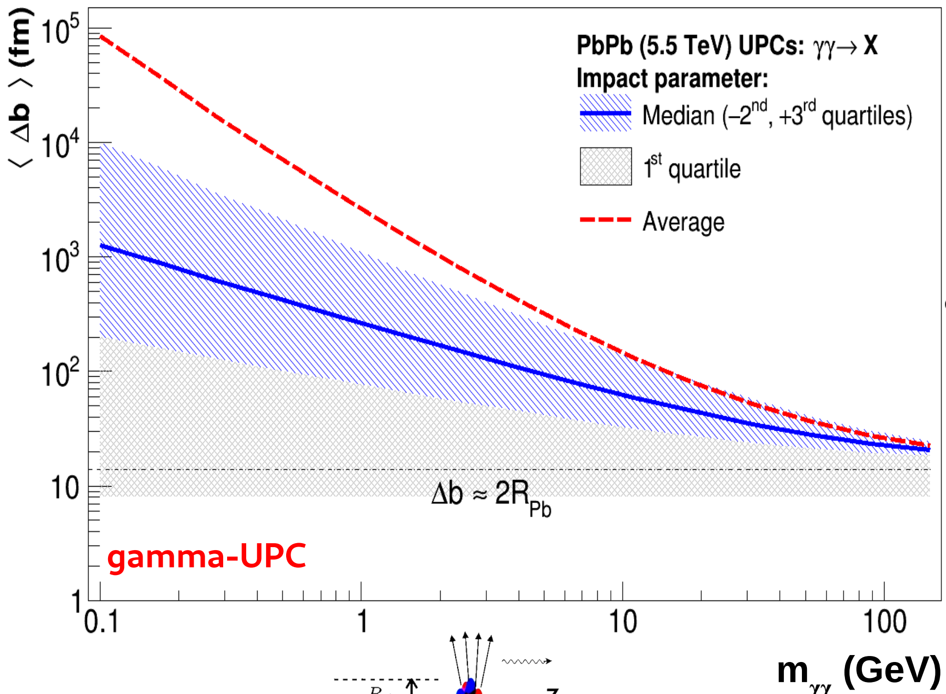
  $m_{\gamma\gamma}$ < 5 GeV: $\langle\Delta b\rangle$ > 100 fm

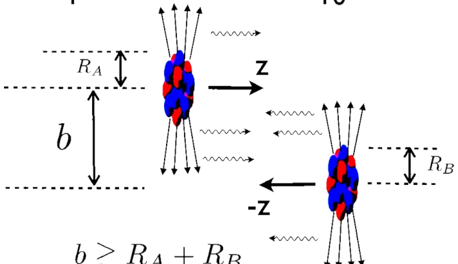
  $m_{\gamma\gamma}$ >100 GeV: $\langle\Delta b\rangle$ ~20 fm

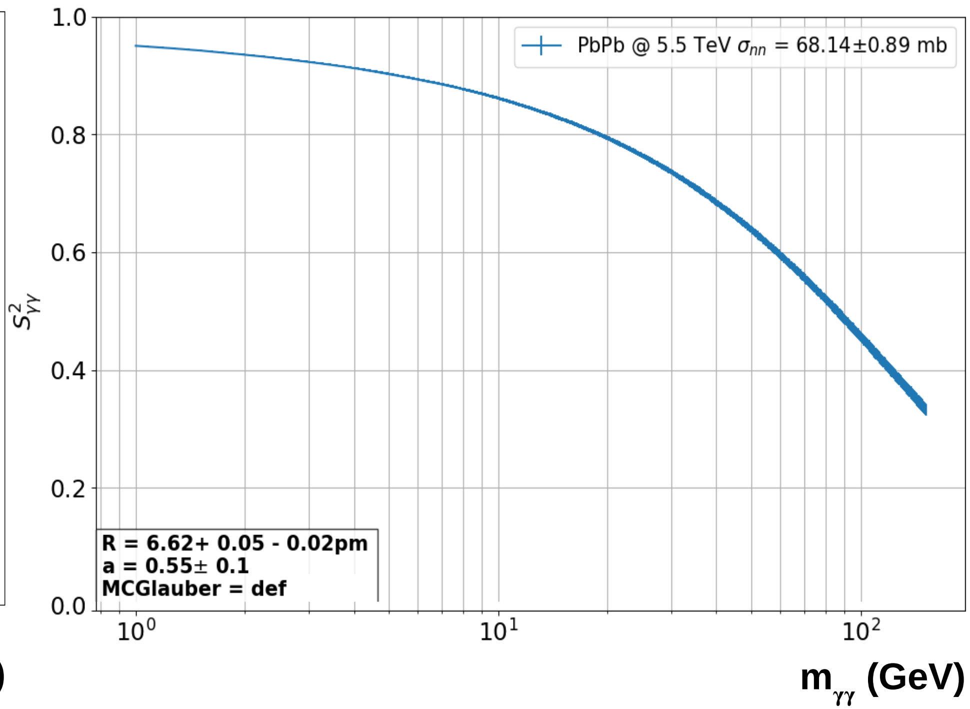
- Pb-Pb survival probab. vs. $m_{\gamma\gamma}$:

  $m_{\gamma\gamma}$ < 5 GeV: $\langle P_{\text{non-overlap}}\rangle$ > 90%

  $m_{\gamma\gamma}$ > 100 GeV: $\langle P_{\text{non-overlap}}\rangle$ < 40%







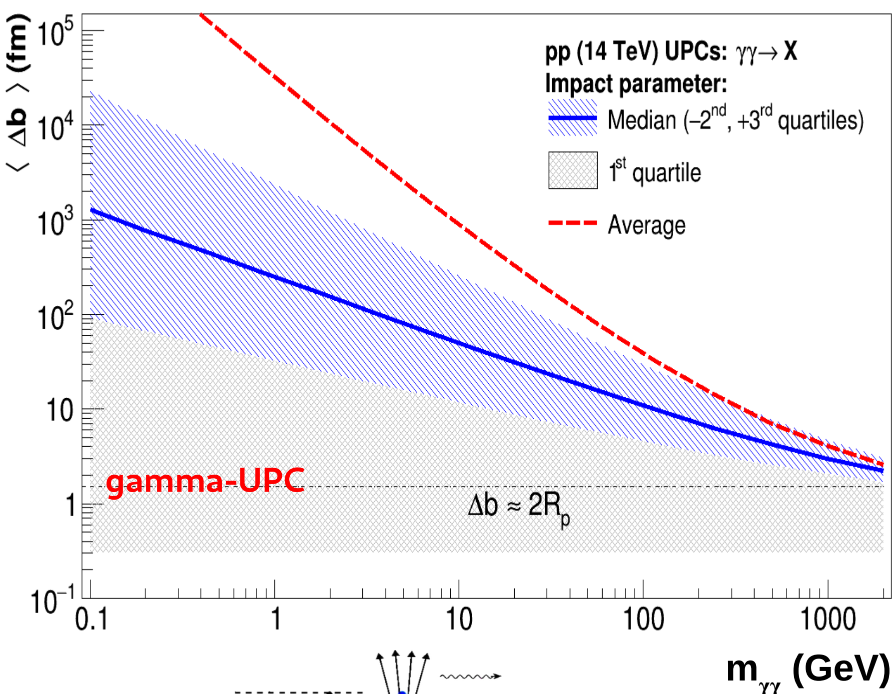
$$S^2_{\gamma\gamma} = \frac{\int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2\, P_{\text{no inel}}(\boldsymbol{b}_1,\boldsymbol{b}_2)\, N_{\gamma_1/Z_1}(E_{\gamma_1},\boldsymbol{b}_1) N_{\gamma_2/Z_2}(E_{\gamma_2},\boldsymbol{b}_2)}{\int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2\, N_{\gamma_1/Z_1}(E_{\gamma_1},\boldsymbol{b}_1)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

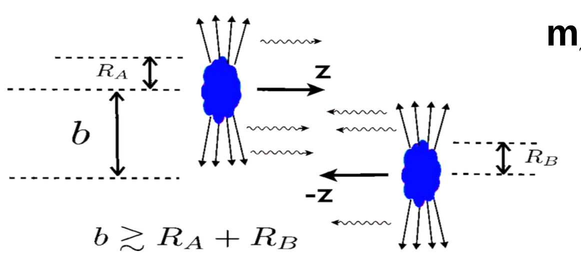
How peripheral are p-p UPCs at the LHC?

- 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

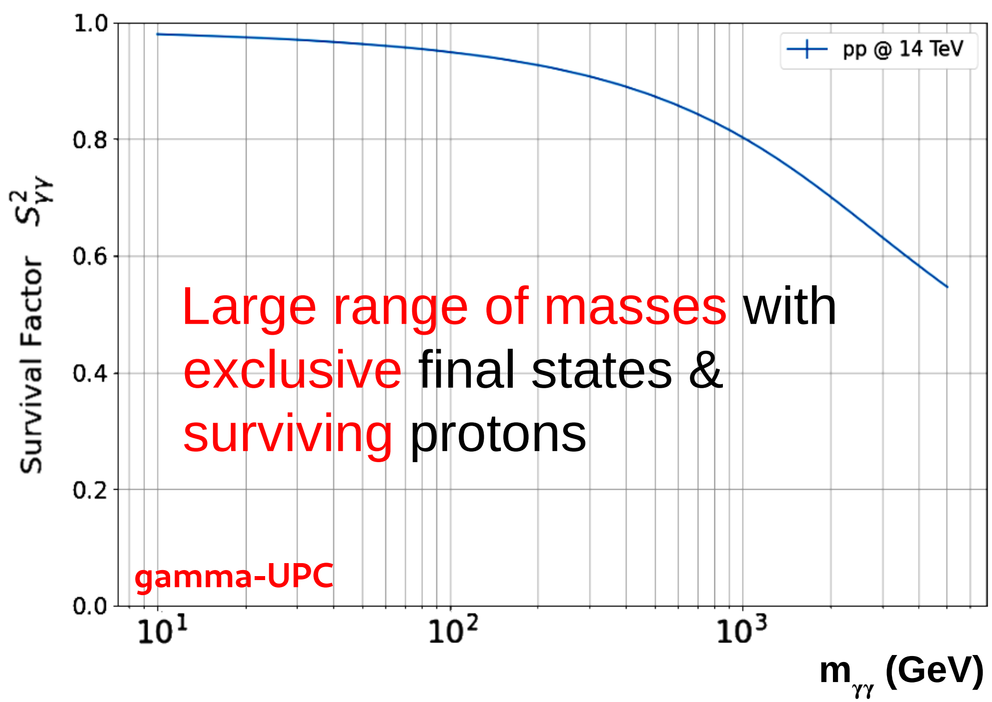




- p-p survival probab. vs. $m_{\gamma\gamma}$:

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

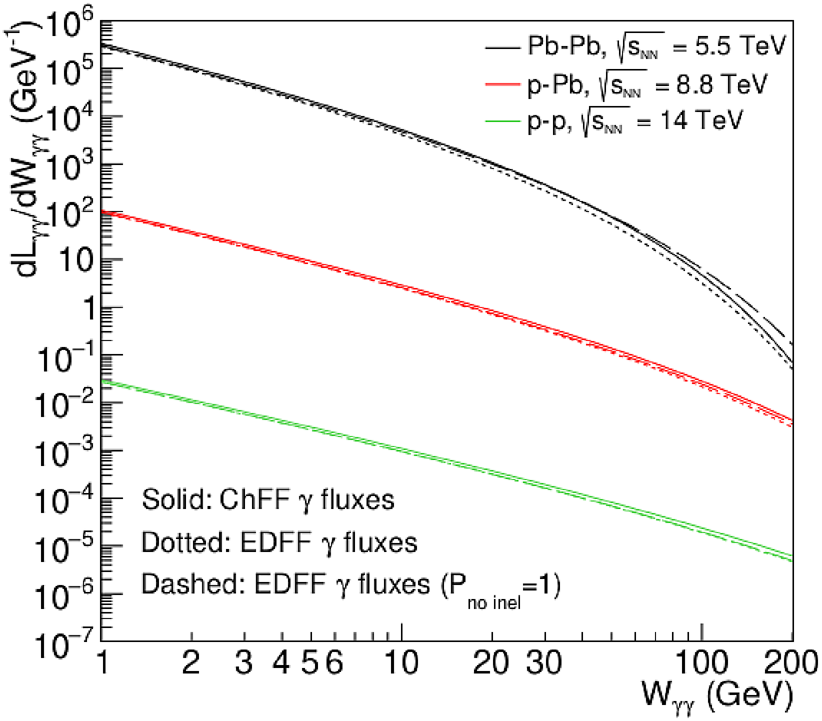
  $m_{\gamma\gamma}$ > 1 TeV: $\langle P_{\text{non-overlap}} \rangle$ < 80%

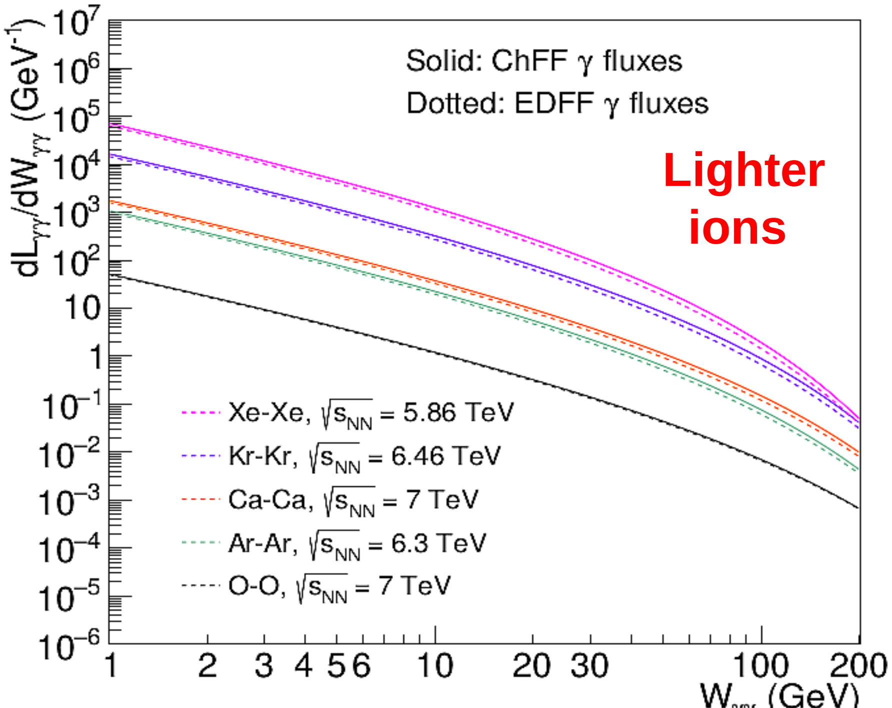


$$S^2_{\gamma\gamma} = \frac{\int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2\, P_{\text{no inel}}(\boldsymbol{b}_1,\boldsymbol{b}_2)\, N_{\gamma_1/Z_1}(E_{\gamma_1},\boldsymbol{b}_1) N_{\gamma_2/Z_2}(E_{\gamma_2},\boldsymbol{b}_2)}{\int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2\, N_{\gamma_1/Z_1}(E_{\gamma_1},\boldsymbol{b}_1)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

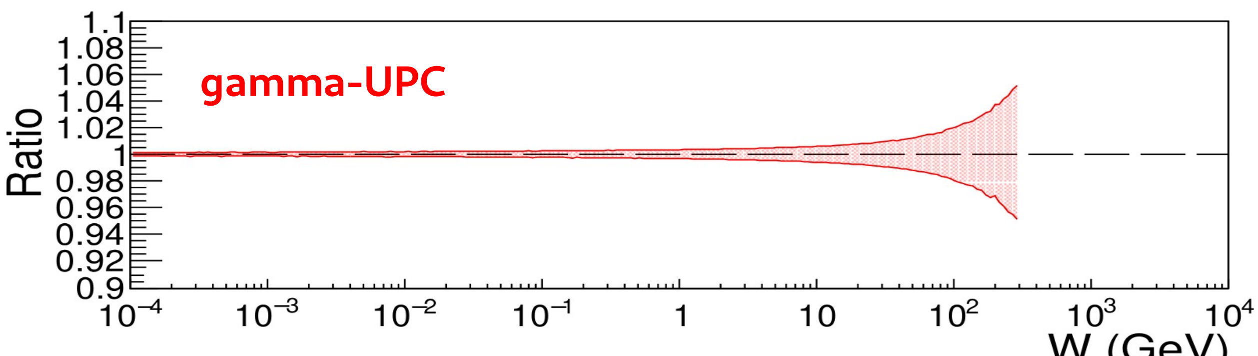
Effective γγ luminosities (p-p, p-A, A-A)

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





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



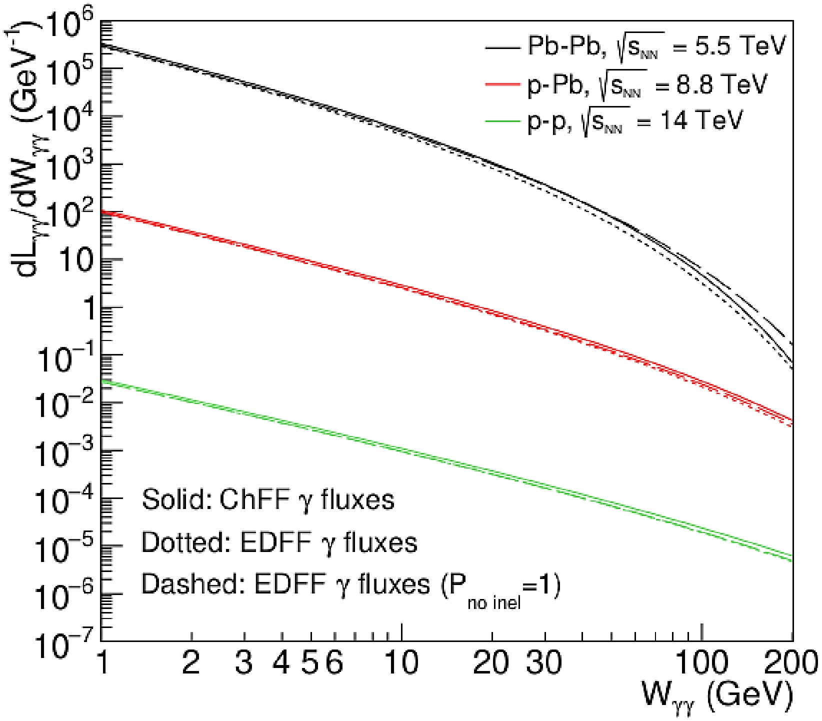
ChFF γ spectra.

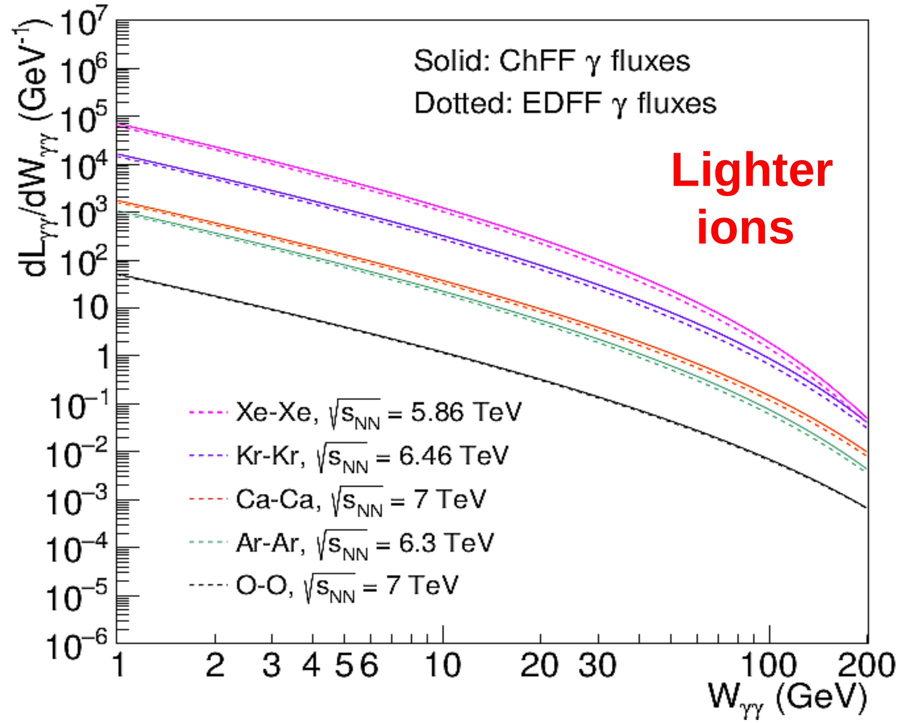
Glauber MC:

Variations of R,a,σ_{NN}

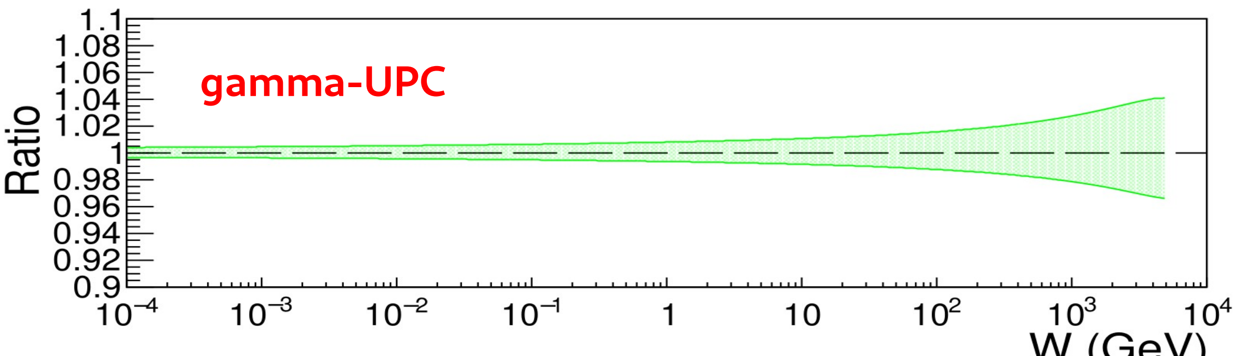
Effective γγ luminosities (p-p, p-A, A-A)

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





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

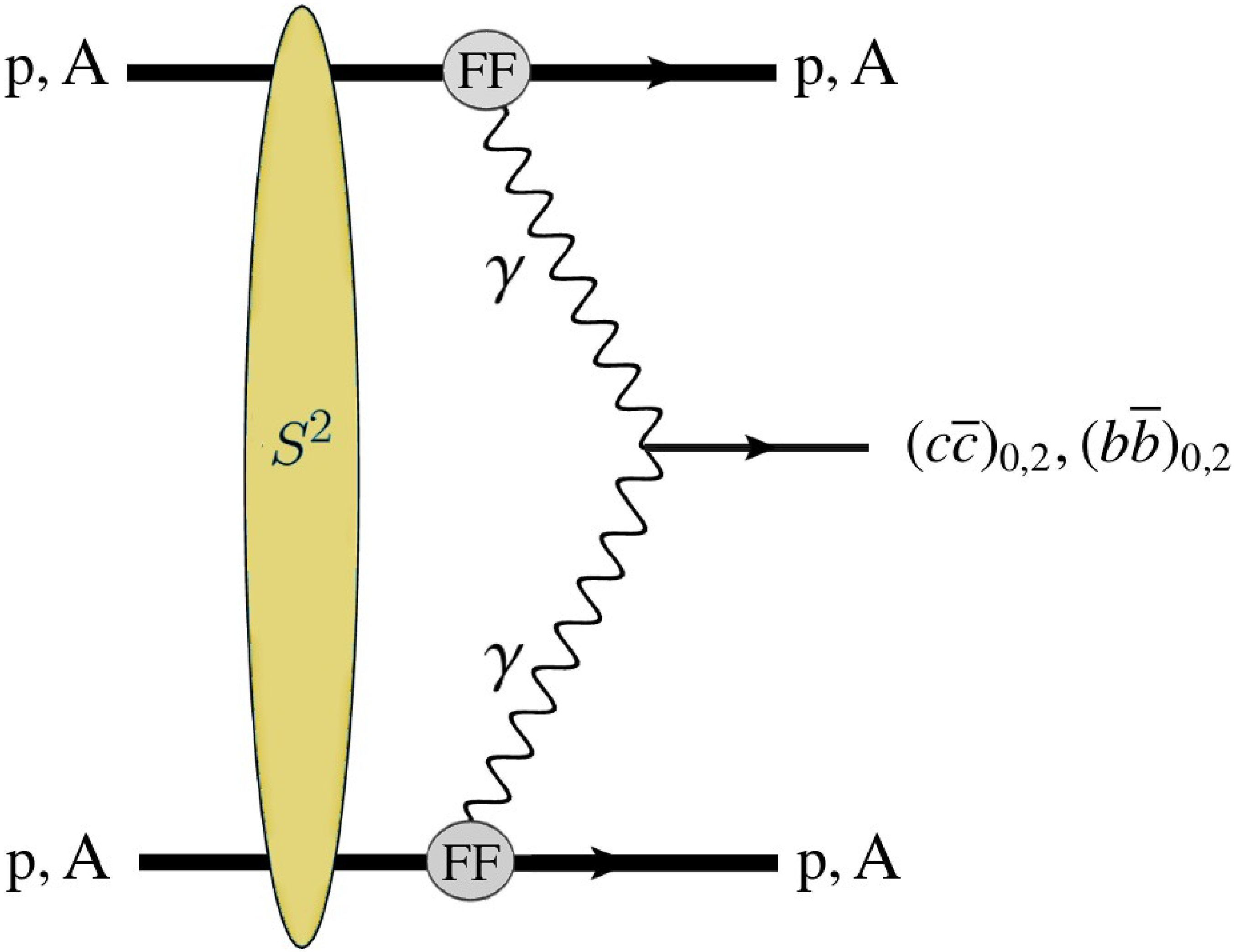


ChFF γ spectra.

Glauber MC:

Variations of b_0

$\gamma\gamma \rightarrow$ even-spin quarkonium production



$\gamma\gamma \to$ even-spin quarkonium production

- Breit-Wigner cross section for the $\gamma\gamma$ production of resonance X with mass m_X, even-spin J, total width Γ_{tot}, and two-photon width $\Gamma_{\gamma\gamma}$:

$$\hat{\sigma}_{\gamma\gamma\to X}(\hat{s}_{\gamma\gamma}) = 8\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}\Gamma_{tot}}{\left(\hat{s}_{\gamma\gamma}-m_X^2\right)^2+(m_X\Gamma_{tot})^2} = 4\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}}{m_X^2}\delta\left(\hat{s}_{\gamma\gamma}-m_X^2\right)$$

- "Pocket-formula" x-section in UPCs: $\sigma(AB \xrightarrow{\gamma\gamma} A\,X\,B) = 4\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}}{m_X^2}\left.\frac{d\mathcal{L}_{\gamma\gamma}^{(AB)}}{d\hat{s}_{\gamma\gamma}}\right|_{\hat{s}_{\gamma\gamma}=m_X}$

- 8 scalar & tensor $Q\bar{Q}$ states producible in UPCs (not all have measured $\Gamma_{\gamma\gamma}$):

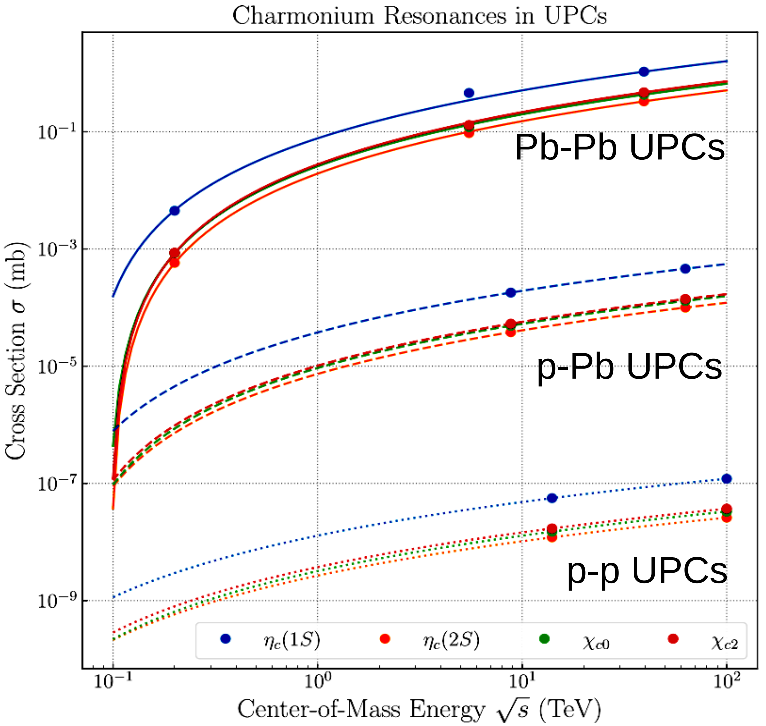
Resonance	J^{PC}	m_X (GeV)	Γ_{tot} (MeV)	$\Gamma_{\gamma\gamma}$ (MeV)	Dominant decay ($\mathcal{B}$)
$\eta_c(1S)$	0^{-+}	2.9841 ± 0.0004	30.5 ± 0.5	$(6.788 \pm 0.061)\cdot 10^{-3}$ (*)	$2\left(\pi^+\pi^-\pi^0\right)$ $(15.9 \pm 2.0\%)$
$\eta_c(2S)$	0^{-+}	3.6377 ± 0.0009	11.8 ± 1.6	$(2.12 \pm 1.45)\cdot 10^{-3}$	$K\bar{K}\pi$ $(1.9 \pm 1.2\%)$
χ_{c0}	0^{++}	3.41471 ± 0.00030	10.7 ± 0.6	$(2.1828 \pm 0.16)\cdot 10^{-3}$	$\pi^+\pi^-\pi^0\pi^0$ $(3.3 \pm 0.4\%)$
χ_{c2}	2^{++}	3.55617 ± 0.0007	1.98 ± 0.09	$(5.781 \pm 0.354)\cdot 10^{-4}$	$\gamma J/\psi(1S)$ $(19.0 \pm 0.5\%)$
$\eta_b(1S)$	0^{-+}	9.3987 ± 0.0020	10^{+5}_{-4}	$(5.57 \pm 0.32)\cdot 10^{-4}$ (*)	gg $(\approx 100\%)$
$\eta_b(2S)$	0^{-+}	9.999 ± 0.004	5^{+3}_{-2}	$(2.4^{+1.2}_{-1.0})\cdot 10^{-4}$ (**)	gg $(\approx 100\%)$
χ_{b0}	0^{++}	9.85944 ± 0.00052	$2.60^{+0.79}_{-0.57}$	$(0.15^{+0.05}_{-0.03})\cdot 10^{-3}$ (**)	$\Upsilon(2S)\gamma$ $(1.94 \pm 0.27\%)$
χ_{b2}	2^{++}	9.91221 ± 0.00040	$0.180^{+0.016}_{-0.057}$	$(9.3^{+1.3}_{-6.2})\cdot 10^{-6}$ (**)	$\Upsilon(1S)\gamma$ $(18.0 \pm 1.0\%)$

(*) Lattice QCD (**) NRQCD: $\frac{\Gamma(\Upsilon(1S)\to e^+e^-)}{\Gamma(\eta_b(1S)\to\gamma\gamma)} = \frac{1}{3Q_b^2}(1-0.302-0.115)$

$\gamma\gamma \to (c\bar{c})_{0,2}$ production in UPCs at the LHC

- Large LHC production rates for all C-even charmonium (m_X = 2.98–3.55 GeV):
  - – Cross sections: 100–500 μb (10–60 pb) for Pb-Pb (p-p).
  - – Yields (mostly soft hadronic decays): $\mathcal{O}(10^6)$ for Pb-Pb, $\mathcal{O}(10^4)$ for p-Pb & p-p UPCs

Colliding system, $\sqrt{s_{NN}}$	$\sigma(\gamma\gamma \to X)$ $\eta_c(1S)$	$\eta_c(2S)$	χ_{c0}	χ_{c2}
Au-Au, 0.2 TeV	5.65 ± 0.05 μb	0.58 ± 0.38 μb	0.85 ± 0.04 μb	0.86 ± 0.03 μb
$N_{evts}(\mathcal{L}$=1 nb^{-1})	5.6×10^4	5.6×10^3	8.5×10^3	8.8×10^3
Pb-Pb, 5.5 TeV	0.62 ± 0.01 mb	96 ± 63 μb	0.12 ± 0.01 mb	0.13 ± 0.01 mb
$N_{evts}(\mathcal{L}$=10 nb^{-1})	6.2×10^6	9.1×10^5	1.2×10^6	1.4×10^6
p-Pb, 8.8 TeV	220 ± 2 nb	35.2 ± 23.0 nb	43.9 ± 2.0 nb	53.0 ± 1.9 nb
$N_{evts}(\mathcal{L}$=1 pb^{-1})	2.2×10^5	3.4×10^4	4.4×10^4	5.0×10^4
p-p, 14 TeV	56.0 ± 4.1 pb	12.0 ± 7.8 pb	15.0 ± 0.7 pb	17.0 ± 0.6 pb
$N_{evts}(\mathcal{L}$=1 fb^{-1})	5.6×10^4	1.2×10^4	1.5×10^4	1.7×10^4



- No existing measurement in UPCs !
- UPC measurements would help solve two issues:
  - – Inconsistency between $\Gamma(\eta_c(1S) \to \gamma\gamma) \approx$ 11 keV decay measurement (BES-III) and lattice-QCD result: $\Gamma(\eta_c(1S) \to \gamma\gamma) \approx$ 6 keV.
  - – Badly known $\eta_c(2S)$ diphoton width: ±60% uncertainty

$\gamma\gamma \rightarrow (c\bar{c})_{0,2}$ production in UPCs at the LHC

- **Large LHC production rates** for all C-even charmonium (m_X = 2.98–3.55 GeV):
  – Cross sections: 100–500 μb (10–60 pb) for Pb-Pb (p-p).
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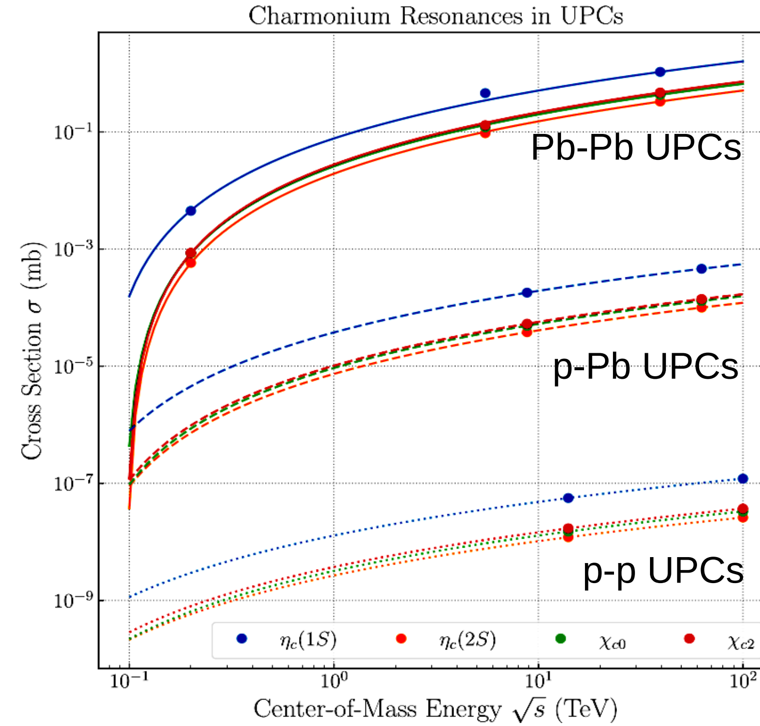


- Measurable in **PbPb, pPb, pp w/o pileup** with **low-p_T charged particle & photon PID/reco** (ALICE, LHCb).

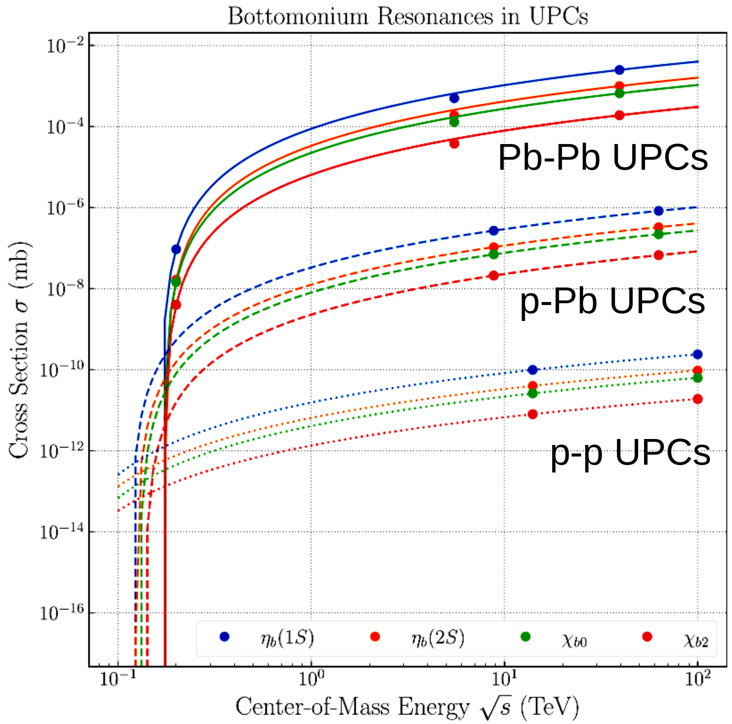
- **Badly known $\eta_c(1S)$, $\eta_c(2S)$ diphoton widths** can be extracted from the measured UPC x-section & known γγ luminosity:

$$\Gamma_{X\rightarrow\gamma\gamma} = \frac{\sigma(AB \xrightarrow{\gamma\gamma} A\,X\,B)}{4\pi^2(2J+1)}\, m_X^2 \left[\frac{d\mathcal{L}^{(AB)}_{\gamma\gamma}}{d\hat{s}_{\gamma\gamma}} \Big|_{\hat{s}_{\gamma\gamma}=m_X} \right]^{-1}$$

$\gamma\gamma \to (b\bar{b})_{0,2}$ production in UPCs at the LHC

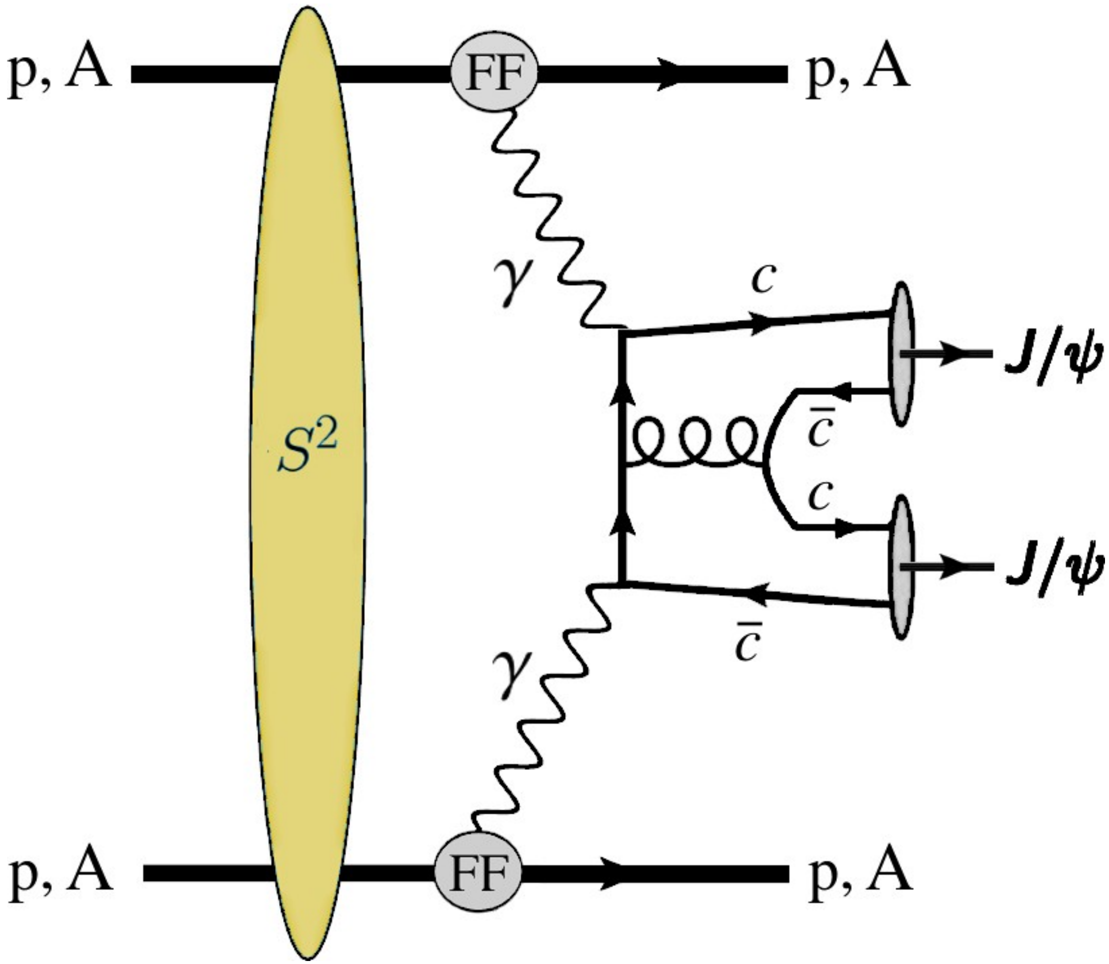
- All C-even bottomonium mesons (m_X =9.4–9.99 GeV) are producible at the LHC:
  - – Cross sections: 40–500 nb (10–100 fb) for Pb-Pb (p-p).
  - – Yields (mostly soft hadronic decays): $\mathcal{O}$(1000) for Pb-Pb, $\mathcal{O}$(10-100) for p-Pb & p-p

Colliding system, $\sqrt{s_{NN}}$	$\sigma(\gamma\gamma \to X)$ $\eta_b(1S)$	$\eta_b(2S)$	χ_{b0}	χ_{b2}
Au-Au, 0.2 TeV	0.11 ± 0.01 nb	$16.8^{+8.4}_{-7.0}$ pb	$14.5^{+4.8}_{-2.9}$ pb	$4.0^{+0.6}_{-2.7}$ pb
$N_{evts}(\mathcal{L}$=1 nb^{-1})	1	0.1	0.15	0.04
Pb-Pb, 5.5 TeV	0.57 ± 0.03 μb	$0.19^{+0.10}_{-0.08}$ μb	$0.13^{+0.04}_{-0.03}$ μb	38^{+5}_{-25} nb
$N_{evts}(\mathcal{L}$=10 nb^{-1})	5700	1900	1300	380
p-Pb, 8.8 TeV	0.27 ± 0.02 nb	106^{+53}_{-44} pb	70^{+23}_{-14} pb	21^{+3}_{-14} pb
$N_{evts}(\mathcal{L}$=1 pb^{-1})	270	100	70	20
p-p, 14 TeV	99^{+56}_{-41} fb	40^{+20}_{-16} fb	26^{+8}_{-5} fb	$8.0^{+1.1}_{-5.3}$ fb
$N_{evts}(\mathcal{L}$=1 fb^{-1})	100	40	26	8

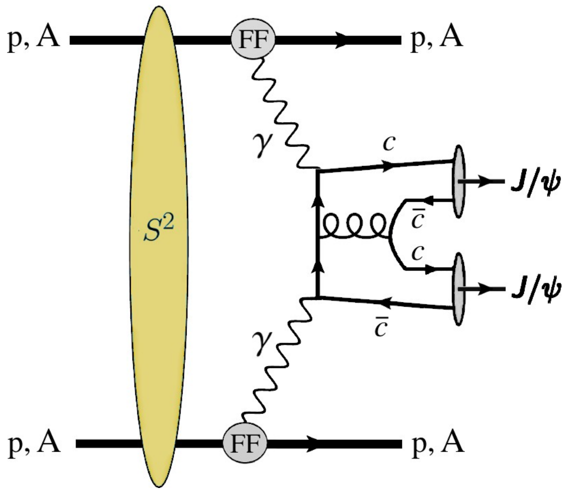


- No existing measurement in UPCs.
- Potentially measurable in PbPb with charged particle & γ PID/reco (all LHC exps.)
- Unknown diphoton widths measurable: $\Gamma_{X\to\gamma\gamma} = \frac{\sigma(AB \xrightarrow{\gamma\gamma} A\,X\,B)}{4\pi^2(2J+1)} m_X^2 \left[\frac{d\mathcal{L}^{(AB)}_{\gamma\gamma}}{d\hat{s}_{\gamma\gamma}} \Big|_{\hat{s}_{\gamma\gamma}=m_X} \right]^{-1}$

γγ → double-quarkonium production



$\gamma\gamma \to$ double-quarkonium production



- Process computed with gamma-UPC+HelacOnia at LO accuracy:

$$\sigma \propto q_Q^4 \cdot \alpha^2 \cdot \alpha_s(m_{QQ})^2 \cdot |R(0)|^4 \cdot d\mathcal{L}_{\gamma\gamma}/dm|_{m=2m} \cdot [2m_{QQ}]^{-4}$$

Process: $\gamma\gamma \to J/\psi J/\psi$	gamma-UPC	
Colliding system, c.m. energy	σ	N_{evts}
p-p at 14 TeV ($\mathcal{L}$=1 fb^{-1})	23^{+13}_{-7} fb	20
p-Pb at 8.8 TeV ($\mathcal{L}$=1 pb^{-1})	64^{+35}_{-18} pb	60
Pb-Pb at 5.52 TeV ($\mathcal{L}$=10 nb^{-1})	128^{+71}_{-36} nb	1300

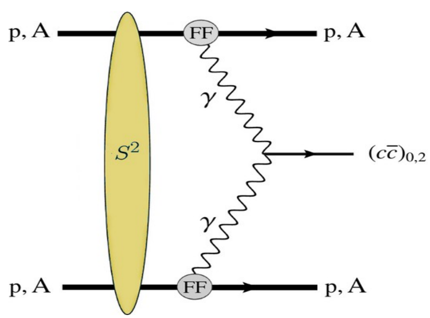
Dominant theoretical uncertainties: +50%,−20%
(varying renormalization scale within $\times$2)

- Double-J/ψ has relative low x-sections in UPCs:
  - Cross sections: 100 nb for Pb-Pb, 60 pb for p-Pb, and 20 fb for p-p.
  - Yields: ~15 exclusive 4-lepton (4μ, 4e, 2μ2e) events expected in PbPb UPCs
- Double-η_c is of the same order (given same $|R(0)|^2$), but double-Υ & double-η_b rates are negligible: (much) smaller q_Q^4, $\alpha_s(m_{QQ})^2$, $\mathcal{L}_{\gamma\gamma}$, m_{QQ}^{-4} factors
- Note $\gamma\gamma \to J/\psi+\gamma$, $\Upsilon+\gamma$ also calculable with gamma-UPC+HelacOnia.

Exclusive quarkonia in γγ collisions: Summary

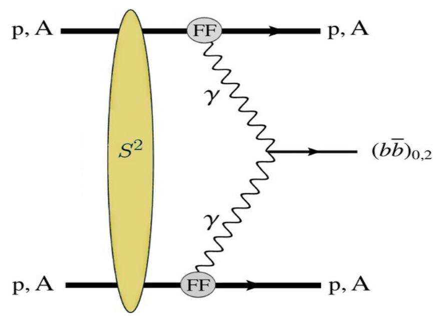
- LHC is a unique γγ collider thanks to PbPb, pPb, pp UPCs. Any photon-coupled object is producible with masses $m_{\gamma\gamma} < 0.16, 2.5, 4.5$ TeV, respectively.
- gamma-UPC (+MG5, +HelacOnia) is available to compute x-sections & generate UPC events for any colliding system & final state:
  - Two different γ fluxes (but ChFF preferred).
  - Realistic hadron survival probabilities with few % parametric uncertainties.
  - NLO QED and/or QCD corrections implementable.
- Quarkonia states can be produced singly (even spin) or in pairs (spin-1):

Spin-0,2 charmonia:



- Large yields: $\mathcal{O}(10^6)$ for Pb-Pb
- (Soft) hadron decays measurable in ALICE/LHCb.
- Improve badly known η_c(1S,2S) diphoton widths

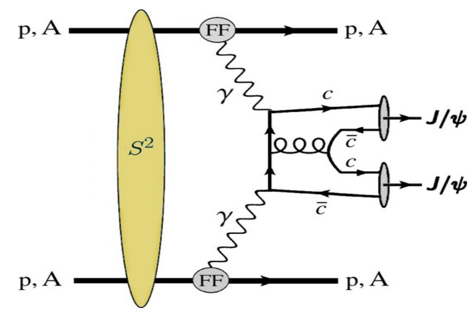
Spin-0,2 bottomonia:



- Moderate yields: $\mathcal{O}(1000)$ for Pb-Pb
- Decays measurable by all LHC exps.
- Measure all unknown diphoton widths

$$\Gamma_{X\to\gamma\gamma} = \frac{\sigma(AB \xrightarrow{\gamma\gamma} A\,X\,B)}{4\pi^2(2J+1)} m_X^2 \left[\left. \frac{d\mathcal{L}_{\gamma\gamma}^{(AB)}}{d\hat{s}_{\gamma\gamma}} \right|_{\hat{s}_{\gamma\gamma}=m_X} \right]^{-1}$$

Double-J/ψ:



~15 exclusive 4-lepton events expected in PbPb

- All these processes are interesting & measurable at the LHC!

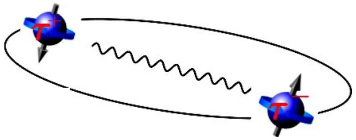
Backup slides

Para-ditauonium via $\gamma\gamma \to \mathcal{T}_0 \to \gamma\gamma$?

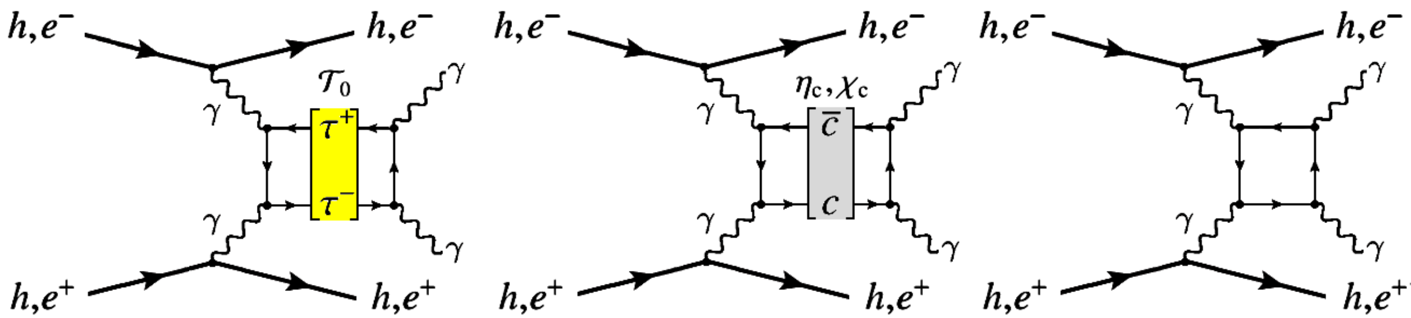
- Ditauonium $\mathcal{T} \equiv (\tau^+\tau^-)$, never observed, is smallest & most-bound leptonium state:

  Mass: $m_{\mathcal{T}} = 2m_\tau + E_{bind} =$ 3553.6962 ± 0.2400 MeV, $E_{bind} = -\alpha^2 m_\tau/(4n^2) = -23.7$ keV

  Bohr radius: $a_0 = 2/(\alpha\, m_\tau) =$ 30.4 fm (×3500 smaller than positronium)



- Signal & background x-sections: $\sigma(a\,b \to a\,b + X) = 4\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}(X)}{m_X^2}\left.\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{(a\,b)}}{\mathrm{d}W_{\gamma\gamma}}\right|_{W_{\gamma\gamma}=m_X}$



[DdE, H-S. Shao, PRD105 (2022)093008]

Colliding system, c.m. energy, $\mathcal{L}_{int}$, exp.	$\sigma \times \mathcal{B}_{\gamma\gamma}$						$N \times \mathcal{B}_{\gamma\gamma}$	
	$\eta_c(1S)$	$\eta_c(2S)$	$\chi_{c,0}(1P)$	$\chi_{c,2}(1P)$	LbL	$\mathcal{T}_0$	$\mathcal{T}_0$	$\chi_{c,2}(1P)$
e^+e^- at 3.78 GeV, 20 fb^{-1}, BES III	120 fb	3.6 ab	15 ab	13 ab	30 ab	0.25 ab	–	–
e^+e^- at 10.6 GeV, 50 ab^{-1}, Belle II	1.7 fb	0.35 fb	0.52 fb	0.77 fb	1.7 fb	0.015 fb	750	38 500
e^+e^- at 91.2 GeV, 50 ab^{-1}, FCC-ee	11 fb	2.8 fb	3.9 fb	6.0 fb	12 fb	0.11 fb	5 600	$3 \cdot 10^5$
p-p at 14 TeV, 300 fb^{-1}, LHC	7.9 fb	2.0 fb	2.8 fb	4.3 fb	6.3 fb	0.08 fb	24	1290
p-Pb at 8.8 TeV, 0.6 pb^{-1}, LHC	25 pb	6.3 pb	8.7 pb	13 pb	21 pb	0.25 pb	0.15	8
Pb-Pb at 5.5 TeV, 2 nb^{-1}, LHC	61 nb	15 nb	21 nb	31 nb	62 nb	0.59 nb	1.2	62

Largest x-sections (0.6 nb) in PbPb UPC but only ~1 evt expected. Visible at e^+e^-