Review of Monte Carlo efforts for UPC collisions

Hua-Sheng Shao

Diffraction and Low-x 2024
Hotel Tonnara Trabia, Sicily
11 September 2024

My

Review of Monte Carlo efforts for UPC collisions

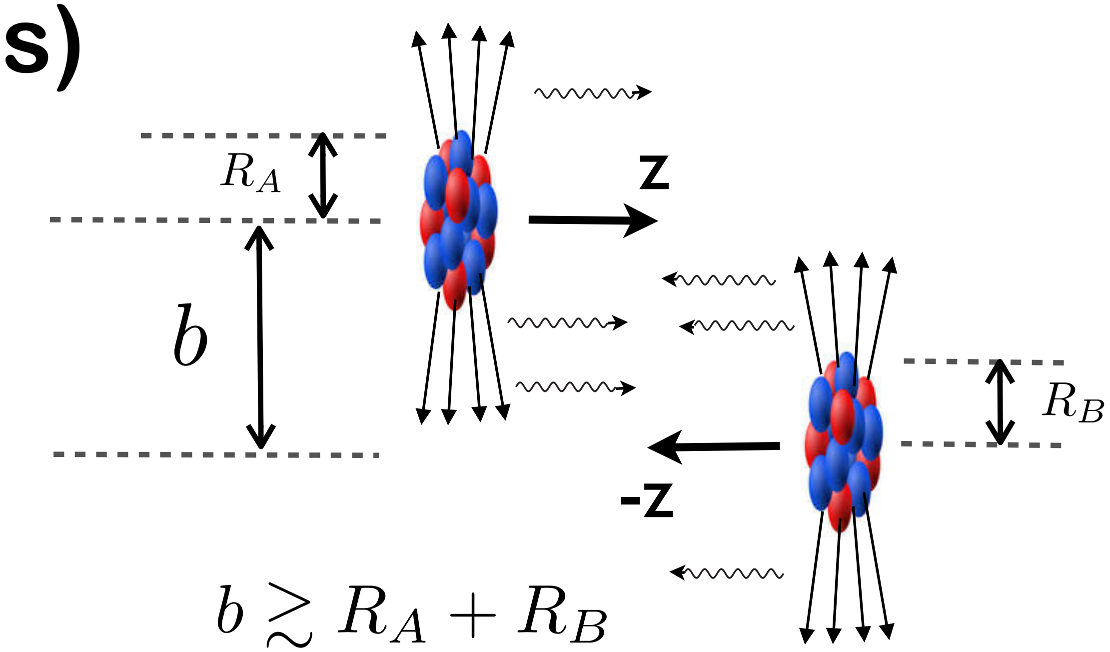
Hua-Sheng Shao

Diffraction and Low-x 2024
Hotel Tonnara Trabia, Sicily
11 September 2024

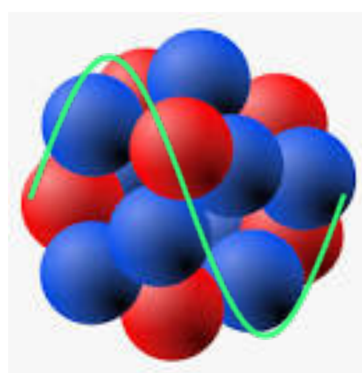
Introduction

- **Ultra-Peripheral Collisions (UPCs)**
- **Large photon flux** $\propto Z^2$
- **Cross section enhanced by** Z^4

  E.g., PbPb is Z^4 = 45M times larger than pp & e+e-



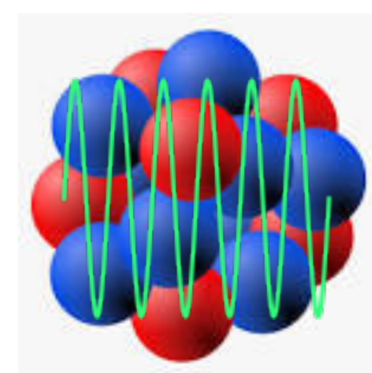
- **Photon may interact either coherently or incoherently**



$\lambda \gtrsim R_A$

Coherent

vs



$\lambda < R_A$

Incoherent

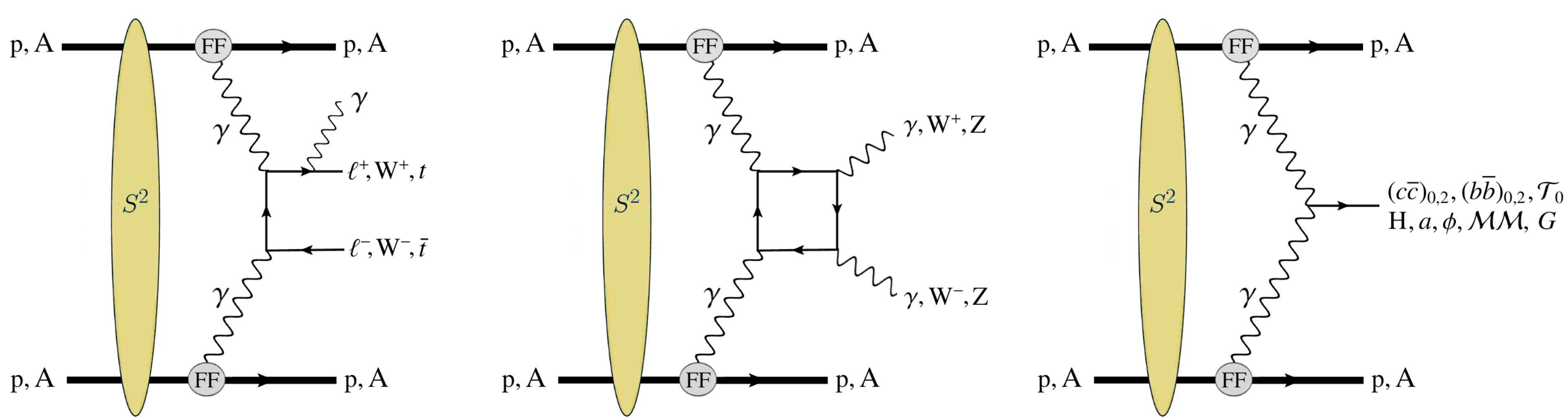
- **Coherent photon virtuality** $Q^2 < R_A^{-2}$

⇨ Equivalent Photon Approximation

- **Gold-plated SM and BSM processes**

Loop-induced in SM !

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, Z$\gamma, \cdots$	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],...



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

Why do we need gamma-UPC ?

LPTHE LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

- **(Dedicated) Monte Carlo event generators on the market**

STARlight

Two-Photon Channels

Particle	Jetset ID
e^+e^- pair	11
$\mu^+\mu^-$ pair	13
$\tau^+\tau^-$ pair	15
$\tau^+\tau^-$ pair, polarized decay	10015*
ρ^0 pair	33
$a_2(1320)$ decayed by PYTHIA	115
η decayed by PYTHIA	221
$f_2(1270)$ decayed by PYTHIA	225
η' decayed by PYTHIA	331
$f_2(1525) \to K^+K^-(50\%), K^0\bar{K}^0(50\%)$	335
η_c decayed by PYTHIA	441
$f_0(980)$ decayed by PYTHIA	9010221

SuperChic

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

See the talk by Lucian Harland-Lang

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   CepGen

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

Why do we need gamma-UPC ?

- **Our aim is to generate any final state of interest**

MadGraph5_aMC@NLO

- Final state of elementary particles in SM and BSM both at LO and NLO QCD+EW

HELAC-Onia

- Final state of elementary particles and quarkonia (including B_c) in SM at tree level

✦ Both can generate the standard Les Houches event files to allow to interface to general-purpose Monte Carlo tools (e.g. Pythia)

- **We need (realistic) photon-photon flux in UPC**

→ **gamma-UPC**

Theoretical Framework

- **Cross section:**

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

Theoretical Framework

- **Cross section:**

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

- **Effective two-photon luminosity:**

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

Theoretical Framework

LPTHE LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

- **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:**

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

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

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

Theoretical Framework

- **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:**

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

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

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

Glauber model

Theoretical Framework

- **Cross section:**

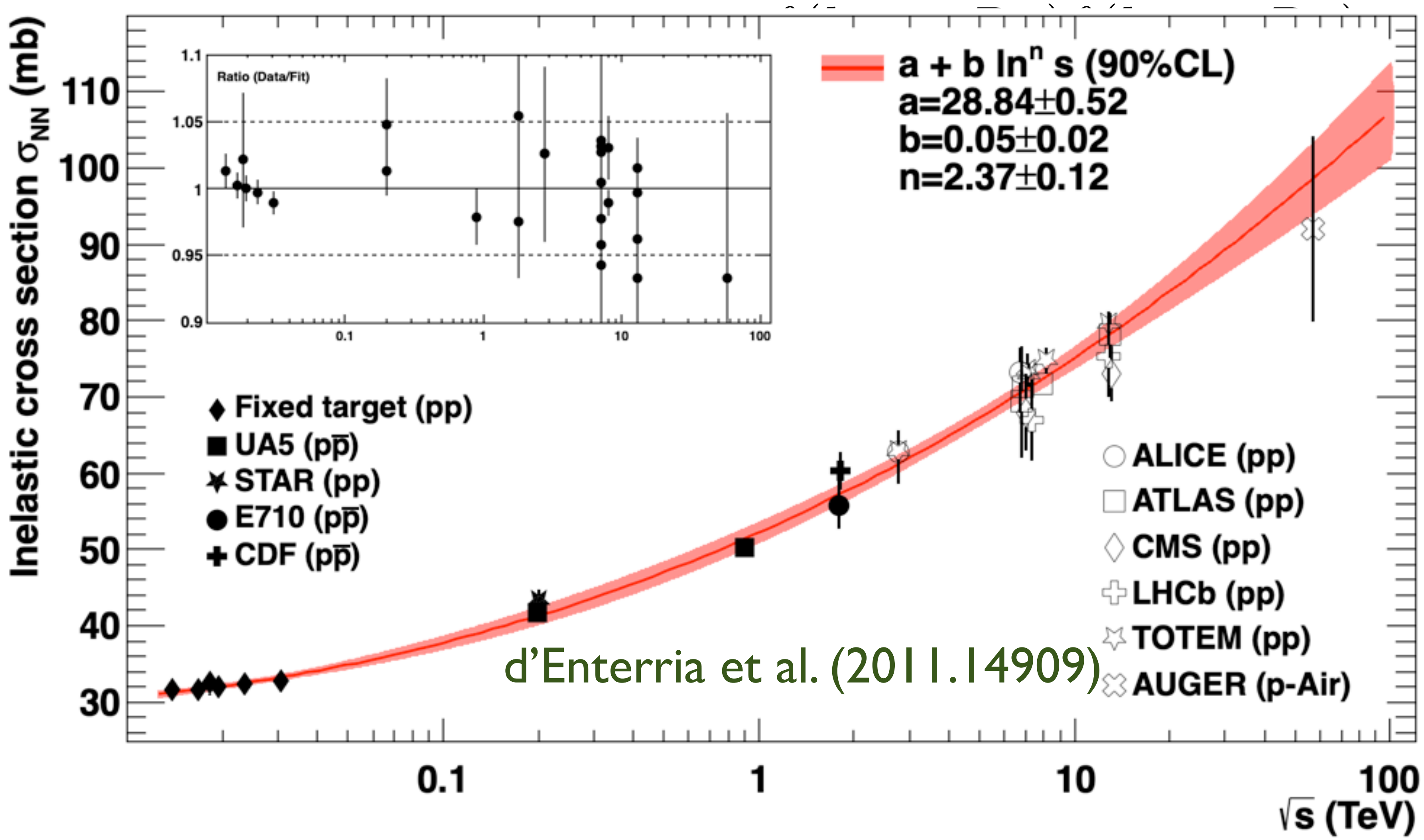
$$\sigma(\mathrm{A}\ \mathrm{B} \xrightarrow{\gamma\gamma} \mathrm{A}\ X\ \mathrm{B}) = \int \frac{dE_{\gamma_1}}{E_{\gamma_1}} \frac{dE_{\gamma_2}}{E_{\gamma_2}} \frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} \sigma_{\gamma\gamma\to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

- **Effective two-photon luminosity:**

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

- **No hadronic/inela**

$$P_{\text{no inel}}(b) = \begin{cases} e^{-\sigma^{\mathrm{NN}}_{\mathrm{inel}}\cdot T_{\mathrm{A}}} \\ e^{-\sigma^{\mathrm{NN}}_{\mathrm{inel}}\cdot T_{\mathrm{A}}} \\ |1-\Gamma(s_{\mathrm{N}} \end{cases}$$



d'Enterria et al. (2011.14909)

Theoretical Framework

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

- **Cross**

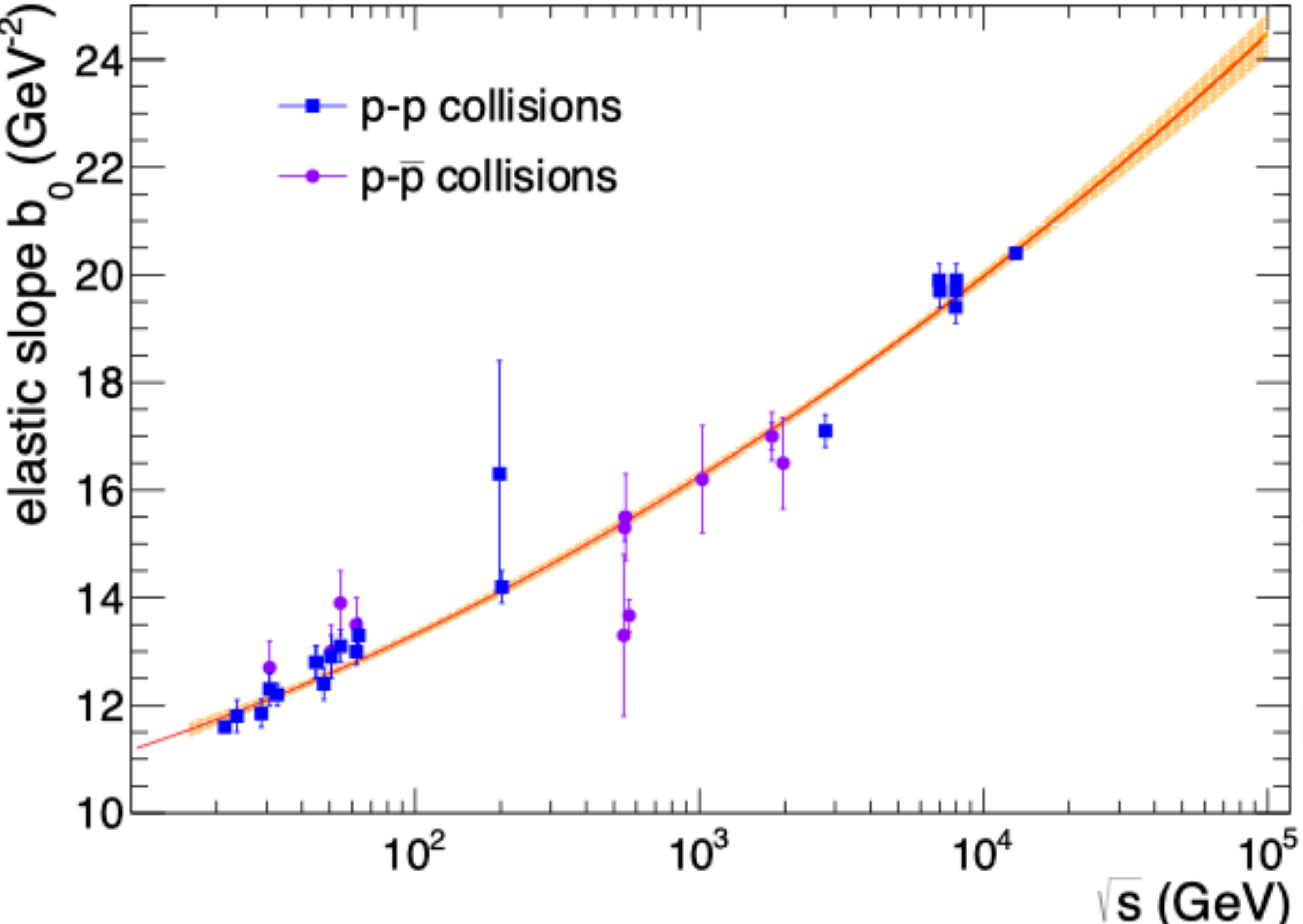
$\sigma(\mathrm{A}$ ... $\cdot\sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$

- **Effect**

$\frac{\mathrm{d}^2N^{(\mathrm{AE}}_{\gamma_1/\mathrm{Z}}}{\mathrm{d}E_{\gamma_1}}$ ... $_{\gamma_1},\boldsymbol{b}_1)N_{\gamma_2/\mathrm{Z}_2}(E_{\gamma_2},\boldsymbol{b}_2)$

... $_1-\epsilon R_\mathrm{A})\theta(b_2-\epsilon R_\mathrm{B})$

- **No ha** ... **ity density:**



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

Theoretical Framework

- **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:**

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

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

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

- **The photon number density:**
  - Two form factors

Two Form Factors

- **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)**

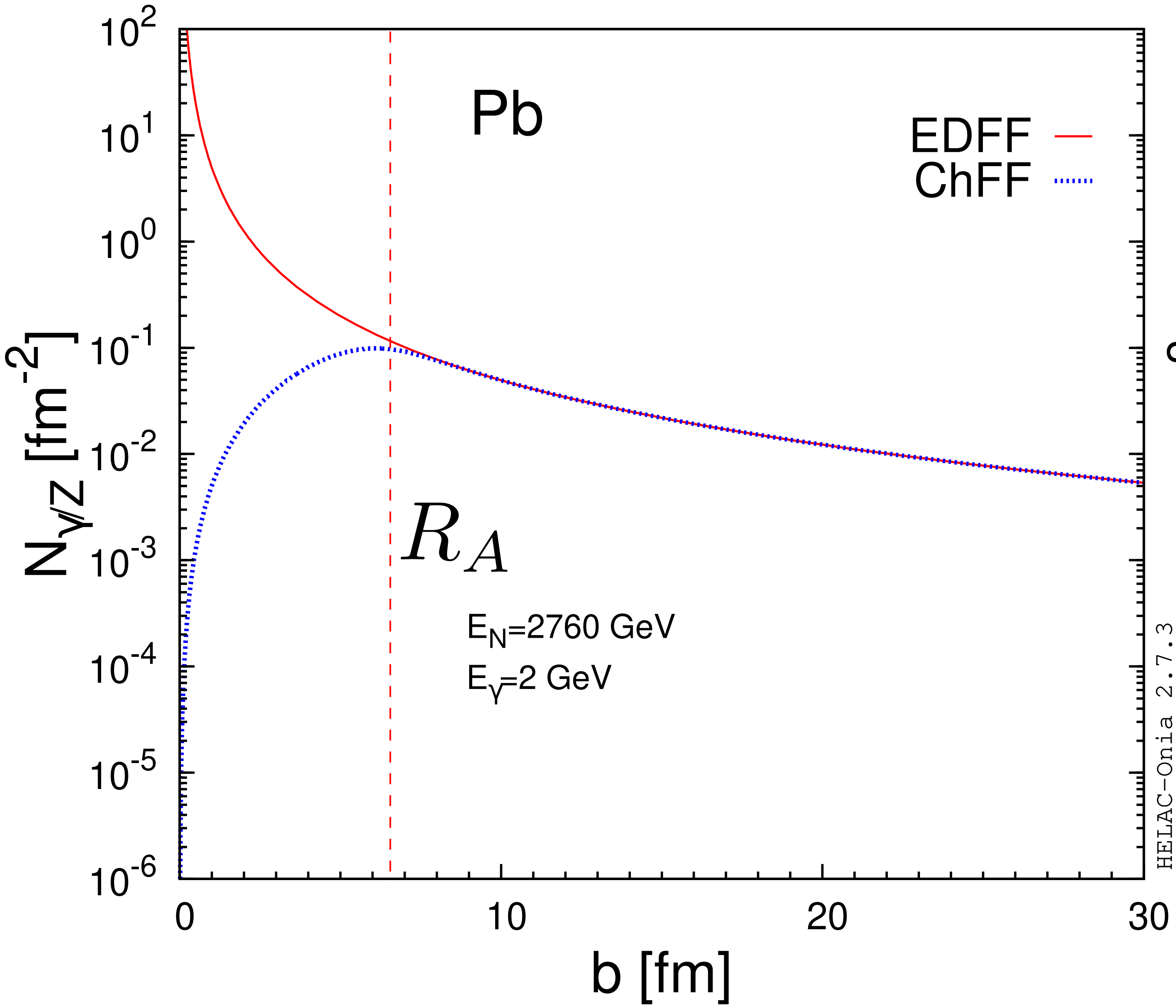
$$N^{\mathrm{ChFF}}_{\gamma/\mathrm{Z}}(E_\gamma, b) = \frac{Z^2\alpha}{\pi^2}\left|\int_0^{+\infty}\frac{dk_\perp k_\perp^2}{k_\perp^2 + E_\gamma^2/\gamma_\mathrm{L}^2}F_{\mathrm{ch,A}}\left(\sqrt{k_\perp^2 + E_\gamma^2/\gamma_\mathrm{L}^2}\right)J_1\left(bk_\perp\right)\right|^2$$

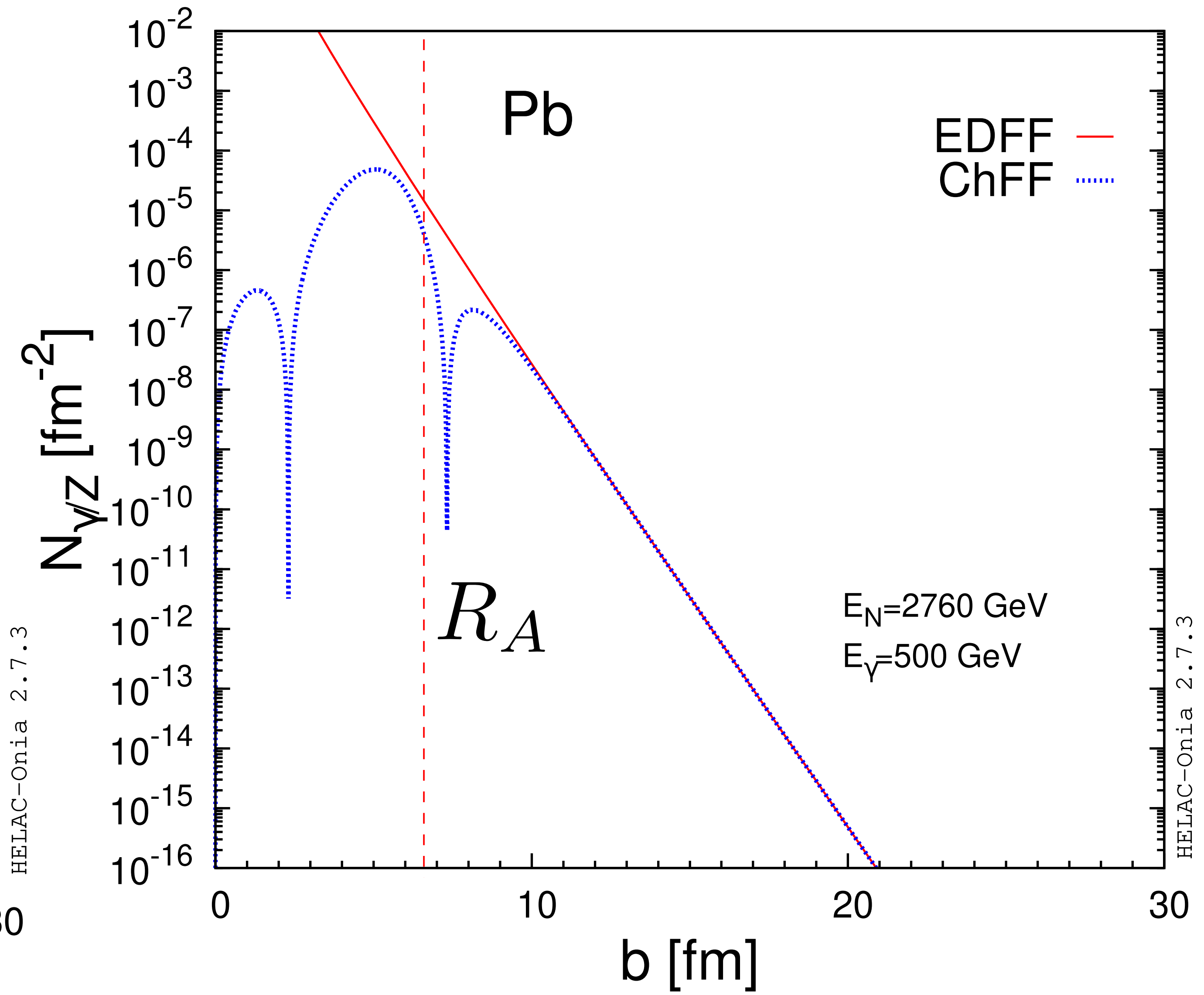
$$F_{\mathrm{ch,A}}(q) = \int \mathrm{d}^3\boldsymbol{r}e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\rho_\mathrm{A}(\boldsymbol{r}) = \frac{4\pi}{q}\int_0^{+\infty}\mathrm{d}r\rho_\mathrm{A}(r)r\sin\left(qr\right)$$

density profile of nuclei normalised to unity

Photon number density

- **EDFF vs ChFF**

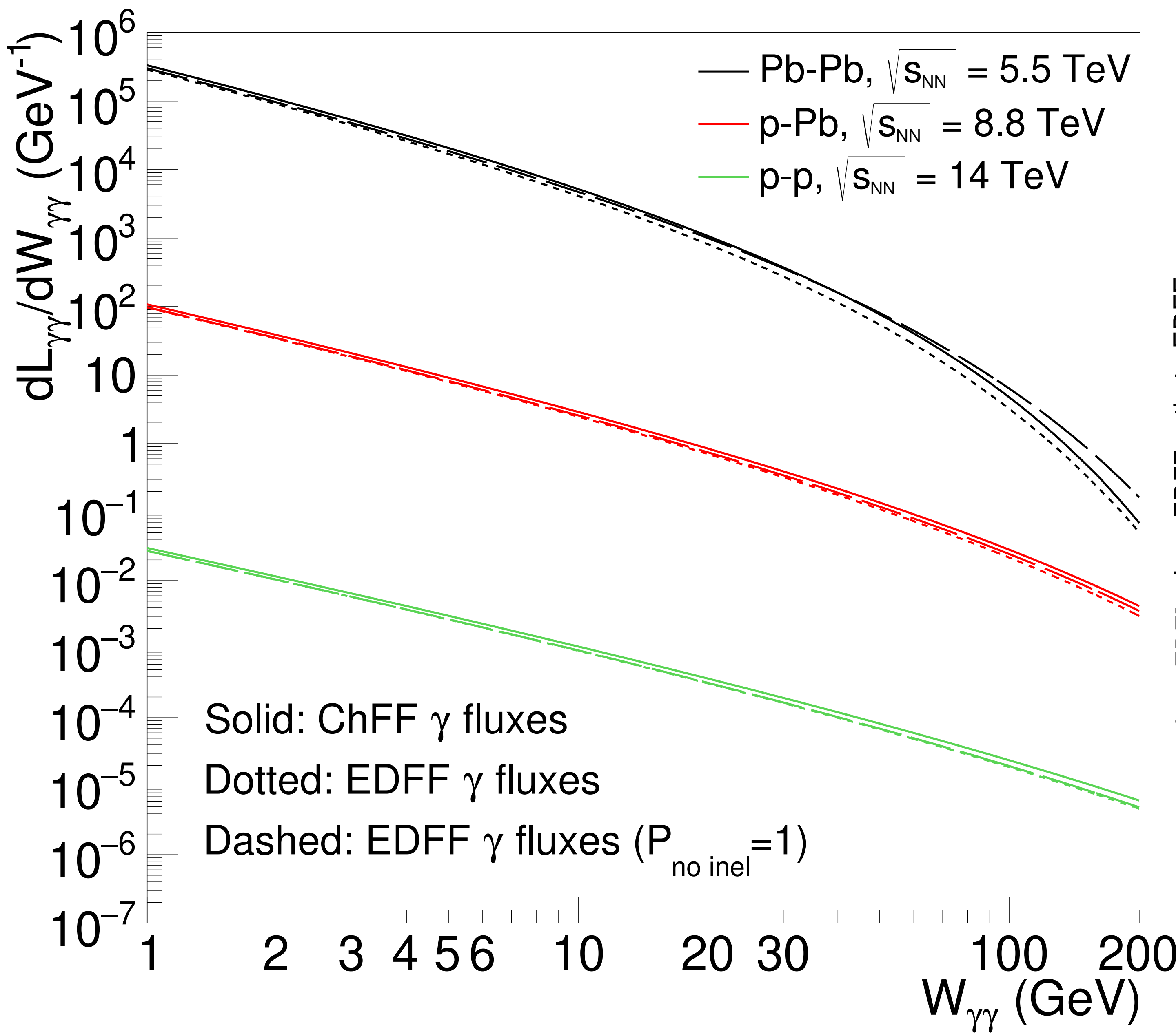


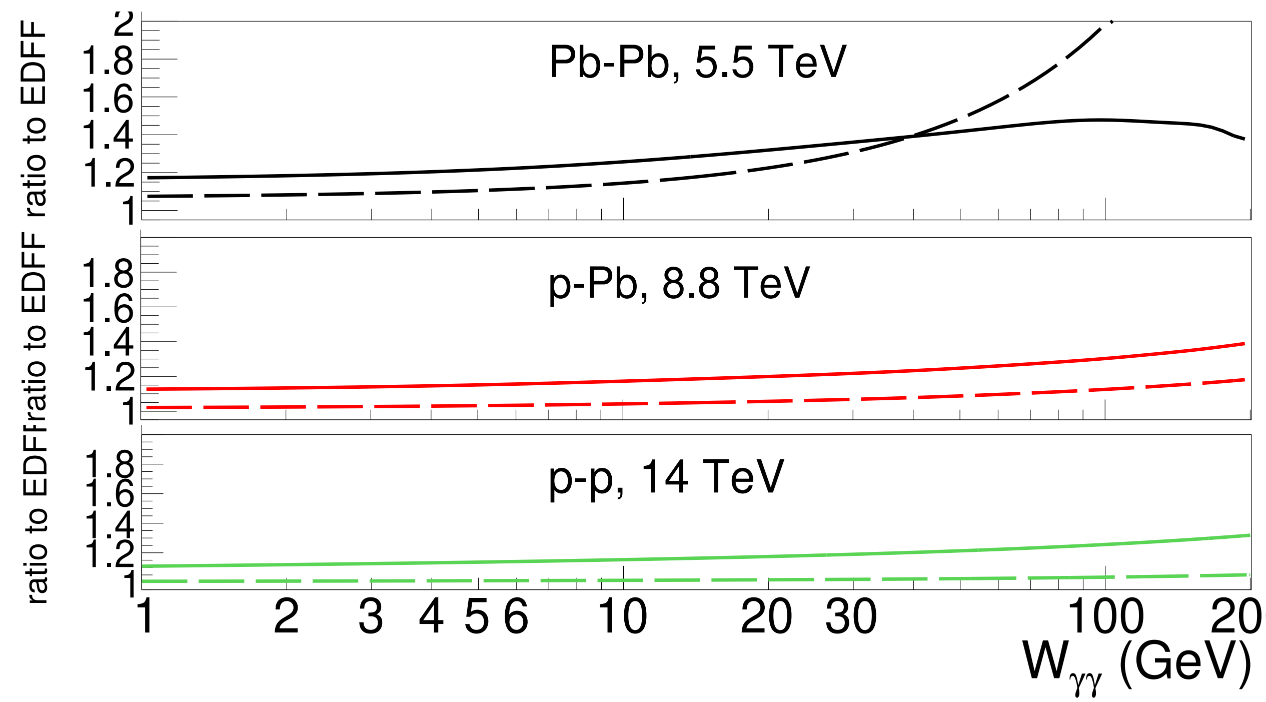


- Main difference comes from the $b < R_A$ regime
- EDFF photon number density is divergent at $b = 0$
  - Need a (arbitrary) cutoff when convoluting with ME

Effective two-photon luminosity

- **EDFF vs ChFF**





- Survival probability reduces luminosity

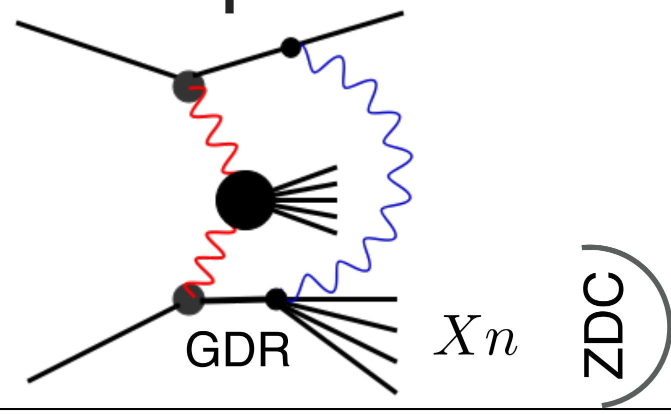
  impact: $\mathrm{AA} > \mathrm{pA} > \mathrm{pp}$ *and increase with* $\mathrm{W}_{\gamma\gamma}$

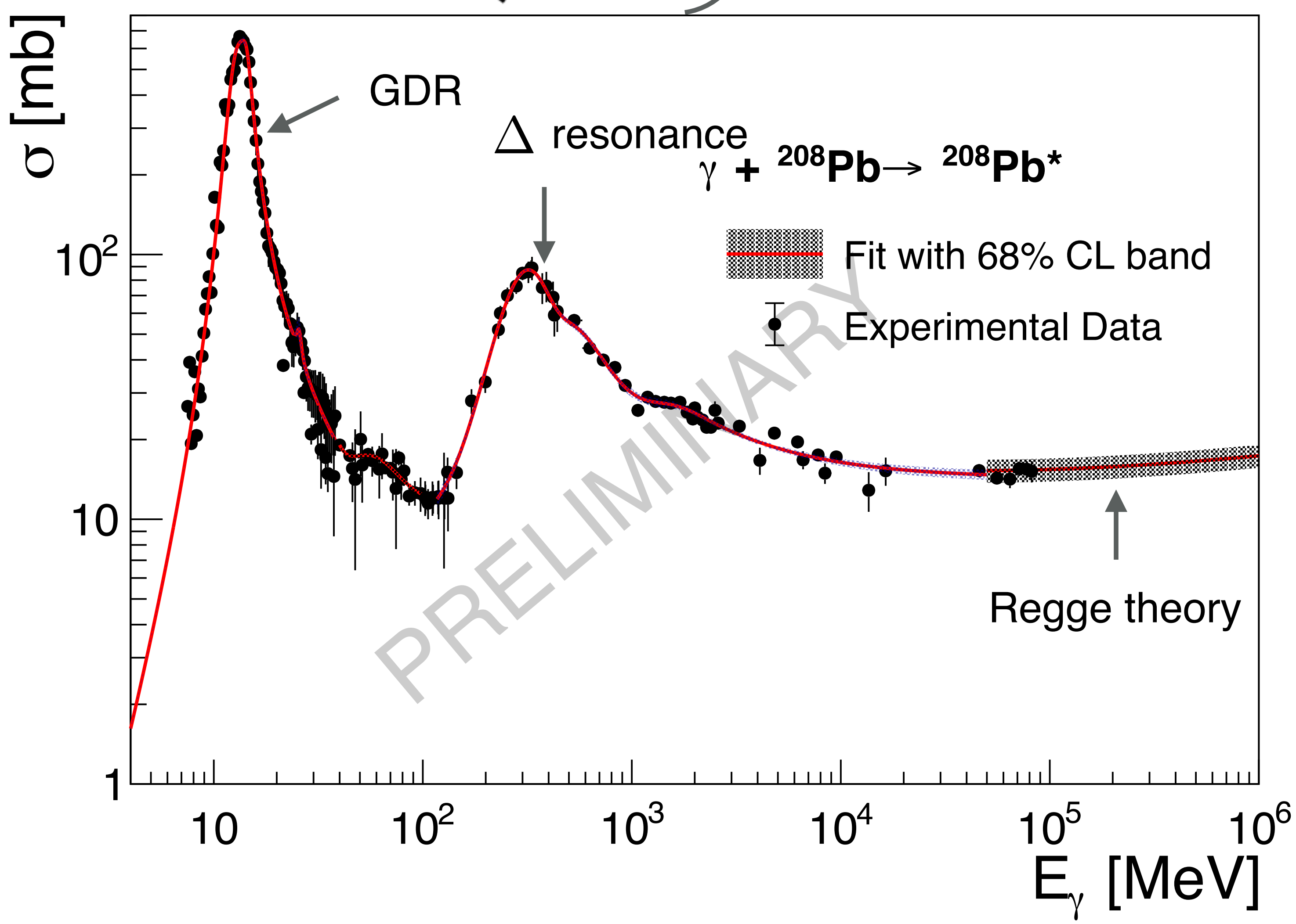
- ChFF > EDFF and enhancement increases slowly with $\mathrm{W}_{\gamma\gamma}$

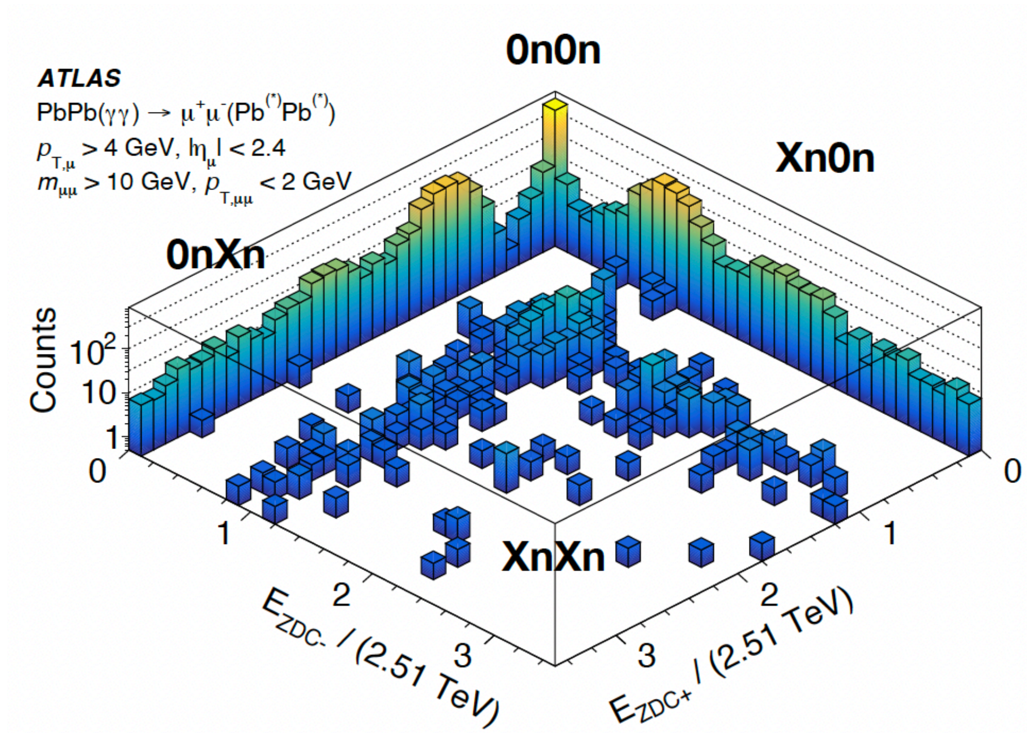
Forward neutron emission

- **Exclusive processes can still excite the ions, via photon exchange**
  - Giant Dipole Resonance: all protons vibrating against all neutrons

Crépet, d'Enterria, HSS (in prep)



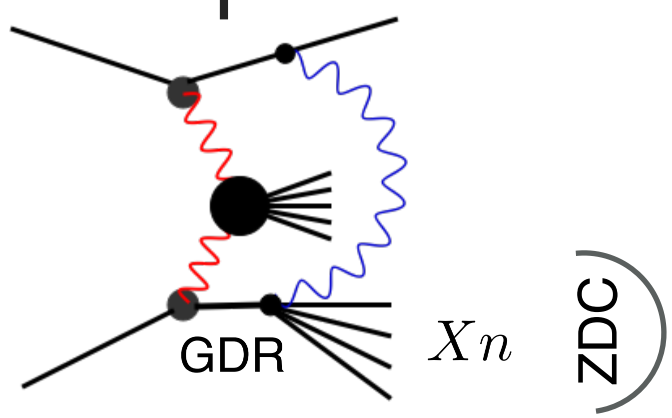




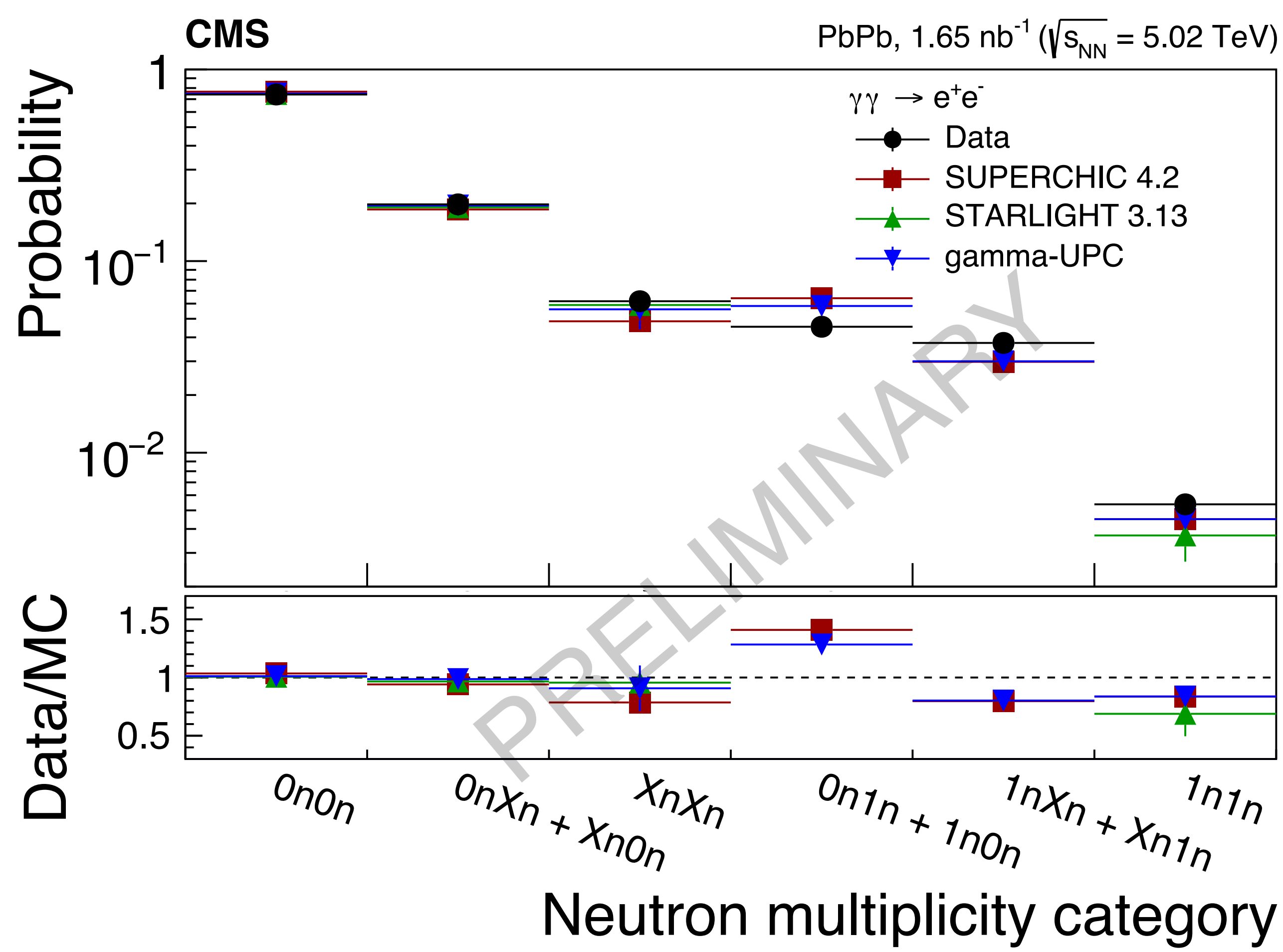
- **0n0n** - no neutrons on either side
- **Xn0n/0nXn** - neutrons on one side
- **XnXn** - neutrons on both sides

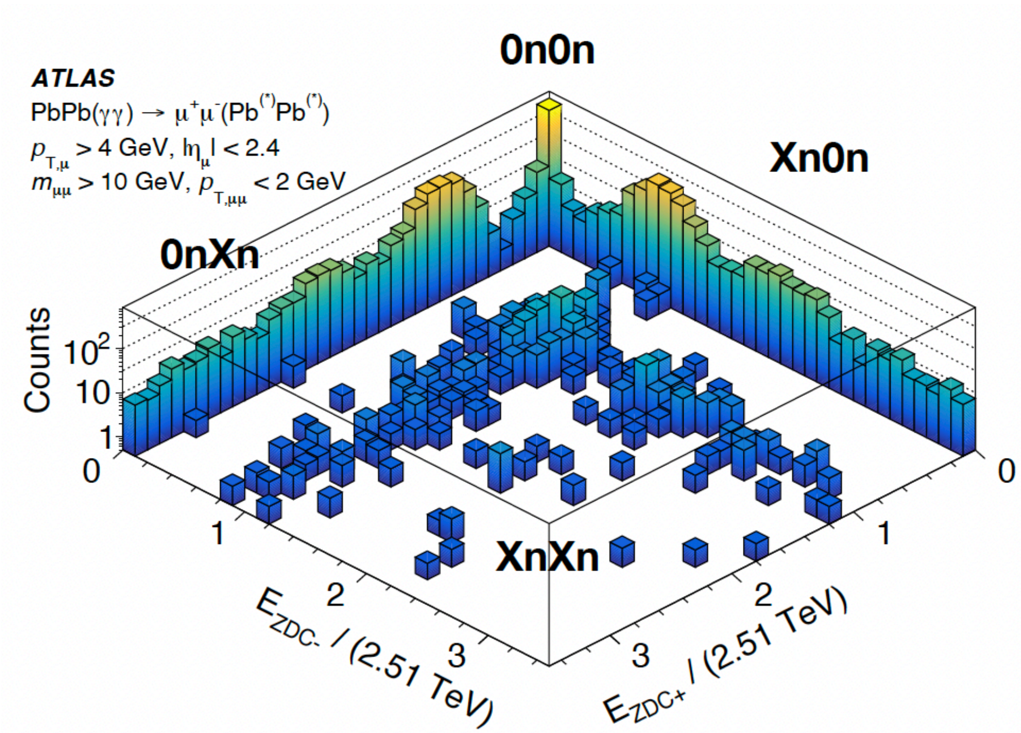
Forward neutron emission

- **Exclusive processes can still excite the ions, via photon exchange**
  - Giant Dipole Resonance: all protons vibrating against all neutrons



Crépet, d'Enterria, HSS (in prep)





- **0n0n** - no neutrons on either side
- **Xn0n/0nXn** - neutrons on one side
- **XnXn** - neutrons on both sides

Reintroduction of photon virtuality

- **Charge form factor (ChFF) in k_T space** HSS, d'Enterria (2407.13610)

$$N_{\gamma/Z}^{\rm ChFF}(E_\gamma,k_T)=2\pi k_T\frac{Z^2\alpha}{\pi^2}\left|\int_0^\infty\frac{{\rm d}bk_T^2}{k_T^2+E_\gamma^2/\gamma_{\rm L}^2}F_{{\rm ch},A}\left(\sqrt{k_T^2+E_\gamma^2/\gamma_{\rm L}^2}\right)J_1(bk_T)\right|^2$$

$$=\frac{2Z^2\alpha}{\pi}\frac{k_T^3}{\left(k_T^2+E_\gamma^2/\gamma_{\rm L}^2\right)^2}\left[F_{{\rm ch},A}\left(\sqrt{k_T^2+E_\gamma^2/\gamma_{\rm L}^2}\right)\right]^2$$

$$\Rightarrow\quad {\rm d}N_{\gamma/Z}^{\rm ChFF}(x_\gamma,Q^2)=\frac{Z^2\alpha}{\pi}\frac{{\rm d}x_\gamma}{x_\gamma}\frac{{\rm d}Q^2}{Q^2}\left(1-\frac{Q^2_{\rm min}}{Q^2}\right)\left[F_{{\rm ch},A}(Q)\right]^2$$

1. Sampling over Q^2

2. Momentum reshuffling

Reintroduction of photon virtuality

- **Charge form factor (ChFF) in k_T space**

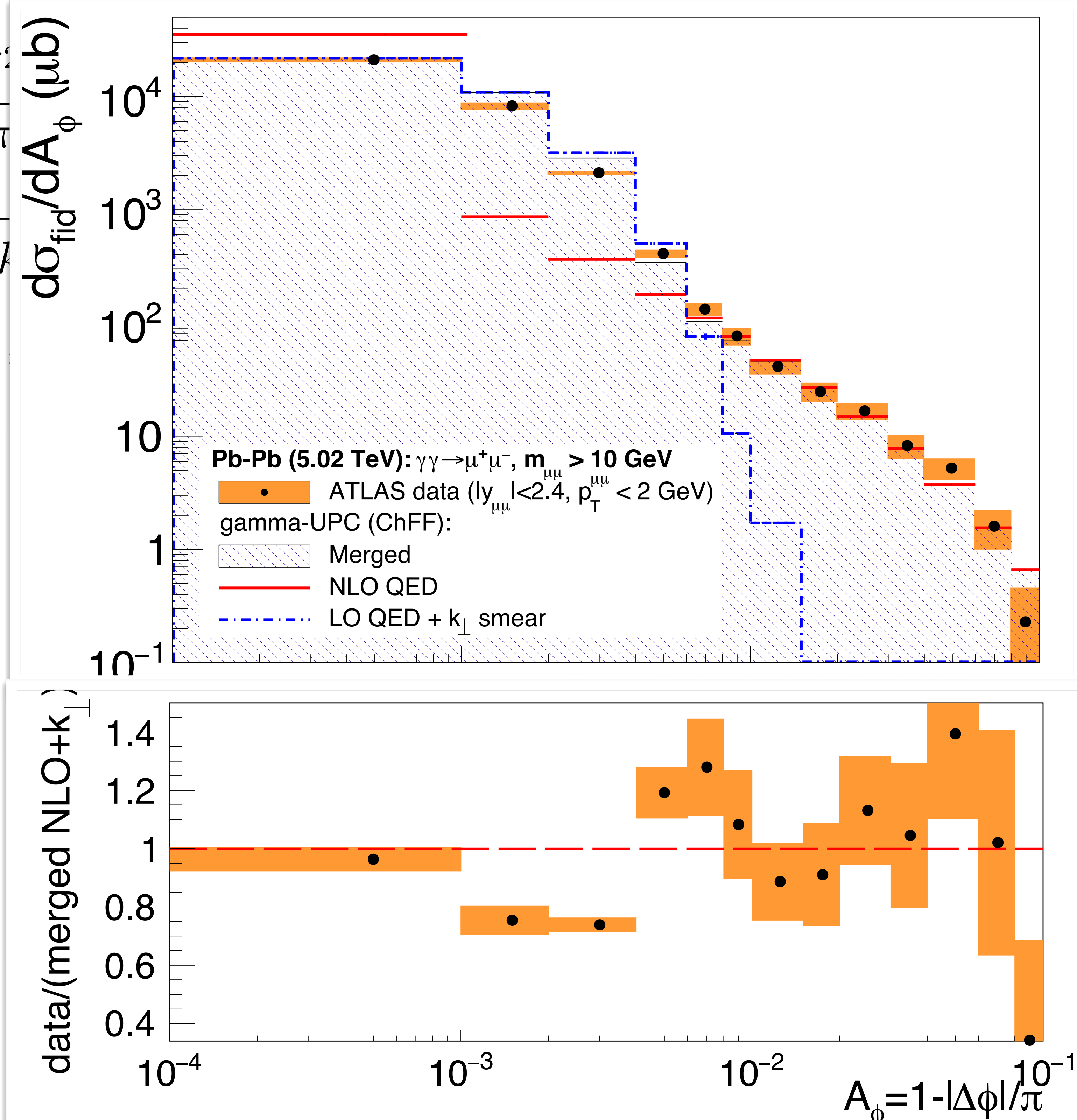
HSS, d'Enterria (2407.13610)

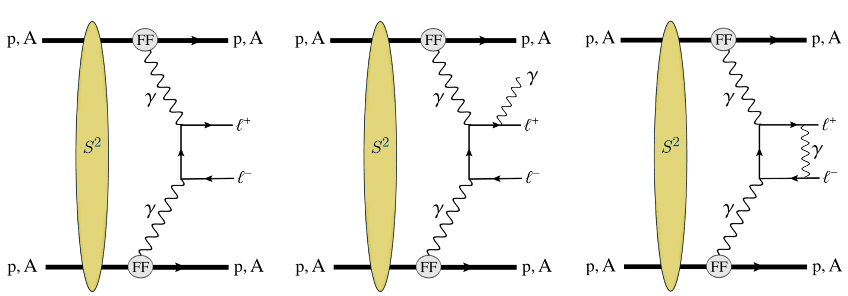
$$N^{\mathrm{ChFF}}_{\gamma/Z}(E_\gamma, k_T) = 2\pi k_T \frac{Z^2}{\pi \ldots}$$

$$= \frac{2Z^2\alpha}{\pi} \frac{\ldots}{(\ldots}$$

$$\rightarrow \mathrm{d}N^{\mathrm{ChFF}}_{\gamma/Z}(x_\gamma, Q^2) \ldots$$

1. Sampling over Q^2
2. Momentum reshuffling





A few selected results

- **Total cross sections**
  - Quarkonia

Process: $\gamma\gamma \to J/\psi J/\psi$	gamma-UPC σ		
Colliding system, c.m. energy	EDFF	ChFF	average
p-p at 14 TeV	20^{+11}_{-6} fb	23^{+13}_{-7} fb	$22^{+12}_{-7} \pm 2$ fb
p-Pb at 8.8 TeV	55^{+30}_{-16} pb	64^{+35}_{-18} pb	$60^{+32}_{-17} \pm 4$ pb
Pb-Pb at 5.52 GeV	103^{+57}_{-29} nb	128^{+71}_{-36} nb	$115^{+64}_{-32} \pm 12$ nb

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

Process: $\gamma\gamma \to Z\gamma$	gamma-UPC σ		
Colliding system, c.m. energy	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: $\gamma\gamma \to ZZ$	gamma-UPC σ		
Colliding system, c.m. energy	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

A few selected results

- **Total cross sections**
  - NLO QCD *(with a private version of MadGraph5_aMC@NLO)*

Process: $\gamma\gamma \to t\bar{t}$	gamma-UPC $\sigma_{\rm LO}$		gamma-UPC $\sigma_{\rm NLO}$		
Colliding system, c.m. energy	EDFF	ChFF	EDFF	ChFF	average
p-p at 14 TeV	0.164 fb	0.238 fb	$0.198^{+0.004}_{-0.003}$ fb	$0.287^{+0.005}_{-0.004}$ fb	$0.242^{+0.005}_{-0.004} \pm 0.045$ fb
p-Pb at 8.8 TeV	28.3 fb	46.4 fb	$36.5^{+0.8}_{-0.7}$ fb	$59.3^{+1.3}_{-1.1}$ fb	$48^{+1.0}_{-0.9} \pm 11$ fb
Pb-Pb at 5.52 TeV	9.23 fb	13.6 fb	$12.6^{+0.4}_{-0.3}$ fb	$18.8^{+0.5}_{-0.4}$ fb	$15.7^{+0.5}_{-0.4} \pm 3.1$ fb

  - BSM interactions

$$\mathcal{L} \supset \frac{c_{WWW}}{\Lambda^2}{\rm Tr}\left[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}\right].$$

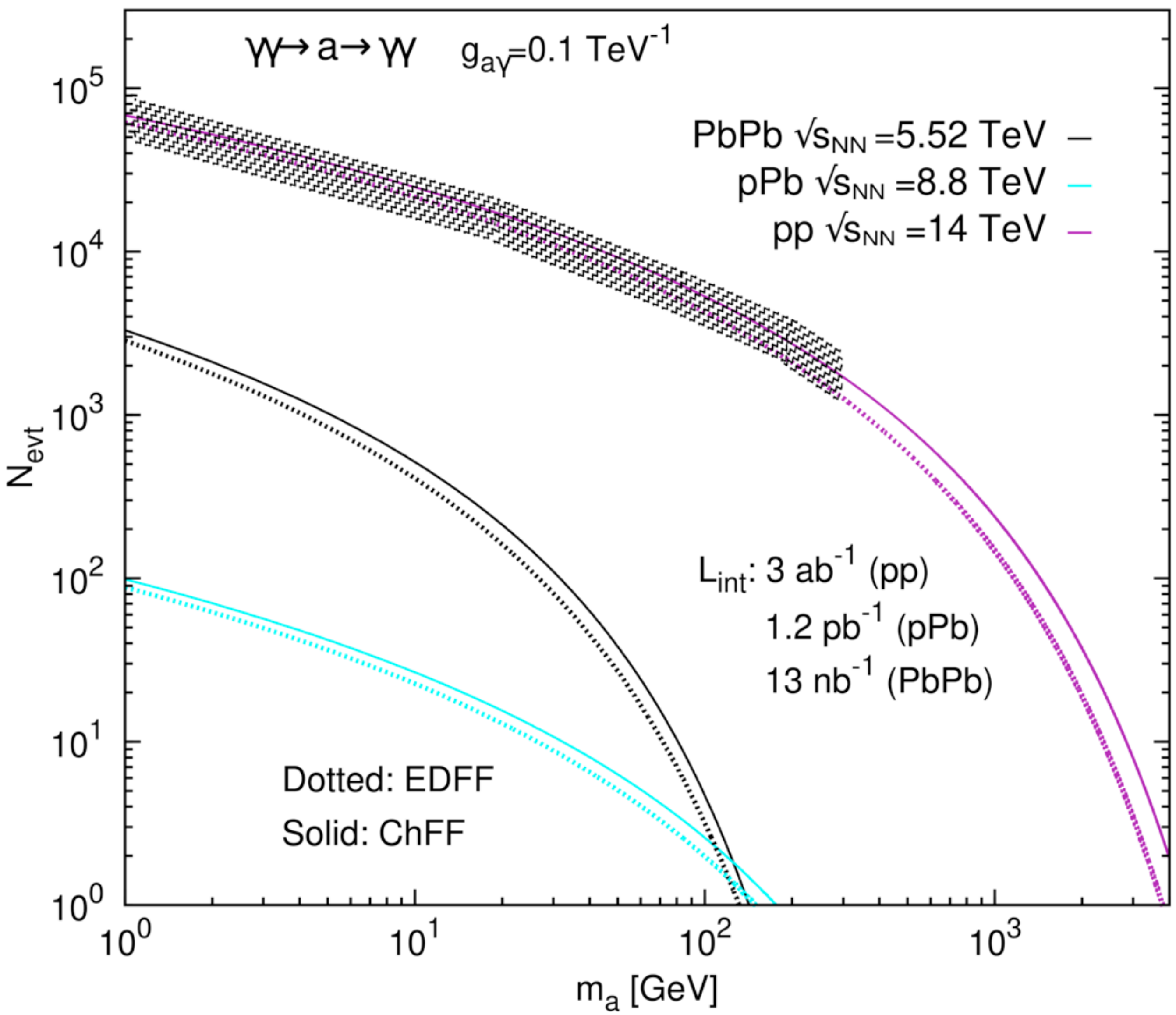
$$\sigma = \sigma_{\rm SM} + \left(\frac{c_{WWW}}{\Lambda^2} \times 1~{\rm TeV}^2\right)\sigma_{WWW}$$

Process: $\gamma\gamma \to W^+W^-$	gamma-UPC EDFF		gamma-UPC ChFF		gamma-UPC average	
Colliding system, c.m. energy	$\sigma_{\rm SM}$	σ_{WWW}	$\sigma_{\rm SM}$	σ_{WWW}	$\sigma_{\rm SM}$	σ_{WWW}
p-p at 14 TeV	52.4 fb	44.7 ab	73.6 fb	60.6 ab	63 ± 11 fb	53 ± 8 ab
p-Pb at 8.8 TeV	20.9 pb	23.1 fb	30.3 pb	32.8 fb	26 ± 5 pb	28 ± 5 fb
Pb-Pb at 5.52 TeV	233 pb	330 fb	321 pb	458 fb	277 ± 44 pb	394 ± 64 fb

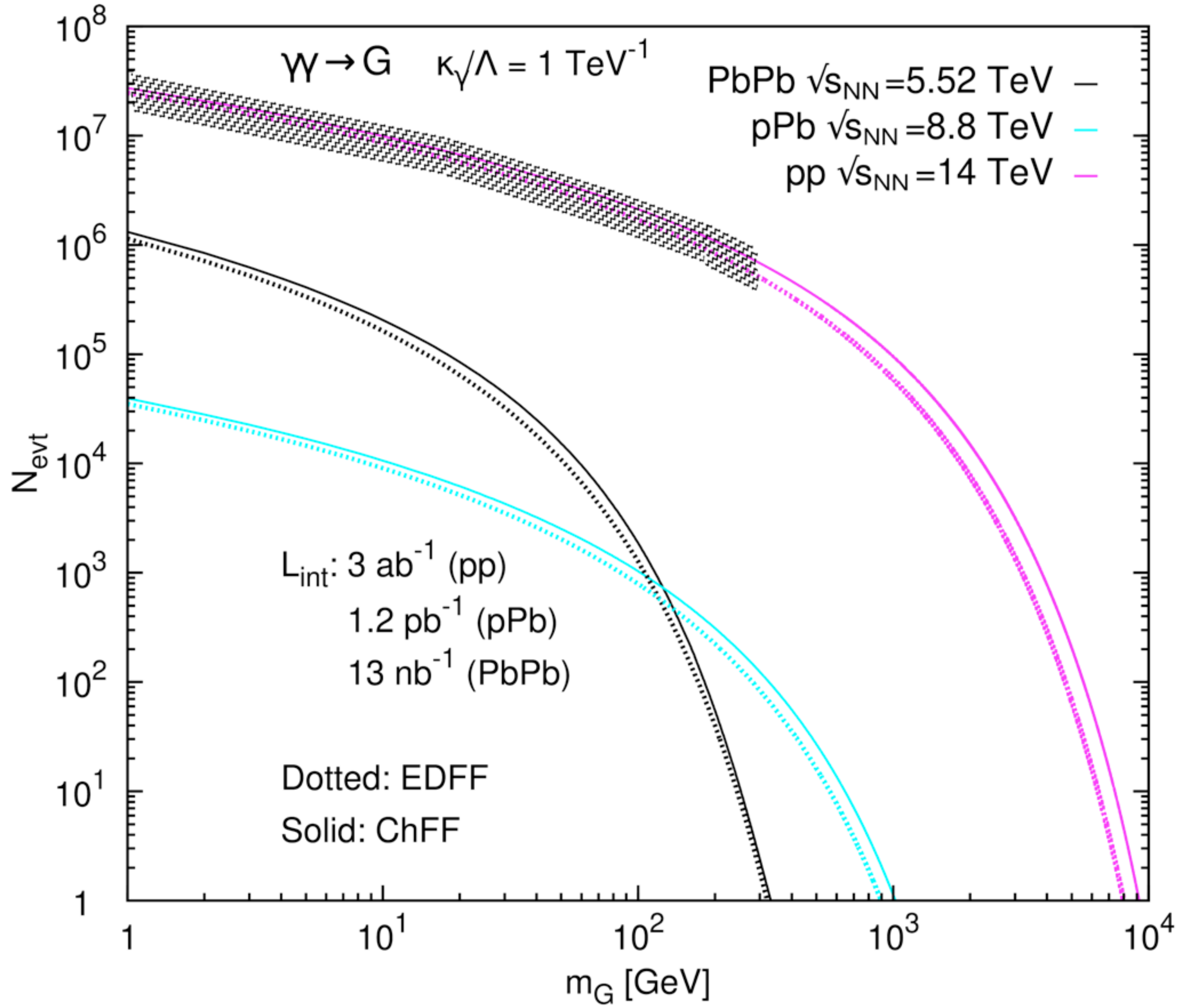
A few selected results

- **Total cross sections**
  - BSM particles

Axion



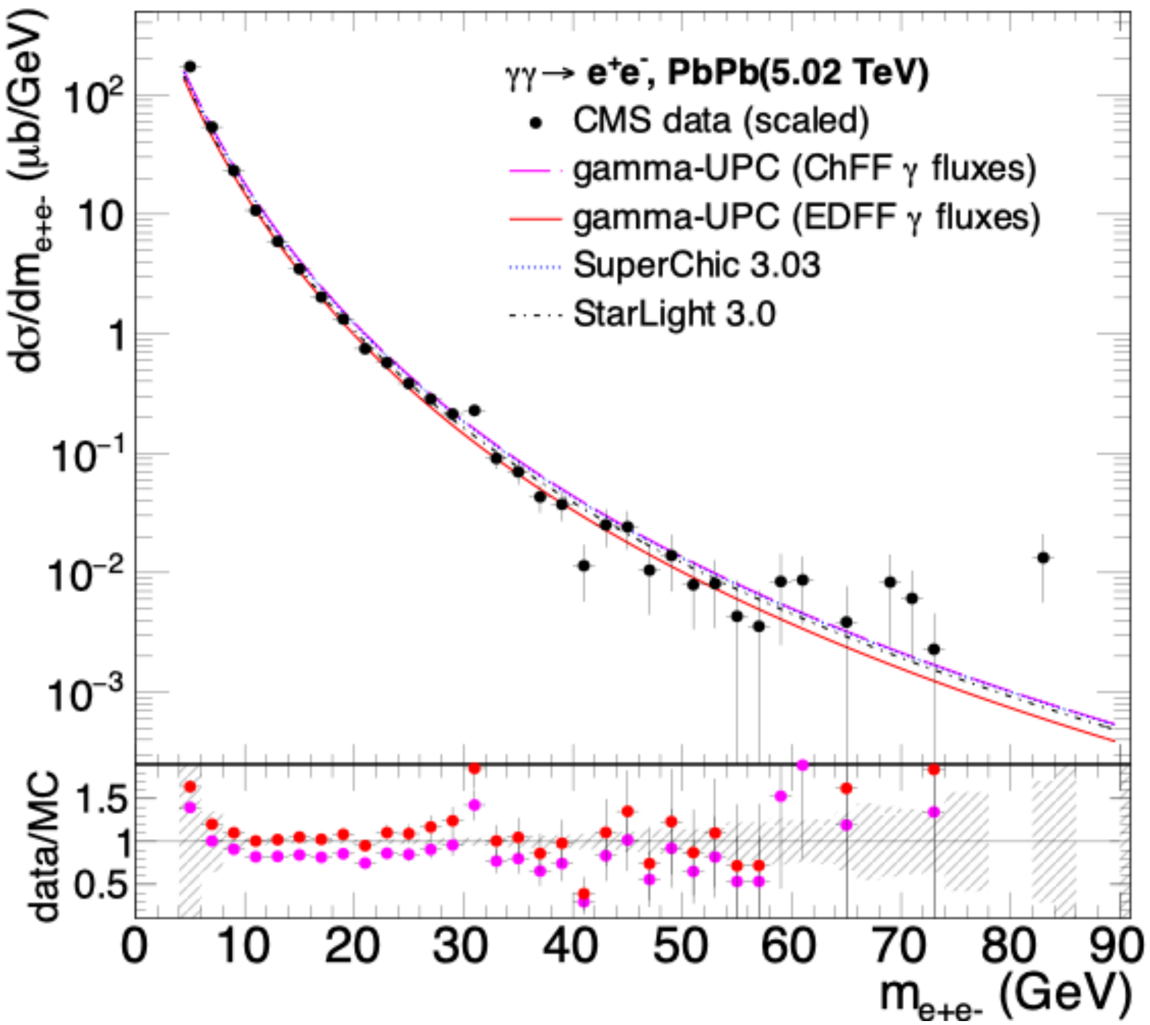
Graviton

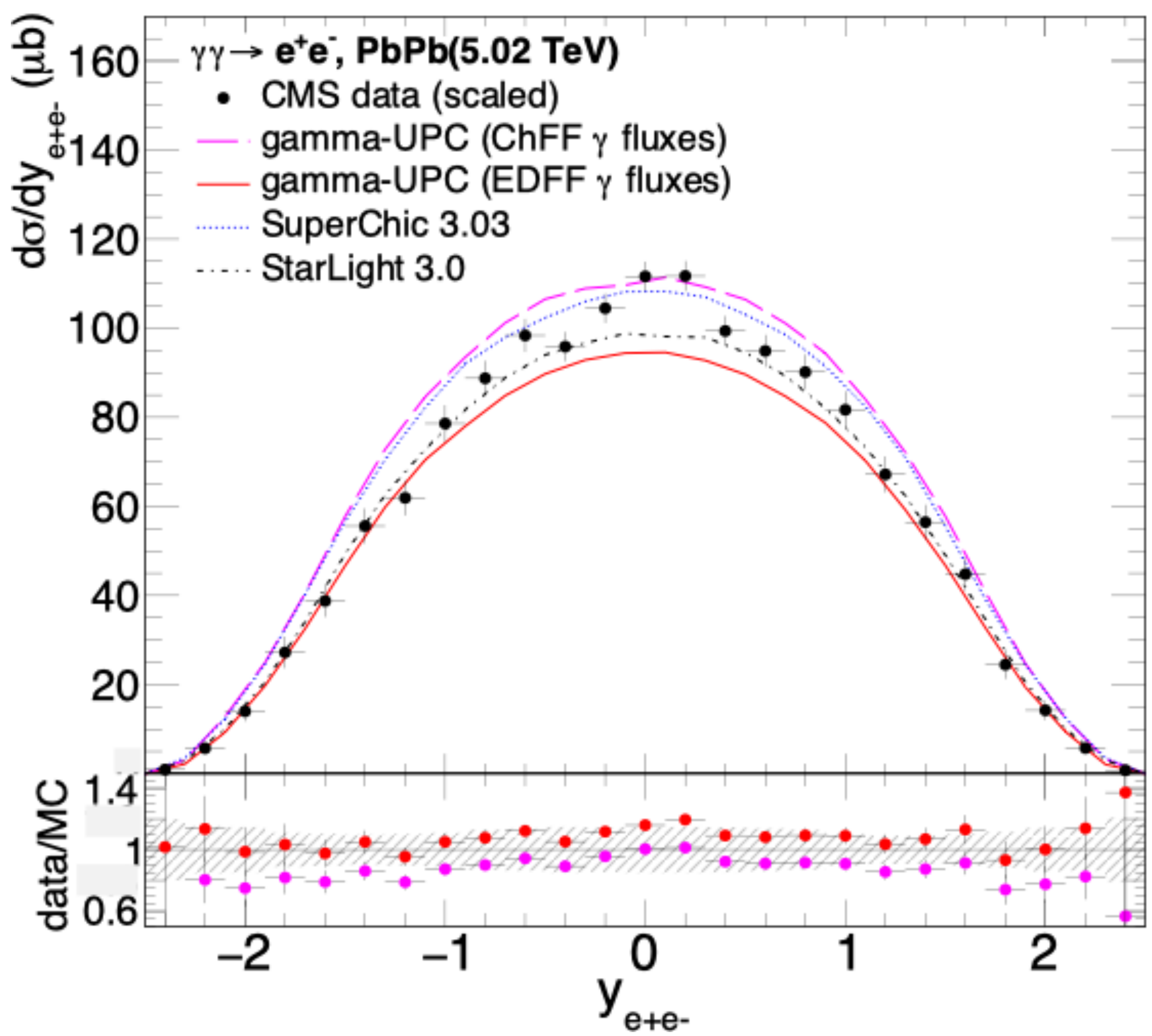


A few selected results

- **Fiducial and differential cross sections**
  - Electron-positron

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





A general observation: EDFF ~ STARlight & ChFF ~ SuperChic

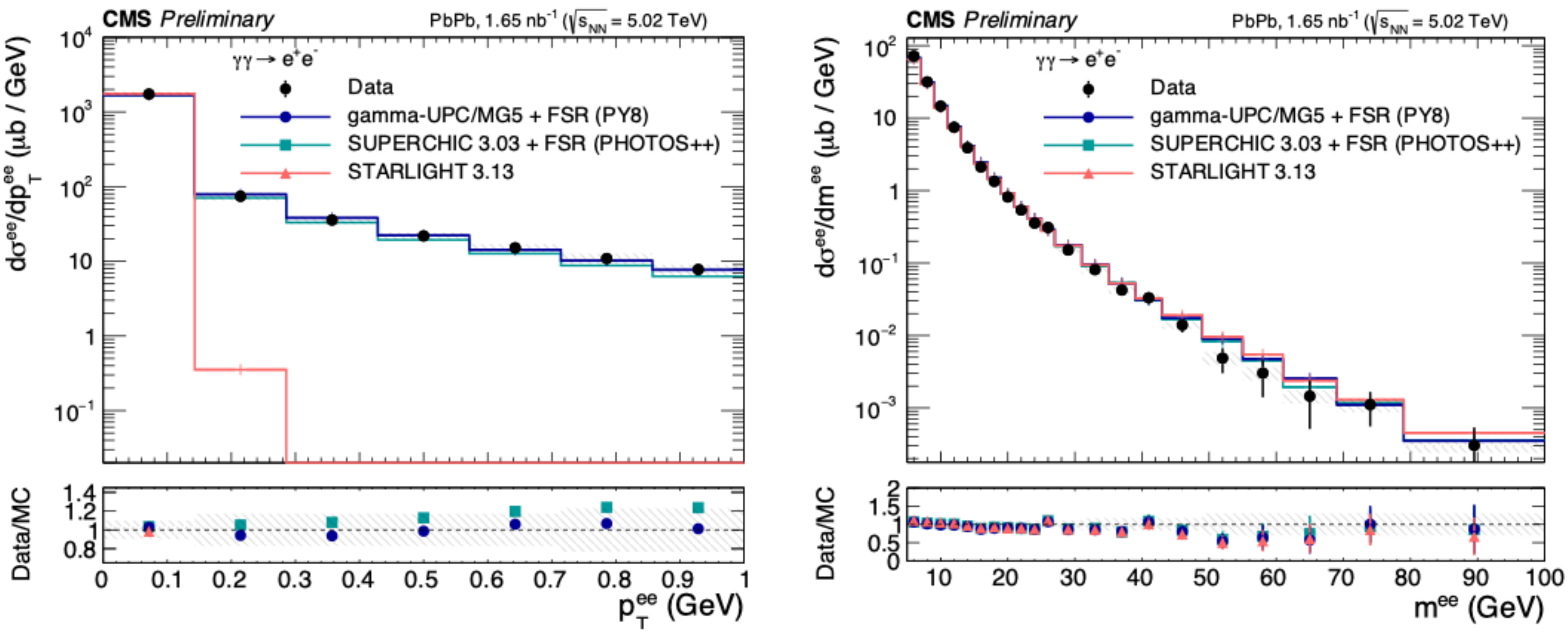
A few selected results

- **Fiducial and differential cross sections**
  - Electron-positron

CMS-PAS-HIN-21-015

$$\sigma_{\rm CMS} = 271.5 \pm 1.9_{\rm stat} \pm 18.3_{\rm syst}\ \mu{\rm b}$$

STARlight (no FSR)	SuperChic+Photos++	gamma-UPC (ChFF)+PY8
$251\ \mu$b	$261\ \mu$b	$265\ \mu$b



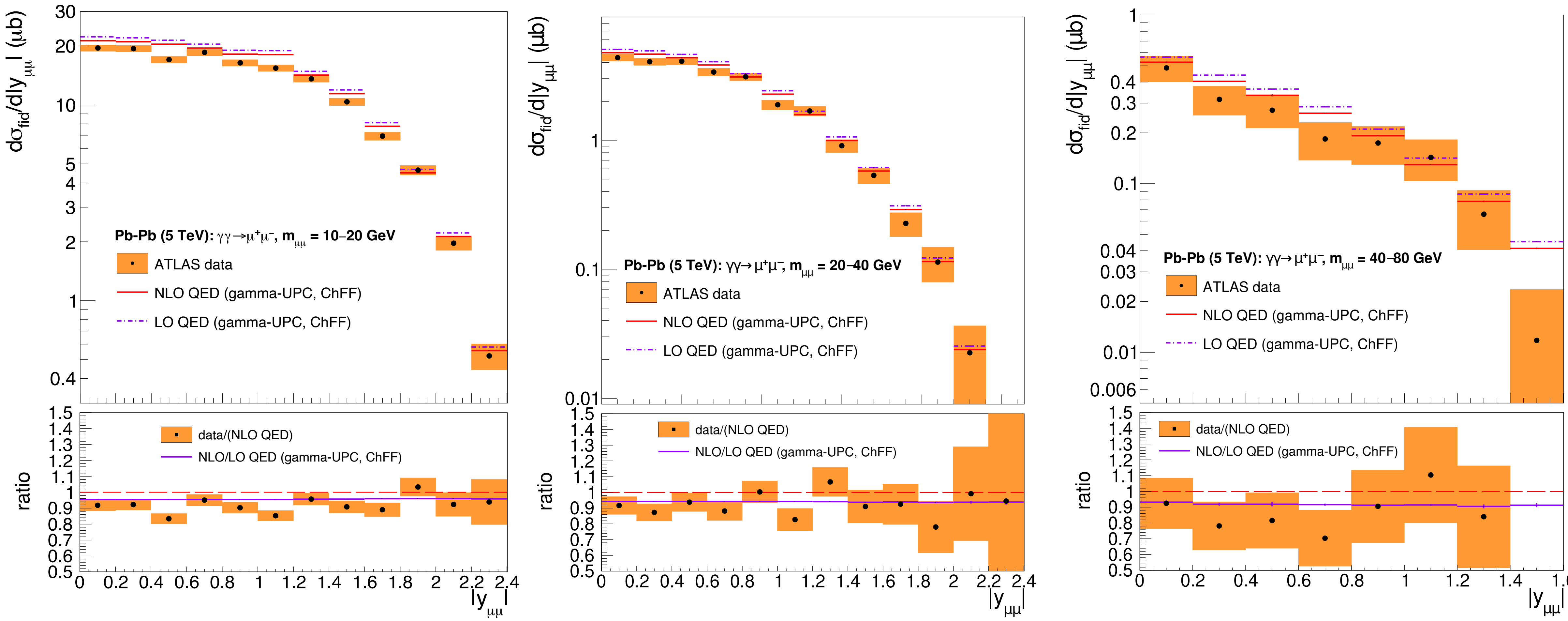
Importance of final state radiation !

A few selected results

- **Fiducial and differential cross sections**
  - Dimuon

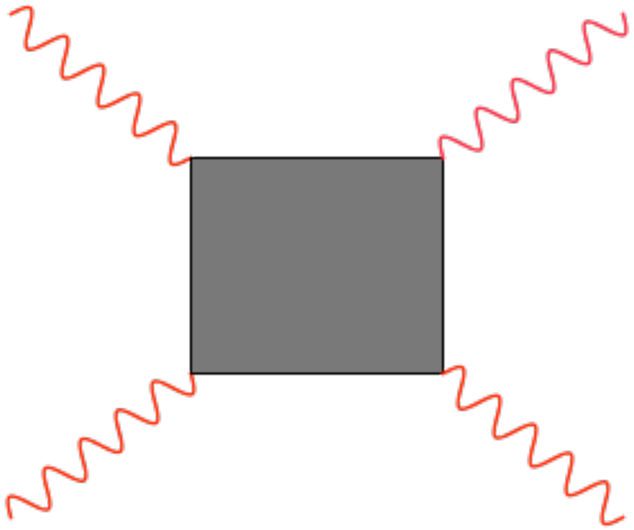
HSS, d'Enterria (2407.13610)

$\gamma\gamma \to \mu^+\mu^-$ System, experiment	measured $\sigma^{\rm data}$	gamma-UPC $\sigma^{\rm LO}$ ChFF (EDFF)	gamma-UPC $\sigma^{\rm NLO}$ ChFF (EDFF)	ratio $\sigma^{\rm data}/\sigma^{\rm NLO}$ ChFF (EDFF)
p-p at 7 TeV, CMS [54]	$3.38^{+0.62}_{-0.59}$ 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 [37]	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 [55]	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 [58]	34.1 ± 0.8 μb	39.4 (31.5) μb	37.5 (30.0) μb	0.91 ± 0.02 (1.14 ± 0.03)



Importance of NLO and ChFF !

Light-by-light scattering



w/ Ajjath A.H., E. Chaubey, M. Fraaije and V. Hirschi
(arXiv:2312.16956 [PLB'24], arXiv:2312.16966 [JHEP'24])

Theory status

- **Going beyond LO (for fermions)**
  - Low-energy (LE) approx. : NLO from Euler-Heisenberg Lagrangian

    Martin, Schubert & Villaneuva Sandoval NPB'03
  - High-energy (HE) approx. : NLO from unitarity-based technique

    Bern, De Freitas, Dixon, Ghinculov & Wong JHEP'01
  - Our aim is to have NLO without approximation

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

Theory status

- **Going beyond LO (for fermions)**
  - Low-energy (LE) approx. : NLO from Euler-Heisenberg Lagrangian

    Martin, Schubert & Villaneuva Sandoval NPB'03
  - High-energy (HE) approx. : NLO from unitarity-based technique

    Bern, De Freitas, Dixon, Ghinculov & Wong JHEP'01
  - Our aim is to have NLO without approximation

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

gamma-UPC

HSS & d'Enterria JHEP'22

Theory status

- **Going beyond LO (for fermions)**
  - Low-energy (LE) approx. : NLO from Euler-Heisenberg Lagrangian

    Martin, Schubert & Villaneuva Sandoval NPB'03
  - High-energy (HE) approx. : NLO from unitarity-based technique

    Bern, De Freitas, Dixon, Ghinculov & Wong JHEP'01
  - Our aim is to have NLO without approximation

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

$$\overline{\sum}_{\vec{\lambda}} \left|\mathcal{M}_{\vec{\lambda}}\right|^2$$

arXiv: 2312.16956, arXiv:2312.16966

Analytical approach for 2-loop

- **A traditional approach with a fully analytic control**

Feynman diagram gener. : Qgraf/FeynArts

Algebraic calc. & integral family proj.: Form/Mathematica

Integral reduction: FiniteFlow/Kira

Solving master integrals: DEs in Mathematica

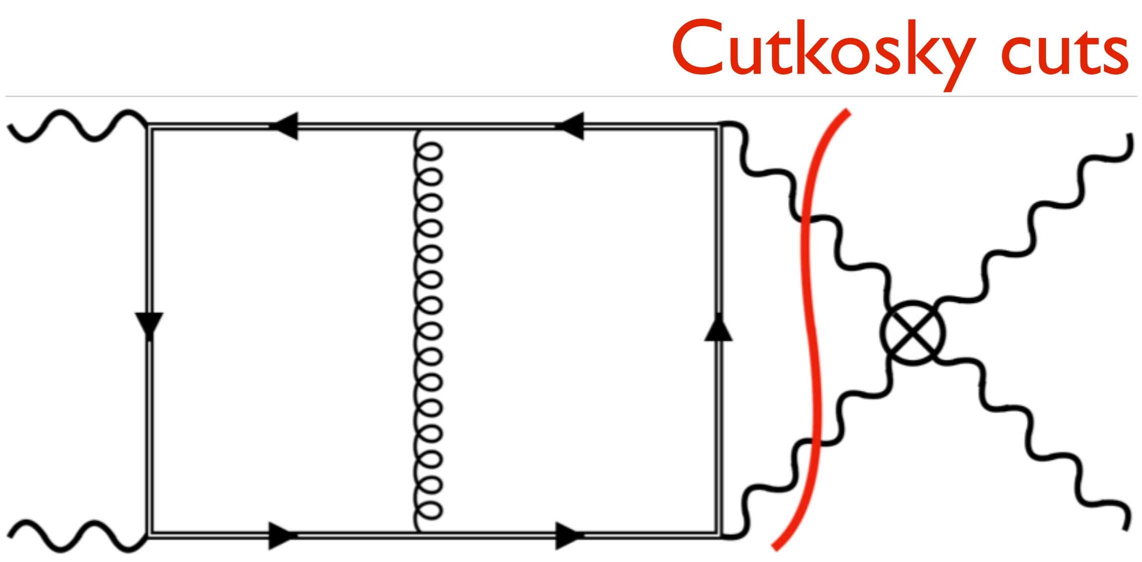
Simplifying amplitudes: FiniteFlow/MultivariateApart

arXiv:2312.16966

	Initial	Final
#integrals in d dims	> 10k	30 + crossing
#integrals w/ eps exp.	> 300	84
#rational coeff.	> 200	31 + crossing
amplitude size	> 300 MB	Few pages

Numerical approach for 2-loop

- **Local unitarity construction with loop-tree duality tech.**



16 non-isomorphic 3-loop FSGs

alphaLoop team (V. Hirschi et al.)
Capatti et al. JHEP'20, JHEP'22

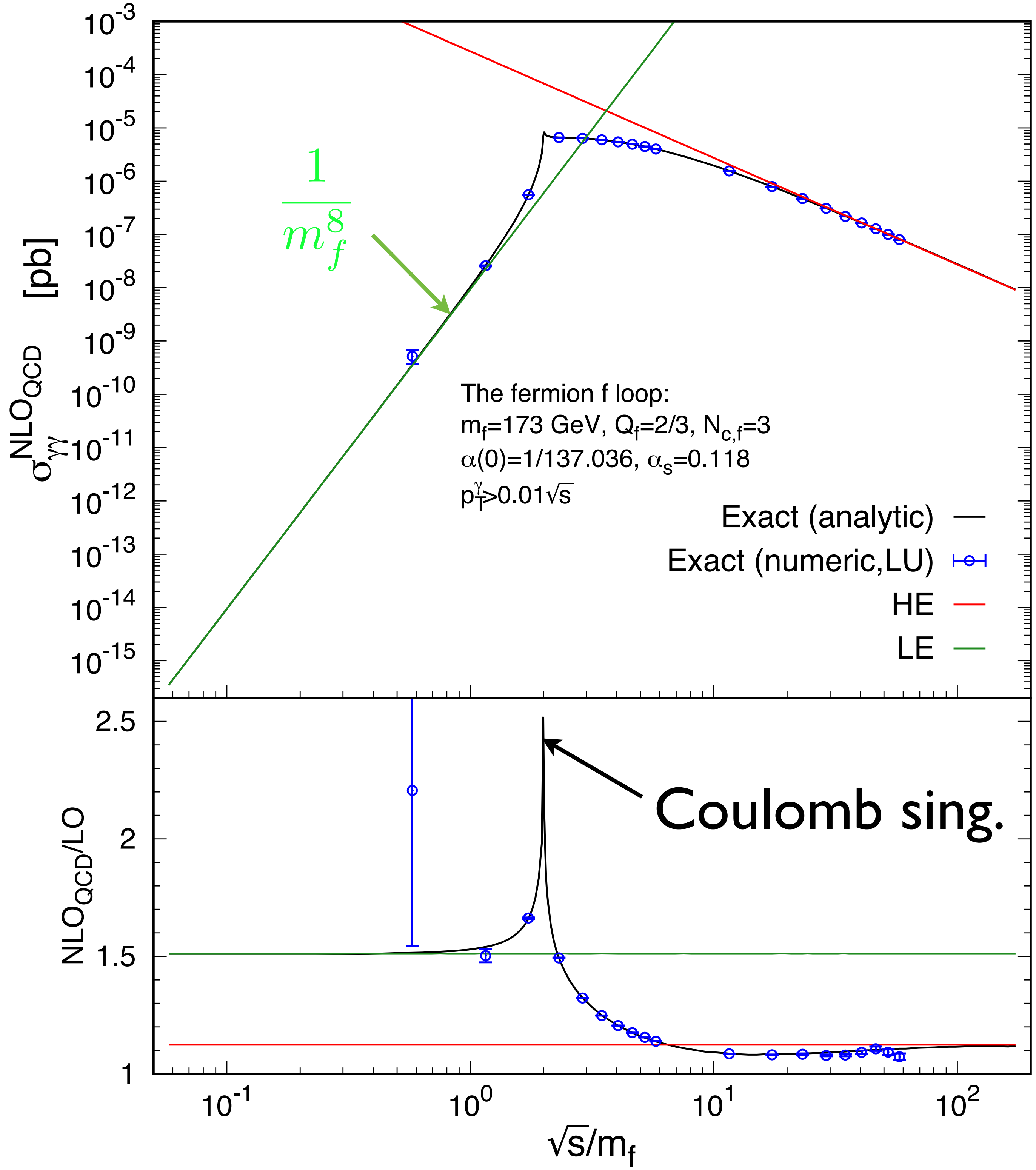
- Fully differential
- No need of loop-integral reduction
- No need of (FS) IR subtraction
- New paradigm of loop calculations

- ***Main idea***: converting a four-dimensional Minkowski loop integration measure into a three-dimensional Euclidean phase-space measure

L-loop FSG ⟶ ***3L-dim momentum-space UV/IR finite integrals***

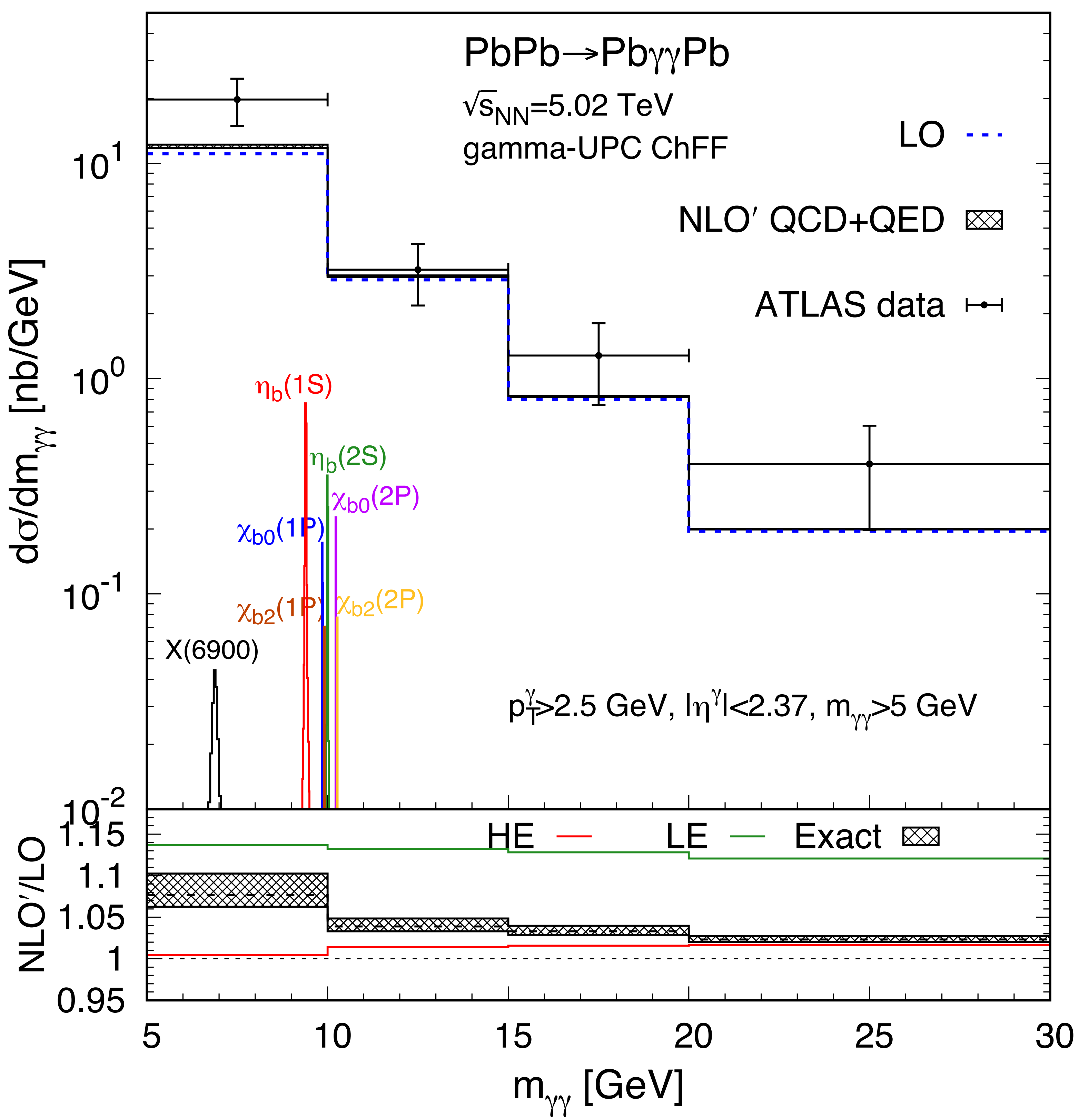
Cross section

- **Let us first consider only a fermion species**



- Exact result agrees with the approximations in their applicable regimes
- Analytical exact result agrees with the numerical exact one.
- The structure of the exact K factor is more rich than the approximations
- The exact K factor approaches the HE K factor rather slowly

Theory-data comparison



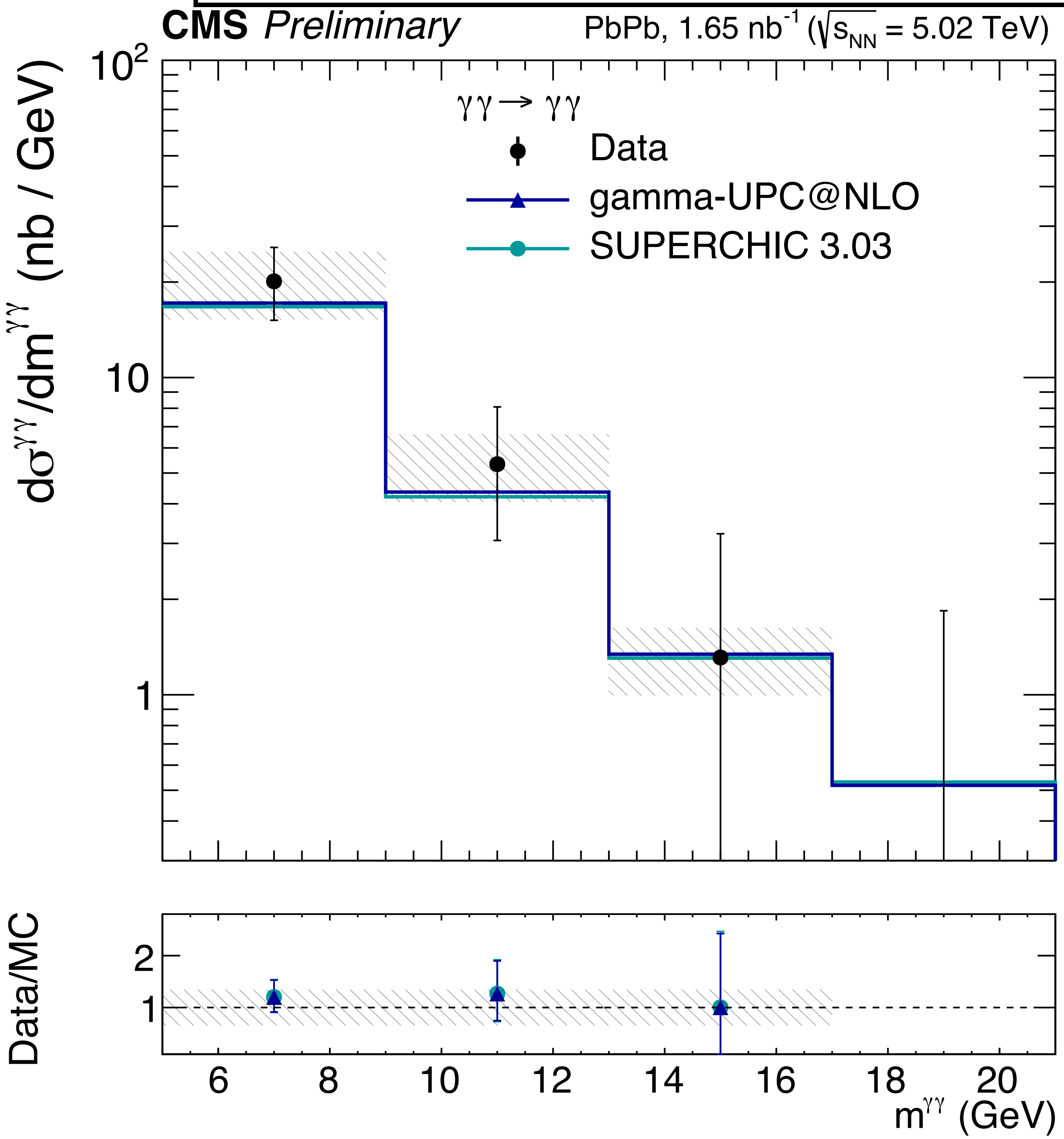
$$\sigma_{\mathrm{ATLAS}} = 120 \pm 22 \text{ nb}$$
vs $\sigma_{\mathrm{LO}} = 76 \text{ nb}$
vs $\sigma_{\mathrm{NLO'}} = 81.2^{+1.6}_{-0.9} \text{ nb}$

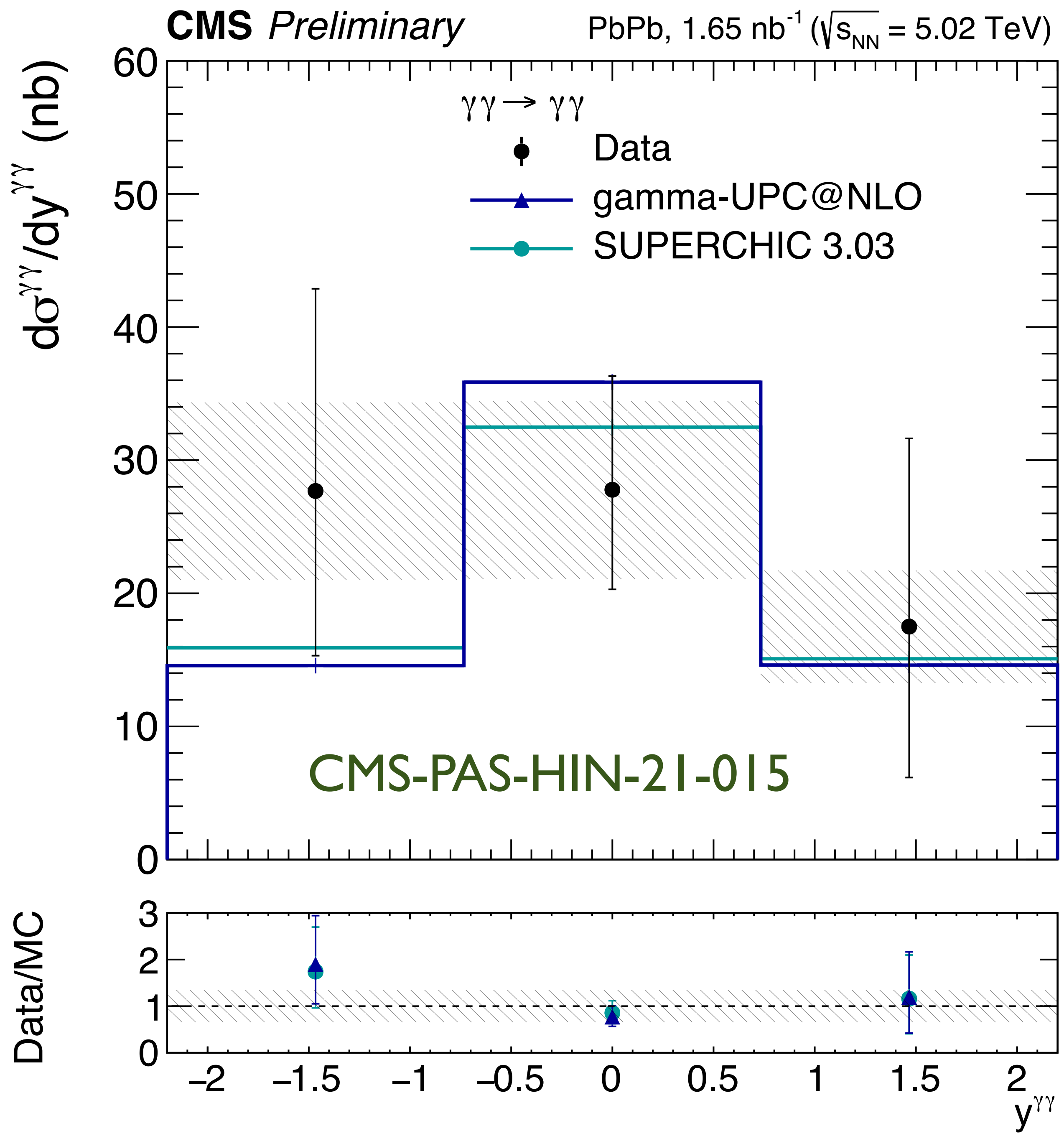
- Tension persists though is reduced a bit
- H(L)E under(over)estimates the size of quantum corr.
- 6 C-even bottomonia and X(6900) cannot explain the discrepancy neither

Caveat: some di-photon widths are not well constrained (only theory calc.) !

Theory-data comparison

$$\sigma_{\rm CMS} = 107 \pm 33_{\rm stat} \pm 20_{\rm syst}\ \text{nb} \qquad \textbf{vs}$$
$$\sigma_{\rm NLO'} = 95.4\ \left({}^{+2.0}_{-1.0}\right)_{\rm scale} \left({}^{+1.0}_{-1.5}\right)_{\rm param}\ \text{nb}$$





- No excess in CMS vs NLO

Conclusion

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

- LHC is a unique photon-photon collider
  - Novel BSM programmes: axions, gravitons, monopole, anomalous couplings, ...
  - Increasing number of SM rare/precise measure: LbL, tau g-2, ...
- gamma-UPC is a new versatile code to generate any photon-photon exclusive processes in UPCs with protons and ions
  - Interfaced to MadGraph5_aMC@NLO and HELAC-Onia
  - Some custom codes, like LbLatNLO
- Exclusive photon-photon processes, such as LbL, provide an ideal testing ground for novel multi-loop techniques
- A subfield for fruitful experiment-theory collaborations

Conclusion

- LHC is a unique photon-photon collider
  - Novel BSM programmes: axions, gravitons, monopole, anomalous couplings, ...
  - Increasing number of SM rare/precise measure: LbL, tau g-2, ...
- gamma-UPC is a new versatile code to generate any photon-photon exclusive processes in UPCs with protons and ions
  - Interfaced to MadGraph5_aMC@NLO and HELAC-Onia
  - Some custom codes, like LbLatNLO
- Exclusive photon-photon processes, such as LbL, provide an ideal testing ground for novel multi-loop techniques
- A subfield for fruitful experiment-theory collaborations

Thank you for your attention !

Backup Slides

Usage in MadGraph5_aMC@NLO

- **It has been released since MG5_aMC version 3.5.0**
  - Only LO and loop-induced modes are supported now (NLO in future)

```
./bin/mg5_aMC
MG5_aMC> import model <a model>
MG5_aMC> generate <a process>
MG5_aMC> output; launch
```

Usage in MadGraph5_aMC@NLO

- **It has been released since MG5_aMC version 3.5.0**
  - Only LO and loop-induced modes are supported now (NLO in future)

```
#*********************************************************************
# Collider type and energy                                          *
# lpp: 0=No PDF, 1=proton, -1=antiproton,                           *
#               2=elastic photon of proton/ion beam                 *
#            +/-3=PDF of electron/positron beam                     *
#            +/-4=PDF of muon/antimuon beam                         *
#*********************************************************************
  2     = lpp1 ! beam 1 type
  2     = lpp2 ! beam 2 type
  7000.0        = ebeam1 ! beam 1 total energy in GeV
  574080.0      = ebeam2 ! beam 2 total energy in GeV

#*********************************************************************
# PDF CHOICE: this automatically fixes alpha_s and its evol.        *
# pdlabel: lhapdf=LHAPDF (installation needed) [1412.7420]          *
#          iww=Improved Weizsaecker-Williams Approx.[hep-ph/9310350] *
#          eva=Effective W/Z/A Approx.       [2111.02442]           *
#          edff=EDFF in gamma-UPC            [22yy.zzzzz]           *
#          chff=ChFF in gamma-UPC            [22yy.zzzzz]           *
#          none=No PDF, same as lhapdf with lppx=0                  *
#*********************************************************************
  edff  = pdlabel ! PDF set

#*********************************************************************
# Heavy ion PDF / rescaling of PDF                                  *
#*********************************************************************
  1    = nb_proton1 # number of protons for the first beam
  0    = nb_neutron1 # number of neutrons for the first beam
  82   = nb_proton2 # number of protons for the second beam
  126  = nb_neutron2 # number of neutrons for the second beam
```

Usage in HELAC-Onia

- **It has been released** (download from here)

```
<HELAC-Onia Path>/ho_cluster
HO> set colpar = 14
HO> set nuclearA_beam1 = <an integer>
HO> set nuclearA_beam2 = <an integer>
HO> set nuclearZ_beam1 = <an integer>
HO> set nuclearZ_beam2 = <an integer>
HO> set UPC_photon_flux_type = <an integer>
HO> generate <a process>
HO> launch
```

How peripheral are Pb-Pb UPCs ?

Crépet, d'Enterria, HSS (in prep)

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

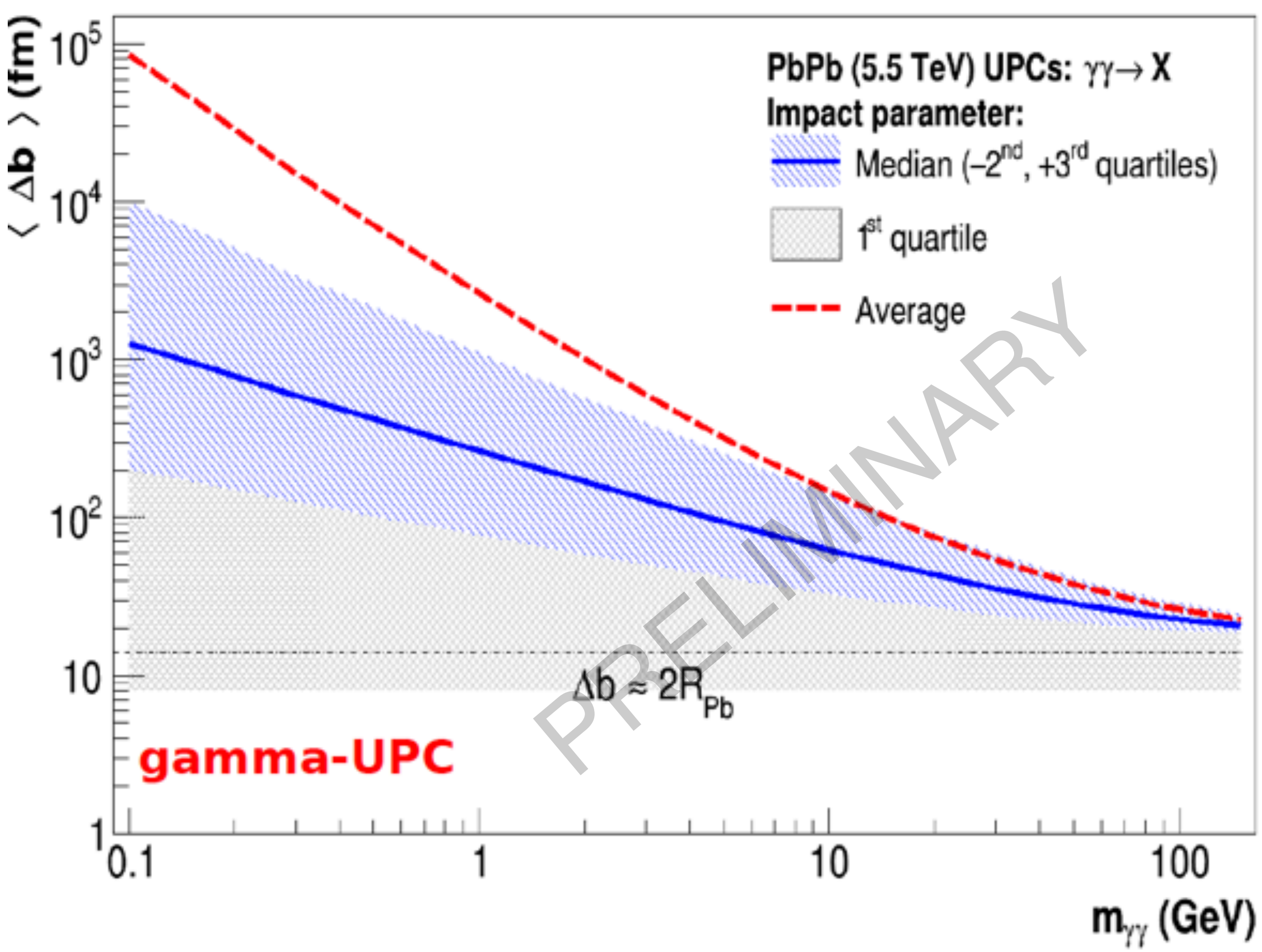
  $m_{\gamma\gamma} < 5$ GeV: $\langle\Delta b\rangle > 100$ fm

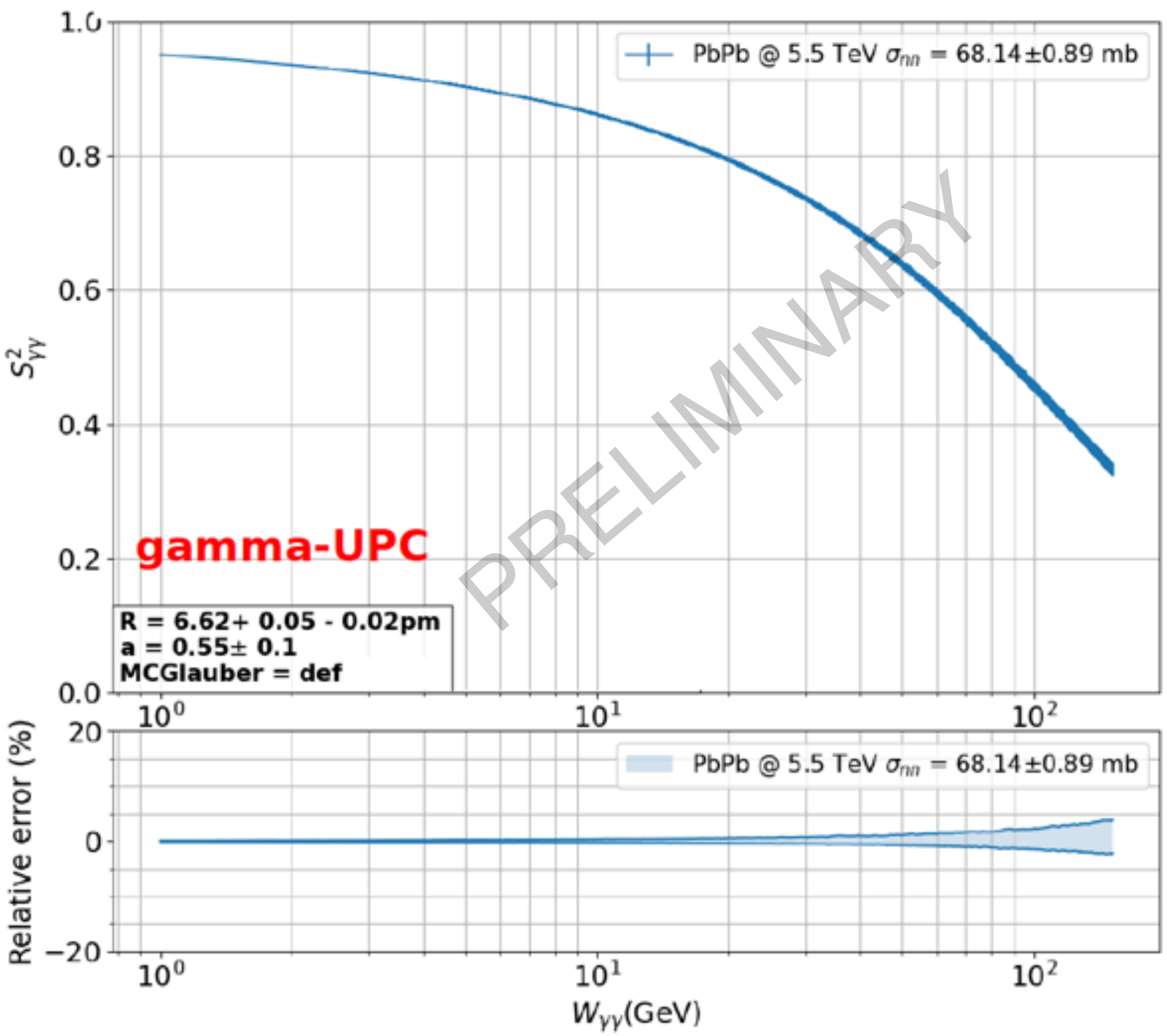
  $m_{\gamma\gamma} > 100$ GeV: $\langle\Delta b\rangle \sim 20$ fm

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

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

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





How peripheral are p-p UPCs ?

Crépet, d'Enterria, HSS (in prep)

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

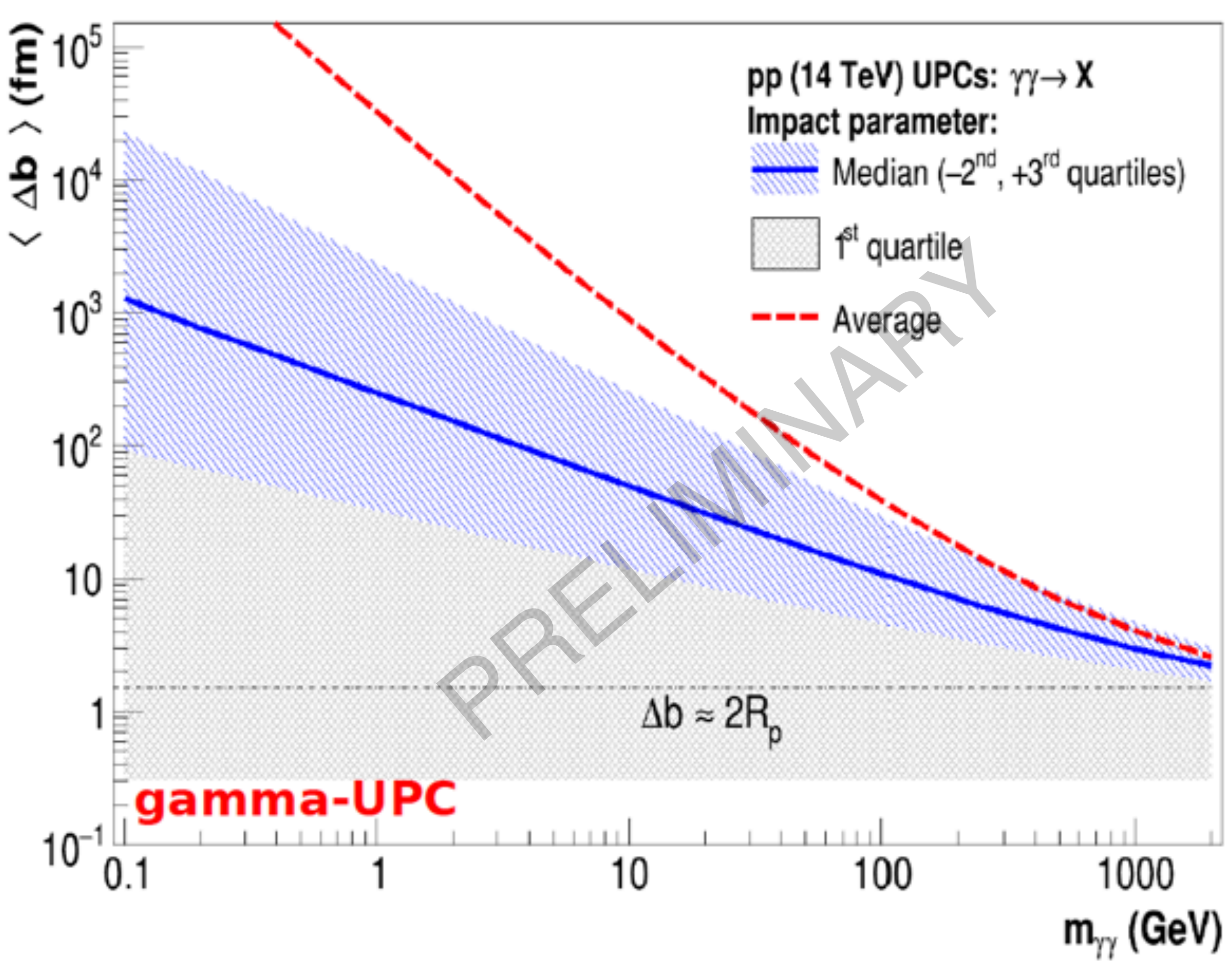
  $m_{\gamma\gamma}$ < 10 GeV: $\langle\Delta b\rangle$ > 50 fm

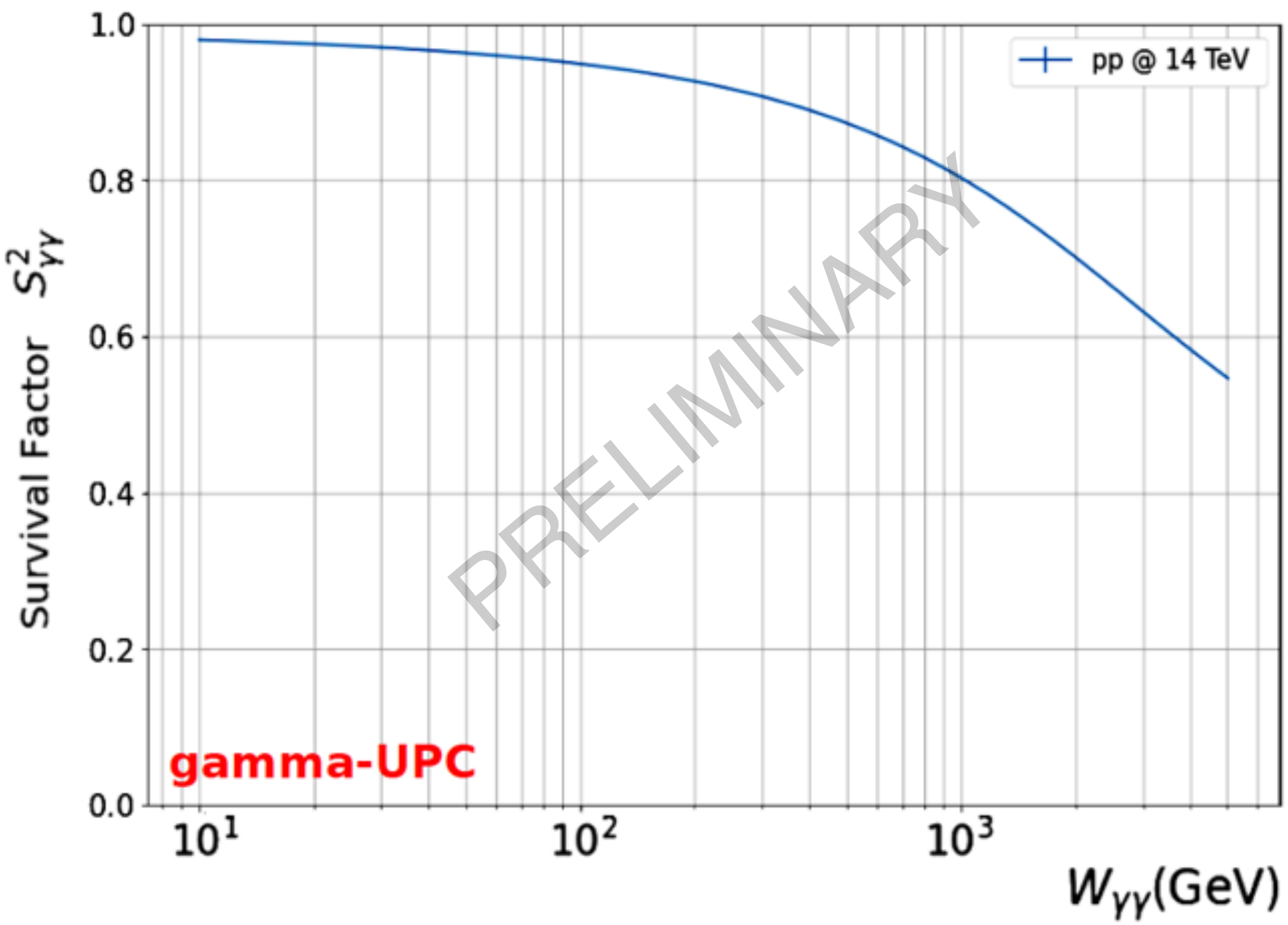
  $m_{\gamma\gamma}$ > 1 TeV: $\langle\Delta b\rangle$ < 3 fm

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

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

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

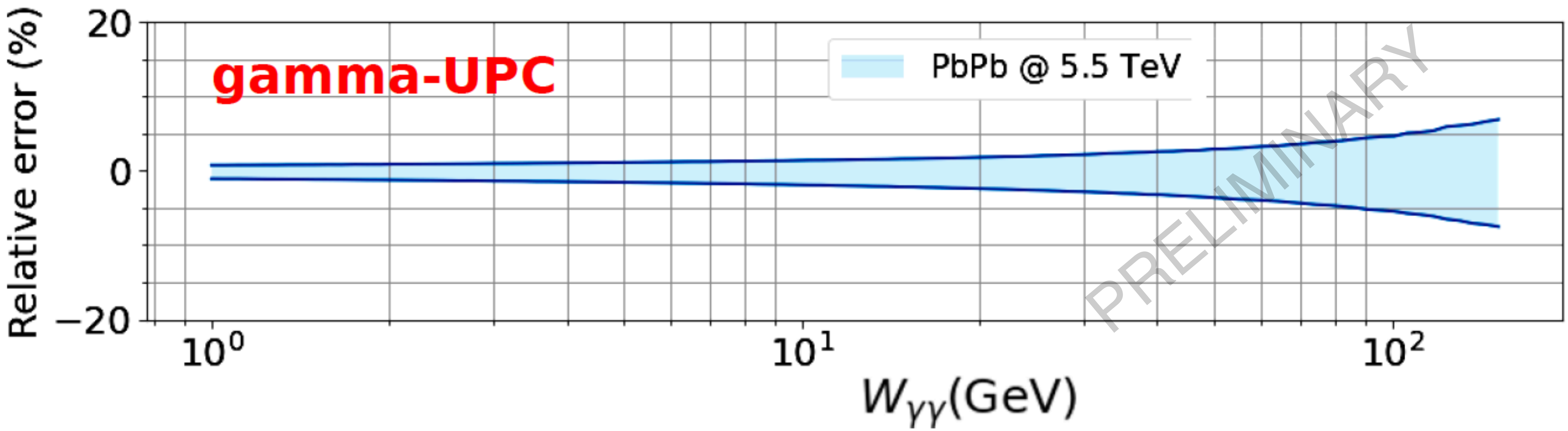




Parametric uncertainty

Crépet, d'Enterria, HSS (in prep)

- **Parametric uncertainty of modelling photon-photon flux**
  - ChFF & Glauber MC: variations of $R_A, a_A, \sigma_{\rm inel}^{\rm NN}$

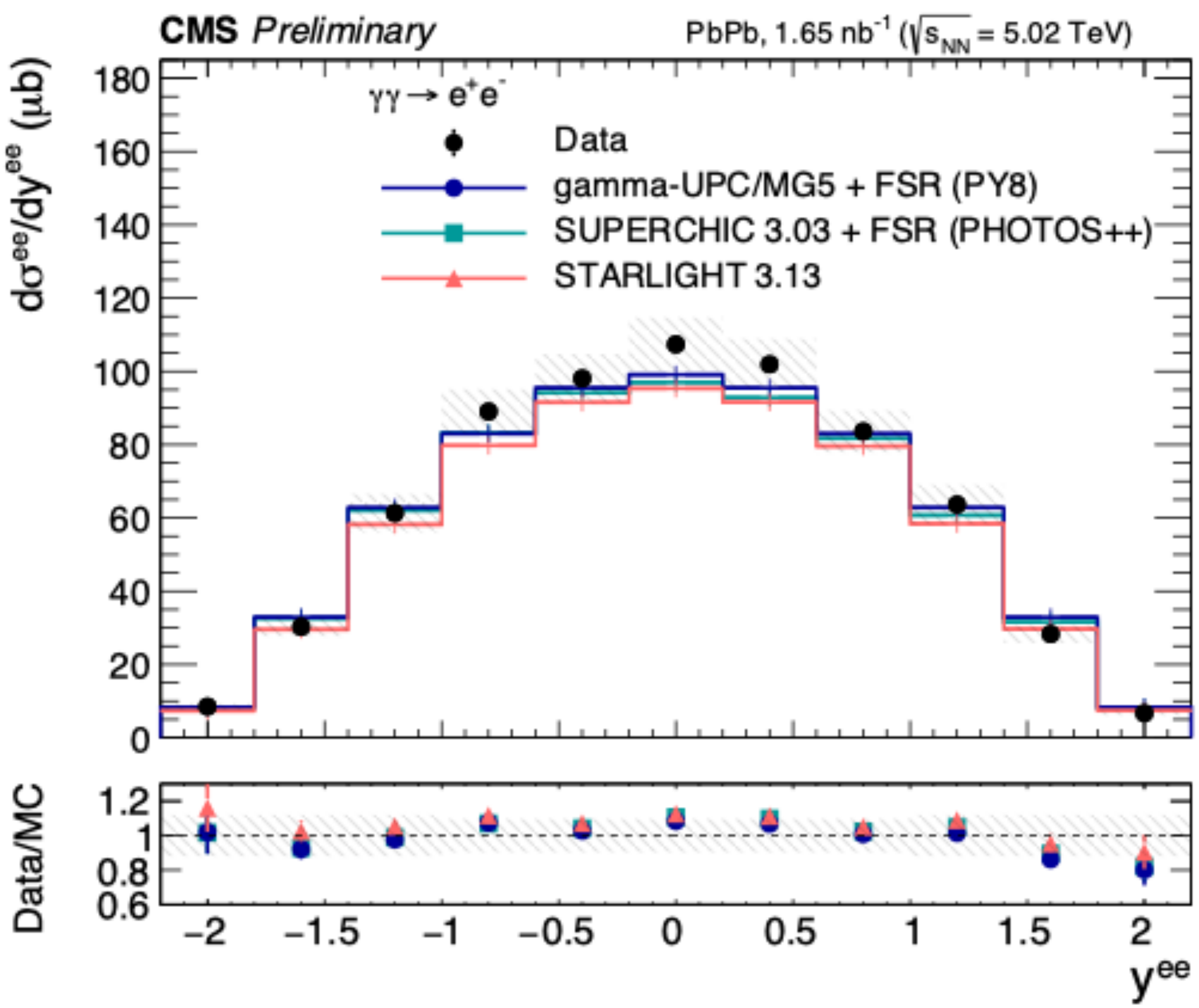


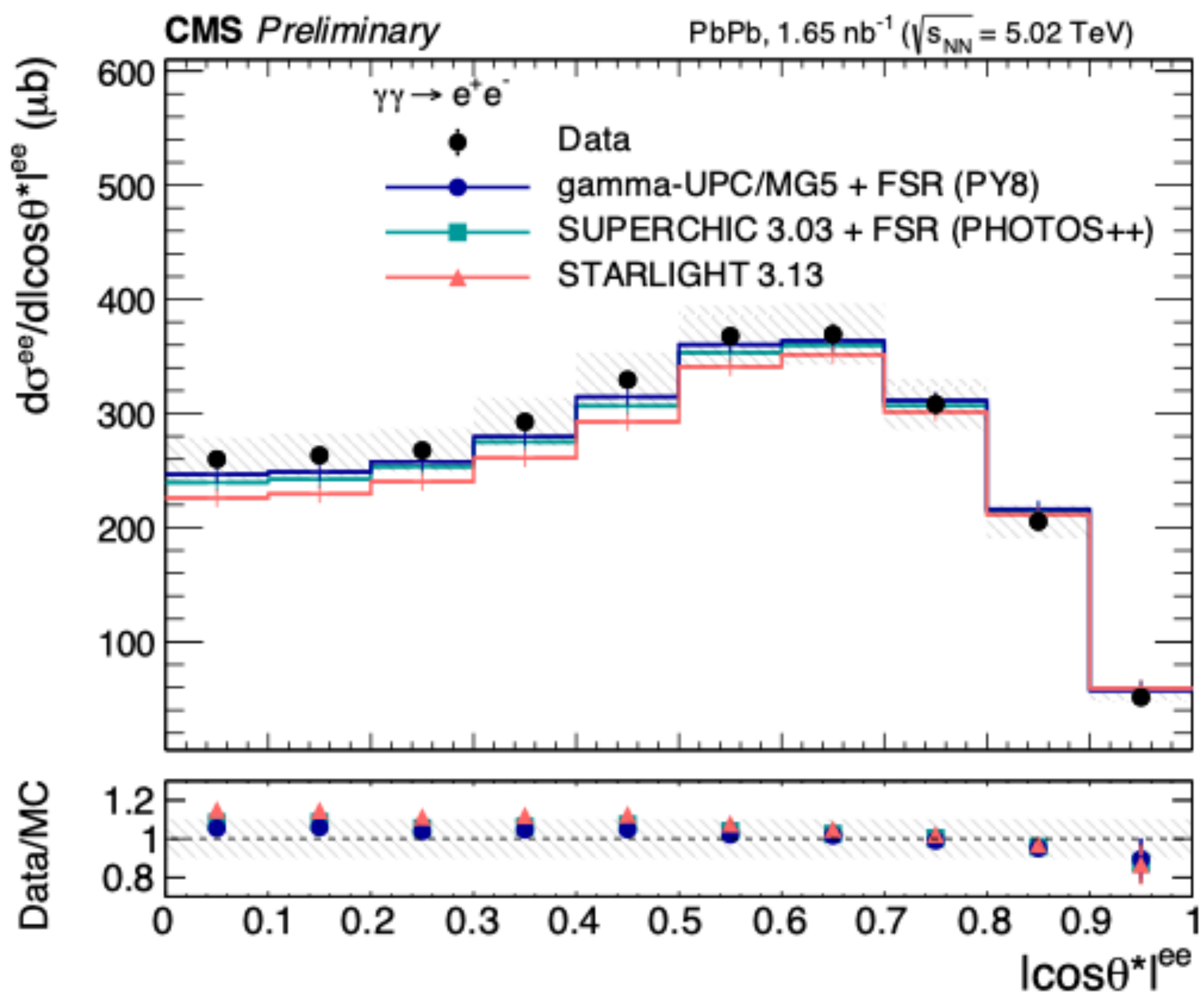
- Low-mass: a few %
- High-mass: ~7 %

Breit-Wheeler process

- **Fiducial and differential cross sections**
  - Electron-positron

CMS-PAS-HIN-21-015

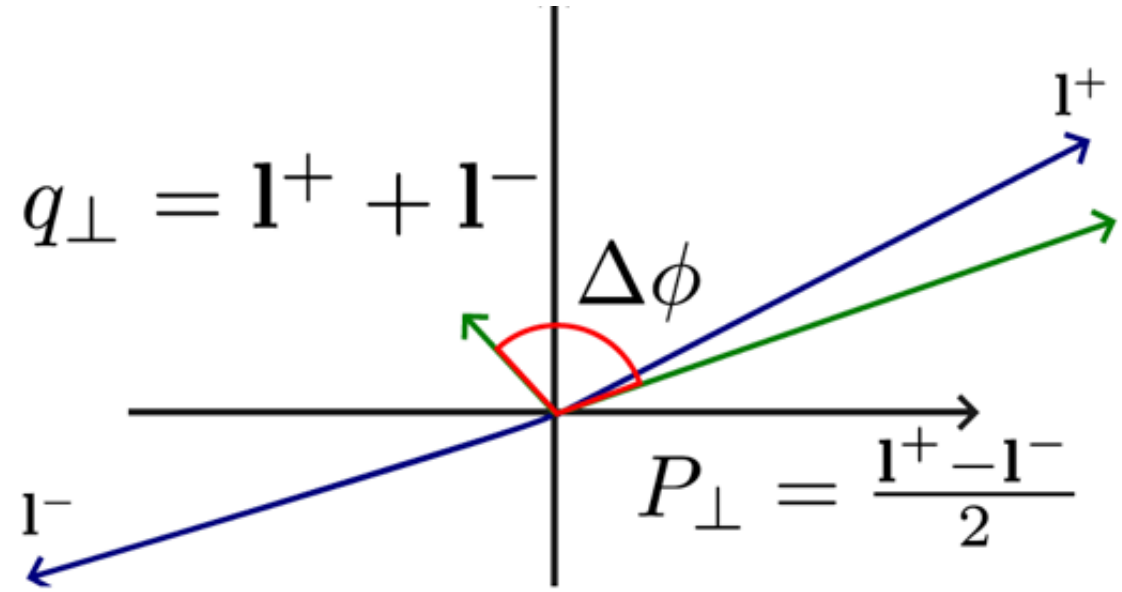




Azimuthal modulation

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

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



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

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

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

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

- Photon TMD:

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

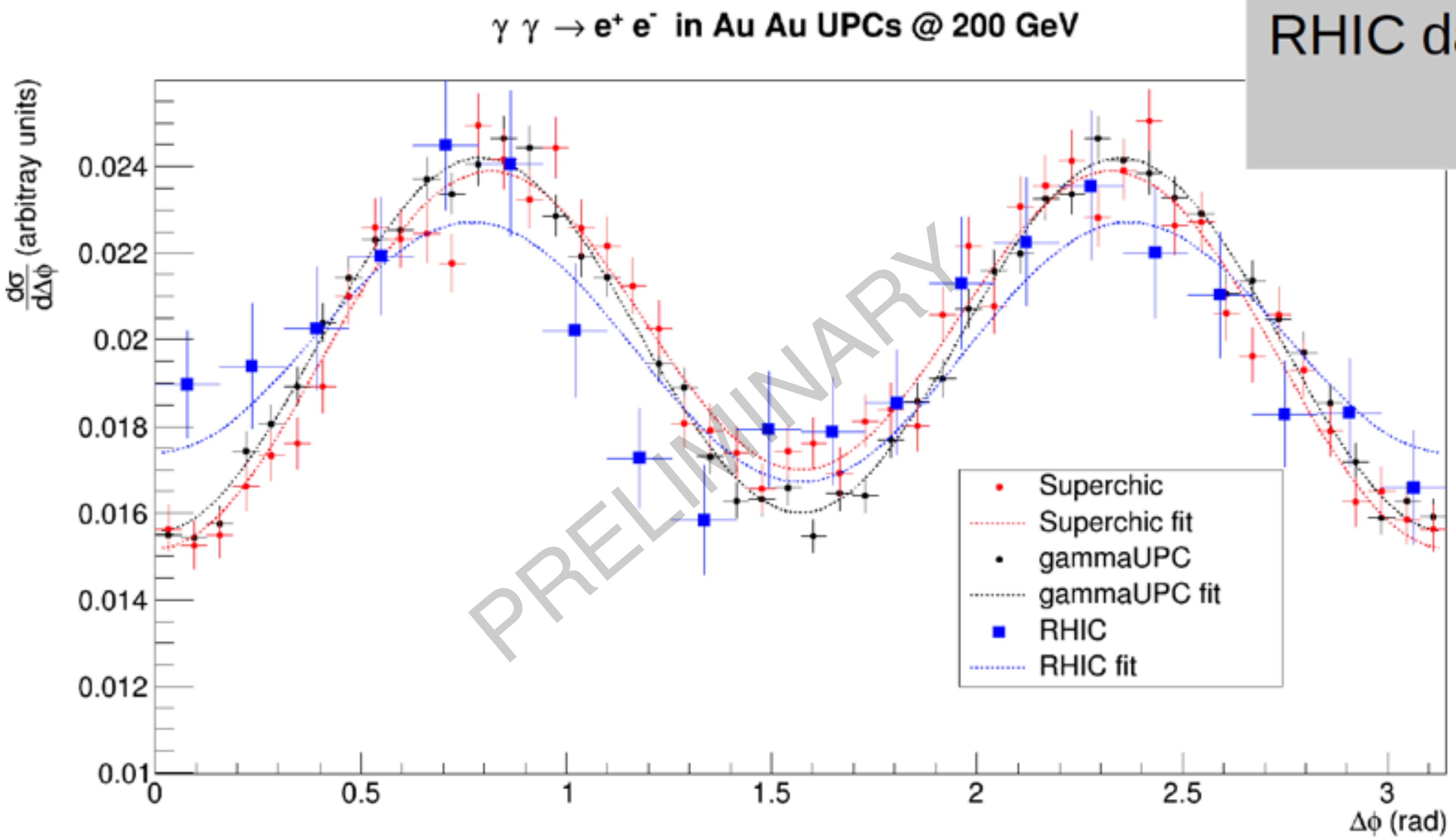
Slide by Nicolas Crépet at DIS2024

Azimuthal modulation

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

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

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

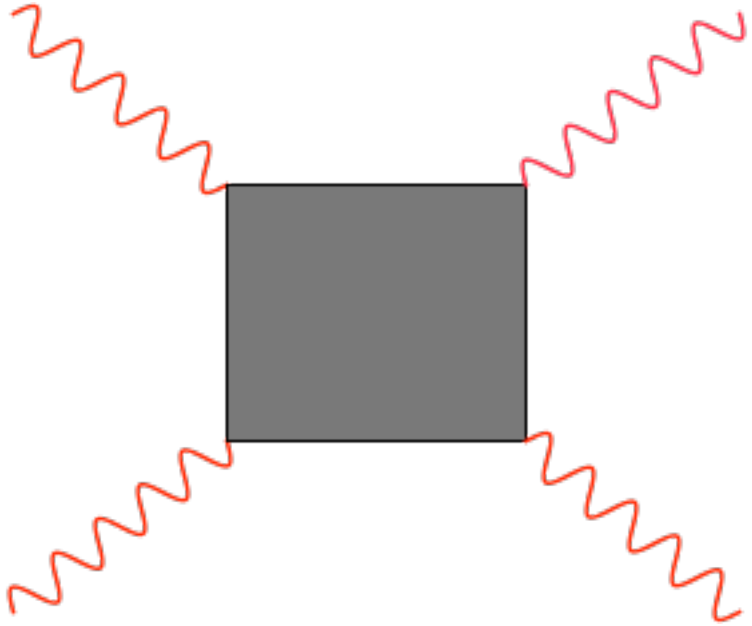


$$p_T^{pair} < 0.1\text{GeV}$$
$$0.45 < m_{ee} < 0.76\text{GeV}$$
$$p_T^e > 0.2\text{GeV}$$

Crépet, d'Enterria, HSS (in prep)

RHIC data:
arXiv:1910.12400

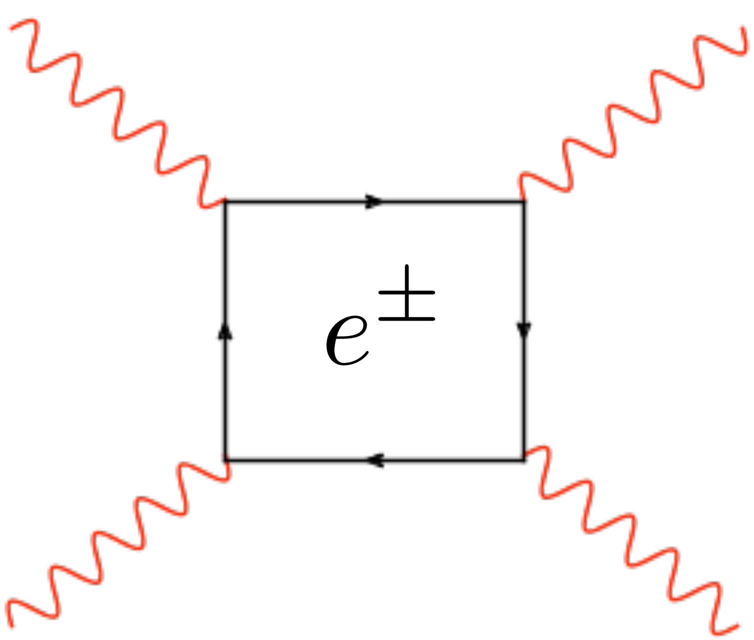
- **Scattering of Light-by-Light (LbL)**



Introduction

- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s

    Euler-Heisenberg Lagrangian for low energy limit



Consequences of Dirac's Theory of the Positron

W. Heisenberg and H. Euler in Leipzig[1]

22. December 1935

Abstract

According to Dirac's theory of the positron, an electromagnetic field tends to create pairs of particles which leads to a change of Maxwell's equations in the vacuum. These changes are calculated in the special case that no real electrons or positrons are present and the field varies little over a Compton wavelength. The resulting effective Lagrangian of the field reads:

$$\mathfrak{L}=\frac{1}{2}(\mathfrak{E}^2-\mathfrak{B}^2)+\frac{e^2}{\hbar c}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{i\eta^2(\mathfrak{E}\mathfrak{B})\cdot\frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{conj.}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{conj.}} + |\mathfrak{E}_k|^2+\frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}$$

$\mathfrak{E},\mathfrak{B}$ field strengths

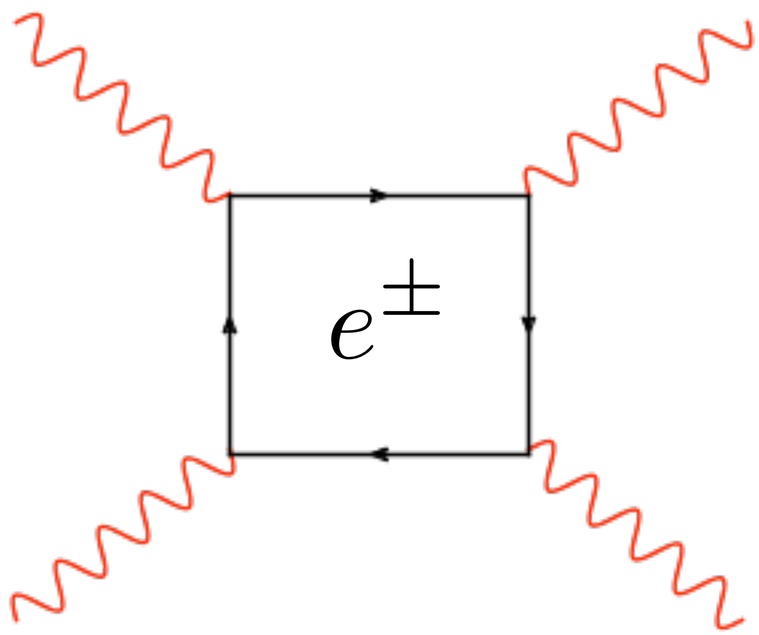
$|\mathfrak{E}_k|=\frac{m^2c^3}{e\hbar}=\frac{1}{137}\frac{e}{(e^2/mc^2)^2}=$ critical field strengths

The expansion terms in small fields (compared to $\mathfrak{E}$) describe light-light scattering. The simplest term is already known from perturbation theory. For large fields, the equations derived here differ strongly from Maxwell's equations. Our equations will be compared to those proposed by Born.

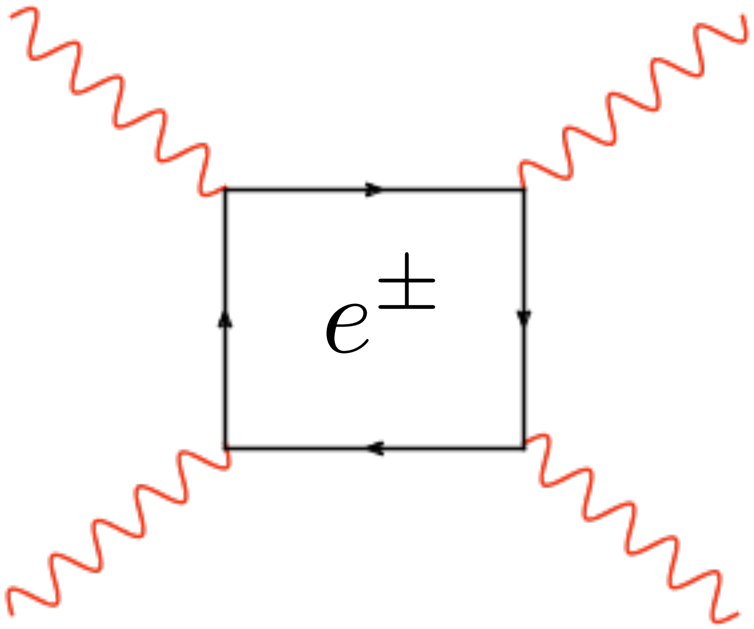
German title: "Folgerungen aus der Diracschen Theorie des Positrons" Zeitschr. Phys. *98*, 714 (1936).

Introduction

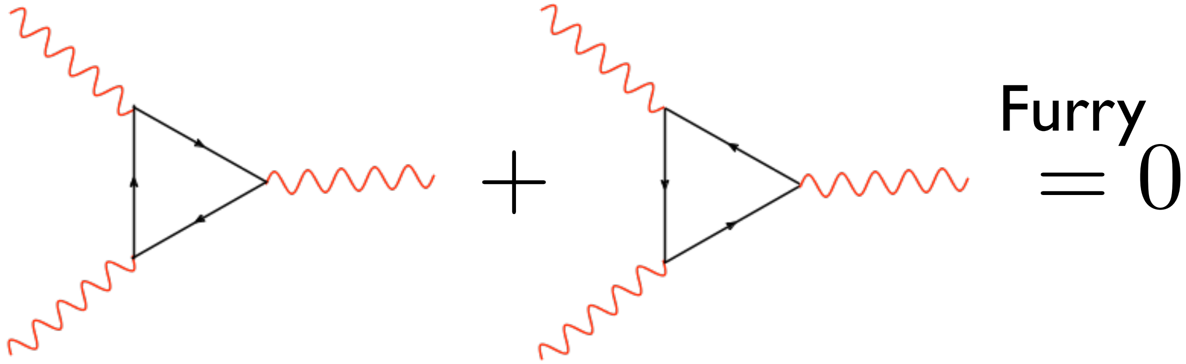
- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51

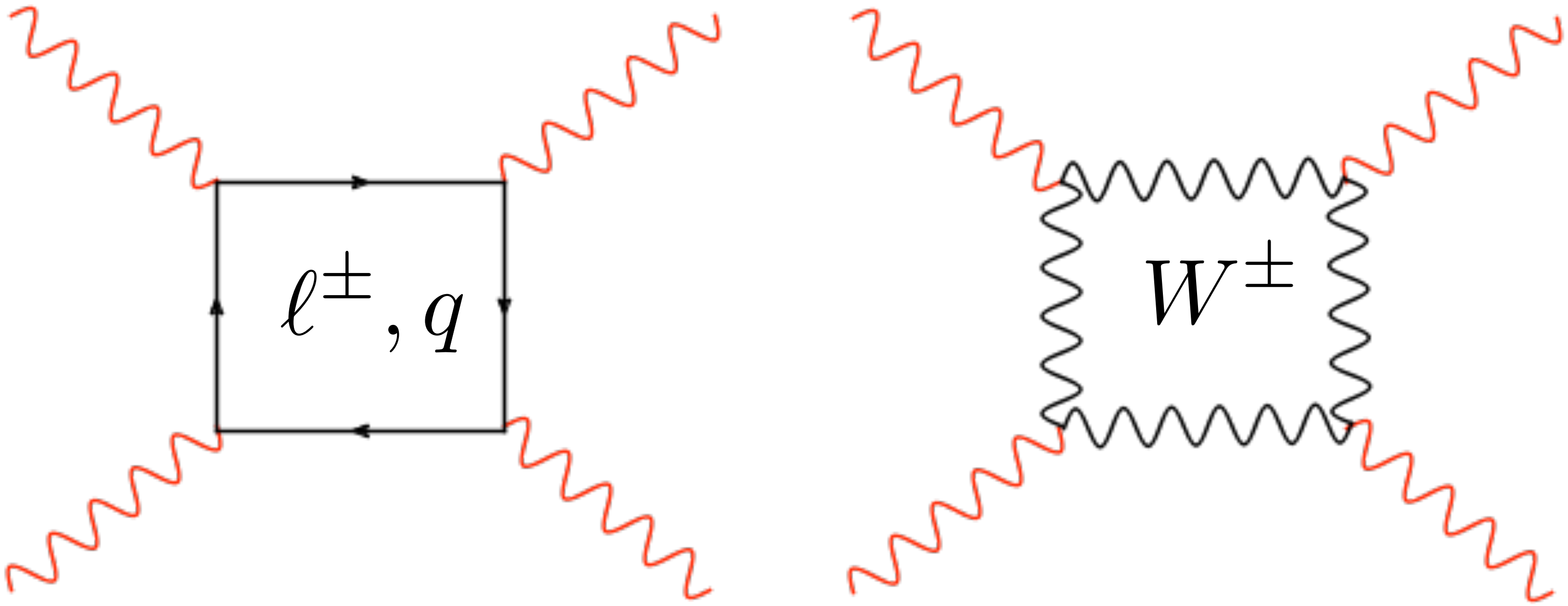


- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51
  - A fundamental process for many interesting questions ...



- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51
  - A fundamental process for many interesting questions ...
    - *How light interacts with itself ?*

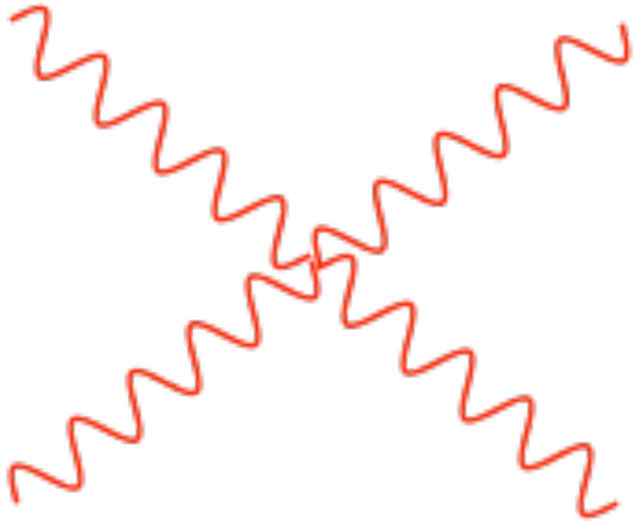




SM

$\mathcal{O}(\alpha^4)$ @LO

- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51
  - A fundamental process for many interesting questions ...
    - *How light interacts with itself ?*

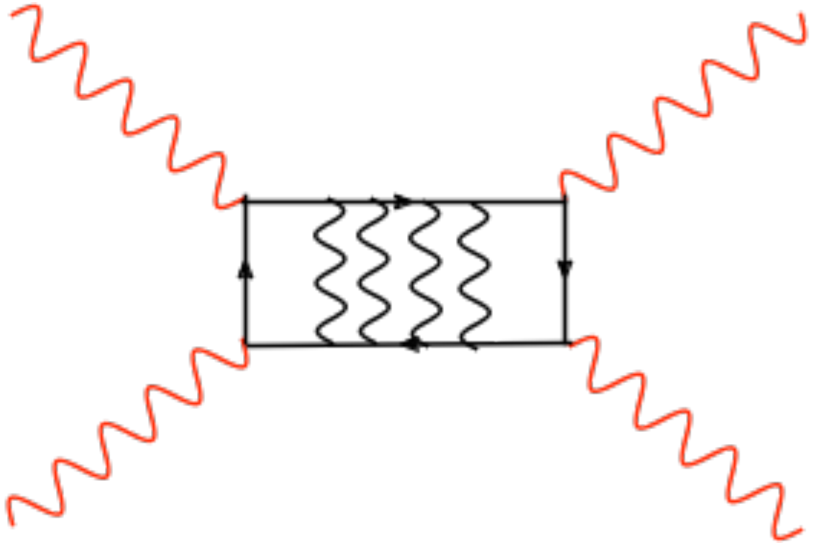


$$\mathcal{L}_{\mathrm{dim-8}} \supset \frac{1}{\Lambda^4} FFFF, \frac{1}{\Lambda^4} FF\tilde{F}\tilde{F}$$

$$\mathcal{L}_{\mathrm{Born-Infeld}} = \beta^2 \left(1 - \sqrt{1 + \frac{1}{2\beta^2} F_{\mu\nu}F^{\mu\nu} - \frac{1}{16\beta^4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2}\right)$$

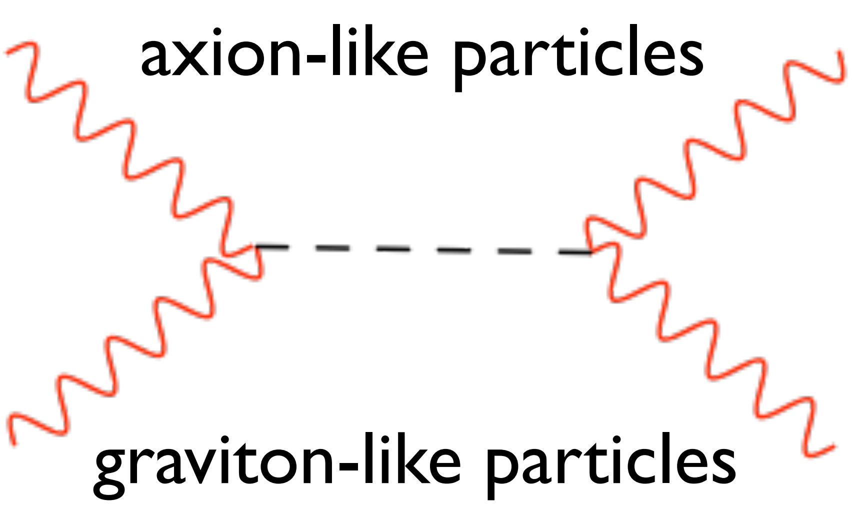
Introduction

- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51
  - A fundamental process for many interesting questions …
    - *How light interacts with itself ?*
    - *SM resonances ?*

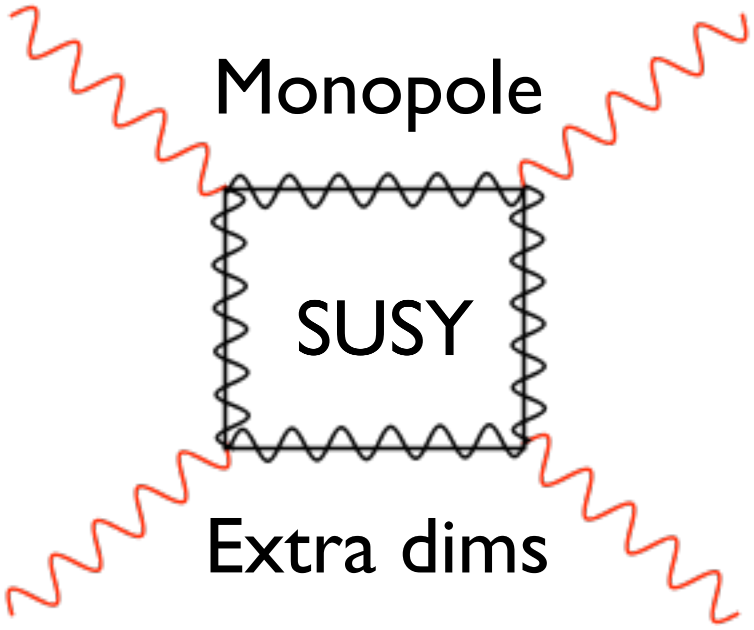


Introduction

- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51
  - A fundamental process for many interesting questions …
    - *How light interacts with itself ?*
    - *SM resonances ?*
    - *BSM resonances ?*

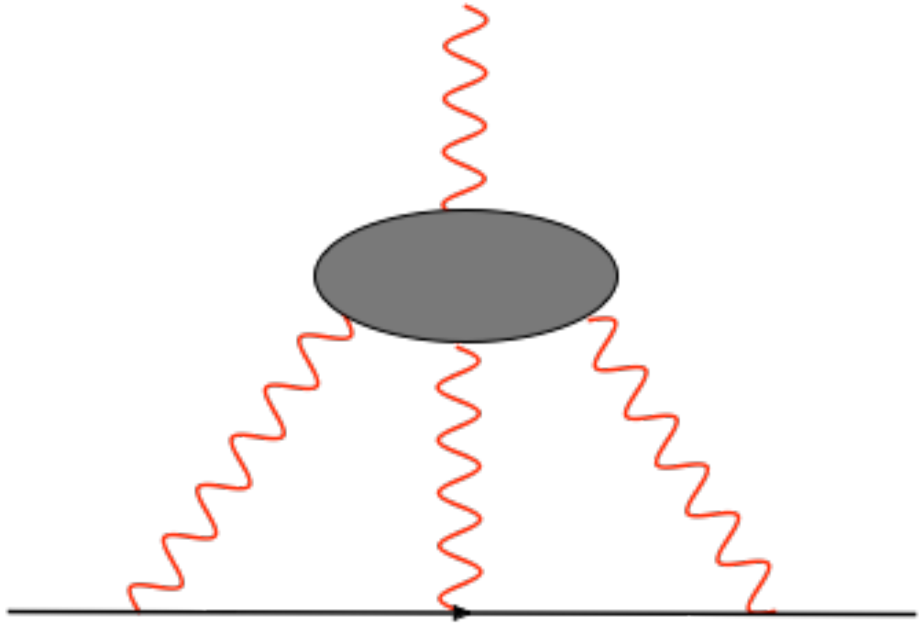


- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51
  - A fundamental process for many interesting questions …
    - *How light interacts with itself ?*
    - *SM resonances ?*
    - *BSM resonances ?*
    - *BSM particles in loops ?*



Introduction

- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51
  - A fundamental process for many interesting questions ...
    - *How light interacts with itself ?*
    - *SM resonances ?*
    - *BSM resonances ?*
    - *BSM particles in loops ?*
    - *g-2 indirectly ?*



Introduction

- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51
  - A fundamental process for many interesting questions ...
    - *How light interacts with itself ?*
    - *SM resonances ?*
    - *BSM resonances ?*
    - *BSM particles in loops ?*
    - *g-2 indirectly ?*
  - An ideal testing ground for new methods for loops

Gauge invariance & IR finiteness ⟶ *Cancellations among diagrams*

String-inspired, unitarity- or cuts-based, numerical local unitarity ...

Introduction

- **Scattering of Light-by-Light (LbL)**
  - One of the earliest predictions in Dirac's theory Heisenberg & Euler 30s
    Euler-Heisenberg Lagrangian for low energy limit
  - The first complete LO calculation in QED Karplus & Neuman PR'51
  - A fundamental process for many interesting questions ...
    - *How light interacts with itself ?*
    - *SM resonances ?*
    - *BSM resonances ?*
    - *BSM particles in loops ?*
    - *g-2 indirectly ?*
  - An ideal testing ground for new methods for loops

Gauge invariance & IR finiteness ⟶ *Cancellations among diagrams*

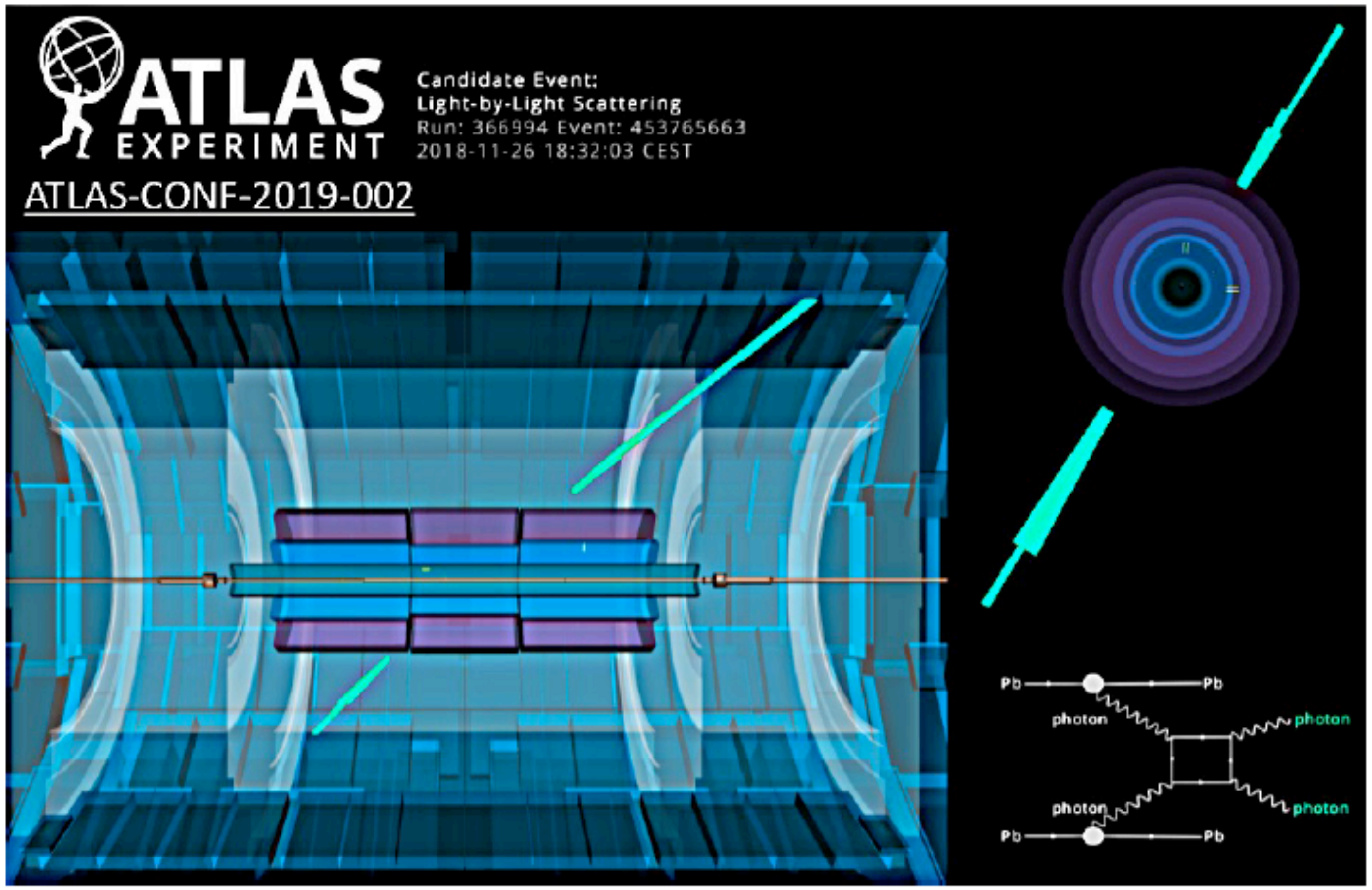
String-inspired, unitarity- or cuts-based, numerical local unitarity ...

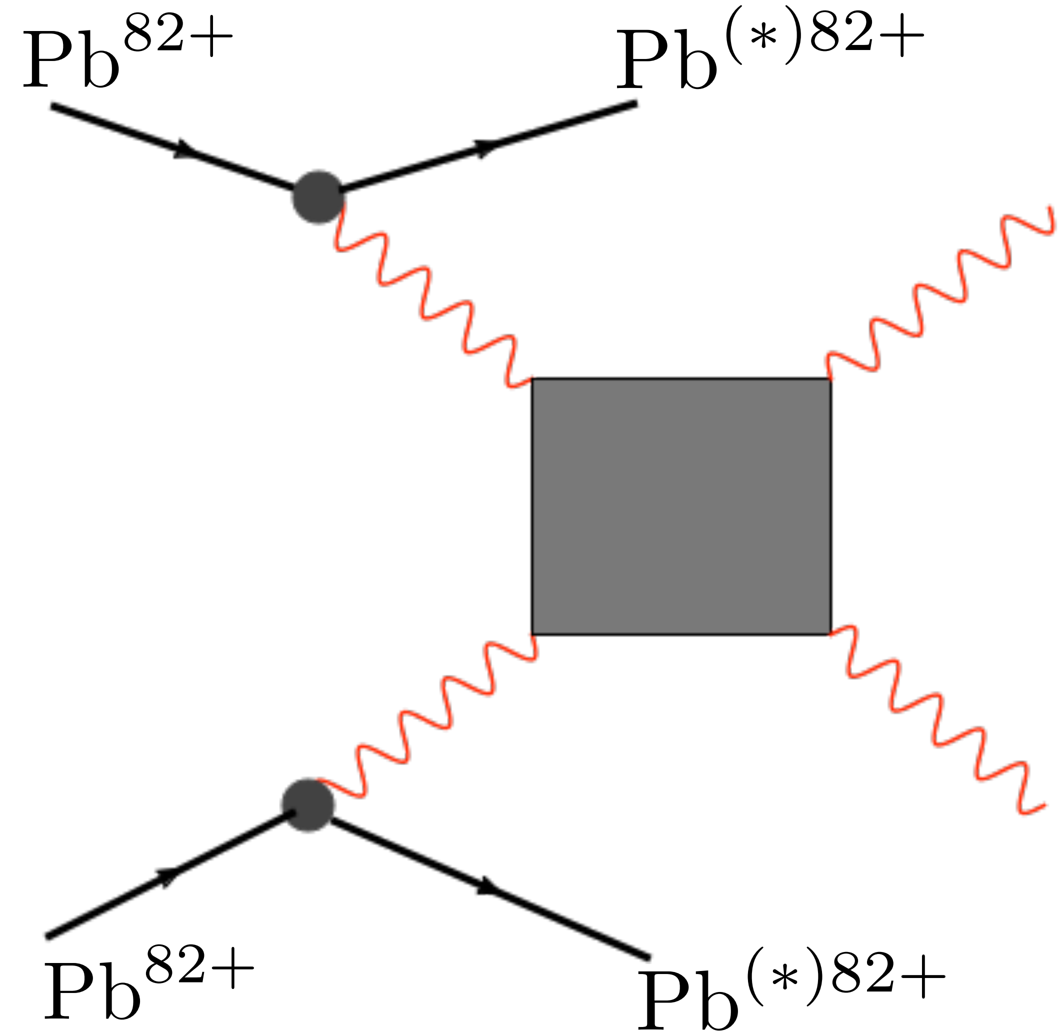
⇨ *How to measure it ?*

Introduction

- **First directly observed by ATLAS in 2019** ATLAS PRL'19

Earlier evidence: ATLAS Nature Physics '17, CMS PLB'19

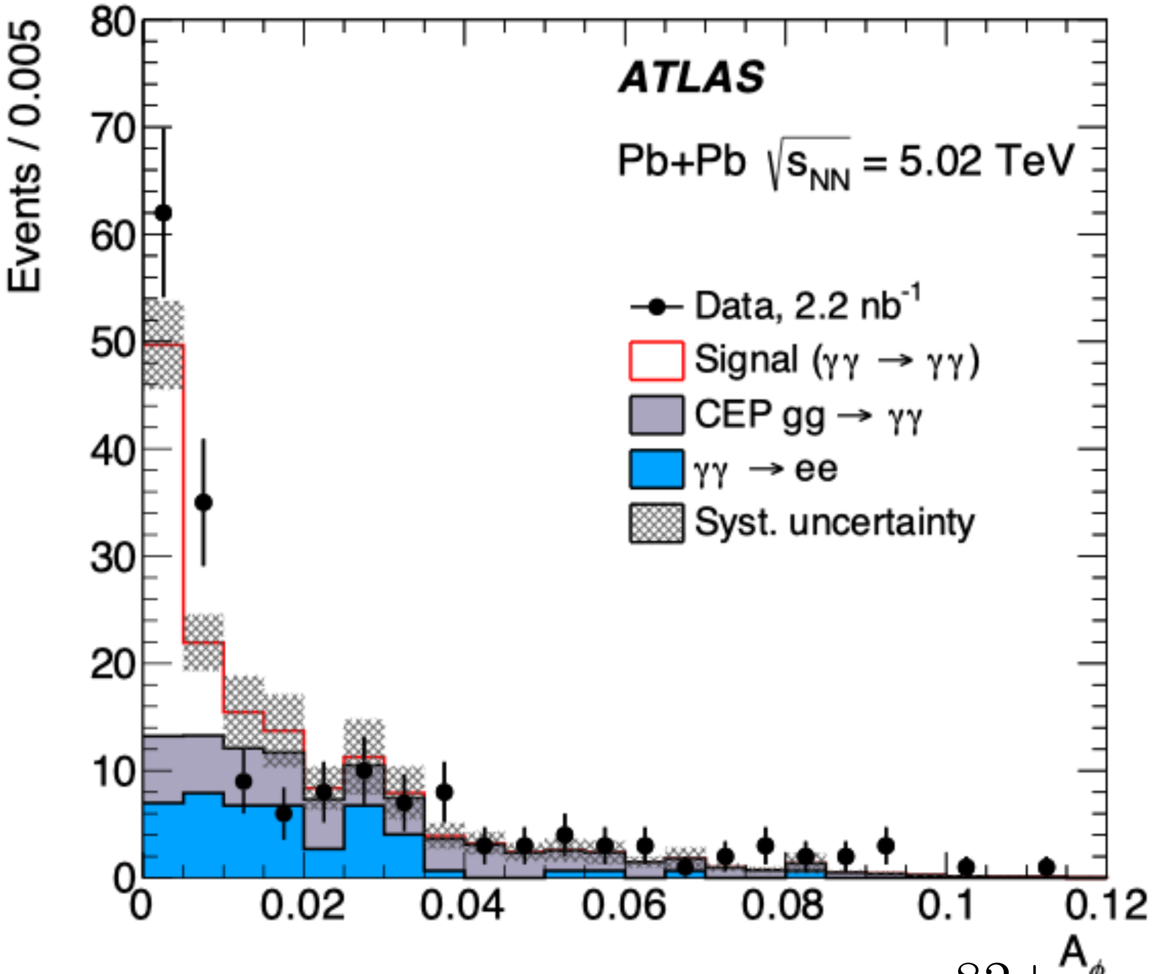


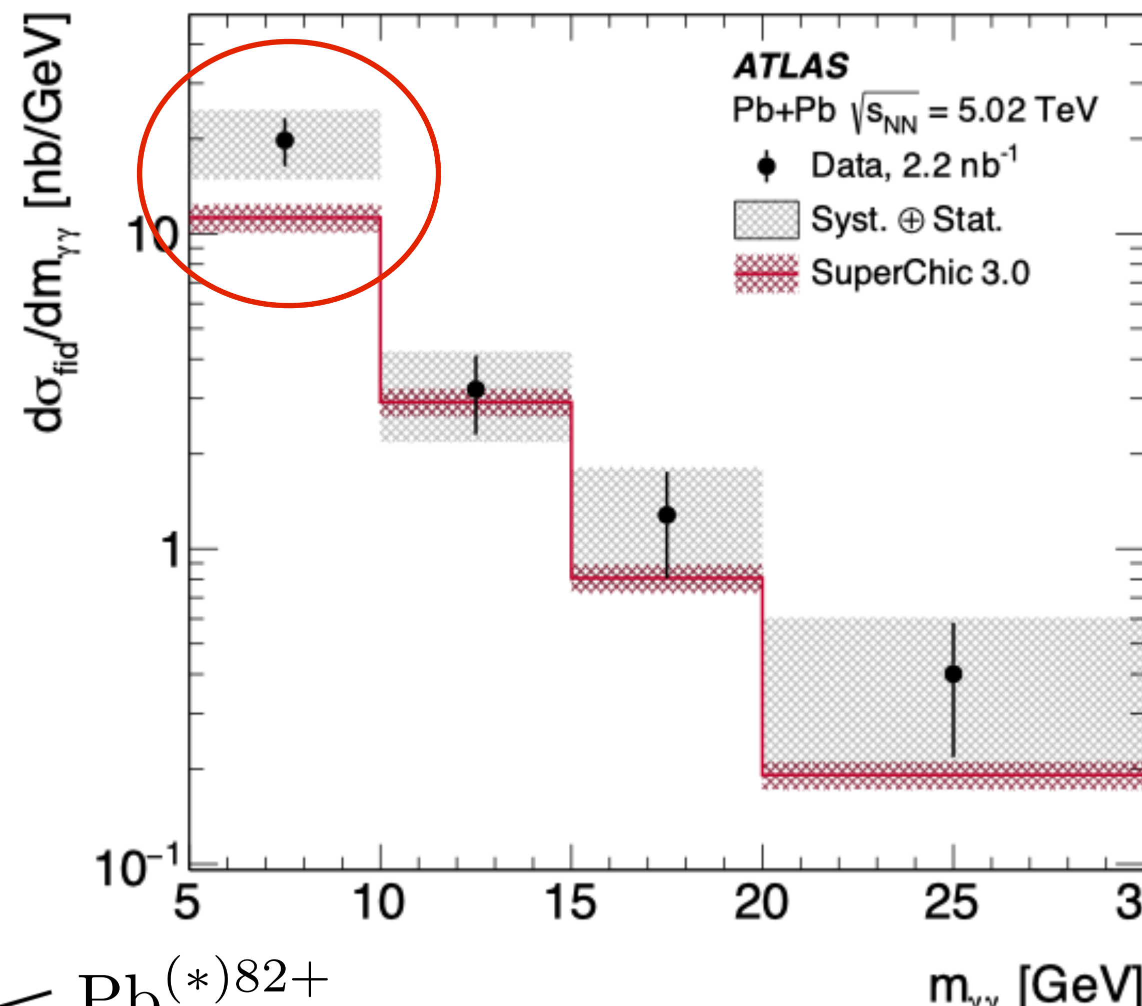


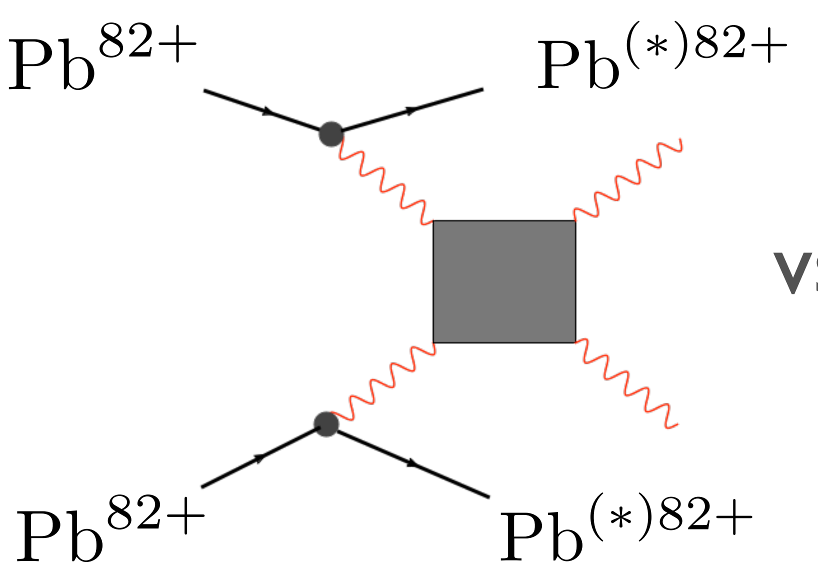
- PbPb 5.02 TeV
- 1.73 nb^{-1} (2018 data)
- 59 events vs 12 background events
- 8.2 std dev.

- **Discrepancies between theory (LO) and ATLAS measure**

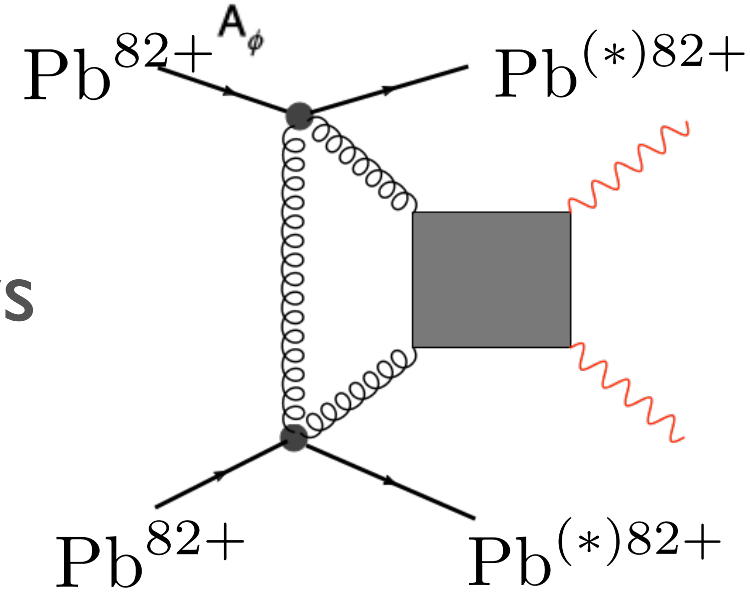
ATLAS JHEP'21







vs



- PbPb 5.02 TeV
- 2.2 nb^{-1} (2015+2018 data)
- 97 events vs 27 backg.

$\sigma_{\rm fid} = 120 \pm 22$ nb vs

$\sigma_{\rm LO} = 76$ nb

Helicity amplitudes

$$\gamma(p_1,\lambda_1)+\gamma(p_2,\lambda_2)+\gamma(p_3,\lambda_3)+\gamma(p_4,\lambda_4)\to 0$$

arXiv:2312.16966

- **Lorentz decomposition**

$$\mathcal{M}_{\vec{\lambda}} = \left(\prod_{i=1}^{4}\varepsilon_{\lambda_i,\mu_i}(p_i)\right)\mathcal{M}^{\mu_1\mu_2\mu_3\mu_4}$$

$$\mathcal{M}^{\mu_1\mu_2\mu_3\mu_4} = A_1 g^{\mu_1\mu_2}g^{\mu_3\mu_4} + A_2 g^{\mu_1\mu_3}g^{\mu_2\mu_4} + A_3 g^{\mu_1\mu_4}g^{\mu_2\mu_3}$$
$$+\sum_{j_1,j_2=1}^{3}\left(B^1_{j_1j_2}g^{\mu_1\mu_2}p^{\mu_3}_{j_1}p^{\mu_4}_{j_2} + B^2_{j_1j_2}g^{\mu_1\mu_3}p^{\mu_2}_{j_1}p^{\mu_4}_{j_2} + B^3_{j_1j_2}g^{\mu_1\mu_4}p^{\mu_2}_{j_1}p^{\mu_3}_{j_2} + B^4_{j_1j_2}g^{\mu_2\mu_3}p^{\mu_1}_{j_1}p^{\mu_4}_{j_2} + B^5_{j_1j_2}g^{\mu_2\mu_4}p^{\mu_1}_{j_1}p^{\mu_3}_{j_2} + B^6_{j_1j_2}g^{\mu_3\mu_4}p^{\mu_1}_{j_1}p^{\mu_2}_{j_2}\right)$$
$$+\sum_{j_1,j_2,j_3,j_4=1}^{3} C_{j_1j_2j_3j_4}p^{\mu_1}_{j_1}p^{\mu_2}_{j_2}p^{\mu_3}_{j_3}p^{\mu_4}_{j_4}$$

$$s=(p_1+p_2)^2, t=(p_2+p_3)^2, u=(p_1+p_3)^2$$

$$s+t+u=0$$

$$A_i, B^i_{jk}, C_{ijkl} : (s,t,u,m_f^2) \sim r(s,t,u,m_f^2)I(s,t,u,m_f^2)$$

138 form factors

↓ Tranversality $\varepsilon(p_i)\cdot p_i = 0$, Bose symmetry, Gauge invariance

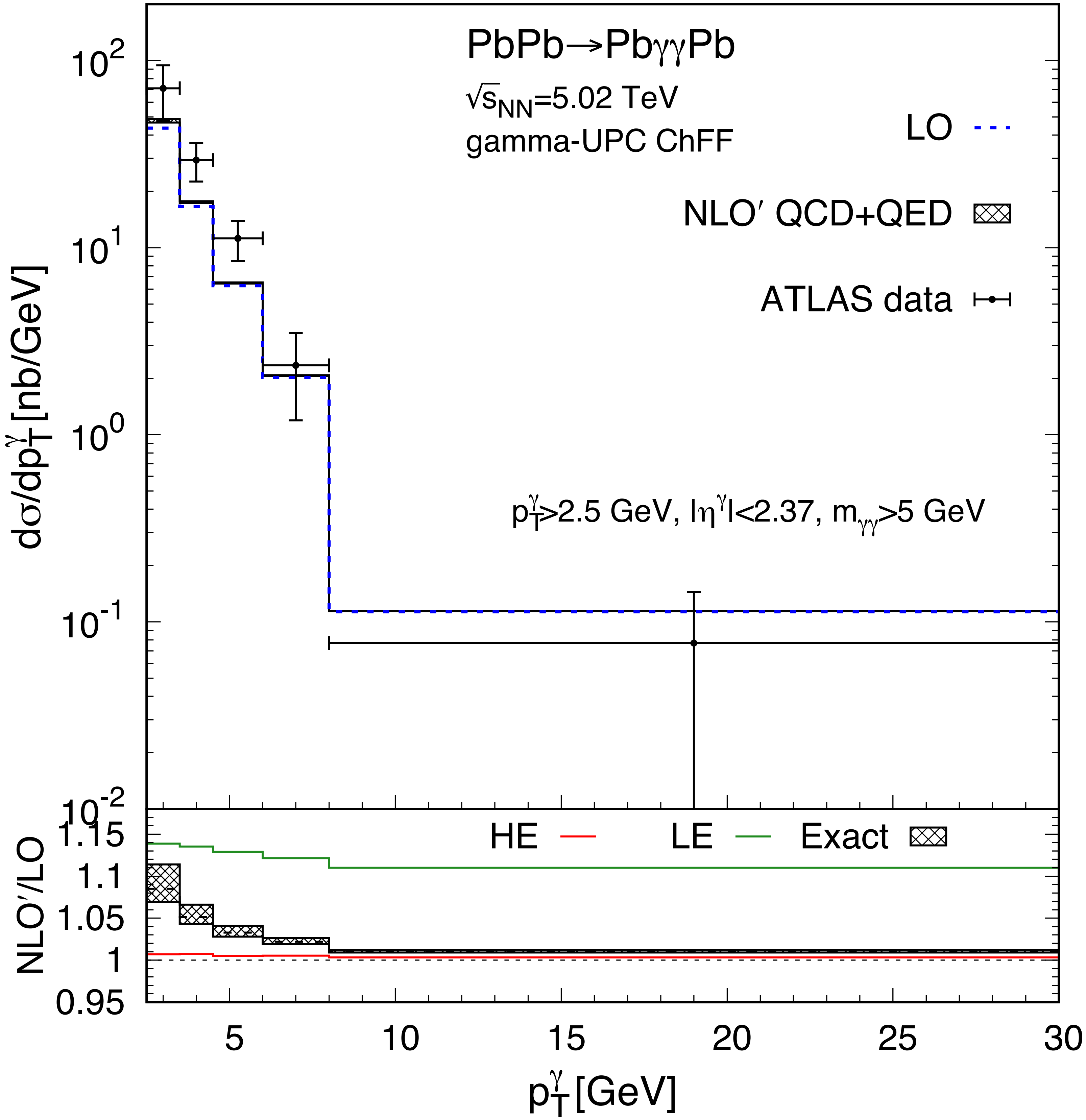
5 independent linear combinations

- **5 independent helicity amplitudes**

$$\mathcal{M}_{++++} \quad \mathcal{M}_{-+++} \quad \mathcal{M}_{--++} \quad \mathcal{M}_{+-+-} \quad \mathcal{M}_{+--+}$$

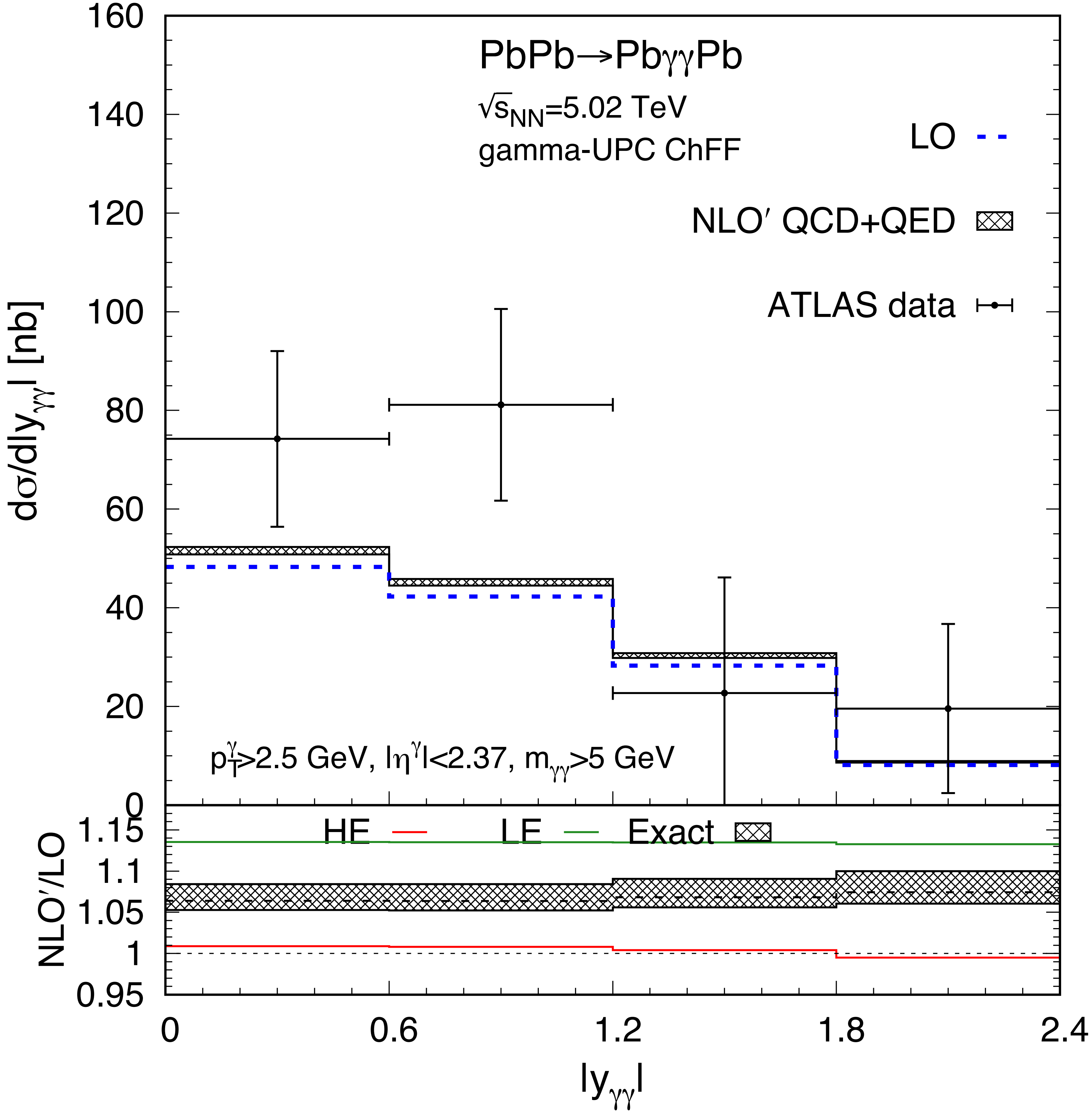
Theory-data comparisons of LbL

arXiv:2312.16956



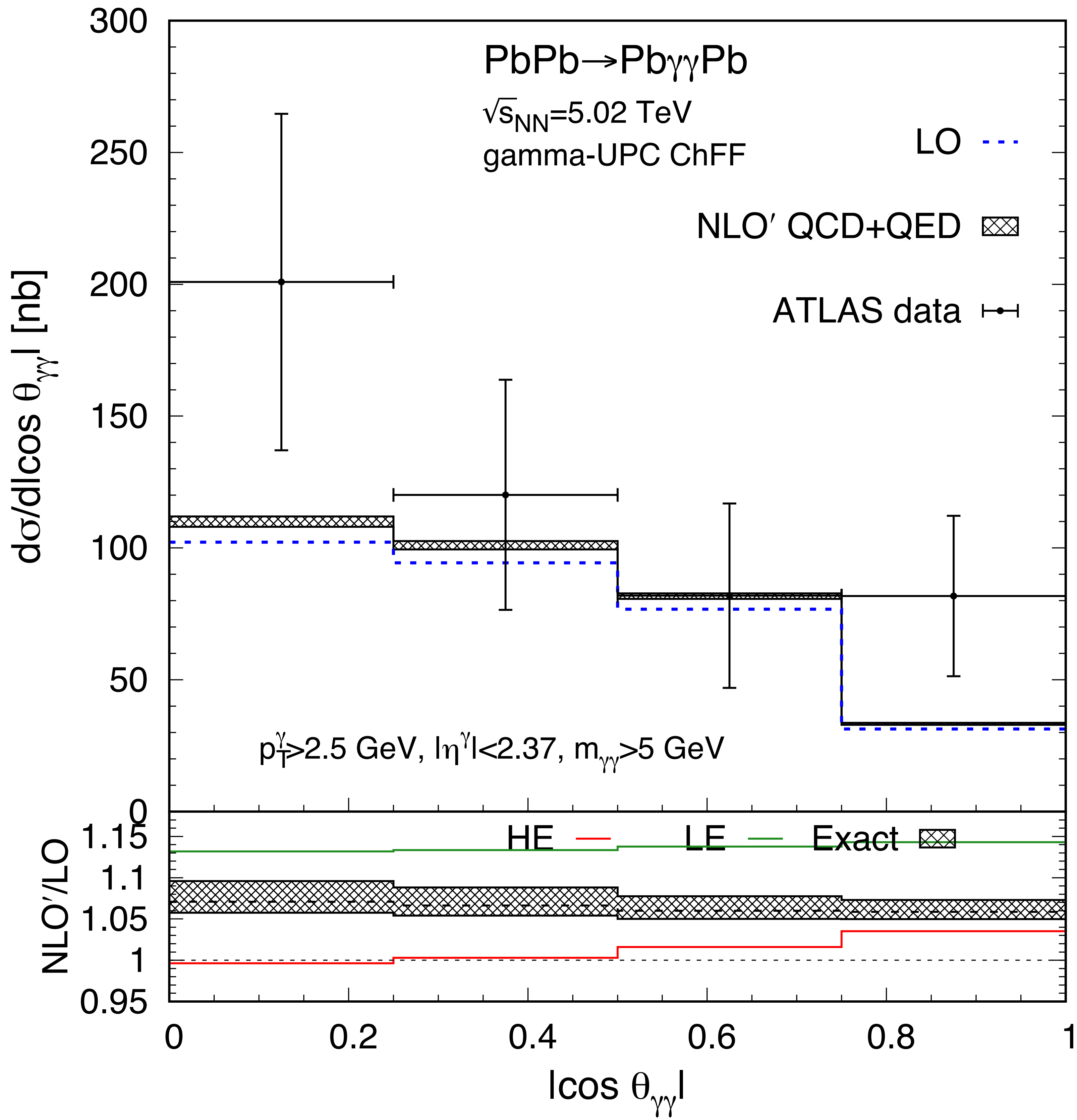
Theory-data comparisons of LbL

arXiv:2312.16956



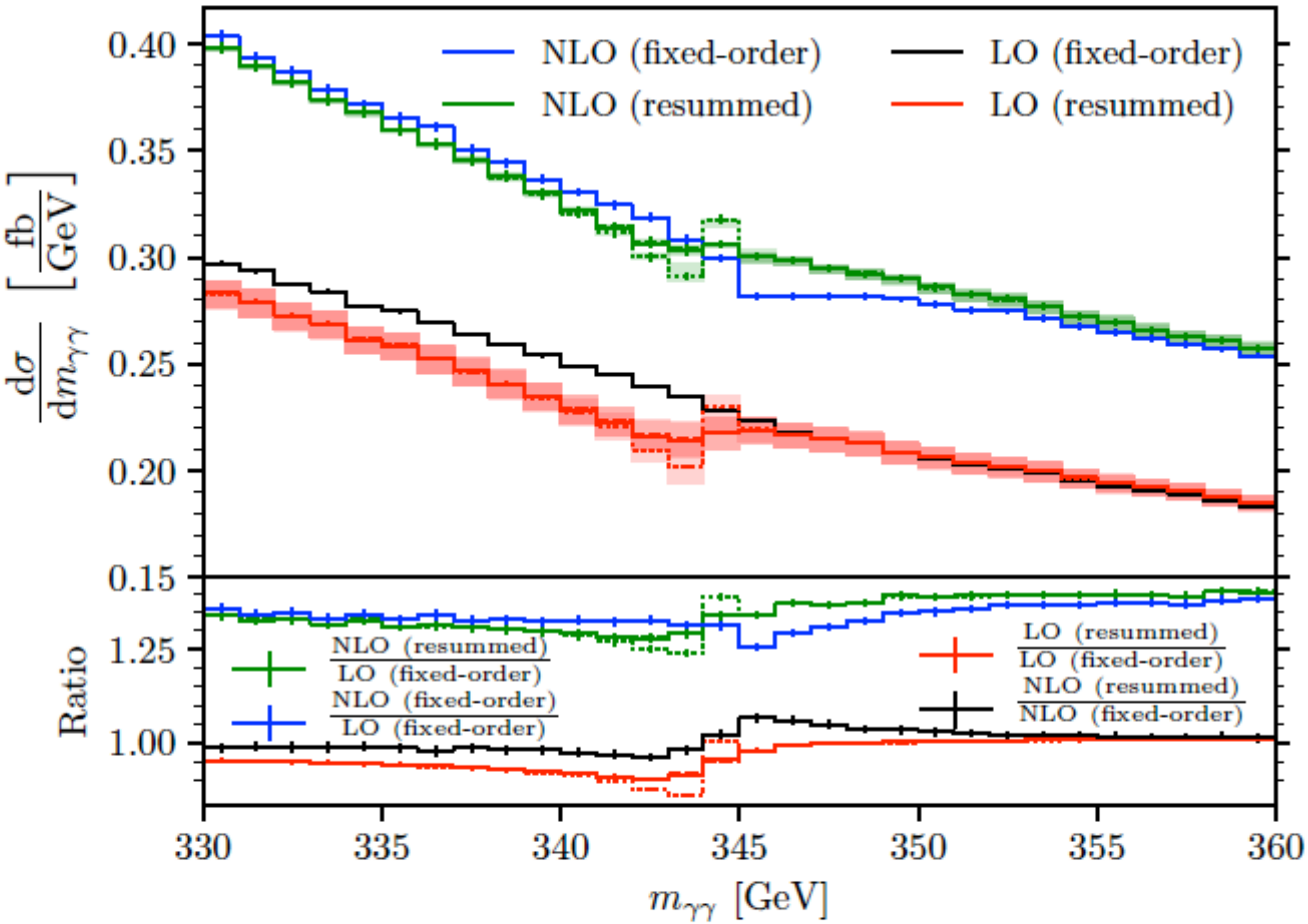
Theory-data comparisons of LbL

arXiv:2312.16956



Coulomb resummation

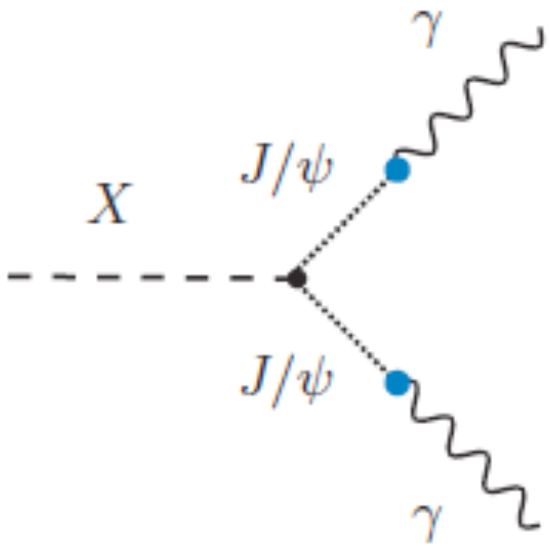
- **The Coulomb resummation for** $gg \to \gamma\gamma$ Chen et al. JHEP'20



Two photon decay of X(6900)

- **Vector meson dominance**

Biloshytskyi et al. PRD'22



Parameter	Interference	No-interference
m_X [MeV]	$6886 \pm 11 \pm 11$	$6905 \pm 11 \pm 7$
$\Gamma_{X \to J/\psi J/\psi}$ [MeV]	$168 \pm 33 \pm 69$	$80 \pm 19 \pm 33$
$\mathrm{Br}^{\mathrm{Fit}}_{X \to \gamma\gamma}$	$4.0^{+0.9}_{-1.1} \cdot 10^{-4}$	$5.6^{+1.3}_{-1.6} \cdot 10^{-4}$
$\mathrm{Br}^{\mathrm{VMD}}_{X \to \gamma\gamma}$	$2.8 \pm 0.4 \cdot 10^{-6}$	$6.4 \pm 0.8 \cdot 10^{-6}$

$J^{PC} =$ 0^{++} 0^{-+}

Two photon decays of bottomonia

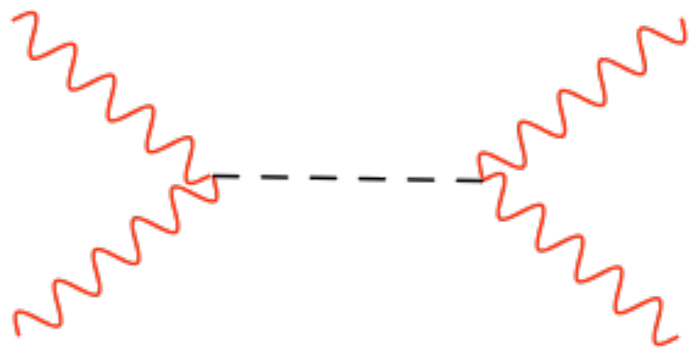
Wang et al. EPJC'18

State	Channels	This work		Expt. [52]		GI [26]		Ref. [27]	
		Width	$\mathcal{B}(\%)$	Width	$\mathcal{B}(\%)$	Width	$\mathcal{B}(\%)$	Width	$\mathcal{B}(\%)$
$\eta_b(1S)$	gg	17.9 MeV	∼100	···	···	16.6 MeV	∼100	20.18 MeV	∼100
	$\gamma\gamma$	1.05	5.87×10^{-3}	···	···	0.94	5.7×10^{-3}	0.69	3.42×10^{-3}
	Total	17.9 MeV	100	10^{+5}_{-4} MeV	···	16.6 MeV	100	20.18 MeV	100
$\eta_b(2S)$	gg	8.33 MeV	∼100	···	···	7.2 MeV	∼100	10.64 MeV	99.86
	$\gamma\gamma$	0.489	5.86×10^{-3}	···	···	0.41	5.7×10^{-3}	0.36	3.38×10^{-3}
	$h_b(1^1P_1)\gamma$	2.467	2.96×10^{-2}	···	···	2.48	3.4×10^{-2}	2.85	2.68×10^{-2}
	$\Upsilon(1^3S_1)\gamma$	0.0706	8.47×10^{-4}	···	···	0.068	9.4×10^{-4}	0.045	4.22×10^{-4}
	$\eta_b(1^1S_0)\pi\pi$	10.3	0.124	···	···	12.4	0.17	11.27	0.1058
	Total	8.34 MeV	100	<24 MeV	···	7.2 MeV	100	10.66 MeV	100
$\chi_{b0}(1^3P_0)$	$\gamma\gamma$	0.199	5.87×10^{-3}	···	···	0.15	5.8×10^{-3}	0.12	5.91×10^{-3}
	gg	3.37 MeV	99.4	···	···	2.6 MeV	∼100	2.00 MeV	98.61
	$\Upsilon(1^3S_1)\gamma$	22.8	0.673	···	1.76 ± 0.35	23.8	0.92	28.07	1.38
	Total	3.39 MeV	100	···	···	2.6 MeV	100	2.03 MeV	100
$\chi_{b2}(1^3P_2)$	$\gamma\gamma$	0.0106	5.41×10^{-3}	···	···	9.3×10^{-3}	5.2×10^{-3}	3.08×10^{-3}	2.51×10^{-3}
	gg	165	84.2	···	···	147	81.7	83.69	68.13
	$\Upsilon(1^3S_1)\gamma$	31.4	16.0	···	19.1 ± 1.2	32.8	18.2	39.15	31.87
	$h_b(1^1P_1)\gamma$	9.37×10^{-5}	4.78×10^{-5}	···	···	9.6×10^{-5}	5.3×10^{-5}	8.88×10^{-5}	7.23×10^{-5}
	Total	196	100	···	···	180	100	122.84	100

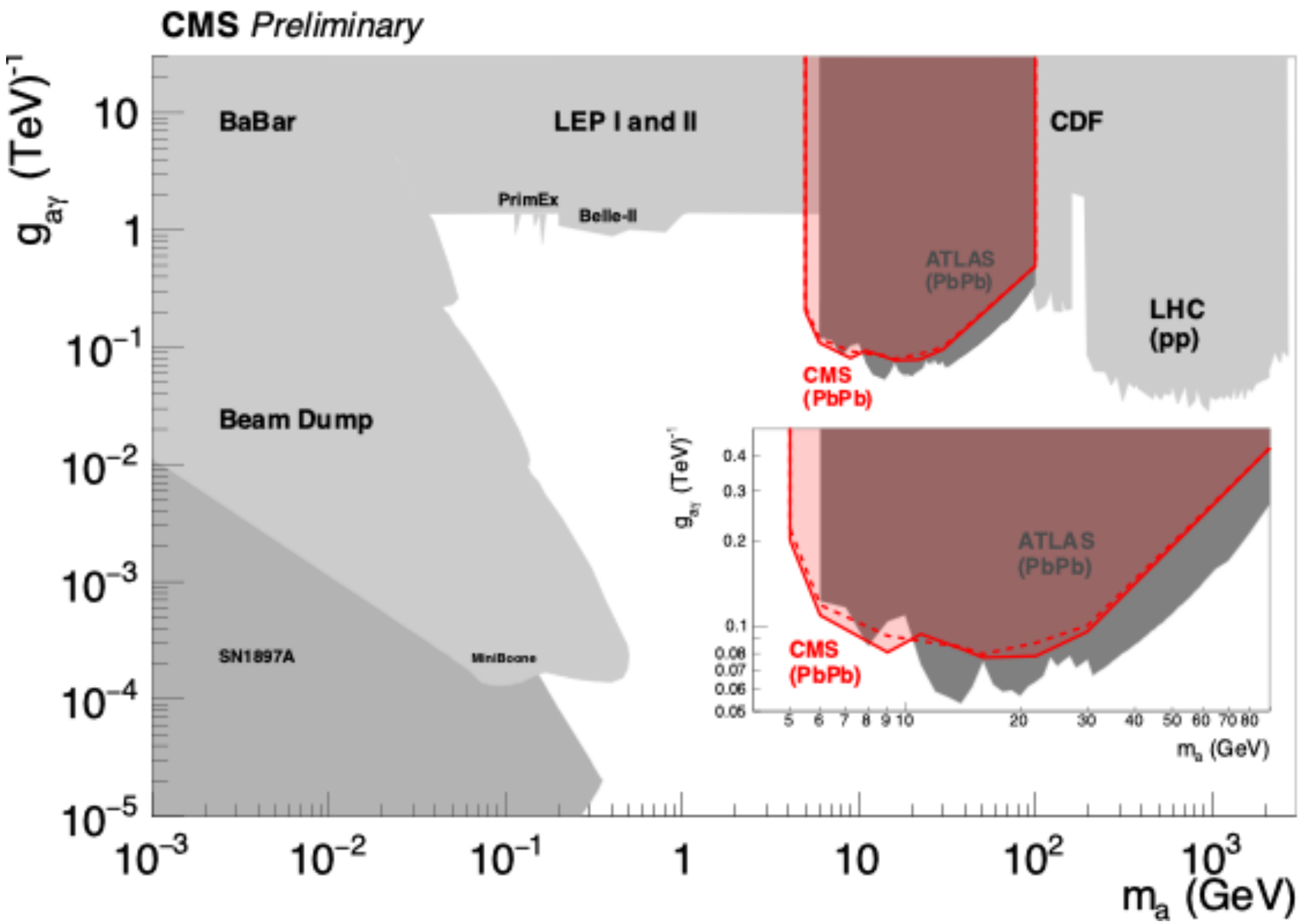
Limits on axion-like particles

- **Absence of excess over LbL continuum**

CMS-PAS-HIN-21-015



$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 - \frac{g_{a\gamma}}{4} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$



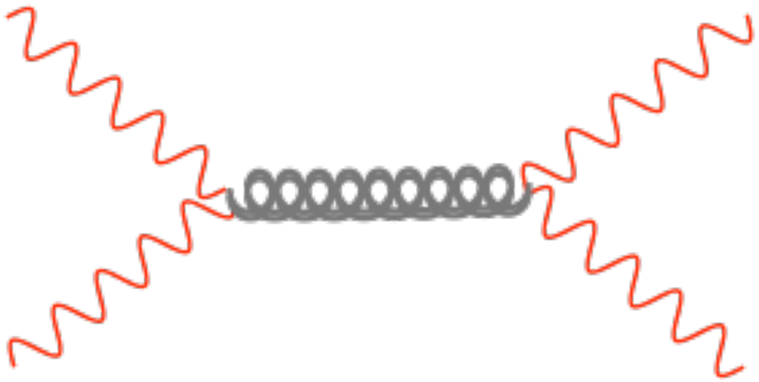
- Strongest limits on ALPs over mass above 5 GeV !

$$\mathrm{Br}(a \to \gamma\gamma) = 100\%$$

Limits on graviton-like particles

- **Absence of excess over LbL continuum**

arXiv:2306.15558



$$\mathcal{L} \supset g_{G\gamma} T^{V,f}_{\mu\nu} G^{\mu\nu}$$

Universal coupling