# Measuring light-by-light scattering at the LHC/FCC

**EDS Blois Conference**
**Corsica, June 2015**

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*[DdE & G.G. da Silveira, PRL 111 (2013) 080405; arXiv:1305.7142]*

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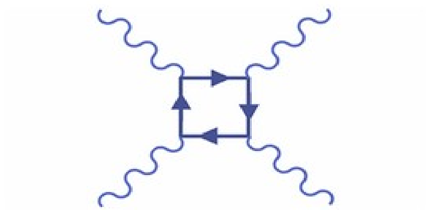
# Synopsis: Spotlight on Photon-Photon Scattering



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**Observing Light-by-Light Scattering at the Large Hadron Collider**
David d'Enterria and Gustavo G. da Silveira
Phys. Rev. Lett. **111**, 080405 (2013)
Published August 22, 2013

Despite what movie lightsabers suggest, light beams pass through each other without effect. However, two photons will, on rare occasion, bounce off each other. This elastic photon-photon scattering, which occurs via intermediate particles, has never been observed directly, but a new analysis in *Physical Review Letters* shows that the Large Hadron Collider (LHC) at CERN could detect around 20 photon-photon events per year.

Photons only interact with charged particles, so they shouldn't interact with themselves. But quantum physics allows for a photon to temporarily fluctuate into a particle-antiparticle pair (such as an electron-positron pair), and one of these charged particles can absorb a second photon. When these intermediate particles recombine, they emit two photons. The whole process appears as two photons ricocheting off each other, but it has only been observed indirectly by its effect on the magnetic moments of the electron and muon.

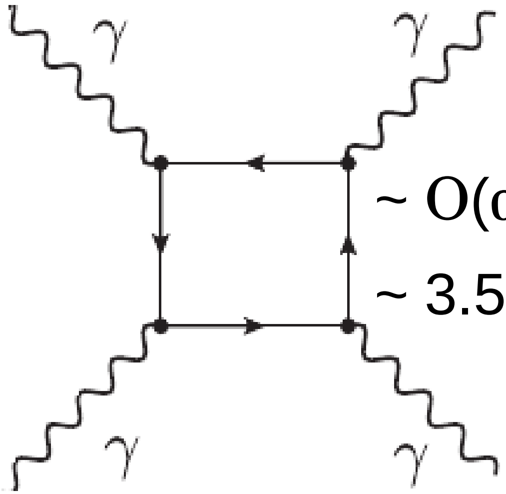
In their direct detection strategy, David d'Enterria of CERN, Switzerland, and Gustavo Silveira of the Catholic University of Louvain in Belgium propose using the large flux of "quasireal" photons in the LHC. These are not physical photons but instead are the carriers of the strong electromagnetic forces that surround the protons or lead ions zooming around in the collider. If two quasireal photons scatter off each other, they assume a real nature and can be detected in the LHC detectors. Using computer simulations, the authors show that lead-lead collisions provide the best opportunity for seeing these photon-photon scattering events. Any deviation from the predicted counts could be evidence of new physics, such as the existence of supersymmetry. – *Michael Schirber*

Previous synopsis | Next synopsis

(We extend the study here to cover also FCC energies)

# Scattering of light-by-light: $\gamma\gamma \rightarrow \gamma\gamma$

- Elastic two-photon collision = fundamental quantum-mechanical process which remains experimentally unobserved so far.



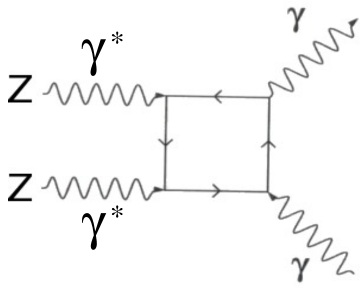

~ $O(\alpha^4)$

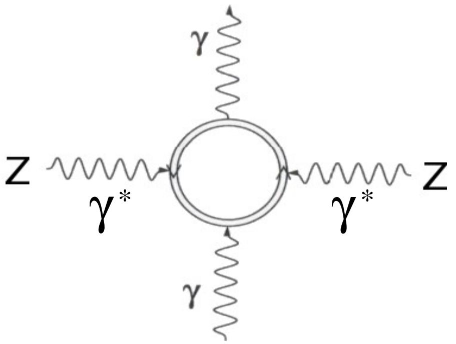
~ $3.5 \cdot 10^{-9}$

(Only similar Delbrück scattering,

$\gamma$ deflection in nucleus Coulomb field,

observed so far in the lab):



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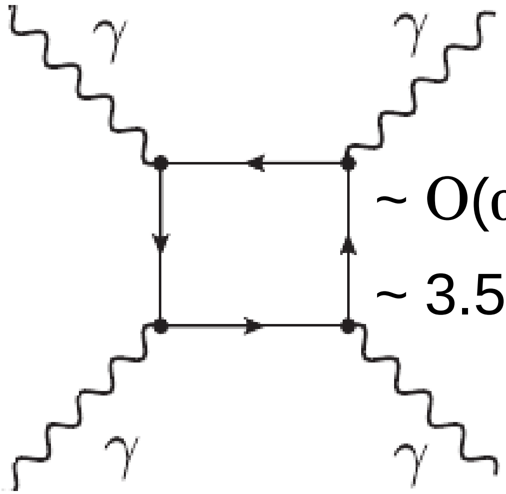


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Loop contains virtual charged particles (q,$\ell$,$W^\pm$) from the SM.

+ New ch. particles (sparticles, monopoles, unparticles,...)?
+ Low-scale gravity effects?
+ non-conmutative interactions ?

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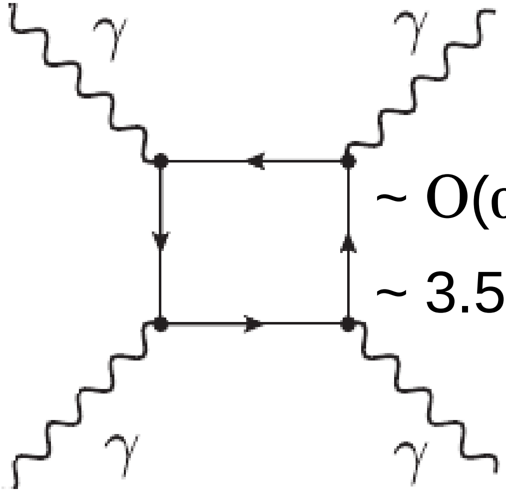


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+ Low-scale gravity effects?

+ non-conmutative interactions ?

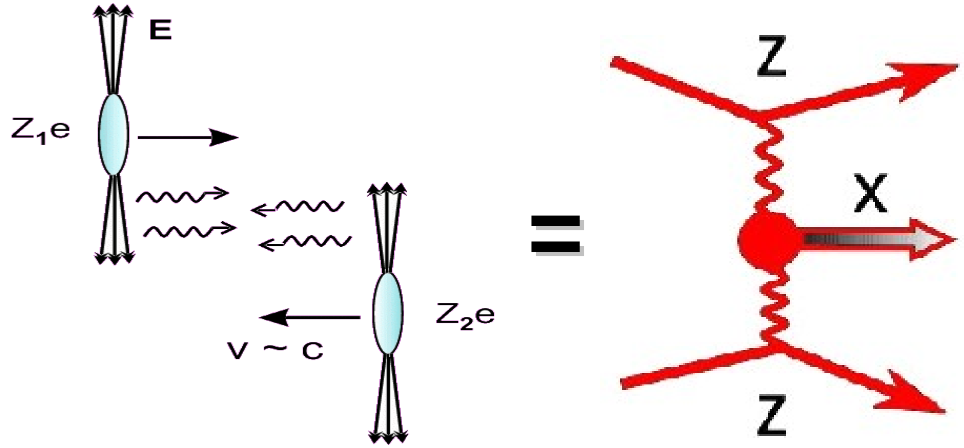
- Experimental approaches proposed:

  - Compton-backscattered photons against laser photons.
  - Collisions of photons from microwave waveguides, cavities, high-power lasers.
  - Collisions at photon colliders (via Compton-backscattering laser-light off $e^{\pm}$ beams).

- How about using UPCs from p,Pb beams at the LHC/FCC?

# Photon-induced collisions at the LHC

- Electromagnetic ultra-peripheral collisions (UPC): $b_{min} > R_A + R_B$
- HE ions generate strong EM fields from coherent emission of Z=82 p's:



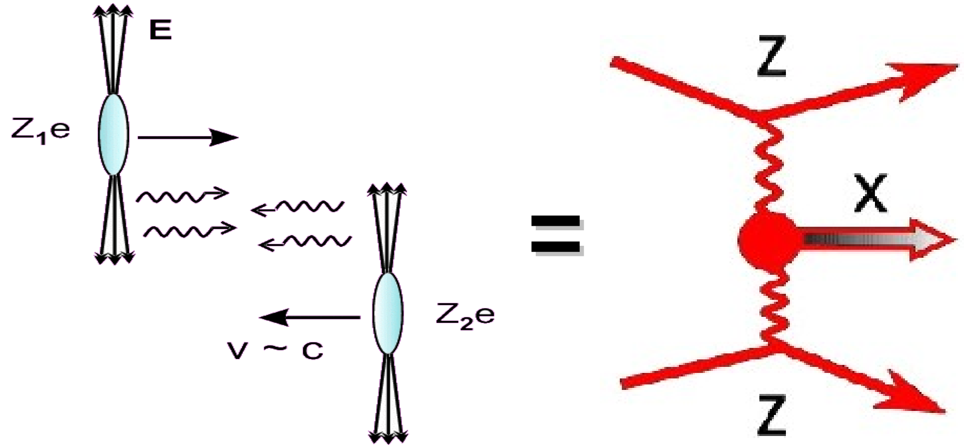

- Huge photon fluxes:
  $\sigma(\gamma\text{-}\gamma) \sim Z^4$ (~$5{\cdot}10^7$ for PbPb) larger than p,$e^\pm$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

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

| System | $\sqrt{s_{NN}}$ (TeV) | $\gamma$ | $R_A$ (fm) | $\omega_{max}$ (GeV) | $\sqrt{s_{\gamma\gamma}^{max}}$ (GeV) |
|---|---|---|---|---|---|
| $p$-$p$ | 14 | 7455 | **0.6** | 2450 | 4500 |
| $p$-Pb | 8.8 | 4690 | 7.1 | 130 | 260 |
| Pb-Pb | 5.5 | 2930 | 7.1 | 80 | 160 |

# Photon-induced collisions at the FCC

- Electromagnetic ultra-peripheral collisions (UPC): $b_{min}>R_A+R_B$
- HE ions generate strong EM fields from coherent emission of Z=82 p's:

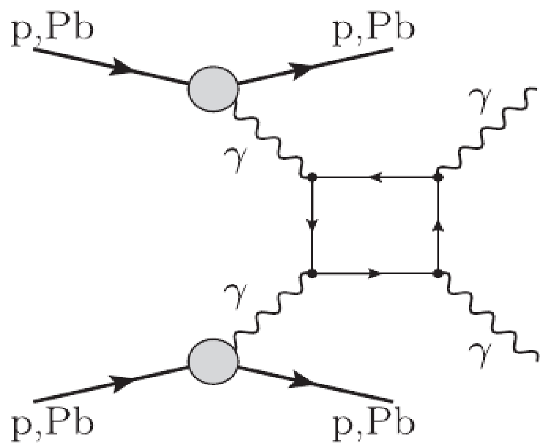



- Huge photon fluxes:
  $\sigma(\gamma\text{-}\gamma) \sim Z^4$ (~$5\cdot10^7$ for PbPb) larger than p,$e^\pm$
- Beam-energy dependence:
  Photon luminosities increase as $\propto\log^3(\sqrt{s})$

- Quasi-real photons (coherence): Q ~ 1/R ~ 0.06 GeV (Pb), 0.28 GeV (p)
- Maximum γ energies (FCC): $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 0.6 TeV (Pb), ~ 18 TeV (p)

| System | $\sqrt{s_{NN}}$ (TeV) | $\gamma$ | $R_A$ (fm) | $\omega_{max}$ (TeV) | $\sqrt{s_{\gamma\gamma}^{max}}$ (TeV) |
|---|---|---|---|---|---|
| $p$-$p$ | 100. | 53000 | 0.6 | 17.6 | 35.2 |
| $p$-Pb | 63. | 33500 | 7.1 | 0.95 | 1.9 |
| Pb-Pb | 39. | 21000 | 7.1 | 0.59 | 1.2 |

# Theoretical setup




- MadGraph v5.0 MC event generator.
- Equivalent photon approximation:

$$\sigma^{\mathrm{excl}}_{\gamma\gamma\to\gamma\gamma} = \sigma(AB \xrightarrow{\gamma\gamma} A\gamma\gamma B) = \int d\omega_1 d\omega_2 \frac{f_{\gamma/A}(\omega_1)}{\omega_1}\frac{f_{\gamma/B}(\omega_2)}{\omega_2}\sigma_{\gamma\gamma\to\gamma\gamma}\left(\sqrt{s_{\gamma\gamma}}\right)$$

- Photon fluxes:

p: Budnev et al. elastic FF [Phys. Rep. 15 (1975)181]

A: $f_{\gamma/A}(x) = \frac{\alpha Z^2}{\pi}\frac{1}{x}\left[2x_i K_0(x_i)K_1(x_i) - x_i^2(K_1^2(x_i) - K_0^2(x_i))\right]$

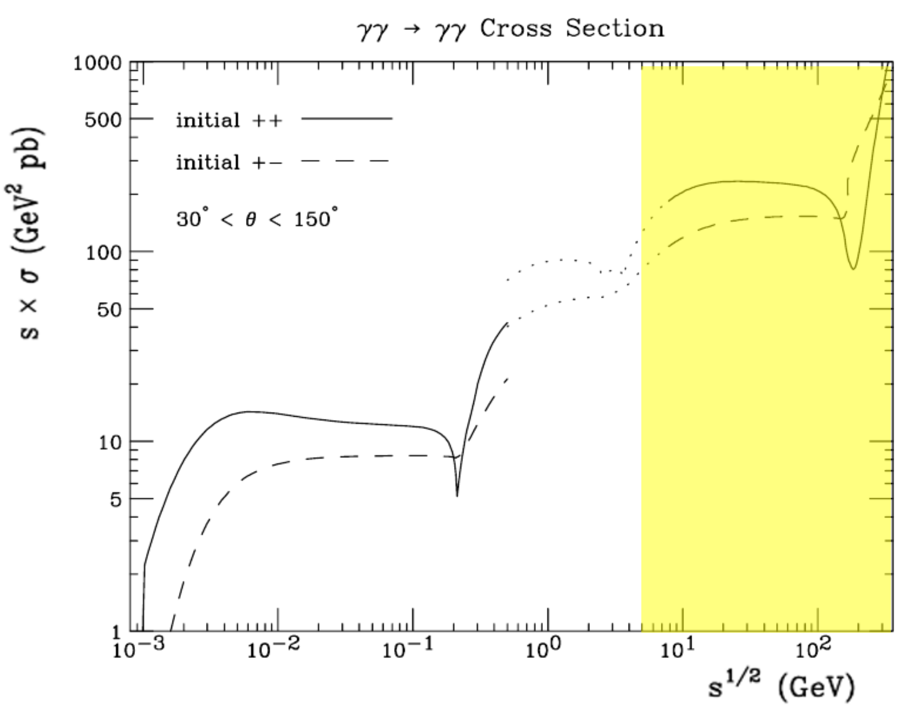
- Elementary NLO σ(γ γ →γ γ) from Bern et al. [JHEP 11 (2001) 031]

➜ LO expression: since NLO/LO<1.1 & gap survival factor $S^2$~0.9–1.0.

➜ Just q,lepton loops: W only relevant for very-high γγ masses.

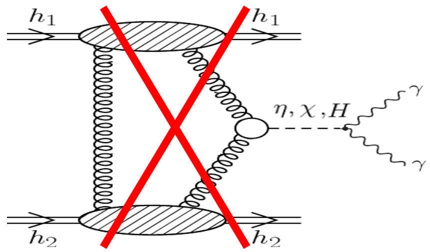
➜ $m_{\gamma\gamma}$>5 GeV: Above hadronic loops

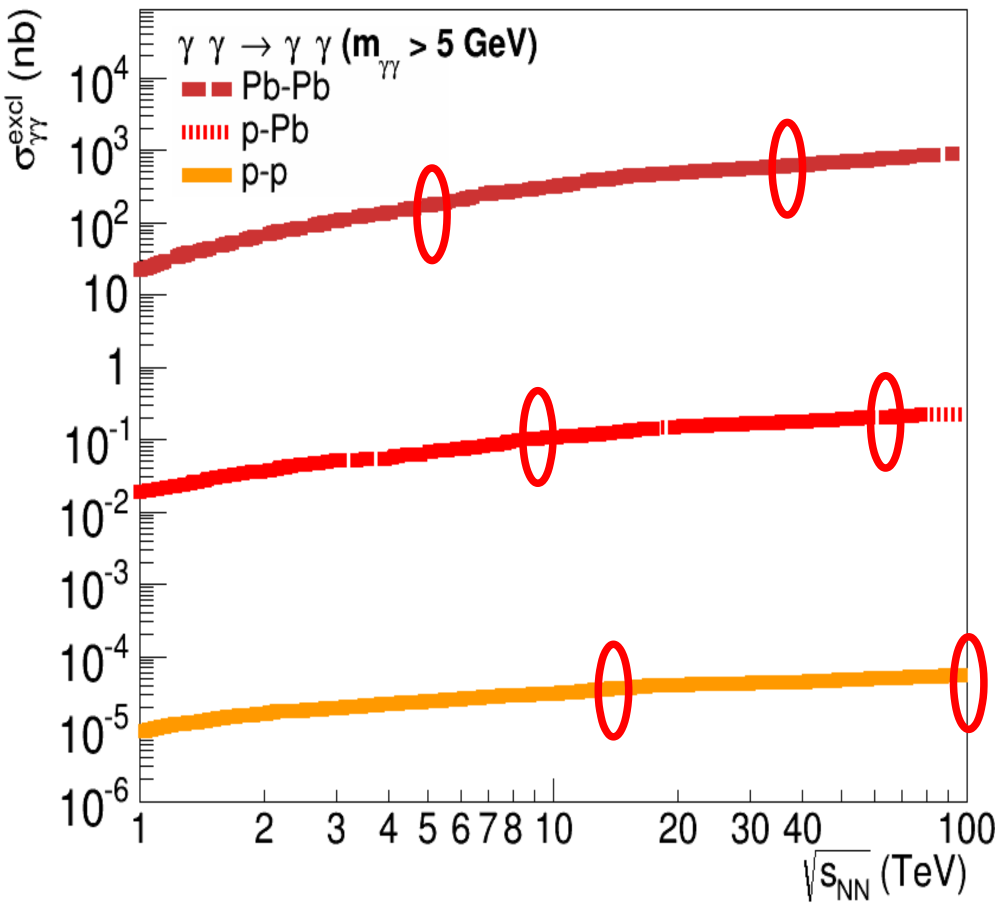
- Uncertainties (γ flux, form-factors): ±10% (pp, pPb), ±20%(PbPb)



# $\gamma\,\gamma \to \gamma\,\gamma$ x-sections in p-p, p-Pb, Pb-Pb

- LbyL continuum computed for $m_{\gamma\gamma}$>5 GeV:
  - Above hadron di-$\gamma$ decays: $\pi^0$,$\eta$, ... $\chi_c$(3.5-3.9 GeV)
  - Experimental trigger $E_\gamma$>2.5 GeV




- LbyL x-sections:

| System | $\sqrt{s_{NN}}$ (TeV) | $\sigma^{excl}_{\gamma\gamma\to\gamma\gamma}$ [$m_{\gamma\gamma} > 5$ GeV] |
|---|---|---|
| $p$-$p$ | 14 | 12 ± 1 fb |
| $p$-Pb | 8.8 | 26 ± 3 pb |
| Pb-Pb | 5.5 | 35 ± 7 nb |
| $p$-$p$ | 100. | 51 ± 5 fb |
| $p$-Pb | 63. | 172 ± 17 pb |
| Pb-Pb | 39. | 455 ± 90 nb |

► $Z^4$ factor enhances significantly the cross-section for Pb-Pb compared to p-Pb & p-p !

► $\sigma$(FCC) ~ (4–13)×$\sigma$(LHC)

# Expected γ γ → γ γ signal yields (LHC)

- Experimental setup (Atlas,CMS):
  - EMCal |η|<2.5 for photons (plus tracking, to remove $\gamma\gamma \to e^+e^-$)
  - Δη(rapgap)~10 for exclusivity requirement
  - ZDCs: to veto neutral fragments from diffractive/CEP/γ|P processes
- Acceptance & efficiency losses:
  - Acc~0.5 (p-p,p-Pb), 0.85 (Pb-Pb, softer EPA: more central γγ)
  - Eff~0.8 (standard γ reco & id)

$$\varepsilon_{\rm pp,pPb\to\gamma\gamma,PbPb\to\gamma\gamma} = \varepsilon_{\rm trig}\cdot\varepsilon_{\rm acc}\cdot\varepsilon^2_{\rm rec,id\gamma} \approx 0.3, 0.55$$

- Luminosities:
  - Full nominal p-Pb, Pb-Pb lumis (Note: negligible pileup)
  - 1 $fb^{-1}$ for p-p (1% of $L_{int}$, at possibly low pileup)
- Total number of γγ pairs/year: $N^{\rm excl}_{\gamma\gamma} = \varepsilon_{\gamma\gamma}\cdot\sigma^{\rm excl}_{\gamma\gamma}\cdot\mathcal{L}_{AB}\cdot\Delta t$

| System | $\sqrt{s_{NN}}$ (TeV) | $\mathcal{L}_{AB}\cdot\Delta t$ (per year) | $\sigma^{\rm excl}_{\gamma\gamma\to\gamma\gamma}$ [$m_{\gamma\gamma} > 5$ GeV] | $N^{\rm excl}_{\gamma\gamma}$ (per year) [$m_{\gamma\gamma} > 5$ GeV, after cuts] |
|---|---|---|---|---|
| $p$-$p$ | 14 | 1 $\rm fb^{-1}$ | $12 \pm 1$ fb | 3 |
| $p$-Pb | 8.8 | 200 $\rm nb^{-1}$ | $26 \pm 3$ pb | 2 |
| Pb-Pb | 5.5 | 1 $\rm nb^{-1}$ | $35 \pm 7$ nb | 18 |

# Expected $\gamma\gamma \to \gamma\gamma$ signal yields (FCC)

- Experimental setup (CMS+LHCb):
  - EMCal $|\eta|<5.0$ for photons (plus tracking, to remove $\gamma\gamma \to e^+e^-$)
  - $\Delta\eta$(rapgap)~10 for exclusivity requirement
  - ZDCs: to veto neutral fragments from diffractive/CEP/$\gamma$|P processes
- Acceptance & efficiency losses:
  - Acc~0.8 (p-p,p-Pb), 0.95 (Pb-Pb, softer EPA: more central $\gamma\gamma$)
  - Eff~0.8 (standard $\gamma$ reco & id)

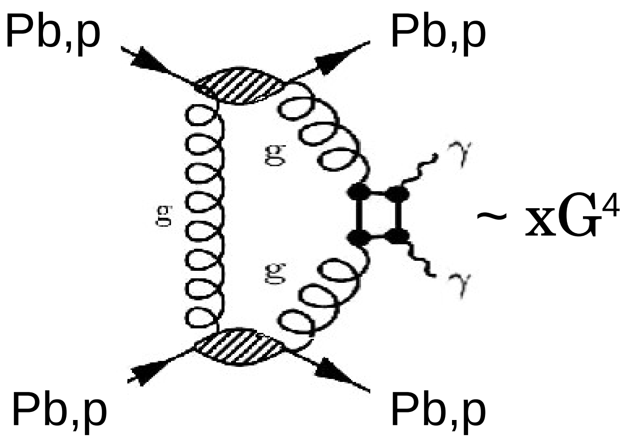
$$\varepsilon_{\mathrm{pp,pPb}\to\gamma\gamma,\mathrm{PbPb}\to\gamma\gamma} = \varepsilon_{\mathrm{trig}} \cdot \varepsilon_{\mathrm{acc}} \cdot \varepsilon^2_{\mathrm{rec,id}\gamma} \approx 0.5, 0.6$$

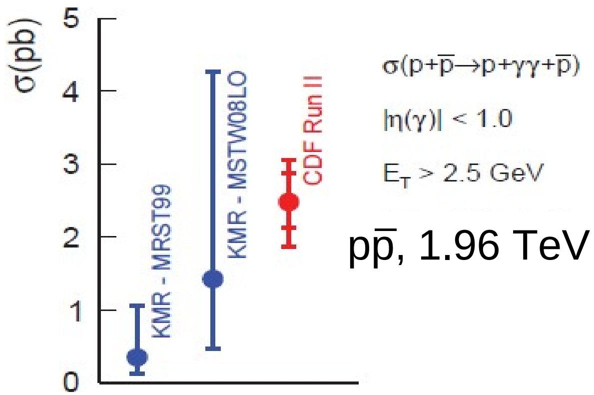
- Luminosities:
  - $L_{int}$(p-Pb) = 1 pb$^{-1}$, $L_{int}$(Pb-Pb) = 5 nb$^{-1}$ (Note: negligible pileup)
  - $L_{int}$(p-p) = 1 fb$^{-1}$ (at low pileup)
- Total number of $\gamma\gamma$ pairs/year: $N^{\mathrm{excl}}_{\gamma\gamma} = \varepsilon_{\gamma\gamma} \cdot \sigma^{\mathrm{excl}}_{\gamma\gamma} \cdot \mathcal{L}_{AB} \cdot \Delta t$

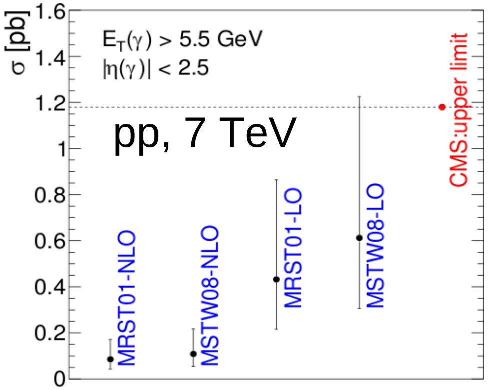
| System | $\sqrt{s_{\mathrm{NN}}}$ (TeV) | $\mathcal{L}_{AB} \cdot \Delta t$ (per year) | $\sigma^{\mathrm{excl}}_{\gamma\gamma\to\gamma\gamma}$ [$m_{\gamma\gamma} > 5$ GeV] | $N^{\mathrm{excl}}_{\gamma\gamma}$ (per year) [$m_{\gamma\gamma} > 5$ GeV, after cuts] |
|---|---|---|---|---|
| $p$-$p$ | 14 | 1 fb$^{-1}$ | 51 ± 5 fb | 25 |
| $p$-Pb | 8.8 | 1 pb$^{-1}$ | 172 ± 17 pb | 85 |
| Pb-Pb | 5.5 | 5 nb$^{-1}$ | 455 ± 90 nb | 1350 |

# CEP background to $\gamma\gamma \to \gamma\gamma$

- Experimental signal signature:
  2 isolated photons ($E_\gamma$>2.5 GeV) & $\Delta\eta$~5 rap-gaps
- Backgrounds: Central-Exclusive (|P|P, $\gamma$|P di-$\gamma$ final-states have lower $\sigma_{vis}$)



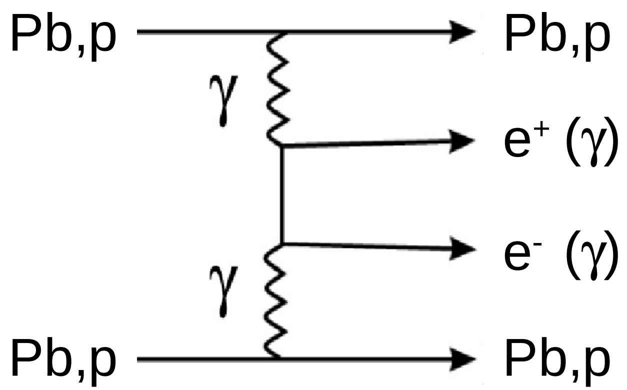




[Other CEP $\gamma\gamma$ final-states: $\sigma(\pi^0\pi^0,\eta\eta)$~1–100 pb, but negligible after BR & $\gamma\gamma$ accept.]

- SuperCHIC MC: $\sigma_{\text{CEP gg-}\gamma\gamma}$(LHC)~ 10–20 pb (×3,×1/3 uncert.: PDF,$S^2$)
  Reducible by factor of x1/35 by imposing $p_{Tmin}$ & acoplanarity cuts:
  $d\sigma/dt \sim e^{-bt}$, b($\gamma\gamma$) << b(|P|P): $p_T^{\gamma\gamma} \lesssim 0.1$ GeV, $\Delta\phi_{\gamma\gamma} - \pi \lesssim 0.04$
- Signal/Background: $\sigma$(LbyL)/$\sigma$(CEP) ~ 1/50 (p-p), 1 (p-Pb), 4 (Pb-Pb)
  +ZDC cuts possible for any diffractive remainders in PbPb (Pb fragile:8 MeV/nucleon)

# QED background to $\gamma\gamma \to \gamma\gamma$

- Experimental signal signature:
  2 isolated photons ($E_\gamma$>2.5 GeV) & $\Delta\eta$~5 rap-gaps
- Backgrounds: QED $e^+e^-$ (misidentified by $\gamma$'s)




(Starlight MC)

LHC: $\sigma_{\text{QED PbPb-ee}}$ ($m_{\gamma\gamma}$> 5GeV)~ 5 mb

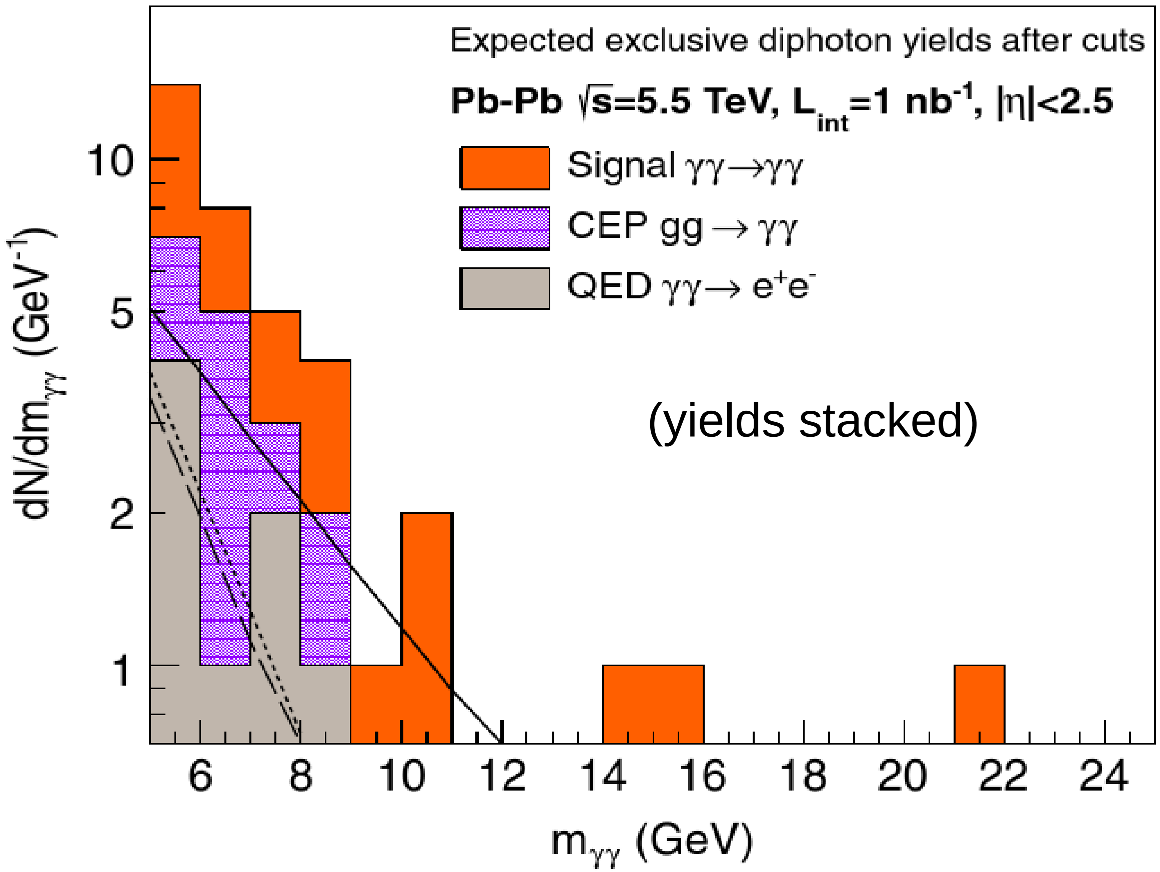
FCC: $\sigma_{\text{QED PbPb-ee}}$ ($m_{\gamma\gamma}$> 5GeV)~ 70 mb

- Reduction factor ~ $2.5\ 10^{-6}$ : Acceptance(both $\gamma$'s central) ~ 10%
  f(e-$\gamma$ misid')$^2$ ~ (0.5%)$^2$
- Signal/Background (Pb-Pb): $\sigma$(LbyL)/$\sigma$(QED) ~ 3

Additional cuts (e.g. acollinearity) possible for extra bckgds, e.g. $(\gamma\gamma \to q\bar{q} \to \pi^0\pi^0)$

# Final result: $\gamma\gamma$ mass distribution (LHC)

- Combination of LbyL signal + CEP & QED backgrounds after cuts Pb-Pb at 5.5 TeV ($L_{int}$ = 1 $nb^{-1}$):




$N_{\gamma\gamma-\gamma\gamma}$ ~ 18

$N_{CEP-\gamma\gamma}$ ~ 9

$N_{QED\text{-}ee}$ ~ 8

Significance:

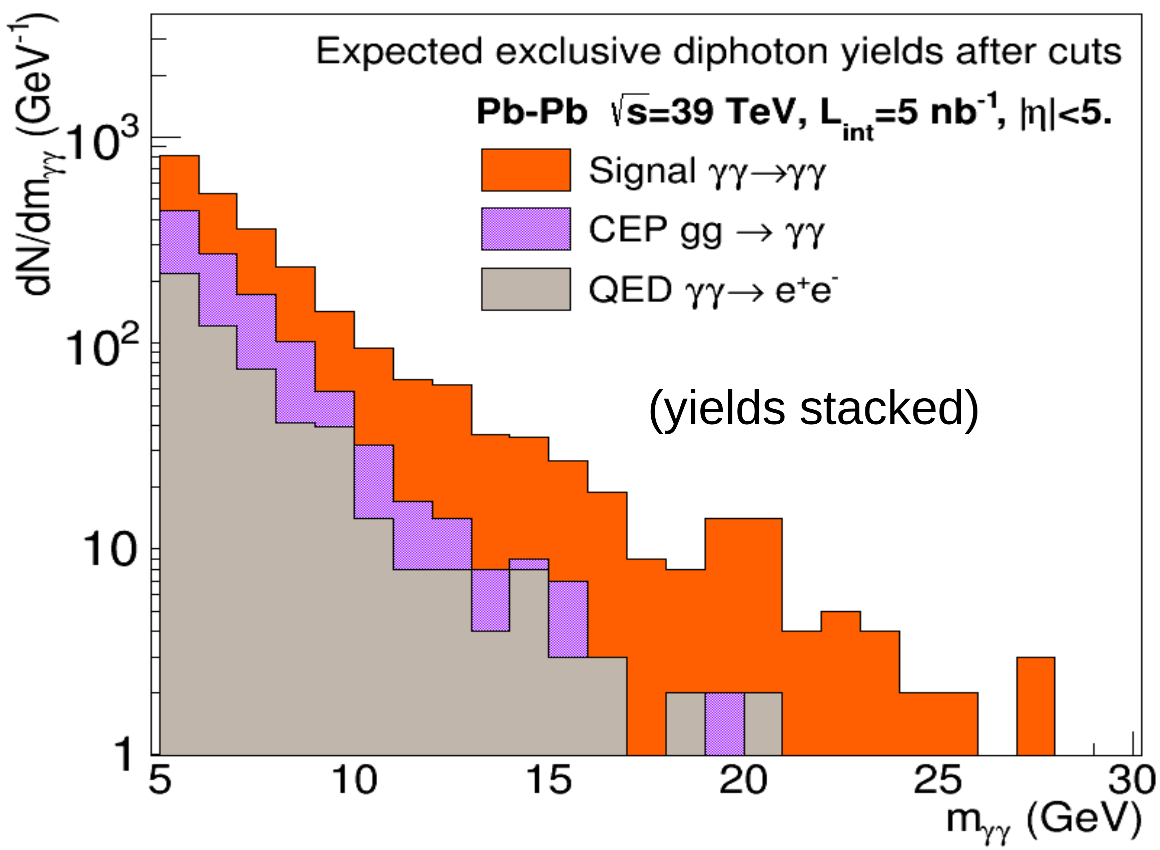
$S/\sqrt{B}$~4.4

- LbyL signal clearly observable over backgrounds (esp. high $m_{\gamma\gamma}$)

# Final result: γγ mass distribution (FCC)

- Combination of LbyL signal + CEP & QED backgrounds after cuts Pb-Pb at 5.5 TeV ($L_{int}$ = 5 $nb^{-1}$):

PRELIMINARY




$N_{\gamma\gamma-\gamma\gamma}$ ~ 1350

$N_{CEP-\gamma\gamma}$ ~ 600

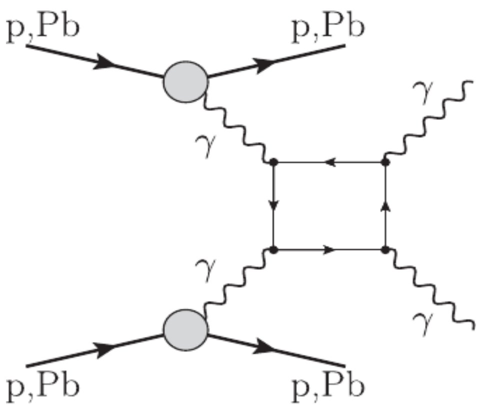
$N_{QED\text{-}ee}$ ~ 550

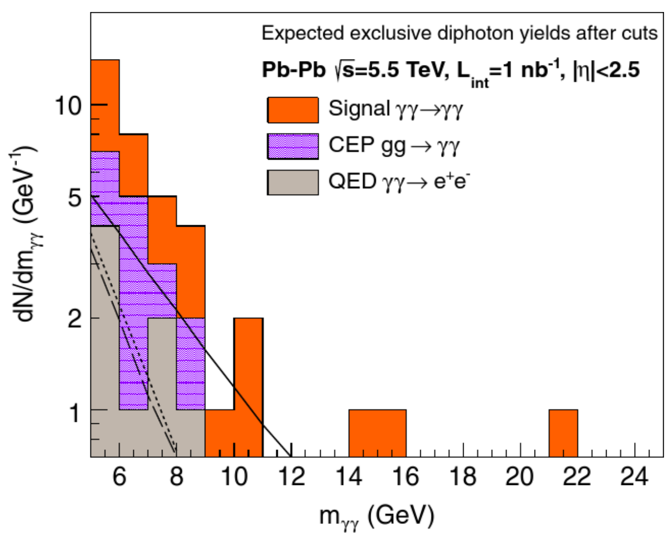
Significance:
$S/\sqrt{B}$~40

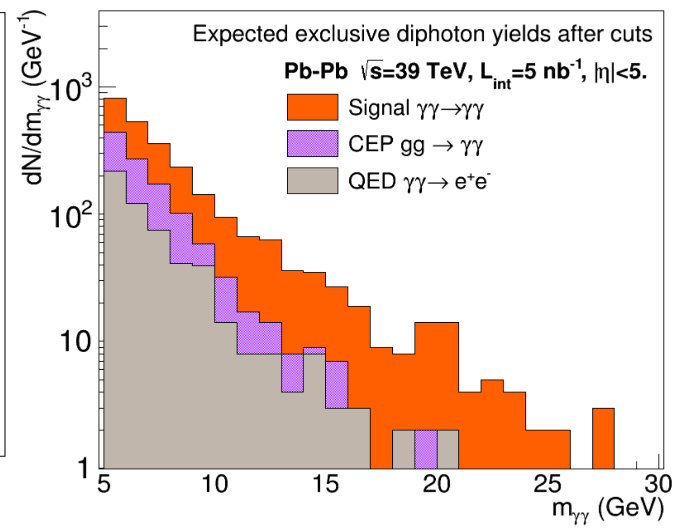
- LbyL signal clearly observable over backgrounds (esp. high $m_{\gamma\gamma}$)

# Conclusion

- Elastic light-by-light scattering accessible in UPC at the LHC&FCC
  pp,pPb,PbPb → γ γ → p(Pb) γ γ p(Pb), $\sqrt{s}$=(5.5,8.8,14)–(39,63,100) TeV
- Cross sections (EPA + MadGraph + Bern et al.):
  LHC: σ(γ γ →γ γ) ~ 12 fb, 26 pb, 35 nb. Rates: 3, 2, 18 pairs/year
  FCC: σ(γ γ →γ γ) ~ 51 fb, 170 pb, 450 nb. Rates: 25, 85, 1350 pairs/year
  → Pb-Pb preferred: Maximum rates, minimum backgds (also no pileup)




- LbyL signal clearly observable(S/√B~4.4,40) over CEP+QED backgds
→ LHC: 1st observation of such a fundamental QM process in the lab.
→ FCC: Very large yields. Sensitivity to new physics in charged loops.

# Back-up slides