



The diagram shows two incoming particles, labeled 'p, Pb', entering from the top. They interact through a central vertex (a circle) which emits a photon (represented by a wavy line). This photon then interacts with another central vertex (a circle) which emits two outgoing particles, also labeled 'p, Pb', at the bottom. A second photon (represented by a wavy line) is shown interacting with the second vertex, and another photon (represented by a wavy line) is shown interacting with the first vertex. The overall process is light-by-light scattering via photon fusion.

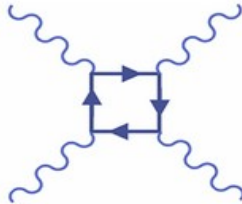
# Light-by-light scattering via photon-fusion at the LHC/FCC

**Vacuum birefringence Workshop**  
**DESY, Nov. 2015**

**David d'Enterria (CERN)**

*D.d'E & G.G. da Silveira PRL 111 (2013) 080405 [Erratum] + In preparation*

## 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.

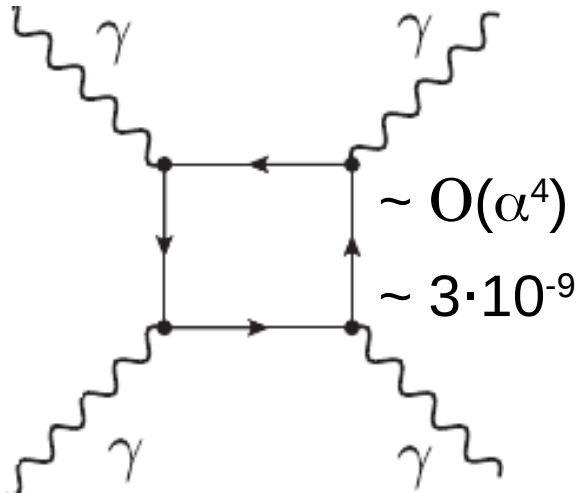
Photons only interact with charged particles, so they shouldn't interact with themselves. But quantum physics allows for a photon to temporarily fluctuate into a particle-antiparticle pair (such as an electron-positron pair), and one of these charged particles can absorb a second photon. When these intermediate 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*

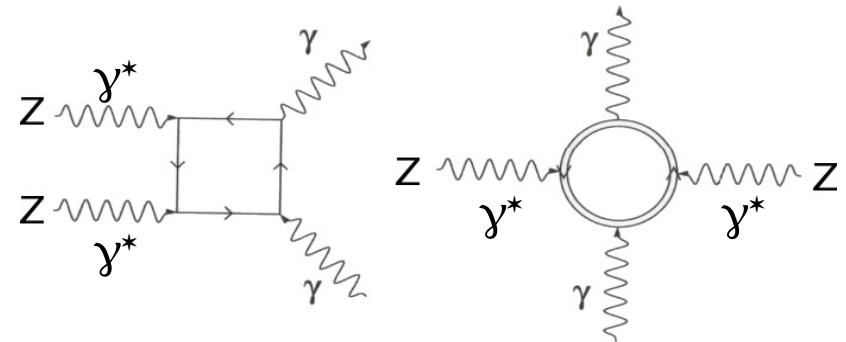
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# Scattering of light-by-light: $\gamma \gamma \rightarrow \gamma \gamma$

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

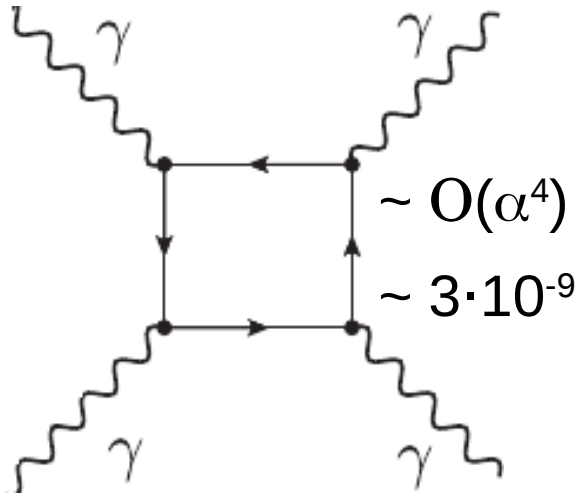


(Only **similar Delbrück scattering**,  $\gamma$  deflection in nucleus Coulomb field, observed so far in the lab):



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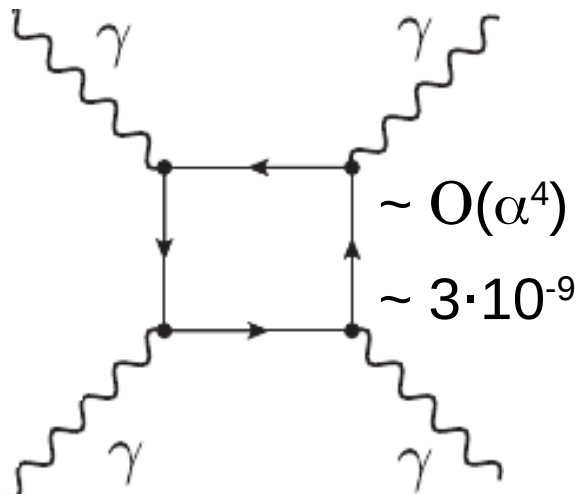


Loop contains **virtual charged particles** ( $q, \ell, W^\pm$ ) from the SM.

- + New ch. particles (**sparticles**)?
- + New resonances (**axions, monopoles, ...**)?
- + Low-scale **gravity** effects?
- + **non-commutative** interactions ?

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- + **non-commutative** interactions ?

- Experimental **approaches proposed**:

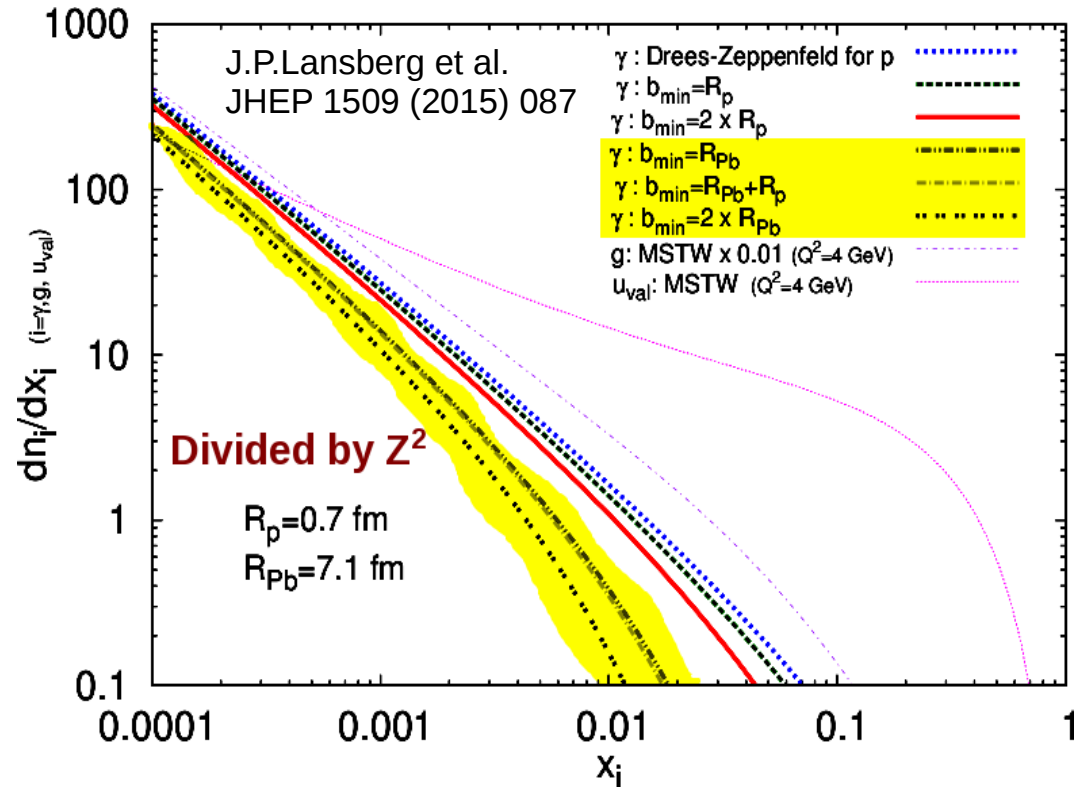
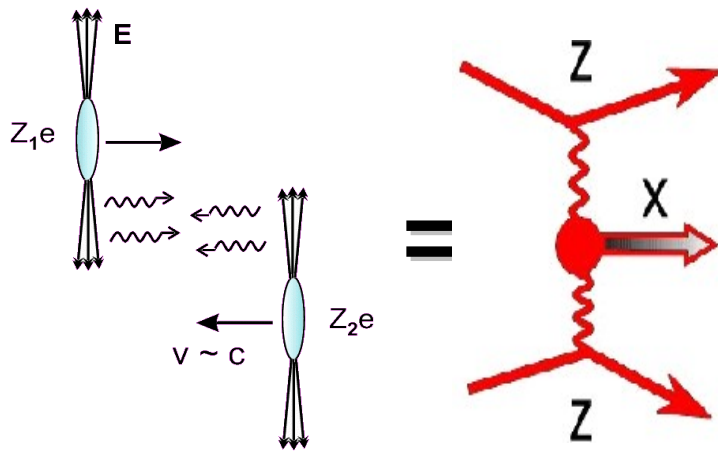
- 1) **Compton-backscattered photons against laser photons.**
- 2) Collisions of **photons from microwave waveguides, cavities, high-power lasers.**
- 3) Collisions at **photon colliders** (via Compton-backscattering laser-light off  $e^\pm$  beams).

- How about using **e.m. interactions from p,Pb beams at LHC/FCC?**

# Photon-photon collisions at colliders

- **Electromagnetic** ultra-peripheral collisions (UPC):  $b_{\min} > R_A + R_B$
- HE ions create **huge EM fields** ( $10^{14}$  T) from coherent action of  $Z$  protons:

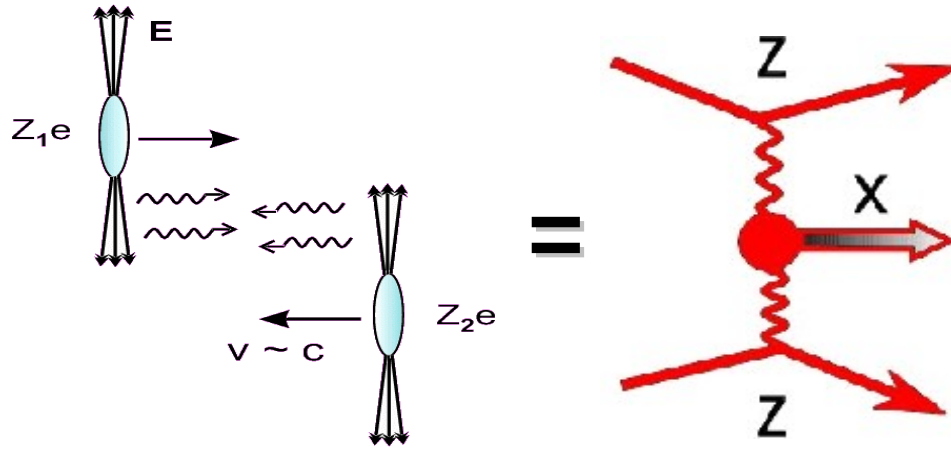
Weizsäcker-Williams (EPA) power-law photon flux:



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

# Photon-photon collisions at the LHC

- **Electromagnetic** ultra-peripheral collisions (UPC):  $b_{\min} > R_A + R_B$
- HE ions generate **huge EM fields** ( $10^{14}$  T) from coherent action of  $Z=82$  p:



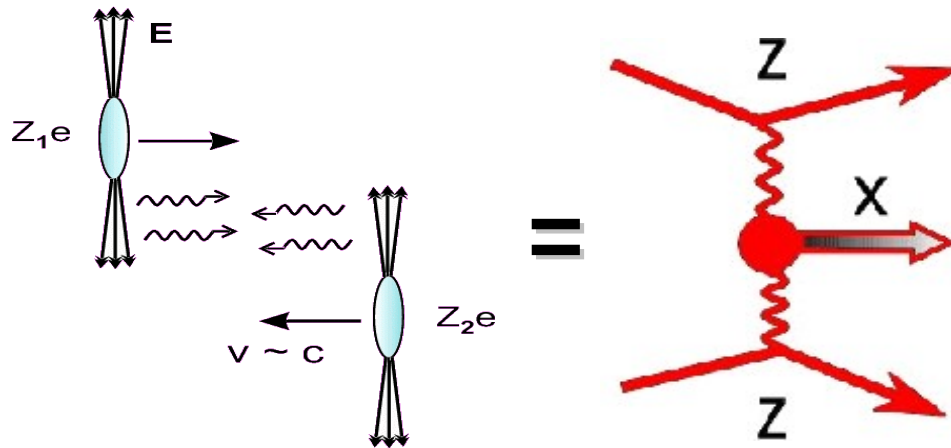
- **Huge photon fluxes:**  
 $\sigma(\gamma-\gamma) \sim Z^4$  ( $\sim 5 \cdot 10^7$  for PbPb)  
 larger than  $p, e^\pm$
- **Beam-energy dependence:**  
 Photon luminosities increase as  $\propto \log^3(\sqrt{s})$

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

System	$\sqrt{s_{NN}}$ (TeV)	$\gamma$	$R_A$ (fm)	$\omega_{\max}$ (GeV)	$\sqrt{s_{\gamma\gamma}^{\max}}$ (GeV)
$p-p$	14	7455	0.7	2450	4500
$p-Pb$	8.8	4690	7.1	130	260
$Pb-Pb$	5.5	2930	7.1	80	160

# Photon-photon collisions at the FCC

- **Electromagnetic** ultra-peripheral collisions (UPC):  $b_{\min} > R_A + R_B$
- HE ions generate **huge EM fields** ( $10^{14}$  T) from coherent action of  $Z=82$  p:



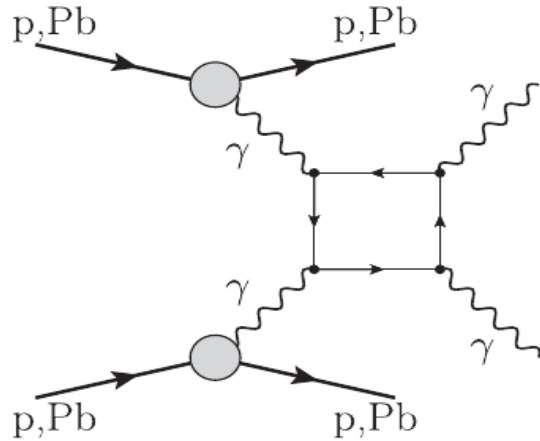
- **Huge photon fluxes:**  
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- **Beam-energy dependence:**  
 Photon luminosities increase as  $\propto \log^3(\sqrt{s})$

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

System	$\sqrt{s_{NN}}$ (TeV)	$\gamma$	$R_A$ (fm)	$\omega_{\max}$ (TeV)	$\sqrt{s_{\gamma\gamma}^{\max}}$ (TeV)
<i>p-p</i>	<b>100.</b>	<b>53 000</b>	0.7	<b>17.6</b>	<b>35.2</b>
<i>p-Pb</i>	<b>63.</b>	<b>33 500</b>	7.1	<b>0.95</b>	<b>1.9</b>
<b>Pb-Pb</b>	<b>39.</b>	<b>21 000</b>	7.1	<b>0.59</b>	<b>1.2</b>



# Theoretical setup



- **MadGraph** v5.0 MC event generator.

- Equivalent photon approximation (EPA):

$$\sigma_{\gamma\gamma \rightarrow \gamma\gamma}^{\text{excl}} = \sigma(AB \xrightarrow{\gamma\gamma} A\gamma\gamma B) = \int d\omega_1 d\omega_2 \frac{f_{\gamma/A}(\omega_1)}{\omega_1} \frac{f_{\gamma/B}(\omega_2)}{\omega_2} \sigma_{\gamma\gamma \rightarrow \gamma\gamma}(\sqrt{s_{\gamma\gamma}})$$

- **Photon fluxes:**

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

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

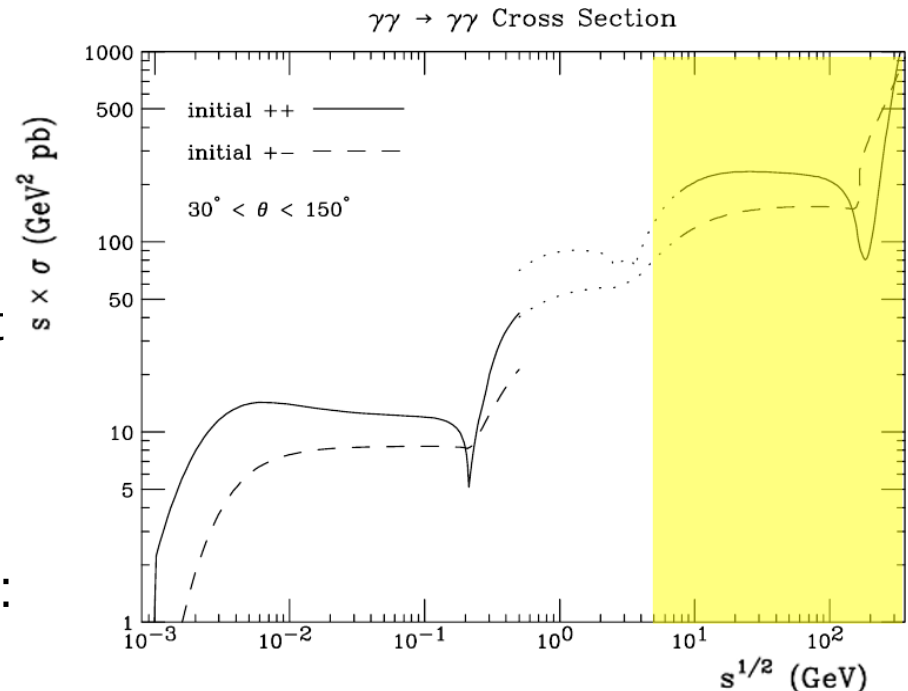
- **Elementary NLO  $\sigma(\gamma\gamma \rightarrow \gamma\gamma)$**  from Bern et al. [JHEP 11 (2001) 031]

→ **LO expression:** since  $\text{NLO}/\text{LO} < 1.1$  & gap survival factor  $S^2 \sim 0.9-1.0$ .

→ Just **q, lepton loops**. W only relevant for  $m(\gamma\gamma) > 200$  GeV.

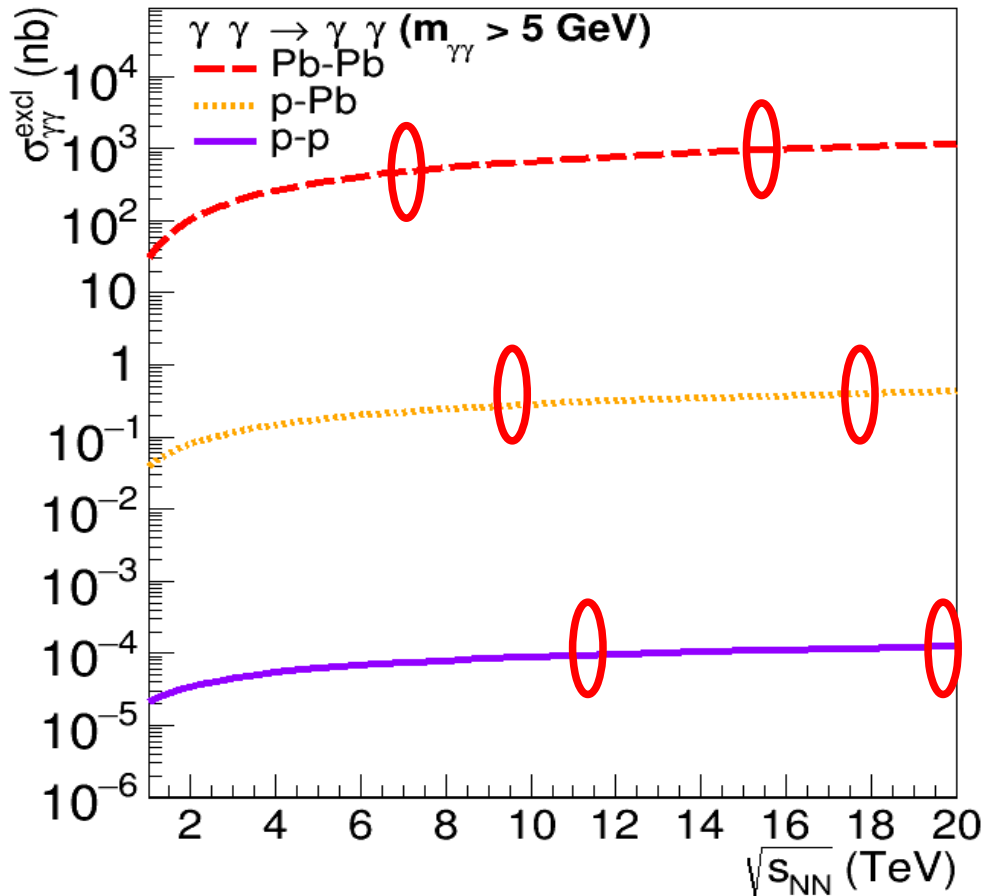
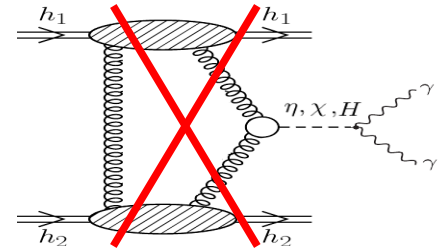
→  **$m_{\gamma\gamma} > 5$  GeV:** Above hadronic loops

- **Uncertainties** ( $\gamma$  flux, form-factors):  $\pm 10\%$  (pp, pPb),  $\pm 20\%$  (PbPb)



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

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



## ■ LbyL x-sections:

System	$\sqrt{s_{NN}}$ (TeV)	$\sigma_{\gamma\gamma \rightarrow \gamma\gamma}^{\text{excl}}$ [ $m_{\gamma\gamma} > 5$ GeV]
p-p	14	$105 \pm 10$ fb
p-Pb	8.8	$260 \pm 26$ pb
Pb-Pb	5.5	$370 \pm 70$ nb
p-p	100	$240 \pm 24$ fb
p-Pb	64	$780 \pm 78$ pb
Pb-Pb	39	$1.85 \pm 0.37$ $\mu\text{b}$

- ▶  $Z^4$  factor enhances significantly the cross-section for Pb-Pb compared to p-Pb & p-p !
- ▶  $\sigma(\text{FCC}) \sim (2-5) \times \sigma(\text{LHC})$

# Expected $\gamma\gamma \rightarrow \gamma\gamma$ signal yields (LHC)

## ■ Experimental setup (Atlas,CMS):

- EMCal  $|\eta| < 2.5$  for photons (plus tracking, to remove  $\gamma\gamma \rightarrow e^+e^-$ )
- Trigger:  $p_{T,\gamma} > 2$  GeV + Exclusivity: No activity over  $\Delta\eta(\text{rapgap}) \sim 5$
- ZDCs: to veto neutral fragments from diffractive/CEP/ $\gamma|P$  processes

## ■ Acceptance & efficiency losses:

- Acc  $\sim 0.2$  (p-p,p-Pb), 0.3 (Pb-Pb, softer EPA: more central  $\gamma\gamma$ )
- Eff  $\sim 0.8$  (standard  $\gamma$  reco & id)

$$\epsilon_{pp,pPb \rightarrow \gamma\gamma, PbPb \rightarrow \gamma\gamma} = \epsilon_{\text{trig}} \cdot \epsilon_{\text{acc}} \cdot \epsilon_{\text{rec,id}\gamma}^2 \approx 0.12, 0.20$$

## ■ Luminosities:

- Full nominal p-Pb, Pb-Pb lumis (Note: **negligible pileup**)
- $1 \text{ fb}^{-1}$  for p-p (1% of  $L_{\text{int}}$ , at possibly low pileup)

## ■ Total number of $\gamma\gamma$ pairs/year: $N_{\gamma\gamma}^{\text{excl}} = \epsilon_{\gamma\gamma} \cdot \sigma_{\gamma\gamma}^{\text{excl}} \cdot \mathcal{L}_{AB} \cdot \Delta t$

System	$\sqrt{s_{\text{NN}}}$ (TeV)	$\mathcal{L}_{AB} \cdot \Delta t$ (per year)	$\sigma_{\gamma\gamma \rightarrow \gamma\gamma}^{\text{excl}}$ [ $m_{\gamma\gamma} > 5$ GeV]	$N_{\gamma\gamma}^{\text{excl}}$ (per year) [ $m_{\gamma\gamma} > 5$ GeV, after cuts]
p-p	14	$1 \text{ fb}^{-1}$	$105 \pm 10 \text{ fb}$	12
p-Pb	8.8	$200 \text{ nb}^{-1}$	$260 \pm 26 \text{ pb}$	6
Pb-Pb	5.5	$1 \text{ nb}^{-1}$	$370 \pm 70 \text{ nb}$	70

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

## ■ Experimental setup (CMS+LHCb):

- EMCAL  $|\eta| < 5.0$  for photons (plus tracking, to remove  $\gamma\gamma \rightarrow e^+e^-$ )
- Trigger:  $p_T^\gamma > 2$  GeV + Exclusivity: No activity over  $\Delta\eta(\text{rapgap}) \sim 5$
- ZDCs: to veto neutral fragments from diffractive/CEP/ $\gamma|P$  processes

## ■ Acceptance & efficiency losses:

- Acc  $\sim 0.3$  (p-p, p-Pb), 0.4 (Pb-Pb, softer EPA: more central  $\gamma\gamma$ )
- Eff  $\sim 0.8$  (standard  $\nu$  reco & id)

$$\epsilon_{pp, pPb \rightarrow \gamma\gamma, PbPb \rightarrow \gamma\gamma} = \epsilon_{\text{trig}} \cdot \epsilon_{\text{acc}} \cdot \epsilon_{\text{rec, id}\gamma}^2 \approx 0.20, 0.25$$

## ■ Luminosities:

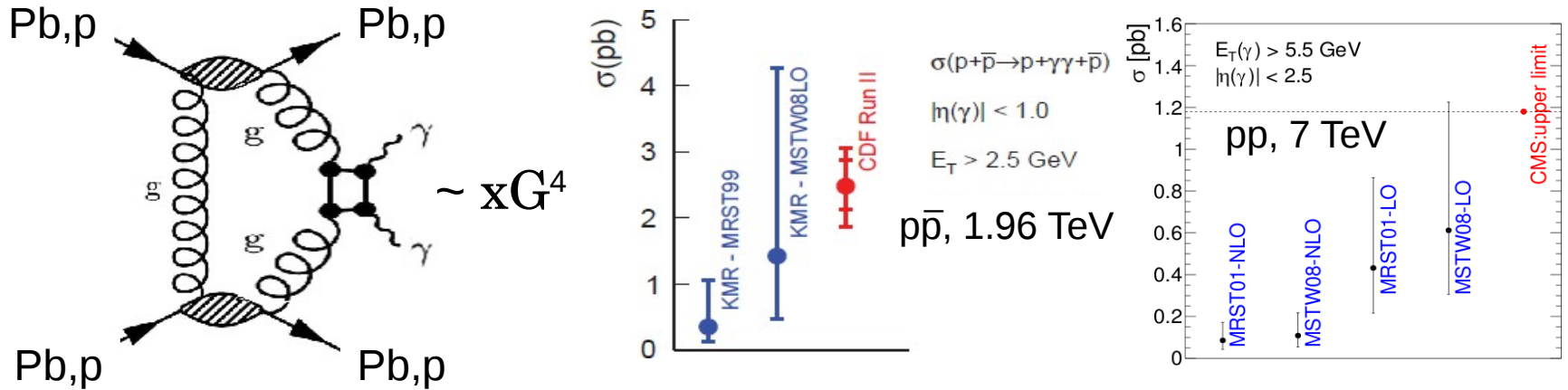
- $L_{\text{int}}(\text{p-Pb}) = 1 \text{ pb}^{-1}$ ,  $L_{\text{int}}(\text{Pb-Pb}) = 5 \text{ nb}^{-1}$  (Note: negligible pileup)
- $L_{\text{int}}(\text{p-p}) = 1 \text{ fb}^{-1}$  (at low pileup)

## ■ Total number of $\gamma\gamma$ pairs/year: $N_{\gamma\gamma}^{\text{excl}} = \epsilon_{\gamma\gamma} \cdot \sigma_{\gamma\gamma}^{\text{excl}} \cdot \mathcal{L}_{AB} \cdot \Delta t$

System	$\sqrt{s_{\text{NN}}}$ (TeV)	$\mathcal{L}_{AB} \cdot \Delta t$ (per year)	$\sigma_{\gamma\gamma \rightarrow \gamma\gamma}^{\text{excl}}$ [ $m_{\gamma\gamma} > 5$ GeV]	$N_{\gamma\gamma}^{\text{cuts}}$ [ $m_{\gamma\gamma} > 5$ GeV]
p-p	100	1 fb <sup>-1</sup>	240 ± 24 fb	40
p-Pb	63	1 pb <sup>-1</sup>	780 ± 78 pb	150
Pb-Pb	39	5 nb <sup>-1</sup>	1.85 ± 0.37 μb	2 500

# CEP background to $\gamma\gamma \rightarrow \gamma\gamma$ (LHC)

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

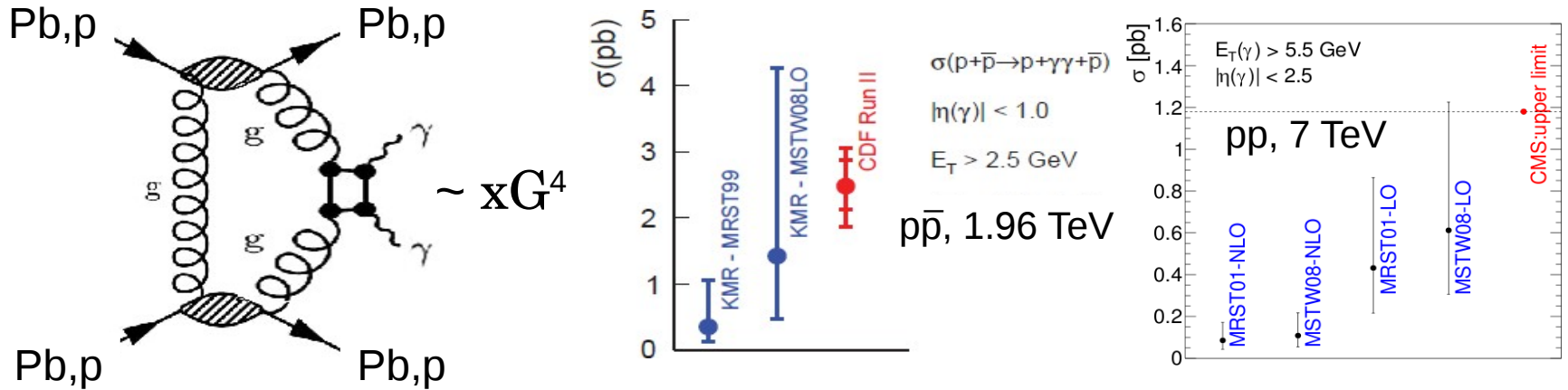


[Other CEP  $\gamma\gamma$  final-states:  $\sigma(\pi^0\pi^0, \eta\eta) \sim 1-100$  pb, but negligible after BR &  $\gamma\gamma$  accept.]

- **SuperCHIC MC**:  $\sigma_{\text{CEP } g\bar{g} \rightarrow \gamma\gamma}$  (LHC)  $\sim 10-20$  pb ( $\times 3, \times 1/3$  uncert.: PDFs,  $S^2$ )  
Reducible by factor of  $\times 1/35$  by imposing  $p_{T\text{min}}$  & acoplanarity cuts:  
 $d\sigma/dt \sim e^{-bt}$ ,  $b(\gamma\gamma) \ll b(|P|P)$ :  $p_T^{\gamma\gamma} \lesssim 0.1$  GeV,  $\Delta\phi_{\gamma\gamma} - \pi \lesssim 0.04$
- **Signal/Background**:  $\sigma(\text{LbyL})/\sigma(\text{CEP}) \sim 1/20$  (p-p), 1 (p-Pb), 10 (Pb-Pb)  
+ZDC cuts possible for any diffractive remainders in PbPb (Pb fragile: 8 MeV/nucleon)

# CEP background to $\gamma\gamma \rightarrow \gamma\gamma$ (FCC)

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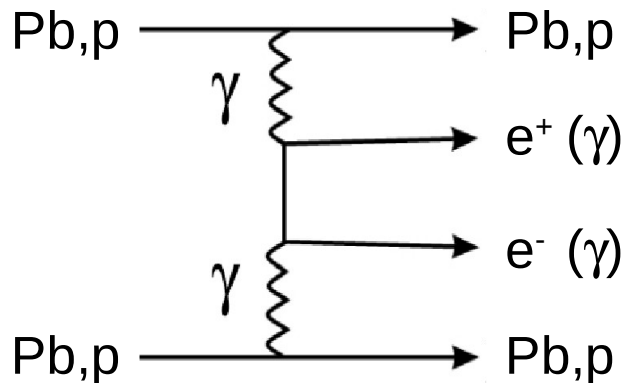


[Other CEP  $\gamma\gamma$  final-states:  $\sigma(\pi^0\pi^0, \eta\eta) \sim 10-100$   $\mu\text{b}$ , but negligible after BR &  $\gamma\gamma$  accept.]

- **SuperCHIC MC**:  $\sigma_{\text{CEP } gg\text{-}\gamma\gamma}$  (FCC, PbPb)  $\sim 14$   $\mu\text{b}$  ( $\times 3, \times 1/3$  uncert.: PDFs,  $S^2$ )  
Reducible by factor of  $\times 1/35$  by imposing  $p_{T\text{min}}$  & acoplanarity cuts:  
 $d\sigma/dt \sim e^{-bt}$ ,  $b(\gamma\gamma) \ll b(|P|P)$ :  $p_T^{\gamma\gamma} \lesssim 0.1$  GeV,  $\Delta\phi_{\gamma\gamma} - \pi \lesssim 0.04$
- **Signal/Background**:  $\sigma(\text{LbyL})/\sigma(\text{CEP}) \sim 1$  (Pb-Pb)  
+ZDC cuts possible for any diffractive remainders in PbPb (Pb fragile: 8 MeV/nucleon)

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

- Experimental signal **signature**:  
2 isolated photons ( $E_\gamma > 2. \text{ GeV}$ ) &  $\Delta\eta \sim 5$  rap-gaps
- **Backgrounds**: QED  $e^+e^-$  (misidentified by  $\gamma$ 's)



(Starlight MC)

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

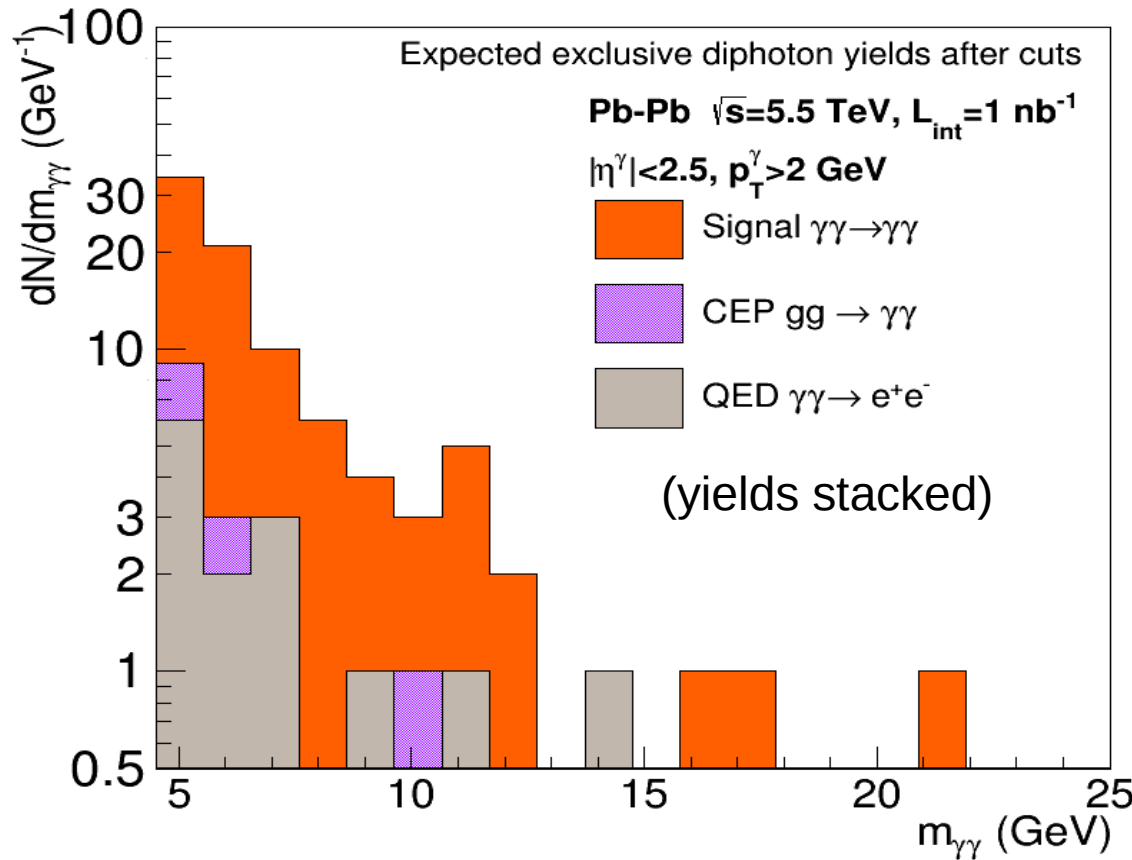
FCC:  $\sigma_{\text{QED PbPb-ee}} (m_{\gamma\gamma} > 5\text{GeV}) \sim 70 \text{ mb}$

- **Reduction factor**  $\sim 2.5 \cdot 10^{-6}$ :  
Acceptance(both  $\gamma$ 's central)  $\sim 10\%$   
 $f(\text{e-}\gamma \text{ misid}')^2 \sim (0.5\%)^2$
- **Signal/Background (Pb-Pb)**:  $\sigma(\text{LbyL})/\sigma(\text{QED}) \sim 4$  (LHC, FCC)

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

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

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



$$N_{\gamma\gamma-\gamma\gamma} \sim 70$$

$$N_{\text{CEP}-\gamma\gamma} \sim 6$$

$$N_{\text{QED-ee}} \sim 15$$

Significance  $\sim 6$ .

Profile likelihood with:

LbyL: 20% TH uncert.

CEP: 50% TH uncert.

QED: measured beforehand

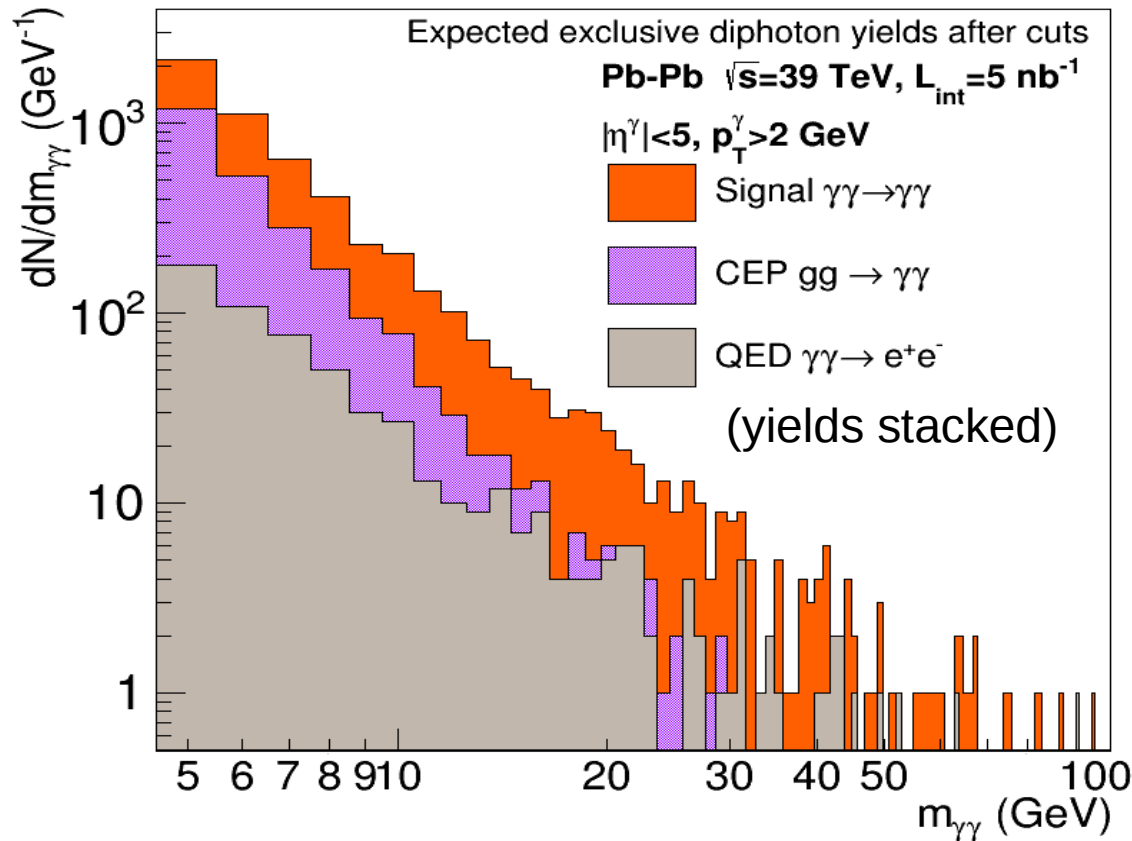
- **LbyL signal** clearly observable over backgrounds (esp. high  $m_{\gamma\gamma}$ )



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

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

**PRELIMINARY**



$$N_{\gamma\gamma-\gamma\gamma} \sim 2500$$

$$N_{\text{CEP}-\gamma\gamma} \sim 2000$$

$$N_{\text{QED-ee}} \sim 600$$

Significance  $\sim 35$ .

Profile likelihood with:

LbyL: 20% TH uncert.

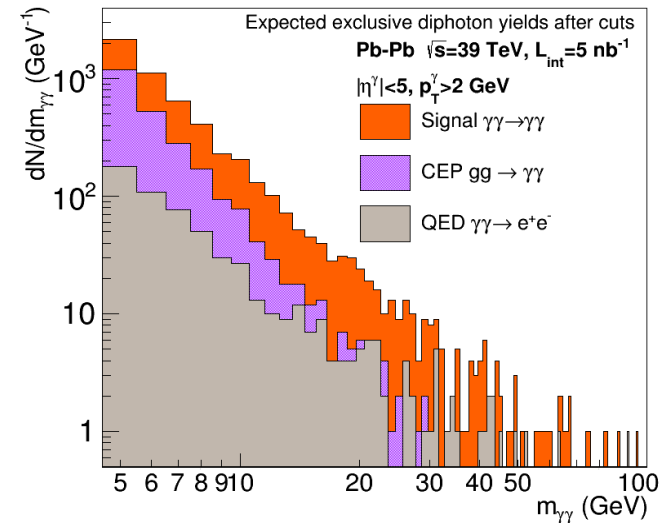
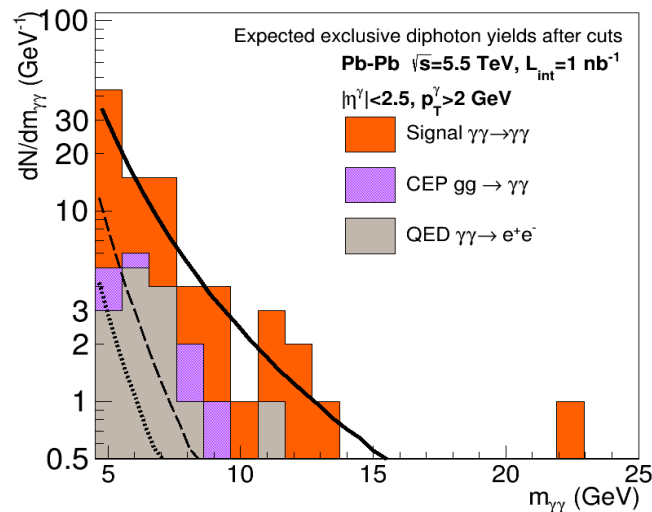
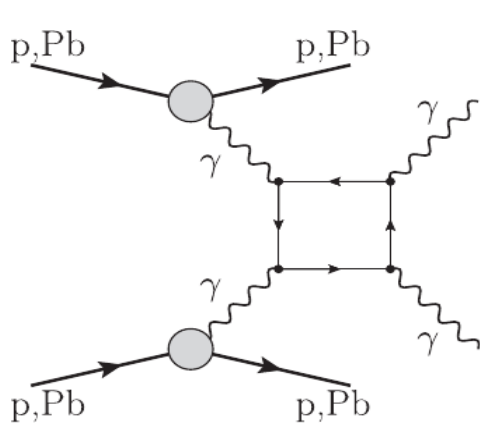
CEP: 50% TH uncert.

QED: measured beforehand

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

# Conclusion

- Elastic light-by-light scattering accessible in UPC at the LHC&FCC  
 $pp, pPb, PbPb \rightarrow \gamma\gamma \rightarrow p(Pb)\gamma\gamma p(Pb)$ ,  $\sqrt{s}=(5.5, 8.8, 14)-(39, 63, 100)$  TeV
- Cross sections (EPA + MadGraph + Bern et al.):  
**LHC:**  $\sigma(\gamma\gamma \rightarrow \gamma\gamma) \sim 105$  fb, 260 pb, 370 nb. Rates: 12, 6, 70 pairs/year  
**FCC:**  $\sigma(\gamma\gamma \rightarrow \gamma\gamma) \sim 240$  fb, 780 pb, 1.8  $\mu$ b. Rates: 40, 150, 2500 pairs/year  
 → Pb-Pb preferred: Maximum rates, minimum backgds (also no pileup)



- LbyL signal clearly observable (Signif  $\sim 6, 35$ ) over CEP+QED backgds
- LHC: 1<sup>st</sup> observation of such a fundamental QM process in the lab.
- FCC: Very large yields. Sensitivity to new physics in charged loops.

# Back-up slides