Anomalous quartic gauge couplings and searches for axion-like particles in p-p, p-A and A-A collisions at the LHC

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Overview

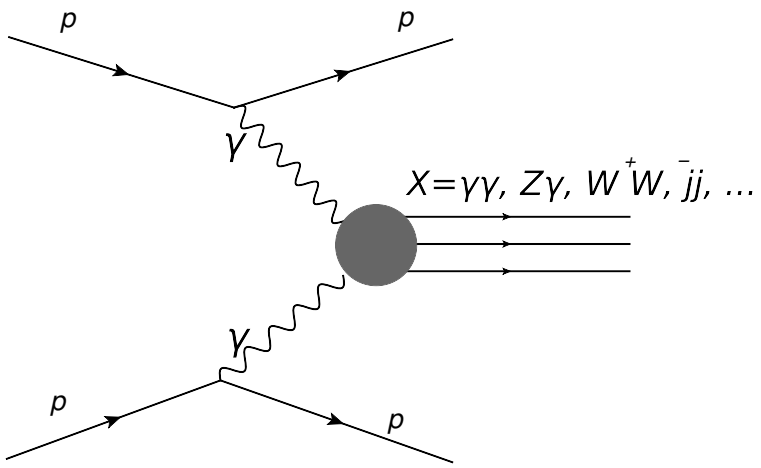
- Anomalous quartic gauge couplings in central exclusive production in p-p collisions at the HL-LHC; contribution to the Yellow Report for the HL-LHC;
- Axion-like particles (ALPs) in light-by-light scattering:
  - Searching for ALPs in p-p collisions using proton tagging (work in collaboration with Sylvain Fichet, Gero von Gersdorff, Christophe Royon, JHEP06(2018)131),
  - Extending search efforts for ALPs in p-A and A-A collisions (ongoing work in collaboration with Laurent Schoeffel, Samira Hassani, Christophe Royon)

Anomalous quartic gauge couplings in central exclusive production events $pp \to pXp$ at the HL-LHC

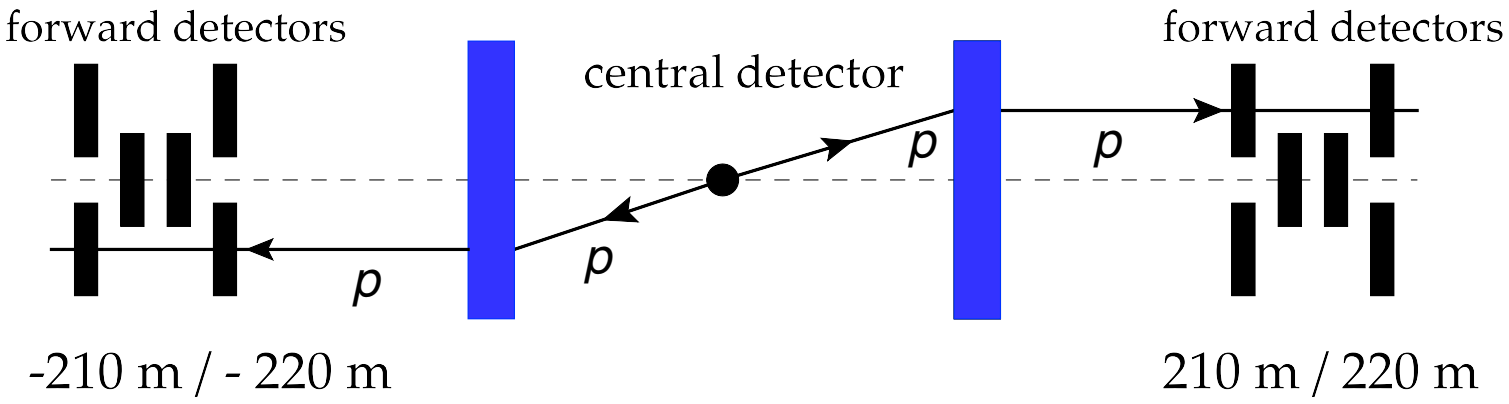
Contribution to Yellow Report, **CB, Christophe Royon**

Photon-exchange processes in p-p collisions

- Central exclusive reactions $pp \to p + X + p$ can be studied by measuring $X = \gamma\gamma, \gamma Z, W^+W^-, \ldots$ in a central detector and tagging the outgoing intact protons with forward detectors at 210 m w.r.t. the interaction point.
- Proton fractional momentum loss $\xi = \Delta p/p$ is reconstructed with the forward proton detectors.
- Select central exclusive processes by comparing $m_{\gamma\gamma}$ with $m_{pp} = \sqrt{\xi_1 \xi_2 s}$ and $y_{\gamma\gamma}$ with $y_{pp} = \frac{1}{2}\ln(\xi_1/\xi_2)$.
- Can be used to search fo New Physics, e.g., anomalous quartic gauge couplings.



Forward proton detectors



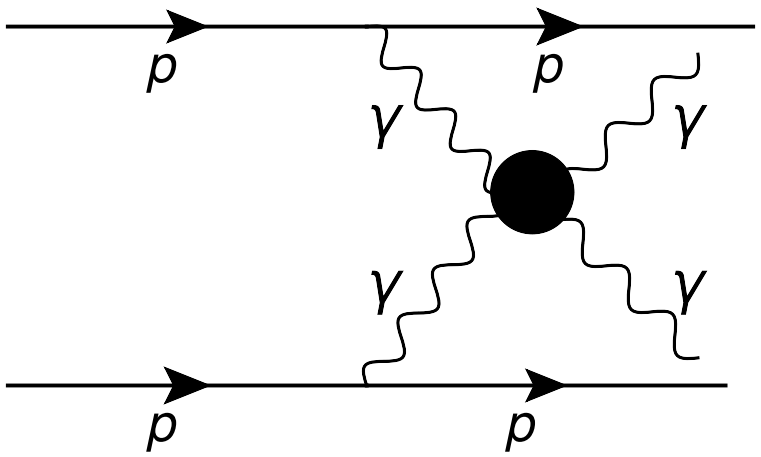
- Central system X (e.g., diphoton) measured in central detector and the intact protons are tagged with forward proton detectors; final state is completely reconstructed;
- LHC magnetic lattice (**blue** rectangles) used as a precise proton longitudinal momentum spectrometer;
- ATLAS Forward Physics (**AFP**) and CMS-TOTEM Precision Proton Spectrometer (**CT-PPS**) are able to operate (and have collected data) with forward proton spectrometers at high instantaneous luminosities;
- Photon-physics above electroweak scale is a reality!; First physics results by CMS and TOTEM collaborations **JHEP 07 (2018) 153** by observing $pp \to p^{(*)}\ell^+\ell^- p$

Probing the anomalous $\gamma\gamma\gamma\gamma$ coupling in light-by-light scattering

Presence of new electrically charged particles would induce the anomalous light-by-light scattering (induced via loop corrections or resonant production). Effective interaction operators at low energies,

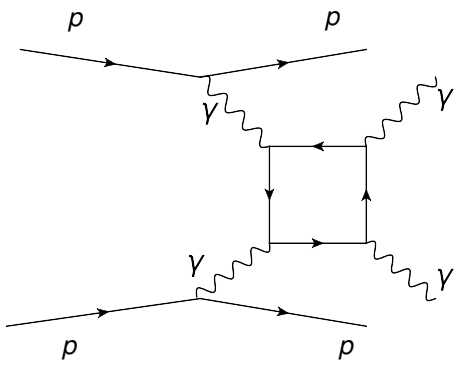
$$\mathcal{L}_{\gamma\gamma\gamma\gamma} = \zeta_1^{4\gamma} F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} F_{\rho\sigma} + \zeta_2^{4\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

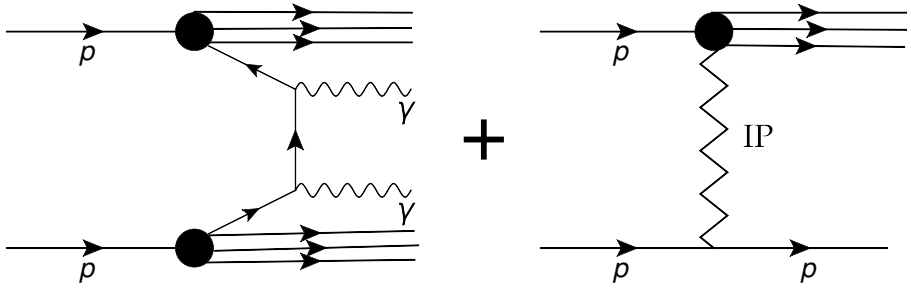
Induces anomalous light-by-light scattering, which can be probed in photon-induced processes in p-p collisions,



Studies by C. Royon, S. Fichet, G. von Gersdorff, JHEP 1502 (2015) 165; Phys. Rev. D89 (2014) 114004; Phys. Rev. D81 (2010) 074003; Phys. Rev. D78 (2008) 073005

Background





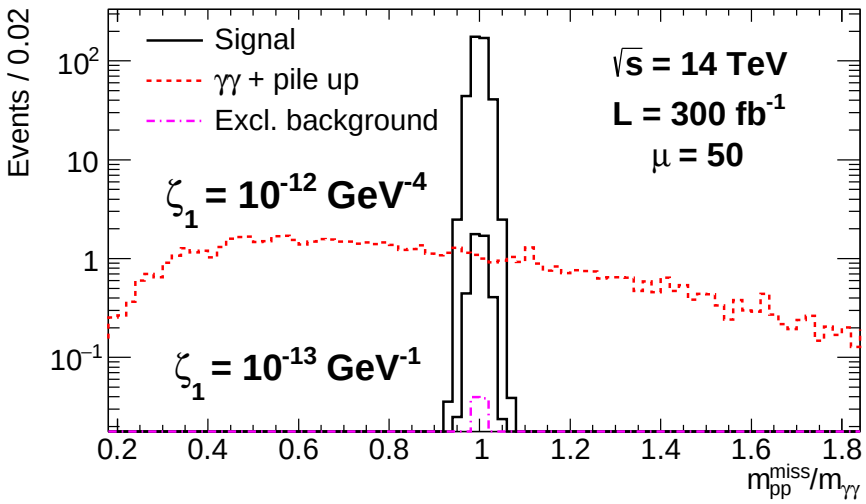
Exclusive background (irreducible)

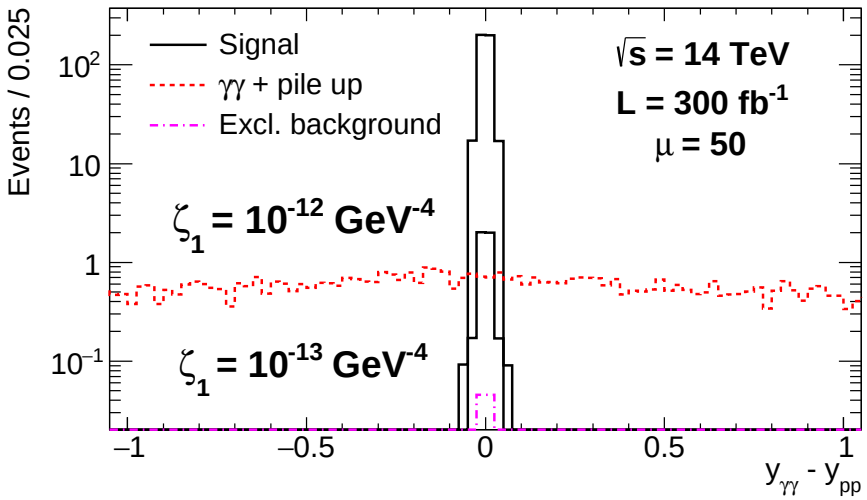
- SM light-by-light scattering;
- Small cross section ($\sim 10^{-1}$ fb) for mass range accessible w/ proton taggers;
- ($gg \to \gamma\gamma$ contribution is heavily suppressed for large diphoton masses $m_{\gamma\gamma} > 300$ GeV in p-p collisions)

Non-exclusive background (reducible)

- Non-exclusive diphoton production overlapped with diffractive protons from secondary interactions (pileup) is the dominant background.
- Fakes from jets and electrons (positrons) overlapped with diffractive protons.
- Reducible by matching forward-central kinematics.

Exclusive selection





Figs. from S. Fichet, G. von Gersdorff, C. Royon, M. Saimpert, JHEP 1502 (2015) 165

- Non-exclusive events can be rejected by comparing the kinematics of forward and central systems, leading to a robust background suppression;
- Ratio of $m_{\gamma\gamma}$ with diphoton mass reconstructed with forward protons $m_{pp} = \sqrt{s\xi_1\xi_2}$, exclusive processes peak at 1;
- Compare rapidity reconstructed centrally $y_{\gamma\gamma}$ with diphoton rapidity reconstructed with forward protons $y_{pp} = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$, exclusive processes peak at 0;
- Apply both selections simultaneously to suppress pileup background.

Sensitivity to $\gamma\gamma\gamma\gamma$ anomalous coupling

Expected sensitivity at 95% CL at the end of Run-2 of the LHC, assuming 300 fb^{-1},

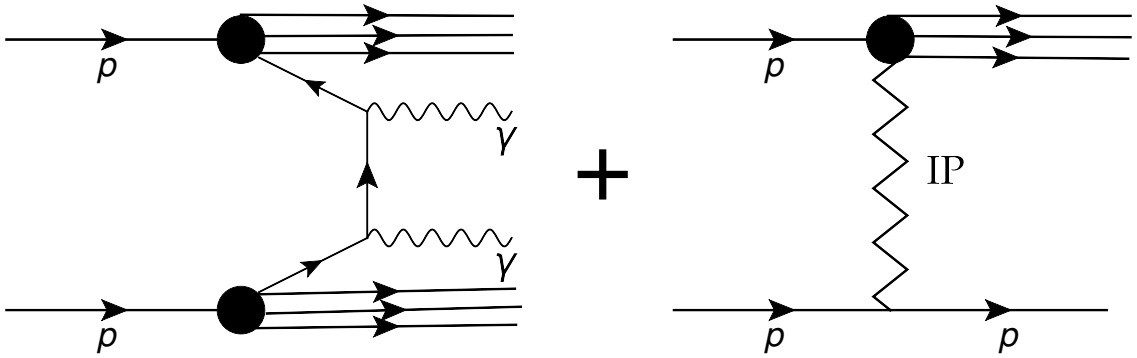
$$\sqrt{48\zeta_1^2 + 11\zeta_2^2 + 40\zeta_1\zeta_2} \leq 2.4 \cdot 10^{-13}\,\mathrm{GeV}^{-4}$$

Could be improved at the HL-LHC and the use of precise time-of-flight measurements for pileup suppression.

Working hypotheses:

- Assume similar acceptance in ξ as for Run-2 of the LHC;
- Average number of secondary interactions per bunch crossing is 200;
- In addition to rapidity and mass matching selections, consider time-of-flight information to constrain longitudinal coordinate of event vertex;

Secondary interactions per bunch crossing (pile-up)



Non-exclusive diphoton-like event overlapped with uncorrelated proton(s) from pileup yields signal-like signature. Up to 200 interactions per bunch crossing at the HL-LHC!

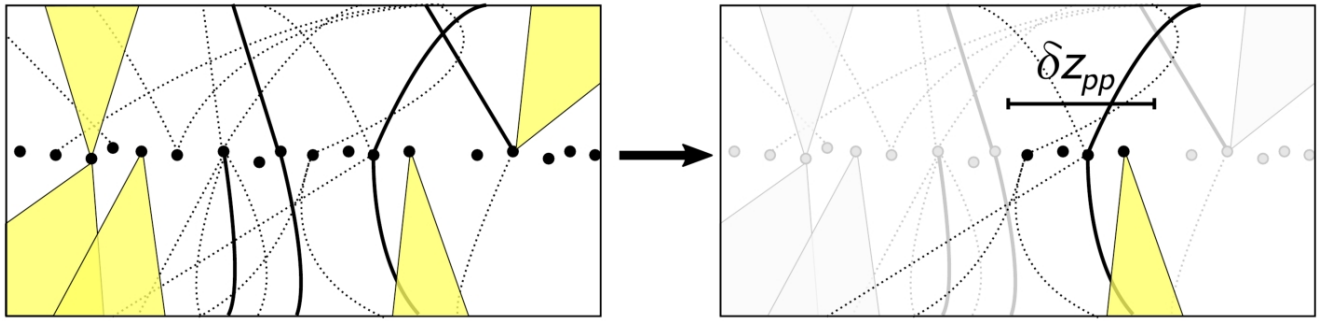
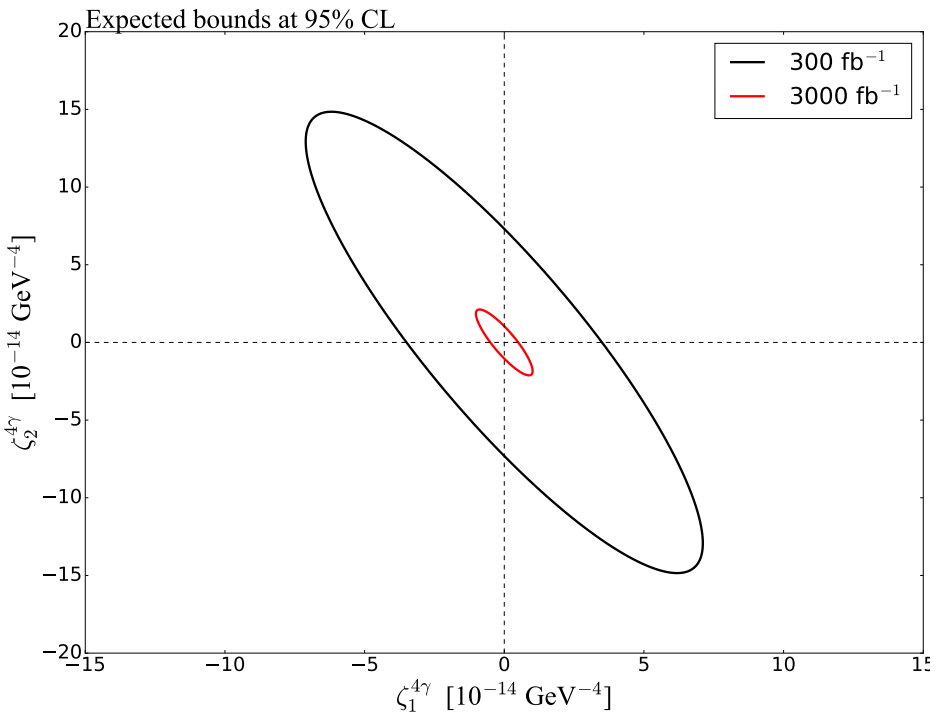
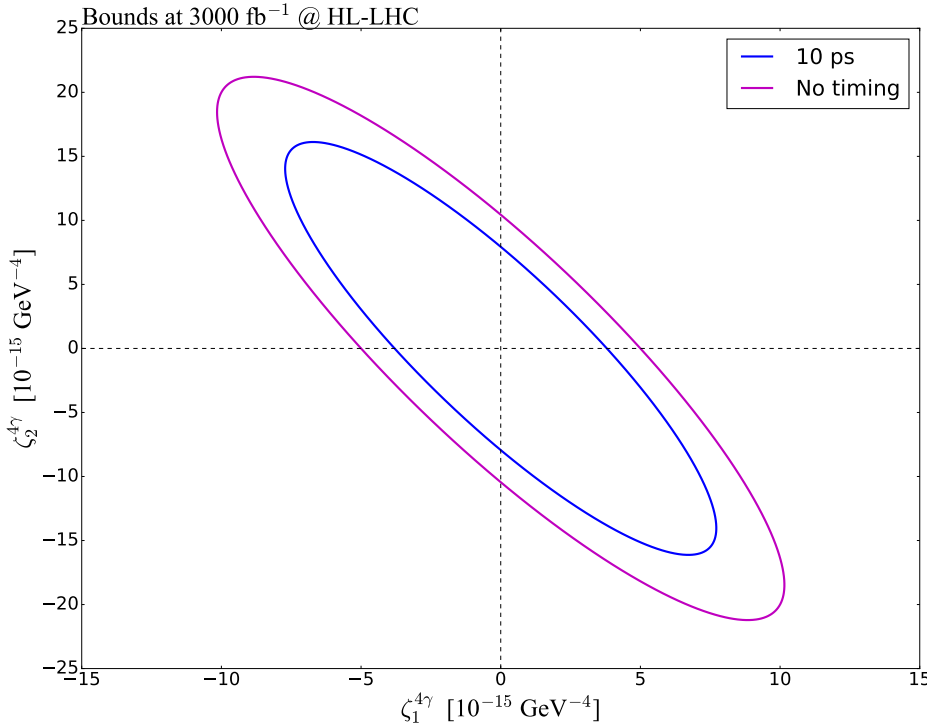


Fig. by L. Forthomme

Precise time-of-flight measurement allows discrimination of pileup vertices. Vertex precision $\delta z_{pp} = \frac{c}{\sqrt{2}}\delta t$. Timing precision of $\delta t = 10$ ps yields $\delta z_{pp} \sim 2$ mm.

Sensitivity on anomalous couplings $\zeta^{4\gamma}$ improvement @ HL-LHC





Left: Comparison between current instantaneous luminosity LHC 300 fb^{-1} and HL-LHC 3000 fb^{-1}. **Right:** Comparison between the use of timing and $\delta t = 10$ ps (not much difference if 5 ps and 2 ps are used).

Bound could improve at the HL-LHC down to,

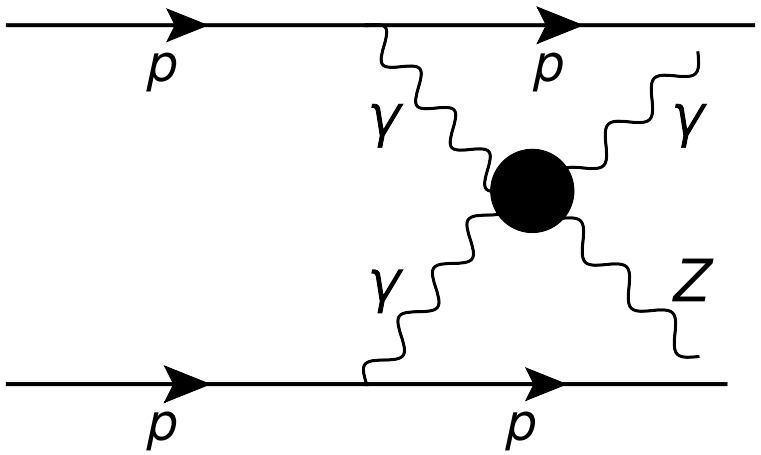
$$\sqrt{48\zeta_1^2 + 11\zeta_2^2 + 40\zeta_1\zeta_2} \leq 4.2 \cdot 10^{-14}\,\mathrm{GeV}^{-4}$$

Probing the anomalous $\gamma\gamma\gamma Z$ coupling

The presence of new particles charged under SU(2)$_L \times$ U$_Y(1)$ induce the anomalous $\gamma\gamma\gamma Z$ coupling via loop corrections. Effective interaction operators at low energies,

$$\mathcal{L}_{\gamma\gamma\gamma Z} = \zeta_1^{3\gamma Z} F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} Z_{\rho\sigma} + \zeta_2^{3\gamma Z} F^{\mu\nu} \tilde{F}_{\mu\nu} F^{\rho\sigma} \tilde{Z}_{\rho\sigma}$$

where $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$. The quartic coupling induces anomalous $\gamma\gamma \to \gamma Z$ scattering,



The Z boson could decay into a pair of charged leptons or hadronically (dijet or large radius jet configurations).

Sensitivity to the $\gamma\gamma\gamma Z$ coupling

Existing bound at 95%CL set via measurement of $\mathcal{B}(Z \to \gamma\gamma\gamma)$ at 7 TeV by the ATLAS collaboration Eur. Phys. J. C 76(4),

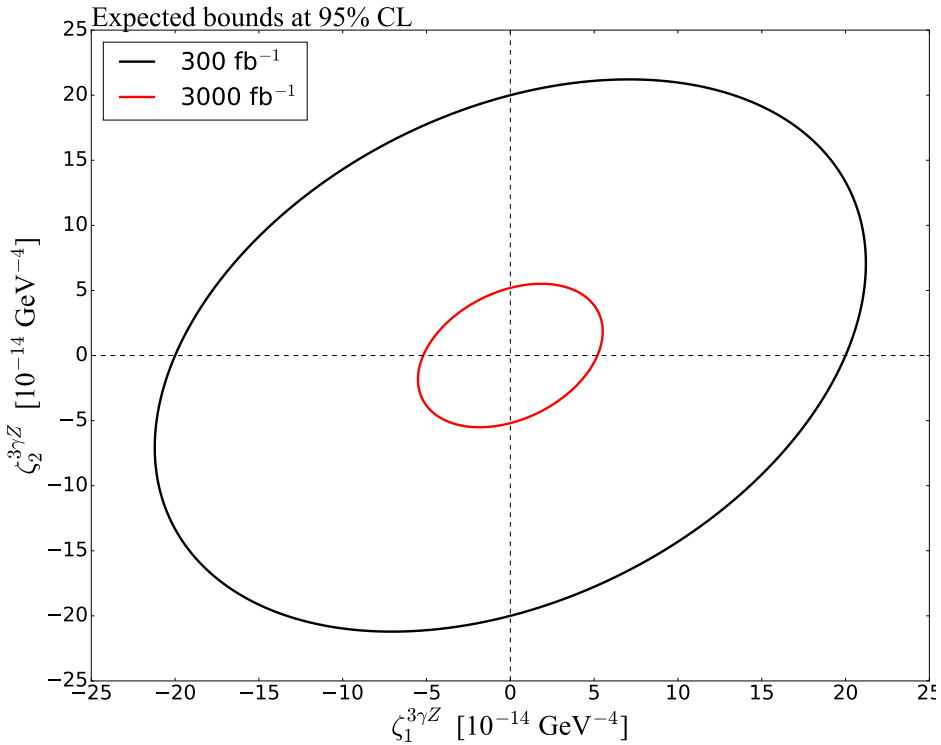
$$\sqrt{\zeta_1^2 + \zeta_2^2 - \frac{2}{3}\zeta_1\zeta_2} \leq 1.3 \cdot 10^{-9}\,\mathrm{GeV}^{-4}$$

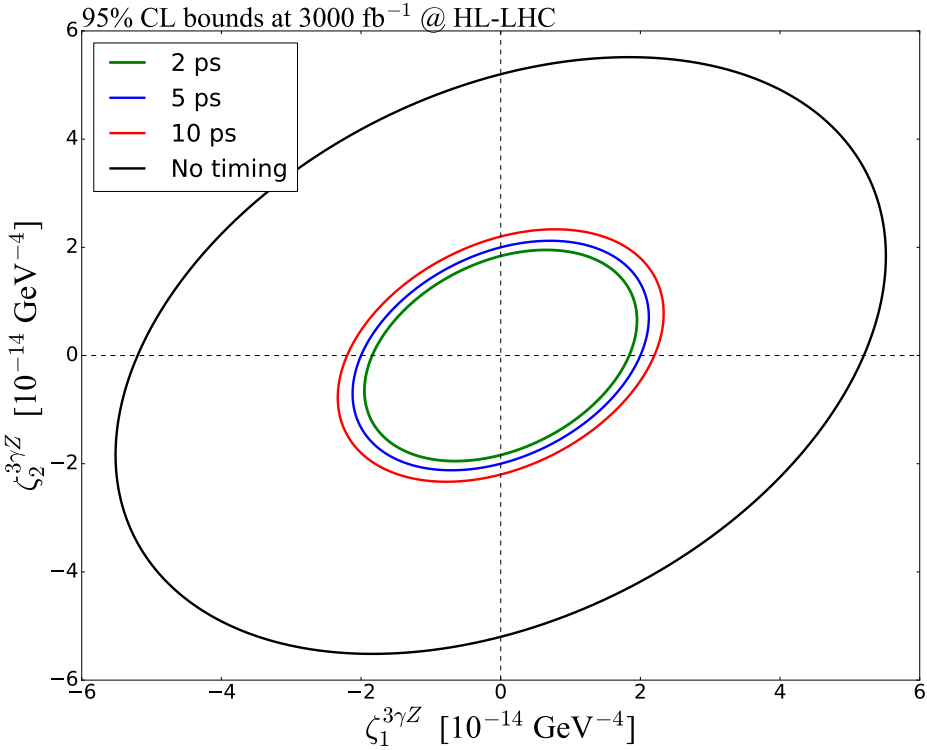
Expected bound at 95% CL at the end of Run-2 of the LHC by measuring the reaction $pp \to p\gamma Zp$ with 300 fb^{-1} (combining searches with the Z decaying leptonically and hadronically),

$$\sqrt{\zeta_1^2 + \zeta_2^2 - \frac{2}{3}\zeta_1\zeta_2} \leq 1.5 \cdot 10^{-13}\,\mathrm{GeV}^{-4}$$

CB, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1706 (2017) 142

Sensitivity improvement on the anomalous coupling $\zeta_{1,2}^{3\gamma Z}$ @ HL-LHC





Left: Comparison between 300 fb^{-1} and 3000 fb^{-1} (HL-LHC). **Right:** Comparison between the use of timing with $\delta t = 2, 5, 10$ ps.

Sensitivity on quartic couplings at 95% CL could improve roughly one order of magnitude,

$$\sqrt{\zeta_1^2 + \zeta_2^2 - \frac{2}{3}\zeta_1\zeta_2} \leq 1.6 \cdot 10^{-14}\,\mathrm{GeV}^{-4}$$

Observations

- As a prototype, we studied $\gamma\gamma \to \gamma\gamma$, and $\gamma\gamma \to \gamma Z$ scattering, assuming a similar forward proton detector setup as in Run-2 of the LHC. We assumed an average pileup of 200 and an int. luminosity of 3000 fb^{-1} at 14 TeV for our projections;
- Improvement of roughly one order of magnitude in sensitivity for anomalous quartic couplings.

Axion-like particles at the LHC in coherent photon exchange processes

- Searching for axion-like particles with proton tagging at the LHC, CB, S. Fichet, G. von Gersdorff, C. Royon, JHEP06(2018)131
- (Work in progress) Searching for axion-like particles in p-A and AA collisions, work in collaboration with S. Hassani, L. Schoeffel and C. Royon;

Axion-like particles (ALPs)

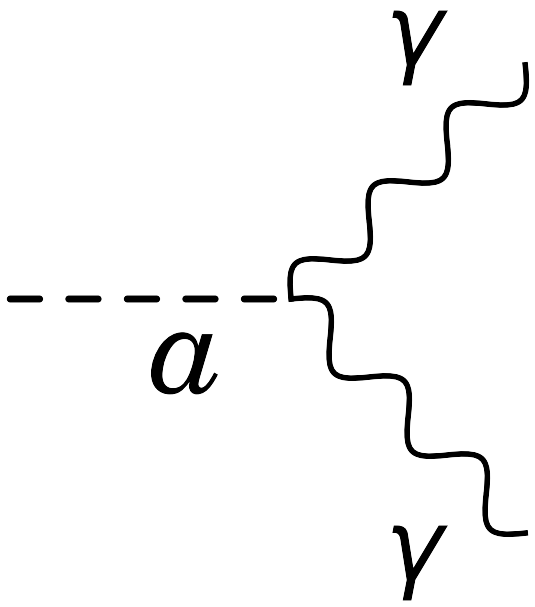
- Pseudoscalars weakly coupled to SM particles are generally known as axion-like particles (ALPs).
- We focus solely on the coupling of ALP to photons; no further assumptions on the ALP–SM particles couplings are necessary!
- Model ALP–photon coupling via dimension-five operator,

$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{1}{f} a F \tilde{F}$$

where a is the ALP field, $\frac{1}{f}$ is the ALP–photon coupling;

- Partial decay width,

$$\Gamma(a \to \gamma\gamma) = \frac{1}{4\pi}\frac{m_a^3}{f^2}$$



ALP–photon coupling

Constraining axion-like particles

- Landscape of ALP–photon coupling versus ALP mass;
- ALPs are strongly constrained at low masses ($m_a = 10^{-15} - 10^{-1}$ GeV), mainly by axion helioscopes.
- ALPs constraints at multi-GeV masses are collider-based:
  - Very hard to constrain ALPs relying **only** on its coupling to photons!
  - Bounds are based on multi-photon measurements at LEP, Tevatron and LHC;
- Constraints are especially difficult for ALPs masses accessible at the LHC in p-p, p-A and A-A collisions (circled in red)

Existing constraints

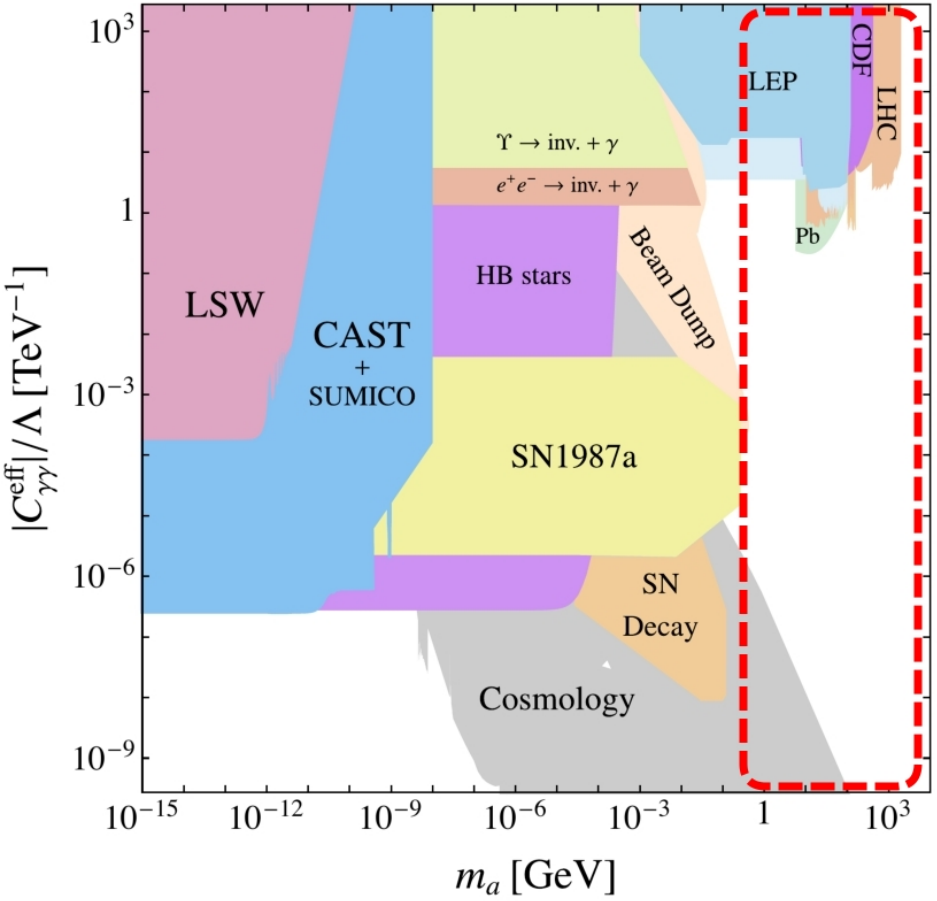
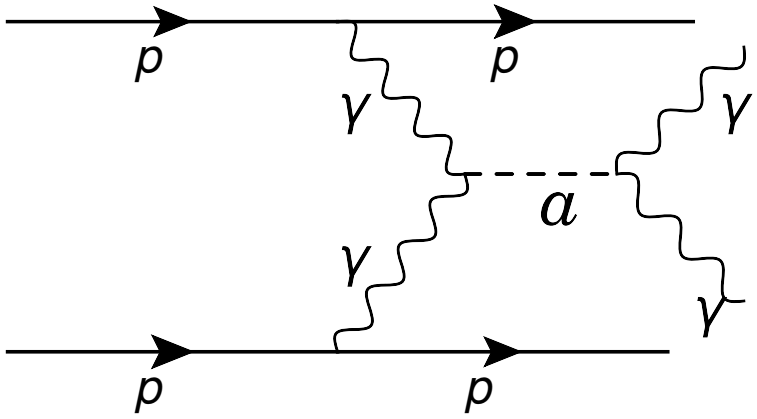


Fig. from Bauer, Neubert, Thamm, **JHEP12(2017)044**

Updated collider-bounds computed by Knapen, Lin, Lou, Melia, **PhysRevLett.118.171801**

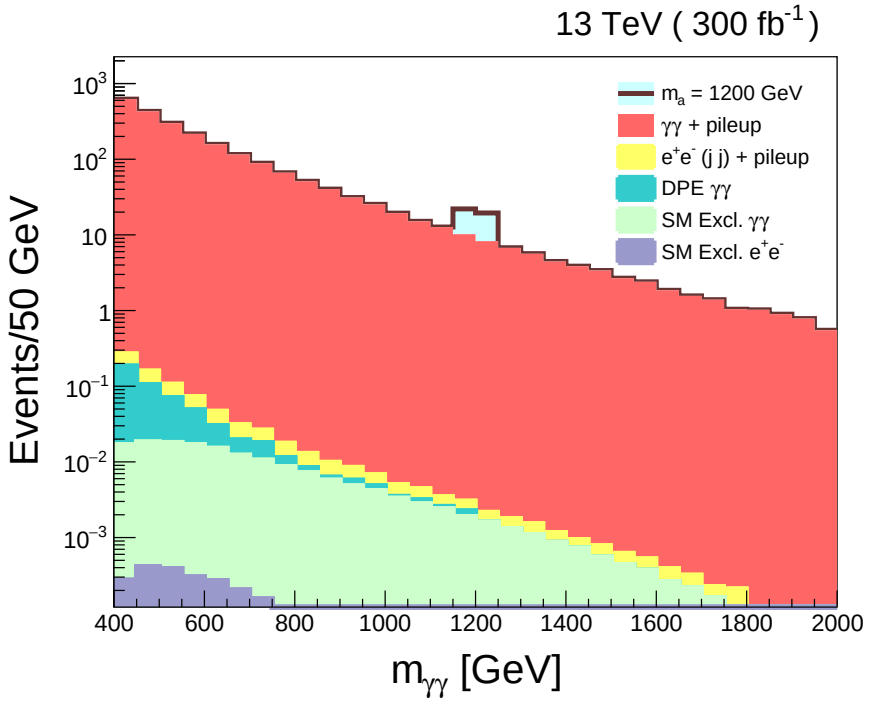
Searching for ALPs in light-by-light scattering

- ALPs coupled to photons induce anomalous light-by-light scattering (LbL);
- Search in ultraperipheral heavy-ion collisions (Knapen, Lin, Lou, Melia, **PhysRevLett.118.171801**);
  - Great sensitivity due to Z^4 enhancement of photon-flux;
  - ALP mass range is limited in UPCs (1 GeV to $\sim$100 GeV for resonant production);
  - Search relies on bump-search over SM-LbL lineshape.
- Exclusive diphoton production in p-p collisions with proton tagging:
  - Access larger invariant diphoton mass (600 GeV to 2 TeV)
    $\hookrightarrow$ Sensitivity is enhanced since ALP production rate increases with $m_{\gamma\gamma}$;
  - Production rates are smaller in comparison to UPCs in Pb-Pb collisions;
  - Search does not rely on bump-search, since SM LbL is highly suppressed in p-p collisions.



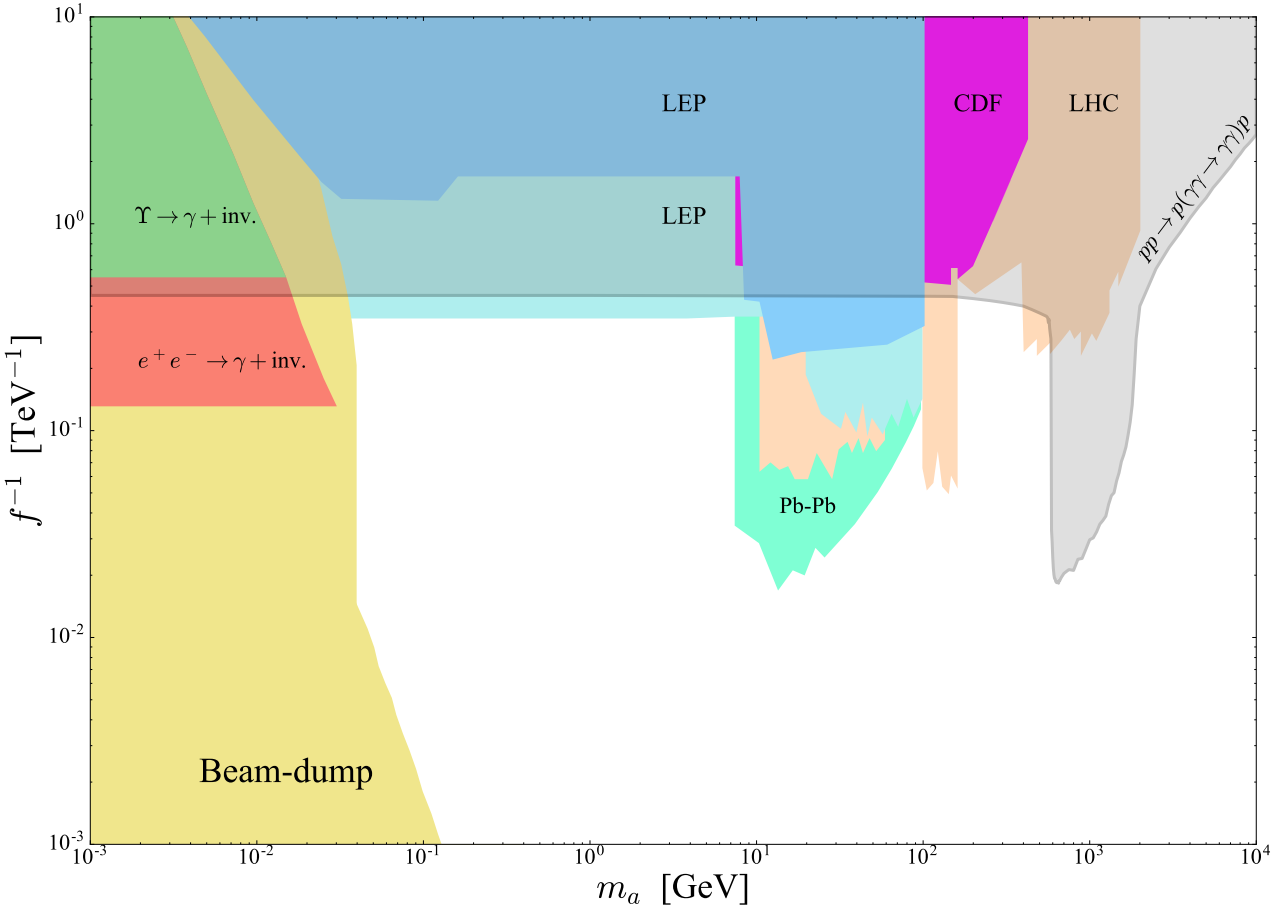
Event selection

- Two photons with minimum $p_T^\gamma > 100$ GeV and $|\eta^\gamma| < 2.5$;
- Protons reconstructed on each side with $0.015 \leq \xi \leq 0.15$, where the proton taggers are efficient;
- Exclusive processes topology selection:
  - $|\Delta\phi_{\gamma\gamma} - \pi| < 0.01$ rad
  - $p_{T,2}^\gamma / p_{T,1}^\gamma > 0.95$
- Minimum diphoton invariant mass of $m_{\gamma\gamma} > 600$ GeV; suppresses background with rate steeply falling $m_{\gamma\gamma}$ rate.
- Forward-central system matching: strong rejection of non-exclusive processes!



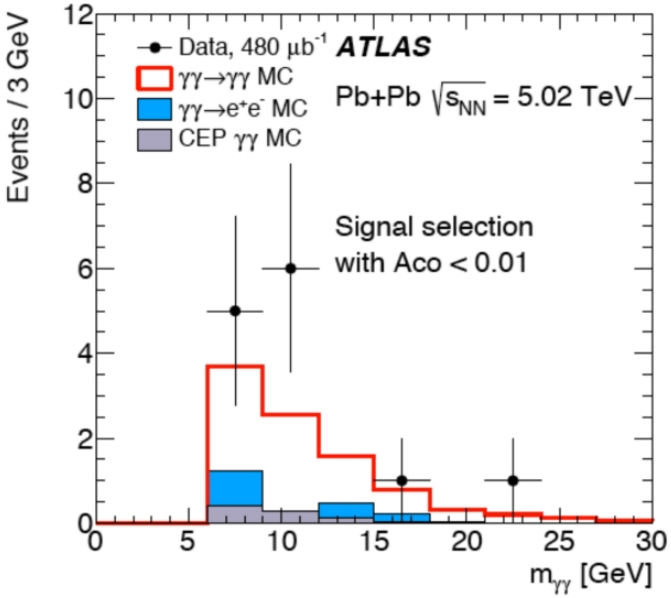
- Assume 300 fb^{-1} of data for our projections in p-p collisions at 13 TeV w/ pileup of 50 interactions;
- Background dominated by inelastic diphoton production overlapped with diffractive protons (in red);
- Signal instance in cyan at $m_a = 1.2$ TeV for $f^{-1} = 0.1$ TeV^{-1};

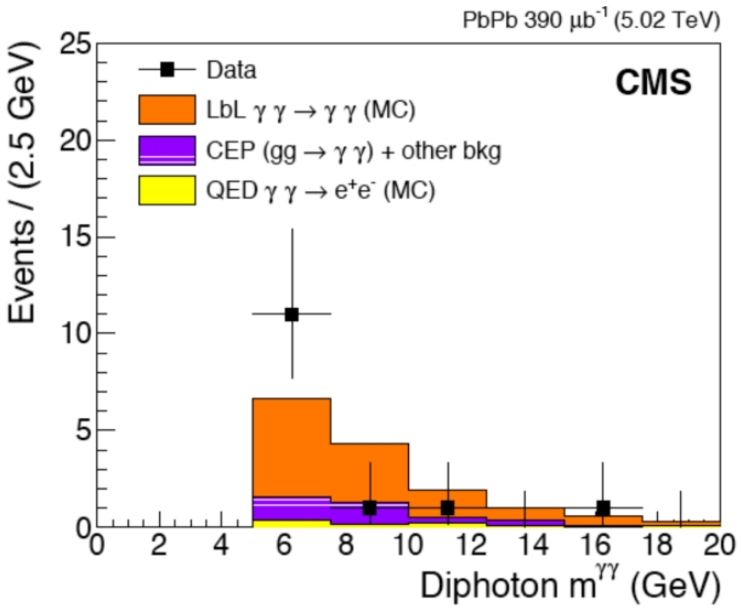
Results



Expected 95% CL sensitivity in central exclusive production assuming $\mathcal{B}(a \to \gamma\gamma) = 1$.
Strong exclusion power for resonant ALP production in the collider-bounds region (down to $1/f = 0.02$ TeV^{-1})!

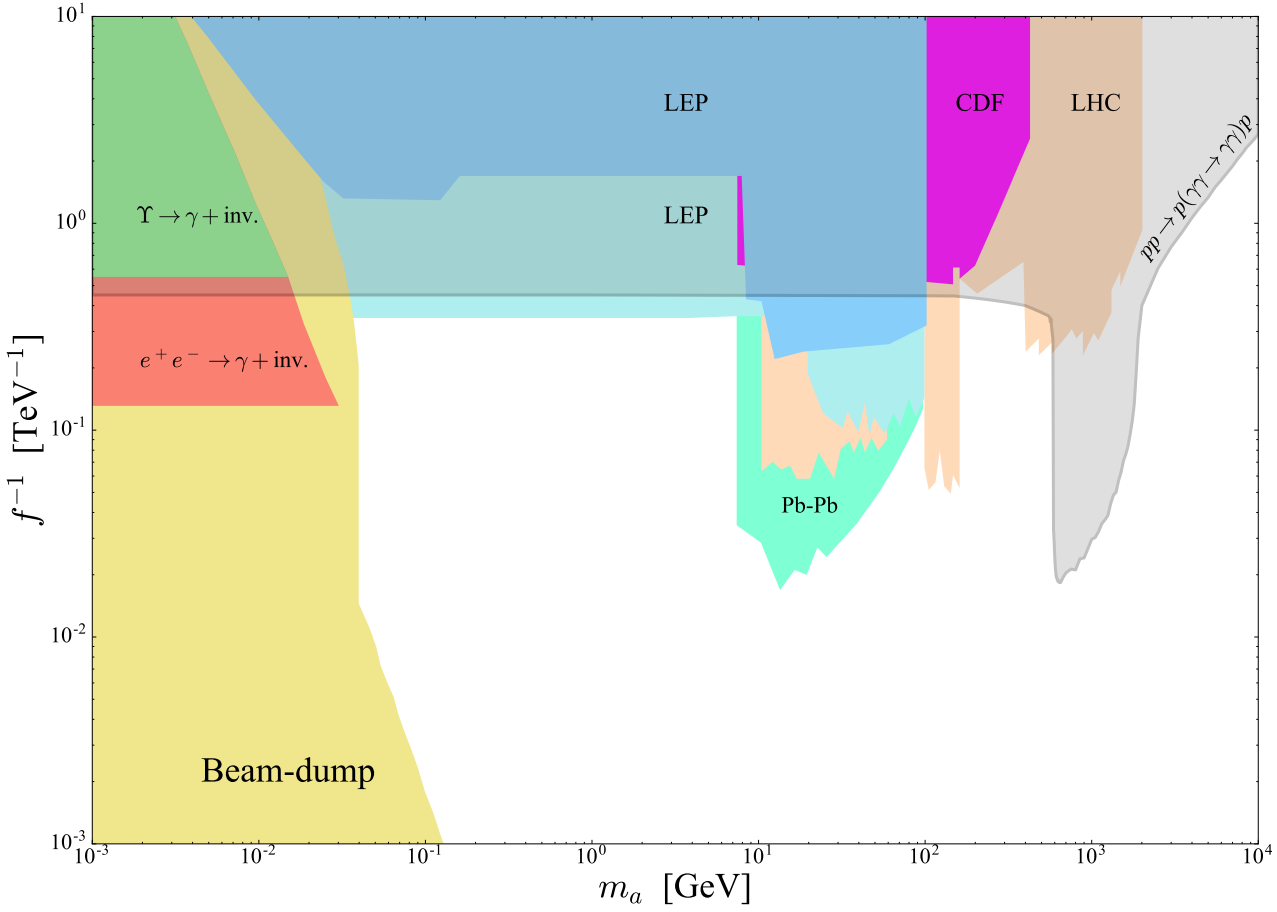
Light-by-light scattering in Pb-Pb collisions





- Both ATLAS (Nature Physics 13 (2017) 852) and CMS (Subm. to Phys. Lett. B., CERN-EP-2018-271) observed events consistent with light-by-light scattering in ultraperipheral heavy-ion collisions at $\sqrt{s_{NN}} = 5.02$ TeV in Pb-Pb collisions;
- Cross section is enhanced by Z^4, but is bounded at high mass due to the minimum impact parameter in UPCs
- Pb-Pb and p-p cover complementary kinematic regimes;

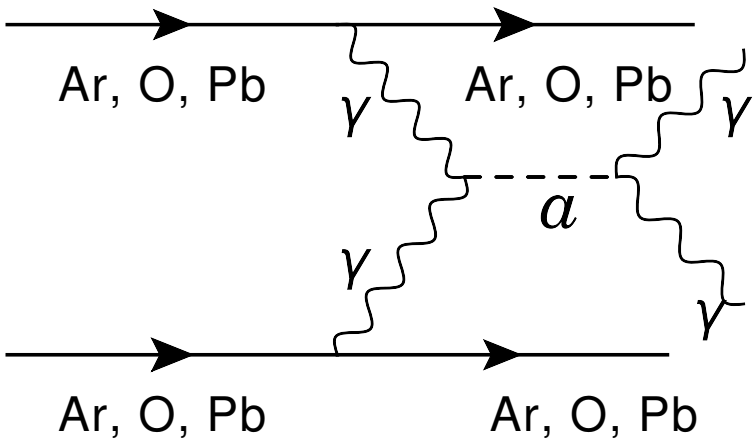
How can one cover the gap between these two regions?

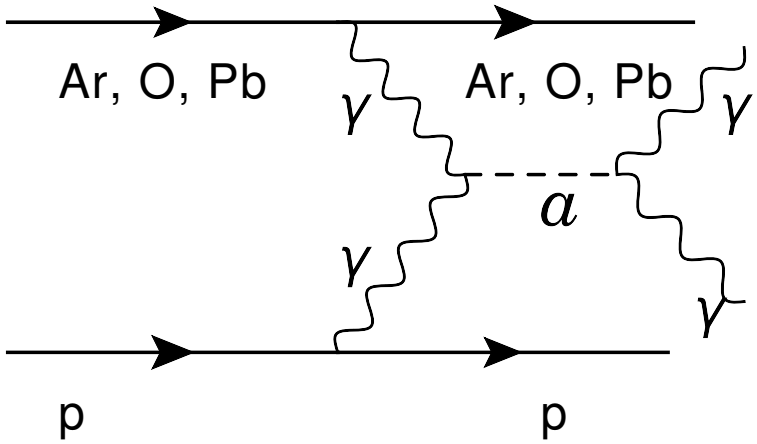


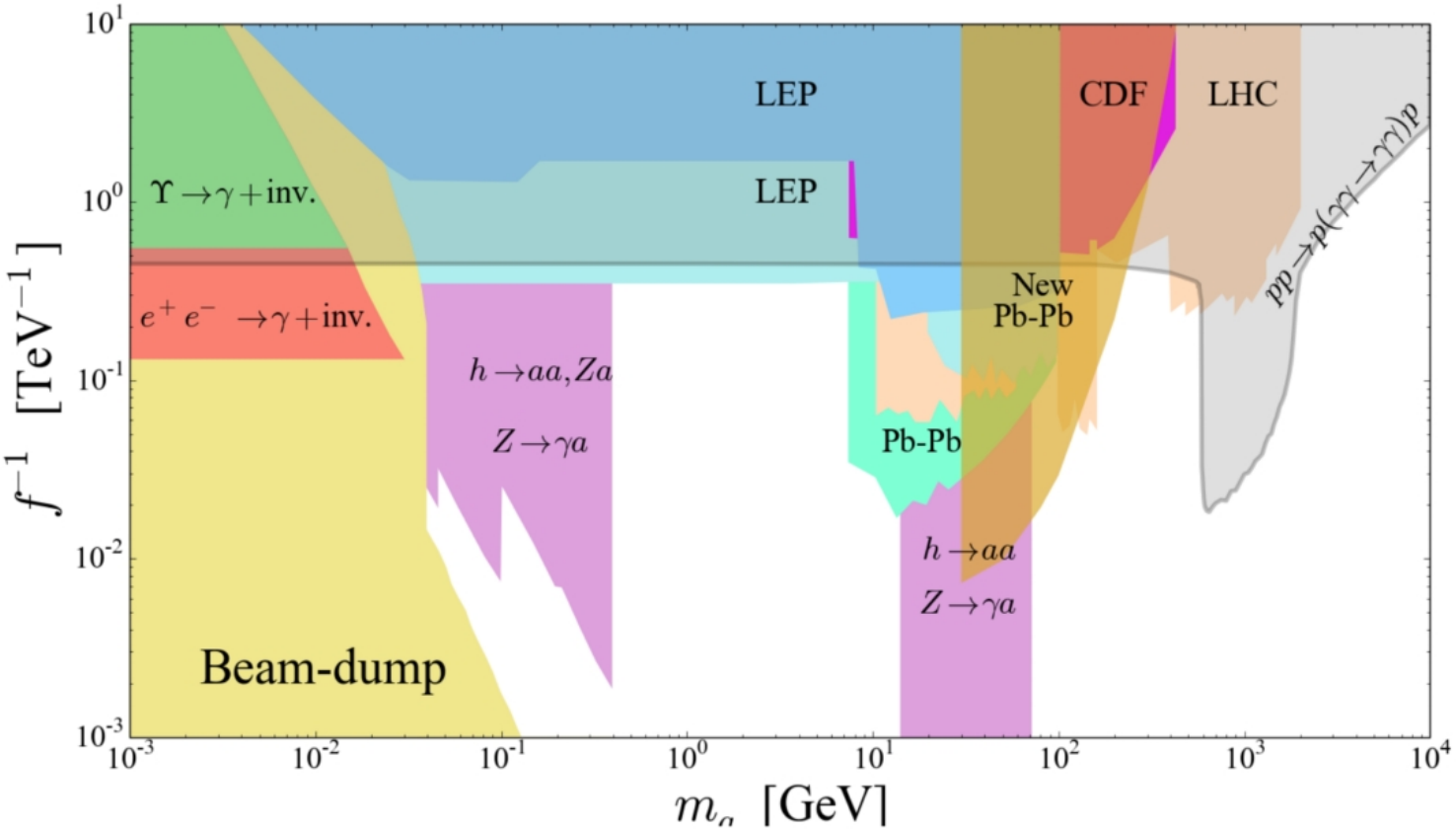
Searches in UPCs in Pb-Pb collisions are limited in mass (up to roughly 120 GeV), while searches in p-p collisions are bounded from below at about 350 GeV.

Extending the constraint landscape in p-A and in A-A collisions

- **UPCs in other species of heavy-ions:**
  - **Oxygen-Oxygen collisions (O-O):** The minimum impact parameter for UPCs is smaller, which yields more energetic photon beams. However, cross section is much smaller due to low proton number Z.
  - **Argon-Argon collisions (Ar-Ar):** Access to more energetic photon beams, which gives access to large diphoton invariant masses. Does not require as much luminosity to compensate for smaller Z in comparison w/ O-O.
- **UPCs in p-Pb collisions:** production rate is suppressed by a factor of Z^2 for the photon flux relative to Pb-Pb, but in turn access larger diphoton invariant masses. Integrated luminosities are larger than in the Pb-Pb collisions ($\mathcal{O}(100)$ nb^{-1});
- **UPCs in p-Ar or p-O collisions:** Photons beam energies are larger, although production rate for diphoton events is more suppressed than in the p-Pb case. Cases worth considering.







Work in progress in collaboration w/ Laurent Schoeffel, Samira Hassani, Christophe Royon.

Transparent-yellow region corresponds to the expected sensitivity in Pb-Pb collisions considering 10 nb^{-1} of luminosity, for diphotons passing a similar selection as in the ATLAS and CMS analyses.

Do same exercise for the aforementioned configurations.

Conclusions and observations

- We examined the possibility of searching for ALPs in central exclusive production of photon pairs in p-p collisions at 13 TeV for an integrated luminosity of 300 fb^{-1} with proton tagging;
- We are exploring the possibility of extending the search strategy for axion-like particles with electromagnetic coupling in p-A and A-A collisions.

Thank you!

Back-up slides

Signal simulation framework

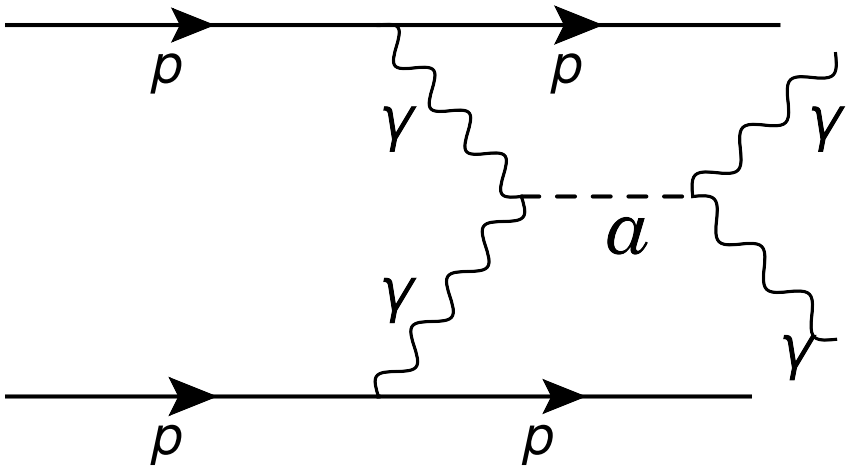
- Light-by-light scattering production rates are computed in the Equivalent Photon Approximation:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}^{pp\to p\gamma\gamma p} = \int \frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\hat{s}}^{\gamma\gamma} \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\Omega}^{\gamma\gamma\to\gamma\gamma} \mathrm{d}\hat{s}$$

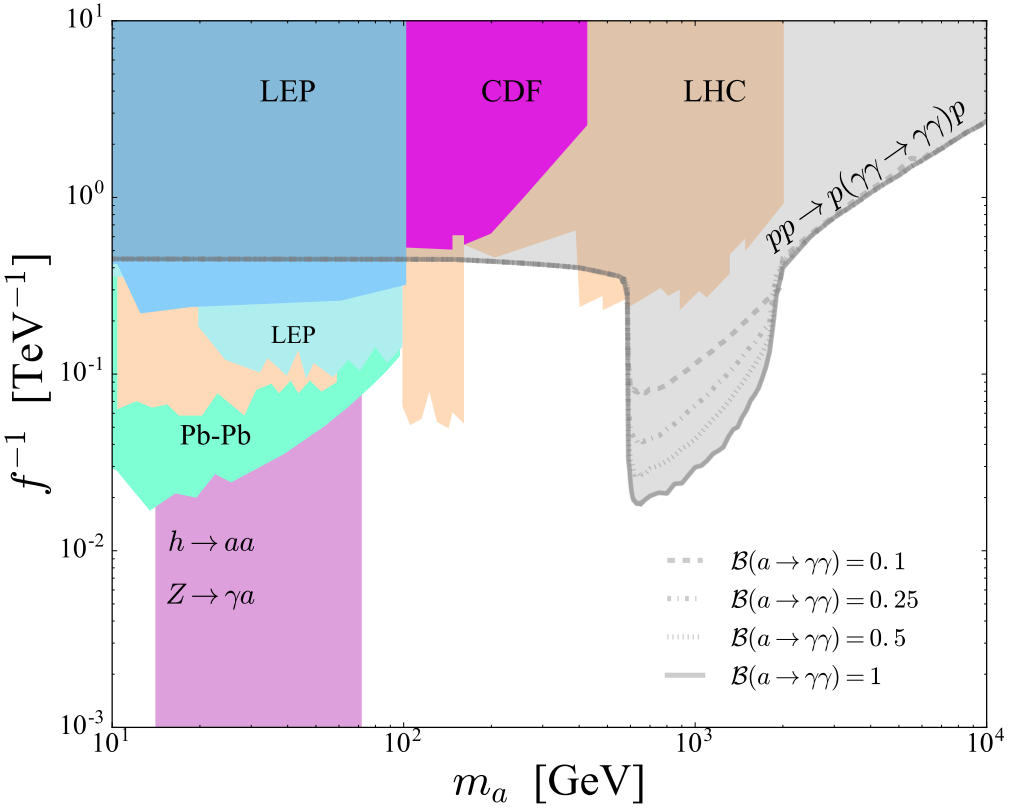
  where $\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\hat{s}}^{\gamma\gamma}$ is the two-photon effective luminosity spectrum;

- $\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\Omega}^{\gamma\gamma\to\gamma\gamma}$ is derived from the ALP–photon interaction;

- Exclusive $pp \to p(\gamma\gamma \to a \to \gamma\gamma)p$ production was implemented in the Forward Physics Monte Carlo (**FPMC**) event generator.



Results across branching ratios



Projections for various branching ratio assumptions.

Statistical framework

We calculate our projections for the total signal rate over the whole mass range (0.6 to 2 TeV). We assume a set of observed data. Assume there are no statistical fluctuations in these imaginary data, dubbed as ”Asimov data”. The observed events follow a Poisson distribution. We have the likelihood function,

$$\mathcal{L}(\sigma) = Pr(n'|b + \sigma L)$$

$$Pr(\hat{n}|n) = \frac{n^{\hat{n}} e^{-n}}{\hat{n}!}$$

w/ $L = 300$ fb^{-1}. For this analysis, the expected number of events from background b is very small.

The posterior probability is $\mathcal{L}(\sigma)\pi(\sigma)$ with flat prior $\pi(\sigma)$. We assume no event is observed $n' = 0$. The non-observation sets an upperbound on the signal event rate.

The higher posterior density region at $1 - \alpha$ is solved analytically in this case, and is given by,

$$1 - \alpha = 1 - e^{-\sigma_\alpha L} \tag{1}$$

where $\alpha = 0.05$ for 95% CL.

Sequential cut flow

Sequential selection	ALP	Excl. SM	DPE $\gamma\gamma$	e^+e^- / dijet +pileup	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{\mathrm{T1,(2)}} > 200, (100)$ GeV$]$	23.1	0.1	0.1	1.2	1246
$m_{\gamma\gamma} > 600$ GeV	23.1	0.06	0	0.1	440
$[p_{\mathrm{T2}}/p_{\mathrm{T1}} > 0.95,$ $\lvert\Delta\phi^{\gamma\gamma} - \pi\rvert < 0.01]$	23.1	0.06	0	0	35
$\lvert m_{pp}/m_{\gamma\gamma} - 1\rvert < 0.03$	21.8	0.06	0	0	1.2
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	21	0.06	0	0	0.2

Table 1. Signal and background yields after applying the event sequential selections. For illustrative purposes, we choose an ALP with mass $m_a = 1200$ GeV and a coupling value of $f^{-1} = 0.1$ TeV^{-1}. We assume an integrated luminosity of 300 fb^{-1} an average of 50 additional interactions per bunch crossing at $\sqrt{s} = 13$ TeV. Excl. stands for the exclusive backgrounds and DPE for double pomeron exchange background. Non-exclusive diphoton overlapped with soft diffractive protons (rightmost column) constitute the dominating background. The first two rows correspond to the diphoton offline preselection. The third row corresponds to the elastic selection. The last two rows correspond to the exclusive selection, with $m_{pp} = \sqrt{\xi_1\xi_2 s}$ and $y_{pp} = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$.

Motivation for ALP searches in LbL

- One of the main goals of Particle Physics is the search for New Physics;
- Photon-physics above the electroweak scale opens new paths for novel searches for New Physics complementary to the standard efforts at the LHC;
- Of particular interest are pseudoscalars weakly coupled to SM particles, known as axion-like particles (ALPs).
- ALPs appear in many extensions of the SM:
  - Pseudo Nambu-Goldstone bosons after spontaneous breaking of a global symmetry;
  - String theory landscape;
  - Mediators between hidden sectors and the SM;

Description	Cut
Photon Acceptance	$\lvert\eta\rvert < 2.37$, $1.37 < \lvert\eta\rvert < 1.52$ excluded
Photon Transverse energy	$E_{\mathrm{T}} > 3$ GeV
Number of Photons	$n == 2$
Track veto	$n_{\mathrm{tracks}}^{\mathrm{looseElectron}} == 0$
Diphoton invariant mass	$m_{\gamma\gamma} > 6$ GeV
Diphoton transverse momentum	$p_{\mathrm{T}}^{\gamma\gamma} < 2$ GeV
Diphoton acoplanarity	$aco < 0.01$

Diphoton event selection applied to Pb-Pb (and to be applied to Ar-Ar and O-O collisions)