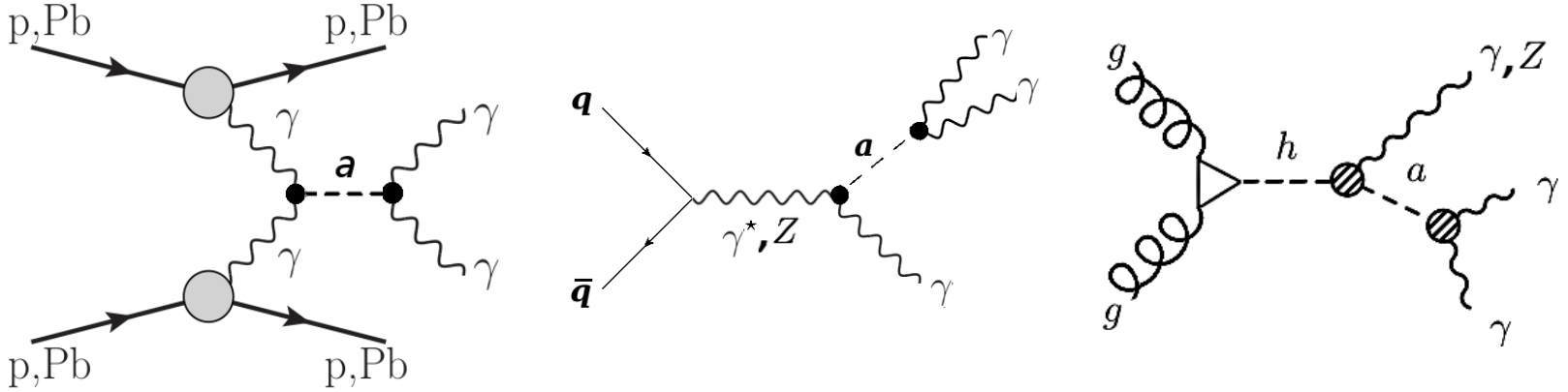
Searches for axion-like particles (ALPs) at the LHC

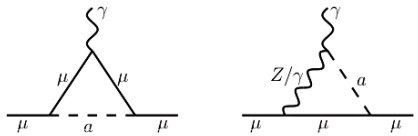


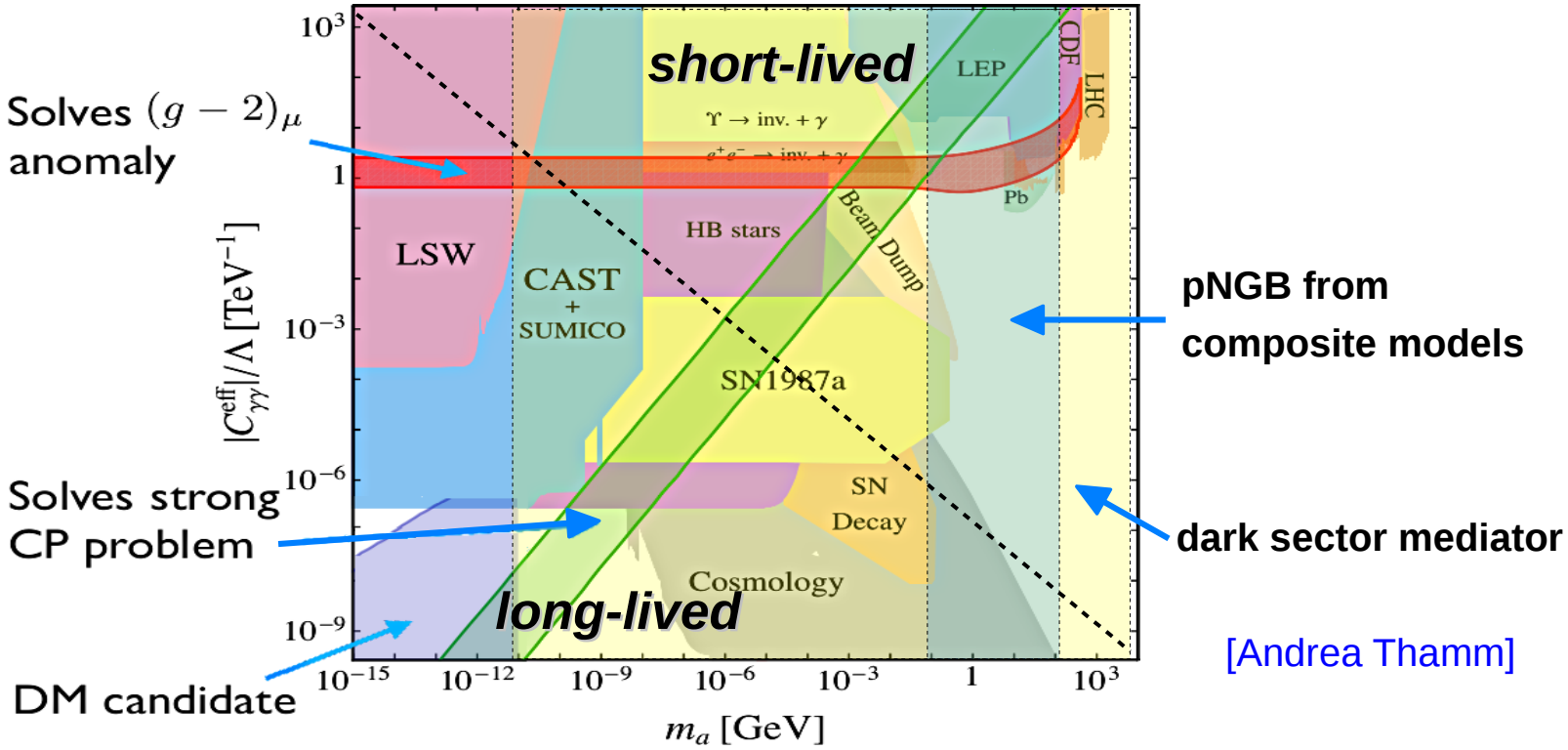
Feebly Interacting Particles (FIPs) Workshop
CERN, 3th Sept. 2020

David d'Enterria (CERN)

Axion-like particles (ALPs) motivations

- Elementary pseudoscalar suggested in many SM extensions:
  - (1) Solve strong CP problem (with explicit m_a vs. SM-couplings proportionality).
  - (2) Dark Matter candidate (for stable very light m_a), or dark sector mediator.
  - (3) Pseudo Nambu-Goldstone boson of new spontaneously broken global symmetries (π^0-like) in high-energy SM extensions (for m_a~GeV).
  - (4) Solve (g-2)μ problem (over narrow SM coupling range):





ALPs searches at the LHC

- Elementary pseudoscalar suggested in many SM extensions:

  (1) Dominant coupling to pairs of EW gauge bosons (γ, Z), Higgs (H). Also g,...

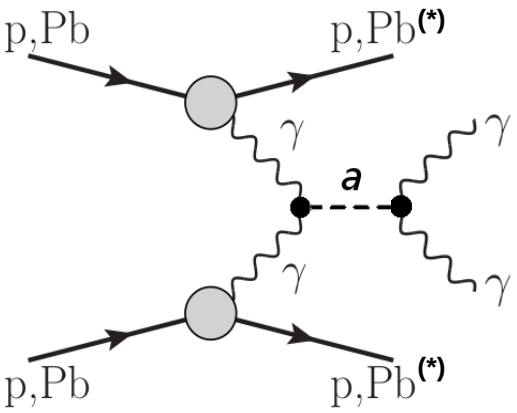
  (2) If long-lived (usually for m_a<1 GeV): MET in LHC detector.

  (3) If short-lived (usually for m_a > 1 GeV): Decay inside LHC detector volume.

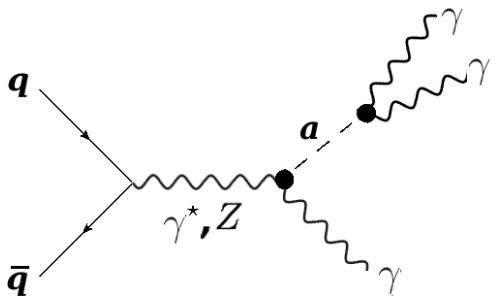
  (4) Standard LHC searches for m_a > 5 GeV in di-, tri, 4-photon final states:

  Exclusive diphotons, inclusive $\gamma\gamma$ resonances, and exotic Z or Higgs decays:

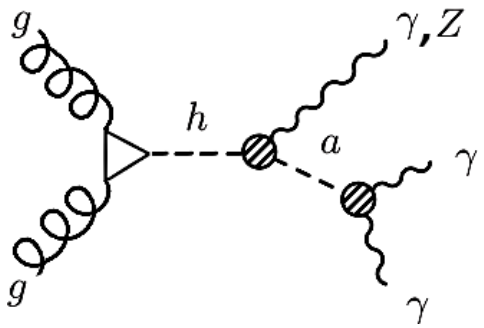
pp,PbPb → $\gamma\gamma$ → a($\gamma\gamma$)



pp → Z → a($\gamma\gamma$)+γ

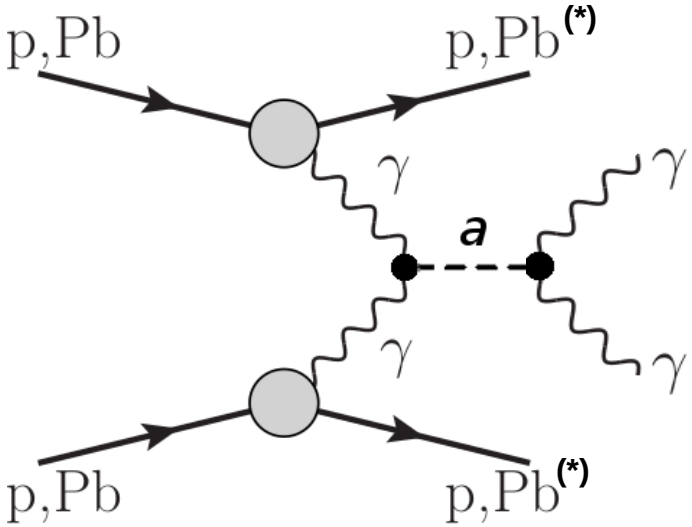


pp → H → a($\gamma\gamma$)+Z,γ
pp → H → a($\gamma\gamma$)+a($\gamma\gamma$)



- NB: *Many ALP bounds not directly extracted by LHC experiment themselves (but by subsequent pheno recasts of generic 2γ, 3γ, 4γ resonance searches).*

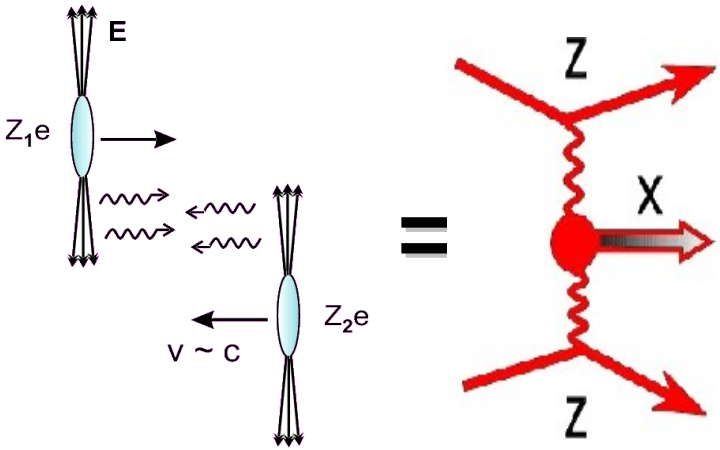
(1) ALP bounds from exclusive $\gamma\gamma$ at the LHC

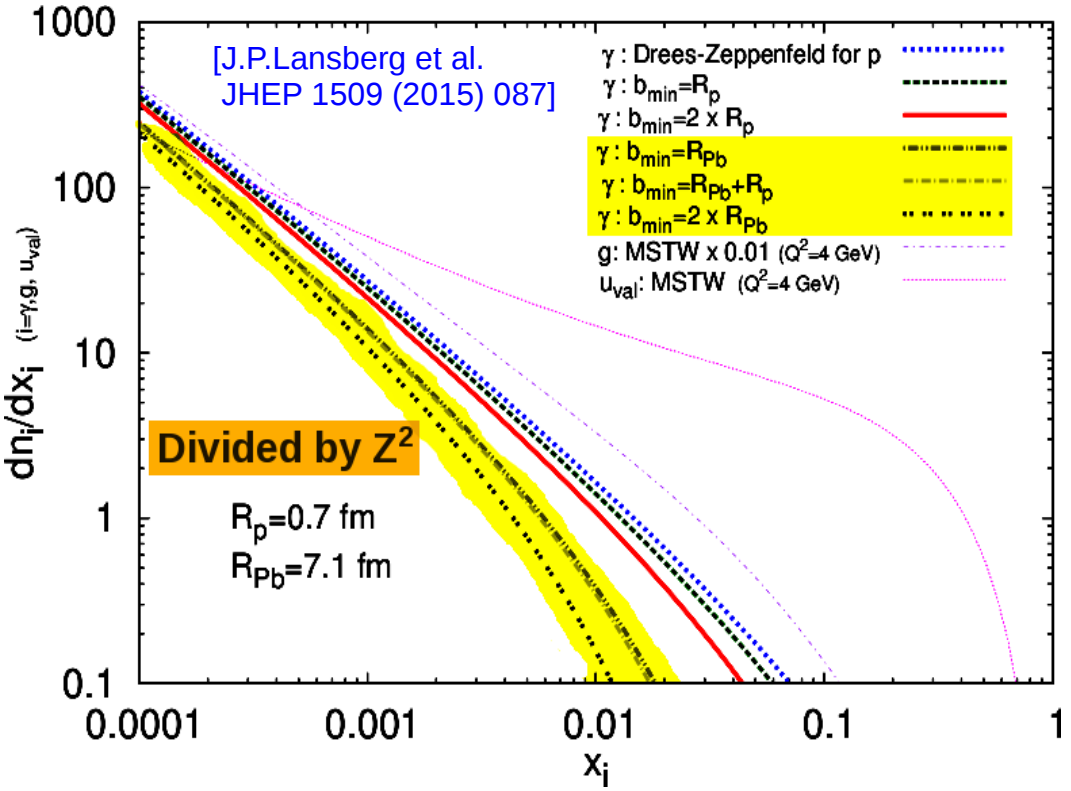


ALPs via exclusive γ-γ collisions at the LHC

- 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:

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





- Quasi-real photons (coherence): Q ~ 1/R ~ 0.06 GeV (Pb), 0.3 GeV (p)
- Maximum γ energies (LHC): $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 80 GeV (Pb), ~ 2.5 TeV (p)

ALPs via exclusive γ-γ collisions at the LHC

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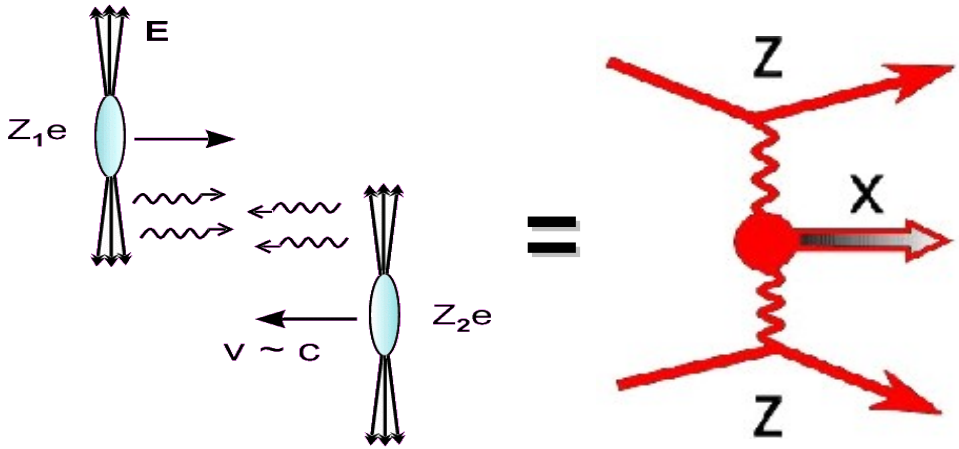


- Huge photon fluxes:
  $\sigma(\gamma\gamma) \sim Z^4$ (~$5 \cdot 10^7$ for PbPb)
  larger than p,$e^{\pm}$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

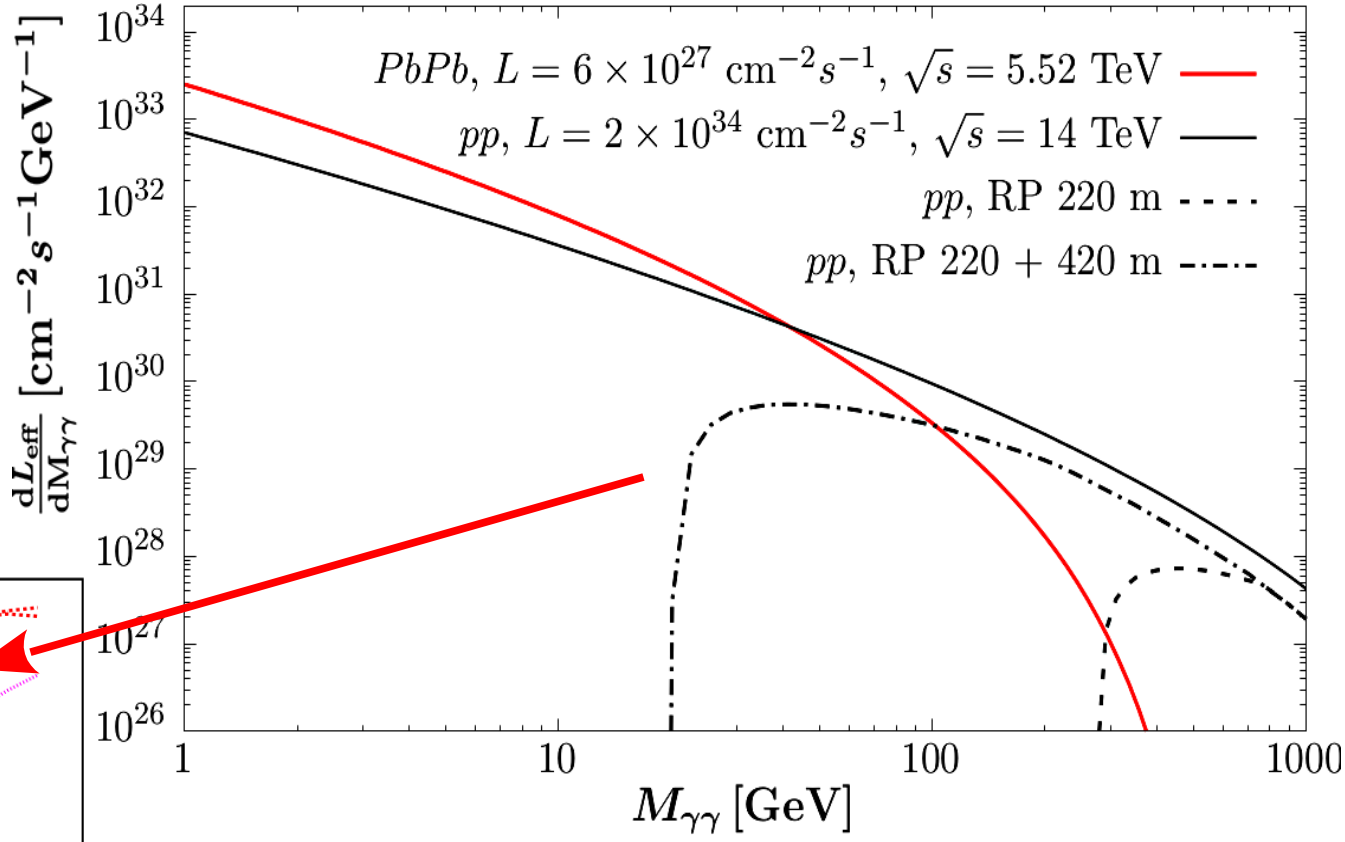
- Quasi-real photons (coherence): Q ~ 1/R ~ 0.06 GeV (Pb), 0.3 GeV (p)
- Maximum γ energies (LHC): $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ~ 80 GeV (Pb), ~ 2.5 TeV (p)

System	$\sqrt{s_{NN}}$ (TeV)	γ	R_A (fm)	ω_{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

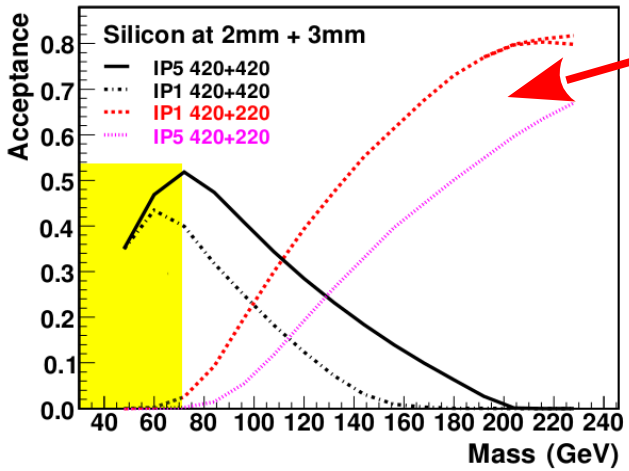
[Dd'E, G. Silveira, PRL 111 (2013) 080405]

Effective γ-γ luminosities at the LHC

- Thanks to $Z^4 \sim 5 \cdot 10^7$ factor, PbPb γ-γ luminosities are well above pp ones up to $W_{\gamma\gamma}$~300 (100) GeV, assuming fwd. proton-taggers at 220 (420) m required to remove huge p-p pileup(!).



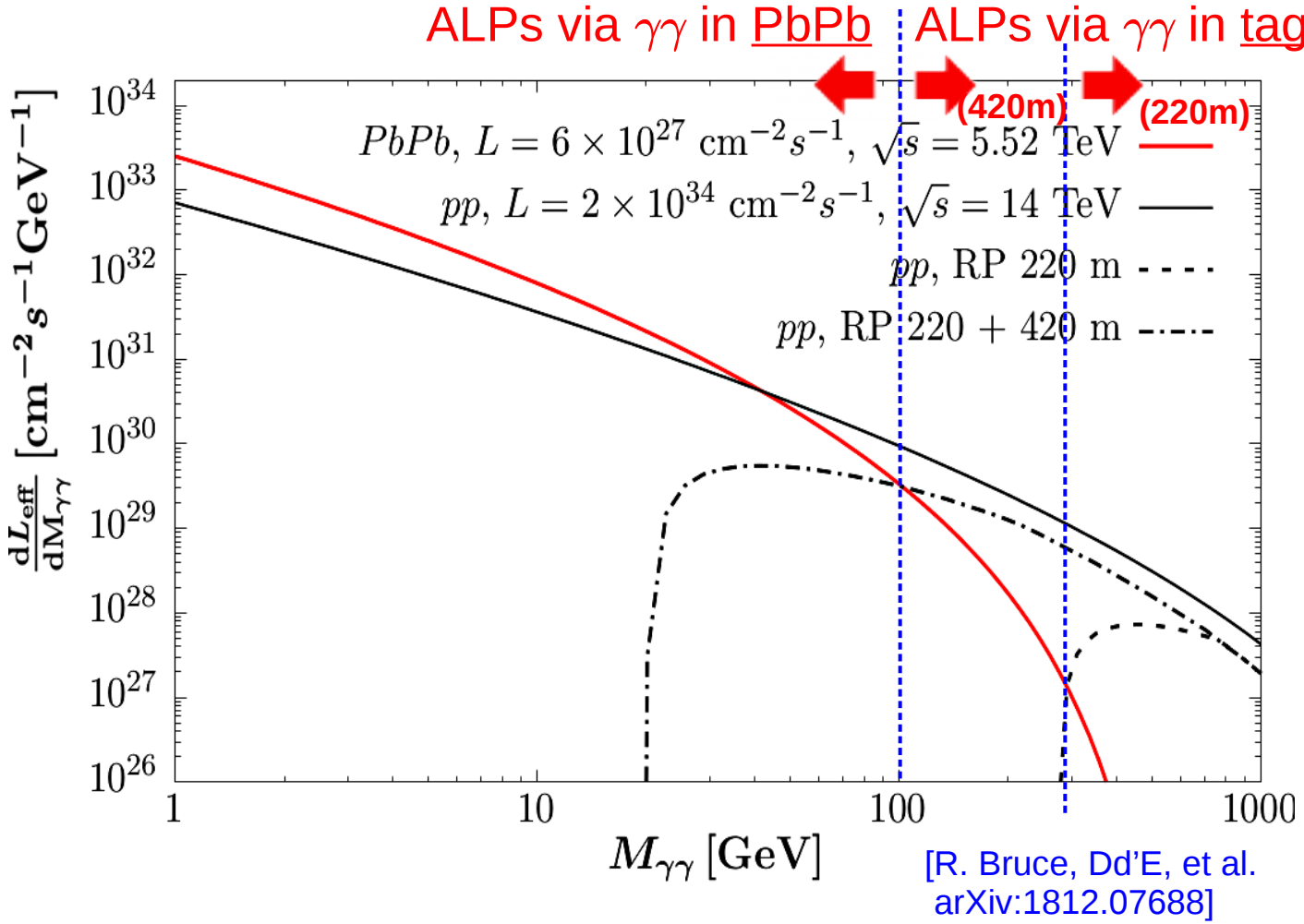
- Fwd-p acceptance vs. central mass:



[R. Bruce, Dd'E, et al. arXiv:1812.07688]

Effective γ-γ luminosities at the LHC

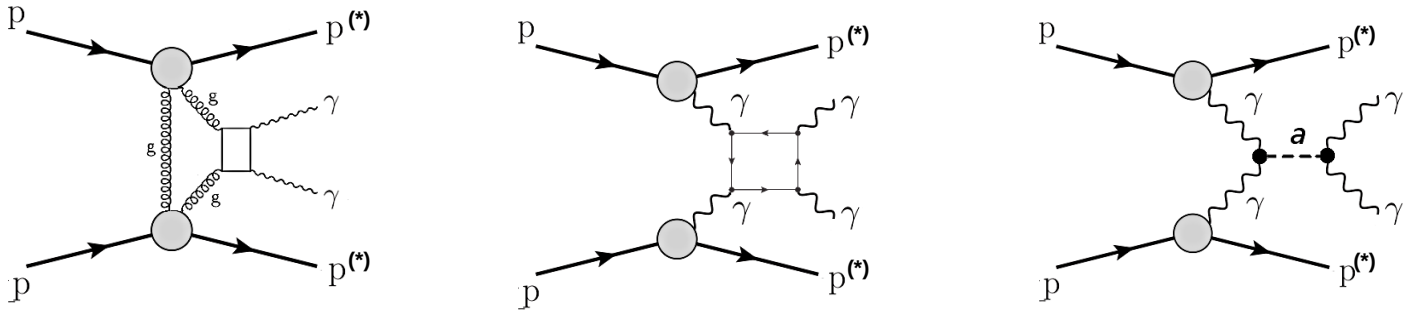
- Competitive mass range for ALPs (generic BSM) searches in UPCs PbPb:
  $W_{\gamma\gamma}$ ~ 1–100 GeV ($W_{\gamma\gamma}^{min}$~0.5 GeV for ALICE/LHCb, ~4 GeV for ATLAS/CMS)



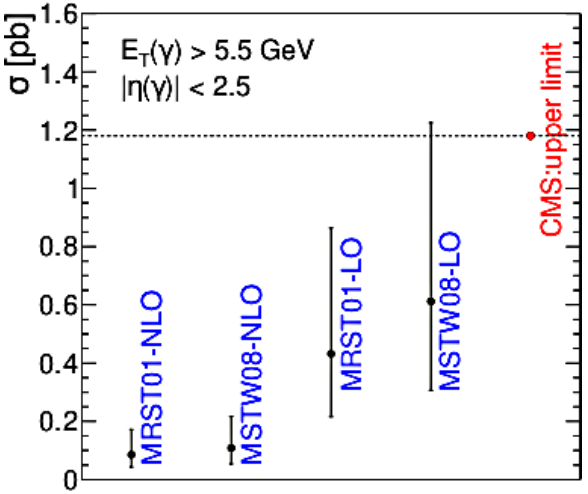
[R. Bruce, Dd'E, et al. arXiv:1812.07688]

Low-mass pp → p $\gamma\gamma$ p search (7 TeV)

- First exclusive diphoton search at the LHC (CMS, pp 7 TeV, 36 pb^{-1}):
  - 2 photons (E_T>2.5 GeV, $|\eta|$<2.5) with no hadronic activity over $|\eta|$<5.2
  - Sensitive to central-exclusive (CEP), light-by-light (LbL), and ALPs production:



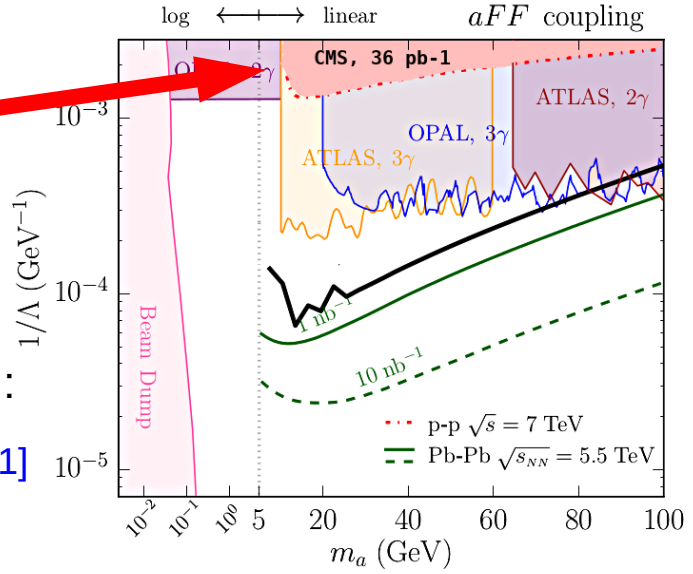
  - NO event found. Upper CEP/LbL/ALP x-section: σ(pp → pγγp)>1.18 pb (95% C.L.)



[**CMS**, JHEP 11 (2012) 080]

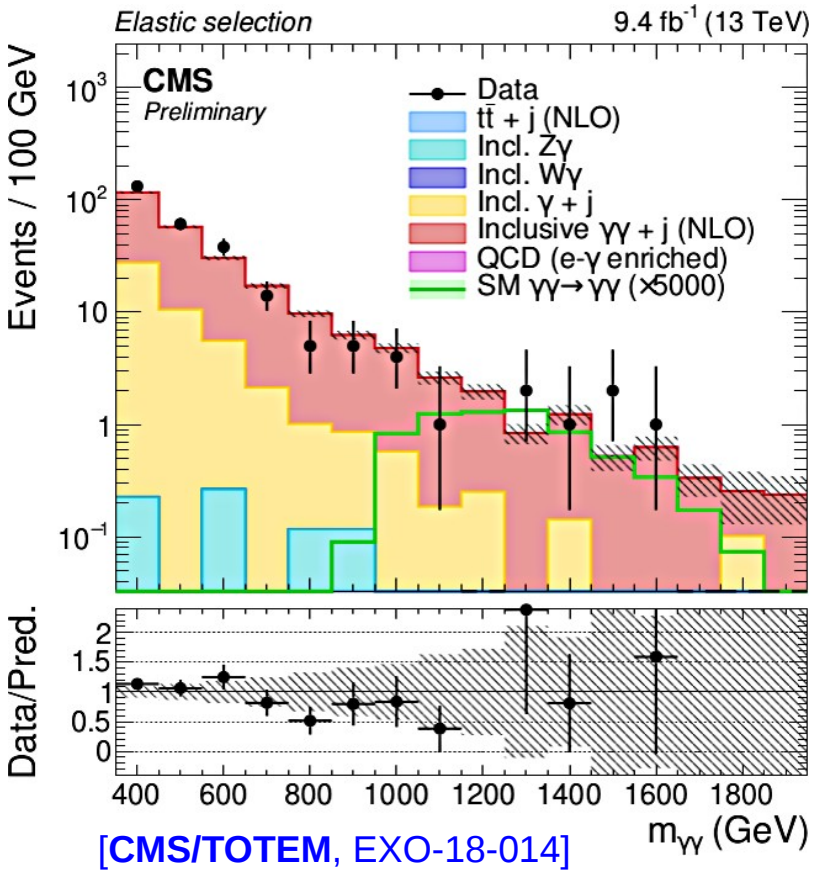
Recast into 1st ALP limit at LHC by S. Knapen et al.:

[PRL 118 (2017) 171801]



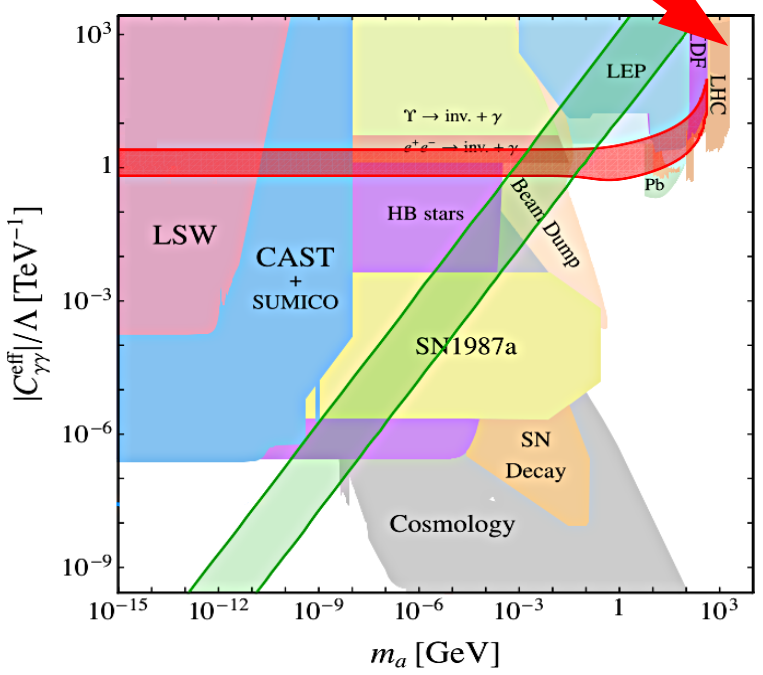
High-mass pp → p γγ p search (13 TeV)

- Exclusive diphoton search with fwd proton tagging (CT-PPS, 9.4 fb^{-1}):
  - 2 photons (E_T>75 GeV, $|\eta|$<2.5) with $m_{\gamma\gamma}$> 350 GeV, and low acoplanarity
  - Pileup removal: Kinematic matching between $m_{\gamma\gamma}$ & m_{pp} and $y_{\gamma\gamma}$ & y_{pp}
- NO excess found. Upper limit on fid. x-section σ(pp → pγγp) > 3.0 fb (95% C.L.)
  (limits set on anomalous quartic 4-γ couplings)



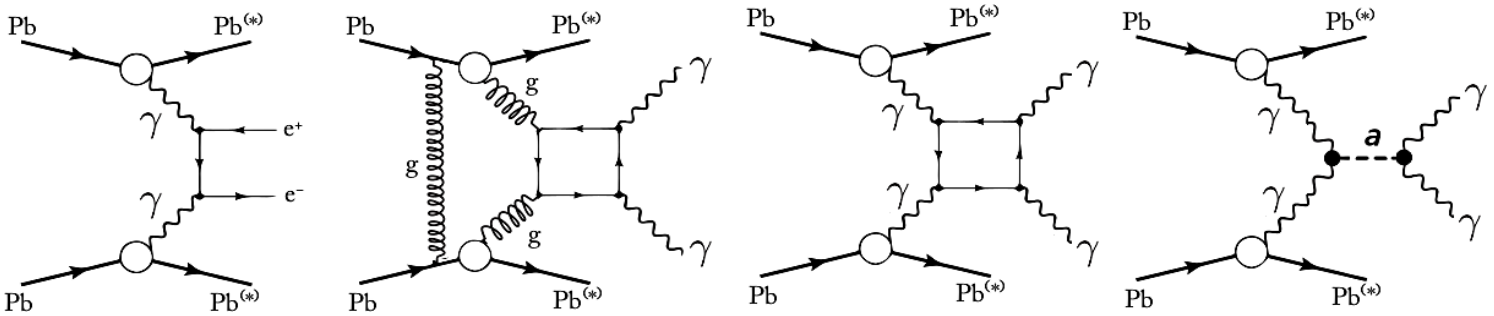
[**CMS/TOTEM**, EXO-18-014]

Result to be recast into ALP bounds in the m_a = 0.4–2 TeV range

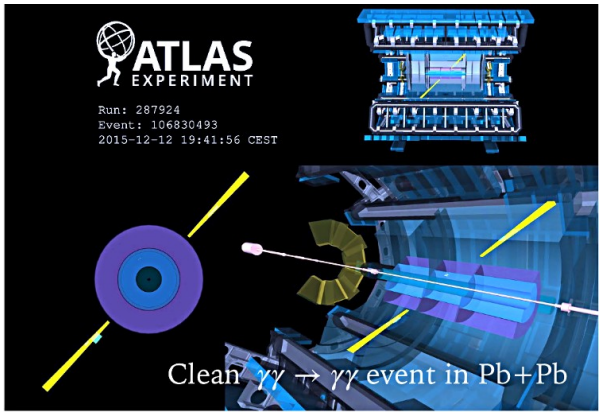


Evidence for $\gamma\gamma \to \gamma\gamma$ (PbPb, 5 TeV)

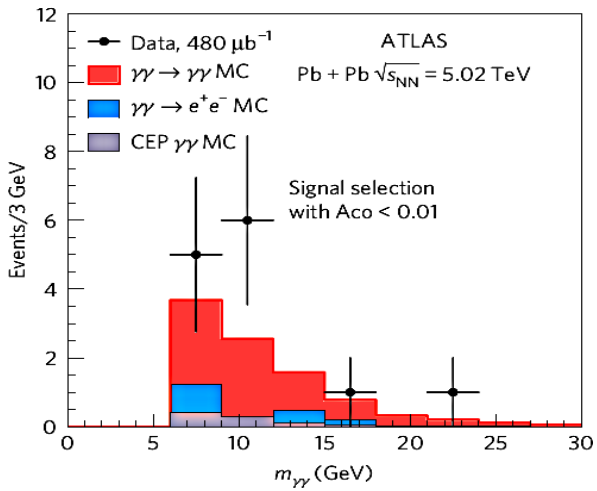
- First evidences for exclusive diphoton in PbPb colls at 5 TeV (~0.5 nb^{-1}):
  - 2 photons (E_T>2–3 GeV, $|\eta|$<2.5, $m_{\gamma\gamma}$>5 GeV) with no hadronic activity over $|\eta|$<5
  - Photon pair: p_T<1 GeV, acoplanarity $A\varphi$ < 0.03–0.01 (coherent quasireal γ's with p_T~0)
  - Sensitive to LbL and ALPs production. Backgrounds: QED e^+e^- and CEP.

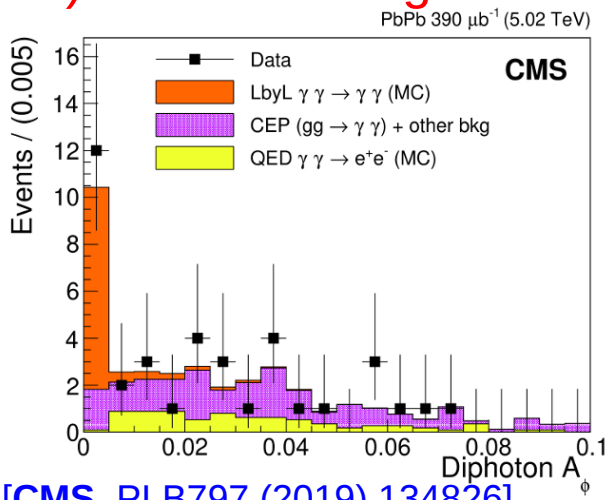


- ATLAS, CMS measure 13, 14 exclusive $\gamma\gamma$ counts (on top of 2.6, 3.8 backgds.) consistent (4.3σ, 4.1σ) with the (very-rare) LbL scattering:



[**ATLAS**, Nat.Phys. 13 (2017) 852]

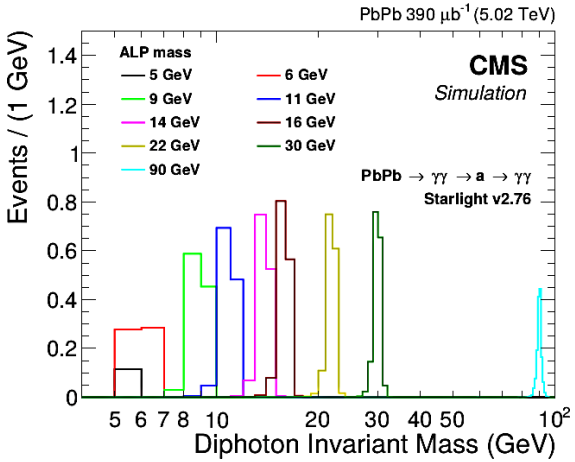




[**CMS**, PLB797 (2019) 134826]

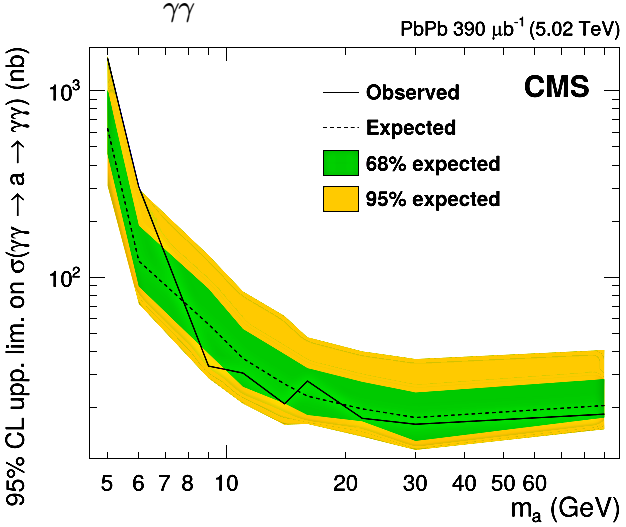
First ALPs limits via $\gamma\gamma \to a \to \gamma\gamma$ (PbPb, 5 TeV)

- Injected ALP signals, with BR($a \to \gamma\gamma$) = 100%, on CMS $m_{\gamma\gamma}$ distribution:

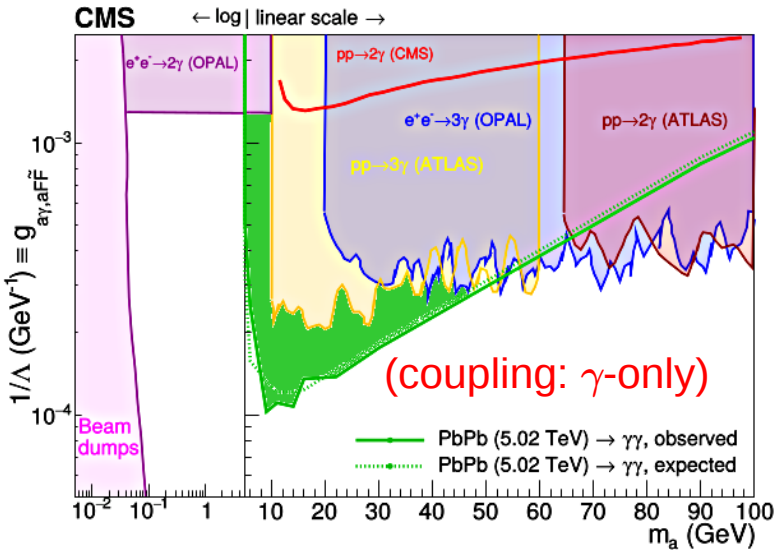


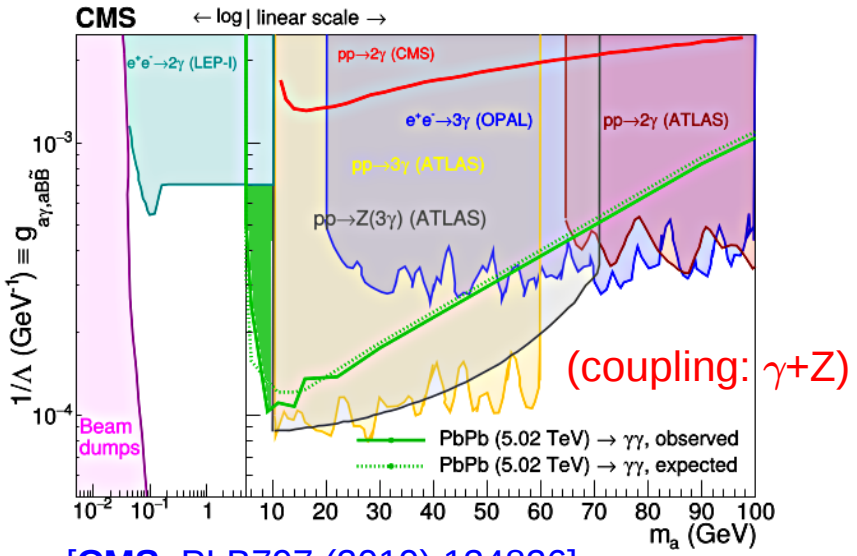
No significant excess observed:

$\sigma(\gamma\gamma \to a \to \gamma\gamma) >$ 20–100 nb excluded (95% C.L.)



- Most competitive ALPs bounds over m_a = 5–50 GeV:

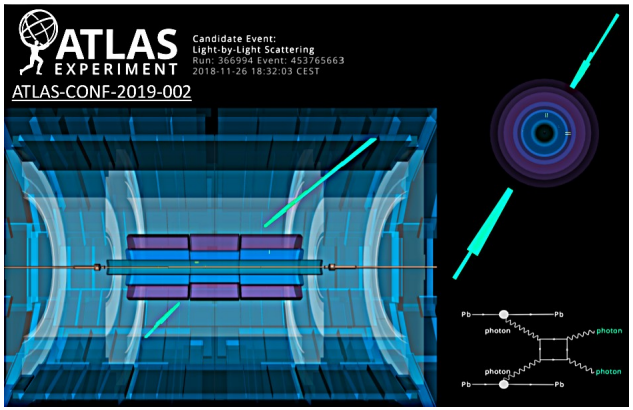




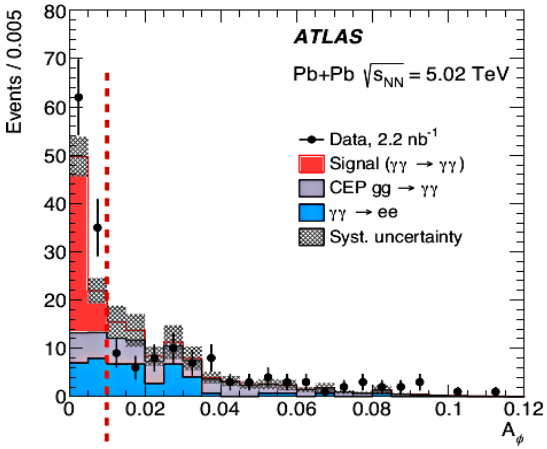
[**CMS**, PLB797 (2019) 134826]

Observation of $\gamma\gamma \rightarrow \gamma\gamma$ (PbPb, 5 TeV)

- Observation of light-by-light scattering in PbPb colls at 5 TeV (2.2 nb^{-1}):
  - 2 photons (E_T>2.5 GeV, $|\eta|$<2.4, $m_{\gamma\gamma}$>5 GeV) with no hadronic activity over $|\eta|$<5
  - Photon pair: p_T<1 GeV, Acoplanarity cut: $A\varphi$ < 0.01 to remove backgds.



[**ATLAS**, PRL123 (2019) 052001]



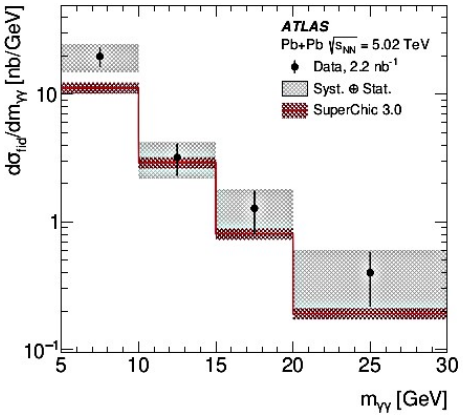
Observed: 97 evts
Expected: 45 signal
+ 27 backgd.

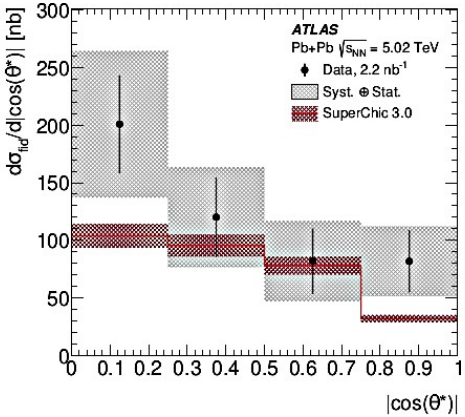
- Combination of ATLAS (2015+2018) data, compared to LbL prediction:

– LbL observation: Signif. = 8.8σ

– Fiduc. x-section $\sigma(\gamma\gamma \rightarrow \gamma\gamma)$ = 120±22 nb is ~1.5 higher than theory (80±8 nb). Shape of differential distributions consistent with MC within uncertainties

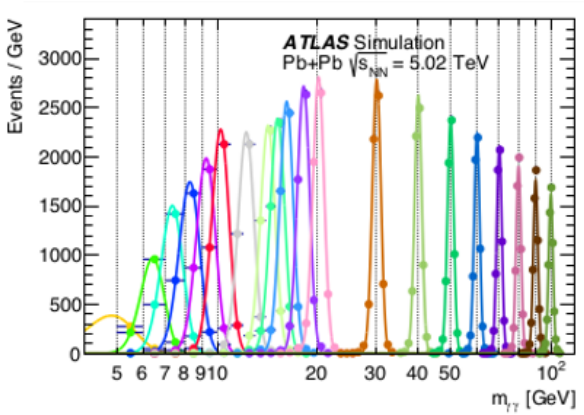
[**ATLAS**, arXiv:2008.05355]

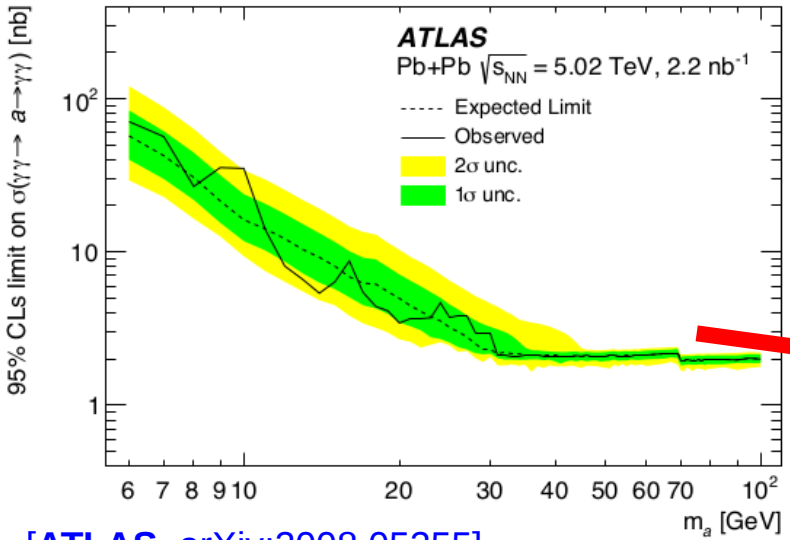


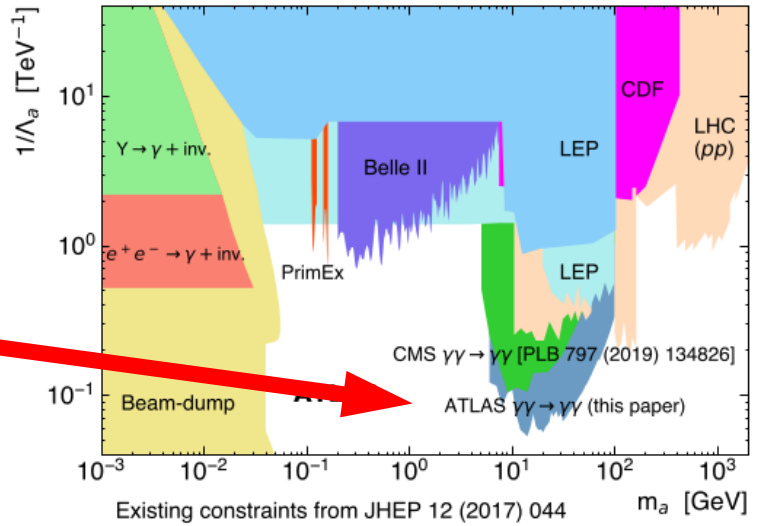


ALPs limits via $\gamma\gamma \to a \to \gamma\gamma$ (PbPb, 5 TeV)

- Recasting exclusive $\gamma\gamma$ measurement as ALP search on top of LbL continuum:
  - ALP signal produced using STARlight for various m_a
  - Limits on $\sigma_{\gamma\gamma\to a\to\gamma\gamma}$ extracted
    - Cast into limits on $a\gamma\gamma$ coupling ($1/\Lambda_a$) assuming BR($a\to\gamma\gamma$)=1
    - Reco effic.: ~20% (6 GeV), ~45% (>40 GeV). ALP width dominated by exp. resolution.







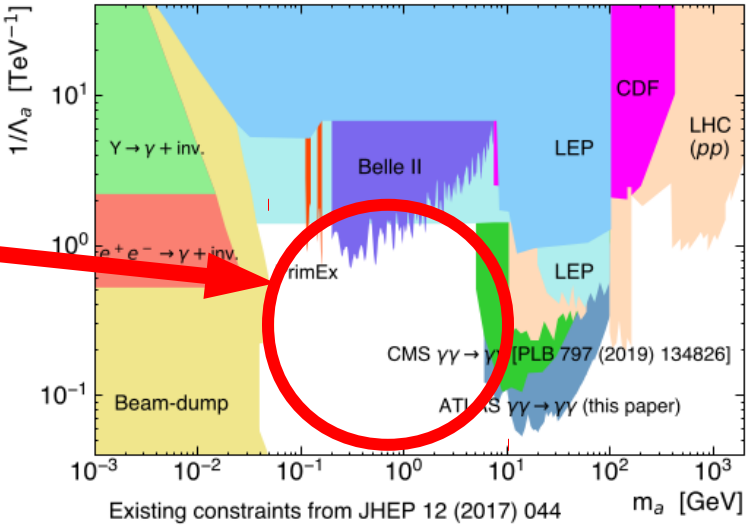
[**ATLAS**, arXiv:2008.05355]

- Most stringent limits to date on ALPs over m_a = 6–100 GeV
- $\sigma(\gamma\gamma\to a\to\gamma\gamma)$ > 2–70 nb excluded at 95% C.L. over that mass interval.

O(1 GeV) ALPs via $\gamma\gamma \to a \to \gamma\gamma$ (PbPb, 5 TeV)?

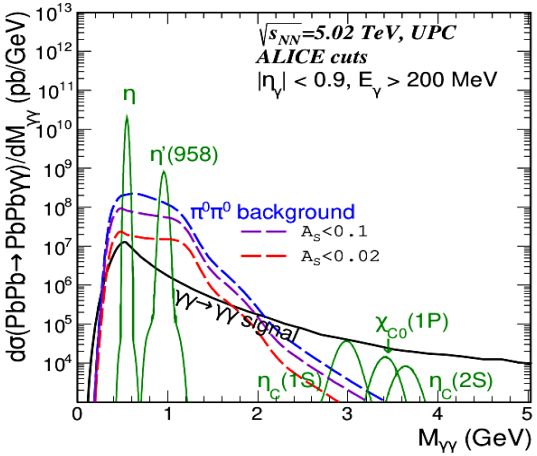
- Wide window of unexplored parameter space m_a = 0.1–5 GeV between bounds from Belle-II, beam-dumps, and CMS/ATLAS:

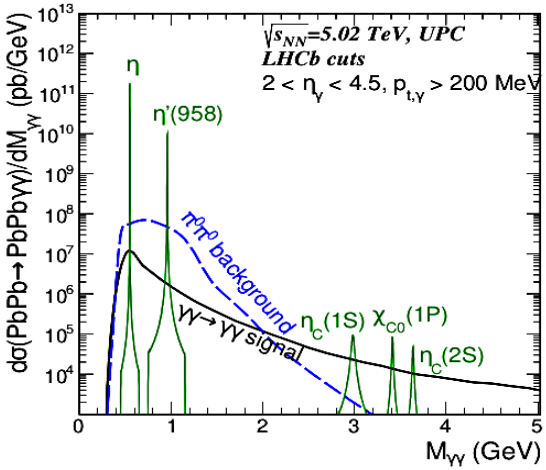
  Too low-p_T photons for trigger/ reconstruction in ATLAS/CMS...



- Possible measurement in PbPb UPCs below $m_{\gamma\gamma}$ = 5 GeV by ALICE/LHCb? (via direct low-p_T γ reco or $\gamma \to e^+e^-$ conversion)?

[M. Kłusek-Gawenda et al. PRD99 (2019) 093013]

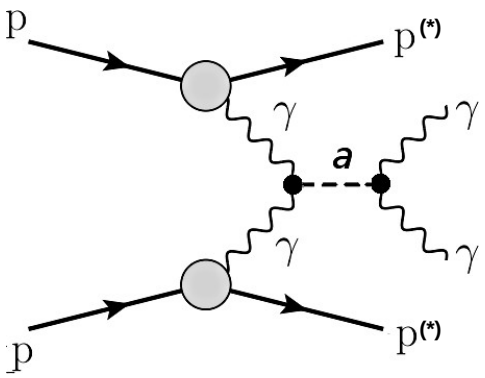


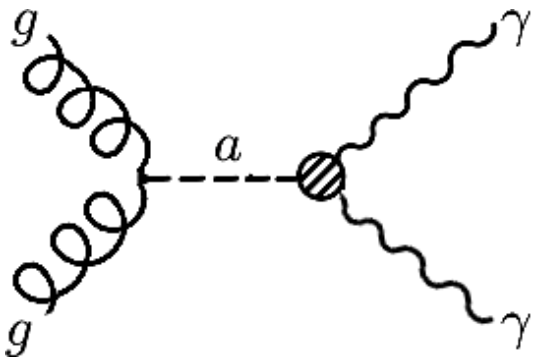


Pheno analysis. Should be redone with full detector response sim. by ALICE/LHCb experiments...

- Challenges: (i) $m_{\gamma\gamma}$ resolution, (ii) spin-0,-2 hadron decay backgrounds,...

(2) ALP bounds from inclusive $\gamma\gamma$ at the LHC

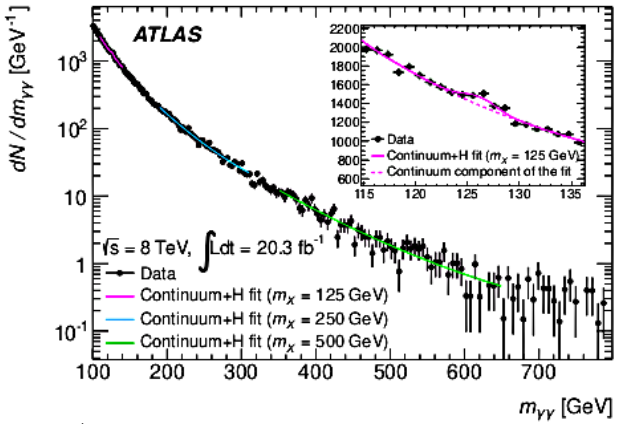


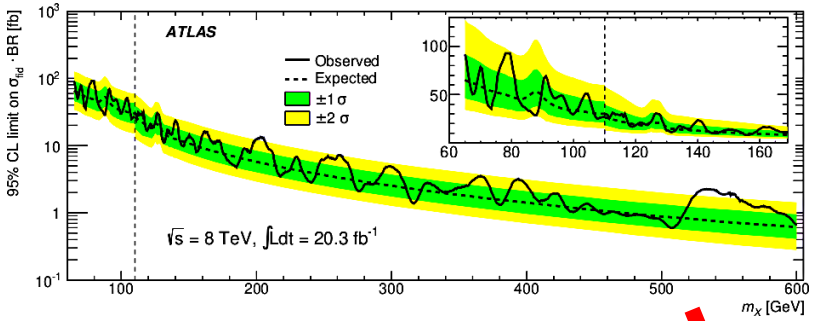


...

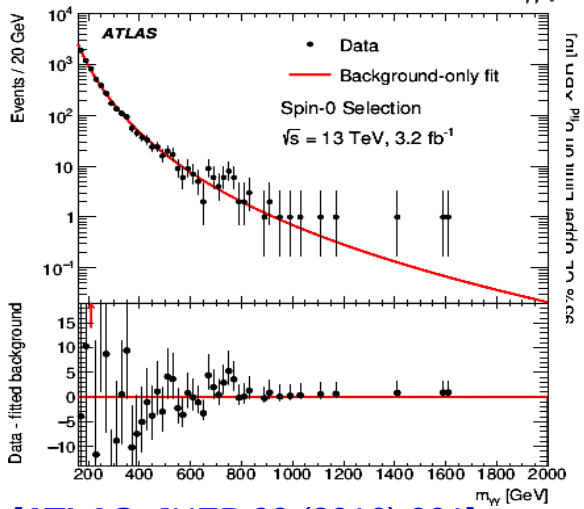
ALP bounds from pp→$X(\gamma\gamma)$+X searches (8, 13 TeV)

- Generic spin-0 (ext.-Higgs) diphoton searches over $m_{\gamma\gamma}$ = 60 GeV–2 TeV:

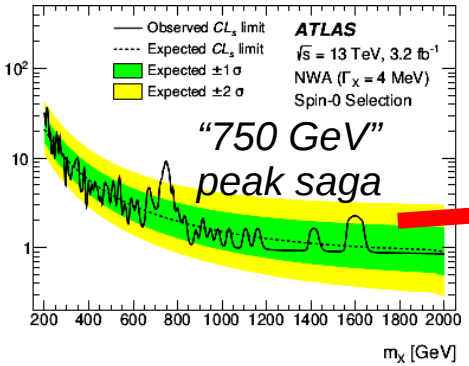




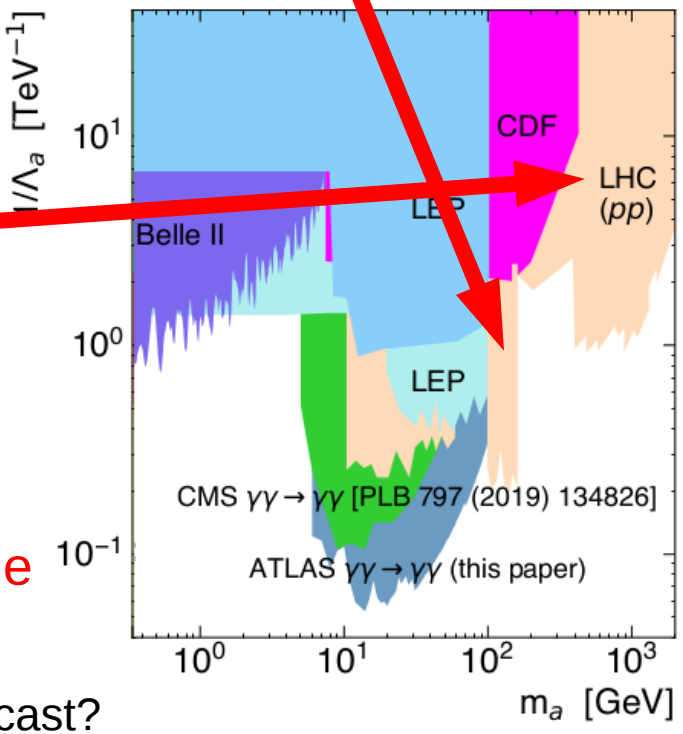
[**ATLAS**, PRL 113 (2014) 171801]



[**ATLAS**, JHEP 09 (2016) 001]



(Similar upper limit plots for varying widths Γ_X = 2-10% m_X)

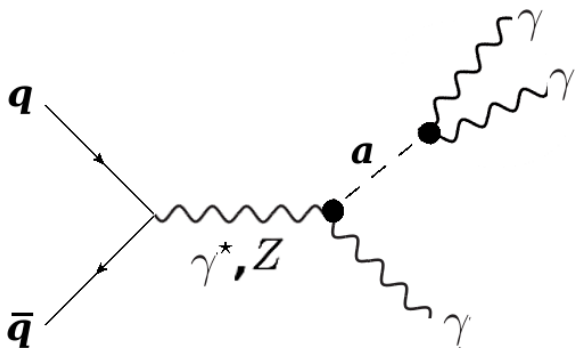


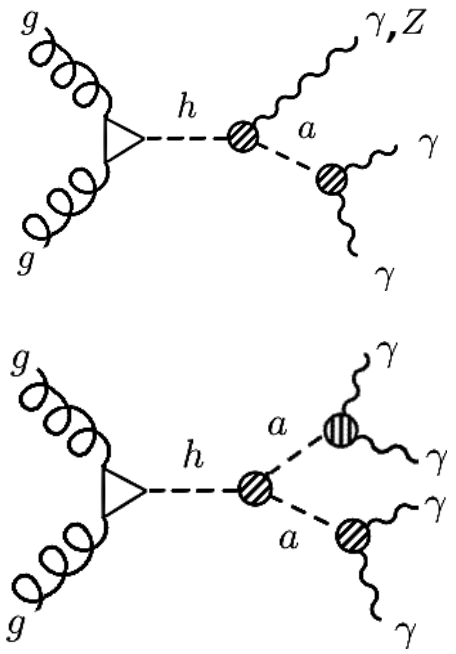
- Recast onto ALP bounds in $(m_a, g_{a\gamma\gamma})$ plane

  Best limits today over m_a = 0.1–2 TeV:

- All LHC (2γ,3γ,4γ) searches available today, recast?

(3) ALP bounds from exotic Z, H boson photon decays

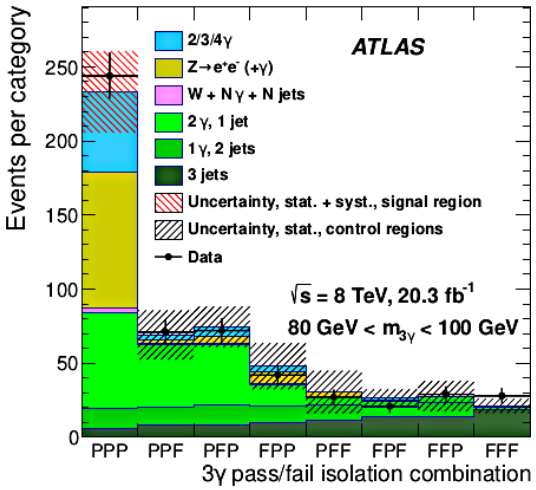


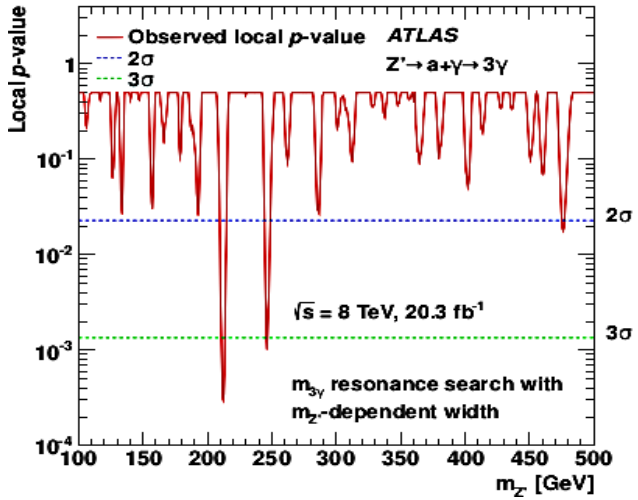


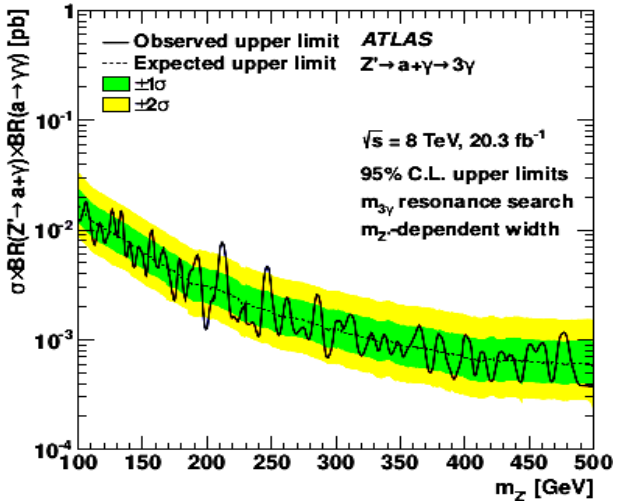
ALPs limits via $Z \to \gamma\gamma\gamma$ searches (pp, 8 TeV)

- Tri-photon resonance searches (pp, 20.3 fb^{-1}):

[**ATLAS**, EPJC76 (2016) 210]



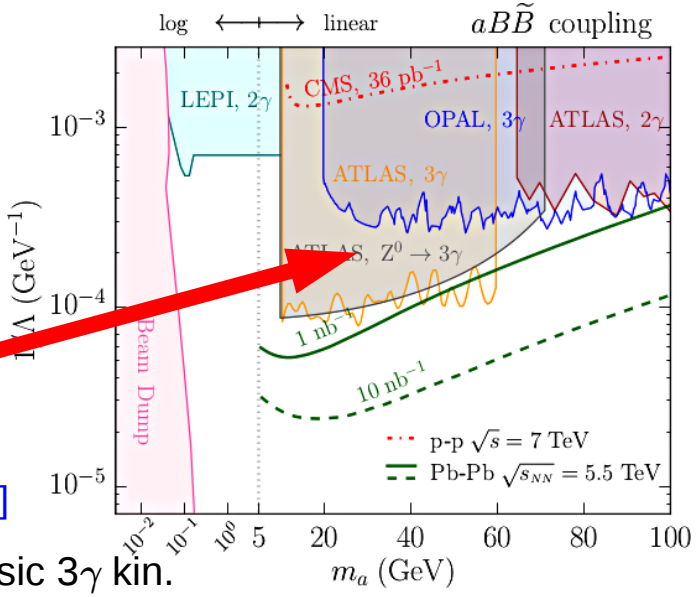




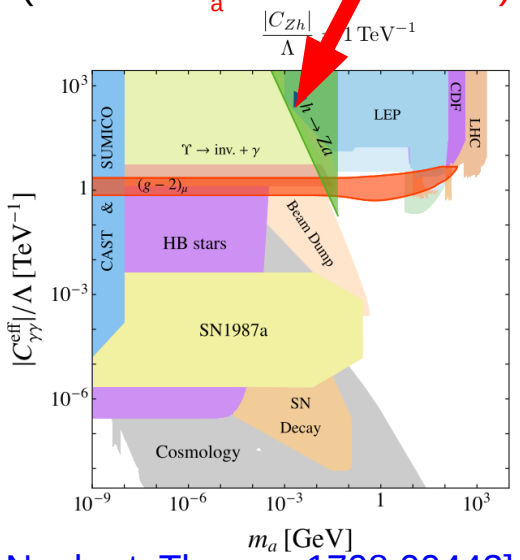
- Recast into ALP bounds with hypercharge coupling:

  Best limits (better than PbPb) for m_a = 10–60 GeV:

  [S.Knapen et al., PRL 118 (2017) 171801]



(also for m_a = 10^{-3}–0.1 GeV):

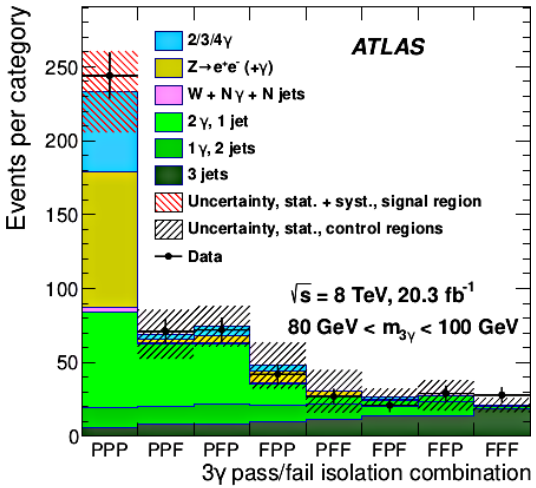


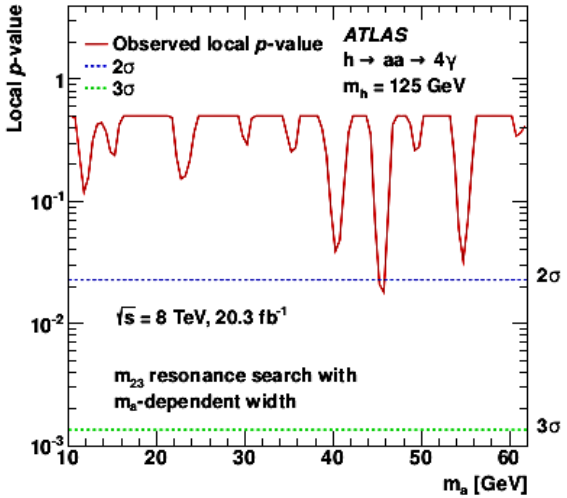
[Bauer, Neubert, Thamm: 1708.00443]

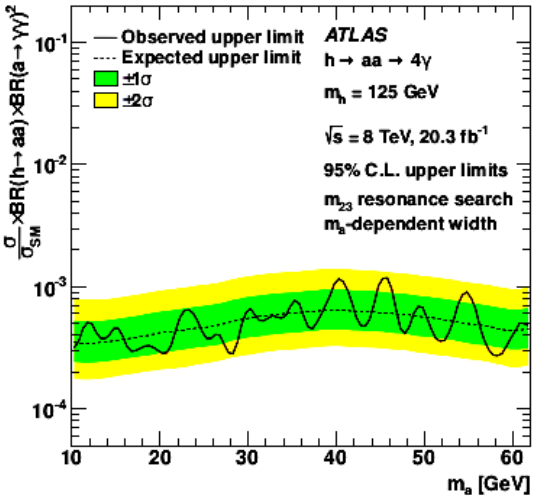
NB: Approx. bounds due to intrinsic 3γ kin. combinatorics uncertainties. Should be redone by experiment.

ALPs limits via H → Za,aa searches (pp, 8 TeV)

- Tri-, and 4-photon resonance searches (pp, 20.3 fb^{-1}): [**ATLAS**, EPJC76 (2016) 210]



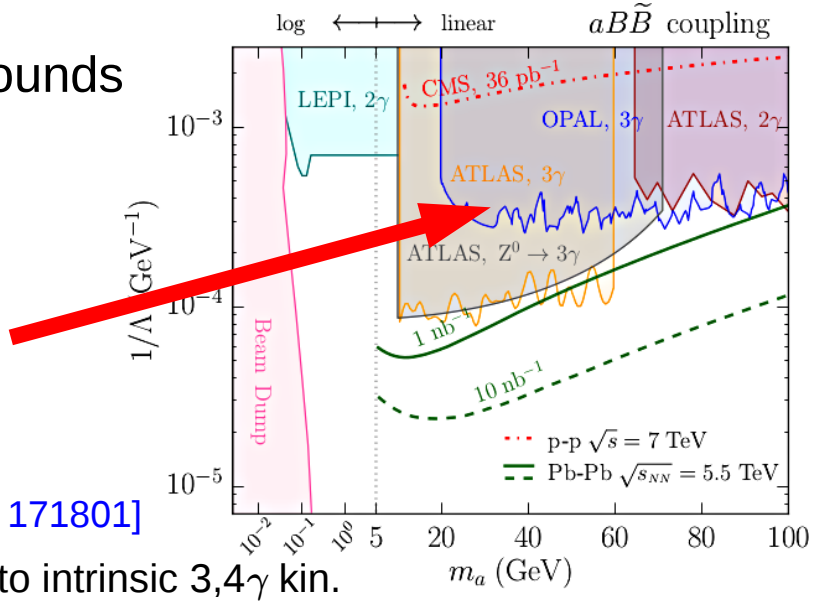




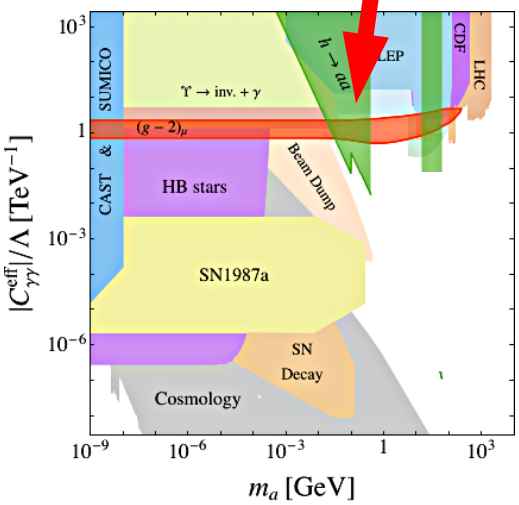
- Recast into ALP bounds with hypercharge coupling:

  Comparable limits to Z → γγγ for m_a = 10–60 GeV:

  [S.Knapen et al., PRL 118 (2017) 171801]



(also for $m_a = 10^{-2}$–1 GeV):

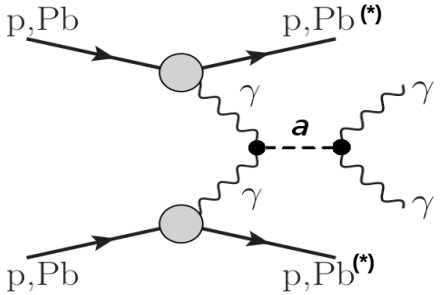


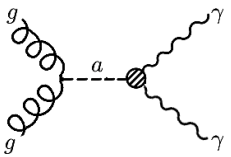
NB: Approx. bounds due to intrinsic 3,4γ kin. combinatorics uncertainties. Should be redone by experiment.

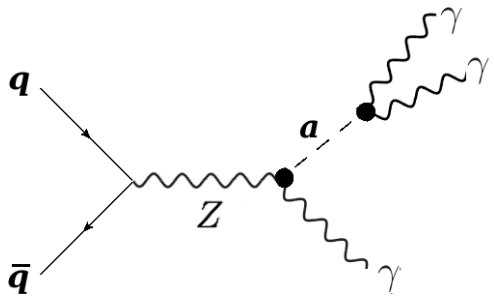
[Bauer, Neubert, Thamm: 1708.00443]

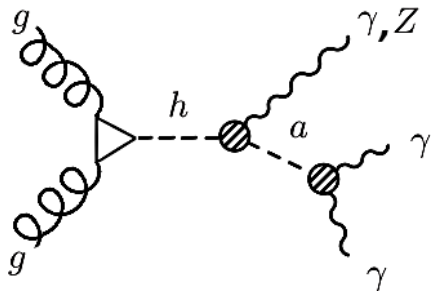
Summary of ALP searches at the LHC

- LHC provides best ALP searches over m_a = 5 GeV – 2 TeV in 2-,3-,4-γ final states:







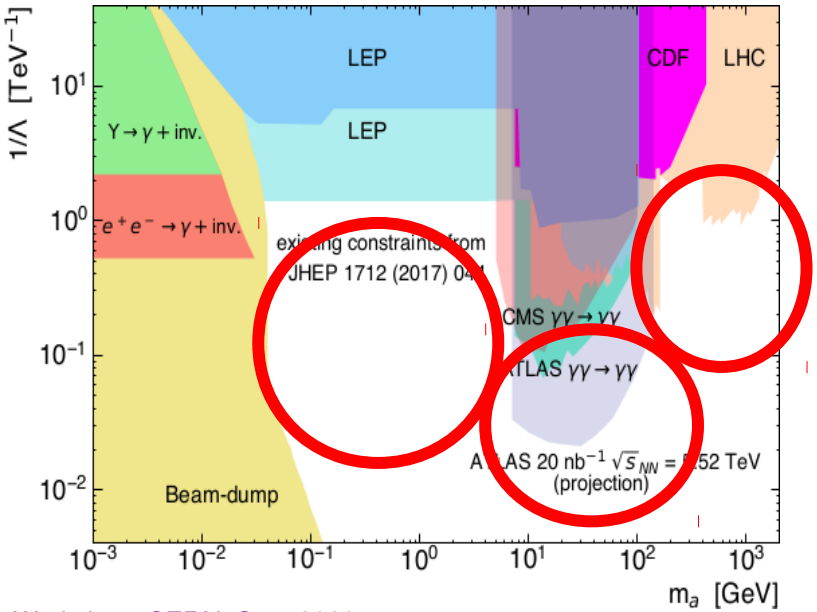


Exclusive diphotons:
Best for m_a= 5–100 GeV (PbPb)
Best for m_a > 350 GeV (pp tagging)

$Z \rightarrow \gamma\gamma\gamma$ in pp collisions:
Best for m_a= 10–100 GeV
(for hypercharge-coupled ALP)

$H \rightarrow 3\gamma, 4\gamma$ in pp collisions:
Provide extra constraints
on dim-6,-7 operators

- All current LHC (2γ,3γ,4γ) searches recast? Target space to be covered over the 2020s:



- We haven't yet observed an ALP peak in the LHC data...

but ALPs feature a monotonically rising "interest peak" over the last 10 years.

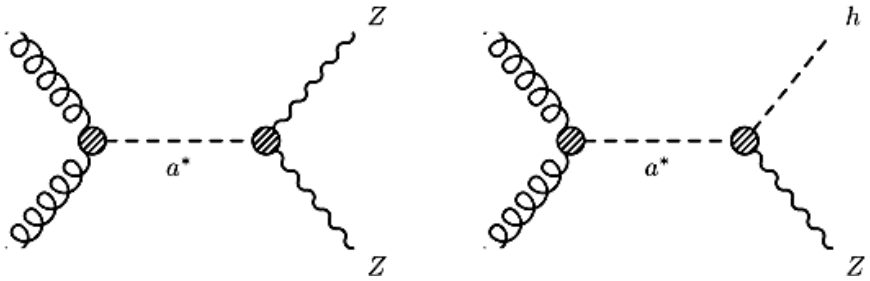
To be continued for the next 15+ yrs...

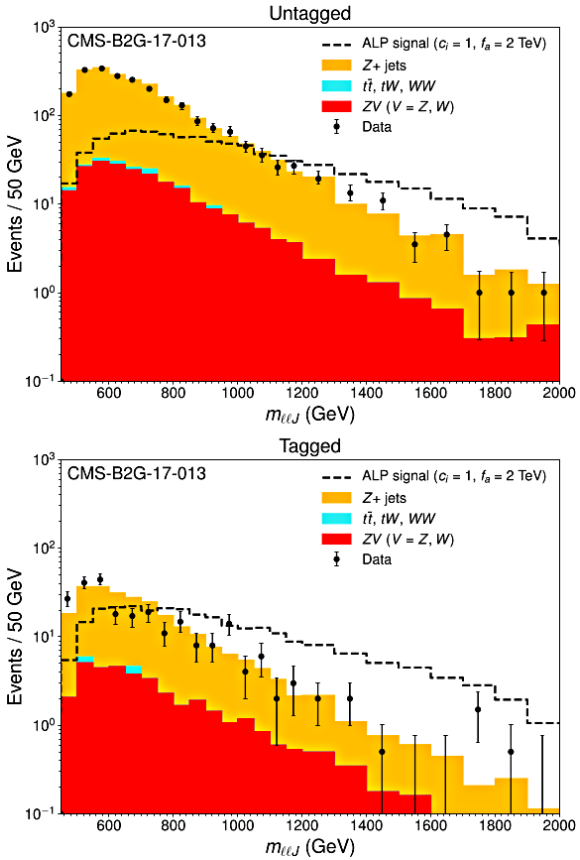
Back-up slides

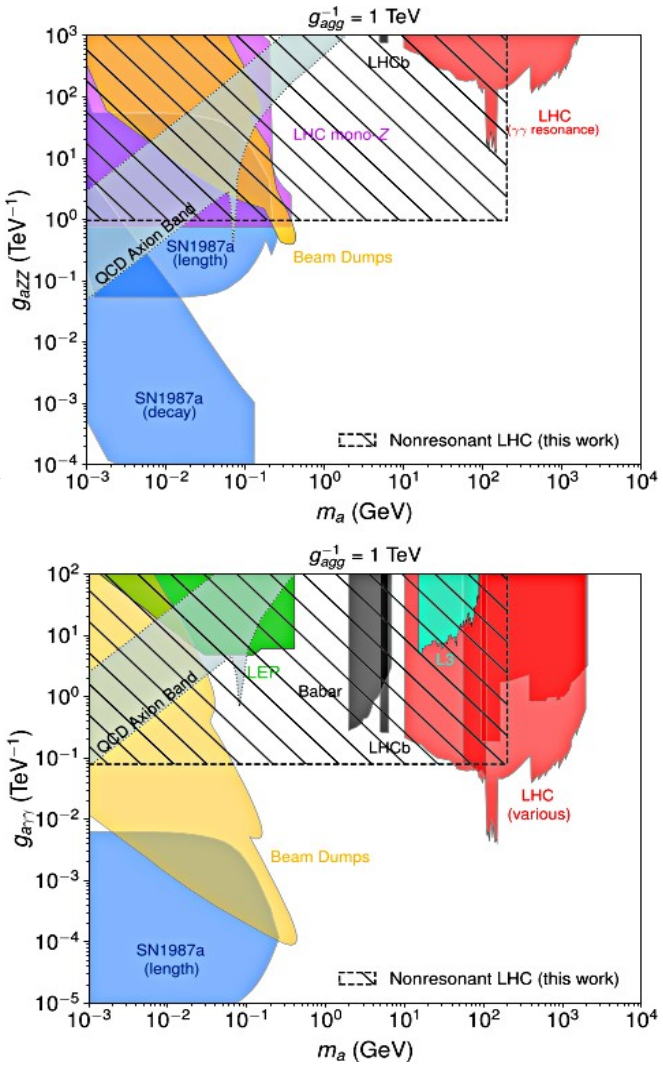
Non-resonant ALPs limits at the LHC

- LHC bounds for NON-resonant ALPs (coupling to gluons):

[M.B. Gavela et al. PRL 124 (2020)051802]

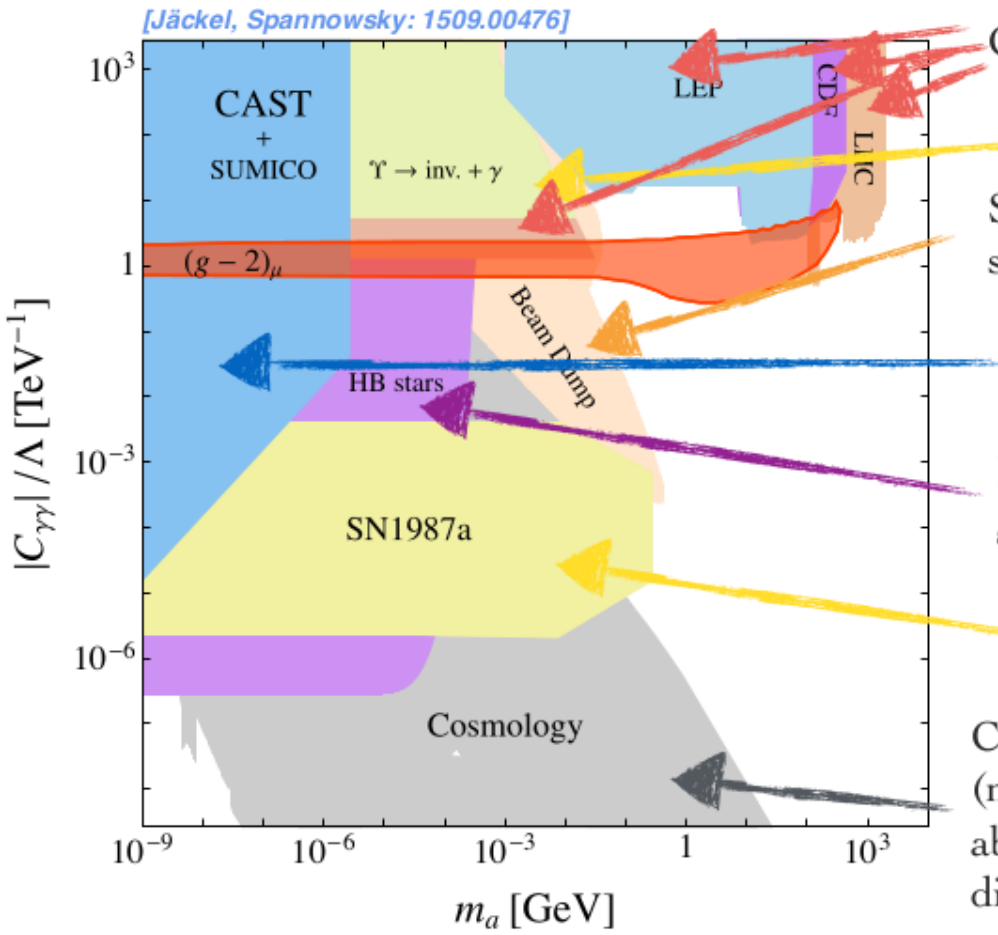






ALPs limits from non-LHC results

- Current ALPs bounds from cosmology, astrophysics, fixed-target, e^+e^- colls.:



Collider searches for $e^+e^- \to a + \gamma, 3\gamma$

CLOE and BaBar: $\Upsilon \to a + \gamma$

SLAC: measurement of photon - nuclei scattering (Primakoff effect)

Axion helioscopes: Tokyo Axion Helioscope and CERN axion solar telescope

Energy loss of stars constrained by ratio of red giant to younger stars of horizontal branch

Absence of photon burst after supernova

Combination of cosmological bounds (measurement of Neff, primordial deuterium abundance, modification to BB nucleosynthesis, distortion of CMB, diffuse photon background,…)

[Andrea Thamm]