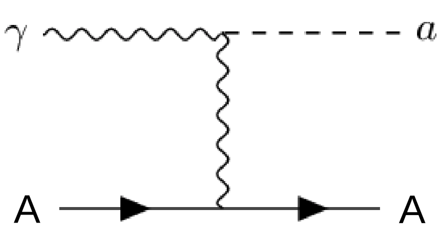
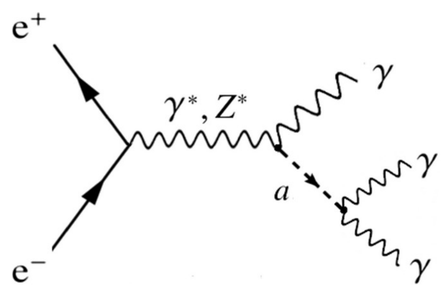
# Review of ALP searches at accelerators

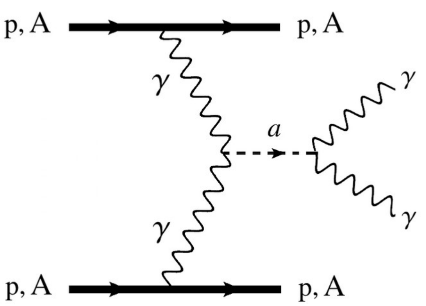
(fixed target, beam dumps)




($e^+e^-$ colliders)




(LHC)



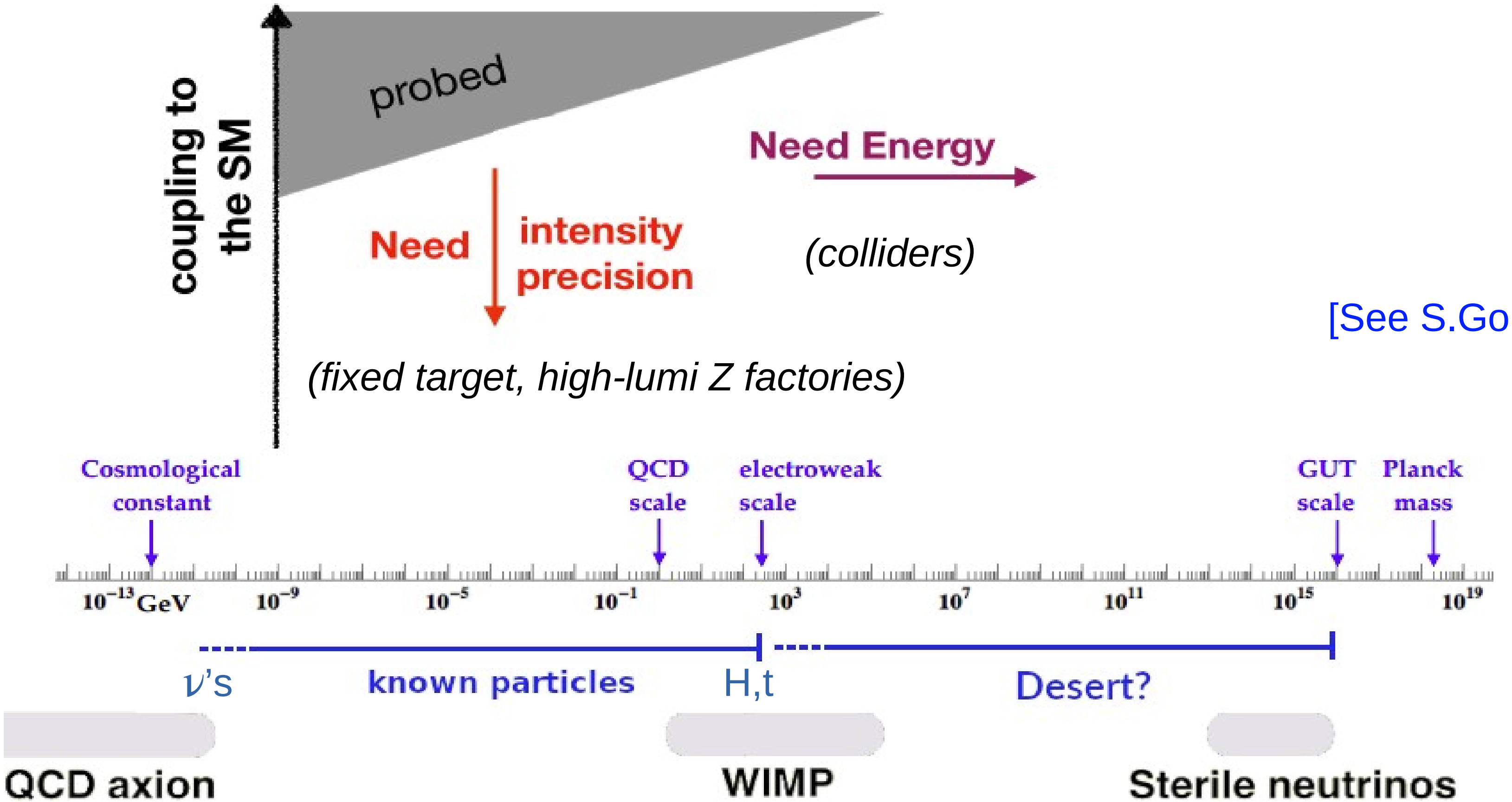

**The Axion Quest 2024 Conference**

**Qhy Nhon, 6th Aug. 2024**


**David d'Enterria (CERN)**

# Searches for new physics at accelerators

- The SM is an incomplete theory with many unsolved issues: dark matter, matter-antimatter asymm., neutrino masses, EW-Planck hierarchy, strong CP,...
- Current (future) experiments probe NP scales below 10 (100) TeV
- Unknown BSM energy scale => Broad search: high masses, low couplings

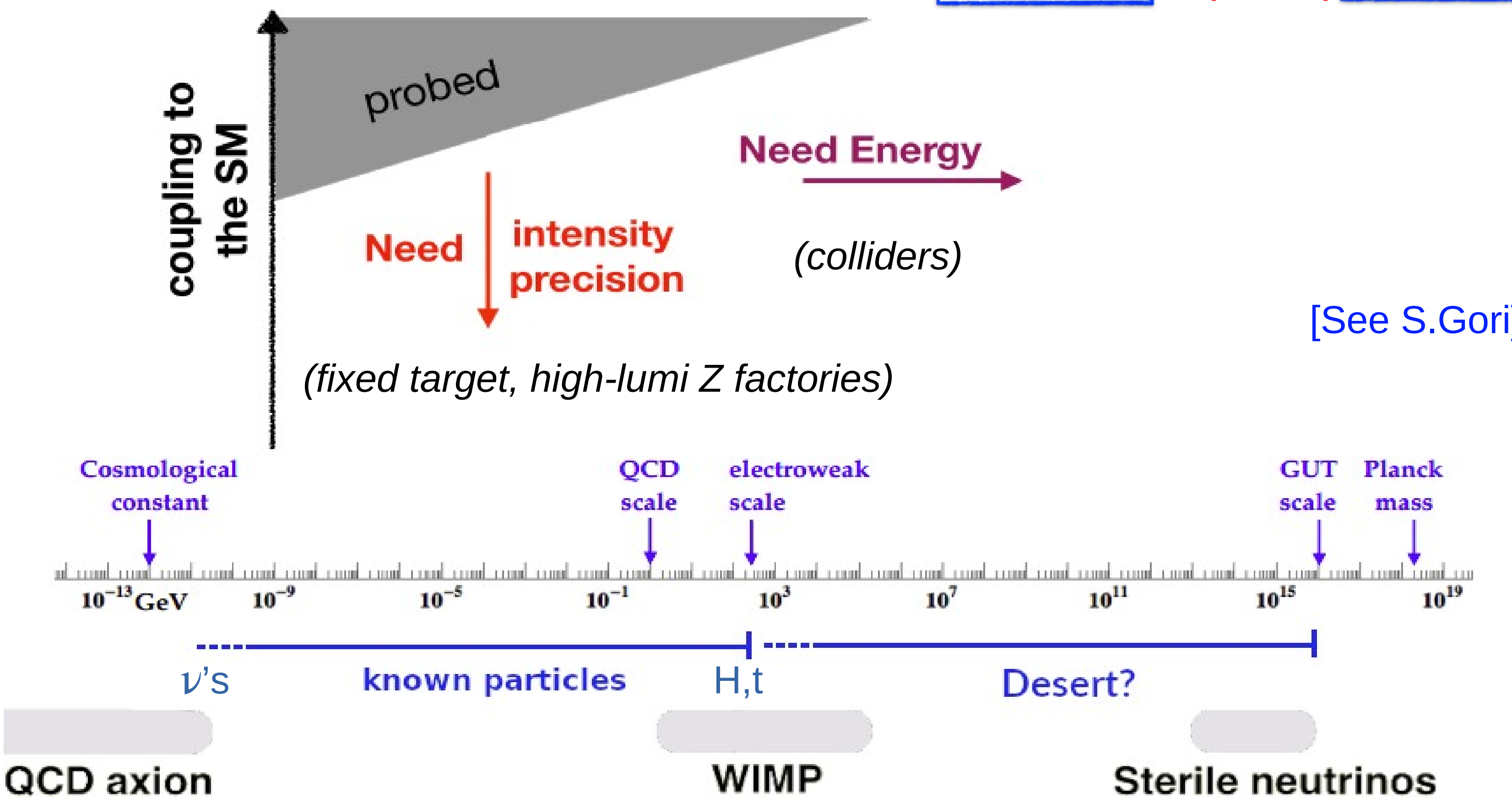



[See S.Gori]

# Searches for new physics at accelerators

- Dark sector particles (not charged under SM gauge symms.) are high priority.
- 4 generic "portals" (DM mediators):

| | |
|---|---|
| Higgs *(scalar)* | $\kappa\|H\|^2\|S\|^2$ |
| Dark photon *(vector)* | $\epsilon Z^{\mu\nu}A'_{\mu\nu}$ |
| Axion *(pseudoscalar)* | $\frac{1}{f_s}F_{\mu\nu}\tilde{F}_{\mu\nu}a$ |
| Heavy Neutrino *(fermion)* | $yHLN$ |



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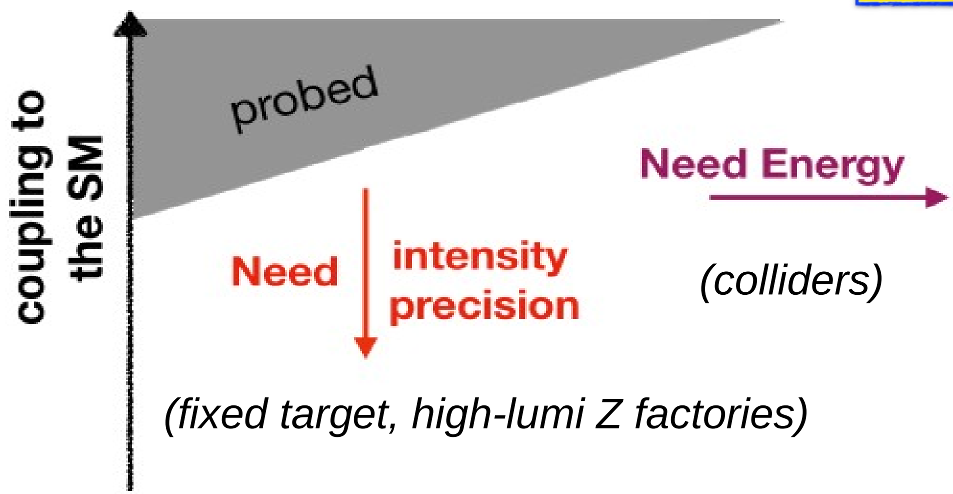
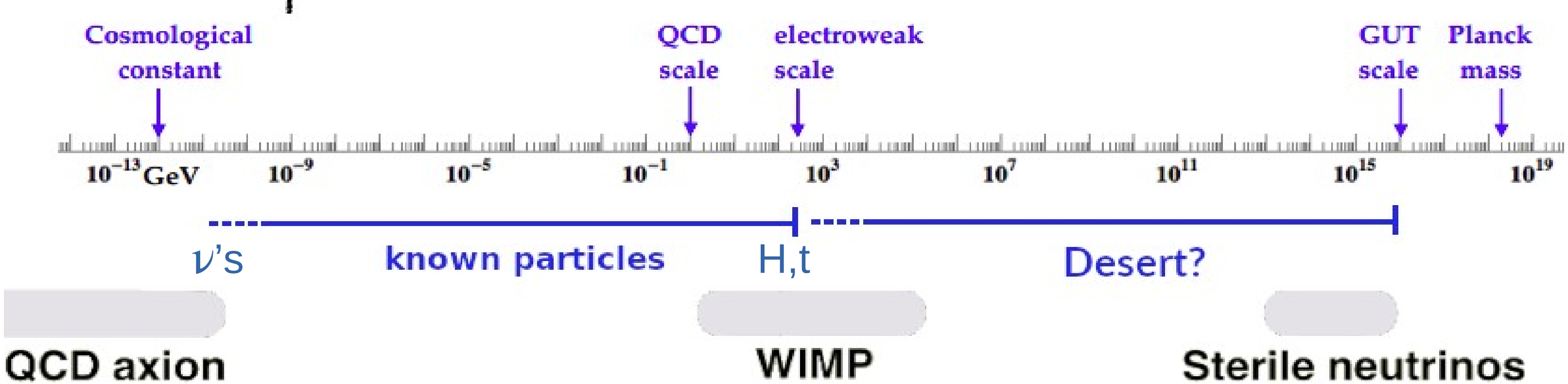


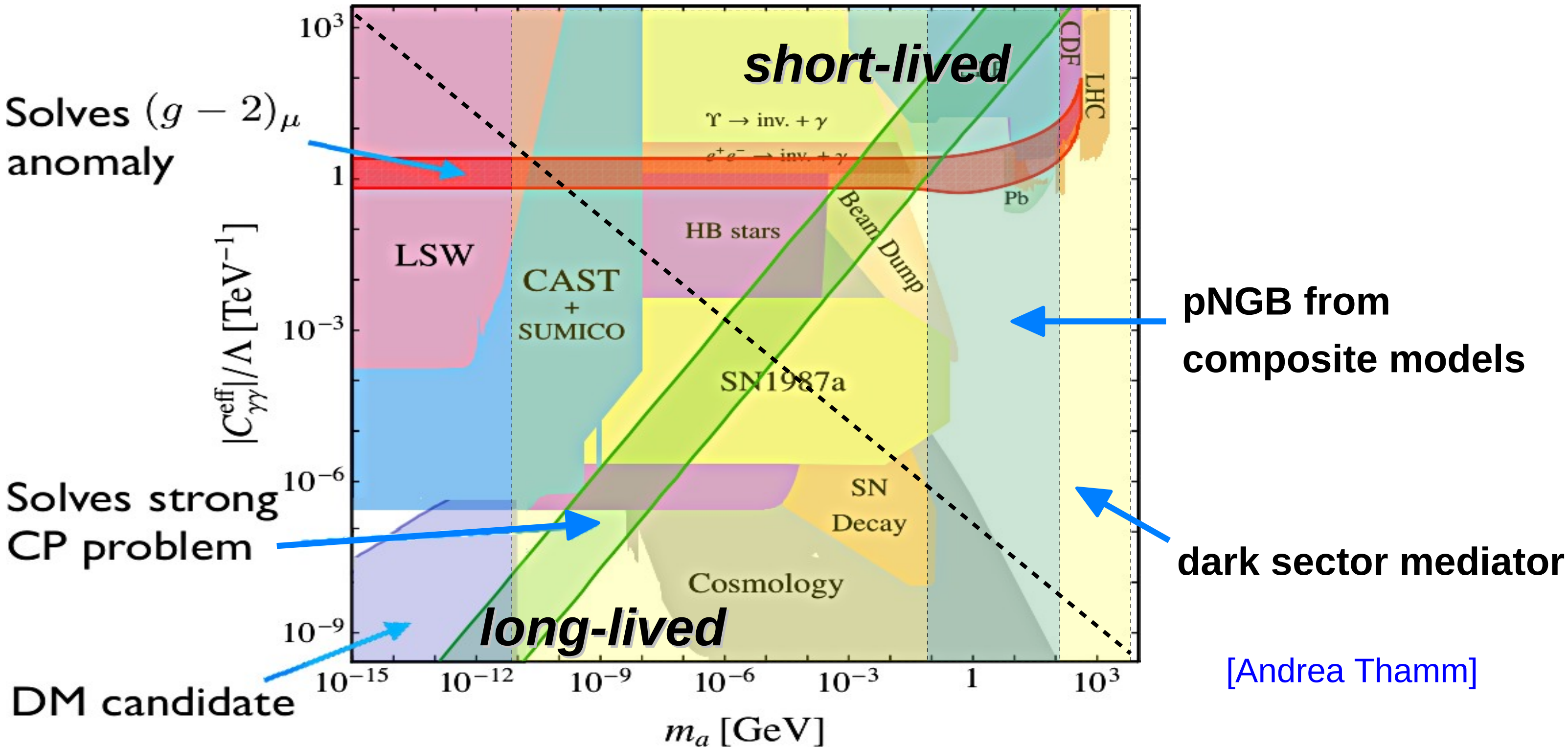

**Pseudoscalar particles:**
**weakly-coupled**
**light to heavy (1MeV–2 TeV)**
**short-lived (mostly visible decay)**

[See S.Gori]



# Axion-like particles (ALPs) motivations

- Elementary pseudoscalar suggested in many SM extensions:
  - (1) Solve strong CP problem (with explicit $m_a$ vs. SM-coupling proportionality).
  - (2) Cold Dark Matter (DM) candidate (for stable very light $m_a$), or dark sector mediator.
  - (3) Pseudo Nambu-Goldstone boson ($\pi^0$ like) of new spontaneously broken U(1) global symmetry in high-energy SM extensions (for $m_a$ > GeV): familon,R-axion...
  - (4) Generic pheno. pseudoscalar: extend. Higgs sectors, relaxion, string TH models..




[Andrea Thamm]

# ALP couplings to SM particles

- ALP coupling to EW bosons, g's, fermions via EFT Lagrangian: $g_{aX} = C_{XX}/\Lambda$

- Interactions at dimension-5

[Weinberg: PRL 40 (1978) 223]
[Wilczek: PRL 40 (1978) 279]
[Georgi, Kaplan, Randall: Phys. Lett.169 B (1986)]

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{\Lambda}\bar{f}\gamma_\mu\gamma_5 f + g_s^2\, C_{GG}\frac{a}{\Lambda}G^A_{\mu\nu}\tilde{G}^{\mu\nu,A}$$
$$+ e^2 C_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}C_{\gamma Z}\frac{a}{\Lambda}F_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}C_{ZZ}\frac{a}{\Lambda}Z_{\mu\nu}\tilde{Z}$$

Decay into photons, leptons, hadrons

[Andrea Thamm]

- W-coupled ALPs are quite constrained by non-FCNC meson decays.

  Searches mostly focus on neutral EW ($\gamma$/Z) couplings:

  – $c_B \sim c_W$: $g_{a\gamma Z} << g_{a\gamma\gamma}$ (photon coupling)

  – $c_B >> c_W$: $g_{a\gamma Z} \sim - g_{a\gamma\gamma}$ (hypercharge coupling)

- These fully determine ALPs production & decay modes.

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Decay into photons, leptons, hadrons

[Andrea Thamm]

  - Higgs interactions at dimension-6 and 7

$$\mathcal{L}_{\rm eff}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2}(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{Zh}^{(7)}}{\Lambda^3}(\partial^\mu a)\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \dots$$

$h \to aa$

$h \to Za$

Andrea Thamm

[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]

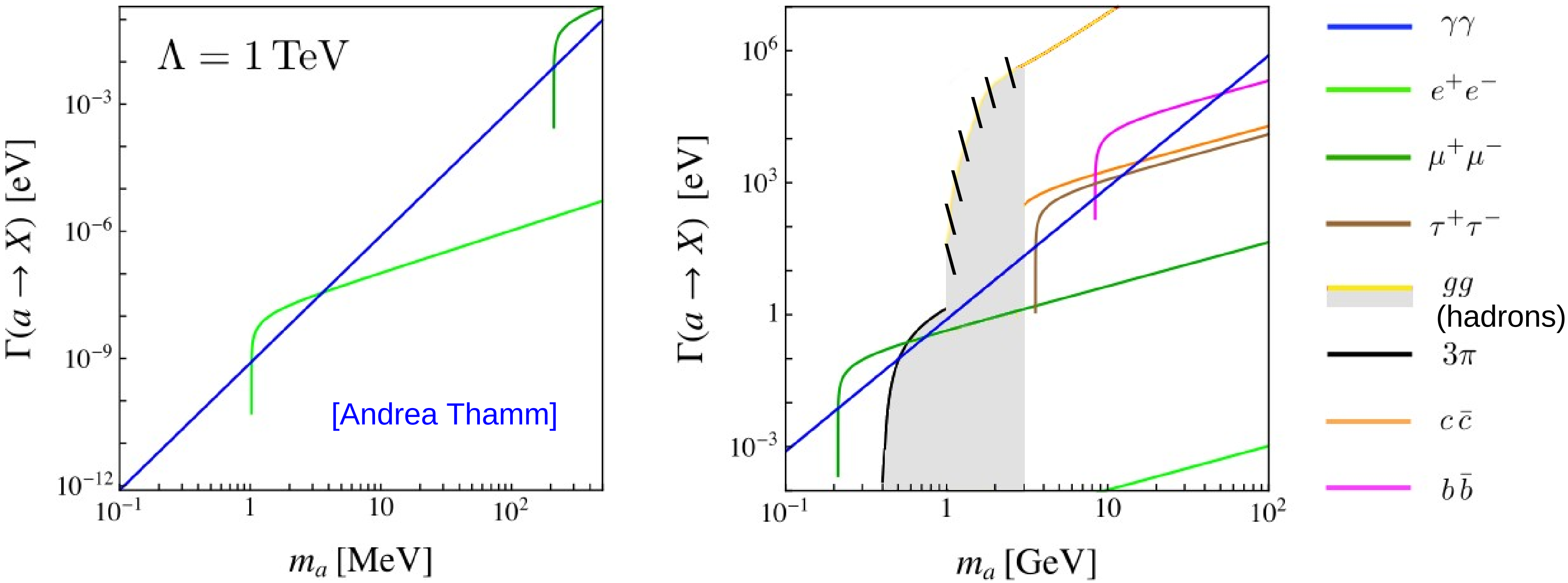
[Bauer, Neubert, Thamm: 1607.01016]

- These fully determine ALPs production & decay modes.

# ALP decay modes

- Light ALPs ($m_a$ < 1 MeV) are long-lived & can only decay to photons (& $\nu$'s)
- Increasingly heavy ALPs ($m_a$ > 1 MeV) can decay to other particles:

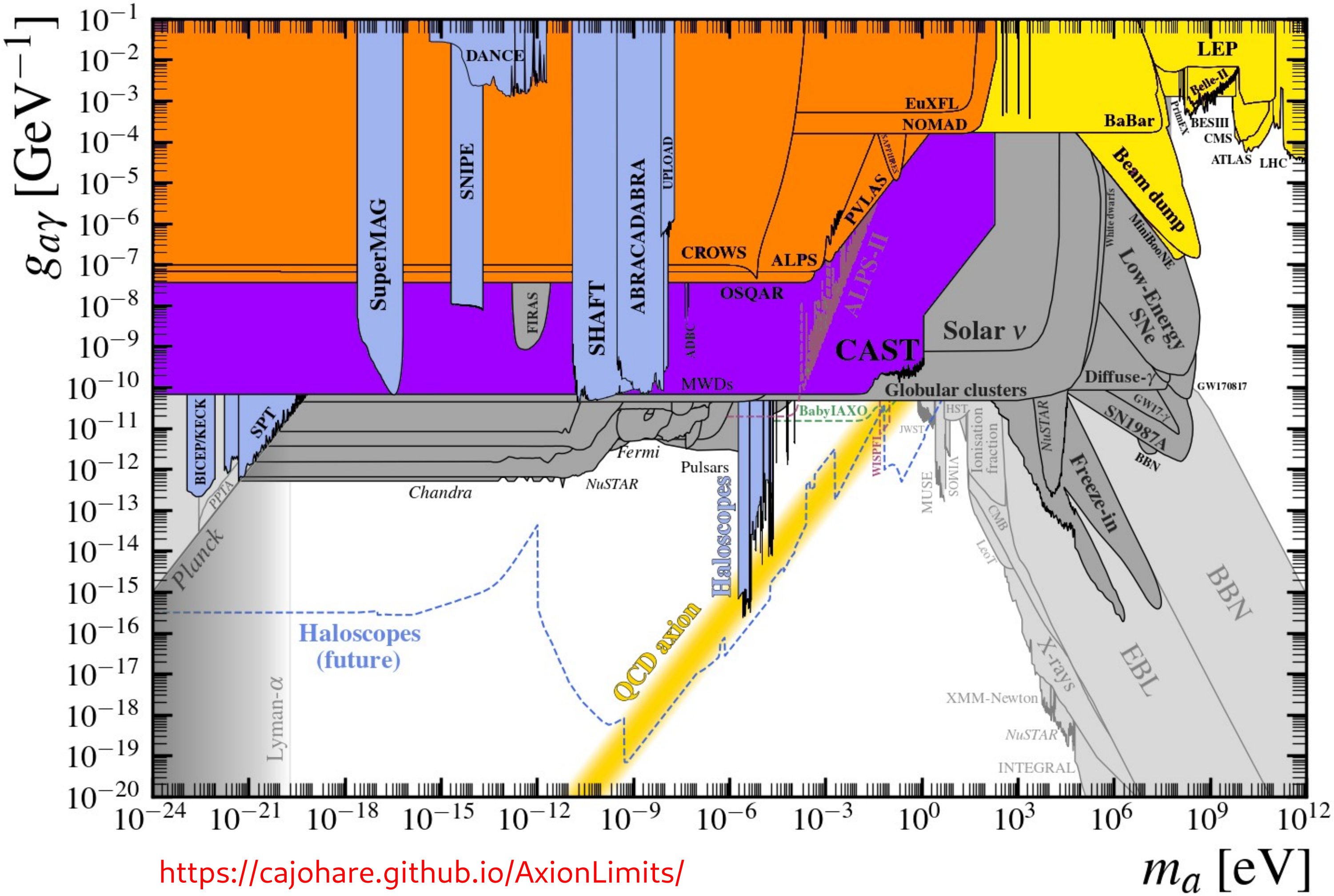
(Assuming effective Wilson coefficients to be 1, i.e. $g_{aX}=1/\Lambda$)




- Decays $a\to\gamma\gamma$ and $a\to gg$ dominate, as they have a $\Gamma\sim(m_a)^3$ dependence, but $a\to gg$ ($m+m+m$, $m+m+\gamma$, 2 VM) difficult to observe: Accelerator searches mostly focus on simplified $a\to\gamma\gamma$ "photophilic" case (direct comparison w/ light ALPs limits).

# Axion & ALP searches

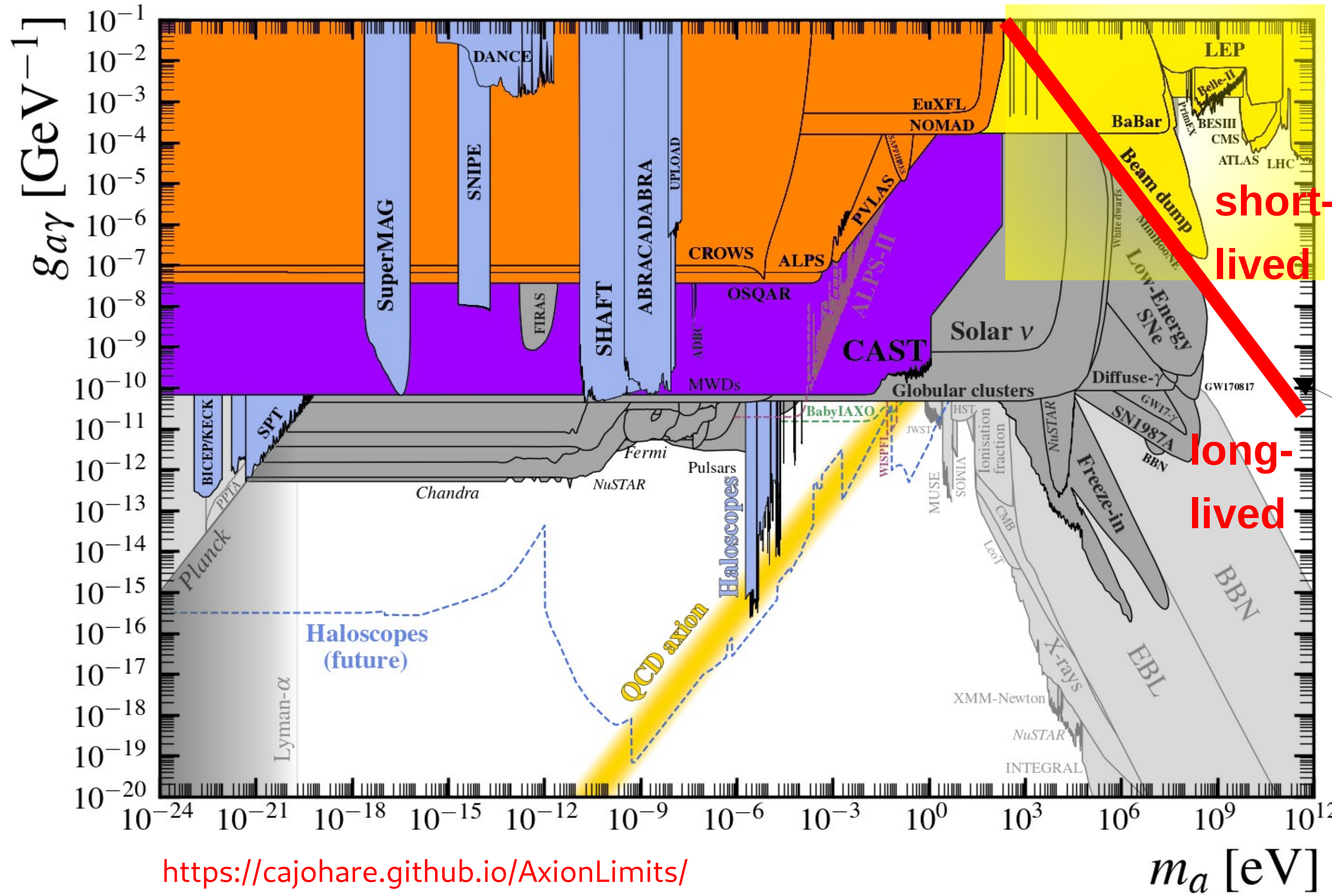
- Most searches focus on ALPs coupling to photons (production & decay):




https://cajohare.github.io/AxionLimits/

# ALP searches at accelerators/colliders

- Most accelerator/collider searches focus on ALPs coupling to photons (production & decay), masses $m_a > 1$ MeV & short-lived (detector scale):




https://cajohare.github.io/AxionLimits/

Diphoton decay length:

$$\Gamma_a = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

$L_a = 1/\Gamma_a$

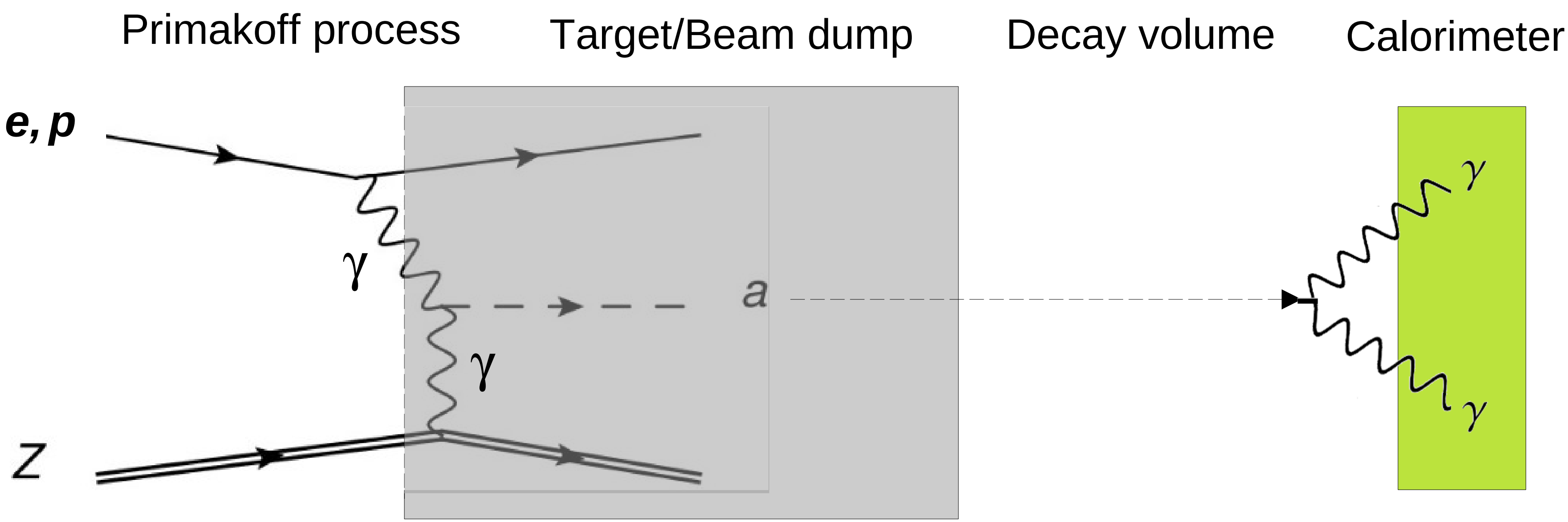
$L_a \approx 100$ m

$$\langle L_T \rangle = \langle \gamma\beta \rangle L_a \sin\theta = \langle (\gamma\beta)_T \rangle L_a = 64\pi \langle p_T \rangle g_{\gamma\gamma}^{-2} m_a^{-4}$$

$L_a \approx g_{\gamma\gamma}^{-2}\, m_a^{-4}$

- Many limits set by PH recasts (rather than EXP analyses) of existing/future data

# (1) ALP searches at fixed target & beam dumps

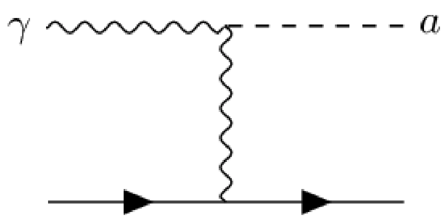



[See also S.Gori, next]

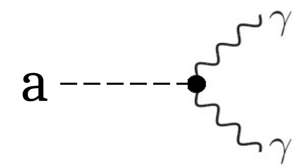
(di)photon peak over (small) neutral backgds.

# ALPs searches at fixed-target & beam dumps

- Primakoff production: Proton/Electron beam on fixed target emits/produces photon that fuses with EPA photon of target (Z) atoms: $\gamma\gamma \rightarrow a(\gamma\gamma)$




Followed by $a \rightarrow \gamma\gamma$ downstream:




(also missing energy from LL ALP at FTs)

$$\sigma(\gamma\gamma \rightarrow a) = \frac{\pi g^2_{a\gamma\gamma} m_a}{16} \delta(m_{\gamma\gamma} - m_a)$$

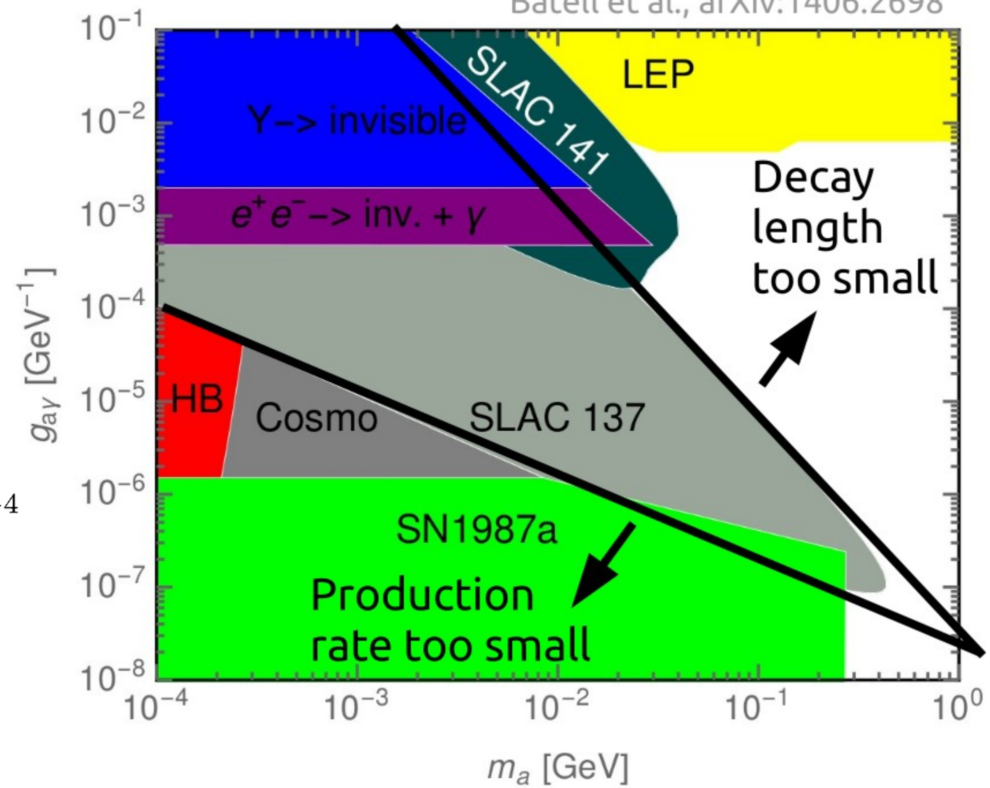
- If ALP is long-lived, decay length is of a few meters:

$$l_a = \beta\,\gamma\,\tau \approx \frac{64\pi\, E_a}{g^2_{a\gamma}\, m_a^4}$$

$$\approx 40\ \mathrm{m} \times \frac{E_a}{10\ \mathrm{GeV}} \left(\frac{g_{a\gamma}}{10^{-5}\ \mathrm{GeV}^{-1}}\right)^{-2} \left(\frac{m_a}{100\ \mathrm{MeV}}\right)^{-4}$$

- Masses & couplings probed:
  $m_a \approx 0.1$ MeV – 500 MeV
  $g_{a\gamma} \approx 10^{-1} - 10^{-7}$ GeV$^{-1}$

Izaguirre et al., arXiv:1307.6554
Batell et al., arXiv:1406.2698




Jaeckel/Spanowsky, PLB 753 (2016) 482

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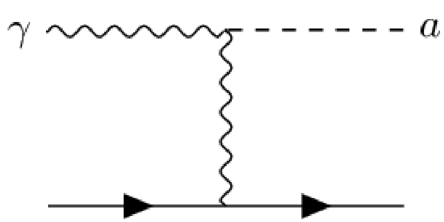


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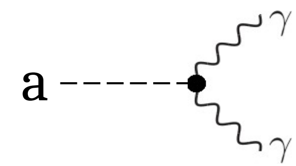


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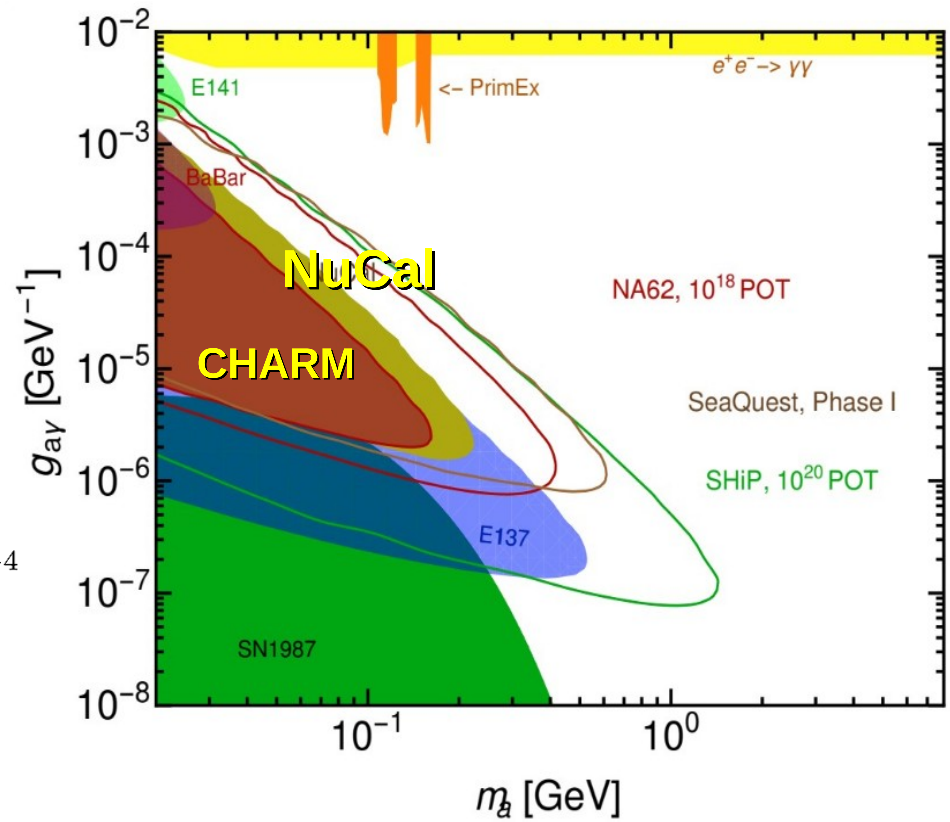


B.Dobrich et al., JHEP 02 (2016) 018, JHEP 05 (2019) 213

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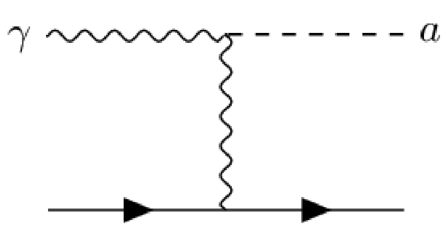


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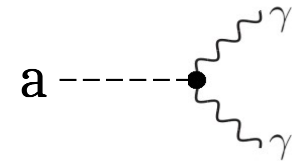


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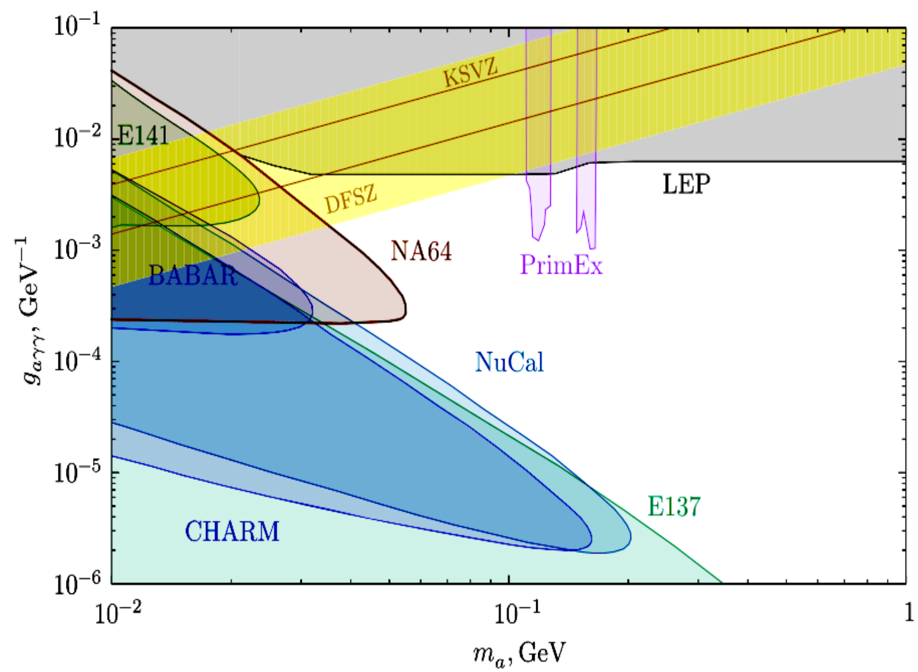


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NA64: Hard bremsstrahlung photons from 100 GeV electron beam

NA64, PRL125 (2020) 081801

# ALPs perspectives at future FTs & beam dumps

- Estimated limits for other future proton FT exps.:

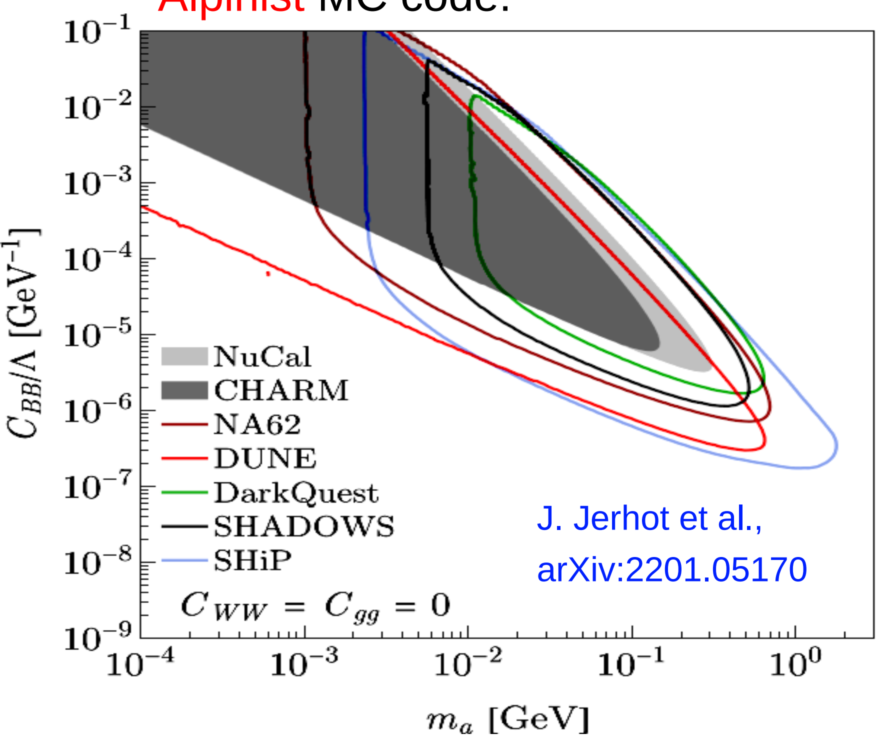
$$\mathcal{L}_{\text{int}} = \frac{N_{\text{pt}}}{53\,A^{0.77}}\ \text{mb}^{-1}$$

$m_a \approx 0.1$ MeV – 1 GeV

| Experiment | Status | $E_{\text{beam}}$ [GeV] | $N_{\text{POT}}$ [$10^{18}$] | Target | $l_{\text{n,DV}}$ [m] | $l_{\text{c,DV}}$ [m] | $z_{\text{DV}}$ [m] | $\theta_{\text{off}}$ [mrad] | $\Omega_{\text{cov}}$ [μsr] |
|---|---|---|---|---|---|---|---|---|---|
| CHARM | completed | 400 | 2.4 | Cu | 35 | 35 | 480 | 10 | 34 |
| NuCal | completed | 70 | 1.7 | Fe | 23 | 23 | 64 | 0 | 700 |
| NA62 | running | 400 | 10 | Cu | 139 | 81 | 82 | 0 | 84 |
| DUNE ND[6] | proposed | 120 | 1100 | C | 10 | 10 | 575 | 0 | 36 |
| DarkQuest | proposed | 120 | 1.44 | Fe | 13.5 | 1 | 5 | 0 | 12000 |
| SHADOWS | proposed | 400 | 10 | Cu | 26 | 23 | 10 | 75 | 9200 |
| SHiP | proposed | 400 | 200 | Mo | 50 | 28 | 45 | 0 | 4500 |

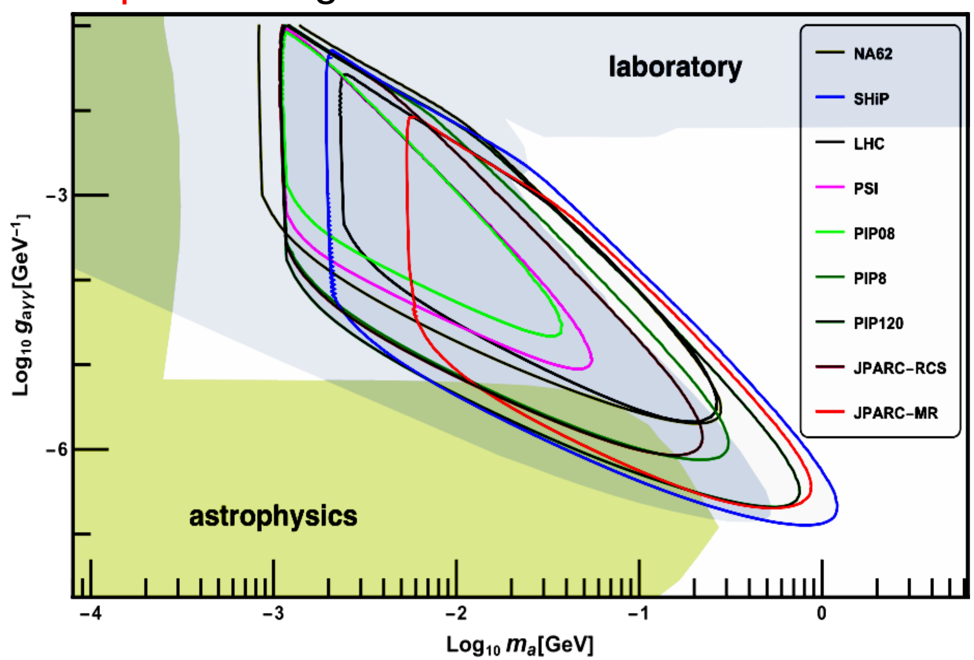
[NA62: See also E.Goudzovski, Fri.]

Alpinist MC code:




J. Jerhot et al., arXiv:2201.05170

Alpaca MC generator:




L. Harland-Lang et al., arXiv:1902.04878

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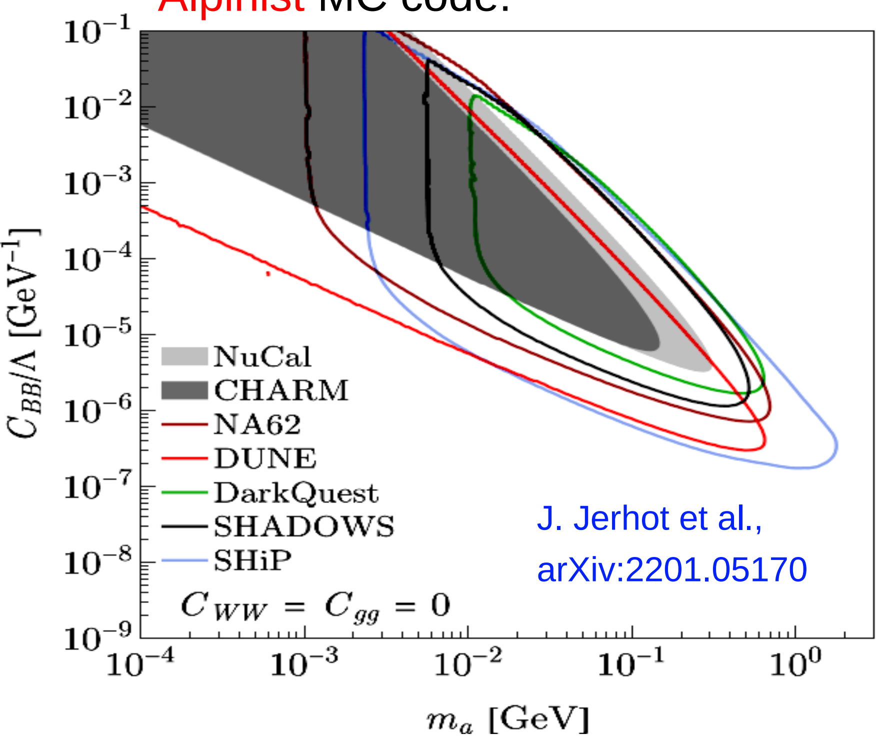


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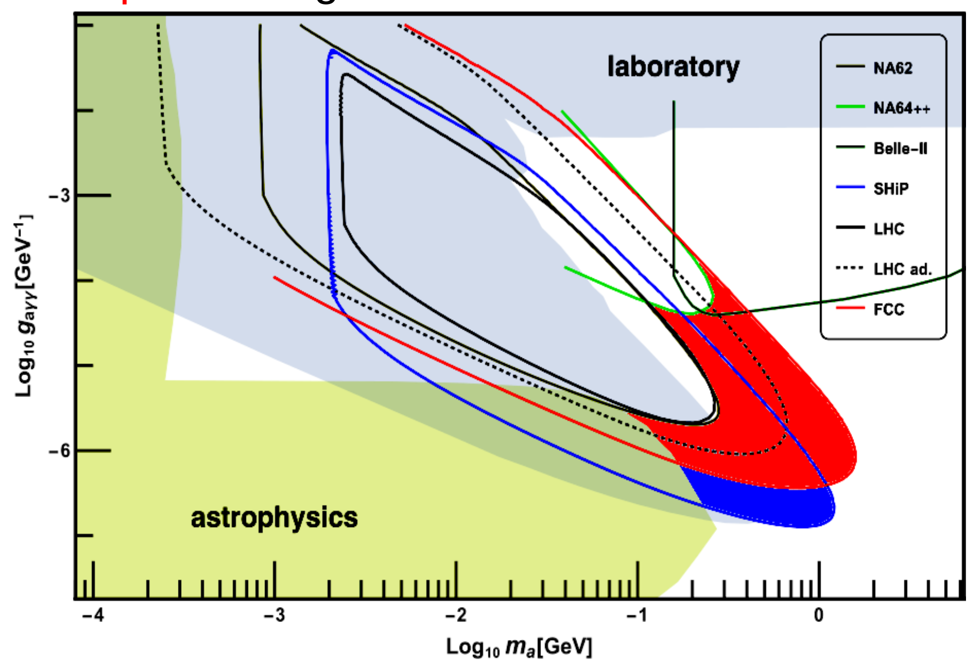
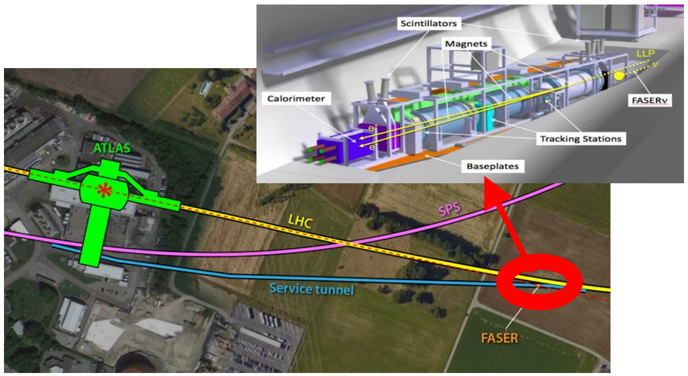



L. Harland-Lang et al., arXiv:1902.04878

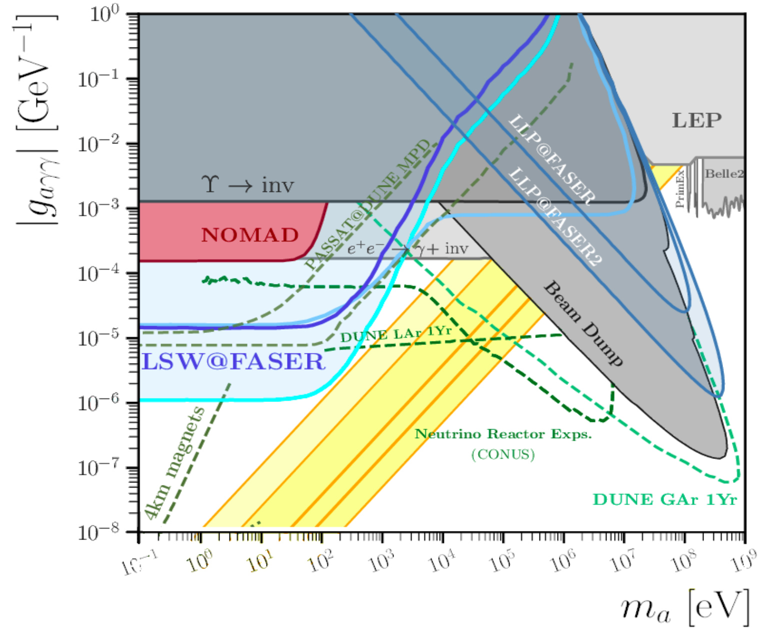
# ALPs perspectives at LHC fixed-target exps.

- Estimated limits for FASER & MATHUSLA fixed-target detectors at the LHC:



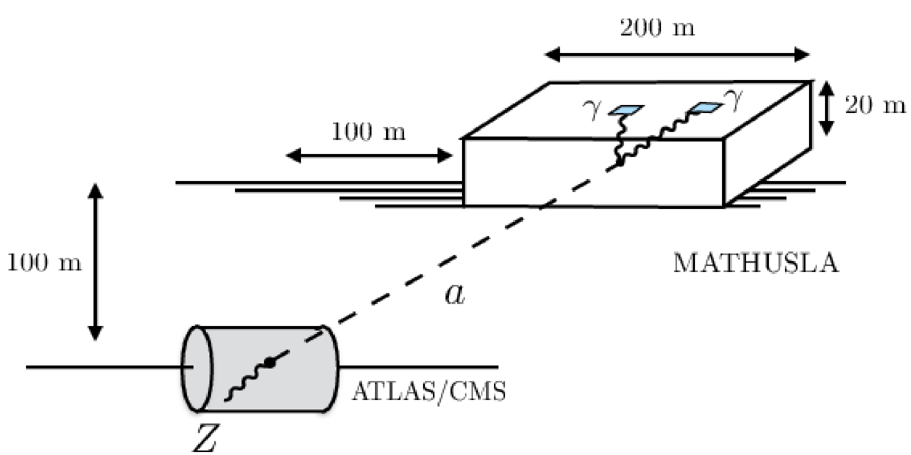

Feng et al. PRD 98 (2018) 055021

Kling&Quilez, PRD 106 (2022) 055036

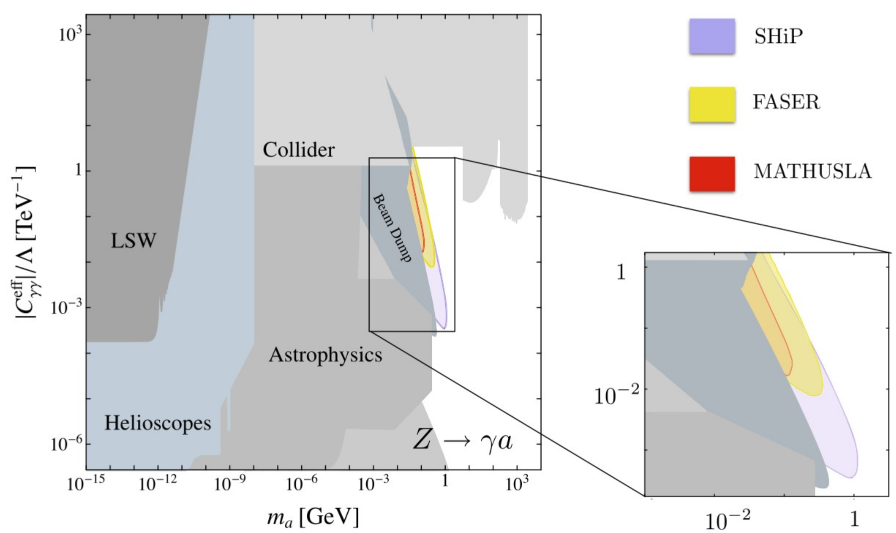



[See S.Zhang, next]

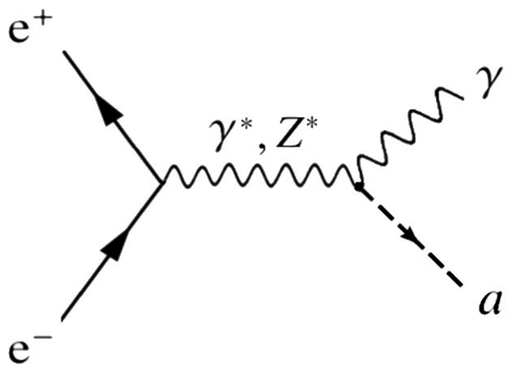
[See Xin Chen, Thu.]

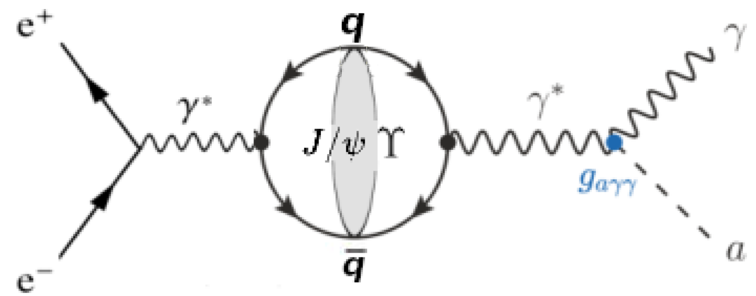


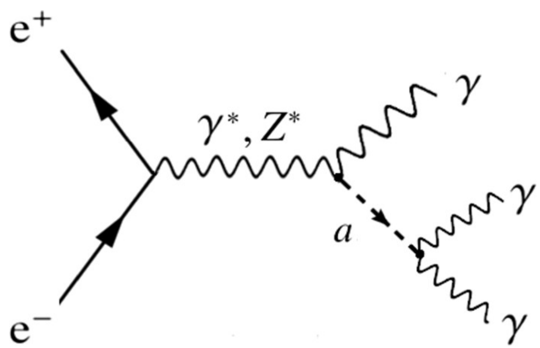

M.Bauer et al. EPJC 79 (2019) 74

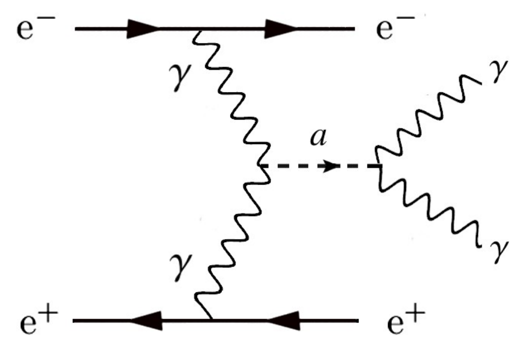


# (2) ALP searches at $e^+e^-$ colliders




[See also Marcello Campajola, Thu.]

# ALPs searches at $e^+e^-$ colliders: BaBar/LEP

- Recast BaBar monophoton (Z' search) data to search for long-lived light ALP:

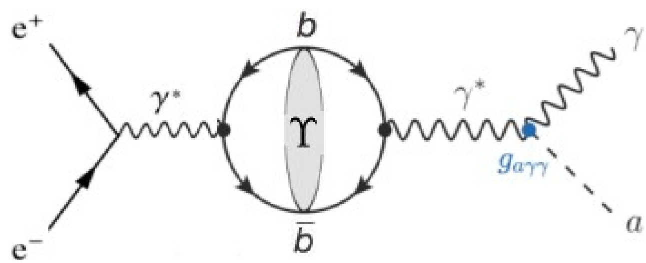
  $e^+e^- \rightarrow \Upsilon$ with $\Upsilon \rightarrow$ a(invisible)+$\gamma$

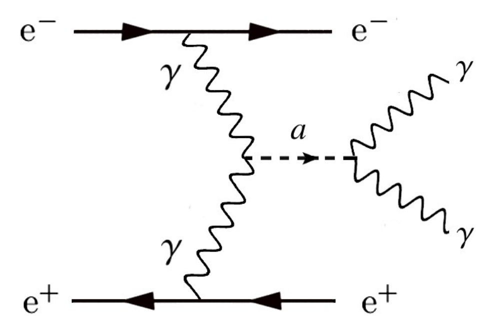
- Recast LEP data to search for ALPs:

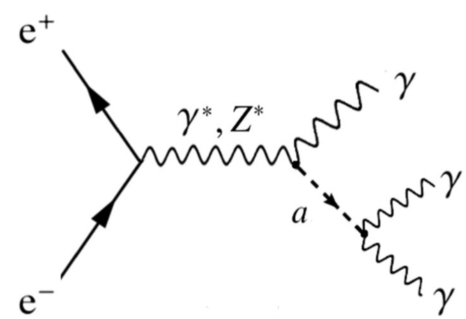
  Monophoton: $e^+e^- \rightarrow$ a(invisible)+$\gamma$

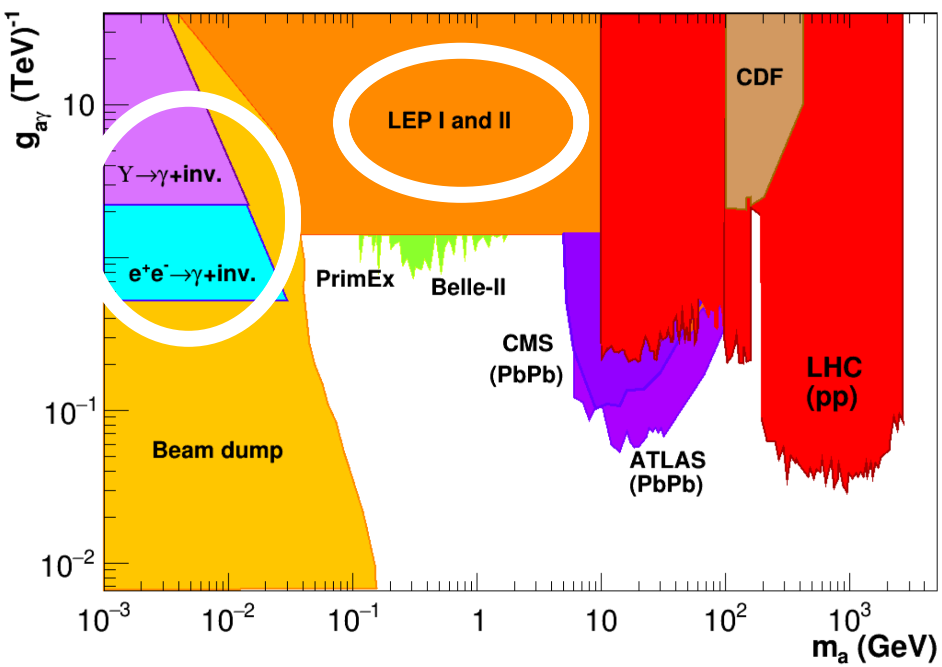
  Diphoton: $e^+e^- \rightarrow \gamma\gamma \rightarrow a(\gamma\gamma)$

  Triphoton: $e^+e^- \rightarrow Z \rightarrow a\gamma \rightarrow 3\gamma$




M.J.Dolan et al., JHEP 1712 (2017) 094

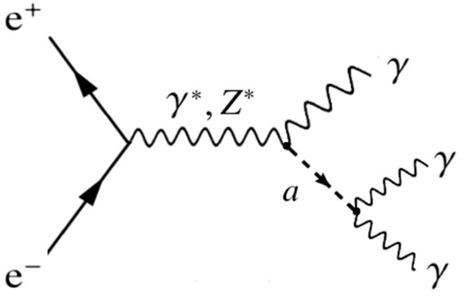
S. Knapen et al., PRL118 (2017)171801

# ALPs searches at $e^+e^-$ colliders: BELLE-II

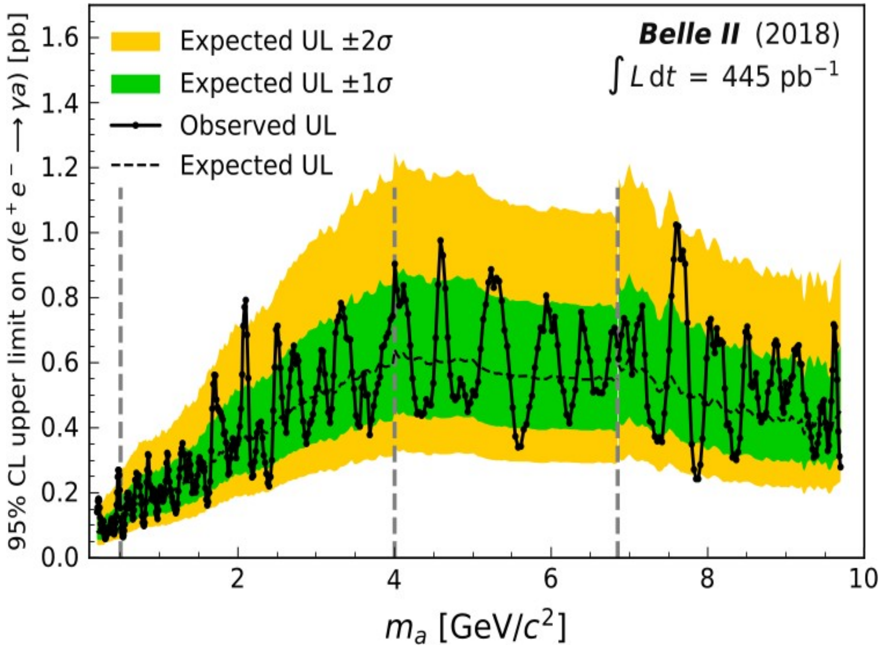
- Search for $e^+e^- \to a\gamma \to 3\gamma$ over $m_a$=0.2–9.7 GeV with $L_{int}$ = 445 $pb^{-1}$

Scan $m_{inv}(\gamma\gamma)$ to search for narrow $m_a$ peak resonance with 3 resolved photons or in the single-$\gamma$ recoil-mass distribution:

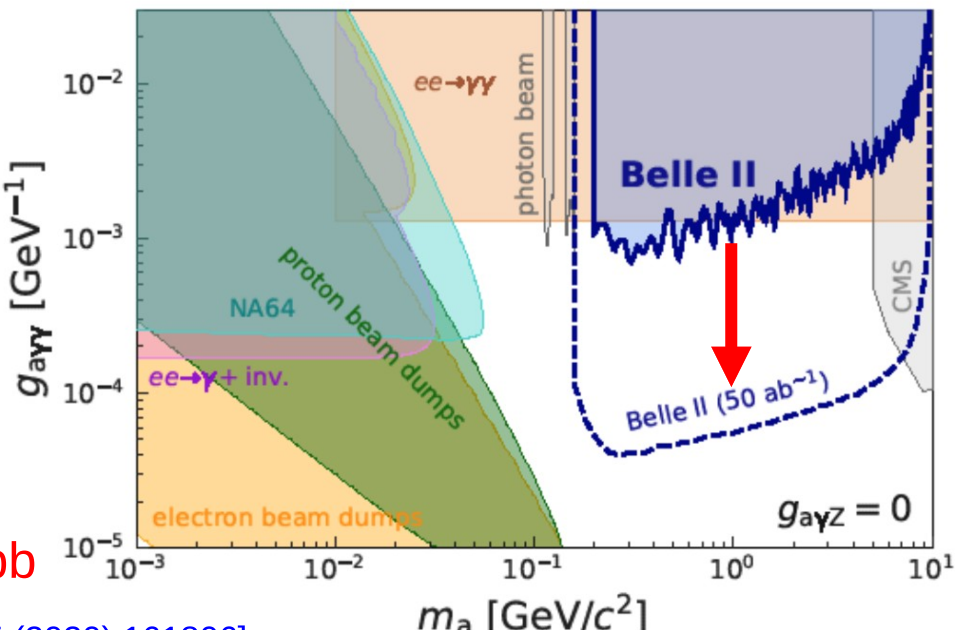
$$M^2_{\rm recoil} = s - 2\sqrt{s}E^{\rm c.m.}_{{\rm recoil}\gamma}$$




[See also D.Marcantonio, Fri.]




Assuming sensitivity scales as $\sqrt{L_{int}}$: Final bounds ×30 better down to $g_{a\gamma} \approx 4 \cdot 10^{-5}$ $GeV^{-1}$



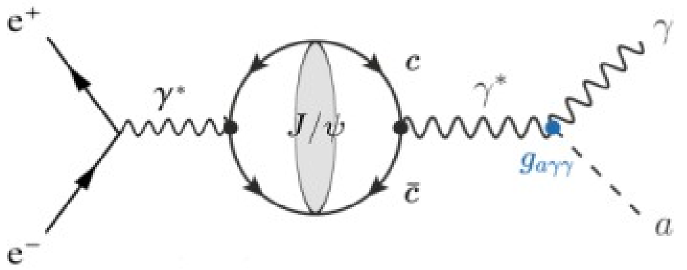

- 95% CL limit: $\sigma(e^+e^- \to a(\gamma\gamma)\gamma)$<0.1-0.5 pb

[PRL 125 (2020) 161806]

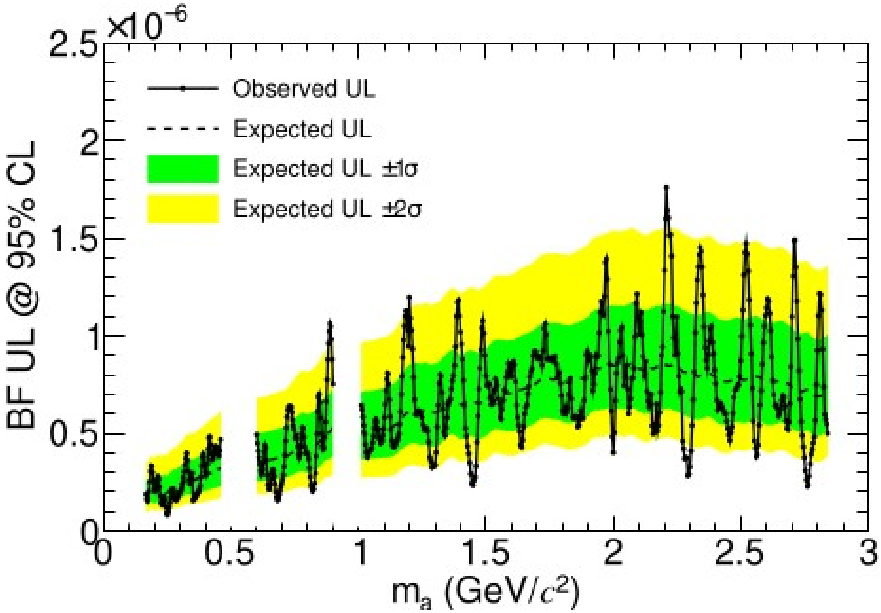
# ALPs searches at $e^+e^-$ colliders: BESIII

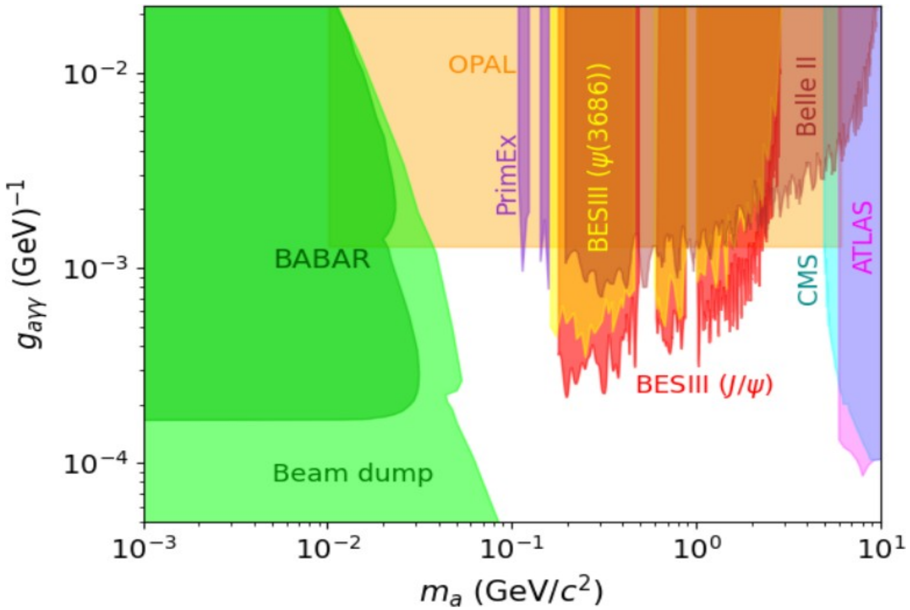
- Search for $e^+e^- \to \psi(3686) \to \pi^+\pi^- J/\psi$ and $e^+e^- \to J/\Psi$; followed by $J/\Psi \to a(\gamma\gamma)\gamma$ over $m_a$=0.18–2.9 GeV with $10^{10}$ $J/\Psi$ mesons:

  Scan $m_{inv}(\gamma\gamma)$ to search for narrow $m_a$ peak resonance in evts with 3 resolved photons:




[PLB 838 (2023) 137698 & arXiv:2404.04640 ]

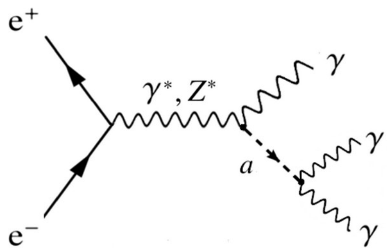



- Limits at 95% CL: $BR(J/\Psi \to a(\gamma\gamma)\gamma) < (3–50)10^{-8}$ | $g_{a\gamma} < (3–50)10^{-4}$ GeV$^{-1}$

# ALP perspectives at future $e^+e^-$ colliders: FCC-ee

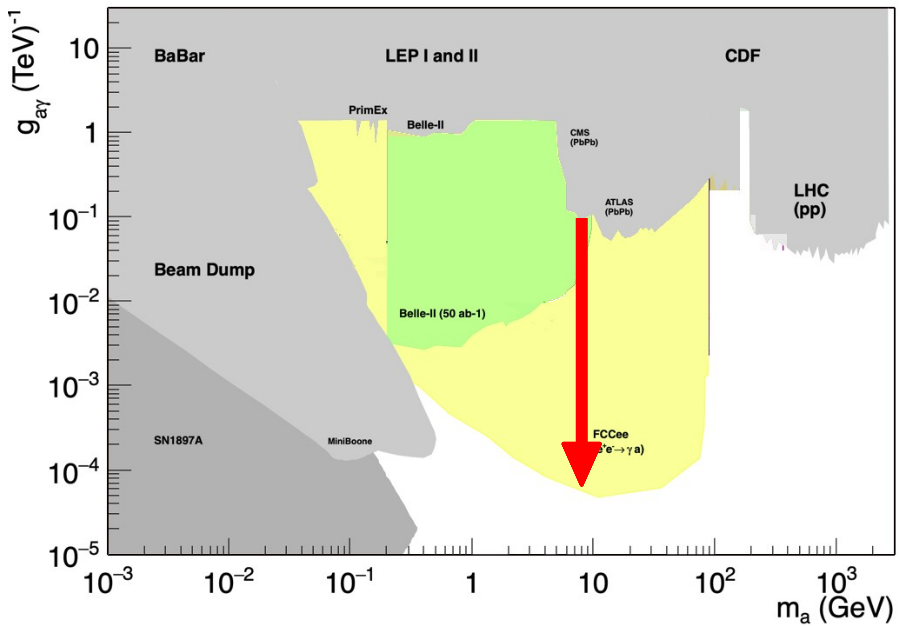
- Search for $e^+e^- \to Z \to a\gamma \to 3\gamma$ over $m_a = 0.2$–$91$ GeV with $6\cdot10^{12}$ Z's(!)



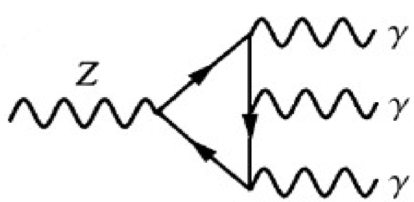

ALPs visible down to $g_{a\gamma} \approx 6\cdot10^{-5}$ TeV$^{-1}$

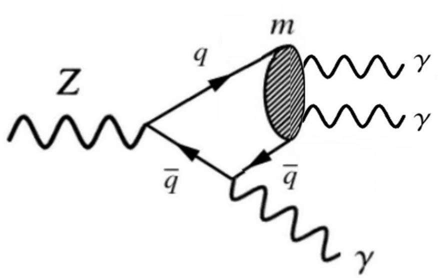
$\times10^3$ improved sensitivity wrt. today

M.Bauer et al. EPJC 79 (2019) 74




- However, $e^+e^- \to 3\gamma$ SM backgds are not negligible anymore!




BR($Z \to 3\gamma$)=$6.4\cdot10^{-10}$

BR($Z \to m(\gamma\gamma)+\gamma \to 3\gamma$)=$1.8\cdot10^{-10}$

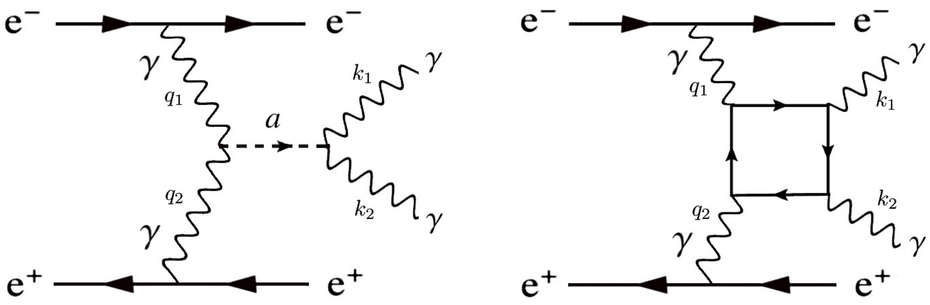
| $Z \to \gamma$ | + | $X(\gamma\gamma)$ | Branching fraction |
|---|---|---|---|
| | | $\pi^0(\gamma\gamma)$ | $9.7 \times 10^{-12}$ |
| | | $\eta(\gamma\gamma)$ | $6.3 \times 10^{-11}$ |
| | | $\eta'(\gamma\gamma)$ | $1.1 \times 10^{-10}$ |
| | | $\eta_c(\gamma\gamma)$ | $2.1 \times 10^{-12}$ |
| $Z \to \gamma$ | + | $\chi_{c0}(\gamma\gamma)$ | $7.6 \times 10^{-14}$ |
| | | $\chi_{c1}(\gamma\gamma)$ | $1.5 \times 10^{-14}$ |
| | | $\chi_{c2}(\gamma\gamma)$ | $9.6 \times 10^{-14}$ |
| | | $\chi_{b0}(\gamma\gamma)$ | $1.6 \times 10^{-14}$ |
| | | $\chi_{b2}(\gamma\gamma)$ | $1.6 \times 10^{-14}$ |
| Sum | | | $1.8 \times 10^{-10}$ |
| $Z$ | $\longrightarrow$ | $\gamma\gamma\gamma$ | $6.4 \times 10^{-10}$ |

Expect N($3\gamma$)~1300 backgd events.

DdE & Dung, JPG [arXiv:2312.11211]

# ALP perspectives at future $e^+e^-$ colliders: FCC-ee

- Search for $e^+e^- \to \gamma\gamma \to a \to \gamma\gamma$ over light-by-light scattering continuum $m_a$=0.2–350 GeV exploiting 4 FCC-ee runs (Z,WW,HZ,ttbar):

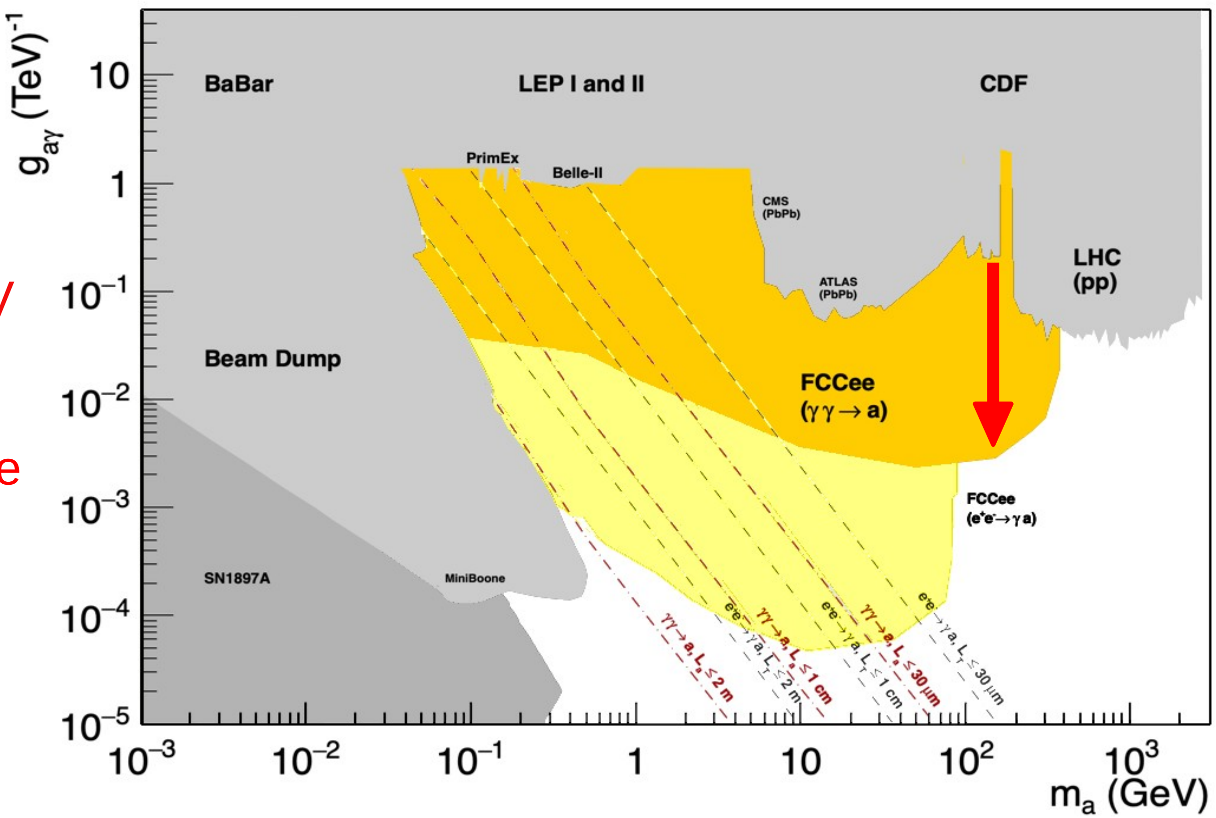



[P.Rebello, DdE et al., PRD 109 (2024) 5]

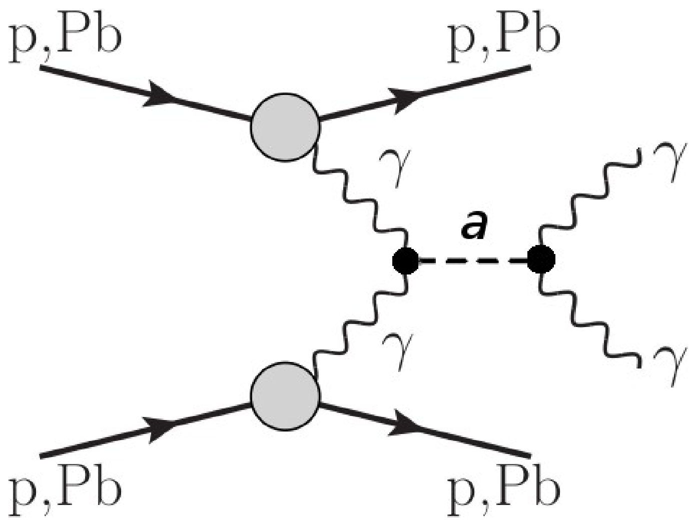
Heavy ALPs visible down to $g_{a\gamma} \approx 2\cdot10^{-3}$ TeV$^{-1}$

$\times 10^2$ improved sensitivity wrt. today for $m_a > 91$ GeV

Most of $\gamma\gamma\to a$ ALPs will have $L_a < 1$ cm, whereas $Z \to a\gamma$ ALPs will have $L_a \gtrsim 1$ cm (1 m) for $m_a \lesssim 10$ (1) GeV (displaced diphoton vtx.)



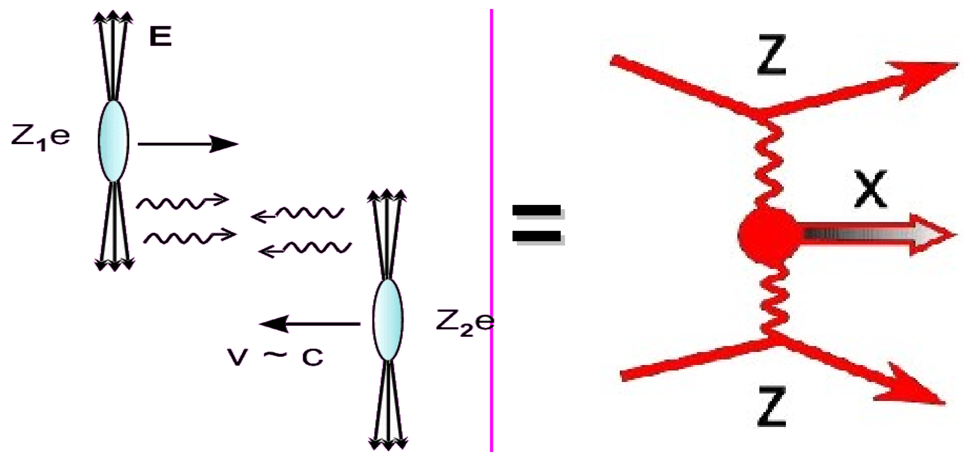
# (3) ALP searches from exclusive $\gamma\gamma$ at the LHC




[See also: Jeremi Niedziela, Thu.]

# LHC = unique photon-photon collider

- Electromagnetic ultra-peripheral colls. (UPCs): $b_{min} > R_A + R_B$, hadrons survive
- EM field = Weizsäcker-Williams (Equivalent Photon Approx.) photon flux:




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

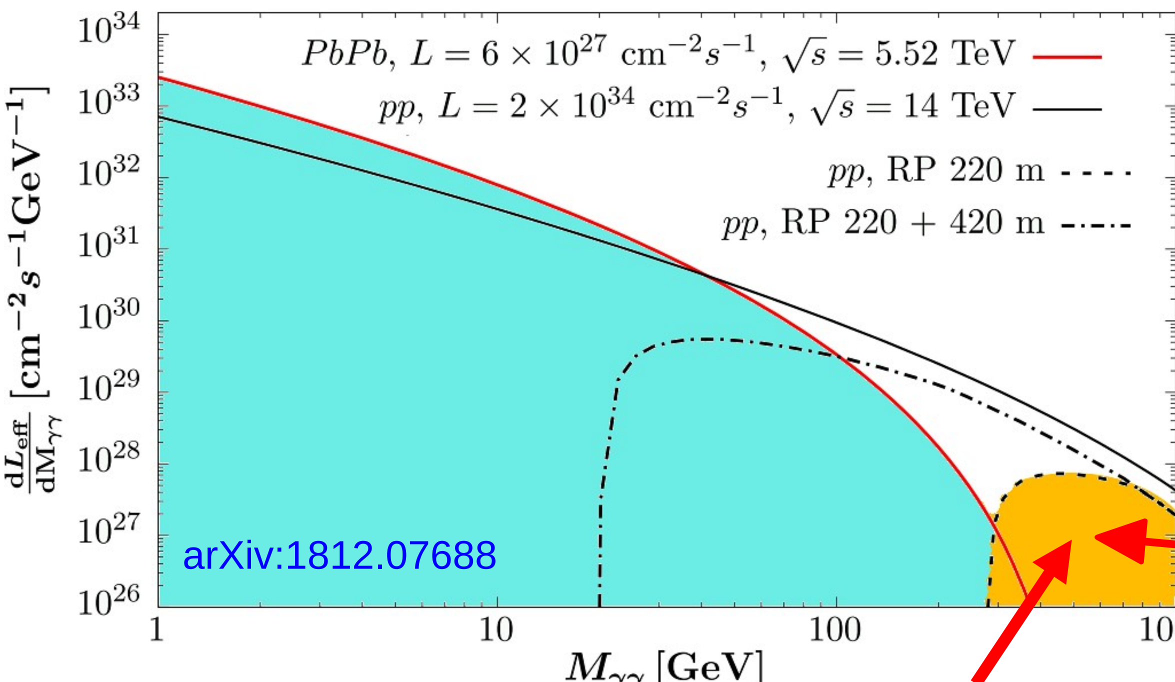
- Quasi-real $\gamma$ (coherent emission): $Q \approx 1/R \approx 0.03$ GeV (Pb), 0.28 GeV (p)
- Max. (longitudinal) $\gamma$ energies: $\omega < \omega_{max} \approx \frac{\gamma}{R} \approx$ 80 GeV (Pb), 2.5 TeV (p)

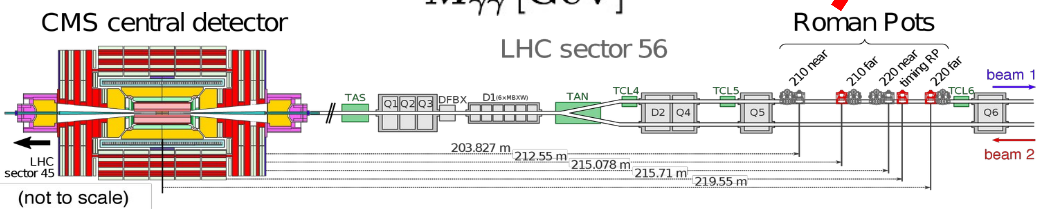
| System | $\sqrt{s_{NN}}$ | $\mathcal{L}_{int}$ | $E_{beam1} + E_{beam2}$ | $\gamma_L$ | $R_A$ | $E_\gamma^{max}$ | $\sqrt{s_{\gamma\gamma}^{max}}$ |
|---|---|---|---|---|---|---|---|
| Pb-Pb | 5.52 TeV | 5 nb$^{-1}$ | 2.76 + 2.76 TeV | 2960 | 7.1 fm | 80 GeV | 160 GeV |
| p-Pb | 8.8 TeV | 1 pb$^{-1}$ | 7.0 + 2.76 TeV | 7450, 2960 | 0.7, 7.1 fm | 2.45 TeV, 130 GeV | 2.6 TeV |
| p-p | 14 TeV | 150 fb$^{-1}$ | 7.0 + 7.0 TeV | 7450 | 0.7 fm | 2.45 TeV | 4.5 TeV |

▶ Single $X$ = C-even (spin 0,2) resonances only (Landau-Yang + C symmetry)

# Effective γγ luminosities (LHC): pp vs. PbPb

- PbPb feature $5 \cdot 10^7$ boost & no pileup. But pp has $\mathcal{O}(10^6)$ larger $L_{int}$ & taggers:
  - PbPb "wins out" up to $m_{\gamma\gamma} \approx 80$ GeV.
  - pp w/ double-arm p tagging at PPS (~220 m) "wins out" for $m_{\gamma\gamma} \geq 300$ GeV (+ central-fwd kinematic matching required to remove huge pp pileup):

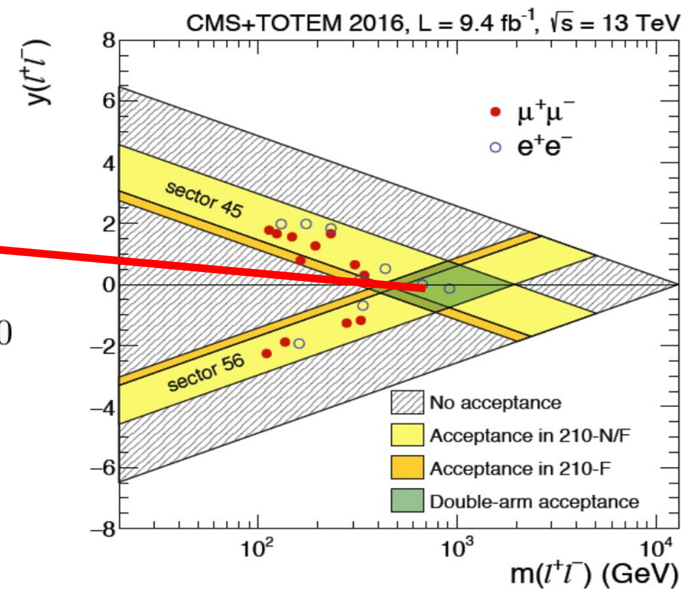



Proton kinematics: $t = (p_f - p_i)^2$

$$\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} \qquad M_X = \sqrt{s\xi_1\xi_2} \qquad y_X = \frac{1}{2}\log\left(\frac{\xi_1}{\xi_2}\right)$$

PPS p-p acceptance vs. central mass & y:



# Effective γγ luminosities (LHC): pp vs. PbPb

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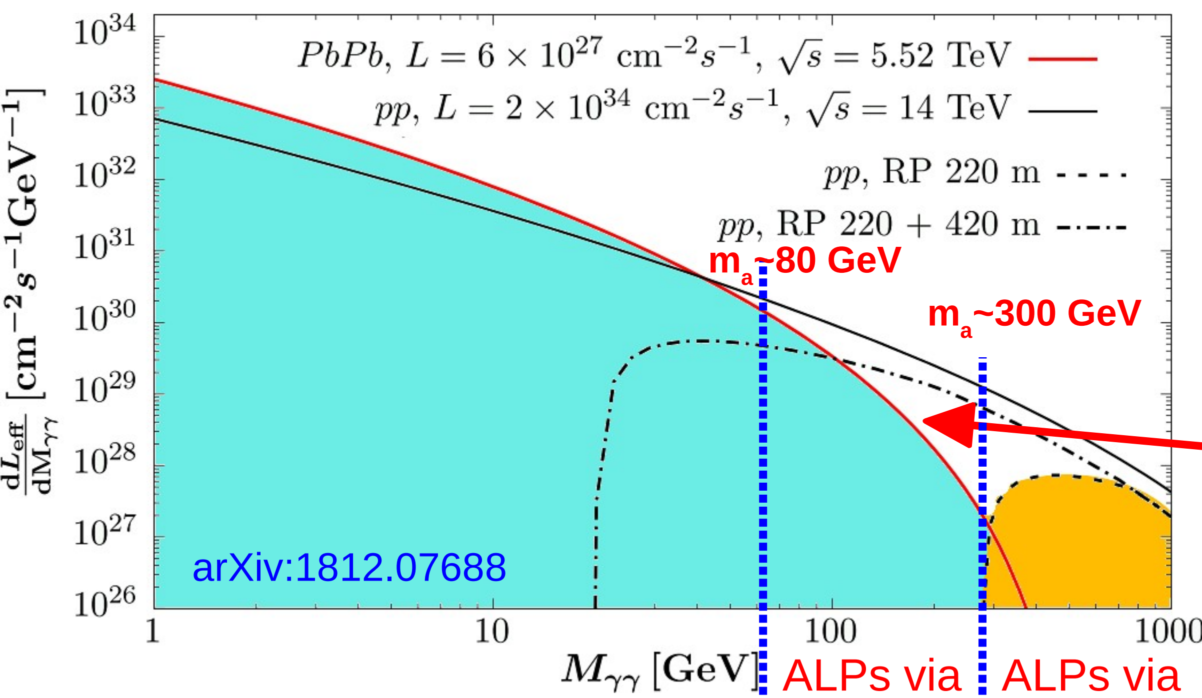


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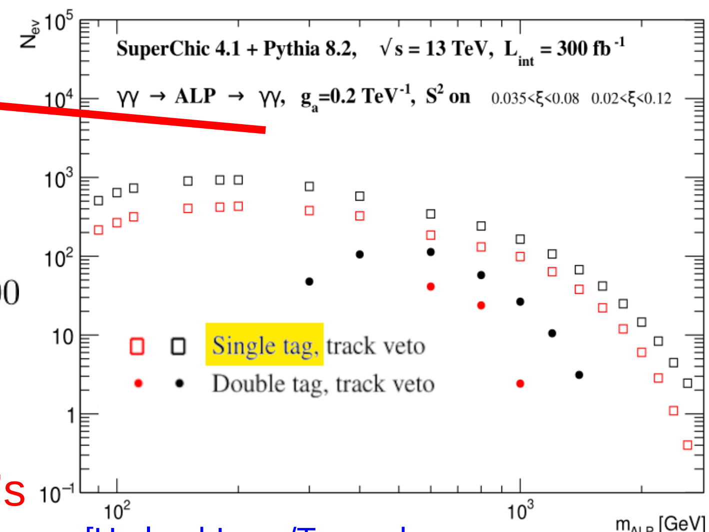
PPS p-p acceptance vs. central mass & y:




[Harland-Lang/Tasevsky PRD 107 (2023) 3033001]

Rule of thumb:

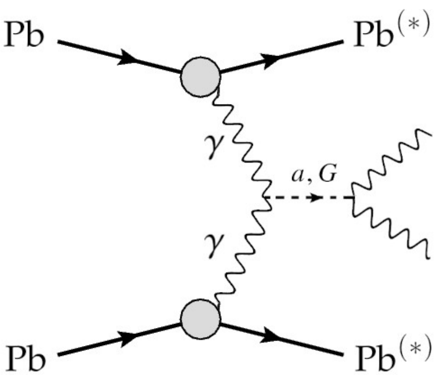
ALPs via γγ in Pb-Pb

ALPs via γγ in p-p with 1 tagged p

ALPs via γγ in p-p with 2 tagged p's

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

■ Search for $\gamma\gamma \to a \to \gamma\gamma$ excess over LbL ($\gamma\gamma \to \gamma\gamma$) continuum in PbPb(5.02 TeV):



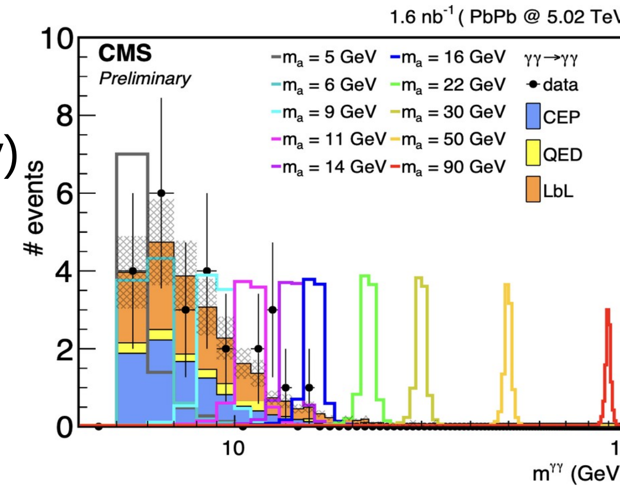

- Analysis strategy:

  Exclusive $\gamma\gamma$ (zero extra activity)

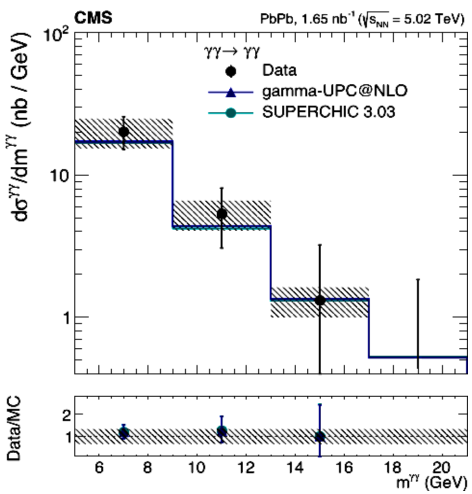
  $m_{\gamma\gamma}$ > 5 GeV (softest $\gamma$ possible)

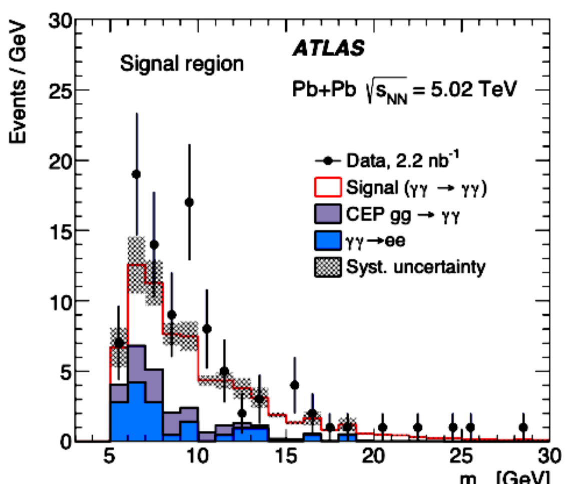
  $Aco_{\gamma\gamma}$<1% ($\gamma\gamma$ back-to-back)

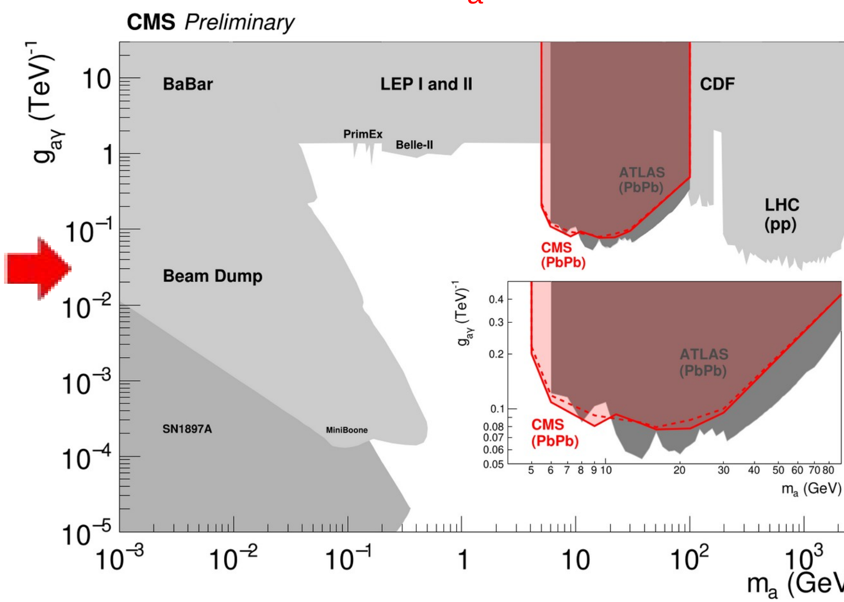
- Injected ALPs signals:




■ No excess: Most stringent ALPs limits ($g_{a\gamma}$ >0.05 $TeV^{-1}$) over $m_a$ = 5–100 GeV

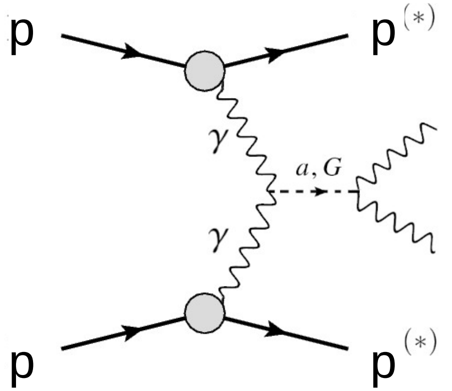


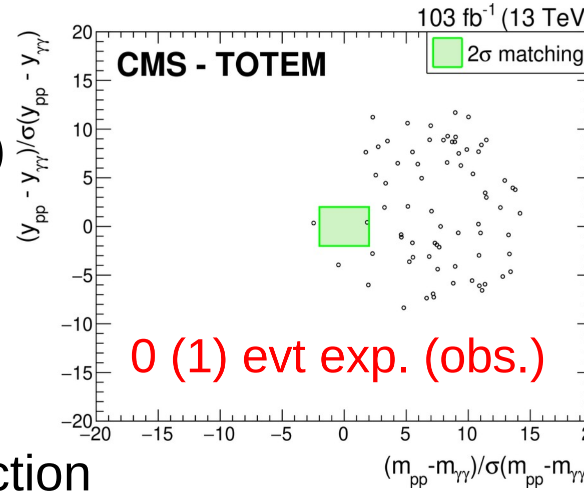



# ALPs searches via $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ (pp, 13 TeV)

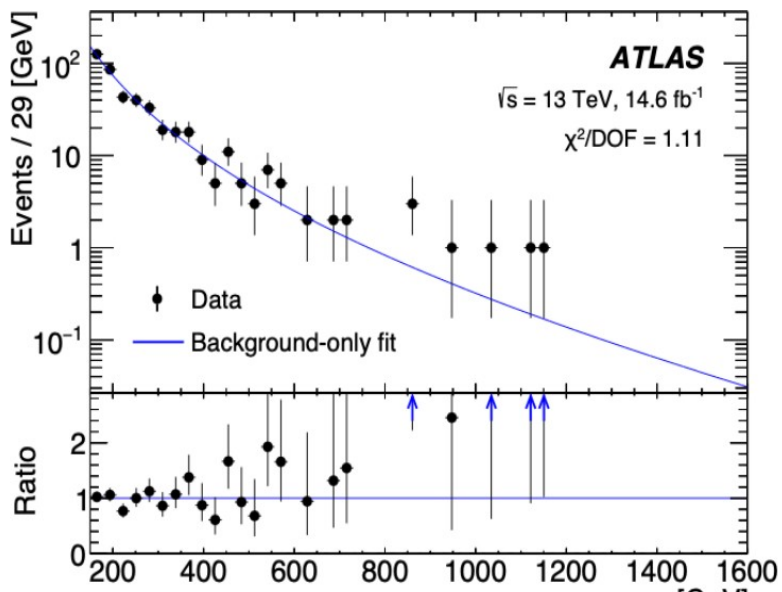
■ Search for $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ excess over LbL ($\gamma\gamma \rightarrow \gamma\gamma$) continuum in p-p (13 TeV):



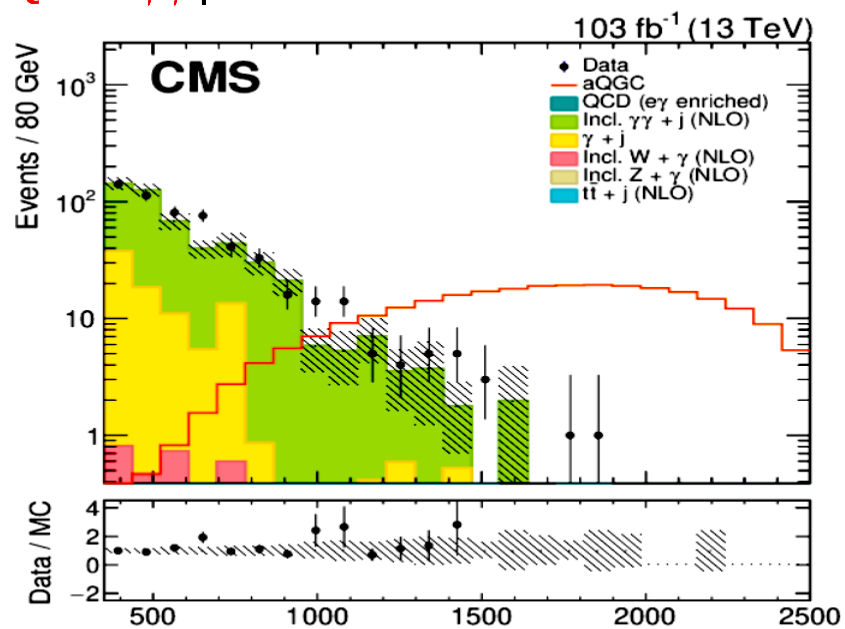

- Analysis strategy:
  - $m_{\gamma\gamma}$ > 350 GeV (p's in PPS accept.)
  - $Aco_{\gamma\gamma}$<1% ($\gamma\gamma$ back-to-back)
  - Matching $m_{\gamma\gamma}$ & $y_{\gamma\gamma}$ in PPS & ECAL




■ Background: Random pileup pp tags + QCD $\gamma\gamma$ production



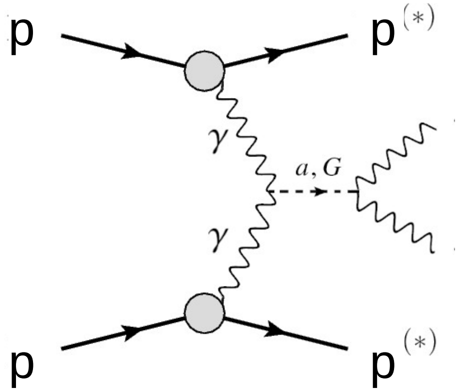

[ATLAS: JHEP 07 (2023) 234]




[CMS: PRD 110 (2024) 012010]

# ALPs searches via $\gamma\gamma \to a \to \gamma\gamma$ (pp, 13 TeV)

■ Search for $\gamma\gamma \to a \to \gamma\gamma$ excess over LbL ($\gamma\gamma \to \gamma\gamma$) continuum in p-p (13 TeV):

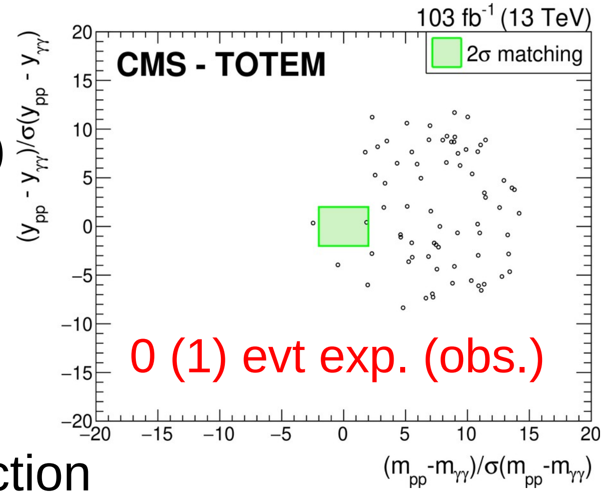



- Analysis strategy:

  $m_{\gamma\gamma}$ > 350 GeV (p's in PPS accept.)

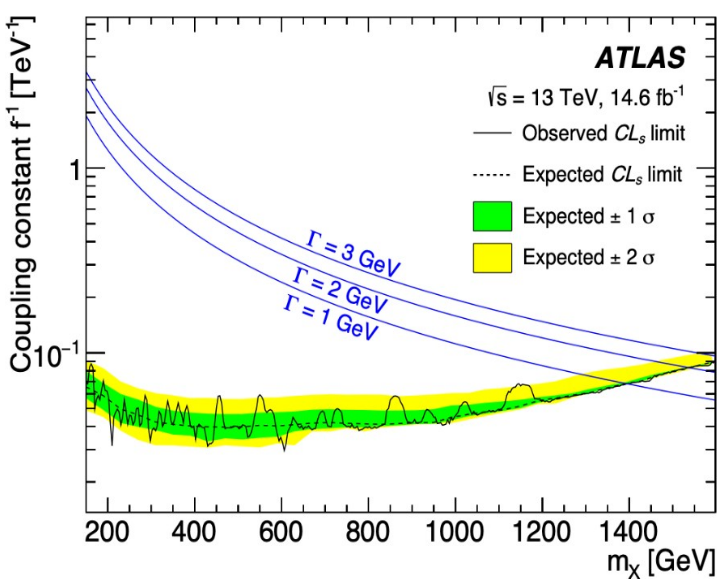
  $Aco_{\gamma\gamma}$<1% ($\gamma\gamma$ back-to-back)

  Matching $m_{\gamma\gamma}$ & $y_{\gamma\gamma}$ in PPS & ECAL

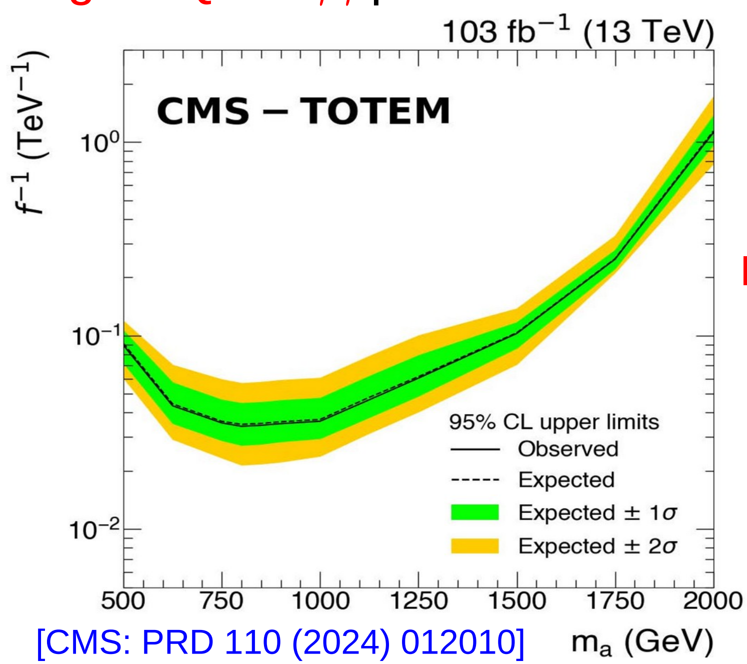



0 (1) evt exp. (obs.)

■ Background: Random pileup pp tags + QCD $\gamma\gamma$ production




[ATLAS: JHEP 07 (2023) 234]




[CMS: PRD 110 (2024) 012010]

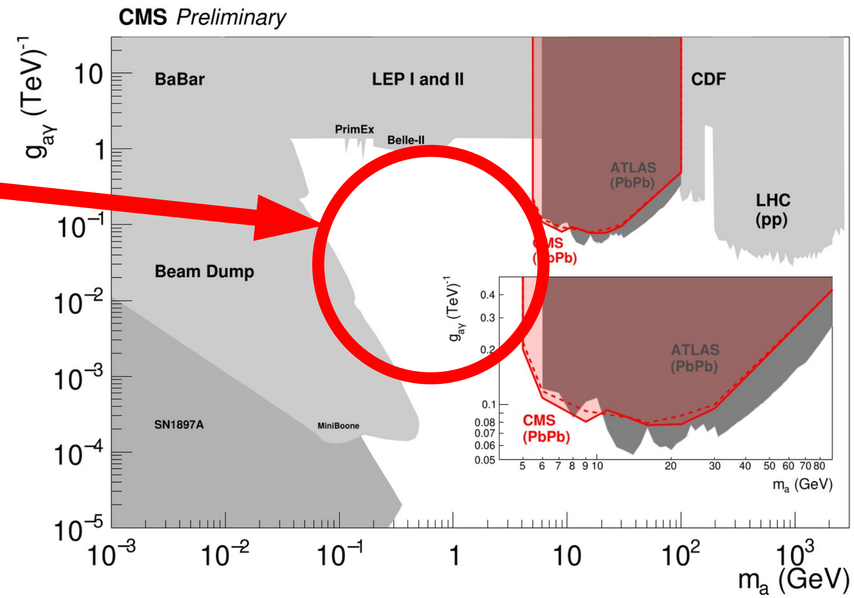
BR($a \to \gamma\gamma$)=1

■ Most stringent ALP limits over $m_a$ = 0.5–2 TeV: $g_{a\gamma}$ > 0.1–1 TeV$^{-1}$

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

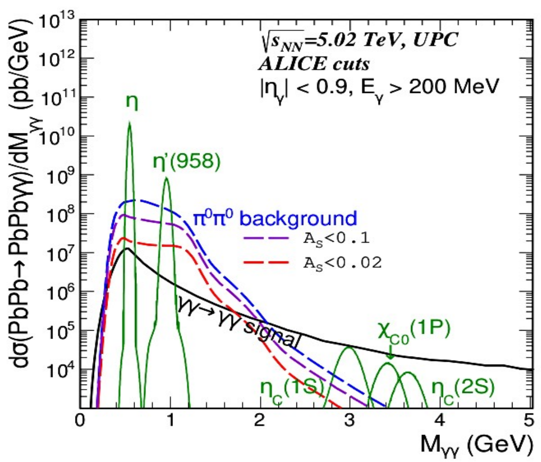
- Wide window of unexplored parameter space $m_a$ = 0.1–5 GeV between bounds from Belle-II, beam-dumps, and CMS/ATLAS:

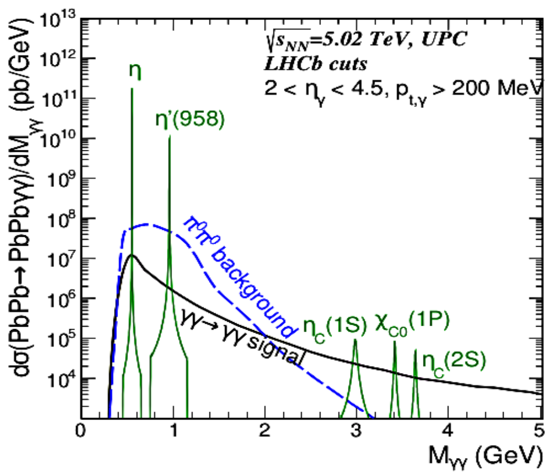
  Too low-$p_T$ photons for trigger/ reconstruction in ATLAS/CMS...




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

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

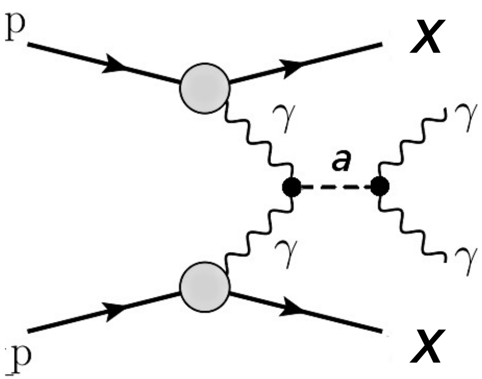


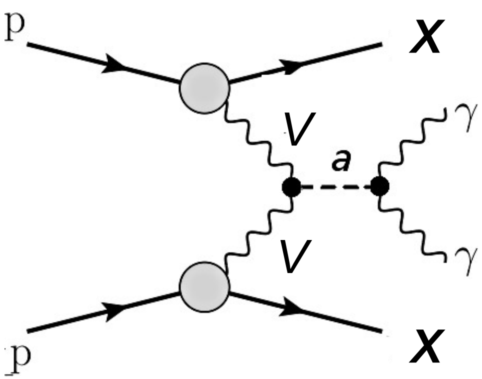



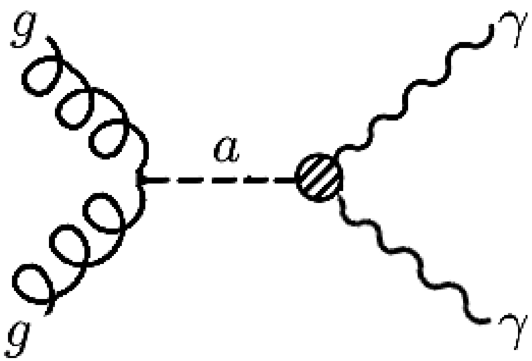

*Pheno analysis. Should be redone with full detector response sim. by ALICE/LHCb experiments...*

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

# (4) ALP searches from inclusive $\gamma\gamma$ at the LHC



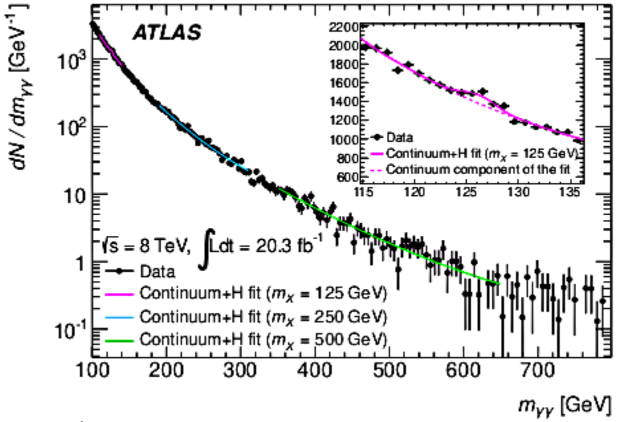



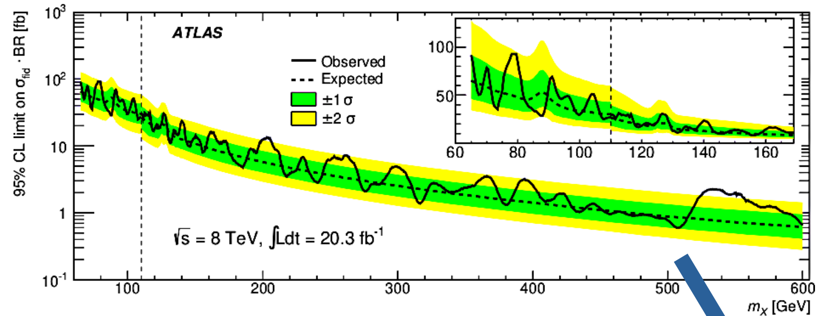




...

# ALP bounds from pp→$a(\gamma\gamma)$+X searches

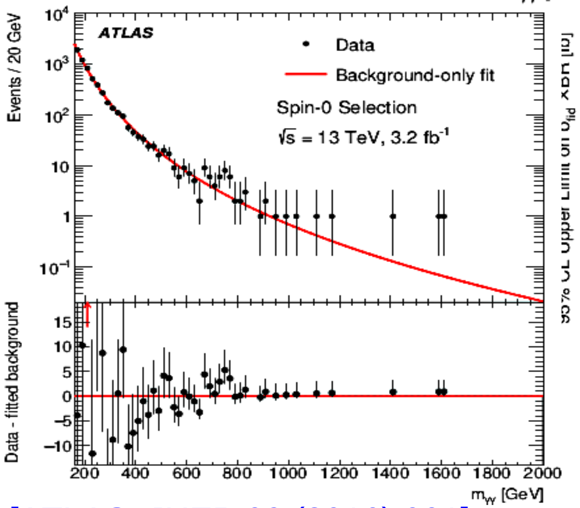
- Generic spin-0 (extended Higgs) diphoton searches over $m_{\gamma\gamma}$ = 60 GeV–2 TeV:



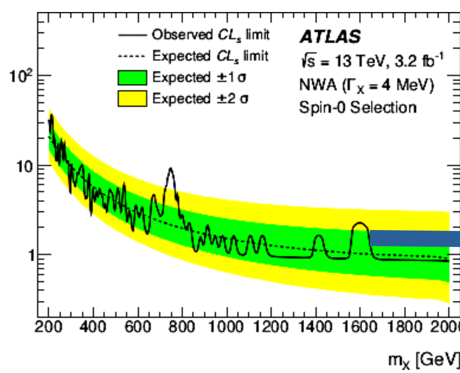




[ATLAS, PRL 113 (2014) 171801]

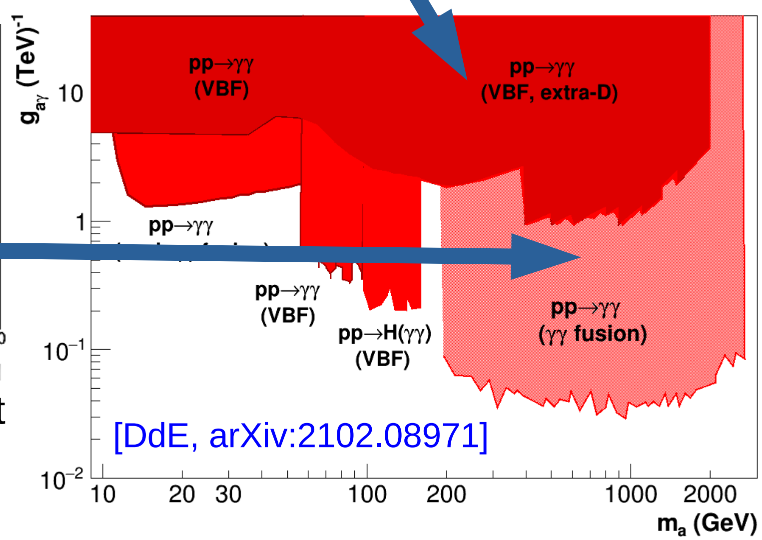
*"750 GeV" peak saga (2017)*




[ATLAS, JHEP 09 (2016) 001]




(Similar upper limit plot for varying widths $\Gamma_X$ = 2-10% $m_X$)

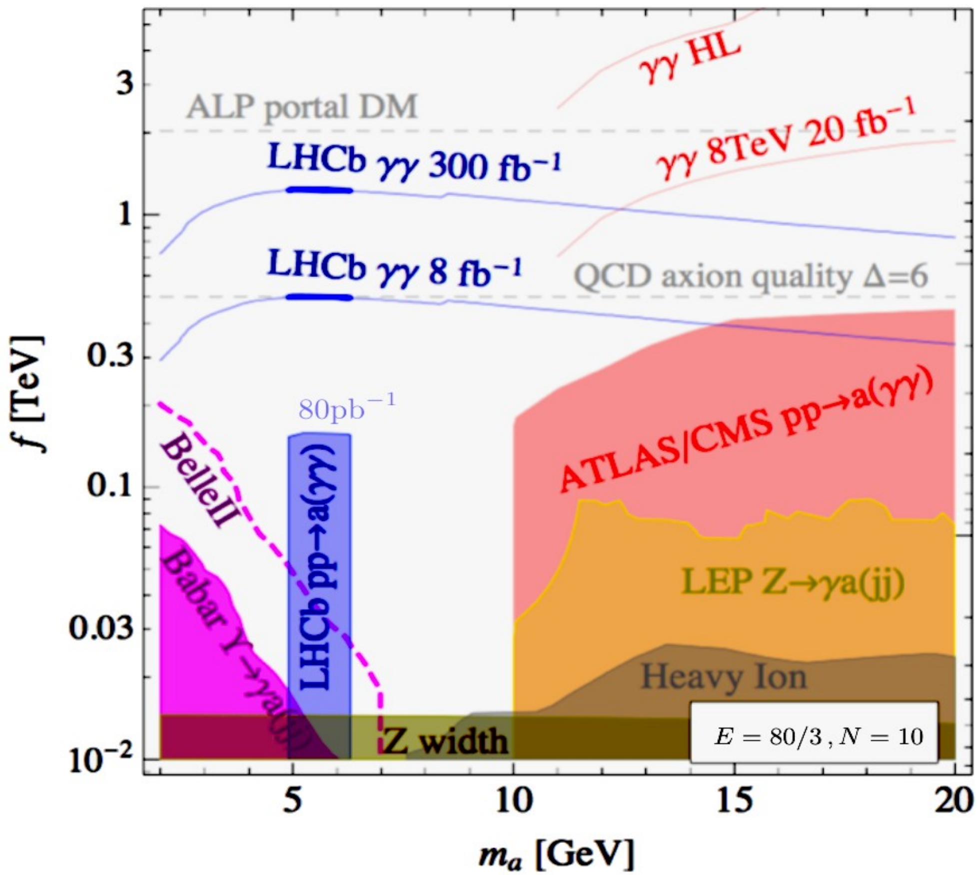



[DdE, arXiv:2102.08971]

- Recast onto ALP bounds in $(m_a, g_{a\gamma})$ plane: Similar to excl.-γγ over $m_a$ = 0.3–2 TeV
- Many more LHC (2γ,3γ,4γ) searches available today: ALP reinterpretation needed

# ALP bounds from pp→$a(\gamma\gamma)$+X searches

- LHCb has unique trigger/reconstruction capabilities for low $p_T$ objects:
- Photon-triggered data ($B_s \to \gamma\gamma$) reinterpreted:



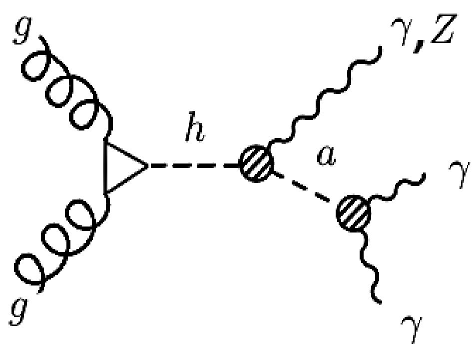

[Cid-Vidal et al., JHEP 01 (2019) 113]

[See also L.Henry, next]

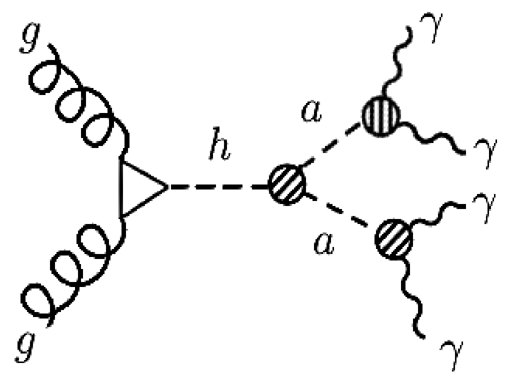
- Complementary searches with ATLAS/CMS for $m_a \approx$ 1–50 GeV

# (5) ALP searches from exotic H boson photon decays

pp → H → a($\gamma\gamma$)+Z,$\gamma$



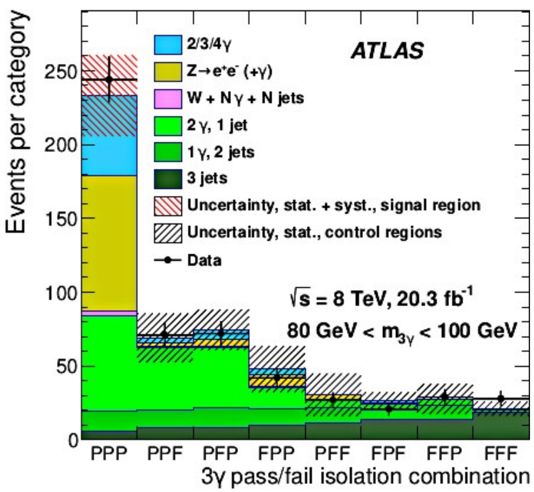

pp → H → a($\gamma\gamma$)+a($\gamma\gamma$)

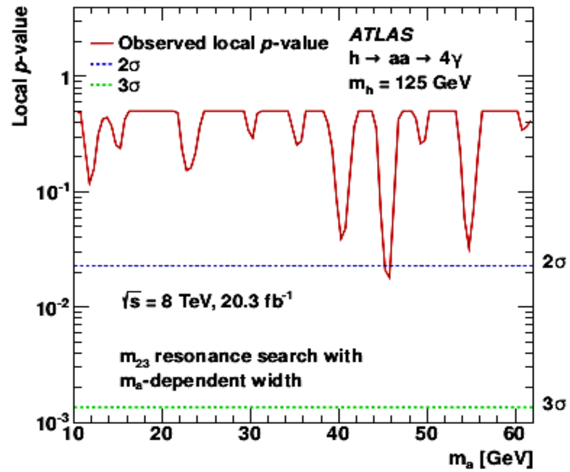


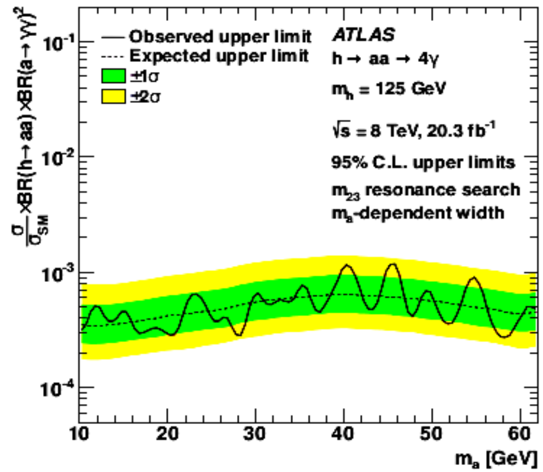

[See also: Jeremi Niedziela, Thu.]

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

- Triphoton and 4-photon resonance searches (pp, 20.3 $fb^{-1}$):



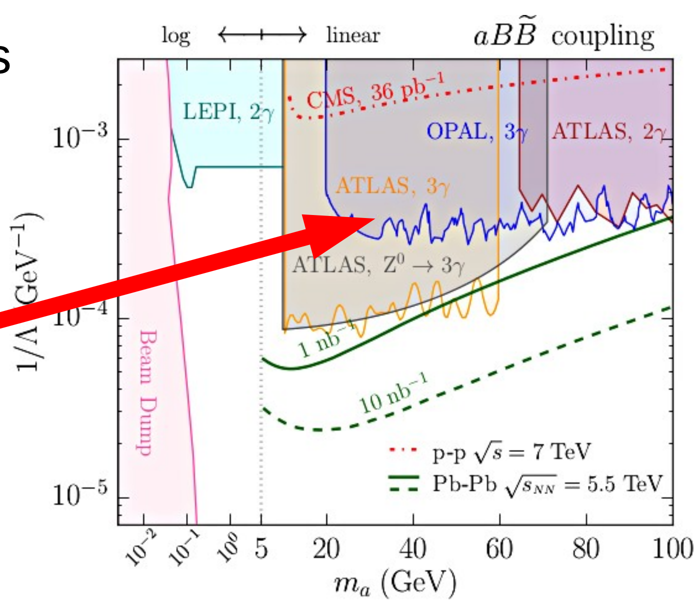



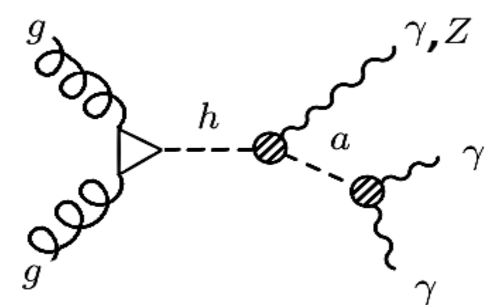

[ATLAS, EPJC76 (2016) 210]

- Recast into ALP bounds with hypercharge coupling:

  Comparable limits to Z → $\gamma\gamma\gamma$ for $m_a$ = 10–60 GeV:

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



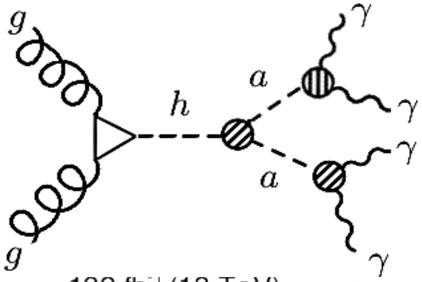



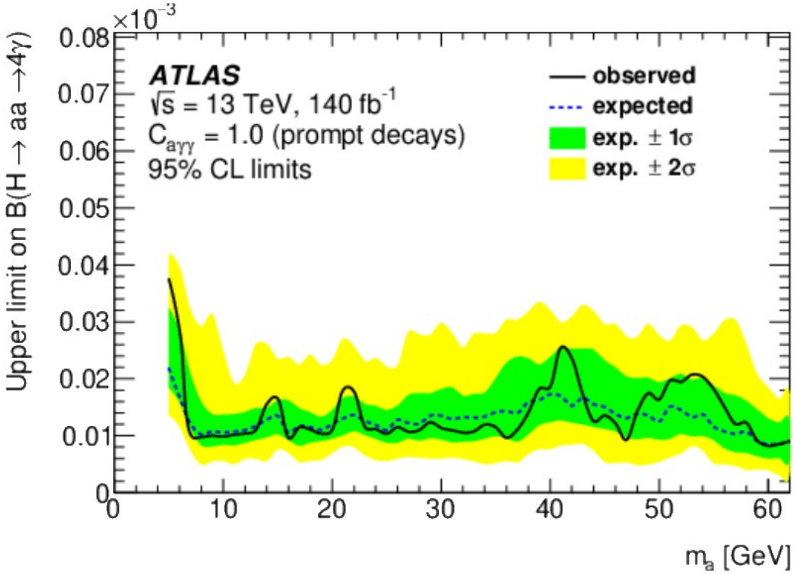

NB: Approx. bounds due to intrinsic 3,4$\gamma$ kinem. combinatorics uncerts. Should be redone by experiments.

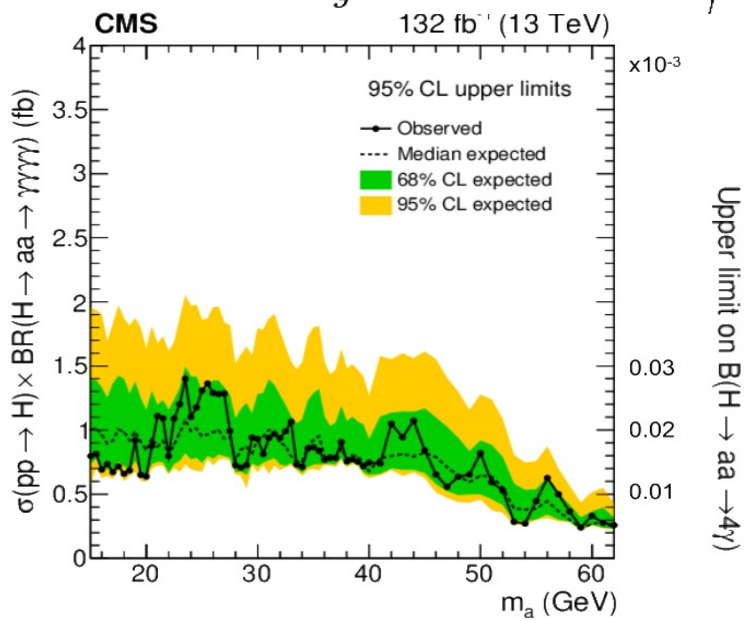
# ALPs limits via H → aa searches (pp, 13 TeV)

- H → a(γγ)+a(γγ) resonance searches with full Run-2 (pp, 140 fb$^{-1}$):
  - 4 resolved photons (allowing some of them to be missing)
  - Merged photons using neural networks

  Scan $m_{inv}(\gamma\gamma)$ to search for narrow $m_a$ peaks:



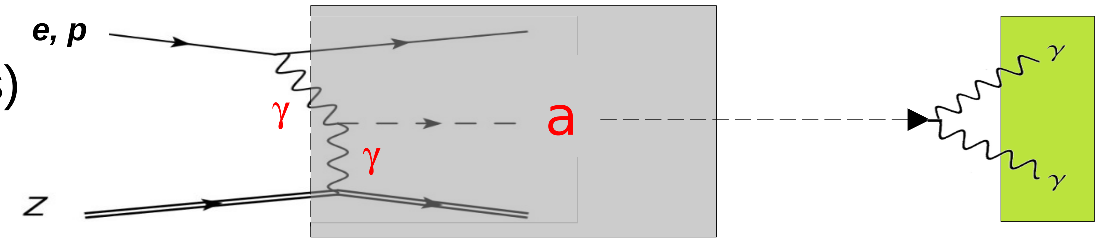




BR > 10$^{-5}$ excluded for $m_a \approx$ 5–60 GeV

- Exotic Higgs decays H → a(γγ)a(γγ) not directly translatable into ($m_a$, $g_{a\gamma}$) plane ($C_{HZ}$ and $C_{Ha}$ coeffs. generally not related to $C_{\gamma\gamma}$) but interesting constraints on dim-6,7 EFT ops.

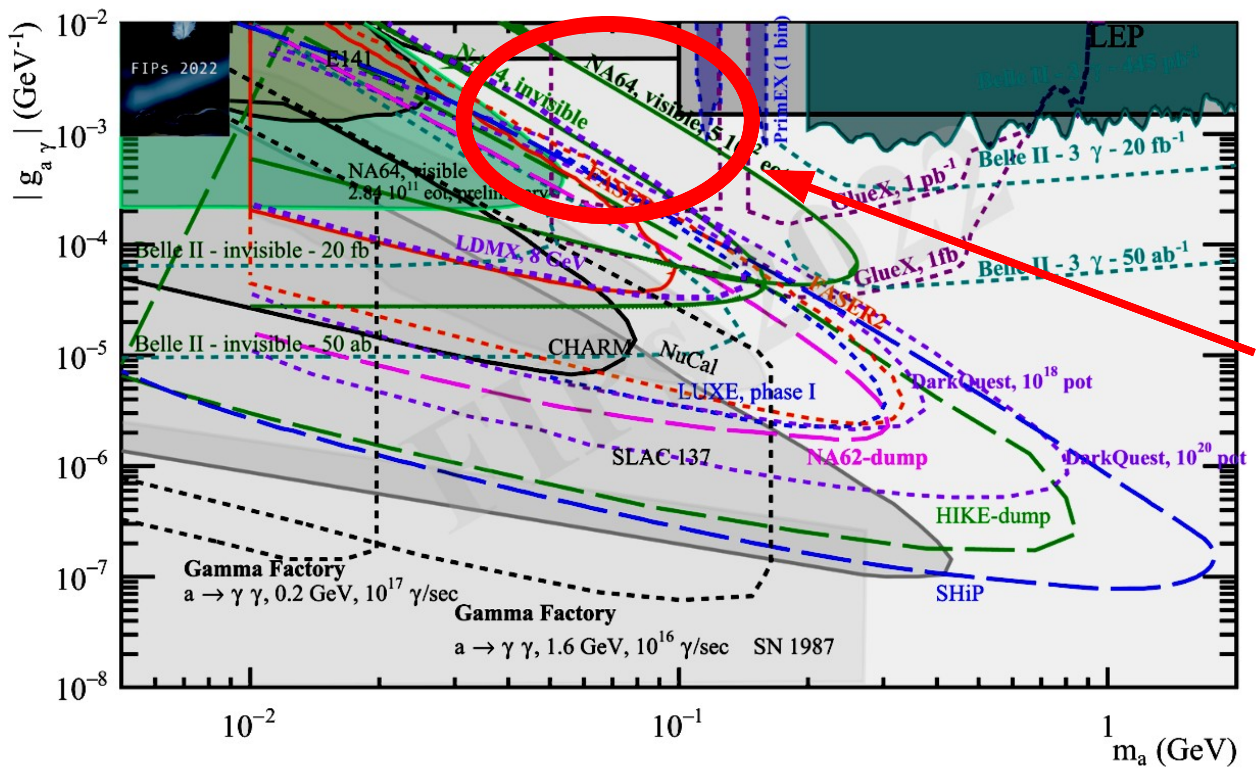
# Summary (1): ALP searches with fixed targets

- Fixed-target & beam dumps (via $\gamma\gamma \to a$ Primakoff process) provide best ALP searches over $m_a \approx 0.1 - 100$ MeV




SLAC141/137 → CHARM/NuCal → NA64 → NA62 (soon?): $g_{a\gamma} > 10^{-3}$–$10^{-6}$ GeV$^{-1}$

- Future experiments (Dune, DarkQuest, SHiP, FASER, MATHUSLA,...) will extend current limits down to $g_{a\gamma} \approx 10^{-7}$ GeV$^{-1}$ over $m_a \approx 0.1$ MeV – 1 GeV

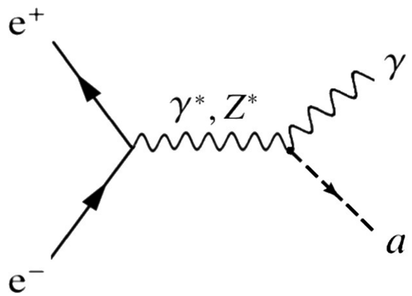


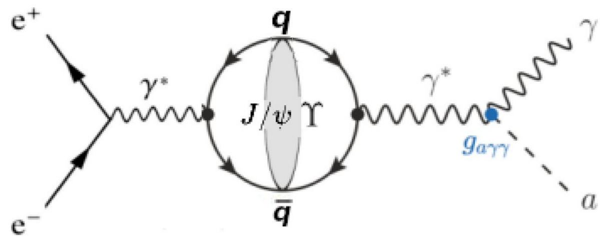

[BC9 ALP photon dominance, FIPs 2022]

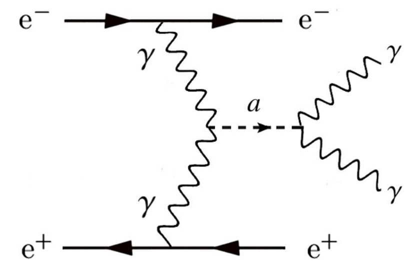
There is a difficult and interesting "wedge" between NA64 and GlueX/Belle-II to be covered!

# Summary (2): ALP searches at $e^+e^-$ colliders

- $e^+e^-$ colliders provides best ALP searches over $m_a$ = 0.5–5 GeV today




Monophoton + miss. energy from LL ALP

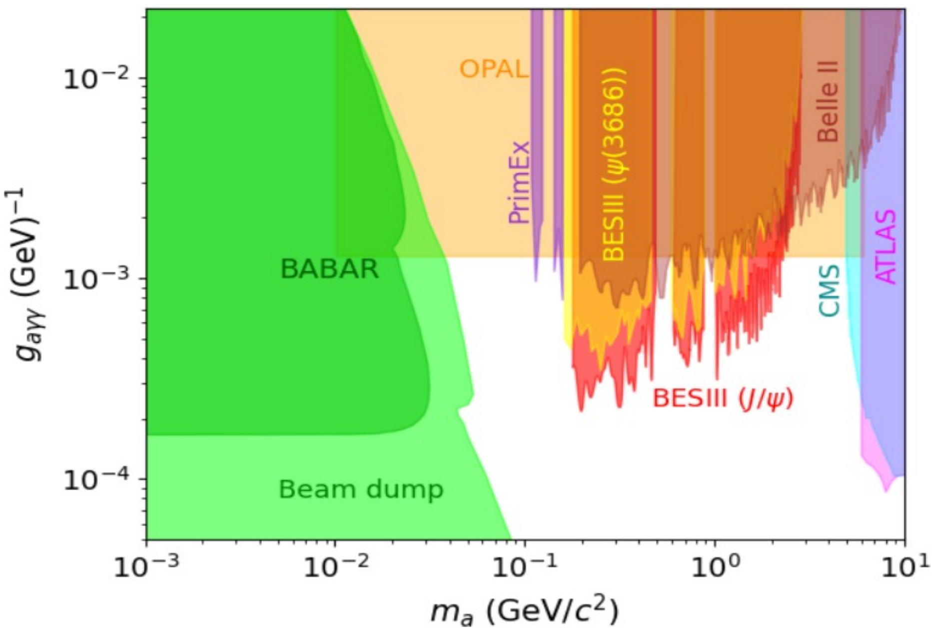
Best for $m_a$ < 50 MeV

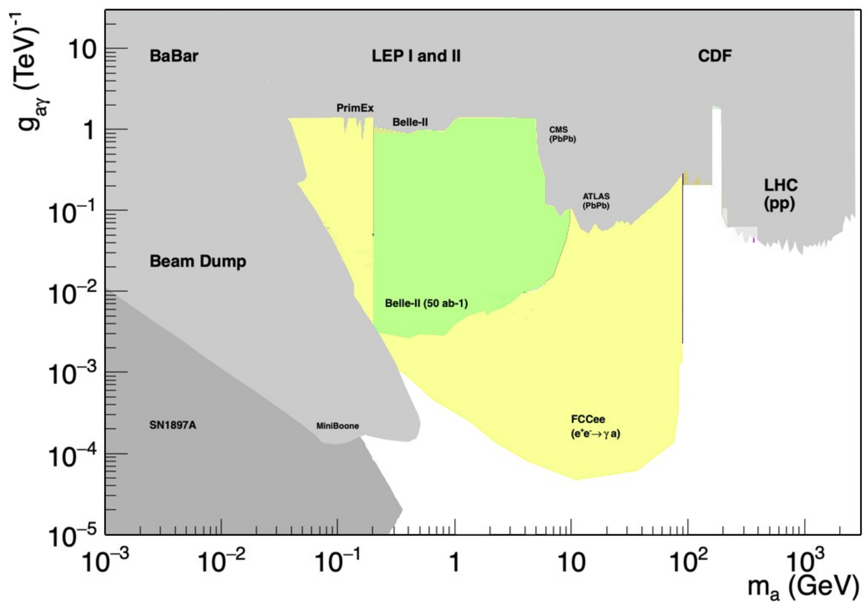
3-gamma final state:

Best for $m_a$ = 50 MeV – 10 (90) GeV

$\gamma\gamma$ fusion

Best for $m_a$= 90–350 GeV

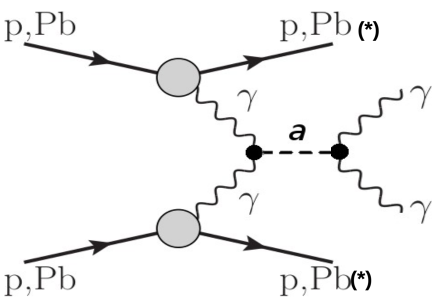


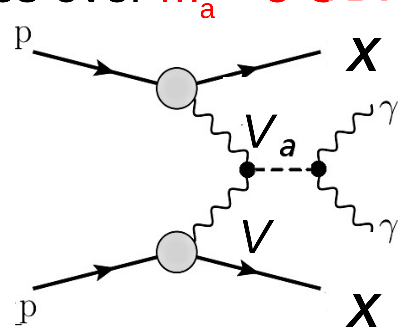

- Tera-Z factory will have $\times 10^3$ improved sensitivity over $m_a$ = 0.2–91 GeV down to $g_{a\gamma} \approx 6\cdot10^{-5}$ TeV$^{-1}$

# Summary (3): ALP searches at the LHC

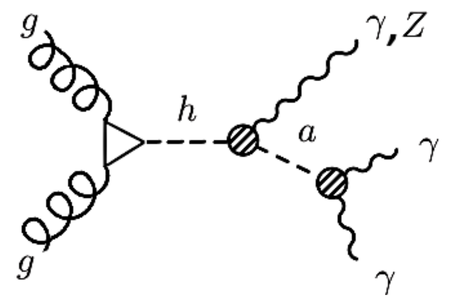
- LHC provides best ALP searches over $m_a$ = 5 GeV – 2 TeV in 2-,3-,4-$\gamma$ final states:



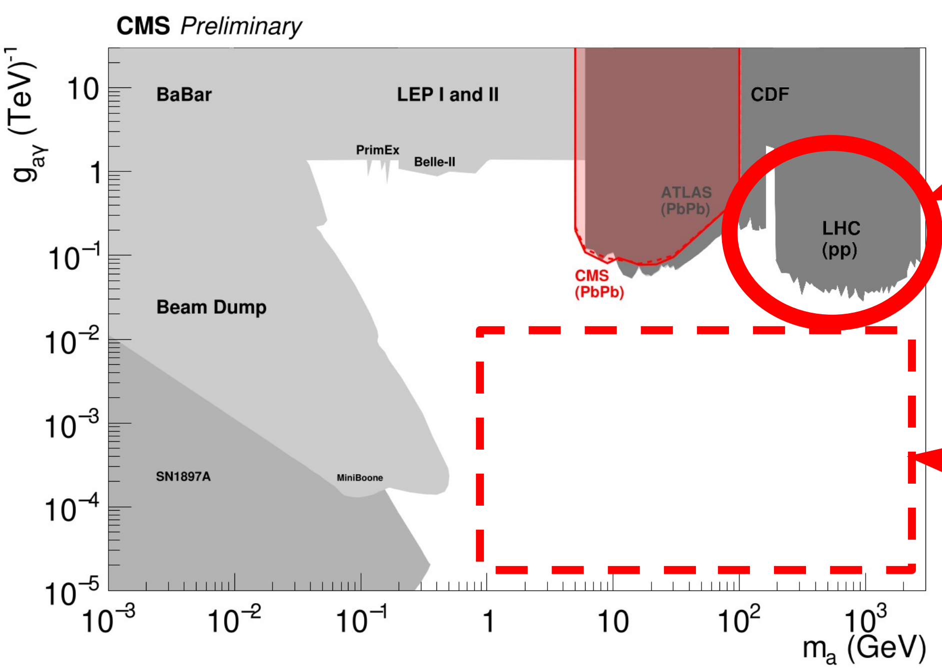

Exclusive diphotons:
Best for $m_a$= 5–100 GeV (PbPb)
Best for $m_a$ = 0.1–2 TeV (pp tagging)




Inclusive diphotons
Best for $m_a$= 0.1–10 TeV




H→3γ,4γ in pp collisions:
Provide extra constraints on dim-6,-7 operators



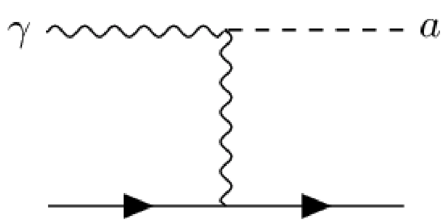

Need to recast many existing inclusive 2γ,3γ,4γ BSM searches

Target phase space for HL-LHC:
Lots of room to go to much lower $g_{a\gamma}$ couplings over
$m_a \approx$ 1 GeV – 10 TeV

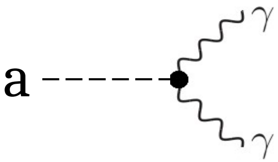
# Back-up slides

# ALPs searches at fixed-target & beam dumps

- Primakoff production: Proton/Electron beam on fixed target emits/produces photon that fuses with EPA photon of target (Z) atoms: $\gamma\gamma \to a(\gamma\gamma)$




Followed by $a \to \gamma\gamma$ downstream:




(also missing energy from LL ALP at FTs)

$$\sigma(\gamma\gamma \to a) = \frac{\pi g^2_{a\gamma\gamma} m_a}{16}\delta(m_{\gamma\gamma} - m_a)$$

- If ALP is long-lived, decay length is of a few meters:

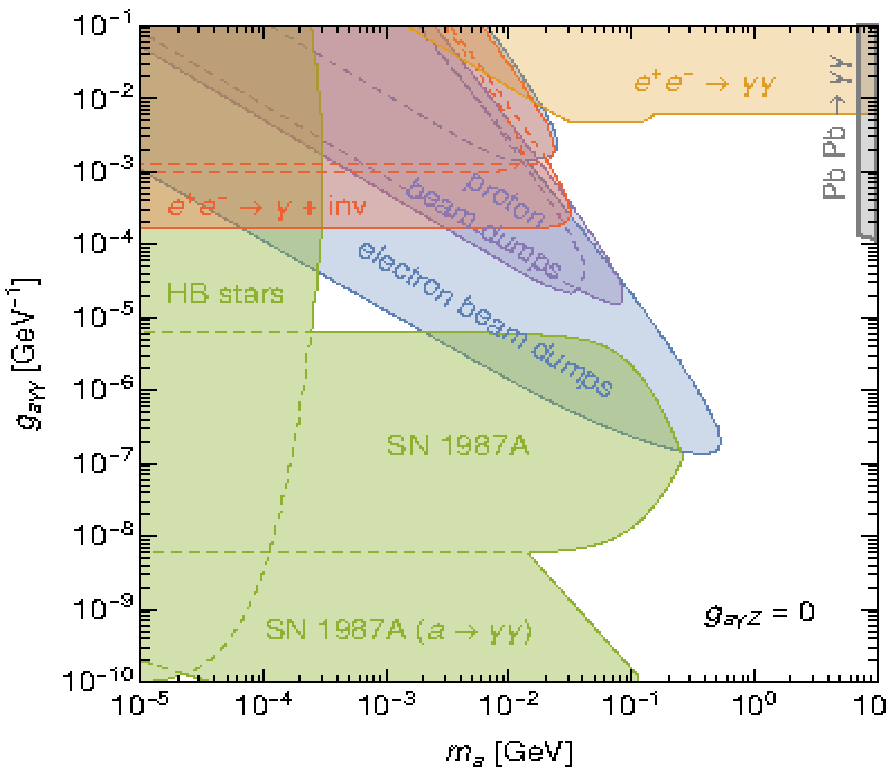
$$l_a = \beta\gamma\tau \approx \frac{64\pi\, E_a}{g^2_{a\gamma}\, m_a^4}$$

$$\approx 40\,\mathrm{m} \times \frac{E_a}{10\,\mathrm{GeV}}\left(\frac{g_{a\gamma}}{10^{-5}\,\mathrm{GeV}^{-1}}\right)^{-2}\left(\frac{m_a}{100\,\mathrm{MeV}}\right)^{-4}$$

- Masses & couplings probed:

  $m_a \approx 0.1$ MeV – 500 MeV

  $g_{a\gamma} \approx 10^{-1} - 10^{-7}$ GeV$^{-1}$




M.J.Dolan et al., JHEP 1712 (2017) 094

# ALP coupling to gluons

- Coupling structure analogous to QCD axions (but with additional mass term)

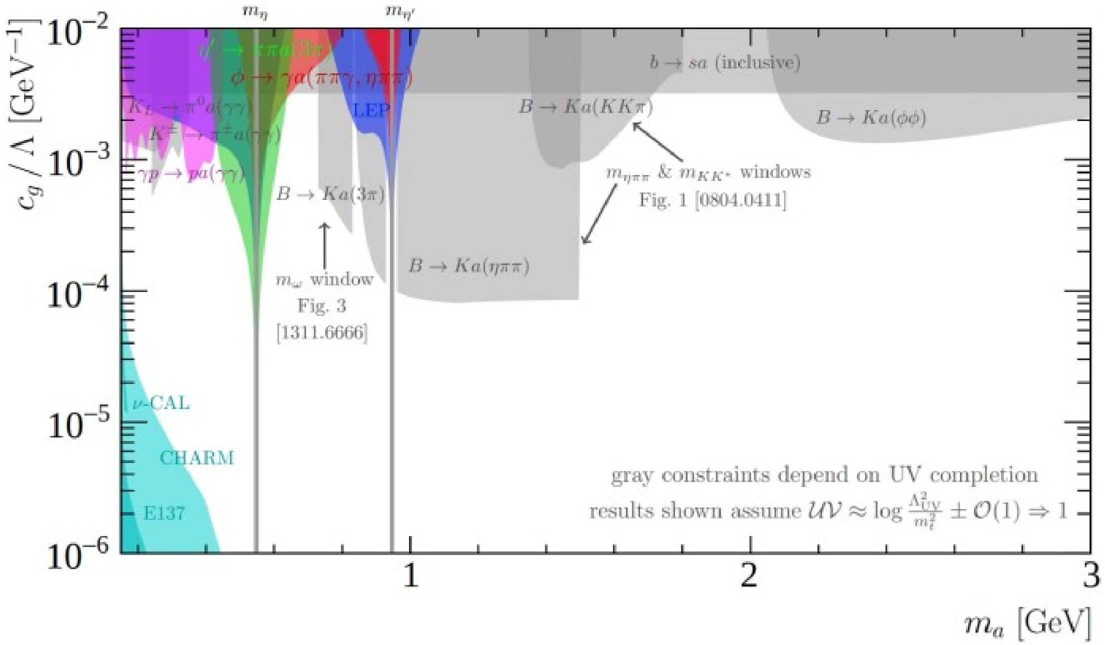
$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + g_s^2 \, C_{GG} \frac{a}{\Lambda} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

- At low energies, this interaction induces both ALP-photon couplings and ALP-fermion couplings

→ Interesting combination of the cases discussed before

→ E.g. ALP production via rare meson decays followed by ALP decay into photons

Aloni et al., arXiv:1811.03474

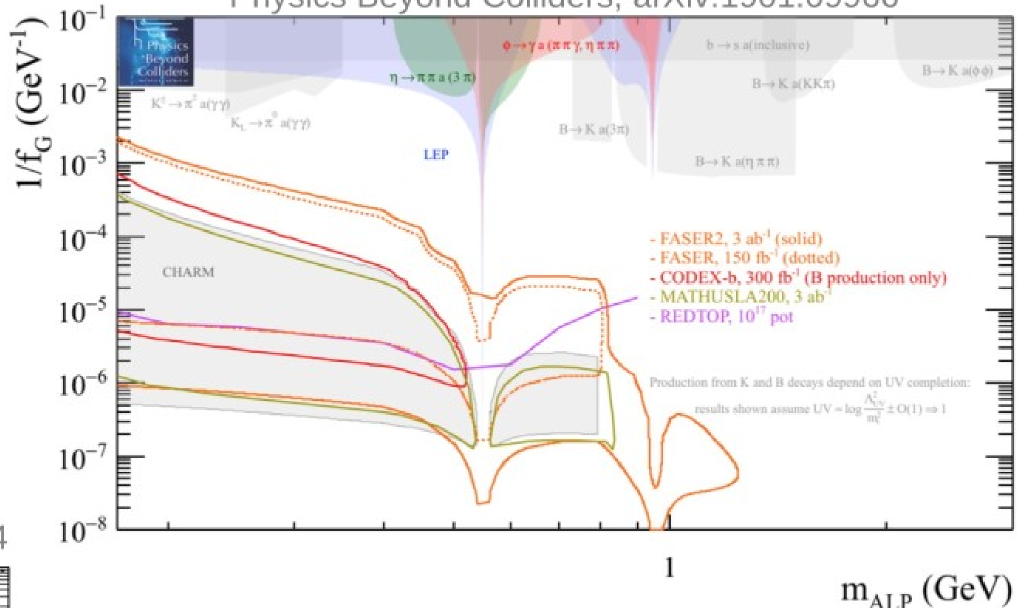



[F. Kahlhoefer, FIPs 2020]

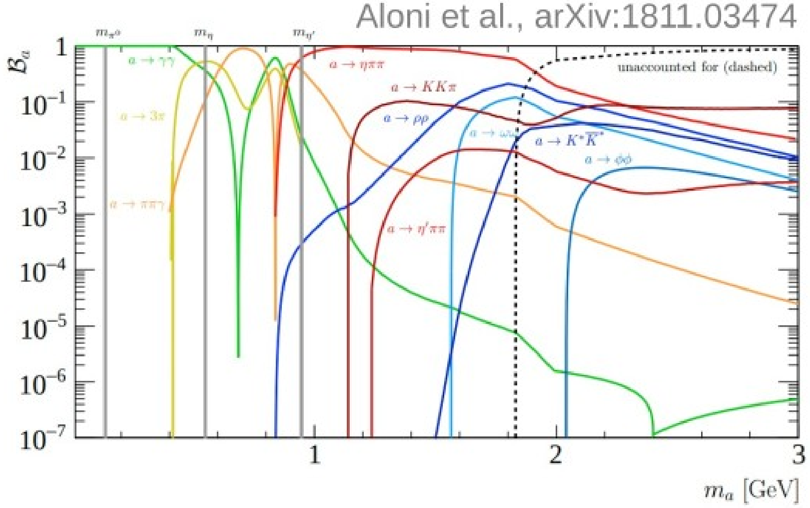
# ALP coupling to gluons at fixed targets

- ALPs coupled to gluons can be produced in a number of different ways:
  - ALP-meson mixing
  - Primakoff production
  - Rare decays
- At the same time, many different decay modes contribute to total width

Physics Beyond Colliders, arXiv:1901.09966




Aloni et al., arXiv:1811.03474

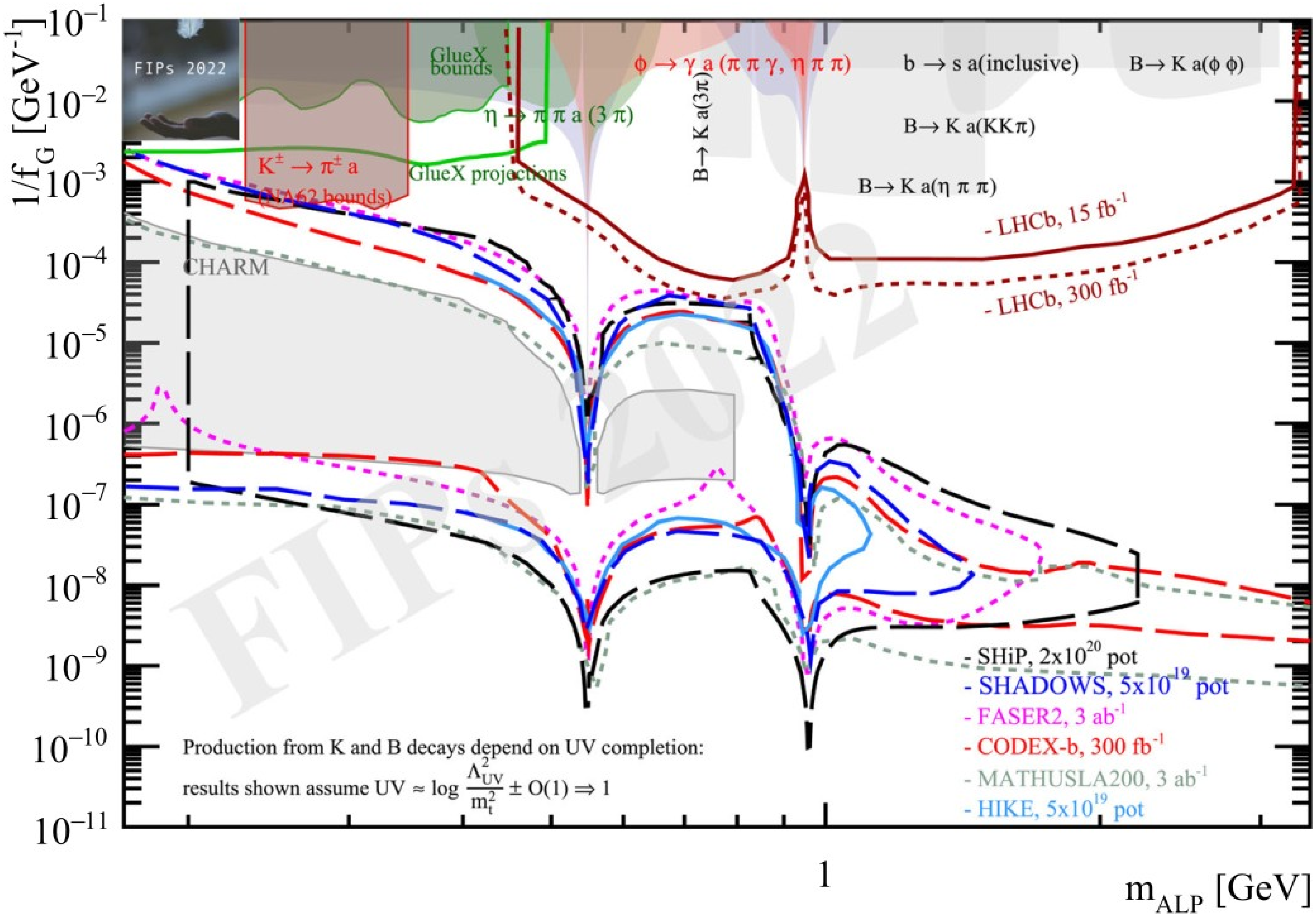



- So far no comprehensive study of experimental sensitivities including all relevant effects
- Exciting opportunity for theory–experiment collaboration

Döbrich, Ertas, Jerhot, FK and Spadaro, in preparation

[F. Kahlhoefer, FIPs 2020]

# ALP coupling to gluons at fixed targets & LHCb




[BC11 ALP gluon dominance, FIPs 2022]

# ALPs searches at the LHC

- Elementary pseudoscalar suggested in many SM extensions:

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

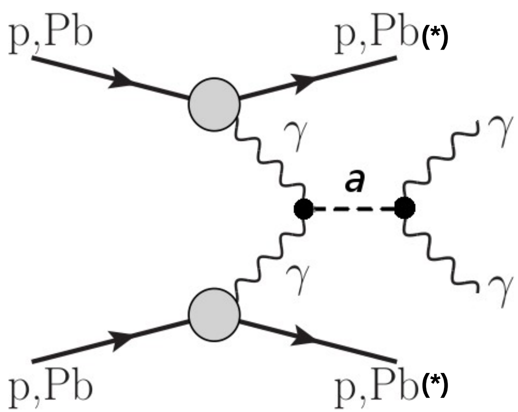
  (2) If long-lived (usually for $m_a$<1 GeV): MET in LHC detector.

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

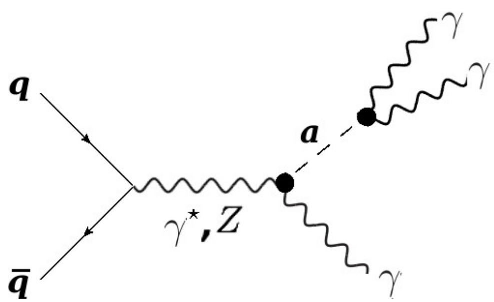
  (4) Standard LHC searches for $m_a$ > 5 GeV in di-, tri, 4-photon final states:

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

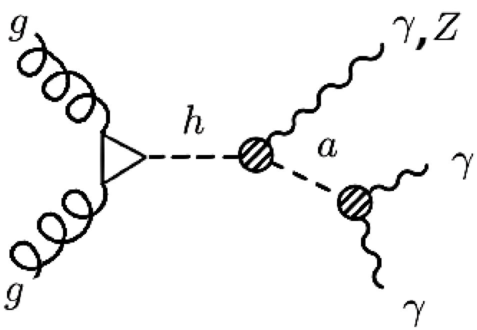
pp,PbPb → $\gamma\gamma$ → a($\gamma\gamma$)




pp → Z → a($\gamma\gamma$)+$\gamma$




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

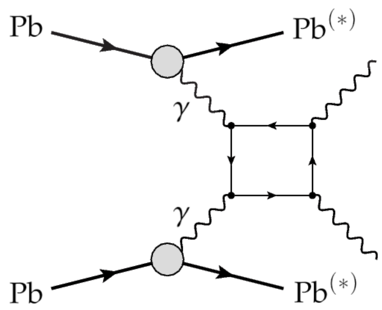



- NB: *Many ALP bounds not always extracted by LHC experiment themselves (but by subsequent pheno recasts of generic 2$\gamma$, 3$\gamma$, 4$\gamma$ resonance searches).*

# Observation of LbL scattering via $\gamma\gamma \to \gamma\gamma$

[CMS-HIN-21-015]

- Light-by-light scattering $\gamma\gamma \to \gamma\gamma$ in PbPb(5.02 TeV) UPCs:

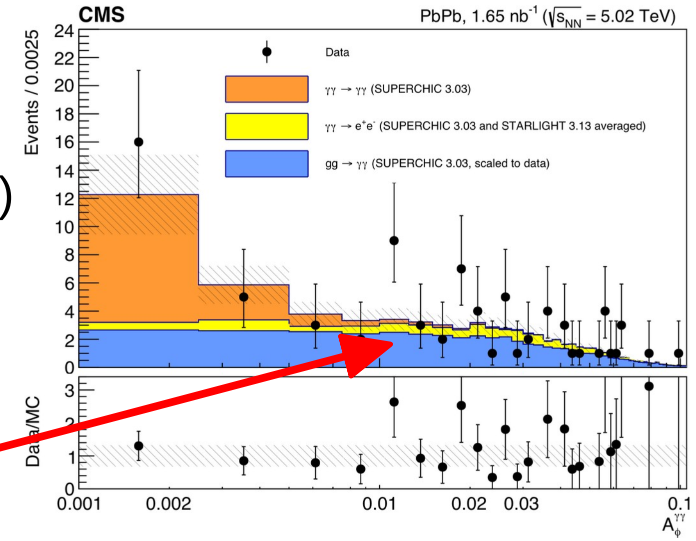



- Analysis strategy:

  Exclusive $\gamma\gamma$ (zero extra activ.)

  $m_{\gamma\gamma}$ > 5 GeV (softest $\gamma$ possible)

  $Aco_{\gamma\gamma}$<1% ($\gamma\gamma$ back-to-back)




- Irreducible backgrounds:

  CEP $gg \to \gamma\gamma$: normalized to high-Aco tail.

  Mis'id $\gamma\gamma \to e^+e^-$: obtained from direct measurement

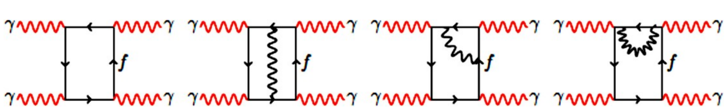
Signal significance: 5.2$\sigma$

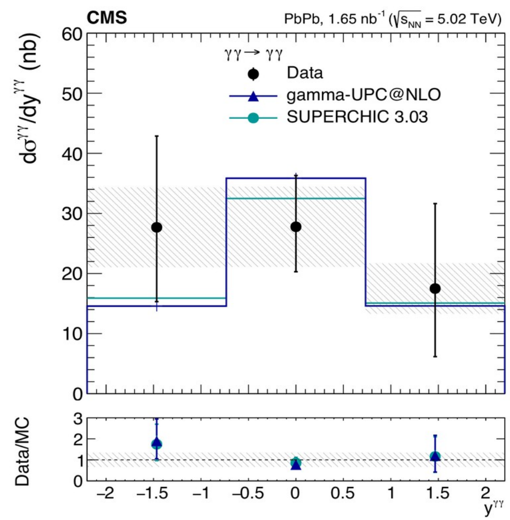
- Measured x-section agrees well with NLO QED+QCD:

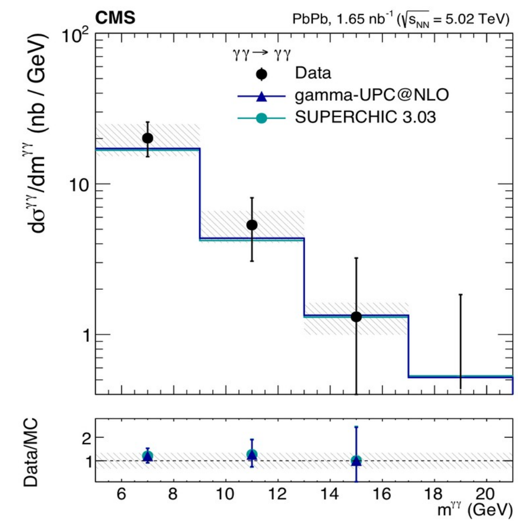
$$\sigma_{\rm fid}(\gamma\gamma \to \gamma\gamma) = 107 \pm 33\,(\text{stat}) \pm 20\,(\text{syst})\,\text{nb}$$

$$\sigma_{\rm NLO}(\gamma\gamma \to \gamma\gamma) = 95.4 \pm 2.0\,\text{nb}$$

K-factor NLO/LO ≈ few %





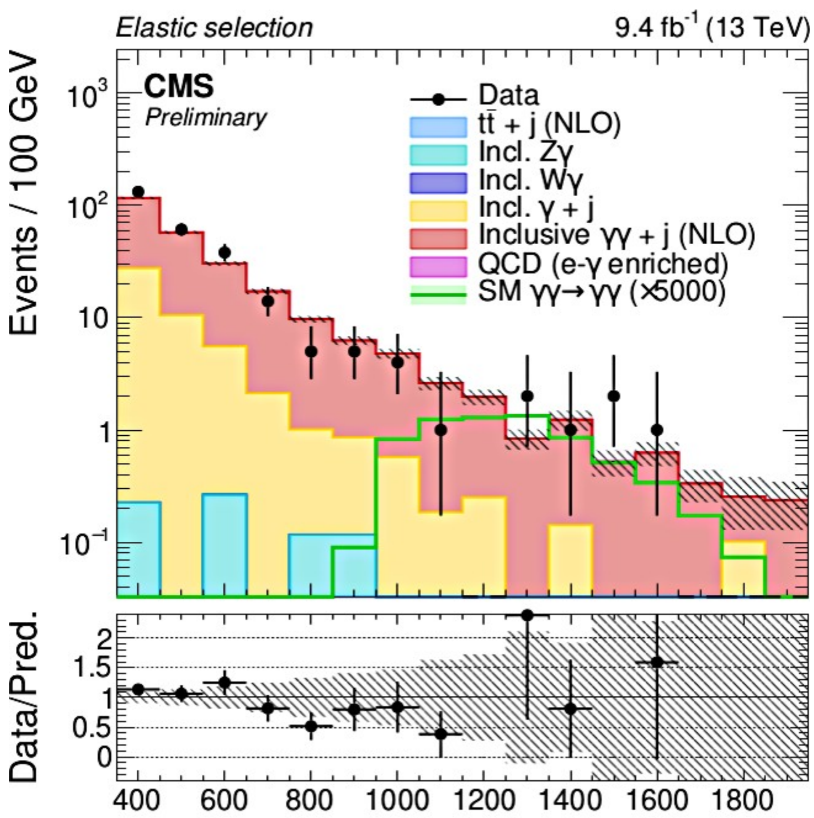




[NLO: A.A.H et al. JHEP 03 (2024) 121, PLB 851(2024) 138555]

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

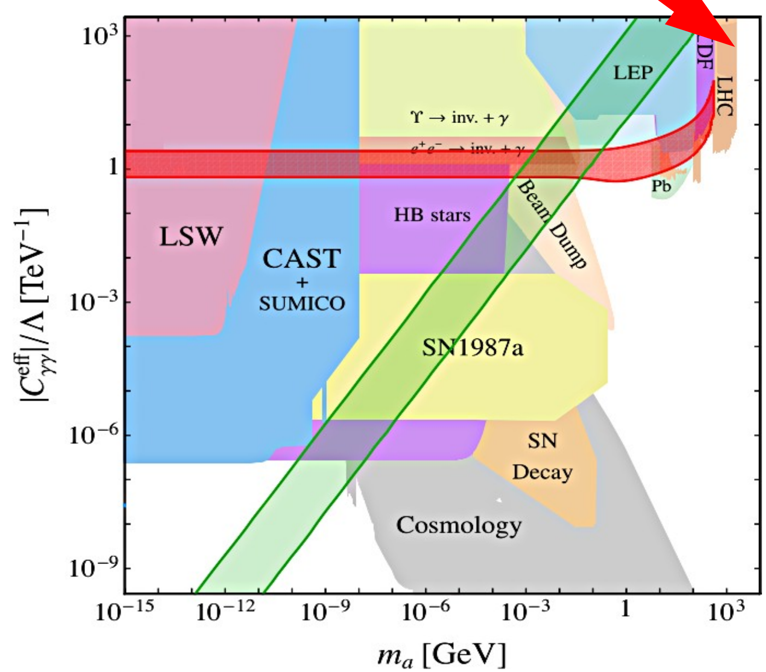
- Exclusive diphoton search with fwd proton tagging (CT-PPS, 9.4 $fb^{-1}$):
  - 2 photons ($E_T$>75 GeV, $|\eta|$<2.5) with $m_{\gamma\gamma}$ > 350 GeV, and low acoplanarity
  - Pileup removal: Kinematic matching between $m_{\gamma\gamma}$ & $m_{pp}$ and $y_{\gamma\gamma}$ & $y_{pp}$
- NO excess found.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

(limits set on anomalous quartic 4-γ couplings)



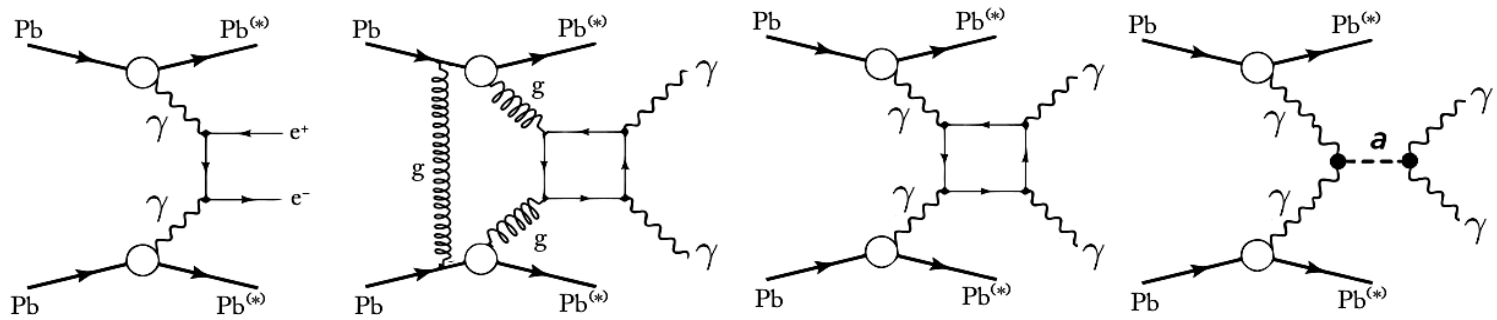

[CMS/TOTEM, EXO-18-014]

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

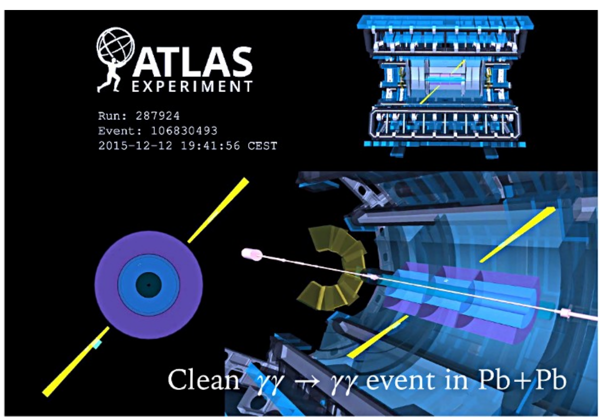


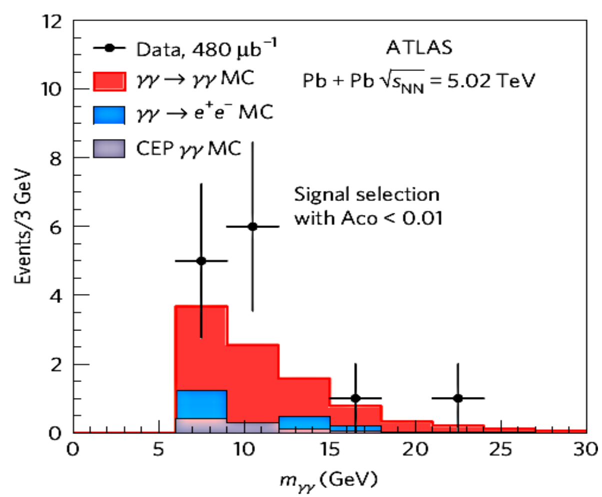
# Evidence for $\gamma\gamma \to \gamma\gamma$ (PbPb, 5 TeV)

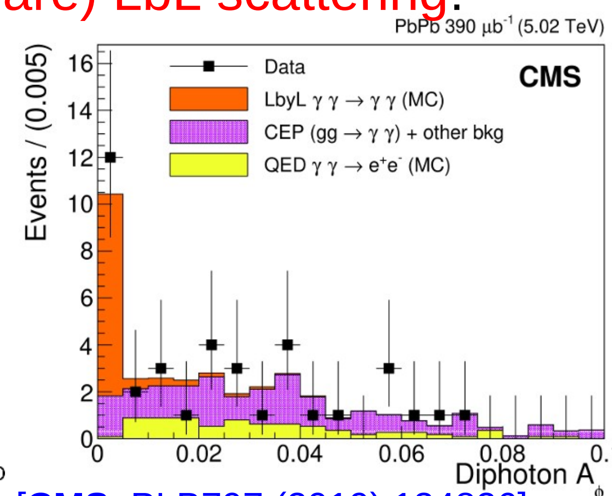
- First evidences for exclusive diphoton in PbPb colls at 5 TeV (~0.5 $nb^{-1}$):
  - 2 photons ($E_T$>2–3 GeV, $|\eta|$<2.5, $m_{\gamma\gamma}$>5 GeV) with no hadronic activity over $|\eta|$<5
  - Photon pair: $p_T$<1 GeV, acoplanarity $A\varphi$ < 0.03–0.01 (coherent quasireal $\gamma$'s with $p_T$~0)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



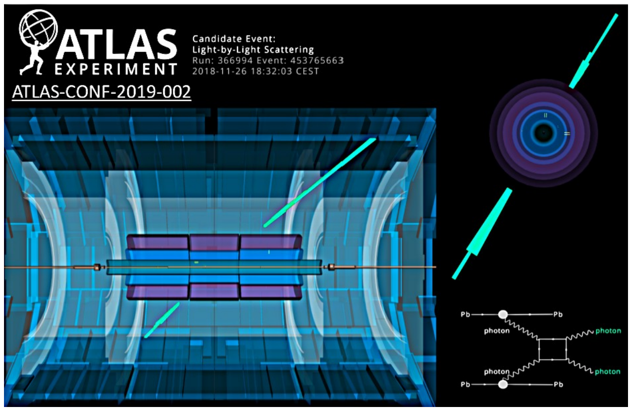




[ATLAS, Nat.Phys. 13 (2017) 852]

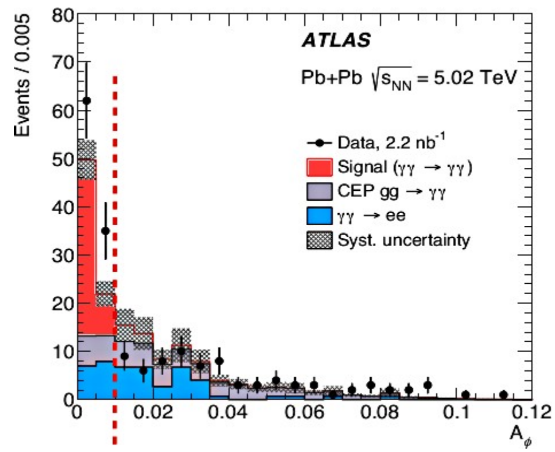
[CMS, PLB797 (2019) 134826]

# 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]

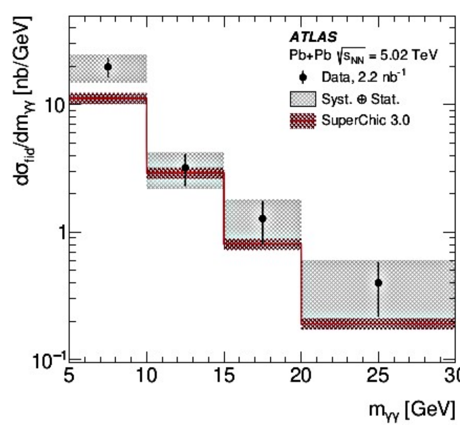


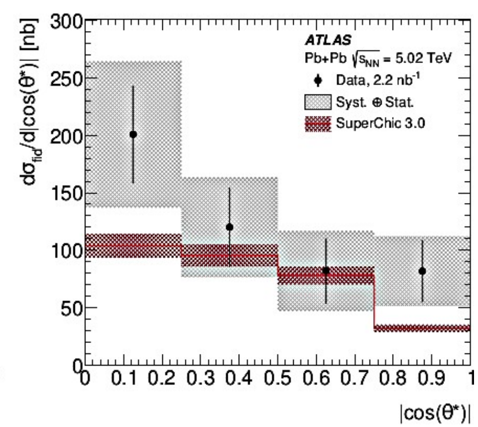

Observed: 97 evts
Expected: 45 signal
+ 27 backgd.

- 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

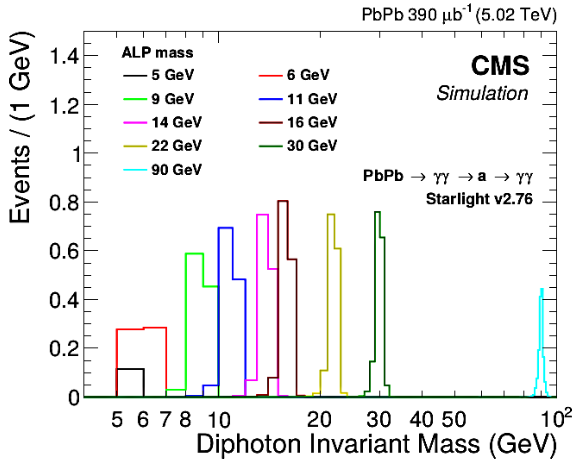



[**ATLAS**, arXiv:2008.05355]

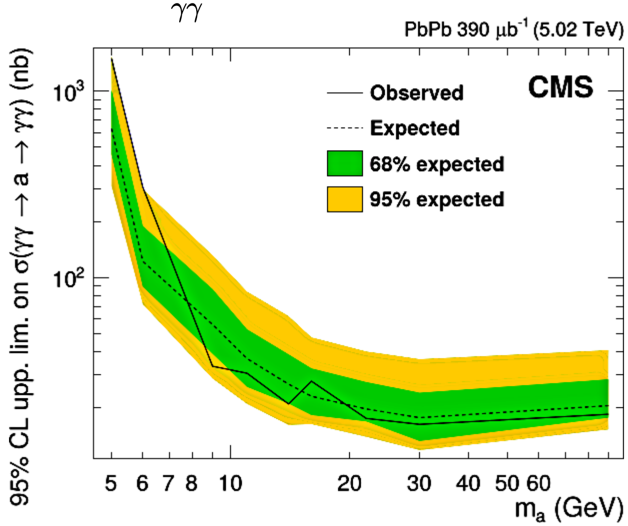
# First ALPs limits via $\gamma\gamma \to a \to \gamma\gamma$ (PbPb, 5 TeV)

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

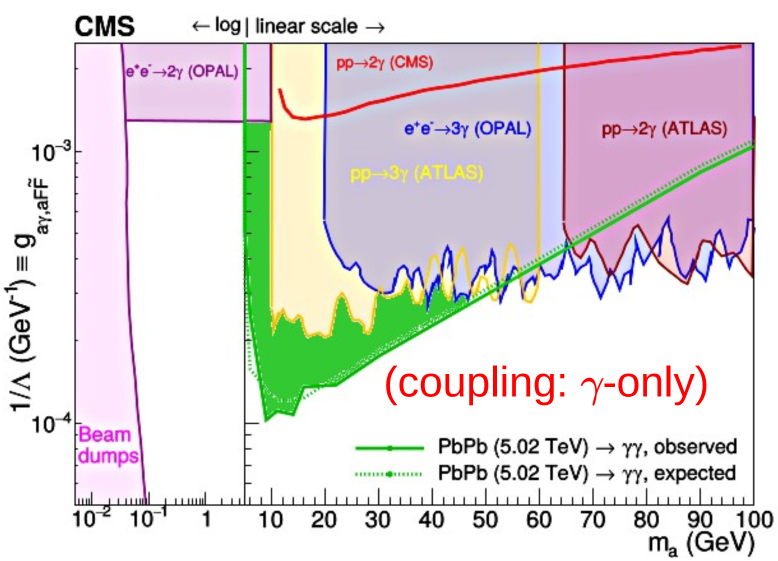


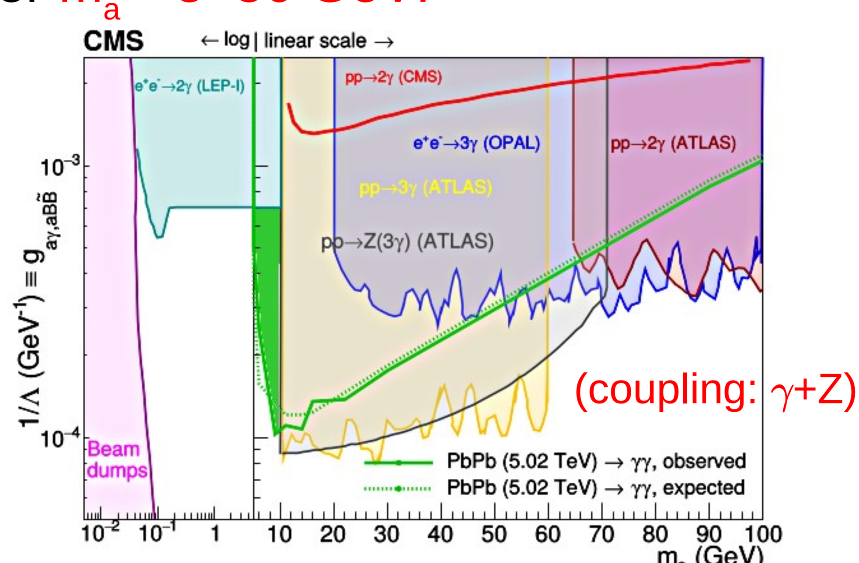

No significant excess observed:

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




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

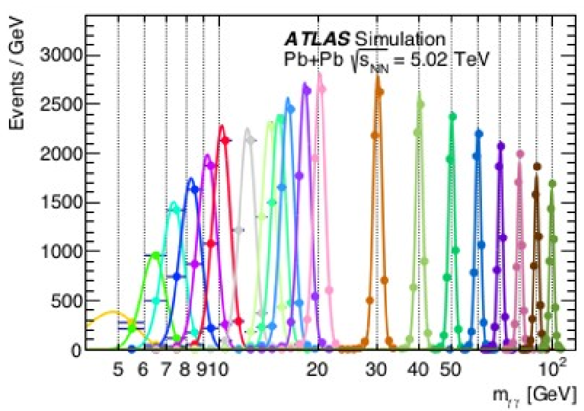


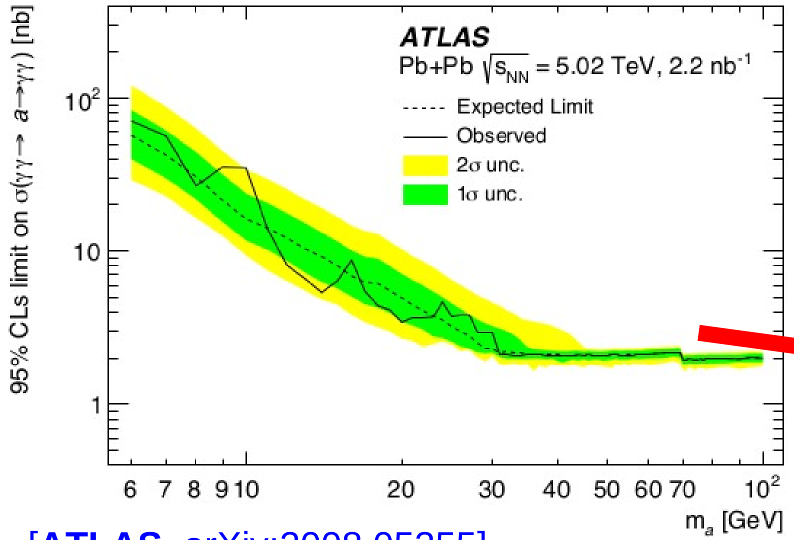



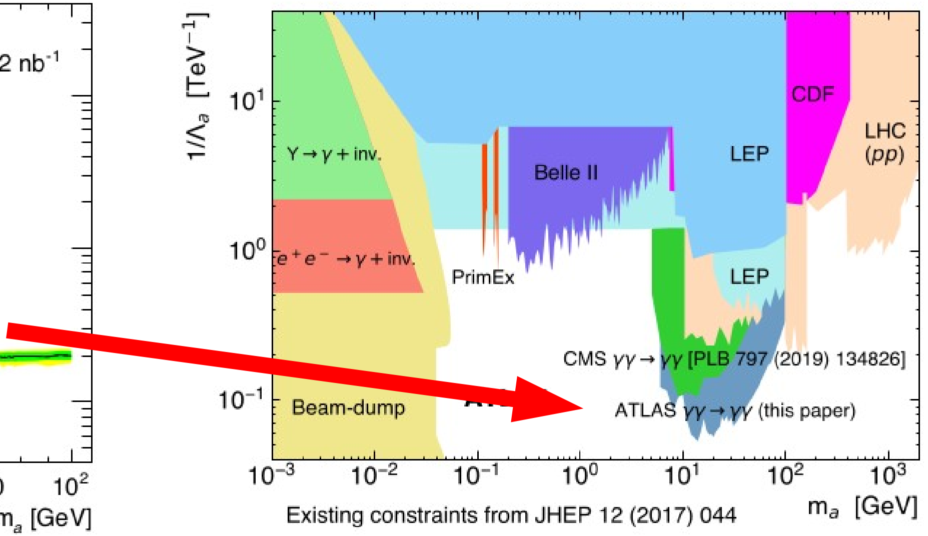

[CMS, PLB797 (2019) 134826]

# 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.



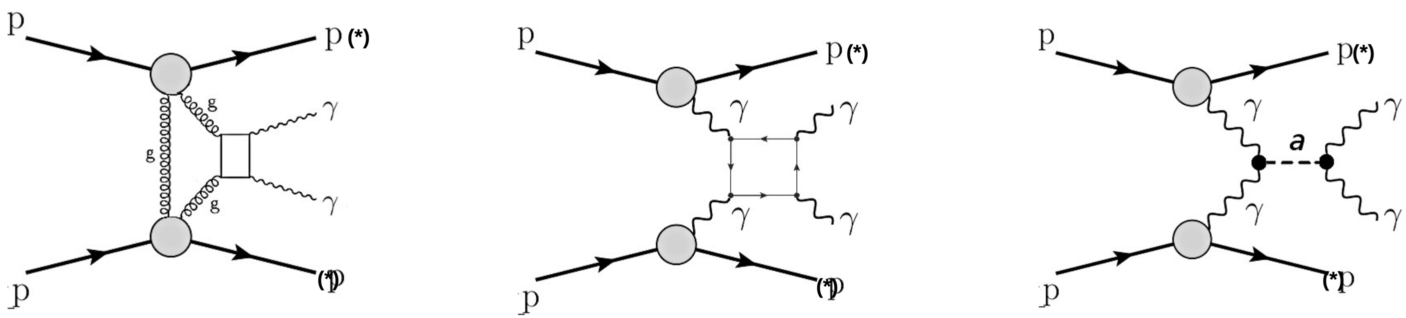




[ATLAS, arXiv:2008.05355]

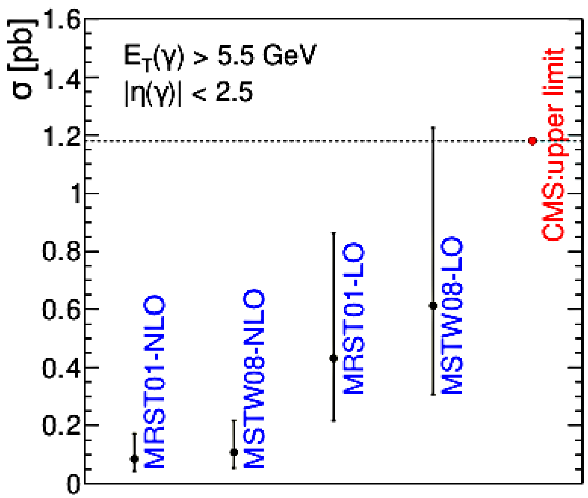
- Most stringent limits to date on ALPs over $m_a$ = 6–100 GeV
- $\sigma(\gamma\gamma\to a\to\gamma\gamma)$ > 2–70 nb excluded at 95% C.L. over that mass interval.

# Low-mass pp → p γγ 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:



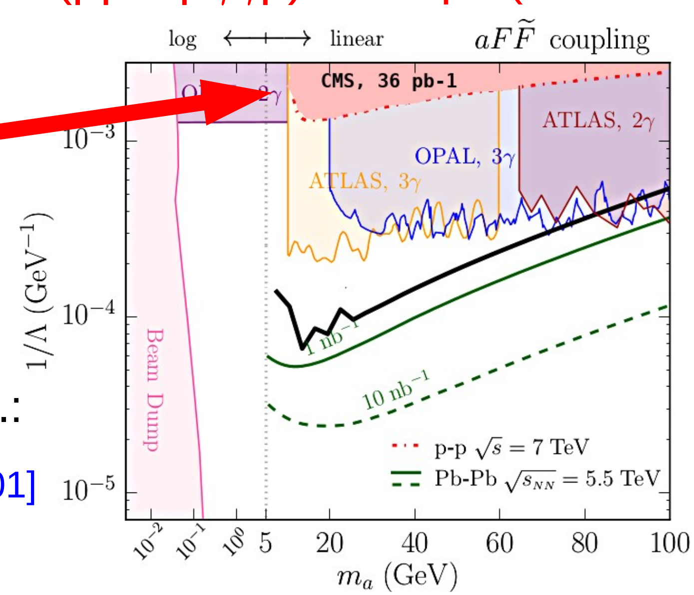

  - NO event found. Upper CEP/LbL/ALP x-section: σ(pp → pγγp)>1.18 pb (95% C.L.)




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

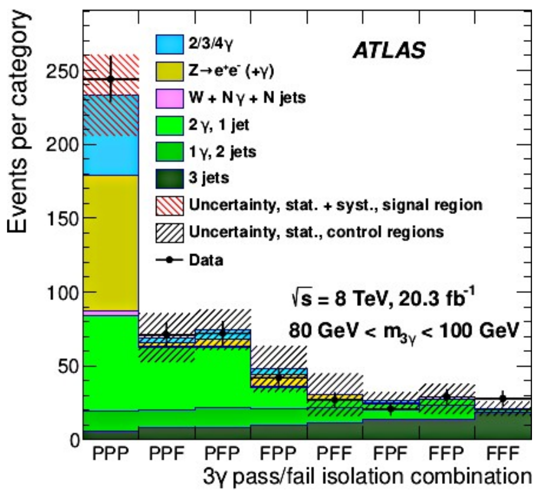
Recast into 1st ALP limit at LHC by S. Knapen et al.:

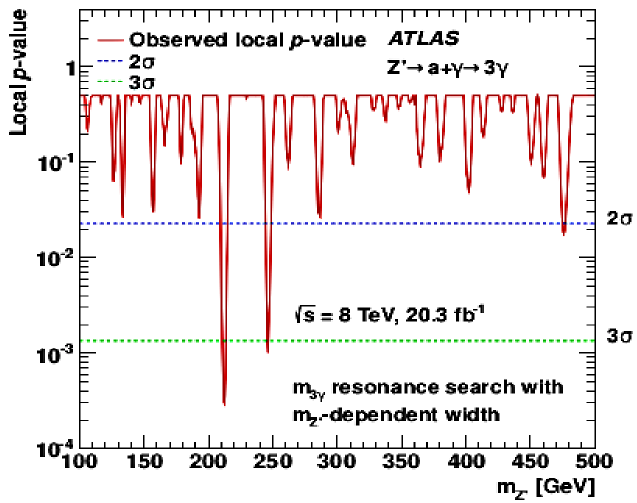
[PRL 118 (2017) 171801]

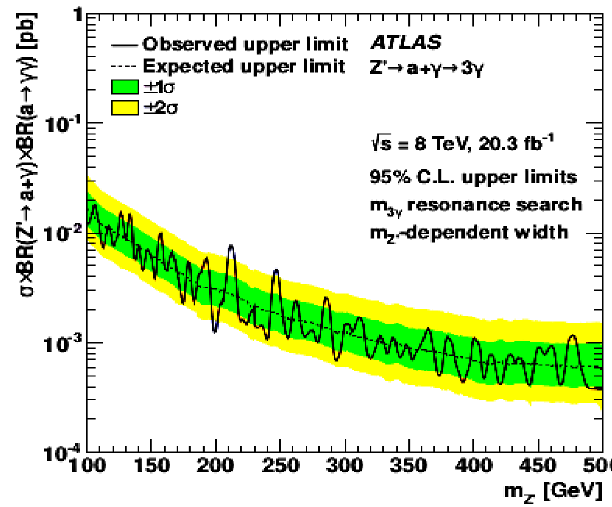


# ALPs limits via Z → $\gamma\gamma\gamma$ searches (pp, 8 TeV)

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



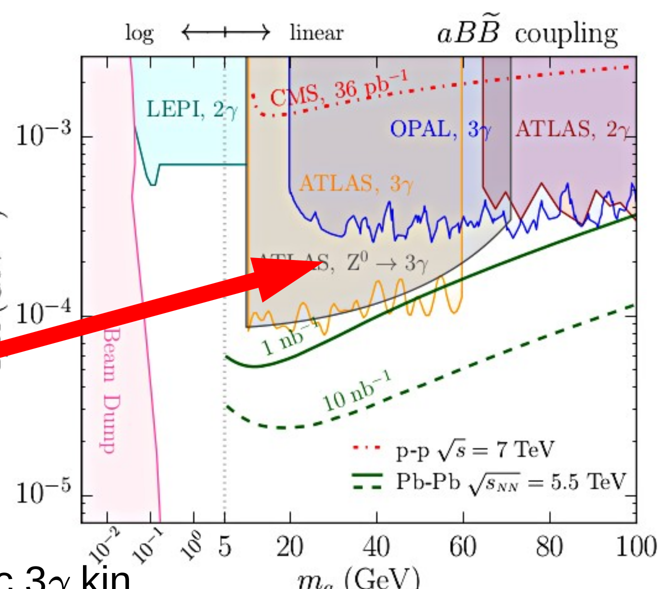



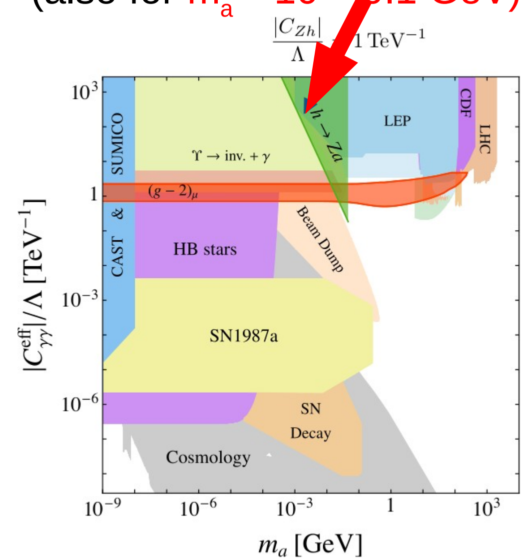

- Recast into ALP bounds with hypercharge coupling:

  Comparable limits with PbPb UPCs for $m_a$ = 10–60 GeV:

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




(also for $m_a = 10^{-3}$–0.1 GeV):



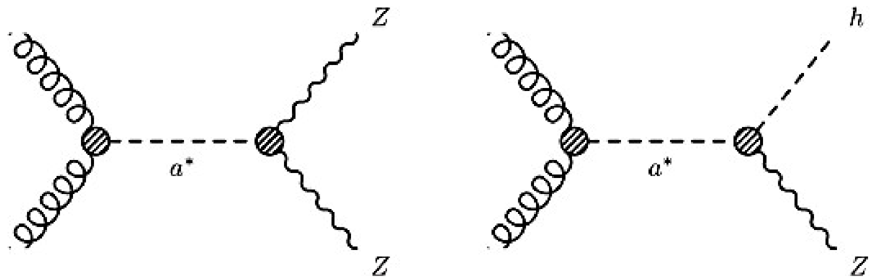

M.Bauer et al. EPJC 79 (2019) 74

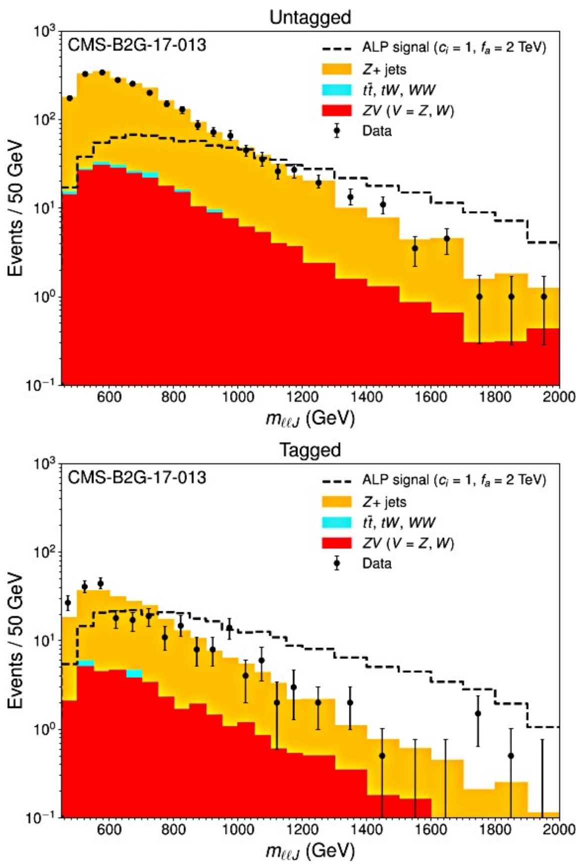
NB: Approx. bounds due to intrinsic 3$\gamma$ kin. combinatorics uncertainties. Should be redone by experiments

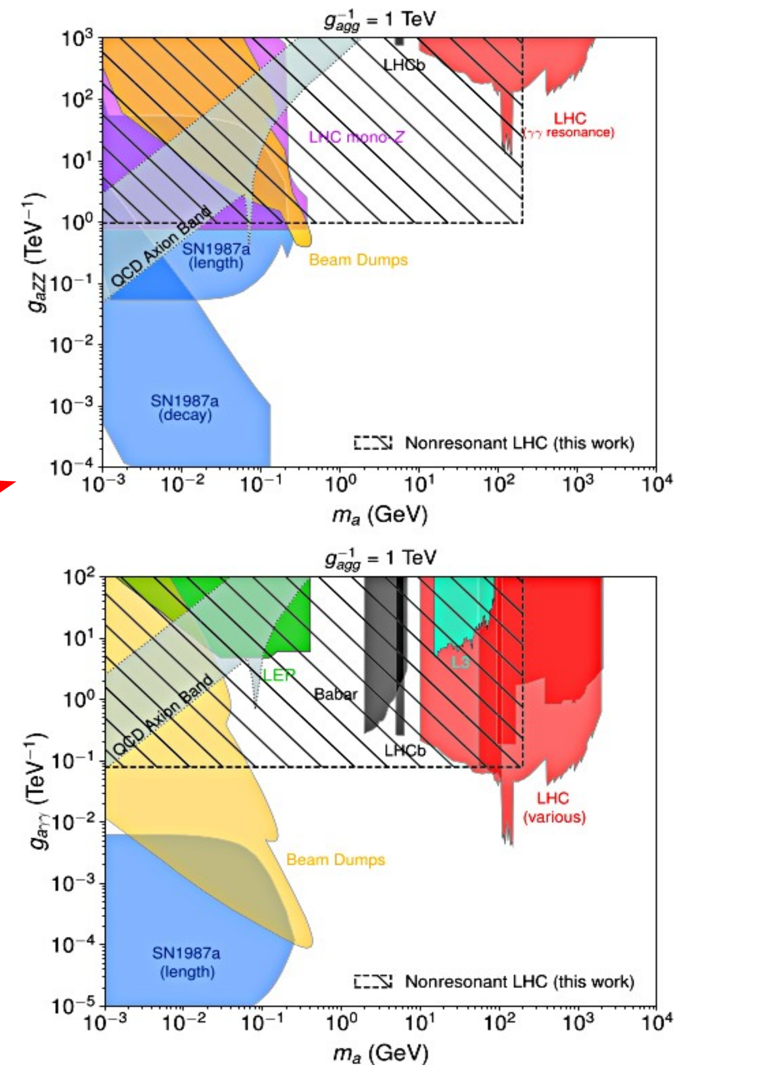
# Non-resonant ALPs limits at the LHC

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

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



# ALPs searches at accelerators/colliders

- Searches at accelerators focuse on $m_a$ >1 MeV: