Axion-like particles at colliders

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Université catholique de Louvain

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Overview

- Introduction to axion-like particles (ALPs)
  - General effective Lagrangian & couplings to gauge bosons
- Selection of astrophysical & indirect constraints
- ALPs at colliders
  - Parallels with DM/mediator signatures
  - Missing energy: “mono-X”
  - Resonance searches in multi-boson final states
  - Exotic decays
  - Collider constraints on gauge boson couplings
- Discuss potential for future machines
  - Rough ideas & numbers for CLIC

Introduction

- SM does not posses any fundamental pseudo-scalar d.o.f
- We have observed one fundamental(?) scalar state
  - Properties consistent with SM Higgs
- ALPs or more generally, pseudo-scalars - i.e. states with $J^P=0^-$ - are interesting candidates for physics beyond the SM.

Strong CP

Composite/
Goldstone Higgs

2HDM

SUSY
(NMSSM, R-axion)

DM candidates/
mediators…

ALP interactions - bottom up

$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{1}{2}m_a^2\,a^2 + ic_{a\varphi}\frac{\partial^\mu a}{f_a}\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)$$
$$- c_B\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} - c_W\frac{a}{f_a}W^I_{\mu\nu}\tilde{W}_I^{\mu\nu}$$
$$- c_G\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}_A^{\mu\nu} + \sum_\psi c_{a\psi}\frac{\partial^\mu a}{f_a}\bar{\psi}\gamma_\mu\gamma^5\psi$$

- General $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ invariant effective Lagrangian for a $J^P=0^-$ field *[Georgi, Kaplan & Randall; PLB 169 73 (1986)]*
  - Approximate shift symmetry characteristic of 'Axion-like' property
  - (a → a + constant) invariance: dominantly derivative interactions
  - QCD-axion models: $f_a\, m_a \propto f_\pi\, m_\pi$ → ultra light & weakly coupled
  - Generic "simplified model" for singlet pseudo Nambu-Goldstone boson coupled to SM with linearly realised EWSB

Gauge boson interactions

$$\begin{aligned}\mathcal{L}_{V\tilde{V}} &= -\, c_B \frac{a}{f_a} B_{\mu\nu}\tilde{B}^{\mu\nu} - c_W \frac{a}{f_a} W^I_{\mu\nu}\tilde{W}^{\mu\nu}_I - \, c_G \frac{a}{f_a} G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A \\ &= -\, c_{\gamma\gamma} \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} - \, c_{ZZ} \frac{a}{f_a} Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \, c_{Z\gamma} \frac{a}{f_a} F_{\mu\nu}\tilde{Z}^{\mu\nu} \\ &\quad - c_W \frac{a}{f_a} W^+_{\mu\nu}\tilde{W}^{\mu\nu}_- - \, c_G \frac{a}{f_a} G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A\end{aligned}$$

$$\begin{aligned}c_{\gamma\gamma} &= c_B \cos^2\theta_W + c_W \sin^2\theta_W \\ c_{ZZ} &= c_B \sin^2\theta_W + c_W \cos^2\theta_W \\ c_{Z\gamma} &= (c_W - c_B)\sin\theta_W \cos\theta_W\end{aligned}$$

- "Anomaly" induced couplings
  - Focus of this talk
  - EW sector - 4 couplings determined by 2 parameters
  - di-photon coupling is relevant for cosmological constraints on light ALPs
  - gluon coupling must be present for theories addressing strong CP - explicitly breaks shift symmetry & induces mixing with the pion

Higgs & fermion coupings

$$ic_{a\varphi}\frac{\partial^\mu a}{f_a}\left(\langle\varphi^\dagger\rangle\overleftrightarrow{D}_\mu\langle\varphi\rangle\right) \propto c_{a\varphi}\frac{v^2}{f_a}\partial^\mu a\, Z_\mu$$

- Higgs-current operator induces a linear mixing of the ALP with the Z boson after EWSB
  - (1) removed by an ALP-dependent Higgs field redefinition at the price of generating some Yukawa-like operators
  - (2) chiral redefinition of the fermion fields moves effect back into original fermionic operators & shifts ALP-gauge boson couplings (non-invariance of the path integral measure) *[Fujikawa; PRD 21 2848 (1980)]*
  - (3) quark-current operators are physically equivalent to pseudoscalar Yukawa coupling via integration by parts & Dirac equation

(1) $\varphi \to \exp\left(ic_{a\varphi}\frac{a}{f_a}\right)\varphi: \quad ic_{a\varphi}\frac{\partial^\mu a}{f_a}\left(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi\right) \to ic_{a\varphi}\frac{a}{f_a}\left(\mathbf{Y_u}\bar{Q}_L\tilde{\varphi}u_R - \mathbf{Y_d}\bar{Q}_L\varphi d_R - \mathbf{Y_e}\bar{L}_L\varphi e_R + \text{h.c.}\right)$

(2) $\psi_L \to \exp\left(iX_{\psi_L}\frac{a}{f_a}\right)\psi_L, \quad \psi_R \to \exp\left(iX_{\psi_R}\frac{a}{f_a}\right)\psi_R: \quad \{c_V,\, c_{a\psi}\} \to \{c'_V,\, c'_{a\psi}\}$

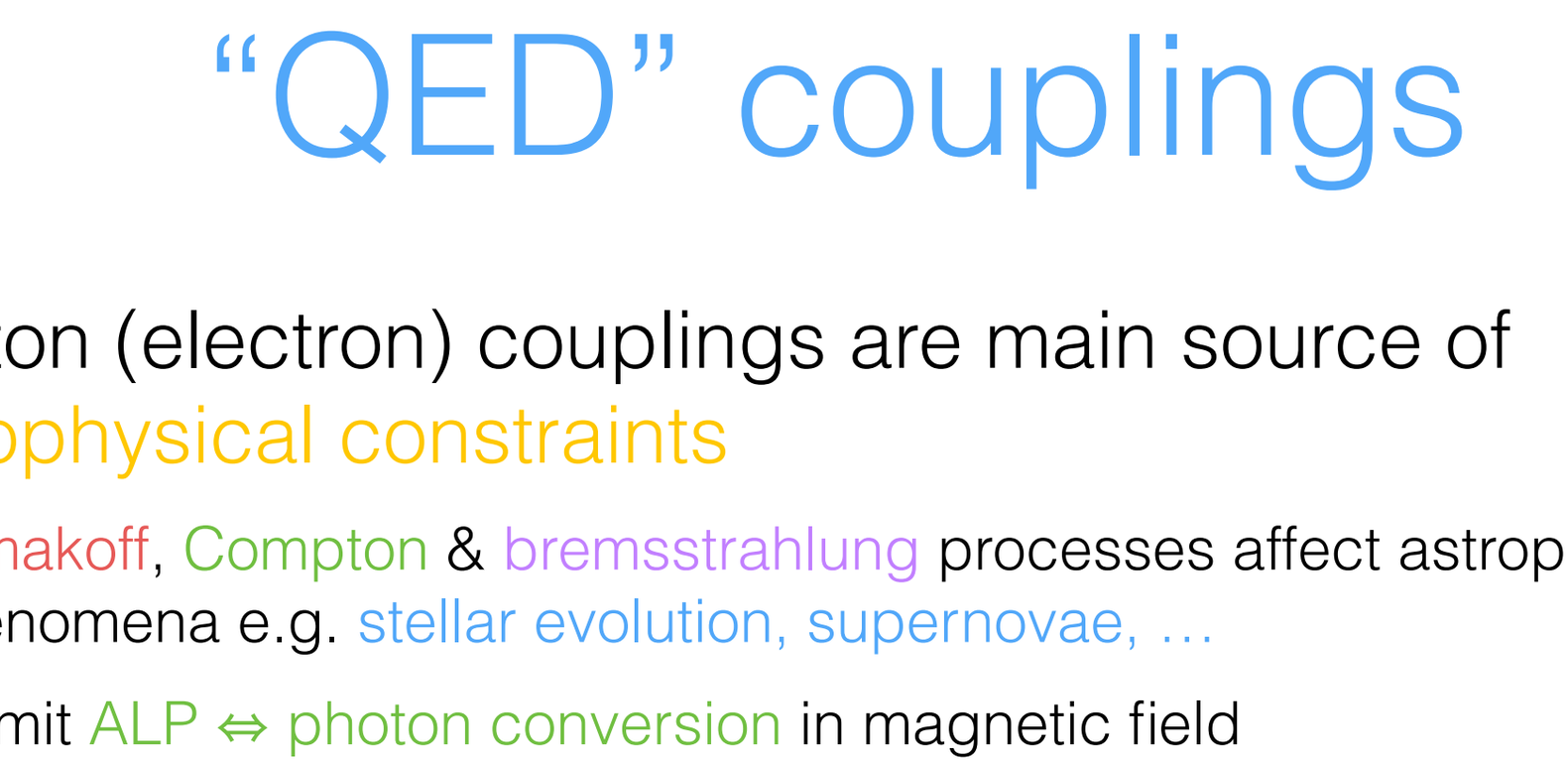
(3) $i\frac{\partial^\mu a}{f_a}\bar{\psi}\gamma_\mu\gamma^5\psi \equiv -2m_\psi\, a\,\bar{\psi}\gamma^5\psi$

→ L_{ALP} is fully general at D=5

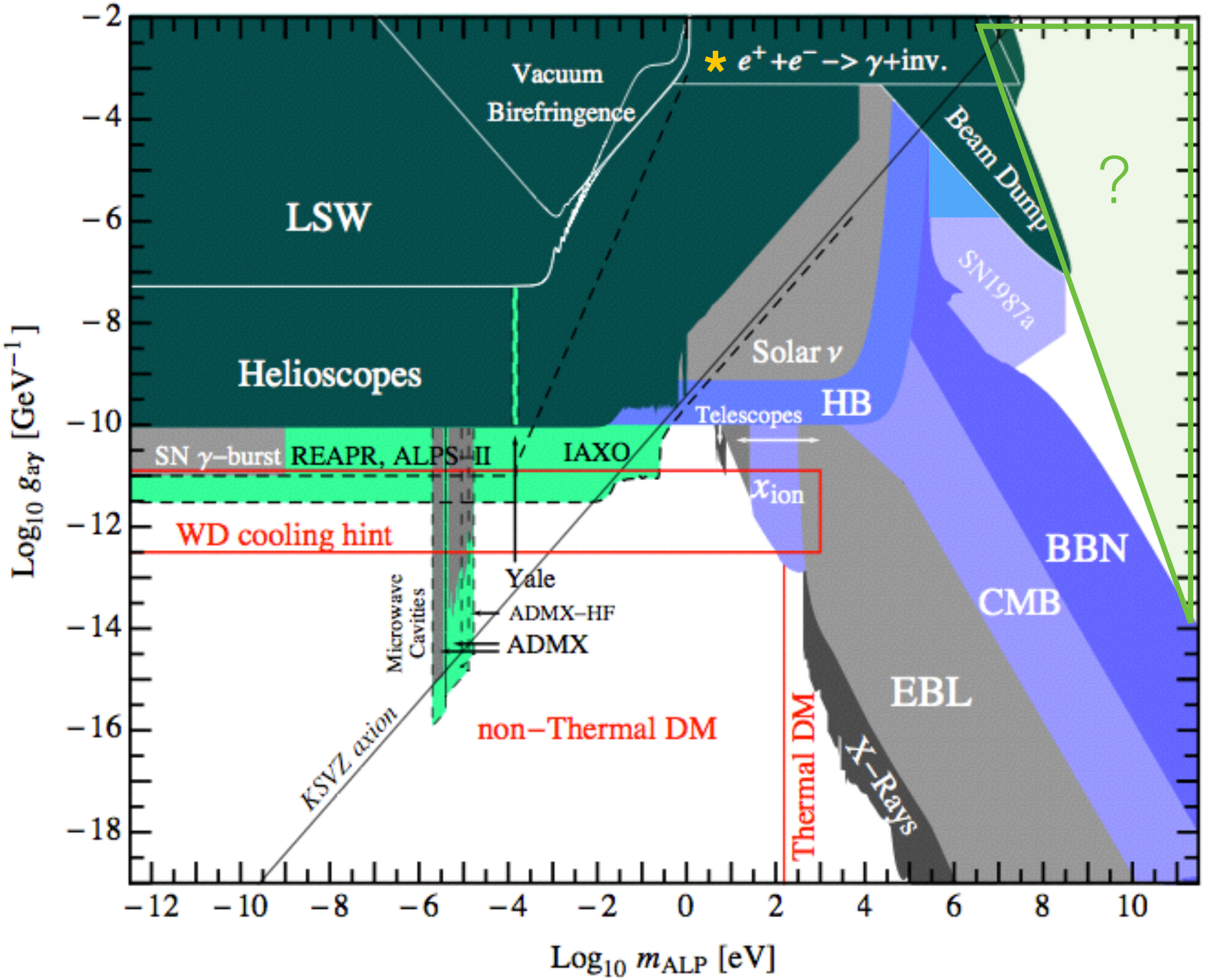
“QED” couplings

- Photon (electron) couplings are main source of astrophysical constraints
  - Primakoff, Compton & bremsstrahlung processes affect astrophysical phenomena e.g. stellar evolution, supernovae, …
  - Permit ALP ⇔ photon conversion in magnetic field
  - Allows for detection of ALP flux, disappearance/reappearance of photons

[J. Redondo, JCAP 1312 (2013) 008]



Constraints: di-photon coupling



Early universe (lifetime)

Supernova 1987a

Helium ignition in Red Giants

White Dwarf cooling

Helioscopes (e.g. CAST)

Solar neutrinos

‘Horizontal Branch’ stars

Microwave cavities

‘Light shining through a wall’

Beam dumps

LEP mono-photon (*)

high energy colliders?
LEP, LHC, future…

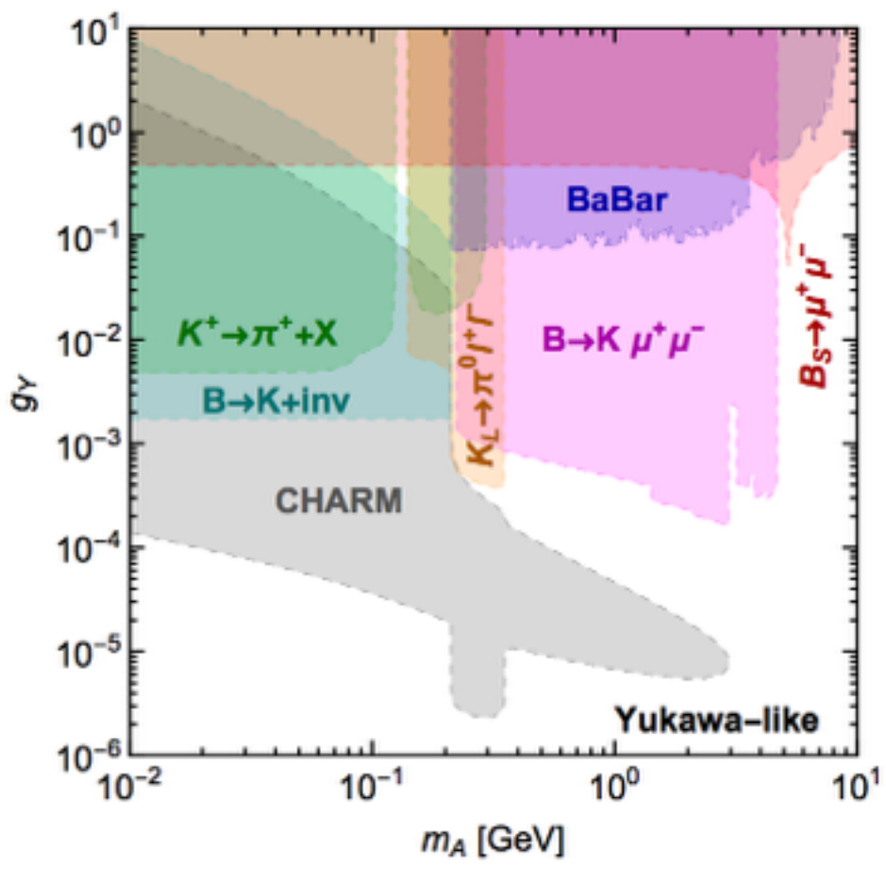
[ANL-HEP-TR-12-25], [SLAC-R-991], [FERMILAB-CONF-12-879-PPD]

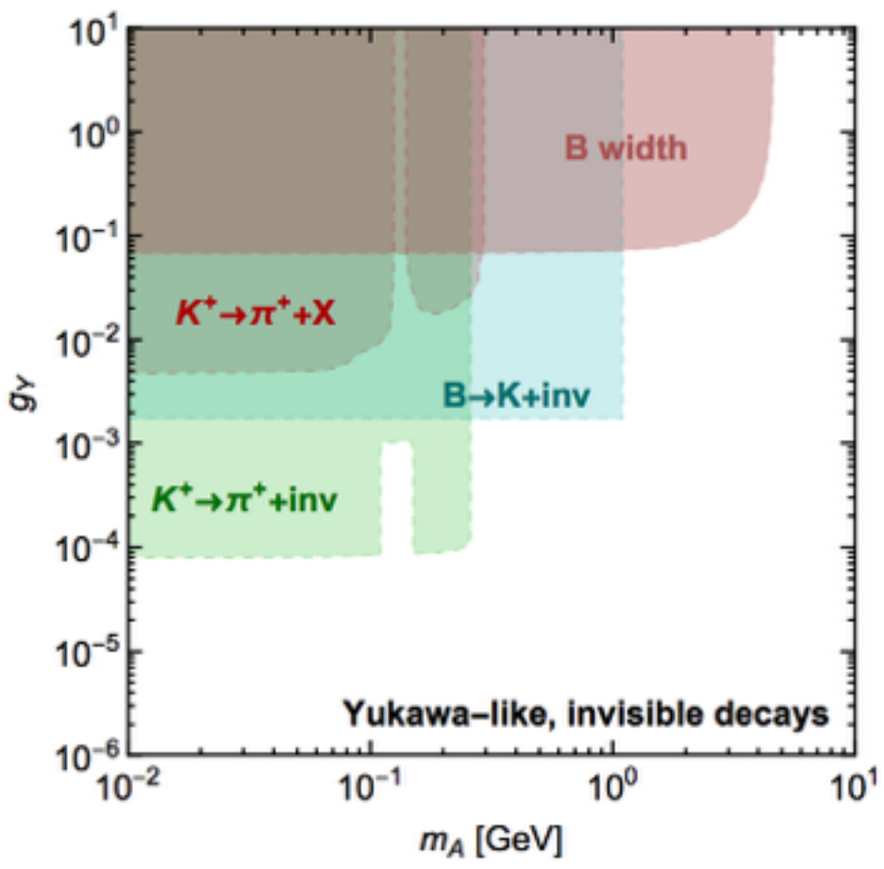
Constraints: FCNC

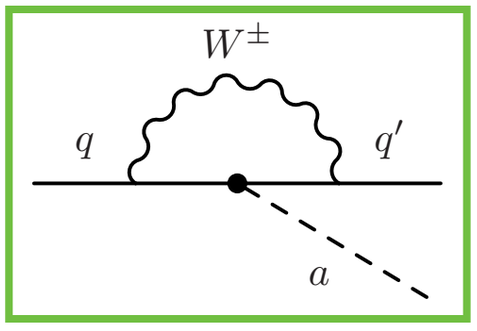
$$c_{a\psi}\frac{\partial^\mu a}{f_a}\bar{\psi}\gamma_\mu\gamma^5\psi$$

- Fermion couplings can be flavour violating in principle
  - Tree-level FCNC effects very tightly constrained
- Flavour diagonal fermion couplings of light ALPs in loops
  - Total widths, FCNC decays of kaons (K → π a) & B-mesons (B → K a)
  - Radiative decays of Upsilon (Υ → γ a)

[Dolan, Kahlhoefer, McCabe & Schmidt-Hoberg; JHEP 1503 (2015) 171]







Limits:

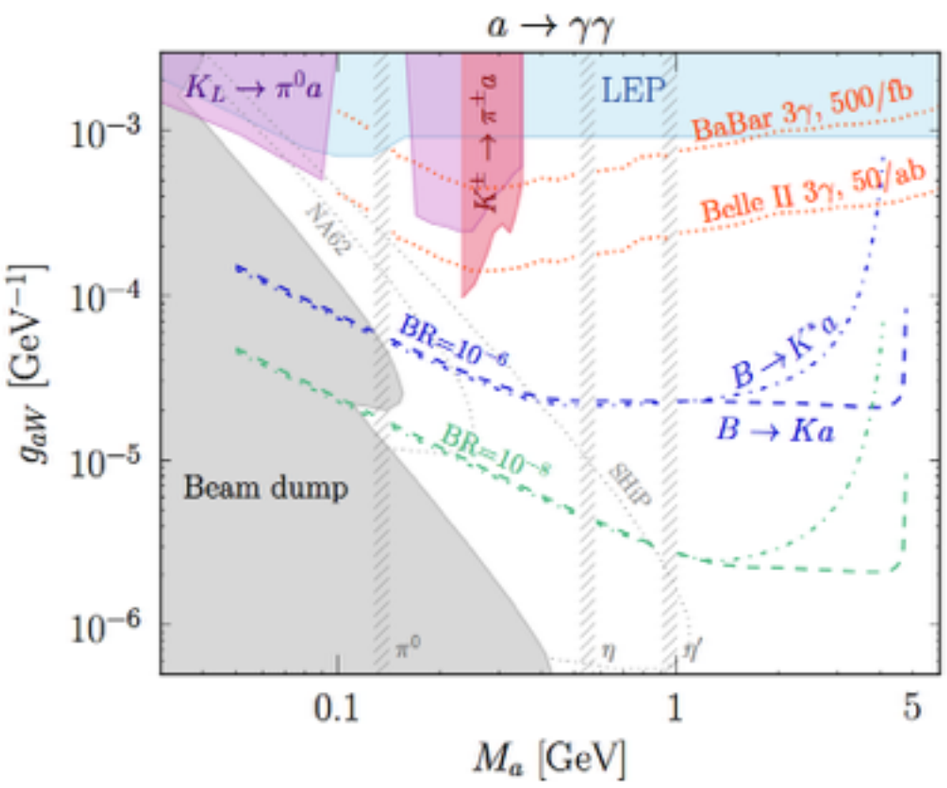
$c_{a\psi} \lesssim [10^{-7}, 10^{-2}]$
for $m_a \lesssim 10\,\text{GeV}$

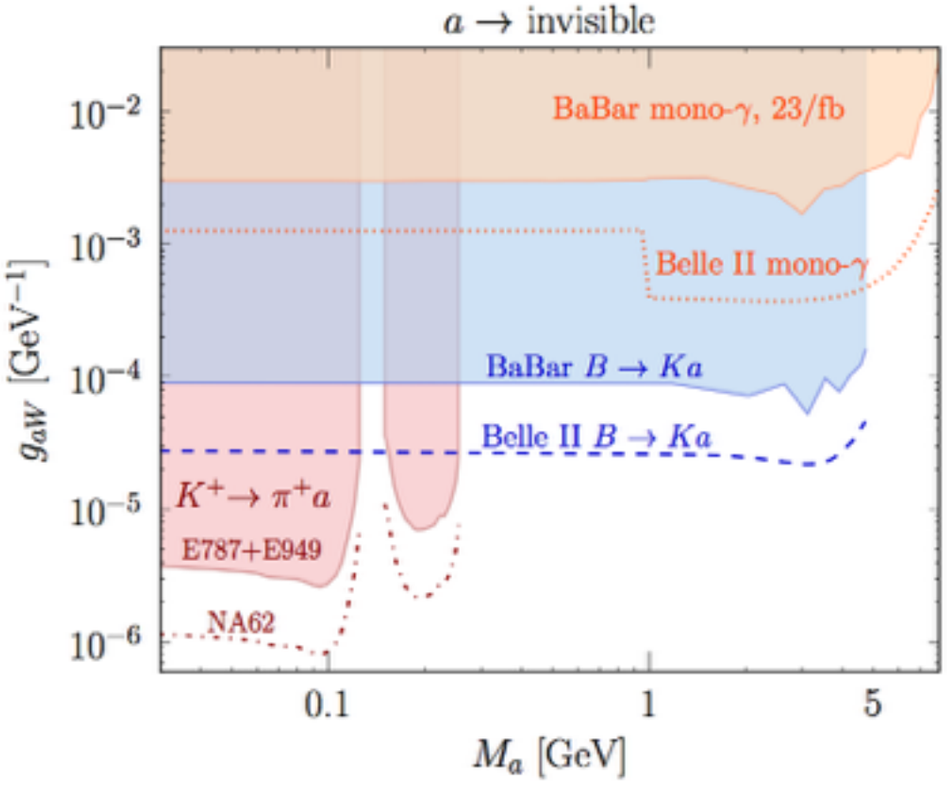
Constraints: FCNC

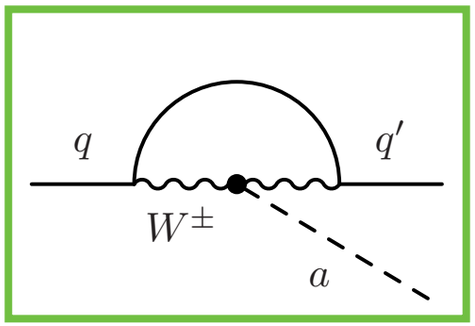
$$-\, c_G \frac{a}{f_a} G^A_{\mu\nu} \tilde{G}^{\mu\nu}_A$$

$$-\, c_W \frac{a}{f_a} W^+_{\mu\nu} \tilde{W}^{\mu\nu}_-$$

- Similar processes can be mediated by the aWW operator
  - Interestingly, the contribution of this operator to FC (q → q' a) are UV finite
  - Most competitive searches in this mass range for the aWW coupling







$$c_W/f_a \lesssim [10^{-5}, 10^{-2}]\ \mathrm{GeV}^{-1} \text{ for } m_a \lesssim 5\,\mathrm{GeV}$$

[Izaguirre, Lin & Shuve; PRL 118 (2017) 111802]

- aGG coupling also leads to kaon decays via pion mixing

$$c_G/f_a \lesssim 3 \times 10^{-6}\ \mathrm{GeV}^{-1} \text{ for } m_a \lesssim 60\,\mathrm{MeV}$$

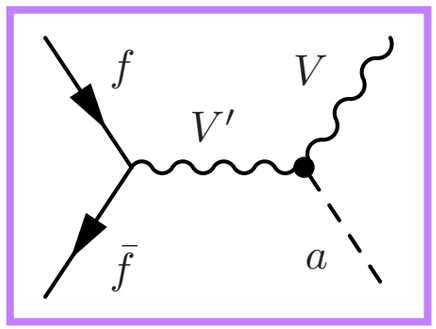
[Fukuda, Harigaya, Ibe & Yanagida; PRD 92 (2015) 015021]

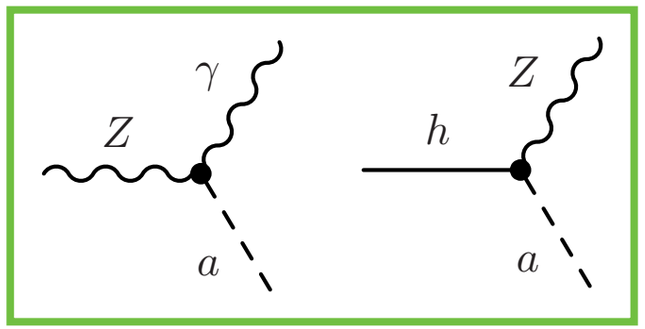
Why colliders?

- Many existing limits on light pseudoscalars are "indirect"
  - Astrophysical/cosmological in nature
  - Assumptions about particles in loops ~ potential UV dependence
- Kinematically limited by characteristic energy of process
  - Temperature of astrophysical body
  - Mass of decaying particle
- Colliders are a welcome complementary search platform
  - Access direct production at leading order in the EFT
  - Greatly extend kinematic reach (higher masses)
  - Sensitive to a different range of (larger) couplings
  - Depend on independent set of assumptions & uncertainties

ALPs at colliders

- Pseudoscalar with derivative couplings to SM bosons
- Associated production with a vector boson
  - Rate does not depend on partonic centre-of-mass energy, $\sqrt{s} \gg m_V$
  - $m_a \lesssim 1$ GeV: ALP is ‘stable’ w.r.t detector volume - mono-V (Higgs) signatures
  - $m_a \gtrsim 1$ GeV: ALP decays into gauge boson pair - V’ V V signatures
- Exotic SM decays
  - $Z \to \gamma\, a$ & $h \to Z\, a$
- Other possibilities
  - top quark coupling, VV-fusion,…
  - Many decay modes

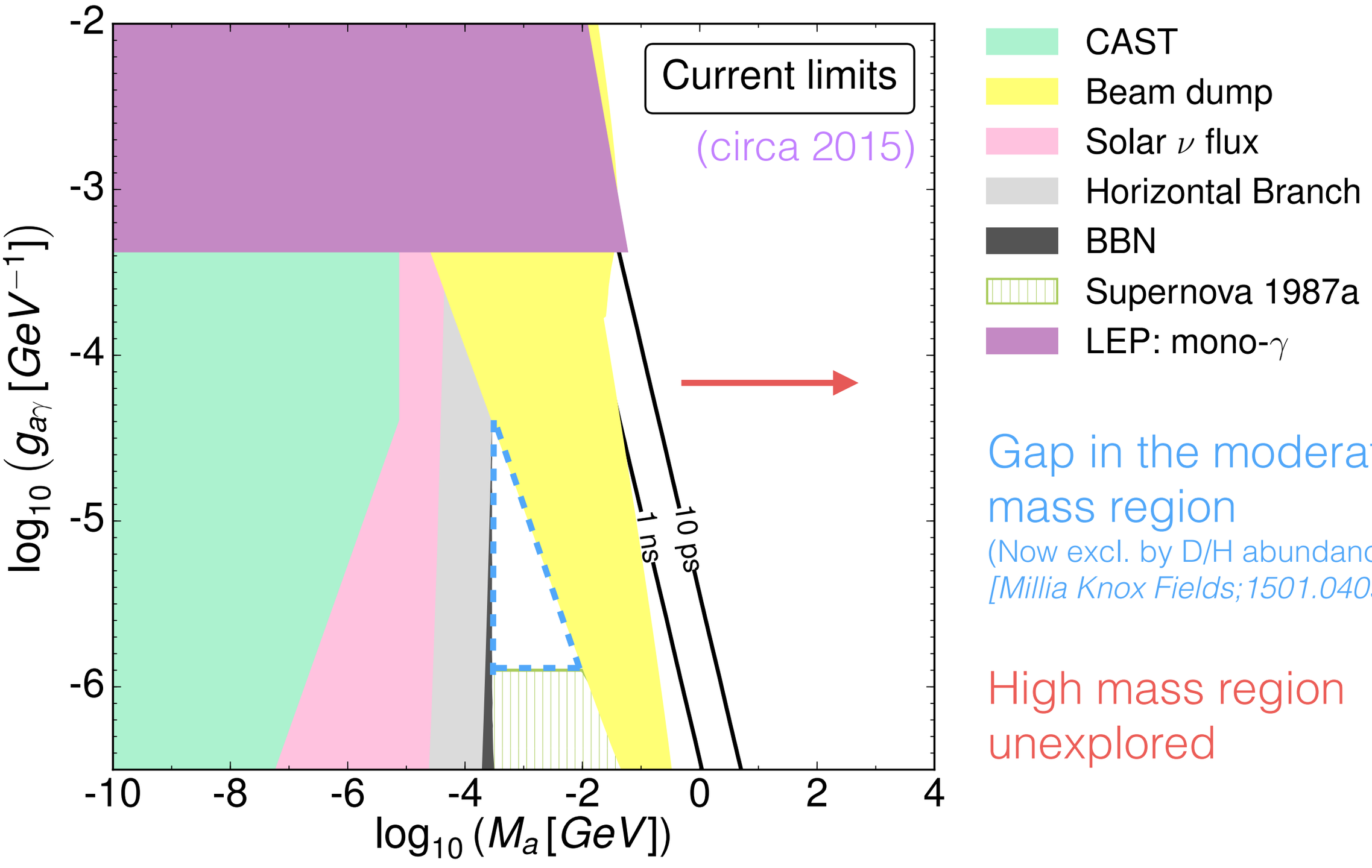




$$-\frac{g_{a\gamma}}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

[KM & V. Sanz ; JHEP 1506 (2015) 173]
See also: [M. Kleban, R. Rabadan; arXiv:hep-ph/0510183]

ALP-photon coupling



Gap in the moderate mass region
(Now excl. by D/H abundance *[Millia Knox Fields;1501.04097]*)

High mass region unexplored

Searches

- Run-1 mono-X
  - LHC @ 7 TeV mono-photon, 5 fb^{-1} — *[CMS; PRL 108 (2013) 261803] [ATLAS; PRL 110 (2013) 011802]*
  - LHC @ 8 TeV mono-photon, 20 fb^{-1} — *[ATLAS-CONF-2012-147] [CMS; PLB 755 (2016) 102]*
  - LHC @ 8 TeV mono-jet, 20 fb^{-1} — *[CMS; EPJC 75 (2015) 235] [ATLAS; EPJC 75 (2015) 299]*
- Pre-LHC tri-photon
  - LEP I @ MZ, 66 pb^{-1} — *[L3; PLB 345 (1995) 609]*
  - LEP II @ 189 GeV, 153 pb^{-1} — *[DELPHI, CERN-OPEN-99-410]*
  - Tevatron @ 1.92 TeV, 1.2 fb^{-1} — *[http://www-cdf.fnal.gov/physics/exotic/r2a/20060908.diphotonPlusX/]*
- Future mono & tri-photon prospects
  - LHC @ (8)13 TeV, (20 fb^{-1}) 3 ab^{-1}
  - TLEP @ 1 TeV, 10 ab^{-1}
  - ILC @ 240 GeV, 1 ab^{-1}
  - Belle II @ 10.6 GeV 50 ab^{-1}

[KM & V. Sanz ; JHEP 1506 (2015) 173]
See also: [M. Kleban, R. Rabadan; arXiv:hep-ph/0510183]

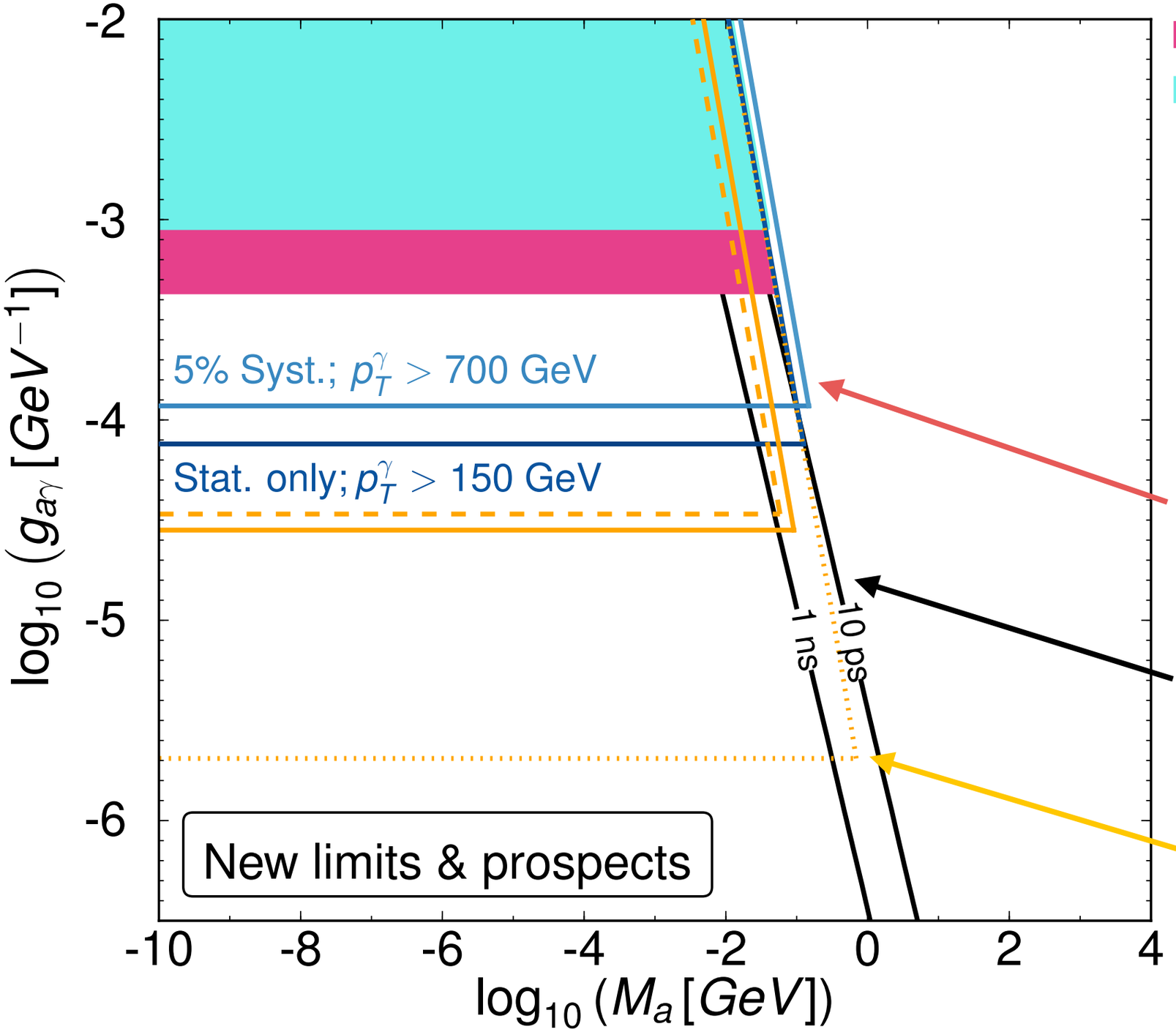
ALP-photon coupling

- Studied limits on ALP production in association with a photon at the Tevatron, LHC, LEP and future e^+e^- colliders
- Mono-photon from a light ALP
  - Recast LHC 7 & 8 TeV analyses (optimised for DM/ExtraDim searches)
  - Derived prospects by cut & count vs. SM $Z\,\gamma$ ($Z \to \nu\nu$) background
    - For LHC13, ILC, TLEP (FCC-ee) & Belle II
- e^+e^- colliders have much better kinematic control
  - Cut on the photon p_T and E sufficient to control background

	Statistics only			5% systematics		
Collider	p_T [GeV]	E [GeV]	$\log_{10}(g_{a\gamma}^{95})$	p_T [GeV]	E [GeV]	$\log_{10}(g_{a\gamma}^{95})$
ILC	80	115	-4.6	110	115	-4.5
TLEP	330	495	-4.2	350	495	-3.9
Belle II	3	5	-5.7	4	5	-5.1

mono-photon

[KM & V. Sanz ; JHEP 1506 (2015) 173]
See also: [M. Kleban, R. Rabadan; arXiv:hep-ph/0510183]



Collider stability: require the ALP to decay outside of the radius of the detectors

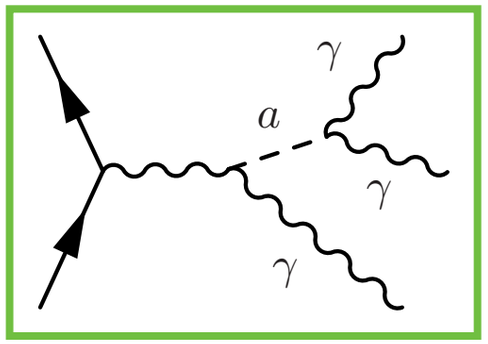
ALP lifetime assuming only decays to photon

For light ALPs, its a luminosity game

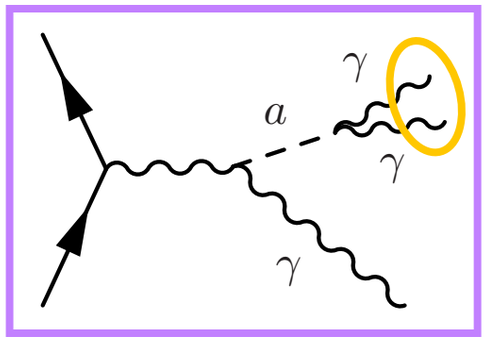
13 TeV now available

Heavy ALPs

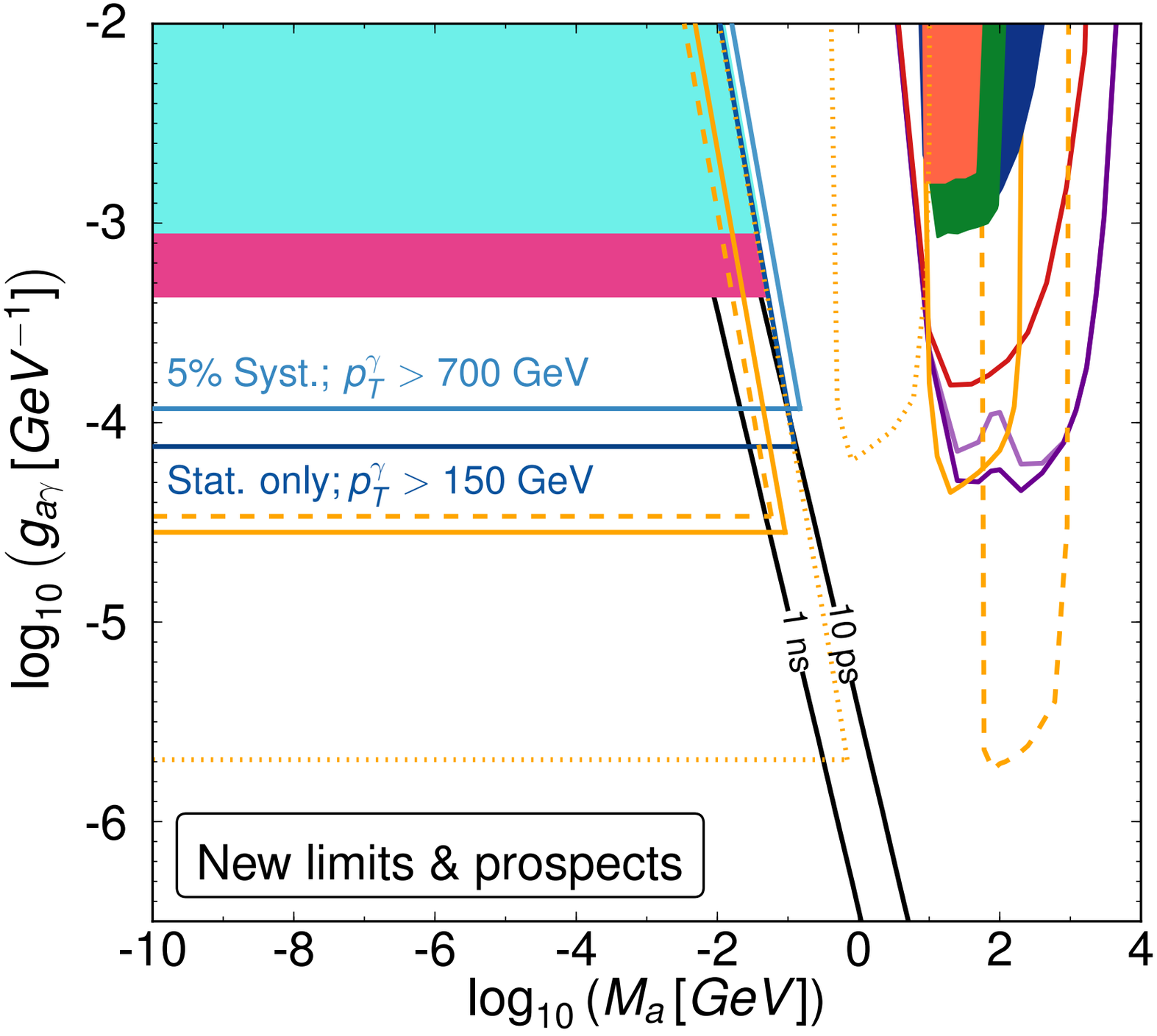
- Tri-photon (m_a > 0.1-1 GeV)
  - ALP decays into a resonant pair of photons
  - Irreducible background: SM tri-photon
  - Hadron colliders may suffer significant di-photon + jet fake background
  - Mass sensitivity ⇔ collider energy: at some point ALP is too boosted and decay photons cannot be resolved (di-photon?)



- Existing analyses at LEP1, LEP2, CDF
  - Anomalous Z-decay modes
  - SM tri photon measurement
  - techni-pion searches, falling into broad category of ALPs
  - Typical selection: two well isolated, energetic photons accompanied by a third fulfilling additional requirements optimised for BSM scenario



tri-photon



LEP @ M_Z: tri-γ, 66 pb^{-1}

LEP @ 189 GeV: tri-γ, 153 pb^{-1}

CDF: 3-γ, 1.2 fb^{-1}

LHC @ 13 TeV: tri-γ, 3 ab^{-1}

LHC @ 8 TeV: tri-γ, 19.6 fb^{-1}

ILC @ 240 GeV, 1 ab^{-1}

TLEP @ 1 TeV, 10 ab^{-1}

Belle II @ 10.6 GeV, 50 ab^{-1}

Future colliders:

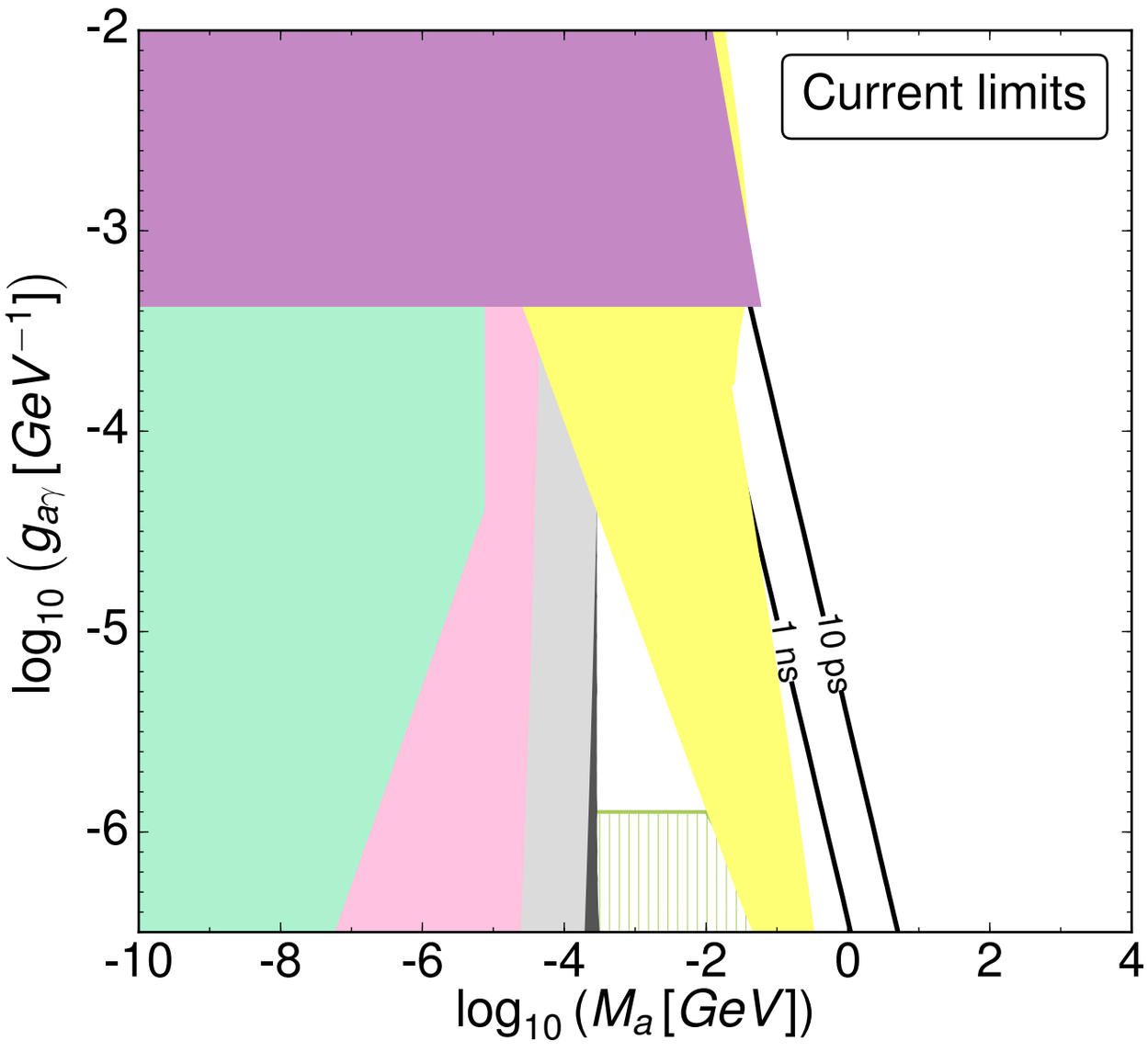
Resonant di-photon search accompanied by hard photon

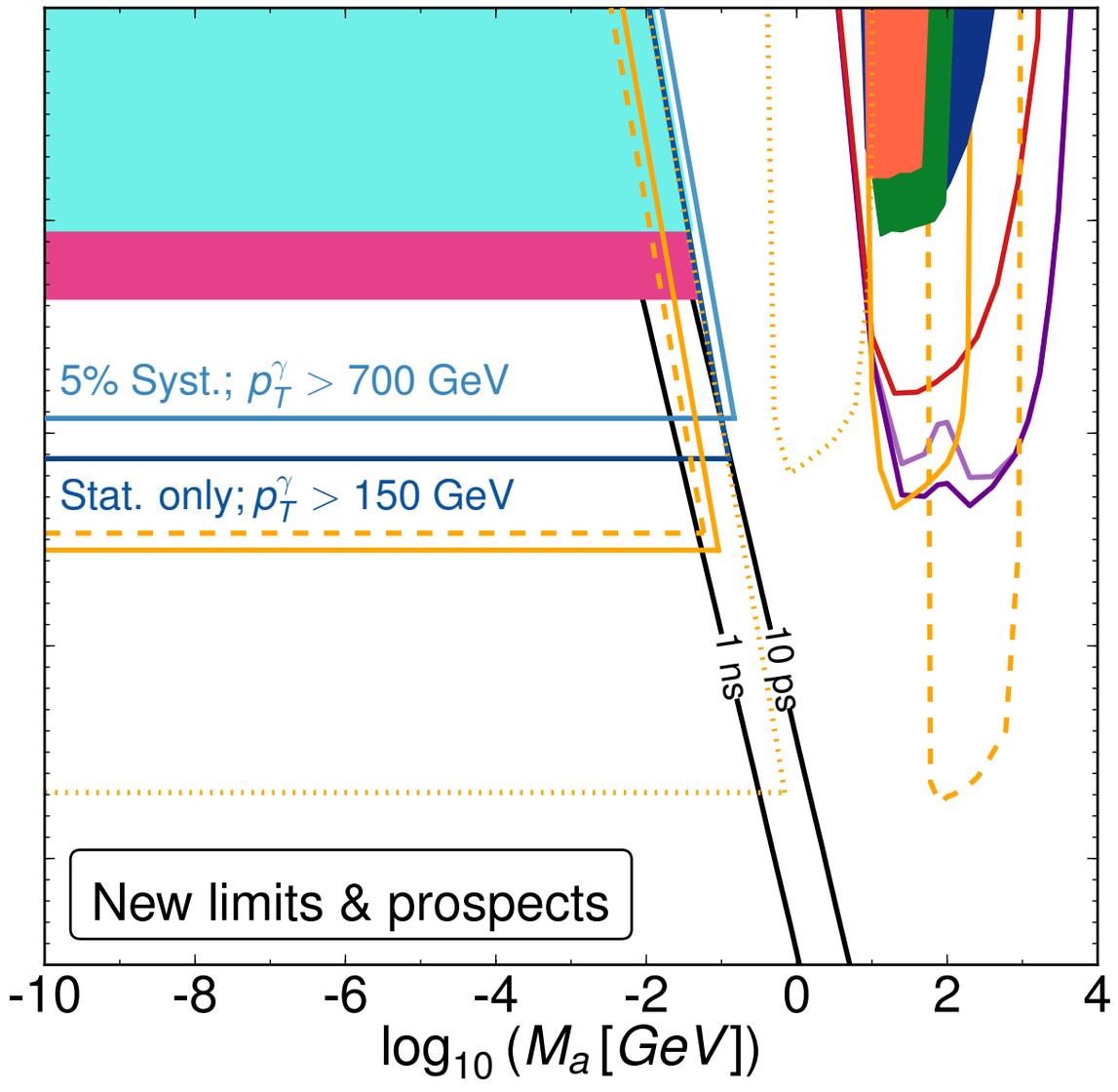
Energy of recoil photon and angular separation of resonant pair are fixed in terms of m_a and $\sqrt{s}$

Other Bounds
- CAST
- Beam dump
- Solar ν flux
- Horizontal Branch
- BBN
- Supernova 1987a

Collider Bounds
- LHC @ 7 TeV: mono-γ, 5 fb^{-1}
- LHC @ 8 TeV: mono-γ, 19.6 fb^{-1}
- LEP @ M_Z: tri-γ, 66 pb^{-1}
- LEP @ 189 GeV: tri-γ, 153 pb^{-1}
- CDF: 3-γ, 1.2 fb^{-1}
- LEP: mono-γ

Future Reach
- ILC @ 240 GeV, 1 ab^{-1}
- TLEP @ 1 TeV, 10 ab^{-1}
- Belle II @ 10.6 GeV, 50 ab^{-1}
- LHC @ 13 TeV: mono-γ, 3 ab^{-1}
- LHC @ 13 TeV: tri-γ, 3 ab^{-1}
- LHC @ 8 TeV: tri-γ, 19.6 fb^{-1}



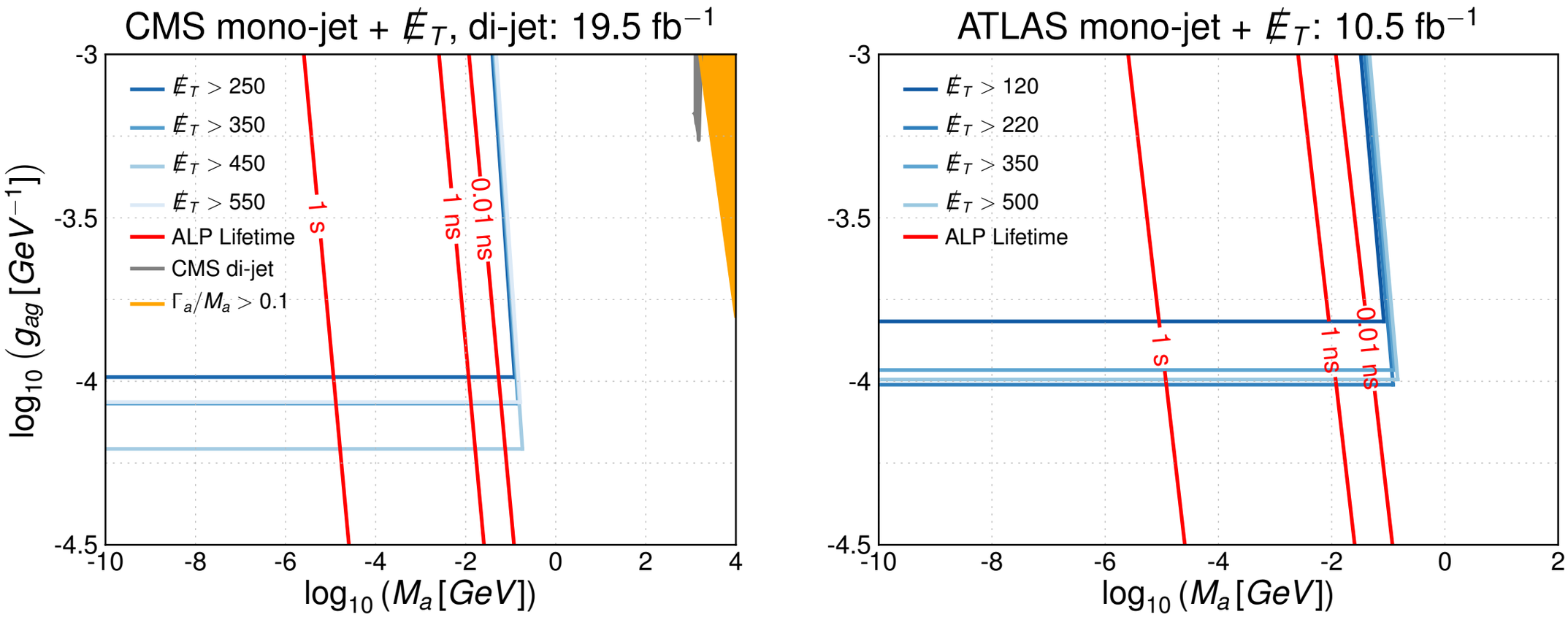


$$-\frac{g_{ag}}{4} G^A_{\mu\nu} \tilde{G}^{\mu\nu}_A$$

ALP-gluon coupling

- Same method to constrain ALP-gluon coupling
  - Mono-jet signature
  - Dominant contribution from g g initial state
  - Factor 8 in ALP decay width → stability limit reached earlier
- Reinterpreted 8 TeV ATLAS & CMS mono-jet analyses
  - One hard jet
  - Lepton + additional jet vetos (above a certain p_T)
  - Several signal regions categorised by missing energy
  - Stability limit set by ATLAS calorimetry radius
- Limits on g_{ag} of $O(10^{-4})$
  - Not far from the limits from kaon decay via pion-mixing
  - Run-2 reloads will improve this

Mono-jet



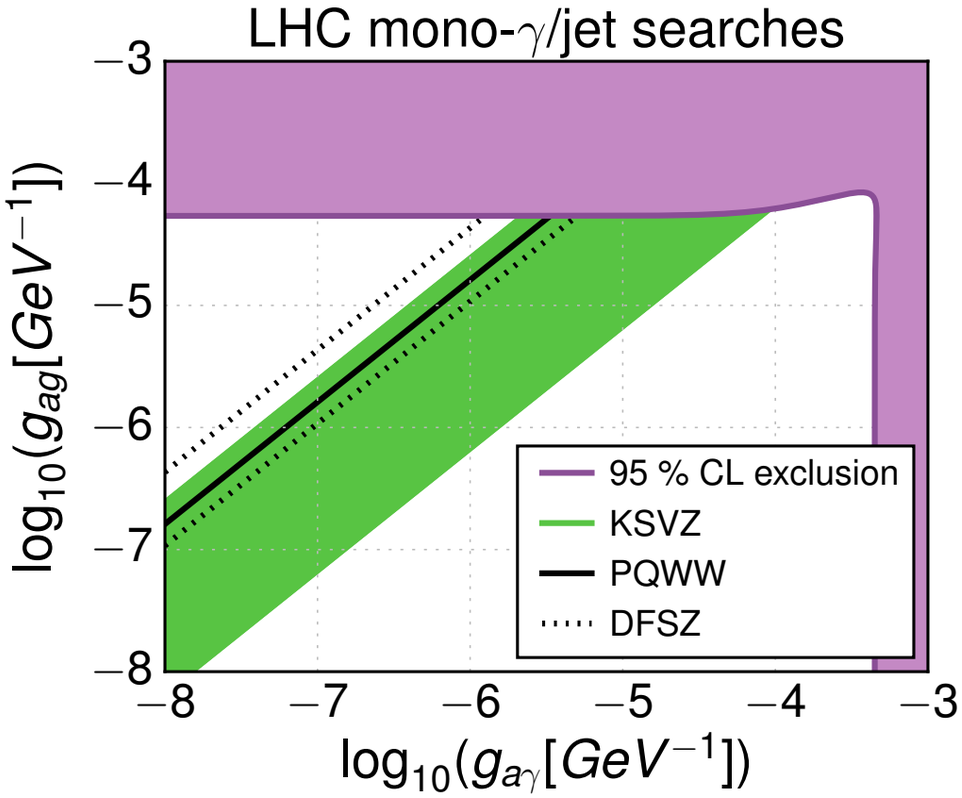
- Once ALP becomes unstable → tri-jet signature
  - Multi-jet background may be problematic
  - Super-heavy ALP can be produced by g g fusion
  - 8 TeV dijet limits also shown, width quickly exceeds 10% of mass…

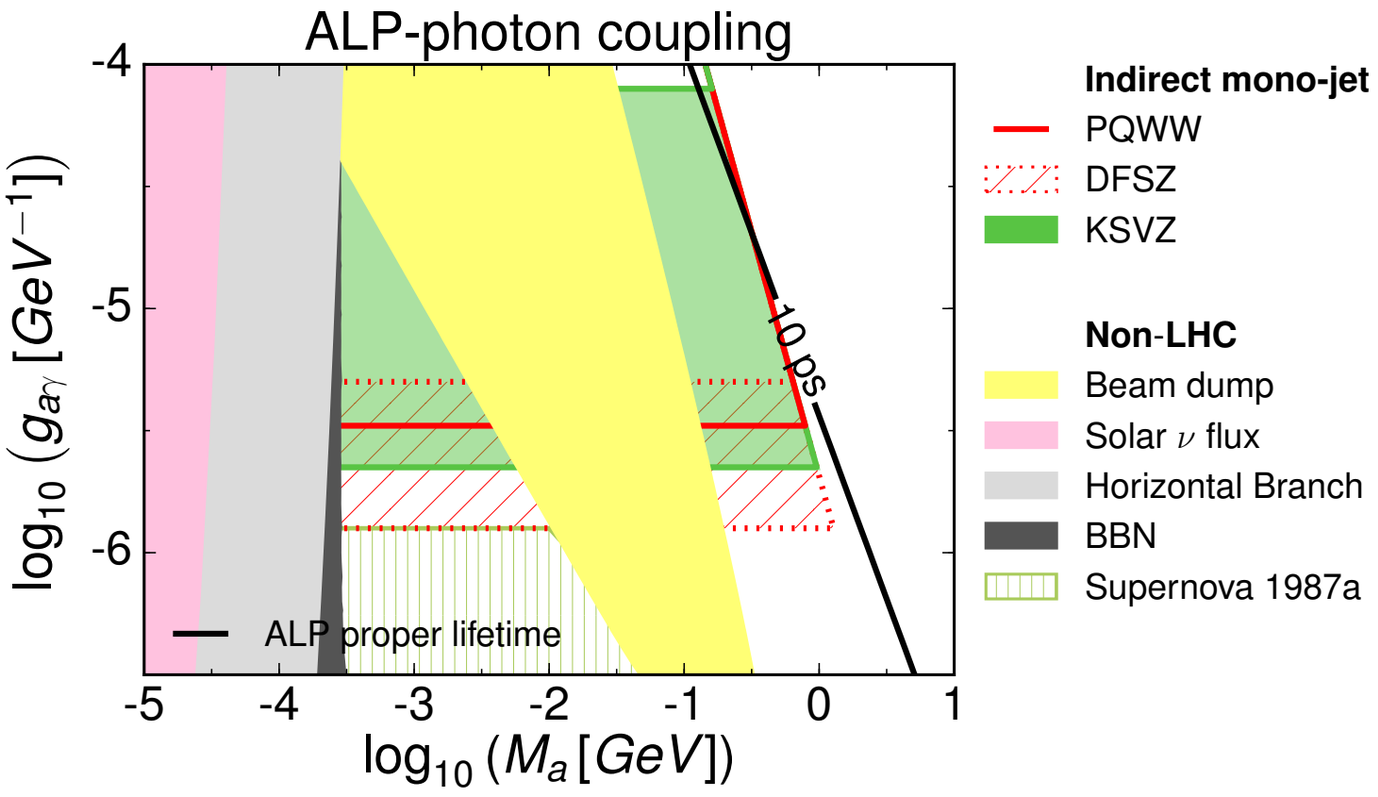
[CMS, Phys. Rev. D 91 (2015) 052009]

  - Boosted dijet analyses for lighter masses

Correlations in models

- Correlating limits on $g_{a\gamma}$ & g_{ag}
  - Often models relate the two couplings
  - e.g. assume couplings arise from axial anomaly: $g_{a\gamma} \sim \frac{\alpha_{EW}}{\alpha_S} g_{ag}$
  - g_{ag} limit from mono-jet leads to stronger indirect constraints on $g_{a\gamma}$ than LHC mono-photon



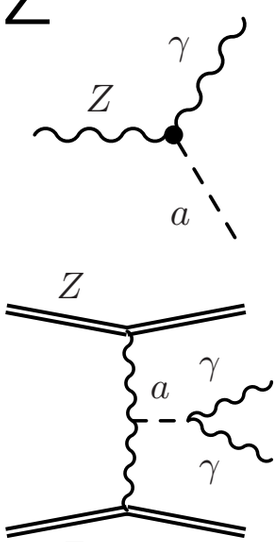


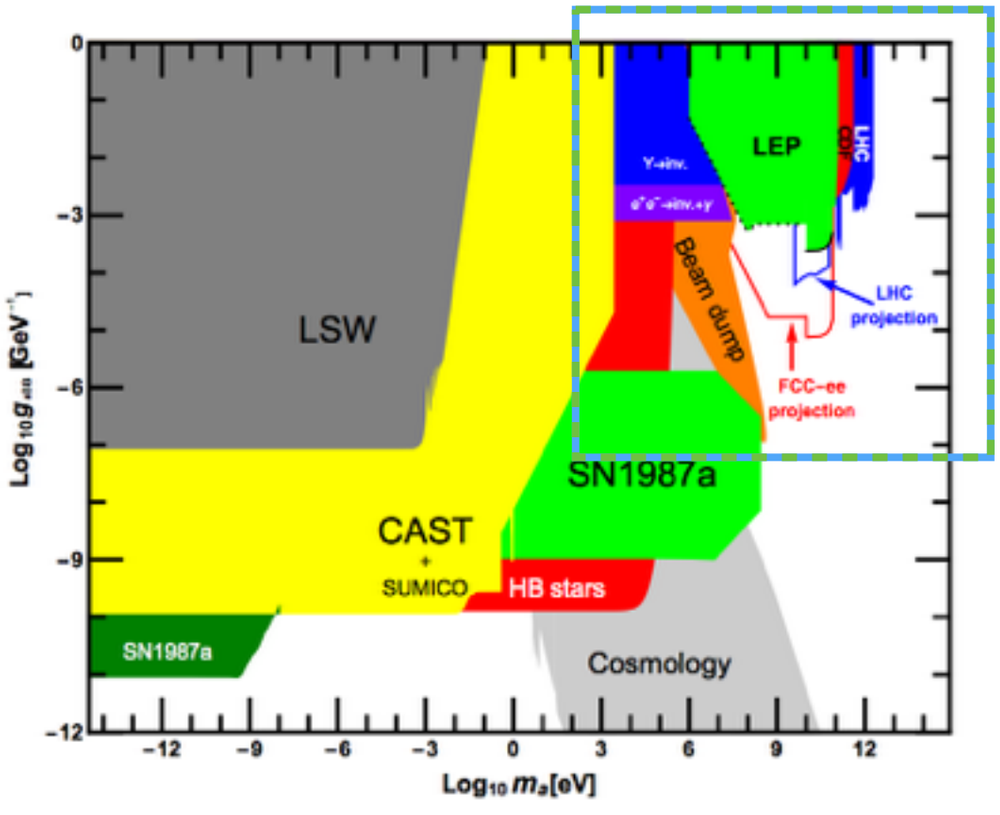
[J. Jaeckel, M.Janowiak, M. Spannowsky; Phys.Dark Univ. 2 (2013) 111-117]
[J. Jaeckel, M. Spannowsky; PLB 753 (2016) 482-487]

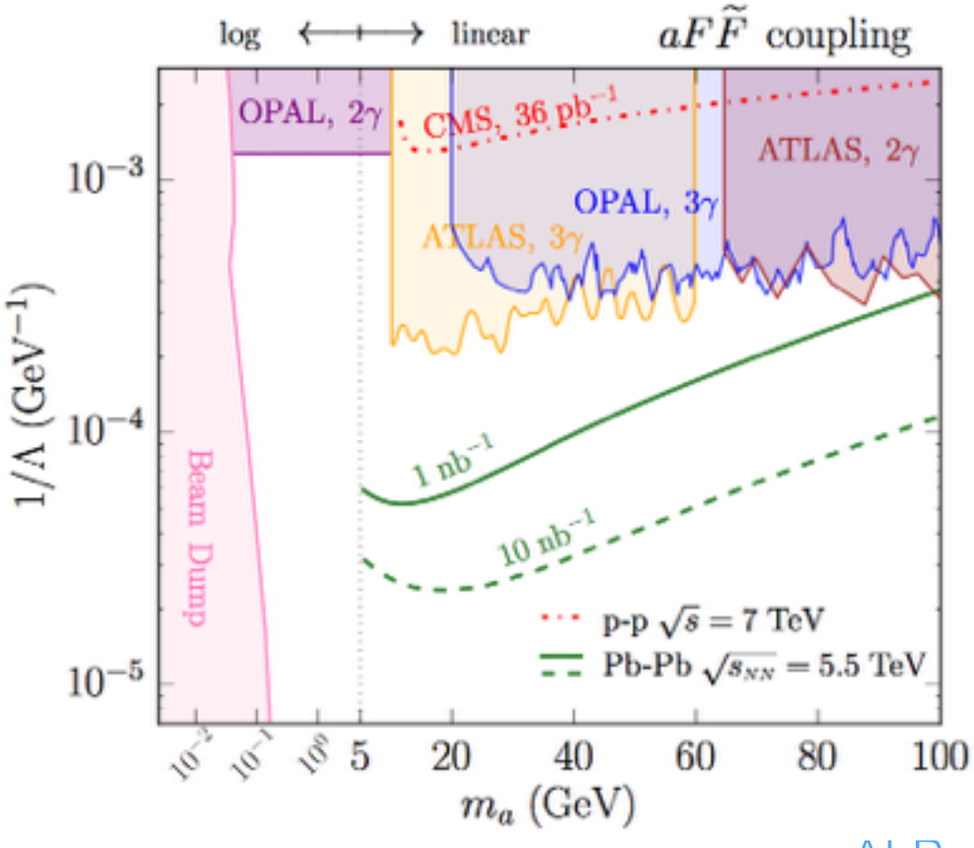
[Knapen, Lin, Lou & Melia; PRL 118 (2017) 071801]

ALP-photon/Z coupling

- c_W & c_B operators lead to couplings to both photons & Z
  - LEP: on-shell Z decay into three photons via Z → a γ for $m_a \gtrsim 10$ GeV
  - Makes use of Z → $\gamma\,\gamma$ (= a → $\gamma\,\gamma$) for the low mass, collimated region
- Ultra-peripheral heavy ion collisions @ LHC
  - $\gamma\,\gamma$ → a → $\gamma\,\gamma$ rate Z^4 enhanced, sensitive to ~10^{-4} -10^{-5} GeV^{-1}







[Brivio, Gavela, KM, Merlo, No, del Rey & Sanz; arXiv: 1701.05379]

ALP-EW couplings

- Strong limits on the photon coupling in the low mass region, where ALP = missing energy
  - Present & future colliders can probe orthogonal direction in (c_W, c_B) space
  - No couplings to $\gamma\gamma$ but enhanced ZZ and $Z\gamma$ interactions (also WW)
  - Very predictive scenario: all couplings controlled by one parameter
    - LHC & future can work towards closing this parameter plane
    - e.g. Z & W associated production

$$\begin{aligned} c_{\gamma\gamma} &= c_B \cos^2\theta_W + c_W \sin^2\theta_W \\ c_{ZZ} &= c_B \sin^2\theta_W + c_W \cos^2\theta_W \\ c_{Z\gamma} &= (c_W - c_B)\sin\theta_W \cos\theta_W \end{aligned} \quad \xrightarrow{c_B \simeq -c_W \tan^2\theta_W} \quad \begin{aligned} c_{\gamma\gamma} &\simeq 0 \\ c_{ZZ} &= c_W(1 - \tan^2\theta_W) \\ c_{Z\gamma} &= c_W \tan\theta_W \end{aligned}$$

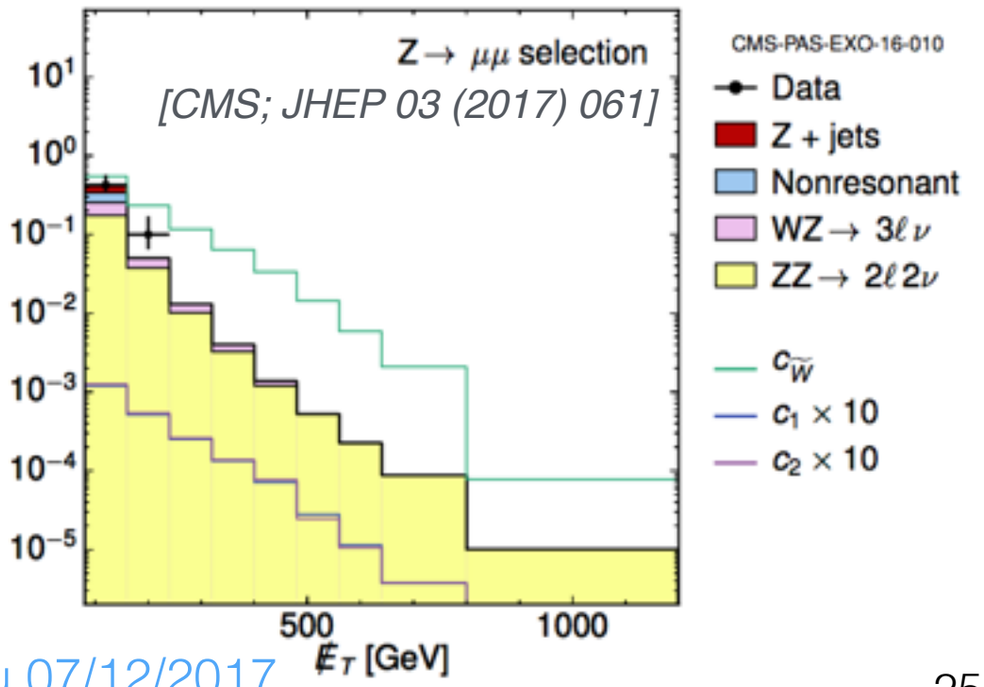
- For ~ GeV masses, e.g. astro limits are much weaker
  → consider full parameter space

[Brivio, Gavela, KM, Merlo, No, del Rey & Sanz; arXiv: 1701.05379]

ALP-EW couplings

- Only existing LEP constraint on a light ALP in this restricted scenario is the Z-decay width
  - Requiring the exotic decay to lie within the uncertainty (< 2 MeV) gives a bound $c_W/f_a \sim 10^{-3}$ GeV^{-1}
- Current LHC mono-Z(W) searches have similar sensitivity
  - Projecting for 300-3000 fb^{-1}, we expect an improvement of a factor of about an order of magnitude

LHC mono-Z



	$c_{\tilde{W}}$ (mono-Z)			
ℓ	e		μ	
Luminosity [fb^{-1}]	300	3000	300	3000
$f_a/c_{\tilde{W}}$ [TeV]	10.47	15.81	9.79	14.33
$f_a/c_{\tilde{W}}$ [TeV] [Syst.×1/2]	11.10	18.40	10.39	16.67
$f_a/c_{\tilde{W}}$ [TeV] [No Syst.]	11.64	21.47	10.91	19.64

Validity of the EFT

- Constrain model-agnostic ALP effective Lagrangian
  - What is the cutoff, Λ, vs characteristic energy of experiment?
  - Hadron colliders: mono-X = p_T cuts & tri-X = ~M_a
  - e^+e^- colliders: CM energy
- In a more familiar EFT language

$$\frac{g_{aX}}{4} = \frac{c_X}{\Lambda}$$

  - Assessment depends on sensitivity and assumed c_X
    - naive: $c_X \sim 1$

$$E_{\rm exp} < \Lambda_{\rm eff} = \frac{4}{g_{aX}}$$

    - pNGB ALP: loop factor & $\Lambda = 4\pi f_a$ (decay constant)
    - Effective cutoff reduced by structure constant α_X

$$\frac{g_{aX}}{4} = \frac{\alpha_X}{4\pi f_a}$$

$$E_{\rm exp} < \Lambda_{\rm eff} = \frac{4}{g_{aX}}\alpha_X$$

Validity of the EFT

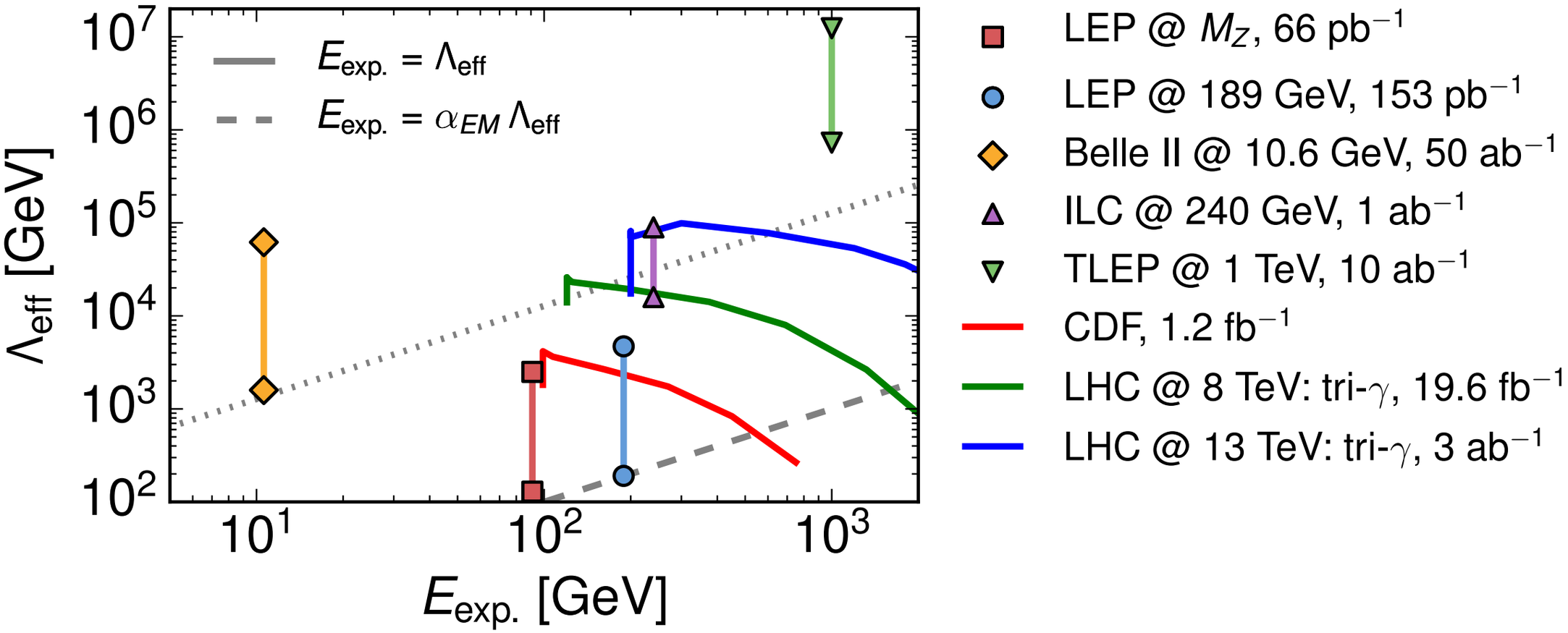
- All limits naively probe cutoff in the multi-TeV region
  - LHC: p_T → E_{exp} via fiducial η range
  - 8 TeV mono-photon: Λ_{eff} ~ 4.5 TeV → 35 GeV
  - Belle II, 10.6 GeV: Λ_{eff} ~ 2 PeV → 15 TeV
  - LHC mono-jet : Λ_{eff} ~ 40 TeV → 5 TeV
  - Strong coupling: mono-jet less “punished”

Analysis	$E_{\rm exp}$ [TeV]	$\Lambda_{\rm eff}$ [TeV]	$\log_{10}(g^{95}_{a\gamma}\,[\mathrm{GeV}])$
LHC7	0.26–2.6	9.4	−3.37
LHC8	0.5–1.1	4.5	−3.05
LHC14 (Stat)	0.3–1.8	50	−4.12
LHC14 (5% Syst.)	1.4–8.6	34	−3.93
ILC	0.24	140	−4.47
TLEP	1	118	−4.55
Belle II	0.0106	1960	−5.69

Analysis	$E_{\rm exp}$ [TeV]	$\Lambda_{\rm eff}$ [TeV]	$\log_{10}(g^{95}_{ag}\,[\mathrm{GeV}])$
CMS	-	-	-
$\not{E}_T > 250GeV$	0.5–2.8	36	−3.95
$\not{E}_T > 350GeV$	0.7–3.9	50	−4.1
$\not{E}_T > 450GeV$	0.9–5	63	−4.2
$\not{E}_T > 550GeV$	1.1–6.1	50	−4.1
ATLAS	-	-	-
$\not{E}_T > 120GeV$	0.24–0.9	28	−3.85
$\not{E}_T > 220GeV$	0.44–1.7	40	−4.0
$\not{E}_T > 350GeV$	0.7–2.6	31	−3.9
$\not{E}_T > 500GeV$	1.0–3.8	40	−4.0

Validity of the EFT

- Tri-photon searches

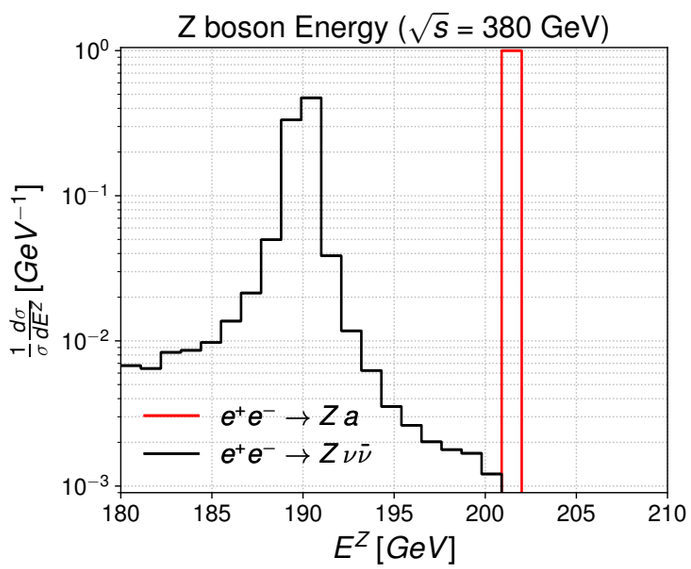


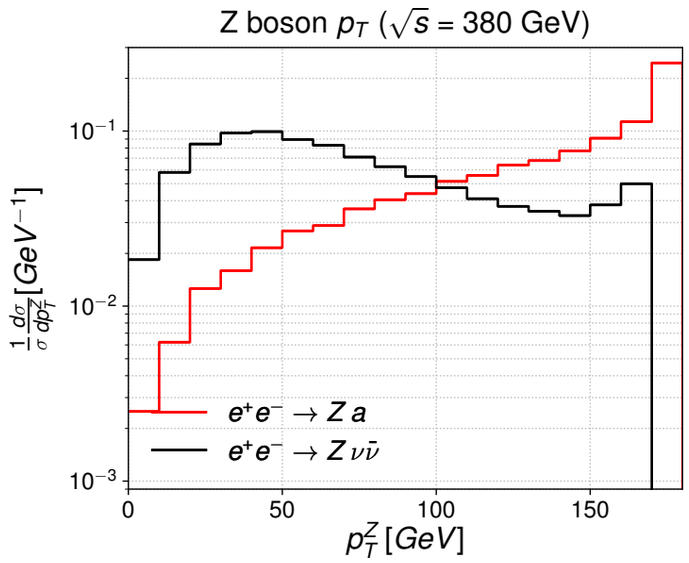
- Favours indirect constraints from mono-jet searches over those considering the ALP-photon coupling for a given model/cutoff

Future e^+e^- machines

- Mono-γ searches can exceed LEP/LHC sensitivity to light ALPs with a photon coupling
  - It appears low-energy/high luminosity options may perform better (Belle II)
  - Consider constrained scenario with suppressed photon coupling
- mono-Z/γ as probe of c_W/c_B are both interesting
  - Rate ~ independent of CM energy
  - Main irreducible backgrounds are Z $\nu\nu$ and γ (Z $\rightarrow \nu\nu$) respectively
  - Scale differently with energy
  - 2 → 2 vs 2 → 3 kinematics can be exploited to eliminate background
  - Higher energies = boosted Z

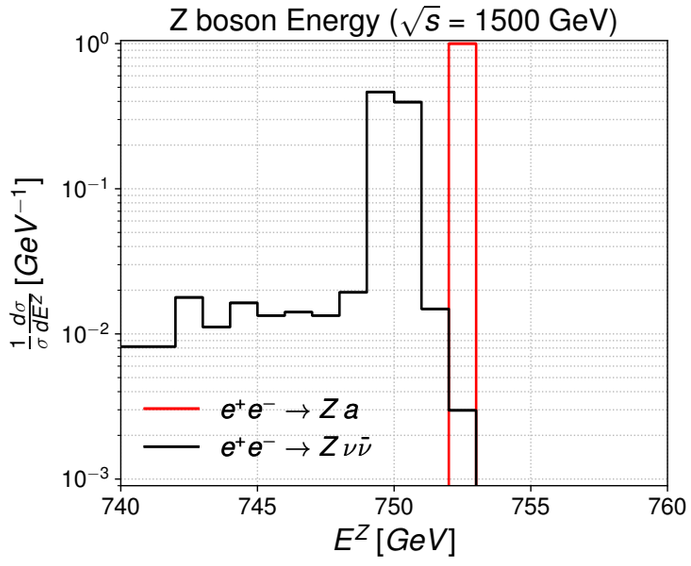
Mono-Z/γ at CLIC

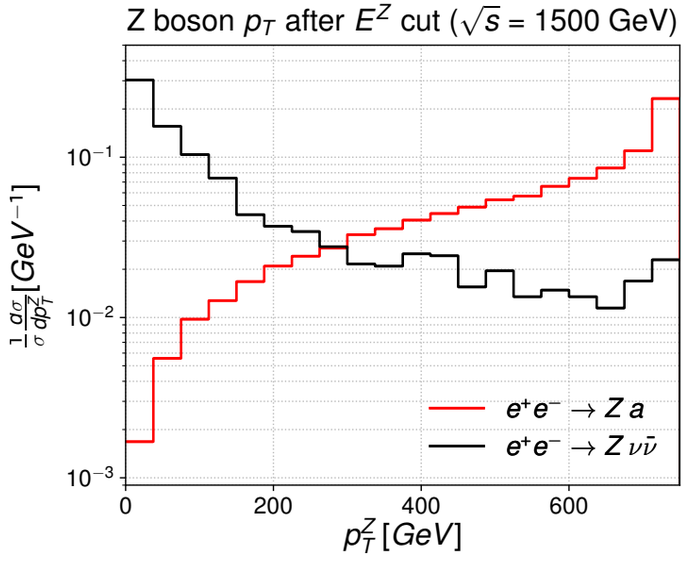




$|E_Z - E_0| < 0.03\ E_0$ cut

> 100% sig efficiency
< 0.5% bkg efficiency





Additional handle on Z p_T helps at high energy when bkg $E_Z \sim E_0$

> 80% sig efficiency
< 0.5% bkg efficiency

$m_a \sim 0$

$$\sigma_{\text{mono-Z}} \simeq 60\ \text{fb} \times \left(c_W \cdot \frac{1\ \text{TeV}}{f_a}\right)^2$$

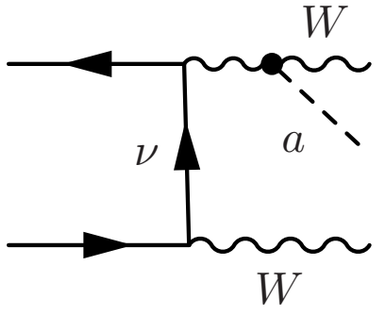
$$\sigma_{\text{mono-}\gamma} \simeq 15\ \text{fb} \times \left(c_W \cdot \frac{1\ \text{TeV}}{f_a}\right)^2$$

$\sqrt{s}$ [GeV]	380	1500	3000
$Z\,\nu\,\bar{\nu}$ [pb]	0.4	1.3	2.1
$\gamma\,\nu\,\bar{\nu}$ [pb]	2.1	2.7	2.1

Rough sensitivity:
$c_W/f_a \sim 10^{-5}$ GeV^{-1}

Other production modes

W W - associated



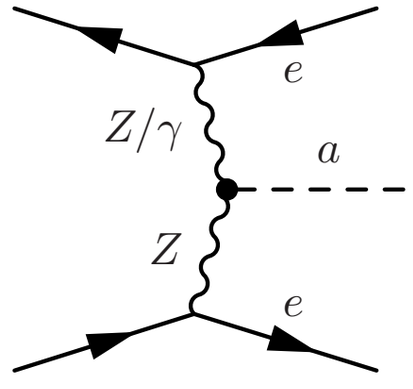
Access WW coupling

Large WW background decreases with √s

kinematic discrimination semi-leptonic/hadronic?

$\sqrt{s}$ [GeV]	$\sigma\left(c_W \cdot \frac{1\text{ TeV}}{f_a}\right)^2$	σ_{bkg}
380	1.4 fb	10 pb
1500	9.7 fb	1.4 pb
3000	17.5 fb	0.45 pb

Z/γ - fusion



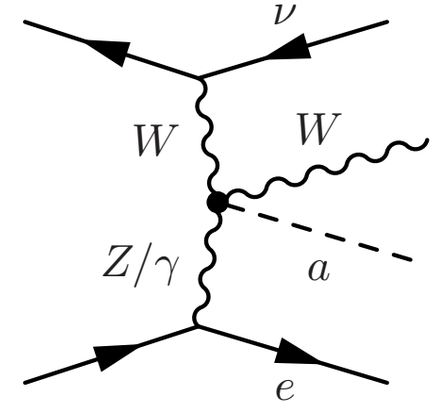
Complementary to mono-Z/γ

$e^+e^-\nu\nu$ background stable over √s

Forward e

$\sqrt{s}$ [GeV]	$\sigma\left(c_W \cdot \frac{1\text{ TeV}}{f_a}\right)^2$	σ_{bkg}
380	0.8 fb	0.2 pb
1500	3.8 fb	0.2 pb
3000	5.2 fb	0.15 pb

W e ν - associated



4-point interactions

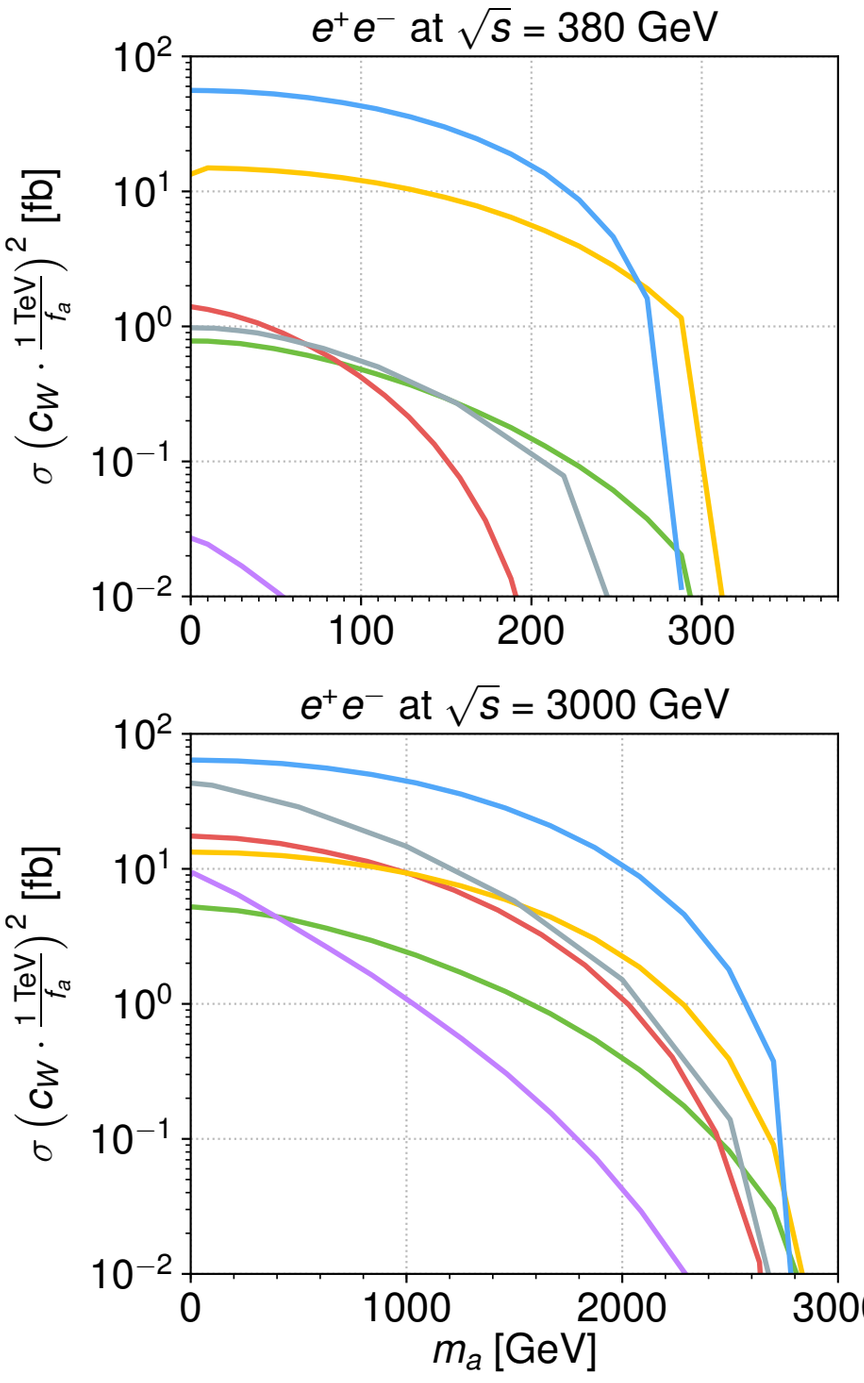
W e ν background decreases with √s

Forward e

$\sqrt{s}$ [GeV]	$\sigma\left(c_W \cdot \frac{1\text{ TeV}}{f_a}\right)^2$	σ_{bkg}
380	0.03 fb	2.6 pb
1500	1.5 fb	1.5 pb
3000	9 fb	0.92 pb

S/B improves with √s unlike mono-Z/γ

Heavy ALPs in e^+e^-



mono-Z
mono-γ
WW-fusion
WW-associated
Zγ-fusion
W$l\nu$-associated

Alternative production modes become more relevant at higher energies

Rates are correlated, controlled by one parameter

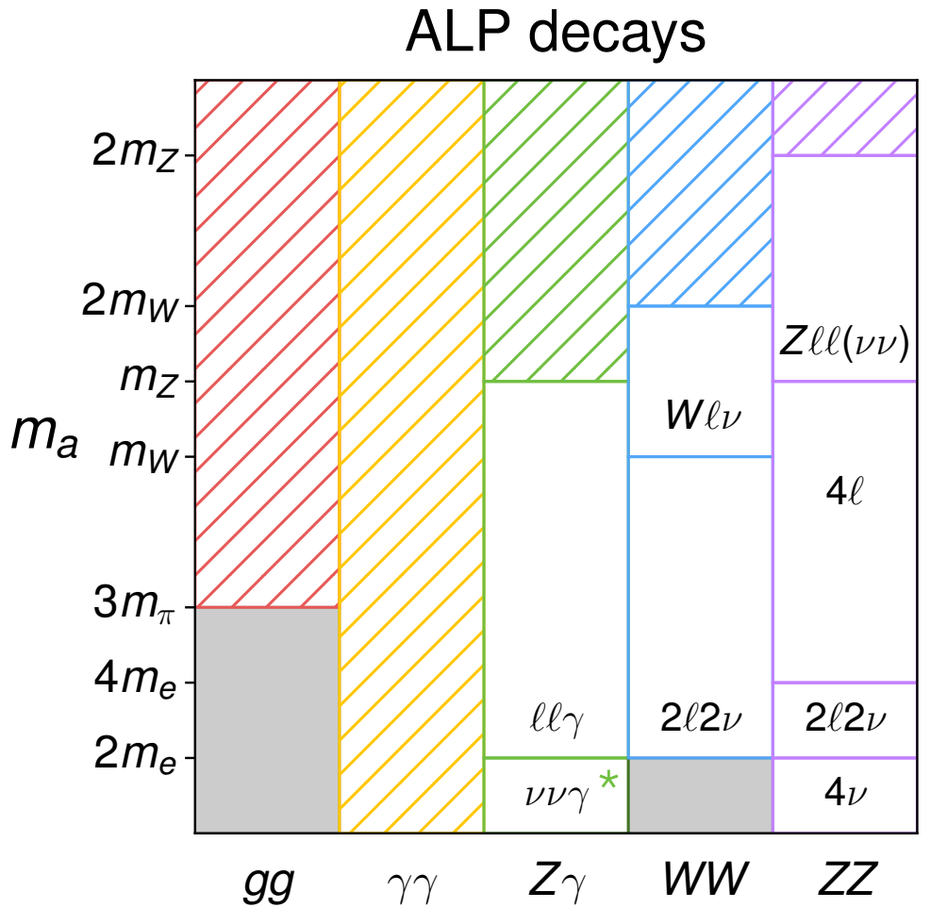
All processes have a pp-collider analogue

Rich phenomenology in production modes

Future searches

- Multitude of production/decay modes leads to many possibilities for resonant ALP searches
  - Multi-boson final states
  - Hadronic final states for gg/qq couplings
  - Part/fully invisible decays (DM connection)
  - Largely unexplored
  - Reinterpret existing searches

    ATLAS-CONF-2017-051
    diboson resonance (VBF→qqlv)
    search: $c_W \sim 10^{-2}$-10^{-3}
  - Boosted dijet, low mass diphoton
  - Motivate/inspire new searches
  - Much to look forward to!



*ALP → γνν is "long lived"
up to $m_a \sim$ 5-10 GeV

Conclusion

- Brief overview of ALPs at colliders
  - Overlap with collider phenomenology of DM
  - Light/stable scenario: $\gamma\gamma$ coupling very constrained
  - Orthogonal direction in EW gauge boson couplings can be probed at colliders to similar levels as indirect (1-loop) flavour constraints via mono-X
  - Alternative production modes become interesting at higher energies
  - Heavier ALPs: resonant multi-boson final states
- Scenario with well defined interactions
  - Connection with DM mediator, low scale “axion”, composite Higgs models
  - Rich pheno with many unexplored avenues
  - What existing searches could already be sensitive?
  - High multiplicity final states, boosted techniques, displaced vertices, exotic higgs decays

Backup

ALP stability

$$\Gamma_{a\to XX} = \frac{g_{aX}^2 M_a^3}{64\pi} \cdot C_X$$

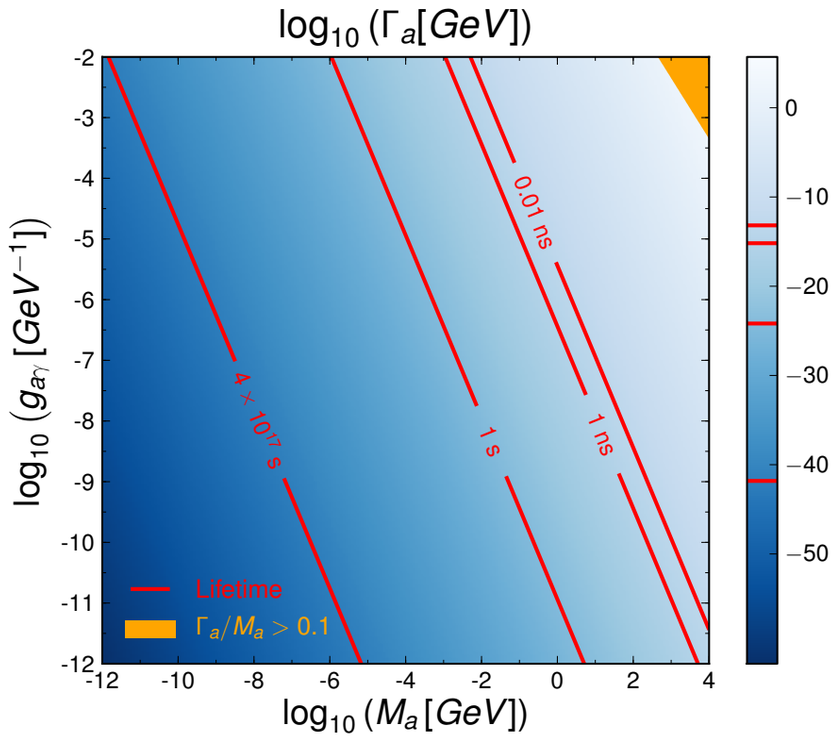
$$\tau = \hbar/\Gamma$$

$$\tau_{\text{univ.}} = 4 \times 10^{-17}\, s$$

$$\tau_{\text{bbn}} = 1\, s$$

$$\tau_{\text{stab.}} \lesssim 1\, ns$$

$$\tau_{\text{prompt}} > 0.01\, ns$$



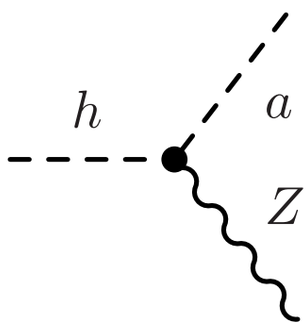
photon coupling

- Partial width to gauge bosons grows rapidly with m_a
  - Transition from missing energy to prompt decay signature ~ GeV
  - Narrow window for displaced signatures
  - Stable ALP = effectively massless at high energy colliders
  - Eventually the narrow width approximation breaks down at ~ TeV

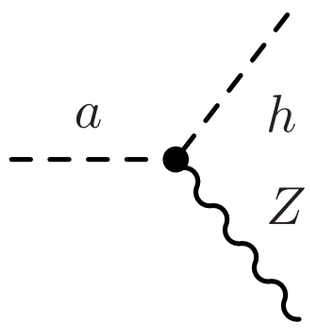
[Brivio, Gavela, KM, Merlo, No, del Rey & Sanz; arXiv: 1701.05379]
[Bauer, Neubert & Thamm; PRL 119 (2017) 031802 & arXiv: 1708.00443]

Higgs-Z-ALP coupling

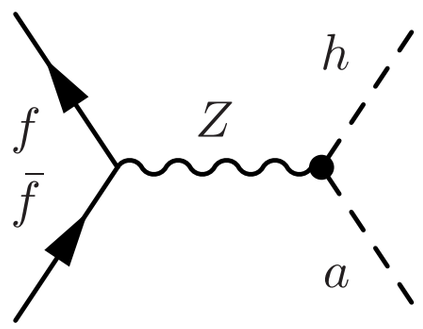
- The Higgs current operator can be removed by EOM etc.
  - Simultaneously removes Z-ALP mixing & tree-level H-Z-ALP coup
  - Regenerated by loops or induced by higher dimension operators
- If EWSB is non-linearly realised, it can appear at tree-level
  - Different power counting (derivatives vs canonical mass dimension)
  - Higgs field is now a singlet, h and h^2 components de-correlated where previously $|\Phi|^2 \rightarrow (h^2 + 2\,v\,h + v^2)$



Exotic Higgs decay



New ALP decay mode



Mono-Higgs