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Heavy ALPs at CLIC in EW gauge boson final staes

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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 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

$$\mathcal{L}_a = -\frac{c_1\alpha_1}{4\pi}\frac{a}{f_a}B_{\mu\nu}\widetilde{B}^{\mu\nu} - \frac{c_2\alpha_2}{4\pi}\frac{a}{f_a}W^I_{\mu\nu}\widetilde{W}^{\mu\nu}_I - \frac{c_3\alpha_3}{4}\frac{a}{f_a}G^A_{\mu\nu}\widetilde{G}^{\mu\nu}_A + \frac{\partial_\mu a}{f_a}\sum_\psi \bar{\psi}_i\gamma_\mu c^{ij}_\psi\psi_j$$

$$\mathcal{L}_{EW} = -c_{\gamma\gamma}\frac{e^2}{4\pi^2}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} - c_{ZZ}\frac{e^2}{4\pi^2}\frac{a}{f_a}Z_{\mu\nu}\tilde{Z}^{\mu\nu} - c_{Z\gamma}\frac{e^2}{4\pi^2}\frac{a}{f_a}F_{\mu\nu}\tilde{Z}^{\mu\nu} - c_2\frac{g_2^2}{4\pi^2}\frac{a}{f_a}W^+_{\mu\nu}\tilde{W}^{\mu\nu}_-$$

- General $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant effective interactions for a $J^P=0^-$ field *[Georgi, Kaplan & Randall; PLB 169 73 (1986)]*
  - Approximate shift symmetry characteristic of 'Axion-like' property
  - QCD-axion models: $f_a\, m_a \propto f_\pi\, m_\pi \rightarrow$ ultra light & weakly coupled
  - EW sector - 4 couplings determined by 2 parameters
  - Di-photon coupling is relevant for cosmological constraints on light ALPs
  - All couplings interesting for heavy ALPs

The photophobic ALP

General

$$c_{\gamma\gamma} = \frac{1}{4}(c_1 + c_2),$$

$$c_{ZZ} = \frac{1}{4}\left(c_1 \tan^2\theta_W + \frac{c_2}{\tan^2\theta_W}\right),$$

$$c_{Z\gamma} = \frac{1}{2}\left(c_1 \tan\theta_W - \frac{c_2}{\tan\theta_W}\right).$$

Photophobic: $c_1 = -c_2$

$$c_{\gamma\gamma} \simeq 0,$$

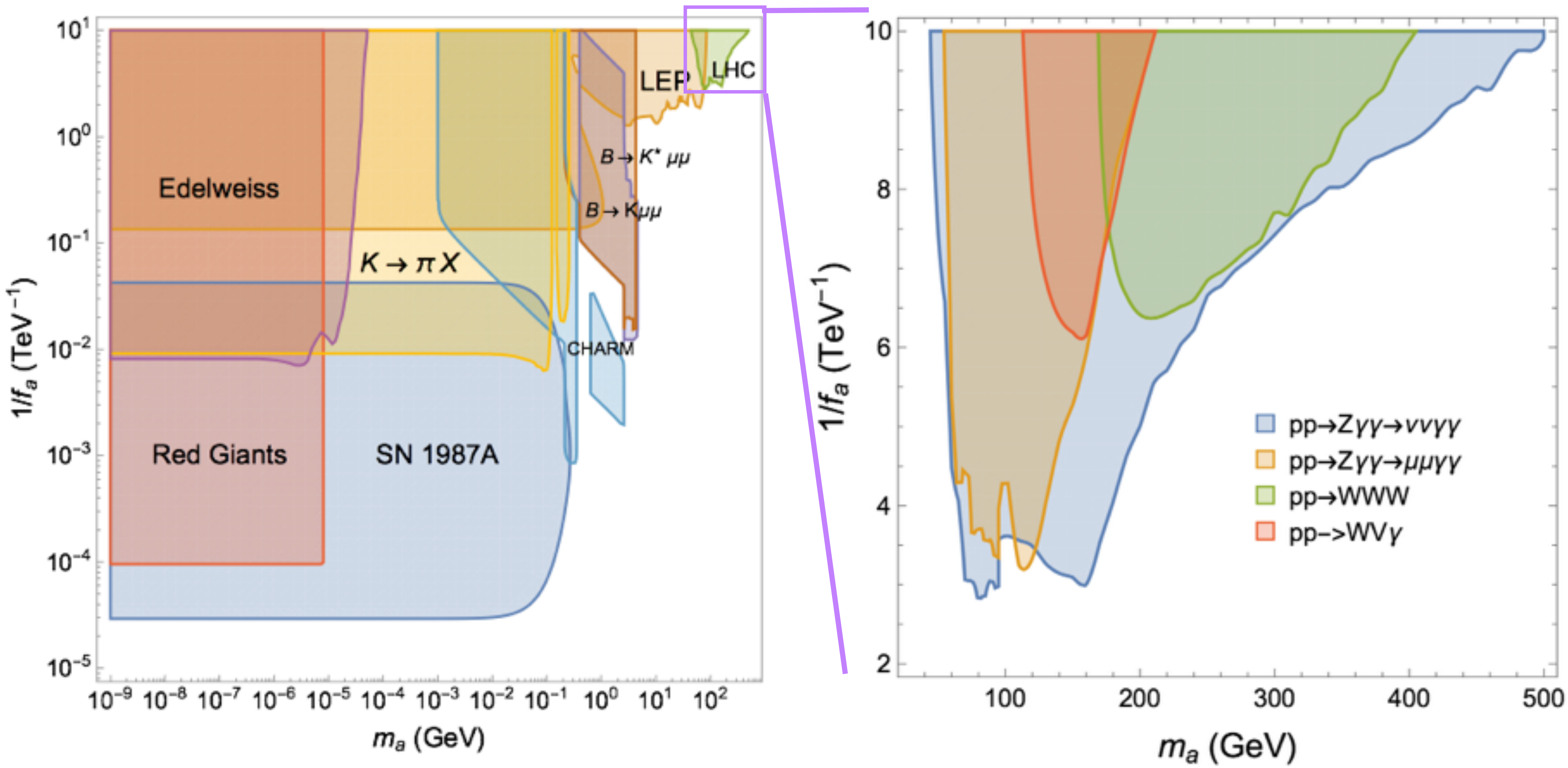
$$c_{ZZ} \simeq \frac{\cos 2\theta_W}{\sin^2 2\theta_W} c_2,$$

$$c_{Z\gamma} \simeq -\frac{c_2}{\sin 2\theta_W}.$$

- For light ALPs, $c_{\gamma\gamma}$ is constrained beyond collider reach
  - Photophobic scenario more relevant for non-cosmological probes
- Specific relation between c_1 and c_2: fine tuned?
  - Recent work has argued that this scenario is natural and photophobia is protected under RGE in the massless limit *[Craig, Hook & Kasko; arXiv:1805.06538]*
  - Exact photophobia impossible: irreducible (loop suppressed) photon interactions induced by ALP mass
- For heavy ALPs (~GeV), both scenarios are viable
  - Today: CLIC reach on photophobic case

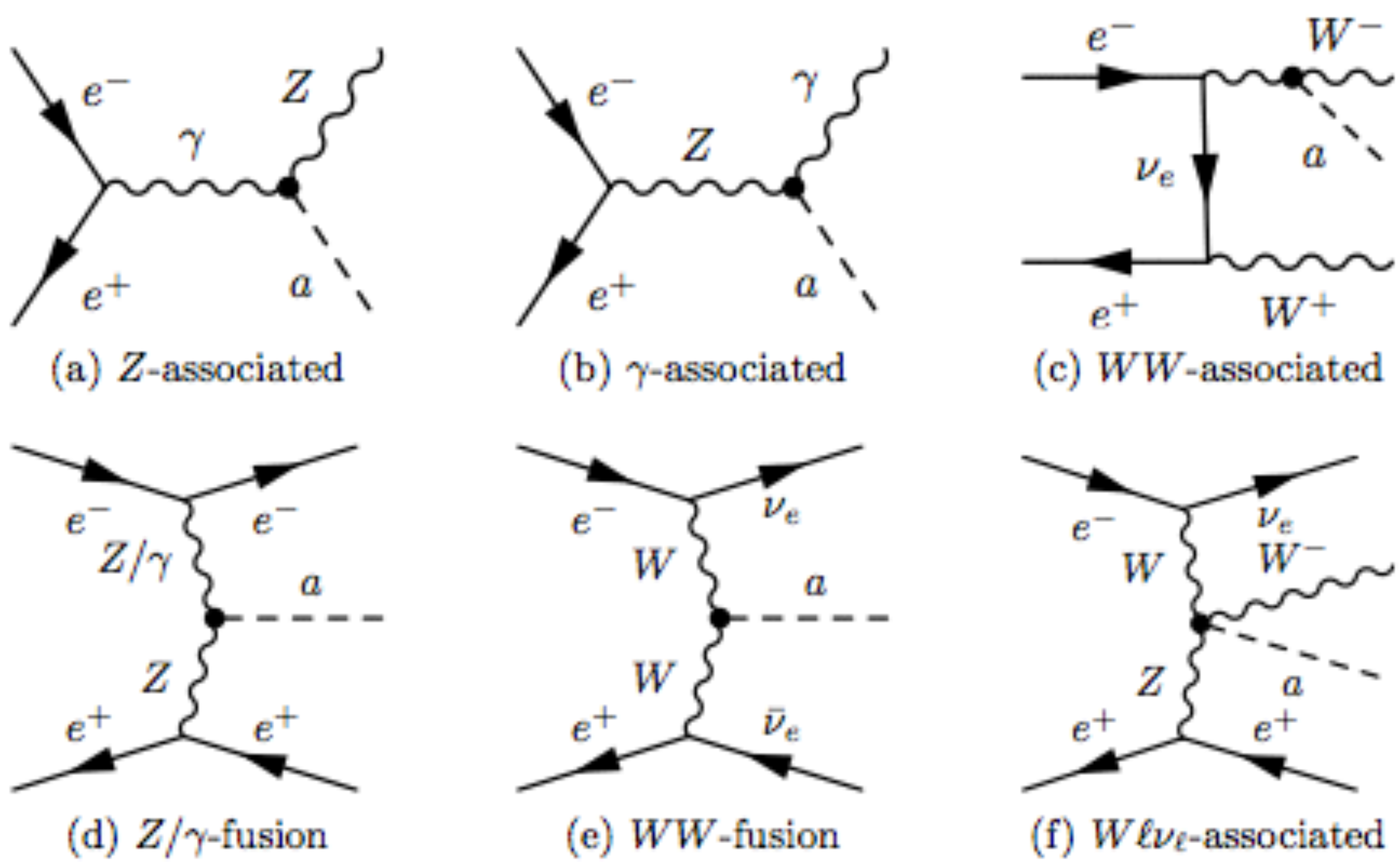
Constraints: photophobia

[Craig, Hook & Kasko; arXiv:1805.06538]



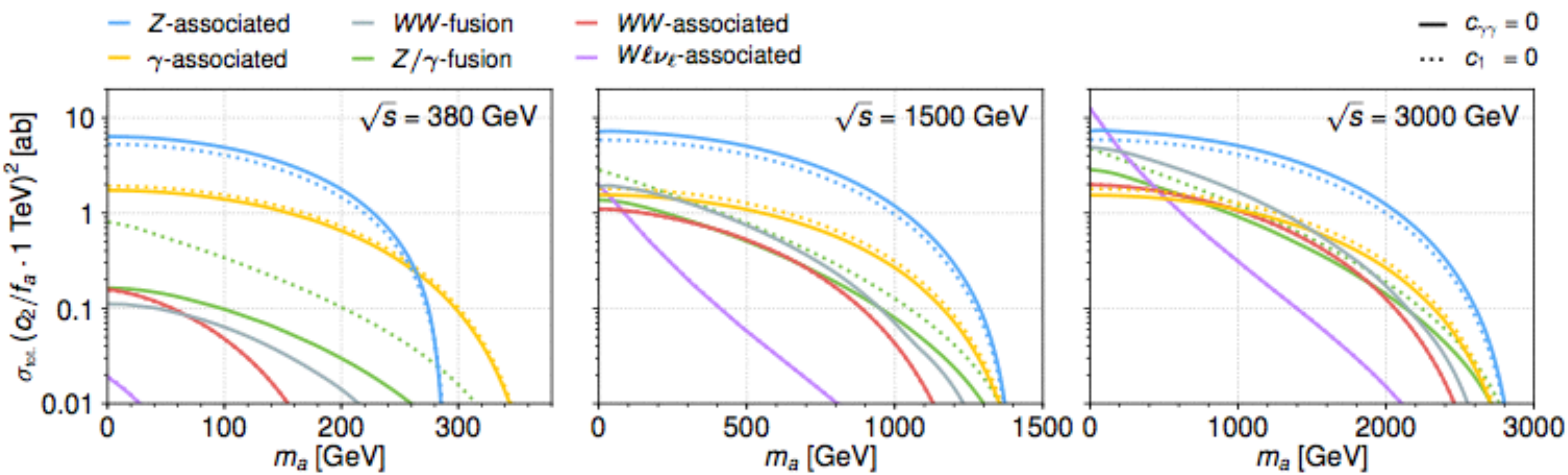
- Irreducible $c_{\gamma\gamma}$ relaxes cosmological constraints by 1-loop
  - Colliders complementary in the heavy region > 1 GeV
  - LHC multiboson recasts, Z-decays at LEP & rare meson decays

ALP production at CLIC



- Production mechanisms ~same between general & photophobic scenarios
  - Associated production (Z, photon, WW)
  - VBF (e^+e^-- and νν-associated)

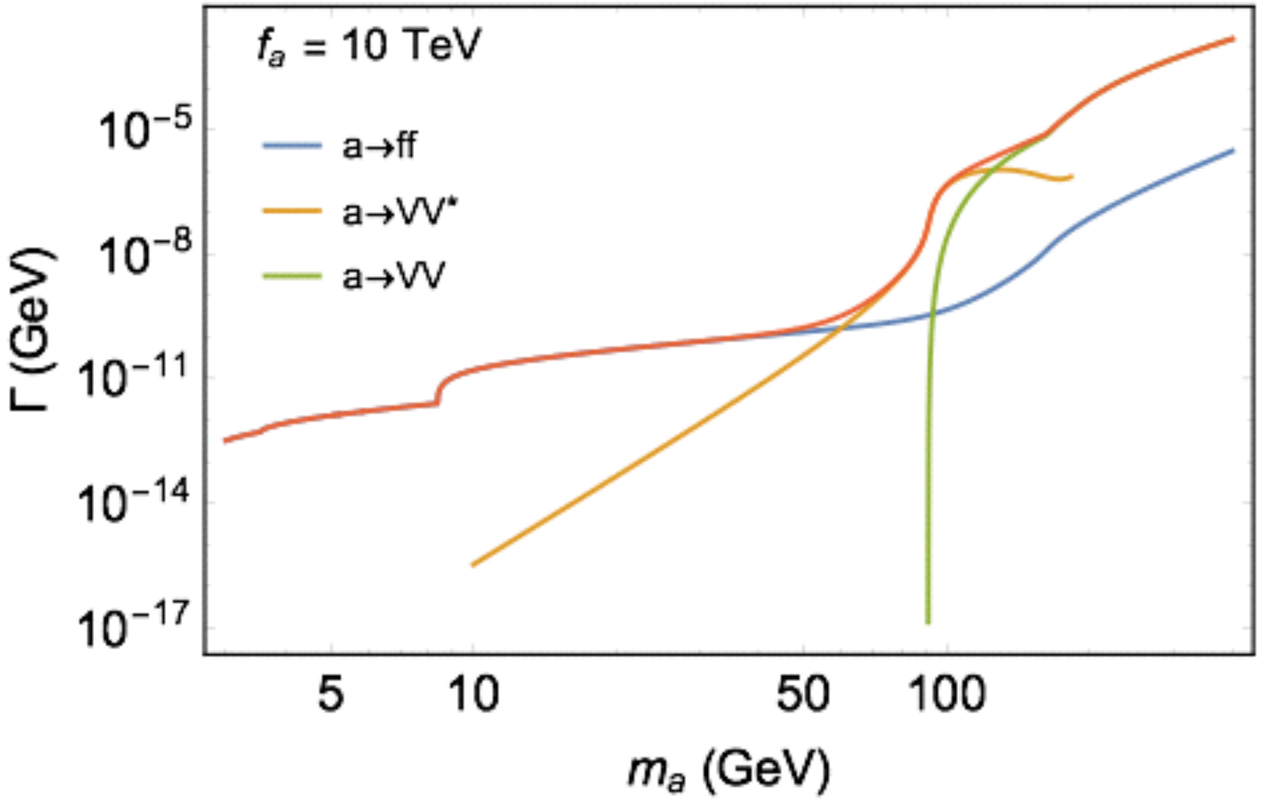
ALP production at CLIC

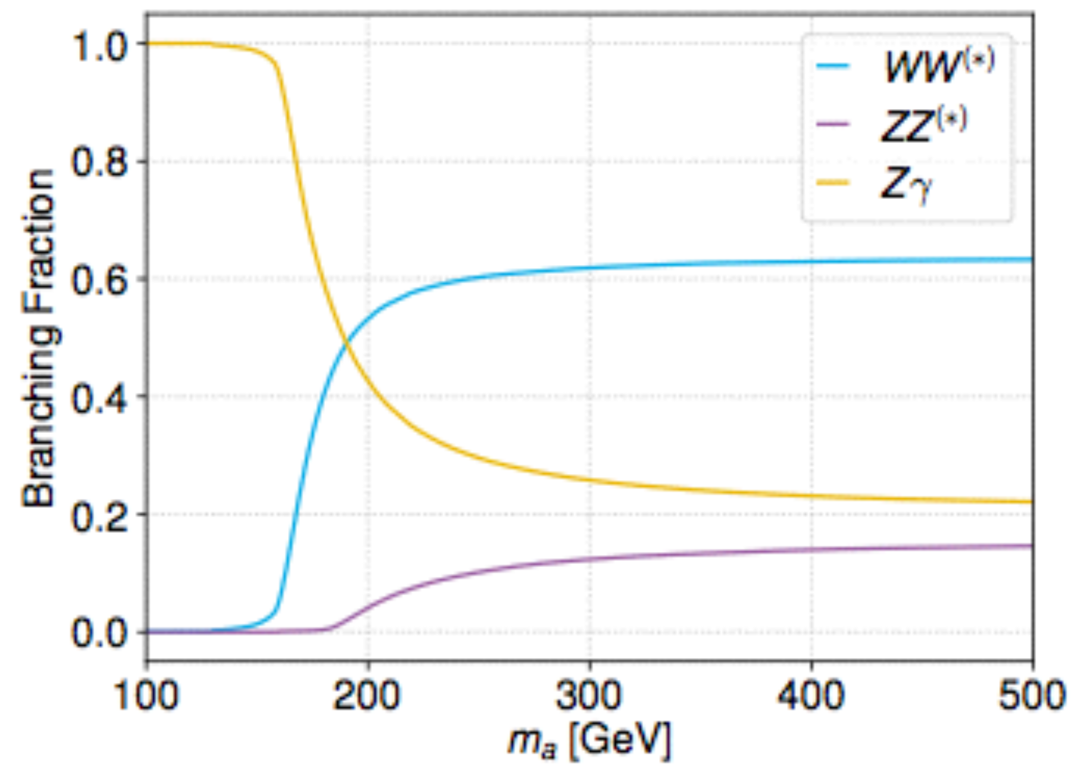


- Z & photon associated production are the primary modes
  - Z still needs to decay, branching fraction cost
- Other processes become relevant with increasing energy
  - Particularly WW-fusion & $Wl\nu_l$ at low masses
  - Not a huge difference between photophobic & c_1=0 case except Z/γ-fusion

Photophobic ALP decays

[Craig, Hook & Kasko; arXiv:1805.06538]





- Diphoton decay negligible above 2me
- Fermion decay modes until ~ 70 GeV
- Above Z threshold, EW modes dominate
  - BR purely kinematics driven, independent of c_2
  - Plateau at: 65% WW, 20% $Z\gamma$ and 15% ZZ

Heavy ALP signatures

Decay	Z-assoc.	γ-assoc.	WW-fusion	WW-assoc.	$Z\gamma$-fusion	$W\ell\nu$-assoc.
WW	ZWW	γWW	$WW + \not{E}$	$WWWW$	$eeWW$	$We\nu WW$
$Z\gamma$	$ZZ\gamma$	$\gamma Z\gamma$	$Z\gamma + \not{E}$	$WWZ\gamma$	$eeZ\gamma$	$We\nu Z\gamma$
ZZ	ZZZ	γZZ	$ZZ + \not{E}$	$WWZZ$	$eeZZ$	$We\nu ZZ$

- Many resonant multi-boson signatures
  - Some with overlapping final states (different resonant structure)
- Focus on $Z\gamma$ decay mode
  - No missing energy & only one Z boson BR penalty
  - As a first study for simplicity, leptonic Z decays
- 1) γ-associated production: γ + resonant γl^+l^-
- 2) WW-fusion: νν + resonant γl^+l^-
  - Overlaps with Z-associated with Z→νν, also included
  - Should provide additional sensitivity at 380 GeV where WWF is small

Sensitivity study

- Signal/ Background generation with MG5_aMC@NLO
    - with c_2/f = 0.1 GeV^{-1}, width below 10%, until m_a~ 2 TeV
    - Decays with MadSpin, assume narrow width approximation
- Detector response with CLIC-specific Delphes card
- Dominant background
    - γ-associated: SM $Z\gamma\gamma$ production
    - $\nu\nu$-associated: SM $(Z\to\nu\nu)Z\gamma$ production & $Z\gamma\gamma$ with one γ out of acceptance
- Event selection using Neural Network classifier
    - Clean resonant structure: cut and count would be ~OK
    - Ensure maximum sensitivity with NN
- Evaluated 95% CL sensitivity on c_2/f with CLs method

γ-associated production

2 photons & leptons (closest to m_Z)

γll system reconstructs m_a

$c_2/f = 1\ \text{GeV}^{-1}$

$\sqrt{s} = 380$ GeV			$\sqrt{s} = 1.5$ TeV			$\sqrt{s} = 3$ TeV		
m_a [GeV]	$\sigma_{\text{tot.}}$ [fb]	$\sigma \cdot \mathcal{A} \cdot \varepsilon$ [fb]	m_a [GeV]	$\sigma_{\text{tot.}}$ [fb]	$\sigma \cdot \mathcal{A} \cdot \varepsilon$ [fb]	m_a [GeV]	$\sigma_{\text{tot.}}$ [fb]	$\sigma \cdot \mathcal{A} \cdot \varepsilon$ [fb]
100	94	43	100	103	4.3	100	103	0.52
120	85	45	300	24	11	300	26	3.2
140	74	43	500	16	8.2	600	19	5.5
160	61	37	800	7.7	3.6	900	16	4.6
200	19	10	1000	3.5	1.4	1200	12	3.1
240	7.8	5.0	1200	0.91	0.30	1600	7.6	1.4
280	3.1	1.9	1400	0.045	0.011	2000	3.5	0.46
320	0.76	0.44				2400	0.91	0.12
						2800	0.045	0.003
BKG: $Z\gamma\gamma$	26.7	7.8	$Z\gamma\gamma$	4.5	0.63	$Z\gamma\gamma$	1.7	0.11

- Production xs times branching fraction
  - Inclusive vs. after acceptance & basic selection (before NN classifier)
  - At high energies compared to m_a, boosted ALP leads to collimated decay productions and loss of acceptance

νν-associated production

1 photon & 2 leptons (closest to m_Z)

γll system reconstructs m_a

c_2/f=1 GeV^{-1}

$\sqrt{s}=380$ GeV			$\sqrt{s}=1.5$ TeV			$\sqrt{s}=3$ TeV		
m_a [GeV]	$\sigma_{\text{tot.}}$ [fb]	$\sigma\cdot\mathcal{A}\cdot\varepsilon$ [fb]	m_a [GeV]	$\sigma_{\text{tot.}}$ [fb]	$\sigma\cdot\mathcal{A}\cdot\varepsilon$ [fb]	m_a [GeV]	$\sigma_{\text{tot.}}$ [fb]	$\sigma\cdot\mathcal{A}\cdot\varepsilon$ [fb]
100	71	31	100	224	33	100	422	39
120	62	37	300	45	26	300	96	38
140	52	34	500	27	16	600	59	27
160	41	28	800	10	5.7	900	41	17
200	10	7.4	1000	4.3	2.0	1200	28	8.9
240	2.9	2.1	1200	0.95	0.34	1600	14	3.1
280	0.18	0.13	1400	0.0046	0.0013	2000	5.7	0.86
320	0.0016	0.0012				2400	1.3	0.14
						2800	0.037	0.0030
$Z\gamma\nu\bar{\nu}$	1.6	0.73	$Z\gamma\nu\bar{\nu}$	8.3	3.3	$Z\gamma\nu\bar{\nu}$	17.3	5.9
$Z\gamma(\gamma)$	26.7	3.0	$Z\gamma(\gamma)$	4.5	0.44	$Z\gamma(\gamma)$	1.7	0.10

BKG

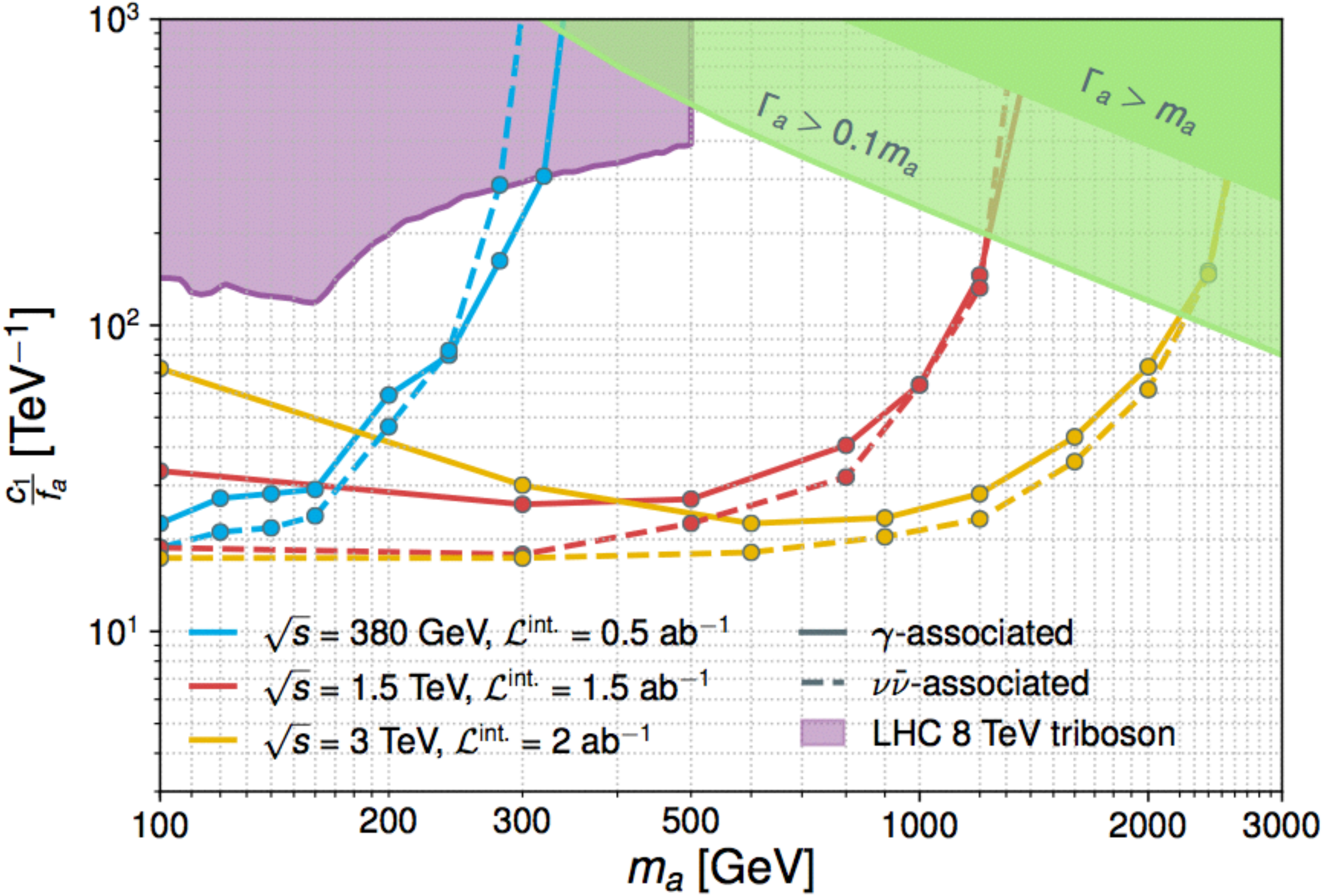
- Production xs times branching fraction
  - Less boosted ALP leads to better acceptance for high energies vs m_a
  - Comparable rates even for 380 GeV thanks to Z-associated contribution
  - Switch in relative importance of two backgrounds form 380 to 1500 GeV

NN signal selection

- Traditional kinematic classifier between signal and background events
  - Trained independently for each mass hypothesis
  - γ-associated: binary classifier
  - vv-associated: multi-class discriminant trained to identify signal and two dominant backgrounds
- Cut on NN discriminant to identify signal region
  - vv-associated: construct 2 combined outputs to distinguish signal from each background separately
  - 2D cut on outputs: allows for a smooth transition between collider energies and mass hypotheses where backgrounds contribute with varying weight
  - Generally obtain O(0.5) signal efficiency vs 10^3 background rejection

$$P_A = \frac{P_{\nu\bar{\nu}a}}{P_{\nu\bar{\nu}a} + P_{Z\gamma\nu\bar{\nu}}} \quad \text{and} \quad P_B = \frac{P_{\nu\bar{\nu}a}}{P_{\nu\bar{\nu}a} + P_{Z\gamma\gamma}}$$

Results



10^3
10^2
10^1
$\frac{c_1}{f_a}$ [TeV^{-1}]
100
200
300
500
1000
2000
3000
m_a [GeV]
$\Gamma_a > 0.1 m_a$
$\Gamma_a > m_a$
$\sqrt{s}$ = 380 GeV, $\mathcal{L}^{\text{int.}}$ = 0.5 ab^{-1}
$\sqrt{s}$ = 1.5 TeV, $\mathcal{L}^{\text{int.}}$ = 1.5 ab^{-1}
$\sqrt{s}$ = 3 TeV, $\mathcal{L}^{\text{int.}}$ = 2 ab^{-1}
γ-associated
$\nu\bar{\nu}$-associated
LHC 8 TeV triboson

Conclusion

- CLIC improves existing sensitivity to ALPs by at least one order of magnitude
  - Different complementary channels for different energy stages
  - Boosted light ALPS affect reco efficiency
  - WW fusion does not have this effect
- Outlook
  - Hadronic gauge boson decay modes an important avenue to explore
  - Many other interesting channels to consider: rich pheno
  - Final YR contribution will include results from two other studies
  - One on non-photophobic scenarios

    [Butazzo, Redigolo, Sala & Tesi; arXiv:1807.04743]

Backup