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Non-Resonant ALP Searches at the LHC: Implications for VBS

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Theoretical Background

- ALPs (Axion-like Particles) are well motivated theoretically as neutral pseudo-scalar Pseudo-Goldstone Bosons (PGB) of a new spontaneously broken global symmetry.

- ALP interactions parameterized with a general Effective Field Theory Lagrangian, consistent with SM gauge symmetries and CP. Two implementations of EFTs: linear (related to weakly coupled new physics models) and chiral (related to strongly coupled new physics models). In this talk we focus on the linear EFT.

$$\delta\mathscr{L}_{\rm ALP} \supset -c_{\tilde{B}}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} - c_{\tilde{W}}\frac{a}{f_a}W^i_{\mu\nu}\tilde{W}^{i\mu\nu} - c_{\tilde{G}}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{A\mu\nu} + ic_{a\Phi}\frac{\partial^\mu a}{f_a}\Phi^\dagger \overleftrightarrow{D}_\mu \Phi$$

- ALP interactions are derivative: they grow with momentum; couplings are proportional to coefficient c_i and inversely proportional to new physics energy scale f_a.

- Classical searches for ALPs consider couplings to photons and gluons (cG). More recently, interest in this area has extended to consider ALP couplings to EWK-bosons: ZZ, WW and Z gamma. At LO all these and the coupling to photons are related by gauge symmetry to two basic EWK couplings: cW and cB.

Non-Resonant ALP-Mediated Processes

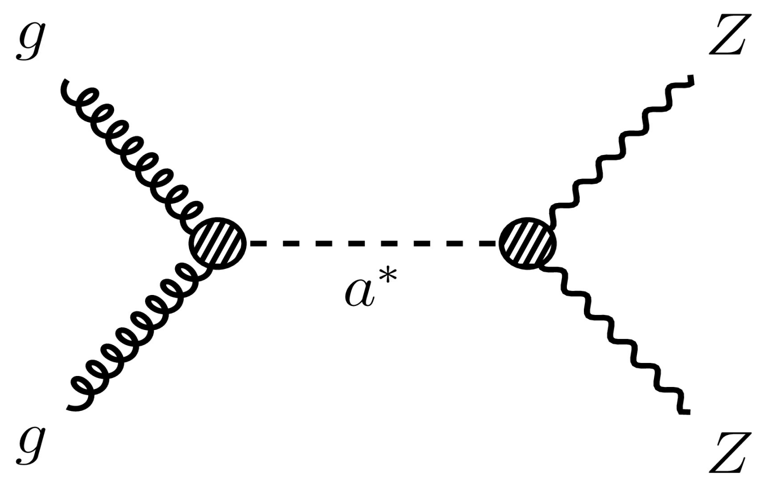
- Gluon-initiated non-resonant ALP-mediated processes provide more possibilities to test the ALP universe.

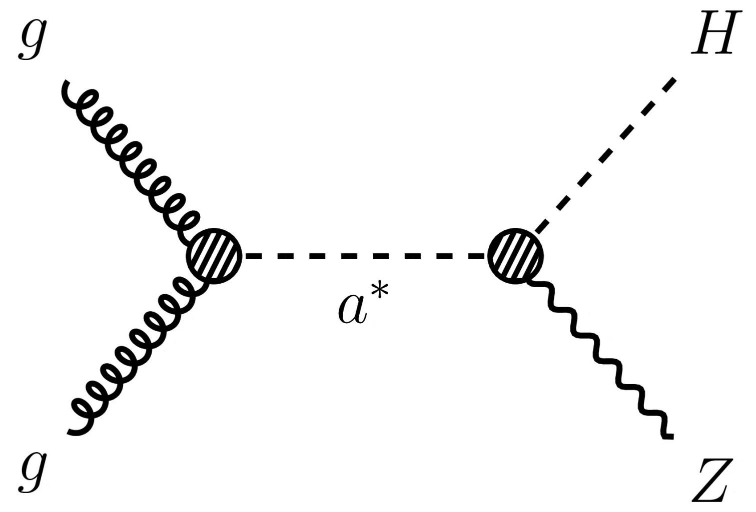
- ALPs are s-channel mediators in ggF diboson production with s-hat >> M_a. The size of s-hat is enhanced by the mass threshold of the on-shell diboson system and, most importantly, by the hard pT spectrum provided by the derivative couplings.

- The analysis looks for high-pT / high-mass deviations in the tails of the experimental distributions with respect to SM expectations.

- These channels are sensitive to the product of the ALP coupling to gluons times the coupling to EWK dibosons.

- Cross-sections, kinematical distributions and limits are found independent of M_a from the very-light limit, up to masses of order of 100 GeV.





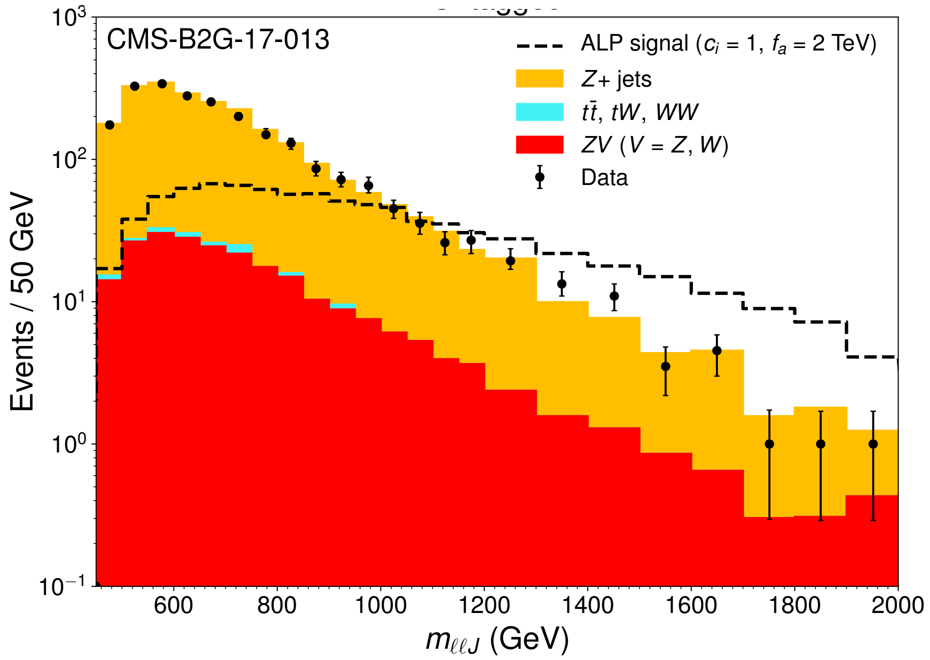
Gavela, No, Sanz, Trocóniz; PRL 124 (2020) 051802

Non-Resonant ALP Searches at the LHC

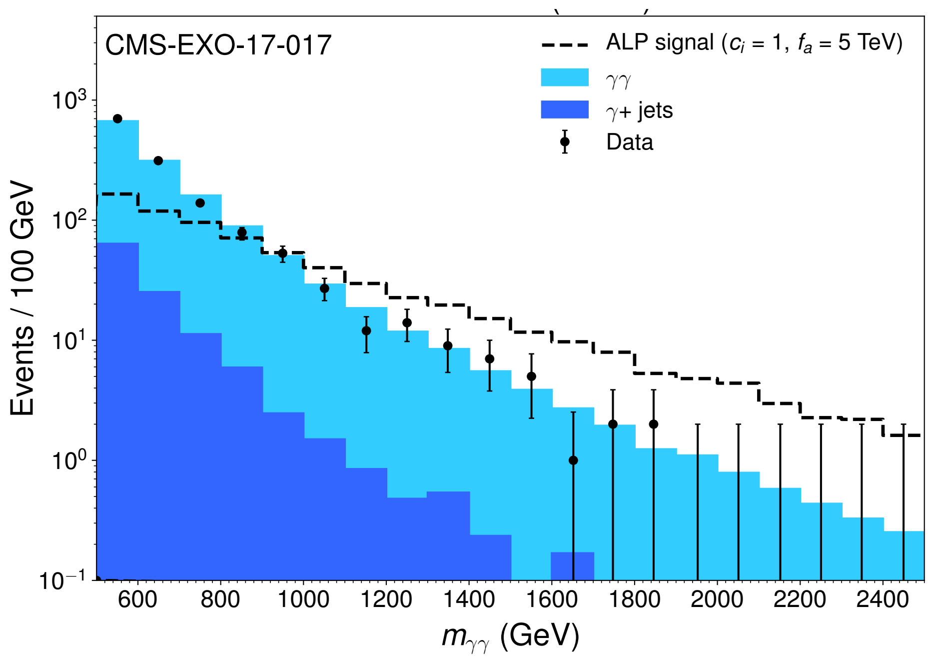
Cross-sections are large enough to constraint significantly the theoretical models using Run 2 data. For instance: Linear EFT, photofobic benchmark case, cG/fa = cW/fa = 1/TeV, Ma = 1 MeV. Syst. uncertainties: 7% renorm. / fact. scales; 1.2% pdfs.

- gg => ZZ 40 pb (80 pb for cB = cW)
- gg => WW 180 pb
- gg => Z gamma 60 pb
- gg => gamma gamma 50 pb cB = cW; M(γγ) > 0.5 TeV

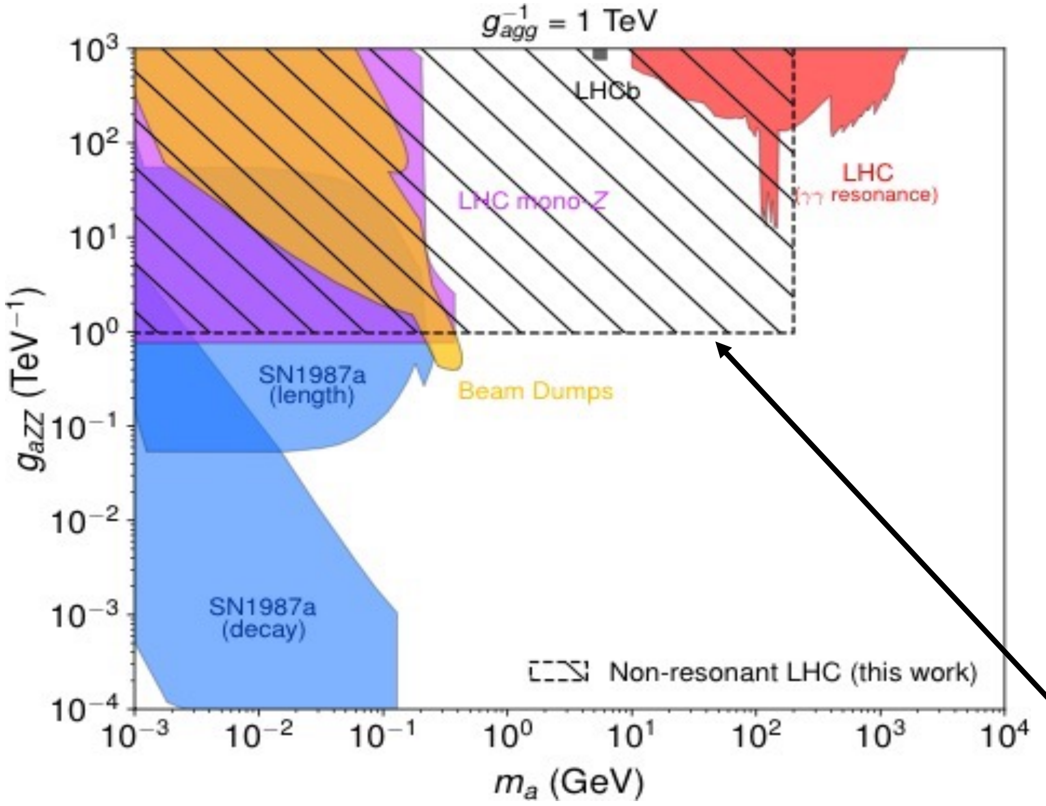
ZZ CMS-BSG-17-013

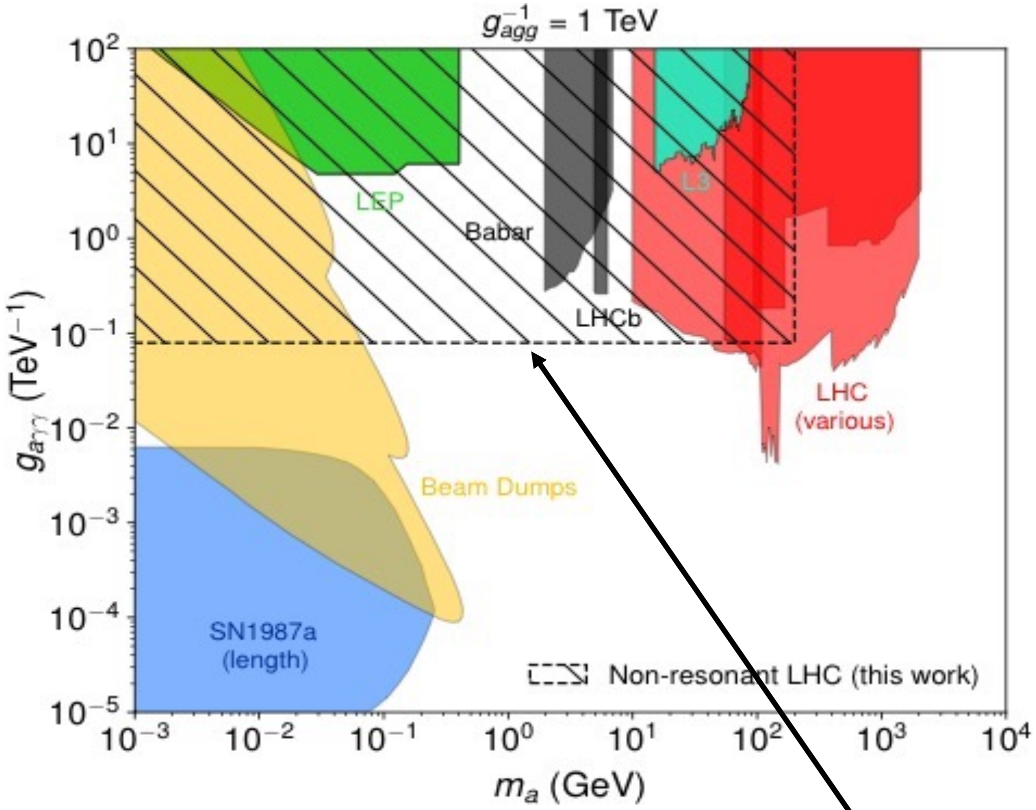


Diphoton CMS-EXO-17-017



LHC Run 2 ALP Limits





- Gavela, et al.; PRL 124 (2020) 051802: CMS $|cZ|/fa < 0.23$ TeV^{-1}, $|c\boldsymbol{\gamma}|/fa < 0.02$ TeV^{-1}, for $|cG|/fa = 0.25$ TeV^{-1}.
- Carrá, et al.; hep-ex 2106.10085: ATLAS $|cW|/fa < 0.15$ TeV^{-1}, $|cW\text{-}cB|/fa < 0.11$ TeV^{-1}, for $cG/fa = 0.25$ TeV^{-1}.

+ new experimental searches (check other presentations at EPS HEP 21).

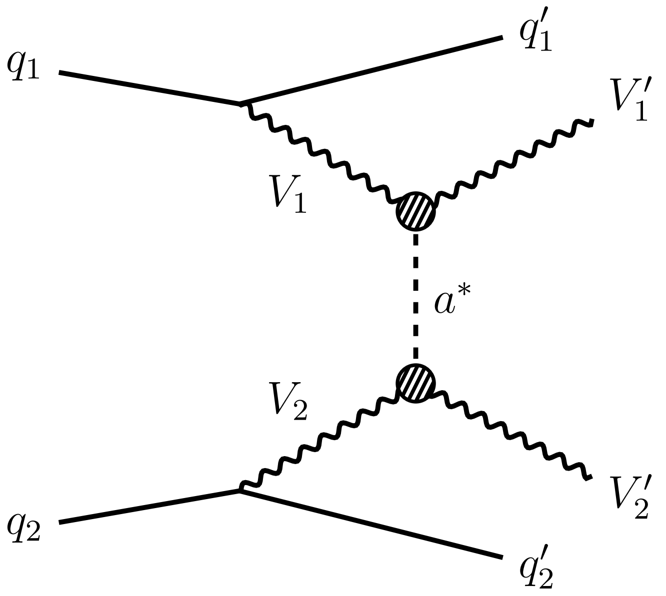
Non-Resonant ALPs in VBS

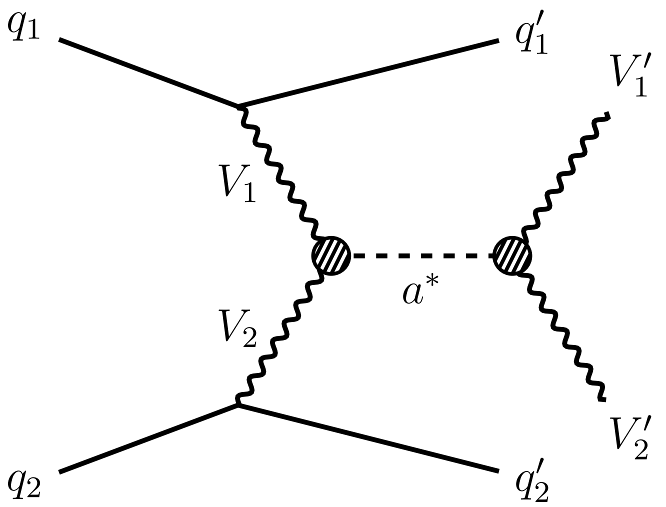
- Non-resonant ALP-mediated processes in VBS channels are sensitive to ALP EWK couplings independently of the ALP gluon coupling.

- in the explored region of ALP EWK couplings |cW|/fa, |cB|/fa >~ 1 TeV^{-1}, experimental ggF NR ALP limits make the gluon-initiated ALP VBS contribution subdominant; |cG|/fa <~ 0.03 TeV^{-1}.

- The VBS diagrams contain an off-shell ALP interchanged in the t-channel; s-channel is relevant for the ZZ and the Z gamma final states.

- ATLAS / CMS have recently published Run 2 VBS measurements. Allow first comparison to the data, calibration of the simulation tools, calculation of educated predictions for higher luminosities.





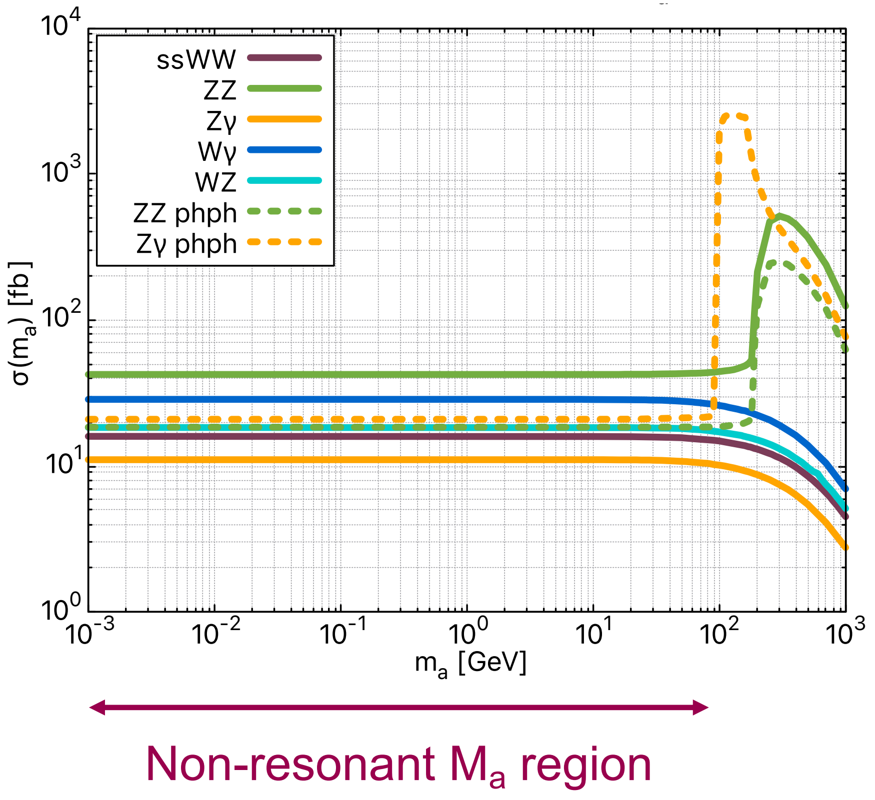
Non-Resonant ALPs in VBS

- Cross-sections, kinematical distributions and limits are found still independent of M_a from the very-light limit, up to masses of order of 100 GeV.

- Simulation of ALP signals based on ALP EFT linear model implementation in MadGraph, by Brivio, Gavela, No, Sanz, et al.

- We have started a re-interpretation of five CMS VBS papers with leptonic / photonic final states. Results reported here should be considered preliminary.

- Expected numbers of events in the next slides use the selections, luminosities and backgrounds in the CMS publications.



- Limits calculated for large fa (>~ 4 TeV, in practice) and for fa = 2 TeV. Numbers of signal events reduced to ~85% due to EFT consistency condition M(VV) < f_a = 2 TeV.

- Delphes simulation efficiencies “calibrated” using CMS SM EWK VBS expected yields; assigned 20% systematics.

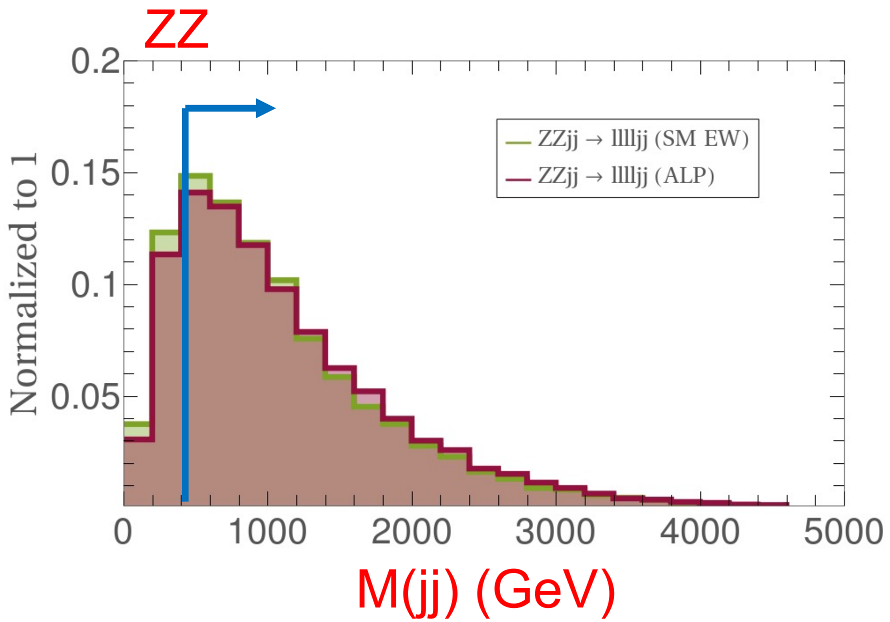
ALP VBS Cross-Sections @ 13 TeV

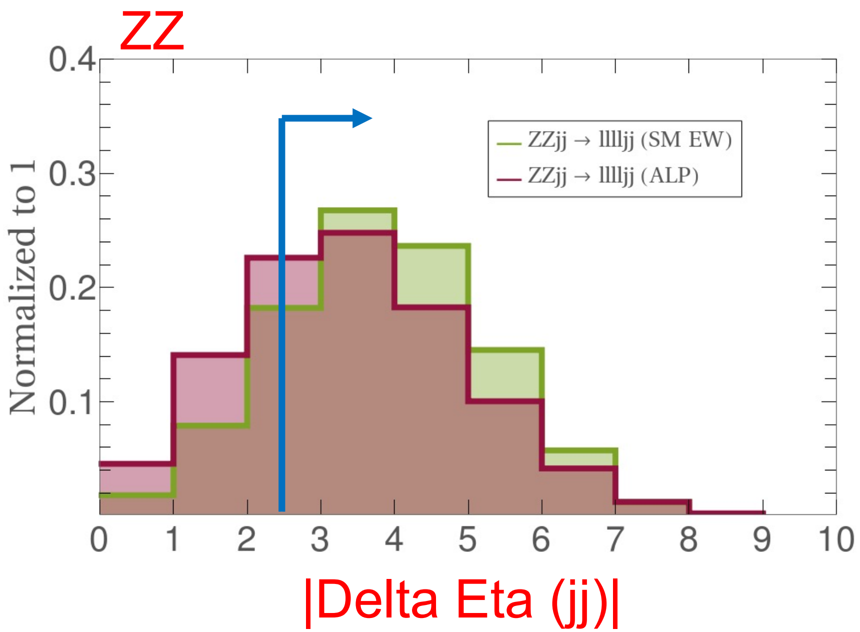
- Linear EFT, benchmark case (1): cB/fa = cW/fa = 1/TeV, Ma = 1 MeV; case (2): photophobic, cW/fa = 1/TeV; Mjj > 120 GeV. Systematic uncertainties: 11% renorm. / fact. scales; 4% pdfs.

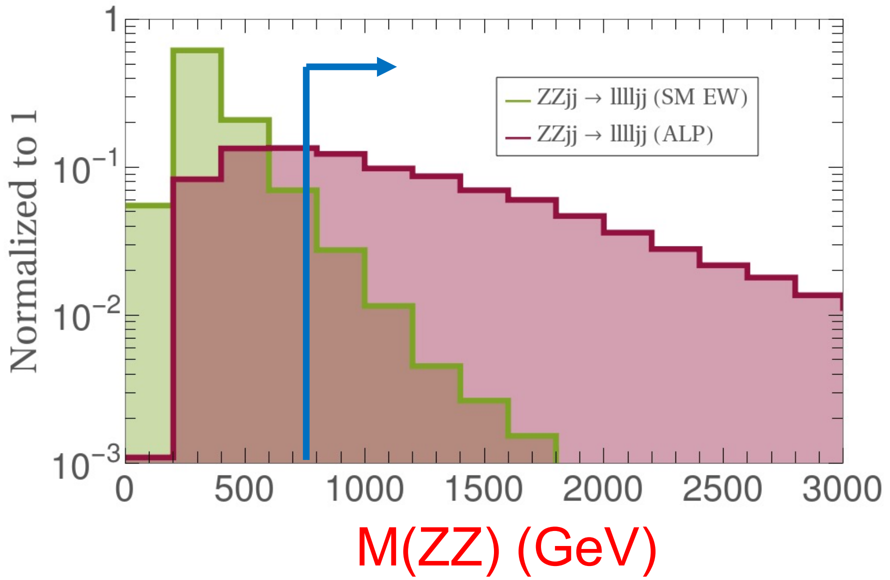
	SM VBS EWK	ALP case (1) sgnl. / interf.	ALP case (2) sgnl. / interf.	# dilepton events at CMS	int. lum. (fb^{-1})
ZZ	100 fb	42 / -13 fb	18 / -9 fb	9.3 / -3.2	137
WZ	390 fb	18 / 1.7 fb	24 / -0.1 fb	4.2 / 0.05	137
ssWW	260 fb	16 / -4.0 fb		18 / -5.5	137
W gamma	990 fb	29 / 4.3 fb	5.4 / 1.7 fb	3.6 / -0.04	36
Z gamma	390 fb	11 / 0.3 fb	21 / -9 fb	3.8 / 0.02	36

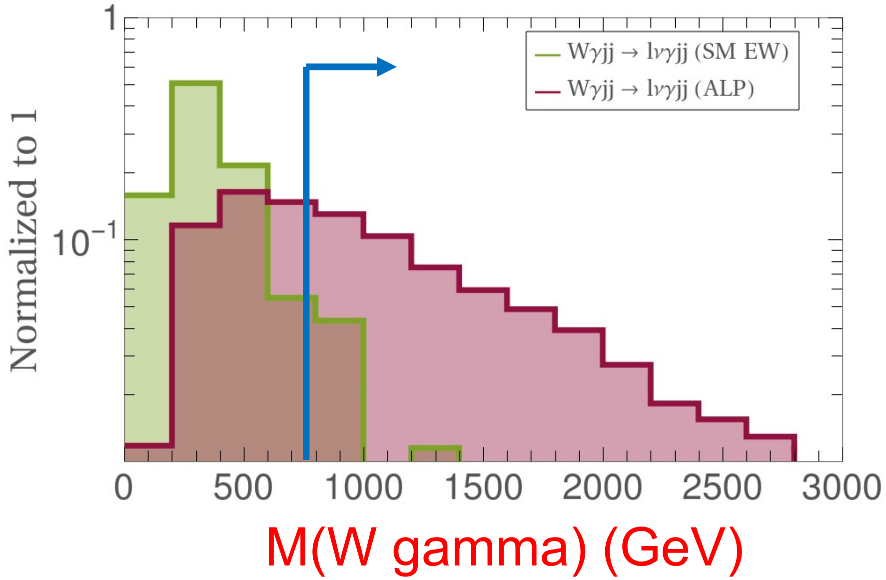
- Interference effects subdominant. Selection efficiencies range from 5% to 30%, depending on the dijet selection cuts.

VBS Observables: ALP vs. SM EWK



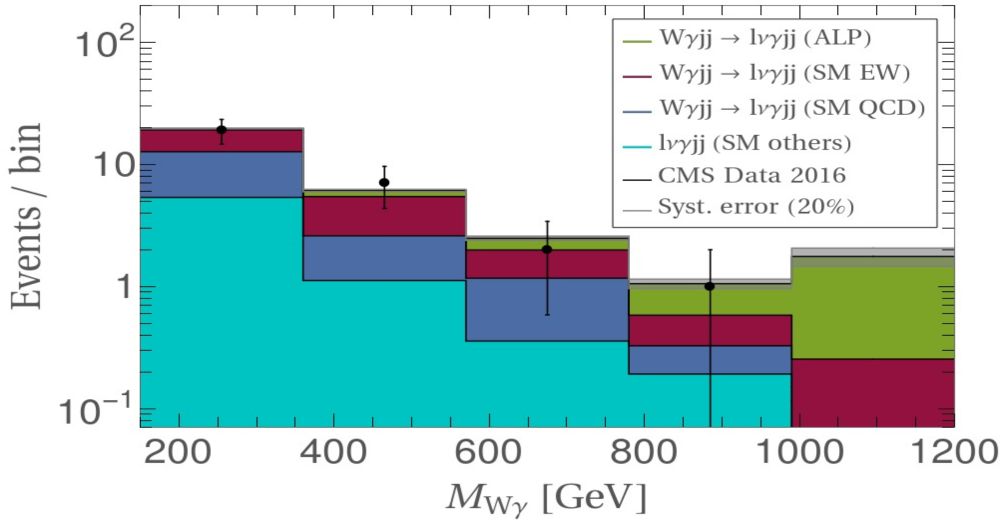




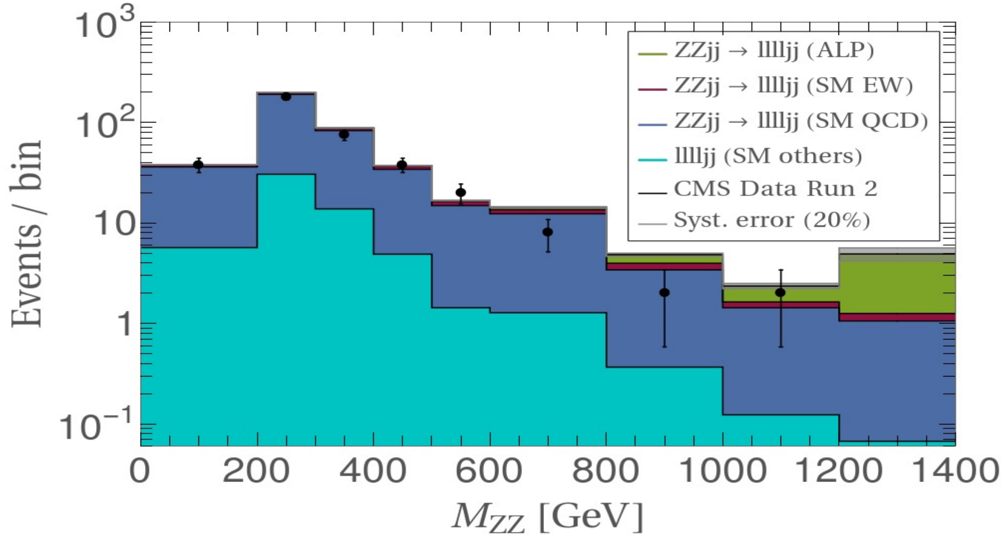


ALP M(VV) in CMS Leptonic / Photonic Analyses

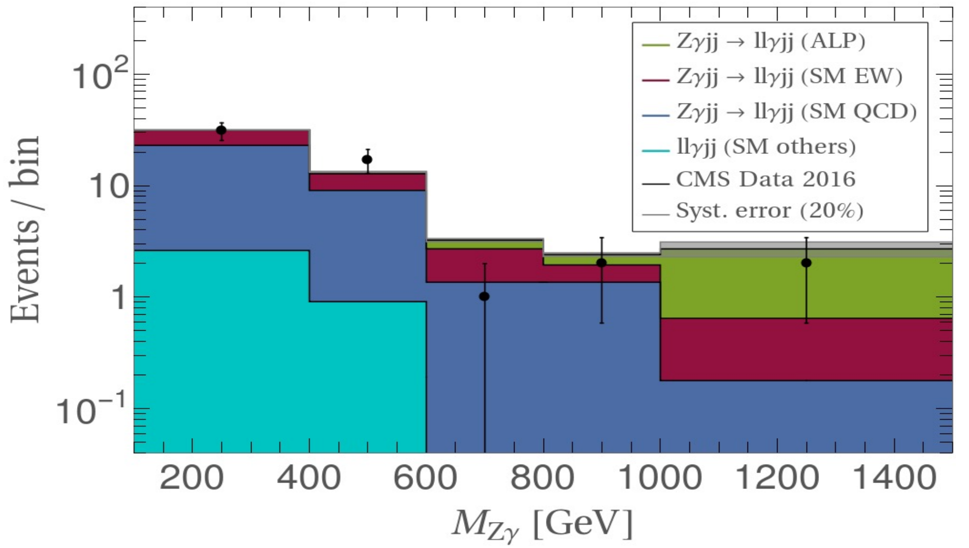
W gamma CMS-SMP-19-008



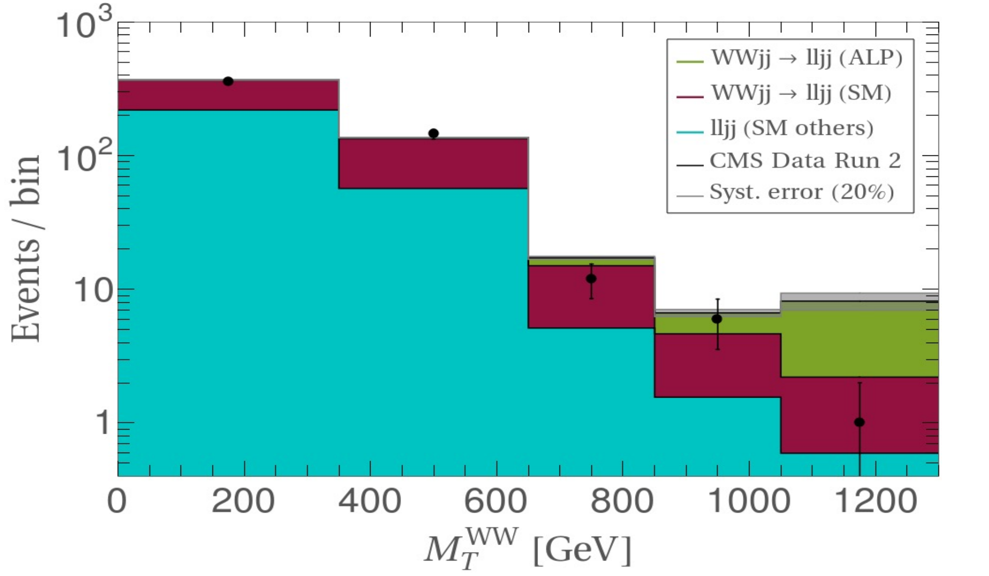
ZZ CMS-SMP-20-001 (Mjj > 100 GeV)



Z gamma CMS-SMP-18-007

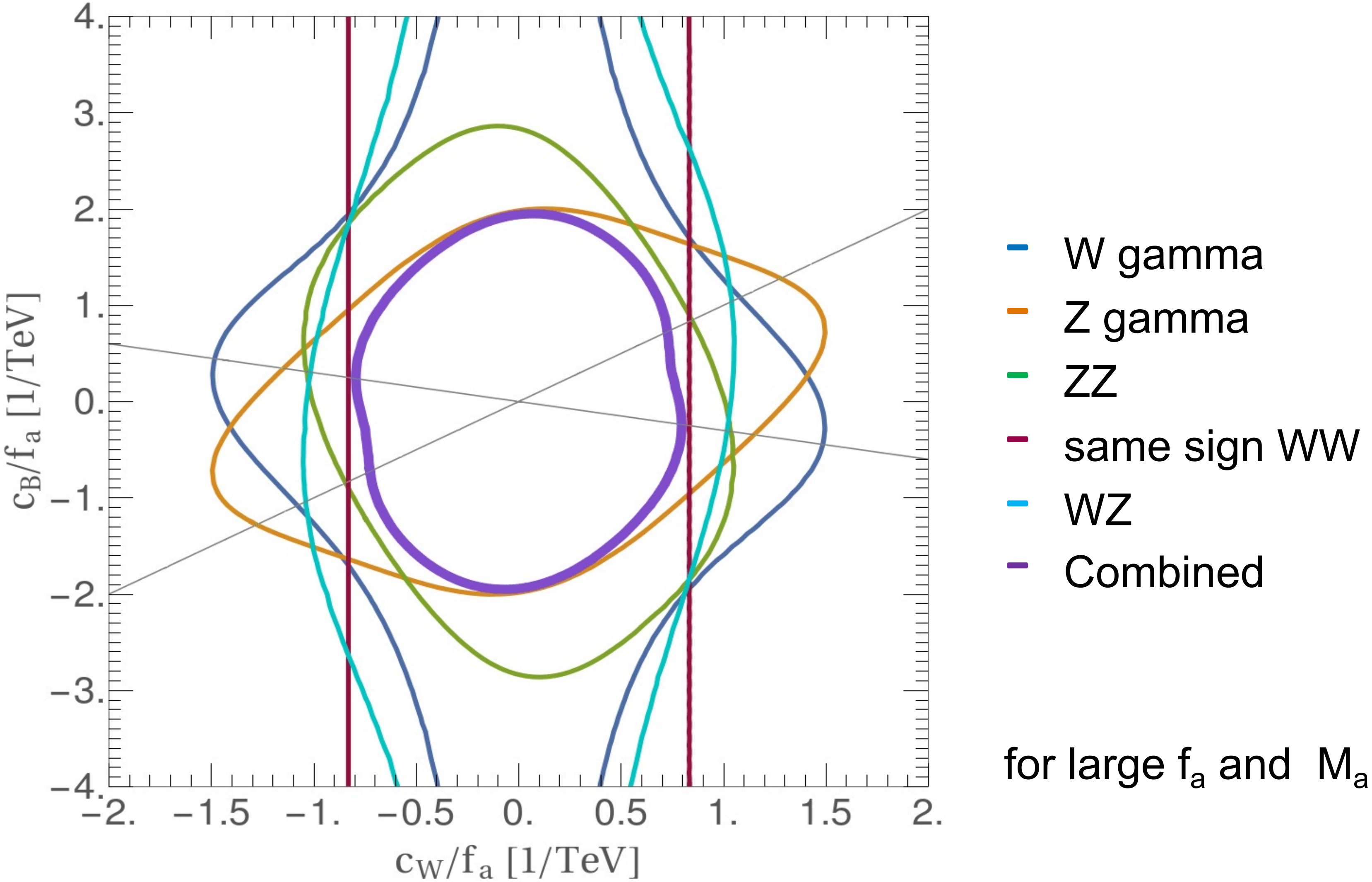


ssWW CMS-SMP-19-012



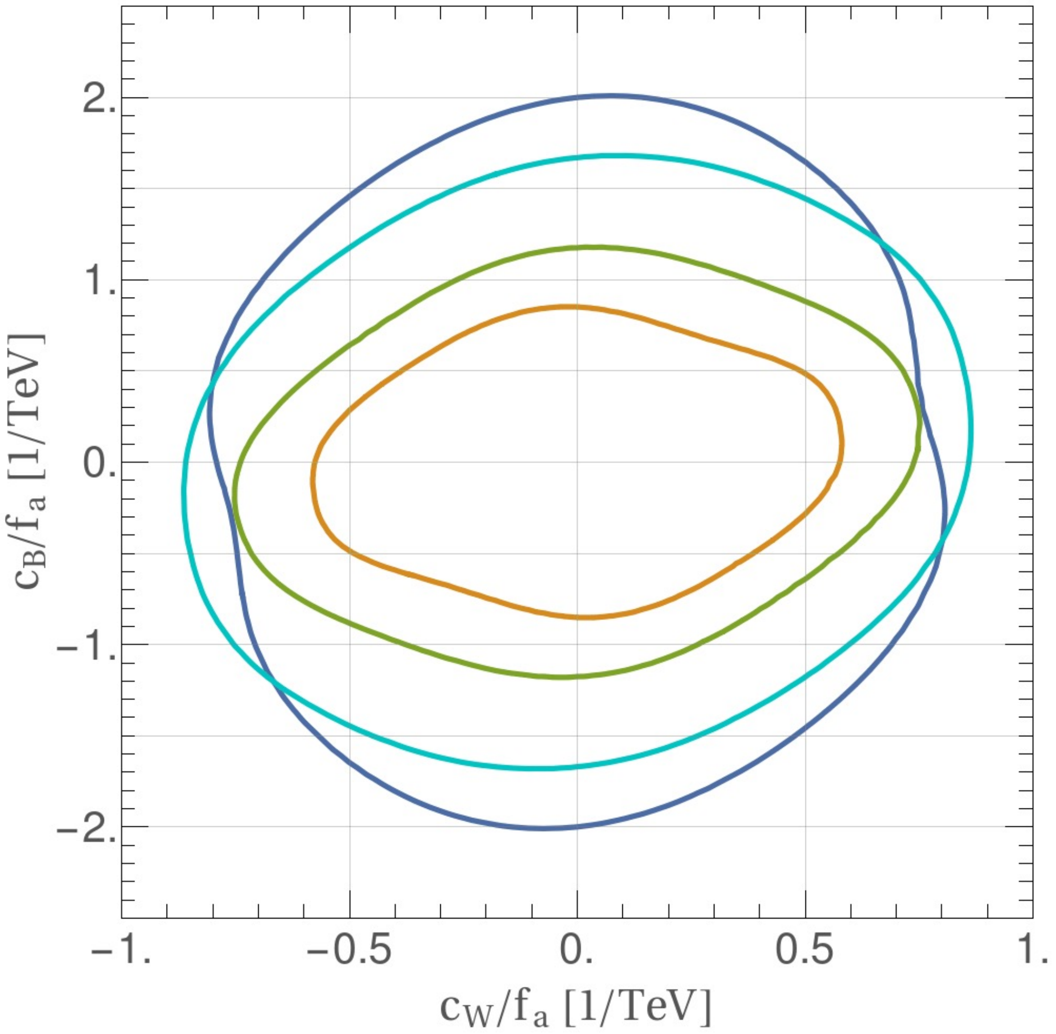
Current Limits w/ CMS Run 2 Data

Expected dsigma / dM(VV) are parameterized in the (cW/fa, cB/fa) plane with fourth- / second-degree polynomials for pure signal / interference ALP components.



for large f_a and M_a < 100 GeV

Projected Limits at Run3 and HL-LHC



- CMS Run2 observed
- CMS Run2 expected
- Expected 300 fb^{-1}
- Expected 3000 fb^{-1}

for large f_a and M_a < 100 GeV

Conclusions

- Non-resonant ALP-mediated diboson searches is a promising new technique at the LHC.
- Very competitive ATLAS / CMS limits from ggF NR ALP analyses at Run 2.
- VBS NR ALP allows testing the (cW/fa, cB/fa) plane, independently of cG, for ALP masses up to 100 GeV.
- VBS NR ALP Run2 analyses at the limit of small statistics.
- Plan to incorporate new Z gamma CMS SMP-20-016 full Run 2 result ASAP.
- Sensitivity at Run 3 and HL-LHC will profit from higher luminosities.