2021 Winter Topical Meeting on VBS

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

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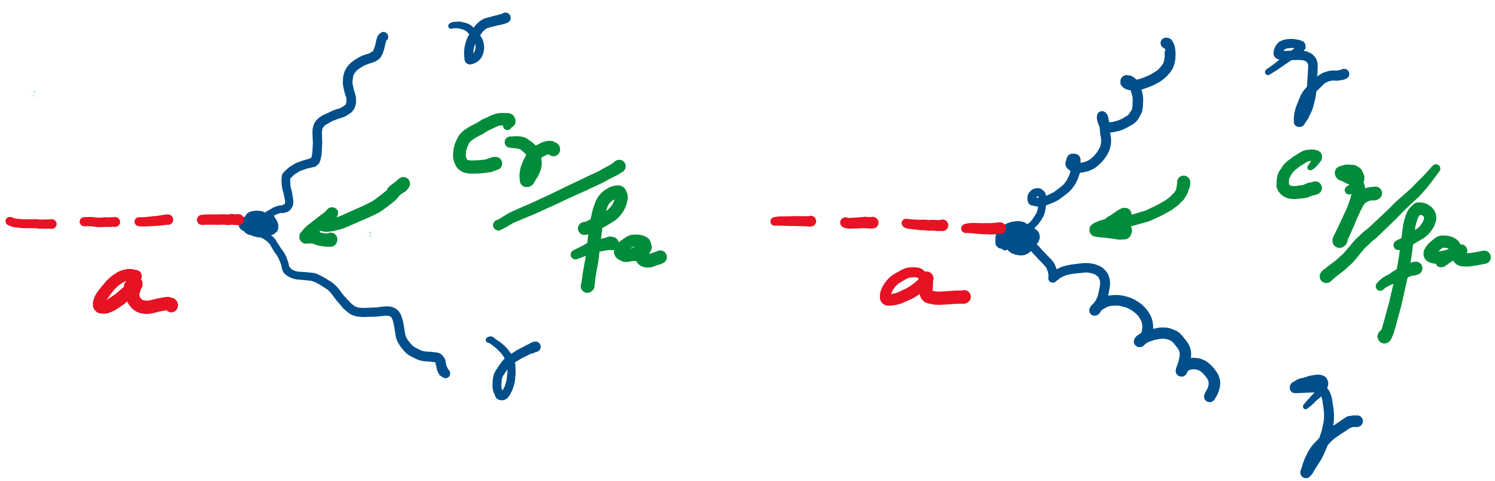
Theoretical / Phenomenological Background

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

- 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, minimal) and chiral (related to strongly coupled new physics models, more parameters). In this talk we focus on the linear EFT.



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

Theoretical / Phenomenological Background

- Colliders allow searches in a wide range of ALP masses and couplings. We can explore ALP masses beyond astrophysical constraints, and even there, provide important crosschecks. At the LHC, natural sensitivity is to f_a scales in the TeV region.

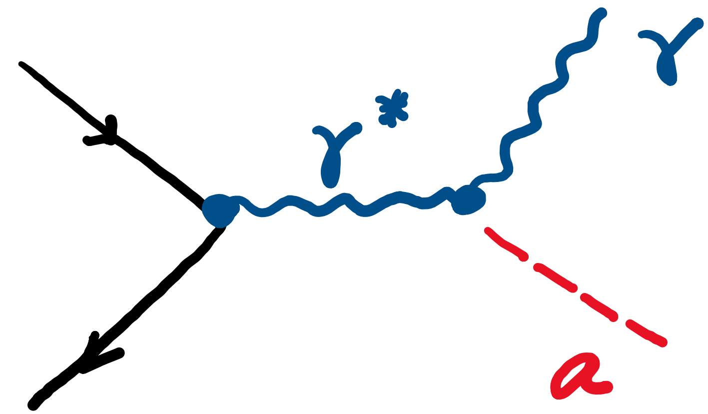
Classical Searches

- Classical searches for ALPs at colliders consider its couplings to photons and gluons: c_gamma and 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 invariance to two basic EWK couplings: cW and cB.

- For ALPs with light masses, they can be considered stable (i.e., can go undetected => MET), use the mono-X signature. Mono-X signatures allow setting limits to ALP couplings “one-by-one”.

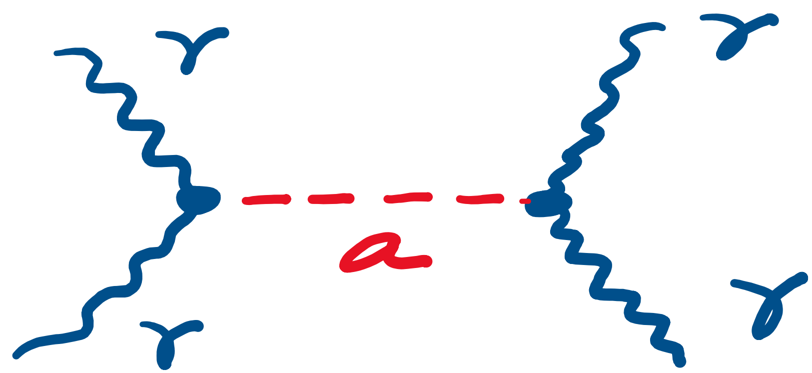
Classical Searches

- Examples:
  - - Mono-photon, gamma + (a => MET);
  - - Mono-jet, jet + (a => MET);
  - - Mono-Z, mono-W, mono-H.



At the LHC, these channels are covered in ATLAS/CMS EXO searches for DM signals.

- Alternatively, ALPs can have large masses, where they are assumed to have widths wide enough to decay promptly in the detector; yet narrow enough with respect to experimental resolution.

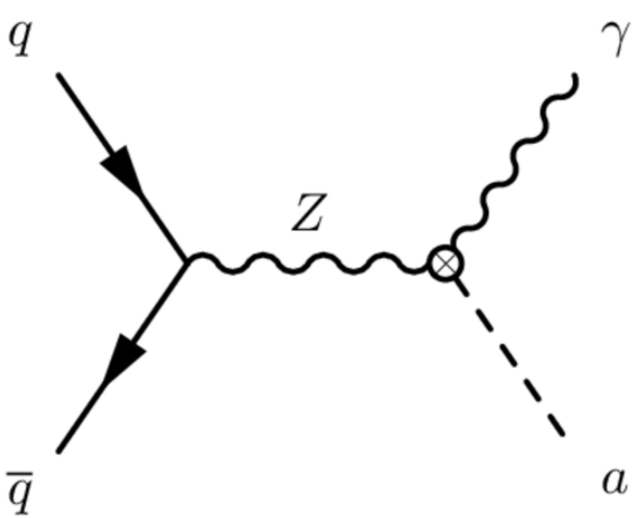


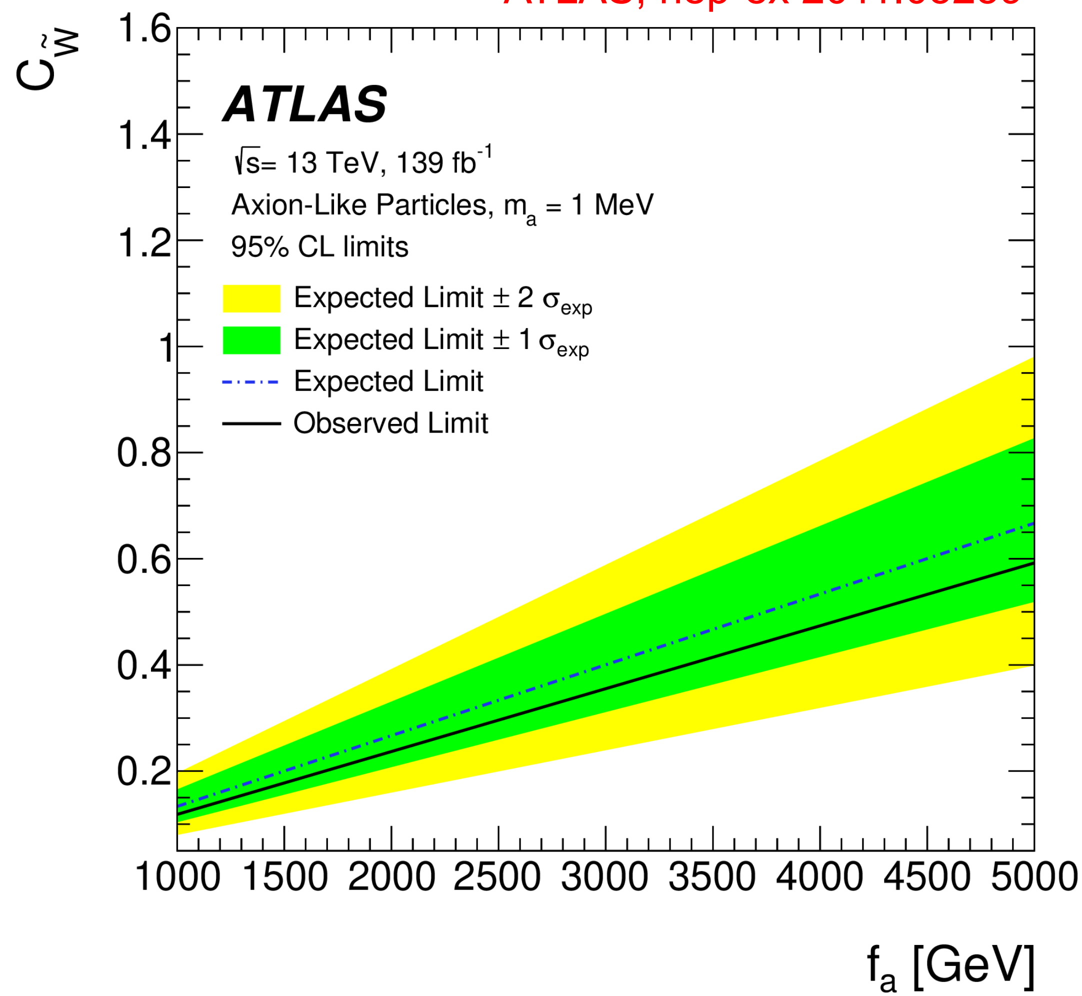
- Examples:
  - - Dijet and diphoton resonances.
  - - Light-by-Light scattering: on-shell ALP production, a => 2 photons.

ATLAS Mono-Photon Limits

ATLAS; hep-ex 2011.05259

- ATLAS, 139 fb^{-1}
- ALP ”detected” as MET
- 1 MeV < M_ax < 1 GeV
- photophobic



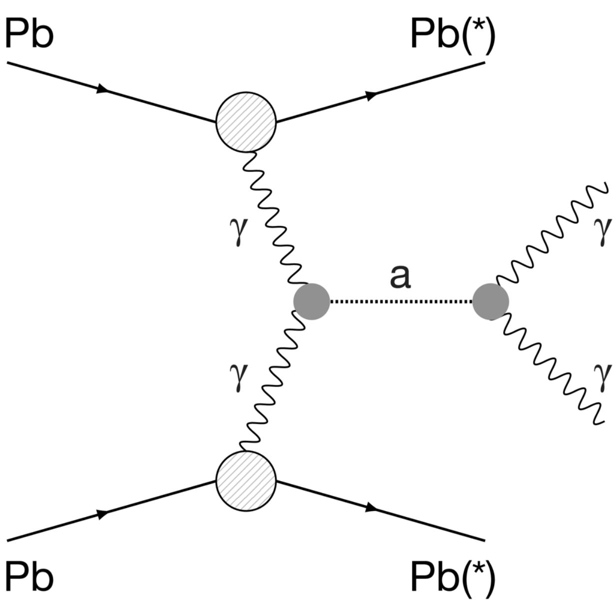


f_a / c_W > 8 TeV @ 95% CL,

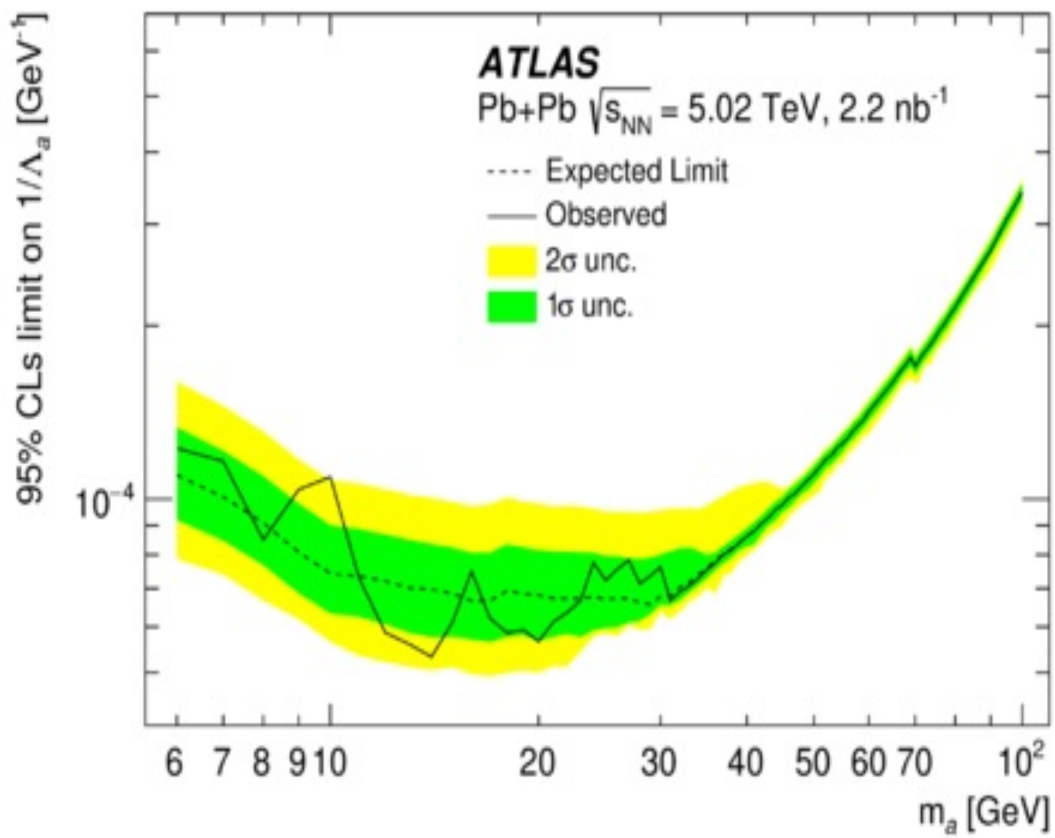
for c_{gamma} = 0, c_g = 0

ATLAS / CMS LbyL On-shell ALP Limits

- For instance: ATLAS, Pb+Pb, 2.2 nb^{-1}
- On-shell ALP production, BR(gamma gamma) = 100%
- 6 GeV < M_ax < 100 GeV



ATLAS; hep-ex 2008.05355

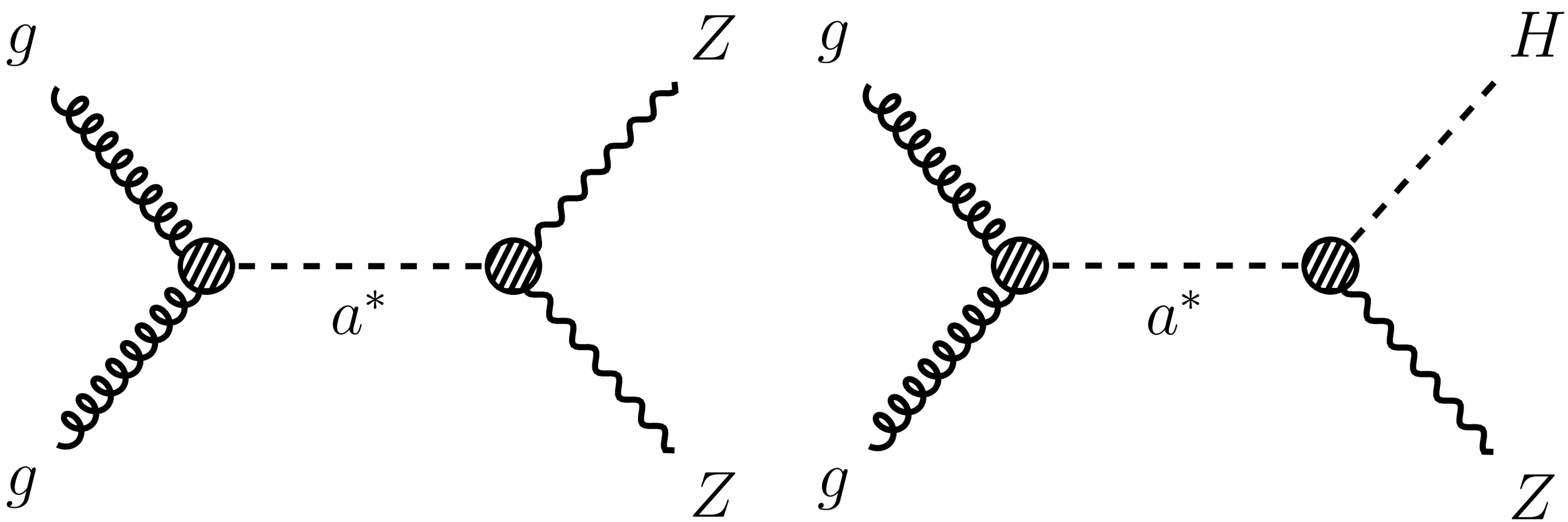


Limits on $4\, c_{gamma} / f_a$ @ 95% CL, for $c_g = 0$

GGF ALP-Mediated Processes

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

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



Gavela, No, Sanz, JFT; hep-ph 1905.12953

GGF Non-Resonant ALP-Mediated Processes

- Off-shell ALP production. This is very promising because the cross-sections are large enough to constraint significantly the theoretical models using Run 2 data.

- ALPs are s-channel mediators in gg => VV production with s-hat >> M_a + many Gamma_a. The size of s-hat is enhanced by the mass threshold of the on-shell diboson system in the final state; but most importantly by the hard pT-spectrum provided by the derivative couplings.

- The analysis uses the ZV, WW, ZH searches looking for high-pT / high-mass deviations in the tails of the transverse momentum / mass spectra with respect to SM expectations.

- This works for ALPs light enough, and cross-sections and limits are independent of M_a from the very-light limit, up to masses of order of 100 GeV.

Cross-Section Estimates @ 13 TeV

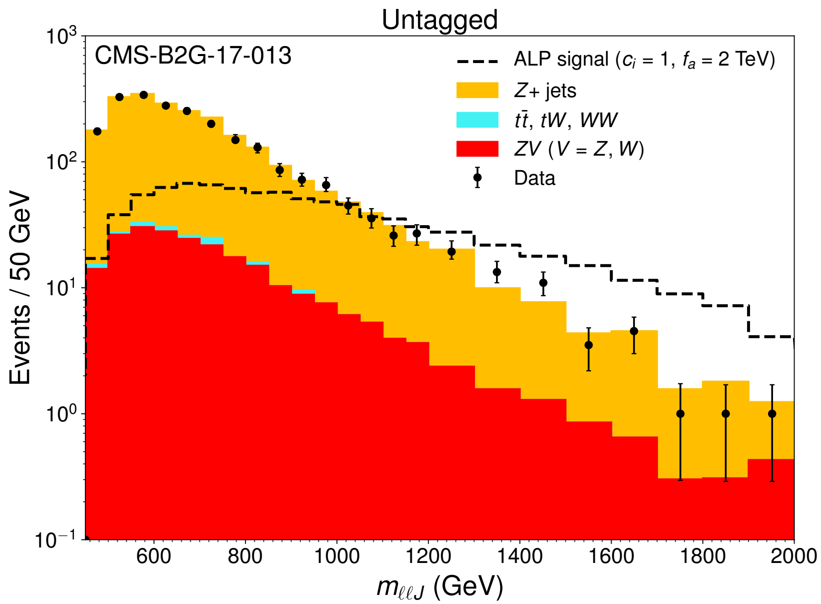
❑ Linear EFT: photofobic, cg/fa = cW/fa = 1/TeV, M_a = 1 MeV

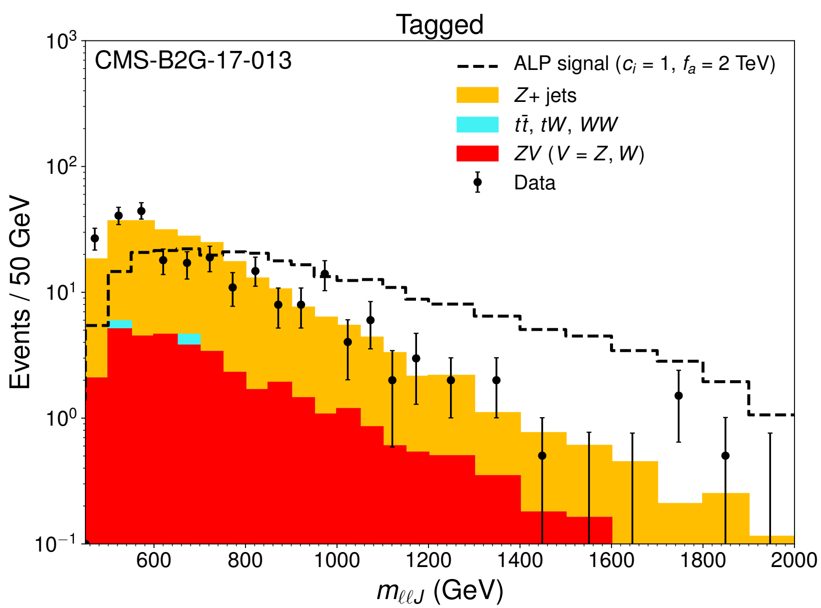
- qqbar => Z a — 5 pb
- gg => ZZ — 40 pb (80 pb for cB = cW)
- gg => WW — 180 pb
- gg => Z gamma — 60 pb
- gg => gamma gamma — 50 pb cB = cW; M(γγ) > 0.5 TeV

❑ Chiral EFT: a_tilde_2D = 1, cg/fa = 1/TeV, M_ax = 1 MeV

- qqbar => H a — 0.2 pb
- gg => ZH — 70 pb

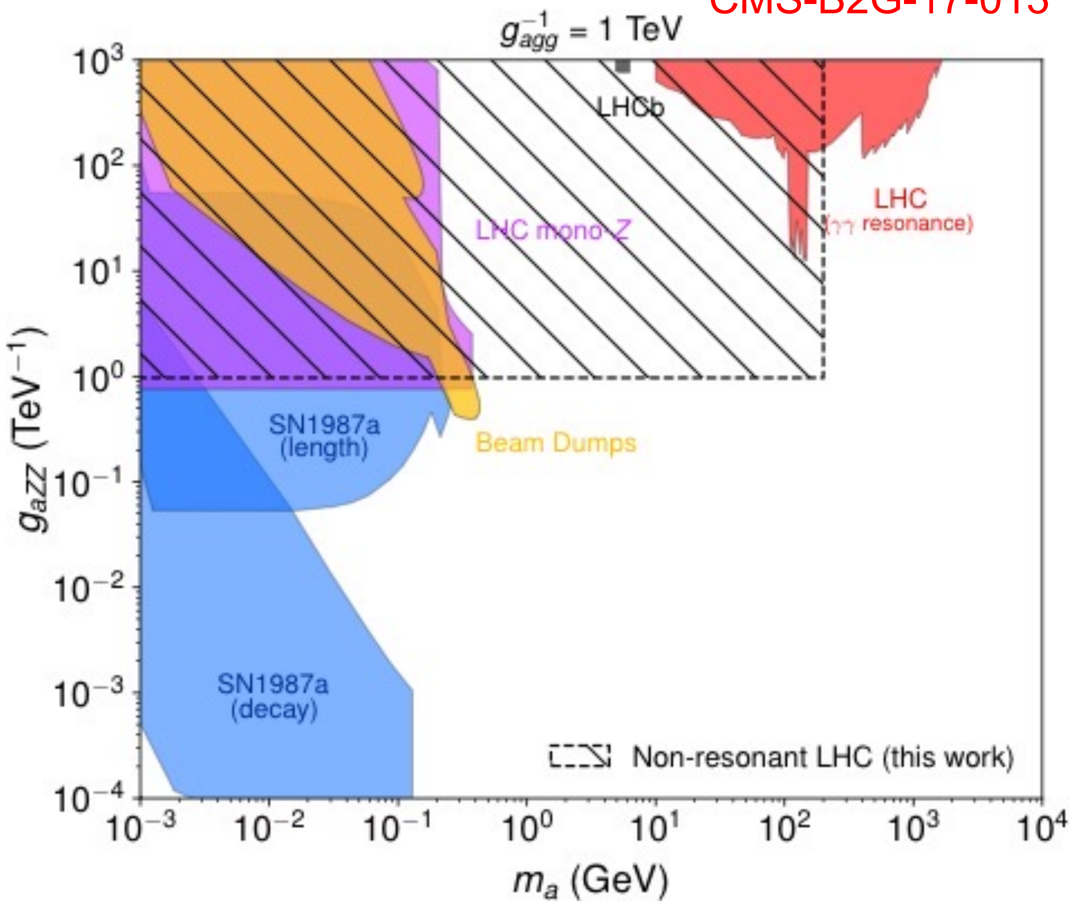
High-Mass ZZ 2L2Q Limits





Gavela, No, Sanz, JFT; hep-ph 1905.12953

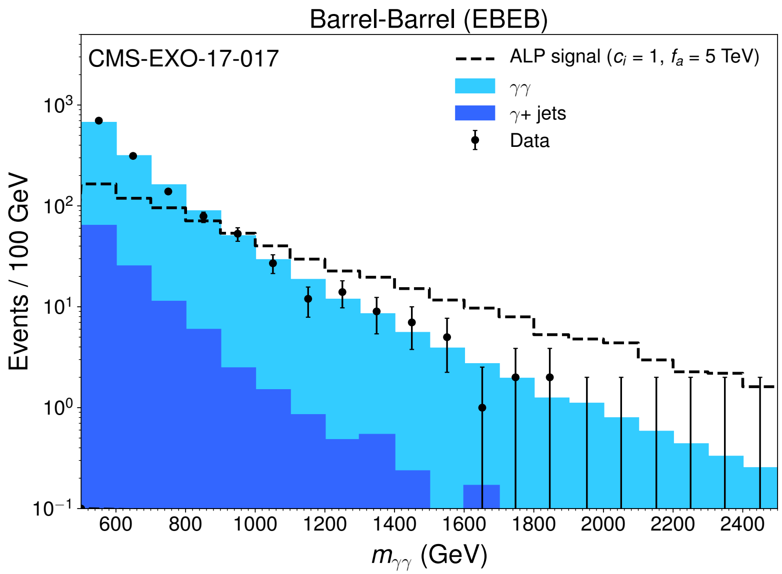
CMS-B2G-17-013

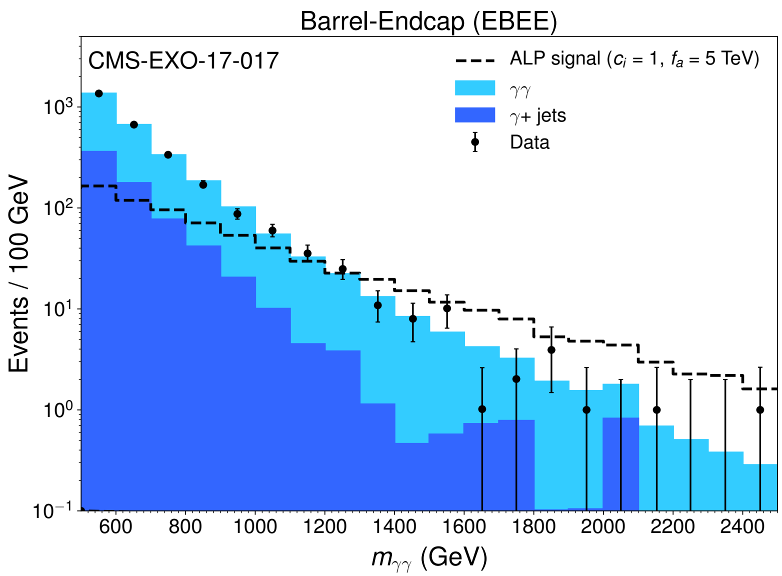


f_a / c_Z > 17 TeV @ 95% CL,

for f_a / c_g < 1 TeV

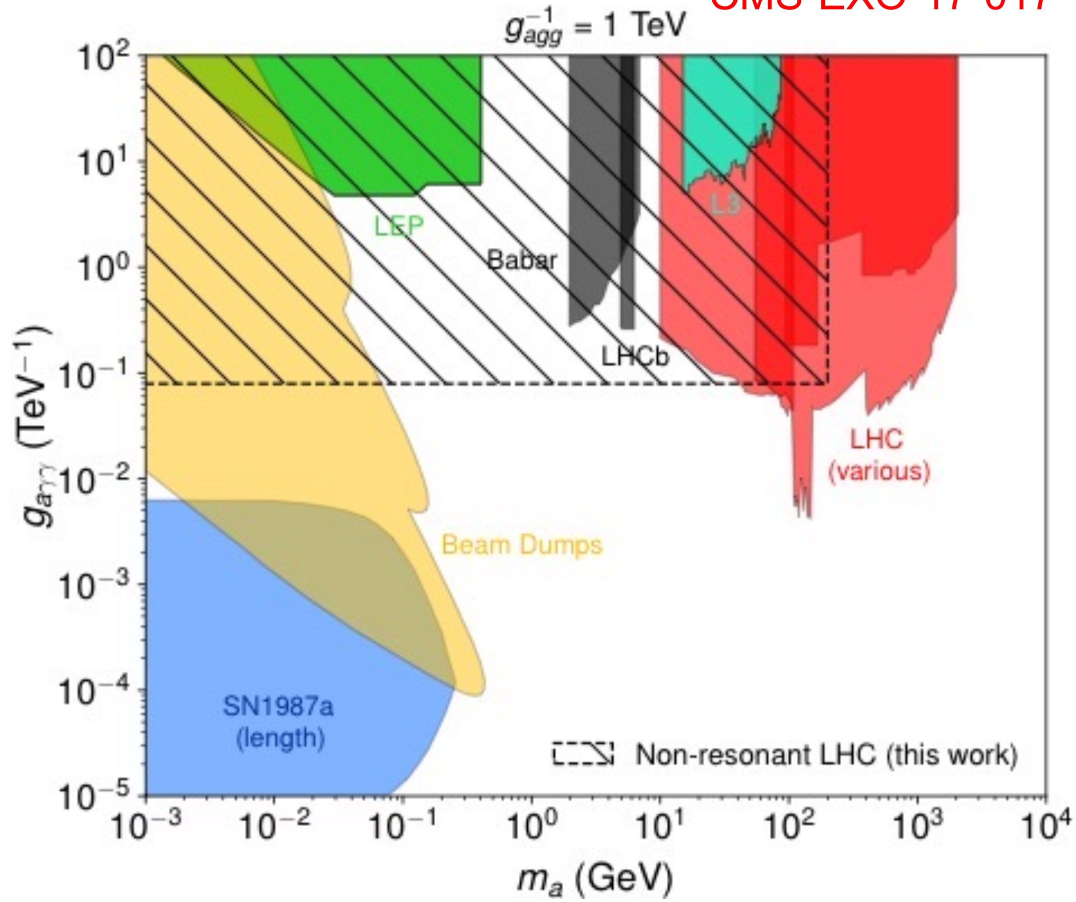
High-Mass Diphoton Limits





Gavela, No, Sanz, JFT; hep-ph 1905.12953

CMS-EXO-17-017



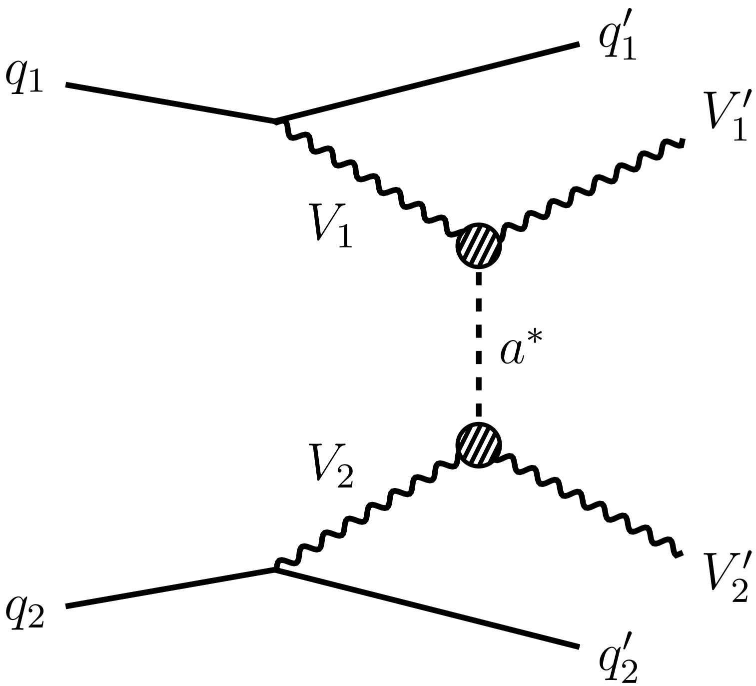
f_a / c_{gamma} > 200 TeV @ 95% CL,

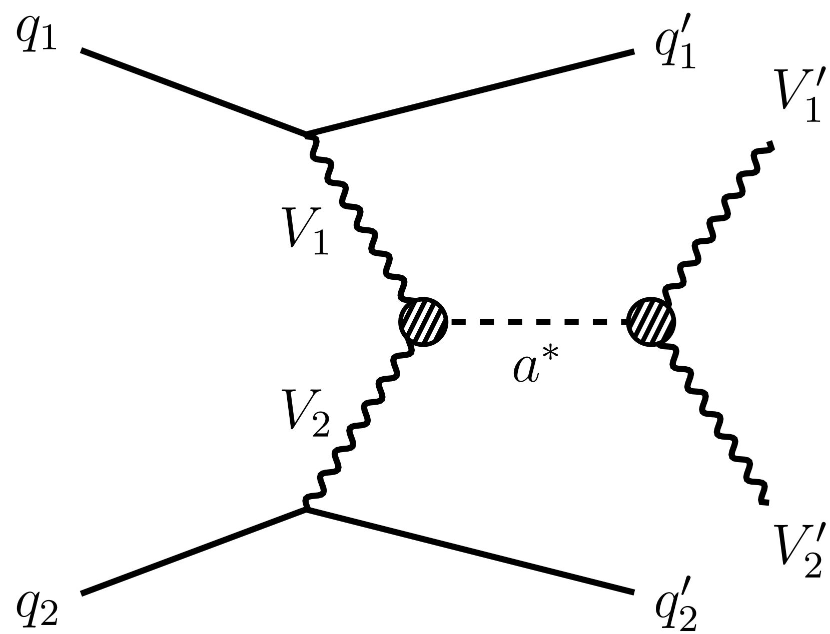
for f_a / c_g < 1 TeV

Non-Resonant ALPs in VBS

- Besides its intrinsic interest, non-resonant ALP-mediated processes in VBS channels are useful because they provide limits on ALP couplings to vector bosons independently of the gluon coupling.

- 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.





Non-Resonant ALPs in VBS

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

- Last but not least, ATLAS / CMS have recently published Run 2 measurements. Allows first comparison to the data, calibration of the simulation tools, calculation of educated predictions for higher luminosities.

Non-Resonant ALPs in VBS

Bonilla, Brivio, Machado, JFT, preprint in prep.

- We have started a re-interpretation of five CMS VBS papers with lepton / photon final states. Results reported here should be considered preliminary.
- Simulation of ALP signals based on ALP EFT linear model implementation in MadGraph, by Brivio, Gavela, No, Sanz, et al.
- Expected numbers of events in the next slides use the selections and integrated luminosities in the CMS publications.
- Numbers of events reduced ~85% due to EFT consistency condition M(VV) < f_a ~ 2 TeV.
- Delphes simulation efficiencies "calibrated" using SM EWK VBS channel.

ALP VBS Cross-Sections @ 13 TeV

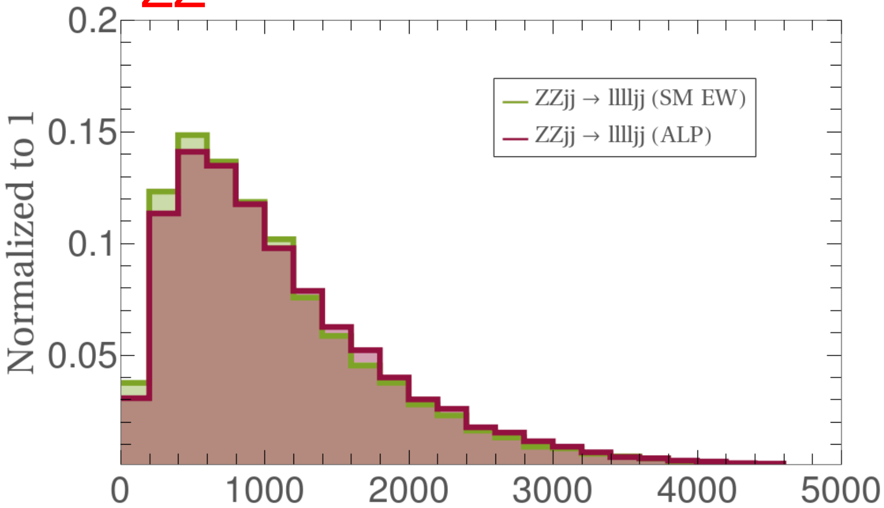
- Linear EFT Benchmark Case (1): cB/fa = cW/fa = 1/TeV, M_a = 1 MeV; Case (2): photophobic, cW/fa = 1/TeV.

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

- Selection efficiencies range from 5% to 30%, depending on the dijet selection cuts. Typical efficiency is ~15%.

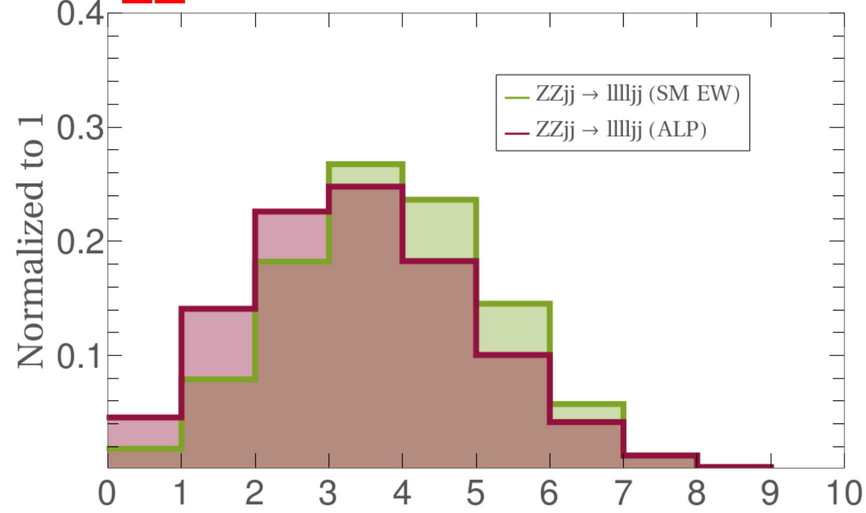
VBS Observables: ALP vs. SM EWK

ZZ

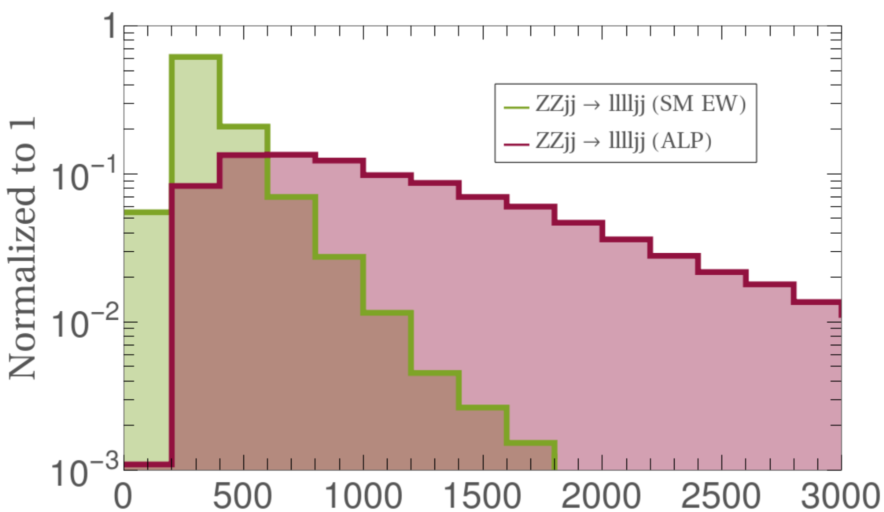


M(jj) (GeV)

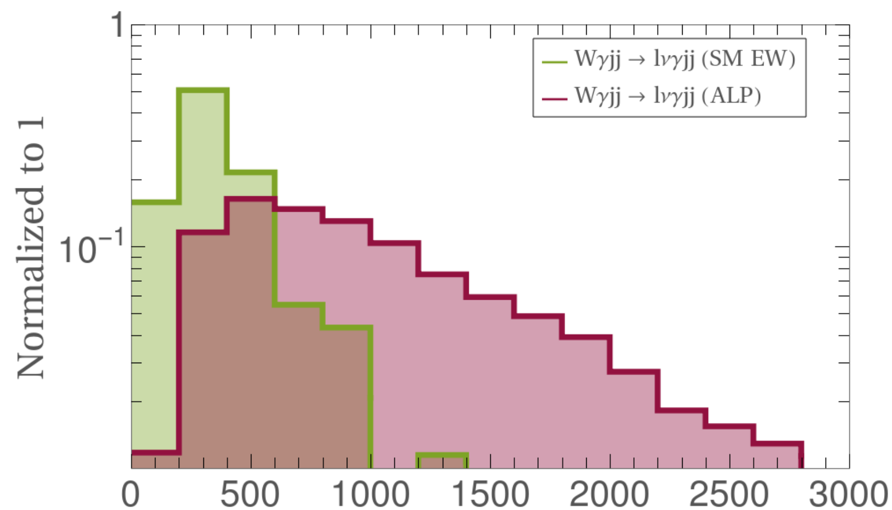
ZZ



|Delta Eta (jj)|



M(ZZ) (GeV)

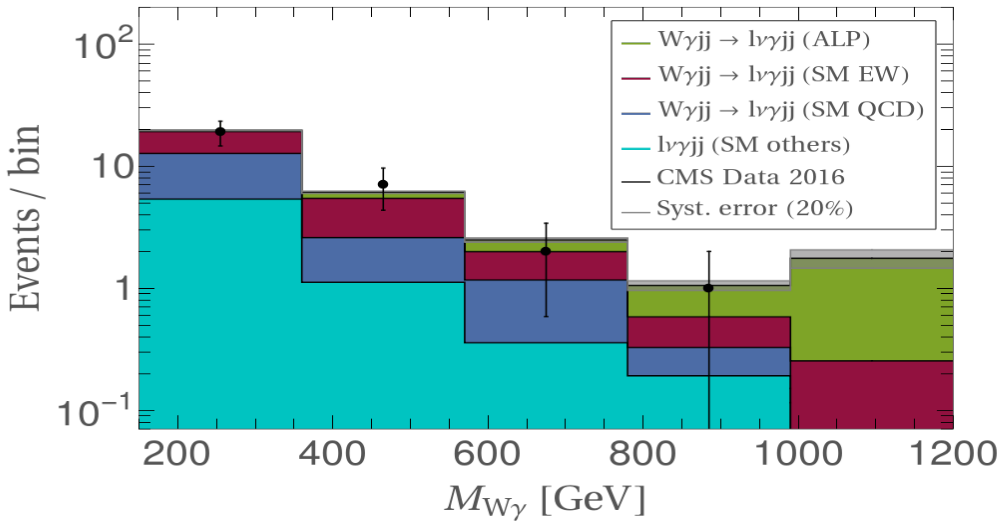


M(W gamma) (GeV)

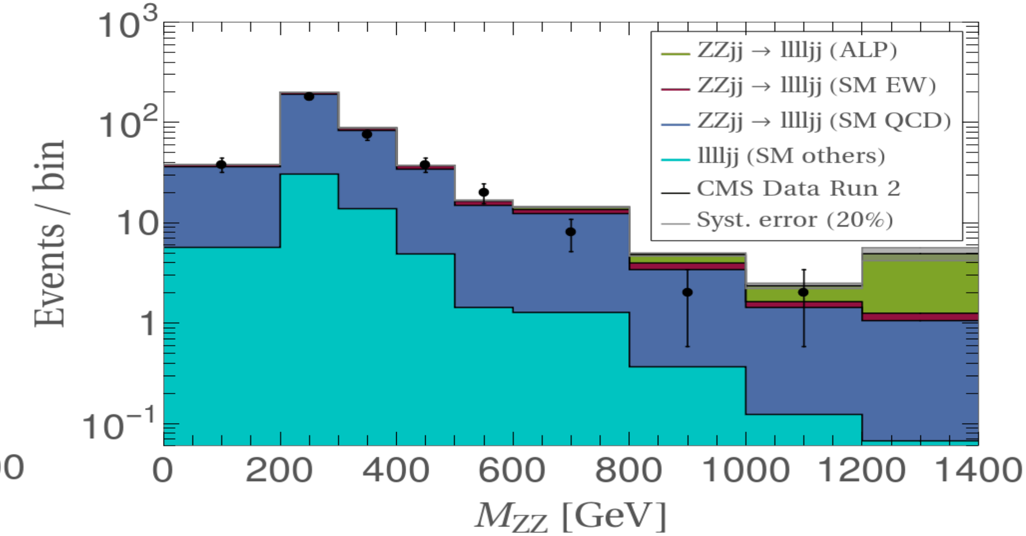
plots by Bonilla, Brivio, Machado

ALP M(VV) in CMS Leptonic Analyses

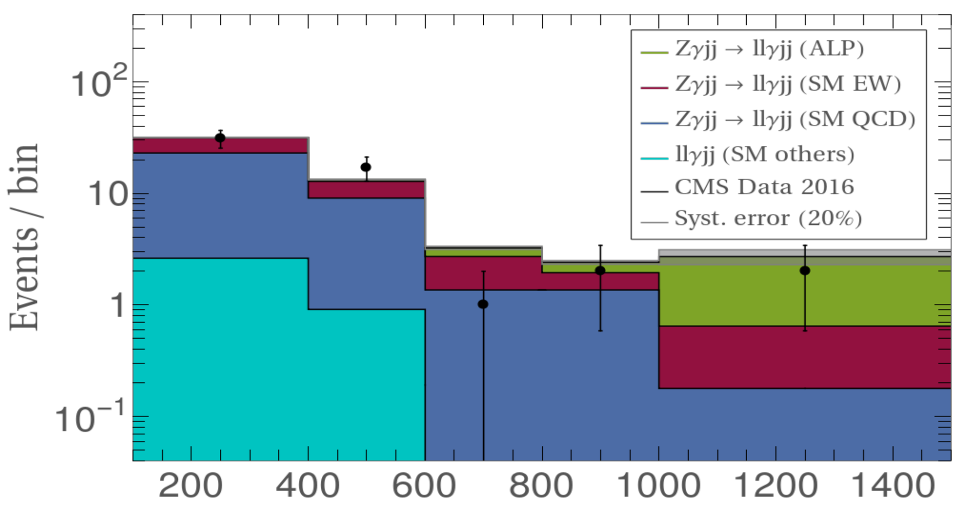
W gamma CMS-SMP-19-008



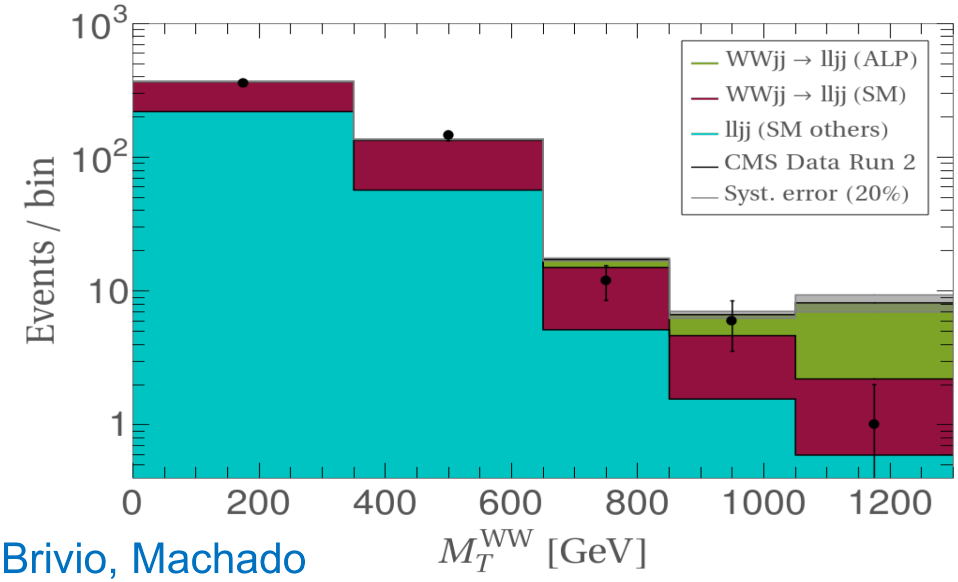
ZZ CMS-SMP-20-001



Z gamma CMS-SMP-18-007

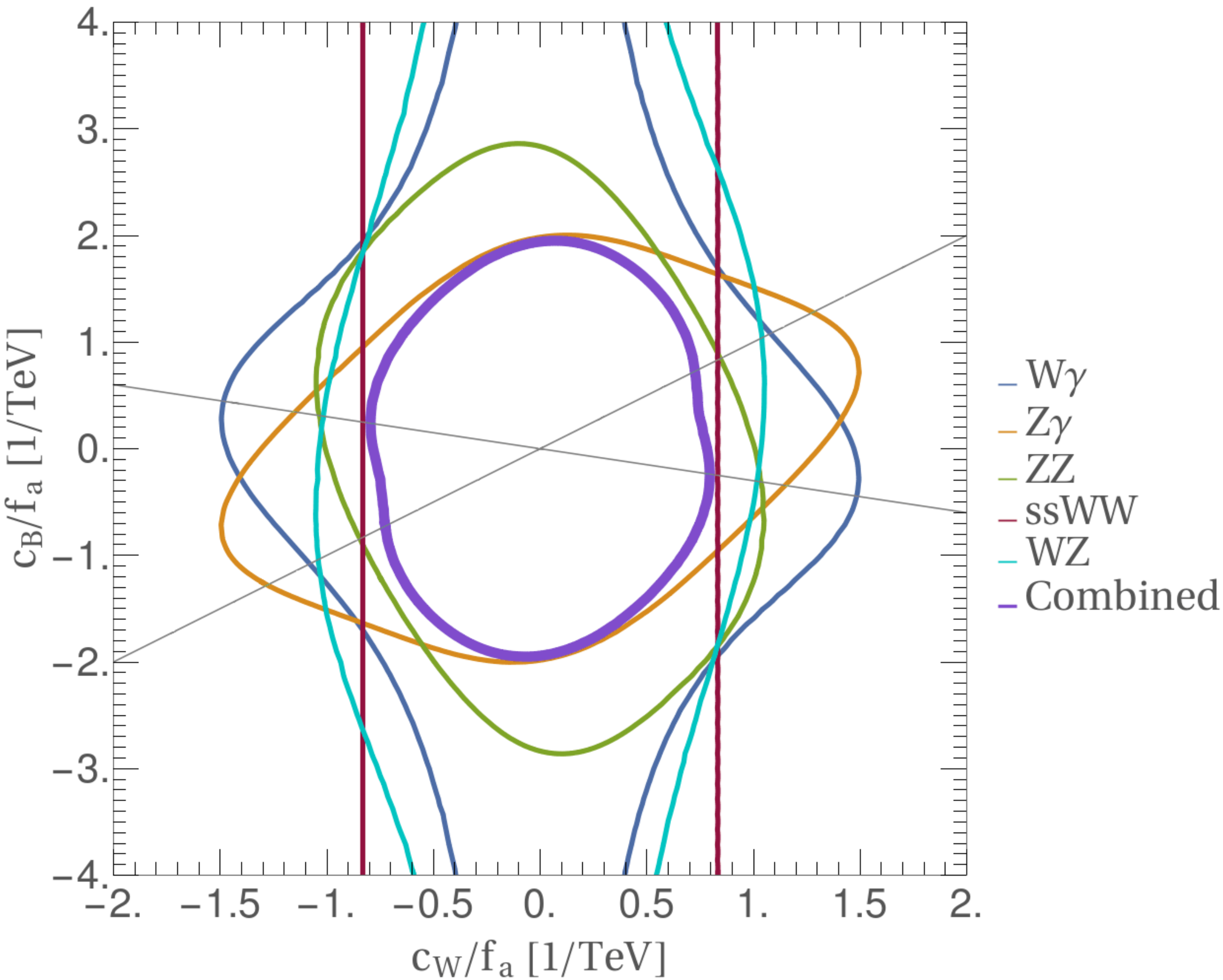


ssWW CMS-SMP-19-012



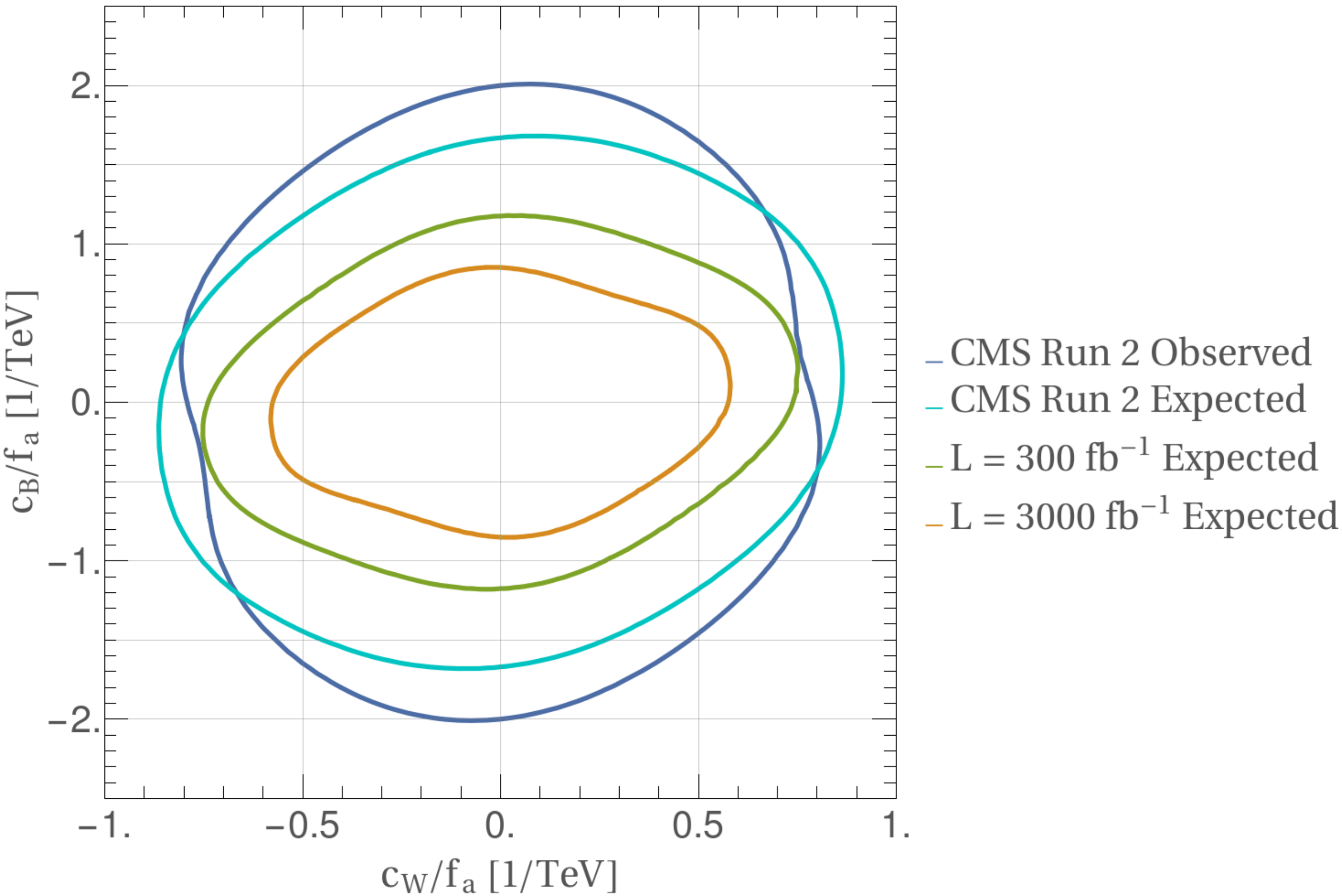
plots by Bonilla, Brivio, Machado

Current Limits w/ CMS Run 2 Data



plots by Bonilla, Brivio, Machado

Projected Limits at Run3 and HL-LHC



plots by Bonilla, Brivio, Machado

Expected Results and Conclusions

- Current analysis at the limit of (small) statistics.
- Expected limits on f_a / c_W in the 1 – 2 TeV region.
- Next exercise, calculate expectations at larger LHC luminosities.