New collider search window for ALPs

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Universidad Autónoma de Madrid - Instituto de Física Teórica

Based on: J. Bonilla , I. Brivio, J. M.R., J. F. de Trocóniz

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Rencontres de Moriond 2023

La Thuile, 21st March 2023

Axion-Like Particles

- Axion-Like Particles (or ALPs) are **neutral pseudo scalar** pseudo Goldston Bosons

- **Effective Field Theory** (EFT) consistent with SM gauge and CP symmetries

- Either **shift-invariant** and/or **anomalous couplings** interactions

$$\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\psi$$

$$\frac{a}{f_a}X_{\mu\nu}\widetilde{X}^{\mu\nu}$$

- ALP interactions with SM particles have a **derivative character**: they grow with momentum

Axion-Like Particles

$$\mathscr{L}_{ALP} \supset -c_{\tilde{B}} \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} - c_{\tilde{W}} \frac{a}{f_a} W^i_{\mu\nu} \tilde{W}^{i\mu\nu} - c_{\tilde{G}} \frac{a}{f_a} G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$$

f_a : New physics scale

- Classical searches: ALP couplings to gluons and photons
- ALP couplings to **EWK bosons**: WW, ZZ, and $Z\gamma$
- **Depend on 2 parameters**
- ALP-gauge interactions at ATLAS and CMS:
  - Mono-X
  - Resonant
  - **New idea: nonresonant ALP searches**

$$\begin{cases} g_{a\gamma\gamma} = \frac{4}{f_a}(s_\theta^2 c_{\widetilde{W}} + c_\theta^2 c_{\widetilde{B}}) \\ g_{a\gamma Z} = \frac{4}{f_a} s_{2\theta}(c_{\widetilde{W}} - c_{\widetilde{B}}) \\ g_{aZZ} = \frac{4}{f_a}(c_\theta^2 c_{\widetilde{W}} + s_\theta^2 c_{\widetilde{B}}) \\ g_{aWW} = \frac{4}{f_a} c_{\widetilde{W}} \end{cases}$$

θ: Weinberg angle

Imposed by gauge invariance

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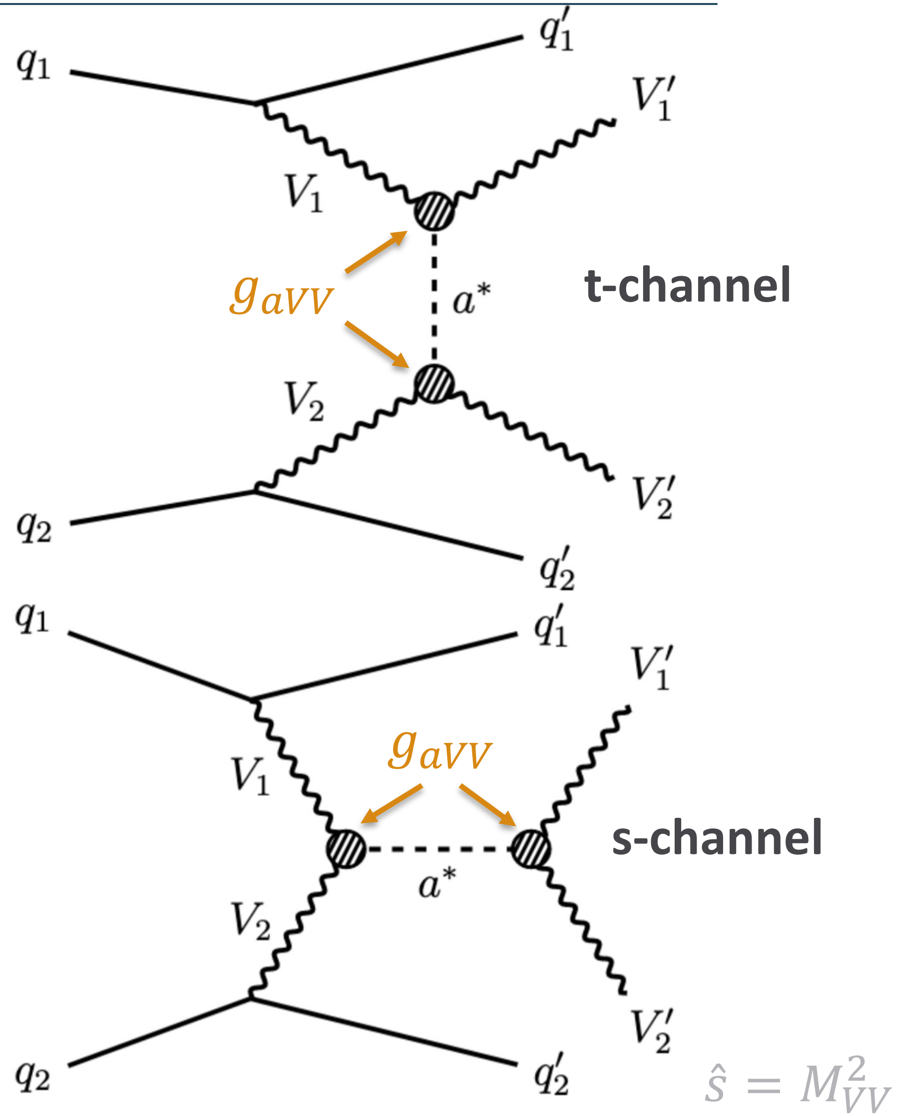
A Novel Approach:
Nonresonant ALPs in VBS

- Vector Boson Scattering (VBS)
- Nonresonant ALP searches proposed by M.B. Gavela, J.M. No, V. Sanz and **J.F. de Trocóniz** [1905.12953]
  - ALP as a very off-shell mediator $m_a^2 \ll \hat{s}$
  - Signals **independent of ALP mass and width up to $m_a \lesssim 100$ GeV**
  - **Harder scaling with $\hat{s} = M_{VV}^2$**

Why VBS?

- **Limits on ALP couplings to vector boson independently of the gluon coupling**

→ $c_{\tilde{B}}$ $c_{\tilde{W}}$ ~~$c_{\tilde{G}}$~~ → **2** parameters



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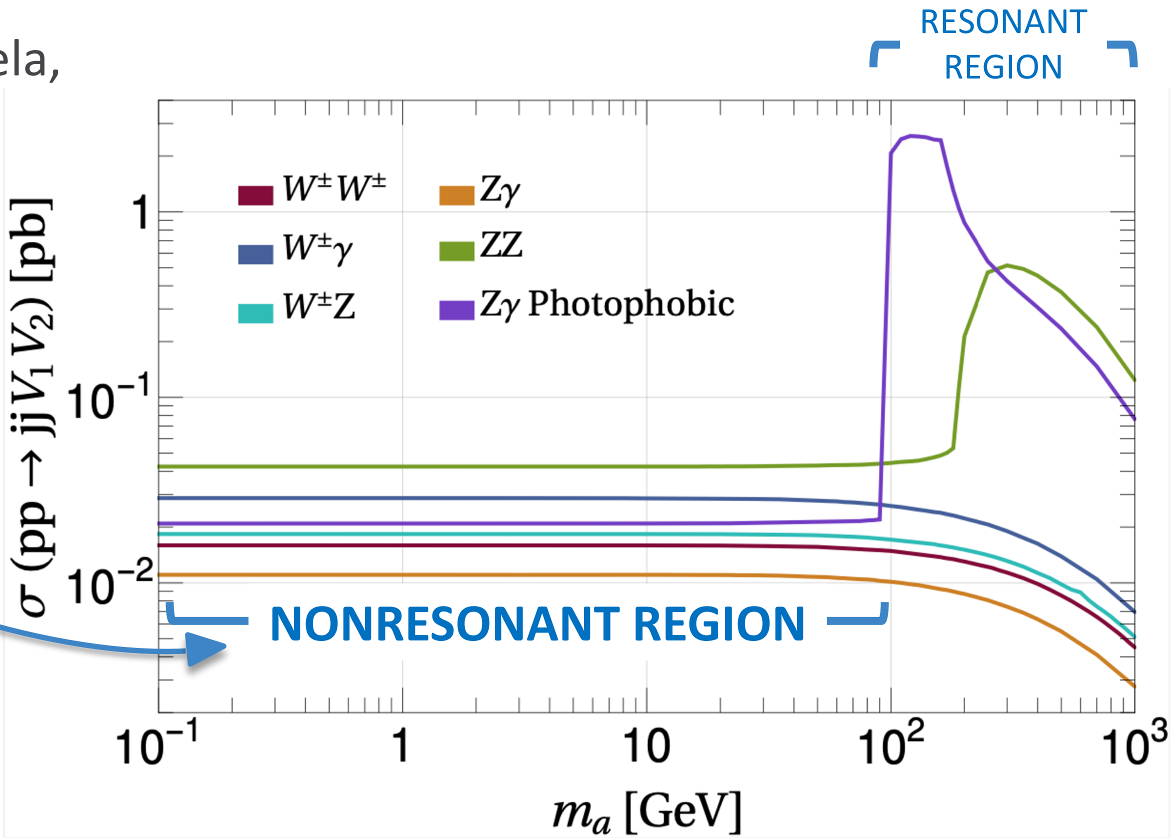

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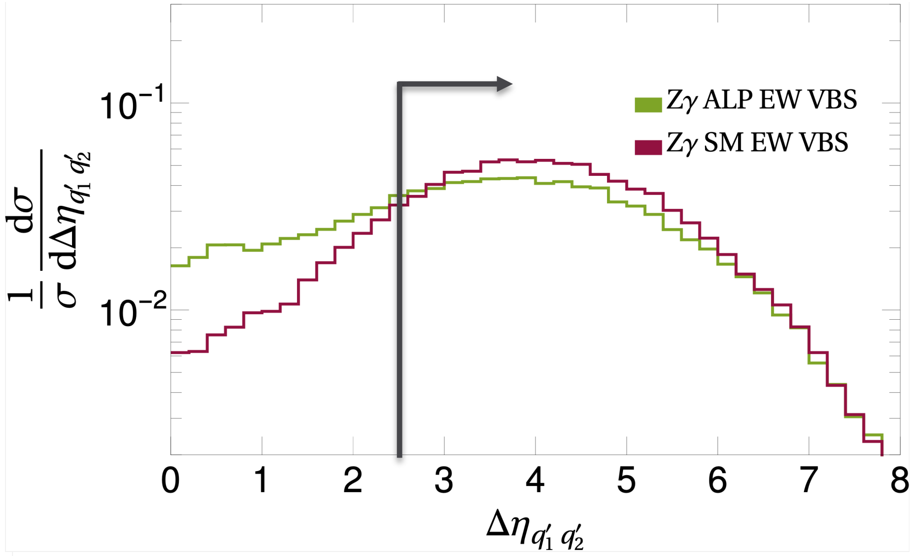
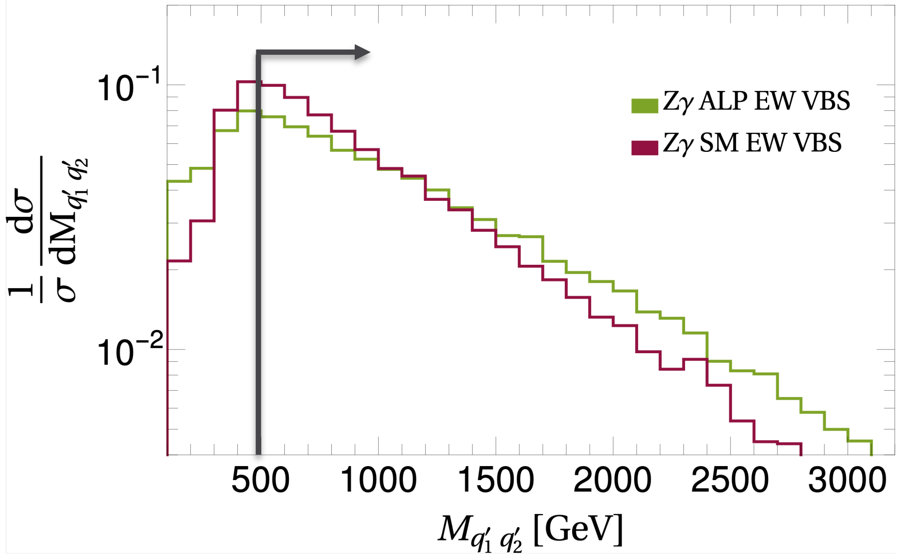
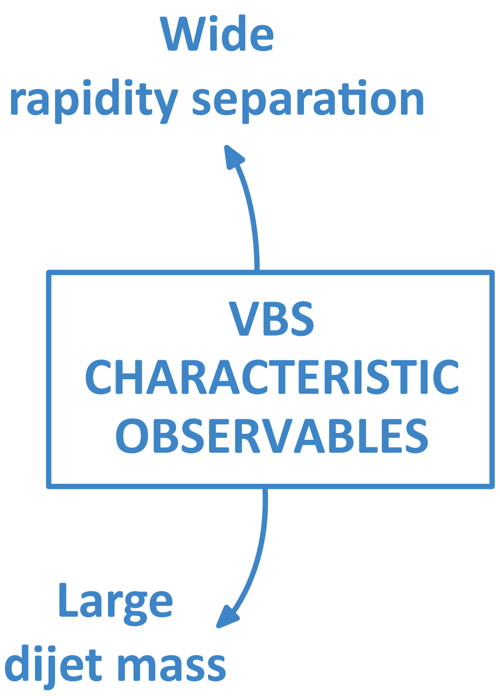
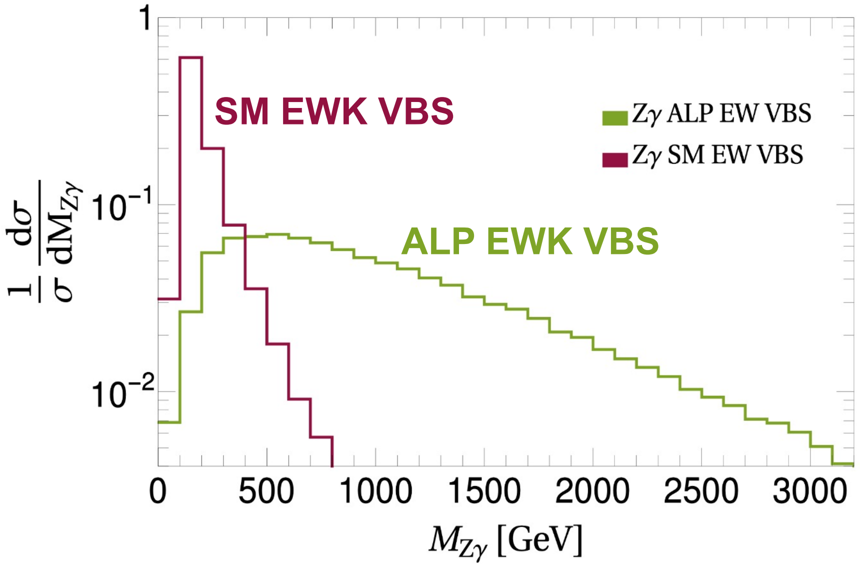






Diboson Mass



Derivative nature of ALP interactions: **deviations in the tail** of the **diboson mass** with respect to the SM

ALP Diboson Mass in CMS Leptonic Analyses

- **ATLAS/CMS Run 2 measurements**: first comparison to data, calibration of simulation tools and calculation of educated predictions for higher luminosities.

- **Reinterpretation of five CMS VBS analyses** with lepton/photon final states:
  - ZZ: CMS-SMP-20-01
  - $W^\pm W^\pm$ and WZ: CMS-SMP-19-012
  - $Z\gamma$: CMS-SMP-20-016
  - $W\gamma$: CMS-SMP-19-008
- Look at **high energy deviations** in the tail of the transverse momentum/mass spectra

- Selections cuts, data and backgrounds in the CMS papers

- **Generation of ALP VBS**: MadGraph_aMC@NLO + Pythia8 + Delphes3

- **Calibrate** our **Delphes detector simulation** using the SM EWK channel

ALP Diboson Mass in CMS Leptonic Analyses

	$c_{\tilde{W}} = c_{\tilde{B}}$ signal / interf. [fb]	Photophobic signal / interf. [fb]	Expected Lepton Events	Int. lum. [fb^{-1}]
ZZ	42.4 / -13.5	18.5 / -9.3	9.3 / -3.2	137
WZ	18.4 / 1.7	23.9 / -0.14	4.2 / 0.05	137
$W^{\pm}W^{\pm}$	16.0 / -4.0	16.0 / -4.0	18 / -5.5	137
$W\gamma$	28.7 / 4.3	5.4 / 1.7	3.6 / -0.04	35.9
$Z\gamma$	11.1 / 0.3	20.9 / -9.1	15.1 / 0.07	137
	$g_{a\gamma Z} = 0$	$g_{a\gamma\gamma} = 0$		

Results

- **Maximum likelihood fit** of signal and background to the **diboson invariant/transverse masses**

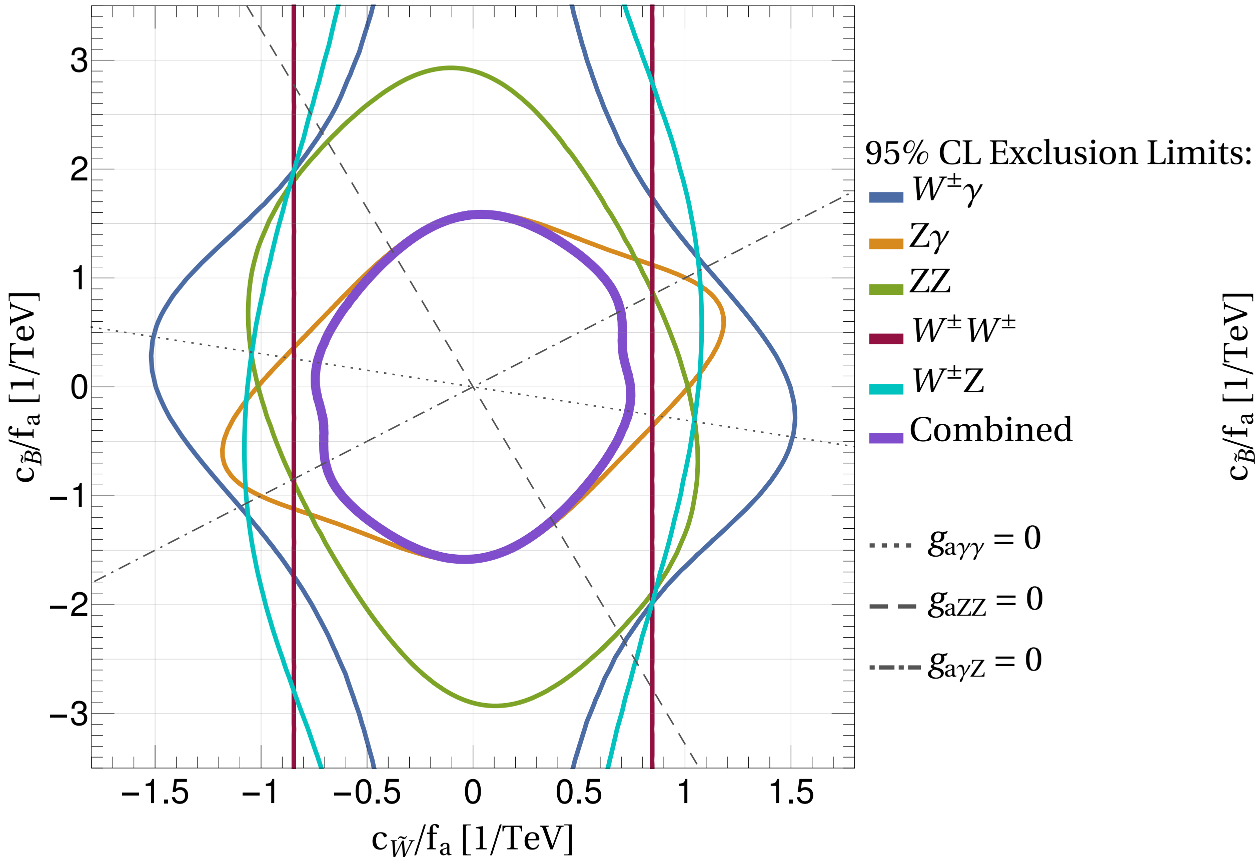
- No excess found with respect to SM expectations

- **Current limits** with CMS Run 2 data and **projected limits** at Run 3 and HL-LHC in the ALP $(c_{\tilde{W}}, c_{\tilde{B}})$ parameter space

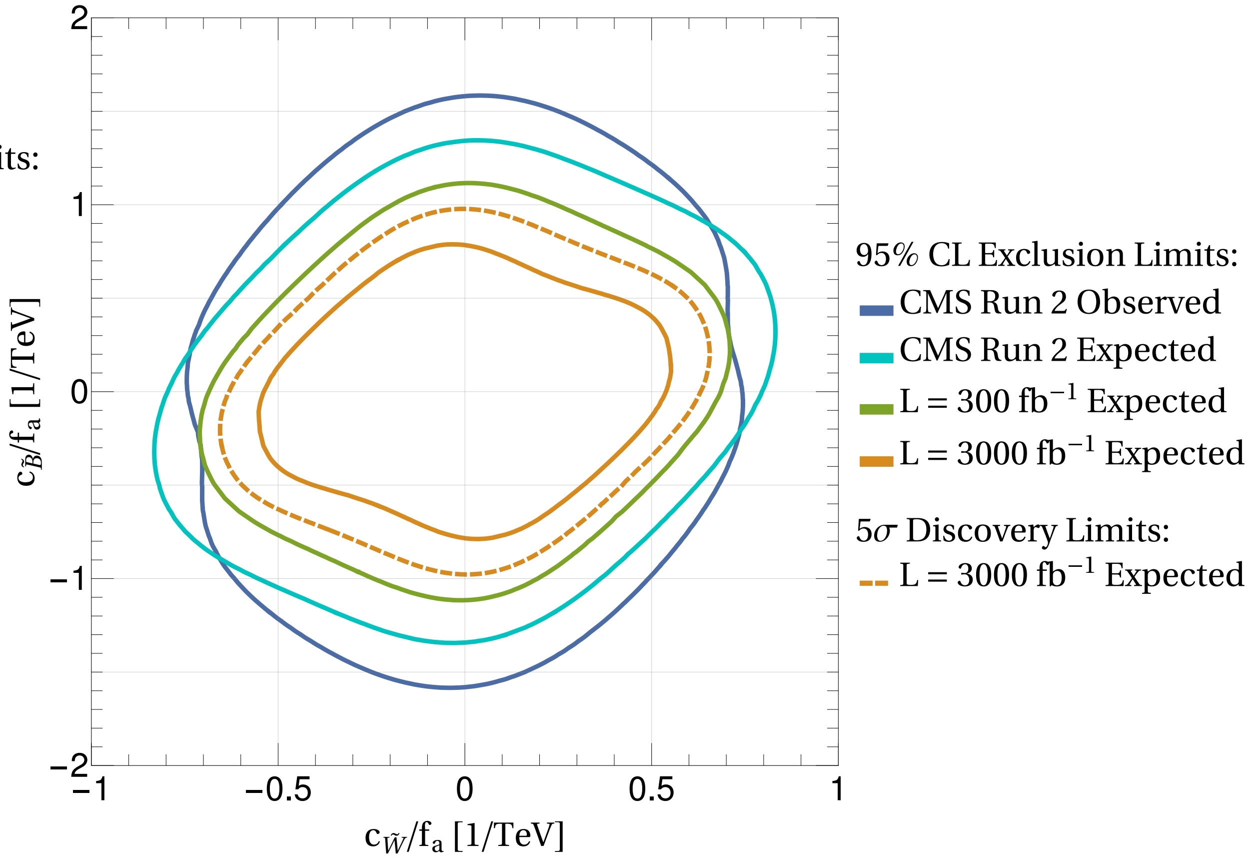
- **Expected diff. cross-sections are parameterized** in the $(c_{\tilde{W}}, c_{\tilde{B}})$ plane with quartic / quadratic **polynomials** for pure signal / interference ALP components.

Results

CURRENT LIMITS



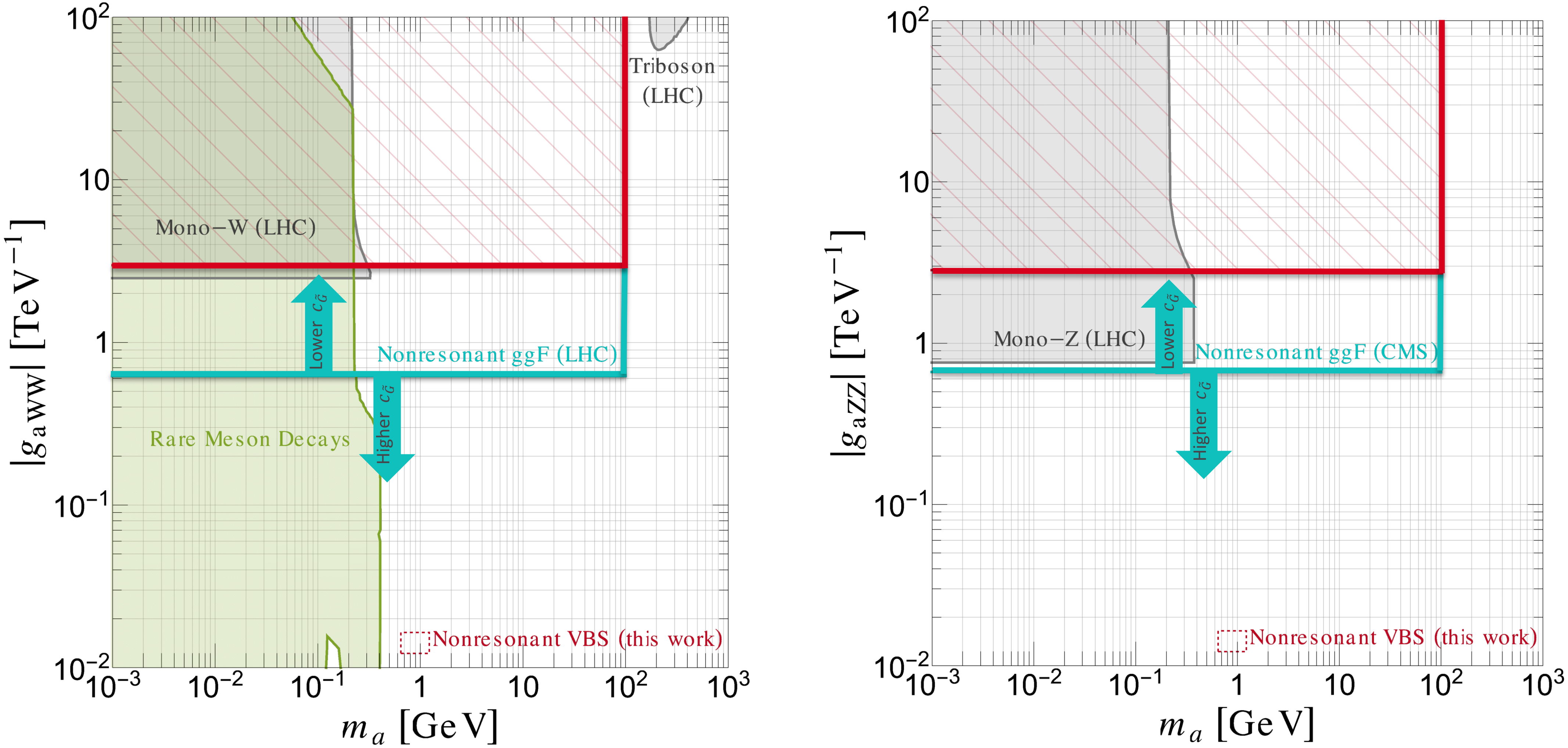
PROJECTED LIMITS



(for $f_a > 4$ TeV and $M_a < 100$ GeV)

Results: comparison to existing bounds

- Limits are **very competitive** and probe **previously unexplored regions** of the param. space



Conclusions

- Access to **EWK couplings independently of the gluons**

- Current limits (CMS Run 2 data) and projected limits (Run 3 and HL-LHC)

- Limits **independent** of the **ALP mass and decay width** ($m_a \lesssim 100$ GeV)

- **Limits** are **very competitive** and probe **previously unexplored regions** of the param. space

- Great opportunity for **dedicated ALP searches** at Run 3 and HL-LHC

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Thank you!

Lagrangian and physical couplings

$$\mathscr{L}_{ALP} = \frac{1}{4}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 - c_{\widetilde{B}}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} - c_{\widetilde{W}}\frac{a}{f_a}W^i_{\mu\nu}\tilde{W}^{i\mu\nu} - c_{\widetilde{G}}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$

EWSB

$$\mathscr{L}_{ALP,EW} = -\frac{g_{a\gamma\gamma}}{4}aF^{\mu\nu}\tilde{F}_{\mu\nu} - \frac{g_{a\gamma Z}}{4}aZ^{\mu\nu}\tilde{F}_{\mu\nu} - \frac{g_{aZZ}}{4}aZ^{\mu\nu}\tilde{Z}_{\mu\nu} - \frac{g_{aWW}}{2}aW^{+\mu\nu}\tilde{W}^{-}_{\mu\nu}$$

(Unitary gauge)

$$g_{a\gamma\gamma} = \frac{4}{f_a}(s_\theta^2 c_{\widetilde{W}} + c_\theta^2 c_{\widetilde{B}}) \qquad g_{a\gamma Z} = \frac{4}{f_a}s_{2\theta}(c_{\widetilde{W}} - c_{\widetilde{B}}) \qquad g_{agg} = \frac{4}{f_a}c_{\widetilde{G}}$$

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Nonresonant ALP-mediated diboson production

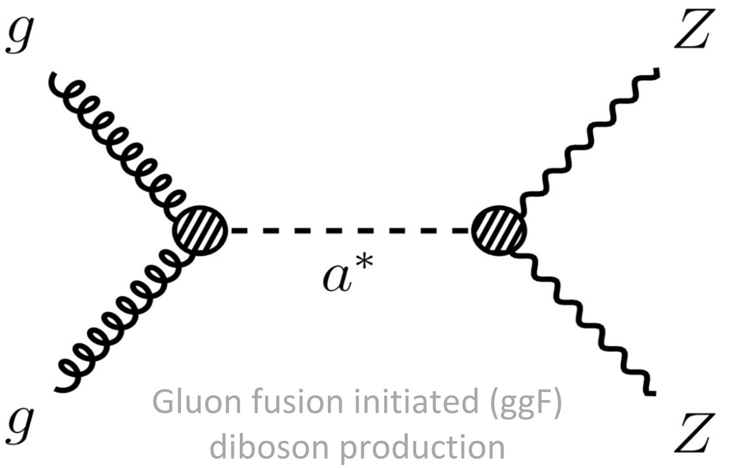
- M.B. Gavela, J.M. No, V. Sanz and **J.F. de Trocóniz** [1905.12953]

- ALP acts as a **very off-shell mediator** ⟶ $m_a^2 \ll \hat{s}$

- Signals **independent of ALP mass m_a and** its **decay width Γ_a** up to $m_a \lesssim 100$ GeV: allows to explore large areas in the paramater space

- Suppression from $\hat{s}$ **compensated by derivative character** of ALP interactions

$$\hat{\sigma} \propto \hat{s}/f_a^4$$ ⟵ **Harder scaling**



Gluon fusion initiated (ggF) diboson production

$$\hat{s} = M_{VV}^2$$

Nonresonant ALP-mediated diboson production

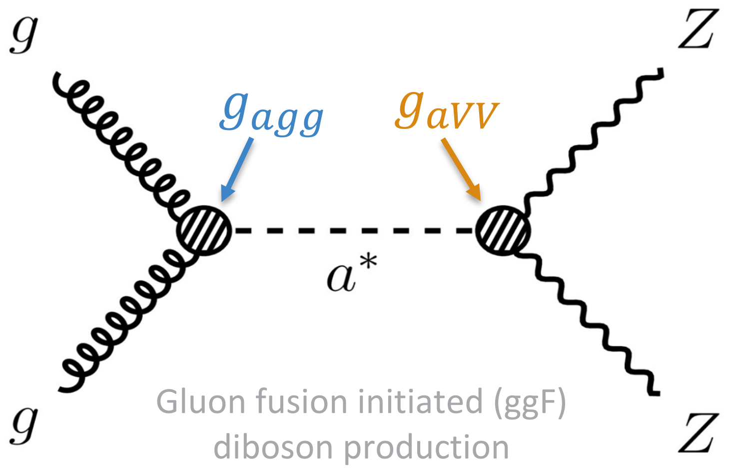
- Reinterpreation of CMS analyses:
    - $gg \to ZZ$ (CMS-B2G-17-013)
    - $gg \to \gamma\gamma$ (CMS-EXO-17-017)

- Sensitive to (**ALP coupling to gluons** x **ALP coupling to EWK diboson**)

$$g_{agg} \times g_{aVV}$$

- Cross-sections large enough to constrain significantly the theoretical models using Run 2 data.

- **Dedicated ALP search at CMS**: $gg \to a^* \to ZZ/ZH$ (CMS-B2G-20-013)



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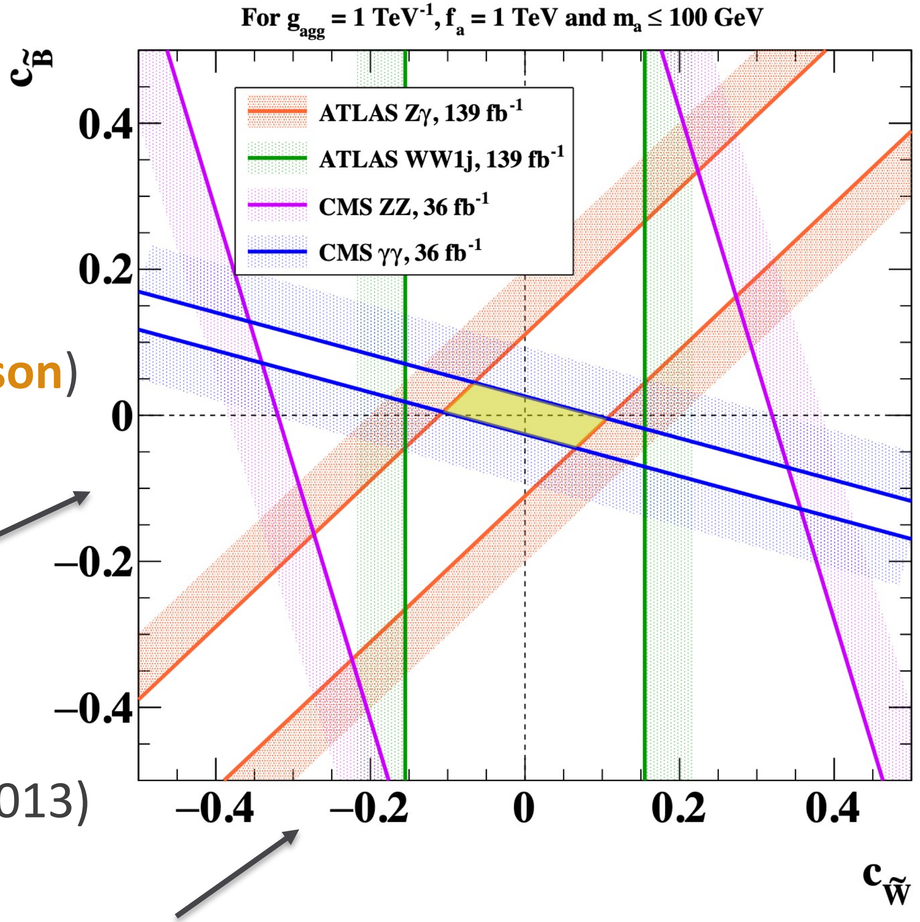
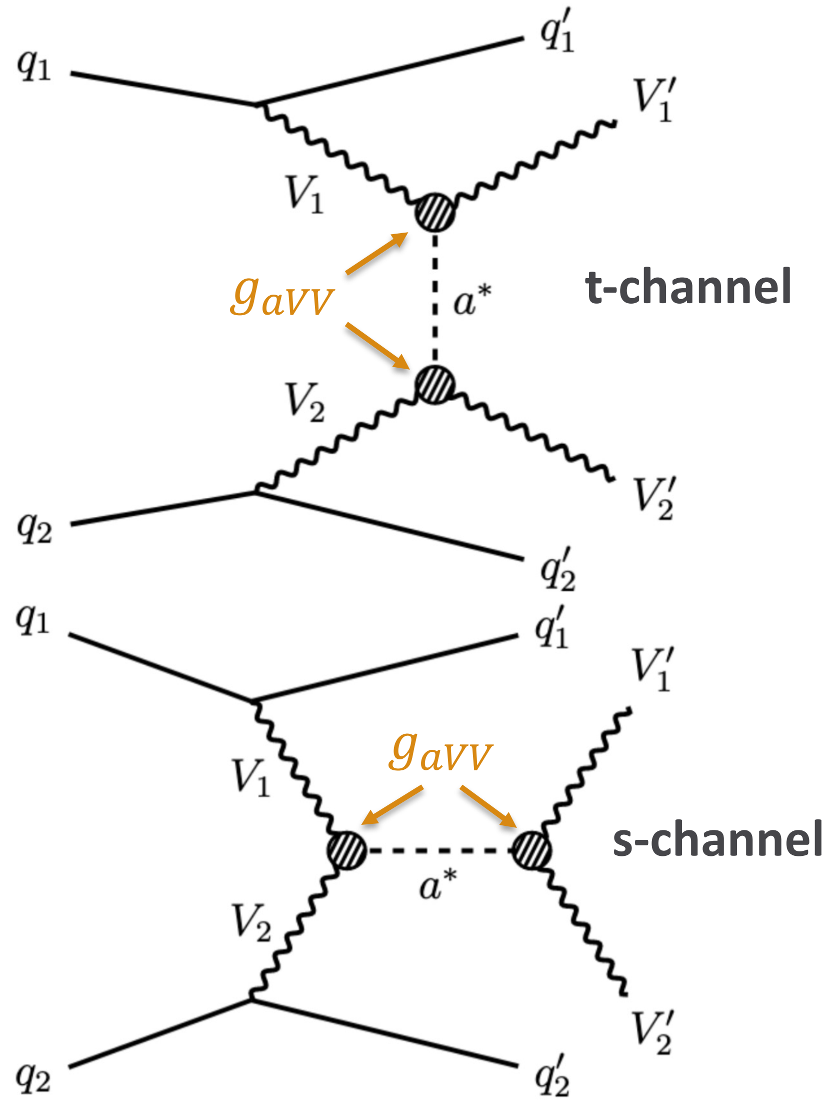
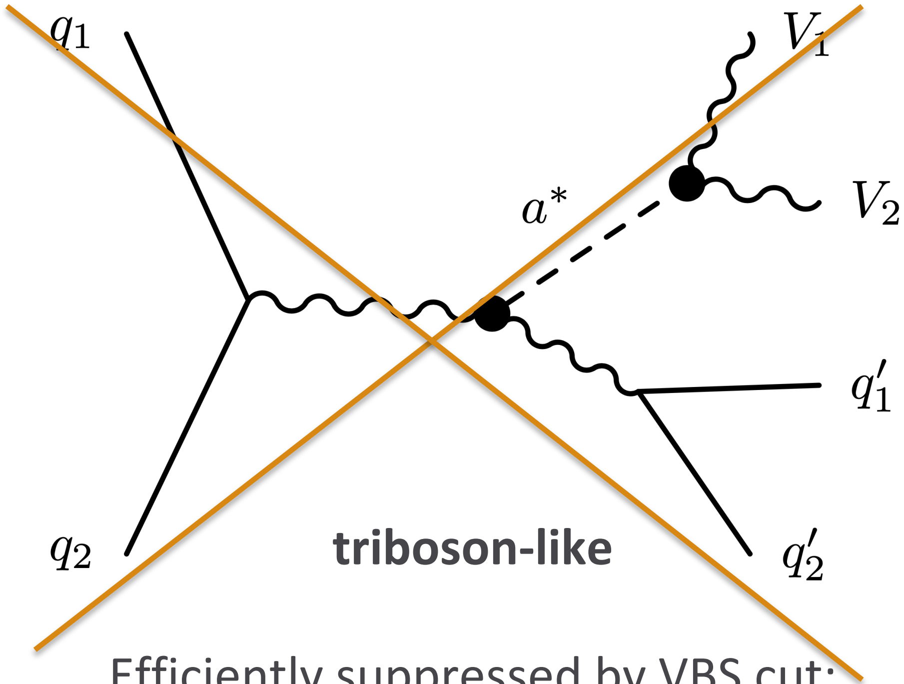


S. Carrá, V. Goumarre, R. Gupta, S. Heim, B. Heinemann, J. Küchler, F. Meloni, P. Quilez and Y.C. Yap reinterpretation of ATLAS analyses, [2106.10085]: $Z\gamma$ (CERN- EP-2019-228), WWj (CERN-EP-2021-030)

Nonresonant ALPs in VBS





Efficiently suppressed by VBS cut:
$M_{q'1q'2} > 120$ GeV

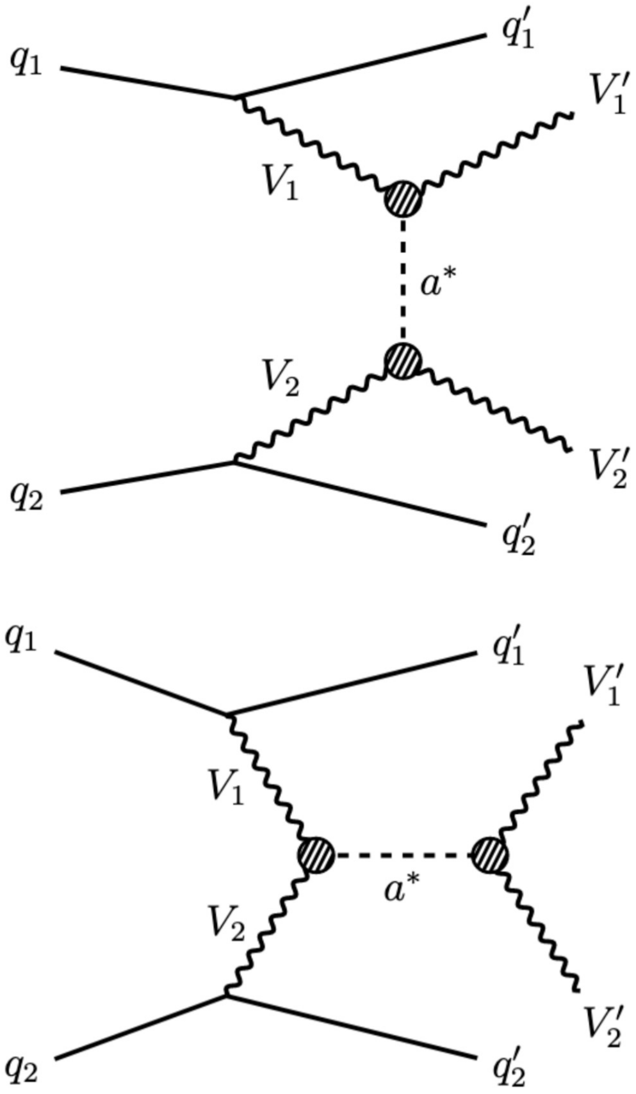
Contribution from gluons

- Same-sign WW, WZ, Wγ: ALP QCD absent at tree level

- ZZ and Zγ: ALP QCD strongly reduced
  - Consistency with previous nonresonant limits [1905.12953], [2106.10085], [2111.13669]
  - VBS selection cuts
  - Large diboson masses

- For the tested region of the ALP parameter space, the theoretical prediction is dominated by ALP VBS

- Conservative: QCD ALP is positive with a subdominant contribution from its interference with EWK ALP



VBS $pp \to V_1 V_2 jj$ LO diagrams.

ALP Diboson Mass in CMS Leptonic Analyses

- **Calibrate** our **Delphes detector simulation** using the SM EWK channel ⟶ **EWK scale factor**
- Compare EWK SM VBS expected yields from the CMS simulation and ours ⟶ $\rho = \frac{N^{simulated}_{SM\ EWK}}{N^{CMS}_{SM\ EWK}}$

Channel	Obs.	Lum. [fb^{-1}]	Selection Criteria	ρ
ZZ	M_{ZZ}	137	$M_{jj} > 100\,\mathrm{GeV}$	0.8 ± 0.1
$Z\gamma$	$M_{Z\gamma}$	137	$M_{jj} > 500\,\mathrm{GeV},\ \Delta\eta_{jj} > 2.5,\ p_T^{\gamma} > 120\,\mathrm{GeV}$	1.4 ± 0.2
$W^{\pm}\gamma$	$M_{W\gamma}$	35.9*	$M_{jj} > 800\,\mathrm{GeV},\ \Delta\eta_{jj} > 2.5,\ p_T^{\gamma} > 100\,\mathrm{GeV}$	3.1 ± 0.5
$W^{\pm}Z$	M^{T}_{WZ}	137	$M_{jj} > 500\,\mathrm{GeV},\ \Delta\eta_{jj} > 2.5$	1.5 ± 0.4
$W^{\pm}W^{\pm}$	M^{T}_{WW}	137	$M_{jj} > 500\,\mathrm{GeV},\ \Delta\eta_{jj} > 2.5$	1.3 ± 0.2

Table 3. Summary of the CMS VBS analyses: the diboson mass observable, the integrated luminosity, the most important selection criteria and the normalization scale factor ρ.

* Recent update at 138 fb^{-1}: CMS PAS SMP-21-011

ALP Diboson Mass in CMS Leptonic Analyses

- **$\sim$20 % signal systematics**: PDFs + renormalization and factorization scales + MadGraph@aMC
- **Background uncertainties** from CMS analyses
- Consistency of the ALP EFT and estimation of the impact of the highest-energy bins

  ➡ **upper cut on diboson mass M_{VV}**

- Two benchmarks:
  - $M_{vv} < 2$ TeV: $\sim$85 % efficiency
  - $M_{vv} < 4$ TeV: $>$99 % efficiency

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- Consistency of the ALP EFT and estimation of the impact of the highest-energy bins

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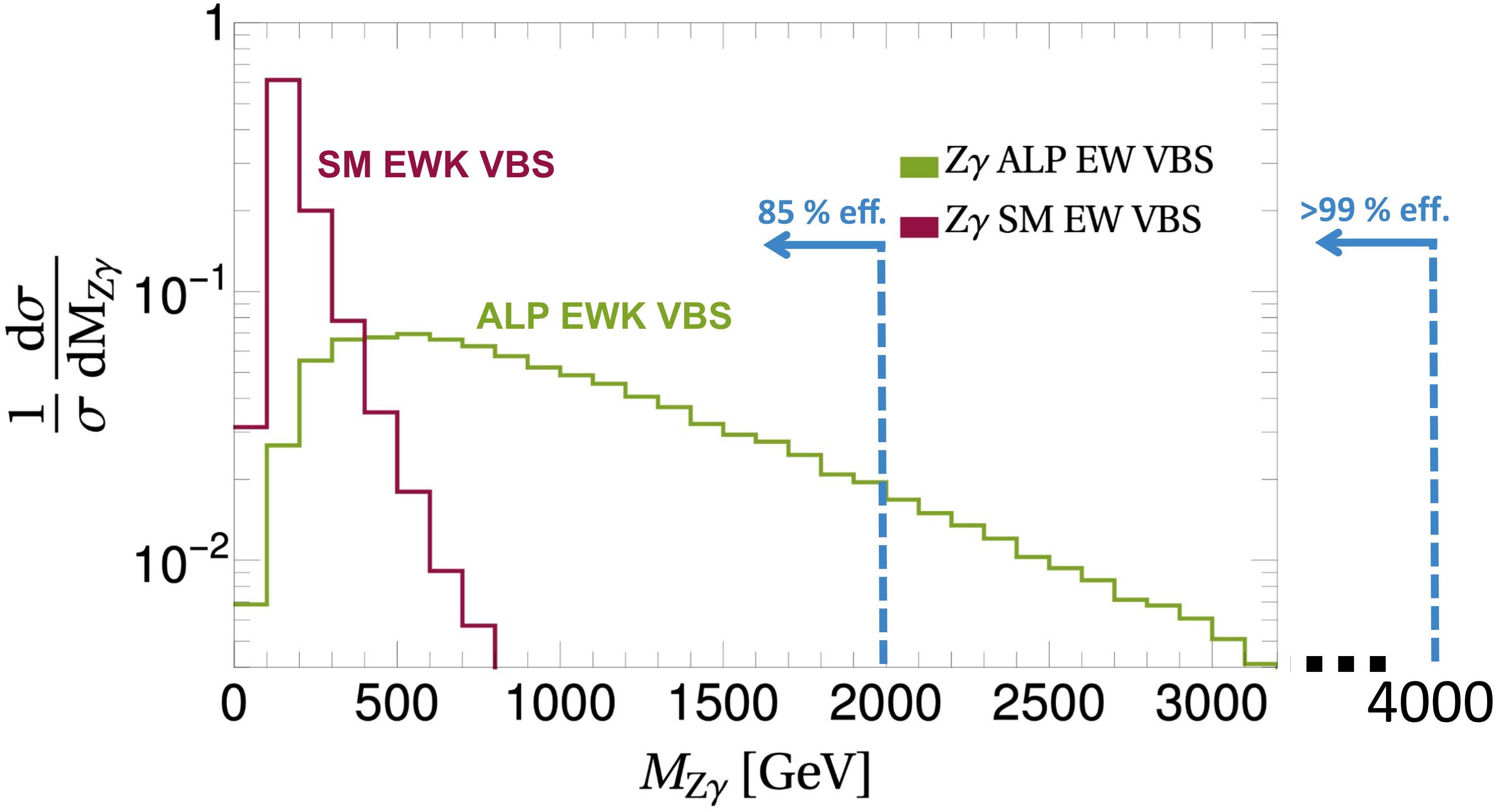

ALP Diboson Mass in CMS Leptonic Analyses

- **Generation cuts:**

$$p_T(q'_{1,2}) > 20\,\mathrm{GeV}\,, \quad \eta(q'_{1,2}) < 6\,, \quad \Delta R(q'_1 q'_2) > 0.1\,, \quad M_{q'_1 q'_2} > 120\,\mathrm{GeV}$$
$$p_T(\gamma) > 10\,\mathrm{GeV}\,, \quad \eta(\gamma) < 2.5\,, \quad \Delta R(\gamma q'_{1,2}) > 0.4\,,$$

- **Selection cuts:**

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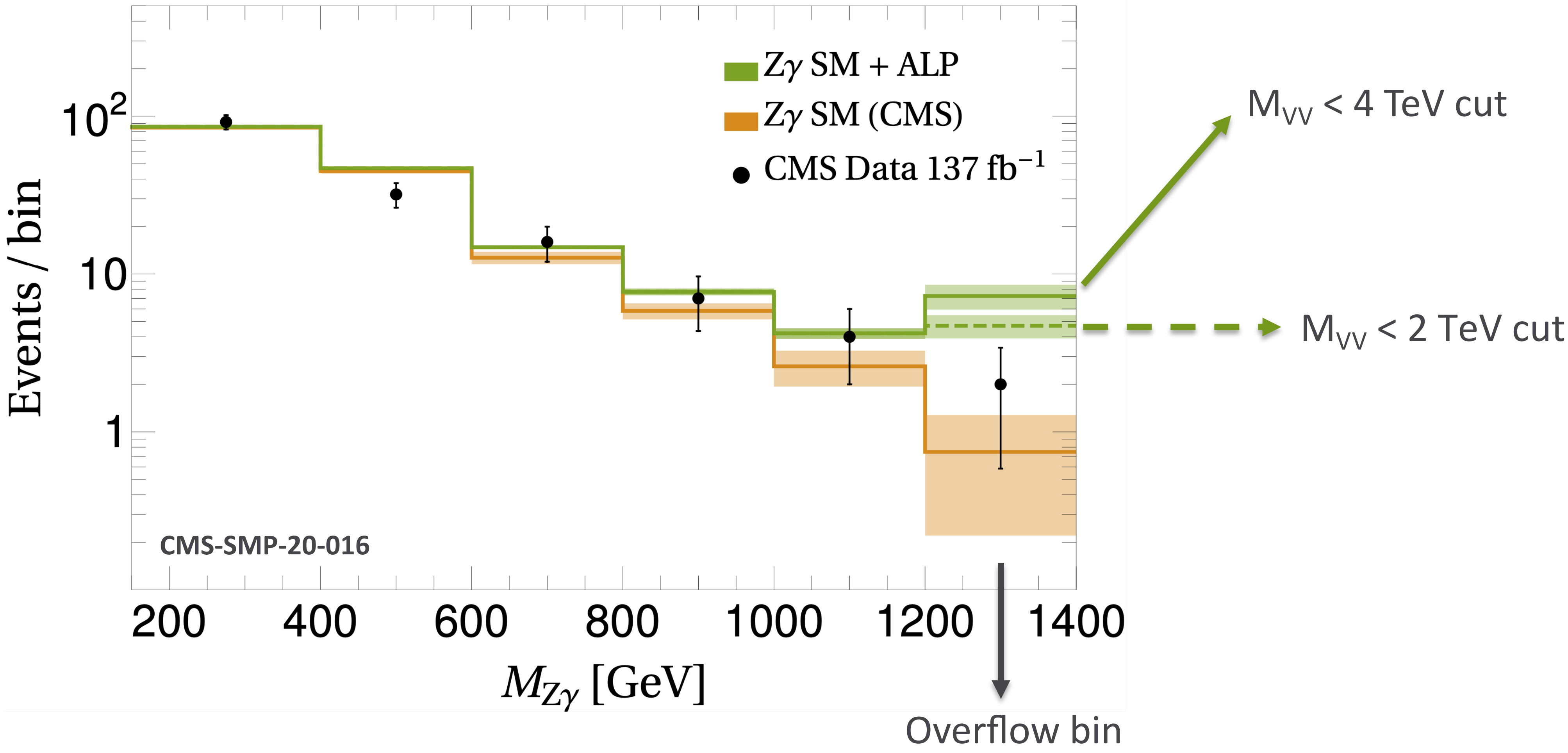
ALP Diboson Mass in CMS Leptonic Analyses

Process	σ_{SM} [fb]	Point	$\sigma_{\text{interf.}}$ [fb]	σ_{signal} [fb]
$pp \to jjZZ$	98 ± 1	p_0	-13.5 ± 0.1	42.4 ± 0.2
		p_4	-9.3 ± 0.1	18.5 ± 0.1
$pp \to jjZ\gamma$	393 ± 1	p_0	0.3 ± 0.1	11.1 ± 0.1
		p_4	-9.1 ± 0.1	20.9 ± 0.1
$pp \to jjW^{\pm}\gamma$	994 ± 3	p_0	4.3 ± 0.1	28.7 ± 0.1
		p_4	1.7 ± 0.1	5.4 ± 0.1
$pp \to jjW^{\pm}Z$	386 ± 1	p_0	1.7 ± 0.1	18.4 ± 0.1
		p_4	0.1 ± 0.1	23.9 ± 0.1
$pp \to jjW^{\pm}W^{\pm}$	256 ± 1	p_0, p_4	-4.0 ± 0.1	16.0 ± 0.1

- **EW VBS SM and ALP signal cross sections**
- Generation cuts
- Two benchmark points:
  - $p_0 \equiv g_{a\gamma Z} = 0$
  - $p_4 \equiv g_{a\gamma\gamma} = 0$

ALP Diboson Mass in CMS Leptonic Analyses



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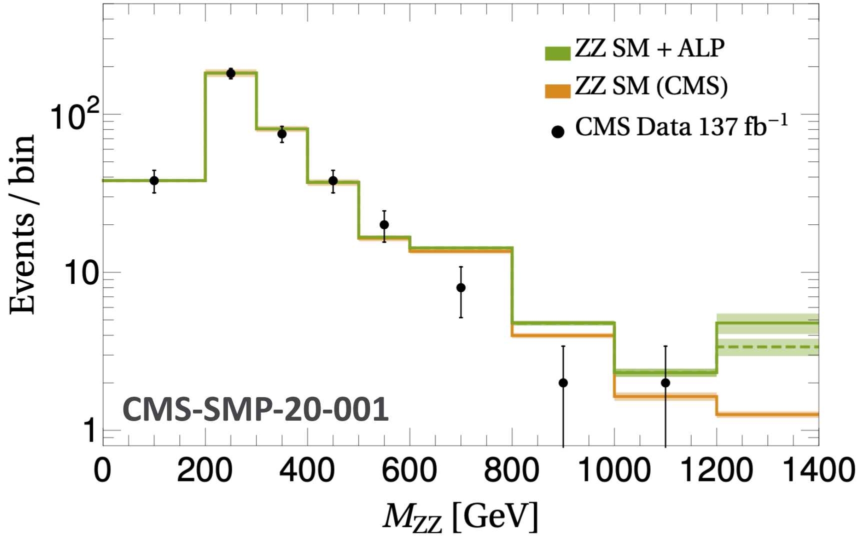
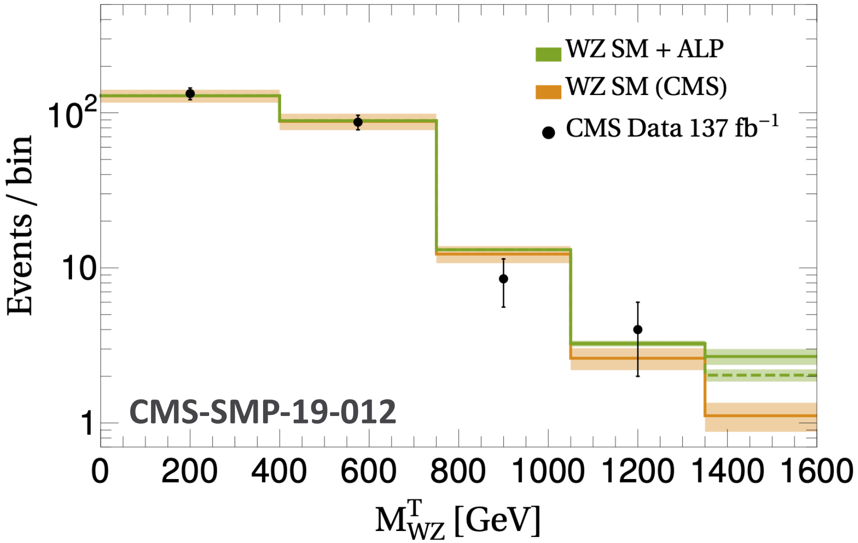
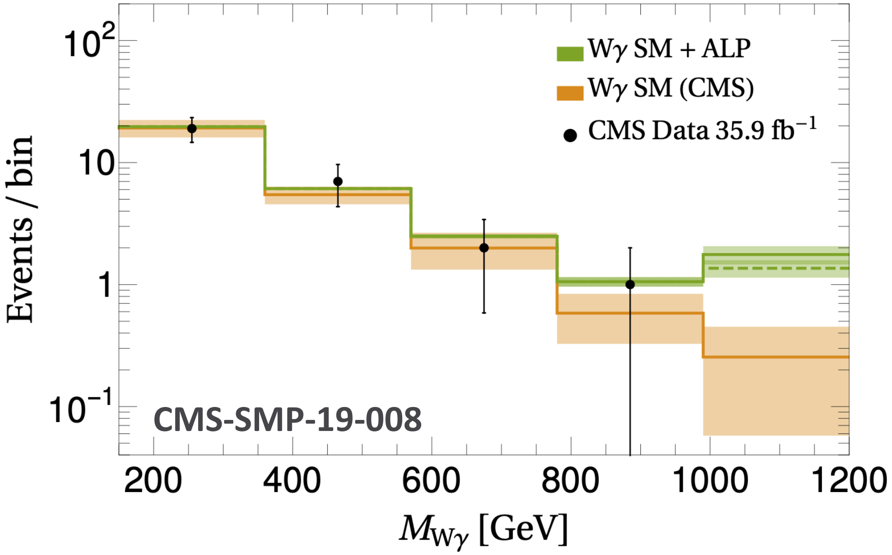
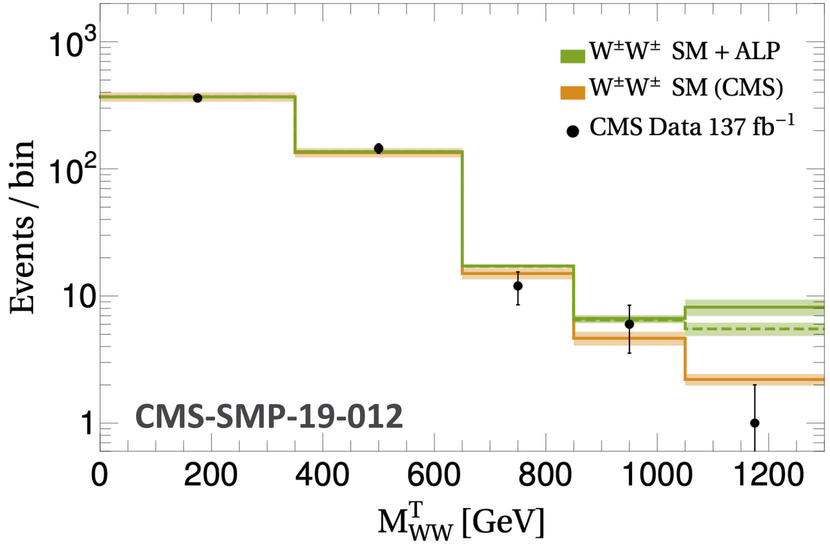








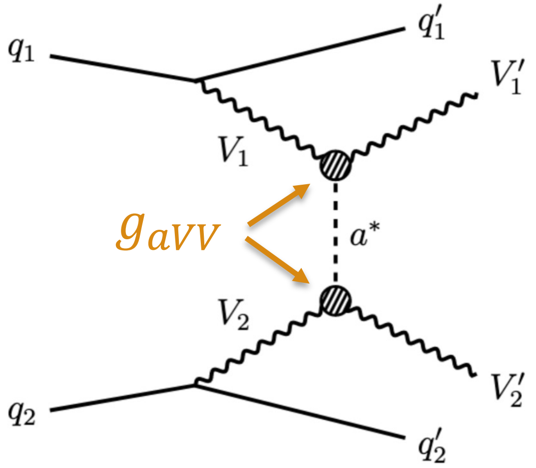
Branching fractions and selection efficiencies

Analysis	ZZ	$Z\gamma$	$W^{\pm}\gamma$	$W^{\pm}Z$	$W^{\pm}W^{\pm}$
Branching fraction	0.45%	6.7%	22%	1.5%	4.8%
Efficiency	35.7%	14.0%	1.6%	11.3%	17.0%

Table 4. Summary of branching fractions and selection efficiencies for each VBS channel. The efficiencies are relative to the simulated events in which the W and Z bosons decay to electrons or muons.

Differential cross-sections

- **Expected diff. cross-sections are parameterized** in the $(c_{\tilde{W}}, c_{\tilde{B}})$ plane with quartic / quadratic **polynomials** for pure signal / interference ALP components.



$$i\mathcal{M}_{ALP} \sim g_{aVV}{}^{2} \sim O(c_{\tilde{V}}{}^{2}) \longrightarrow \begin{cases} \sigma_{signal} \sim O\,(c_{\tilde{V}}{}^{4}) \\ \sigma_{interf} \sim O(c_{\tilde{V}}{}^{2}) \end{cases}$$

- MadGraph5_aMC@NLO reweighting tool for the generation at different points in the $(c_{\tilde{W}}, c_{\tilde{B}})$ plane:

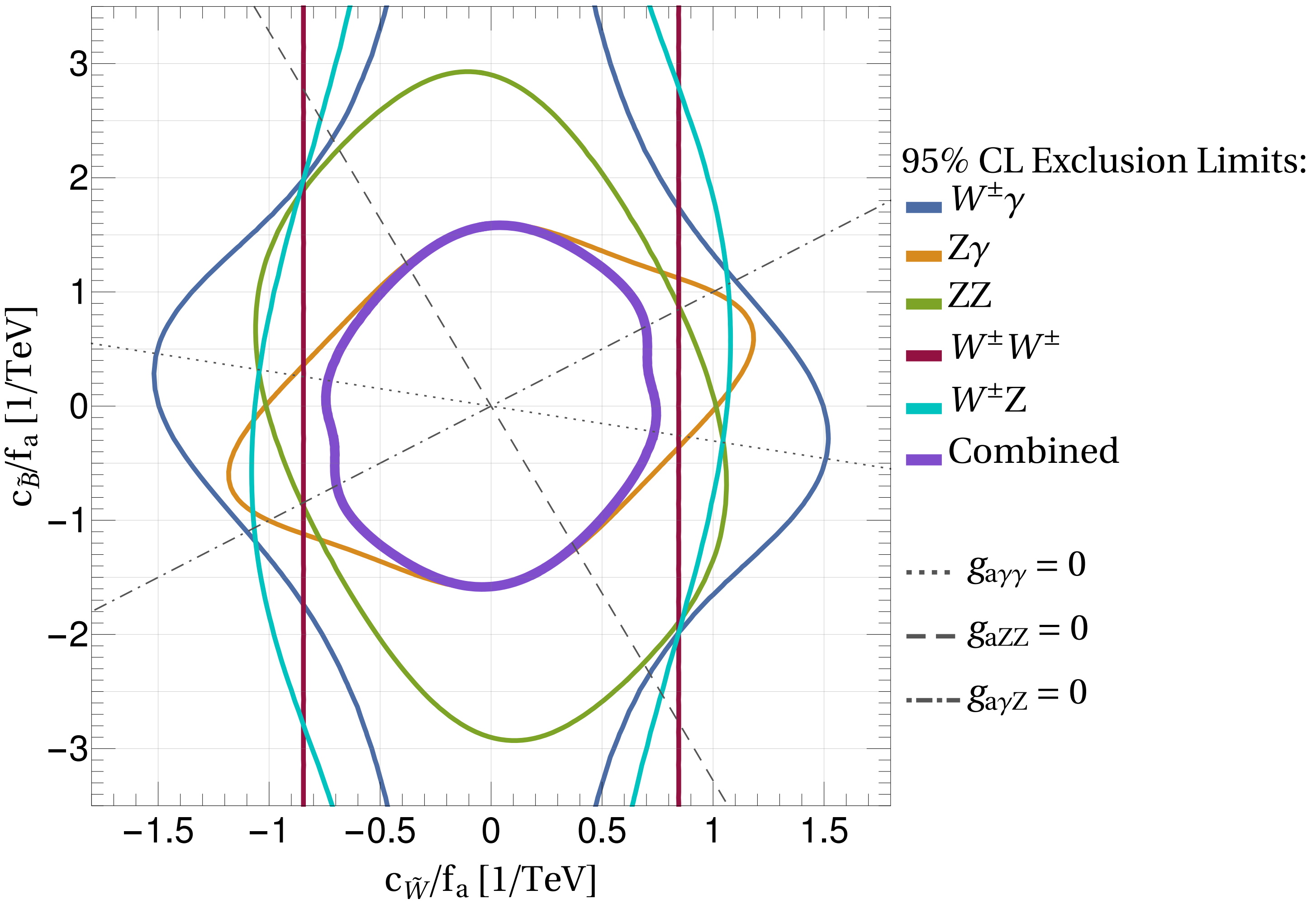
$$p_0 = (1,1), \quad p_1 = (0,2), \quad p_2 = (1,0),$$
$$p_3 = (1,-1), \quad p_4 = (1,-0.305), \quad p_5 = (1,-3.279)$$

$g_{a\gamma Z} = 0$ → p_0; $g_{a\gamma\gamma} = 0$ → p_4; $g_{aZZ} = 0$ → p_5

Results

CURRENT LIMITS

- Only ZZ and $Z\gamma$ can constrain $c_{\tilde{B}}/f_a$
- Most promising channels: $Z\gamma$ and $W^{\pm}W^{\pm}$

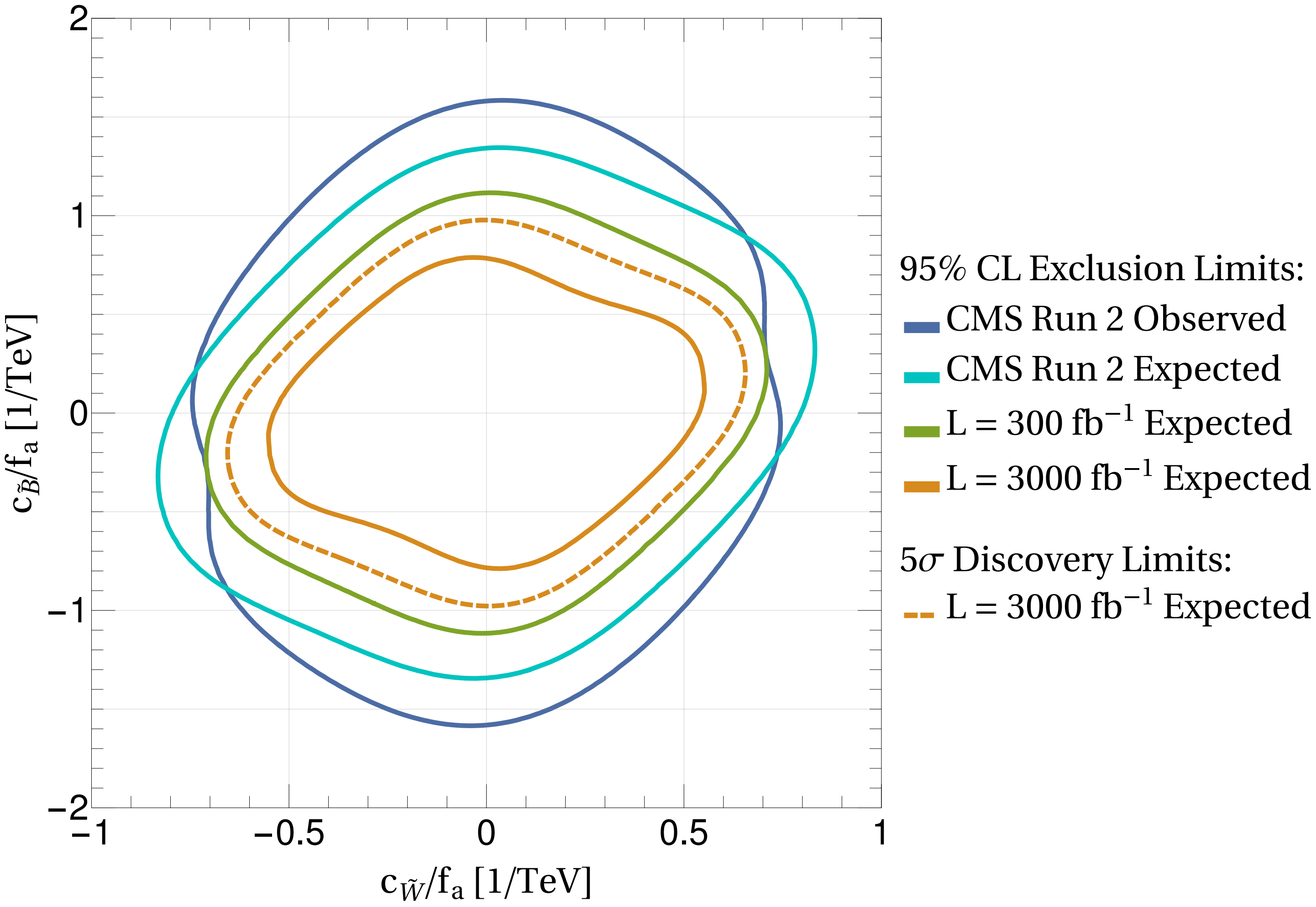


(for f_a > 4 TeV and M_a < 100 GeV)

Results

PROJECTED LIMITS

- HL-LHC limits on ALP couplings decrease by a factor $\sim 1.5 - 1.7$
- HL-LHC limits on ALP cross sections decrease by a factor $\sim 5 - 8$



(for $f_a > 4$ TeV and $M_a < 100$ GeV)

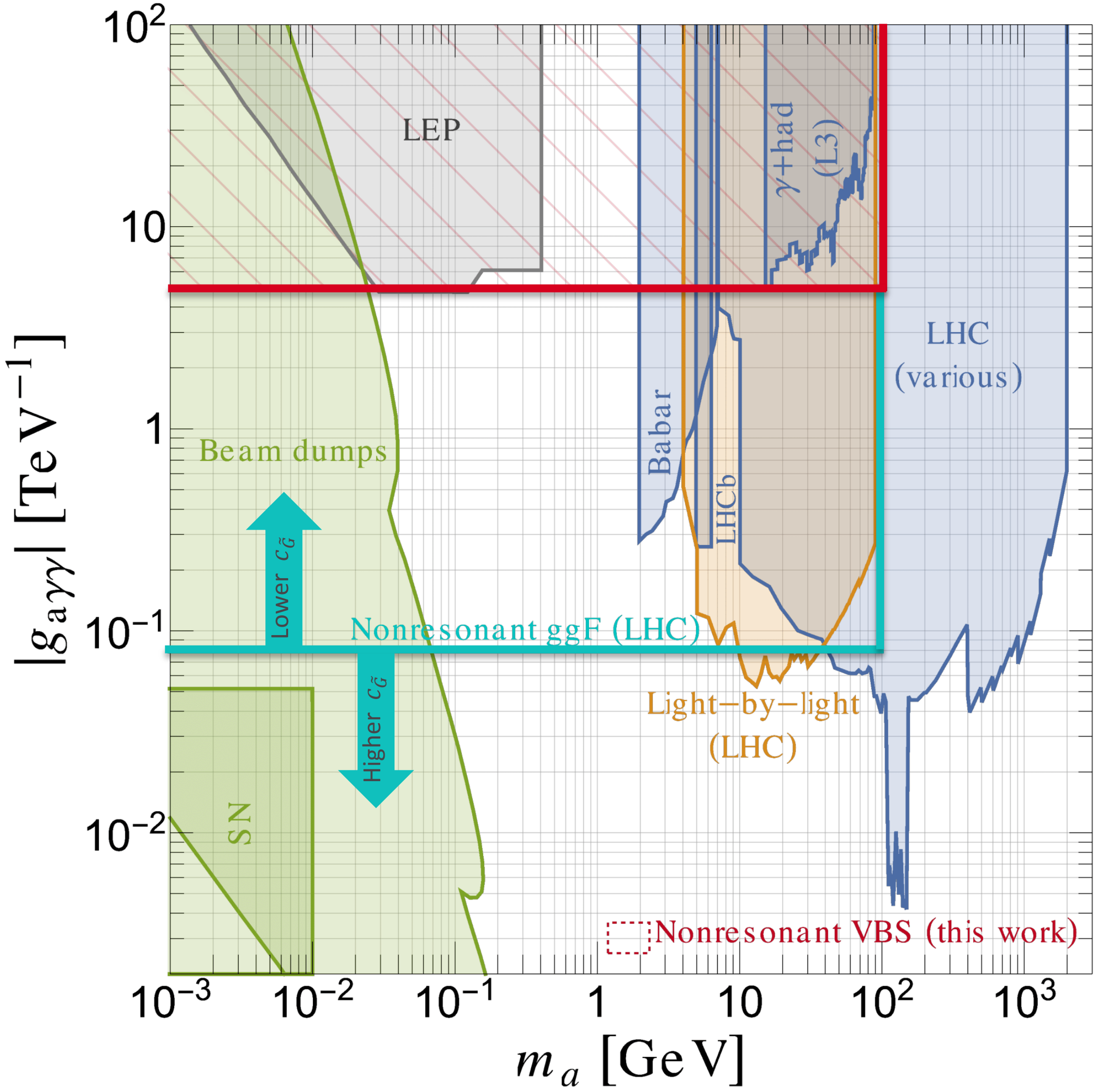
Results

Coupling [TeV^{-1}]	Run 2 Observed (Expected) $M_{V_1V_2} < 4\,\text{TeV}$	$< 2\,\text{TeV}$	$300\,\text{fb}^{-1}$ $< 4\,\text{TeV}$	$< 2\,\text{TeV}$	$3000\,\text{fb}^{-1}$ $< 4\,\text{TeV}$	$< 2\,\text{TeV}$
$\lvert c_{\widetilde{W}}/f_a \rvert$	0.75 (0.83)	0.86 (0.94)	0.71	0.80	0.55	0.62
$\lvert c_{\widetilde{B}}/f_a \rvert$	1.59 (1.35)	1.73 (1.47)	1.12	1.23	0.79	0.87
$\lvert g_{a\gamma\gamma} \rvert$	4.99 (4.24)	5.45 (4.63)	3.50	3.84	2.43	2.68
$\lvert g_{a\gamma Z} \rvert$	5.54 (4.74)	6.15 (5.25)	3.98	4.42	2.94	3.30
$\lvert g_{aZZ} \rvert$	2.84 (3.02)	3.19 (3.38)	2.53	2.81	1.94	2.16
$\lvert g_{aWW} \rvert$	2.98 (3.33)	3.43 (3.74)	2.84	3.18	2.21	2.49

- **95% CL upper limits**
- CMS Run 2 measurements
- Projected sensitivities @ $\sqrt{s} = 14$ TeV

(for f_a > 4 TeV and M_a < 100 GeV)

Comparison to existing bounds



- **Red:** this work
- **Green:** no assumptions
- **Light blue:** nonresonant ggF. Depend on the coupling to gluons and asume g_{agg} = 1 TeV^{-1}
- **Dark blue:** gluon dominance $g_{agg} \gg g_{aV_1V_2}$
- **Orange:** $BR(a \to \gamma\gamma)$= 1
- **Grey:** more elaborate assumptions on the EWK sector

Comparison to existing bounds