Nonresonant Searches for Axion-Like Particles in Vector Boson Scattering Processes at the LHC

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Based on: J. Bonilla , I. Brivio, J. Machado-Rodríguez, J. F. de Trocóniz

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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

$$\left\{ \begin{array}{l} \dfrac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \psi \\[2ex] \dfrac{a}{f_a} X_{\mu\nu} \widetilde{X}^{\mu\nu} \end{array} \right.$$

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

Axion-Like Particles

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

- Classical searches: ALP couplings to gluons and photons
- ALP couplings to **EWK bosons**: WW, ZZ, and $Z\gamma$
- **Depend on two 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 ALP-mediated diboson production

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

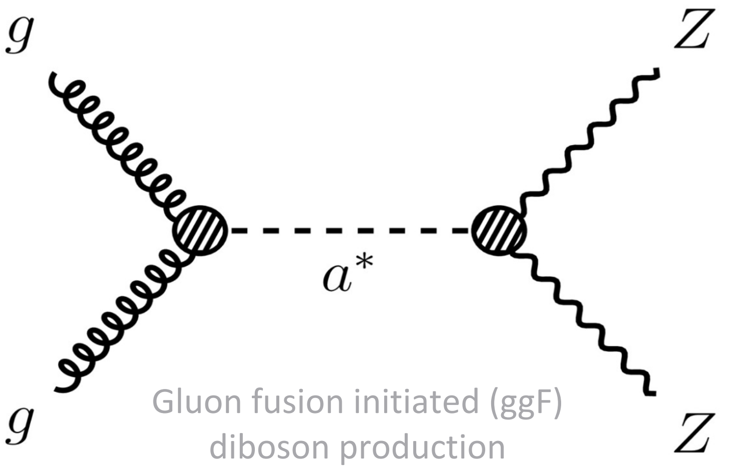
- ALP acts as a **very off-shell mediator** ⟶ $m_a^2 \ll \hat{s}$

- 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

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

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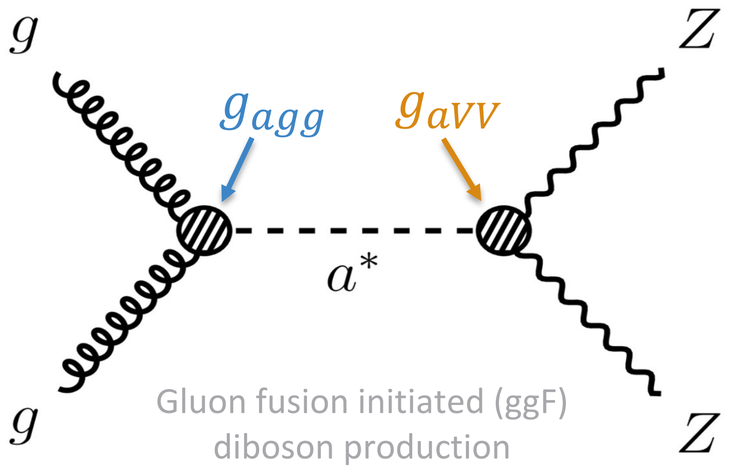
- Reinterpreation of CMS analyses:
  - $gg \to ZZ$ (CMS-B2G-17-013)
  - $gg \to \gamma\gamma$ (CMS-EXO-17-017)
- Sensitive to (**ALP coupling to gluons** x **ALP coupling to EWK diboson**)

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

- 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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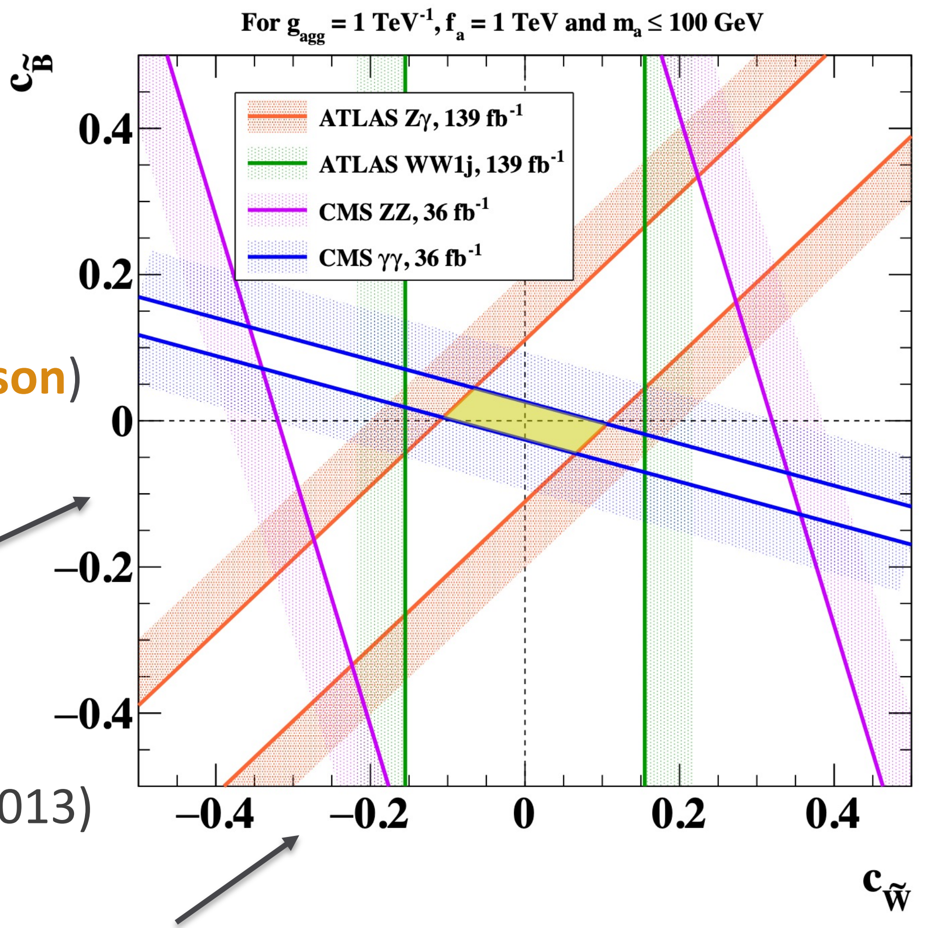


S. Carrá, V. Goumarre, R. Gupta, S. Heim, B. Heinemann, J. Küchler, F. Meloni, P. Quilez and Y.C. Yap reinterpretation of ATLAS analyses, [2106.10085]: $Z\gamma$ (CERN- EP-2019-228), WWj (CERN-EP-2021-030)

Nonresonant ALPs in VBS

- Vector Boson Scattering (VBS): $q_1 q_2 \rightarrow V'_1 V'_2 q'_1 q'_2$

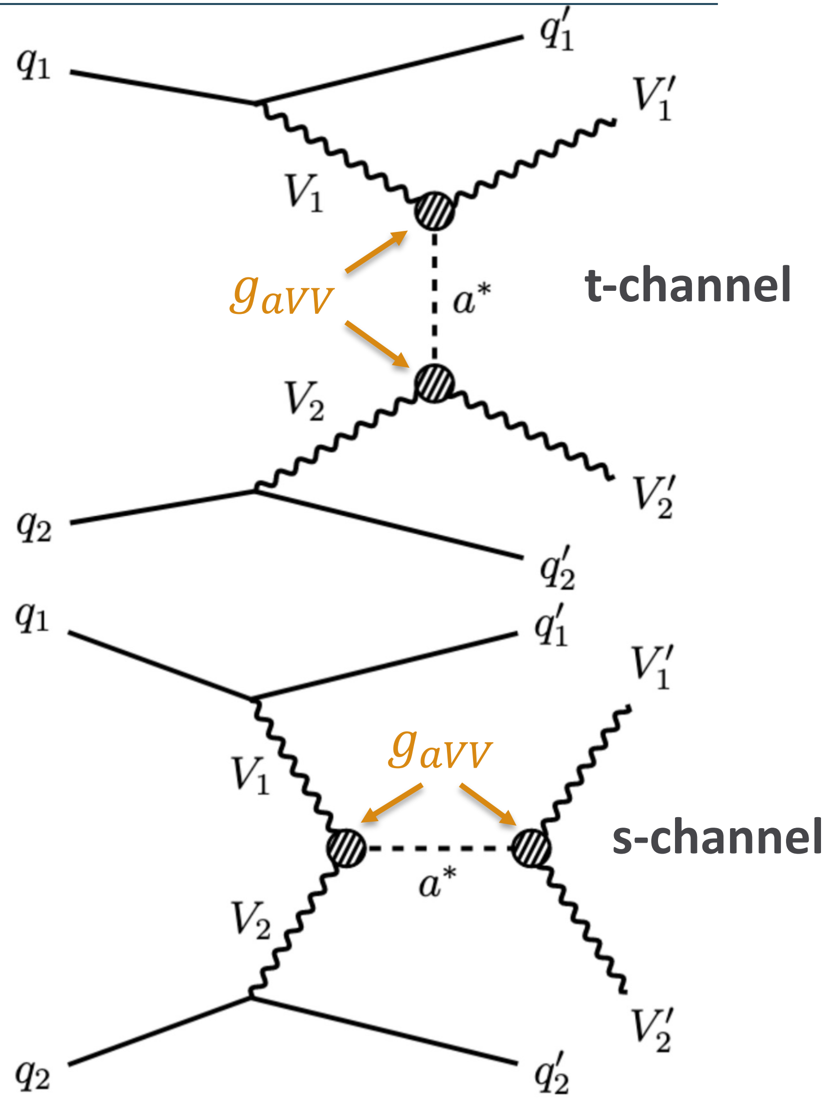
  $V'_1 V'_2 = ZZ,\ Z\gamma,\ W^{\pm}\gamma,\ WZ,\ W^{\pm}W^{\pm}$

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

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

- Nonresonant ALP: **independent of ALP mass m_a and its decay width up to $m_a \lesssim 100$ GeV**

Why VBS?



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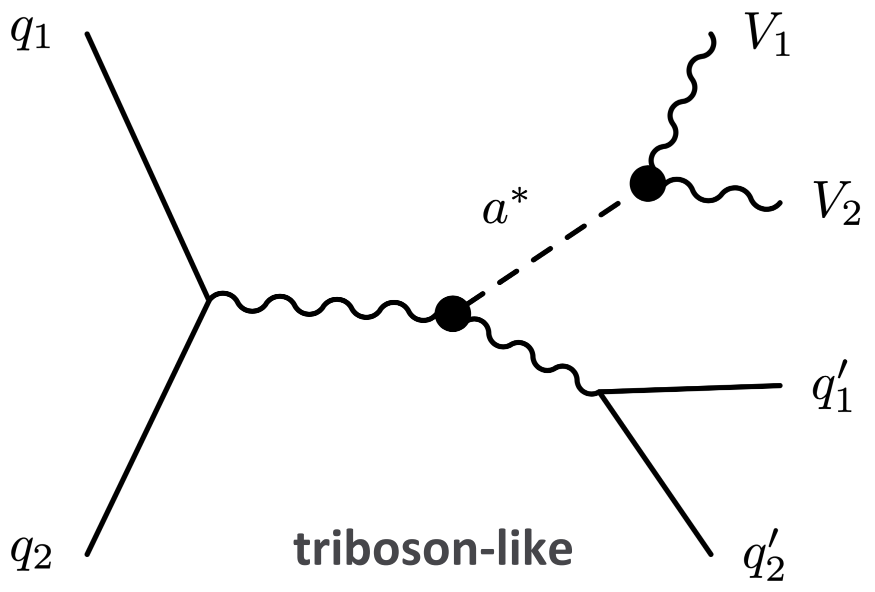

Efficiently suppressed by VBS cut: $M_{q'1q'2} > 120$ GeV

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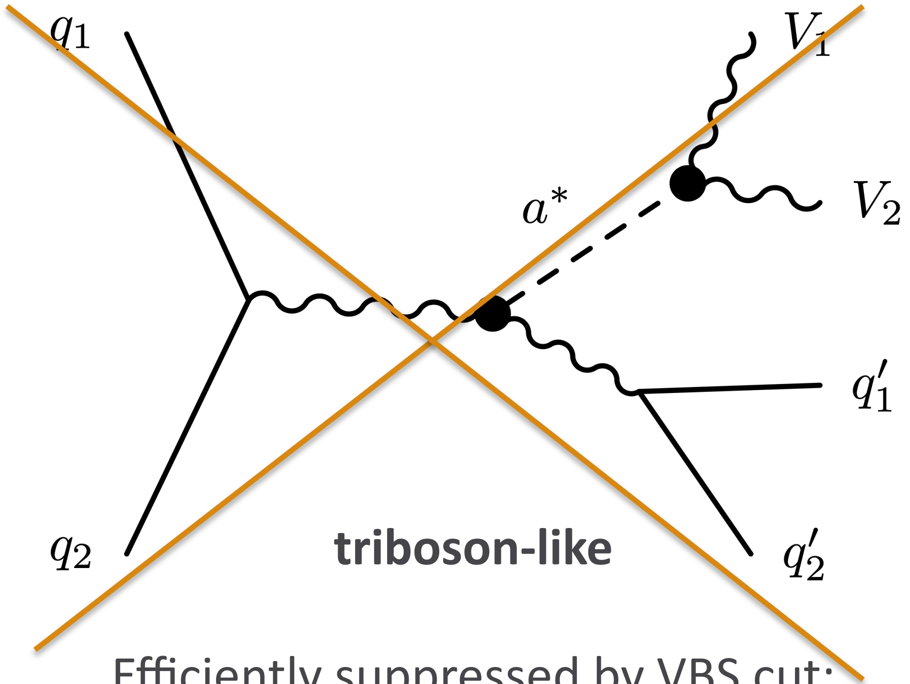

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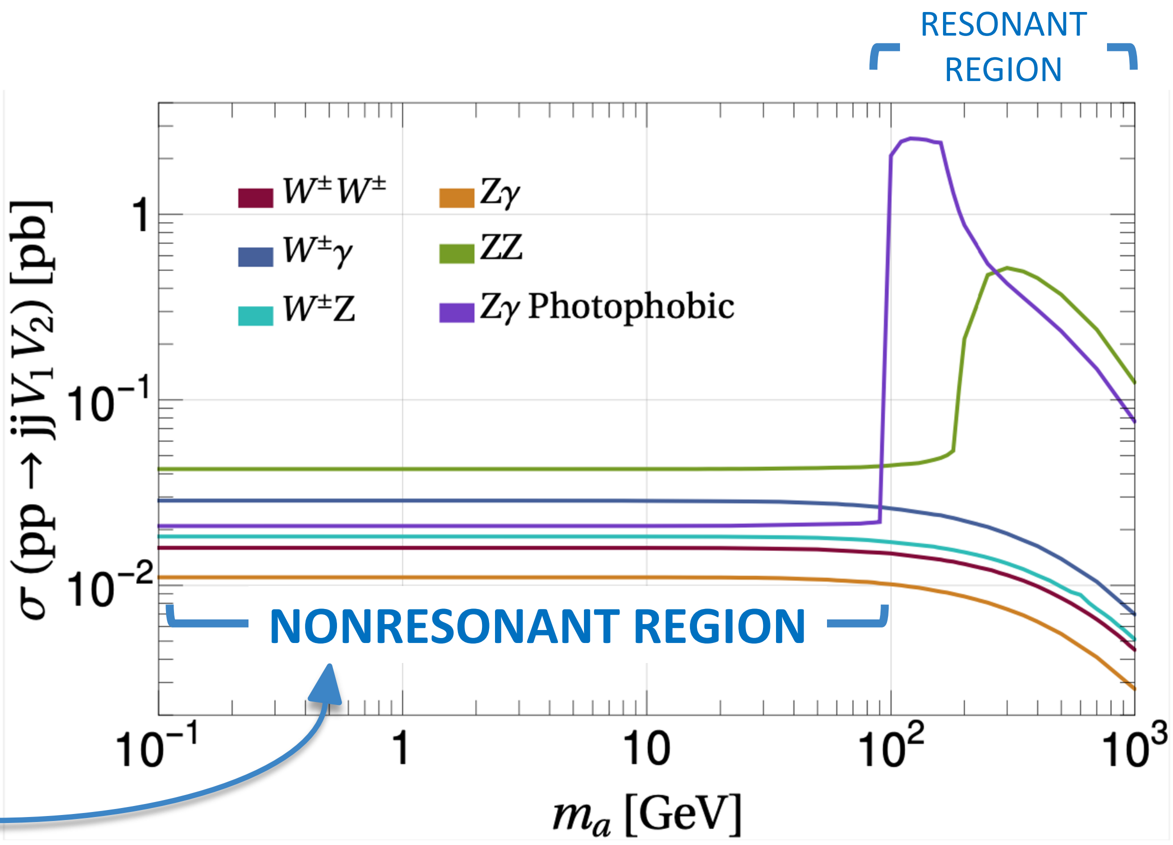

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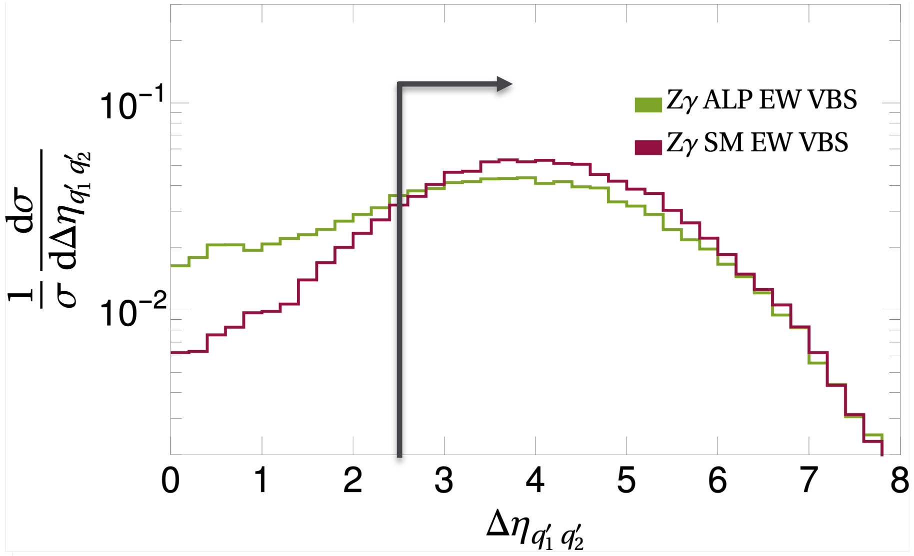
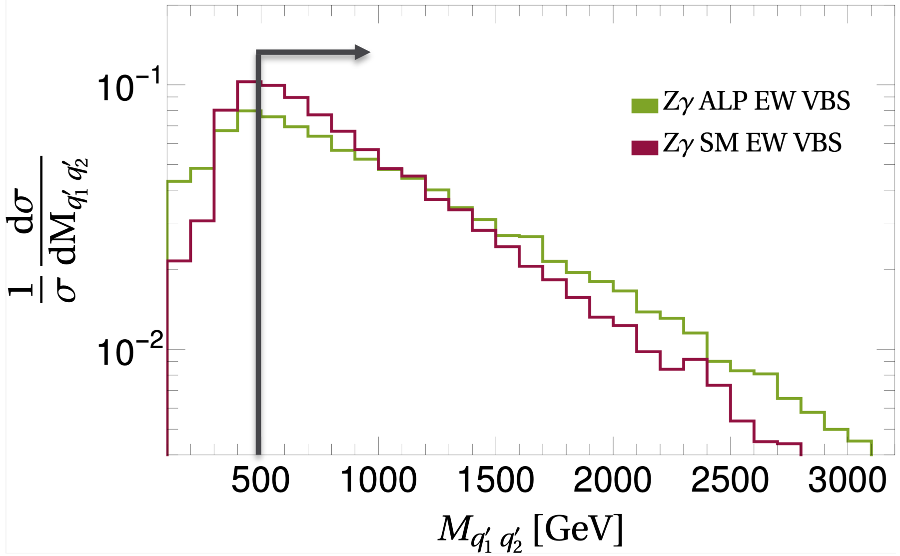


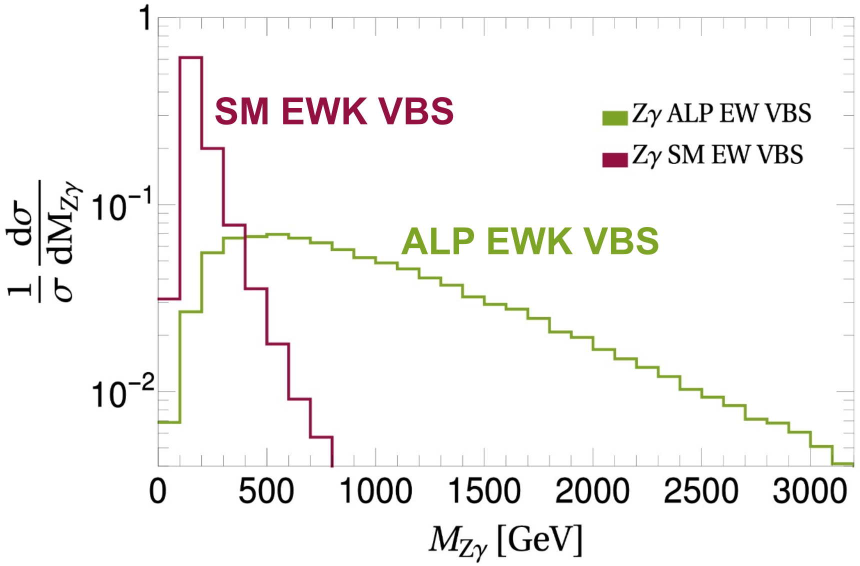


Wide rapidity separation

VBS CHARACTERISTIC OBSERVABLES

Large dijet mass

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

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 ⟶ $\rho = \frac{N_{SM\ EWK}^{simulated}}{N_{SM\ EWK}^{CMS}}$

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

- **~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: ~85 % efficiency
  - $M_{vv} < 4$ TeV: >99 % efficiency

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

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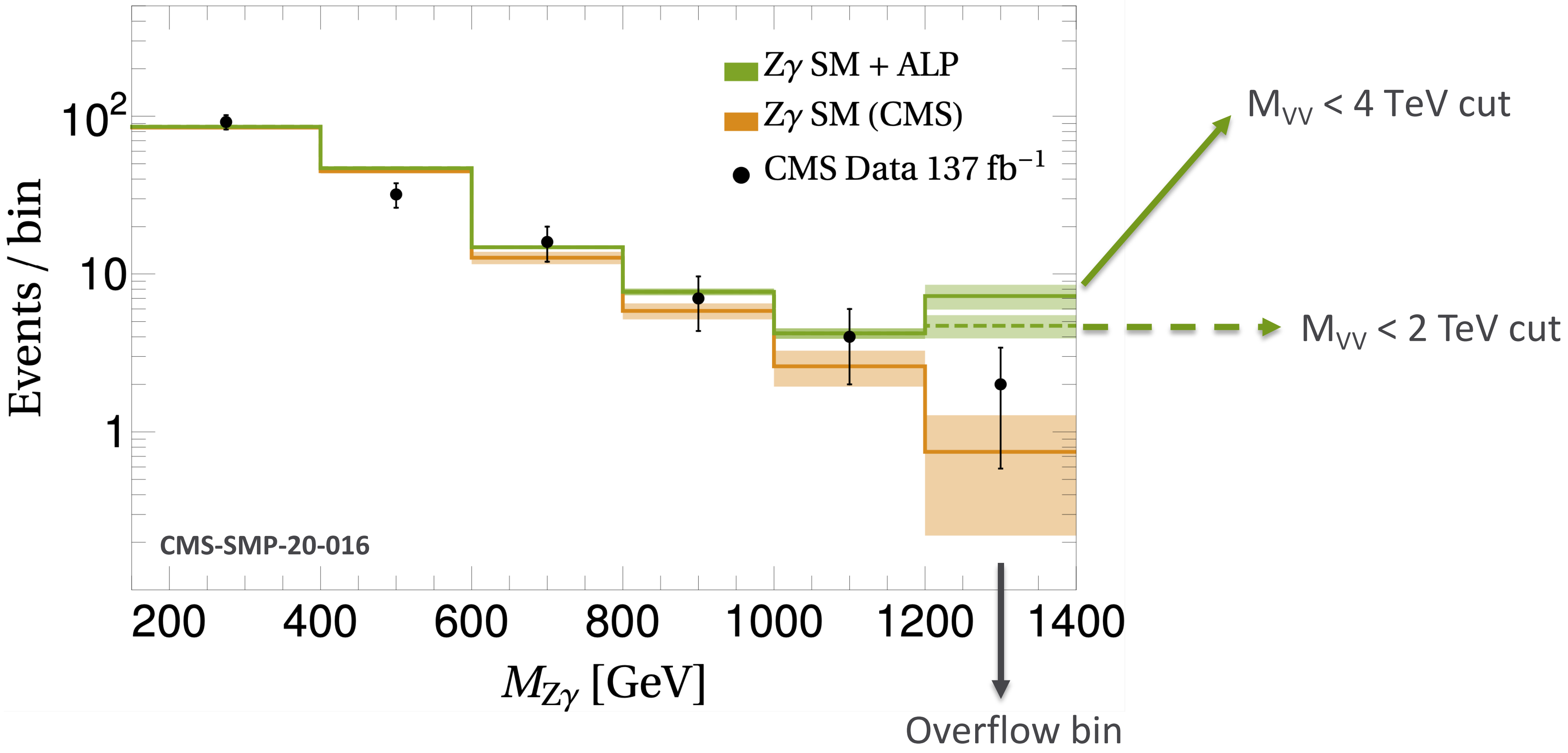


Results

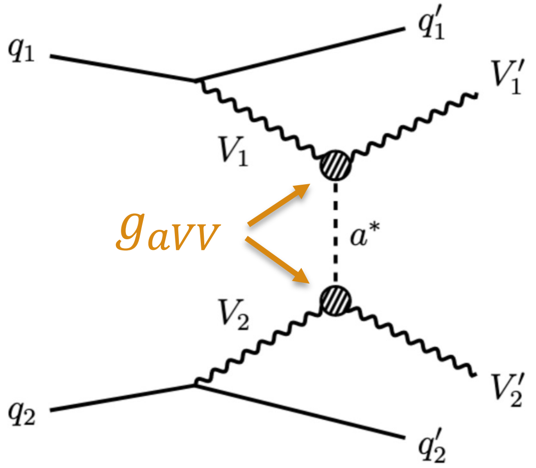
- **Maximum likelihood fit** of signal and background to the **diboson invariant/transverse masses**

- 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

Results

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



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

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

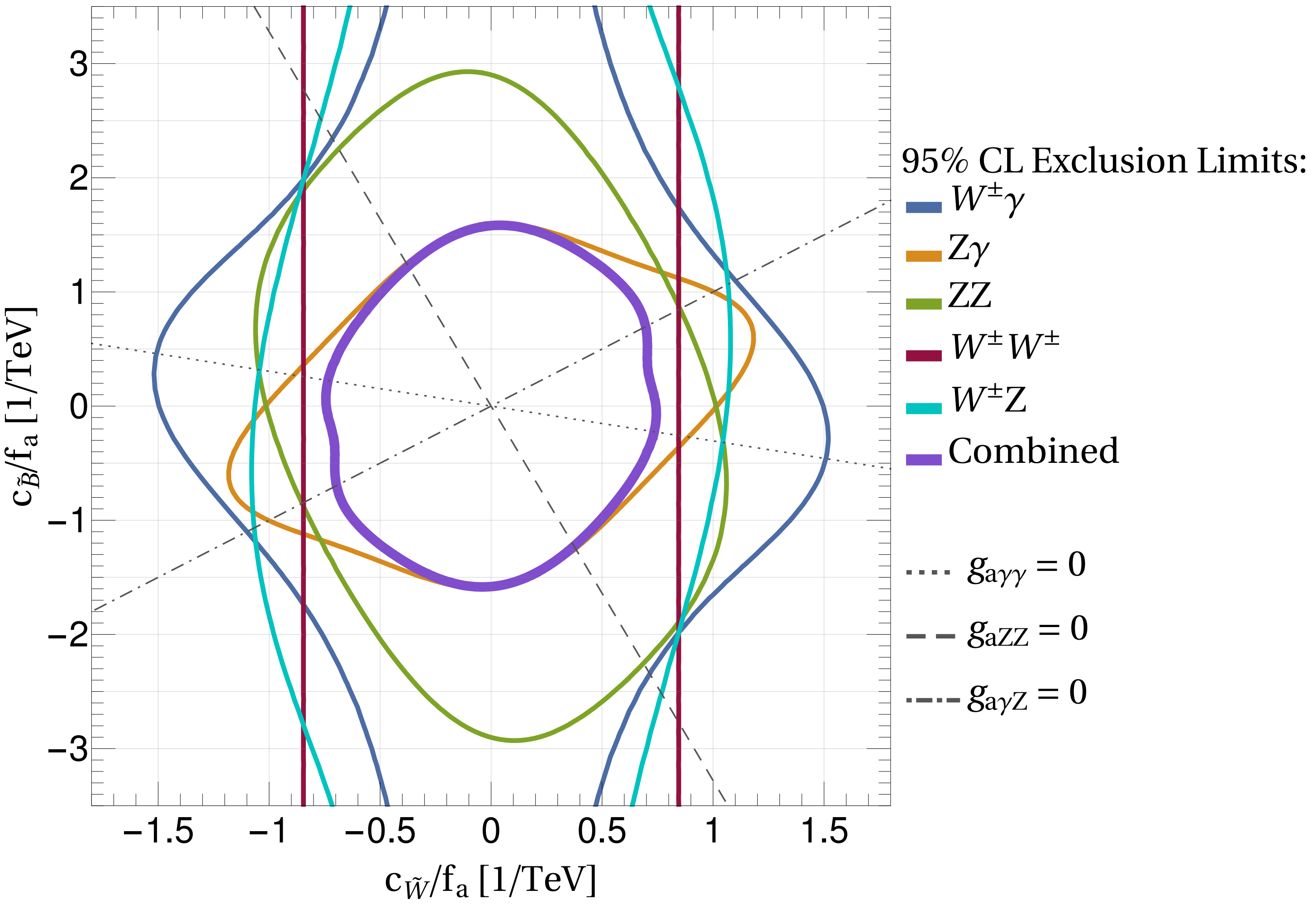
$$p_0 = (1, 1), \quad p_1 = (0, 2), \quad p_2 = (1, 0),$$
$$p_3 = (1, -1), \quad p_4 = (1, -0.305), \quad p_5 = (1, -3.279)$$

$g_{a\gamma Z} = 0$ (→ p_0), $g_{a\gamma\gamma} = 0$ (→ p_4), $g_{aZZ} = 0$ (→ p_5)

Results

CURRENT LIMITS

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

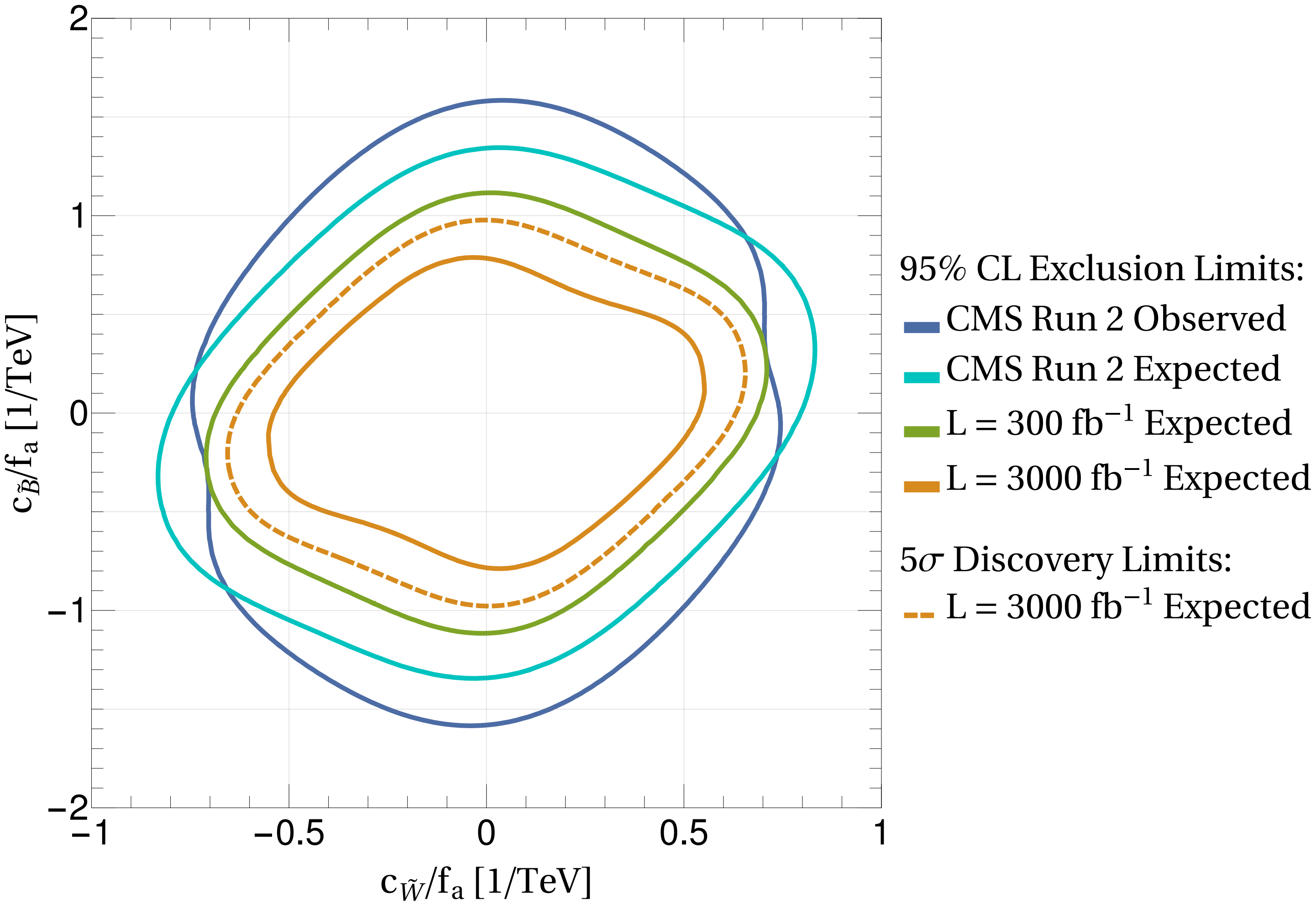


(for f_a > 4 TeV and M_a < 100 GeV)

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 $\sim 5 - 8$



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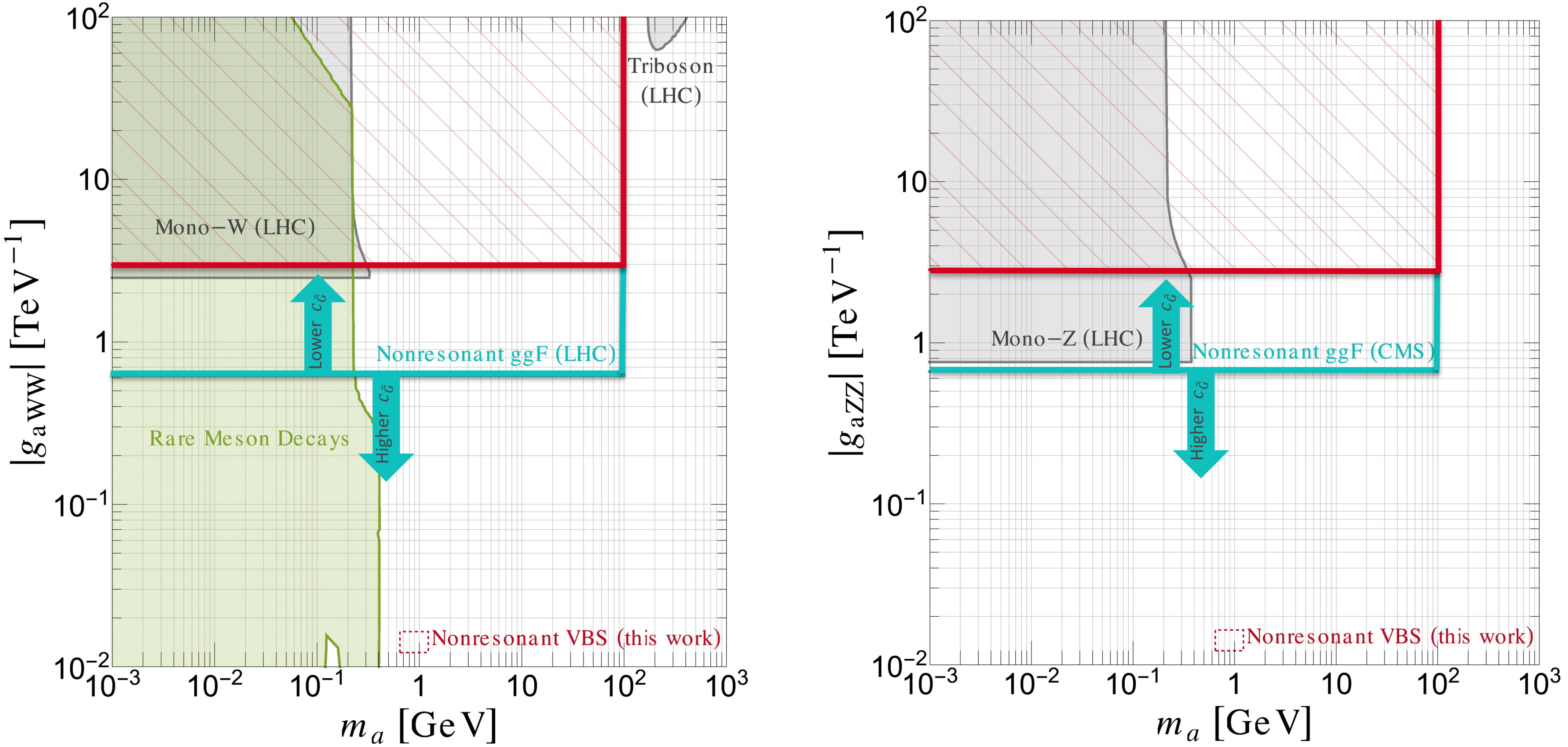
Results: comparison to existing bounds

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



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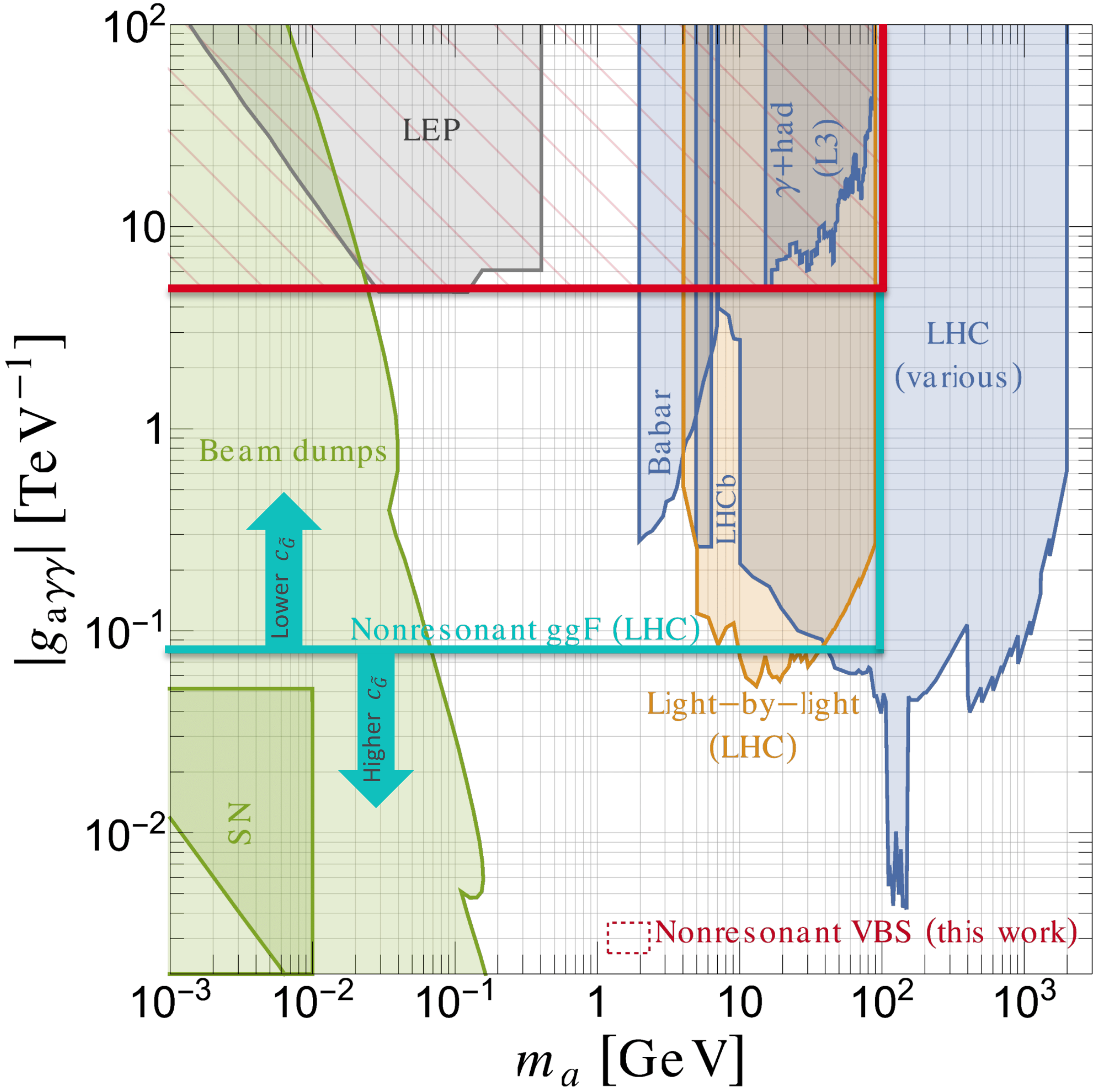

- **Red:** this work
- **Green:** no assumptions
- **Light blue:** nonresonant ggF. Depend on the coupling to gluons and asume g_{agg} = 1 TeV^{-1}
- **Dark blue:** gluon dominance, i.e., $g_{agg} \gg g_{aV_1V_2}$
- **Orange:** $BR(a \rightarrow \gamma\gamma)$= 1
- **Grey:** more elaborate assumptions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

Conclusions

- Access to **EWK couplings independently of the gluons**
- Current limits (CMS Run 2 data) and projected limits (Run 3 and HL)
- 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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Kinematic cuts

- 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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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.

Diboson mass upper cuts

- 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: ~ 85 % efficiency
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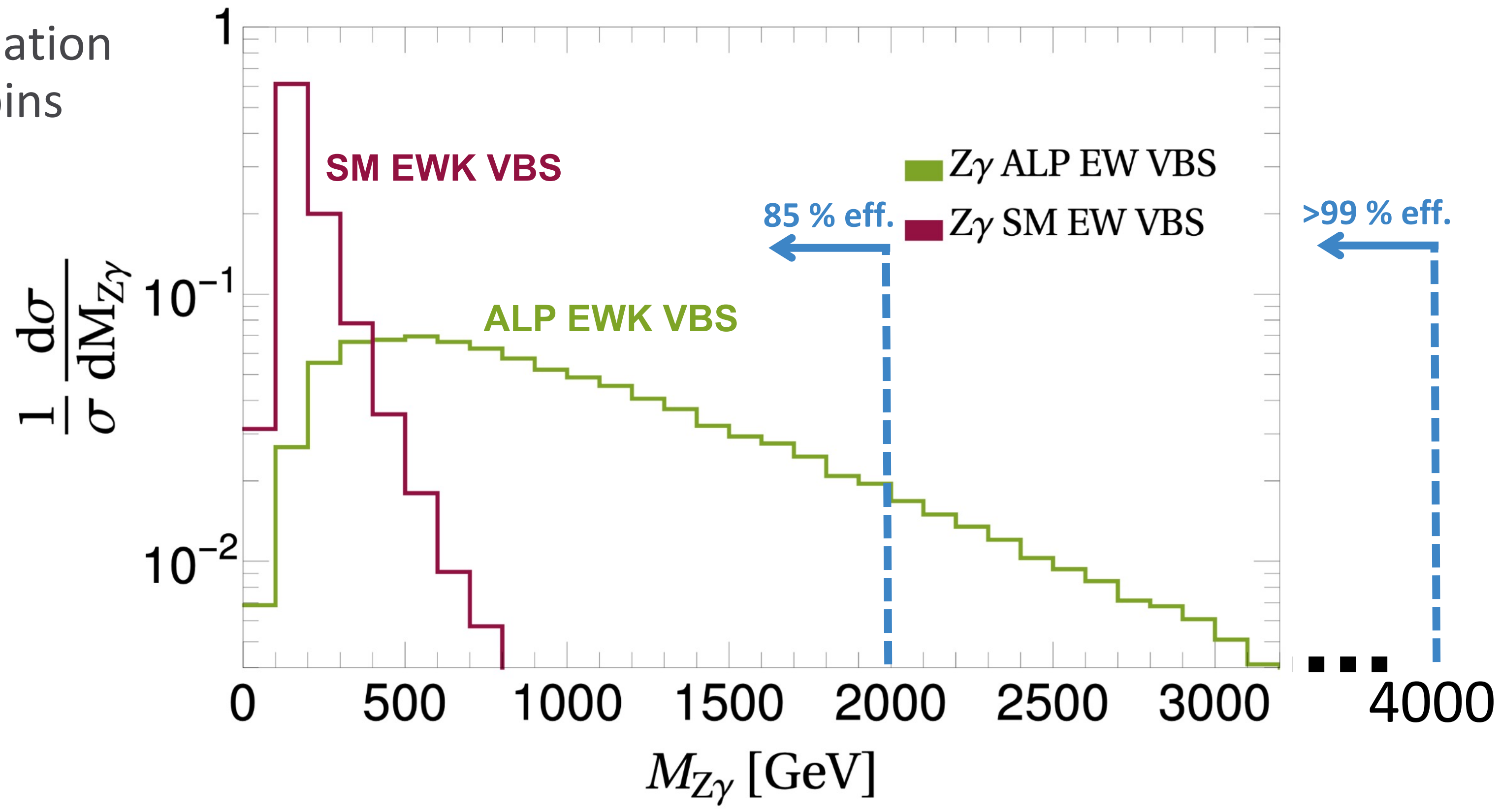


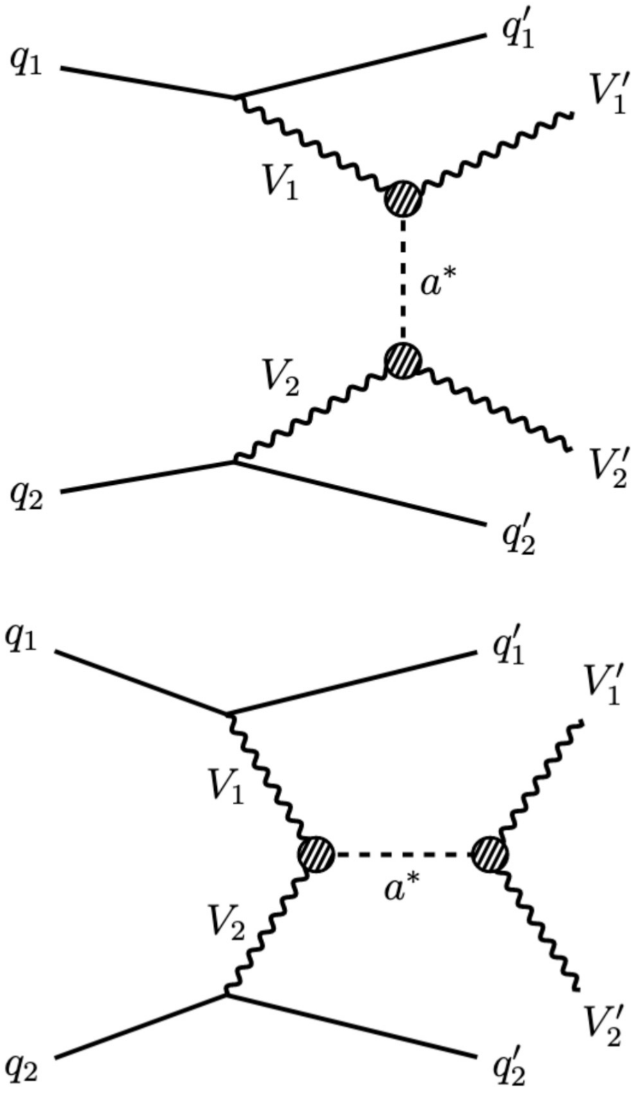
Contribution from gluons

- 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

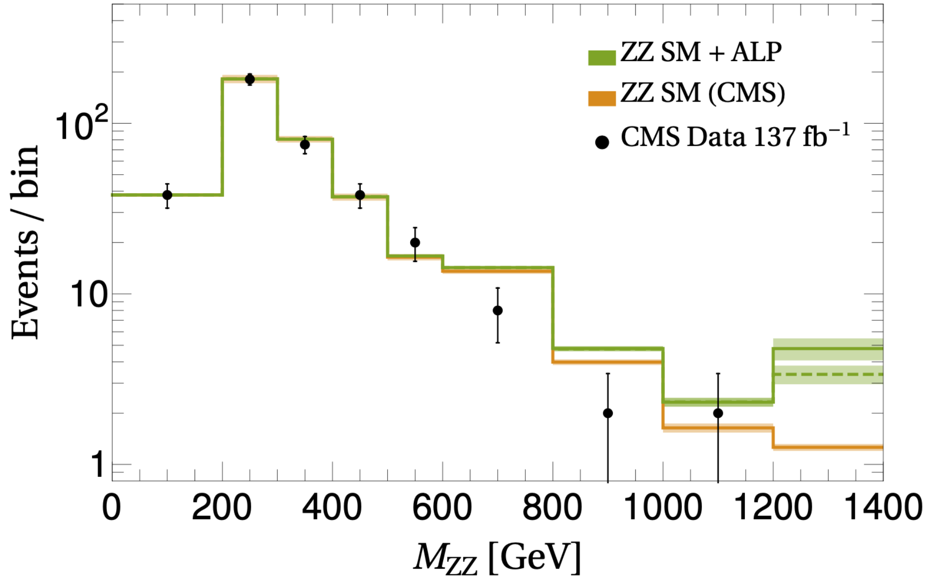
- For the tested region of the ALP parameter space, the theoretical prediction is dominated by ALP VBS

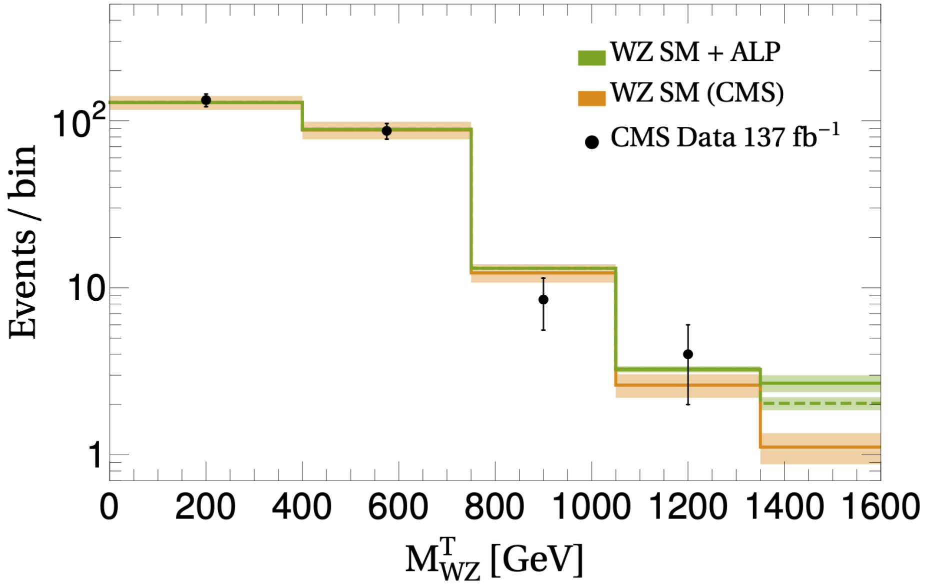
- Conservative: QCD ALP is positive with a subdominant contribution from its interference with EWK ALP

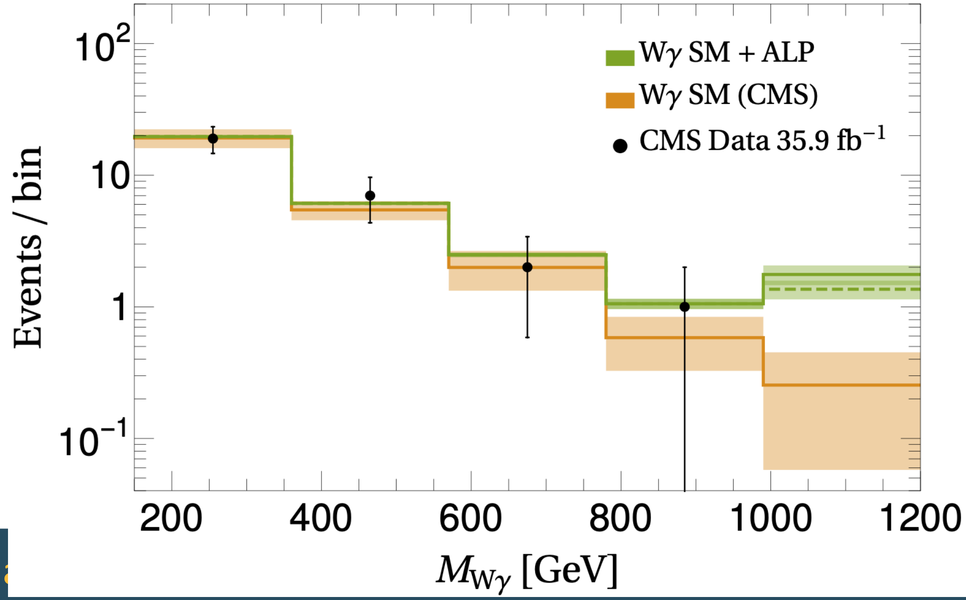


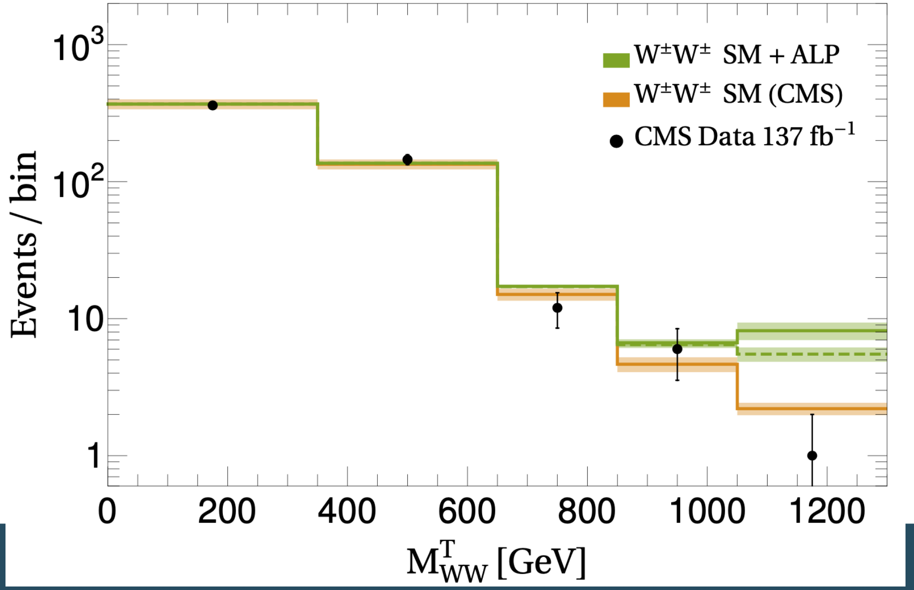
VBS $pp \to V_1V_2jj$ LO diagrams.

ALP Diboson Mass in CMS Leptonic Analyses









Results: comparison to existing bounds