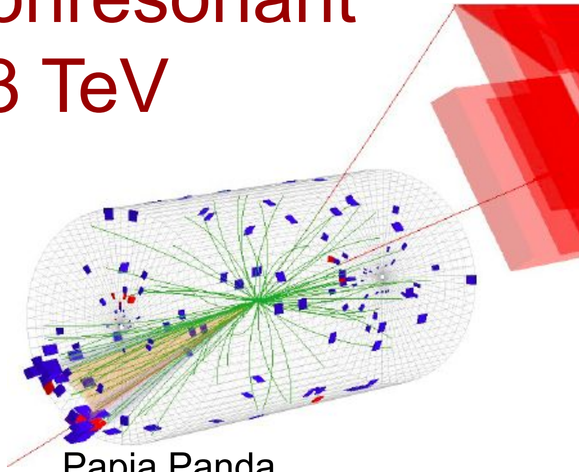
Search for heavy resonances decaying to ZZ or ZW and axion-like particles mediating nonresonant ZZ or ZH production at $\sqrt{s}$ = 13 TeV

JHEP 04 (2022) 087

The CMS Collaboration



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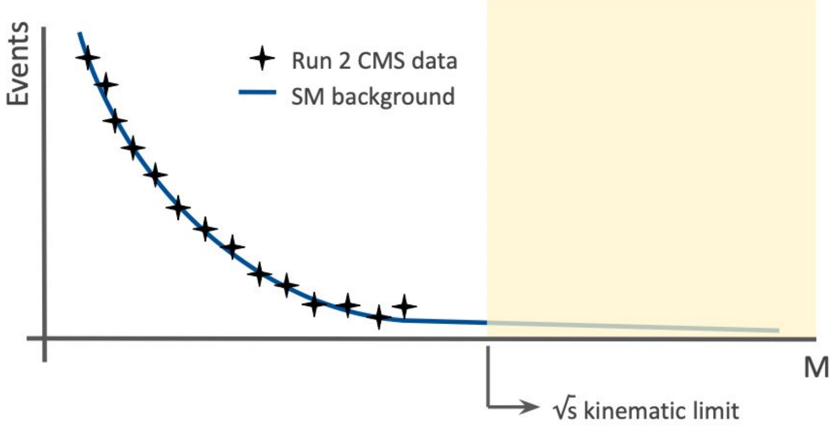
Introduction

- ➜ SM extensions predict additional heavy gauge bosons, or deviations in the variables of the *2l2q* system.
- ➜ Search for new physics in **diboson** ZZ / ZW / ZH events with **2 leptons and 2 quarks** final states.
- ➜ Using pp collision, at $\sqrt{s}$ = 13 TeV, Run 2 (L = 138 fb^{-1}) dataset recorded by CMS experiment.

Analysis strategy:

- ➜ Search from deviations w.r.t. the SM prediction.
- ➜ Discriminant variable: invariant mass of the 2l2j system.
- ➜ Both resonant and non-resonant deviations.
- ➜ If no deviation is found, upper limit on the σ will be set.



What's new?:

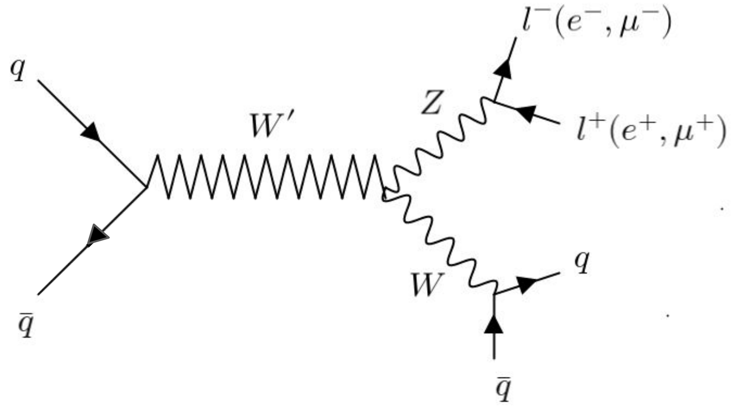
- ➜ First search for the Axion-Like Particles (ALP) mediated ZZ / ZH production at the LHC.

Models

➜ Resonant models:

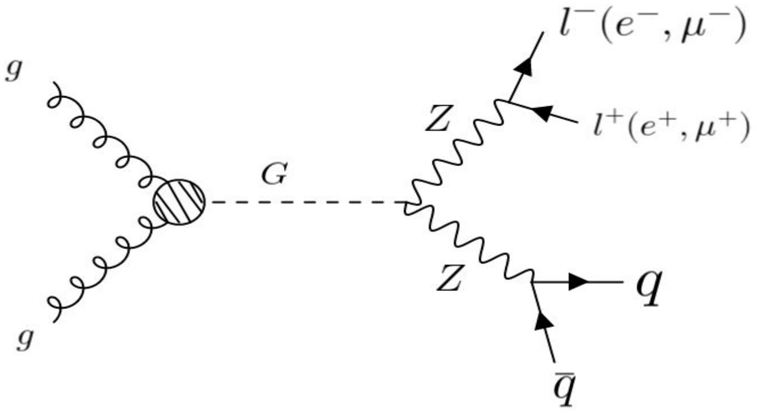
Heavy Vector Triplet (HVT) model

spin-1 : W'→ ZW



Warped Extra Dimensions (WED) model

spin-2, Graviton: G → ZZ



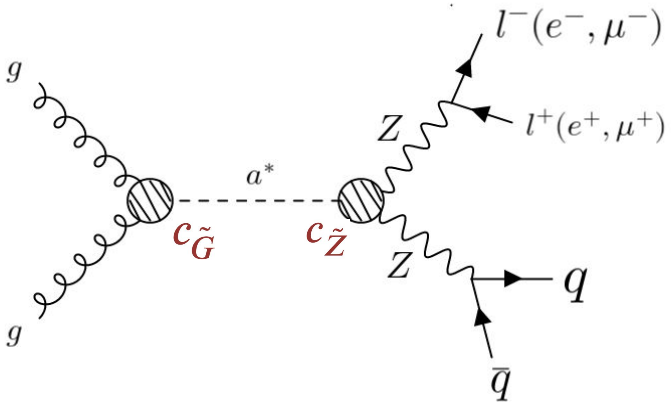
➜ Resonance mass range: [450, 2000] GeV

Models

➜ Non-resonant models: **axion-like particles (ALP)** neutral pseudo-scalar boson as mediators.

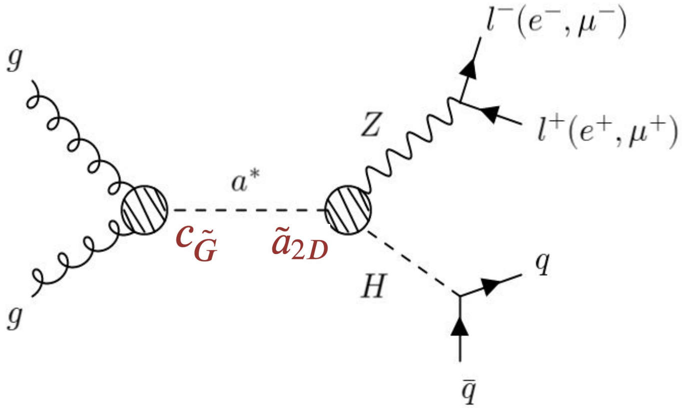
Linear model

a* → ZZ



Chiral model

a* → ZH



Sensitive to 2-dimensional parameter space: the couplings $|c_{\tilde{G}} c_{\tilde{Z}}|$ $|c_{\tilde{G}} \tilde{a}_{2D}|$ and the scale of new physics f_a.

Signal simulation

Simulated with Madgraph at LO

➜ **Gravitons (WED):** m(G) = 450 - 2000 GeV and curvature parameter κ of WED metric
Bulk graviton production cross sections, etc. are taken from [1404.0102]

➜ **W′ bosons (HVT):** m(W′) = 450 - 2000 GeV
W′ production cross sections, widths, branching fractions etc. are taken from [JHEP 2009 20(2014) 20060]

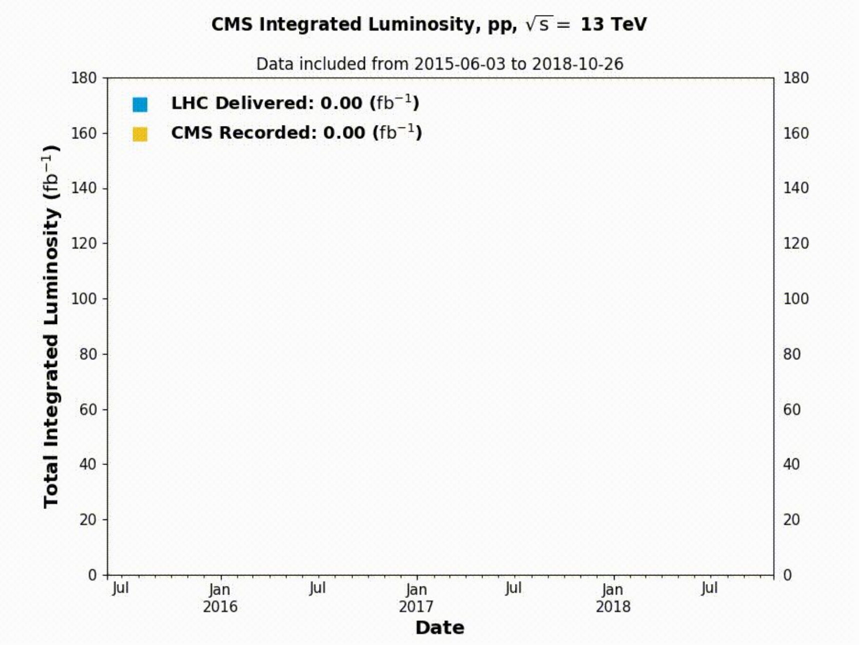
- Model A (gauge $SU_1(2) \times SU_2(2) \times U_Y(1)$) with coupling strength g_V=1
- Model B (minimal composite Higgs model SO(5)→SO(4)) with coupling strength g_V=3

➜ **ALPs (non-resonance):** m(a*) = 1 MeV, f_a (new physics energy scale), derivative coupling

- Linear EFT: $c_{\tilde{G}}/f_a = c_{\tilde{Z}}/f_a = 1\ \mathrm{TeV}^{-1}$ (coupling for a-g-g and a-Z-Z)
- Chiral EFT: $c_{\tilde{G}}/f_a = \tilde{a}_{2D}/f_a = 1\ \mathrm{TeV}^{-1}$ (coupling for a-g-g and a-Z-H)

Data and simulation

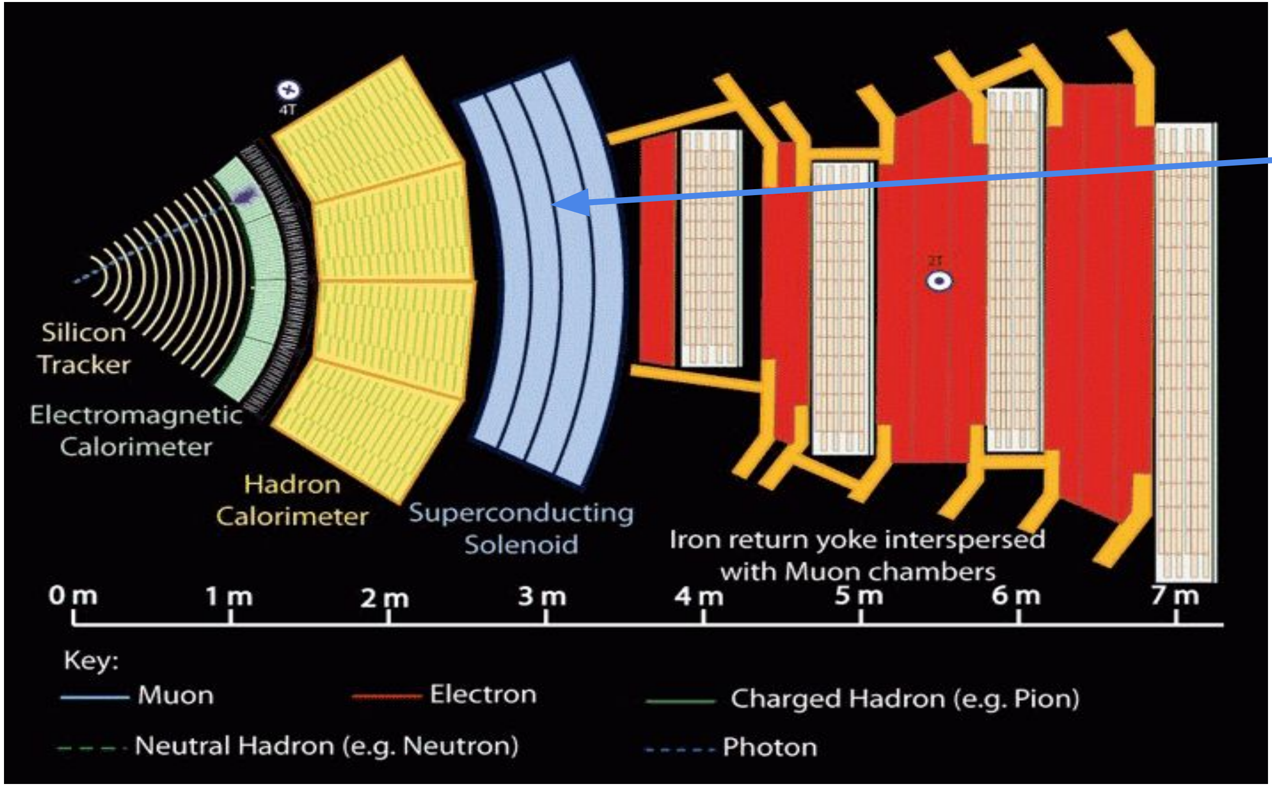
➜ **Data**: proton-proton collisions recorded by CMS during Run2 (2016-2018), L = 138 fb^{-1}



➜ **Simulation:**

- Madgraph simulator
  1. Z+jets at LO and NLO
  2. ZZ, ZW, ZH at NLO
  3. Signal at LO
- Parton showering and Hadronization: PYTHIA8
- PDF: NNPDF3.0 (2016) and NNPDF3.1 (2017, 2018, ALP)
- Detector simulation: GEANT4

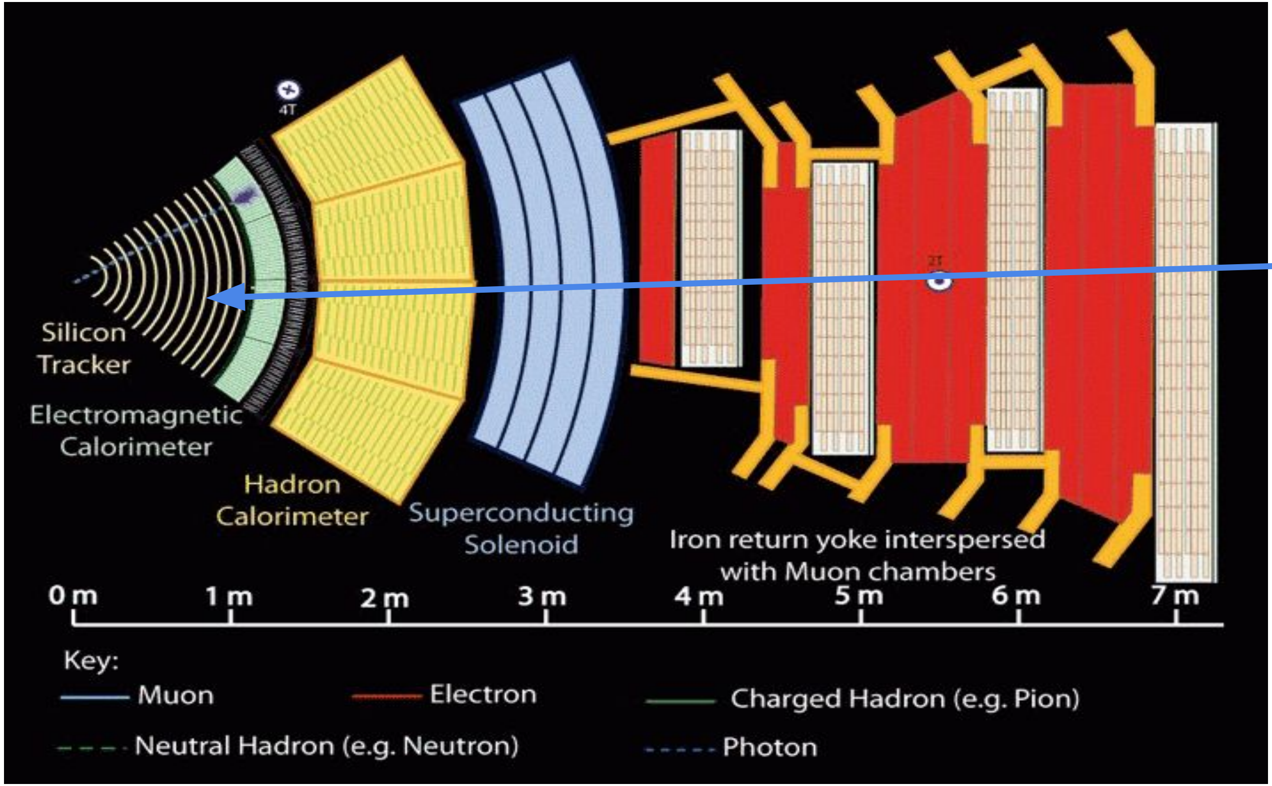
CMS detector



COMPONENTS OF THE DETECTOR

- ➜ **3.8T Solenoid Magnet**: bending particles
- ➜ **Silicon Tracker**: measurement of the momentum of charged particles
- ➜ **ECAL and HCAL**: Measurement of the energy for electron and hadrons
- ➜ **Muon Chambers** (DTs, CSCs, RPCs): measurement of the muon momentum

CMS detector



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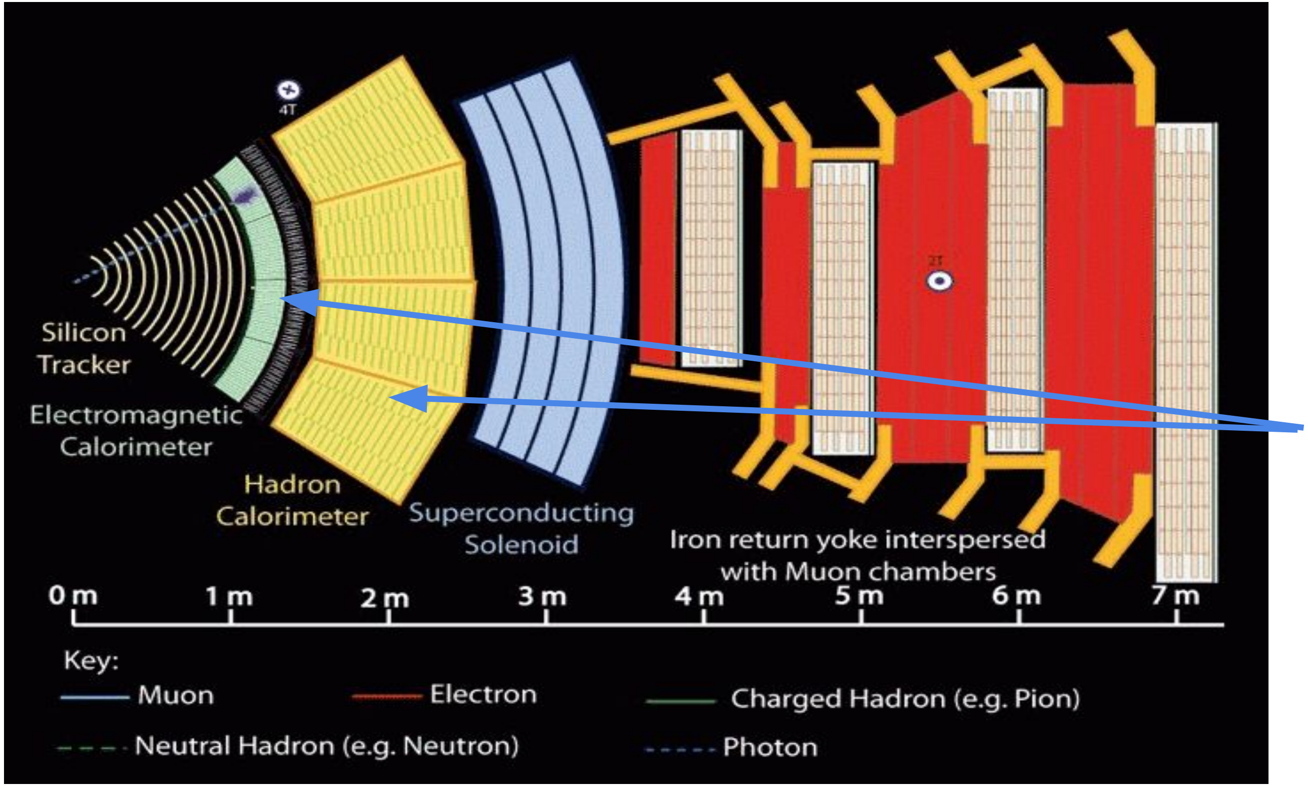

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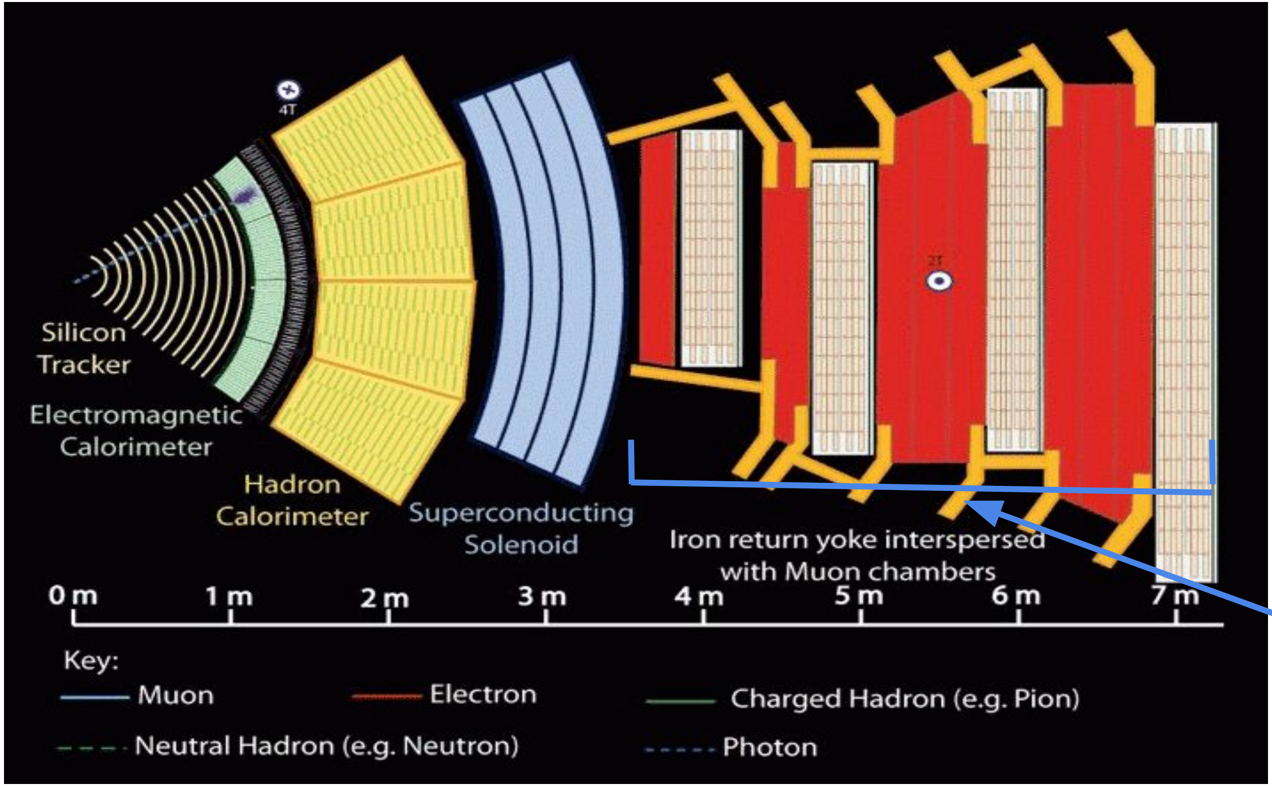

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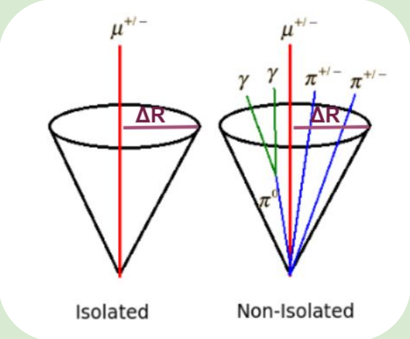
Reconstruction

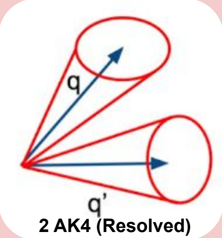
coverage: $|\eta| < 2.4$

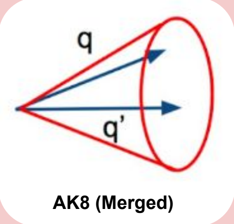
LEPTONS

	p_T resolution	Isolation
Electron	1.7 - 4.5%	$\Delta R = 0.3$
Muon	1 - 3% up to p_T = 100 GeV, < 7% up to p_T = 1 TeV	$\Delta R = 0.4$



JETS

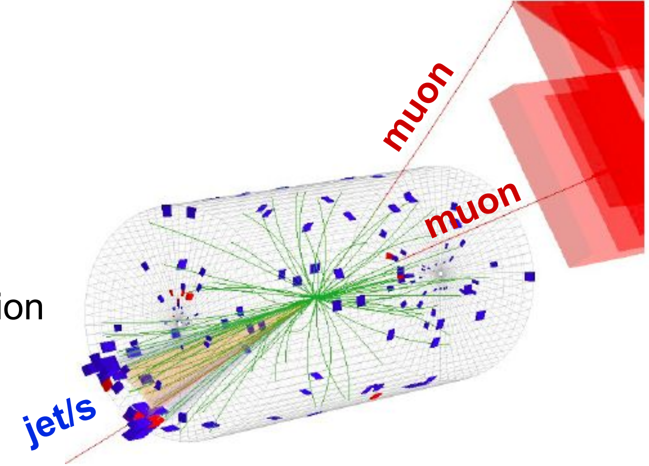




p_T resolution	Isolation from leptons	b-tagging
5-10%	$\Delta R > 0.8$ (0.4) for AK8 (AK4) jets	NN (DeepCSV) ➜ Loose (medium) ➜ 84 (64) % efficiency

- Anti-kT jet clustering
- Pileup rejection (PUPPI)
- Cleaning/grooming (softdrop)
- Quark/gluon AK8 jets rejected using subjettiness variable τ_{21}

Event Selection



➜ **Trigger selection:**

- Electron: [p_T > 27 (32) GeV for the 2016 (2017 and 2018) sample; tight identification] OR [electron p_T > 115 GeV; no isolation]
- Muon: p_T > 24 (27) GeV for 2016 and 2018 (2017); tight identification and loose isolation

➜ **Leptonic Z reconstruction:**

- p_T(l) > 40 GeV, p_T(ll) > 150 GeV (resolved) and p_T(ll) > 200 GeV (boosted), 76 < m(ll) < 106 GeV

➜ **Boosted W / Z / H [AK8(J)]:**

- p_T(ll) > 200 GeV; p_T(J) > 200 GeV
- m_{SD} (J) > 30 GeV
- τ_{21} < 0.40 (0.45) in 2016 (2017 and 2018)
- Tight ID

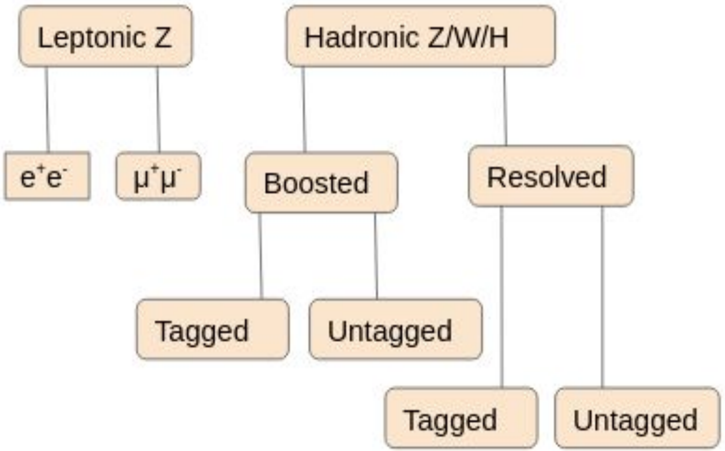
➜ **Resolved W / Z / H [AK4(j)]:**

- veto boosted
- dijet combination with m(jj) > 30 GeV
- p_T(ll) > 150 GeV, p_T(jj) > 150 GeV
- ΔR(jj) < 1.5; PU-beta > 0.2
- Tight ID

Event Categorization

To increase the sensitivity to the signal, events are split into **8 categories** by combining:

- ➜ electrons/muons
- ➜ boosted/resolved
- ➜ tagged/untagged



Each category is further split into **3 regions**:

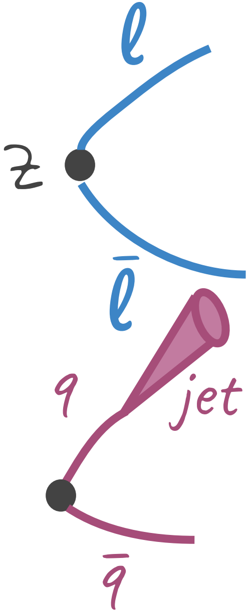
- ➜ SR1: signal region sensitive to ZV
- ➜ SR2: signal region sensitive to ZH
- ➜ SB: background enriched sideband region

	Boosted	**Resolved**
SR1	$65 < m_{SD}(J) < 105$ GeV	$65 < m(jj) < 110$ GeV
SR2	$95 < m_{SD}(J) < 135$ GeV	$95 < m(jj) < 135$ GeV
SB	$30 < m(jj) < 65$ GeV & $135 < m(jj) < 300$ GeV	$30 < m(jj) < 65$ GeV & $135 < m(jj) < 180$ GeV

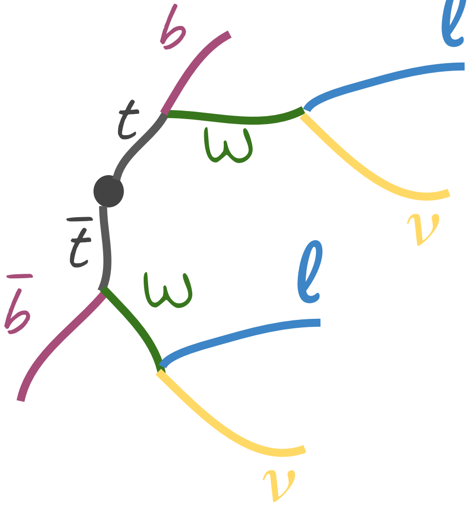
Background estimation

Background = processes whose final state is the same or can be mistaken as that of the signal (dilepton+dijet)

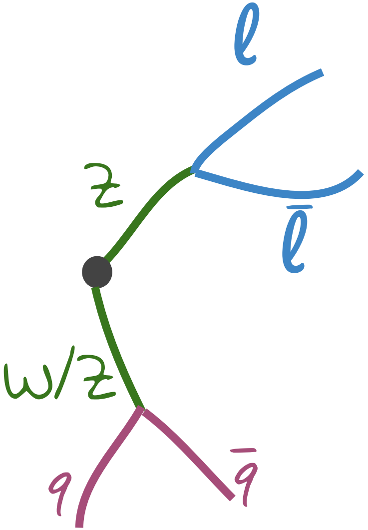
Z + jets



t + X



SM ZV



Background estimation

Z + jets (dominant)

➜ Linear fit of the m_{ZX} shape in each SB category to match MC to data within uncertainties:

$$\mathrm{corr}(\mathrm{m_{ZX}}, s) = 1 + s(\mathrm{m_{ZX}} - 500\,\mathrm{GeV})/(500\,\mathrm{GeV})$$

SM ZV: ZZ and ZW with Z→ll (3-20%)

➜ Estimated from MC simulation

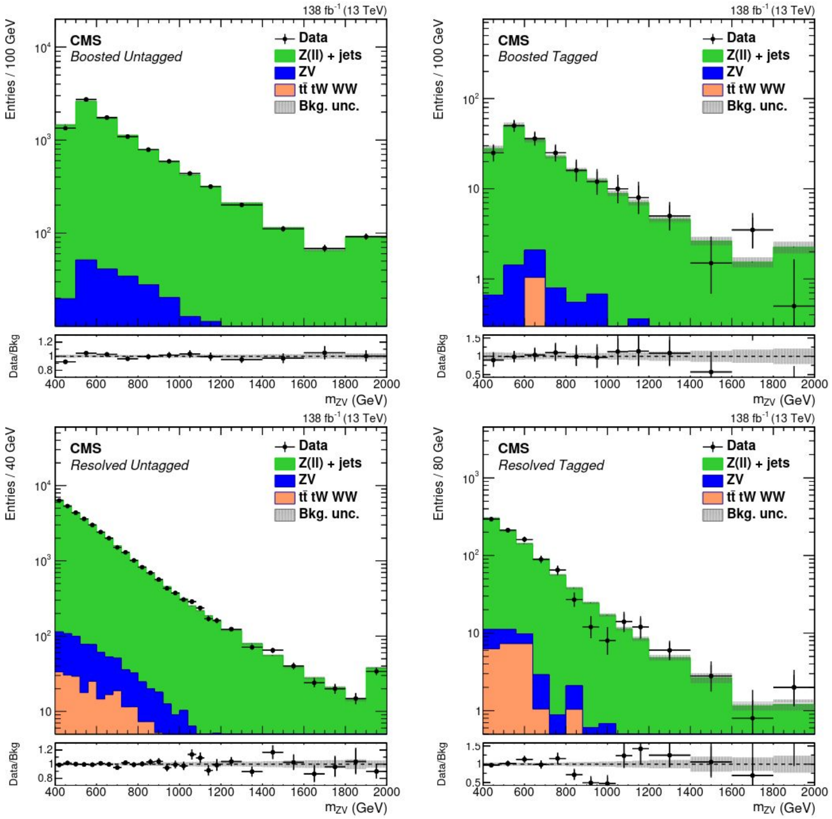
t + X: tt, tW, WW, Z→ττ, fakes (4%)

➜ Lepton flavor symmetric backgrounds determined from eμ data using a top quark-enriched control region

m_{ZV} distributions:

Untagged

Tagged



Boosted

Resolved

Systematics

The systematic uncertainties influence both the **normalization** and **shape** of the background and signal.

Dominant effect: background shape correction uncertainty.
Quantized by calculating the change on the fitted signal cross section when a given parameter is displaced by ±1 std from its post-fit value.

Fraction of signal σ total uncertainty (%)	Boosted		Resolved	
	Untagged	Tagged	Untagged	Tagged
Bulk graviton	11	13	3	3
ALP linear ZZ	42	42	16	16
ALP chiral ZH	9	44	7	23

Systematics:

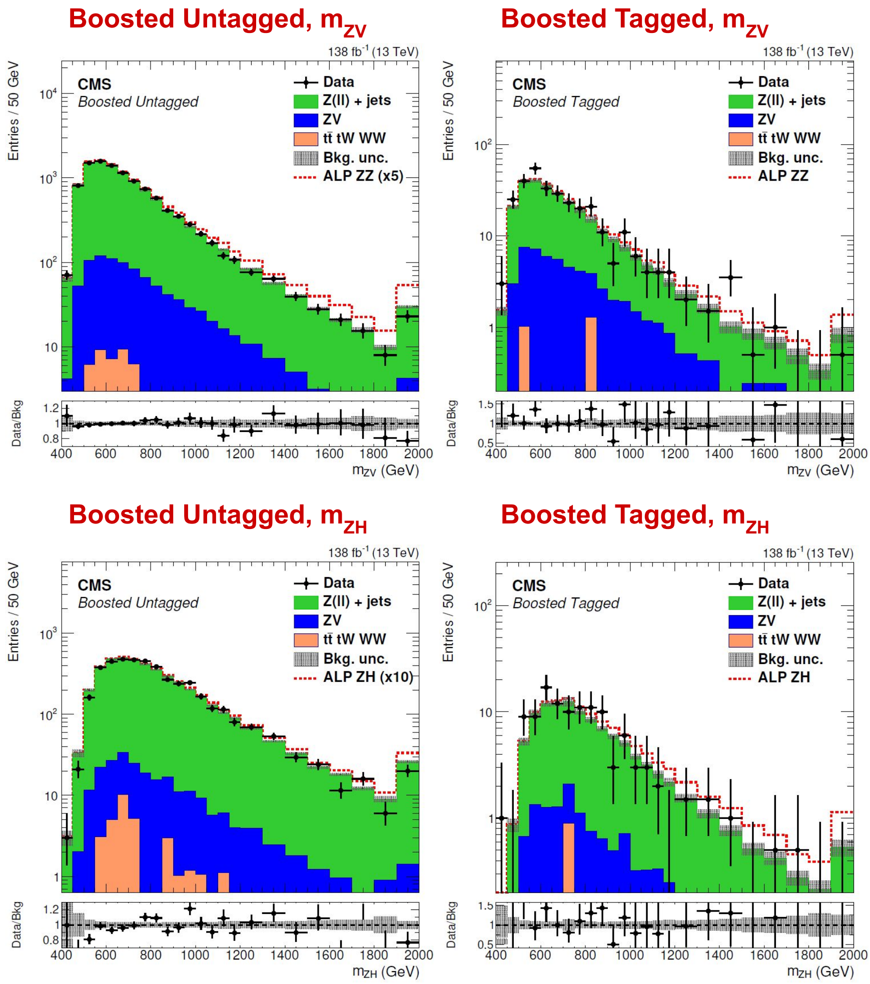
Background and signal **normalization** uncertainties (%)

Source	Boosted Background	Boosted Signal	Resolved Background	Resolved Signal
Integrated luminosity	1.8		1.8	
Electron trigger and ident.	2.0		2.0	
Muon trigger and ident.	1.5		1.5	
Electron energy scale	0.8	<0.1–0.2	0.9	<0.1
Muon momentum scale	0.5	<0.1–0.1	0.6	<0.1
Jet energy scale	1.0	<0.1–0.1	2.8	0.1–1.9
Jet energy resolution	0.3	<0.1–0.3	0.3	1.0
V/H identification (τ_{21})	5 (ZV)	5	—	—
V/H identification (extrap.)	—	2.6–6.0	—	—
V/H mass scale	0.6 (ZV)	0.4–0.8	—	—
V/H mass resolution	5.0 (ZV)	5.0–6.0	—	—
b tag SF, untagged	0.1	1.0–7.4	0.1	0.7–2.2
b tag SF, tagged	12	12	3.6	4
Mistag SF, untagged	0.3	<0.1–0.2	0.2	0.1
Mistag SF, tagged	3.5	0.1–0.3	3.8	0.4–1.0
SM ZV production	12	—	12	—
t + X normalization	4 ($e\mu$)	—	4 ($e\mu$)	—
SR-to-SB norm. ratio	3 (Z + jets)	—	5 (Z + jets)	—
PDFs	—	1.5–1.6	—	0.3–1.1
Renorm. and fact. scales	—	0.1–0.3	—	0.2–0.3
Pileup	0.5	0.1–0.2	0.1	0.1–0.2
MC statistics, untagged	0.3	0.7	0.2	1
MC statistics, tagged	2	1.5	1.5	2
Total, untagged	4	8–13	6	3–4
Total, tagged	13	14–16	8	5–6

Fitting procedure

* Signal selection efficiency: 30~40 %

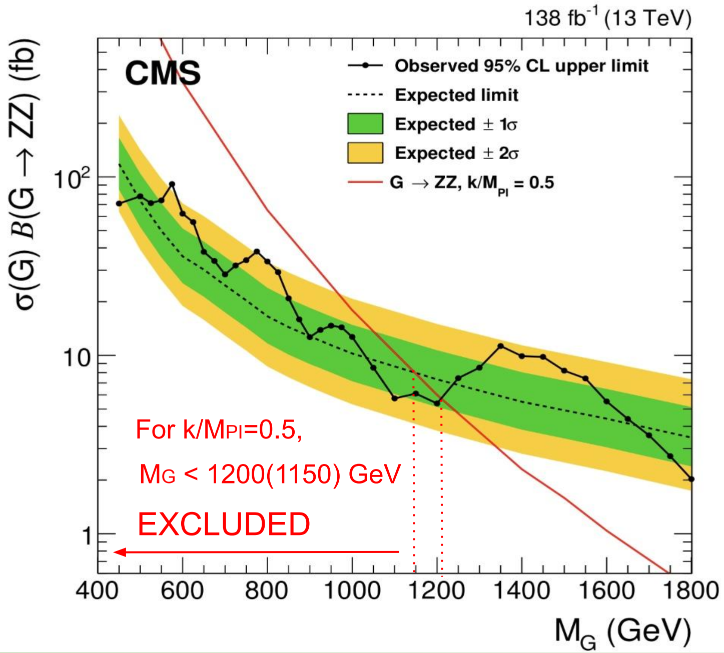
- ➜ Maximum-likelihood fit to m_{ZV} / m_{ZH} distributions for electrons / muons, boosted / resolved, tagged / untagged categories in SR (SR1 for m_{ZV} , SR2 for m_{ZH}) + SB simultaneously.
- ➜ The background-only hypothesis is tested against the signal + background hypothesis.
- ➜ Systematic and MC statistical uncertainties included as nuisance parameters in the fit.
- ➜ Z+jets normalizations and shape corrections float in the fit, independently for each categories.
- ➜ In the ALP fits, for given value of the f_a scale, events with m_{ZV} or m_{ZH} > f_a are excluded from the fit.



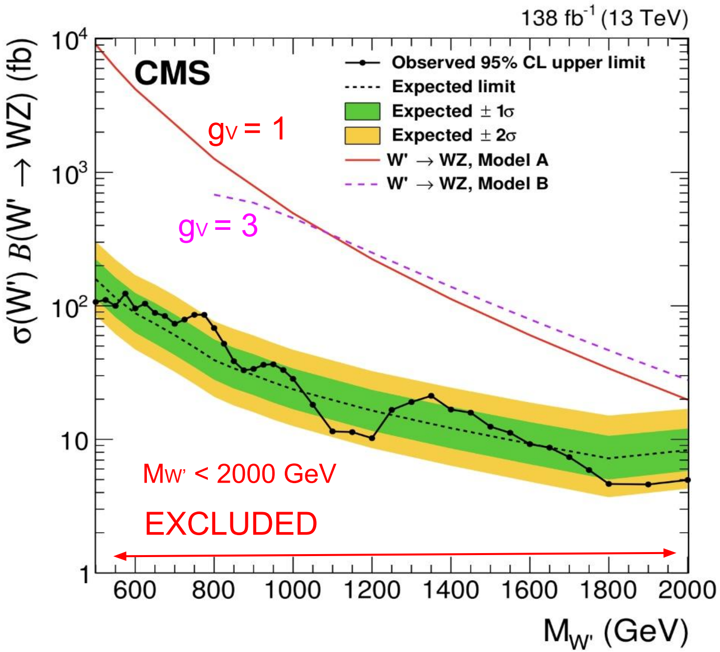
Results: G and W′

- No significant excess was observed wrt the SM prediction.
- Upper limits on the production cross section times the branching ratio as a function of the resonance mass is computed, at 95% confidence level.

Graviton bulk G → ZZ



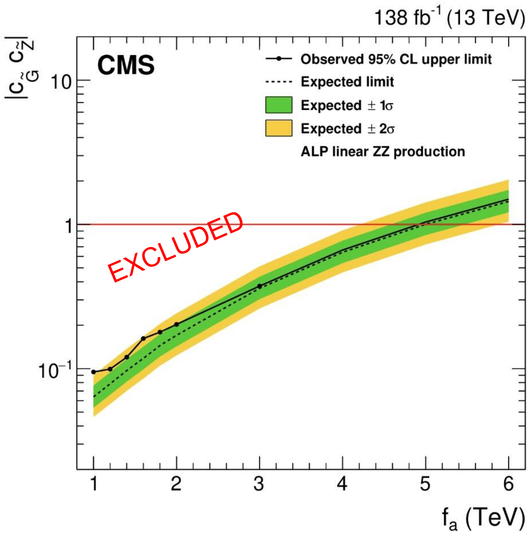
HVT: W′ → WZ



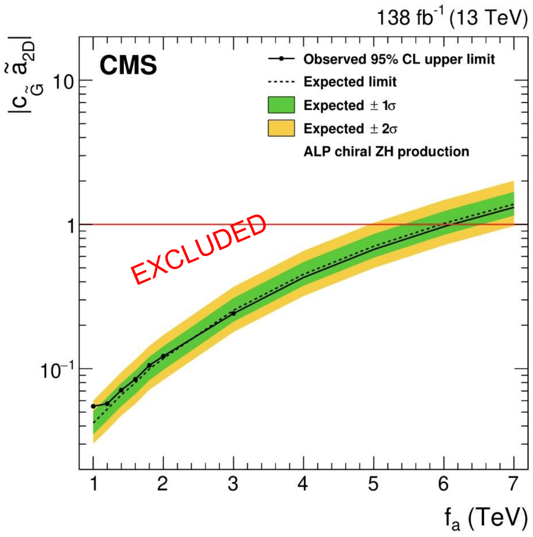
Results: ALP

- No significant excess was observed.
- Upper limits on the coupling strengths as a function of f_a is computed, at 95% CL for m_a < 100 GeV.

$a^* \rightarrow ZZ$



$a^* \rightarrow ZH$



- Upper limits on σ(gg → a* → ZZ/ZH) at 95% CL for f_a = 3 TeV.

Model (fb)	Expected -2σ	Expected -1σ	Expected Median	Expected $+1\sigma$	Expected $+2\sigma$	Observed
ALP linear ZZ	79	107	151	218	304	162
ALP chiral ZH	32	39	64	94	134	57

Summary

➜ The work presents a search of new physics processes in the 2l2j final states.

- Resonances: heavy new resonances W′ and G decaying to ZZ / ZW dibosons.
- Non-resonant ZZ or ZH production mediated by axion-like particles (ALPs).
- The search is sensitive to the mass range of (450-2000) GeV.

➜ No significant excess is observed in the data above the standard model expectations.

➜ Upper limits at 95 % CL:

- Graviton: σ(G) x *B*(G → ZZ) < (2-90) fb. Masses below 1200 GeV were excluded.
- W′ boson: σ(W′) x *B*(W′ → ZW) < (5-120) fb. Masses below 2000 GeV were excluded.
- Production of ZZ (ZH) mediated by non-resonant ALP: σ < 162 (57) fb.
- Constrain on the couplings, $|c_{\tilde{G}} c_{\tilde{Z}}|$ and $|c_{\tilde{G}} \tilde{a}_{2D}|$ vs the scale f_a.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THANK YOU!

BACKUP

Data and Simulation (detail list of simulation program)

2016-2018 LHC dataset

	Signal simulation w/ Madgraph	Parton showering and hadronization w/ PYTHIA	PDFs of colliding protons w/
Graviton, W'	LO	v8226 CUETP8M1(2016) v8230 CP5 (2017, 2018)	NNPDF30(2016) NNPDF31(2017, 2018)
ALPs	LO	v8230 CUETP8M1	NNPDF31
SM->Z(ll) jets	2016 (NLO) 2017, 2018 (LO) reweight	v8226 CUETP8M1(2016) v8230 CP5 (2017, 2018)	NNPDF30(2016) NNPDF31(2017, 2018)
SM->ZZ, ZW, ZH	NLO		

*All sample are processed via simulation of CMS detector using GEANT4

ALPs theory

PhysRevLett.124.051802 & Eur. Phys. J. C (2017) 77:572

Considering Model

-Pseudo Nambu-Goldstone boson of SSB at f_a

-Neglect small interactions between axions and fermions

- $g_{agg} \lesssim 1.1 \times 10^{-5}\,\mathrm{GeV}^{-1}$ (90% CL) for $m_a \lesssim 60\,\mathrm{MeV}$

-No information for axion-Z-Z bound

NLO

$$\delta\mathcal{L}_{\text{eff}} \supset -\frac{g_{agg}}{4} aG_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{g_{a\gamma\gamma}}{4} aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{aZ\gamma}}{4} aF_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} aZ_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} aW_{\mu\nu}\tilde{W}^{\mu\nu},$$

where

$$g_{agg} = \frac{4}{f_a} c_{\tilde{G}}, \qquad g_{a\gamma\gamma} = \frac{4}{f_a}(s_w^2 c_{\tilde{W}} + c_w^2 c_{\tilde{B}}),$$

$$g_{aWW} = \frac{4}{f_a} c_{\tilde{W}}, \qquad g_{aZZ} = \frac{4}{f_a}\underbrace{(c_w^2 c_{\tilde{W}} + s_w^2 c_{\tilde{B}})}_{c_{\tilde{Z}}},$$

$$g_{a\gamma Z} = \frac{8}{f_a} s_w c_w (c_{\tilde{W}} - c_{\tilde{B}}),$$

Linear EFT

Linear expansions of gauge invariant operators built on the SM field -> *NLO are listed in the box*

Chiral EFT

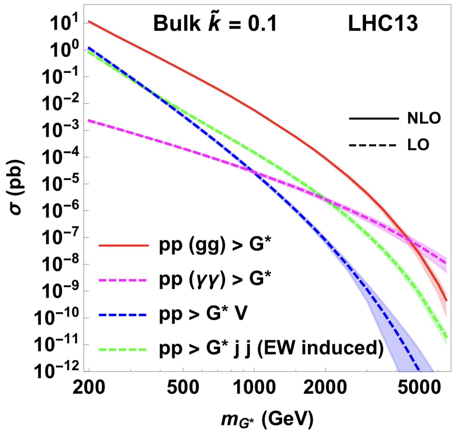
The Higgs field is realized by (1) $U=e^{i\sigma\pi/v}$ (π are longitudinal components of gauge fields *W, B)* & (2) higgs *h* -> construct invariant lagrangian -> *a-H-Z coupling appears at LO and those listed in the box at NLO*

Gravitons theory

Considering Model

- Gravition couples SM particles through Energy momentum tensor
- Two model parameters (m_G, k)

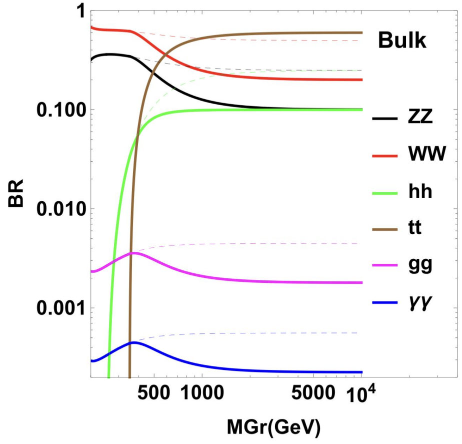
$$\mathcal{L} = -\frac{x_1 \tilde{k}}{m_G} h^{\mu\nu(1)} \times d_i T^i_{\mu\nu}$$



Massless Boson coupling

$$\sigma^{(gg/\gamma\gamma)}_{bulk}[m_{G^*}, \tilde{k}] = \left(\frac{d_g(m_{G^*}, \tilde{k})}{d_g(m_{G^*}, \tilde{k} = 0.1)} \times \frac{\tilde{k}}{0.1} \right)^2 \sigma^{(gg/\gamma\gamma)}_{bulk}[m_{G^*}, \tilde{k} = 0.1] \,.$$

$$d_g = \frac{2}{k \pi r_c} \frac{(1 - J_0(x_1))}{x_1^2 |J_2(x_1)|}$$



W′ theory

- W′ (BSM candidate) is based on "HVT" model.
  a. Model A: **Extended gauge symmetry:**
     - Gauge symmetry: $SU_1(2) \times SU_2(2) \times U_Y(1)$
     - SM H transforms as (2,1,½)
     - Additional field φ transforms as (2,2,0)
     - φ get vev after SSB and gauge symmetry breaks as $SU_L(2) \times U_Y(1)$
     - Couplings present is this model: c_H= coupling between SM vector bosons and Higgs, c_F: coupling between fermions, g_V: interaction of W' with SM fermions(=1).

  b. Model B: **MCHM (Minimal composite Higgs model):**
     - Higgs generates mass via symmetry breaking of SO(5) to SO(4)
     - Additional field ρ_μ transforms as (3,1) under SO(4)
     - g_V: interaction of W′ with SM fermions(=3)

W′ theory

Considering Model

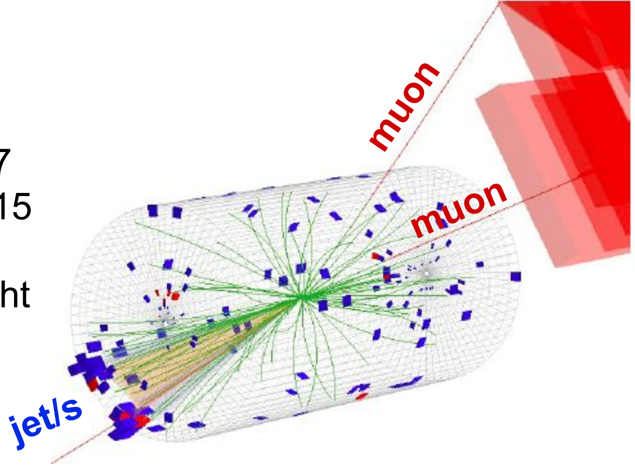
- Additional real vector V embedding W′ and Z′

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\, a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\, a}$$
$$+ i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\, a}_F$$
$$+ \frac{g_V}{2} c_{VVV} \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu} V^{\nu]c} + g_V^2 c_{VVHH} V^a_\mu V^{\mu\, a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\, a} V^b_\mu V^c_\nu \,. \qquad (2.2)$$

Event Selection

➜ **Trigger selection:**

- Electron: One electron with p_T > 27 (32) GeV and for the 2016 (2017 and 2018); passing tight identification and isolation ; electron p_T > 115 GeV; no isolation
- Muon: p_T > 24 (27) GeV and |η| < 2.4 for 2016 and 2018 (2017); tight identification and loose isolation



➜ **Leptonic Z reconstruction:**

- Two electron or two muon with opposite charge
- Leading and subleading p_T(l) > 40 GeV, p_T(ll) > 150 GeV (resolved) and p_T> 200 GeV(boosted), 76 < m(ll) < 106 GeV

➜ **Boosted W/Z/H Tagging [AK8(J)]:**

- p_T(ll) > 200 GeV; p_T(J) > 200 GeV
- PUPPI softdrop mass m_{SD} (J) > 30 GeV
- PUPPI τ_{21} HP cut
- Tight ID

➜ **Resolved [AK4(j)]:**

- veto boosted
- dijet combination with m(jj) > 30 GeV
- p_T(ll) > 150 GeV, p_T(jj) > 150 GeV
- ΔR(jj) < 1.5; PU-beta > 0.2
- Tight ID

B-Tagging Categorization of events based on DeepCSV Tagged: 1 Medium and 1 Loose tag.

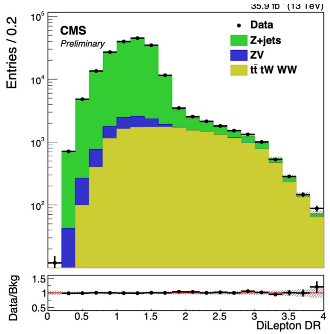
Background Estimation (t+X)

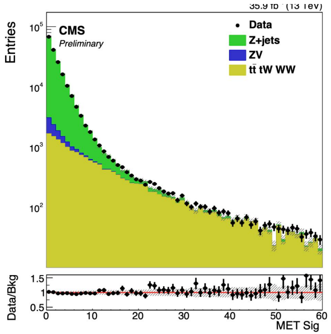
Data driven background

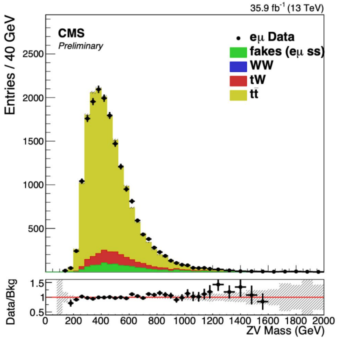
- Data driven background from eμ data

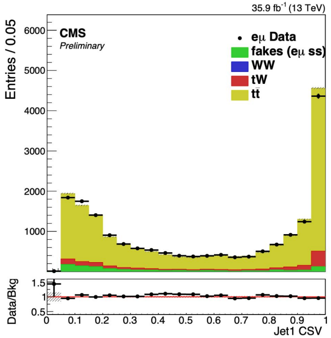
- Leptonic Z cut loosened (m(ll) > 50 GeV) to enhance the t+X background
  - Good agreement between the data and the estimation of the non-Z decay background

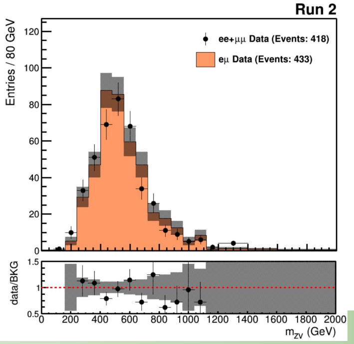
- Tested in the top quark-enriched control region: MET significance > 6, |m(ll) - m(Z)| > 10 GeV, 1 medium DeepCSV tag



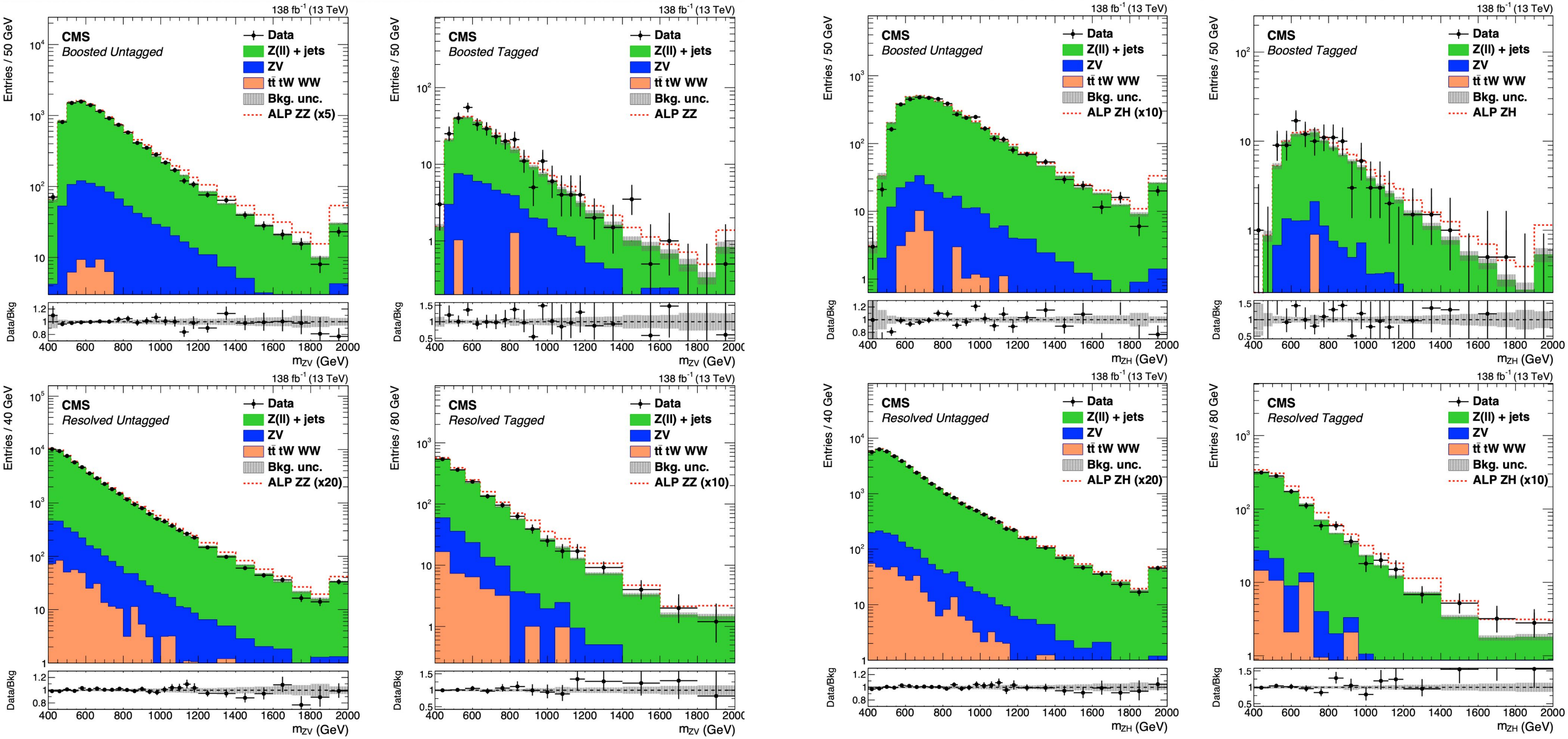








Results



SR1

SR2

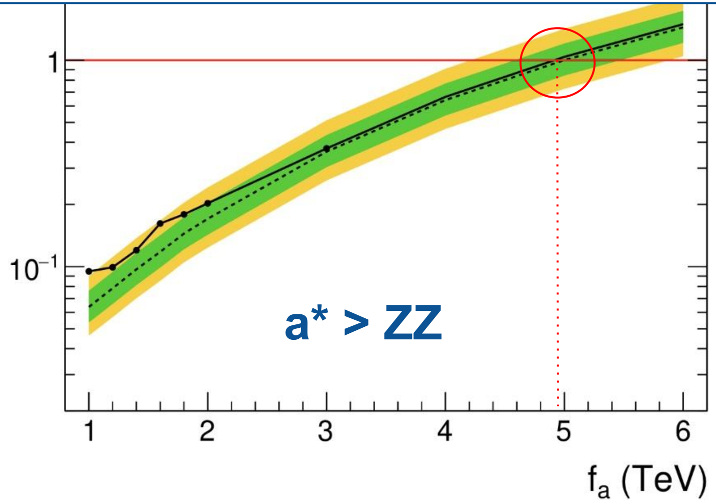
Results: Examples of ALP coupling coefficients

Example

$$|C_{\tilde{G}} C_{\tilde{Z}}| = 1 \quad \& \quad f_a \sim 4.9 \text{ TeV}$$

$$|C_{\tilde{G}} C_{\tilde{Z}}| / f_a^2 \sim 0.0415(0.0400) \text{ TeV}^{-2}$$

$$|C_{\tilde{G}}| / f_a = |C_{\tilde{Z}}| / f_a = 0.204(0.200) \text{ TeV}^{-1}$$

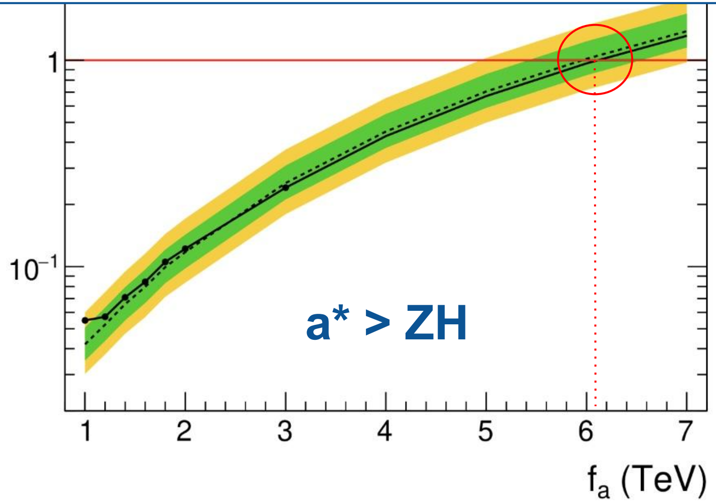


Example

$$|C_{\tilde{G}} \tilde{a}_{2D}| = 1 \quad \& \quad f_a \sim 6.1 \text{ TeV}$$

$$|C_{\tilde{G}} \tilde{a}_{2D}| / f_a^2 \sim 0.0269(0.0281) \text{ TeV}^{-2}$$

$$|C_{\tilde{G}}| / f_a = |\tilde{a}_{2D}| / f_a = 0.164(0.168) \text{ TeV}^{-1}$$



Comparison with other heavy resonances measurements

- CMS Collaboration, “Search for a heavy resonance decaying into a Z boson and a Z or W at $\sqrt{s}$ = 13 TeV”, *JHEP* **09** (2018) 101

Upper limit	CMS 36.5 fb^{-1}	**CMS 139 fb^{-1} (our result)**
$\sigma(G) \times B(G \to ZZ)$	(1.5-400) fb	(2-90) fb
$\sigma(W') \times B(W' \to ZW)$	(3-3000) fb	(5-120) fb

This analysis importantly benefits from the increase in the amount of data collected.

- ATLAS Collaboration, “Search for heavy resonances decaying into a pair of Z bosons in the $l^+l^-l'^+l'^-$ and $l^+l^-\nu\bar{\nu}$ final states using 139 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector”, *Eur. Phys. J. C* **81** (2021) 332

Mass exclusion range	ATLAS (fully leptonic final state)	**CMS 139 fb^{-1} (our result)**
M_G	< 1800 GeV	< 1200 GeV

Fully leptonic final states seem to provide stronger exclusion limits.