Improved constraints on the heavy gauge bosons decaying into a vector boson and a Higgs boson at the LHC

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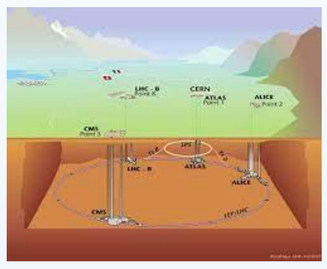


Abstract

The full CMS and ATLAS Run 2 datasets with time-integrated luminosity of 137/fb and 139/fb in the diboson channels are used to probe benchmark models with extended gauge sectors such as left-right symmetric (LR) and the sequential standard model (extended gauge model, EGM), that predict the existence of neutral Z - and charged W - bosons decaying to a pair of bosons ZH and WH in the semileptonic final state. These benchmark models are used to interpret the results. Exclusion limits at the 95\% C.L. on the and resonance production cross section times branching ratio to electroweak gauge boson pairs in the resonance mass range between 1.0 and TeV are here converted to constraints on Z-Z and W-W mixing parameters and masses. We present exclusion regions on the parameter spaces of the and and show that the obtained exclusion regions are significantly extended compared to thosederived from the previous analysis performed with Tevatron data as well as with the CMS and ATLAS data collected at 7 and 8 TeV in Run1. The reported limits are the most restrictive to date.

Introduction

Preamble

- In 2009 LHC era started
- Main goals of LHC:
  - Search for Higgs boson, check of the Standard Model, etc.
  - Search for New Physics effects:
    SUSY, **Z'**, **W'**, Extra Dimensions, LQ, heavy Higgs-like scalars, …
- From 2009 to 2021, LHC operated
  - in Run 1 data taking (2011/12), E_{CM}=7/8 TeV, L_{int}=30/fb
  - in Run 2 data taking (2015/18), E_{CM}=13 TeV, L_{int}=140/fb

  Nothing new (beyond the SM) was discovered so far.

  Searching for new physics **will go on**
  - in Run 3 data taking (2021/23), E_{CM}=14 TeV, L_{int}=300/fb
  - in HL-LHC option (2026/36-??), E_{CM}=14 TeV, L_{int}=3000/fb

Here: focus on

- "Classical" models of ***Z'(W')***–bosons with extended gauge sector (SSM, E6, LR, ALR)
- DY as a principal ***Z'(W')*** discovery channel:

$$pp \to Z'(W') \to l^+l^-(l\nu) + X \quad (l = e, \mu)$$

- Study the potential of the LHC to observe of ***Z-Z' (W-W')*** mixing effects

in

$$pp \to Z'(W') \to W^+W^-(WZ) + X$$
$$pp \to Z'(W') \to ZH(WH) + X$$

(i) extension of previous analysis of ATLAS data collected at 36.1/fb (reported in 2019)

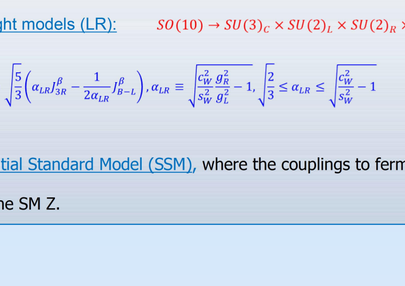
(ii) quantify Z-Z' (W-W') mixing angles using ATLAS and CMS **Run2** data taking (139/fb, 140/fb)

Comparison with current limits: LHC Run2 vs Tevatron, LHC Run1 and EW data

Z' boson

Current limits on Z' mass from LHC @13 TeV in Run 2:
M > 4 – 5.1 TeV (depending on a model)

Z-Z' mixing angle (mostly from LEP1 and SLC):



Search for diboson resonances

Direct searches for a heavy W^+W^-, WZ, ZH, WH resonances:

- **Tevatron with CDF** and **D0** collaborations
- **LHC with ATLAS and CMS** collaborations at collider energies of 7-8 TeV (**Run I**) and 13 TeV (**Run II**)

Models of Z'-bosons:

The list of ***Z'***-models that will be considered in our analysis is the following:

1) E_6 models: $E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$

$$Z'(\beta) = \chi \cos\beta + \psi \sin\beta$$

three popular possible U(1) Z' scenarios originating from the exceptional group E_6 breaking:

$\chi - \text{model}\ (\cos\beta = 1); \psi - \text{model}\ (\cos\beta = 0); \eta - \text{model}\ (\tan\beta = -\sqrt{\frac{5}{3}})$

2) Left-Right models (LR): $SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$J^\beta_{LR} = \sqrt{\frac{5}{3}}\left(\alpha_{LR} J^\beta_{3R} - \frac{1}{2\alpha_{LR}} J^\beta_{B-L}\right), \alpha_{LR} \equiv \sqrt{\frac{c^2_W g^2_R}{s^2_W g^2_L} - 1}, \sqrt{\frac{2}{3}} \le \alpha_{LR} \le \sqrt{\frac{c^2_W}{s^2_W} - 1}$$

3) Sequential Standard Model (SSM), where the couplings to fermions are the same as those of the SM Z.

V-V' mixing

I.A. Serenkova, P. Osland and A. A. Pankov
Phys.Rev.D 2019, 2021; Eur.Phys.C 2020

In present analysis, we **follow parametrization** used by CDF collaboration (PRL2010) in interpretation of diboson production data:

two free parameters: $\xi_{Z-Z'}$ and $M_{Z'}$.

Note: in extended models it corresponds to assumption that all SU(2) breaking is due to Higgs doublets and singlets, where ρ_0=1, but with no U(1)' assignments of the Higgs fields (see, e.g. Langacker 2009).

Z-Z'-mixing

The mass eigenstates Z and Z' are admixtures of the weak eigenstates Z^0 of $SU(2) \times U(1)$ and $Z^{0\prime}$ of the extra $U(1)'$, respectively:

$$Z = Z^0 \cos\phi + Z^{0\prime} \sin\phi,$$
$$Z' = -Z^0 \sin\phi + Z^{0\prime} \cos\phi.$$

$$\tan^2\phi = \frac{M^2_{Z^0} - M^2_Z}{M^2_{Z'} - M^2_{Z^0}} \simeq \frac{2M_{Z^0}\Delta M}{M^2_{Z'}},$$

$\Delta M = M_{Z^0} - M_Z > 0$ mass shift due to Z-Z' mixing; $M_{Z^0} = \frac{M_W}{\sqrt{\rho_0}\cos\theta_W}$

Hadron production and decay of Z' and W' bosons

Z' production and decay at parton level

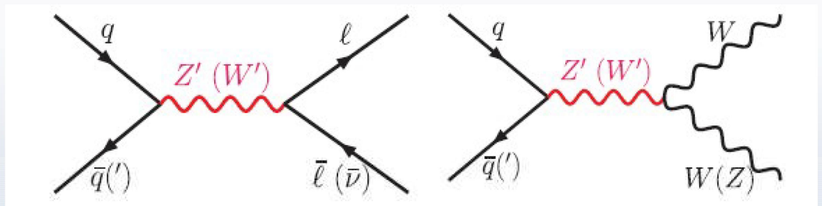


FIG. 1. Parton-level Feynman diagrams for Z' (W') production with dilepton and diboson decays.

EGM W' bosons

$$pp \to W'X \to WZX.$$

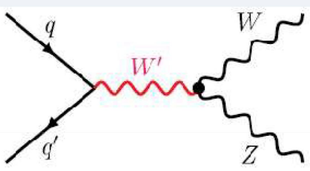
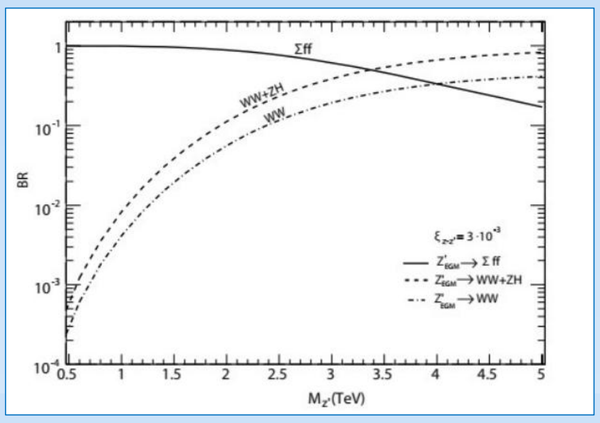


FIG. 2. Lowest-order Feynman diagram for the W' boson production and decay to the diboson WZ final state.

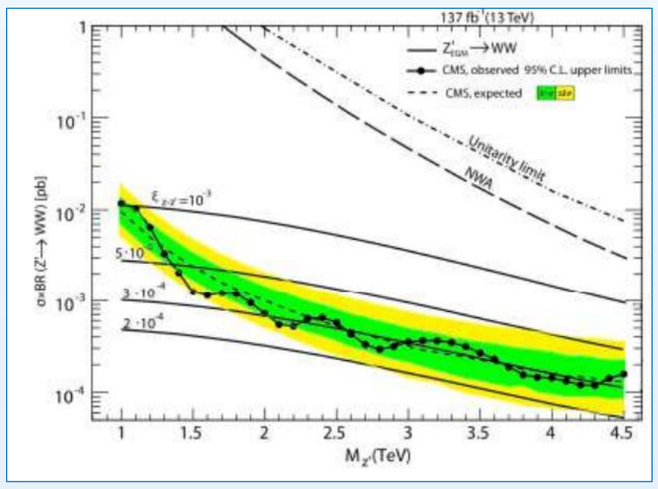
$$\Gamma_{Z'} = \sum_f \Gamma^{ff}_{Z'} + \Gamma^{WW}_{Z'} + \Gamma^{ZH}_{Z'}$$

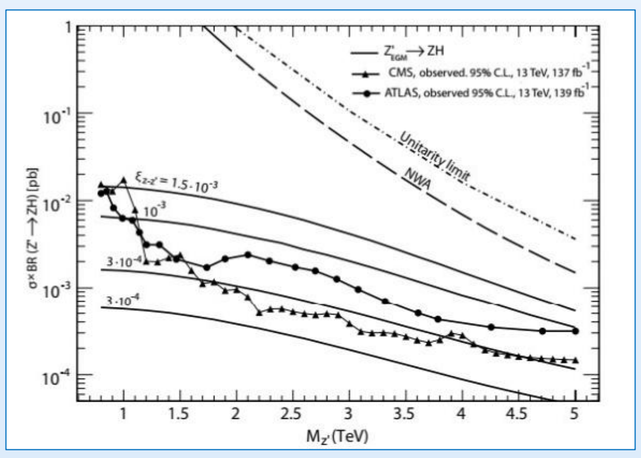
$$\Gamma^{WW}_{Z'} = \frac{\alpha_{em}}{48}\cot^2\theta_W M_{Z'}\left(\frac{M_{Z'}}{M_W}\right)^4\left(1 - 4\frac{M^2_W}{M^2_{Z'}}\right)^{3/2} \times \left[1 + 20\left(\frac{M_W}{M_{Z'}}\right)^2 + 12\left(\frac{M_W}{M_{Z'}}\right)^4\right] \cdot \xi^2_{Z\text{-}Z'}$$

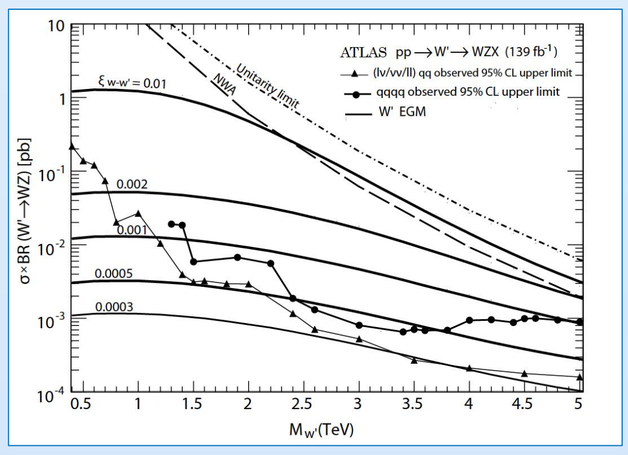
$$\xi_{Z\text{-}Z'} \equiv |\sin\phi|$$

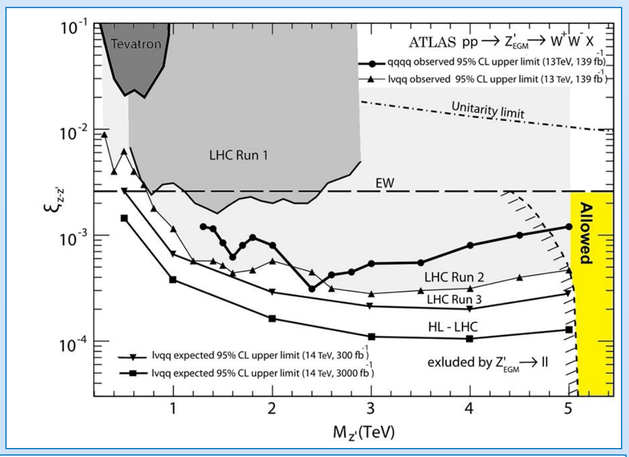


Constarints on V-V' mixing and Mv'









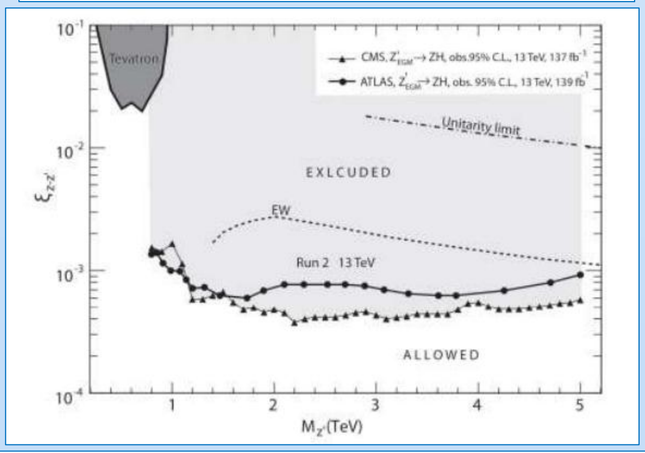


TABLE III. Upper limits on mixing parameters $\xi_{Z\text{-}Z'}$ and $\xi_{W\text{-}W'}$ at 95% C.L. in different models, processes, and experiments (past, Tevatron; present, EW and LHC; future, ILC). We also compare with the expected ILC reach.

Collider, process	$\xi^W_{Z\text{-}Z'}$	$\xi^H_{Z\text{-}Z'}$	$\xi^\chi_{Z\text{-}Z'}$	$\xi^{LR}_{Z\text{-}Z'}$	$\xi^{EGM}_{Z\text{-}Z'}$	$\xi^{EGM}_{W\text{-}W'}$	@M'_V (TeV)
Tevatron, $p\bar{p} \to Z'/W' \to WW/WZ(\to \ell\nu qq)$ [34]	···	···	···	···	2×10^{-2}	2×10^{-2}	0.4–0.9
EW data [1,15]	1.8×10^{-3}	4.7×10^{-3}	1.6×10^{-3}	1.3×10^{-3}	2.6×10^{-3}	$\sim 10^{-2}$	···
LHC@13 TeV, 139 fb^{-1}: run 2 (this work)							
$pp \to Z'/W' \to WW/WZ(\to qqqq)$	2.9×10^{-4}	2.7×10^{-4}	3.8×10^{-4}	3.0×10^{-4}	3.1×10^{-4}	4.3×10^{-4}	1.3–5.0
$pp \to Z' \to WW(\to \ell\nu qq)$	2.5×10^{-4}	2.4×10^{-4}	3.3×10^{-4}	2.7×10^{-4}	2.8×10^{-4}	···	0.5–5.0
$pp \to W' \to WZ(\to \ell\nu/\ell\ell/\nu\nu qq)$	···	···	···	···	···	2.9×10^{-4}	0.5–5.0
ILC@0.5 TeV, 0.5 ab^{-1}, $e^+e^- \to W^+W^-$ [63]	2.3×10^{-3}	1.6×10^{-3}	1.5×10^{-3}	1.4×10^{-3}	1.2×10^{-3}	···	≥3
ILC@1.0 TeV, 1.0 ab^{-1}, $e^+e^- \to W^+W^-$ [63]	0.6×10^{-3}	0.5×10^{-3}	0.4×10^{-3}	0.4×10^{-3}	0.3×10^{-3}	···	≥3

Conclusion

Present analysis of processes, pp→Z'→W^+W^- ,pp→Z'→ZH and pp→W'→WZ , pp→W'→WH, is based on current pp collision data collected by the ATLAS and CMS experiments in Run2 at the LHC with time-integrated luminosities of ≈ 139/fb and137/fb, respectively.
We derived **large improvement** over previously published results obtained at the Tevatron, LHC Run1 at the collider energy of 7/8 TeV, LHC Run2 at 36.1/fb and precision electroweak data (EW); we obtained the most stringent exclusion limits to date on $Z - Z'$ (W-W') mixing.

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