LHC Measurements in Global SFitter Analyses

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Modern LHC physics

Classic motivation

- dark matter
- baryogenesis
- Higgs mechanism
- ~~mass and coupling measurements~~

LHC strengths

- fundamental Lagrangians
- huge high-precision data set
- first-principle precision simulations

→ (Effective) Lagrangian of the LHC

Role of SMEFT

- start from reliable basis
- provide precision theory
- broaden hypotheses piece by piece

→ Define all-LHC analysis

Higgs-gauge analysis

Old story: likelihood over model space [1812.07587]

- Higgs-gauge operators

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = \cdots$$

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \, \phi^\dagger \, (D^\mu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

- Yukawa structure $f_{\tau,b,t}$
- one more operator for TGV

$$\mathcal{O}_{WWW} = \mathrm{Tr} \left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^{\mu}_{\rho} \right)$$

- gauge-fermion operators [$qqVH$ vertex]

$$\mathcal{O}^{(1)}_{\phi L} = \phi^\dagger \overleftrightarrow{D}_\mu \phi (\bar{L}_i \gamma^\mu L_i) \qquad \mathcal{O}^{(1)}_{\phi e} = \phi^\dagger \overleftrightarrow{D}_\mu \phi (\bar{e}_{R,i} \gamma^\mu e_{R,i}) \qquad \mathcal{O}^{(3)}_{\phi L} = \phi^\dagger \overleftrightarrow{D}^a_\mu \phi (\bar{L}_i \gamma^\mu \sigma_a L_i)$$

$$\mathcal{O}^{(1)}_{\phi Q} = \cdots \qquad \mathcal{O}^{(1)}_{\phi d} = \cdots \qquad \mathcal{O}^{(3)}_{\phi Q} = \cdots$$

$$\mathcal{O}^{(1)}_{\phi ud} = \tilde{\phi}^\dagger \overleftrightarrow{D}_\mu \phi (\bar{u}_{R,i} \gamma^\mu d_{R,i}) \qquad \mathcal{O}^{(1)}_{\phi u} = \cdots \qquad \mathcal{O}_{LLLL} = (\bar{L}_1 \gamma_\mu L_2)\, (\bar{L}_2 \gamma^\mu L_1)$$

- ubiquitous triple-gluon coupling

$$\mathcal{O}_G = g_s f_{abc} G^\rho_{a\nu} G^\nu_{b\lambda} G^\lambda_{c\rho}$$

$\to$ Confronted with Higgs, di-boson, exotics measurements

My favorite results

CMS-B2G-19-006

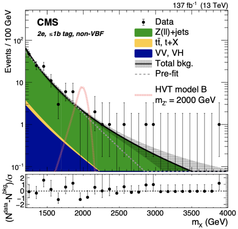
CERN-EP-2021-009
2021/08/12

Search for a heavy vector resonance decaying to a Z boson and a Higgs boson in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search is presented for a heavy vector resonance decaying into a Z boson and the standard model Higgs boson, where the Z boson is identified through its leptonic decays to electrons, muons, or neutrinos, and the Higgs boson is identified through its hadronic decays. The search is performed in a Lorentz-boosted regime and is based on data collected from 2016 to 2018 at the CERN LHC, corresponding to an integrated luminosity of 137 fb^{-1}. Upper limits are derived on the production of a narrow heavy resonance Z′, and a mass below 3.5 and 3.7 TeV is excluded at 95% confidence level in models where the heavy vector boson couples predominantly to fermions and to bosons, respectively. These are the most stringent limits placed on the Heavy Vector Triplet Z′ model to date. If the heavy vector boson couples exclusively to standard model bosons, upper limits on the product of the cross section and branching fraction are set between 23 and 0.3 fb for a Z′ mass between 0.8 and 4.6 TeV, respectively. This is the first limit set on a heavy vector boson coupling exclusively to standard model bosons in its production and decay.



ATLAS CONF Note

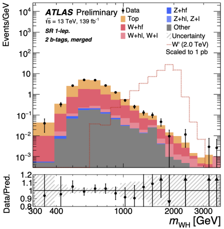
ATLAS-CONF-2021-026

18th June 2021

Search for heavy resonances decaying into a W boson and a Higgs boson in final states with leptons and b-jets in 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

This note presents a search for a new resonance W' decaying into a W boson and a 125 GeV Higgs boson H in the $\ell^{\pm}\nu b\bar{b}$ final state, where $\ell = e$ or μ, using pp collision data at 13 TeV corresponding to an integrated luminosity of 139 fb^{-1} collected by the ATLAS detector at the LHC. The search is conducted by examining the reconstructed invariant mass distributions of $W' \to WH$ candidates in the mass range from 400 GeV to 5 TeV. No significant excess is observed and 95% confidence level upper limits between 1.3 pb and 0.56 fb are placed on the production cross-section times branching fraction of W' bosons in Heavy-Vector-Triplet models.

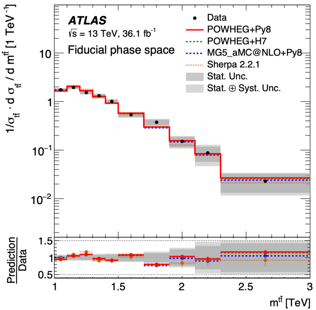


Top sector

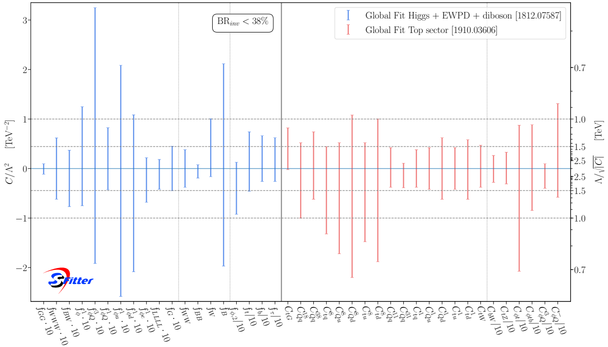
Theory uncertainty: consistently NLO [1910.03606]

- production channels $t\bar{t}$, $t\bar{t}V$, tj, tV, decays
- unfolded m_{tt}, $p_{T,t}$ exciting
- highly correlated 4-fermion sector
- flat directions circular, not obvious

$\rightarrow$ Many technical and physics questions



Single link $\mathcal{O}_{tG}$ [Sanz etal, Maltoni etal, Rojo etal, Ubiali etal, HEPfit...]



Matching

How to interpret for models [2108.01094]

- usual vector triplet benchmark

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}\tilde{V}^{\mu\nu A}\tilde{V}^{A}_{\mu\nu} - \frac{\tilde{g}_M}{2}\,\tilde{V}^{\mu\nu A}\tilde{W}^{A}_{\mu\nu} + \frac{\tilde{m}_V^2}{2}\tilde{V}^{\mu A}\tilde{V}^{A}_{\mu}$$
$$+ \sum_f \tilde{g}_f\,\tilde{V}^{\mu A}J^{fA}_{\mu} + \tilde{g}_H\,\tilde{V}^{\mu A}J^{HA}_{\mu} + \frac{\tilde{g}_{VH}}{2}\,|H|^2\tilde{V}^{\mu A}\tilde{V}^{A}_{\mu}$$

1- effect of one-loop matching?

2- theory uncertainty from matching scale Q?

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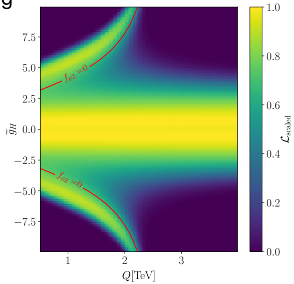
Impact

- SMEFT consistency only relevant when matching
- new matching scale uncertainty [Dawson & Homiller]
- higher-order effect though errors [DUH!]
- EFT uncertainty part of matching
- SMEFTed limits weaker than full model

→ Whatever...



Statistics

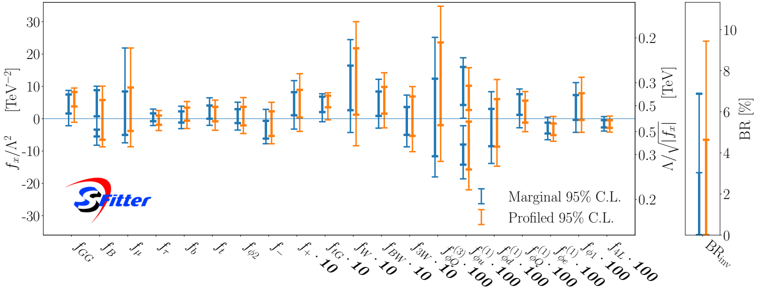
Bayesian marginalization vs profiling [2208.08454]

- exclusive likelihood universal starting point
  systematics — statistics — theory
  correlations crucial
- physics parameters
  nuisance parameters

$\rightarrow$ 1D and 2D physics results for plots?

Physics case

- add WH/ZH fat-jet and WW resonance searches



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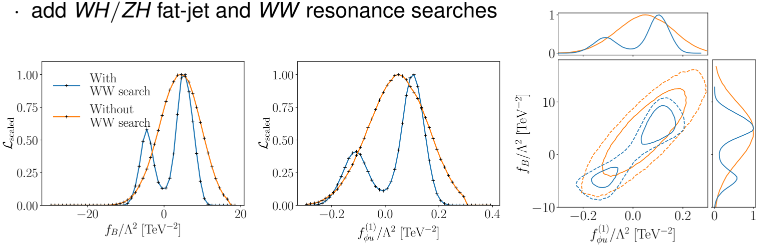

$\rightarrow$ Understood volume effects in tails

Future plans

Likelihoods replacing backwards engineering [Nina Elmer, Nikita Schmal for SFitter]

- extract SM-likelihood
- implement experimental uncertainties
- play with theoretical uncertainties
- change SM predictions to SMEFT predictions
- add new signals (boosted searches)

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$\to$ Playing with $t\bar{t}$ likelihood... [2006.13076]

Category	Reproduced $\frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}}$ [%]	Paper $\frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}}$ [%]
Shower/Hadronization:	2.9	2.9
Scale variations:	2.0	2.0
Reweighting:	1.1	1.1
hdamp:	1.0	1.1
PDF:	1.5	1.5
MC background modeling:	1.7	2.0
Multijet background:	0.7	0.6
Jet reconstruction:	2.5	2.6
Lumi:	1.7	1.7
Flavour tagging:	1.3	1.3
MET + pileup:	0.3	0.3
Muon reconstruction:	0.4	0.5
Electron reconstruction:	0.3	0.6
Simulation stat. uncertainty:	0.6	0.7
Data stat:	0.05	0.05

Uncertainty	Reproduced $\frac{\Delta\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}Z}}$ [%]	Paper $\frac{\Delta\sigma_{t\bar{t}Z}}{\sigma_{t\bar{t}Z}}$ [%]
ttZ parton shower:	3.1	3.1
tWZ modeling:	2.9	2.9
b-tagging:	2.9	2.9
WZ/ZZ + jets modeling:	2.7	2.8
tZq modeling:	2.6	2.6
Lepton:	2.3	2.3
Luminosity:	2.2	2.2
Jets + E_T^{miss}:	2.1	2.1
Fake leptons:	2.1	2.1
$t\bar{t}Z$ ISR:	1.7	1.6
$t\bar{t}Z\mu_F$ and μ_r scales:	0.9	0.9
Other backgrounds:	0.8	0.7
Pile-up:	0.7	0.7
$t\bar{t}Z$ PDF:	0.2	0.2
Stat:	5.2	5.2

Outlook

SFitter SMEFT analyses

- show that global LHC analyses are possible
- result predictable
  error bars (mildly) interesting
- interesting theory questions
  interesting pheno questions
  interesting statistics questions
- pre-digested data too boring
  more exciting data painfully extracted
  1-year paper frequency due to analysis implementation

$\rightarrow$ Need more likelihoods! [Thank you Sabine, Tomas, Lukas, see Humperto's talk]

Modern phenomenology

Information geometry for LHC

- remember Neyman-Pearson lemma:
  how well can a data set compare two hypotheses?
- modern LHC physics:
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- wanted: covariance matrix [measurement error in model space **g**]

$$C_{ij}(\mathbf{g}) \equiv E\left[(\hat{g}_i - \bar{g}_i)(\hat{g}_j - \bar{g}_j)\middle|\mathbf{g}\right]$$

- from simulation: Fisher information [sensitivity in model space]

$$I_{ij}(\mathbf{g}) \equiv -E\left[\frac{\partial^2 \log f(\mathbf{x}|\mathbf{g})}{\partial g_i\, \partial g_j}\middle|\mathbf{g}\right]$$

- Cramèr-Rao bound defining best measurement [lowest possible covariance]

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Accounting for lost information [MadMiner: Brehmer, Kling, Espejo, Cranmer]

- $Z \to \nu\nu$ losing longitudinal momenta
  $H \to bb$ detector resolution
  backgrounds with different final state
- needed likelihood ratio at detector level

$\to$ ML-magic...

Analysis benchmarking

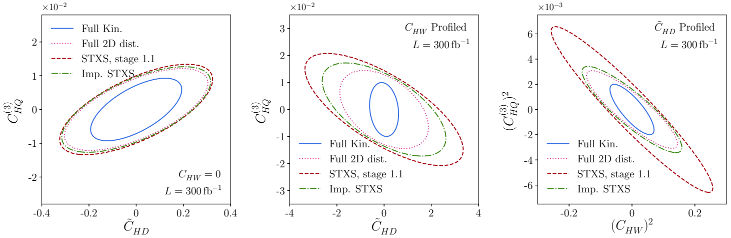
Information geometry for benchmarking [Brehmer, Dawson, Homiller, Kling, TP]

- find best analysis for VH [wf vs vertex structure vs 4-point]

$$\widetilde{\mathcal{O}}_{HD} = (\phi^\dagger \phi)\Box(\phi^\dagger \phi) - \frac{1}{4}(\phi^\dagger D^\mu \phi)^*(\phi^\dagger D_\mu \phi)$$

$$\mathcal{O}_{HW} = \phi^\dagger \phi W^a_{\mu\nu} W^{\mu\nu a} \qquad \mathcal{O}^{(3)}_{Hq} = (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\overline{Q}_L \sigma^a \gamma^\mu Q_L)$$

- including detector and backgrounds
- favorite 2D-observables $p_{T,W} - m_{T,\text{tot}}$ vs STXSs vs full kinematics



→ Kinematics means modern simulation tools