Combined Interpretations

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Universität Heidelberg

CERN, April 2022

Modern BSM Physics

Classic motivation

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

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BSM theory

- QFT and Lagrangian language obvious
- (1) new physics models [built to solve problems, extrapolating to high scales, think SUSY or axions]
  (2) simplified models [light-ish new particles, theoretically poor]
  (3) effective Lagrangians [heavy new physics, SMEFT]

	effective Lagrangian	simplified models	full models
agnostic	×		
data-driven		×	
theory-driven		×	

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	effective Lagrangian	simplified models	full models
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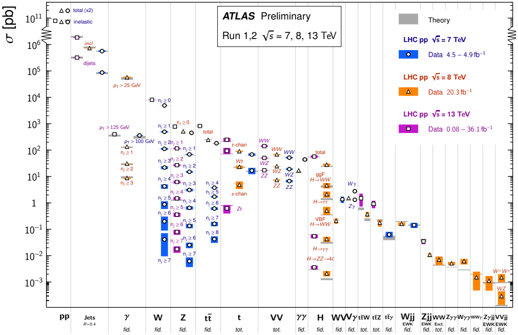
theory-driven	pointless	×	dreaming

Experiment and Theory

Show-off LHC

- many processes
- vastly different rates
- high precision
- predicted by theory



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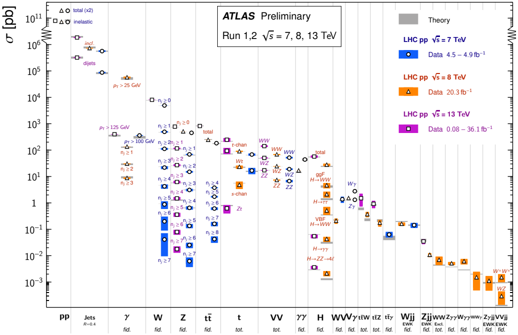
Simulation-based inference

- precision predictions
- precision simulations
- global analyses

$\to$ Theory crucial



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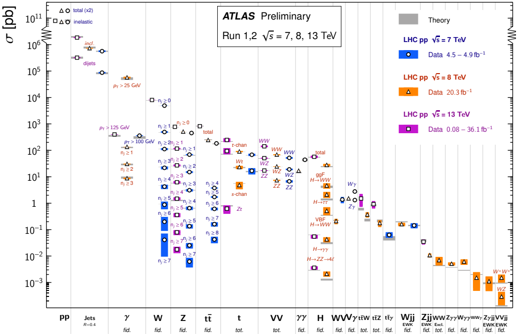

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Role of SMEFT [and models]

- relate different rate measurements
- define all-LHC analysis
- link to other experiments

→ Learn about fundamental questions

Higgs-gauge analysis

D6 Lagrangian from Run 2

- Higgs-gauge operators

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

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

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

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

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

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- ubiquitous triple-gluon coupling

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

$\to$ Higgs–electroweak–exotics combination [da Blas, Durieux, Grojean, Gu, Paul]

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 $\sqrt{s} = 13$ 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

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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.

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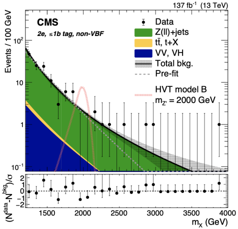

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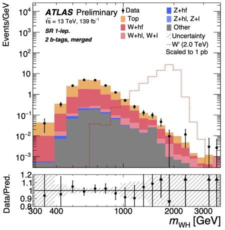
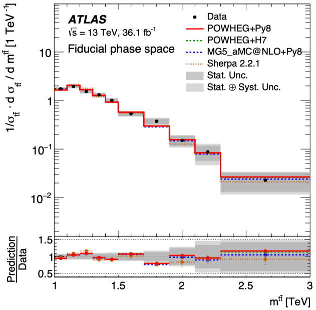


Top analysis

Top sector, executive summary

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

$\rightarrow$ Many open questions



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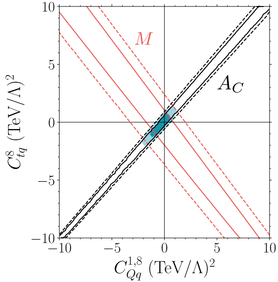
Top chirality

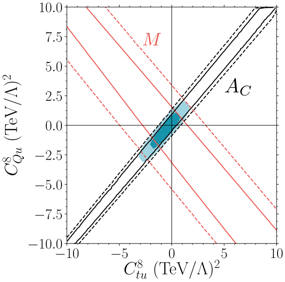
- 4-quark operator chirality

$$O^{1,8}_{Qq} = (\bar{q}_i \gamma^\mu T^A q_i)(\bar{Q}\gamma_\mu T^A Q)$$
$$O^8_{tq} = (\bar{q}_i \gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$$
$$O^8_{tu} = (\bar{u}_i \gamma^\mu T^A u_i)(\bar{t}\gamma_\mu T^A t)$$
$$O^8_{Qu} = (\bar{u}_i \gamma_\mu T^A u_i)(\bar{Q}\gamma^\mu T^A Q)$$

- top chirality from $|y_t| - |y_{\bar{t}}|$ asymmetry [NLO]

→ Improvement from FCC? [earlier talk]





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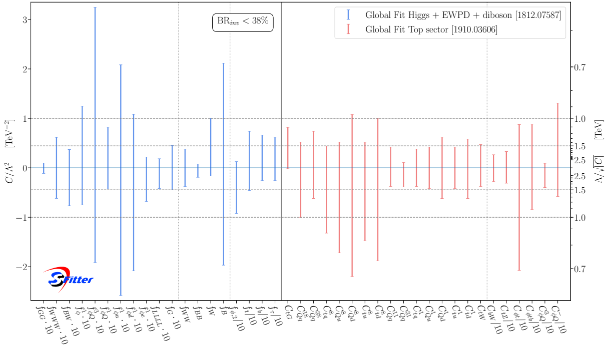
Combined SMEFT analysis incuding FCCee?

[Sanz etal, Maltoni etal, Rojo etal, Ubiali etal, HEPfit...]



Models as afterthought

SMEFT vs full model analyses

[Brivio, Bruggisser, Geoffray, Kilian, Krämer, Luchmann, TP, Summ]

- usual vector triplet benchmark

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}\tilde{V}^{\mu\nu A}\tilde{V}^{A}_{\mu\nu} - \frac{\tilde{g}_M}{2}\tilde{V}^{\mu\nu A}\tilde{W}^{A}_{\mu\nu} + \frac{\tilde{m}_V^2}{2}\tilde{V}^{\mu A}\tilde{V}^{A}_{\mu}$$
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1- effect of one-loop matching?

2- theory uncertainty from matching scale Q?

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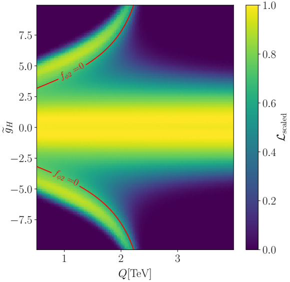
1- effect of one-loop matching?

2- theory uncertainty from matching scale Q?

Impact [cf Dawson, Giardino, Homiller]

- higher-order effect though errors [DUH!]
- EFT uncertainty part of matching
- SMEFT effects smaller than full model
  SMEFT limits weaker than full model

$\to$ Whatever...



Modern phenomenology

Information geometry for LHC

- remember Neyman-Pearson lemma:
  how well can a data set compare two hypotheses?
- modern LHC physics:
  how much would a data set say about a continuous parameter?

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- wanted: covariance matrix [measurement error in model space **g**]

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

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

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

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

$$C_{ij}(\mathbf{g}) \geq (I^{-1})_{ij}(\mathbf{g})$$

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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]

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

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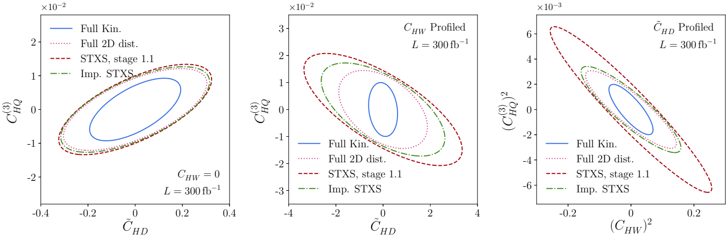
- including detector and backgrounds
- favorite 2D-observables $p_{T,W} - m_{T,\text{tot}}$ vs STXSs vs full kinematics



→ Kinematics means modern simulation tools

Beyond SMEFT

Higgs self-coupling and baryogenesis

- Sakharov conditions

  baryon number violation
  C and CP violation
  departure from thermal equilibrium → 1st-order e-w phase transition

- D6-Higgs potential [Grojean, Servant, Wells]
  general potential [Reichert, Eichhorn, Gies, Pawlowski, TP, Scherer]

$$\Delta V_6 = \lambda_6 \frac{\phi^6}{\Lambda^2}$$

$$\Delta V_{\ln,2} = -\lambda_{\ln,2} \frac{\phi^2\Lambda^2}{100} \ln \frac{\phi^2}{2\Lambda^2} \qquad \Delta V_{\ln,4} = \lambda_{\ln,4} \frac{\phi^4}{10} \ln \frac{\phi^2}{2\Lambda^2}$$

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Beyond SMEFT

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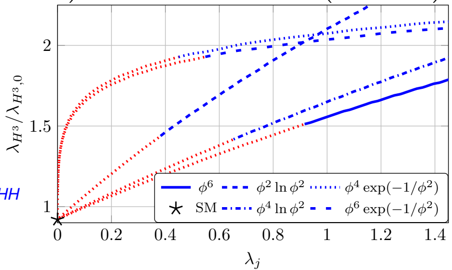
$\to$ requiring 50% enhanced λ_{HHH}



Outlook

HL-LHC the benchmark data set

- precision hadron collider physics
- combined with precision predictions/simulations
- combined with SMEFT framework

$\rightarrow$ Fully understandable from first principles

Ideal LHC measurements

- kinematic information crucial
- unfolding beats STXS

$\rightarrow$ Setting FCC stage

Combination with FCCee

- always part of global analysis
- input variables to LHC analyses?
- Yukawa-mass relation?
- top chirality?
- 4-fermion interactions?

$\rightarrow$ Should be easy to benchmark... [talk Reinhard]