Global SMEFT Analyses at the LHC

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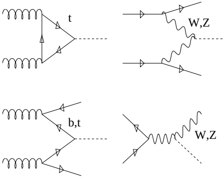
Higgs couplings



How the LHC became a precision machine

– assume: narrow *CP*-even scalar
  Standard Model operators

– Lagrangian like non-linear symmetry breaking

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible} + \text{unobservable}$$

$$\boxed{\begin{array}{lll} gg & \to H & \\ gg & \to H+j & \text{(boosted)} \\ gg & \to H^* & \text{(off-shell)} \\ qq & \to qqH & \\ gg & \to t\bar{t}H & \\ qq' & \to VH & \end{array}} \quad \longleftrightarrow \quad \boxed{g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)} \quad \longleftrightarrow \quad \boxed{\begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \\ H \to \text{invisible} \end{array}}$$

Brilliant Run 1 analyses, but...

1 not renormalizable

2 no event kinematics

3 not full SM

Higgs-gauge operators

D6 Lagrangian for Run 2 [SMEFT]

– Higgs operators [renormalizable]

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

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

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

– basis after equation of motion, field re-definition, integration by parts

$$\mathcal{L}_{\text{D6}} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_{B} + \frac{f_W}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

– Higgs couplings [derivatives = momentum]

$$\begin{aligned} \mathcal{L}_{\text{D6}} = \; & g_g \; H G^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \; H A_{\mu\nu} A^{\mu\nu} \\ & + g_Z^{(1)} \; Z_{\mu\nu} Z^\mu \partial^\nu H + g_Z^{(2)} \; H Z_{\mu\nu} Z^{\mu\nu} + g_Z^{(3)} \; H Z_\mu Z^\mu \\ & + g_W^{(1)} \; \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.} \right) + g_W^{(2)} \; H W^+_{\mu\nu} W^{-\,\mu\nu} + g_W^{(3)} \; H W^+_\mu W^{-\,\mu} + \cdots \end{aligned}$$

plus Yukawa structure $f_{\tau,b,t}$

– one more operator for TGV

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

$\Rightarrow$ Bosonic electroweak sector: 10 operators

LHC kinematics

Ideal LEP and flavor worlds

– unique EFT Lagrangian: linear realization matching unbroken phase

– chain of well separated energy scales $E \ll \Lambda_1 \ll ... \ll \Lambda_N$

$\Rightarrow$ systematic expansion in E/Λ and α [example: ew precision data]

Rotten LHC world [Brehmer, Freitas, Lopez-Val, TP]

– range of (partonic) energy scales [making things worse $v \sim E_{\text{LHC}}$]

– limited precision

$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \approx 10\% \qquad \stackrel{g=1}{\Longleftrightarrow} \qquad \Lambda \approx 400 \quad \text{GeV}$$

– reach from energy

$\Rightarrow$ D8 operators not obviously suppressed

Task for LHC theory: develop D6-framework

– keep some self respect

– SMEFT analysis just limit setting

– UV-models what we care about

SFitter analysis

SFitter global analysis [Lafaye, TP, Rauch, Zerwas, Duhrssen (2009)]

– signal and background rates from ATLAS/CMS publications
– statistical/systematic/theory uncertainties
– theory uncertainties flat [RFit, CKMFitter]
– correlations through nuisance parameters
– Markov chains weighted, cooling, etc
– 1D and 2D profile likelihoods
– truncation uncertainties as matching uncertainties

$\Rightarrow$ Independent analysis with focus on uncertainties

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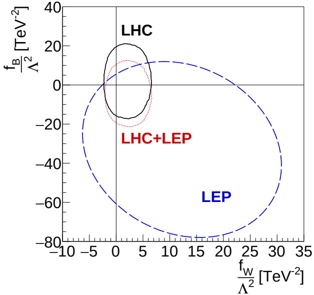
⇒ Independent analysis with focus on uncertainties

LHC vs LEP [Butter, Eboli, Gonzalez-Fraile, Gonzales-Garcia, TP, Rauch]

- Run 1 gauge legacy
- triple vertices g_1, κ, λ vs operators
- generic EFT feature:

  LEP driven by precision
  LHC driven by energy

⇒ LHC the leading SMEFT machine



Fermionic operators

Enlarging operator basis [Biekötter, Corbett, TP; Zhang; Baglio, Dawson, Lewis; Alves etal]

– gauge-fermion operators visible [*qqVH* vertex]

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

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

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

– bosonic operators bounded by EWPD

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \; \phi \phi^\dagger \; (D^\mu \phi) \qquad \mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi$$

– bigger and better basis

$$\begin{aligned}\mathcal{L}_{\text{eff}} = & -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{WWW}}{\Lambda^2} \mathcal{O}_{WWW} \\ & + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2} + \sum_{\tau bt} \frac{m_f}{v} \frac{f_f}{\Lambda^2} \mathcal{O}_f + \frac{f_{\phi,1}}{\Lambda^2} \mathcal{O}_{\phi 1} + \frac{f_{BW}}{\Lambda^2} \mathcal{O}_{BW} + \frac{f_{LLLL}}{\Lambda^2} \mathcal{O}_{LLLL} \\ & + \frac{f^{(1)}_{\phi Q}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi Q} + \frac{f^{(1)}_{\phi d}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi d} + \frac{f^{(1)}_{\phi u}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi u} + \frac{f^{(1)}_{\phi e}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi e} + \frac{f^{(3)}_{\phi Q}}{\Lambda^2} \mathcal{O}^{(3)}_{\phi Q}\end{aligned}$$

$\Rightarrow$ Physics: rates vs kinematics vs EWPD

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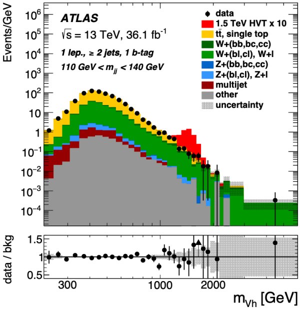
Higgs constraints from no-Higgs measurements

– m_{VH} perfect SMEFT kinematics

Search for heavy resonances decaying into a W or Z boson and a Higgs boson in final states with leptons and b-jets in 36 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

A search is conducted for new resonances decaying into a W or Z boson and a 125 GeV Higgs boson in the $\nu\bar{\nu}b\bar{b}$, $\ell^\pm \nu b\bar{b}$, and $\ell^+\ell^- b\bar{b}$ final states, where $\ell^\pm = e^\pm$ or $\mu^\pm$, in pp collisions at $\sqrt{s}$ = 13 TeV. The data used correspond to a total integrated luminosity of 36.1 fb^{-1} collected with the ATLAS detector at the Large Hadron Collider during the 2015 and 2016 data-taking periods. The search is conducted by examining the reconstructed invariant or transverse mass distributions of Wh and Zh candidates for evidence of a localised excess in the mass range of 220 GeV up to 5 TeV. No significant excess is observed and the results are interpreted in terms of constraints on the production cross-section times branching fraction of heavy W' and Z' resonances in heavy-vector-triplet models and the CP-odd scalar boson A in two-Higgs-doublet models. Upper limits are placed at the 95% confidence level and range between 9.0×10^{-4} pb and 8.1×10^{-1} pb depending on the model and mass of the resonance.



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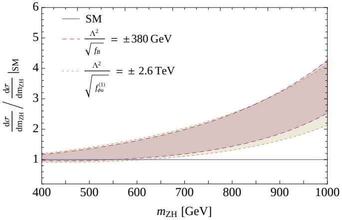
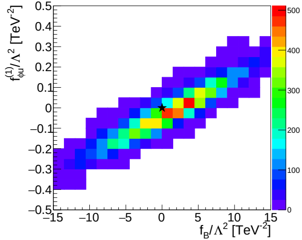
– hierarchy $\mathcal{O}^{(1)}_{\phi u} \to g_{qqZH}$ vs $\mathcal{O}_W \to g_{ZZH}$





More operators

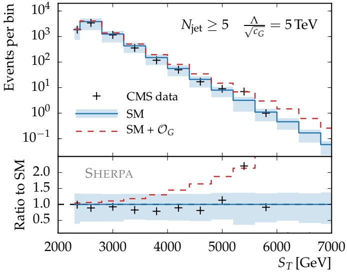
Ubiquitous QCD operator [Simmons etal; Dixon etal; TP, Krauss, Kuttimalai]

– anomalous gluon coupling

$$\mathcal{O}_G = g_s\, f_{abc} G^{\rho}_{a\nu}\, G^{\nu}_{b\lambda}\, G^{\lambda}_{c\rho}$$

– multi-jet production [black hole search]

4-fermion operator for $N_{\text{jets}} = 2, 3$
gluon operator for $N_{\text{jets}} \geq 5$



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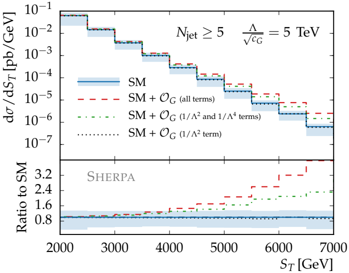

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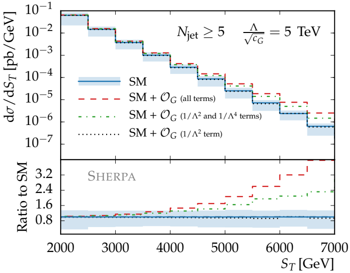
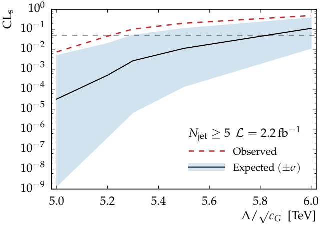
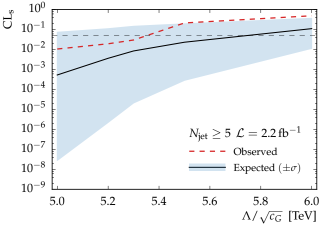


Limiting kinematic range

– avoid inconsistent regions
require for hypothesis testing $S_T < \Lambda$

– remember that upwards fluctuation...



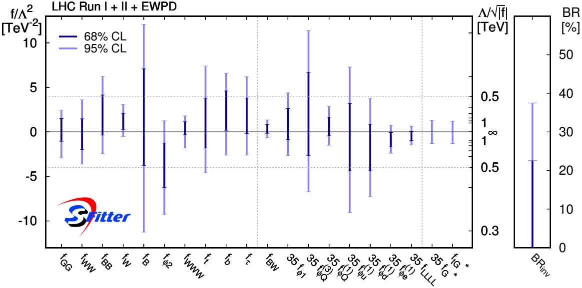


Higgs-gauge-top legacy

Combined Run II analysis [Biekötter, Corbett, TP]

- quote f_{tG} [Sanz etal: not good assumption]
- quote multi-jet
- hierarchical limits

$\Rightarrow$ Okay, no anomalies, not that interesting



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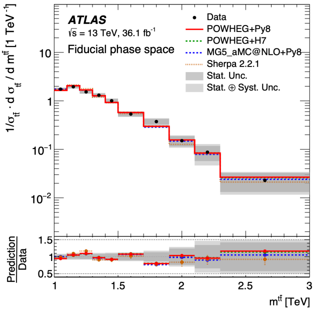
Top sector, executive summary [Brivio, Bruggisser, Maltoni, Moutafis, TP, Vryonidou, Westhoff, Zhang]

– production channels $t\bar{t}$, $t\bar{t}V$, tj, tV, plus top decays
– NLO predictions, theory uncertainties not only from scales
– $m_{tt}, p_{T,t}$ distributions unfolded
– highly correlated 4-fermion sector
– flat directions circular
$\Rightarrow$ Still no anomalies, not that interesting

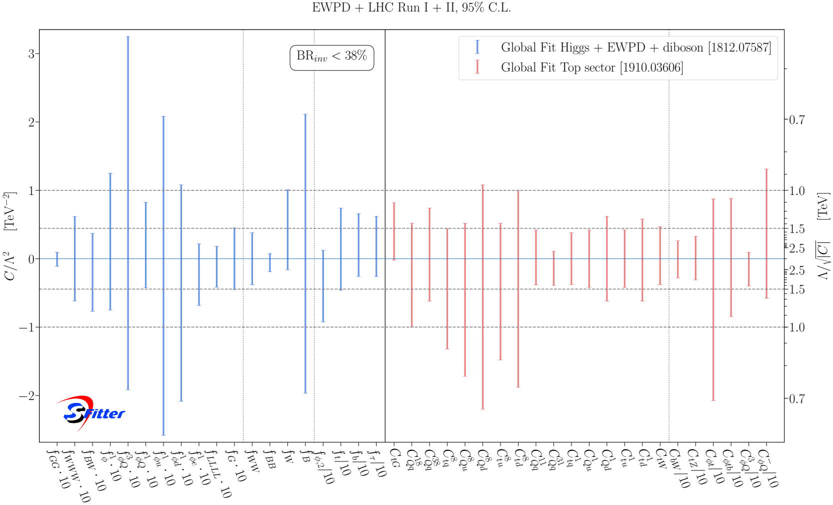


Run 2 done

Combined Run II analysis [Sanz etal, Maltoni etal]

– Higgs–gauge and top sectors almost factorized

$\Rightarrow$ closing in on SMEFT fit, but is that our future?



Quantifying available information

Information geometry for LHC [Brehmer, Cranmer, Kling]

– remember Neyman-Pearson lemma:
  how well can a data set compare two hypotheses?
– modern LHC physics:
  how much would a data set tell me about a continuous measurement?

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

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

– computable: Fisher information [sensitivity in model space]

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

over phase space [phase space **x**, additive]

$$I_{ij} = \frac{L}{\sigma}\,\frac{\partial\sigma}{\partial g_i}\,\frac{\partial\sigma}{\partial g_j} - L\,\sigma\,E\left[\frac{\partial^2 \log f^{(1)}(\mathbf{x}|\mathbf{g})}{\partial g_i\,\partial g_j}\right]$$

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

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

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

– parametrization-invariant elipses of constant reach in model space

– diagonalize I_{ij}, define model-space eigenvectors

– compute information in distributions or phase space regions

$\Rightarrow$ method to benchmark analysis ideas

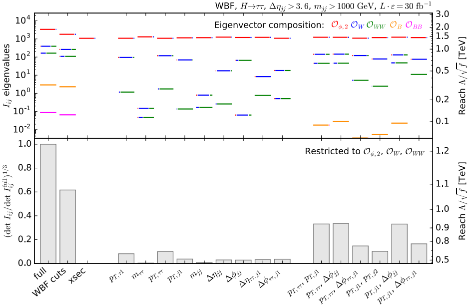
Parton level

Simple SMEFT application on parton level [Brehmer, Cranmer, Kling, TP]

– impact of kinematics in WBF?

– worth inclusing $H \to 4f$?

– rare processes like Ht?



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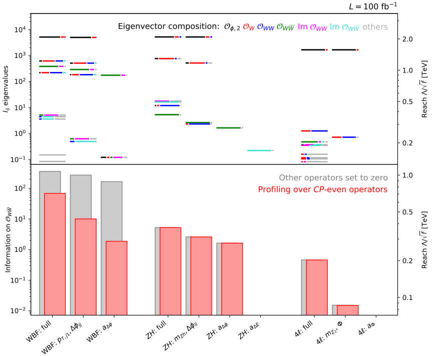
Link to optimal observables [Brehmer, Kling, TP, Tait]

- searches for CP-violation in VVH vertex
- compare crossed amplitudes: $H \to 4f$ vs $qq \to ZH$ vs WBF
- optimal observable $\propto \sin \Delta\phi_{jj}$
- D6 momentum dependence

$\Rightarrow$ All with quantitative answers



Detector level — MadMiner

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

– problem:
  $Z \to \nu\nu$ keeping only missing transverse momentum
  $H \to bb$ spreading out momentum measurement
  backgrounds with different final state

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– reconstruct likelihood ratio at detector level [following 1808.01324 Sec.3]

$$\log \frac{p(x_d|\vec{g}_s)}{p(x_d|\vec{g}_b)} = \log \frac{\int dx_p \, p(x_d|x_p) \; p(x_p|\vec{g}_s)}{\int dx_p \, p(x_d|x_p) \; p(x_p|\vec{g}_b)}$$

– start with minimization problem for

$$F(x_d) = \int dx_p \;\; |g(x_d, x_p) - \hat{g}(x_d)|^2 \;\; p(x_d|x_p) \; p(x_p|\vec{g})$$

defining proxy

$$\hat{g}_*(x_d) = \frac{\int dx_p \, g(x_d, x_p) \; p(x_d|x_p) \; p(x_p|\vec{g})}{p(x_d|\vec{g})}$$

– smart choice

$$g(x_d, x_p) = \frac{p(x_p|\vec{g}_s)}{p(x_p|\vec{g}_b)} \qquad \Rightarrow \qquad \hat{g}_*(x_d) = \frac{p(x_d|\vec{g}_s)}{p(x_d|\vec{g}_b)}$$

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$$g(x_d, x_p) = \frac{p(x_p|\vec{g}_s)}{p(x_p|\vec{g}_b)} \qquad \Rightarrow \qquad \hat{g}_*(x_d) = \frac{p(x_d|\vec{g}_s)}{p(x_d|\vec{g}_b)}$$

– likelihood ratio at detector level [matrix element method]

$\Rightarrow$ Minimization means ML-era

Analysis benchmarking

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

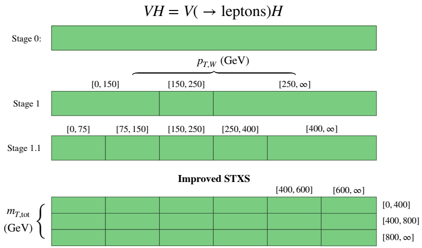
– find best analysis for VH [wf vs vertex structure vs 4-point]

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

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

– including detector and backgrounds

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



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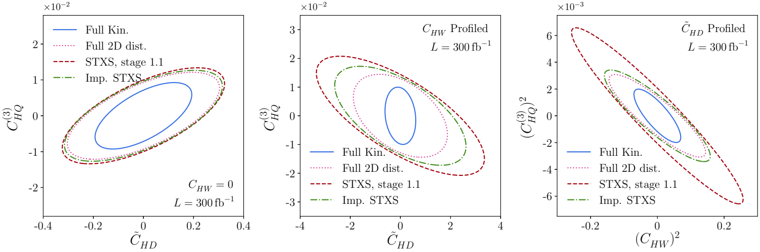
– scientific answer [rather than physics by committee]



⇒ Why not use modern simulation tools?

Matching

SMEFT vs full model analyses [Geoffray, Luchmann, ... (soon)]

– usual vector triplet benchmark

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

– weakened model limits using D6-SMEFT analyses? [regimes in $c \sim g/m_V^2$]

– effect of one-loop matching?

– theory uncertainty from matching scale

⇒ Reminder that SMEFT is not LHC physics

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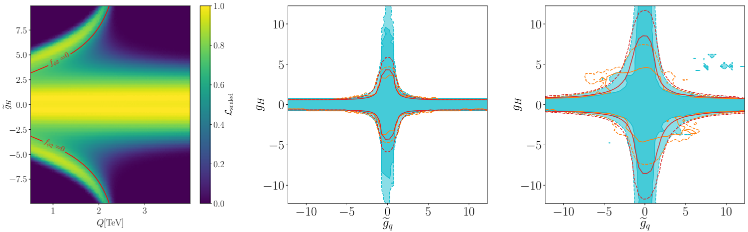
Preview



Questions

Theory contribution to bottom-up precision physics at the LHC

Is it really the Standard Model Higgs? [no]

Is there WIMP dark matter? [yes]

Is there TeV-scale physics beyond the Standard Model? [yes]

Is it fun to work with data? [sure]

Are EFT analyses un-inspired? [totally]

Are there nice theory aspects to work on? [plenty]

Are there nice statistics aspects to work on? [even more]

Will I stop doing EFT once we find new physics? [definitely]

$\Rightarrow$ Welcome to a data-driven era!