Higgs effective field theory phenomenology made easy with FEYNRULES and MADGRAPH 5

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Based on:

- Alloul, Fuks & Sanz, arXiv:1310.5150
- Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mawatari, Ravindran, Seth, Torrielli, Zaro, arXiv:1306.6464

Brainstorming and Discussion on EFT for Higgs couplings

CERN
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Outline

1. A framework for Higgs effective field theories using MadGraph 5 and FeynRules
2. From theory to phenomenology in 5 minutes
3. A few phenomenological examples
4. Summary

A framework for Higgs physics at the LHC

- Studied physics: the Higgs boson properties (coupling strengths and structures, *etc.*)
  - Any subprocess from production to decay
  - Any observable
- Fully automated
  - From the Lagrangian to the histograms
- Flexible
  - Easily extendable: new operators, NLO, *etc.* (→ theorists)
  - Easily useable (*via* Monte Carlo events) in LHC analyses (→ experimentalists)
- Fast and efficient
  - Should run in a decent amount of time (minutes) on a laptop

Effective field theories for Higgs physics

- The effective field theory (EFT) approach
  - All new phenomena are assumed to appear at a scale Λ
  - No assumption on the form of new physics
    - ★ Addition of higher-dimensional operators
    - ★ We restrict ourselves to dimension six
  - Renormalizable order by order in the scale Λ
  - Not predictive at scales larger than Λ (loss of unitarity)

- In the context of the Higgs boson: construction of simple EFTs
  - EFT are excellent approaches to characterize the properties of any new state
  - First possibility: [Artoisenet *et al.* (arXiv:1306.6464)]
    - ★ Couplings of the physical Higgs boson to the Standard Model (physical) states
    - ★ One operator associated with a single coupling
    - ★ No assumption on the Higgs boson spin
  - Second possibility: [Alloul, BenjFuks, Sanz (arXiv:1310.5150]
    - ★ Only using Standard Model gauge-eigenstates
    - ★ Several operators may be associated with a single coupling
    - ★ One operator associated with several couplings

The Lagrangian in the gauge basis

[from Contino, Ghezzi, Grojean, Muhlleitner, Spira (JHEP '13)]

✦ 39 (with two redundant) operators have been implemented

$$\mathcal{L}_{\rm SILH} = \frac{\bar c_H}{2v^2}\partial^\mu\big[\Phi^\dagger\Phi\big]\partial_\mu\big[\Phi^\dagger\Phi\big] + \frac{\bar c_T}{2v^2}\big[\Phi^\dagger \overleftrightarrow{D}^\mu\Phi\big]\big[\Phi^\dagger \overleftrightarrow{D}_\mu\Phi\big] - \frac{\bar c_6\lambda}{v^2}\big[H^\dagger H\big]^3 - \Big[\frac{\bar c_u}{v^2}y_u\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar Q_L u_R + \frac{\bar c_d}{v^2}y_d\Phi^\dagger\Phi\ \Phi\bar Q_L d_R + \frac{\bar c_l}{v^2}y_\ell\ \Phi^\dagger\Phi\ \Phi\bar L_L e_R + {\rm h.c.}\Big] + \frac{ig\ \bar c_W}{m_W^2}\big[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\big]D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar c_B}{2m_W^2}\big[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\big]\partial^\nu B_{\mu\nu} + \frac{2ig\ \bar c_{HW}}{m_W^2}\big[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\big]W^k_{\mu\nu} + \frac{ig'\ \bar c_{HB}}{m_W^2}\big[D^\mu\Phi^\dagger D^\nu\Phi\big]B_{\mu\nu} + \frac{\bar g'^2\ c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{\bar g_s^2\ c_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu}\ ,$$

$$\mathcal{L}_{CP} = \frac{ig\ \tilde c_{HW}}{m_W^2}D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\widetilde W^k_{\mu\nu} + \frac{ig'\ \tilde c_{HB}}{m_W^2}D^\mu\Phi^\dagger D^\nu\Phi\widetilde B_{\mu\nu} + \frac{g'^2\ \tilde c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde B^{\mu\nu} + \frac{g_s^2\ \tilde c_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}\widetilde G_a^{\mu\nu} + \frac{g^3\ \tilde c_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho\widetilde W^{\rho\mu k} + \frac{g_s^3\ \tilde c_{3G}}{m_W^2}f_{abc}G^a_{\mu\nu}G^{\nu b}{}_\rho\widetilde G^{\rho\mu c}$$

$$\mathcal{L}_G = \frac{g^3\ \bar c_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho W^{\rho\mu k} + \frac{g_s^3\ \bar c_{3G}}{m_W^2}f_{abc}G^a_{\mu\nu}G^{\nu b}{}_\rho G^{\rho\mu c} + \frac{\bar c_{2W}}{m_W^2}D^\mu W^k_{\mu\nu}D_\rho W_k^{\rho\nu} + \frac{\bar c_{2B}}{m_W^2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu} + \frac{\bar c_{2G}}{m_W^2}D^\mu G^a_{\mu\nu}D_\rho G_a^{\rho\nu}\ ,$$

$$\mathcal{L}_{F_1} = \frac{i\bar c_{HQ}}{v^2}\big[\bar Q_L\gamma^\mu Q_L\big]\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big] + \frac{4i\bar c'_{HQ}}{v^2}\big[\bar Q_L\gamma^\mu T_{2k}Q_L\big]\big[\Phi^\dagger T_2^k\overleftrightarrow{D}_\mu\Phi\big] + \frac{i\bar c_{Hu}}{v^2}\big[\bar u_R\gamma^\mu u_R\big]\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big] + \frac{i\bar c_{Hd}}{v^2}\big[\bar d_R\gamma^\mu d_R\big]\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big] - \Big[\frac{i\bar c_{Hud}}{v^2}\big[\bar u_R\gamma^\mu d_R\big]\big[\Phi\cdot\overleftrightarrow{D}_\mu\Phi\big] + {\rm h.c.}\Big] + \frac{i\bar c_{HL}}{v^2}\big[\bar L_L\gamma^\mu L_L\big]\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big] + \frac{4i\bar c'_{HL}}{v^2}\big[\bar L_L\gamma^\mu T_{2k}L_L\big]\big[\Phi^\dagger T_2^k\overleftrightarrow{D}_\mu\Phi\big] + \frac{i\bar c_{He}}{v^2}\big[\bar e_R\gamma^\mu e_R\big]\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big]\ ,$$

$$\mathcal{L}_{F_2} = \Big[-\frac{2g'\ \bar c_{uB}}{m_W^2}y_u\ \Phi^\dagger\cdot\bar Q_L\gamma^{\mu\nu}u_R\ B_{\mu\nu} - \frac{4g\ \bar c_{uW}}{m_W^2}y_u\ \Phi^\dagger\cdot(\bar Q_L T_{2k})\gamma^{\mu\nu}u_R\ W^k_{\mu\nu} - \frac{4g_s\ \bar c_{uG}}{m_W^2}y_u\ \Phi^\dagger\cdot\bar Q_L\gamma^{\mu\nu}T_a u_R G^a_{\mu\nu} + \frac{2g'\ \bar c_{dB}}{m_W^2}y_d\ \Phi\bar Q_L\gamma^{\mu\nu}d_R\ B_{\mu\nu} + \frac{4g\ \bar c_{dW}}{m_W^2}y_d\ \Phi(\bar Q_L T_{2k})\gamma^{\mu\nu}d_R\ W^k_{\mu\nu} + \frac{4g_s\ \bar c_{dG}}{m_W^2}y_d\ \Phi\bar Q_L\gamma^{\mu\nu}T_a d_R G^a_{\mu\nu} + \frac{2g'\ \bar c_{eB}}{m_W^2}y_\ell\ \Phi\bar L_L\gamma^{\mu\nu}e_R\ B_{\mu\nu} + \frac{4g\ \bar c_{eW}}{m_W^2}y_\ell\ \Phi(\bar L_L T_{2k})\gamma^{\mu\nu}e_R\ W^k_{\mu\nu} + {\rm h.c.}\Big]$$

The Lagrangian in the mass basis

[from Contino, Ghezzi, Grojean, Muhlleitner, Spira (JHEP '13)]

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$$\mathcal{L}_G = \frac{g^3\;\bar c_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho W^{\rho\mu k} + \frac{g_s^3\;\bar c_{3G}}{m_W^2}f_{abc}G^a_{\mu\nu}G^{\nu b}{}_\rho G^{\rho\mu c} + \frac{\bar c_{2W}}{m_W^2}D^\mu W^k_{\mu\nu}D_\rho W_k^{\rho\nu} + \frac{\bar c_{2B}}{m_W^2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu} + \frac{\bar c_{2G}}{m_W^2}D^\mu G^a_{\mu\nu}D_\rho G_a^{\rho\nu}\,,$$

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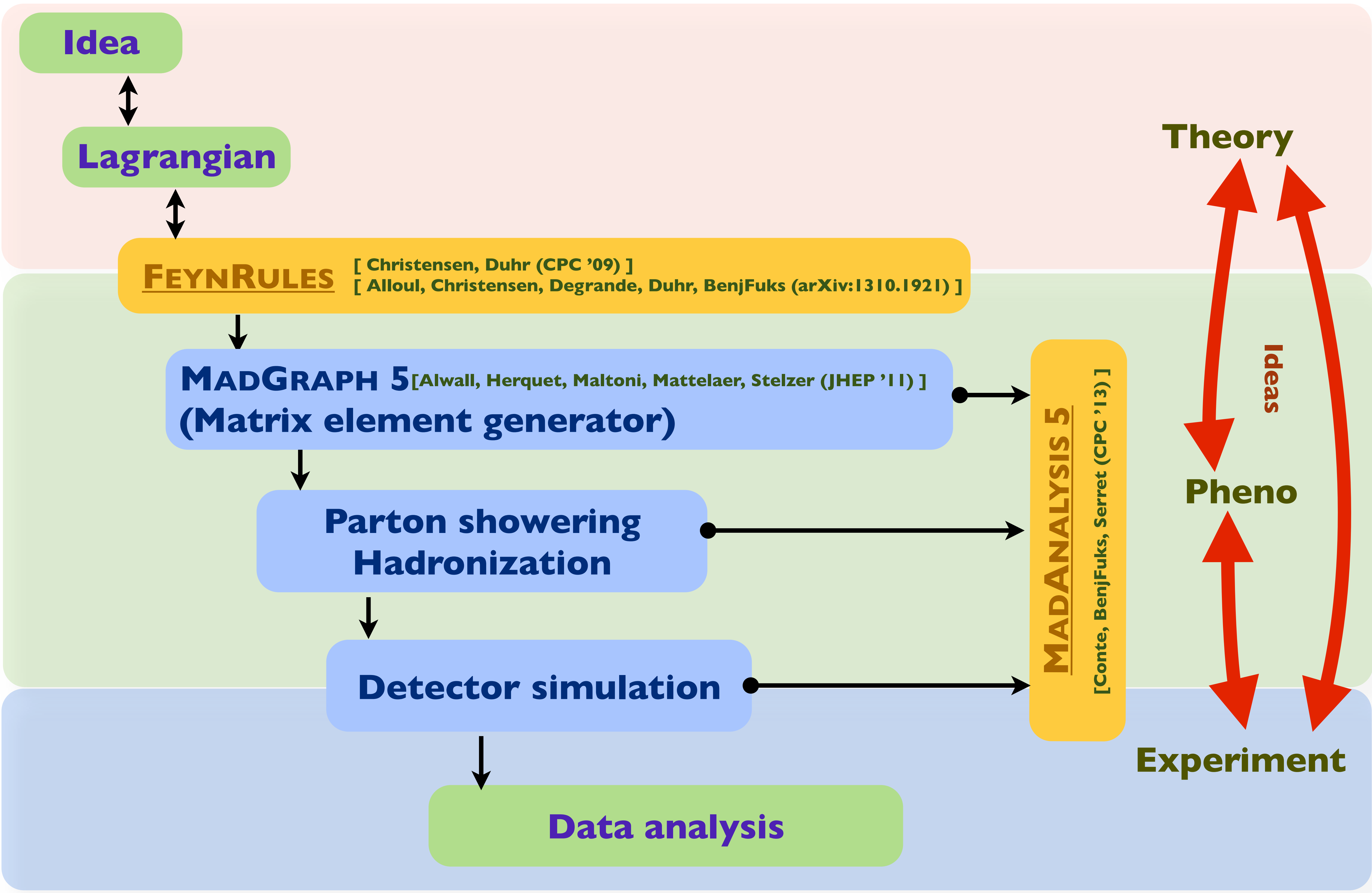
$$\mathcal{L}_{F_2} = \Big[-\frac{2g'\;\bar c_{uB}}{m_W^2}y_u\;\Phi^\dagger\cdot\bar Q_L\gamma^{\mu\nu}u_R\;B_{\mu\nu} - \frac{4g\;\bar c_{uW}}{m_W^2}y_u\;\Phi^\dagger\cdot(\bar Q_L T_{2k})\gamma^{\mu\nu}u_R\;W^k_{\mu\nu} - \frac{4g_s\;\bar c_{uG}}{m_W^2}y_u\;\Phi^\dagger\cdot\bar Q_L\gamma^{\mu\nu}T_a u_R G^a_{\mu\nu} + \frac{2g'\;\bar c_{dB}}{m_W^2}y_d\;\Phi\bar Q_L\gamma^{\mu\nu}d_R\;B_{\mu\nu} + \frac{4g\;\bar c_{dW}}{m_W^2}y_d\;\Phi(\bar Q_L T_{2k})\gamma^{\mu\nu}d_R\;W^k_{\mu\nu} + \frac{4g_s\;\bar c_{dG}}{m_W^2}y_d\;\Phi\bar Q_L\gamma^{\mu\nu}T_a d_R G^a_{\mu\nu} + \frac{2g'\;\bar c_{eB}}{m_W^2}y_\ell\;\Phi\bar L_L\gamma^{\mu\nu}e_R\;B_{\mu\nu} + \frac{4g\;\bar c_{eW}}{m_W^2}y_\ell\;\Phi(\bar L_L T_{2k})\gamma^{\mu\nu}e_R\;W^k_{\mu\nu} + \text{h.c.}\Big]$$

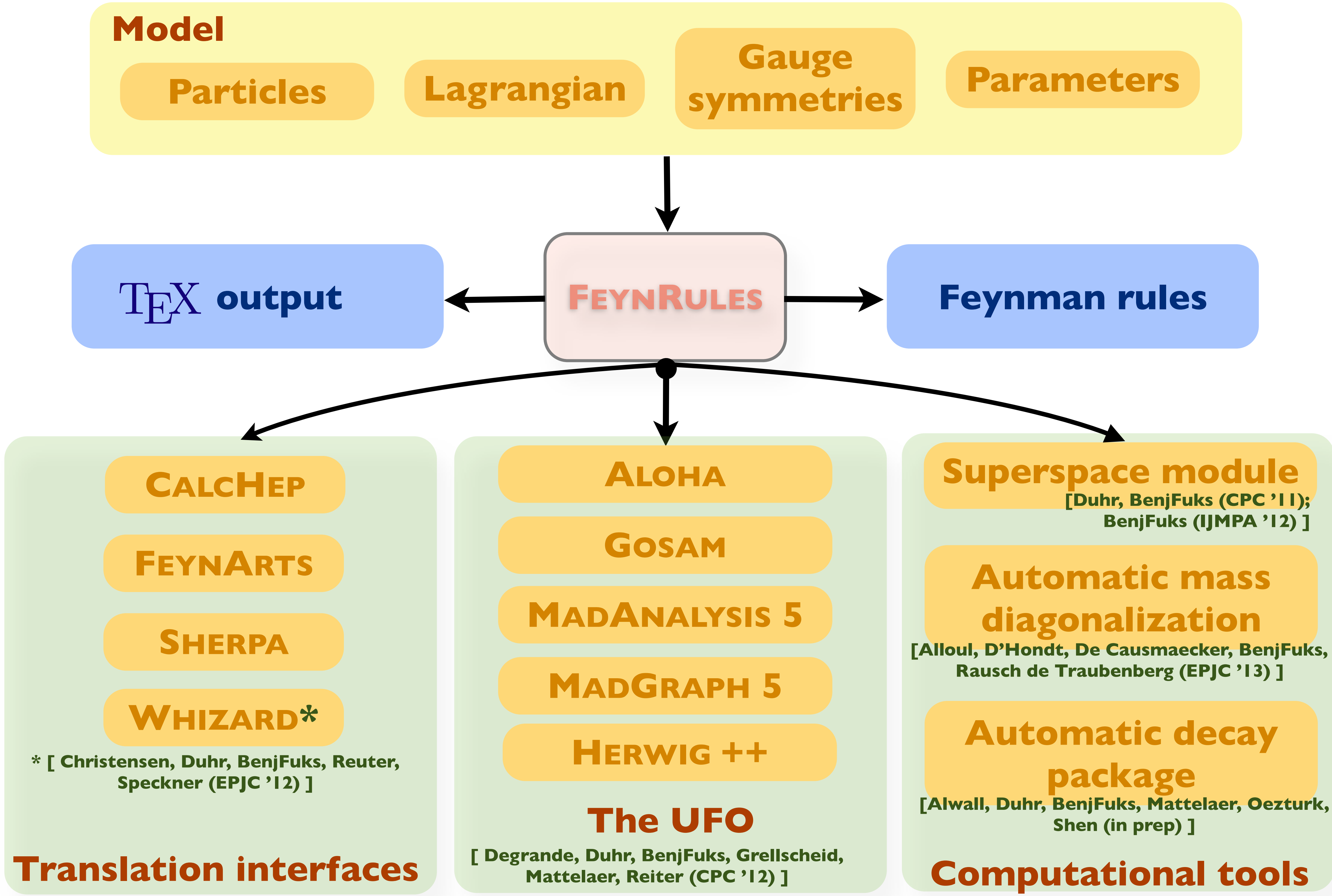
✦ Plus spin-1 and spin-2 interactions

A framework for LHC analyses



From FeynRules to Monte Carlo tools

[Christensen, Duhr (CPC '09); Alloul, Christensen, Degrande, Duhr, BenjFuks (arXiv:1309.7806; arXiv:1310.1921)]



From Lagrangians to histograms

1. Implementation of the model in FEYNRULES:

https://feynrules.irmp.ucl.ac.be/wiki/HEL
https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

2. Generation of the UFO model files

```
WriteUFO[lag]
```

3. Event generation with MADGRAPH 5
(including parton showering / hadronization / merging with PYTHIA 6)

```
./bin/mg5
> import model HC
> generate p p > X0 e+ ve
> add process p p > X0 e+ ve j
> add process p p > X0 e+ ve j j
> output HWJETS_mass
> launch
```

```
./bin/mg5
> import model HEL_UFO
> generate p p > h e+ ve
> add process p p > h e+ ve j
> add process p p > h e+ ve j j
> output HWJETS_gauge
> launch
```

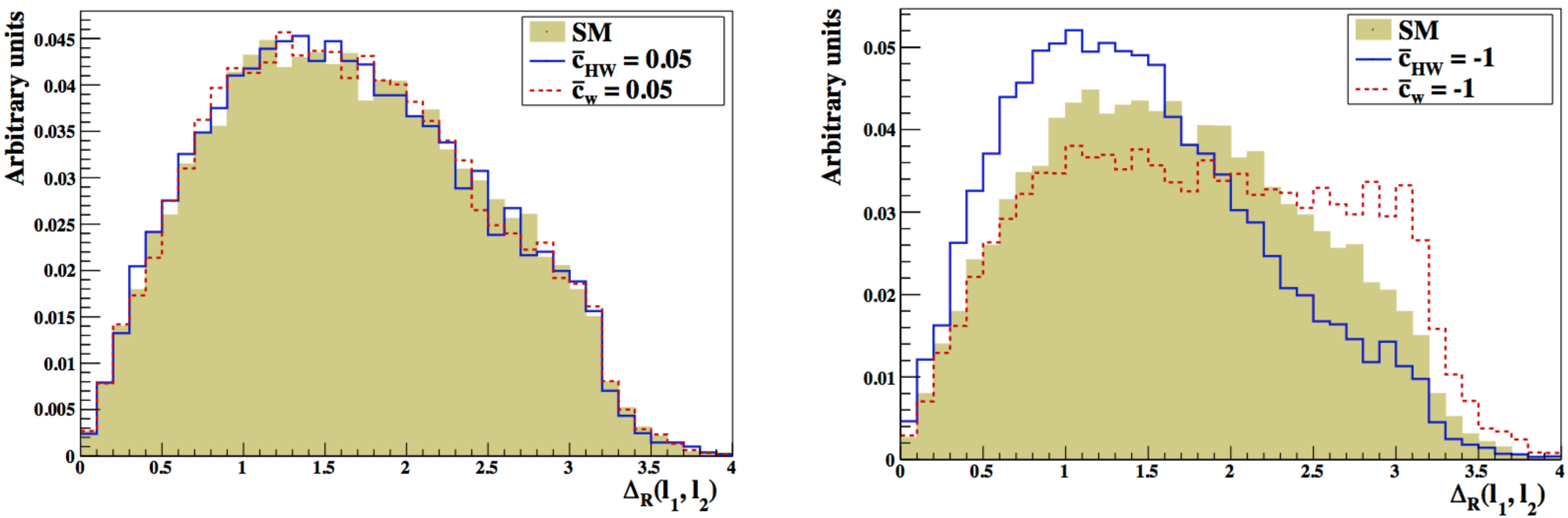
4. Event analysis with MADANALYSIS 5

```
./bin/ma5
> plot MET 50 0 500 [logY]
> plot PT(e+[1]) 25 0 500 [logY]
> submit
```

Effects on the Higgs decays into 4 fermions

[Alloul, BenjFuks, Sanz (arXiv:1310.5150)]

- We focus on the process $g\,g \to h \to W^* W^{(*)} \to (f_1 \bar{f}_1)\,(f_2 \bar{f}_2)$
  - We consider two operators: $\frac{ig\ \bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi\right] D^\nu W^k_{\mu\nu} + \frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu \Phi^\dagger T_{2k} D^\nu \Phi\right] W^k_{\mu\nu}$
  - Contribute to the h-W-W vertex
- Angular separation between the two charged leptons arising from the W-boson decays
  - Small couplings: no visible signal
  - Larger couplings: distortions are expected



Correlations from partial width measurements

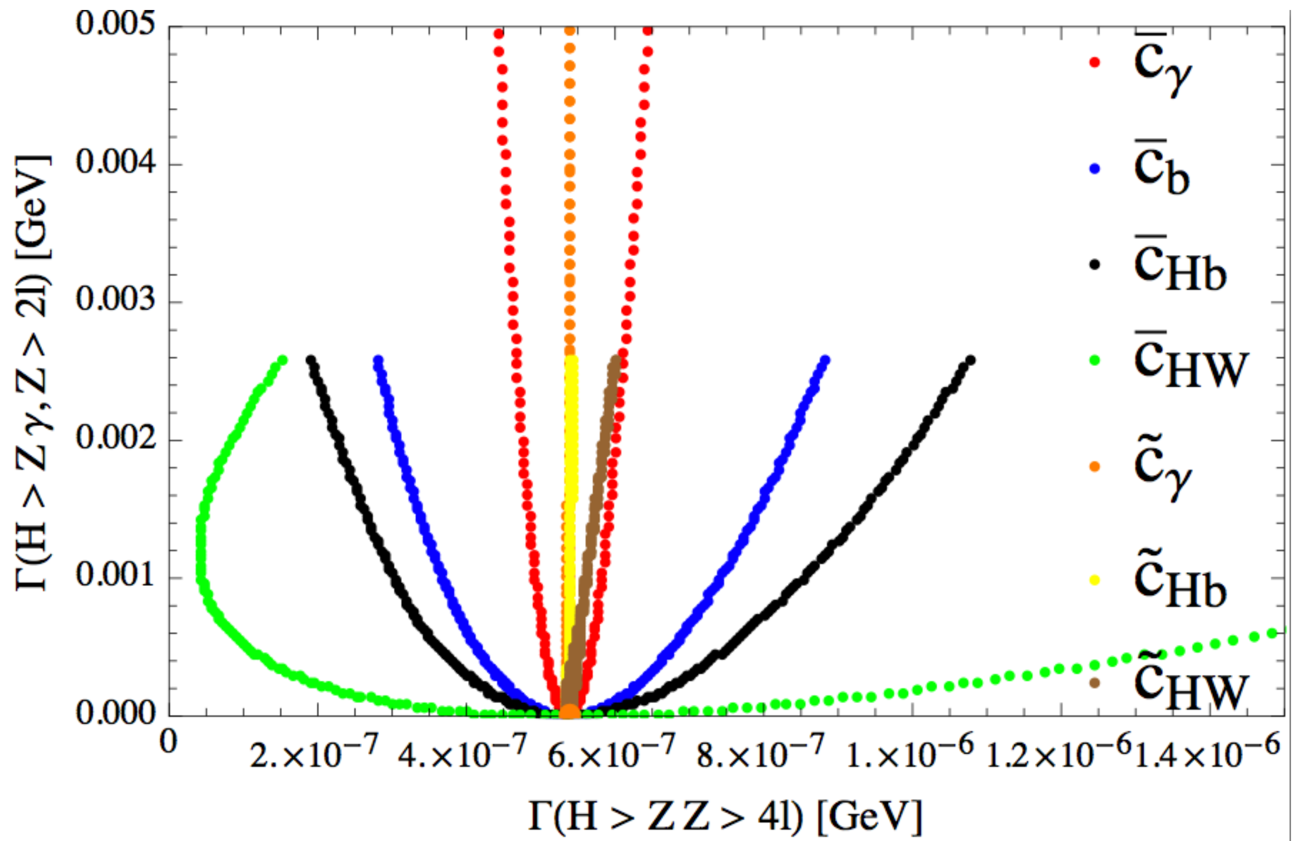
[Alloul, BenjFuks, Sanz (arXiv:1310.5150)]

- ✦ One operator
  - ✤ Induces several new physics couplings among the mass-eigenstates
  - ✤ Partial width measurements can constrain the coupling strength parameter space
- ✦ Example:
  - ✤ 4 CP-conserving and 3 CP-violating

$$\frac{ig'\,\bar{c}_B}{2m_W^2}\left[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right]\partial^\nu B_{\mu\nu} + \frac{2ig\,\bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k} D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\,\bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu}$$

$$+\frac{\bar{g}'^2\,c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{ig\,\tilde{c}_{HW}}{m_W^2}D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\widetilde{W}^k_{\mu\nu} + \frac{ig'\,\tilde{c}_{HB}}{m_W^2}D^\mu\Phi^\dagger D^\nu\Phi\widetilde{B}_{\mu\nu} \quad + \frac{g'^2\,\tilde{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde{B}^{\mu\nu}$$

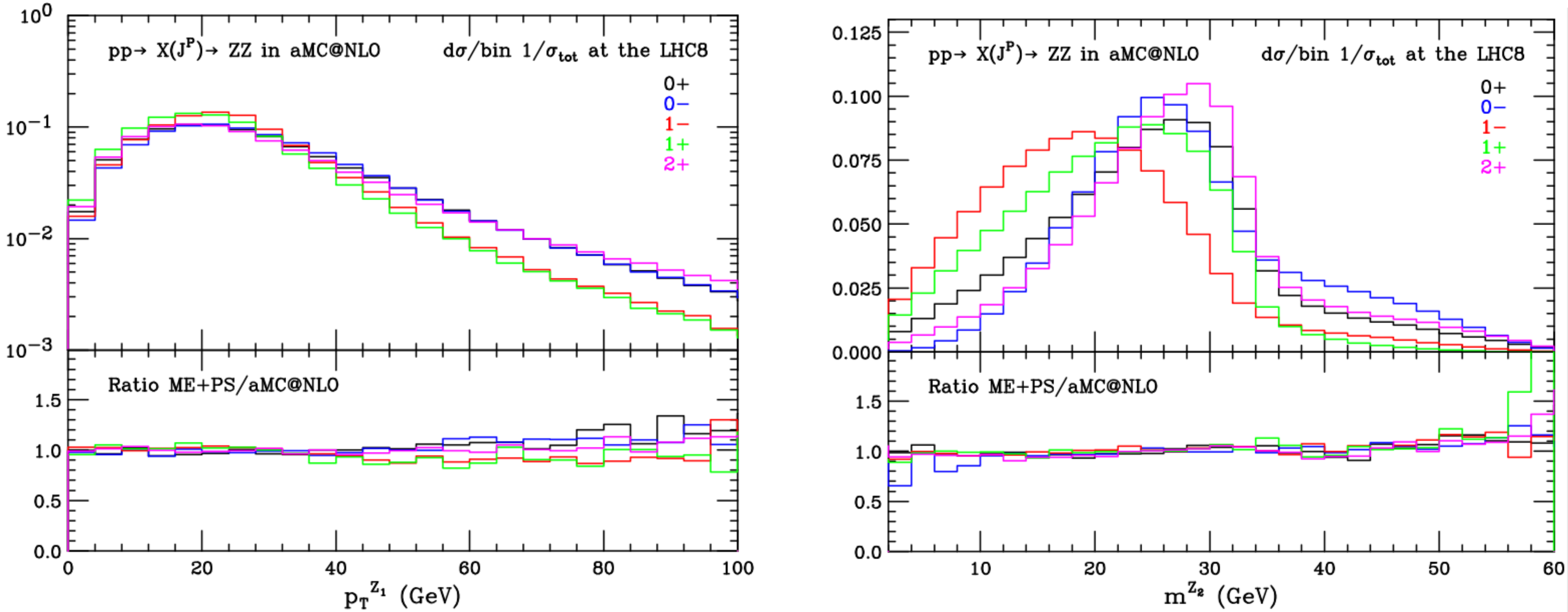
- ✤ Each operator induces h-Z-Z and h-photon-Z couplings
- ✤ Partial width measurements could probe which of these is/are non-zero



Higgs production via gluon fusion at NLO

[Artoisenet *et al* (arXiv:1306.6464)]

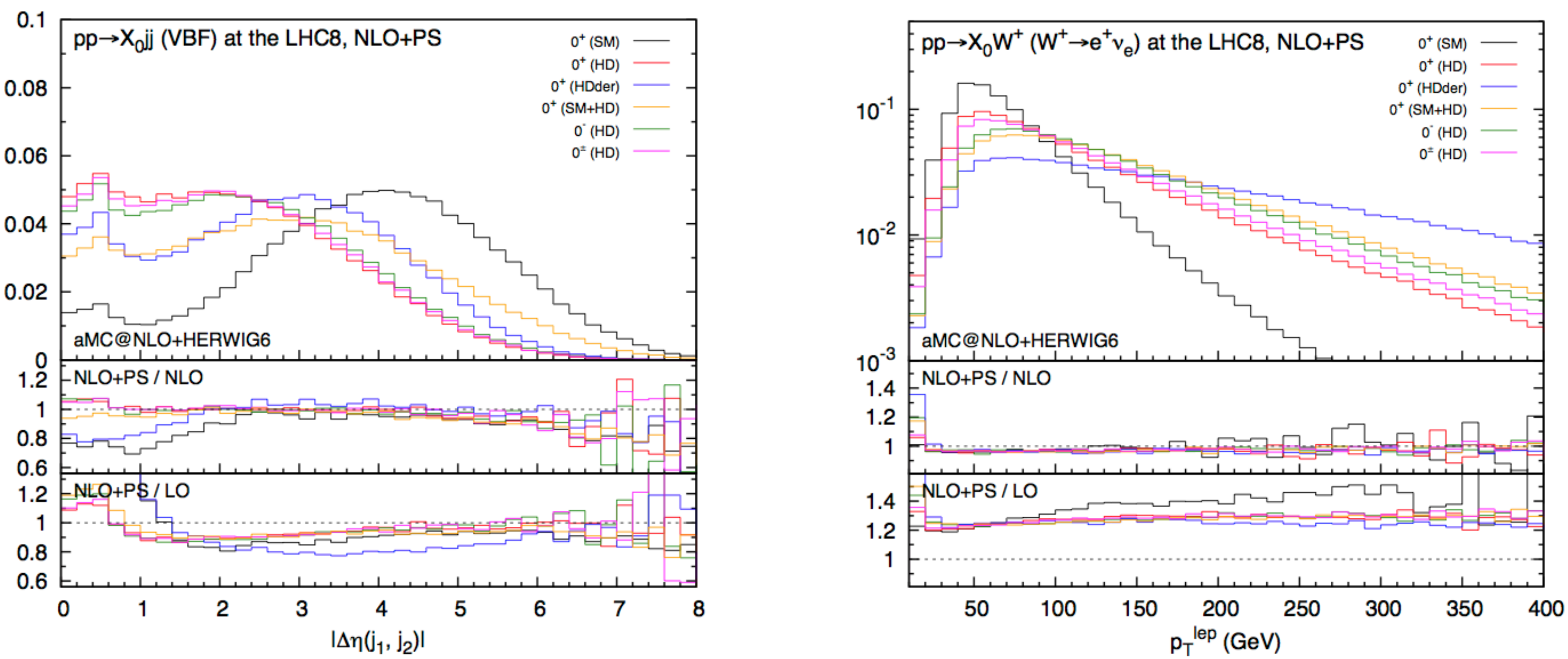
- Higgs production via gluon fusion at NLO, with a subsequent decay into 4 leptons
  - Comparing MADGRAPH5_AMC@NLO to merged matrix elements
    - ★ Good agreement (slightly worse for high p_T/invariant masses)
  - Different spin / CP hypotheses for the Higgs
  - Different kinematical distributions depending on the Higgs spin



Other Higgs production modes (VBF/VH) at NLO

[Maltoni, Mawatari, Zaro (arXiv:1311.1829)]

- Higgs production via vector boson fusion and associated production with V at NLO
  - Comparing MADGRAPH5_AMC@NLO to fixed order calculations at LO and NLO
    - Importance of the parton shower effects
  - Different benchmark points for a (pseudo)scalar Higgs boson
  - Different kinematical distributions depending on the new physics scenario



Summary

- We have implemented 39 operators related to Higgs physics in FeynRules
  - We implement them fully in the gauge basis
  - One single operator induces several physics effects (*i.e.*, couplings in the mass basis)
- In parallel, a complete model is also available in the mass basis
  - Relaxing the Higgs boson spin hypothesis
  - One single operator induces one single physics effects
- We have used the FeynRules - UFO - MadGraph5_aMC@NLO - MadAnalysis 5 chain for various phenomenological examples
- Is anything missing?