Higgs BSM simulations

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disclaimer (Who am I?)

- I'm a pheno person.
- I'd stayed for about 9 years in Europe and worked with 'MAD' people, so…

Plan of my talk

- Introduction: bottom-up
- BSM simulation framework
- Higgs Characterisation, SMEFT, …
- Discussions

The SM cannot be the ultimate theory !

How can we find BSM physics?

✓ Find new particles/ phenomena.

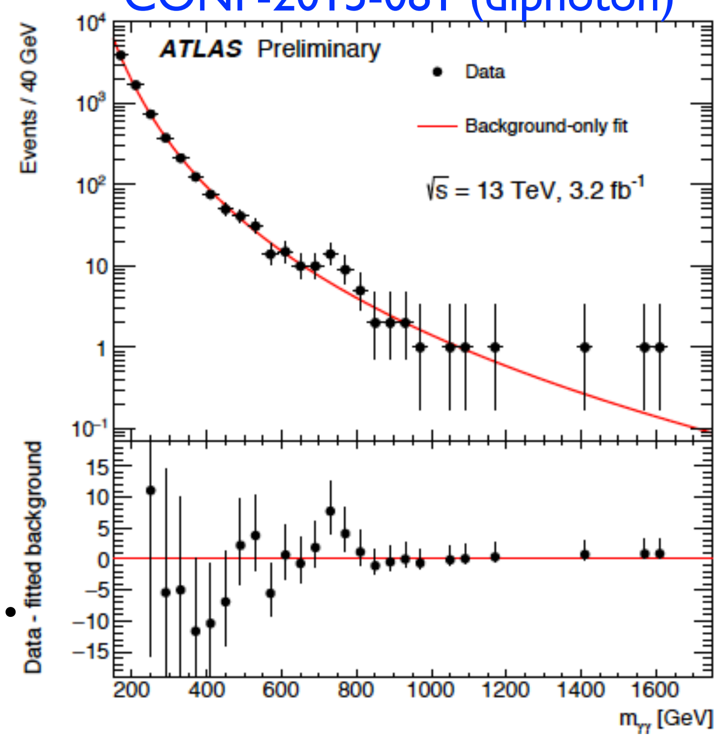
➡ Top-down approach: SUSY, ExtraDim, 2HDM, ...

✓ Find small deviations from the SM expectation.

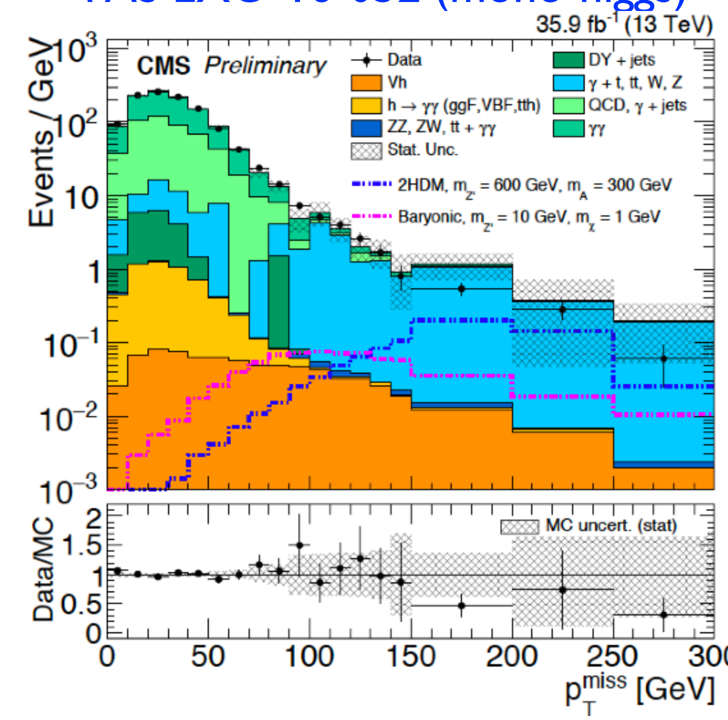
➡ Top-down approach: SUSY, ExtraD, 2HDM, ...

➡ Bottom-up approach: Effective field theory (EFT)

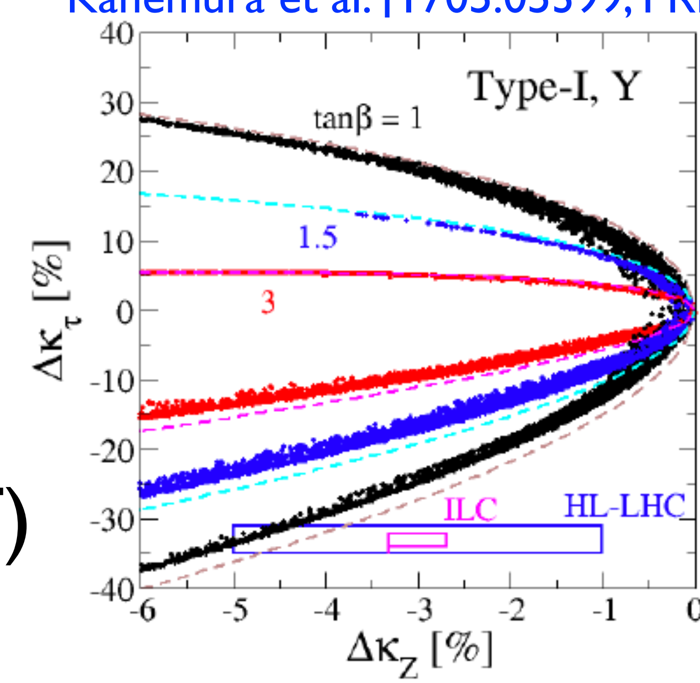
CONF-2015-081 (diphoton)



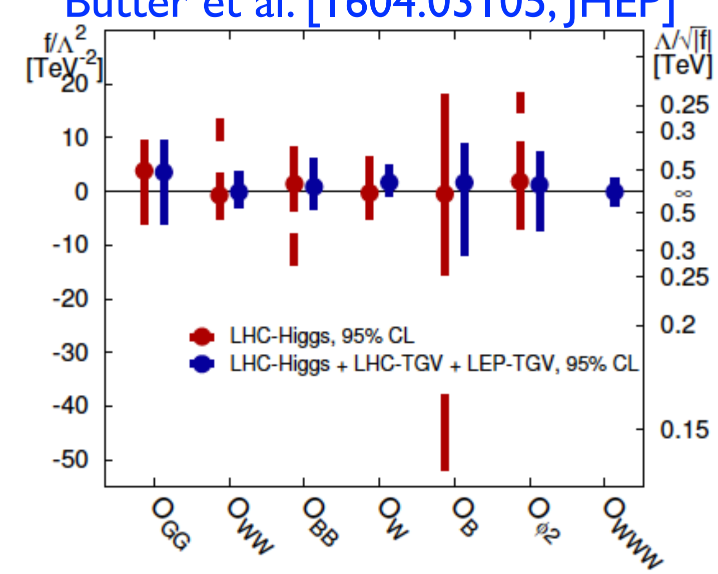
PAS EXO-16-052 (mono-higgs)



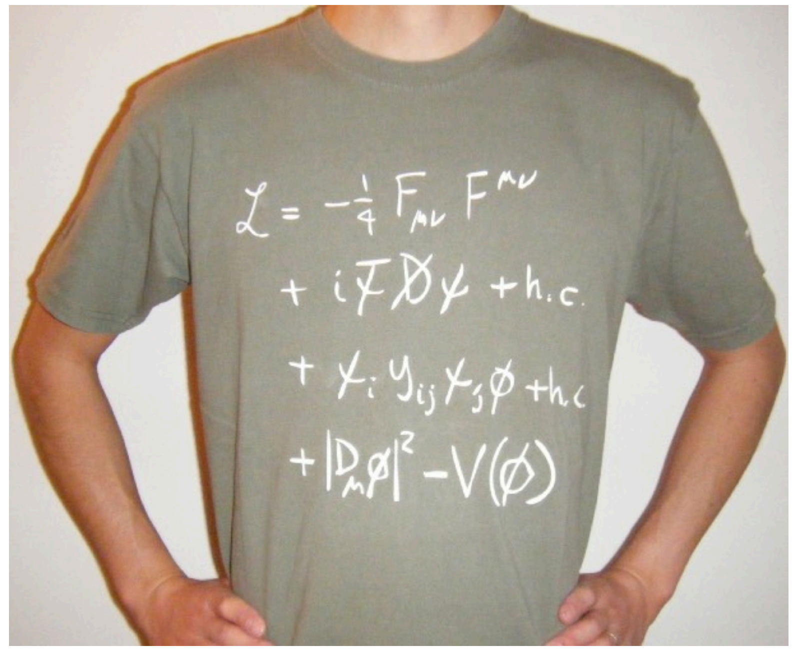
Kanemura et al. [1705.05399, PRD]

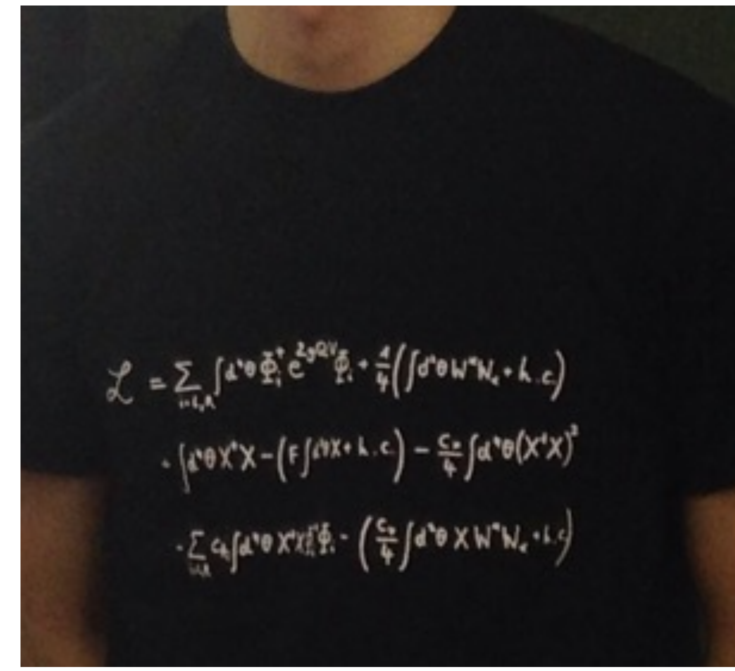


Butter et al. [1604.03105, JHEP]



Extending the SM Lagrangian





Top-down approach

predict ↓

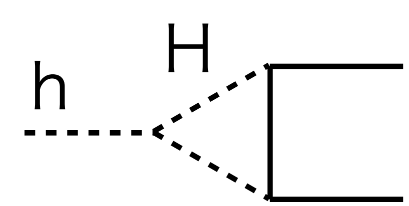
deviation from SM

find ↑

Bottom-up approach

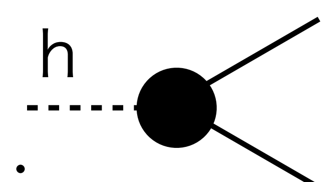
<u>UV model</u> : SUSY, ExtraDim, extended Higgs, ⋯

$$\{\mathcal{L}; m_1, m_2, \cdots, g_1, g_2, \cdots\}$$



<u>EFT</u> : SM gauge group, particles

$$\{\mathcal{L}; \Lambda, c_1, c_2, \cdots\} \quad \mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i O_i^{\rm D6} + \cdots$$



renormalizable order by order, systematically improvable

Deviation patterns → BSM model

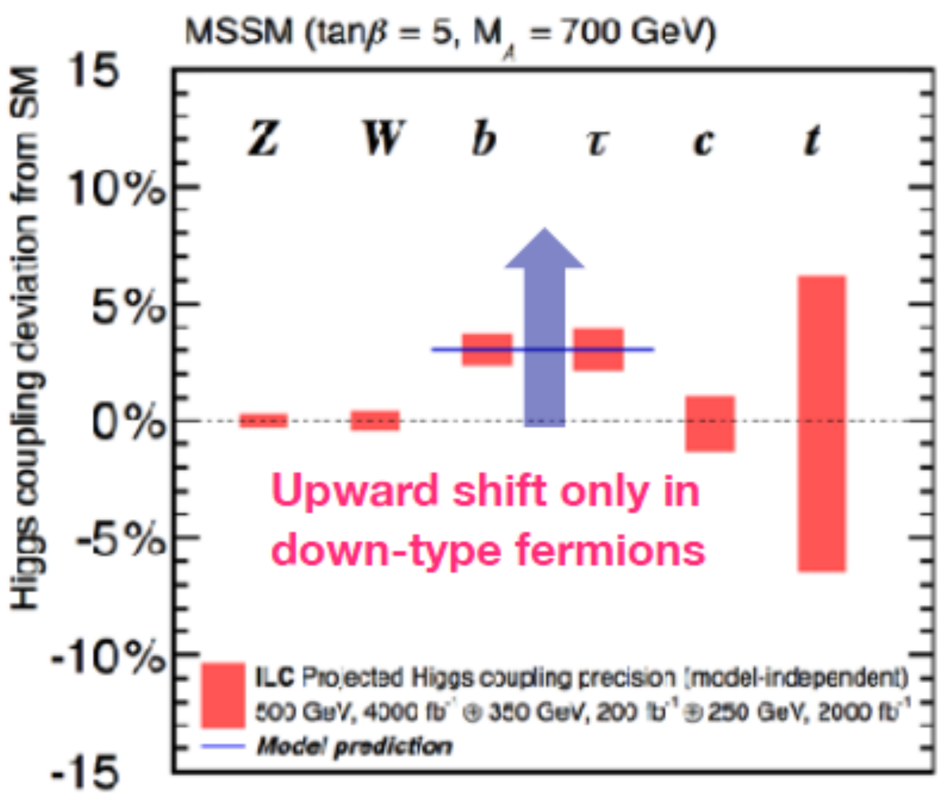
H20 Scenario
arXiv: 1506.05992
arXiv: 1506.07830

Fingerprinting

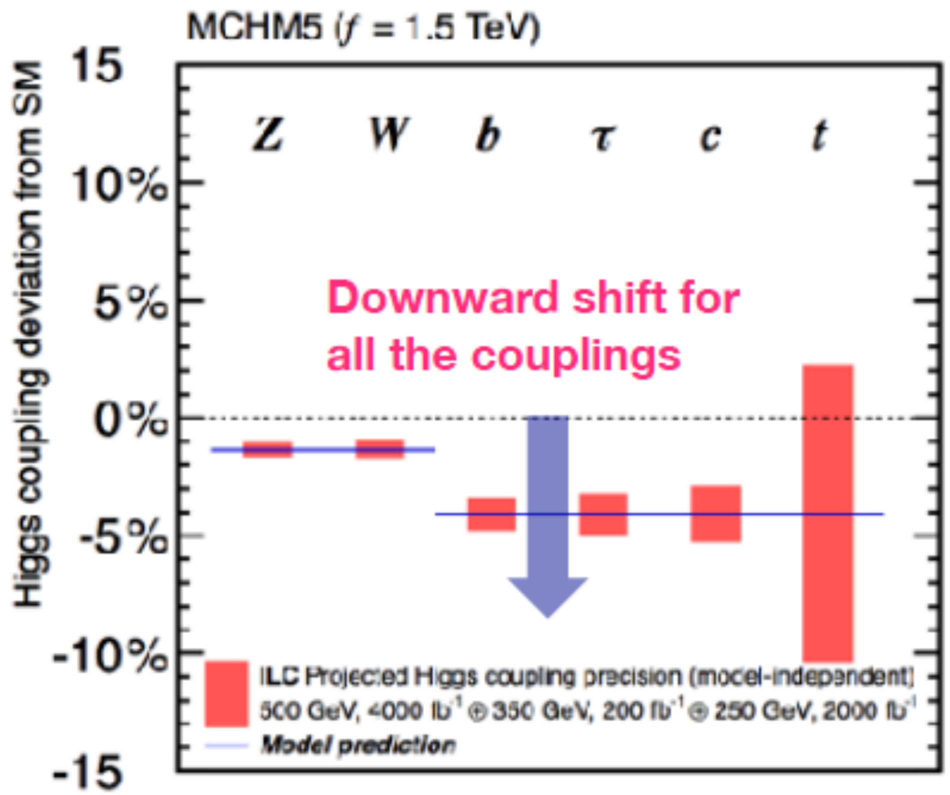
by K. Fujii

Elementary v.s. Composite?

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



ILC 250+500 LumiUP

Complementary to direct searches at LHC: Depending on parameters, ILC's sensitivity far exceeds that of LHC!

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Bottom-up strategy

- Use EFT to find the deviations from SM expectations systematically.
  1. deviations !

     ➡deviation patterns can select UV models

     ➡learn the mass scale in the loops

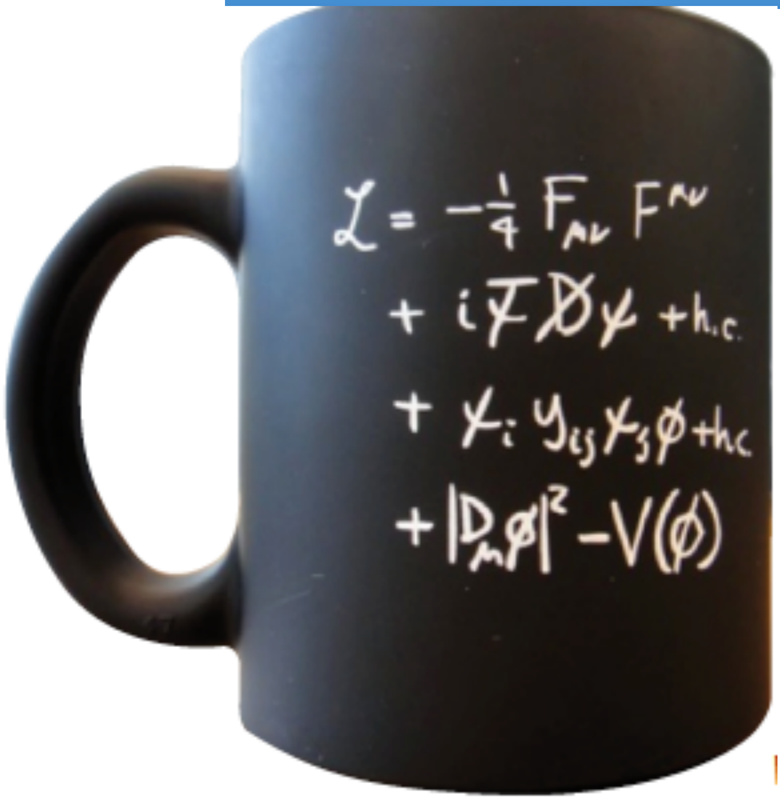
     ➡build a100TeV collider ?
  2. no deviations …

     ➡constraints UV models

     ➡learn the lowest mass scale in the loops

     ➡switch to astro-particle, string ?

Lagrangian (TH) ⇔ Data (EXP)

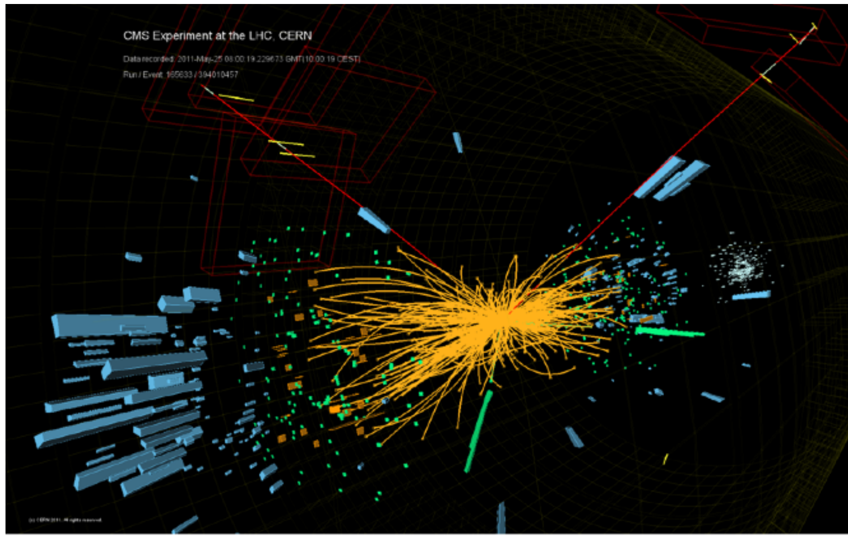


simulation tools

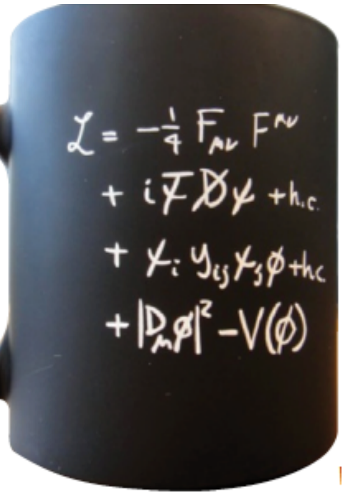
prediction

interpretation

Higgs Couplings 2017

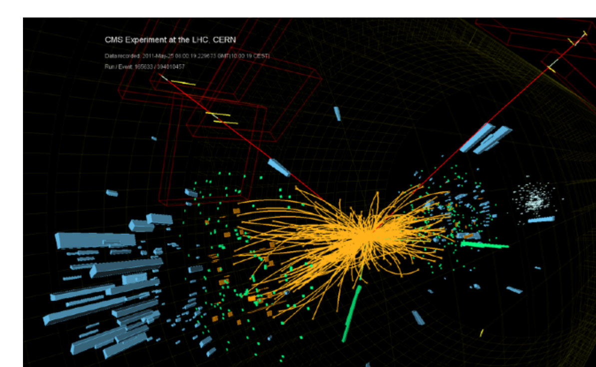


BSM workflow (I) before LHC (Tilman's generation)

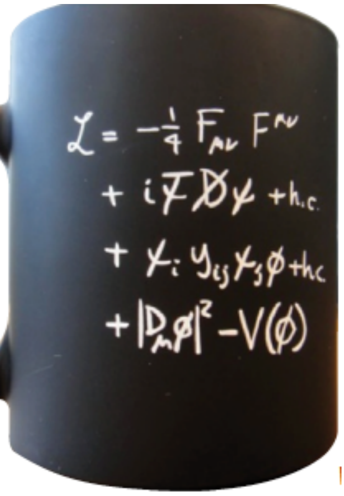


- take a BSM model (symmetry, particle contents,…), i.e. Lagrangian
  - derive the Feynman rules
    - draw Feynman diagrams for interesting 2→2 processes
      - compute the amplitude (squared)
        - implement it into a generator manually
          - generate events
            - parton-shower/hadronisation

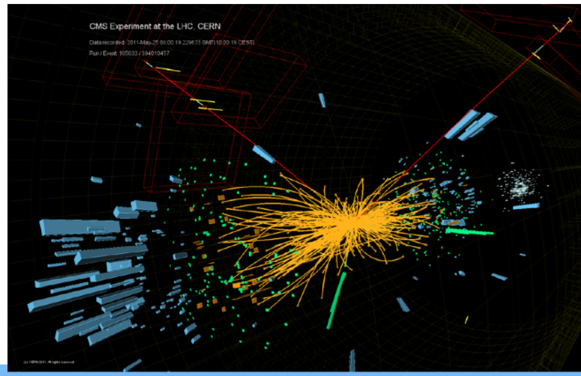
              Herwig, Pythia
              - detector simulation
                - analysis



BSM workflow (II) before LHC (Tilman's generation)

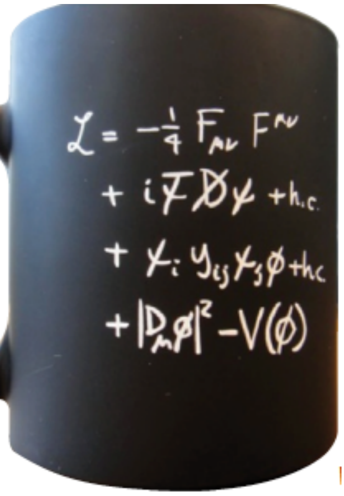


- take a BSM model (symmetry, particle contents,…), i.e. Lagrangian
  - derive the Feynman rules
    - make the model file (make subroutines to compute helicity amplitudes)
      - draw Feynman diagrams for interesting any processes
        - compute the amplitude (squared) MadGraph4
          - generate events
            - parton-shower/hadronisation Herwig, Pythia
              - detector simulation
                - analysis

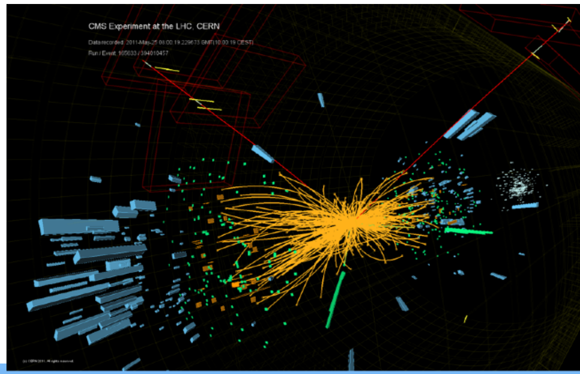


BSM workflow after LHC (my generation)

at NLO (QCD) partially



- take a BSM model (symmetry, particle contents,…), i.e. Lagrangian
  - derive the Feynman rules — Model providers
    - draw Feynman diagrams for interesting any processes
      - compute the amplitude (squared) — Matrix-element generators
        - generate events
          - parton-shower/hadronisation — Shower MC
            - detector simulation — Detector simulation tools
              - analysis — Analysis tools



FeynRules in a nutshell

FR1: Christensen, Duhr [0806.4194, CPC]
FR2: Alloul, Christensen, Degrande, Duhr, Fuks [1310.1921, CPC]
NLOCT: Degrande [1406.3030, CPC]

FeynRules: http://feynrules.irmp.ucl.ac.be/

- a Mathematica package that allows to derive Feynman rules from a Lagrangian.
- allows to export the Feynman rules to various matrix element generators, e.g. CalcHEP, FeynArts, MadGraph, Sherpa, Whizard, ...

- The only requirements on the Lagrangian are Locality and Lorentz invariance; no limitation for the dimensionality.
- Supported filed types are spin-0, 1/2, 1, 3/2, and 2 (as well as superfields).

BSM models in the FeynRules model database

feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

FeynRules model database

This page contains a collection of models that are already implemented in FeynRules. For each model, a complete model-file is available, containing all the information that is needed, as well as the Lagrangian, as well as the references to the papers were this Lagrangian was taken from. All model-files can be freely downloaded and changed, serving like this as the starting point for building new models. A TeX-file for each model containing a summary of the Feynman Rules produced by FeynRules is also available.

The Standard model model-file is already included in the distribution of the FeynRules, but it can also be downloaded independently from the corresponding link below.

We encourage model builders writing a FeynRules implementation of their model to make their model file(s) public in the FeynRules model database, in order to make them useful to a community as wide as possible. For further information on how to make your model implementation public via the FeynRules model database, please send an email to

- neil@...
- celine.degrande@...
- claude.duhr@...
- benjamin.fuks@...

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous	
NLO	Models ready for NLO computations

EFT models in the FeynRules model database

feynrules.irmp.ucl.ac.be

wiki: EffectiveModels

スタートページ | ページ一覧 | 履歴

最終更新 7週前

Strongly-coupled models and effective field theories

Model	Short Description	Contact	Status
Axion-Like Particles	Effective Theories for a light Axion-Like Particle	I. Brivio	**Available**
Anomalous Gauge Boson Couplings	Model including anomalous couplings among gauge bosons	O.J.P. Eboli, M.C. Gonzalez-Garcia	**Available**
BSM Characterisation	The SM EFT Lagrangian in the mass basis	B. Fuks, K. Mawatari	**Available**
Chiral perturbation theory	The effective Lagrangian describing the low-energy interaction of mesons.	C. Degrande	**Available**
Effective theory for 4 top production	Dimension-six operators invariant under the SM symmetries affecting 4 top interactions	C.Degrande	**Available**
Effective theory for weak gauge boson production	Dimension-six operators invariant under the SM symmetries affecting triple gauge boson interactions	C.Degrande	**Available**
Effective top-Higgs interactions	Dimension 6 Higgs-top interactions.	E. Salvioni and J. Dror	**Available**
FCNC Higgs interactions	The SM plus higher-dimensional flavor changing Higgs interactions.	S. Krastanov	**Available**
FCNC Top interactions	The SM plus higher-dimensional flavor changing top-quark interactions.	A. Amorim, J. Santiago, N. Castro, R. Santos	**Available**
HiggsCharacterisation	The model file for the spin/parity characterisation of a 125 GeV resonance.	F. Demartin, K. Mawatari	**Available**
Higgs Effective Lagrangian	Higgs effective Lagrangian including operators up-to dimension 6.	A. Alloul, B. Fuks and V. Sanz	**Available**
Higgs effective theory	An add-on for the SM implementation containing the dimension 5 gluon fusion operator.	C. Duhr	**Available**
Mimimal Higgsless Model (3-Site Model)	A higgsless model, including new heavy fermions and a Z' and a W' boson.	N. Christensen	**Available**
nTGC Effective theory	dimension-8 operators invariant under the SM symmetries affecting neutral triple gauge boson couplings	C. Degrande	**Available**
Strongly Interacting Light Higgs	A model including higher-dimensional SM operators to describe strongly coupled theories of EWSB.	C. Degrande	**Available**
Technicolor	The Minimal Walking Technicolor Model	M. Järvinen, T. Hapola, E. Del Nobile, C. Pica	**Available**
EFT mass basis	The SM EFT Lagrangian in the mass basis	B. Fuks, K. Mawatari	**Available**
TFCNC	The SM, plus FCNC top interactions.	M. Buchkremer, G. Cacciapaglia, A. Deandrea, L. Panizzi	**Available**
The SMEFT in the Warsaw basis	Standard Model Effective Field Theory	I. Brivio, Y. Jiang, M. Trott,	**Available**
Top Effective theory	Higher-dimensional operators invariant under the SM symmetries affecting top production and decay	C. Degrande	**Available**
Top Effective theory for FCNC	Dimension-six operators invariant under the SM symmetries affecting top FCNC	C.Degrande, G. Durieux, F. Maltoni, C. Zhang	**Available**

YR4. Deciphering the nature of the Higgs sector

[HXSWG, 1610.07922]

Abstract

… The main goal of the working group was to present the state-of-the-art of Higgs physics at the LHC, integrating all new results that have appeared in the last few years. …

Contents

WG1: HiggsXS&BR
WG2: Higgs properties
WG3: BSM Higgs

Effective Field Theory Predictions (WG2)

SMEFTsim

BSM simulation tools

- Impressive progresses during the last 10 years.
  - We can simulate any processes in any BSM models (specific models and EFT) at the tree level by ME+PS merging.
  - Fully automatic NLO-QCD computations for SM processes as well as for several BSM processes, e.g. simplified SUSY and DM models, are already publicly available.
  - A lots of developments of EFT-related tools are on-going.
- What is our short-term (by the end of Run-II) goal ?
- What should we do toward higher precision data (HL-LHC, ILC, etc) ?

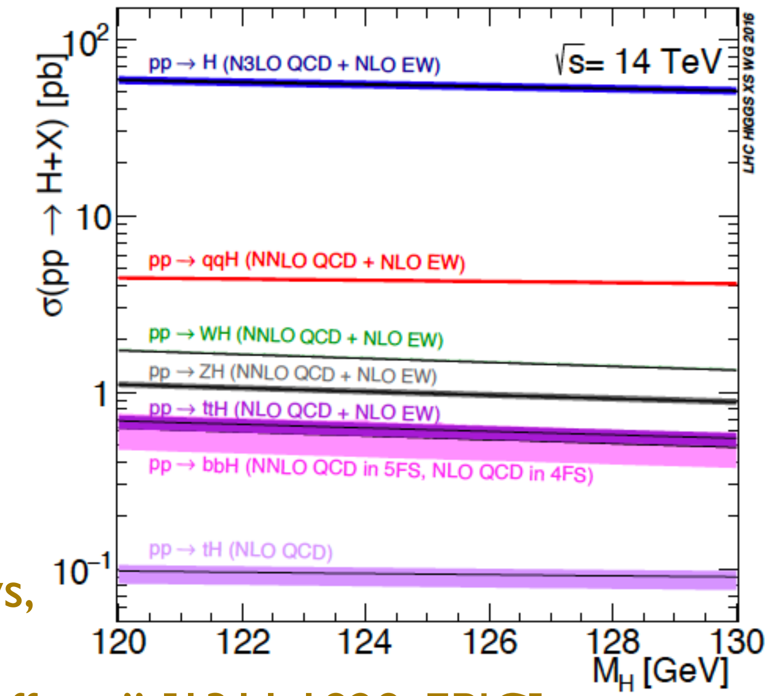
Higgs Characterisation (HC)

via the FeynRules and MadGraph5_aMC@NLO frameworks

• provides an automated NLO(QCD)+PS accurate tool and predictions to accomplish the general and accurate characterisation of Higgs interactions in the main production and decay modes at the LHC.

• is equally useful for theorists (it can be systematically improved, changed easily) and experimentalists (event generation easily).

• is publicly available at the FeynRules repository:
https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation



‣ HC1 (spin-0,1,2): "A framework for Higgs characterisation" [1306.6464, JHEP]
Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro

‣ HC2 (VBF/VH): "Higgs characterisation via VBF/VH: NLO and parton-shower effects" [1311.1829, EPJC]
Maltoni, Mawatari, Zaro

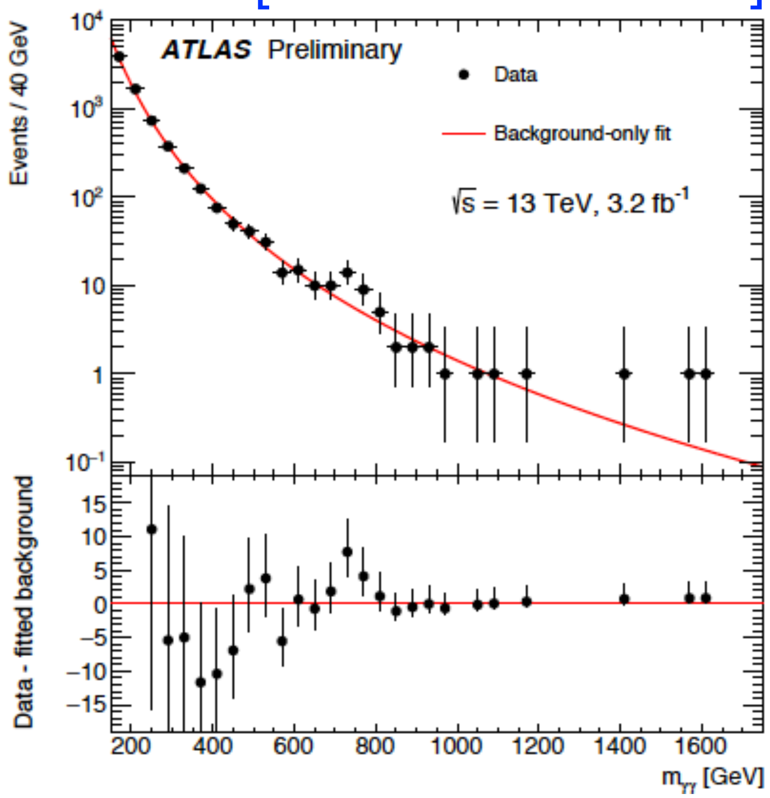
‣ HC3 (GF(H+jets)/ttH): "Higgs characterisation at NLO: CP properties of the top Yukawa" [1407.5089, EPJC]
Demartin, Maltoni, Mawatari, Page, Zaro

‣ HC4 (tH): "Higgs production in association with a single top quark at the LHC" [1504.00611, EPJC]
Demartin, Maltoni, Mawatari, Zaro

‣ HC5 (tWH): "tWH associated production at the LHC" [1607.05862, EPJC]
Demartin, Maier, Maltoni, Mawatari, Zaro

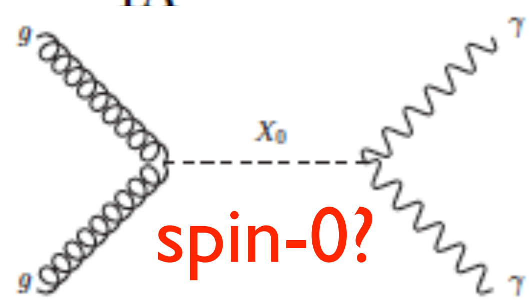
???GeV resonance characterisation

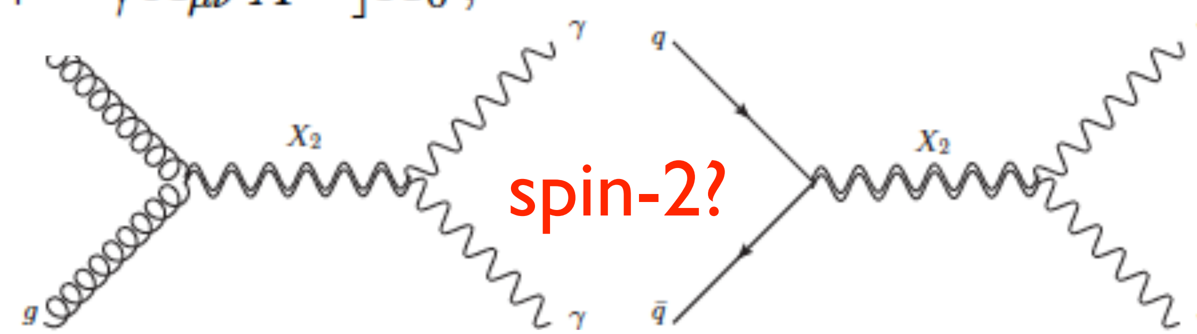
[ATLAS CONF-2015-081]



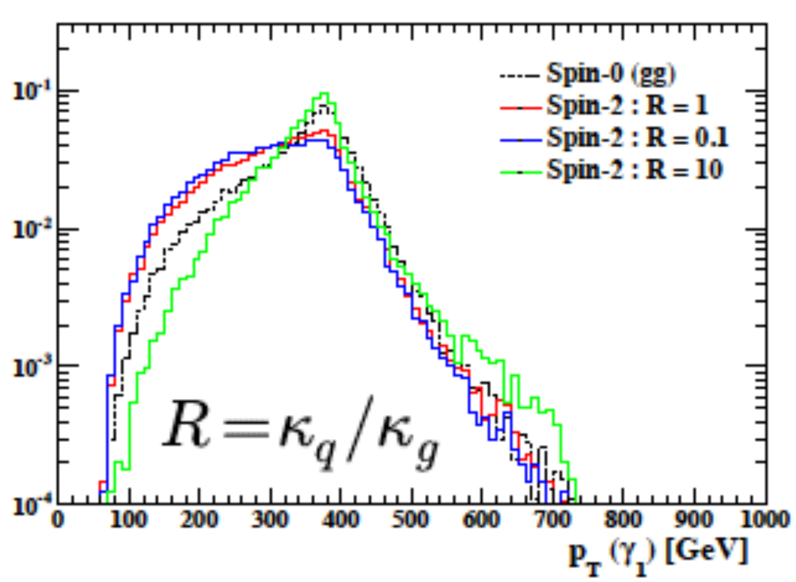
Bernon, Goudelis, Kraml, KM, Sengupta [1603.03421, JHEP]

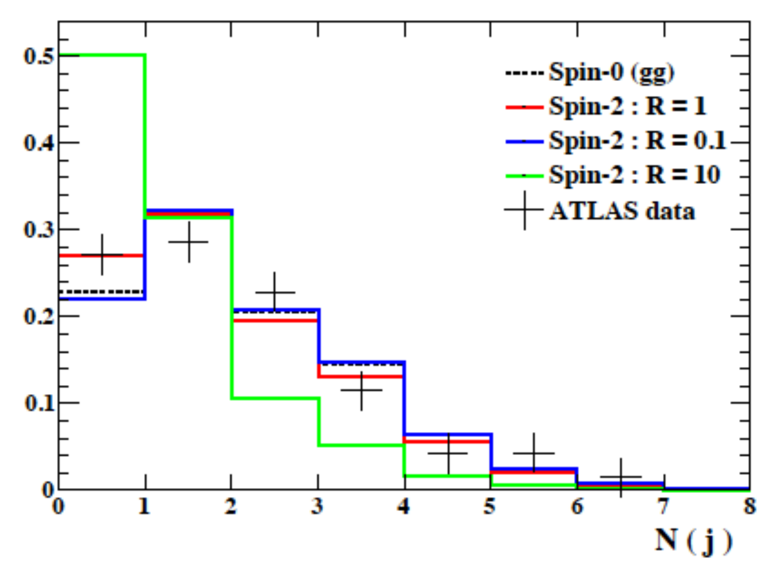
$$\mathcal{L}_0^g = \frac{1}{4\Lambda}\left[\overset{(\sim)}{\kappa}_g\, G^a_{\mu\nu}\overset{(\sim)}{G}{}^{a,\mu\nu} + \overset{(\sim)}{\kappa}_\gamma\, A_{\mu\nu}\overset{(\sim)}{A}{}^{\mu\nu}\right] X_0\,,$$

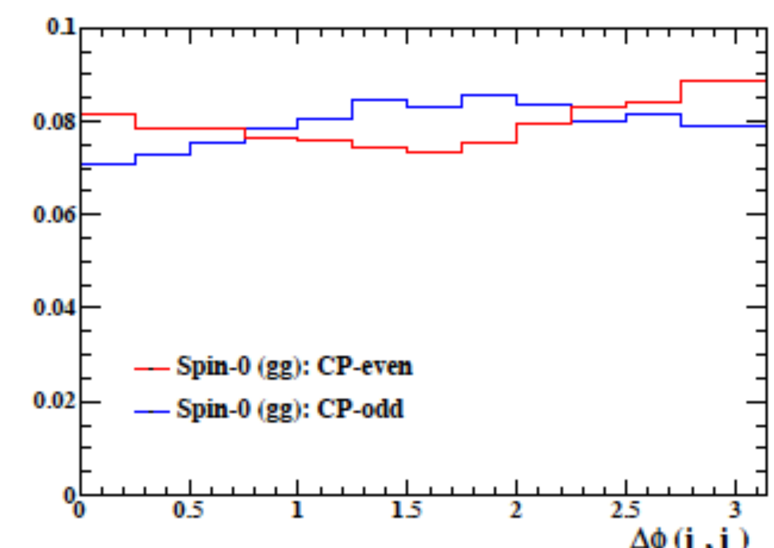




$$\mathcal{L}_2 = -\frac{1}{\Lambda}\left[\kappa_g\, T^g_{\mu\nu} + \kappa_q\, T^q_{\mu\nu} + \kappa_\gamma\, T^\gamma_{\mu\nu}\right] X_2^{\mu\nu}\,,$$







HC effective Lagrangian -- spin0

$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar\psi_f \big(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \gamma_5\big)\psi_f X_0$$

$$\begin{aligned}\mathcal{L}_0^{Z,W} = \Big\{ & c_\alpha \kappa_{\rm SM}\Big[\frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\Big] \\ & -\frac{1}{4}\frac{1}{\Lambda}\Big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\Big] \\ & -\frac{1}{2}\frac{1}{\Lambda}\Big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\Big] \\ & -\frac{1}{\Lambda} c_\alpha\Big[\kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} \\ & \quad + \big(\kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\Big]\Big\} X_0\,,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_0^{\rm loop} = \Big\{ & -\frac{1}{4}\Big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} \\ & \quad + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\Big] \\ & -\frac{1}{4}\Big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} \\ & \quad + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\Big] \\ & -\frac{1}{2}\Big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} \\ & \quad + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\Big]\Big\} X_0\,,\end{aligned}$$

parameter	description
Λ [GeV]	cutoff scale
c_α ($\equiv \cos\alpha$)	mixing between 0^+ and 0^-
κ_i	dimensionless coupling parameter

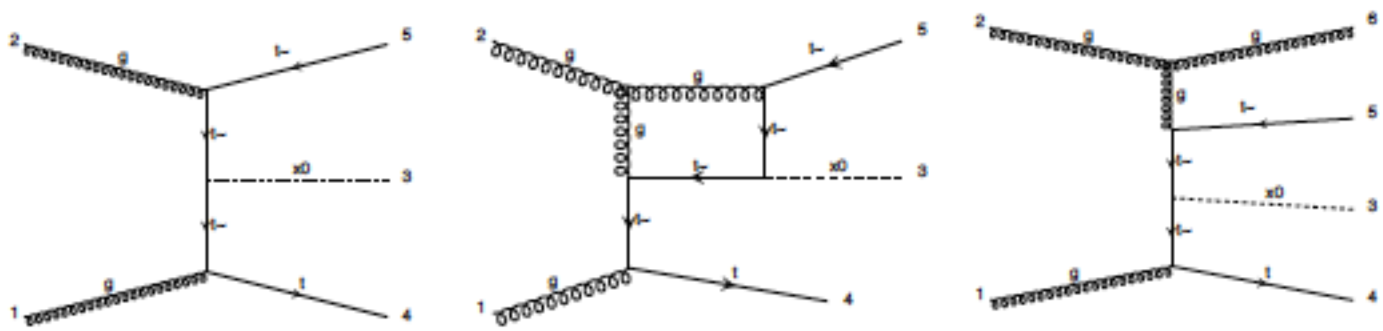
Dimensionful couplings g are set as internal parameters so as to reproduce a SM Higgs for κ=1.

$g_{Xyy'} \times v$	ff	ZZ/WW	$\gamma\gamma$	$Z\gamma$	gg
H	m_f	$2m^2_{Z/W}$	$47\alpha_{\rm EM}/18\pi$	$C(94\cos^2\theta_W - 13)/9\pi$	$-\alpha_s/3\pi$
A	m_f	0	$4\alpha_{\rm EM}/3\pi$	$2C(8\cos^2\theta_W - 5)/3\pi$	$\alpha_s/2\pi$

Higgs characterisation in ttH

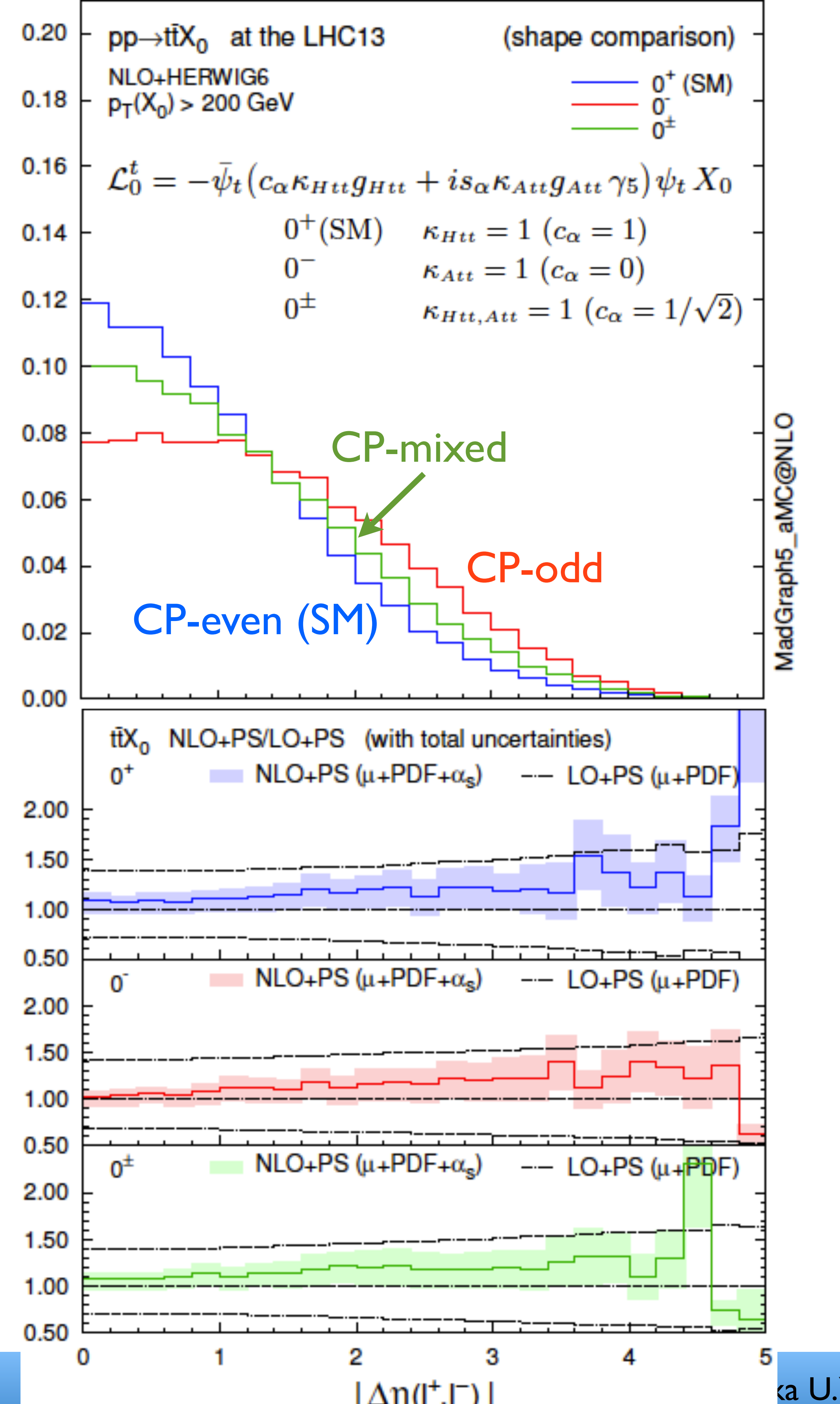
HC3: Demartin, Maltoni, KM, Page, Zaro [arXiv:1407.5089]

```
./bin/mg5_aMC
>import model HC_NLO_X0
>generate p p > x0 t t~ [QCD]
>output
>launch
```



scenario		$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	K
	0^+	$468.6(4)\ ^{+32.8}_{-22.8}\ \pm4.5\%$	$525.1(7)\ ^{+5.7}_{-8.7}\ \pm2.1\%$	1.12
LHC 13 TeV	0^-	$196.8(2)\ ^{+37.1}_{-25.2}\ \pm7.5\%$	$224.3(3)\ ^{+6.8}_{-10.5}\ \pm3.2\%$	1.14
	$0^\pm$	$332.4(3)\ ^{+34.0}_{-23.5}\ \pm5.4\%$	$374.1(5)\ ^{+6.0}_{-9.3}\ \pm2.5\%$	1.13

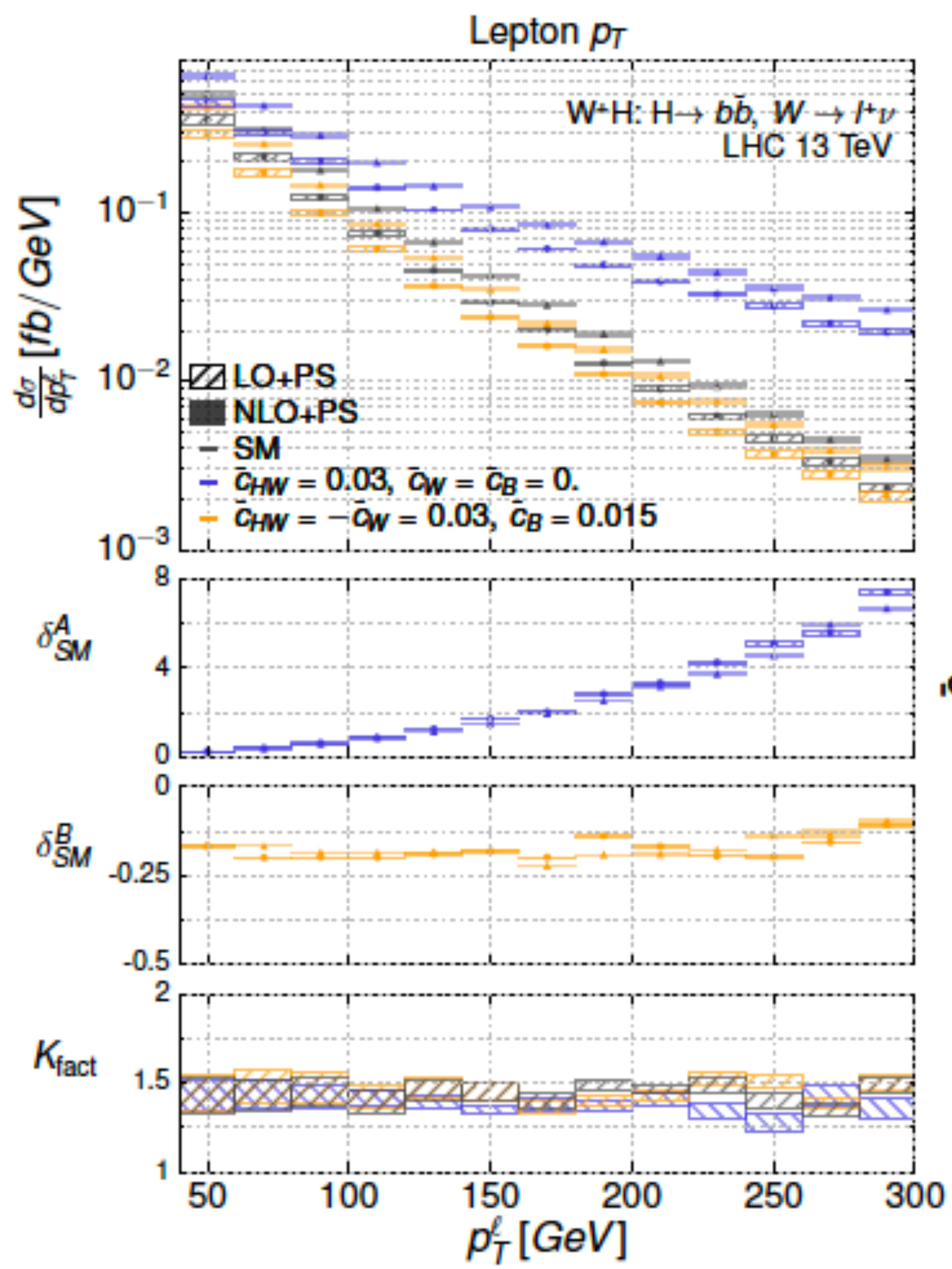
- The total rate and the correlations between top and antitop decay products can be sensitive to the CP nature of the Higgs boson.
- NLO corrections cannot be described by an overall *K* factor and the constant theoretical uncertainties.



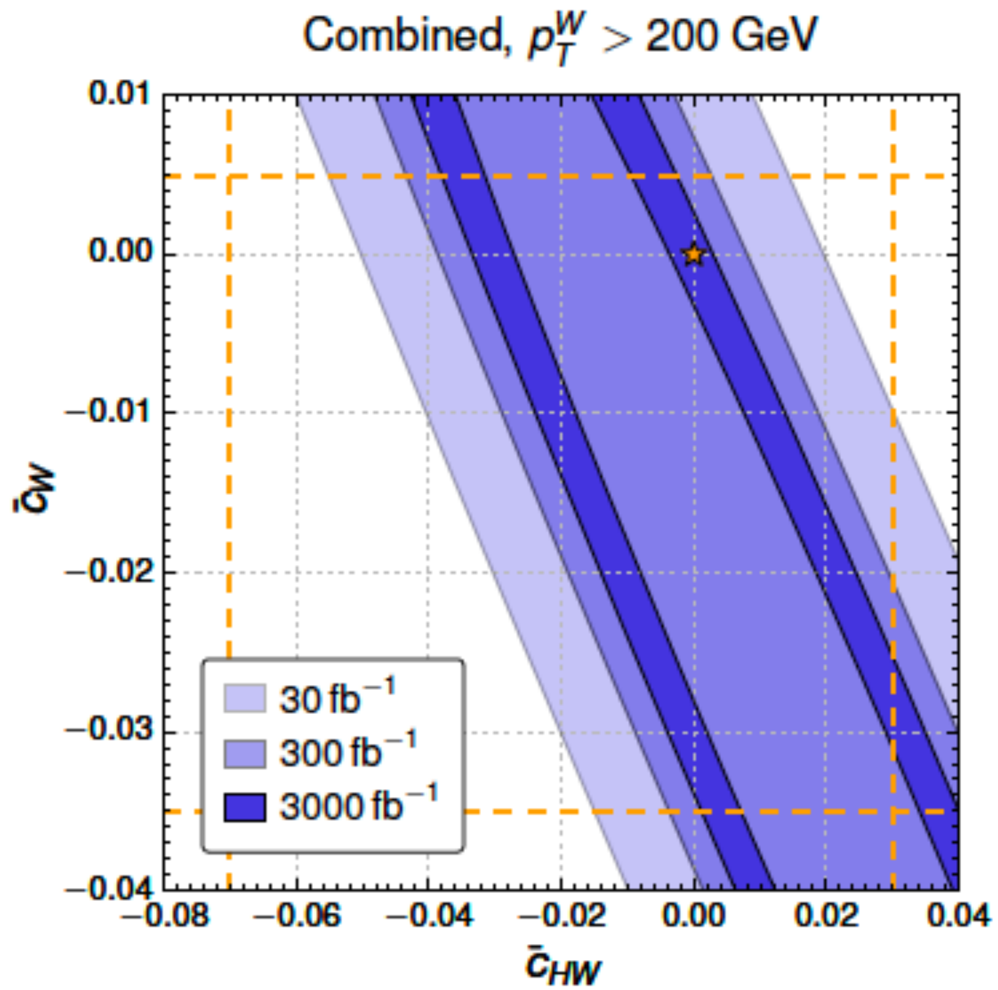
Towards a complete SMEFT at NLO(QCD)

Degrande, Fuks, KM, Mimasu, Sanz [1609.04833, EPJC]

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\rm SM} &+ \frac{g'^2}{4\Lambda^2}\bar{c}_{BB}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} \\ &+ \frac{ig}{2\Lambda^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu} \\ &+ \frac{ig'}{2\Lambda^2}\bar{c}_B\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]\partial_\nu B^{\mu\nu} \\ &+ \frac{ig}{\Lambda^2}\bar{c}_{HW}\left[D_\mu\Phi^\dagger T_{2k}D_\nu\Phi\right]W^{k,\mu\nu} \\ &+ \frac{ig'}{\Lambda^2}\bar{c}_{HB}\left[D_\mu\Phi^\dagger D_\nu\Phi\right]B^{\mu\nu}\ .\end{aligned}$$



validation with MCFM/Powheg
Mimasu, Sanz, Williams [1512.02572, JHEP]



Time for discussions

- The EFT (bottom-up) approach is not so exciting, but rather crucial to explore BSM.

- What is our short-term (by the end of Run-II) goal ?
- What should we do toward higher precision experiments (HL-LHC, ILC, etc) ?