Tools for Higgs Physics

Cross Section

ggF
HIGLU (NNLO QCD+NLO EW)
iHixs (NNLO QCD+NLO EW)
FeHiPro (NNLO QCD+NLO EW)
HNNLO, HRes (NNLO+NNLL QCD)
SusHi (NNLO QCD)
RGHiggs (NNLO+NNNLL QCD)
ggHiggs (approx. NNNLO QCD)

VBF
VV2H (NLO QCD)
VBFNLO (NLO QCD)
HAWK (NLO QCD+EW)
VBF@NNLO (NNLO QCD)

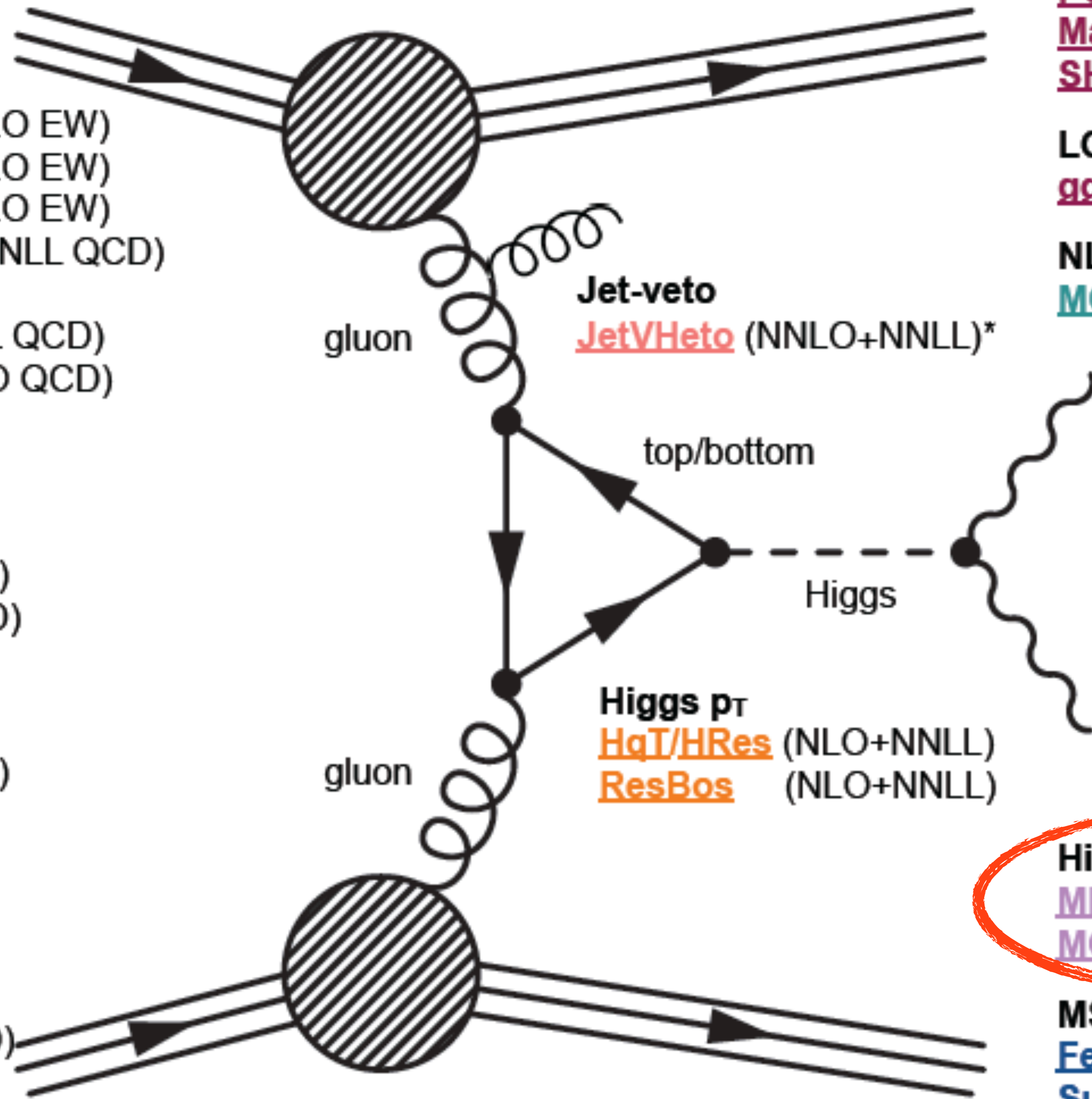
WH/ZH
V2HV (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

ttH
HQQ (LO QCD)

bbH
bbh@NNLO (NNLO QCD)

HH
HPAIR (NLO QCD)

+ private codes.



Jet-veto
JetVHeto (NNLO+NNLL)*

Higgs p$_T$
HqT/HRes (NLO+NNLL)
ResBos (NLO+NNLL)

PDF: MSTW, CTEQ, NNPDF, etc.
LHAPDF, HOPPET, APFEL

NLO MC
POWHEG MiNLO
MadGrapn5_aMC@NLO
SHERPA MEPS@NLO

LO MC
gg2VV

NLO ME
MCFM, MG5_aMC@NLO

Higgs Decay
HDECAY (NLO++)
Prophecy4f (NLO)

Higgs Properties
MELA/JHU, MEKD
MG5_aMC@NLO (HC)

in this talk

MSSM/2HDM
FeynHiggs, CPSuperH
SusHi+2HDMC
HIGLU+HDECAY

* NLO+NNLL in differential

Compiled by R. Tanaka, Jan. 2014

Higgs Characterisation

via the FeynRules and MadGraph5_aMC@NLO frameworks

Kentarou Mawatari

(Vrije Universities Brussel and International Solvay Institutes)

- Sec.11 in YR3 of the LHC Higgs Cross Section Working Group [arXiv:1307.1347]

- Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, KM, Ravindran, Seth, Torrielli, Zaro
"A framework for Higgs characterisation" JHEP11(2013)043 [arXiv:1306.6464]

- Maltoni, KM, Zaro
"Higgs characterisation via VBF/VH" EPJC74(2014)2710 [arXiv:1311.1829]

- Alloul, Fuks, Sanz
"Phenomenology of the Higgs Effective Lagrangian via FR" JHEP04(2014)110 [arXiv:1310.5150]

Contents

- Introduction
  - Effective field theory
  - Gauge/mass basis implementations
- Higgs characterisation framework (mass basis)
  - Effective Lagrangians -- $X(J=0,1,2)$
  - NLO QCD effects
- Summary

Is this the Standard Model scalar boson?

➡ Higgs boson precision measurement

➡ determination of the Higgs boson Lagrangian

- the structure of the operators, linked to the spin/parity of a Higgs boson
  - distributions
- the coupling strength
  - rate

➡ How do we approach to get them?

Effective field theory approach

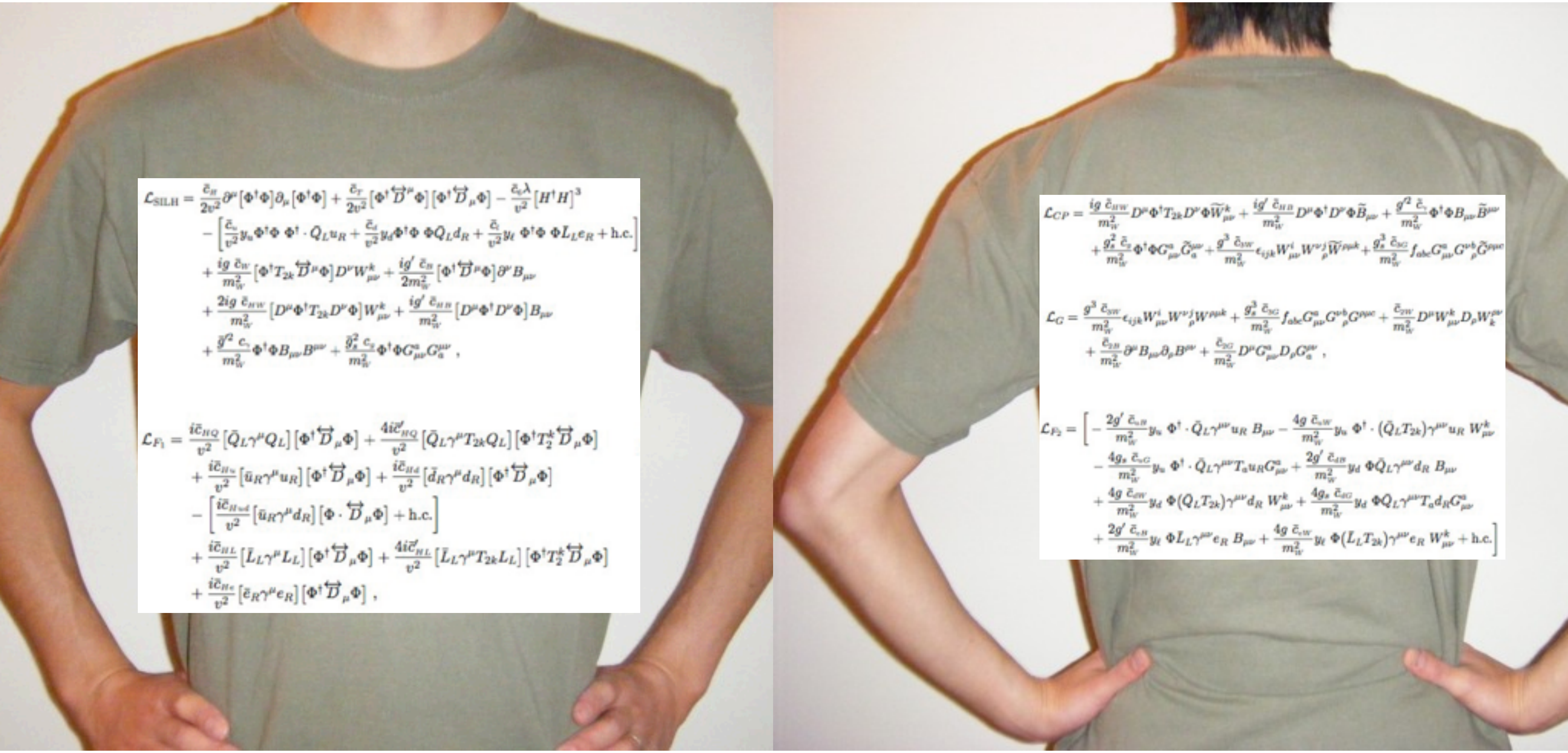
- Given the fact that only a 125 GeV SM-like boson and nothing else so far, the effective field theory approach is one of the best way to explore BSM effects.

- All new particles and phenomena are assumed to appear at some scale Λ.
- Not predictive at scales larger than Λ → loss of unitarity
- Below Λ, all new physics effects are parametrized by higher dimensional gauge invariant operators made of SM fields. → many parameters 59!
- No assumption on the form of new physics → model independent
- Renormalisable order by order in the scale Λ → systematically improvable

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots \qquad \mathcal{L}_6 = \sum_i C_i Q_i$$

Buchmuller&Wyler 1986 ...
Grzadkowski et al. 2010

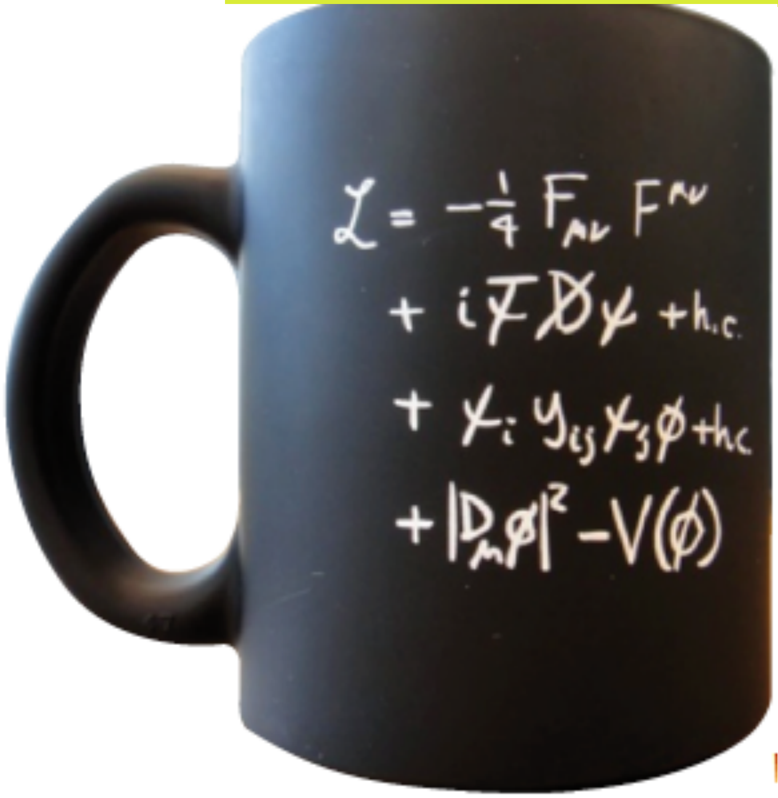
SM Lagrangian up to D6



from Contino, Ghezzi, Grojean, Muhlleitner, Spira [arXiv: 1303.3876]

Vrije Universiteit Brussel

Lagrangian (TH) ⇔ Data (EXP)



FeynRules

UFO model file

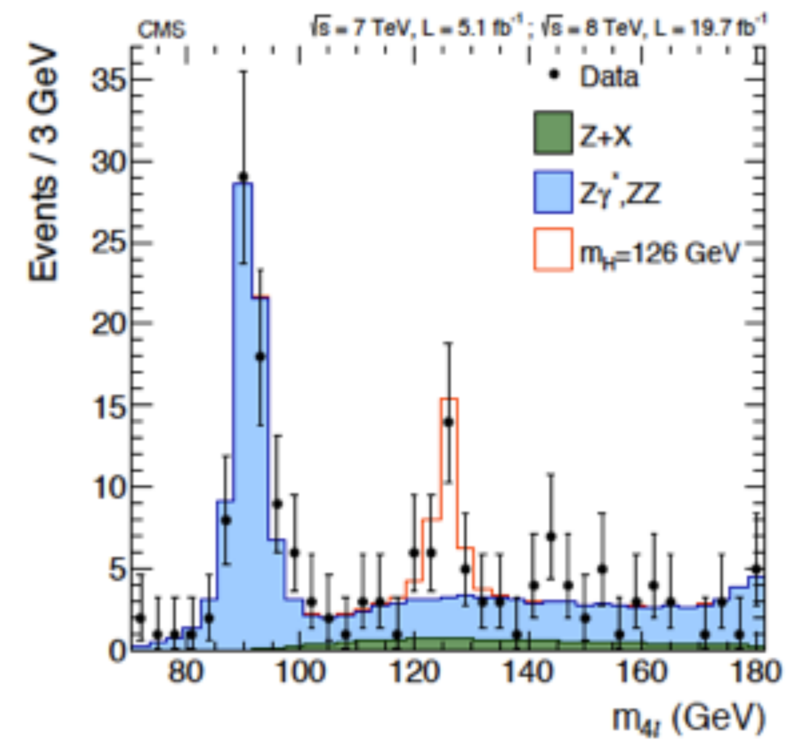
MadGraph5_aMC@NLO
(Pythia, Herwig)

StdHep event file

Delphes

LHCO event file

MadAnalysis5



Higgs effective Lagrangian before vs. after EW symmetry breaking

- D6 (the gauge basis): HEL [Alloul, Fuks, Sanz, arXiv:1310.5150]
  - Only using Standard Model gauge-eigenstates
  - Several operators may be associated with a single coupling (in the mass basis)
  - One operator associated with several couplings (in the mass basis)
  - https://feynrules.irmp.ucl.ac.be/wiki/HEL
- D5 (the mass basis): HC [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 (and Lorentz structure)
  - No assumption on the Higgs boson spin
  - https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

D6 Higgs Effective Lagrangian

[from Contino, Ghezzi, Grojean, Muhlleitner, Spira (JHEP '13)]
[Alloul, Fuks, Sanz (1310.5150)]

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

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

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

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

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

✦ The model file is publicly available. (https://feynrules.irmp.ucl.ac.be/wiki/HEL)

Mapping between the D6 and D5 operators

HC [arXiv: 1306.6464]

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

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right]$$
$$- \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \widetilde{A}^{\mu\nu} \right]$$
$$- \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \widetilde{A}^{\mu\nu} \right]$$
$$- \frac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \widetilde{G}^{a,\mu\nu} \right]$$
$$- \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \right]$$
$$- \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu} \right]$$
$$- \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma} Z_\nu \partial_\mu \ldots \right.$$
$$+ \left(\kappa_{H\partial W} W \ldots \right.$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V = A, Z, W^\pm), \quad \widetilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$$
$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c ,$$

HEL [arXiv: 1310.5150]

Eq. (2.25)	Ref. [46]	Section 2.1
g_{hgg}	$c_\alpha \kappa_{Hgg} g_{Hgg}$	$g_H - \frac{4\bar c_g g_s^2 v}{m_W^2}$
$\tilde g_{hgg}$	$s_\alpha \kappa_{Agg} g_{Agg}$	$-\frac{4\tilde c_g g_s^2 v}{m_W^2}$
$g_{h\gamma\gamma}$	$c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}$	$a_H - \frac{8g\bar c_\gamma s_W^2}{m_W}$
$\tilde g_{h\gamma\gamma}$	$s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}$	$-\frac{8g\tilde c_\gamma s_W^2}{m_W}$
$g_{hzz}^{(1)}$	$\frac{1}{\Lambda} c_\alpha \kappa_{HZZ}$	$\frac{2g}{c_W^2 m_W}\left[\bar c_{HB} s_W^2 - 4\bar c_\gamma s_W^4 + c_W^2 \bar c_{HW}\right]$
$\tilde g_{hzz}$	$\frac{1}{\Lambda} s_\alpha \kappa_{AZZ}$	$\frac{2g}{c_W^2 m_W}\left[\tilde c_{HB} s_W^2 - 4\tilde c_\gamma s_W^4 + c_W^2 \tilde c_{HW}\right]$
$g_{hzz}^{(2)}$	$\frac{1}{\Lambda} c_\alpha \kappa_{H\partial Z}$	$\frac{g}{c_W^2 m_W}\left[(\bar c_{HW} + \bar c_W) c_W^2 + (\bar c_B + \bar c_{HB}) s_W^2\right]$
$g_{hzz}^{(3)}$	$c_\alpha \kappa_{SM} g_{HZZ}$	$\frac{g m_W}{c_W^2}\left[1 - \frac{1}{2}\bar c_H - 2\bar c_T + 8\bar c_\gamma \frac{s_W^4}{c_W^2}\right]$
$g_{haz}^{(1)}$	$c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}$	$\frac{g s_W}{c_W m_W}\left[\bar c_{HW} - \bar c_{HB} + 8\bar c_\gamma s_W^2\right]$
[illegible]	[illegible]	$\frac{g s_W}{\ldots}\left[\tilde c_{HW} - \tilde c_{HB} + 8\tilde c_\gamma s_W^2\right]$
[illegible]	[illegible]	$\left[\bar c_{HW} - \bar c_{HB} - \bar c_B + \bar c_W\right]$
[illegible]	[illegible]	$\ldots W$
[illegible]	[illegible]	$\frac{\ldots}{m_W} \ldots HW$
$g_{hww}^{(2)}$	$\frac{1}{\Lambda} c_\alpha \kappa_{H\partial W}$	$\frac{g}{m_W}\left[\bar c_W + \bar c_{HW}\right]$

Two approaches equivalent as they can be mapped into one another.

Higgs Characterisation model

- We implemented an effective Lagrangian featuring bosons

$$X(J^P=0^+,0^-,1^+,1^-,2^+)$$

in FeynRules.

  - Effective field theory approach, valid up to a cutoff scale Λ
  - Only one new bosonic state $X(J^P)$ at the EW scale (No other state below the cutoff Λ)
  - Any new physics is described by the lowest dimensional operators.

The parametrization is based on the recent work [Englert, Goncalves-Netto, KM, Plehn (2013)].

Effective Lagrangian -- spin0

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

$$\begin{aligned}\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM}\big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big] \\ & - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\ & - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\ & - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G_{\mu\nu}^a \widetilde{G}^{a,\mu\nu}\big] \\ & - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big] \\ & - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu}\big] \\ & - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} \\ & \qquad + \big(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\big)\big] \Big\} X_0\end{aligned}$$

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

```
######################################
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######################################
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    2 1.000000e+00 # ca
    3 1.000000e+00 # kSM
    4 1.000000e+00 # kHtt
    5 1.000000e+00 # kAtt
    6 1.000000e+00 # kHbb
    7 1.000000e+00 # kAbb
    8 1.000000e+00 # kHll
    9 1.000000e+00 # kAll
   10 1.000000e+00 # kHaa
   11 1.000000e+00 # kAaa
   12 1.000000e+00 # kHza
   13 1.000000e+00 # kAza
   14 1.000000e+00 # kHgg
   15 1.000000e+00 # kAgg
   16 0.000000e+00 # kHzz
   17 0.000000e+00 # kAzz
   18 0.000000e+00 # kHww
   19 0.000000e+00 # kAww
   20 0.000000e+00 # kHda
   21 0.000000e+00 # kHdz
   22 0.000000e+00 # kHdwR
   23 0.000000e+00 # kHdwI
```

Effective Lagrangian -- spin0

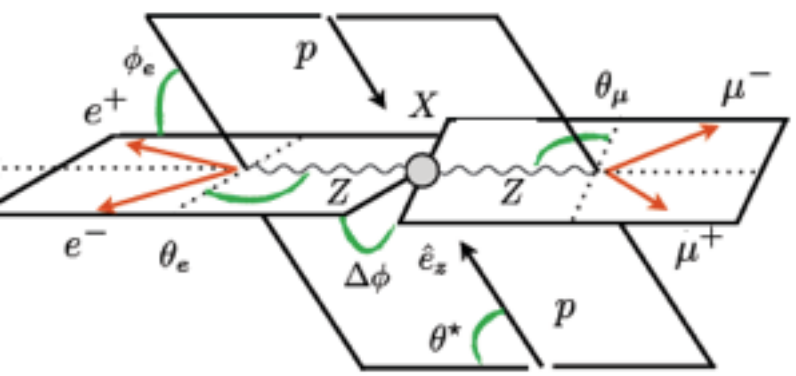
$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar\psi_f \big(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \gamma_5\big)\psi_f X_0$$

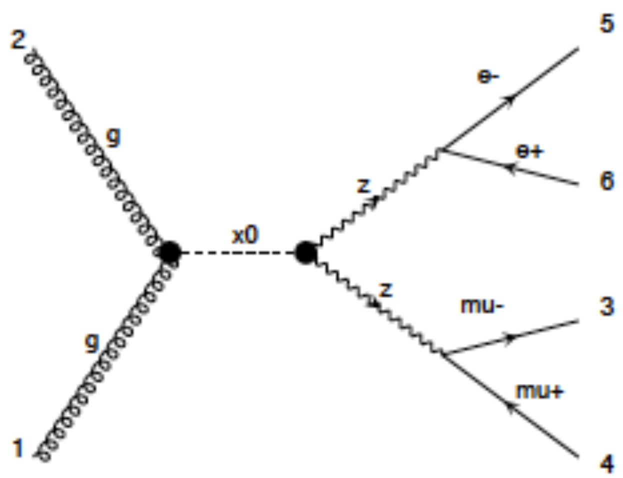
$$\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu}\widetilde{A}^{\mu\nu}\big]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

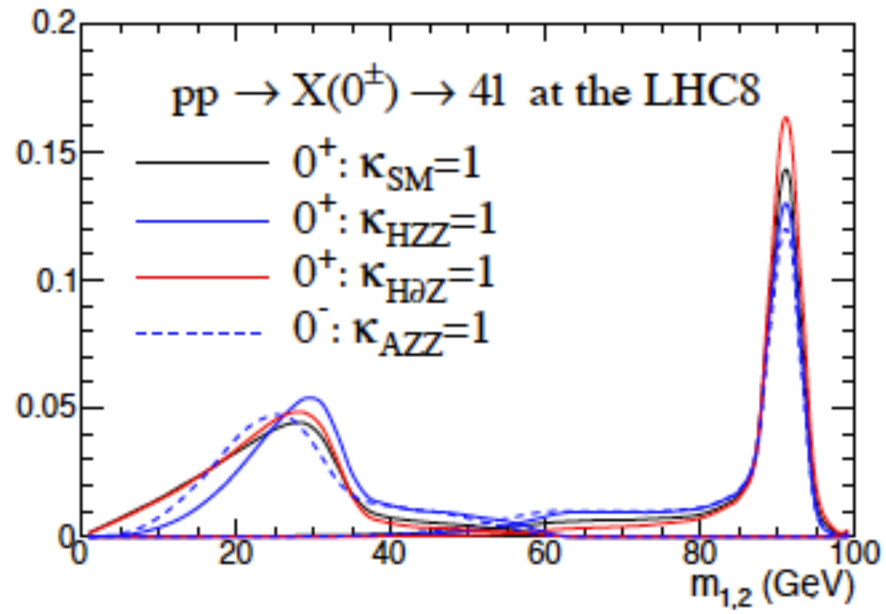
Dimensionful couplings g are set as internal parameters so as to reproduce a SM Higgs for κ=1.

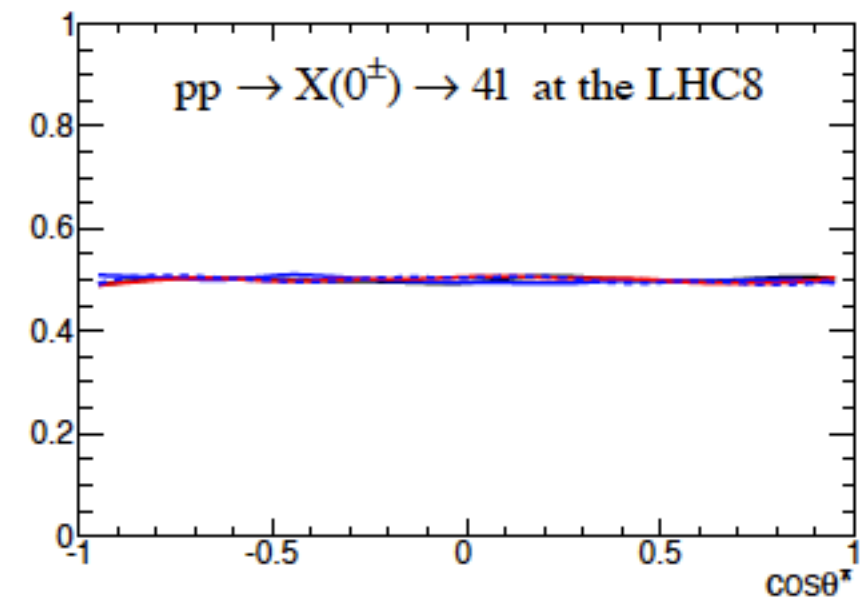
$g_{Xyy'} \times v$	ff	ZZ/WW	$\gamma\gamma$	$Z\gamma$	gg
H	m_f	$2m^2_{Z/W}$	$47\alpha_{\rm EM}/18\pi$	$C(94\cos^2\theta_W - 13)/9\pi$	$-\alpha_s/3\pi$
A	m_f	0	$4\alpha_{\rm EM}/3\pi$	$2C(8\cos^2\theta_W - 5)/3\pi$	$\alpha_s/2\pi$

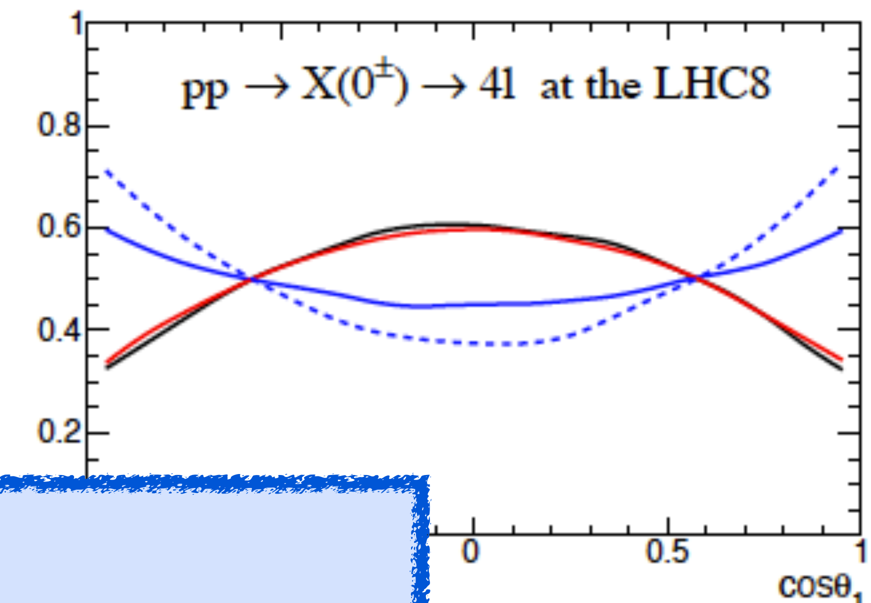
Mass and angular distributions -- spin0

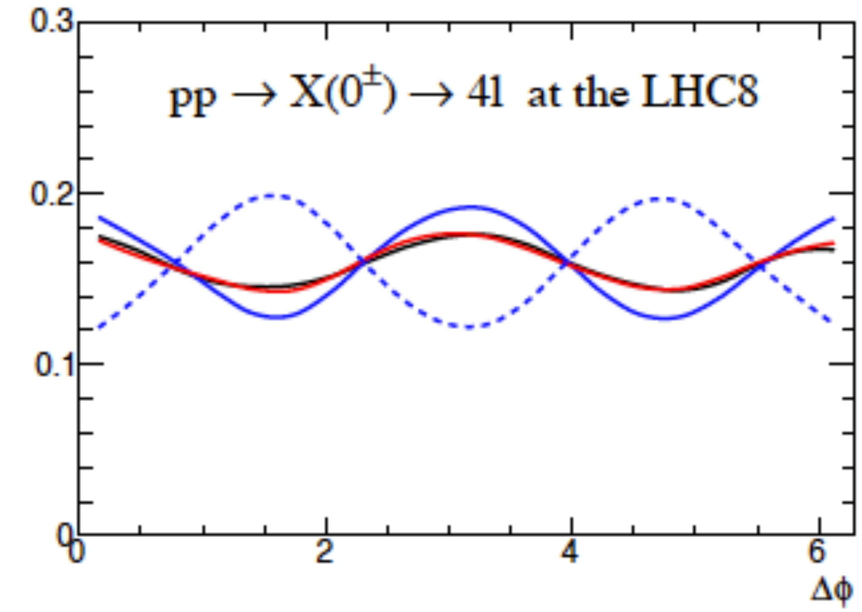













```
./bin/mg5_aMC
>import model HC
>generate p p > x0, x0 > mu- mu+ e- e+
>launch
```

Effective Lagrangian -- spin1

- The most general interactions at the lowest canonical dimension:

$$\mathcal{L}_1^f = \sum_{f=q,\ell} \bar{\psi}_f \gamma_\mu (\kappa_{f_a} a_f - \kappa_{f_b} b_f \gamma_5) \psi_f X_1^\mu$$

$$\begin{aligned}\mathcal{L}_1^W = & \, i\kappa_{W_1} g_{WWZ} (W^+_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^{+\mu}) X_1^\nu + i\kappa_{W_2} g_{WWZ} W^+_\mu W^-_\nu X_1^{\mu\nu} \\ & - \kappa_{W_3} W^+_\mu W^-_\nu (\partial^\mu X_1^\nu + \partial^\nu X_1^\mu) \\ & + i\kappa_{W_4} W^+_\mu W^-_\nu \widetilde{X}_1^{\mu\nu} - \kappa_{W_5} \epsilon_{\mu\nu\rho\sigma} [W^{+\mu} (\partial^\rho W^{-\nu}) - (\partial^\rho W^{+\mu}) W^{-\nu}] X_1^\sigma\end{aligned}$$

$$\mathcal{L}_1^Z = -\kappa_{Z_1} Z_{\mu\nu} Z^\mu X_1^\nu - \kappa_{Z_3} X_1^\mu (\partial^\nu Z_\mu) Z_\nu - \kappa_{Z_5} \epsilon_{\mu\nu\rho\sigma} X_1^\mu Z^\nu (\partial^\rho Z^\sigma)$$

- Parity conservation implies that
  - for X_1- $\kappa_{f_b} = \kappa_{V_4} = \kappa_{V_5} = 0$
  - for X_1+ $\kappa_{f_a} = \kappa_{V_1} = \kappa_{V_2} = \kappa_{V_3} = 0$

Effective Lagrangian -- spin2

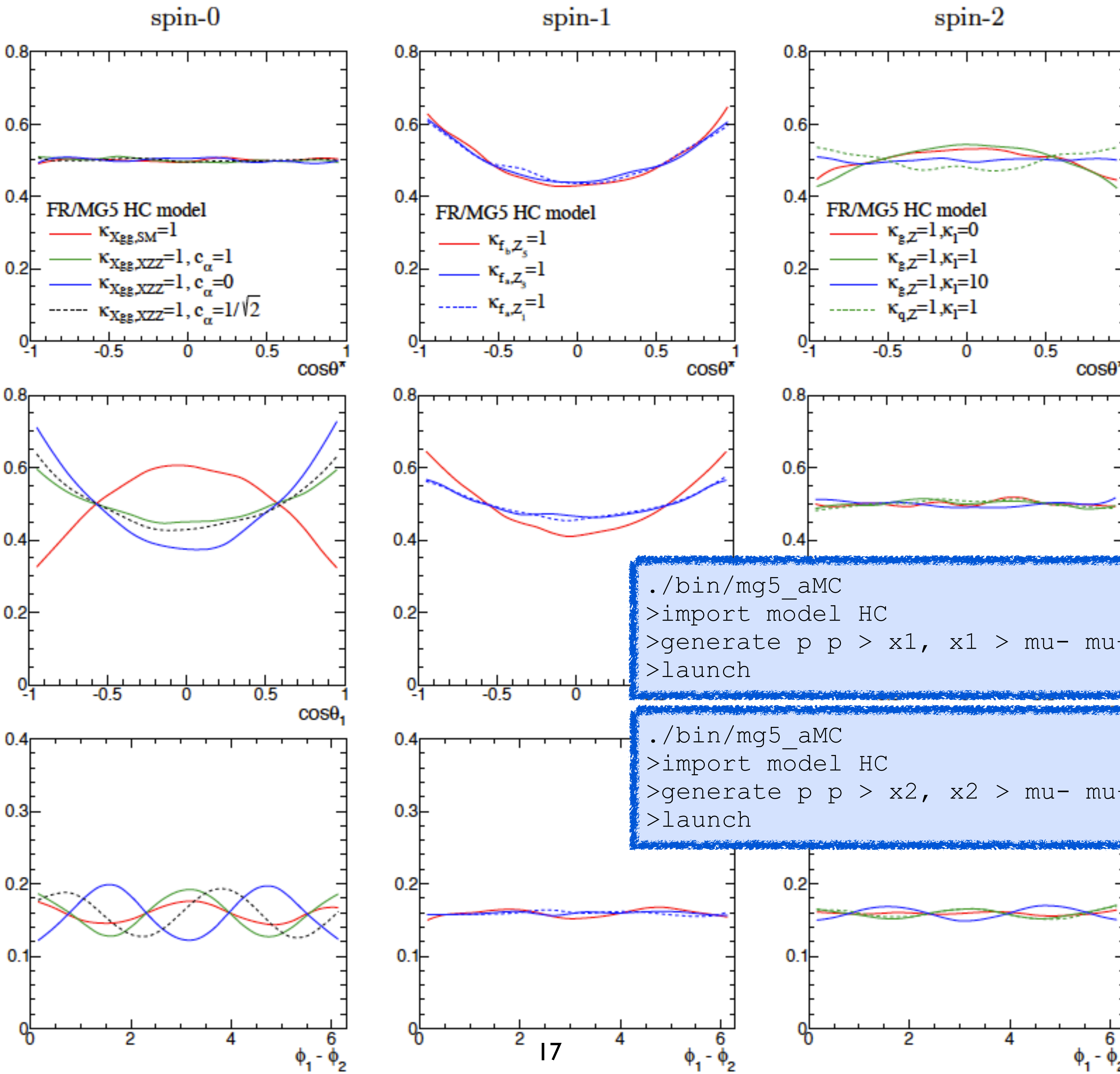
- via the energy-momentum tensor of the SM fields, starting from D5:

$$\mathcal{L}_2^f = -\frac{1}{\Lambda} \sum_{f=q,\ell} \kappa_f T^f_{\mu\nu} X_2^{\mu\nu}$$

$$\mathcal{L}_2^V = -\frac{1}{\Lambda} \sum_{V=Z,W,\gamma,g} \kappa_V T^V_{\mu\nu} X_2^{\mu\nu}$$

  - The E-M tensor for QED:

$$\begin{aligned} T^f_{\mu\nu} =& - g_{\mu\nu}\Big[\bar\psi_f(i\gamma^\rho D_\rho - m_f)\psi_f - \frac{1}{2}\partial^\rho(\bar\psi_f i\gamma_\rho\psi_f)\Big] \\ &+ \Big[\frac{1}{2}\bar\psi_f i\gamma_\mu D_\nu\psi_f - \frac{1}{4}\partial_\mu(\bar\psi_f i\gamma_\nu\psi_f) + (\mu\leftrightarrow\nu)\Big], \\ T^\gamma_{\mu\nu} =& - g_{\mu\nu}\Big[-\frac{1}{4}A^{\rho\sigma}A_{\rho\sigma} + \partial^\rho\partial^\sigma A_\sigma A_\rho + \frac{1}{2}(\partial^\rho A_\rho)^2\Big] \\ &- A_\mu^{\ \rho}A_{\nu\rho} + \partial_\mu\partial^\rho A_\rho A_\nu + \partial_\nu\partial^\rho A_\rho A_\mu\,, \end{aligned}$$

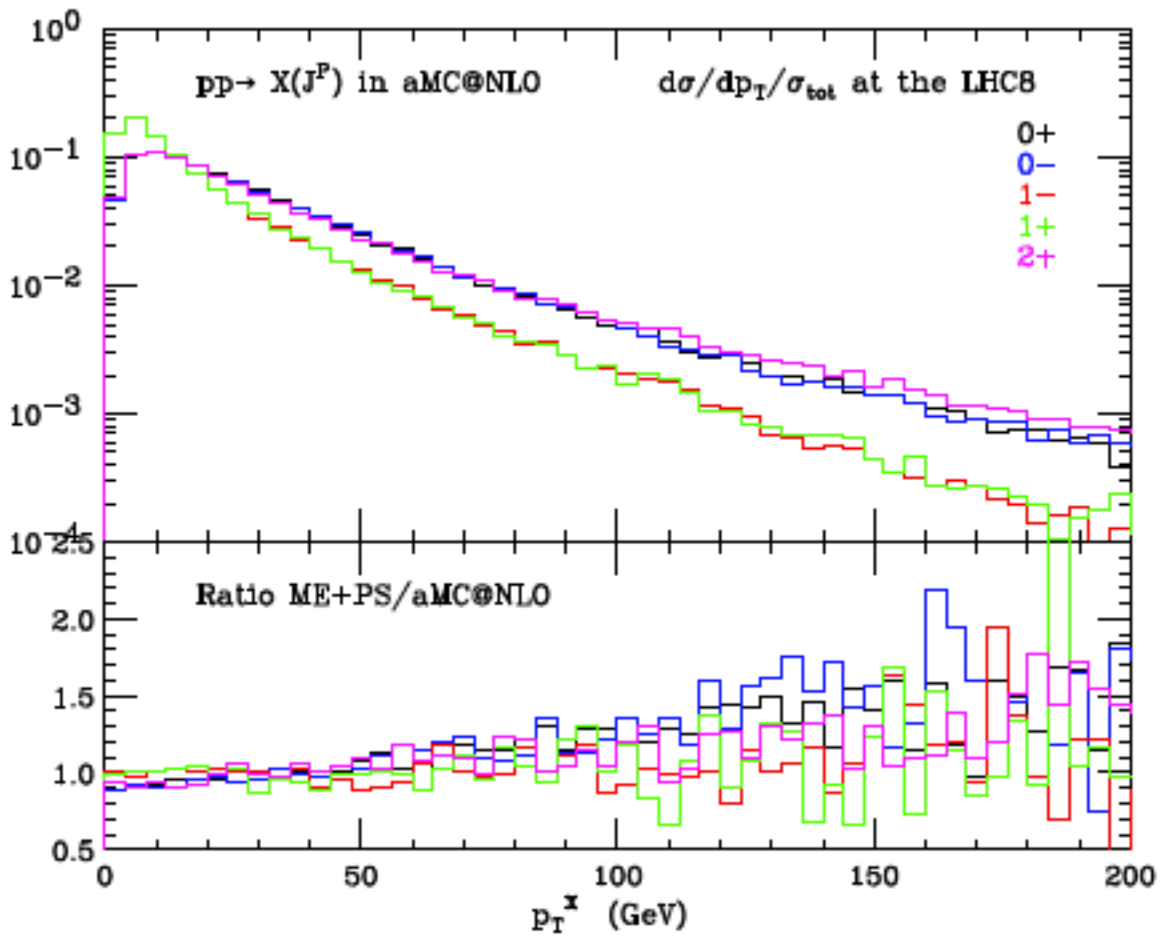


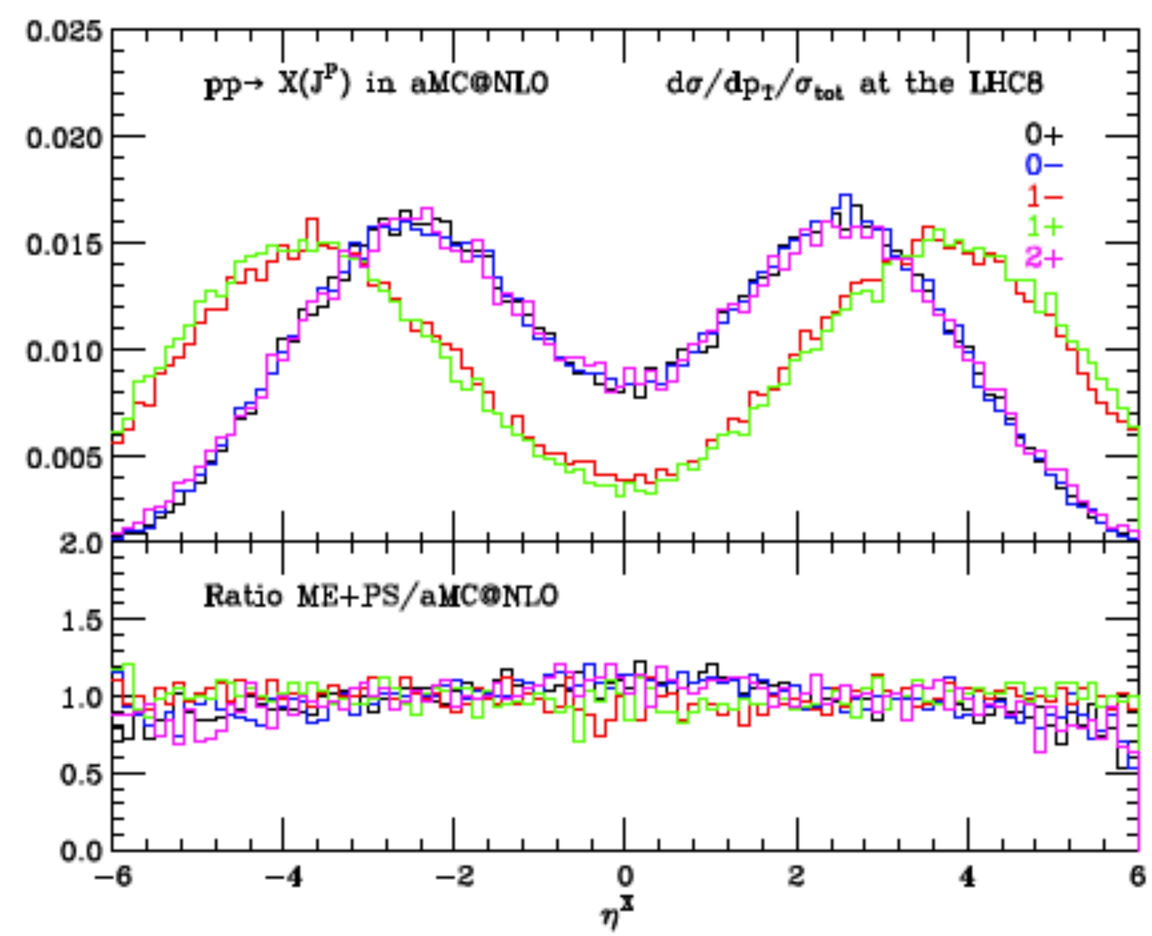

```
./bin/mg5_aMC
>import model HC
>generate p p > x1, x1 > mu- mu+ e- e+
>launch
```

```
./bin/mg5_aMC
>import model HC
>generate p p > x2, x2 > mu- mu+ e- e+
>launch
```

Higher order effects in QCD

- The LO predictions can be systematically improved by including the effects due to the emission of QCD partons.
  - LO Matrix-Element/Parton-Shower merging [ME+PS]
  - full-NLO matrix element with parton-shower [aMC@NLO+Pythia/Herwig]





VBF

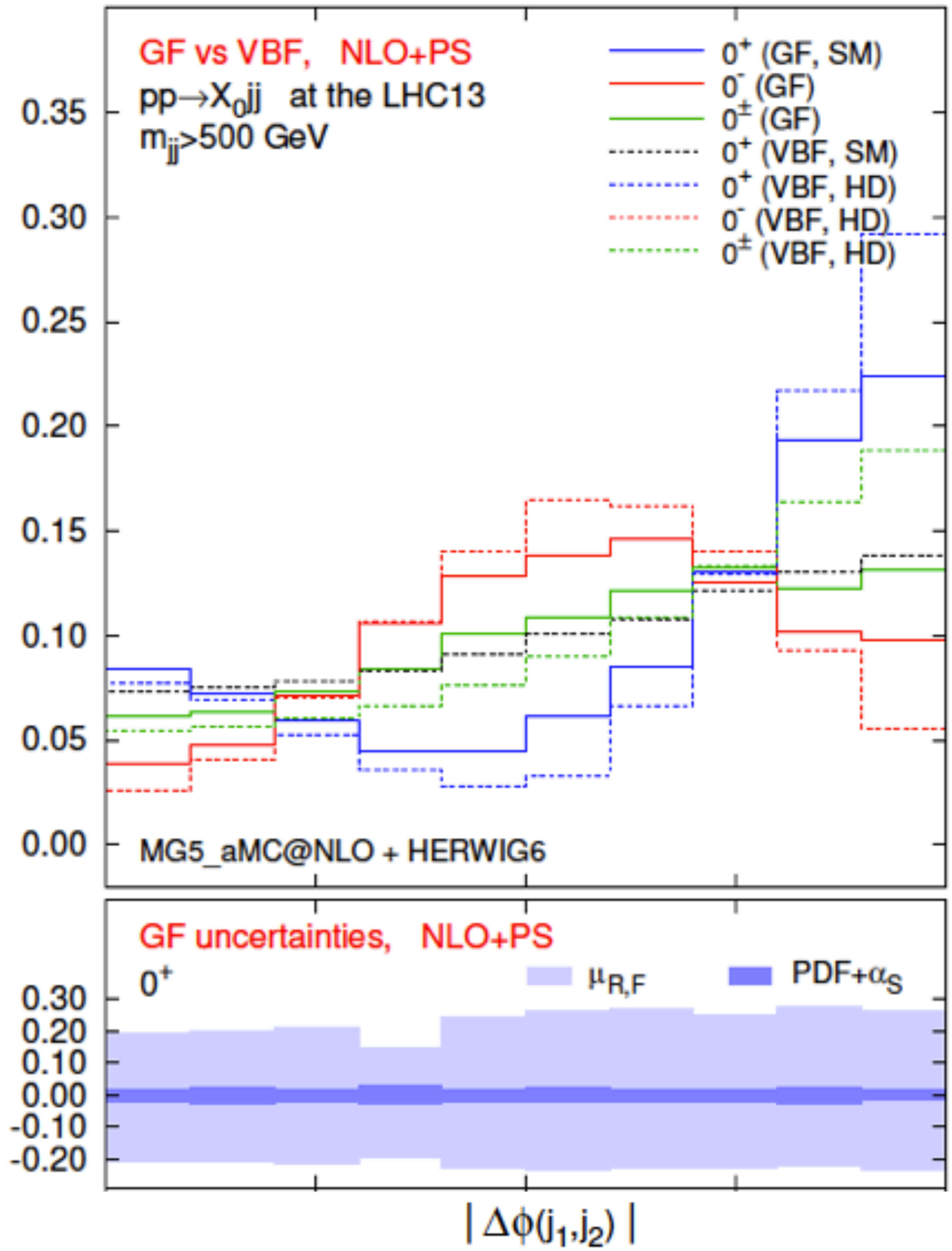
Maltoni, KM, Zaro [arXiv:1311.1829]

```
./bin/mg5_aMC
> import model HC_NLO
> generate p p > x0 j j QCD=0[QCD]
> launch
```

Demartin, Maltoni, KM, Page, Pittau, Zaro [in progress]

```
./bin/mg5_aMC
> import model HC_NLO-heft
> generate p p > x0 j j / t [QCD]
> launch
```

scenario		σ_{LO} (pb)	σ_{NLO} (pb)
LHC 8 TeV	0^+	$1.351(1)\ ^{+67.1}_{-36.8}\ ^{+4.3\%}_{-4.3\%}$	$1.702(6)\ ^{+19.7}_{-20.8}\ ^{+1.7\%}_{-1.7\%}$
	0^-	$2.951(3)\ ^{+67.2}_{-36.8}\ ^{+4.4\%}_{-4.4\%}$	$3.660(15)\ ^{+19.1}_{-20.6}\ ^{+1.7\%}_{-1.7\%}$
	$0^\pm$	$2.142(2)\ ^{+67.1}_{-36.8}\ ^{+4.4\%}_{-4.4\%}$	$2.687(10)\ ^{+19.6}_{-20.8}\ ^{+1.7\%}_{-1.7\%}$
LHC 13 TeV	0^+	$4.265(4)\ ^{+61.5}_{-34.9}\ ^{+3.3\%}_{-3.3\%}$	$5.092(23)\ ^{+15.4}_{-17.9}\ ^{+1.2\%}_{-1.2\%}$
	0^-	$9.304(9)\ ^{+61.6}_{-34.9}\ ^{+3.4\%}_{-3.4\%}$	$11.29(4)\ ^{+16.0}_{-18.2}\ ^{+1.2\%}_{-1.2\%}$
	$0^\pm$	$6.775(6)\ ^{+61.5}_{-34.9}\ ^{+3.3\%}_{-3.3\%}$	$8.055(35)\ ^{+15.8}_{-18.2}\ ^{+1.2\%}_{-1.2\%}$

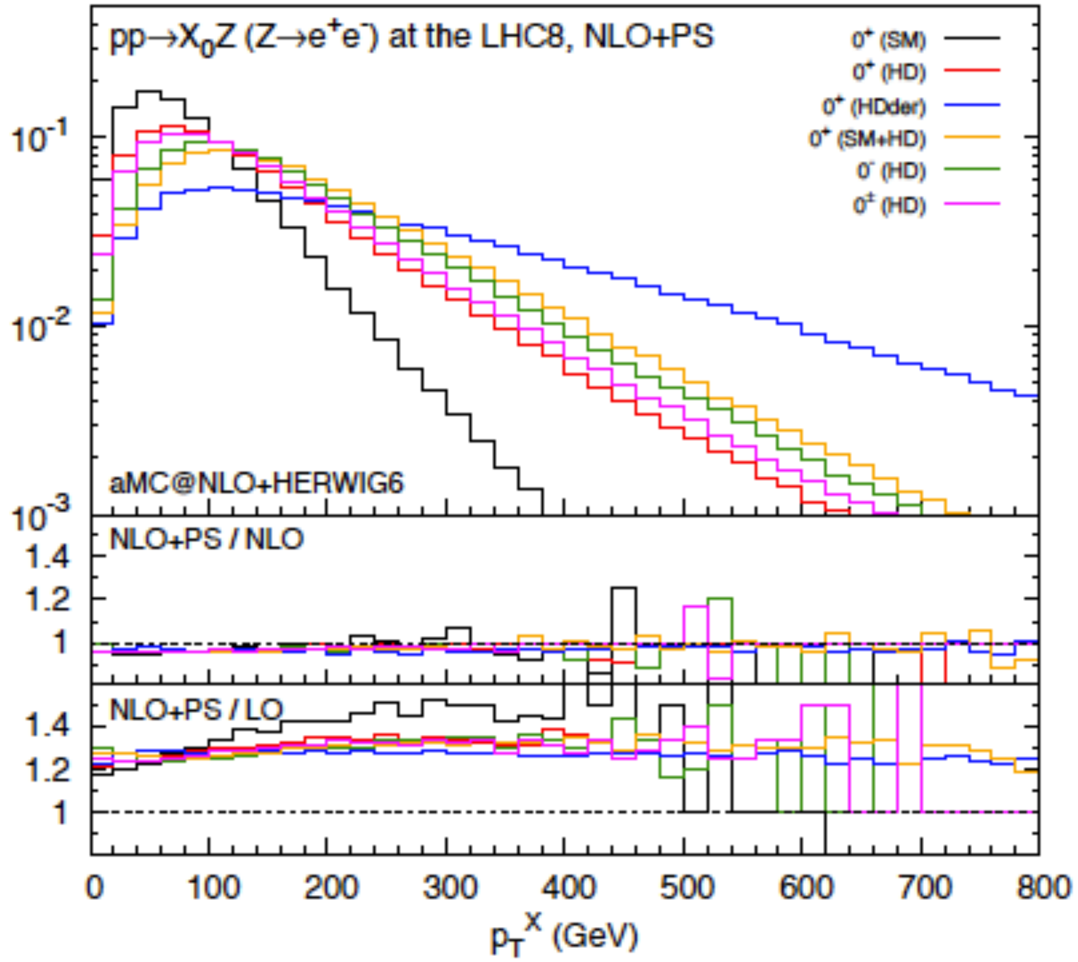


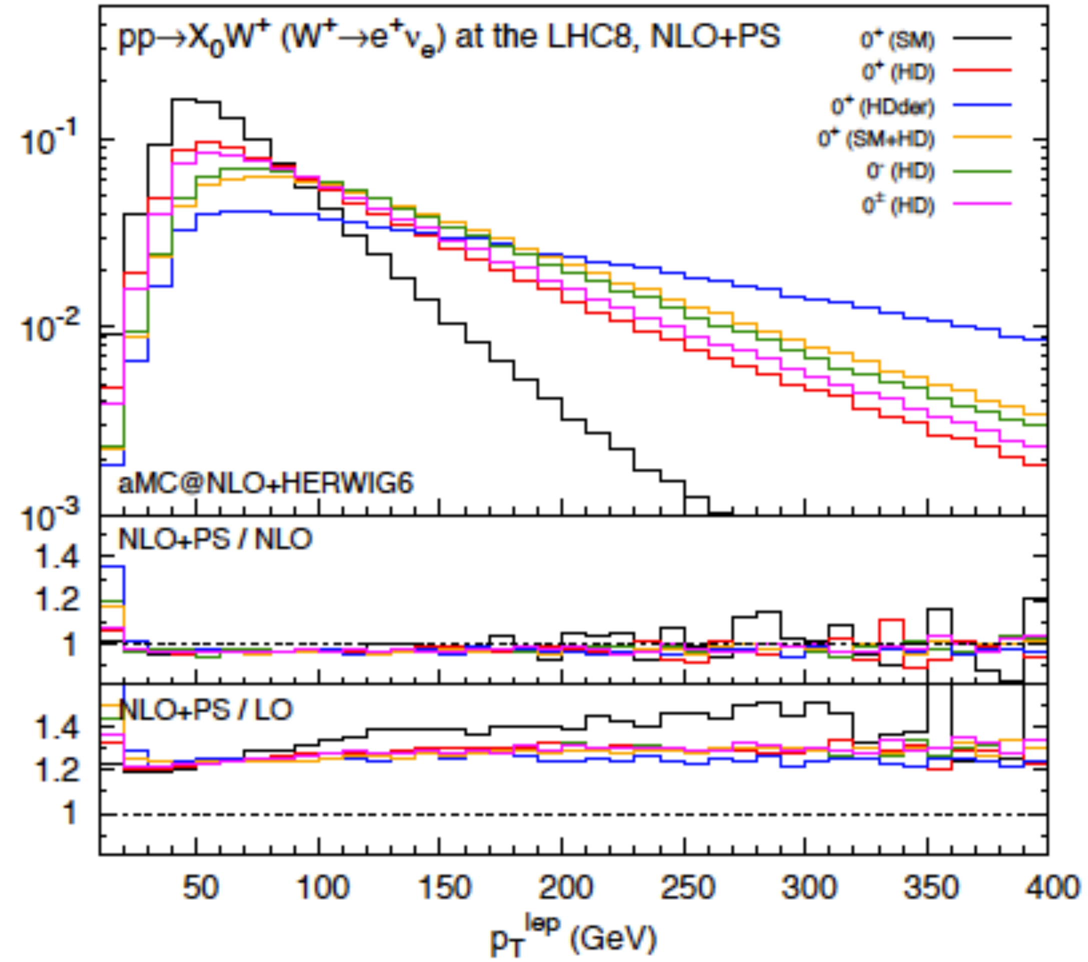
VH

Maltoni, KM, Zaro [arXiv:1311.1829]

```
./bin/mg5_aMC
> import model HC_NLO
> generate p p > x0 e+ e- [QCD]
> launch
```

scenario	σ_{LO} (fb)	σ_{NLO} (fb)	K
0^+(SM)	$39.58(3)\ ^{+0.1\%}_{-0.6\%}$	$51.22(5)\ ^{+2.2\%}_{-1.8\%}$	1.29
0^+(HD)	$13.51(1)\ ^{+1.5\%}_{-1.7\%}$	$17.51(1)\ ^{+1.9\%}_{-1.3\%}$	1.30
0^+(HDder)	$324.2(2)\ ^{+4.7\%}_{-4.3\%}$	$416.1(4)\ ^{+2.3\%}_{-2.1\%}$	1.28
0^+(SM+HD)	$118.8(1)\ ^{+3.0\%}_{-2.9\%}$	$154.2(1)\ ^{+1.8\%}_{-1.6\%}$	1.30
0^-(HD)	$8.386(7)\ ^{+2.6\%}_{-2.6\%}$	$10.89(1)\ ^{+1.8\%}_{-1.5\%}$	1.30
$0^\pm$(HD)	$10.96(1)\ ^{+1.9\%}_{-2.1\%}$	$14.22(1)\ ^{+1.8\%}_{-1.3\%}$	1.30





Summary

- After the discovery of a Higgs-like resonance at the LHC, the main focus of the analyses now is the determination of the Higgs Lagrangian.
- This includes
  - the structure of the operators, linked to the spin/parity of a 'Higgs' boson.
  - the coupling strength.
- MC tools to study the property of the SM-like boson are publicly available, e.g. JHUGen, MEKD, HC, HEL.
- Event generation at NLO is possible for (several) spin 0,1,2 hypothesis and can be used to validate merged samples.

Vrije Universiteit Brussel

HiggsCharacterisation - FeynRules

http://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

gmail KEKmail VUBintra VUBmail raptools mawatari IIHE CP3 cluster translate inspire Wolfram workshop alc mac install Apple Wiki

The Higgs Characterisation model

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Description of the model

This is a model file for the characterisation of the boson recently discovered at the LHC. Our effective lagrangian consists of the SM (except for the Higgs itself), expressed through the physical degrees of freedom present below the EWSB scale, plus a new bosonic state $X(J^P)$ with spin/parity assignments $J^P = 0^+, 0^-, 1^+, 1^-$, or 2^+. The new state can couple to SM particles via interactions of the lowest possible dimensions. In addition, the state 0^+ is allowed to mix with the 0^- one, and can interact with SM particles with higher-dimensional operators beyond those of the SM. See more details in

- 1306.6464 : P. Artoisenet, P. de Aquino, F. Demartin, R. Frederix, S. Frixione, F. Maltoni, M. K. Mandal, P. Mathews, K. Mawatari, V. Ravindran, S. Seth, P. Torrielli, M. Zaro, "A framework for Higgs characterisation" (JHEP11(2013)043).
- 1307.5607 : P. de Aquino, K. Mawatari, "Characterising a Higgs-like resonance at the LHC" (Proceedings for HPNP2013).
- 1311.1829 : F. Maltoni, K. Mawatari, M. Zaro, "Higgs characterisation via vector-boson fusion and associated production: NLO and parton-shower effects" (EPJC74(2014)2710).

Model files for LO

- HC.fr : the main model file.
- SM_HC.fr : This model requires the modified Standard Model implementation of FeynRules.
- Massless.rst, Cabibbo.rst : SM restriction files.
- HC.nb : this is an example Mathematica notebook that loads the model, calculates the Feynman rules and extract the model files within the UFO format.
- HC_UFO.zip : The model files in UFO format (for MadGraph5).

Model files for NLO (only for the J=0 case)

A few remarks before use; see the README file in the model.

- HC_NLO_X0_UFO.zip : The model files in UFO format (for MadGraph5).