Vrije Universiteit Brussel

Higgs Characterisation

via the FeynRules and MadGraph5_aMC@NLO frameworks

Kentarou Mawatari

(Vrije Universities Brussel and International Solvay Institutes)

- 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]

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

- Maltoni, KM, Zaro
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- Demartin, Maltoni, KM, Page, Zaro
"Higgs characterisation: CP properties of the top Yukawa interaction" [arXiv:1407.5089]

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appeared today!

Contents

How can we find the BSM physics?

✓ Find new particles/phenomena.

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

✓ Find small deviations from the SM expectation.

➡ Bottom-up approach: Effective field theory

How can we find the BSM physics?

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➡ Bottom-up approach: Effective field theory

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

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
- No assumption on the form of new physics → model independent
- Renormalisable order by order in the scale Λ → systematically improvable

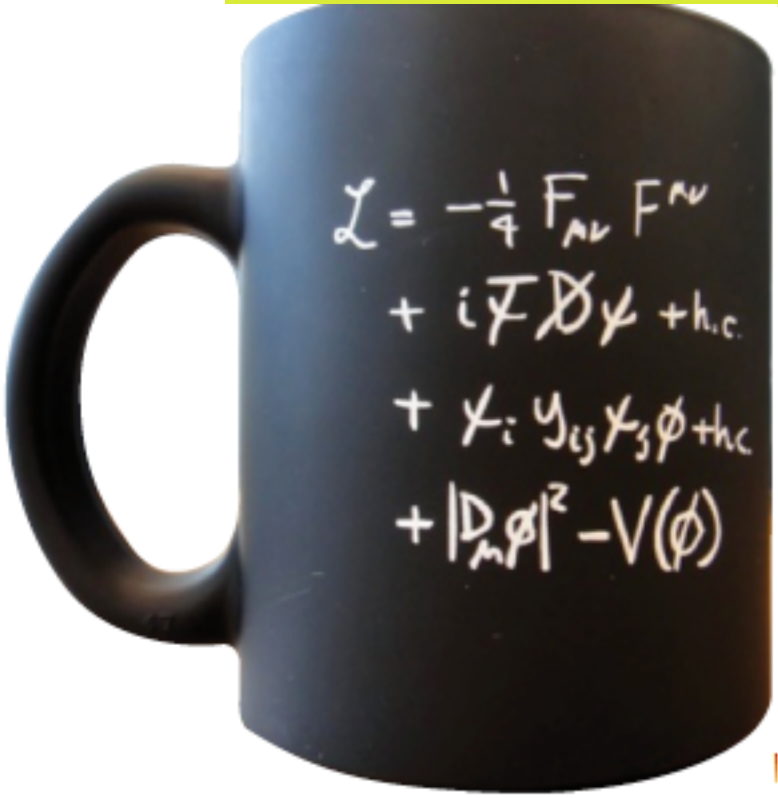
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots \qquad \mathcal{L}_6 = \sum_i C_i Q_i$$

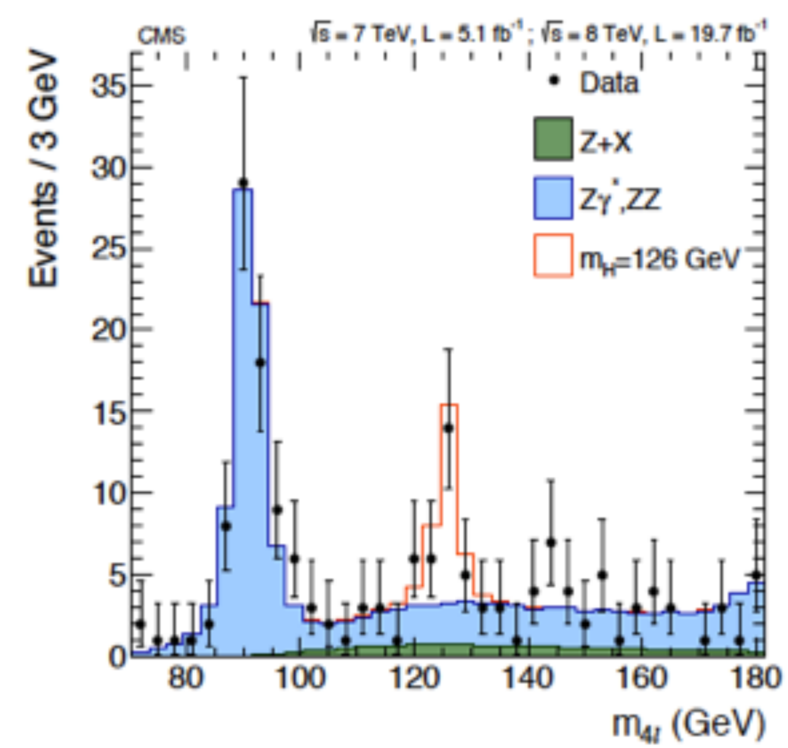
Buchmuller&Wyler 1986 ...
Grzadkowski et al. 2010

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)
  - The relation between the Higgs and gauge sectors
  - 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 relation between the Higgs and gauge sectors
  - No assumption on the Higgs boson spin
  - https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

Lagrangian (TH) ⇔ Data (EXP)





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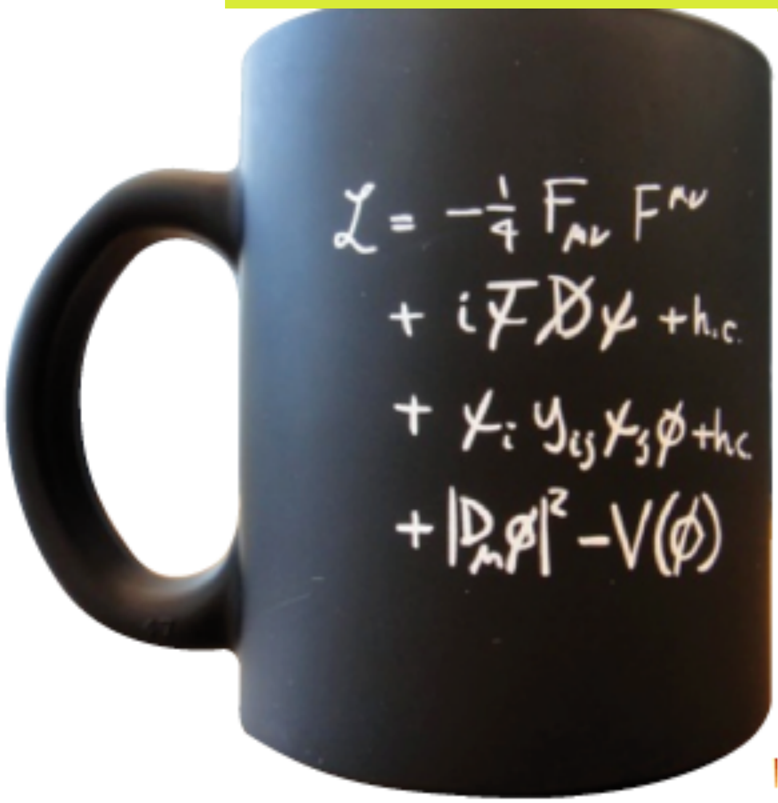


FeynRules

↓ UFO model file

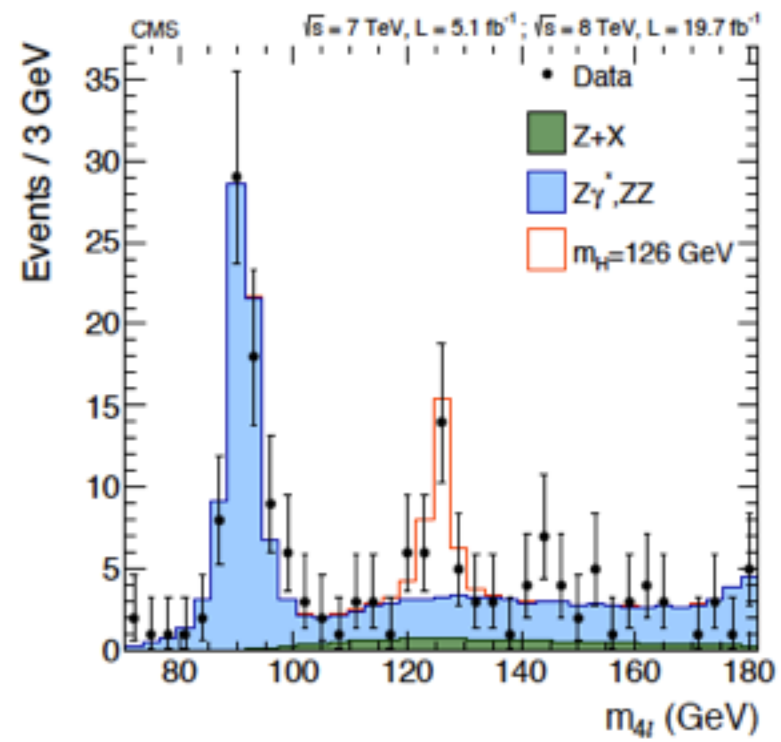
MadGraph5_aMC@NLO
(Herwig, Pythia)

↓ StdHep event file

Delphes

↓ LHCO event file

MadAnalysis5



FeynRules(v2.0) in a nutshell

Alloul, Christensen, Degrande, Duhr, Fuks [arXiv:1310.1921]

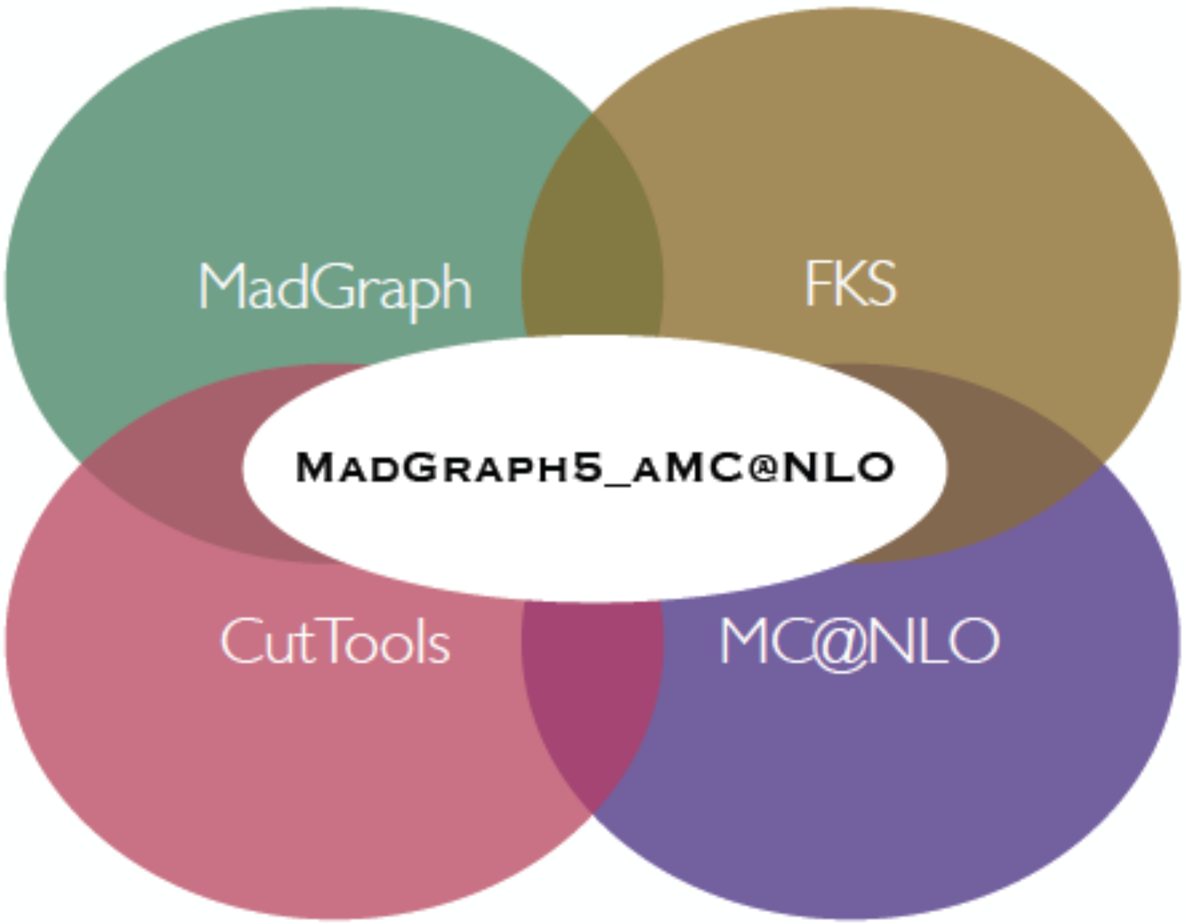
- a Mathematica package that allows to derive Feynman rules from a Lagrangian.
- allows to export the Feynman rules to various matrix element generators, e.g. CalcHEP, FeynArts, MadGraph, Sherpa, Whizard, ...

- 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).

[Christensen, de Aquino, Deutschmann, Duhr, Fuks, Garcia-Cely, Mattelaer, KM, Oexl, Takaesu, EPJC(2013)]

MadGraph5_aMC@NLO in a nutshell

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro [arXiv:1405.0301]



- performs automatic computations of tree-level and NLO differential cross sections
- matches LO and NLO calculations to parton showers via the MC@NLO method
- merges LO (MLM) and NLO (FxFx) samples that differ in parton multiplicities.

Higgs Characterisation (HC) model

- We implemented an effective Lagrangian featuring bosons

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

in FeynRules.

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

  - any-process, any-decay, any-observable
  - Equally useful for theorists (it can be systematically improved, changed easily) and experimentalists (event generation easily).
  - Adaptable to the present/future analyses and accuracy targets.

Effective Lagrangian -- spin0

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

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

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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param_card.dat

```
######################################
## INFORMATION FOR FRBLOCK
######################################
Block frblock
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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
```

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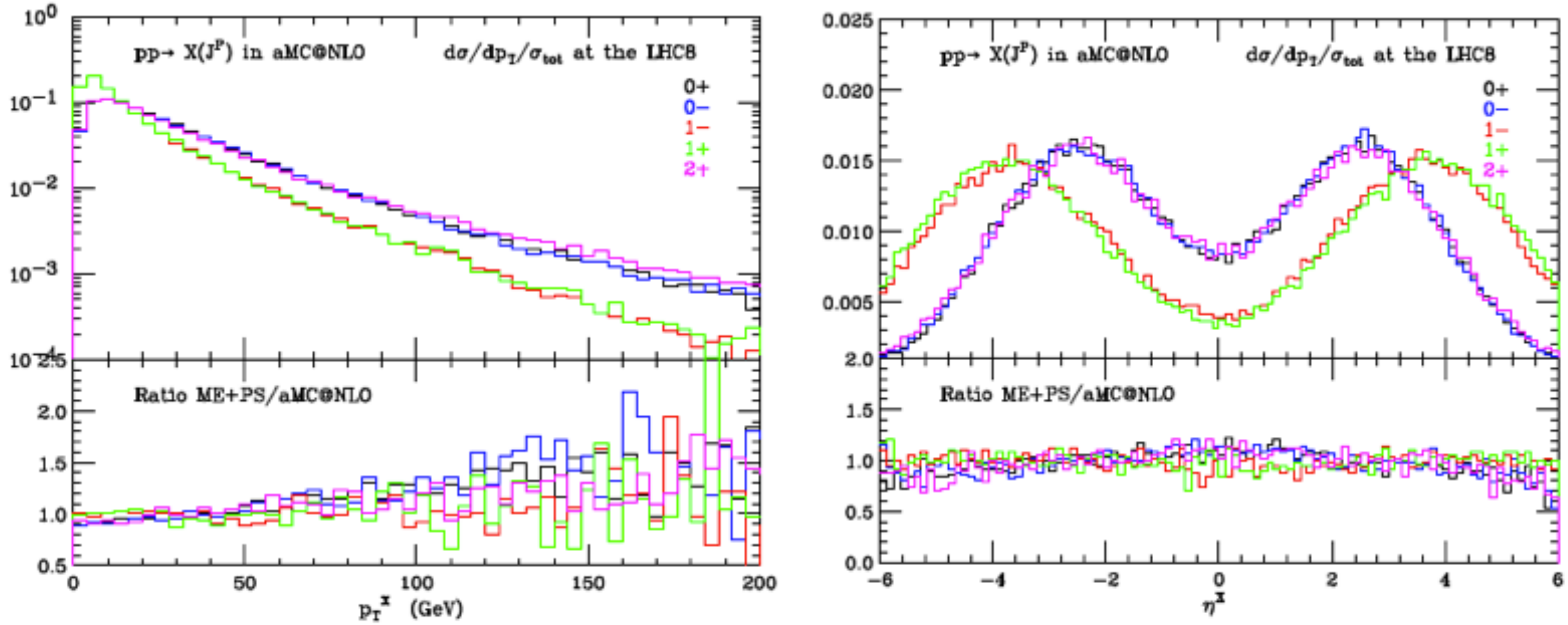
Dimensionful couplings g are set as internal parameters so as to reproduce a SM Higgs for κ=1.

$g_{Xyy'} \times v$	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	$4\alpha_{\rm EM}/3\pi$	$2C(8\cos^2\theta_W - 5)/3\pi$	$\alpha_s/2\pi$

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 [MG5_aMC+Herwig/Pythia]



Good agreement between the ME+PS and MG5_aMC predictions for most observables.

1-min MadGraph5_aMC@NLO tutorial

FeynRules: http://feynrules.irmp.ucl.ac.be/
MG5_aMC: https://launchpad.net/mg5amcnlo

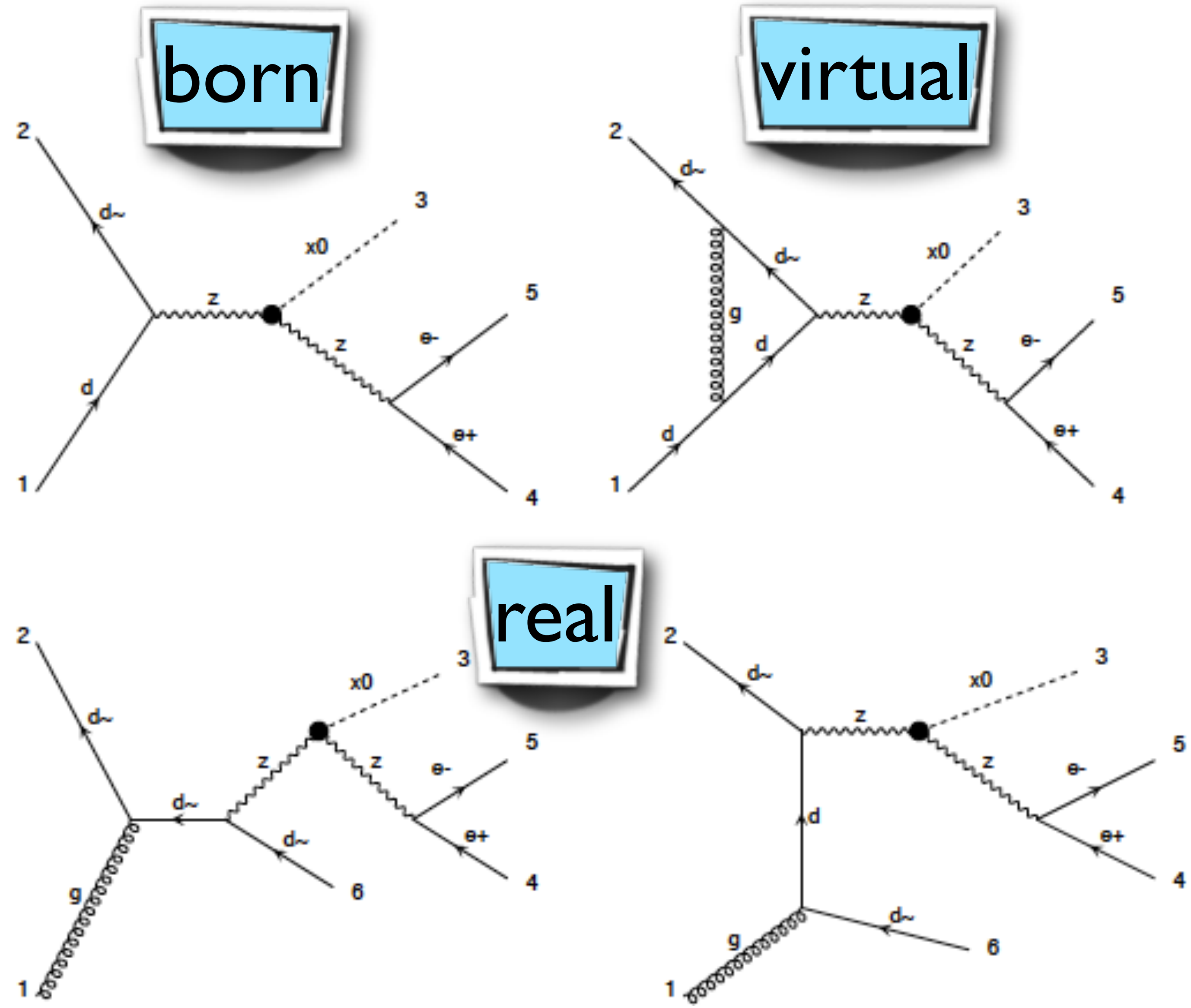
```
./bin/mg5_aMC
>import model HC_NLO_X0
>generate p p > x0 e+ e- [QCD]
>output
>launch
```

- Start the MG5_aMC shell
- Import the model
- Generate the process
- Write the code
- Generate the LO/NLO events

SubProcesses and Feynman diagrams

Directory	Type	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P0_ddx_x0epem_no_a	born	1	2	postscript	d d~ > x0 e+ e- XGLU=1 WEIGHTED=6 QNP=1 [QCD] , s s~ > x0 e+ e- XGLU=1 WEIGHTED=6 QNP=1 [QCD]
	virt	1	2	postscript	d d~ > x0 e+ e- WEIGHTED=6 QNP=1 QED=2 [QCD] , s s~ > x0 e+ e- WEIGHTED=6 QNP=1 QED=2 [QCD]
	real	2	2	postscript	d d~ > x0 e+ e- g XGLU=1 WEIGHTED=7 QNP=1 [QCD] , s s~ > x0 e+ e- g XGLU=1 WEIGHTED=7 QNP=1 [QCD]
	real	2	2	postscript	g d~ > x0 e+ e- d~ XGLU=1 WEIGHTED=7 QNP=1 [QCD] , g s~ > x0 e+ e- s~ XGLU=1 WEIGHTED=7 QNP=1 [QCD]
	real	2	2	postscript	d g > x0 e+ e- d XGLU=1 WEIGHTED=7 QNP=1 [QCD] , s g > x0 e+ e- s XGLU=1 WEIGHTED=7 QNP=1 [QCD]

1-min MadGraph5_aMC@NLO tutorial



$$
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& - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
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\end{aligned}
$$

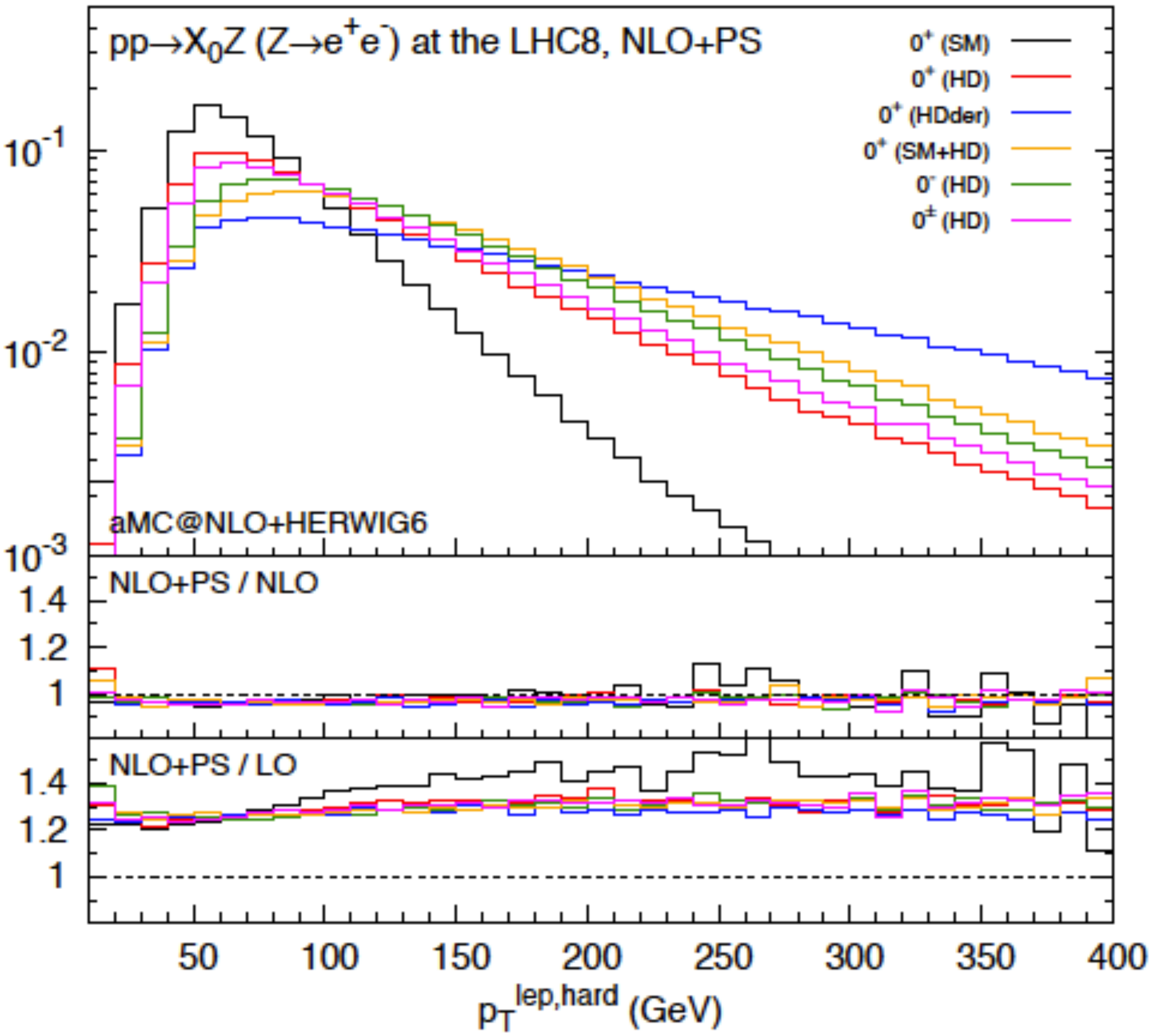
Vector-boson associated production (VH)

scenario	HC parameter choice
0^+(SM)	$\kappa_{SM} = 1$ ($c_\alpha = 1$)
0^+(HD)	$\kappa_{HZZ,HWW} = 1$ ($c_\alpha = 1$)
0^+(HDder)	$\kappa_{H\partial Z,H\partial W} = 1$ ($c_\alpha = 1$)
0^+(SM+HD)	$\kappa_{SM,HZZ,HWW} = 1$ ($c_\alpha = 1$, $\Lambda = v$)
0^-(HD)	$\kappa_{AZZ,AWW} = 1$ ($c_\alpha = 0$)
$0^\pm$(HD)	$\kappa_{HZZ,AZZ,HWW,AWW} = 1$ ($c_\alpha = 1/\sqrt{2}$)

scenario	σ_{LO} (fb)	σ_{NLO} (fb)	K
0^+(SM)	$10.13(1)^{+0.0\%}_{-0.5\%}$	$13.24(1)^{+2.2\%}_{-1.7\%}$	1.31
0^+(HD)	$2.638(2)^{+1.4\%}_{-1.7\%}$	$3.461(3)^{+1.9\%}_{-1.3\%}$	1.31
0^+(HDder)	$48.61(4)^{+4.2\%}_{-3.9\%}$	$63.59(5)^{+2.1\%}_{-1.9\%}$	1.31
0^+(SM+HD)	$19.95(1)^{+3.1\%}_{-3.1\%}$	$26.24(2)^{+1.8\%}_{-1.6\%}$	1.32
0^-(HD)	$1.480(1)^{+2.6\%}_{-2.7\%}$	$1.952(1)^{+1.7\%}_{-1.5\%}$	1.32
$0^\pm$(HD)	$2.061(1)^{+1.9\%}_{-2.0\%}$	$2.705(2)^{+1.8\%}_{-1.3\%}$	1.31

- Scale and PDF uncertainties are evaluated automatically at no extra computing cost via a reweighting technique.
- Such information is available on an event-by-event basis and therefore uncertainty bands can be plotted for any observables of interest.

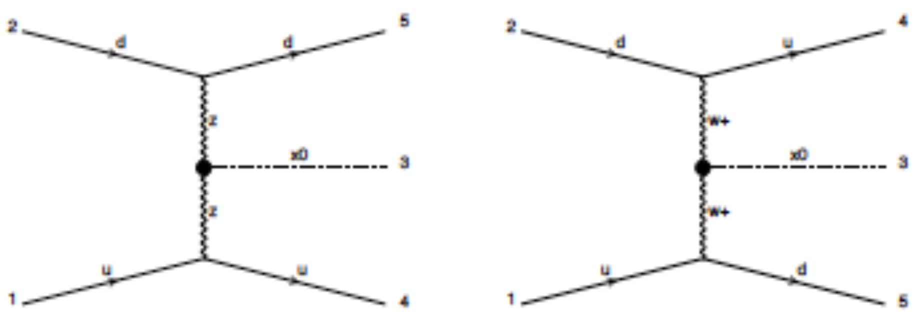
Maltoni, KM, Zaro [arXiv:1311.1829]



Higgs + 2 jets

Maltoni, KM, Zaro [arXiv:1311.1829]

```
./bin/mg5_aMC
>import model HC_NLO_X0
>generate p p > x0 j j $$ w+ w- z QCD=0 [QCD]
>output
>launch
```

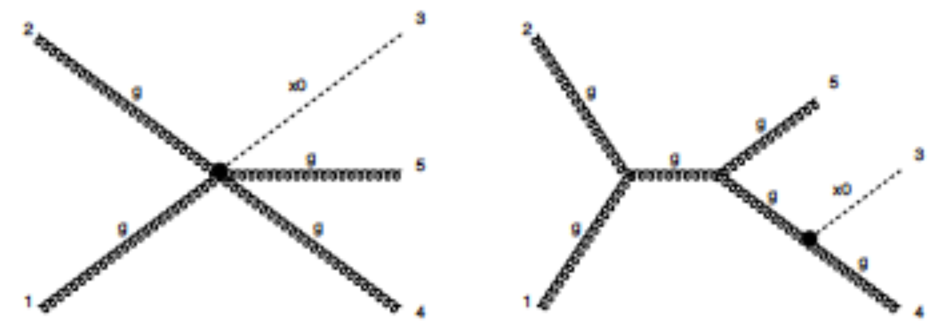


LHC 8 TeV

Scenario	σ_{LO} (fb)	σ_{NLO} (fb)	K
0^+(SM)	$1509(1)\ ^{+4.7\,\%}_{-4.4\,\%}$	$1633(2)\ ^{+2.0\,\%}_{-1.5\,\%}$	1.08
0^+(HD)	$69.66(6)\ ^{+7.5\,\%}_{-6.6\,\%}$	$67.08(13)\ ^{+2.2\,\%}_{-2.3\,\%}$	0.96
0^+(HDder)	$721.9(6)\ ^{+11.0\,\%}_{-9.0\,\%}$	$684.9(1.5)\ ^{+2.3\,\%}_{-2.8\,\%}$	0.95
0^+(SM+HD)	$3065(2)\ ^{+5.6\,\%}_{-5.1\,\%}$	$3144(5)\ ^{+1.6\,\%}_{-1.1\,\%}$	1.03
0^-(HD)	$57.10(4)\ ^{+7.7\,\%}_{-6.7\,\%}$	$55.24(11)\ ^{+2.1\,\%}_{-2.5\,\%}$	0.97
$0^\pm$(HD)	$63.46(5)\ ^{+7.6\,\%}_{-6.7\,\%}$	$61.07(13)\ ^{+2.3\,\%}_{-2.0\,\%}$	0.96

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

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

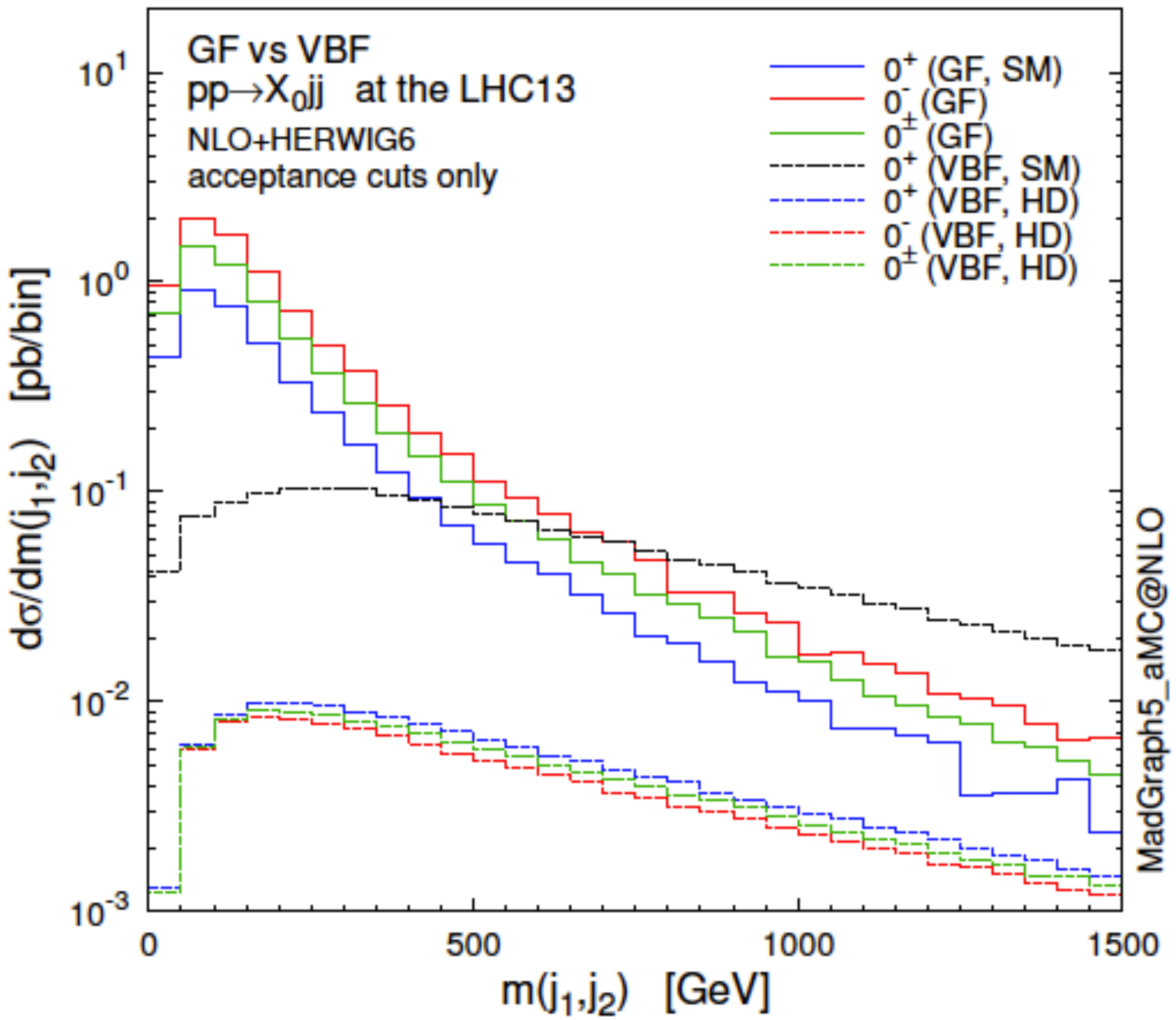


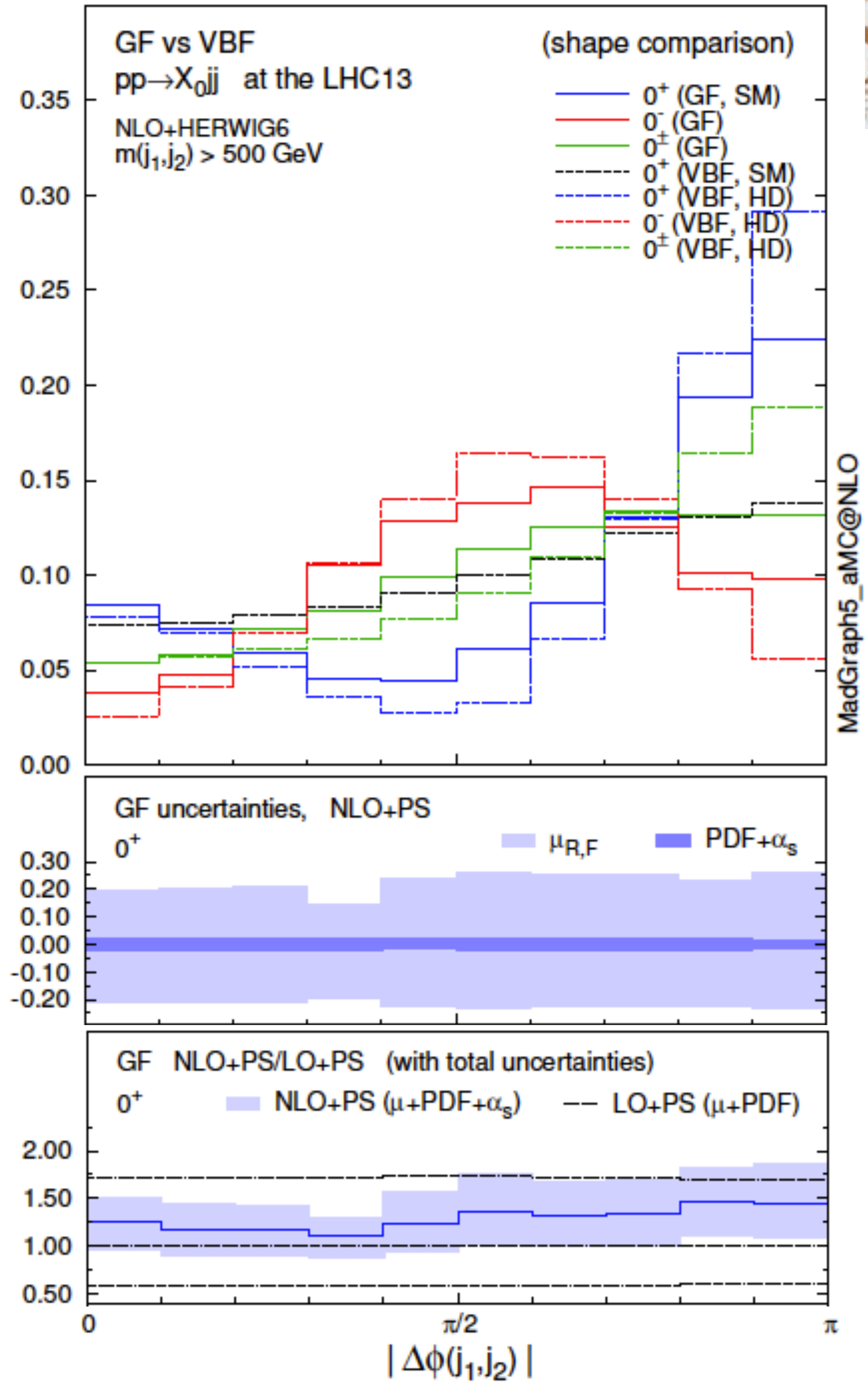
scenario		σ_{LO} (pb)	σ_{NLO} (pb)	K
LHC 8 TeV	0^+	$1.351(1)\ ^{+67.1}_{-36.8} \pm 4.3\%$	$1.702(6)\ ^{+19.7}_{-20.8} \pm 1.7\%$	1.26
	0^-	$2.951(3)\ ^{+67.2}_{-36.8} \pm 4.4\%$	$3.660(15)\ ^{+19.1}_{-20.6} \pm 1.7\%$	1.24
	$0^\pm$	$2.142(2)\ ^{+67.1}_{-36.8} \pm 4.4\%$	$2.687(10)\ ^{+19.6}_{-20.8} \pm 1.7\%$	1.25

- NLO corrections improve the predictions of the total rates by reducing the scale dependence and the PDF+αs uncertainty.

GF vs. VBF

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



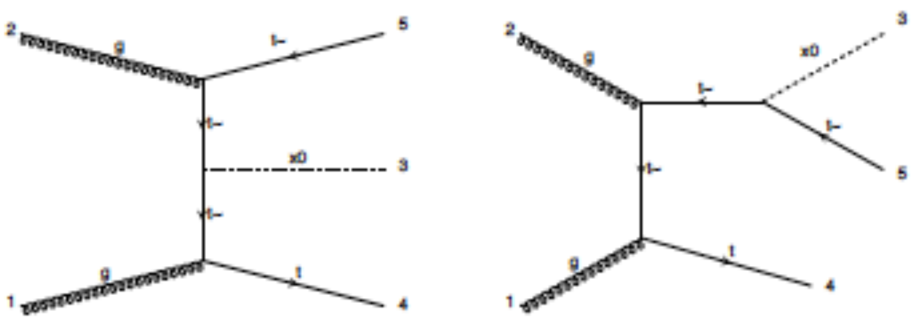


- Di-jet correlations are still sensitive probes of the CP mixing of the Higgs boson even after PS.

Top-pair associated (ttH)

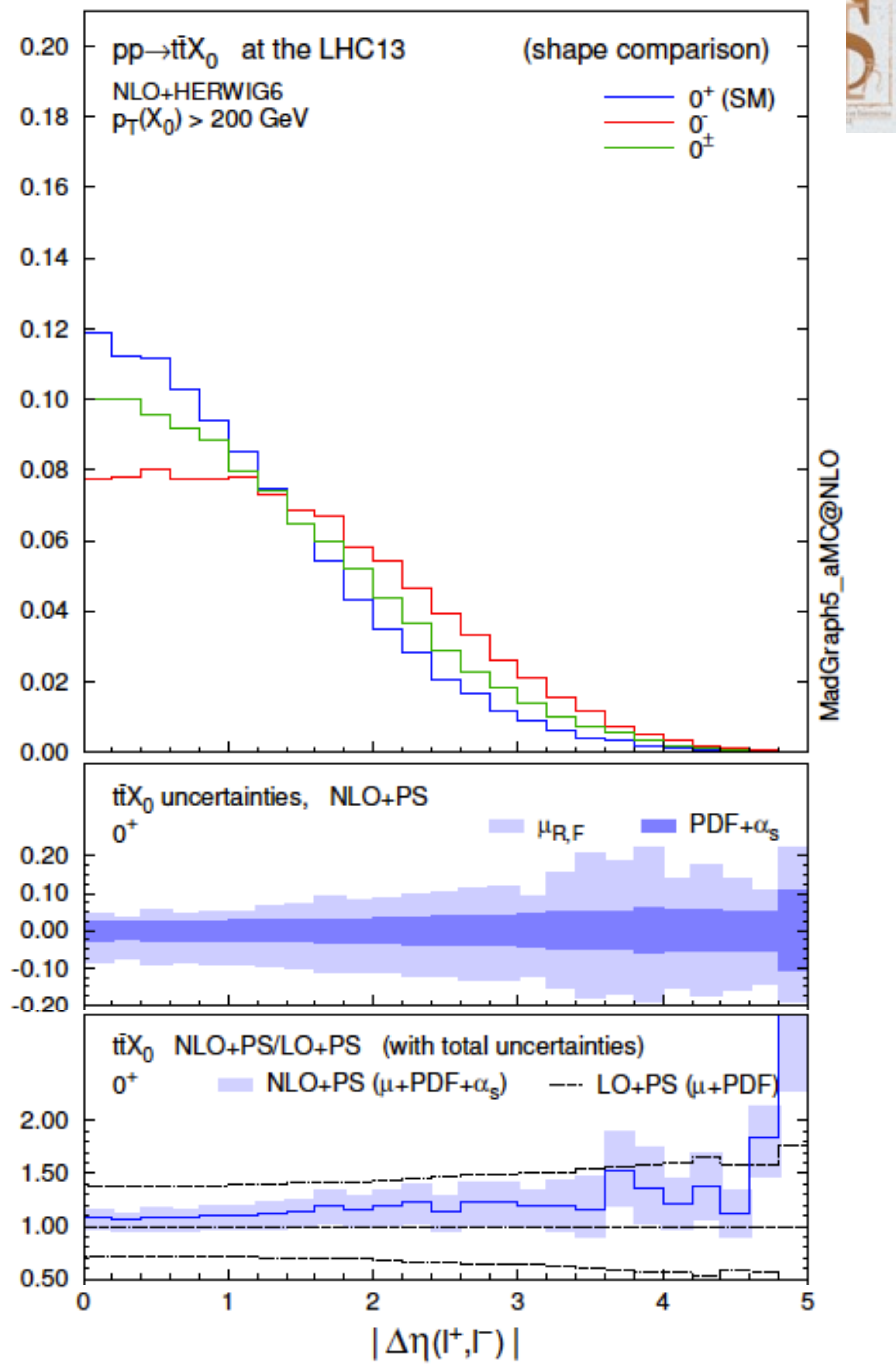
Demartin, Maltoni, KM, Page, Zaro [arXiv:1407.5089]

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



scenario		σ_{LO} (fb)	σ_{NLO} (fb)	K
LHC 8 TeV	0^+	$130.3(1)\ ^{+36.8}_{-24.6}\ \pm5.9\%$	$134.9(2)\ ^{+3.2}_{-8.3}\ \pm3.0\%$	1.04
	0^-	$44.49(4)\ ^{+42.5}_{-27.6}\ \pm10.3\%$	$47.07(6)\ ^{+6.5}_{-11.5}\ \pm4.9\%$	1.06
	$0^\pm$	$87.44(8)\ ^{+38.2}_{-25.4}\ \pm6.9\%$	$90.93(12)\ ^{+3.9}_{-9.1}\ \pm3.4\%$	1.04
LHC 13 TeV	0^+	$468.6(4)\ ^{+32.8}_{-22.8}\ \pm4.5\%$	$525.1(7)\ ^{+5.7}_{-8.7}\ \pm2.1\%$	1.12
	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

- NLO corrections cannot be described by an overall *K* factor and the constant theoretical uncertainties.



Summary

- After the discovery of a Higgs-like resonance at the LHC, the main focus of the studies now is the determination of the Higgs Lagrangian.
- This includes
  - the structure of the operators,
  - the coupling strength.
- The Higgs Characterisation (HC) results at NLO+PS are obtained in a fully automatic way through the implementation of the relevant interactions in FeynRules and then performing event generation in the MadGraph5_aMC@NLO framework.
- NLO corrections improve the predictions by reducing the theoretical uncertainties, and NLO+PS effects need to be accounted for to make accurate predictions on the kinematical distributions.

Back-up

Vrije Universiteit Brussel

D6 Higgs Effective Lagrangian

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

$$
\begin{aligned}
\mathcal{L}_{\rm SILH} = &\frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{\bar{c}_T}{2v^2}\left[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] - \frac{\bar{c}_6\lambda}{v^2}\left[H^\dagger H\right]^3 \\
&- \left[\frac{\bar{c}_u}{v^2} y_u \Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L u_R + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger\Phi\ \Phi\bar{Q}_L d_R + \frac{\bar{c}_l}{v^2} y_\ell\ \Phi^\dagger\Phi\ \Phi\bar{L}_L e_R + \text{h.c.}\right] \\
&+ \frac{ig\ \bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right] D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\
&+ \frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k} D^\nu\Phi\right] W^k_{\mu\nu} + \frac{ig'\ \bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right] B_{\mu\nu} \\
&+ \frac{g'^2\ \bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu}\ ,
\end{aligned}
$$

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

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

$$
\begin{aligned}
\mathcal{L}_{F_1} = &\frac{i\bar{c}_{HQ}}{v^2}\left[\bar{Q}_L\gamma^\mu Q_L\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] + \frac{4i\bar{c}'_{HQ}}{v^2}\left[\bar{Q}_L\gamma^\mu T_{2k}Q_L\right]\left[\Phi^\dagger T_2^k\overleftrightarrow{D}_\mu\Phi\right] \\
&+ \frac{i\bar{c}_{Hu}}{v^2}\left[\bar{u}_R\gamma^\mu u_R\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] + \frac{i\bar{c}_{Hd}}{v^2}\left[\bar{d}_R\gamma^\mu d_R\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] \\
&- \left[\frac{i\bar{c}_{Hud}}{v^2}\left[\bar{u}_R\gamma^\mu d_R\right]\left[\Phi\cdot\overleftrightarrow{D}_\mu\Phi\right] + \text{h.c.}\right] \\
&+ \frac{i\bar{c}_{HL}}{v^2}\left[\bar{L}_L\gamma^\mu L_L\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] + \frac{4i\bar{c}'_{HL}}{v^2}\left[\bar{L}_L\gamma^\mu T_{2k}L_L\right]\left[\Phi^\dagger T_2^k\overleftrightarrow{D}_\mu\Phi\right] \\
&+ \frac{i\bar{c}_{He}}{v^2}\left[\bar{e}_R\gamma^\mu e_R\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]\ ,
\end{aligned}
$$

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

✦ 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]

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

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

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

HEL [arXiv: 1310.5150]

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

Mapping between the D6 and D5 operators

HC [arXiv: 1306.6464]

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

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

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V = A, Z, W^\pm), \quad \widetilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}V^{\rho\sigma}$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu ,$$

HEL [arXiv: 1310.5150]

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

Mapping between the D6 and D5 operators

HC [arXiv: 1306.6464]

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

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

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V = A, Z, W^\pm), \quad \widetilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$$

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c \,,$$

HEL [arXiv: 1310.5150]

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

Mapping between the D6 and D5 operators

HC [arXiv: 1306.6464]

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

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

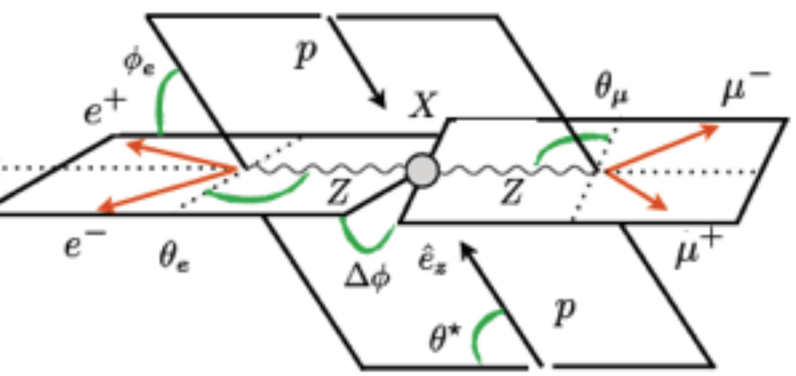
$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad (V = A, Z, W^\pm), \quad \widetilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}V^{\rho\sigma}$$
$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu\,,$$

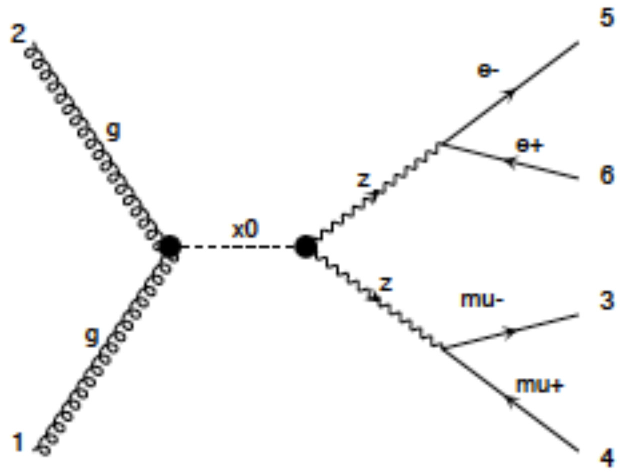
HEL [arXiv: 1310.5150]

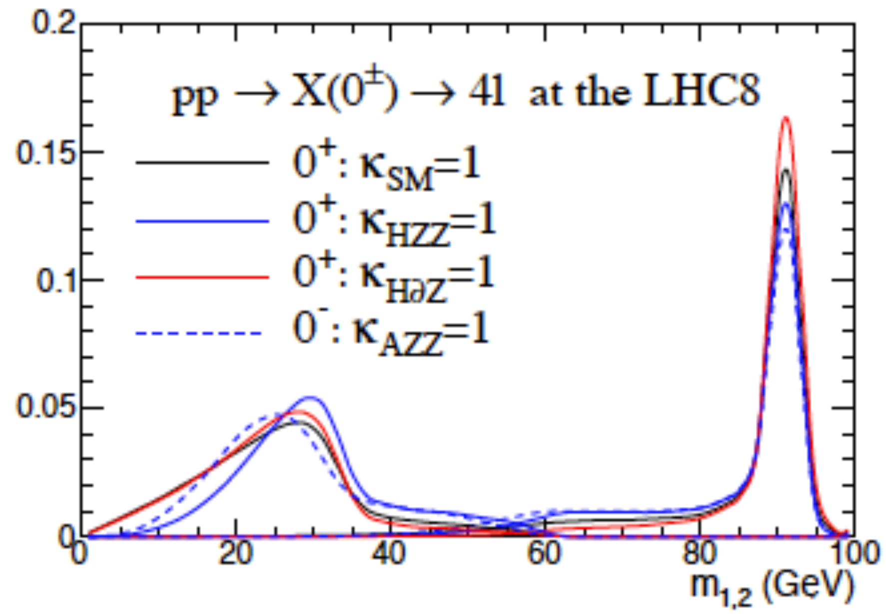
Eq. (2.25)	Ref. [46]	Section 2.1
g_{hgg}	$c_\alpha \kappa_{Hgg} g_{Hgg}$	$g_H - \frac{4\bar c_g g_s^2 v}{m_W^2}$
$\tilde g_{hgg}$	$s_\alpha \kappa_{Agg} g_{Agg}$	$-\frac{4\tilde c_g g_s^2 v}{m_W^2}$
$g_{h\gamma\gamma}$	$c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}$	$a_H - \frac{8 g \bar c_\gamma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

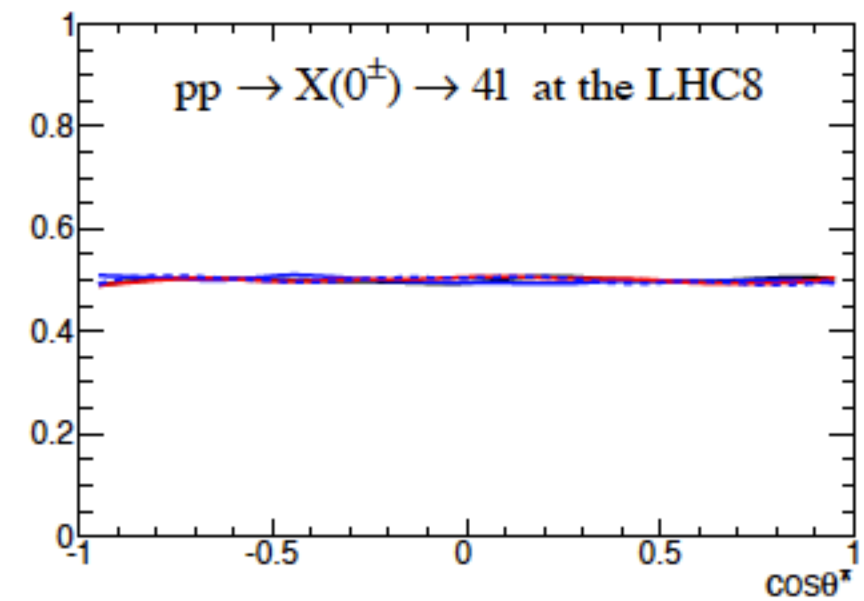
Two approaches equivalent as they can be mapped into one another.

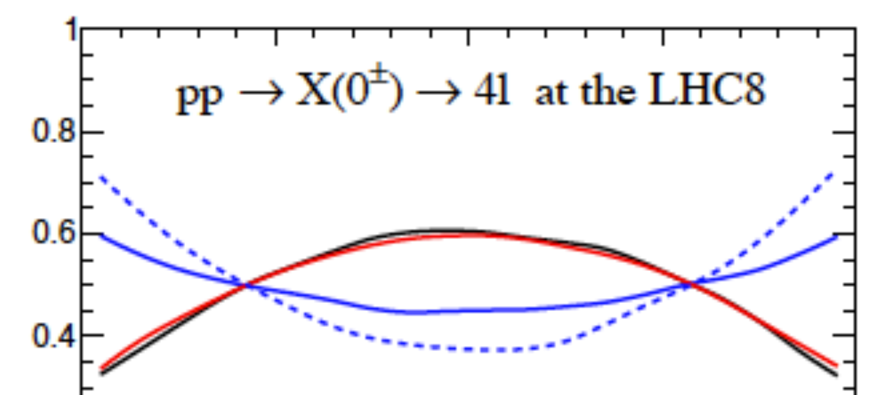
Mass and angular distributions -- spin0

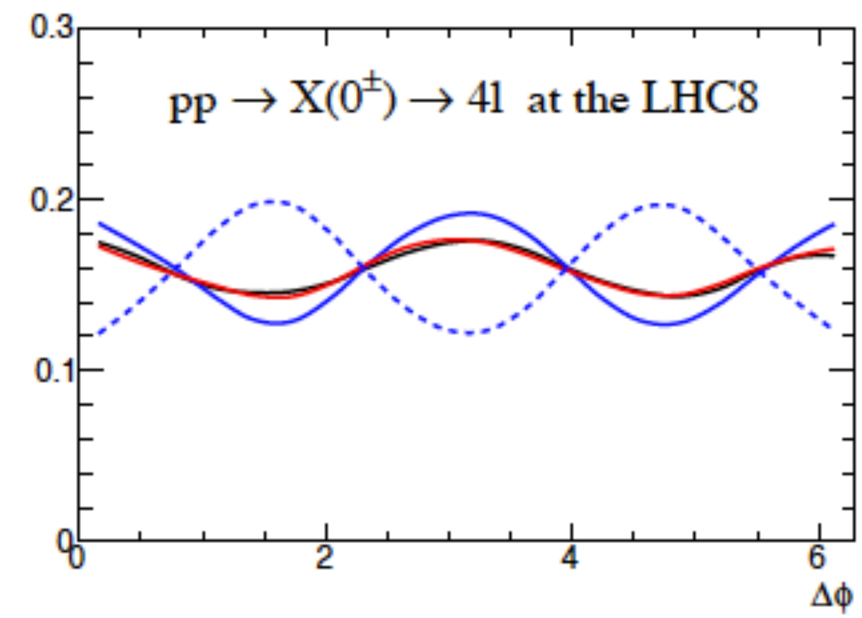













```
./bin/mg5_aMC
>import model HC
>generate p p > x0, x0 > mu- mu+ e- e+
>launch
```

Effective Lagrangian -- spin1

- The most general interactions at the lowest canonical dimension:

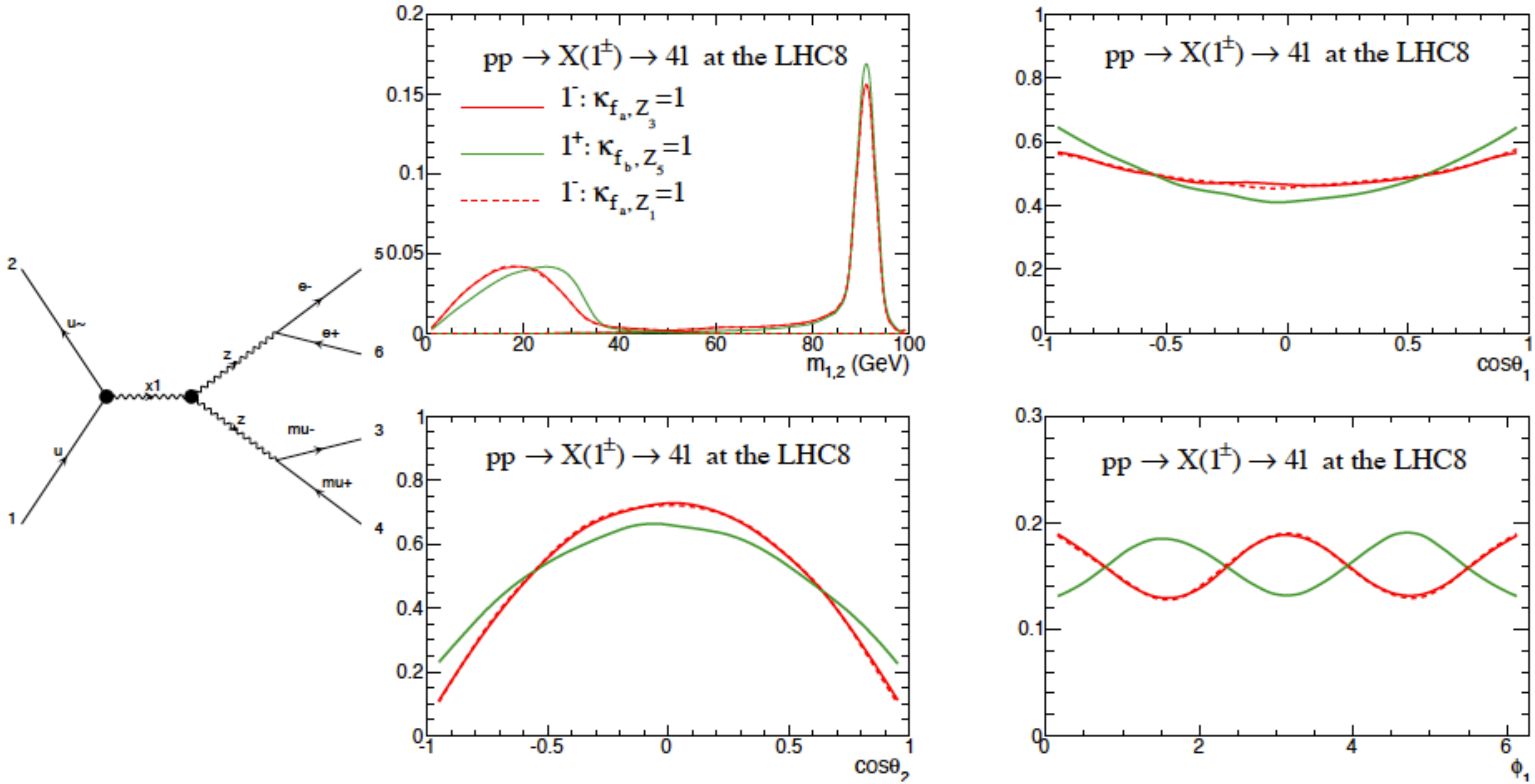
$$\mathcal{L}_1^f = \sum_{f=q,\ell} \bar{\psi}_f \gamma_\mu (\kappa_{f_a} a_f - \kappa_{f_b} b_f \gamma_5) \psi_f X_1^\mu$$

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

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

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

Mass and angular distributions -- spin1



Effective Lagrangian -- spin2

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

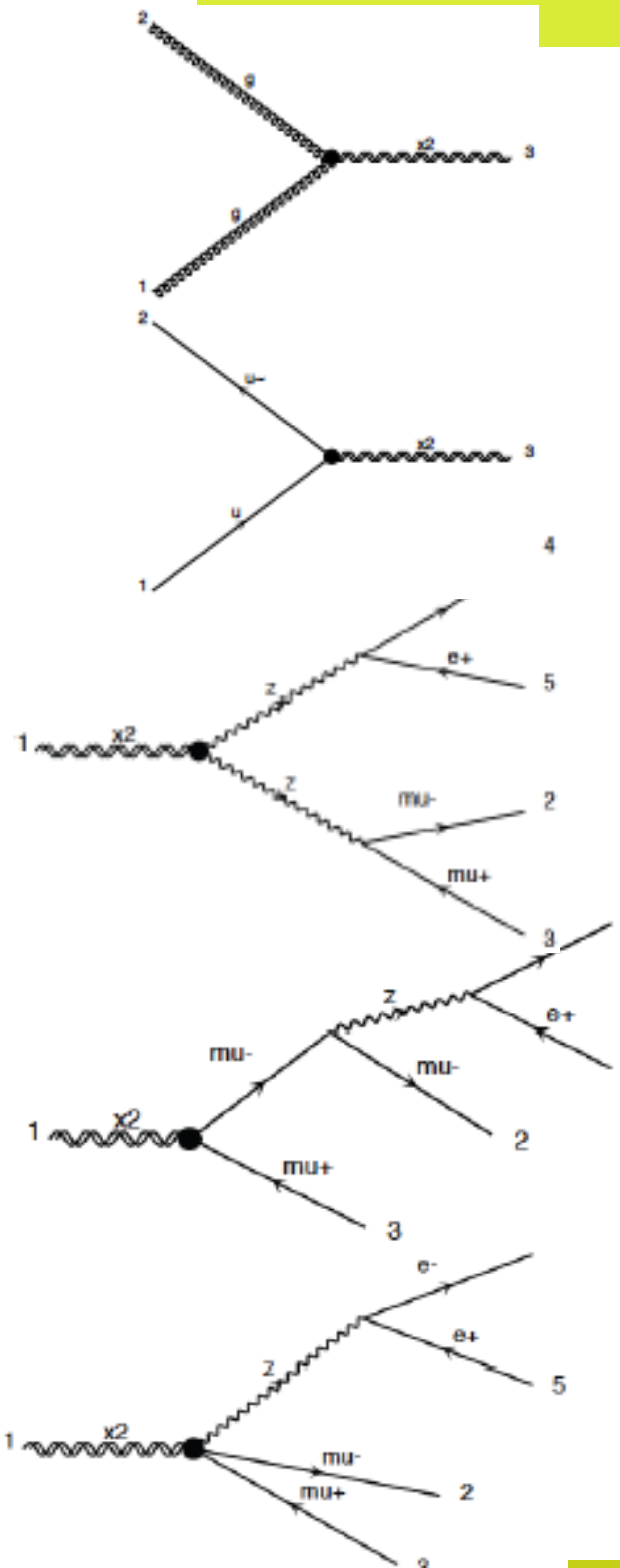
$$\mathcal{L}_2^f = -\frac{1}{\Lambda}\sum_{f=q,\ell} \kappa_f T^f_{\mu\nu} X_2^{\mu\nu}$$

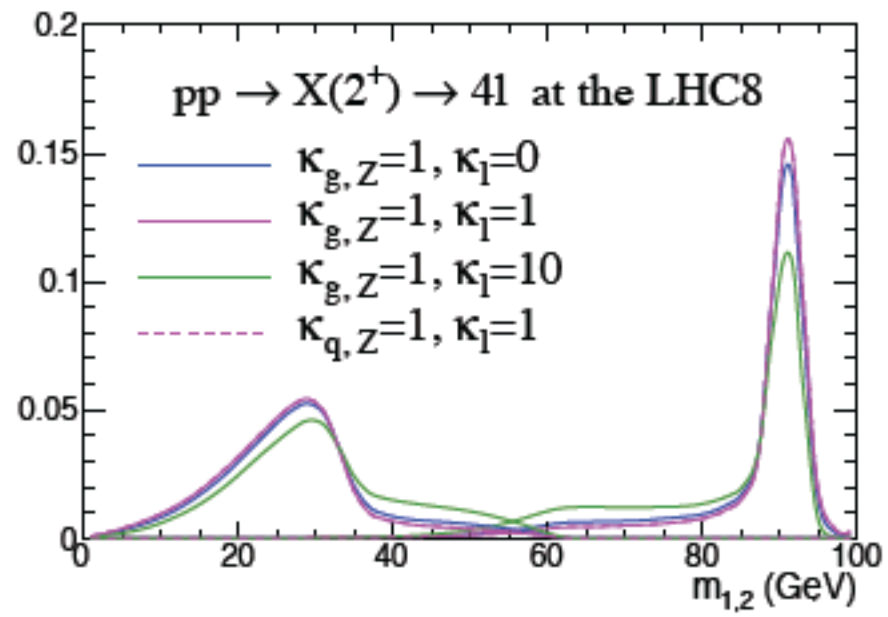
$$\mathcal{L}_2^V = -\frac{1}{\Lambda}\sum_{V=Z,W,\gamma,g} \kappa_V T^V_{\mu\nu} X_2^{\mu\nu}$$

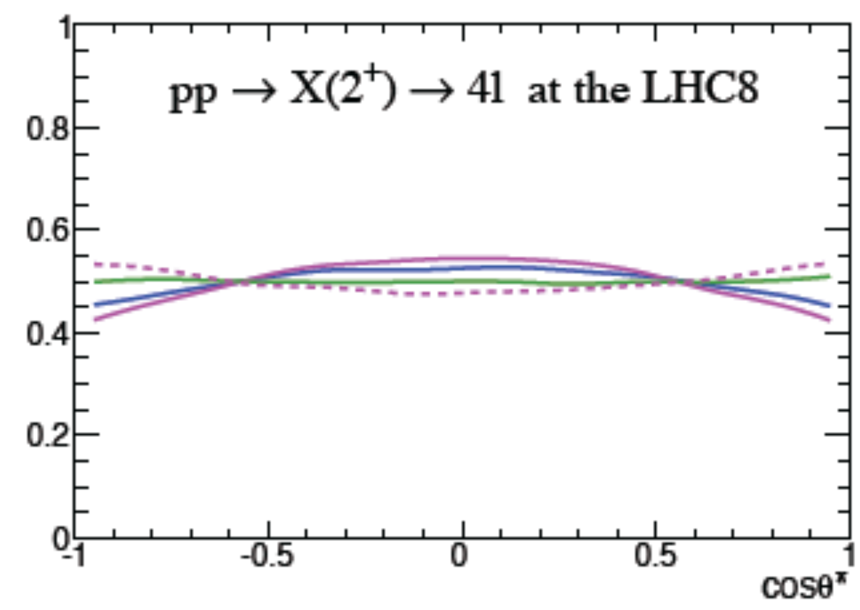
  - The E-M tensor for QED:

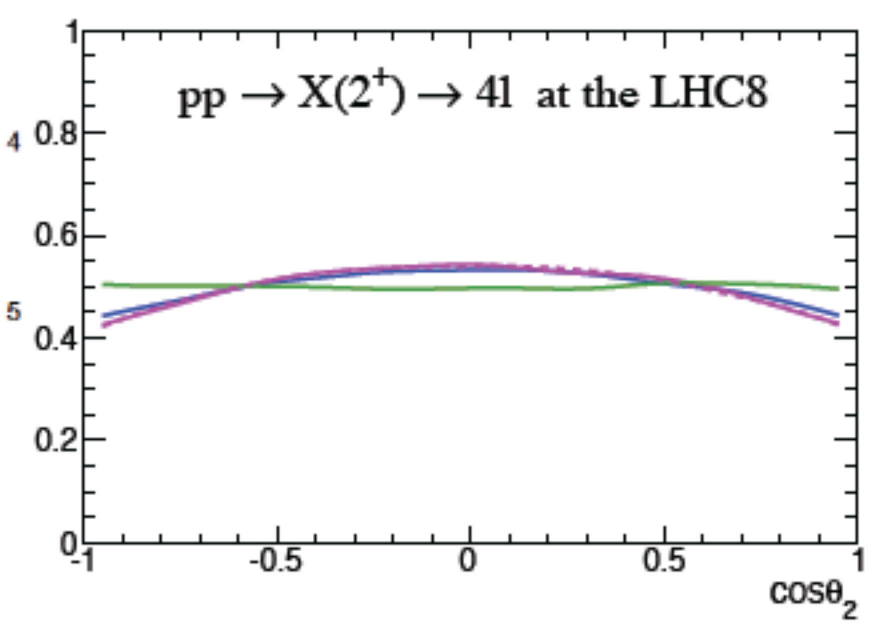
$$\begin{aligned} T^f_{\mu\nu} =& - g_{\mu\nu}\Big[\bar\psi_f(i\gamma^\rho D_\rho - m_f)\psi_f - \frac{1}{2}\partial^\rho(\bar\psi_f i\gamma_\rho\psi_f)\Big] \\ &+ \Big[\frac{1}{2}\bar\psi_f i\gamma_\mu D_\nu\psi_f - \frac{1}{4}\partial_\mu(\bar\psi_f i\gamma_\nu\psi_f) + (\mu\leftrightarrow\nu)\Big]\,,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

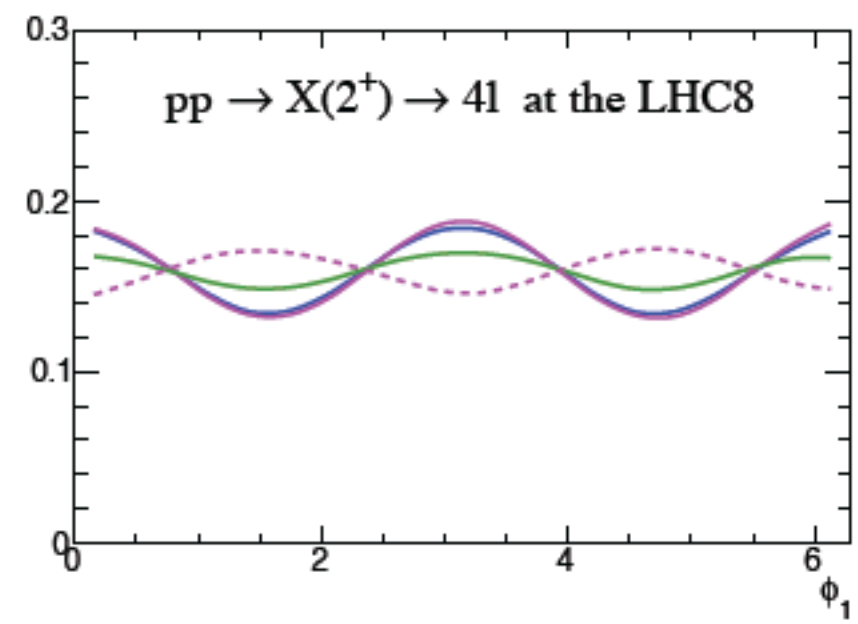
Mass and angular distributions -- spin2

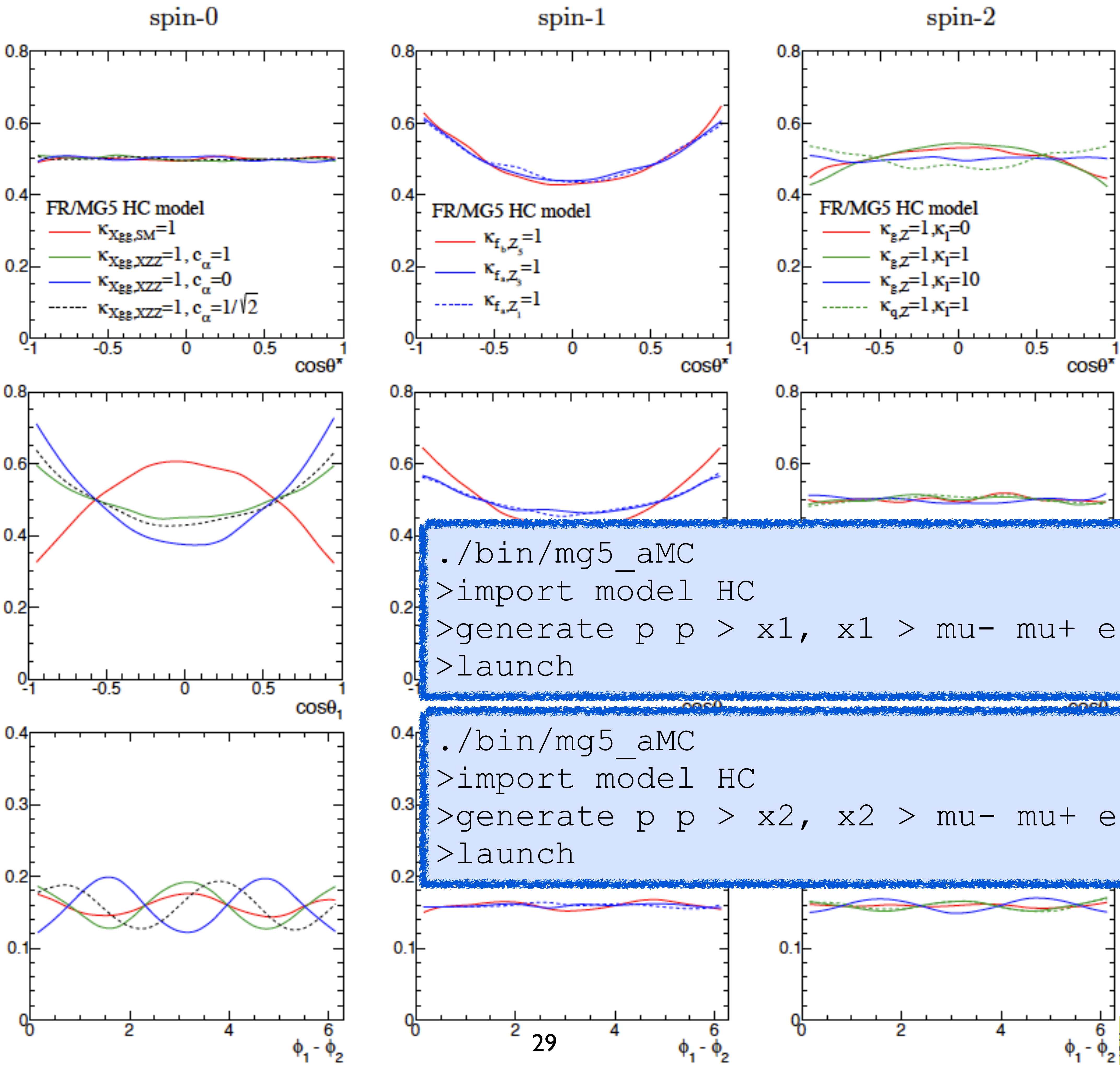








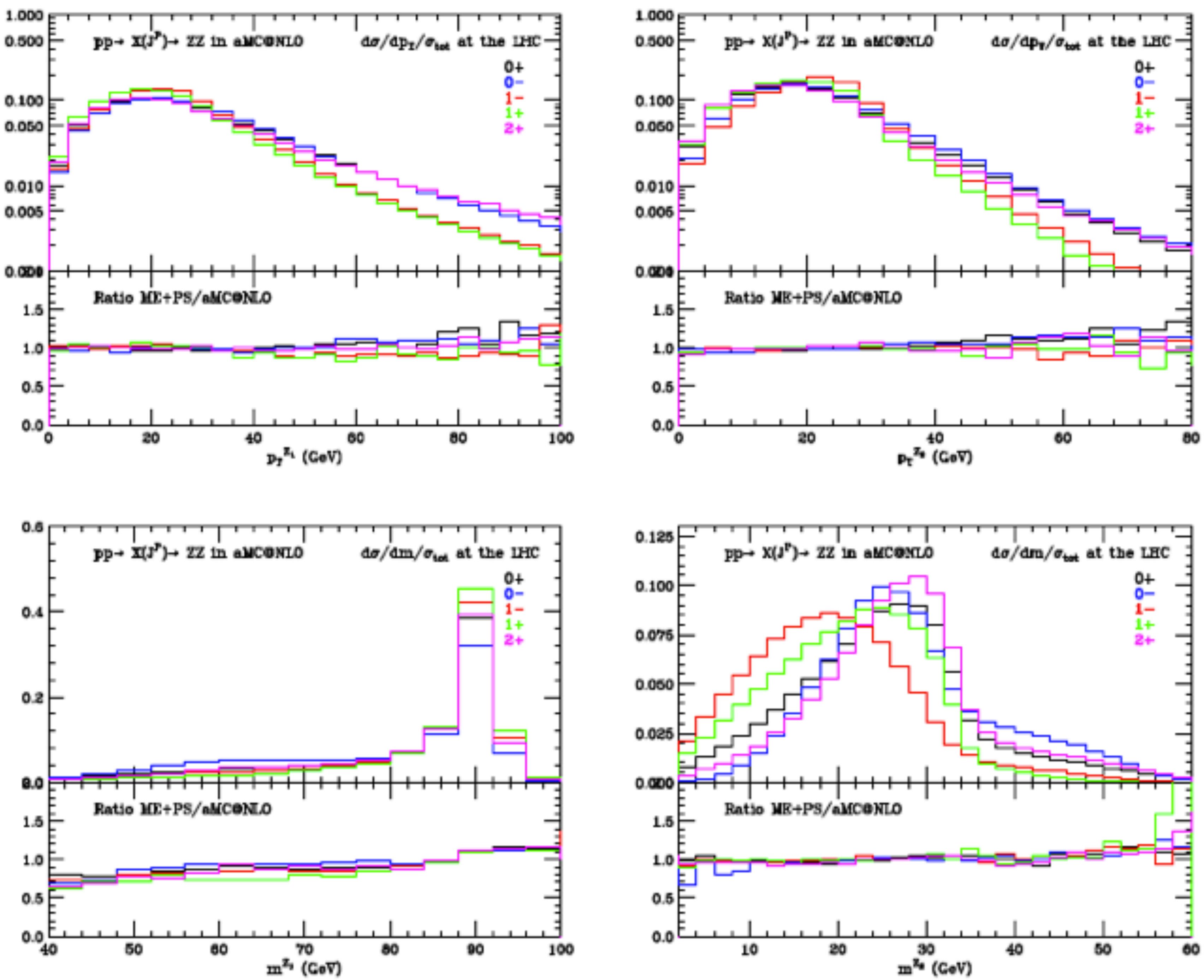





```
./bin/mg5_aMC
>import model HC
>generate p p > x1, x1 > mu- mu+ e- e+
>launch
```

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

aMC@NLO vs. ME+PS

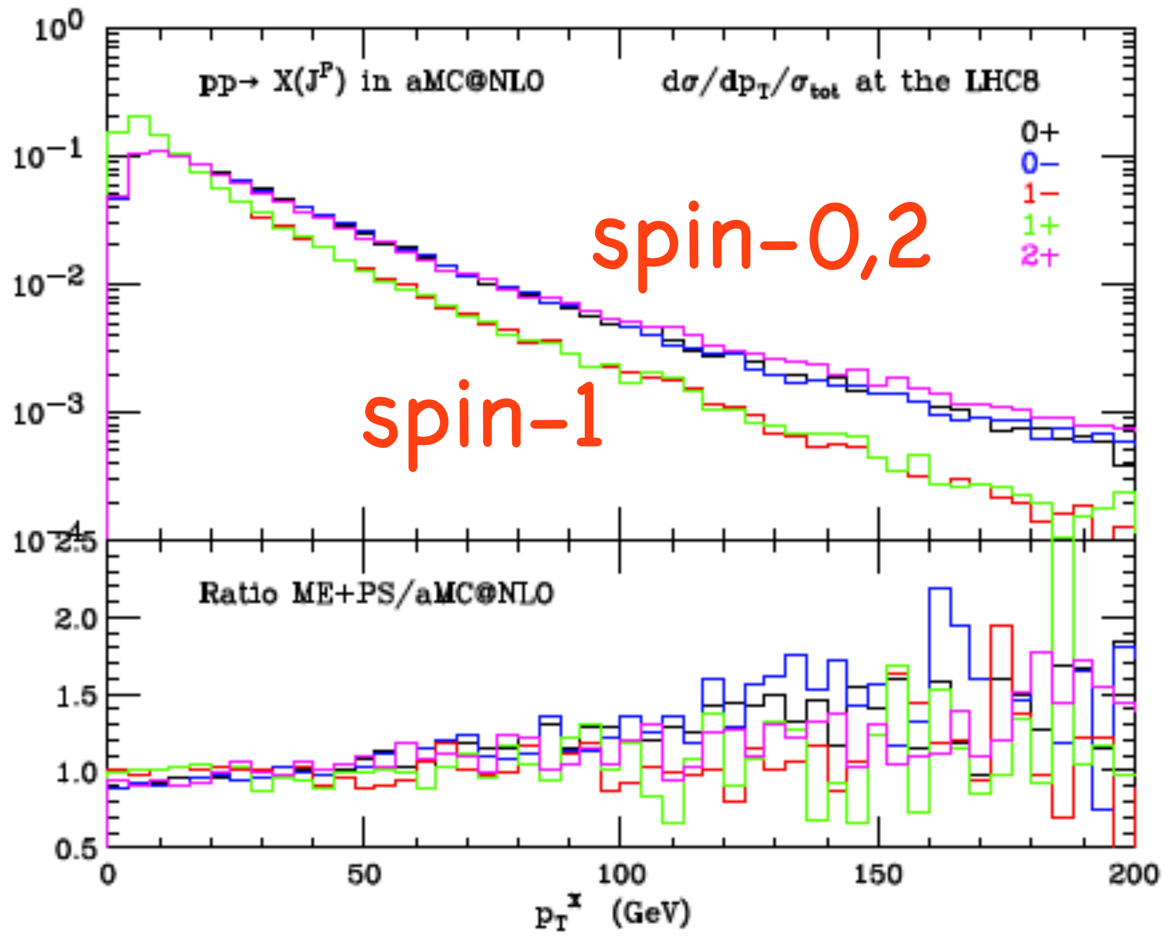


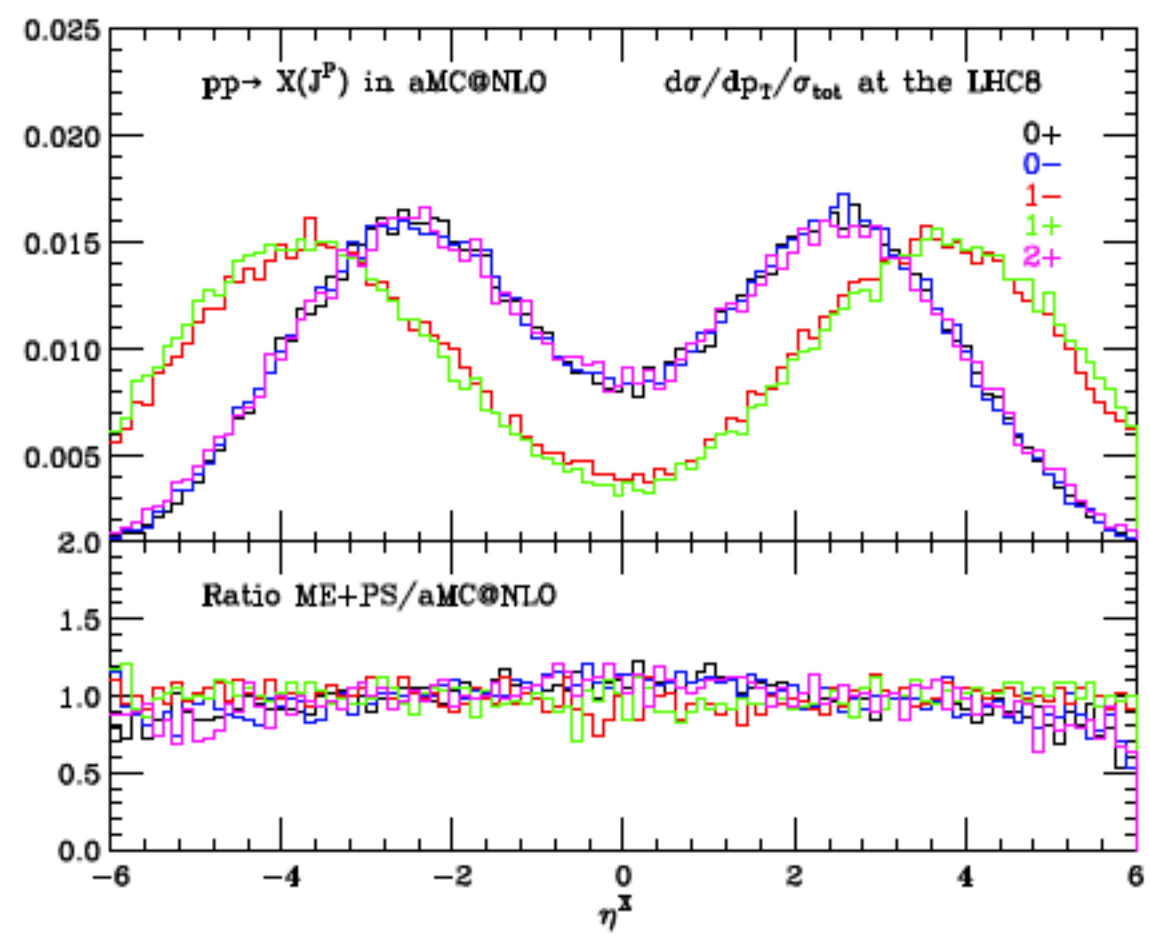
Good agreement between the ME+PS and aMC@NLO predictions for most observables.

For spin0, the production and decay factorize, for spin 1 and 2 this does not happen and the full 2->4,5 matrix elements need to be used.

Higher order effects in QCD (I)

inclusive production in pp → X(J^P)





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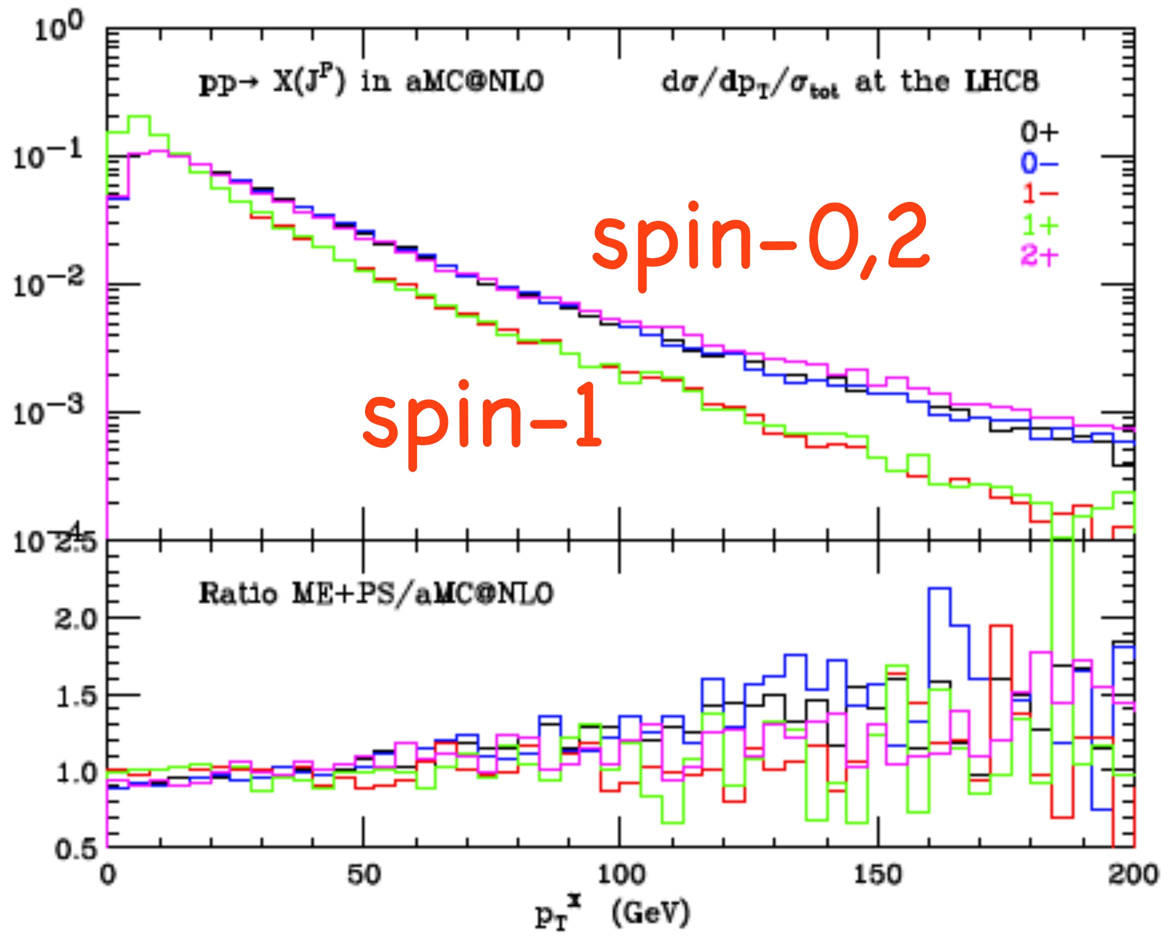
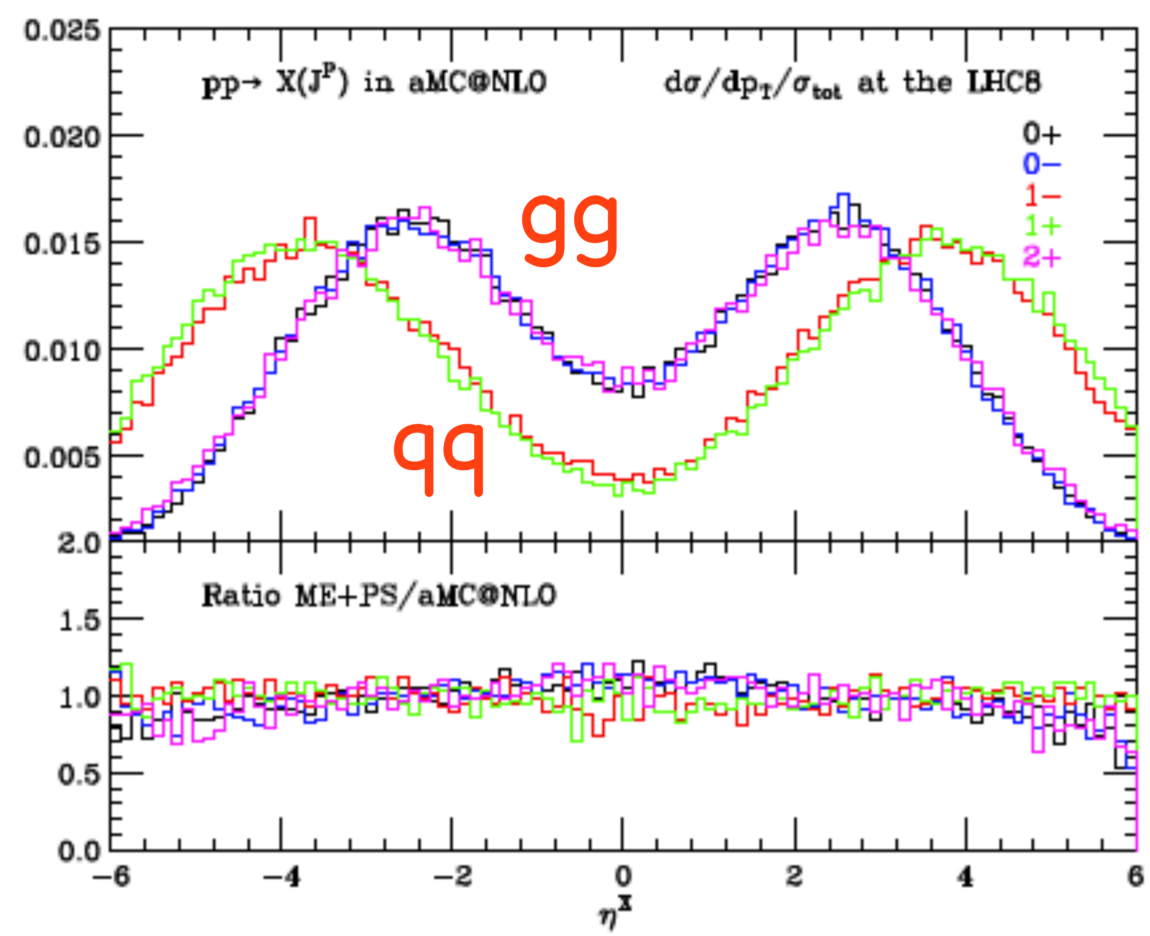
Higher order effects in QCD (I)

inclusive production in pp → X(J^P)



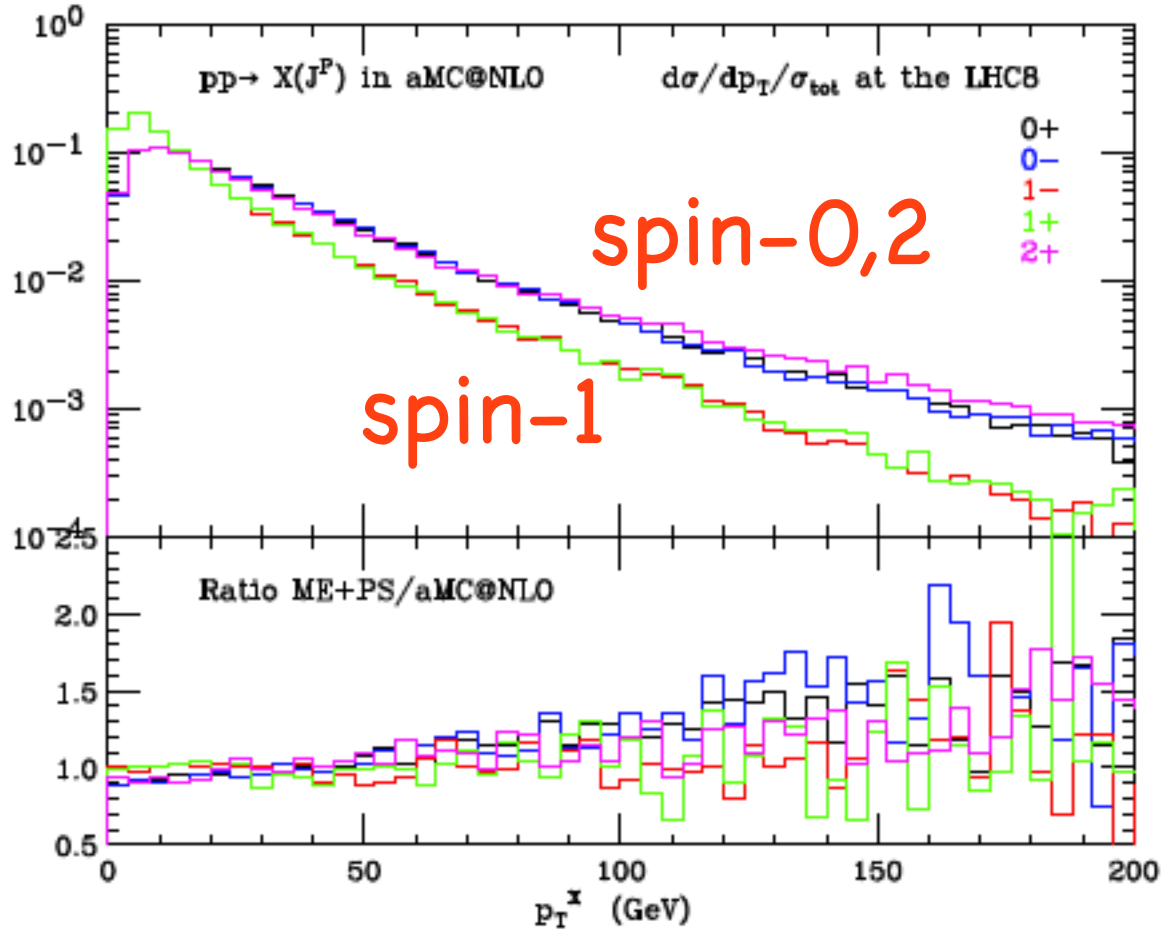


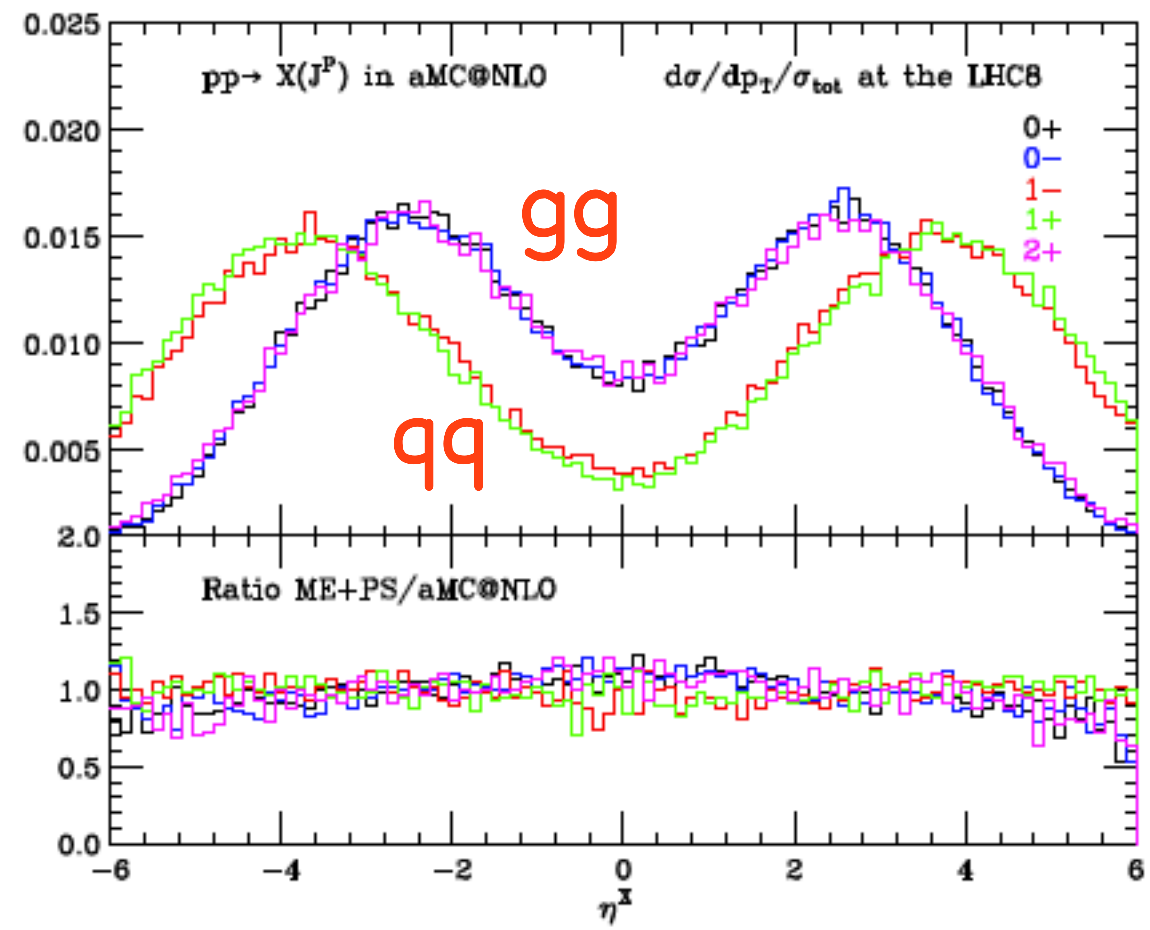
The matched sample is harder than aMC@NLO at large pT due to the extra 2 ME patrons in the matched sample.

The different shapes are due to the different initial state.

Higher order effects in QCD (I)

inclusive production in pp → X(J^P)





The matched sample is harder than aMC@NLO at large pT due to the extra 2 ME patrons in the matched sample.

The different shapes are due to the different initial state.

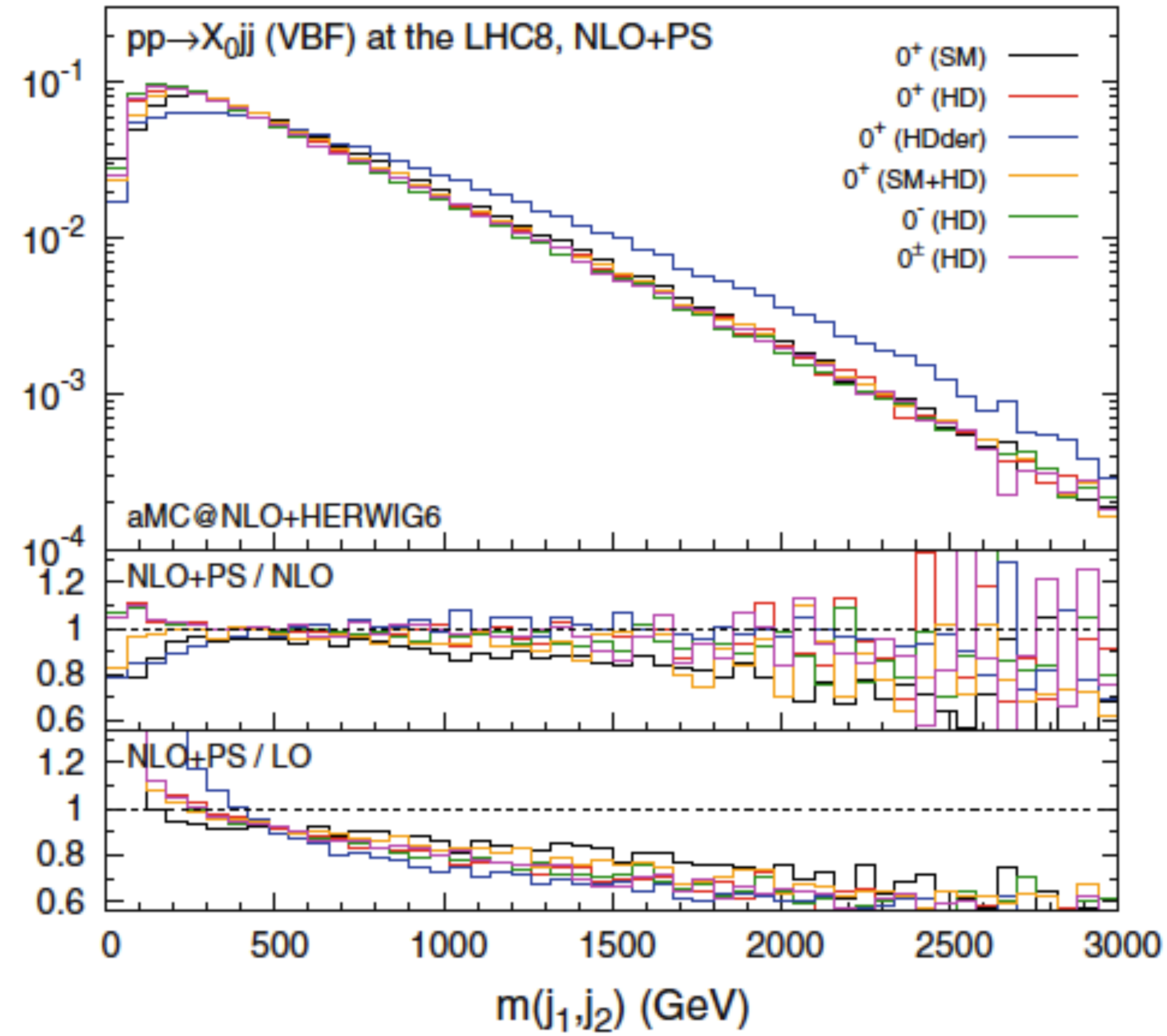
excellent agreement between ME+PS and aMC@NLO

Mjj distributions

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

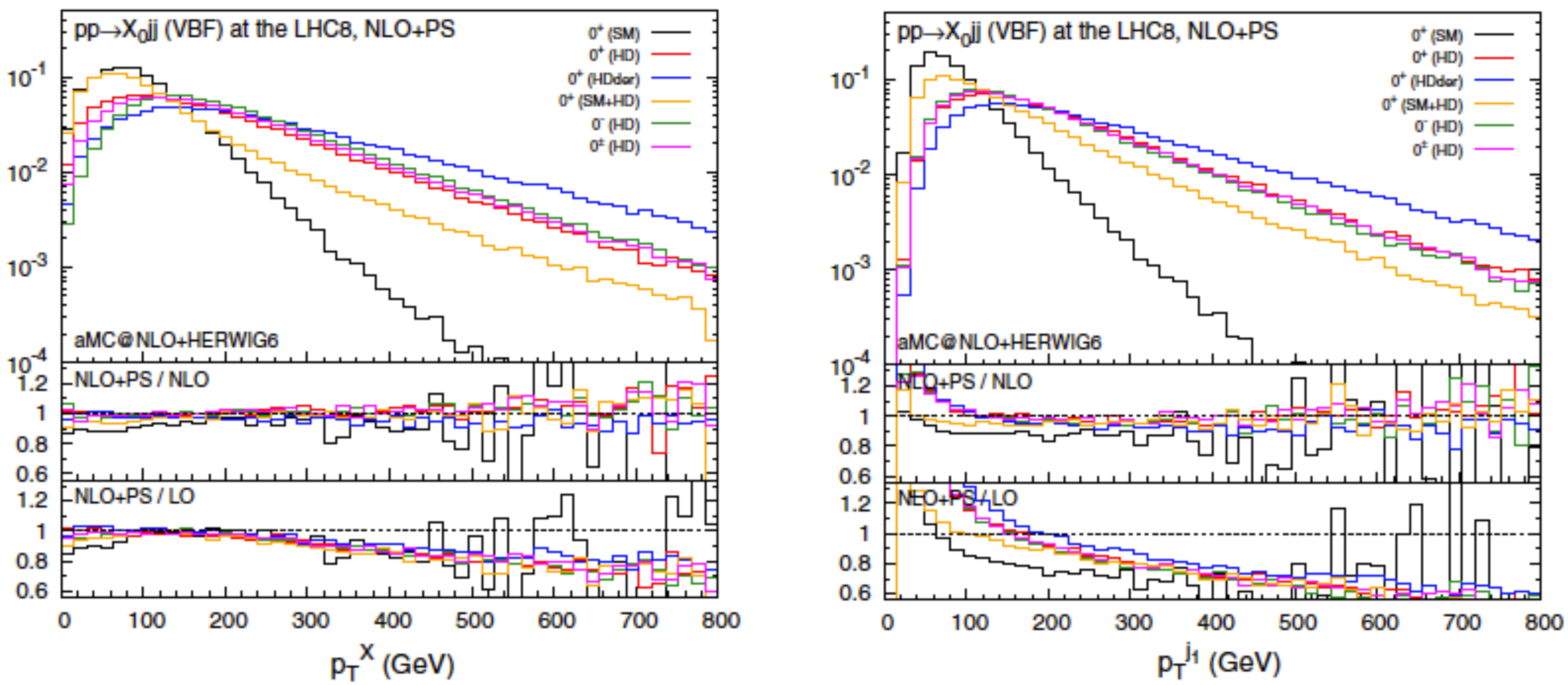
Scenario	HC parameter choice
0^+(SM)	$\kappa_{SM} = 1$ ($c_\alpha = 1$)
0^+(HD)	$\kappa_{HZZ,HWW} = 1$ ($c_\alpha = 1$)
0^+(HDder)	$\kappa_{H\partial Z,H\partial W} = 1$ ($c_\alpha = 1$)
0^+(SM+HD)	$\kappa_{SM,HZZ,HWW} = 1$ ($c_\alpha = 1,\ \Lambda = v$)
0^-(HD)	$\kappa_{AZZ,AWW} = 1$ ($c_\alpha = 0$)
$0^\pm$(HD)	$\kappa_{HZZ,AZZ,HWW,AWW} = 1$ ($c_\alpha = 1/\sqrt{2}$)

Scenario	σ_{LO} (fb)	σ_{NLO} (fb)	K
0^+(SM)	$1509(1)\ ^{+4.7\ \%}_{-4.4\ \%}$	$1633(2)\ ^{+2.0\ \%}_{-1.5\ \%}$	1.08
0^+(HD)	$69.66(6)\ ^{+7.5\ \%}_{-6.6\ \%}$	$67.08(13)\ ^{+2.2\ \%}_{-2.3\ \%}$	0.96
0^+(HDder)	$721.9(6)\ ^{+11.0\ \%}_{-9.0\ \%}$	$684.9(1.5)\ ^{+2.3\ \%}_{-2.8\ \%}$	0.95
0^+(SM+HD)	$3065(2)\ ^{+5.6\ \%}_{-5.1\ \%}$	$3144(5)\ ^{+1.6\ \%}_{-1.1\ \%}$	1.03
0^-(HD)	$57.10(4)\ ^{+7.7\ \%}_{-6.7\ \%}$	$55.24(11)\ ^{+2.1\ \%}_{-2.5\ \%}$	0.97
$0^\pm$(HD)	$63.46(5)\ ^{+7.6\ \%}_{-6.7\ \%}$	$61.07(13)\ ^{+2.3\ \%}_{-2.0\ \%}$	0.96



- The mjj distributions are all very similar (except the scenario with the derivative operator.
- The QCD corrections tend to make the tagging jets softer.

pT distributions

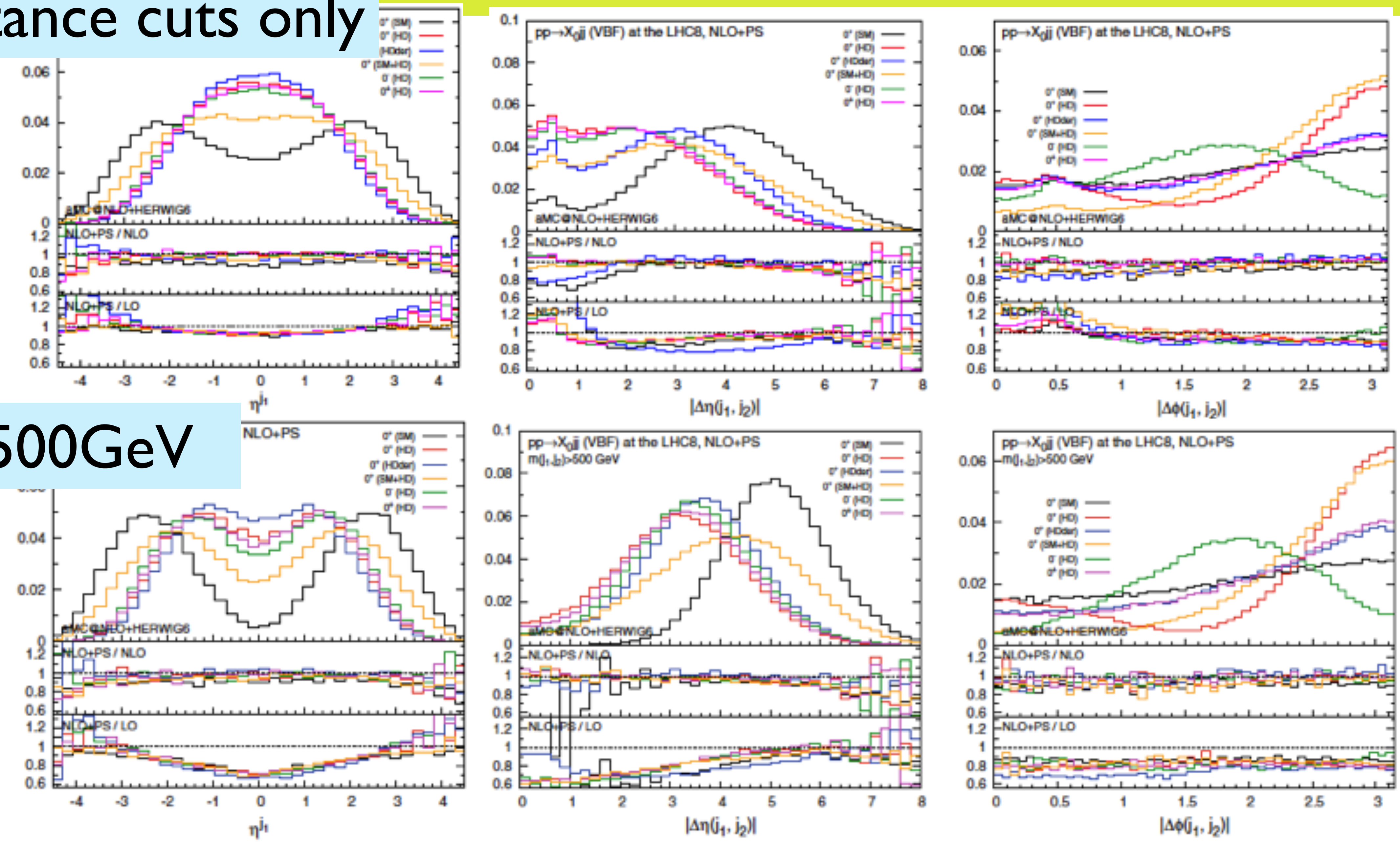


- The unitarity violating behavior of the HD interactions, especially HDder, clearly manifests itself.

mjj cuts

acceptance cuts only

mjj>500GeV



- The mjj cut effectively suppresses the central jet activity, especially for SM.
- The difference among the scenarios becomes more pronounced.
- NLO corrections cannot be described by an overall K factor, and also depends on the applied cuts.