Higgs characterisation project

Kentarou Mawatari

(Vrije Universities Brussel and International Solvay Institutes)

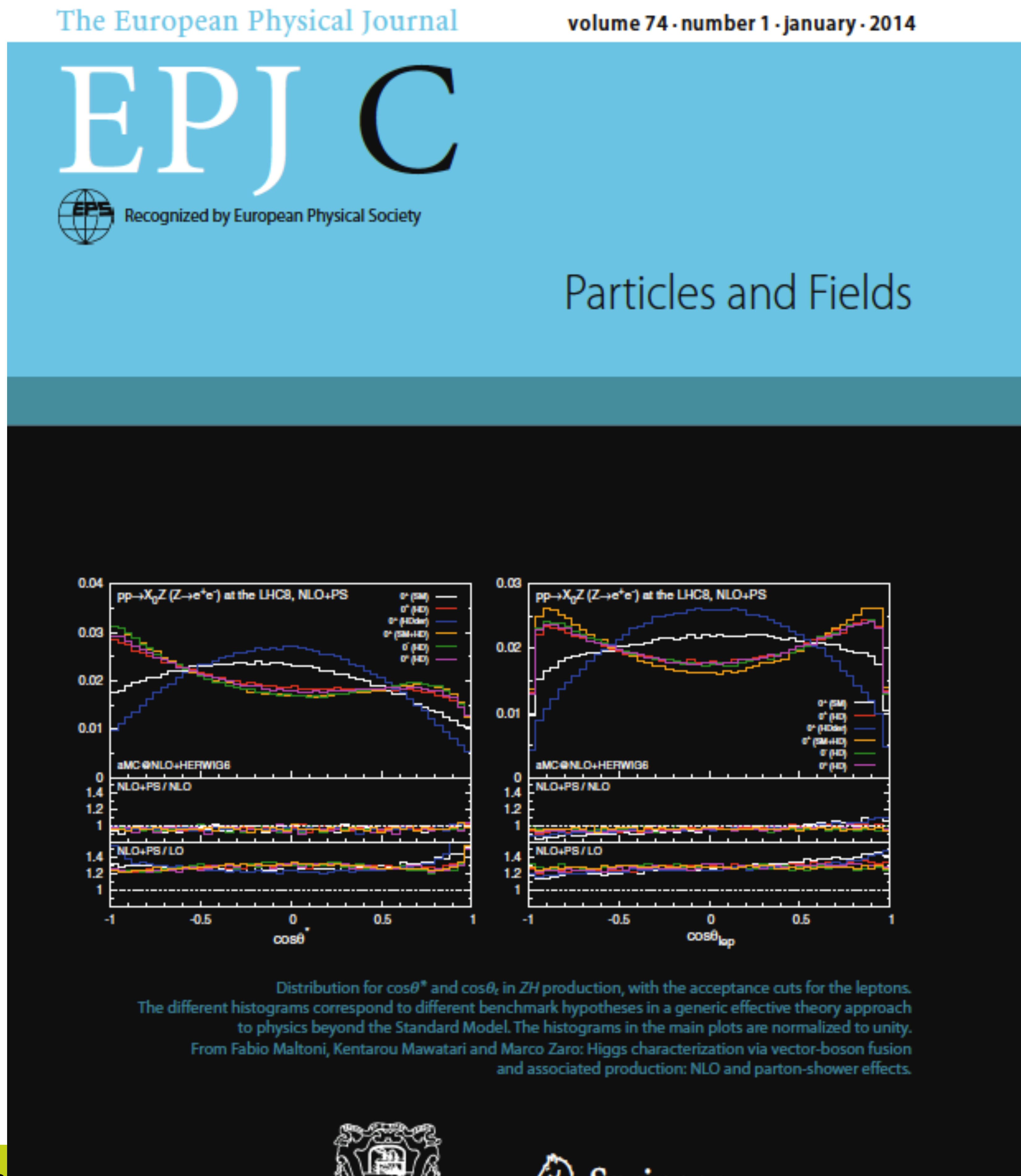
- HC1: "A framework for Higgs characterisation"
  Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro, JHEP11(2013)043 [arXiv:1306.6464]

- HC2: "Higgs characterisation via VBF/VH: NLO and parton-shower effects"
  Maltoni, Mawatari, Zaro, EPJC74(2014)2710 [arXiv:1311.1829]

- HC3: "Higgs characterisation at NLO in QCD: CP properties of the top Yukawa"
  Demartin, Maltoni, Mawatari, Page, Zaro, EPJC74(2014)3065 [arXiv:1407.5089]

- HC4: Higgs production in association with a single top quark at the LHC
  Demartin, Maltoni, Mawatari, Zaro, [arXiv:1504.xxxxx]

  - Sec.11 (spin/CP) in YR3 of the LHC Higgs Cross Section Working Group (HXSWG)
    de Aquino, Mawatari [arXiv:1307.1347]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EPJ C
Recognized by European Physical Society
Particles and Fields
pp→X0Z (Z→e+e-) at the LHC8, NLO+PS
aMC@NLO+HERWIG6
NLO+PS / NLO
NLO+PS / LO
cosθ*
cosθlep
Distribution for cosθ* and cosθl in ZH production, with the acceptance cuts for the leptons.
The different histograms correspond to different benchmark hypotheses in a generic effective theory approach
to physics beyond the Standard Model. The histograms in the main plots are normalized to unity.
From Fabio Maltoni, Kentarou Mawatari and Marco Zaro: Higgs characterization via vector-boson fusion
and associated production: NLO and parton-shower effects.
Springer

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Higgs observation, evidence, precision, ...

- 2012 July
  - Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
  - Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
- 2013 July
  - Evidence for the spin-0 nature of the Higgs boson using ATLAS data
- 2013 October
  - Physics Nobel Prize [F. Englert (Brussels) and P. Higgs (Edinburgh)]
- 2015 Spring
  - LHC Run-II

looking for deviations from the SM ⇔ Higgs precision

- effective field theory (EFT) approach
- theory predictions as precise as possible

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A framework for Higgs characterisation

[arXiv: 1306.6464]

The FeynRules and MadGraph5 framework

FeynRules model
P. de Aquino, K. Mawatari (Vrije U. Brussel)

aMC@NLO
F. Demartin, F. Maltoni, M. Zaro (UC Louvain)
R. Frederix, S. Frixione (CERN)
P. Torrielli (Zurich)

MadWeight
P. Artoisenet (Nikhef)

spin2 in aMC@NLO
M.K. Mandal (Harish-Chandra)
P. Mathews, S. Seth (Saha Inst.)
V. Ravindran (CIT)

Higgs Characterisation (HC)
via the FeynRules and MadGraph5_aMC@NLO frameworks
NLO+PS (parton-shower) effects

- HC provides an automated NLO+PS accurate tool and predictions to accomplish the most general and accurate chracterisation of Higgs interactions in the main production and decay modes at the LHC.
- The code is publicly available at the FeynRules repository: https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

- HC1: "A framework for Higgs characterisation" JHEP11(2013)043 [arXiv:1306.6464]
  Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro
  ➡ HC framework based on the effective filed theory (EFT) approach
- HC2: "Higgs characterisation via VBF/VH: NLO and parton-shower effects" EPJC74(2014)2710 [arXiv:1311.1829]
  Maltoni, Mawatari, Zaro
  ➡ VBF and VH @ automated NLO+PS
- HC3: "Higgs characterisation at NLO in QCD: CP properties of the top Yukawa" EPJC74(2014)3065 [arXiv:1407.5089]
  Demartin, Maltoni, Mawatari, Page, Zaro
  ➡ GF (H+jets) and ttH @ automated NLO+PS
- HC4: "Higgs production in associated with a single top quark at the LHC" [arXiv:1504.xxxxx]
  Demartin, Maltoni, Mawatari, Zaro
  ➡ tH @ automated NLO+PS

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)

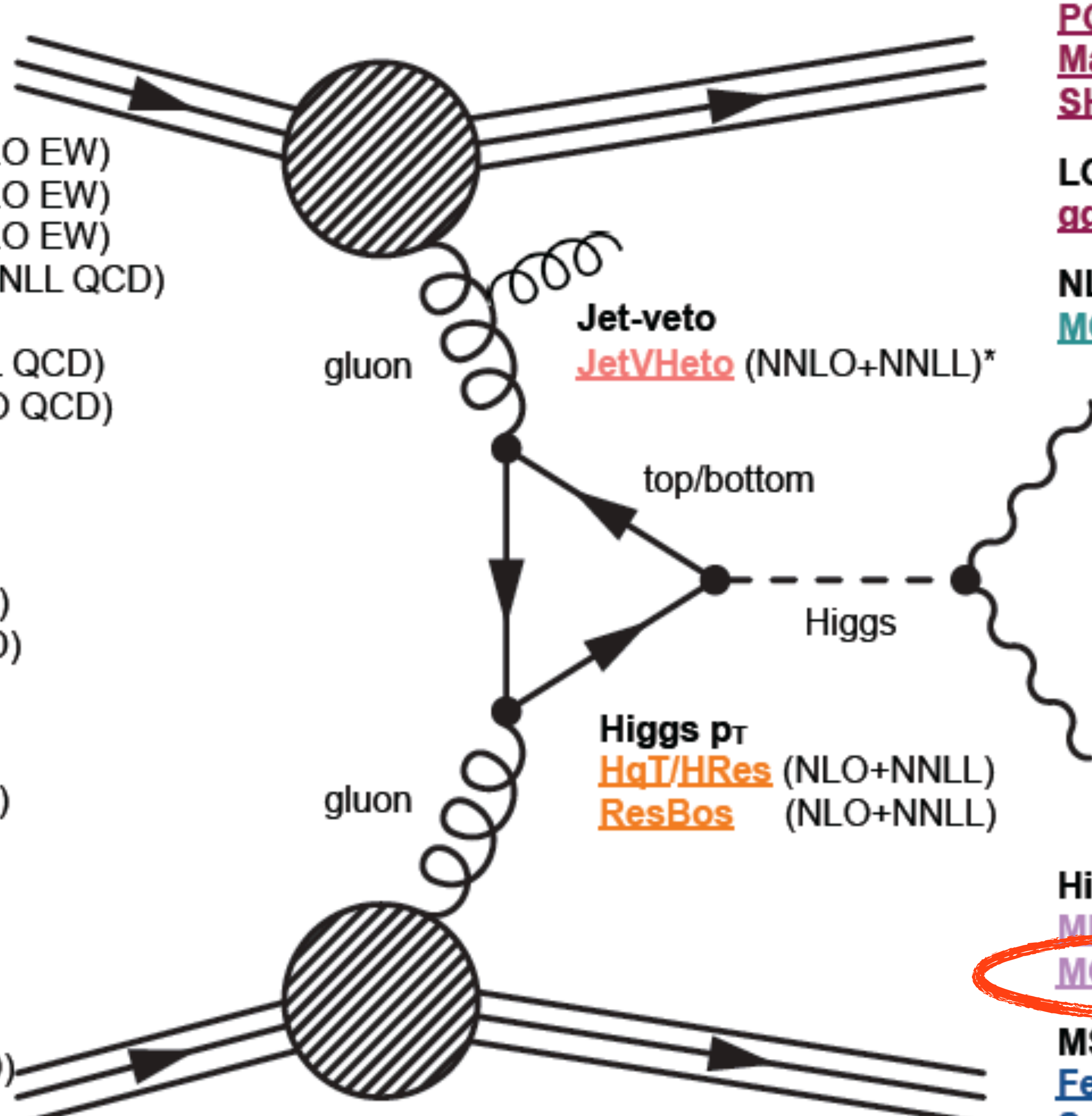
WH/ZH
V2HV (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

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)

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

* NLO+NNLL in differential

Compiled by R. Tanaka, Jan. 2014

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 (thanks to event generators, e.g. MadGraph5_aMC@NLO)
  - 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.
  - The code is publicly available at the FeynRules repository: https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

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

param_card.dat

```
######################################
## INFORMATION FOR FRBLOCK
######################################
Block frblock
    1 1.000000e+03 # Lambda
    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

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

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

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

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3-min MadGraph5_aMC@NLO tutorial (ttH)

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 t t~ [QCD]
>output mg5amcfemto
>launch
```

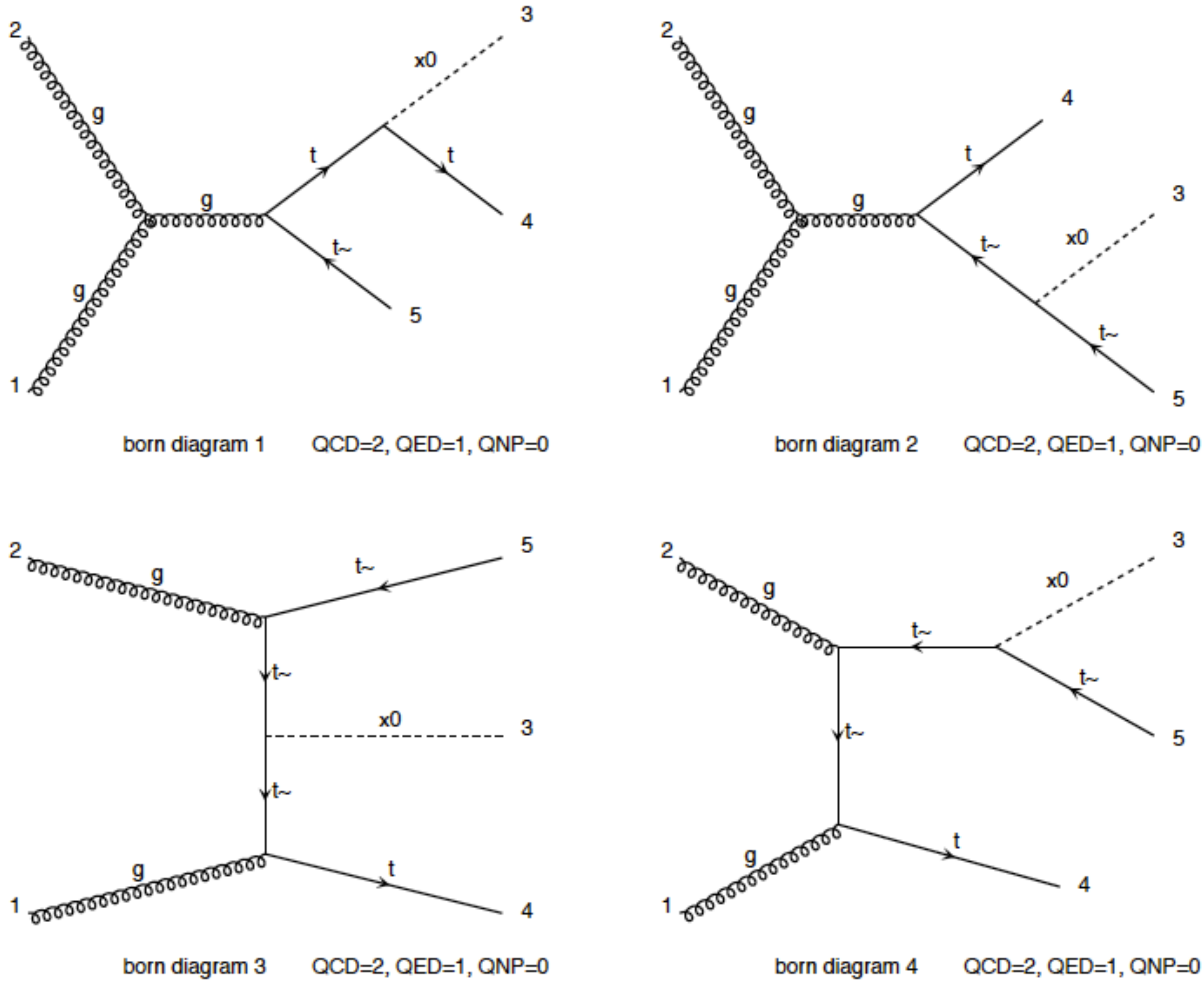
- Start the MG5_aMC shell
- Import the model
- Generate the process
- Write the code (including html)
- Generate the LO/NLO events

/Users/mawatari/work/tools/madgraph5/mg5amcfemto/index.html

SubProcesses and Feynman diagrams

Directory	Type	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P0_gg_x0ttx	born	8	1	postscript	g g > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD] WEIGHTED=1
	virt	184	1	postscript	g g > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD]
	real	50	1	postscript	g g > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [QCD]
	real	12	4	postscript	d~ g > x0 t t~ d~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , u~ g > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , s~ g > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , c~ g > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [QCD]

born (ttH)



2
g
g
g
1
t
t~
x0
t
3
4
5
born diagram 1 QCD=2, QED=1, QNP=0
2
g
g
g
1
t
4
t~
x0
3
t~
5
born diagram 2 QCD=2, QED=1, QNP=0
2
g
t~
5
t~
x0
3
t~
g
1
t
4
born diagram 3 QCD=2, QED=1, QNP=0
2
g
t~
x0
3
t~
5
t~
g
1
t
4
born diagram 4 QCD=2, QED=1, QNP=0

SubProcesses and Feynman diagrams

Directory	Type	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P0_gg_x0ttx	born	8	1	postscript	g g > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD] WEIGHTED=1
	virt	184	1	postscript	g g > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD]
	real	50	1	postscript	g g > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [QCD]
	real	12	4	postscript	d~ g > x0 t t~ d~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , u~ g > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , s~ g > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , c~ g > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [QCD]
	real	12	4	postscript	d g > x0 t t~ d XGLU=1 WEIGHTED=5 QNP=1 [QCD] , u g > x0 t t~ u XGLU=1 WEIGHTED=5 QNP=1 [QCD] , s g > x0 t t~ s XGLU=1 WEIGHTED=5 QNP=1 [QCD] , c g > x0 t t~ c XGLU=1 WEIGHTED=5 QNP=1 [QCD]
	real	12	4	postscript	g d~ > x0 t t~ d~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g u~ > x0 t t~ u~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g s~ > x0 t t~ s~ XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g c~ > x0 t t~ c~ XGLU=1 WEIGHTED=5 QNP=1 [QCD]
	real	12	4	postscript	g d > x0 t t~ d XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g u > x0 t t~ u XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g s > x0 t t~ s XGLU=1 WEIGHTED=5 QNP=1 [QCD] , g c > x0 t t~ c XGLU=1 WEIGHTED=5 QNP=1 [QCD]
P0_uux_x0ttx	born	2	4	postscript	u u~ > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD] , c c~ > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD] , d d~ > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD] , s s~ > x0 t t~ XGLU=1 WEIGHTED=4 QNP=1 [QCD]
	virt	41	4	postscript	u u~ > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD] , c c~ > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD] , d d~ > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD] , s s~ > x0 t t~ WEIGHTED=4 QNP=0 QED=1 QCD=2 [QCD]
	real	12	4	postscript	u u~ > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [QCD] , c c~ > x0 t t~ g XGLU=1 WEIGHTED=5 QNP=1 [QCD] , [illegible]

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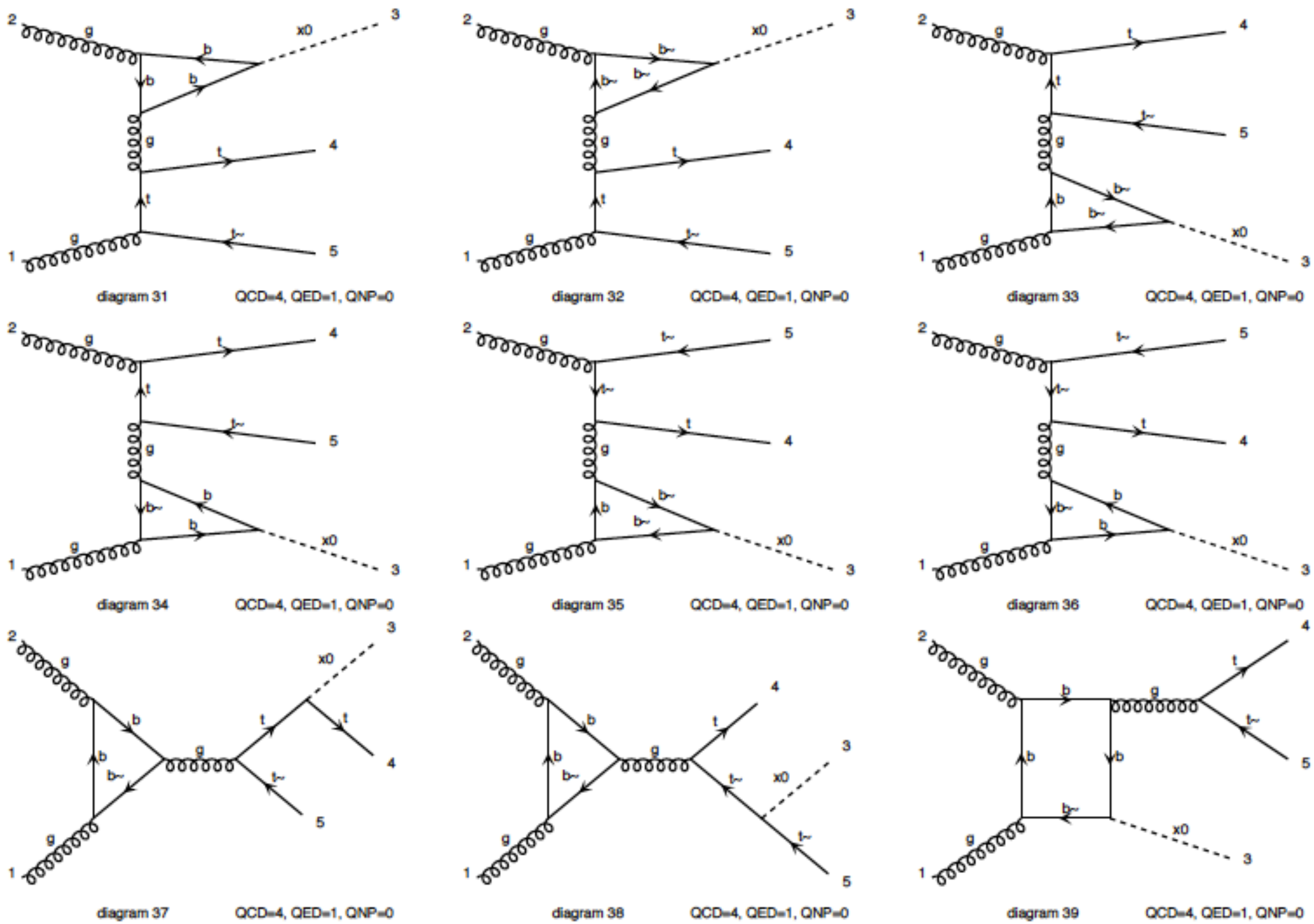
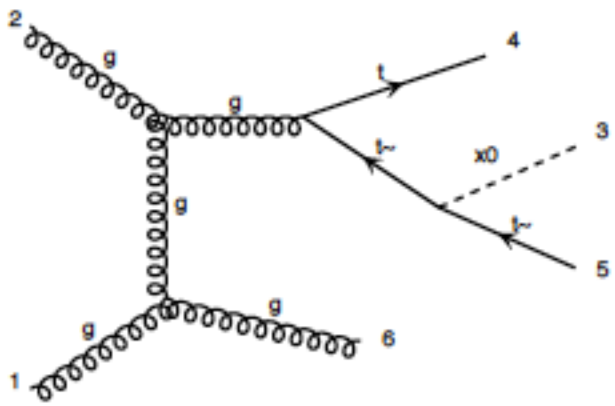
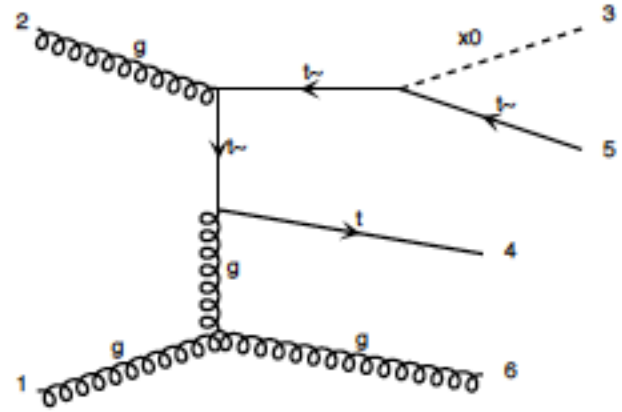
virtual (ttH)



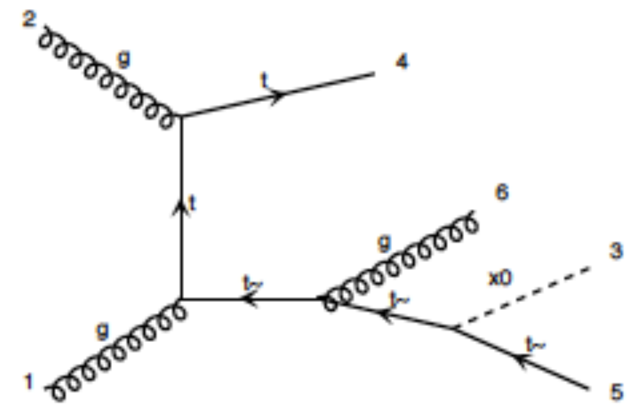
real (ttH)



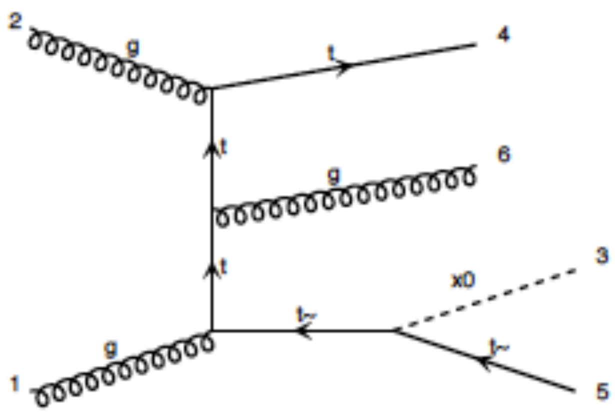
real diagram 31 QCD=3, QED=1, QNP=0



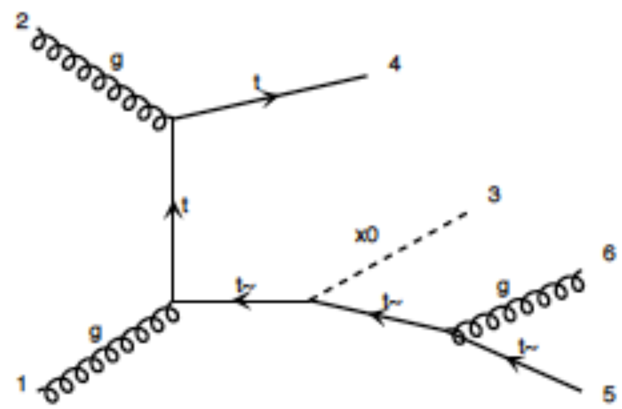
real diagram 32 QCD=3, QED=1, QNP=0



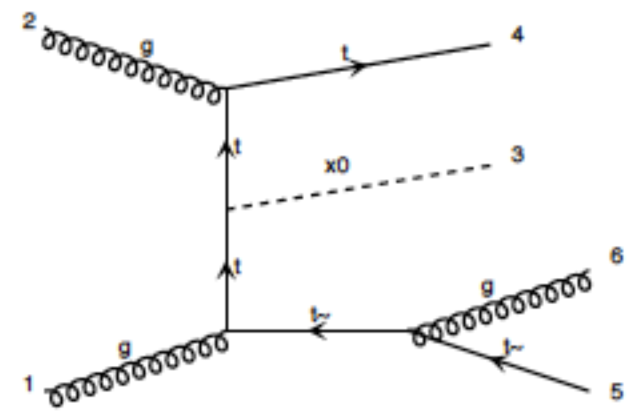
real diagram 33 QCD=3, QED=1, QNP=0



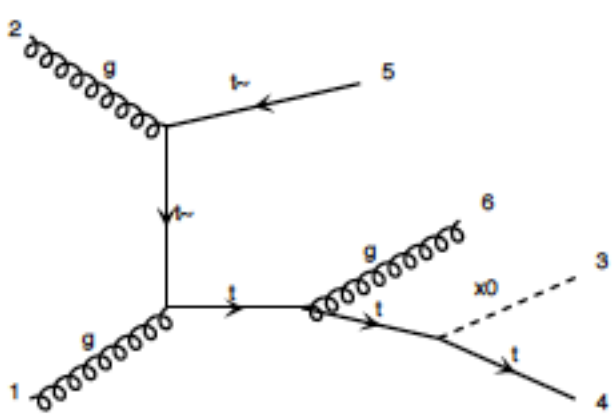
real diagram 34 QCD=3, QED=1, QNP=0



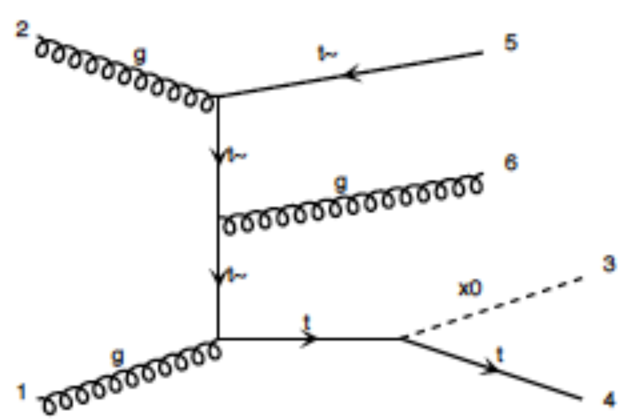
real diagram 35 QCD=3, QED=1, QNP=0



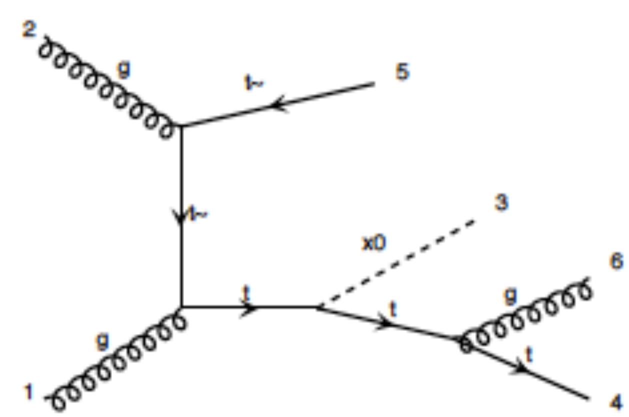
real diagram 36 QCD=3, QED=1, QNP=0



real diagram 37 QCD=3, QED=1, QNP=0



real diagram 38 QCD=3, QED=1, QNP=0



real diagram 39 QCD=3, QED=1, QNP=0

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3-min MadGraph5_aMC@NLO tutorial (ttH)

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 t t~ [QCD]
>output mg5amcfemto
>launch
```

- Start the MG5_aMC shell
- Import the model
- Generate the process
- Write the code (including html)
- Generate the LO/NLO events

```
The following switches determine which operations are executed:
 1 Perturbative order of the calculation:                            order=NLO
 2 Fixed order (no event generation and no MC@[N]LO matching):   fixed_order=OFF
 3 Shower the generated events:                                     shower=ON
 4 Decay particles with the MadSpin module:                        madspin=ON
  Either type the switch number (1 to 4) to change its default setting,
  or set any switch explicitly (e.g. type 'order=LO' at the prompt)
  Type '0', 'auto', 'done' or just press enter when you are done.
 [0, 1, 2, 3, 4, auto, done, order=LO, order=NLO, ... ]
>
```

MadSpin: Artoisenet, Frederix, Mattelaer, Rietkerk [arXiv:1212.3460]

- allows one to decay narrow resonances in Les Houches Monte Carlo events.
- preserves both spin correlation and finite width effects.

3-min MadGraph5_aMC@NLO tutorial (ttH)

```
Do you want to edit a card (press enter to bypass editing)?
  1 / param      : param_card.dat
  2 / run        : run_card.dat
  3 / madspin    : madspin_card.dat
  4 / shower     : shower_card.dat
 [0, done, 1, param, 2, run, 3, madspin, 4, enter path, ... ]
>
```

param_card.dat

```
###################################
## INFORMATION FOR FRBLOCK
###################################
Block frblock
    1 1.000000e+03 # Lambda
    2 1.000000e+00 # cosa
    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
```

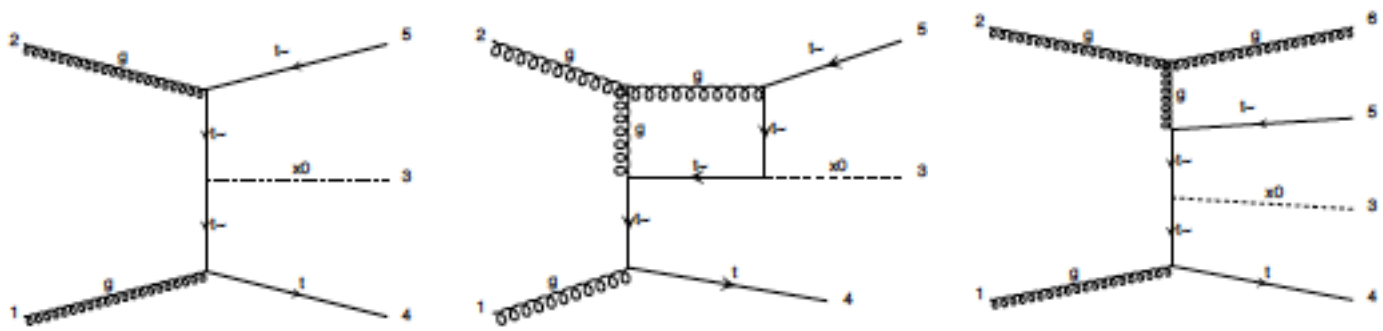
run_card.dat

```
#***********************************************************************
# Collider type and energy                                             *
#***********************************************************************
   1    = lpp1    ! beam 1 type (0 = no PDF)
   1    = lpp2    ! beam 2 type (0 = no PDF)
 6500   = ebeam1  ! beam 1 energy in GeV
 6500   = ebeam2  ! beam 2 energy in GeV
#***********************************************************************
# PDF choice: this automatically fixes also alpha_s(MZ) and its evol.  *
#***********************************************************************
 nn23nlo   = pdlabel    ! PDF set
 230000    = lhaid      ! if pdlabel=lhapdf, this is the lhapdf number
#***********************************************************************
# Include the NLO Monte Carlo subtr. terms for the following parton    *
# shower (HERWIG6 | HERWIGPP | PYTHIA6Q | PYTHIA6PT | PYTHIA8)         *
# WARNING: PYTHIA6PT works only for processes without FSR!!!!          *
#***********************************************************************
  HERWIG6    = parton_shower
```

Higgs characterisation in ttH

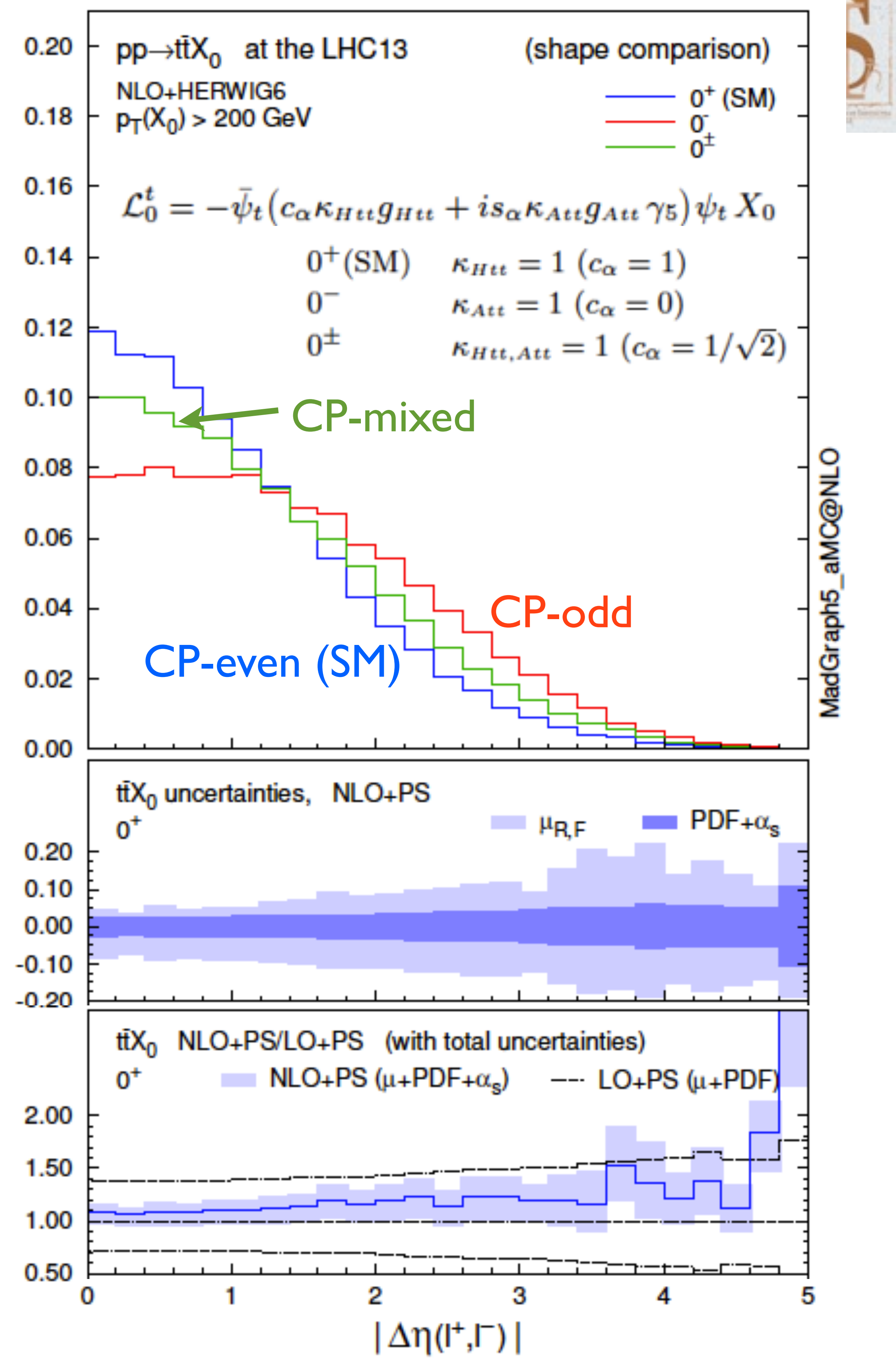
HC3: Demartin, Maltoni, KM, Page, Zaro [arXiv:1407.5089]

```
./bin/mg5_aMC
>import model HC_NLO_X0
>generate p p > x0 t t~ [QCD]
>output mg5amcfemto
>launch
```



scenario		$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	K
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

- 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.



Back-up

Total cross sections (ttH)

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

$$\mathcal{L}_0^t = -\bar{\psi}_t (c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att} \gamma_5) \psi_t X_0$$

0^+(SM)	$\kappa_{Htt} = 1$ $(c_\alpha = 1)$
0^-	$\kappa_{Att} = 1$ $(c_\alpha = 0)$
$0^\pm$	$\kappa_{Htt,Att} = 1$ $(c_\alpha = 1/\sqrt{2})$

$$\mu_0^{(t\bar{t}H)} = \sqrt[3]{m_T(t)\, m_T(\bar{t})\, m_T(X_0)}$$

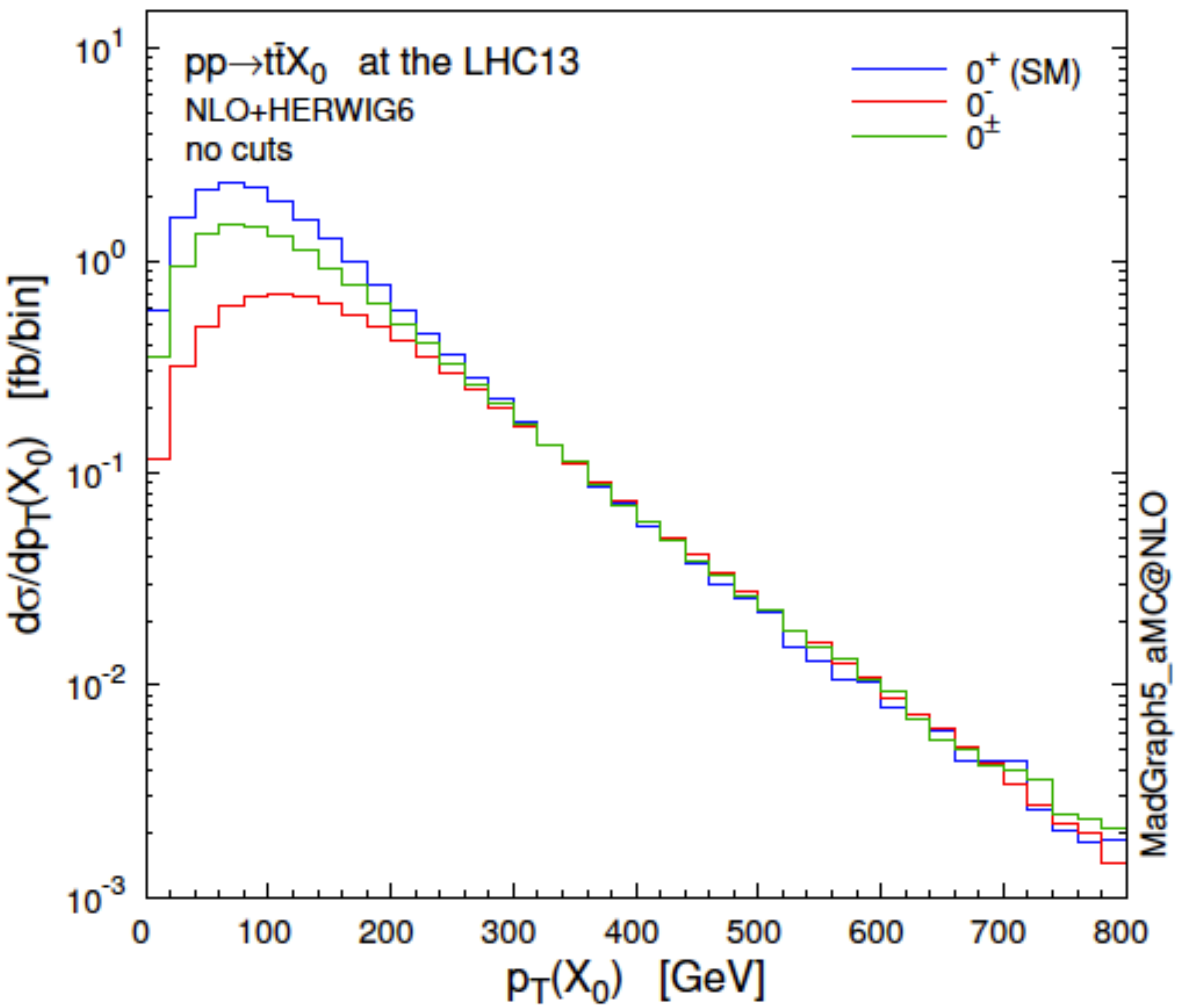
$$1/2 < \mu_{R,F}/\mu_0 < 2$$

scenario		$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	K
LHC 8 TeV	0^+	$130.3(1)\ ^{+36.8}_{-24.6} \pm 5.9\%$	$134.9(2)\ ^{+3.2}_{-8.3} \pm 3.0\%$	1.04
	0^-	$44.49(4)\ ^{+42.5}_{-27.6} \pm 10.3\%$	$47.07(6)\ ^{+6.5}_{-11.5} \pm 4.9\%$	1.06
	$0^\pm$	$87.44(8)\ ^{+38.2}_{-25.4} \pm 6.9\%$	$90.93(12)\ ^{+3.9}_{-9.1} \pm 3.4\%$	1.04
LHC 13 TeV	0^+	$468.6(4)\ ^{+32.8}_{-22.8} \pm 4.5\%$	$525.1(7)\ ^{+5.7}_{-8.7} \pm 2.1\%$	1.12
	0^-	$196.8(2)\ ^{+37.1}_{-25.2} \pm 7.5\%$	$224.3(3)\ ^{+6.8}_{-10.5} \pm 3.2\%$	1.14
	$0^\pm$	$332.4(3)\ ^{+34.0}_{-23.5} \pm 5.4\%$	$374.1(5)\ ^{+6.0}_{-9.3} \pm 2.5\%$	1.13

- σ(0+) > σ(0-)
- σ(0±) = (σ(0+)+σ(0-))/2
- Δσ(0-) > Δσ(0+)

- Scale and PDF uncertainties are evaluated automatically at no extra computing cost via a reweighting technique. Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli [arXiv:1110.4738]
- Such information is available on an event-by-event basis and therefore uncertainty bands can be plotted for any observables of interest.

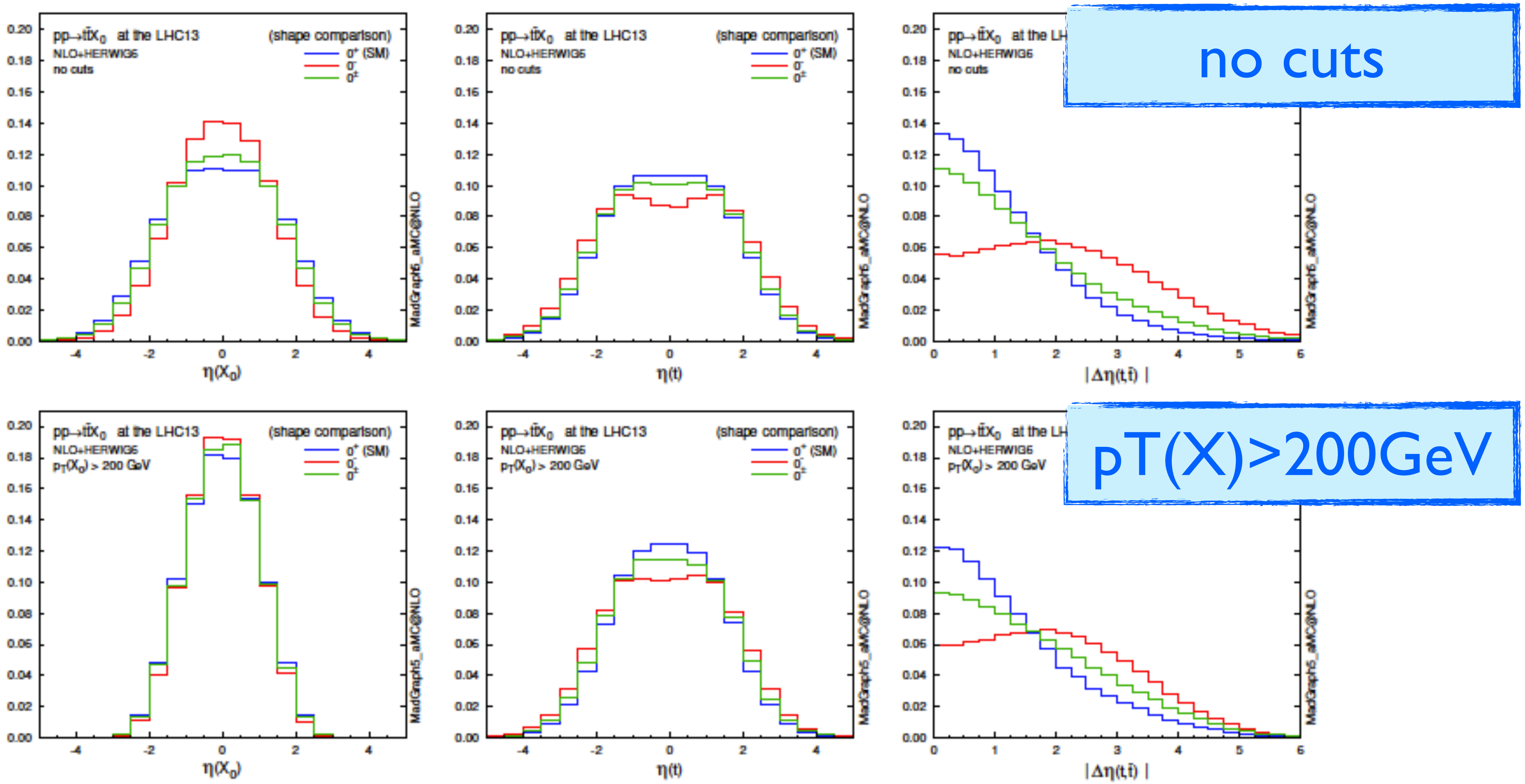
Distributions (ttH)



- The difference is significant in the low pT region.
- The high-pT tail is not sensitive to the CP mixing.

➡ Is the boosted-Higgs analyses still sensitive to the CP mixing?

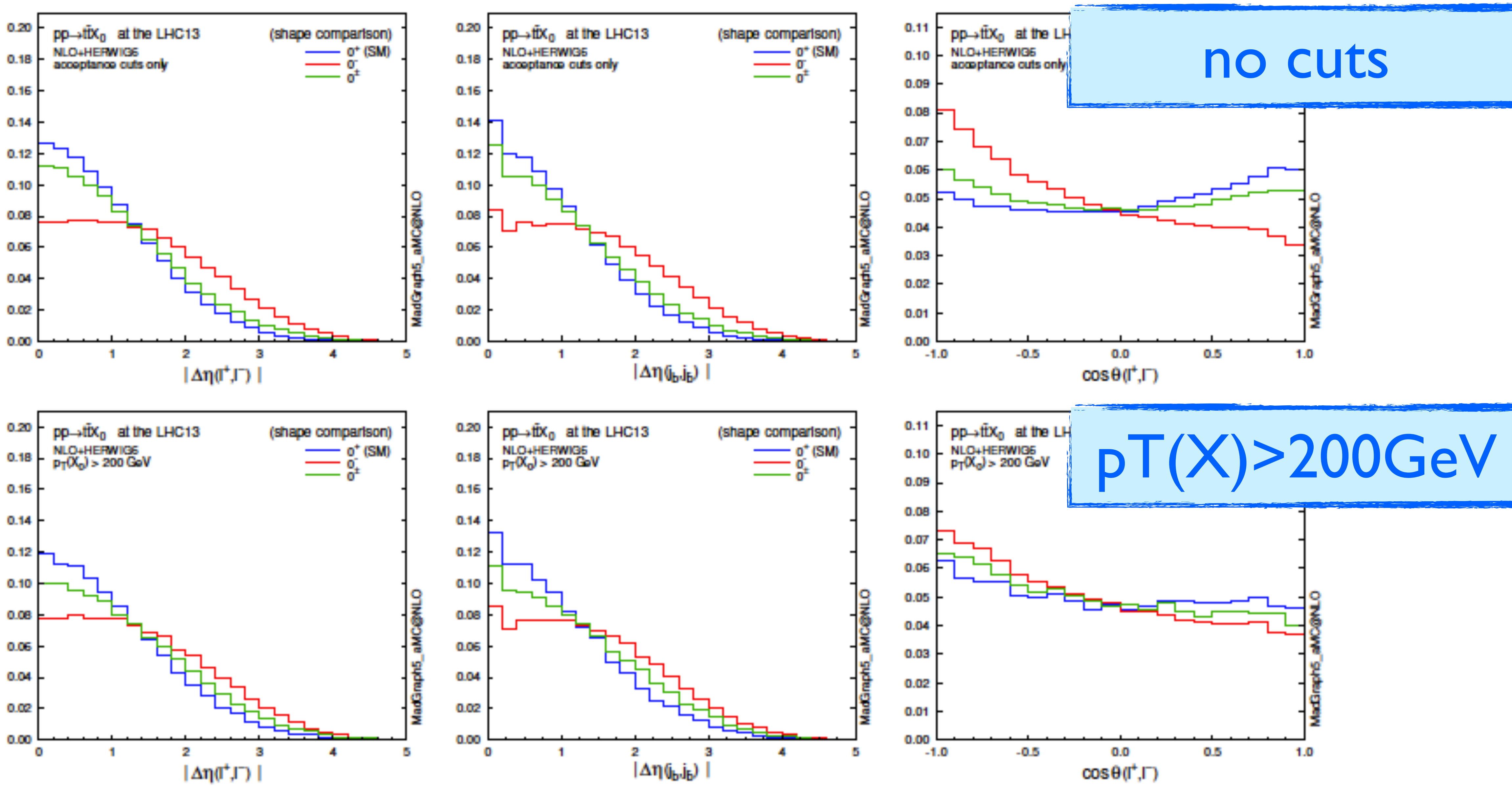
Distributions without and with a boosted Higgs (ttH)



- The most CP sensitive distribution is the rapidity difference between the top and antitop, which is hardly affected by the pT(X) cut.

Correlations between the top-decay products (ttH)

(in the di-leptonic channel)



- As expected from the Δη(t), Δη(l) and Δη(b) are almost insensitive to the pT(X) cut, while the angle between the leptons (b jets) is significantly affected by the boost.

Theoretical uncertainties (ttH)

scenario		$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (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
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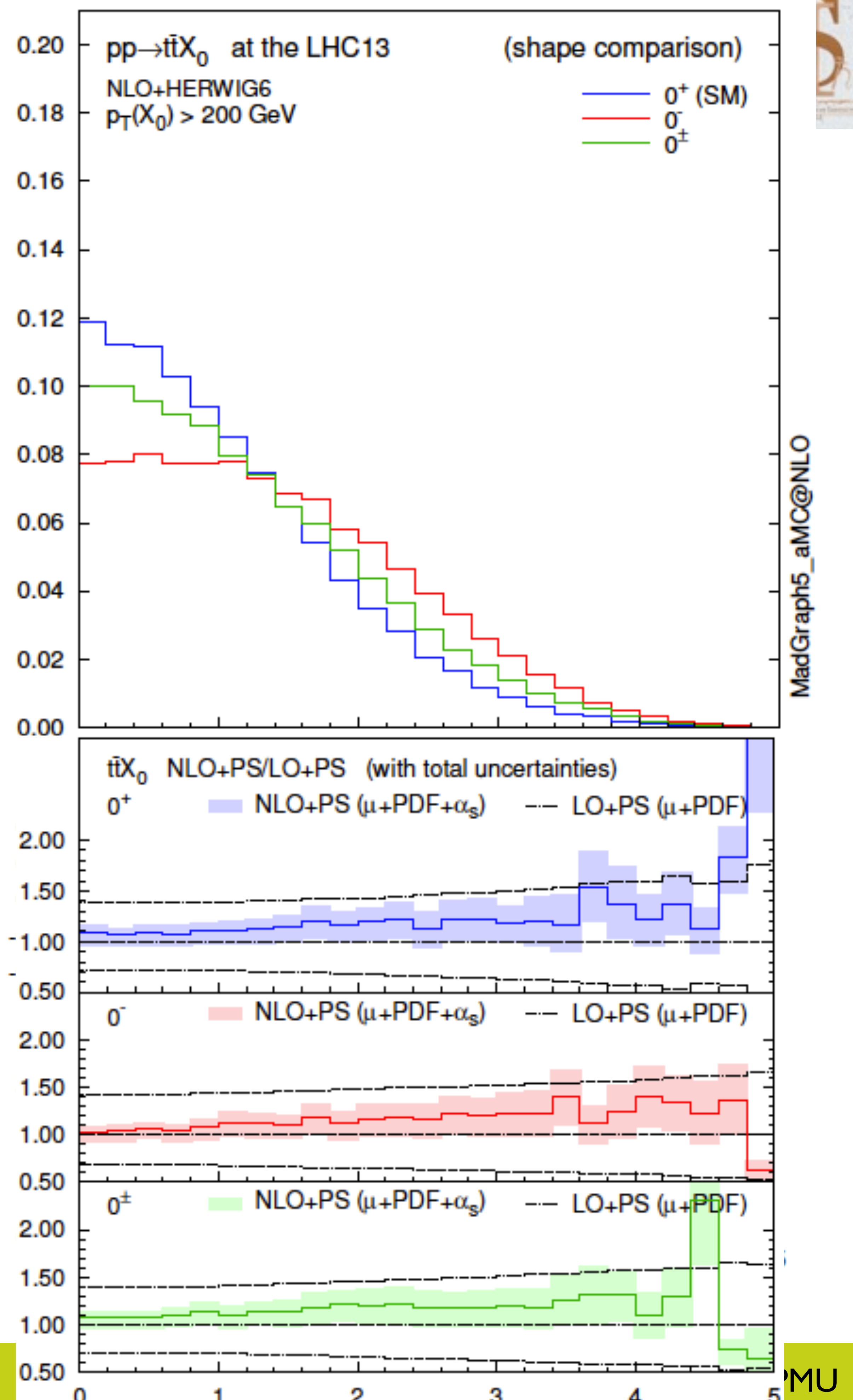
	0^-	$196.8(2)\ ^{+37.1}_{-25.2}\ \pm7.5\%$	$224.3(3)\ ^{+6.8}_{-10.5}\ \pm3.2\%$	1.14
	$0^\pm$	$332.4(3)\ ^{+34.0}_{-23.5}\ \pm5.4\%$	$374.1(5)\ ^{+6.0}_{-9.3}\ \pm2.5\%$	1.13



The NLO corrections

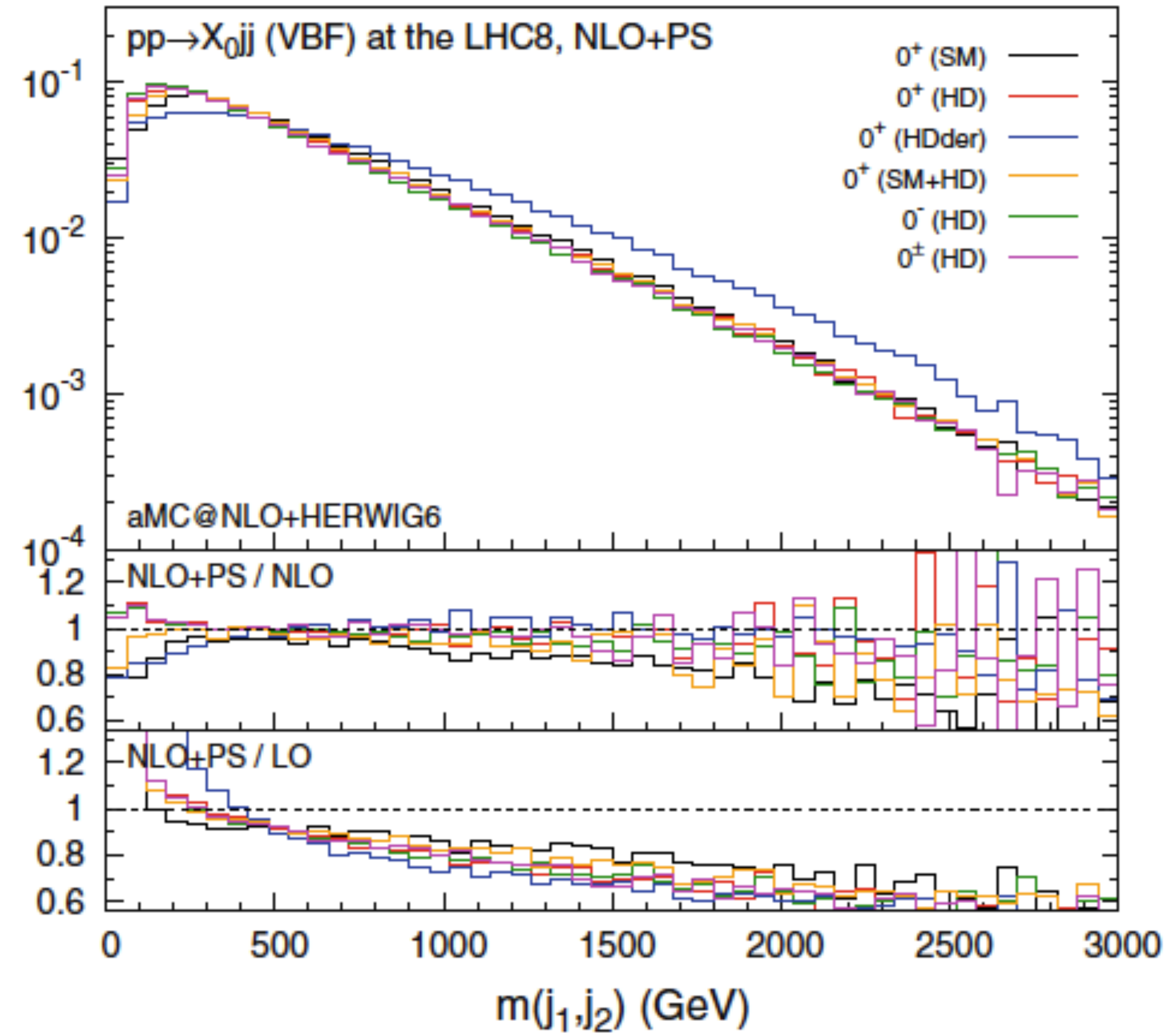
- considerably reduce the theoretical uncertainties.
- cannot be described by an overall *K* factor and the constant theoretical uncertainties.

VBF

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

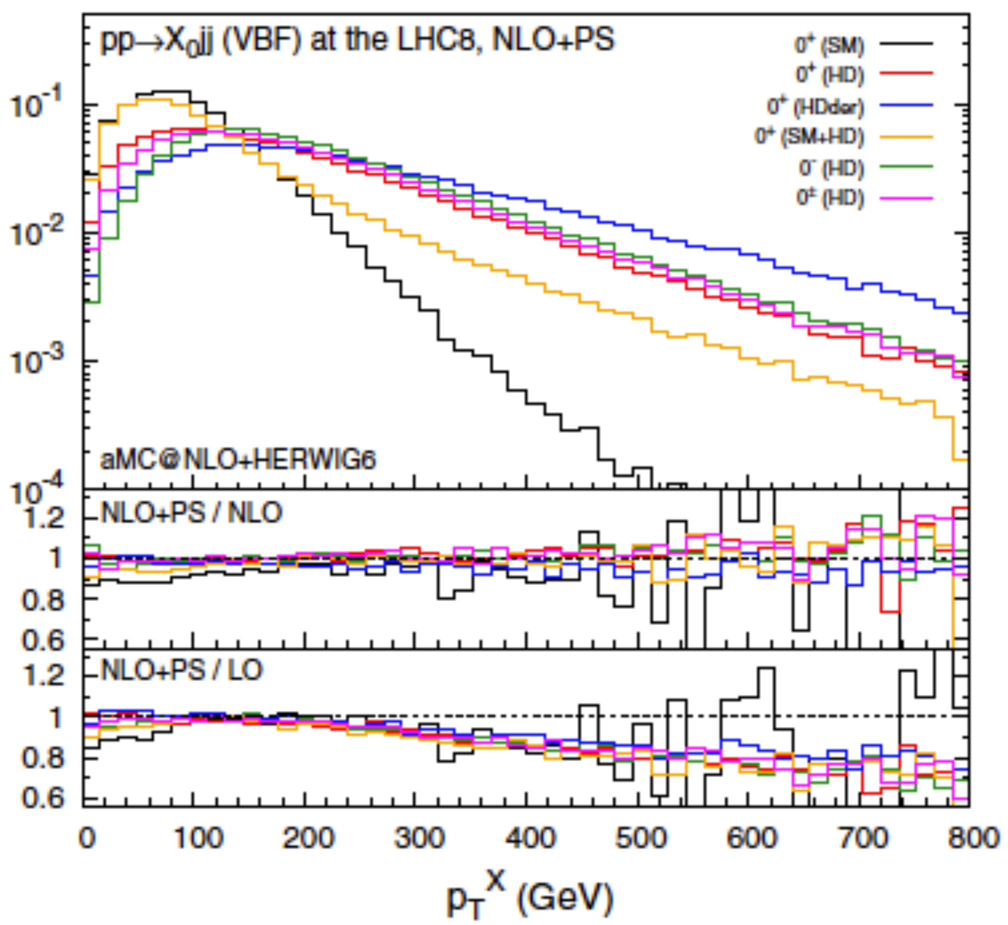
Scenario	HC parameter choice
0^+(SM)	$\kappa_{SM} = 1$ $(c_\alpha = 1)$
0^+(HD)	$\kappa_{HZZ,HWW} = 1$ $(c_\alpha = 1)$
0^+(HDder)	$\kappa_{H\partial Z,H\partial W} = 1$ $(c_\alpha = 1)$
0^+(SM+HD)	$\kappa_{SM,HZZ,HWW} = 1$ $(c_\alpha = 1,\ \Lambda = v)$
0^-(HD)	$\kappa_{AZZ,AWW} = 1$ $(c_\alpha = 0)$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

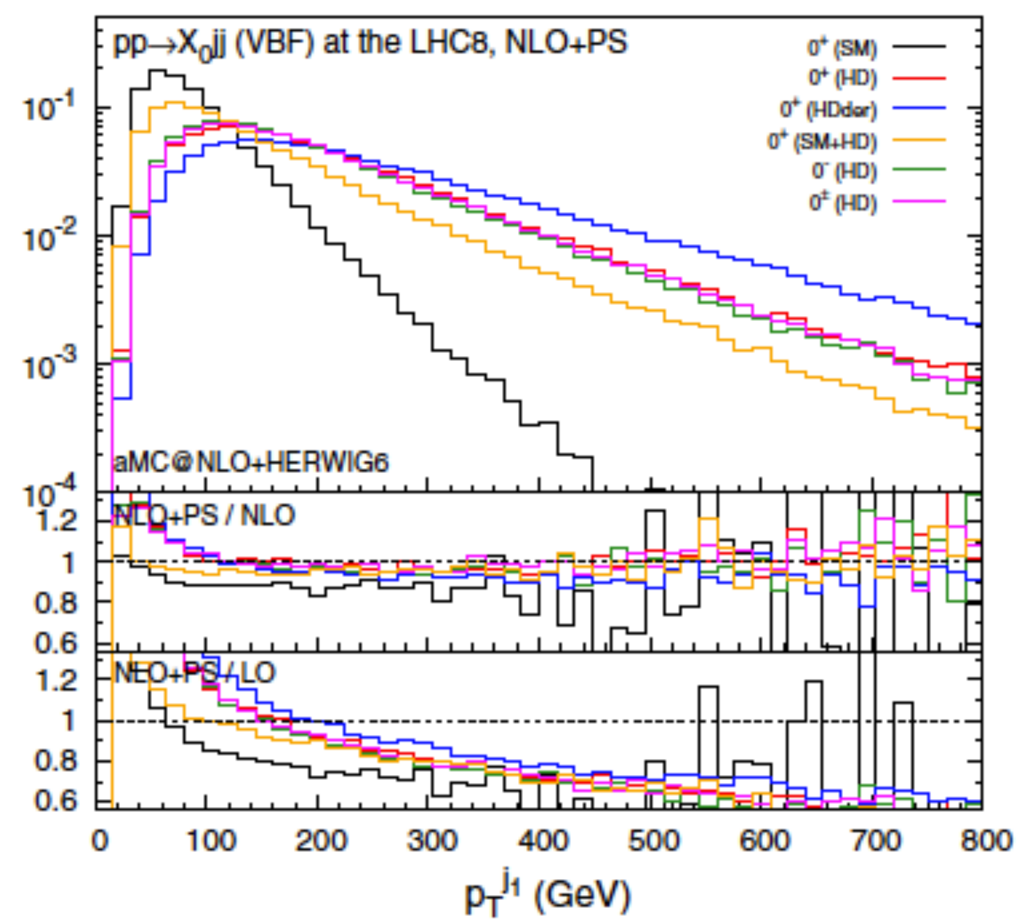
Scenario	σ_{LO} (fb)	σ_{NLO} (fb)	K
0^+(SM)	$1509(1)\ ^{+4.7\,\%}_{-4.4\,\%}$	$1633(2)\ ^{+2.0\,\%}_{-1.5\,\%}$	1.08
0^+(HD)	$69.66(6)\ ^{+7.5\,\%}_{-6.6\,\%}$	$67.08(13)\ ^{+2.2\,\%}_{-2.3\,\%}$	0.96
0^+(HDder)	$721.9(6)\ ^{+11.0\,\%}_{-9.0\,\%}$	$684.9(1.5)\ ^{+2.3\,\%}_{-2.8\,\%}$	0.95
0^+(SM+HD)	$3065(2)\ ^{+5.6\,\%}_{-5.1\,\%}$	$3144(5)\ ^{+1.6\,\%}_{-1.1\,\%}$	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 (VBF)



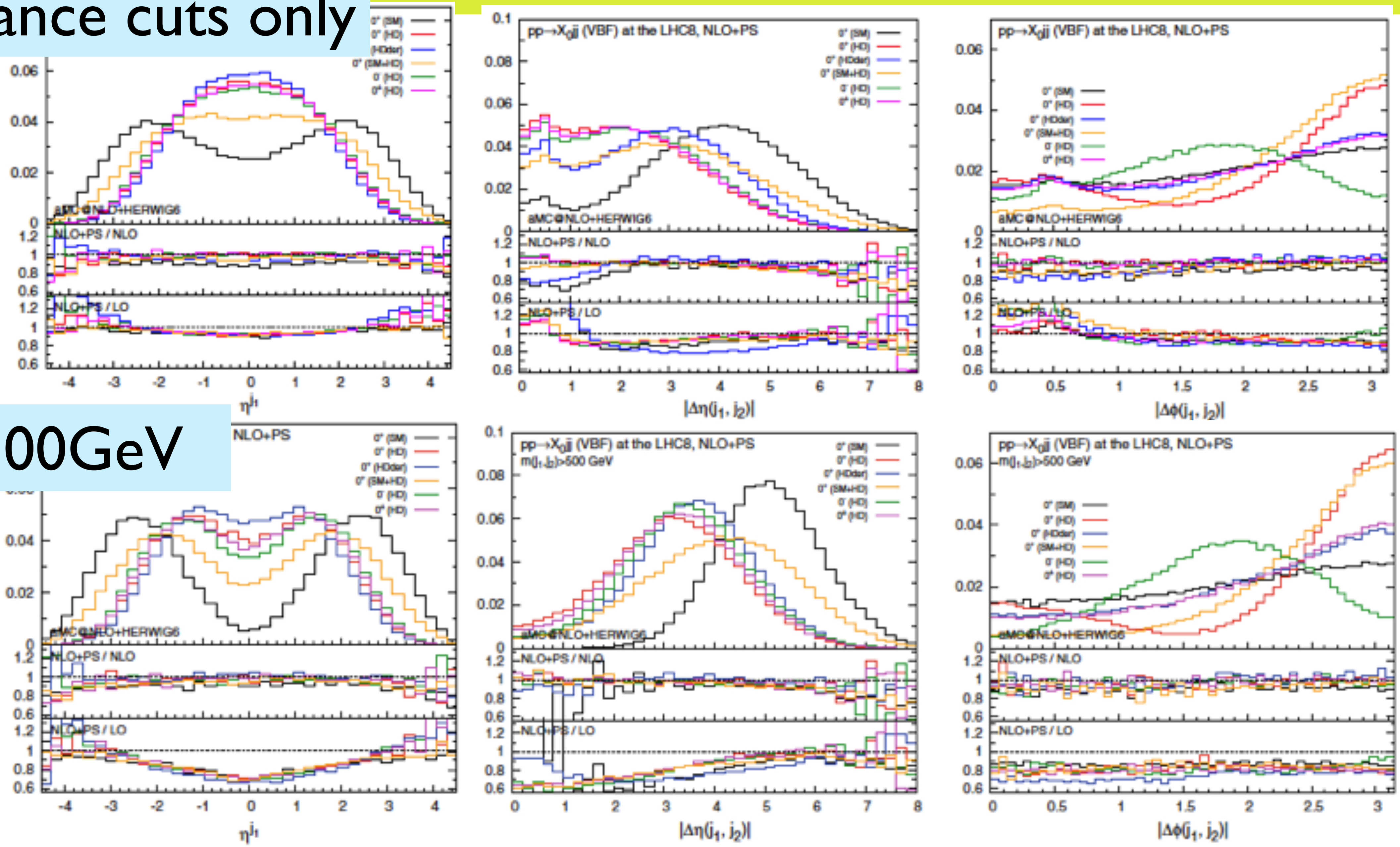


- The unitarity violating behavior of the HD interactions, especially HDder, clearly manifests itself.

mjj cuts (VBF)

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.

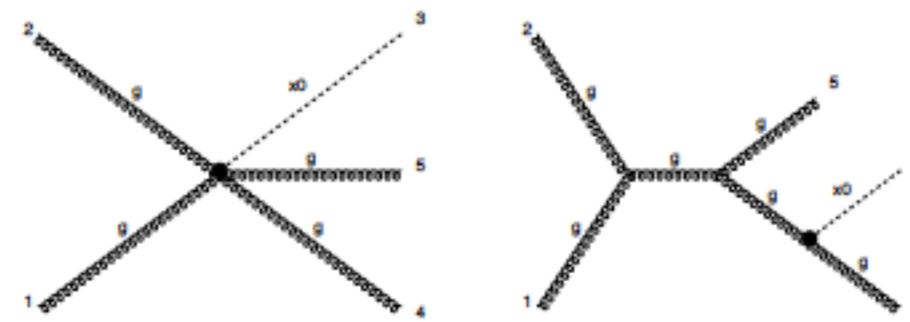
Higgs + 2 jets

HC2: 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
```

HC3: 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
```



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

$$\mathcal{L}_0^g = -\frac{1}{4}\left(c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\right) X_0$$

0^+(SM) $\quad \kappa_{Hgg} = 1 \ (c_\alpha = 1)$

0^- $\quad \kappa_{Agg} = 1 \ (c_\alpha = 0)$

$0^\pm$ $\quad \kappa_{Hgg,Agg} = 1 \ (c_\alpha = 1/\sqrt{2})$

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

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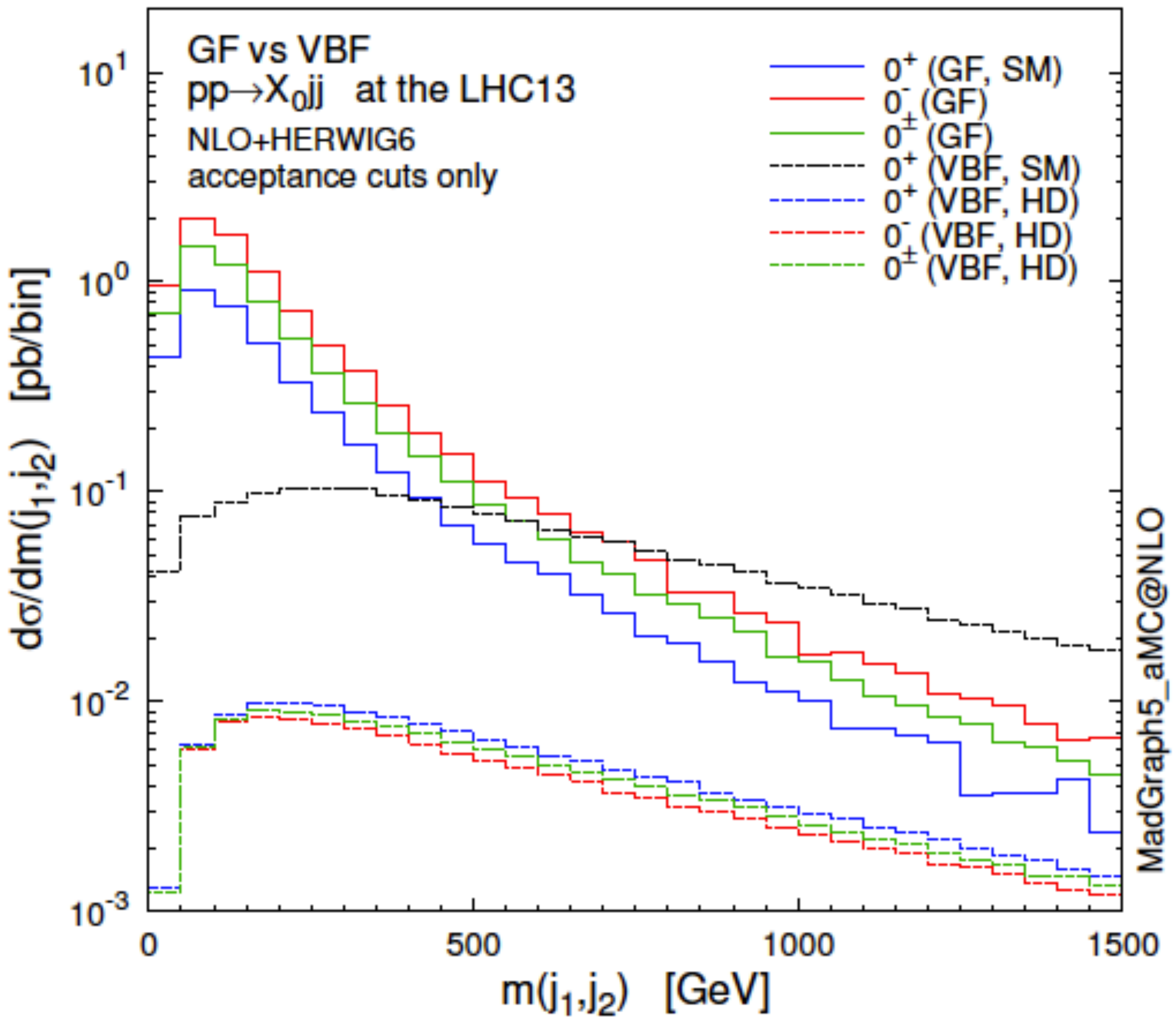
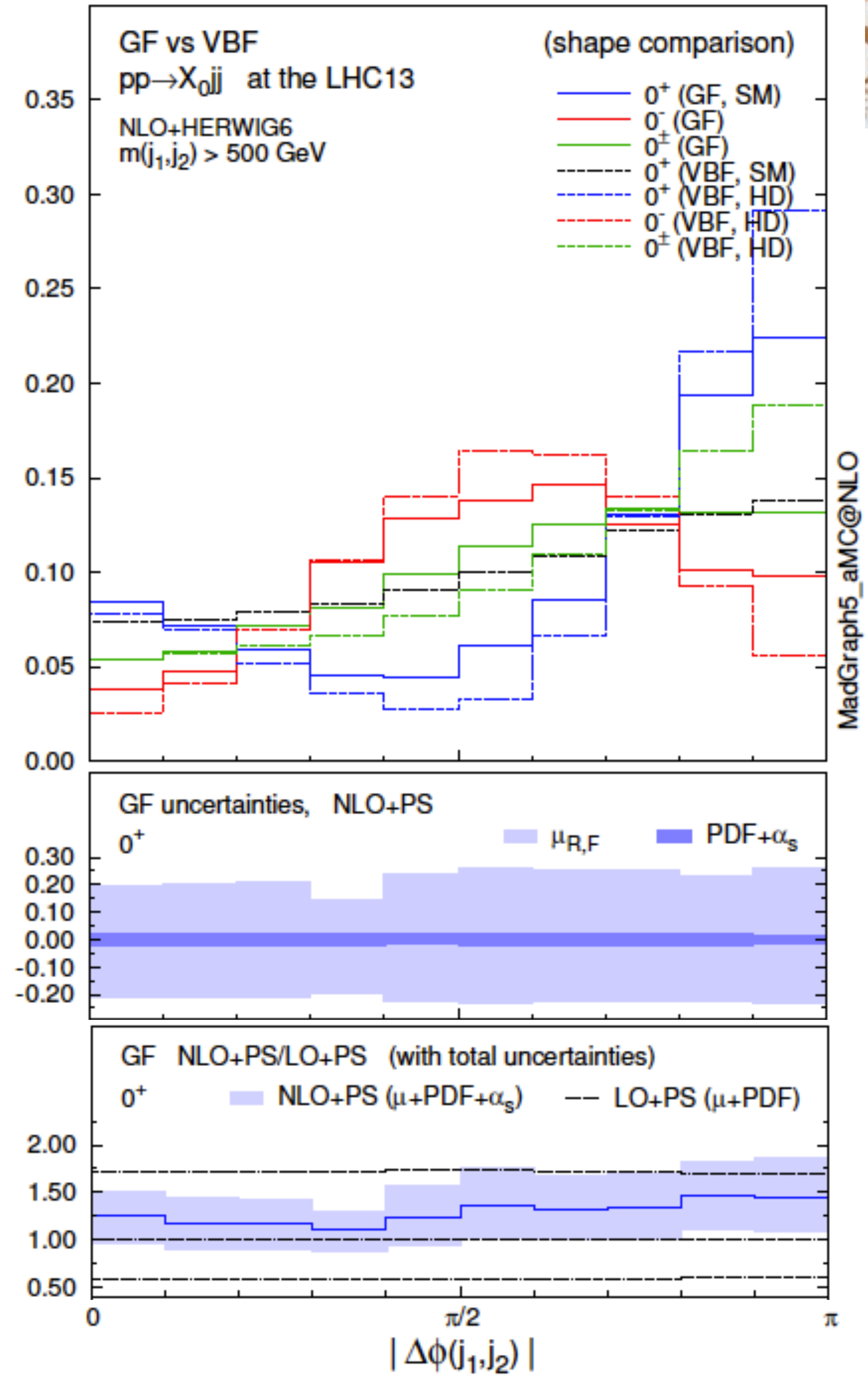
GF vs. VBF

HC3: 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.

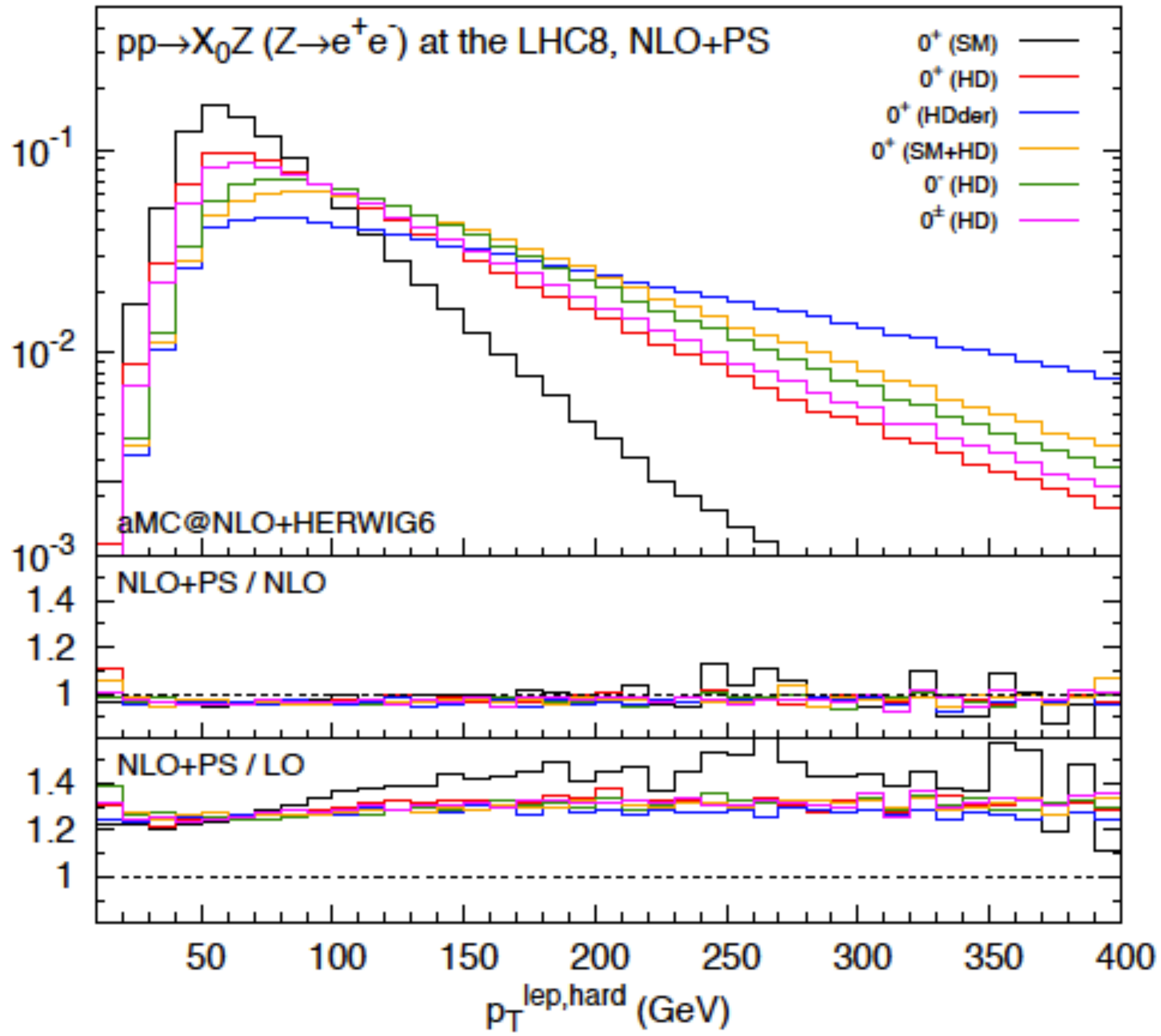
Vector-boson associated production (VH)

scenario	HC parameter choice
0^+(SM)	$\kappa_{\rm SM} = 1\ (c_\alpha = 1)$
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)	$\kappa_{HZZ,AZZ,HWW,AWW} = 1\ (c_\alpha = 1/\sqrt{2})$

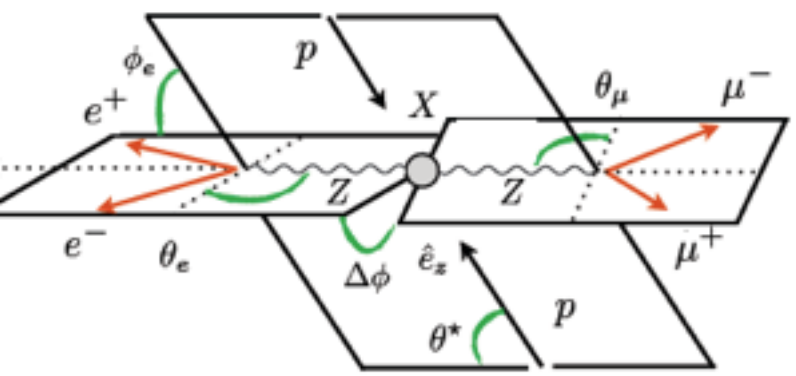
scenario	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	K
0^+(SM)	$10.13(1)\ ^{+0.0\%}_{-0.5\%}$	$13.24(1)\ ^{+2.2\%}_{-1.7\%}$	1.31
0^+(HD)	$2.638(2)\ ^{+1.4\%}_{-1.7\%}$	$3.461(3)\ ^{+1.9\%}_{-1.3\%}$	1.31
0^+(HDder)	$48.61(4)\ ^{+4.2\%}_{-3.9\%}$	$63.59(5)\ ^{+2.1\%}_{-1.9\%}$	1.31
0^+(SM+HD)	$19.95(1)\ ^{+3.1\%}_{-3.1\%}$	$26.24(2)\ ^{+1.8\%}_{-1.6\%}$	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

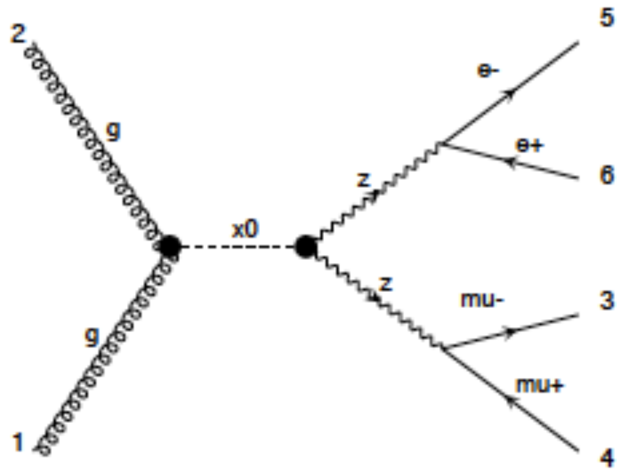
- Scale and PDF uncertainties are evaluated automatically at no extra computing cost via a reweighting technique.
- Such information is available on an event-by-event basis and therefore uncertainty bands can be plotted for any observables of interest.

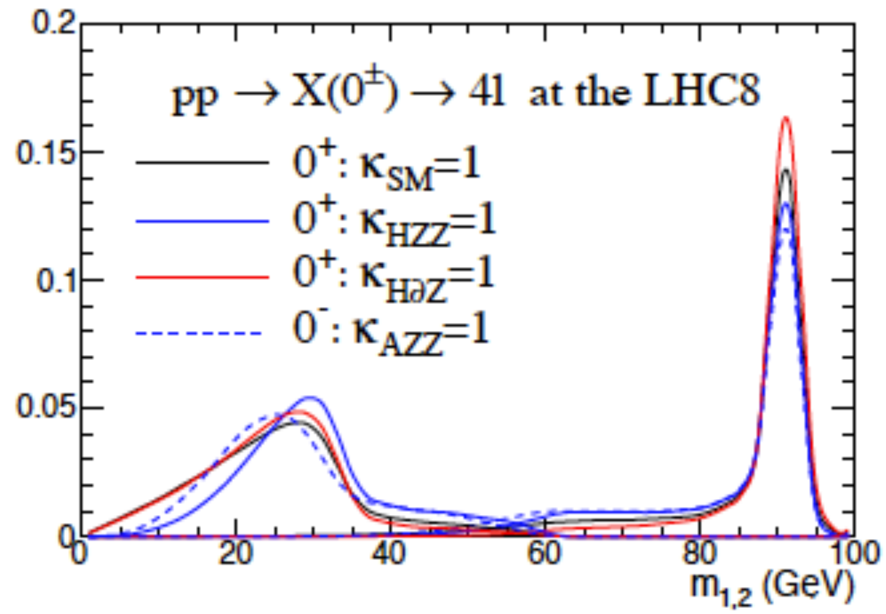
Maltoni, KM, Zaro [arXiv:1311.1829]

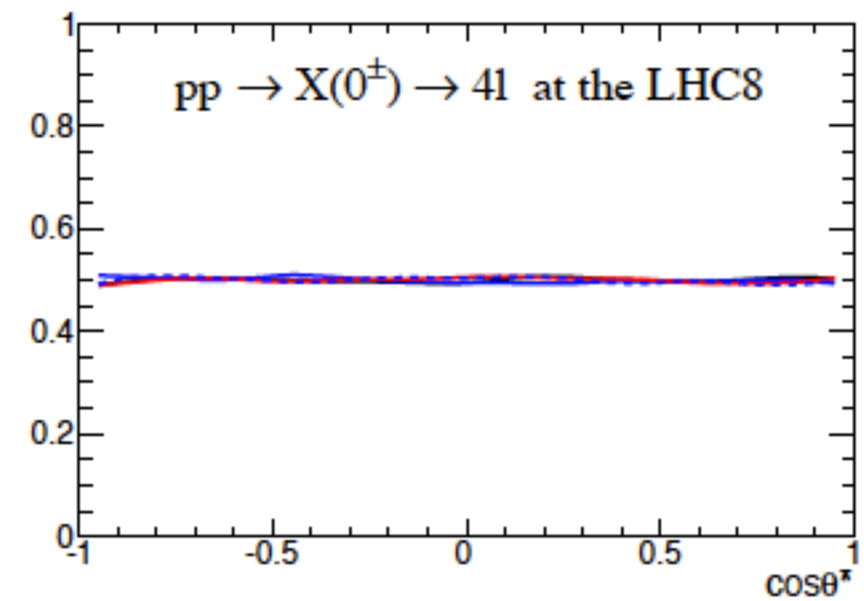


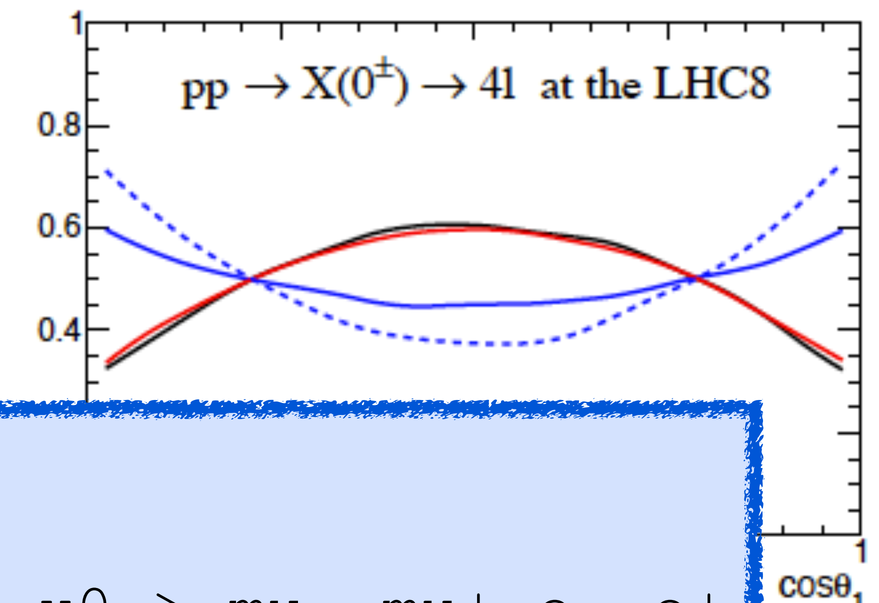
Higgs decay to 4 leptons

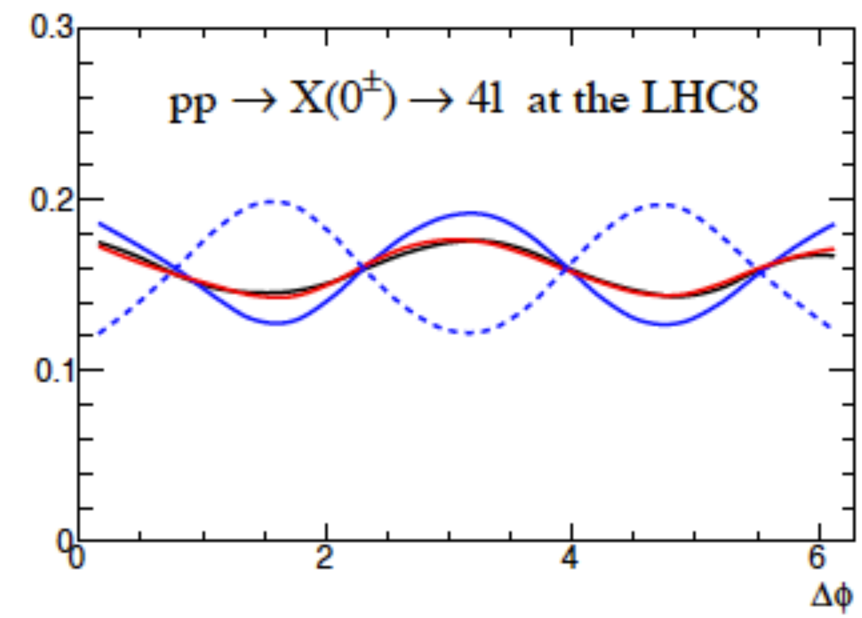













```
./bin/mg5_aMC
>import model HC
>generate p p > x0, x0 > mu- mu+ e- e+
>launch
```