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Effective theory approach in H-boson coupling determination

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(Vrije Universities Brussel and International Solvay Institutes)

on behalf of the HC (HiggsCharacterisation) collaboration

Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro

Alloul, Fuks, Sanz

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  - Effective Lagrangians -- *X(J=0,1,2)*
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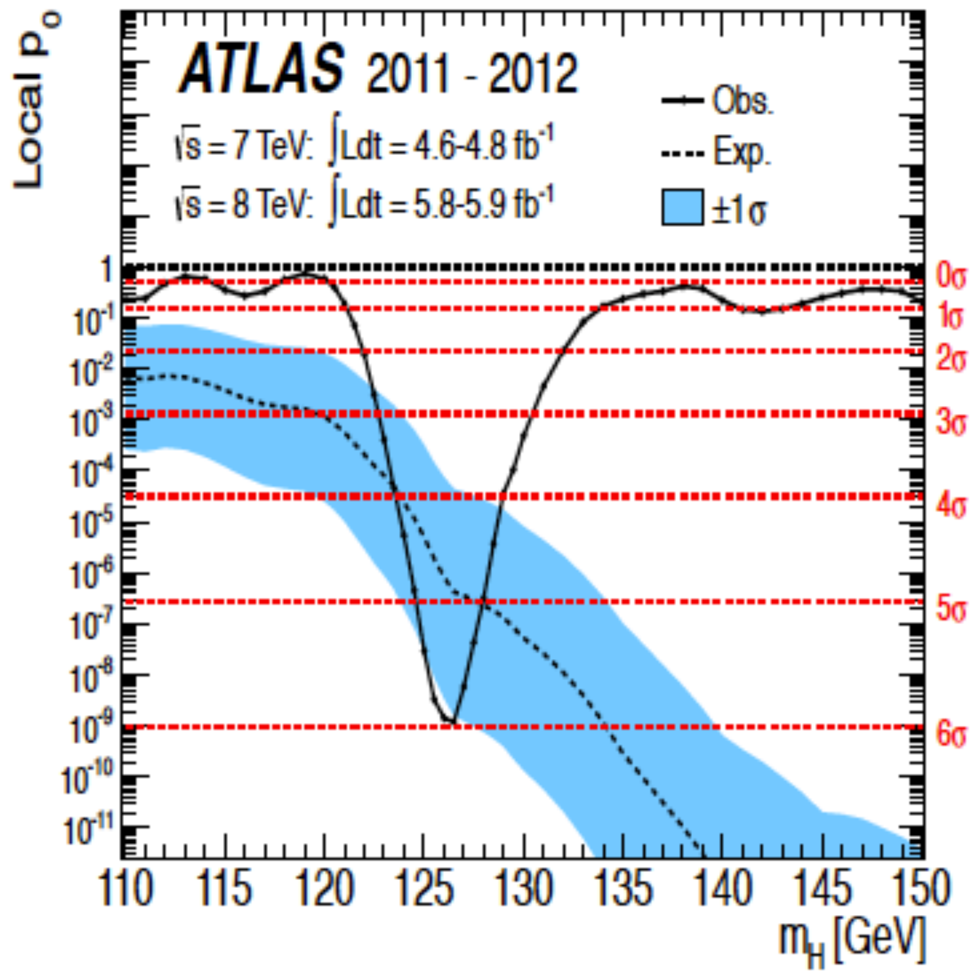
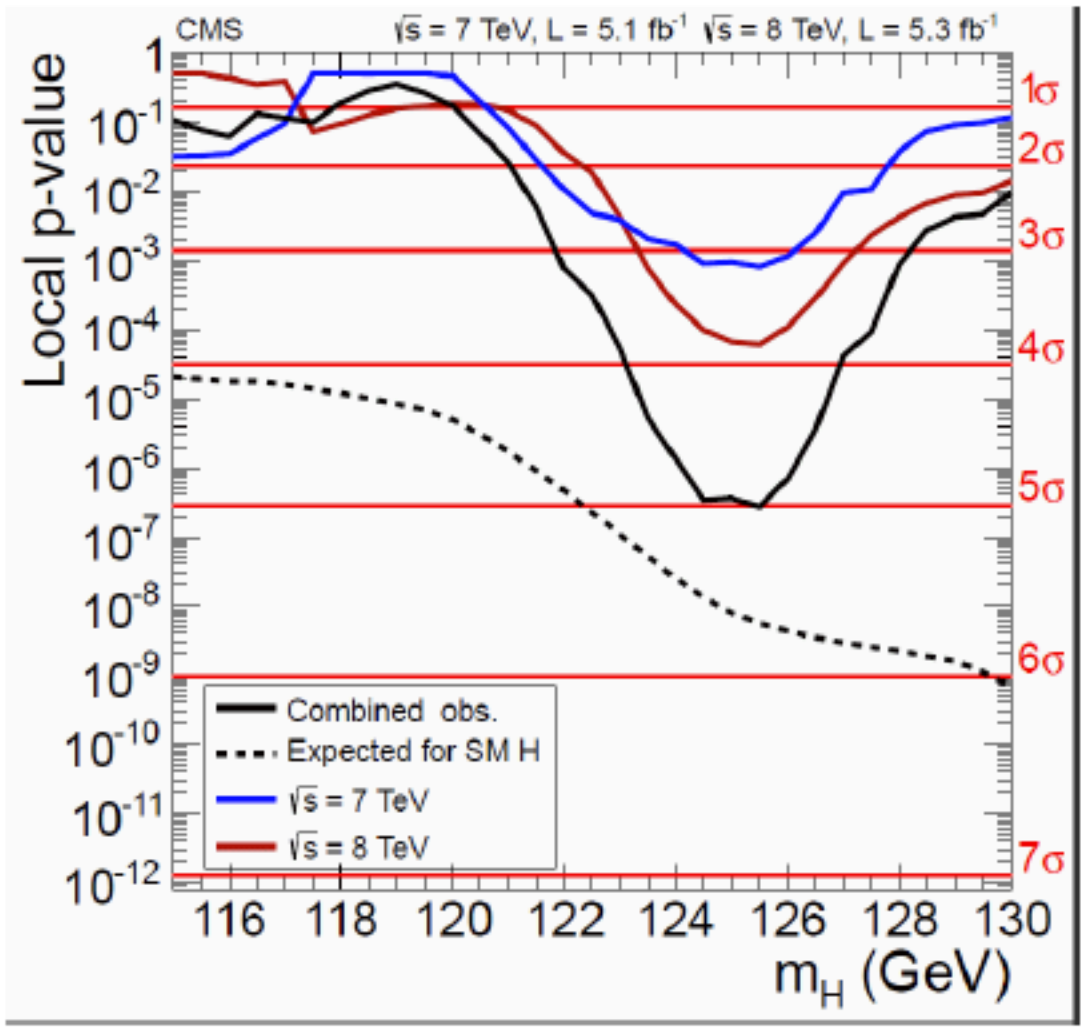
- Summary

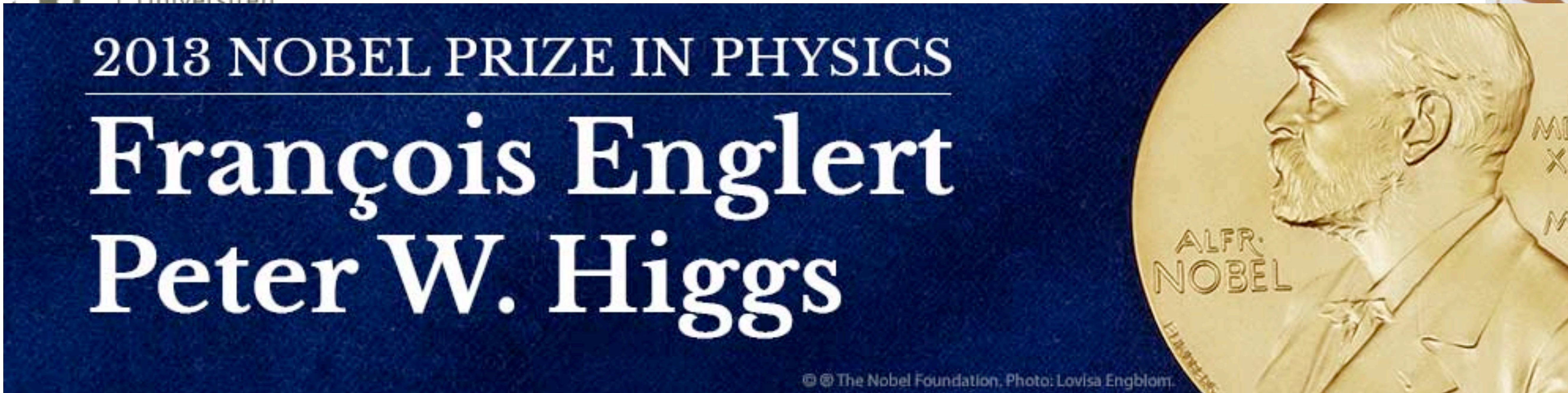
1. The discovered Higgs is NOT the SM Higgs

Fact I:

We have a discovery!







BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider" [http://www.nobelprize.org]

Fact I & II:

We have a discovery!

The SM cannot be the ultimate theory!

Q: Does the BSM physics have any (relevant) impact on the Higgs?

A: check changed properties in this talk

A: check for additional Higgs bosons

- heavier than 125.5 GeV
- lighter than 125.5 GeV $\Rightarrow$ possible at the LHC?

Sven Heinemeyer, SM@LHC, Ciemat, 08.04.2014 *4*

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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?

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Physics beyond the SM:

Top-down

Interesting (new) physics models :

- 2HDM:
  - two Higgs doublets more natural than one
- (N)MSSM:
  - solves hierarchy problem, goes towards gravity
  - automatic electroweak symmetry breaking
  - gauge coupling unification
  - cold dark matter candidate
  - $(g-2)_\mu$ solved easily
- Little Higgs:
  - (partially) solves the hierarchy problem
  - cold dark matter candidate
- Extra dimensions:
  - solves the hierarchy problem
  - cold dark matter candidate
- ...

bottom-up

in this talk

⇒ pick your favorite model now – I pick the 2HDM, (N)MSSM

Sven Heinemeyer, SM@LHC, Ciemat, 08.04.2014 5

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 improbable

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

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

HEFT2013 - Higgs Effective Field theories

chaired by Michael Robert Trott (CERN), Gian Giudice (CERN), Roberto Contino (Sapienza Universita' di Roma), Riccardo Rattazzi (Ecole Polytechnique Federale de Lausanne (EPFL)), Christophe Grojean (ICREA - Institucio catalana de recerca estudis avancats (ES))

from Wednesday, 9 October 2013 at **08:00** to Friday, 11 October 2013 at **18:20** (Europe/Zurich)
at **CERN (4-3-006 - TH Conference Room)**

Description The purpose of this workshop is to gather experts to discuss the current state of the art in Effective Field Theory approaches to the Higgs sector. Workshop attendance is anticipated to be approximately 35 people and is initially by invitation. Details on the workshop program will be posted at a later date. Invitee registration is closed, public registration is now open.

Video Services Vidyo public room : HEFT2013_-_Higgs_Effective_Field_theories More Info | **Join Now!**

Go to day

Wednesday, 9 October 2013

09:30 - 10:00 Welcome coffee/discussion (4-2-011 - TH common room)
Welcome in common room

10:00 - 11:00 Higgs Effective Field Theories *1h0'*
Speaker: A. Manohar (UCSD)
Material: **Slides** **Video in CDS**

11:00 - 12:00 59 ways to leave the SM & implications for Higgs physics *1h0'*
Speaker: A Pomarol (IFAE)
Material: **Slides**

HEFT2014 (28 - 30 September 2014)

@ the Instituto de Física Teórica (UAM-CSIC), Madrid

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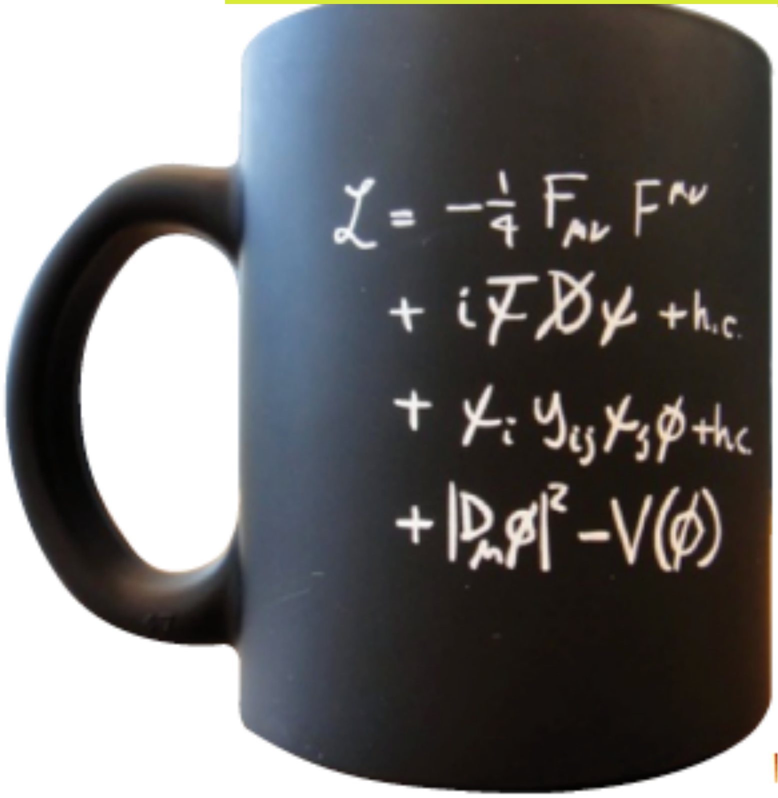
Tool development (example)



FeynRules(v2.0)

↓ UFO model file

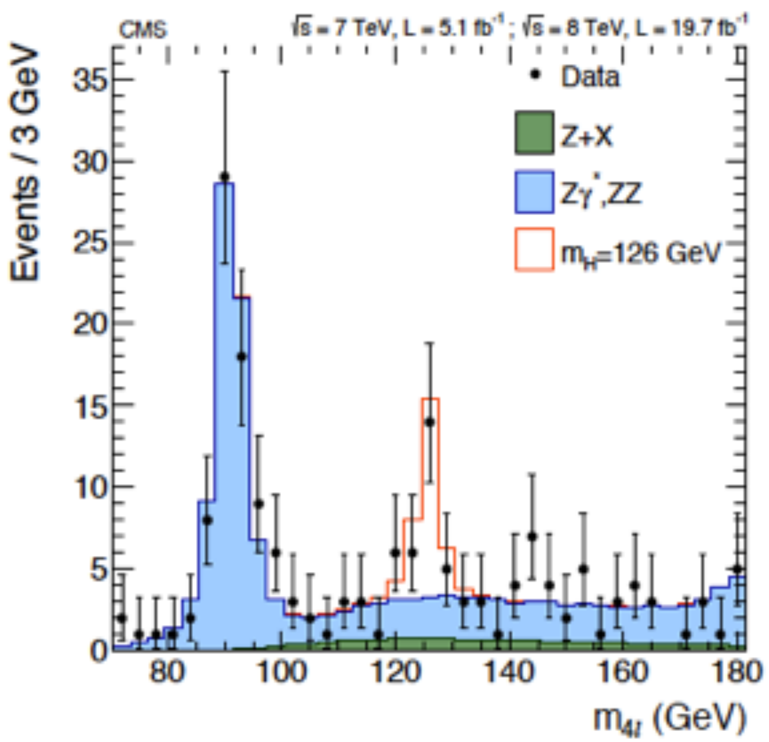
MadGraph5_aMC@NLO
(Pythia, Herwig)

↓ StdHep event file

Delphes

↓ LHCO event file

MadAnalysis5



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)

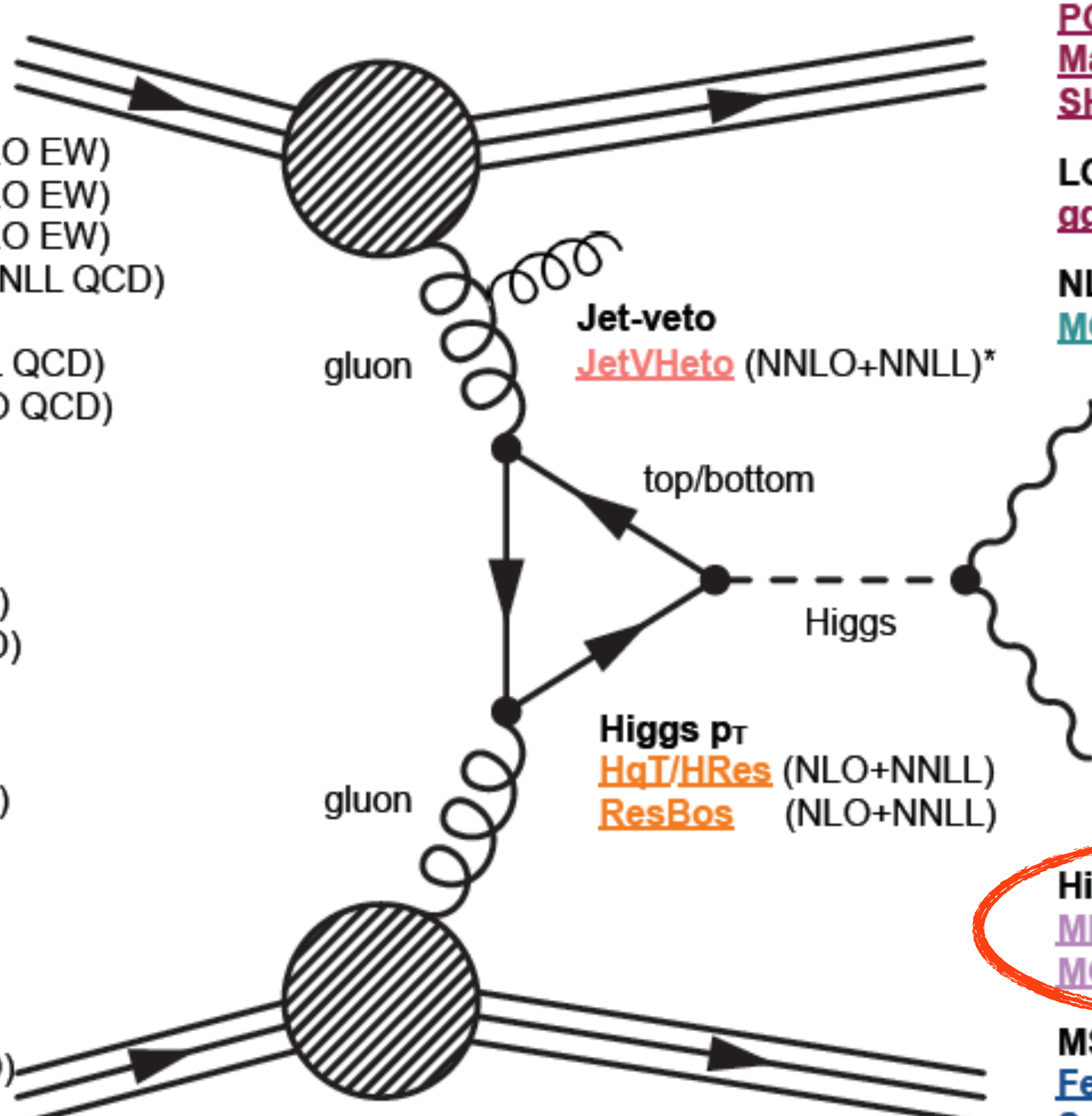
WH/ZH
V2HV (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

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

Tools for Higgs properties

- The general scattering amplitude approach

$$A(X_{J=0} \to VV) = v^{-1}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

  - Couplings can be momentum dependent form factors and can be complex.
  - Public code: e.g. `JHUGen` [1001.3396, 1208.4018, 1309.4819]

- The effective field theory approach

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

  - Public code: e.g. `HEL (HiggsEffectiveLagrangian)` [1310.5150]
    `HC (HiggsCharacterisation)` [1306.6464, 1311.1829]

D6 Higgs Effective Lagrangian

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

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

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

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

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

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

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

before vs. after EW symmetry breaking

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

Vrije Universiteit Brussel

A framework for Higgs characterisation

JHEP11(2013)043 [arXiv: 1306.6464]
EPJC74(2014)2710 [arXiv:1311.1829]

The FeynRules and MadGraph5_aMC@NLO framework

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

MadWeight
P. Artoisenet (Nikhef)

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

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

Desiderata for a HC framework

- Study Higgs quantum numbers, coupling strengths and structures in a model independent way.
- Go beyond the “one-process, one-decay, one-observable” approach, i.e. go to “any-process, any-decay, any-observable” one.
- Equally useful for theorists (it can be systematically improved, changed - easily) and experimentalists (MC’s event generation directly in analyses).
- Adaptable to the present/future analyses and accuracy targets.

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

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

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

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

```
###################################
## 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

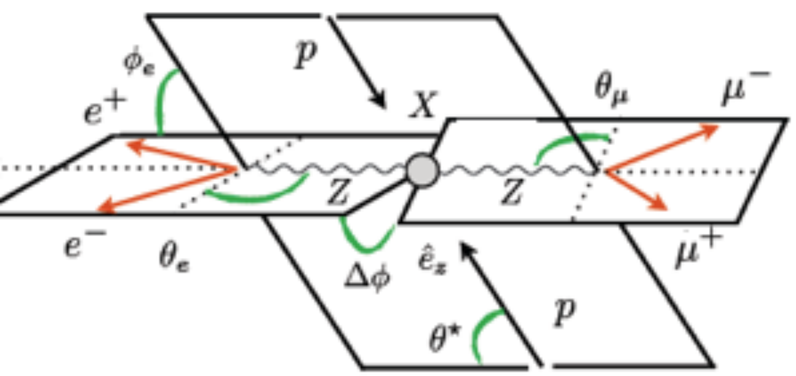
$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar{\psi}_f (c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \gamma_5) \psi_f X_0$$

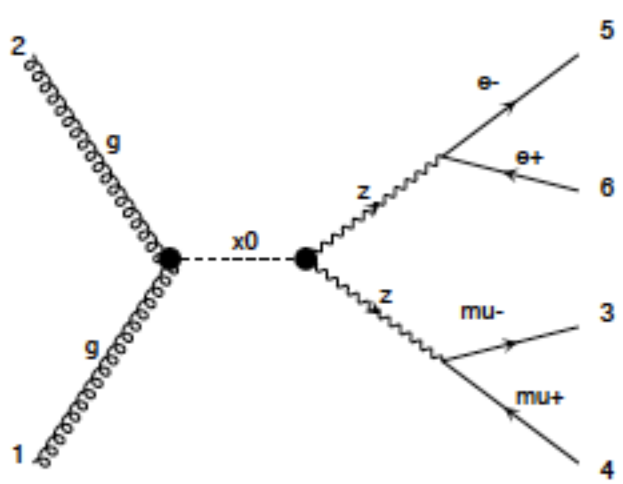
$$\begin{aligned}\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\big] \\ & - \tfrac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu}\big]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

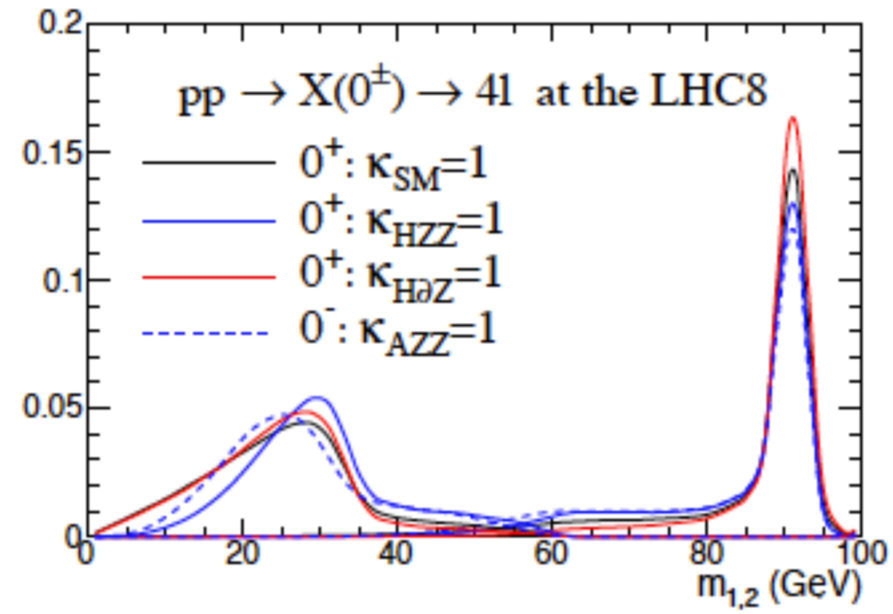
Dimensionful couplings g are set as internal parameters so as to reproduce a SM Higgs for κ=1.

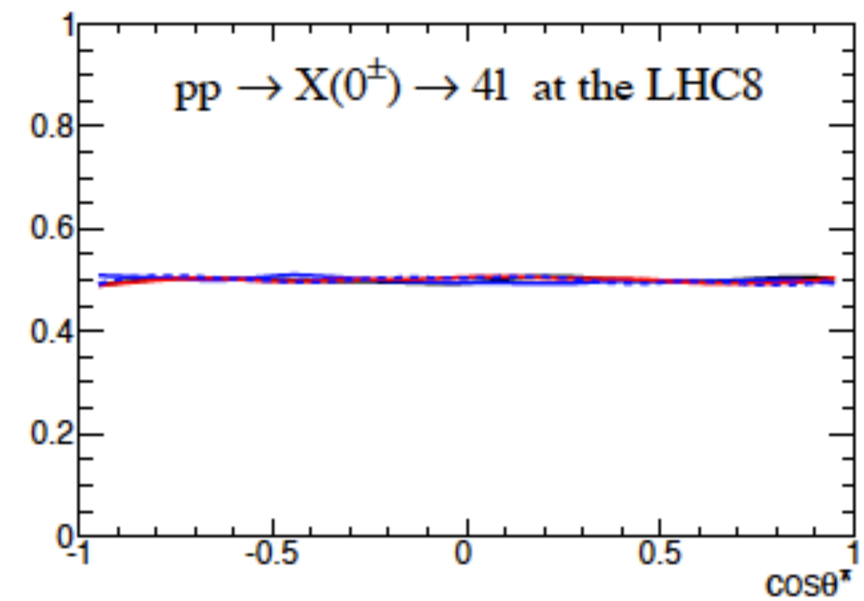
$g_{Xyy'} \times v$	ff	ZZ/WW	$\gamma\gamma$	$Z\gamma$	gg
H	m_f	$2m^2_{Z/W}$	$47\alpha_{\rm EM}/18\pi$	$C(94\cos^2\theta_W - 13)/9\pi$	$-\alpha_s/3\pi$
A	m_f	0	$4\alpha_{\rm EM}/3\pi$	$2C(8\cos^2\theta_W - 5)/3\pi$	$\alpha_s/2\pi$

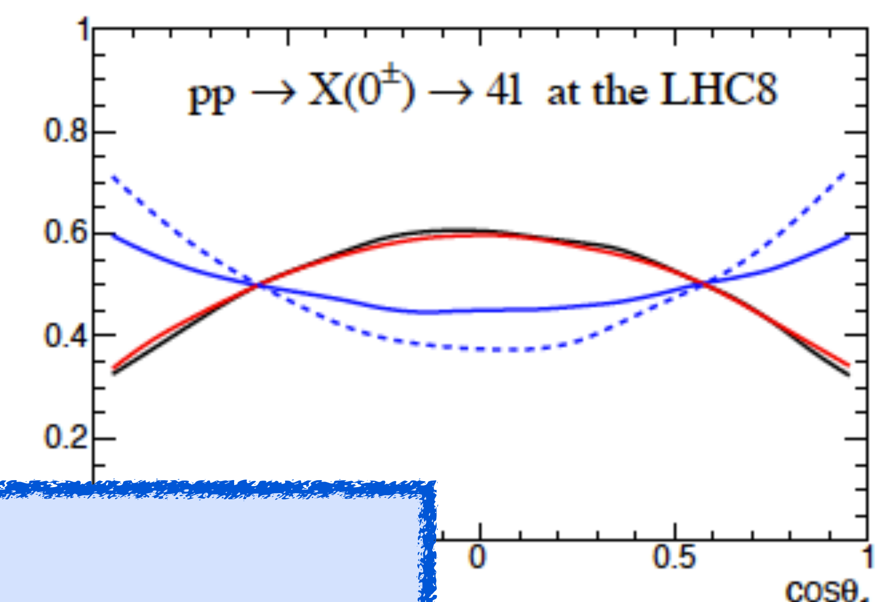
Mass and angular distributions -- spin0

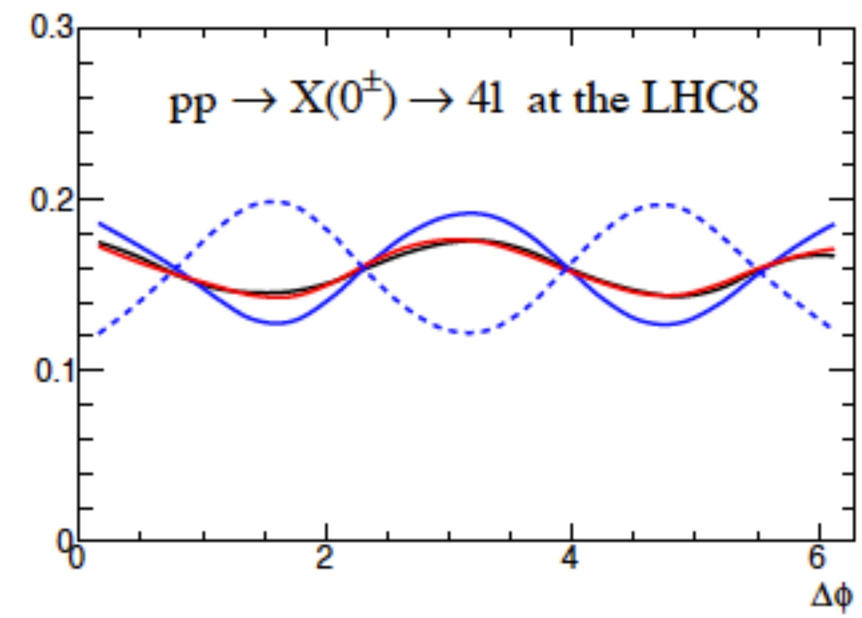













```
./bin/mg5_aMC
>import model HC
>generate p p > x0, x0 > mu- mu+ e- e+
>launch
```

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

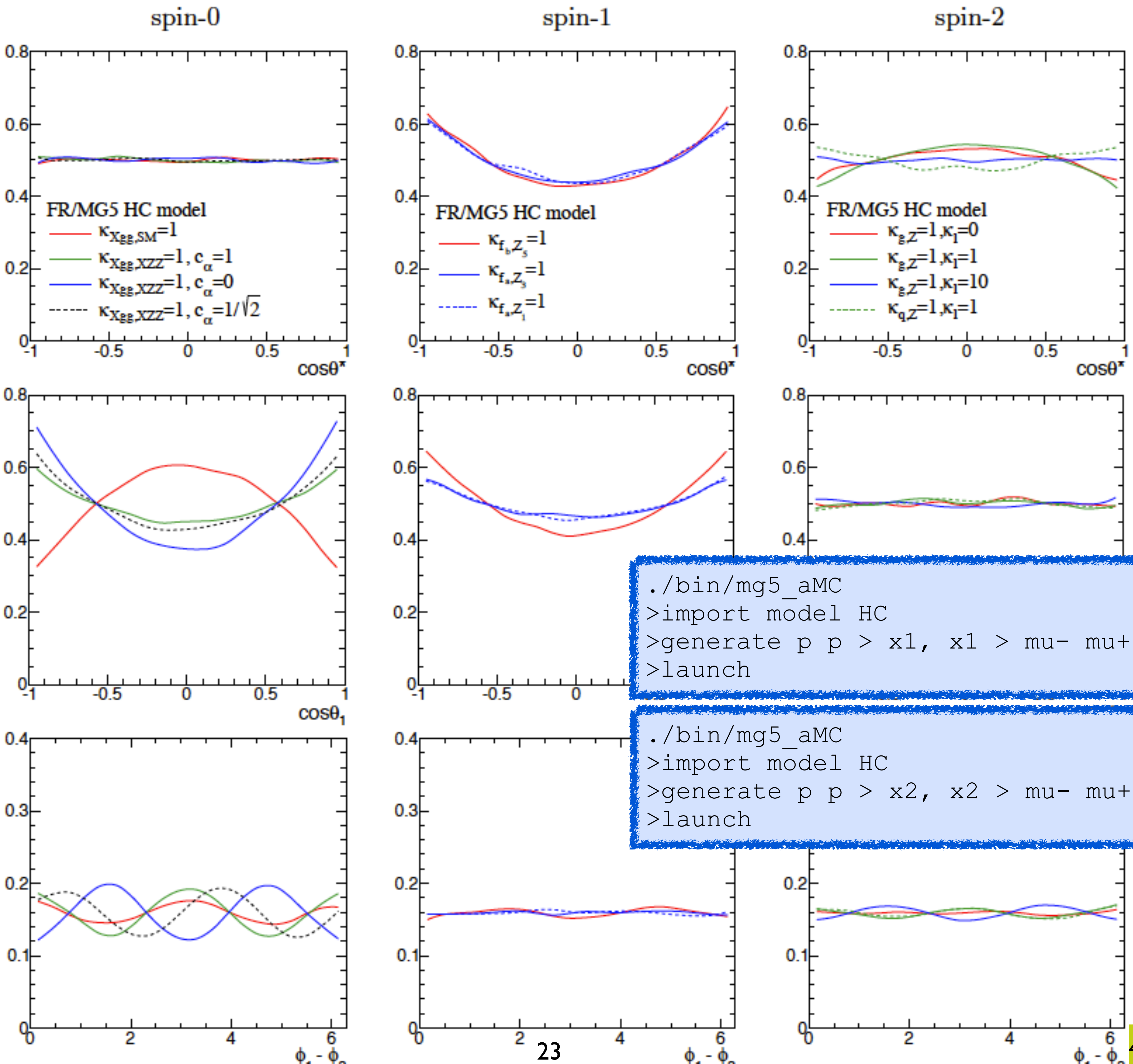
- via the energy-momentum tensor of the SM fields, starting from D5:

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

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

- The E-M tensor for QED:

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

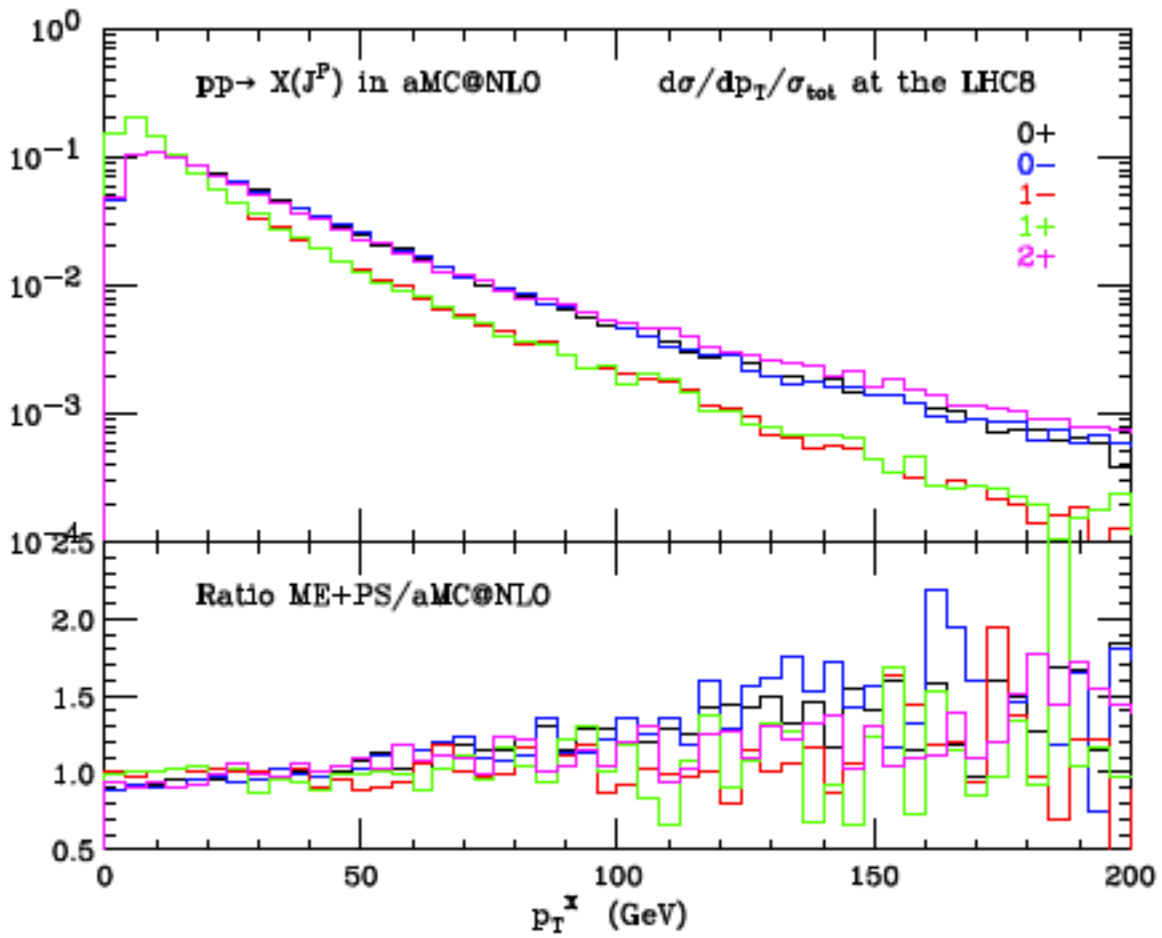


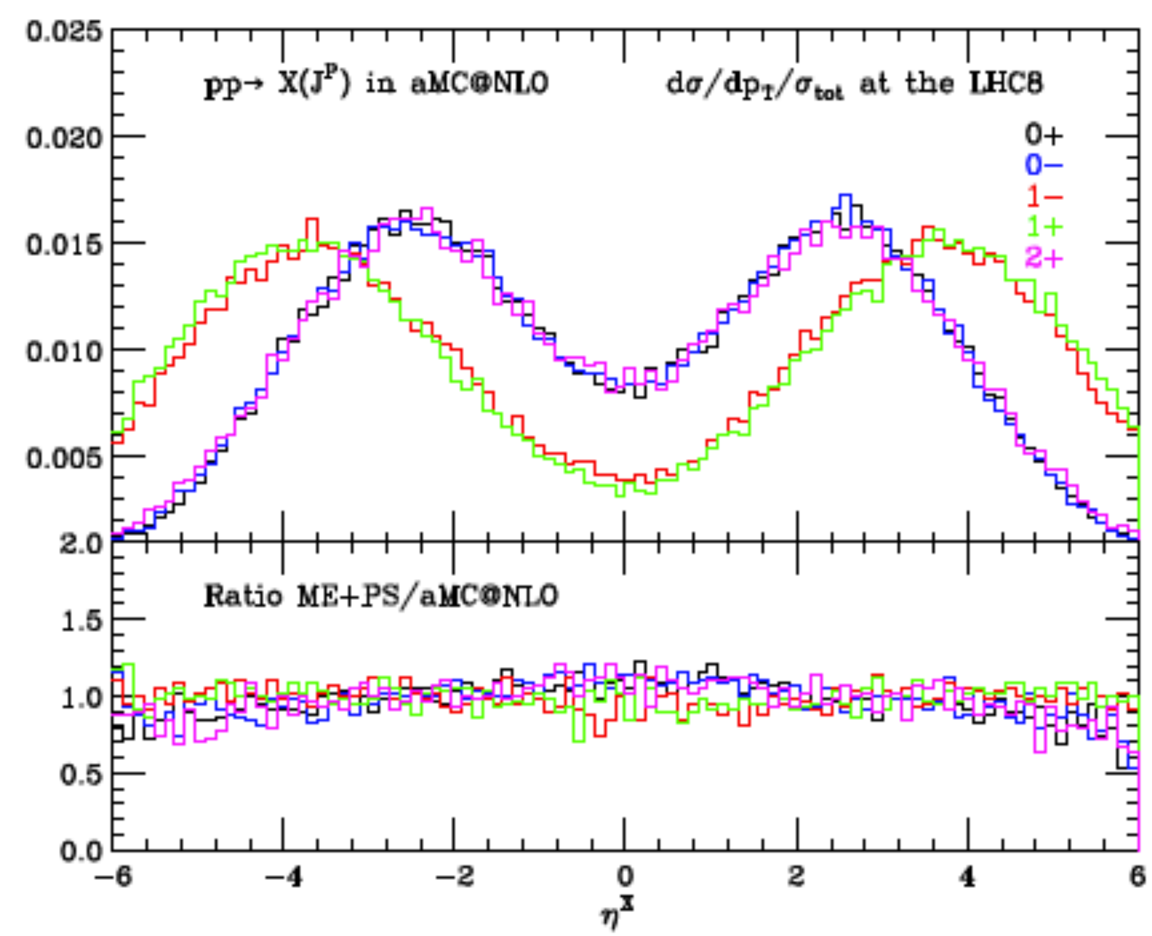

```
./bin/mg5_aMC
>import model HC
>generate p p > x1, x1 > mu- mu+ e- e+
>launch
```

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

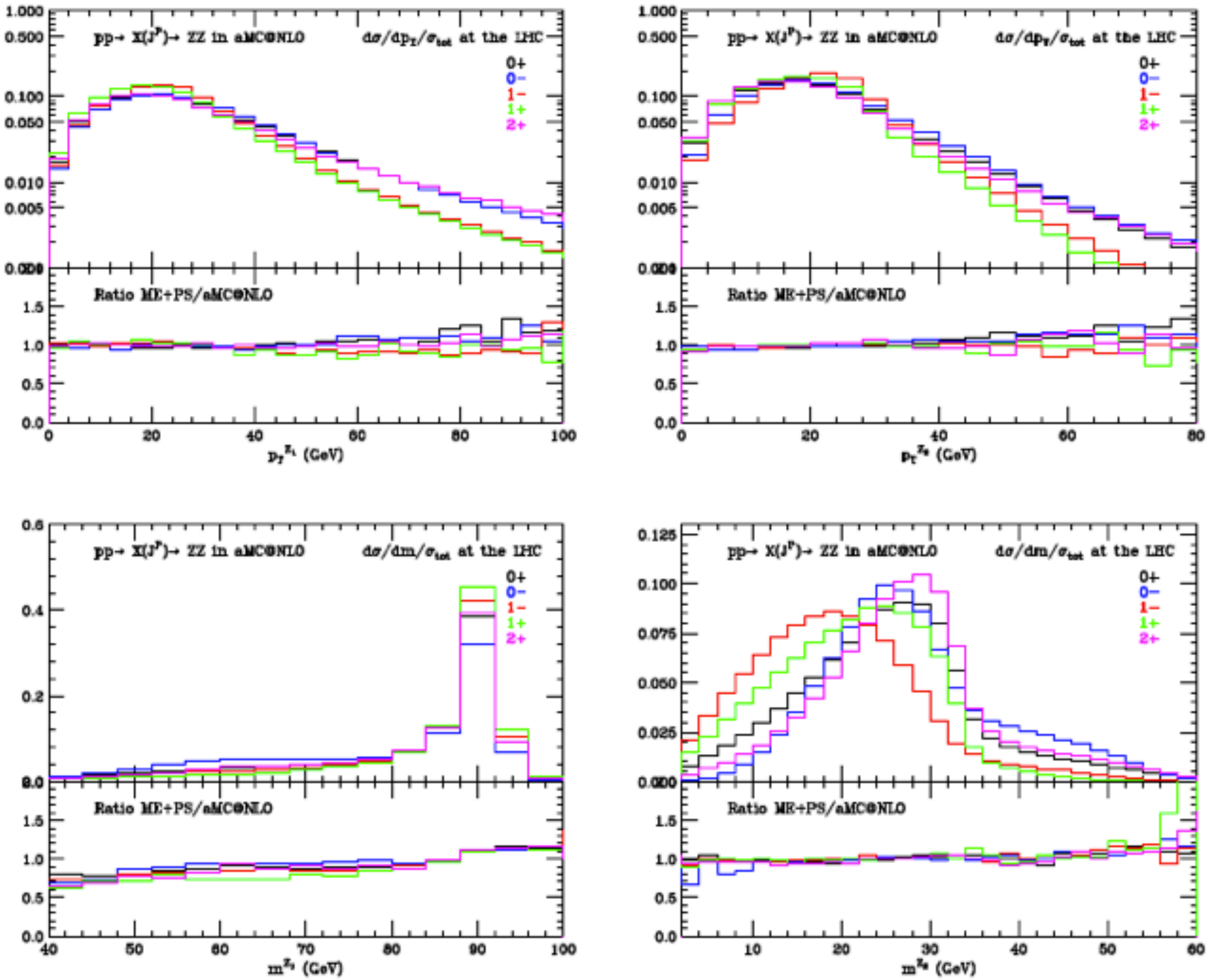
Higher order effects in QCD

- 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]





aMC@NLO vs. ME+PS



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

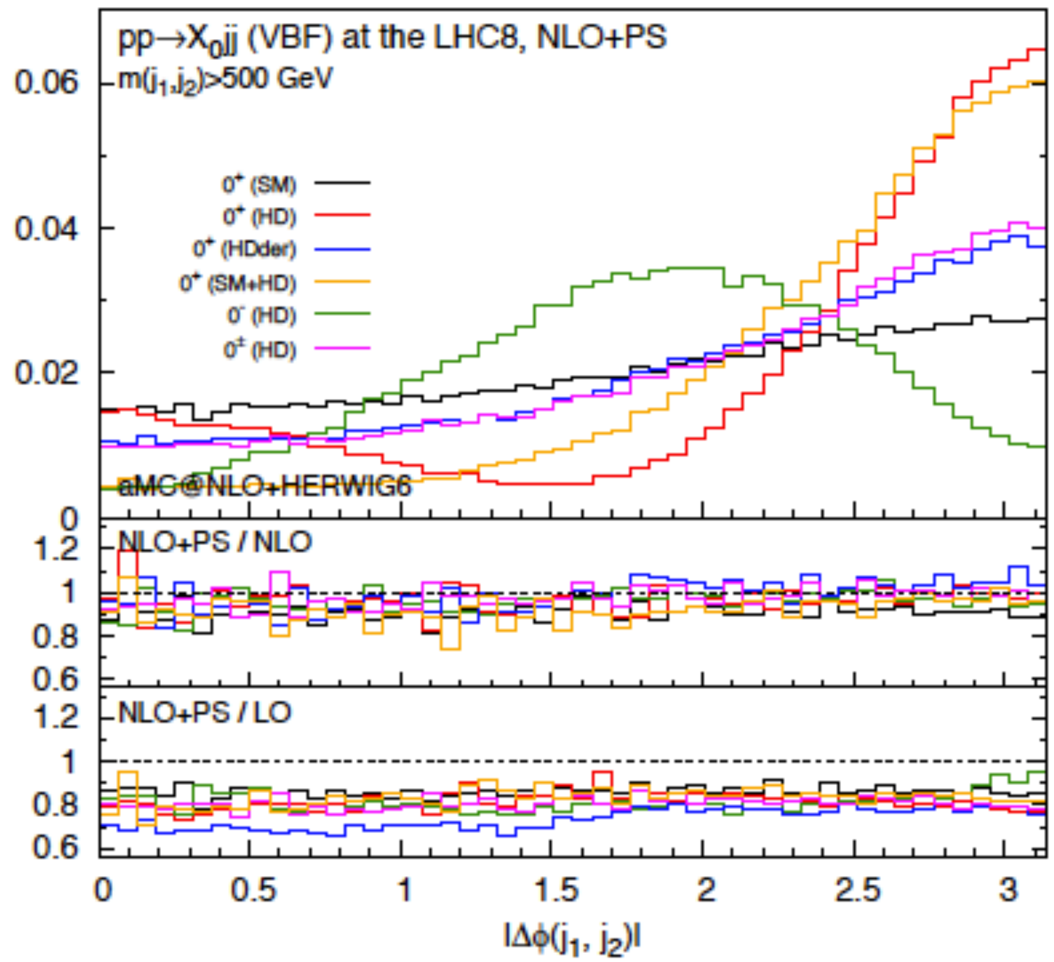
For spin0, the production and decay factorize, for spin 1 and 2 this does not happen and the full 2->4,5 matrix elements need to be used.

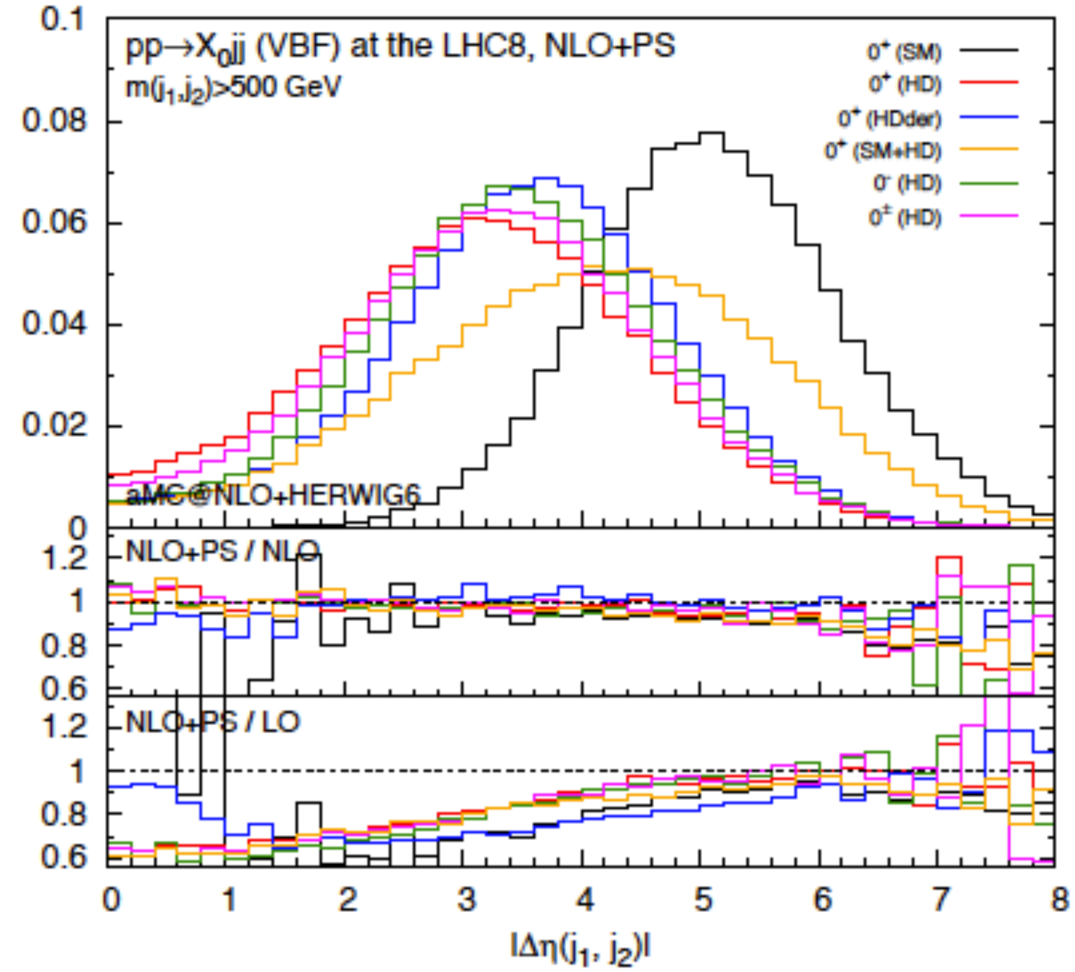
VBF

F.Maltoni, KM, M.Zaro [arXiv:1311.1829]

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

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



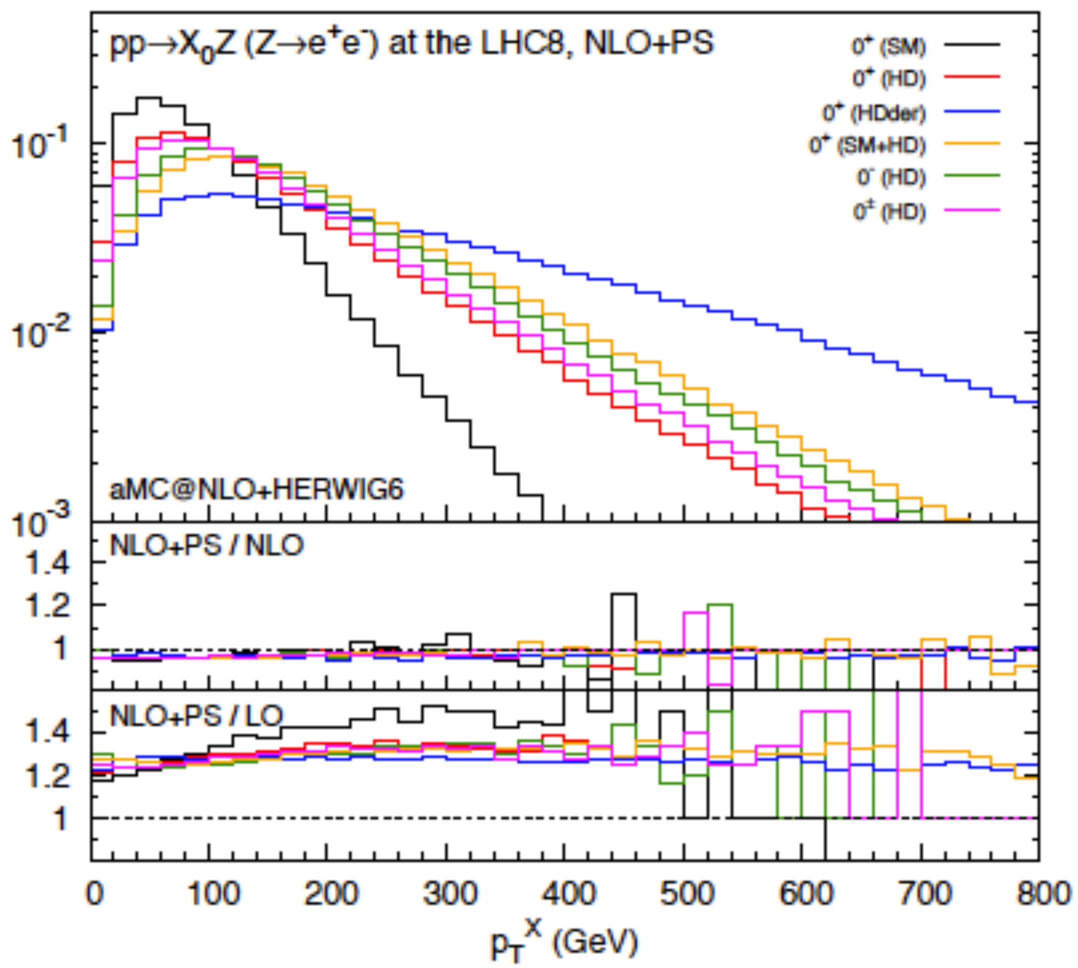


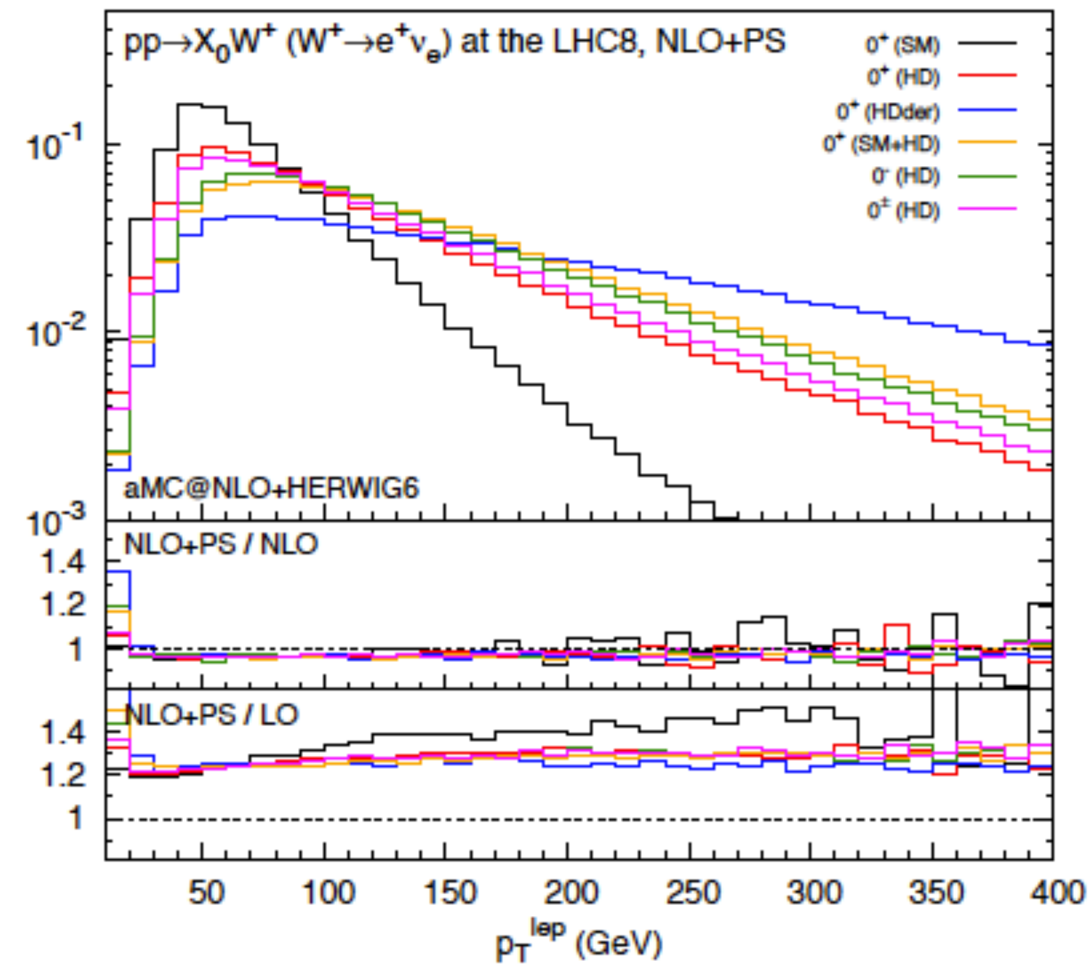
VH

F.Maltoni, KM, M.Zaro [arXiv:1311.1829]

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

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

Authors

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  - Priscila de Aquino & Kentarou Mawatari (Vrije Universiteit Brussel)
    - Emails: kentarou.mawatari @ vub.ac.be
- NLO
  - Federico Demartin (Universite Catholique de Louvain) & Marco Zaro (LPTHE, Paris)
    - Emails: federico.demartin @ uclouvain.be

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).

back-up

Vrije Universiteit Brussel

FeynRules(v2.0) in a nutshell

Alloul, Christensen, Degrande, Duhr, Fuks, http://feynrules.irmp.ucl.ac.be

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

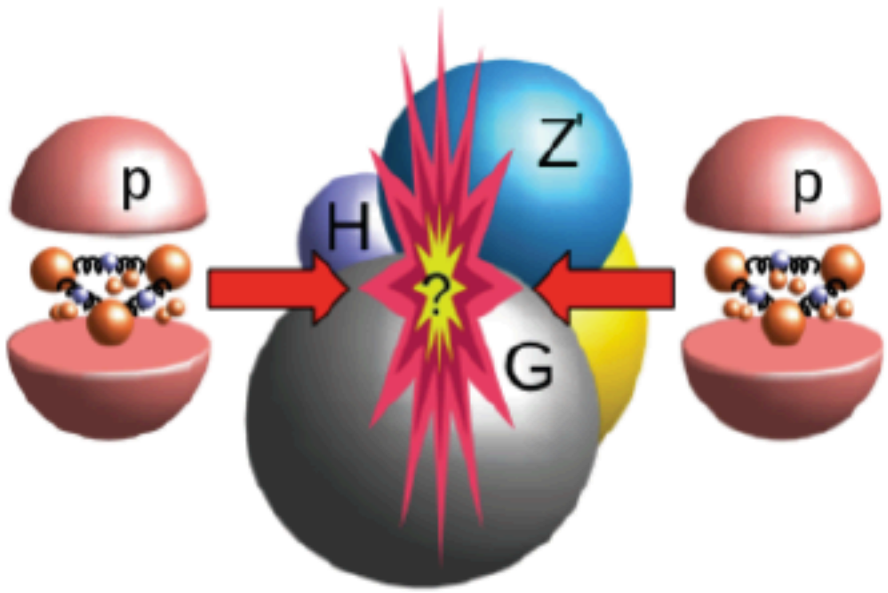
- The only requirements on the Lagrangian are:
  - ✓ Locality, Lorentz and gauge invariance
  - ✓ Supported filed types: spin-0, 1/2, 1, 3/2, and 2 (as well as superfields). [Christensen, de Aquino, Deutschmann, Duhr, Fuks, Garcia-Cely, Mattelaer, Mawatari, Oexl, Takaesu, EPJC(2013)]

new!

JHU Generator

www.pha.jhu.edu/spin/

Most Visited · Getting Started · Latest Headlines · madgolem_slept...



MC Generator based on the papers:

"Spin-Determination of Single-Produced Resonances at Hadron Colliders"
Yanyan Gao, Andrei V. Gritsan, Zijin Guo, Kirill Melnikov, Markus Schulze and Nhan V. Tran
http://arxiv.org/abs/1001.3396

"On the Spin and Parity of a Single-Produced Resonance at the LHC"
Sara Bolognesi, Yanyan Gao, Andrei V. Gritsan, Kirill Melnikov, Markus Schulze, Nhan V. Tran and Andrew Whitbeck
http://arxiv.org/abs/1208.4018

"Constraining anomalous HVV interactions at proton and lepton colliders"
Ian Anderson, Sara Bolognesi, Fabrizio Caola, Yanyan Gao, Andrei V. Gritsan, Christopher B. Martin, Kirill Melnikov, Markus Schulze, Nhan V. Tran, Andrew Whitbeck, Yaofu Zhou
http://arxiv.org/abs/1309.4819

contacts: Markus Schulze, Nhan Tran (email us)

Home Download (requires registration) Manual

References:
Please reference the above papers and refer to "JHU generator" when using the simulation program and "MELA" when using the matrix element likelihood analysis technique. The latter was also introduced in [1, 2]. The matrix element package (MELA) also depends on MCFM libraries for background parameterization which should be referenced [3] when used.

Generator for pp → X → VV, VBF, X+JJ, pp → VX, ee → VX

Description:
A generator giving parton-level information including full spin and polarization correlations for the processes ab → X → VV (V=Z,W,gamma), VBF, X+JJ, pp → VX, ee → VX. The Fortran program produces a single-produced X resonance via either the gluon fusion, qqbar, VBF, or VH processes for either the Tevatron, the LHC, or an e+e- collider. The resonance X can be a spin-zero, -one, or -two particle with general couplings defined in the study. The output is in the LHE format and can be input to any parton showering program. Please see the manual file for further technical details.

Requirements:
ifort (Intel Fortran compiler) or gfortran (part of gcc)

Effective Lagrangian → Amplitudes

$$\mathcal{L} = \frac{1}{2} c_\alpha \kappa_{\rm SM} g_{HZZ}\, Z_\mu Z^\mu X_0 \longrightarrow i c_\alpha \kappa_{\rm SM} g_{HZZ}\, g_{\mu\nu}$$

(g1 term in JHU)

$$-\frac{1}{4}\frac{1}{\Lambda} c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} \longrightarrow i c_\alpha \frac{\kappa_{HZZ}}{\Lambda} \left(g_{\mu\nu} q_1.q_2 - q_{2\mu} q_{1\nu}\right)$$

(g2 term in JHU)

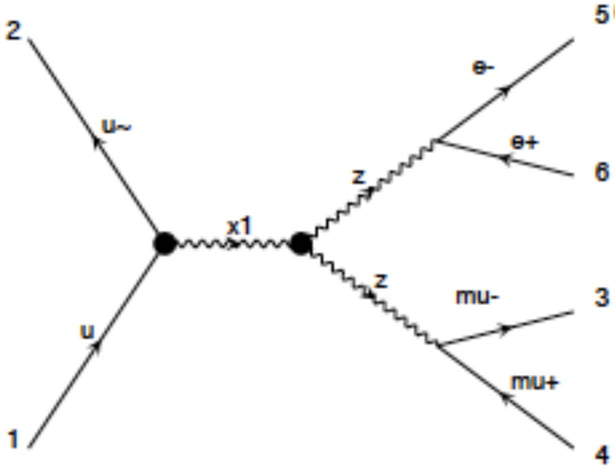
$$-\frac{1}{4}\frac{1}{\Lambda} s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \longrightarrow i s_\alpha \frac{\kappa_{AZZ}}{\Lambda} \epsilon_{\mu\nu\rho\sigma} q_2^\rho q_1^\sigma$$

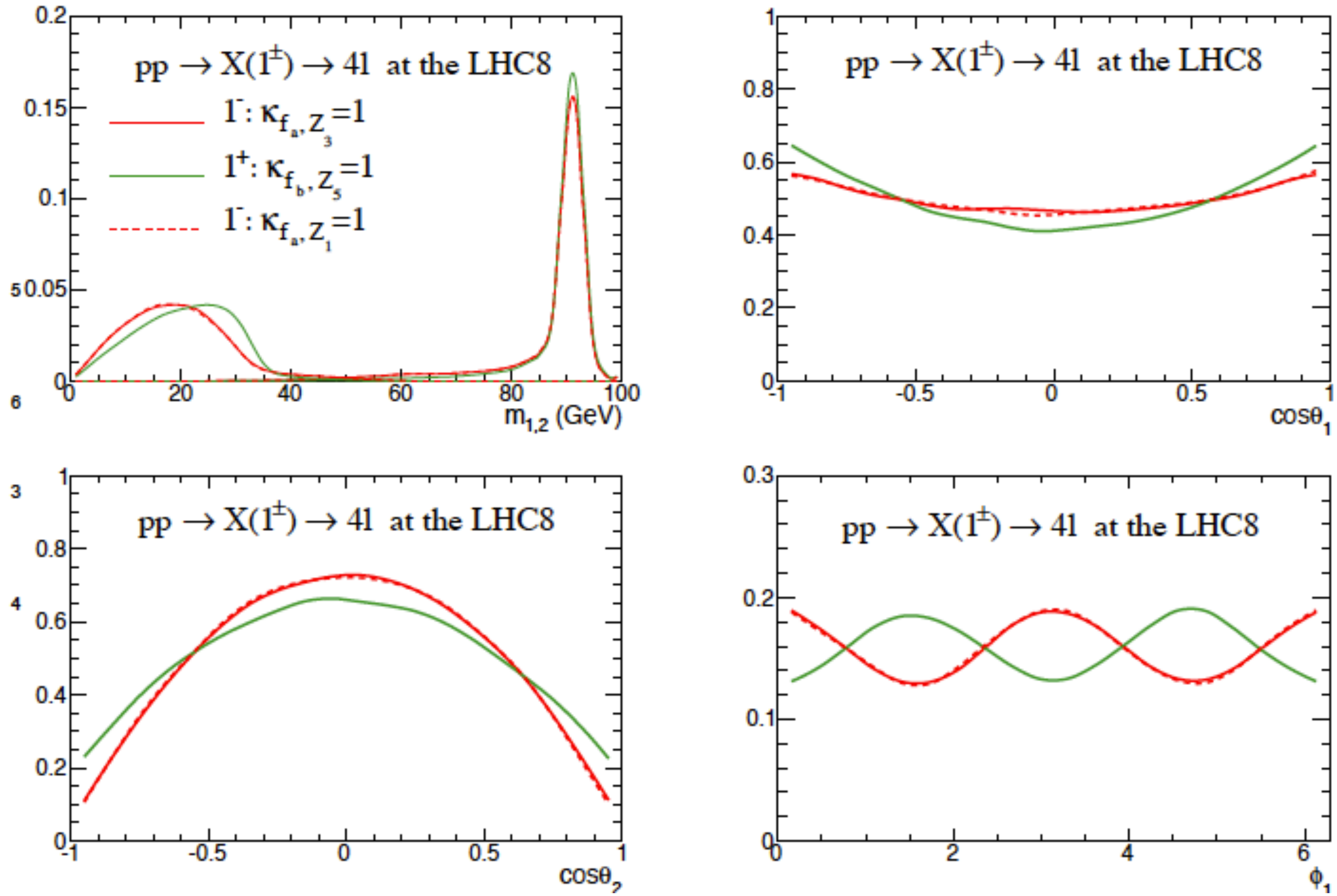
(g4 term in JHU)

$$-\frac{1}{\Lambda} c_\alpha \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} \longrightarrow i c_\alpha \frac{\kappa_{H\partial Z}}{\Lambda} \left[g_{\mu\nu}(q_1.q_1 + q_2.q_2) - q_{1\mu} q_{1\nu} - q_{2\mu} q_{2\nu}\right]$$

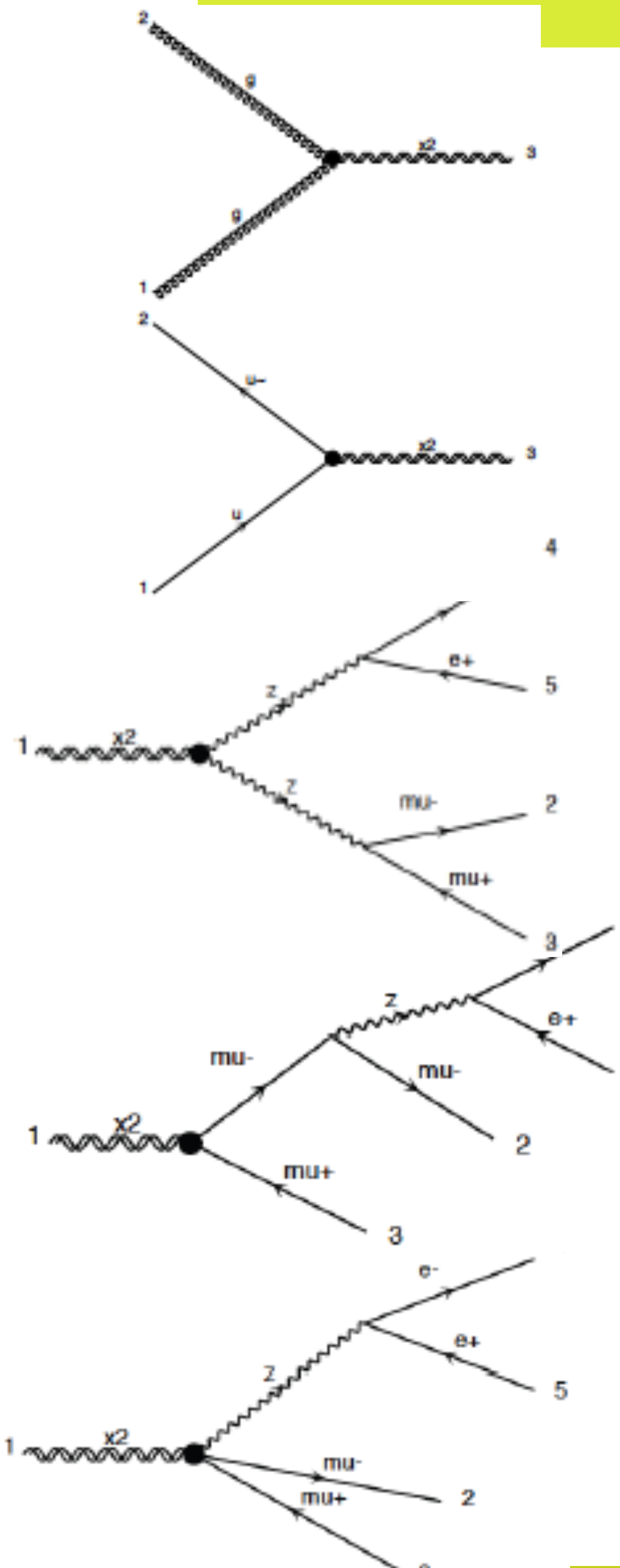
JHU scenario	HC parameter choice	
	X production	X decay
0^+_m	$\kappa_{Hgg} \neq 0$	$\kappa_{\rm SM} \neq 0$ ($c_\alpha = 1$)
0^+_h	$\kappa_{Hgg} \neq 0$	$\kappa_{H\gamma\gamma,HZZ,HWW} \neq 0$ ($c_\alpha = 1$)
0^-	$\kappa_{Agg} \neq 0$	$\kappa_{A\gamma\gamma,AZZ,AWW} \neq 0$ ($c_\alpha = 0$)
1^+	$\kappa_{f_a,f_b} \neq 0$	$\kappa_{Z_5,W_5} \neq 0$
1^-	$\kappa_{f_a,f_b} \neq 0$	$\kappa_{Z_3,W_3} \neq 0$
2^+_m	$\kappa_g \neq 0$	$\kappa_{\gamma,Z,W} \neq 0$

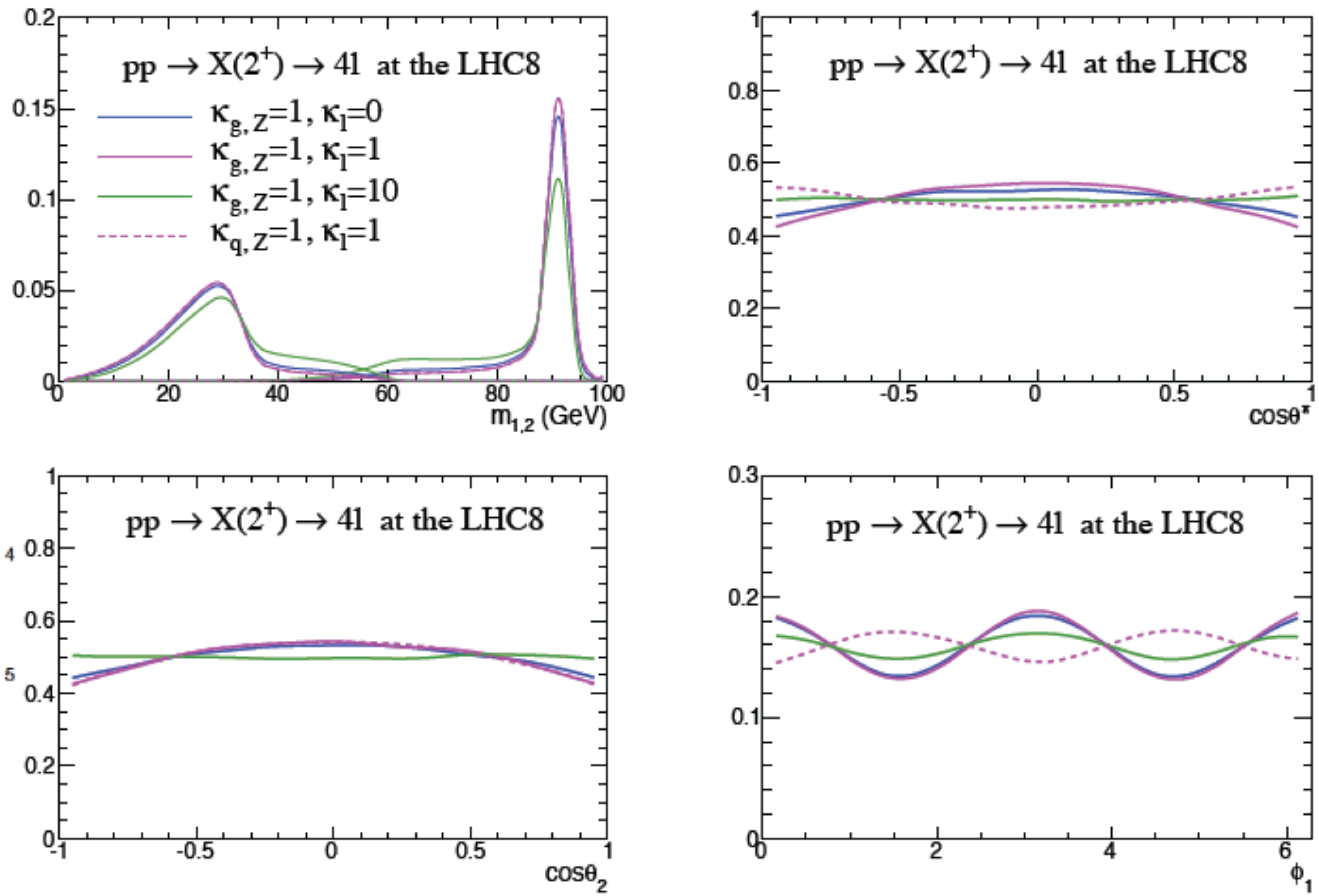
Mass and angular distributions -- spin1





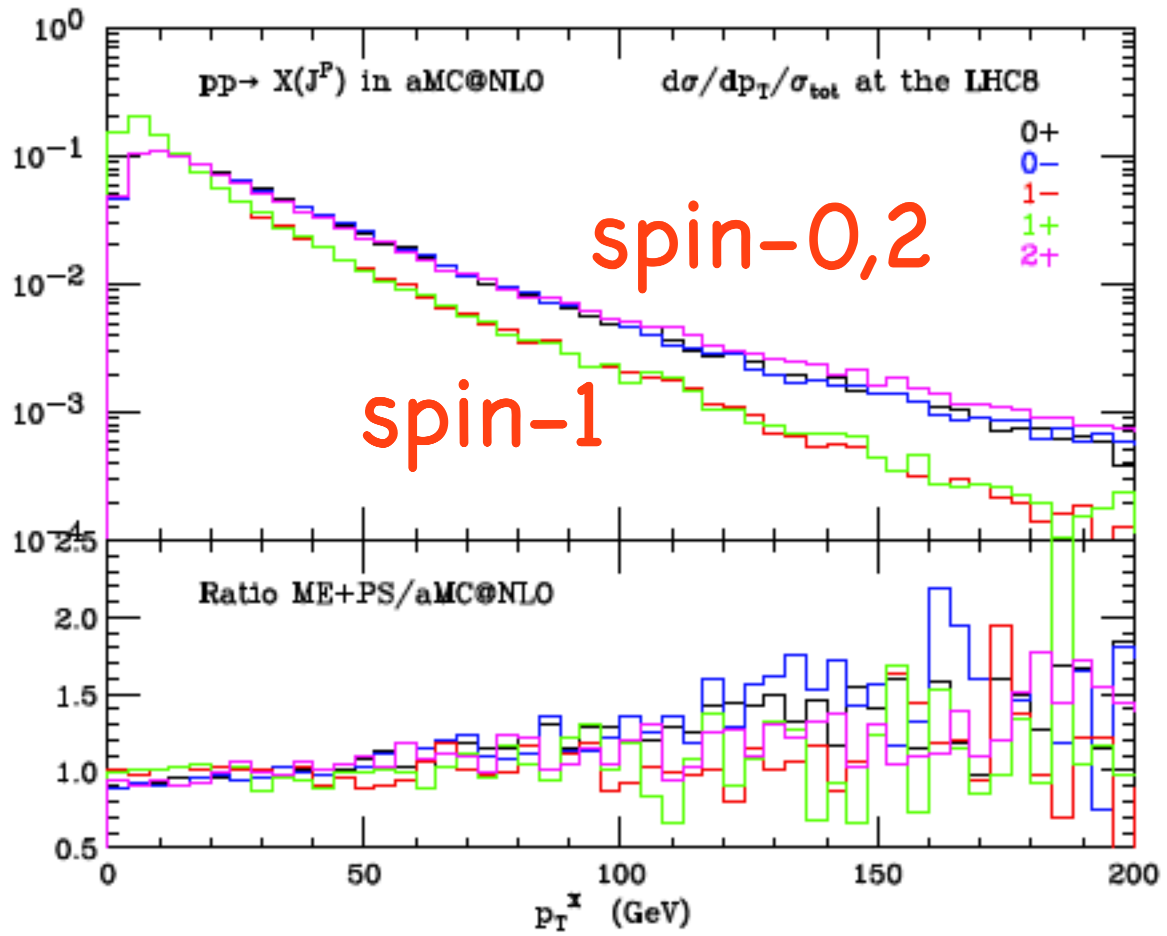
Mass and angular distributions -- spin2

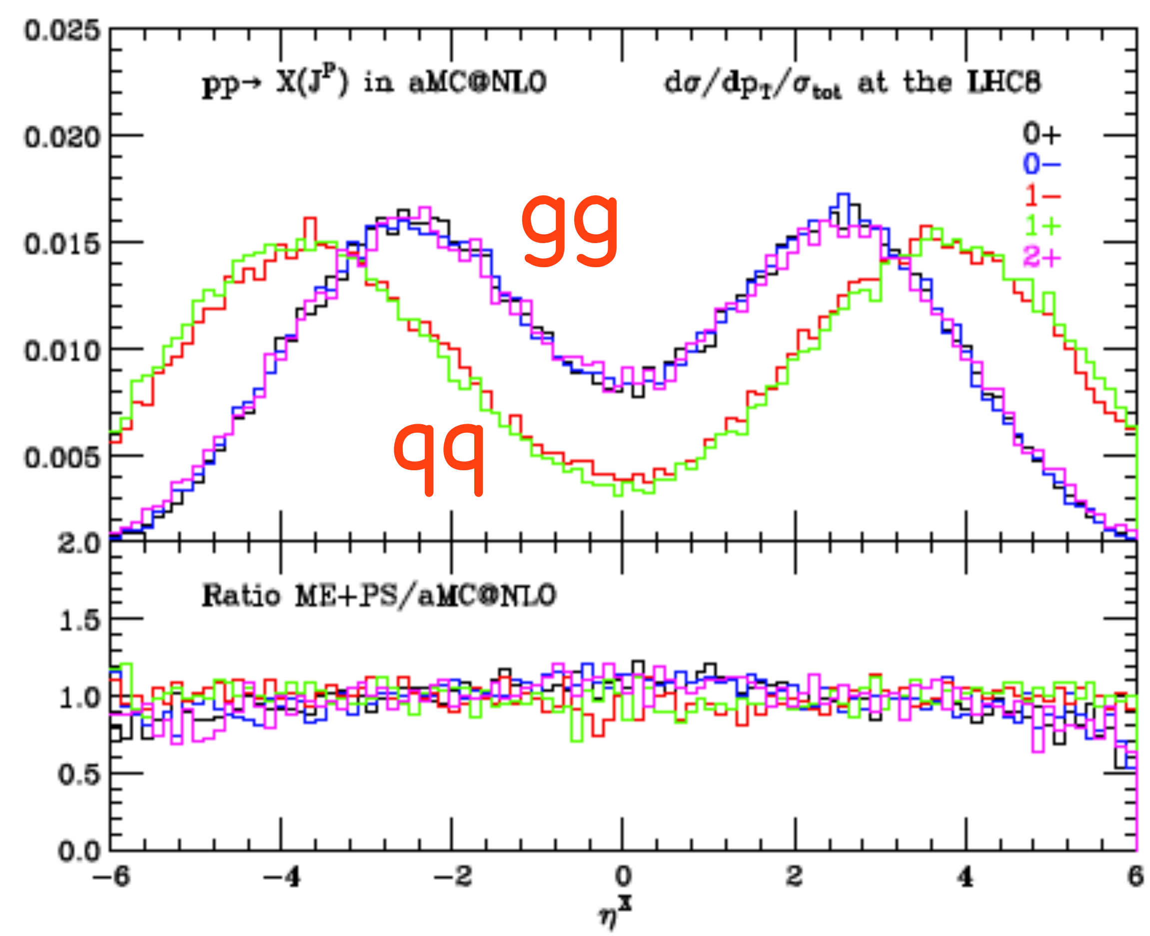




Higher order effects in QCD (I)

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.

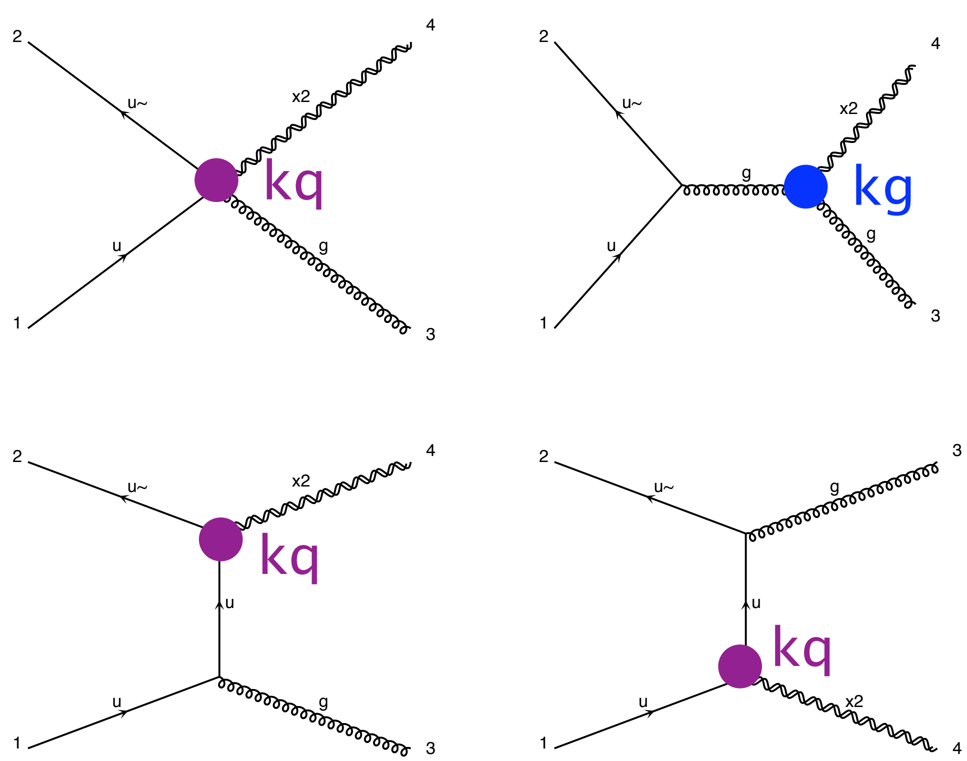
The different shapes are due to the different initial state.

excellent agreement between ME+PS and aMC@NLO

Higher order effects in QCD (II)

unitarity-violating behavior of models with a spin-2 state

$$\mathcal{L} = -\frac{1}{\Lambda}\kappa_q T^q_{\mu\nu} X_2^{\mu\nu} - \frac{1}{\Lambda}\kappa_g T^g_{\mu\nu} X_2^{\mu\nu}$$



$$|\mathcal{M}|^2 \propto s/\Lambda^2 \quad \text{for } \kappa_q = \kappa_g$$

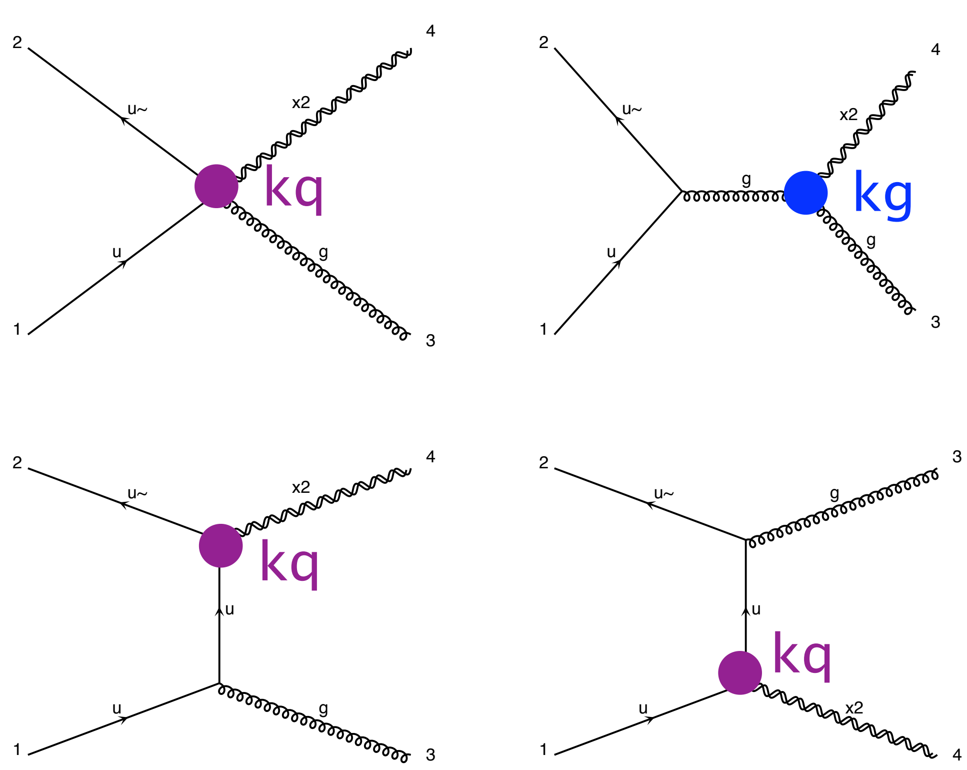
$$|\mathcal{M}|^2 \propto s^3/m^4\Lambda^2 \quad \text{for } \kappa_q \neq \kappa_g$$

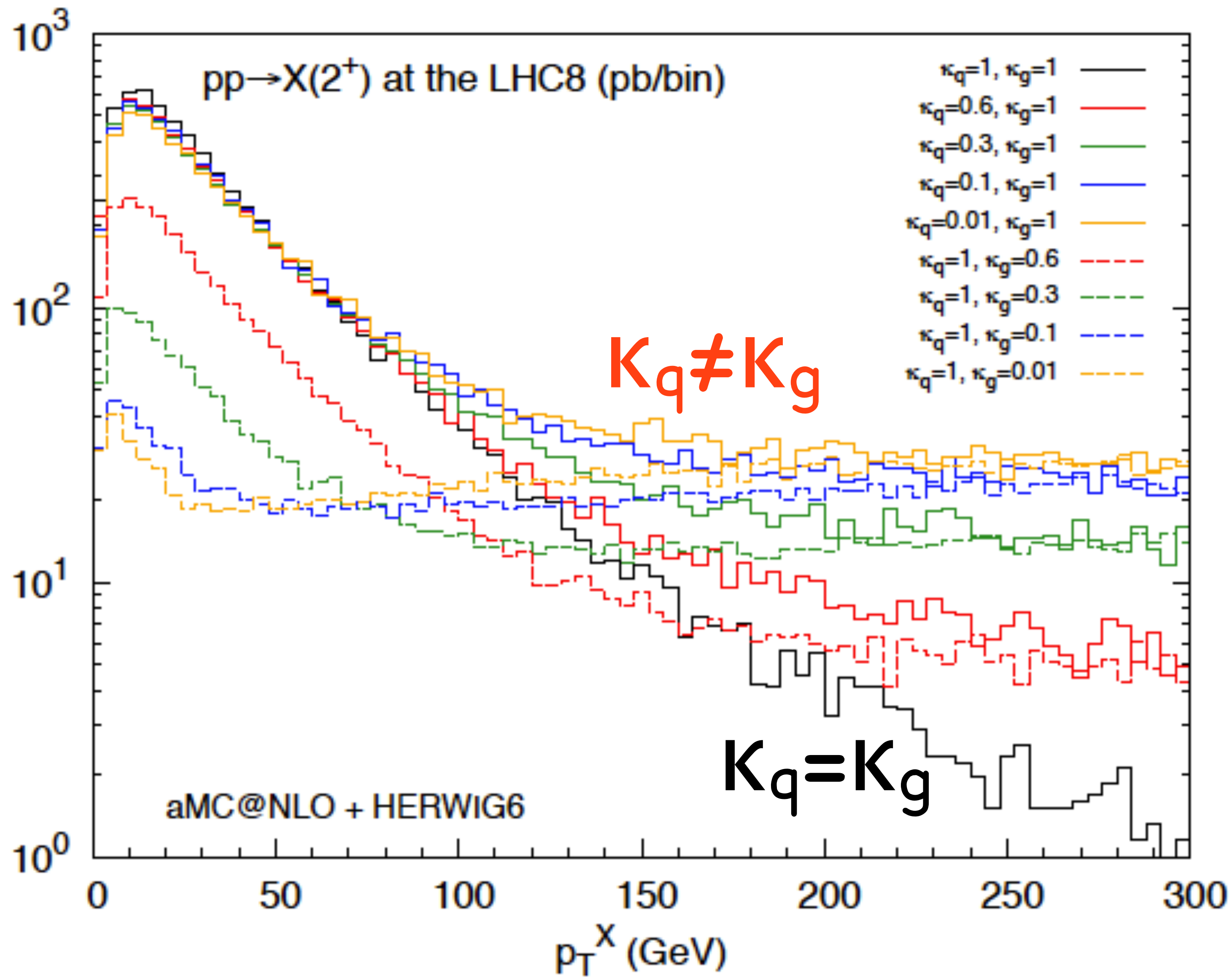
$$\begin{aligned}|\mathcal{M}|^2 = \frac{N}{\Lambda^2 s\, t\, u\, m^4}\Big\{ & 3\kappa_g^2 m^4 \left[2m^4 - 2m^2(t+u) + t^2 + u^2\right]\left[m^4 - m^2(t+u) + 4tu\right] \\ & + (\kappa_q - \kappa_g)\, 6\,\kappa_g m^4 s \left[m^6 + m^2 s(s+2u) - 2su(s+u)\right] \\ & + (\kappa_q - \kappa_g)^2 s \big[6m^{10} - 6m^8(t+u) + 3m^6(t^2+u^2) - 12m^4 tu(t+u) \\ & \quad + 2m^2 tu(t^2 + 12tu + u^2) - 2tu(t^3 + t^2 u + tu^2 + u^3)\big]\Big\}, \quad (4.2)\end{aligned}$$

Higher order effects in QCD (II)

unitarity-violating behavior of models with a spin-2 state

$$\mathcal{L} = -\frac{1}{\Lambda}\kappa_q T^q_{\mu\nu} X_2^{\mu\nu} - \frac{1}{\Lambda}\kappa_g T^g_{\mu\nu} X_2^{\mu\nu}$$

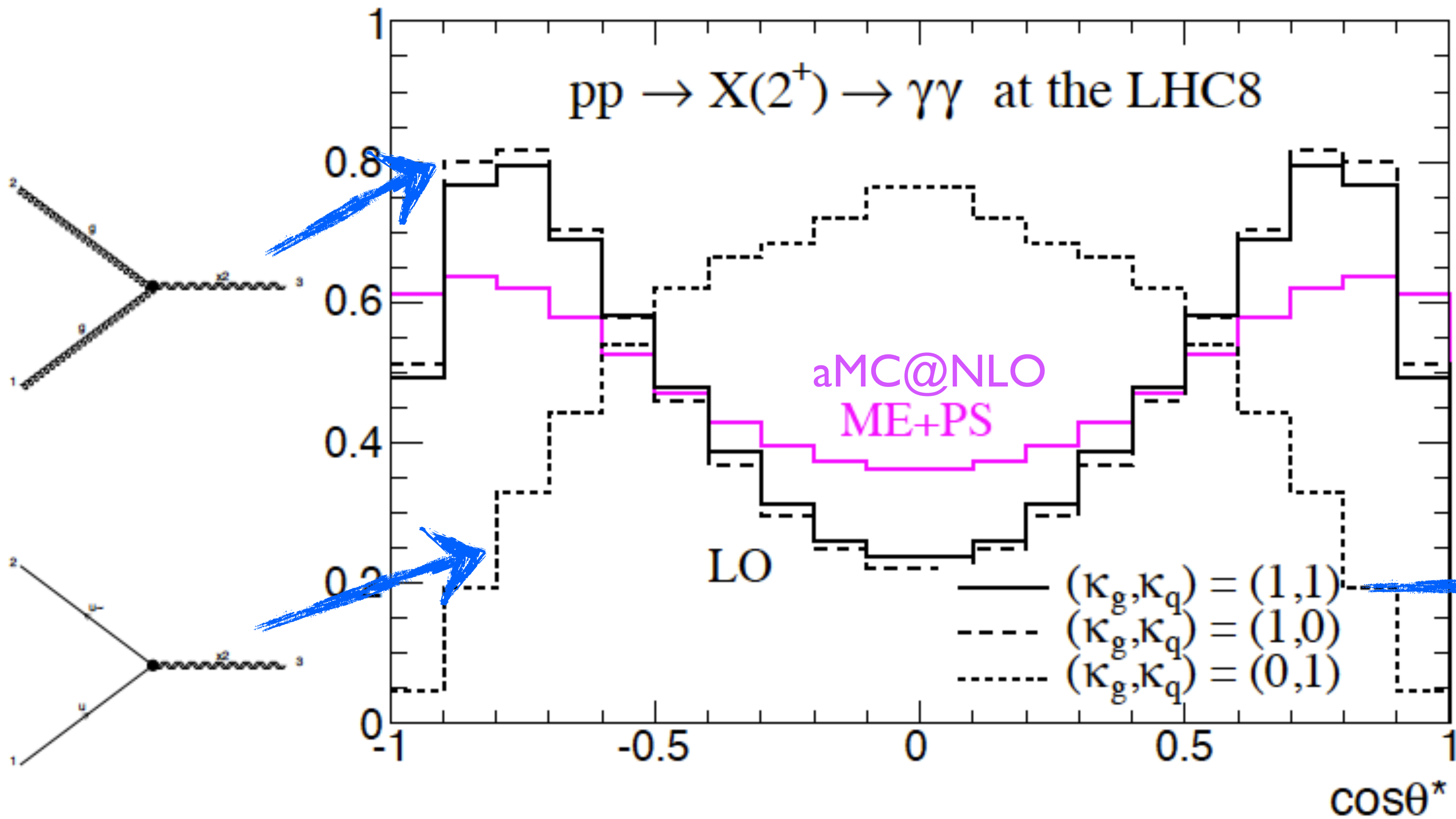




A model with non-universal couplings dramatically changes the pT(X) spectrum.

Higher order effects in QCD (III)

on spin observables for a spin-2 state



σ_{gg}/σ_{tot} $\sim$96%

scattering angle in $pp \to X \to \gamma\gamma$

$$\frac{d\sigma(gg)}{d\cos\theta^*} \propto |d^2_{22}(\theta^*)|^2 + |d^2_{2-2}(\theta^*)|^2 = \frac{1}{8}(1 + 6\cos^2\theta^* + \cos^4\theta^*)\,,$$

$$\frac{d\sigma(q\bar{q})}{d\cos\theta^*} \propto |d^2_{12}(\theta^*)|^2 + |d^2_{1-2}(\theta^*)|^2 = \frac{1}{2}(1 - \cos^4\theta^*)\,.$$