Higgs Characterisation

in the effective field theory approach
via the FeynRules and MadGraph5_aMC@NLO frameworks

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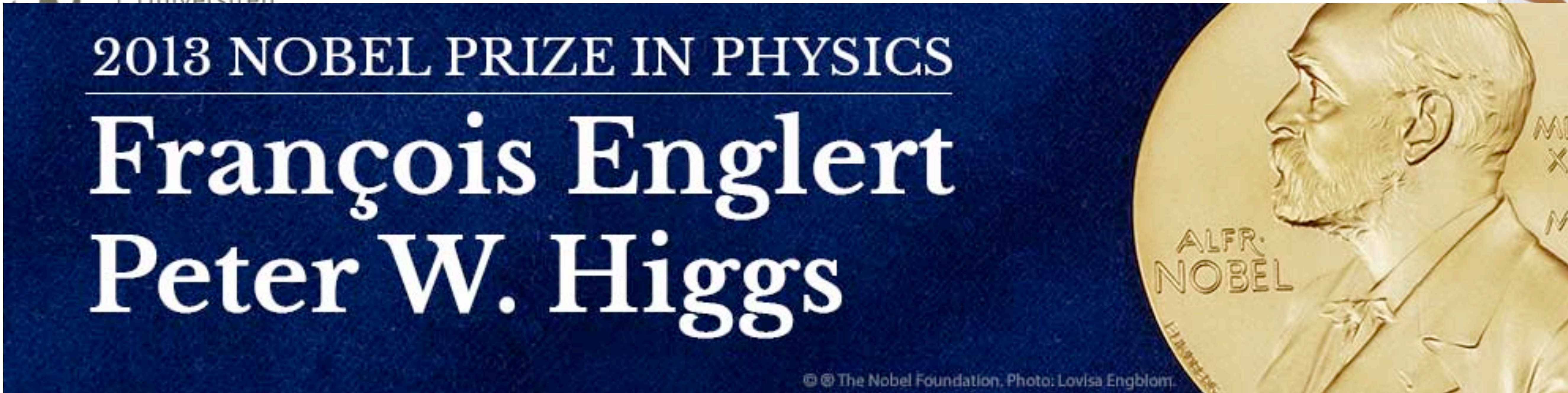
- Sec.11 in YR3 of the LHC Higgs Cross Section Working Group [arXiv:1307.1347]

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

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

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



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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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]

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- Introduction
  - H>ZZ*>4l vs. VBF
  - Effective field theory approach
- Higgs characterisation framework
  - Effective Lagrangians -- *X(J=0,1,2)*
  - NLO QCD effects
- Summary

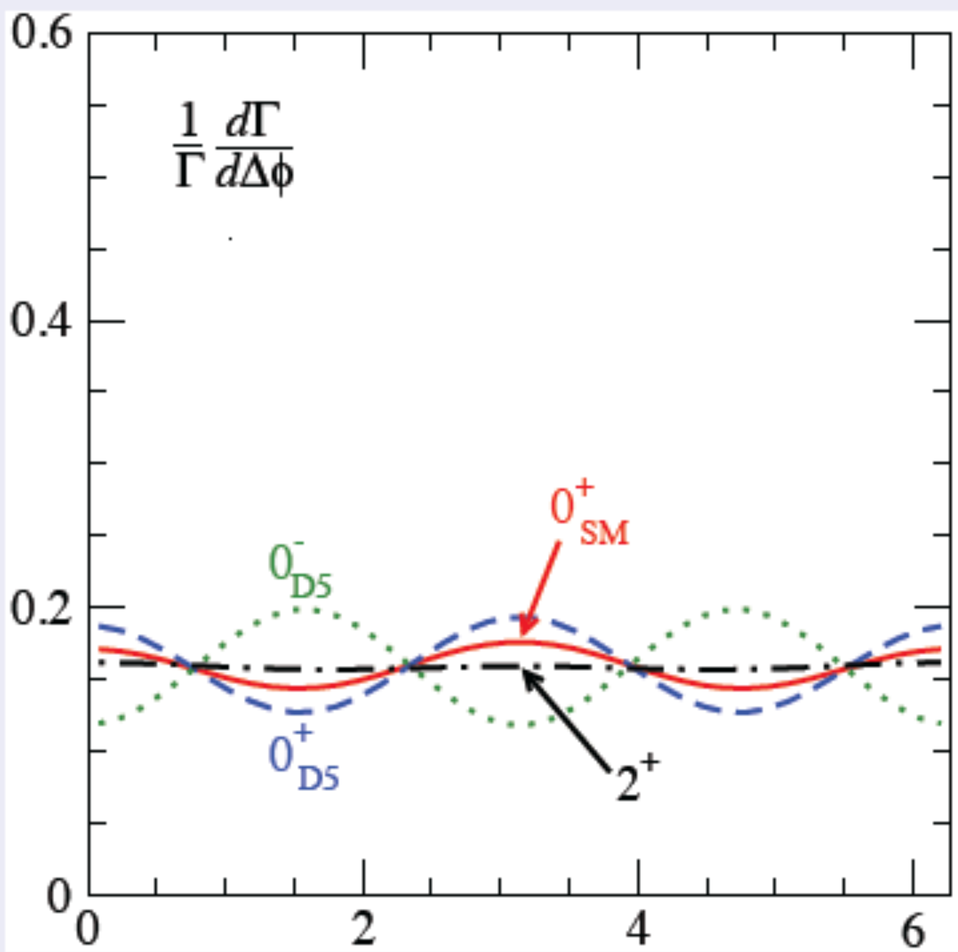
Spin/parity determination
$X \to VV^* \to 4l$

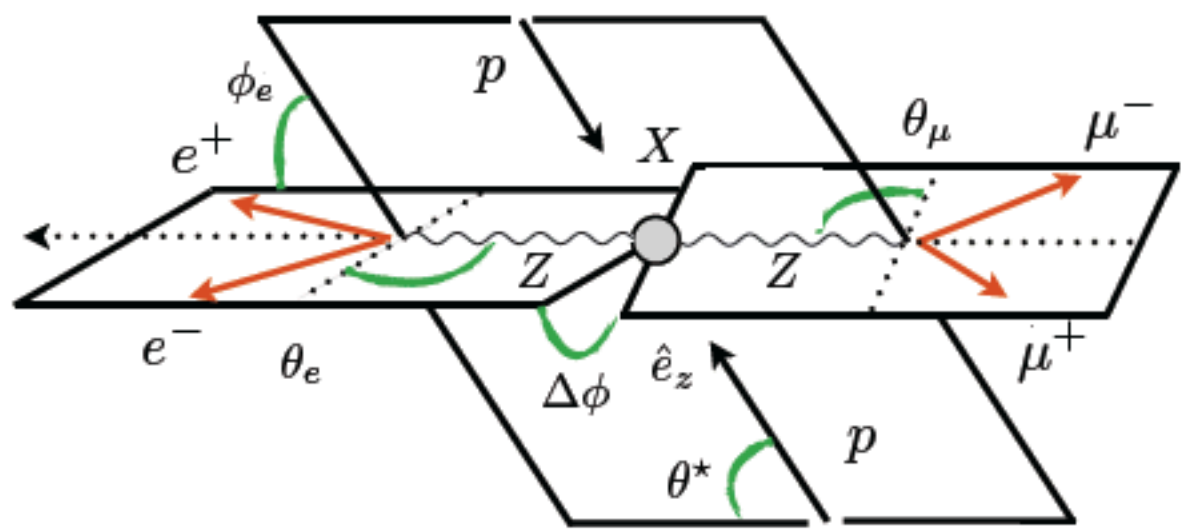
[Dell'Aquilla, Nelson, PRD(1986)]
[Choi, Miller, Mühlleitner, Zerwas, PLB(2003)]
[Gao et al, PRD(2010)] ...

[Bolognesi et al, PRD(2012)]

$$\mathcal{L}_{0^+_{\rm SM}} = g_{0^+_{\rm SM}} V_\mu V^\mu X_0$$
$$\mathcal{L}_{0^+_{\rm D5}} = g_{0^+_{\rm D5}} V_{\mu\nu} V^{\mu\nu} X_0$$
$$\mathcal{L}_{0^-_{\rm D5}} = g_{0^-_{\rm D5}} V_{\mu\nu} \widetilde{V}^{\mu\nu} X_0$$

$X \to ZZ^* \to 4\ell$





$$d\sigma/d\Delta\phi \sim \text{const. for } 0^+_{\rm SM}, \qquad d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi \text{ for } 0^\pm_{\rm D5}.$$

Spin/parity determination
X→VV*→4l vs. VBF

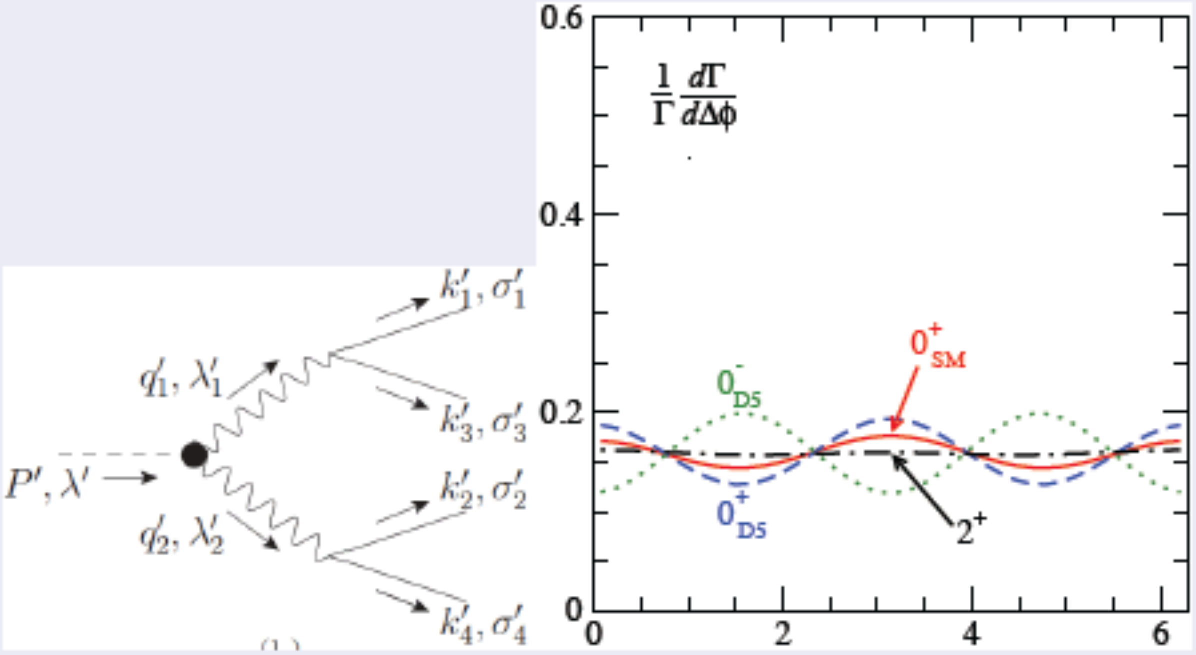
[Choi, Miller, Mühlleitner, Zerwas, PLB(2003)]
[Gao et al, PRD(2010)] ...

[Bolognesi et al, PRD(2012)]

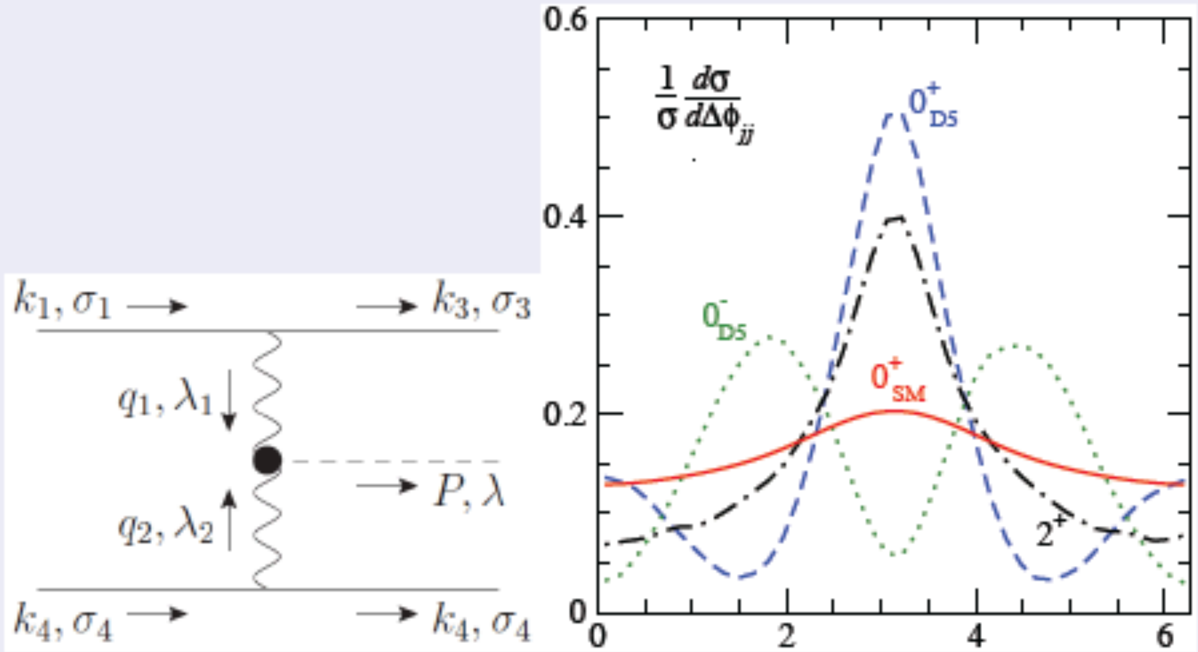
[Plehn, Rainwater, Zeppenfeld, PRL(2002)]
[Hagiwara, Li, KM, JHEP(2009)] ...

[Englert, Goncalves-Netto, KM, Plehn, JHEP(2013)]

$X \to ZZ^* \to 4\ell$



Vector boson fusion (VBF)



$$d\sigma/d\Delta\phi \sim \text{const. for } 0^+_{\mathrm{SM}}, \quad d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi \text{ for } 0^\pm_{\mathrm{D5}}.$$

Nontrivial azimuthal angle correlations of the decay planes ($X \to ZZ$) and the jets (VBF) can be explained as the quantum interference among different helicity states of the intermediate vector-bosons.

The SM cannot be the ultimate theory !

- 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

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?

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)

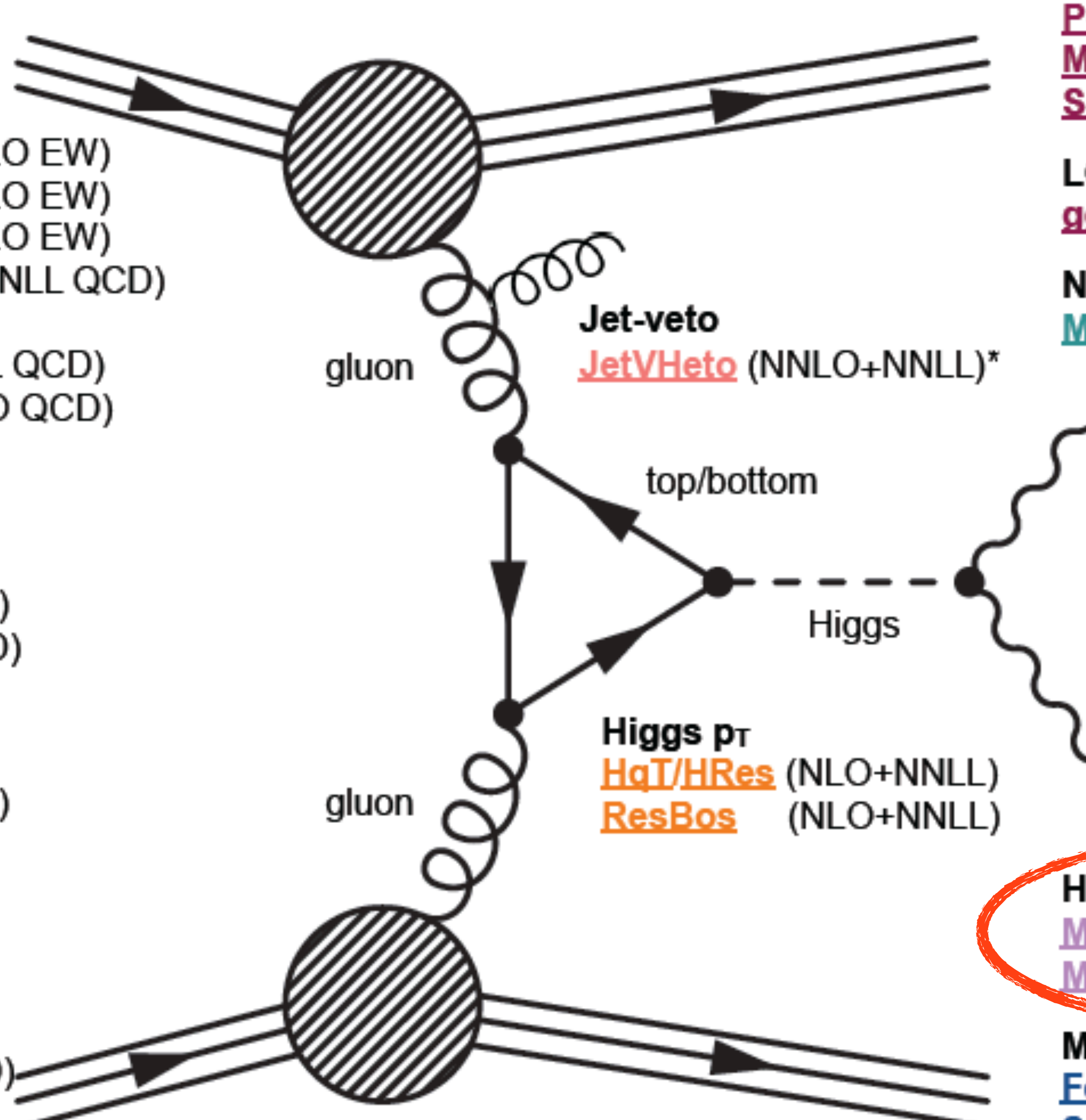
WH/ZH
V2HV (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

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

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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)
  - https://feynrules.irmp.ucl.ac.be/wiki/HEL
- D5 (the mass basis): HC [Artoisenet et al., arXiv:1306.6464]
  - Couplings of the physical Higgs boson to the Standard Model (physical) states
  - One operator associated with a single coupling (and Lorentz structure)
  - No assumption on the Higgs boson spin
  - https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

D6 Higgs Effective Lagrangian

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

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

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

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

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

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

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

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Mapping between the D6 and D5 operators

HC [arXiv: 1306.6464]

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

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

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

HEL [arXiv: 1310.5150]

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

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

Higgs Characterisation model

- We implemented an effective Lagrangian featuring bosons

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

in FeynRules.

- any-process, any-decay, any-observable
- 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.

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

Effective Lagrangian -- spin0

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

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

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

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

Effective Lagrangian -- spin0

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

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

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

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

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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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

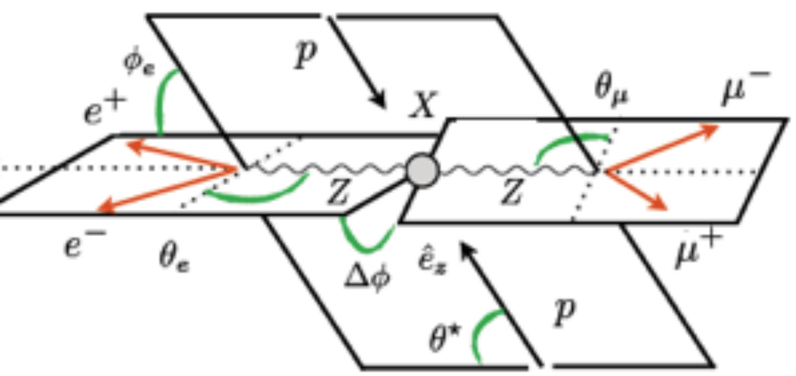
- HC.fr : the main model file.
- SM_HC.fr : This model requires the modified Standard Model implementation of FeynRules.
- Massless.rst, Cabibbo.rst : SM restriction files.
- HC.nb : this is an example Mathematica notebook that loads the model, calculates the Feynman rules and extract the model files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

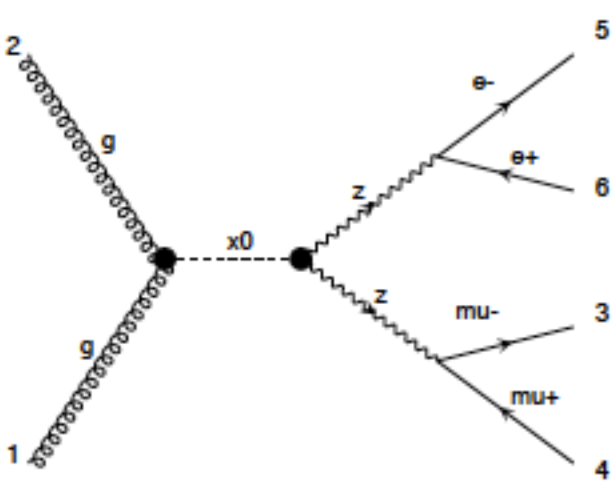
Model files for NLO (only for the J=0 case)

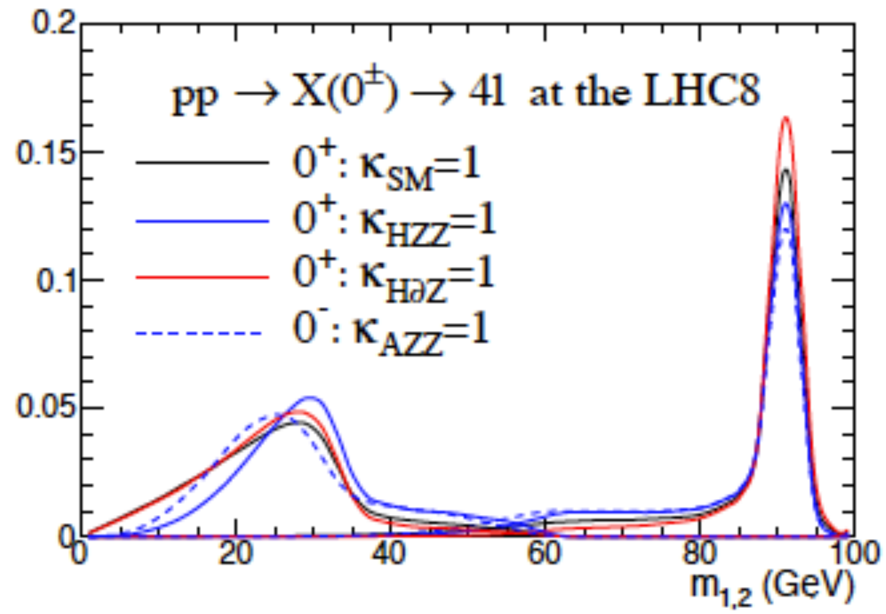
A few remarks before use; see the README file in the model.

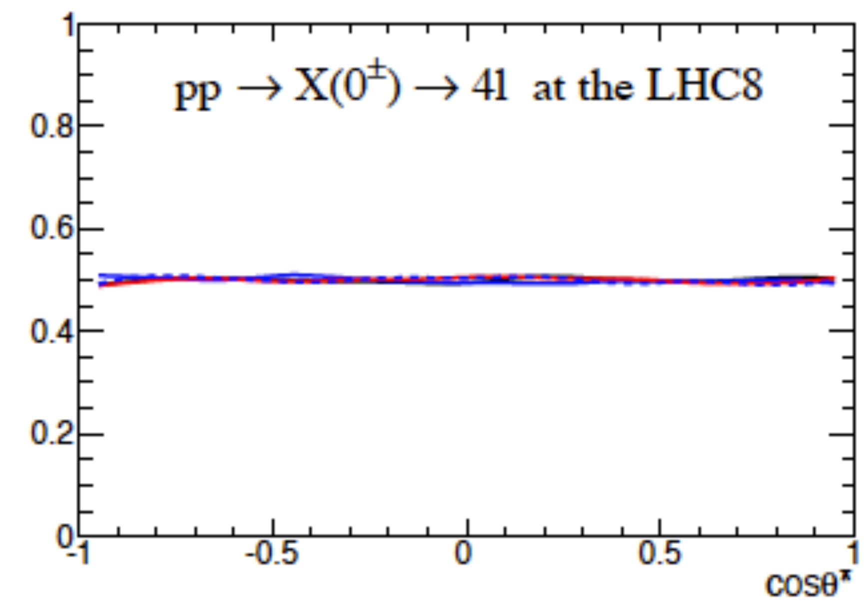
- HC_NLO_X0_UFO.zip : The model files in UFO format (for MadGraph5).

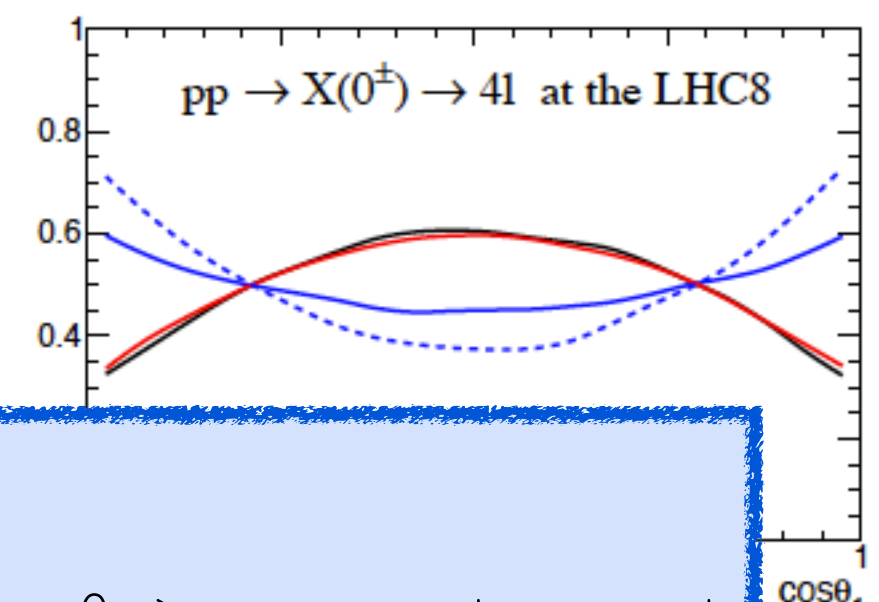
Mass and angular distributions -- spin0

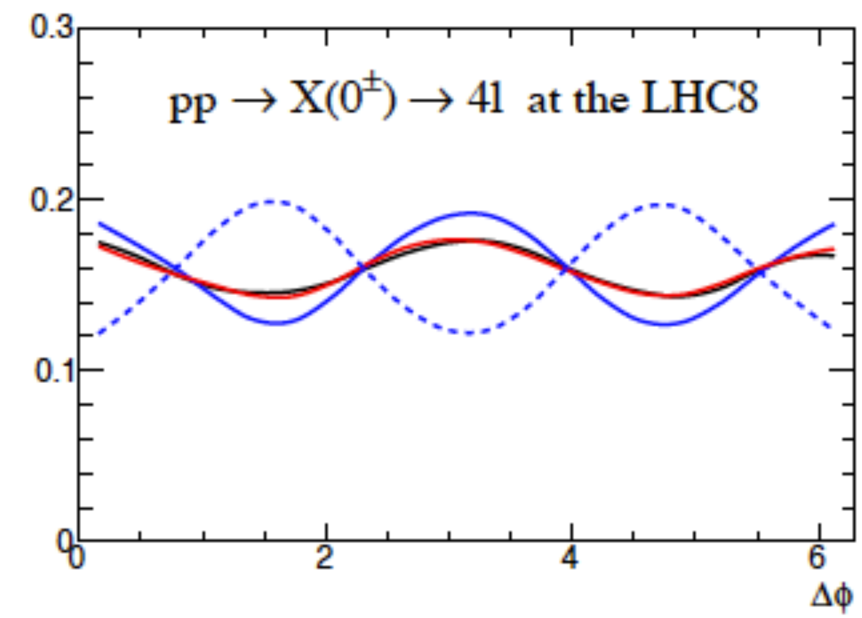













```
./bin/mg5_aMC
>import model HC
>generate p p > x0, x0 > mu- mu+ e- e+
>launch
```

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+ $\quad \kappa_{f_a} = \kappa_{V_1} = \kappa_{V_2} = \kappa_{V_3} = 0$

Effective Lagrangian -- spin2

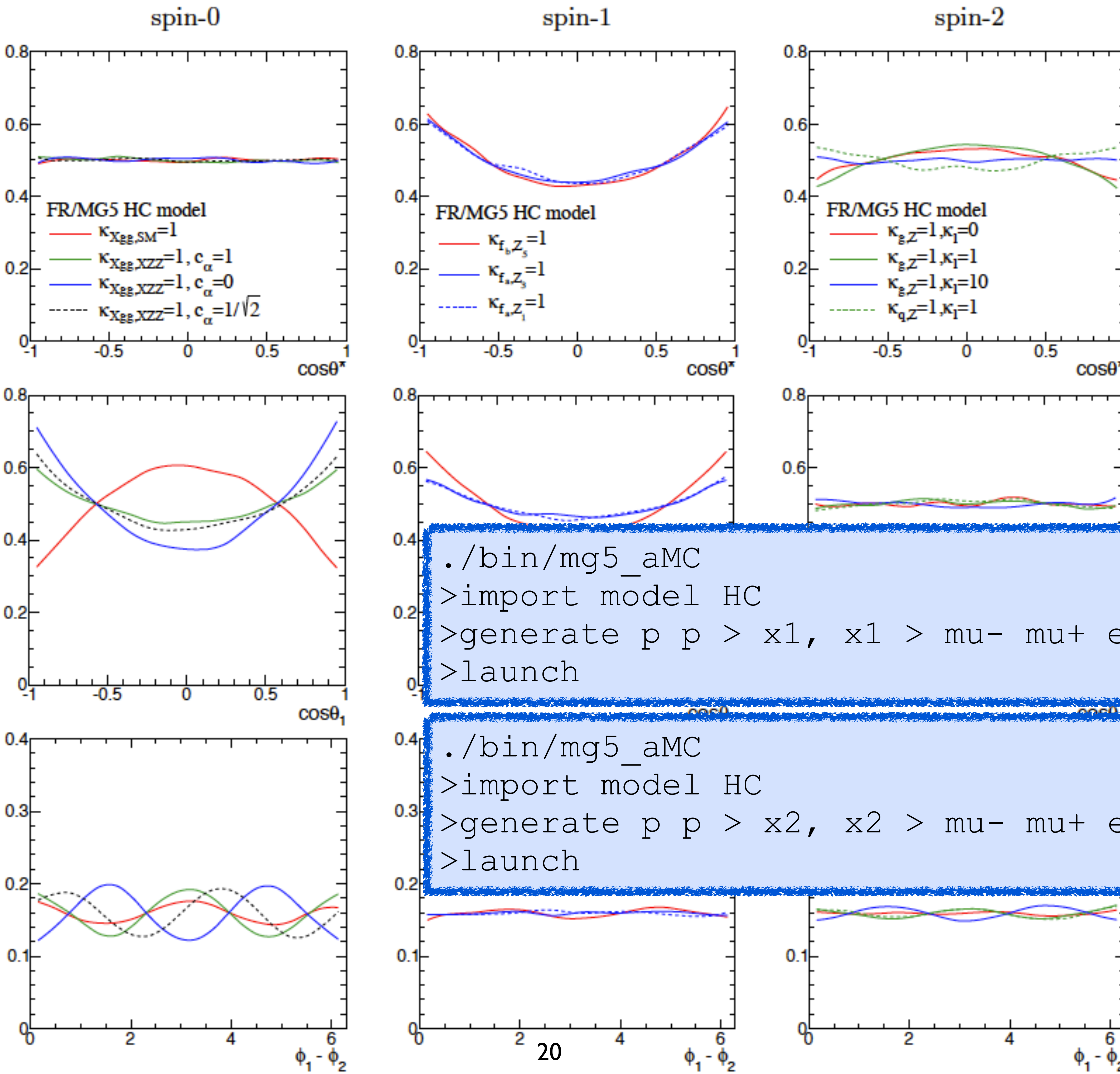
- via the energy-momentum tensor of the SM fields, starting from D5:

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

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

  - The E-M tensor for QED:

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

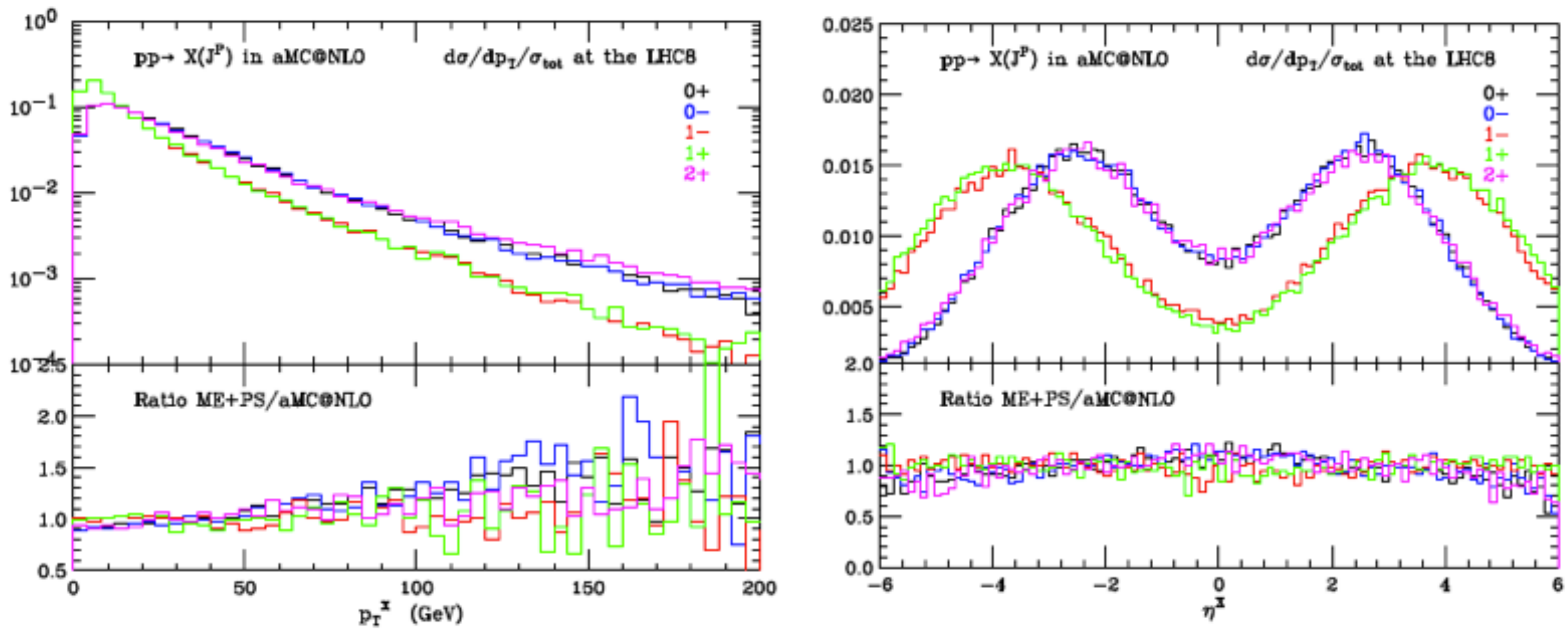



```
./bin/mg5_aMC
>import model HC
>generate p p > x1, x1 > mu- mu+ e- e+
>launch
```

```
./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]

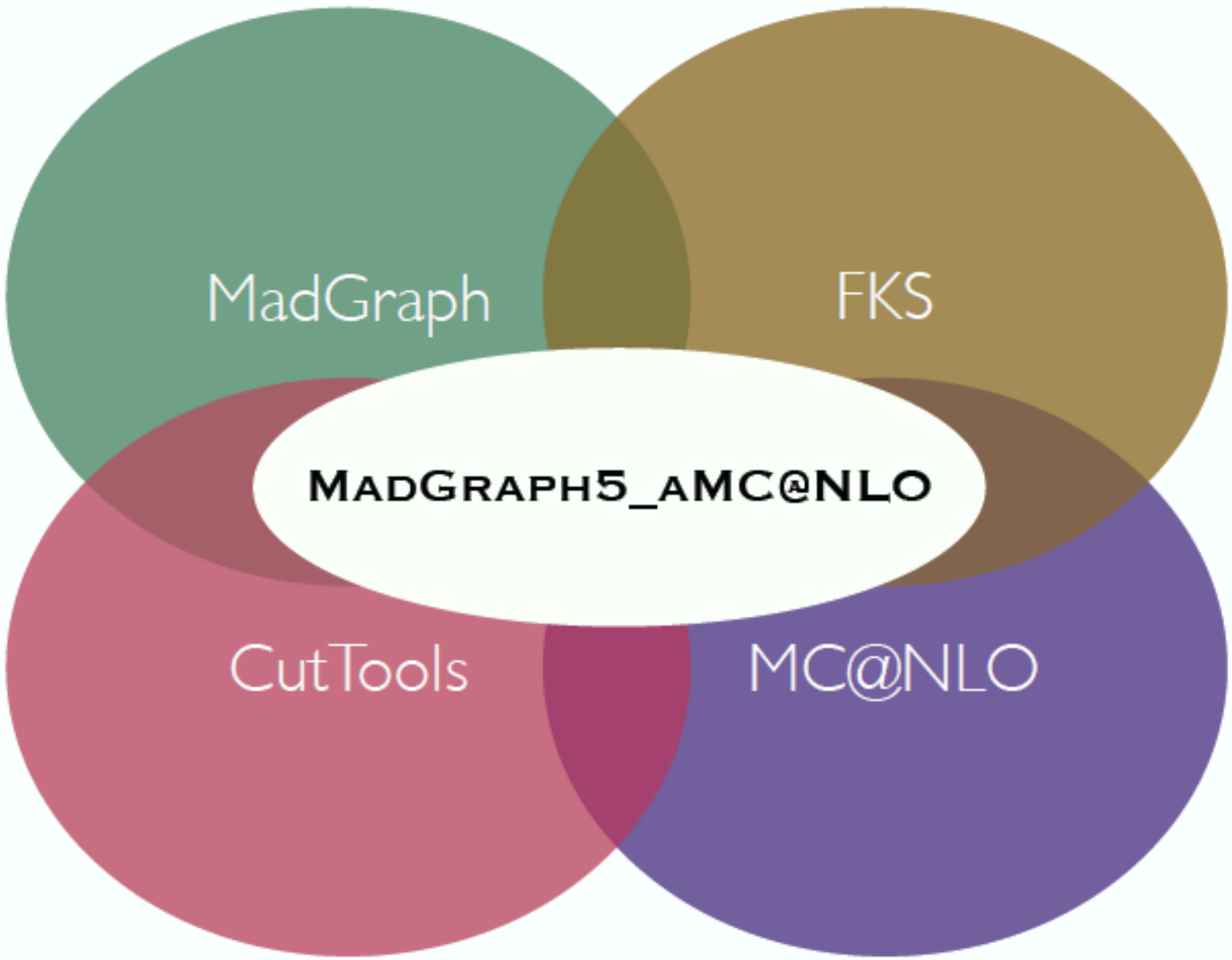


Good agreement between the ME+PS and aMC@NLO predictions for most observables.

MADGRAPH5_AMC@NLO

J. Alwall, R. Frederix, S. Frixione, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, V. Hirschi, MZ

arXiv:1405.0301



Marco Zaro, 19-05-2014 11 LHCPhenoNet

Process		Syntax	Cross section (pb)			
Vector boson +jets			LO 13 TeV		NLO 13 TeV	
a.1	$pp\to W^\pm$	p p > wpm	$1.375\pm0.002\cdot10^{5}$	$^{+15.4\%}_{-16.6\%}$ $^{+2.0\%}_{-1.6\%}$	$1.773\pm0.007\cdot10^{5}$	$^{+5.2\%}_{-9.4\%}$ $^{+1.9\%}_{-1.6\%}$
a.2	$pp\to W^\pm j$	p p > wpm j	$2.045\pm0.001\cdot10^{4}$	$^{+19.7\%}_{-17.2\%}$ $^{+1.4\%}_{-1.1\%}$	$2.843\pm0.010\cdot10^{4}$	$^{+5.9\%}_{-8.0\%}$ $^{+1.3\%}_{-1.1\%}$
a.3	$pp\to W^\pm jj$	p p > wpm j j	$6.805\pm0.015\cdot10^{3}$	$^{+24.5\%}_{-18.6\%}$ $^{+0.8\%}_{-0.7\%}$	$7.786\pm0.030\cdot10^{3}$	$^{+2.4\%}_{-6.0\%}$ $^{+0.9\%}_{-0.8\%}$
a.4	$pp\to W^\pm jjj$	p p > wpm j j j	$1.821\pm0.002\cdot10^{3}$	$^{+41.0\%}_{-27.1\%}$ $^{+0.5\%}_{-0.5\%}$	$2.005\pm0.008\cdot10^{3}$	$^{+0.9\%}_{-6.7\%}$ $^{+0.6\%}_{-0.5\%}$
a.5	$pp\to Z$	p p > z	$4.248\pm0.005\cdot10^{4}$	$^{+14.6\%}_{-15.8\%}$ [illegible]	$5.410\pm0.022\cdot10^{4}$	$^{+4.6\%}_{-8.6\%}$ $^{+1.9\%}_{-1.5\%}$
a.6	$pp\to Zj$	p p > z j	$7.209\pm0.005\cdot10^{3}$	$^{+19.3\%}_{-17.0\%}$ [illegible]	[illegible]	[illegible]
a.7	$pp\to Zjj$	p p > z j j	$2.348\pm0.006\cdot10^{3}$	$^{+24.3\%}_{-18.5\%}$ $^{+0.6\%}_{-0.6\%}$	[illegible]	[illegible]
a.8	$pp\to Zjjj$	p p > z j j j	$6.314\pm0.008\cdot10^{2}$	$^{+40.8\%}_{-27.0\%}$ $^{+0.5\%}_{-0.5\%}$	$6.996\pm0.028\cdot10^{2}$	$^{+1.1\%}_{-6.8\%}$ $^{+0.5\%}_{-0.5\%}$
a.9	$pp\to\gamma j$	p p > a j	$1.964\pm0.001\cdot10^{4}$	$^{+31.2\%}_{-26.0\%}$ $^{+1.7\%}_{-1.8\%}$	$5.218\pm0.025\cdot10^{4}$	$^{+24.5\%}_{-21.4\%}$ $^{+1.4\%}_{-1.6\%}$
a.10	$pp\to\gamma jj$	p p > a j j	$7.815\pm0.008\cdot10^{3}$	$^{+32.8\%}_{-24.2\%}$ $^{+0.9\%}_{-1.2\%}$	$1.004\pm0.004\cdot10^{4}$	$^{+5.9\%}_{-10.9\%}$ $^{+0.8\%}_{-1.2\%}$

Process		Syntax	Cross section (pb)			
Vector-boson pair +jets			LO 13 TeV		NLO 13 TeV	
b.1	$pp\to W^+W^-$ (4f)	p p > w+ w-	$7.355\pm0.005\cdot10^{1}$	$^{+5.0\%}_{-6.1\%}$ $^{+2.0\%}_{-1.5\%}$	$1.028\pm0.003\cdot10^{2}$	$^{+4.0\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$
b.2	$pp\to ZZ$	p p > z z	$1.097\pm0.002\cdot10^{1}$	$^{+4.5\%}_{-5.6\%}$ $^{+1.9\%}_{-1.5\%}$	$1.415\pm0.005\cdot10^{1}$	$^{+3.1\%}_{-3.7\%}$ $^{+1.8\%}_{-1.4\%}$
b.3	$pp\to ZW^\pm$	p p > z wpm	$2.777\pm0.003\cdot10^{1}$	$^{+3.6\%}_{-4.7\%}$ $^{+2.0\%}_{-1.5\%}$	$4.487\pm0.013\cdot10^{1}$	$^{+4.4\%}_{-4.4\%}$ $^{+1.7\%}_{-1.3\%}$
b.4	$pp\to\gamma\gamma$	p p > a a	$2.510\pm0.002\cdot10^{1}$	$^{+22.1\%}_{-22.4\%}$ $^{+2.4\%}_{-2.1\%}$	$6.593\pm0.021\cdot10^{1}$	$^{+17.6\%}_{-18.8\%}$ $^{+2.0\%}_{-1.9\%}$
b.5	$pp\to\gamma Z$	p p > a z	$2.523\pm0.004\cdot10^{1}$	$^{+9.9\%}_{-11.2\%}$ $^{+2.0\%}_{-1.6\%}$	$3.695\pm0.013\cdot10^{1}$	$^{+5.4\%}_{-7.1\%}$ $^{+1.8\%}_{-1.4\%}$
b.6	$pp\to\gamma W^\pm$	p p > a wpm	$2.954\pm0.005\cdot10^{1}$	$^{+9.5\%}_{-11.0\%}$ $^{+2.0\%}_{-1.7\%}$	$7.124\pm0.026\cdot10^{1}$	$^{+9.7\%}_{-9.9\%}$ $^{+1.5\%}_{-1.3\%}$
b.7	$pp\to W^+W^-j$ (4f)	p p > w+ w- j	$2.865\pm0.003\cdot10^{1}$	$^{+11.6\%}_{-10.0\%}$ $^{+1.0\%}_{-0.8\%}$	$3.730\pm0.013\cdot10^{1}$	$^{+4.9\%}_{-4.9\%}$ $^{+1.1\%}_{-0.8\%}$
b.8	$pp\to ZZj$	p p > z z j	$3.662\pm0.003\cdot10^{0}$	$^{+10.9\%}_{-9.3\%}$ $^{+1.0\%}_{-0.8\%}$	$4.830\pm0.016\cdot10^{0}$	$^{+5.0\%}_{-4.8\%}$ $^{+1.1\%}_{-0.9\%}$
b.9	$pp\to ZW^\pm j$	p p > z wpm j	$1.605\pm0.005\cdot10^{1}$	$^{+11.6\%}_{-10.0\%}$ $^{+0.9\%}_{-0.7\%}$	$2.086\pm0.007\cdot10^{1}$	$^{+4.9\%}_{-4.8\%}$ $^{+0.9\%}_{-0.7\%}$
b.10	$pp\to\gamma\gamma j$	p p > a a j	$1.022\pm0.001\cdot10^{1}$	$^{+20.3\%}_{-17.7\%}$ $^{+1.2\%}_{-1.5\%}$	$2.292\pm0.010\cdot10^{1}$	$^{+17.2\%}_{-15.1\%}$ $^{+1.0\%}_{-1.4\%}$
b.11*	$pp\to\gamma Zj$	p p > a z j	$8.310\pm0.017\cdot10^{0}$	$^{+14.5\%}_{-12.8\%}$ $^{+1.0\%}_{-1.0\%}$	$1.220\pm0.005\cdot10^{1}$	$^{+7.3\%}_{-7.4\%}$ $^{+0.9\%}_{-0.9\%}$
b.12*	$pp\to\gamma W^\pm j$	p p > a wpm j	$2.546\pm0.010\cdot10^{1}$	$^{+13.7\%}_{-12.1\%}$ $^{+0.9\%}_{-1.0\%}$	$3.713\pm0.015\cdot10^{1}$	$^{+7.2\%}_{-7.1\%}$ $^{+0.9\%}_{-1.0\%}$
b.13	$pp\to W^+W^+jj$	p p > w+ w+ j j	$1.484\pm0.006\cdot10^{-1}$	$^{+25.4\%}_{-18.9\%}$ $^{+2.1\%}_{-1.5\%}$	$2.251\pm0.011\cdot10^{-1}$	$^{+10.5\%}_{-10.6\%}$ $^{+2.2\%}_{-1.6\%}$
b.14	$pp\to W^-W^-jj$	p p > w- w- j j	$6.752\pm0.007\cdot10^{-2}$	[illegible]	[illegible]	[illegible]
b.15	$pp\to W^+W^-jj$ (4f)	p p > w+ w- j j	$1.144\pm0.002\cdot10^{1}$	[illegible]	[illegible]	[illegible]
b.16	$pp\to ZZjj$	p p > z z j j	$1.344\pm0.002\cdot10^{0}$	$^{+26.6\%}_{-19.6\%}$ $^{+0.7\%}_{-0.6\%}$	$1.706\pm0.011\cdot10^{0}$	[illegible]
b.17	$pp\to ZW^\pm jj$	p p > z wpm j j	$8.038\pm0.009\cdot10^{0}$	$^{+26.7\%}_{-19.7\%}$ $^{+0.7\%}_{-0.5\%}$	$9.139\pm0.031\cdot10^{0}$	$^{+3.1\%}_{-5.1\%}$ $^{+0.7\%}_{-0.5\%}$
b.18	$pp\to\gamma\gamma jj$	p p > a a j j	$5.377\pm0.029\cdot10^{0}$	$^{+26.2\%}_{-19.8\%}$ $^{+0.6\%}_{-1.0\%}$	$7.501\pm0.032\cdot10^{0}$	$^{+8.8\%}_{-10.1\%}$ $^{+0.6\%}_{-1.0\%}$
b.19*	$pp\to\gamma Zjj$	p p > a z j j	$3.260\pm0.009\cdot10^{0}$	$^{+24.3\%}_{-18.4\%}$ $^{+0.6\%}_{-0.6\%}$	$4.242\pm0.016\cdot10^{0}$	$^{+6.5\%}_{-7.3\%}$ $^{+0.6\%}_{-0.6\%}$
b.20*	$pp\to\gamma W^\pm jj$	p p > a wpm j j	$1.233\pm0.002\cdot10^{1}$	$^{+24.7\%}_{-18.6\%}$ $^{+0.6\%}_{-0.6\%}$	$1.448\pm0.005\cdot10^{1}$	$^{+3.6\%}_{-5.4\%}$ $^{+0.6\%}_{-0.7\%}$

Process		Syntax	Cross section (pb)			
Three vector bosons +jet			LO 13 TeV		NLO 13 TeV	
c.1	$pp\to W^+W^-W^\pm$ (4f)	p p > w+ w- wpm	$1.307\pm0.003\cdot10^{-1}$	$^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.5\%}$	$2.109\pm0.006\cdot10^{-1}$	$^{+5.1\%}_{-4.1\%}$ $^{+1.6\%}_{-1.2\%}$
c.2	$pp\to ZW^+W^-$ (4f)	p p > z w+ w-	$9.658\pm0.065\cdot10^{-2}$	$^{+0.8\%}_{-1.1\%}$ $^{+2.1\%}_{-1.6\%}$	$1.679\pm0.005\cdot10^{-1}$	$^{+6.3\%}_{-5.1\%}$ $^{+1.6\%}_{-1.2\%}$
c.3	$pp\to ZZW^\pm$	p p > z z wpm	$2.996\pm0.016\cdot10^{-2}$	$^{+1.0\%}_{-1.4\%}$ $^{+2.0\%}_{-1.6\%}$	$5.550\pm0.020\cdot10^{-2}$	$^{+6.8\%}_{-5.5\%}$ $^{+1.5\%}_{-1.1\%}$
c.4	$pp\to ZZZ$	p p > z z z	$1.085\pm0.002\cdot10^{-2}$	$^{+0.0\%}_{-0.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.417\pm0.005\cdot10^{-2}$	$^{+2.7\%}_{-2.1\%}$ $^{+1.9\%}_{-1.5\%}$
c.5	$pp\to\gamma W^+W^-$ (4f)	p p > a w+ w-	$1.427\pm0.011\cdot10^{-1}$	$^{+1.9\%}_{-2.6\%}$ $^{+2.0\%}_{-1.5\%}$	$2.581\pm0.008\cdot10^{-1}$	$^{+5.4\%}_{-4.2\%}$ $^{+1.4\%}_{-1.1\%}$
c.6	$pp\to\gamma\gamma W^\pm$	p p > a a wpm	$2.681\pm0.007\cdot10^{-2}$	$^{+4.4\%}_{-5.6\%}$ $^{+1.9\%}_{-1.6\%}$	$8.251\pm0.032\cdot10^{-2}$	$^{+7.6\%}_{-7.0\%}$ $^{+1.0\%}_{-1.0\%}$
c.7	$pp\to\gamma ZW^\pm$	p p > a z wpm	$4.994\pm0.011\cdot10^{-2}$	$^{+0.8\%}_{-1.4\%}$ $^{+1.9\%}_{-1.6\%}$	$1.117\pm0.004\cdot10^{-1}$	$^{+7.2\%}_{-5.9\%}$ $^{+1.2\%}_{-0.9\%}$
c.8	$pp\to\gamma ZZ$	p p > a z z	$2.320\pm0.005\cdot10^{-2}$	$^{+2.0\%}_{-2.9\%}$ $^{+1.9\%}_{-1.5\%}$	$3.118\pm0.012\cdot10^{-2}$	$^{+2.8\%}_{-2.7\%}$ $^{+1.8\%}_{-1.4\%}$
c.9	$pp\to\gamma\gamma Z$	p p > a a z	$3.078\pm0.007\cdot10^{-2}$	$^{+5.6\%}_{-6.8\%}$ $^{+1.9\%}_{-1.6\%}$	$4.634\pm0.020\cdot10^{-2}$	$^{+4.5\%}_{-5.0\%}$ $^{+1.7\%}_{-1.3\%}$
c.10	$pp\to\gamma\gamma\gamma$	p p > a a a	$1.269\pm0.003\cdot10^{-2}$	$^{+9.8\%}_{-11.0\%}$ $^{+2.0\%}_{-1.8\%}$	$3.441\pm0.012\cdot10^{-2}$	$^{+11.8\%}_{-11.6\%}$ $^{+1.4\%}_{-1.5\%}$
c.11	$pp\to W^+W^-W^\pm j$ (4f)	p p > w+ w- wpm j	$9.167\pm0.010\cdot10^{-2}$	$^{+15.0\%}_{-12.2\%}$ $^{+1.0\%}_{-0.7\%}$	$1.197\pm0.004\cdot10^{-1}$	$^{+5.2\%}_{-5.6\%}$ $^{+1.0\%}_{-0.8\%}$
c.12*	$pp\to ZW^+W^-j$ (4f)	p p > z w+ w- j	$8.340\pm0.010\cdot10^{-2}$	$^{+15.6\%}_{-12.6\%}$ $^{+1.0\%}_{-0.7\%}$	$1.066\pm0.003\cdot10^{-1}$	$^{+4.5\%}_{-5.2\%}$ $^{+1.0\%}_{-0.7\%}$
c.13*	$pp\to ZZW^\pm j$	p p > z z wpm j	$2.810\pm0.004\cdot10^{-2}$	$^{+16.1\%}_{-13.0\%}$ $^{+1.0\%}_{-0.7\%}$	$3.660\pm0.013\cdot10^{-2}$	$^{+4.8\%}_{-5.6\%}$ $^{+1.0\%}_{-0.7\%}$
c.14*	$pp\to ZZZj$	p p > z z z j	$4.823\pm0.011\cdot10^{-3}$	$^{+14.2\%}_{-11.8\%}$ $^{+1.4\%}_{-1.0\%}$	$6.341\pm0.025\cdot10^{-3}$	$^{+4.9\%}_{-5.4\%}$ $^{+1.4\%}_{-1.0\%}$
c.15*	$pp\to\gamma W^+W^-j$ (4f)	p p > a w+ w- j	$1.182\pm0.004\cdot10^{-1}$	$^{+13.4\%}_{-11.2\%}$ $^{+0.8\%}_{-0.7\%}$	$1.233\pm0.004\cdot10^{2}$	$^{+18.9\%}_{-19.9\%}$ $^{+1.0\%}_{-1.5\%}$
c.16	$pp\to\gamma\gamma W^\pm j$	p p > a a wpm j	$4.107\pm0.015\cdot10^{-2}$	$^{+11.8\%}_{-10.2\%}$ $^{+0.6\%}_{-0.8\%}$	$5.807\pm0.023\cdot10^{-2}$	$^{+5.8\%}_{-5.5\%}$ $^{+0.7\%}_{-0.7\%}$
c.17*	$pp\to\gamma ZW^\pm j$	p p > a z wpm j	$5.833\pm0.023\cdot10^{-2}$	$^{+14.4\%}_{-12.0\%}$ $^{+0.7\%}_{-0.6\%}$	$7.764\pm0.025\cdot10^{-2}$	$^{+5.1\%}_{-5.5\%}$ $^{+0.8\%}_{-0.6\%}$
[illegible]	[illegible]	[illegible] j	$9.995\pm0.013\cdot10^{-3}$	$^{+12.5\%}_{-10.6\%}$ $^{+1.2\%}_{-0.9\%}$	$1.371\pm0.005\cdot10^{-2}$	$^{+5.6\%}_{-5.5\%}$ $^{+1.2\%}_{-0.9\%}$
c.19*	$pp\to\gamma\gamma Zj$	p p > a a z j	$1.372\pm0.003\cdot10^{-2}$	$^{+10.9\%}_{-9.4\%}$ $^{+1.0\%}_{-0.9\%}$	$2.051\pm0.011\cdot10^{-2}$	$^{+7.0\%}_{-6.2\%}$ $^{+1.0\%}_{-0.9\%}$

Process		Syntax	Cross section (pb)			
Four vector bosons			LO 13 TeV		NLO 13 TeV	
c.21*	$pp\to W^+W^-W^+W^-$ (4f)	p p > w+ w- w+ w-	$5.721\pm0.014\cdot10^{-4}$	$^{+2.7\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$9.959\pm0.035\cdot10^{-4}$	$^{+7.4\%}_{-6.0\%}$ $^{+1.7\%}_{-1.2\%}$
c.22*	$pp\to W^+W^-W^\pm Z$ (4f)	p p > w+ w- wpm z	$6.391\pm0.076\cdot10^{-4}$	$^{+4.4\%}_{-4.1\%}$ $^{+2.4\%}_{-1.8\%}$	$1.188\pm0.004\cdot10^{-3}$	$^{+8.4\%}_{-6.8\%}$ $^{+1.7\%}_{-1.2\%}$
c.23*	$pp\to W^+W^-W^\pm\gamma$ (4f)	p p > w+ w- wpm a	$8.115\pm0.064\cdot10^{-4}$	$^{+2.5\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.546\pm0.005\cdot10^{-3}$	$^{+7.9\%}_{-6.2\%}$ $^{+1.5\%}_{-1.1\%}$
c.24*	$pp\to W^+W^-ZZ$ (4f)	p p > w+ w- z z	$4.320\pm0.013\cdot10^{-4}$	$^{+4.4\%}_{-4.1\%}$ $^{+2.4\%}_{-1.7\%}$	$7.107\pm0.020\cdot10^{-4}$	$^{+7.0\%}_{-5.7\%}$ $^{+1.8\%}_{-1.2\%}$
c.25*	$pp\to W^+W^-Z\gamma$ (4f)	p p > w+ w- z a	$8.403\pm0.016\cdot10^{-4}$	$^{+3.0\%}_{-2.9\%}$ $^{+2.2\%}_{-1.7\%}$	$1.483\pm0.004\cdot10^{-3}$	$^{+7.2\%}_{-5.8\%}$ $^{+1.6\%}_{-1.2\%}$
c.26*	$pp\to W^+W^-\gamma\gamma$ (4f)	p p > w+ w- a a	$5.198\pm0.012\cdot10^{-4}$	$^{+0.6\%}_{-0.9\%}$ $^{+2.1\%}_{-1.6\%}$	$9.381\pm0.032\cdot10^{-4}$	$^{+6.7\%}_{-5.2\%}$ $^{+1.4\%}_{-1.1\%}$
c.27*	$pp\to W^\pm ZZ$	p p > wpm z z	$5.862\pm0.010\cdot10^{-5}$	$^{+5.1\%}_{-4.7\%}$ $^{+2.4\%}_{-1.8\%}$	$1.240\pm0.004\cdot10^{-4}$	$^{+9.9\%}_{-8.0\%}$ $^{+1.7\%}_{-1.2\%}$
c.28*	$pp\to W^\pm ZZ\gamma$	p p > wpm z z a	$1.148\pm0.003\cdot10^{-4}$	$^{+2.6\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$2.945\pm0.008\cdot10^{-4}$	$^{+10.8\%}_{-8.7\%}$ $^{+1.2\%}_{-1.0\%}$
c.29*	$pp\to W^\pm Z\gamma\gamma$	p p > wpm z a a	$1.054\pm0.004\cdot10^{-4}$	$^{+1.7\%}_{-1.9\%}$ $^{+2.1\%}_{-1.7\%}$	$3.033\pm0.010\cdot10^{-4}$	$^{+10.6\%}_{-8.6\%}$ $^{+1.1\%}_{-0.8\%}$
c.30*	$pp\to W^\pm\gamma\gamma\gamma$	p p > wpm a a a	$3.600\pm0.013\cdot10^{-5}$	$^{+0.4\%}_{-1.0\%}$ $^{+2.0\%}_{-1.6\%}$	$1.246\pm0.005\cdot10^{-4}$	$^{+9.8\%}_{-8.1\%}$ $^{+0.9\%}_{-0.8\%}$
c.31*	$pp\to ZZZZ$	p p > z z z z	$1.989\pm0.002\cdot10^{-5}$	$^{+2.8\%}_{-2.6\%}$ $^{+2.2\%}_{-1.7\%}$	$2.629\pm0.008\cdot10^{-5}$	$^{+2.5\%}_{-2.0\%}$ $^{+2.2\%}_{-1.7\%}$
c.32*	$pp\to ZZZ\gamma$	p p > z z z a	$3.945\pm0.007\cdot10^{-5}$	$^{+1.9\%}_{-2.1\%}$ $^{+2.1\%}_{-1.6\%}$	$5.224\pm0.016\cdot10^{-5}$	$^{+2.2\%}_{-2.7\%}$ $^{+2.1\%}_{-1.6\%}$
c.33*	$pp\to ZZ\gamma\gamma$	p p > z z a a	$5.513\pm0.017\cdot10^{-5}$	$^{+0.0\%}_{-0.2\%}$ $^{+2.1\%}_{-1.6\%}$	$7.518\pm0.032\cdot10^{-5}$	$^{+2.4\%}_{-2.6\%}$ $^{+2.0\%}_{-1.5\%}$
c.34*	$pp\to Z\gamma\gamma\gamma$	p p > z a a a	$4.790\pm0.012\cdot10^{-5}$	$^{+2.2\%}_{-3.1\%}$ $^{+2.0\%}_{-1.6\%}$	$7.103\pm0.026\cdot10^{-5}$	$^{+2.4\%}_{-2.2\%}$ $^{+1.6\%}_{-1.5\%}$
c.35*	$pp\to\gamma\gamma\gamma\gamma$	p p > a a a a	$1.594\pm0.004\cdot10^{-5}$	$^{+4.7\%}_{-5.7\%}$ $^{+1.9\%}_{-1.7\%}$	$3.389\pm0.012\cdot10^{-5}$	$^{+7.0\%}_{-6.7\%}$ $^{+1.2\%}_{-1.2\%}$

Process		Syntax	Cross section (pb)			
Heavy quarks and jets			LO 13 TeV		NLO 13 TeV	
d.1	$pp\to jj$	p p > j j	$1.162\pm0.001\cdot10^{6}$	$^{+24.9\%}_{-18.8\%}$ $^{+0.8\%}_{-0.9\%}$	$1.580\pm0.007\cdot10^{6}$	$^{+8.4\%}_{-9.0\%}$ $^{+0.7\%}_{-0.9\%}$
d.2	$pp\to jjj$	p p > j j j	$8.940\pm0.021\cdot10^{4}$	$^{+42.8\%}_{-28.4\%}$ $^{+1.2\%}_{-1.4\%}$	$7.791\pm0.037\cdot10^{4}$	$^{+2.1\%}_{-22.2\%}$ $^{+1.1\%}_{-1.2\%}$
d.3	$pp\to b\bar b$ (4f)	p p > b b~	$3.743\pm0.004\cdot10^{3}$	$^{+25.2\%}_{-18.9\%}$ $^{+1.5\%}_{-1.8\%}$	$6.438\pm0.028\cdot10^{3}$	$^{+15.9\%}_{-13.2\%}$ $^{+1.5\%}_{-1.7\%}$
d.4*	$pp\to b\bar bj$ (4f)	p p > b b~ j	$1.050\pm0.002\cdot10^{3}$	$^{+44.1\%}_{-28.5\%}$ $^{+1.6\%}_{-1.8\%}$	$1.327\pm0.007\cdot10^{3}$	$^{+6.8\%}_{-11.6\%}$ $^{+1.5\%}_{-1.8\%}$
d.5*	$pp\to b\bar bjj$ (4f)	p p > b b~ j j	$1.852\pm0.006\cdot10^{2}$	$^{+61.8\%}_{-35.6\%}$ $^{+2.1\%}_{-2.4\%}$	$2.471\pm0.012\cdot10^{2}$	$^{+8.2\%}_{-16.4\%}$ $^{+2.0\%}_{-2.3\%}$
d.6	$pp\to b\bar bb\bar b$ (4f)	p p > b b~ b b~	$5.050\pm0.007\cdot10^{-1}$	$^{+61.7\%}_{-35.6\%}$ $^{+2.9\%}_{-3.4\%}$	$8.736\pm0.034\cdot10^{-1}$	$^{+20.9\%}_{-22.0\%}$ $^{+2.9\%}_{-3.4\%}$
d.7	$pp\to t\bar t$	p p > t t~	$4.584\pm0.003\cdot10^{2}$	$^{+29.0\%}_{-21.1\%}$ $^{+1.8\%}_{-2.0\%}$	$6.741\pm0.023\cdot10^{2}$	$^{+9.8\%}_{-10.9\%}$ $^{+1.8\%}_{-2.1\%}$
d.8	$pp\to t\bar tj$	p p > t t~ j	$3.135\pm0.002\cdot10^{2}$	$^{+45.1\%}_{-29.0\%}$ $^{+2.2\%}_{-2.5\%}$	$4.106\pm0.015\cdot10^{2}$	$^{+8.1\%}_{-12.2\%}$ $^{+2.1\%}_{-2.5\%}$
d.9	$pp\to t\bar tjj$	p p > t t~ j j	$1.361\pm0.001\cdot10^{2}$	$^{+61.4\%}_{-35.6\%}$ $^{+2.6\%}_{-3.0\%}$	$1.795\pm0.006\cdot10^{2}$	$^{+9.2\%}_{-16.1\%}$ $^{+2.4\%}_{-2.9\%}$
d.10	$pp\to t\bar tt\bar t$	p p > t t~ t t~	$4.505\pm0.005\cdot10^{-3}$	$^{+63.8\%}_{-36.5\%}$ $^{+5.4\%}_{-5.7\%}$	$9.201\pm0.028\cdot10^{-3}$	$^{+30.8\%}_{-25.6\%}$ $^{+5.5\%}_{-5.9\%}$
d.11	$pp\to t\bar tb\bar b$ (4f)	p p > t t~ b b~	$6.119\pm0.004\cdot10^{0}$	$^{+62.1\%}_{-35.7\%}$ $^{+2.9\%}_{-3.5\%}$	$1.452\pm0.005\cdot10^{1}$	$^{+37.6\%}_{-27.5\%}$ $^{+2.9\%}_{-3.5\%}$

Process		Syntax	Cross section (pb)			
Heavy quarks+vector bosons			LO 13 TeV		NLO 13 TeV	
e.1	$pp\to W^\pm b\bar b$ (4f)	p p > wpm b b~	$3.074\pm0.002\cdot10^{2}$	$^{+42.3\%}_{-29.2\%}$ $^{+2.0\%}_{-1.6\%}$	$8.162\pm0.034\cdot10^{2}$	$^{+29.8\%}_{-22.6\%}$ $^{+1.5\%}_{-1.2\%}$
e.2	$pp\to Zb\bar b$ (4f)	p p > z b b~	$6.993\pm0.003\cdot10^{2}$	$^{+33.5\%}_{-24.4\%}$ $^{+1.0\%}_{-1.4\%}$	$1.235\pm0.004\cdot10^{3}$	$^{+19.9\%}_{-17.4\%}$ $^{+1.0\%}_{-1.4\%}$
e.3	$pp\to\gamma b\bar b$ (4f)	p p > a b b~	$1.731\pm0.001\cdot10^{3}$	$^{+51.9\%}_{-34.8\%}$ $^{+1.6\%}_{-2.1\%}$	$4.171\pm0.015\cdot10^{3}$	$^{+22.7\%}_{-27.1\%}$ $^{+1.4\%}_{-1.9\%}$
e.4*	$pp\to W^\pm b\bar bj$ (4f)	p p > wpm b b~ j	$1.861\pm0.003\cdot10^{2}$	$^{+42.5\%}_{-27.7\%}$ $^{+0.7\%}_{-0.7\%}$	$3.957\pm0.013\cdot10^{2}$	$^{+27.0\%}_{-21.0\%}$ $^{+0.7\%}_{-0.6\%}$
e.5*	$pp\to Zb\bar bj$ (4f)	p p > z b b~ j	$1.604\pm0.001\cdot10^{2}$	$^{+42.4\%}_{-27.6\%}$ $^{+0.9\%}_{-1.1\%}$	$2.805\pm0.009\cdot10^{2}$	$^{+21.0\%}_{-17.6\%}$ $^{+0.8\%}_{-1.0\%}$
e.6*	$pp\to\gamma b\bar bj$ (4f)	p p > a b b~ j	$7.812\pm0.017\cdot10^{2}$	$^{+51.2\%}_{-32.0\%}$ $^{+1.0\%}_{-1.5\%}$	$1.233\pm0.004\cdot10^{3}$	$^{+18.9\%}_{-19.9\%}$ $^{+1.0\%}_{-1.5\%}$
e.7	$pp\to t\bar tW^\pm$	p p > t t~ wpm	$3.777\pm0.003\cdot10^{-1}$	$^{+23.9\%}_{-18.0\%}$ $^{+2.1\%}_{-1.6\%}$	$5.662\pm0.021\cdot10^{-1}$	$^{+11.2\%}_{-10.6\%}$ $^{+1.7\%}_{-1.2\%}$
e.8	$pp\to t\bar tZ$	p p > t t~ z	$5.273\pm0.004\cdot10^{-1}$	$^{+30.5\%}_{-21.8\%}$ $^{+1.8\%}_{-2.1\%}$	$7.598\pm0.026\cdot10^{-1}$	$^{+9.7\%}_{-11.1\%}$ $^{+1.9\%}_{-2.2\%}$
e.9	$pp\to t\bar t\gamma$	p p > t t~ a	$1.204\pm0.001\cdot10^{0}$	$^{+29.6\%}_{-21.3\%}$ $^{+1.6\%}_{-1.8\%}$	$1.744\pm0.005\cdot10^{0}$	$^{+9.8\%}_{-11.0\%}$ $^{+1.7\%}_{-2.0\%}$
e.10*	$pp\to t\bar tW^\pm j$	p p > t t~ wpm j	$2.352\pm0.002\cdot10^{-1}$	$^{+40.9\%}_{-27.1\%}$ $^{+1.2\%}_{-1.0\%}$	$3.404\pm0.011\cdot10^{-1}$	$^{+11.2\%}_{-14.0\%}$ $^{+1.2\%}_{-0.9\%}$
e.11*	$pp\to t\bar tZj$	p p > t t~ z j	$3.953\pm0.004\cdot10^{-1}$	$^{+46.2\%}_{-29.5\%}$ $^{+2.7\%}_{-3.0\%}$	$5.074\pm0.016\cdot10^{-1}$	$^{+7.0\%}_{-12.9\%}$ $^{+2.5\%}_{-2.9\%}$
e.12*	$pp\to t\bar t\gamma j$	p p > t t~ a j	$8.726\pm0.010\cdot10^{-1}$	$^{+45.4\%}_{-29.1\%}$ $^{+2.2\%}_{-2.6\%}$	$1.135\pm0.004\cdot10^{0}$	$^{+7.5\%}_{-12.2\%}$ $^{+2.2\%}_{-2.5\%}$
e.13*	$pp\to t\bar tW^-W^+$ (4f)	p p > t t~ w+ w-	$6.675\pm0.006\cdot10^{-3}$	$^{+30.9\%}_{-21.9\%}$ $^{+2.1\%}_{-2.0\%}$	$9.904\pm0.026\cdot10^{-3}$	$^{+10.9\%}_{-11.8\%}$ $^{+2.1\%}_{-2.1\%}$
e.14*	$pp\to t\bar tW^\pm Z$	p p > t t~ wpm z	$2.404\pm0.002\cdot10^{-3}$	$^{+26.6\%}_{-19.6\%}$ $^{+2.5\%}_{-1.8\%}$	$3.525\pm0.010\cdot10^{-3}$	$^{+10.6\%}_{-10.8\%}$ $^{+2.3\%}_{-1.6\%}$
e.15*	$pp\to t\bar tW^\pm\gamma$	p p > t t~ wpm a	$2.718\pm0.003\cdot10^{-3}$	$^{+25.4\%}_{-18.9\%}$ $^{+2.3\%}_{-1.8\%}$	$3.927\pm0.013\cdot10^{-3}$	$^{+10.3\%}_{-10.4\%}$ $^{+2.0\%}_{-1.5\%}$
e.16*	$pp\to t\bar tZZ$	p p > t t~ z z	$1.349\pm0.014\cdot10^{-3}$	$^{+29.3\%}_{-21.1\%}$ $^{+1.7\%}_{-1.5\%}$	$1.840\pm0.007\cdot10^{-3}$	$^{+7.9\%}_{-9.9\%}$ $^{+1.7\%}_{-1.5\%}$
e.17*	$pp\to t\bar tZ\gamma$	p p > t t~ z a	$2.548\pm0.003\cdot10^{-3}$	$^{+30.1\%}_{-21.5\%}$ $^{+1.7\%}_{-1.6\%}$	$3.656\pm0.012\cdot10^{-3}$	$^{+9.7\%}_{-11.0\%}$ $^{+1.8\%}_{-1.9\%}$
e.18*	$pp\to t\bar t\gamma\gamma$	p p > t t~ a a	$3.272\pm0.006\cdot10^{-3}$	$^{+28.4\%}_{-20.6\%}$ $^{+1.3\%}_{-1.1\%}$	$4.402\pm0.015\cdot10^{-3}$	$^{+7.8\%}_{-9.7\%}$ $^{+1.4\%}_{-1.4\%}$

Process		Syntax	Cross section (pb)			
Single-top			LO 13 TeV		NLO 13 TeV	
f.1	$pp\to tj$ (t-channel)	p p > tt j $$ w+ w-	$1.520\pm0.001\cdot10^{2}$	$^{+9.4\%}$ $^{+0.4\%}$ [illegible]	$1.563\pm0.006\cdot10^{2}$	$^{+1.4\%}$ $^{+0.4\%}$ [illegible]

Automation? Yes!

to be continued...

Marco Zaro, 09-05-2014

13

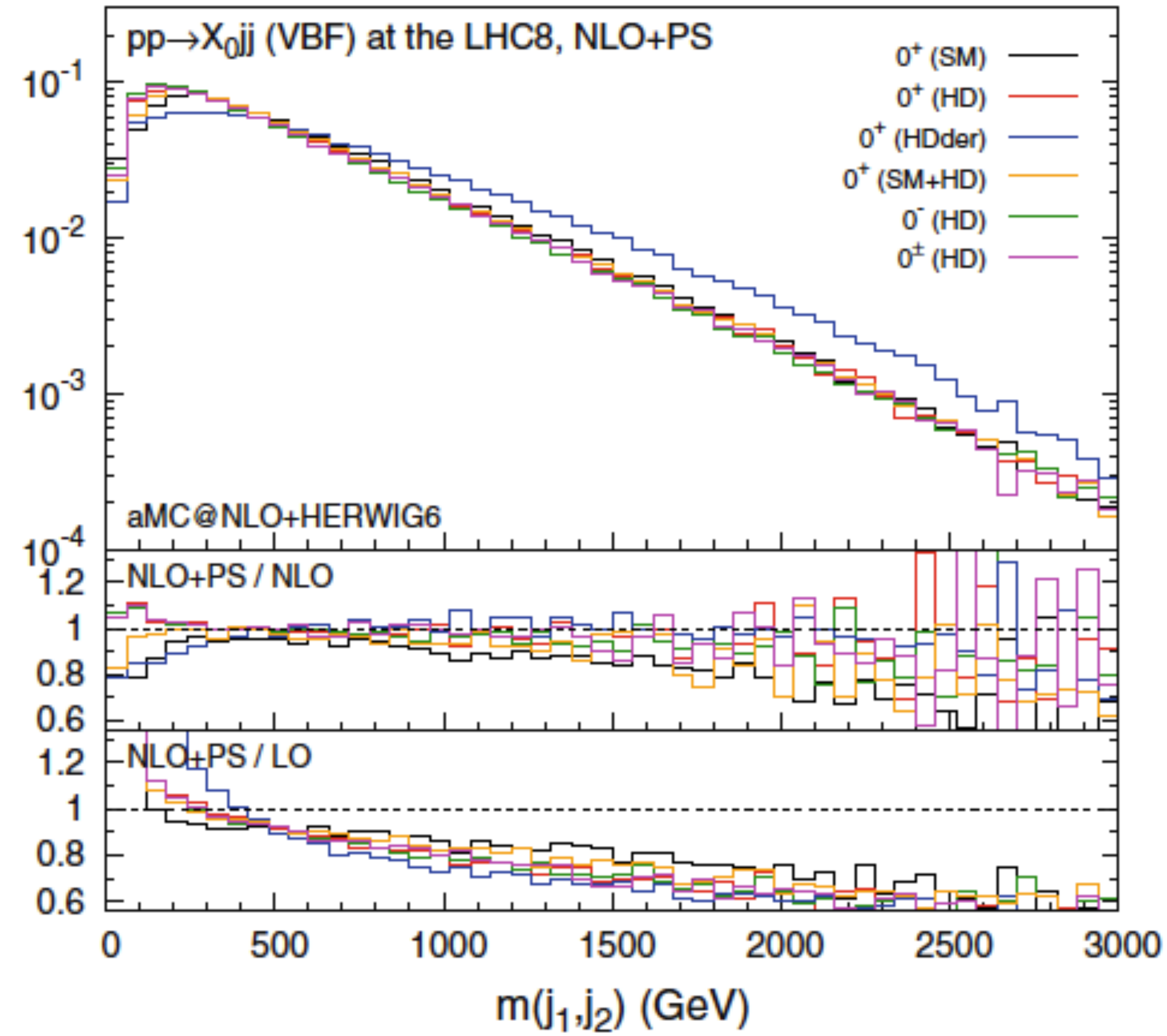
LHCPhenoNet

Mjj distributions

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

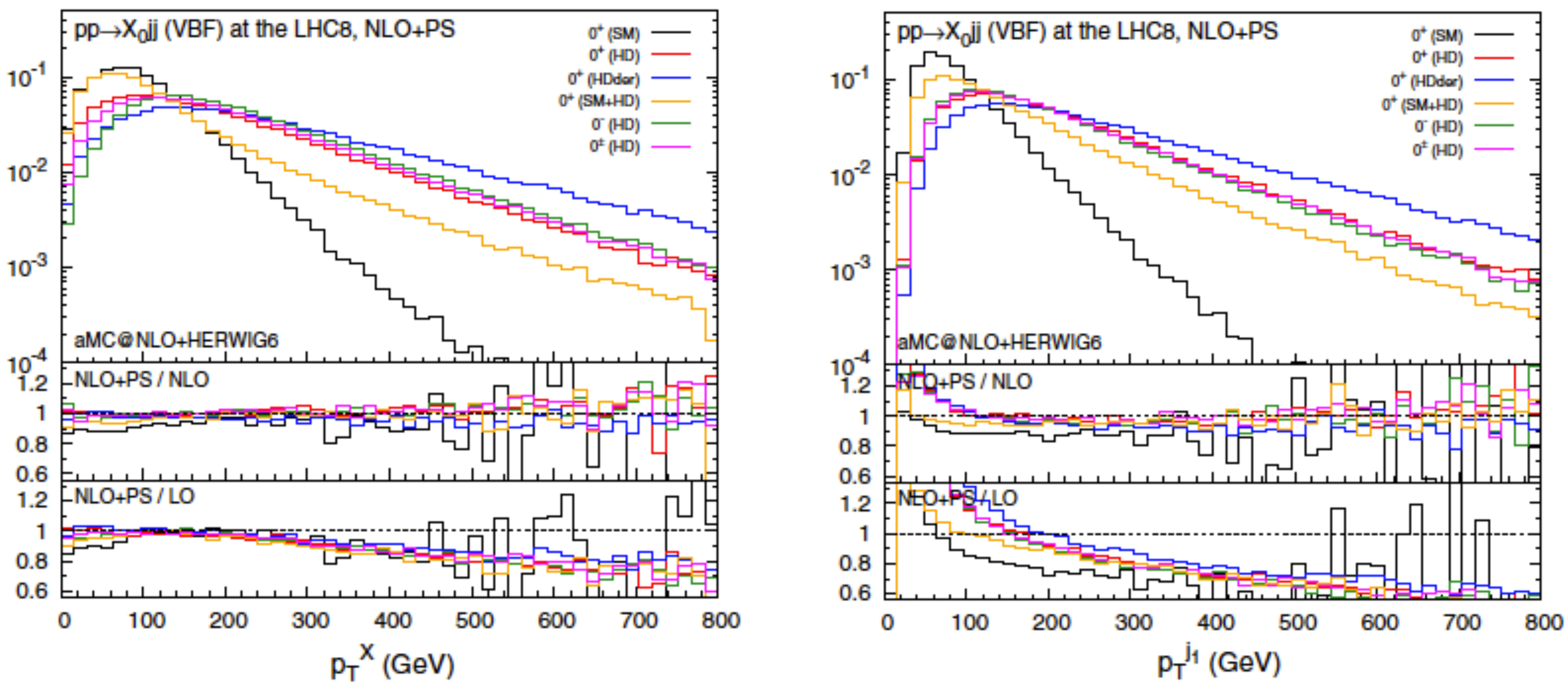
Scenario	HC parameter choice
0^+(SM)	$\kappa_{SM} = 1$ ($c_\alpha = 1$)
0^+(HD)	$\kappa_{HZZ,HWW} = 1$ ($c_\alpha = 1$)
0^+(HDder)	$\kappa_{H\partial Z,H\partial W} = 1$ ($c_\alpha = 1$)
0^+(SM+HD)	$\kappa_{SM,HZZ,HWW} = 1$ ($c_\alpha = 1$, $\Lambda = v$)
0^-(HD)	$\kappa_{AZZ,AWW} = 1$ ($c_\alpha = 0$)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

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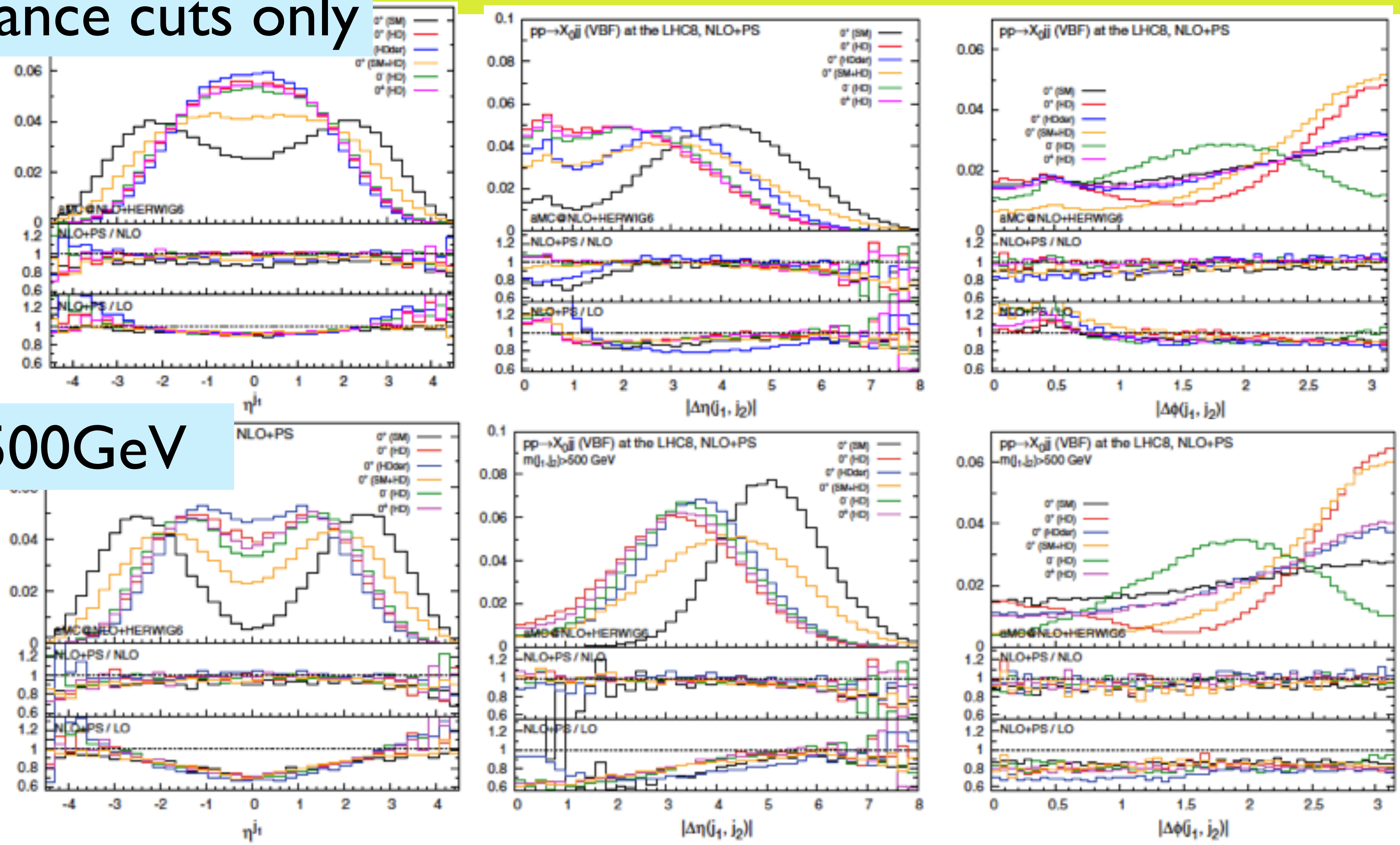
mjj cuts

acceptance cuts only

mjj>500GeV

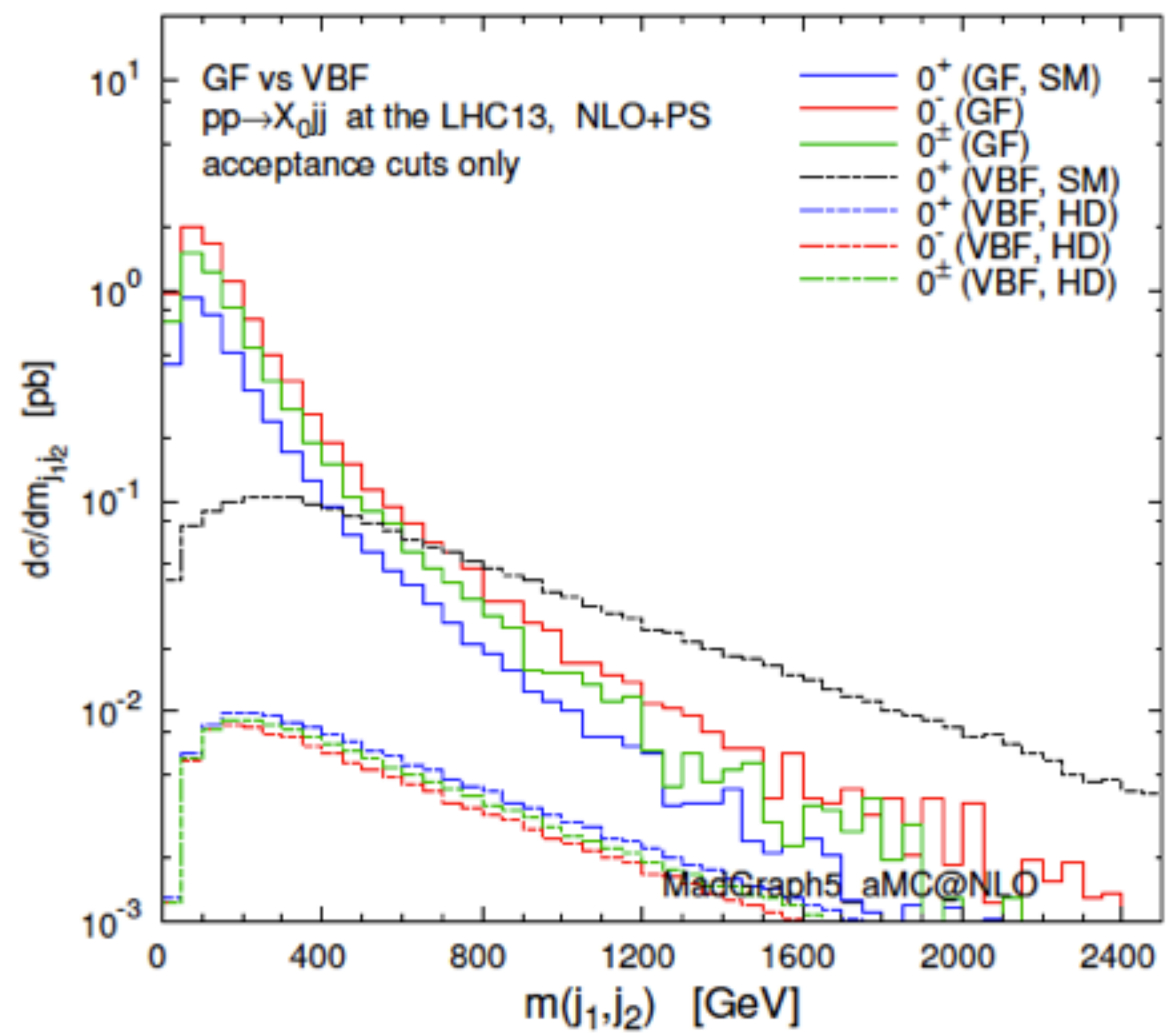


- The mjj cut effectively suppresses the central jet activity, especially for SM.
- The difference among the scenarios becomes more pronounced.
- NLO corrections cannot be described by an overall K factor, and also depends on the applied cuts.

(weak) VBF vs. GF (plus 2jets)

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

K～1.2



(weak) VBF vs. GF (plus 2jets)

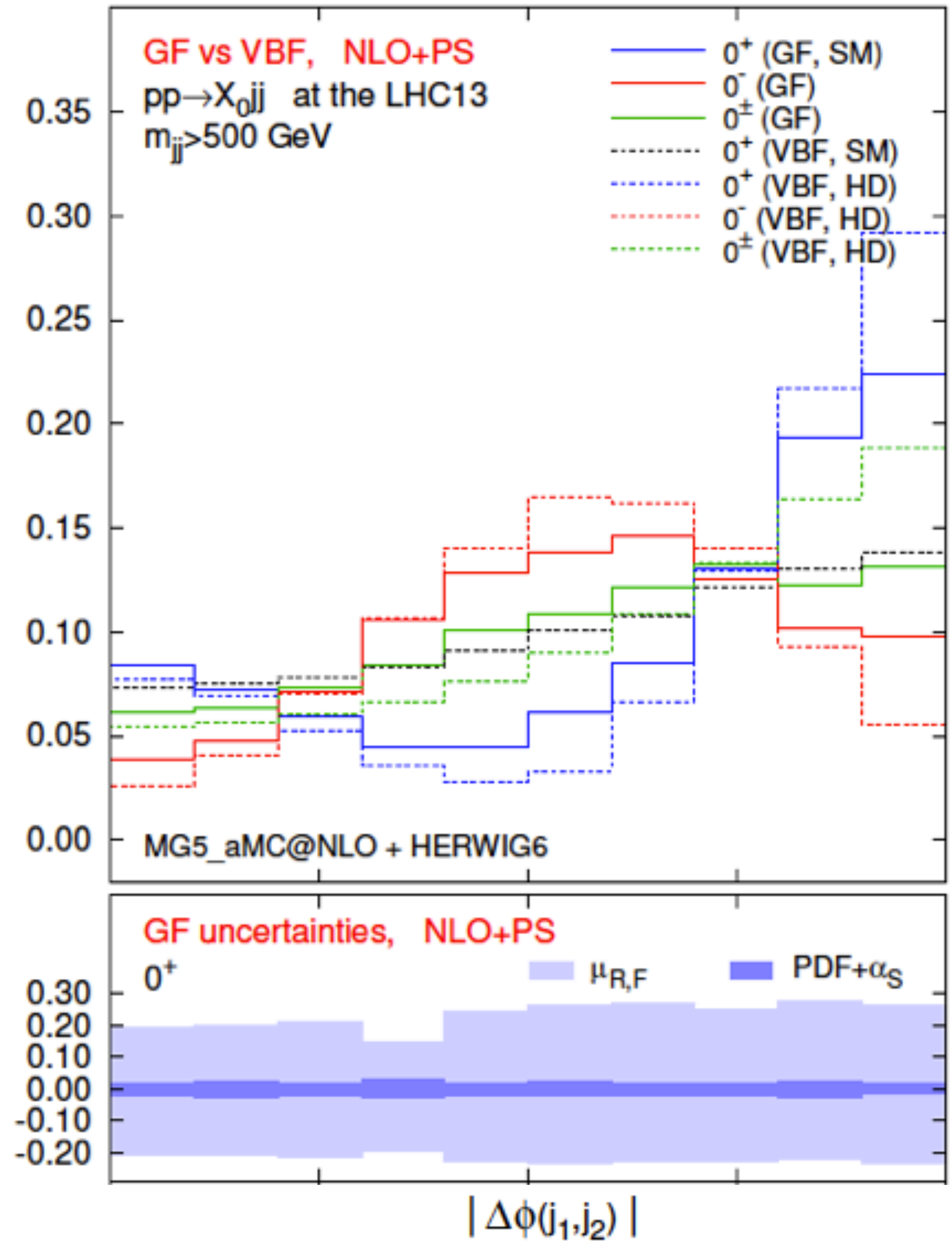
Maltoni, KM, Zaro [arXiv:1311.1829]

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

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

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

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

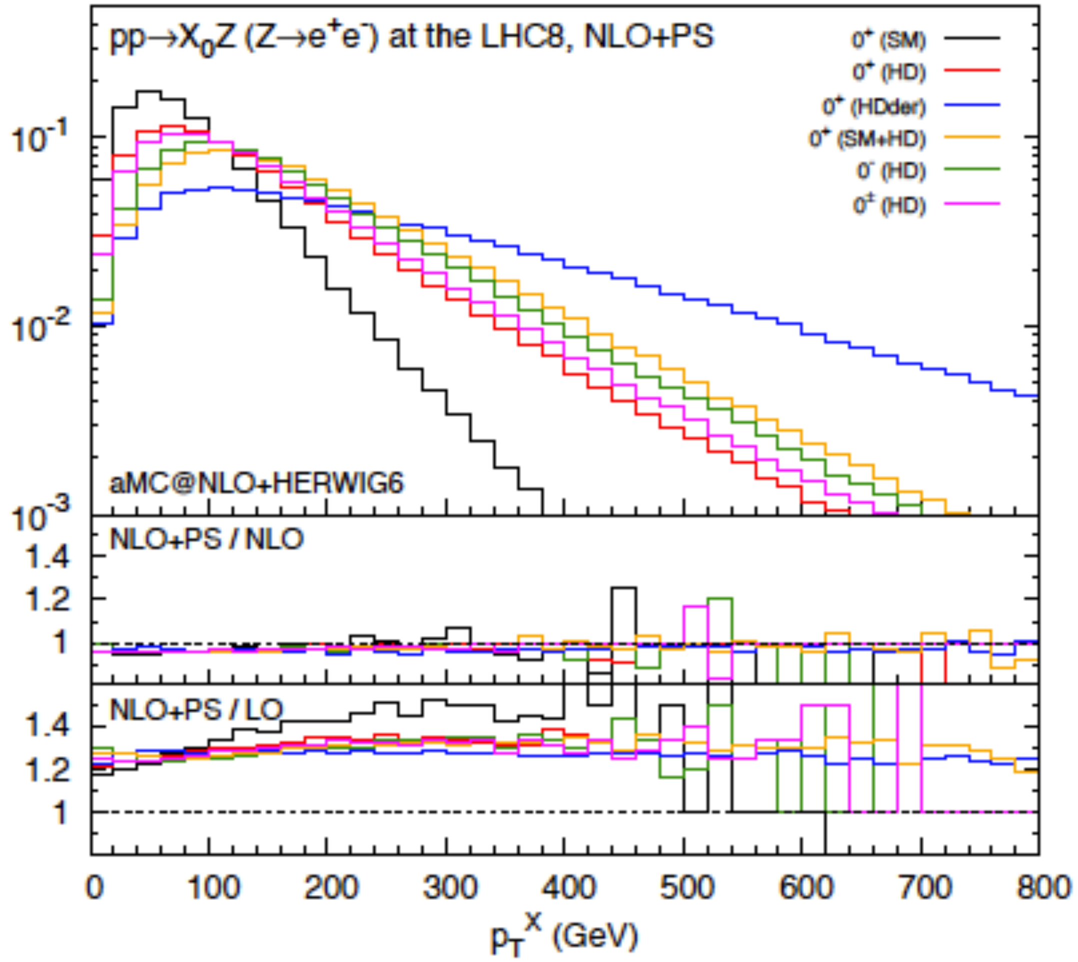


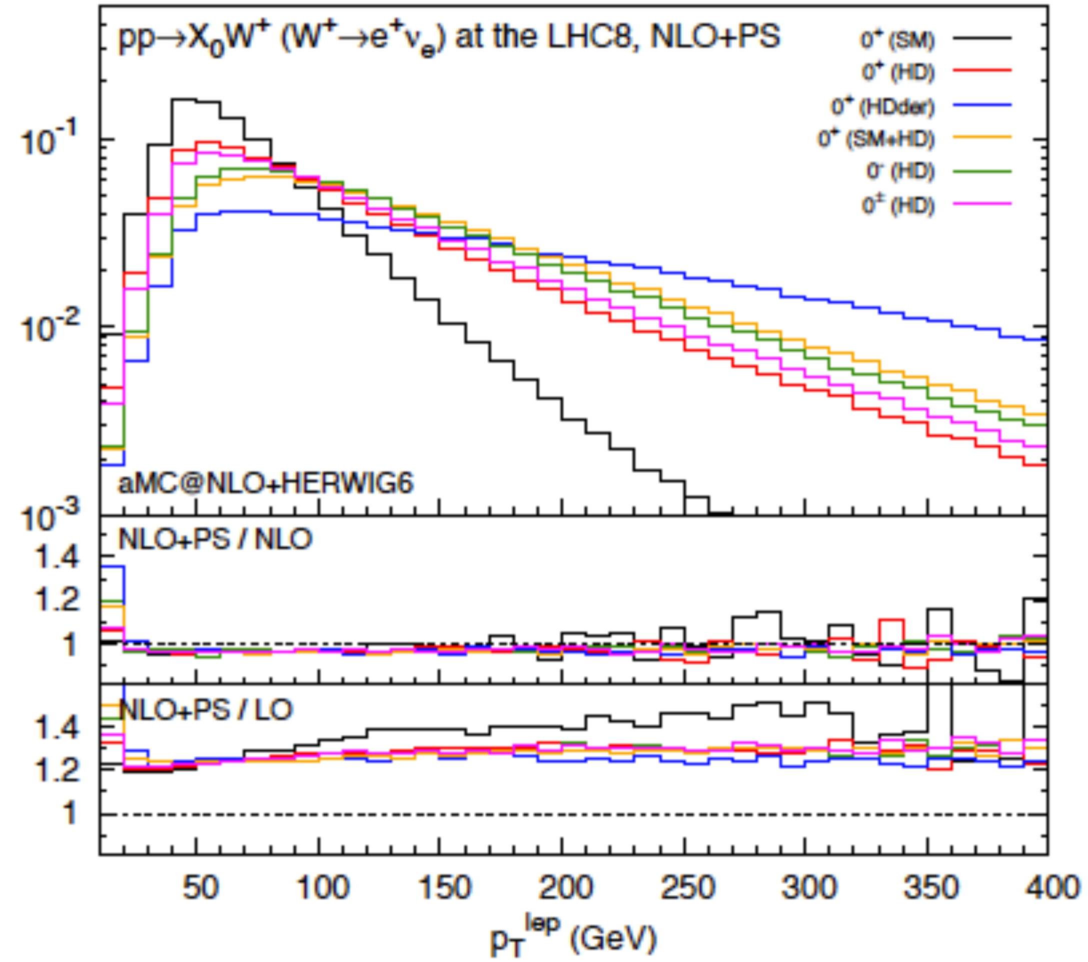
VH

Maltoni, KM, Zaro [arXiv:1311.1829]

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

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



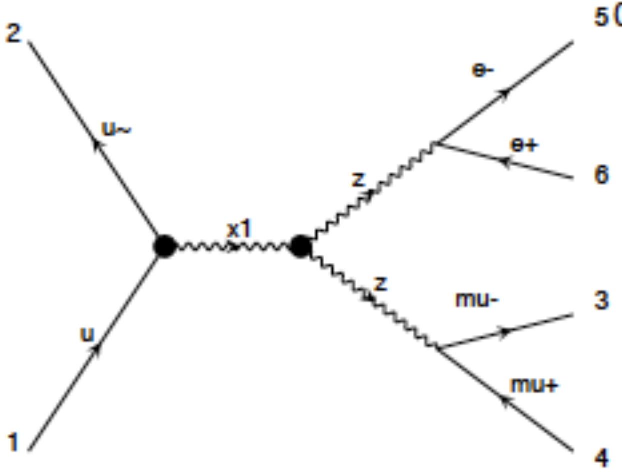


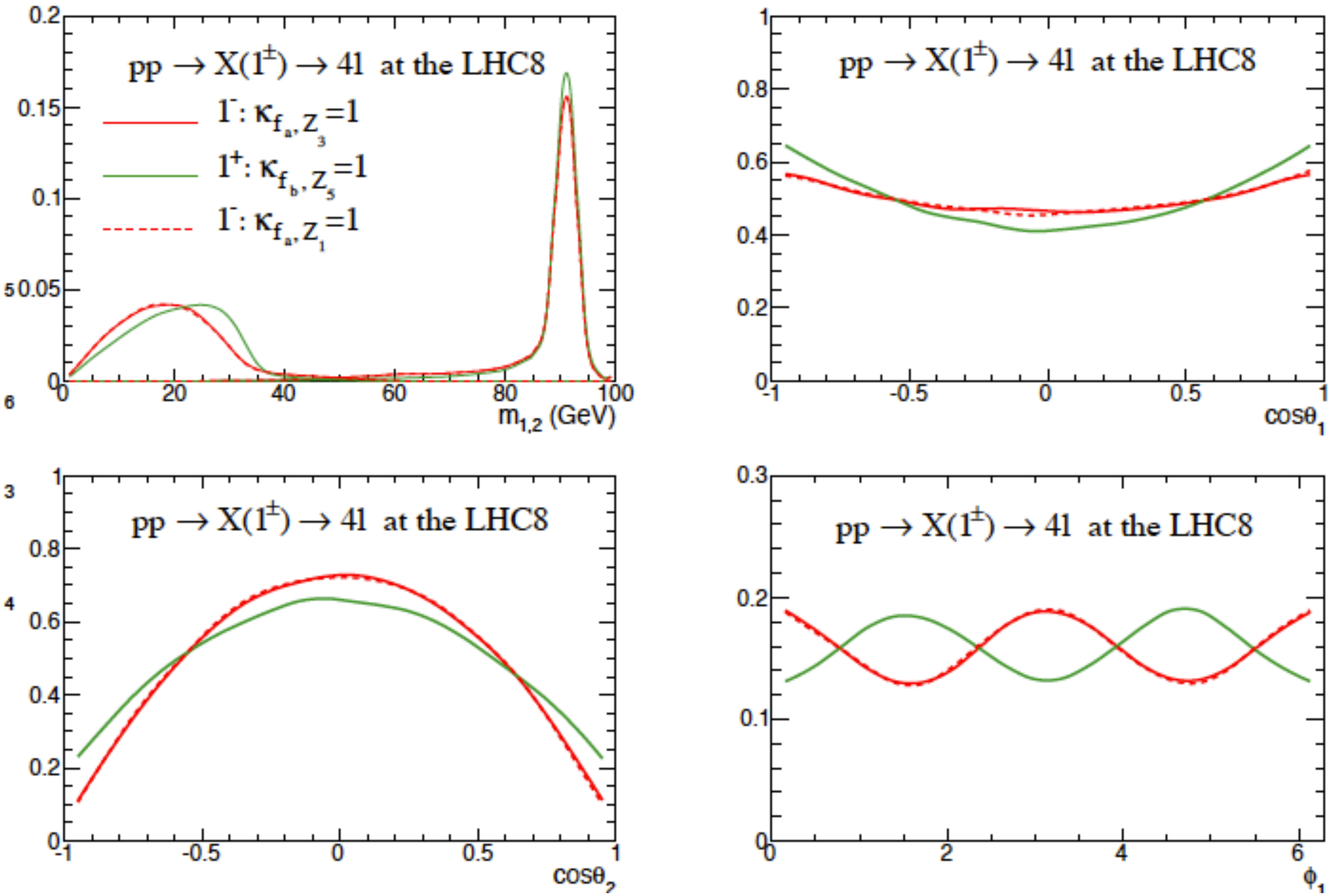
Summary

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

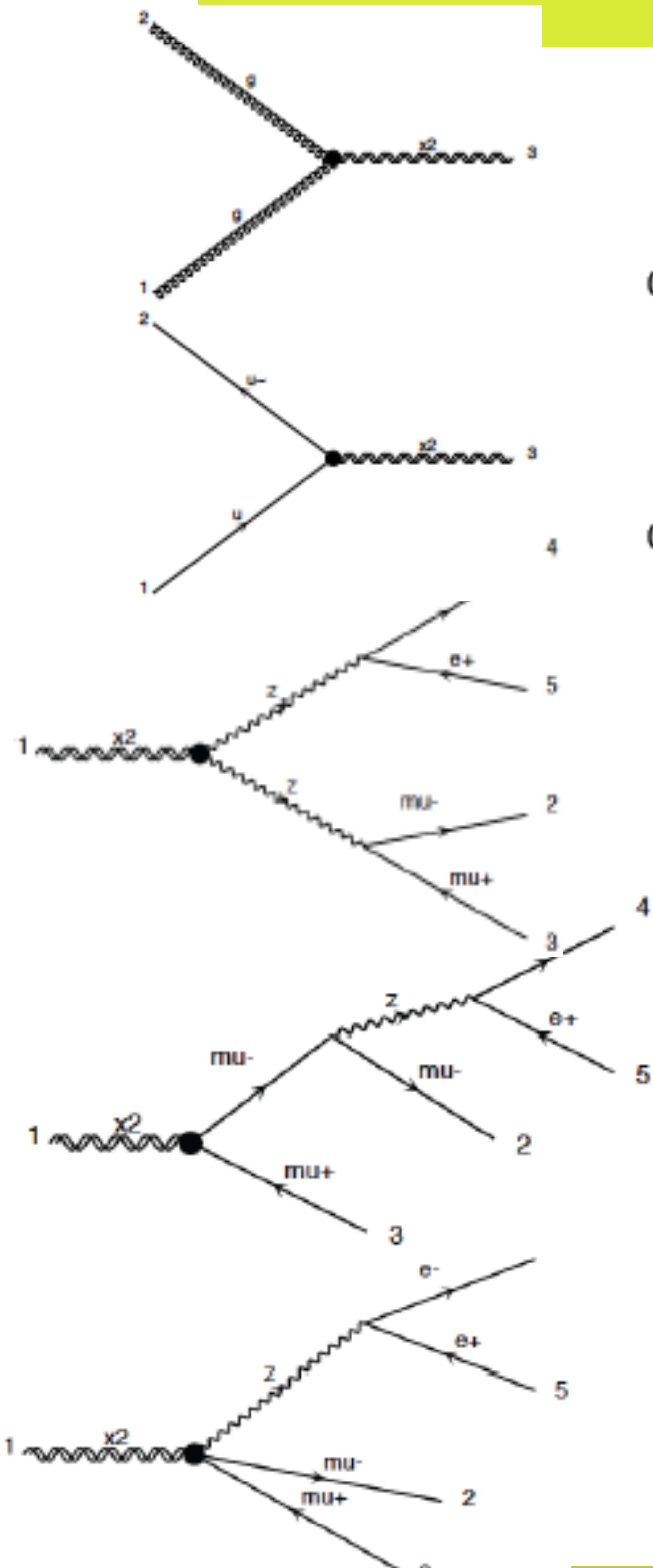
Back-up

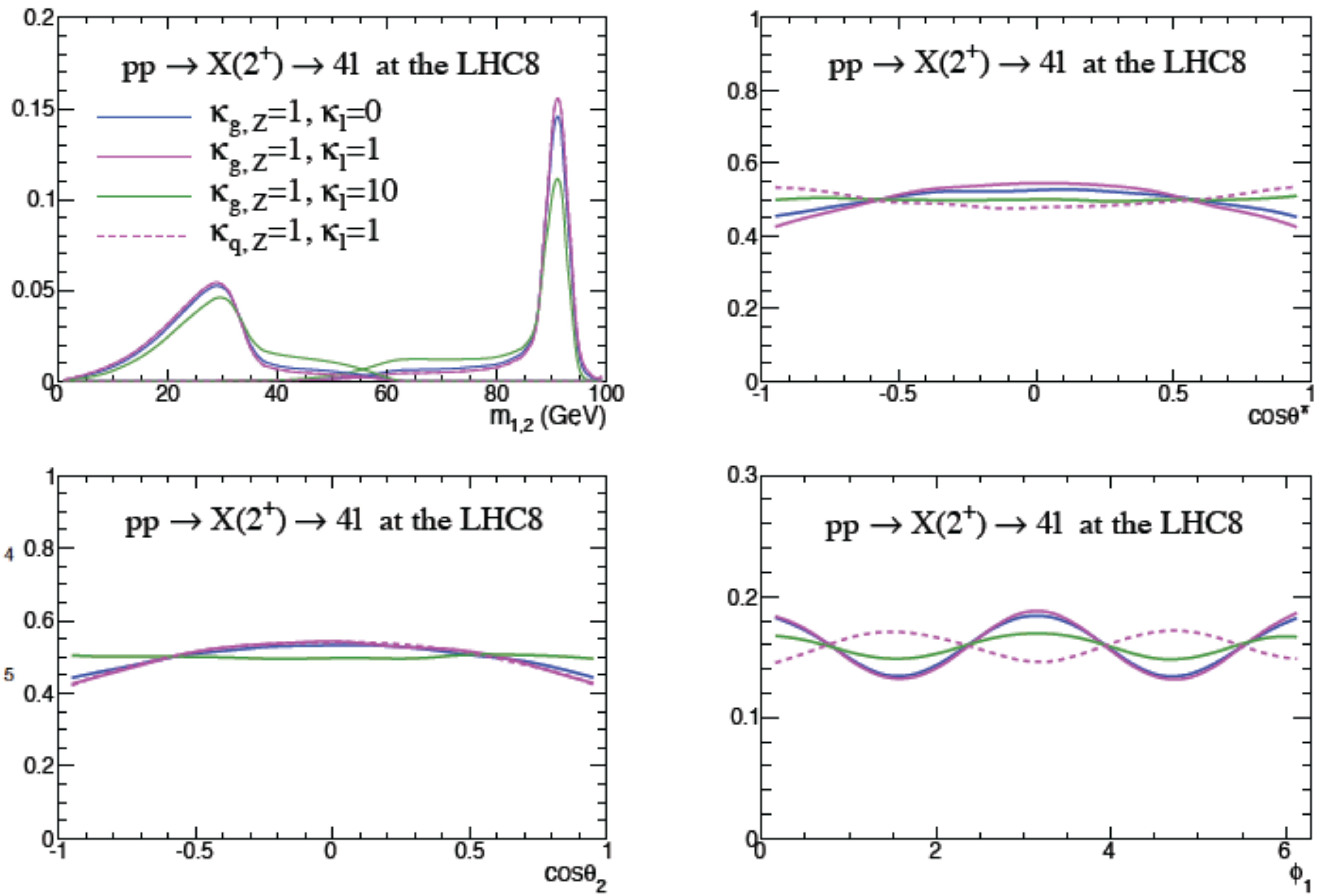
Mass and angular distributions -- spin1



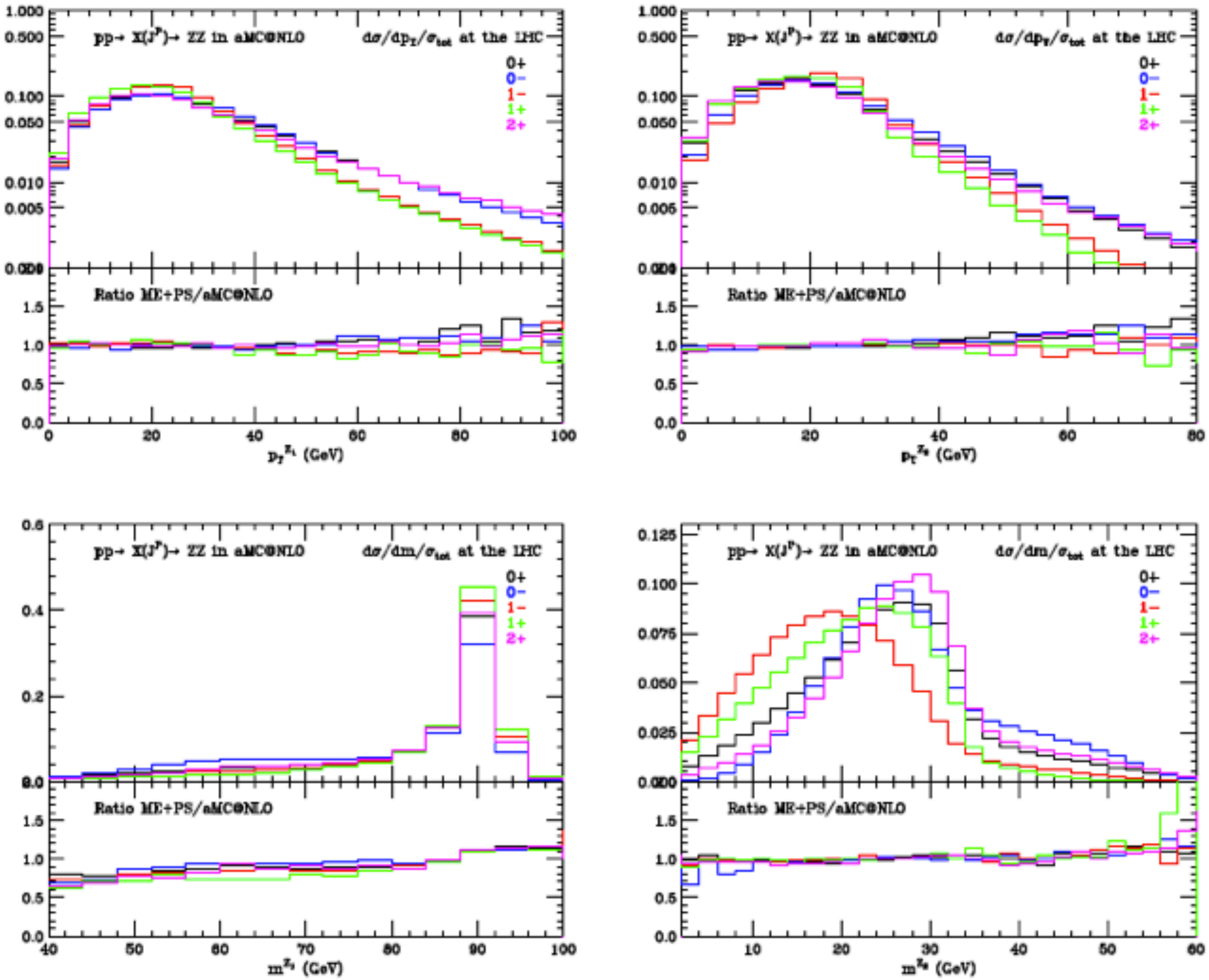


Mass and angular distributions -- spin2





aMC@NLO vs. ME+PS

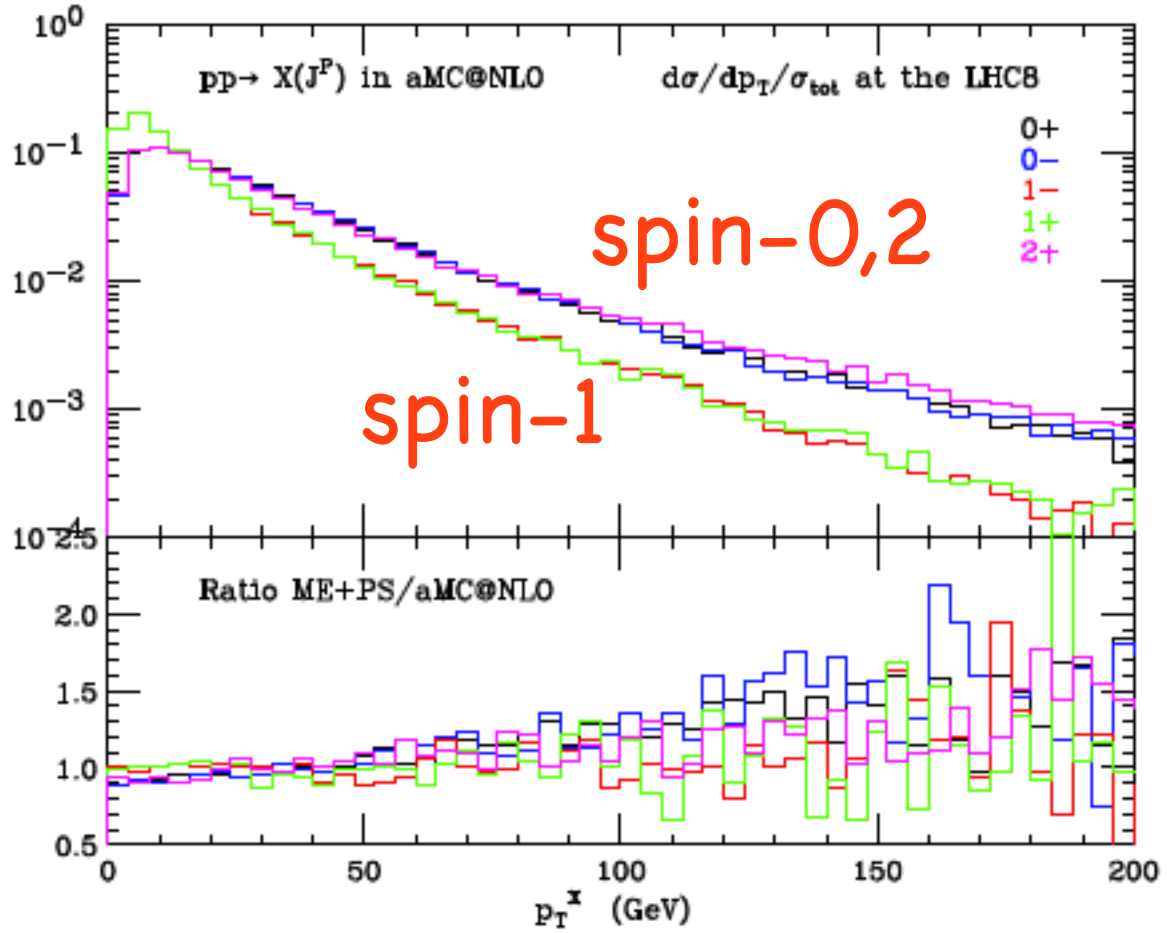


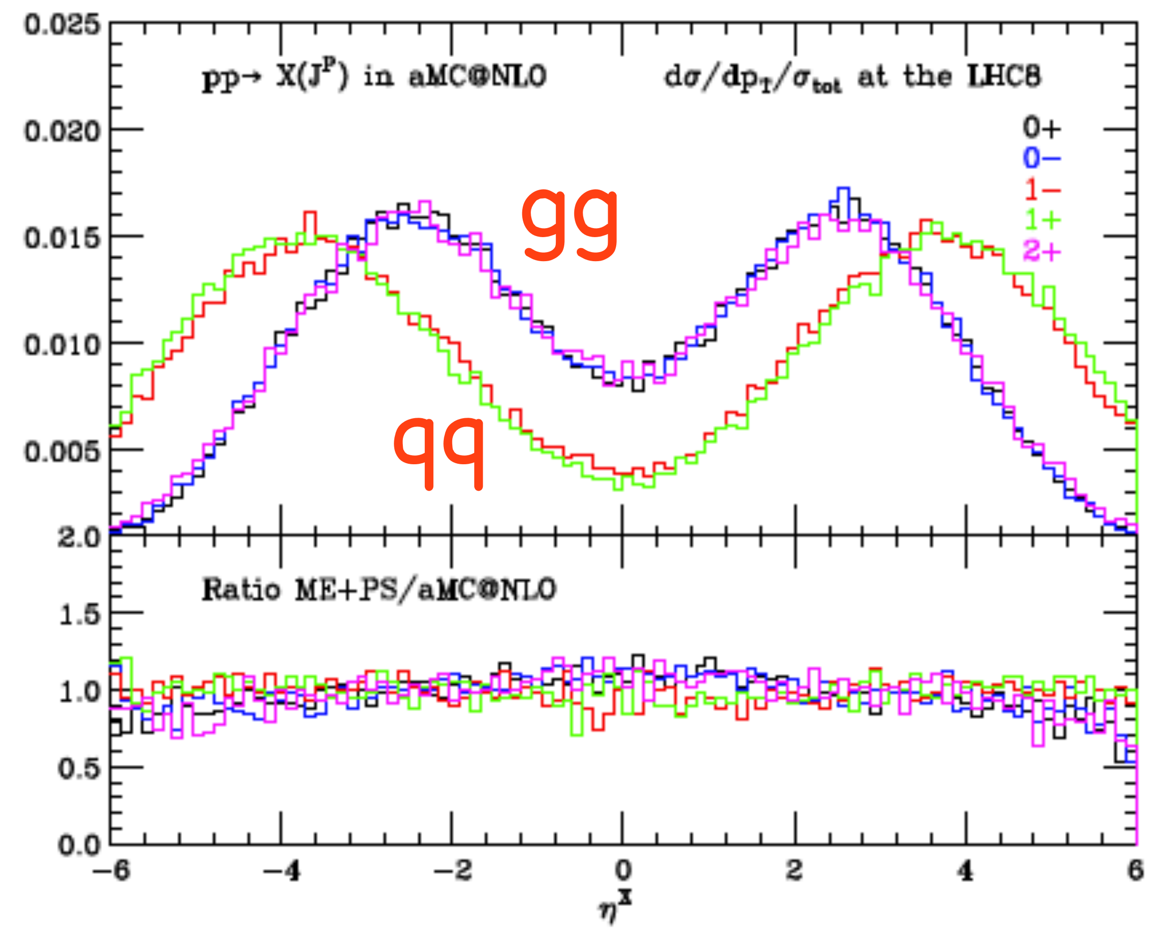
Good agreement between the ME+PS and aMC@NLO predictions for most observables.

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 → $X(J^P)$





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

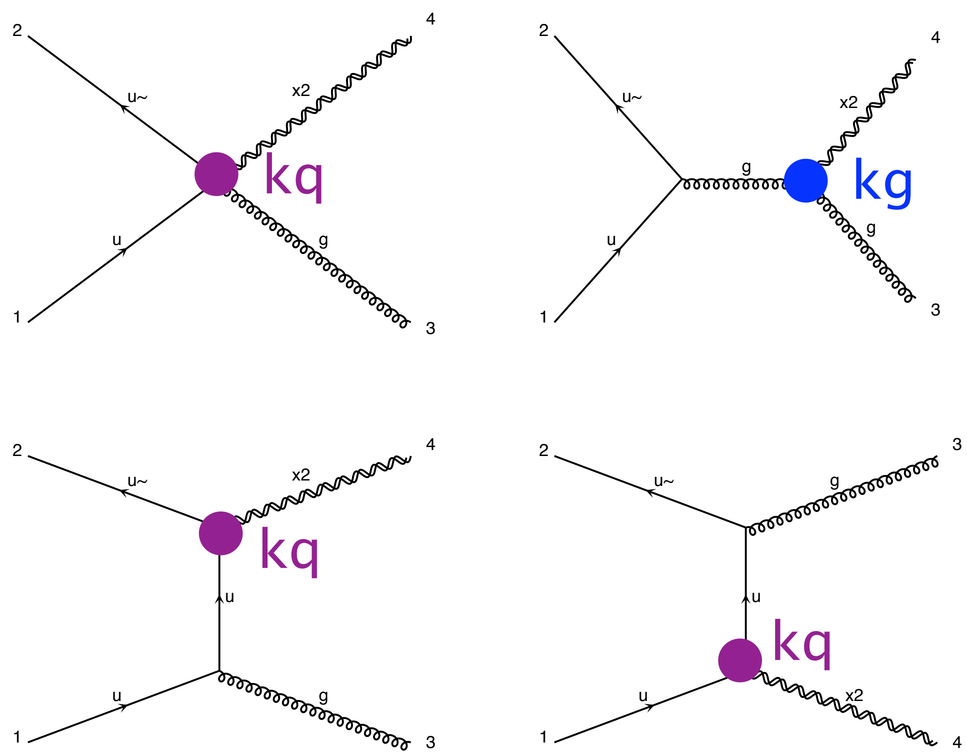
The different shapes are due to the different initial state.

excellent agreement between ME+PS and aMC@NLO

Higher order effects in QCD (II)

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

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



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

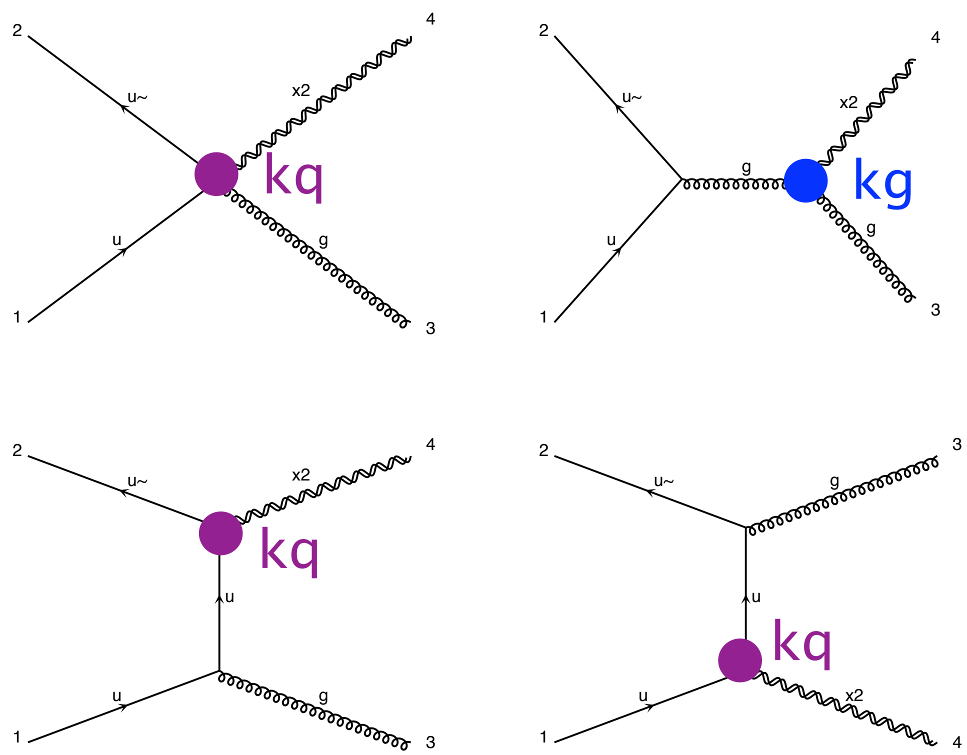
$$|\mathcal{M}|^2 \propto s^3/m^4\Lambda^2 \quad \text{for } \kappa_q \neq \kappa_g$$

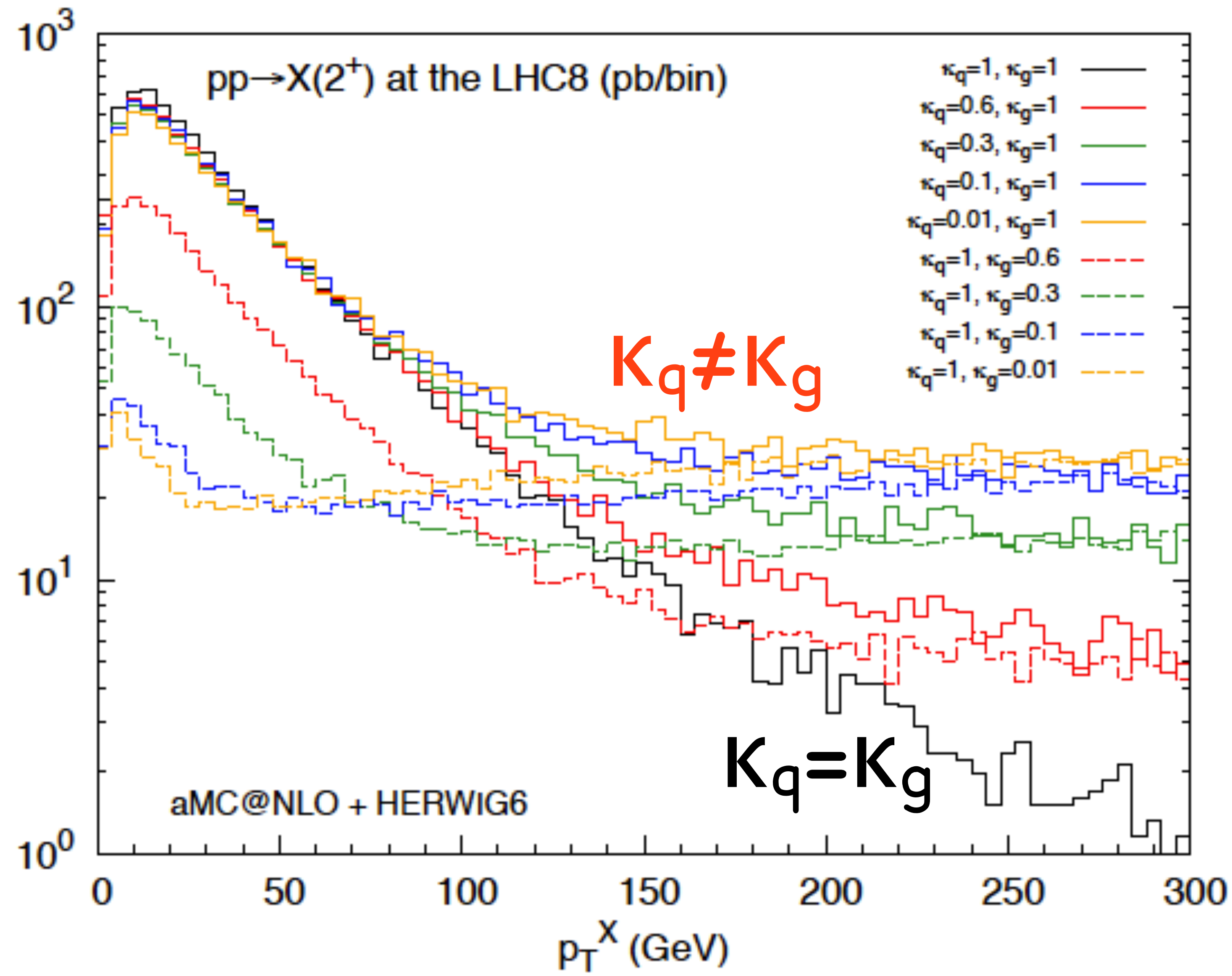
$$\begin{aligned}|\mathcal{M}|^2 = \frac{N}{\Lambda^2 s\,t\,u\,m^4}\Big\{ & 3\kappa_g^2 m^4 \left[2m^4 - 2m^2(t+u) + t^2 + u^2\right]\left[m^4 - m^2(t+u) + 4tu\right] \\ & + (\kappa_q - \kappa_g)\, 6\,\kappa_g m^4 s \left[m^6 + m^2 s(s+2u) - 2su(s+u)\right] \\ & + (\kappa_q - \kappa_g)^2 s\left[6m^{10}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

Higher order effects in QCD (II)

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

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

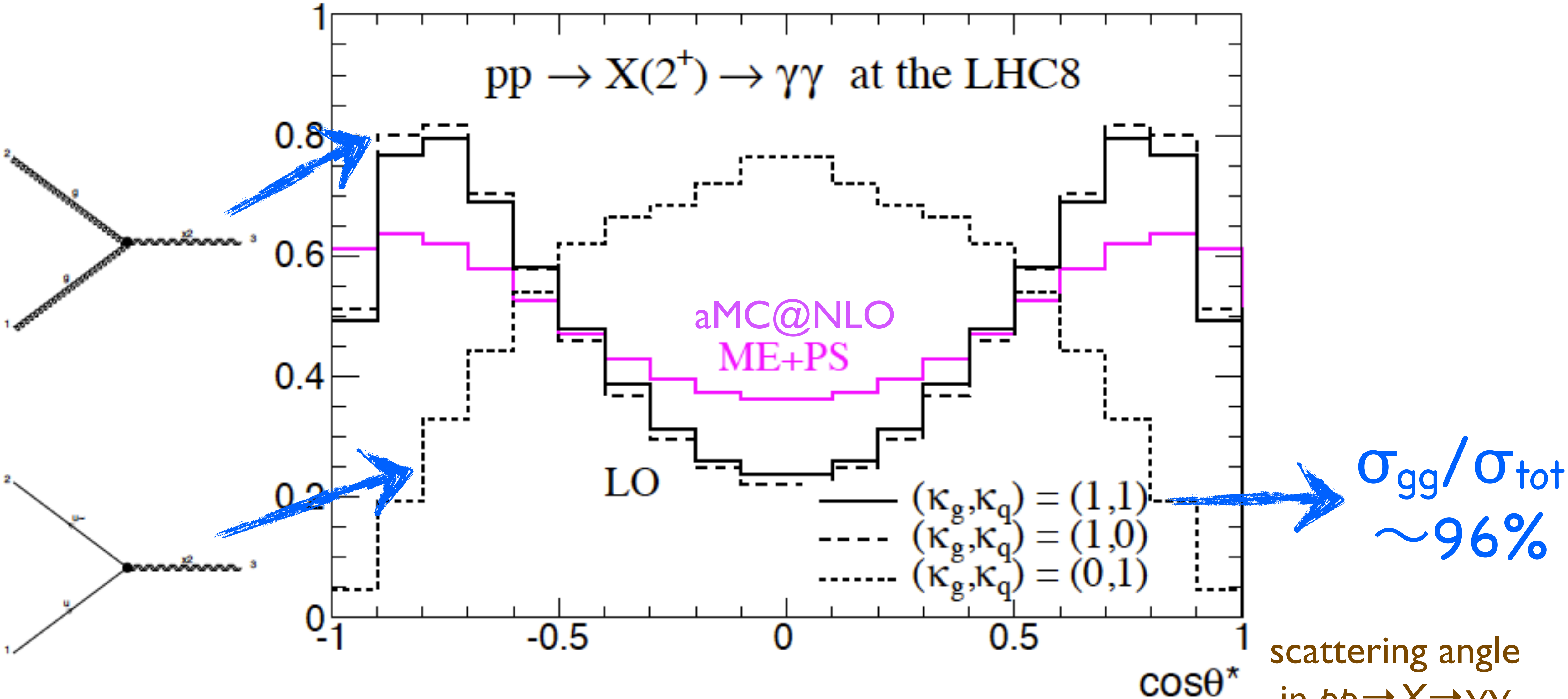




A model with non-universal couplings dramatically changes the pT(X) spectrum.

Higher order effects in QCD (III)

on spin observables for a spin-2 state



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

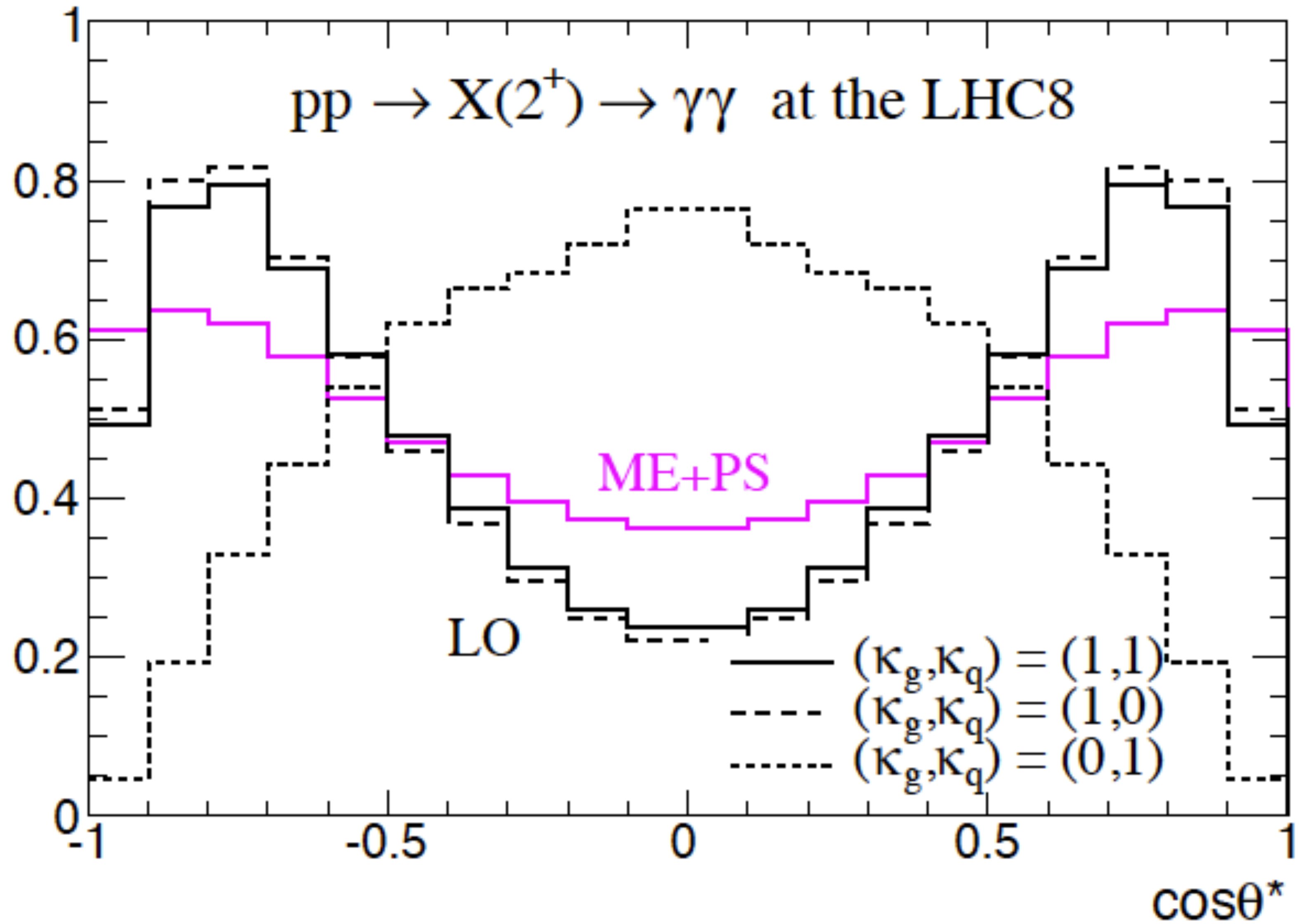
$$\frac{d\sigma(gg)}{d\cos\theta^*} \propto |d^2_{22}(\theta^*)|^2 + |d^2_{2-2}(\theta^*)|^2 = \frac{1}{8}(1 + 6\cos^2\theta^* + \cos^4\theta^*)\,,$$

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

How can we get the spin/parity information?

1. $X \to \gamma\gamma$
2. $X \to VV^* \to 4l$
3. $pp \to jjX$
4. $pp \to VX$
5. $X \to \tau\tau$

Spin/parity determination
1. X→γγ



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

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

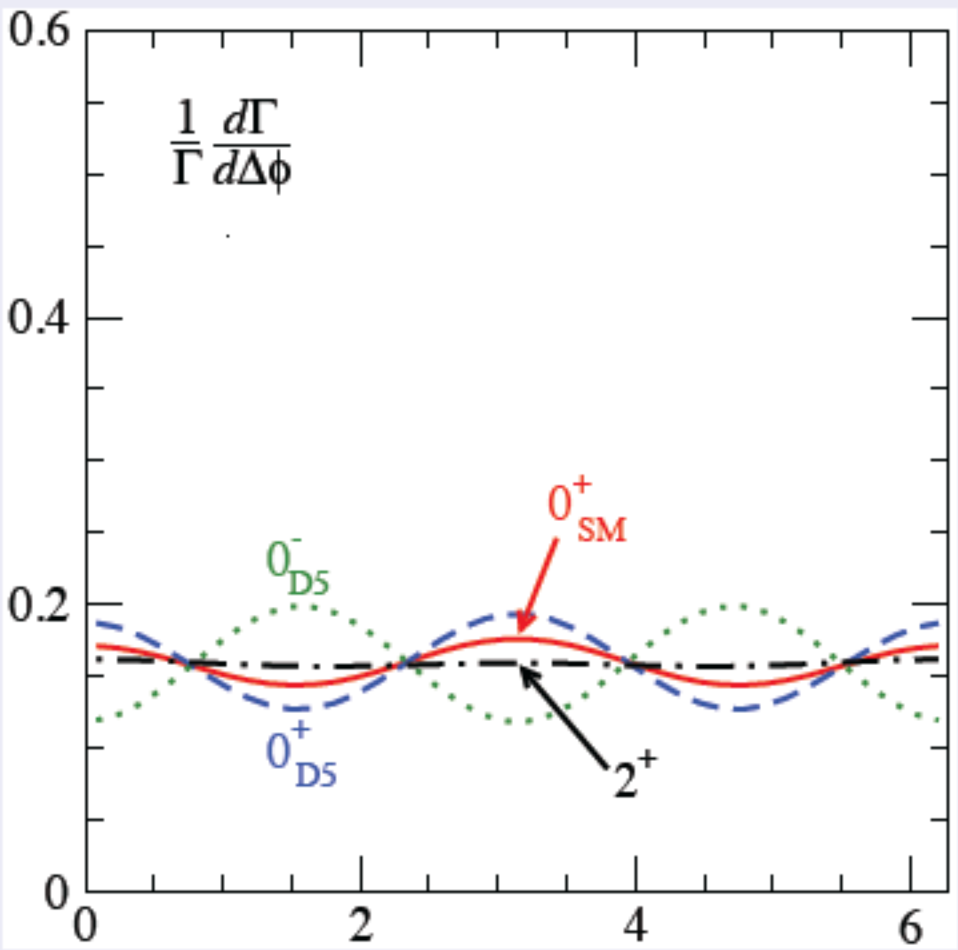
Spin/parity determination
2. X→VV*→4l

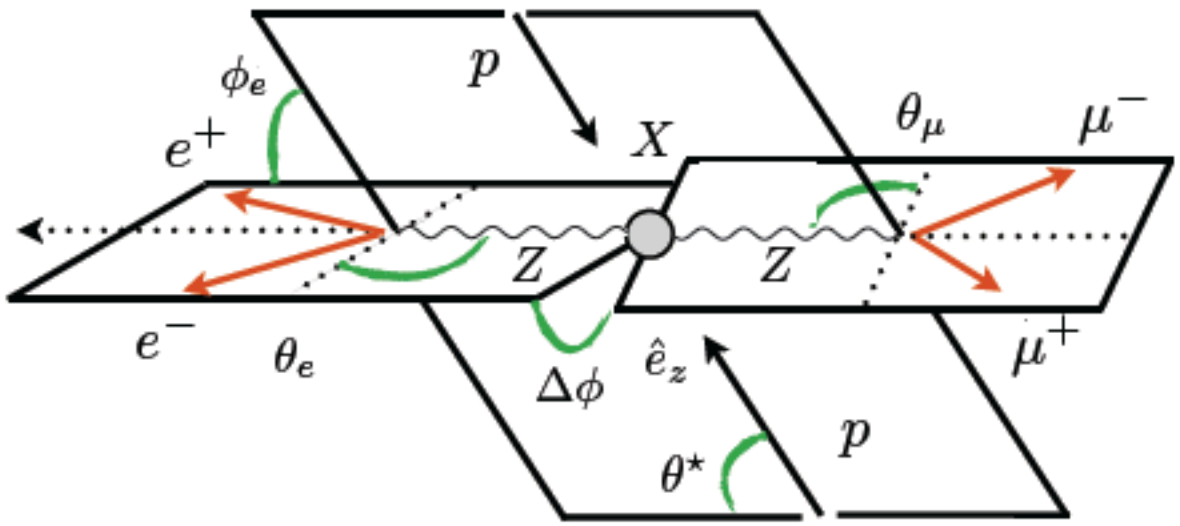
[Dell'Aquilla, Nelson, PRD(1986)]
[Choi, Miller, Mühlleitner, Zerwas, PLB(2003)]
[Gao et al, PRD(2010)] ...

[Bolognesi et al, PRD(2012)]

$$\mathcal{L}_{0^+_{\rm SM}} = g_{0^+_{\rm SM}} V_\mu V^\mu X_0$$
$$\mathcal{L}_{0^+_{\rm D5}} = g_{0^+_{\rm D5}} V_{\mu\nu} V^{\mu\nu} X_0$$
$$\mathcal{L}_{0^-_{\rm D5}} = g_{0^-_{\rm D5}} V_{\mu\nu} \widetilde{V}^{\mu\nu} X_0$$

$X \to ZZ^* \to 4\ell$



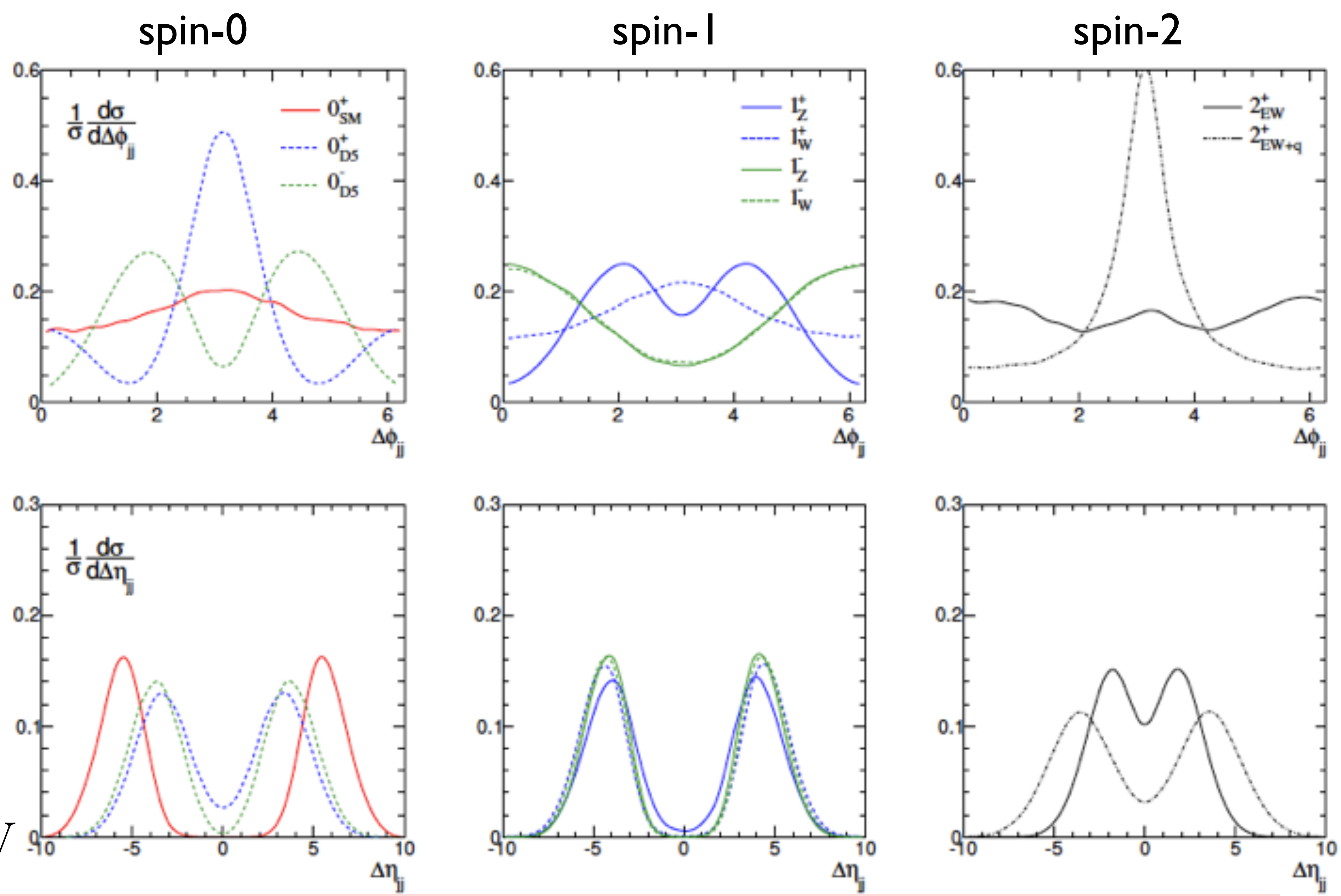


$d\sigma/d\Delta\phi \sim$ const. for $0^+_{\rm SM}$, $\quad d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi$ for $0^\pm_{\rm D5}$.

Spin/parity determination
3. pp→jjX

di-jet correlations

Englert, Goncalves-Netto, KM, Plehn (2013)



$\sqrt{s} = 14$ TeV

$p_{T_j} > 20$ GeV

$\Delta R_{jj} > 0.6$

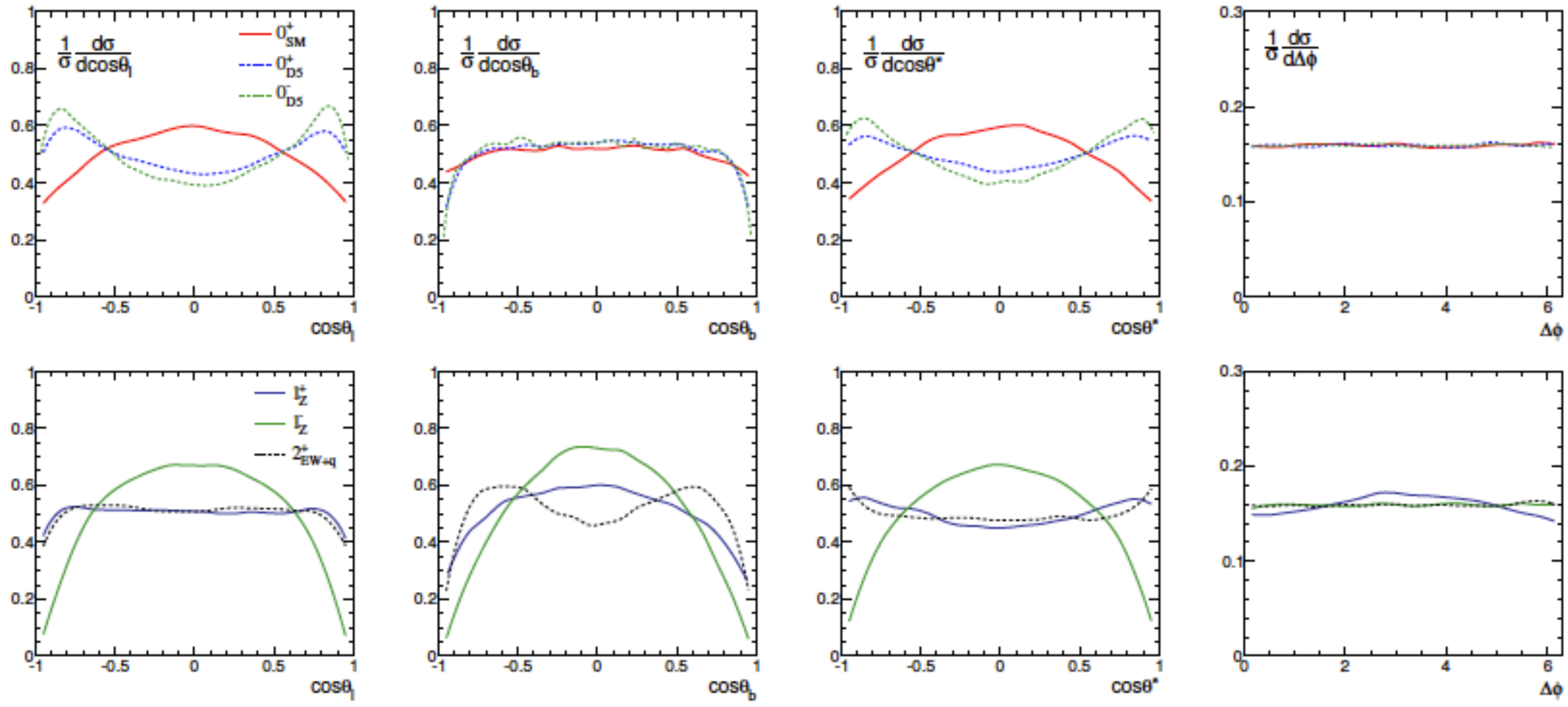
$|\eta_j| < 5$

$m_{jj} > 600$ GeV

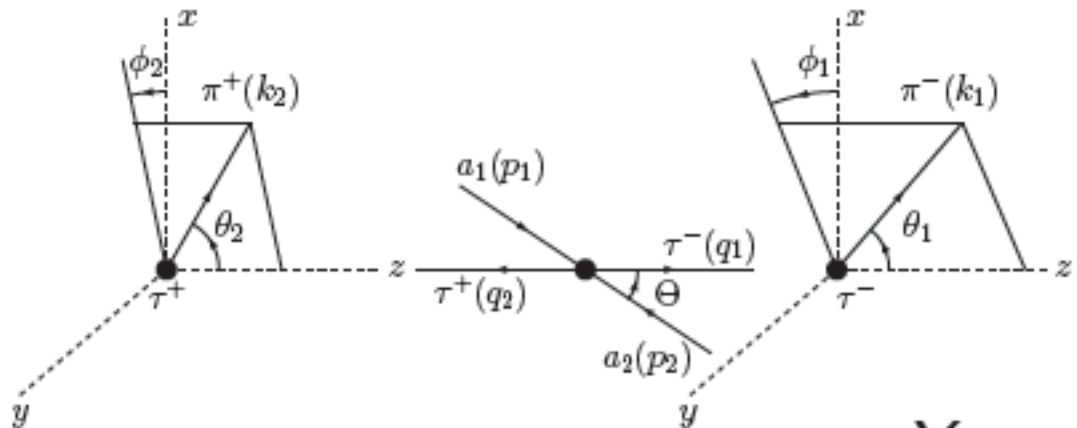
Δη as well as ΔΦ are the powerful observables.

Spin/parity determination
4. pp→ZX

Englert, Goncalves-Netto, KM, Plehn (2013)



Spin/parity determination
5. X→ττ

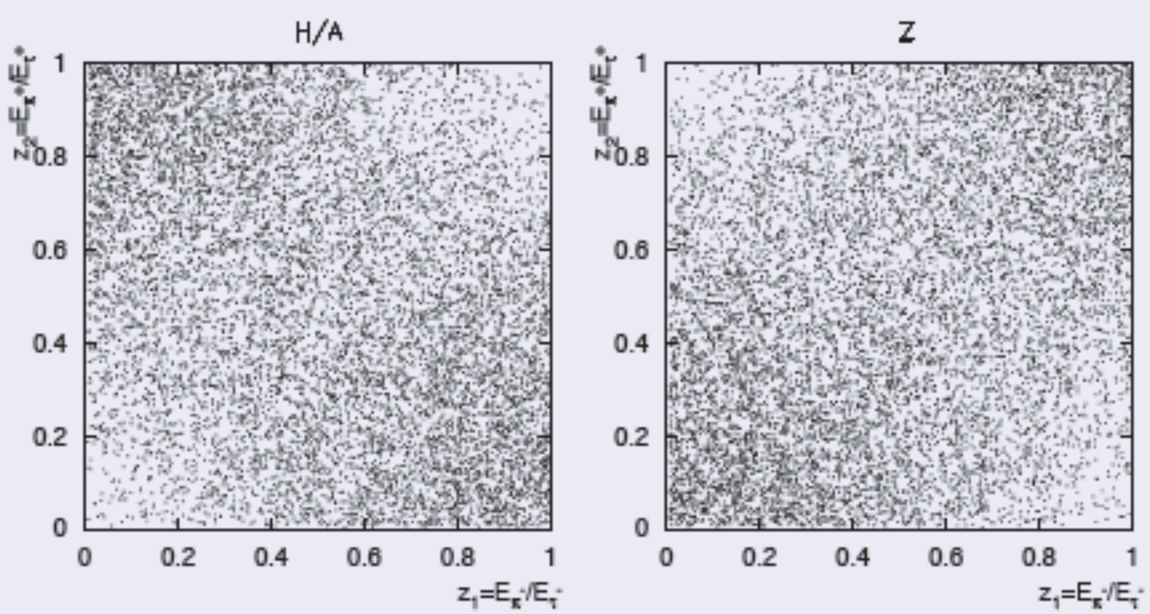


[Bullock, Hagiwara, Martin, NPB(1993)]
[Krämer, Kühn, Stong, Zerwas, ZPC(1994)]
[Pierzchala, Richter-Was, Was, Worek, APPB(2001,2002,...)]

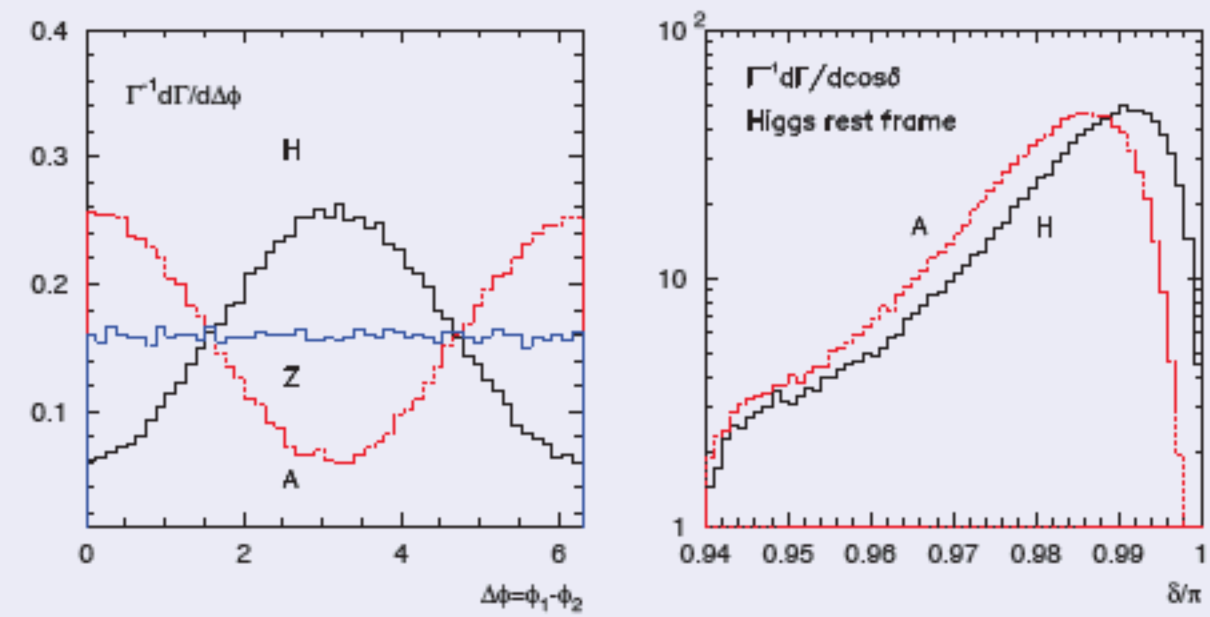
[Hagiwara, Li, KM, Nakamura, 1212.6247]

$$pp \to X \to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$$

Longitudinal spin (helicity) effect



Transverse spin effect



$d^2\Gamma/dz_1dz_2 \sim 1 \mp z_1z_2$ for spin-0/1, $\quad d\Gamma/d\Delta\phi \sim 1 \mp A\cos\Delta\phi$ for $0^\pm$

τ could be a spin/parity analyzer!