Accurate predictions for Higgs Characterisation

Marco Zaro, LPTHE - UPMC Paris VI

based on

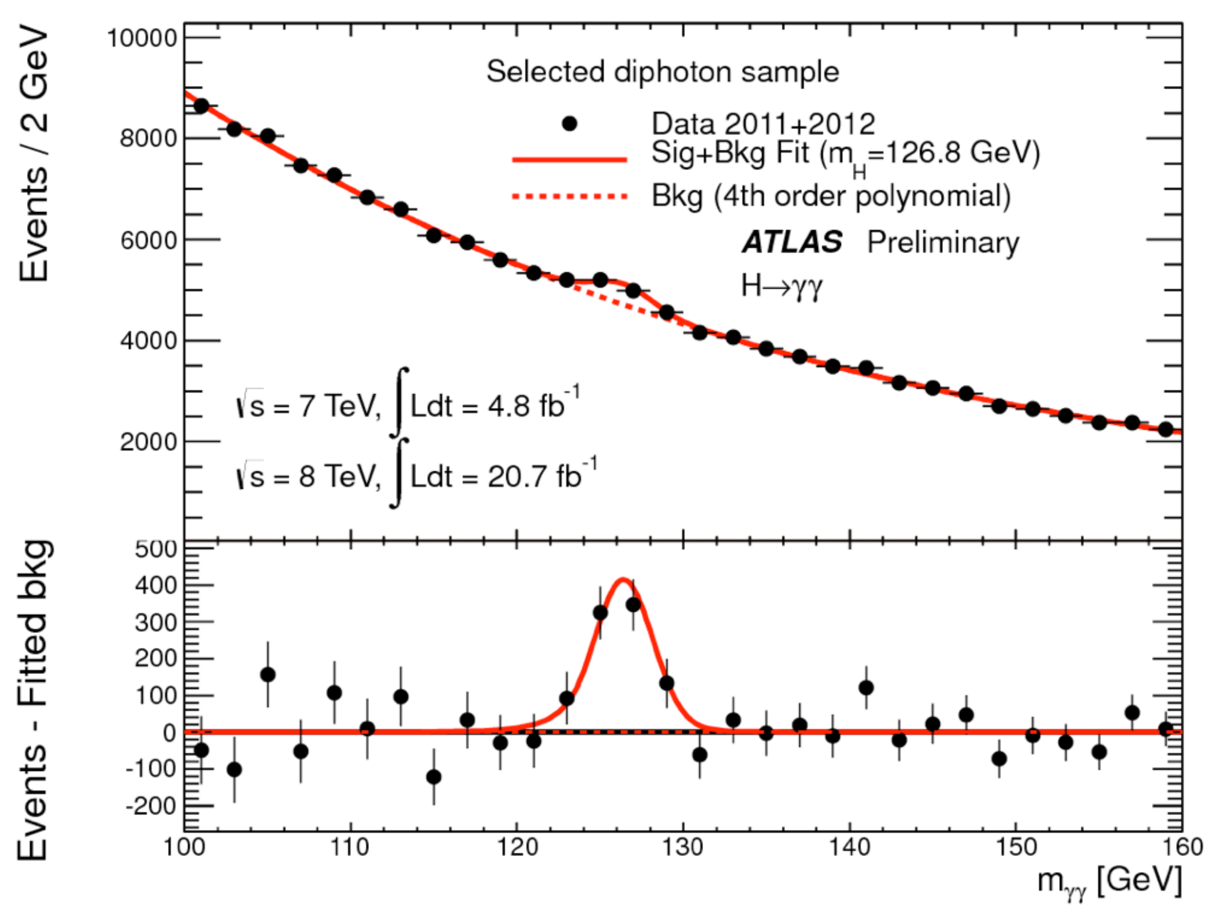
Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, MZ, arXiv:1306.6464
Maltoni, Mawatari, MZ, arXiv:1311.1829
Demartin, Maltoni, Mawatari, Page, MZ, arXiv:1407.5089

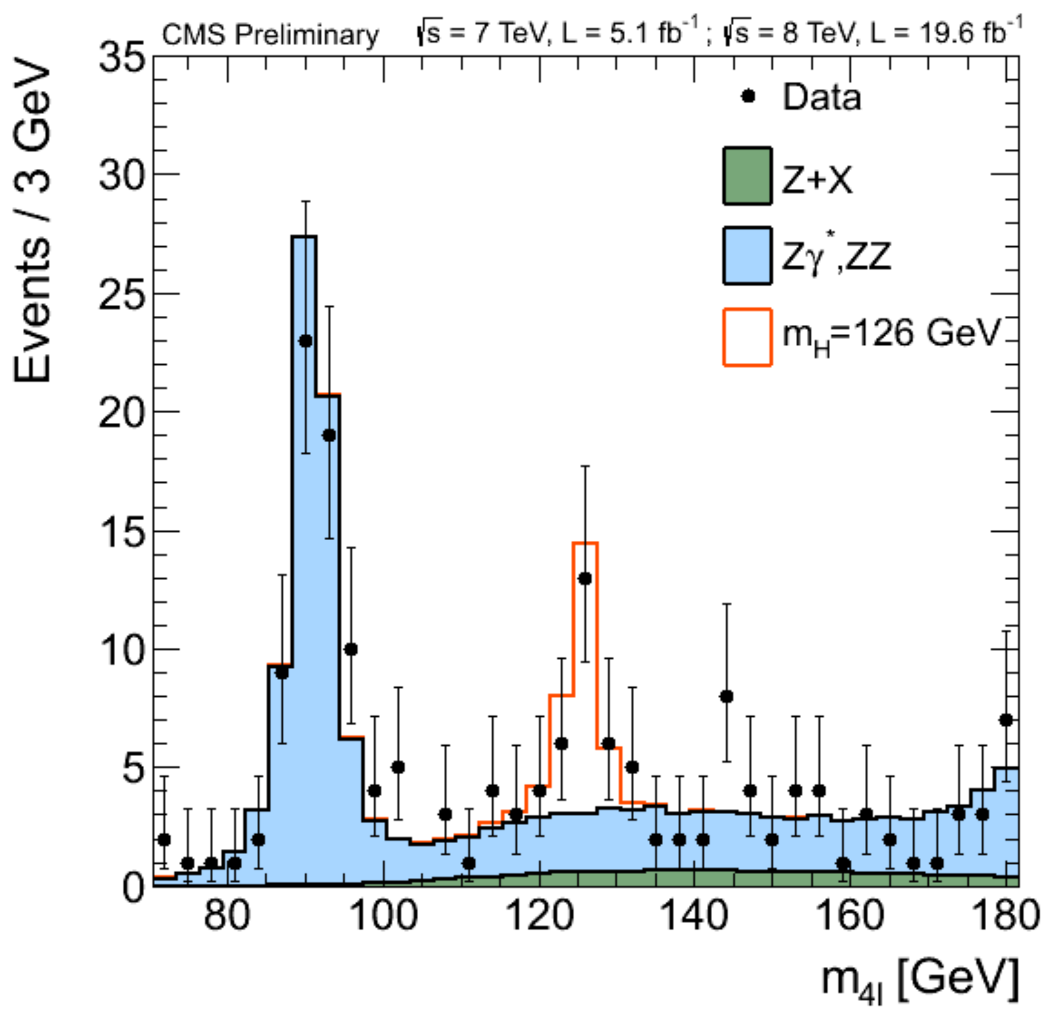
HEFT 2014 @IFT Madrid

September 30, 2014

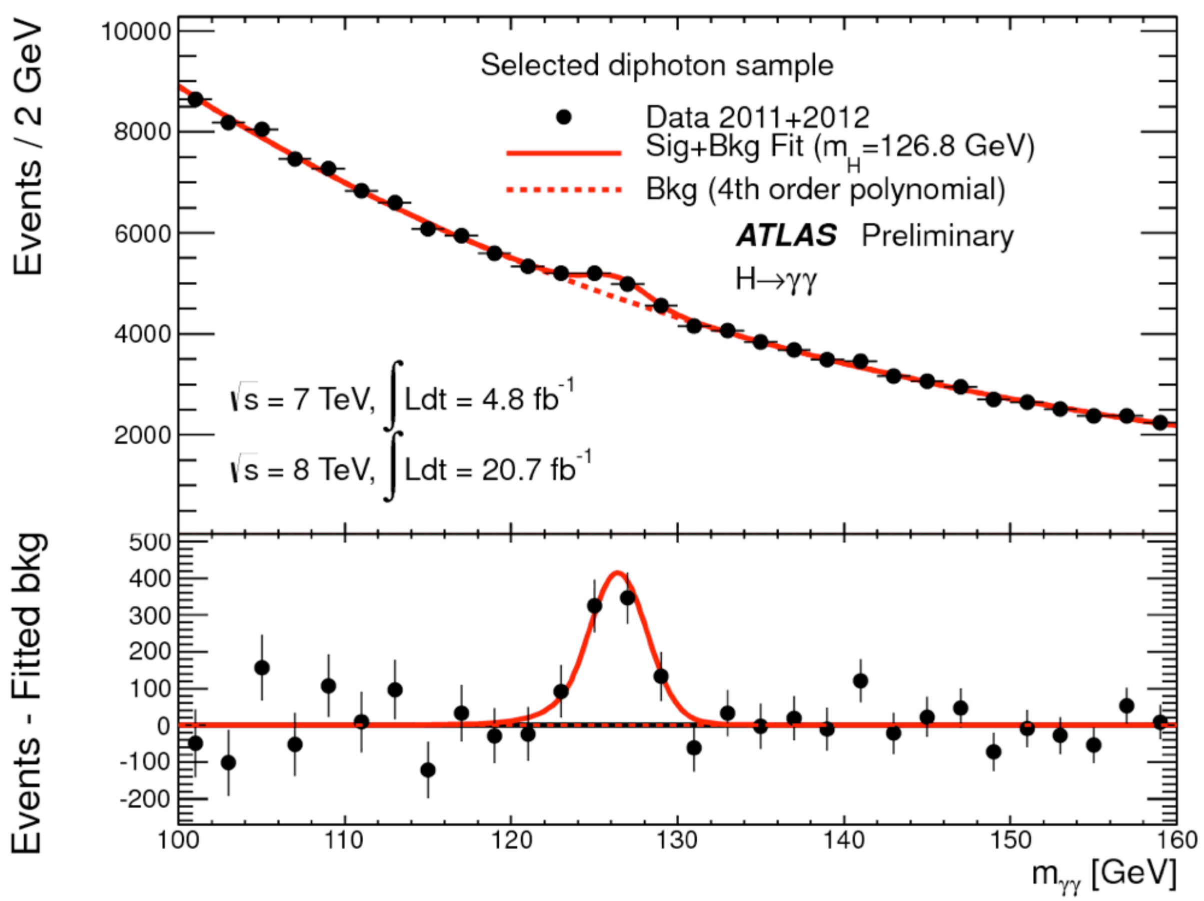
LHCPhenoNet

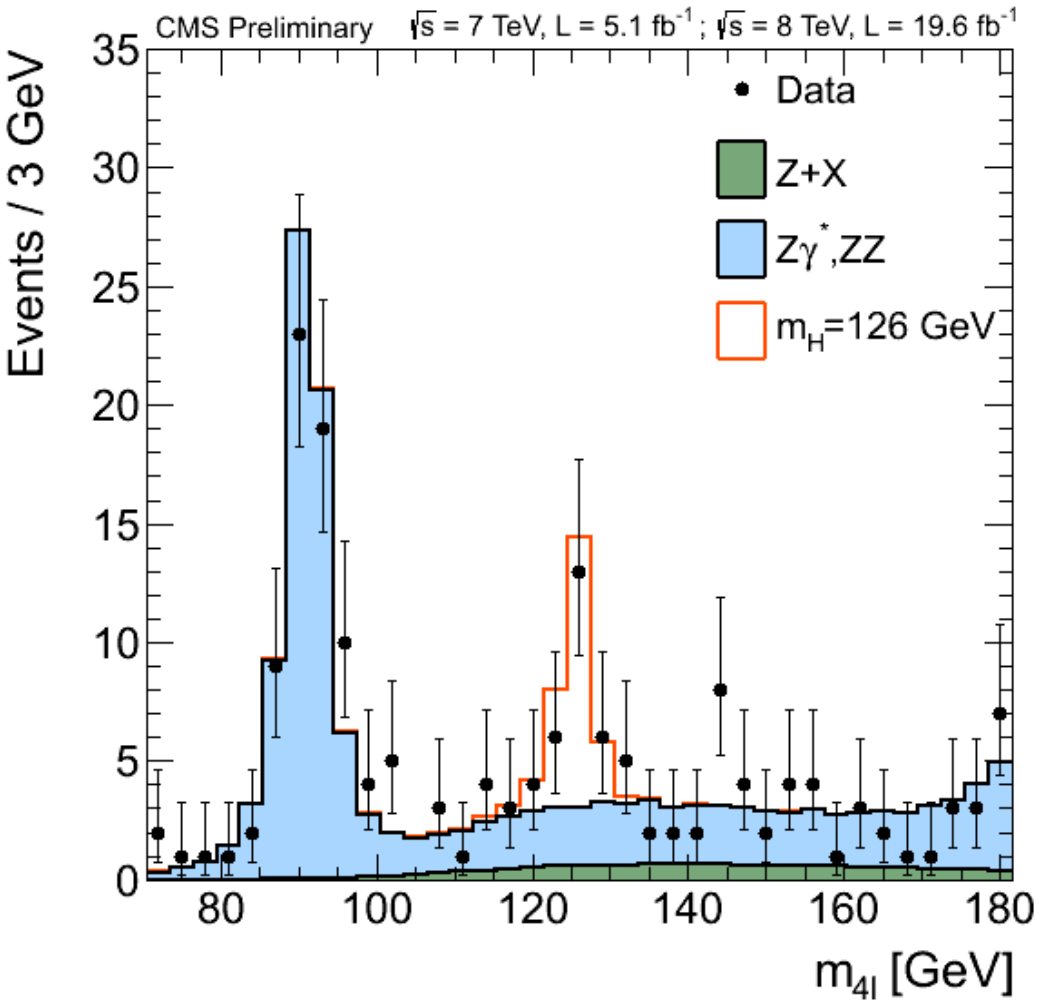
Any major discovery is the beginning of a new journey…





Any major discovery is the beginning of a new journey…





What is that peak??

Is it THE Higgs boson *as expected in the SM?*

NAME
Higgs boson
DATE OF BIRTH
Jul 4th 2012 (presumed)
SPIN 0
CP even
FERMIONIC COUPLING
m_f/v
BOSONIC COUPLING
$2m_V^2/v$
SELF COUPLING
$\lambda=M_H^2/2v^2$

How to answer the question(s)?

- (at least) Two approaches can be used:

Anomalous couplings (AC)
e.g JHU (arXiv: 1001.3396, 1208.4018)
✔ Only requirement is Lorentz symmetry
✔ Agnostic on new physics
✘ Non renormalizable
✘ Large number of extra couplings
✘ Possibly violate unitarity, yet can include model dependent form factors

Effective field theory (EFT)

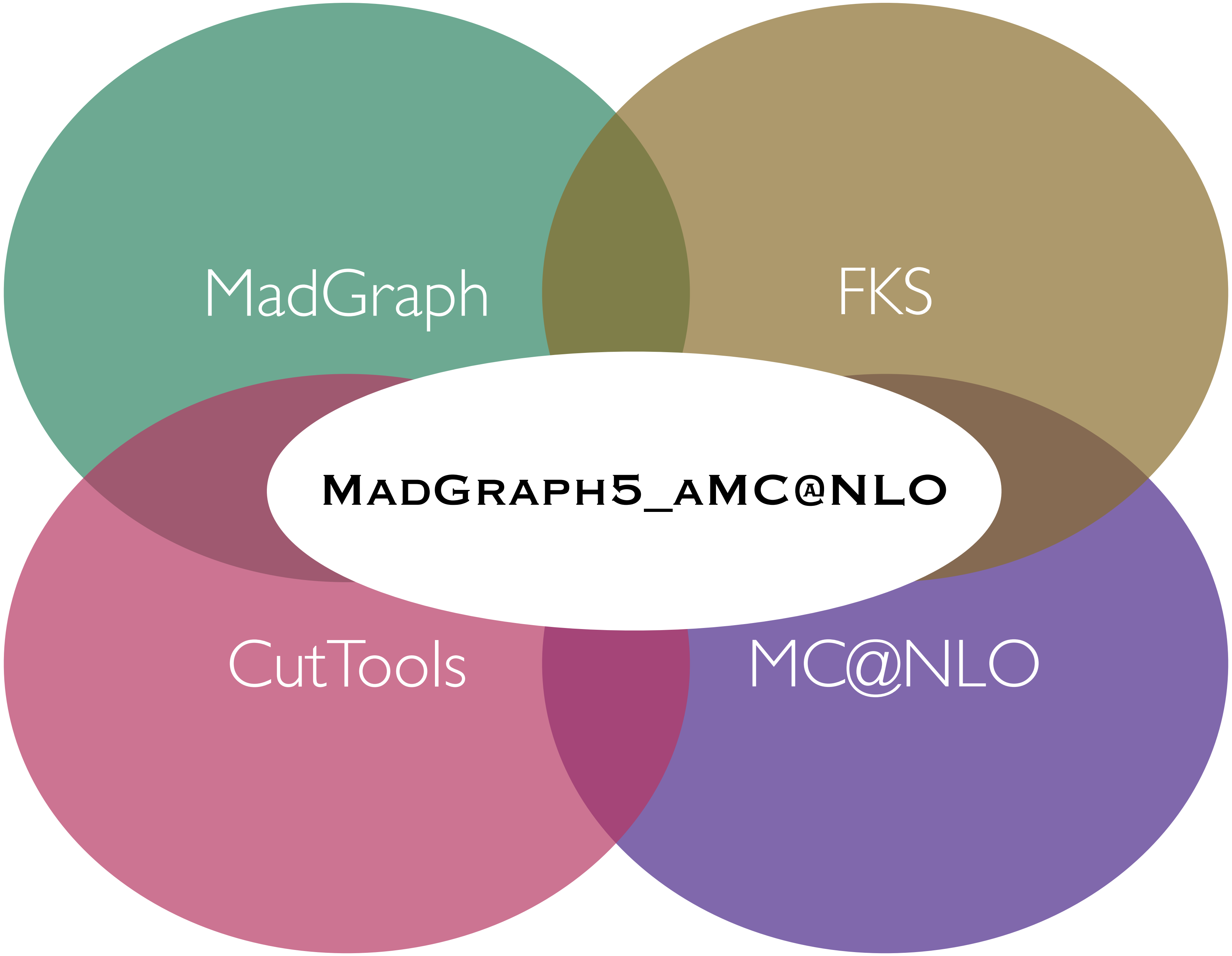
✔ Based on SM symmetries
✘ Valid only up to a scale Λ
✔/✘ New physics heavier than the resonance itself
✔ Renormalizable (order by order in $1/\Lambda$) → can include QCD corrections
✔ Reduce number of extra couplings by using symmetries and dimensional analyses

The HC-EFT approach

- Use the Higgs dim-6 effective Lagrangian and implement it in FeynRules → UFO model
- Add missing pieces needed for NLO QCD corrections UV/R_2
  - SM + Hgg
- Include QCD corrections in the MADGRAPH5_AMC@NLO framework → events (rates & distributions) at NLO in QCD
- Study different production and decay channels, keeping spin-correlations
- Disclaimer: we *assume* the EFT approach to be valid in all the phase-space

The MadGraph5_aMC@NLO framework

Alwall, Frederix, Frixione, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Hirschi, MZ, arXiv:1405.0301



Above the EW scale:

D6 Higgs Effective Lagrangian

slide from K. Mawatari@MC4BSM 2014

Buchmuller, Wyler, Nucl.Phys.B177 (1986)
Grzadkowski, Iskrzynski, Misiak, Rosiek, arXiv:1008.4884
Contino, Ghezzi, Grojean, Muhlleitner, Spira, arXiv:1303.3876
Alloul, Fuks, Sanz, arXiv:1310.5150

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

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

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

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

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

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

Below the EW scale:

Mapping between the D6 and D5 operators

slide from K. Mawatari@MC4BSM 2014

HC [arXiv: 1306.6464]

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

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big]$$

$$- \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big]$$

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

$$- \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big]$$

$$- \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big]$$

$$- \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big]$$

$$- \frac{1}{\Lambda} c_\alpha \big[\ldots$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad \ldots, \quad \widetilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} \ldots$$

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

HEL [arXiv: 1310.5150]

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

The two approaches are equivalent
NLO implementation extendible to HEL

The Lagrangian: Spin-0

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

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

cnrs

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The Lagrangian: Spin-0

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

SM

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

The Lagrangian: Spin-0

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

SM

$$\mathcal{L}_0^V = \Big\{ \boxed{c_\alpha \kappa_{\rm SM} \left[\frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\right]}$$

HD

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

The Lagrangian: Spin-0

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

SM

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

HD

0^+

The Lagrangian: Spin-0

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

SM

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

HD

0^+

0^-

The Lagrangian: Spin-0

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

SM

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

HD

0^+

0^-

0^+Der

The Lagrangian: Spin-1

[K. Hagiwara, R.D. Peccei, D. Zeppenfeld, Nuclear Physics B282 (1987)]

$$\mathcal{L}_1^f = \sum_{f=q,b,t,\ell,\tau} \bar{\psi}_f \gamma_\mu (\kappa_{f_a} a_f - \kappa_{f_b} b_f \gamma_5) \psi_f X_1^\mu, \quad \mathcal{L}_1^Z = -\kappa_{V_3} X_1^\mu (\partial^\nu Z_\mu) Z_\nu - \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma} X_1^\mu Z^\nu (\partial^\rho Z^\sigma).$$

$$\begin{aligned}\mathcal{L}_1^W = &+ i\kappa_{V_1} g_{WWZ} (W^+_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^{+\mu}) X_1^\nu \\ &+ i\kappa_{V_2} g_{WWZ} W^+_\mu W^-_\nu X_1^{\mu\nu} \\ &- \kappa_{V_3} W^+_\mu W^-_\nu (\partial^\mu X_1^\nu + \partial^\nu X_1^\mu) \\ &+ i\kappa_{V_4} W^+_\mu W^-_\nu \widetilde{X}_1^{\mu\nu} \\ &- \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma} [W^{+\mu} (\partial^\rho W^{-\nu}) - (\partial^\rho W^{+\mu}) W^{-\nu}] X_1^\sigma,\end{aligned}$$

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$$\begin{aligned}
\mathcal{L}_1^W = & + i\kappa_{V_1} g_{WWZ} (W^+_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^{+\mu}) X_1^\nu \\
& + i\kappa_{V_2} g_{WWZ} W^+_\mu W^-_\nu X_1^{\mu\nu} \\
& - \kappa_{V_3} W^+_\mu W^-_\nu (\partial^\mu X_1^\nu + \partial^\nu X_1^\mu) \\
& + i\kappa_{V_4} W^+_\mu W^-_\nu \widetilde{X}_1^{\mu\nu} \\
& - \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma} [W^{+\mu} (\partial^\rho W^{-\nu}) - (\partial^\rho W^{+\mu}) W^{-\nu}] X_1^\sigma,
\end{aligned}$$

- 1^- in parity-conserving scenarios

The Lagrangian: Spin-1

[K. Hagiwara, R.D. Peccei, D. Zeppenfeld, Nuclear Physics B282 (1987)]

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

$$\mathcal{L}_1^Z = - \kappa_{V_3} X_1^\mu (\partial^\nu Z_\mu) Z_\nu - \kappa_{V_5} \epsilon_{\mu\nu\rho\sigma} X_1^\mu Z^\nu (\partial^\rho Z^\sigma).$$

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- 1^- in parity-conserving scenarios
- 1^+ in parity-conserving scenarios

The Lagrangian: Spin-2

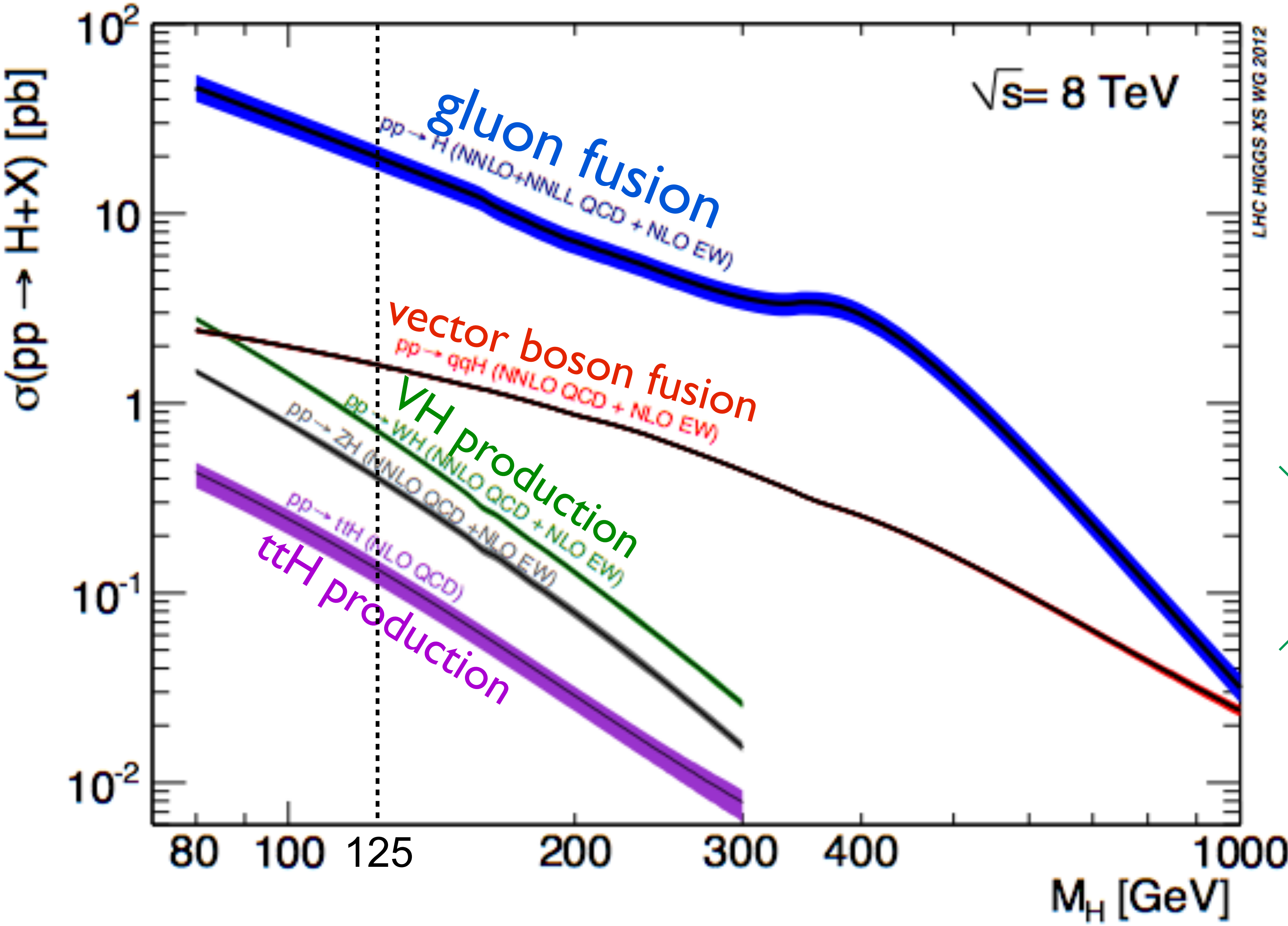
$$\mathcal{L}_2 = \frac{1}{\Lambda} \sum_{i=V,\gamma,g,\psi} k_i \, \mathcal{T}^i_{\mu\nu} \, X^{\mu\nu}$$

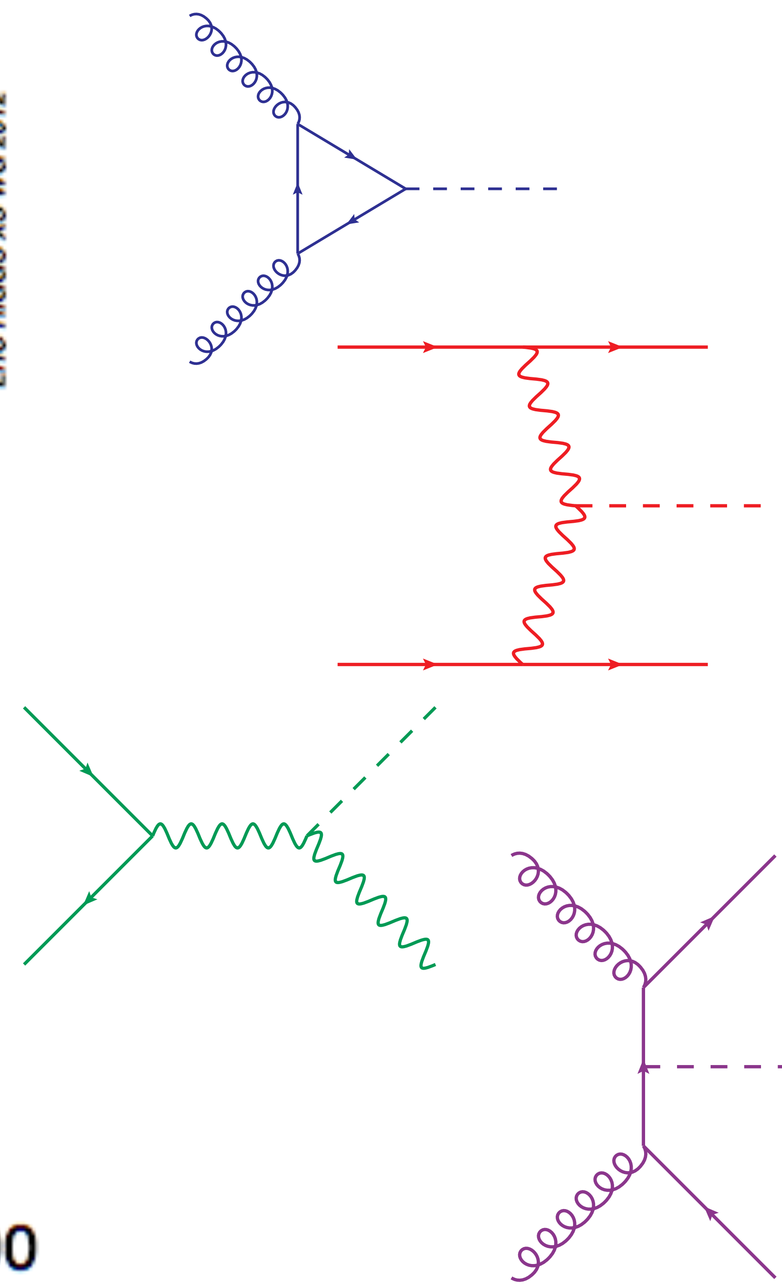
$$\mathcal{T}^V_{\mu\nu} = \frac{1}{4}\eta_{\mu\nu} F^{\rho\sigma} F_{\rho\sigma} - F_\mu^{\ \rho} F_{\nu\rho}$$

$$\mathcal{T}^\psi_{\mu\nu} = -\eta_{\mu\nu} \left(\bar\psi \, i \, \gamma^\rho D_\rho \psi - m \bar\psi \, \psi\right) + \frac{1}{2}\bar\psi \, i \, \gamma_\mu D_\nu \psi +$$
$$+ \frac{1}{2}\bar\psi \, i \, \gamma_\nu D_\mu \psi + \frac{1}{2}\eta_{\mu\nu}\partial^\rho(\bar\psi \, i \, \gamma_\rho \psi) - \frac{1}{4}\partial_\mu(\bar\psi \, i \, \gamma_\nu \psi)\frac{1}{4}\partial_\nu(\bar\psi \, i \, \gamma_\mu \psi)$$

The minimal spin-2 particle is graviton like (2+)
Higher dimension operators and 2- available

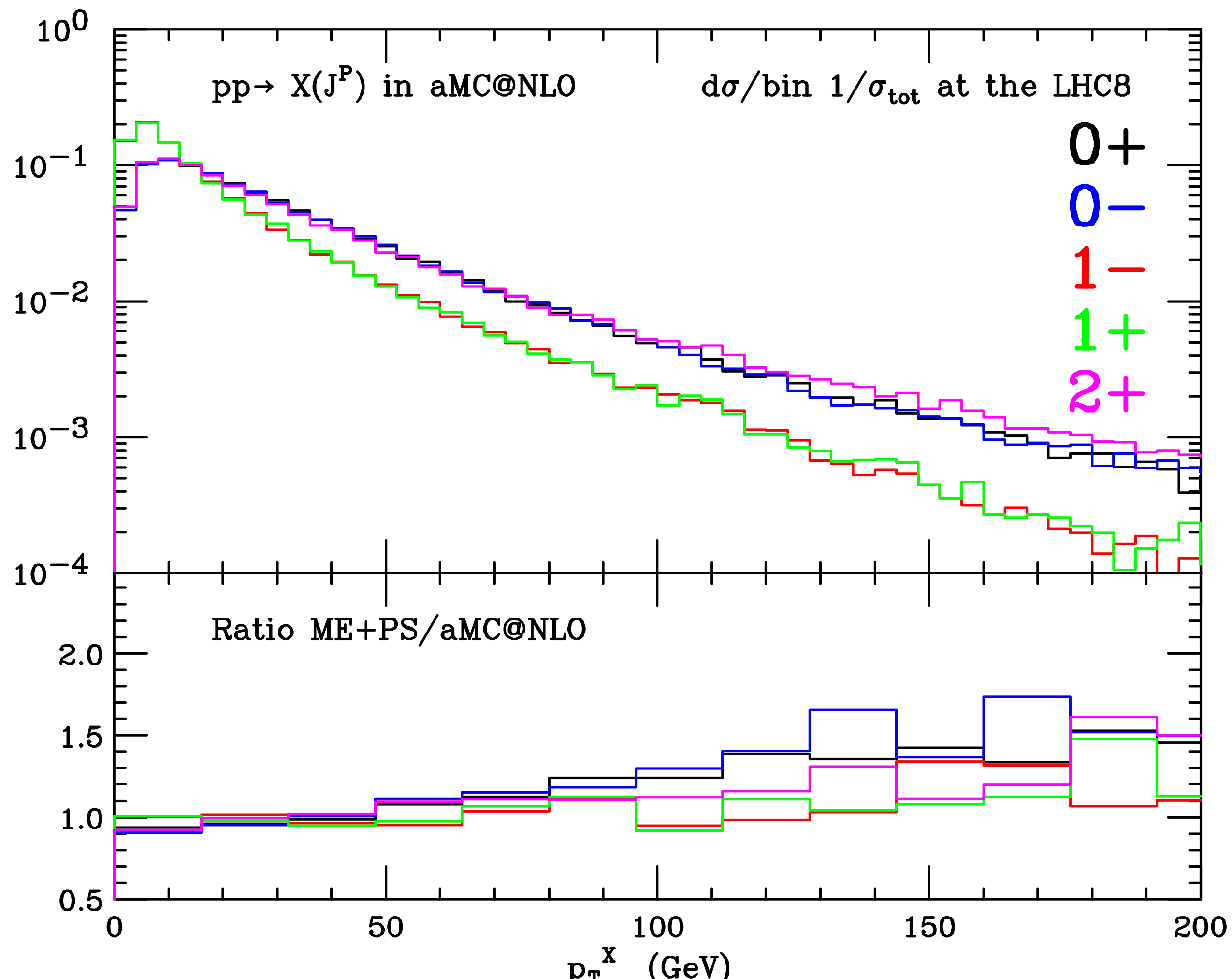
HC in the various production channels

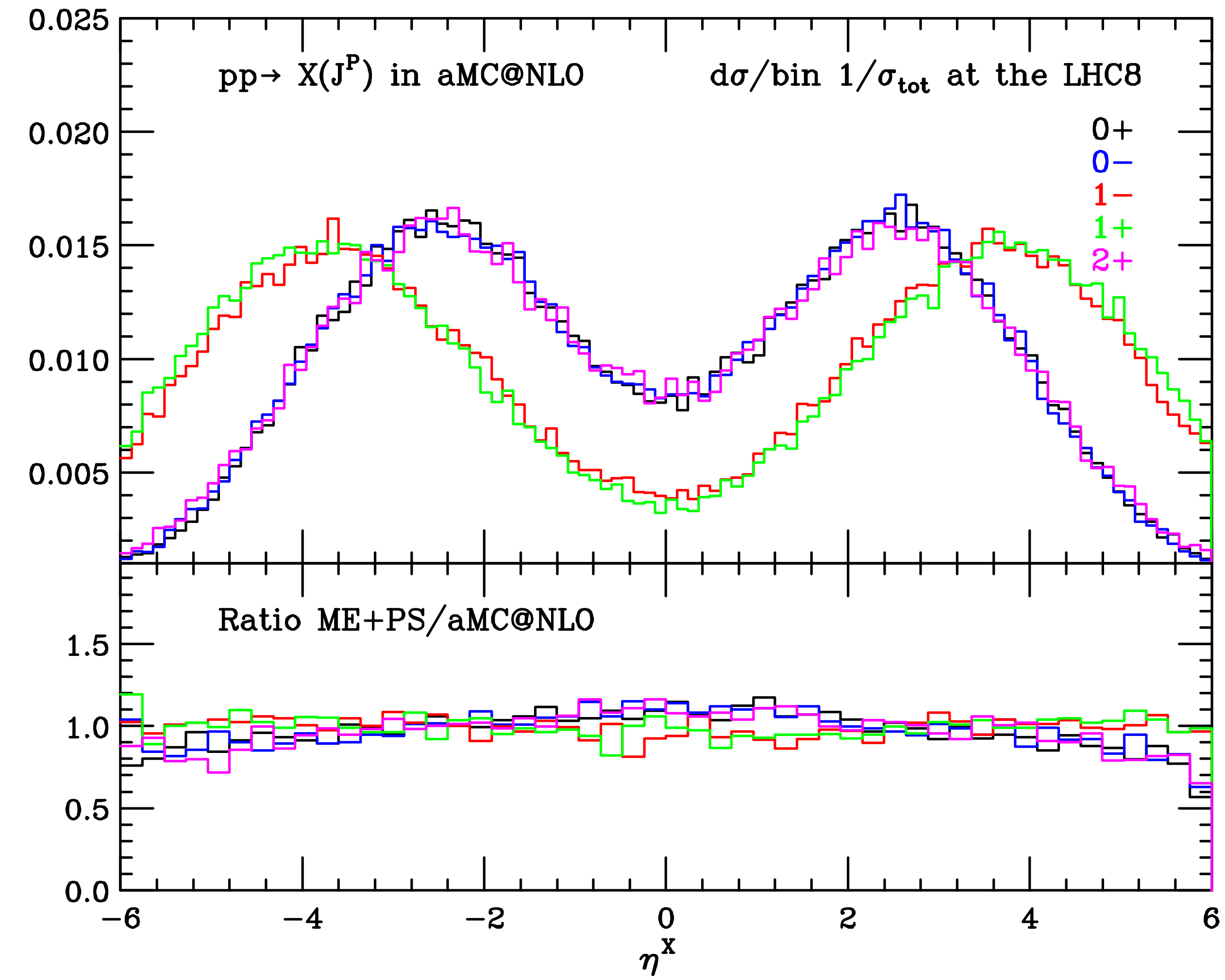




Chapter 1: spin/CP analysis in gg→X→…

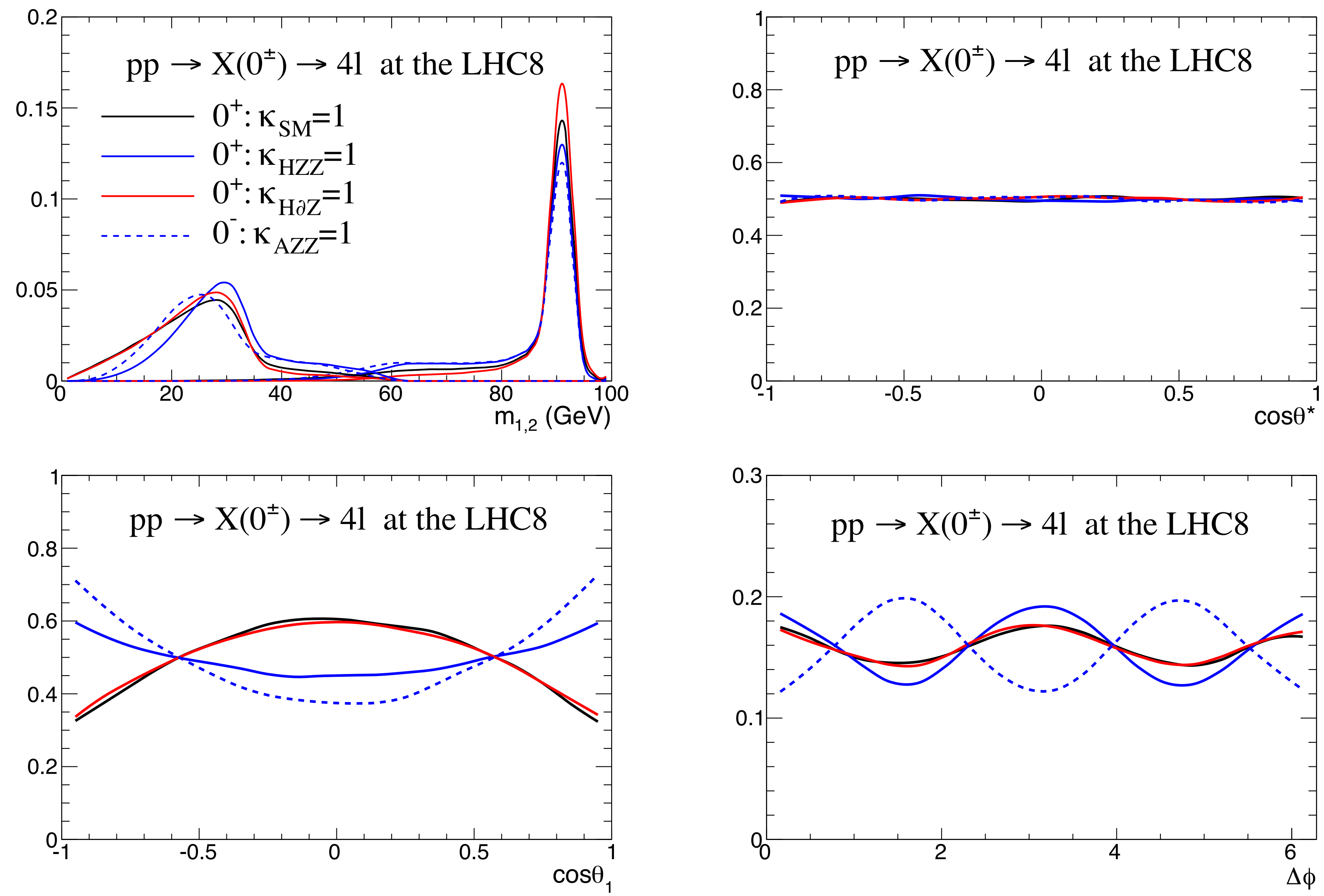
Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, MZ, arXiv:1306.6464





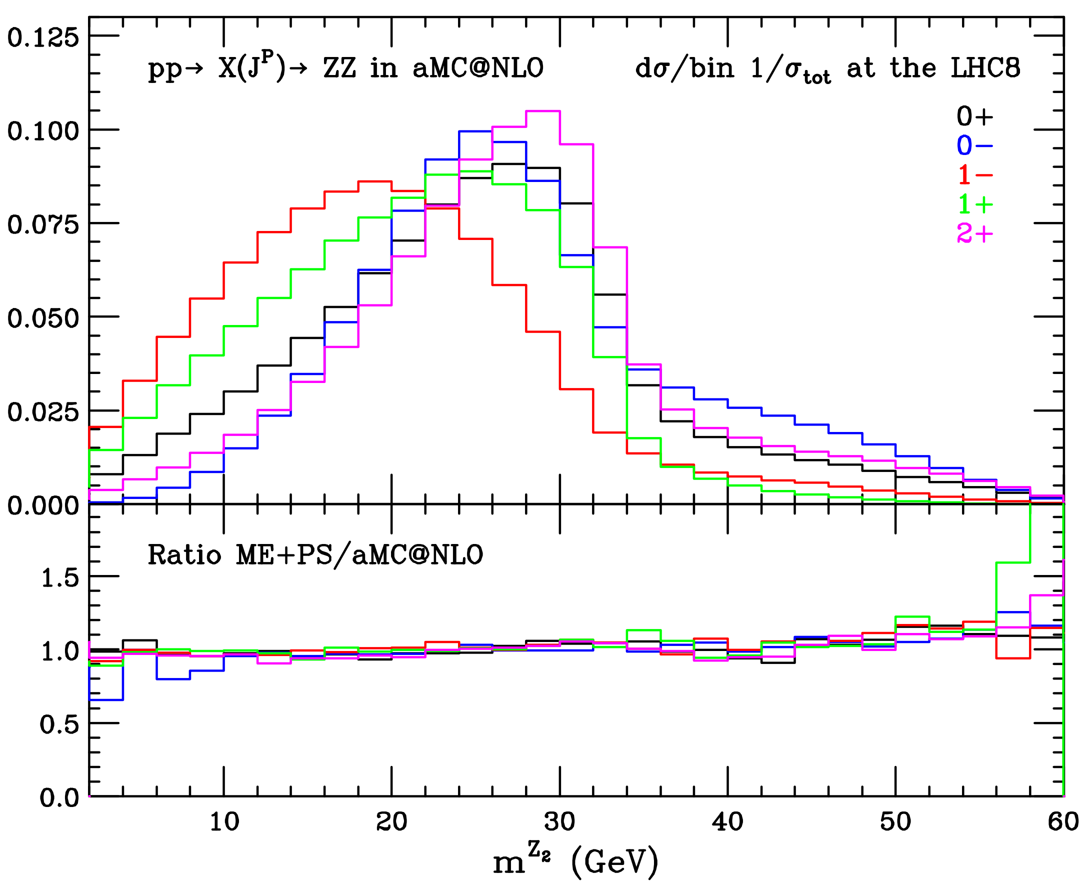
- Differences in shape are due to the different dominant initial state ($q\bar{q}$ for X^1, gg for X^0, X^2)
- MLM distributions are harder (as expected), otherwise agreement is quite good

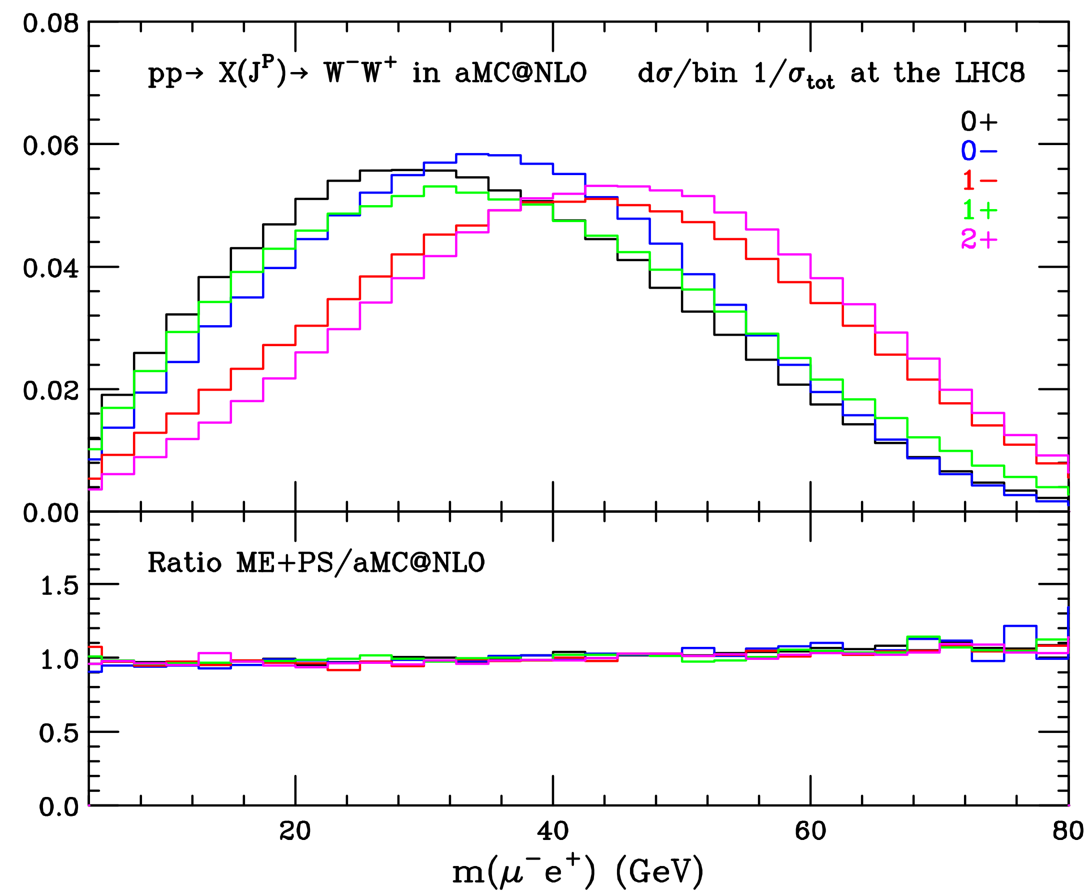
Results: decay into VV→4l at LO



Angles defined in Bolognesi et al. arXiv:1208.4018

Results:
decay into VV→4l /2l2ν at NLO+PS





Chapter 2:
HD effects in the VVH interactions

Maltoni, Mawatari, MZ, arXiv:1311.1829

SM

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \left[\frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\right]$$

HD

0+

$$- \frac{1}{4}\left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\right]$$

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

$$- \frac{1}{4}\left[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}\right]$$

$$- \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\right]$$

$$- \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\right]$$

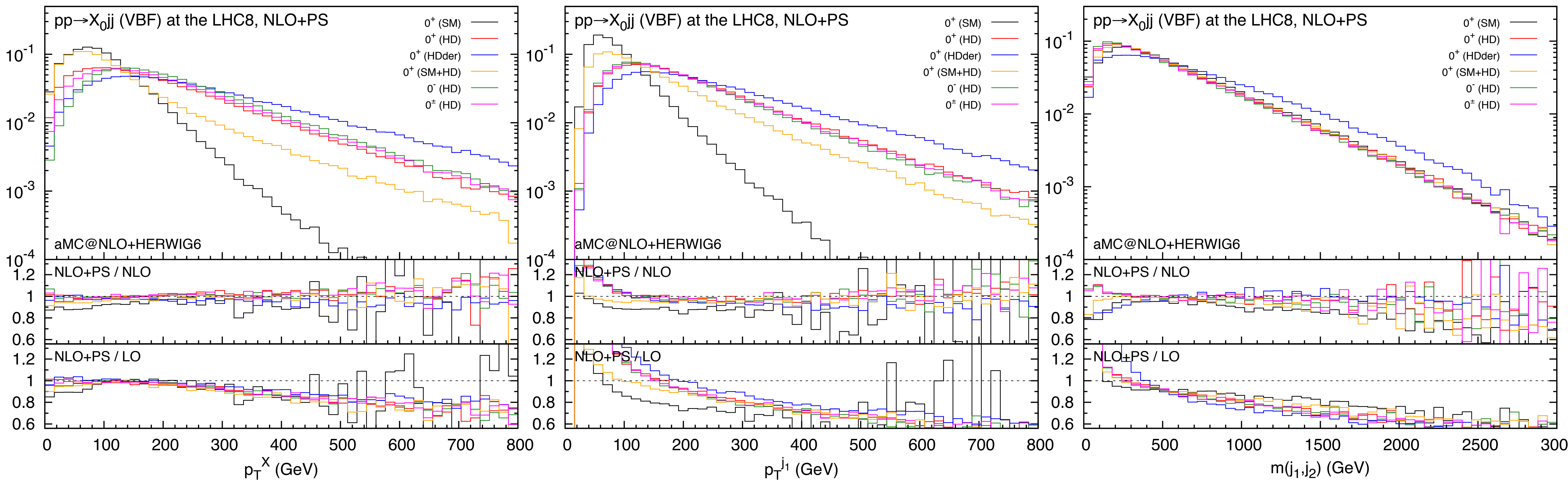
0-

$$- \frac{1}{\Lambda} c_\alpha \Big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu}$$

$$+ \left(\kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\right)\Big]\Big\} X_0\,, \qquad (1)$$

0+Der

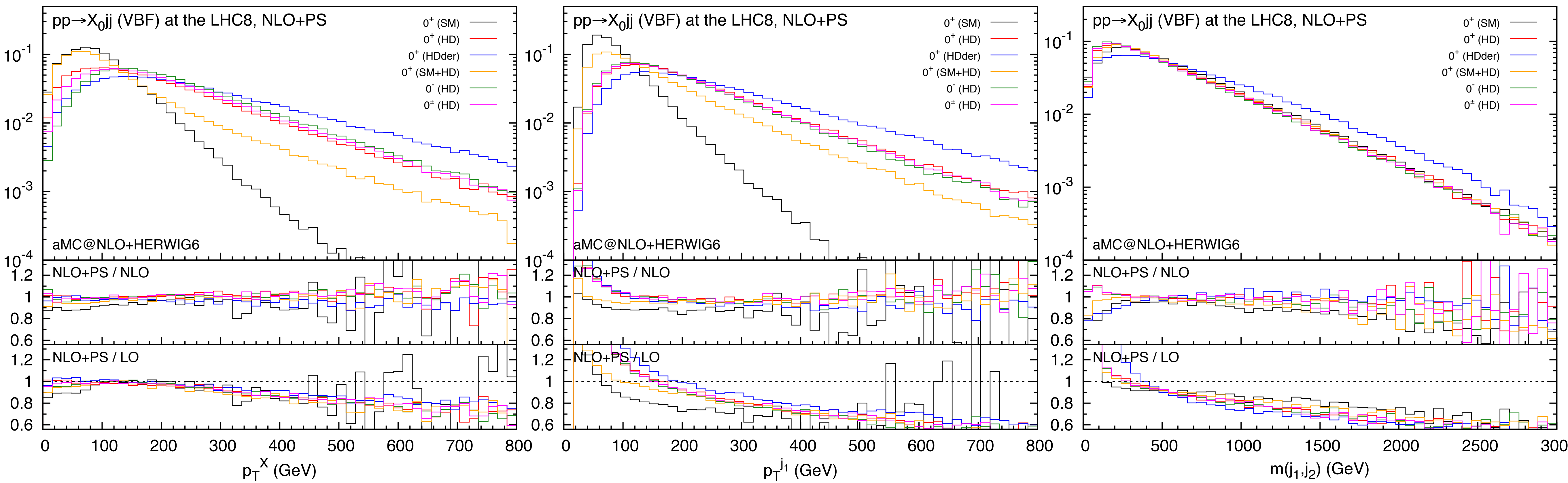
VBF



- SM case shows a softer behaviour (not for M_{jj})
- NLO and PS effects are important (in particular for jet-related observables)

0^+ (SM)
0^+ (HD)
0^+ (HDder)
0^+ (SM+HD)
0^- (HD)
$0^\pm$ (HD)

VBF



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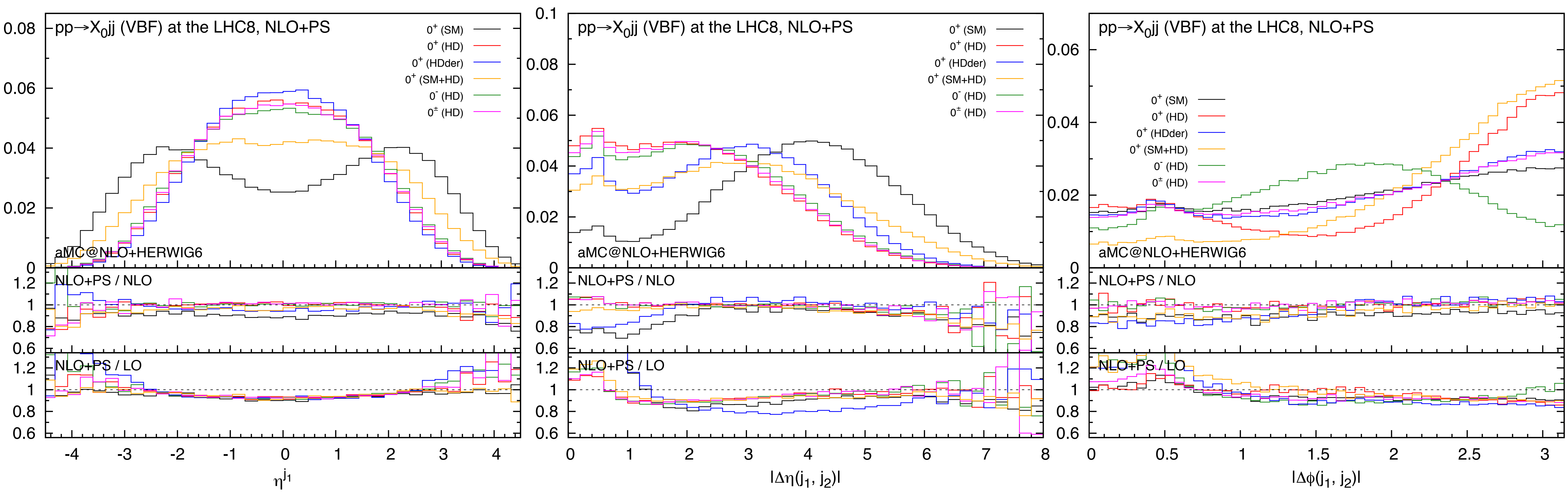
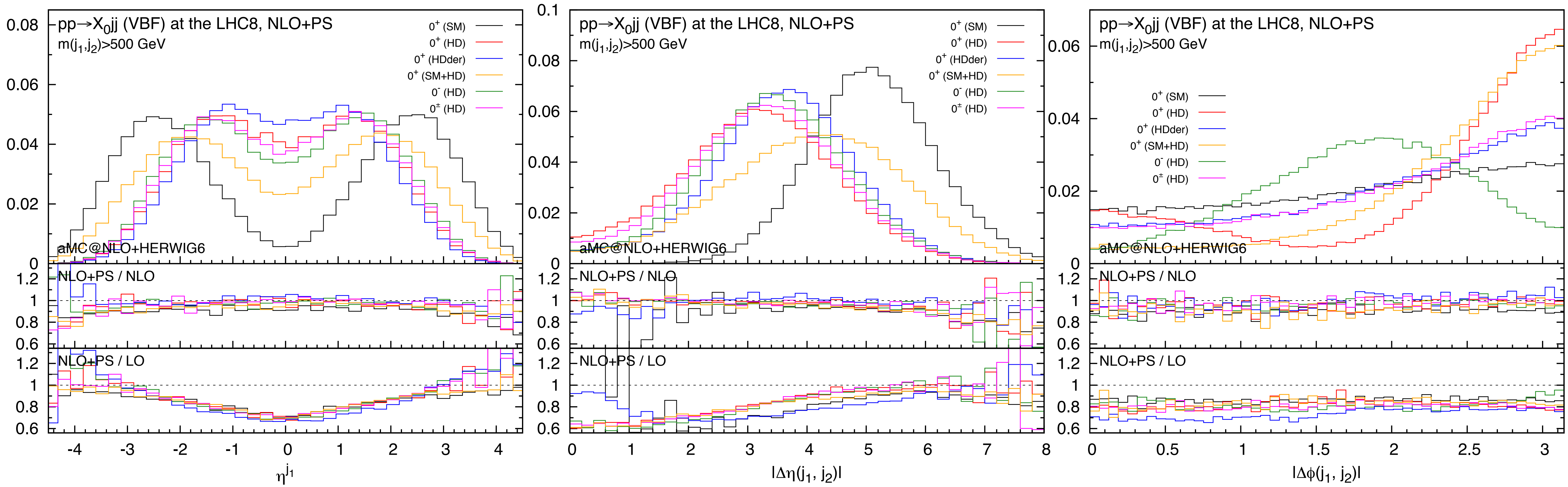
VBF



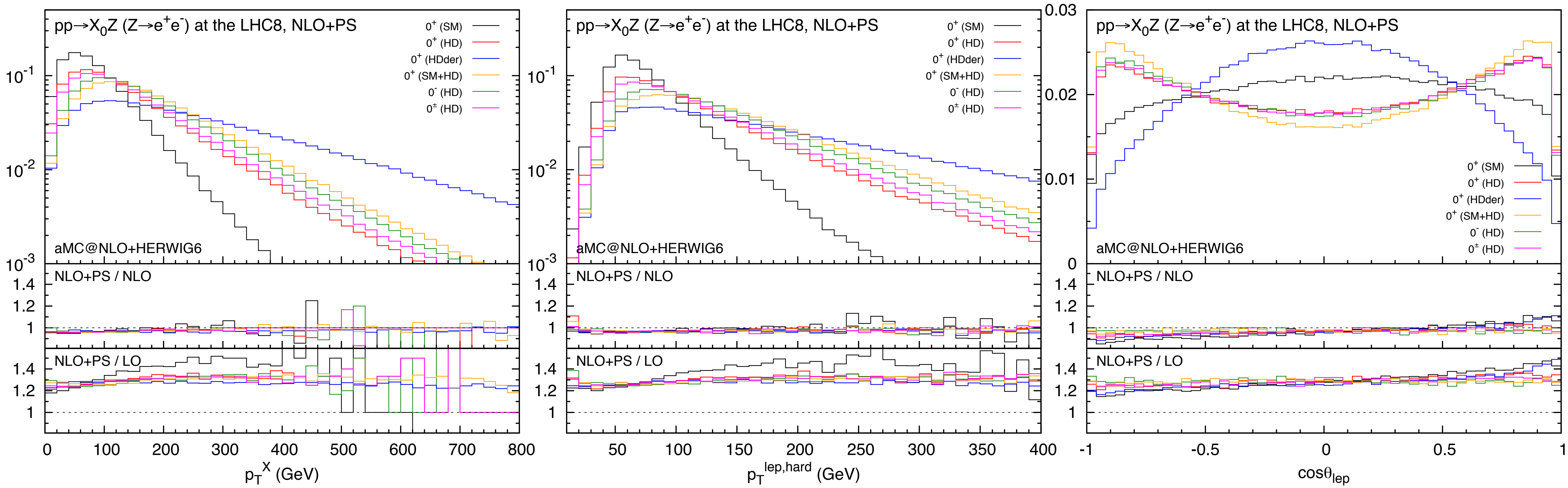
- In SM case jets are more forward: HD scenarios feature a different signature
- Jet correlations Δϕ, Δη are sensitive to the HVV structure

VBF (with extra M_{jj} cut):



- The extra M_{jj} cut pushes jets to be more separated
- No dramatic effects on angular correlations

ZX$_0$:



- SM is softer, HD harder, HDder much harder (contact interaction)
- QCD effects are less important than for VBF
- Similar features for WH

Chapter 3:
CP properties of the top Yukawa

Demartin, Maltoni, Mawatari, Page, MZ, arXiv:1407.5089

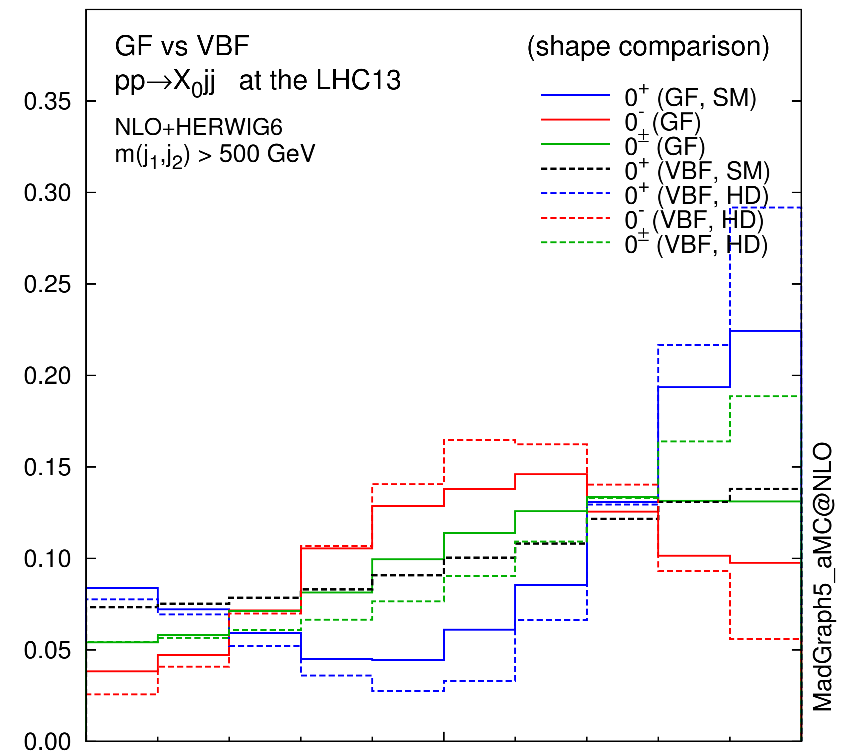
$$
\begin{aligned}
\mathcal{L}_0^{\rm loop} = \Big\{ & -\boxed{\frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu}} \\
& + \boxed{s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}}\big] \\
& - \boxed{\frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu}} \\
& + \boxed{s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\big]} \\
& - \boxed{\frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu}} \\
& + \boxed{s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \Big\}} X_0
\end{aligned}
$$

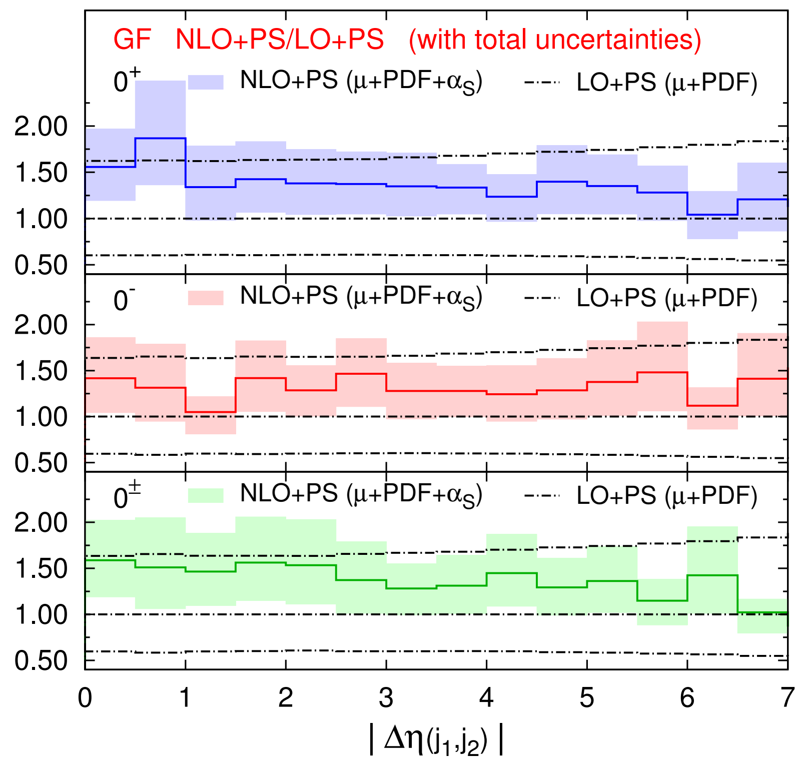
0^+

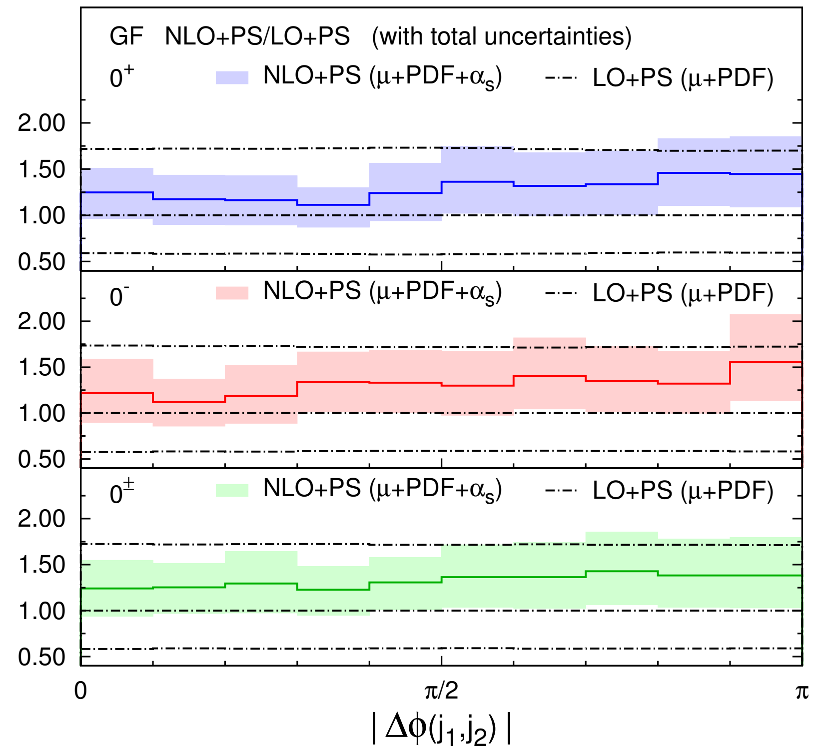
0^-

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

Jet correlations in X_0jj





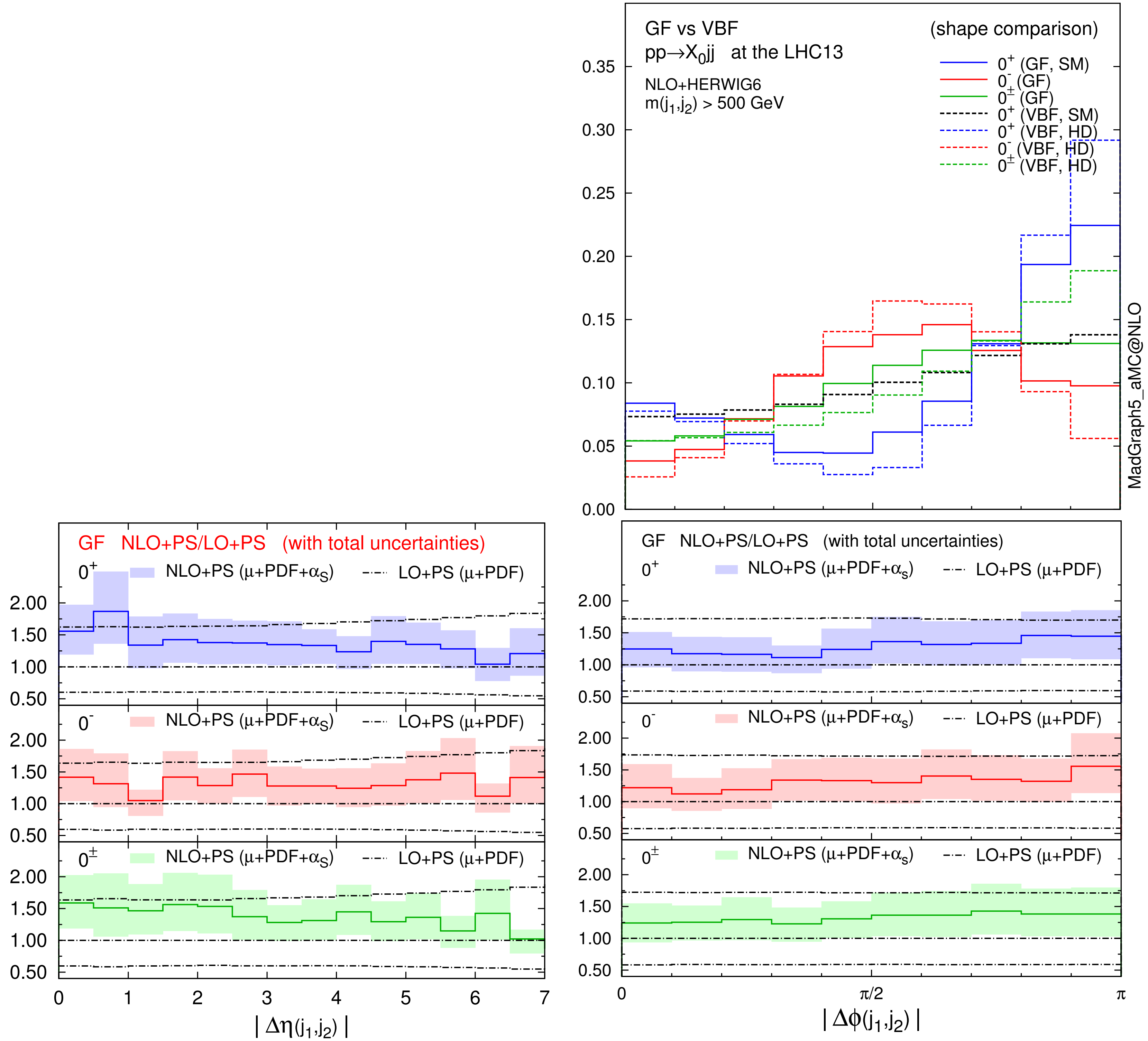


- VBF-like cuts enhance the *t*-channel gluon exchange, which is more sensitive to CP

Hagiwara, Li, Mawatari, arXiv:0915.4314

- NLO corrections are large, (~30%) and not flat

Jet correlations in X_0jj

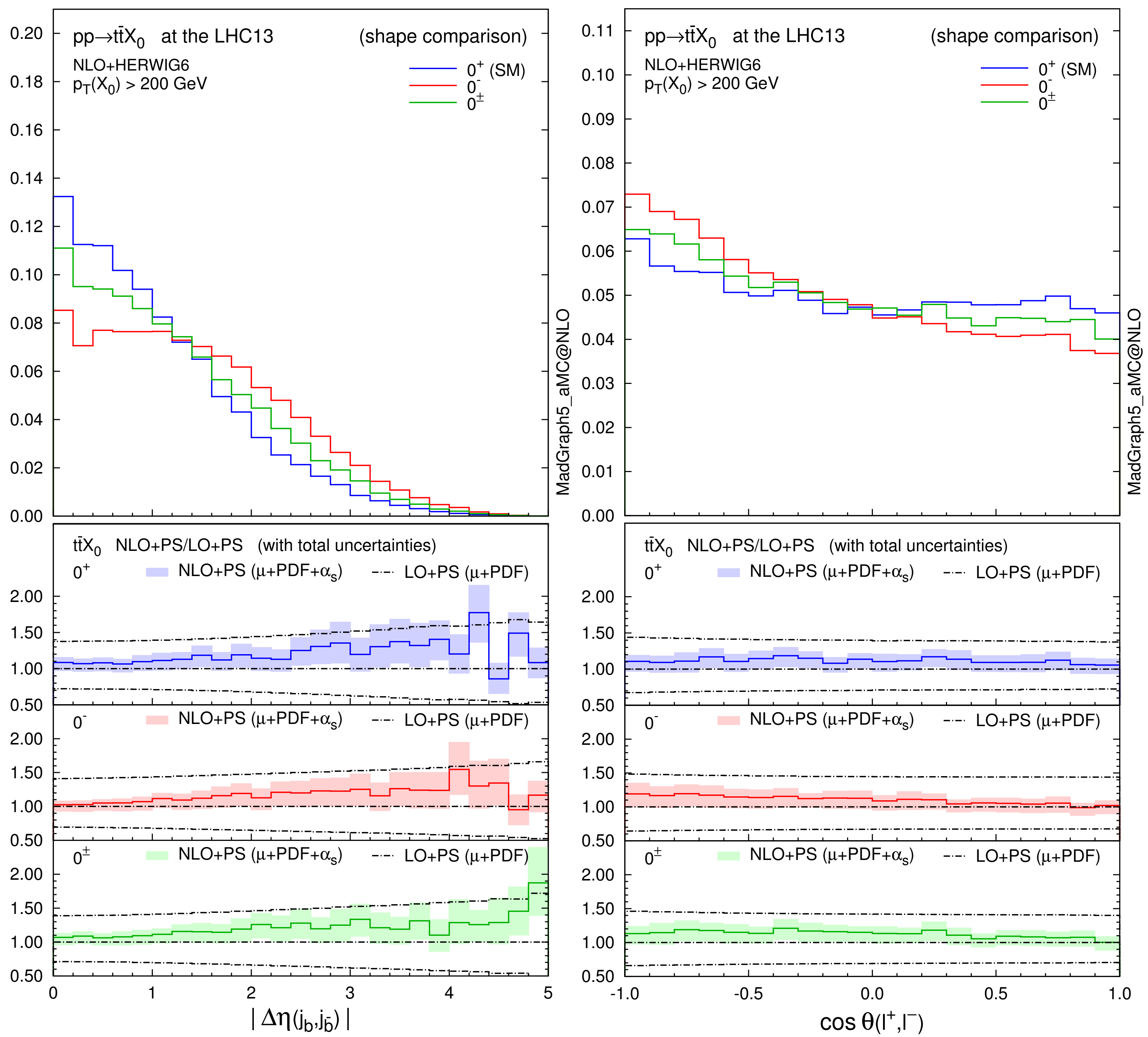


- VBF-like cuts enhance the *t*-channel gluon exchange, which is more sensitive to CP

Hagiwara, Li, Mawatari, arXiv:0915.4314

- NLO corrections are large, (~30%) and not flat

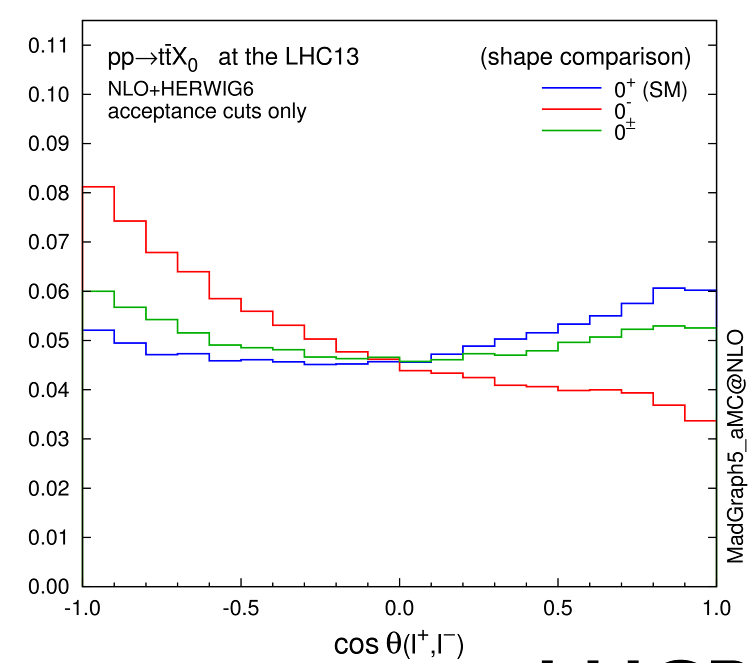
Spin correlation effects in $t\bar{t}X_0$



- Spin correlations of the top decay products kept with MadSpin

Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

- Requiring a boosted Higgs reduces CP sensitivity for angular correlations
- NLO effects of ~20%, not flat



Do it yourself!

- The code for the shown processes can be automatically generated with MadGraph5_aMC@NLO (available at http://amcatnlo.cern.ch)
- The HC-NLO model (with UV/R2 counterterms) is publicly available on the FeynRules database https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation
- E.g. $t\bar{t}X_0$:

Do it yourself!

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- The HC-NLO model (with UV/R2 counterterms) is publicly available on the FeynRules database https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation
- E.g. $t\bar{t}X_0$:

```
> import model HC-NLO
> generate p p > X0 t t~ [QCD]
```

Conclusions

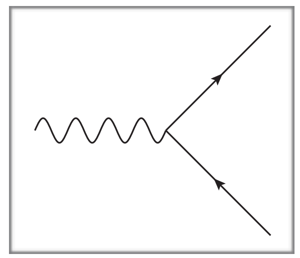
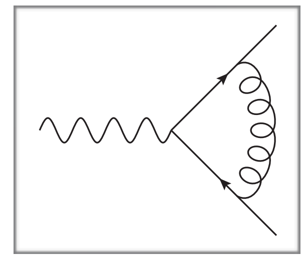
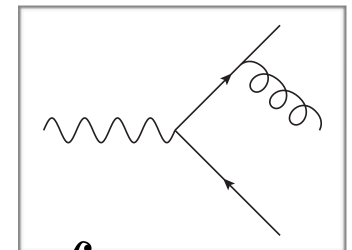
- After the discovery of the Higgs boson, huge efforts have been set up in order to tell wether it is the SM Higgs
- EFT is a powerful tool for understanding the spin/CP/coupling nature of the Higgs
  - No hypotheses on the NP
  - Can be improved beyond the LO
- HC-EFT approach applied to all the main Higgs production channels, including NLO+PS QCD corrections
- Model publicly available and easy to use with MadGraph5_aMC@NLO
- The best is yet to come! (aka let's wait for LHC13 data)

Thank you for your attention!

Backup slides

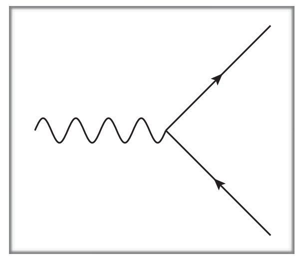
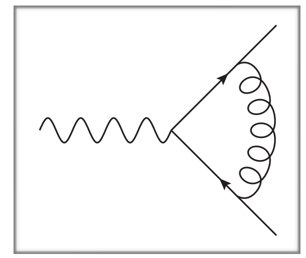
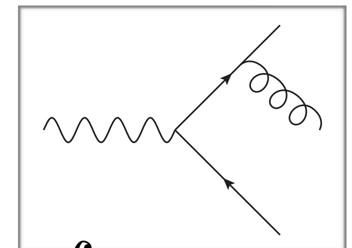
NLO: how to?

NLO: how to?

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

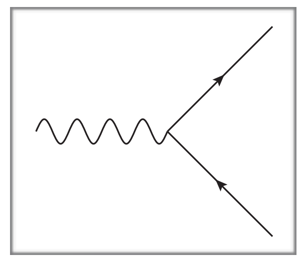
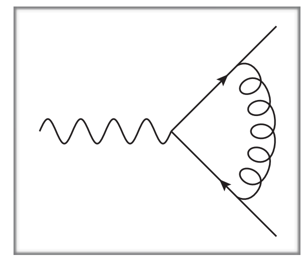
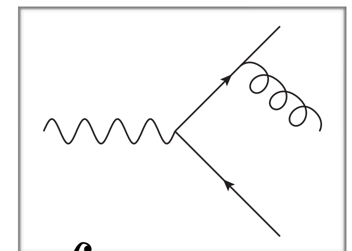
NLO: how to?

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \; d\sigma^{n+1}_R$$

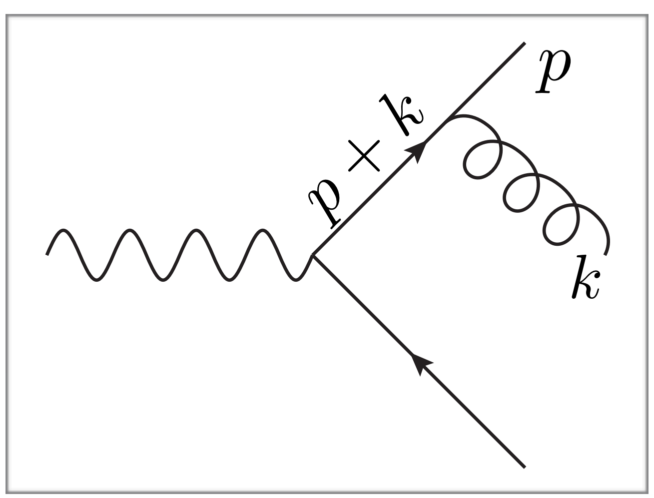
- Warning! Real emission ME is divergent!
  - Divergences cancel with those from virtuals (in D=4-2eps)
  - Need to cancel them before numerical integration (in D=4)

NLO: how to?

$$d\sigma^n_{NLO} \quad = \quad d\sigma^n_{LO} \quad + \quad d\sigma^n_V \quad + \int d\Phi_1 \; d\sigma^{n+1}_R$$

- Warning! Real emission ME is divergent!
  - Divergences cancel with those from virtuals (in D=4-2eps)
  - Need to cancel them before numerical integration (in D=4)
- Structure of divergences is universal:

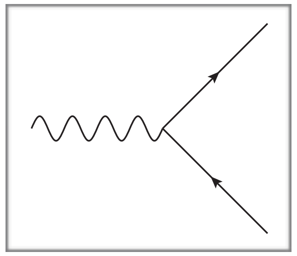
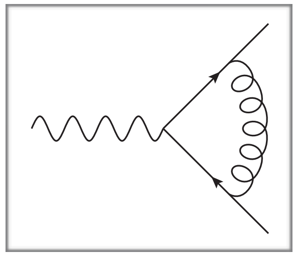
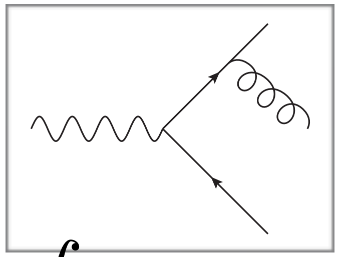


$$(p+k)^2 = 2E_p E_k (1 - \cos\theta_{pk})$$

$$\lim_{p//k} |M_{n+1}|^2 \simeq |M_n|^2 \; P^{AP}(z)$$

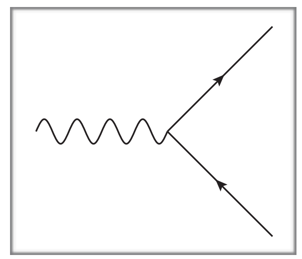
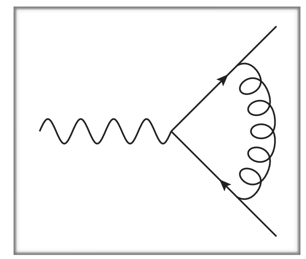
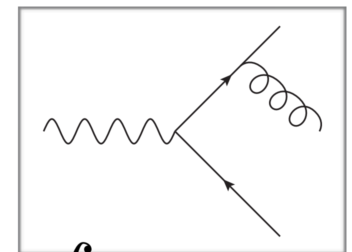
$$\lim_{k \to 0} |M_{n+1}|^2 \simeq \sum_{ij} |M_n^{ij}|^2 \frac{p_i p_j}{p_i k \; p_j k}$$

NLO: how to?

$$d\sigma^{n}_{NLO} \quad = \quad d\sigma^{n}_{LO} \quad + \quad d\sigma^{n}_{V} \quad + \int d\Phi_1 \; d\sigma^{n+1}_{R}$$

NLO: how to?

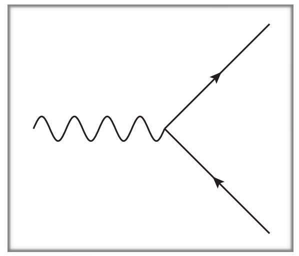
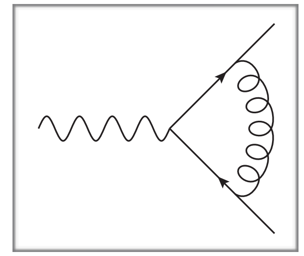
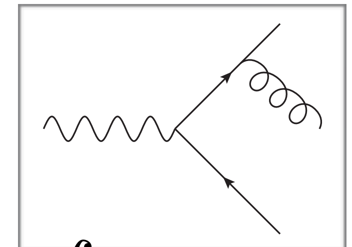
  

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V - \int d\Phi_1 \, C + \int d\Phi_1 \, \left(C + d\sigma^{n+1}_R\right)$$

- Add local counterterms in the singular regions and subtract its integrated finite part (poles will cancels against the virtuals)
- The *n* and *n+1* body integral now are finite in 4 dimension
  - Can be integrated numerically

NLO: how to?

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How to do this in an efficient way?

The FKS subtraction

Frixione, Kunszt, Signer, arXiv:hep-ph/9512328

- Soft/collinear singularities arise in many PS regions
- Find parton pairs *i*, *j* that can give collinear singularities
- Split the phase space into regions with one collinear sing
  - Soft singularities are split into the collinear ones

$$|M|^2 = \sum_{ij} S_{ij} |M|^2 = \sum_{ij} |M|^2_{ij} \qquad \sum S_{ij} = 1$$

$$S_{ij} \to 1 \text{ if } k_i \cdot k_j \to 0 \qquad S_{ij} \to 0 \text{ if } k_{m\neq i} \cdot k_{n\neq j} \to 0$$

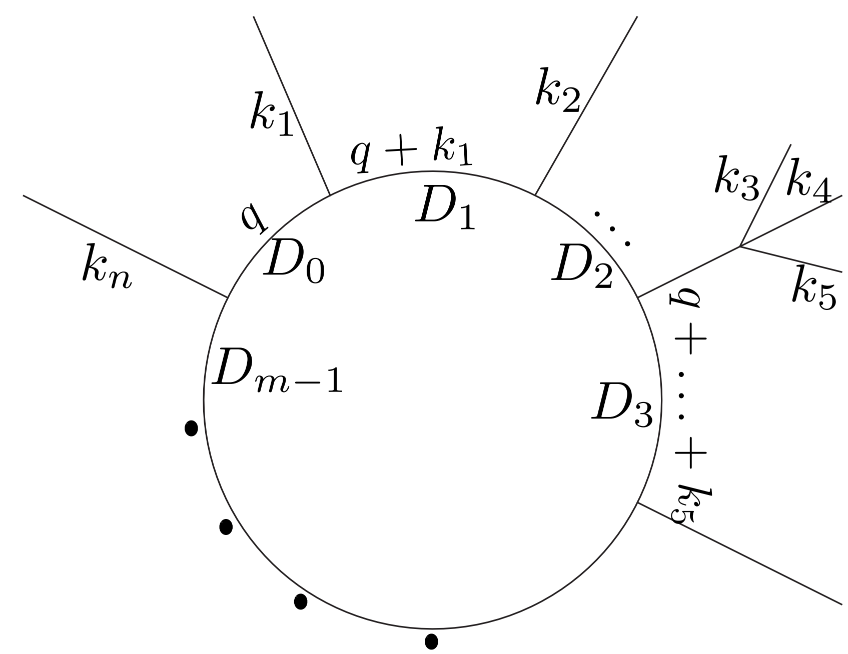
- Integrate them independently
  - Parallelize integration
  - Choose ad-hoc phase space parameterization
- Advantages:
  - # of contributions ~ n^2
  - Exploit symmetries: 3 contributions for `X Y > ng`

Loops: the OPP Method

Ossola, Papadopoulos, Pittau, arXiv:hep-ph/0609007 & arXiv:0711.3596

- Passarino & Veltman reduction:
  - Write the amplitude at the integral level as linear combination of 1-...-4-point scalar integrals

$$
\begin{aligned}
A(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1} d(i_0 i_1 i_2 i_3) D_0(i_0 i_1 i_2 i_3) \\
&+ \sum_{i_0<i_1<i_2}^{m-1} c(i_0 i_1 i_2) C_0(i_0 i_1 i_2) \\
&+ \sum_{i_0<i_1}^{m-1} b(i_0 i_1) B_0(i_0 i_1) \\
&+ \sum_{i_0}^{m-1} a(i_0) A_0(i_0) \\
&+ R
\end{aligned}
$$



  - Do this at the integrand level

Loops: the OPP Method

Ossola, Papadopoulos, Pittau, arXiv:hep-ph/0609007 & arXiv:0711.3596

$$A(\bar{q}) = \frac{N(q)}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

$$\begin{aligned} N(q) \ = \ & \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)\right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i \\ + & \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)\right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\ + & \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1)\right] \prod_{i \neq i_0, i_1}^{m-1} D_i \\ + & \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0)\right] \prod_{i \neq i_0}^{m-1} D_i \\ + & \tilde{P}(q) \prod_{i}^{m-1} D_i \,. \end{aligned}$$

- Sample the numerator at complex values of the loop momenta in order to reconstruct the *a,b,c,d* coefficients and part of the rational terms (R1)
- Use CutTools: fed with the loop numerator outputs the coefficients of the scalar integrals and CC rational terms (R1)
- Add R2-rational terms/UV counterterms
  - Model dependent but process-independent

Loop ME evaluation: MadLoop

Hirschi et al. arXiv:1103.0621

- Load the NLO UFO model
- Generate Feynman diagrams to evaluate the loop ME
- Add R2/UV renormalisation counter terms
- Interface to CutTools or to tensor reduction programs (in progress)
- Check PS point stability (and switch to QP if needed)
- Improved with the OpenLoops method

  Cascioli, Maierhofer, Pozzorini arXiv:1111.5206
- And much more (can be used as standalone or external OLP via the BLHA, handle loop-induced processes, …)

Matching in MC@NLO

- Use suitable counterterms to avoid double counting the emission from shower and ME, keeping the correct rate at order α_s:

$$\frac{d\sigma_{MC@NLO}}{dO} = \underbrace{\boxed{\left(\mathcal{B} + \mathcal{V} + \int d\Phi_1 MC\right) d\Phi_n \; I^n_{MC}(O)}}_{\text{S-events}} + \underbrace{\boxed{(\mathcal{R} - MC)\, d\Phi_n \; d\Phi_1 \; I^{n+1}_{MC}(O)}}_{\text{H-events}}$$

- MC depends on the PSMC's Sudakov:

$$MC = \left| \frac{\partial\left(t^{MC}, z^{MC}, \phi\right)}{\partial \Phi_1} \right| \frac{1}{t^{MC}} \frac{\alpha_s}{2\pi} \frac{1}{2\pi} P\left(z^{MC}\right) \mathcal{B}$$

- Available for Herwig6, Pythia6 (virtuality-ordered), Herwig++, Pythia8 (in the new release)
- MC acts as local counterterm
- Some weights can be negative (unweighting up to sign)
  - Only affects statistics