UCL
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MC tools for EFT studies at the LHC

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Niels Bohr Institute, Copenhagen

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Overview

- Guided tour of current EFT tools market - mainly Higgs
- Status of theory predictions for LHC processes
  - Higher order calculations
  - MC event generation
- EFT at the LHC
  - Contrast with anomalous coupling description from MC implementation & LHC analysis point of view
- Overview of available tools & what they can do
  - Specific production processes
  - More general model/event generation frameworks
  - Higgs decays, global fits & EFT basis translation

The goal

- Develop the required technology to make accurate & precise predictions for EFT at the LHC
- Include all processes sensitive to the Wilson coefficients of our operator expansion
- Combine run 1 & 2 data with low energy experiments into global fits
- EFT interpretation may guide is in searching for and constraining new physics at the TeV scale

How to get there

- Theory
  - Increasing precision (loops) in predictions including EFT operators
  - QFT: theory uncertainty (PDF/scale) under control
  - EFT: theory uncertainty more complex, coupled to the question of the validity of the expansion in addition to scale dependence & mixing of operators.
  - Can we be truly model independent?
- Practical
  - Tools for higher order calculations, event generation
  - Fixed order & matching/merging with parton shower
- Experimental
  - Reporting & analysis of results compatible with EFT interpretation

State of the art

- Continuing progress in higher order calculations for LHC processes
- NLO QCD is the new LO
- NNLO (N^3LO) in QCD and/or N(N)LO EW corrections are the cutting edge
- MC tools are following suit
  - Wide array of integrator/event generation software to choose from
  - Essential components of the precision LHC programme
  - Automation at NLO in QCD: from Lagrangian to LHC events
  - Also some EW corrections

EFT at the LHC

- The LHC will continue to provide much complementary information to previous constraints
  - Probing blind directions in fits
  - Higher order predictions are needed to keep up with data & improve sensitivity
- Theory
  - Basis definitions & anomalous coupling (AC) Lagrangians (+ translations)
  - We know how to perform loop calculations & renormalise EFT

[R. Alonso, E. Jenkins, A. Manohar & M. Trott;*
JHEP 1310 (2013) 087, JHEP 1401 (2014) 035 & JHEP 1404 (2014) 159]*

- Tools
  - Increasing numbers of predictions including anomalous coupling/EFT exist
  - A great deal of experimental interest in expanding these

EFT & AC: implementation

- Anomalous coupling Lagrangians start out in the mass eigenbasis of SM fields e.g. after EWSB
    - Physically intuitive & can directly calculate/implement MC generators
    - SU(3) x $U(1)_Q$ gauge symmetry only
    - Expand in canonical dimension, derivatives,…
- EFT expansions are the mapping from UV theories
    - Linear: Higgs is a doublet, $SU(2)_L$ symmetry also present
    - Non-linear: Higgs as a singlet + chiral EW Lagrangian
- Must first break EW symmetry and map to the mass eigenbasis in order to make predictions for the LHC
    - Generally a one-way map EFT → AC & parameters will be (cor)related

EFT & AC: map

$$\begin{aligned}\mathcal{O}_H =& \frac{\bar{c}_H}{2}\partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)\\ =& \frac{\bar{c}_H}{\Lambda^2}\frac{v^2}{2}\partial_\mu h\partial^\mu h + \mathcal{O}(h^3, h^2)\end{aligned}$$

$$h \to h(1+\delta h), \quad \delta h = -\frac{\bar{c}_H}{\Lambda^2}\frac{v^2}{4}$$

$$\begin{aligned}\mathcal{O}_W|_{\Phi=\langle\Phi\rangle} =& \frac{ig}{2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu}|_{\Phi=\langle\Phi\rangle}\\ =& \frac{gv^2}{16}\bar{c}_W\left[2gW_+^{\mu\nu}W^-_{\mu\nu} + g(W_3^{\mu\nu} - g' B^{\mu\nu})W^3_{\mu\nu}\right] + \text{aGC}\end{aligned}$$

$$\begin{aligned}W^\mu_\pm \to& W^\mu_\pm\left[1+\delta W\right]\\ B^\mu \to& B^\mu\left[1+\delta B\right] + yW^\mu_3\\ W^\mu_3 \to& W^\mu_3\left[1+\delta W\right] + zB^\mu\end{aligned}$$

$$\boxed{y + z \equiv -\frac{v^2}{\Lambda^2}\frac{gg'}{4}\left(\bar{c}_B + \frac{\bar{c}_W}{2}\right)}$$

- Canonical mass eigenbasis Lagrangian generically different from the SM case
  - Non canonical kinetic terms & kinetic mixing
  - Infinite freedom in how one redefines fields (equivalent up to $1/\Lambda^2$)
  - EFT contributions to masses and couplings
- Some extra book-keeping required…

EFT & AC: map

- 'SM-like' EW sector is modified
  - New relations between SM inputs and EW parameters
  - $v(G_F, c_i)$, $\sin\theta_W(m_W, m_Z, \alpha_{EM}, c_i)$, …
  - Higgs couplings rescaled
  - Z couplings to fermions
  - SM gauge bosons self interactions
  - Many of these effects are constrained pre-LHC (i.e. by EWPO)
- Additional $1/\Lambda^2$ pieces on top of direct effects from new operators/Lorentz structures
  - Depends on SM input scheme used
  - Can contribute to SM backgrounds!

[Trott & Passarino; LHCHXSWG-DRAFT-2016-005]
[Falkowski et.al; LHCHXSWG-INT-2015-001]
[Williams, KM & Sanz; JHEP 1608 (2016) 039]
[Ge, He & Xiao; JHEP 1610 (2016) 007]
[Degrande, Fuks, Mawatari, KM, Sanz; 1609.04833]

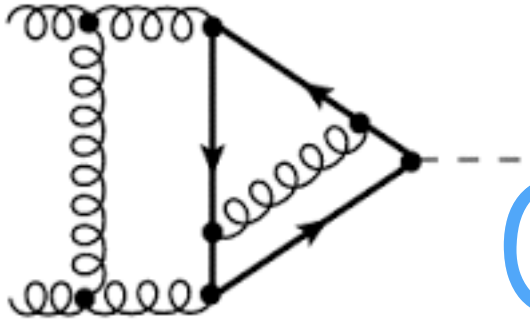
EFT & AC: interpretation

- Tree-level effects
  - Important to ensure it is consistent before moving to higher orders in PT
- AC implementations do not need to consider such things
  - Potentially complicates the ‘one-way map’
  - There is a way to at least preserve SM input relations (Higgs Basis)

[A. Falkowski et.al; LHCHXSWG-INT-2015-001]

- If AC are used to simulate signal & interpret data
  - From a pure Lorentz structure basis, the EFT parameter space is a subset of the general AC description
  - Mapping constraints from a multi parameter AC fit to an EFT interpretation may be tricky & relevant parameter space is larger than it originally seems
  - e.g. H→WW: might also need to include rescalings of the WW background
  - Assess how big these effects can be

Tools for LHC processes



Gluon-gluon fusion

$$\mathcal{L}_{\text{SILH}} = y_u \frac{g_s^2 \bar{c}_g}{m_W^2} |\Phi|^2 - y_u \frac{\bar{c}_u}{v^2} |\Phi|^2 \bar{Q}_L \tilde{\Phi}\, u_R + \frac{\bar{c}_H}{2v^2} \partial^\mu |\Phi|^2 \partial_\mu |\Phi|^2 - \lambda \frac{\bar{c}_6}{v^2} |\Phi|^6$$

$$\mathcal{L}_{\text{eff.}} = -m_t\, \bar{t}t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{2v^2} \right) - \frac{m_h^2}{2v} c_3 h^3 + \frac{\alpha_S}{\pi} G^{\mu\nu} G_{\mu\nu} \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right)$$

- Much effort had been invested into this process
- EFT: Modified Higgs, top & gluon interactions
  - Contribution from chromomagnetic operator often not included
  - Arises at one-loop in perturbative UV completions
  - First calculated in: *[C. Degrande et al.; JHEP 1207 (2012) 036]*
  - Included in implementation of:

[F. Maltoni, E. Vryonidou, C. Zhang, arXiv:1607.05330]

Single Higgs

- HiGlu

[M. Spira; arXiv:hep-ph/9510347]

http://tiger.web.psi.ch/higlu

  - QCD: NNLO for SM
  - Quark mass effects at NLO
  - NLO EW & NNLO EW/QCD in the SM
  - EFT: rescaling of top yukawa (NNLO QCD) & c_g (NNLL scale dep. only)

[R. Harlander, S. Liebler, H. Mantler; arXiv:1605.03190]

http://sushi.hepforge.org

- SusHi
  - QCD: NNLO, N^3LO in heavy top limit + $1/m_t$ expansion
  - Recently included Dim-5 gg operator c_g (no $1/m_t$ expansion)
  - EFT: now same as HiGlu
  - Event generation: aMCSusHi - MadGraph5_aMC@NLO interface (no c_g)

Double Higgs

- HPAIR

[S. Dawson, M. Dittmaier, M. Spira; Phys. Rev. D58:115012]

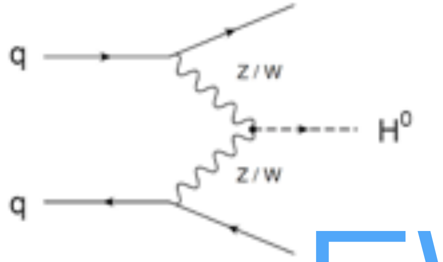
http://tiger.web.psi.ch/hpair

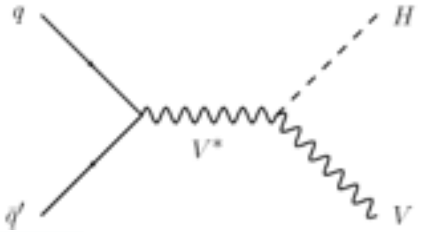
  - NLO in QCD in either SM or MSSM (heavy top limit)
  - Events: HiggsPair - HERWIG++

https://herwig.hepforge.org

- EFT contribution
  - 5-parameter anomalous coupling Lagrangian
  - Alternative 'SILH' basis input maps to the anomalous couplings
  - No dipole operator
  - Also LO events: HiggsPair in HERWIG 7.0 *[F. Goertz et al.; JHEP 1504 (2015) 167]*

$$c_t = 1 - \frac{\bar{c}_H}{2} - \bar{c}_u, \quad c_{tt} = -\frac{1}{2}(\bar{c}_H - 3\bar{c}_u), \quad c_3 = 1 - \frac{3\bar{c}_H}{2} + \bar{c}_6, \quad c_g = c_{gg} = \frac{4\pi}{\alpha_2}\bar{c}_g$$





EW production: VH, VBF

$$
\begin{aligned}
\mathcal{L}_\Phi &= \frac{\bar c_H}{\Lambda^2}\partial^\mu|\Phi|^2\partial_\mu|\Phi|^2 + \frac{\bar c_T}{\Lambda^2}\big[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\big]\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big] - \lambda\,\frac{\bar c_6}{\Lambda^2}|\Phi|^6\\
\mathcal{L}_G &= \frac{g'^2}{4\Lambda^2}\bar c_{BB}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{ig}{2\Lambda^2}\bar c_W\big[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\big]D_\nu W^{k,\mu\nu} + \frac{ig'}{2\Lambda^2}\bar c_B\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big]\partial_\nu B^{\mu\nu}\\
&\quad + \frac{ig}{\Lambda^2}\bar c_{HW}\big[D_\mu\Phi^\dagger T_{2k}D_\nu\Phi\big]W^{k,\mu\nu} + \frac{ig'}{\Lambda^2}\bar c_{HB}\big[D_\mu\Phi^\dagger D_\nu\Phi\big]B^{\mu\nu}\\
\mathcal{L}_C &= \frac{i\bar c_{HQ}}{v^2}\big[\bar Q_L\gamma^\mu Q_L\big]\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big] + \frac{4i\bar c'_{HQ}}{v^2}\big[\bar Q_L\gamma^\mu T_{2k}Q_L\big]\big[\Phi^\dagger T^{2k}\overleftrightarrow{D}_\mu\Phi\big]\\
&\quad + \frac{i\bar c_{Hu}}{v^2}\big[\bar u_R\gamma^\mu u_R\big]\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big] + \frac{i\bar c_{Hd}}{v^2}\big[\bar d_R\gamma^\mu Q_R\big]\big[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big] - \left[\frac{i\bar c_{Hud}}{v^2}\big[\bar u_R\gamma^\mu Q_R\big]\big[\tilde\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\big] + \text{h.c.}\right]
\end{aligned}
$$

- Many more operators can contribute
  - Operators also affect non Higgs rates i.e. backgrounds
  - “Classic” new V-V-h Lorentz structure
  - V-h-f-f Contact interactions

EW production: VH, VBF

- The usually considered bunch that maps to the familiar “L3” parametrisation of anomalous Higgs couplings to gauge bosons
  - Deviations in the tails of distributions probing large momentum flow in the production vertex
  - “Easy” for QCD corrections as they factorise to the initial state quark lines

$$\begin{aligned}\mathcal{L}_G = {} & \frac{g'^2}{4\Lambda^2}\bar{c}_{BB}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{ig}{2\Lambda^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu} + \frac{ig'}{2\Lambda^2}\bar{c}_B\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]\partial_\nu B^{\mu\nu} \\ & + \frac{ig}{\Lambda^2}\bar{c}_{HW}\left[D_\mu\Phi^\dagger T_{2k}D_\nu\Phi\right]W^{k,\mu\nu} + \frac{ig'}{\Lambda^2}\bar{c}_{HB}\left[D_\mu\Phi^\dagger D_\nu\Phi\right]B^{\mu\nu} \quad \text{+ CP violating}\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{HAC} = & -\frac{1}{4}g^{(1)}_{hzz}Z_{\mu\nu}Z^{\mu\nu}h - g^{(2)}_{hzz}Z_\nu\partial_\mu Z^{\mu\nu}h + \frac{1}{2}g^{(3)}_{hzz}Z_\mu Z^\mu h - \frac{1}{4}\tilde{g}_{hzz}Z_{\mu\nu}\tilde{Z}^{\mu\nu}h \\ & -\frac{1}{2}g^{(1)}_{hww}W^{\mu\nu}W^\dagger_{\mu\nu}h - \left[g^{(2)}_{hww}W^\nu\partial^\mu W^\dagger_{\mu\nu}h + \text{h.c.}\right] + g^{(3)}_{hww}W_\mu W^{\dagger\mu}h - \frac{1}{2}\tilde{g}_{hww}W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu}h \\ & -\frac{1}{2}g^{(1)}_{haz}Z_{\mu\nu}F^{\mu\nu}h - g^{(2)}_{haz}Z_\nu\partial_\mu F^{\mu\nu}h - \frac{1}{2}\tilde{g}_{haz}Z_{\mu\nu}\tilde{F}^{\mu\nu}h\end{aligned}$$

EW production: VH, VBF

- HAWK

[A. Denner et al.; JHEP 1203 (2012) 075]

http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk

  - VH & VBF
  - NLO in EW/QCD for the SM
  - Anomalous coupling NLO in QCD, 2 parameter subset given others constrained by LEP

- VBFNLO

[J. Baglio et al.; arXiv:1404.3940]

https://www.itp.kit.edu/vbfnlo

  - General purpose tool for Higgs and weak boson production
  - NLO QCD (LO event generation)
  - Focus on VBF topologies, many processes available:
  - H+X, V+X, HH+X, VV+X, VVV+X (also WH)
  - Full L3 AC parametrisation

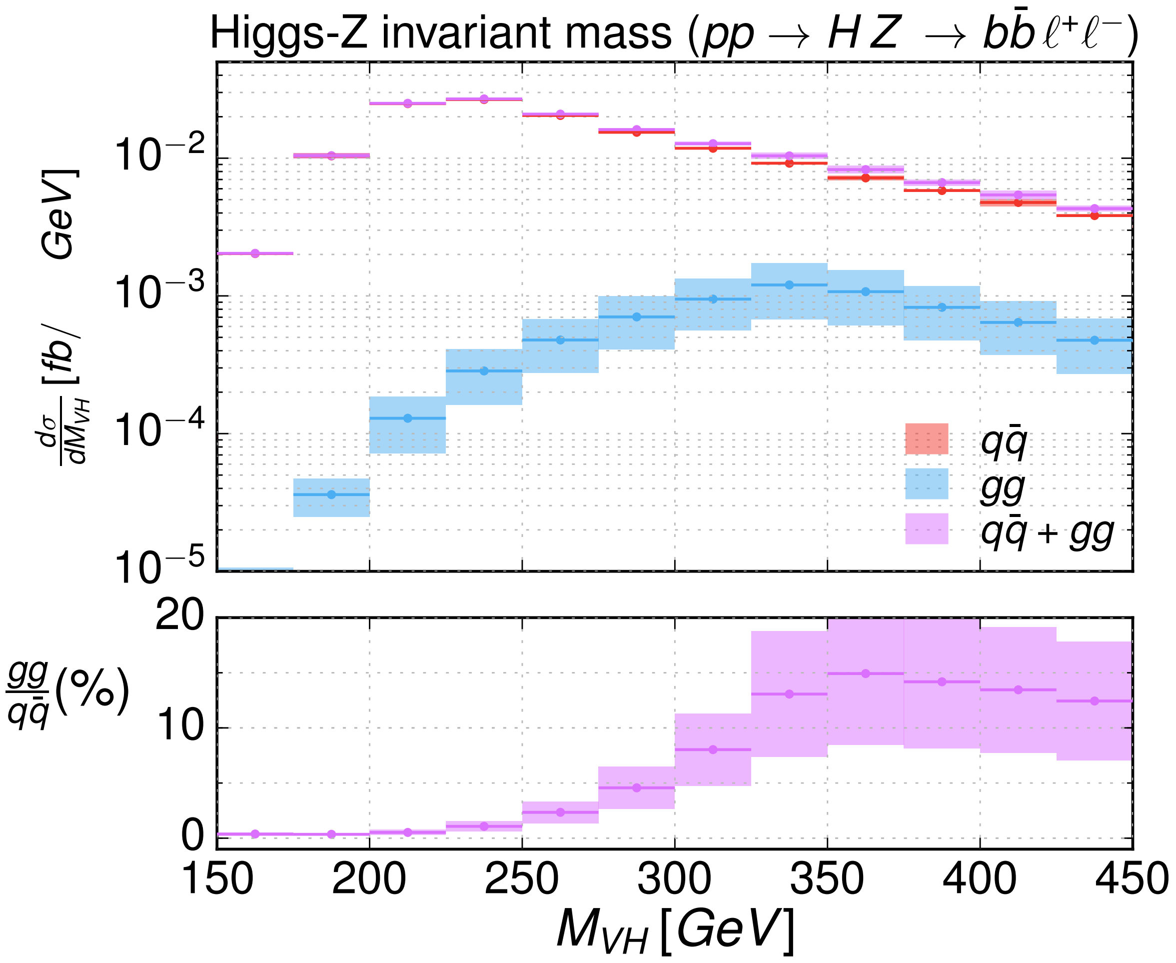
POWHEG-BOX/MCFM

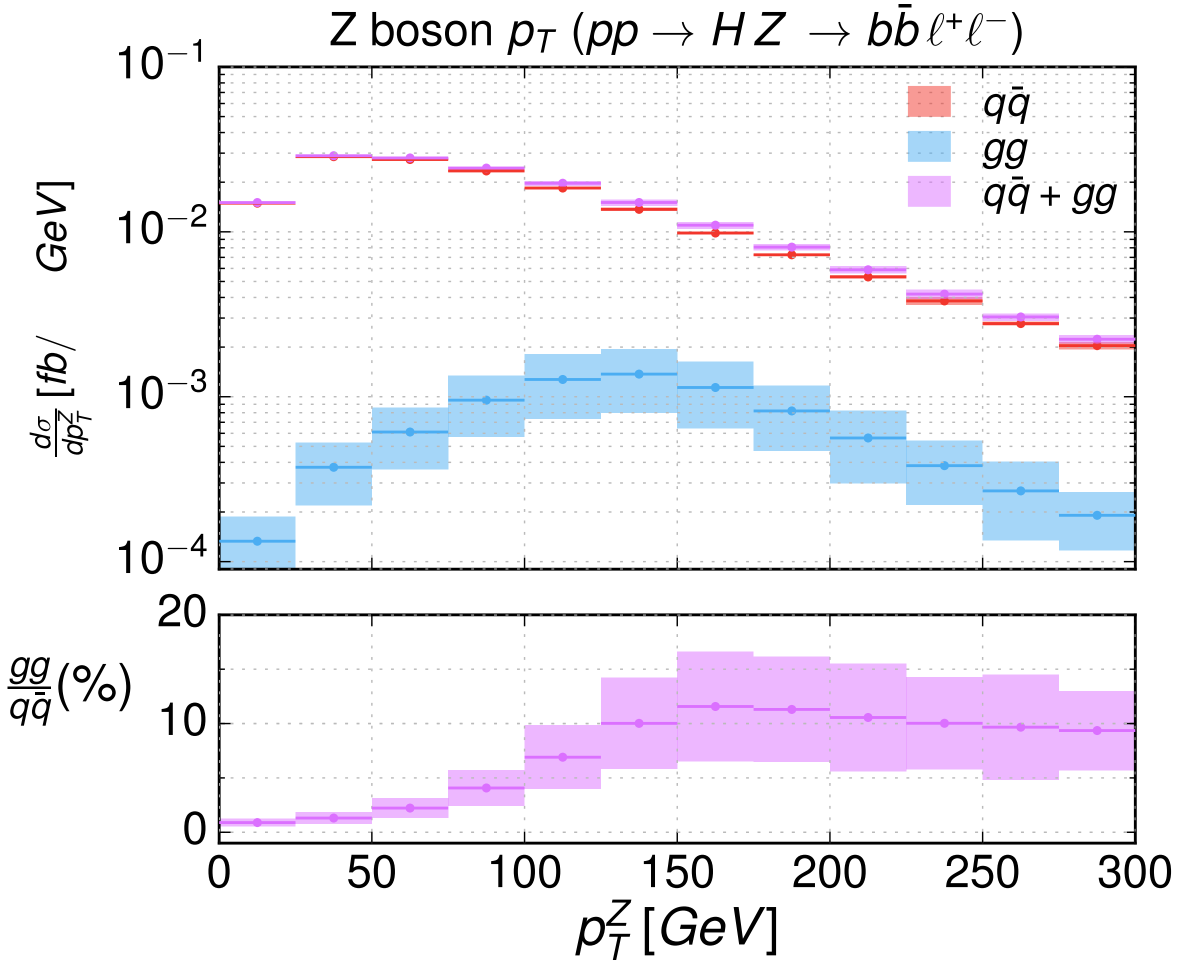
- Implementation of WH/ZH in POWHEG-BOX framework
  - NLO in QCD and matched to parton shower
  - Built from MCFM matrix elements for the SM processes
  - gg→ZH contribution should be added separately, widely available
- EFT contribution
  - Map from “gauge” part of SILH to anomalous couplings (5 operators)
  - Also includes CP-violating operators
  - Relevant modifications to EW parameter relations taken into account
- In the paper
  - gg-contribution, K-factors
  - Distributions for benchmarks based on current constraints & UV models

[Gorbahn, No & Sanz; JHEP 1510 (2015) 036]

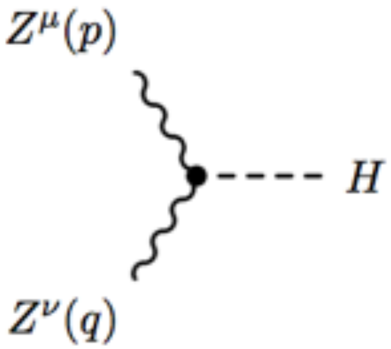
$gg \rightarrow Z\,H \rightarrow l^{+}l^{-}\,bb$

- gg initiated process (formally NNLO)
  - Gluon PDF plus kinematics of EFT searches warrant its inclusion
  - Well known to ‘mimic’ EFT effects if not properly taken into account


Higgs-Z invariant mass ($pp \rightarrow H\,Z \rightarrow b\bar{b}\,\ell^{+}\ell^{-}$)


Z boson p_T ($pp \rightarrow H\,Z \rightarrow b\bar{b}\,\ell^{+}\ell^{-}$)

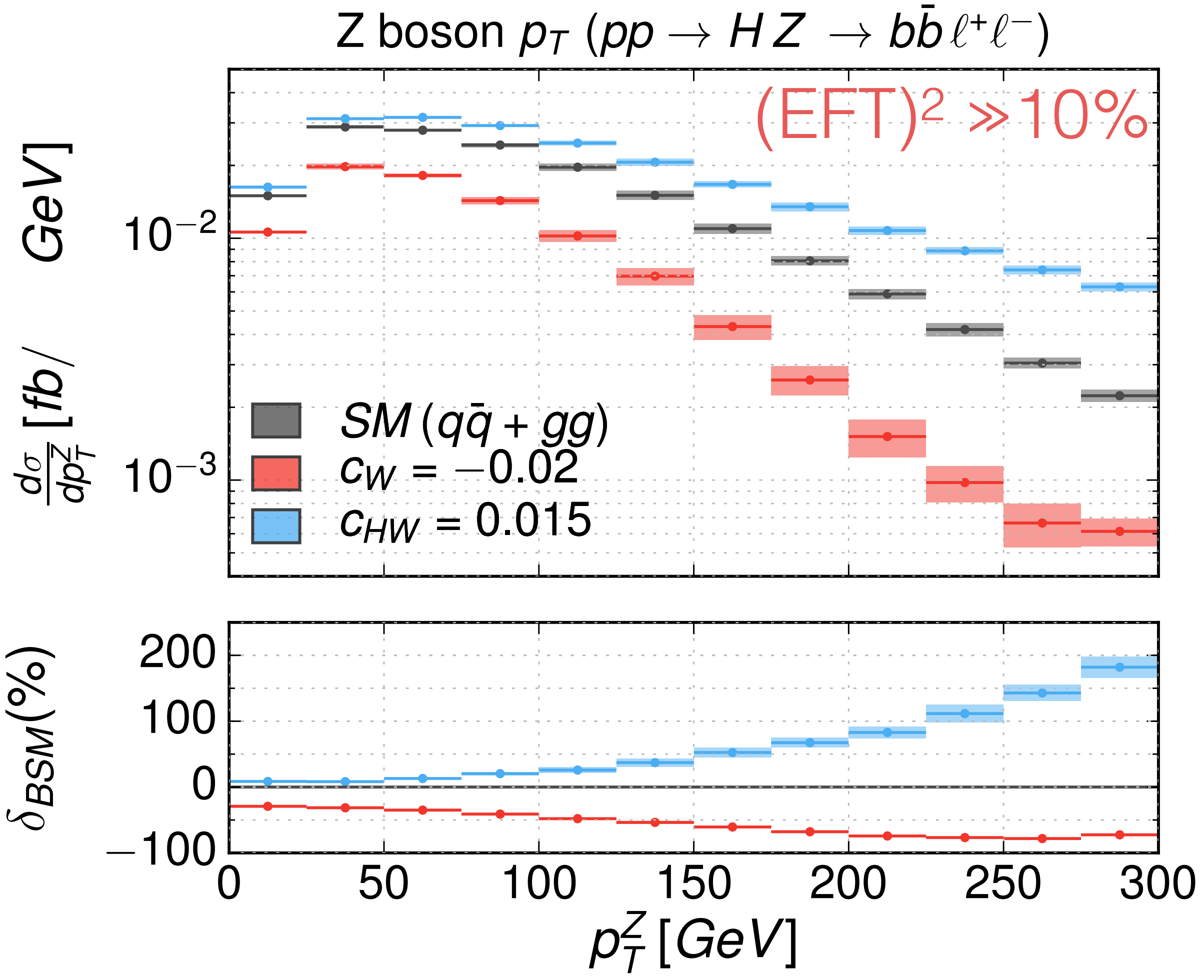
pp → Z H → l^+l^- bb

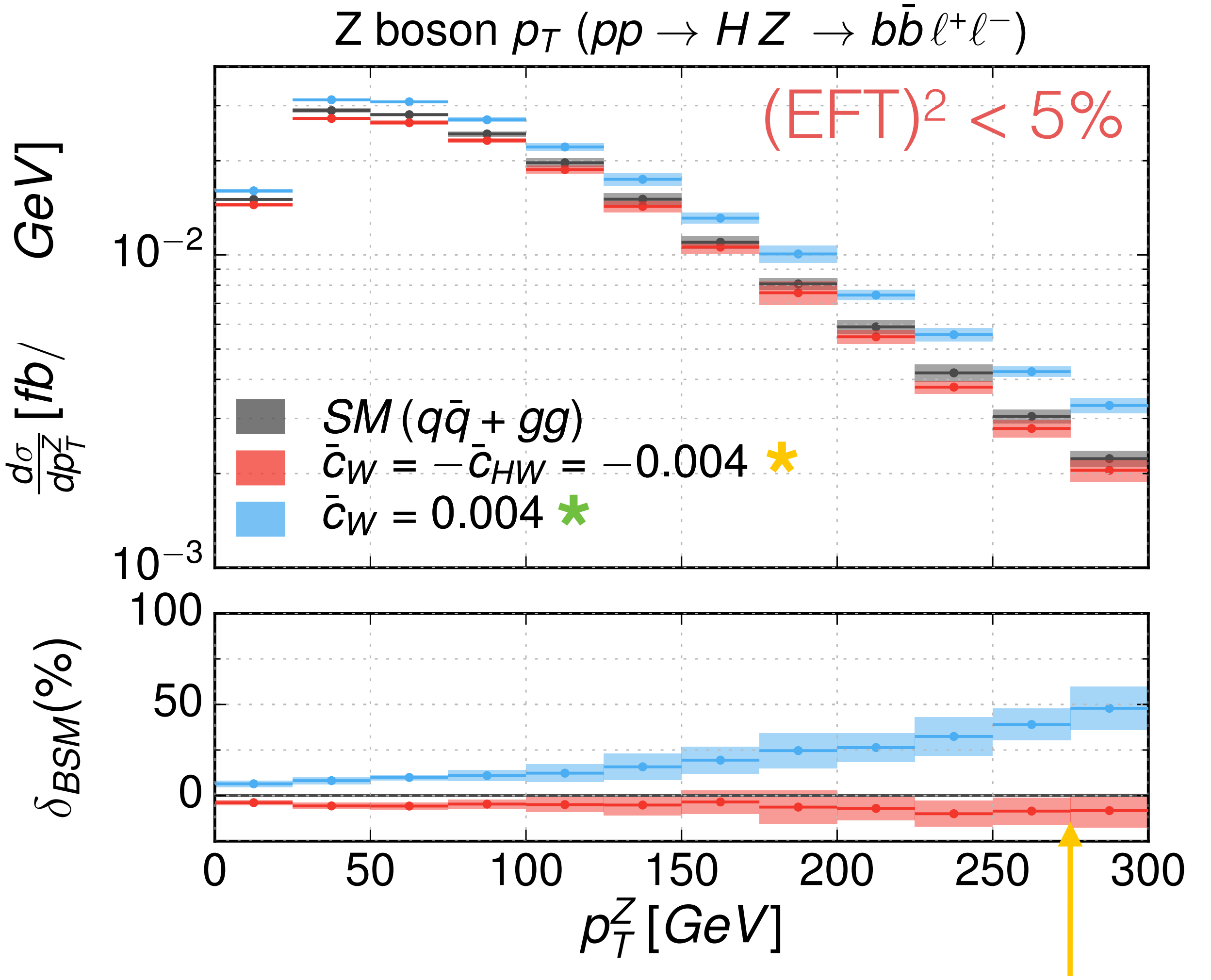


$$g^{(1)}_{hzz} \propto \bar{c}_{HW}\,, \quad g^{(2)}_{hzz} \propto (\bar{c}_{HW} + \bar{c}_W)$$

$$i\left[\frac{g}{\cos\theta_W} M_Z \boxed{+\, g^{(1)}_{hzz}\,\left(\eta^{\mu\nu} p\cdot q - q^\mu p^\nu\right)} + \boxed{g^{(2)}_{hzz}\,\left((p^2+q^2)\eta^{\mu\nu} - p^\mu p^\nu + q^\mu q^\nu\right)}\right]$$

“BM B” “BM A”





* Benchmark B does not show “EFT-like” features

EW production: VH, VBF

- Not commonly considered contact interactions
  - Also affect V-f-f vertices: constrained by previous experiments e.g. LEP
  - Not all of them much more than LHC constraints on (c_W,c_B,c_{HW},c_{HB})
  - Flavour matrices: FCNC,… interplay between LHC and other experiments
  - Coloured particles: non-trivial QCD corrections
  - Curious to see how much they can impact VH, VBF at the LHC given existing constraints or conversely, whether LHC can be complementary

$$\mathcal{L}_C = \frac{i\bar{c}_{HQ}}{v^2}\left[\bar{Q}_L\gamma^\mu Q_L\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] + \frac{4i\bar{c}'_{HQ}}{v^2}\left[\bar{Q}_L\gamma^\mu T_{2k} Q_L\right]\left[\Phi^\dagger T^{2k} \overleftrightarrow{D}_\mu \Phi\right]$$
$$+ \frac{i\bar{c}_{Hu}}{v^2}\left[\bar{u}_R\gamma^\mu u_R\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] + \frac{i\bar{c}_{Hd}}{v^2}\left[\bar{d}_R\gamma^\mu Q_R\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] - \left[\frac{i\bar{c}_{Hud}}{v^2}\left[\bar{u}_R\gamma^\mu Q_R\right]\left[\tilde{\Phi}^\dagger \overleftrightarrow{D}_\mu \Phi\right] + \text{h.c.}\right]$$

+ lepton currents (some of which affect SM inputs)

Only HiggsPO includes these so far: more work required!

MC event generation frameworks

Frameworks

- WHIZARD

[W. Kilian, T. Ohl, J.Reuter; Eur.Phys.J. C71, 1742]

http://whizard.hepforge.org

  - General purpose LO event generator w/ internal parton shower
  - Possibility to interface with loop-level matrix elements
  - EFT operators involving tops/higgs/gauge bosons

- JHU generator & MELA

http://spin.pha.jhu.edu

  - Dedicated LO event generator for Higgs production/characterisation
  - pp → X → VV, VBF, X+JJ, pp → VX, ee → VX
  - Matrix Element Likelihood Analysis package for sophisticated signal optimisation techniques

- VBFNLO could have been in this section too

Frameworks

- FeynRules/Madgraph5_aMC@NLO suite
  - Most popular event generation framework https://launchpad.net/mg5amcnlo
  - NLO in QCD + PS, loop-induced processes
- Interfaces to many useful particle physics software
  - FeynRules + NLOCT for "automated" generation of NLOQCD-ready model file from Lagrangian: compatible with many MC event genrators
  - PYTHIA/HERWIG for parton shower
  - Delphes for fast detector simulation
  - SysCalc, MadDM, Madspin,…
- Brings NLO QCD to the masses!
  - EFT community has been making great use of this suite
  - NLO calculations/implementations owe much to the EFT-RGE calculation

[F. Maltoni et al.; Eur.Phys.J. C74 (2014) 2710]
[F. Demartin et al.; Eur.Phys.J. C74 (2014) 3065
& Eur.Phys.J. C75 (2015) 267]

Higgs Characterisation

- Anomalous coupling Lagrangian for Higgs couplings
    - General Lorentz structures in EW gauge-Higgs sector
    - Gluon-gluon effective vertex (LO)
    - Currently used by experimental collaborations for some Higgs analyses
- UFO (FeynRules) model at NLO in QCD
    - VBF, VH + CP-violating
- Related model: BSM Characterisation (LO)
    - Extends to a larger set of operators: all except four fermion
    - Based on collection of Lorentz structure in Higgs Basis definition
    - Output for ROSETTA: basis translator program which implements maps from popular EFT basis choices to the mass eigenbasis

HiggsPO

- Alternative but related framework for Higgs couplings
  - Lorentz structures weighted by general form factors
  - Defined at the amplitude level
  - Momentum expansion around poles of gauge bosons
- UFO model at NLO in QCD
  - Higgs decays to 4 leptons,..
  - EW Higgs production
  - Including hVff contact terms

[M .Gonzalez-Alonso et al.; Eur.Phys.J. C75 (2015) 128
& Eur.Phys.J. C75 (2015) 341]
[M. Bordone et al.; Eur.Phys.J. C75 (2015) 8, 385
[A. Greljo et al.; Eur.Phys.J. C76 (2016) 3, 158]

Higgs Effective Lagrangian

- LO FeynRules model for the 'SILH' basis of dim-6 EFT
  - 39 operators included (no four fermion operator)
  - Effect of field redefinitions and SM inputs included
  - Largest collection of dim-6 EFT operators in one place

[A. Alloul, B. Fuks & V. Sanz; JHEP 1404 (2014) 110]

http://feynrules.irmp.ucl.ac.be/wiki/HEL

- Upgrade to NLO QCD has begun
  - First results for EW Higgs production: VH & VBF
  - So far, only 5 operators that map to the L3 parametrisation
  - These require no new counterterms for QCD corrections
  - Cross checked VH with POWHEG-BOX/MCFM implementation

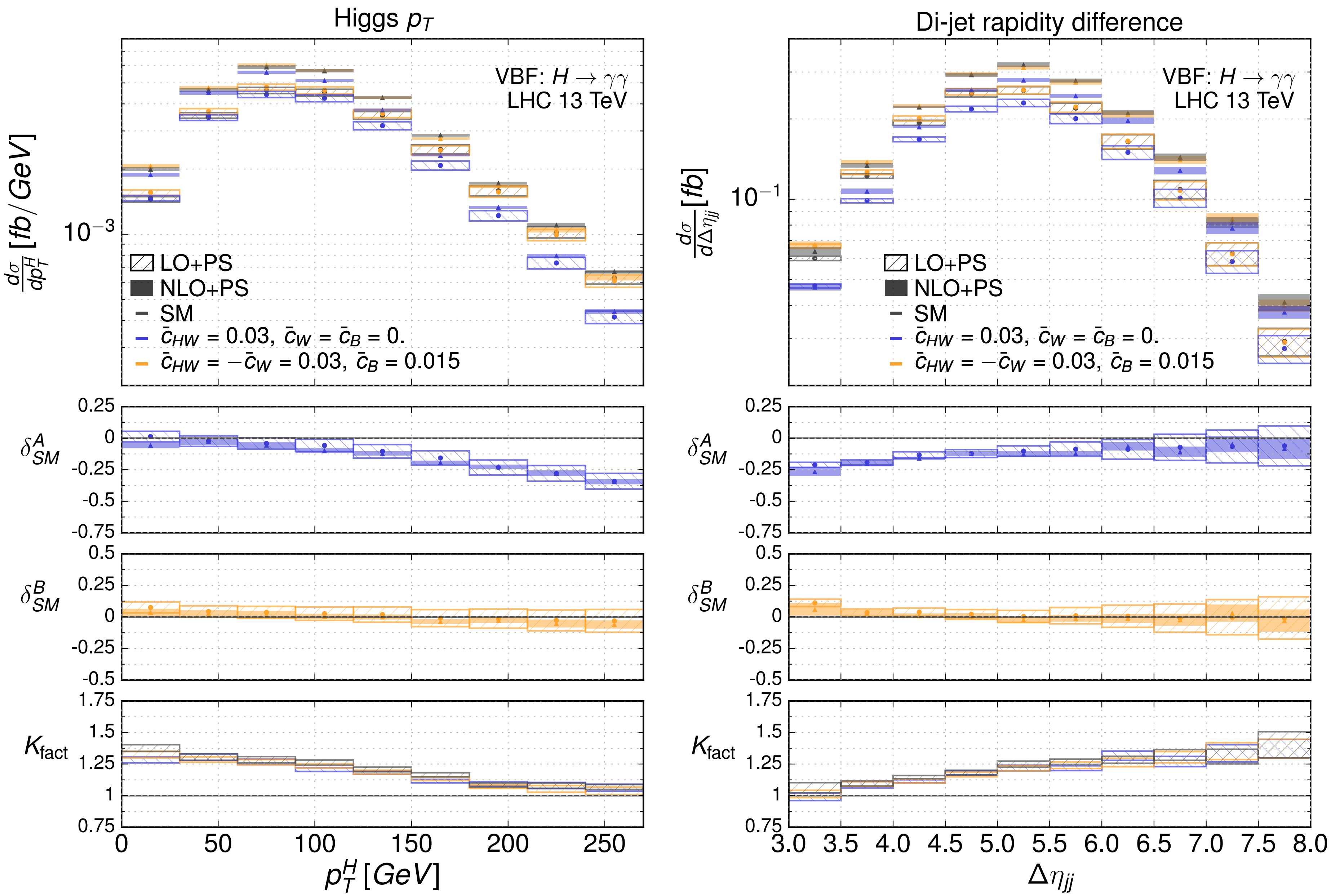
[C. Degrande, B. Fuks, K. Mawatari, KM & V. Sanz; arXiv:1609.04833]

http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO

$pp \rightarrow H\, j\, j \rightarrow \gamma\, \gamma\, j\, j$

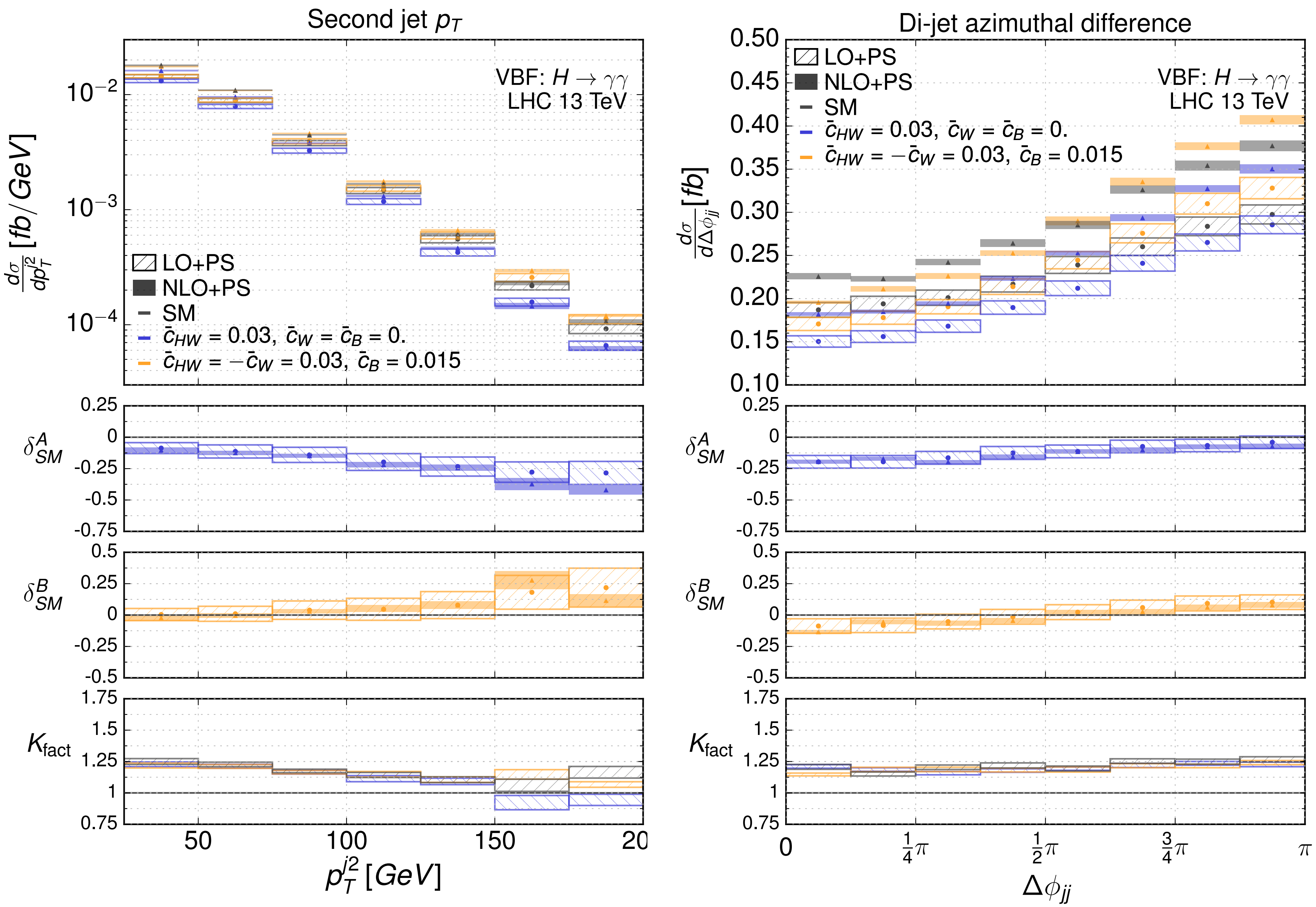
```
generate p p > h j j $$ w+ w- z a QCD=0 [QCD]
```

No ggF but VBF cuts, fixed scale of m_W



pp → H j j→γ γ j j

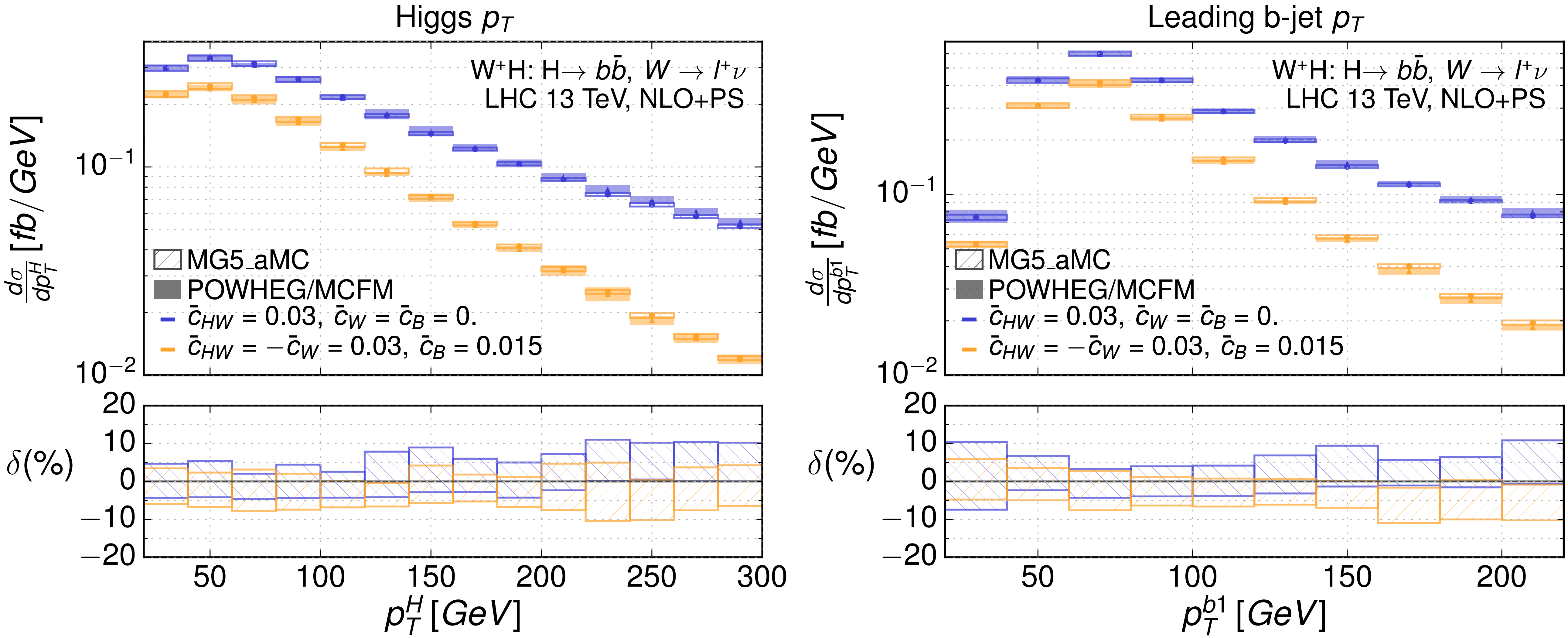
Generally effects of order 25-50% present, mild sensitivity to “benchmark B”. Correlating VH & VBF may help disentangle this coupling structure.



Reduced scale uncert. improves prospects of distinguishing ‘UV motivated’ benchmark B

Validation

Reasonable agreement between POWHEG/MCFM & Madgraph5_aMC@NLO implementations



Top/Higgs EFT@NLO

- Cen’s talk yesterday (talk to him to request models?)
- NLO model implementations of dim-6 operators relevant for:
  - tt (e^+e^-, pp), single top, ttH, ttV
  - H, HH, Hj
  - top FCNC

[C. Degrande et al.; PRD 91 (2015) 034024]
[G. Durieux et al.; PRD 91 (2015) no.7, 074017]
[O. Bylund et al.; JHEP 1605 (2016) 052]
[C. Zhang; PRL 116 (2016) no.16, 162002]
[F. Maltoni et al.; arXiv:1607.05330]

- Coloured operators: non trivial QCD corrections
  - Compared RGE-improved vs. full NLO
  - Incorporate a new theory error contribution based on EFT scale dependence
  - Doesn’t cancel in, e.g., cross section ratios as opposed to usual PDF, scale uncertainties
- Big step towards global EFT fit at NLO QCD accuracy

Others

[R. Contino et al.; Comp. Phys. Comm. 185 (2014) 3412-3423]

Higgs decays: eHDECAY

https://www.itp.kit.edu/~maggie/eHDECAY/

- Extension of HDECAY

  [A. Djouadi, J. Kalinowski, M. Spira, Comp. Phys. Comm. 108 (1998) 56]
- QCD & EW corrections to Higgs BRs
- EFT contribution truncated at $(1/\Lambda)^2$
  - Anomalous coupling (“non-linear”) Lagrangian
  - Alternative ‘SILH’ basis input maps to the anomalous couplings
  - SILH input also includes some NLO EW corrections
  - Unclear if modifications to EW parameters from SM inputs included
- Only publicly available tool
  - ROSETTA interface to this program exists for other basis choices
  - See Darren’s talk for improved calculation in some final states

Michael's & Tevongs talks

Fitting

- There are many active EFT fitting collaborations
- LHC Higgs, EWPO, top, Flavour & combinations thereof
- So far, mostly LO EFT predictions used
  - The next generation will at least employ NLO QCD
  - Allow for study of theory uncertainties
- Mostly private theorist codes & experimental analyses
- One public tool: HEPfit
  - Statistical code for combination of direct/indirect constraints on new physics from Flavour, EWPO, Higgs signal strengths,…
  - Allows for definition of general model & effects on observables of interest
  - Implements EW chiral Lagrangian

http://hepfit.roma1.infn.it

[A. Falkowski et al.; EPJC 75 (2015) 12, 583 & LH proceedings arXiv:1605.02684 (p158)]

Rosetta

Version 2.0 just out!
Original definitions of
Warsaw & SILH bases

http://rosetta.hepforge.org

- Operator basis translation tool for SMEFT
  - Encodes relations between EFT “bases”
  - SILH, Warsaw, Higgs, HISZ,…
  - Special BSMC Lagrangian output for FeynRules model
- Opens up user base for basis specific codes
- Modular + extendable: user defined bases
- Existing interfaces: eHDECAY, Lilith (Higgs rates), EWPO
- Future
  - “Basis independent” implementation of RGEs
  - Output for HC (caveats..) and HELatNLO models

Outlook

- Constant progress in higher order calculations & MC tools
    - Anomalous couplings descriptions abound
    - First theoretical results at NLO in EFT
    - EFT implementations via automation of NLO QCD
- We are heading towards a complete basis at NLO in QCD
    - Top sector: almost there
    - Higgs sector: a little way to go
- Next generation of global fits will hopefully incorporate there

Thoughts

- When experiments employ anomalous coupling description, careful when mapping to EFT interpretation
  - At this point its a practical matter for experiments to use AC descriptions
- We should continue discussion on definitions of EFT theory errors & effect on constraints
  - Missing higher orders, amplitudes squared, EFT scale
  - EFT "validity" might be considered as a part of the theory uncertainty
  - Blows up as EFT is approaches its limits for a given observable?
  - Can MC tools incorporate these effects?

End of the tour.
Thank you

Backup

HiGlu

- Single Higgs production cross section via gluon fusion
  - NNLO in QCD in either SM or MSSM
  - Includes quark mass effects at NLO
  - CP-even or -odd scalar
  - Some differential distributions
  - SM NLO EW & NNLO QCD/EW contributions
- EFT contribution
  - Rescaling of top Yukawa, c_t
  - Non-zero dim-5 gluon-gluon operator, c_g

$$\mathcal{L}_{\text{eff.}} = \frac{\alpha_S}{\pi}\left(\frac{c_t}{12}(1+\delta) + c_g\right) G^{\mu\nu}G_{\mu\nu}\frac{h}{v}, \quad \text{(or CP-odd)}$$

NNLO in QCD NNLL scale dependence only

SusHi

- Single Higgs production cross section via gluon fusion
  - Recently included dim-5 gluon-gluon operator
  - Quark mass effects also at NLO
  - NNLO, N^3LO in heavy top limit + $1/m_t$ expansion
  - CP-even or -odd scalar
- EFT contribution
  - Same as HiGlu
  - $1/m_t$ expansion not available when including c_g
- aMCSusHi interface for MadGraph5_aMC@NLO (no c_g)

$$\mathcal{L}_{\text{eff.}} = \frac{\alpha_S}{\pi}\left(\frac{c_t}{12}(1+\delta) + c_g\right) G^{\mu\nu}G_{\mu\nu}\frac{h}{v}, \quad \text{(or CP-odd)}$$

[S. Dawson, M. Dittmaier, M. Spira; Phys. Rev. D58:115012]
[F. Goertz et al.; JHEP 1504 (2015) 167]

http://tiger.web.psi.ch/hpair
https://herwig.hepforge.org

HPAIR

- Higgs pair production cross section via gluon fusion
  - NLO in QCD in either SM or MSSM
  - Heavy top limit
- EFT contribution
  - 5-parameter anomalous coupling Lagrangian
  - Alternative ‘SILH’ basis input maps to the anomalous couplings
  - Dipole operator?

$$\mathcal{L}_{\rm SILH} = y_u \frac{g_s^2 \bar{c}_g}{m_W^2}|\Phi|^2 - y_u \frac{\bar{c}_u}{v^2}|\Phi|^2 \bar{Q}_L \tilde{\Phi}\, u_R + \frac{\bar{c}_H}{2v^2}\partial^\mu |\Phi|^2 \partial_\mu |\Phi|^2 - \lambda \frac{\bar{c}_6}{v^2}|\Phi|^6$$

$$\mathcal{L}_{\rm eff.} = -m_t\, \bar{t}t \left(c_t \frac{h}{v} + c_{tt}\frac{h^2}{2v^2}\right) - \frac{m_h^2}{2v} c_3 h^3 + \frac{\alpha_S}{\pi} G^{\mu\nu}G_{\mu\nu}\left(c_g \frac{h}{v} + c_{gg}\frac{h^2}{2v^2}\right)$$

$$c_t = 1 - \frac{\bar{c}_H}{2} - \bar{c}_u, \quad c_{tt} = -\frac{1}{2}(\bar{c}_H - 3\bar{c}_u), \quad c_3 = 1 - \frac{3\bar{c}_H}{2} + \bar{c}_6, \quad c_g = c_{gg} = \frac{4\pi}{\alpha_2}\bar{c}_g$$

Also HiggsPair: LO event generation with HERWIG 7.0

SILH operators

- Higgs-EW gauge boson operators in SILH basis

$$\mathcal{L}_{D6} = \frac{1}{\Lambda^2}\Big[\frac{g'^2}{4}\bar{c}_{BB}\Phi^\dagger\Phi B^{\mu\nu}B_{\mu\nu} + \frac{ig}{2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'}{2}\bar{c}_B\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu}$$

$$+\, ig\,\bar{c}_{HW}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + ig'\,\bar{c}_{HB}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu}$$

$$+\, \frac{g'^2}{4}\tilde{c}_{BB}\Phi^\dagger\Phi B^{\mu\nu}\tilde{B}_{\mu\nu} + ig\,\tilde{c}_{HW}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]\widetilde{W}^k_{\mu\nu} + ig'\,\tilde{c}_{HB}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]\tilde{B}_{\mu\nu}\Big]$$

$$\Phi^\dagger\overleftrightarrow{D}^\mu\Phi \equiv \left(D^\mu\Phi^\dagger\right)\Phi - \Phi^\dagger\left(D^\mu\Phi\right)$$

MCFM/POWHEG-box implementation:
operator definition has a factor 1/2 for (c_W,c_{HW})

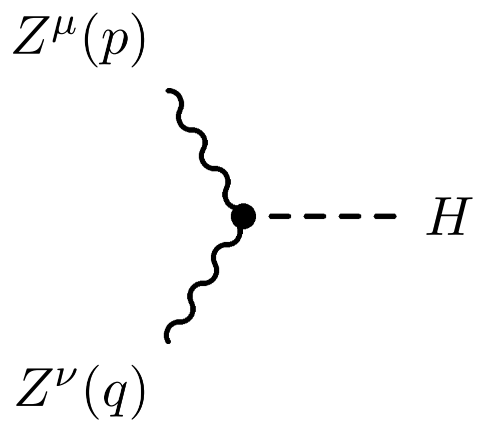
- New Lorentz structures (1) & (2):

$$\mathcal{L}_{HAC} = -\frac{1}{4}g^{(1)}_{hzz}Z_{\mu\nu}Z^{\mu\nu}h - g^{(2)}_{hzz}Z_\nu\partial_\mu Z^{\mu\nu}h + \frac{1}{2}g^{(3)}_{hzz}Z_\mu Z^\mu h - \frac{1}{4}\tilde{g}_{hzz}Z_{\mu\nu}\tilde{Z}^{\mu\nu}h$$

$$-\frac{1}{2}g^{(1)}_{hww}W^{\mu\nu}W^\dagger_{\mu\nu}h - \left[g^{(2)}_{hww}W^\nu\partial^\mu W^\dagger_{\mu\nu}h + \text{h.c.}\right] + g^{(3)}_{hww}W_\mu W^{\dagger\mu}h - \frac{1}{2}\tilde{g}_{hww}W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu}h$$

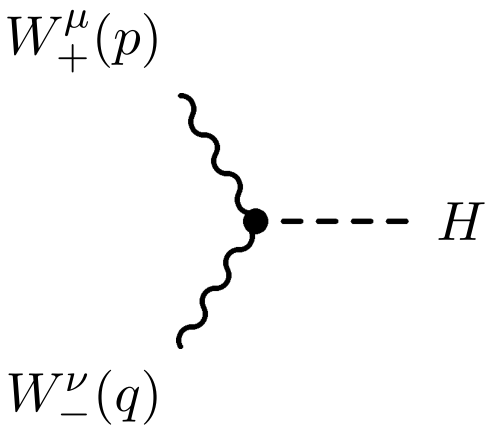
$$-\frac{1}{2}g^{(1)}_{haz}Z_{\mu\nu}F^{\mu\nu}h - g^{(2)}_{haz}Z_\nu\partial_\mu F^{\mu\nu}h - \frac{1}{2}\tilde{g}_{haz}Z_{\mu\nu}\tilde{F}^{\mu\nu}h$$

Feynman Rules



:

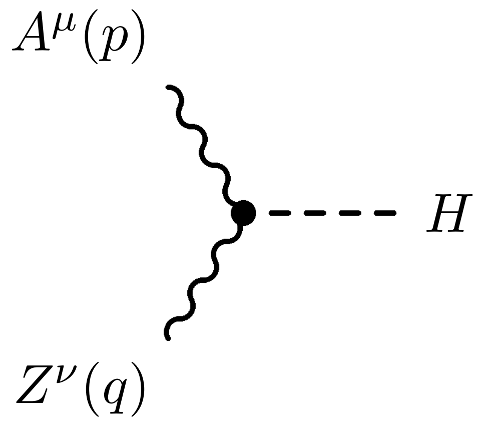
$$i\left[\eta^{\mu\nu}\left(\frac{g}{\cos\theta_W}M_Z + g^{(1)}_{hzz}\,p\cdot q + g^{(2)}_{hzz}\,(p^2+q^2)\right) - g^{(1)}_{hzz}\,q^\mu p^\nu - \tilde{g}_{hzz}\epsilon^{\mu\nu\rho\sigma}\,q_\rho p_\sigma - g^{(2)}_{hzz}\,(p^\mu p^\nu + q^\mu q^\nu)\right]$$



:

$$i\left[\eta^{\mu\nu}\left(gM_W + g^{(1)}_{hww}\,p\cdot q + g^{(2)}_{hww}\,(p^2+q^2)\right) - g^{(1)}_{hww}\,q^\mu p^\nu - \tilde{g}_{hww}\epsilon^{\mu\nu\rho\sigma}\,q_\rho p_\sigma - g^{(2)}_{hww}\,(p^\mu p^\nu + q^\mu q^\nu)\right]$$

BSM→



:

$$i\left[\eta^{\mu\nu}\left(g^{(1)}_{haz}\,p\cdot q + g^{(2)}_{haz}\,p^2\right) - g^{(1)}_{haz}\,q^\mu p^\nu - \tilde{g}_{haz}\epsilon^{\mu\nu\rho\sigma}\,q_\rho p_\sigma - g^{(2)}_{haz}\,p^\mu p^\nu\right]$$

*Inflowing momenta

Mapping to AC/(i.e. HC)

Coupling	HEL@NLO
$g^{(1)}_{hzz}$	$\frac{e^2 v}{2\hat{c}_W^2 \hat{s}_W^2} \frac{1}{\Lambda^2} \left[\hat{c}_W^2 \bar{c}_{HW} + 2\hat{s}_W^2 \bar{c}_{HB} - 2\hat{s}_W^4 \bar{c}_{BB}\right]$
$g^{(2)}_{hzz}$	$\frac{e^2 v}{4\hat{s}_W^2 \hat{c}_W^2 \Lambda^2} \left[\hat{c}_W^2 (\bar{c}_{HW} + \bar{c}_W) + 2\hat{s}_W^2 (\bar{c}_B + \bar{c}_{HB})\right]$
$g^{(3)}_{hzz}$	$\frac{g^2 v}{2\hat{c}_W^2} + \frac{e^4 v^3}{8\hat{c}_W^4 \hat{s}_W^2 \Lambda^2} \left[\hat{c}_W^2 \bar{c}_W + 2\bar{c}_B\right]$
$g^{(1)}_{haz}$	$\frac{e^2 v}{4\hat{s}_W \hat{c}_W \Lambda^2} \left[\bar{c}_{HW} - 2\bar{c}_{HB} + 4\hat{s}_W^2 \bar{c}_{BB}\right]$
$g^{(2)}_{haz}$	$\frac{e^2 v}{4\hat{s}_W \hat{c}_W \Lambda^2} \left[\bar{c}_{HW} + \bar{c}_W - 2(\bar{c}_B + \bar{c}_{BB})\right]$
$g^{(1)}_{hww}$	$\frac{e^2 v}{2\hat{s}_W^2 \Lambda^2} \bar{c}_{HW}$
$g^{(2)}_{hww}$	$\frac{v e^2}{4\Lambda^2 \hat{s}_W^2} \left[\bar{c}_W + \bar{c}_{HW}\right]$
$g^{(3)}_{hww}$	$\frac{g^2 v}{2}$

Anomalous couplings (AC) equivalent to
Higgs Characterisation (HC)

Limits from global fits

- A number of global fits to data deriving constraints on EFT Wilson coefficients have been performed
    - LHC, LEP & other low-energy experiments
- Marginalised constraints from EWPO + LHC Run 1 data on coefficients of interest

[Sanz et al.; JHEP 1503 (2015) 157]

Operator	Coefficient	Constraints
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger T_{2k} \overleftrightarrow{D}^\mu H\right) D^\nu W^k_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(\frac{\bar{c}_W}{2} - \bar{c}_B)$	(-0.035,0.005)
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(\frac{\bar{c}_W}{2} + \bar{c}_B)$	$(-0.0033, 0.0018)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger T_{2k}(D^\nu H)W^k_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}\bar{c}_{HW}$	$(-0.07, 0.03)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}\bar{c}_{HB}$	$(-0.045, 0.075)$

stronger & weaker directions…

See also: [Falkowksi & Riva; JHEP 1502 (2015) 039], [Berthier & Trott; JHEP 1505 (2015) 024], [Corbett et al.; JHEP 1508 (2015) 156], [Englert et al.; EPJC 76 (2016) 7, 393]

EFT Benchmarks

- To showcase the usage of both implementations, we select points in c_W, c_{HW} parameter space that:
  - Approximately saturate these limits
  - Select particular Lorentz structures in the new vertices
  - Are also motivated from a BSM point of view
- Tightly constrained direction in (c_B, c_W) forces $c_B \sim -c_W/2$

$$\mathcal{L}_{\text{new}} = -\frac{1}{4} g^{(1)}_{hvv} V_{\mu\nu} V^{\mu\nu} h - g^{(2)}_{hvv} V_\nu \partial_\mu V^{\mu\nu} h$$

- We then pick benchmark points that single out:

I) $V_\nu \partial_\mu V^{\mu\nu} h \, : \, g^{(1)}_{hvv} = 0, \, g^{(2)}_{hvv} \neq 0 \rightarrow \bar{c}_{HW} = 0, \, \bar{c}_W \neq 0$

II) $V_{\mu\nu} V^{\mu\nu} h \, : \, g^{(2)}_{hvv} = 0, \, g^{(1)}_{hvv} \neq 0 \rightarrow \bar{c}_W = -\bar{c}_{HW}$

EFT Benchmarks

- Pattern II) is a feature of matching conditions that arise in a large class of UV completions, e.g. 2HDM

[Gorbahn, No & Sanz; JHEP 1510 (2015) 036]

- Constraints then become tighter:

$$c_{HW} = -\bar{c}_W = (0.0008, 0.04)$$

- Summary of benchmarks used, roughly compatible with current limits

POWHEG/MCFM	$\bar{c}_{HW}$	$\bar{c}_W$	$\bar{c}_B$	$g^{(1)}_{hvv}$	$g^{(2)}_{hvv}$
I	0	0.008	0	X	✓
II	0.008	-0.008	0	✓	X
MG5_aMC					
A	0.03	0	0	✓	✓
B	0.03	-0.03	0.015	✓	X

Selection of results

- ZH in POWHEG-BOX/MCFM, including SM gg→ZH
- WH, VBF in FR-NLOCT/Madgraph5_aMC@NLO
- Used PYTHIA8 for Higgs decay, PS and Hadronisation
    - Rescaled rates by eHDECAY BRs to capture EFT contributions
- Events were reconstructed using Fastjet thanks to MadAnalysis5 “reco” mode and analysed according to some realistic event selection procedure also in MA5
- Theoretical uncertainties due to scale variation were quantified but not PDF uncertainties

[KM, Sanz, Williams; arXiv:1512.02572]

POWHEG-BOX/MCFM

- Higgs associated production with a leptonically decaying W or Z at NLO in QCD matched to parton shower
  - Include EFT effects via a mapping to AC/HC (also CP violating)
- At NLO, the initial state current factorises from the final state, even when the Higgs decays to b's
  - Drell-Yan-like NLO corrections which are well known
- Builds upon previous work in the SM matched to parton shower in the same framework as well as fixed order predictions including anomalous couplings
- Matrix elements based on MCFM code interfaced with POWHEG-BOX for which the SM process was already implemented

Simulation

- For definiteness we specified that the Higgs decay to bb, allowing PYTHIA to perform the decay but scaling the rates by the BR predicted by eHDECAY
- Used CTEQ10 PDFs for NLO predictions and CTEQ6L1 PDFs for LO comparisons
- Modification of EW parameters taken into account in the (m_Z, m_W, G_F) input scheme
- Scale uncertainty determined by varying μ_R, μ_F together around a central scale of $\mu_0 = m_{VH}$
  - Envelope of $\mu_0/2$ and 2 μ_0

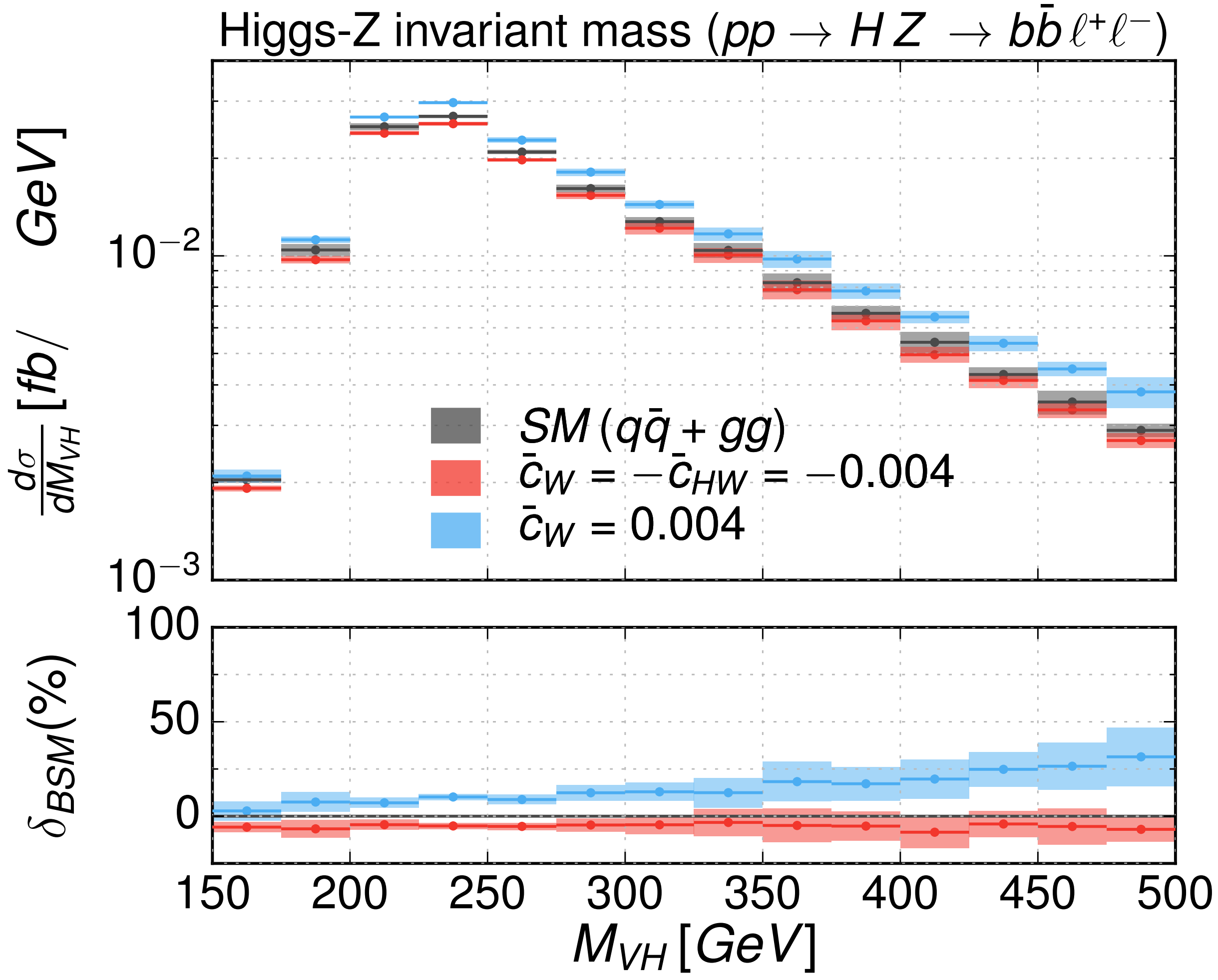
Selection

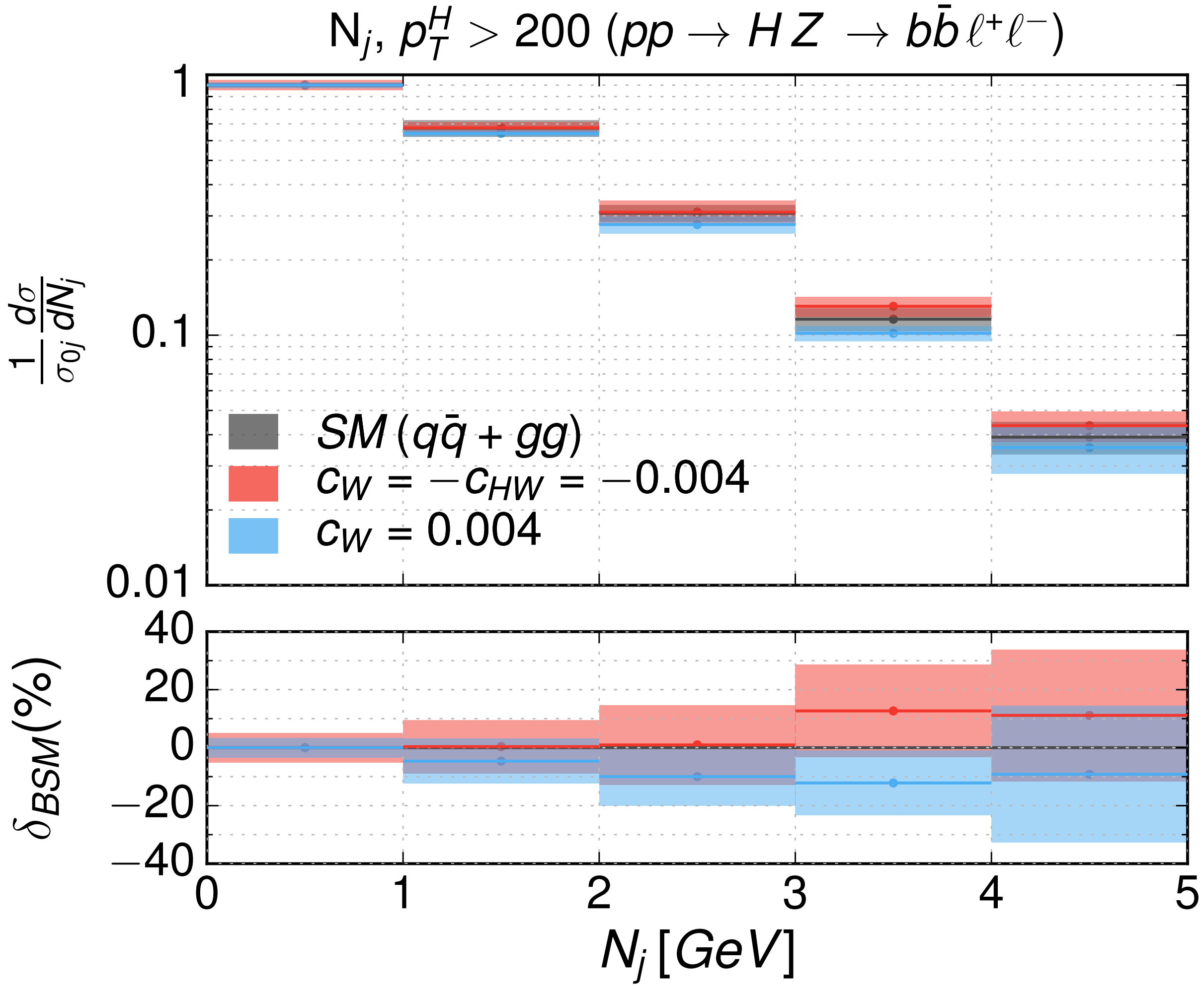
Process	
$H\,Z \to b\bar{b}\,\ell^+\ell^-$	$H\,W \to b\bar{b}\,\ell\nu$
Jets	
k_T algorithm: ΔR=0.4, $p_T > 25$ GeV & $\eta_b < 2.5$	
Cuts	
2 b-jets, $p_T > 25$ GeV, $\eta_b < 2.5$	
1 lepton, $\ell^\pm$ (e or μ)	2 leptons, ℓ^+, ℓ^- (e or μ)
$p_T^\ell < 25$ GeV, $\|\eta_\ell\| < 2.5$	

MA5 performs b-jet identification based on truth level jet information (presence of b-hadrons in jet)

$pp \to Z\,H \to l^+l^-\,bb$

Nj exhibits some difference but stats too low to distinguish

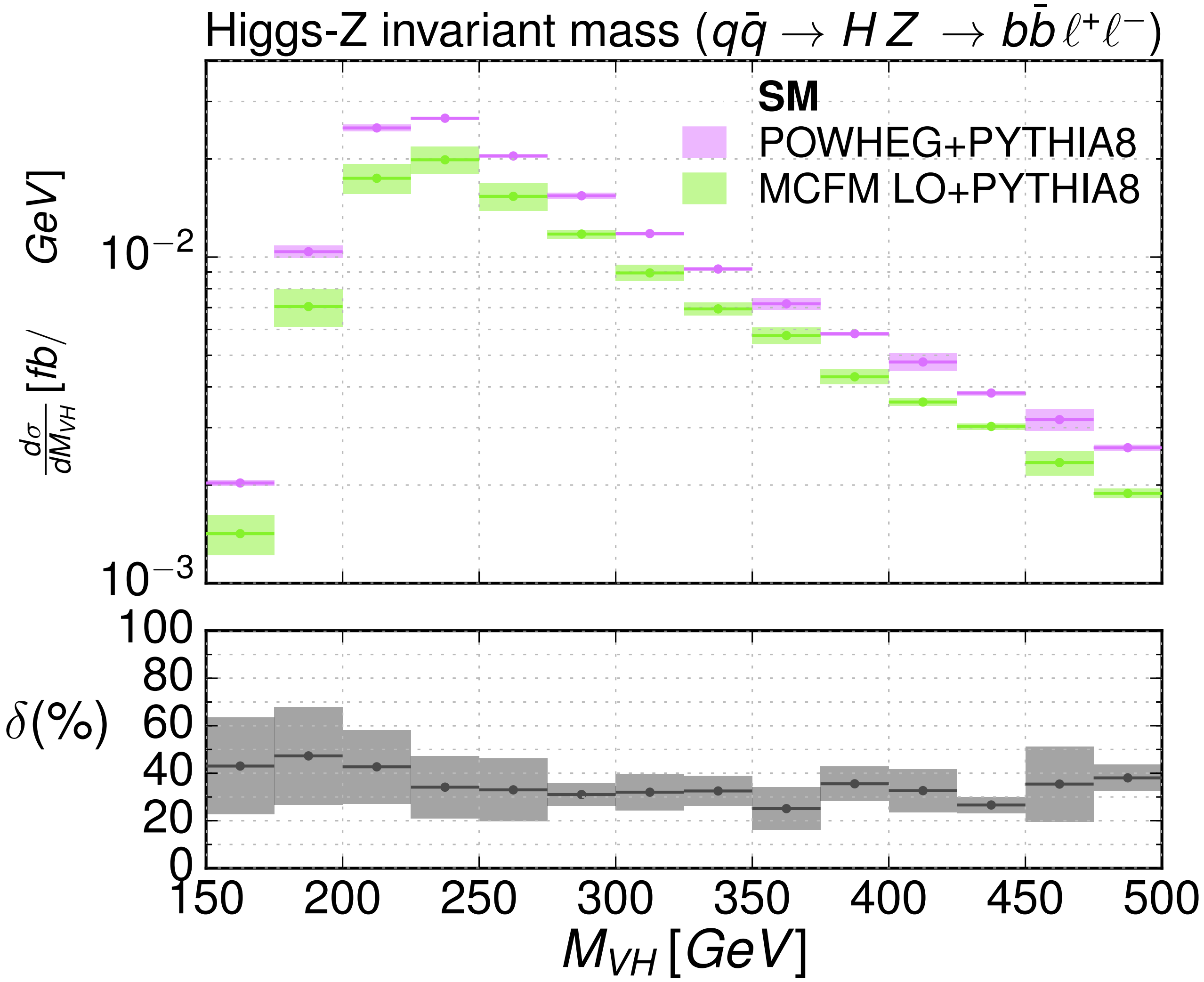


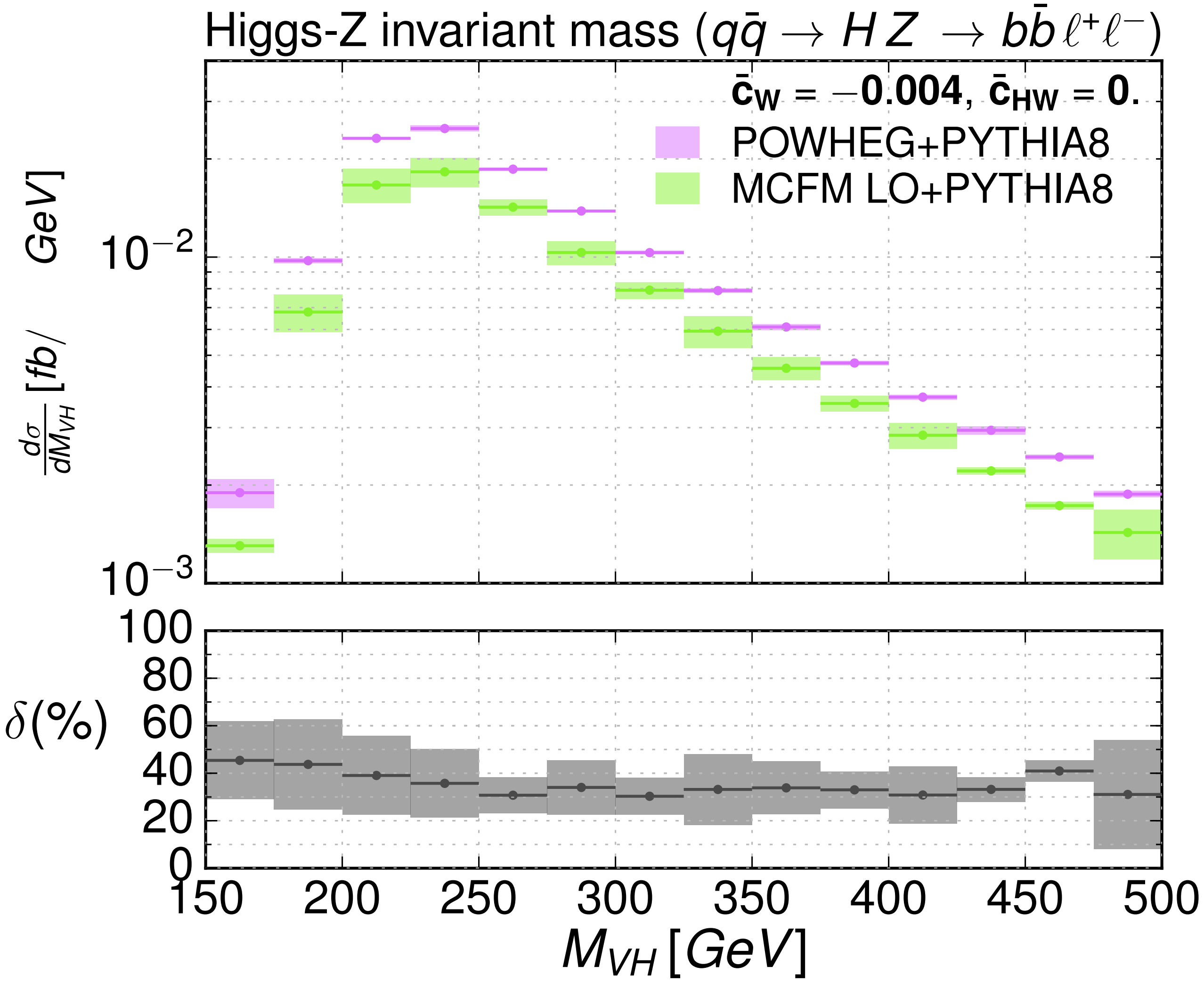


K-factors

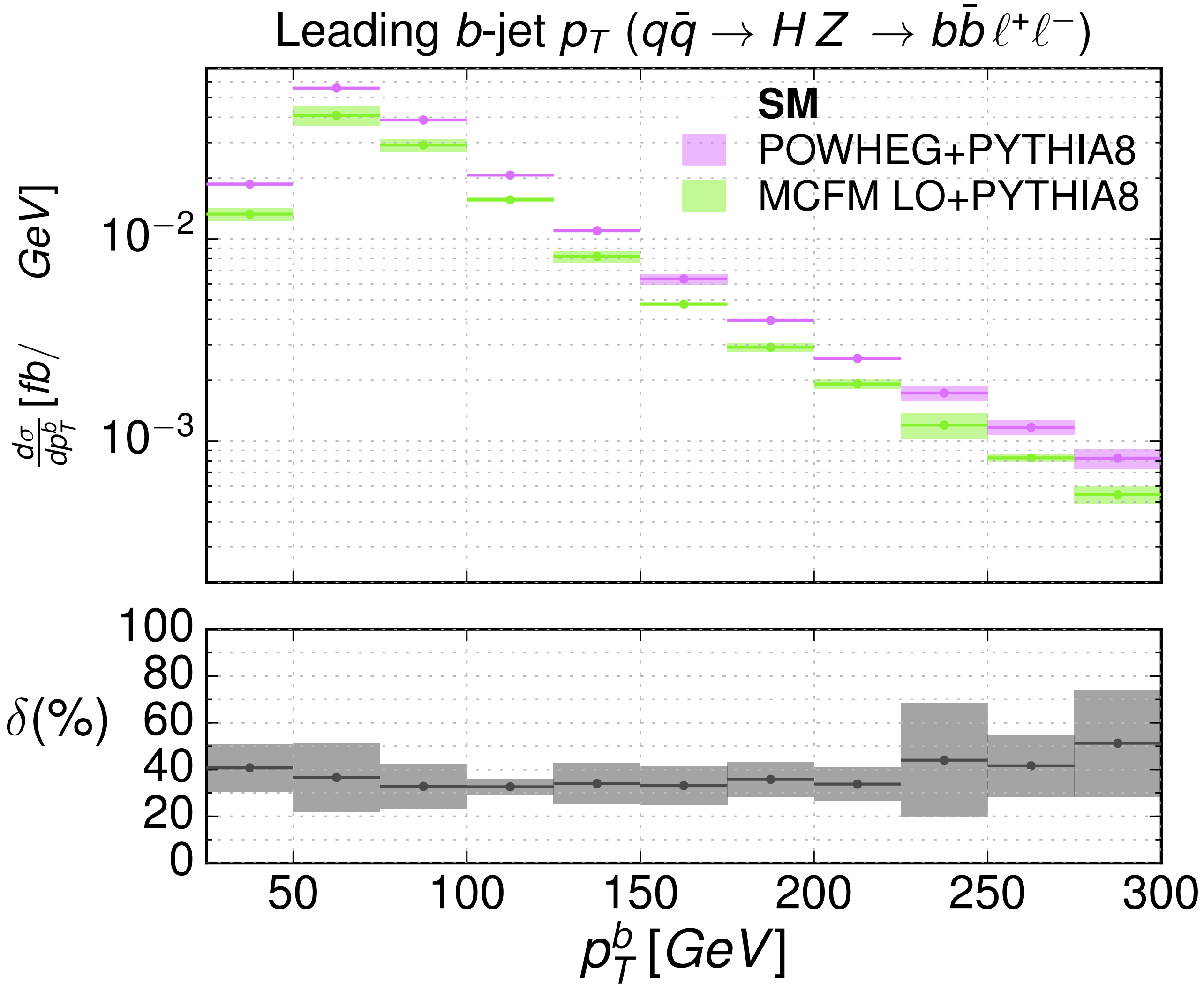
No significant difference between SM & EFT

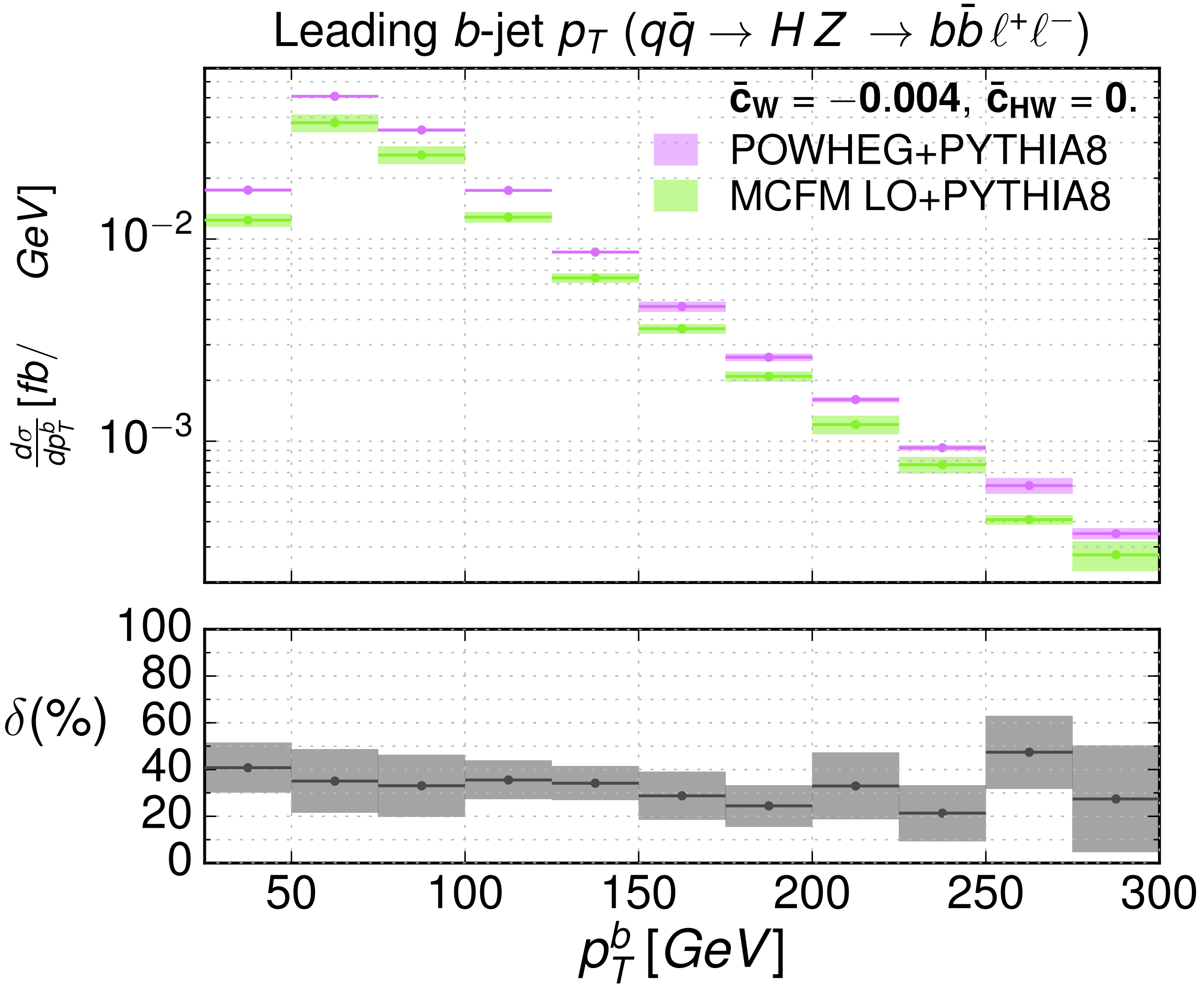
Relatively flat





K-factors


Leading b-jet p_T ($q\bar{q} \to HZ \to b\bar{b}\,\ell^+\ell^-$)


Leading b-jet p_T ($q\bar{q} \to HZ \to b\bar{b}\,\ell^+\ell^-$)

[Degrande, Fuks, Mawatari, KM, Sanz; arXiv:1609.04833]

FR+NLOCT/MG5_aMC@NLO

http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO

- HEL@NLO: Alternative & independent implementation within the FeynRules + NLOCT framework
  - Generate NLO ready UFO file
  - Simulation performed with MadGraph5_aMC@NLO ~ any process!

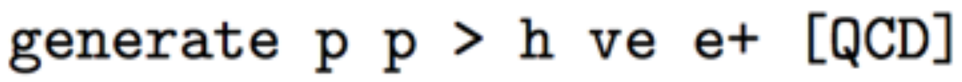
[Alloul, Fuks & Sanz; JHEP 1404 (2014) 110]

- Builds upon previous LO implementation of full SILH basis
- Modification of EW parameters fully taken into account in the (m_Z, α_S, G_F) input scheme
- Scale uncertainty determined by varying (reweighting) μ_R, μ_F independently around a central scale of μ_0
  - Envelope of 9 combinations of (1/2, 2) x μ_0

[KM, Sanz, WIlliams; arXiv:1512.02572]

Simulation

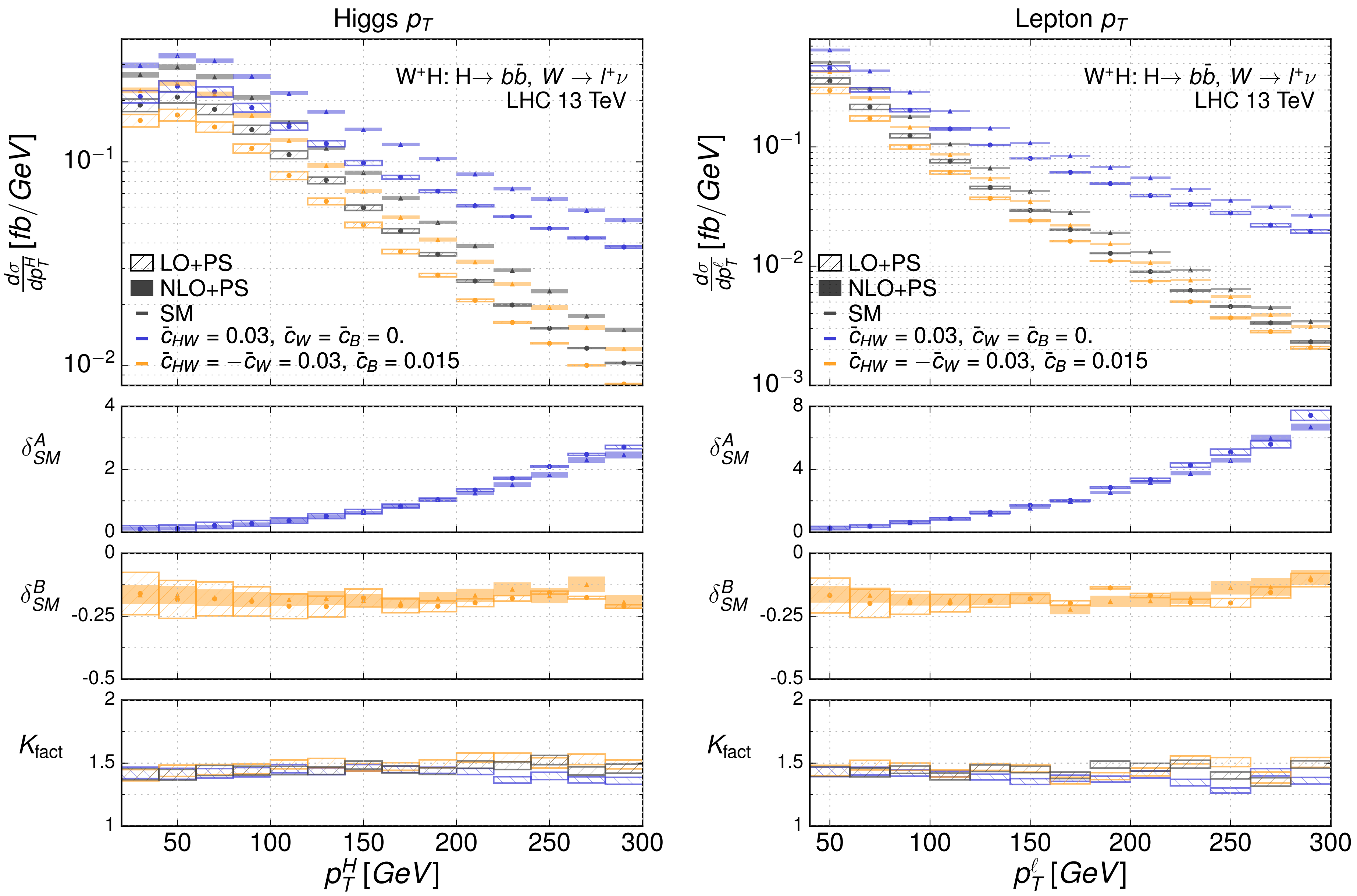
- For WH we specified that the Higgs decay to bb, as in previous example while for VBF, decay Higgs to photons
- Used NNPDF23_nlo_as_0118_qed PDFs
- Made use of recent MG5 feature to select only interference terms for comparison
    - Specify coupling order squared , e.g., “NP^2<=2” to get interference
- Validated results against POWHEG-BOX implementation



```
generate p p > h ve e+ [QCD]
```

$pp \to W^+ H \to l^+ \nu bb$

Benchmarks correspond to ‘large’ values of Wilson coefficients as described in previous analysis since they saturate current limits



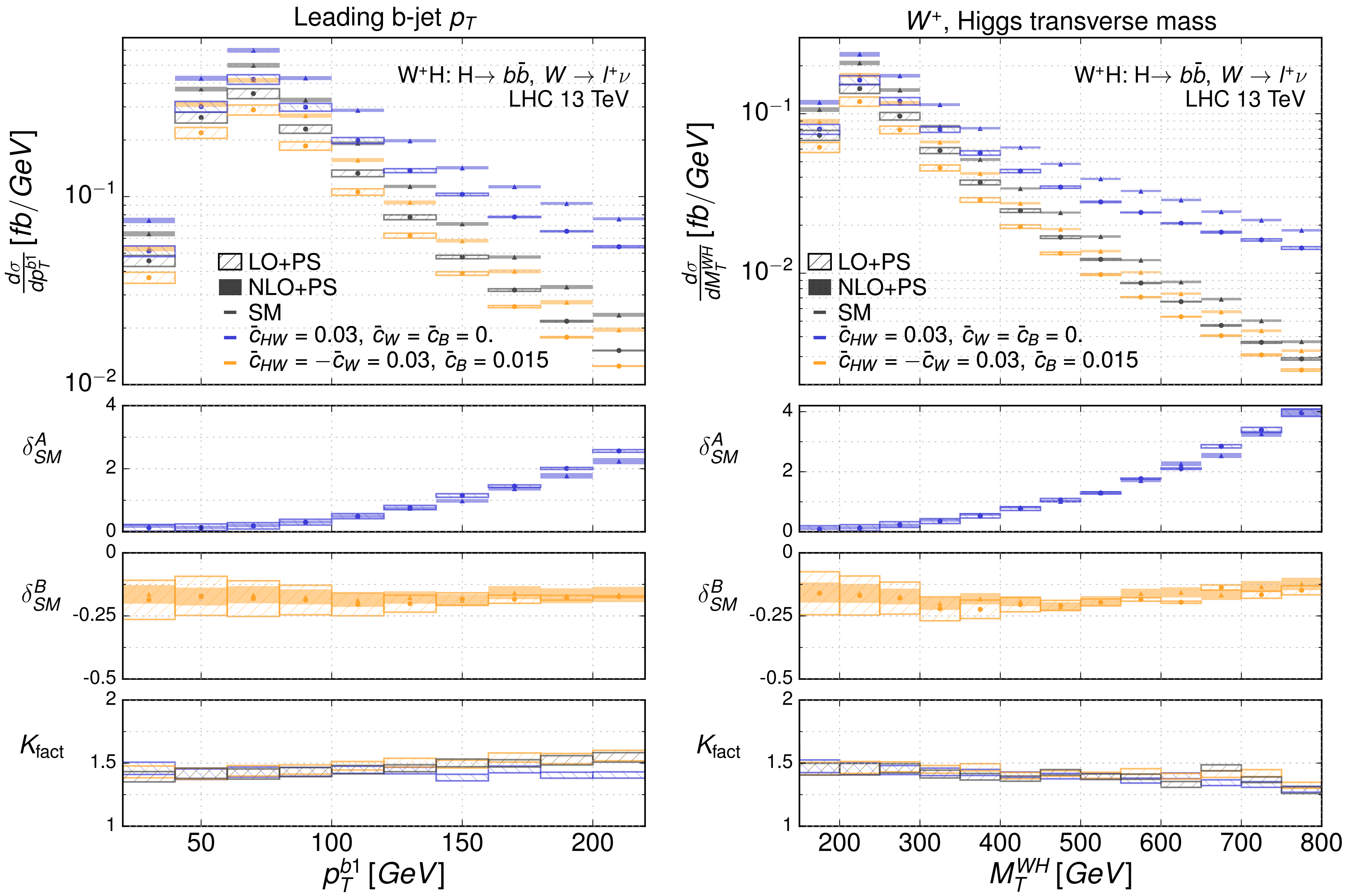
δ = TOT/SM-1

NLO/LO

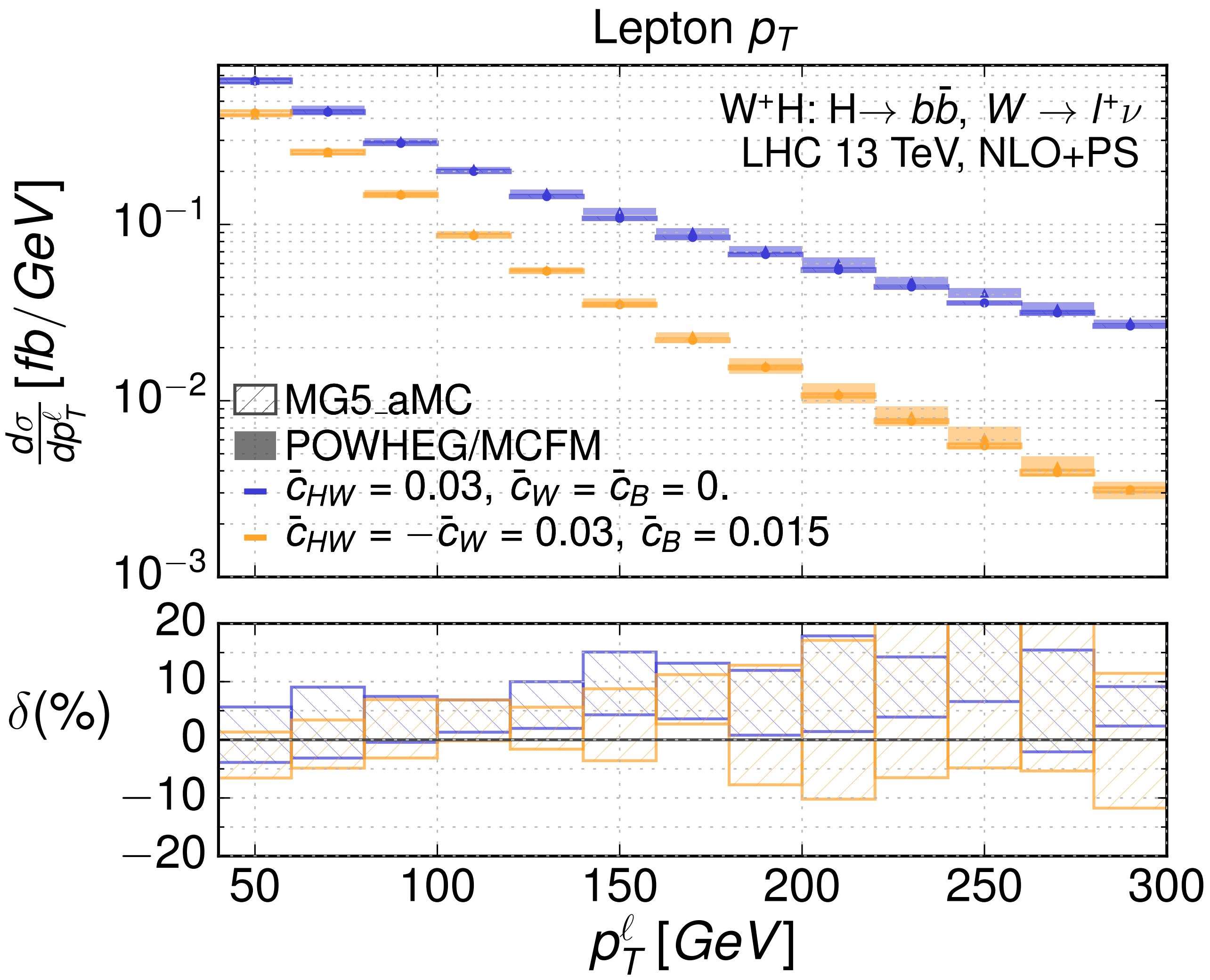
$pp \rightarrow W^+ H \rightarrow l^+ v\ bb$

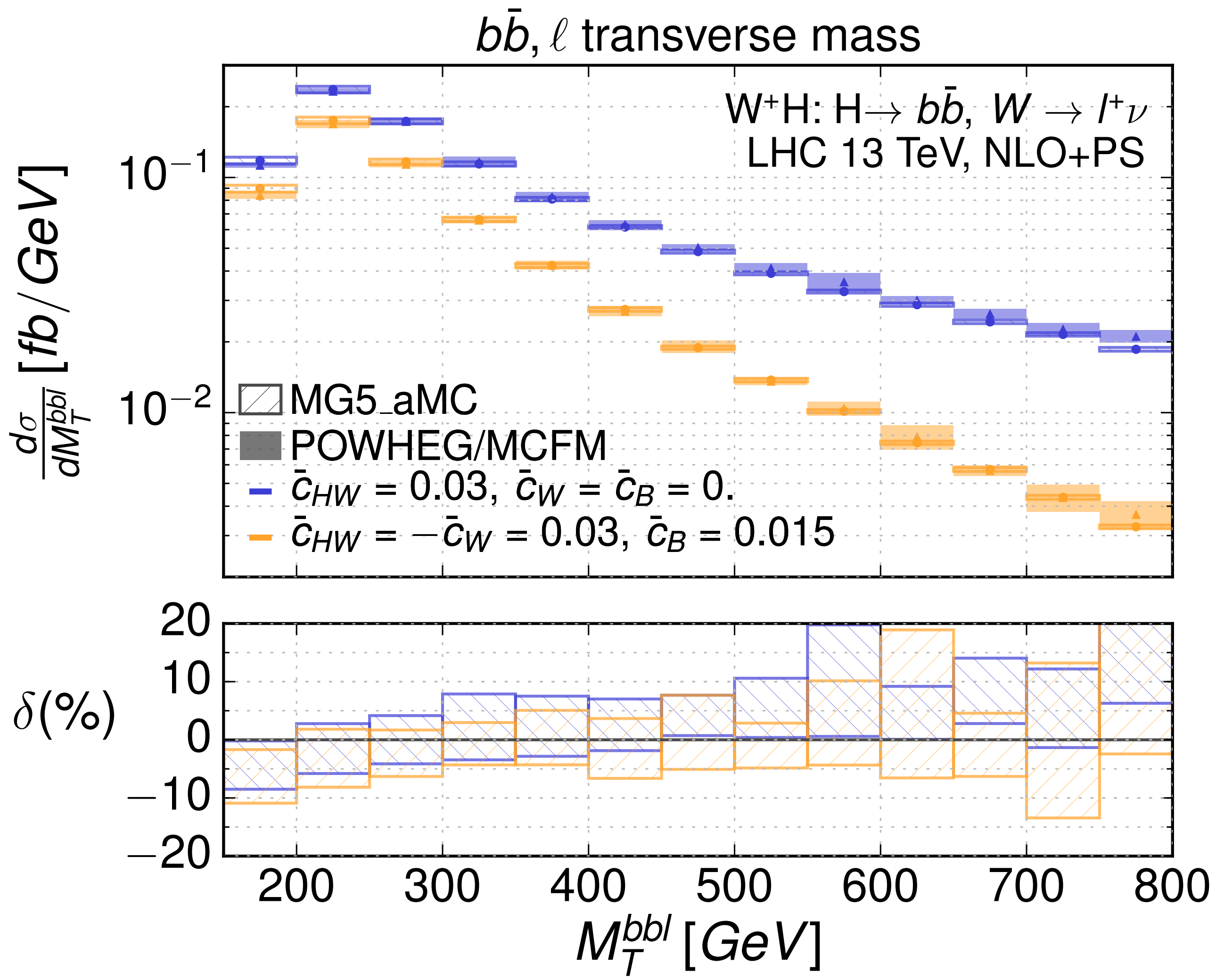
Again, benchmark **B)** does not exhibit strong “EFT” features

The $g_{hvv}^{(2)}$ Lorentz structure is responsible for these



Validation


Lepton p_T
W⁺H: H→ $b\bar{b}$, $W \to l^+\nu$
LHC 13 TeV, NLO+PS
$\frac{d\sigma}{dp_T^\ell}$ [fb/GeV]
10^{-1}
10^{-2}
10^{-3}
MG5_aMC
POWHEG/MCFM
$\bar{c}_{HW} = 0.03,\ \bar{c}_W = \bar{c}_B = 0.$
$\bar{c}_{HW} = -\bar{c}_W = 0.03,\ \bar{c}_B = 0.015$
$\delta(\%)$
20
10
0
−10
−20
50
100
150
200
250
300
p_T^ℓ [GeV]


$b\bar{b}, \ell$ transverse mass
W⁺H: H→ $b\bar{b}$, $W \to l^+\nu$
LHC 13 TeV, NLO+PS
$\frac{d\sigma}{dM_T^{bbl}}$ [fb/GeV]
10^{-1}
10^{-2}
MG5_aMC
POWHEG/MCFM
$\bar{c}_{HW} = 0.03,\ \bar{c}_W = \bar{c}_B = 0.$
$\bar{c}_{HW} = -\bar{c}_W = 0.03,\ \bar{c}_B = 0.015$
$\delta(\%)$
20
10
0
−10
−20
200
300
400
500
600
700
800
M_T^{bbl} [GeV]