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SMEFT@NLO in QCD

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Multi-Boson Interactions 2017
Karlsruher Institut für Technologie

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Outline

- Overview of recent progress in MC event generation for SMEFT at NLO in QCD matched to parton shower
    - FeynRules/NLOCT/UFO → MadGraph5_aMC@NLO
    - Towards complete public implementation
- Top/Higgs/Electroweak SMEFT @ the LHC
- Results from the implementations of operators affecting Higgs couplings to gauge bosons/tops
    - Selection: ttH, VH and VBF
    - EFT "validity" and future reach for HL-LHC
- In progress: combined SMEFT model for these sectors

Going NLO

- The LHC is entering a precision era
  - No clear evidence for new physics as we approach the limits of the 'energy frontier'
  - Fully complementary approach to search for deviations in SM processes
  - Many channels are becoming systematics dominated & require high precision theory input from higher order corrections (FO & PS)
- EFT: theoretically consistent, model independent approach to deviations of interactions between SM fields
  - Active area of research that is moving towards NLO predictions
  - NLO important for capturing potentially large QCD K-factors in total rates → greater sensitivity
  - Verify stability of differential information beyond leading order
  - Consistent scale uncertainty estimates

Going NLO

- State-of-the-art in MC event generation is well beyond LO
  - Software like FeynRules+NLOCT+MG5_aMC@NLO provides automated event generation at NLO in QCD from Lagrangian
  - Other matching/merging schemes exist on a process-by-process basis, e.g., POWHEG-BOX,…
  - Individual codes exist for specific processes, up to NNLO QCD + NLO EW
- Public implementations largely restricted to SM predictions although some codes permit the inclusion of anomalous couplings
  - See, e.g., Higgs Characterisation *[Demartin, Maltoni, Mawatari, Page & Zaro; EPJC 74 (2014) 9, 3065]*
  - Several others: HAWK, VBFNLO, HiggsPO…
  - Full SM-EFT descriptions are naturally well motivated and will provide a valuable addition to the existing toolbox

Going NLO

- NLO+PS accurate predictions in QCD are a necessary step for precision EFT analysis at LHC run 2 & beyond
- Other important avenues…
- NLO EW corrections
  - Potentially important but much harder
  - Automation on the way via SHERPA (S. Schumann's talk), Madgraph5_aMC@NLO
- RG-improved predictions thanks to recent anomalous dimension matrix calculation
  - Very helpful for cross checking NLO implementations

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

FeynRules/NLOCT/UFO

- FeynRules *[Christensen & Duhr; Comp. Phys. Comm. 180 (2009) 1614]* *[Alloul et al.; Comp. Phys. Comm. 185 (2014) 2250]*
  - Framework: Lagrangian → Feynman rules → UFO model → MC events
- Universal FeynRules Output (UFO) *[Degrande et al.; Comp. Phys. Comm. 183 (2012) 1201]*
  - Model file with particle content, internal/external parameters, Feynman rules, Lorentz structures,…
  - Compatible with many MC event generators (MG5, Sherpa, Whizard,…)
- NLOCT *[Degrande; Comp. Phys. Comm. 197 (2015) 239]*
  - Automatic calculation of UV and R_2 counter-terms from FeynRules model
  - Implemented as additional Feynman rules in the UFO format
  - UV: On-shell renormalisation procedure for masses/wavefunction, MSbar for higher point functions
  - R_2: numerical artefacts of dimensional regularisation

SMEFT

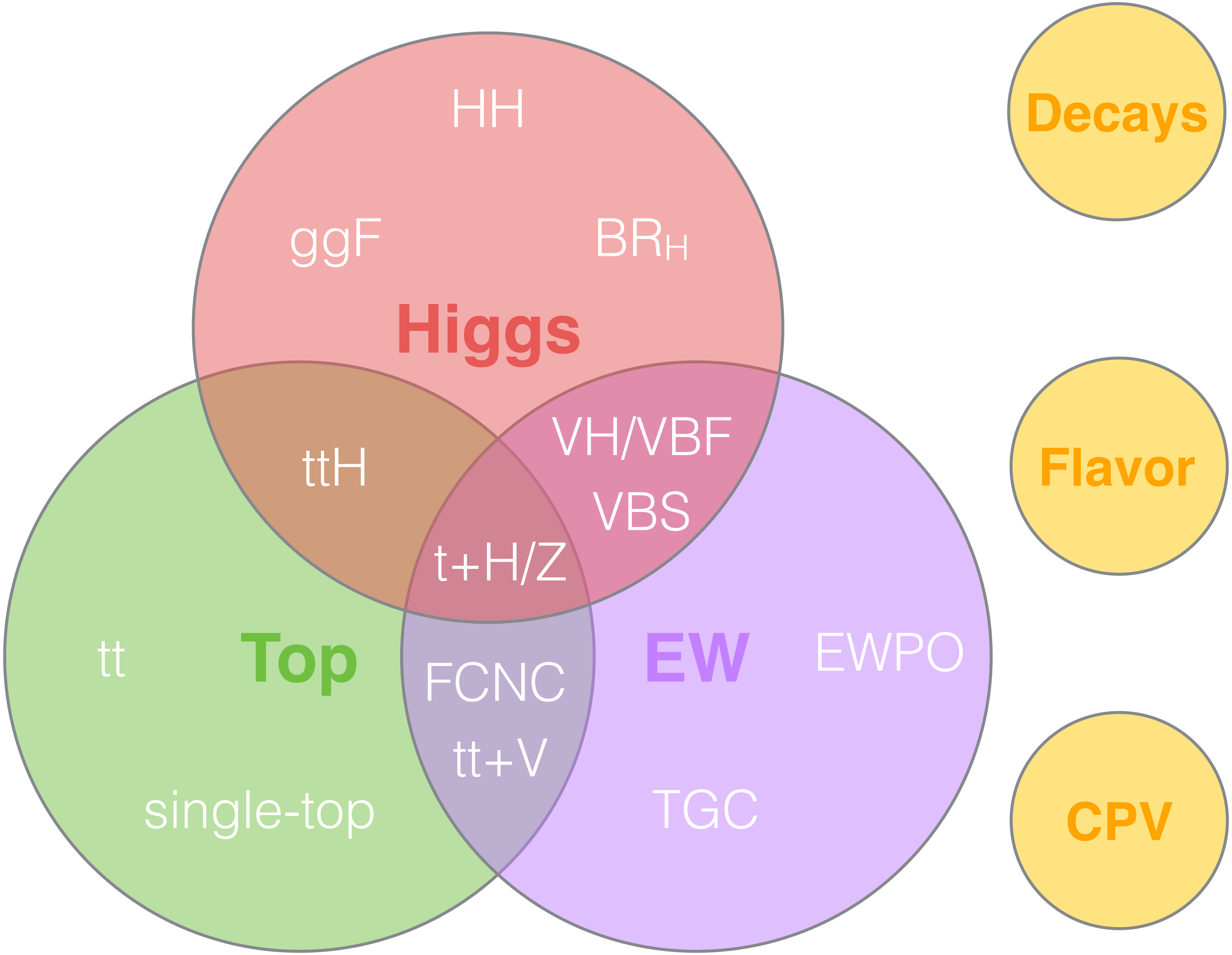
- Plenty of EFT introductions already at this workshop
  - Expansion in the cutoff scale, Λ, using only SM fields
  - Truncated at dimension 6
  - Introduces operators to which we are sensitive via large momentum flows through vertices (i.e. tails of energy distributions)
- Operator expansion: $$\mathcal{L}_{\rm eff} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$ more: fields derivatives
- In the SM: 59 (76 real) - 2499 operators depending on assumptions regarding CP/flavour structure etc.

[Buchmuller & Wyler; Nucl.Phys. B268 (1986) 621]
[Grzadkowski et al.; JHEP 1010 (2010) 085]

- Dimension 8 now known ~ 895 (36971) operators!

[Lehman et al.; PRD 91 (2015) 105014]
[Henning et al.; Commun.Math.Phys. 347 (2016) no.2, 363-388 & arXiv:1512.03433]

SMEFT @ the LHC: key players



SM(Higgs)-EFT

- Single Higgs state of the art @ fixed order:
  - Yukawa & HGG ops. (NNLO+NNLL) *[Grazzini et al.; arXiv:1705.05143]*
  - Top chromomagnetic op. (NLO) *[Deutschmann et al.; arXiv:1705.05143]*
- Public codes with partial SMEFT contributions @ NLO
  - HiGlu *[Spira; arXiv:hep-ph/9510347]*
  - SusHi (aMC-SusHi) *[Harlander, Liebler & Mantler; arXiv:1605.03190]*
- Double Higgs
  - HPAIR *[Dawson, Dittmaier & Spira; Phys. Rev. D58:115012]*
  - HiggsPair (HERWIG++) *[Goertz et al.; JHEP 1504 (2015) 167]*
- eHDECAY for BR *[Contino et al.; Comp. Phys. Comm. 185 (2014) 3412-3423]*
- Full 1-loop H→$\gamma\gamma$ and H→bb *[Hartmann & Trott; PRL115 (2015) 191801]* *[Gauld, Scott & Pecjak; PRD94 (2016) 074045]*

SM(Top+X)-EFT

- Most developed sector of SMEFT@NLO in QCD
  - Top-Higgs-W/Z couplings/masses are related in SM: unitarity cancellations
  - “Indirectly” relevant for multi-boson interactions
- Coloured sector, strongly coupled to the Higgs
  - Large corrections to inclusive rates (~1 K-factors)
  - Non-trivial shape corrections at differential level
  - Non-trivial renormalisation/operator mixing
- Selection of studies
  - ttH
  - tt+Z/γ
  - single top
  - top FCNC

UFO models available upon request

[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

[Bylund et al.; JHEP 1605 (2016) 052]

[Zhang; PRL 116 (2016) 162002]

[Degrande et al.; PRD 91 (2015) 034024]

[Durieux, Maltoni & Zhang; PRD 91 (2015) 074017]

[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

ttH in SMEFT

$$\begin{aligned}\mathcal{O}_{t\varphi} &= (\varphi^\dagger\varphi)(\bar{Q}_L\,\tilde{\varphi}\,t_R)\\ \mathcal{O}_{\varphi G} &= (\varphi^\dagger\varphi)\,G^A_{\mu\nu}G^{\mu\nu}_A\\ \mathcal{O}_{tG} &= (\bar{Q}_L\sigma_{\mu\nu}\,T^A\;t_R)\,\tilde{\varphi}\,G^{\mu\nu}_A\end{aligned}$$

- Operators involving the top/Higgs/gluon
  - gg→H & tt production partly constrain the Wilson coefficient space
  - ttH is the only direct probe of the Top-Higgs interaction
  - In principle 3-gluon O_G and 4 fermion operators also contribute but turn out to be better constrained by tt and multi-jet measurements
- Predictions for ttH and HH production presented
  - First inclusion of chromomagnetic dipole operator for HH
  - Demonstration of non-trivial K-factors at differential level
  - Comparison of RG improved vs. full NLO (finite terms important)

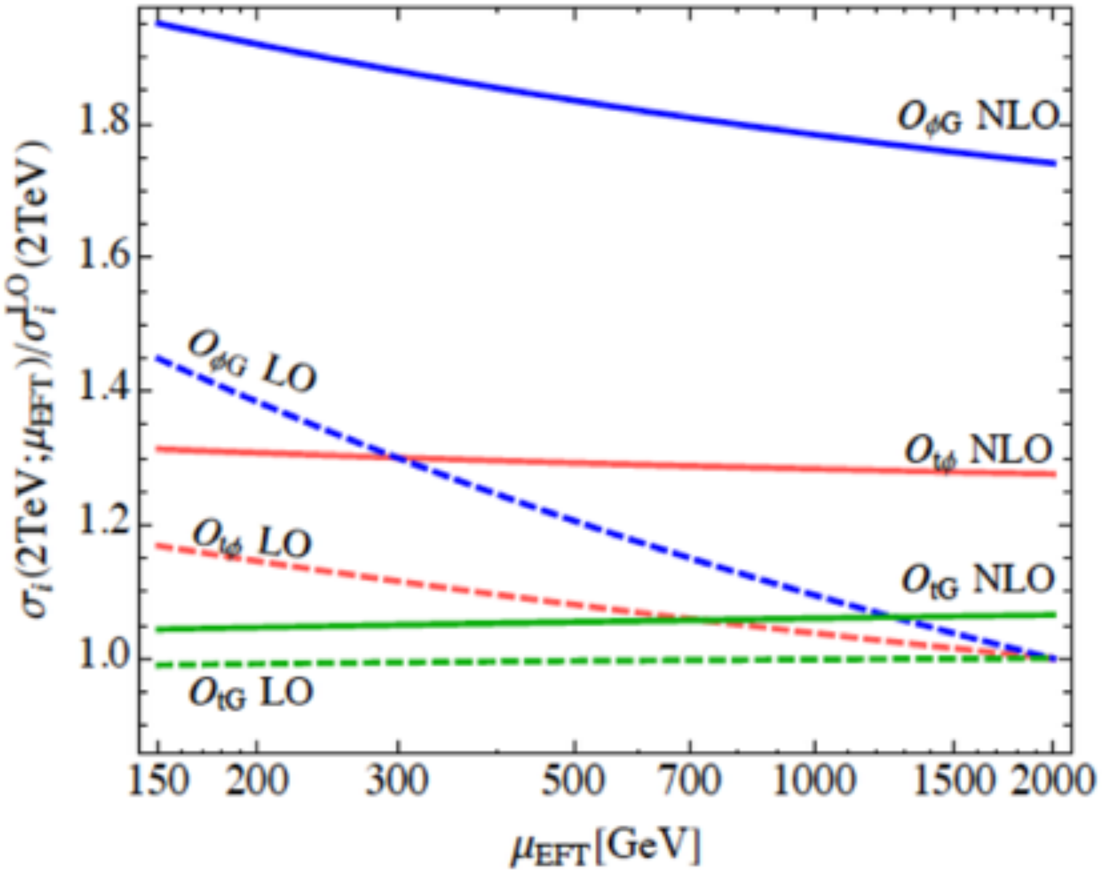
ttH in SMEFT

- Different K-factors among SM/dim-6 operators
- Large Λ^{-4} effects in both shape & normalisation
  - Tied to the question of EFT validity w.r.t to truncation at dim-6
  - Scenarios where “EFT-squared” terms are large but energy is below cutoff
  - Treatment on a case-by-case basis

c.f. talk by A. Pomarol

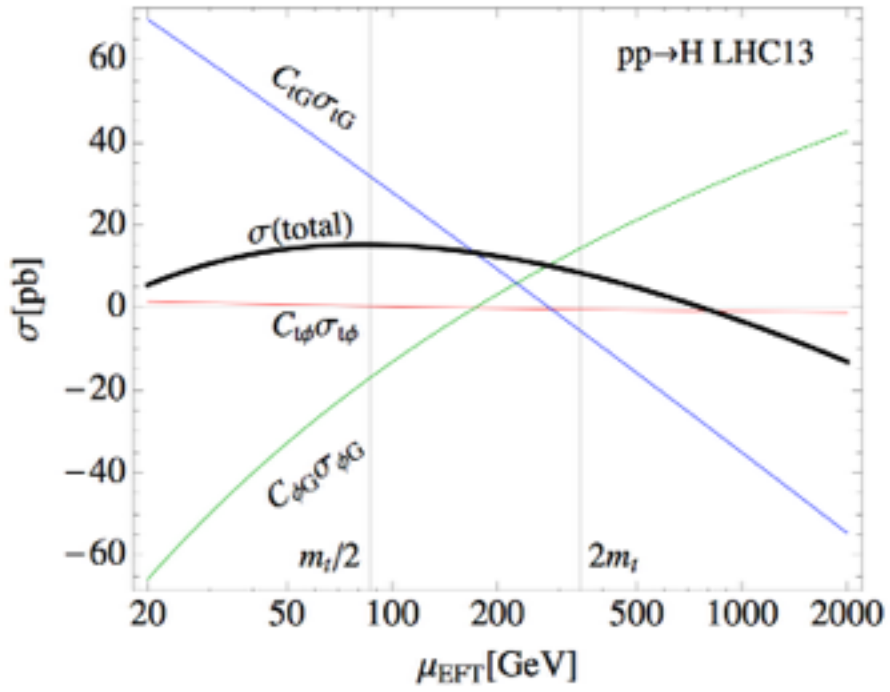
$$\boxed{c_i c_j \frac{E^4}{\Lambda^4} > c_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}}$$

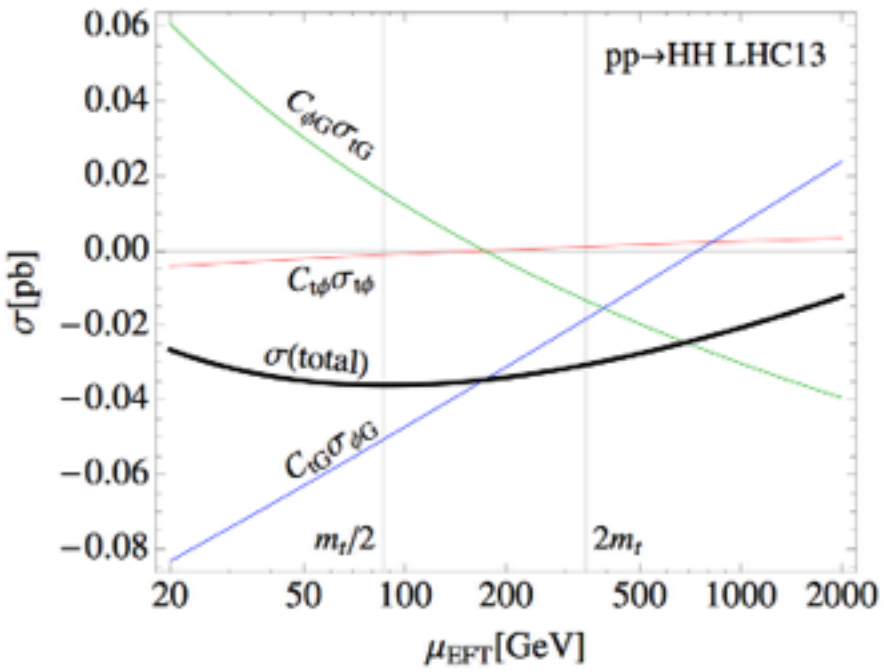
- Stable under scale variation
- Large finite effects: RG improvement underestimates NLO prediction



EFT scale uncertainty

- NLO calculations use scale uncertainty to approximate missing higher orders in perturbative expansion
  - EFT description contains an additional source of scale dependence from the running/mixing of Wilson coefficients
- Proposal for a scale uncertainty estimate
  - Take c_i defined at scales $2\mu_0$ & $\mu_0/2$ and run back to the central scale





Does not cancel in e.g. cross section ratios

SM(Higgs+EW)-EFT

- “Canonical” sector for Higgs studies in SMEFT
- Easier to implement NLO QCD, no RG running
- Implementations build upon previous LO model employing the ‘SILH’ basis of operators
  - SMEFT Basis dependence of HEP tools can be reduced by linear redefinitions using e.g. Rosetta
- Also made use of existing implementations of SM process at NLO

MCFM/ POWHEG-BOX
WH & ZH (incl. gg → ZH)

(in backup)

FeynRules/NLOCT UFO model
via Madgraph5_aMC@NLO
WH & VBF

EW Higgs production

- EFT effects in EW production mechanisms for the Higgs: VH & VBF
  - A small number of relevant & uncoloured operators at D=6 in SM-EFT
  - LHC can provide complementary information to existing fits to lower energy data, i.e. LEP
  - Higgs comes with some additional objects from which we can construct kinematic quantities probing the high energy regime
  - VH: Higgs p_T, M_{VH}, leading lepton p_T,…
  - VBF: Higgs p_T, $\Delta\eta_{jj}$, total H_T,…
- Investigate validity of EFT expansion given current constraints from global fits
- Future reach of HL-LHC

SILH operators

- SMEFT: Higgs-EW gauge boson operators in SILH basis

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

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

linear map

- Anomalous couplings: new Lorentz structures (1) & (2):

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

(+ Higgs-fermion current operators not included here)

Contact interactions

- Not commonly considered for EW production
  - Also affect V-f-f vertices: constrained by previous experiments e.g. LEP
  - Not all of them much more than LHC/LEP constraints on (c_W,c_B,c_{HW},c_{HB})
  - Flavour matrices: FCNC,… interplay between LHC and other experiments
  - How much can they can impact VH, VBF at the LHC given existing constraints or conversely, whether LHC can be complementary

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

+ lepton currents (some of which affect SM inputs)

Only HiggsPO includes these so far at NLO in QCD

[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]

SM inputs

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

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

$$\begin{aligned}\mathcal{O}_W|_{\Phi=\langle\Phi\rangle} =& \frac{ig}{2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu}|_{\Phi=\langle\Phi\rangle}\\ =& \frac{gv^2}{16}\bar{c}_W\left[2gW^{\mu\nu}_+W^-_{\mu\nu} + g(W^{\mu\nu}_3 - g'B^{\mu\nu})W^3_{\mu\nu}\right] + \text{aGC}\end{aligned}$$

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

- After EWSB, canonical mass eigenbasis, different from SM
  - Perform field redefinitions to fix their normalisation
  - Gauge coupling redefinitions can absorb part of the resulting modifications
  - Modifications of gauge bosons masses, interactions, e.g., Z→ff
  - Modifications to the SM parameters as a function of EW inputs
  - Can also affect backgrounds
- Not all tools take these into account
  - Various choices can be made that are all equivalent up to dimension-6

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 $c_B \sim -c_W/2$

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

- We pick benchmark points that, e.g., 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

- 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
  - Envelope of 9 combinations of (1/2, 2) x μ_0
- See backups for ZH in POWHEG-BOX/MCFM, including SM gg→ZH

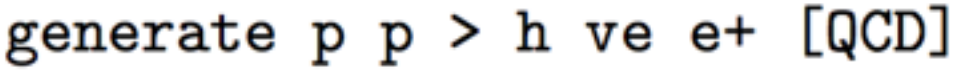
[Degrande, Fuks, Mawatari, KM, Sanz; arXiv:1609.04833]
[Alloul, Fuks & Sanz; JHEP 1404 (2014) 110]

HELatNLO

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

- SMEFT implementation in FeynRules + NLOCT framework
  - Simulation performed with MadGraph5_aMC@NLO ~ any process!
  - First results for VBF in SMEFT @ NLO in QCD
- Includes 5 operators affecting Higgs couplings to W/Z/γ
  - First step for EW Higgs production
- Modification of EW parameters taken into account in the (m_Z, α_S, G_F) input scheme

Simulation



```
generate p p > h ve e+ [QCD]
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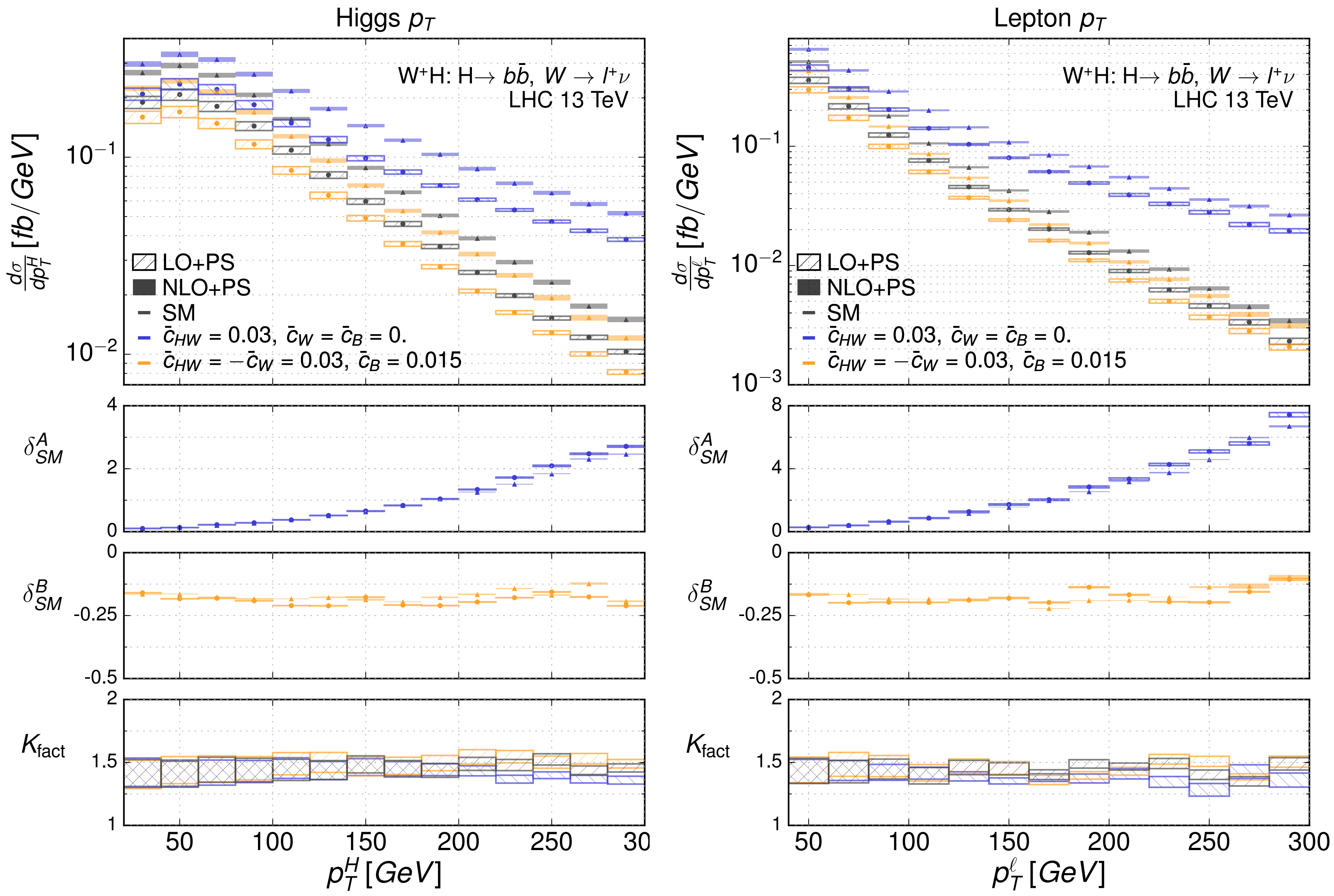
- For WH: Higgs → bb & for VBF: Higgs → $\gamma\,\gamma$
- Made use of MG5 feature to select only interference terms for comparison (LO only)
  - Specify coupling order squared , e.g., “NP^2<=2” to get interference
  - Naive measure of “validity” of EFT interpretation
  - MG5_aMC reweighting technology can upgrade this to NLO
- Validated results against POWHEG-BOX implementation
  - Found reasonable agreement

[KM, Sanz, Williams; JHEP 1608 (2016) 039]

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

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



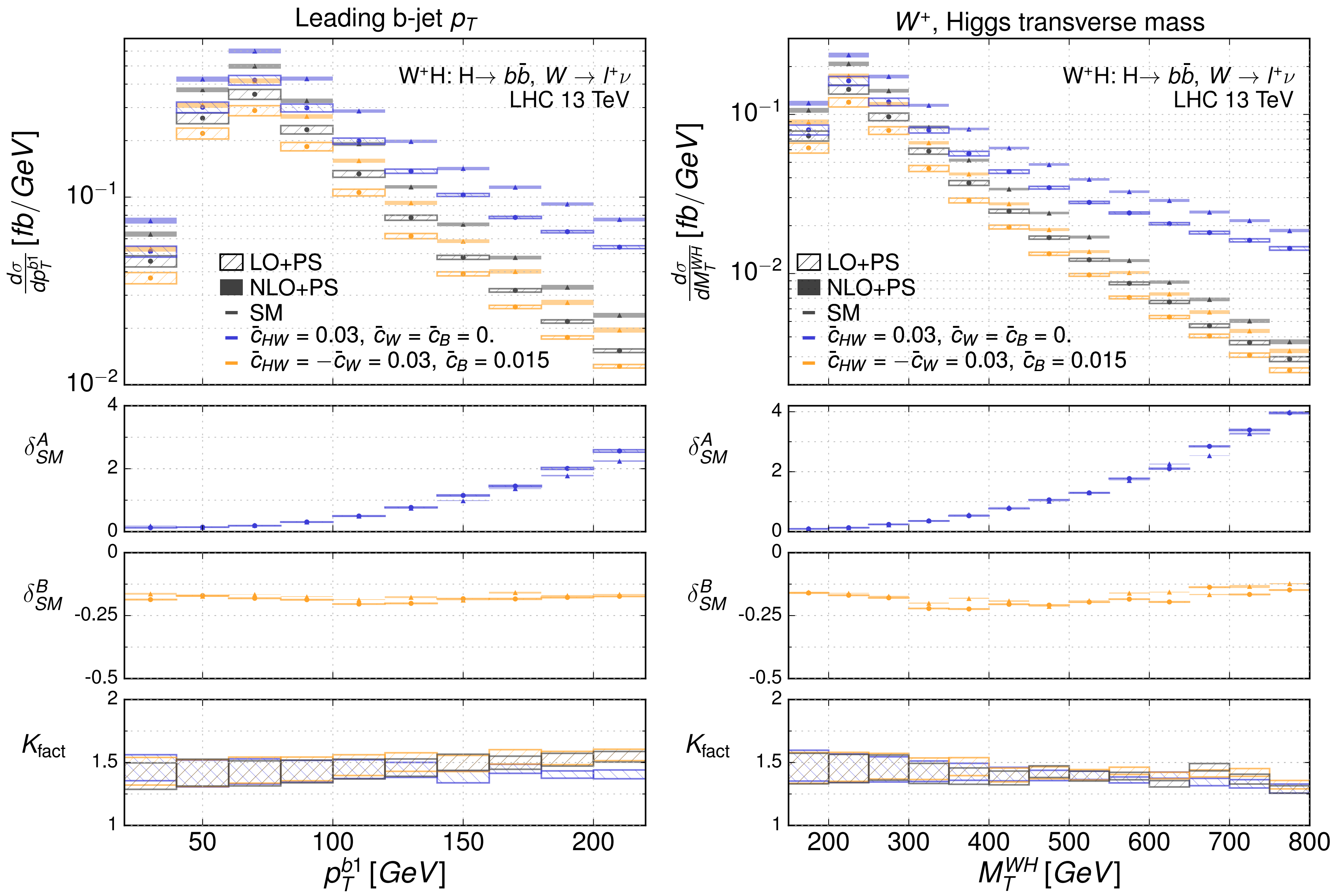
δ = TOT/SM-1

NLO/LO

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

Benchmark **B)** does not exhibit strong “EFT” features

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

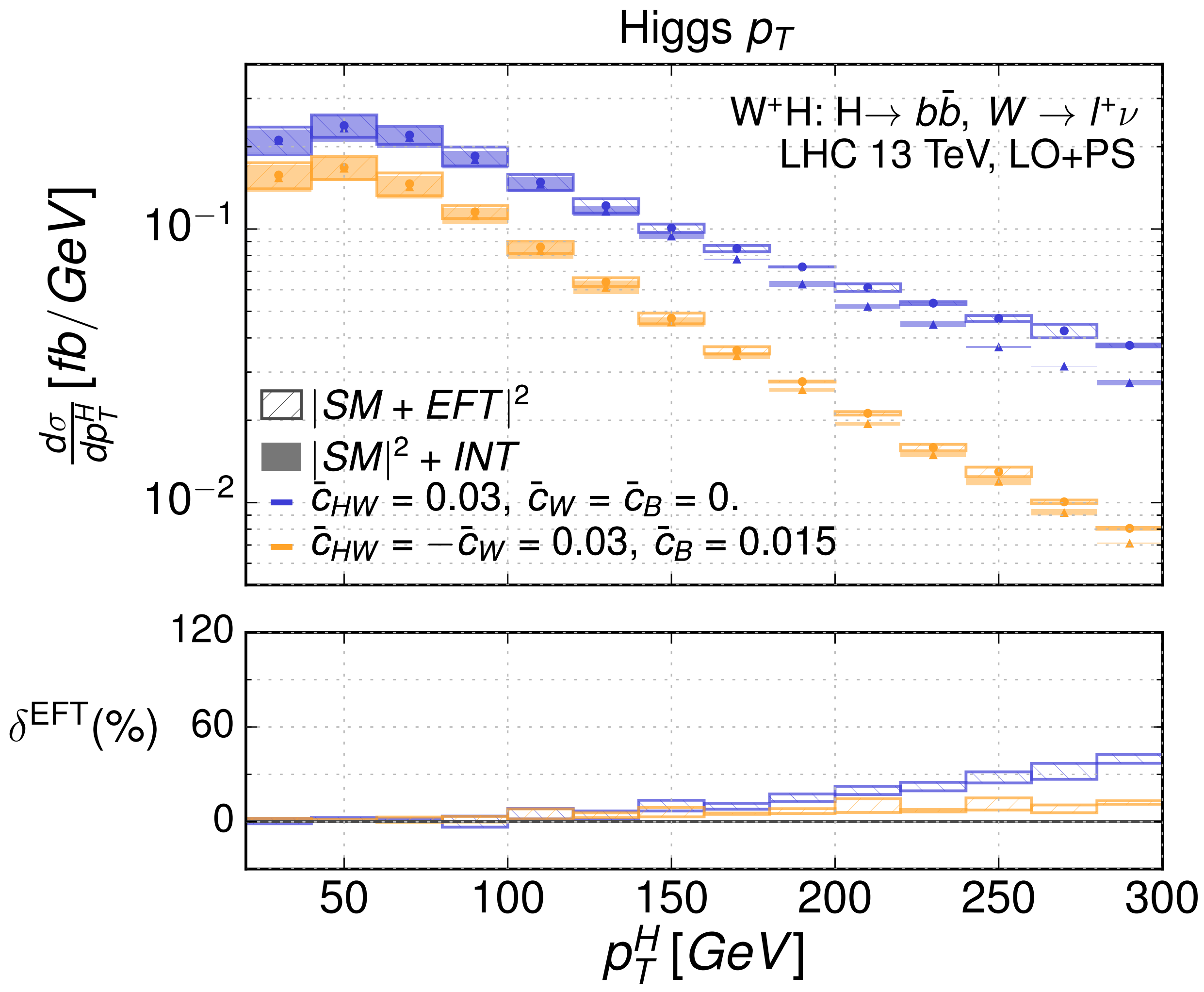


Interference only (LO)

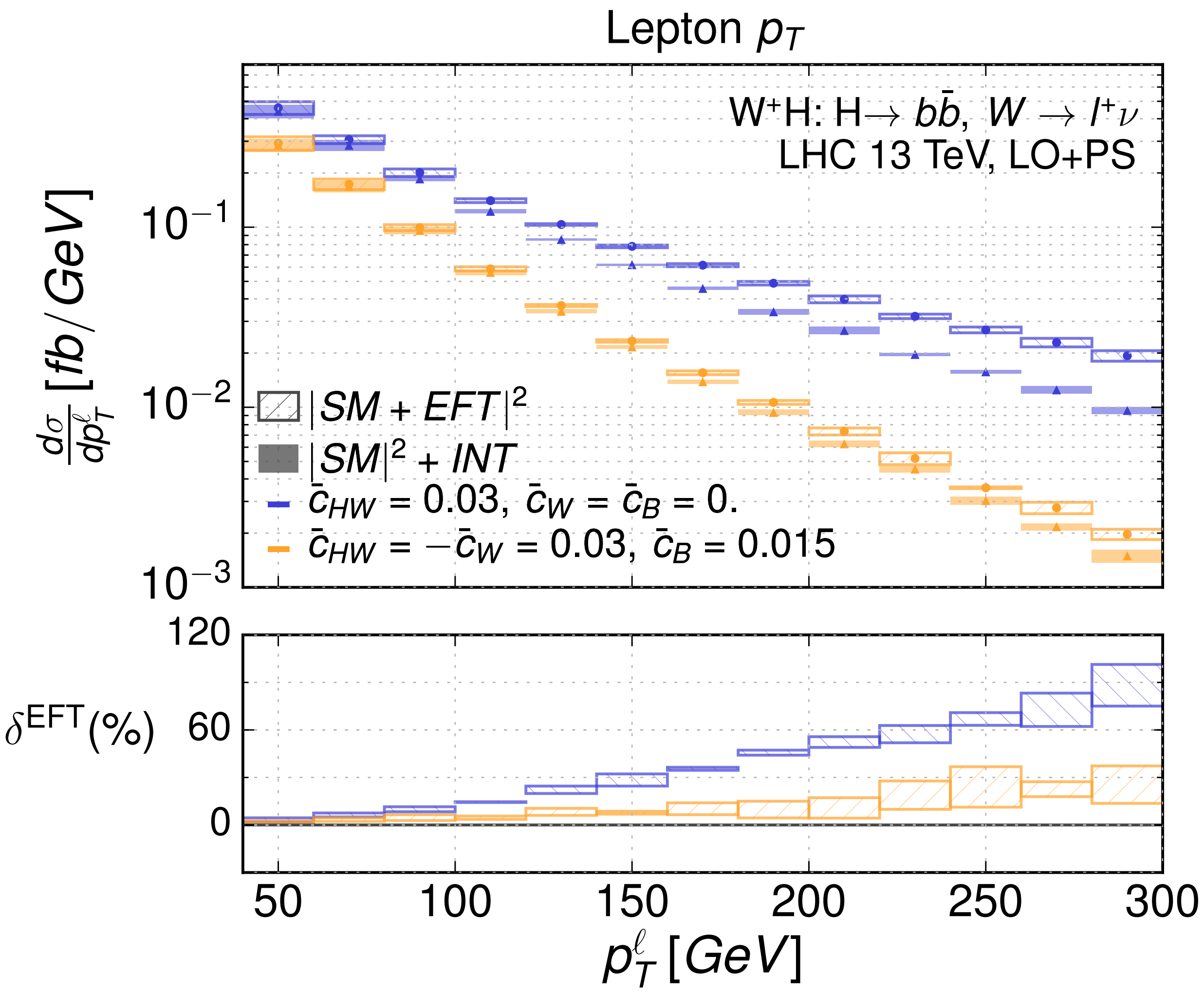
40-80% difference for benchmarks saturating current limits

A possible way to define an additional theory uncertainty?

LHC8 + EWPO not perfect for EFT interpretation of c_W,c_{HW}



Higgs p_T



Lepton p_T

pp → H j j→ɣ ɣ j j

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generate p p > h j j $$ w+ w- z a QCD=0 [QCD]
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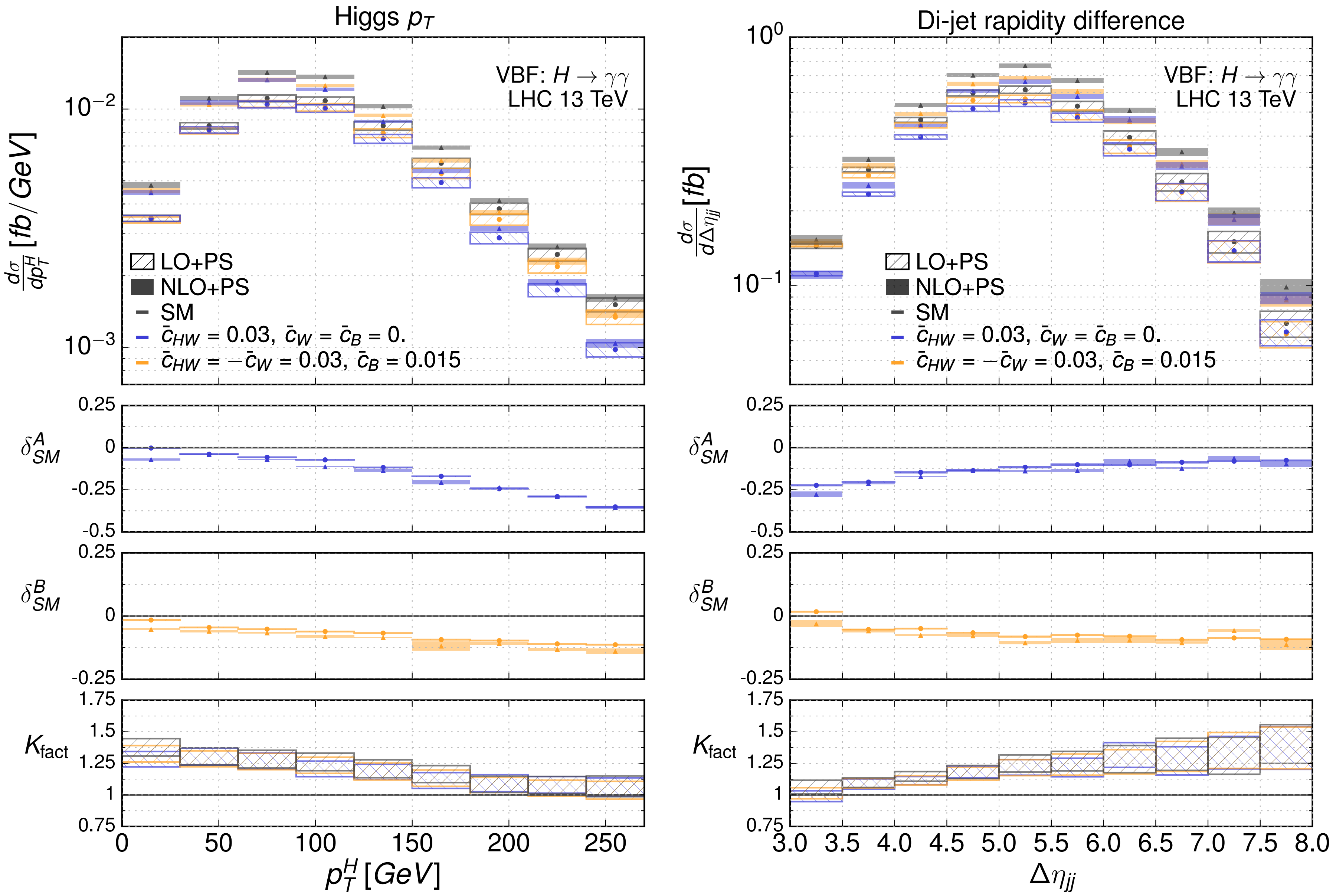
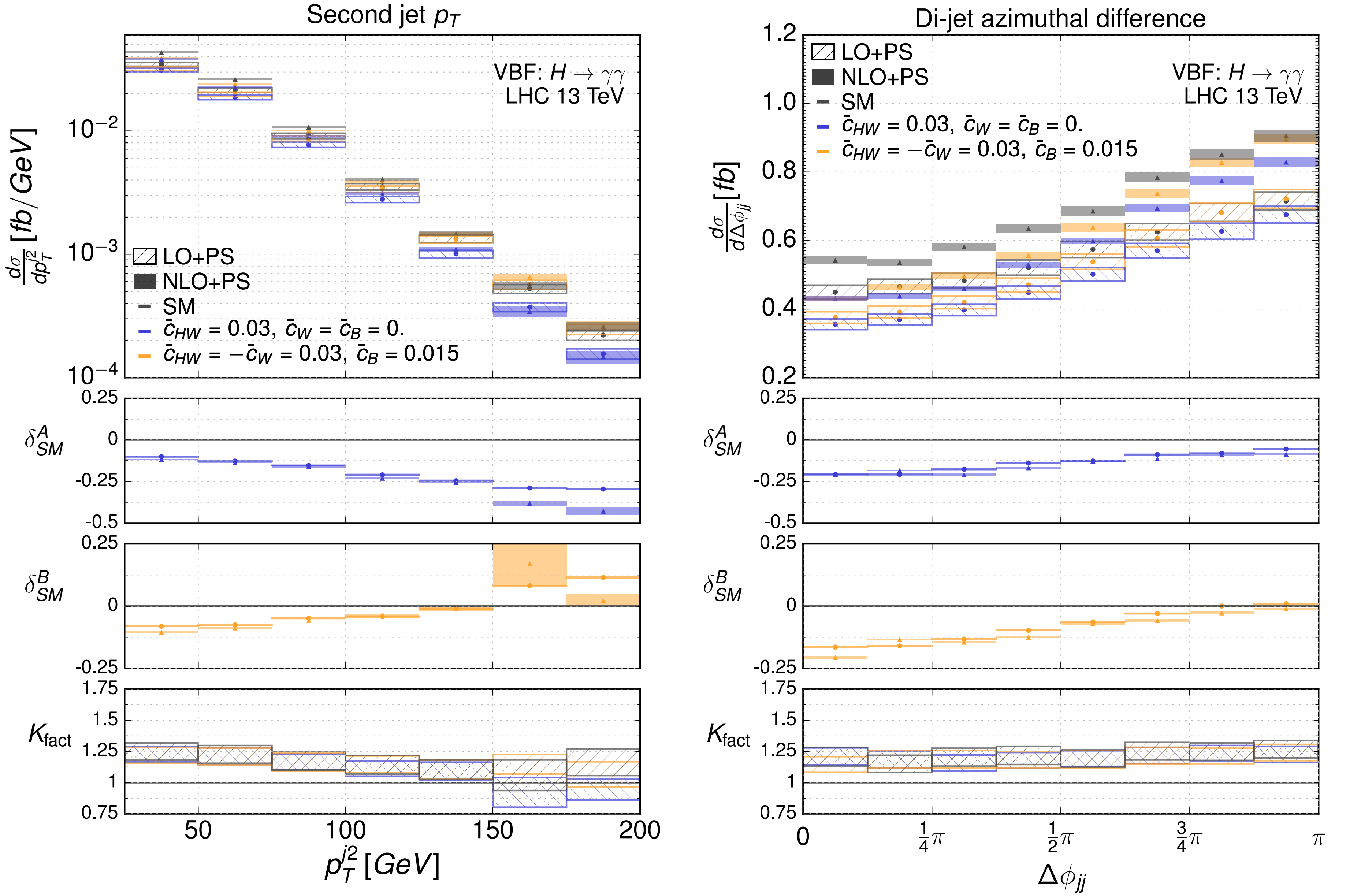
Used a fixed scale of m_W as suggested by literature



K-factors not as flat

pp → H j j→γ γ j j

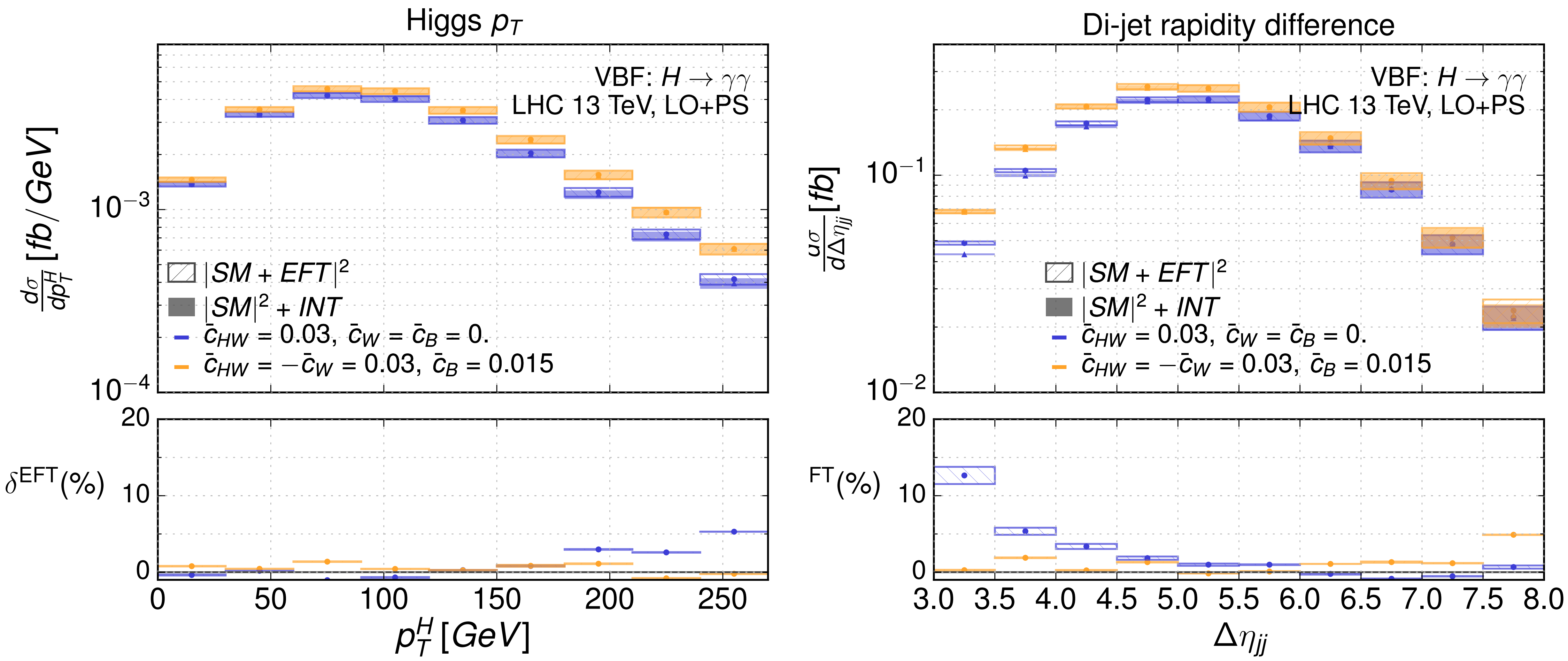
Generally smaller effects of order 25-50% present, sensitivity to benchmark B. Correlating VH & VBF may help disentangle this coupling structure.



Interference only (LO)

Interference vs. square much more under control.

~10% difference



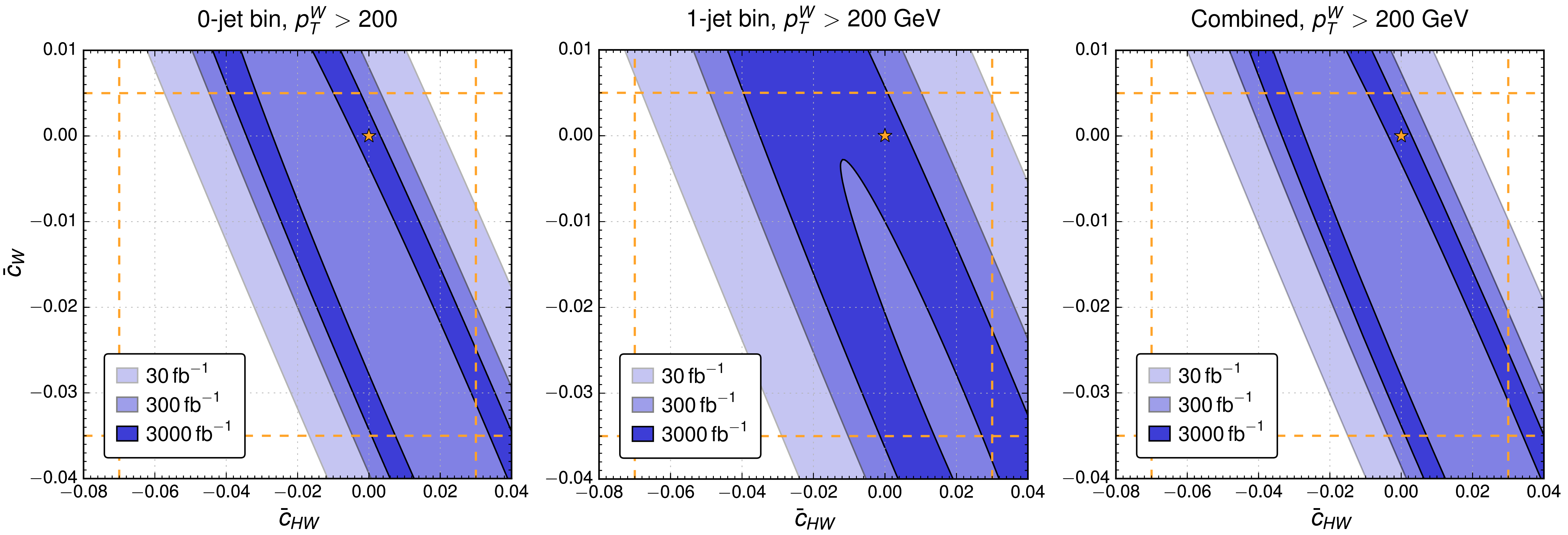
[ATLAS-CONF-2013-079 & ATLAS-CONF-2016-091]

HL-LHC prospects in VH

- 8 & 13 TeV analyses searching for VH → llbb
  - Large fit to many signal & control regions with some floating backgrounds
  - 13 TeV uses multivariate methods = difficult to recast without further info
- Performed a naive projection of the LHC 8 TeV analysis
  - Conservative with respect to the more sophisticated methods that will likely be employed in future updates in this channel
- Signal region: $P_T(W) > 200$ GeV overflow bin in the single lepton channel (WH)
  - Background: determine the change in acceptance x efficiency for the dominant ttbar background from 8 to 13 TeV
  - Rescale fitted background in 8 TeV analysis to estimate yield at 13 TeV

HL-LHC prospects in VH

- Early LHC data should already improve global fits
- Per-mille sensitivity to c_{HW},c_W with 3 ab^{-1}
- Only a couple of bins in a single channel



Future

- Several separate implementations of SMEFT operators in different sectors now exist
- Working on a “merge” of these to obtain a complete SMEFT model at NLO in QCD
  - Full set of operators contributing to EW/Higgs/top processes
  - Currently at testing/validation stage
  - Validation of anomalous dimension matrix calculation
- Basis independent predictions will be accessible via Rosetta translation tool http://rosetta.hepforge.org
- Ultimate goal is to incorporate NLO QCD corrections in a global fit to LHC + low energy data

SMEFT@NLO in QCD

- Merger of HELatNLO and Top/Higgs-EFT
  - Use Warsaw basis but basis independent input choice will be provided by Rosetta (also preparing an MG5_aMC plugin)
  - No four-fermion operators (except leptonic one modifying GF)

	Gauge/Higgs			
Higgs vev & kinetic term	$\mathcal{O}_{\varphi}$	$(\varphi^\dagger\varphi)^3$	–	–
	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	–	–
mZ (cust. sym.)	$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D_\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	–	–
Gauge/Higgs & gauge kinetic terms/mixing	$\mathcal{O}_{\varphi G}$	$\varphi^\dagger\varphi\, G_A^{\mu\nu}G^A_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{G}}$	$\varphi^\dagger\varphi\, G_A^{\mu\nu}\tilde{G}^A_{\mu\nu}$
	$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi\, W_i^{\mu\nu}W^i_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{W}}$	$\varphi^\dagger\varphi\, W_i^{\mu\nu}\tilde{W}^i_{\mu\nu}$
	$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi\, B^{\mu\nu}B_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{B}}$	$\varphi^\dagger\varphi\, B^{\mu\nu}\tilde{B}_{\mu\nu}$
	$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger\sigma^i\varphi\, W_i^{\mu\nu}B_{\mu\nu}$	$\mathcal{O}_{\varphi W\tilde{B}}$	$\varphi^\dagger\sigma^i\varphi\, W_i^{\mu\nu}\tilde{B}_{\mu\nu}$
Triple gauge,…	$\mathcal{O}_{3W}$	$\epsilon^{ijk}W_{i,\,\mu\nu}W_j^{\nu\rho}W^\mu_{k,\,\rho}$	$\mathcal{O}_{3\tilde{W}}$	$\epsilon^{ijk}\tilde{W}_{i,\,\mu\nu}W_j^{\nu\rho}W^\mu_{k,\,\rho}$

CP violation

SMEFT@NLO in QCD

- Work in “minimal flavor violating” hypothesis, keeping only the top Yukawa to begin with *[D’Ambrosio et al.; Nucl. Phys. B645 (2002) 155]*

		Top
Yukawa	$\mathcal{O}_{t\varphi}$	$(\varphi^\dagger\varphi)\,(\bar{Q}\,t)\,\tilde{\varphi}$
Dipole	$\mathcal{O}_{tG}$	$(\bar{Q}\,\sigma_{\mu\nu}T^A\,t)\,\tilde{\varphi}\,G_A^{\mu\nu}$
	$\mathcal{O}_{tW}$	$(\bar{Q}\,\sigma_{\mu\nu}\sigma^i\,t)\,\tilde{\varphi}\,W_i^{\mu\nu}$
	$\mathcal{O}_{tB}$	$(\bar{Q}\,\sigma_{\mu\nu}\,t)\,\tilde{\varphi}\,B^{\mu\nu}$
Current-current	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}^{\,i}_{\mu}\varphi)(\bar{Q}\gamma^\mu\sigma_i Q)$
	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_{\mu}\varphi)(\bar{Q}\gamma^\mu Q)$
	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_{\mu}\varphi)(\bar{t}\gamma^\mu t)$
	$\mathcal{O}_{\varphi b}$	$i(\varphi^\dagger \overleftrightarrow{D}_{\mu}\varphi)(\bar{b}\gamma^\mu b)$
RH charged current	$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi}\,D_\mu\varphi)(\bar{b}\gamma^\mu t)$

$\boxed{\propto\, y_t}$

ttV, single top, EW Higgs production. Some constraints from, e.g. LEP/flavor

[S. Alioli et al.; arXiv:1703.04751]

SMEFT@NLO in QCD

- Include all operators that affect EW input relations
    - Additionally one leptonic SU(2) current-current and one 4-fermion operator that affect muon decay for G_F extraction
- Model files for (α_{EW}, m_Z, G_F) & (m_Z, m_W, G_F) input schemes
- Validate counter-terms against previous implementations & anomalous dimension matrix
- In progress: pheno analysis of tHj/tHZ channels which combines two sectors of EFT operators: EW/Higgs & top/Higgs
- Include basis definition in Rosetta to easily map from any input basis + MG5/Rosetta interface

Conclusion

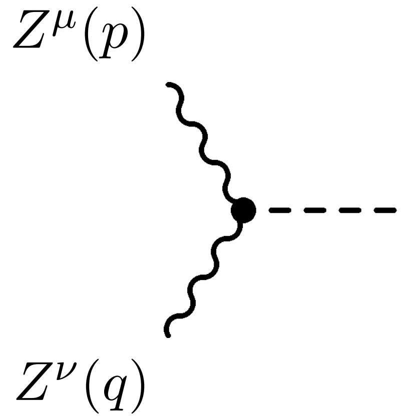
- We are still not far from the beginning of a long and fruitful programme of Higgs characterisation via EFT
- Current global fits allow room for large EFT deviations and precision is now improving to NLO in QCD+PS

A. Butter's talk

- FeynRules/NLOCT framework is being exploited to complete the SMEFT for MC event generation at this order
    - EFT interpretation for all possible processes measurable at the LHC
    - Open to requests for, e.g., dimension-8 multi-boson operators
- Seemingly, benchmarks which saturate current limits can appear slightly beyond the naive "validity" of the EFT
    - Warrants further investigation on a process by process basis

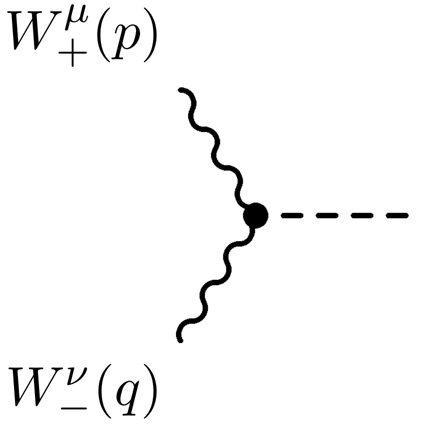
BACKUP

Feynman Rules



:

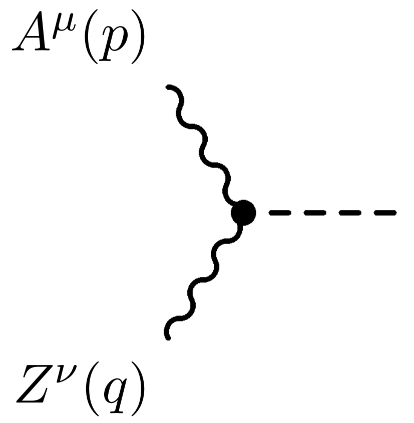
$$i\Bigg[\eta^{\mu\nu}\Big(\frac{g}{\cos\theta_W}M_Z + g^{(1)}_{hzz}\,p\cdot q + g^{(2)}_{hzz}\,(p^2+q^2)\Big) - g^{(1)}_{hzz}\,q^\mu p^\nu - \tilde{g}_{hzz}\epsilon^{\mu\nu\rho\sigma}\,q_\rho p_\sigma - g^{(2)}_{hzz}\,(p^\mu p^\nu + q^\mu q^\nu)\Bigg]$$



:

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

BSM→



:

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

*Inflowing momenta

Mapping to AC/(i.e. HC)

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

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

[KM, Sanz, Williams; JHEP 1608 (2016) 039]

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 (POWHEG)

- 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 $2\ \mu_0$

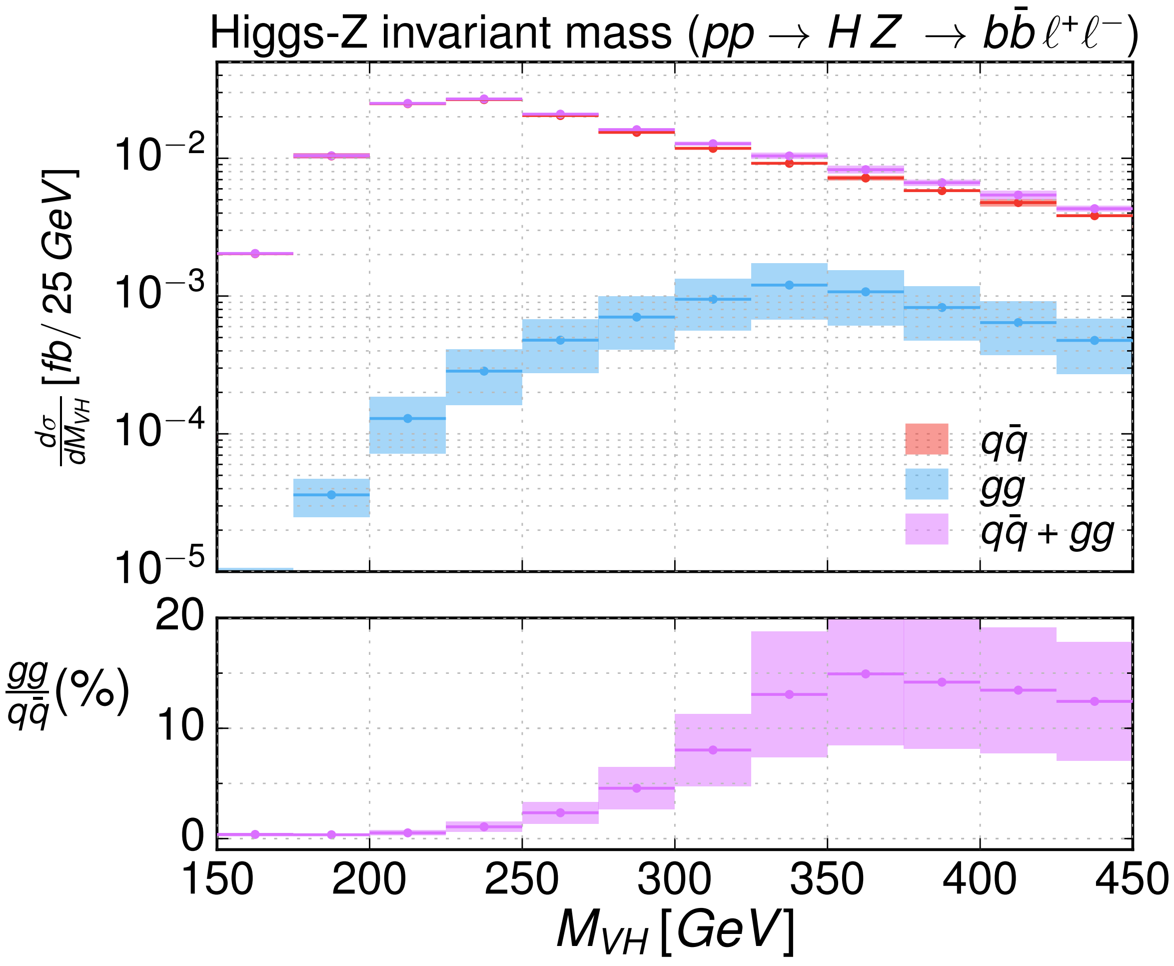
Selection

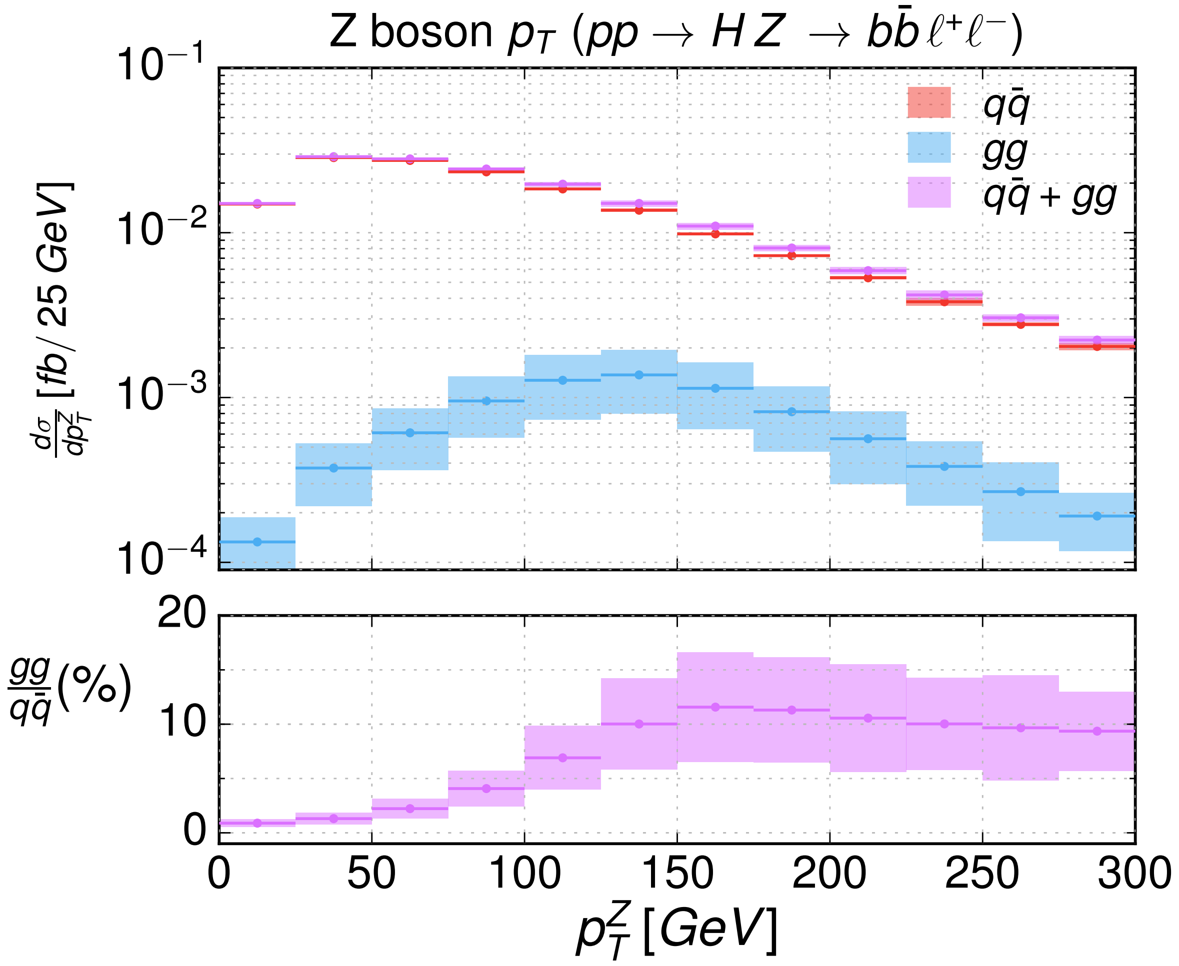
Process	
$H\,Z \to b\bar{b}\,\ell^+\ell^-$	$H\,W \to b\bar{b}\,\ell\nu$
Jets	
k_T algorithm: ΔR=0.4, $p_T > 25$ GeV & $\eta_b < 2.5$	
Cuts	
2 b-jets, $p_T > 25$ GeV, $\eta_b < 2.5$	
1 lepton, $\ell^\pm$ (e or μ)	2 leptons, ℓ^+, ℓ^- (e or μ)
$p_T^\ell < 25$ GeV, $\|\eta_\ell\| < 2.5$	

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

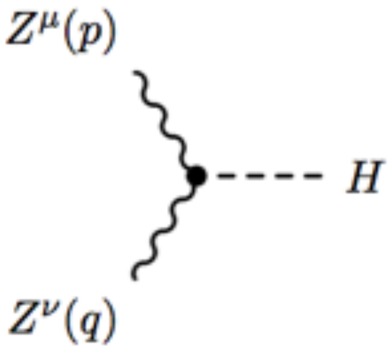
$gg \to ZH \to l^+l^- bb$

- 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



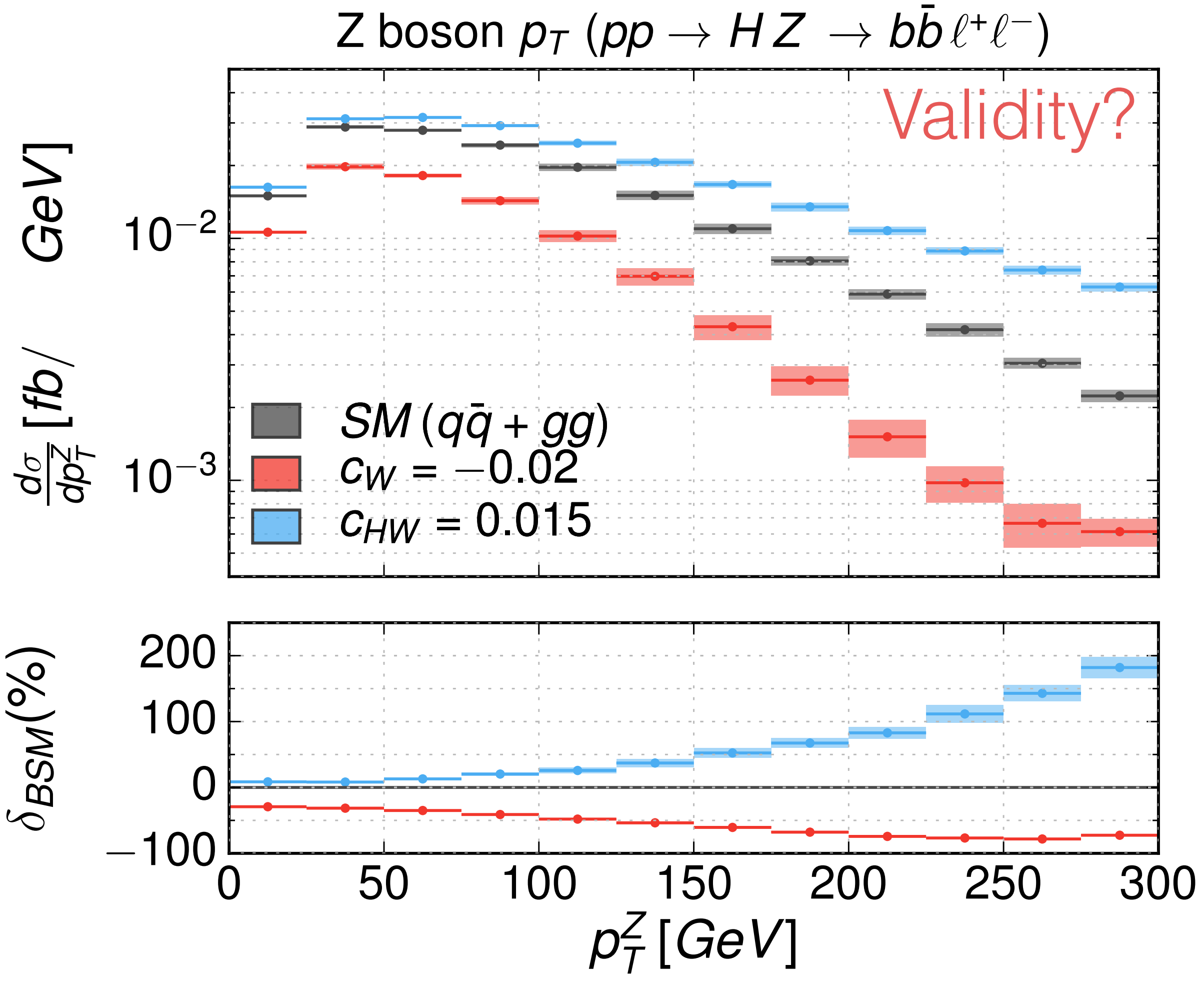


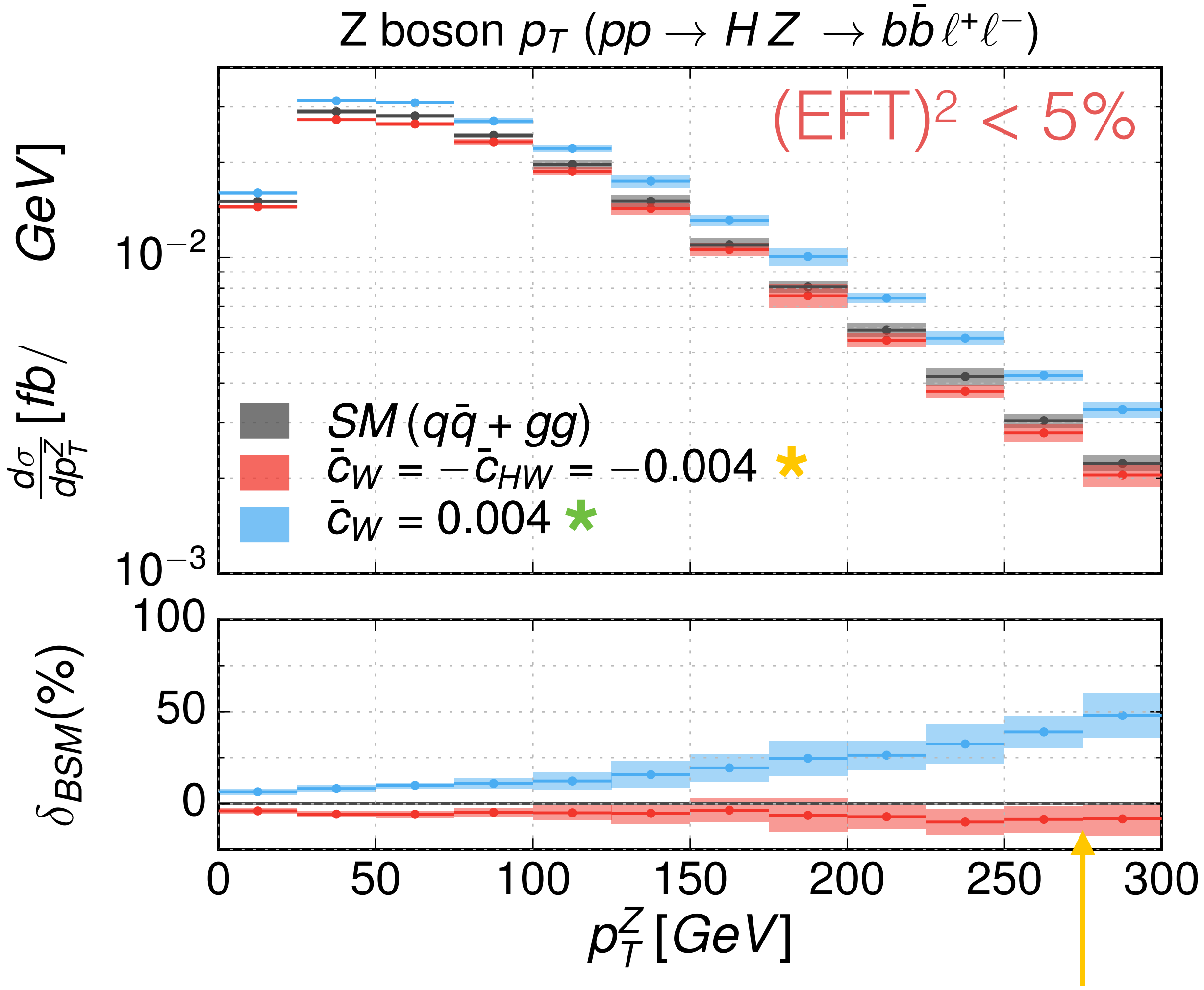
$pp \to Z\,H \to l^+l^-\,bb$



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

$$i\left[\frac{g}{\cos\theta_W} M_Z \underbrace{\boxed{+\, g^{(1)}_{hzz}\;(\eta^{\mu\nu} p\cdot q - q^\mu p^\nu)}}_{\text{“BM II”}} + \underbrace{\boxed{g^{(2)}_{hzz}\;\left((p^2+q^2)\eta^{\mu\nu} - p^\mu p^\nu + q^\mu q^\nu\right)}}_{\text{“BM I”}}\right]$$

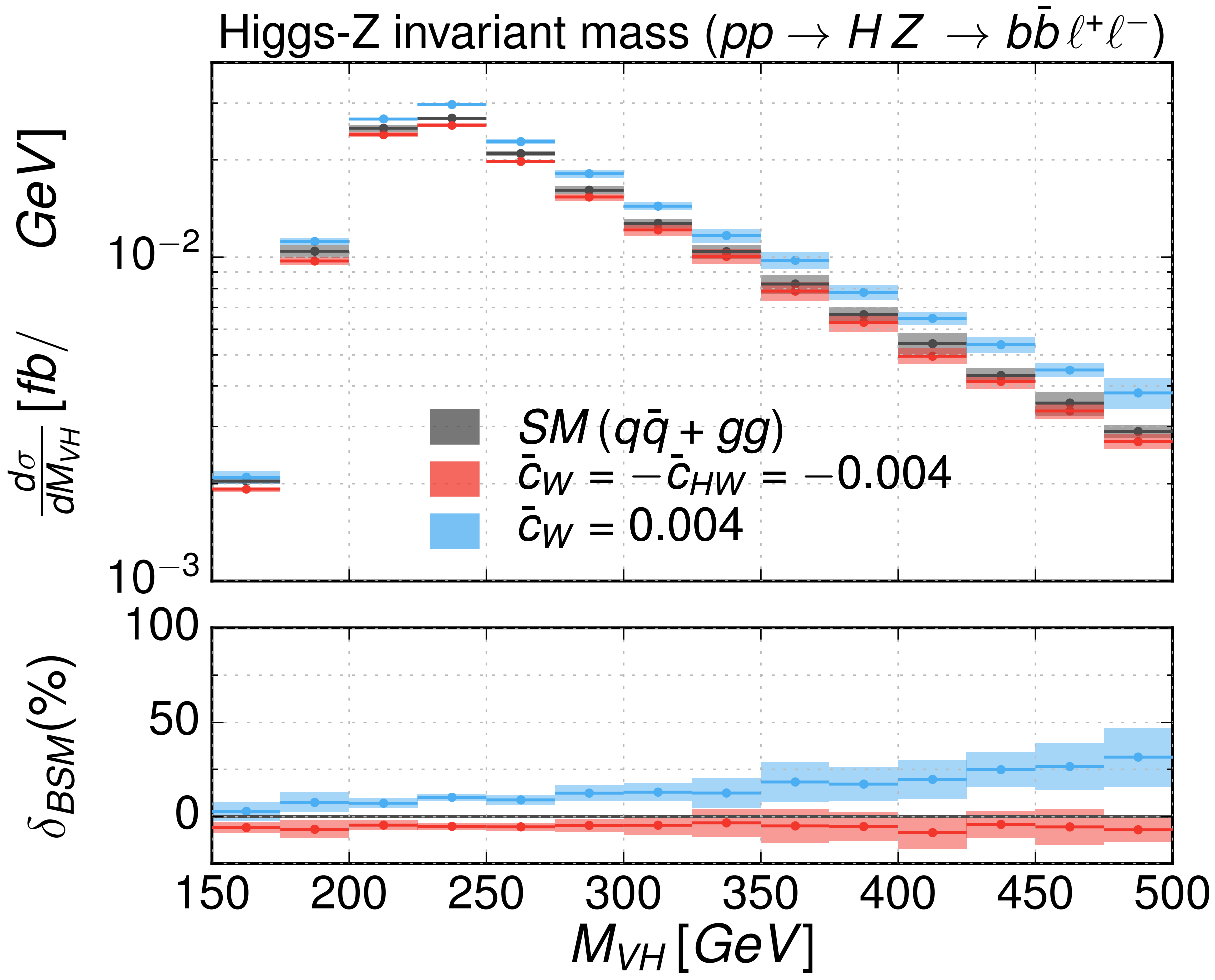


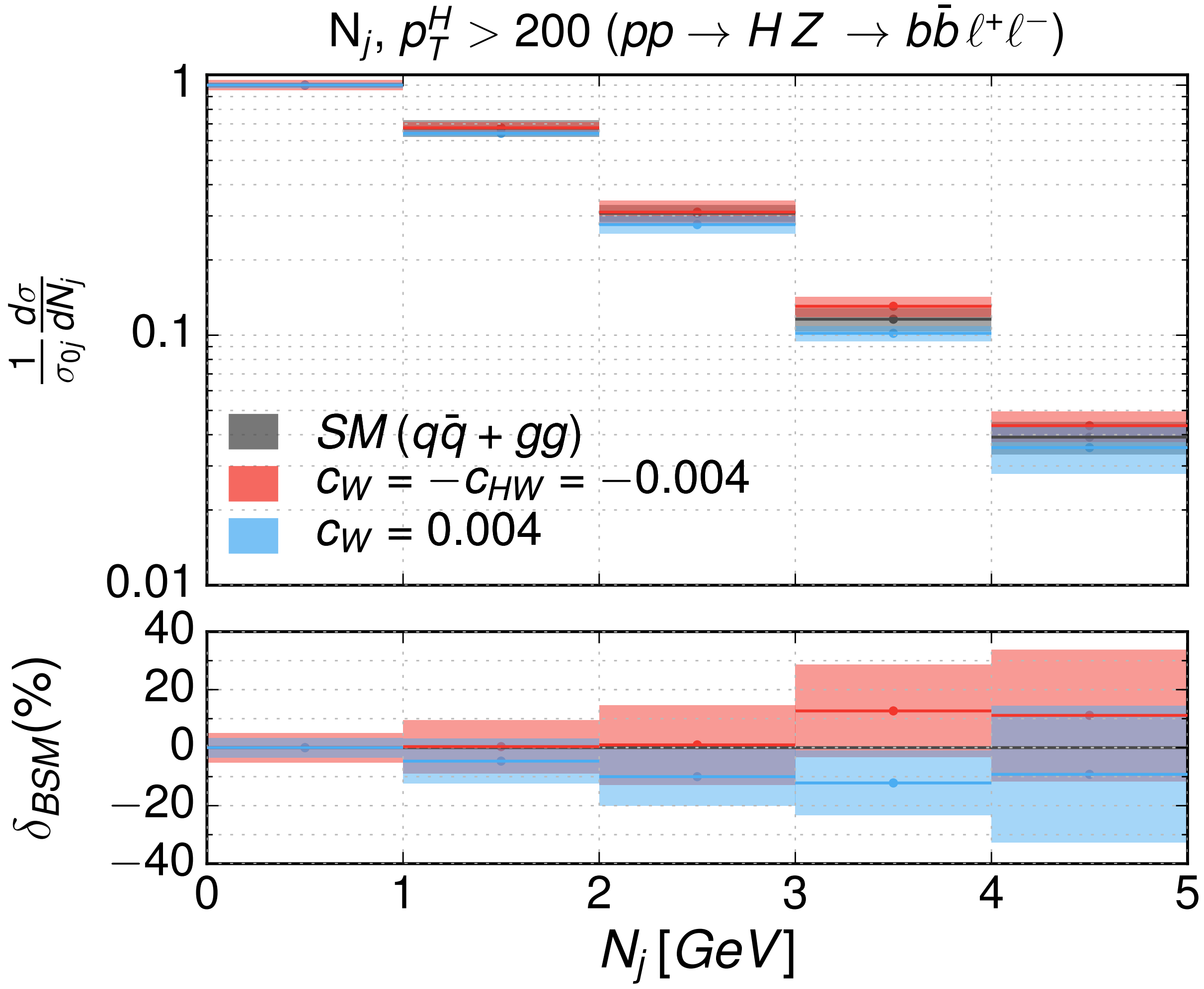


* Benchmark II does not show “EFT-like” features

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

Nj exhibits some difference but stats too low to distinguish

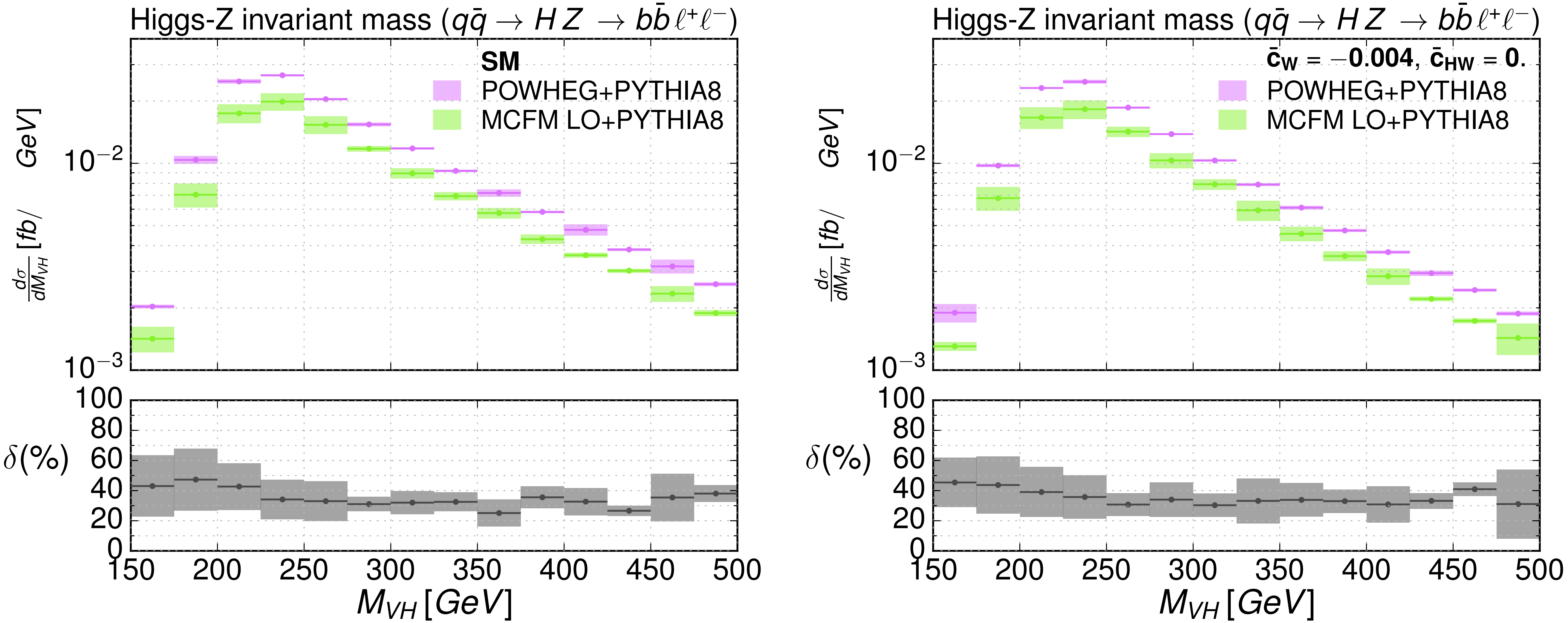




K-factors

No significant difference between SM & EFT

Relatively flat



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

eHDECAY

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

- Extension of HDECAY

  [A. Djouadi, J. Kalinowski, M. Spira, Comp. Phys. Comm. 108 (1998) 56]

- QCD corrections
  - qq: Interpolation between massive NLO corrections near threshold & massless O(a_S^4) far above threshold
  - gg: N^{3}LO in heavy quark limit neglecting higher order terms in $(m_H/\Lambda)^2$
  - ɣɣ: NLO
  - WW, ZZ, Zɣ: LO
- 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 form SM inputs included