UCL
Université catholique de Louvain

Electroweak Higgs production in SMEFT at NLO in QCD

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[C. Degrande, B. Fuks, K. Mawatari, KM, V. Sanz; arXiv:1609.04833]
(to appear in EPJC)

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Outline

- Motivation & brief intro to standard model effective field theory (SMEFT)
- EW Higgs production in SMEFT at the LHC
- Results from the implementation of operators affecting Higgs couplings to gauge bosons
  - Current constraints from global fits & resulting benchmark choices
  - FeynRules/NLOCT UFO model via MadGraph5_aMC@NLO
  - Differential distributions @ NLO in QCD
  - Validity of the EFT
  - Future sensitivity in WH production at HL-LHC

Going NLO

- The LHC is now in the precision era
  - No clear evidence for new physics as we approach the limits of the 'energy frontier'
  - Fully complementary approach: search for deviations in SM processes
  - Require high precision theory input including higher order corrections
- 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

SMEFT

- Parametrise new physics effects at experimental energy E
  - BSM states are 'decoupled' *i.e.* live at an energy Λ >> E
  - Generalised, gauge-invariant interactions between SM degrees of freedom
- Operator expansion:

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

more: fields, derivatives

  - Introduces higher-derivative operators to which we are sensitive via large momentum flows through vertices (tails of energy distributions)
- Dimension 6: 59 (76 real) - 2499 operators depending on assumptions regarding CP, flavour…

  [Buchmuller & Wyler; Nucl.Phys. B268 (1986) 621] & [Grzadkowski et al.; JHEP 1010 (2010) 085]
- Dimension 8: ~ 895 (36971) operators!

  [Lehman et al.; PRD 91 (2015) 105014] & [Henning et al.; Comm.Math.Phys. 347 (2016) 2, 363]

EW Higgs production

- LHC can provide complementary information to existing fits to lower energy data, i.e. LEP
- Higgs comes with additional objects
  - We can construct kinematic observables probing the high energy regime
  - Higgs p_T, M_{VH}, leading lepton p_T, $\Delta\eta_{jj}$,…
- Look into the tails…
- Investigate validity of EFT expansion/interpretation given current constraints from global fits
- Consider future reach of HL-LHC to constrain relevant Wilson coefficients

D=6 operators

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

[Contino et al.; JHEP 1307 (2013) 35]

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

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

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

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

Limits from global fits

- Many global fits to data constrain EFT Wilson coefficients
  - 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

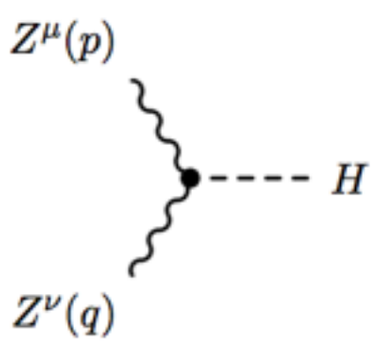
See also: [Falkowksi & Riva; JHEP 1502 (2015) 039], [Berthier & Trott; JHEP 1505 (2015) 024], [Corbett et al.; JHEP 1508 (2015) 156], [Englert et al.; EPJC 76 (2016) 7, 393]

EFT Benchmarks

- Select (c_W, c_{HW}) benchmarks that:
  - Approximately saturate global fit limits
  - Select new Lorentz structures in the new vertices

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

- Tightly constrained direction in (c_B, c_W) forces $c_B \sim -c_W/2$
- Benchmarks that single out $g^{(1)}$ & $g^{(2)}$ structures



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

Benchmark B Benchmark A

- Pattern B 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]

Selection of results

- WH, VBF differential distributions (MG5_aMC@NLO)
- Used PYTHIA8 for Higgs decay, PS and Hadronisation
  - Rescaled rates by eHDECAY BRs to capture EFT contributions
    [R. Contino et al.; Comp. Phys. Comm. 185 (2014) 3412-3423]
- Events were reconstructed using Fastjet thanks to MadAnalysis5 “reco” mode and analysed according to some realistic event selection procedure also in MA5
- Included a basic ‘fiducial’ event selection
- Theoretical uncertainties due to scale variation were quantified but not PDF uncertainties
  - Envelope of 9 combinations of (1/2, 2) x μ_0

HELatNLO

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

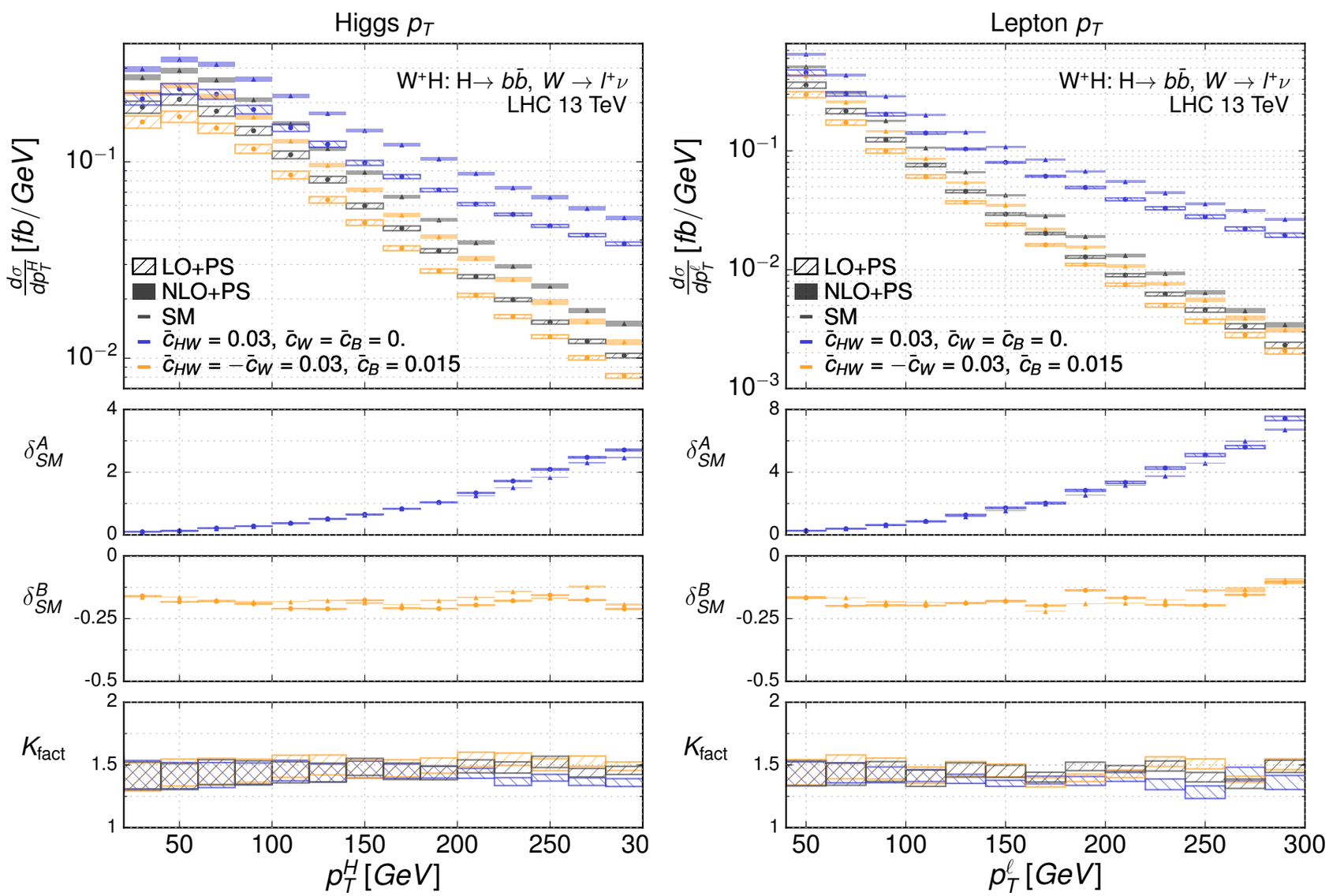
- SMEFT implementation in FeynRules + NLOCT framework
  - Generate NLO UFO file & simulate with MG5_aMC@NLO ~ any process!
  - First results for VBF in SMEFT @ NLO in QCD
- Includes 5 operators affecting Higgs couplings to W/Z/γ
  - First step for EW Higgs production
- Builds upon previous LO implementation of full SILH basis
- Modification of EW parameters due to SILH operators taken into account in the (m_Z, α_S, G_F) input scheme
  [Alloul, Fuks & Sanz; JHEP 1404 (2014) 110]
- Validated WH & ZH against existing POWHEG-BOX/ MCFM implementation [KM, Sanz & Williams.; JHEP 1608 (2016) 039]

pp → W+ H → l+ ν bb

Flat K-factors (as expected) & consistent definition of scale uncertainty allows for more confident SM/EFT discrimination

δ = TOT/SM-1

NLO/LO

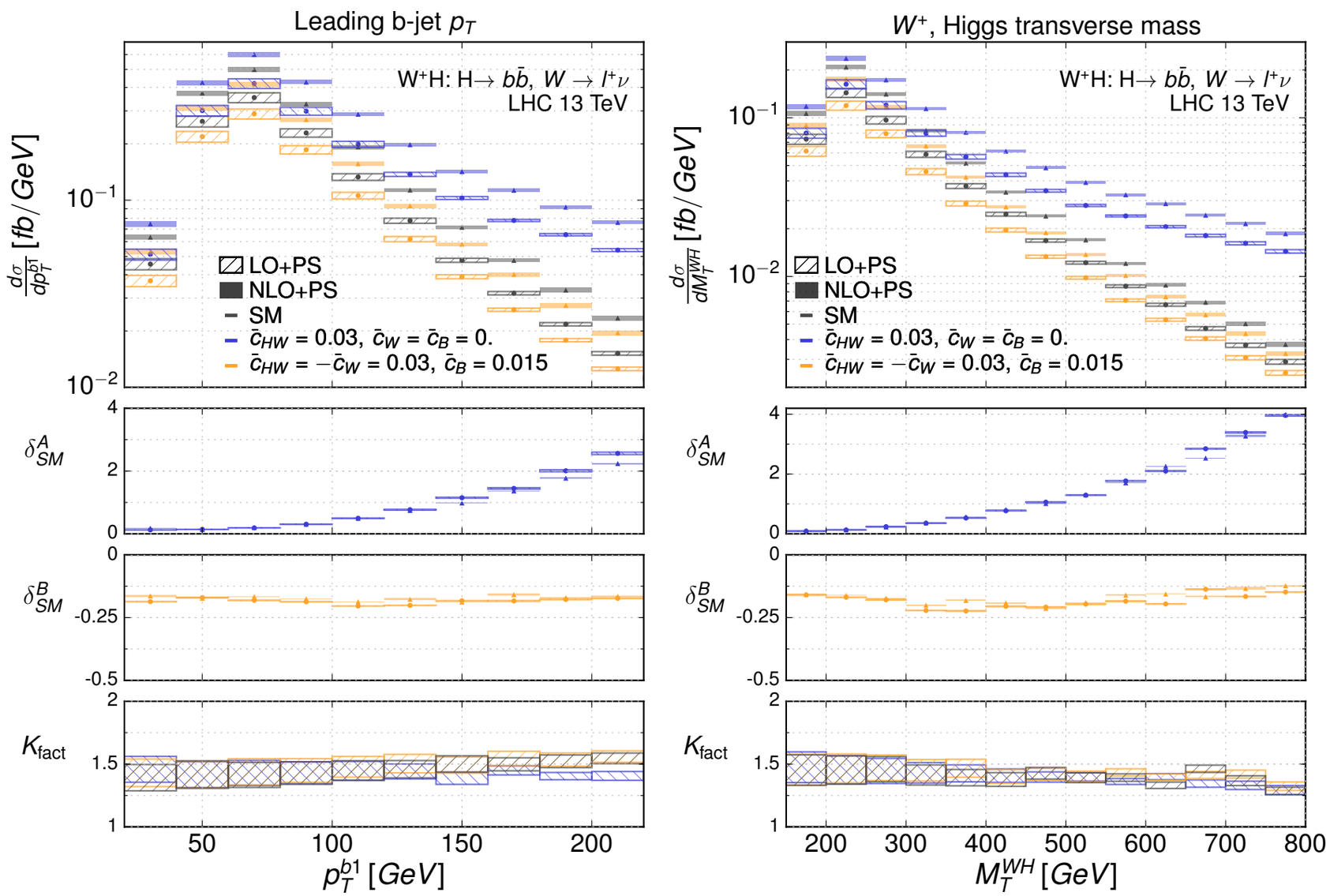


Big effects

Small effects

pp → W+ H → l+ ν bb

Benchmark **B)** does not exhibit strong "EFT" features
→ The $g_{hvv}^{(2)}$ Lorentz structure is responsible for these



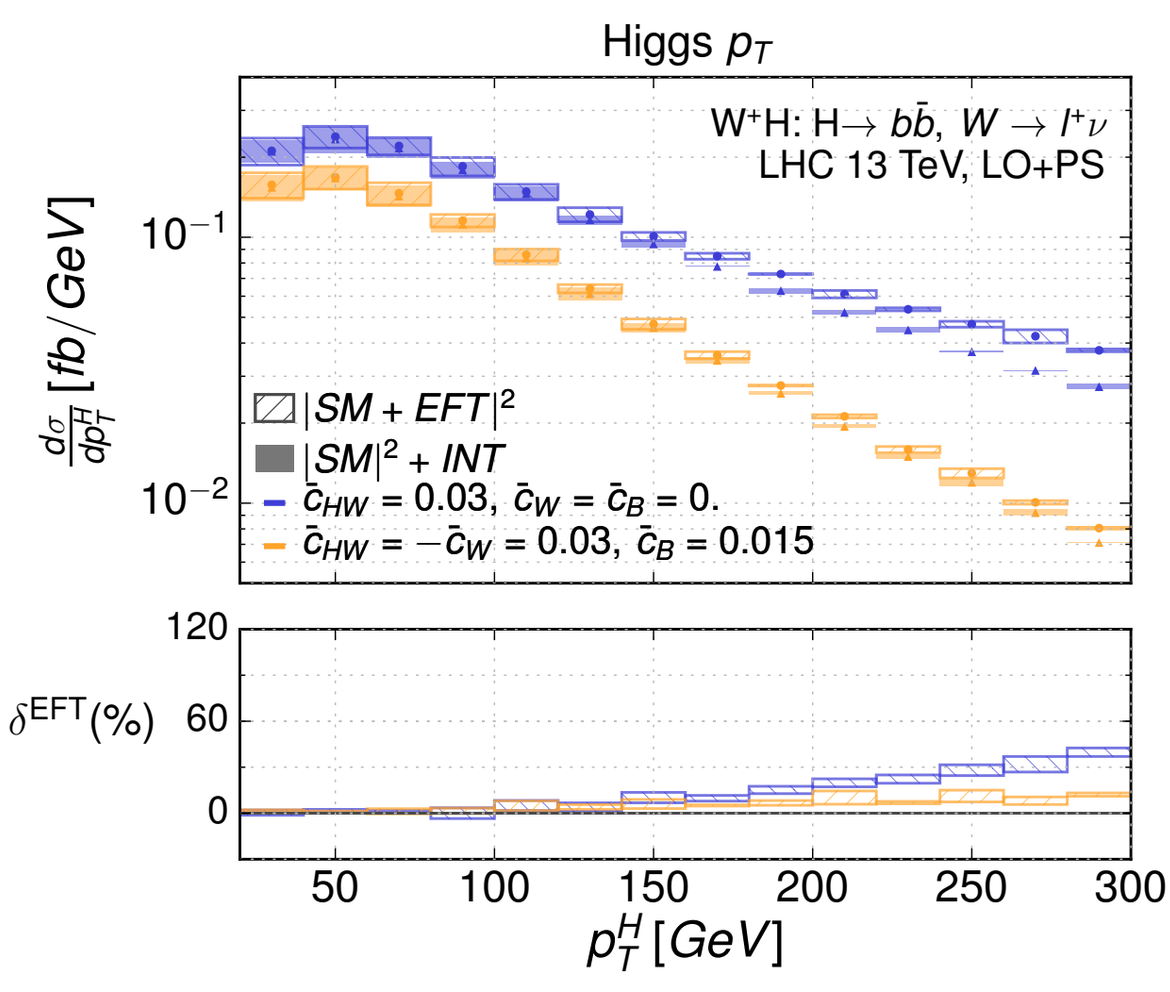
EFT validity

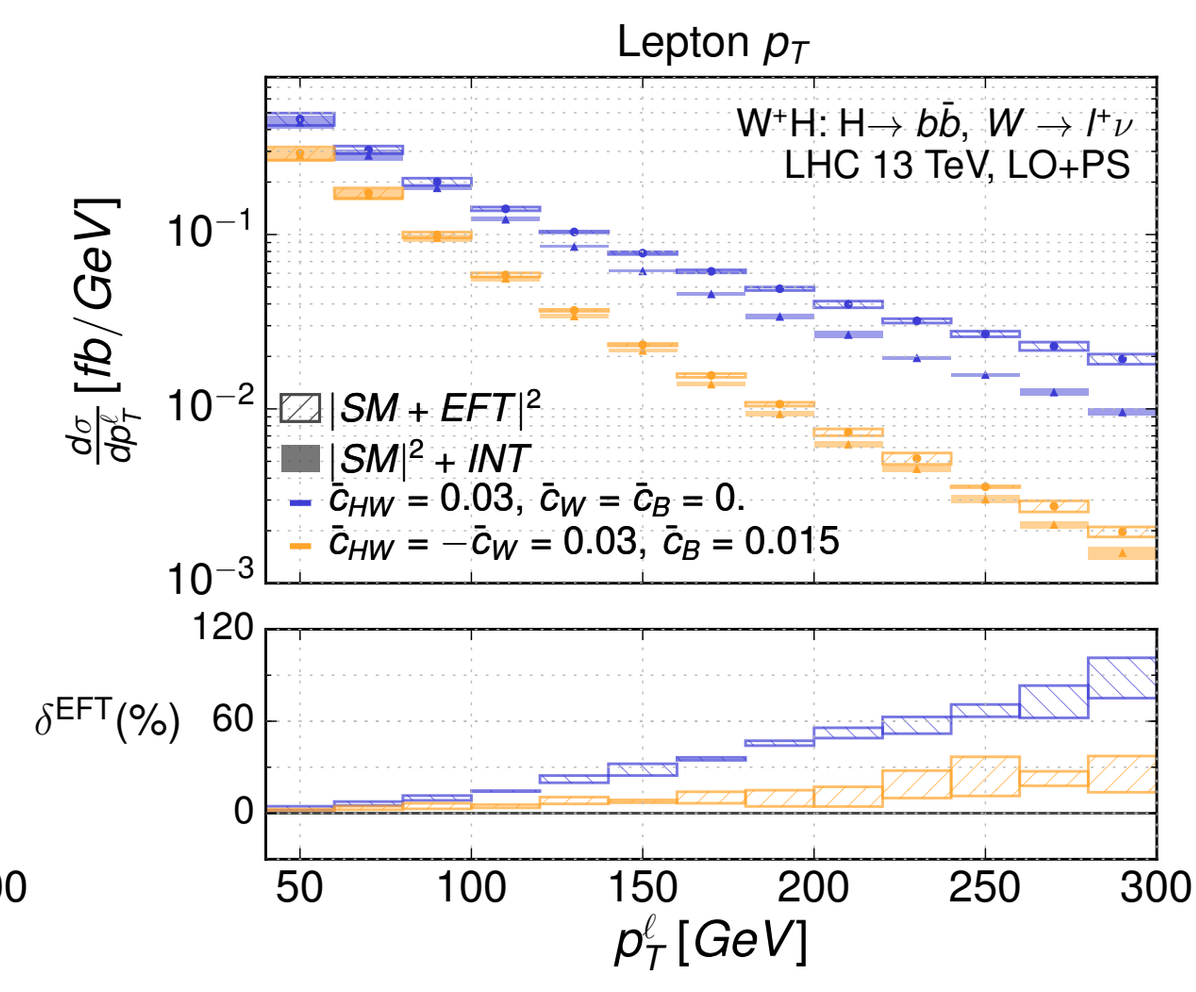
- Relative size of SM/EFT interference ($1/\Lambda^2$) and $|EFT|^2$ terms ($1/\Lambda^4$) is a naive measure of the EFT validity
  - We don't (want to) include SM/D=8 interference
- Can be used to assess at which energy scales the expansion breaks down
  - Test how appropriate the EFT interpretation is given current constraints from global fits
- MG5_aMC@NLO provides this functionality (at LO)
  - Select only interference

Interference only (LO)

40-80% difference for our benchmarks…

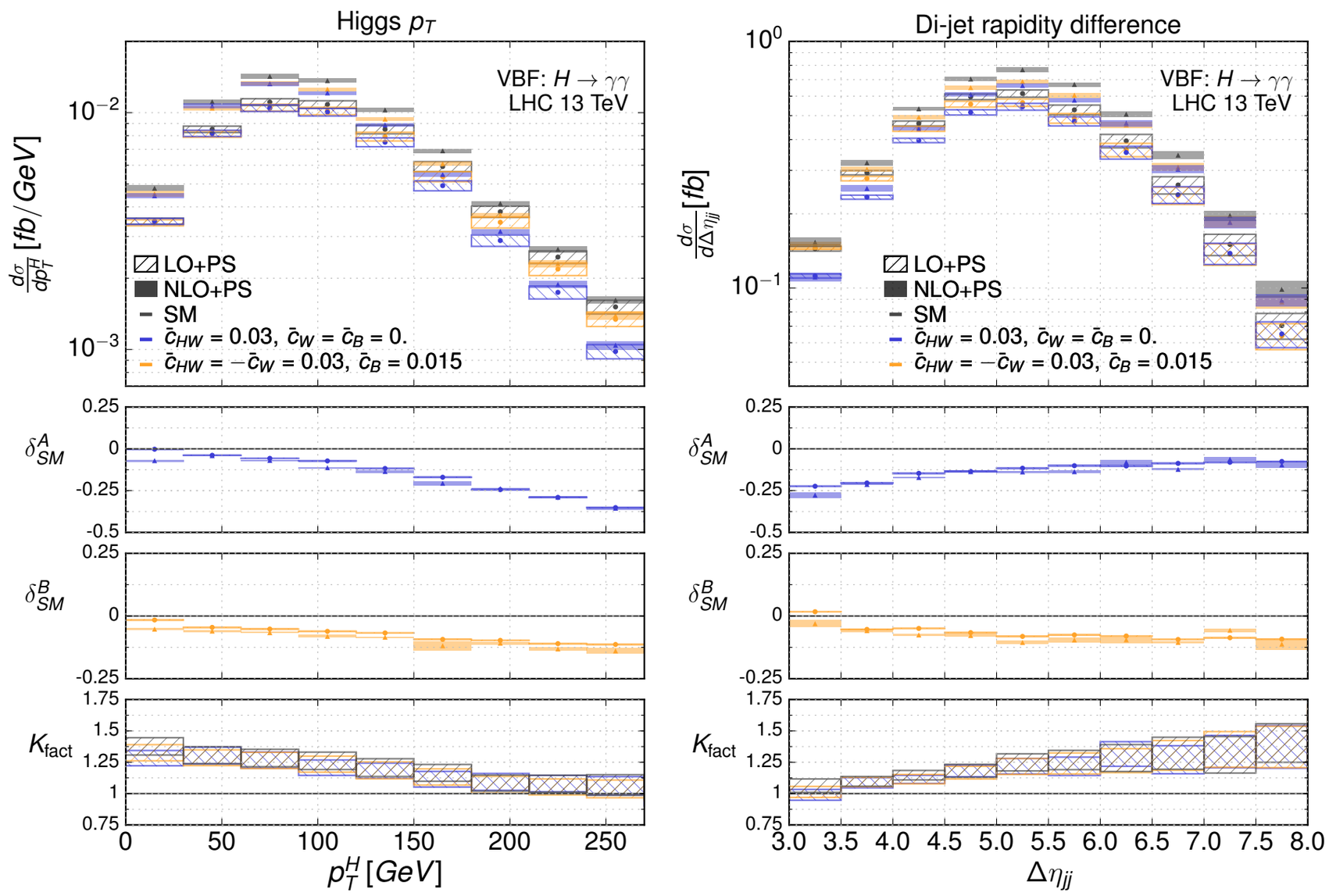
A possible way to define an additional theory uncertainty?





pp → H j j→γ γ j j

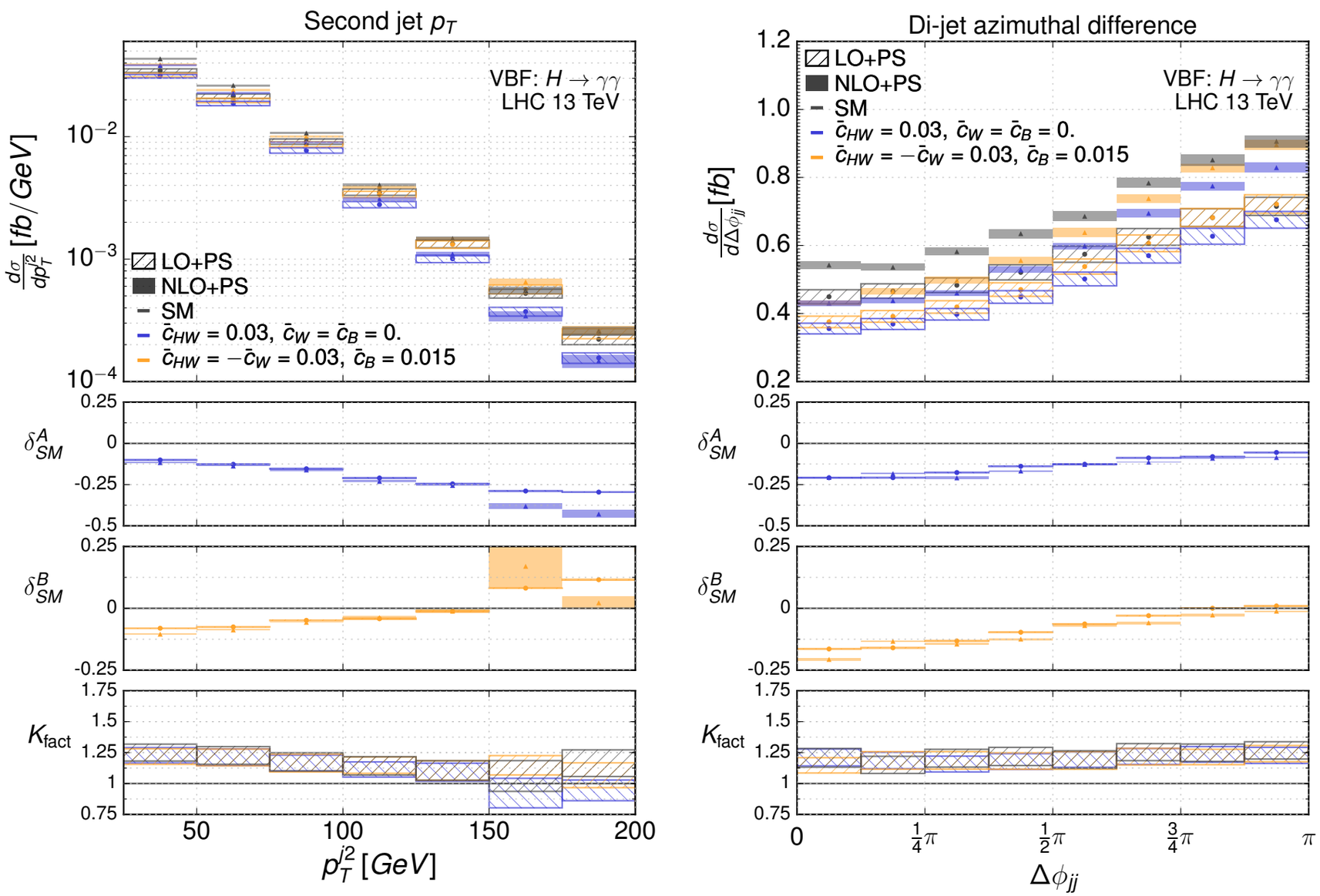
Included "VBF" cuts on M_{jj} and $\Delta\eta_{jj}$
Smaller effects (25-50%), sensitivity to benchmark B



K-factors not as flat

pp → H j j→γ γ j j

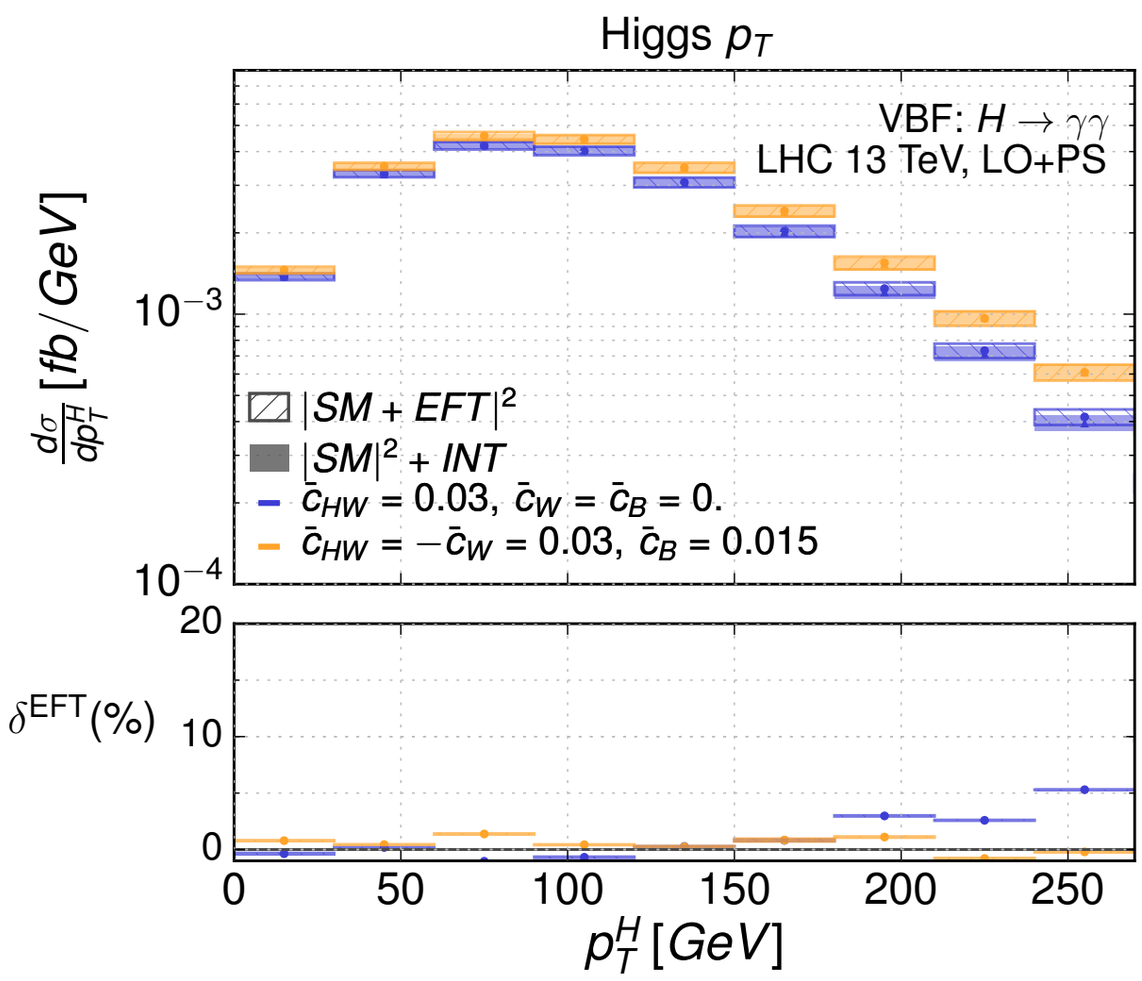
Correlating VH & VBF may help disentangle $g^{(2)}$ coupling structure

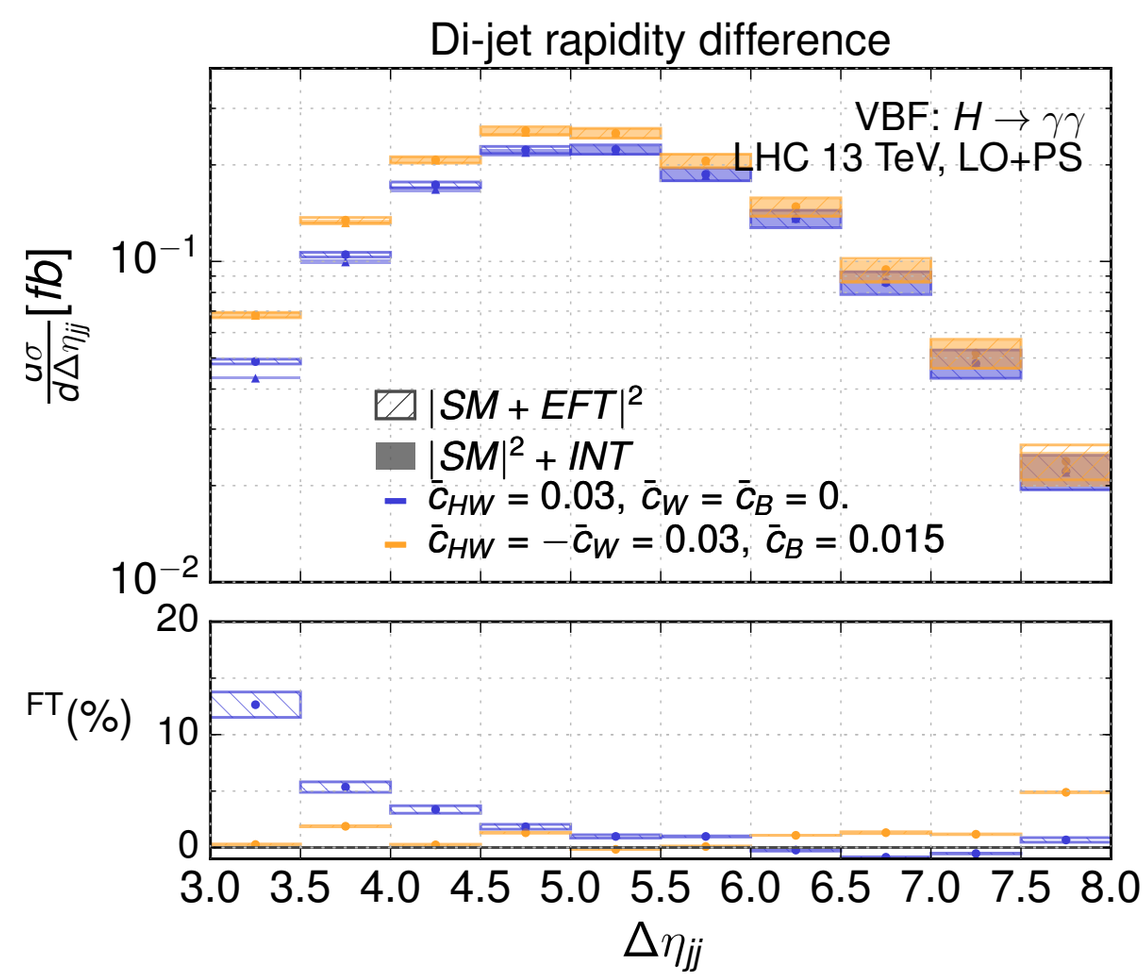


Interference only (LO)

Interference vs. square much more under control.

~10% difference



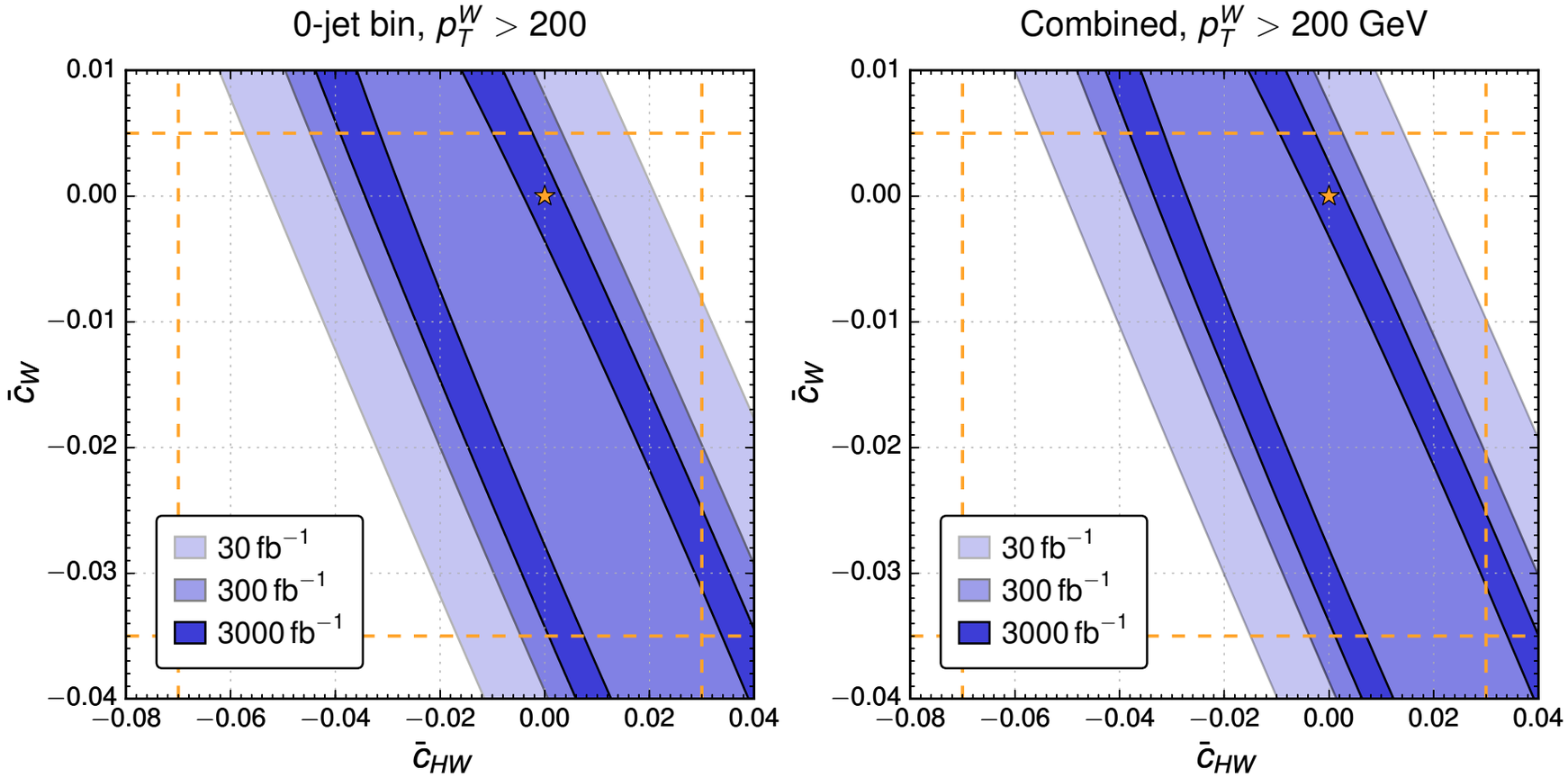


HL-LHC prospects in VH

- 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: PTV > 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 contribution at 13 TeV

HL-LHC prospects in VH

- Also considered +1 jet category where ttbar contribution is even more dominant
- Single overflow bin of a single signal region ~ per mille sensitivity to c_{HW},c_W with 3 ab^{-1}



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 production processes
  - 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

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BACKUP

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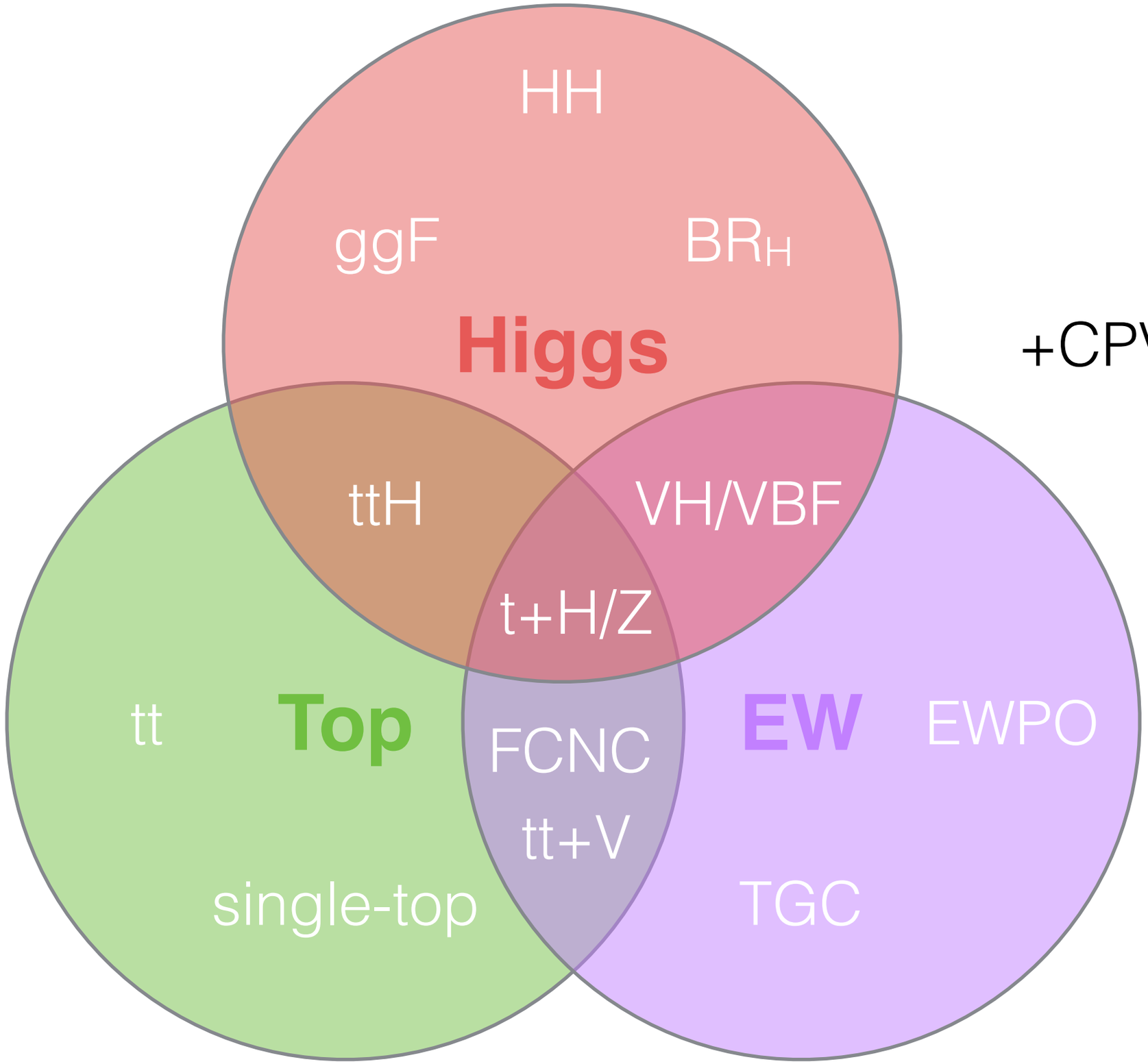
SMEFT @ the LHC



+CPV, flavor,…

EFT → AC map

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

[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

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

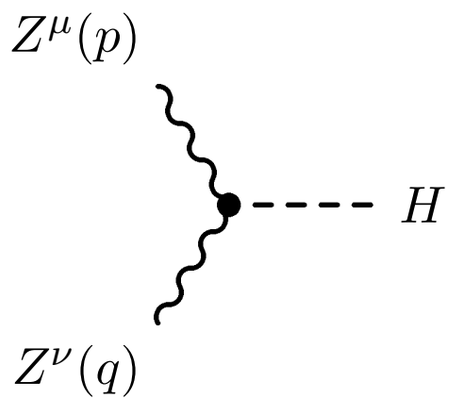
$$h \to h(1+\delta h), \quad \delta h = -\frac{\bar{c}_H}{\Lambda^2}\frac{v^2}{4}$$

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

$$W^\mu_\pm \to W^\mu_\pm\left[1+\delta W\right]$$
$$B^\mu \to B^\mu\left[1+\delta B\right] + yW^\mu_3$$
$$W^\mu_3 \to W^\mu_3\left[1+\delta W\right] + zB^\mu$$

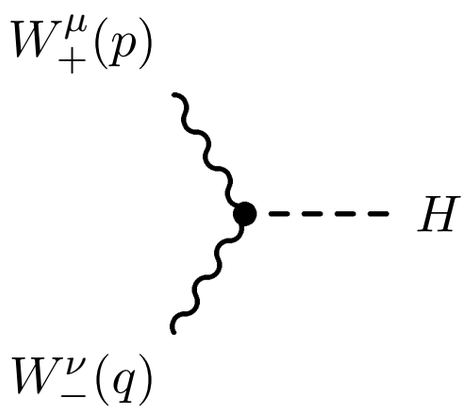
- After EWSB, canonical mass eigenbasis, different from SM
  - Perform field & coupling redefinitions to fix their normalisation
  - Modifications of gauge bosons masses, interactions, e.g., Z→ff
  - Modifications to the SM parameters as a function of EW inputs
  - Can also affect backgrounds!
- Not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

Feynman Rules



:

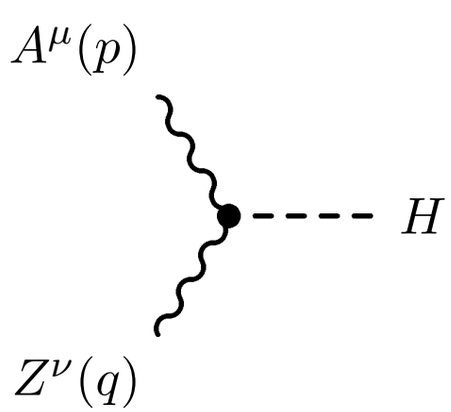
$$i\left[\eta^{\mu\nu}\left(\frac{g}{\cos\theta_W}M_Z + g^{(1)}_{hzz}\,p\cdot q + g^{(2)}_{hzz}\,(p^2+q^2)\right) - g^{(1)}_{hzz}\,q^\mu p^\nu - \tilde{g}_{hzz}\epsilon^{\mu\nu\rho\sigma}\,q_\rho p_\sigma - g^{(2)}_{hzz}\,(p^\mu p^\nu + q^\mu q^\nu)\right]$$



:

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

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

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

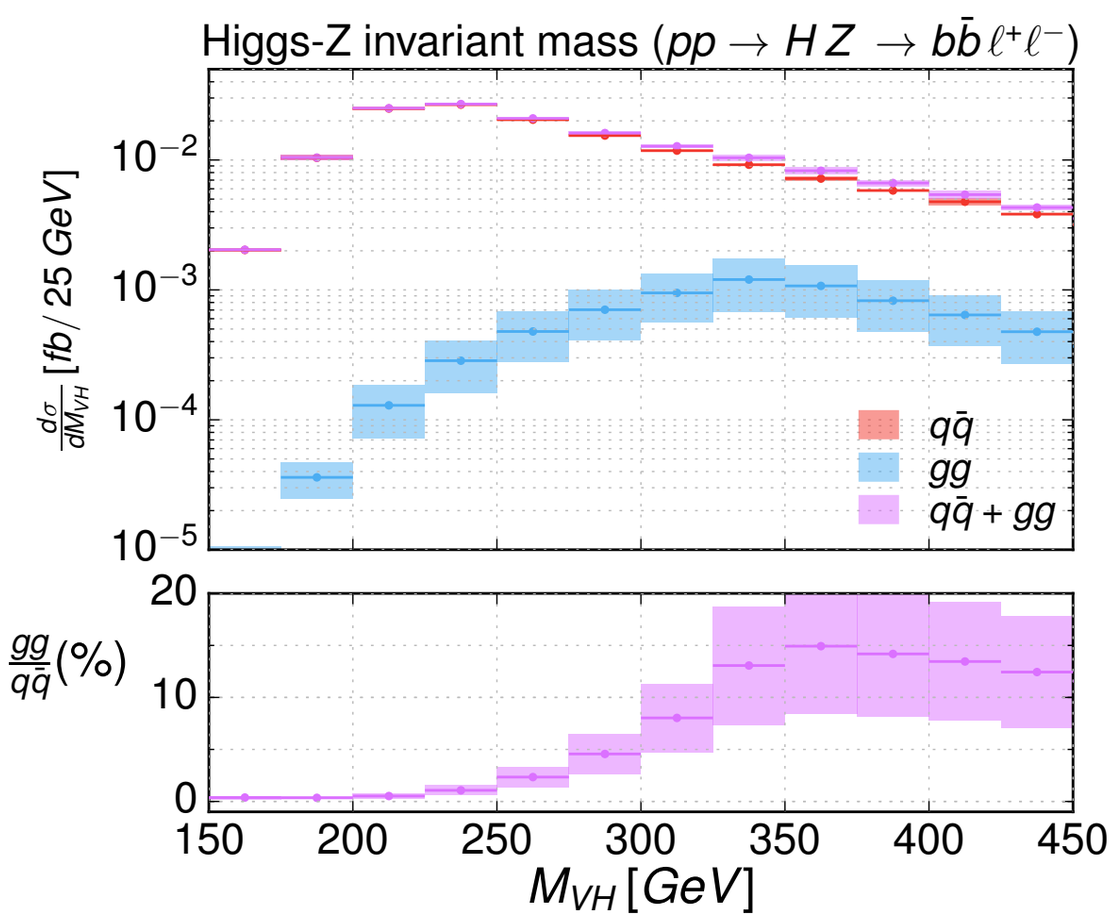
Selection

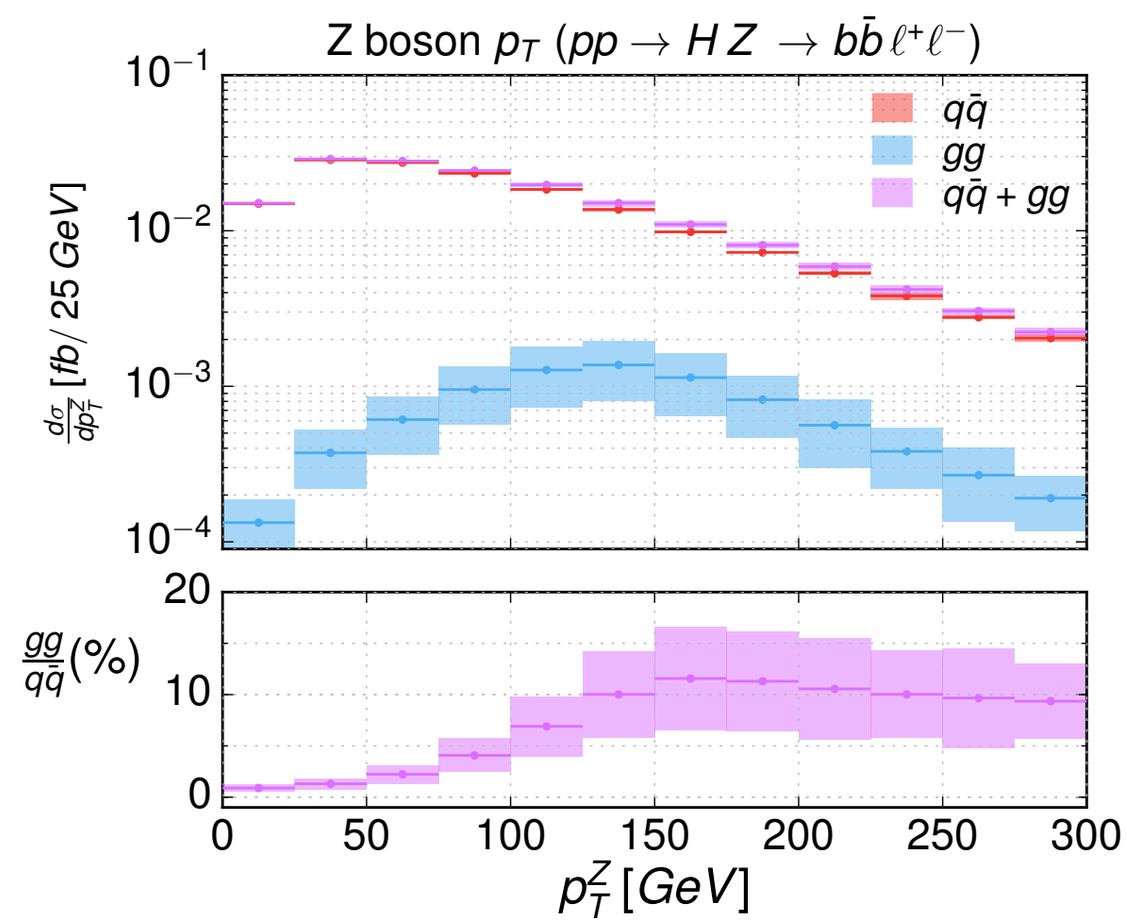
Process	
$H\,Z \to b\bar{b}\,\ell^+\ell^-$	$H\,W \to b\bar{b}\,\ell\nu$
Jets	
k_T algorithm: ΔR=0.4, $p_T > 25$ GeV & $\eta_b < 2.5$	
Cuts	
2 b-jets, $p_T > 25$ GeV, $\eta_b < 2.5$	
1 lepton, $\ell^\pm$ (e or μ)	2 leptons, ℓ^+, ℓ^- (e or μ)
$p_T^\ell < 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$	

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

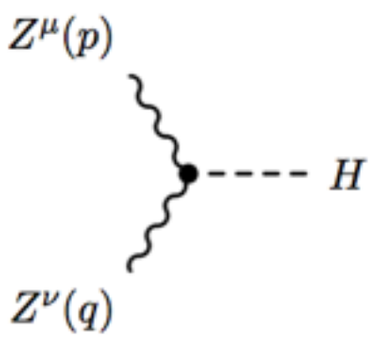
gg → Z H → l+l- bb

- 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





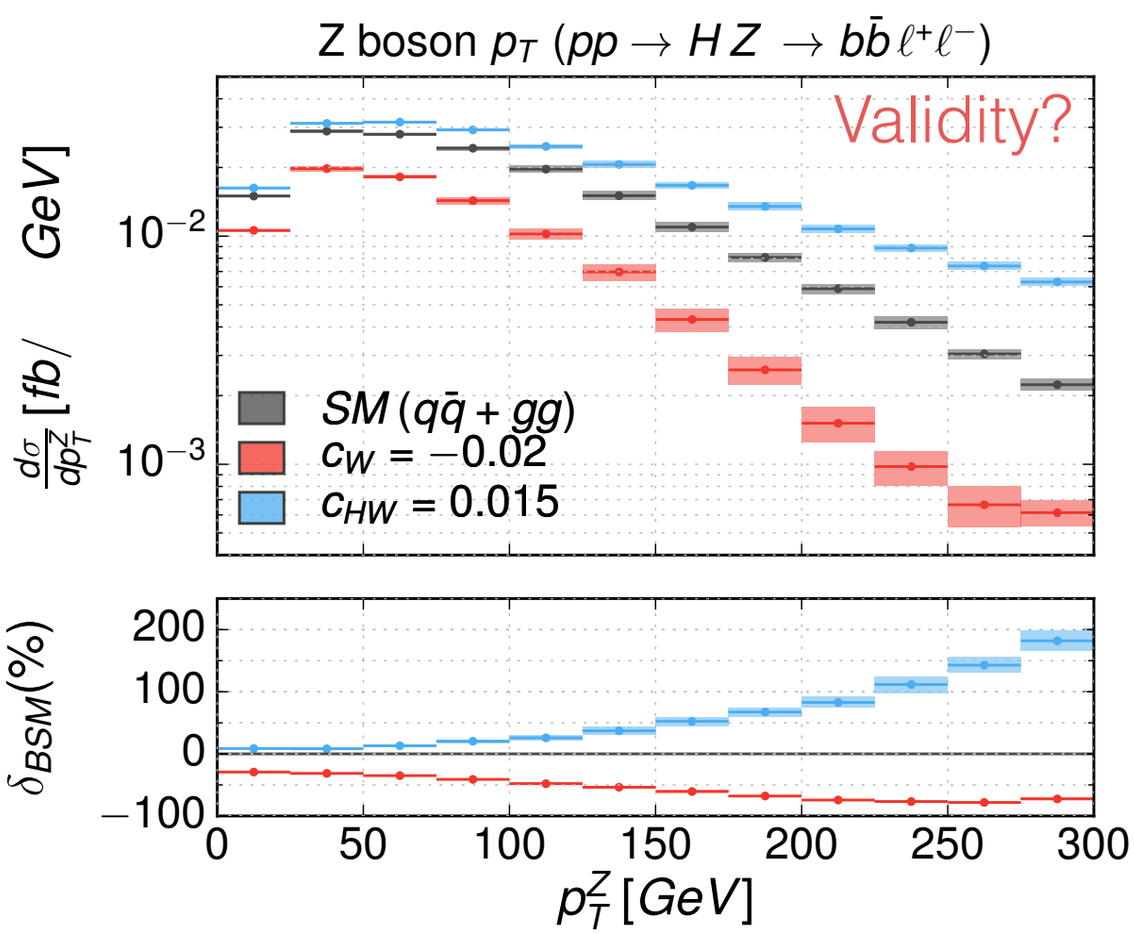
pp → Z H → l+l- bb

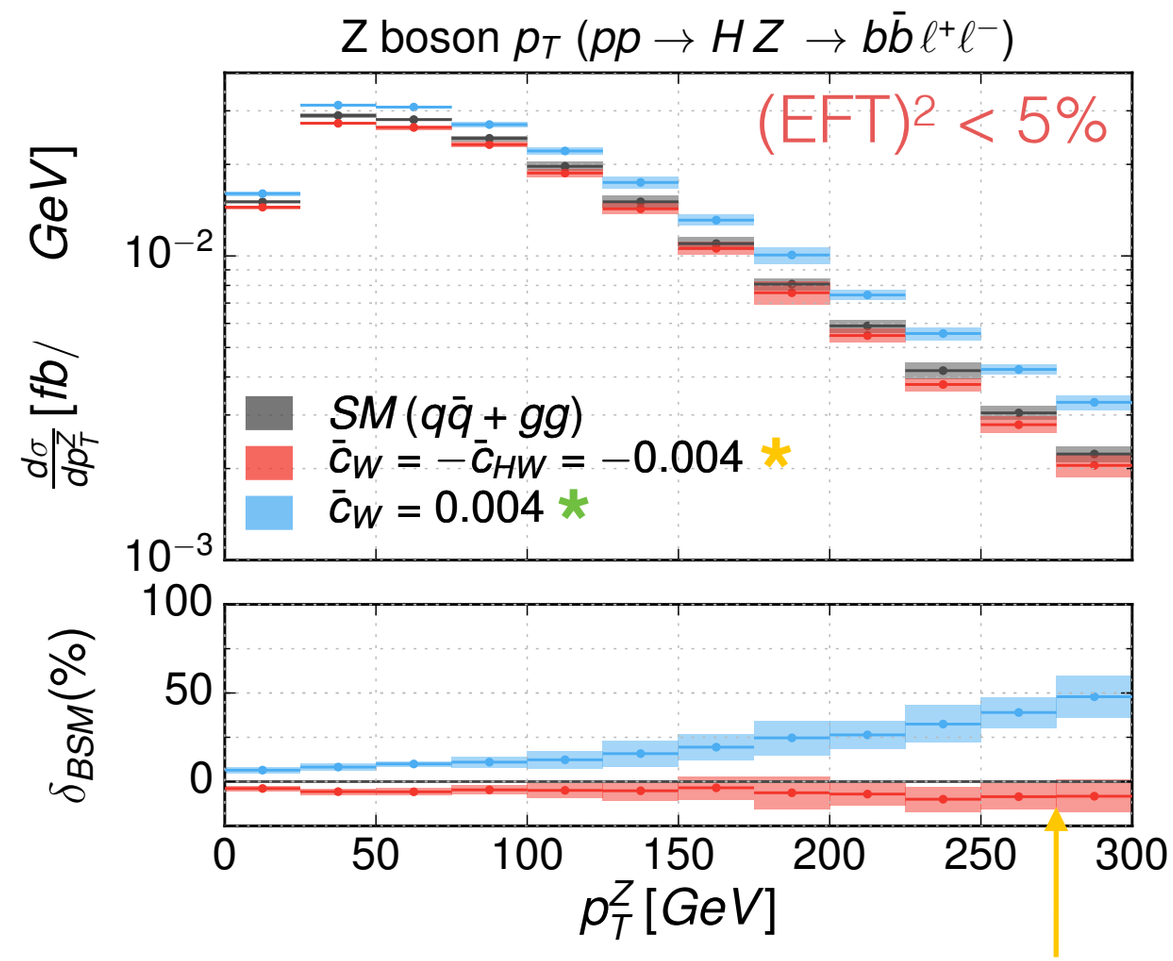


$$g^{(1)}_{hzz} \propto \bar{c}_{HW}, \quad g^{(2)}_{hzz} \propto (\bar{c}_{HW} + \bar{c}_W)$$

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

"BM II" "BM I"

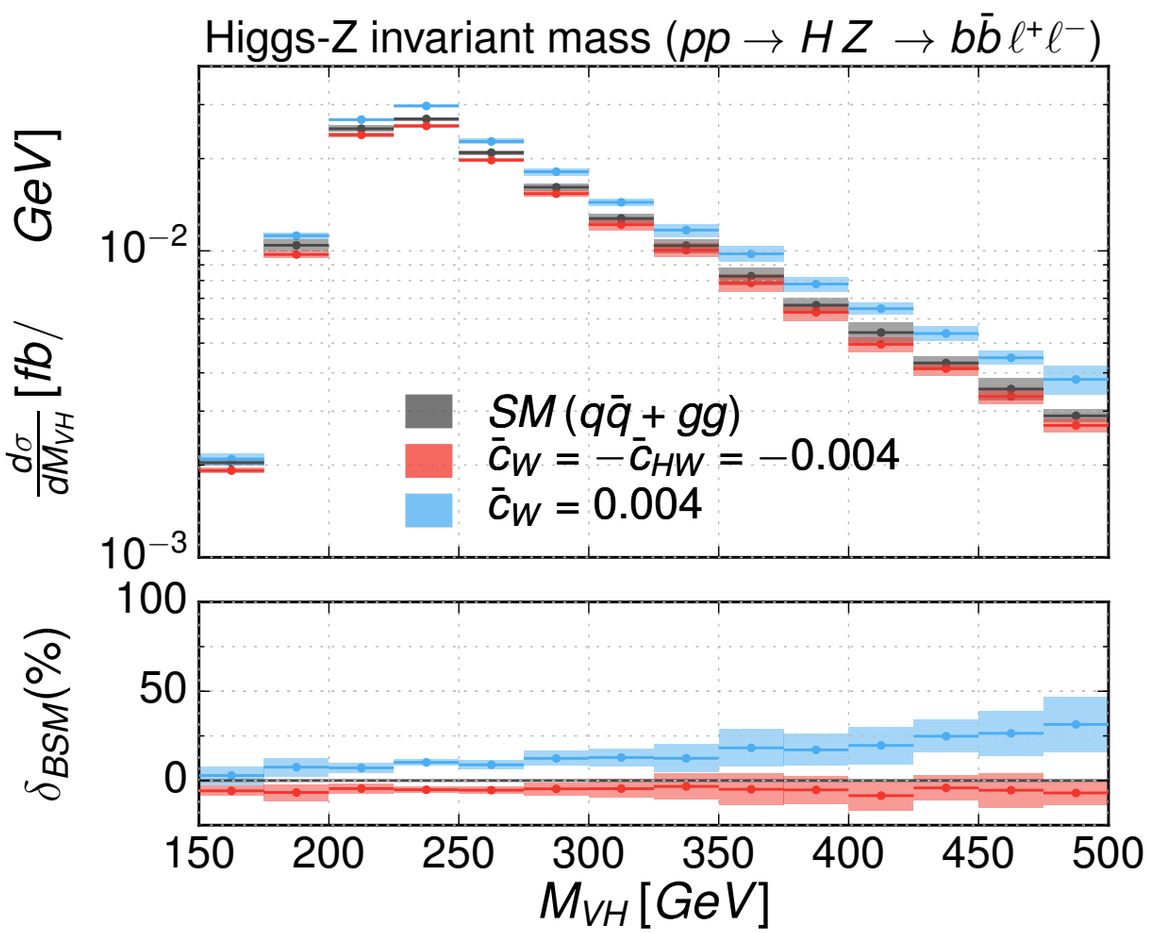


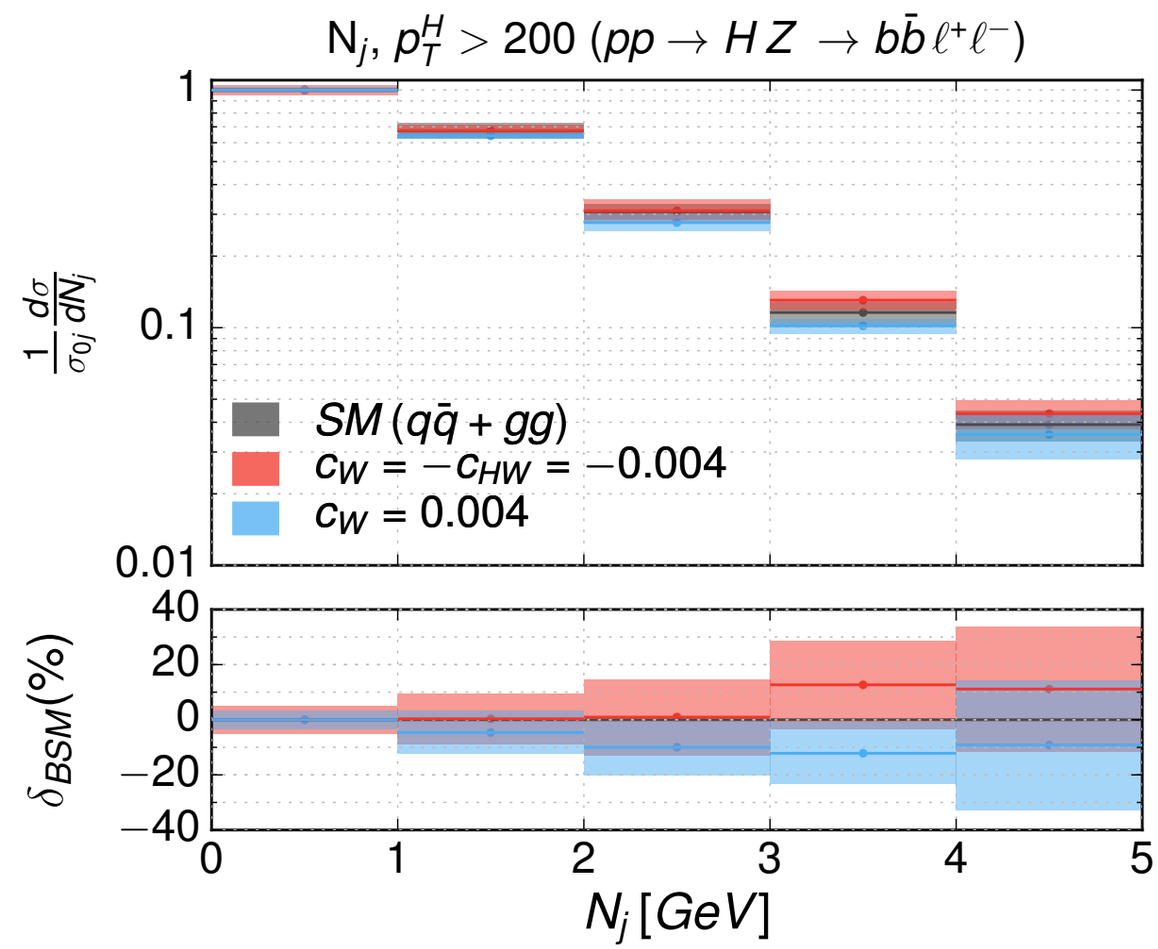


* Benchmark II does not show "EFT-like" features

pp → Z H → l+l- bb

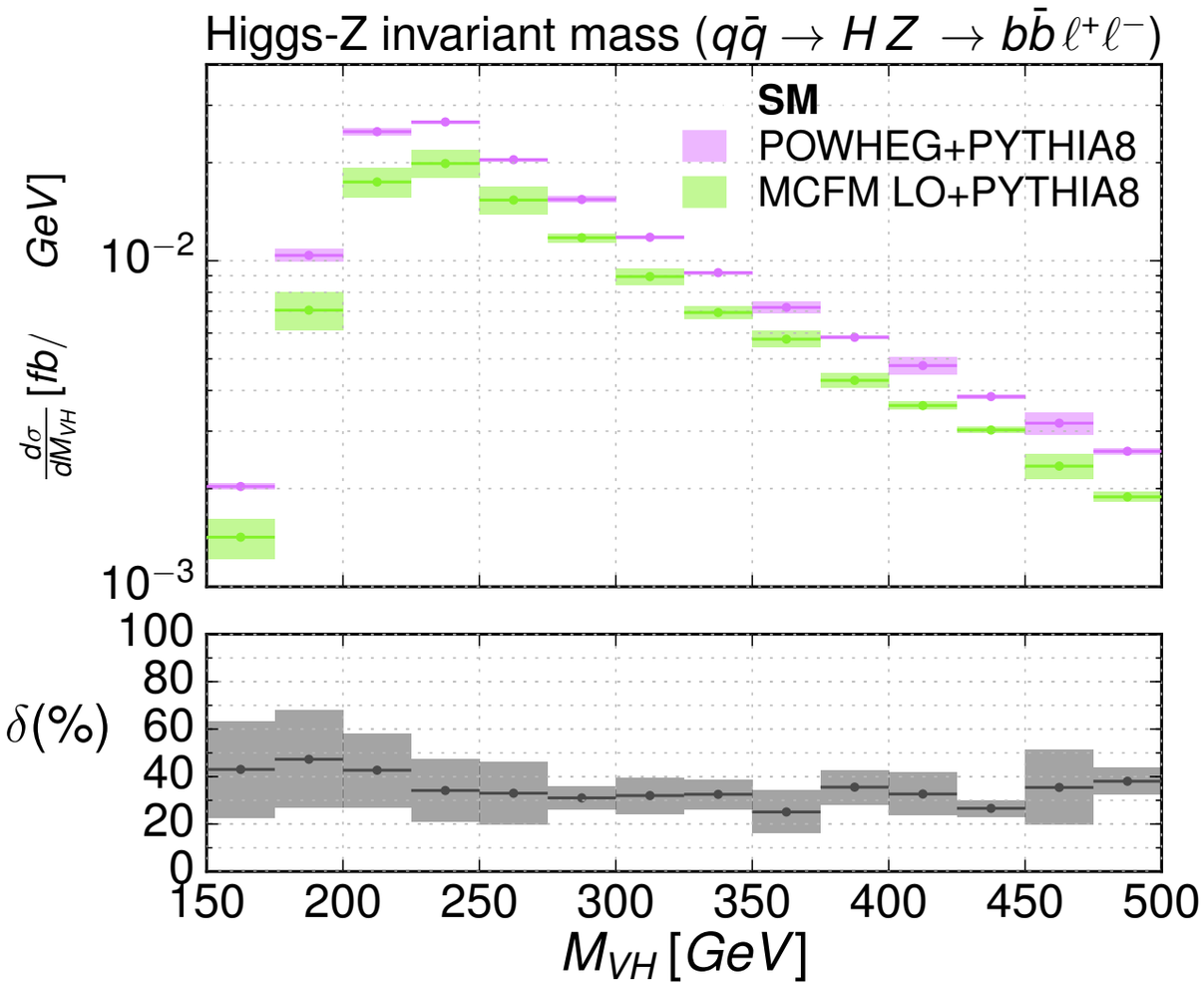
Nj exhibits some difference but stats too low to distinguish

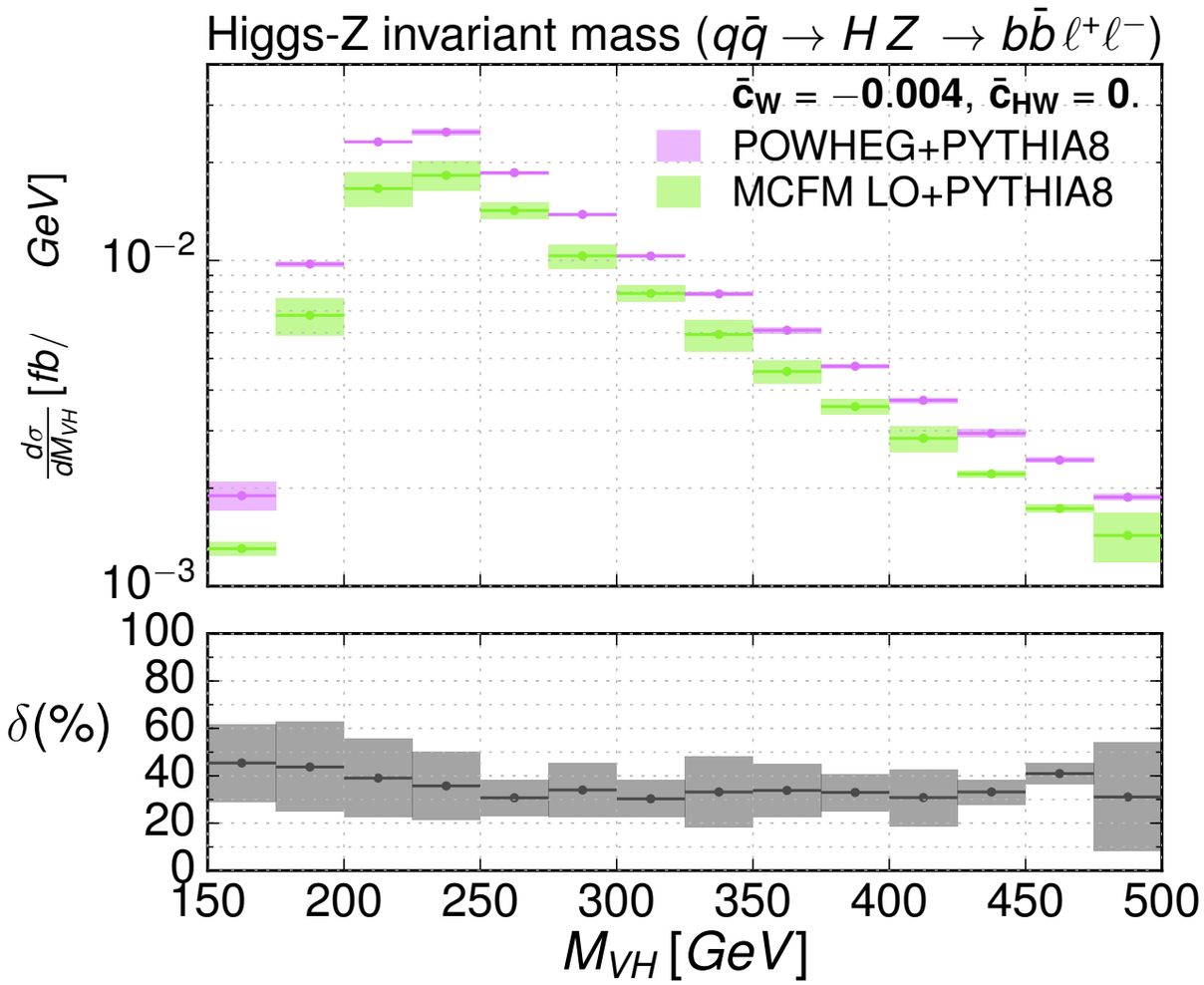




K-factors

No significant difference between SM & EFT
Relatively flat

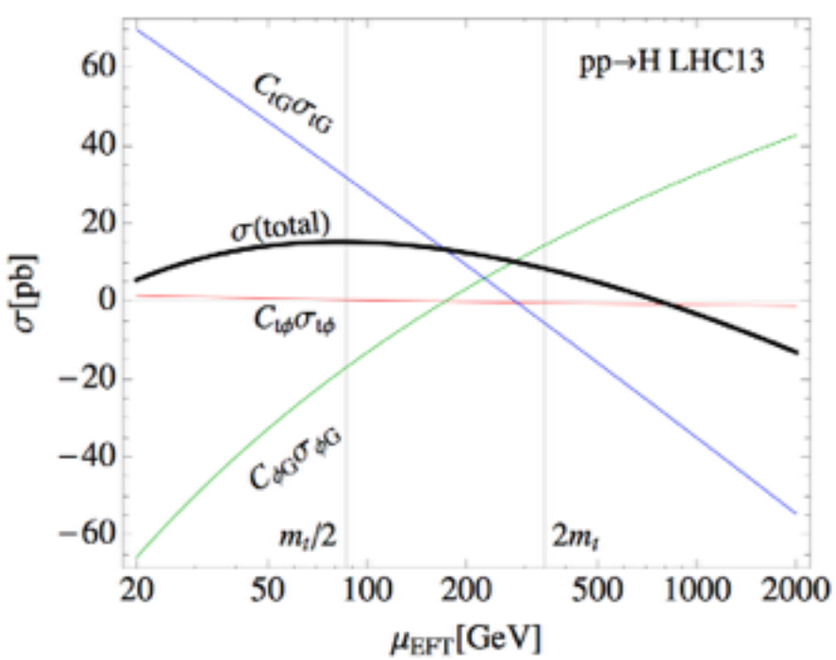


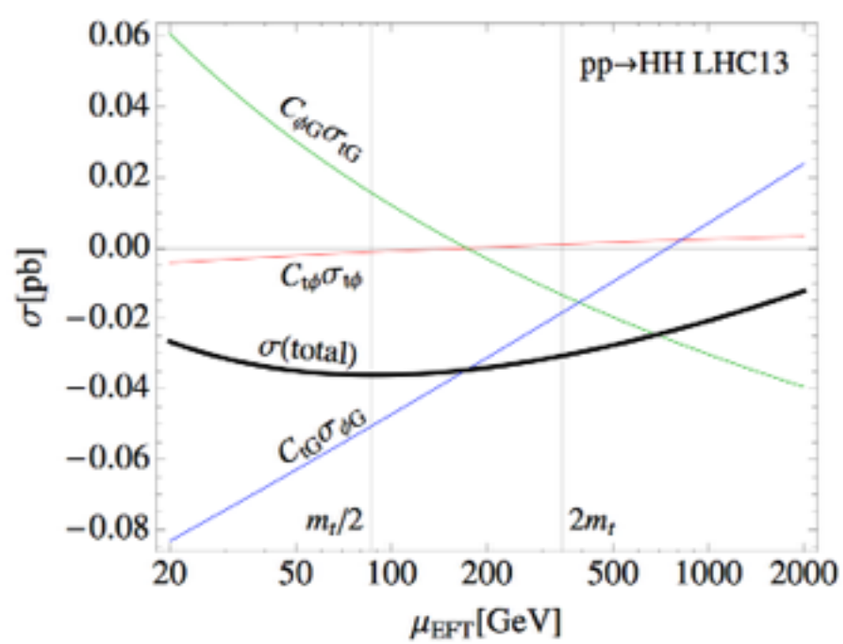


[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

New 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 new scale uncertainty component
  - 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 for which traditional scale uncertainty drops out