EW Higgs production in SMEFT at NLO in QCD

HXSWG meeting, CERN

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[arXiv: 1609.04833]
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Outline

- Overview of our recent progress in implementations of MC event generation of SM-EFT at NLO in QCD matched to parton shower
- Brief outline of EFT
  - Relevant operators for EW Higgs production
  - Effect on SM inputs & EW parameters
  - Current constraints from global fits & resulting benchmark choices
- Results from the implementations of operators affecting Higgs couplings to gauge bosons
  - EW production: WH, ZH and VBF

Going NLO

- State-of-the-art in MC event generation is well beyond LO
  - Software like MG5_aMC@NLO provides fully automated event generation at NLO in QCD
  - 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
- Implementations largely restricted to SM predictions although some codes permit the inclusion of anomalous couplings

  [Demartin, Maltoni, Mawatari, Page & Zaro; EPJC 74 (2014) 9, 3065]
  - See, e.g., Higgs Characterisation
  - Several others: HAWK, VBFNLO, POs…
  - 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
- Other important avenues…
- NLO EW corrections
  - Potentially important but much harder
  - Available for specific processes
  - Automation on the way via Madgraph5_aMC@NLO
- RG-improved predictions thanks to recent anomalous dimension matrix calculation
  - Plans to implement this in Rosetta

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

SM(Higgs)-EFT

- Basic introduction to EFT is unnecessary at this meeting
  - Suffice to say that we employ an EFT expansion in some cutoff scale, Λ
  - Truncated at canonical dimension 6
  - Introduces higher-derivative operators to which we are sensitive through large momentum flows through vertices (i.e. tails of energy distributions)
- Implementations build upon previous work done at LO employing the ‘SILH’ basis of operators
  - SMEFT Basis dependence of HEP tools can be reduced by linear redefinitions using e.g. Rosetta

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

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

EW Higgs production

- We focus on EFT effects in EW production mechanisms for the Higgs: VH & VBF
  - Promising channels for the LHC
  - 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

SILH operators

- Higgs-EW gauge boson operators in SILH basis

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

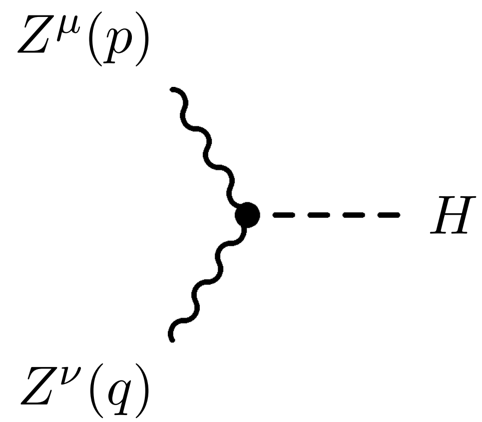
$$\Phi^\dagger\overleftrightarrow{D}^\mu\Phi \equiv \left(D^\mu\Phi^\dagger\right)\Phi - \Phi^\dagger\left(D^\mu\Phi\right)$$

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

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

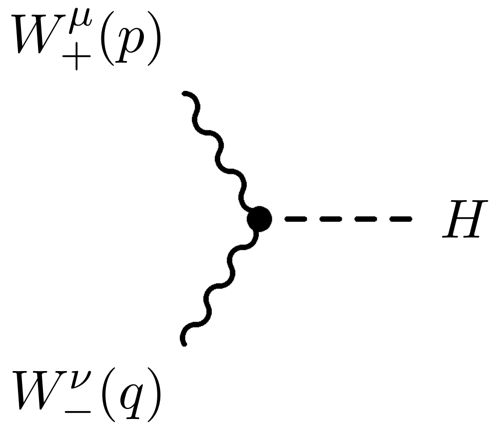
$$\mathcal{L}_{HAC} = -\frac{1}{4}g^{(1)}_{hzz}Z_{\mu\nu}Z^{\mu\nu}h - g^{(2)}_{hzz}Z_\nu\partial_\mu Z^{\mu\nu}h + \frac{1}{2}g^{(3)}_{hzz}Z_\mu Z^\mu h - \frac{1}{4}\tilde{g}_{hzz}Z_{\mu\nu}\tilde{Z}^{\mu\nu}h$$
$$-\frac{1}{2}g^{(1)}_{hww}W^{\mu\nu}W^\dagger_{\mu\nu}h - \left[g^{(2)}_{hww}W^\nu\partial^\mu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

Feynman Rules



:

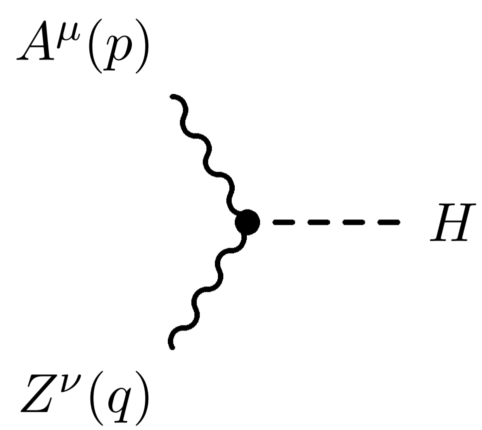
$$i\left[\eta^{\mu\nu}\left(\frac{g}{\cos\theta_W}M_Z + g^{(1)}_{hzz}\,p\cdot q + g^{(2)}_{hzz}\,(p^2+q^2)\right) - g^{(1)}_{hzz}\,q^\mu p^\nu - \tilde{g}_{hzz}\epsilon^{\mu\nu\rho\sigma}\,q_\rho p_\sigma - g^{(2)}_{hzz}\,(p^\mu p^\nu + q^\mu q^\nu)\right]$$



:

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

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

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

Sidenote: SM inputs

$$\frac{g'^2}{4}\bar{c}_{BB}\Phi^\dagger\Phi B^{\mu\nu}B_{\mu\nu} \to \frac{g'^2v^2}{8}\bar{c}_{BB}B^{\mu\nu}B_{\mu\nu} + \cdots$$

- After EWSB, several of the operators included in our implementations lead to non-canonical gauge boson kinetic terms
  - Perform field redefinitions to fix their normalisation
  - Gauge coupling redefinitions can absorb part of the resulting modifications
  - In general, leads to modifications of gauge bosons masses, interactions, e.g., Z→ff
  - Also modifications to the SM parameters as a function of EW inputs
- Not all tools take these into account
  - Various choices can be made that are all equivalent up to dimension-6

[Williams, KM & Sanz; JHEP 1608 (2016) 039]
[Ge, He & Xiao; JHEP 1610 (2016) 007]
[Degrande, Fuks, Mawatari, KM, Sanz; 1609.04833]

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 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

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

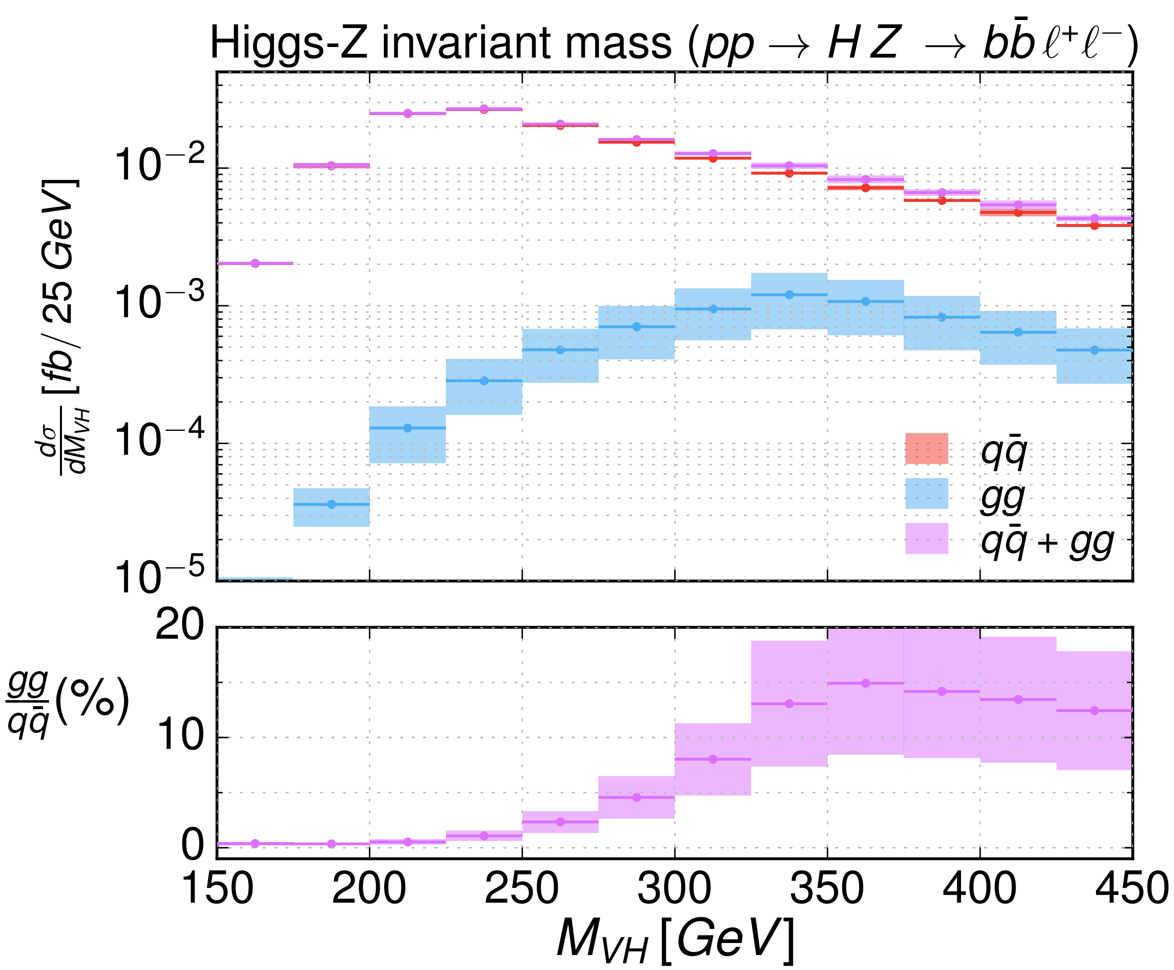
Selection

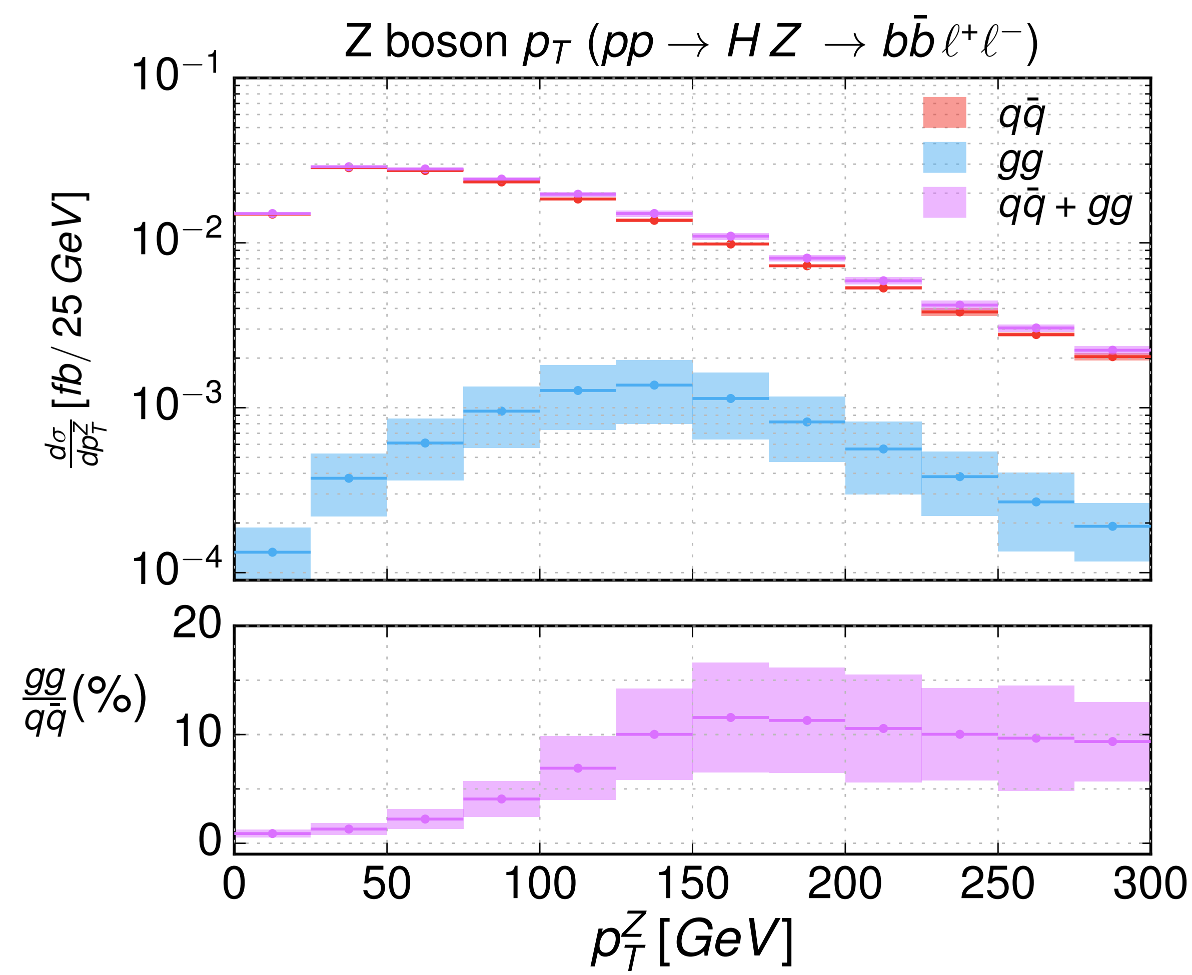
Process	
$H\,Z \to b\bar{b}\,\ell^+\ell^-$	$H\,W \to b\bar{b}\,\ell\nu$
Jets	
k_T algorithm: ΔR=0.4, $p_T > 25$ GeV & $\eta_b < 2.5$	
Cuts	
2 b-jets, $p_T > 25$ GeV, $\eta_b < 2.5$	
1 lepton, $\ell^{\pm}$ (e or μ)	2 leptons, ℓ^+, ℓ^- (e or μ)
$p_T^{\ell} < 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$	

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

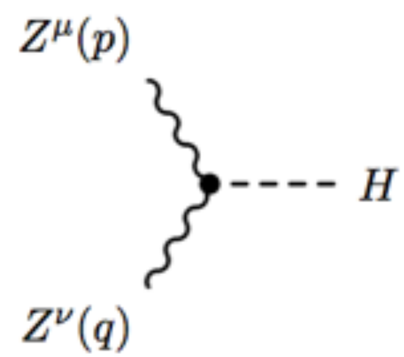
gg → Z H → l+l- bb

- 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



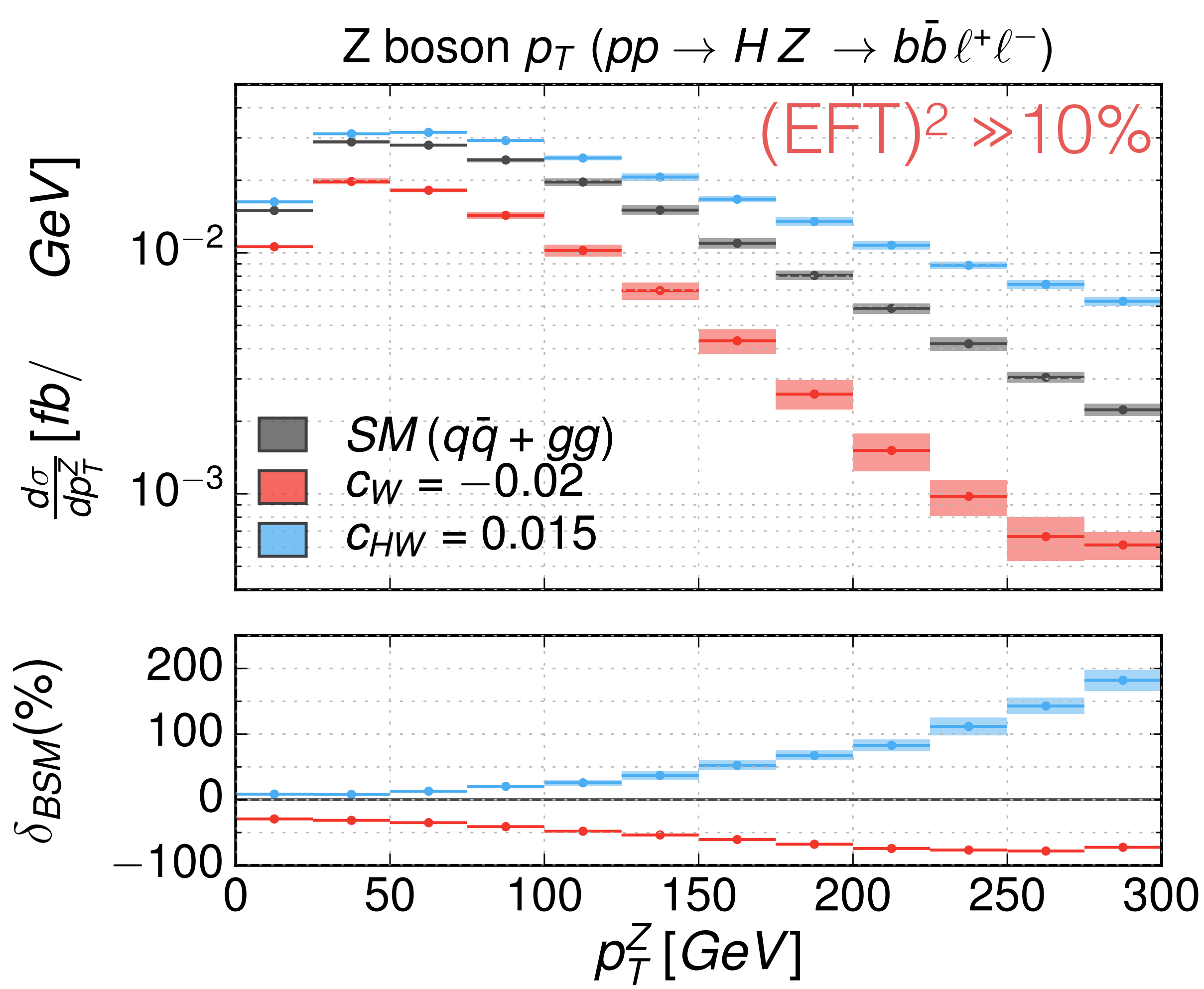


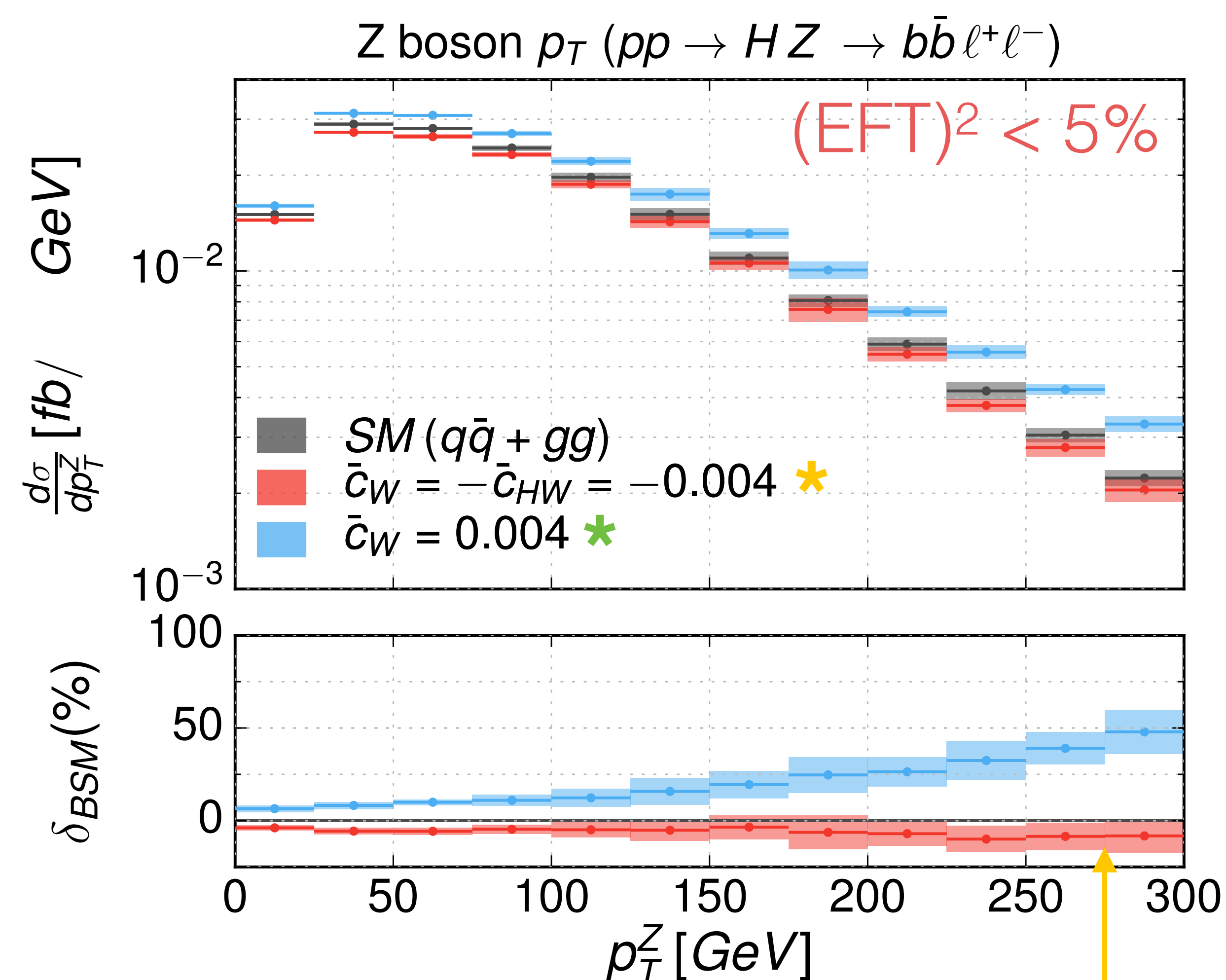
pp → Z H → l+l- bb



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

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

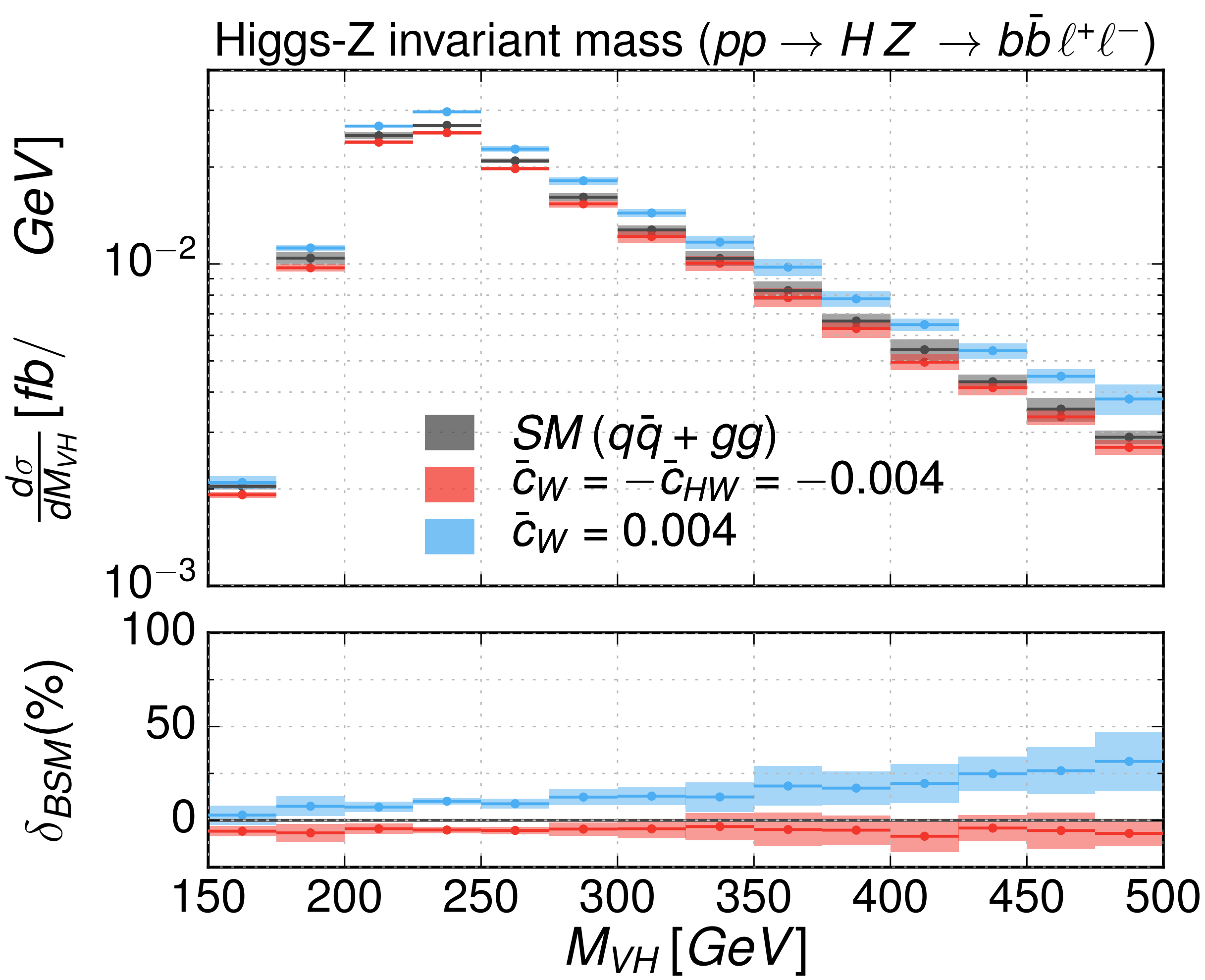


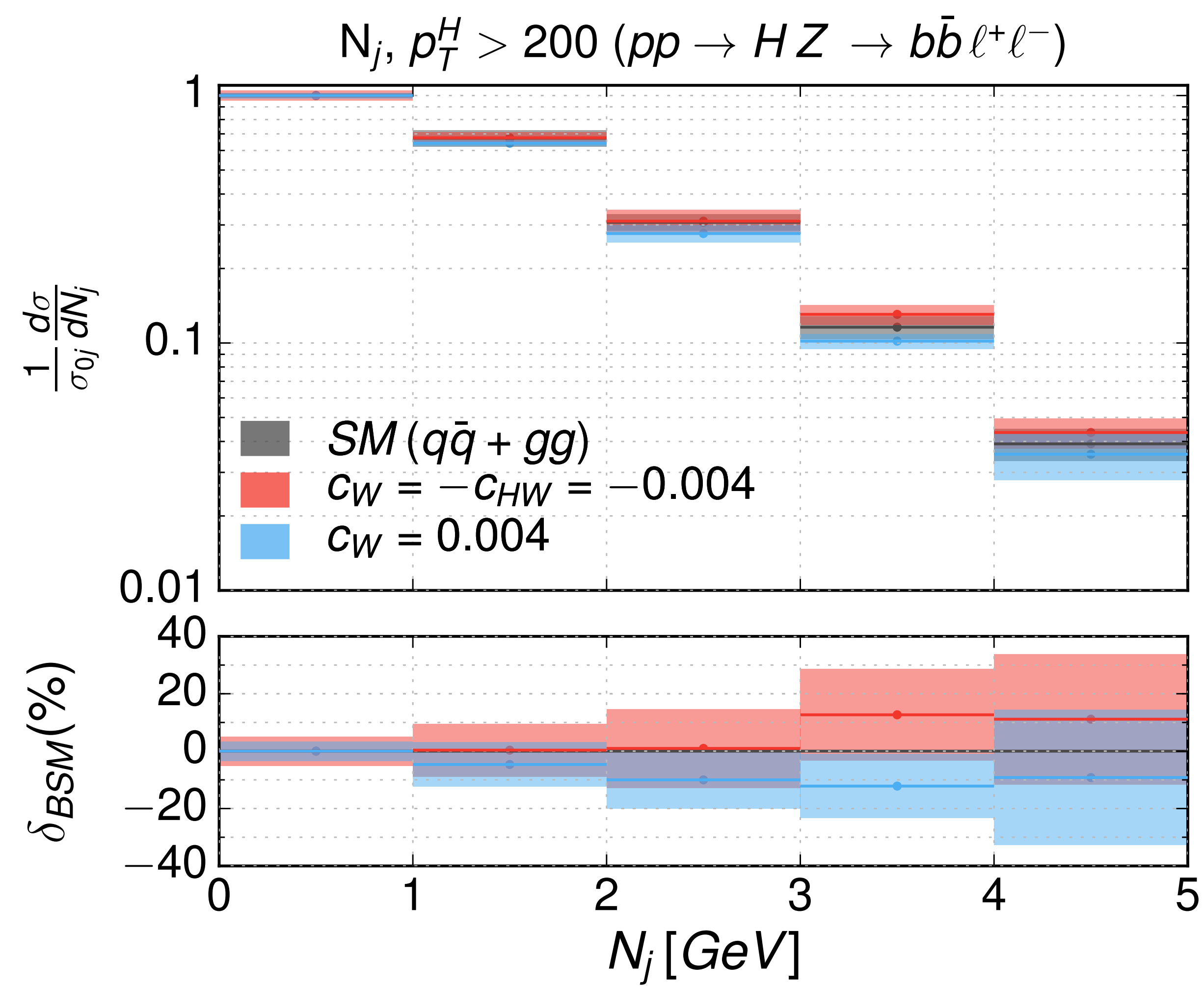


* Benchmark II does not show “EFT-like” features

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

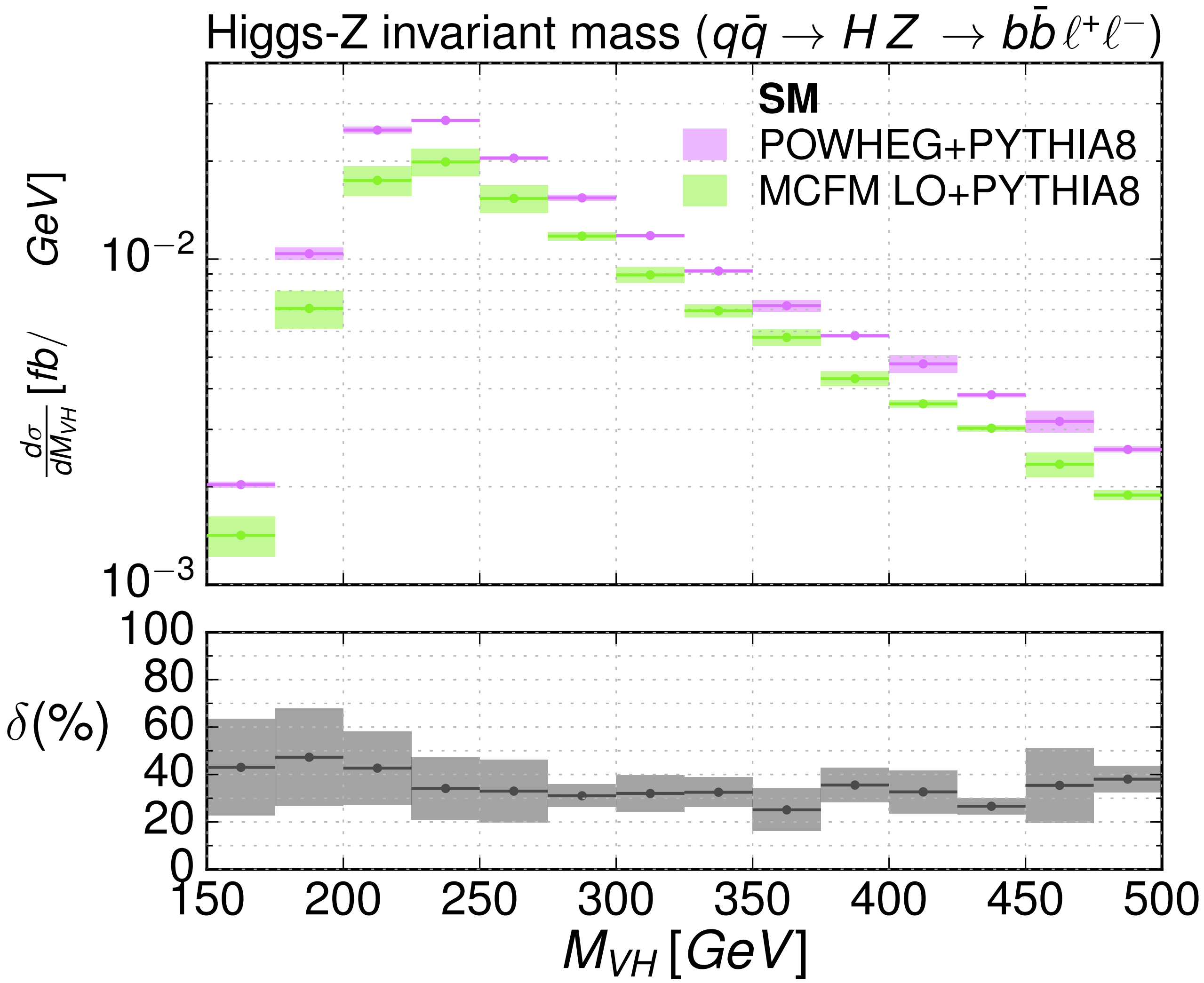
Nj exhibits some difference but stats too low to distinguish

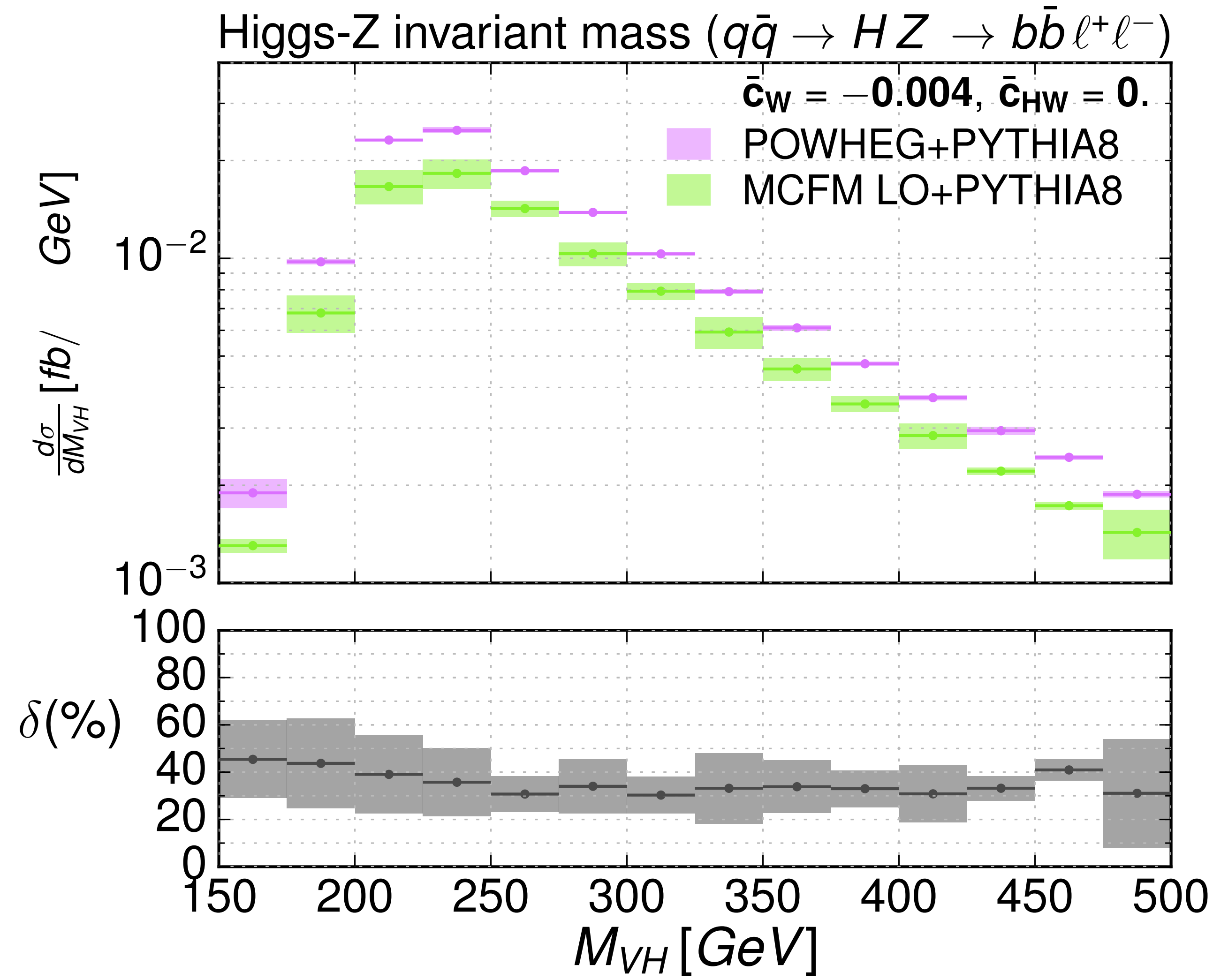




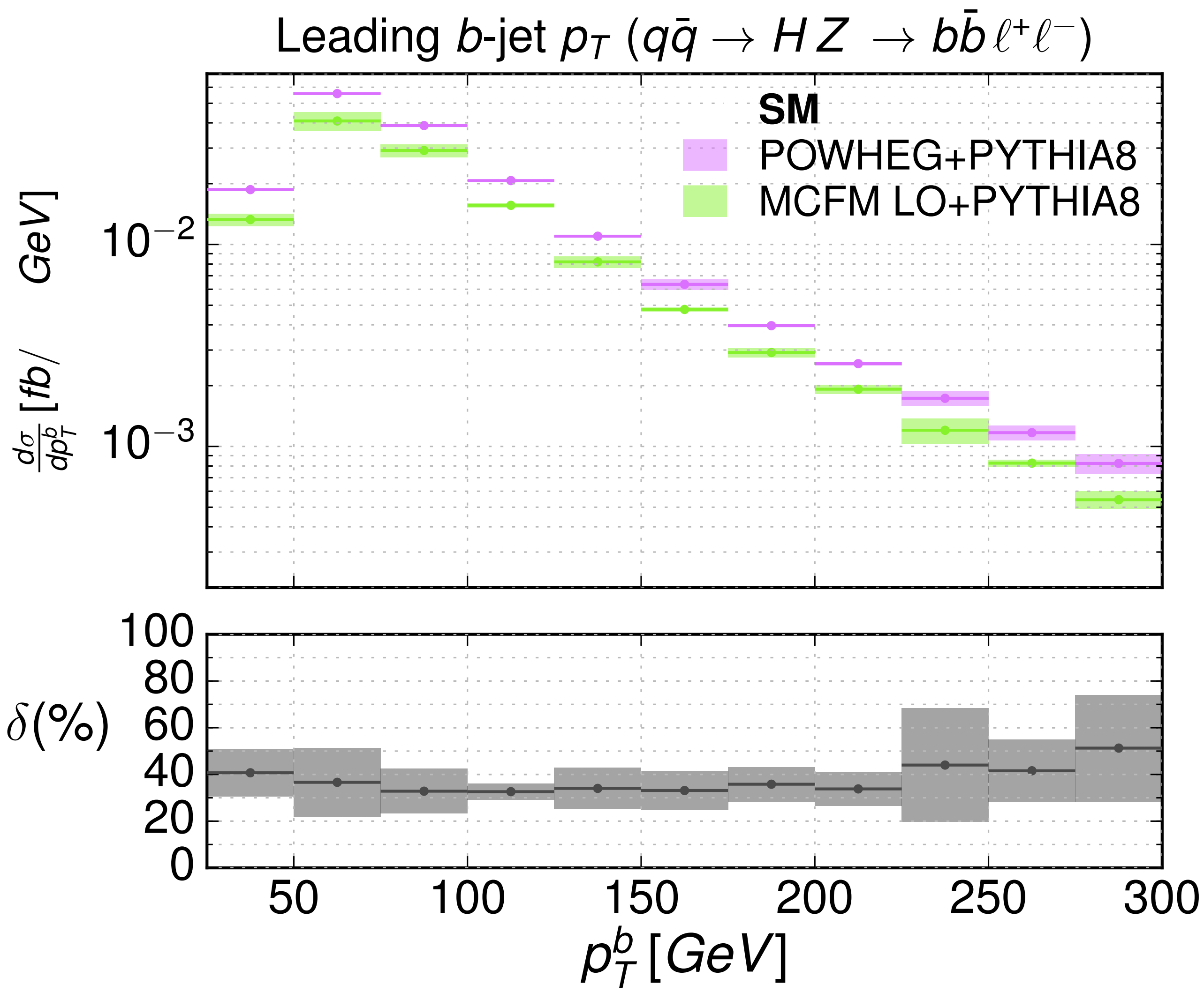
K-factors

No significant difference between SM & EFT
Relatively flat

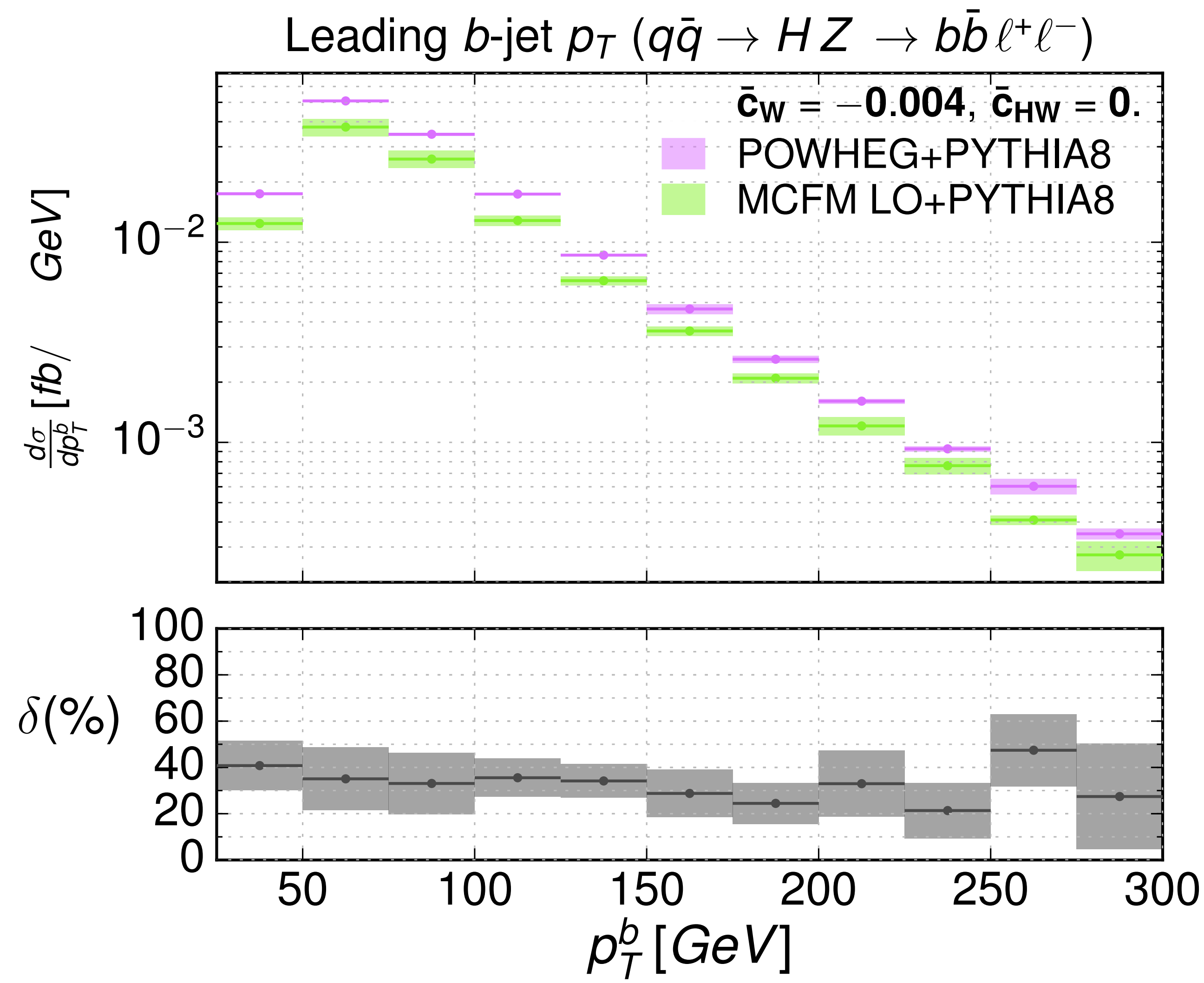




K-factors



Leading b-jet p_T ($q\bar{q} \to HZ \to b\bar{b}\,\ell^+\ell^-$)
SM
POWHEG+PYTHIA8
MCFM LO+PYTHIA8
$\frac{d\sigma}{dp_T^b}$ [fb/ GeV]
10^{-2}
10^{-3}
δ(%)
100
80
60
40
20
0
50
100
150
200
250
300
p_T^b [GeV]



Leading b-jet p_T ($q\bar{q} \to HZ \to b\bar{b}\,\ell^+\ell^-$)
$\bar{c}_W = -0.004$, $\bar{c}_{HW} = 0$.
POWHEG+PYTHIA8
MCFM LO+PYTHIA8
$\frac{d\sigma}{dp_T^b}$ [fb/ GeV]
10^{-2}
10^{-3}
δ(%)
100
80
60
40
20
0
50
100
150
200
250
300
p_T^b [GeV]

[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

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

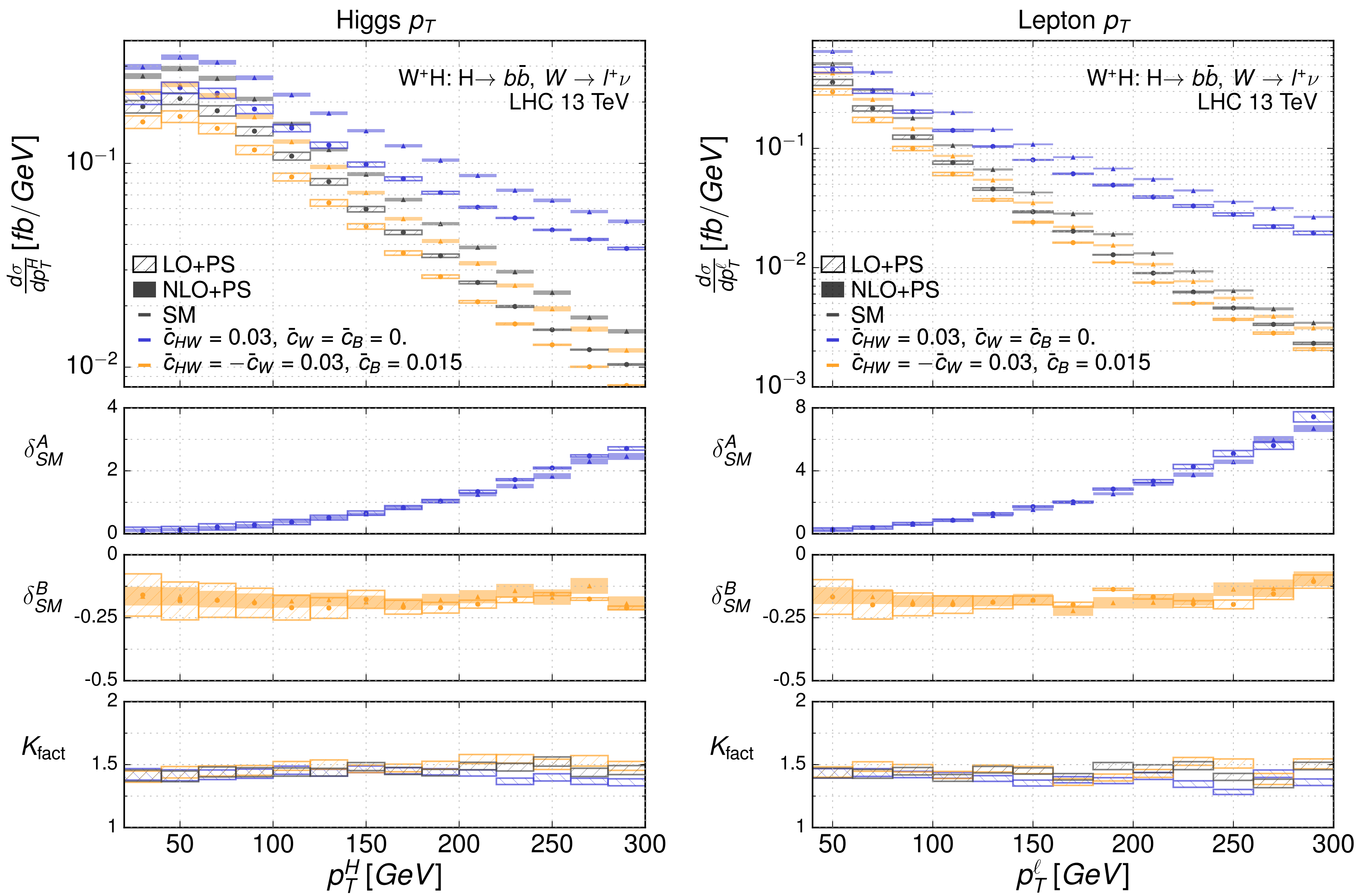
```
generate p p > h ve e+ [QCD]
```

pp → W+ H → l+ ν 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



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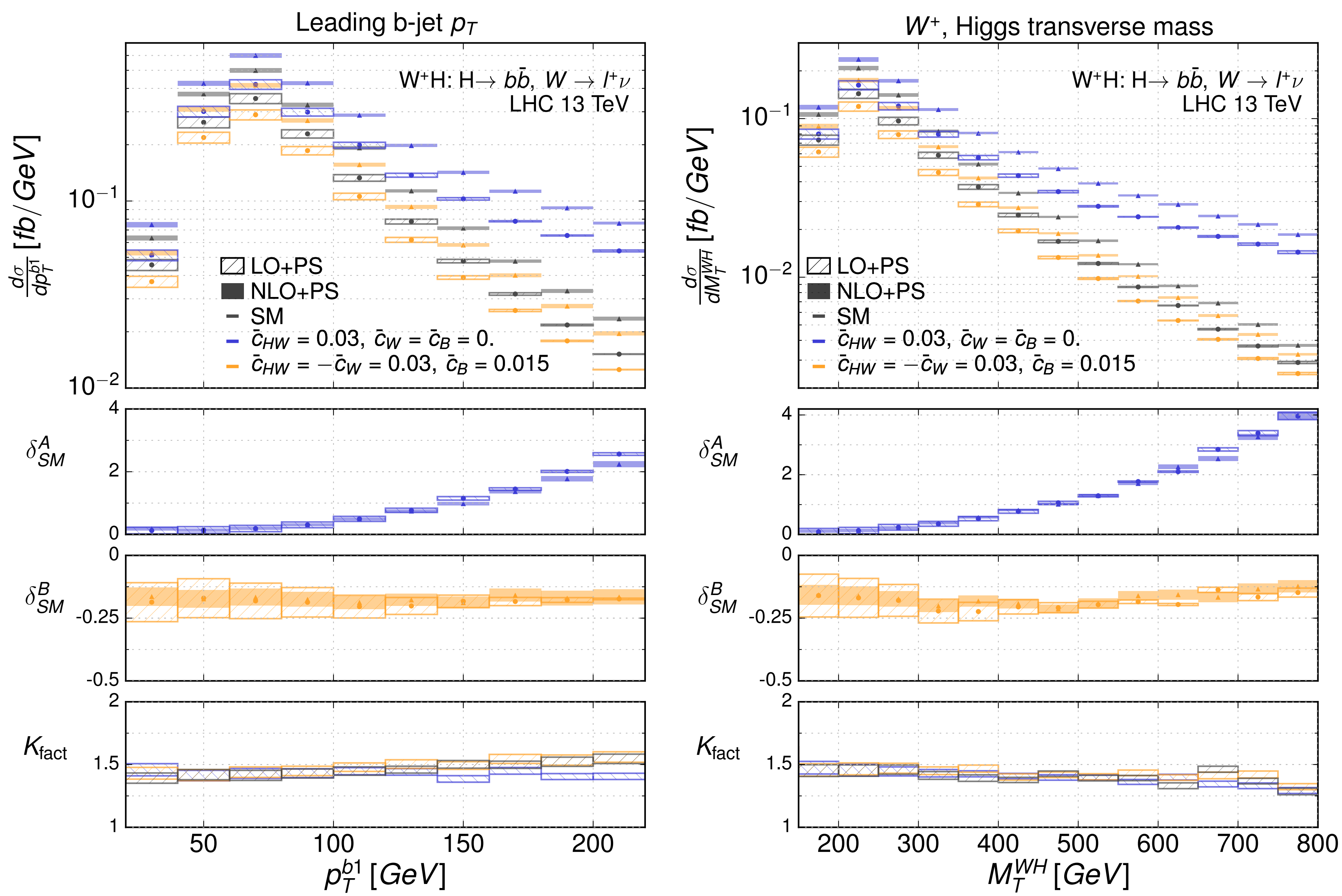
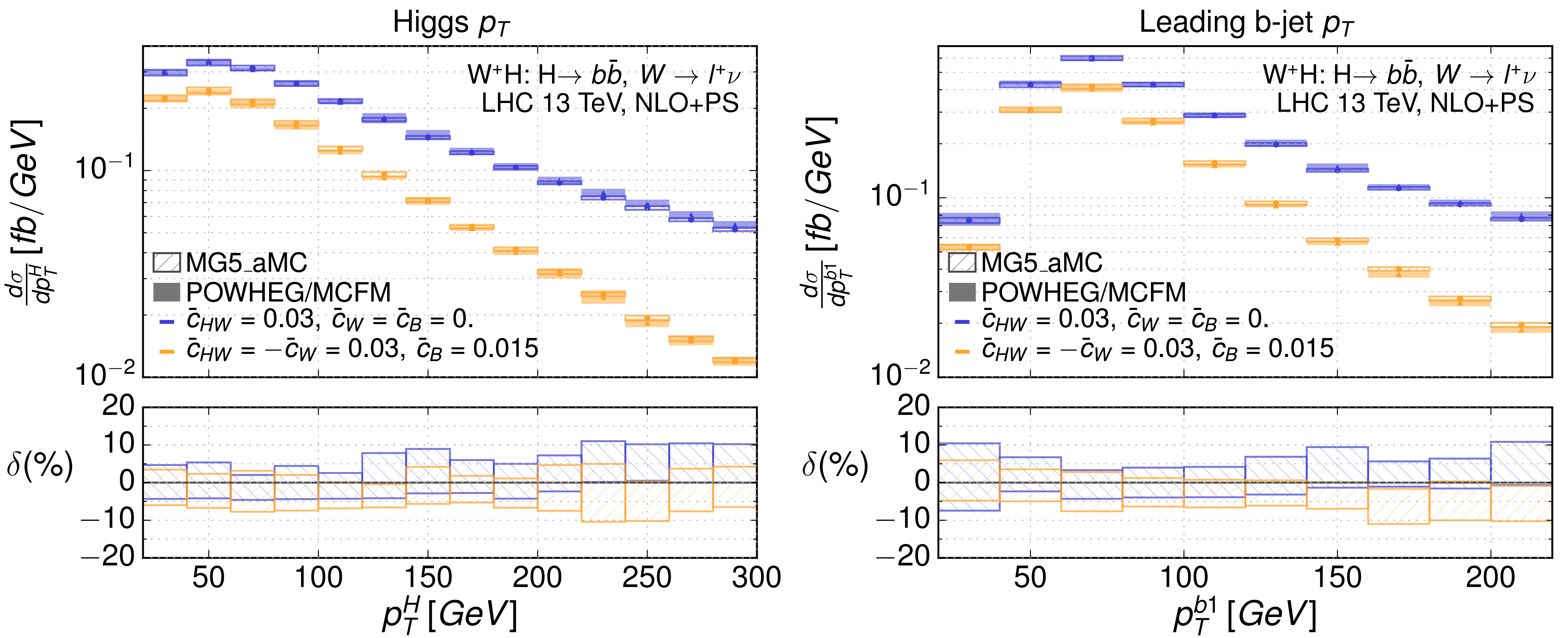
pp → W⁺ H → l⁺ ν bb

Again, benchmark **B)** does not exhibit strong “EFT” features
The $g_{hvv}^{(2)}$ Lorentz structure is responsible for these

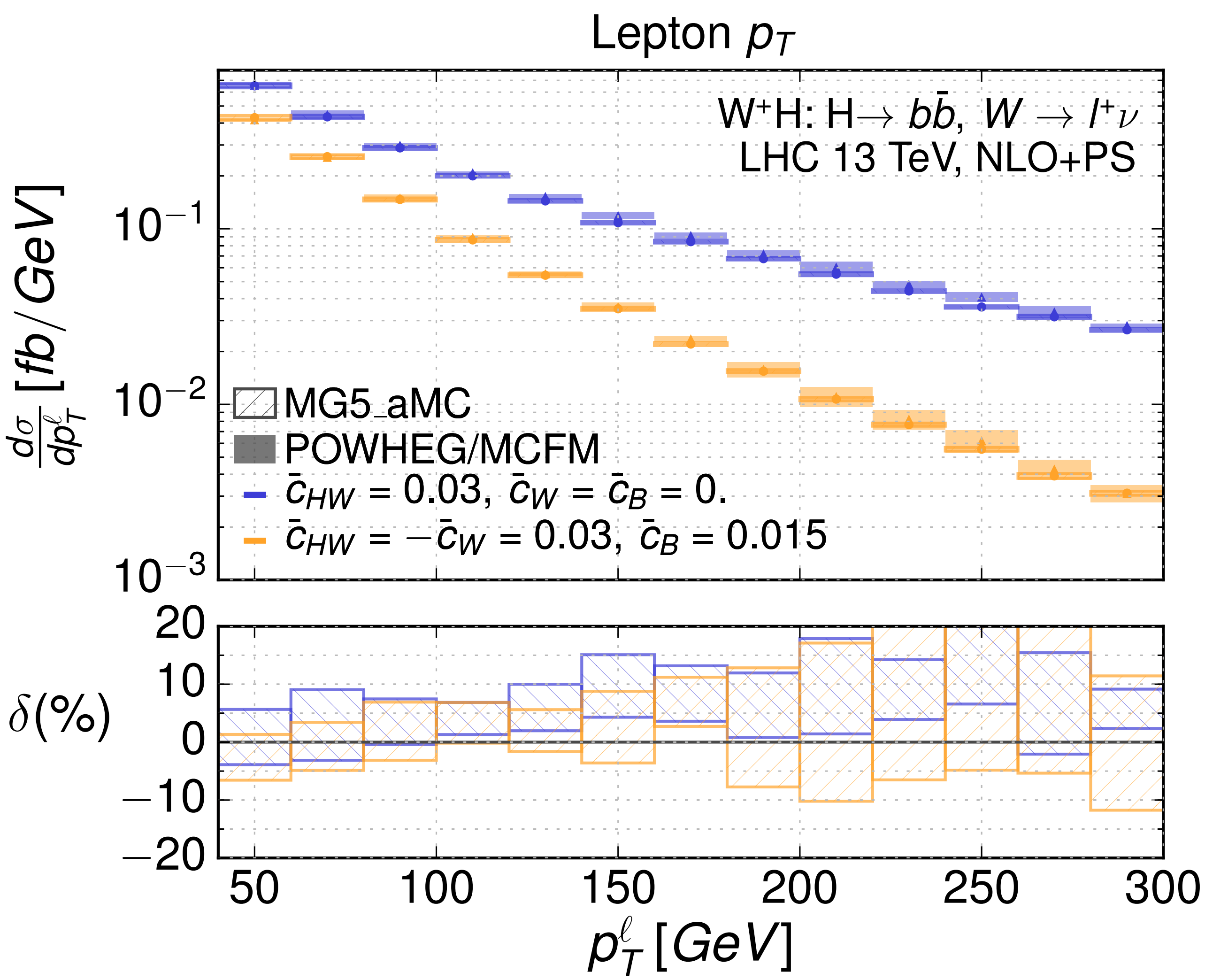


Validation

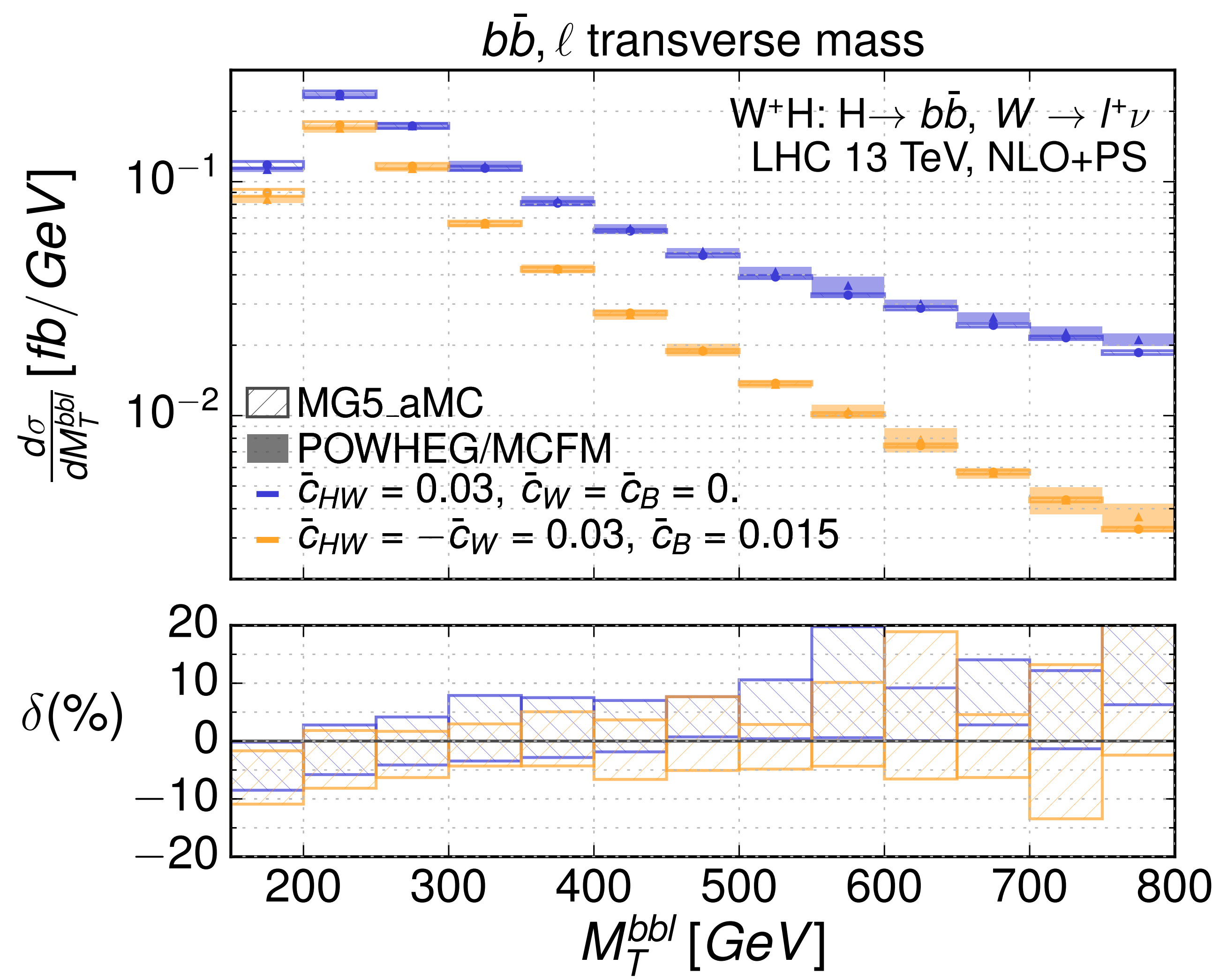
Reasonable agreement between POWHEG/MCFM & Madgraph5_aMC@NLO implementations



Validation



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

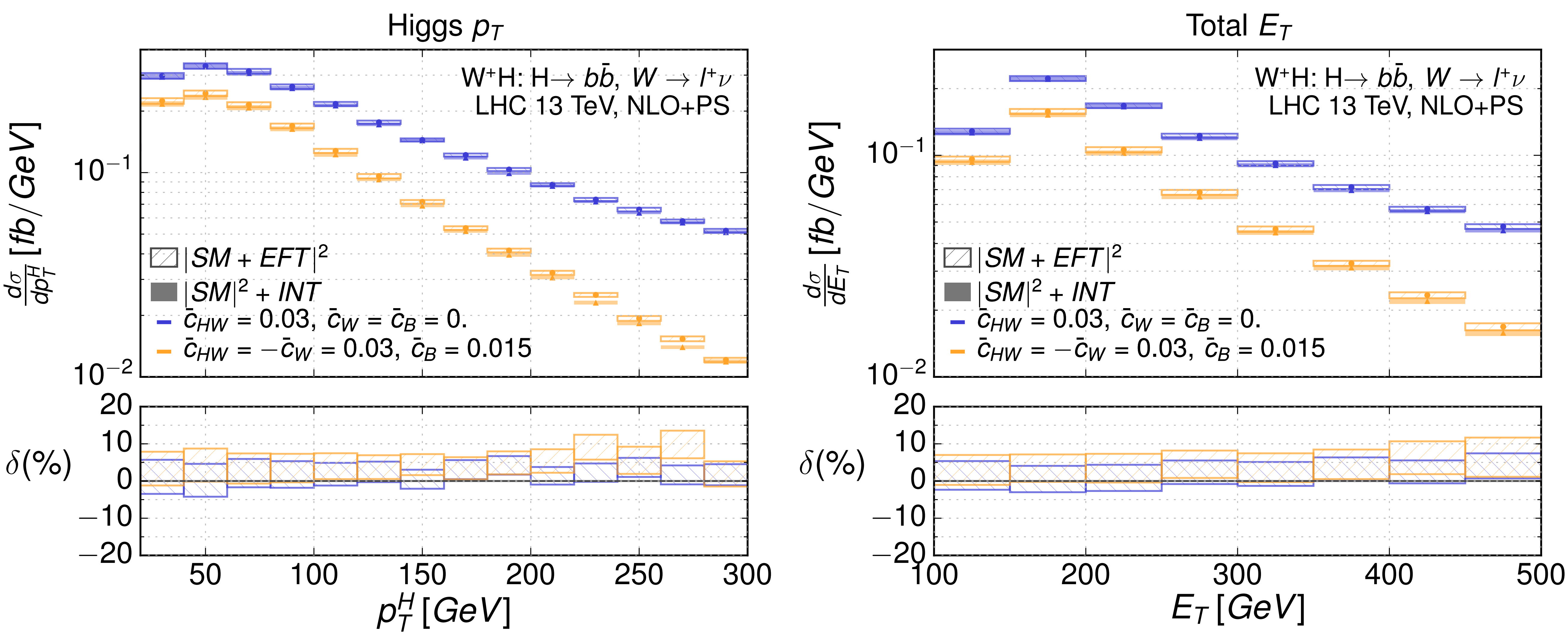


$b\bar{b}, \ell$ transverse mass
W⁺H: H→ $b\bar{b}$, $W \to l^+\nu$
LHC 13 TeV, NLO+PS
MG5_aMC
POWHEG/MCFM
$\bar{c}_{HW} = 0.03$, $\bar{c}_W = \bar{c}_B = 0.$
$\bar{c}_{HW} = -\bar{c}_W = 0.03$, $\bar{c}_B = 0.015$
$\frac{d\sigma}{dM_T^{bbl}}$ [fb/GeV]
$\delta(\%)$
M_T^{bbl} [GeV]

Interference only

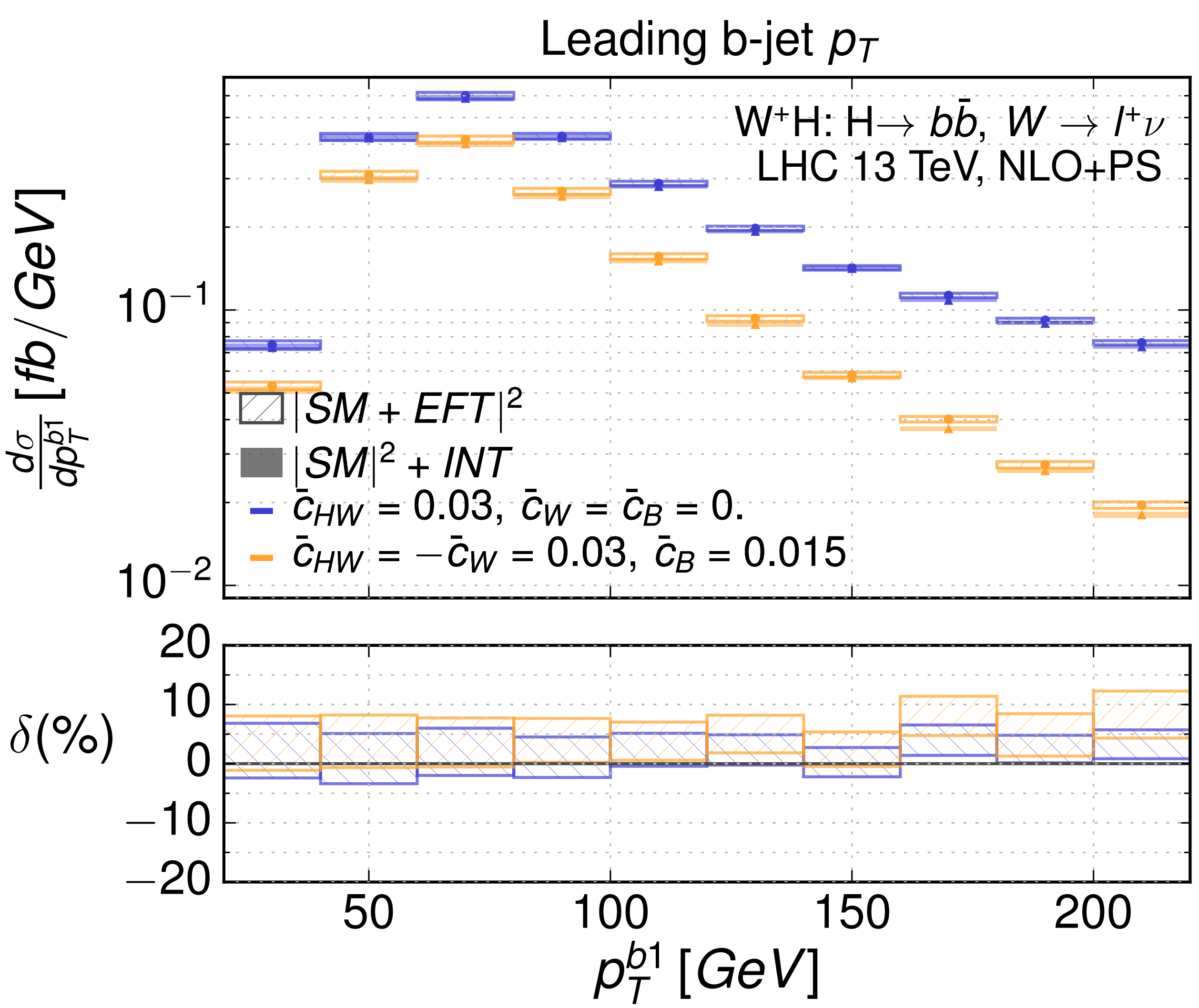
```
generate p p > ve e+ h NP^2<=1 HIG=0 [QCD]
```

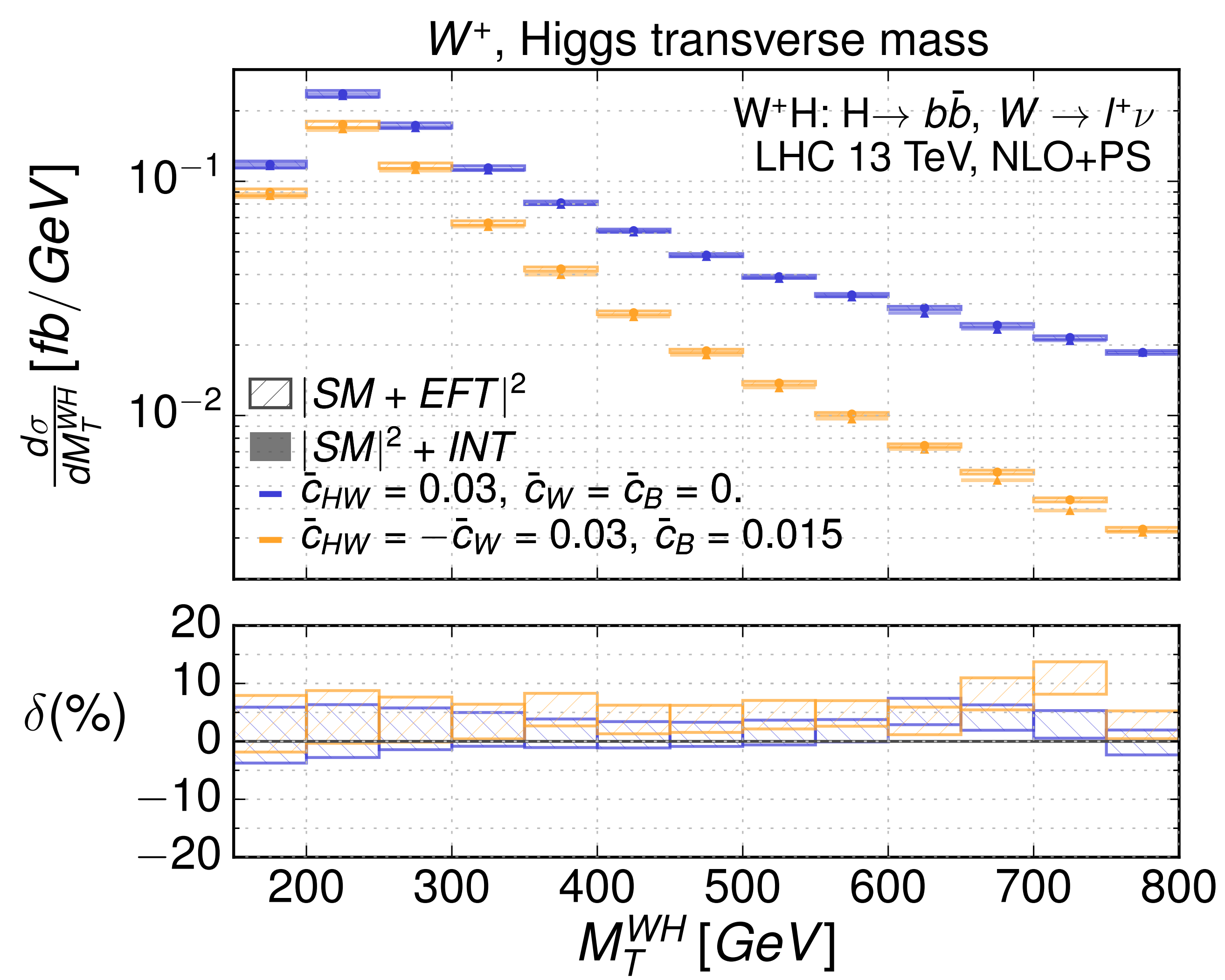
Seemingly not a great difference between the two
Comparable to scale uncertainty



Interference only

A possible way to define an additional theory uncertainty?





EFT theory uncertainty

A proposal to define an additional theory uncertainty?

- Make use of this nice feature of MG5_aMC
- For any given process, compute both
  - NP<=1 $(|SM+EFT|^2)$
  - NP^2<=1 $(|SM|^2)+SMxEFT)$
- Generate the observables of interest & take the difference of the two predictions as a theory error
- A model independent estimate of the effect of truncating your EFT expansion at D=6 for your set of Wilson coefficient values
- This can in principle also be worked out for other tools

pp → H j j → γ γ j j

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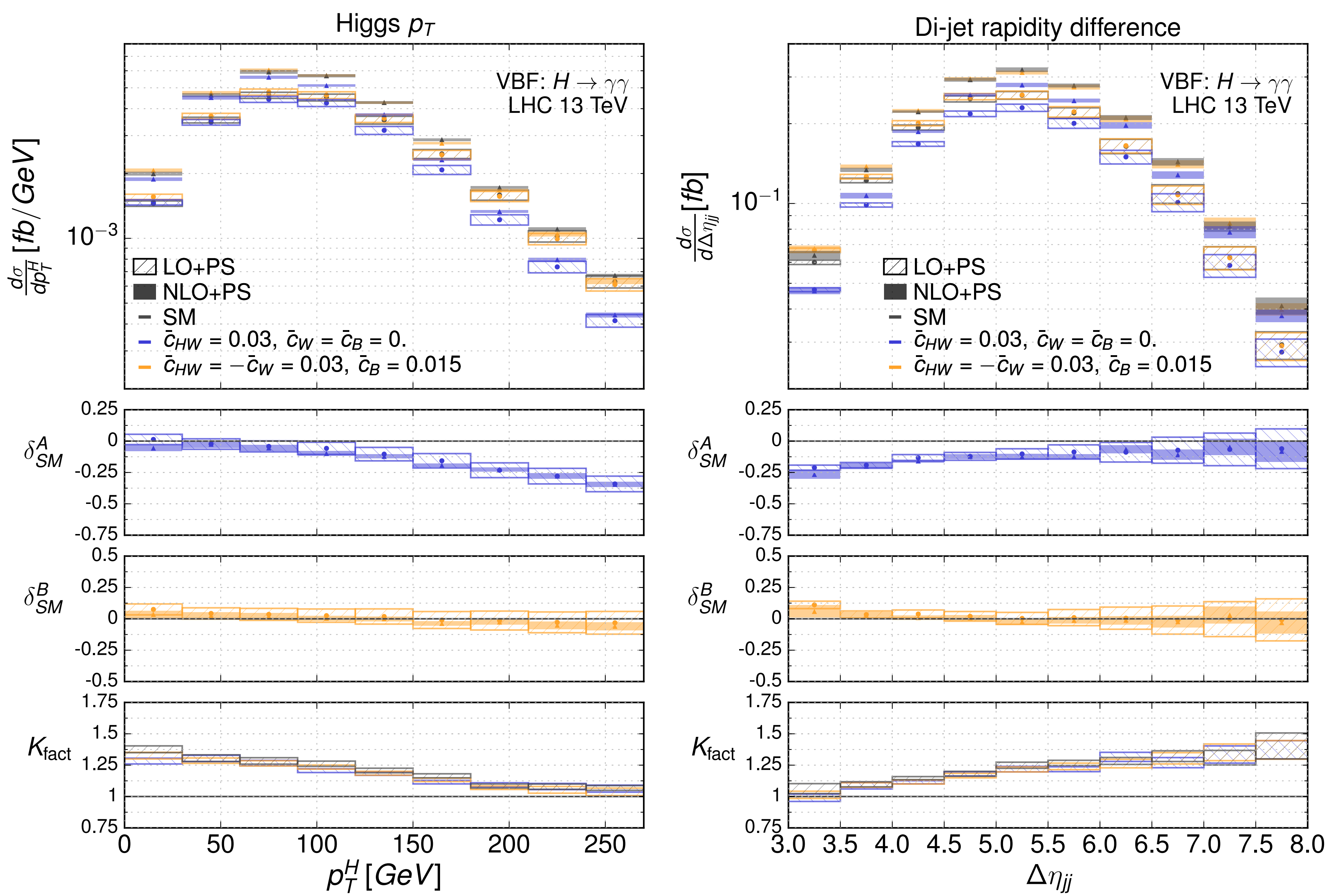
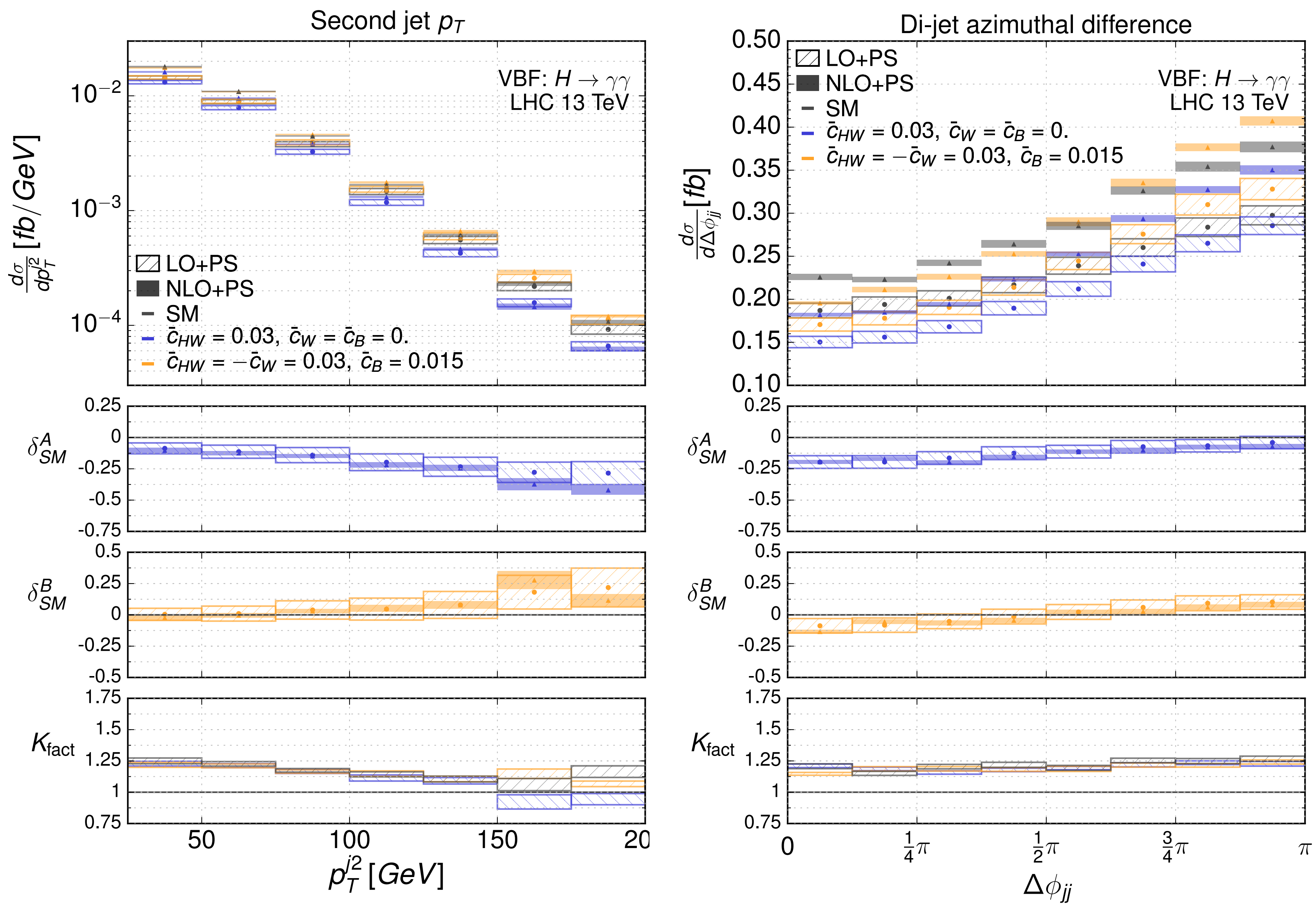
Used a fixed scale of m_W as suggested by literature



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

Conclusion

- We are near the beginning of a long and fruitful programme of Higgs characterisation via EFT
- Current precision of global fit allow for much room for large EFT deviations and precision is now improved to NLO in QCD+PS
- For VH, k-factors are relatively flat, nothing crazy going on, as expected
  - Also validated implementations between one another for WH
- Seemingly, benchmarks which saturate current limits are not wildly beyond the “validity” of the EFT in the sense that the impact of the squared contributions is of the order of the scale uncertainty

Conclusion

- Propose a "naive" way of quantifying some element of the associated theory uncertainty & will likely become important at the next order in perturbation theory
- NLO-QCD+PS accurate Tools for MC event generation are a necessary ingredient for the EFT programme
- Two independent implementations presented & will be public soon
  - POWHEG-BOX currently only WH/ZH but open to requests for, e.g., VBF
  - FR+NLOCT/MG5_aMC@NLO can generate any process in principle
  - Only a small subset of operators currently present: we aim to extend this for HEL@NLO in the coming months

Rosetta compatibility

- Rosetta interfaces for HEL@NLO description also work in progress to directly produce SLHA output card for UFO
- We also plan to include a way to map D=6 EFT bases to the Higgs Characterisation model
- Towards ‘basis independent’ generation for at NLO QCD accuracy