Challenges for EFTs at Run2 LHC

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HEFT2015, Chicago

Outline

- EFTs: how do we look for New Physics with them
- Challenges for EFTs: precision and breakdown
- Precision: NLO QCD
- Breakdown: Benchmarks in extended Higgs sectors

Effective Field Theory
heavy New Physics

Buchmuller and Wyler. NPB (86)

New Physics could be heavy as compared with the typical energy of the channel we look at

EFT: expansion in higher-dimensional operators (HDOs)

Advantages of EFT

model independent

Systematic studies

One operator, corrs.

Translation to thy

Expansion in inverse powers of NP scale

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \bar{c}_i \mathcal{O}_i$$

dim6, dim8, …

coupling HWW at dim-6

$$\frac{ig\ \bar{c}_W}{m_W^2} \left[\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi\right] D^\nu W^k_{\mu\nu}$$

$$\frac{2ig\ \bar{c}_{HW}}{m_W^2} \left[D^\mu \Phi^\dagger T_{2k} D^\nu \Phi\right] W^k_{\mu\nu}$$

Contino et al. 1303.3873

here, assuming Higgs doublet

non-linear: see talks by Merlo, Krause, Panico

How do we look for HDOs?

Rates and differential distributions

New Physics induces new coupling structures of SM particles, incl the Higgs

Higgs anomalous couplings

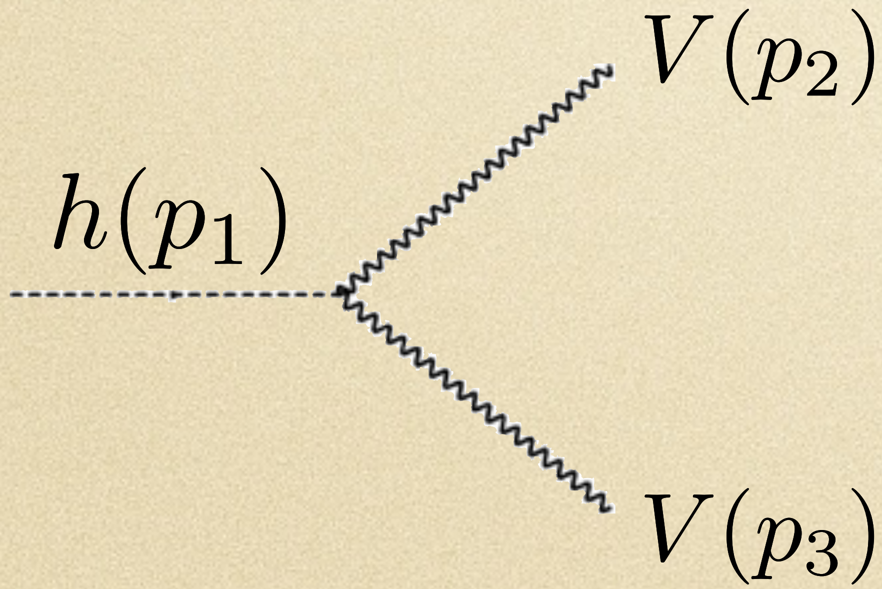
HDOs generate HVV interactions with more derivatives ⇒

$$-\frac{1}{4} h\, \underline{g^{(1)}_{hVV}}\, V_{\mu\nu} V^{\mu\nu}$$

$$-h\, \underline{g^{(2)}_{hVV}}\, V_{\nu} \partial_{\mu} V^{\mu\nu}$$

$$-\frac{1}{4} h\, \underline{\tilde{g}_{hVV}}\, V_{\mu\nu} \tilde{V}^{\mu\nu}$$

ex. Feynman rule if mh>2mV



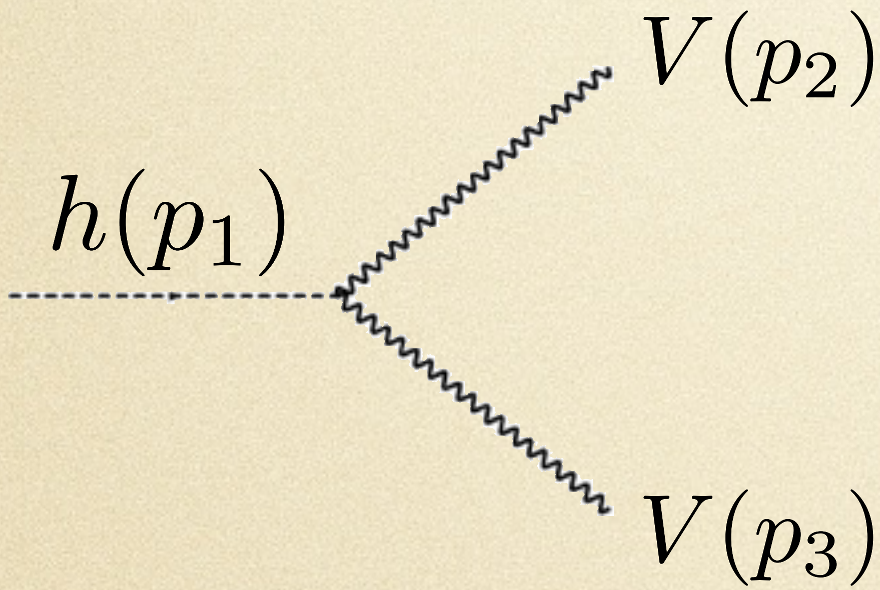
$$i\eta_{\mu\nu} \left(\underline{g^{(1)}_{hVV}} \left(\frac{\hat{s}}{2} - m_V^2 \right) + 2\underline{g^{(2)}_{hVV}} m_V^2 \right)$$

$$-i\underline{g^{(1)}_{hVV}} p_3^{\mu} p_2^{\nu}$$

$$-i\underline{\tilde{g}_{hVV}} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

New Physics induces new coupling structures of SM particles, incl the Higgs

Higgs anomalous couplings



$$i\eta_{\mu\nu}\left(\underline{g^{(1)}_{hVV}}\left(\frac{\hat{s}}{2}-m_V^2\right)+2\underline{g^{(2)}_{hVV}}m_V^2\right)$$

$$-i\underline{g^{(1)}_{hVV}}p_3^{\mu}p_2^{\nu}$$

$$-i\underline{\tilde{g}_{hVV}}\epsilon^{\mu\nu\alpha\beta}p_{2,\alpha}p_{3,\beta}$$

Changes in

total rates and differential information

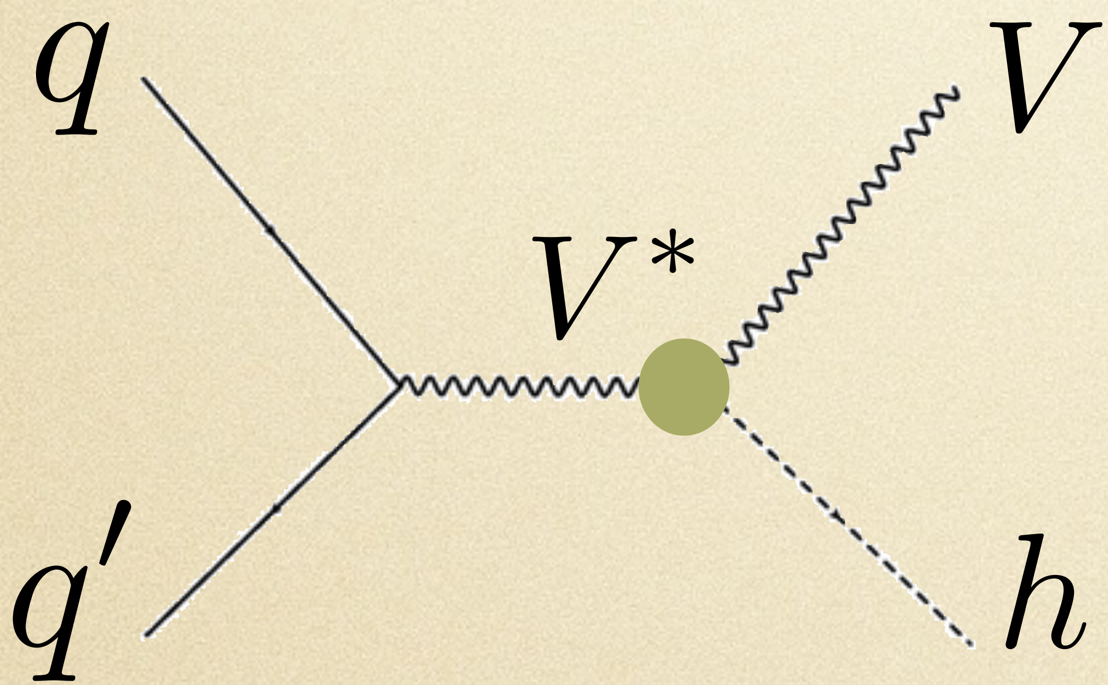
Anomalous couplings vs EFT coefficients

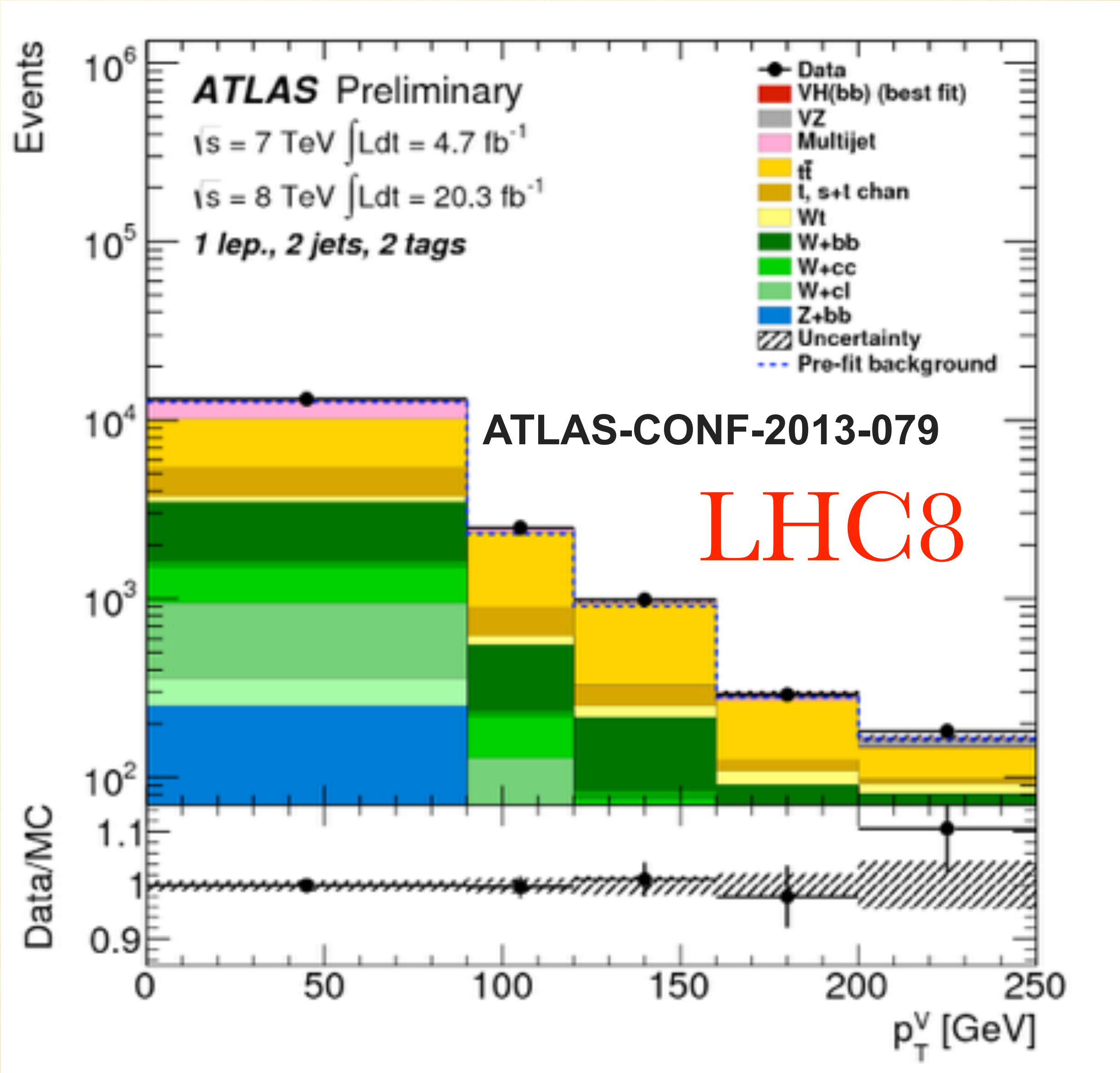
$\mathcal{L}_{3h}$ **Couplings** *vs* $SU(2)_L \times U(1)_Y$ $(D \leq 6)$ **Wilson Coefficients**
$g^{(1)}_{hhh} = 1 + \frac{5}{2}\,\bar{c}_6$, $\quad g^{(2)}_{hhh} = \frac{g}{m_W}\,\bar{c}_H$, $\quad g_{hgg} = g^{\rm SM}_{hgg} - \frac{4\,g_s^2\,v\,\bar{c}_g}{m_W^2}$, $\quad g_{h\gamma\gamma} = g^{\rm SM}_{h\gamma\gamma} - \frac{8\,g\,s_W^2\,\bar{c}_\gamma}{m_W}$
$g^{(1)}_{hww} = \frac{2g}{m_W}\bar{c}_{HW}$, $\quad g^{(1)}_{hzz} = g^{(1)}_{hww} + \frac{2g}{c_W^2\,m_W}\left[\bar{c}_{HB}s_W^2 - 4\bar{c}_\gamma s_W^4\right]$, $\quad g^{(2)}_{hww} = \frac{g}{2\,m_W}\left[\bar{c}_W + \bar{c}_{HW}\right]$
$g^{(2)}_{hzz} = 2\,g^{(2)}_{hww} + \frac{g\,s_W^2}{c_W^2\,m_W}\left[(\bar{c}_B + \bar{c}_{HB})\right]$, $\quad g^{(3)}_{hww} = g\,m_W$, $\quad g^{(3)}_{hzz} = \frac{g^{(3)}_{hww}}{c_W^2}(1 - 2\,\bar{c}_T)$
$g^{(1)}_{haz} = \frac{g\,s_W}{c_W\,m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} + 8\,\bar{c}_\gamma\,s_W^2\right]$, $\quad g^{(2)}_{haz} = \frac{g\,s_W}{c_W\,m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W\right]$

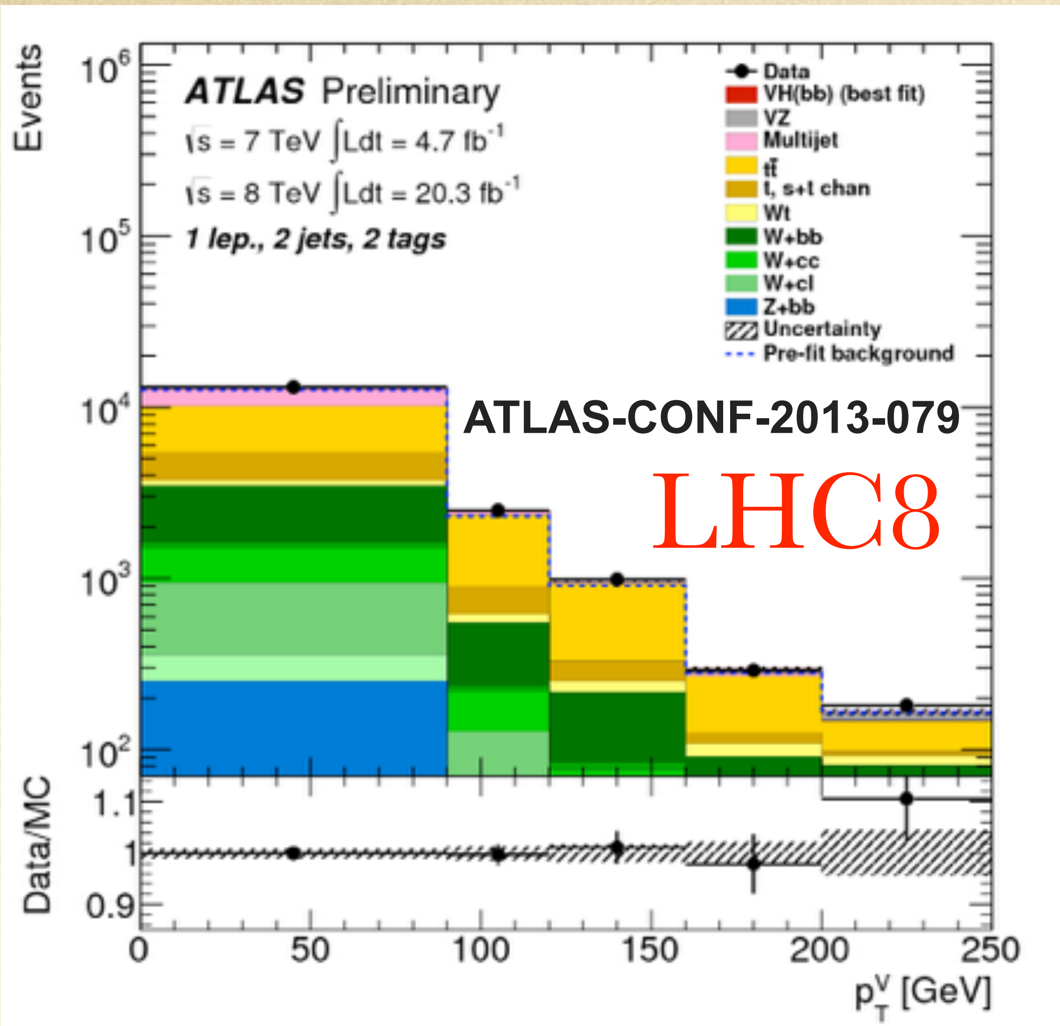
$\mathcal{L}_{3V}$ **Couplings** *vs* $SU(2)_L \times U(1)_Y$ $(D \leq 6)$ **Wilson Coefficients**
$g_1^Z = 1 - \frac{1}{c_W^2}\left[\bar{c}_{HW} - (2s_W^2 - 3)\bar{c}_W\right]$, $\quad \kappa_Z = 1 - \frac{1}{c_W^2}\left[c_W^2\bar{c}_{HW} - s_W^2\bar{c}_{HB} - (2s_W^2 - 3)\bar{c}_W\right]$
$g_1^\gamma = 1$, $\quad \kappa_\gamma = 1 - 2\,\bar{c}_W - \bar{c}_{HW} - \bar{c}_{HB}$, $\quad \lambda_\gamma = \lambda_Z = 3\,g^2\,\bar{c}_{3W}$

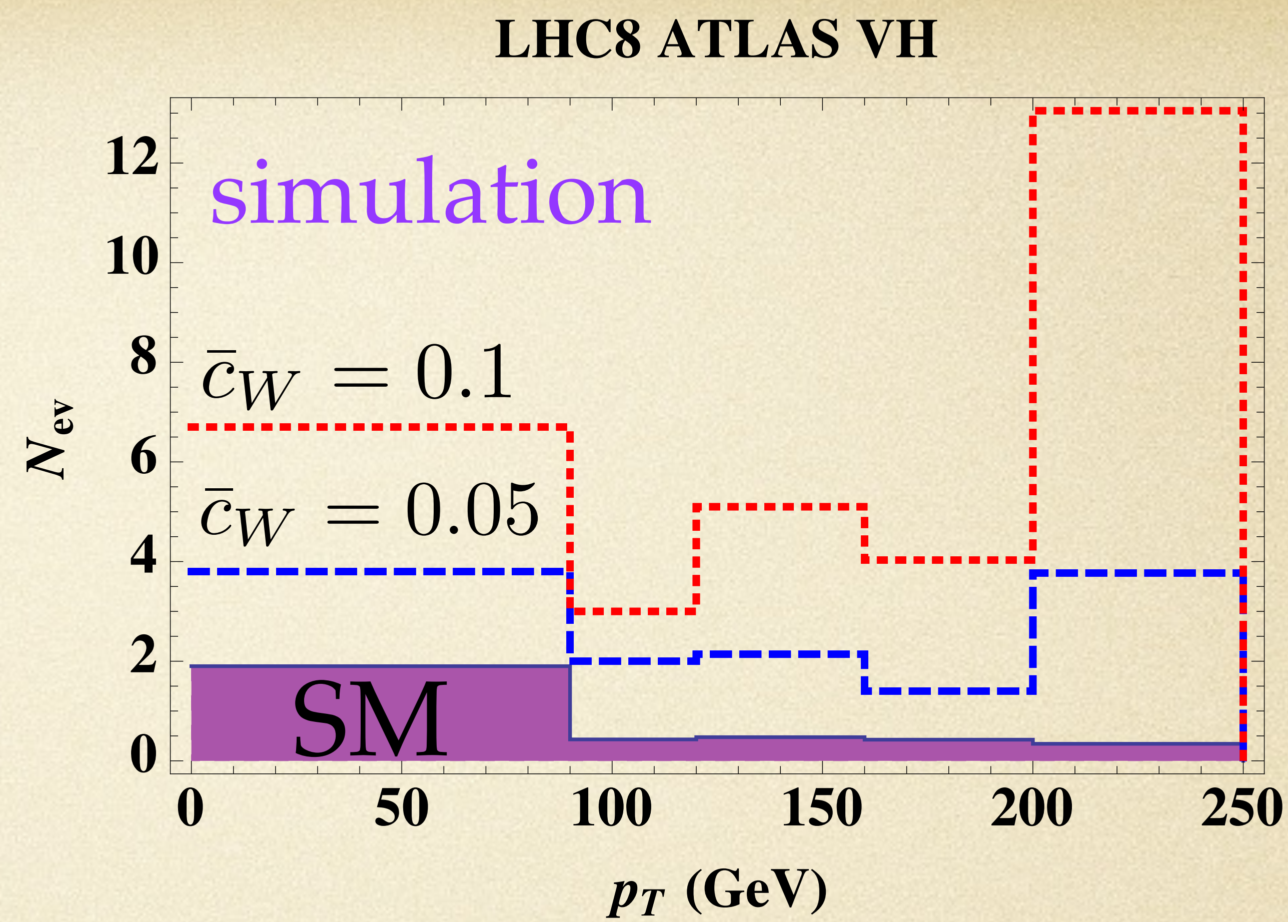
Gorbahn, No, VS. 1502.07352

Differential information:
channels which probe a large kinematic regime
e.g. VH and H+j





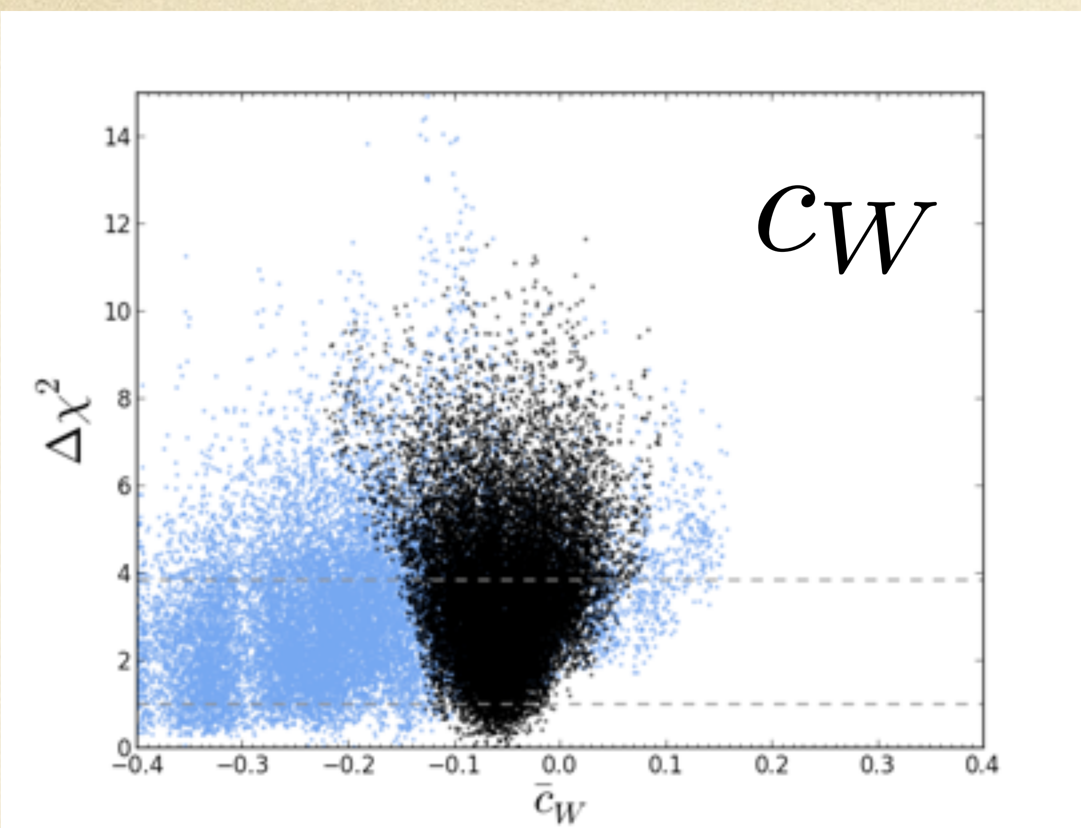




Ellis, VS and You. 1404.3667, 1410.7703

Feynrules -> MG5-> pythia->Delphes3

verified for SM/BGs => expectation for EFT



Global fit

inclusive cross section is less sensitive than distribution

How bad is it?

Run1 constraints

Ellis, VS and You. 1410.7703

one-by-one global

Operator	Coefficient	LHC Constraints Individual	Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W - c_B)$	$(-0.022, 0.004)$	$(-0.035, 0.005)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HW}$	$(-0.042, 0.008)$	$(-0.035, 0.015)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HB}$	$(-0.053, 0.044)$	$(-0.045, 0.075)$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_\mu W^b_{\nu\rho} W^{c\rho\mu}$	$\frac{m_W^2}{\Lambda^2} c_{3W}$	$(-0.083, 0.045)$	$(-0.083, 0.045)$
$\mathcal{O}_g = g_s^2 \|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_g$	$(0, 3.0) \times 10^{-5}$	$(-3.2, 1.1) \times 10^{-4}$
$\mathcal{O}_\gamma = g'^2 \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_\gamma$	$(-4.0, 2.3) \times 10^{-4}$	$(-11, 2.2) \times 10^{-4}$
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \|H\|^2)^2$	$\frac{v^2}{\Lambda^2} c_H$	$(-0.14, 0.194)$	$(-, -)$
$\mathcal{O}_f = y_f \|H\|^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$	$\frac{v^2}{\Lambda^2} c_f$	$(-0.084, 0.155)(c_u)$ $(-0.198, 0.088)(c_d)$	$(-, -)$ $(-, -)$

stronger in classes of models

e.g. extended Higgs sectors

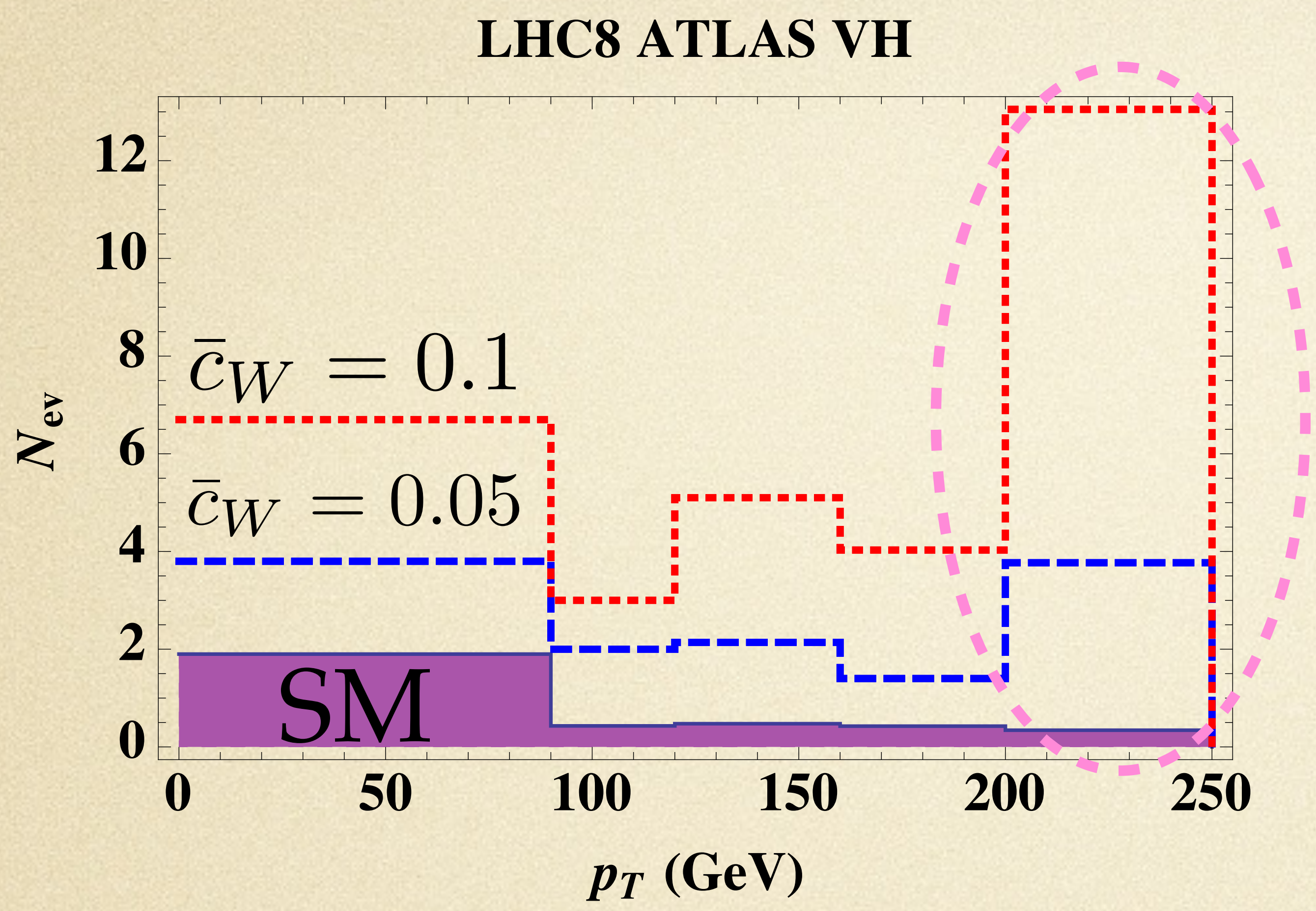
Gorbahn, No, VS. 1502.07352

global

$$\bar{c}_W \in -(0.02, 0.0004)$$
$$\bar{c}_g \in -(0.00004, 0.000003)$$
$$\bar{c}_\gamma \in -(0.0006, -0.00003)$$

Best sensitivity to new physics
exploiting differential information

Challenges for EFTs at Run2



most sensitive bin:
overflow (last) bin

At high-pT
sensitive to dynamics of new physics
breakdown of EFT
To what extent can we use this bin?
how far does it extend?

Generally speaking

Challenges of looking at tails of distributions

1. **Precise determination**
   Higher-order SM and EFT under control

2. **Range of validity**
   Need of benchmarks

Precision, precision

Differential distributions

Better theory calculations,
but also inclusion in a MC generator

depend on cuts
need radiation and detector effects

Simulation tools

theory

$$\mathcal{L}_{eff} = \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$$

→

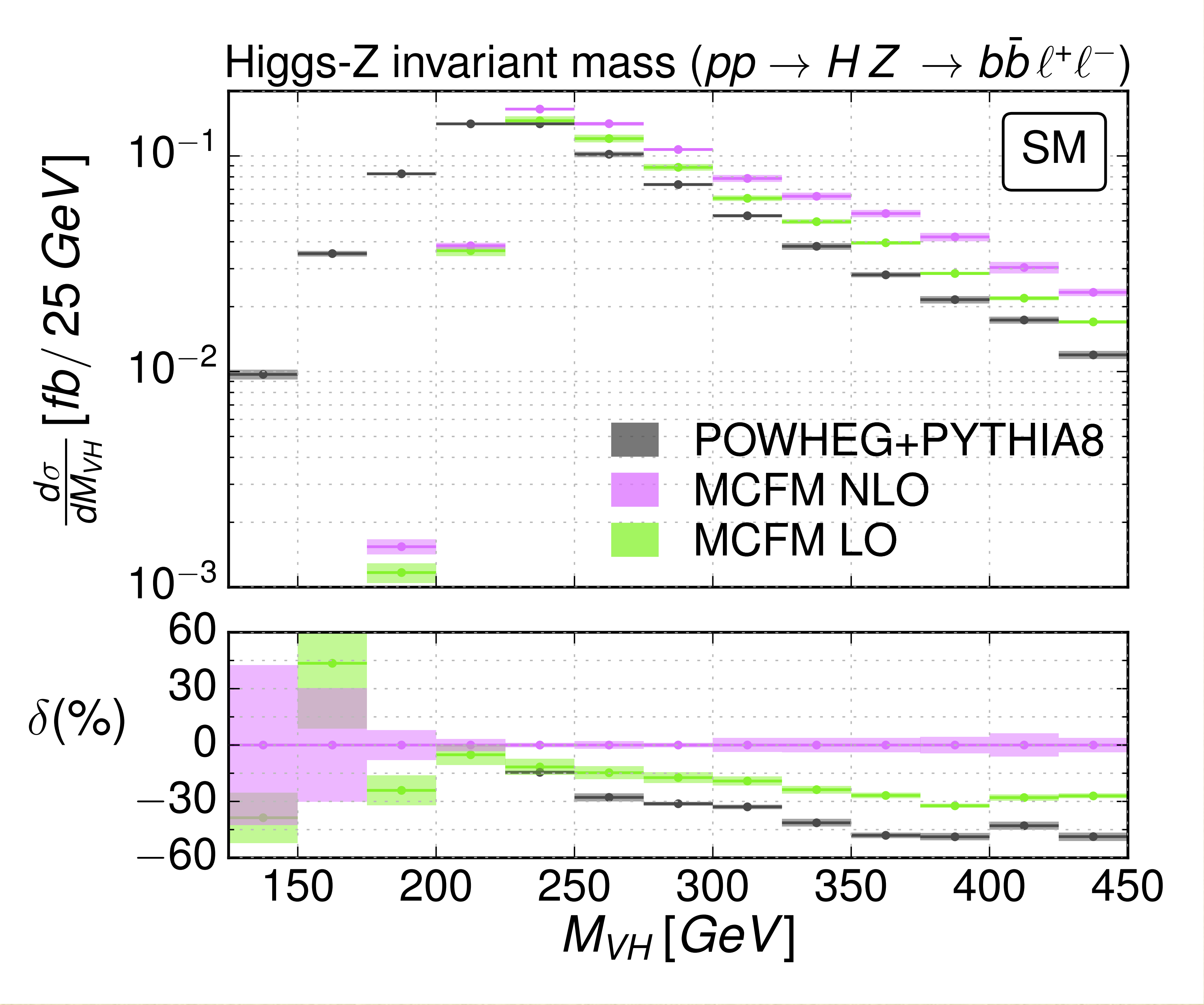
Collider simulation

observables

Limit coefficients
= new physics

example: NLO QCD in VH

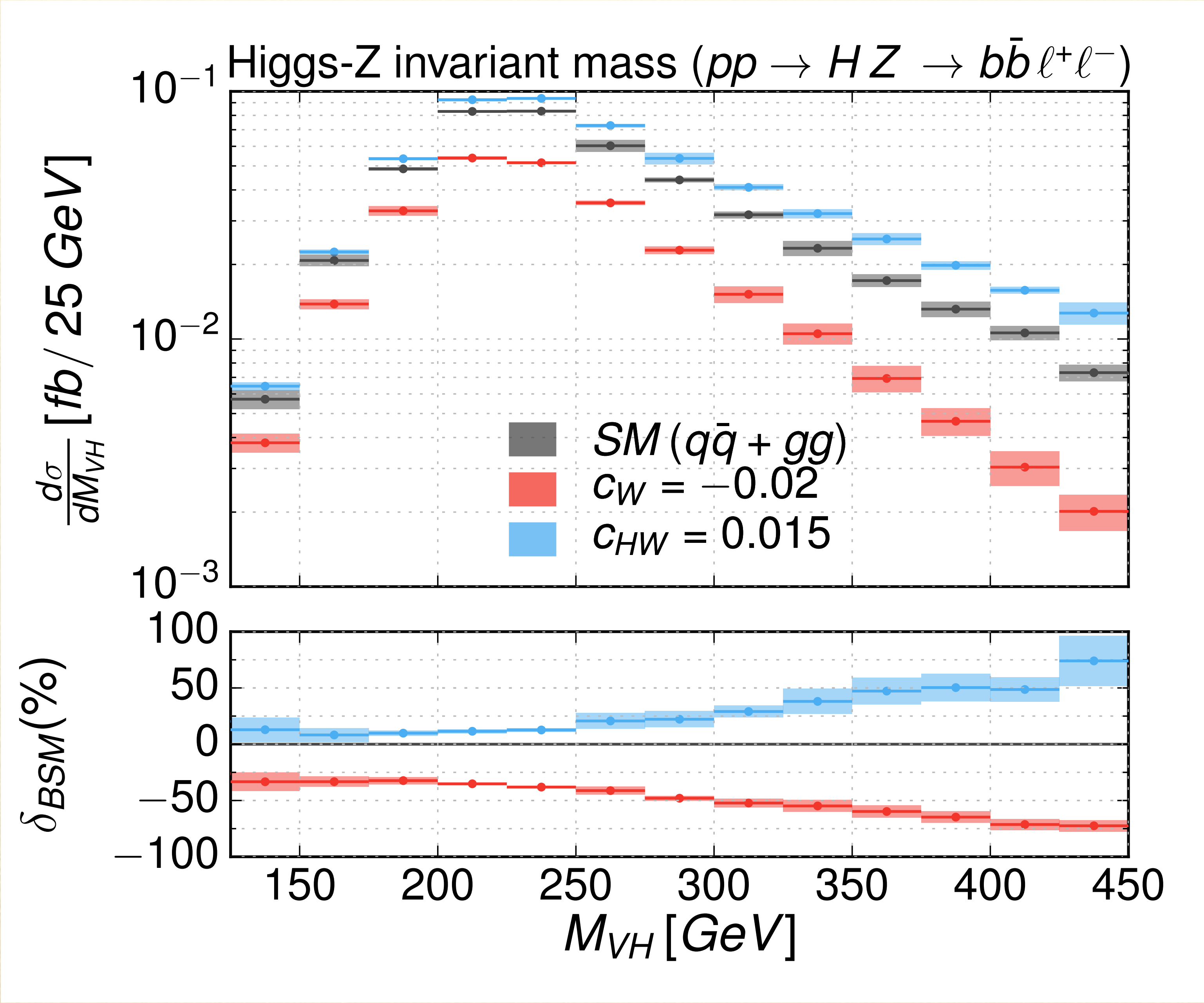
LO vs NLO, showering effects



Mimasu, VS, Williams. in prep

example: NLO QCD in VH

NLO QCD POWHEG+PYTHIA8



Mimasu, VS, Williams. in prep

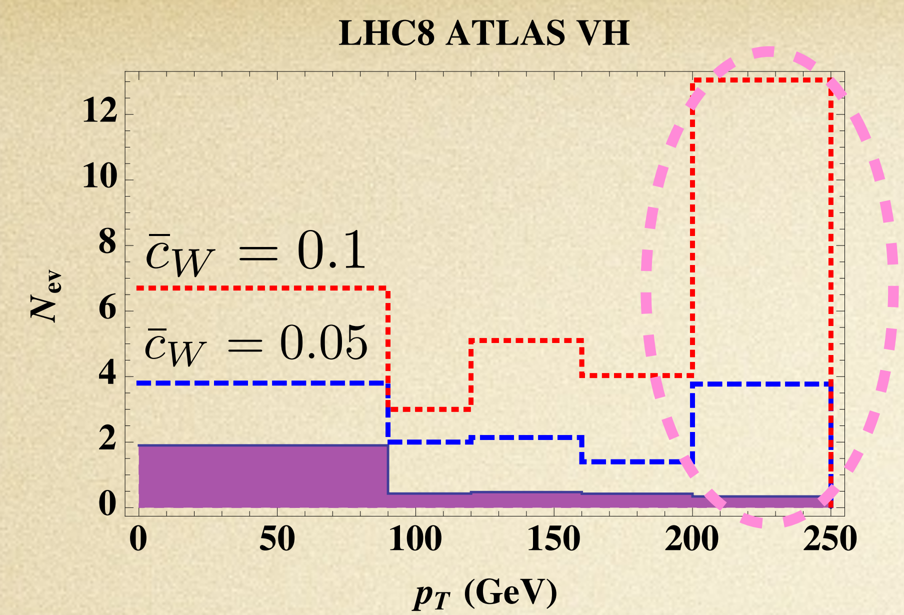
alternative tool in aMC@NLO

deGrande, Fuks, Mawatari, Mimasu, VS. in prep

Matching UV completions to the EFT

Gorbahn, No, VS. 1502.07352

recent paper by Brehmer, Freitas, Lopez-Val , Phlehn. 1510.03443



Where/how does the EFT break down? depends on UV completion

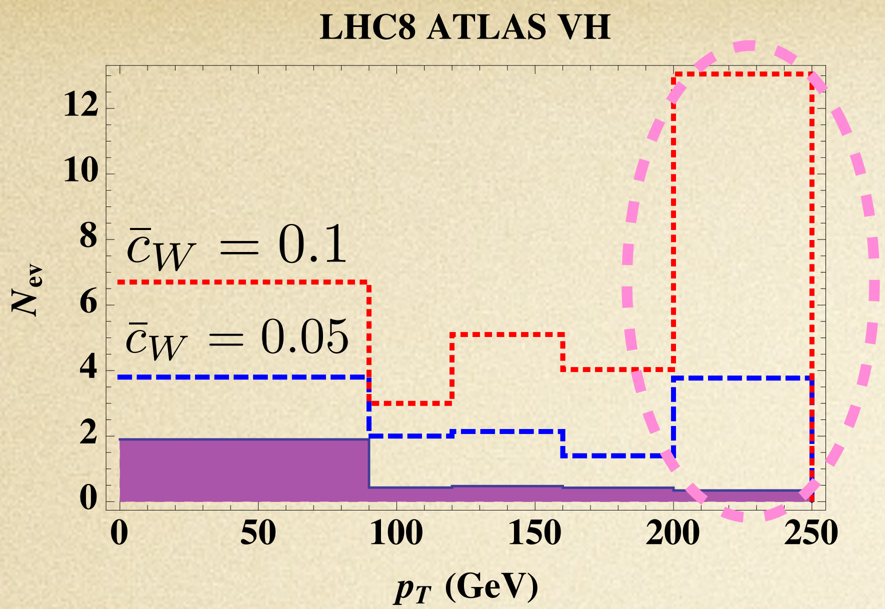
Need benchmarks to test the validity of the approach

Breakdown depends on loop-induced or tree-level

Benchmarks: Extended Higgs sectors

Gorbahn, No, VS. 1502.07352

1. Tree-level mixing: Higgs+Singlet
2. Loop-induced EFT: 2HDMs
3. Tree-level exchange: Radion/Dilaton



Where/how does the EFT break down? depends on UV completion

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Breakdown depends on loop-induced or tree-level

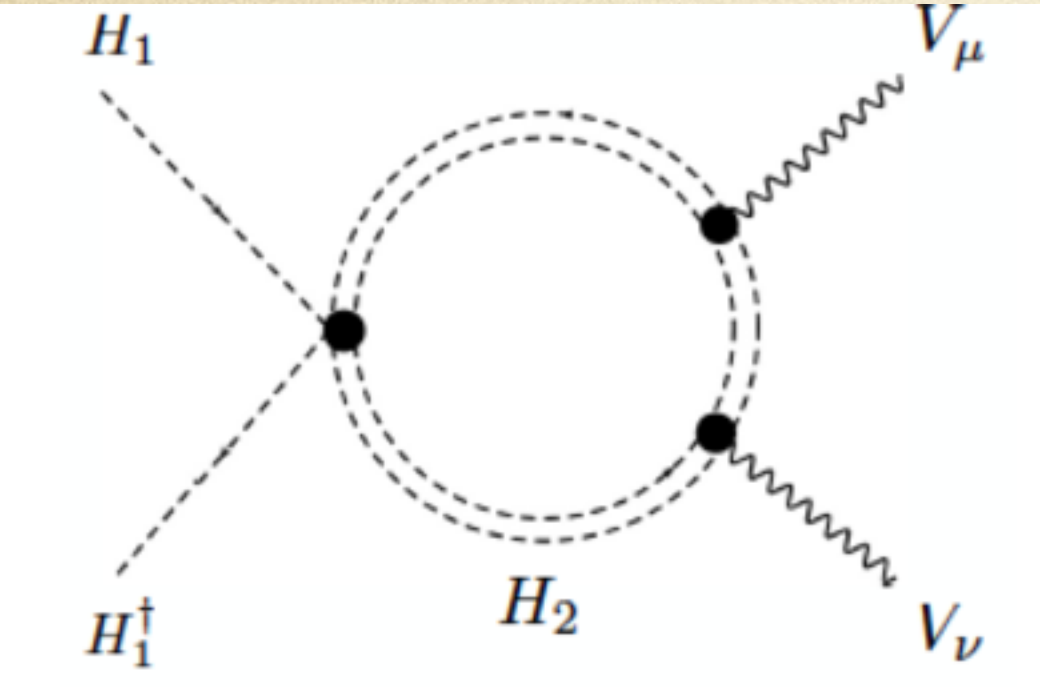
In a nutshell, we did the matching EFT to UV models

	$\bar{c}_H$	$\bar{c}_6$	$\bar{c}_T$	$\bar{c}_W$	$\bar{c}_B$	$\bar{c}_{HW}$	$\bar{c}_{HB}$	$\bar{c}_{3W}$	$\bar{c}_\gamma$	$\bar{c}_g$
Higgs Portal (G)	L	L	X	X	X	X	X	X	X	X
Higgs Portal (Spontaneous $\not{G}$)	T	L	RG	RG	RG	X	X	X	X	X
Higgs Portal (Explicit $\not{G}$)	T	T	RG	RG	RG	X	X	X	X	X
2HDM Benchmark A ($c_{\beta-\alpha} = 0$)	L	L	L	L	L	L	L	L	L	X
2HDM Benchmark B ($c_{\beta-\alpha} \neq 0$)	T	T	L	L	L	L	L	L	L	X
Radion/Dilaton	T	T	RG	T	T	T	T	L	T	T

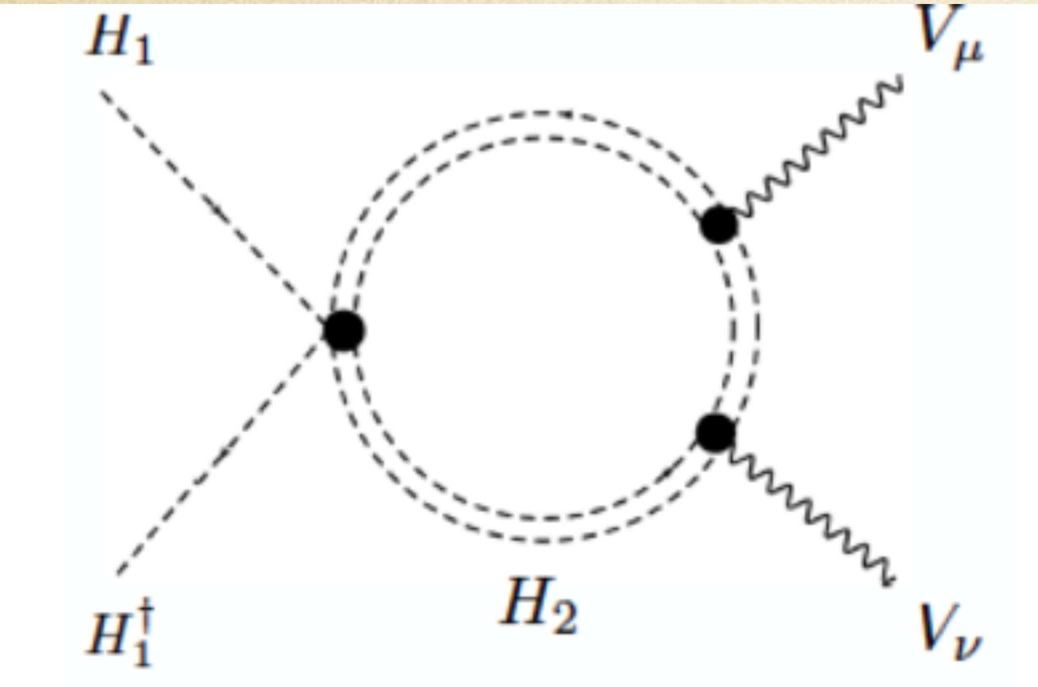
and combined EWPTs, Direct searches and Higgs limits in this framework

50 pages of gory details…

For example, for 2HDM



For example, for 2HDM



checked the results by matching in the broken theory

Matching to EFT: unbroken phase

$$\bar{c}_H = -\left[-4\tilde{\lambda}_3\tilde{\lambda}_4 + \tilde{\lambda}_4^2 + \tilde{\lambda}_5^2 - 4\tilde{\lambda}_3^2\right]\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_6 = -\left(\tilde{\lambda}_4^2 + \tilde{\lambda}_5^2\right)\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_T = (\tilde{\lambda}_4^2 - \tilde{\lambda}_5^2)\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_W = -\bar{c}_{HW} = \frac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = \frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

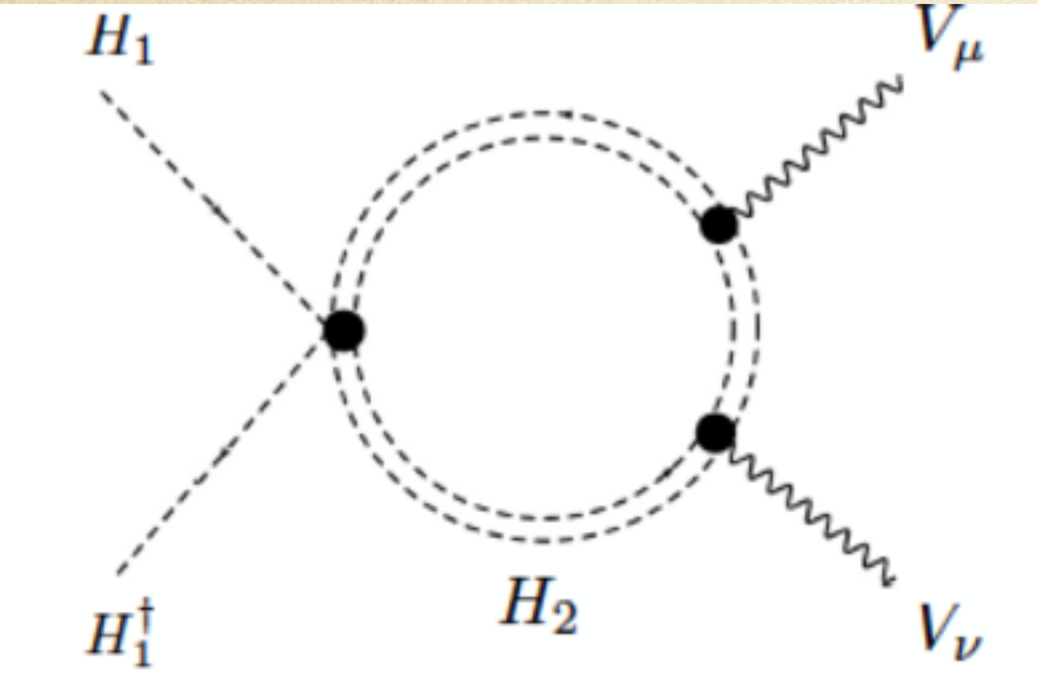
$$\bar{c}_{3W} = \frac{\bar{c}_{2W}}{3} = \frac{m_W^2}{1440\,\pi^2\,\tilde{\mu}_2^2}$$

EWPTs limits

$$\bar{c}_T(m_Z) \simeq \bar{c}_T(\tilde{\mu}_2) - \frac{3\,g'^2}{32\,\pi^2}\,\bar{c}_H(\tilde{\mu}_2)\log\left(\frac{\tilde{\mu}_2}{m_Z}\right)$$

$$\bar{c}_W(m_Z) + \bar{c}_B(m_Z) \simeq c_W(\tilde{\mu}_2) + \bar{c}_B(\tilde{\mu}_2) + \frac{1}{24\,\pi^2}\,\bar{c}_H(\tilde{\mu}_2)\log\left(\frac{\tilde{\mu}_2}{m_Z}\right).$$

For example, for 2HDM



Sensitivity
sizeable quartic couplings
or light particles

Matching to EFT: unbroken phase

$$\bar{c}_H = -\left[-4\tilde{\lambda}_3\tilde{\lambda}_4 + \tilde{\lambda}_4^2 + \tilde{\lambda}_5^2 - 4\tilde{\lambda}_3^2\right] \frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_6 = -\left(\tilde{\lambda}_4^2 + \tilde{\lambda}_5^2\right) \frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_T = (\tilde{\lambda}_4^2 - \tilde{\lambda}_5^2) \frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_W = -\bar{c}_{HW} = \frac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = \frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_{3W} = \frac{\bar{c}_{2W}}{3} = \frac{m_W^2}{1440\,\pi^2\,\tilde{\mu}_2^2}$$

Next step

quantify the EFT breakdown within these benchmarks

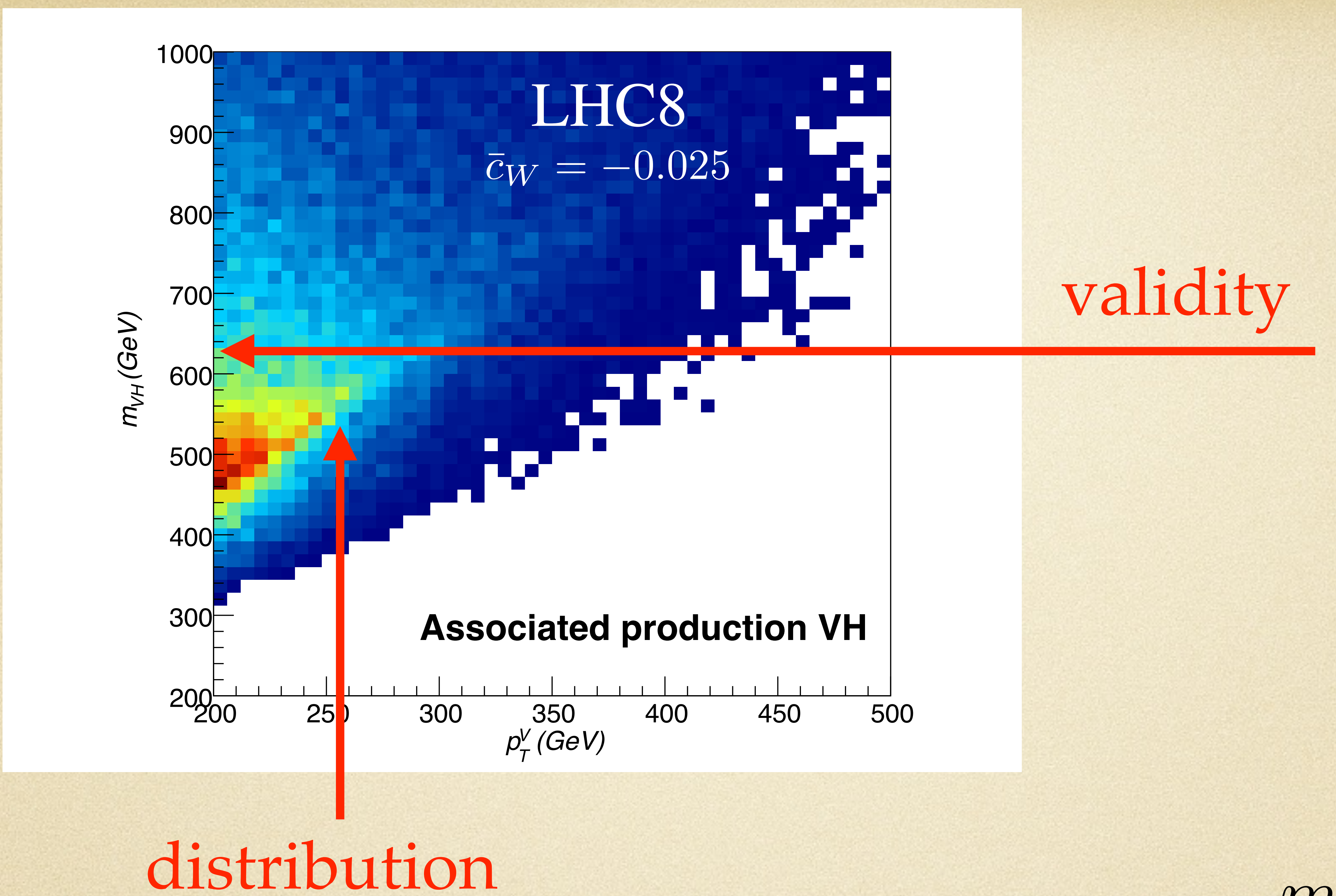
Mimasu, No, VS. in prep. See also, Brehmer, Freitas, Lopez-Val , Phlehn.1510.03443

Conclusion

- Best sensitivity to NP in EFTs requires handling differential distributions
- Challenges: Precision and breakdown
- Precision: push understanding of SM and EFTs at higher orders, implementation in tools for simulations
- Breakdown: model-dependent question. Propose benchmarks, matching between EFT and UV models, include them in tools (e.g. loop-induced requires form-factors), quantify differences

In the Higgs basis

$$V_{\text{tree}}(H_1, H_2) = \tilde{\mu}_1^2 |H_1|^2 + \tilde{\mu}_2^2 |H_2|^2 - \tilde{\mu}^2 \left[H_1^\dagger H_2 + \text{H.c.} \right] + \frac{\tilde{\lambda}_1}{2} |H_1|^4$$
$$+ \frac{\tilde{\lambda}_2}{2} |H_2|^4 + \tilde{\lambda}_3 |H_1|^2 |H_2|^2 + \tilde{\lambda}_4 \left| H_1^\dagger H_2 \right|^2 + \frac{\tilde{\lambda}_5}{2} \left[\left(H_1^\dagger H_2 \right)^2 + \text{H.c.} \right]$$
$$+ \tilde{\lambda}_6 \left[|H_1|^2 H_1^\dagger H_2 + \text{H.c.} \right] + \tilde{\lambda}_7 \left[|H_2|^2 H_1^\dagger H_2 + \text{H.c.} \right]$$



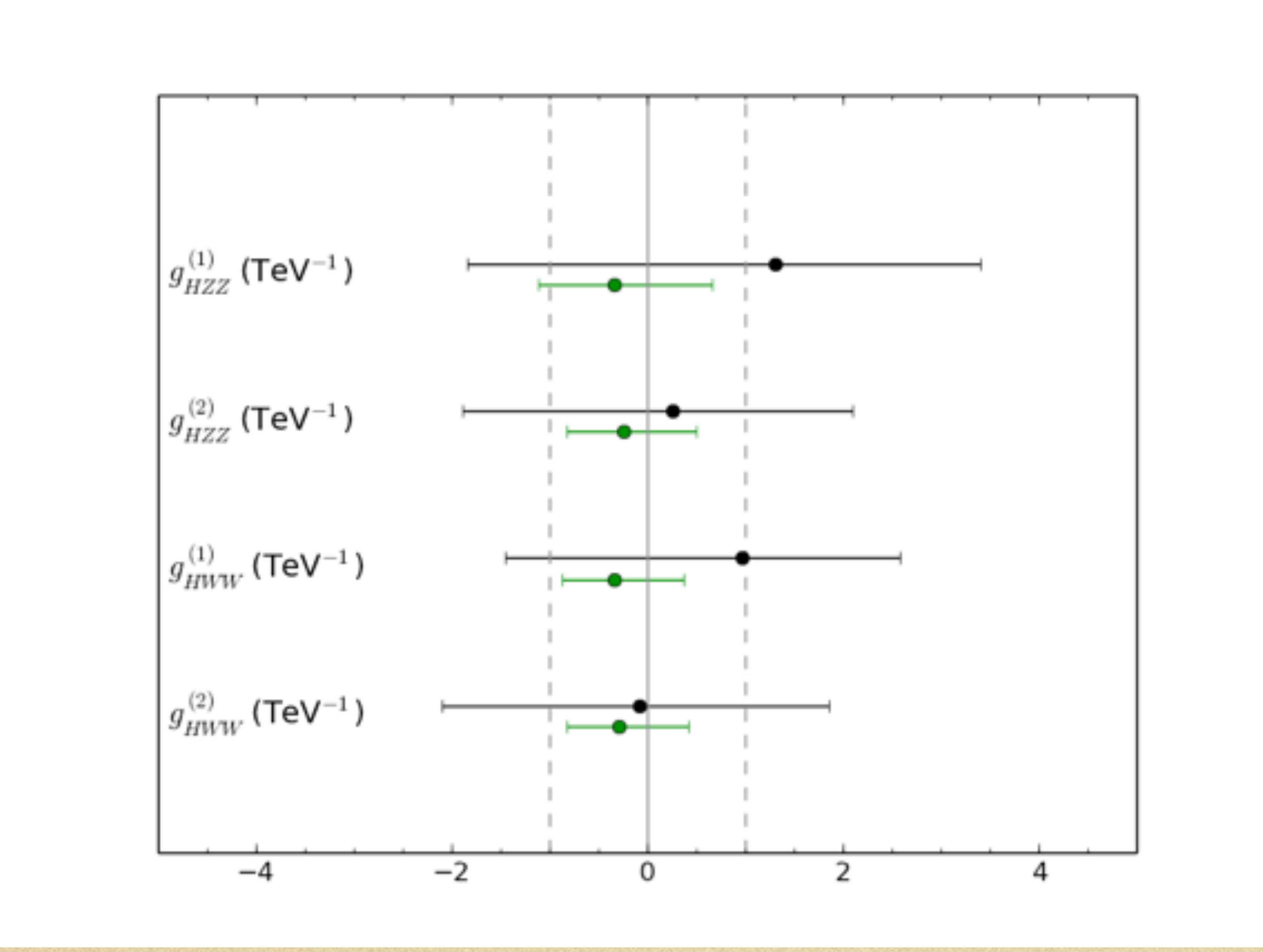
$$\sqrt{c} = g_{NP} \frac{m_W}{\Lambda_{NP}}$$

$$\Lambda_{NP} \simeq g_{NP} (\ 0.5 \ \text{TeV} \ )$$

Ellis, VS, You. 1404.3667

In terms of Higgs' anomalous couplings

$$\mathcal{L} \supset -\frac{1}{4} g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu\nu} h - g^{(2)}_{HZZ} Z_\nu \partial_\mu Z^{\mu\nu} h$$
$$-\frac{1}{2} g^{(1)}_{HWW} W^{\mu\nu} W^\dagger_{\mu\nu} h - \left[g^{(2)}_{HWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.} \right],$$



black global fit
green one-by-one fit