Direct EFT approach

Veronica Sanz (Sussex)

EFT approach

Well-defined theoretical approach (Manohar's talk)
Assumes New Physics states are heavy
Write Effective Lagrangian with only light (SM) particles
BSM effects can be incorporated as a momentum expansion

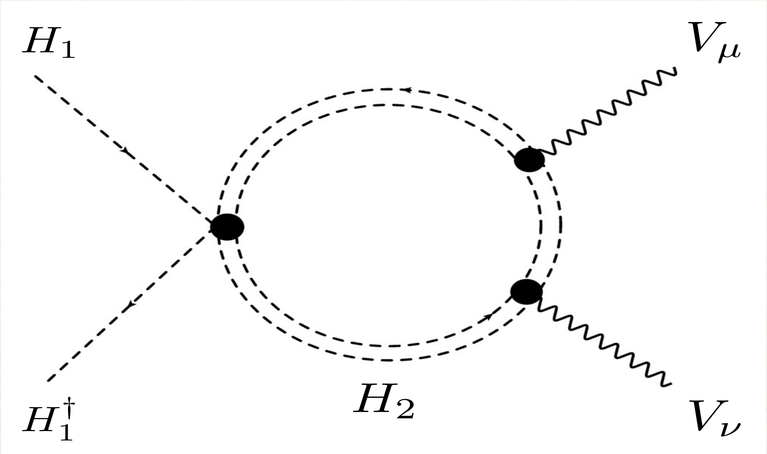
dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\, \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\, \mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles

example:

2HDM



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

where $\bar{c}_W = \dfrac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$

EFT approach

THEORY

Model-independent parametrization deformations respect to the SM

Well-defined theory
can be improved order by order in momentum expansion
consistent addition of higher-order QCD and EW corrections

Connection to models is straightforward

EXPERIMENT

Beyond kappa-formalism: Allows for a richer and generic set of kinematic features

Higher-order precision in QCD/EW

The way to combine all Higgs channels and EW production (Dawson's talk)

Beyond the kappa formalism

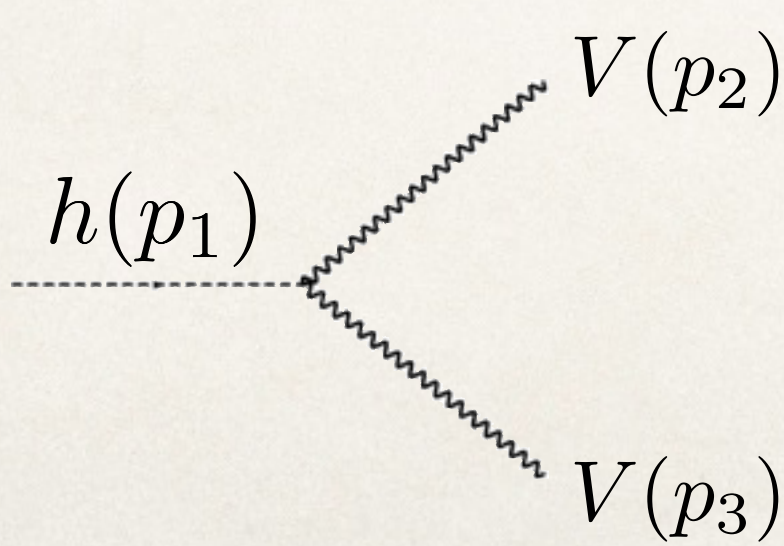
Kappa-formalism is useful when new physics effects are *very simple*

Just change the overall rates

squarks EWinos $(\kappa_\gamma, \kappa_g)$	non-linear, CHM singlet mixing (κ_f, κ_V)

Models offer richer kinematics, and EFT approach captures them

$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu} \quad -h\, g^{(2)}_{hVV} V_\nu \partial_\mu V^{\mu\nu} \quad -\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$



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

$$-i g^{(1)}_{hVV} p_3^\mu p_2^\nu \quad -i\tilde{g}_{hVV} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

+ *off-shell pieces*

Beyond the kappa formalism

Besides EFT, there are other ways to improve upon the kappa-formalism

Higgs characterization	Pseudo-observables
Maltoni et al	*Isidori et al*
Higgs anomalous couplings defined at Lagrangian level	Generic Lorentz structures defined at the amplitude level
Generic Lorentz structures consistent with U(1)	momentum expansion around poles (Gino's talk)

These approaches are related to each other

EFT : AC : PO

We have mappings among them

channel by channel

EFT vs others

Disclaimer: I don't advocate for EFTs as the *only* way to interpret data each approach has pros and cons (Gino's talk, HC authors)

<u>Advantages of EFTs</u>

Clear pathway to achieve

- **Combination**: LHC Higgs and EW production, low energy, EWPTs
- **Precision:** higher-order EW and QCD, dimension-eight, validity EFT
- **Consistency:** Backgrounds and signal
- **Matching:** Direct connection to models

examples to follow →

Combination of data

Global analyses using EFTs

EFTs induce effects in many channels

ideal framework for combination

$\mathcal{L}_{3h}$ Couplings *vs* $SU(2)_L \times U(1)_Y$ ($D \leq 6$) Wilson Coefficients

$$g^{(1)}_{hhh} = 1 + \frac{5}{2}\,\bar{c}_6 \,, \quad g^{(2)}_{hhh} = \frac{g}{m_W}\,\bar{c}_H \,, \quad g_{hgg} = g^{\rm SM}_{hgg} - \frac{4\,g_s^2\,v\,\bar{c}_g}{m_W^2} \,, \quad g_{h\gamma\gamma} = g^{\rm SM}_{h\gamma\gamma} - \frac{8\,g\,s_W^2\,\bar{c}_\gamma}{m_W}$$

$$g^{(1)}_{hww} = \frac{2g}{m_W}\bar{c}_{HW} \,, \quad g^{(1)}_{hzz} = g^{(1)}_{hww} + \frac{2g}{c_W^2 m_W}\Big[\bar{c}_{HB} s_W^2 - 4\bar{c}_\gamma s_W^4\Big] \,, \quad g^{(2)}_{hww} = \frac{g}{2\,m_W}\Big[\bar{c}_W + \bar{c}_{HW}\Big]$$

$$g^{(2)}_{hzz} = 2\,g^{(2)}_{hww} + \frac{g\,s_W^2}{c_W^2 m_W}\Big[(\bar{c}_B + \bar{c}_{HB})\Big] \,, \quad g^{(3)}_{hww} = g\,m_W \,, \quad g^{(3)}_{hzz} = \frac{g^{(3)}_{hww}}{c_W^2}(1 - 2\,\bar{c}_T)$$

$$g^{(1)}_{haz} = \frac{g\,s_W}{c_W\,m_W}\Big[\bar{c}_{HW} - \bar{c}_{HB} + 8\,\bar{c}_\gamma\,s_W^2\Big] \,, \quad g^{(2)}_{haz} = \frac{g\,s_W}{c_W\,m_W}\Big[\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W\Big]$$

$\mathcal{L}_{4h}$ Couplings *vs* $SU(2)_L \times U(1)_Y$ ($D \leq 6$) Wilson Coefficients

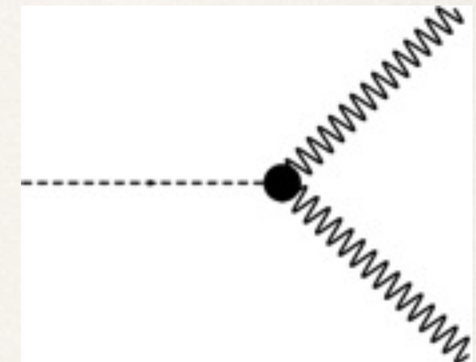
$$g^{(1)}_{hhhh} = 1 + \frac{15}{2}\,\bar{c}_6 \,, \quad g^{(2)}_{hhhh} = \frac{g^2}{4\,m_W^2}\,\bar{c}_H \,, \quad g_{hhgg} = -\frac{4\,g_s^2\,\bar{c}_g}{m_W^2} \,, \quad g_{hh\gamma\gamma} = -\frac{4\,g^2\,s_W^2\,\bar{c}_\gamma}{m_W^2}$$

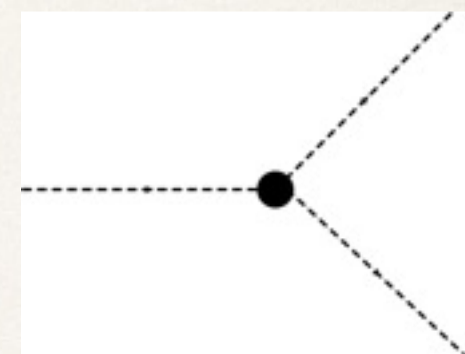
$$g^{(1,2)}_{hhxy} = \frac{g}{2\,m_W}\,g^{(1,2)}_{hxy} \quad (x, y = W, Z, \gamma) \,, \quad g^{(3)}_{hhww} = \frac{g^2}{2} \,, \quad g^{(3)}_{hhzz} = \frac{g^{(3)}_{hhww}}{c_W^2}(1 - 6\,\bar{c}_T)$$

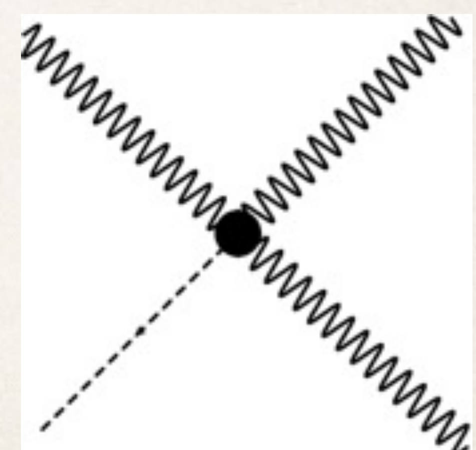
$$g^{(1)}_{haww} = \frac{g^2\,s_W}{m_W}\Big[2\,\bar{c}_W + \bar{c}_{HW} + \bar{c}_{HB}\Big] \,, \quad g^{(1)}_{hzww} = \frac{g^2}{c_W\,m_W}\Big[c_W^2\,\bar{c}_{HW} - s_W^2\bar{c}_{HB} + (3 - 2s_W^2)\,\bar{c}_W\Big]$$

$$g^{(2)}_{haww} = \frac{2\,g^2\,s_W}{m_W}\,\bar{c}_W \,, \quad g^{(2)}_{hzww} = \frac{g^2}{c_W\,m_W}\Big[\bar{c}_{HW} + (3 - 2s_W^2)\,\bar{c}_W\Big]$$

$$g^{(3)}_{haww} = \frac{g^2\,s_W}{m_W}\Big[\bar{c}_W + \bar{c}_{HW}\Big] \,, \quad g^{(3)}_{hzww} = \frac{s_W}{c_W}\,g^{(3)}_{haww}$$







Alloul, Fuks, VS. 1310.5150
Gorbahn, No, VS. 1502.07352

Global analyses using EFTs

EFTs induce effects in many channels
ideal framework for combination

TGCs, QGCs

$\mathcal{L}_{3V}$ **Couplings** *vs* $SU(2)_L \times U(1)_Y$ $(D \leq 6)$ **Wilson Coefficients**

$$g_1^Z = 1 - \frac{1}{c_W^2}\Big[\bar{c}_{HW} - (2s_W^2 - 3)\bar{c}_W\Big] \;, \quad \kappa_Z = 1 - \frac{1}{c_W^2}\Big[c_W^2\bar{c}_{HW} - s_W^2\bar{c}_{HB} - (2s_W^2 - 3)\bar{c}_W\Big]$$

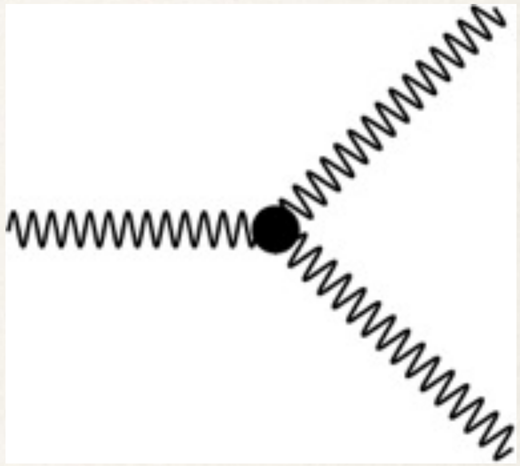
$$g_1^\gamma = 1 \;, \quad \kappa_\gamma = 1 - 2\,\bar{c}_W - \bar{c}_{HW} - \bar{c}_{HB} \;, \quad \lambda_\gamma = \lambda_Z = 3\,g^2\,\bar{c}_{3W}$$

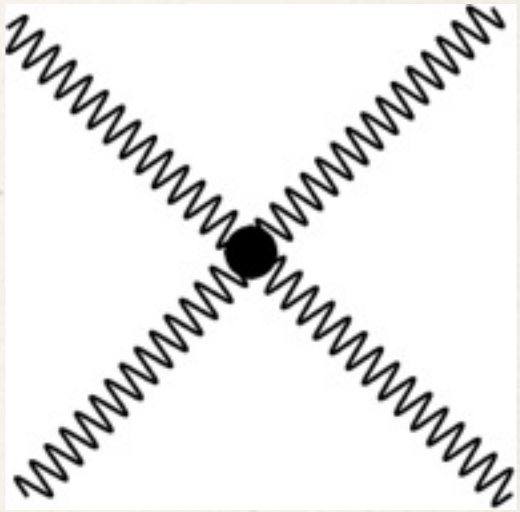
$\mathcal{L}_{4V}$ **Couplings** *vs* $SU(2)_L \times U(1)_Y$ $(D \leq 6)$ **Wilson Coefficients**

$$g_2^W = 1 - 2\,\bar{c}_{HW} - 4\,\bar{c}_W \;, \quad g_2^Z = 1 - \frac{1}{c_W^2}\Big[2\,\bar{c}_{HW} + 2\,(2 - s_W^2)\,\bar{c}_W\Big]$$

$$g_2^\gamma = 1 \;, \quad g_2^{\gamma Z} = 1 - \frac{1}{c_W^2}\Big[\bar{c}_{HW} + (3 - 2s_W^2)\,\bar{c}_W\Big]$$

$$\lambda_W = \lambda_{\gamma W} = \lambda_{\gamma Z} = \lambda_{WZ} = 6\,g^2\,\bar{c}_{3W}$$

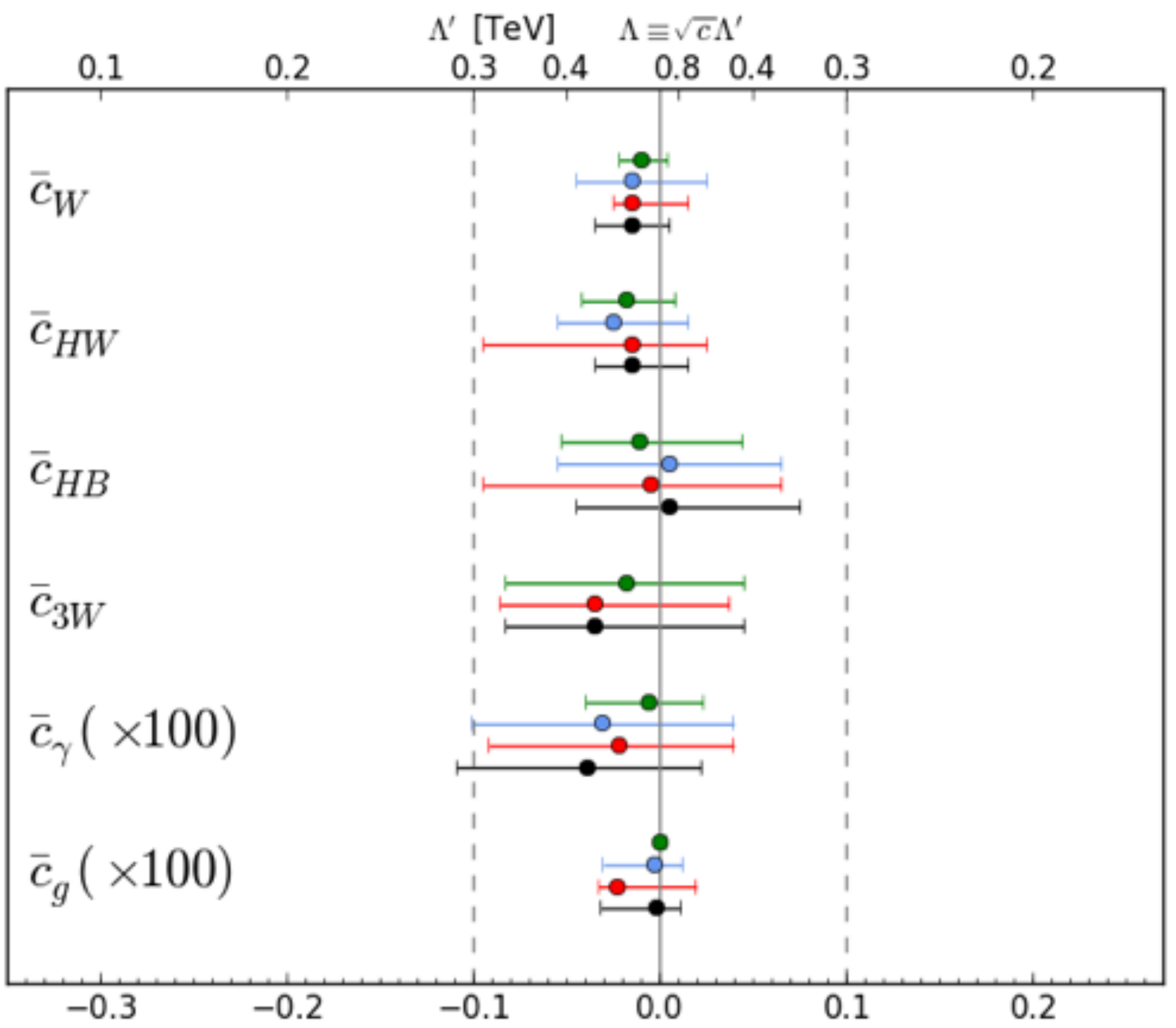




ALLOUL, FUKS, VS. 1310.5150
GORBAHN, NO, VS. 1502.07352

Global analyses using EFTs

Although the EFT has many parameters, the LHC is sensitive to a handful of them



Example: Global fit in

ELLIS, VS, YOU. 1410.0773

LEP and LHC Run1 data

(Dawson's talk, Plehn et al)

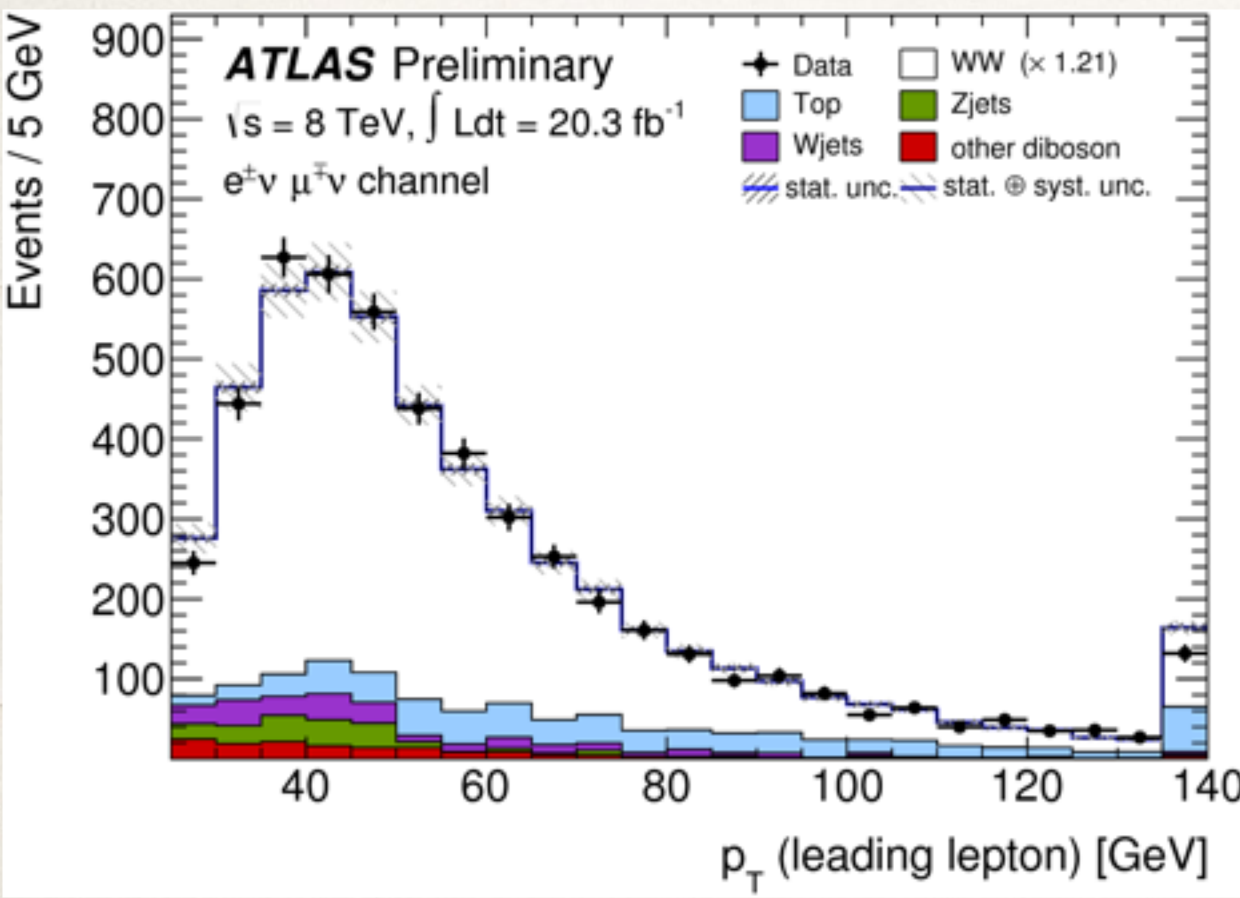
green: one-by-one

black: global fit

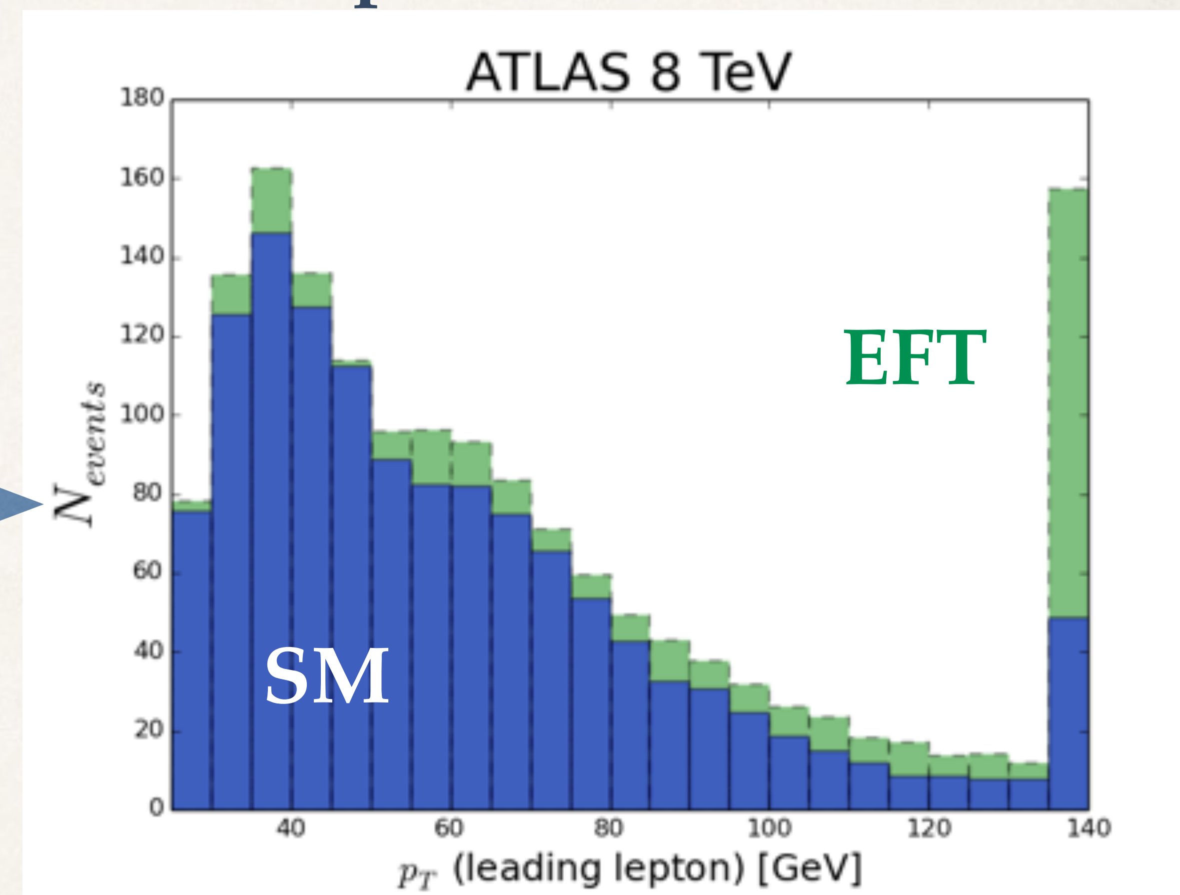
Global analyses using EFTs

sensitivity relies on combination of channels and on use of differential information

WW production



Dependence on EFT



Feynrules -> MG5-> pythia->Delphes3

verified for SM/BGs => expectation for EFT

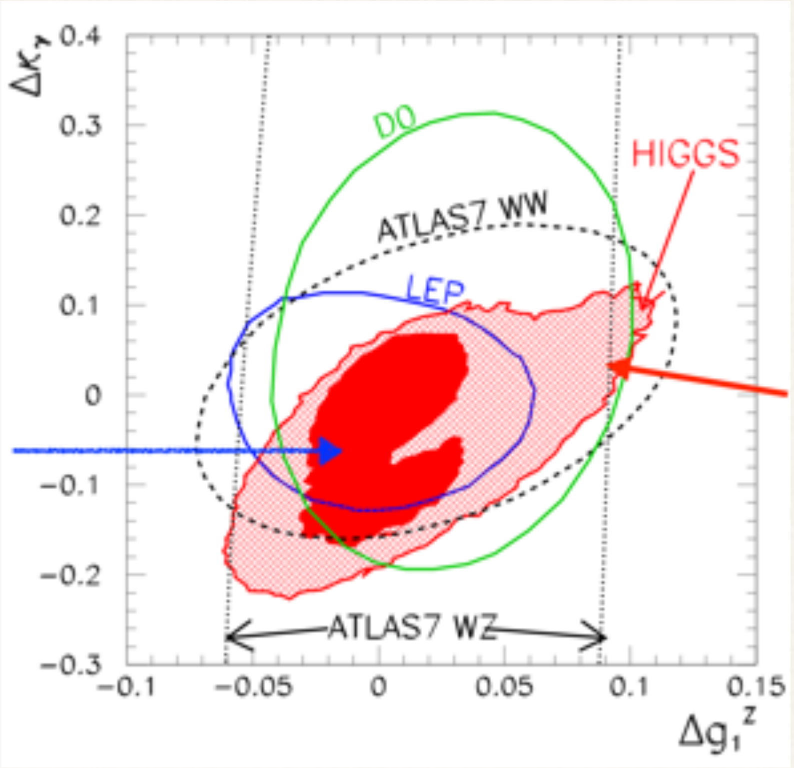
we (theorists) cannot push this program further without help from the experiments

Global analyses using EFTs

more on differential information

EBOLI, GONZALEZ-GARCIA, PLEHN ET AL. 1604.03105, …

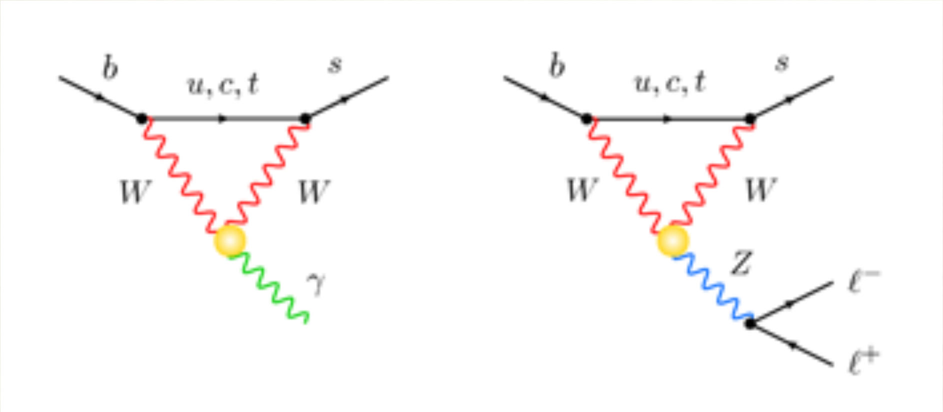
differential information

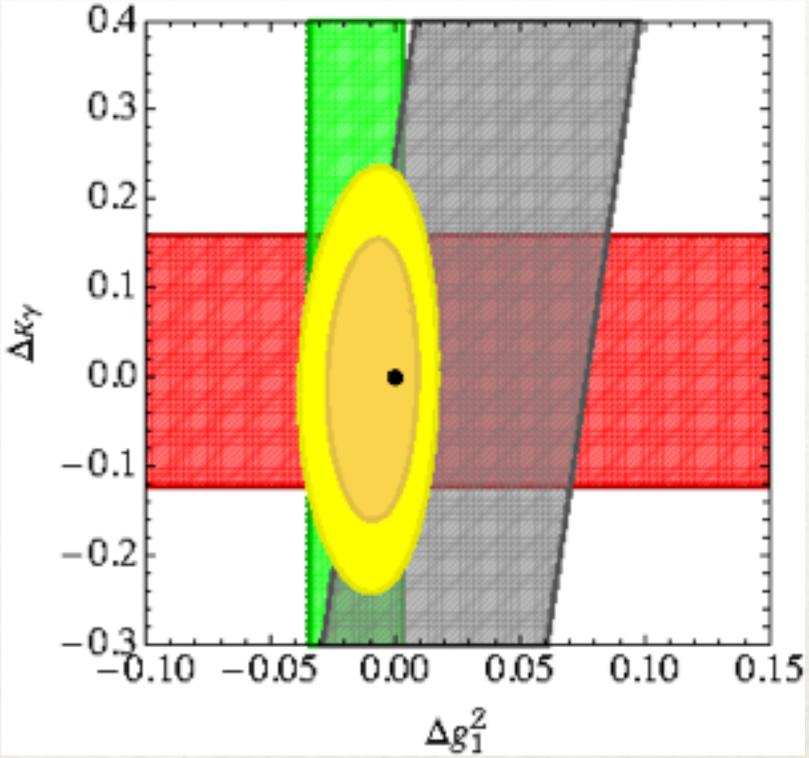


just rate

link to low-energy

BOBETH, HAISCH. 1410.0773





$$B \to X_s \gamma$$

$$Z \to b\bar{b}$$

$$B \to \mu^+ \mu^-$$

Precision

Precision

Within the EFT approach

- incorporate higher-order QCD and EW effects
- higher-order EFT effects (dimension-8)
- check validity of the approach

Need to exploit differential information
simulate cuts and detector effects in analysis
MC tools should match the level of SM BGs

slowly we are starting to incorporate the EFT at QCD NLO

Monte Carlo EFT@NLO QCD

At LO there are a handful of EFT implementations, incl SM NLO

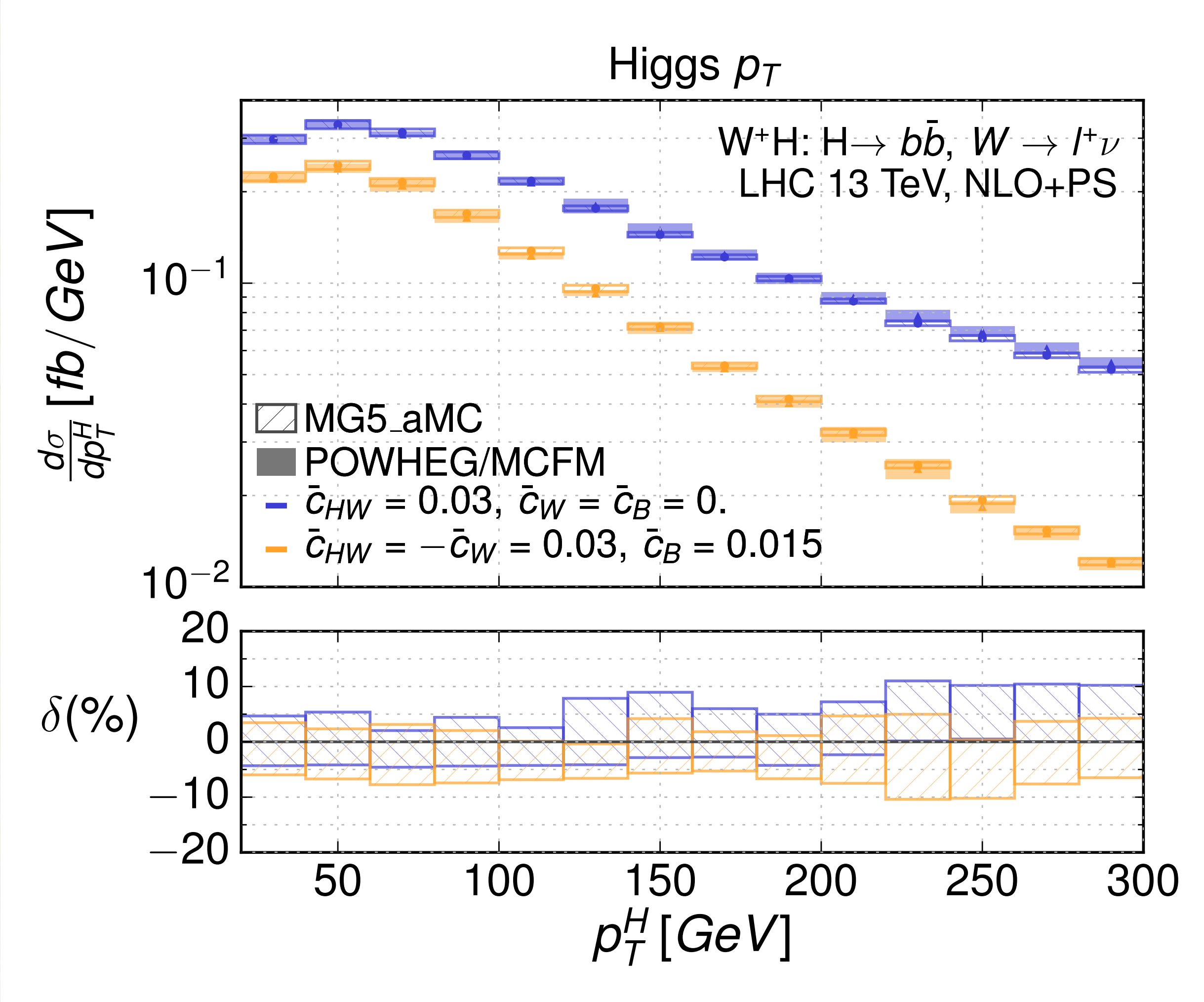
WHIZARD, JHU, VBFNLO, AMC@NLO, POWHEG

Largest collection of EFT operators in one MC (39 operators)

ALLOUL, FUKS, VS. 1310.5150

written in the SILH basis, we link to *Rosetta* for change of basis

MIMASU ET AL. 1508.05895



we started incorporating QCD NLO EFT effects for a handful of operators

codes are now public

POWHEG-BOX

MIMASU, VS, WILLIAMS. 1512.02572

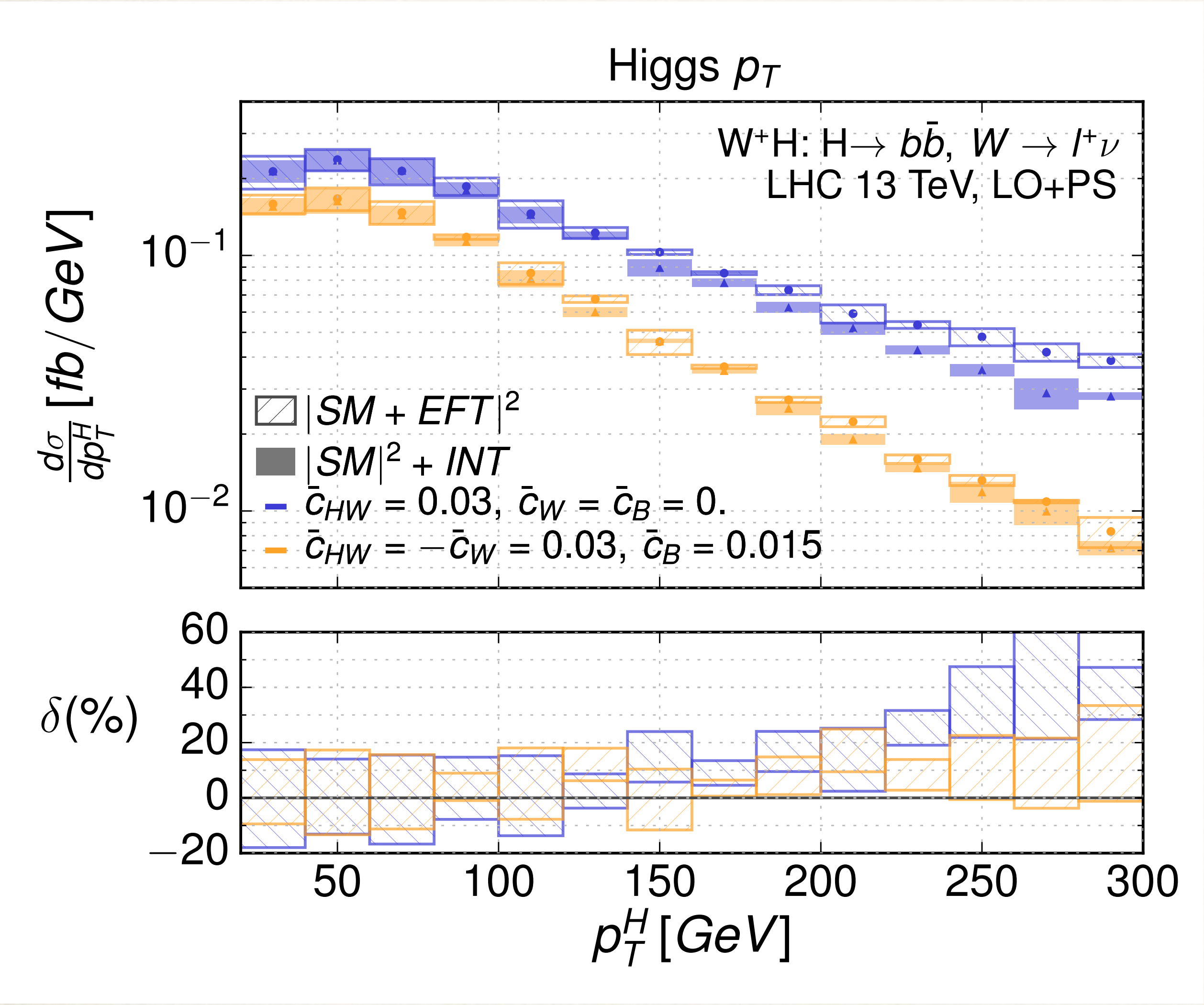
aMC@NLO

DEGRANDE ET AL. 1609.04833

Monte Carlo EFT and validity

The issue of validity of the EFT approach with the use of differential distributions is a hot topic of discussion

(Dawson's talk)



Degrande et al. 1609.04833

EFT momentum expansion can be addressed as a source of systematic error within the MC

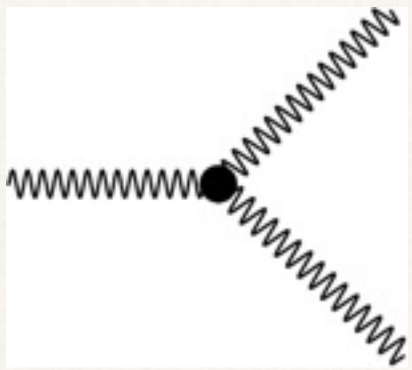
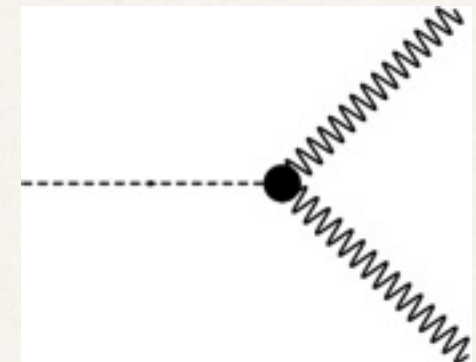
At the level of the distribution we ***propose*** to use the difference between bin content with and without the quadratic terms

Consistency

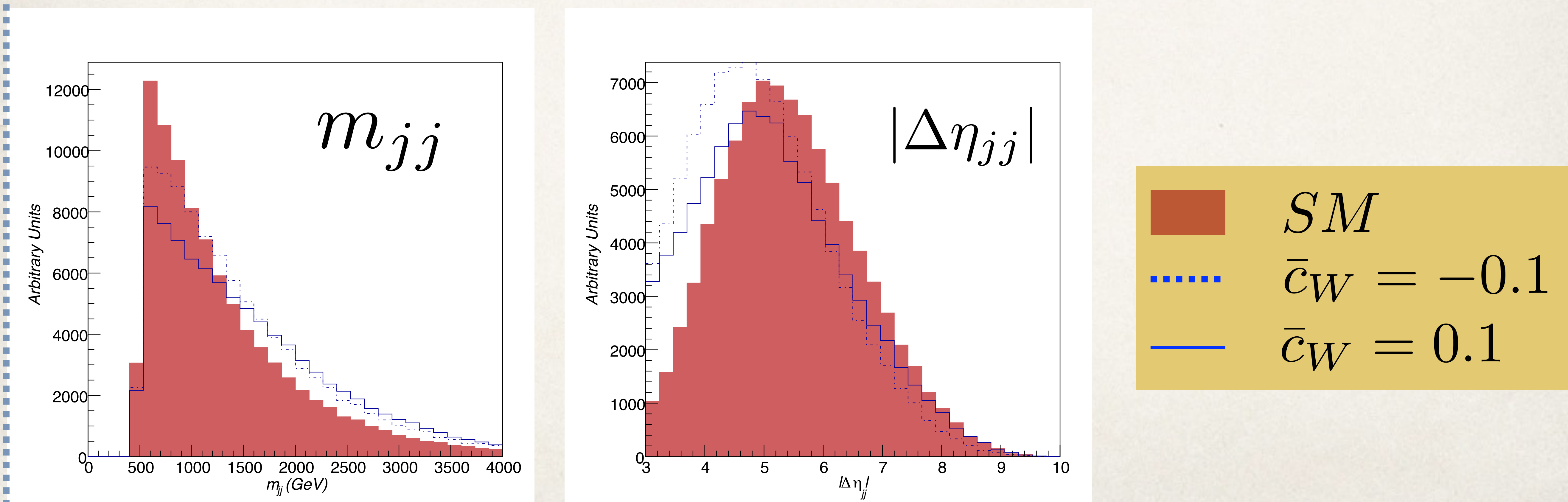
Consistency

With the EFT one can/should ask questions such as

1. Backgrounds and signal may be affected by the same EFT

e.g.  diboson vs Higgs decays 

2. The optimal definition of fiducial regions depends new physics



Matching to models

Matching to UV theories

Within the EFT, connection to models is *straightforward*

EFT

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

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

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

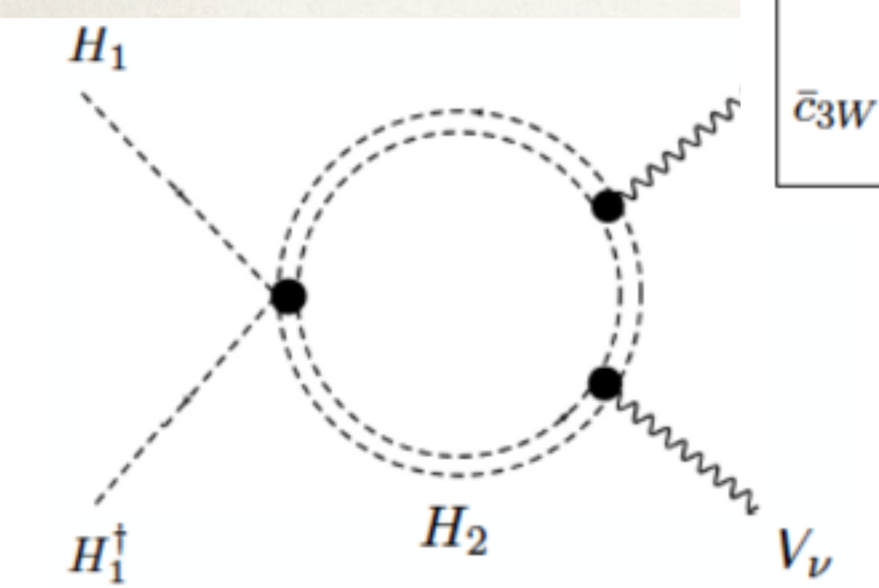
$$\bar{c}_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

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

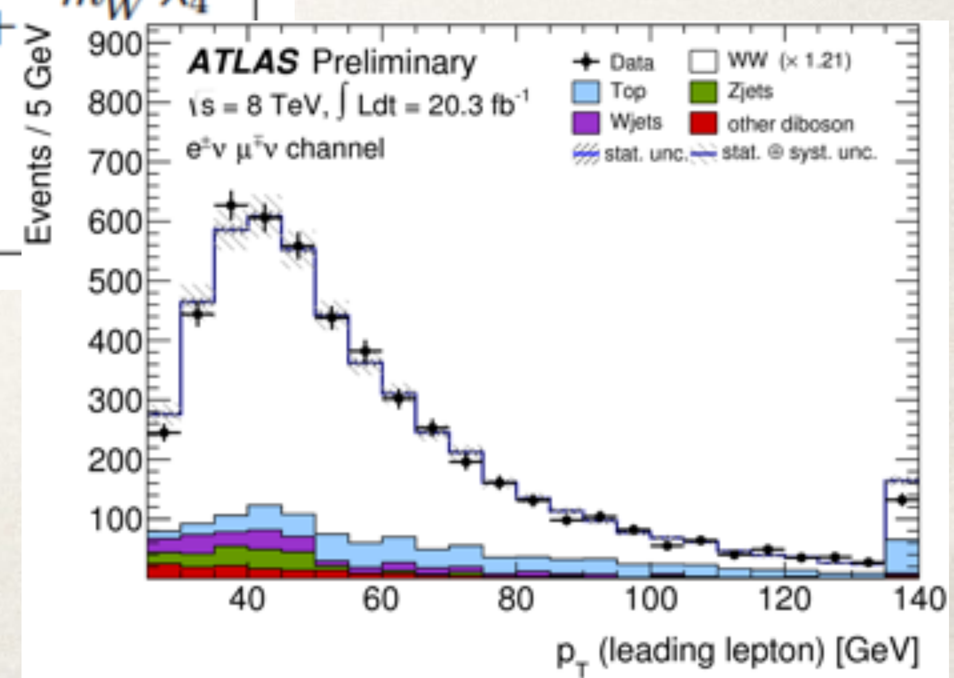
$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\,\bar{c}_\gamma + m_W^2\,\tilde{\lambda}_4$$

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

MODELS



DATA



Conclusions and outlook

- Interpretation of data in terms of EFTs allows to consistently: combine different channels, push precision, test the validity of the approach, incorporate correlations with backgrounds and match to models

- It’s a theorist-friendly procedure, does not substitute the need for releasing public distributions, and does not invalidate other options (PO or others)

- To continue this program we need more experimental involvement. Theorists are developing NLO MC tools to facilitate this communication