EFT at QCD NLO

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HXSWG WG2, July 2016

Outline

- Status of EFT after Run1
- How do we get the best limits (LO)
- Matching with UV models
- Do we need NLO for Run2?
- Tools: current status

Apologies:

Will be focusing on results with own EFT tools

please see also

eHDECAY

VBF@NLO

and in the SILH basis

see *Rosetta* for translation tool

Status of EFT after Run1

where do we stand

LEP constraints

Ellis, VS and You. 1404.3667, 1410.7703

one-by-one global

Operator	Coefficient	LEP Constraints Individual	Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W + c_B)$	$(-0.00055, 0.0005)$	$(-0.0033, 0.0018)$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$\frac{v^2}{\Lambda^2}c_T$	$(0, 0.001)$	$(-0.0043, 0.0033)$
$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L\sigma^a\gamma^\mu L_L)(\bar{L}_L\sigma^a\gamma_\mu L_L)$	$\frac{v^2}{\Lambda^2}c_{LL}^{(3)l}$	$(0, 0.001)$	$(-0.0013, 0.00075)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$	$\frac{v^2}{\Lambda^2}c_R^e$	$(-0.0015, 0.0005)$	$(-0.0018, 0.00025)$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\frac{v^2}{\Lambda^2}c_R^u$	$(-0.0035, 0.005)$	$(-0.011, 0.011)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\frac{v^2}{\Lambda^2}c_R^d$	$(-0.0075, 0.0035)$	$(-0.042, 0.0044)$
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2}c_L^{(3)q}$	$(-0.0005, 0.001)$	$(-0.0044, 0.0044)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2}c_L^q$	$(-0.0015, 0.003)$	$(-0.0019, 0.0069)$

Run1 constraints

Ellis, VS and You. 1404.3667, 1410.7703

one-by-one global

Operator	Coefficient	LHC Constraints Individual	LHC Constraints 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

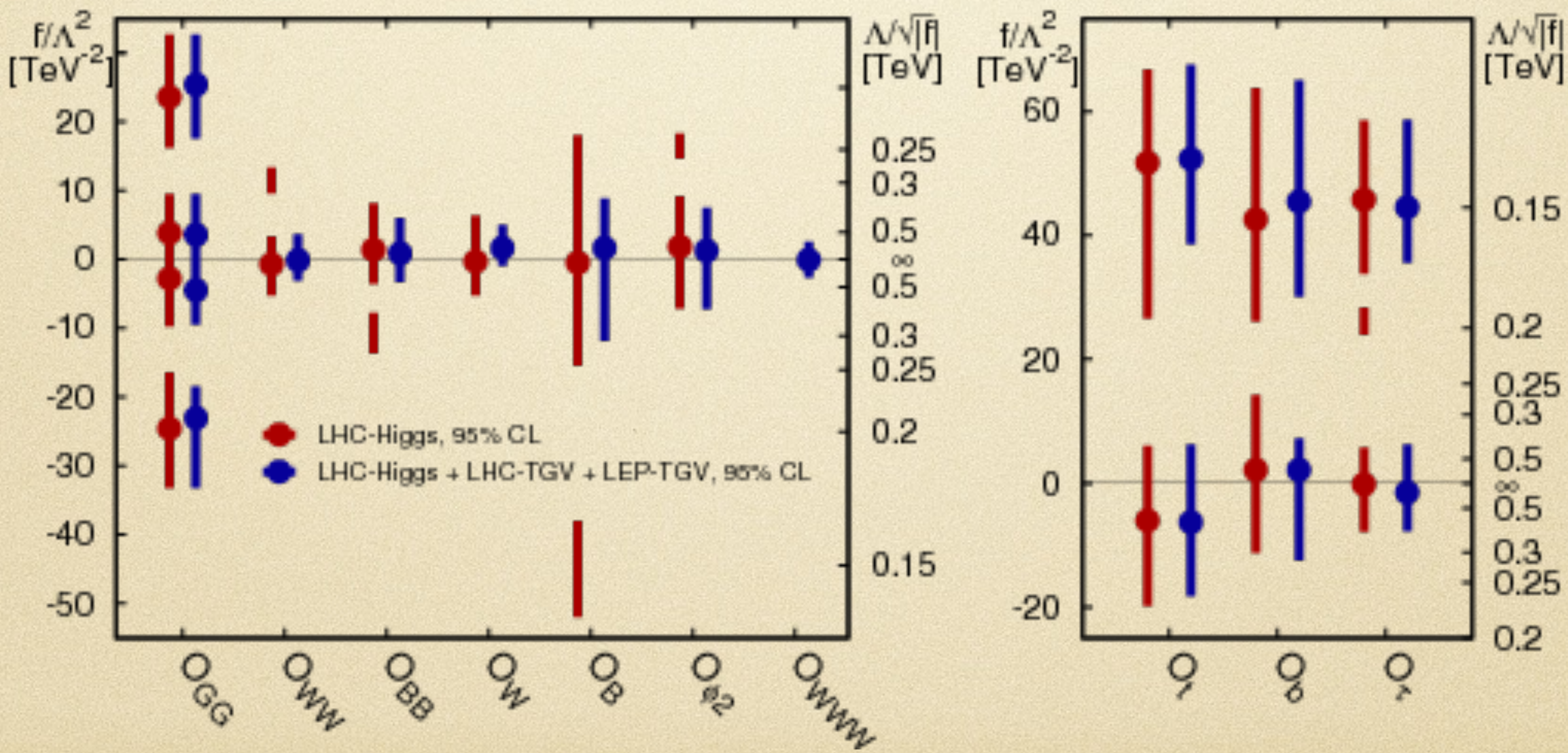
$$
\begin{aligned}
\bar{c}_W &\in -(0.02, 0.0004) \\
\bar{c}_g &\in -(0.00004, 0.000003) \\
\bar{c}_\gamma &\in -(0.0006, -0.00003)
\end{aligned}
$$

Run1 constraints

please see an analysis along the same lines by

Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn et al.

1604.03105, 1505.05516

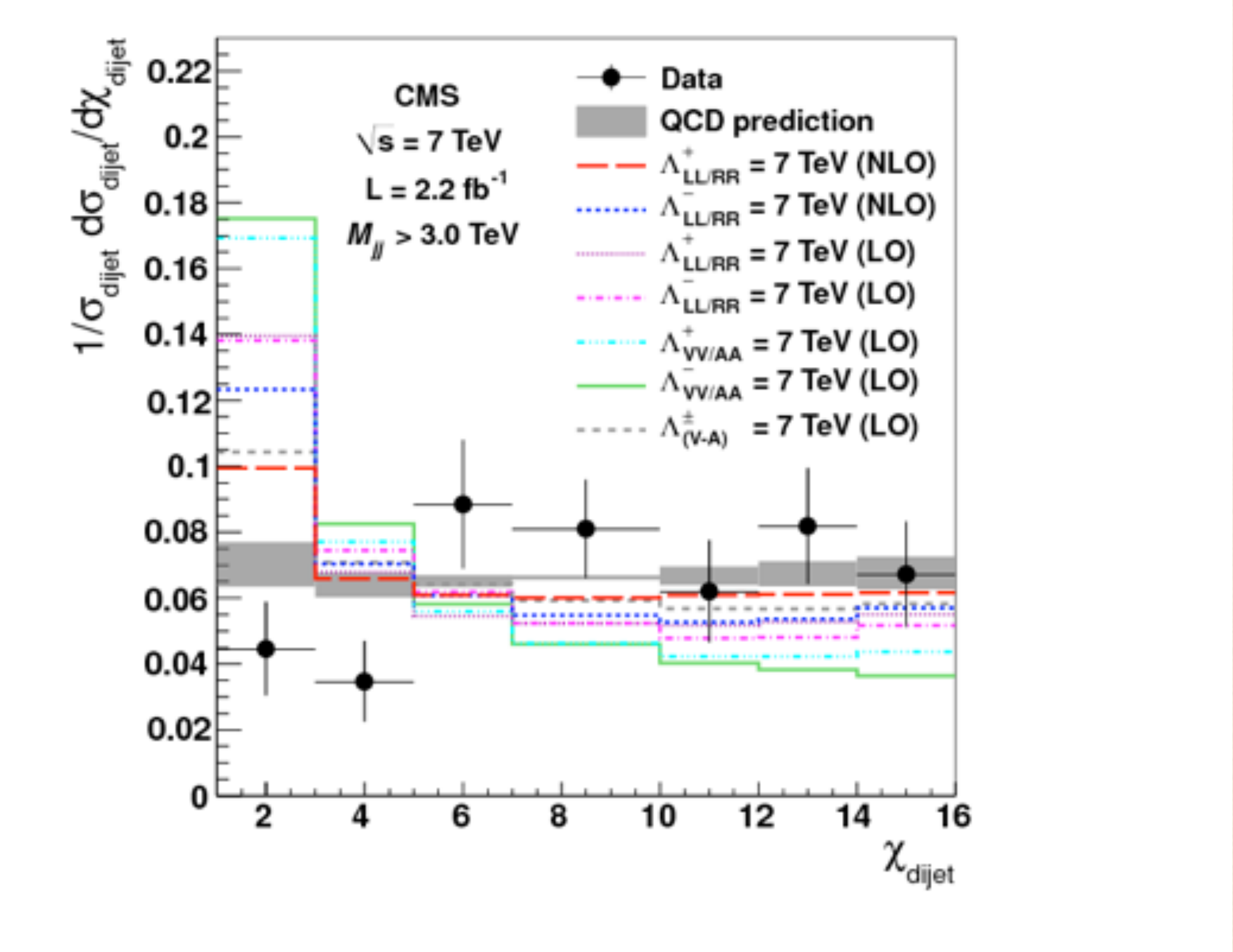


How do we get the best limits?

EFT affects momentum dependence: angular, pT and inv mass distributions

Usual searches,

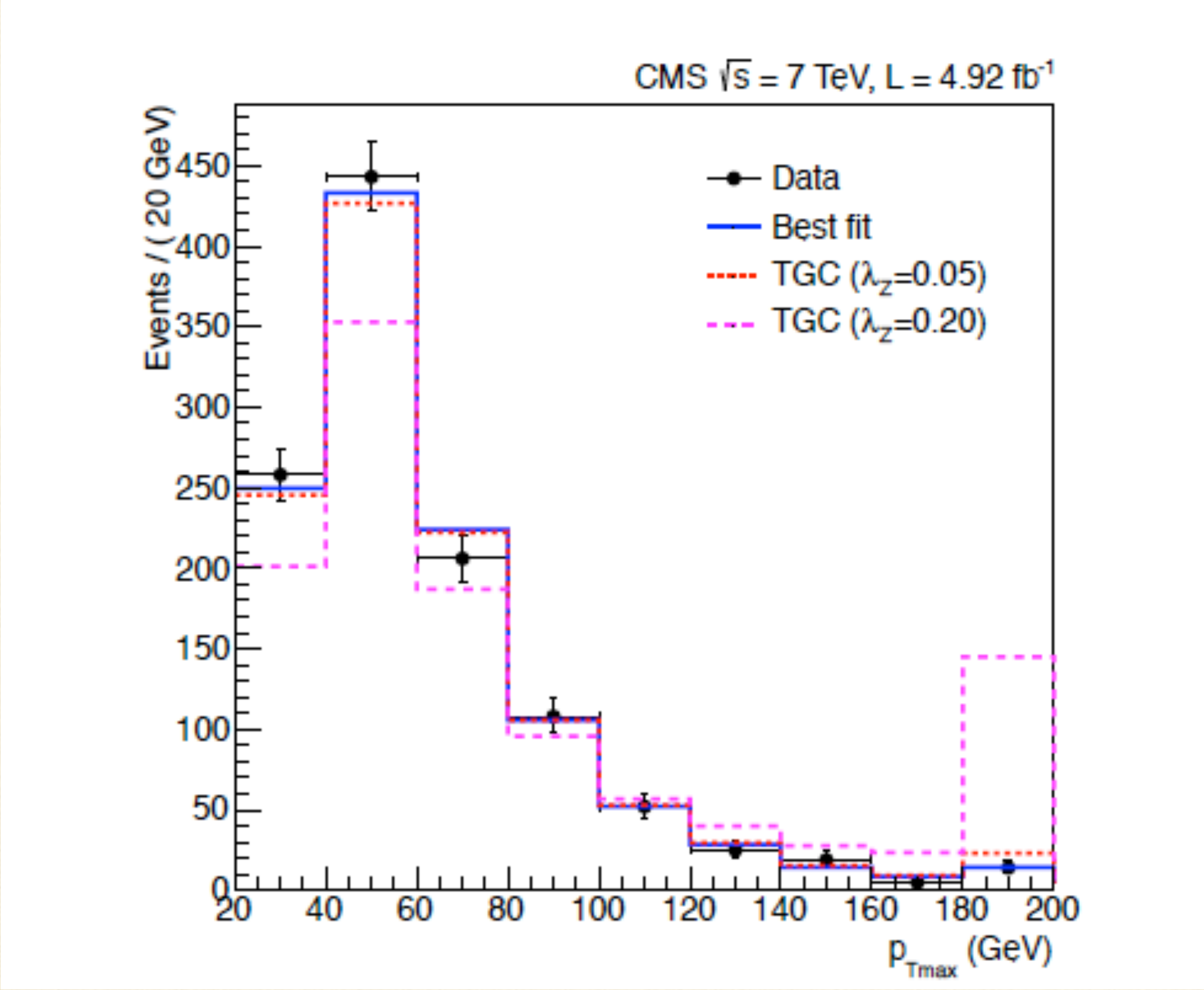
dijet searches



Dijet angular distribution

EFT affects momentum dependence: angular, pT and inv mass distributions

Usual searches,



leading lepton pT

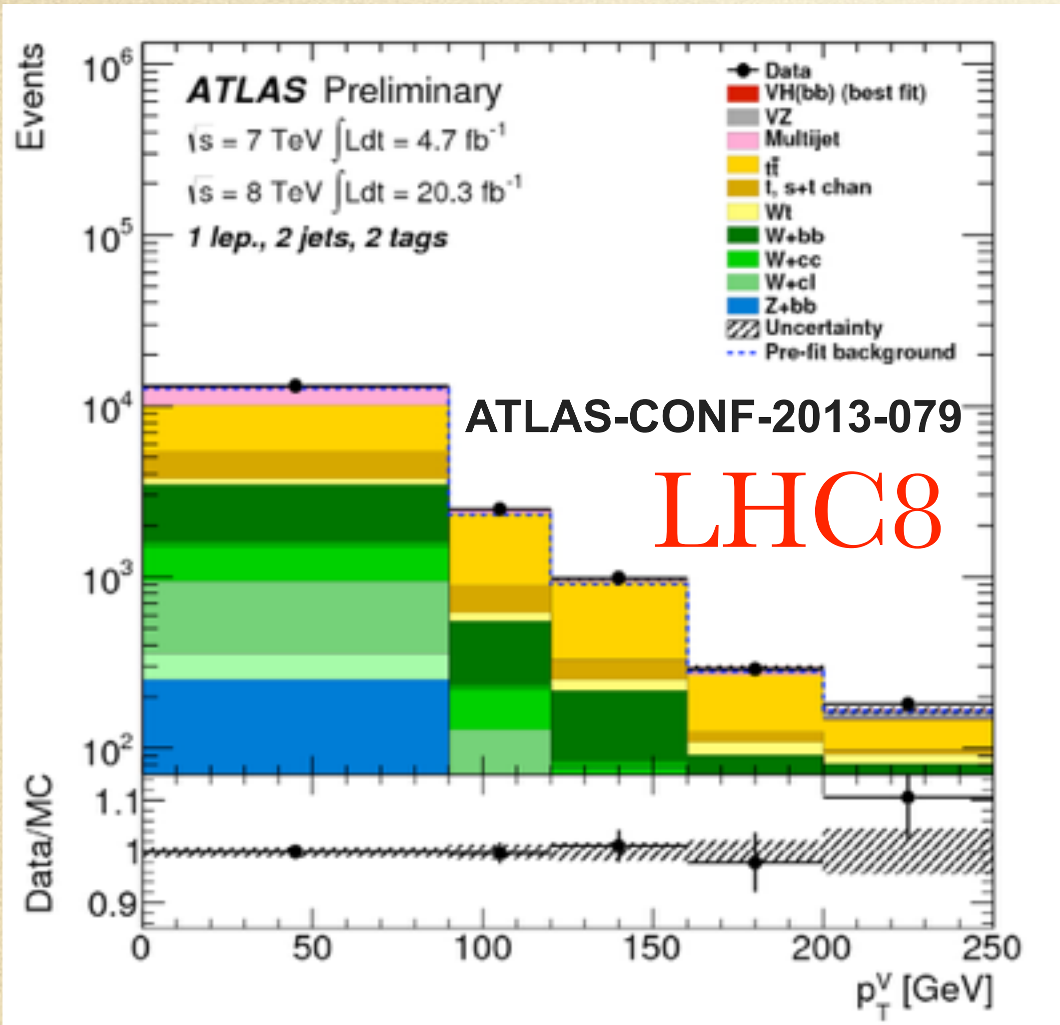
ex. TGCs

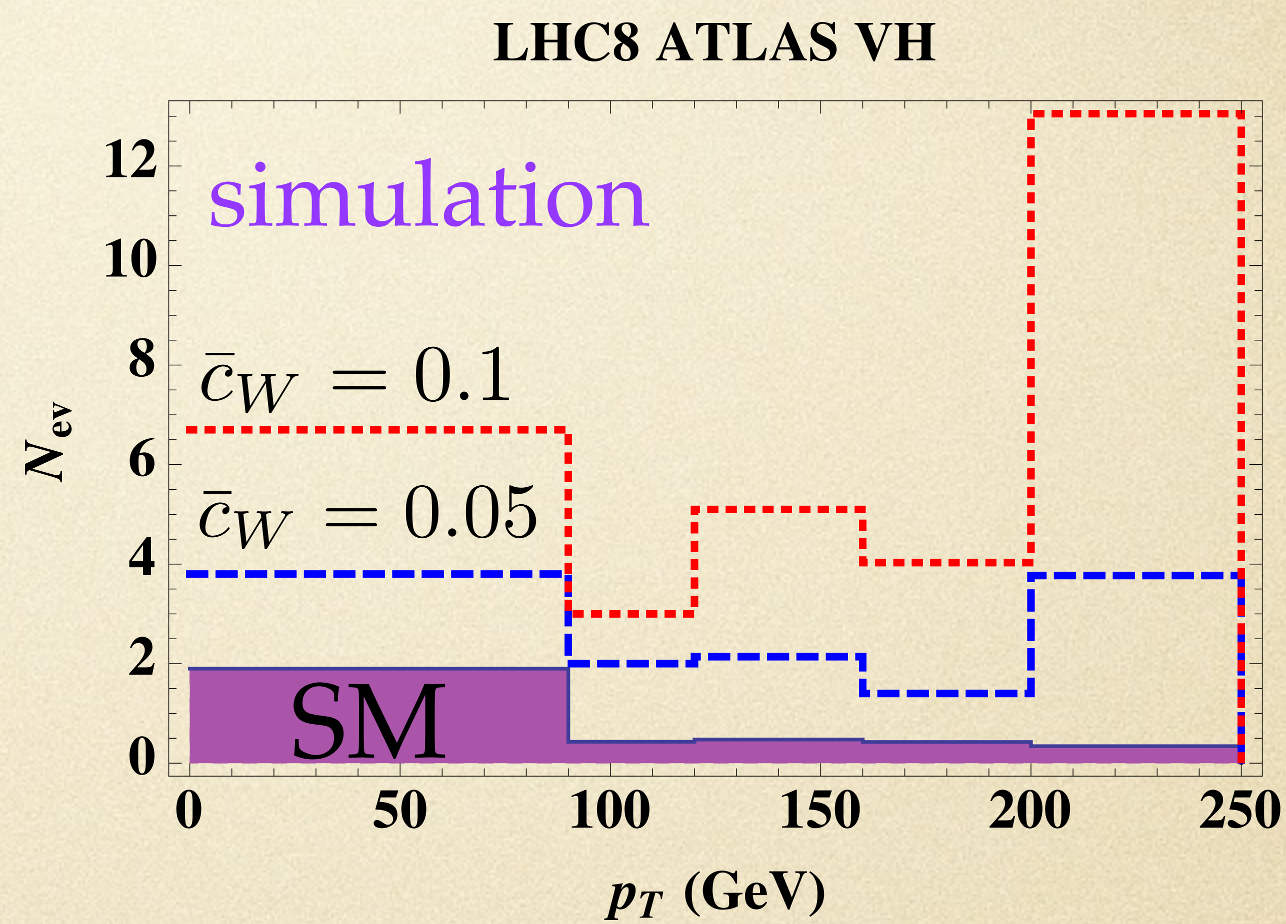
kinematic distribution best way to bound TGCs

growth at high energies cutoff: resolve the dynamics of the heavy NP

Kinematics of associated production at LHC8

Ellis, VS and You. 1404.3667, 1410.7703





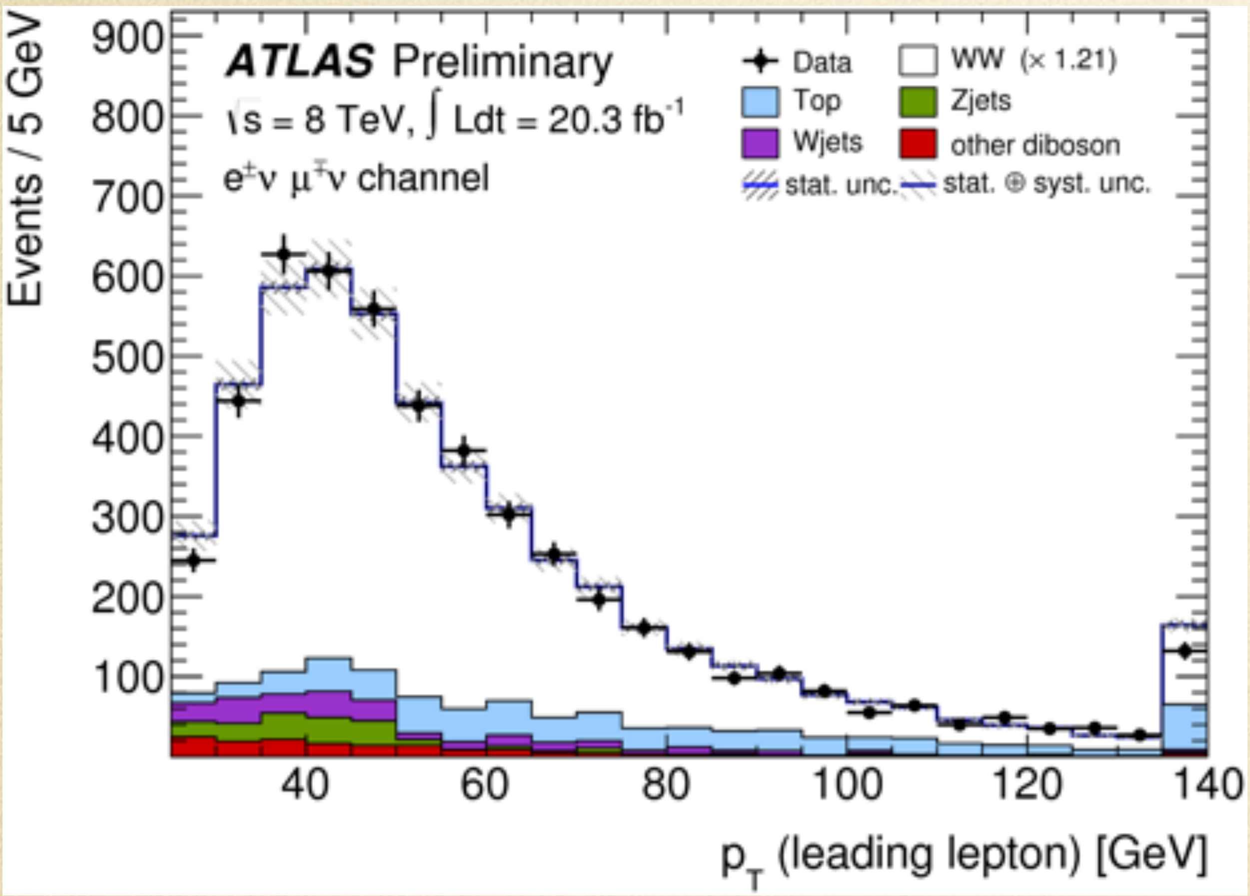
Feynrules -> MG5-> pythia->Delphes3

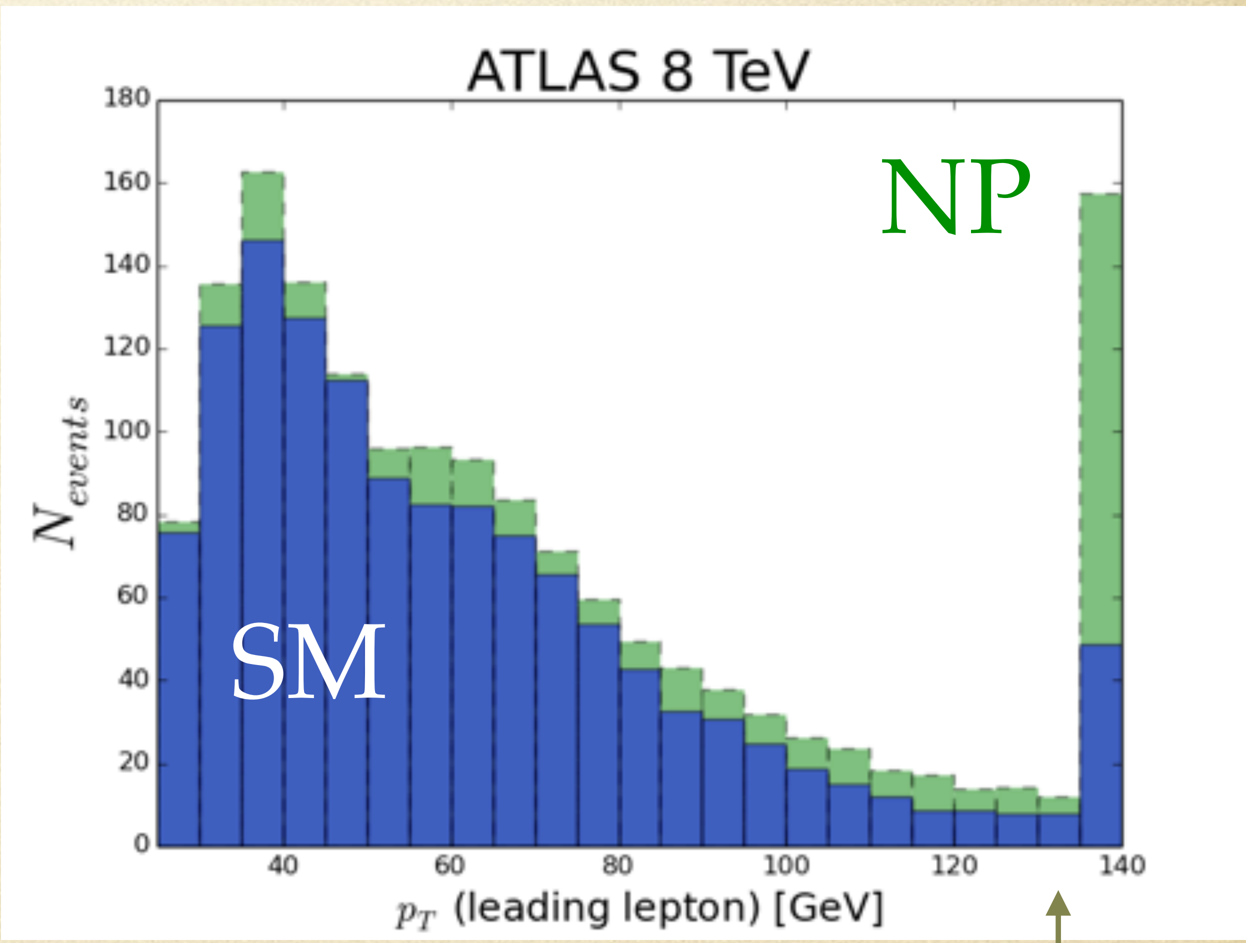
verified for SM/BGs => expectation for EFT

inclusive cross section is less sensitive than distribution

TGCs constrains new physics too

Ellis, VS and You. 1404.3667, 1410.7703





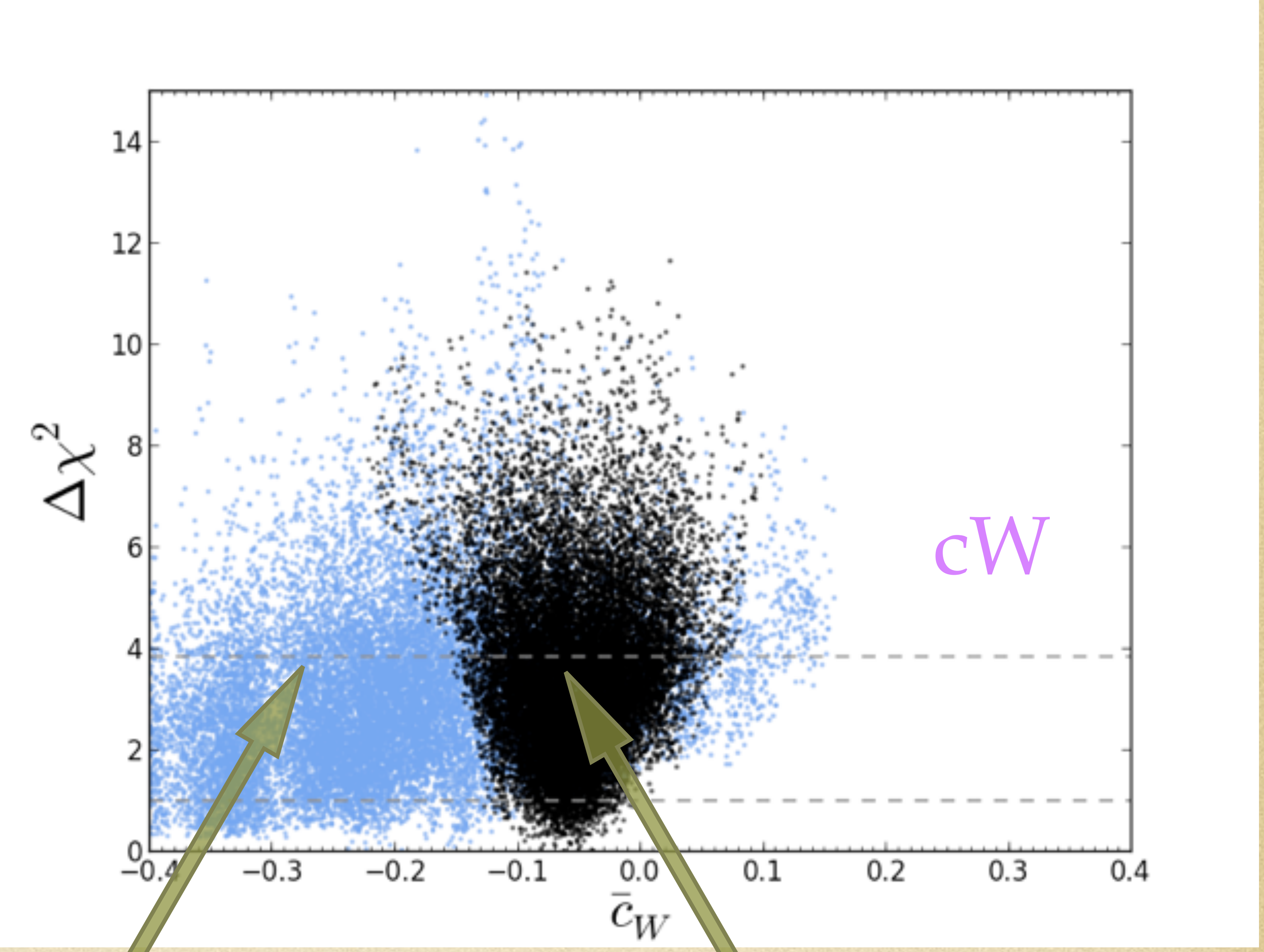
ATLAS-CONF-2014-033

overflow bin

we followed same validation procedure-> constrain EFT

breaking blind directions requires information on VH production

Global fit



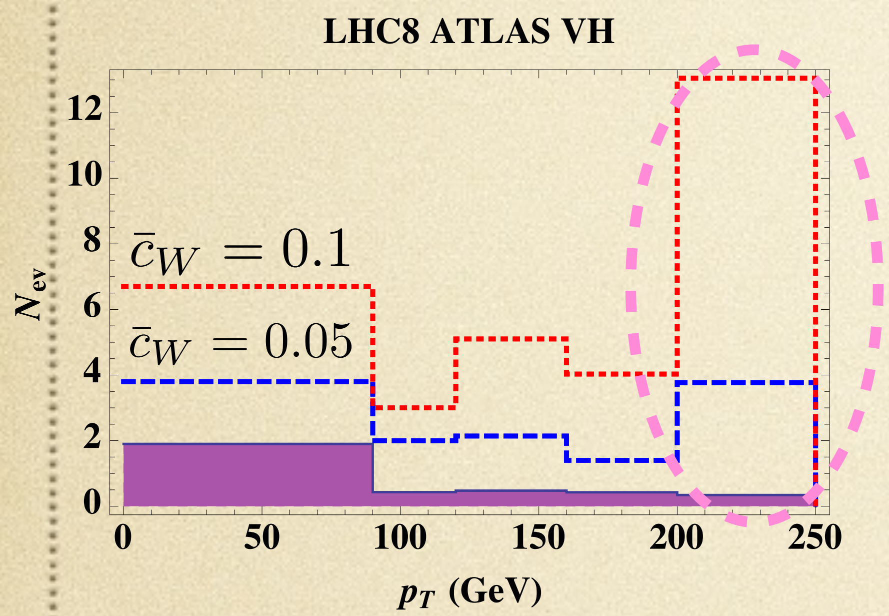
cW

without VH

with VH

Matching with UV theories

At the end of the day, we want to explore new physics
EFT model-independent approach umbrella for many models
parallel to EFT analysis, provides link to WG3



besides matching is useful because
we need benchmarks to test the validity
Where/how does the EFT break down?

Breakdown depends on loop-induced or tree-level

Benchmarks: Extended Higgs sectors

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

Gorbahn, No, VS. 1502.07352

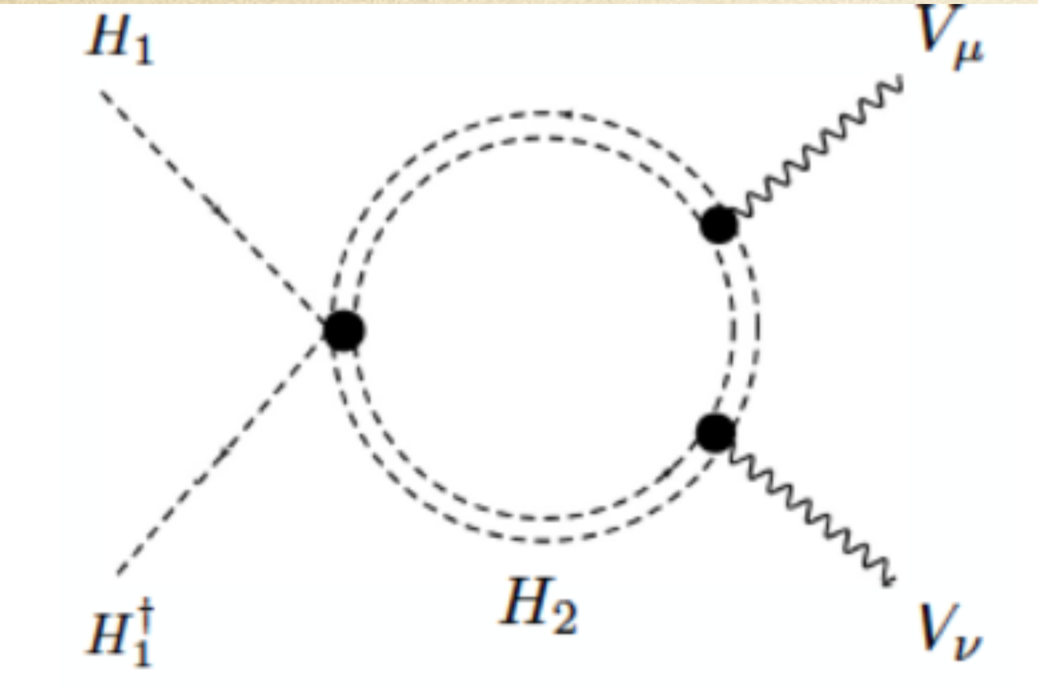
In a nutshell, we did the matching EFT to UV models

	$\bar{c}_H$	$\bar{c}_6$	$\bar{c}_T$	$\bar{c}_W$	$\bar{c}_B$	$\bar{c}_{HW}$	$\bar{c}_{HB}$	$\bar{c}_{3W}$	$\bar{c}_\gamma$	$\bar{c}_g$
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

see 50 pages of gory details

For example, for 2HDM



checked the results by matching in the broken theory

Matching to EFT: unbroken phase

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

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

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

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

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

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

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

In UV models one can quantify the breakdown of the EFT

see e.g. Brehmer, Freitas, Lopez-Val , Plehn.1510.03443

Do we need NLO for Run2?

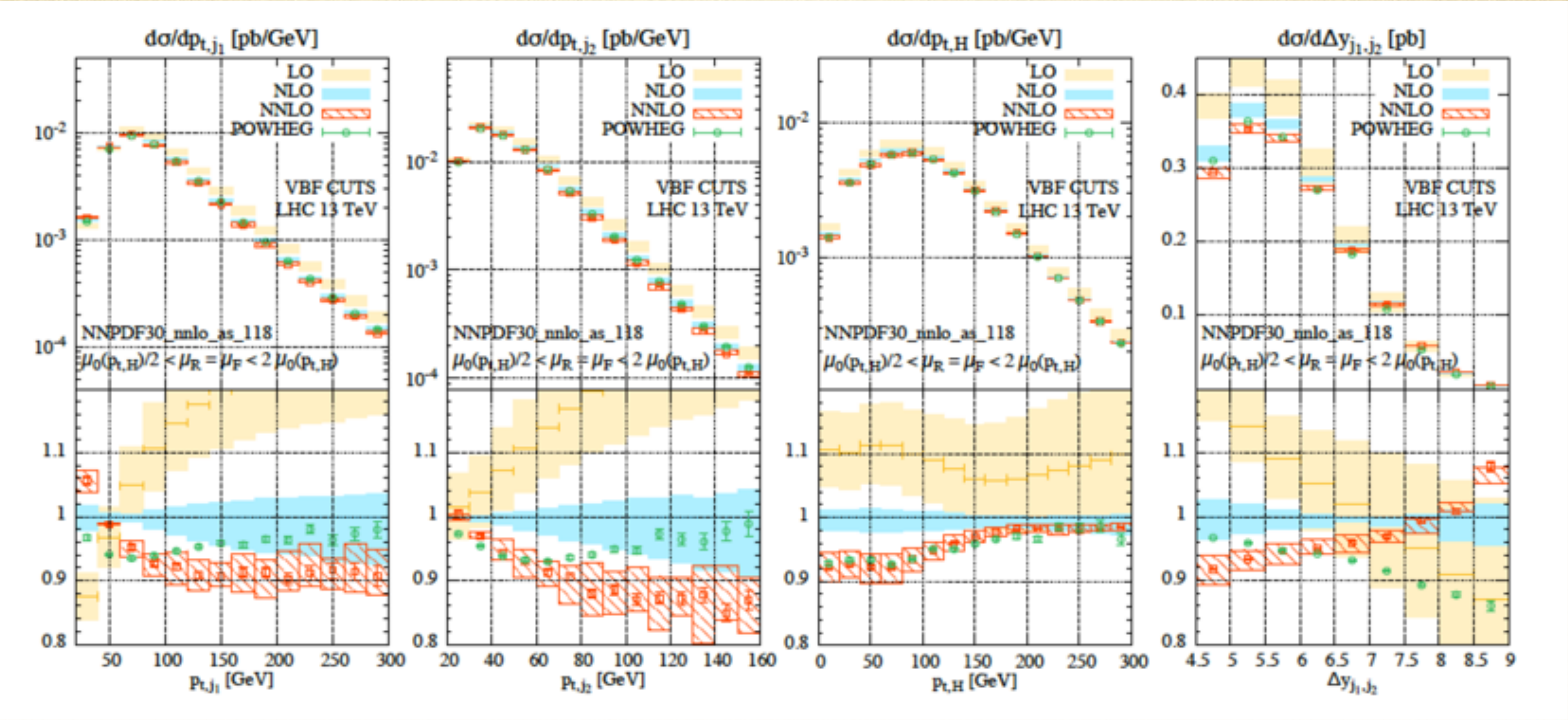
focusing on differential information

SM NLO QCD

Clearly important

VH, VBF, H+jet, WW

e.g. VBF



Cacciari et al. 1506.02660 (VBF)

see also

Maltoni et al. 1306.6464, 1311.1829,1407.5089,1503.01656

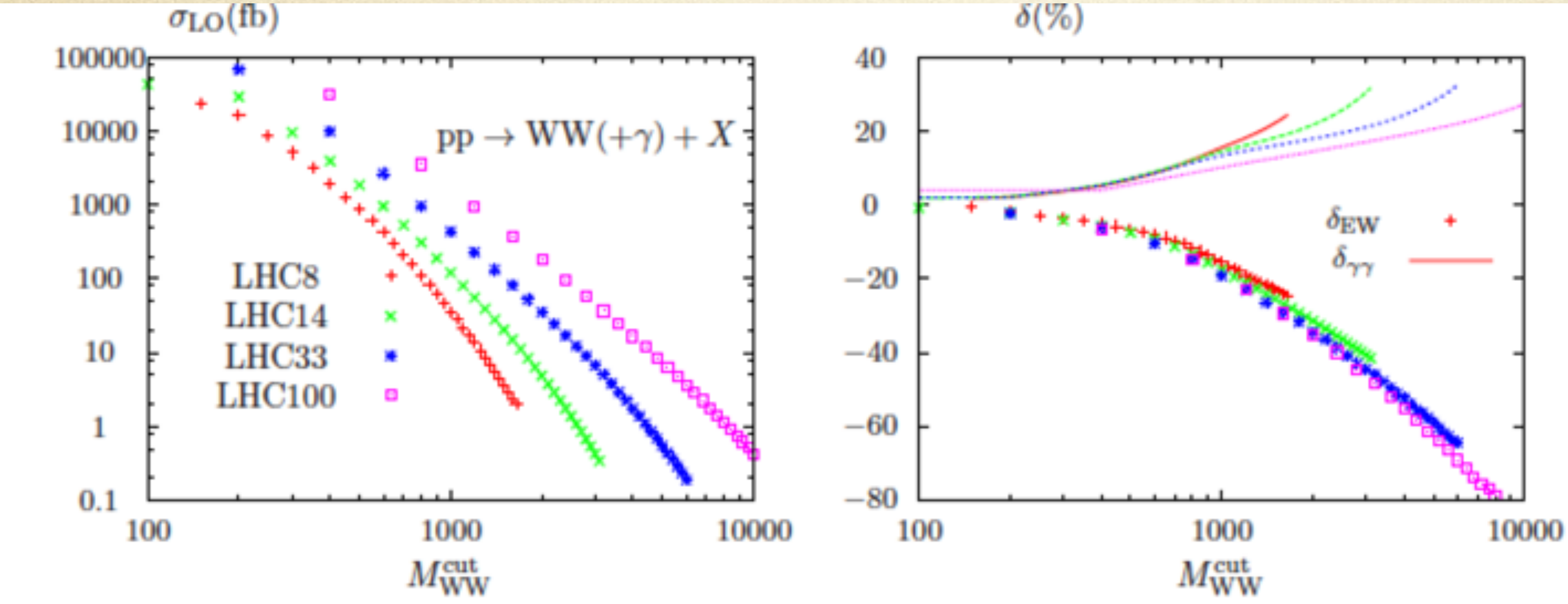
Spira et al. 1407.7971 (SUSY)

Grazzini et al. 1107.1164

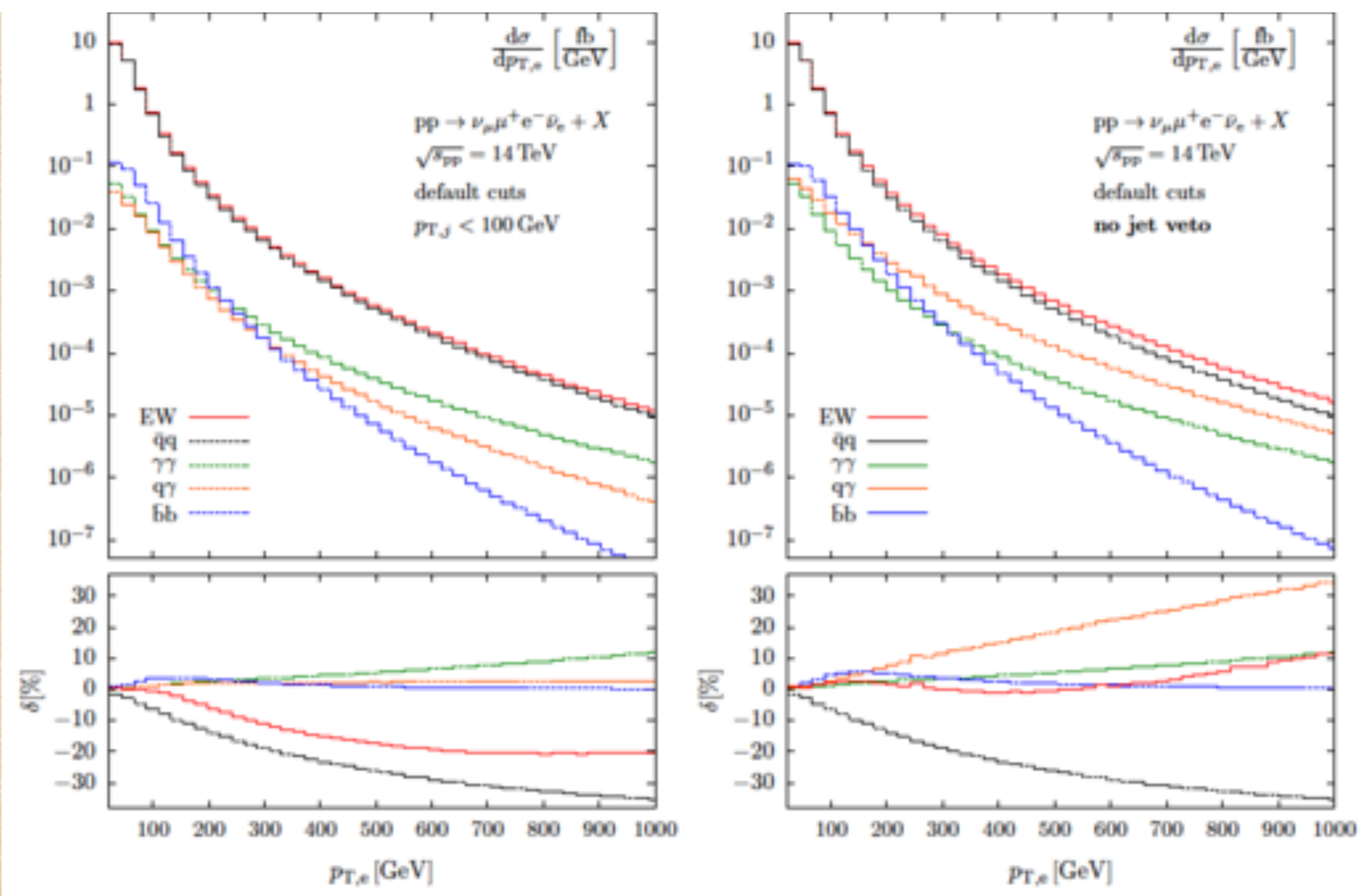
Cansino, Banfi. 1207.0674...

SM NLO EW

esp. diboson production



1308.1430



Billoni et al. 1310.1564

see discussion this morning

EFT tools: current status

SMEFT at NLO QCD
in the SILH basis

1. POWHEG/MCFM **Mimasu, VS, Williams. 1512.02572**

VH incorporated

other channels (VBF, ggF) can be added as well

please contact Ciaran for newest version

(ciaranwi@buffalo.edu)

2. aMC@NLO **deGrande, Fuks, Mawatari, Mimasu and VS. 1607.XXXX**

In final stages of writing

Independent of process

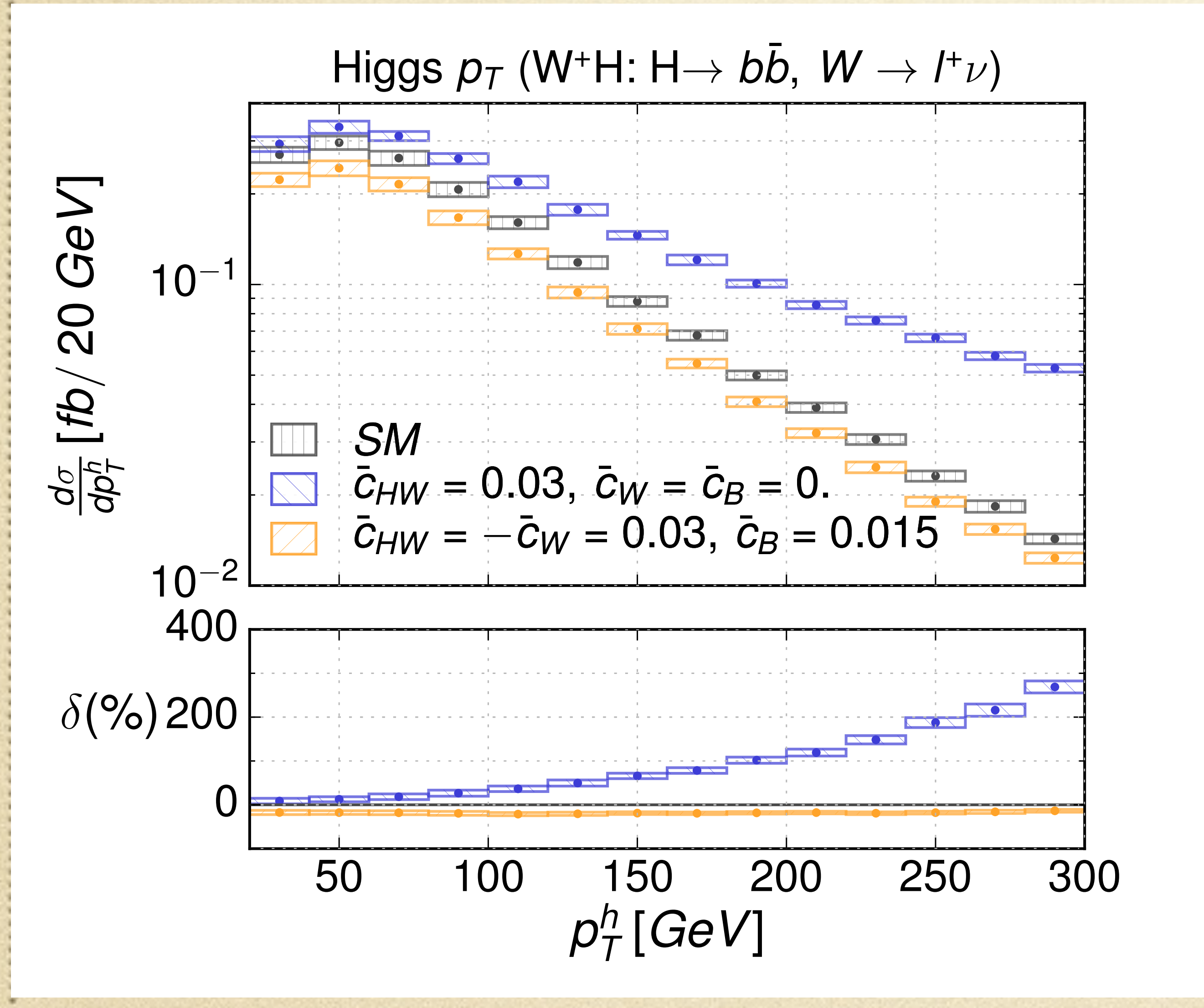
VH, VBF/VV and ggF automatic

please contact any of us for latest version

Some results using aMC@NLO

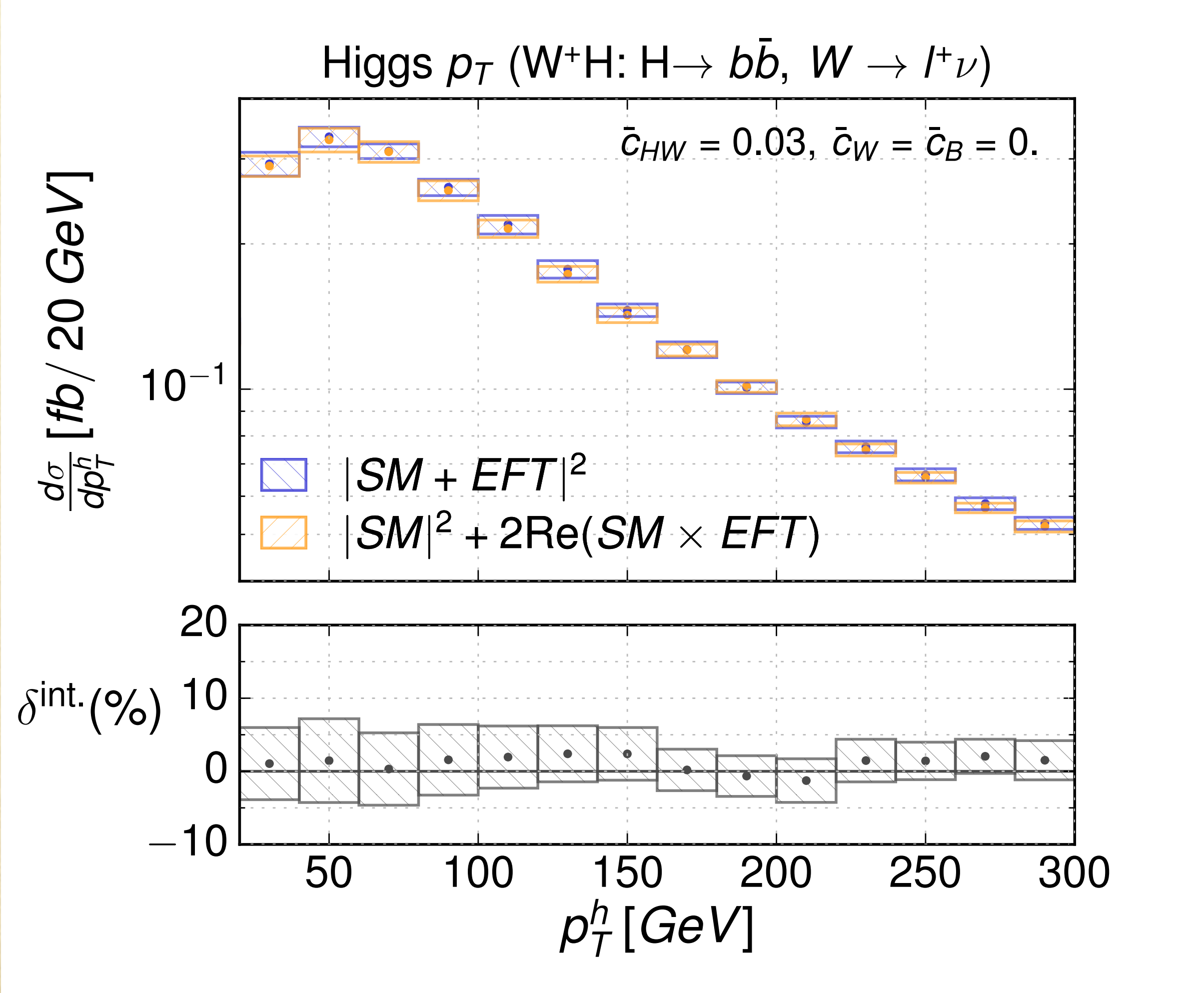
showered with pythia

example of WH



one can check **validity**

effect of EFT^2 terms



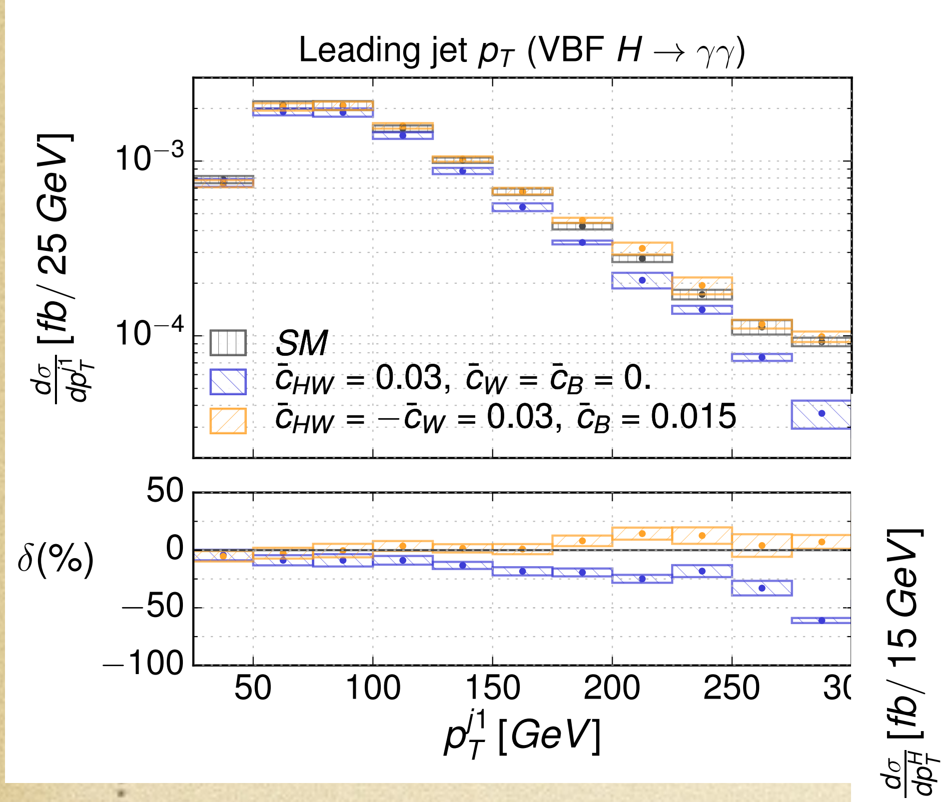
EFT values consistent Run1 global fit

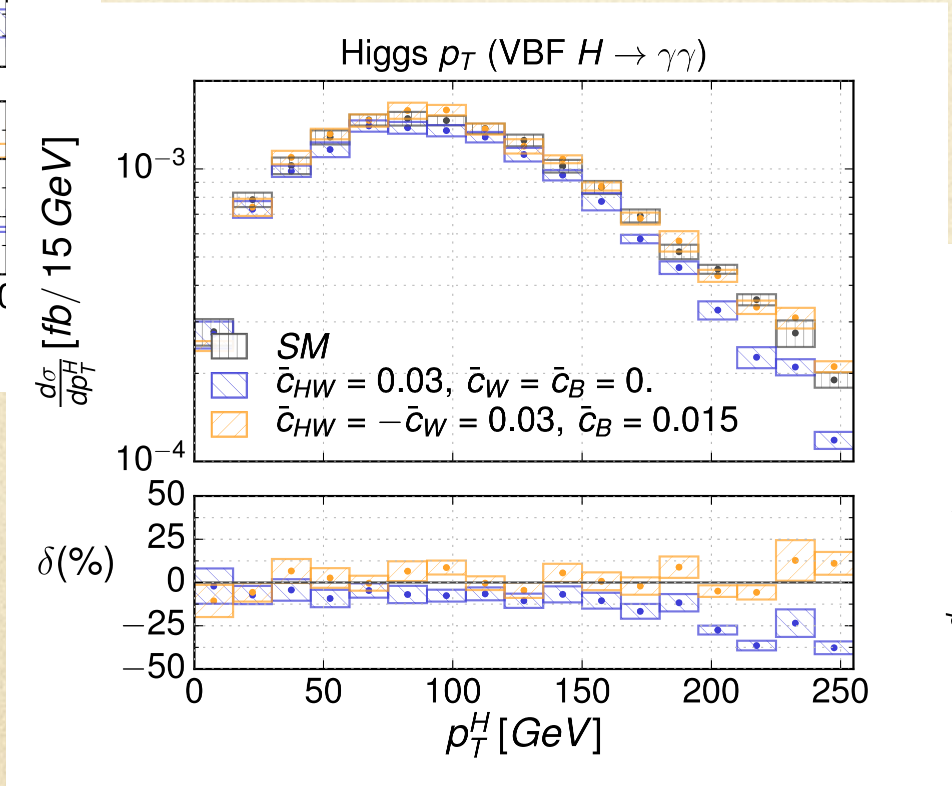
large effects in the high-pT region

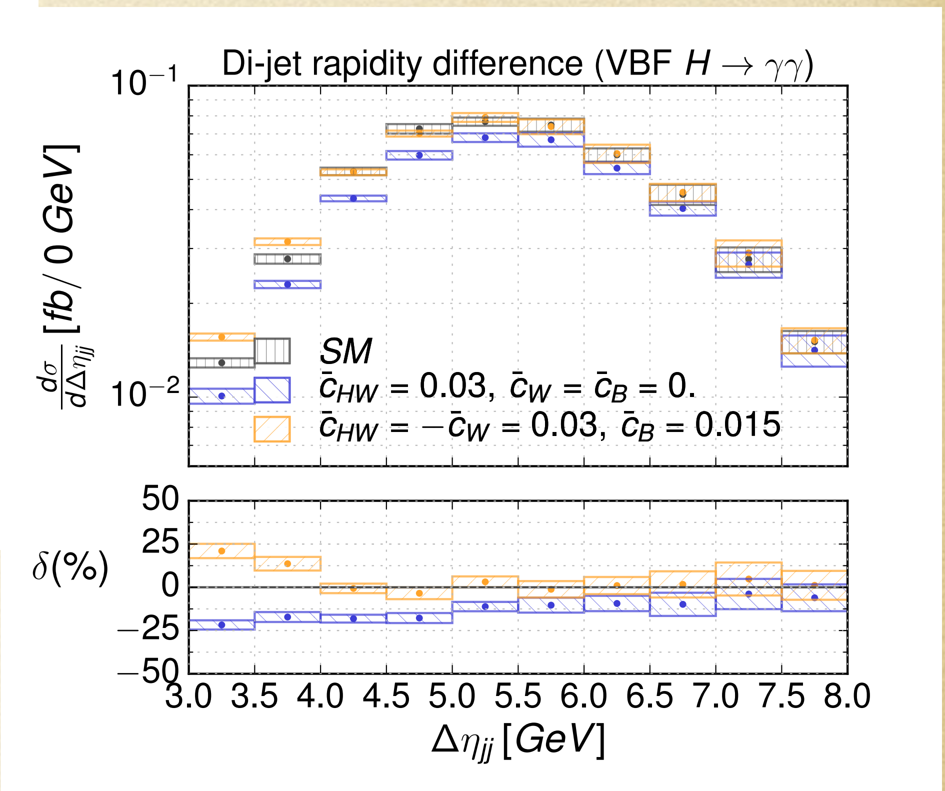
Some results using aMC@NLO

showered with pythia

example of VBF







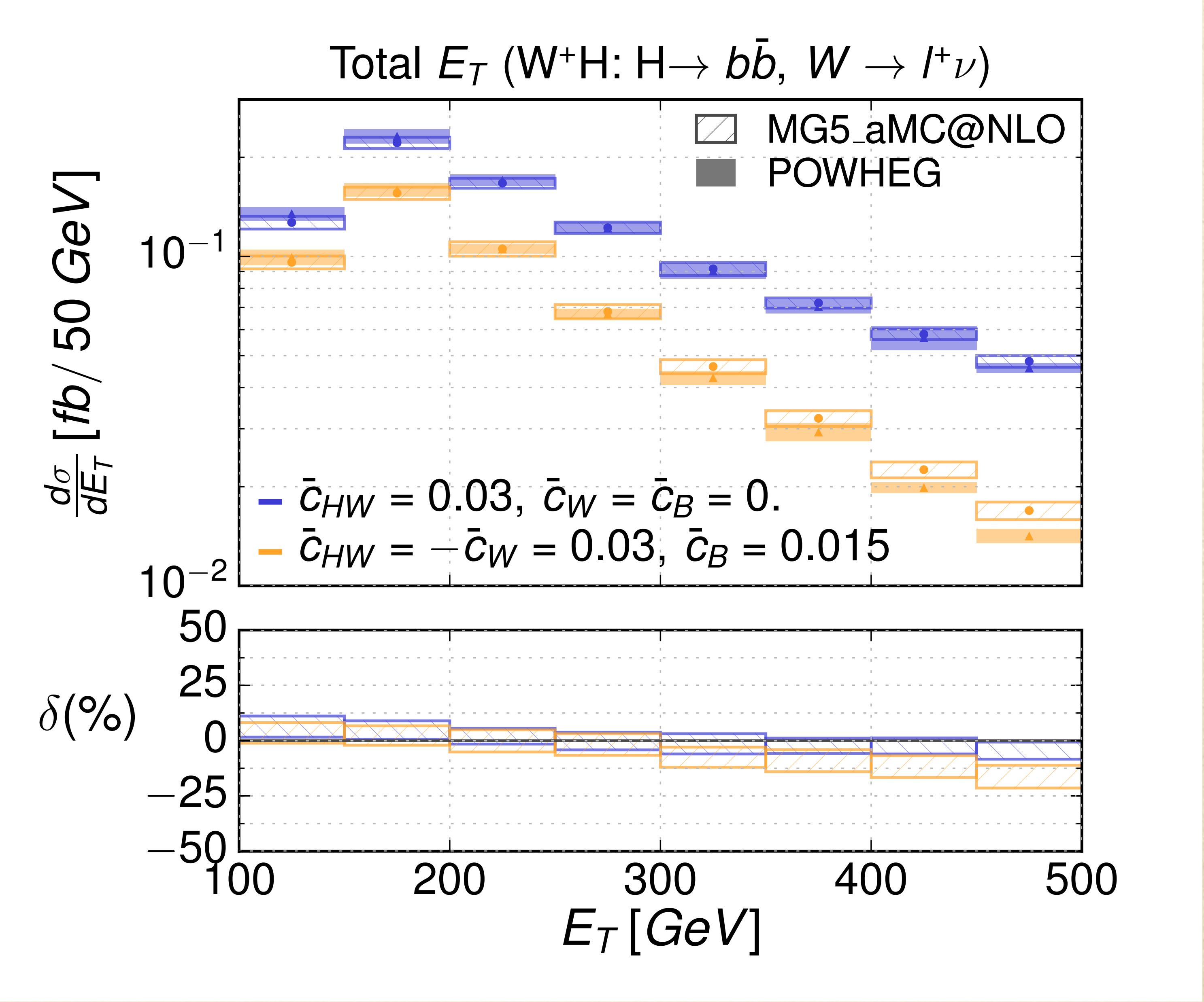
generating more stats for final results

Why *two* tools?

different dealing of parton shower

part of the systematic uncertainties

comparison in WH



Wrapping up

Interpretation of Higgs/EW data as EFT global fit

useful to *theorists*: model independent and simple connection to models and *experimentalists*: allows combination of channels and correlation with WG3 activities

The BSM Higgs affects total rates,
but is more BSMish in specific kinematic regions

(Remember backgrounds to Higgs signal are also subject to NP effects)

Validity of the EFT and correlation with direct searches/EWPT
can be done in benchmarks
could be part of the interpretation of a global analysis

QCD NLO effects are important on these BSM-sensitive regions

POWHEG and aMC@NLO tools are available
comparison showering effects and removal of EFT^2 terms is now possible

Thanks!

NLO calculations with MadGraph5_aMC@NLO

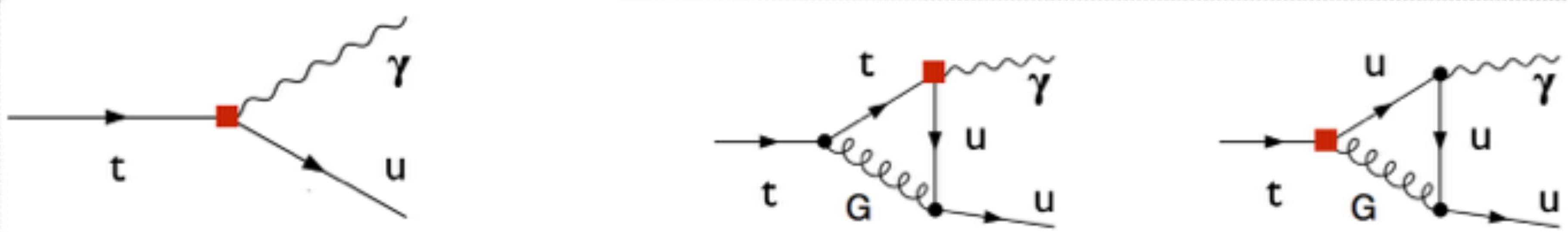
✦ Effective field theories at NLO (in QCD)

- ✤ Non-renormalizable?
  - ★ No: renormalization order by order in $1/\Lambda^2$
- ✤ Precision?
  - ★ Yes: including the QCD corrections

$$
\begin{array}{ccccccc}
\sigma \approx 1 & + & O(\alpha_s) & + & O(1/\Lambda) & + & O(\alpha_s/\Lambda) \\
\downarrow & & \downarrow & & \downarrow & & \downarrow \\
\text{SM@LO} & & \text{SM@NLO} & & \text{EFT@LO} & & \text{EFT@NLO}
\end{array}
$$

✦ Issue: operator mixings

- ✤ The structure of a given operators can be generated from another operator
  - ★ Example: gtu (NLO-QCD) corrections to the γtu operator



EFT@LO EFT@NLO EFT@NLO

- ✤ In full generality, we may need to include all operators allowed by gauge invariance…

III *eHDECAY*

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

- $h \to f\bar{f}$:

$$\Gamma(\bar{\psi}\psi)\big|_{SILH} = \Gamma_0^{SM}(\bar{\psi}\psi)\left[1 - \bar{c}_H - 2\bar{c}_\psi + \frac{2}{|A_0^{SM}|^2}\mathrm{Re}\left(A_0^{*SM} A_{1,ew}^{SM}\right)\right]\left[1 + \delta_\psi\,\kappa^{QCD}\right]$$

$$\Gamma(\bar{\psi}\psi)\big|_{NL} = c_\psi^2\,\Gamma_0^{SM}(\bar{\psi}\psi)\left[1 + \delta_\psi\,\kappa^{QCD}\right]$$

A_0^{SM}: SM tree-level amplitude
$A_{1,ew}^{SM}$: SM elw. amplitude [real corrections treated analogously]

- factorization of QCD $\leftrightarrow$ elw. [limit small m_h]

- NL: no elw. corrections!

- other decay modes analogous

from Spira, (N)NLO ATLAS

Higgs BRs eHDECAY Contino et al. 1303.3876 and 1403.3381

Production rates and kinematic distributions

depend on cuts

need radiation and detector effects

Simulation tools

coefficients

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

→

Collider simulation

observables

Limit coefficients = new physics

The guide to discover New Physics may come from precision, and not through direct searches

The guide to discover New Physics may come from precision, and not through direct searches

New Physics could be heavy

as compared with the channel we look at

Effective Theory approach

The guide to discover New Physics may come from precision, and not through direct searches

New Physics could be heavy

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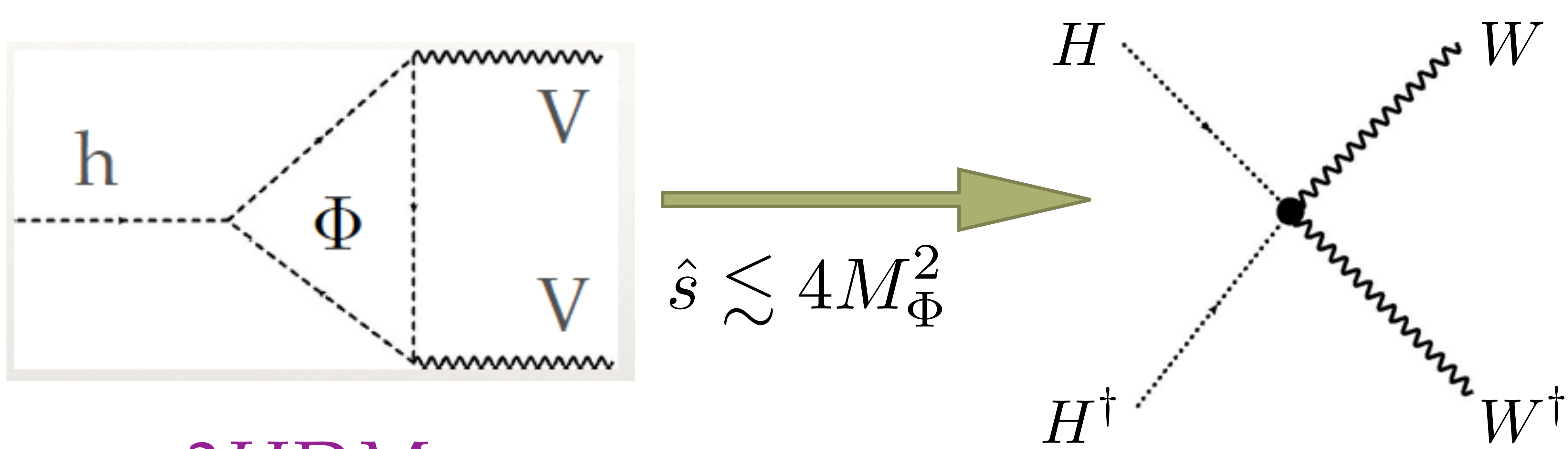
Effective Theory approach

Example.



2HDMs

$$(H^\dagger \sigma^a D^\mu H)\, D^\nu W^a_{\mu\nu}$$

EFT

Bottom-up approach

operators w/ SM particles and symmetries, plus the newcomer, the Higgs

Buchmuller and Wyler. NPB (86)

$$\mathcal{L}_{BSM} = \mathcal{L}_{SM} + \mathcal{L}_{d=6} + \ldots$$

$$\Big\downarrow \text{HDOs}$$

modification of couplings of SM particles

Many such operators, but few affect the searches we do

EFT

Bottom-up approach

operators w/ SM particles and symmetries, plus the newcomer, the Higgs

Many such operators but few affect the searches we do

Example 1. LEP physics

Operator
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ + $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$
$\mathcal{O}_L^{(3)q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$

Ellis, VS, You. 1410.7703

Anomalous couplings vs EFT

HDOs generate HVV interactions with more derivatives parametrization in terms of anomalous couplings

Example. Higgs anomalous couplings

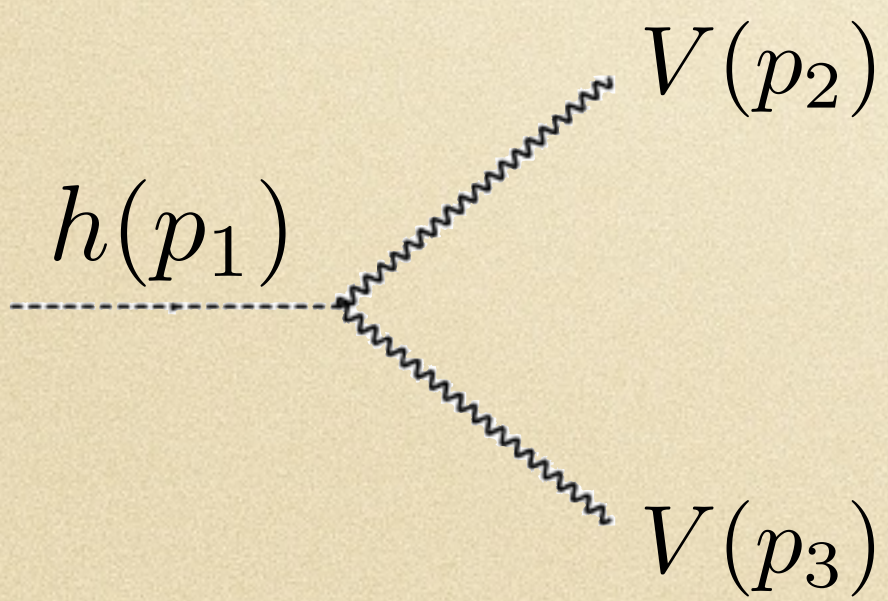
$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu} \quad -h\, g^{(2)}_{hVV} V_{\nu} \partial_{\mu} V^{\mu\nu} \quad -\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$

HDOs generate HVV interactions with more derivatives parametrization in terms of anomalous couplings

Example. Higgs anomalous couplings

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

Feynman rule for mh>2mV



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

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

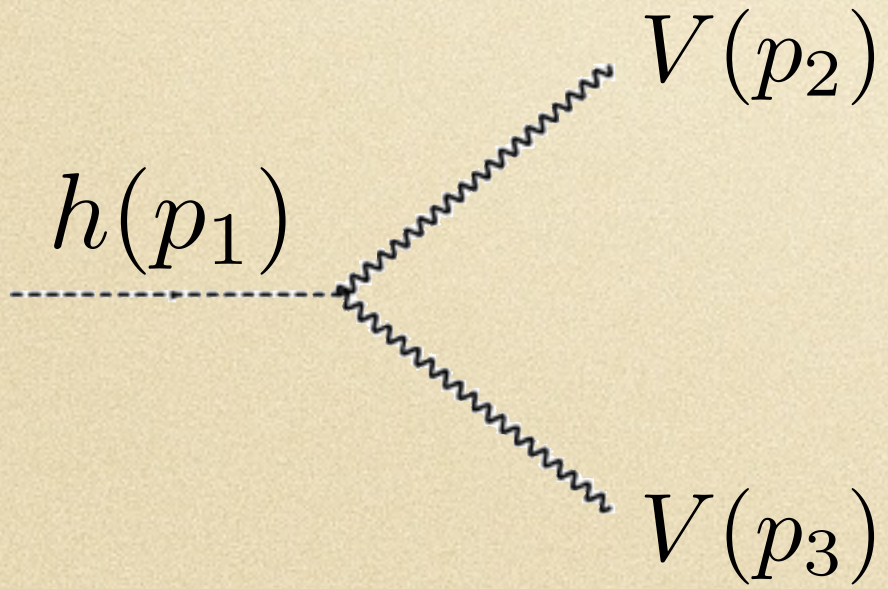
$$-i \tilde{g}_{hVV} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

HDOs generate HVV interactions with more derivatives
parametrization in terms of anomalous couplings

Example. Higgs anomalous couplings

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

Feynman rule for mh>2mV



total rates, COM, angular, inv mass and pT distributions

Translation between EFT and Anomalous couplings

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

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

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

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

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

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

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Gorbahn, No, VS. In preparation

Translation between EFT and Anomalous couplings

Within the EFT there are relations among anomalous couplings, e.g. TGCs and Higgs physics

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

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

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

similarly for QGCs: also function of the same HDOs

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The set-up

In this talk I use

1. Feynrules HDOs involving Higgs and TGCs

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links to CalcHEP, LoopTools, Madgraph...

HEFT->Madgraph-> Pythia... -> FastSim/FullSim

2.QCD NLO HDOs involving Higgs and TGCs

VS and Williams. In prep.

MCFM and POWHEG

Pythia, Herwig... -> FastSim/FullSim

de Grande, Fuks, Mawatari, Mimasu, VS. In preparation for MC@NLO