Higgs precision from LHC to FCC-ee

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FCC-ee meeting, CERN

Outline

- Why the EFT approach
- Status of SM EFT after Run1
- Intrinsic limitations
- Practical limitations
- Connection to UV models
- LHC to FCC-ee

Why using the EFT approach

Many options for New Physics
EFT model-independent way of
parametrizing deformations of the SM

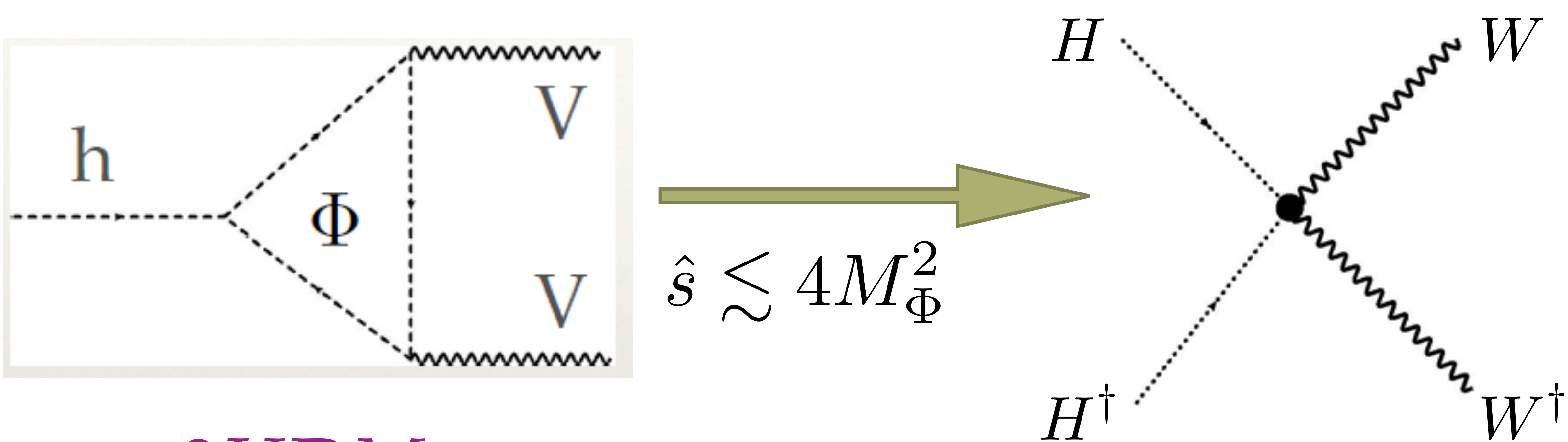
The guide to discover New Physics may come from precision, and not through direct searches

New Physics could be **heavy**

as compared with the channel we look at

Effective Theory approach

Example.



2HDMs

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

The Effective Field Theory

Bottom-up approach:
operators w/ SM particles and symmetries,
plus the newcomer, the Higgs

Buchmuller and Wyler. NPB (86)

A

Realization of EWSB

Linear or non-linear

B

And the Higgs could be

Weak doublet or singlet

This talk: linear, for non-linear see talks by Cata et al (HXSWG)

Once this choice is made, expand...

$$\frac{1}{\Lambda^2}$$ Integrating out new physics

$$\frac{v^2}{f^2}$$ Non-linearity $U = e^{i\Pi(h)/f}$

...order-by-order

For example, some operators Higgs-massive vector bosons

ex.

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

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \widehat{W}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger (D_\nu \Phi)\ \widehat{B}^{\mu\nu}$$

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}^{\mu\nu} \widehat{W}_{\mu\nu} \Phi$$

$$\mathcal{O}_{BB} = (\Phi^\dagger \Phi)\ \widehat{B}^{\mu\nu} \widehat{B}_{\mu\nu}$$

C

UV theory: tree-level or loop

may need a model bias

ex. SILH

$$\frac{2igc_{HW}}{m_W^2} (D^\mu \Phi^\dagger) \hat{W}_{\mu\nu} (D^\nu \Phi)$$

Giudice, Grojean, Pomarol, Rattazzi. 0703164 redundancies trade off operators using EOM

D Choice of basis

Rosetta
Higgs: SILH: Warsaw

see talk by Mimasu (HXSWG)

And, **finally**

Observables as a function of EFT coefficients

SM EFT

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

Many such operators, but few affect specific sectors

Status of SM EFT after Run1

where do we stand

SM EFT

Define a complete basis at leading order in EFT (SMEFT) and compare it with EWPT and LHC data

Perform a global fit to LEP and LHC Run1 observables, with no theory bias including differential information (not just total rates)

Ellis, VS and You. 1404.3667, 1410.7703

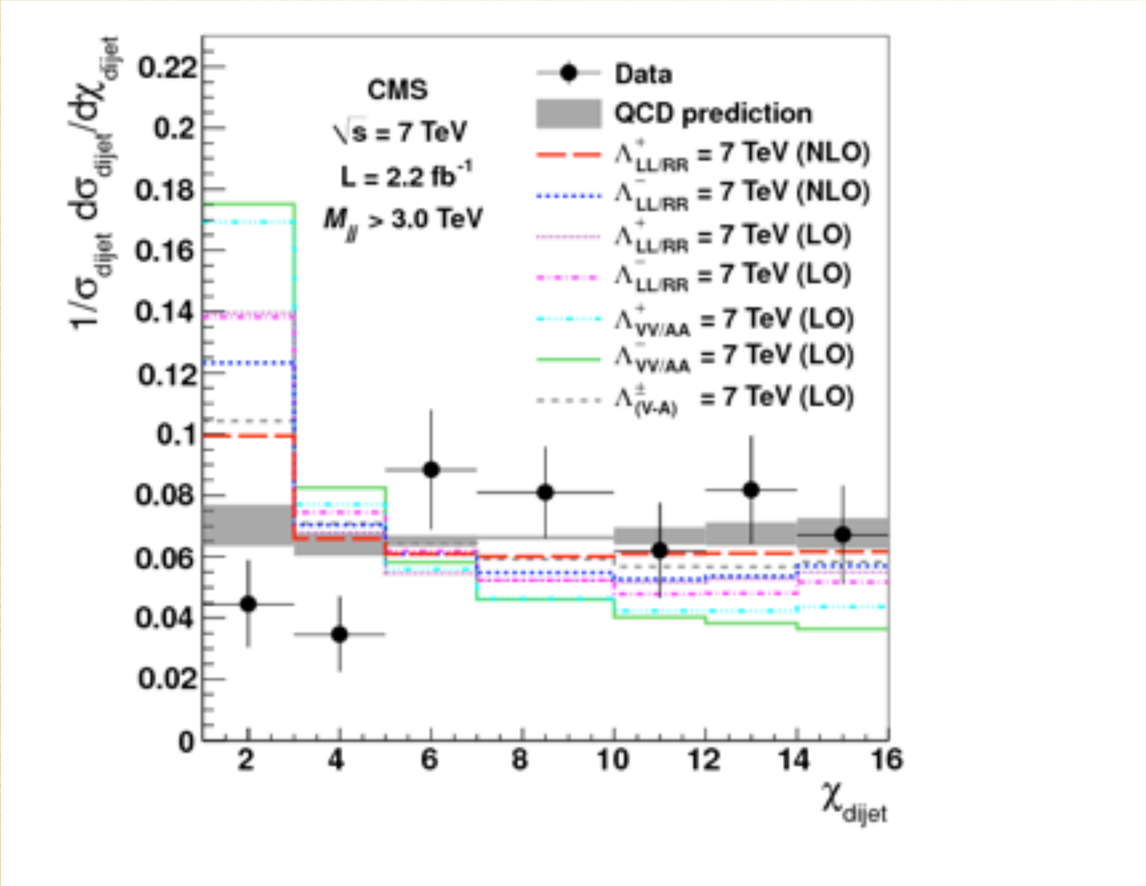
see Tevong's talk on EWPTs

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

kinematic distribution best sensitivity

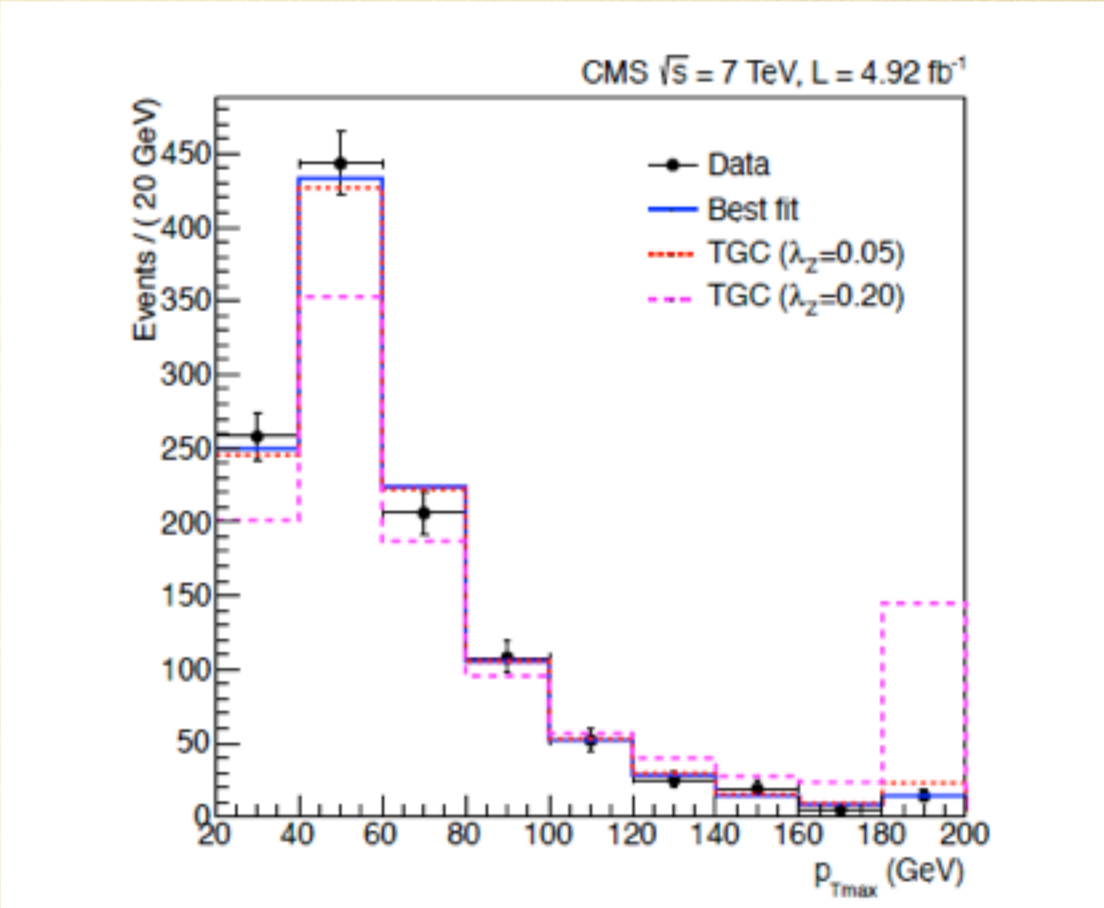
Usual searches,

ex. dijet searches



Dijet angular distribution

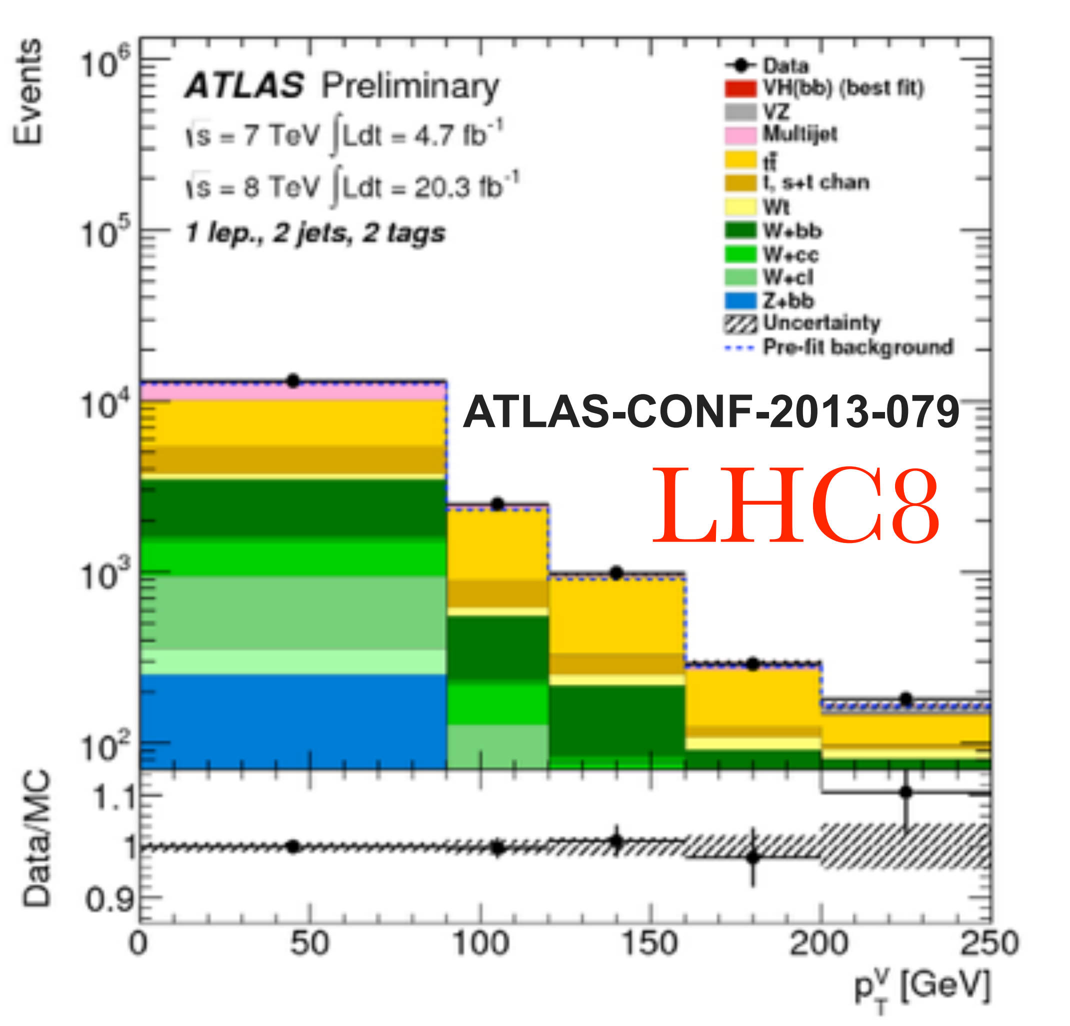
ex. TGCs

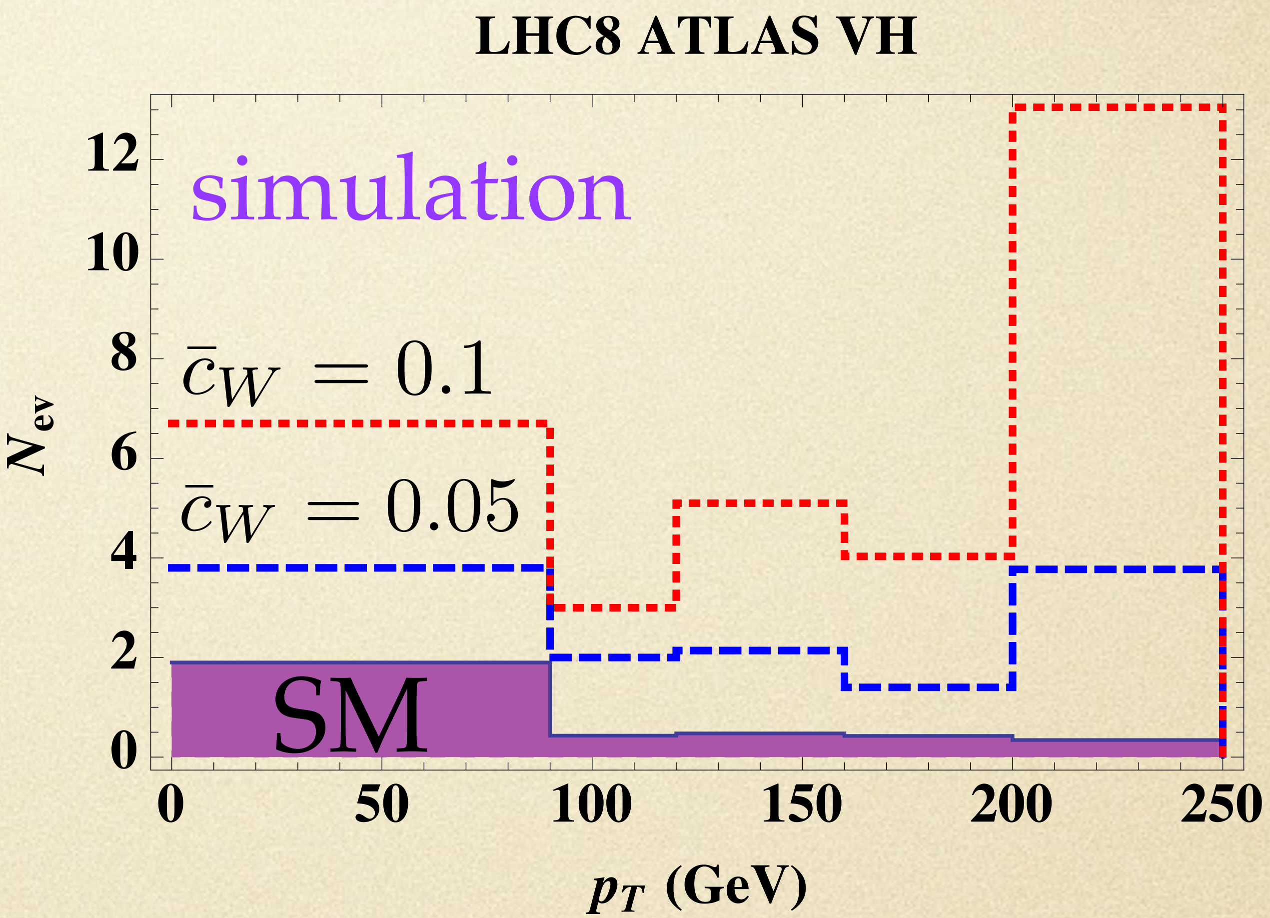


leading lepton pT

Kinematics of associated production at LHC8

Ellis, VS and You. 1404.3667, 1410.7703





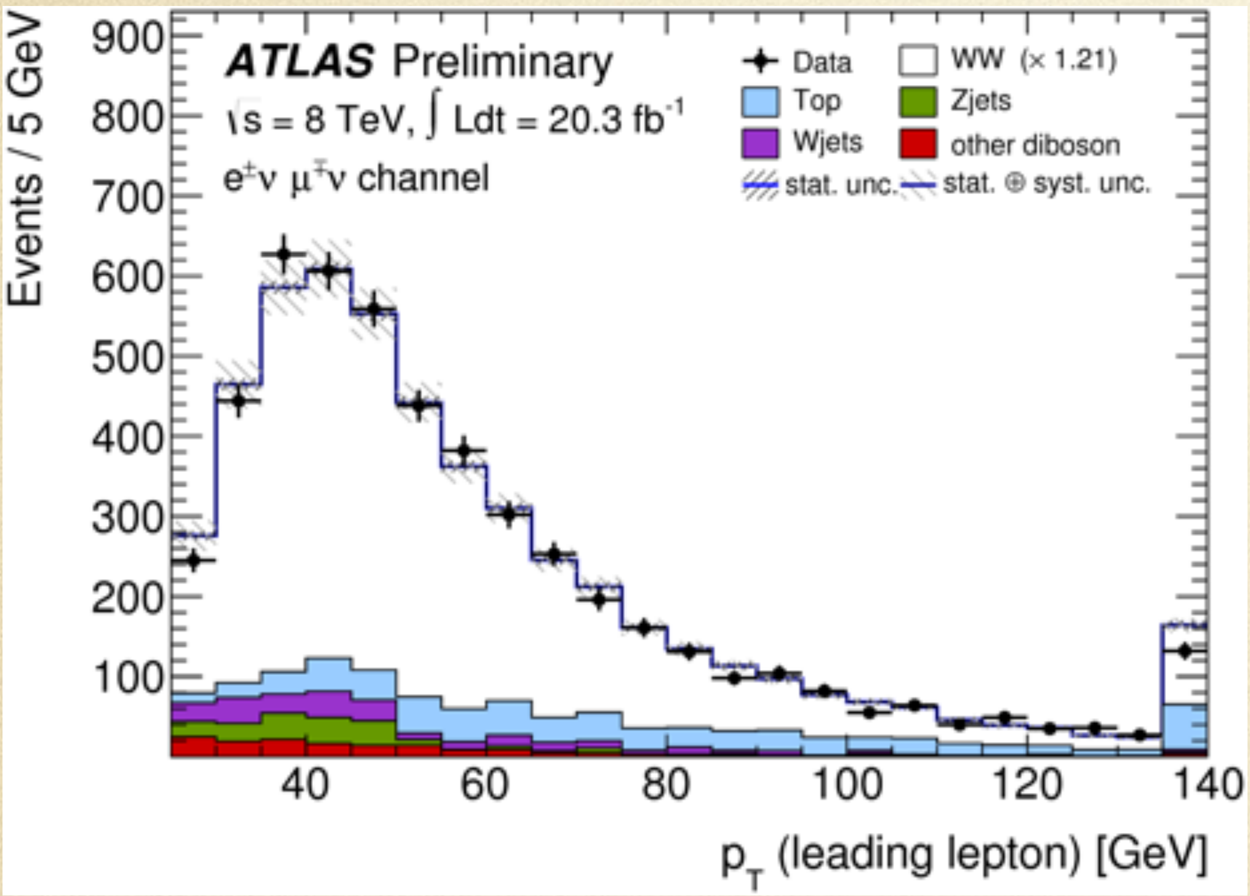
Feynrules -> MG5-> pythia->Delphes3

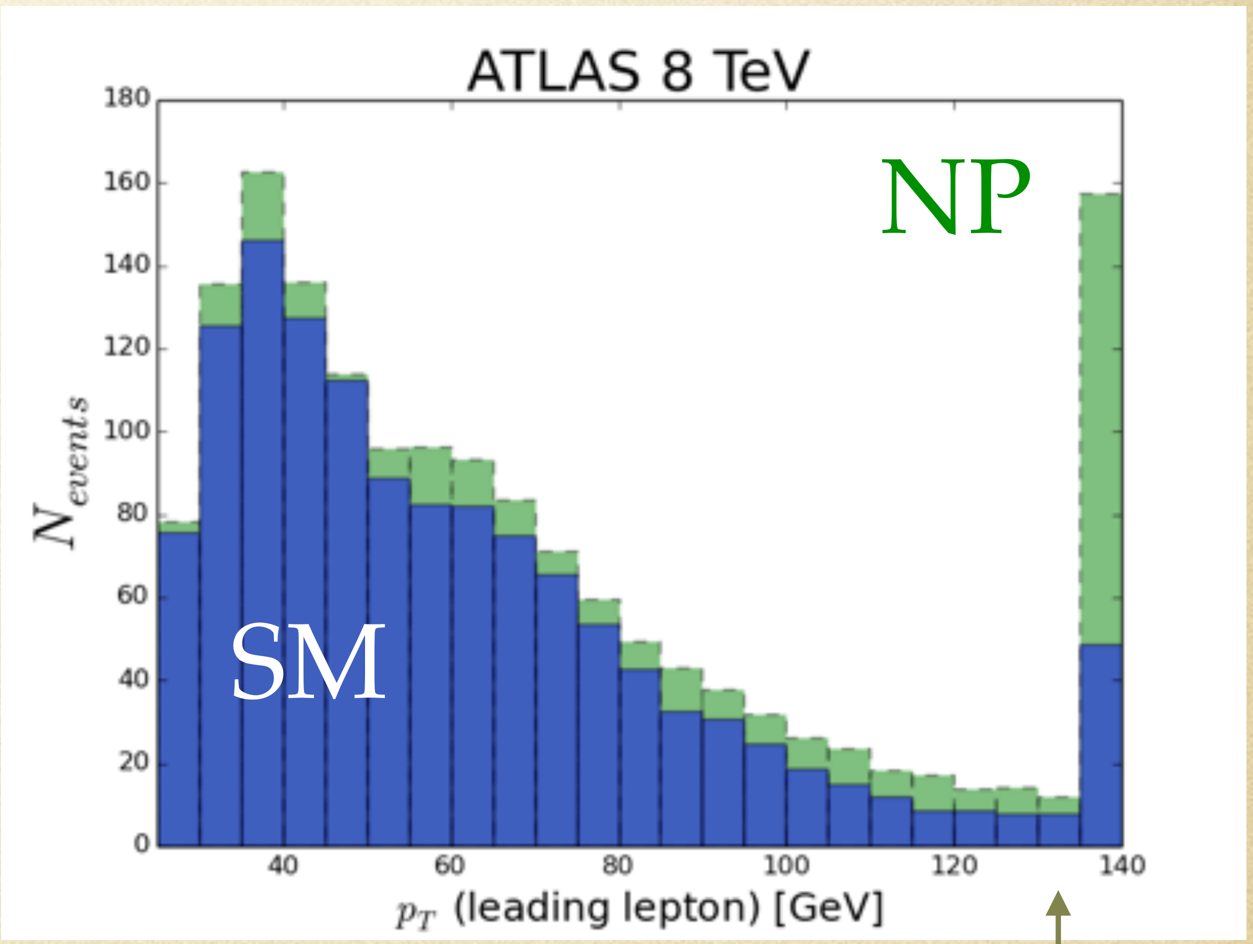
verified for SM/BGs => expectation for EFT

inclusive cross section is less sensitive than distribution

Diboson production at LHC8

Ellis, VS and You. 1404.3667, 1410.7703





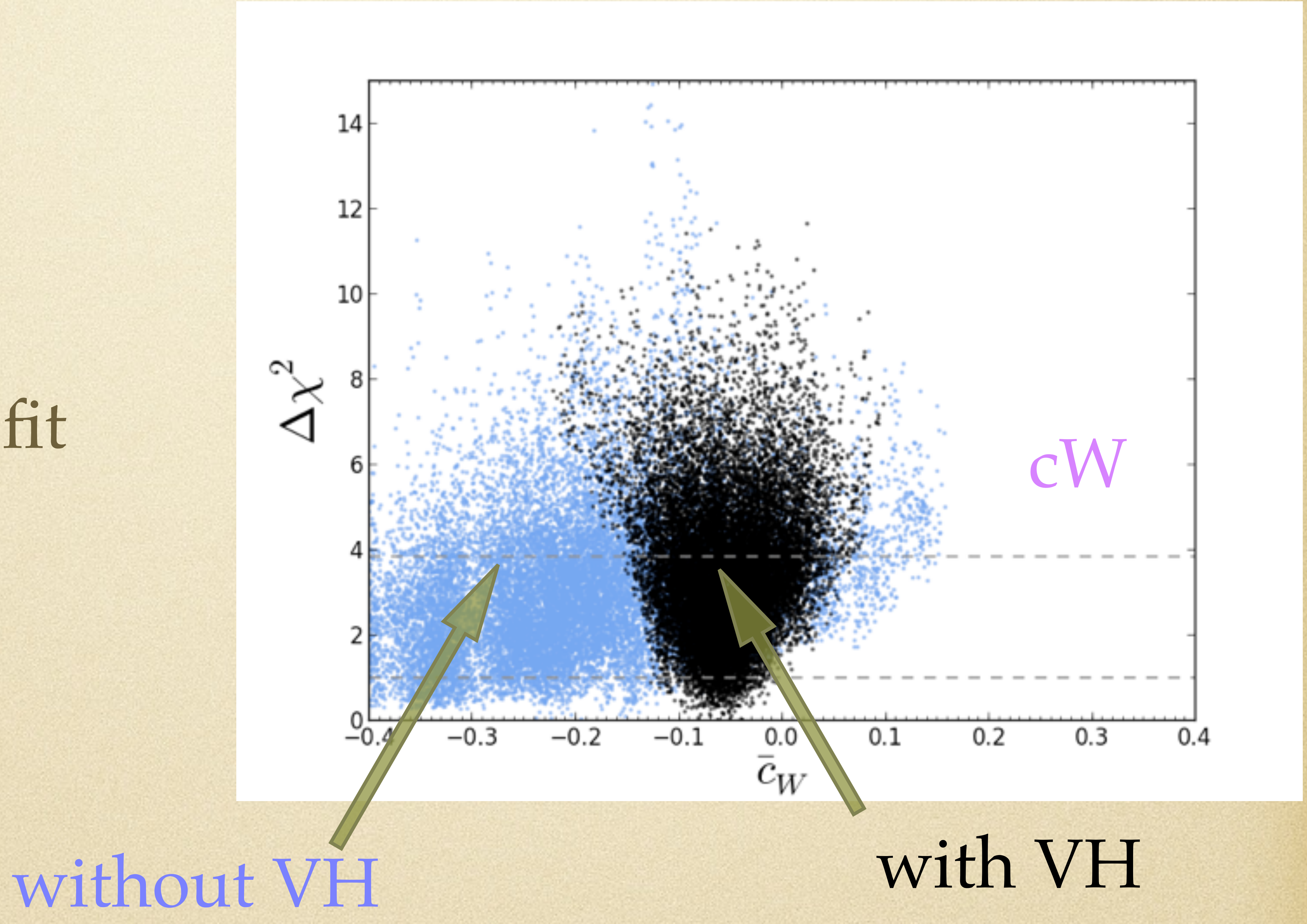
ATLAS-CONF-2014-033

overflow bin

we followed same validation procedure-> constrain EFT

breaking blind directions requires information on VH/diboson production

Global fit



Run1 constraints

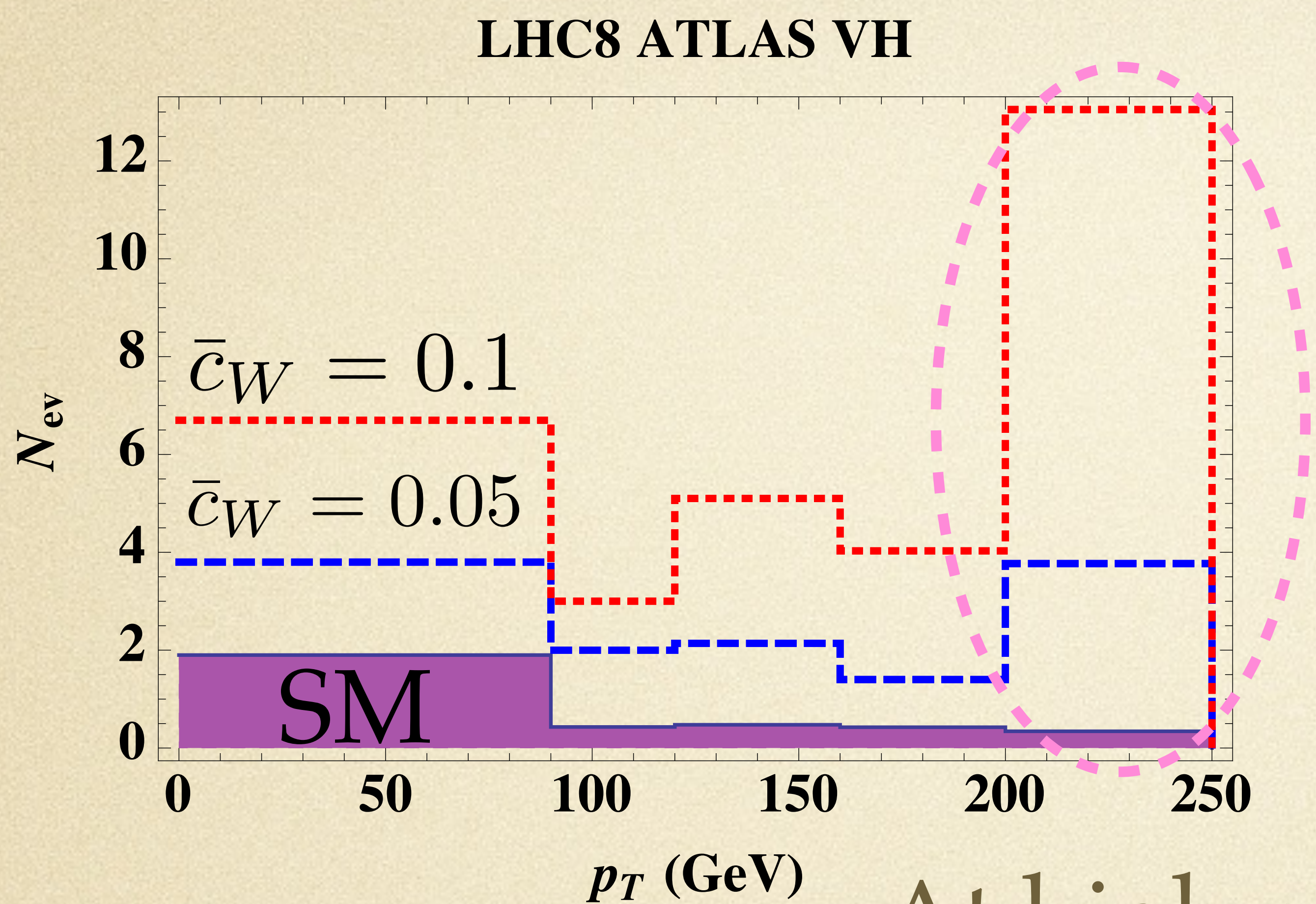
Ellis, VS and You. 1404.3667, 1410.7703

one-by-one global

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

Intrinsic limitations of the EFT

Validity of the EFT expansion

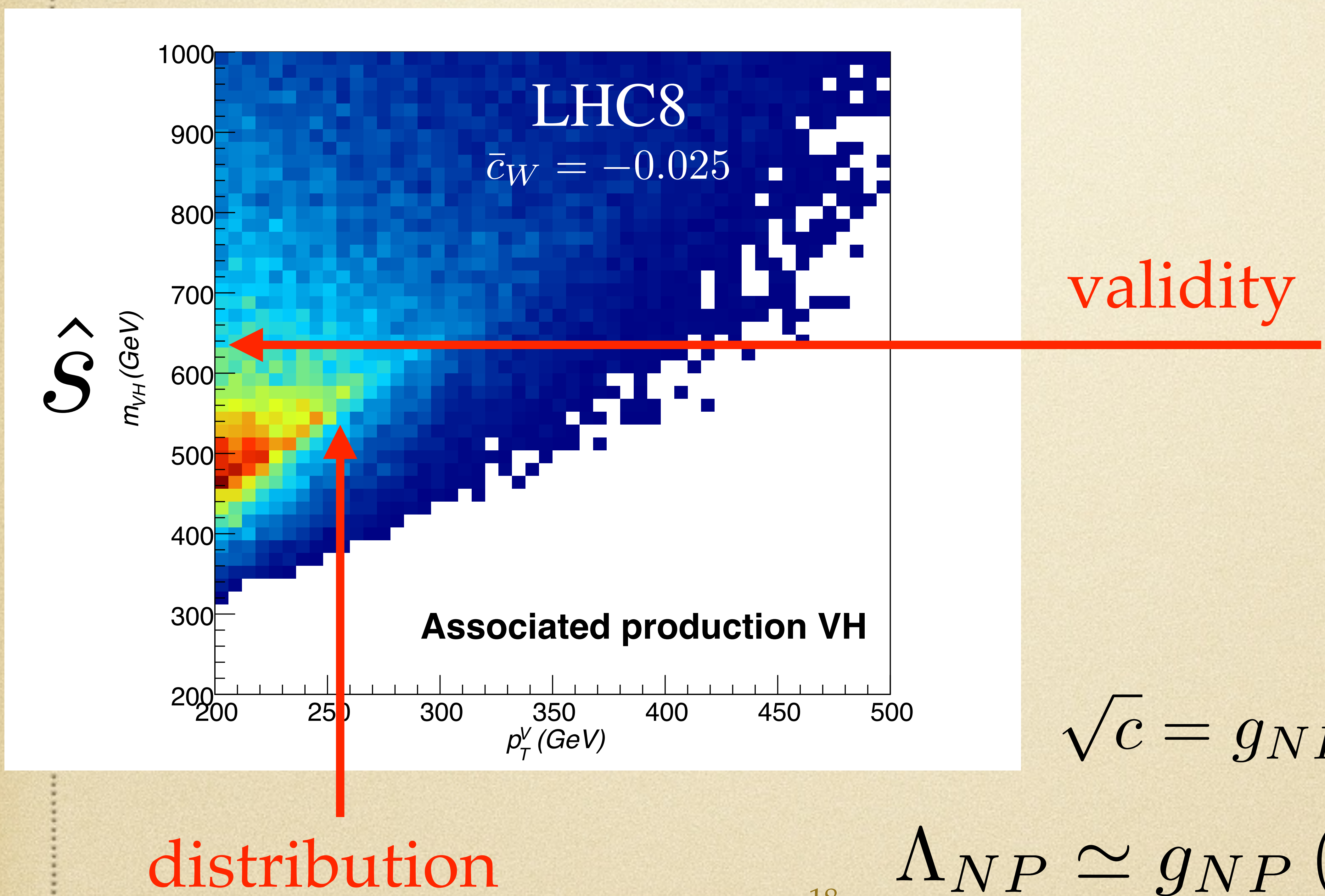


most sensitive bin:
overflow (last) bin

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?

see also
Biechoetter et al 1406.7320 Englert+Spannowsky. 1408.5147 Dawson, Lewis, Zeng 1409.6299

The distributions are cut-off by PDFs
quantitative breakdown depends on channel (cuts, final state) and on UV model (mass and type of operator)



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

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

Practical limitations

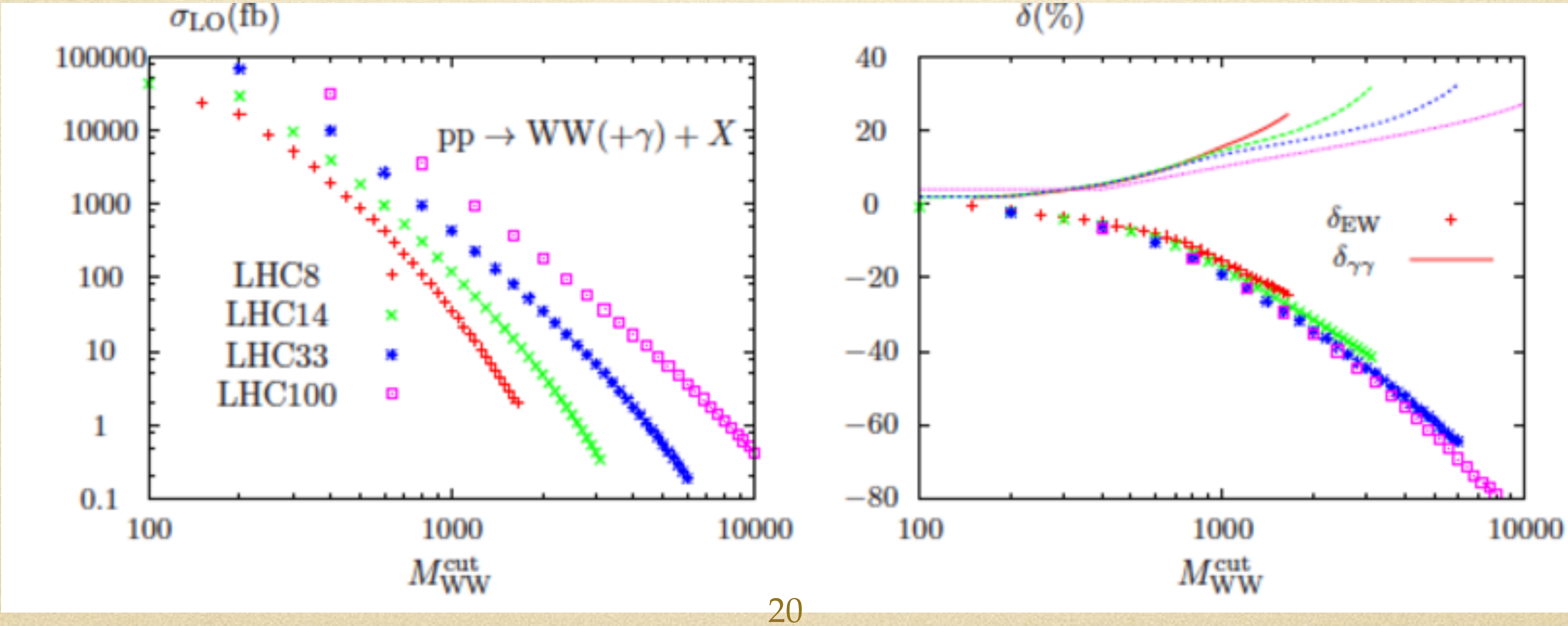
Precision, precision!

see next talk by Passarino

EFTs, anomalous couplings
tails on distributions
similar to higher-order SM effects

VH, VBF, H+jet, WW

NLO QCD and EW
if uncontrolled, mimic EFTs



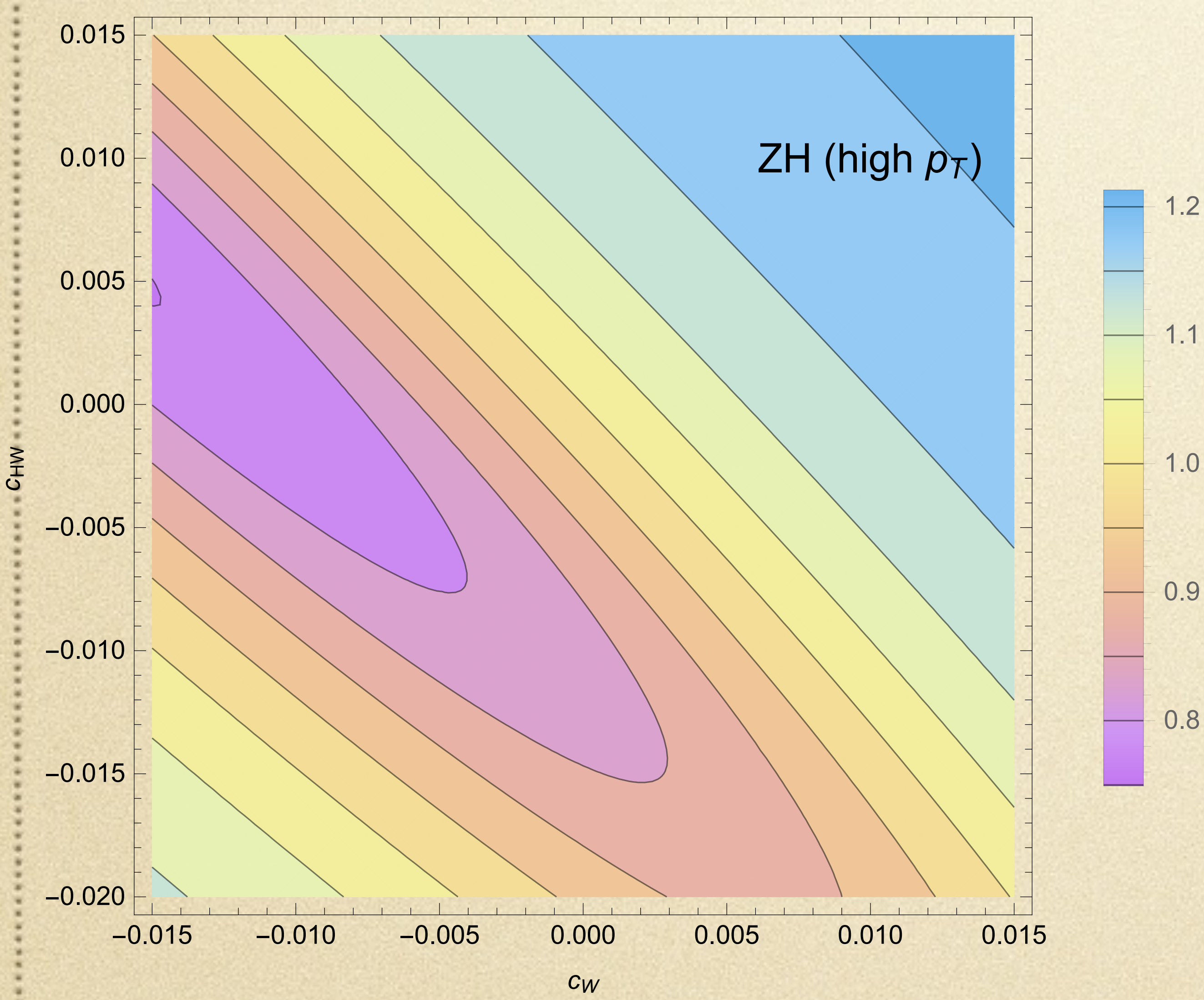
Snowmass QCD. 1308.1430

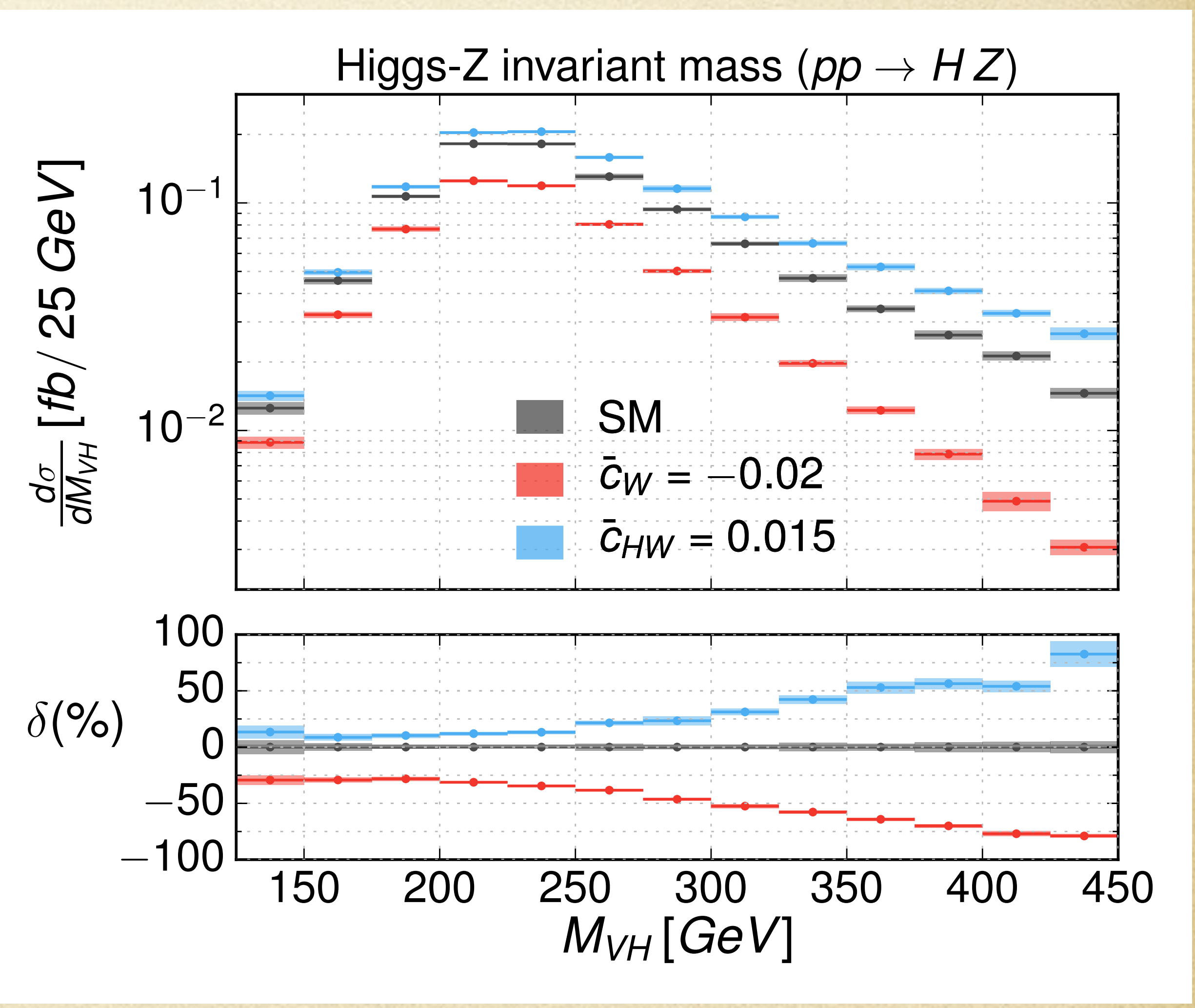
SM+EFT NLO QCD

Mimasu, VS, Williams. in prep

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

e.g. ZH





$$\mathcal{R}^{NLO}(\bar{c}_W, \bar{c}_{HW}) = \frac{\sigma^{NLO}(\bar{c}_W, \bar{c}_{HW})}{\sigma^{NLO}(0,0) + \sigma^{LO}(\bar{c}_W, \bar{c}_{HW}) - \sigma^{LO}(0,0)}$$

Connection to UV models

Does the EFT at LHC reach well-motivated models?

Run1 EFTs

Operator	Coefficient	LHC Constraints Individual	LHC Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W - c_B)$	$(-0.022, 0.004)$	$(-0.035, 0.005)$
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$\mathcal{O}_f = y_f\|H\|^2\bar{F}_L H^{(c)} f_R + \text{h.c.}$	$\frac{v^2}{\Lambda^2}c_f$	$(-0.084, 0.155)(c_u)$ $(-0.198, 0.088)(c_d)$	$(-,-)$ $(-,-)$

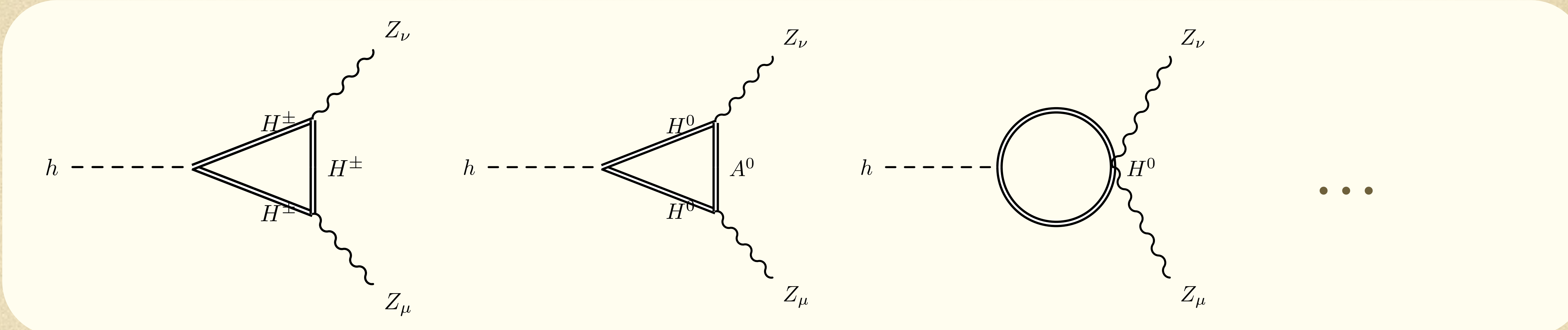
in units of the EW scale

Run2, ~order of magnitude increase
if differential distributions are/can be used

How do these numbers relate to models?

Example: 2HDM

Gorbahn, No and VS. 1502.07352



Matching to EFT

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

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

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

$$\bar{c}_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{192\,\pi^2\,\tilde{\mu}_2^2}$$

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

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

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

Run1 global fit

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

Ellis, VS and You. 1410.7703

still quite poor

$$m_{H,A} \simeq \mathcal{O}(100 \text{ GeV }) \text{ for } \lambda \simeq \mathcal{O}(1)$$

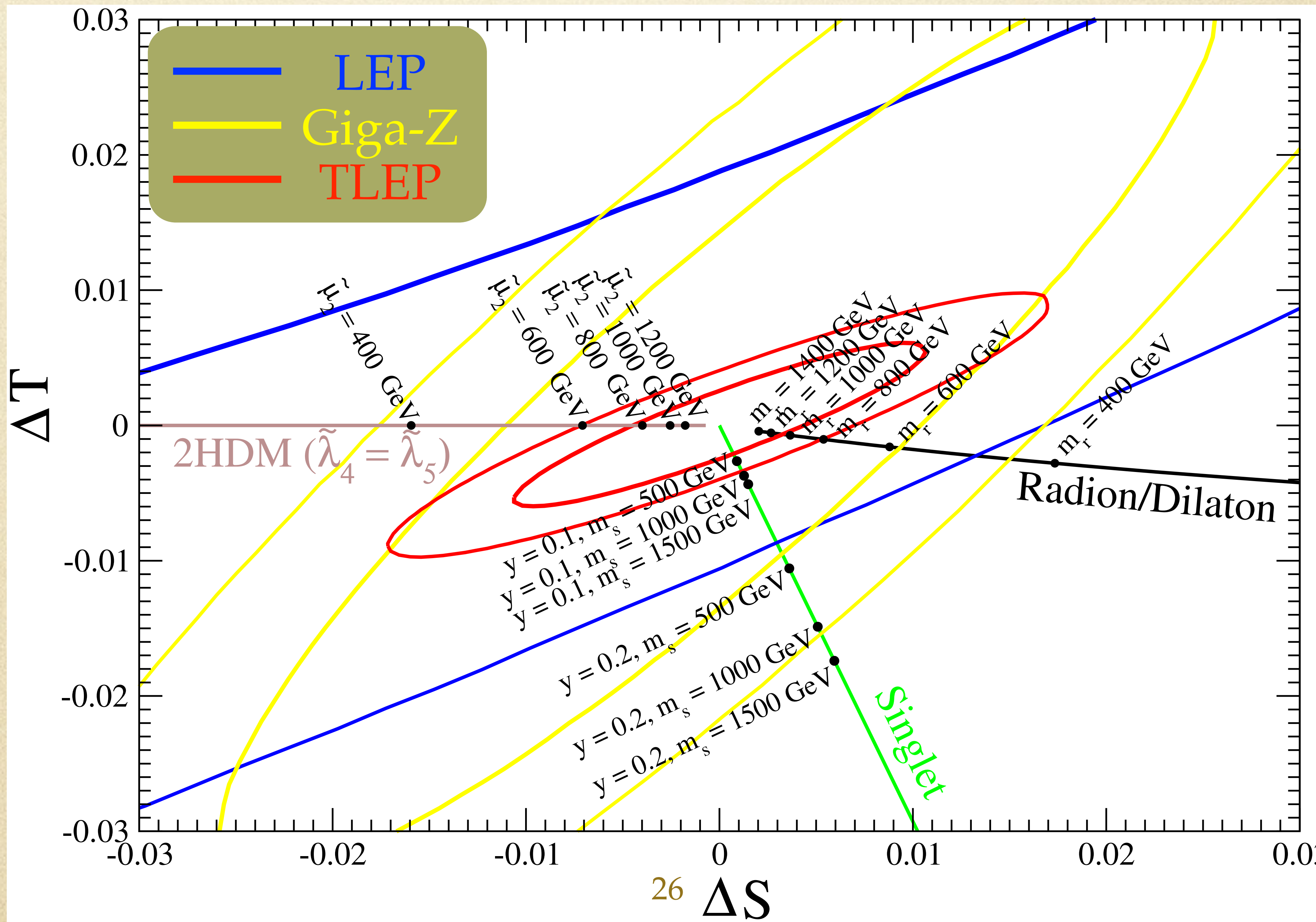
LHC to FCC-ee

The gain of precision

At a leptonic machine, LHCs practical and intrinsic limitations for EFTs can be circumvented
Also, increase in sensitivity means higher mass reach

Extended Higgs sectors

ILC-GigaZ 250 GeV, 1150 ifb
LEP 240 GeV, 500 ifb



Gorbahn, No and VS. 1502.07352

Conclusions

Absence of hints in direct searches

EFT approach to Higgs physics

Higgs anomalous couplings:

rates but also kinematic distributions

Complete global fit at the level of dimension-six operators

enhanced using differential information

SM precision crucial: excess as genuine new physics

Exploring the validity of EFT

propose benchmarks

Benchmarks

correlations among coefficients, input for fit

Leptonic machine

more suited for an EFT approach

impressive mass reach for weakly coupled models