Using kinematic distributions within EFTs

Veronica Sanz (Sussex)

Higgs+jets (IPPP, Durham)

Outline

- New Physics and EFTs
- Anomalous couplings vs EFTs
- The set-up
- Current status
- EFT->Models
- Limitations of EFTs

New Physics and EFTs

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

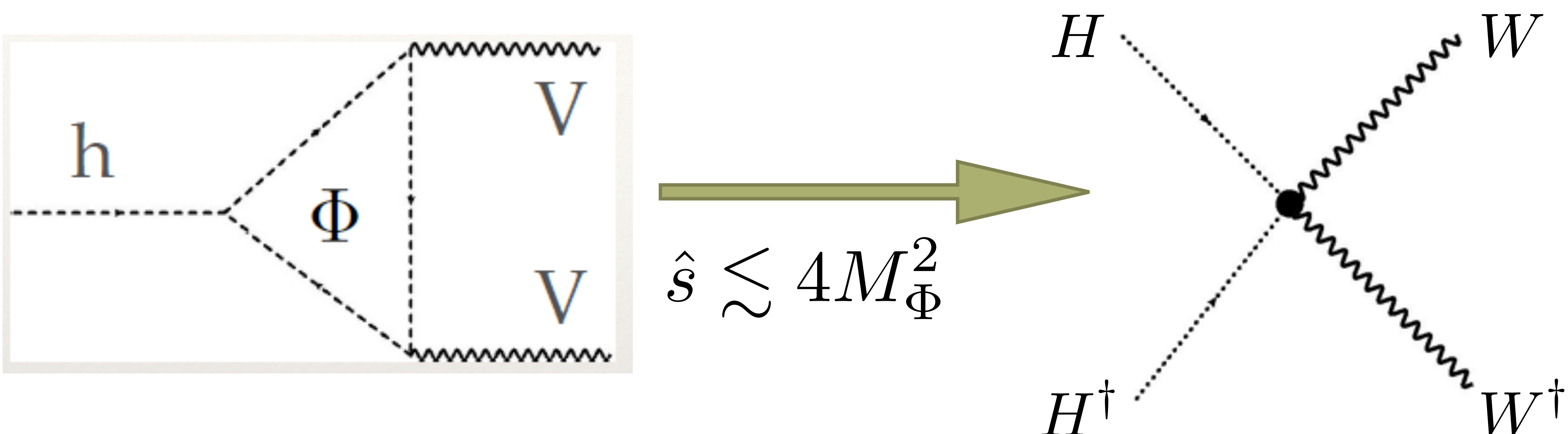
The guide to discover New Physics may come from precision, and not through direct searches

New Physics could be **heavy**

as compared with the channel we look at

Effective Theory approach

Example.



2HDMs

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

EFT

Bottom-up approach

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

Buchmuller and Wyler. NPB (86)

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

↓ 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

EFT

<u>Bottom-up approach</u>

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

Many such operators but few affect the searches we do

Example 2. LHC physics

operators **not** constrained by LEP

Operator
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$
$\mathcal{O}_\gamma = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$
$\mathcal{O}_f = y_f \lvert H\rvert^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$

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

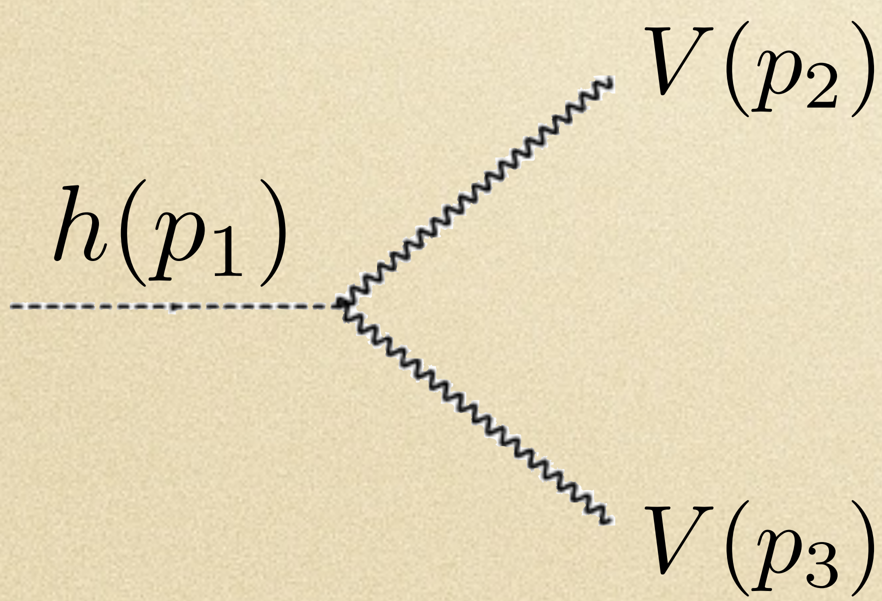
$$-\frac{1}{4}h\, g^{(1)}_{hVV} V_{\mu\nu}V^{\mu\nu} \quad -h\, g^{(2)}_{hVV} V_{\nu}\partial_{\mu}V^{\mu\nu} \quad -\frac{1}{4}h\, \tilde{g}_{hVV} V_{\mu\nu}\tilde{V}^{\mu\nu}$$

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

Example. Higgs anomalous couplings

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

Feynman rule for mh>2mV



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

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

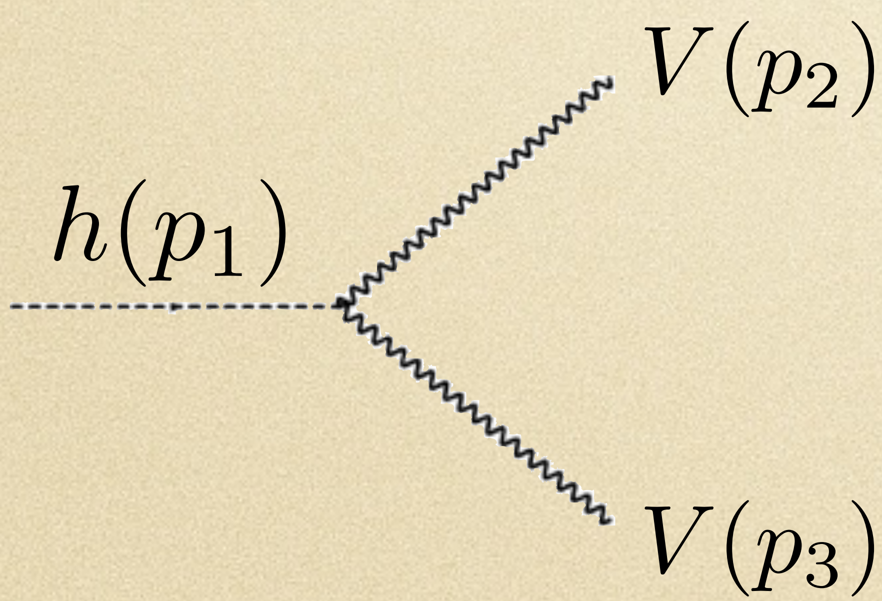
$$-i \tilde{g}_{hVV} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

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

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

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

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

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

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

Alloul, Fuks, VS. 1310.5150
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**

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

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

similarly for QGCs: also function of the same HDOs

Alloul, Fuks, VS. 1310.5150

Gorbahn, No, VS. In preparation

The set-up

Higgs BRs eHDECAY

Contino et al. 1303.3876

Higgs BRs eHDECAY Contino et al. 1303.3876

Production rates and kinematic distributions

depend on cuts

need radiation and detector effects

Simulation tools

Higgs BRs eHDECAY Contino et al. 1303.3876

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

In this talk I use

1. Feynrules   HDOs involving Higgs and TGCs

Alloul, Fuks, VS. 1310.5150

links to CalcHEP, LoopTools, Madgraph...

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

In this talk I use

1. Feynrules HDOs involving Higgs and TGCs

Alloul, Fuks, VS. 1310.5150

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

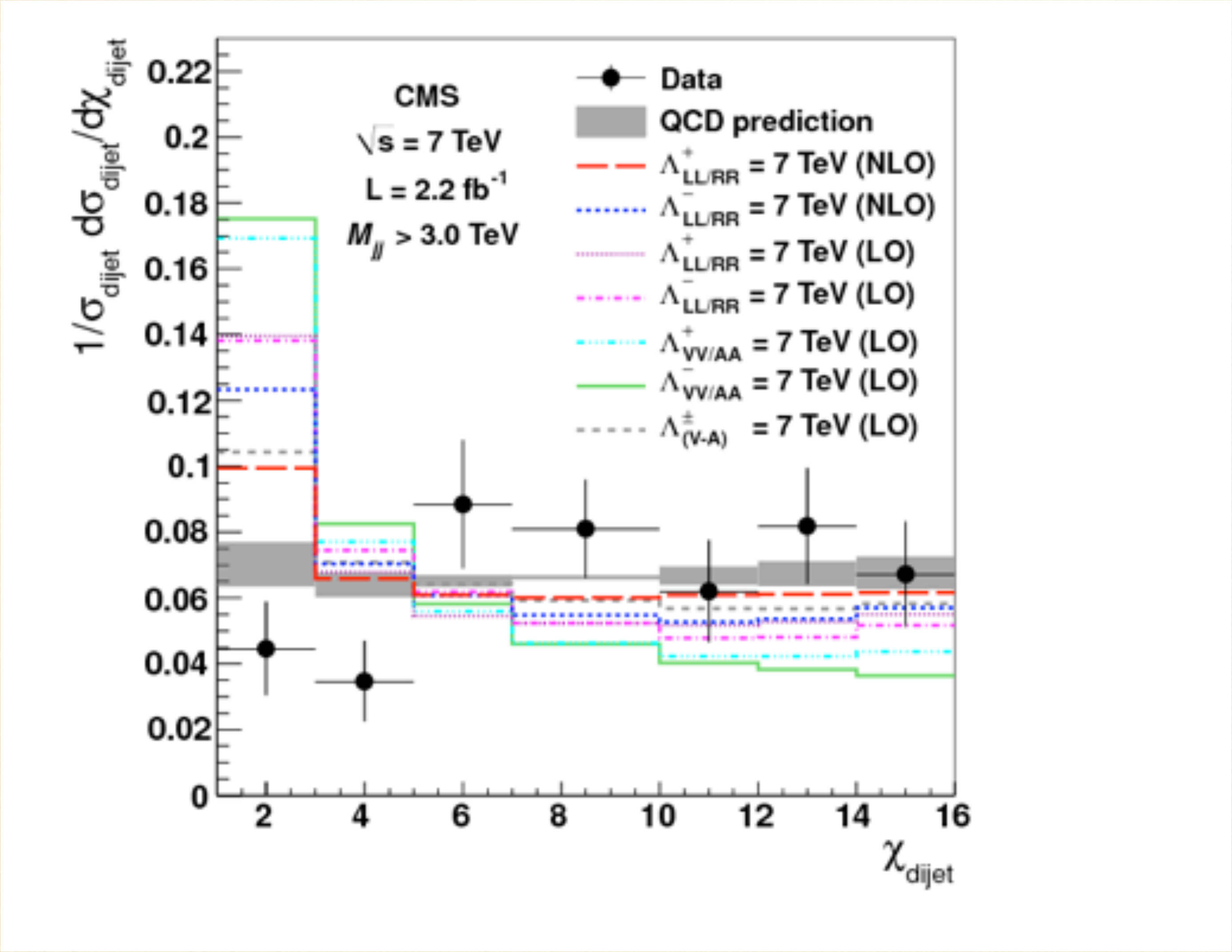
de Grande, Fuks, Mawatari, Mimasu, VS. In preparation for MC@NLO

Looking for heavy New Physics current status

Ellis, VS and You. 1404.3667, 1410.7703

HDOs affect momentum dependence: angular, pT and inv mass distributions

Usual searches,

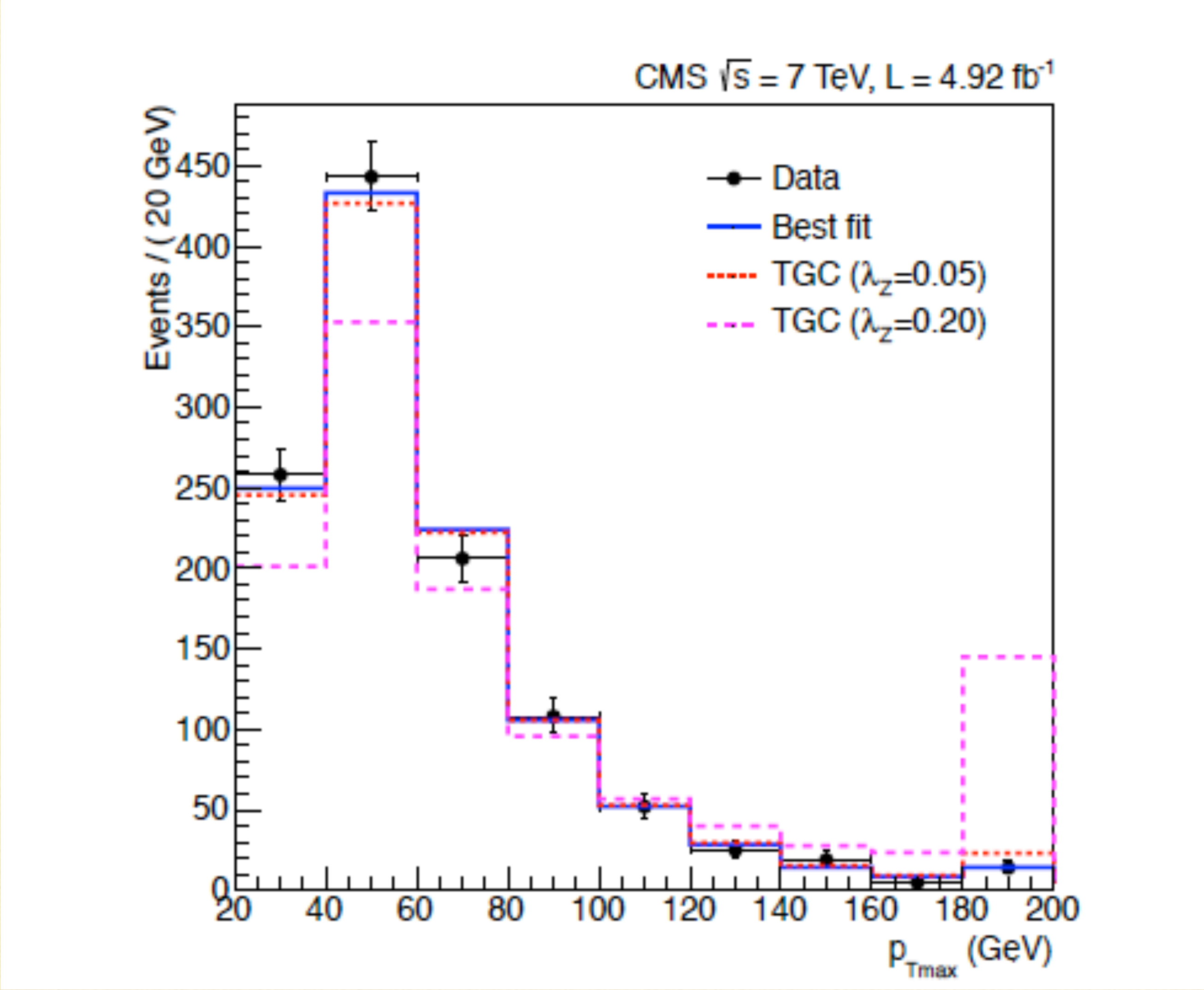


Dijet angular distribution

ex. dijet searches

HDOs affect momentum dependence: angular, pT and inv mass distributions

Usual searches,



leading lepton pT

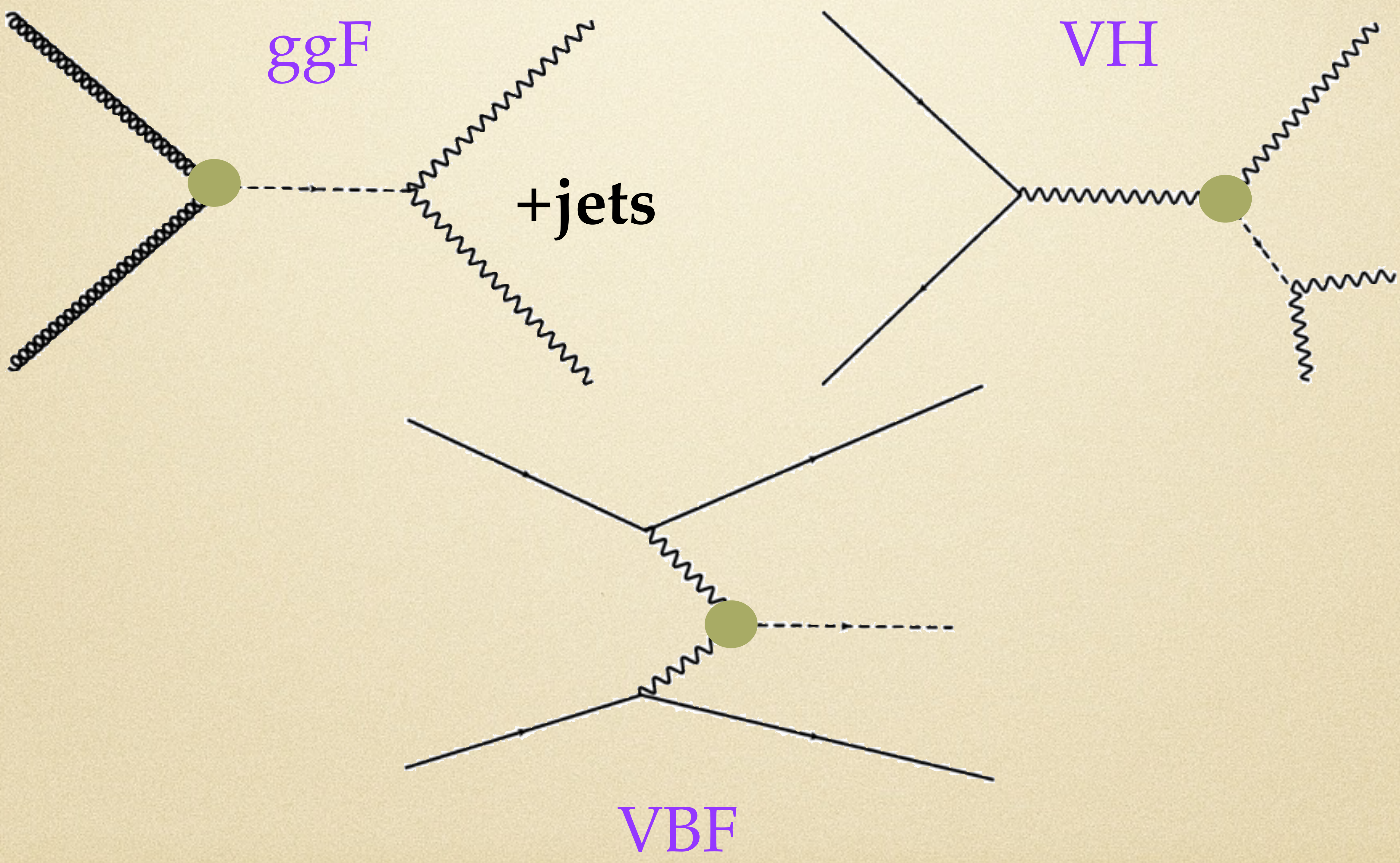
ex. TGCs

kinematic distribution best way to bound TGCs

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

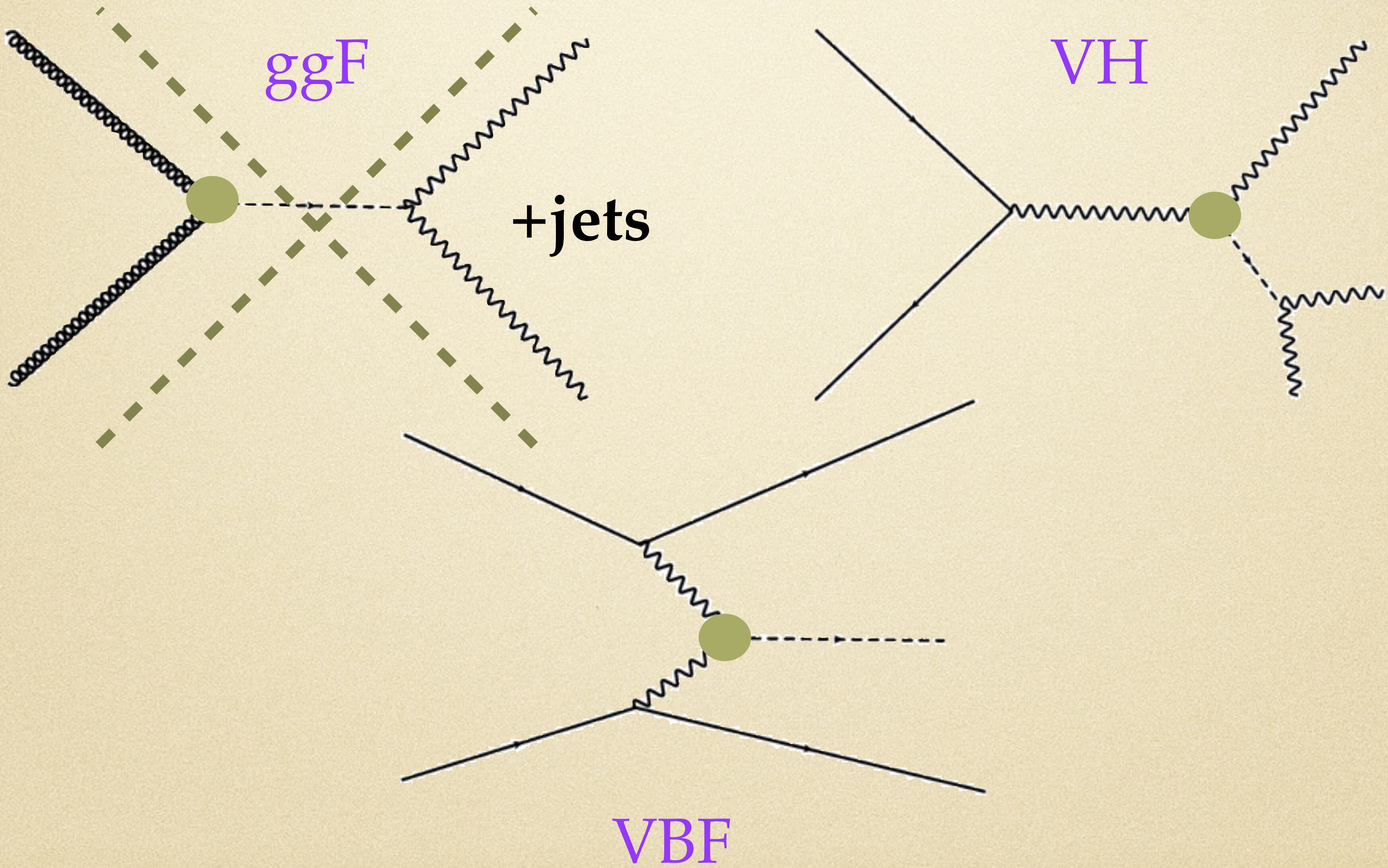
What about Higgs physics?

Using kinematics for NP : a non-SM HDO and some boost

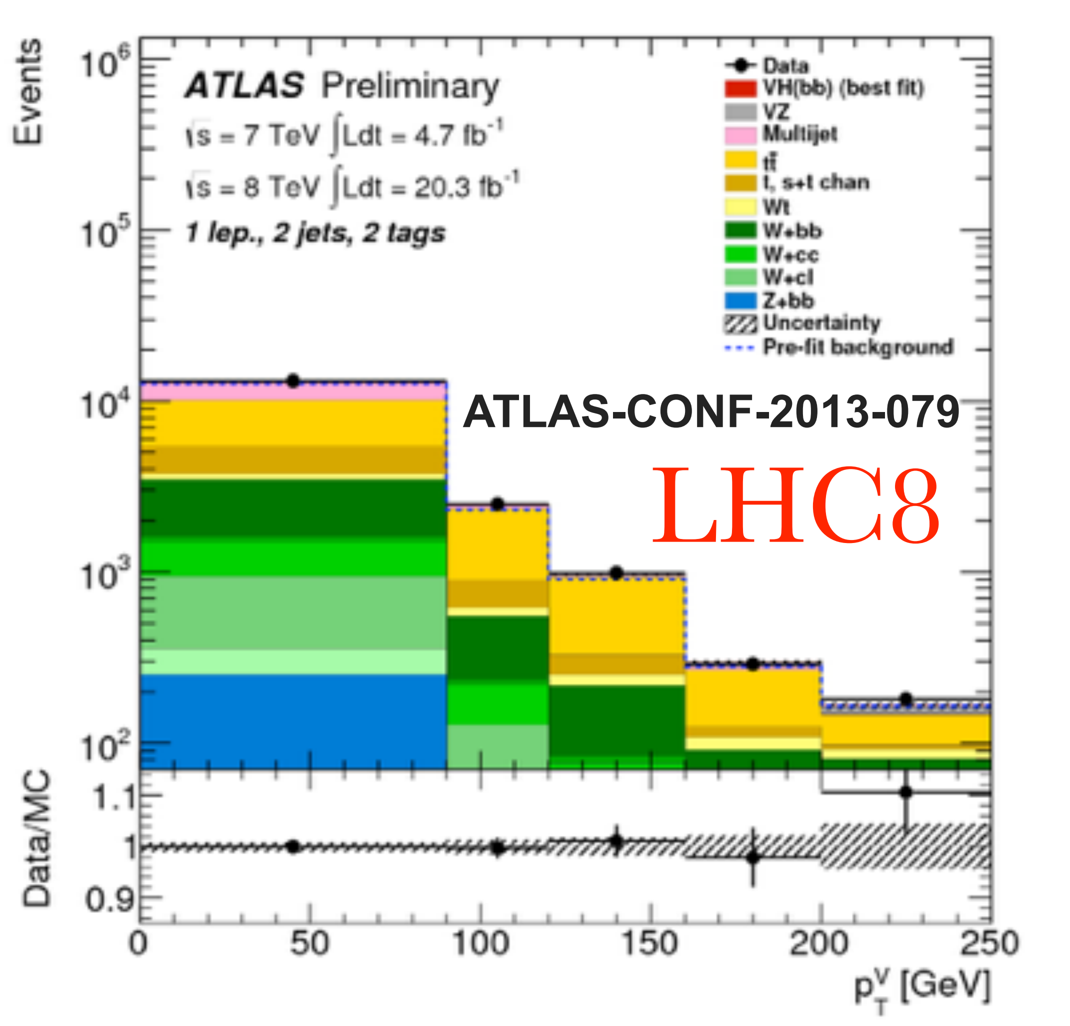


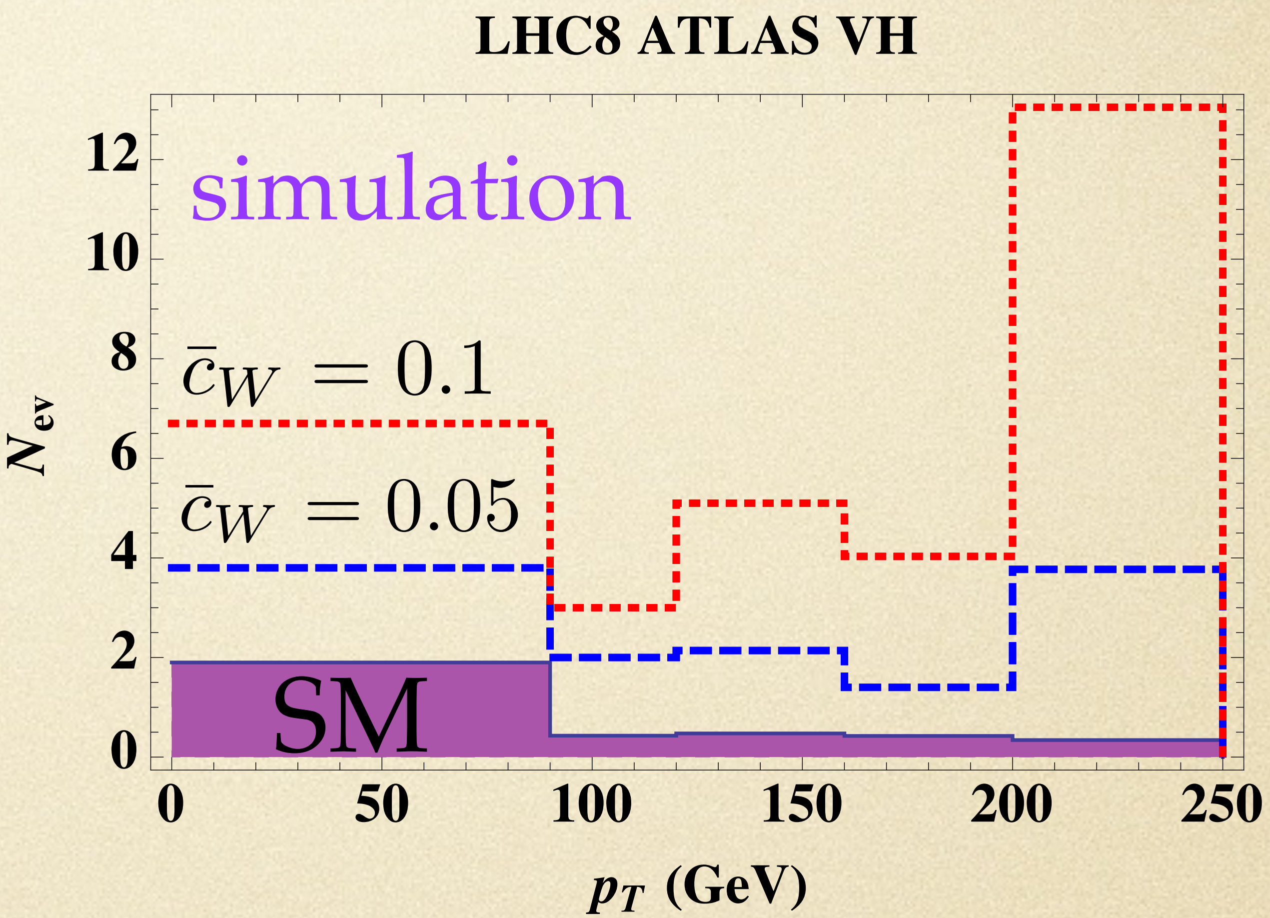
What about Higgs physics?

Using kinematics for NP : a non-SM HDO and some boost



Kinematics of associated production at LHC8





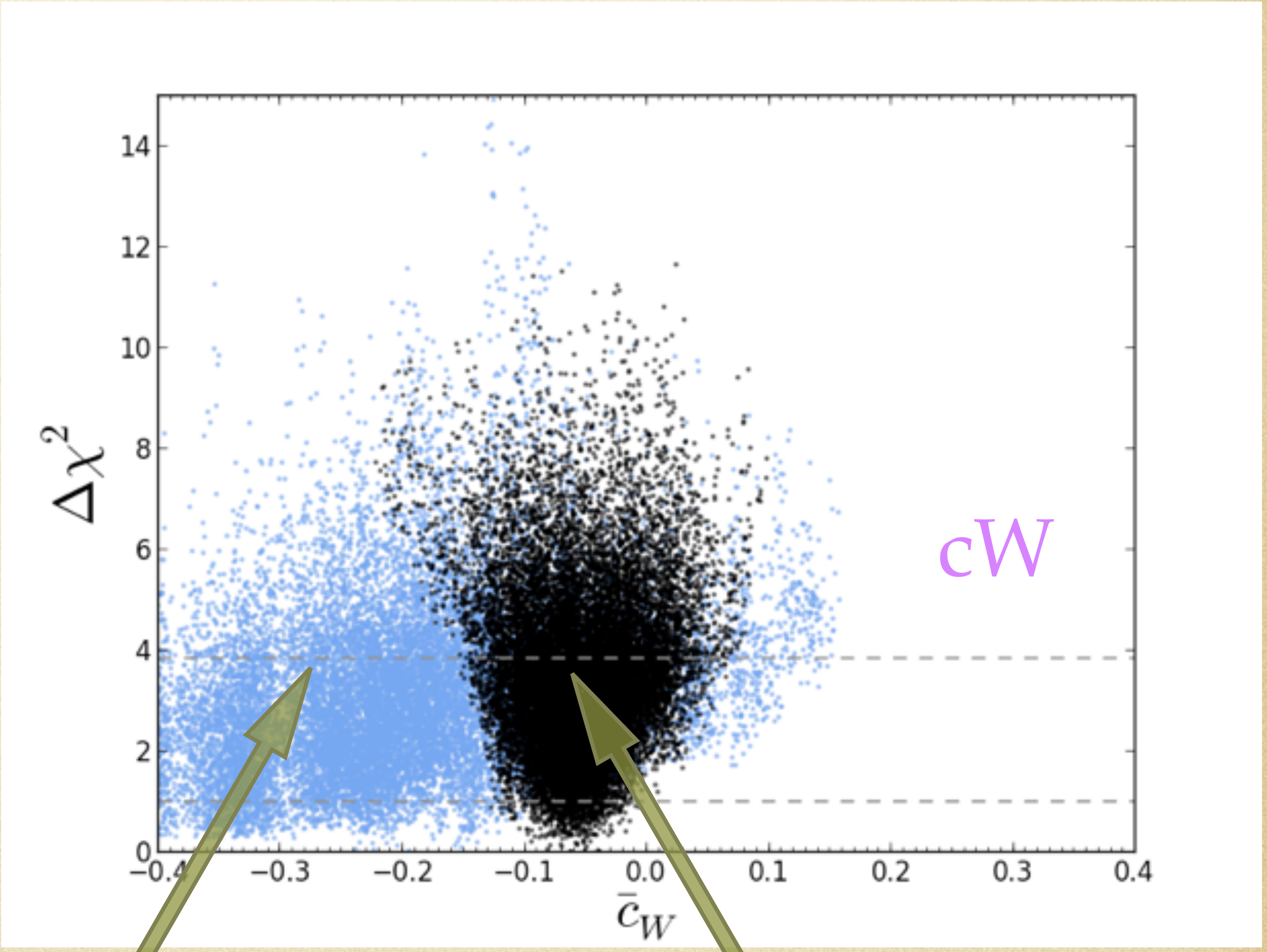
Feynrules -> MG5-> pythia->Delphes3

verified for SM/BGs => expectation for EFT

inclusive cross section is less sensitive than distribution

Besides, breaking of blind directions requires information on HV production

Global fit

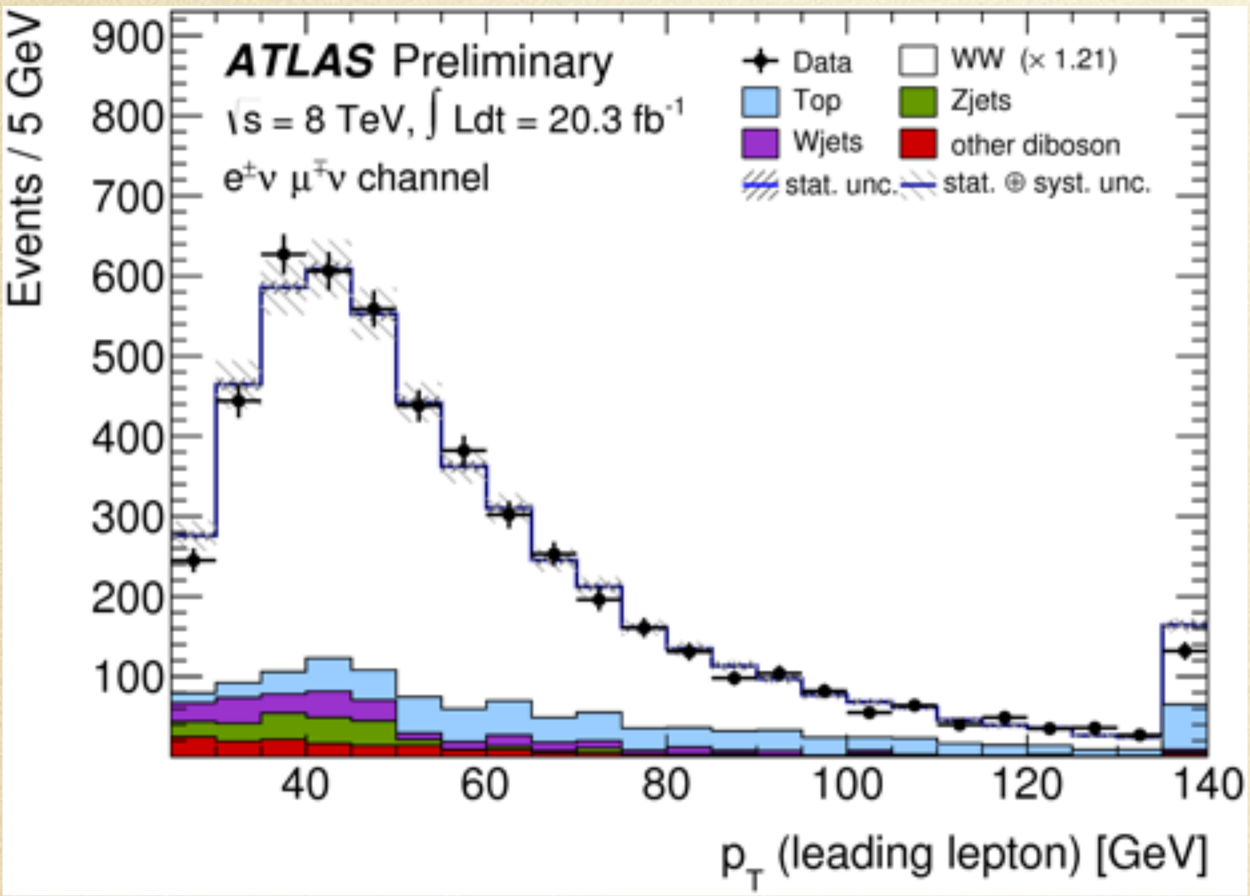


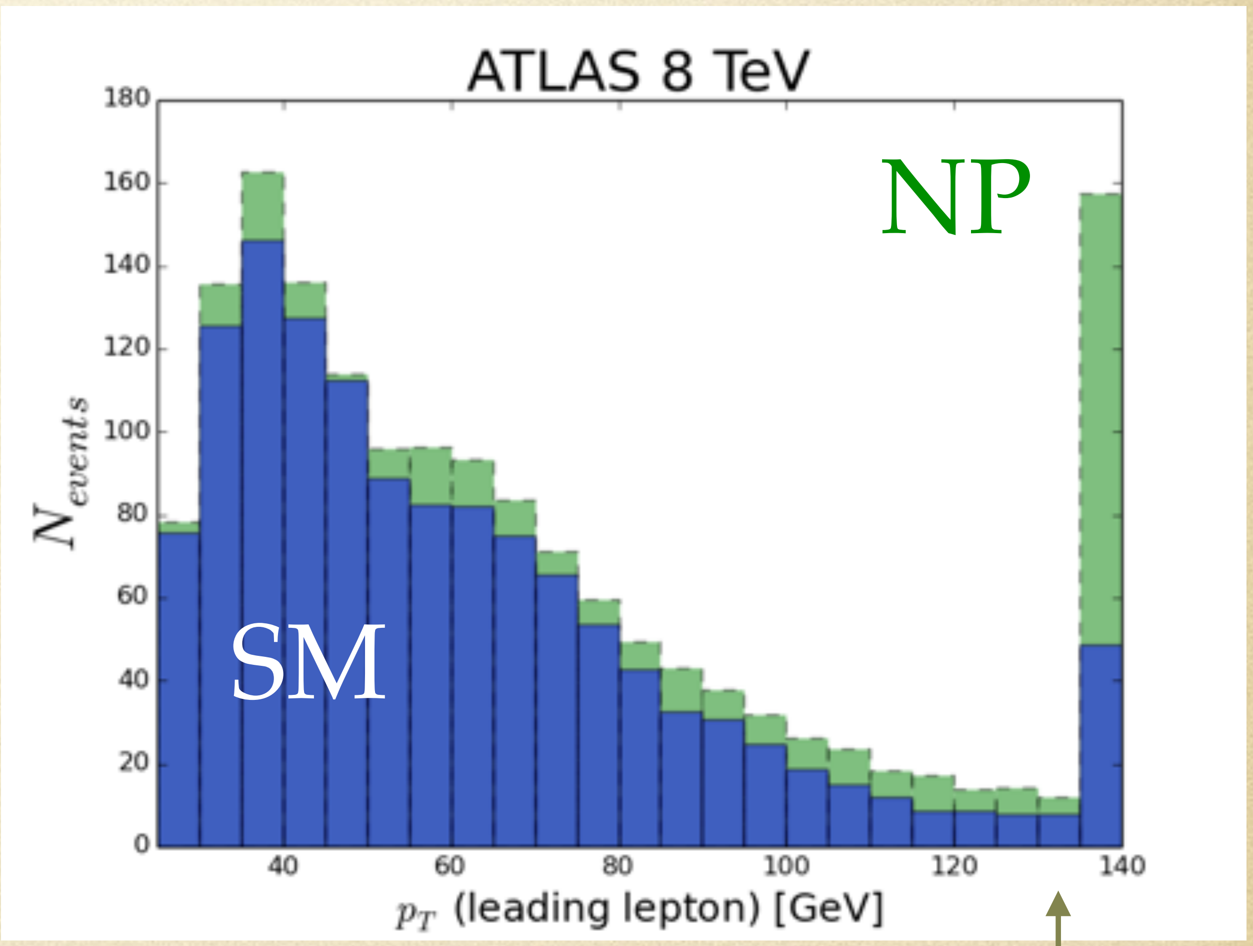
cW

without VH

with VH

TGCs constrains new physics too



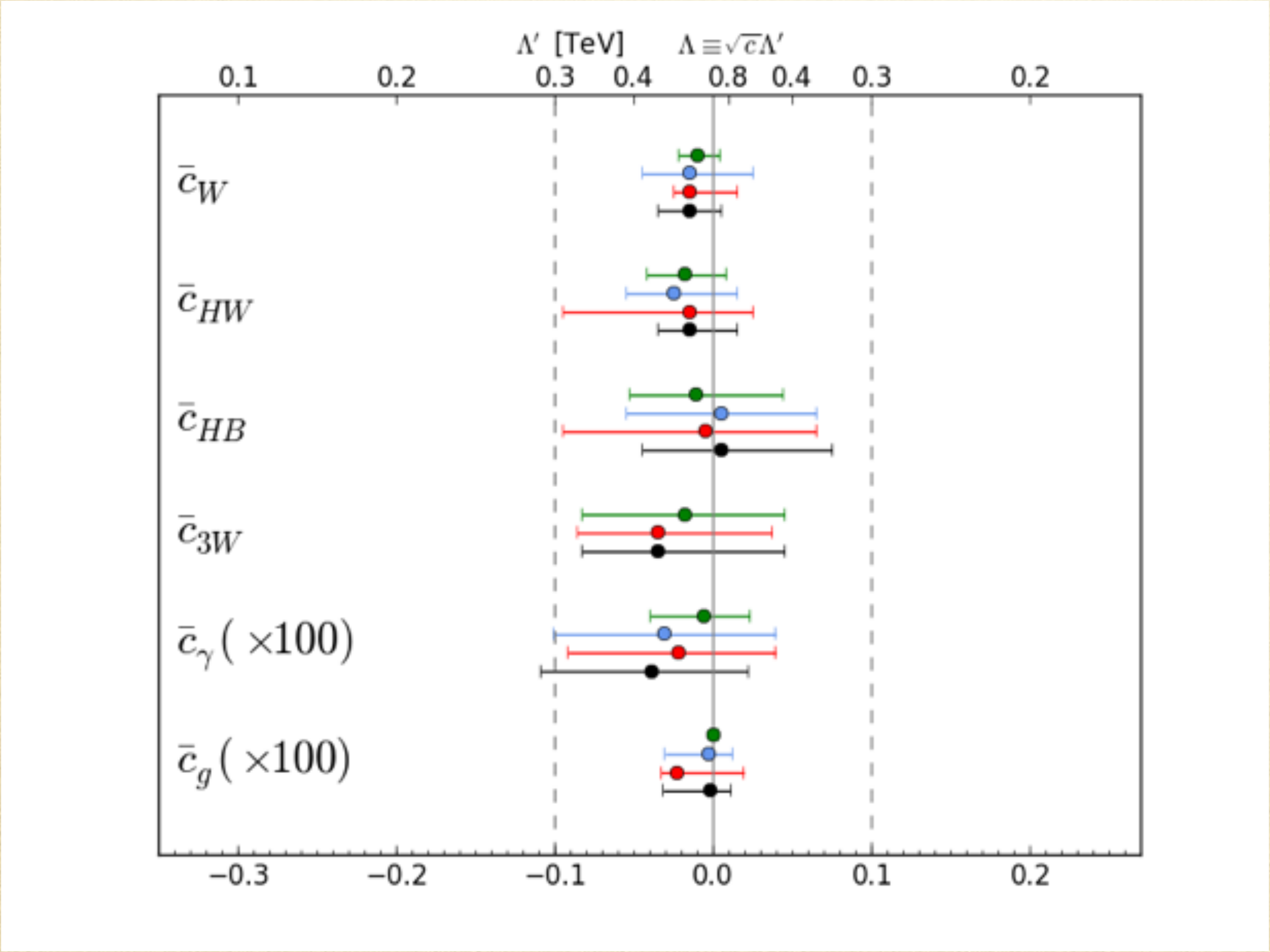


ATLAS-CONF-2014-033

overflow bin

we followed same validation procedure-> constrain HDOs

Kinematic distributions in TGC and VH are complementary



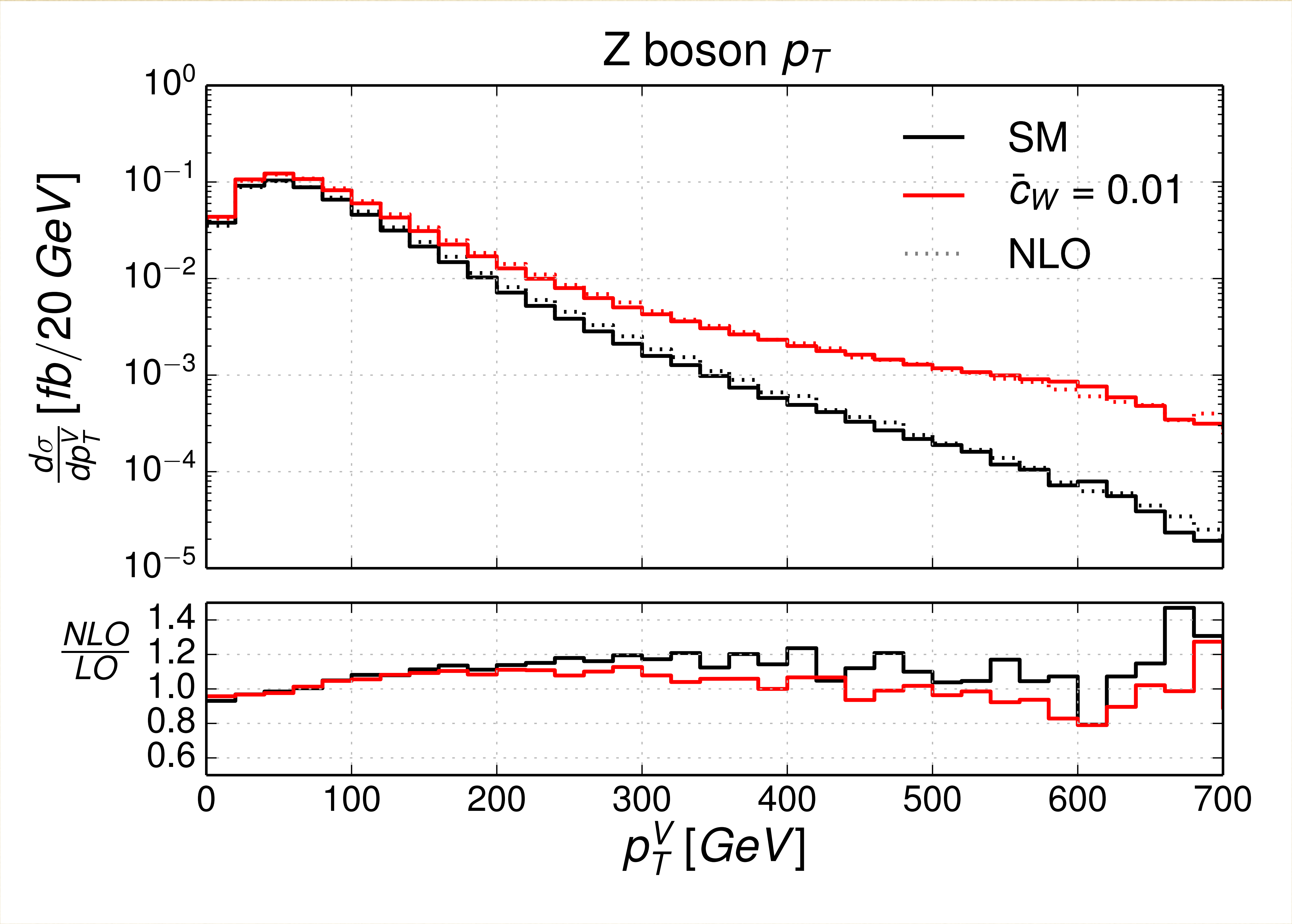
muhat+VH

muhat+TGC

all

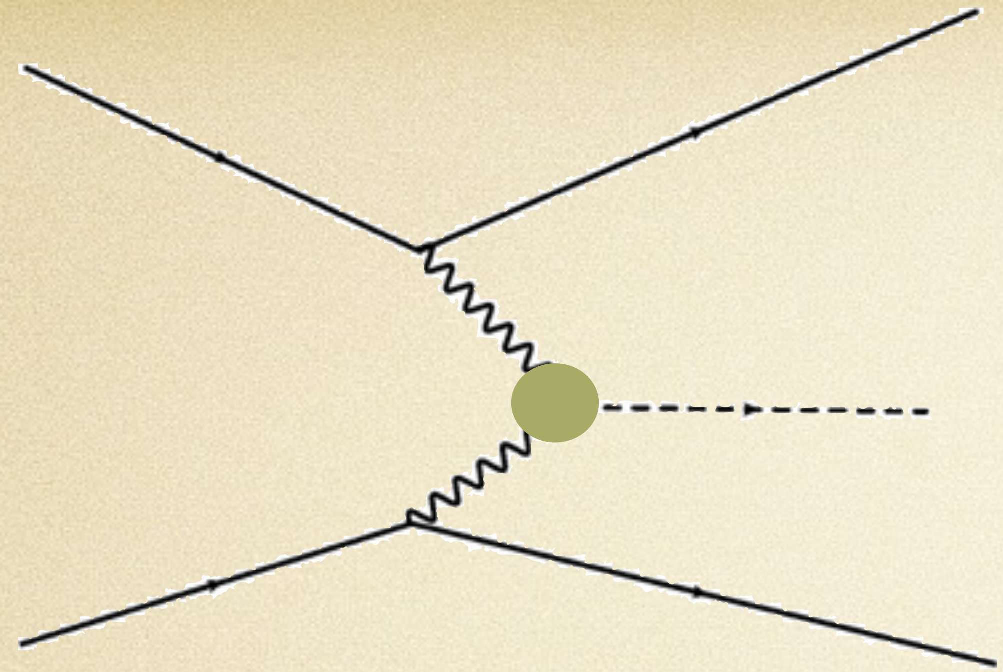
Operator	Coefficient	LHC Constraints Individual	LHC Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W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

LO vs NLO, briefly

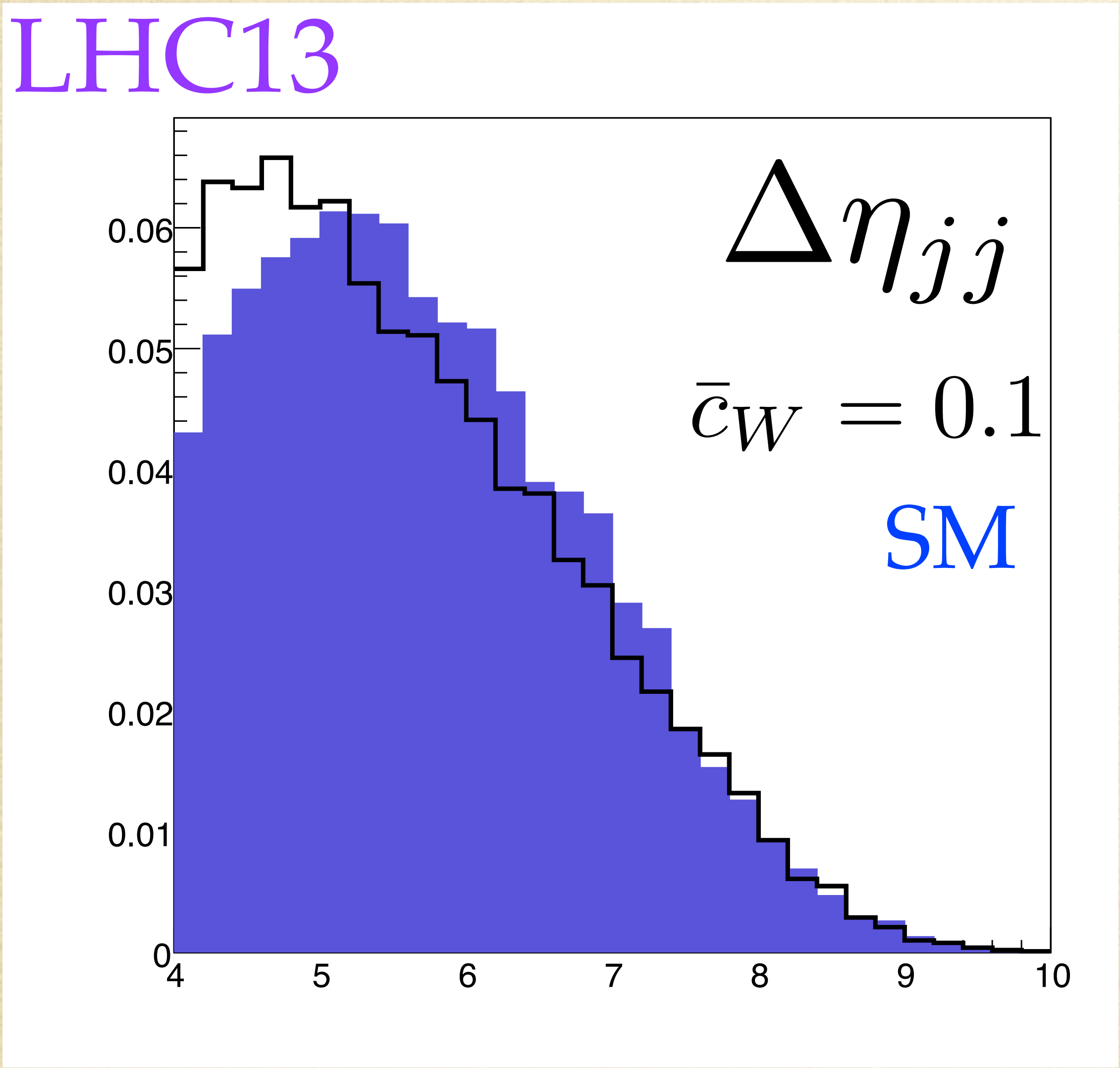


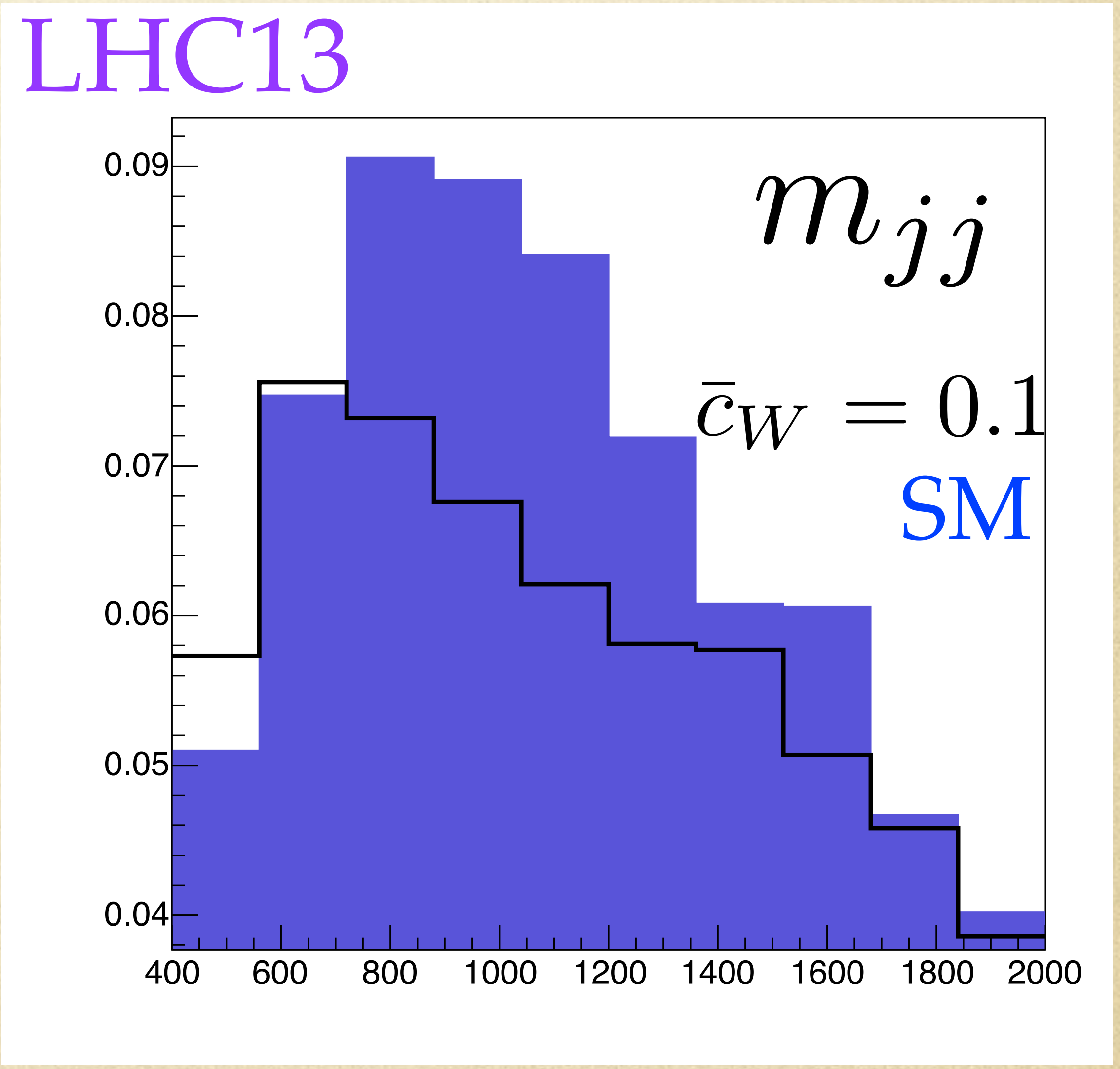
MCFM *in development*

VBF, briefly



Kinematics of VBF also modified yet more difficult discrimination





EFT->Models

Masso and VS. 1211.1320

Gorbahn, No and VS. In preparation

EFT (linear realization) vs UV-completions

UV models

Example 1.

tree-level operators

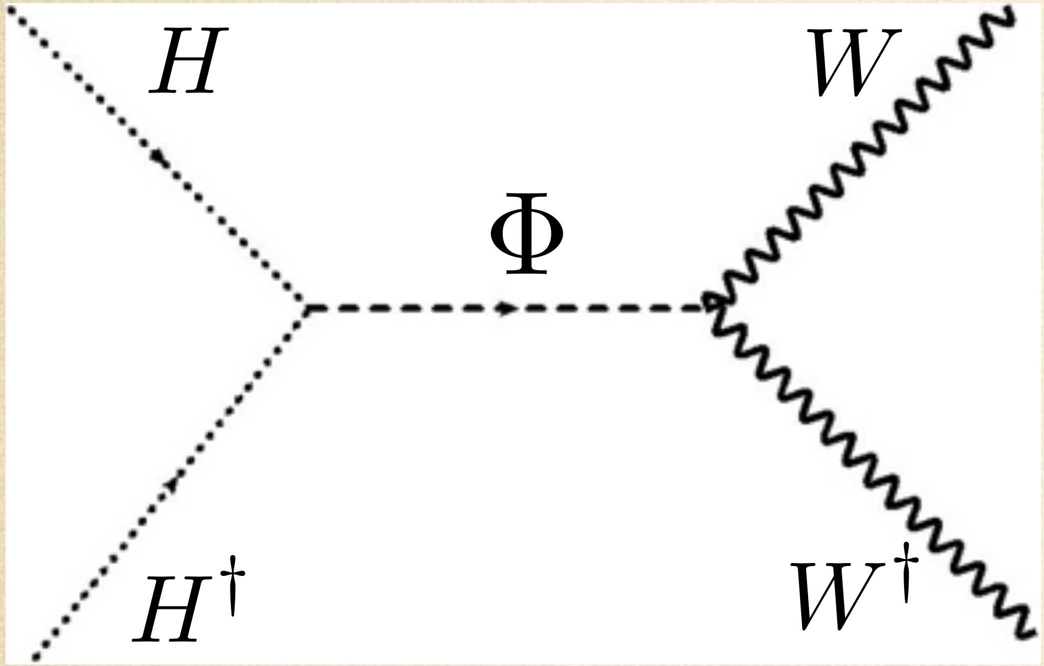
radion/dilaton exchange

Example 2.

loop-induced operators

2HDM and SUSY spartners

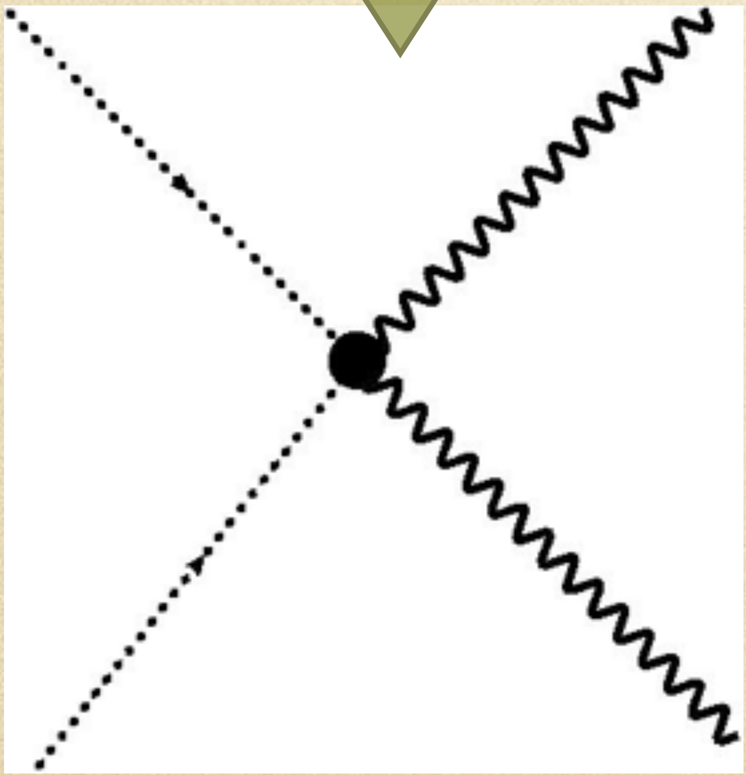
Example 1. Tree-level exchange *radion/dilaton*



$$\frac{g_\Phi^2}{\hat{s} - M_\Phi^2} \simeq -\frac{g_\Phi^2}{M_\Phi^2}\left(1 - \frac{\hat{s}}{M_\Phi^2} + \dots\right)$$

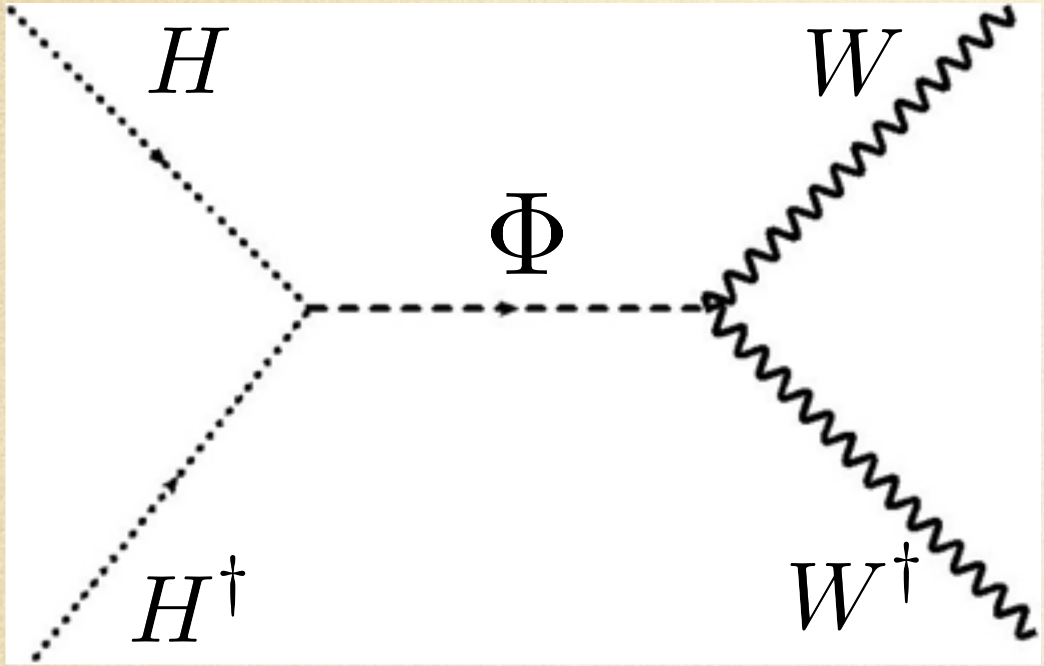
$$\hat{s} \lesssim M_\Phi^2$$

HEFT

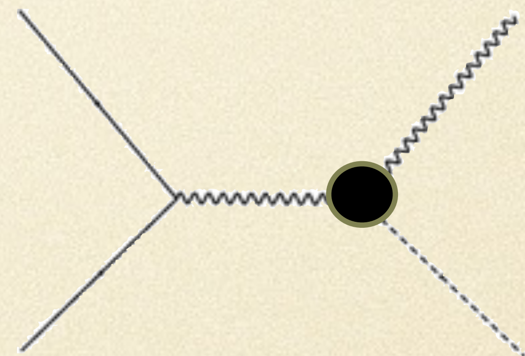


$$\bar{c}_W \simeq \left(\frac{m_H v}{\Lambda M_\Phi}\right)^2$$

Example 1. Tree-level exchange *radion/dilaton*

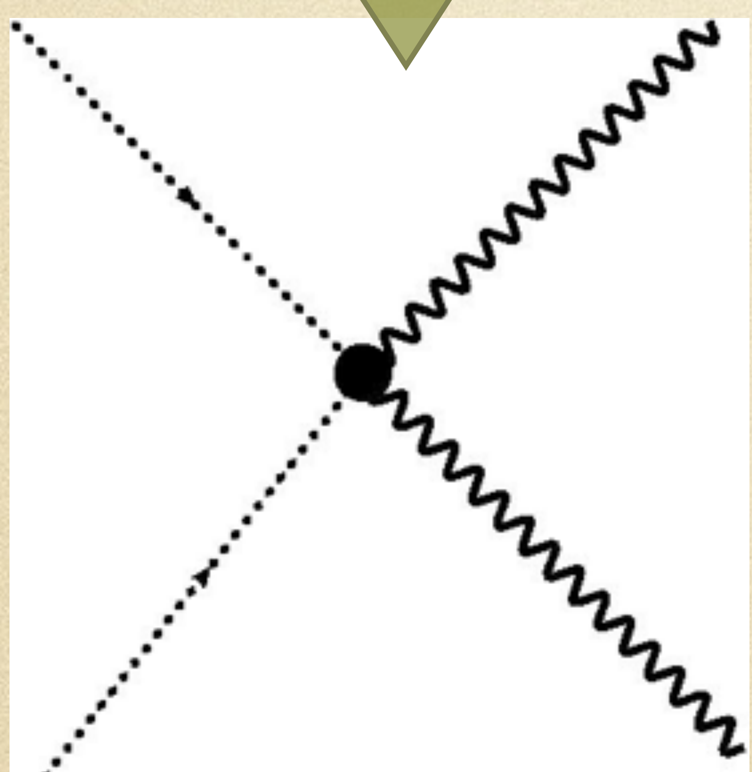


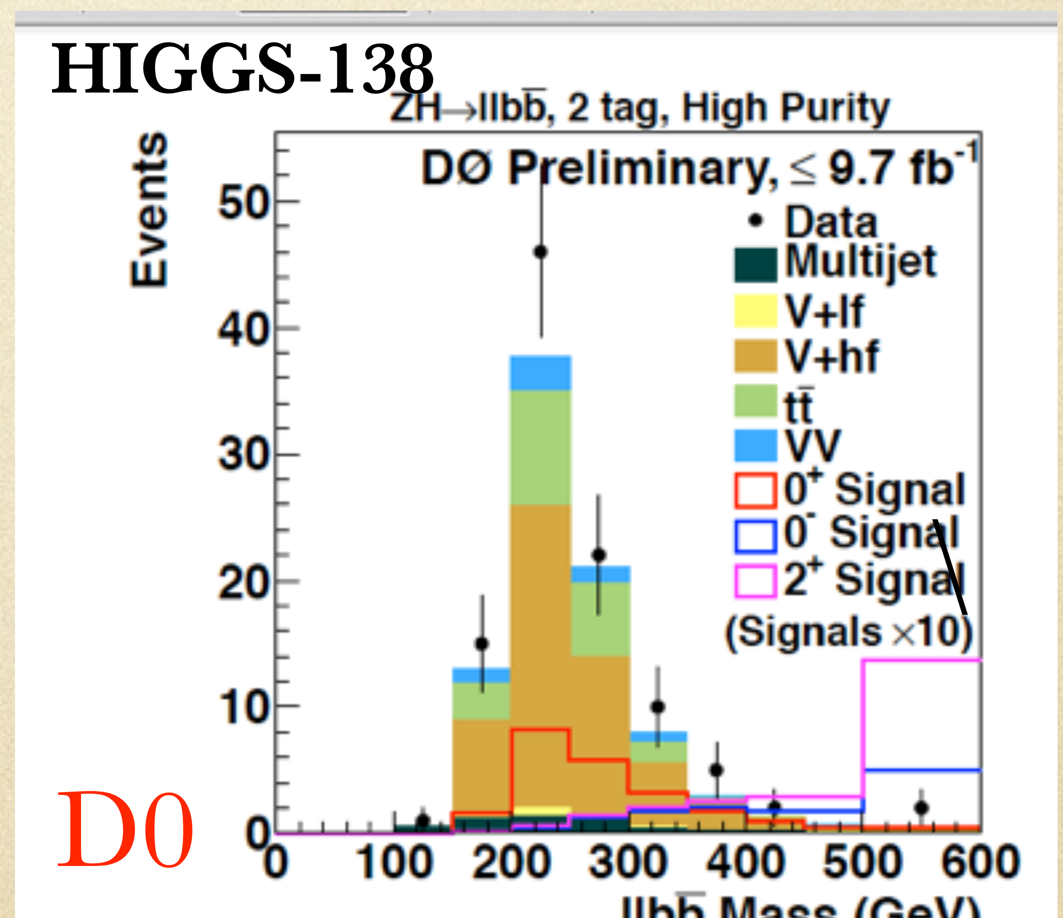
$$\frac{g_\Phi^2}{\hat{s} - M_\Phi^2} \simeq -\frac{g_\Phi^2}{M_\Phi^2}\left(1 - \frac{\hat{s}}{M_\Phi^2} + \ldots\right)$$



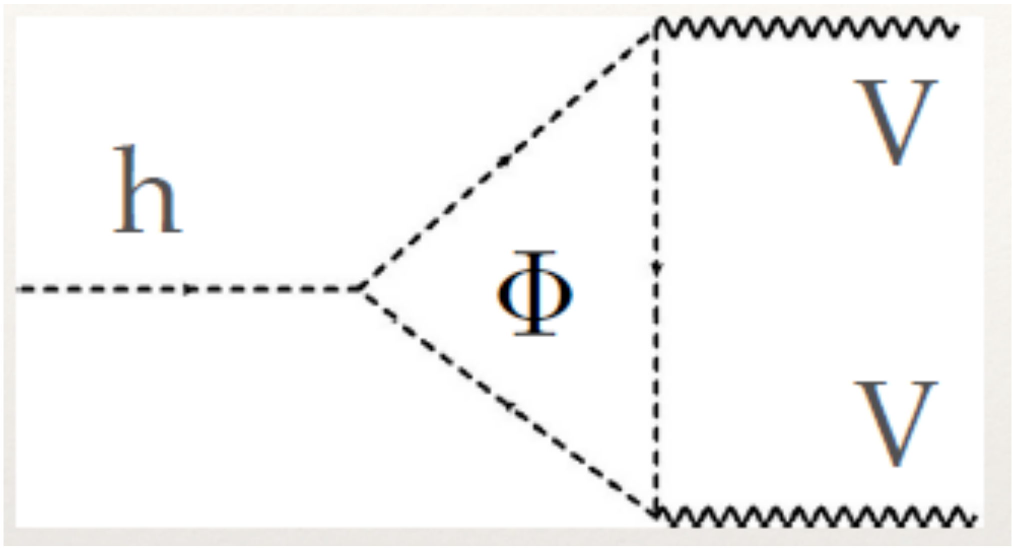
$$m_{Vh}$$

HEFT

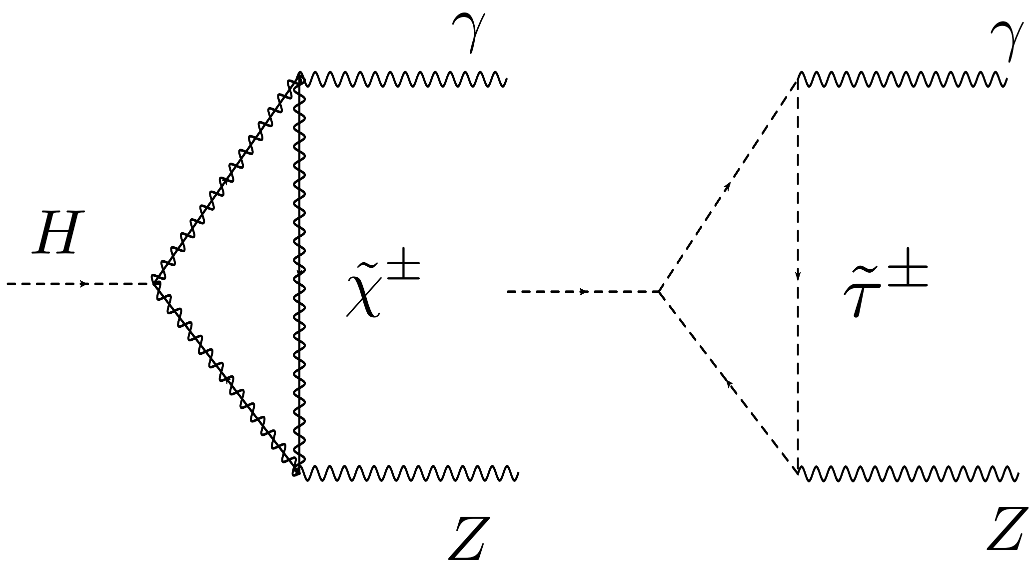




Example 2. Loop-induced



2HDMs

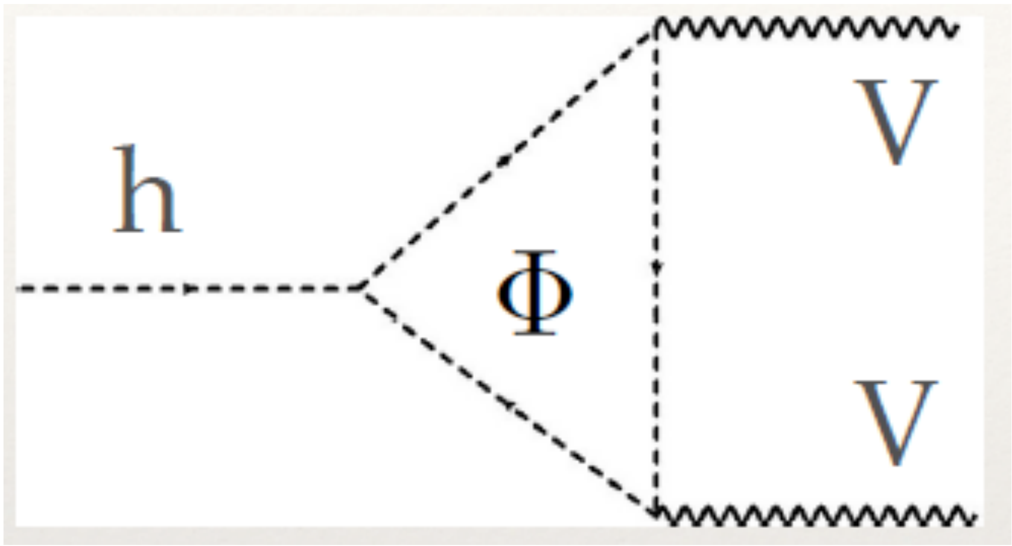


SUSY spartners

validity is now

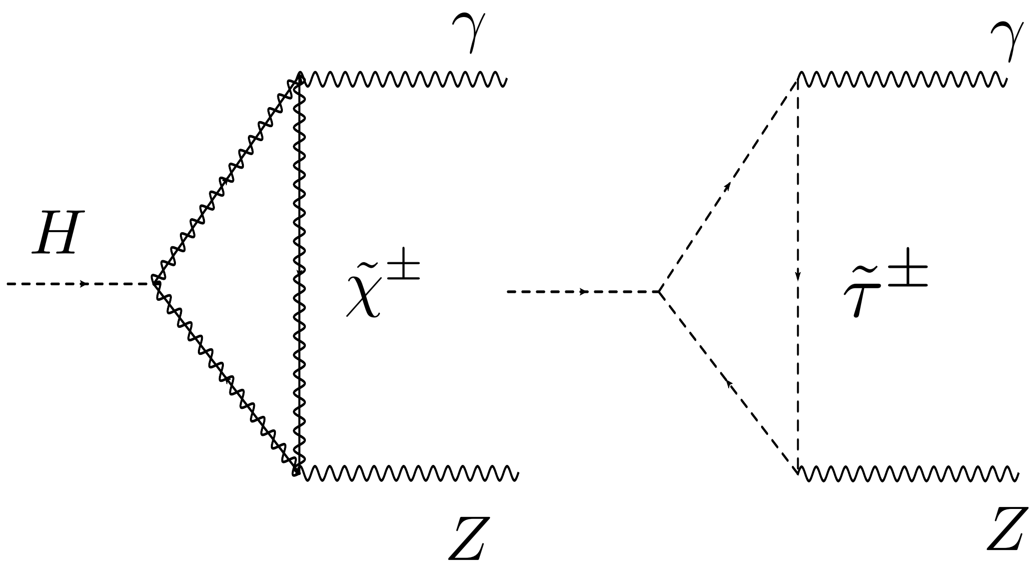
$$\hat{s} \lesssim 4M_{\Phi}^2$$

Example 2. Loop-induced



2HDMs

Gorbahn, No and VS. In preparation



SUSY spartners

Masso and VS. 1211.1320

General predictions:

$$\bar{c}_W - \bar{c}_B = -(\bar{c}_{HW} - \bar{c}_{HB}) = 4\,\bar{c}_\gamma$$

$$\bar{c}_{HW} = -\bar{c}_W \qquad \bar{c}_{HB} = -\bar{c}_B$$

2HDMs

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

$$\bar{c}_{HW} = -\bar{c}_W = \frac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{96\,\pi^2\,\tilde{\mu}_2^2} = \frac{16\,\bar{c}_\gamma}{3} + \frac{m_W^2\,\tilde{\lambda}_4}{96\,\pi^2\,\tilde{\mu}_2^2}$$

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

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

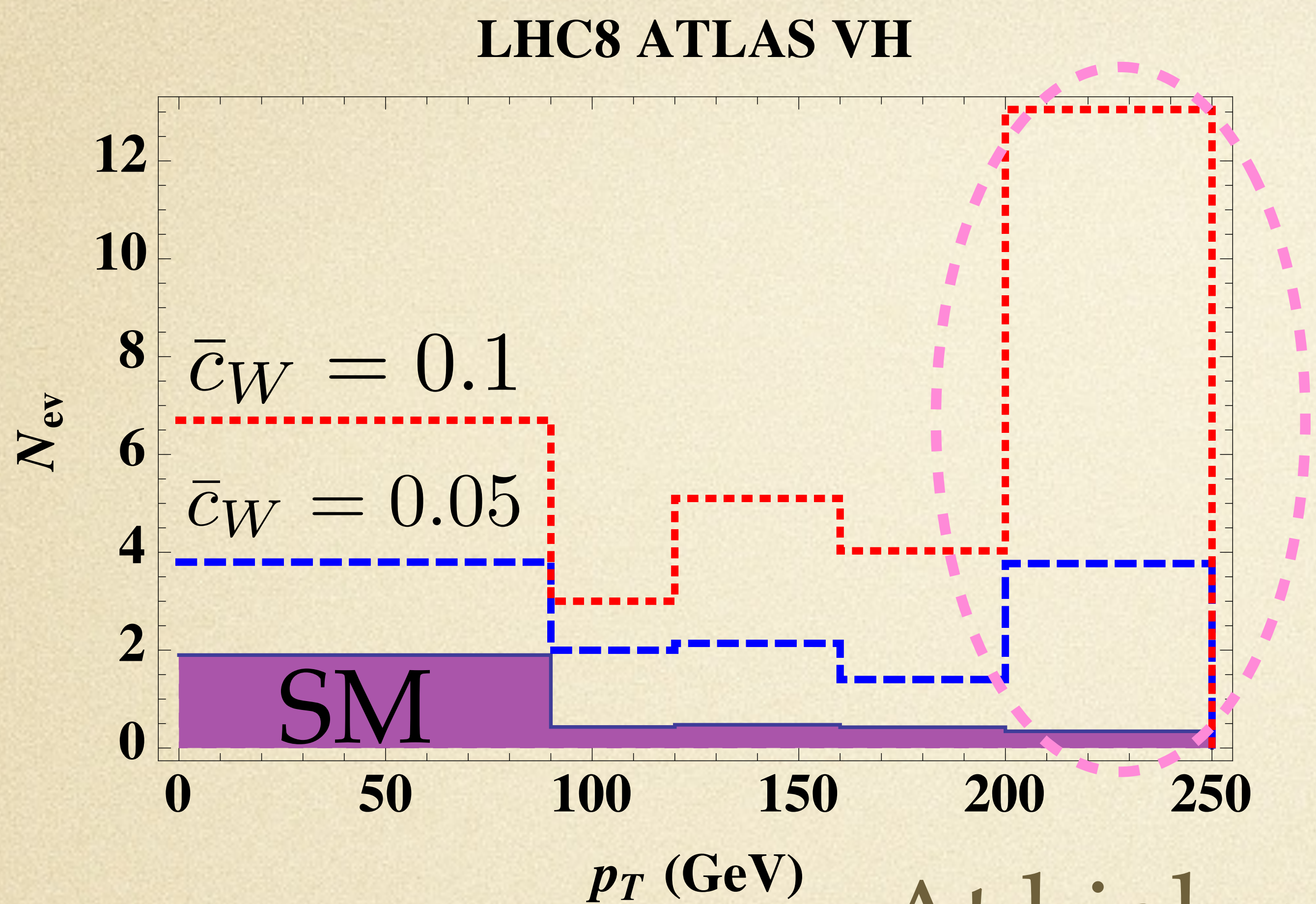
work in progress

LHC8 constraints:

one order of magnitude better than a global fit

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

Limitations of EFTs



most sensitive bin:
overflow (last) bin

At high-pT

sensitive to dynamics of new physics

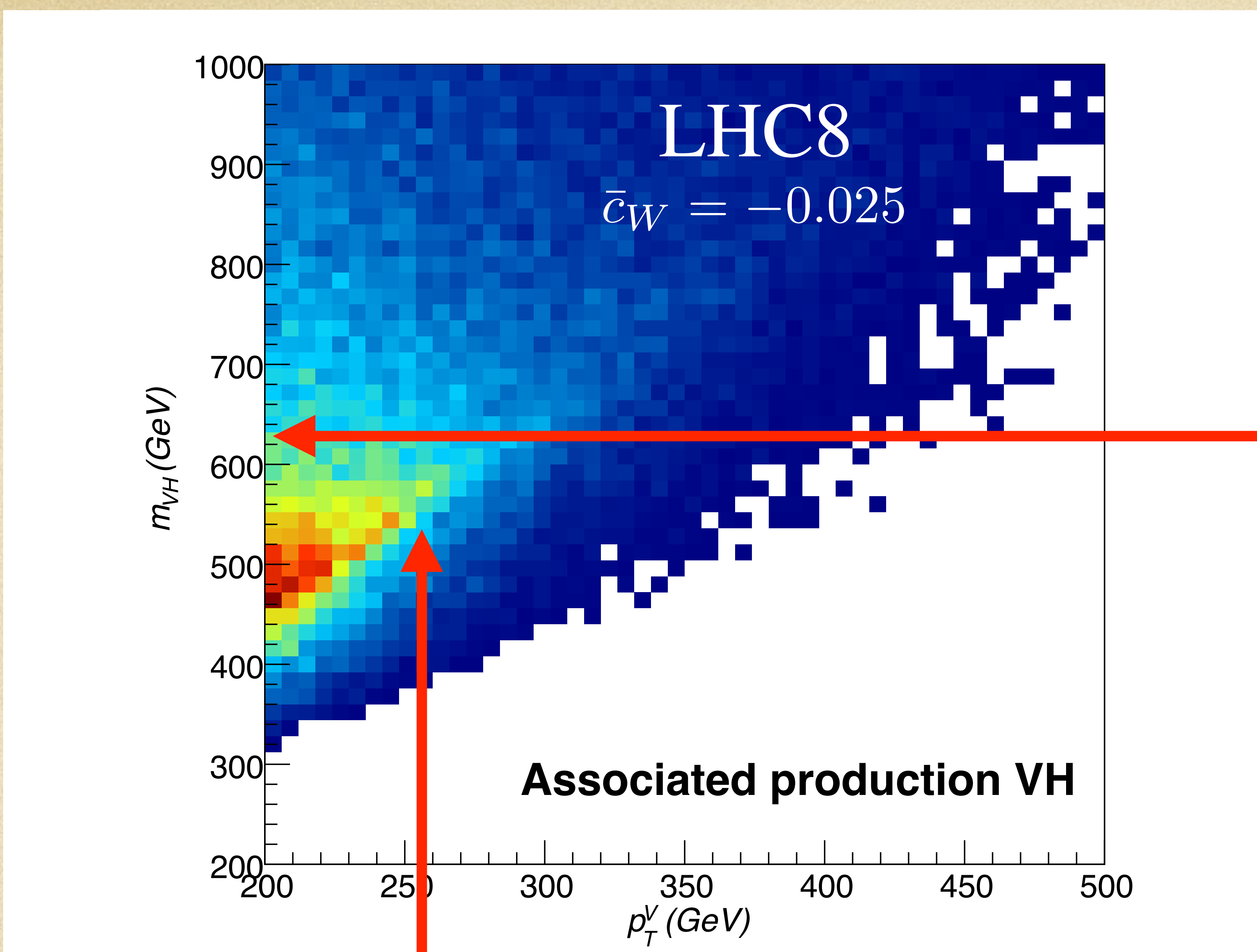
breakdown of EFT

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



validity

distribution

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

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

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

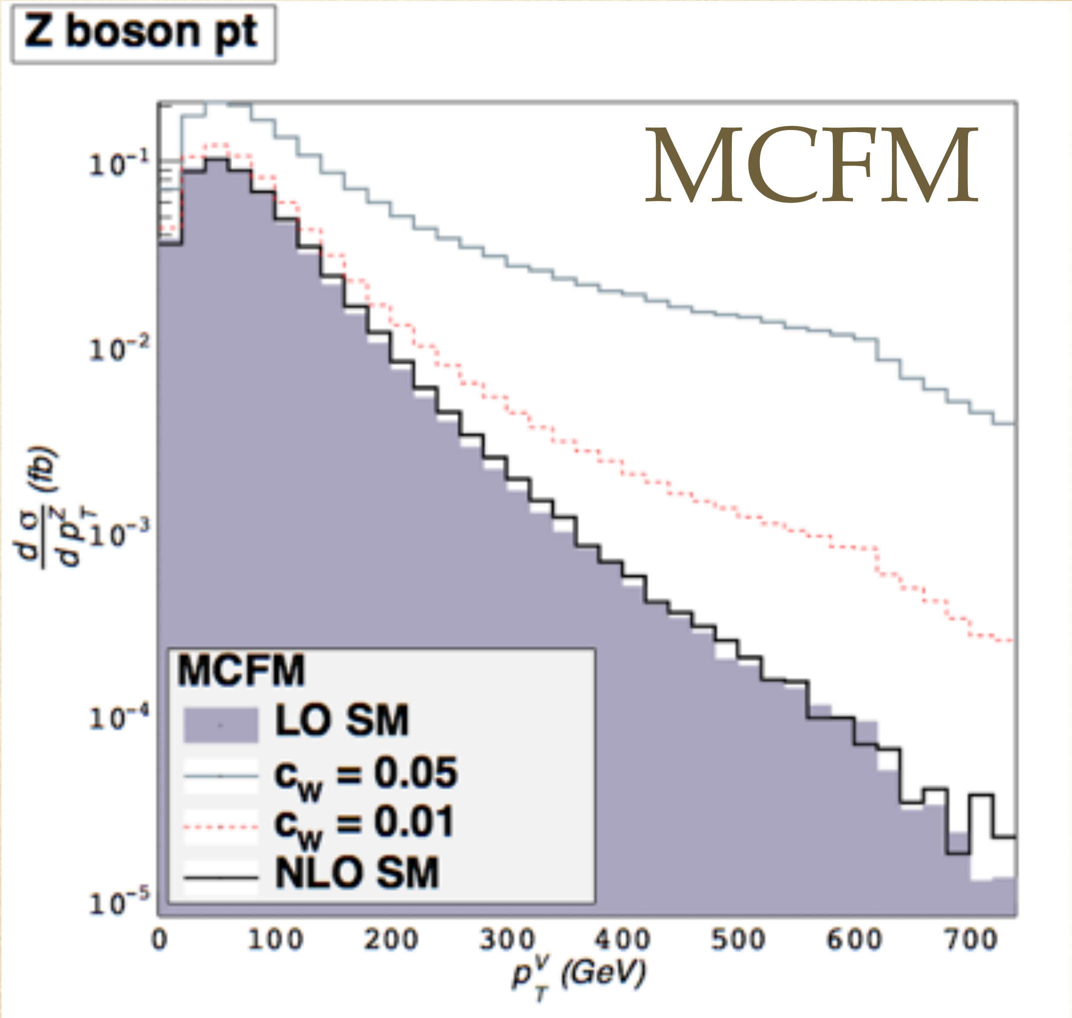
SM precision crucial: excess as genuine new physics

Exploring the validity of EFT
propose benchmarks

Benchmarks
correlations among coefficients, input for fit

Kinematics of associated production

pTV is more sensitive than mVH to QCD NLO
but effect not yet at the level of operator values we can bound



VS and Williams. In prep.

Boring and necessary details

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

Boring and necessary details

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

A

Realization of EWSB

Linear or non-linear

Boring and necessary details

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

A

Realization of EWSB

Linear or non-linear

B

And the Higgs could be

Weak doublet or singlet

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.

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

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

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

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

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

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

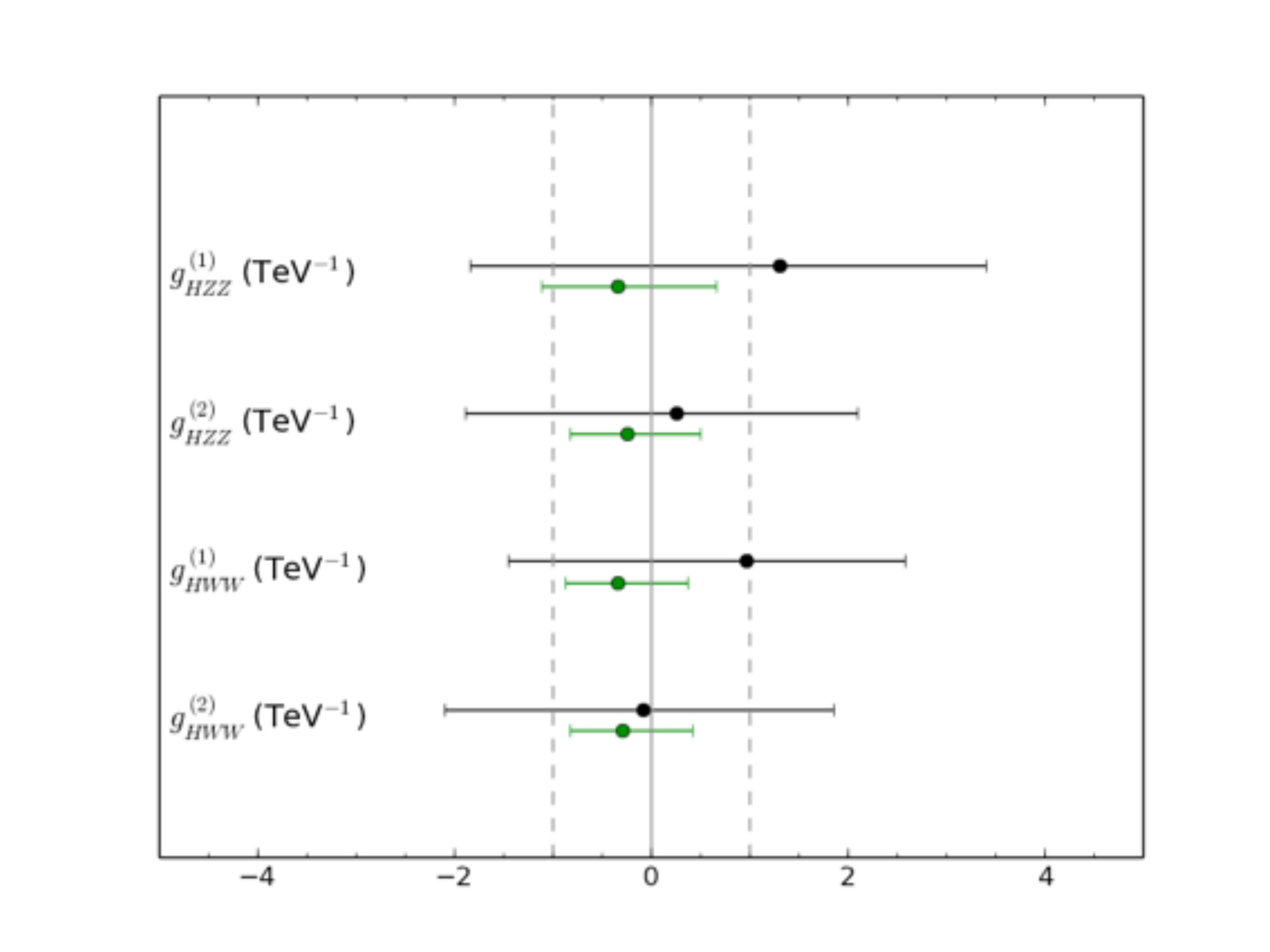
And, **finally**

Observables as a function of HDOs coefficients

In summary

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

Global fit to signal strengths
and kinematic distributions

Conclusions of the analysis

1. Breaking of blind directions requires information on associated production (AP)

2. Kinematic distributions in AP is as sensitive (or more) than total rates

Global fit to signal strengths and kinematic distributions

Conclusions of the analysis

1. Breaking of blind directions requires information on associated production (AP)

2. Kinematic distributions in AP is as sensitive (or more) than total rates