SMEFT:
The *new* Standard Model

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My aim is to give you a gist of what's up with the SMEFT these days:
why do we do it, where are we going with it

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BTW, I suggest you inflict this pain yourself:
read some nice reviews & do some chi2 fit
Masso ('17), Brivio&Trott ('19)

Setting up the scene

Why do we need a *new* SM?

Particle Physics: today's pulse

Super-excited about new experimental probes
new LHC upgrades, *new* gravitational wave signals, *new* direct detection experiments, *new* experiments looking for XYZ new physics, *new* astrophysical probes
new Opportunities

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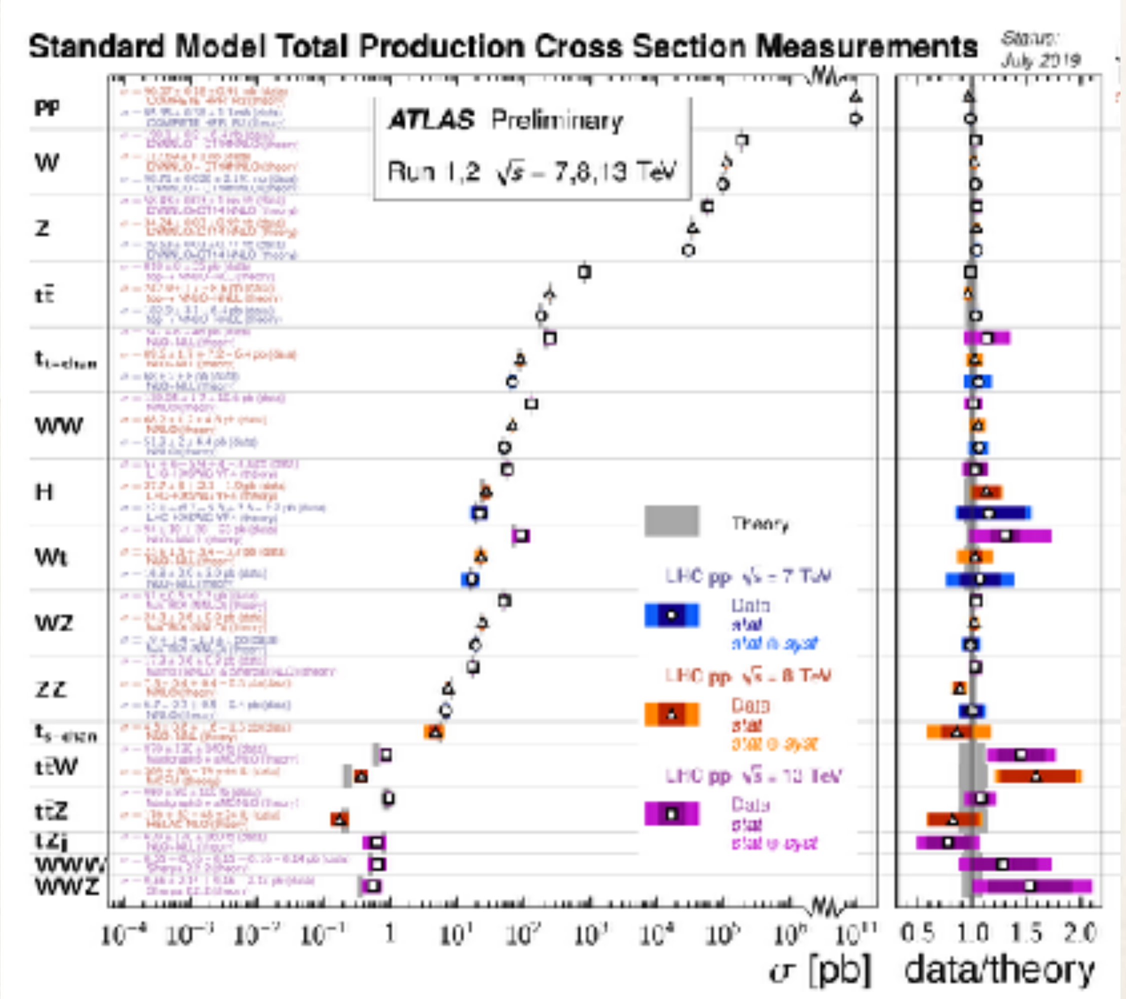
Utterly baffled by the lack of discoveries
'et tu, Naturalness?'
and with a deep theory-fatigue
'A new theory? Bah, humbug! surely a rehash of one of Georgi's old ideas, or a Frankenstein model with complex structure > problems '

(Personal) Statements x10
for illustration purposes

Lack of discoveries…

The LHC is our best probe to microscopic physics:
controlled and well-understood environment
programme already at the precision stage
yet what we have seen so far is (from a BSM perspective)
nothing to write home about



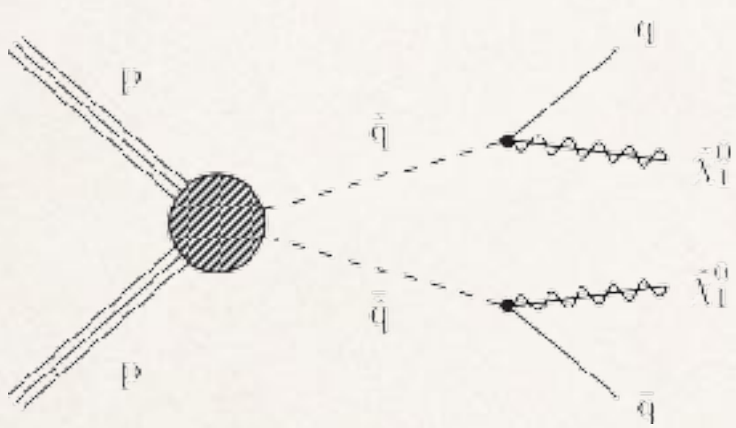
This statement doesn't make justice to the exciting LHC physics programme, and to the legacy of the Higgs discovery

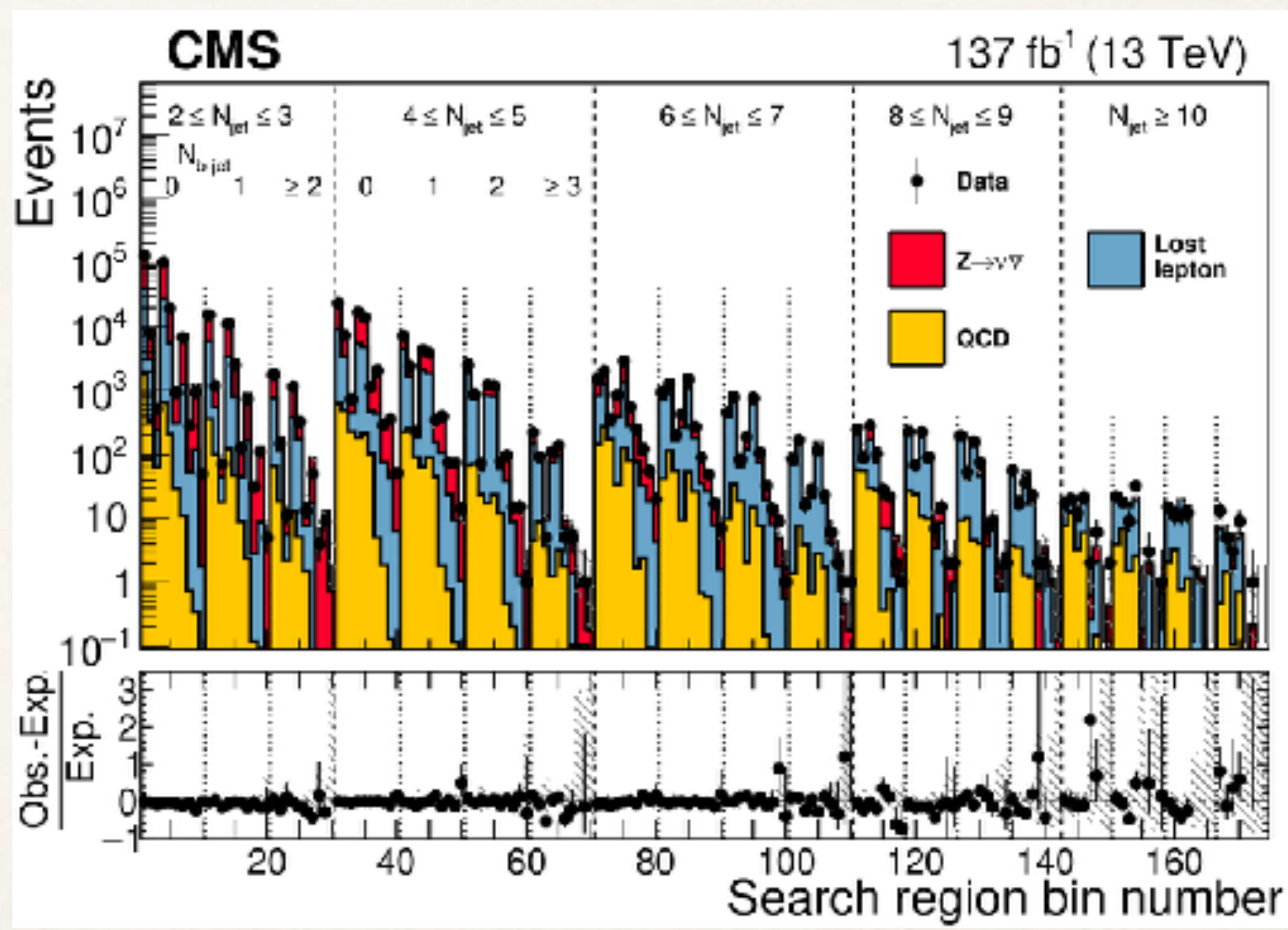
Lots of very precise measurements spanning a good range in energy with Run3&beyond: more to come

Lack of discoveries…

We haven't seen indications of producing BSM particles:
resonances, excesses in MET distributions…

Example: SUSY analysis searching for Dark Matter with jets





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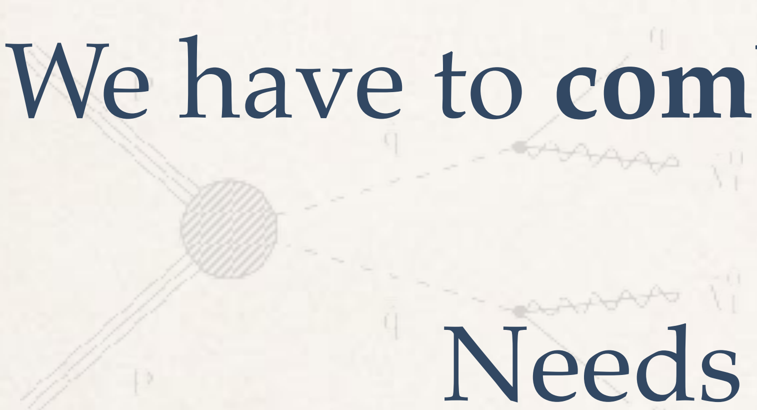
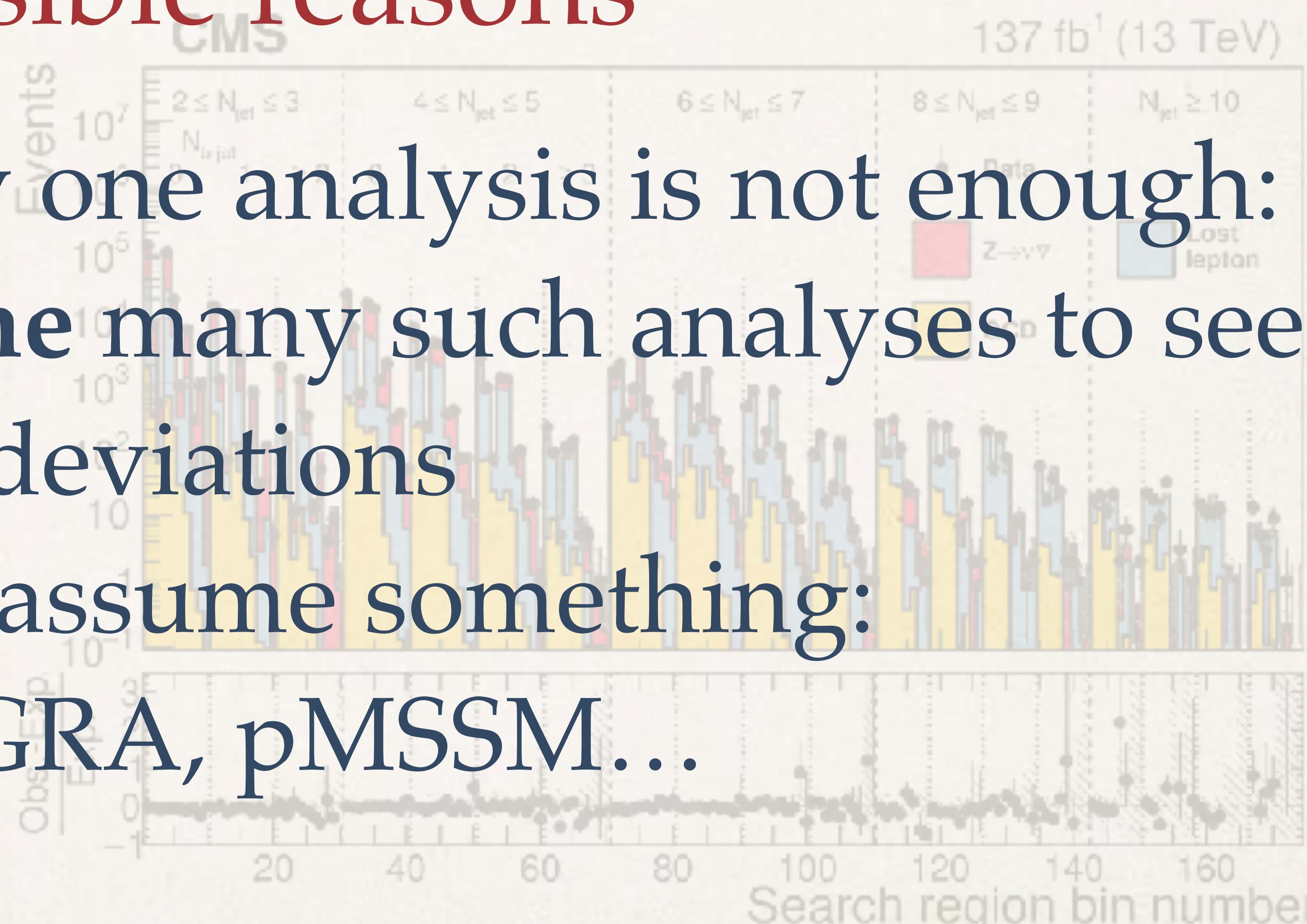
Possible reasons





To reach discovery one analysis is not enough:
We have to **combine** many such analyses to see deviations

Needs to assume something:
mSUGRA, pMSSM…

Lack of discoveries…

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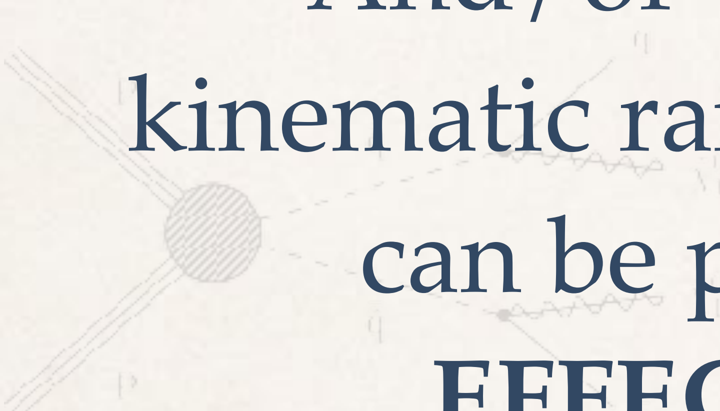
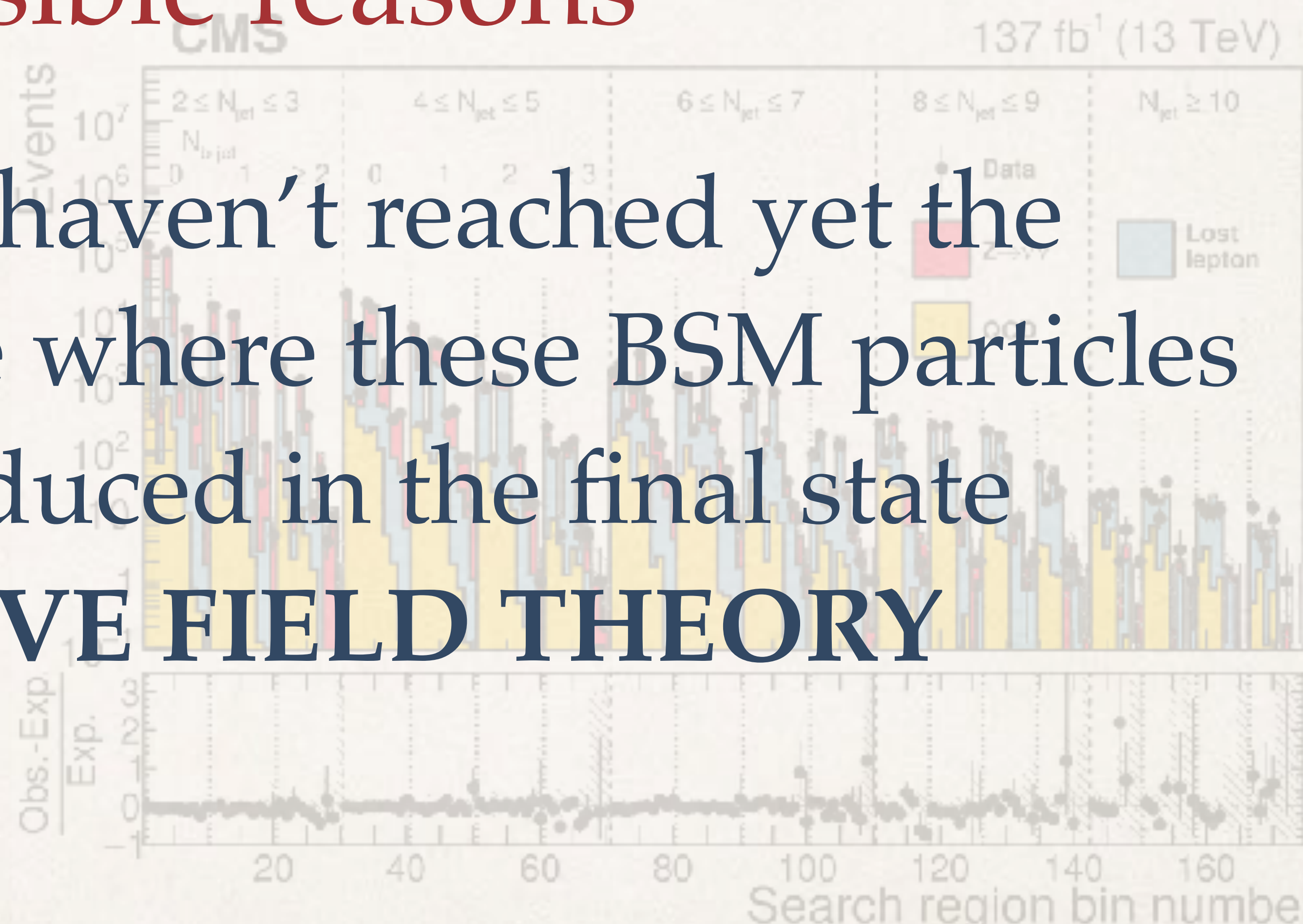




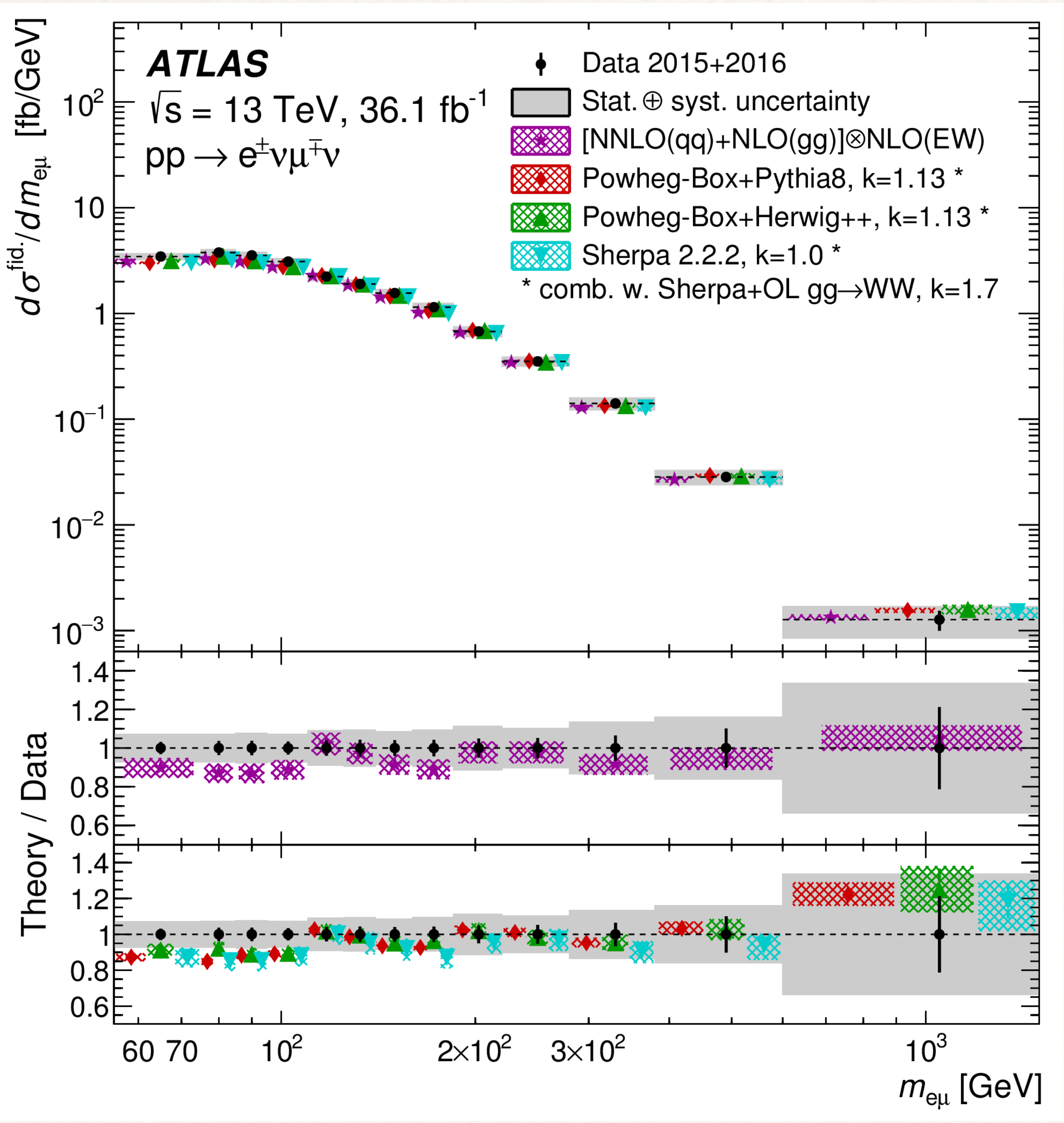
Possible reasons

And/or we haven't reached yet the kinematic range where these BSM particles can be produced in the final state

EFFECTIVE FIELD THEORY

Run3 and beyond

The LHC is a hadron machine, a **discovery** machine
yet it had to re-invent itself to become a **precision** machine



Traditional resonant searches have been so far unfruitful

On the other hand, more statistics and better understanding of the experiment allows diving into extreme kinematic regions

Let's embrace this state-of-affairs to perform different searches for new phenomena, beyond resonances

Casting a wide net: the *new* SM

EFT approach

Well-defined theoretical approach

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

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

BSM effects SM particles

BSM is a **perturbation** around the SM

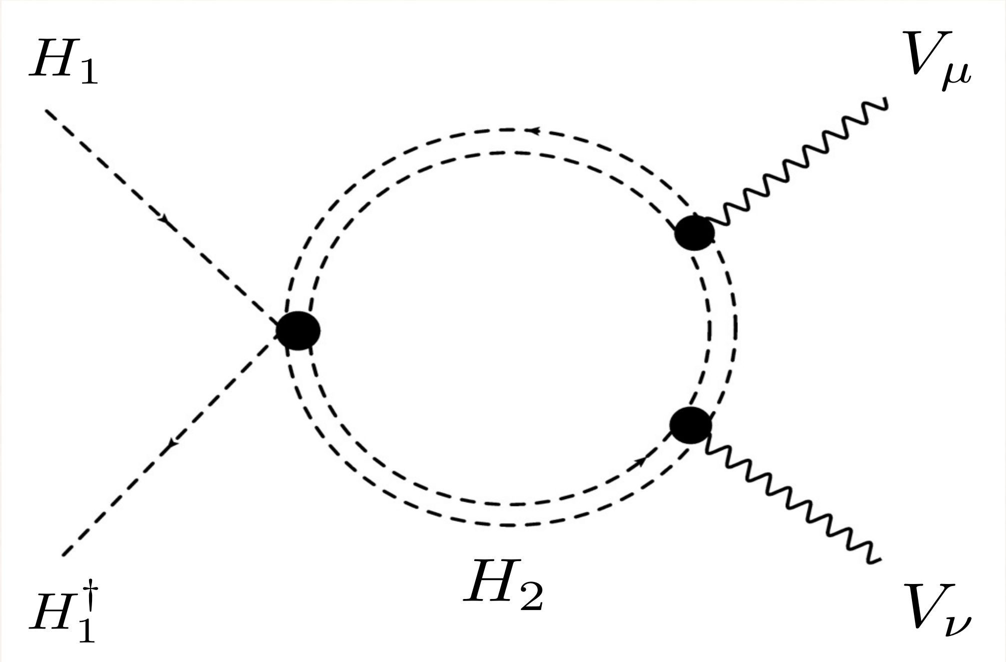
Each operator can be improved at higher orders in QCD and EW corrections

EFT from UV models

As long as the new states are heavy, one can **integrate them out**

example:

2HDM



compute the integral
expand of external momenta
below the mass

GORBAHN, NO, VS. 1502.07352

first terms on the expansion are a number of dimension-six operators e.g.

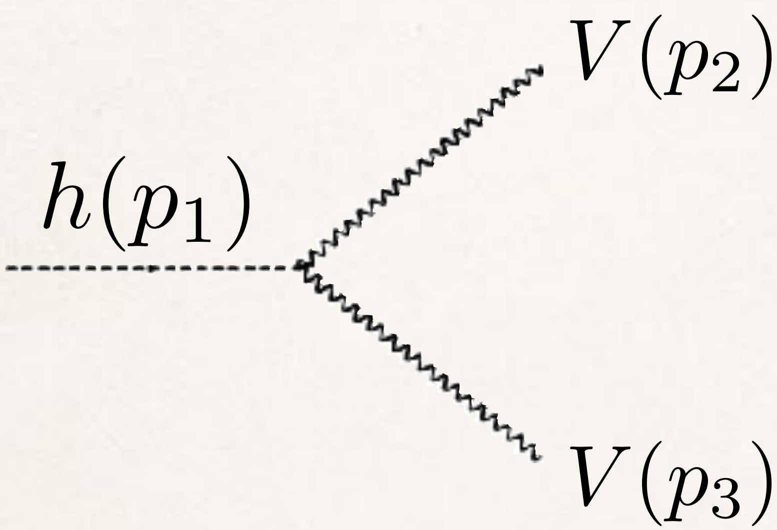
$$\frac{ig}{2m_W^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu} \qquad \text{where } \bar{c}_W = \frac{m_W^2\,(2\,\tilde{\lambda}_3+\tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$$

next term in the expansion: dimension-eight

Differential information is key

Models offer richer kinematics than the kappa-formalism
and the EFT approach captures them

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

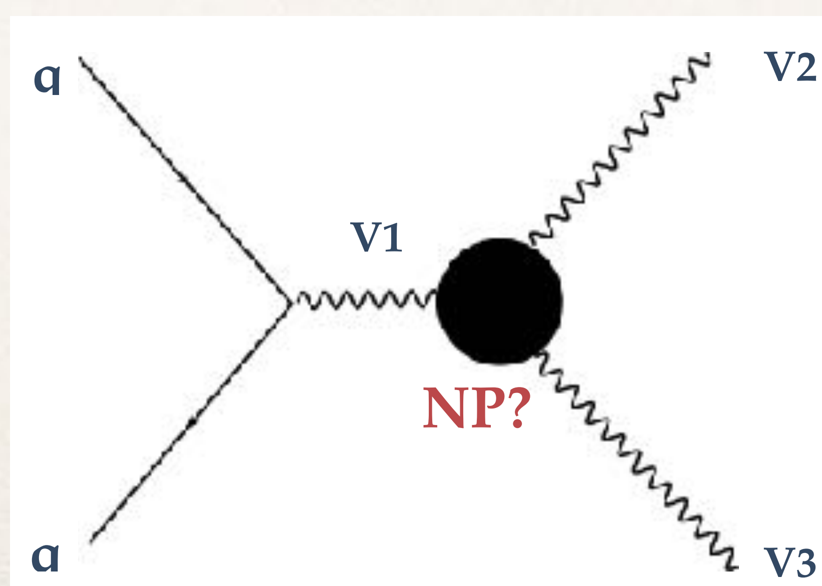


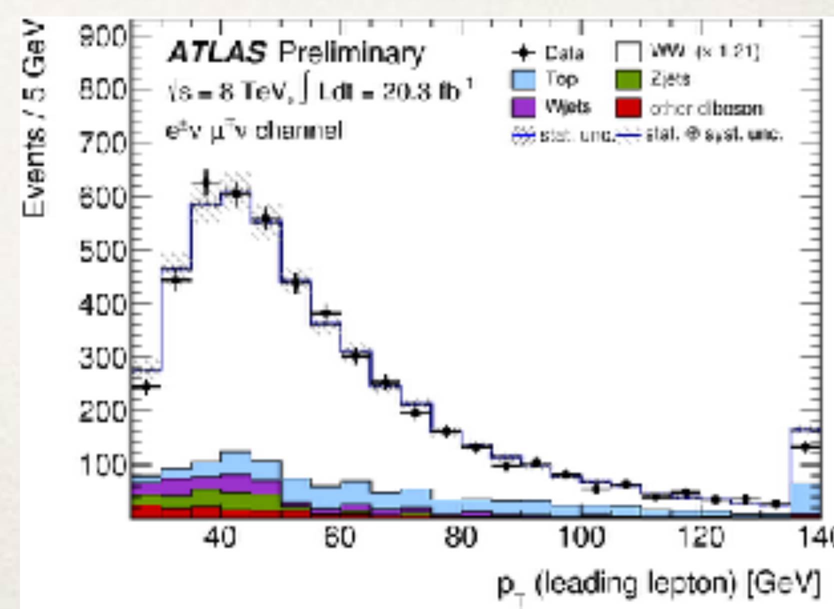
$$i\eta_{\mu\nu} \left(g^{(1)}_{hVV} \left(\frac{\hat{s}}{2} - m_V^2 \right) + 2 g^{(2)}_{hVV} m_V^2 \right)$$

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

+ off-shell pieces

exploited in searches for
anomalous **TGCs**





Matching to UV theories

Gorbahn, No and VS
1502.07352, JHEP

Within the EFT, connection to models is *straightforward*

EFT

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

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

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

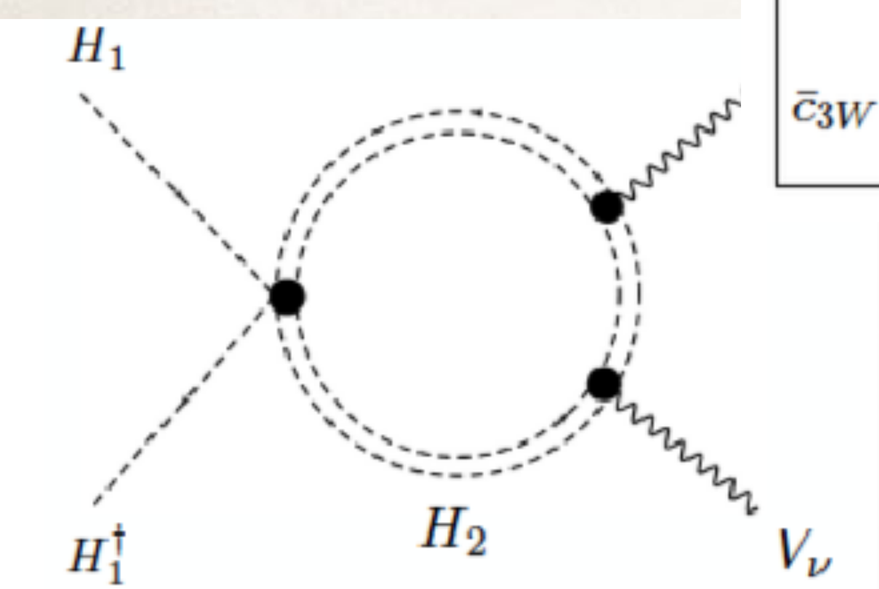
$$c_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

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

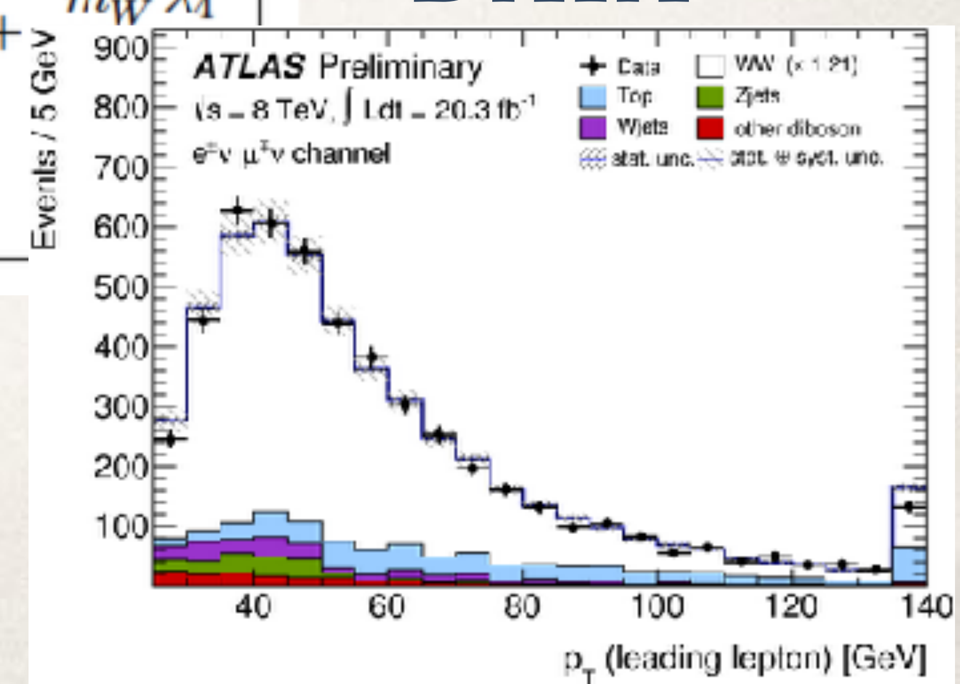
$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\bar{c}_\gamma + m_W^2\,\tilde{\lambda}_4$$

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

MODELS



DATA

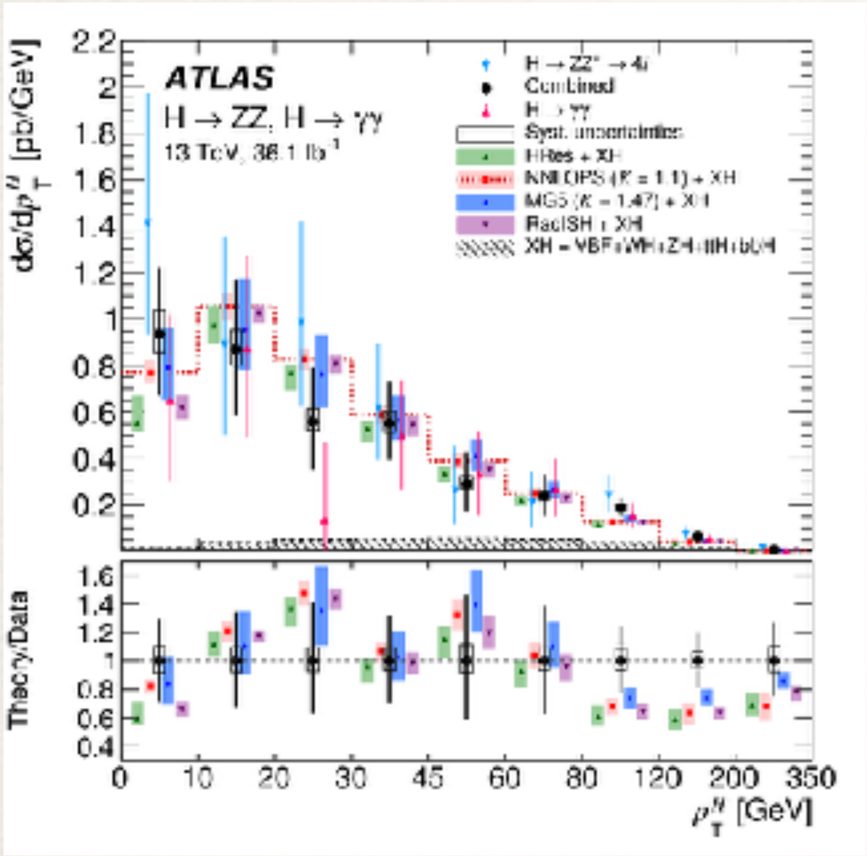


Advantages

- **Combination**: LHC Higgs and EW production, low energy, EWPTs
- **Precision:** higher-order EW and QCD, dimension-eight, chiral logs
- **Consistency:** Backgrounds and signal
- **Reduces model biases:** explore theories beyond known paradigms
- **Matching:** Direct connection to models

Disadvantages

EFTs in PP are an old friend



Maybe you have been working on
low-E flavour/CPV/BLV physics
precision calculations or simply using bounds

What's different for the EFT@EW scale?

We're testing it using a *hadron* collider

flavour physics: heavy means heavy

EW EFT: we are in this border between kinematic reach and precision

& parameter space is very large

Disadvantages

- **Assumptions**: Only SM light states
- **Complexity:** Large number of parameters
- **Validity:** EFT cannot be used in regions of energies ~ scale of new resonances

Recent experimental analysis

ATLAS-CONF-2020-053
29 October 2020

Presented yesterday at CERN

Combination Higgs channels, full Run2 lumi

Exhaustive **STXS** combination used to interpret as an **EFT**

this is going to be a *standard analysis*

STXS Region Stage-0	STXS Region Stage-1.2	$H\to\gamma\gamma$	$H\to ZZ^*\to 4\ell$	$H\to b\bar{b}$ (VH)
ggH	$N_{\text{jets}}=0,\ p_{\text{T}}^{H}<10$	$N_{\text{jets}}=0,\ p_{\text{T}}^{H}<10$	$N_{\text{jets}}=0,\ p_{\text{T}}^{H}<10$	
	$N_{\text{jets}}=0,\ 10<p_{\text{T}}^{H}$	$N_{\text{jets}}=0,\ 10<p_{\text{T}}^{H}$	$N_{\text{jets}}=0,\ 10<p_{\text{T}}^{H}$	
	$N_{\text{jets}}=1,\ p_{\text{T}}^{H}<60$	$N_{\text{jets}}=1,\ p_{\text{T}}^{H}<60$	$N_{\text{jets}}=1,\ p_{\text{T}}^{H}<60$	
	$N_{\text{jets}}=1,\ 60<p_{\text{T}}^{H}<120$	$N_{\text{jets}}=1,\ 60<p_{\text{T}}^{H}<120$	$N_{\text{jets}}=1,\ 60<p_{\text{T}}^{H}<120$	
	$N_{\text{jets}}=1,\ 120<p_{\text{T}}^{H}<200$	$N_{\text{jets}}=1,\ 120<p_{\text{T}}^{H}<200$	$N_{\text{jets}}=1,\ 120<p_{\text{T}}^{H}<200$	
	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ p_{\text{T}}^{H}<60$	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ p_{\text{T}}^{H}<120$	$N_{\text{jets}}\geq 2,\ p_{\text{T}}^{H}\leq 200$	
	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ 60<p_{\text{T}}^{H}<120$	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ p_{\text{T}}^{H}<120$	$N_{\text{jets}}\geq 2,\ p_{\text{T}}^{H}\leq 200$	
	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ 120<p_{\text{T}}^{H}<200$	$N_{\text{jets}}\geq 2,\ m_{jj}<350,\ 120<p_{\text{T}}^{H}<200$	$N_{\text{jets}}\geq 2,\ p_{\text{T}}^{H}\leq 200$	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_{\text{T}}^{H}<200,\ p_{\text{T}}^{Hjj}<25$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ p_{\text{T}}^{H}<200$	$N_{\text{jets}}\geq 2,\ p_{\text{T}}^{H}\leq 200$	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_{\text{T}}^{H}<200,\ 25<p_{\text{T}}^{Hjj}$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ p_{\text{T}}^{H}<200$	$N_{\text{jets}}\geq 2,\ p_{\text{T}}^{H}\leq 200$	
	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_{\text{T}}^{H}<200,\ p_{\text{T}}^{Hjj}<25$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ p_{\text{T}}^{H}<200$	$N_{\text{jets}}\geq 2,\ p_{\text{T}}^{H}\leq 200$	
	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_{\text{T}}^{H}<200,\ 25<p_{\text{T}}^{Hjj}$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ p_{\text{T}}^{H}<200$	$N_{\text{jets}}\geq 2,\ p_{\text{T}}^{H}\leq 200$	
	$200<p_{\text{T}}^{H}<300$	$200<p_{\text{T}}^{H}<300$	$200<p_{\text{T}}^{H}$	
	$300<p_{\text{T}}^{H}<450$	$300<p_{\text{T}}^{H}<450$	$200<p_{\text{T}}^{H}$	
	$450<p_{\text{T}}^{H}<650$	$450<p_{\text{T}}^{H}$	$200<p_{\text{T}}^{H}$	
	$650<p_{\text{T}}^{H}$	$450<p_{\text{T}}^{H}$	$200<p_{\text{T}}^{H}$	
$qq\to Hqq$ "VBF", "$qqVH$ had"	$N_{\text{jets}}=0$	$N_{\text{jets}}\leq 1$		
	$N_{\text{jets}}=1$	$N_{\text{jets}}\leq 1$		
	$N_{\text{jets}}\geq 2,\ m_{jj}<60$	$N_{\text{jets}}\geq 2,\ m_{jj}<60 \vee 120<m_{jj}<350$	VBF	
	$N_{\text{jets}}\geq 2,\ 60<m_{jj}<120$	$N_{\text{jets}}\geq 2,\ 60<m_{jj}<120$	$N_{\text{jets}}\geq 2,\ 60<m_{jj}<120$	
	$N_{\text{jets}}\geq 2,\ 120<m_{jj}<350$	$N_{\text{jets}}\geq 2,\ m_{jj}<60 \vee 120<m_{jj}<350$	VBF	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}\ 200<p_{\text{T}}^{H}$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ 200<p_{\text{T}}^{H}$	$N_{\text{jets}}\geq 2,\ 350<m_{jj},\ 200<p_{\text{T}}^{H}$	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_{\text{T}}^{H}<200,\ p_{\text{T}}^{Hjj}<25$	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_{\text{T}}^{H}<200$	VBF	
	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_{\text{T}}^{H}<200,\ 25<p_{\text{T}}^{Hjj}$	$N_{\text{jets}}\geq 2,\ 350<m_{jj}<700,\ p_{\text{T}}^{H}<200$	VBF	
	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_{\text{T}}^{H}<200,\ p_{\text{T}}^{Hjj}<25$	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_{\text{T}}^{H}<200$	VBF	
	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_{\text{T}}^{H}<200,\ 25<p_{\text{T}}^{Hjj}$	$N_{\text{jets}}\geq 2,\ 700<m_{jj},\ p_{\text{T}}^{H}<200$	VBF	
$qq\to H\ell\nu$ "$qqWH$ lep"	$p_{\text{T}}^{V}<75$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ p_{\text{T}}^{V}<150$	VH lep	$WH\ p_{\text{T}}^{V}<250$
	$75<p_{\text{T}}^{V}<150$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ p_{\text{T}}^{V}<150$	VH lep	$WH\ p_{\text{T}}^{V}<250$
	$150<p_{\text{T}}^{V}<250$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ 150<p_{\text{T}}^{V}$	VH lep	$WH\ p_{\text{T}}^{V}<250$
	$250<p_{\text{T}}^{V}<400$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ 150<p_{\text{T}}^{V}$	VH lep	$WH\ 250<p_{\text{T}}^{V}$
	$400<p_{\text{T}}^{V}$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$WH\ 150<p_{\text{T}}^{V}$	VH lep	$WH\ 250<p_{\text{T}}^{V}$
$qq\to H\ell\ell$ "$qqZH$ lep"	$p_{\text{T}}^{V}<75$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ p_{\text{T}}^{V}<150$	VH lep	$ZH\ p_{\text{T}}^{V}<150$
	$75<p_{\text{T}}^{V}<150$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ p_{\text{T}}^{V}<150$	VH lep	$ZH\ p_{\text{T}}^{V}<150$
	$150<p_{\text{T}}^{V}<250$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_{\text{T}}^{V}$	VH lep	$ZH\ 150<p_{\text{T}}^{V}<250$
	$250<p_{\text{T}}^{V}<400$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_{\text{T}}^{V}$	VH lep	$ZH\ 250<p_{\text{T}}^{V}$
	$400<p_{\text{T}}^{V}$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_{\text{T}}^{V}$	VH lep	$ZH\ 250<p_{\text{T}}^{V}$
$gg\to H\ell\ell$ "$ggZH$ lep"	$p_{\text{T}}^{V}<75$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ p_{\text{T}}^{V}<150$	VH lep	$ZH\ p_{\text{T}}^{V}<150$
	$75<p_{\text{T}}^{V}<150$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ p_{\text{T}}^{V}<150$	VH lep	$ZH\ p_{\text{T}}^{V}<150$
	$150<p_{\text{T}}^{V}<250$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_{\text{T}}^{V}$	VH lep	$ZH\ 150<p_{\text{T}}^{V}<250$
	$250<400$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_{\text{T}}^{V}$	VH lep	$ZH\ 250<p_{\text{T}}^{V}$
	$250<p_{\text{T}}^{V}$ ($N_{\text{jets}}=0$ / $N_{\text{jets}}=1$ / $N_{\text{jets}}\geq 2$)	$ZH\ 150<p_{\text{T}}^{V}$	VH lep	$ZH\ 250<p_{\text{T}}^{V}$
$t\bar{t}H$	$p_{\text{T}}^{H}<60$	$p_{\text{T}}^{H}<60$	$t(t)H$	
	$60<p_{\text{T}}^{H}<120$	$60<p_{\text{T}}^{H}<120$	$t(t)H$	
	$120<p_{\text{T}}^{H}<200$	$120<p_{\text{T}}^{H}<200$	$t(t)H$	
	$200<p_{\text{T}}^{H}<300$	$200<p_{\text{T}}^{H}$	$t(t)H$	
	$300<p_{\text{T}}^{H}$	$200<p_{\text{T}}^{H}$	$t(t)H$	
	$b\bar{b}H$	merged with ggH		
	tH	tH	$t(t)H$	

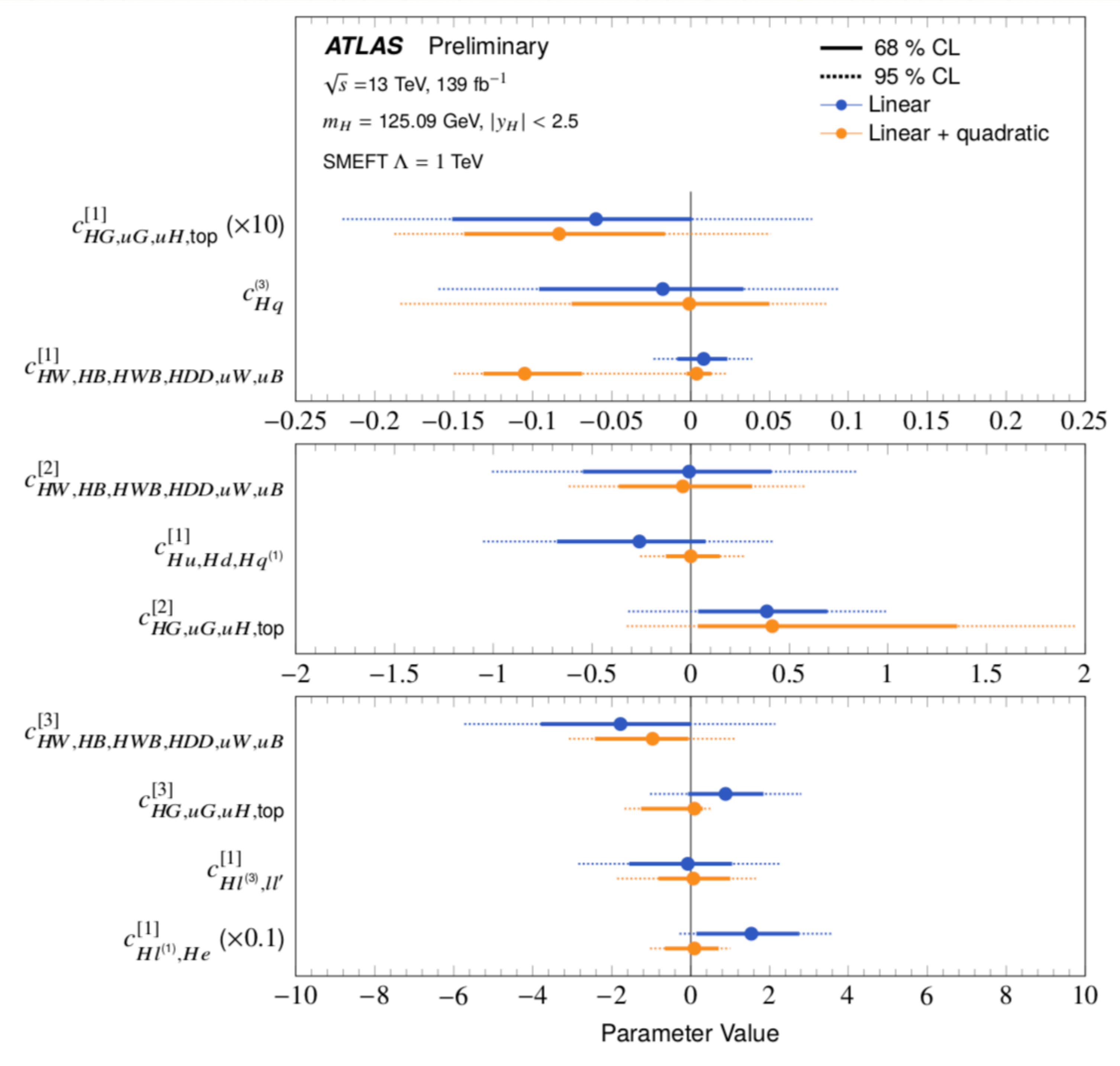
Recent experimental analysis

ATLAS-CONF-2020-053
29 October 2020

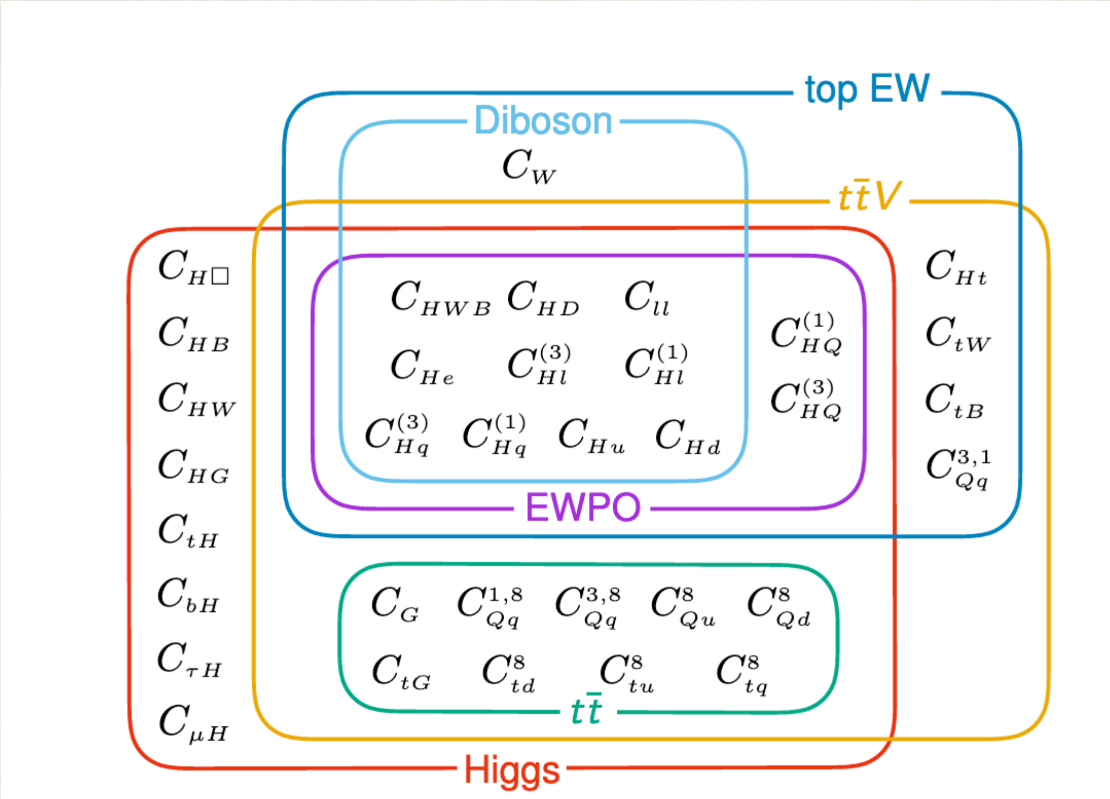
Presented yesterday at CERN

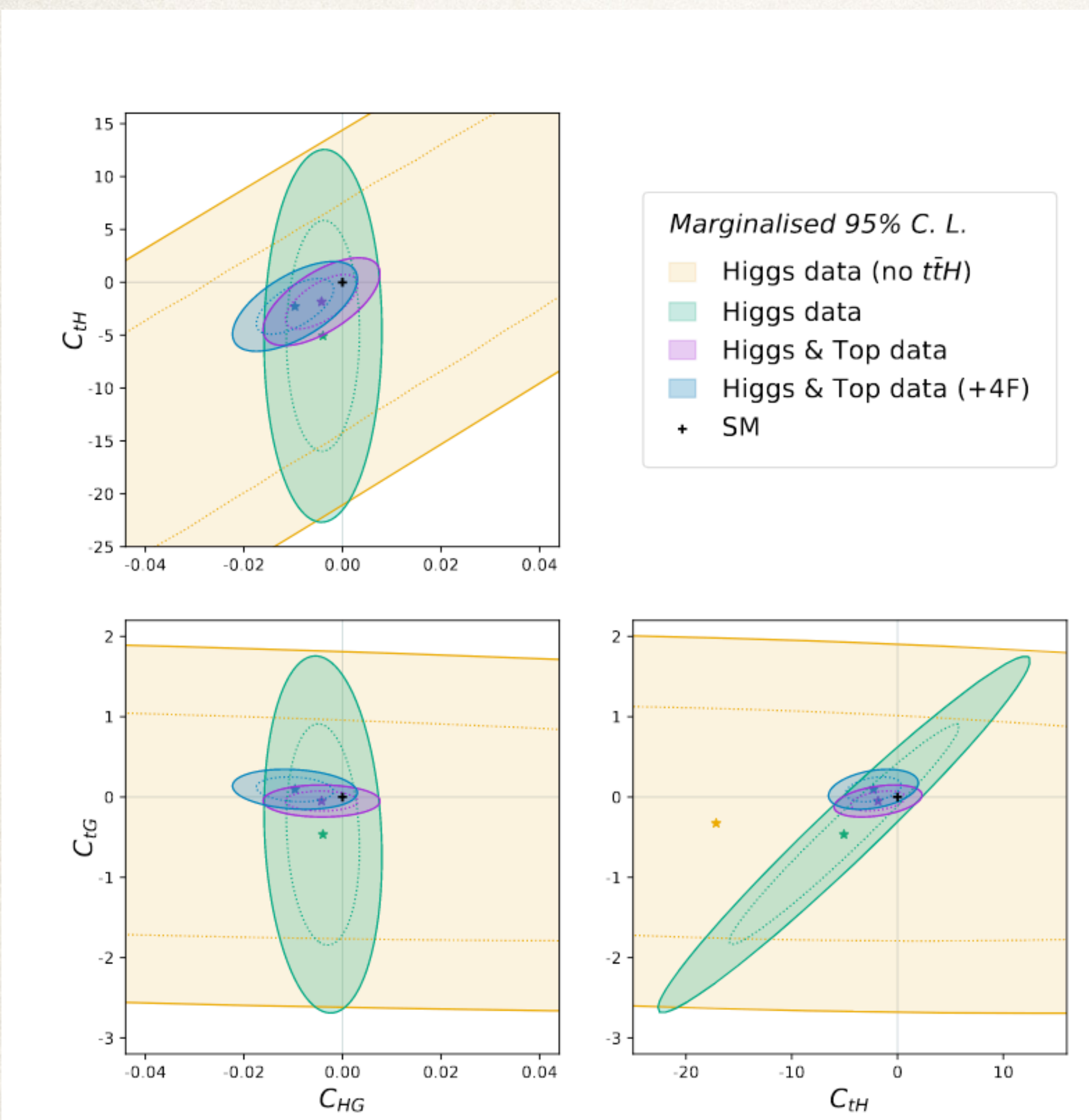
Exhaustive **STXS** combination used to interpret as an **EFT**

limits on sets of coefficients, at linear (blue) and quadratic (orange) level



sets of ops grouped by their dependence on observables and correlations
***multi-TeV** limits for most of these possible BSM effects*





Ellis, Madigan, Mimasu, VS, You
2012.02779, JHEP

A truly global EFT analysis is possible with Run2 data (+LEP)

We performed the most complete global fit with Higgs+Diboson+Top+4F data (341 observables) against 20 (MFV)/34 (top-specific) operators

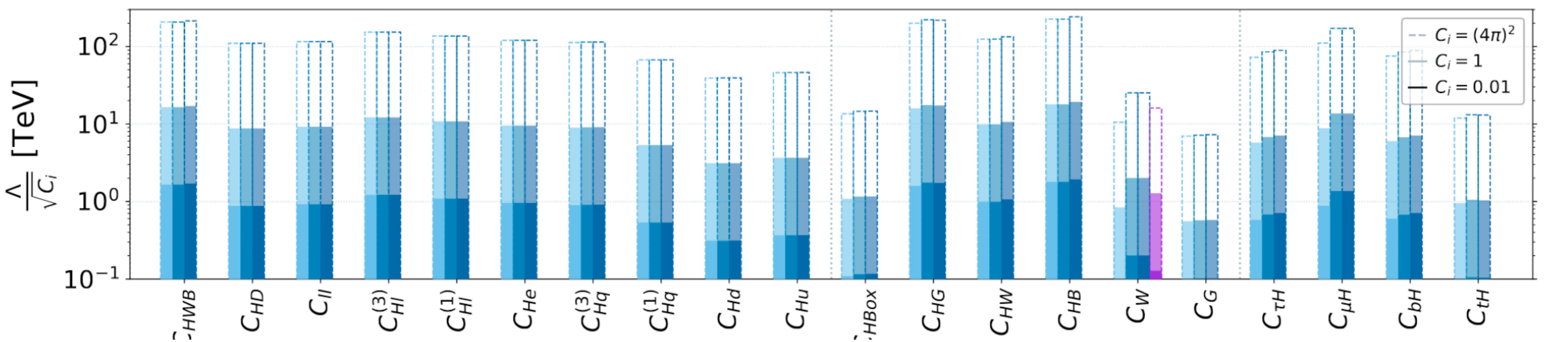
This is an example of the interplay between Higgs (green) and Higgs+Top (pink) information

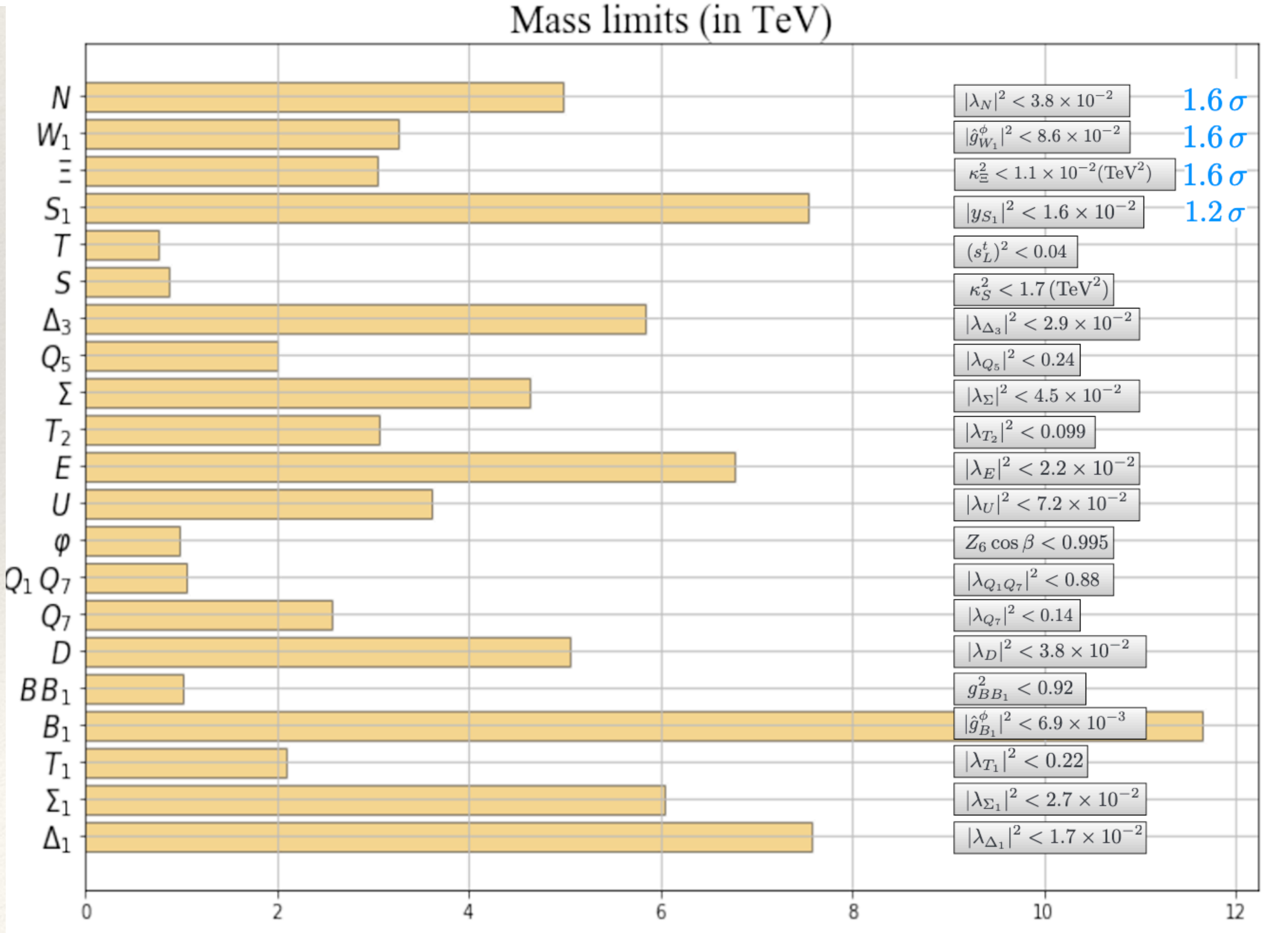
These combinations and *public* frameworks to do fits
(like our ***Fitmaker***)

are going to become state-of-the-art

Current SMEFT constraints reach the TeV for most of t he param space

Ellis, Madigan, Mimasu, VS, You
2012.02779, JHEP





And when translated into vanilla extensions of the SM, the mass limits are also probing the TeV scale

Lots of work needed to advance this area: higher-order calculations, optimisation of strategies, better exp understanding of correlations…

Challenges

1. Theory biases

Is the EFT framework really *model-independent?*

Not completely

e.g. In non-linear realisations of EWSB

the Higgs could be a **SINGLET**

as opposed to the doublet case

Higgs = (vev + higgs particle + W/Z dofs)

CONSEQUENCES

*de-correlation of Higgs and VV

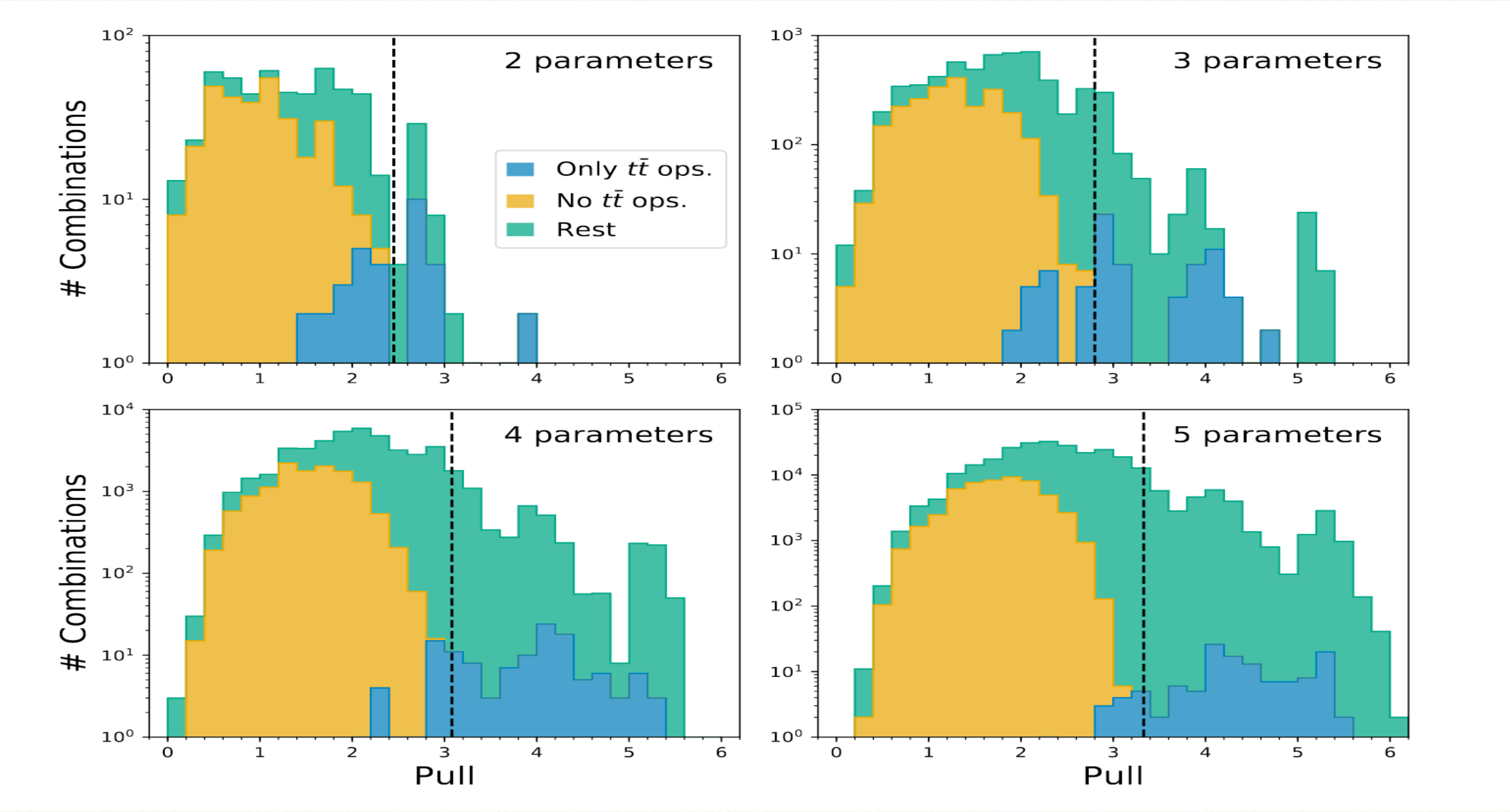
*EFT expansion changes

EFT provides a *large enough* set of deformations from the SM serves the purpose of guiding searches and interpretation in terms of UV models

2. Parameter complexity

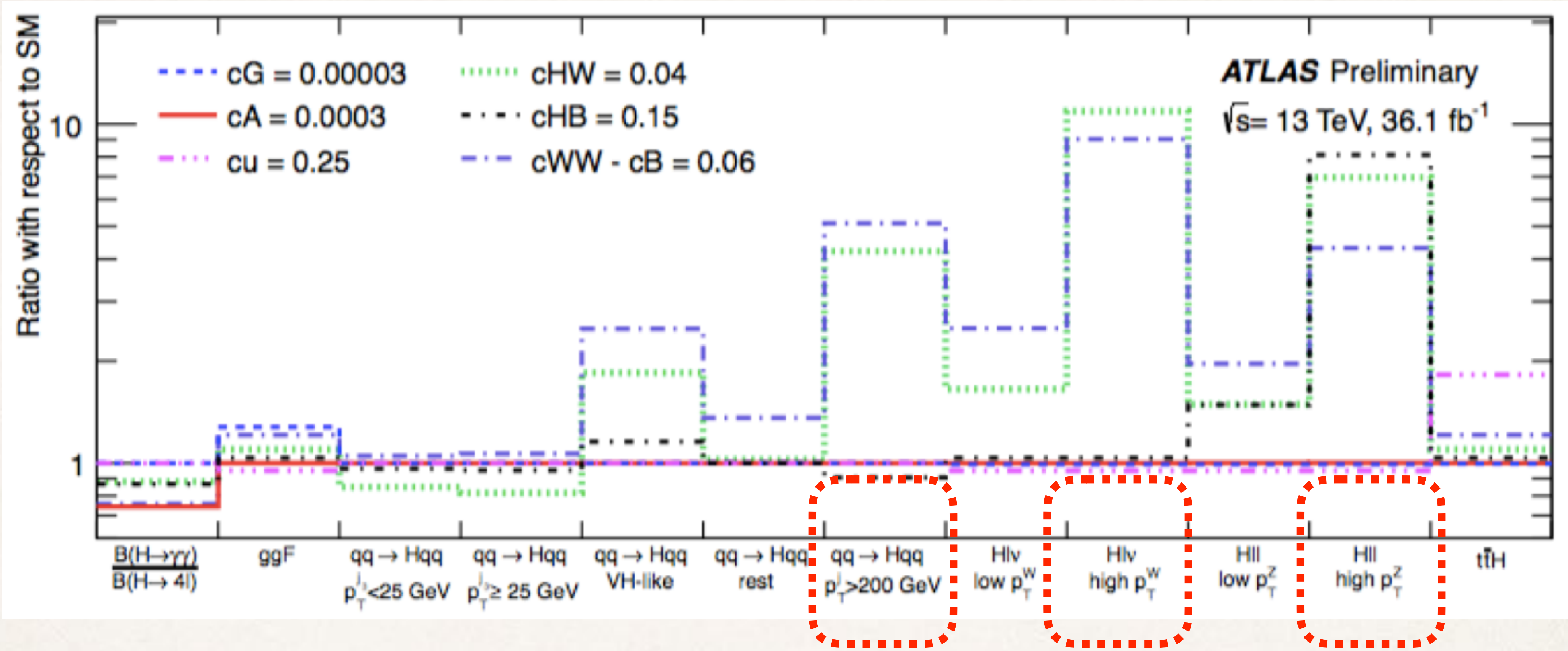
BUT EFT's extra parameters constrained by current measurements
Data can't favour SM yet

Theory	χ^2	χ^2/n_d	p-value
SM	157	0.987	0.532
SMEFT	137	0.987	0.528
SMEFT*	143	0.977	0.564



Combination of many channels is key—> GLOBAL FITS

3. *Extreme* kinematics



In these regions our theoretical/experimental understanding is weaker

e.g. WW at high-pT (large EW corrections)

e.g. Higgs+jet at high-pTH

and the **EFT validity** needs to be taken into account

This problem can be addressed by working harder
Many of us developing MC tools EFT@NLO and dim-8 effects

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New opportunities in the precision era for the LHC
are there any blind spots in experimental searches?
model-building exploration could inspire them
the LHC can probe TeV scale new physics via non-resonant searches, they cover a wide range of models (e.g. 2005.06492), more theoretical effort needed here