Discussion on global fits to EW+Higgs

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SM@LHC, April 2019

Before we get very technical

Why Higgs+EW? Why EFT?

A cosmological Higgs

HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

Phase transitions
Baryogenesis
gravitational waves

Fate of the Universe
Stability

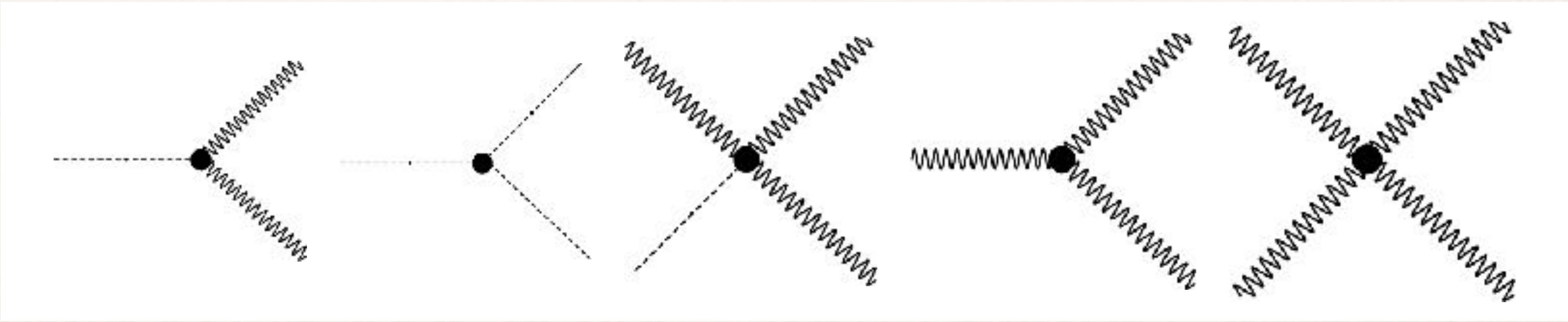
The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales
Exploiting complementarity with cosmo/astro probes

Higgs and EW bosons

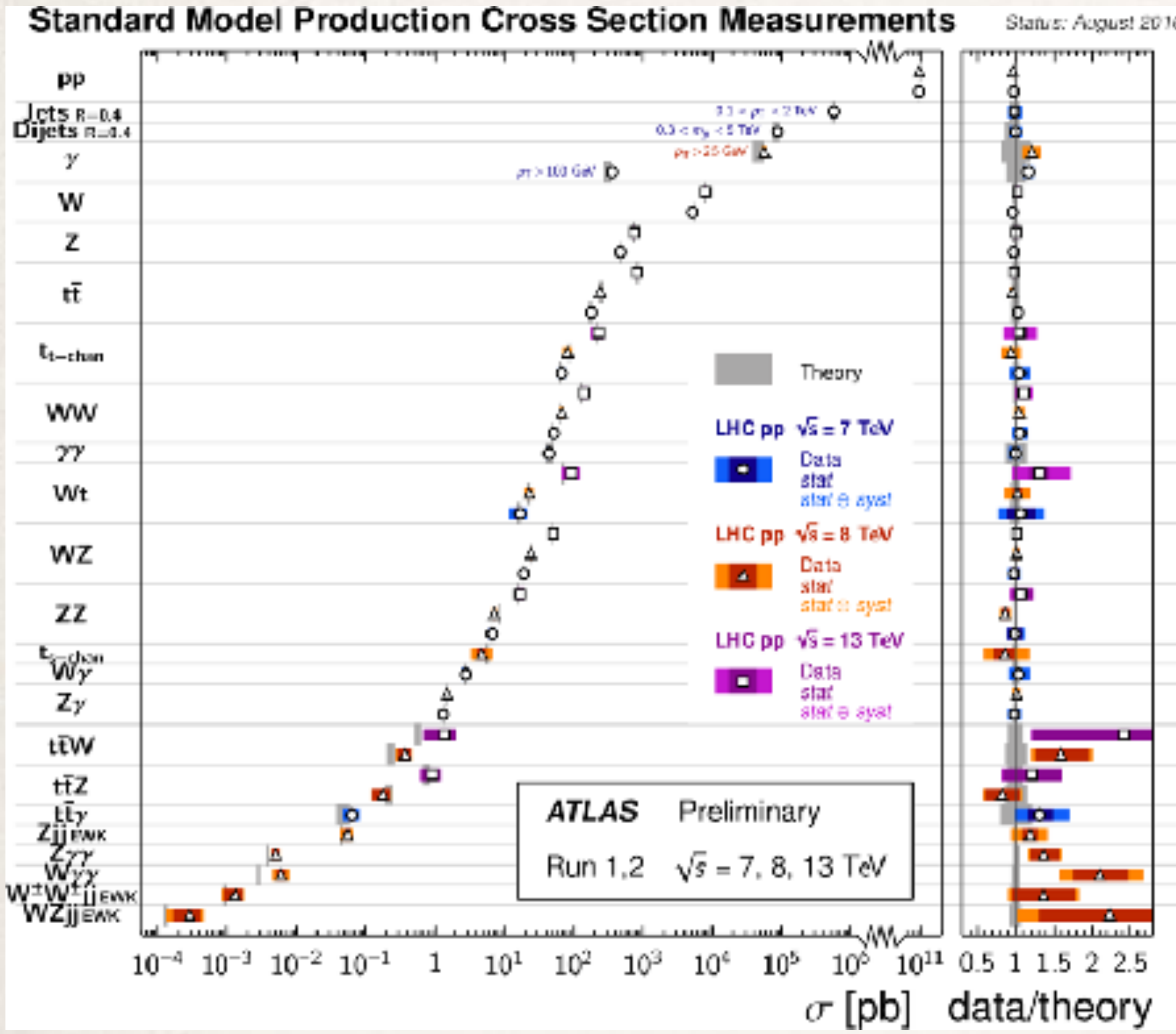
A doublet Higgs has 4 dof

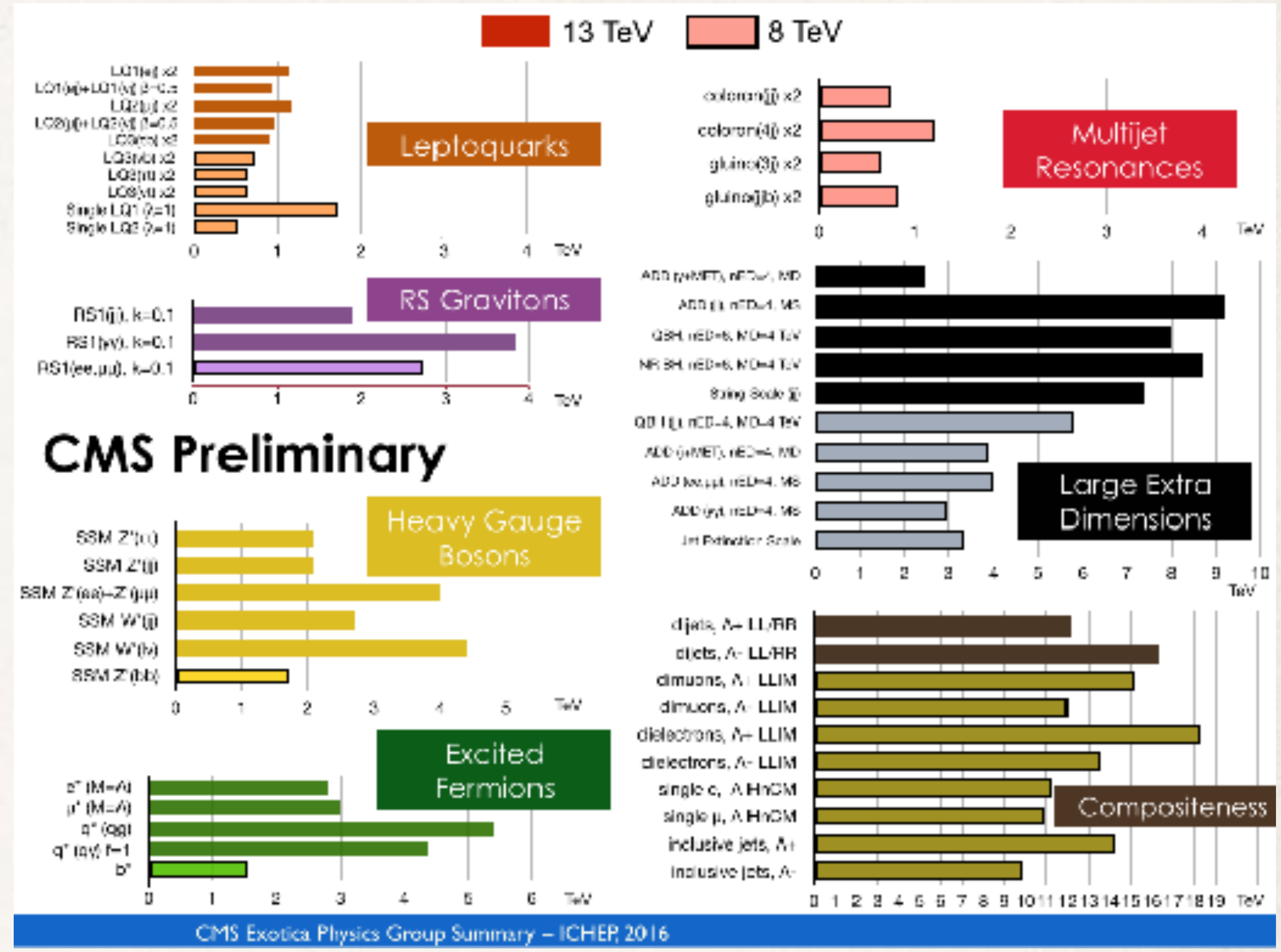
Higgs = (vev + higgs particle + W/Z dofs)

New physics altering the Higgs also alters EW boson production
Higgs observables and diboson production have to be **combined**
to understand the overall structure of EWSB

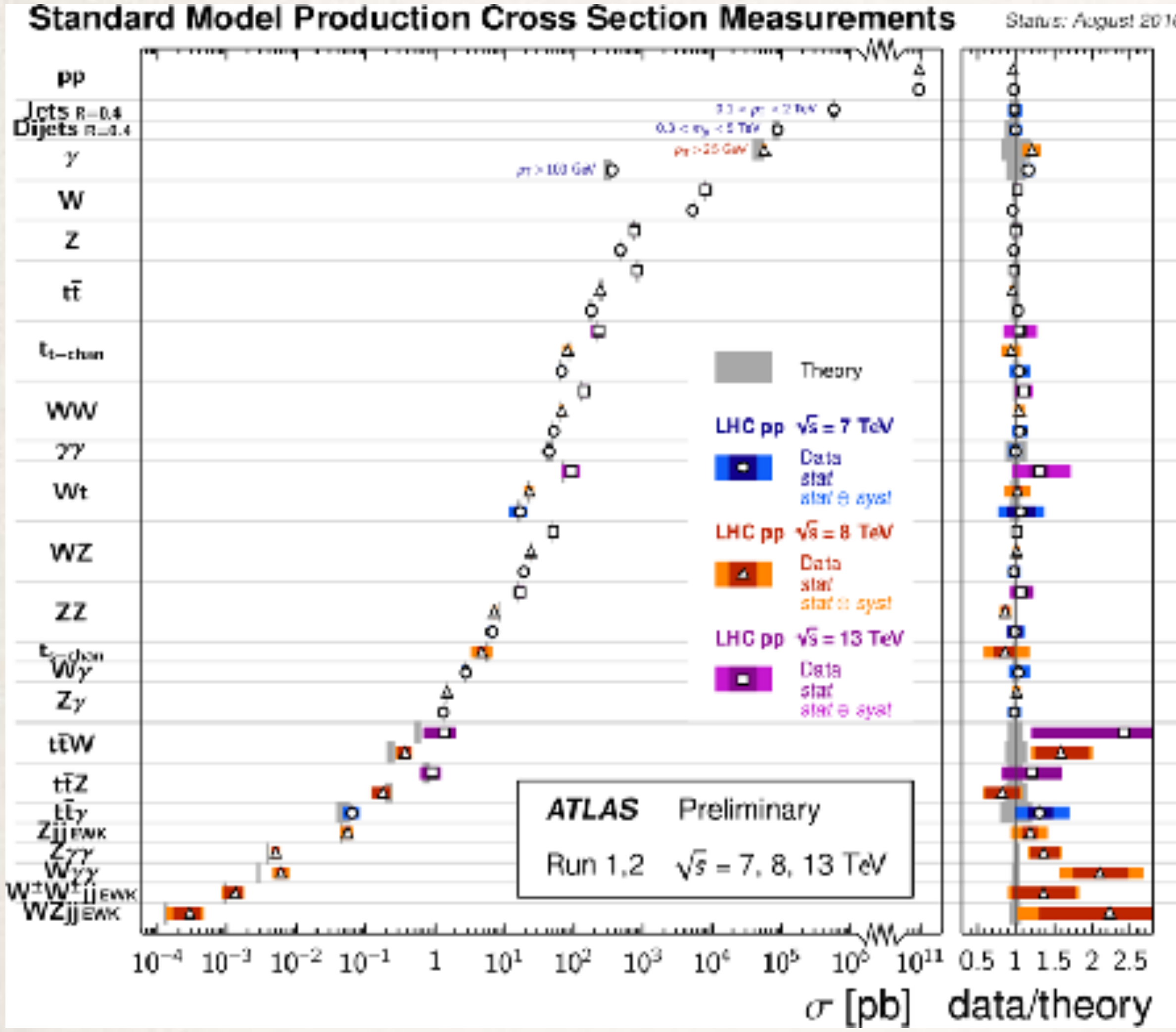


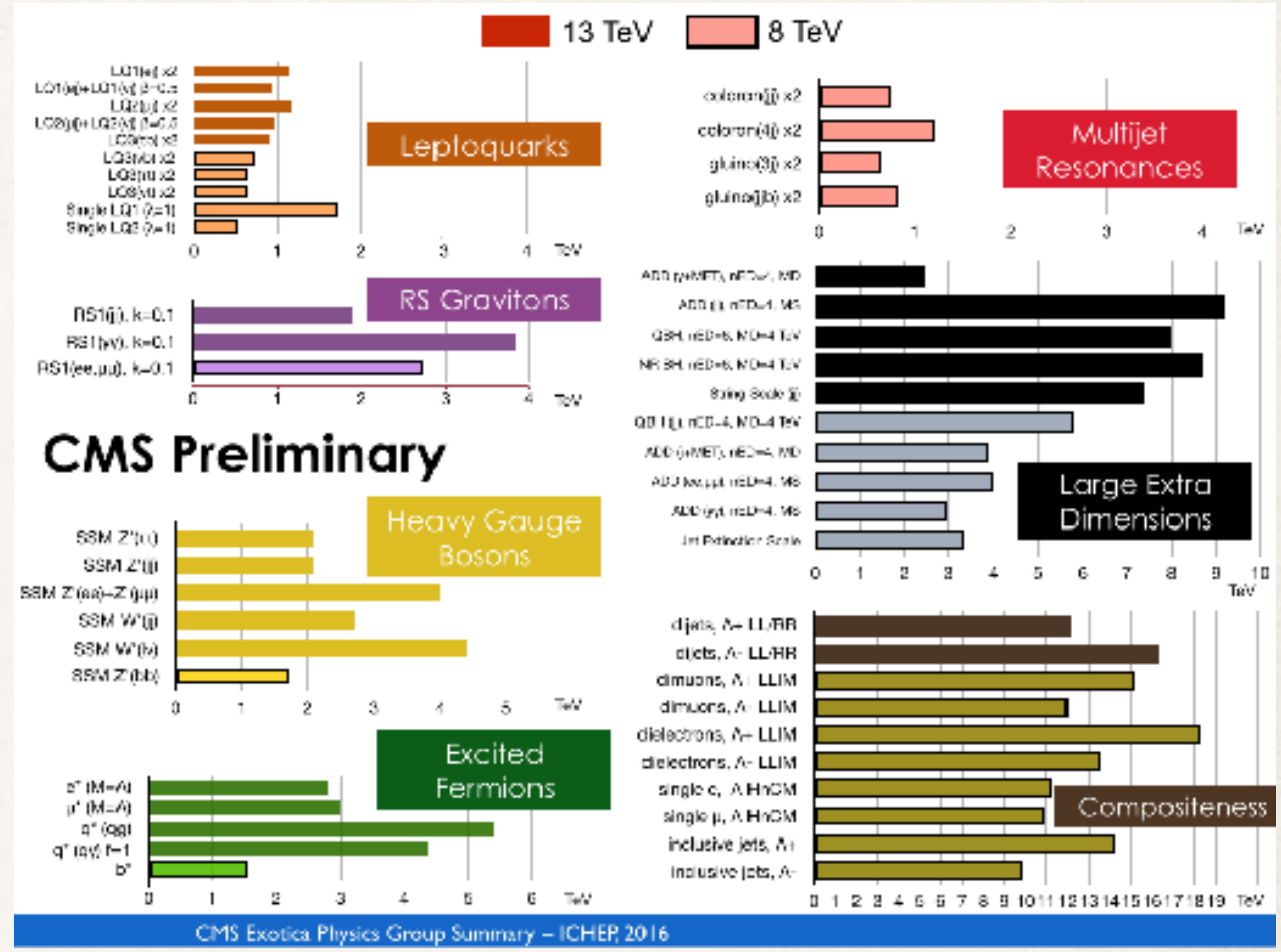
Why EFT?


Standard Model Production Cross Section Measurements
Status: August 2016
pp
Jets
Dijets
W
Z
tt̄
WW
Wt
WZ
ZZ
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
σ [pb]
data/theory


13 TeV
8 TeV
Leptoquarks
Multijet Resonances
RS Gravitons
CMS Preliminary
Large Extra Dimensions
Heavy Gauge Bosons
Excited Fermions
Compositeness
TeV
CMS Exotica Physics Group Summary – ICHEP, 2016

Why EFT?





The SM is a good description of Nature at the LHC

==> new resonances/phenomena may be **heavy**

==> Our hopes for simple/natural models are not realised

==> We should adopt a more **model-independent** strategy when interpreting data

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

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

BSM effects (Λ^2) SM particles ($\mathcal{O}_i^{d=6}$)

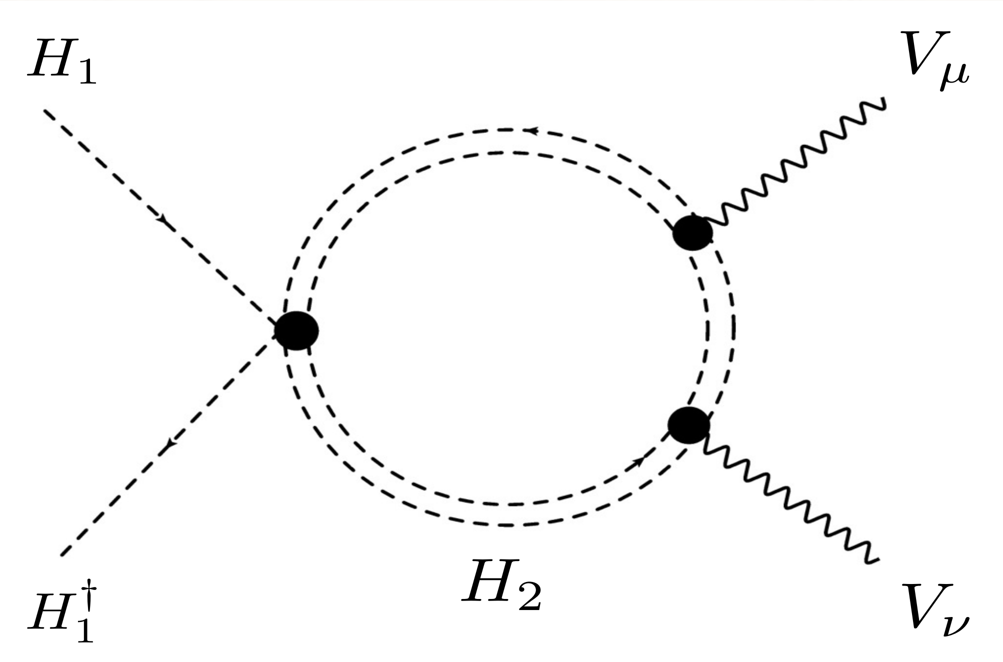
BSM is a **perturbation** around the SM
Each operator can be improved at higher orders in QCD and EW corrections

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.

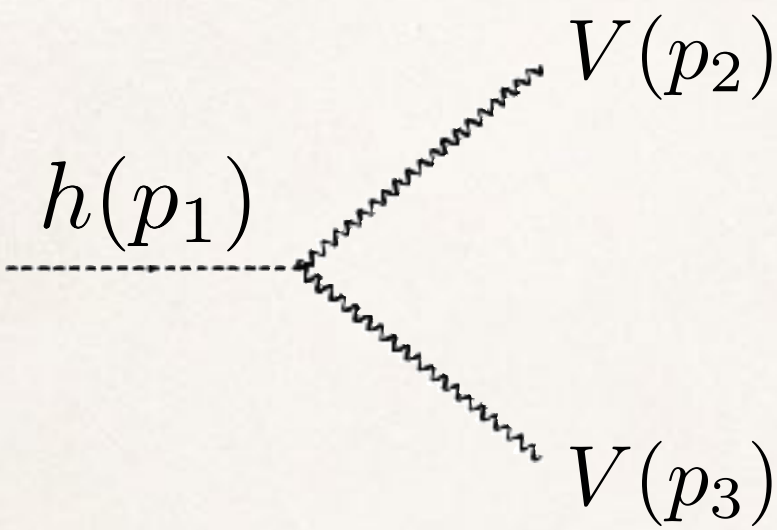
$$\frac{ig}{2m_W^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu} \qquad \text{where } \bar{c}_W = \frac{m_W^2\,(2\,\tilde{\lambda}_3+\tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$$

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

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

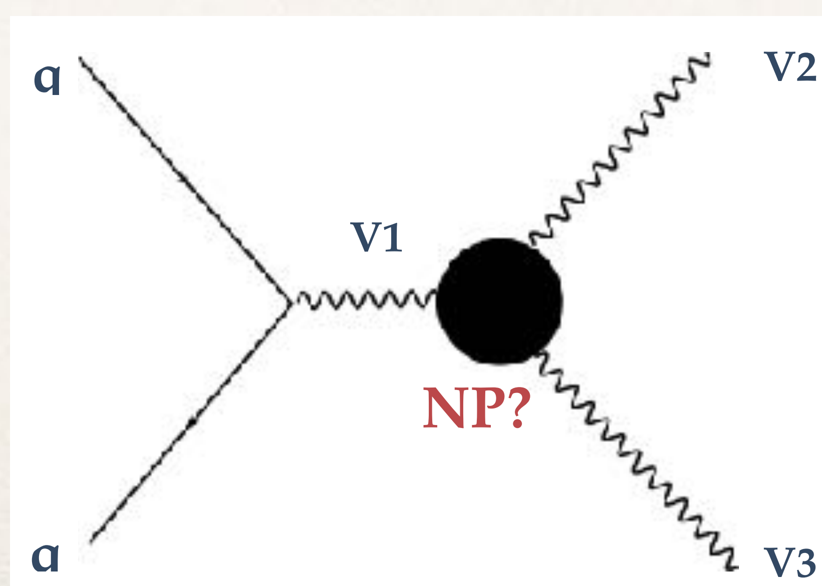


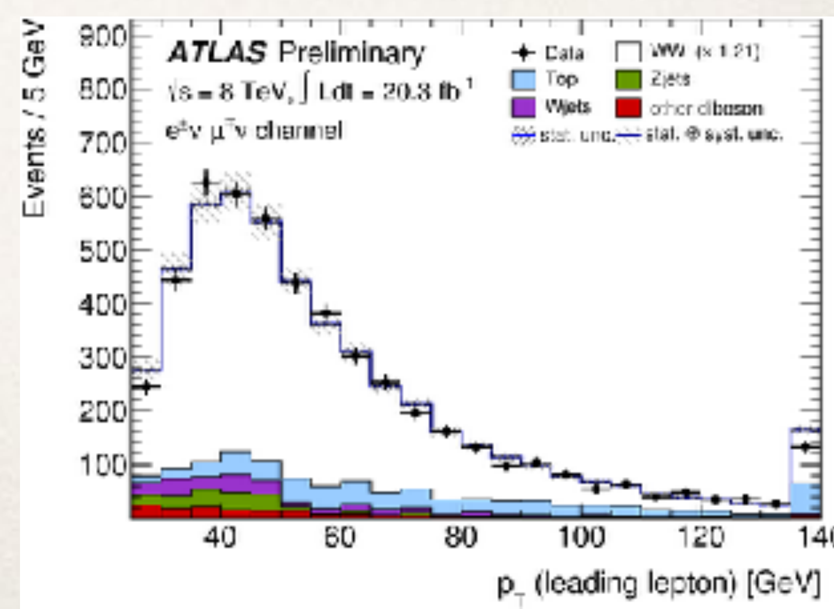
$$i\eta_{\mu\nu} \left(g^{(1)}_{hVV} \left(\frac{\hat{s}}{2} - m_V^2 \right) + 2 g^{(2)}_{hVV} m_V^2 \right)$$

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

+ *off-shell pieces*

exploited in searches for anomalous **TGCs**





Matching to UV theories

Within the EFT, connection to models is *straightforward*

EFT

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

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

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

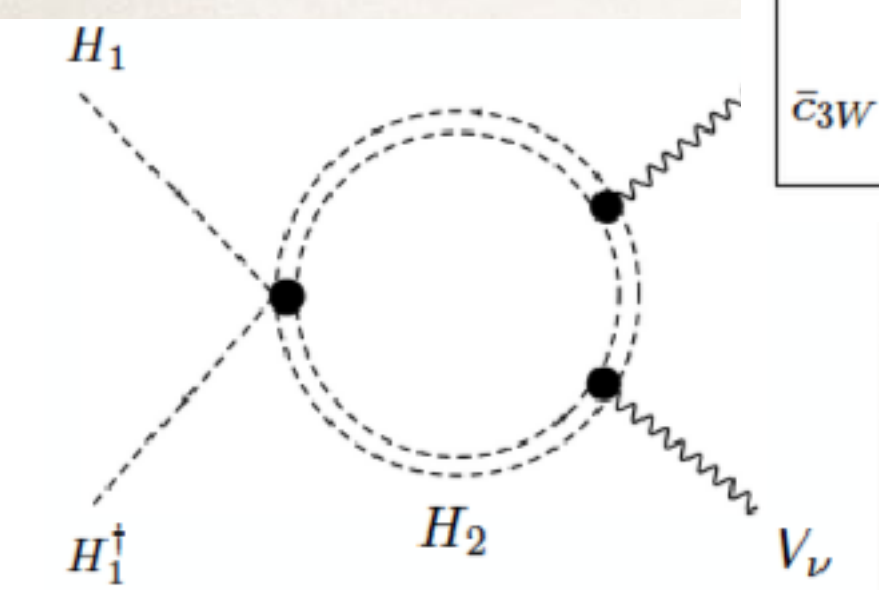
$$c_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

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

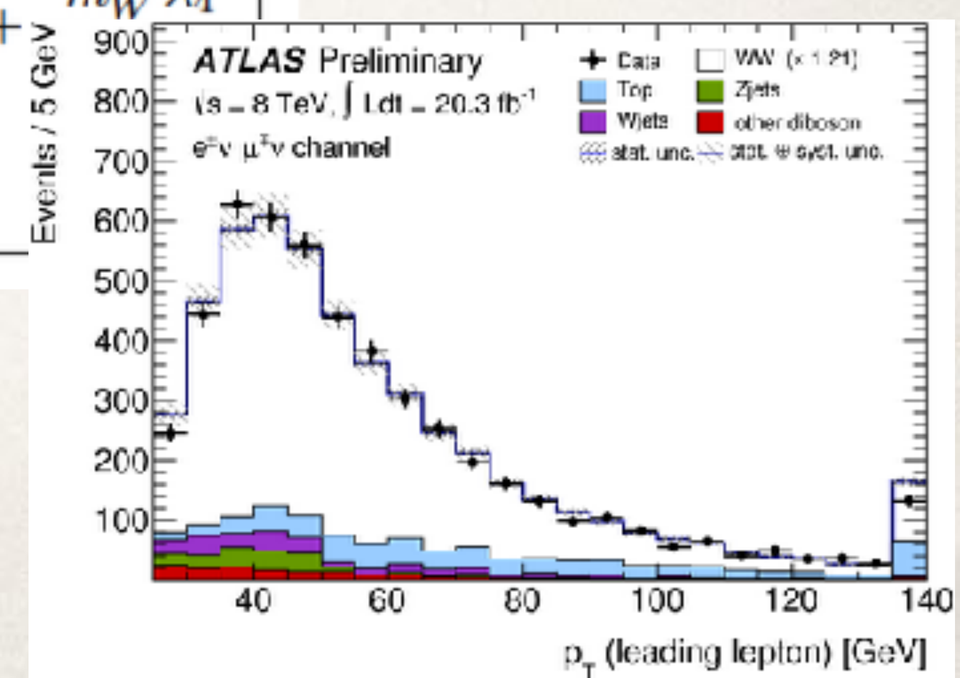
$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\bar{c}_\gamma + m_W^2\,\tilde{\lambda}_4$$

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

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

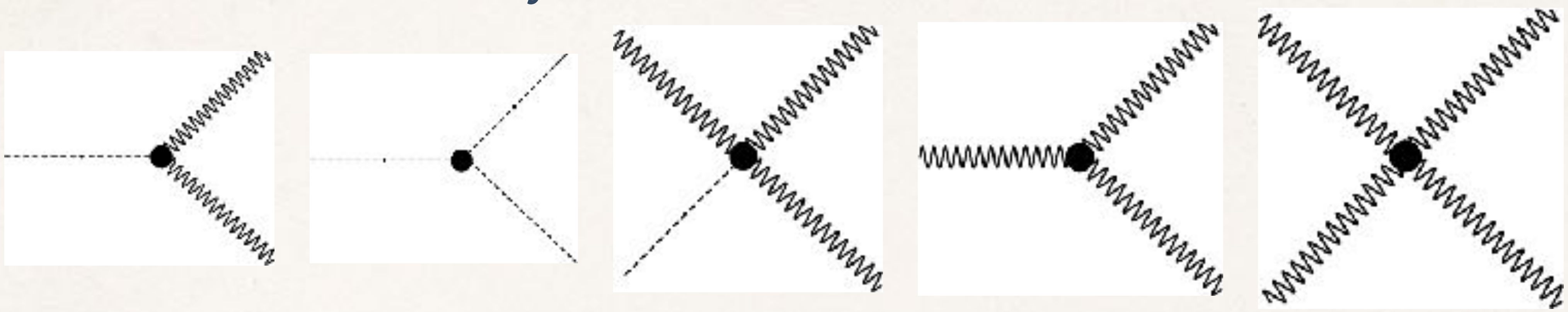
Disadvantages

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

Combination of data — SMEFT

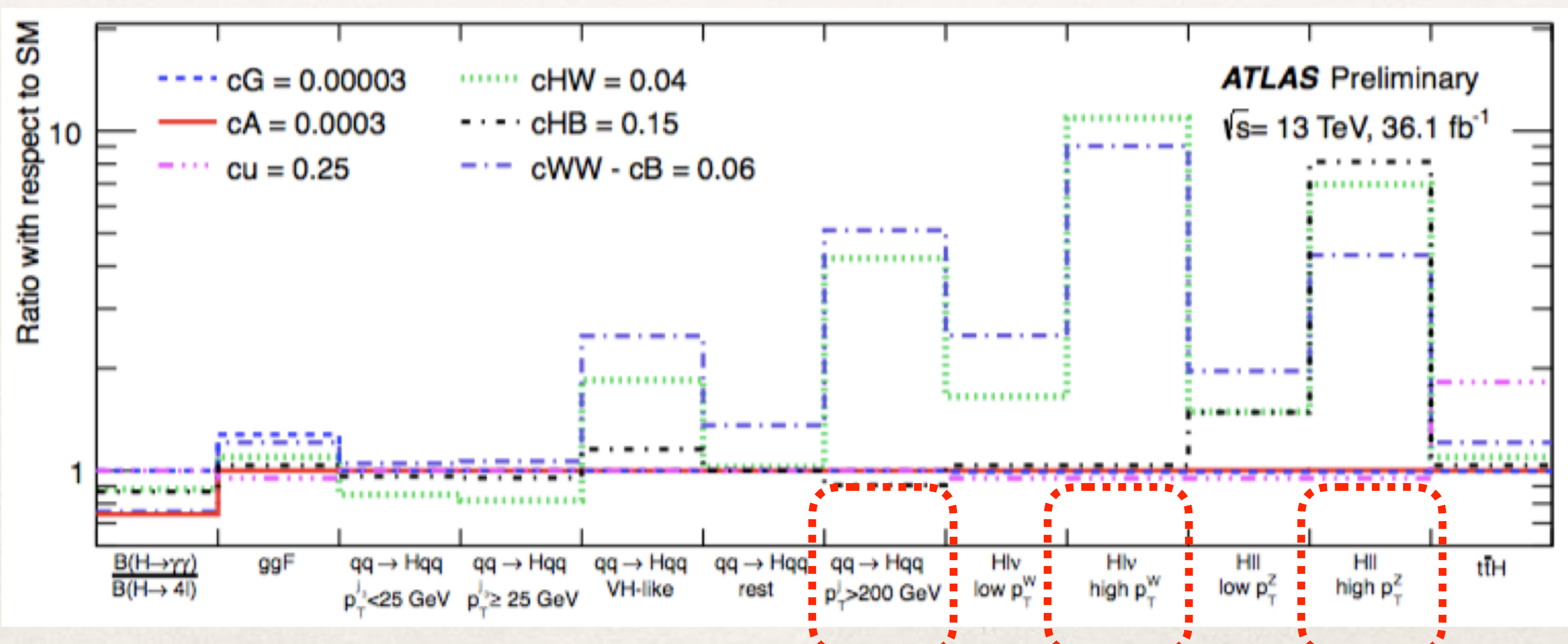
Global analyses using EFTs

EFTs induce effects in many channels, ideal framework for **combination**



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

key use of differential information



SMEFT recent results ELLIS, MURPHY, VS, YOU. 1803.03252

In this work:

Use EWPT, Higgs and diboson data, incl use STXS

Assume linear EWSB, CP-conservation and MFV

Present results in Warsaw and SILH bases, 20 operators

Matching to simplified UV models

e.g. **WARSAW**

$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{\bar{C}_{Hl}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l) + \frac{\bar{C}_{Hl}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l) + \frac{\bar{C}_{ll}}{v^2}(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$
$$+ \frac{\bar{C}_{HD}}{v^2}\left|H^\dagger D_\mu H\right|^2 + \frac{\bar{C}_{HWB}}{v^2}H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$$
$$+ \frac{\bar{C}_{He}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e) + \frac{\bar{C}_{Hu}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u) + \frac{\bar{C}_{Hd}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$
$$+ \frac{\bar{C}_{Hq}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q) + \frac{\bar{C}_{Hq}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q) + \frac{\bar{C}_W}{v^2}\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$$

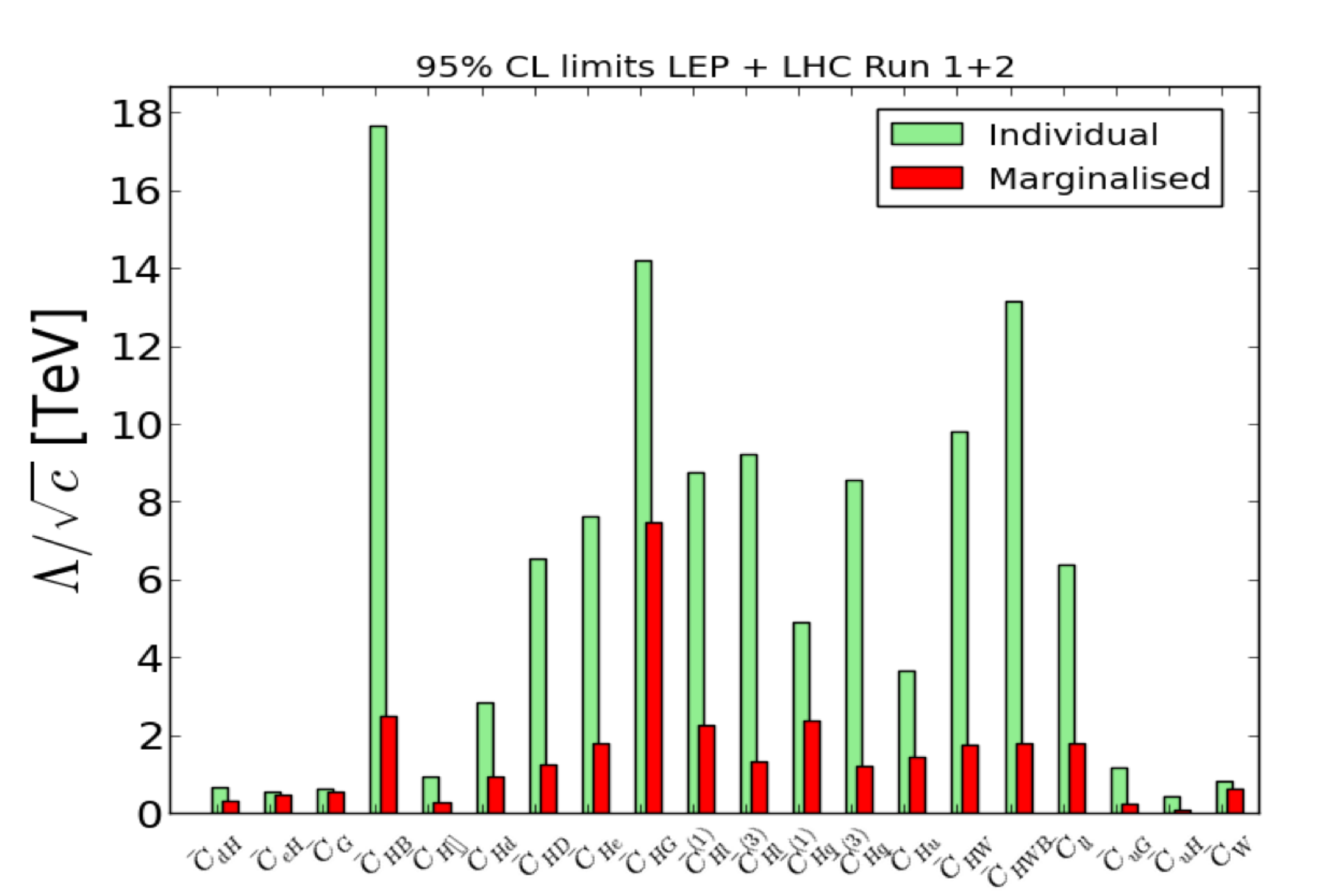
$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{\bar{C}_{eH}}{v^2}(H^\dagger H)(\bar{l}eH) + \frac{\bar{C}_{dH}}{v^2}(H^\dagger H)(\bar{q}dH) + \frac{\bar{C}_{uH}}{v^2}(H^\dagger H)(\bar{q}u\widetilde{H})$$
$$+ \frac{\bar{C}_G}{v^2}f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{\bar{C}_{H\Box}}{v^2}(H^\dagger H)\Box(H^\dagger H) + \frac{\bar{C}_{uG}}{v^2}(\bar{q}\sigma^{\mu\nu}T^A u)\widetilde{H}\,G^A_{\mu\nu}$$
$$+ \frac{\bar{C}_{HW}}{v^2}H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu} + \frac{\bar{C}_{HB}}{v^2}H^\dagger H\, B_{\mu\nu}B^{\mu\nu} + \frac{\bar{C}_{HG}}{v^2}H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}\,.$$

SMEFT recent results ELLIS, MURPHY, VS, YOU. 1803.03252

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

SMEFT: 20 deformations
SMEFT*: 13 deformations
(weakly coupled and renormalizable)

SEE ALSO **MORE RECENT**
GONZALEZ-GARCIA ET AL
1812.01009
PLEHN ET AL. 1812.07587
SIMILAR RESULTS



SMEFT recent results

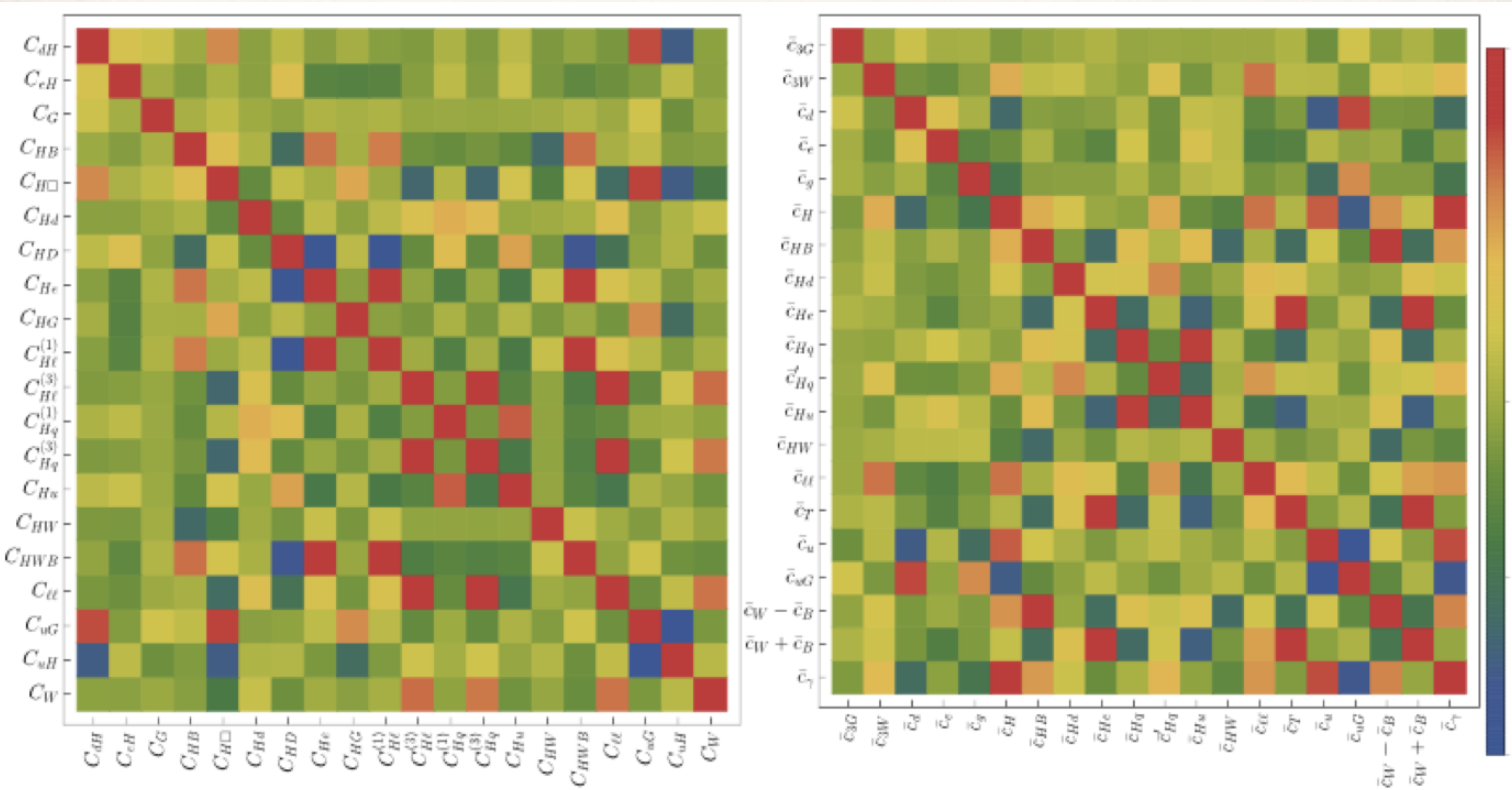
ELLIS, MURPHY, VS, YOU. 1803.03252

We need more resolution on LHC's high-pT WW

Coefficient	Z-pole + m_W	WW at LEP2	Higgs Run1	Higgs Run2	LHC WW high-p_T
$\bar{C}_{dH}$	×	×	36	64	×
$\bar{C}_{eH}$	×	×	49.6	50.4	×
$\bar{C}_{G}$	×	×	2.3	97.7	×
$\bar{C}_{HB}$	×	×	19	81	×
$\bar{C}_{H\Box}$	×	×	19.7	80.3	0.01
$\bar{C}_{Hd}$	99.88	×	0.04	0.07	×
$\bar{C}_{HD}$	99.92	0.06	×	×	×
$\bar{C}_{He}$	99.99	0.01	×	×	×
$\bar{C}_{HG}$	×	×	34	66	0.02
$\bar{C}^{(1)}_{H\ell}$	99.97	0.03	×	×	×
$\bar{C}^{(3)}_{H\ell}$	99.56	0.41	×	×	0.01
$\bar{C}^{(1)}_{Hq}$	99.98	×	0.01	0.01	×
$\bar{C}^{(3)}_{Hq}$	98.6	0.96	0.19	0.23	0.07
$\bar{C}_{Hu}$	99.5	×	0.2	0.3	0.04
$\bar{C}_{HW}$	×	×	18	82	×
$\bar{C}_{HWB}$	57.9	0.02	8.2	33.9	×
$\bar{C}_{\ell\ell}$	99.66	0.32	×	0.01	0.01
$\bar{C}_{uG}$	×	×	7.8	92.2	×
$\bar{C}_{uH}$	×	×	9.5	90.5	×
$\bar{C}_{W}$	×	96.2	×	×	3.8

SMEFT recent results ELLIS, MURPHY, VS, YOU. 1803.03252

Correlations in WARSAW (left) and SILH (right)
no basis is more *diagonal*



SMEFT recent results ELLIS, MURPHY, VS, YOU. 1803.03252

Constraints on simple extensions of the SM

Model	χ^2	χ^2/n_d	Coupling	Mass / TeV
SM	157	0.987	-	-
$\mathcal{S}_1$	156	0.986	$\lvert y_{\mathcal{S}_1}\rvert^2 = (6.3 \pm 5.9) \cdot 10^{-3}$	$M_{\mathcal{S}_1} = (9.0,\ 49)$
φ, Type I	156	0.986	$Z_6 \cdot \cos\beta = -0.64 \pm 0.59$	$M_\varphi = (0.9,\ 4.3)$
Ξ	155	0.984	$\lvert\kappa_\Xi\rvert^2 = (4.2 \pm 3.4) \cdot 10^{-3}$	$M_\Xi = (12,\ 35)$
N	155	0.978	$\lvert\lambda_N\rvert^2 = (1.8 \pm 1.2) \cdot 10^{-2}$	$M_N = (5.8,\ 13)$
$\mathcal{W}_1$	155	0.984	$\left\lvert\hat{g}^\phi_{\mathcal{W}_1}\right\rvert^2 = (3.3 \pm 2.7) \cdot 10^{-3}$	$M_{\mathcal{W}_1} = (4.1,\ 13)$
E	156.9	0.993	$\lvert\lambda_E\rvert^2 = (2.0 \pm 9.7) \cdot 10^{-3}$	$M_E = (9.2,\ \infty)$
Δ_3	156	0.990	$\lvert\lambda_{\Delta_3}\rvert^2 = (0.8 \pm 1.1) \cdot 10^{-2}$	$M_{\Delta_3} = (7.3,\ \infty)$
Σ	156.7	0.992	$\lvert\lambda_\Sigma\rvert^2 = (0.9 \pm 2.0) \cdot 10^{-2}$	$M_\Sigma = (5.9,\ \infty)$
Q_5	156	0.990	$\lvert\lambda_{Q_5}\rvert^2 = 0.08 \pm 0.10$	$M_{Q_5} = (2.4,\ \infty)$
T_2	156.8	0.992	$\lvert\lambda_{T_2}\rvert^2 = (2.0 \pm 5.1) \cdot 10^{-2}$	$M_{T_2} = (3.8,\ \infty)$
$\mathcal{S}$	157	0.993	$\lvert y_\mathcal{S}\rvert^2 < 0.32$	$M_\mathcal{S} > 1.8$
Δ_1	157	0.993	$\lvert\lambda_{\Delta_1}\rvert^2 < 5.7 \cdot 10^{-3}$	$M_{\Delta_1} > 13$
Σ_1	157	0.993	$\lvert\lambda_{\Sigma_1}\rvert^2 < 7.3 \cdot 10^{-3}$	$M_{\Sigma_1} > 12$
U	157	0.993	$\lvert\lambda_U\rvert^2 < 2.8 \cdot 10^{-2}$	$M_U > 6.0$
D	157	0.993	$\lvert\lambda_D\rvert^2 < 1.4 \cdot 10^{-2}$	$M_D > 8.4$
Q_7	157	0.993	$\lvert\lambda_{Q_7}\rvert^2 < 7.7 \cdot 10^{-2}$	$M_{Q_7} > 3.6$
T_1	157	0.993	$\lvert\lambda_{T_1}\rvert^2 < 0.13$	$M_{T_1} > 3.0$
$\mathcal{B}_1$	157	0.993	$\left\lvert\hat{g}^\phi_{\mathcal{B}_1}\right\rvert^2 < 2.4 \cdot 10^{-3}$	$M_{\mathcal{B}_1} > 21$

Classification by DE BLAS, CRIADO, PEREZ-VICTORIA, SANTIAGO 1711.10391

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)

BUT then one cannot explain ρ and λ_{WZ}

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

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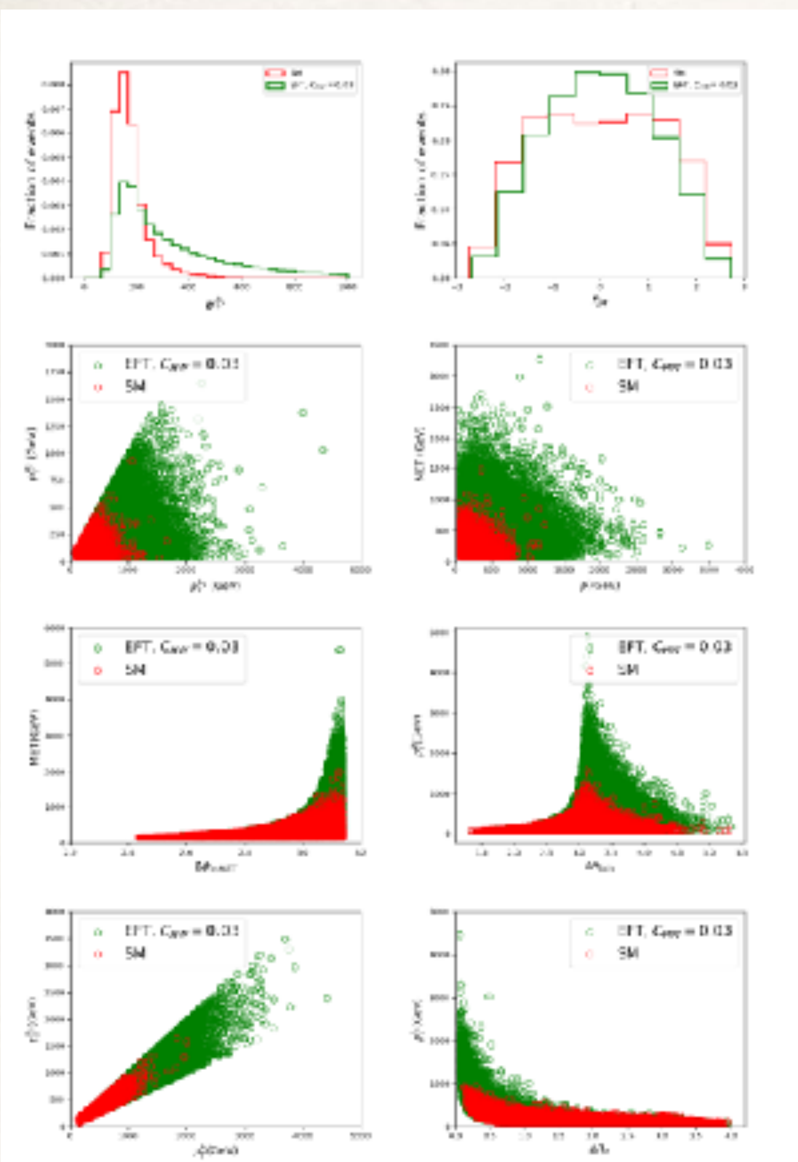
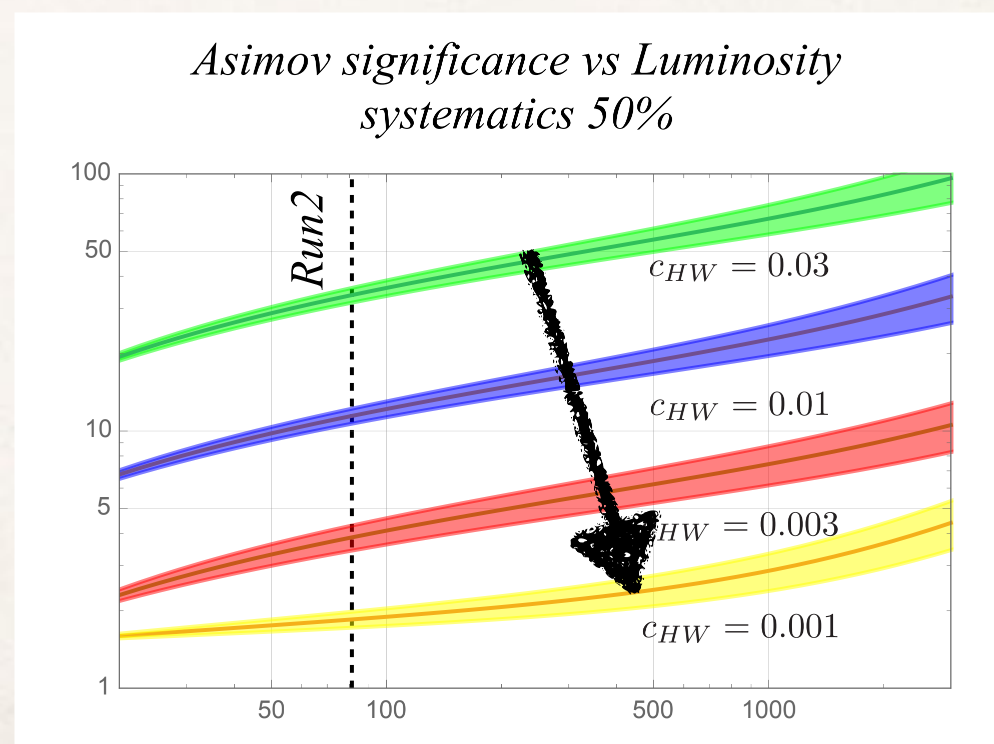


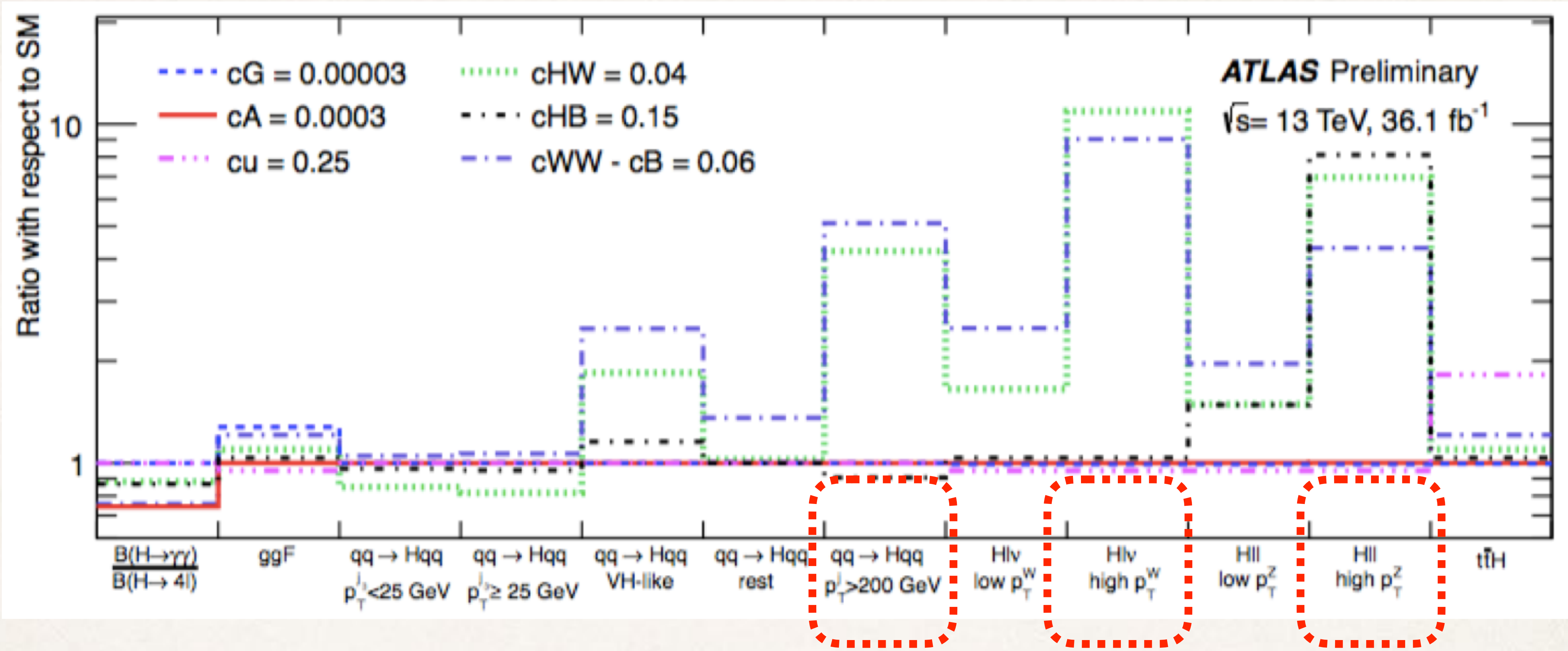
Combination is key: single channel not enough information for EFTs allowed deformations

Kinematics is key: and calls for AI techniques



FREITAS, KAUR AND VS. 1902.05803

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

Conclusions

- The Higgs may be the key to discover new physics: lightness and association with the origin of mass
- The discovery of the Higgs in 2012 opened a new way to look for new physics via quantum effects (indirect). With Run2 at 13 TeV, the LHC is approaching a precision stage for Higgs measurements
- The EFT approach to interpret Higgs data is a theorist-friendly procedure and with a well-defined procedure for systematic improvement. It is motivated by the absence of excesses in direct searches
- Global analysis EWPTs, Higgs and diboson data leads to reach for new physics in the multi-TeV range
- There is a number of challenges, which we can address. To reach the precision needed for discovery, theorists are developing precision MC tools to facilitate the communication with experimentalists

Name	Spin	$SU(3)$	$SU(2)$	$U(1)$	Name	Spin	$SU(3)$	$SU(2)$	$U(1)$
$\mathcal{S}$	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
$\mathcal{S}_1$	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	1	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
$\mathcal{B}$	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
$\mathcal{B}_1$	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
$\mathcal{W}$	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
$\mathcal{W}_1$	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$

Table 6: *Single-field extensions of the SM constrained by our analysis.*