Global SMEFT fit to Higgs and EW observables

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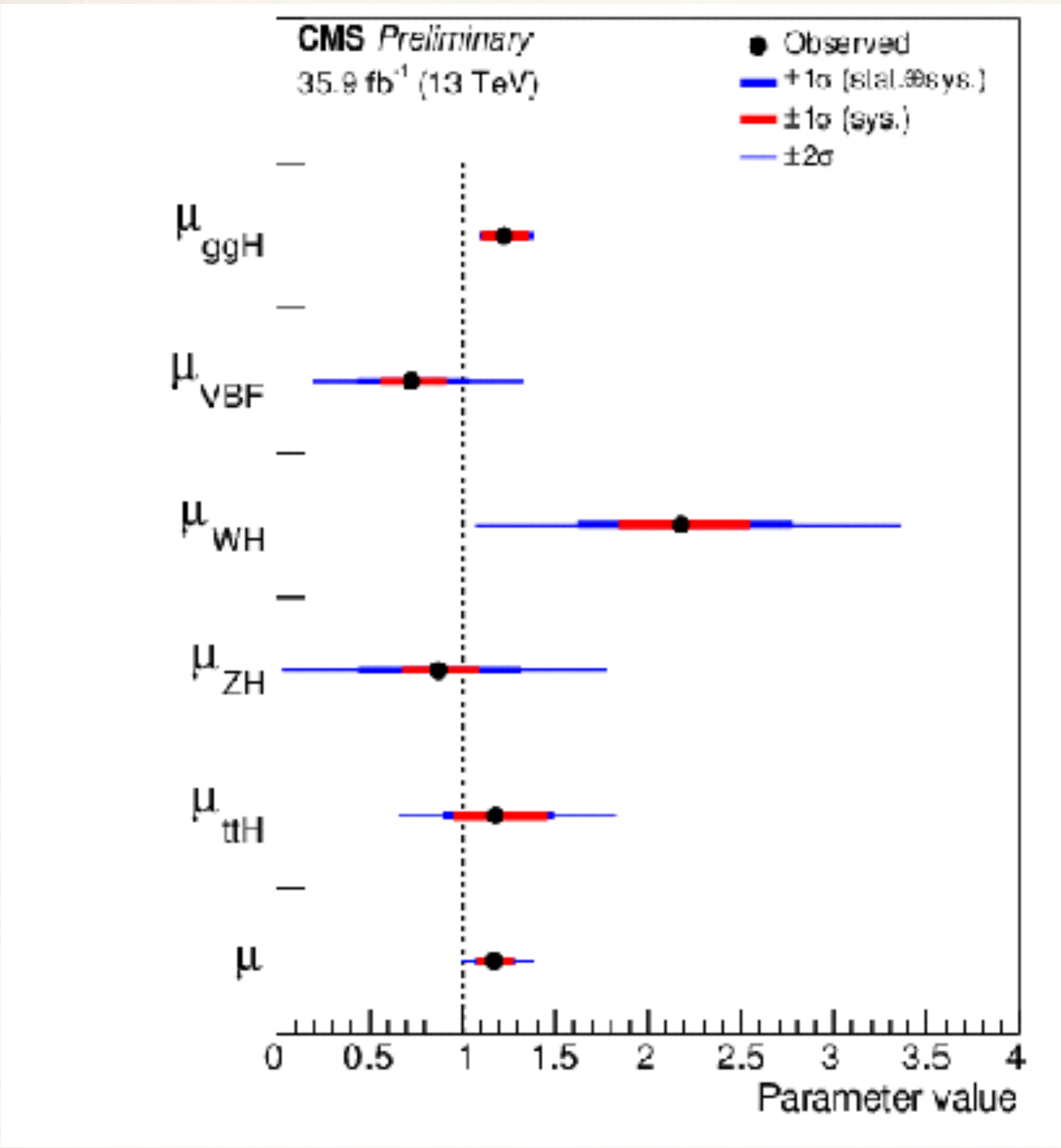
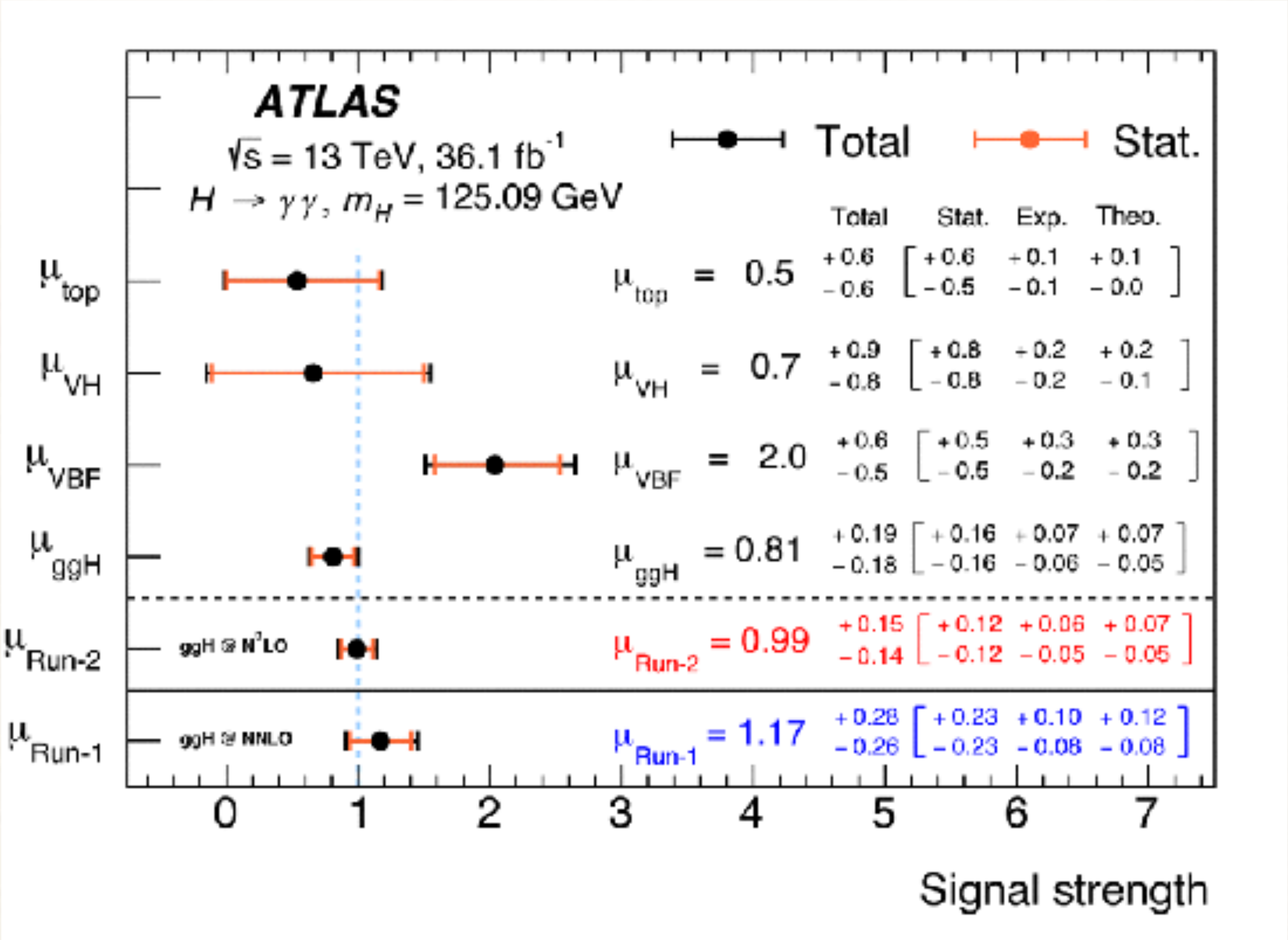
University of Sussex

Reinterpretation workshop (IC), April 2019

SM Higgs — an LHC snapshot

Run2 indicates a *SM-like* Higgs





Why the Higgs?

Before we get very technical

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

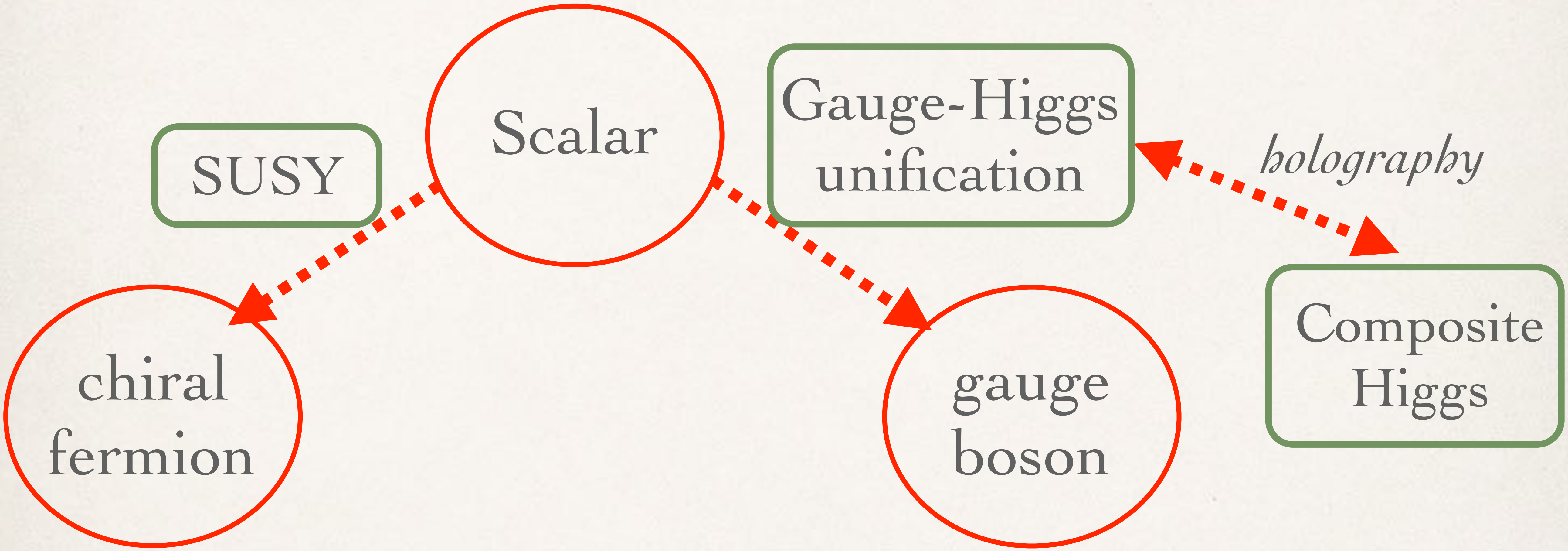
Fate of the Universe
Stability

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

Similar story for Axions and ALPs, scalars are versatile

Light scalars

The light Higgs is a reality
symmetry/duality arguments to explain its nature

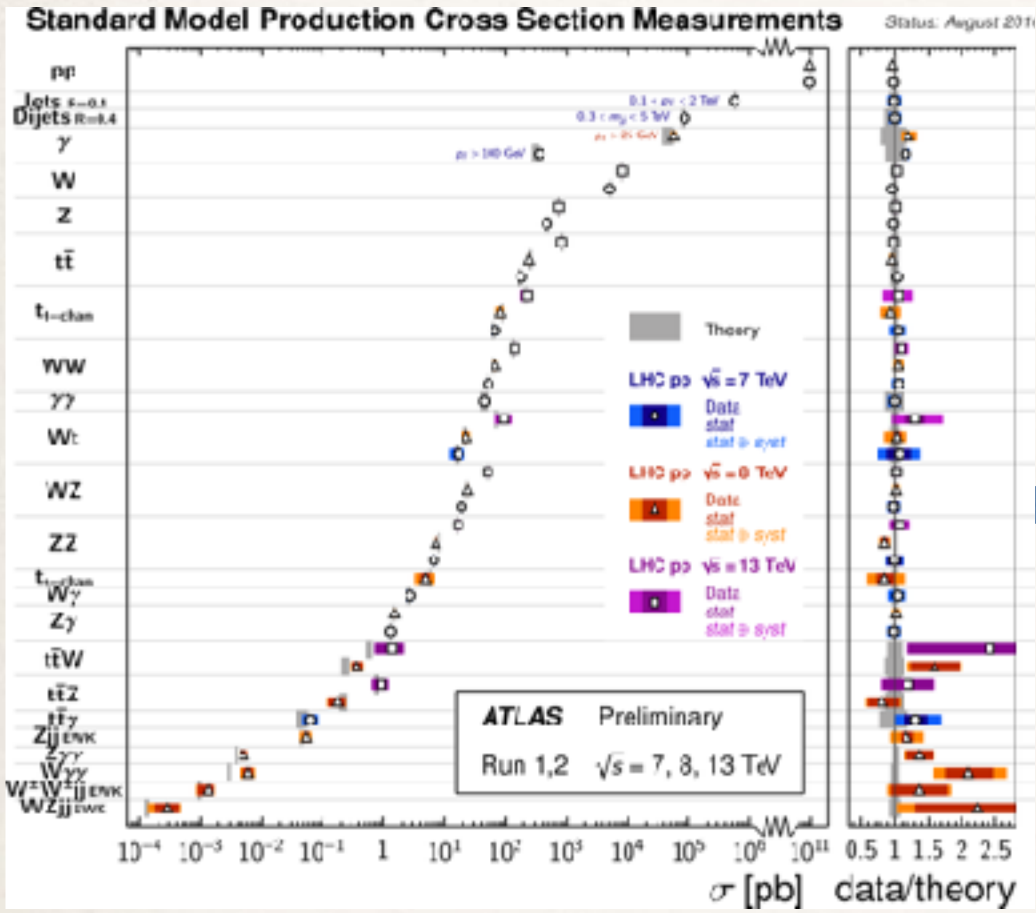


Many, many possible realizations (phenomenology)
Predict new states, to be discovered
(SUSY partners, techni-baryons and mesons, spin-two…)
AND induce deviations in the Higgs behaviour

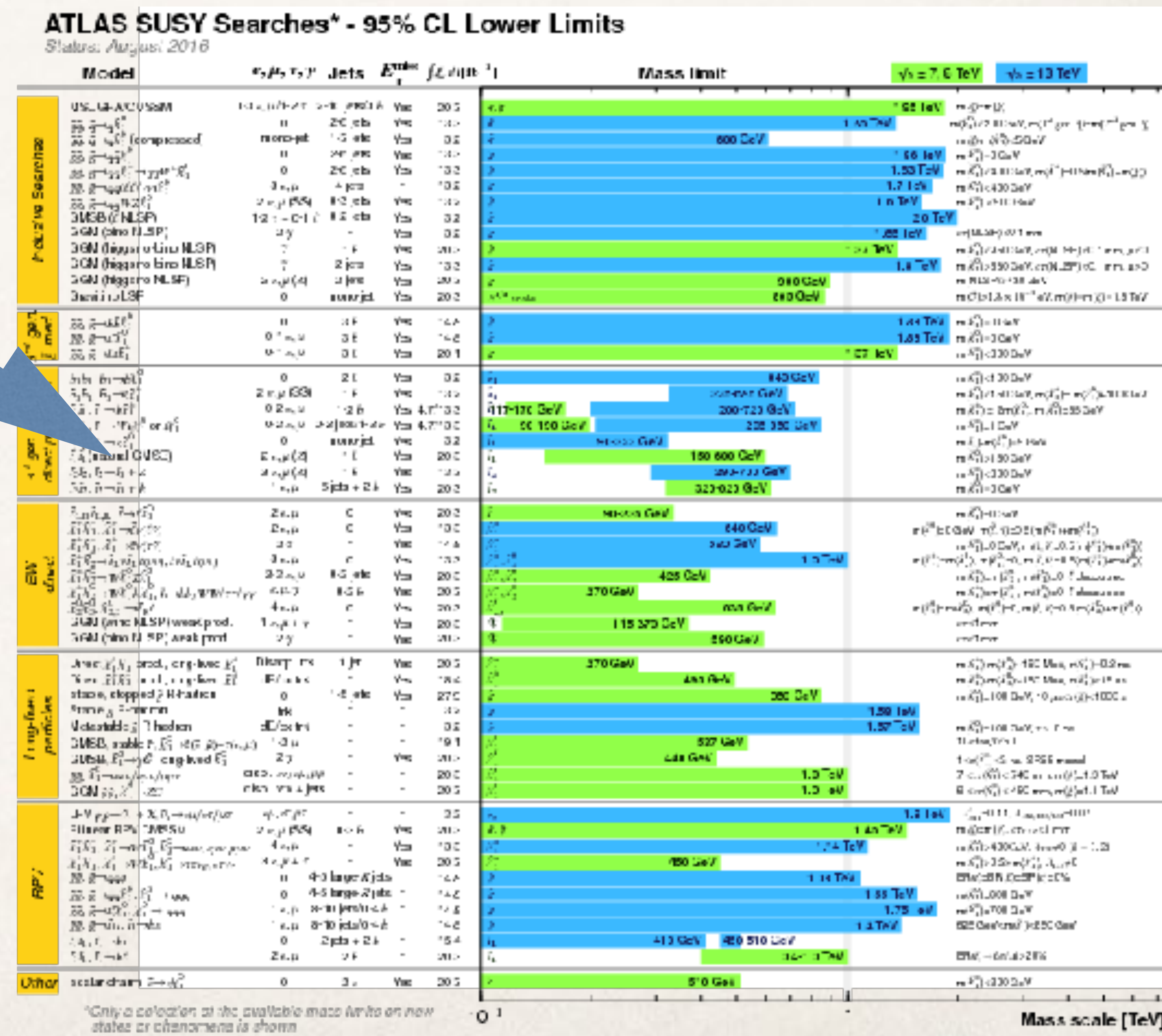
Direct versus indirect searches

Direct searches for new phenomena

consistency of data vs SM predictions



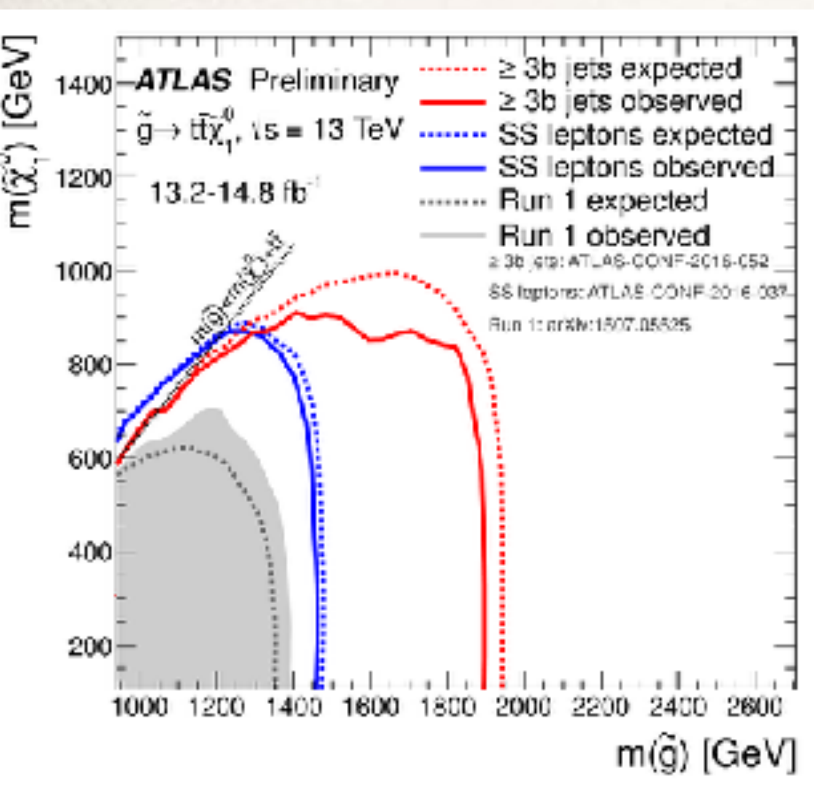
Interpretation in models: exclusion regions

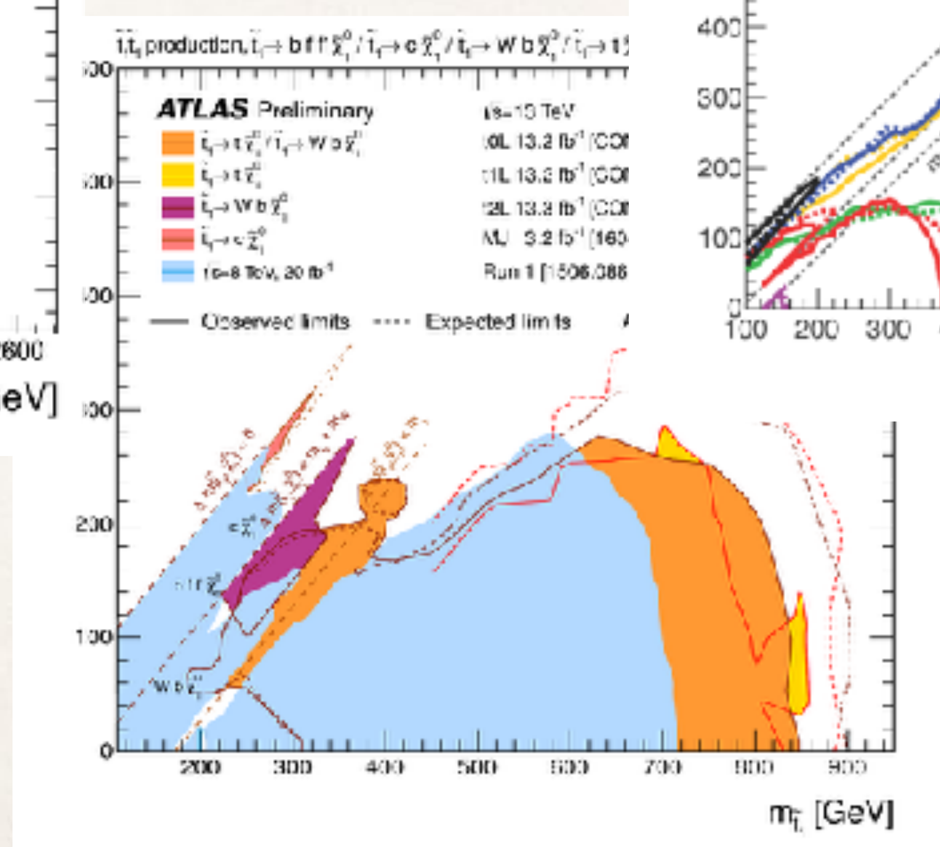


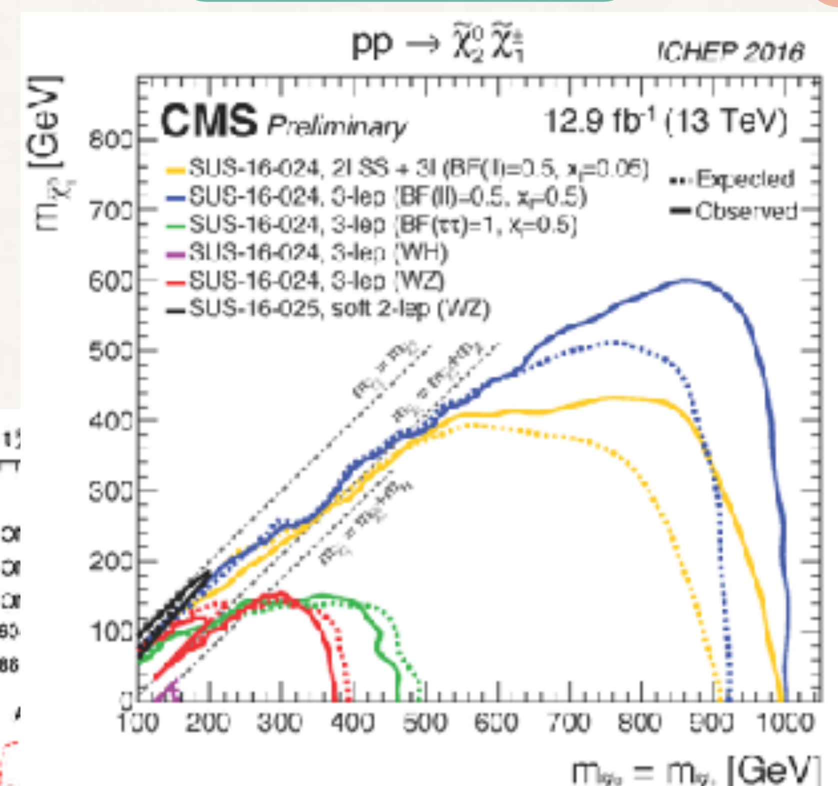
Example: coloured SUSY

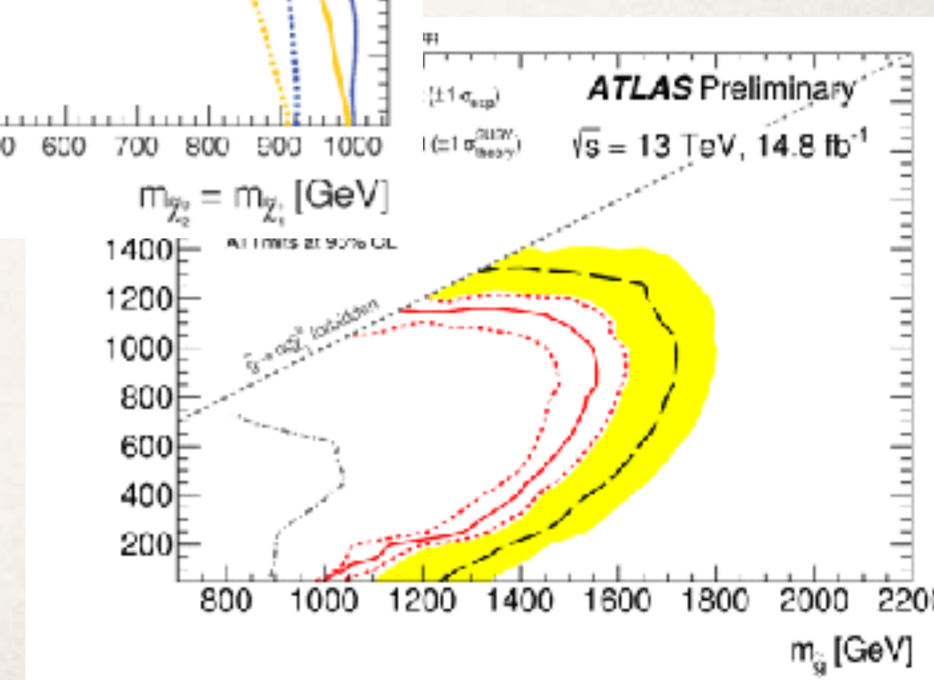
The 13 TeV data pushing hard the limits on coloured states

Vanilla SUSY | **Natural SUSY** | **EW SUSY** | **some-SUSY**







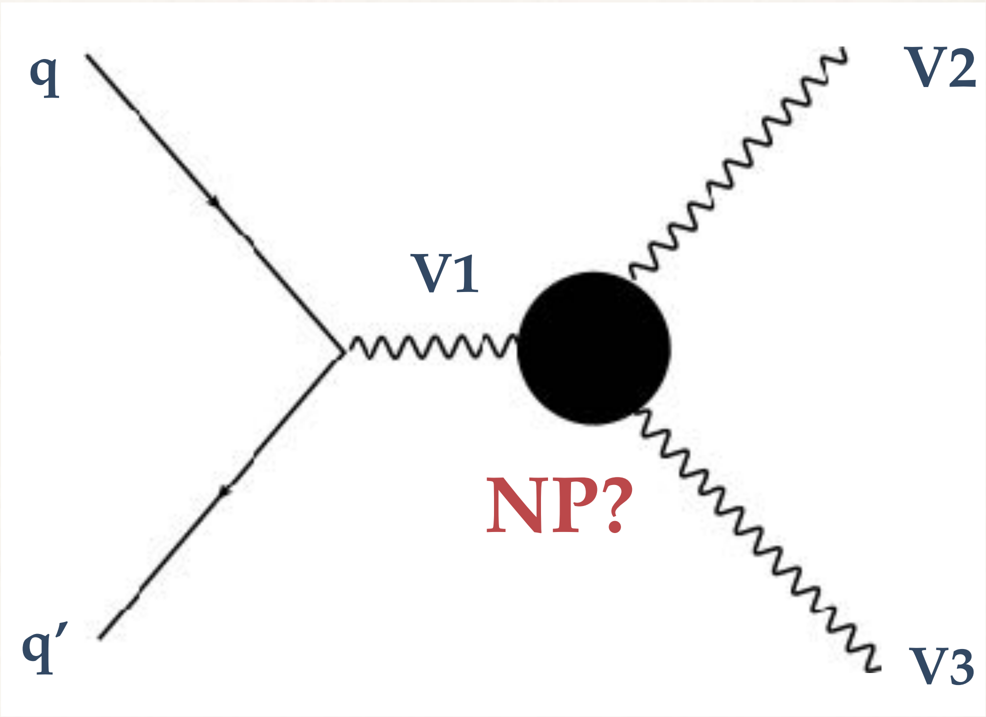


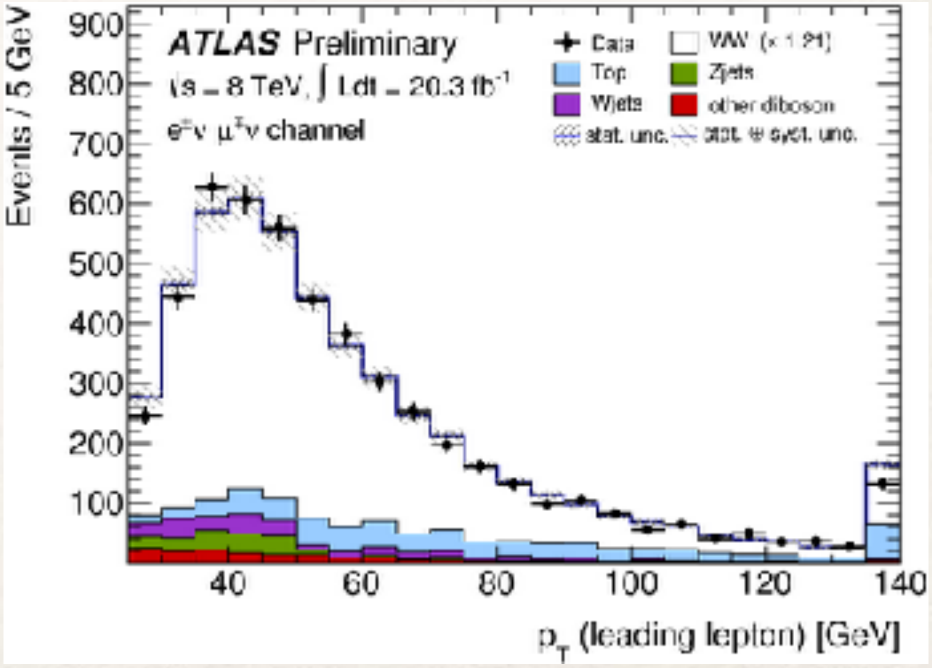
Indirect searches

Focus on SM particles' behaviour
precise determination of couplings
and kinematics
comparison with SM,
search for deviations

Indirect searches using the Higgs
since 2012, relatively new
Higgs as a window to NP
expect deviations in its behaviour
Run2 data and beyond
precision Higgs Physics

e.g. Anomalous trilinear gauge couplings, aka **TGCs**





LEP, Tevatron, LHC

The EFT approach

Looking for small deviations from the 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

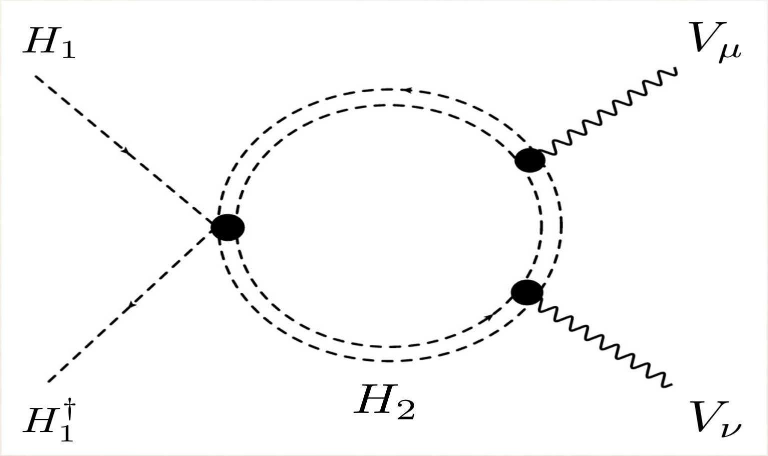
dimension-6 dimension-8

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

BSM effects SM particles

example:

2HDM



$$\boxed{\frac{ig}{2m_W^2}\bar{c}_W}\left[\Phi^\dagger T_{2k} \overleftrightarrow{D}_\mu \Phi\right] D_\nu W^{k,\mu\nu}$$

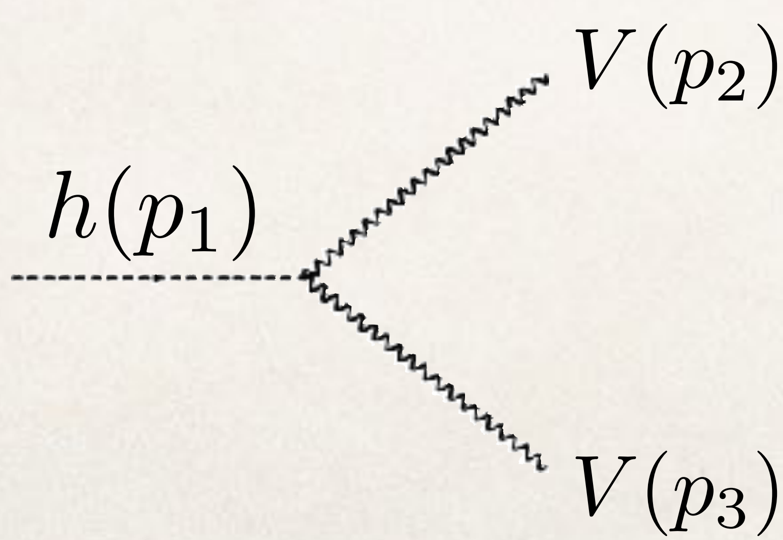
where $\bar{c}_W = \dfrac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$

Advantages

- **Combination**: LHC Higgs and EW production, low energy, EWPTs
- **Precision:** higher-order EW and QCD, dimension-eight, validity EFT
- **Consistency:** Backgrounds and signal
- **Matching:** Direct connection to models

Models offer richer kinematics, 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*

Matching to UV theories

Within the EFT, connection to models is *straightforward*

EFT

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

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

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

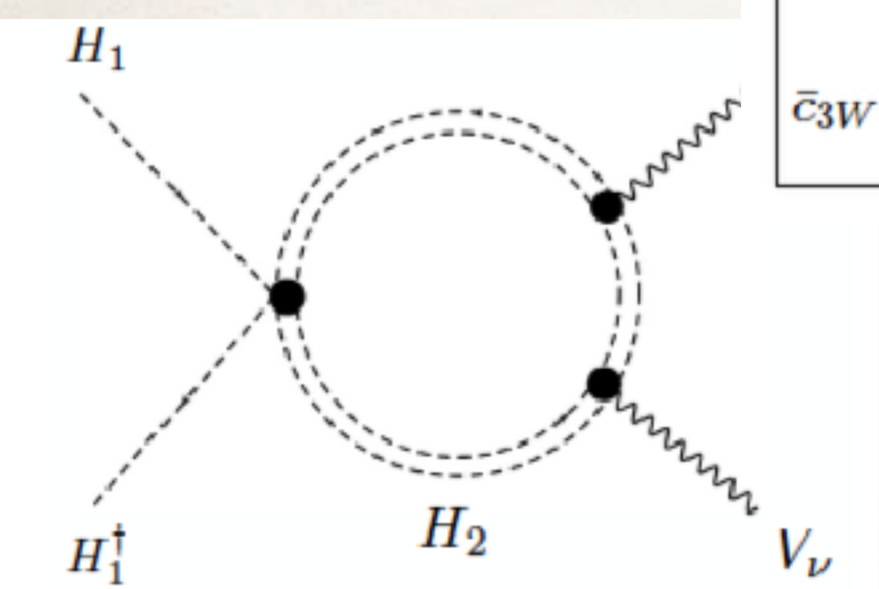
$$c_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

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

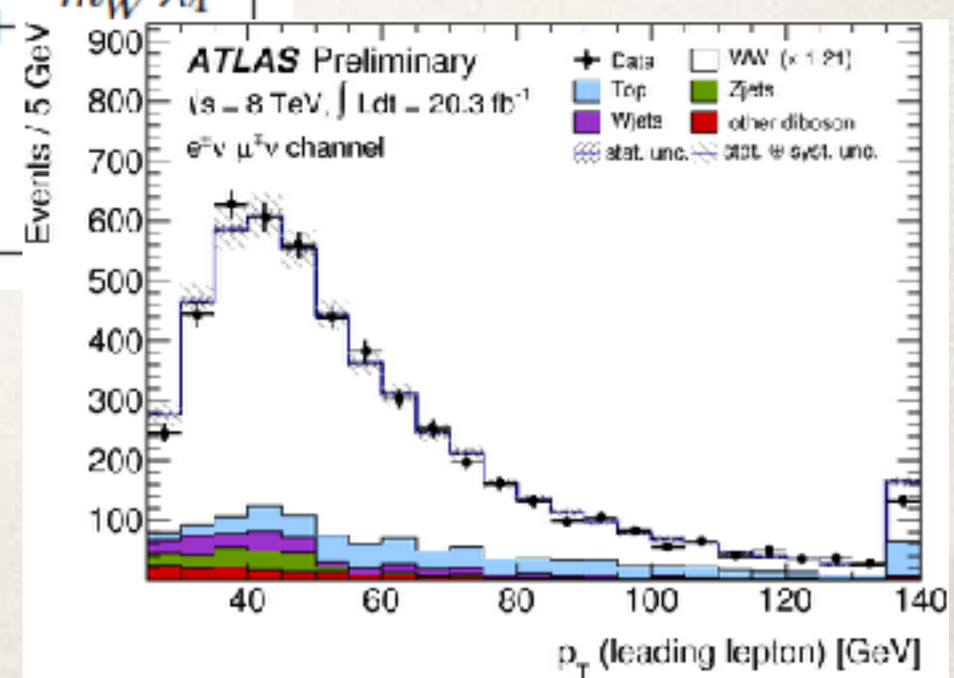
$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{\ldots}$$

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

MODELS



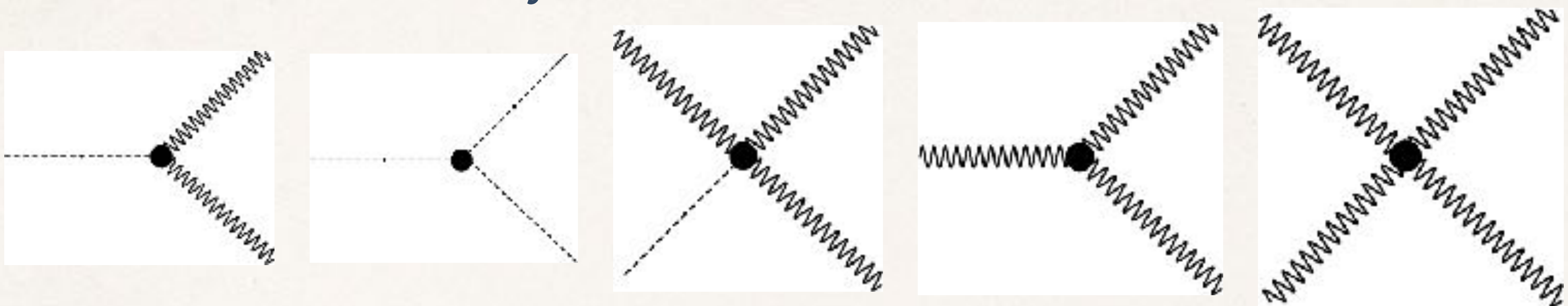
DATA



Combination of data — SMEFT

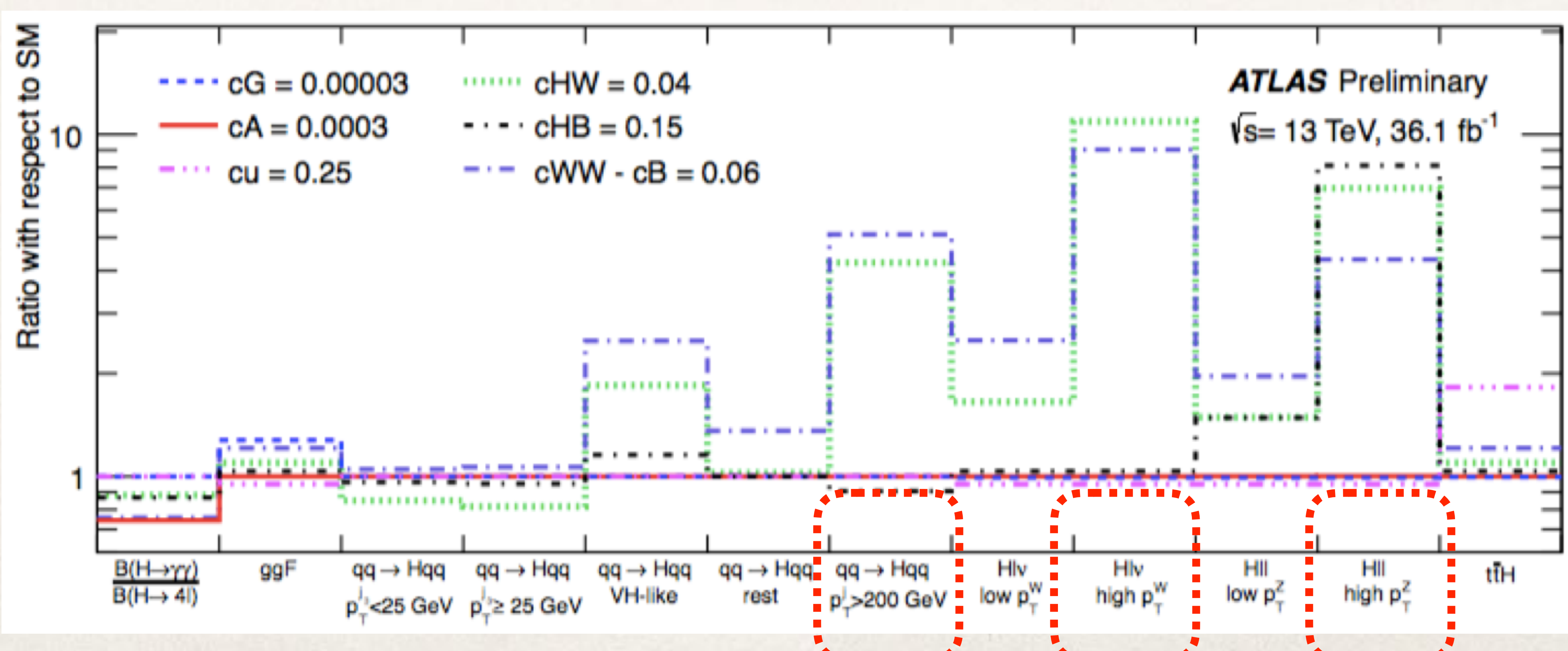
Global analyses using EFTs

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

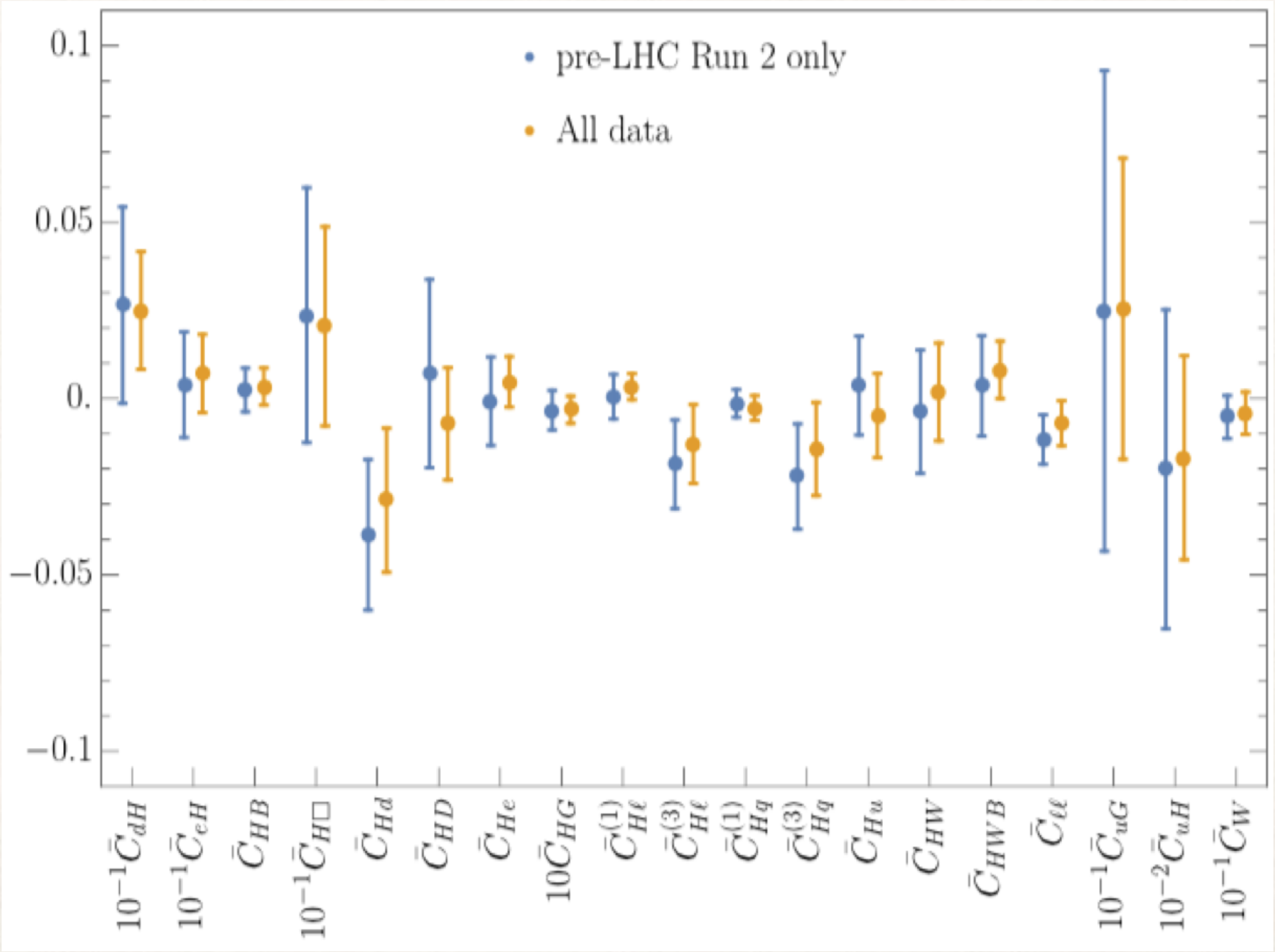
e.g. **WARSAW**

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

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

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

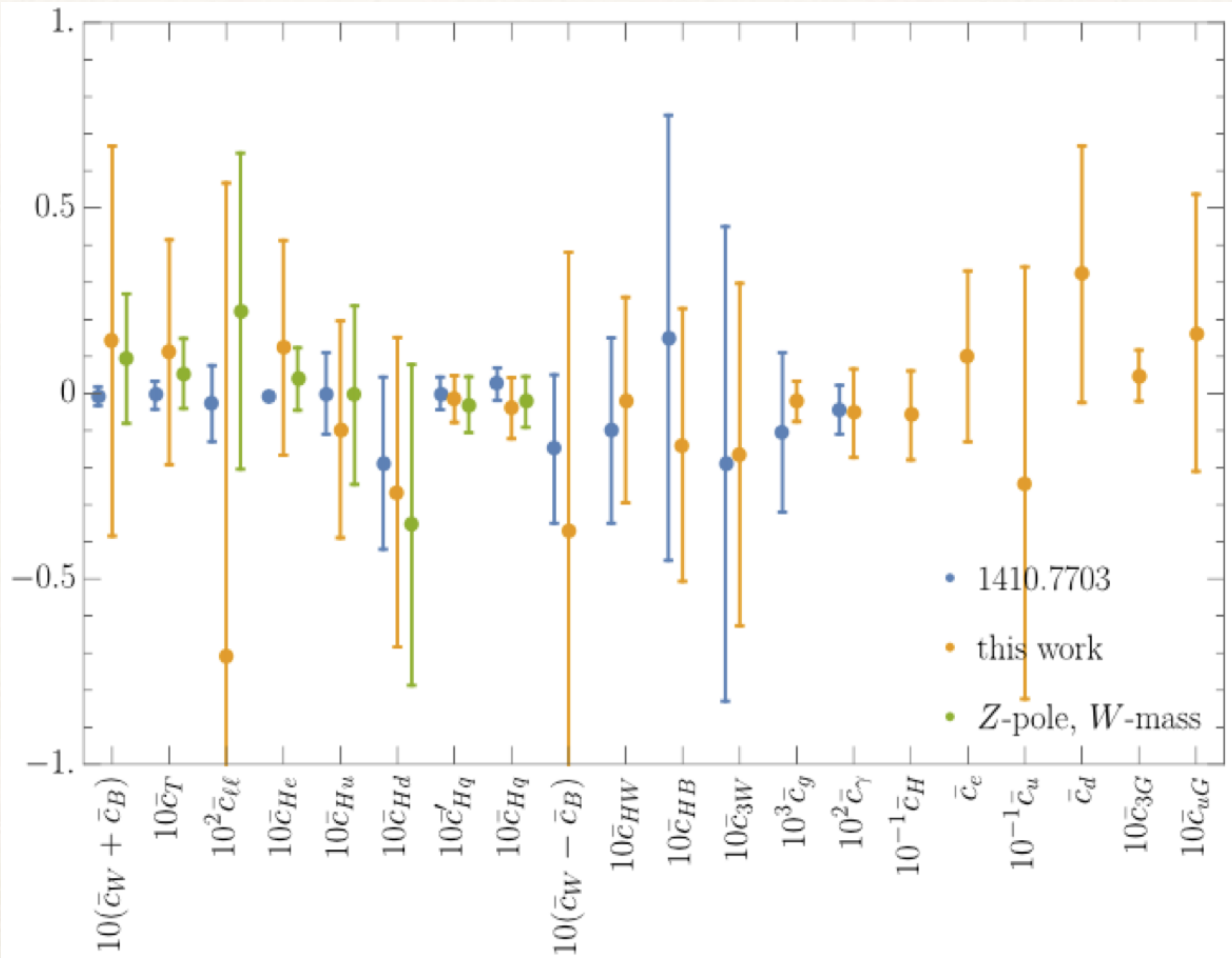
WARSAW basis: fit to all operators simultaneously



SMEFT recent results

ELLIS, MURPHY, VS, YOU. 1803.03252

SILH basis: fit to all operators simultaneously



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

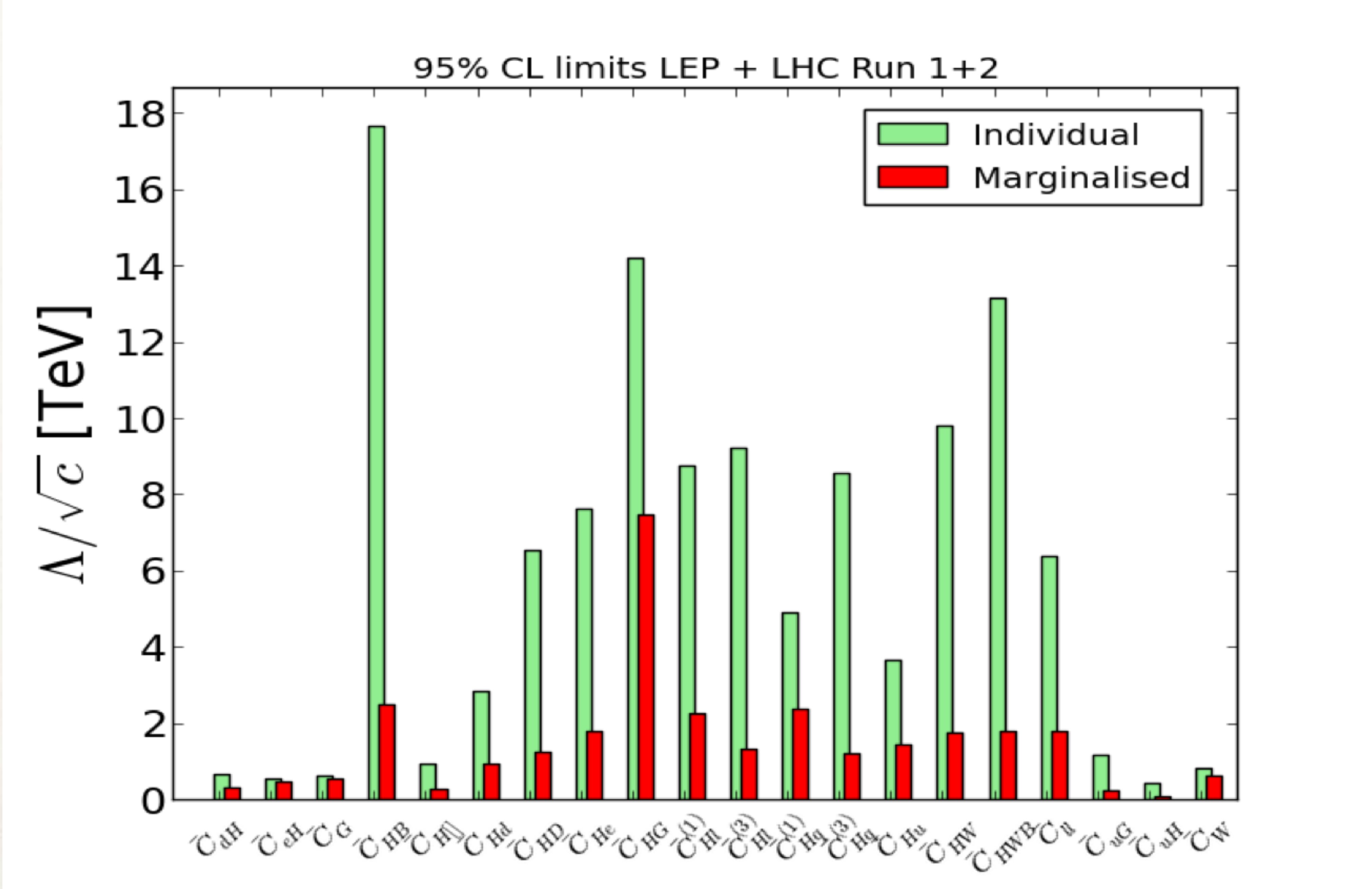
Coefficient	Z-pole + m_W	WW at LEP2	Higgs Run1	Higgs Run2	LHC WW high-p_T
$\bar{C}_{dH}$	×	×	36	64	×
$\bar{C}_{eH}$	×	×	49.6	50.4	×
$\bar{C}_{G}$	×	×	2.3	97.7	×
$\bar{C}_{HB}$	×	×	19	81	×
$\bar{C}_{H\Box}$	×	×	19.7	80.3	0.01
$\bar{C}_{Hd}$	99.88	×	0.04	0.07	×
$\bar{C}_{HD}$	99.92	0.06	×	×	×
$\bar{C}_{He}$	99.99	0.01	×	×	×
$\bar{C}_{HG}$	×	×	34	66	0.02
$\bar{C}_{H\ell}^{(1)}$	99.97	0.03	×	×	×
$\bar{C}_{H\ell}^{(3)}$	99.56	0.41	×	×	0.01
$\bar{C}_{Hq}^{(1)}$	99.98	×	0.01	0.01	×
$\bar{C}_{Hq}^{(3)}$	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

WARSAW

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

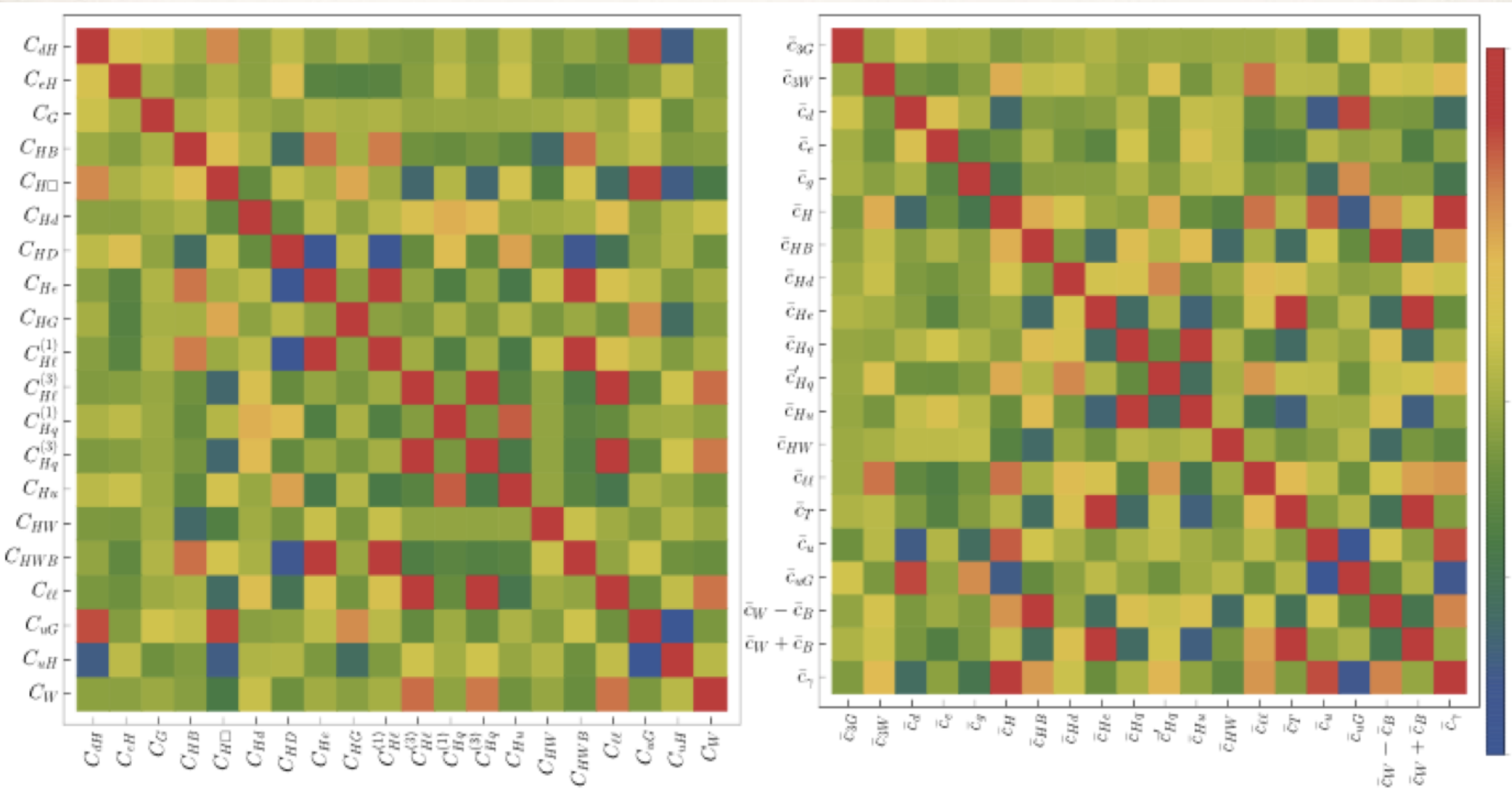
SMEFT: 20 deformations
SMEFT*: 13 deformations
(weakly coupled and renormalizable)



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

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

EFT precision — next steps

- incorporate higher-order QCD and EW effects
- quantify higher-order EFT effects (dimension-8)

Lots of progress on this front, some projects involved in

NLO QCD MC

POWHEG-BOX

Mimasu, VS, williams. 1512.02572

aMC@NLO

degrande, fuks, mawatari, mimasu, VS. 1609.04833

NEW: CP-violating terms— request

DIMENSION-EIGHT

Feynrules—> UFO—> aMC@NLO

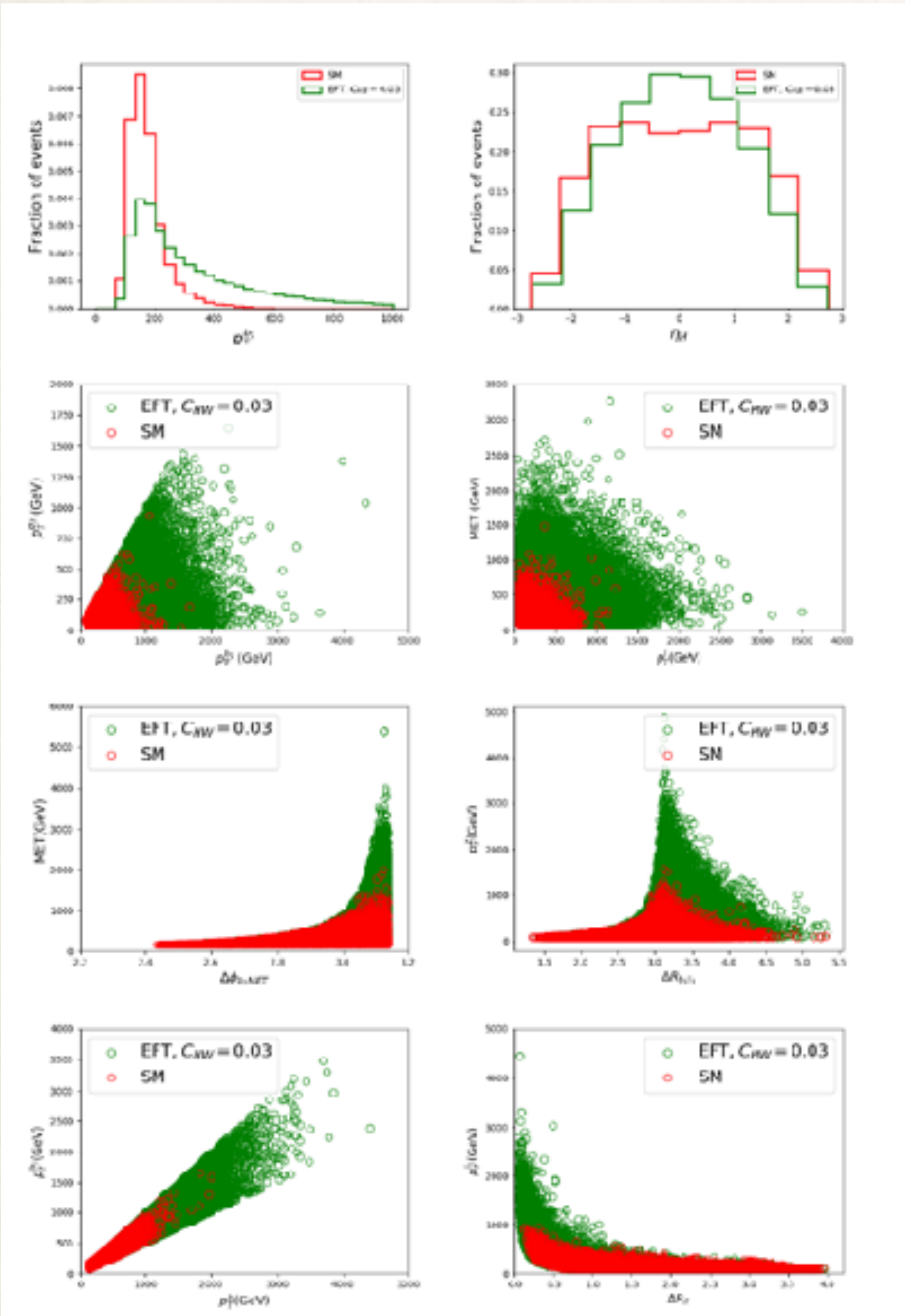
Hays, martin, VS, setford. 1808.00442

Warsaw—>Other using *Rosetta*

mimasu et al. 1508.05895

incorporate these tools to the experimental analyses

Next direction: Machine Learning

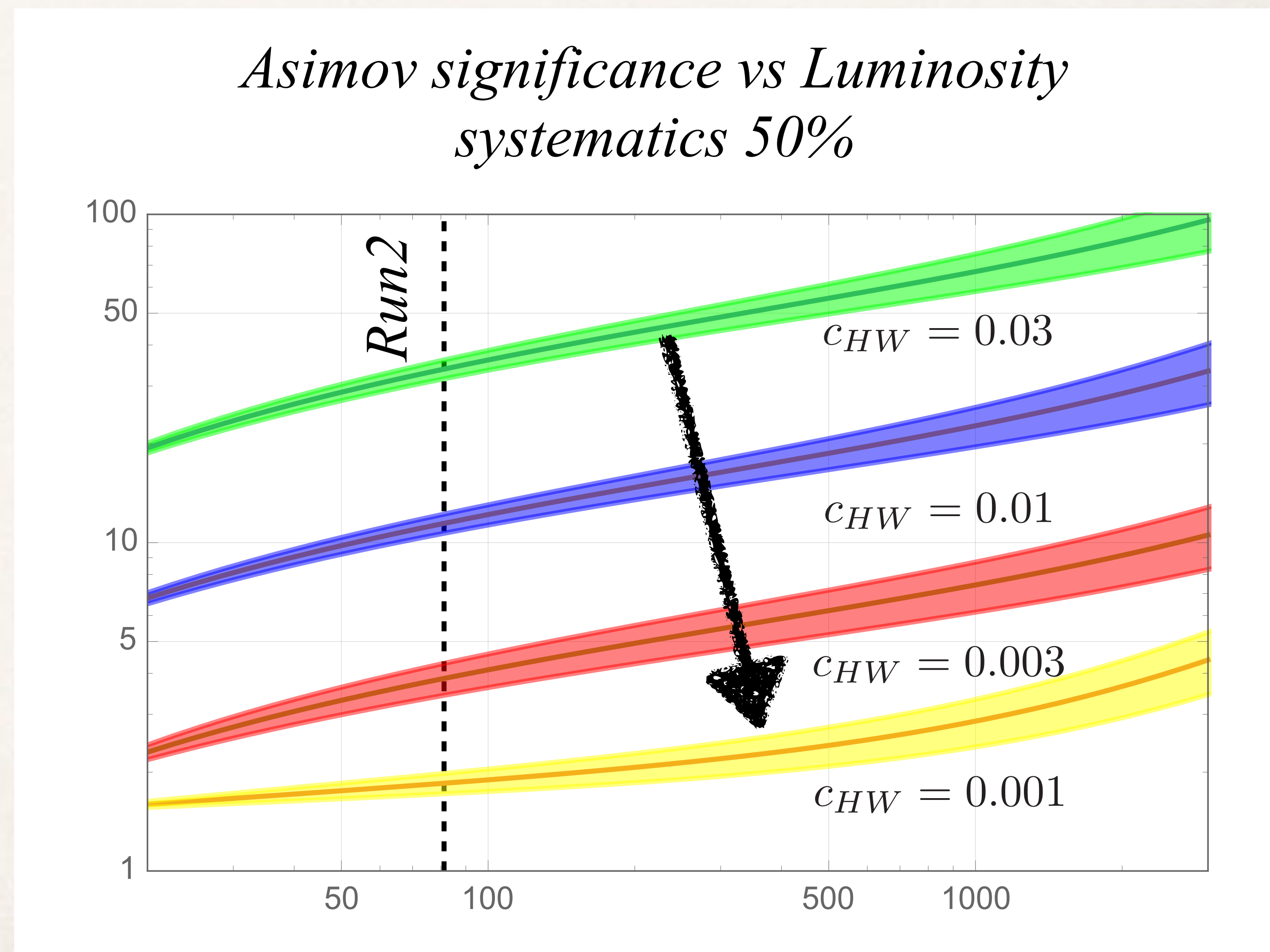


Capture *subtle* details in “images”

supervised or **anomaly** detection

lots of activity in the last months

this is where the cutting-edge is



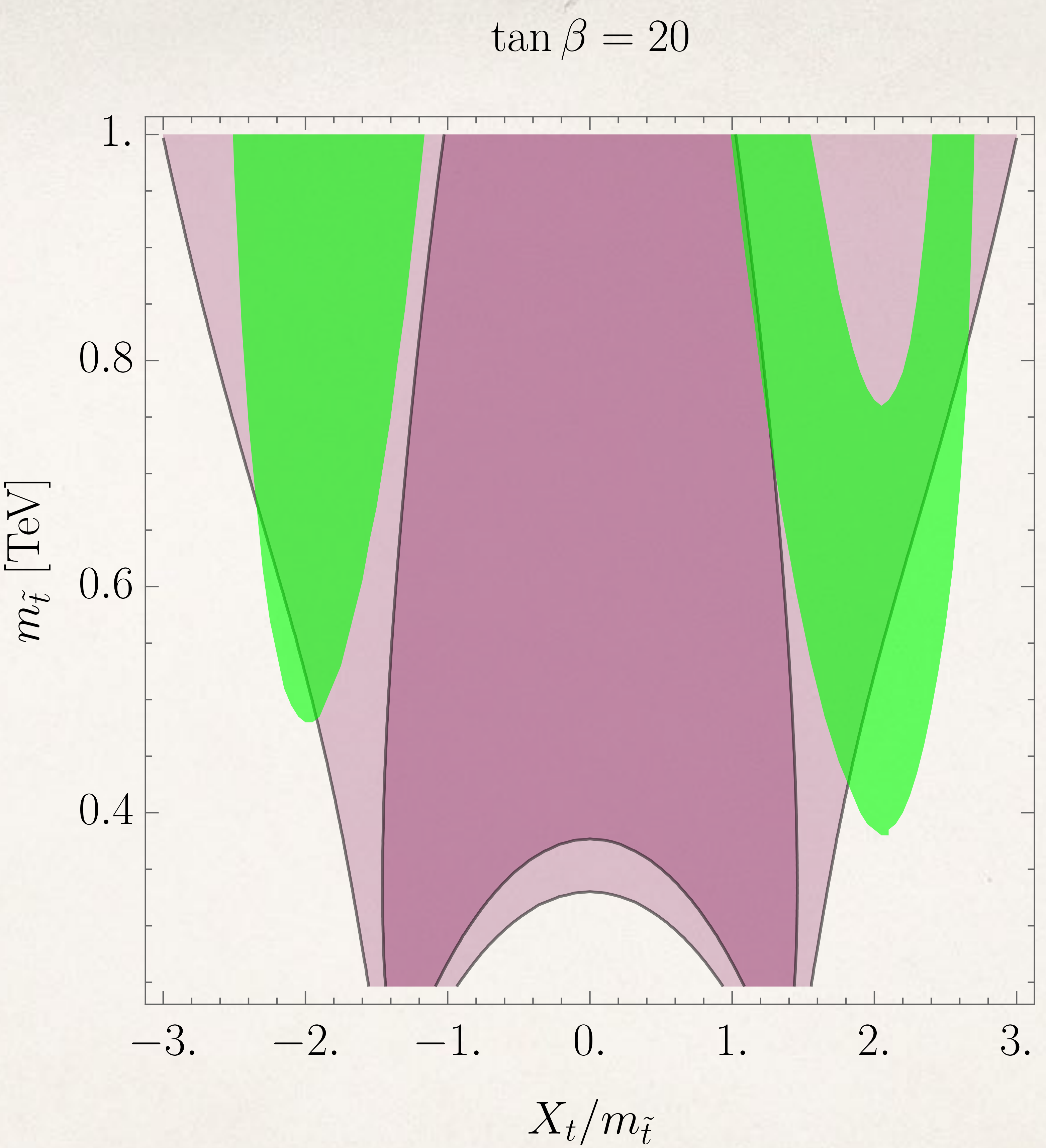
FREITAS, KAUR AND VS. 1902.05803

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
- To reach the precision needed for discovery, theorists are developing precision MC tools to facilitate the communication with experimentalists

de BLAS, criado, perez-victoria, santiago 1711.10391

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	$\frac{2}{3}$


$\tan\beta = 20$
1.
0.8
0.6
0.4
$m_{\tilde{t}}$ [TeV]
−3.
−2.
−1.
0.
1.
2.
3.
$X_t/m_{\tilde{t}}$