LHC Higgs WG general meeting: https://indico.cern.ch/event/1276727

LHC EFT WG general meeting: https://indico.cern.ch/event/1296757

SMEFT (and HEFT)

Ken Mimasu

University of Southampton, STFC ERF

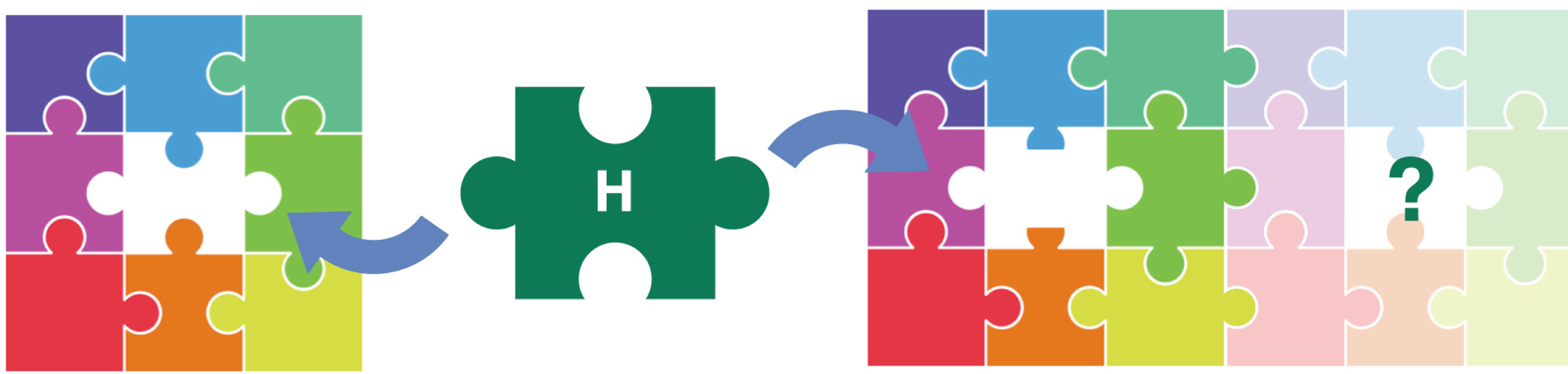
UK HEP forum: *Completing the Higgs-saw puzzle*, Cosener's House

22nd November 2023

Science and Technology Facilities Council

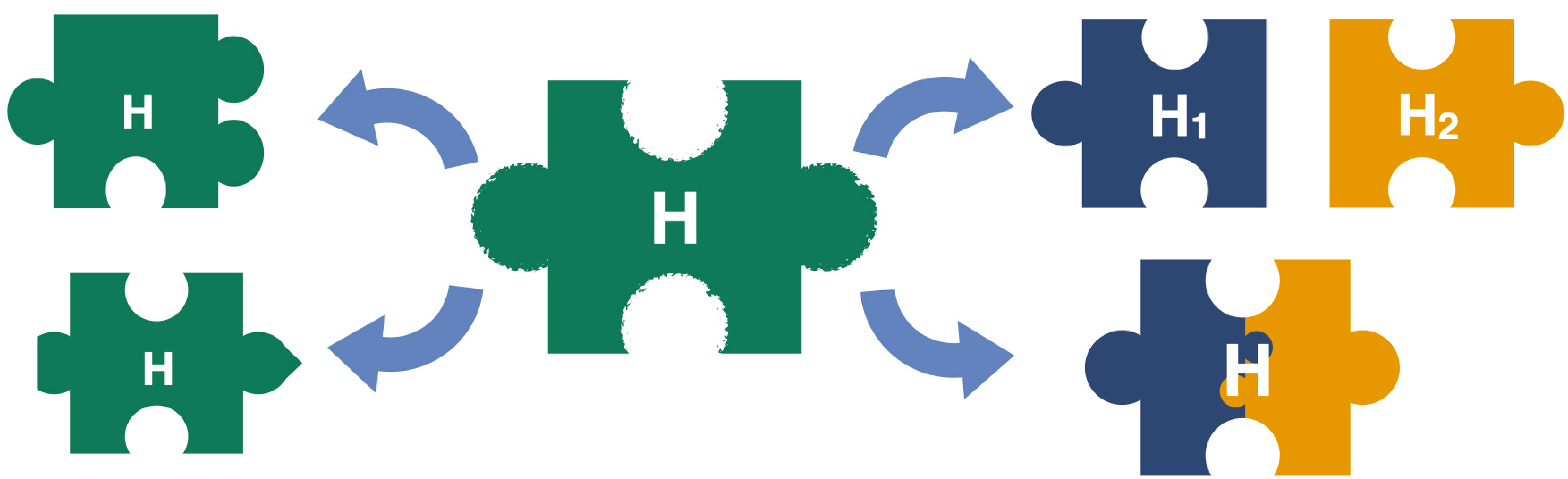
University of Southampton

The Higgs-saw puzzle



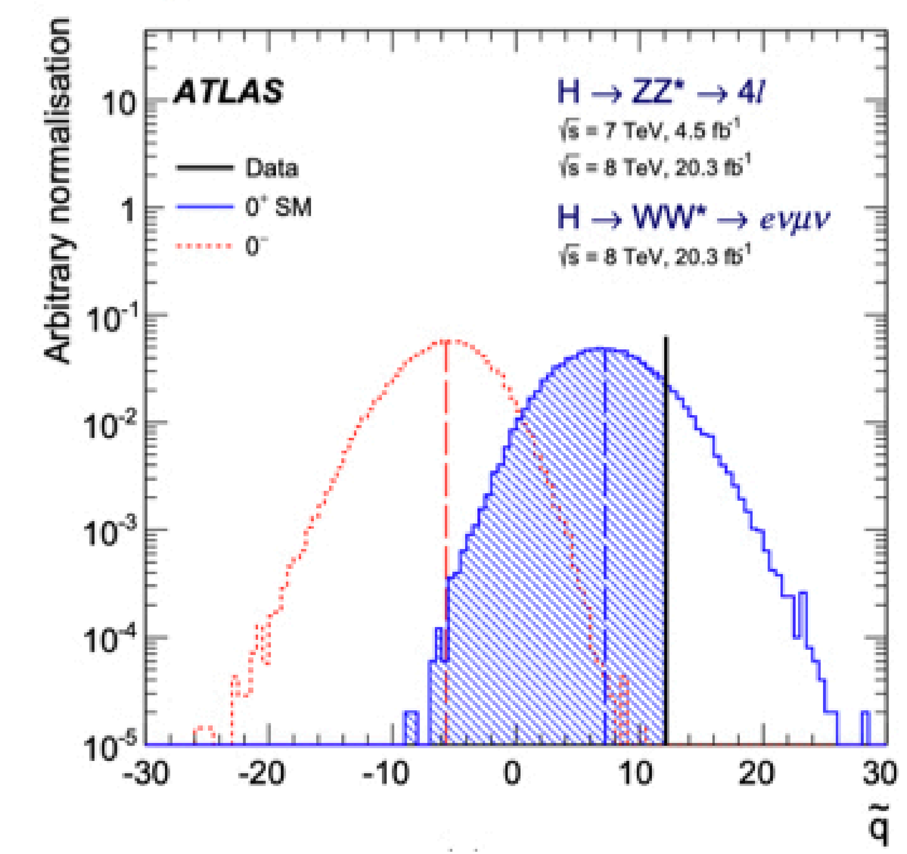
Standard Model

Beyond the Standard Model

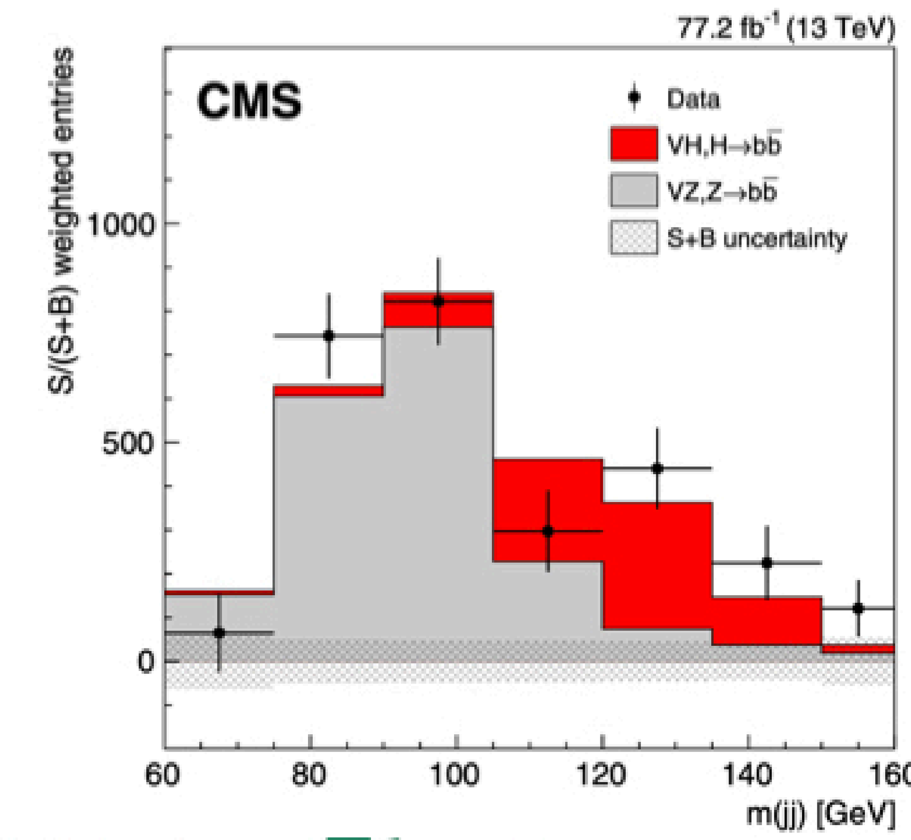


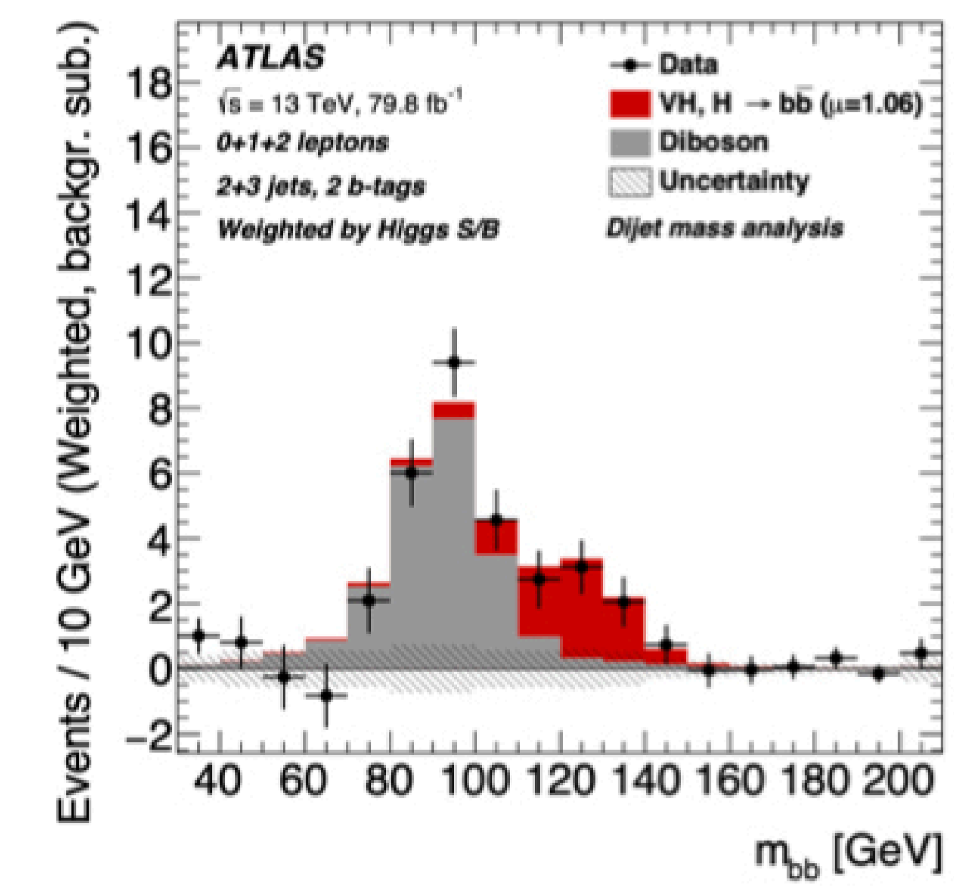
The Higgs-saw piece

2015: CP-odd/spin-2 ruled out

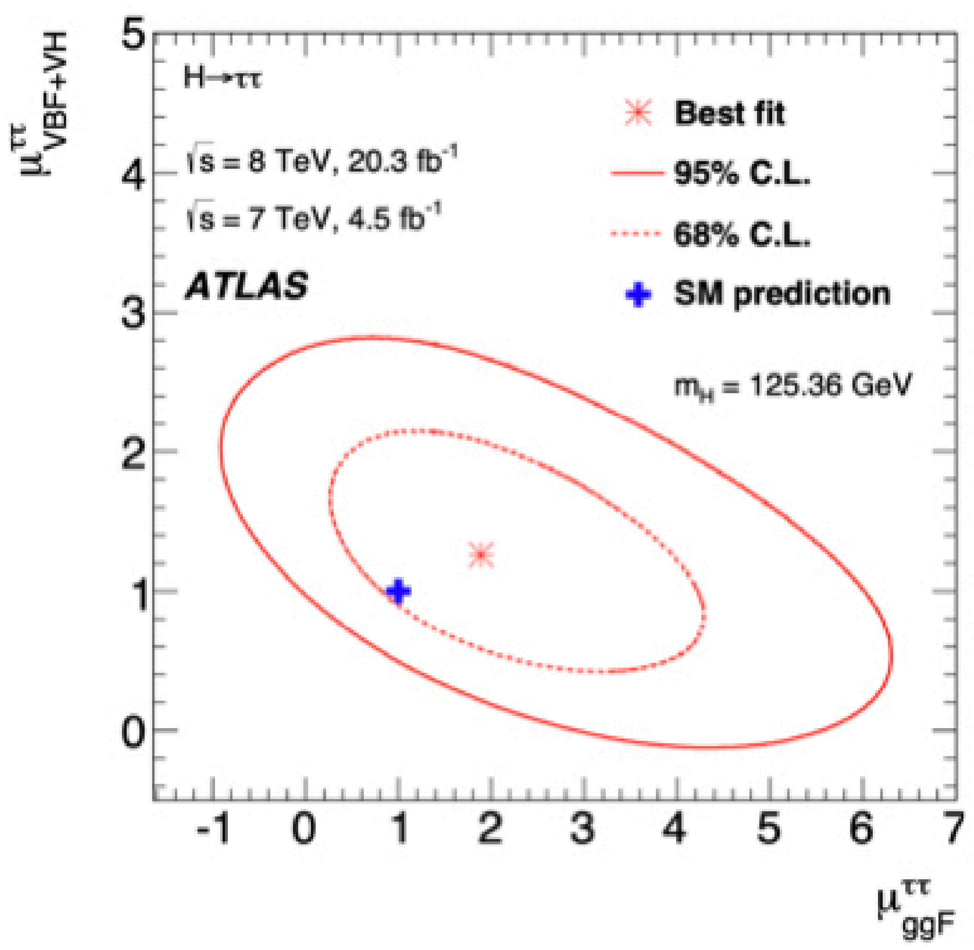


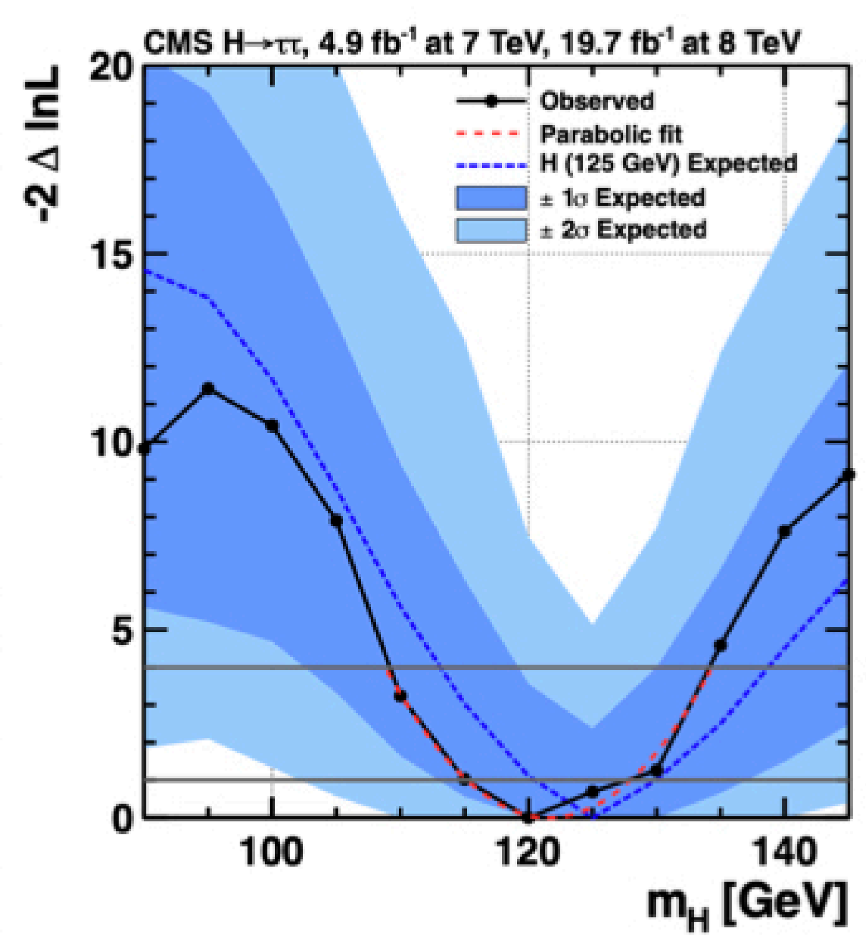
2018: $h \to b\bar{b}$ discovery



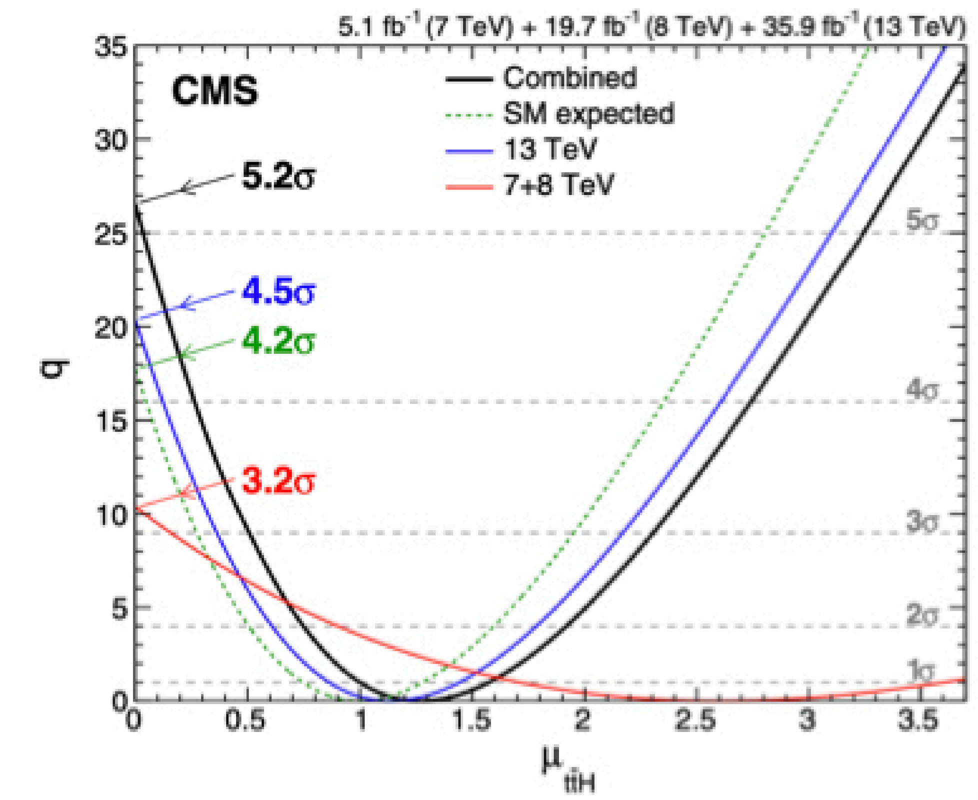


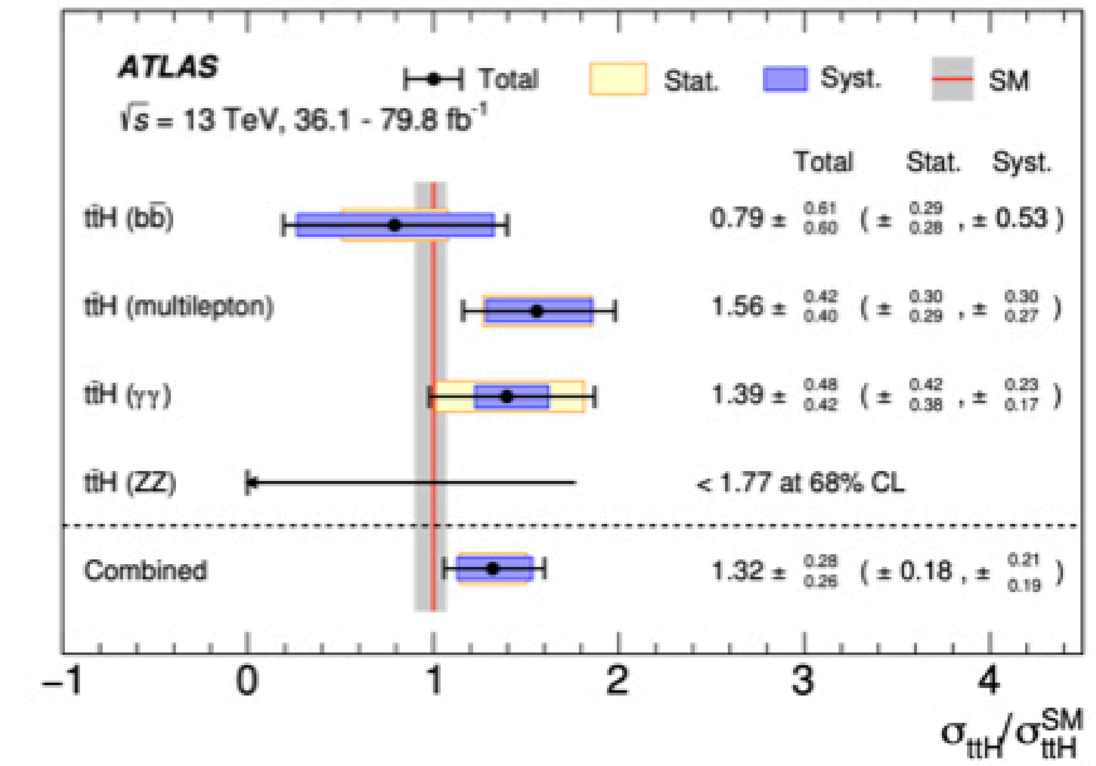
2014: $h \to \tau^+\tau^-$ evidence



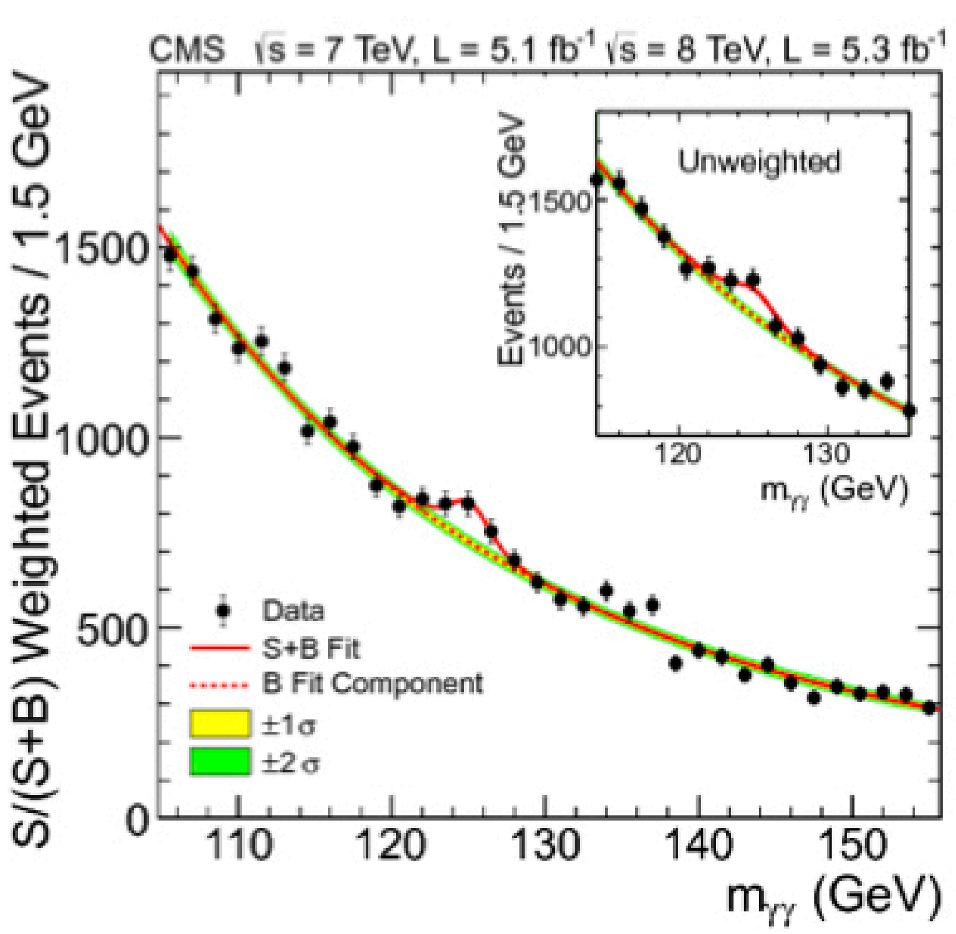


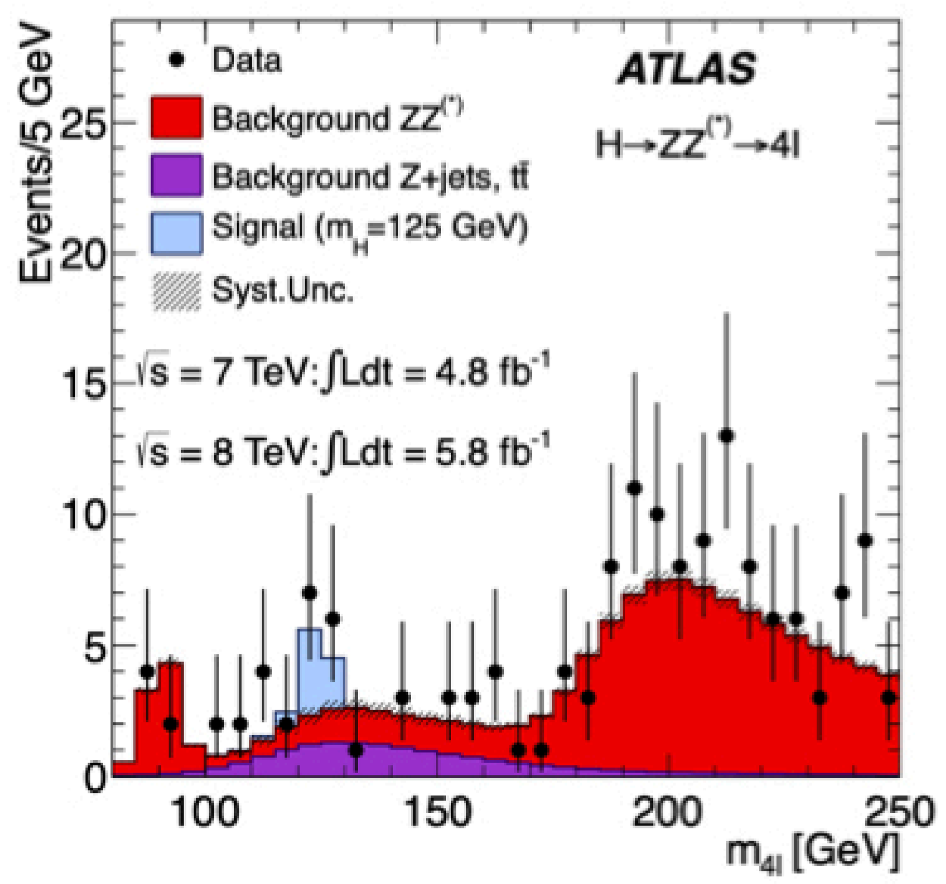
2018: $t\bar{t}h$ discovery



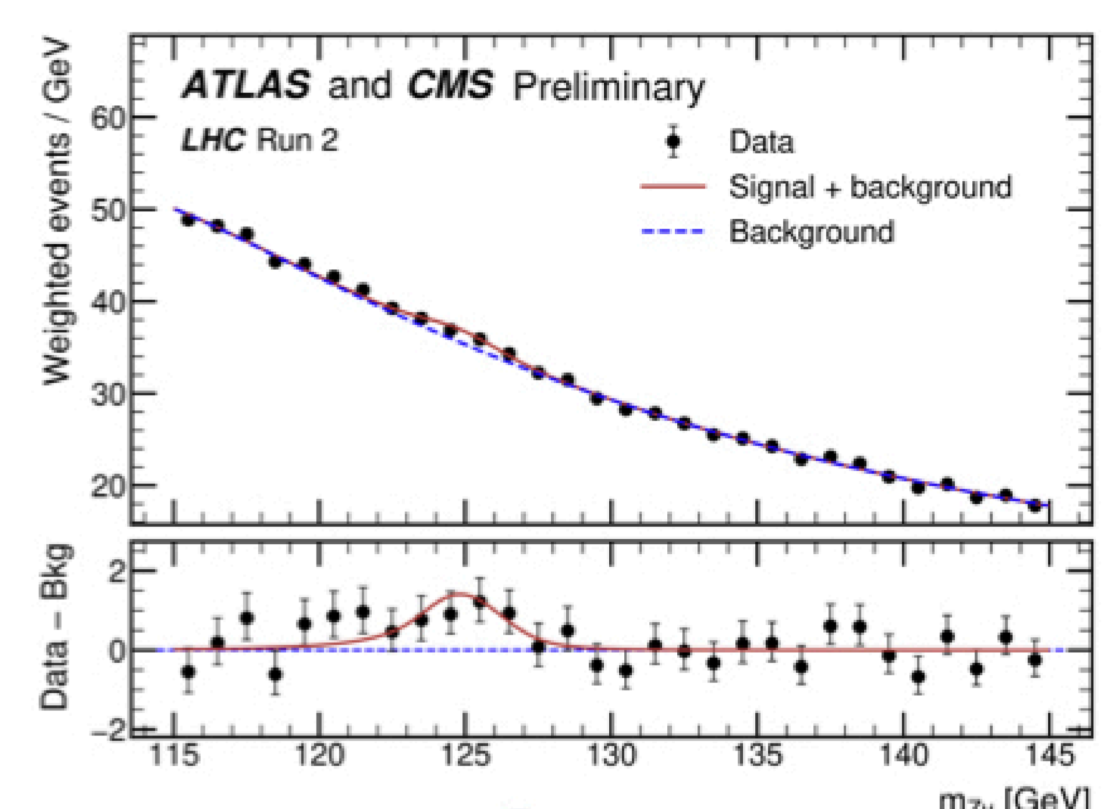


2012: Discovery in $h \to \gamma\gamma/ZZ^*$

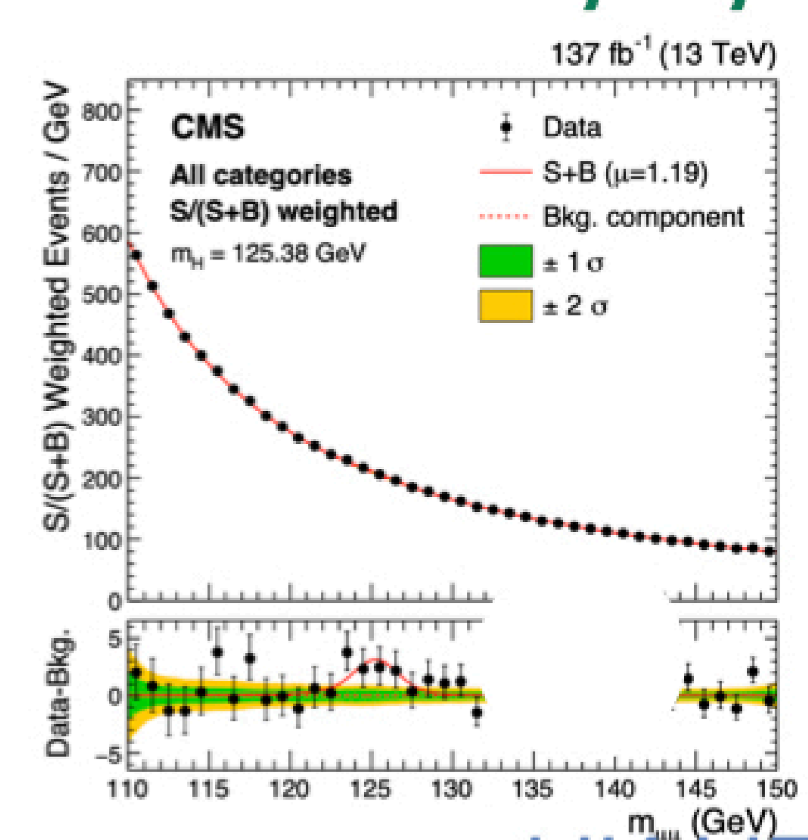




2023: $h \to Z\gamma$ evidence

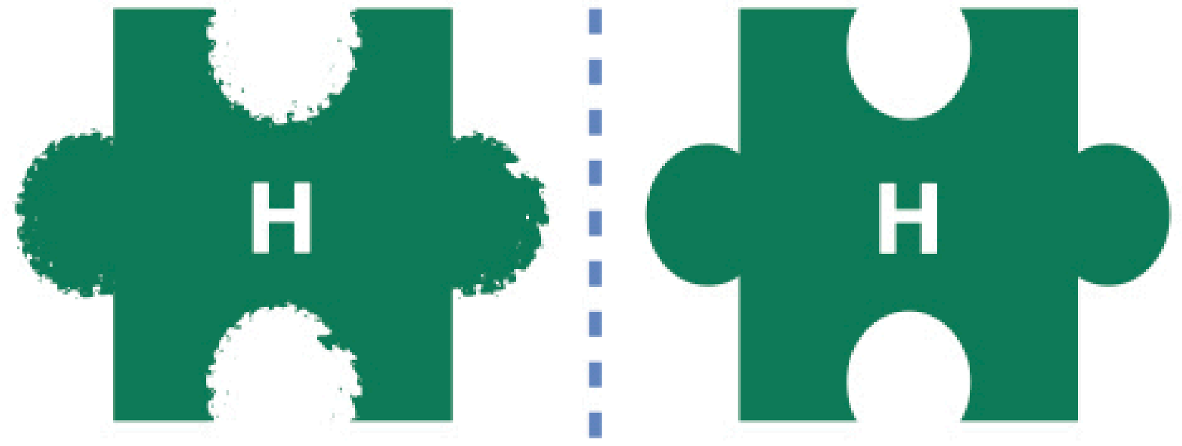


2020: $h \to \mu^+\mu^-$ evidence



Piecing it together

Spot the difference…



Framework to synthesise Higgs data

- Compare Higgs couplings to SM hypothesis
- Uncover hints of new physics

Signal strength parameters

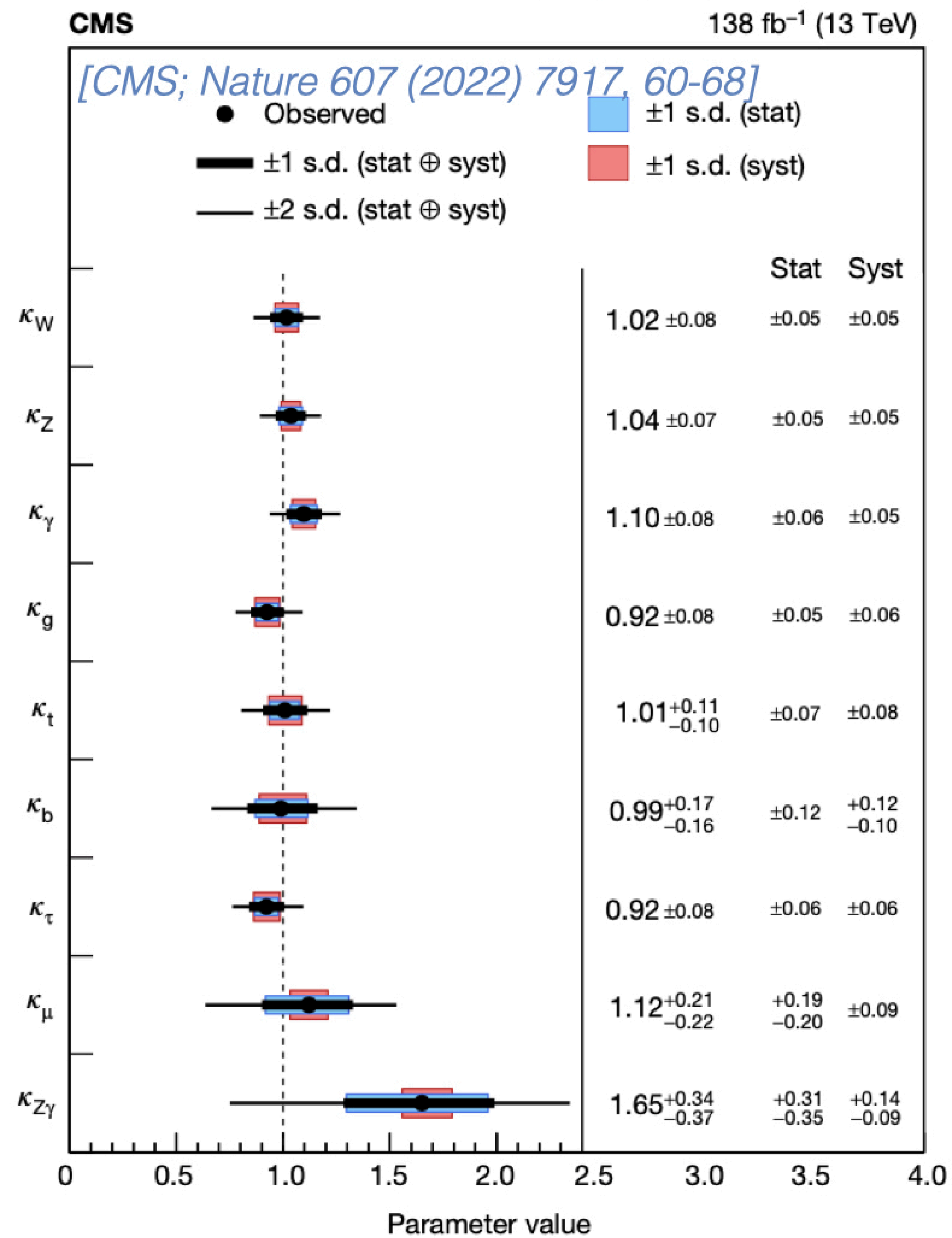
$$\mu_{i\to f} \sim \frac{\sigma_{i\to H} \times \mathrm{BR}_{\mathrm{H}\to\mathrm{f}}}{\sigma^{\mathrm{SM}}_{i\to H} \times \mathrm{BR}^{\mathrm{SM}}_{\mathrm{H}\to\mathrm{f}}}$$

κ-framework interpretation

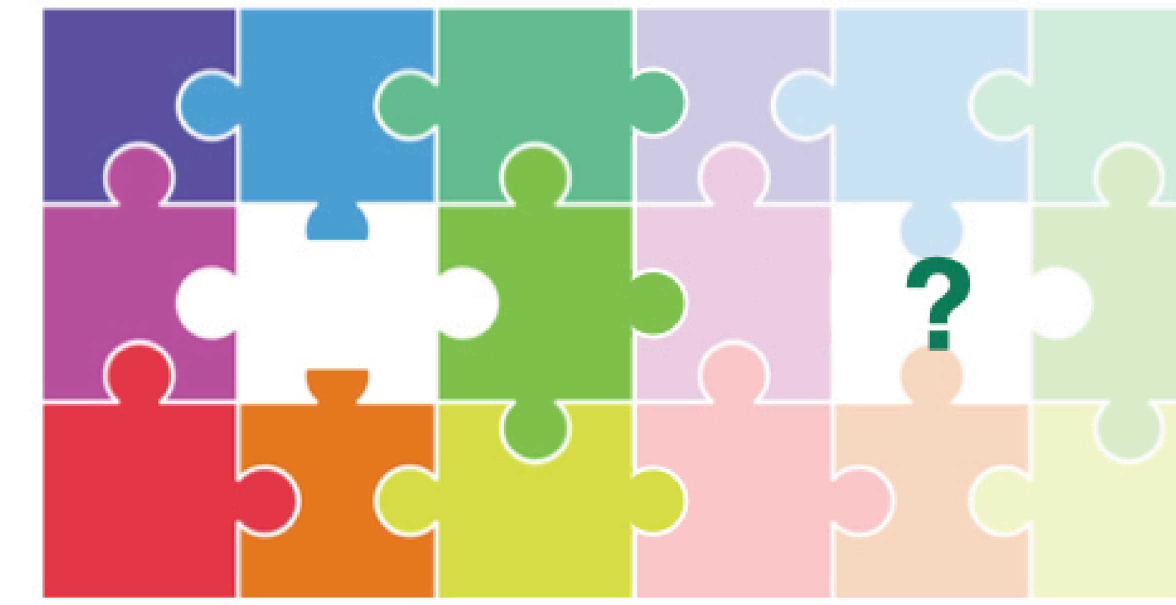
$$\mu_{i\to f} \propto \kappa_i^2 \kappa_f^2$$

PROS
- *Simple*
- *Intuitive*

CONS
- *Incomplete*
- *Theoretically ill-defined*



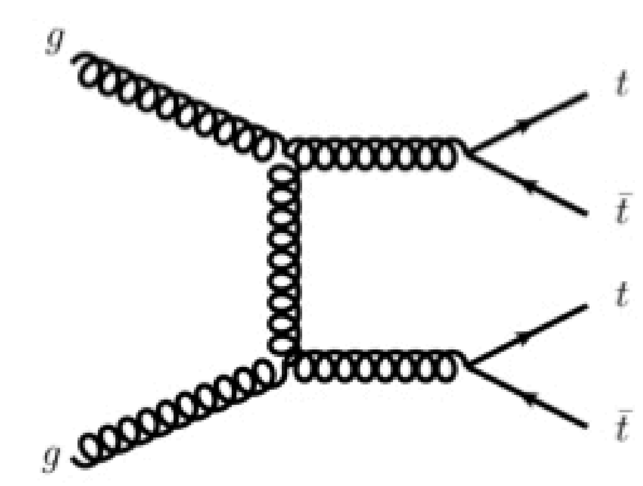
The rest of the puzzle

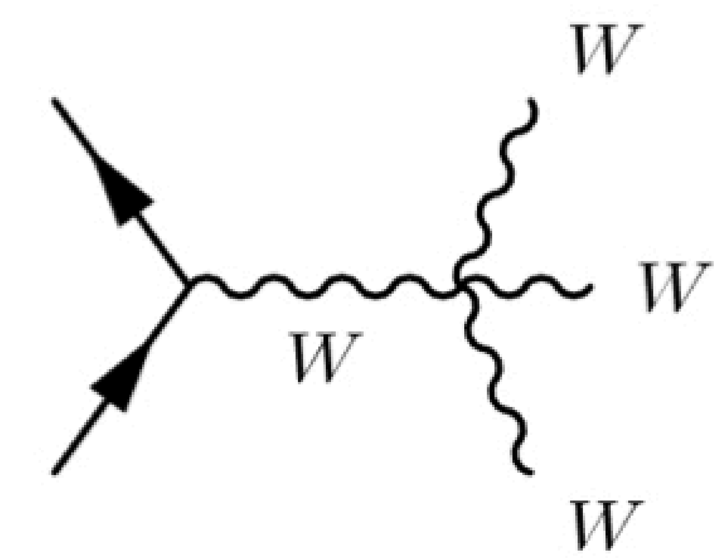


Thriving LHC programmes in other sectors (top, EW, …)

LHC explorer

- Discovering new processes
- Exploring uncharted BSM territory

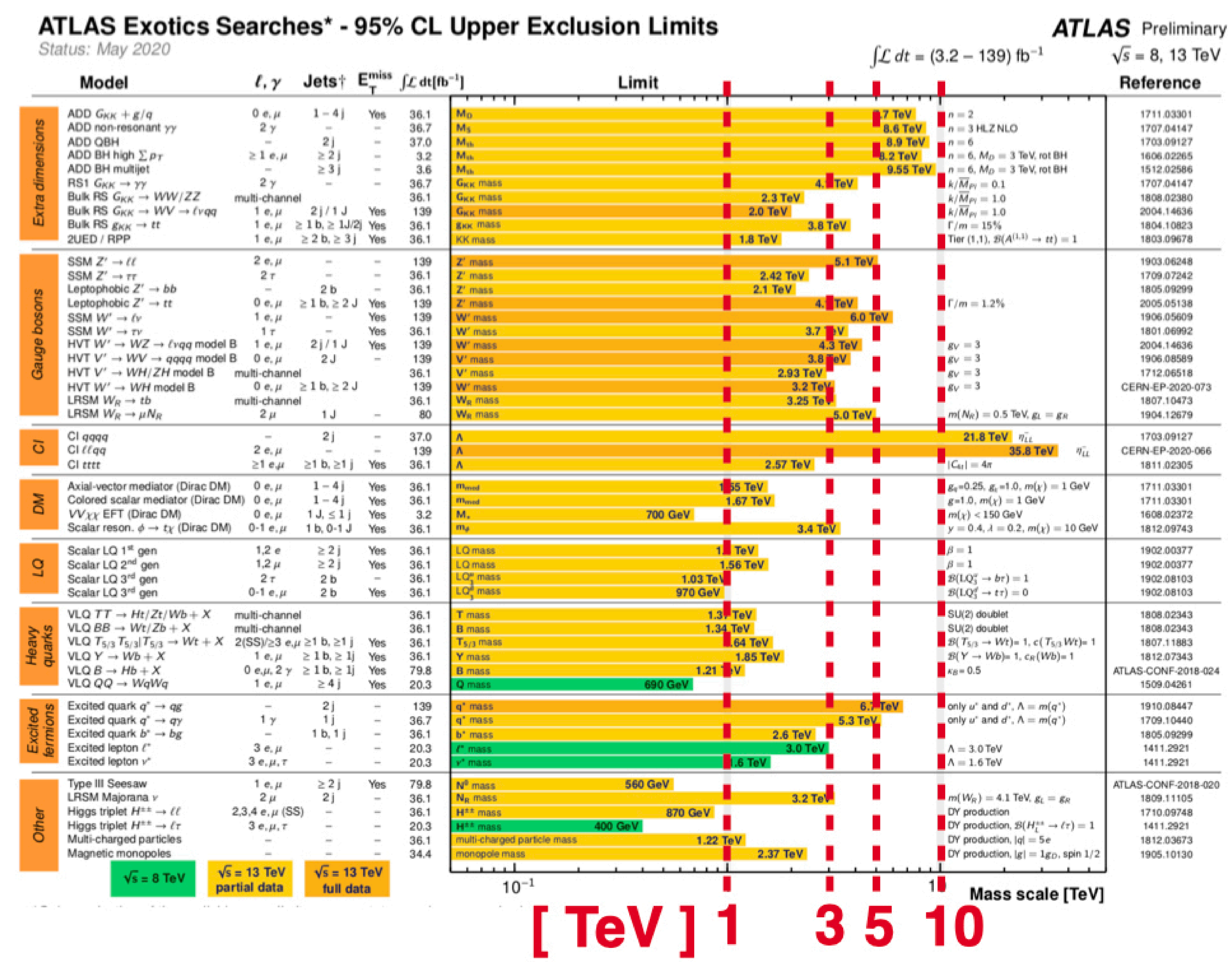




Data is SM-like

⇒ BSM states are…

- Too *weakly coupled*
- Too *exotic*
- **Too *heavy***



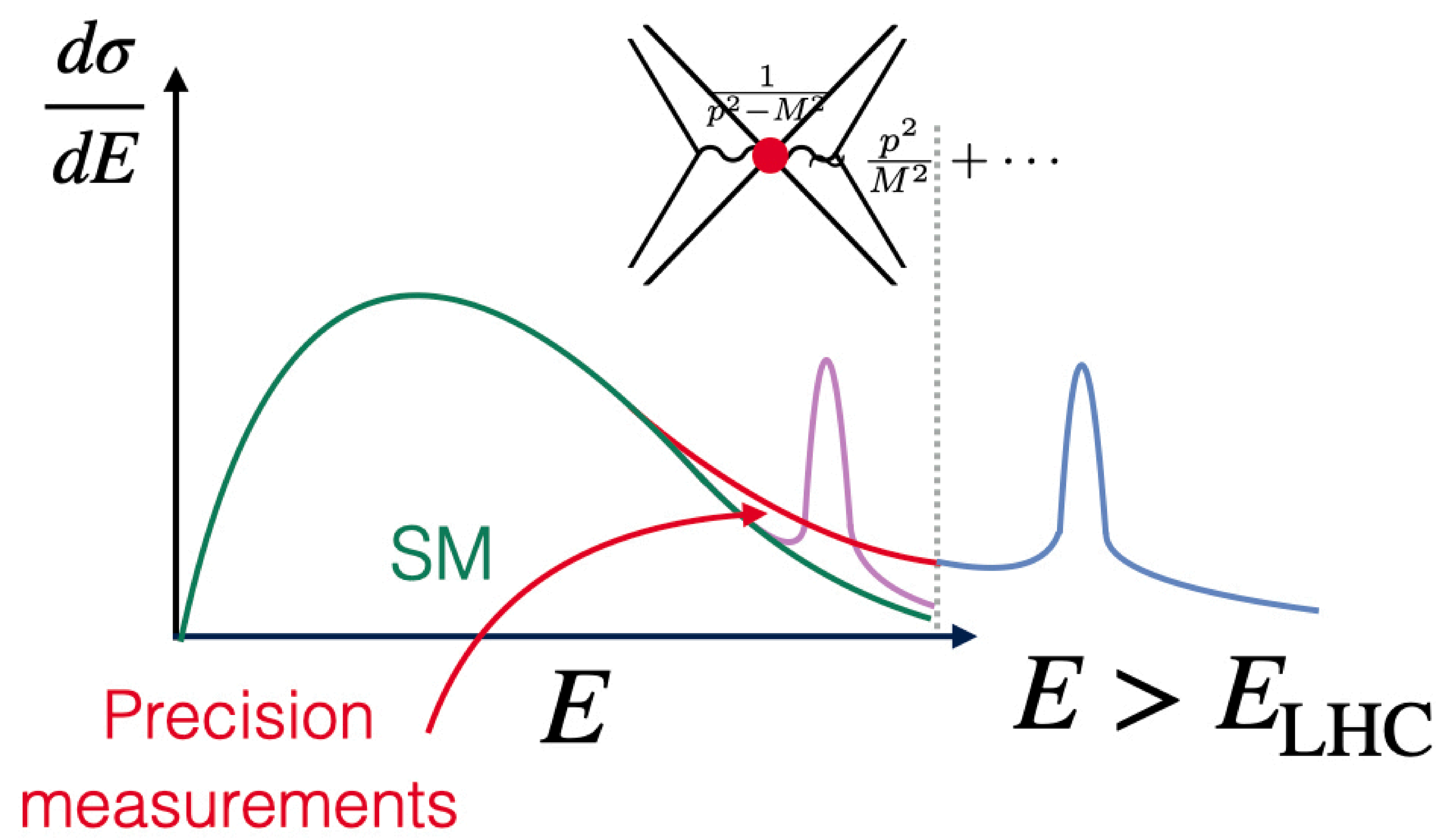
Energy & precision

Paradigm shift at the energy frontier for BSM searches

Direct (bumps)

Indirect (tails)

$\Rightarrow$ New physics is heavy



Heavy new physics
Precision measurements
High energy

Effective Field Theory (EFT)

$$\mathcal{A}^n_{\mathrm{BSM}}(E, M) \sim E^{4-n}\left(\overset{\kappa_i^2}{\overset{\downarrow}{a_0}} + a_1\frac{E}{M} + a_2\frac{E^2}{M^2} + \cdots\right), \quad E \ll M$$

SMEFT: SM v2.0

$(\bar{F}\sigma_{\mu\nu} f \tilde{\varphi})V^{\mu\nu}$ $\quad (\varphi^\dagger\varphi)^3$

$(\bar{f}\gamma_\mu f)(\bar{F}\gamma^\mu F)$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{i,D} \frac{c_i^{(D)}\mathcal{O}_i^{(D)}}{\Lambda^{D-4}}$$

$i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{f}\gamma^\mu f)$

$(\bar{F} f \tilde{\varphi})(\varphi^\dagger\varphi)$ $\quad (\varphi^\dagger\varphi)V^{\mu\nu}V_{\mu\nu}$

BSM particle masses M $\Leftrightarrow$ *Generic new physics scale* Λ

Taylor expansion of $\mathscr{A}_{BSM}$ $\Leftrightarrow$ *Tower of operators* $\mathcal{O}_i^{(D)}$

$\mathcal{O}_i^{(D)} \supset$ SM $W^\pm$ Z H t ... *Low energy (SM) fields & symmetries*

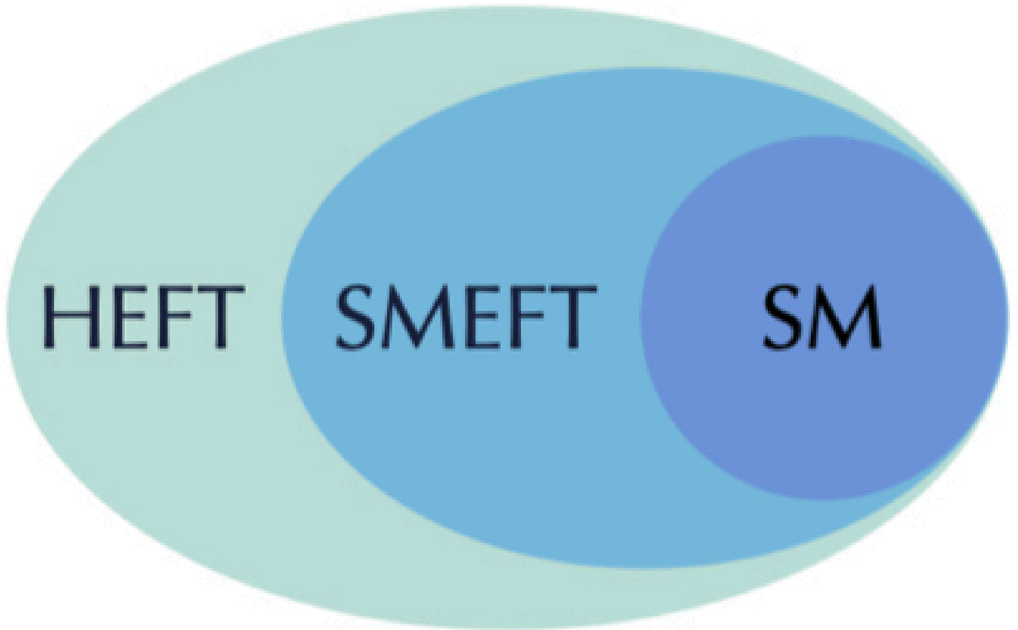
Model parameters $\{g^i_{\rm BSM}, M_k\}$ $\Leftrightarrow$ *Wilson coefficients* $\dfrac{c_j^{(D)}}{\Lambda^{D-4}}(g^i_{\rm BSM}, M_k)$

measure g_i *: new physics model parameters*

"Matching"

measure c_i *: coupling strengths of new BSM interactions*

SMEFT vs HEFT

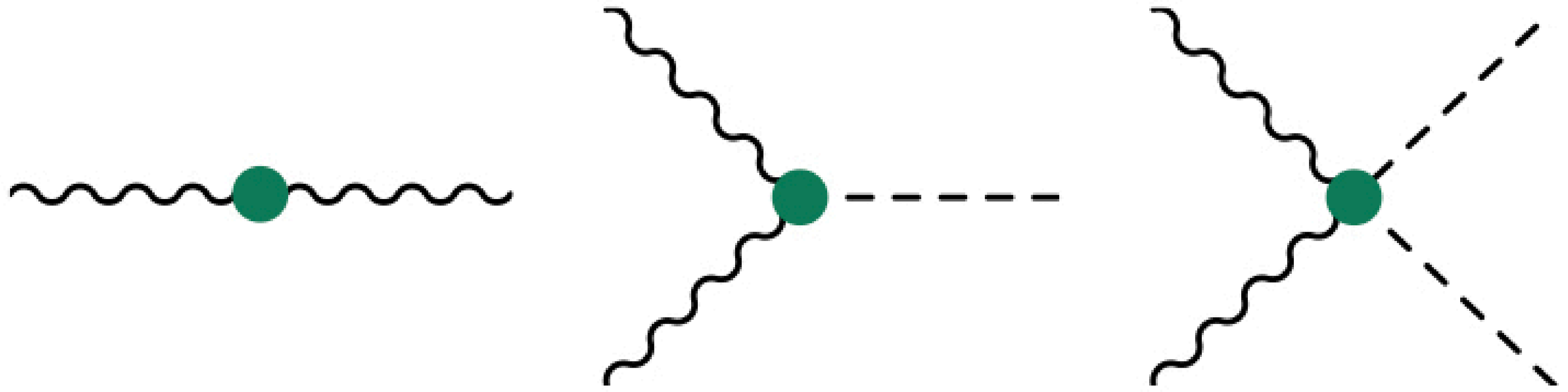


Linear

$$\phi = \begin{pmatrix} G^+ \\ v + h + iG_0 \end{pmatrix}$$

$$\frac{a}{\Lambda^2}(\phi^\dagger\phi)F^{\mu\nu}F_{\mu\nu} = \frac{a}{\Lambda^2}(v+h)^2F^{\mu\nu}F_{\mu\nu}$$

$$= a\frac{v^2}{\Lambda^2}\left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right)F^{\mu\nu}F_{\mu\nu}$$



Linear $\Rightarrow$ Correlated

Non-Linear $\Rightarrow$ Uncorrelated

Non-linear

$$h, U = \exp\left(i\frac{\pi_a \tau_a}{v}\right)$$

$$f(h)F^{\mu\nu}F_{\mu\nu}$$

$$= \left(a_0 + a_1\frac{h}{v} + a_2\frac{h^2}{v^2} + \cdots\right)F^{\mu\nu}F_{\mu\nu}$$

Field-space geometry approach

[Alonso, Jenkins & Manohar;
PLB 754 (2016) 335 & JHEP 08 (2016) 101]
[Falkowski & Ratazzi; JHEP 10 (2019) 255]
[Cohen, Craig, Lu & Sutherland; JHEP 23 (2021) 237]

How can we experimentally distinguish HEFT from SMEFT?

(SM)EFT

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{i,D} \frac{c_i^{(D)} \mathcal{O}_i^{(D)}}{\Lambda^{D-4}}$$

Model independent

Heavy new physics: Λ > E_{exp}
SM field content & symmetries

- Few underlying assumptions

Systematically improvable

- Double expansion *higher dimensions* $\frac{E}{\Lambda}$ & $\{g_S, g_W, g'\}$ *quantum corrections*

Global

- Model independence: **we don't know** what operators new physics will generate
- Patterns & correlations among observables & operators are key
- Ultimate goal: **complete SMEFT likelihood** confronted with HEP dataset

LEP data, Higgs, multiboson, top, flavor physics,…

$\mathscr{L}(c_i) \Rightarrow$ **indirectly constrain many UV models**

EFT interpretation

Maximising sensitivity means improving…

$$\boxed{\Delta o_n} = \boxed{o_n^{\mathrm{EXP}}} - \boxed{o_n^{\mathrm{SM}}} = \sum_i \boxed{a_{n,i}^{(6)}(\mu)\,\frac{c_{n,i}^{(6)}(\mu)}{\Lambda^2}} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Global nature
As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Sensitivity
Experiment:
Best measurements & understanding of uncertainties and correlations

Theory:
Best available SM predictions for observables

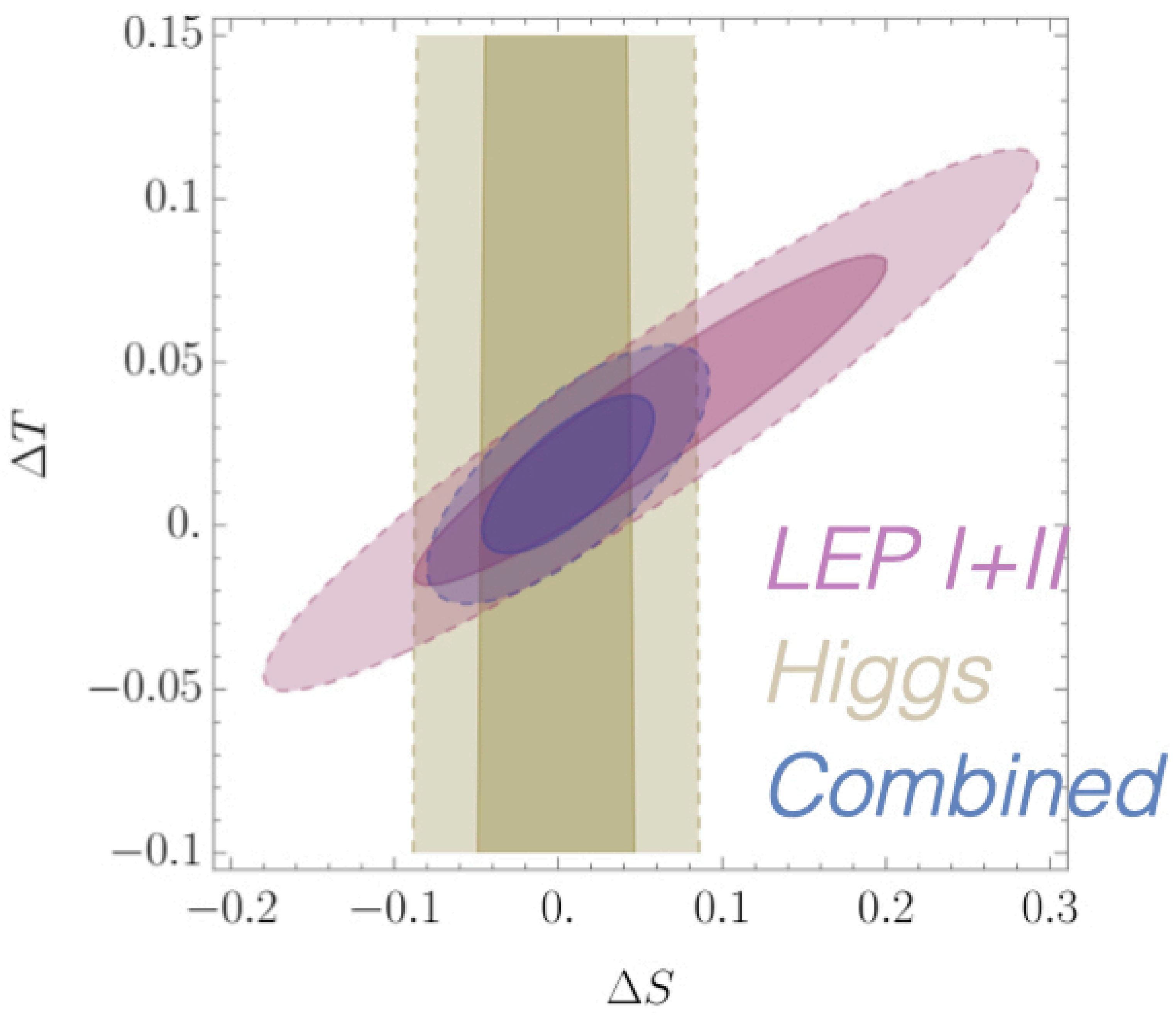
Interpretation
Accurate knowledge of the size & correlations among a_i

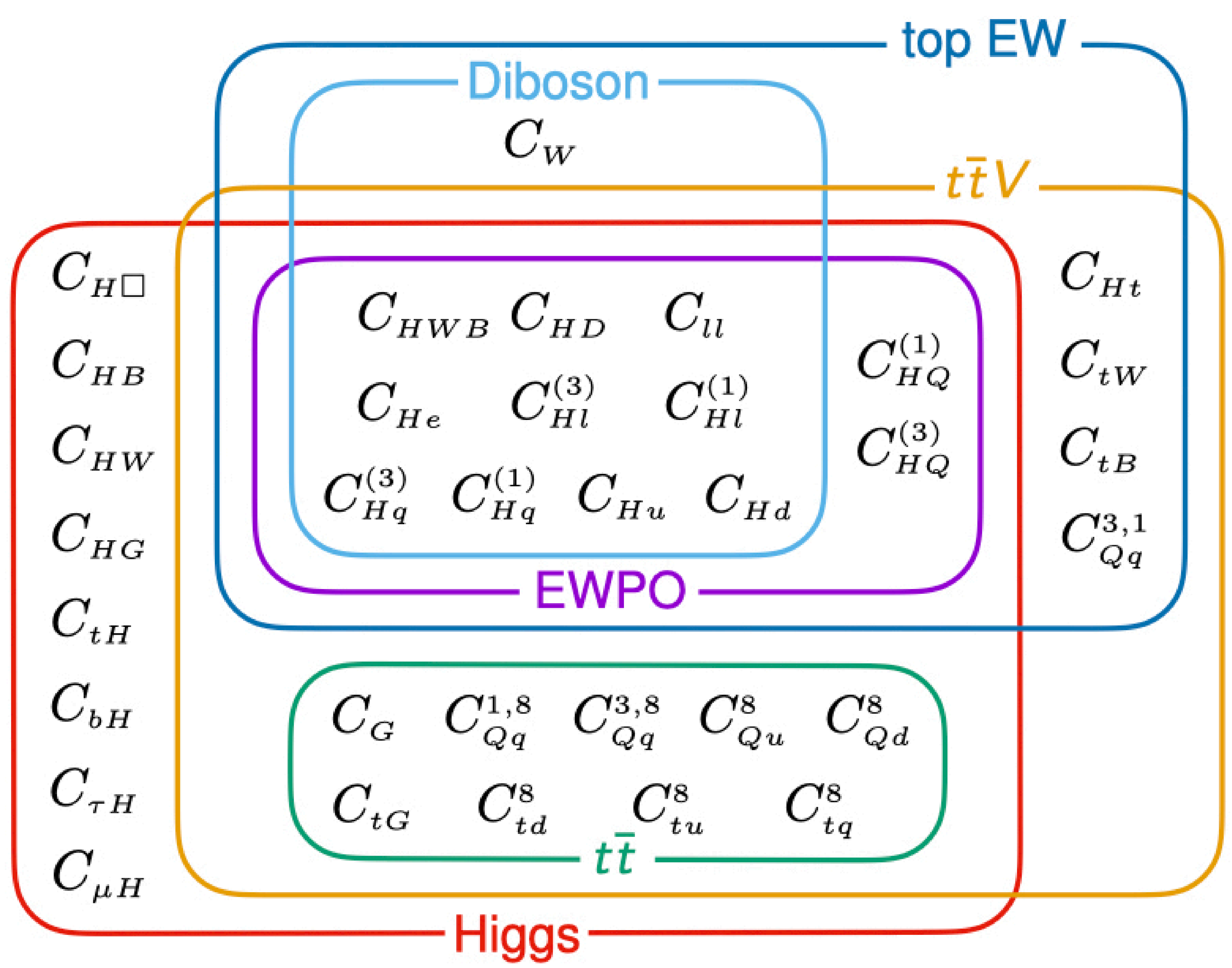
Determining c_i requires most precise available SMEFT predictions

Global approach

How much cross-talk?
Where does being global matter?

[Ellis et al.; JHEP 06 (2018) 146]



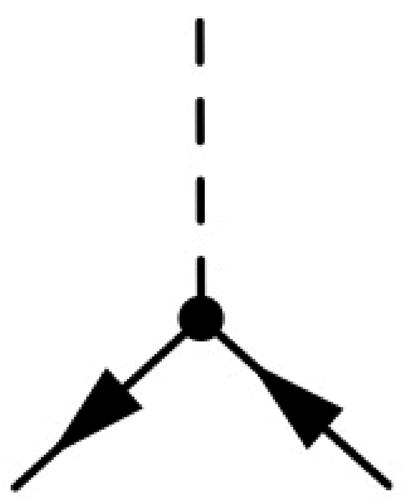


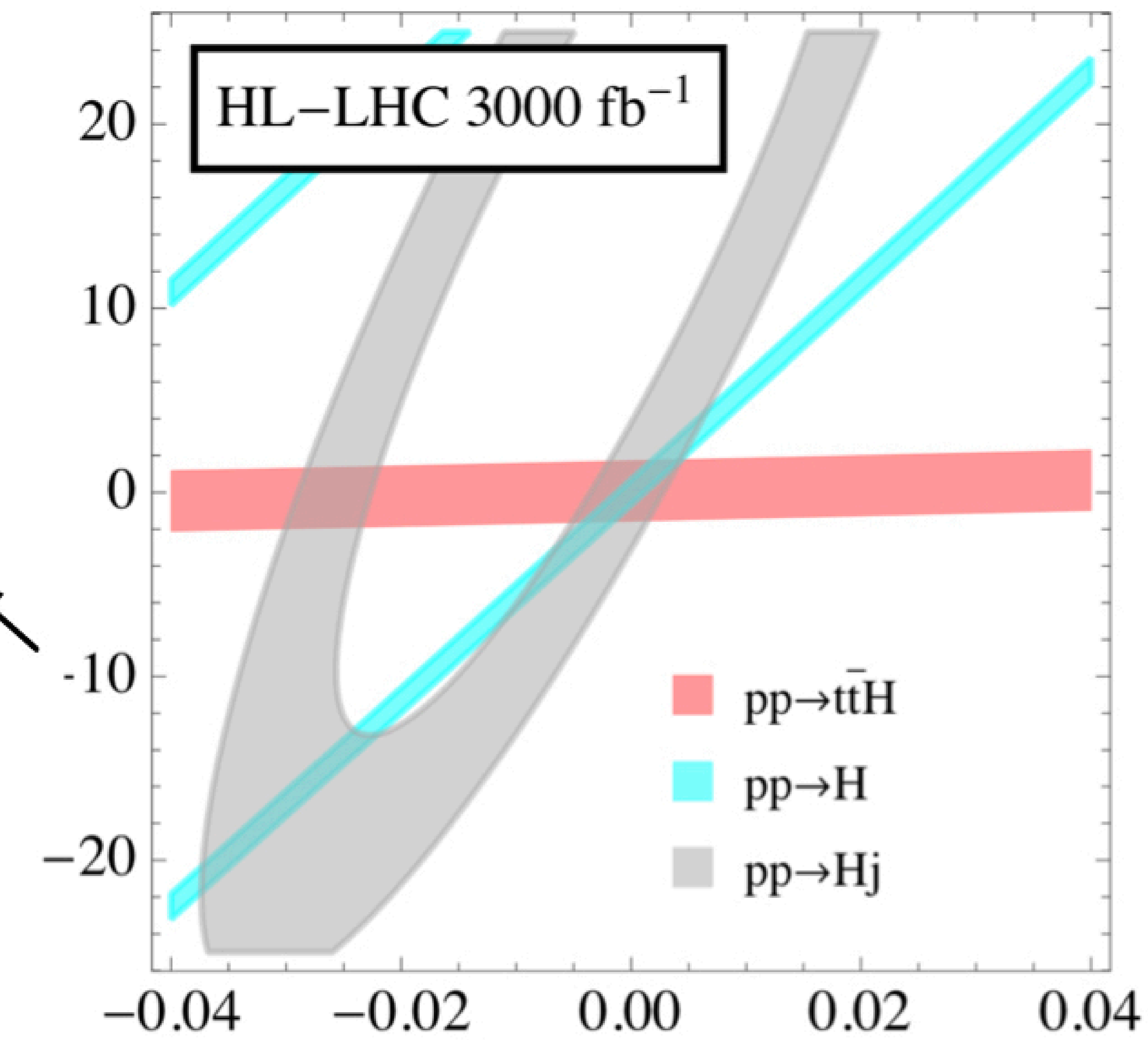
Top & Higgs

[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

Inextricably linked in the SM

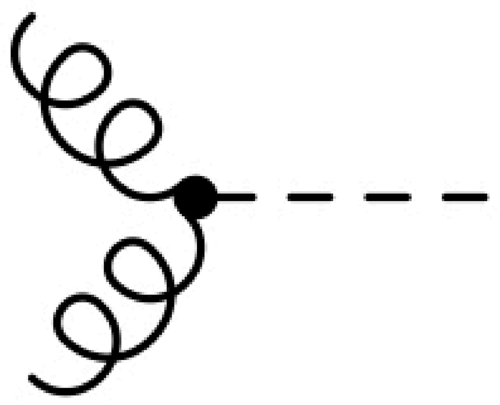
- Yukawa interaction controls ggF
- Strong BSM motivation to study tops



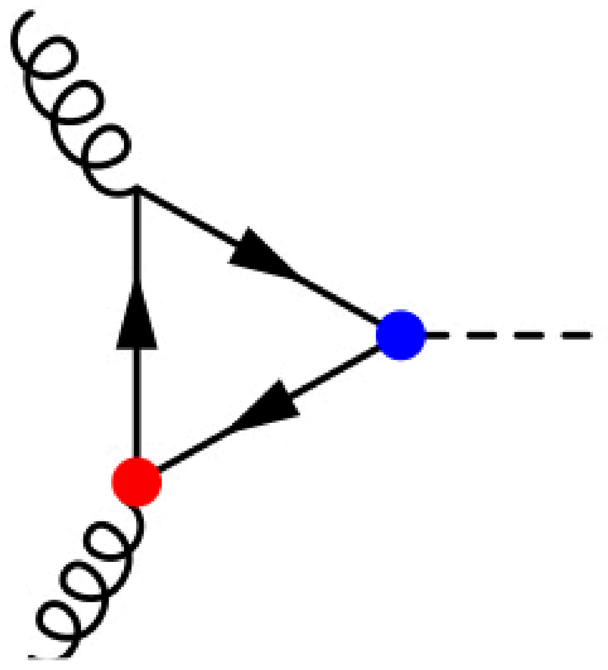


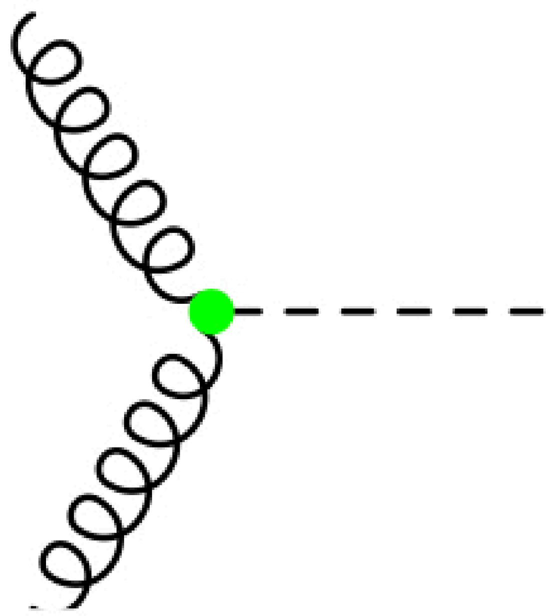
$gg \to h$ is well measured at the LHC

- Does not exclude top partners, anomalous Yukawa!



C_{HG} *Point-like*
C_{tH} *Yukawa*
C_{tG} *Dipole*

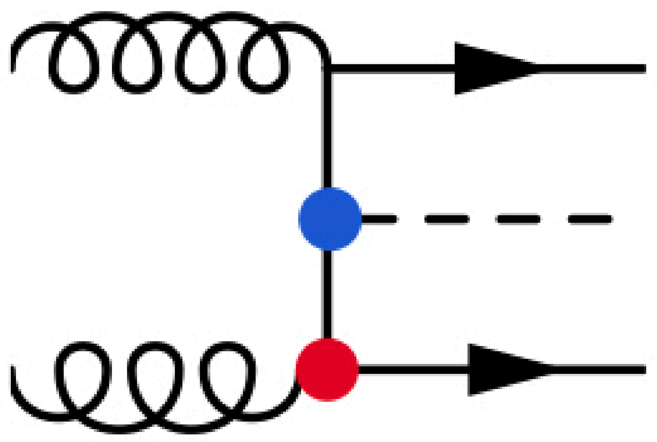


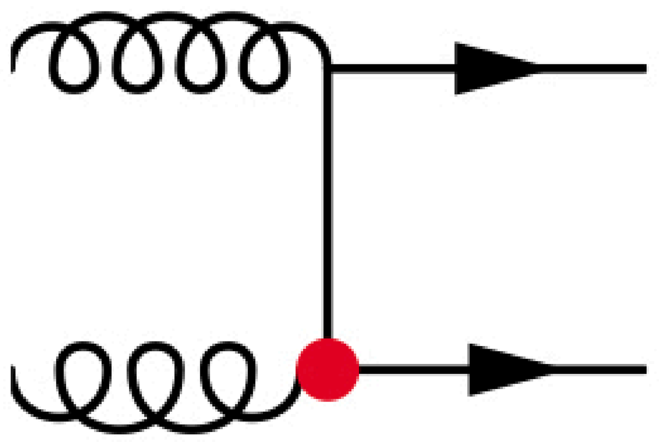


Blind direction in BSM scenarios
=
Effective coupling degeneracy

Need more data to break degeneracy

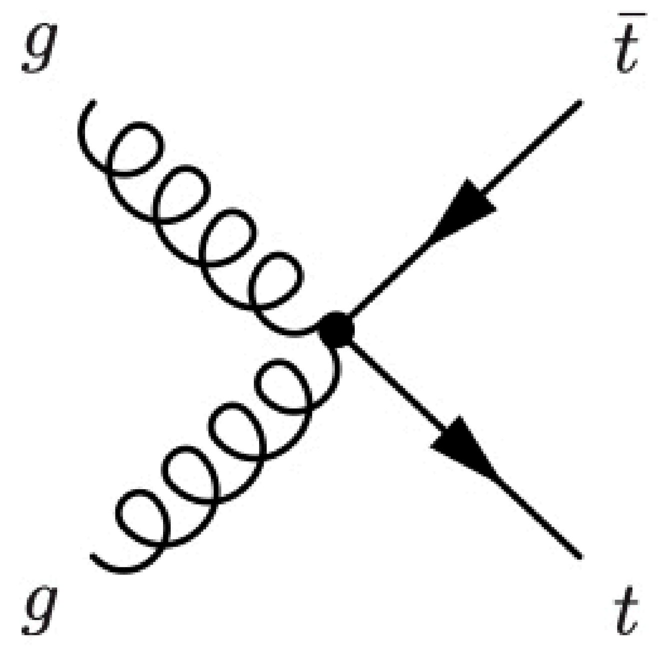
- $t\bar{t}H$ production for direct Yukawa measurement
- $t\bar{t}$ data to constrain dipole





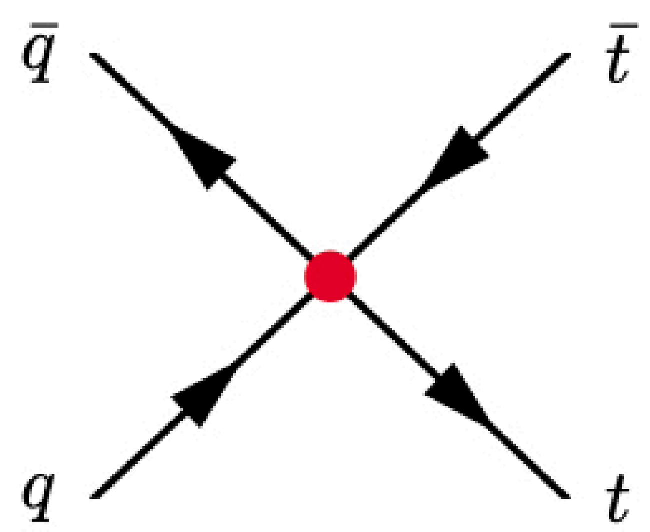
The role of top data

$t\bar{t}$ cross section measurements constrain C_{tG}



- Indirectly improve bounds on C_{HG} and C_{tH}

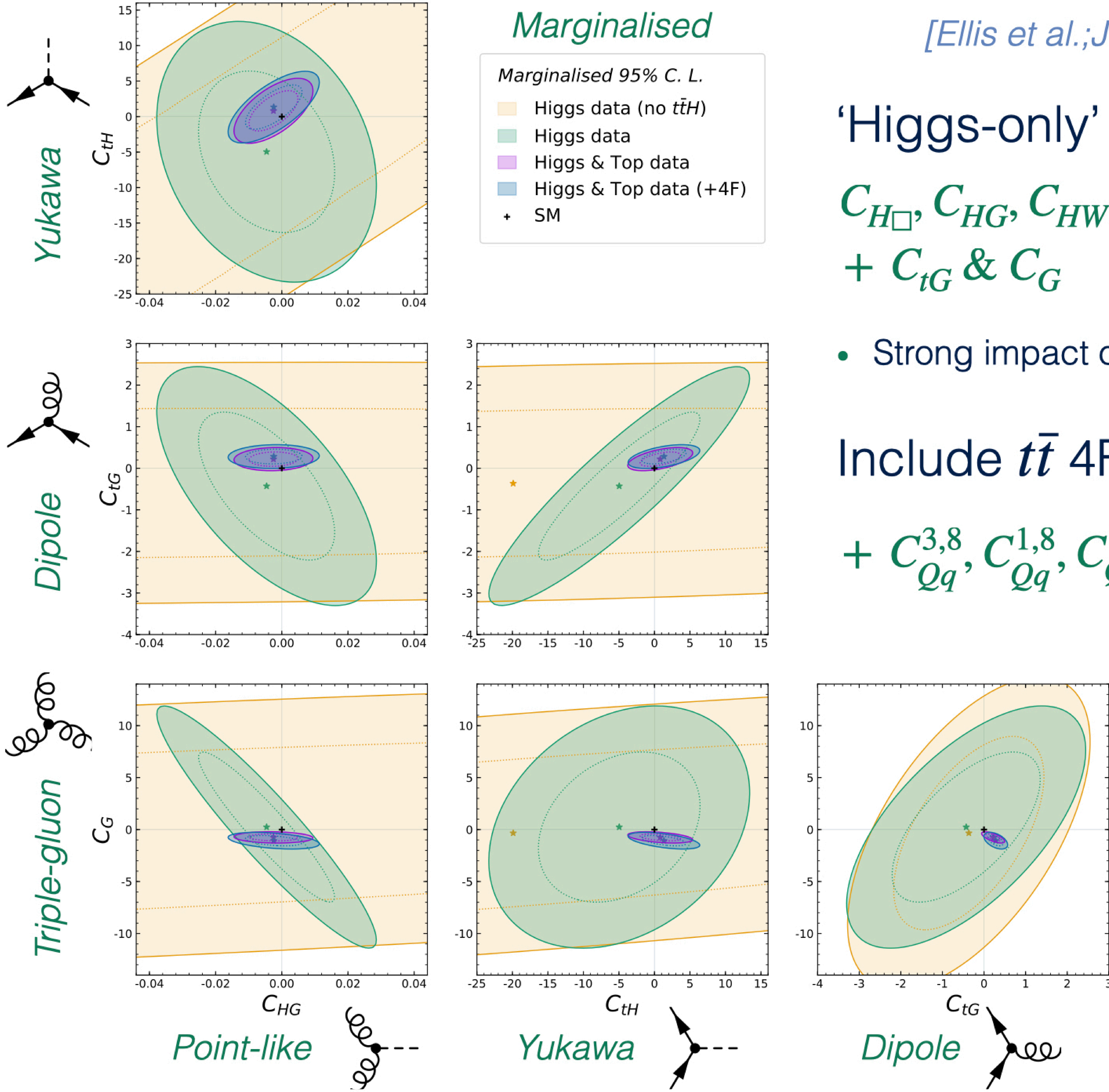
Several other new interactions can affect $t\bar{t}$



- Notably $q\bar{q}t\bar{t}$ operators, of which there are many (14)
- To what extent do these limit ultimate NP sensitivity in top/Higgs sector?

Can only be addressed in combined fit

- Beyond tree-level (at least for ggF) *[Degrande et al.; PRD 103 (2021) 9, 096024]* *http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO*
- Identify other cross-talk (non-trivial correlations)
- Crystallisation of knowledge gained after LHC Run 2
- Broaden range of applicability to UV models



[Ellis et al.;JHEP 04 (2021) 279]

'Higgs-only' operator fit

$C_{H\Box}, C_{HG}, C_{HW}, C_{HB}, C_{tH}, C_{bH}, C_{\tau H}, C_{\mu H}$
$+\ C_{tG}\ \&\ C_G$

- Strong impact of $t\bar{t}H\ \&\ t\bar{t}$

Include $t\bar{t}$ 4F operators

$+\ C^{3,8}_{Qq}, C^{1,8}_{Qq}, C^{8}_{Qu}, C^{8}_{Qd}, C^{8}_{tq}, C^{8}_{tu}, C^{8}_{td}$

- Relatively mild impact
- Preferred $t\bar{t}$ phase space is different

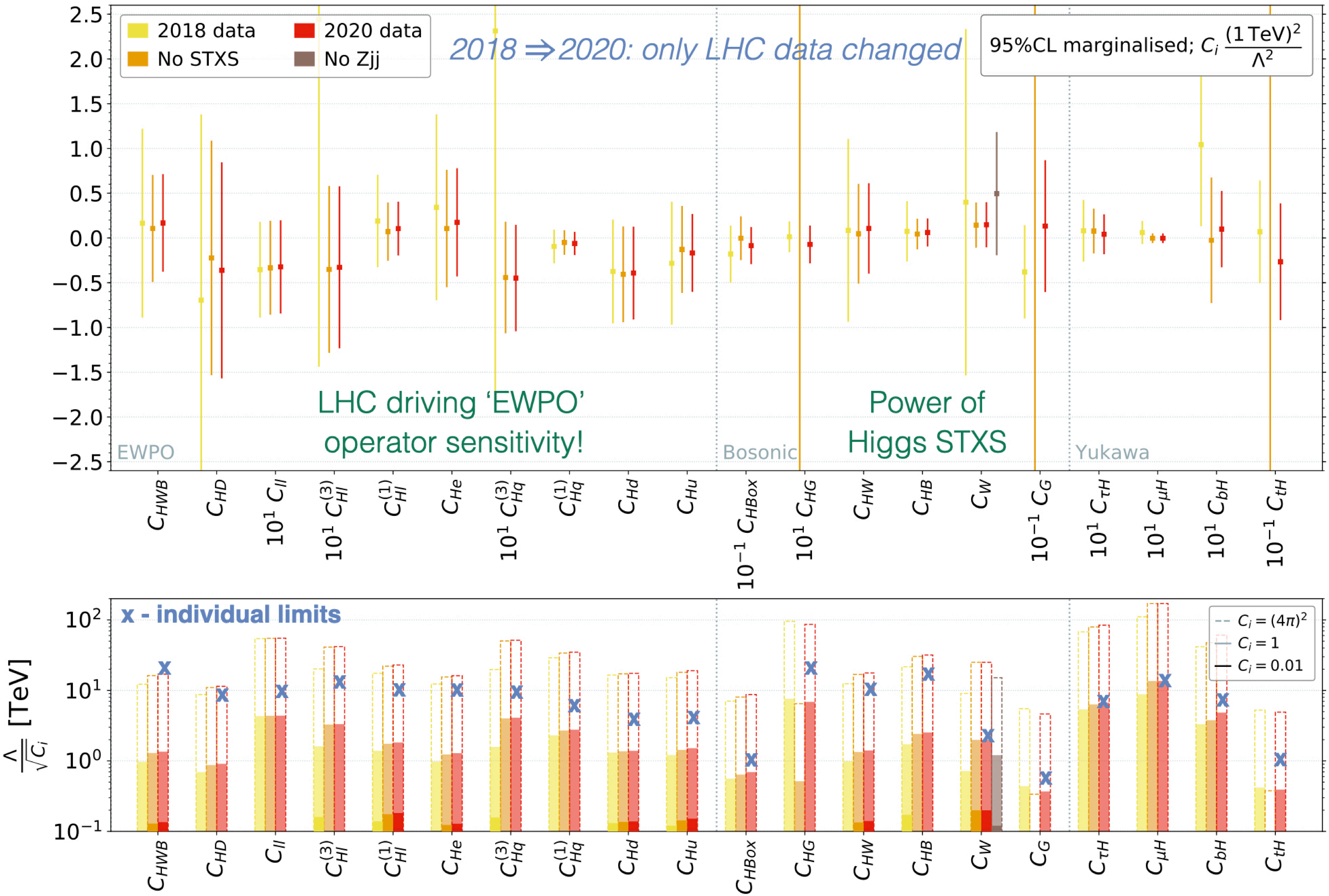
  C_{tG} : low $m_{t\bar{t}}$

  $4F$: high $m_{t\bar{t}}$

- Able to constrain them independently

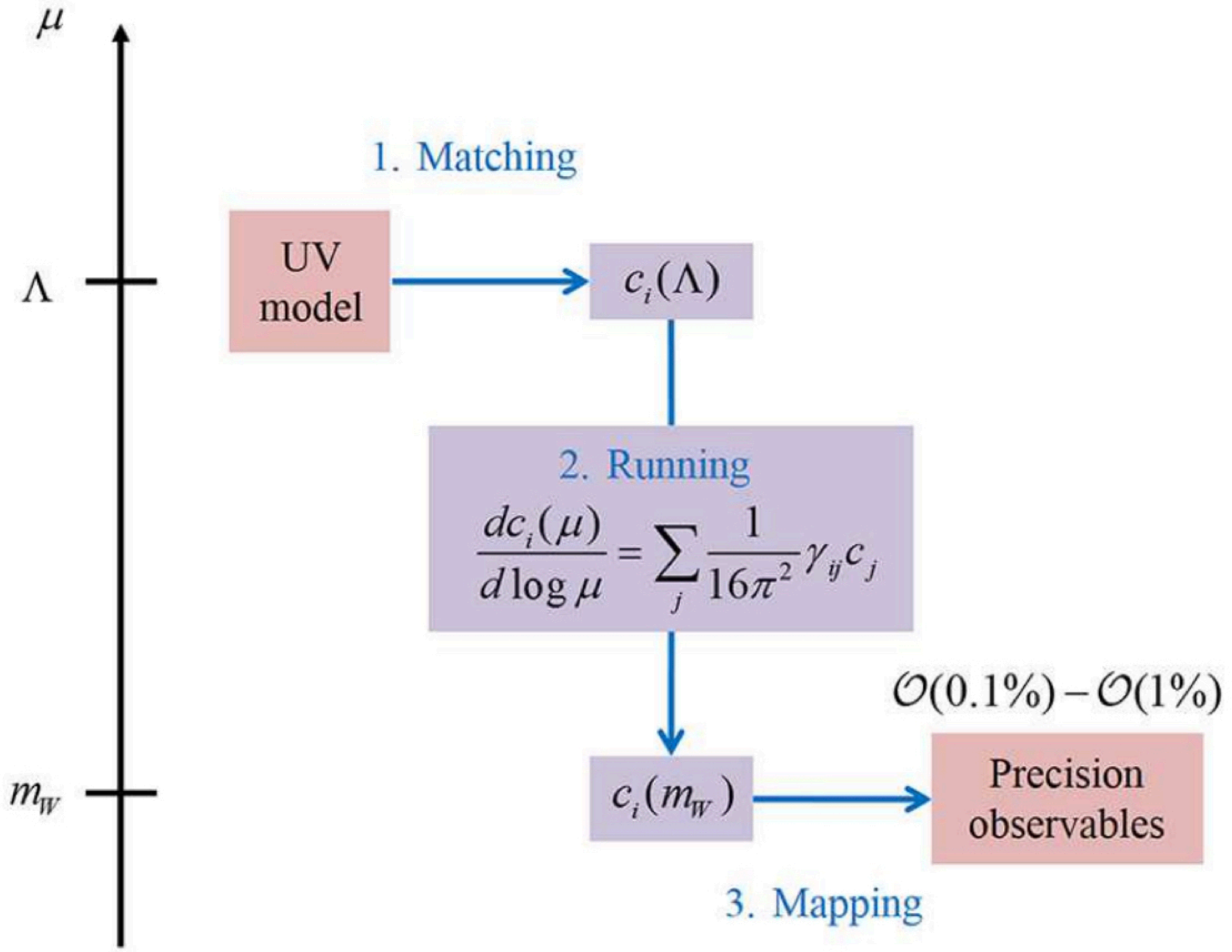
  [ATLAS-CONF-2021-031]

Marginalised limits: U(3)^5 fitmaker https://gitlab.com/kenmimasu/fitrepo

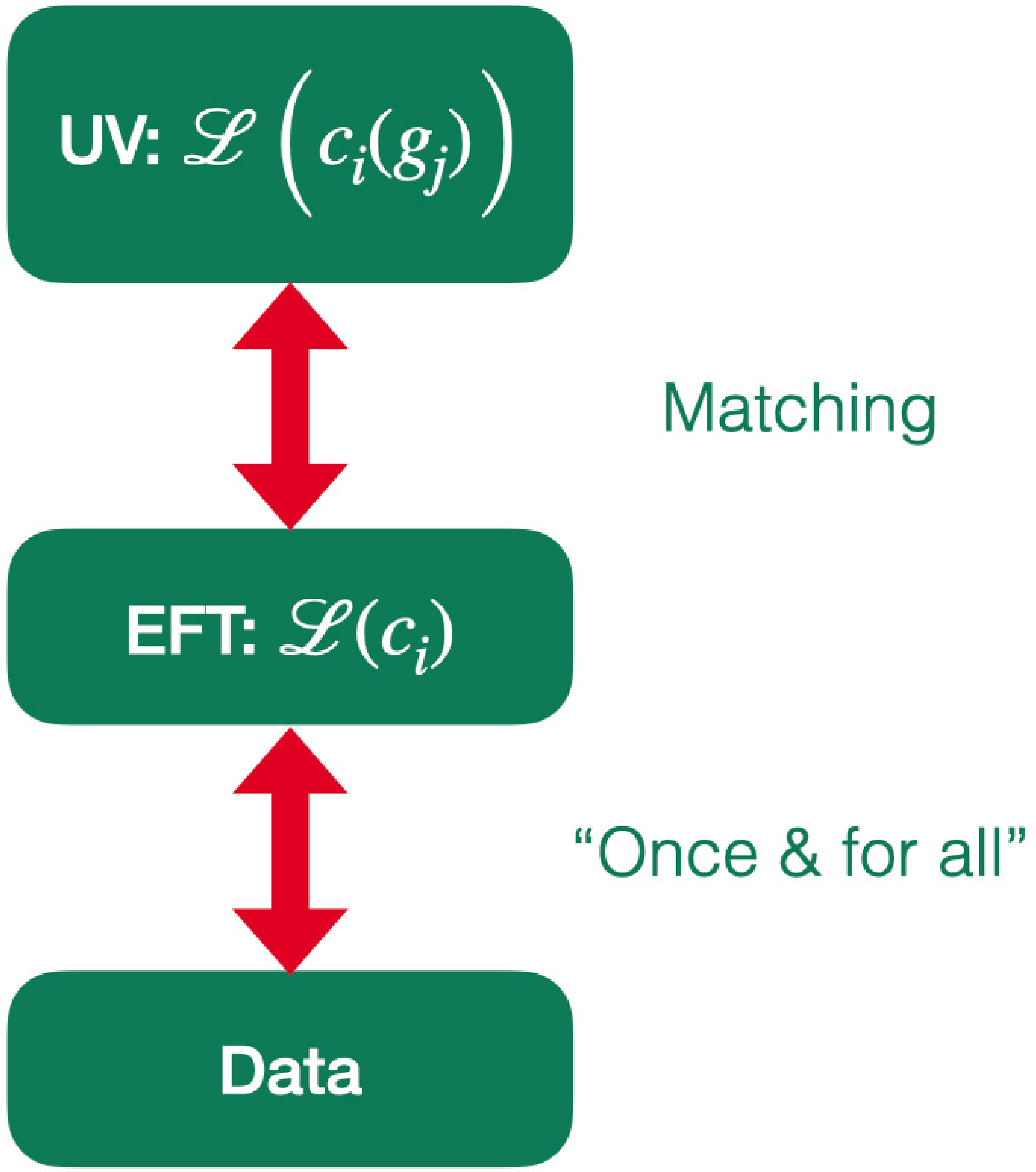


SMEFT strategy

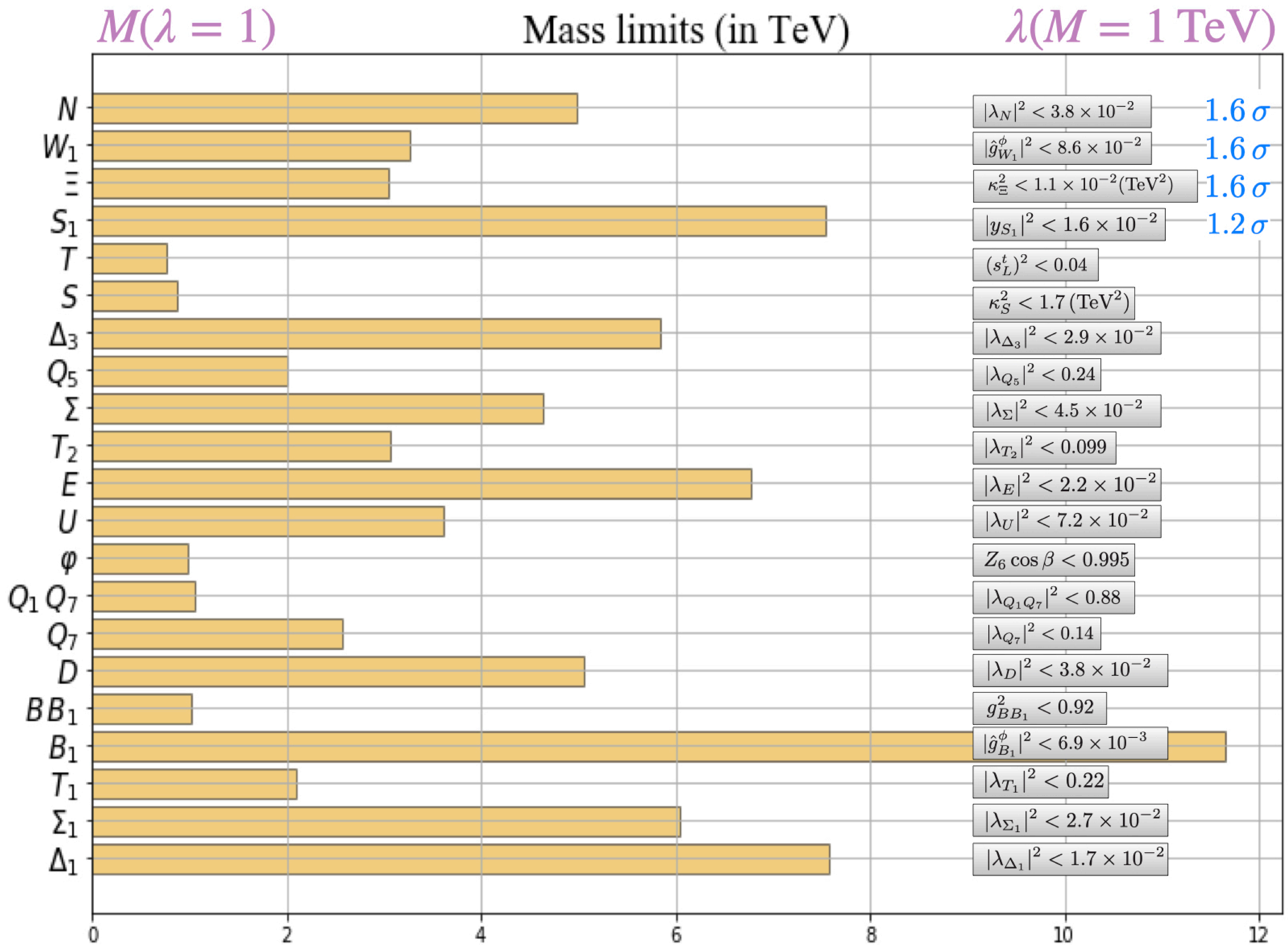
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-4})$$



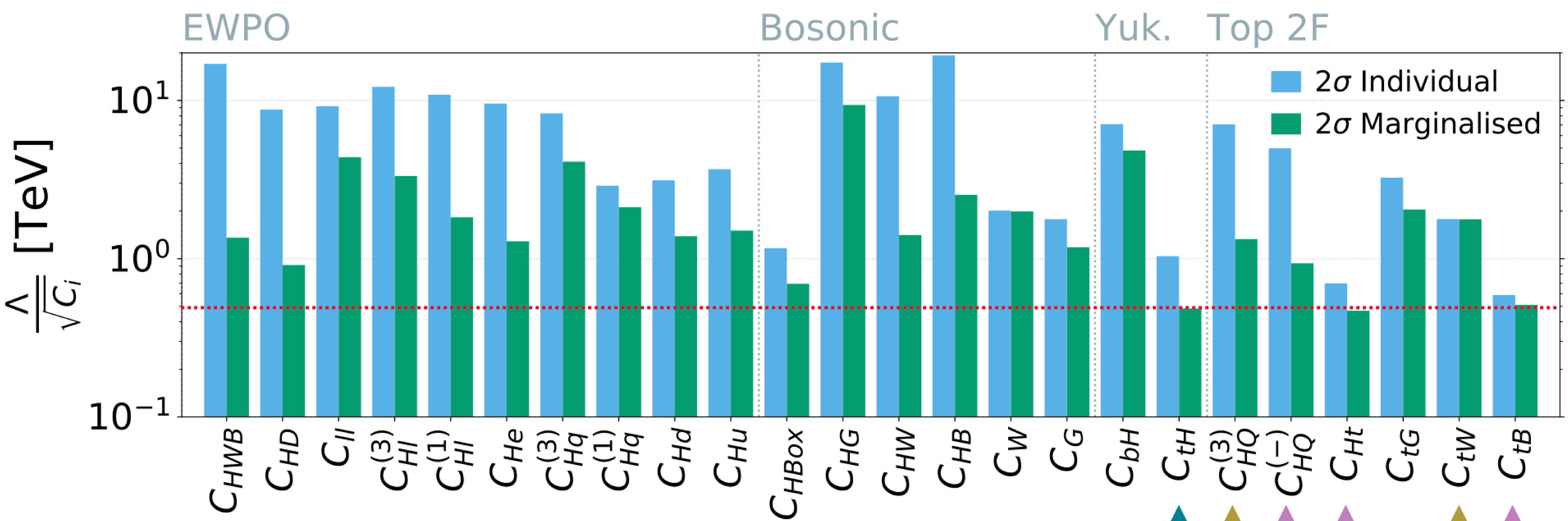
[Henning, Lu & Murayama; JHEP 01 (2016) 023]



One parameter models

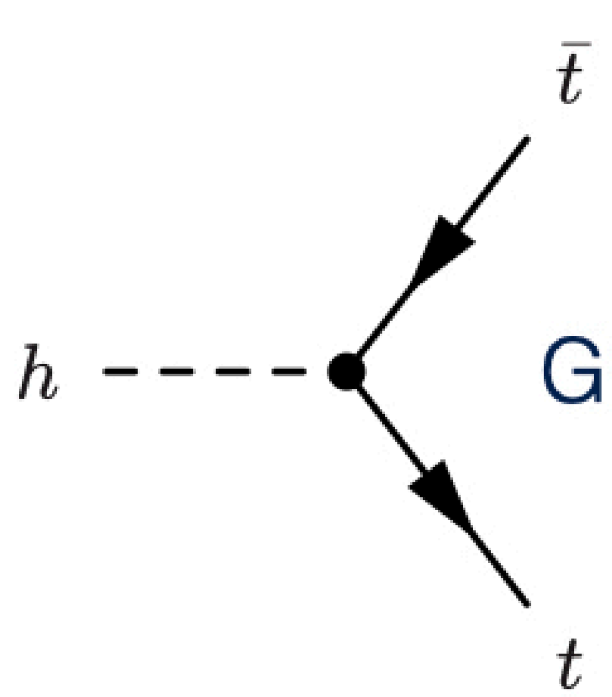


High energy & multiplicity

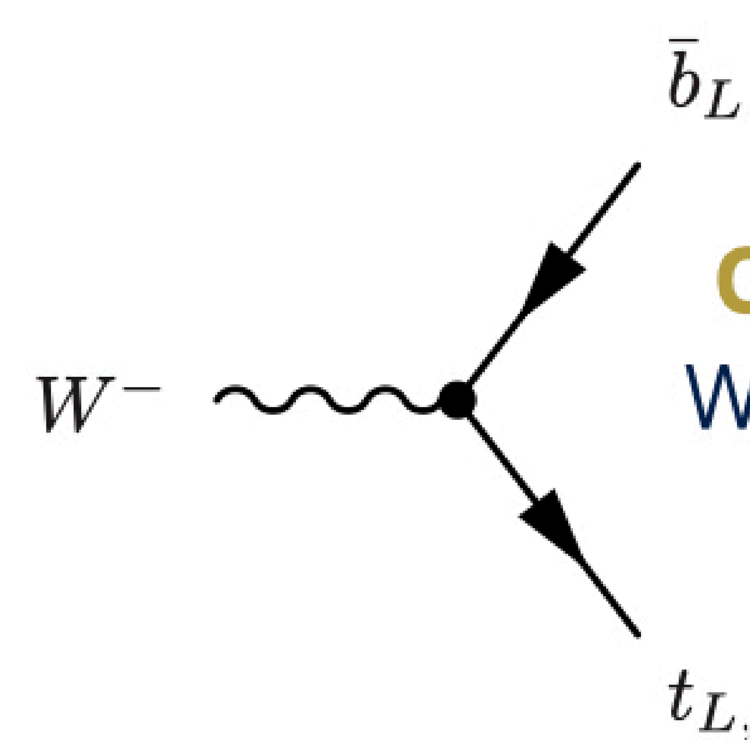


- **Charged current** interactions quite well constrained
- **Yukawa** and **neutral current** are poorly known

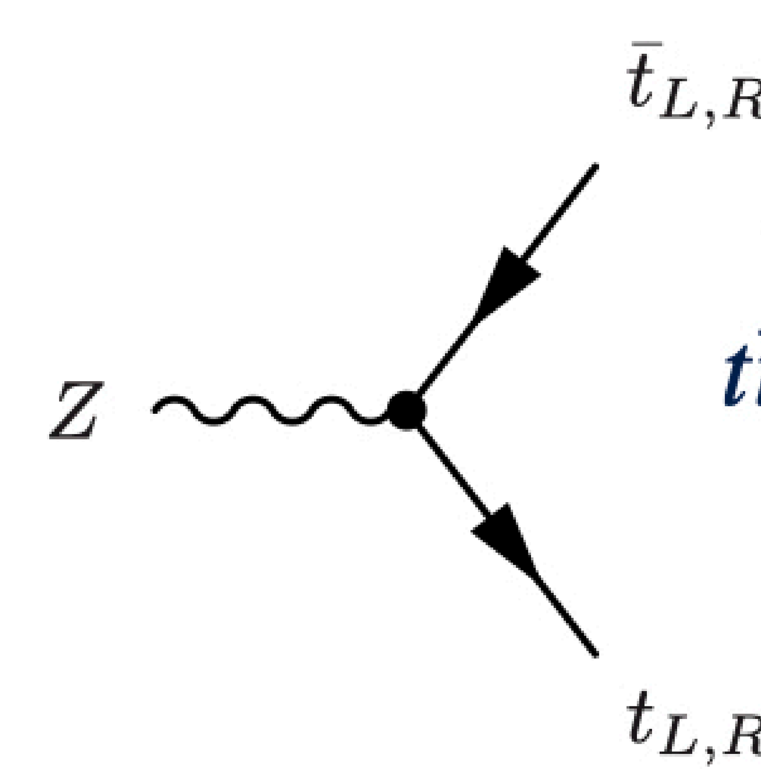
Top couplings



Yukawa
Gluon fusion (indirect)
$t\bar{t}H$ production

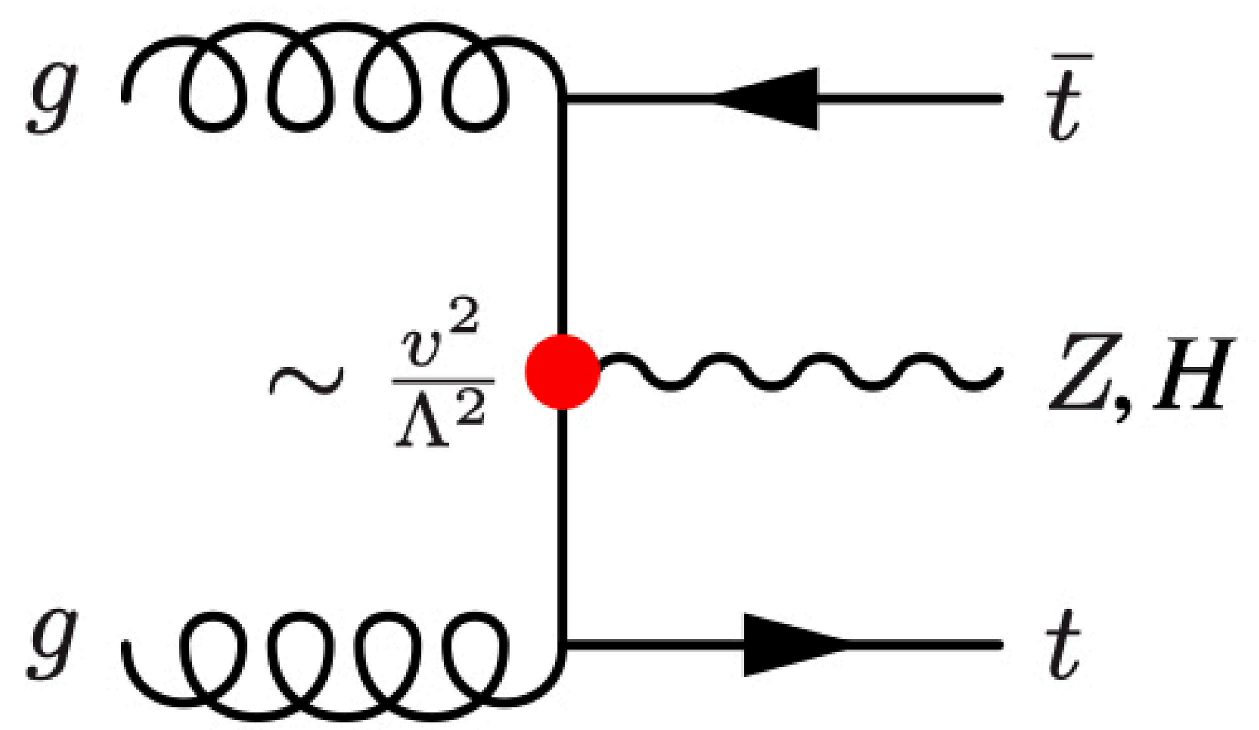


Charged current
W-helicity fractions
Single-top



Neutral current
$t\bar{t}\gamma / t\bar{t}Z$ production

Keep calm, carry on?



$t\bar{t}X$ for Yukawa & neutral current operators

- Relatively rare processes, just collect more data…
- EFT effect $\propto v^2/\Lambda^2$, no energy growth (SM-kinematics)
- Can we look elsewhere, exploiting **characteristic energy growth of EFT?**

$$\mathcal{A} \sim \mathcal{A}_{SM}\left(\boxed{1 + c_i \frac{v^2}{\Lambda^2}} + \boxed{c_j \frac{v\,E}{\Lambda^2} + c_k \frac{E^2}{\Lambda^2}}\right)$$

'Energy helps accuracy'
[Farina et al.; PLB 772 (2017) 210-215]

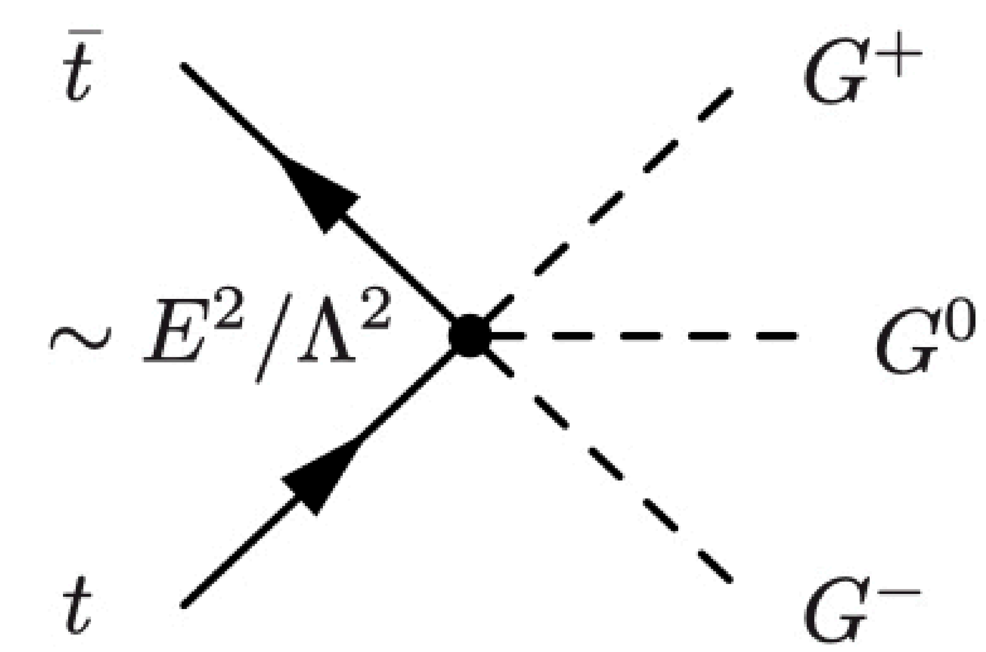
Rate measurements will become systematics dominated
Increasingly high-energy measurements scale with lumi.

There will always be some scattering amplitude that displays maximal (E^2) growth w.r.t the SM

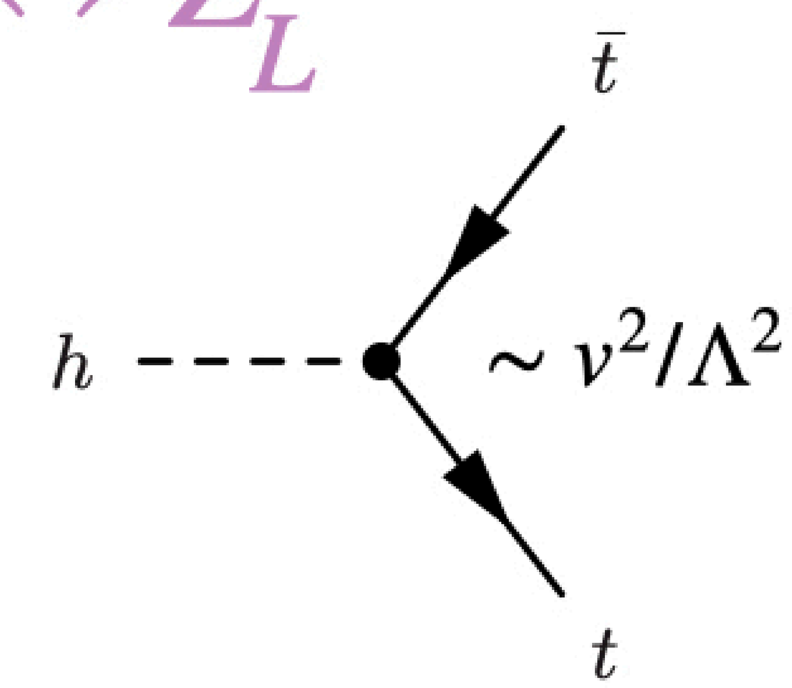
[Dror et al.; JHEP 01 (2016) 071]
[Mantani, Maltoni & KM; JHEP 10 (2019) 004]

Finding the right process

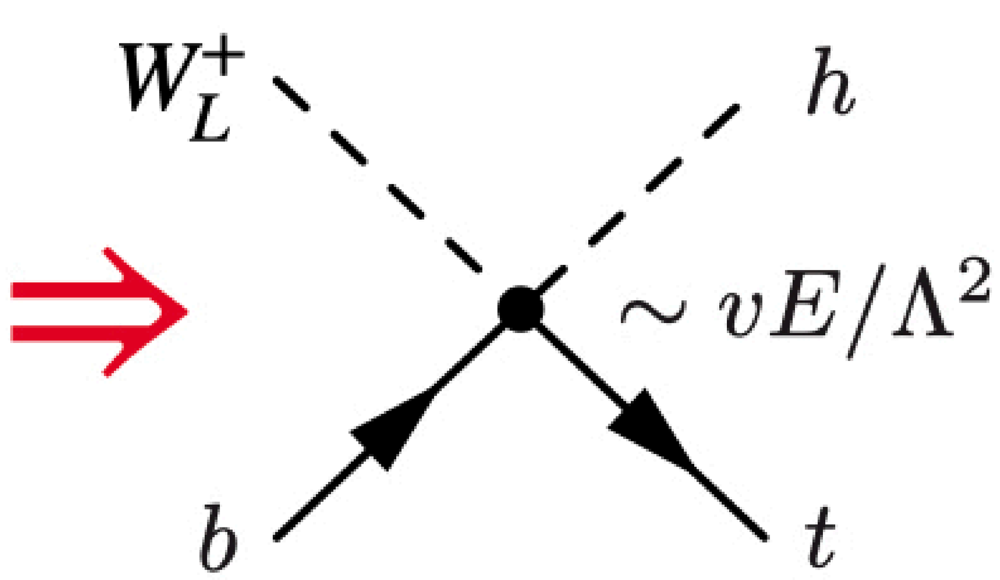
Gauge invariance +
Goldstone equivalence theorem: $\partial^\mu G \leftrightarrow Z_L^\mu$



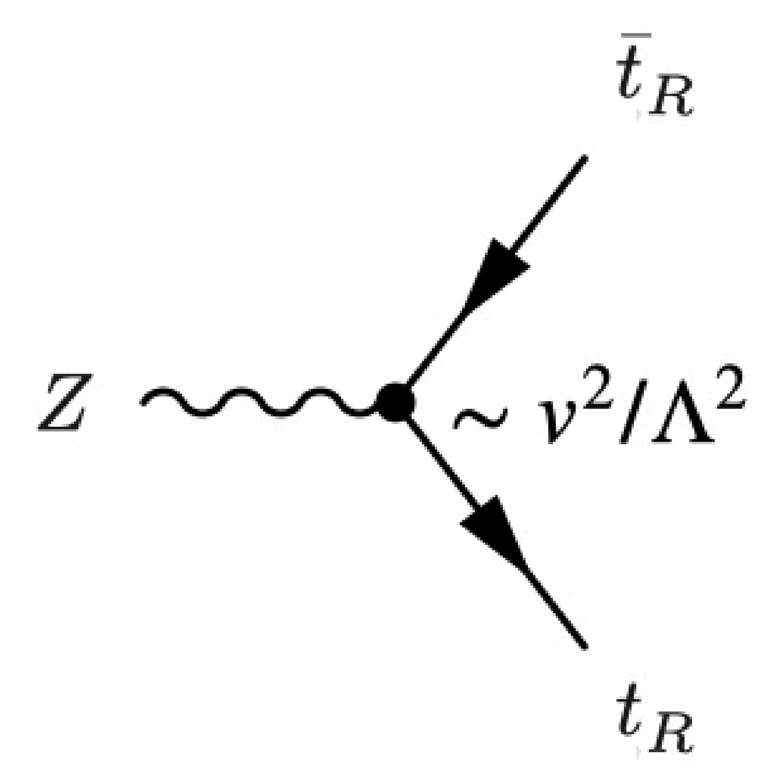
$C_{tH}(H^\dagger H)(\bar{Q}t\tilde{H})$ $\quad \langle H^\dagger H\rangle = v^2 \quad \Rightarrow$



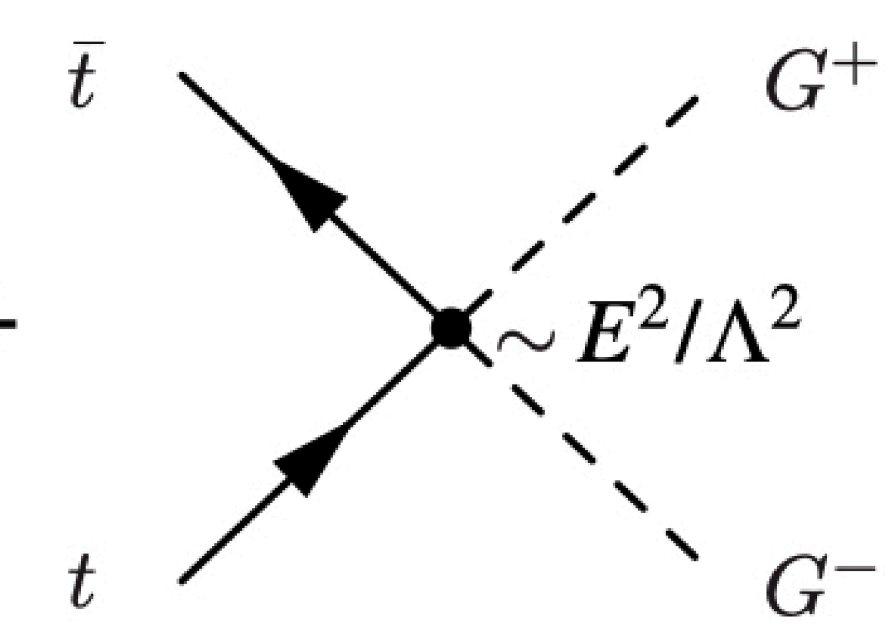
Feynman gauge $\quad \langle H^\dagger H\rangle = v^2 + 2vh + h^2 + G^+G^- + G_0^2 \quad \Rightarrow$



$C_{Ht}\, i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R\gamma^\mu t_R) \quad \Rightarrow$



$+$



$$\boxed{\begin{array}{l} t\,W_L \to t\,W_L \\ t\,Z_L \to t\,h \\ b\,W_L \to t\,Z_L \\ b\,W_L \to t\,h \end{array}}$$

Unitarity non-cancellations in scattering amplitudes $\Leftrightarrow$ **Non-renormalisable contact interactions with Goldstones**

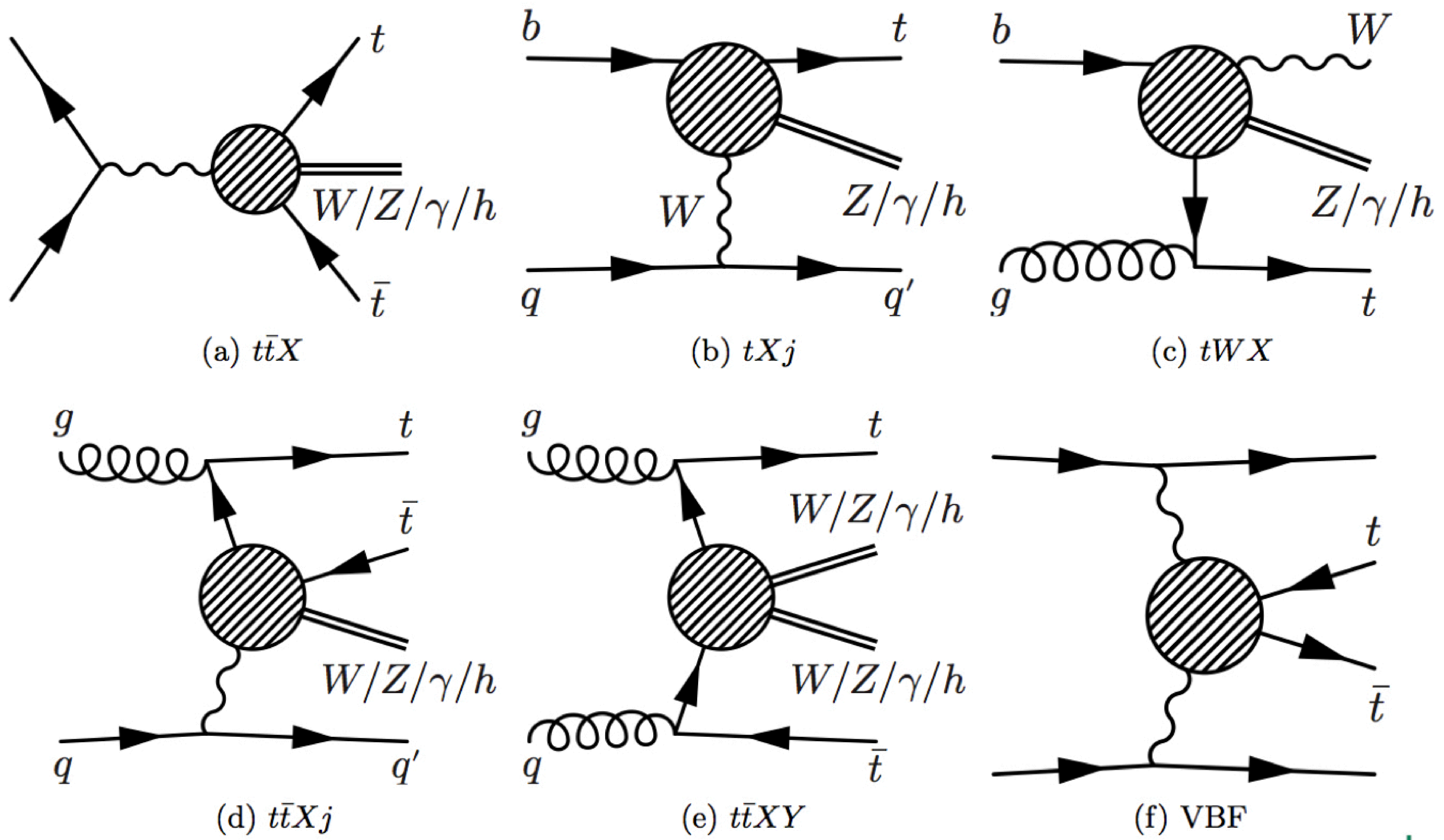
c.f. 'Higgs without Higgs'
[Henning et al.; PRL 123 (2019) 181801]

Less vevs, more legs! (AKA multiplicity)

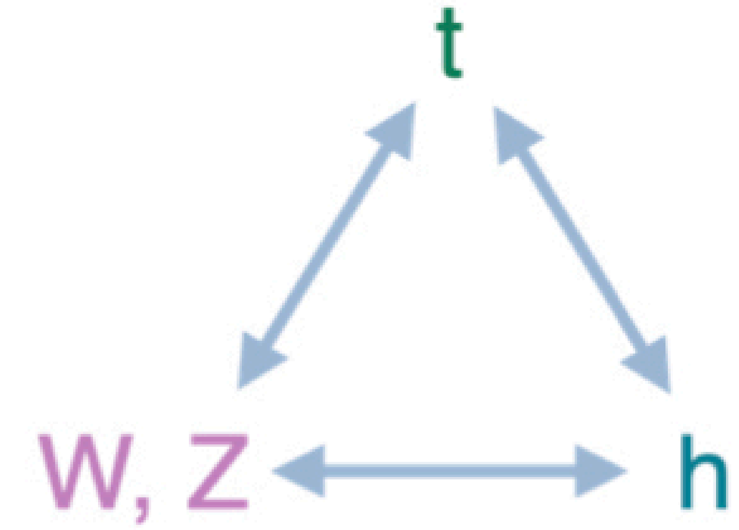
e.g. tWZ: [El Faham al.; JHEP 01 (2022) 100]
[CMS-PAS-TOP-22-008]

Embedding the amplitudes

Collider processes: **high multiplicity, EW top production**



Couplings $\left\{ \begin{array}{l} \text{top EW} \\ \text{Higgs} \\ \text{triple gauge} \end{array} \right.$ $\Rightarrow$ Heart of EWSB sector

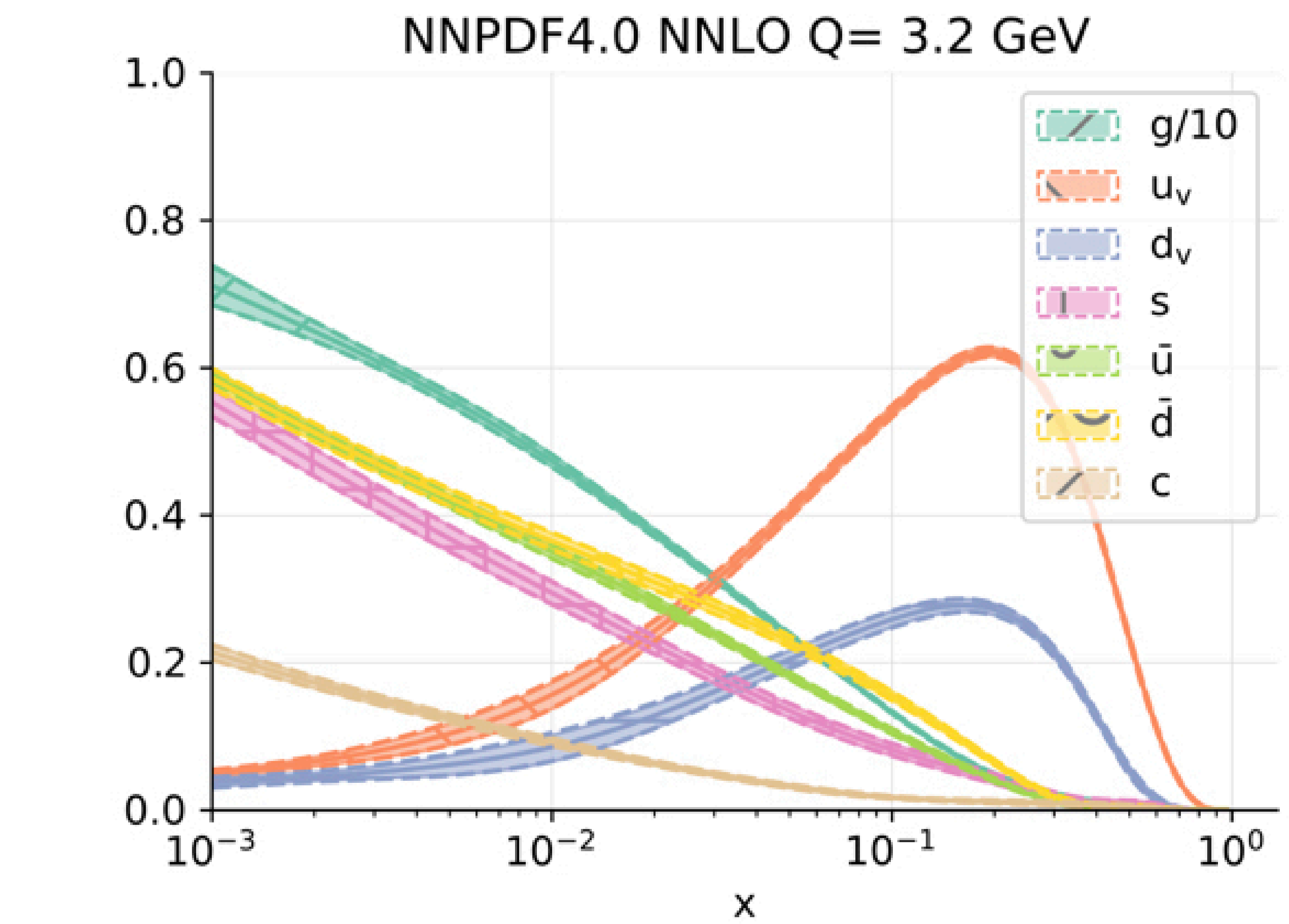


SMEFT & PDFs

[NNPDF; EPJC 82 (2022) 5, 428]

$$\sigma(c_i, \theta_i) = f(\theta_i) \times f(\theta_i) \times \hat{\sigma}(c_i)$$

[Ellis et al.;JHEP 04 (2021) 279]

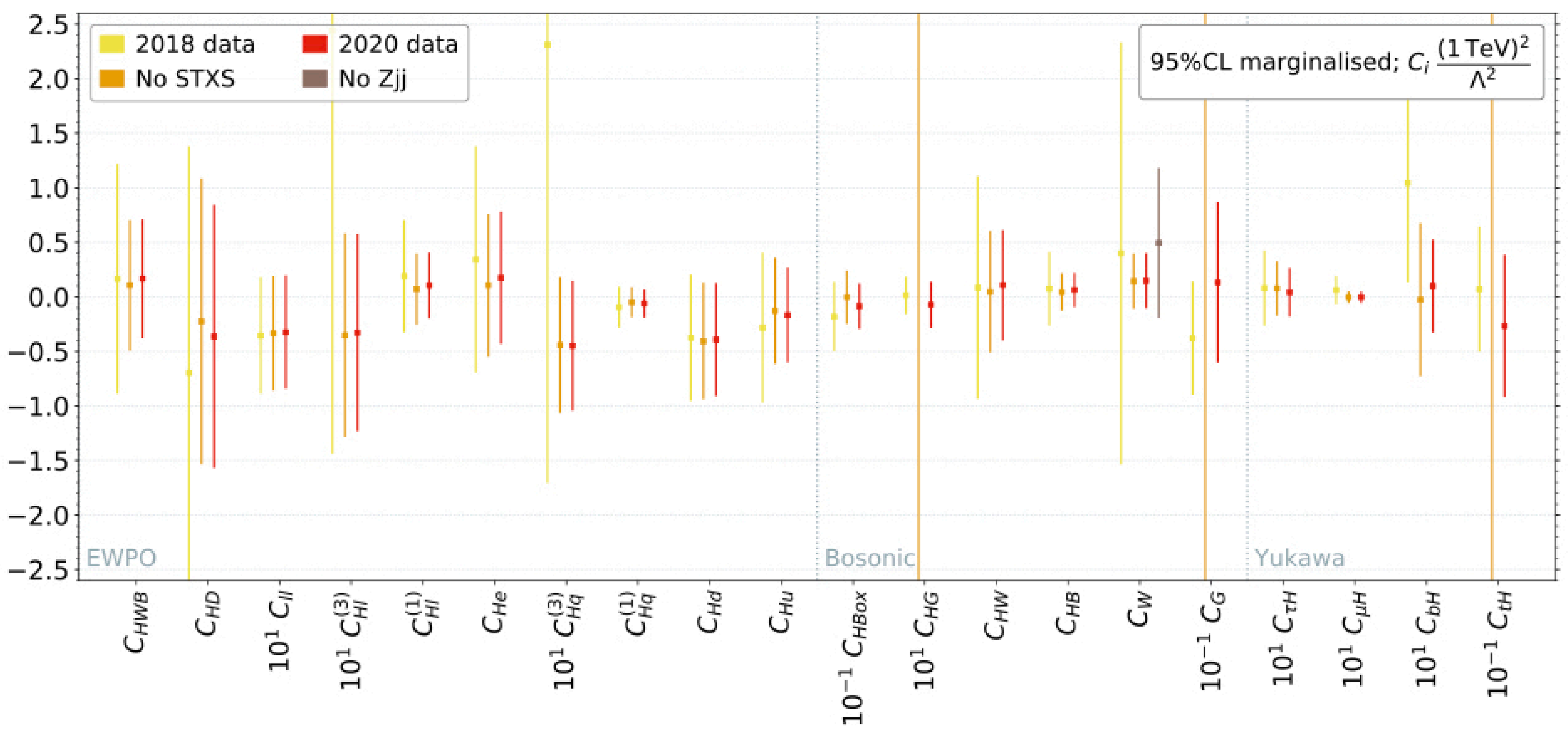


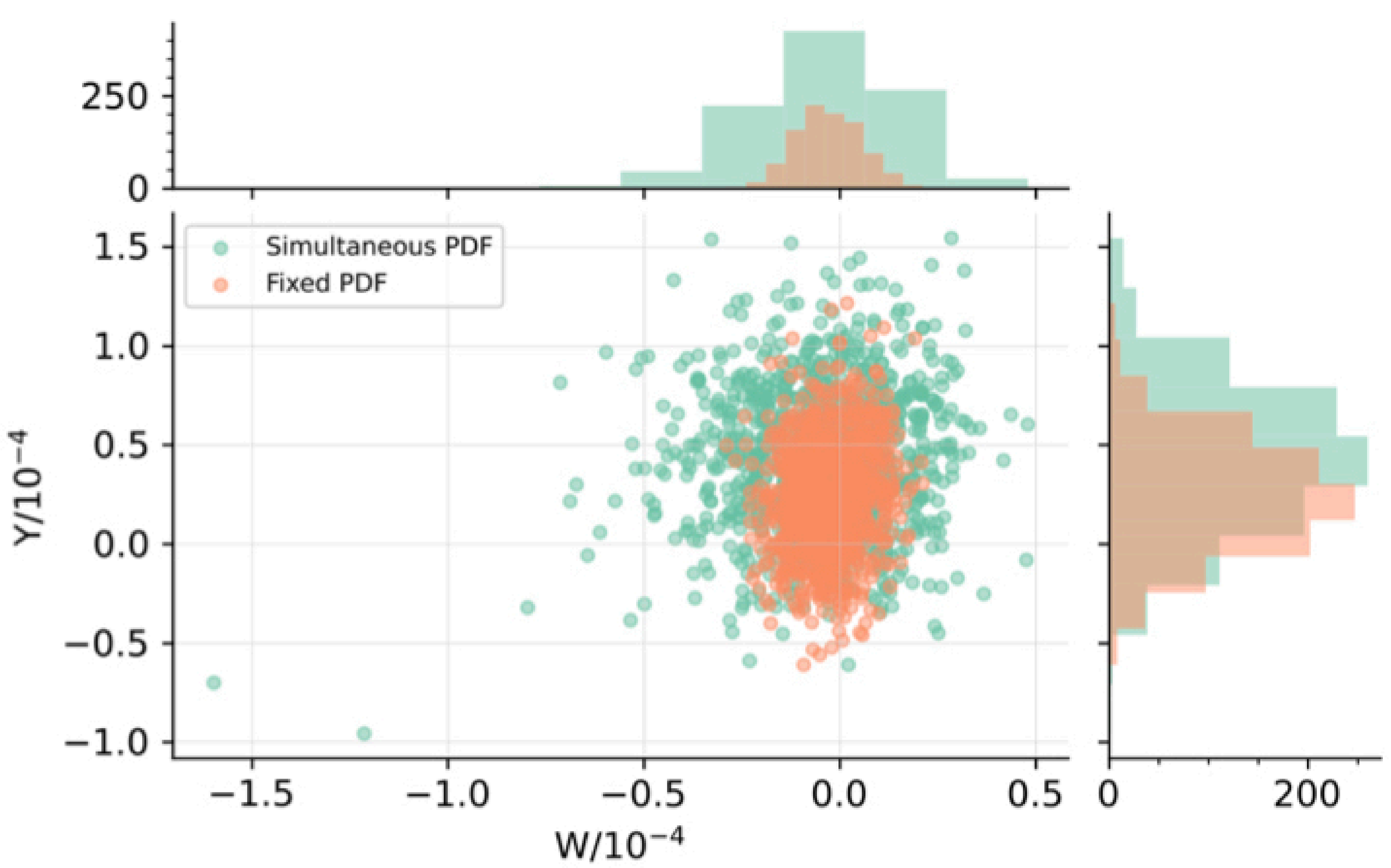
$\Downarrow$

Data

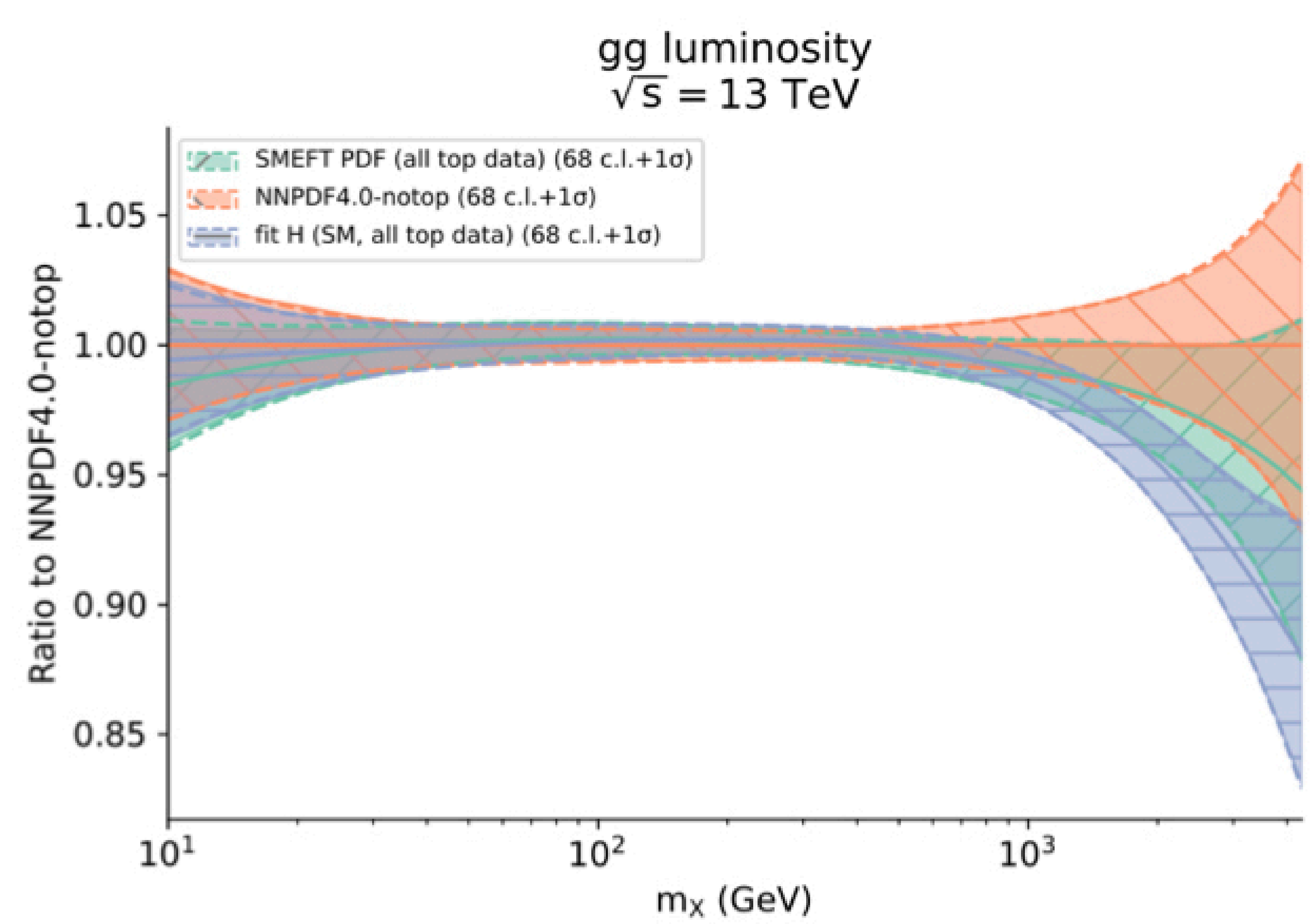
θ_i $\Downarrow$ c_i

$\{\theta_i, c_i\}$





[Iranipour & Ubiali; JHEP 05 (2022) 032]



[Kassabov et al.; JHEP 05 (2023) 205]

Can new physics hide inside the proton?

[Carazza et al.;
PRL123 (2019) 13, 132001]

[Hammou et al.;
JHEP 11 (2023) 090]

Precision SMEFT: why?

In general: improve precision/accuracy of predictions

- Correct normalisations & shapes, better scale & PDF uncertainties

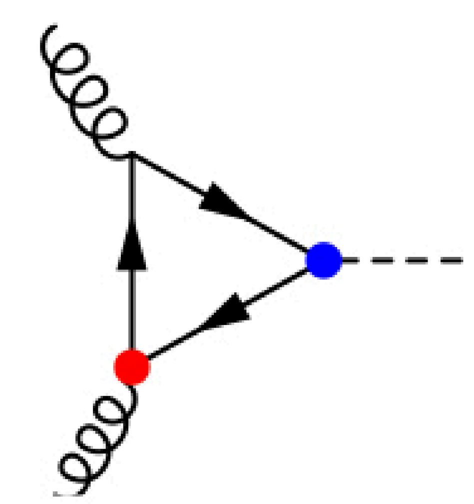
SM reasons:

- QCD corrections: control hadron collider uncertainties
- EW corrections: extra accuracy/in specific phase space regions

Lorenzo Mai's talk

SMEFT reasons:

- **running & mixing** of coefficients
- **loop-induced** sensitivity



$gg \to VV/Vh/hh$

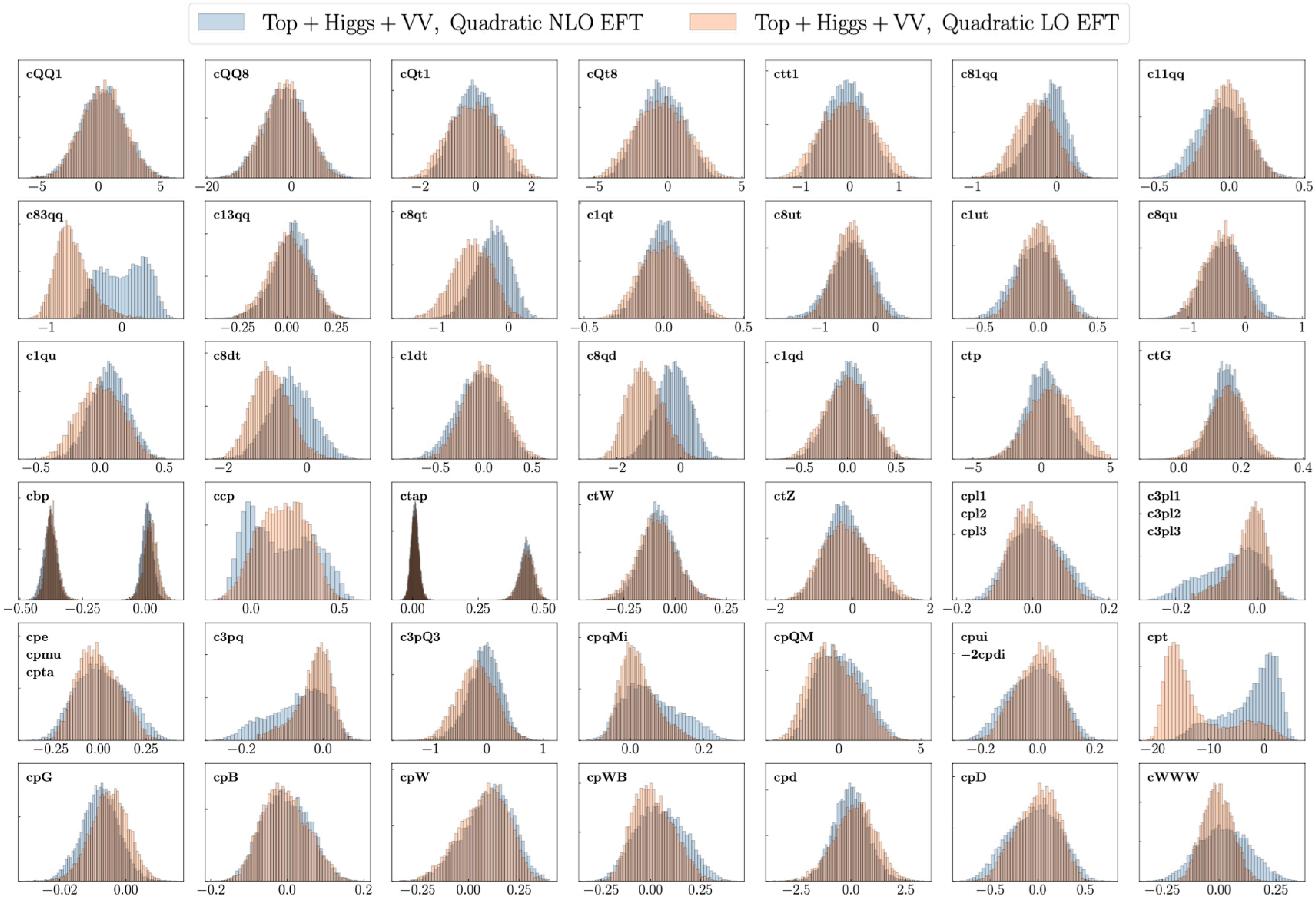
(Marion Thomas' talk)

Deviation	✗	✓
Better:	*Reflection of new physics **reach***	*Pinpointing of new physics **origin***

SMEFT@NLO

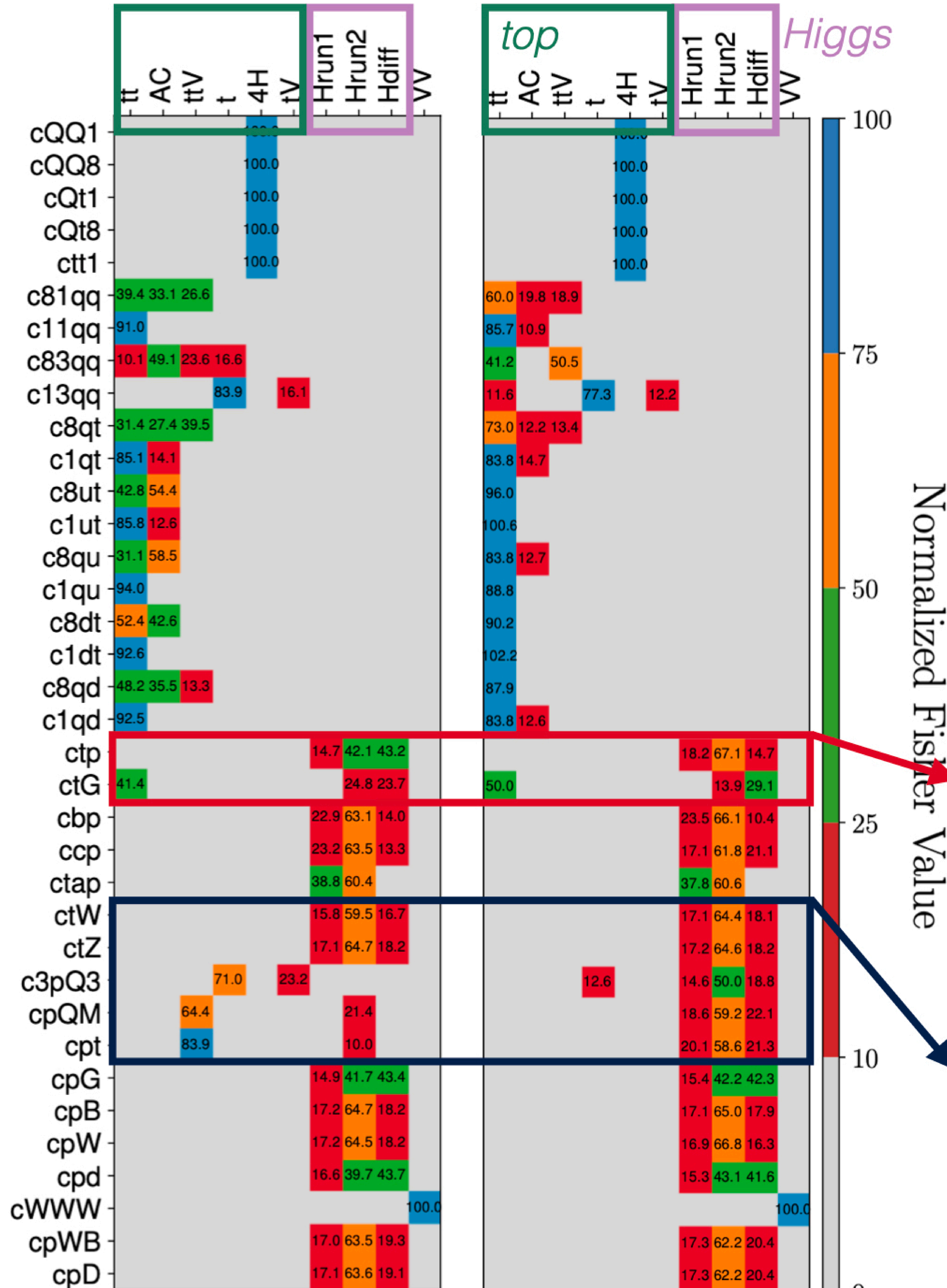
[Degrande et al.; PRD 103 (2021) 9, 096024]
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

NLO vs LO


Top + Higgs + VV, Quadratic NLO EFT
Top + Higgs + VV, Quadratic LO EFT
cQQ1
cQQ8
cQt1
cQt8
ctt1
c81qq
c11qq
c83qq
c13qq
c8qt
c1qt
c8ut
c1ut
c8qu
c1qu
c8dt
c1dt
c8qd
c1qd
ctp
ctG
cbp
ccp
ctap
ctW
ctZ
cpl1
cpl2
cpl3
c3pl1
c3pl2
c3pl3
cpe
cpmu
cpta
c3pq
c3pQ3
cpqMi
cpQM
cpui
−2cpdi
cpt
cpG
cpB
cpW
cpWB
cpd
cpD
cWWW

Constraining power

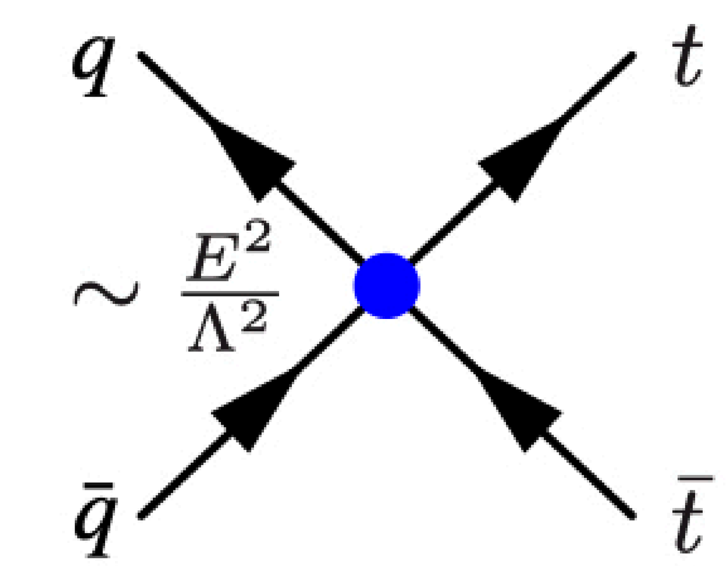
[Ethier et al.; JHEP 11 (2021) 089]



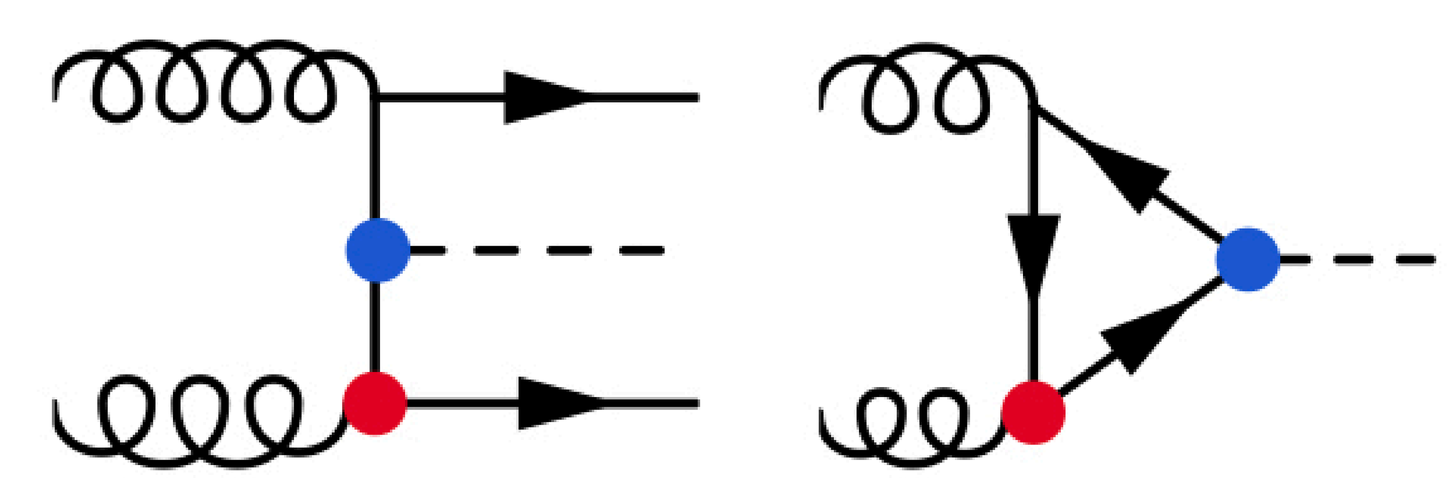
Fisher Information:

Hessian of Log-likelihood at the best-fit point

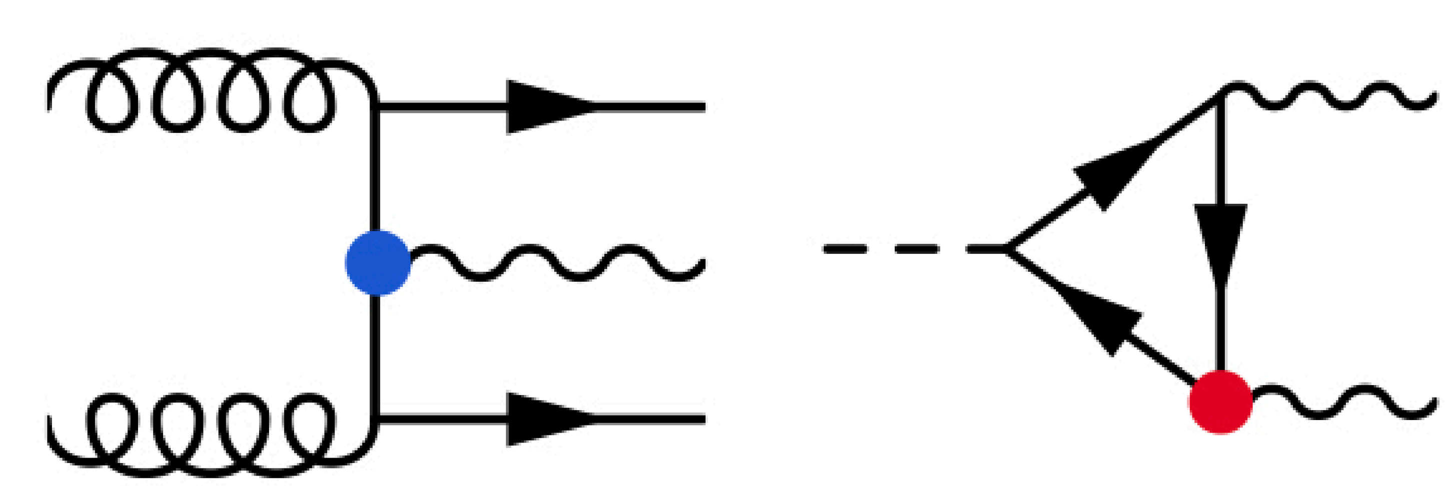
4F operators: mostly top data



Yukawa & Chromo-dipole



$t\bar{t}V$ couplings

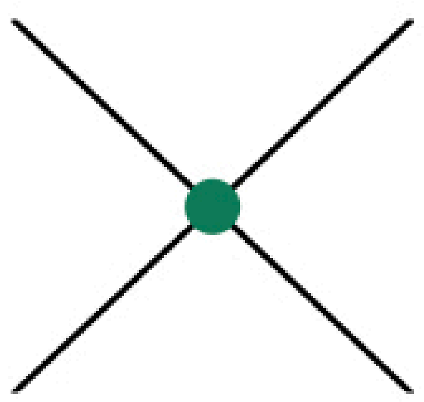


Positivity

[Pham & Troung; PRD 31 (1985 3027)]
[Anathanarayan et al.; PRD 51 (1995) 1093-1100]
[Adams et al.; JHEP 10 (2006) 014]

Can we bound EFT coefficients for theory alone?

- **Yes**, *e.g.*, partial wave unitarity in the EFT

$c_i \frac{s}{\Lambda^2}$ 

$$S^\dagger S = 1 \to i(T^\dagger - T) = T^\dagger T$$
$$M(s,\theta) = 16\pi \sum_\ell (2\ell + 1)\, a_\ell(s)\, P_\ell(\cos\theta)$$
$$\Rightarrow \quad \mathrm{Im}(a_i) < |a_i|^2, \quad c_i \frac{s}{\Lambda^2} < 16\pi$$

We can do more with some reasonable assumptions

- Causal, unitarity & local (yet unknown) UV
- Analytic properties of scattering amplitudes in complex s-plane

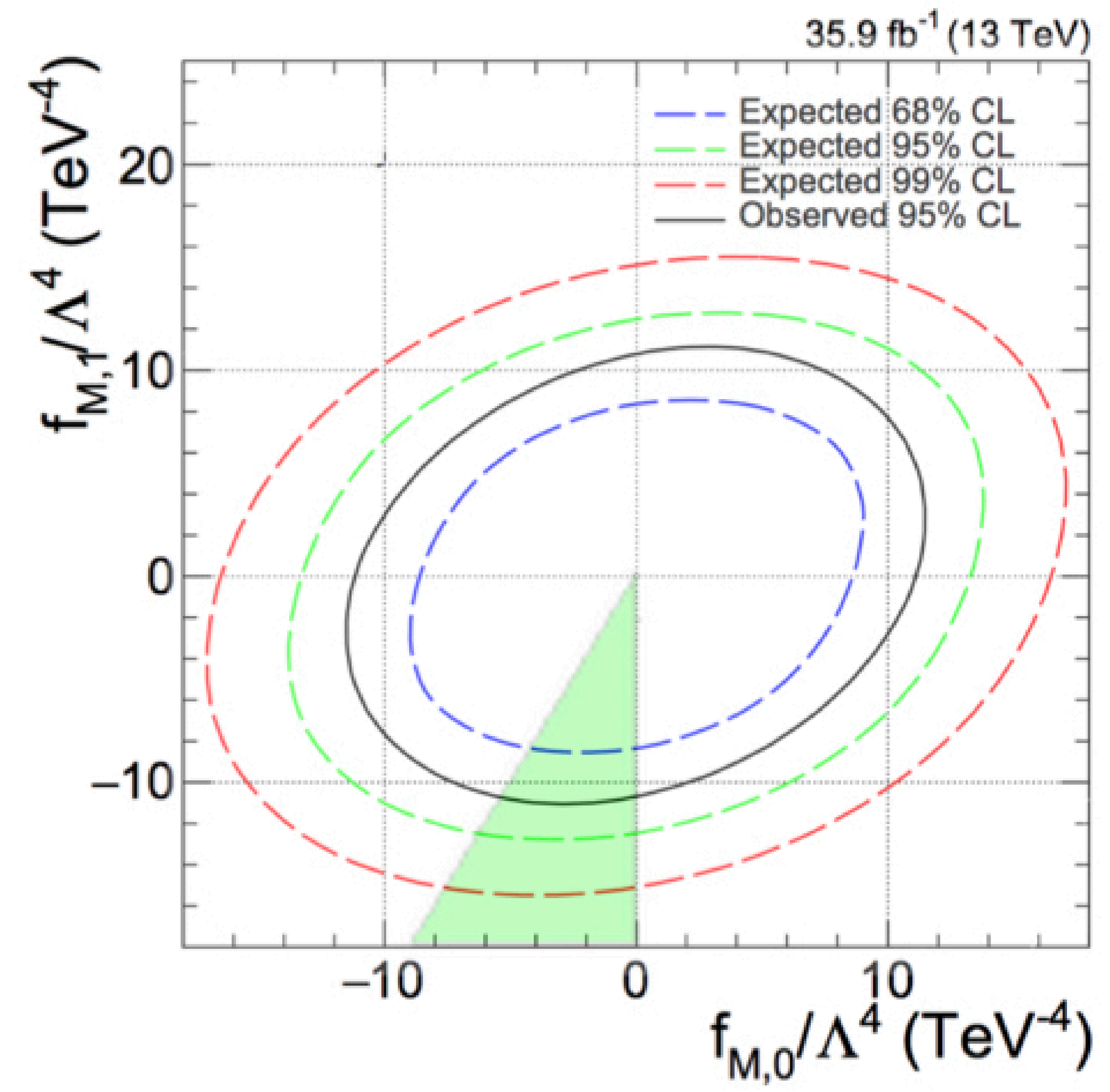
EFT (IR) $\quad \frac{1}{2}\frac{d^2 M(0)}{ds^2} = \int_{\Lambda^2}^{\infty} \frac{d\mu}{2\pi i \mu^3}\, \mathrm{Im}\left(M(\mu)\right) > 0 \quad$ UV $\quad \Rightarrow \quad \sum_i b_i C_i^{(8)} > 0$

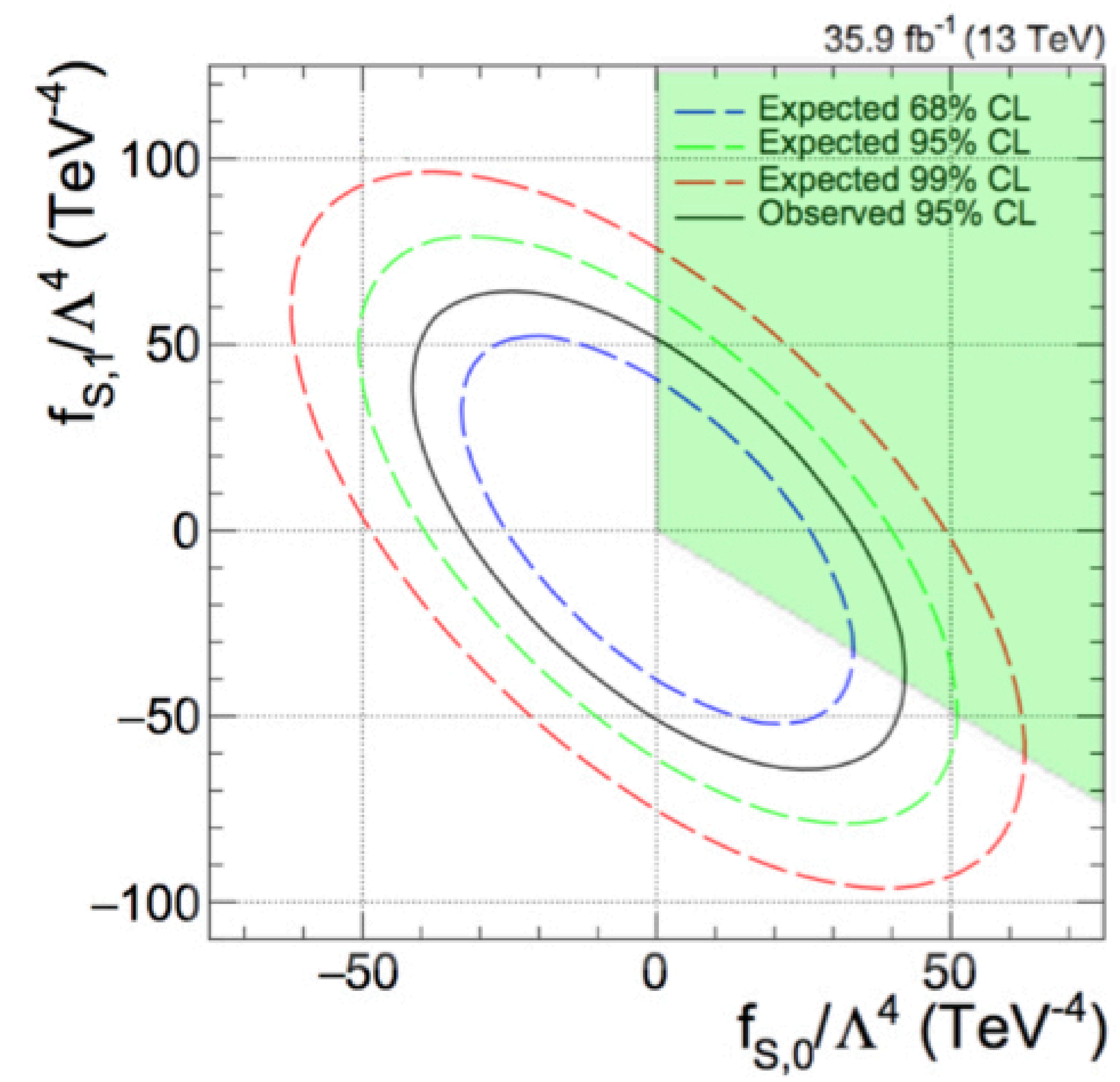
"theory prior" on EFT space **OR** testing QFT axioms of UV

Vector boson scattering

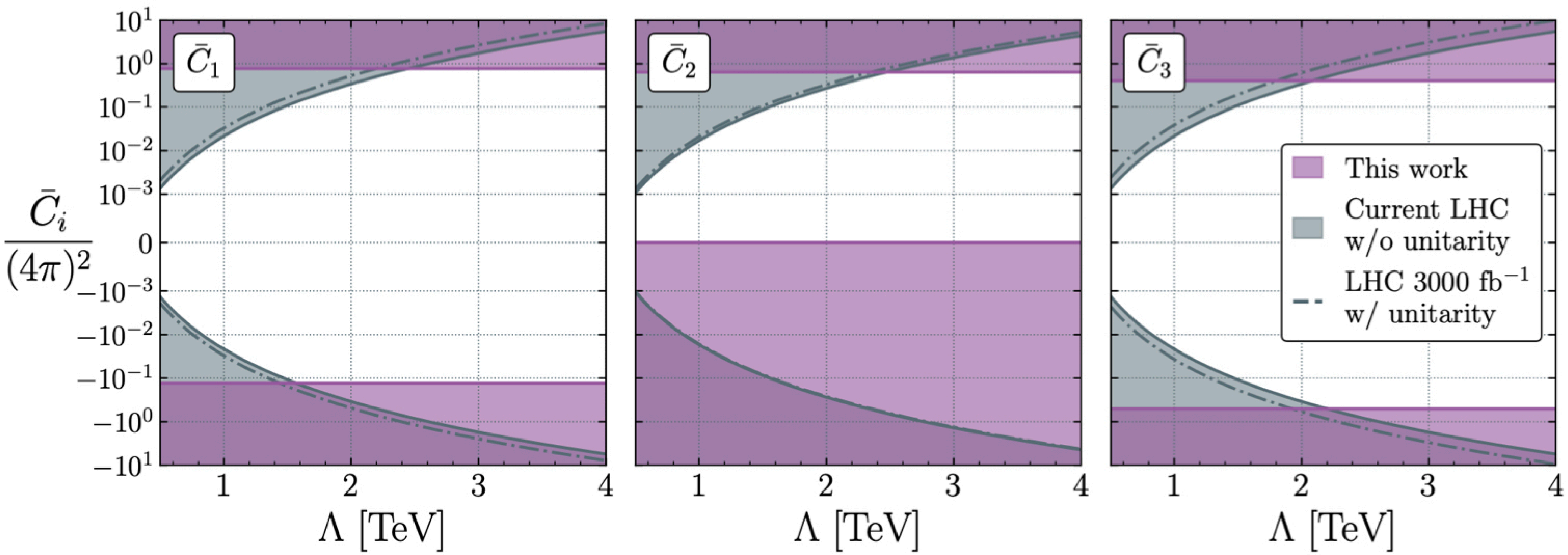
[Bi, Zhang, Zhou; JHEP 06 (2019) 137]

$$O_{S,0} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi]$$
$$O_{S,1} = [(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$$
$$O_{S,2} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\nu\Phi)^\dagger D^\mu\Phi]$$
$$O_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$O_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$





[Chen et al.; 2309.15922]



Positivity

>

EFT unitarity

Conclusion

EFT is a fantastic framework to search for new physics

- Model independent, precision calculations, global interpretations
- Crystallise our understanding of (B)SM interactions: LHC legacy

Provides pieces that could solve the Higgs-saw puzzle

Highly active field, both in exp. and th.

Many things I couldn't mention

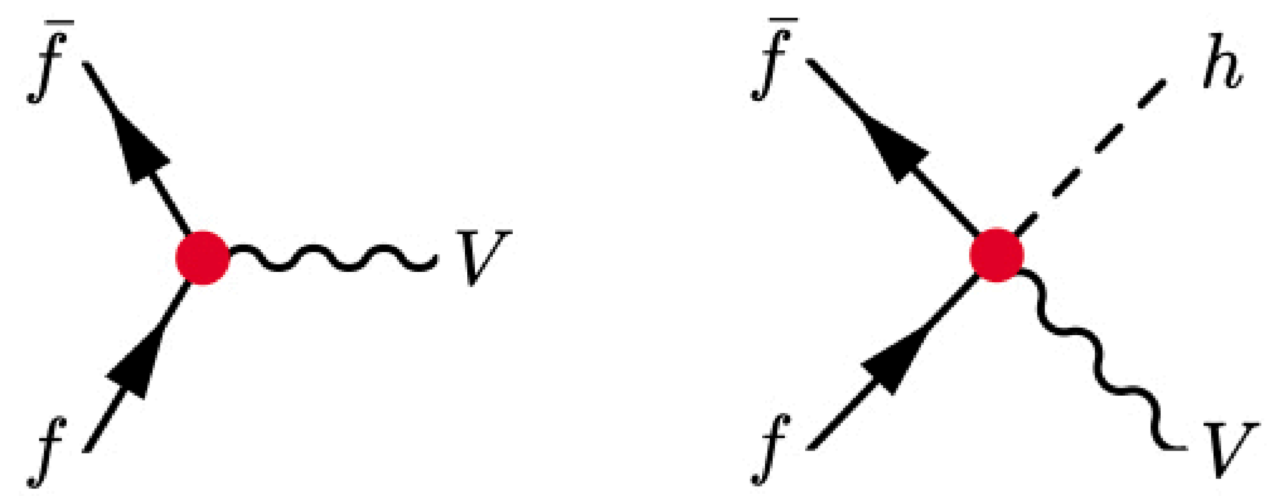
https://lpcc.web.cern.ch/lhc-eft-wg

- Automated matching tools
- EW corrections
- Connection with amplitudes
- Beyond dimension-6
- Distinguishing SMEFT & HEFT
- Models that must lead to HEFT

Backup

Operator glossary

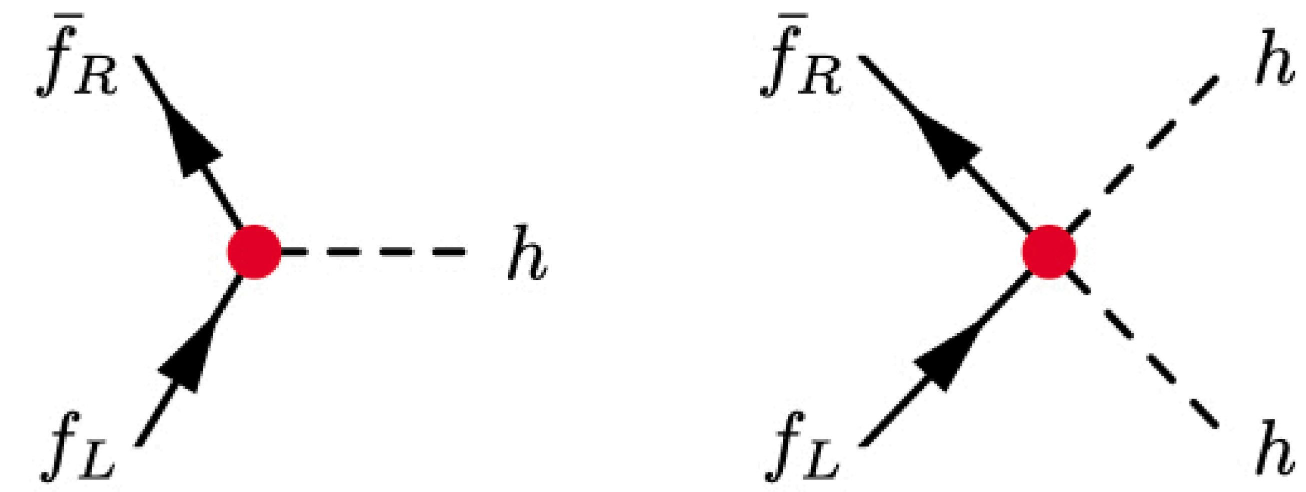
currents $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{f}\gamma^\mu f)$



$C_{\phi f}$

- Shift SM $f\bar{f}V$ couplings
- $f\bar{f}Vh$ contact interactions

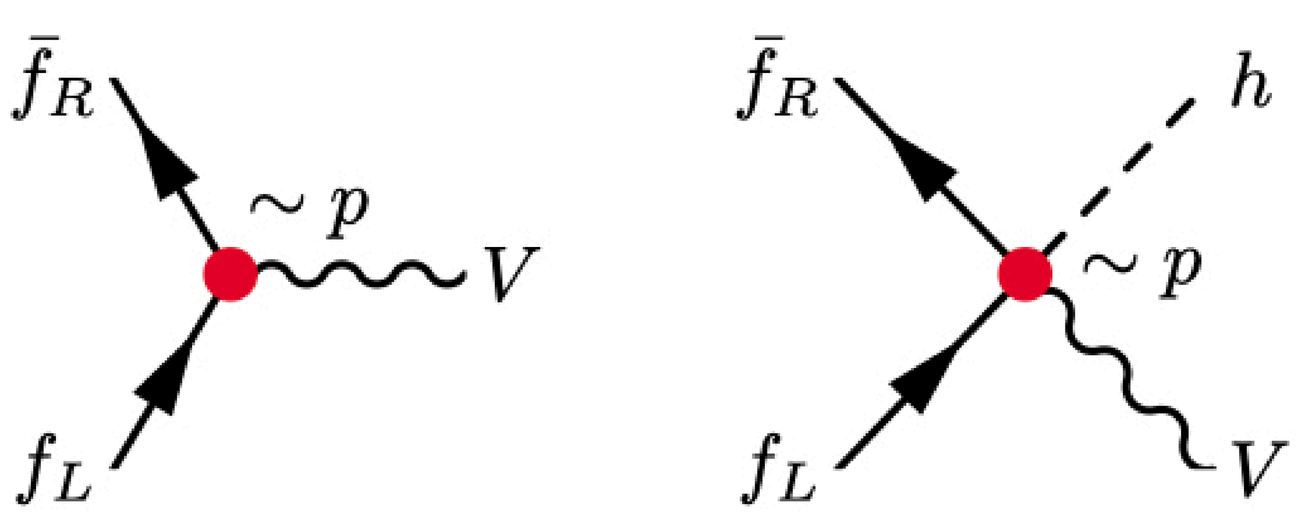
Yukawa $(\bar{q}\, t\, \tilde{\varphi})(\varphi^\dagger \varphi)$



$C_{t\phi}$

- Decouple m_t & y_t
- $t\bar{t}hh(h)$ contact interactions

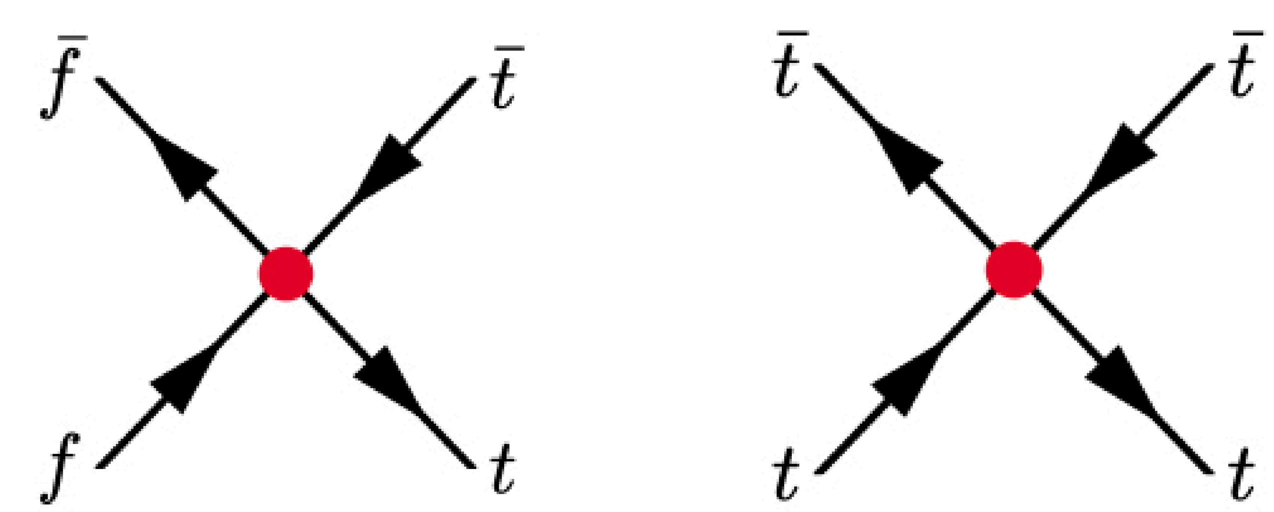
dipole $(\bar{q}\, \sigma_{\mu\nu}\, t\, \tilde{\varphi})V^{\mu\nu}$



C_{tV}

- Chirality flipping $f\bar{f}V$ couplings
- $f\bar{f}V(V)h$ contact interactions
- W, B & G fields

4 fermion $(\bar{q}\gamma_\mu q)(\bar{Q}\gamma^\mu Q)$



C_{ft}

- Contact interactions
- 2-heavy-2-light or 4-heavy
- Numerous (~O(20) w/ top)

The fit

`fitmaker` *https://gitlab.com/kenmimasu/fitrepo*

public-friendly version w/ example notebooks in progress

Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory

John Ellis,[a,b,c] Maeve Madigan,[d] Ken Mimasu,[a] Veronica Sanz[e,f] and Tevong You[b,d,g] *[JHEP 04 (2021) 279]*

Global SMEFT interpretation of 4 categories of data

Based on [Ellis et al.; JHEP 06 (2018) 146]

- 14 • Electroweak Precision Observables (EWPO): Z-pole & W-mass
- 118 • LEP2 & LHC diboson production: differential WW, WZ, Zjj
- 72 • Higgs measurements: signal strengths & STXS
- 137 • Top data: single-top, ttbar & asymmetries, ttV, tZ, tW

Big thanks to authors of SMEFiT analysis [JHEP 04 (2019) 100] for sharing some of their top predictions

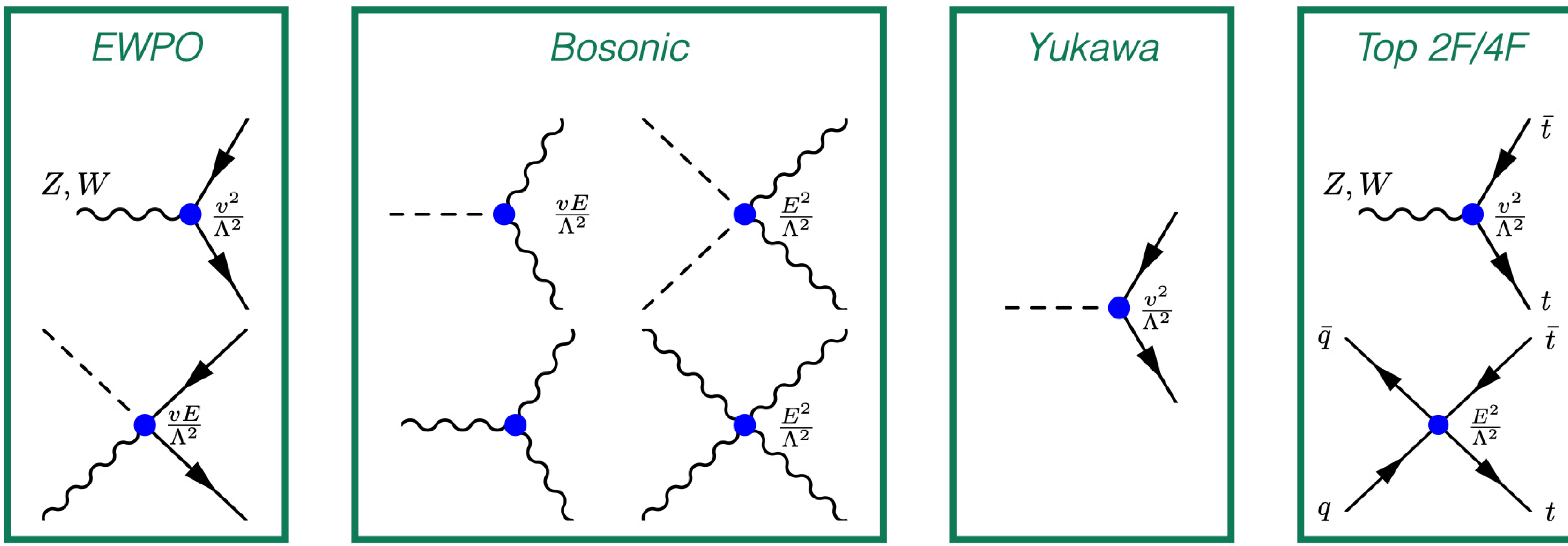
341 measurements across categories

- Chosen to be statistically independent & maximise reach
- Correlations included when publicly available (mostly are)

Linear EFT approximation: $$\mu_X \equiv \frac{X}{X_{SM}} = 1 + \sum_i a_i^X \frac{C_i}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

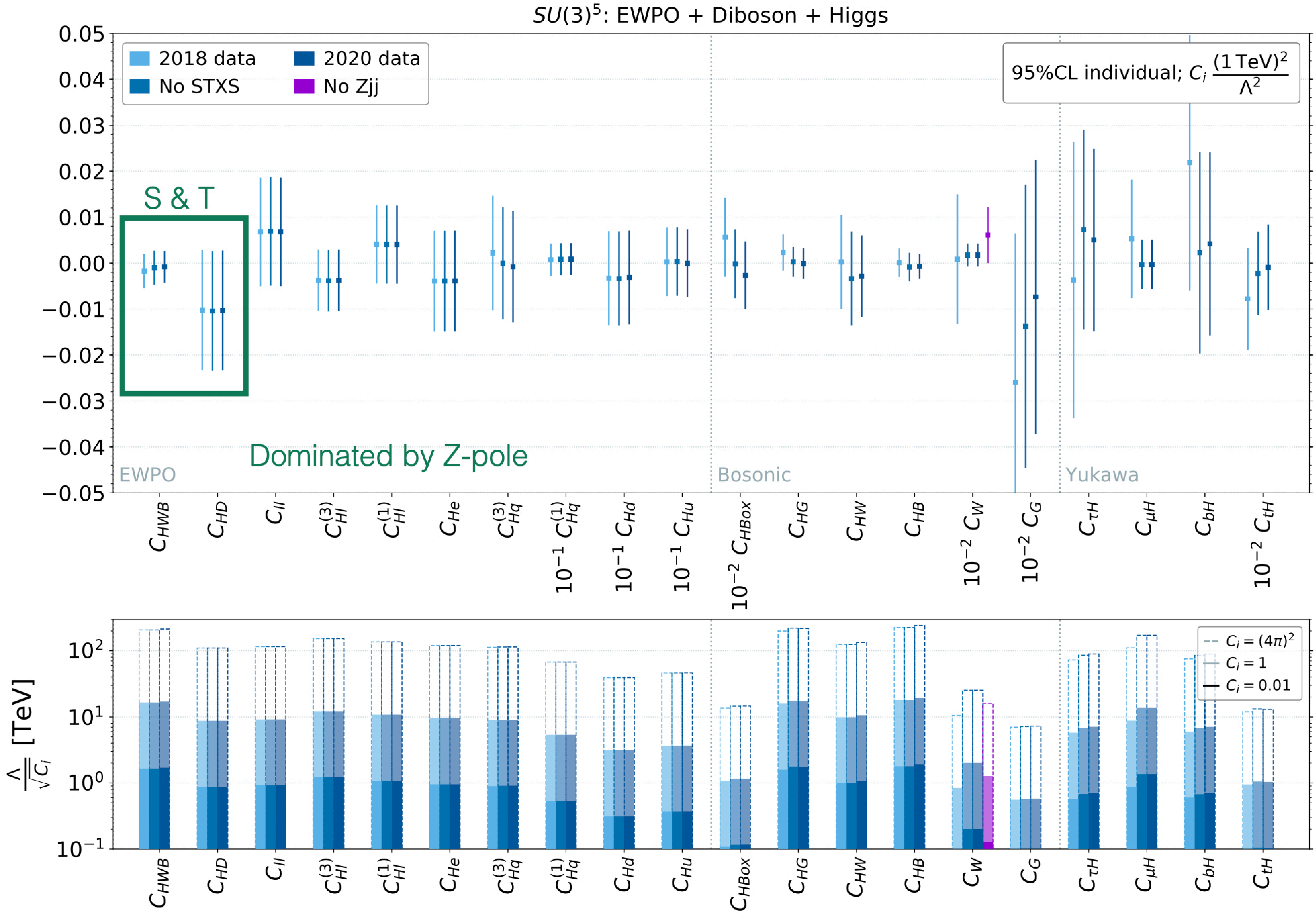
Degrees of freedom

EWPO:	$\mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$	
Bosonic:	$\mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$	
Yukawa:	$\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,,$	20
Top 2F:	$\mathcal{O}_{HQ}^{(3)}\,,\ \mathcal{O}_{HQ}^{(1)}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,$	
Top 4F:	$\mathcal{O}_{Qq}^{3,1}\,,\ \mathcal{O}_{Qq}^{3,8}\,,\ \mathcal{O}_{Qq}^{1,8}\,,\ \mathcal{O}_{Qu}^{8}\,,\ \mathcal{O}_{Qd}^{8}\,,\ \mathcal{O}_{tQ}^{8}\,,\ \mathcal{O}_{tu}^{8}\,,\ \mathcal{O}_{td}^{8}\,.$	+14



Individual limits: U(3)^5

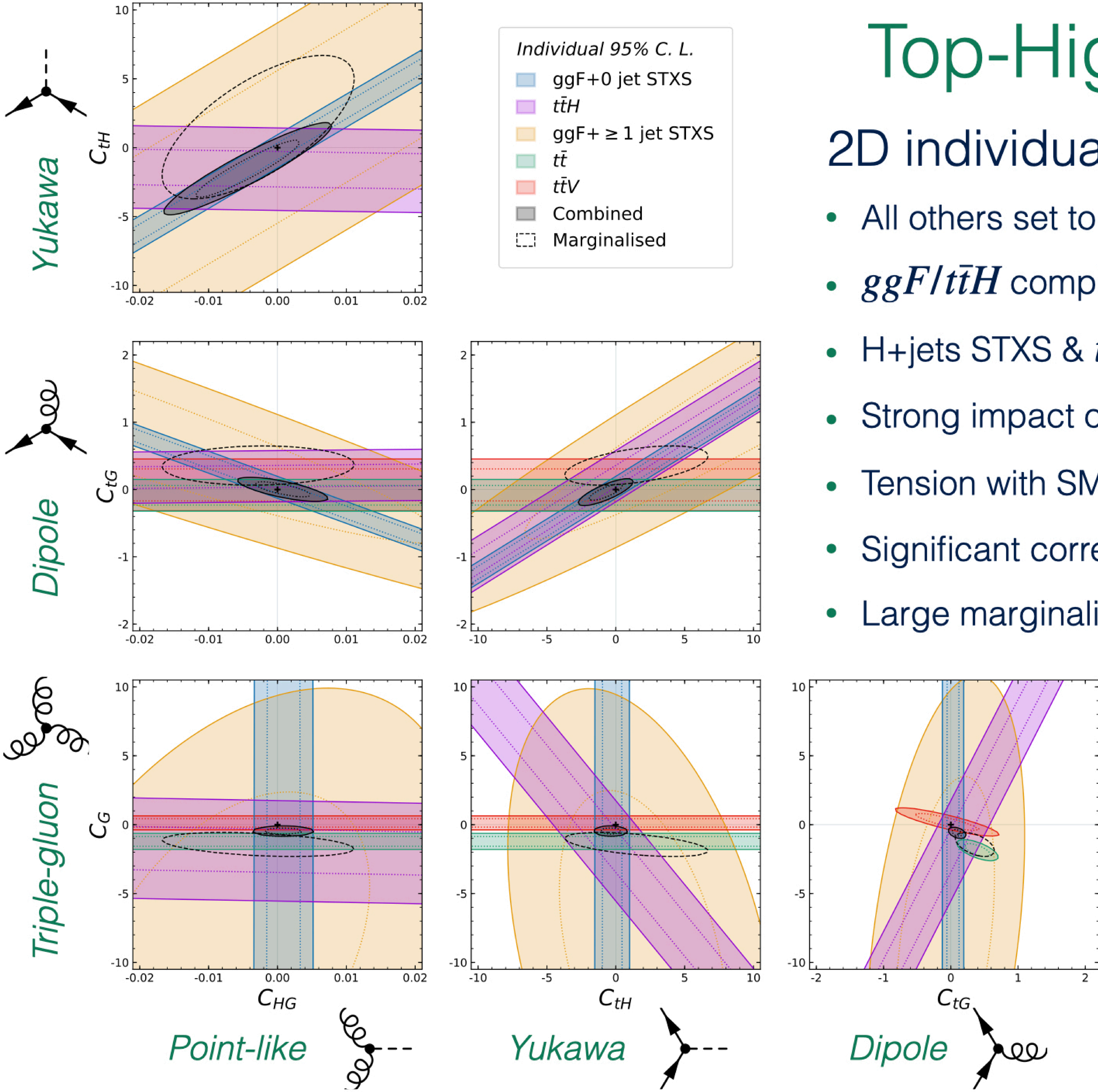
2018 data: [Ellis et al.; JHEP 06 (2018) 146]



Top-Higgs interplay

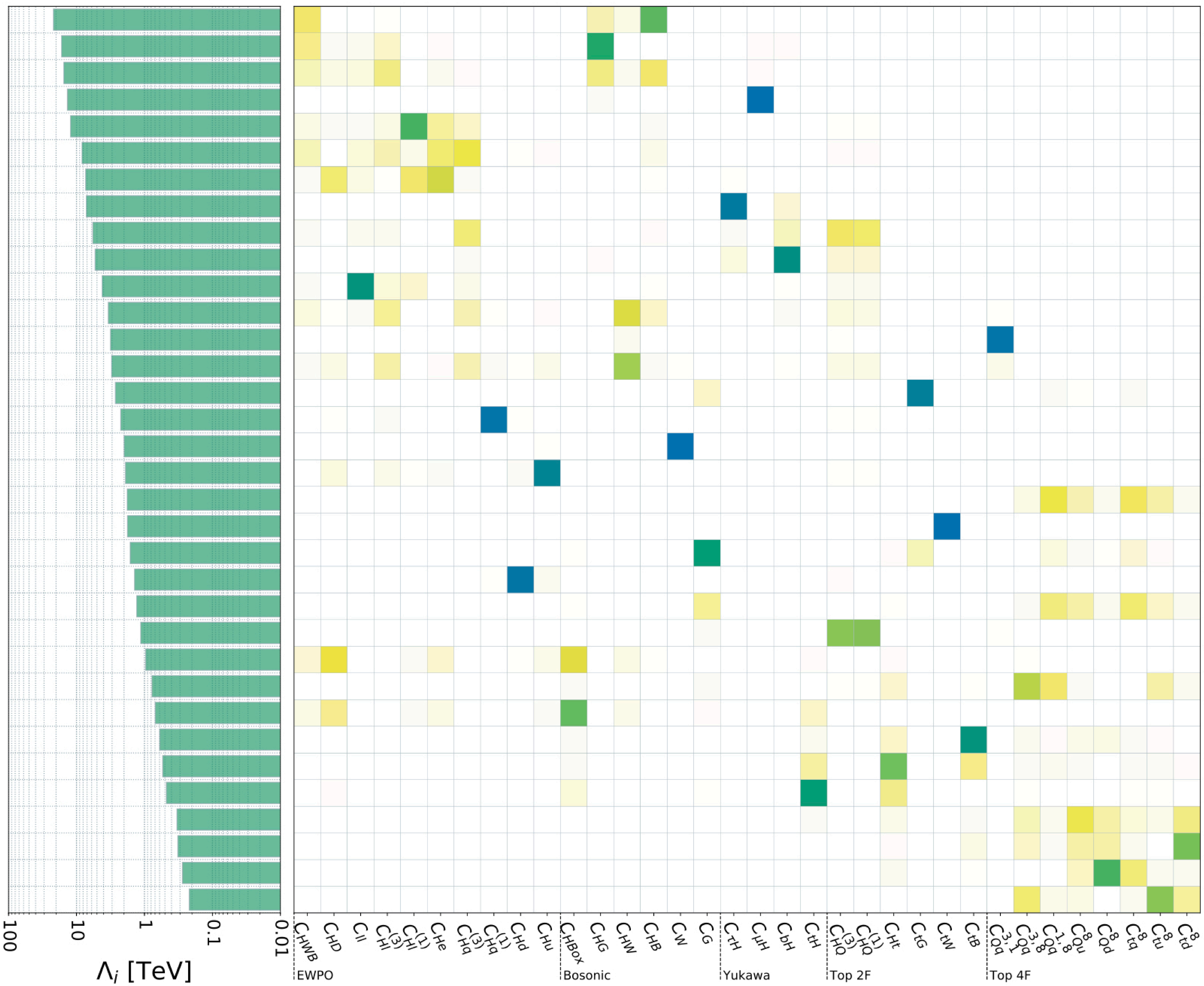
2D individual constraints

- All others set to 0
- $ggF/t\bar{t}H$ complementarity for (C_{HG}, C_{tH})
- H+jets STXS & $t\bar{t}V$ not yet competitive
- Strong impact of $t\bar{t}$ evident for (C_{tG}, C_G)
- Tension with SM $\sim 2\sigma$
- Significant correlations remain
- Large marginalisation effects



What is the concrete impact of 4F?

PCA



Relative constraining power (%)

EWPO	LEP WW	Run 1, μ_i	Run 2, μ_i	STXS	LHC WW	LHC Zjj	$t\bar{t}$	single top	$t\bar{t}V$
6	–	15	29	50	–	–	–	–	–
35	–	13	28	23	–	–	–	–	–
59	–	7	16	18	–	–	–	–	–
–	–	5	94	1	–	–	–	–	–
99	–	–	–	–	–	–	–	–	–
95	–	–	–	–	3	–	–	–	–
99	–	–	–	–	–	–	–	–	–
–	–	21	45	33	–	–	–	–	–
74	–	2	4	14	6	–	–	–	–
18	–	8	19	55	–	–	–	–	–
73	22	–	–	–	3	–	–	–	–
7	2	5	53	4	29	–	–	–	–
–	–	–	3	–	–	–	–	96	–
7	–	2	39	2	46	–	–	3	–
–	–	–	10	4	–	–	57	–	28
94	2	–	–	–	2	–	–	–	–
–	2	–	–	–	11	86	–	–	–
65	14	2	4	10	4	1	–	–	–
–	–	–	–	–	–	–	99	–	–
–	–	–	–	–	–	–	84	15	–
–	–	–	13	6	–	–	48	–	32
90	5	–	–	1	2	–	–	–	–
–	–	–	5	2	–	–	79	–	13
–	–	–	–	–	–	–	3	78	18
2	3	27	40	12	6	–	4	–	4
–	–	1	2	–	–	–	15	4	77
4	4	14	33	23	7	1	12	–	2
–	–	1	3	1	–	–	4	–	89
–	–	3	10	4	–	–	28	2	53
1	–	8	27	16	2	–	32	–	12
–	–	–	–	–	–	–	58	–	41
–	–	–	–	–	–	–	90	–	10
–	–	–	–	–	–	–	61	–	38
–	–	–	–	–	–	–	95	–	5

One parameter models

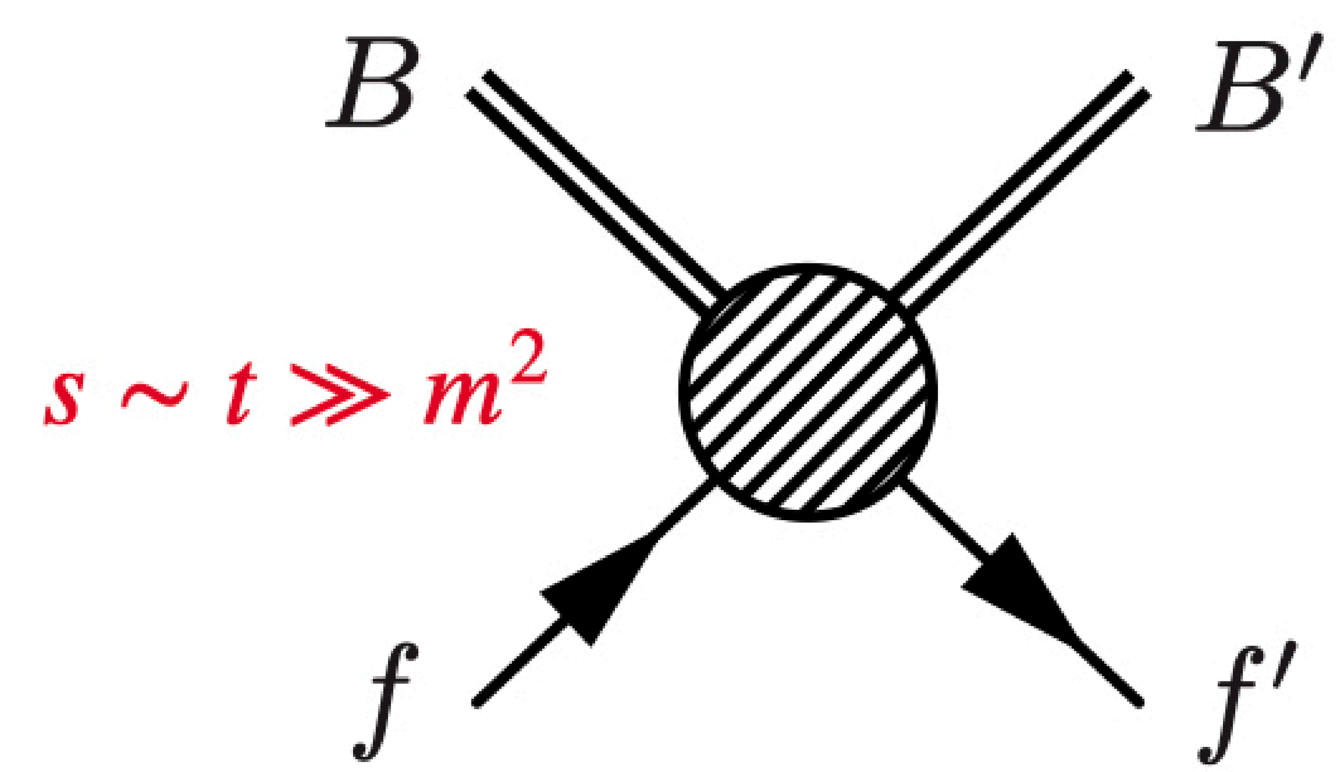
Model	C_{HD}	C_{ll}	C_{Hl}^3	C_{Hl}^1	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						$-\frac{1}{2}$			
S_1		1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$						$-\frac{3}{2}$	$-\ y_\tau$	$-\ y_t$	$-\ y_b$
$\{Q_1, Q_7\}$								y_t	

Model	C_{Hq}^3	C_{Hq}^1	$(C_{Hq}^3)_{33}$	$(C_{Hq}^1)_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}	
U	$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$		
D	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$	
Q_5						$-\frac{1}{2}$		$\frac{y_b}{2}$	
Q_7					$\frac{1}{2}$		$\frac{y_t}{2}$		
T_1	$-\frac{1}{16}$	$-\frac{3}{16}$	$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$	
T_2	$-\frac{1}{16}$	$\frac{3}{16}$	$-\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$	
T			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t \frac{M_T^2}{v^2}$		

$$\times \frac{\lambda^2}{M^2}$$

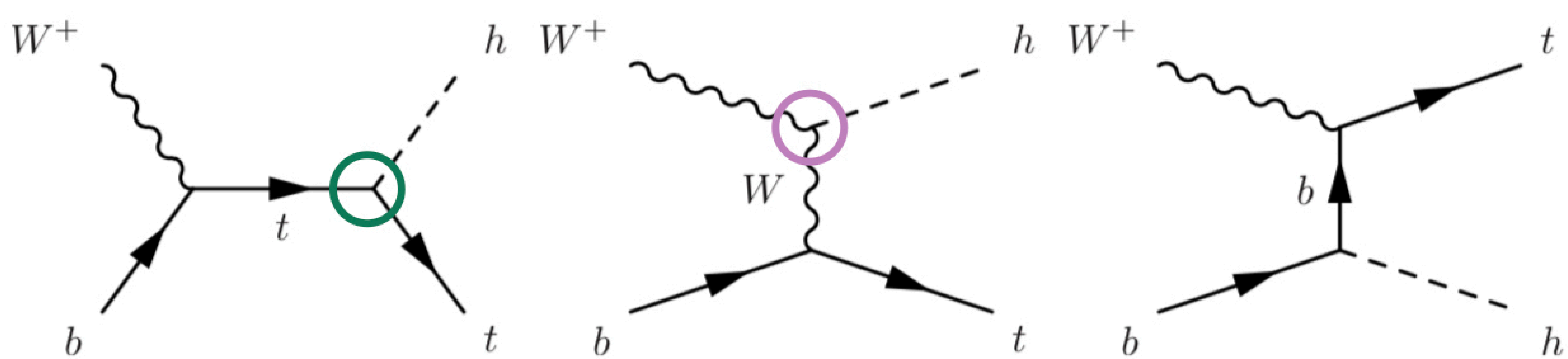
[Dror et al.; JHEP 01 (2016) 071]
[Mantani, Maltoni & KM; JHEP 10 (2019) 004]

EW top scattering



	Single-top	Two-top ($t\bar{t}$)
w/o Higgs	$b\,W \to t\,(Z/\gamma)$	$t\,W \to t\,W$ $t\,(Z/\gamma) \to t\,(Z/\gamma)$
w/ Higgs	$b\,W \to t\,h$	$t\,(Z/\gamma) \to t\,h$ $t\,h \to t\,h$

$2 \to 2$ *top EW scattering amplitudes in high energy limit:*
study of unitarity violating behaviour & helicity structure in dimension-6 SMEFT



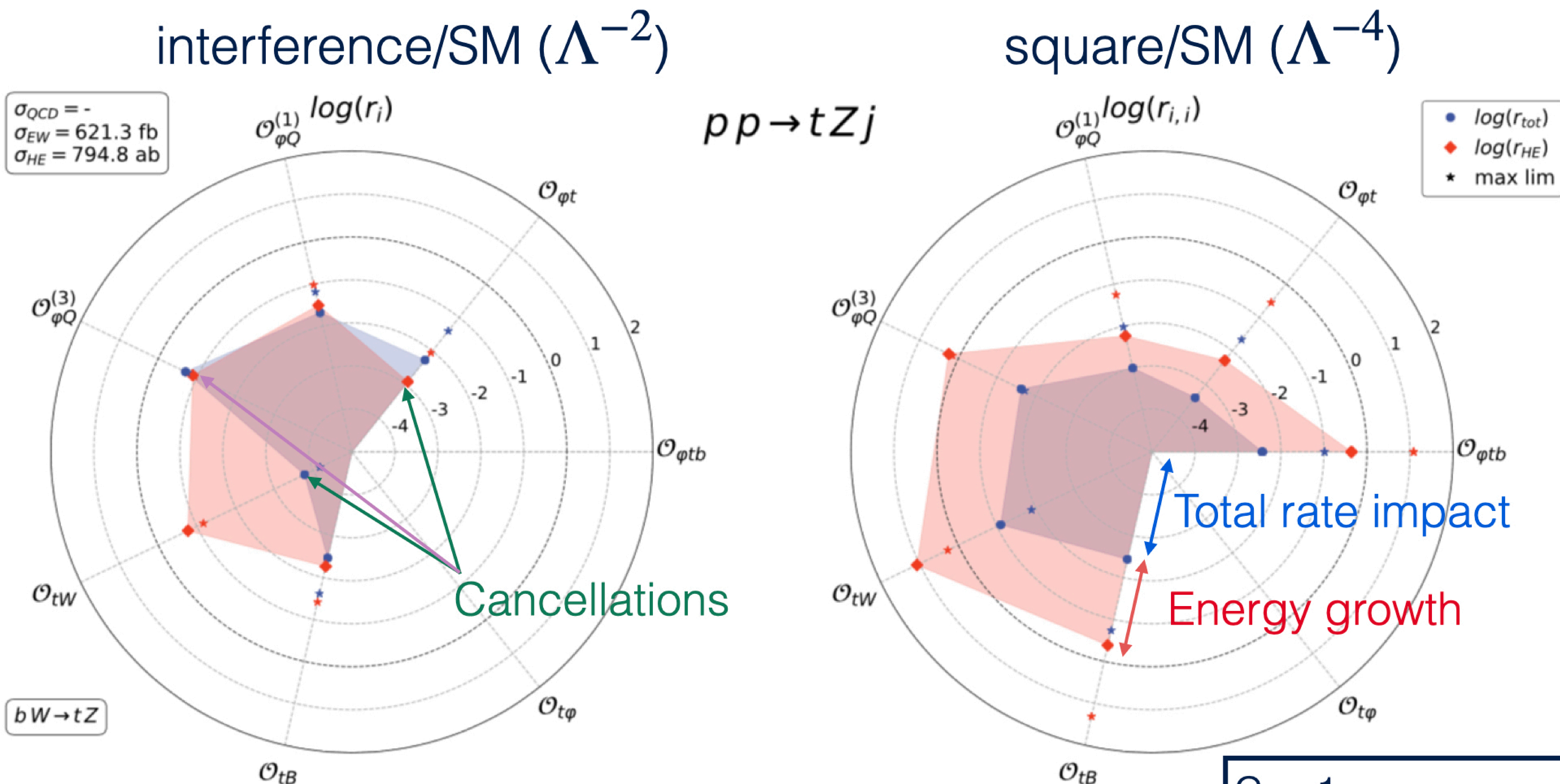
$$\mathcal{A}(b_L, W_L, t_R) \propto \sqrt{-t}(2m_W^2 \boxed{g_{th}} - \boxed{g_{Wh}} m_t)$$

e.g. $bW \to th$ SMEFT $\Rightarrow$

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	s^0	s^0	–	s^0	s^0	$\boxed{\sqrt{s(s+t)}}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	–	–	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+, 0, -$	–	–	$\sqrt{-t}m_t$	–	–	–
$+, 0, +$	–	–	$\sqrt{s(s+t)}$	–	–	–

Where is max-growth?
Behaviour of interference?

tZ radar plot



Expected growth from 2→2 absent!

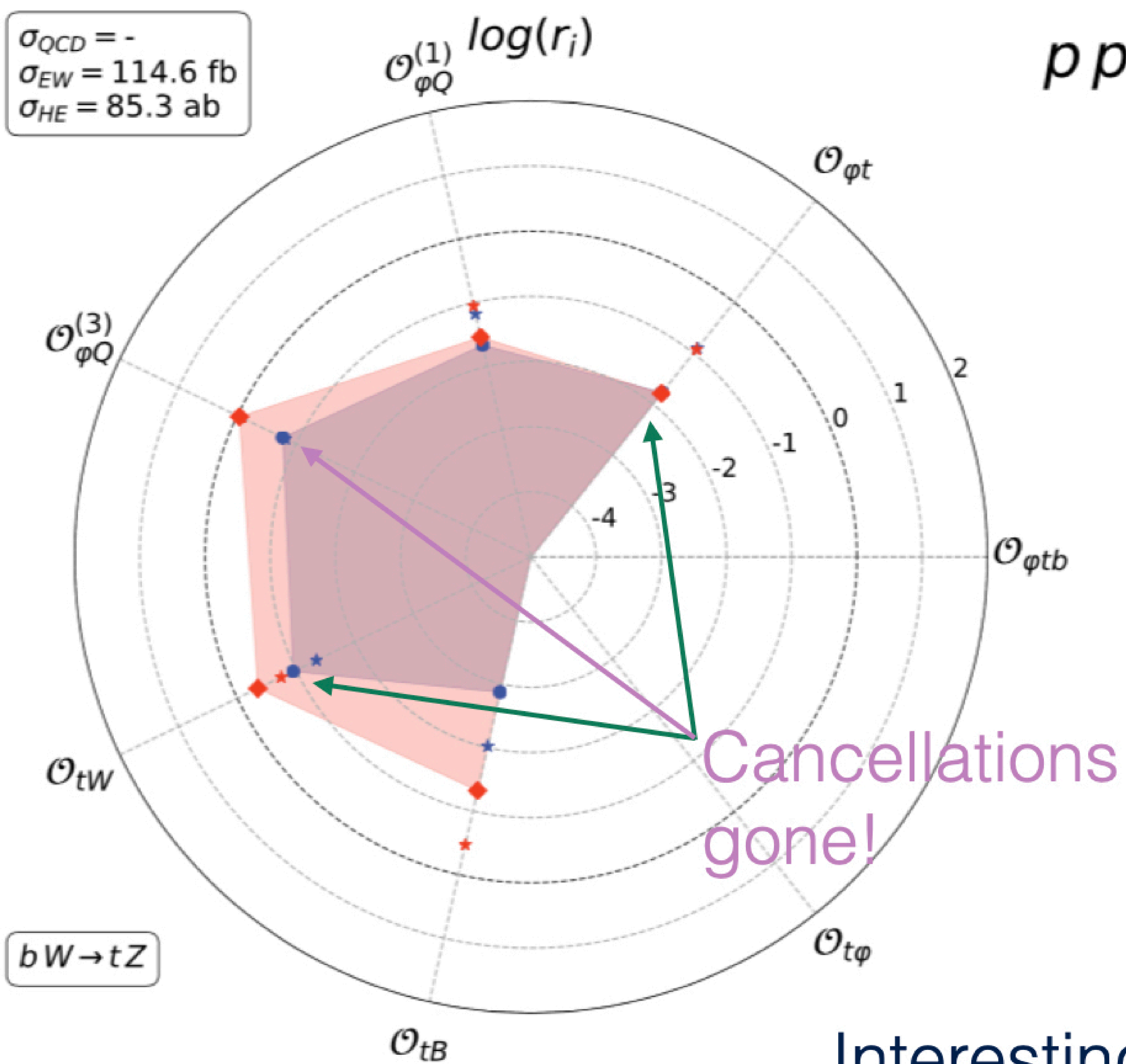
C_i = 1
Inclusive
p_T (Z)> 500 GeV

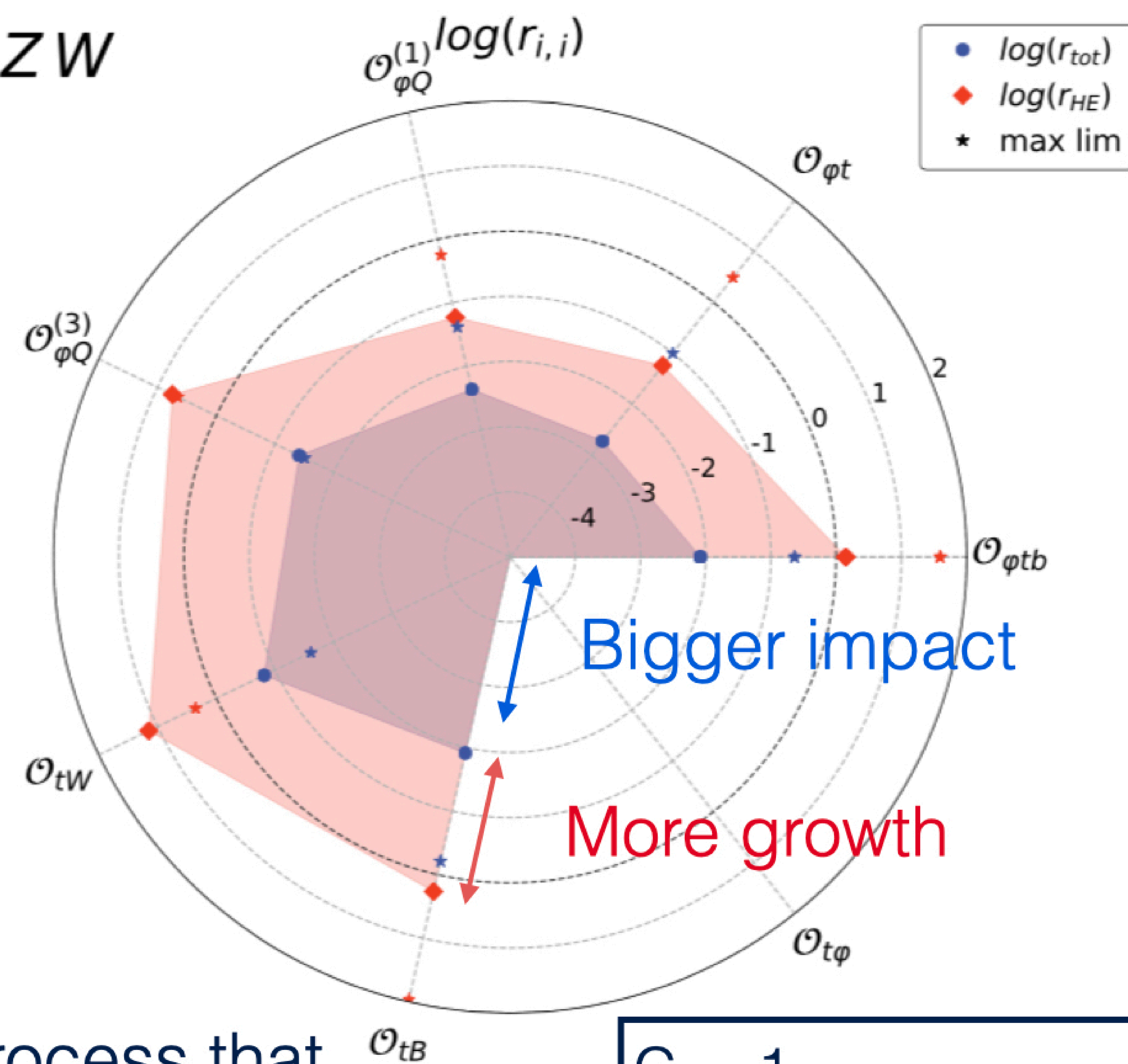
tZW radar plot

interference/SM

square/SM

$pp \to tZW$





Expected growth is there!

Interesting process that should be accessible at the LHC

$C_i = 1$
Inclusive
p_T (W,Z)> 500 GeV

Positivity for dim-8

Set of theoretical constraints on scattering amplitudes

- Apply to a subset of $D \geq 8$ Wilson coefficients

Result from basic assumptions about UV QFT/S-matrix

- Lorentz invariance, unitarity, causality & locality
  [Pham & Troung; PRD 31 (1985 3027)]
  [Anathanarayan et al.; PRD 51 (1995) 1093-1100]
  [Adams et al.; JHEP 10 (2006) 014]

+ many more in recent years…

A. Generalised optical theorem for scattering amplitude $\mathscr{M}_{ij\to kl}$

B. Twice subtracted, forward dispersion relation by analytic continuation in complex s: $M_{ijkl}(s, t = 0)$ $\quad M_{ijkl} \equiv \mathscr{M}_{ij\to kl} - \text{(low energy poles)}$

$$\boxed{\frac{1}{2}\frac{d^2 M_{ijkl}(0)}{ds^2} = \sum_X \int d\Pi_X \int_{\Lambda^2}^{\infty} \frac{d\mu}{2\pi i \mu^3}\left(m_{ij}m^*_{kl} + m_{i\tilde{l}}m^*_{k\tilde{j}}\right) \qquad m_{ij} \equiv M_{ij\to X}(\mu)}$$

Positivity for dim-8

$$\boxed{\frac{1}{2}\frac{d^2 M_{ijkl}(0)}{ds^2} = \sum_X \int d\Pi_X \int_{\Lambda^2}^{\infty} \frac{d\mu}{2\pi\mu^3}\left(m_{ij}m^*_{kl} + m_{i\tilde{l}}m^*_{k\tilde{j}}\right) \qquad m_{ij} \equiv M_{ij\to X}(\mu)}$$

$2 \to n$ amplitudes m_{ij} are unknown complex functions of μ

- Encode masses of new states at & above Λ^2

Elastic ($ij = kl$): $$\frac{1}{2}\frac{d^2 M_{ijkl}(0)}{ds^2} = \sum_X \int d\Pi_X \int_{\Lambda^2}^{\infty} \frac{d\mu}{2\pi\mu^3}\left(|m_{ij}|^2 + |m_{i\tilde{j}}|^2\right) \geq 0$$

Need at least $M_{ijkl}(s, t = 0) \sim s^2 \Rightarrow$ dimension-8

Independent & complimentary to unitarity bounds

- Can be combined with experimental data to improve sensitivity
- Or can be tested by data to probe underlying assumptions about QFT