

Precise SMEFT predictions

Eleni Vryonidou
University of Manchester

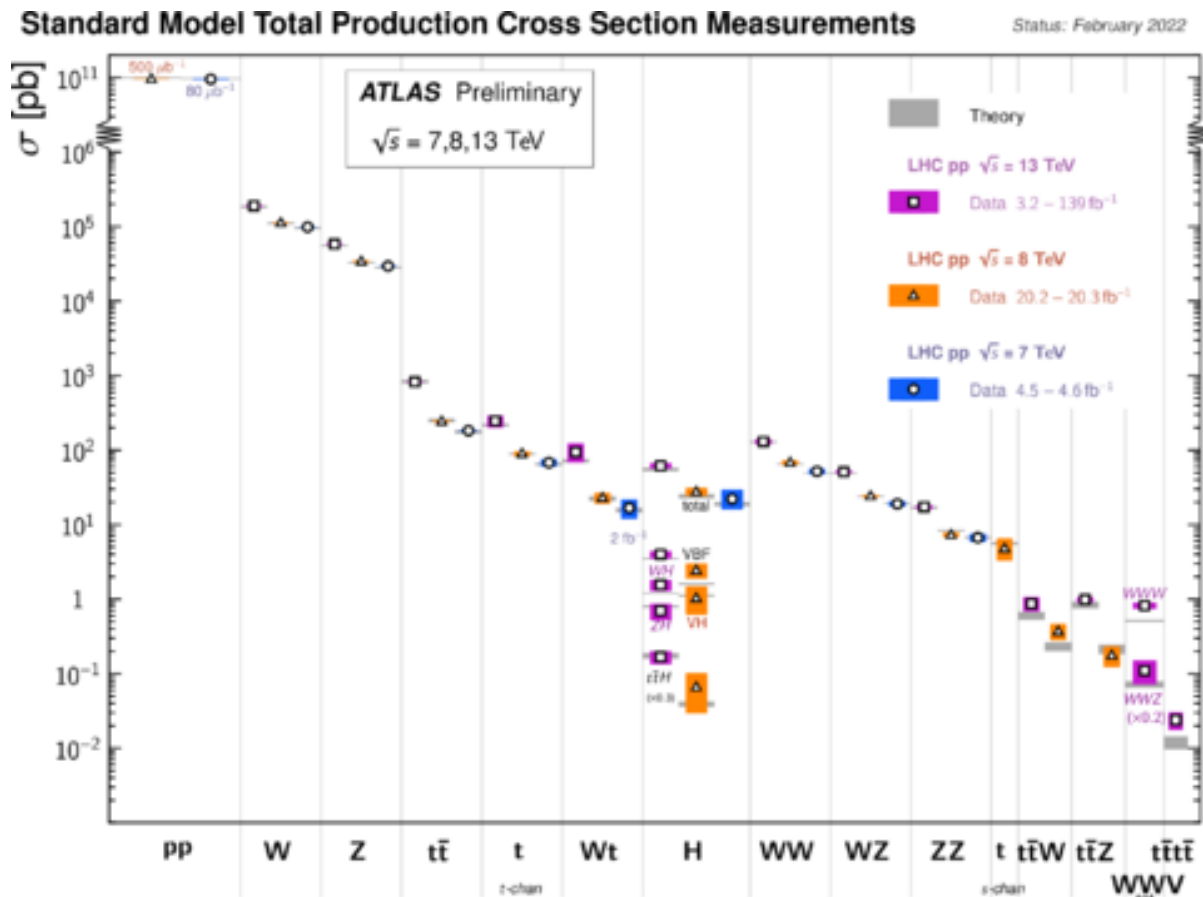


Moriond EW
24/3/2023

LHC: the story so far

Rediscovering the SM

Searching for the unknown



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits
Status: July 2022

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$
 $\sqrt{s} = 8, 13$ TeV

Model	ℓ, γ	Jets †	E^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference		
Extra dimensions	ADD $G_{KK} + g/q$	$0, e, \mu, \tau, \gamma$	$1-4j$	Yes	139	M_0 11.2 TeV, $n=2$	2102.10874	
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_2 8.6 TeV, $n=3$ HLZ NLO	1707.04147	
	ADD QBH	-	$2j$	-	139	M_{BH} 9.4 TeV, $n=6$	1910.08447	
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{BH} 9.55 TeV, $n=6, M_0 = 3 \text{ TeV, rot BH}$	1512.02586	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	k/M_{Pl} 0.1	2102.13405	
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV, $k/M_{\text{Pl}} = 1.0$	1808.02380	
Gauge bosons	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu q\bar{q}$	$1, e, \mu$	$2j/1J$	Yes	139	G_{KK} mass 2.0 TeV, $k/M_{\text{Pl}} = 1.0$	2004.14636	
	Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1, e, \mu$	$\geq 1b, \geq 1J/2j$	Yes	36.1	G_{KK} mass 3.8 TeV, $\Gamma/m = 15\%$	1804.10823	
	ZUED / RPP	$1, e, \mu$	$\geq 2b, \geq 3j$	Yes	36.1	KK mass 1.8 TeV, Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow t\bar{t}) = 1$	1803.09678	
	SSM $Z' \rightarrow \ell\ell$	$2, e, \mu$	-	-	139	Z' mass 5.1 TeV	1903.06248	
	SSM $Z' \rightarrow \tau\tau$	$2, \tau$	-	-	36.1	Z' mass 2.42 TeV	1709.07242	
	Leptophobic $Z' \rightarrow b\bar{b}$	-	$2b$	-	36.1	Z' mass 2.1 TeV	1805.09299	
	Leptophobic $Z' \rightarrow t\bar{t}$	$0, e, \mu$	$\geq 1b, \geq 2J$	Yes	139	Z' mass 4.1 TeV, $\Gamma/m = 1.2\%$	2005.05138	
	SSM $W' \rightarrow \ell\nu$	$1, e, \mu$	-	-	139	W' mass 6.0 TeV	1906.05609	
	SSM $W' \rightarrow \tau\nu$	$1, \tau$	-	-	139	W' mass 5.0 TeV	ATLAS-CONF-2021-025	
	SSM $W' \rightarrow t\bar{b}$	-	$\geq 1b, \geq 1J$	-	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043	
	HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B	$1, e, \mu$	$2j/1J$	Yes	139	W' mass 4.3 TeV	2004.14636	
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C	$3, e, \mu$	$2j$ (VBF)	Yes	139	W' mass 340 GeV	ATLAS-CONF-2022-005	
HVT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$ model B	$1, e, \mu$	$1, 2b, 1, 0j$	Yes	139	W' mass 3.3 TeV	2207.00230		
HVT $Z' \rightarrow ZH \rightarrow \ell\ell\nu\nu b\bar{b}$ model B	$0, 2, e, \mu$	$1, 2b, 1, 0j$	Yes	139	Z' mass 3.2 TeV	2207.00230		
LRSM $W_R \rightarrow \mu N_R$	$2, \mu$	$1, J$	-	80	W_R mass 5.0 TeV	1904.12679		
CI	CI $q\bar{q}q\bar{q}$	$2, e, \mu$	$2j$	-	37.0	A 21.8 TeV, η_{LL}	1703.09127	
	CI $\ell\ell q\bar{q}$	$2, e, \mu$	$1b$	-	139	A 35.8 TeV, η_{LL}	2006.12946	
	CI $e\bar{e}b\bar{b}$	$2, e$	$1b$	-	139	A 1.8 TeV, $g_s = 1$	2105.13847	
	CI $\mu\bar{\mu}b\bar{b}$	$2, \mu$	$1b$	-	139	A 2.0 TeV, $g_s = 1$	2105.13847	
CI $t\bar{t}t\bar{t}$	$\geq 1, e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	A 2.57 TeV, $ C_{t1} = 4\pi$	1811.02305		
DM	Axial-vector med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	$1-4j$	Yes	139	\tilde{m}_{mod} 2.1 TeV	2102.10874	
	Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	$1-4j$	Yes	139	\tilde{m}_{mod} 376 GeV	2102.10874	
	Vector med. Z' -2HDM (Dirac DM)	$0, e, \mu$	$2b$	Yes	139	\tilde{m}_{mod} 3.1 TeV	2108.13391	
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	\tilde{m}_{mod} 560 GeV	ATLAS-CONF-2021-036	
LQ	Scalar LQ 1 st gen	$2, e$	$\geq 2j$	Yes	139	LQ mass 1.8 TeV	2006.05872	
	Scalar LQ 2 nd gen	$2, \mu$	$\geq 2j$	Yes	139	LQ mass 1.7 TeV	2006.05872	
	Scalar LQ 3 rd gen	$1, \tau$	$2b$	Yes	139	LQ ₂ mass 1.2 TeV	2108.07665	
	Scalar LQ 3 rd gen	$0, e, \mu$	$\geq 2j, \geq 2b$	Yes	139	LQ ₂ mass 1.24 TeV	2004.14060	
	Scalar LQ 3 rd gen	$\geq 2, e, \mu, \geq 1, \tau, \geq 1, b$	-	-	139	LQ ₂ mass 1.43 TeV	2101.11582	
	Scalar LQ 3 rd gen	$0, e, \mu, \geq 1, \tau, 0-2j, 2b$	Yes	139	LQ ₂ mass 1.26 TeV	$\mathcal{B}(LQ_2^+ \rightarrow \nu\tau) = 1$	2101.12527	
Vector-like fermions	Vector LQ 3 rd gen	$1, \tau$	$2b$	Yes	139	LQ ₂ mass 1.77 TeV	$\mathcal{B}(LQ_2^+ \rightarrow \nu\tau) = 1$	
	VLO $T\bar{T} \rightarrow Zt + X$	$2e/2\mu/23e, \mu$	$\geq 1b, \geq 1j$	-	139	T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLO $B\bar{B} \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLO $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS)/\geq 3, e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	1807.11883
	VLO $T \rightarrow Ht/Zt$	$1, e, \mu$	$\geq 1b, \geq 3j$	Yes	139	T mass 1.8 TeV	SU(2) singlet, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
	VLO $Y \rightarrow Wb$	$1, e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_B(Wb) = 1$	1812.07343
Excited fermions	VLO $B \rightarrow Hb$	$0, e, \mu$	$\geq 2b, \geq 1j$	Yes	139	B mass 2.0 TeV	SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-019
	VLO $\tau \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1j$	Yes	139	τ' mass 898 GeV	SU(2) doublet	ATLAS-CONF-2022-044
	Excited quark $q^* \rightarrow qg$	-	$2j$	-	139	q^* mass 6.7 TeV	only u^* and d^* , $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \rightarrow q\gamma$	$1, \gamma$	$1j$	-	36.7	q^* mass 5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$	1709.10440
Other	Excited quark $b^* \rightarrow b\gamma$	-	$1b, 1j$	-	139	b^* mass 3.2 TeV	1910.04447	
	Excited lepton ℓ^*	$3, e, \mu$	-	-	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$	1411.2921
	Excited lepton ν^*	$3, e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$	1411.2921
	Type III Seesaw	$2, 3, 4, e, \mu$	$\geq 2j$	Yes	139	N^0 mass 910 GeV	$m(W_0) = 4.1 \text{ TeV}, g_L = g_R$	2202.02039
	LRSM Majorana ν	$2, \mu$	$2j$	-	36.1	N_{μ} mass 3.2 TeV	DY production	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2, 3, 4, e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4, e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010	
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3, e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921	
Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV	DY production, $ g = 5e$	ATLAS-CONF-2022-034	
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	DY production, $ g = 1/2g_p, \text{spin } 1/2$	1905.10130	

*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter j (J).

Good agreement with the SM predictions
No evidence of new light particles

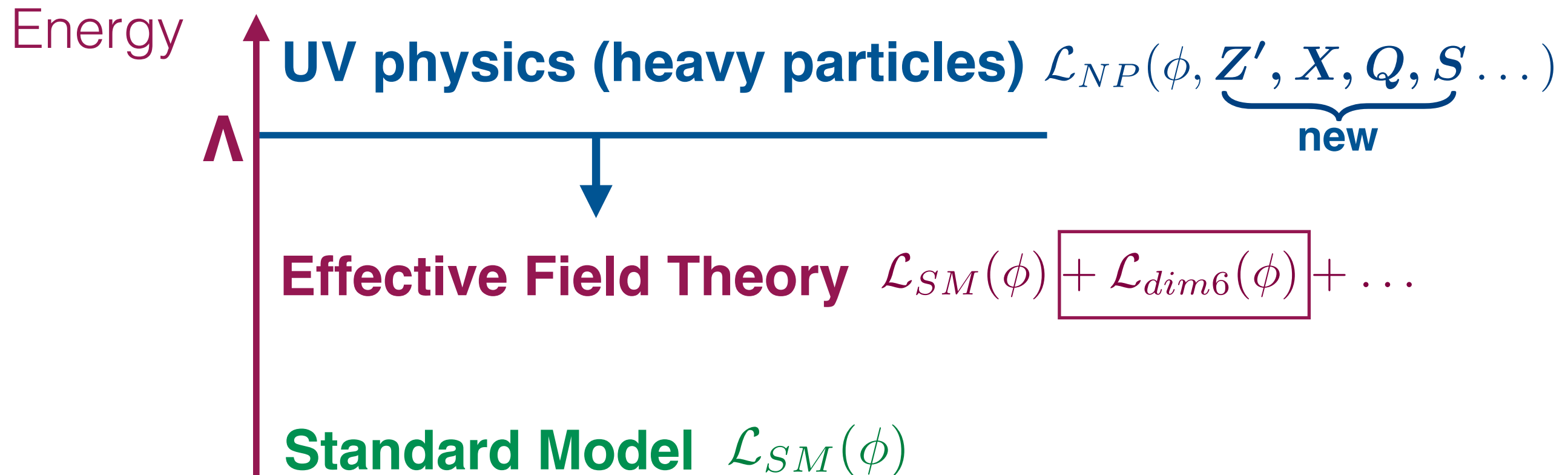
Where is New Physics?

There is a good chance that New Physics is Heavy

 Not enough energy to produce it

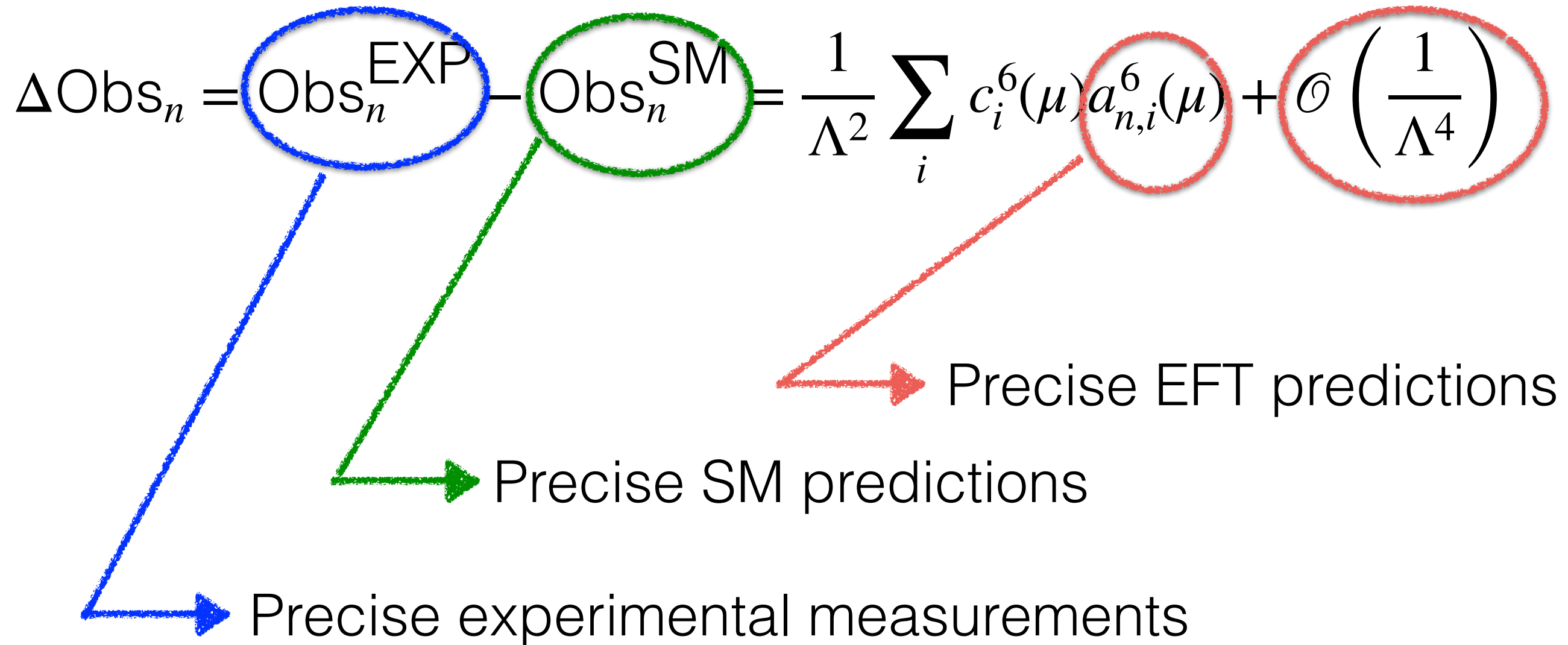
Indirect searches are needed  **SMEFT opens new directions**

Effective Field Theory



Effective Field Theory reveals high energy physics through precise measurements at low energy.

EFT pathway to New Physics



EFT pathway to New Physics

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2} \sum_i c_i^6(\mu) a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

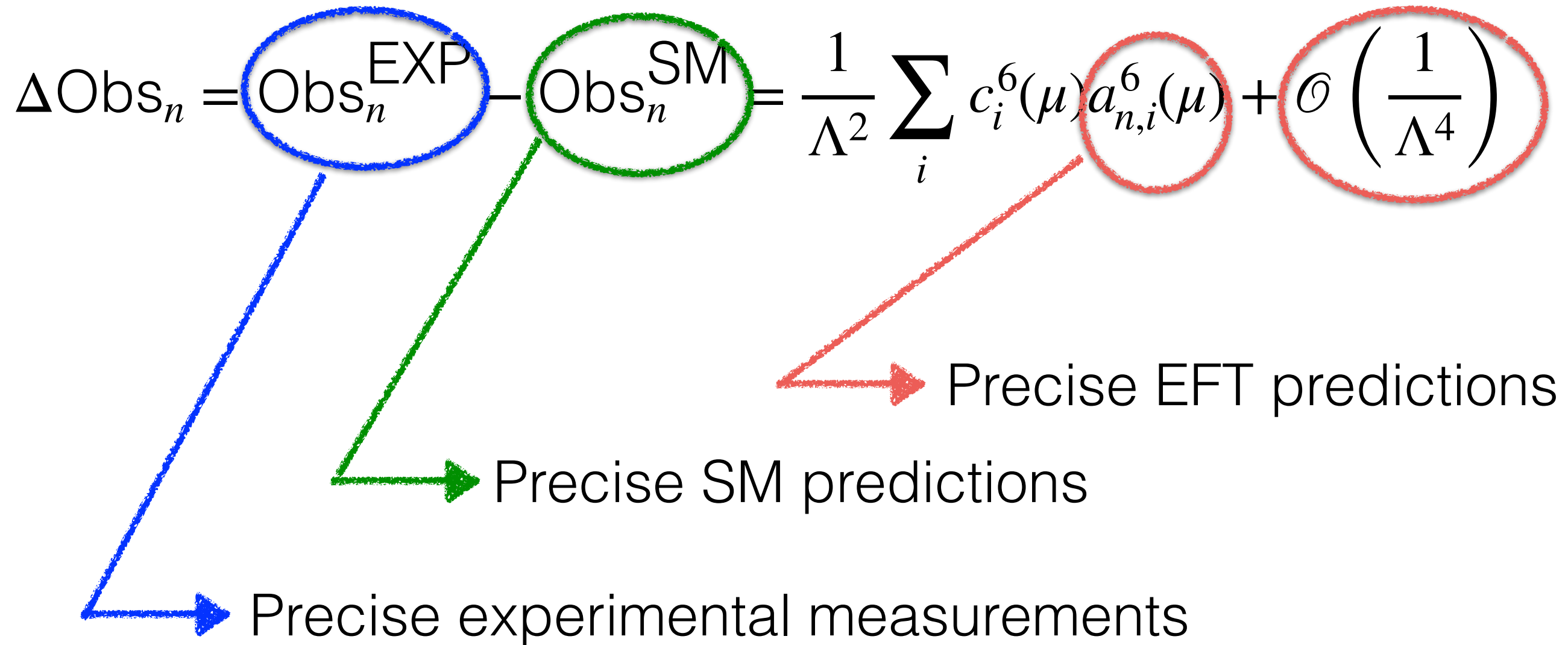
Precise experimental measurements

Precise SM predictions

Precise EFT predictions

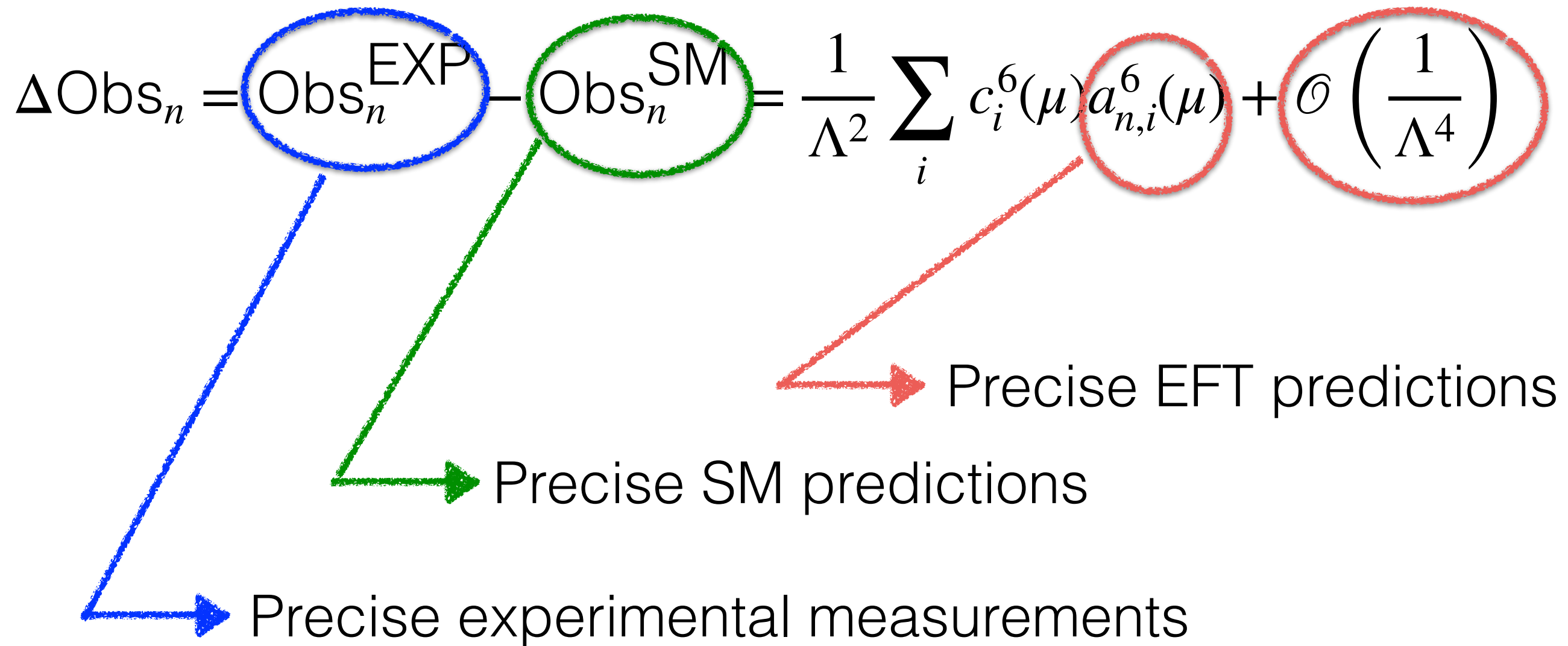
Constraints $\frac{1}{\Lambda^2} c_i^6(\mu)$

EFT pathway to New Physics



Constraints $\frac{1}{\Lambda^2} c_i^6(\mu) \longrightarrow \text{UV}$

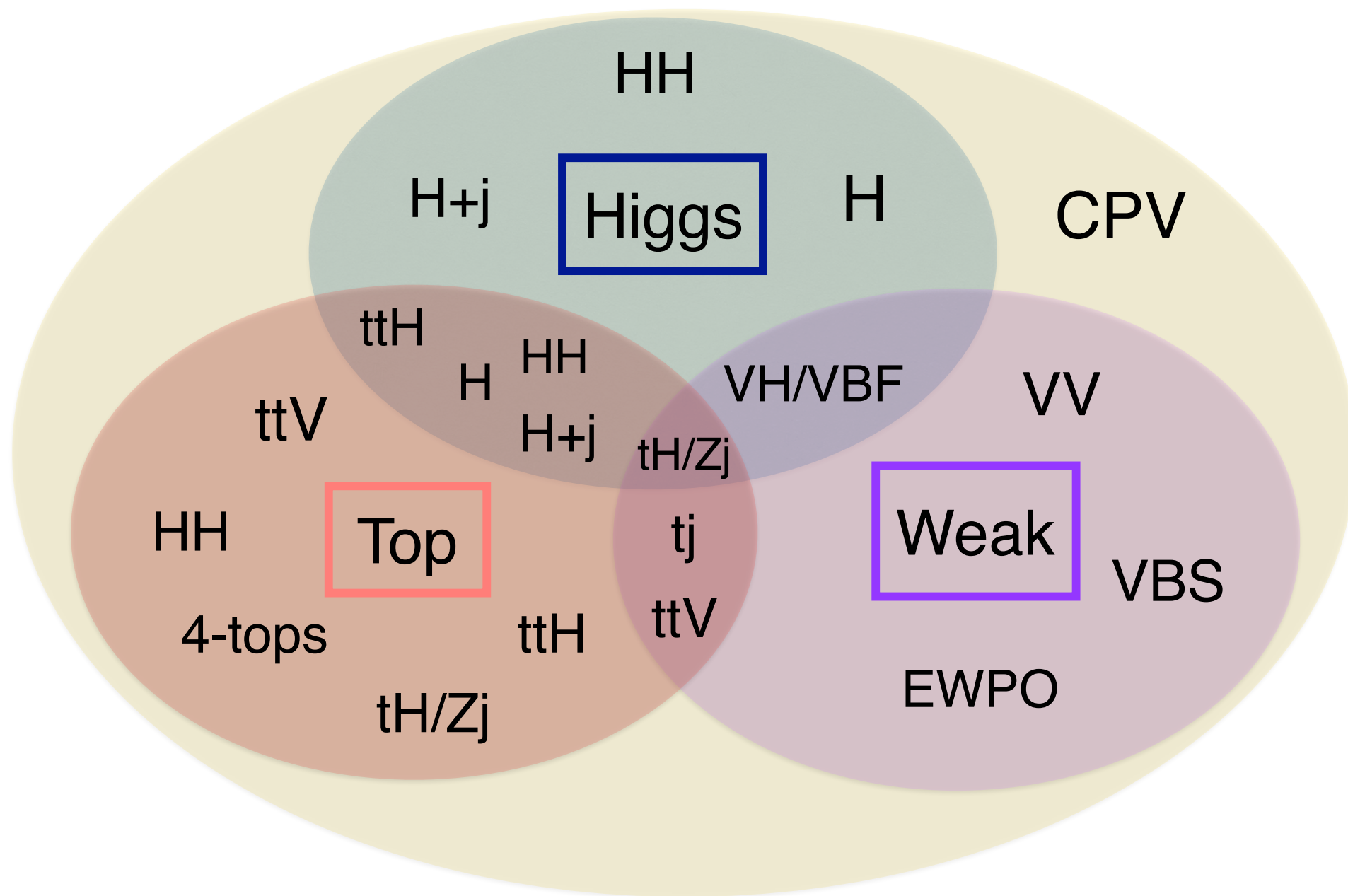
EFT pathway to New Physics



Constraints $\frac{1}{\Lambda^2} c_i^6(\mu) \longrightarrow \text{UV}$

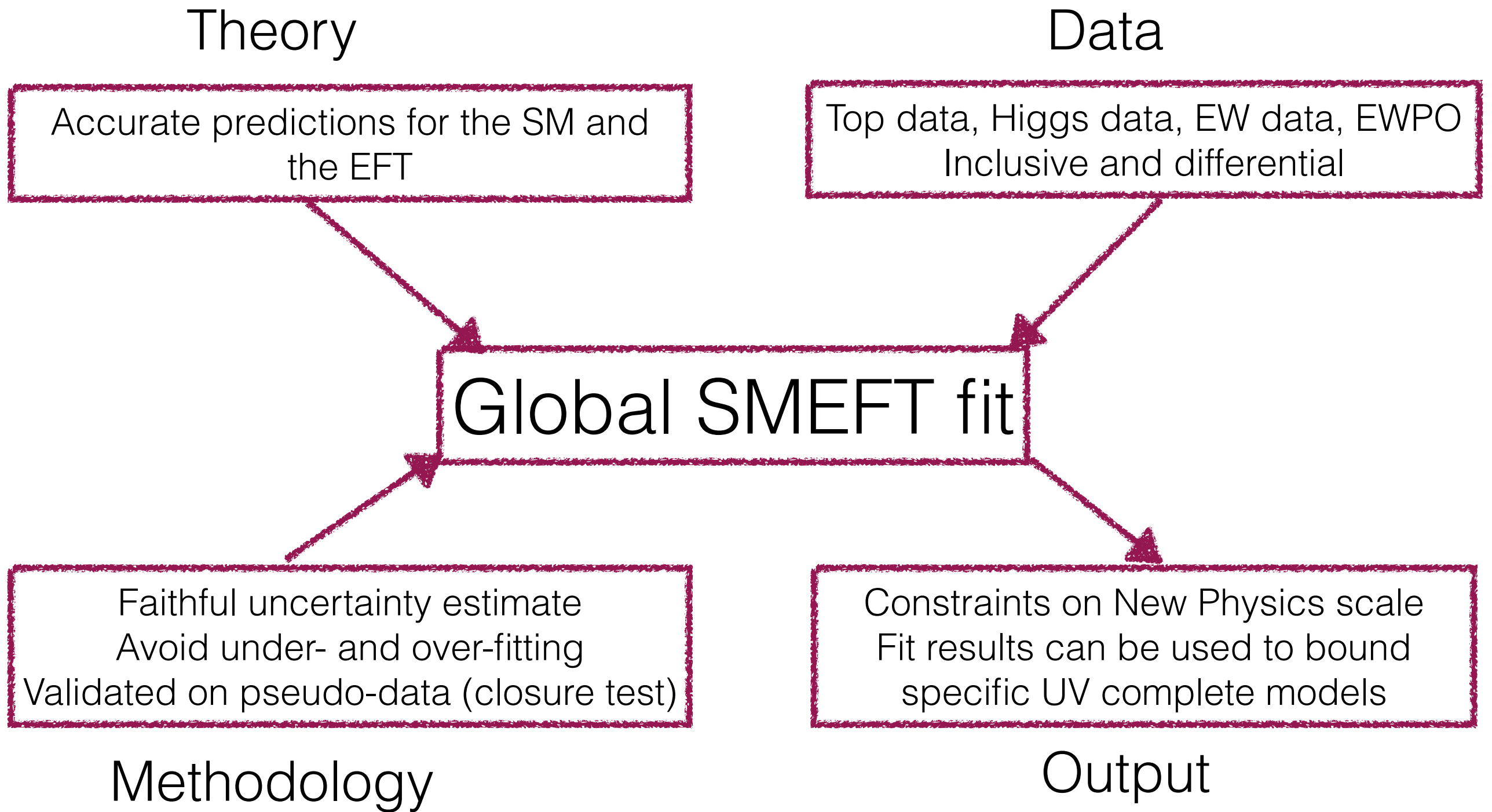
Huge effort to improve each one of these steps!

Global nature of EFT



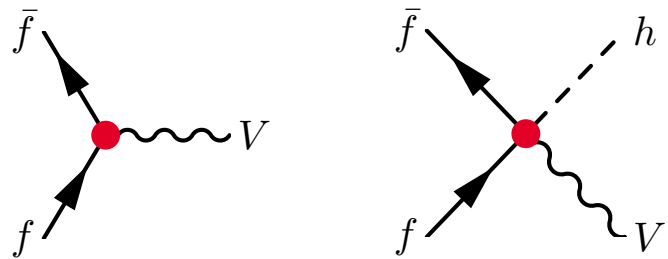
SMEFT correlates different sectors → Global fits

Global fit Setup



Operator examples

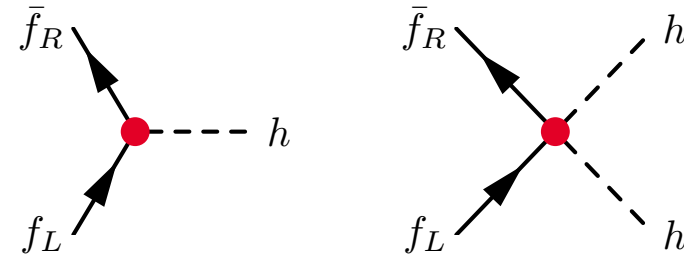
currents $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$



$C_{\phi f}$

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

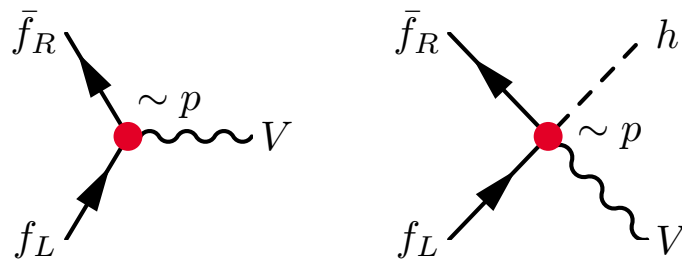
Yukawa $(\bar{q} t \tilde{\varphi})(\varphi^\dagger \varphi)$



$C_{t\phi}$

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

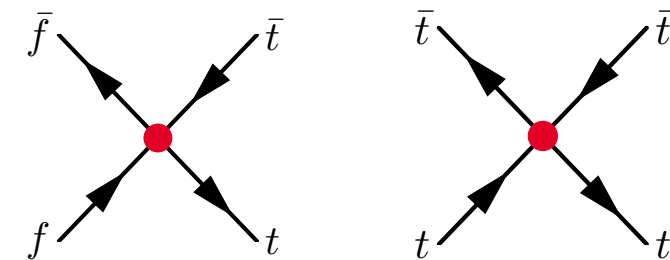
dipole $(\bar{q} \sigma_{\mu\nu} t \tilde{\varphi})V^{\mu\nu}$



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 ($\sim O(20)$ w/ top)

+Purely bosonic operators

From K. Mimasu

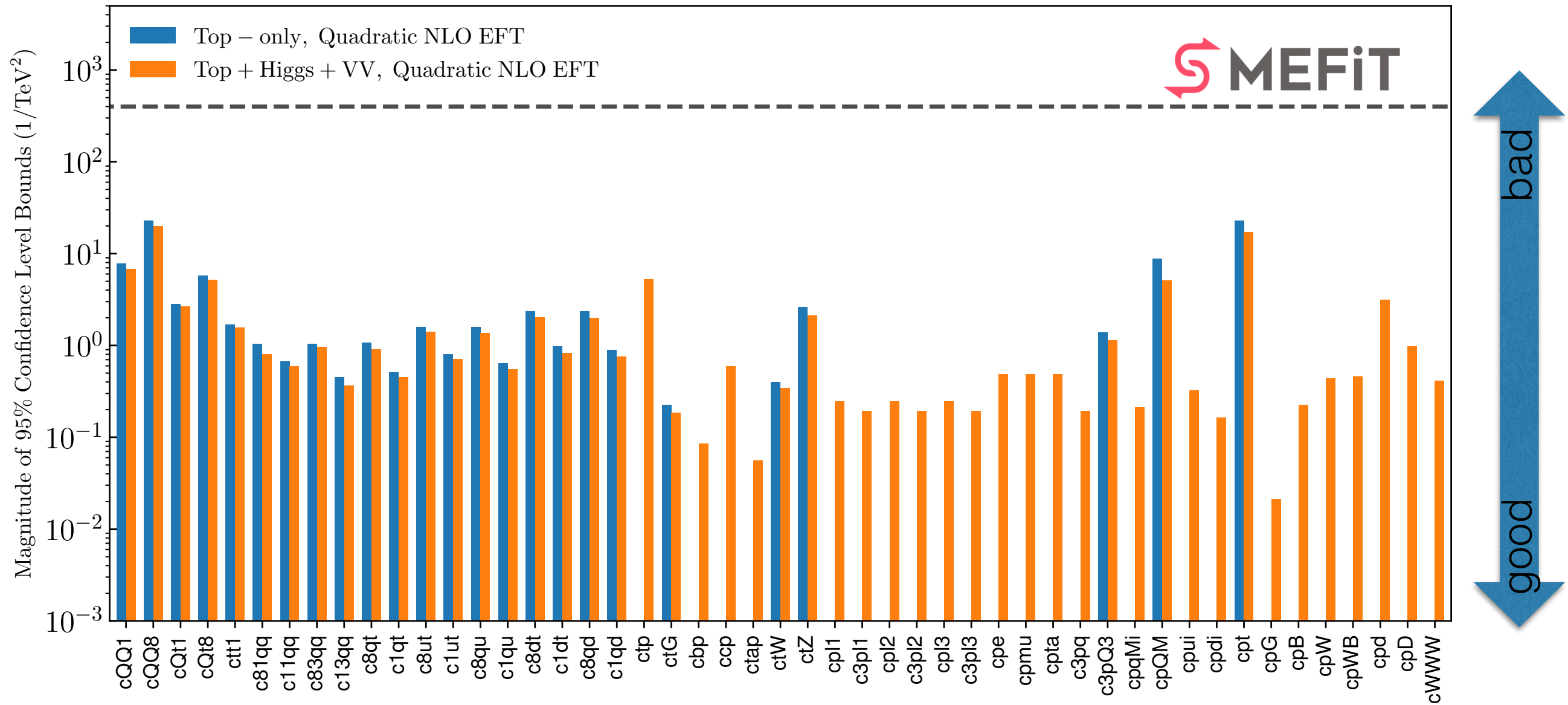
Global fit observables

	Category	Processes	n_{dat}
Top	Top quark production	$t\bar{t}$ (inclusive)	94
		$t\bar{t}Z, t\bar{t}W$	14
		single top (inclusive)	27
		tZ, tW	9
		$t\bar{t}t\bar{t}, t\bar{t}b\bar{b}$	6
		Total	150
Higgs	Higgs production and decay	Run I signal strengths	22
		Run II signal strengths	40
		Run II, differential distributions & STXS	35
		Total	97
EW	Diboson production	LEP-2	40
		LHC	30
		Total	70
	Baseline dataset	Total	317



Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Global fit results



Bounds vary from operator to operator! Lots of information

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

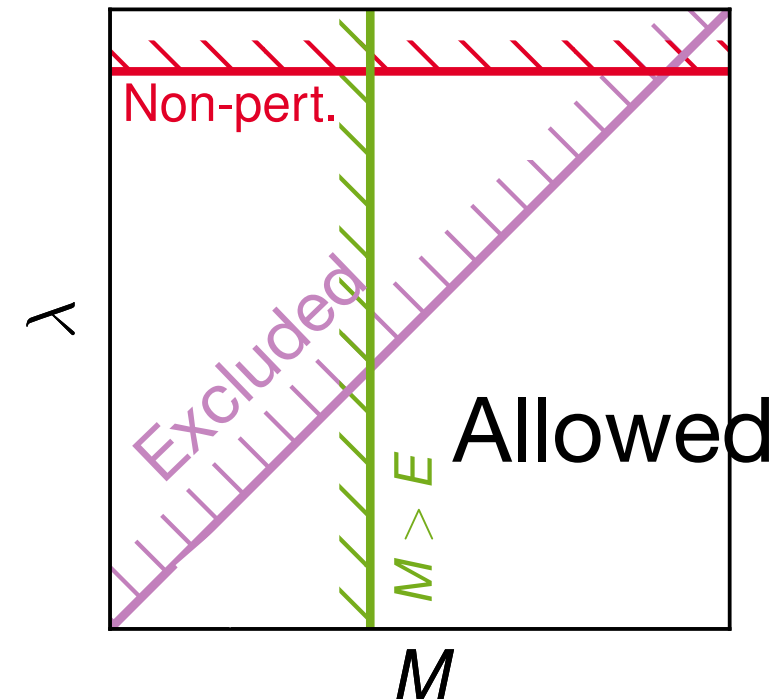
What do we learn from global fits?

Bounds on new physics scale vary from 0.1 TeV (unconstrained) to 10s of TeV.

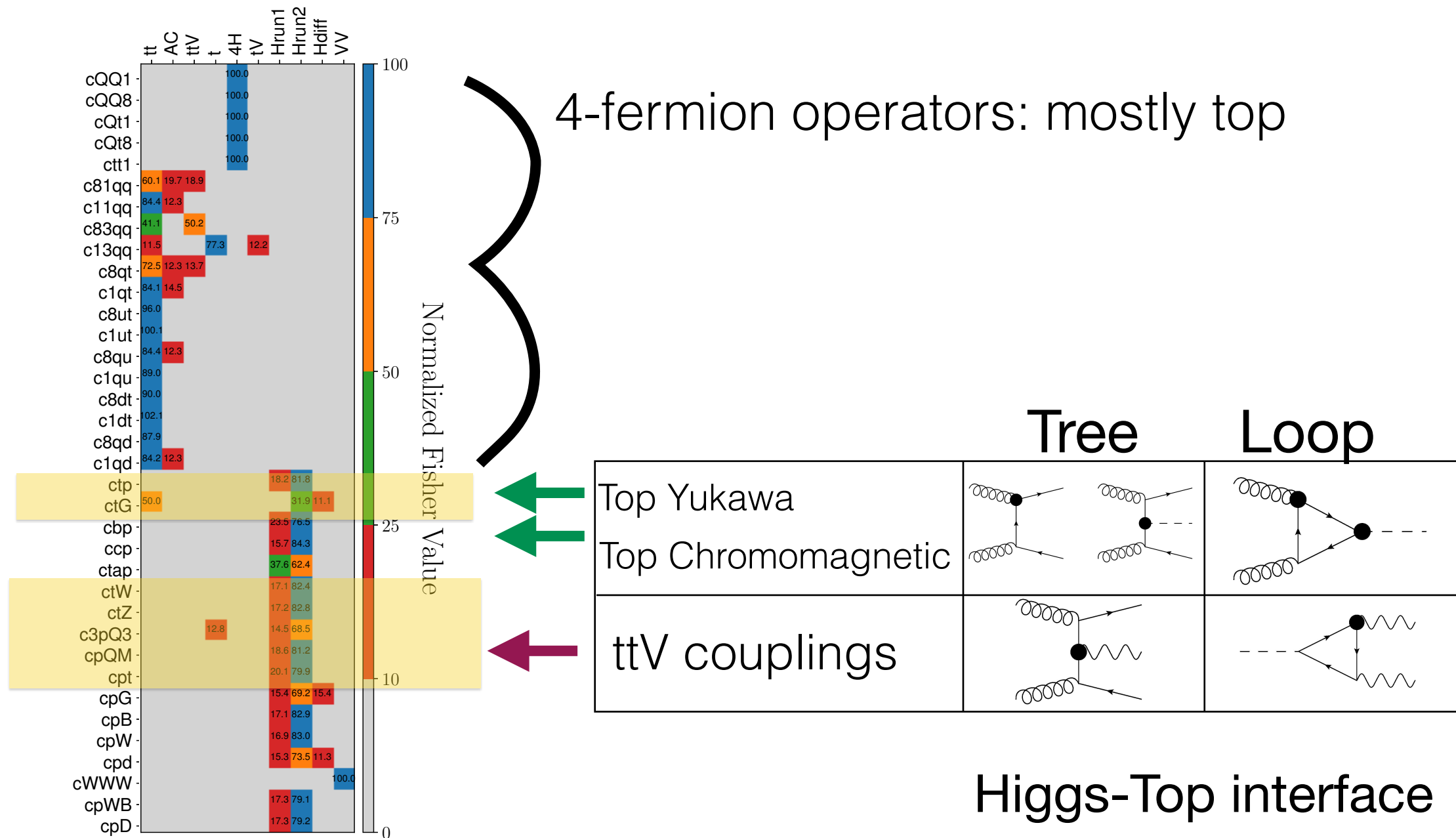
Bounds depend on:

- the operator
- assumption of a strongly or weakly coupled theory
- individual or marginalised bounds (reality is somewhere in-between)
- linear or quadratic bounds

$$\frac{c_i^6(\mu)}{\Lambda^2} = \frac{\lambda^2}{M^2} < X$$



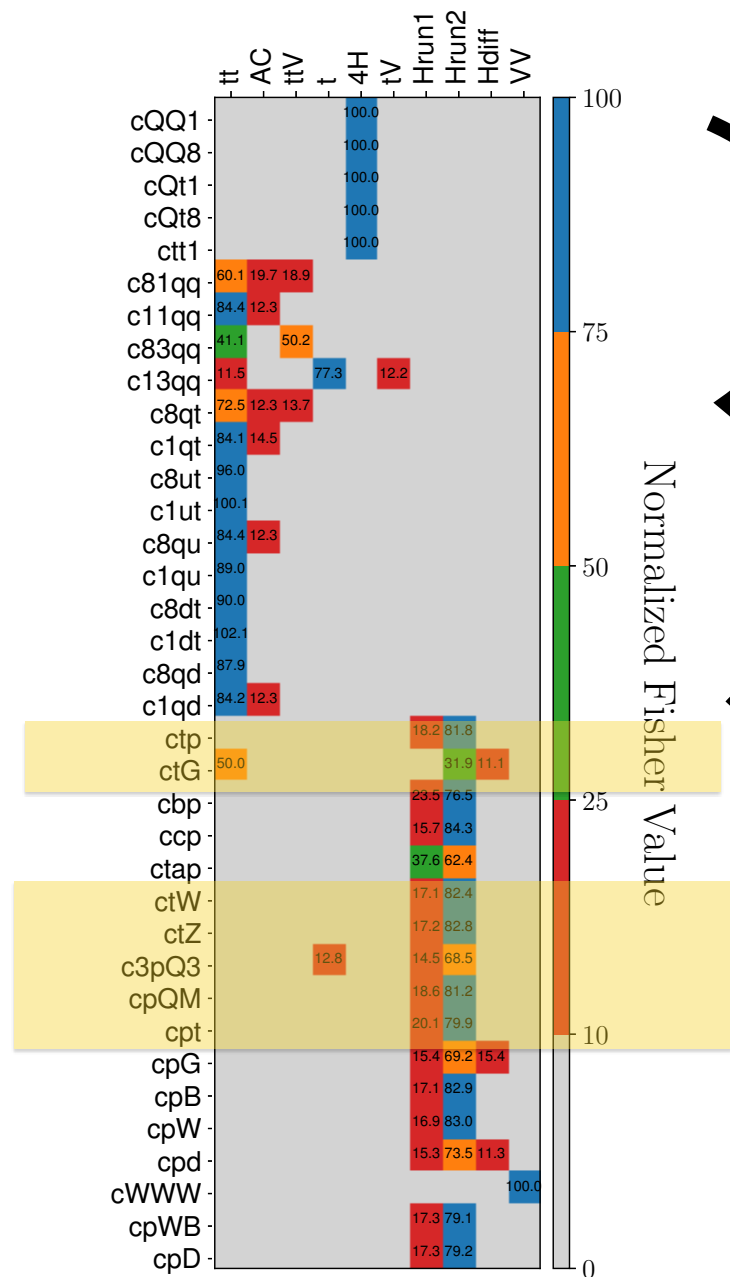
Where is most information from?



Fisher information table

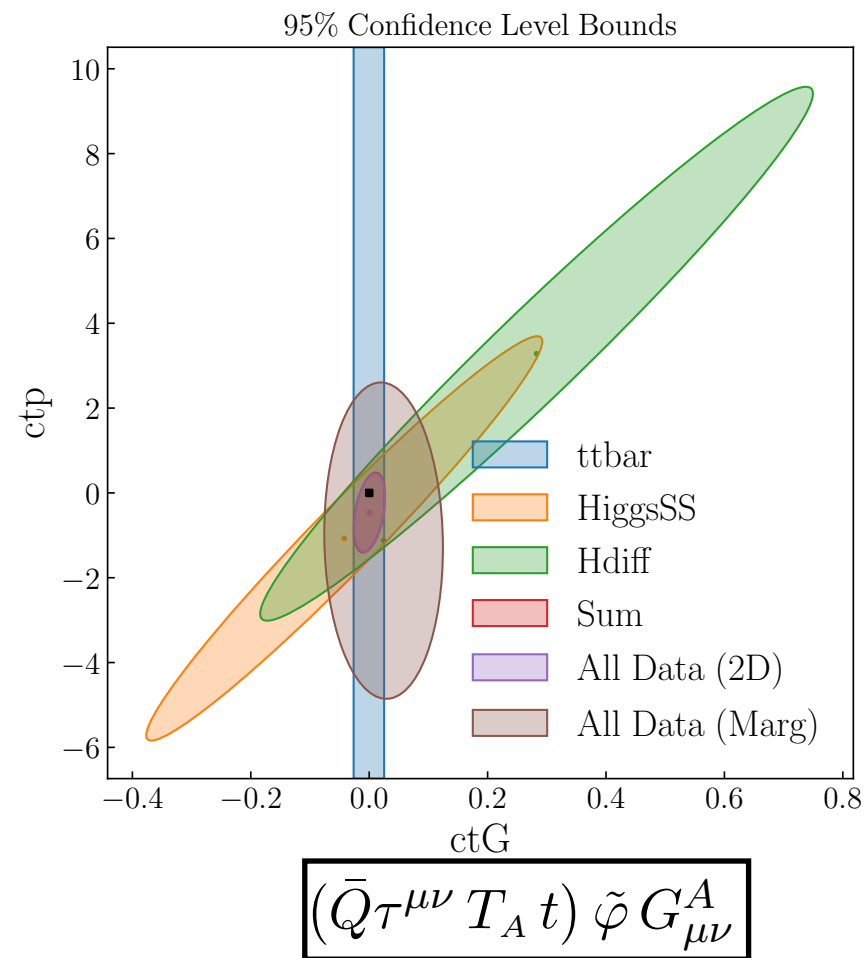
Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Where is most information from?



4-fermion operators: mostly top

$$(\varphi^\dagger \varphi) \bar{Q} t \tilde{\varphi}$$



$$(\bar{Q} \tau^{\mu\nu} T_A t) \tilde{\varphi} G_{\mu\nu}^A$$

Fisher information table

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Future of global fits

More observables:

- particle level observables
- spin correlations
- new final states

More/different operators:

- different flavour assumptions
- dimension-8 operators

Better EFT predictions

Higher Orders in $1/\Lambda^4$

- squared dim-6 contributions
- double insertions of dim-6
- dim-8 contributions

Higher Orders in QCD and EW

EFT is a QFT, renormalisable order-by order in $1/\Lambda^2$

$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right)$$

SMEFT of computations at dimension-6

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} \boxed{a_{n,i}^6(\mu)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Tree level: Done (SMEFTsim)

<https://smeftsim.github.io/> Brivio, arXiv: 2012.11343

NLO QCD: ~Done (SMEFT@NLO)

<http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO>

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

NLO EW: Some examples available, needed to probe unconstrained operators.

SMEFT of computations at dimension-6

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} \boxed{a_{n,i}^6(\mu)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Tree level: Done (SMEFTsim)

<https://smeftsim.github.io/> Brivio, arXiv: 2012.11343

NLO QCD: ~Done (SMEFT@NLO)

<http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO>

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

NLO EW: Some examples available, needed to probe unconstrained operators.

How about this μ ?

Running and mixing in SMEFT

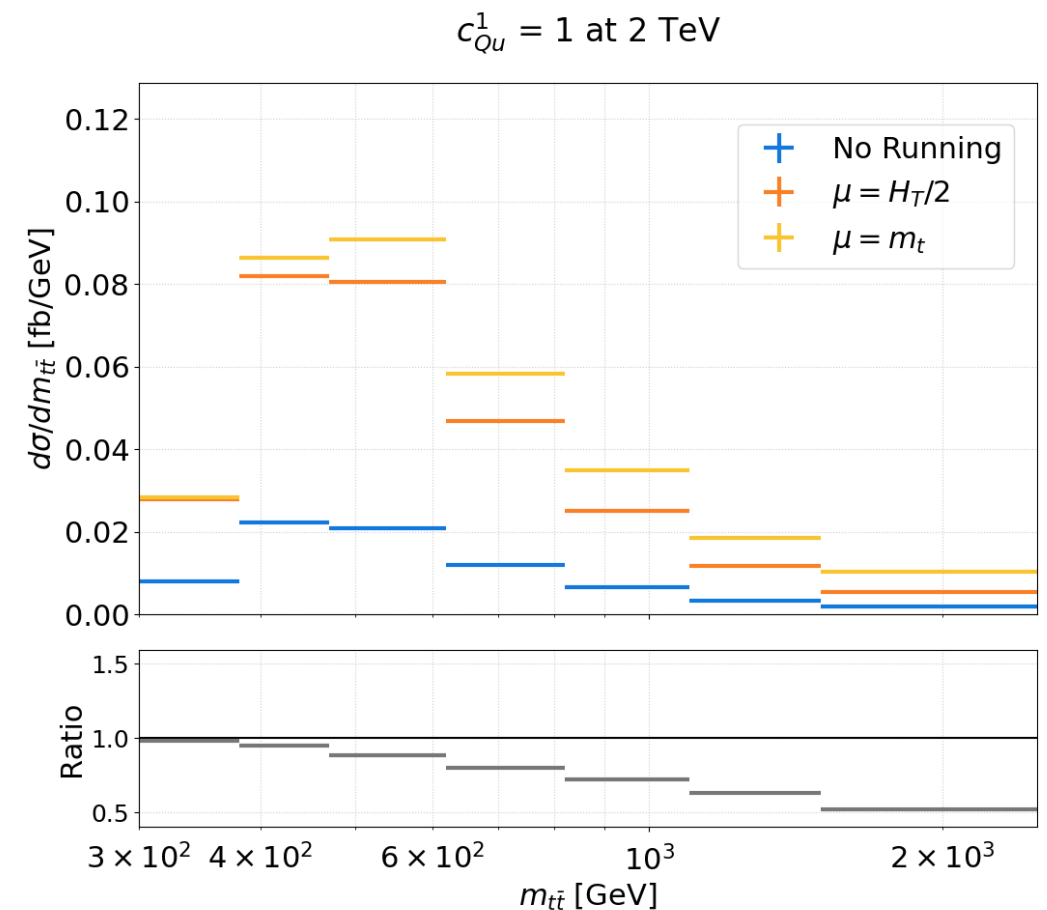
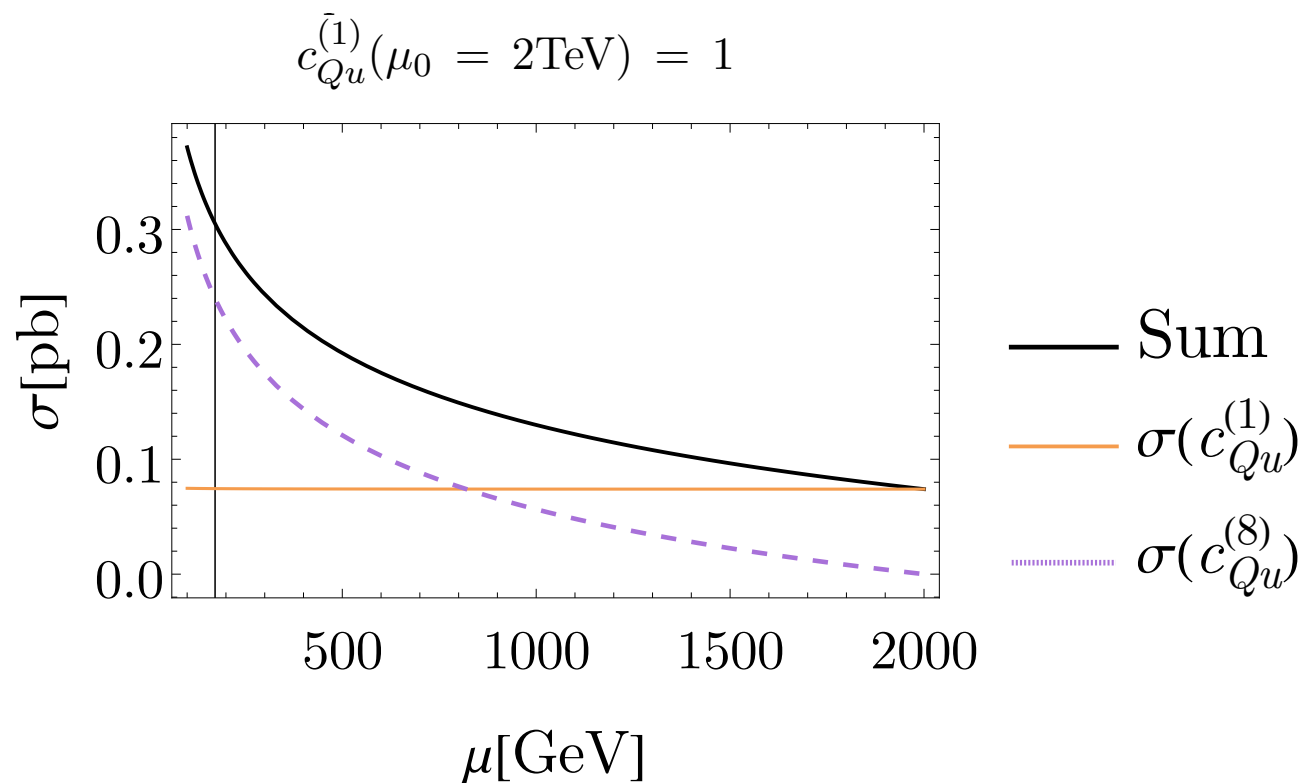
$$\frac{dc_i(\mu)}{d \log \mu} = \gamma_{ij} c_j(\mu)$$

One loop anomalous dimension known:

(Alonso) Jenkins et al arXiv:1308.2627, 1310.4838, 1312.2014

Example: Turn on 1 operator at high-scale

Compute effect on top pair cross-section

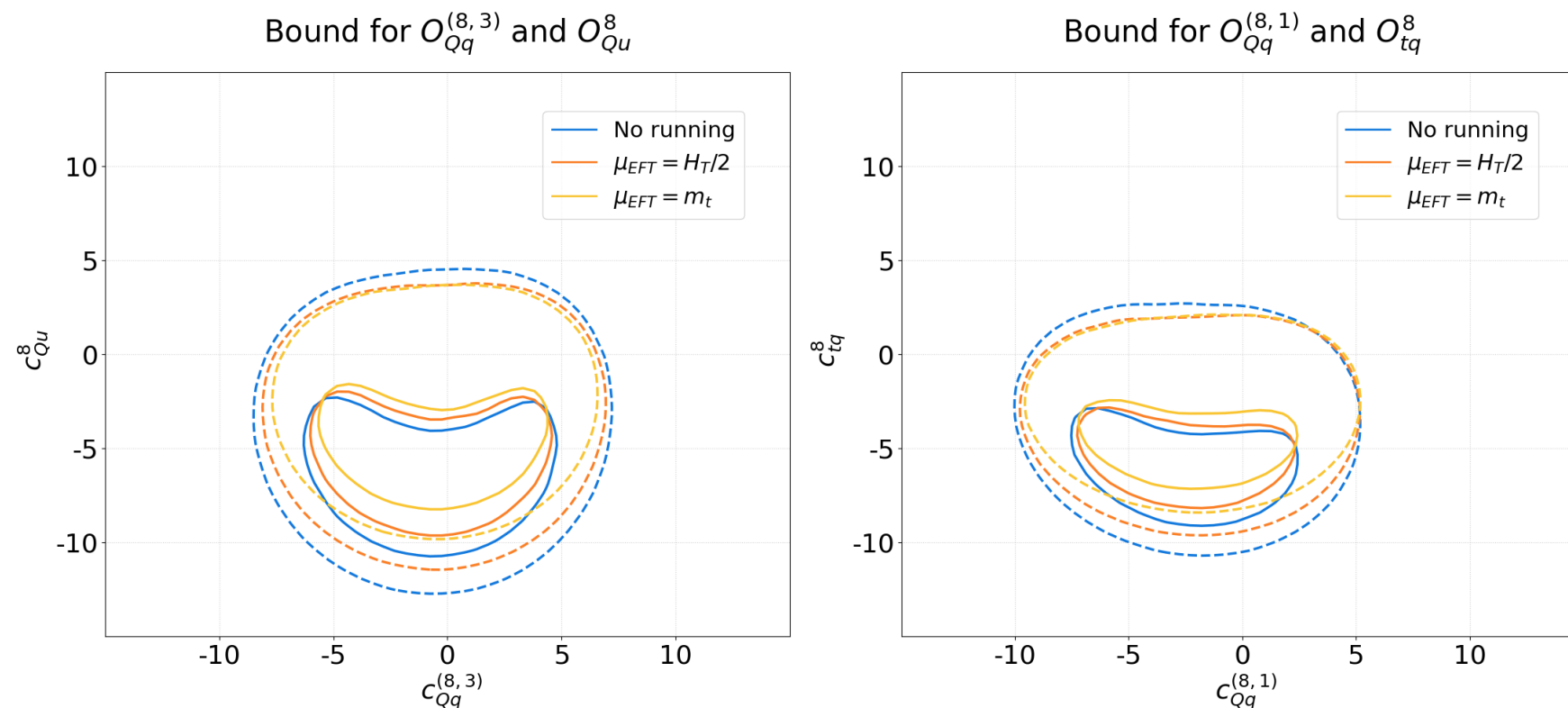


Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

Impact of RGE on constraints

How does running and mixing impacts the constraints?

Top sector fit:



Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

Effect becomes more important for differential distributions & measurements with very different scales

Conclusions

- SMEFT is a consistent way to look for new interactions
- The LHC gives a lot of opportunities to explore SMEFT through a lot of new measurements
- First global fits results already available: important to combine as many processes as possible
- Strong link between Higgs and top sectors
- Precise EFT predictions (NLO, RGE-improved) maximise the potential of EFT probes
- Eventually global fit results give us a clear indication of the scale of potential new physics



Thank you for your attention