Effective Field Theories with applications to collider Phenomenology

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University of Southampton

Outline

Part 1: Intro to Effective Field Theory

- What is an EFT? Fermi theory as an example
- Dimensional analysis & renormalisability
- Matching exercise: tree-level and one loop → anomalous dimensions
- Using EFT to search for new physics

Part 2: The Standard Model as an Effective Field Theory

- The effective theory paradigm at the LHC
- Overview of SMEFT

Part 3: Application - SMEFT in the top/Higgs/EW sector

- Impact of SMEFT: new interactions
- Latest results - Global fit and high energy top quark processes
- Tools for SMEFT - state of the art

References

These lectures are partly based on the following:

Reviews

[Burgess; Annu. Rev. Nucl. Part. Sci. 57 (2007) 329, arXiv:hep-th/0701053]

[Manohar; arXiv:1804.05683]

[Skiba; arXiv:1006.2142]

[Cohen; arXiv:1903.03622]

Lectures from previous schools

[Cen Zhang (2015)] https://www.physics.sjtu.edu.cn/madgraphschool/

[Eleni Vryonidou (2018)] https://indico.ihep.ac.cn/event/7822/

[Gauthier Durieux (2018)] https://indico.ihep.ac.cn/event/7822/

One-loop matching

Can also improve via H.O. corrections in low-energy couplings

Assume fermions couple to the photon with charge Q

- Include NLO QED corrections to the matching

$$\mathcal{L}_{\rm Full} = i\bar{\psi}\partial\!\!\!/\psi \boxed{- \sigma\bar{\psi}\psi} + \frac{1}{2}\left(D_\mu\Phi\right)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\Phi\bar{\psi}\psi$$

$$\mathcal{L}_{\rm EFT} = i\bar{\psi}\partial\!\!\!/\psi \boxed{- \sigma\bar{\psi}\psi} + \frac{c_S}{2M^2}(\bar{\psi}\psi)(\bar{\psi}\psi) \;.$$

IR regulating mass term

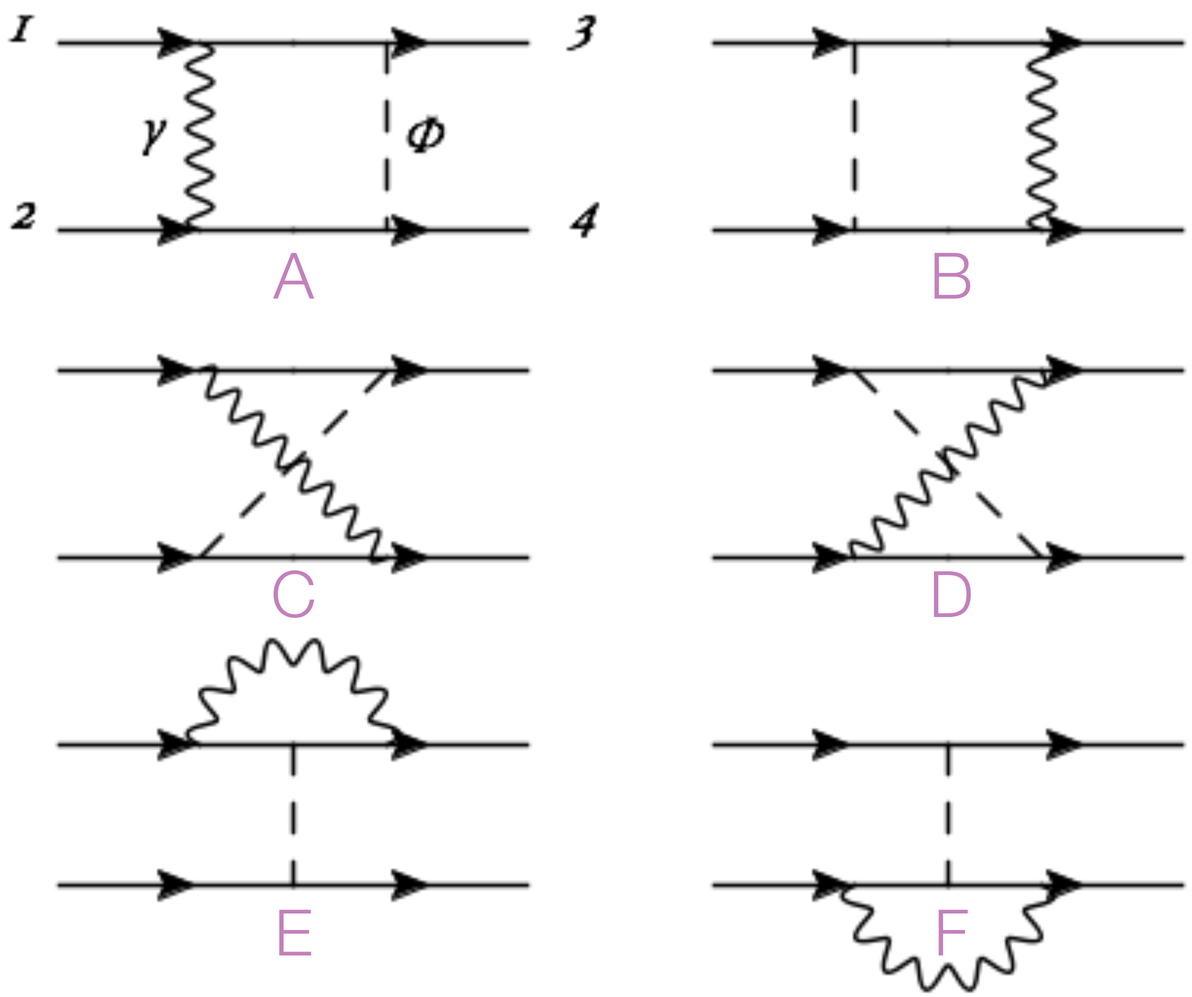
IR divergences between the full theory and EFT must **match & exactly cancel**

- Recall: both descriptions have equivalent IR behaviour, only differ in UV
- Very useful cross-check!

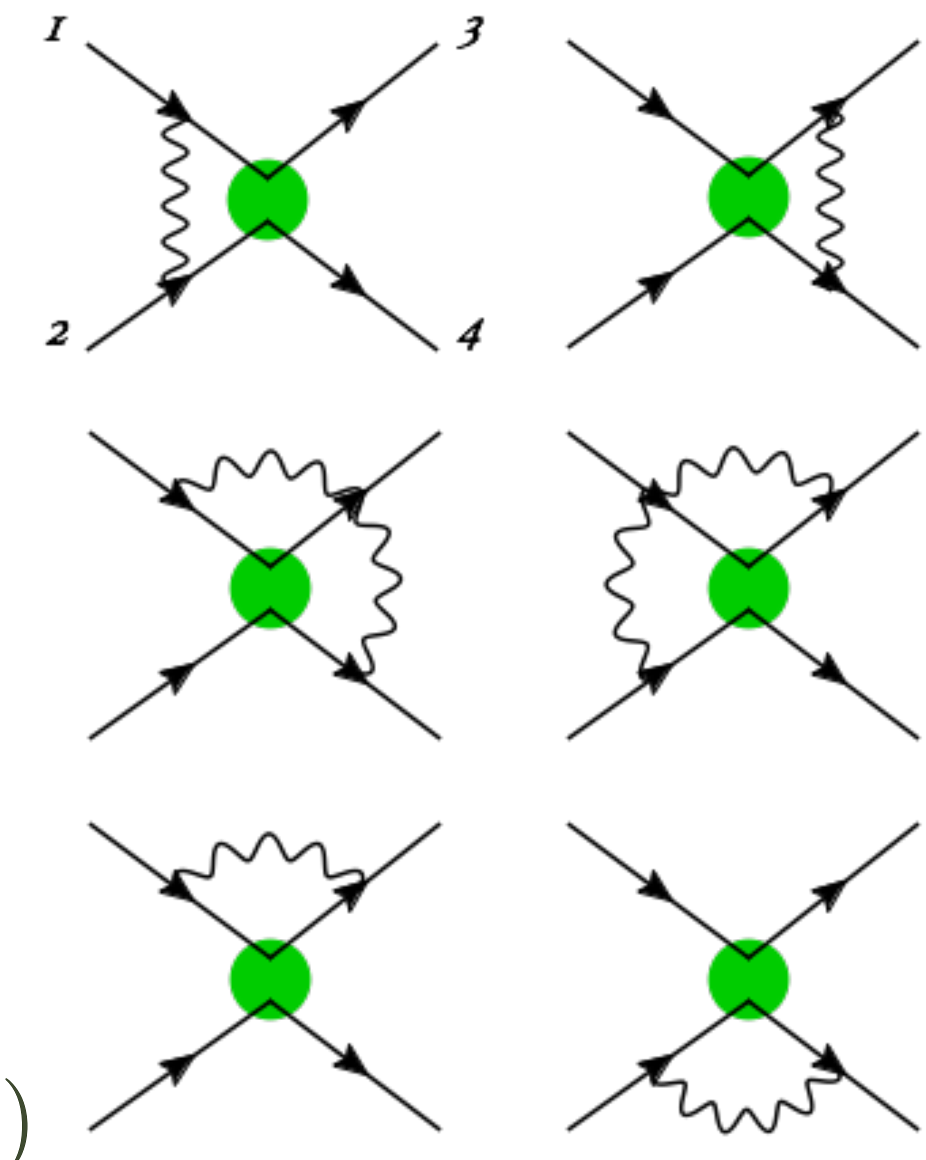
One-loop matching

Calculate corrections to same scattering process

Full



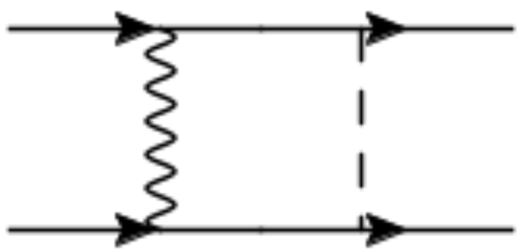
EFT



$$-(3 \leftrightarrow 4)$$

for dim-6, can set external momenta set to 0

One-loop: full theory


A

$$= \int \frac{d^4k}{(2\pi)^4} \bar{u}(p_3)(-i\lambda) \frac{i\not{k}}{k^2-\sigma^2}(ieQ)\gamma^\mu u(p_1)$$

$$\bar{u}(p_4)(-i\lambda)\frac{-i\not{k}}{k^2-\sigma^2}(ieQ)\gamma^\mu u(p_2)\frac{i}{k^2-M^2}\frac{-i}{k^2-\sigma^2}$$

$$= \frac{i\alpha Q^2}{16\pi}\frac{\lambda^2}{\boxed{M^2}}\left[\boxed{\log\frac{\sigma^2}{M^2}}+1\right]\left[\bar{u}(p_3)\gamma^\mu\gamma^\nu u(p_1)\bar{u}(p_4)\gamma_\mu\gamma_\nu u(p_2)\right]$$

required M scaling regulated IR divergence

Diagrams B, C, D permute gamma matrices: $\gamma^\mu\gamma^\nu \to [\gamma^\mu,\gamma^\nu] \equiv -2i\sigma^{\mu\nu}$

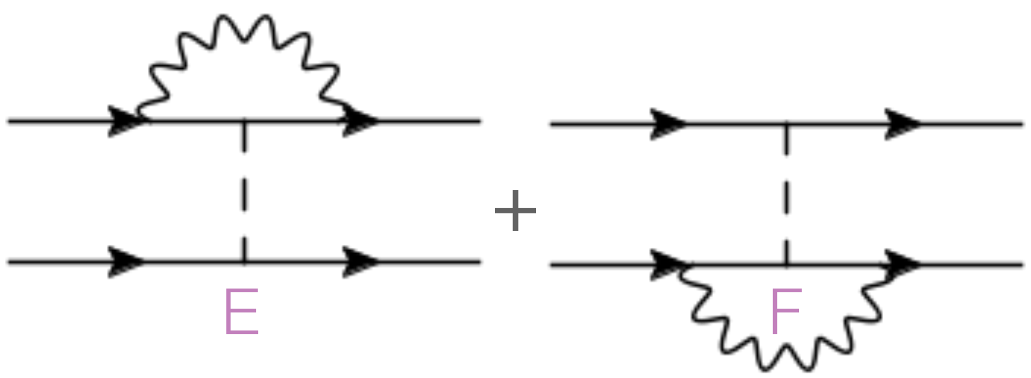
$$M_a + M_b + M_c + M_d = \left(i\frac{\lambda^2}{M^2}\right)\left(\frac{-\alpha Q^2}{4\pi}\right)\mathcal{U}_T\left[\log\frac{\sigma^2}{M^2}+1\right]$$

with: $\mathcal{U}_T = \bar{u}(p_3)\sigma^{\mu\nu}u(p_1)\bar{u}(p_4)\sigma_{\mu\nu}u(p_2) - (3 \leftrightarrow 4)$

Lorentz structure does not match c_S: new operator @ 1-loop

$$\mathcal{L}_{\mathrm{EFT}} = i\bar{\psi}\not{\partial}\psi - \sigma\bar{\psi}\psi + \frac{c_S}{2M^2}(\bar{\psi}\psi)(\bar{\psi}\psi) + \boxed{\frac{c_T}{2M^2}(\bar{\psi}\sigma^{\mu\nu}\psi)(\bar{\psi}\sigma_{\mu\nu}\psi)}$$

One-loop: full theory



$$= \boxed{\mathcal{U}_S}\left(\frac{i\lambda^2}{M^2}\right)\left(\frac{\alpha Q^2}{\pi}\right)\left[\boxed{\frac{2}{\epsilon}} - 2\log\frac{\sigma^2}{\mu^2} - 1\right]$$

c_S Lorentz structure

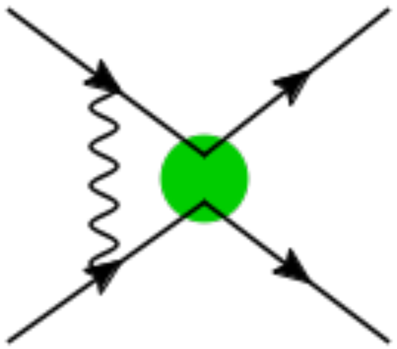
UV divergence related to QED renormalisation of Yukawa, λ

Final result in full theory at $O(M^{-2})$:

$$\lambda\Phi\bar{\psi}\psi$$

$$M_{\text{full}} = \mathcal{U}_S\left(\frac{i\lambda^2}{M^2}\right)\left(\frac{\alpha Q^2}{\pi}\right)\left[\frac{2}{\epsilon} - 2\log\frac{\sigma^2}{\mu^2} - 1\right]$$
$$+\mathcal{U}_T\left(\frac{i\lambda^2}{M^2}\right)\left(\frac{-\alpha Q^2}{4\pi}\right)\left[\log\frac{\sigma^2}{M^2} + 1\right]$$

One-loop: EFT



$$= \int \frac{d^4k}{(2\pi)^4} \frac{ic_S}{M^2} \bar{u}(p_3) \frac{i\not{k}}{k^2-\sigma^2} (ieQ)\gamma^\mu u(p_1) \cdot \bar{u}(p_4) \frac{-i\not{k}}{k^2-\sigma^2} (ieQ)\gamma_\mu u(p_2) \frac{-i}{k^2-\sigma^2}$$

$$= \frac{i\alpha Q^2}{16\pi} \frac{c_S}{M^2} \left[\boxed{-\frac{1}{\epsilon}} + \boxed{\log\frac{\sigma^2}{\mu^2}} - \frac{1}{2}\right] \left[\bar{u}(p_3)\gamma^\mu\gamma^\nu u(p_1)\bar{u}(p_4)\gamma_\mu\gamma_\nu u(p_2)\right]$$

regulated IR divergence

- Heavy propagator replaced by $1/M^2$
- UV pole proportional to c_S: renormalisation of EFT coefficients

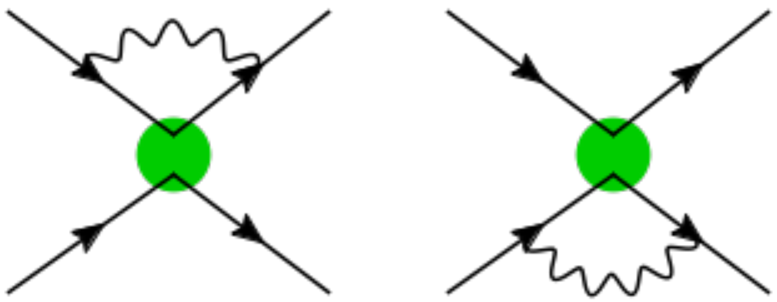
Diagrams B, C, D permute gamma matrices: $\gamma^\mu\gamma^\nu \to [\gamma^\mu, \gamma^\nu] \equiv -2i\sigma^{\mu\nu}$

$$M_A + M_B + M_C + M_D = \left(\frac{ic_S}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\mathcal{U}_T\left[\frac{2}{\epsilon} - 2\log\frac{\sigma^2}{\mu^2} + 1\right]$$

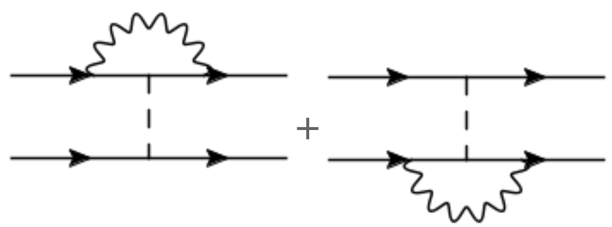
UV divergence is proportional to c_T structure!

- Need a c_T operator counter-term to cancel it
- This will lead to operator mixing under renormalisation group evolution

One-loop: EFT



$$= \mathcal{U}_S \left(\frac{i c_S}{M^2}\right)\left(\frac{\alpha Q^2}{\pi}\right)\left[\boxed{\frac{2}{\epsilon}} - 2\log\frac{\sigma^2}{\mu^2} - 1\right]$$

- Same as 

- UV pole represents QED corrections → renormalisation of c_S

Final result in EFT:

$$M_{\rm EFT} = \mathcal{U}_S \left(\frac{i c_S}{M^2}\right)\left(\frac{\alpha Q^2}{\pi}\right)\left[\frac{2}{\epsilon} - 2\log\frac{\sigma^2}{\mu^2} - 1\right] + \mathcal{U}_T \left(\frac{i c_S}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left[\frac{2}{\epsilon} - 2\log\frac{\sigma^2}{\mu^2} + 1\right]$$

Matching

$$M_{\text{full}} = \mathcal{U}_S \left(\frac{i\lambda^2}{M^2}\right)\left(\frac{\alpha Q^2}{\pi}\right)\left[\frac{2}{\epsilon} - 2\log\frac{\sigma^2}{\mu^2} - 1\right]$$
$$+\,\mathcal{U}_T \left(\frac{i\lambda^2}{M^2}\right)\left(\frac{-\alpha Q^2}{4\pi}\right)\left[\log\frac{\sigma^2}{M^2} + 1\right]$$

$$M_{\text{EFT}} = \mathcal{U}_S \left(\frac{ic_S}{M^2}\right)\left(\frac{\alpha Q^2}{\pi}\right)\left[\frac{2}{\epsilon} - 2\log\frac{\sigma^2}{\mu^2} - 1\right]$$
$$+\,\mathcal{U}_T \left(\frac{ic_S}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left[\frac{2}{\epsilon} - 2\log\frac{\sigma^2}{\mu^2} + 1\right]$$

Matching

Tree Loop Tree Loop

$$\text{EFT}: \; \mathcal{U}_S \left(\frac{ic_S}{M^2}\right)\left[1+\left(\frac{\alpha Q^2}{\pi}\right)\left(\frac{2}{\epsilon}-2\log\frac{\boxed{\sigma^2}}{\mu^2}-1\right)\right]+\mathcal{U}_T\left[\left(\frac{ic_T}{M^2}\right)+\left(\frac{ic_S}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left(\frac{2}{\epsilon}-2\log\frac{\boxed{\sigma^2}}{\mu^2}+1\right)\right]$$

$$\text{Full}: \; \mathcal{U}_S \left(\frac{i\lambda^2}{M^2}\right)\left[1+\left(\frac{\alpha Q^2}{\pi}\right)\left(\frac{2}{\epsilon}-2\log\frac{\boxed{\sigma^2}}{\mu^2}-1\right)\right]+\mathcal{U}_T\left(\frac{i\lambda^2}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left(-2\log\frac{\boxed{\sigma^2}}{M^2}-2\right)$$

At leading order:

$$c_S = \lambda^2 + \mathcal{O}(\alpha)$$ Tree-level plus correction

$$c_T = \mathcal{O}(\alpha)$$ One-loop only

Substitute LO matching result:

- As promised: IR divergences cancel exactly!
- Both theories predict same IR behaviour
- **All** dependence on low scale variables (masses, momenta) will cancel

Matching

Tree Loop Tree Loop

$$\text{EFT}: \ \mathcal{U}_S\left(\frac{ic_S}{M^2}\right)\left[1+\left(\frac{\alpha Q^2}{\pi}\right)\left(\boxed{\frac{2}{\epsilon}}-2\log\frac{\sigma^2}{\mu^2}-1\right)\right]+\mathcal{U}_T\left[\left(\frac{ic_T}{M^2}\right)+\left(\frac{ic_S}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left(\boxed{\frac{2}{\epsilon}}-2\log\frac{\sigma^2}{\mu^2}+1\right)\right]$$

$$\text{Full}: \ \mathcal{U}_S\left(\frac{i\lambda^2}{M^2}\right)\left[1+\left(\frac{\alpha Q^2}{\pi}\right)\left(\boxed{\frac{2}{\epsilon}}-2\log\frac{\sigma^2}{\mu^2}-1\right)\right]+\mathcal{U}_T\left(\frac{i\lambda^2}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left(-2\log\frac{\sigma^2}{M^2}-2\right)$$

At leading order:

$$c_S = \lambda^2 + \mathcal{O}(\alpha)$$ Tree-level plus correction

$$c_T = \mathcal{O}(\alpha)$$ One-loop only

Substitute LO matching result:

- UV poles do not match → that's OK
- Theories are not the same in the UV
- Use a subtraction scheme (e.g. MS) to perform necessary renormalisation

Matching

$$\begin{array}{l} \quad\quad\quad\quad\quad\quad\text{Tree}\quad\quad\quad\quad\quad\text{Loop}\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\text{Tree}\quad\quad\quad\quad\quad\text{Loop} \end{array}$$

$$\text{EFT}: \ \mathcal{U}_S\left(\frac{ic_S}{M^2}\right)\left[1+\left(\frac{\alpha Q^2}{\pi}\right)\left(\frac{2}{\epsilon}-2\log\frac{\sigma^2}{\boxed{\mu^2}}-1\right)\right]+\mathcal{U}_T\left[\left(\frac{ic_T}{M^2}\right)+\left(\frac{ic_S}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left(\frac{2}{\epsilon}-2\log\frac{\sigma^2}{\boxed{\mu^2}}+1\right)\right]$$

$$\text{Full}: \ \mathcal{U}_S\left(\frac{i\lambda^2}{M^2}\right)\left[1+\left(\frac{\alpha Q^2}{\pi}\right)\left(\frac{2}{\epsilon}-2\log\frac{\sigma^2}{\boxed{\mu^2}}-1\right)\right]+\mathcal{U}_T\left(\frac{i\lambda^2}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left(-2\log\frac{\sigma^2}{\boxed{M^2}}-2\right)$$

At leading order:

$$c_S = \lambda^2 + \mathcal{O}(\alpha)$$ Tree-level plus correction

$$c_T = \mathcal{O}(\alpha)$$ One-loop only

Substitute LO matching result:

- log μ^2 (renormalisation) and log M^2 (heavy mass)
- Set μ=M to cancel these terms
- Physically, we have performed matching at the scale M
- Obtaining $c_S(M)$, $c_T(M)$

Matching

There are also functional methods to integrate out heavy d.o.f .and obtain an effective action
See e.g. 'Universal one-loop effective action'
[Henning et al.; JHEP 01 (2016) 023]
[Drozd et al.; JHEP 03 (2016) 80]

Tree Loop Tree Loop

$$\text{EFT}: \; \mathcal{U}_S \left(\frac{ic_S}{M^2}\right)\left[1+\left(\frac{\alpha Q^2}{\pi}\right)\left(\cancel{\frac{2}{\epsilon}} - 2\log\cancel{\frac{\sigma^2}{\mu^2}} - \cancel{1}\right)\right] + \mathcal{U}_T\left[\left(\frac{ic_T}{M^2}\right)+\left(\frac{ic_S}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left(\frac{2}{\epsilon} - 2\log\cancel{\frac{\sigma^2}{\mu^2}}+1\right)\right]$$

$$\text{Full}: \; \mathcal{U}_S \left(\frac{i\lambda^2}{M^2}\right)\left[1+\left(\frac{\alpha Q^2}{\pi}\right)\left(\cancel{\frac{2}{\epsilon}} - 2\log\cancel{\frac{\sigma^2}{\mu^2}} - \cancel{1}\right)\right] + \mathcal{U}_T\left(\frac{i\lambda^2}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left(-2\log\cancel{\frac{\sigma^2}{M^2}} - 2\right)$$

At leading order:

$$c_S = \lambda^2 + \mathcal{O}(\alpha)$$ Tree-level plus correction

$$c_T = \mathcal{O}(\alpha)$$ One-loop only

One-loop matching result:

$$c_S = \lambda^2 + \mathcal{O}(\alpha^2)$$ No one loop correction

$$c_T = -\frac{3\alpha Q^2}{8\pi}\lambda^2 + \mathcal{O}(\alpha^2)$$ Leading order one-loop

Running & mixing

$$\mathrm{EFT}:\ \mathcal{U}_S\left(\frac{ic_S}{M^2}\right)\left[1+\left(\frac{\alpha Q^2}{\pi}\right)\left(\frac{2}{\epsilon}-2\log\frac{\sigma^2}{\mu^2}-1\right)\right]+\mathcal{U}_T\left[\left(\frac{ic_T}{M^2}\right)+\left(\frac{ic_S}{M^2}\right)\left(\frac{\alpha Q^2}{8\pi}\right)\left(\frac{2}{\epsilon}-2\log\frac{\sigma^2}{\mu^2}+1\right)\right]$$

Recall UV poles in EFT prediction

- Contributions to both c_S and c_T Lorentz structures
- Combined with wavefunction renormalisations:

Counter-terms $$\delta c_S = -\frac{3}{2}\frac{\alpha Q^2}{\pi}\frac{1}{\epsilon}c_S,\quad \delta c_T = -\frac{1}{4}\frac{\alpha Q^2}{\pi}\frac{1}{\epsilon}c_S$$

Defines 'anomalous dimension' matrix

$$\gamma = \frac{2Q^2\alpha}{\pi}\begin{array}{cc} & \begin{array}{cc} c_S & c_T \end{array} \\ & \left(\begin{array}{cc} -3/2 & -12 \\ -1/4 & 1/2 \end{array}\right) \end{array}\begin{array}{c} c_S \\ c_T \end{array}\qquad \frac{d}{d\ln\mu}c_i = \gamma_{ij}c_j$$

(-12, 1/2 entries not computed explicitly)

Coefficients run & mix

$$\frac{dc_S(\mu)}{d\ln\mu} = -3\frac{Q^2\alpha}{\pi}c_S(\mu) - 24\frac{Q^2\alpha}{\pi}c_T(\mu)$$
$$\frac{dc_T(\mu)}{d\ln\mu} = -\frac{1}{2}\frac{Q^2\alpha}{\pi}c_S(\mu) + \frac{Q^2\alpha}{\pi}c_T(\mu)$$

Solve RGE to find c(μ) from c(M)

Mini summary

EFT **approximate** physical systems with **scale separation**

- Only include relevant low energy degrees of freedom
- Supplement low energy theory with an operator expansion

$$\mathcal{L}_{\text{eff.}} = \sum_i \frac{c_i \mathcal{O}_i^d}{\Lambda^{4-d}}$$

Order-by-order renormalisable QFT

Well-defined **matching** procedure to predict **Wilson coefficients**

- Systematically improvable through higher order terms in the power counting and perturbation theory

Higher dimension operators have **power-like** contributions to amplitudes as a function of external momenta

- Cross-sections that **grow with energy** below the new physics scale!

Searching for new physics

In our toy model, new physics was a heavy scalar, ϕ

- Now we build a $\psi\psi$-collider to study $\psi\psi$-scattering
- Measure total, differential cross sections → exploit energy-growth
- Use data to constrain/measure c_S, c_T → indirectly probe λ,M

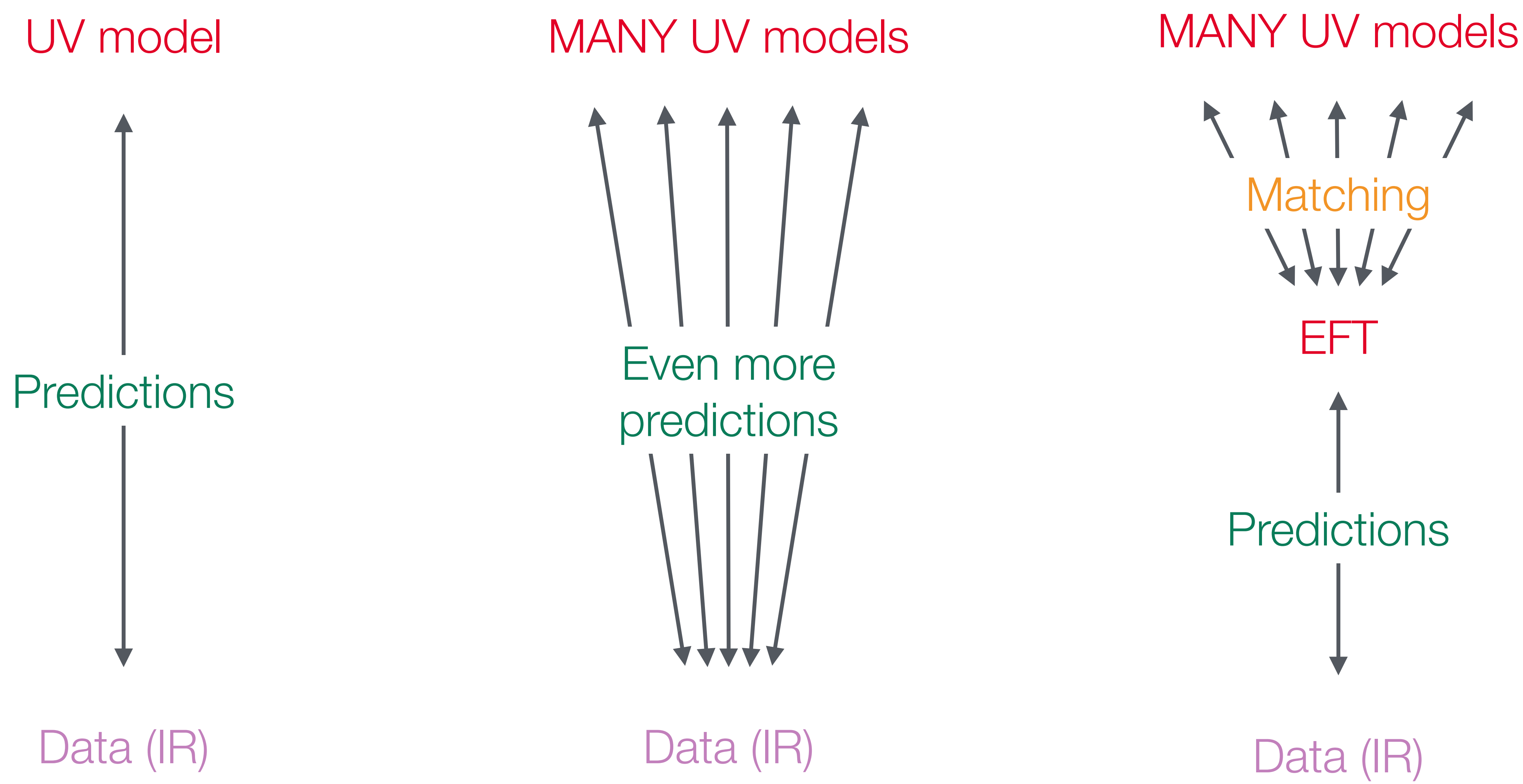
Why is this useful if we already know the full theory?

- We can now compute **any** observable using the EFT, should be easier
- Less obvious for this very simple model

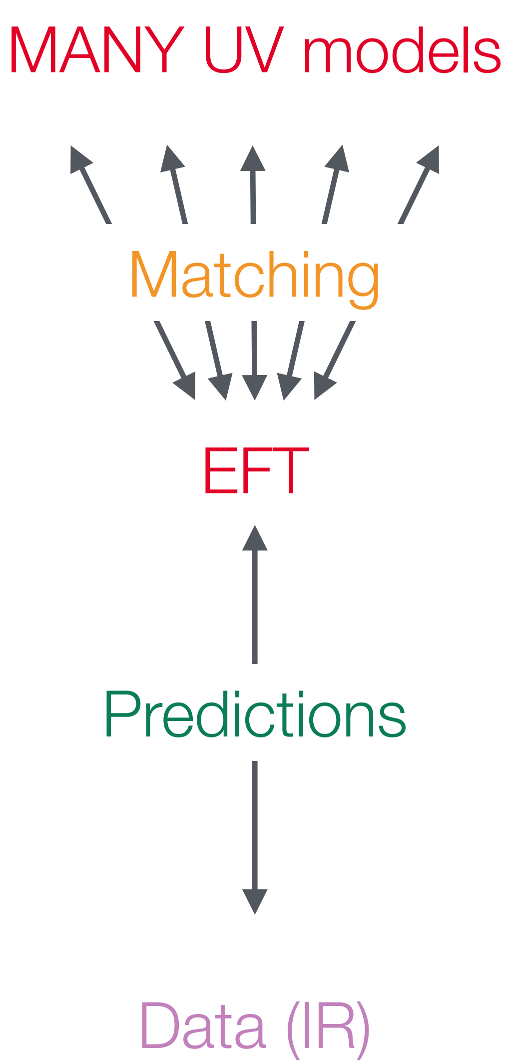
The most useful is if we don't know the full theory

- The EFT is generic and model-independent, applies to all heavy NP
- Get limits on c_S, c_T **once and for all** and indirectly constrain **many models**
- New scalars, vectors, Supersymmmetry, Extra-dimensions,…

Searching for new physics



Searching for new physics



EFT serves as an interface between UV physics and 'low energy' phenomena

- It is the ultimate bottom up theory for arbitrary, heavy new physics
- *That reproduces your low-energy theory in the IR

Provided it is used 'properly' i.e. there are rules:

- Golden rule: new physics scale sufficiently higher than all mass scales in your calculation (m, p_{ext})

➡ 'EFT validity'

- Second rule: only **global** analyses

➡ Include all possible (independent) operators consistent with symmetry assumptions

Valid interpretations

From now we take the bottom-up approach

- Try to measure operator coefficients without thinking about their origin (yet)

parameter space: $$\left(\frac{c_S}{\Lambda^2},\ \frac{c_T}{\Lambda^2}\right)$$ unknowns: $$(c_S\,,\ c_T\,,\ \Lambda)$$

Λ is a fictitious scale, just to make c dimensionless

- **Not** to be directly identified with the true mass scale of new physics, M
- We can only measure c/Λ, inference on M is a matter of **interpretation**
- Depends on the specific predictions for c *(model dependent)*

What is important is to not probe an EFT at energies above the new physics mass scale, M

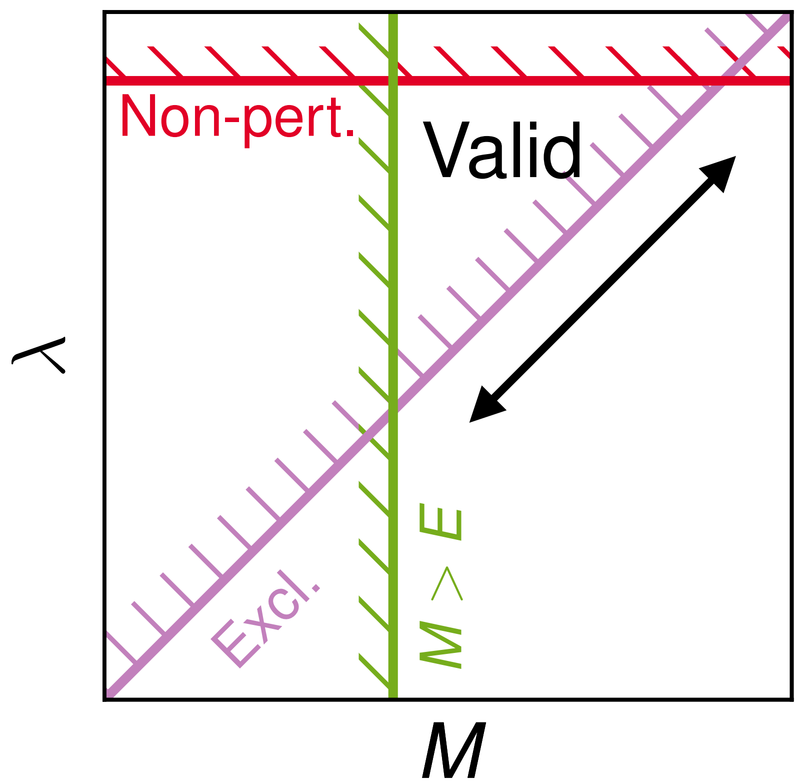
- Expansion breaks down & all orders are important → resonant production of new particles, e.g. Φ, at mass M

Valid interpretations

Testing of validity criterion is an **a posteriori** exercise

Suppose we measure ψψ production at our collider

- Use, e.g., invariant mass distribution to set a limit on c_S: $$\frac{c_S}{\Lambda^2} < 1\,\mathrm{TeV}^{-2}$$
- Infer constraints on ϕ model (λ,M): $$\frac{c_S}{\Lambda^2} = \frac{\lambda^2}{M^2} \qquad c_T = 0$$ (tree-level)



- Beyond some value (≲ 4π) λ is non perturbative
  - ➡ Theory not predictive, can't match
- We measure at some energy/mass bin, E: must be less than M
  - ➡ EFT expansion breakdown
- Valid region only known after measurement
  - ➡ Model dependent (tree/loop, weak/strong)

Global interpretations

We must consider **all possible** operators of a given dimension

- In general, we do not know which operators UV physics could generate
- As we saw, RG evolution mixes operators together
- Only symmetries can protect you and forbid certain operators
- Setting c_i=0 is only possible at one scale

Ignoring operators can lead to over-optimistic bounds

- Operators could cancel each other in observables $$(c_S,\, c_T) = \left(\lambda^2,\, -\frac{3\alpha Q^2}{8\pi}\lambda^2\right)$$
- 'One-at-a-time' operator constraints are instructive but not robust
- A robust statistical analysis will account for simultaneous variations of all relevant coefficients
- This will impact the derived confidence intervals on individual coefficients

Marginalisation/Profiling

Operator basis

All possible operators…

- The space of operators at a given dimension is technically infinite!
- Thankfully there are redundancies, only a finite number are independent
- i.e. independent contributions to on-shell S-matrix elements

Operators can be related by simple identities

- Integration by parts (operators with derivatives) ⇔ momentum conservation
- Fierz identities in Dirac, gauge group algebras

Field redefinitions and/or equations of motion

- Equivalence theorem states that **S-matrix is unchanged** by field redefinitions *[Chisholm; Nucl. Phys. 26 (1961) 469]*
- Can be used to eliminate operators in favour of others *[Arzt; Phys.Lett. B342 (1995) 189]*
- Non-redundant set of operators = **basis**

Eliminating redundancies

Small change in a field induces variation of action

- c.f. Euler-Lagrange equation

$$\delta S[\phi] = \int d^4x\, \mathcal{L}[\phi + \delta\phi] - \mathcal{L}[\phi] = \int d^4x \left(\frac{\partial \mathcal{L}}{\partial \phi} - \partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} \right) \delta\phi + \mathcal{O}(\delta\phi^2)$$

For an effective action:

$$\mathcal{L} = \mathcal{L}_0 + \frac{1}{\Lambda^2}\mathcal{L}_1; \quad \delta\phi = \frac{a}{\Lambda^2} F[\phi]$$

same quantum numbers as ϕ

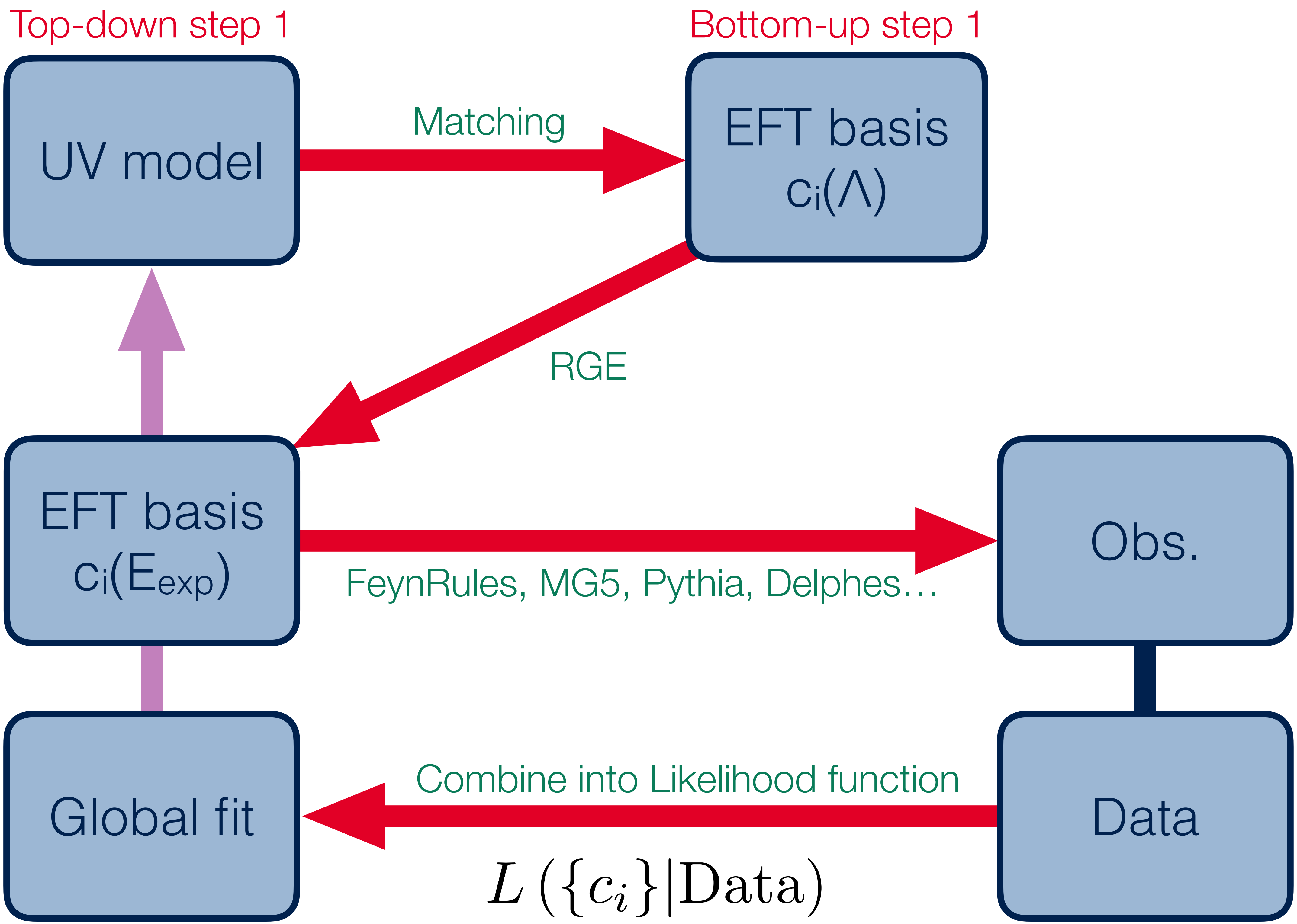
$$\delta S[\phi] = \int d^4x\, \frac{a}{\Lambda^2} \underbrace{\left(\frac{\partial \mathcal{L}_0}{\partial \phi} - \partial_\mu \frac{\partial \mathcal{L}_0}{\partial(\partial_\mu \phi)} \right)}_{0^{\text{th}}\text{ order EOM}} F[\phi] + \underbrace{\mathcal{O}\left(\frac{1}{\Lambda^4}\right)}_{\text{Dimension 8 terms}}$$

Choose *a, F[ϕ]* to eliminate an operator $c_i F[\phi] G[\phi] \subset \mathcal{L}_1,\ G[\phi] \subset \mathrm{EOM}_0$

$$a = -c_i \qquad\qquad \mathcal{L} \to \mathcal{L}_0 + \frac{1}{\Lambda^2}\mathcal{L}_1' + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- New, equivalent action **without O_i** and **shifted coefficients for O_j's**

Bottom-up EFT roadmap

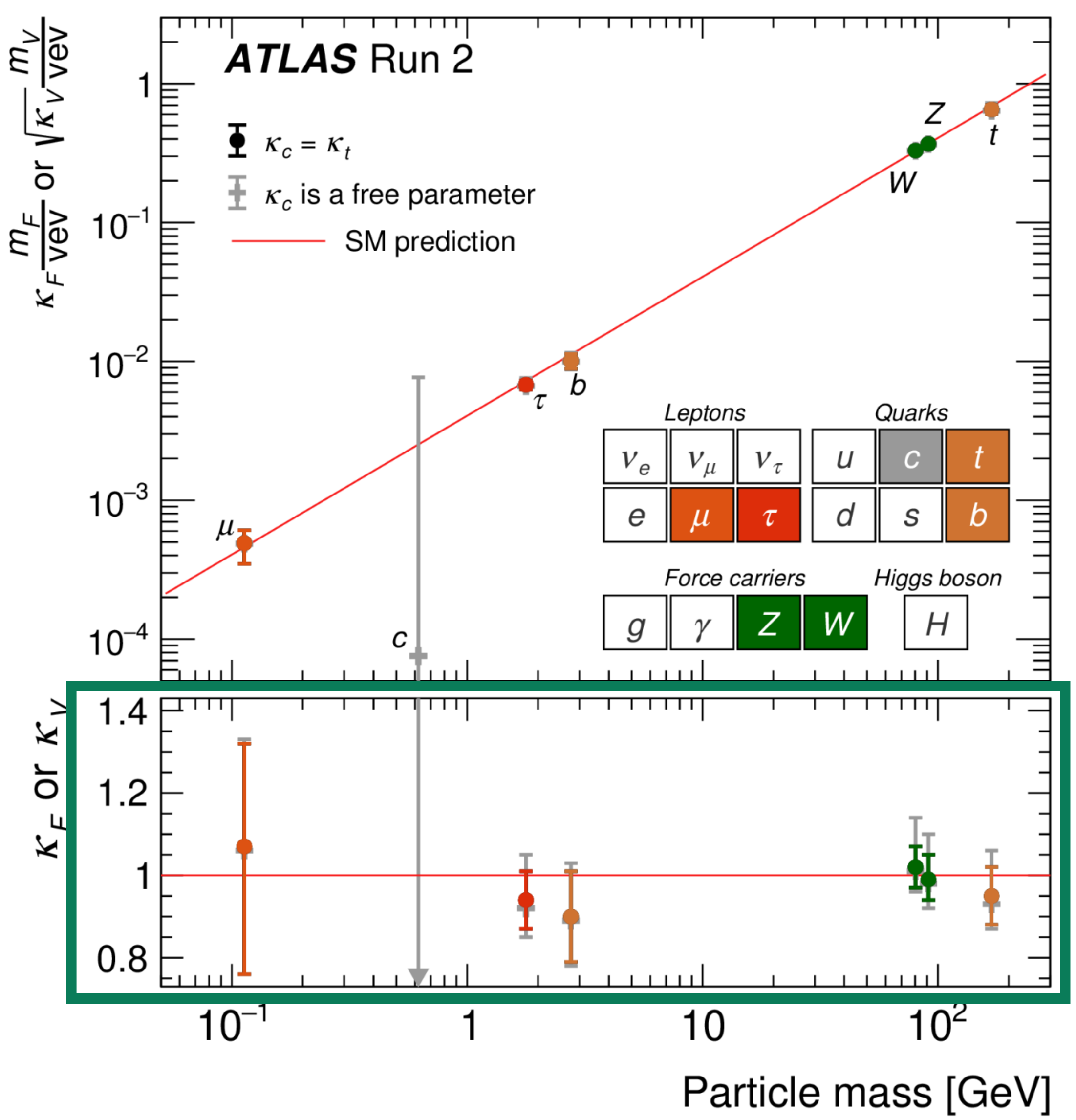


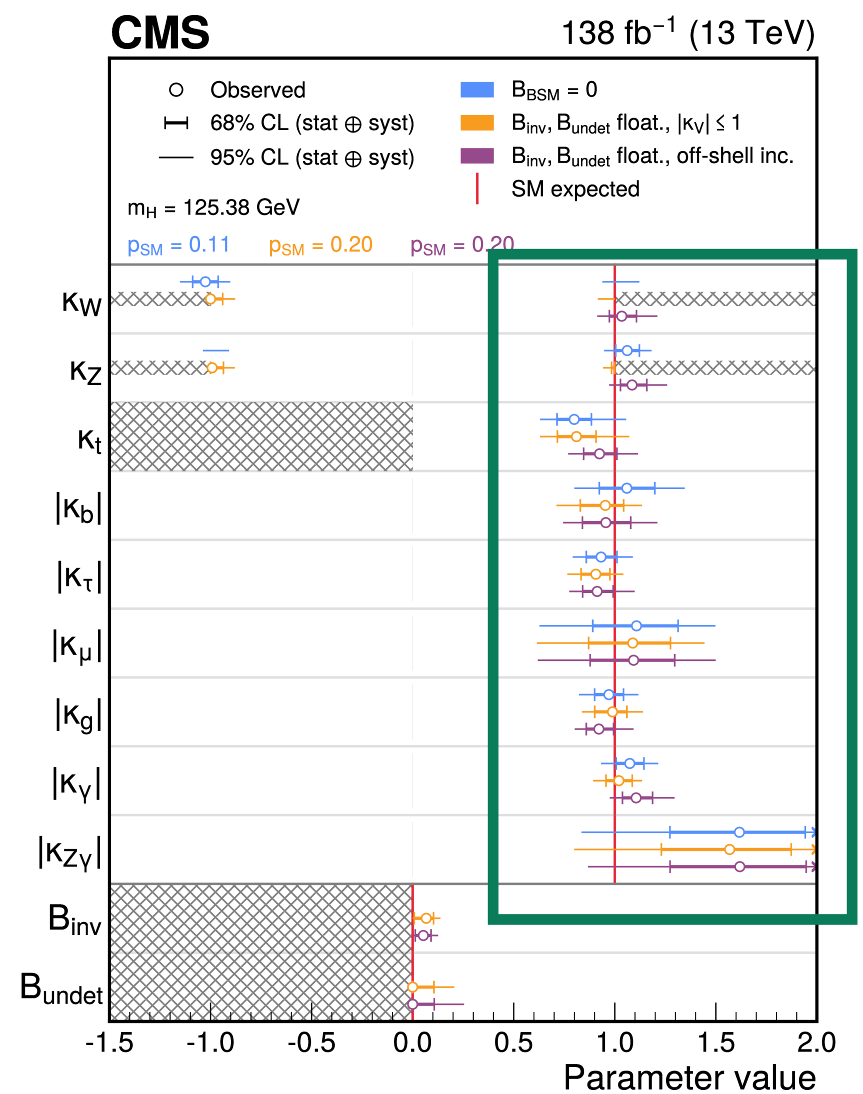
Part 2
The standard model as an EFT

The SM success story

We have found a scalar that couples to mass

- It behaves ***quite a bit*** like the SM Higgs





The SM success story

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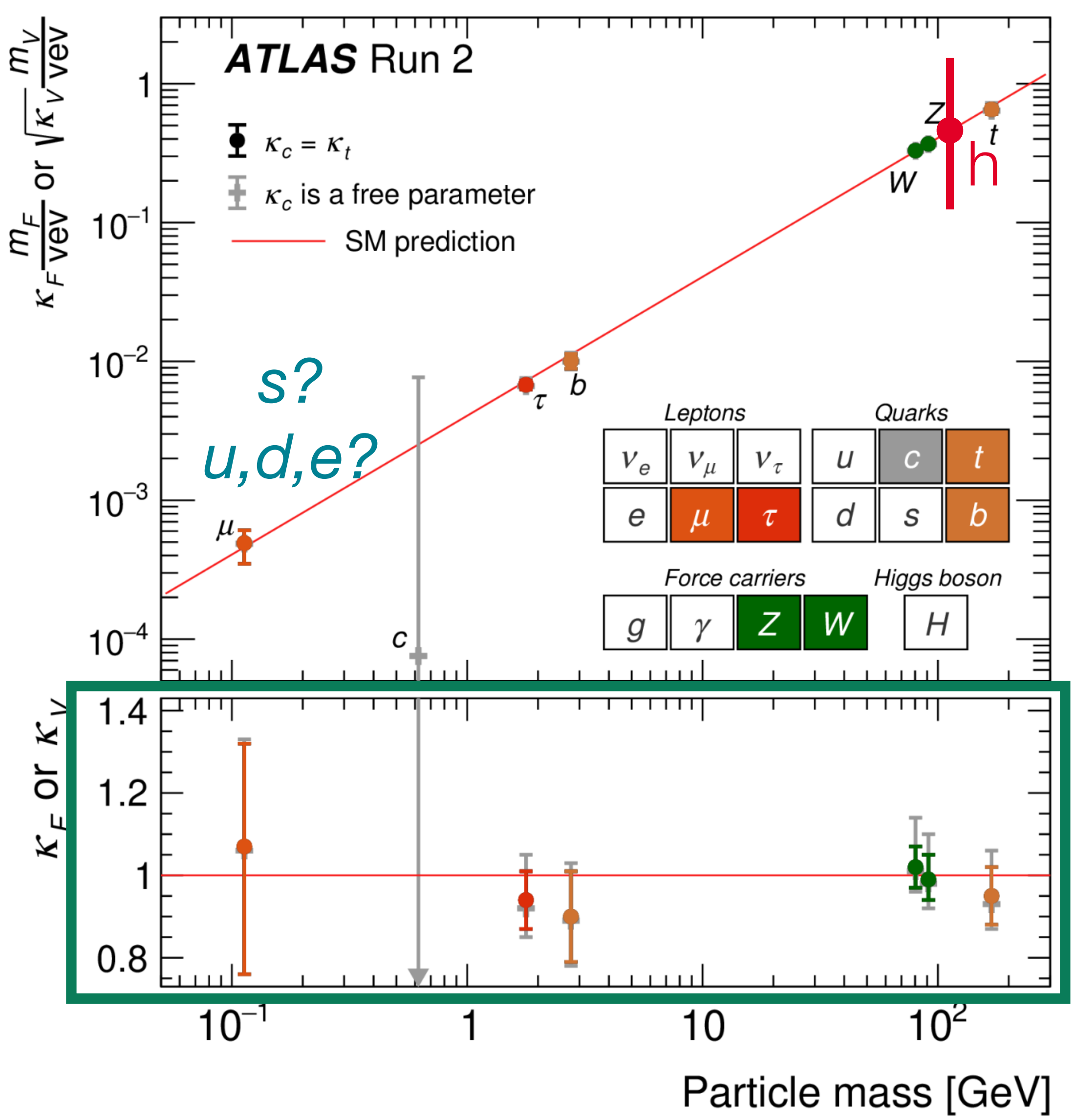


At least *one* missing ingredient…

Still some way to go to pin down precise interactions

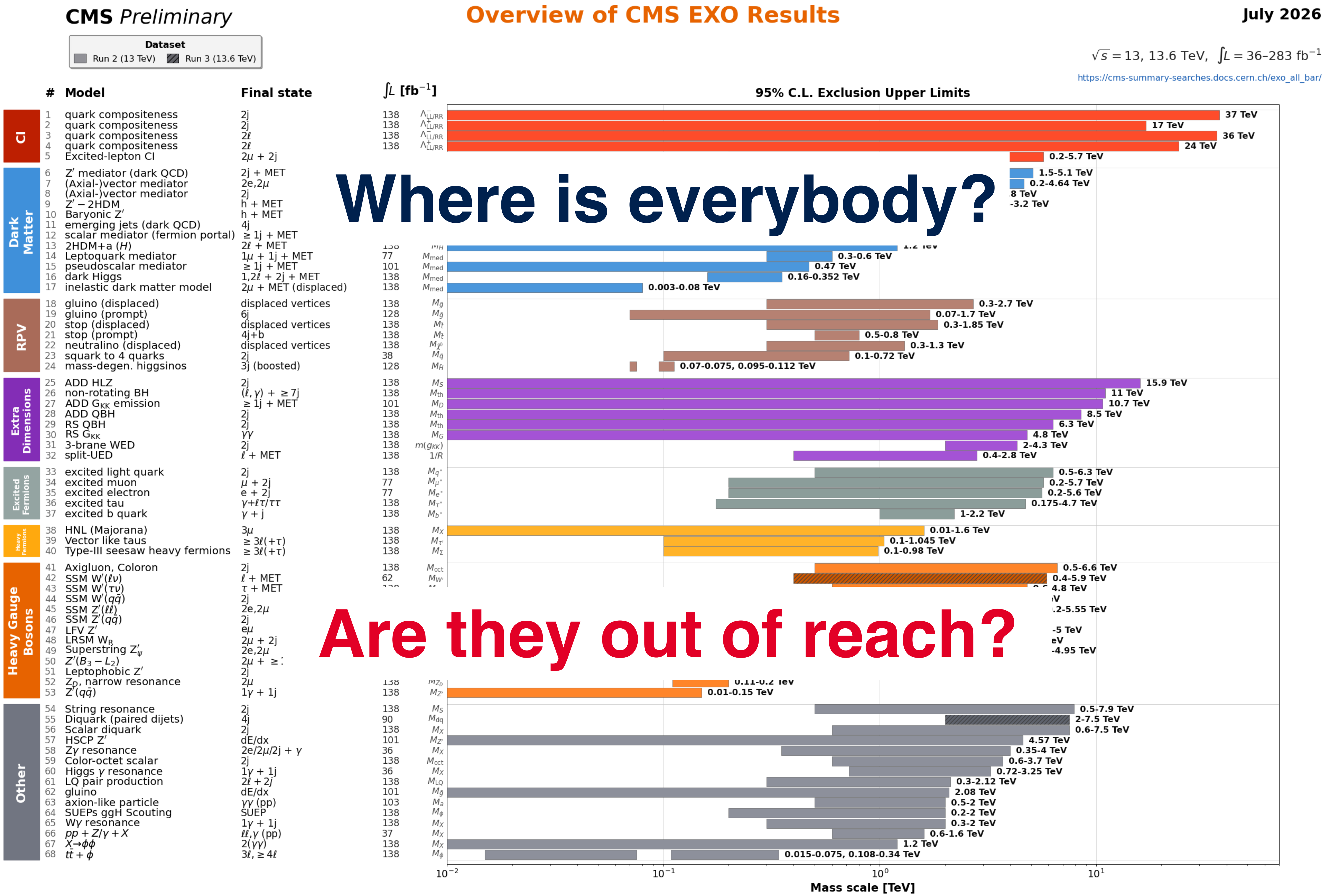
So far, all HEP data is broadly consistent with SM expectations

The LHC mission continues…

Precision measurements

Direct searches

The best motivation for EFT



Where is everybody?

Are they out of reach?

Back to reality

The standard model is a great candidate for an EFT

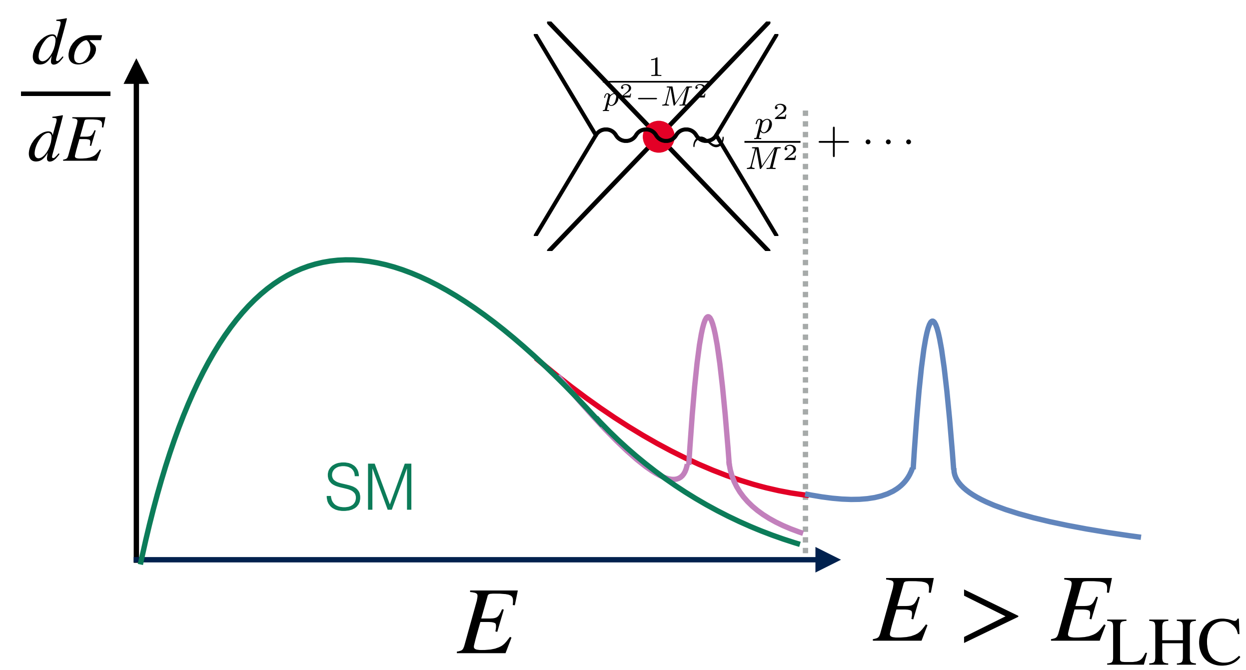
- A well understood low energy theory around the weak scale, v
- Low energy degrees of freedom: $\{Q_i, L_i, u_i, d_i, e_i, g, \gamma, W^\pm, Z, h\}$
- LHC data indicates a scale separation from possible new physics

Paradigm shift at the energy frontier for BSM searches

2010s: direct

2020s: Indirect

$\Rightarrow$ New physics is heavy

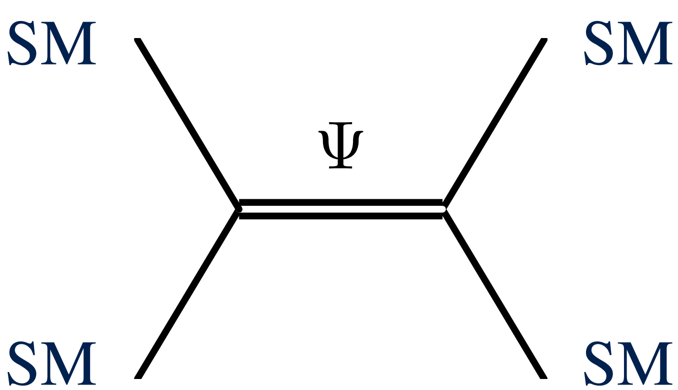


Heavy new physics
Precision measurements
High energy

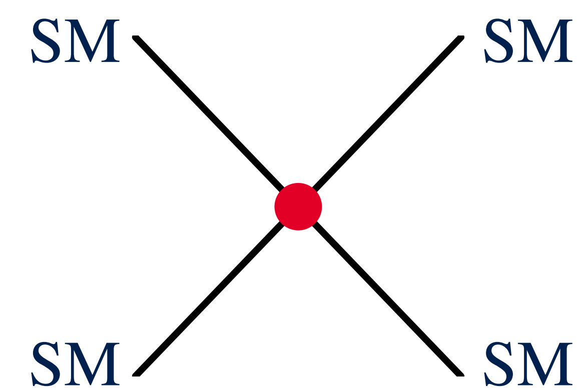
$\Rightarrow$ **Standard Model Effective Field Theory (SMEFT)**

EFT expansion

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



$$\frac{g^2}{p^2 - M^2} \approx -\frac{g^2}{M^2}\left[1 + \frac{p^2}{M^2} + \frac{p^4}{M^4} + \cdots\right]$$



$$\mathscr{L} \sim g\Psi\left(\phi^\dagger\phi\right) \approx \frac{g^2}{M^2}(\phi^\dagger\phi)^2 + \frac{g^2}{M^4}\phi^\dagger\phi\,\partial^\mu\phi^\dagger\partial_\mu\phi + \frac{g^2}{M^6}\partial^\mu\phi^\dagger\partial_\mu\phi\partial^\nu\phi^\dagger\partial_\nu\phi + \cdots$$

$s = p^2 < M^2$: EFT validity criterion

g not too large : Perturbative UV completion

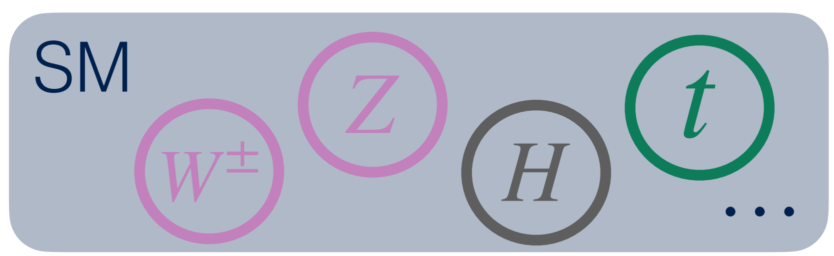
SMEFT: SM v2.0

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

BSM particle masses M ⇔ *Generic new physics scale* Λ

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

$\mathcal{O}_i^{(D)} \supset$



Low energy (SM) fields & symmetries

Model parameters $\left\{g^i_{\text{BSM}}, M_k\right\}$ ⇔ *Wilson coefficients* $\frac{c_j^{(D)}}{\Lambda^{D-4}}\left(g^i_{\text{BSM}}, M_k\right)$

measure g_i *: new physics model parameters*

"Matching"

measure c_i *: coupling strengths of new BSM interactions*

SMEFT

Operator expansion: $\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$ → more fields derivatives

SM gauge symmetry & linear EWSB

- Higgs is an SU(2) **doublet**
- Operators are $SU(3)_C \times SU(2)_L \times U(1)_Y$ **singlets**

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\varphi = \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} : \mathbf{2}_{\frac{1}{2}}$$

Parameter space for new interactions between SM particles

- With all nice features of EFT (gauge symmetry, matching, improvability,…)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

At dimension-5, only one operator

- Lepton number violating Weinberg operator (neutrino masses) $(\bar{L}^c \cdot H)(L \cdot H)$

Dimension-6 is the lowest non-trivial order

Operator classes

Dimension-6 operators of the SMEFT:	Interaction	Impact
$X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	gauge boson self-coupling	diboson
$H^6 : (\varphi^\dagger \varphi)^3$	Higgs potential, self-coupling	di-Higgs
$\psi^2 H^3 : (\varphi^\dagger \varphi)\ (\bar{q}_i\, u_j\, \tilde{\varphi})$	Higgs-fermion (Yukawa)	ttH, H→bb
$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$	gauge-fermion (Z,W)	Z,W prod.
$X^2 H^2 : (\varphi^\dagger \varphi)\ G^a_{\mu\nu} G^{\mu\nu}_a$	gauge-Higgs	ggH, H→VV
$H^4 D^2 : (\varphi^\dagger\, D^\mu \varphi)^* (\varphi^\dagger\, D^\mu \varphi)$	Higgs-Z	m_Z (LEP)
$\psi^2 X H : (\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu}$	dipole	ffV, ffVH
$\psi^4 : (\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$	four fermion	ffff scattering

SM gauge group singlets

[Buchmuller & Wyler; Nucl. Phys. B 268 (1986) 621]

[Grzadkowski et al.; JHEP 10 (2010) 085]

D=6 basis

'Warsaw' basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

59 independent operators (+ 5 B-violating)

real parameters (degrees of freedom)

76: flavor universal — All fermion generations have the same coefficient

2499: flavor general — Independent coefficient for all flavor combinations

Number for Dimension 8 (835, 36971) known (up to D=15!)

[Henning et al.; JHEP 08 (2017) 016]

SMEFT: SM v2.0

The SMEFT Wilson coefficients are **theory input parameters**

- In addition & analogous to SM input parameters $\{\alpha_S, \alpha_{EW}, G_F, m_Z, m_H, m_{f_i}\}$

LHC precision programme

↓

Measure the parameters of the
SM at dimension-6 (and beyond) $\{c_i\}$

↓

Extend the energy reach of our colliders to NP beyond E_{CM}

In order to do this, we must understand the impact of SMEFT interactions on scattering amplitudes in the low energy model (SM)

Impact of SMEFT

A) New Lorentz structures: contact interactions & derivatives

- Explicit source of energy growth

$$\psi^4 : (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l) \qquad X^3 : \epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$$

B) Modification of SM (dim-4) terms

- After electroweak symmetry breaking

Modification

$$\langle \varphi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\mathcal{O}_6 \to v\mathcal{O}_5,\, v^2\mathcal{O}_4$$

$(\varphi^\dagger \varphi)(\bar{q}\, u\, \tilde{\varphi}) \to v^2 (\bar{q}\, u\, \tilde{\varphi})$	Yukawa
$(\varphi^\dagger \varphi)^6 \to v^2 (\varphi^\dagger \varphi)^4, v^4 (\varphi^\dagger \varphi)^2, \ldots$	Higgs potential
$(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{f}\, \gamma^\mu f) \to v^2 Z^\mu (\bar{f}\, \gamma^\mu f)$	gauge-fermion
$(\varphi^\dagger \varphi)^2 F^{\mu\nu} F_{\mu\nu} \to v^2 F^{\mu\nu} F_{\mu\nu}$	gauge kinetic

- Shift of **SM-like** interactions
- Spoiling of unitarity cancellations of the SM → more energy growth
- SM inputs are extracted by comparing a few measurements to theory

➡ Extraction of SM inputs now **depends on c_i**

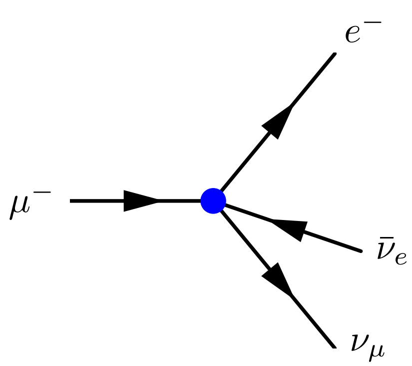
Example: G_F shift

Muon decay data gives: G_F = 1.17x10^{-5} GeV^{-2} → v = 246 GeV

- EFT contribution: A $[\mathcal{O}_{ll}]^{ijkl} = \left[\bar{l}^{(i)}\,\gamma^\mu\, l^{(j)}\right]\left[\bar{l}^{(k)}\,\gamma_\mu\, l^{(l)}\right]$

  B,C $[\mathcal{O}^{(3)}_{\varphi l}]^{ij} = \left[\varphi^\dagger \tau_k \overleftrightarrow{D}_\mu \varphi\right]\left[\bar{l}^{(i)}\,\tau^k \gamma^\mu\, l^{(j)}\right], \quad i = 1, 2.$
- A contains the O_F up to a Fierz transformation $[\mathcal{O}_{ll}]^{1221} = \frac{1}{4}\left(\bar{e}\,\gamma^\mu(1-\gamma_5)\,\nu_\mu\right)\left(\bar{\nu}_e\,\gamma_\mu(1-\gamma_5)\,\mu\right) + \cdots,$
- B,C shifts W couplings to leptons after EWSB $[\mathcal{O}_{ll}]^{2112} = \frac{1}{4}\left(\bar{e}\,\gamma^\mu(1-\gamma_5)\,\nu_\mu\right)\left(\bar{\nu}_e\,\gamma_\mu(1-\gamma_5)\,\mu\right) + \cdots,$

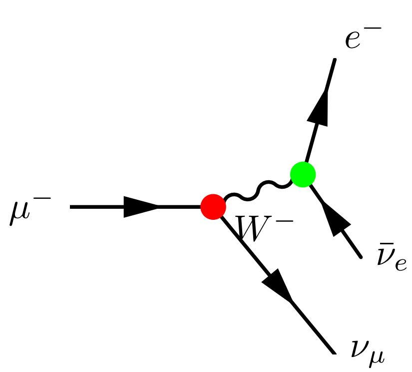
$$-i\frac{g}{\sqrt{2}} \to -i\frac{g}{\sqrt{2}}\left[1 + [C^{(3)}_{\varphi l}]^{ii}\frac{v^2}{\Lambda^2}\right]$$



$$\frac{G_F}{\sqrt{2}} = \frac{1}{2v^2}\left[1 + \frac{v^2}{\Lambda^2}[C^{(3)}_{\varphi l}]^{11}\right]\left[1 + \frac{v^2}{\Lambda^2}[C^{(3)}_{\varphi l}]^{22}\right] - \frac{1}{4}\frac{1}{\Lambda^2}\left([c_{ll}]^{1221} + [c_{ll}]^{2112}\right)$$

$$v_0^2 = \frac{1}{\sqrt{2}G_f}$$

New relation between Higgs vev and Fermi constant



$$v = v_0\left(1 + \left([C^{(3)}_{\varphi l}]^{11} + [C^{(3)}_{\varphi l}]^{22} - [c_{ll}]^{1212} - [c_{ll}]^{1221}\right)\frac{v_0^2}{\Lambda^2}\right)^{\frac{1}{2}}$$

Propagate to all observables that depend on v!
(expanded to order 1/Λ^2)

Computing observables

Pick a SMEFT basis and appropriate symmetries

- Control the number of parameters (2499 is a bit tough)
- Work out the Feynman rules (e.g. using FeynRules)
- Calculate Matrix element of scattering processes e.g. pp→ X for LHC

flavor structure,
CP conservation,
...

Generic contribution from SMEFT is an expansion in Λ^2

$$\mathcal{A} = \mathcal{A}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{A}^i \longrightarrow \sigma = \sigma_{SM} + \sum_i \frac{c_i}{\Lambda^2}\sigma^i_{(\text{int.})} + \sum_{i,j}\frac{c_i c_j}{\Lambda^4}\sigma^{ij}_{(\text{sq.})}$$

single operator insertion

$|\mathcal{A}_{SM}|^2$ $\quad 2\mathrm{Re}[\mathcal{A}^*_{SM}\mathcal{A}_{EFT}]$ $\quad |\mathcal{A}_{EFT}|^2$

Leading contribution from interference

- Quadratic EFT term is formally higher order, although basis independent
- Subleading unless interference forbidden/suppressed (symmetries/helicity)
- Importance with respect to dim-8 operators is model dependent

SMEFT roadmap

Basis → Processes & Observables → Sensitivity → Measurement → Global fit

Degeneracies/blind directions

New processes/observables

Map to UV models

Hints of new physics?

Constrain classes of models

Validity of EFT

***A posteriori**: depends on sensitivity*

Intrinsically model dependent

SMEFT likelihood

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

Model A

Model B

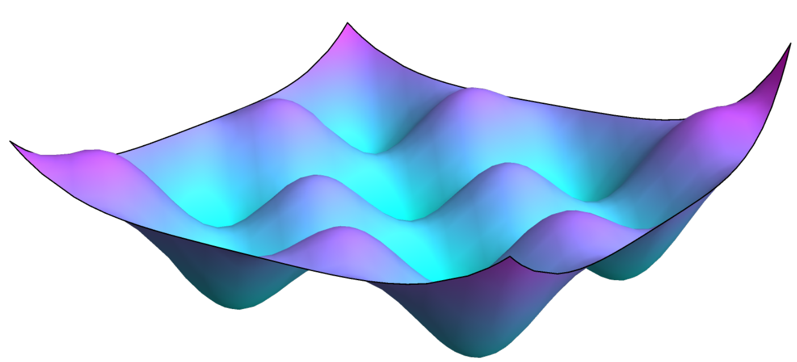
Model C

$U(3)^5 \quad U(2)^5$

$U(3)^3 \times U(2)^2$

$$\mathscr{L}(c_i\,|\,\vec{o})$$

SMEFT likelihood



$\mathscr{L}(g_A) \quad \mathscr{L}(g_B)$

$\mathscr{L}(g_C)$

c_i **bounds**

- Individual
- Marginalised
- Flat directions

Flavour symmetry

Consider SM fermion kinetic terms: $\mathscr{L}_{\text{kin.}} = \sum_{\psi=q,u,d,\ell,e}^{i=1,2,3} \bar{\psi}_i \gamma^\mu D_\mu \psi_i$

- Each term is invariant under a $U(3)_\psi$ flavor rotation

$$\psi_i \to U^\psi_{ij}\,\psi_j$$

all generations equivalent

- Massless SM has a large global flavor symmetry:

$$G_f = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e \Rightarrow U(3)^5$$

- Yukawa interactions break the flavor symmetry G_f

$$\mathscr{L}_{\text{Yuk.}} = y_u^{ij}\,\tilde{\phi}\,\bar{q}_i u_j + y_d^{ij}\,\phi\,\bar{q}_i d_j + y_e^{ij}\,\phi\,\bar{\ell}_i e_j + \text{h.c.}$$

involve two different G_f representations

$$G_f \to U(1)^5 = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_Y$$

New physics can have arbitrary flavor structure

- Flavour symmetry assumptions often used to control number of parameters

Flavour symmetry in SMEFT

Large number of SMEFT coefficients come from flavor indices

$$c_{ijkl}\,\bar{\psi}_i\psi_j\bar{\psi}_k\psi_l \qquad c_{ij}\,|\phi|^3\,\bar{\psi}_i\psi_j \qquad c_{ij}\,(\phi\overleftrightarrow{D}^{\mu}\phi)(\bar{\psi}_i\gamma_\mu\psi_j) \qquad c_{ij}\,\phi(\bar{\psi}_i\sigma_{\mu\nu}\psi_j)F^{\mu\nu}$$

Assume UV theory respects particular flavor symmetry

- $U(3)^5$: single coefficients for each operator a.k.a. *universal theory*
- $U(2)_\psi$: common coefficient for 1st & 2nd generation, independent for 3rd
- $U(2)_q \times U(2)_u \times U(3)^3$: singles out top quark
- Minimal flavor violation: same flavour breaking as the SM (y_ψ^{ij})
  [D'Ambrosio et al.; Nucl. Phys. B 645 (2002) 155]

Coefficients c_{ijkl} will respect that symmetry at the matching scale

SM breaks $U(3)^5 \to U(1)^5$

- Flavour symmetries not preserved by RG evolution (weak loops)