Summary of Lecture-1

Physics of different energy scales: may be connected to each other or NOT.

Two approaches of EFT: Top-Down and Bottom-Up

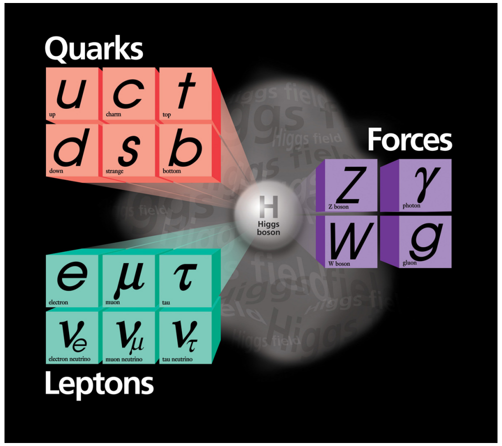
EFT Keywords: Integrating out, Matching, Truncation,...

Construction of Composite operators: Symmetry and IR DOF

Redundancy: IBP, EOM, Total Derivative

The Standard Model

Particle content



Courtesy: Fermilab

Symmetry

Gauge group : $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

$$q_L : (3, 2, 1/6)$$
$$l_L : (1, 2, -1/2)$$
$$e_R : (1, 1, -1)$$
$$u_R : (3, 1, 2/3)$$
$$d_R : (3, 1, -1/3)$$
$$H : (1, 2, 1/2)$$

Feynman PhysRev.76.769

Gross, Wilczek, Politzer
PRL 30.1343, PRL 30.1343

Weinberg PRL 19.1264

The Standard Model of particle physics is successful.

But there are more questions! —— Neutrino oscillation, dark matter, baryon asymmetry, …

(1) Predict new particles yet undiscovered

(2) Enlarge the underlying symmetry

Beyond Standard Model scenarios

- in short BSM scenarios

BSM scenarios and Effective theory

BSM scenarios

No clue about properties of new particles

No clue about underlying gauge symmetry

Hint from history : Fermi's idea of four-fermion vertex

Higher mass dimension operators

$\mathcal{L}_{\rm BSM} \rightarrow \mathcal{L}_{\rm SM}$ + higher mass dimension operators

Utility of EFT : Parameterising lack of information in terms of higher mass dimension operators

Moreover, *if the energy scale of new physics is beyond the reach of recent experiments*

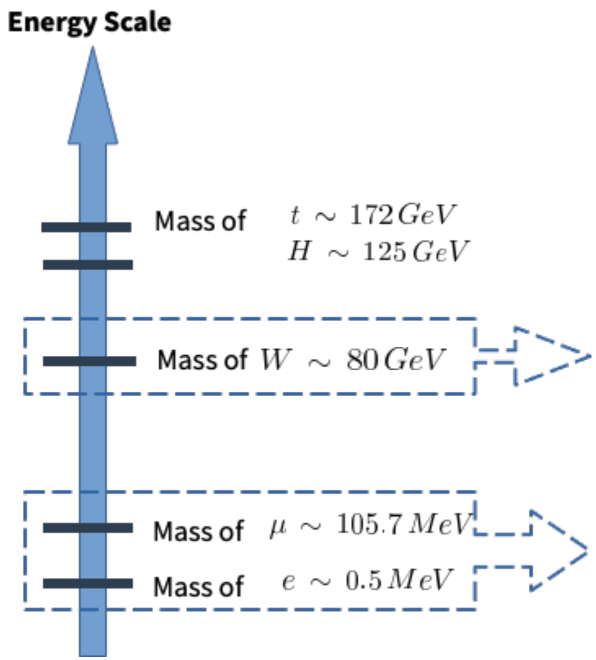
Use of EFT is desirable :

Study the relevant processes — no need to consider the full theory

Georgi ARNPS 1993 43:209-52

Manohar arXiv:1804.05863

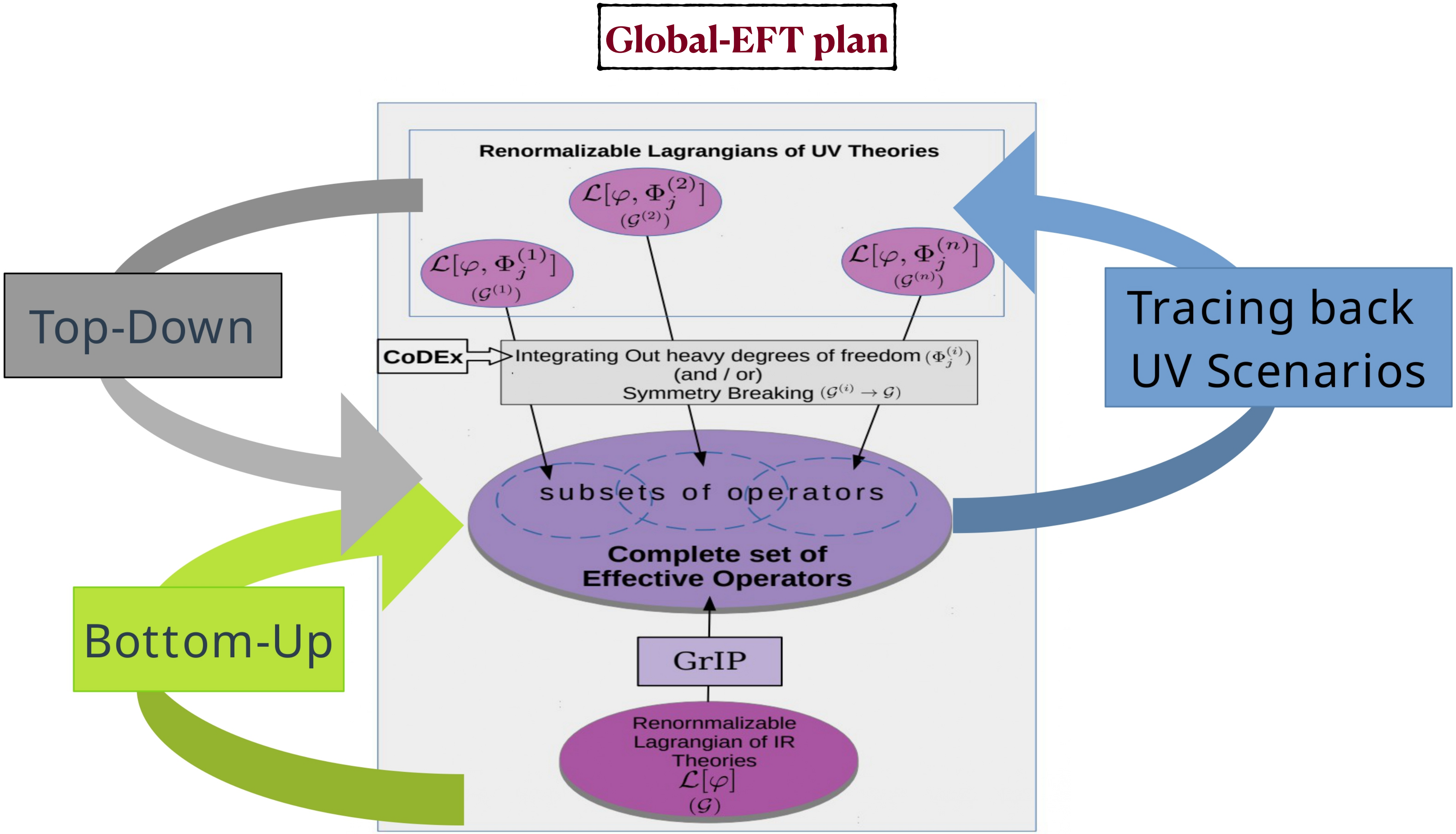
Range of Scales

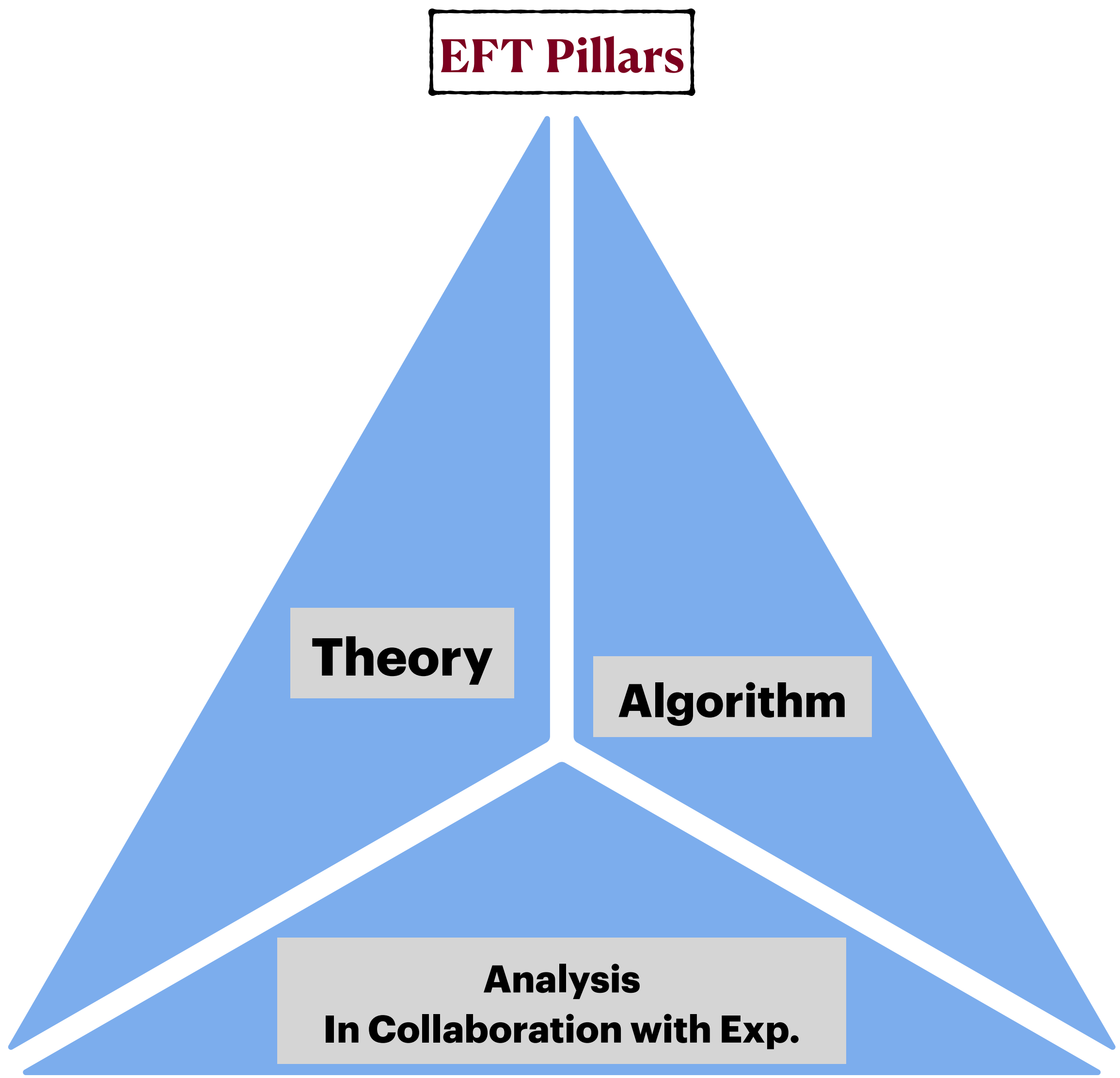


Beyond Standard Model - A complete theory
vs
Standard Model Effective theory (SMEFT)

Standard Model
vs
Low Energy Effective Theory (LEFT)

Energy scale for 4-Fermi theory of muon decay.
Low Energy Theory


Global-EFT plan
Renormalizable Lagrangians of UV Theories
$\mathcal{L}[\varphi, \Phi_j^{(1)}]$ $(\mathcal{G}^{(1)})$
$\mathcal{L}[\varphi, \Phi_j^{(2)}]$ $(\mathcal{G}^{(2)})$
$\mathcal{L}[\varphi, \Phi_j^{(n)}]$ $(\mathcal{G}^{(n)})$
CoDEx
Integrating Out heavy degrees of freedom $(\Phi_j^{(i)})$
(and / or)
Symmetry Breaking $(\mathcal{G}^{(i)} \to \mathcal{G})$
subsets of operators
Complete set of
Effective Operators
GrIP
Renornmalizable
Lagrangian of IR
Theories
$\mathcal{L}[\varphi]$
$(\mathcal{G})$
Top-Down
Bottom-Up
Tracing back
UV Scenarios


EFT Pillars
Theory
Algorithm
Analysis
In Collaboration with Exp.

Some recent References:

Theoretical

1. **One-loop effective action up to any mass-dimension for non-degenerate scalars and fermions including light–heavy mixing**
   Upalaparna Banerjee, Joydeep Chakrabortty, Shakeel Ur Rahaman, Kaanapuli Ramkumar
   Eur.Phys.J.Plus 139 (2024) 2, 169 • e-Print: 2311.12757 [hep-ph].

2. **One-loop Effective Action up to Dimension Eight: Integrating out Heavy Fermion(s)**
   Joydeep Chakrabortty, Shakeel Ur Rahaman, Kaanapuli Ramkumar
   Nucl.Phys.B 1000 (2024) 116488 • e-Print: 2308.03849 [hep-ph]

3. **One-loop Effective Action up to Dimension Eight: Integrating out Heavy Scalar(s)**
   Upalaparna Banerjee, Joydeep Chakrabortty, Shakeel Ur Rahaman, Kaanapuli Ramkumar
   Eur.Phys.J.Plus 139 (2024) 2, 159 • e-Print: 2306.09103 [hep-ph]

4. **EFT, Decoupling, Higgs Mixing and All That Jazz**
   Upalaparna Banerjee, Joydeep Chakrabortty, Christoph Englert, Wrishik Naskar, Shakeel Ur Rahaman, Michael Spannowsky
   e-Print: 2303.05224 [hep-ph].

Some recent References:

Theoretical

5. **EFT Diagrammatica. Part II. Tracing the UV origin of bosonic D6 CPV and D8 SMEFT operators**
Wrishik Naskar, Suraj Prakash, Shakeel Ur Rahaman,
JHEP 08 (2022) 190; e-Print: 2205.00910 [hep-ph].

6. **EFT Diagrammatica: UV Roots of the CP-conserving SMEFT**
Supratim Das Bakshi, Joydeep Chakrabortty, Suraj Prakash, Michael Spannowsky, Shakeel Ur Rahaman.
JHEP 06 (2021) 033; e-Print: 2103.11593 [hep-ph].

7. **Classifying Standard Model Extensions Effectively with Precision Observables**
Supratim Das Bakshi, Joydeep Chakrabortty, Michael Spannowsky.
Phys.Rev.D 103 (2021) 5, 056019; e-Print: 2012.03839 [hep-ph].

8. **Effective Operator Bases for Beyond Standard Model Scenarios: An EFT compendium for discoveries**
Upalaparna Banerjee, Joydeep Chakrabortty, Suraj Prakash, Shakeel Ur Rahaman, Michael Spannowsky.
JHEP 01 (2021) 028; e-Print: 2008.11512 [hep-ph].

Some recent References:

Algorithms

1. **Integrating out heavy scalars with modified equations of motion: Matching computation of dimension-eight SMEFT coefficients**
   Upalaparna Banerjee, Joydeep Chakrabortty, Christoph Englert, Shakeel Ur Rahaman, Michael Spannowsky
   Phys.Rev.D 107 (2023) 5, 055007; e-Print: 2210.14761 [hep-ph].

2. **Characters and group invariant polynomials of (super)fields: road to "Lagrangian"**
   Upalaparna Banerjee, Joydeep Chakrabortty, Suraj Prakash, Shakeel Ur Rahaman.
   Eur.Phys.J.C 80 (2020) 10, 938; e-Print: 2004.12830 [hep-ph].

3. **Hilbert Series and Plethystics: Paving the path towards 2HDM- and MLRSM-EFT**
   Anisha, Supratim Das Bakshi, Joydeep Chakrabortty, Suraj Prakash.
   JHEP 09 (2019) 035; e-Print: 1905.11047 [hep-ph].

4. **CoDEx: Wilson coefficient calculator connecting SMEFT to UV theory**
   Supratim Das Bakshi, Joydeep Chakrabortty, Sunando Kumar Patra.
   Eur.Phys.J.C 79 (2019) 1, 21; e-Print: 1808.04403 [hep-ph].

Some recent References:

Analysis

1. **Effective limits on single scalar extensions in the light of recent LHC data**
   Anisha, Supratim Das Bakshi, Shankha Banerjee, Anke Biekötter, Joydeep Chakrabortty, Michael Spannowsky, Sunando Kumar Patra; *Phys.Rev.D* 107 (2023) 5, 055028; e-Print: 2111.05876 [hep-ph].

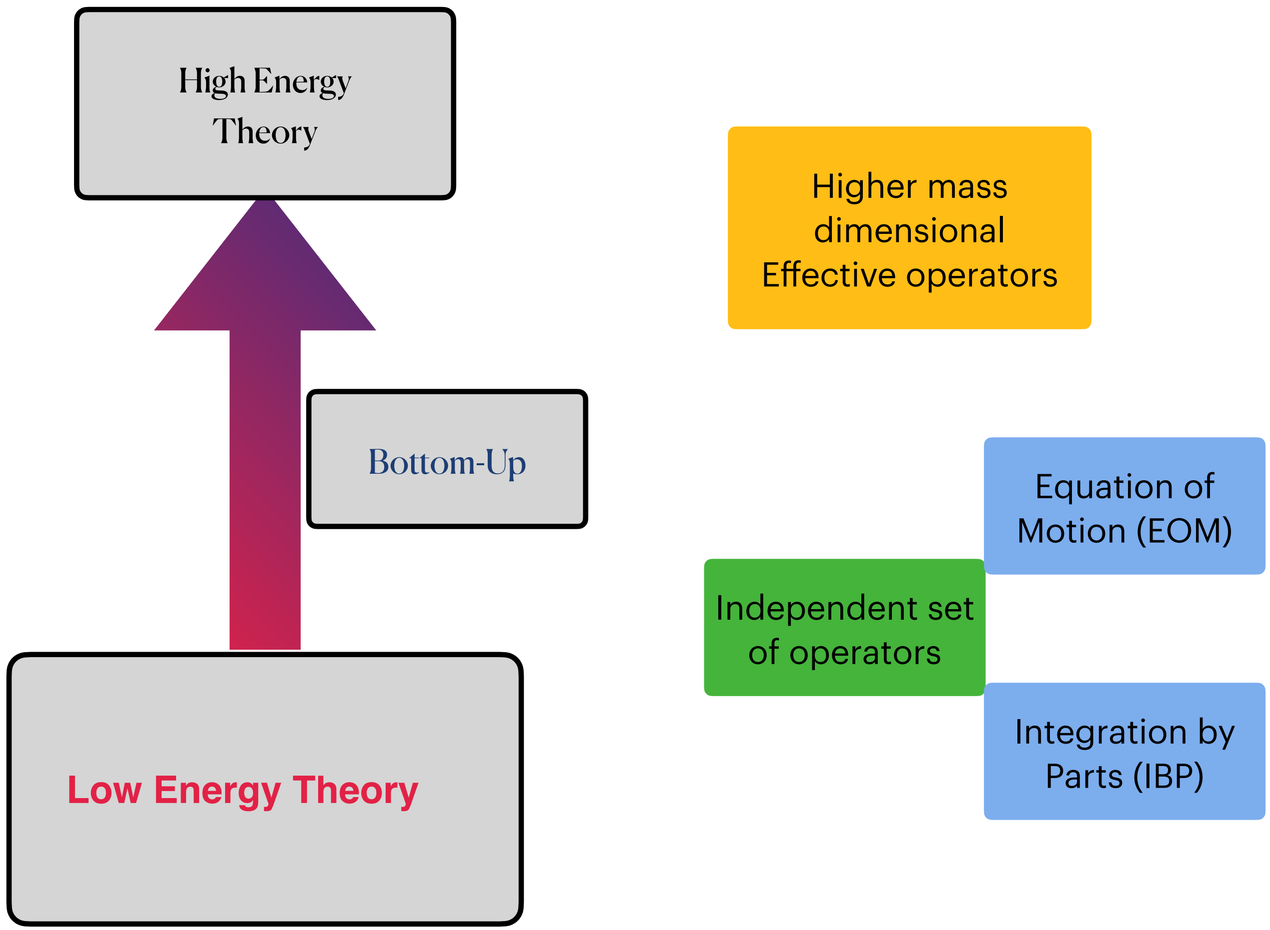
2. **Effective connections of aμ, Higgs physics, and the collider frontier**
   Anisha, Upalaparna Banerjee, Joydeep Chakrabortty, Christoph Englert, Michael Spannowsky, Panagiotis Stylianou. *Phys.Rev.D* 105 (2022) 1, 016019; e-Print: 2108.07683 [hep-ph].

3. **Landscaping CP-violating BSM scenarios**
   Supratim Das Bakshi, Joydeep Chakrabortty, Christoph Englert, Michael Spannowsky, Panagiotis Stylianou. *Nucl.Phys.B* 975 (2022) 115676; e-Print: 2103.15861 [hep-ph].

4. **Extended Higgs boson sectors, effective field theory, and Higgs boson phenomenology**
   Anisha, Upalaparna Banerjee, Joydeep Chakrabortty, Christoph Englert, Michael Spannowsky. *Phys.Rev.D* 103 (2021) 9, 096009; e-Print: 2103.01810 [hep-ph].

5. **A Step Toward Model Comparison: Connecting Electroweak-Scale Observables to BSM through EFT and Bayesian Statistics**
   Anisha, Supratim Das Bakshi, Joydeep Chakrabortty, Sunando Kumar Patra. *Phys.Rev.D* 103 (2021) 7, 076007; e-Print: 2010.04088 [hep-ph].

Theory & Algorithm


High Energy Theory
Bottom-Up
Low Energy Theory
Higher mass dimensional Effective operators
Independent set of operators
Equation of Motion (EOM)
Integration by Parts (IBP)

Subtleties of building effective operators

Mass Dimension:

$$S = \int d^D x \mathcal{L} \ , \ \text{for } D = 3+1, \ [\mathcal{L}] = 4$$

Mass dimension of various types of fields:

$$[\Phi] = 1; \quad [A_\mu] = 1; \quad [\Psi] = \frac{3}{2}; \quad [\mathcal{D}] = 1; \quad [X_{\mu\nu}] = 2$$

Φ :	Scalar Fields
Ψ :	Fermion Fields
A_μ :	Gauge Fields
$\mathcal{D}_\mu$:	Covariant derivative
$X_{\mu\nu}$:	Field Strengtgh

Mass dimension of an operator:

$$\text{Operator: } \mathcal{O} \equiv \Phi^p \times \Psi^q \times \mathcal{D}^r \times X^s$$

$$[\mathcal{O}] = d = p + \frac{3}{2}q + r + 2s$$

$$X_{L,\mu\nu} = \tfrac{1}{2}(X_{\mu\nu} - i\tilde{X}_{\mu\nu})$$

$$X_{R,\mu\nu} = \tfrac{1}{2}(X_{\mu\nu} + i\tilde{X}_{\mu\nu})$$

An operator constituted using various fields is invariant under all the underlying symmetries.

•Space-time Symmetry: $\text{Lorentz Group } SO(3,1) \subset (SU(2)_L \times SU(2)_R)$

Transformation of various field under the Lorentz symmetry:

$$\Phi \equiv (0,0)\,,\ \Psi_L \equiv \left(\frac{1}{2},0\right),\ \Psi_R \equiv \left(0,\frac{1}{2}\right),\ \mathcal{D} \equiv \left(\frac{1}{2},\frac{1}{2}\right),\ X_L \equiv (1,0)\,,\ X_R \equiv (0,1)$$

•Standard Model Gauge Symmetry:

$$SU(3) \otimes SU(2) \otimes U(1)$$

$$\Phi \equiv \{\, H : (1,2,1/2)$$

$$\Psi \equiv \begin{cases} l_L : & (1,2,-1/2) \\ e_R : & (1,1,-1) \\ q_L : & (3,2,1/6) \\ u_R : & (3,1,2/3) \\ d_R : & (3,1,-1/3) \end{cases}$$

$$X \equiv \begin{cases} B_L : & (1,1,0) \\ W_L : & (1,3,0) \\ G_L : & (8,1,0) \end{cases}$$

Example: Φ^5

✓ **Lorentz Scalar**

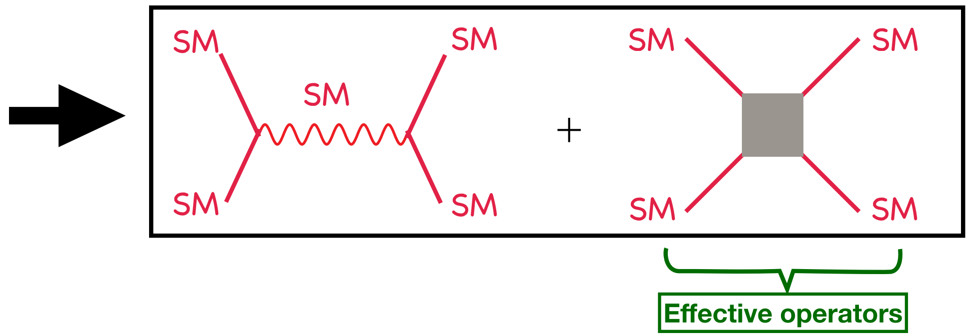
✗ **Not gauge-invaraint**

Bottom-Up approach: *SMEFT*

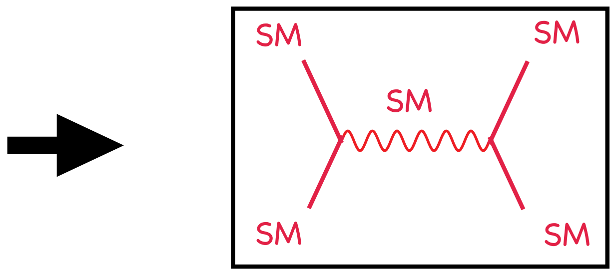
★ **Knowledge of exact nature of new physics is not required**

✤ **Wilson coefficients are free parameters: *origin-less***

$$\mathcal{L}_{\rm SM} + \underbrace{\sum_{j=5,\dots} \sum_i \frac{C_i^{(j)}}{\Lambda^{j-4}} Q_i^{(j)}}_{\text{Effective operators}}$$



$$\mathcal{L}_{\rm SM}$$



Automation

GrIP: https://teamgrip.github.io/GrIP U Banerjee, J Chakrabortty, ***S Prakash,*** SU Rahaman *EPJC* 80 (2020) 10, 938

Mathematica based package with a user friendly interface:

- Model info (symmetry information, field content) read through an input file
- Commands entered through a notebook file
- Results displayed on the same notebook file
- *Familiarity with the Group-theoretic backbone is not required*
- Input files for a plethora of popular models are available with the tarball

package contents →

GrIP.m
GrpInfo.m
Example_SM.nb
MODEL

\+

Example_MSSM.nb
Example_CHaar.nb
CHaar.m

SM extended by

Scalars

Real singlet scalar
Singly and Doubly charged scalars
SU(2) N-plet scalars with various hypercharges
Scalar Lepto-quarks (with non-trivial color charges)

Fermions

Sterile Neutrino
Left-handed SU(2) triplet fermion
Right-handed singlet fermion

Below electro-weak scale models

Light DM candidates

Singlet Scalar
Vector-like fermion pair

Symmetries containing SM

Pati-Salam model
Georgi-Glashow SU(5) model
Minimal Left-Right Symmetric model

GrIP user interface and commands

```
In[1]:= SetDirectory["~/home"]

In[2]:= Get["MODEL/SM_Rep.m"]

In[3]:= Get["GrIP.m"]

In[4]:= DisplayUserInputTable

Out[4]:=
```

Field Name	Self Conjugate	Lorentz Behaviour	Chirality	Baryon Number	Lepton Number	SU3Rep	SU2Rep	U1Rep
H	False	SCALAR	NA	0	0	1	2	1/2
Q	False	FERMION	l	1/3	0	3	2	1/6
u	False	FERMION	r	1/3	0	3	1	2/3
d	False	FERMION	r	1/3	0	3	1	-1/3
L	False	FERMION	l	0	-1	1	2	-1/2
el	False	FERMION	r	0	-1	1	1	-1
Bl	False	VECTOR	l	0	0	1	1	0
Wl	False	VECTOR	l	0	0	1	3	0
Gl	False	VECTOR	l	0	0	8	1	0

```
In[8]:= DisplayHSOutput["MassDim"→4, "OnlyMassDimOutput"→True,
          "ΔB"→0, "ΔL"→0, "Flavours"→1]

In[9]:= DisplayBLviolatingOperators["HighestMassDim"→10, "ΔB"→ +1(−1),
          "ΔL"→ −1(+1), "Flavours"→1]

In[10]:= Polyd6 = SaveHSOutput["MassDim" -> 6, "ΔB" -> "NA", "ΔL" -> "NA", "Flavours" -> Nf];
```

SMEFT (d = 6) operator basis

$1 : X^3$		$2 : H^6$		$3 : H^4 D^2$		$5 : \psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						

$4 : X^2 H^2$		$6 : \psi^2 X H + \text{h.c.}$		$7 : \psi^2 H^2 D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

B Grzadkowski, M Iskrzynski, M Misiak, J Rosiek (2010), arXiv:1008.4884

SMEFT (d = 6) operator basis continued ...

Only B-, L-Conserving

$8:(\bar{L}L)(\bar{L}L)$		$8:(\bar{R}R)(\bar{R}R)$		$8:(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$		$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

B Grzadkowski, M Iskrzynski, M Misiak, J Rosiek (2010), arXiv:1008.4884