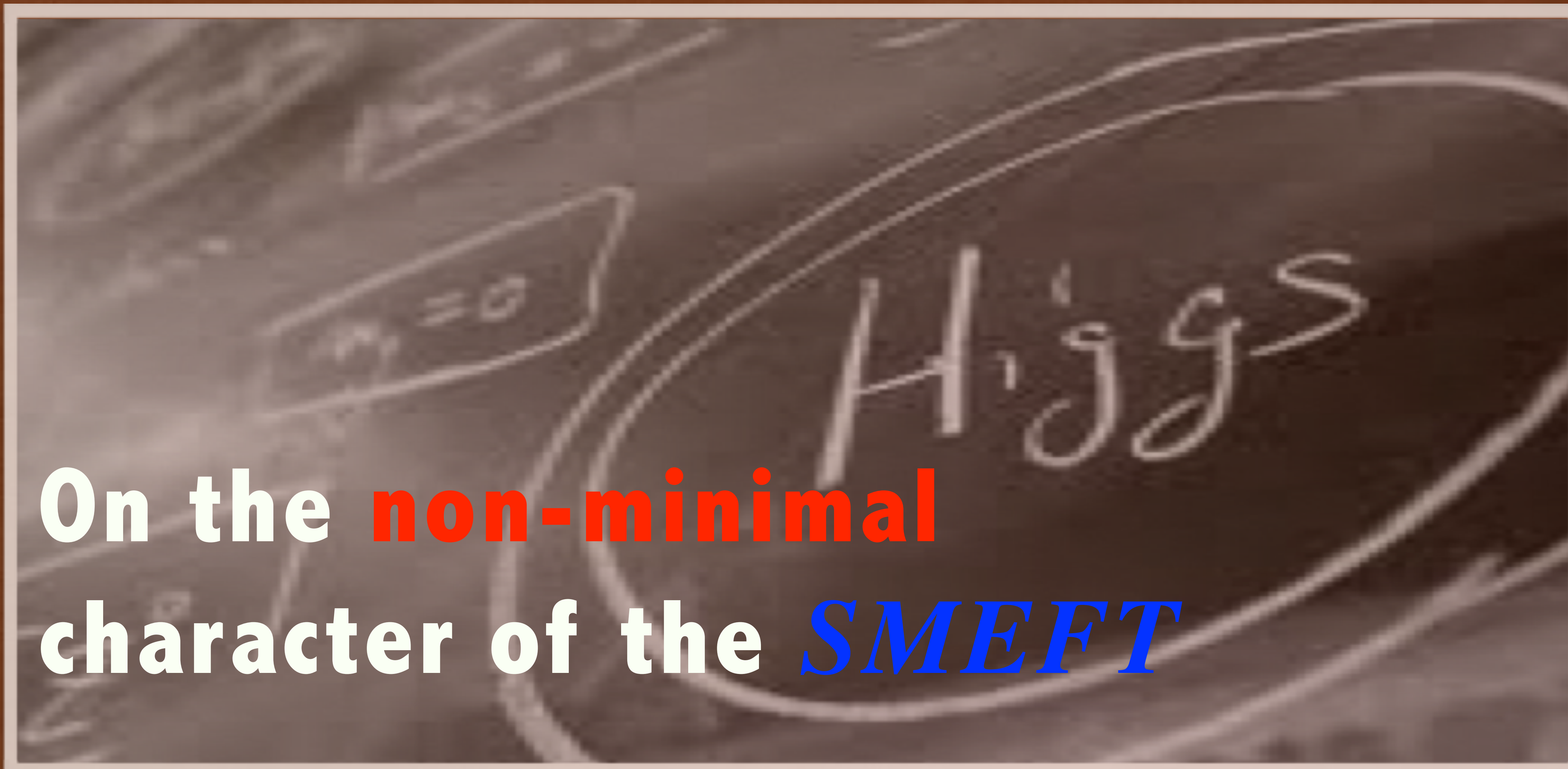
On the non-minimal character of the *SMEFT*



Yun Jiang

Niels Bohr Institute

HEFT2017

2017.05.24

based on PLB 770 (2017) 105, arXiv: 1612.02040 [hep-ph] with M. Trott.

OUTLINES

- Motivation

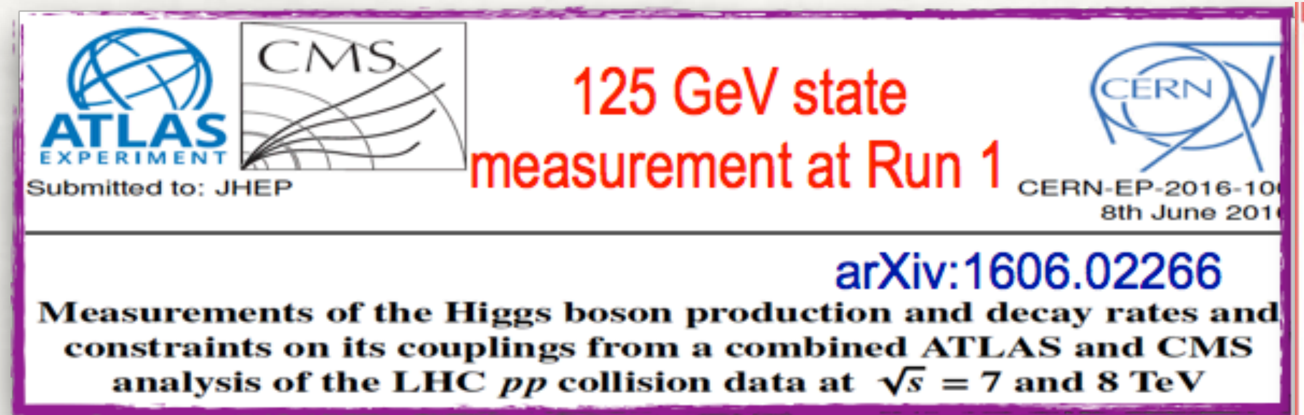
  ① *One operator "at a time"*

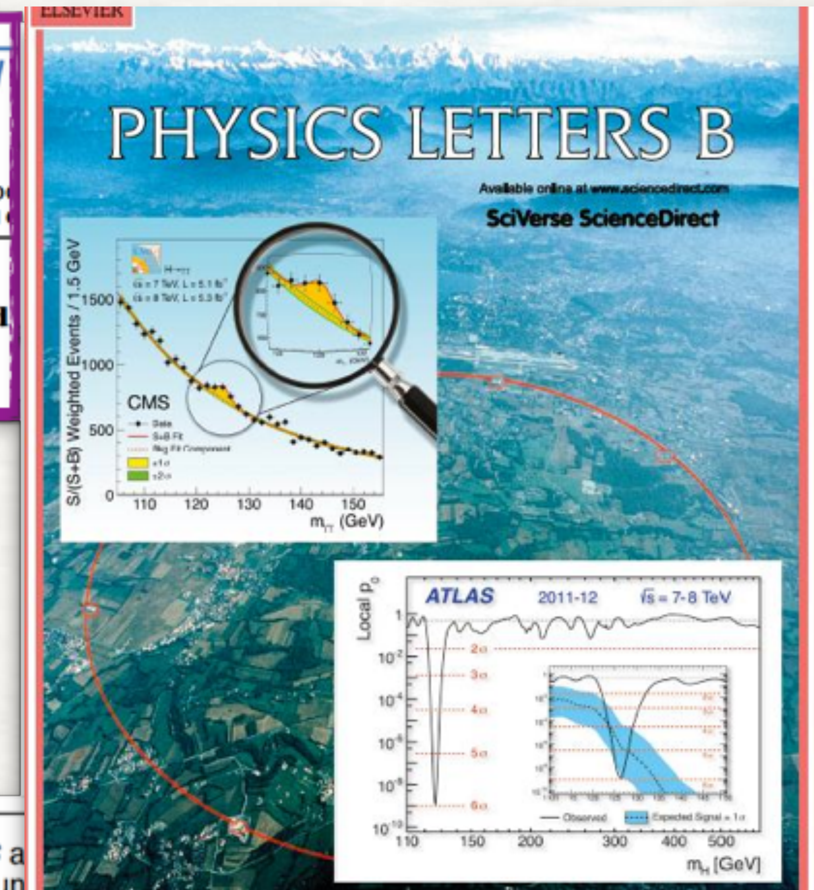
  ② ***Data fits to subsets of operators,*** *a reasonable way of selecting the operators?*

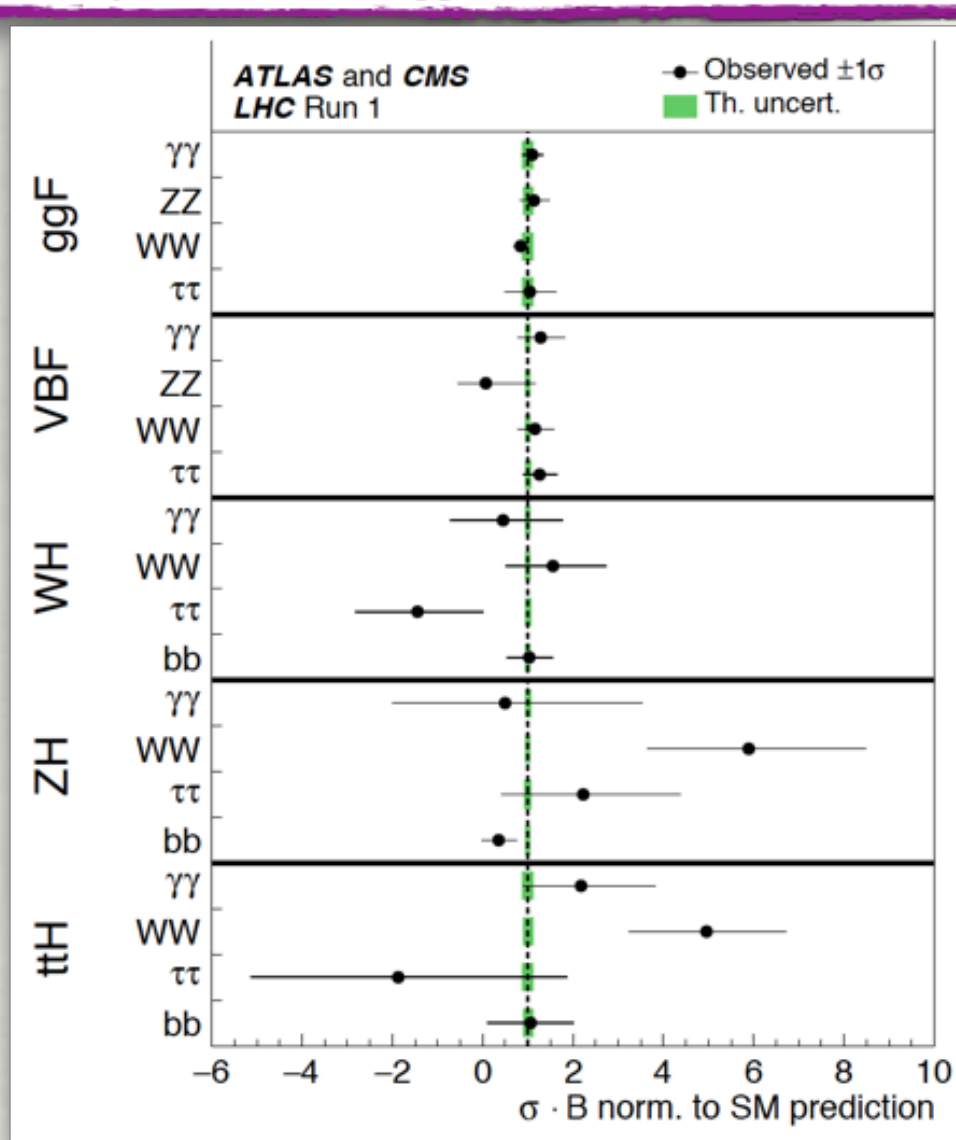
  ③ *Are some operators always simultaneously present?*

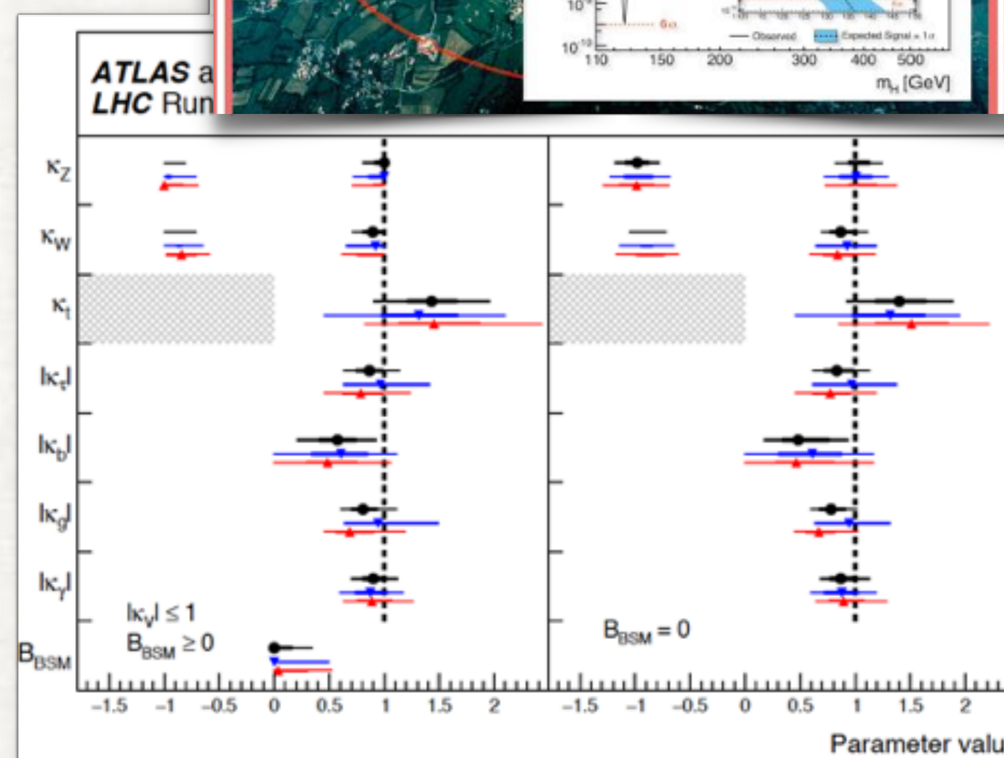
- The tree level matching in the IR limit of the SMEFT
  - The operator profile when integrating out the heavy states.
  - A dynamical source of generating the mass to the UV states
- A sample: one operator vs. global fit
- Conclusions

HIGGS DISCOVERY AT LHC









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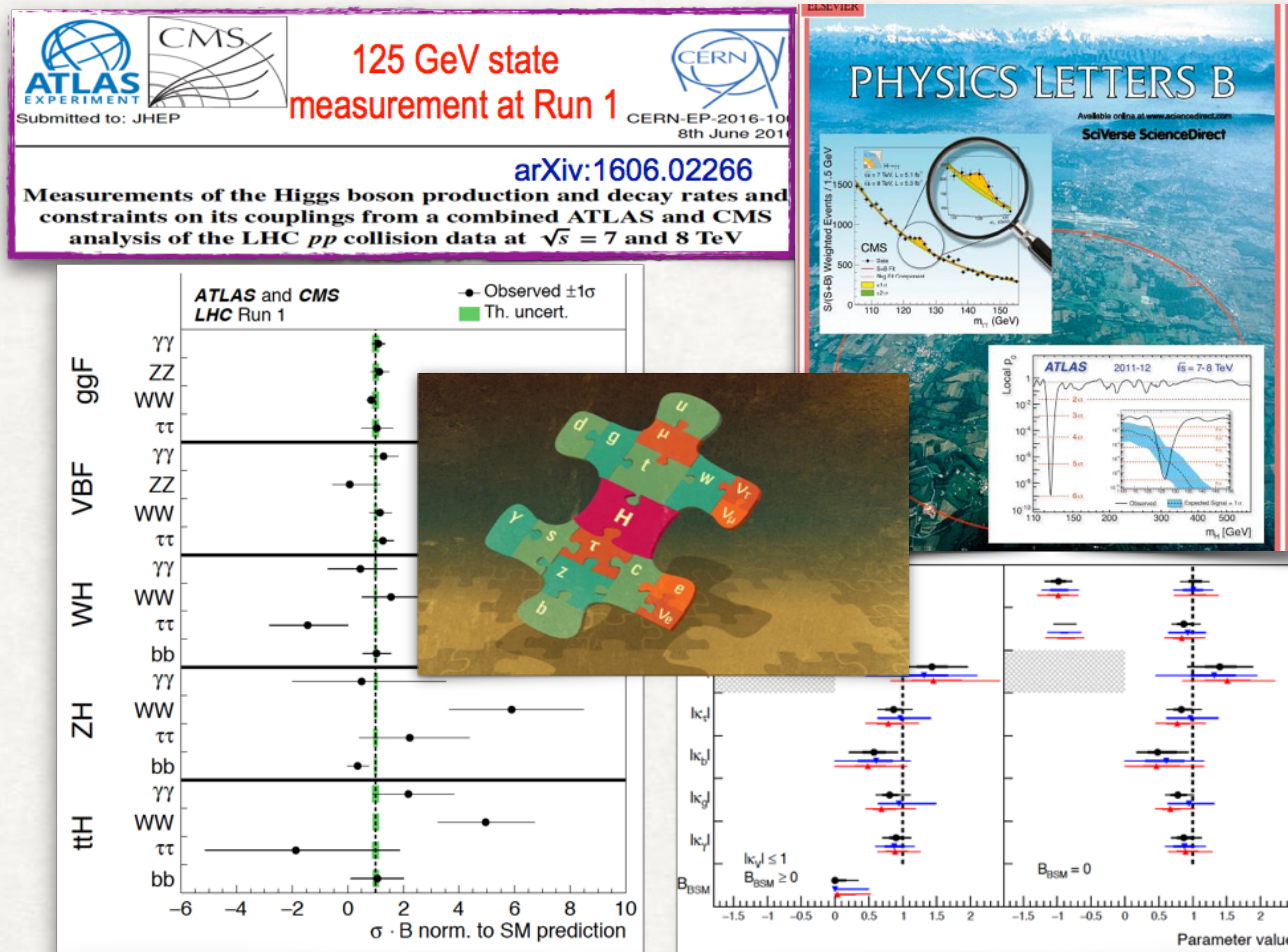
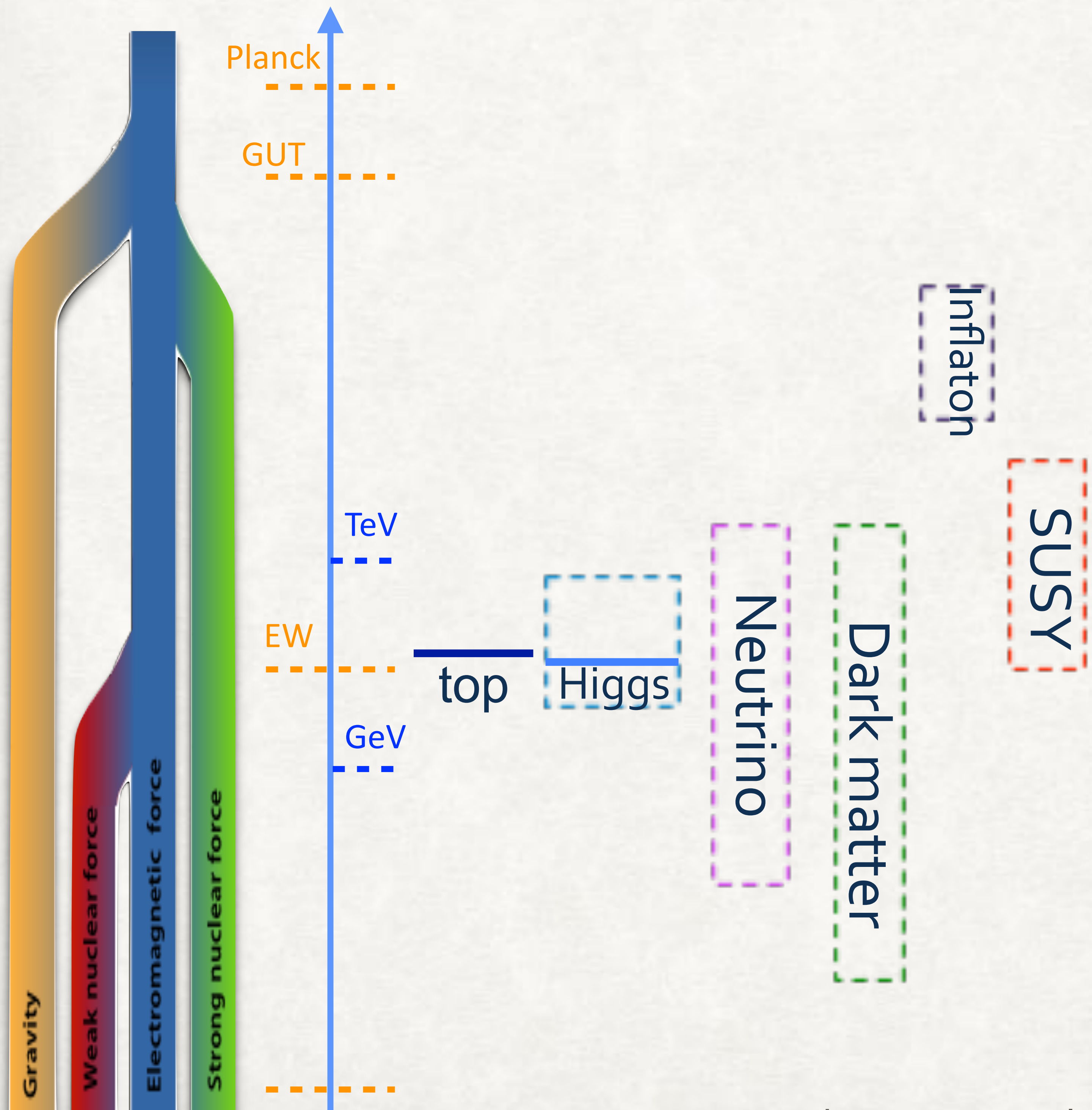


The discovery of Higgs boson has put the final piece of the Standard Model in place.

NEW PHYSICS BEYOND THE SM

The SM works beautifully, no compelling hints for deviations. However, …



- ❑ **EWSB pattern**
  - *Is there only one type of Higgs boson?*
- ❑ **Hierarchy problem**
  - What prevents quantities at the electroweak scale, such as the Higgs boson mass, from getting quantum corrections on the order of the Planck scale?

  The possible solutions are
  - ➢ Supersymmetry
  - ➢ Extra dimensions
- ❑ **Neutrinos**
  - Is mass hierarchy normal or inverted?
  - Is the CP violating phase 0?
- + **Dark matter**
  - What is the identity of DM?
  - Is it a particle?
  - Is it the lightest supersymmetric particle (LSP)?
  - Do the phenomena attributed to DM point not to some form of matter?
- + **Baryon asymmetry**
  - Why is there far more matter than antimatter in the observable universe?
- + **Inflation of early Universe**

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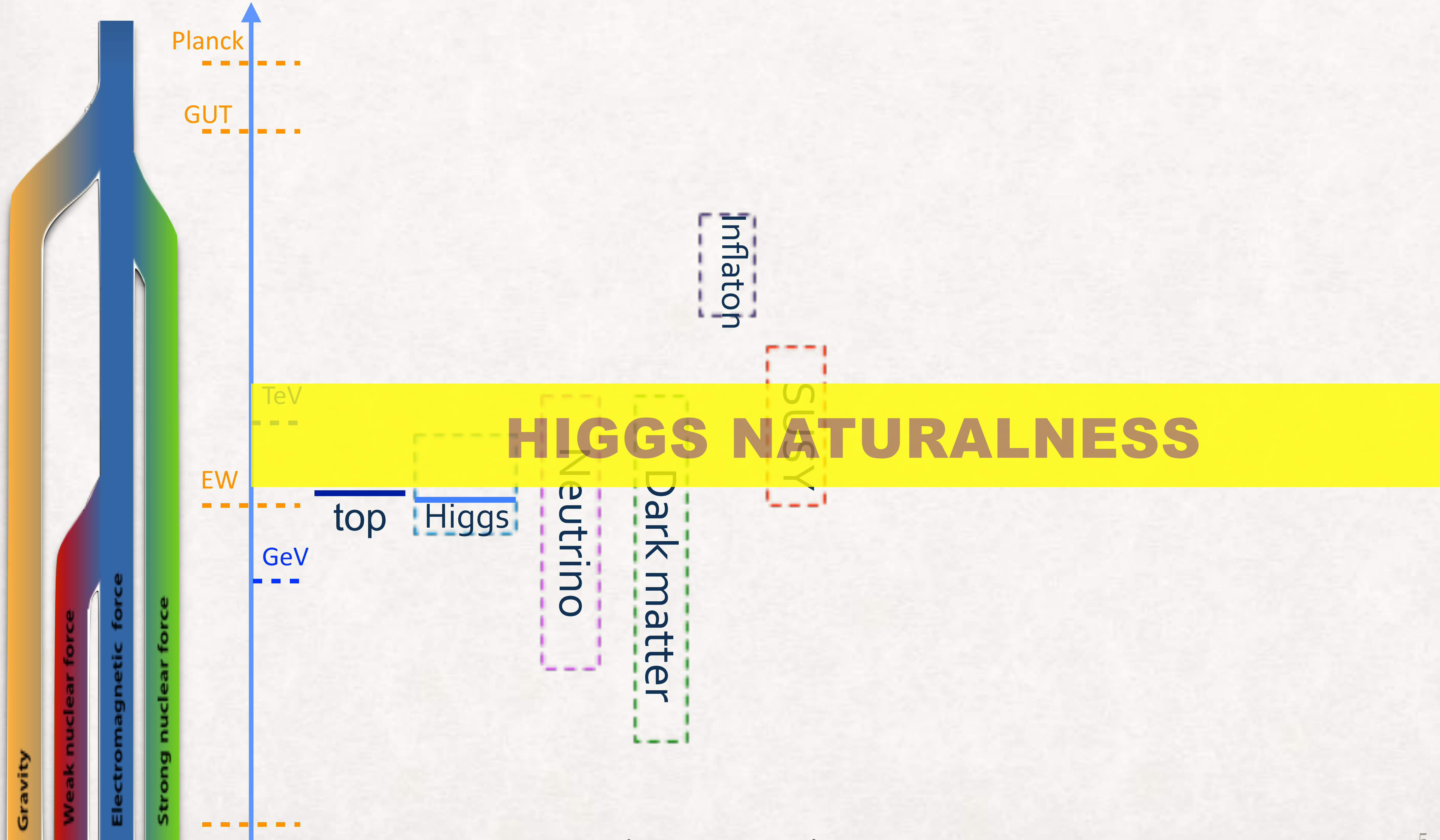

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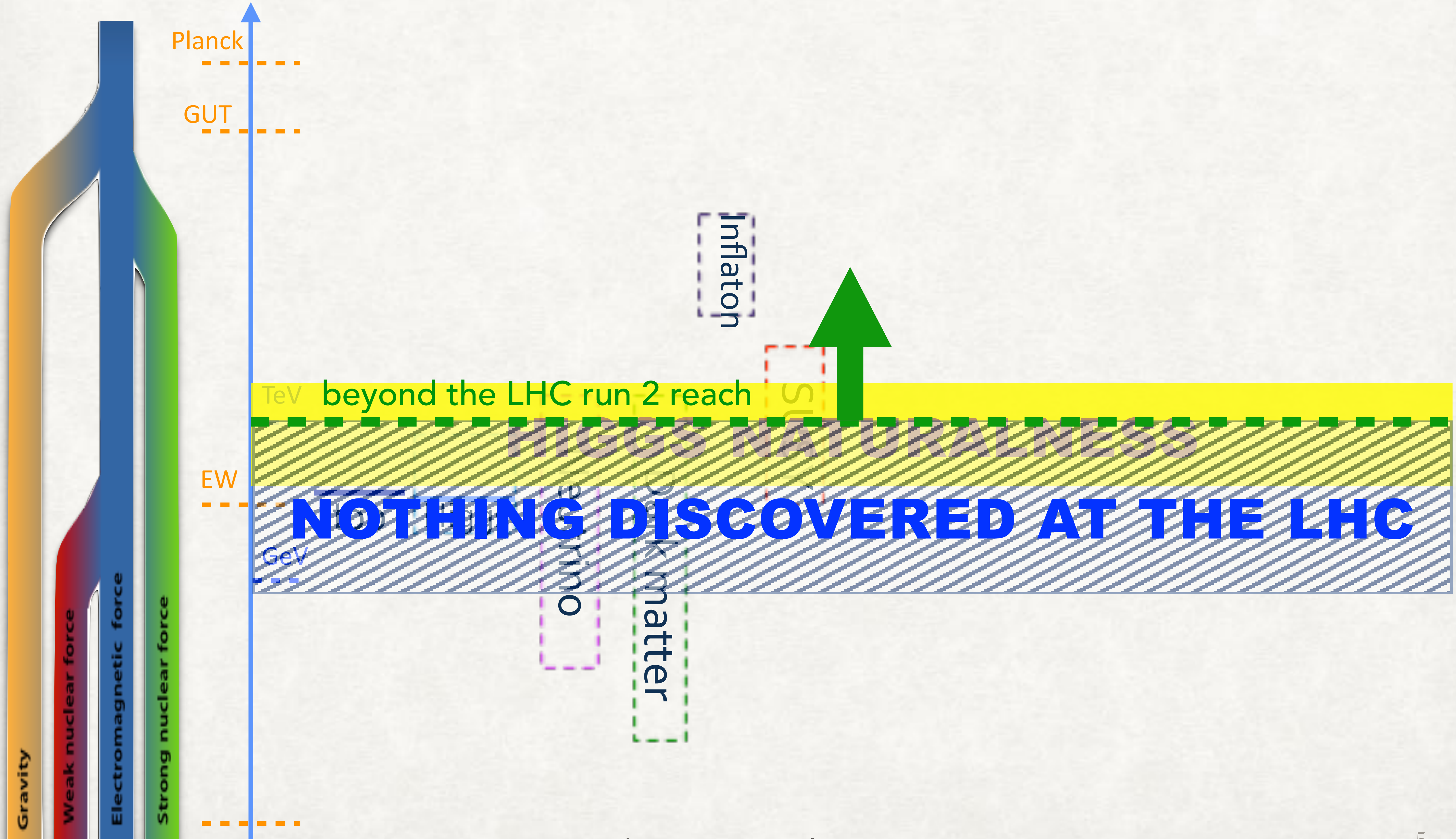

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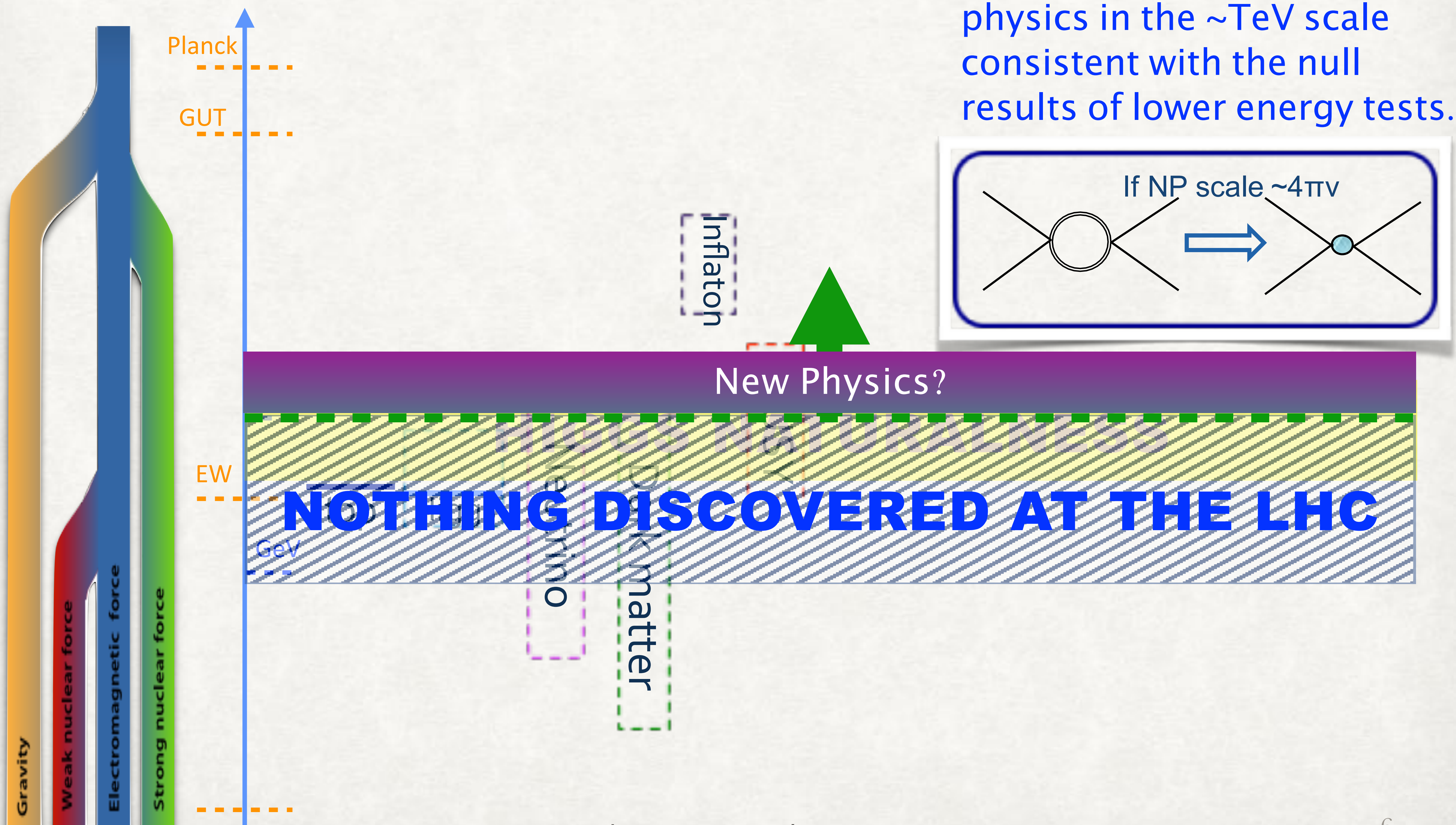


In the SMEFT approach, UV physics in the ~TeV scale consistent with the null results of lower energy tests.

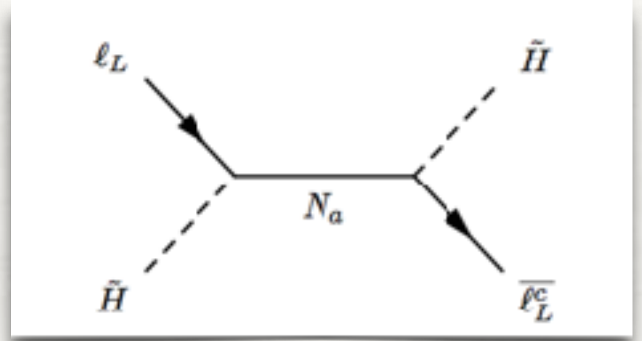
SMEFT (Standard Model Effective Field Theory)

The SM is supplemented with a series of higher dimensional operators:

$$\mathcal{L} = \mathcal{L}_{SM} + \underbrace{\frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B\neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8}_{\text{New physics effect}} + \cdots$$

18 (19) parameters

$$\boxed{\mathcal{L}_5 = \frac{c_{ij}}{2}\left(\overline{L^c_{L,i}}\tilde{H}^\star\right)\left(\tilde{H}^\dagger L_{L,j}\right) + \text{h.c.}}$$



- Only one operator is constructed at dim-5.
- This is an exception due to the charges of the SM fields
- This is not repeated at higher orders in the SMEFT operator expansion.

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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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

6 gauge dual ops

28 non dual operators

25 four fermi ops

59 + h.c. operators

Notation:

$\widetilde{X}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}X^{\rho\sigma} \quad (\varepsilon_{0123} = +1)$

$\widetilde{\varphi}^j = \varepsilon_{jk}(\varphi^k)^\star \qquad \varepsilon_{12} = +1$

$\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi \equiv i\varphi^\dagger\left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$

$\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi \equiv i\varphi^\dagger\left(\tau^I D_\mu - \overleftarrow{D}_\mu\tau^I\right)\varphi$

A complete set of independent operator defined in the "Warsaw basis", JHEP 10(2010)085

“Independent” Effective Operator

Example: Higgs-only operators

Warsaw basis

JHEP 10(2010)085

φ^6 and $\varphi^4 D^2$

Q_φ	$(\varphi^\dagger\varphi)^3$
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$

“SILH”

JHEP 07(2013)035

$$\left(H^\dagger H\right)^3$$

$$\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)$$

$$\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$

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IBP

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$$\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) = -Q_{H\Box} - 4Q_{HD}$$ JHEP 04(2014)159

redundant ops. $$(\varphi^\dagger\tau^I\varphi)\left[(D_\mu\varphi)^\dagger\tau^I(D^\mu\varphi)\right] \overset{(4.3)}{=} 2\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right) - (\varphi^\dagger\varphi)\left[(D_\mu\varphi)^\dagger(D^\mu\varphi)\right],$$

$$(\varphi^\dagger\varphi)\left[(D_\mu\varphi)^\dagger(D^\mu\varphi)\right] \overset{(5.1)}{=} \frac{1}{2}(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) + \boxed{\psi^2\varphi^3} + \boxed{\varphi^6} + m^2\boxed{\varphi^4} + \boxed{E}.$$

"Independent" Effective Operator

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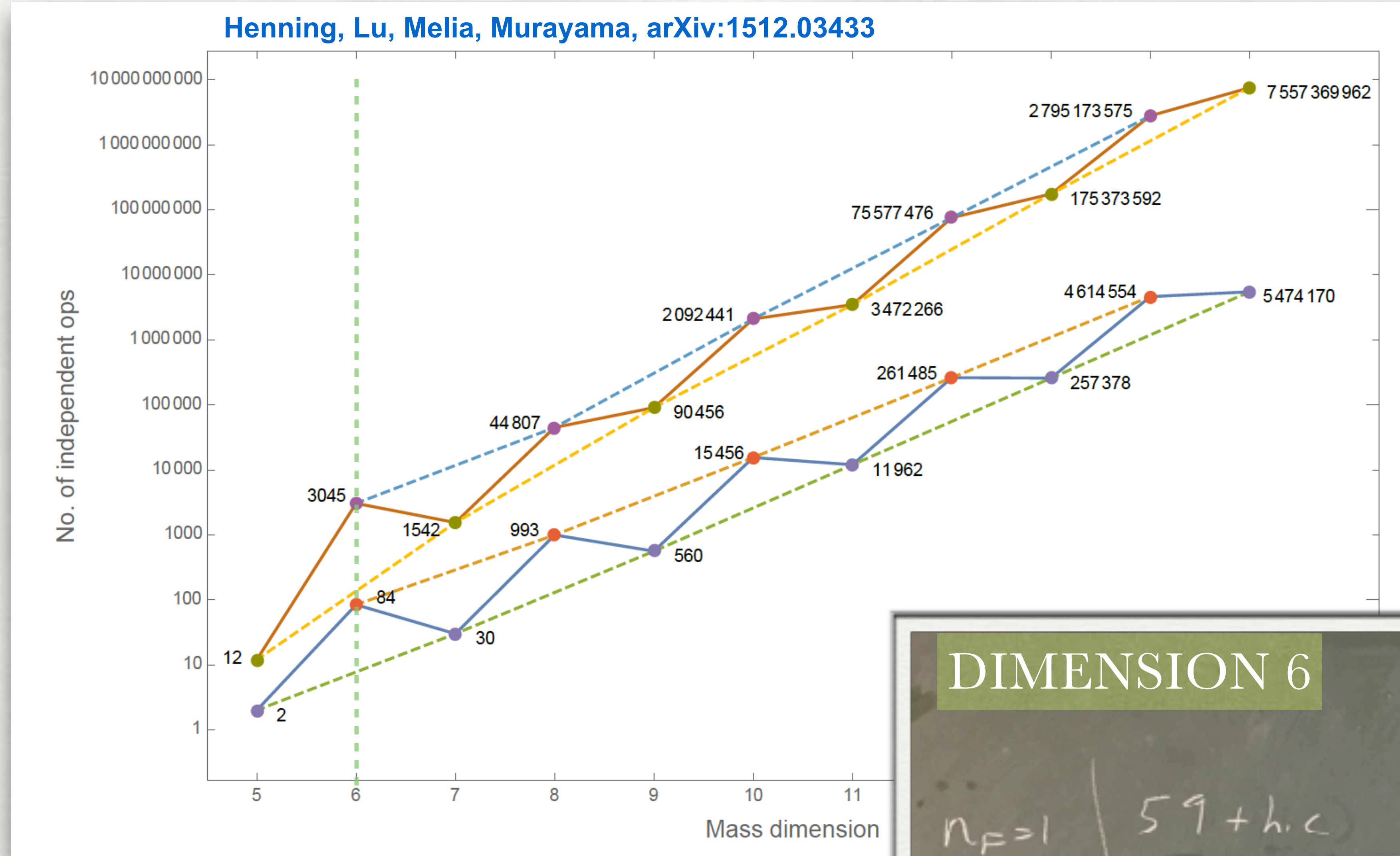
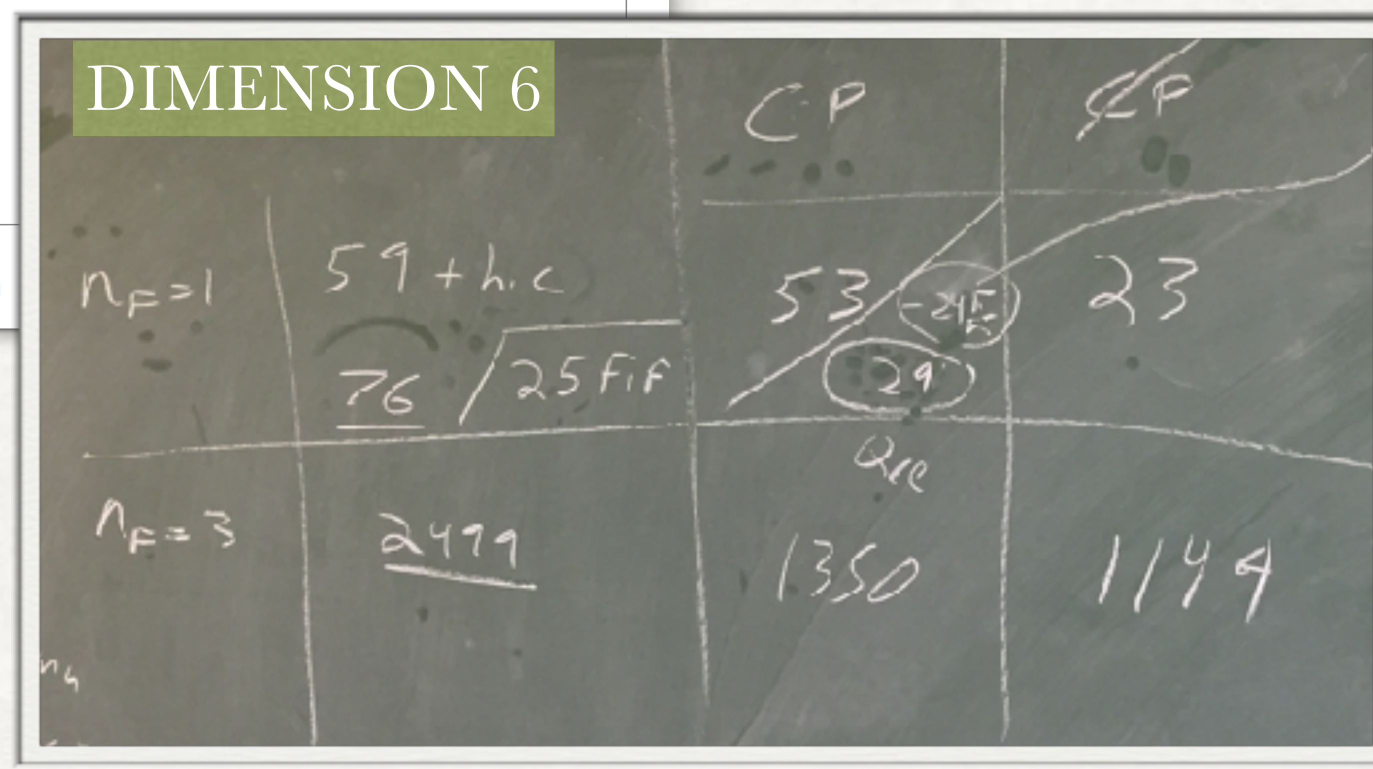
Lessons:

- Picking up a subgroup of the full set is dangerous and of many limitations.
- Multiple basis choices: each one has its own advantage and disadvantage.

Wilson Coefficient Counting





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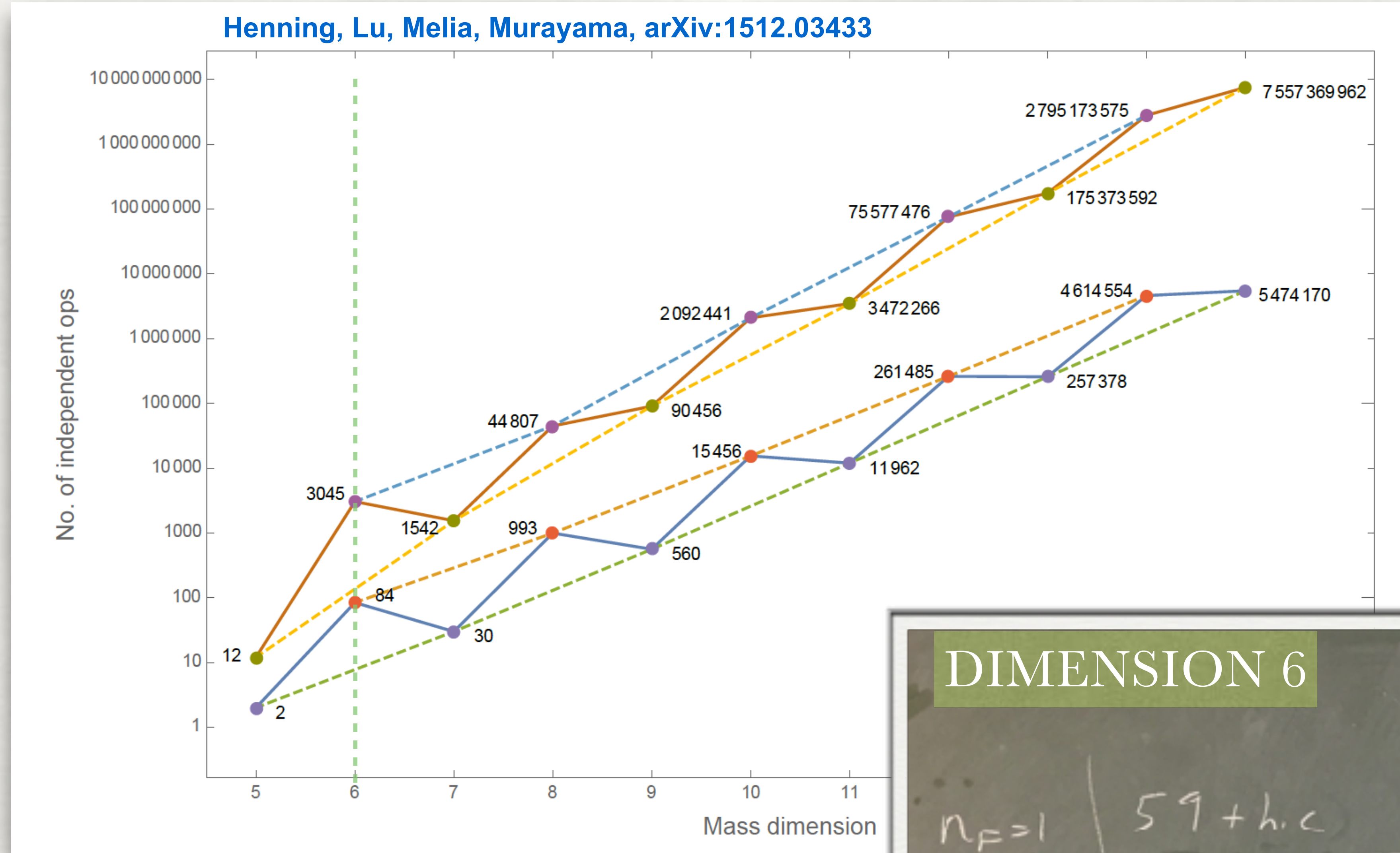

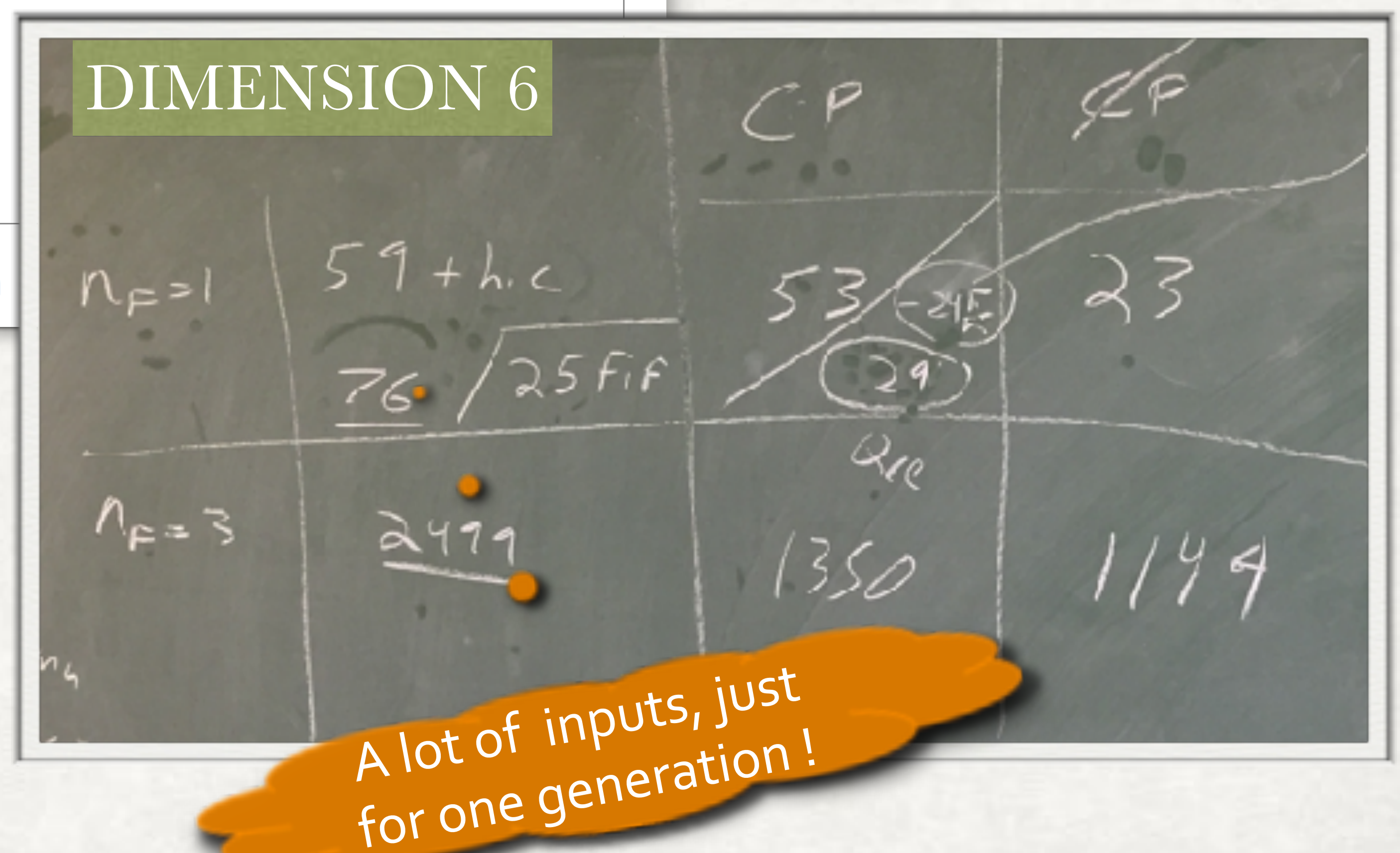

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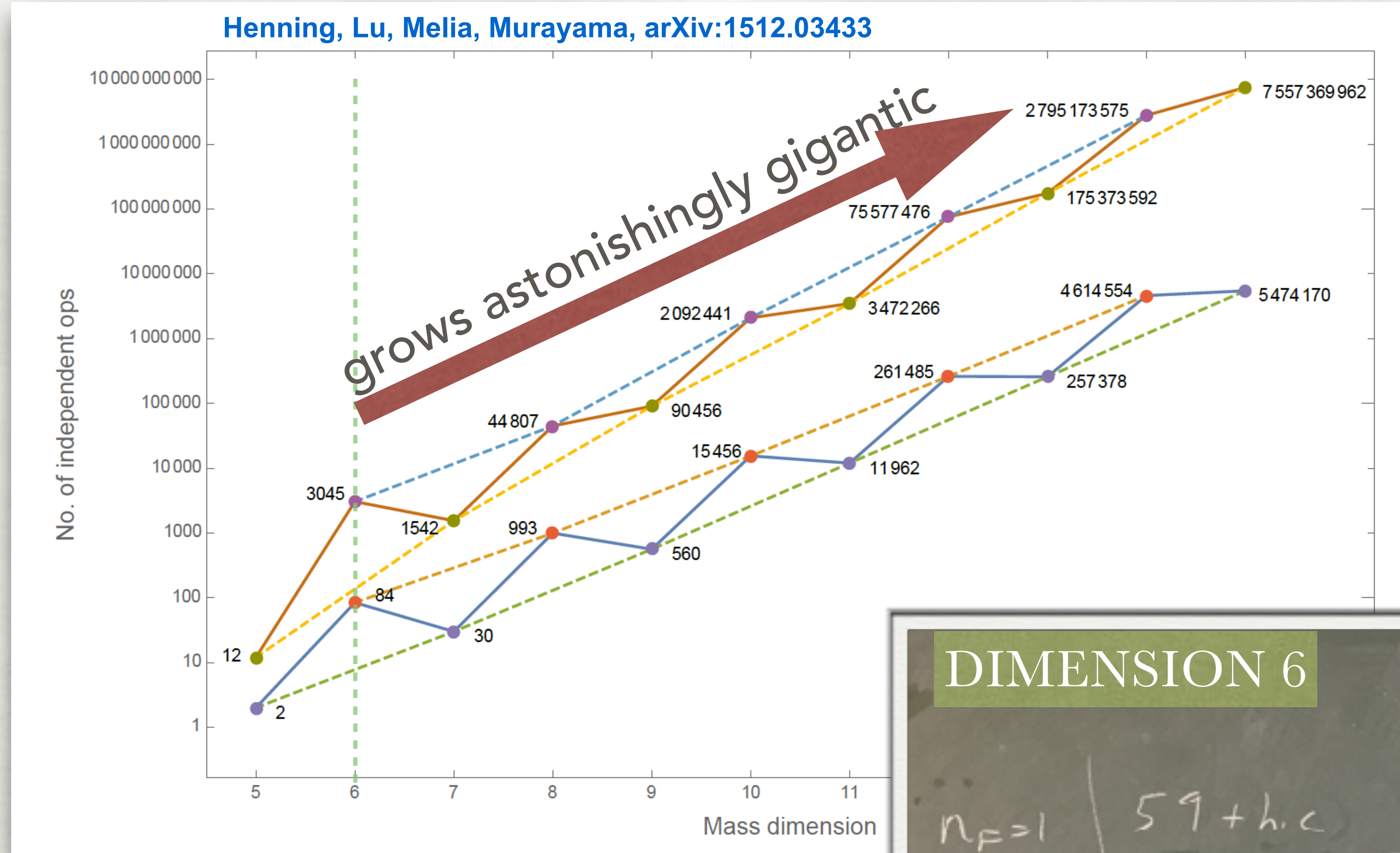

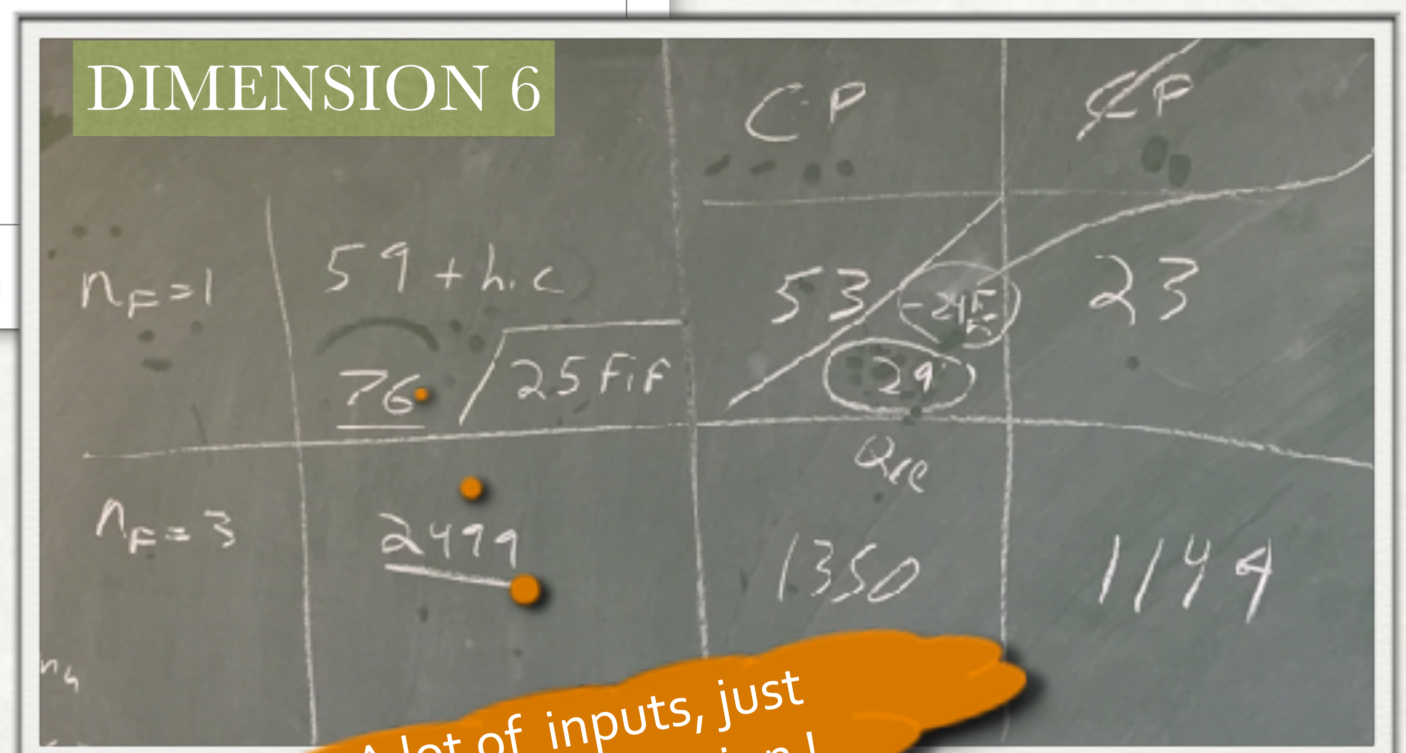

A lot of inputs, just for one generation !

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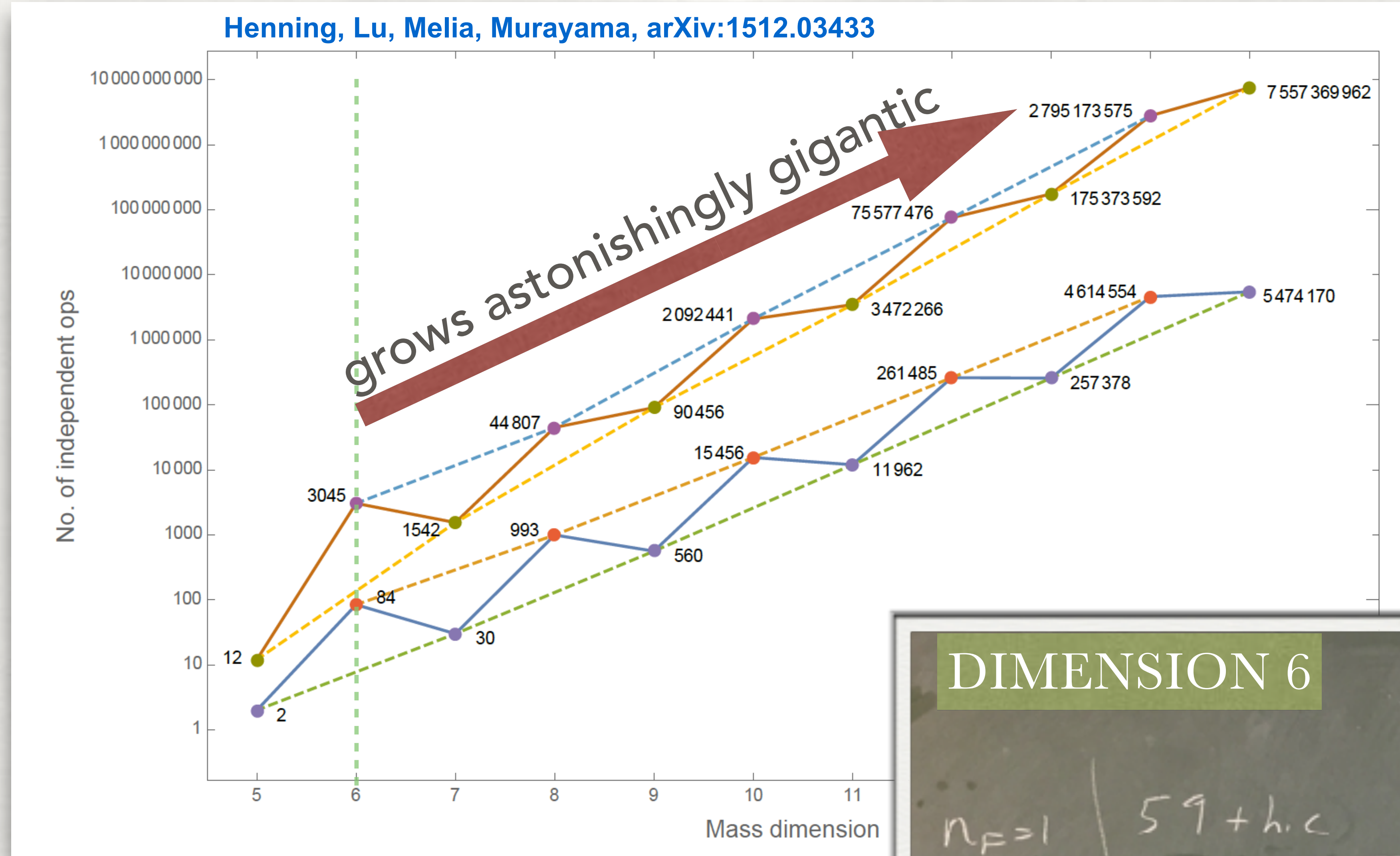

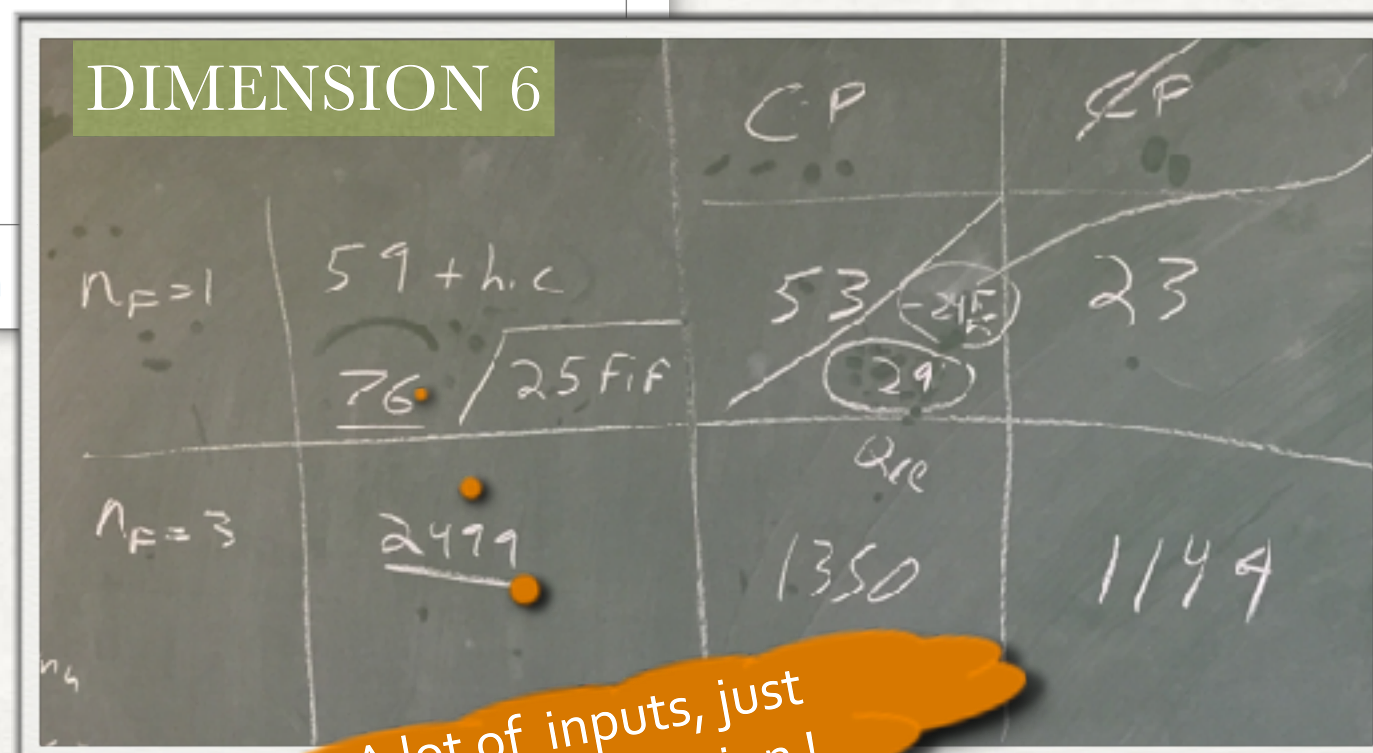

A lot of inputs, just for one generation !

Question: *when integrating out unknown NP sectors, when, if ever, only one operator can be obtained in the tree level matching at the IR limit of the SMEFT?*

Tree-level matching (w/out UV completion)

Assumptions

Symmetry

- $\mathcal{L}_6$ correction due to new physics that (approximately) respects

G = U(1)B ⊗ U(1)L ⊗ SU(3)^5 +discrete CP symmetry

Operator basis

- We focus on Warsaw basis when examining the question.

Spin

- We examine the tree-level matching effects of adding one massive state

Spin-1 ✔✔✔ | Spin-1/2 ✔ | Spin-0 ✔

- Higher spin composite fields (and spin towers) are possible and even required in the presence of UV confining strong interactions.

Case I

Adding spin-1 field

Spin-1 States

BSM candidates:

- Extra gauge bosons
- vector leptoquarks

The requirements:

- d ≤ 4 interaction with SM fields
- Lorentz symmetry
- SM gauge invariance

Global flavor symmetry:

$$G_Q = SU(3)_{u_R} \times SU(3)_{d_R} \times SU(3)_{Q_L},$$
$$G_L = SU(3)_{L_L} \times SU(3)_{e_R}.$$

Cautions:

- UV fields that carry flavor quantum numbers do not necessarily lead to lower

	Case	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	G_Q	G_L	Couples to
QUARK	$\mathcal{V}_{\rm I}^{(1,8)}$	1,8	1	0	(1,1,1)	(1,1)	$\bar{d}_R\,\gamma^\mu\,d_R$
QUARK	$\mathcal{V}_{\rm II}^{(1,8)}$	1,8	1	0	(1,1,1)	(1,1)	$\bar{u}_R\,\gamma^\mu\,u_R$
QUARK	$\mathcal{V}_{\rm III}^{(1,8)}$	1,8	1	0	(1,1,1)	(1,1)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
QUARK	$\mathcal{V}_{\rm IV}^{(1,8)}$	1,8	3	0	(1,1,1)	(1,1)	$\bar{Q}_L\sigma^I\,\gamma^\mu\,Q_L$
QUARK	$\mathcal{V}_{\rm V}^{(1,8)}$	1,8	1	0	(1,8,1)	(1,1)	$\bar{d}_R\,\gamma^\mu\,d_R$
QUARK	$\mathcal{V}_{\rm VI}^{(1,8)}$	1,8	1	0	(8,1,1)	(1,1)	$\bar{u}_R\,\gamma^\mu\,u_R$
QUARK	$\mathcal{V}_{\rm VII}^{(1,8)}$	1,8	1	−1	$(\bar{3},3,1)$	(1,1)	$\bar{d}_R\,\gamma^\mu\,u_R$
QUARK	$\mathcal{V}_{\rm VIII}^{(1,8)}$	1,8	1	0	(1,1,8)	(1,1)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
QUARK	$\mathcal{V}_{\rm IX}^{(1,8)}$	1,8	3	0	(1,1,8)	(1,1)	$\bar{Q}_L\sigma^I\,\gamma^\mu\,Q_L$
QUARK	$\mathcal{V}_{\rm X}^{(3,6)}$	$\bar{3}$,6	2	−1/6	(1,3,3)	(1,1)	$\bar{d}_R\,\gamma^\mu\,Q_L^c$
QUARK	$\mathcal{V}_{\rm XI}^{(3,6)}$	$\bar{3}$,6	2	5/6	(3,1,3)	(1,1)	$\bar{u}_R\,\gamma^\mu\,Q_L^c$
LEPTON	$\mathcal{V}_{\rm I}^{(1)}$	1	1	0	(1,1,1)	(1,1)	$\bar{e}_R\,\gamma^\mu\,e_R$
LEPTON	$\mathcal{V}_{\rm I}^{(1)}$	1	1	0	(1,1,1)	(1,1)	$\bar{L}_L\,\gamma^\mu\,L_L$
LEPTON	$\mathcal{V}_{\rm IV}^{(1)}$	1	3	0	(1,1,1)	(1,1)	$\bar{L}_L\sigma^I\,\gamma^\mu\,L_L$
LEPTON	$\mathcal{V}_{\rm XII}$	1	2	3/2	(1,1,1)	$(\bar{3},\bar{3})$	$\bar{L}_L^c\,\gamma^\mu\,e_R$
LEPTON	$\mathcal{V}_{\rm XIII}$	1	1	0	(1,1,1)	(1,8)	$\bar{e}_R\,\gamma^\mu\,e_R$
LEPTON	$\mathcal{V}_{\rm XXI}$	1	1	0	(1,1,1)	(8,1)	$\bar{L}_L\gamma^\mu\,\bar{L}_L$
LEPTON	$\mathcal{V}_{\rm XXII}$	1	3	0	(1,1,1)	(8,1)	$\bar{L}_L\sigma^I\,\gamma^\mu\,\bar{L}_L$
QUARK-LEPTON	$\mathcal{V}_{\rm XIV}$	$\bar{3}$	2	−1/6	$(\bar{3},1,1)$	$(\bar{3},1)$	$\bar{L}_L^c\,\gamma^\mu\,u_R$
QUARK-LEPTON	$\mathcal{V}_{\rm XV}$	$\bar{3}$	2	5/6	$(1,\bar{3},1)$	$(\bar{3},1)$	$\bar{L}_L^c\,\gamma^\mu\,d_R$
QUARK-LEPTON	$\mathcal{V}_{\rm XVI}$	$\bar{3}$	1	−2/3	$(1,\bar{3},1)$	(1,3)	$\bar{e}_R\,\gamma^\mu\,d_R$
QUARK-LEPTON	$\mathcal{V}_{\rm XVII}$	$\bar{3}$	1	−5/3	$(\bar{3},1,1)$	(1,3)	$\bar{e}_R\,\gamma^\mu\,u_R$
QUARK-LEPTON	$\mathcal{V}_{\rm XVIII}$	$\bar{3}$	2	−5/6	(1,1,3)	(1,3)	$\bar{e}_R\,\gamma^\mu\,Q_L^c$
QUARK-LEPTON	$\mathcal{V}_{\rm XIX}$	$\bar{3}$	1	−2/3	$(1,1,\bar{3})$	(3,1)	$\bar{L}_L\,\gamma^\mu\,Q_L$
QUARK-LEPTON	$\mathcal{V}_{\rm XX}$	$\bar{3}$	3	−2/3	$(1,1,\bar{3})$	(3,1)	$\bar{L}_L\sigma^I\,\gamma^\mu\,Q_L$
HIGGS	$\mathcal{V}_{\rm I}^{(1)}, \mathcal{V}_{\rm II}^{(1)}, \mathcal{V}_{\rm III}^{(1)}$	1	1	0	(1,1,1)	(1,1)	$H^\dagger iD^\mu H$
HIGGS	$\mathcal{V}_{\rm IV}^{(1)}$	1	3	0	(1,1,1)	(1,1)	$H^\dagger\sigma^I iD^\mu H$
HIGGS	$\mathcal{V}_{\rm XXIII}^{(1)}$	1	1	−1	(1,1,1)	(1,1)	$H^T iD_\mu H$
HIGGS	$\mathcal{V}_{\rm XXIV}^{(1)}$	1	3	−1	(1,1,1)	(1,1)	$H^T i\sigma_I D_\mu H$

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- SM gauge invariance

Global flavor symmetry:

$$G_Q = SU(3)_{u_R} \times SU(3)_{d_R} \times SU(3)_{Q_L},$$
$$G_L = SU(3)_{L_L} \times SU(3)_{e_R}.$$

Cautions:

- UV fields that carry flavor quantum numbers do not necessarily lead to lower

	Case	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	G_Q	G_L	Couples to
QUARK	$\mathcal{V}_{\rm I}^{(1,8)}$	1,8	1	0	(1,1,1)	(1,1)	$\bar{d}_R\,\gamma^\mu\,d_R$
	$\mathcal{V}_{\rm II}^{(1,8)}$	1,8	1	0	(1,1,1)	(1,1)	$\bar{u}_R\,\gamma^\mu\,u_R$
	$\mathcal{V}_{\rm III}^{(1,8)}$	1,8	1	0	(1,1,1)	(1,1)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
	$\mathcal{V}_{\rm IV}^{(1,8)}$	1,8	3	0	(1,1,1)	(1,1)	$\bar{Q}_L\sigma^I\,\gamma^\mu\,Q_L$
	$\mathcal{V}_{\rm V}^{(1,8)}$	1,8	1	0	(1,8,1)	(1,1)	$\bar{d}_R\,\gamma^\mu\,d_R$
	$\mathcal{V}_{\rm VI}^{(1,8)}$	1,8	1	0	(8,1,1)	(1,1)	$\bar{u}_R\,\gamma^\mu\,u_R$
	$\mathcal{V}_{\rm VII}^{(1,8)}$	1,8	1	−1	$(\bar{3},3,1)$	(1,1)	$\bar{d}_R\,\gamma^\mu\,u_R$
	$\mathcal{V}_{\rm VIII}^{(1,8)}$	1,8	1	0	(1,1,8)	(1,1)	$\bar{Q}_L\,\gamma^\mu\,Q_L$
	$\mathcal{V}_{\rm IX}^{(1,8)}$	1,8	3	0	(1,1,8)	(1,1)	$\bar{Q}_L\sigma^I\,\gamma^\mu\,Q_L$
	$\mathcal{V}_{\rm X}^{(3,6)}$	$\bar{3}$,6	2	−1/6	(1,3,3)	(1,1)	$\bar{d}_R\,\gamma^\mu\,Q_L^c$
	$\mathcal{V}_{\rm XI}^{(3,6)}$	$\bar{3}$,6	2	5/6	(3,1,3)	(1,1)	$\bar{u}_R\,\gamma^\mu\,Q_L^c$
LEPTON	$\mathcal{V}_{\rm I}^{(1)}$	1	1	0	(1,1,1)	(1,1)	$\bar{e}_R\,\gamma^\mu\,e_R$
	$\mathcal{V}_{\rm I}^{(1)}$	1	1	0	(1,1,1)	(1,1)	$\bar{L}_L\,\gamma^\mu\,L_L$
	$\mathcal{V}_{\rm IV}^{(1)}$	1	3	0	(1,1,1)	(1,1)	$\bar{L}_L\sigma^I\,\gamma^\mu\,L_L$
	$\mathcal{V}_{\rm XII}$	1	2	3/2	(1,1,1)	$(\bar{3},\bar{3})$	$\bar{L}_L^c\,\gamma^\mu\,e_R$
	$\mathcal{V}_{\rm XIII}$	1	1	0	(1,1,1)	(1,8)	$\bar{e}_R\,\gamma^\mu\,e_R$
	$\mathcal{V}_{\rm XXI}$	1	1	0	(1,1,1)	(8,1)	$\bar{L}_L\gamma^\mu\,\bar{L}_L$
	$\mathcal{V}_{\rm XXII}$	1	3	0	(1,1,1)	(8,1)	$\bar{L}_L\sigma^I\,\gamma^\mu\,\bar{L}_L$
QUARK-LEPTON	$\mathcal{V}_{\rm XIV}$	$\bar{3}$	2	−1/6	$(\bar{3},1,1)$	$(\bar{3},1)$	$\bar{L}_L^c\,\gamma^\mu\,u_R$
	$\mathcal{V}_{\rm XV}$	$\bar{3}$	2	5/6	$(1,\bar{3},1)$	$(\bar{3},1)$	$\bar{L}_L^c\,\gamma^\mu\,d_R$
	$\mathcal{V}_{\rm XVI}$	$\bar{3}$	1	−2/3	$(1,\bar{3},1)$	(1,3)	$\bar{e}_R\,\gamma^\mu\,d_R$
	$\mathcal{V}_{\rm XVII}$	$\bar{3}$	1	−5/3	$(\bar{3},1,1)$	(1,3)	$\bar{e}_R\,\gamma^\mu\,u_R$
	$\mathcal{V}_{\rm XVIII}$	$\bar{3}$	2	−5/6	(1,1,3)	(1,3)	$\bar{e}_R\,\gamma^\mu\,Q_L^c$
	$\mathcal{V}_{\rm XIX}$	$\bar{3}$	1	−2/3	$(1,1,\bar{3})$	(3,1)	$\bar{L}_L\,\gamma^\mu\,Q_L$
	$\mathcal{V}_{\rm XX}$	$\bar{3}$	3	−2/3	$(1,1,\bar{3})$	(3,1)	$\bar{L}_L\sigma^I\,\gamma^\mu\,Q_L$
HIGGS	$\mathcal{V}_{\rm I}^{(1)}, \mathcal{V}_{\rm II}^{(1)}, \mathcal{V}_{\rm III}^{(1)}$	1	1	0	(1,1,1)	(1,1)	$H^\dagger iD^\mu H$
	$\mathcal{V}_{\rm IV}^{(1)}$	1	3	0	(1,1,1)	(1,1)	$H^\dagger\sigma^I iD^\mu H$
	$\mathcal{V}_{\rm XXIII}^{(1)}$	1	1	−1	(1,1,1)	(1,1)	$H^T iD_\mu H$
	$\mathcal{V}_{\rm XXIV}^{(1)}$	1	3	−1	(1,1,1)	(1,1)	$H^T i\sigma_I D_\mu H$

Spin-1 States

BSM candidates:

- Extra gauge bosons
- vector leptoquarks

The requirements:

- $d \leq 4$ interaction with SM fields
- Lorentz symmetry
- SM gauge invariance

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	$\mathcal{V}_{\rm XVIII}$	$\boxed{3}$	2	−5/6	(1,1,3)	(1,3)	$\bar{e}_R\,\gamma^\mu\, Q_L^c$
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Integrating Out V Formalism

- Consider an augment of the SM by a vector field $V_\mu{}^a$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_V^0 + \mathcal{L}_V^{\rm int},$$

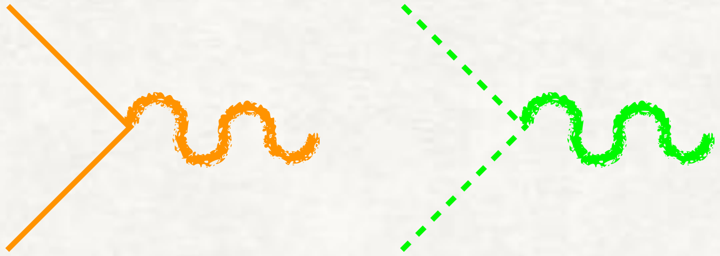
$$\mathcal{L}_V^0 = -\frac{1}{2}[D_\mu V_\nu]^{\dagger a}[D^\mu V^\nu]_a + \frac{1}{2}[D_\mu V_\nu]^{\dagger a}[D^\nu V^\mu]_a \boxed{+ \frac{M_V^2}{2} V_\mu^{\dagger a} V_a^\mu,}$$

$$\mathcal{L}_V^{\rm int} = g_{VV} V_\mu^{\dagger a} V_a^\mu \phi^\dagger \phi - (V_a^{\dagger\mu} J_\mu^{V\,a} + {\rm h.c.}),$$

current $J_a = \{J_\psi^\mu, J_H^\mu\} = \{\bar\psi\, \gamma_\mu \otimes \psi, (D_\mu H)^\dagger \otimes \Phi\},$

At this stage we are not worried about the mechanism of generating the V_μ mass.

QED-like scalar QED-like



group structure embedded in the vertex

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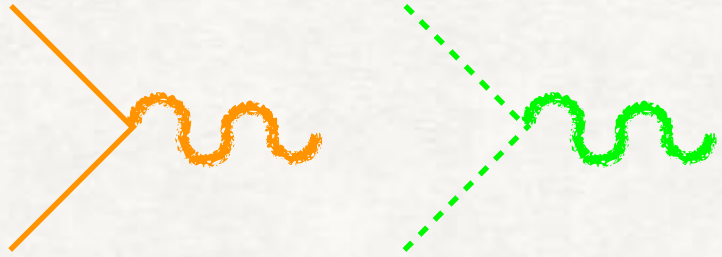

group structure embedded in the vertex

- Solving the EOM

tree-level matching

$$\Delta\mathcal{L}_6 \supset -\frac{1}{M_V^2}(J_a^\mu)^\dagger J_b^\mu.$$

the current product has three types:

- four-fermion: $(J_\psi^\mu)^\dagger\, J_{\psi,\mu}$,
- scalar derivative: $(J_H^\mu)^\dagger\, J_{H,\mu}$,
- mixed scalar-fermion: $(J_\psi^\mu)^\dagger\, J_{H,\mu}, (J_H^\mu)^\dagger\, J_{\psi,\mu}$.

Dim-6 Operator Matching

for a singlet vector under SM gauge symmetries

POSSIBLE CURRENTS

$\bar{d}_R\,\gamma^\mu\,d_R$

$\bar{u}_R\,\gamma^\mu\,u_R$ $\quad$ $\bar{e}_R\,\gamma^\mu\,e_R$

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color octet

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color–octet iso–triplet: $\bar{Q}_L \gamma^\mu Q_L$ $\quad \bar{L}_L \gamma^\mu L_L \quad H^\dagger i D^\mu H$ iso–triplet

color octet

e.g. $(\bar{Q}^p_L \sigma^I T^A \gamma^\mu Q^r_L)(\bar{Q}^s_L \sigma^I T^A \gamma^\mu Q^t_L) =$

$$-\frac{1}{4} Q^{(3)}_{\substack{qq\\ptsr}} + \frac{3}{4} Q^{(1)}_{\substack{qq\\ptsr}} - \frac{1}{6} Q^{(3)}_{\substack{qq\\prst}}$$

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U(1) charge

$H^T i D_\mu H$

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multiple operators induced when projecting into Warsaw basis

Flavor singlet vector fields induce ***more than one*** *operator at tree level when matching onto the SMEFT Warsaw basis.*

This is a basis-dependent conclusion

Dim-6 Operator Matching

Introducing the $G_Q \times G_L$ symmetry,

- In the limit of zero Yukawa matrices

The infrared SMEFT operator profile can be reduced to one operator in the Warsaw basis.

Higgs-Yukawa interactions

$$\mathcal{L}_Y = -(Y_u)^p_r\, \bar{u}_{R,p}\, Q^r_L\, \tilde{H}^\dagger - (Y_d)^p_r\, \bar{d}_{R,p}\, Q^r_L\, H^\dagger - (Y_e)^p_r\, \bar{e}_{R,p}\, L^r_L\, H^\dagger + \text{h.c.}$$

Case	SM group	G_Q	G_L	Op	Couples to
$\mathcal{V}^{(1)}_{\rm VIII}$	$(1,1)_0$	(1,1,8)	(1,1)	$Q^{(1)}_{qq}$	$\bar{Q}_L\,\gamma^\mu\,Q_L$
$\mathcal{V}^{(1)}_{\rm IX}$	$(1,3)_0$	(1,1,8)	(1,1)	$Q^{(1)}_{qq}$	$\bar{Q}_L\sigma^I\,\gamma^\mu\,Q_L$
$\mathcal{V}^{(1)}_{\rm V}$	$(1,1)_0$	(1,8,1)	(1,1)	Q_{dd}	$\bar{d}_R\,\gamma^\mu\,d_R$
$\mathcal{V}^{(1)}_{\rm VI}$	$(1,1)_0$	(8,1,1)	(1,1)	Q_{uu}	$\bar{u}_R\,\gamma^\mu\,u_R$
$\mathcal{V}_{\rm XIII}$	$(1,1)_0$	(1,1,1)	(1,8)	Q_{ee}	$\bar{e}_R\,\gamma^\mu\,e_R$
$\mathcal{V}^{(1)}_{\rm VII}$	$(1,1)_{-1}$	$(\bar{3},3,1)$	(1,1)	$Q^{(1)}_{ud}$	$\bar{d}_R\,\gamma^\mu\,u_R$
$\mathcal{V}^{(\bar{3},6)}_{\rm X}$	$(\bar{3}\text{or}6,2)_{-\frac{1}{6}}$	(1,3,3)	(1,1)	$Q^{(1)}_{qd}$	$\bar{d}_R\,\gamma^\mu\,Q^c_L$
$\mathcal{V}^{(\bar{3},6)}_{\rm XI}$	$(\bar{3}\text{or}6,2)_{\frac{5}{6}}$	(3,1,3)	(1,1)	$Q^{(1)}_{qu}$	$\bar{u}_R\,\gamma^\mu\,Q^c_L$
$\mathcal{V}_{\rm XVIII}$	$(3,2)_{-\frac{5}{6}}$	(1,1,3)	(1,3)	Q_{qe}	$\bar{e}_R\,\gamma^\mu\,Q^c_L$
$\mathcal{V}_{\rm XII}$	$(1,2)_{\frac{3}{2}}$	(1,1,1)	$(\bar{3},\bar{3})$	Q_{le}	$\bar{L}^c_L\,\gamma^\mu\,e_R$
$\mathcal{V}_{\rm XIV}$	$(\bar{3},2)_{-\frac{1}{6}}$	$(\bar{3},1,1)$	$(\bar{3},1)$	Q_{lu}	$\bar{L}^c_L\,\gamma^\mu\,u_R$
$\mathcal{V}_{\rm XV}$	$(\bar{3},2)_{\frac{5}{6}}$	$(1,\bar{3},1)$	$(\bar{3},1)$	Q_{ld}	$\bar{L}^c_L\,\gamma^\mu\,d_R$
$\mathcal{V}_{\rm XVI}$	$(\bar{3},1)_{-\frac{2}{3}}$	$(1,\bar{3},1)$	(1,3)	Q_{ed}	$\bar{e}_R\,\gamma^\mu\,d_R$
$\mathcal{V}_{\rm XVII}$	$(\bar{3},1)_{-\frac{5}{3}}$	$(\bar{3},1,1)$	(1,3)	Q_{eu}	$\bar{e}_R\,\gamma^\mu\,u_R$
$\mathcal{V}_{\rm XIX}$	$(\bar{3},1)_{-\frac{2}{3}}$	$(1,1,\bar{3})$	(3,1)	$Q^{(1)}_{lq}$	$\bar{L}_L\,\gamma^\mu\,Q_L$

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To restore the symmetry, the Yukawa matrices

$$Y_u \sim (3,1,\bar{3},1,1), \quad Y_d \sim (1,3,\bar{3},1,1), \quad Y_e \sim (1,1,1,\bar{3},3).$$

Treating them as spurion fields allows additional interactions with V and SM. Introducing **flavor symmetry breaking**, when the they take the SM values, induce more operators.

Case	SM group	G_Q	G_L	Op	G_Q, G_L Spurion
$\mathcal{V}_{\mathrm{VIII}}^{(1)}$	$(1,1)_0$	(1,1,8)	(1,1)	$Q_{qq}^{(1)}$	$T^A\, Y_u^\dagger Y_u, T^A\, Y_d^\dagger Y_d$
$\mathcal{V}_{\mathrm{IX}}^{(1)}$	$(1,3)_0$	(1,1,8)	(1,1)	$Q_{qq}^{(1)}$	$T^A\, Y_u^\dagger Y_u, T^A\, Y_d^\dagger Y_d$
$\mathcal{V}_{\mathrm{V}}^{(1)}$	$(1,1)_0$	(1,8,1)	(1,1)	Q_{dd}	$T^A\, Y_d^\dagger Y_d$
$\mathcal{V}_{\mathrm{VI}}^{(1)}$	$(1,1)_0$	(8,1,1)	(1,1)	Q_{uu}	$T^A\, Y_u^\dagger Y_u$
$\mathcal{V}_{\mathrm{XIII}}$	$(1,1)_0$	(1,1,1)	(1,8)	Q_{ee}	$T^A\, Y_e^\dagger Y_e$

$\mathcal{V}_{\mathrm{VII}}^{(1)}$	$(1,1)_{-1}$	$(\bar{3},3,1)$	(1,1)	$Q_{ud}^{(1)}$	$\bar{d}_R\, \gamma^\mu\, u_R$

$\mathcal{V}_{\mathrm{X}}^{(\bar{3},6)}$	$(\bar{3}\text{or}6,2)_{-\frac{1}{6}}$	(1,3,3)	(1,1)	$Q_{qd}^{(1)}$	$\bar{d}_R\, \gamma^\mu\, Q_L^c$
$\mathcal{V}_{\mathrm{XI}}^{(\bar{3},6)}$	$(\bar{3}\text{or}6,2)_{\frac{5}{6}}$	(3,1,3)	(1,1)	$Q_{qu}^{(1)}$	$\bar{u}_R\, \gamma^\mu\, Q_L^c$
$\mathcal{V}_{\mathrm{XVIII}}$	$(3,2)_{-\frac{5}{6}}$	(1,1,3)	(1,3)	Q_{qe}	$\bar{e}_R\, \gamma^\mu\, Q_L^c$
$\mathcal{V}_{\mathrm{XII}}$	$(1,2)_{\frac{3}{2}}$	(1,1,1)	$(\bar{3},\bar{3})$	Q_{le}	$\bar{L}_L^c\, \gamma^\mu\, e_R$
$\mathcal{V}_{\mathrm{XIV}}$	$(\bar{3},2)_{-\frac{1}{6}}$	$(\bar{3},1,1)$	$(\bar{3},1)$	Q_{lu}	$\bar{L}_L^c\, \gamma^\mu\, u_R$
$\mathcal{V}_{\mathrm{XV}}$	$(\bar{3},2)_{\frac{5}{6}}$	$(1,\bar{3},1)$	$(\bar{3},1)$	Q_{ld}	$\bar{L}_L^c\, \gamma^\mu\, d_R$
$\mathcal{V}_{\mathrm{XVI}}$	$(\bar{3},1)_{-\frac{2}{3}}$	$(1,\bar{3},1)$	(1,3)	Q_{ed}	$\bar{e}_R\, \gamma^\mu\, d_R$
$\mathcal{V}_{\mathrm{XVII}}$	$(\bar{3},1)_{-\frac{5}{3}}$	$(\bar{3},1,1)$	(1,3)	Q_{eu}	$\bar{e}_R\, \gamma^\mu\, u_R$
$\mathcal{V}_{\mathrm{XIX}}$	$(\bar{3},1)_{-\frac{2}{3}}$	$(1,1,\bar{3})$	(3,1)	$Q_{lq}^{(1)}$	$\bar{L}_L\, \gamma^\mu\, Q_L$

Dim-6 Operator Matching

- Flavor symmetry spurion breaking

An example: color-singlet, flavor-octet

$$\mathcal{L}_{\mathcal{V}^{(1)}_{\rm VIII}} = -\frac{1}{2}\left(D_\mu \mathcal{V}_\nu\, D^\mu \mathcal{V}^\nu - D_\mu \mathcal{V}_\nu\, D^\nu \mathcal{V}^\mu\right) - \frac{M_{\mathcal{V}}^2}{2}\mathcal{V}_\nu \mathcal{V}^\nu + \left(\lambda_{\mathcal{V}} \mathcal{V}_{\mu,A} T^A\, Y_u^\dagger Y_u\, (D^\mu H)^\dagger H + \text{h.c.}\right), + g_{\mathcal{V}} \mathcal{V}_{\mu,A} (\bar{Q}_L T^A \gamma^\mu Q_L). \tag{11}$$

integrating out the heavy vector

$$\begin{aligned}
\Delta\mathcal{L}_6 \supset\ & \frac{g_{\mathcal{V}}^2}{4\,M_{\mathcal{V}}^2}\left[Q^{(1)}_{\substack{qq\\rssr}} - \frac{1}{3}\,Q^{(1)}_{\substack{qq\\rrss}}\right] \\
& + \frac{1}{4\,M_{\mathcal{V}}^2}\Big[\left((\mathrm{Im}\lambda_{\mathcal{V}})^2 - (\mathrm{Re}\lambda_{\mathcal{V}})^2\right)Q_{H\Box} + 4(\mathrm{Im}\lambda_{\mathcal{V}})^2\, Q_{HD} \\
& \qquad +2i(\mathrm{Re}\lambda_{\mathcal{V}})(\mathrm{Im}\lambda_{\mathcal{V}})(Y_b^\dagger Q_{bH} - Y_b Q_{bH}^\dagger) \\
& \qquad -2i(\mathrm{Re}\lambda_{\mathcal{V}})(\mathrm{Im}\lambda_{\mathcal{V}})(Y_u^\dagger Q_{uH} - Y_u Q_{uH}^\dagger)\Big] \\
& \qquad \times\left[\mathrm{Tr}[(Y_u^\dagger Y_u)(Y_u^\dagger Y_u)] - \frac{(\mathrm{diag}(Y_u^\dagger Y_u))^2}{3}\right] \\
& - \frac{g_{\mathcal{V}}\mathrm{Im}[\lambda_{\mathcal{V}}]}{2M_{\mathcal{V}}^2} Q^{(1)}_{\substack{Hq\\pr}}\left[(Y_u^\dagger Y_u)^p_r - \frac{\mathrm{diag}(Y_u^\dagger Y_u)}{3}\delta_{pr}\right] \\
& + i\,\frac{g_{\mathcal{V}}\mathrm{Re}[\lambda_{\mathcal{V}}]}{2M_{\mathcal{V}}^2}\left[((Y_u^\dagger Y_u)Y_a^\dagger)^m_i Q_{\substack{aH\\im}} - (Y_a(Y_u^\dagger Y_u))^i_m Q^\dagger_{\substack{aH\\mi}}\right] \\
& - i\,\frac{g_{\mathcal{V}}\mathrm{Re}[\lambda_{\mathcal{V}}]}{6M_{\mathcal{V}}^2}\mathrm{Tr}[Y_u^\dagger Y_u]\left[(Y_a^\dagger)^m_i Q_{\substack{aH\\im}} - (Y_a)^i_m Q^\dagger_{\substack{aH\\mi}}\right],
\end{aligned} \tag{12}$$

a bunch of operators generated!

Case	SM group	G_Q	G_L	Op	G_Q, G_L Spurion
$\mathcal{V}^{(1)}_{\rm VIII}$	$(1,1)_0$	(1,1,8)	(1,1)	$Q^{(1)}_{qq}$	$T^A\, Y_u^\dagger Y_u, T^A\, Y_d^\dagger Y_d$
$\mathcal{V}^{(1)}_{\rm IX}$	$(1,3)_0$	(1,1,8)	(1,1)	$Q^{(1)}_{qq}$	$T^A\, Y_u^\dagger Y_u, T^A\, Y_d^\dagger Y_d$
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$\mathcal{V}_{\rm XIII}$	$(1,1)_0$	(1,1,1)	(1,8)	Q_{ee}	$T^A\, Y_e^\dagger Y_e$

$\mathcal{V}^{(1)}_{\rm VII}$	$(1,1)_{-1}$	$(\bar{3},3,1)$	(1,1)	$Q^{(1)}_{ud}$	$\bar{d}_R\,\gamma^\mu\,u_R$
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$\mathcal{V}^{(\bar{3},6)}_{\rm XI}$	$(\bar{3}\mathrm{or}6,2)_{\frac{5}{6}}$	(3,1,3)	(1,1)	$Q^{(1)}_{qu}$	$\bar{u}_R\,\gamma^\mu\,Q_L^c$
$\mathcal{V}_{\rm XVIII}$	$(3,2)_{-\frac{5}{6}}$	(1,1,3)	(1,3)	Q_{qe}	$\bar{e}_R\,\gamma^\mu\,Q_L^c$
$\mathcal{V}_{\rm XII}$	$(1,2)_{\frac{3}{2}}$	(1,1,1)	$(\bar{3},\bar{3})$	Q_{le}	$\bar{L}_L^c\,\gamma^\mu\,e_R$
$\mathcal{V}_{\rm XIV}$	$(\bar{3},2)_{-\frac{1}{6}}$	$(\bar{3},1,1)$	$(\bar{3},1)$	Q_{lu}	$\bar{L}_L^c\,\gamma^\mu\,u_R$
$\mathcal{V}_{\rm XV}$	$(\bar{3},2)_{\frac{5}{6}}$	$(1,\bar{3},1)$	$(\bar{3},1)$	Q_{ld}	$\bar{L}_L^c\,\gamma^\mu\,d_R$
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Fields having **$U(1)_Y$ charges** have no spurion interaction.

Dim-6 Operator Matching

SHORT SUMMARY

Single dim-6 operator induced at tree level only for the UV fields that carry

1. ***$U(1)_Y$ charges***
2. ***non-trivial** representation under flavor groups*

$\mathcal{V}^{(1)}_{\mathrm{VII}}$	$(1,1)_{-1}$	$(\bar{3},3,1)$	$(1,1)$	$Q^{(1)}_{ud}$	$\bar{d}_R\,\gamma^\mu\,u_R$
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Dim-6 Operator Matching

SHORT SUMMARY

- The single operators obtained in tree level matchings to the vectors are limited to 4-fermion operator forms.
  - contributes to continuum parton production.
  - parametrically has a Γ/M suppression
- Never obtain only one operator in such a tree level matching that involves the Higgs field.

Single dim-6 operator induced at tree level only for the UV fields that carry

1. ***$U(1)_Y$ charges***
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Stand alone “UV” scenario?

ARGUMENTS ON ORPHANED VECTORS

1) Landau poles

Consider the β-function for the the coupling of the vector field to the fermion bi-linears

$$\boxed{\beta_{g_{\mathcal{V}}} = 2\, g_{\mathcal{V}}\, \epsilon \left(-\frac{\delta_{Z_3}}{\langle \mathcal{O} \rangle} - \frac{1}{2}\delta_{Z_{\bar{\psi}}} - \frac{1}{2}\delta_{Z_{\psi}} - \frac{1}{2}\delta_{Z_{V}} \right)}$$

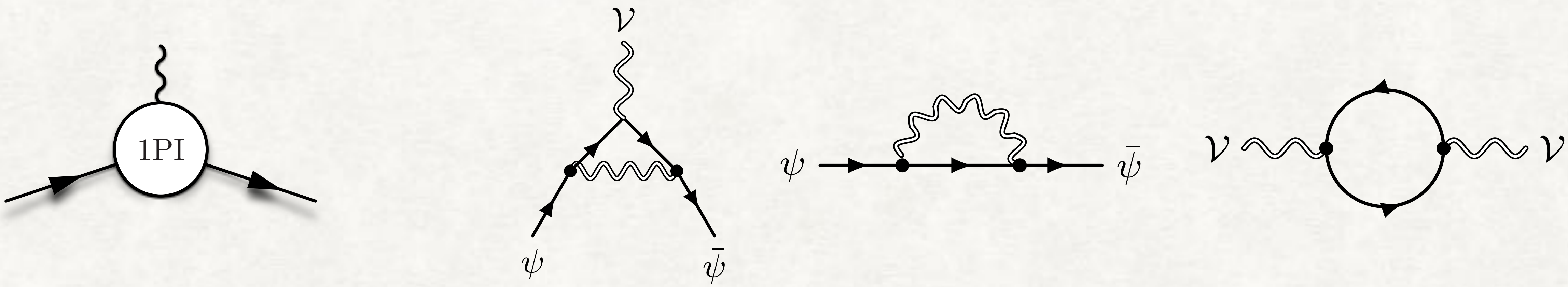
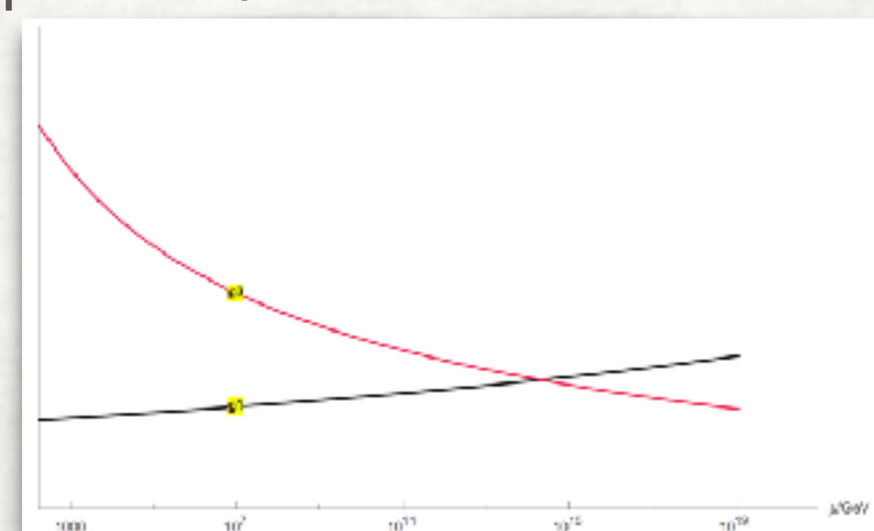


FIG. 1. Diagrams relevant for the renormalization of $g_{\mathcal{V}}$.

Suppose no vector self-interaction, the **β**-function is positive, indicating Landau poles at scale,

$$\Lambda_L \sim M_{\mathcal{V}} \exp\left[g_{\mathcal{V}} / \beta_{g_{\mathcal{V}}} \right].$$

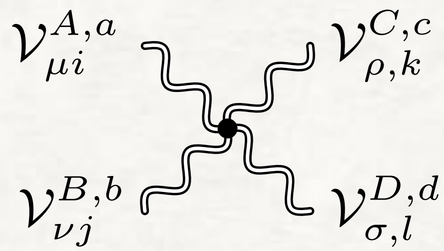
with the exception of color-anti3 case.



ARGUMENTS ON ORPHANED VECTORS

2) Unitary

To make the theory asymptotically free, self-interactions are demanded.



$$\mathcal{M}_4^L = \lambda\left(F_s\frac{t^2-u^2}{4\,M_{\mathcal{V}}^4} + F_t\frac{s^2-u^2}{4\,M_{\mathcal{V}}^4} + F_u\frac{s^2-t^2}{4\,M_{\mathcal{V}}^4}\right)$$

grow as E^4

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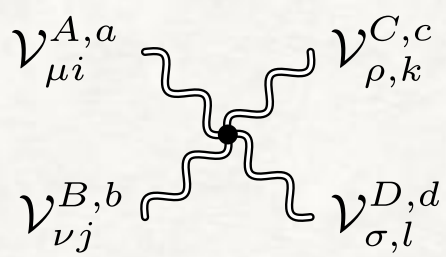

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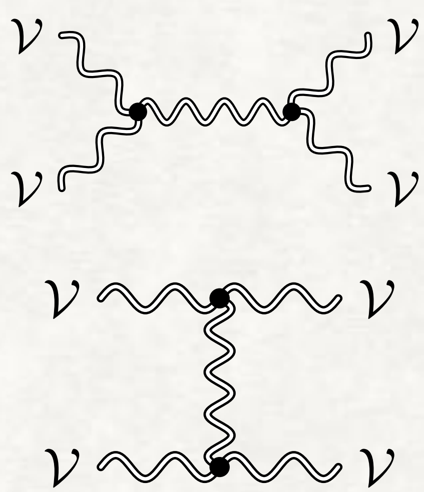

$$\mathcal{M}_{3,\mathrm{s}}^L = (g')^2 F_s \frac{st - su}{4\, M_{\mathcal{V}}^4},$$

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3-point int. present only for U(1) zero vector field

no ghost fields are present as the vectors introduced are not assumed to be the gauge bosons of a larger gauge group

- For Y=0 vector, if $\lambda = (g')^2$: E^4 scaling disappears, alleviating to E^2 scale
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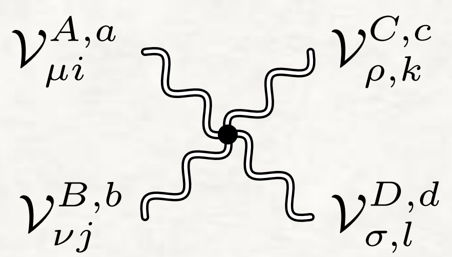

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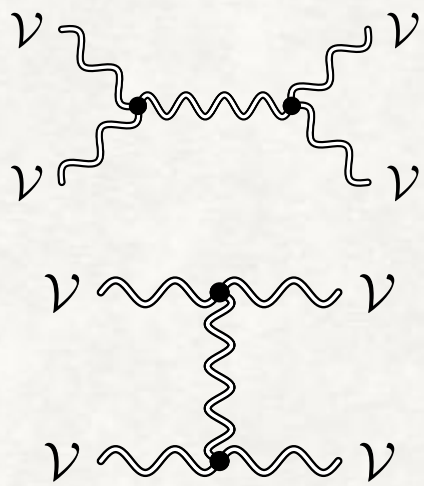

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The UV strong sector should be simultaneously considered, when integrating out it would increase the low energy operator profile (via non-perturbative matching).

ARGUMENTS ON ORPHANED VECTORS

3) Dynamical origin

Option 1: UV Higgs mechanism

At least one sibling field (i.e. a singlet scalar acquiring the VEV) is needed.

$$\mathcal{L}_{SH} = \underline{(D^\mu S)^\dagger (D_\mu S)} - \frac{\lambda'}{4}(S^\dagger S - \frac{v'^2}{2})^2 + \lambda_{SH} S^\dagger S H^\dagger H.$$

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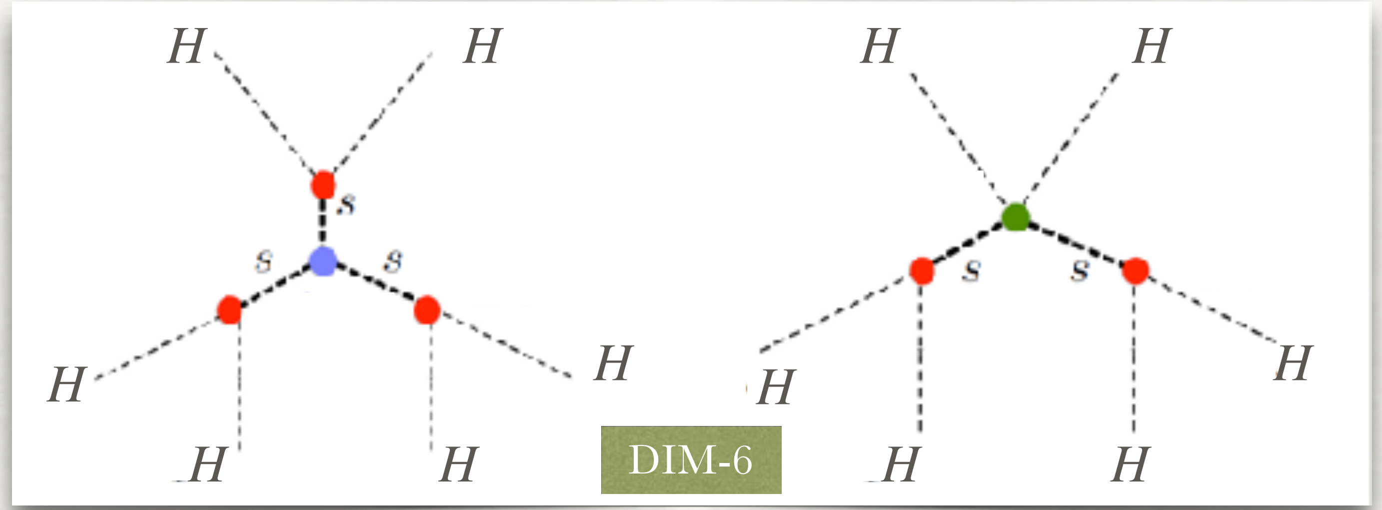

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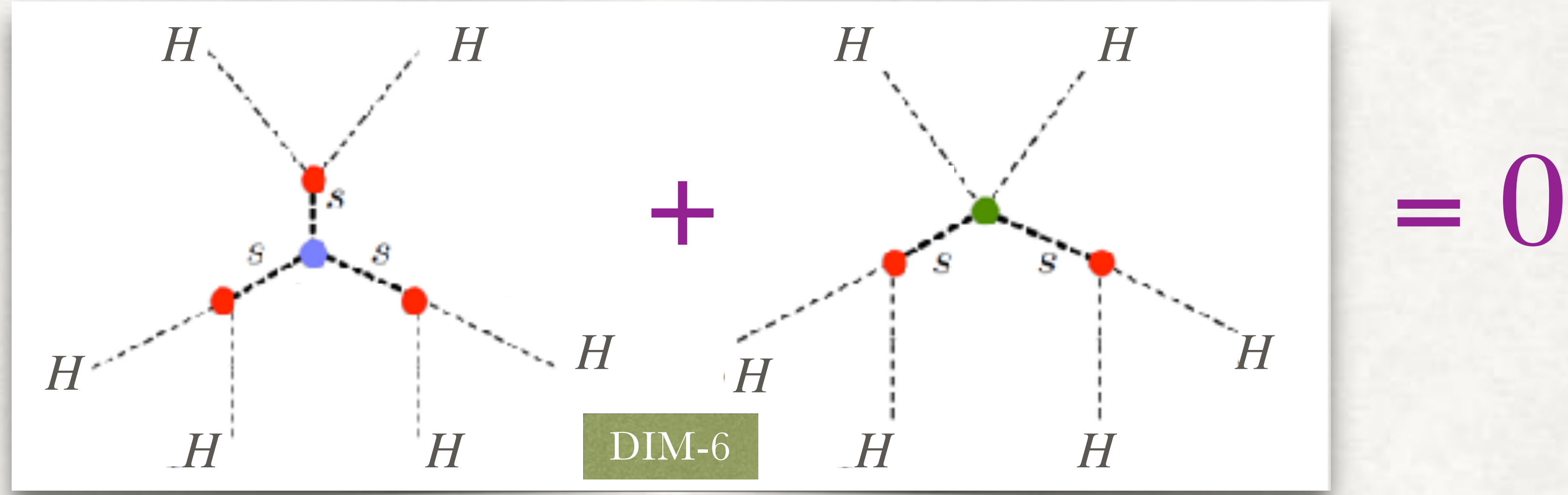

[1502.07352]

leading to one extra operator are generated,

$$\Delta\mathcal{L}_6 = -\frac{2\,\lambda_{SH}^2}{\lambda' m_s^2} Q_{H\Box} - \frac{4}{\lambda'}(\mathcal{V}_\mu \mathcal{V}^\mu)^2 +$$ the ones induced by integrating out the vector field.

ARGUMENTS ON ORPHANED VECTORS

3) Dynamical origin

Option 2: Compositeness

Consider a composite massive vector generated by a hypothetical UV strong sector, with spin-$1/2$ constituents Ψ,

$$\boxed{\mathcal{V}^\mu \ \sim \ \langle \Psi \gamma^\mu \Psi \rangle}$$

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singlet sibling
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$\mathbf{P} \otimes \mathbf{R}$

contains $\mathbf{P} \otimes \bar{\mathbf{P}}, \mathbf{R} \otimes \bar{\mathbf{R}}$

Consequently, a number of operators are induced when integrated out.

Case II

Adding a spin-1/2 field

Vector-like quarks

Case	$SU(2)_L$	$U(1)_Y$	$J_L^{\mathcal{Q}}$	Q_{uH}	Q_{dH}	$Q_{Hq}^{(1)}$	$Q_{Hq}^{(3)}$
$\mathcal{Q}_{\mathrm{I}}^{(1)}$	1	$-\frac{1}{3}$	$\bar{Q}_L H$		$\checkmark$	$\checkmark$	$\checkmark$
$\mathcal{Q}_{\mathrm{I}}^{(3)}$	3	$-\frac{1}{3}$	$\sigma^I \bar{Q}_L H$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
$\mathcal{Q}_{\mathrm{II}}^{(1)}$	1	$\frac{2}{3}$	$\bar{Q}_L H^*$	$\checkmark$		$\checkmark$	$\checkmark$
$\mathcal{Q}_{\mathrm{II}}^{(3)}$	3	$\frac{2}{3}$	$\sigma^I \bar{Q}_L H^*$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$

Case	$SU(2)_L$	$U(1)_Y$	$J_R^{\mathcal{Q}}$	Q_{uH}	Q_{dH}	Q_{Hu}	Q_{Hd}	Q_{Hud}
$\mathcal{Q}_{\mathrm{III}}$	2	$\frac{1}{6}$	$\bar{u}_R H^T$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
$\mathcal{Q}_{\mathrm{IV}}$	2	$\frac{1}{6}$	$\bar{d}_R H^\dagger$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
$\mathcal{Q}_{\mathrm{V}}$	2	$\frac{7}{6}$	$\bar{u}_R H^\dagger$	$\checkmark$		$\checkmark$		
$\mathcal{Q}_{\mathrm{VI}}$	2	$-\frac{5}{6}$	$\bar{d}_R H^T$		$\checkmark$		$\checkmark$	

Case	$SU(2)_L$	$U(1)_Y$	G_Q	$J_R^{\mathcal{Q}}$	Q_{uH}	Q_{dH}	Q_{Hu}	Q_{Hd}
$\mathcal{Q}_{\mathrm{VII}}$	2	$\frac{1}{6}$	(3,1,1)	$\bar{u}_R H^T$	$\checkmark$		$\checkmark$	
$\mathcal{Q}_{\mathrm{VIII}}$	2	$\frac{1}{6}$	(1,3,1)	$\bar{d}_R H^\dagger$		$\checkmark$		$\checkmark$

Vector-like leptons

Case	$SU(2)_L$	$U(1)_Y$	$J_L^{\mathcal{L}}$	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	Q_{eH}	$Q_{He}^{(1)}$
$\mathcal{L}_{\mathrm{I}}^{(1)}$	1	-1	$\bar{L}_L H$	$\checkmark$	$\checkmark$	$\checkmark$	
$\mathcal{L}_{\mathrm{I}}^{(3)}$	3	-1	$\sigma^I \bar{L}_L H$	$\checkmark$	$\checkmark$	$\checkmark$	

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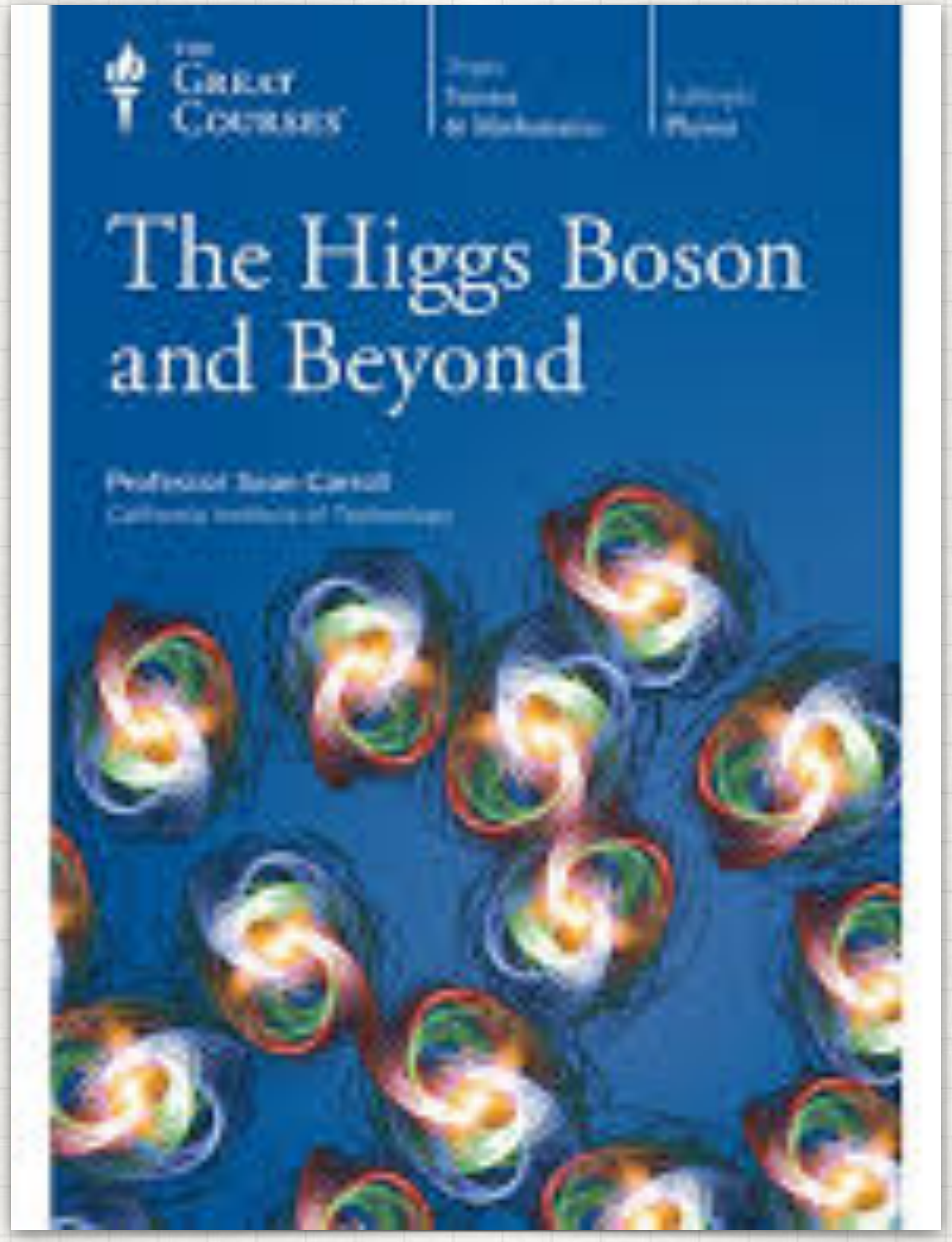
$\mathcal{L}_{\mathrm{III}}$	2	$-\frac{1}{2}$	$\bar{e}_R H^\dagger$			$\checkmark$	$\checkmark$
$\mathcal{L}_{\mathrm{IV}}$	2	$-\frac{3}{2}$	$\bar{e}_R H^T$			$\checkmark$	$\checkmark$

- Multiple operators are induced at tree level when integrating out a vector-like fermion.
- This is also true for chiral fermion.

Case III

Adding a spin-0 field



ADDING A SPIN-0 FIELD

As the bi-linear of scalar and its self-conjugate is always singlet, so a massive scalar can couple into the SM through a number of interactions
$\Rightarrow$ generate many operators in the matching

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As the bi-linear of scalar and its self-conjugate is always singlet, so a massive scalar can couple into the SM through a number of interactions $\Longrightarrow$ generate many operators in the matching

For example, the scalar fields which are either singlet or triplet under SU(2)

Case	$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_\mathrm{Y}$	Couplings	Q_H	$Q_{H\Box}$
$\mathcal{S}_\mathrm{I}^1$	1	0	$(\Lambda_S \mathcal{S}_\mathrm{I} + \mathcal{S}_\mathrm{I}^\dagger \mathcal{S}_\mathrm{I}) H^\dagger H$	$\surd$	$\surd$
$\mathcal{S}_\mathrm{I}^3$	3	0	$\Lambda_S \mathcal{S}_\mathrm{I} \sigma H^\dagger H,\ \mathcal{S}_\mathrm{I}^\dagger \mathcal{S}_\mathrm{I} H^\dagger H$	$\surd$	$\surd$
$\mathcal{S}_\mathrm{II}^1$	1	-1	$\Lambda_S\, \mathcal{S}_\mathrm{II}\, H^T H,\ \mathcal{S}_\mathrm{II}^\dagger \mathcal{S}_\mathrm{II} H^\dagger H$	$\surd$	$\surd$
$\mathcal{S}_\mathrm{II}^3$	3	-1	$\Lambda_S \mathcal{S}_\mathrm{II} \sigma H^T H,\ \mathcal{S}_\mathrm{II}^\dagger \mathcal{S}_\mathrm{II} H^\dagger H$	$\surd$	$\surd$

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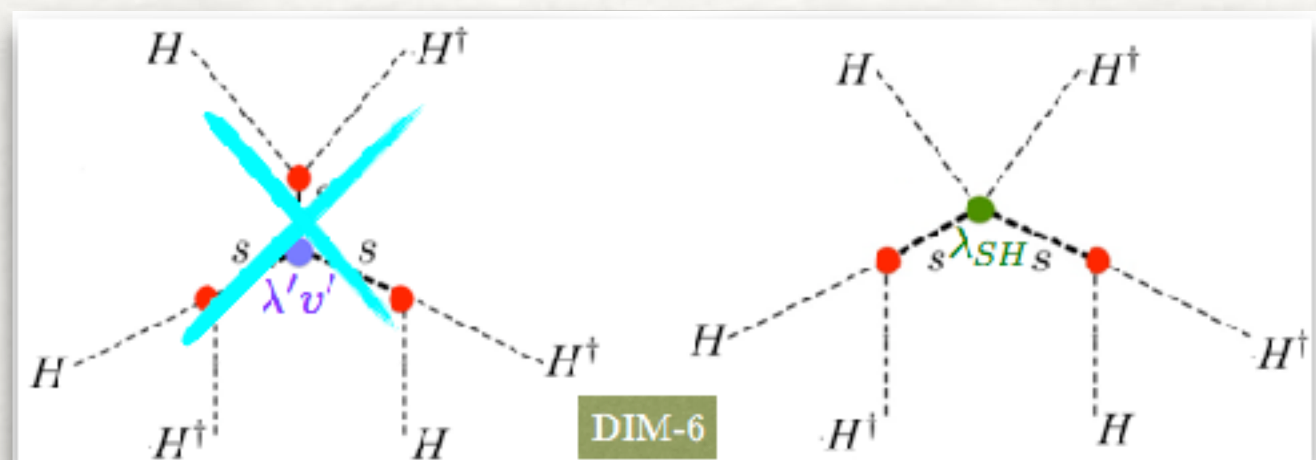
Case	$SU(2)_L$	$U(1)_Y$	Couplings	Q_H	$Q_{H\Box}$
$\mathcal{S}_I^1$	1	0	$(\Lambda_S \mathcal{S}_I + \mathcal{S}_I^\dagger \mathcal{S}_I) H^\dagger H$	$\surd^*$	$\surd$
$\mathcal{S}_I^3$	3	0	$\Lambda_S \mathcal{S}_I \sigma H^\dagger H$, $\mathcal{S}_I^\dagger \mathcal{S}_I H^\dagger H$	$\surd$	$\surd$
$\mathcal{S}_{II}^1$	1	-1	$\Lambda_S\, \mathcal{S}_{II}\, H^T H$, $\mathcal{S}_{II}^\dagger \mathcal{S}_{II} H^\dagger H$	$\surd$	$\surd$
$\mathcal{S}_{II}^3$	3	-1	$\Lambda_S \mathcal{S}_{II} \sigma H^T H$, $\mathcal{S}_{II}^\dagger \mathcal{S}_{II} H^\dagger H$	$\surd$	$\surd$

no S^3 interaction

Integrating out the massive scalar S



No cancellation is present in these cases, leading to the Q_H left.

Thus, two operators are simultaneously produced in tree level matchings.

ADDING A SPIN-0 FIELD

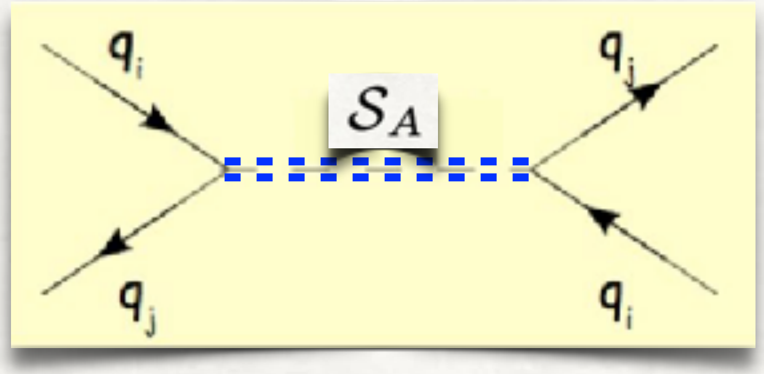
Several exceptional cases

Henning, Lu, Murayama, JHEP 1601 (2016) 023

Case	$\mathrm{SU}(2)_{\mathrm{L}}$	$\mathrm{U}(1)_{\mathrm{Y}}$	Couplings	Q_H	$Q_{H\Box}$
$\mathcal{S}_A$	2	1/2	$V(H, \mathcal{S}_A)$	$\surd$	
$\mathcal{S}_B$	4	3/2	$(H^3)^\dagger\, \mathcal{S}_B + \mathrm{h.c.}$	$\surd$	
$\mathcal{S}_C$	4	1/2	$H^\dagger \mathcal{S}_C H^\dagger H + \mathrm{h.c.}$	$\surd$	

see Gorhahn's talk for fit results

For example, the doublet scalar



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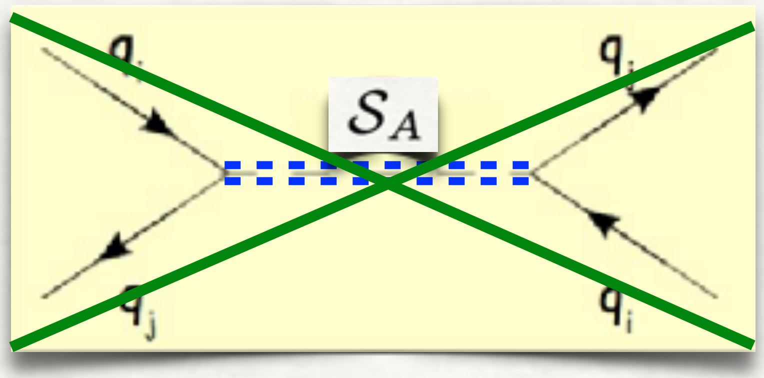


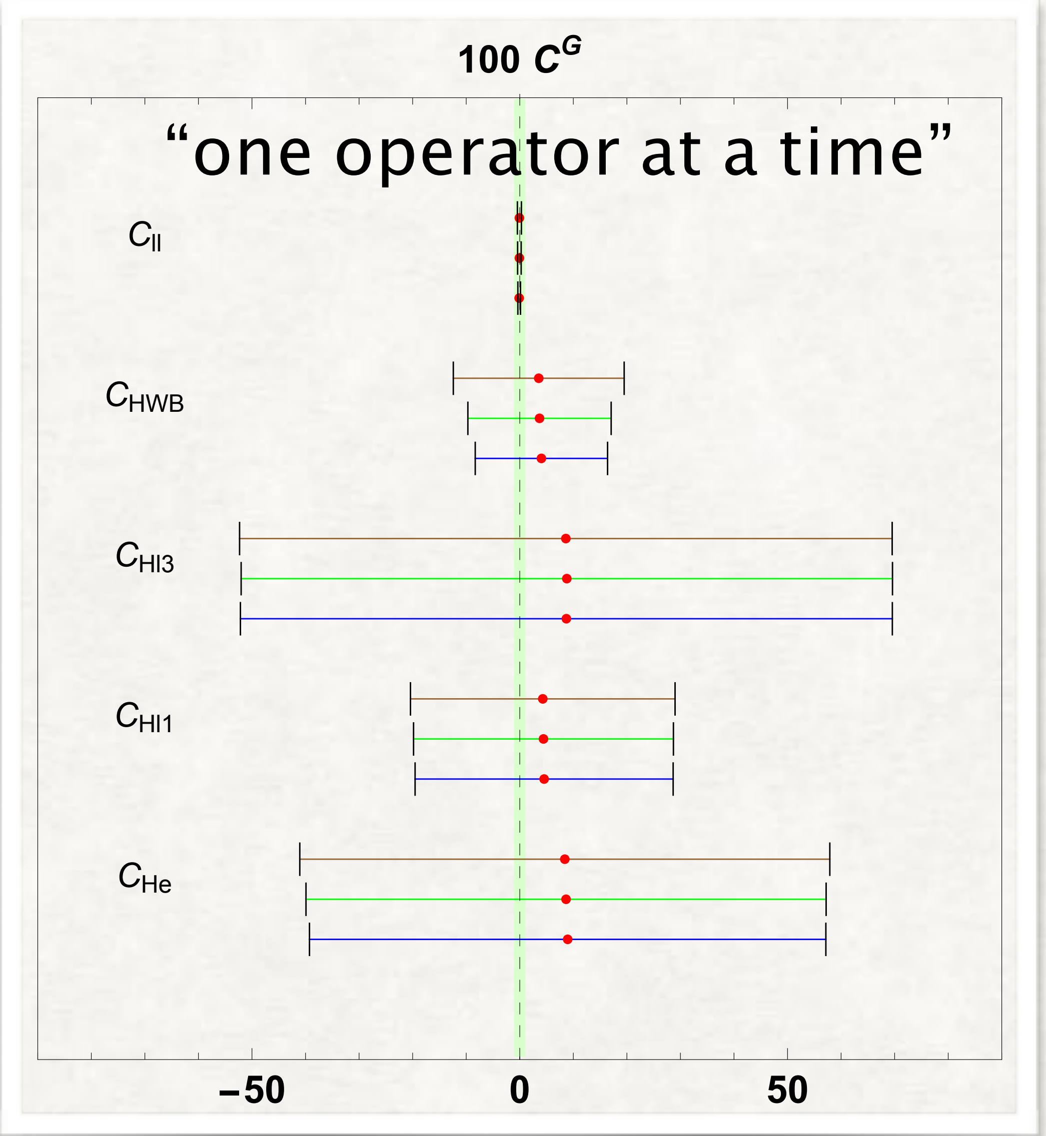
suppressed by discrete or additional U(1) symmetry

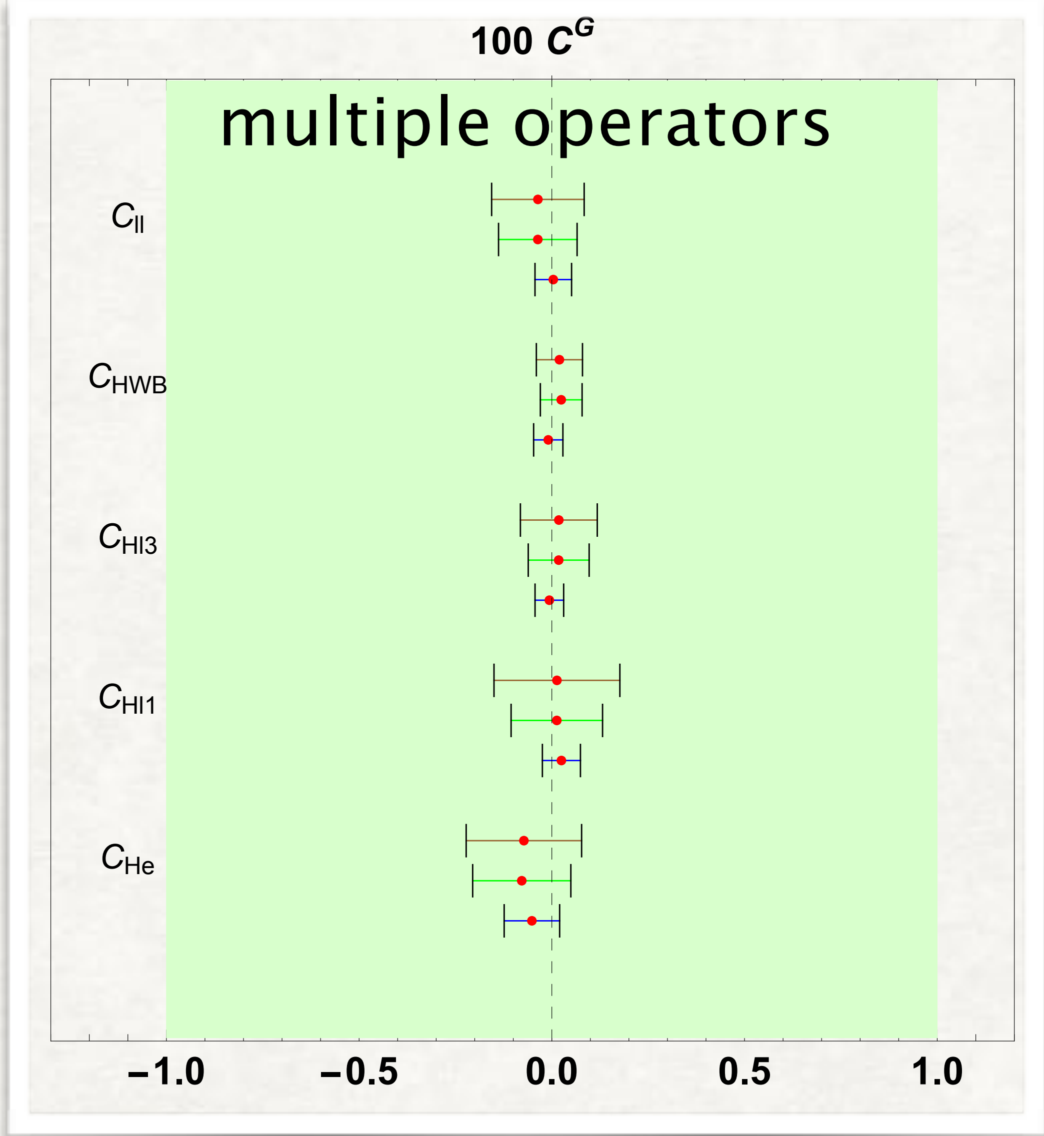
Only one dim−6 operator Q_H , can be obtained if an explicit scale is introduced without a dynamical origin to give the scalar a mass.

Similarly, the scalars that carry flavor quantum number can induce one 4−fermion operator. (see details in the paper)

A sample: EWPD fit

Trott et.al., arXiv: 1606.06693





- The resulting constraints can be relaxed by orders of magnitude, compared to a "one operator at a time" analysis.

CONCLUSIONS

- We address the question: "How can one obtain only one dim-6 operator in the SMEFT from a consistent tree level matching onto an unknown NP sector.

Heavy fermion

Heavy vector

Heavy scalar

one operator

Multiple operators

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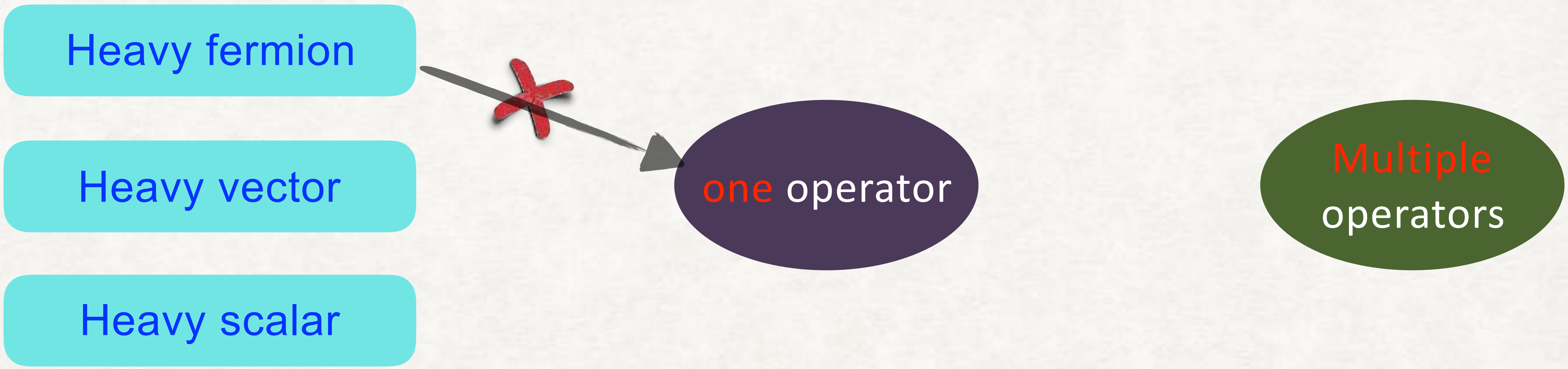

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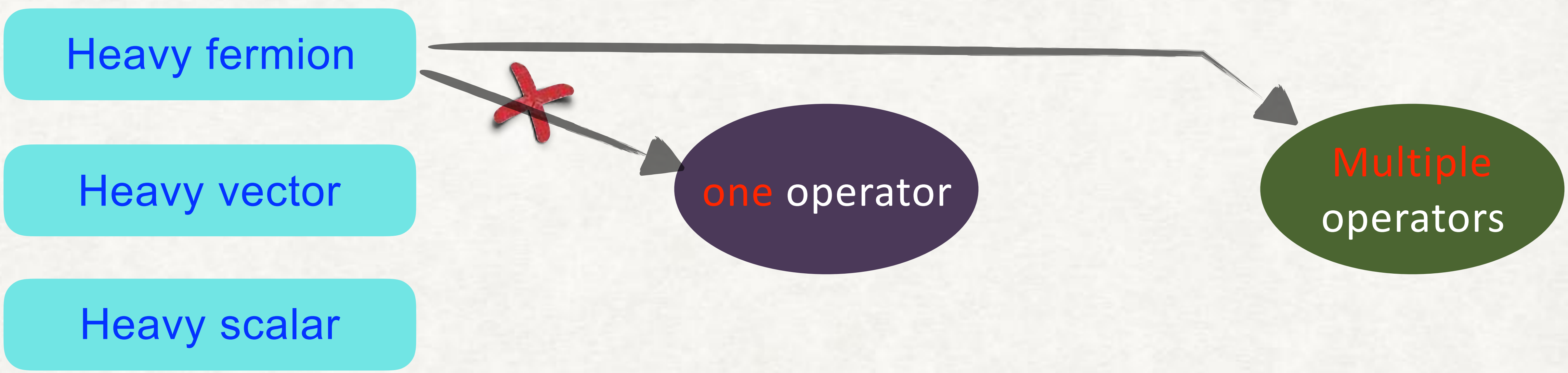

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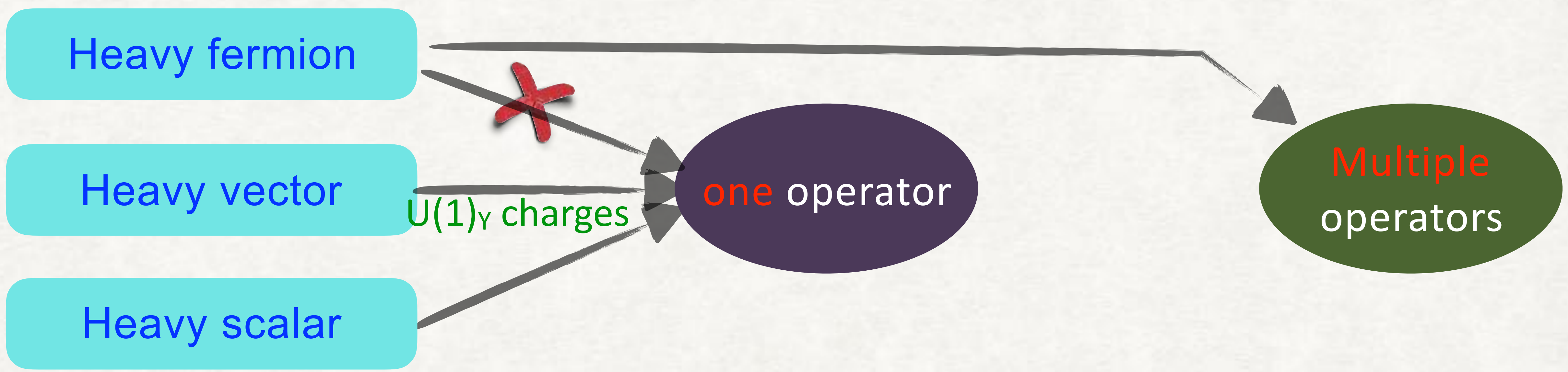

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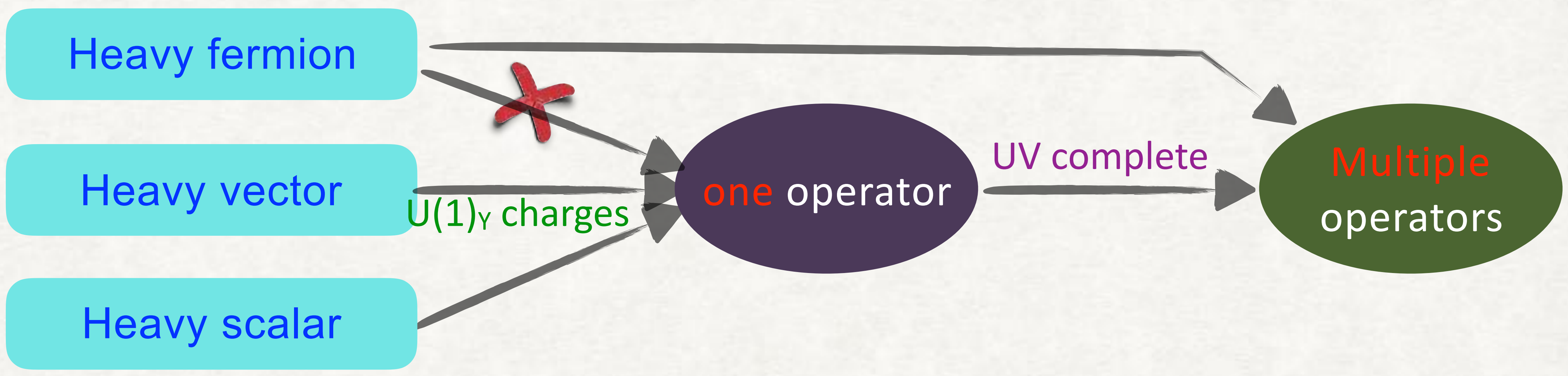

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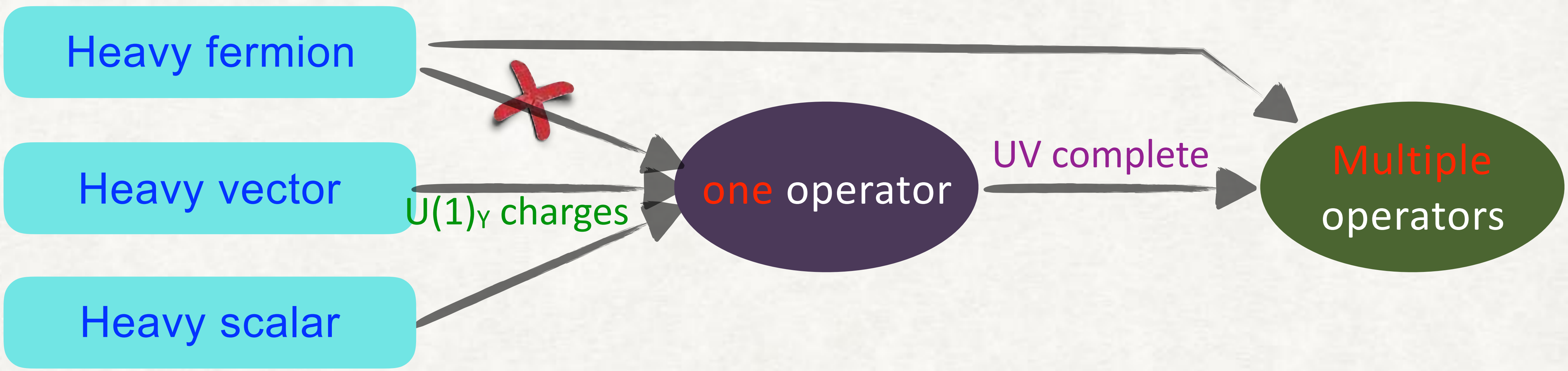
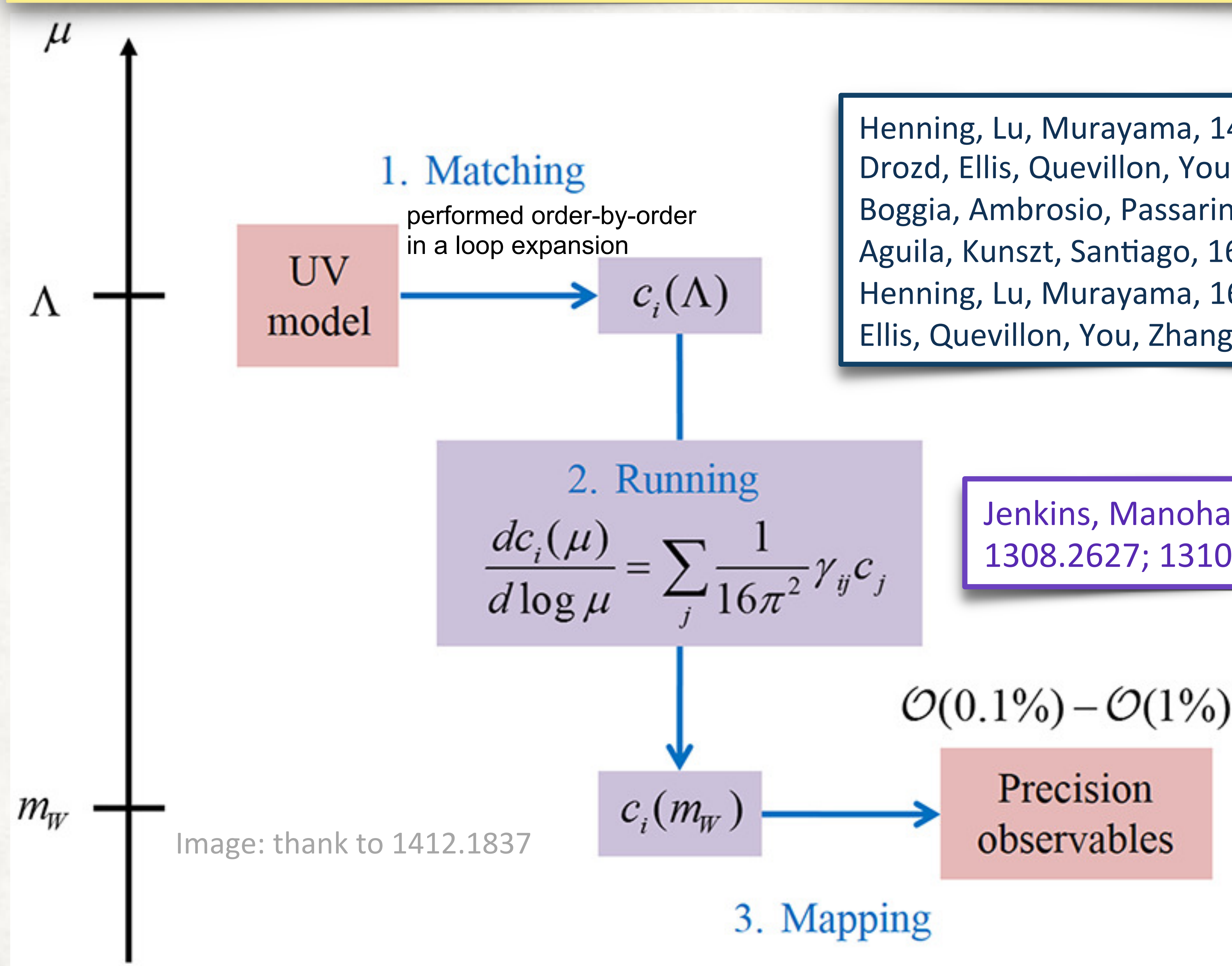


- **Global data analyses** in the SMEFT can and should accommodates this fact.
- The number of operators induced in matching is operator basis dependent. However, the conditions uncovered on the UV field content to reduce the operator profile are still meaningful.

BACK UP

3 STEPS: UV FLOW INTO IR

SMEFT as a bridge to connect UV models and weak scale precision observables.



Henning, Lu, Murayama, 1412.1837
Drozd, Ellis, Quevillon, You, 1512.03003
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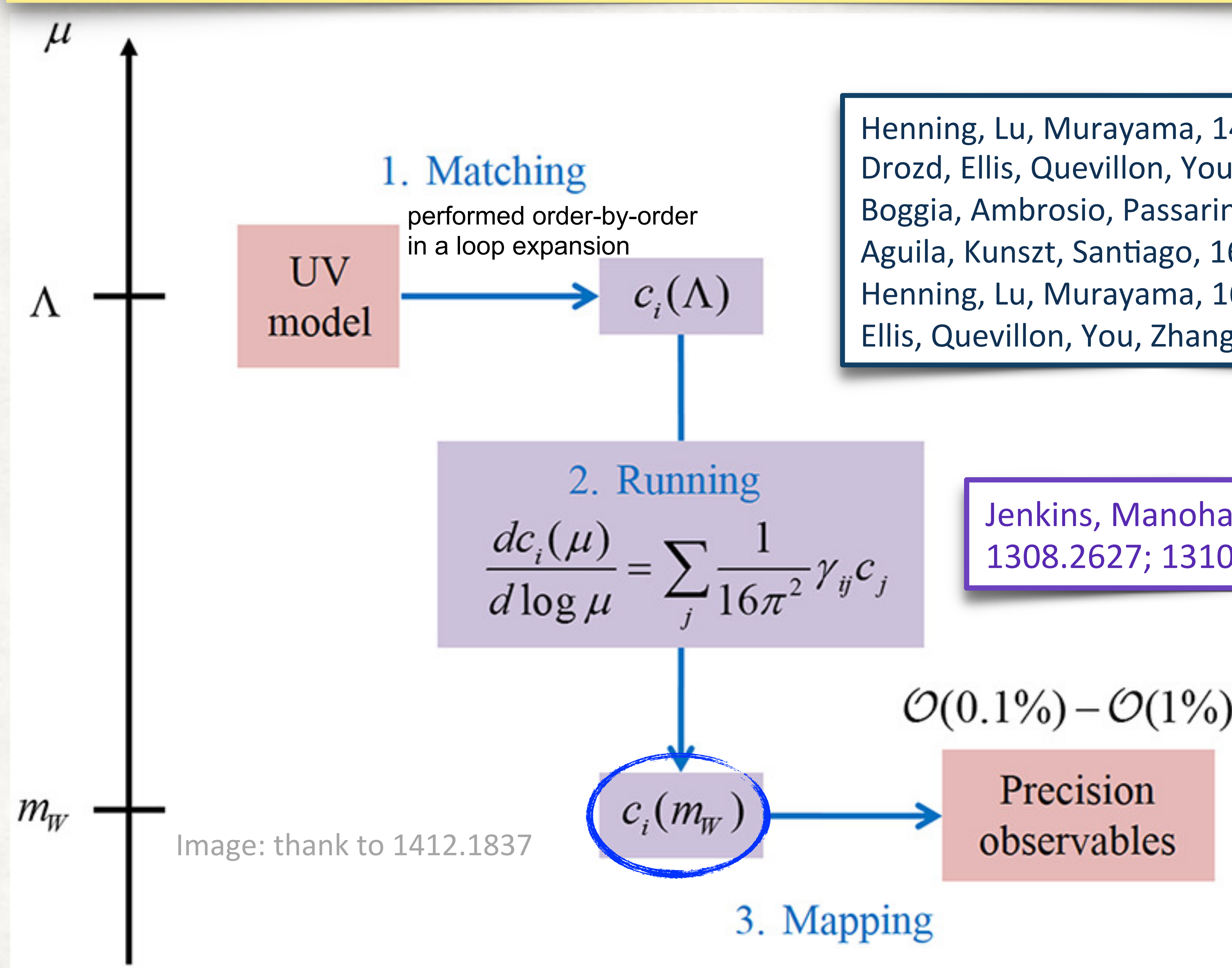

Image: thank to 1412.1837

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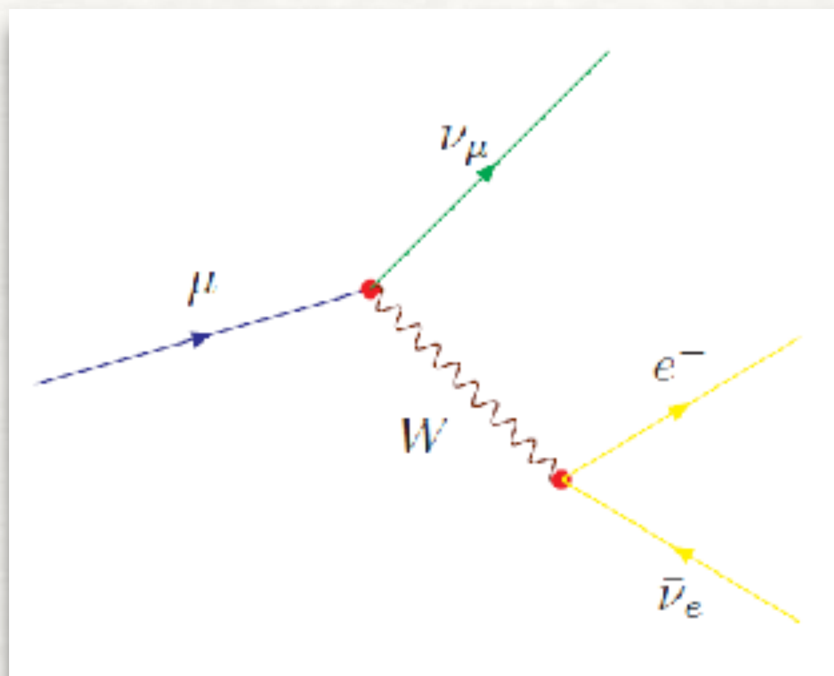
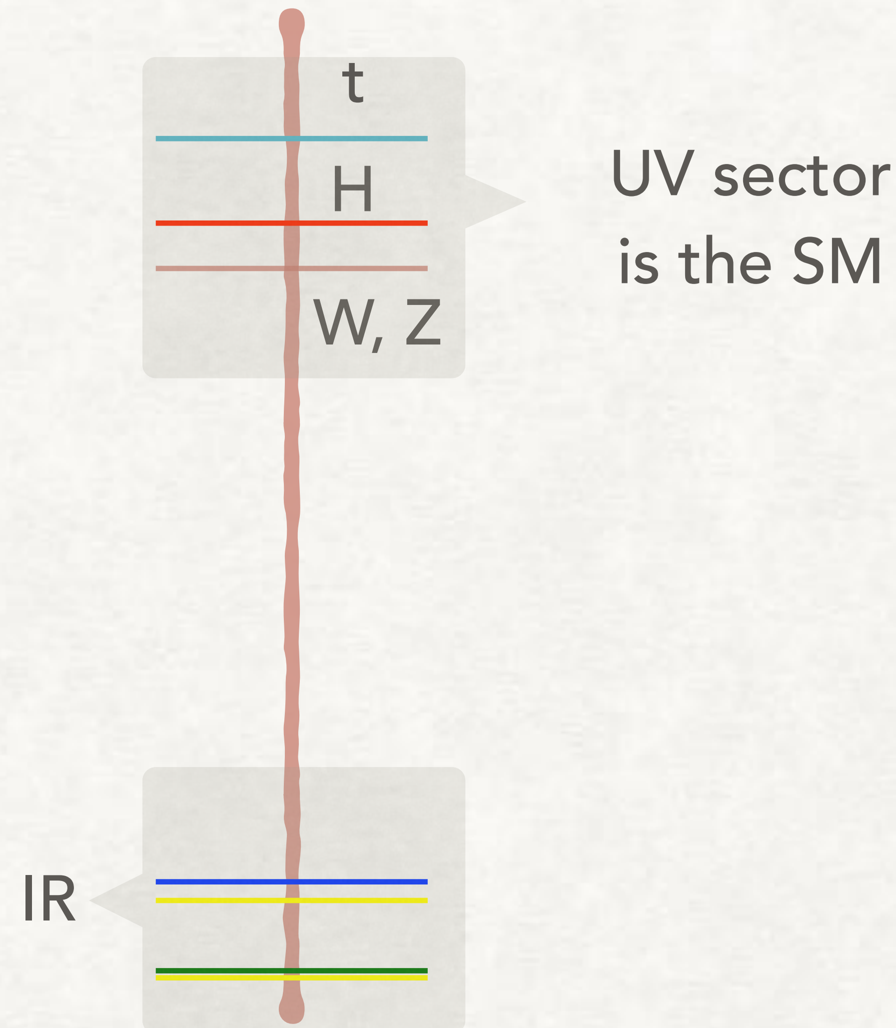
LESSONS ON EFT VALIDITY

FERMI THEORY

$$\boxed{Q_{\substack{\ell\ell \\ \mu\mu ee}} = (\bar{L}_\mu \gamma^\mu P_L L_\mu)\,(\bar{L}_e \gamma_\mu P_L L_e)}$$

generated when the W boson is integrated out





infer the Fermi constant

$$-\frac{4\hat{\mathcal{G}}_F}{\sqrt{2}} = -\frac{2}{\bar{v}_T^2} + \left(C_{\substack{ll \\ \mu ee\mu}} + C_{\substack{ll \\ e\mu\mu e}}\right) - 2\left(C^{(3)}_{\substack{Hl \\ ee}} + C^{(3)}_{\substack{Hl \\ \mu\mu}}\right)$$

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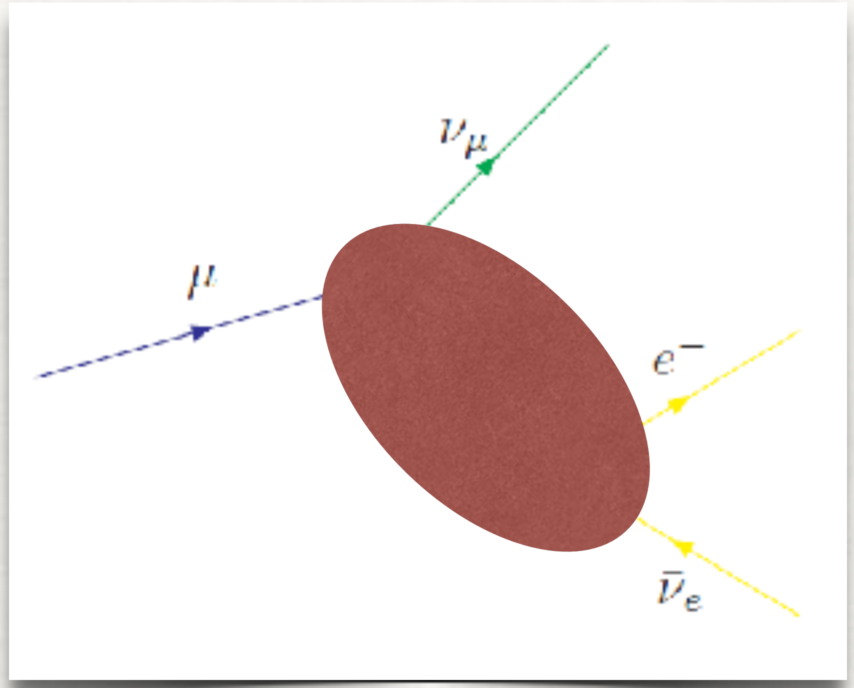

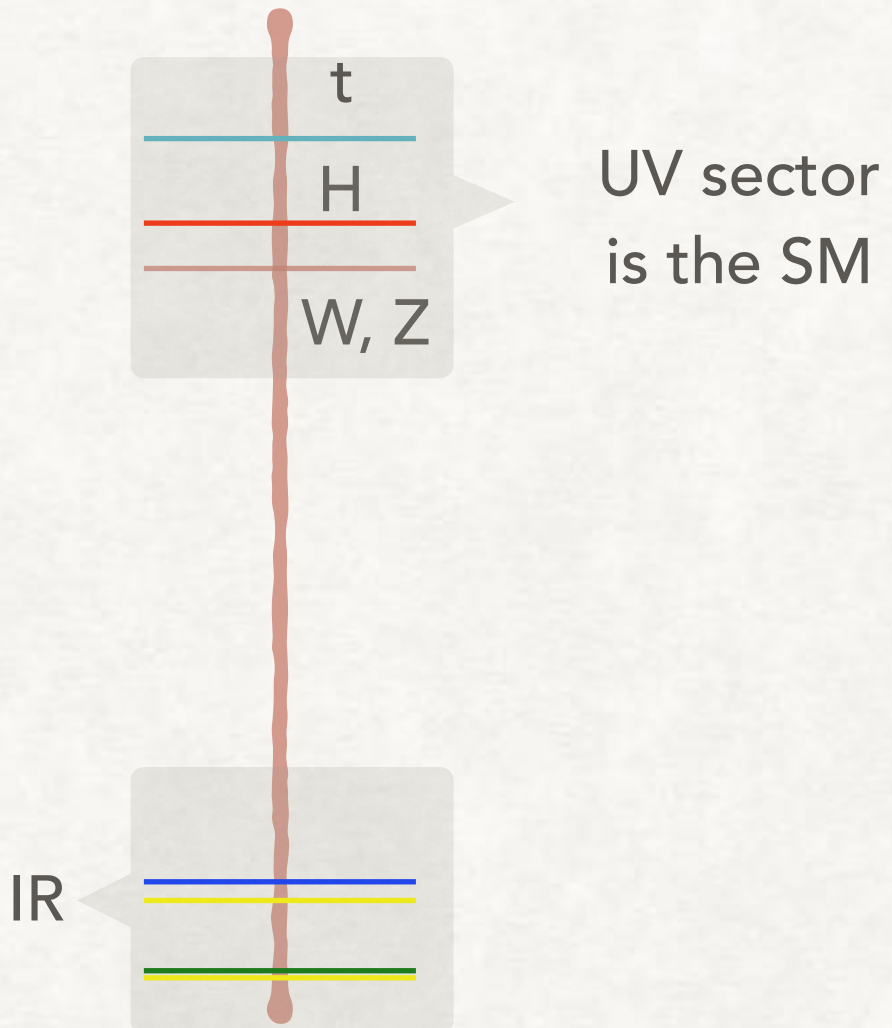

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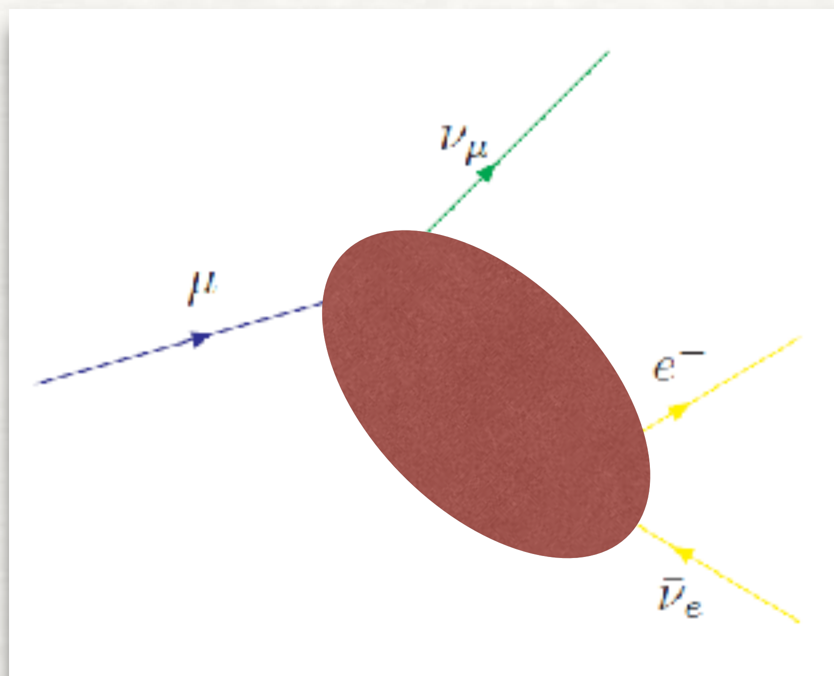

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UV sector is the SM

induces a series of other operators due to the Higgs and Z boson

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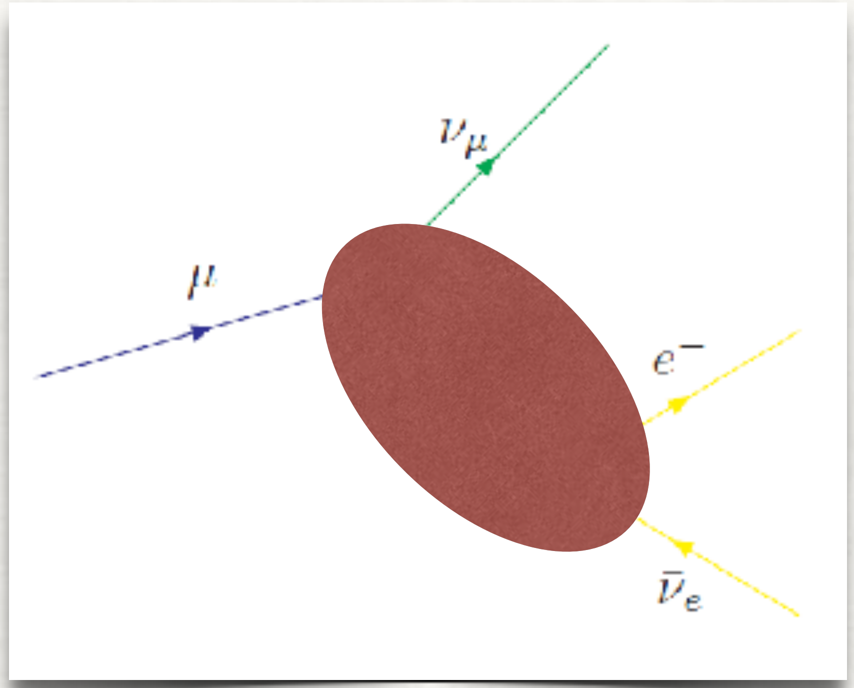

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Formally, Fermi theory is unfortunately not a prototypical EFT