

Dimension-8 Operators in SMEFT and LEFT

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Mostly based on

JHEP 10 (2020) 174 - 2005.00059

JHEP 04 (2021) 101 - 2012.13291

along with a bit of

Phys.Rev.D 96 (2017) 1, 015041 - 1704.07851 w/ S. Dawson

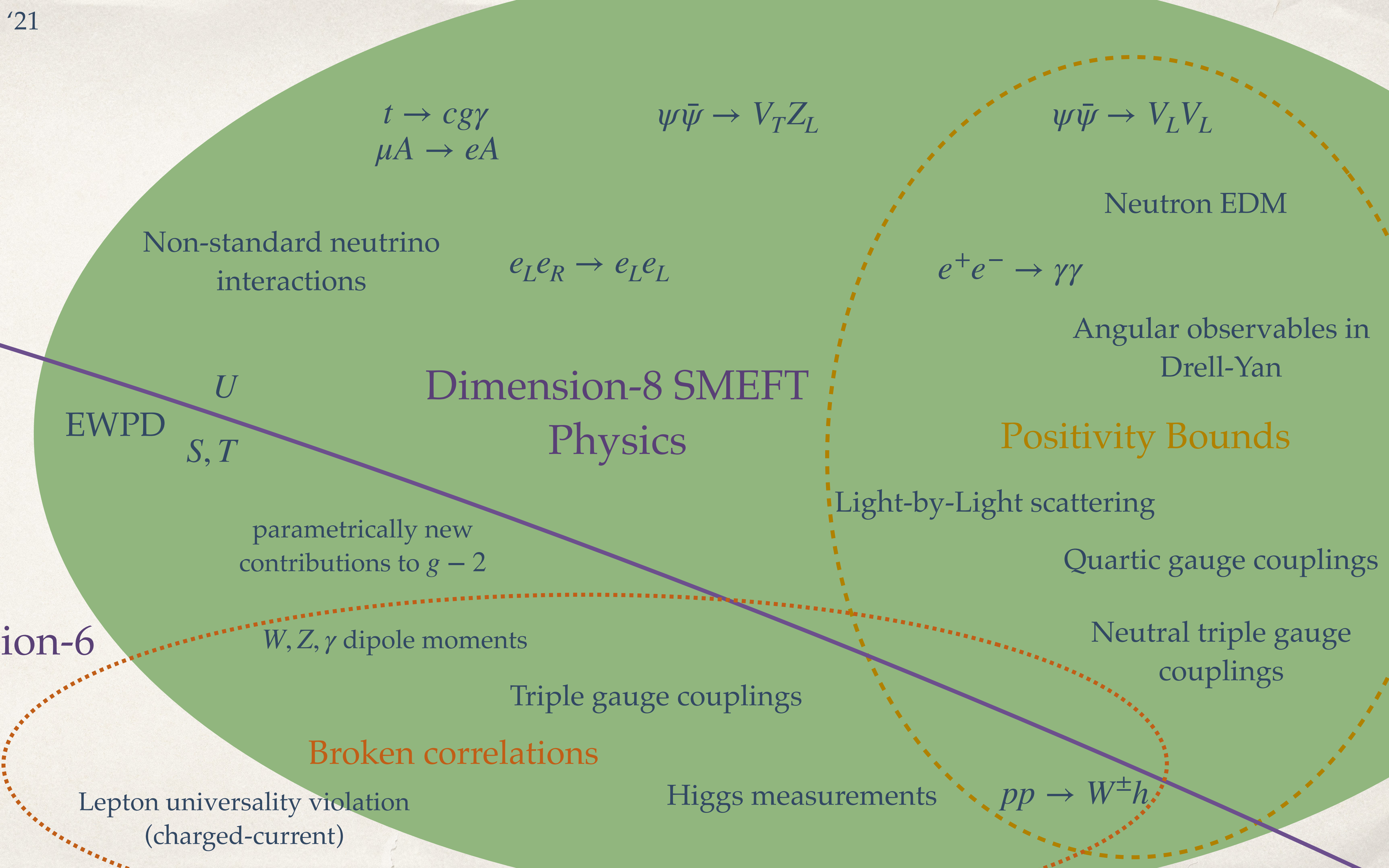
Dimension-8 Operators

❖ Why?

Dimension-8 Operators

Aren't there already
a lot of dimension-6
operators?

❖ Why?



$$t \rightarrow cg\gamma$$

$$\mu A \rightarrow eA$$

$$\psi\bar{\psi} \rightarrow V_T Z_L$$

$$\psi\bar{\psi} \rightarrow V_L V_L$$

Non-standard neutrino interactions

$$e_L e_R \rightarrow e_L e_L$$

$$e^+ e^- \rightarrow \gamma\gamma$$

Neutron EDM

Angular observables in Drell-Yan

Dimension-8 SMEFT Physics

Positivity Bounds

EWPD

U
 S, T

parametrically new contributions to $g - 2$

Light-by-Light scattering

Quartic gauge couplings

Dimension-6

W, Z, γ dipole moments

Neutral triple gauge couplings

Triple gauge couplings

Broken correlations

Lepton universality violation (charged-current)

Higgs measurements

$$pp \rightarrow W^\pm h$$

Standard Model Effective Field Theory

- ❖ Operator counting program has been hugely successful
- ❖ Now need actual (higher d) bases of operators for physics applications
- ❖ Non-trivial task due to:
 - ❖ large number of operators
 - ❖ presence of derivatives and repeated fields

Equations of Motion

- ❖ Avoid EOM redundancy by keeping only highest weight Lorentz reps. - Lehman, Martin 1503.07537
- ❖ $D\psi_L \sim (D\psi_L)_{(ab),\dot{a}}, DX_R \sim (DX_R)_{a,(\dot{a}\dot{b}\dot{c})}, D^2H \sim (D^2H)_{(ab),(\dot{a}\dot{b})}$



$$i(\bar{\psi}\gamma^\mu \overleftrightarrow{D}_\mu \psi)(H^\dagger H)$$



$$i(\bar{\psi}\gamma^\mu \psi)(H^\dagger \overleftrightarrow{D}_\mu H)$$

EOM + Integration by Parts

- ❖ Method based on [Hays, Martin, Sanz, Setford 1808.00442](#)
- ❖ Example: \bar{l}, e, H, B_L field content w / 2 derivatives

EOM + IBP

❖ Example: \bar{l}, e, H, B_L field content w / 2 derivatives

❖ 4 non-EOM-reducible candidate ops., x_{1-4}

$$\begin{aligned}x_1 &= (D\bar{l})_{a,(\dot{a}\dot{c})}e_{\dot{d}}(DH)_{b,\dot{b}}B_{(cd)}\epsilon^{ac}\epsilon^{bd}\epsilon^{\dot{a}\dot{d}}\epsilon^{\dot{c}\dot{b}}, \\x_2 &= \bar{l}_{\dot{c}}(De)_{a,(\dot{a}\dot{d})}(DH)_{b,\dot{b}}B_{(cd)}\epsilon^{ac}\epsilon^{bd}\epsilon^{\dot{a}\dot{c}}\epsilon^{\dot{d}\dot{b}}, \\x_3 &= (D\bar{l})_{a,(\dot{a}\dot{c})}(De)_{b,(\dot{b}\dot{d})}HB_{(cd)}\epsilon^{ac}\epsilon^{bd}\epsilon^{\dot{a}\dot{b}}\epsilon^{\dot{c}\dot{d}}, \\x_4 &= \bar{l}_{\dot{c}}e_{\dot{d}}(D^2H)_{(ab),(\dot{a}\dot{b})}B_{(cd)}\epsilon^{ac}\epsilon^{bd}\epsilon^{\dot{a}\dot{c}}\epsilon^{\dot{b}\dot{d}},\end{aligned}$$

EOM + IBP

❖ Example: \bar{l}, e, H, B_L field content w / 2 derivatives

❖ 4 non-EOM-reducible candidate ops., x_{1-4}

❖ 3 independent IBP constraints, $Dy_{1-3} = 0$

$$x_1 = (D\bar{l})_{a,(\dot{a}\dot{c})} e_{\dot{d}} (DH)_{b,\dot{b}} B_{(cd)} \epsilon^{ac} \epsilon^{bd} \epsilon^{\dot{a}\dot{d}} \epsilon^{\dot{c}\dot{b}},$$

$$x_2 = \bar{l}_{\dot{c}} (De)_{a,(\dot{a}\dot{d})} (DH)_{b,\dot{b}} B_{(cd)} \epsilon^{ac} \epsilon^{bd} \epsilon^{\dot{a}\dot{c}} \epsilon^{\dot{d}\dot{b}},$$

$$x_3 = (D\bar{l})_{a,(\dot{a}\dot{c})} (De)_{b,(\dot{b}\dot{d})} H B_{(cd)} \epsilon^{ac} \epsilon^{bd} \epsilon^{\dot{a}\dot{b}} \epsilon^{\dot{c}\dot{d}},$$

$$x_4 = \bar{l}_{\dot{c}} e_{\dot{d}} (D^2 H)_{(ab),(\dot{a}\dot{b})} B_{(cd)} \epsilon^{ac} \epsilon^{bd} \epsilon^{\dot{a}\dot{c}} \epsilon^{\dot{b}\dot{d}},$$

$$y_1 = (D\bar{l})_{a,(\dot{a}\dot{c})} e_{\dot{d}} H B_{(cd)} \epsilon^{ac} \epsilon^{\dot{a}\dot{d}},$$

$$y_2 = \bar{l}_{\dot{c}} (De)_{a,(\dot{a}\dot{d})} H B_{(cd)} \epsilon^{ac} \epsilon^{\dot{a}\dot{c}},$$

$$y_3 = \bar{l}_{\dot{c}} e_{\dot{d}} (DH)_{a,\dot{a}} B_{(cd)} \frac{1}{2} \epsilon^{ac} (\epsilon^{\dot{a}\dot{c}} + \epsilon^{\dot{a}\dot{d}}).$$

EOM + IBP

❖ Example: \bar{l}, e, H, B_L field content w/ 2 derivatives

❖ 4 non-EOM-reducible candidate ops., x_{1-4}

❖ 3 independent IBP constraints, $Dy_{1-3} = 0$

❖ Keep only $4 - 3 = 1$ combination of x_{1-4}

$$x_1 = (D\bar{l})_{a,(\dot{a}\dot{c})} e_{\dot{d}} (DH)_{b,\dot{b}} B_{(cd)} \epsilon^{ac} \epsilon^{bd} \epsilon^{\dot{a}\dot{d}} \epsilon^{\dot{c}\dot{b}},$$

$$x_2 = \bar{l}_{\dot{c}} (De)_{a,(\dot{a}\dot{d})} (DH)_{b,\dot{b}} B_{(cd)} \epsilon^{ac} \epsilon^{bd} \epsilon^{\dot{a}\dot{c}} \epsilon^{\dot{d}\dot{b}},$$

$$x_3 = (D\bar{l})_{a,(\dot{a}\dot{c})} (De)_{b,(\dot{b}\dot{d})} H B_{(cd)} \epsilon^{ac} \epsilon^{bd} \epsilon^{\dot{a}\dot{b}} \epsilon^{\dot{c}\dot{d}},$$

$$x_4 = \bar{l}_{\dot{c}} e_{\dot{d}} (D^2 H)_{(ab),(\dot{a}\dot{b})} B_{(cd)} \epsilon^{ac} \epsilon^{bd} \epsilon^{\dot{a}\dot{c}} \epsilon^{\dot{b}\dot{d}},$$

$$y_1 = (D\bar{l})_{a,(\dot{a}\dot{c})} e_{\dot{d}} H B_{(cd)} \epsilon^{ac} \epsilon^{\dot{a}\dot{d}},$$

$$y_2 = \bar{l}_{\dot{c}} (De)_{a,(\dot{a}\dot{d})} H B_{(cd)} \epsilon^{ac} \epsilon^{\dot{a}\dot{c}},$$

$$y_3 = \bar{l}_{\dot{c}} e_{\dot{d}} (DH)_{a,\dot{a}} B_{(cd)} \frac{1}{2} \epsilon^{ac} (\epsilon^{\dot{a}\dot{c}} + \epsilon^{\dot{a}\dot{d}}).$$

Repeated Fields & Flavor Representations

- ❖ Method based on [Fonseca 1907.12584](#)
- ❖ Example field content: $q^3 lB$

(this example by CM)

Repeated Fields & Flavor Reps.

permutation group of m objects, S_m

gauge

Lorentz

Field(s)	qqq	l	B_L
Group	S_3	S_1	S_1
$SU(3)_c$	$\left(\begin{array}{c} \square \\ \square \\ \square \end{array} \oplus \begin{array}{cc} \square & \square \\ \square & \end{array} \oplus \begin{array}{ccc} \square & \square & \square \end{array} \right)$		
$SU(2)_L$	$\left(\begin{array}{cc} \square & \square \\ \square & \end{array} \oplus \begin{array}{ccc} \square & \square & \square \end{array} \right)$	$\otimes \square$	
$SU(2)_\ell$	$\left(\begin{array}{cc} \square & \square \\ \square & \end{array} \oplus \begin{array}{ccc} \square & \square & \square \end{array} \right)$	$\otimes \square$	$\otimes \square$

$\{2,1\}$ is $2d$ rep. of S_3 - only 1 non-redundant op.

Repeated Fields & Flavor Reps.

- ❖ Multiply rows together to get valid operator contractions

Field(s)	qqq	l	B_L	$q^3 l B$
Group	S_3	S_1	S_1	
$SU(3)_c$	$\left(\begin{array}{c} \square \\ \square \\ \square \end{array} \oplus \begin{array}{cc} \square & \square \\ \square & \end{array} \oplus \begin{array}{ccc} \square & \square & \square \end{array} \right)$			$= \begin{array}{c} \square \\ \square \\ \square \end{array} \oplus \dots$
$SU(2)_L$	$\left(\begin{array}{cc} \square & \square \\ \square & \end{array} \oplus \begin{array}{ccc} \square & \square & \square \end{array} \right)$	$\otimes \square$		$= \begin{array}{cc} \square & \square \\ \square & \end{array} \oplus \dots$
$SU(2)_\ell$	$\left(\begin{array}{cc} \square & \square \\ \square & \end{array} \oplus \begin{array}{ccc} \square & \square & \square \end{array} \right)$	$\otimes \square$	$\otimes \square$	$= 2 \begin{array}{ccc} \square & \square & \square \\ \square & \square & \square \end{array} \oplus \dots$

Repeated Fields & Flavor Reps.

- ❖ Multiply rows together to get valid operator contractions

enforce Bose or Fermi sym. → Grassmann

Field(s)	qqq	l	B_L	$q^3 l B$
Group	S_3	S_1	S_1	
$SU(3)_c$	$\left(\begin{array}{c} \square \\ \square \\ \square \end{array} \oplus \begin{array}{cc} \square & \square \\ \square & \square \end{array} \oplus \begin{array}{ccc} \square & \square & \square \end{array} \right)$			$= \begin{array}{c} \square \\ \square \\ \square \end{array} \oplus \dots$
$SU(2)_L$	$\left(\begin{array}{cc} \square & \square \\ \square & \square \end{array} \oplus \begin{array}{ccc} \square & \square & \square \end{array} \right)$	$\otimes \square$		$= \begin{array}{cc} \square & \square \\ \square & \square \end{array} \oplus \dots$
$SU(2)_\ell$	$\left(\begin{array}{cc} \square & \square \\ \square & \square \end{array} \oplus \begin{array}{ccc} \square & \square & \square \end{array} \right)$	$\otimes \square \otimes \square$		$= 2 \begin{array}{ccc} \square & \square & \square \\ \square & \square & \square \end{array} \oplus \dots$
	$\otimes \begin{array}{c} \square \\ \square \\ \square \end{array}$	$\otimes \square$		

Repeated Field & Flavor Reps.

- ❖ Multiply rows together to get valid operator contractions
- ❖ Multiply columns together to get flavor representations

Field(s)	qqq	l	B_L	$q^3 l B$
Group	S_3	S_1	S_1	
$SU(3)_c$	$\left(\begin{array}{c} \square \\ \square \\ \square \end{array} \oplus \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \end{array} \oplus \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \end{array} \right)$			$= \begin{array}{ c } \hline \square \\ \square \\ \square \\ \hline \end{array} \oplus \dots$
$SU(2)_L$	$\left(\begin{array}{ c c } \hline \square & \square \\ \hline \end{array} \oplus \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \end{array} \right)$	$\otimes \begin{array}{ c } \hline \square \\ \hline \end{array}$		$= \begin{array}{ c c } \hline \square & \square \\ \hline \end{array} \oplus \dots$
$SU(2)_\ell$	$\left(\begin{array}{ c c } \hline \square & \square \\ \hline \end{array} \oplus \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \end{array} \right)$	$\otimes \begin{array}{ c } \hline \square \\ \hline \end{array} \otimes \begin{array}{ c c } \hline \square & \square \\ \hline \end{array}$		$= 2 \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \end{array} \oplus \dots$
Grassmann	$\begin{array}{ c } \hline \square \\ \square \\ \square \\ \hline \end{array}$	$\otimes \begin{array}{ c } \hline \square \\ \square \\ \square \\ \hline \end{array}$	$\otimes \begin{array}{ c c } \hline \square & \square \\ \hline \end{array}$	
Flavor	$\left(\begin{array}{ c } \hline \square \\ \square \\ \square \\ \hline \end{array} \oplus \begin{array}{ c c } \hline \square & \square \\ \hline \end{array} \oplus \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \end{array} \right) \oplus \begin{array}{ c c } \hline \square & \square \\ \hline \end{array}$	$\otimes \begin{array}{ c } \hline \square \\ \square \\ \square \\ \hline \end{array} \otimes \begin{array}{ c c } \hline \square & \square \\ \hline \end{array}$		

vanishes when there is only 1 generation of q

Lagrangian terms

❖ 4-electron operator: $Q_{1111}^{ee} = (\bar{e}_1 \gamma^\mu e_1)(\bar{e}_1 \gamma_\mu e_1)$

❖ associated “Lagrangian term”: $\Delta \mathcal{L} = \sum_{p,r,s,t} C_{prst}^{ee} Q_{prst}^{ee}$

❖ What should be included in the sum?...

flavor indices



Lagrangian terms

❖ ...A choice for your convenience. Physics is independent of this choice

1. Minimum number of Lagrangian terms

❖ **CM JHEP 10 (2020) 174, 2005.00059**

❖ analogous to Warsaw basis

2. One Lagrangian term per flavor representation

❖ Li, Ren, Shu, Xiao, Yu, Zheng **2005.00008**

❖ At $d = 6$ would have 100 real LTs instead of 84

Low-Energy EFT below the Electroweak Scale

- ❖ Contains SM particles w/ masses parametrically smaller than EW scale
- ❖ Gauge group: QCD \times QED
- ❖ Correct low-energy theory even when SMEFT is not the high-energy EFT
- ❖ $\mathcal{L}_{\text{LEFT}} = \mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{QED}} + \sum_{d>4} \sum_i L_i^{(d)} \mathcal{O}_i^{(d)}$

Dimension-8 Operators in LEFT

- ❖ Four classes of $d = 8$ LEFT operators: $X^4, \psi^2 X^2 D, \psi^4 X, \psi^4 D^2$
 - ❖ all present in SMEFT!
- ❖ Makes constructing a $d = 8$ LEFT basis mostly straightforward...

Dimension-8 Operators in LEFT

❖ ...new types of 4-fermion ops. appear w/o $SU(2)_L$ gauge invariance

$$\begin{aligned}
 \text{❖ } N_{\text{ops.}} &= 21144 \left| \begin{array}{l} \Delta L=0 \\ \Delta B=0 \end{array} \right. + 5442 \left| \begin{array}{l} \Delta L=2 \\ \Delta B=0 \end{array} \right. + 4536 \left| \begin{array}{l} \Delta L=1 \\ \Delta B=1 \end{array} \right. + 3888 \left| \begin{array}{l} \Delta L=-1 \\ \Delta B=1 \end{array} \right. + 48 \left| \begin{array}{l} \Delta L=4 \\ \Delta B=0 \end{array} \right. \\
 &= 35058 \quad \text{with } n_u = 2, n_d = n_e = n_\nu = 3
 \end{aligned}$$

$n \rightarrow pe^{-}\bar{\nu}$

$0\nu 2\beta$

$p \rightarrow e^{+} + \pi^0$

$n \rightarrow e^{-} + \pi^{+}$

$0\nu 4\beta$

CM - JHEP 04 (2021) 101 - 2012.13291 (counting for arbitrary $n_{u,d,e,\nu}$ in paper)

Li, Ren, Xiao, Yu, Zheng - 2012.09188 (also includes $d = 9$)

LEFTovers

- ❖ Matching from SMEFT to LEFT at $d = 8$ is rich
 - ❖ Contact interactions, W/Z exchange to 2nd order, Yukawa suppressed Higgs exchange, double-dipole insertions, triple-gauge insertions
- ❖ LEFT has its own positivity bounds
 - ❖ Assuming SMEFT is the correct UV EFT, is there additional info here?

Selection Rules

- ❖ Alonso, Jenkins, Manohar [1409.0868](#)
- ❖ Cheung, Shen [1505.01844](#)
- ❖ Operators can mix “up” or to the “right,” but not “down” or to the “left”

6	X_L^3	$X_L^2 H^2,$ $X_L \psi^2 H,$ ψ^4	$\psi^2 H^3$	H^6
4			$H^4 D^2,$ $\psi \bar{\psi} H^2 D,$ $\psi^2 \bar{\psi}^2$	$\bar{\psi}^2 H^3$
2				$X_R^2 H^2,$ $X_R \bar{\psi}^2 H,$ $\bar{\psi}^4$
0				X_R^3
	0	2	4	6

w

color coding indicates “tree/loop mixing”

$d = 8$ Selection Rules

- ❖ Operators can mix “up” or to the “right,” but not “down” or to the “left”
- ❖ “Tree/loop mixing” is common at $d = 8$ -
Craig, Jiang, Li, Sutherland 2001.00017

8	X_L^4	$X_L^3 H^2,$ $X_L^2 \psi^2 H,$ $X_L \psi^4$	$X_L^2 H^4,$ $X_L \psi^2 H^3,$ $\psi^4 H^2$	$\psi^2 H^5$	H^8
6		$X_L^2 H^2 D^2,$ $X_L^2 \psi \bar{\psi} D,$ $X_L \psi^2 H D^2,$ $\psi^4 D^2$	$X_L H^4 D^2,$ $X_L^2 \bar{\psi}^2 H,$ $X_L \psi \bar{\psi} H^2 D,$ $\psi^2 H^3 D^2,$ $X_L \psi^2 \bar{\psi}^2,$ $\psi^3 \bar{\psi} H D$	$H^6 D^2,$ $\psi \bar{\psi} H^4 D,$ $\psi^2 \bar{\psi}^2 H^2$	$\bar{\psi}^2 H^5$
4			$X_L^2 X_R^2,$ $X_L X_R H^2 D^2,$ $H^4 D^4,$ $X_L X_R \psi \bar{\psi} D,$ $X_R \psi^2 H D^2,$ $X_L \bar{\psi}^2 H D^2,$ $\psi \bar{\psi} H^2 D^3,$ $\psi^2 \bar{\psi}^2 D^2$	$X_R H^4 D^2,$ $X_R^2 \psi^2 H,$ $X_R \psi \bar{\psi} H^2 D,$ $\bar{\psi}^2 H^3 D^2,$ $X_R \psi^2 \bar{\psi}^2,$ $\psi \bar{\psi}^3 H D$	$X_R^2 H^4,$ $X_R \bar{\psi}^2 H^3,$ $\bar{\psi}^4 H^2$
2				$X_R^2 H^2 D^2,$ $X_R^2 \psi \bar{\psi} D,$ $X_R \bar{\psi}^2 H D^2,$ $\bar{\psi}^4 D^2$	$X_R^3 H^2,$ $X_R^2 \bar{\psi}^2 H,$ $X_R \bar{\psi}^4$
0					X_R^4
	0	2	4	6	8

w

Application: Double Higgs Boson Production

- ❖ Is there a simple UV model that enhances the double Higgs boson production rate that's not already ruled out?
- ❖ Extended scalar sectors are leading candidates
 - ❖ $SU(2)_L$ singlets, triplets, quartets

Matching: Dimension-6 Operators

single Higgs production double Higgs production EWPD (T parameter)

Model	c_H	$c_6 \lambda_{SM}$	c_T	c_f
Real Singlet w/ explicit \mathbb{Z}_2	$\tan^2 \alpha$	$\tan^2 \alpha \left(\lambda_\alpha - \frac{m_2}{v} \tan \alpha \right)$	0	0
Real Singlet w/ spontaneous \mathbb{Z}_2	$\tan^2 \alpha$	0	0	0
Real Triplet	$-\frac{8 \sin^2 \beta m_{H+}^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_{H+}^6}{m_H^4 v^2}$	$\frac{4 \sin^2 \beta m_{H+}^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_{H+}^4}{m_H^4}$
Complex Triplet	$-\frac{4 \sin^2 \beta m_A^4}{m_H^4}$	$\frac{8 \sin^2 \beta m_A^6}{m_H^4 v^2}$	$-\frac{4 \sin^2 \beta m_A^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_A^4}{m_H^4}$
Quartet ₁	0	$\frac{24 \tan^2 \beta m_A^4}{7 m_H^2 v^2}$	0	0
Quartet ₃	0	$\frac{8 \tan^2 \beta m_A^4}{3 m_H^2 v^2}$	0	0

Matching: Dimension-6 Operators

single Higgs production EWPD (*T* parameter)
double Higgs production

Model	c_H	$c_6 \lambda_{SM}$	c_T	c_f
Real Singlet w/ explicit \mathbb{Z}_2	$\tan^2 \alpha$	$\tan^2 \alpha \left(\lambda_\alpha - \frac{m_2}{v} \tan \alpha \right)$	0	0
Real Singlet w/ spontaneous \mathbb{Z}_2	$\tan^2 \alpha$	0	0	0
Real Triplet	$-\frac{8 \sin^2 \beta m_{H+}^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_{H+}^6}{m_H^4 v^2}$	$\frac{4 \sin^2 \beta m_{H+}^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_{H+}^4}{m_H^4}$
Complex Triplet	$-\frac{4 \sin^2 \beta m_A^4}{m_H^4}$	$\frac{8 \sin^2 \beta m_A^6}{m_H^4 v^2}$	$-\frac{4 \sin^2 \beta m_A^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_A^4}{m_H^4}$
Quartet ₁	0	$\frac{24 \tan^2 \beta m_A^4}{7 m_H^2 v^2}$	0	0
Quartet ₃	0	$\frac{8 \tan^2 \beta m_A^4}{3 m_H^2 v^2}$	0	0

$SU(2)_L$ quartets seem like great candidates at $d = 6$ level

EWPD in SMEFT

- ❖ S, T parameters start at $d = 6$
- ❖ U parameter starts at $d = 8$ - Grinstein, Wise [Phys.Lett.B 265 \(1991\)](#)
- ❖ All 3 parameters receive contributions at $d = 8$ (and beyond)

$$\frac{1}{16\pi} S = \frac{v_T^2}{\Lambda^2} c_{HWB} + \sum_{n=0}^{\infty} \frac{v_T^{4+2n}}{2^n \Lambda^{4+2n}} c_{WBH^{4+2n}}^{(1)},$$

$$\bar{\alpha} T = -\frac{v_T^2}{2\Lambda^2} c_{HD} - \frac{v_T^4}{2\Lambda^4} c_{H^6 D^2}^{(2)},$$

$$\frac{1}{16\pi} U = \sum_{n=0}^{\infty} \frac{v_T^{4+2n}}{2^n \Lambda^{4+2n}} c_{W^2 H^{4+2n}}^{(3)},$$

CM - [JHEP 10 \(2020\) 174 - 2005.00059](#)

see also the geoSMEFT papers by Corbett, Hays, Helset, Martin, Trott

Double Higgs vs. EWPD: beyond $d = 6$

Difference in experimental precision necessitates matching beyond $d = 6$

Model	c_H	$c_6 \lambda_{SM}$	c_T	c_f
Real Singlet w/ explicit \mathbb{Z}_2	$\tan^2 \alpha$	$\tan^2 \alpha \left(\lambda_\alpha - \frac{m_2}{v} \tan \alpha \right)$	0	0
Real Singlet w/ spontaneous \mathbb{Z}_2	$\tan^2 \alpha$	0	0	0
Real Triplet	$-\frac{8 \sin^2 \beta m_{H^\pm}^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_{H^\pm}^6}{m_H^4 v^2}$	$\frac{4 \sin^2 \beta m_{H^\pm}^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_{H^\pm}^4}{m_H^4}$
Complex Triplet	$-\frac{4 \sin^2 \beta m_A^4}{m_H^4}$	$\frac{8 \sin^2 \beta m_A^6}{m_H^4 v^2}$	$-\frac{4 \sin^2 \beta m_A^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_A^4}{m_H^4}$
Quartet ₁	0	$\frac{24 \tan^2 \beta m_A^4}{7 m_H^2 v^2}$	$\frac{24 \tan^2 \beta m_A^4}{7 m_H^4}$	0
Quartet ₃	0	$\frac{8 \tan^2 \beta m_A^4}{3 m_H^2 v^2}$	$-\frac{8 \tan^2 \beta m_A^4}{m_H^4}$	0

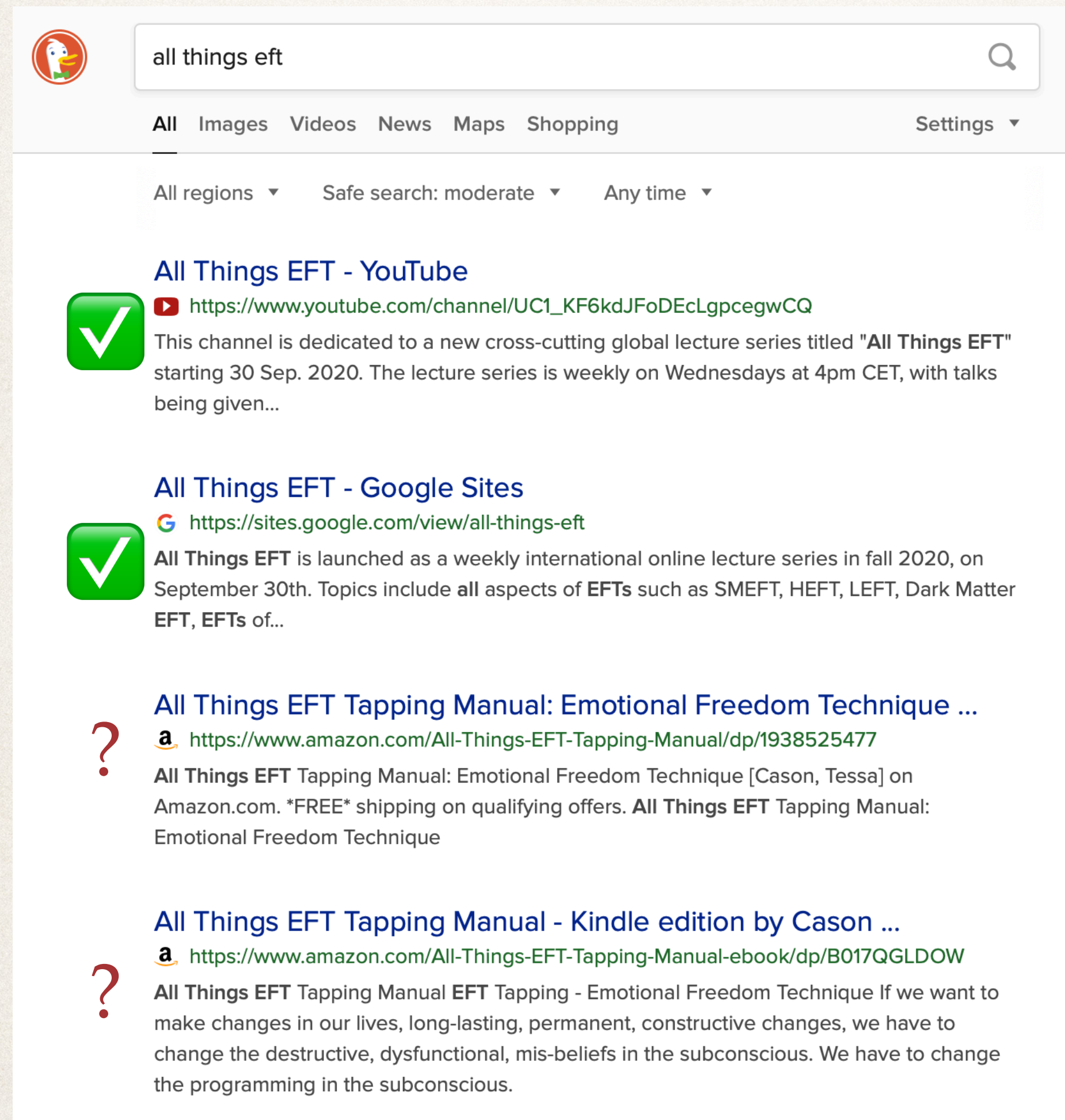
$SU(2)_L$ quartets generate T at $d = 8$ level

Summary

- ❖ Broad physics program at dimension-8
 - ❖ Many different motivations for going beyond $d = 6$
- ❖ Complete bases of $d = 8$ operators in the SMEFT and LEFT are now known
 - ❖ Ops. w/ derivatives & repeated fields are handled in systematic fashion

Thanks!

All Things EFT search engine optimization

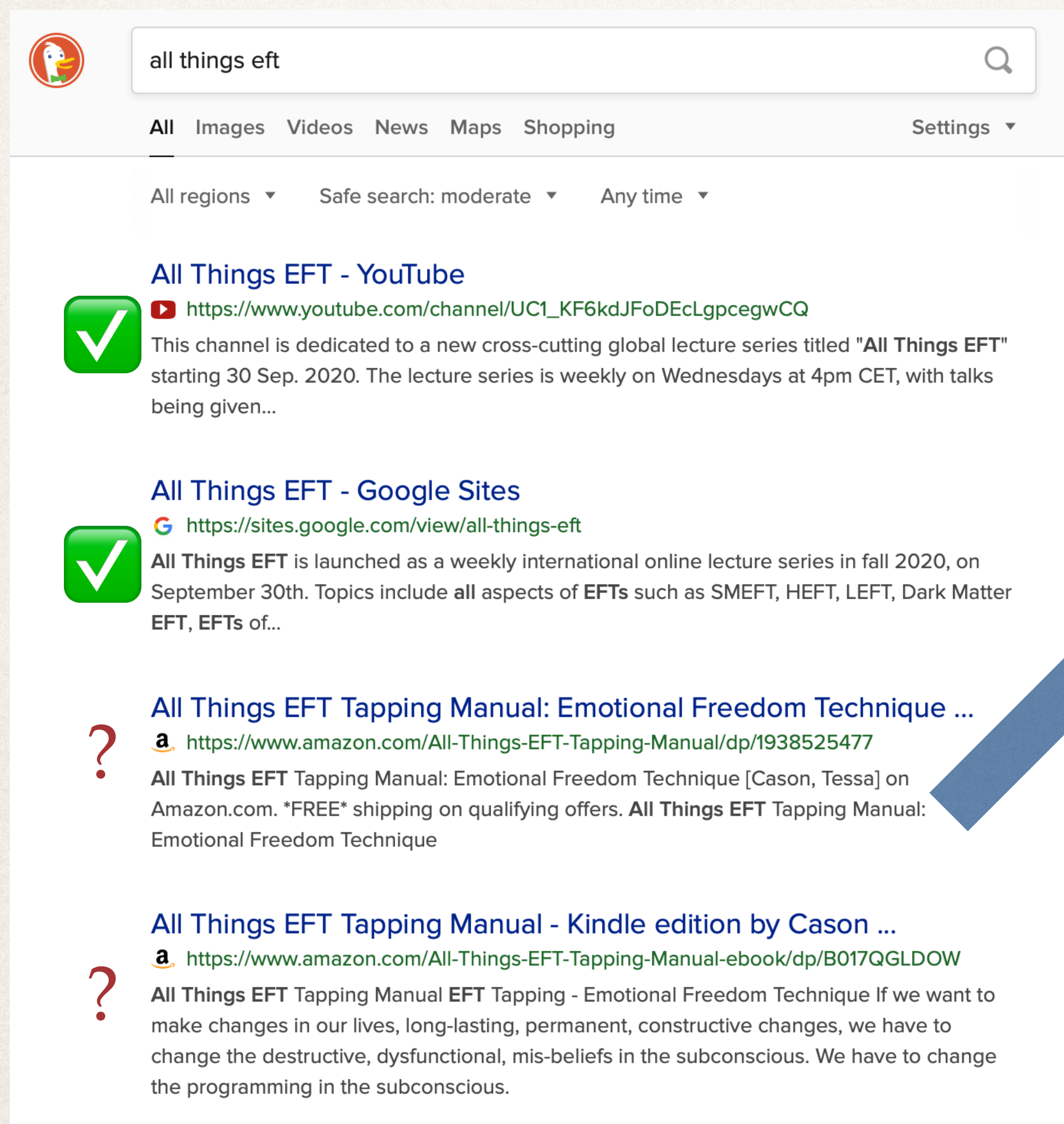


The screenshot shows a search engine interface with the query 'all things eft'. The results are filtered to 'All' (with options for Images, Videos, News, Maps, Shopping) and 'Settings'. The search parameters are set to 'All regions', 'Safe search: moderate', and 'Any time'. The results list four items:

- All Things EFT - YouTube** (marked with a green checkmark): https://www.youtube.com/channel/UC1_KF6kdJFoDEcLgpcegwCQ. Description: "This channel is dedicated to a new cross-cutting global lecture series titled 'All Things EFT' starting 30 Sep. 2020. The lecture series is weekly on Wednesdays at 4pm CET, with talks being given..."
- All Things EFT - Google Sites** (marked with a green checkmark): <https://sites.google.com/view/all-things-efit>. Description: "All Things EFT is launched as a weekly international online lecture series in fall 2020, on September 30th. Topics include all aspects of EFTs such as SMEFT, HEFT, LEFT, Dark Matter EFT, EFTs of..."
- All Things EFT Tapping Manual: Emotional Freedom Technique ...** (marked with a red question mark): <https://www.amazon.com/All-Things-EFT-Tapping-Manual/dp/1938525477>. Description: "All Things EFT Tapping Manual: Emotional Freedom Technique [Cason, Tessa] on Amazon.com. *FREE* shipping on qualifying offers. All Things EFT Tapping Manual: Emotional Freedom Technique"
- All Things EFT Tapping Manual - Kindle edition by Cason ...** (marked with a red question mark): <https://www.amazon.com/All-Things-EFT-Tapping-Manual-ebook/dp/B017QGLDOW>. Description: "All Things EFT Tapping Manual EFT Tapping - Emotional Freedom Technique If we want to make changes in our lives, long-lasting, permanent, constructive changes, we have to change the destructive, dysfunctional, mis-beliefs in the subconscious. We have to change the programming in the subconscious."

← Improvement from October!





EFT disambiguation

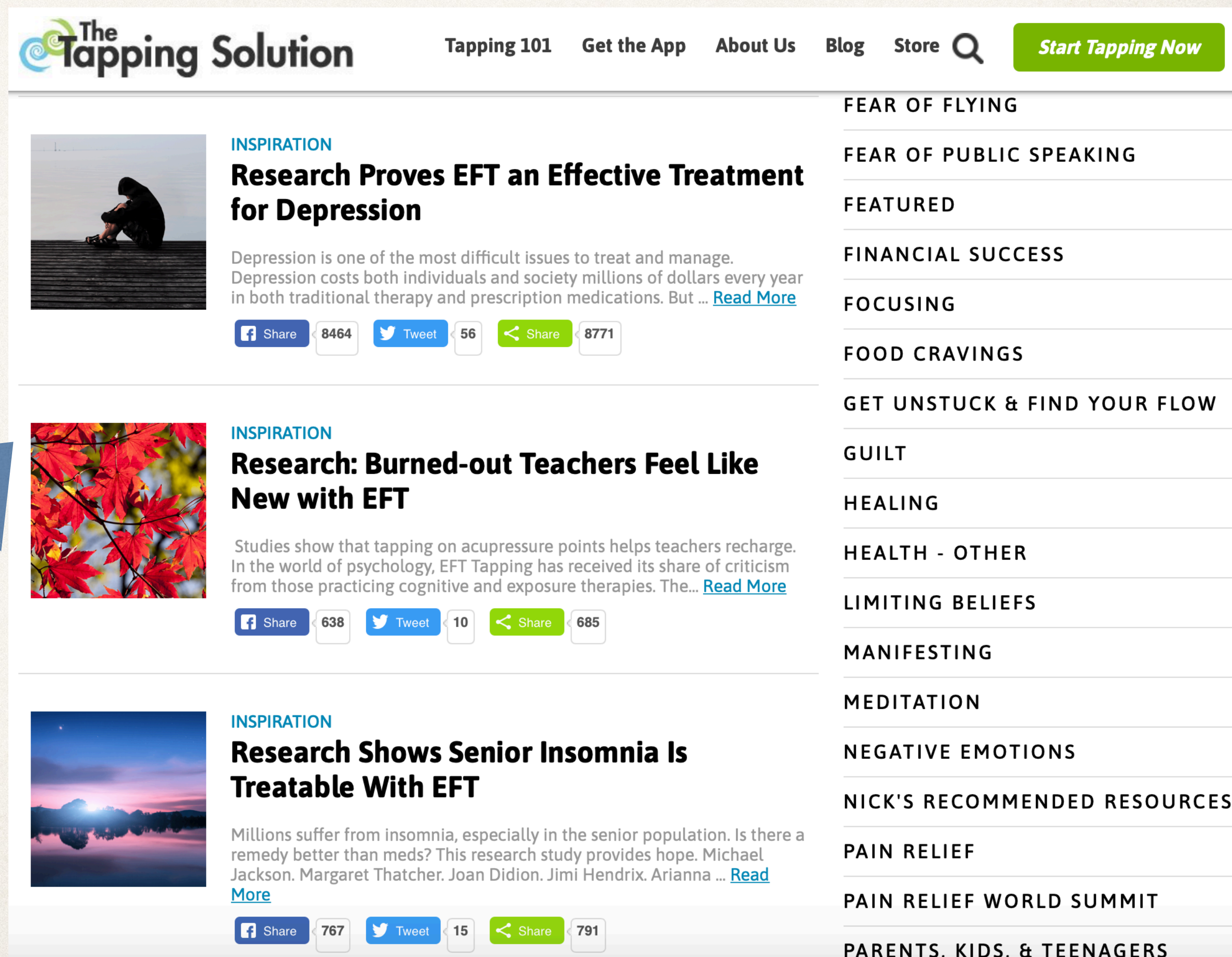


all things eft


All Images Videos News Maps Shopping Settings



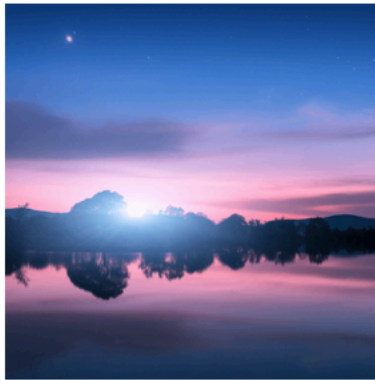
All regions Safe search: moderate Any time

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The Tapping Solution

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- **INSPIRATION**
Research Proves EFT an Effective Treatment for Depression
Depression is one of the most difficult issues to treat and manage. Depression costs both individuals and society millions of dollars every year in both traditional therapy and prescription medications. But ... [Read More](#)
Share 8464 Tweet 56 Share 8771
- **INSPIRATION**
Research: Burned-out Teachers Feel Like New with EFT
Studies show that tapping on acupressure points helps teachers recharge. In the world of psychology, EFT Tapping has received its share of criticism from those practicing cognitive and exposure therapies. The... [Read More](#)
Share 638 Tweet 10 Share 685
- **INSPIRATION**
Research Shows Senior Insomnia Is Treatable With EFT
Millions suffer from insomnia, especially in the senior population. Is there a remedy better than meds? This research study provides hope. Michael Jackson. Margaret Thatcher. Joan Didion. Jimi Hendrix. Arianna ... [Read More](#)
Share 767 Tweet 15 Share 791

- FEAR OF FLYING
- FEAR OF PUBLIC SPEAKING
- FEATURED
- FINANCIAL SUCCESS
- FOCUSING
- FOOD CRAVINGS
- GET UNSTUCK & FIND YOUR FLOW
- GUILT
- HEALING
- HEALTH - OTHER
- LIMITING BELIEFS
- MANIFESTING
- MEDITATION
- NEGATIVE EMOTIONS
- NICK'S RECOMMENDED RESOURCES
- PAIN RELIEF
- PAIN RELIEF WORLD SUMMIT
- PARENTS, KIDS, & TEENAGERS



Repeated Fields & Flavor Reps.

❖ Multiply rows together to get valid operator contractions

❖ Multiply columns together to get flavor representations

Field(s)	qqq	l	B_L	$q^3 l B$
Group	S_3	S_1	S_1	
$SU(3)_c$	$\left(\begin{array}{ c } \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array} \oplus \begin{array}{ c c } \hline \square & \square \\ \hline \square & \square \\ \hline \end{array} \oplus \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \square & \square & \square \\ \hline \end{array} \right)$			$= \begin{array}{ c } \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array} \oplus \dots$
$SU(2)_L$	$\left(\begin{array}{ c c } \hline \square & \square \\ \hline \square & \square \\ \hline \end{array} \oplus \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \square & \square & \square \\ \hline \end{array} \right)$	$\otimes \square$		$= \begin{array}{ c c } \hline \square & \square \\ \hline \square & \square \\ \hline \end{array} \oplus \dots$
$SU(2)_\ell$	$\left(\begin{array}{ c c } \hline \square & \square \\ \hline \square & \square \\ \hline \end{array} \oplus \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \square & \square & \square \\ \hline \end{array} \right)$	$\otimes \square$	$\otimes \begin{array}{ c c } \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}$	$= 2 \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \square & \square & \square \\ \hline \end{array} \oplus \dots$
Grassmann	$\begin{array}{ c } \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array}$	$\otimes \square$	$\otimes \square$	$= \square$
Flavor	$\left(\begin{array}{ c } \hline \square \\ \hline \square \\ \hline \square \\ \hline \end{array} \oplus \begin{array}{ c c } \hline \square & \square \\ \hline \square & \square \\ \hline \end{array} \oplus \begin{array}{ c c c } \hline \square & \square & \square \\ \hline \square & \square & \square \\ \hline \end{array} \right) \oplus \begin{array}{ c c } \hline \square & \square \\ \hline \square & \square \\ \hline \end{array}$	$\otimes \square$	$\otimes \square$	$= \square$

$Q_{lq^3B}^{(1)} \quad \epsilon_{\alpha\beta\gamma}\epsilon_{mn}\epsilon_{jk}(q_p^{m\alpha} C q_r^{j\beta})(q_s^{k\gamma} C \sigma^{\mu\nu} l_t^n) B_{\mu\nu}$

$Q_{lq^3B}^{(2)} \quad \epsilon_{\alpha\beta\gamma}\epsilon_{mn}\epsilon_{jk}(q_p^{m\alpha} C \sigma^{\mu\nu} q_r^{j\beta})(q_s^{k\gamma} C l_t^n) B_{\mu\nu}$

Flavor Reps. Example: $q^3 l B$

- Given a contraction of Lorentz indices, how should the $SU(2)_L$ indices be contracted?

- $\{2,1\}$ is a $2d$ representation of the permutation group S_3

- Consider $Q_{q^3 l B}^{(1)}$ from previous slide and $Q_{q^3 l B}^{(3)} = \epsilon_{\alpha\beta\gamma} \epsilon_{mjk} (q_p^{m\alpha} C q_r^{j\beta}) (q_s^{k\gamma} C \sigma^{\mu\nu} l_t^n) B_{\mu\nu}$

- $$-Q_{q^3 l B}^{(3)} = Q_{q^3 l B}^{(1)} + Q_{q^3 l B}^{(1)}$$

$$prst \quad prst \quad rpst$$

- $p \leftrightarrow r$ symmetry of $Q_{q^3 l B}^{(3)}$ doesn't allow for the antisymmetric $\{1,1,1\}$ rep. of S_3

- whereas $Q_{q^3 l B}^{(1)} + Q_{q^3 l B}^{(1)} = Q_{q^3 l B}^{(1)} + Q_{q^3 l B}^{(1)}$ allows for all 3 flavor representations
$$prst \quad rpst \quad sprt \quad srpt$$

More Selection Rules

- ❖ “Tree/loop mixing” is common at $d = 8$ -
2001.00017 Craig, Jiang, Li, Sutherland
- ❖ Selection rules from angular momentum -
2001.04481 Jiang, Shu, Xiao, Zheng
- ❖ $d = 6$ selection rules at two-loops -
2005.12917 Bern, Parra-Martinez, Sawyer

\bar{w}	8	X_L^4	$X_L^3 H^2,$ $X_L^2 \psi^2 H,$ $X_L \psi^4$	$X_L^2 H^4,$ $X_L \psi^2 H^3,$ $\psi^4 H^2$	$\psi^2 H^5$	H^8
	6		$X_L^2 H^2 D^2,$ $X_L^2 \psi \bar{\psi} D,$ $X_L \psi^2 H D^2,$ $\psi^4 D^2$	$X_L H^4 D^2,$ $X_L^2 \bar{\psi}^2 H,$ $X_L \psi \bar{\psi} H^2 D,$ $\psi^2 H^3 D^2,$ $X_L \psi^2 \bar{\psi}^2,$ $\psi^3 \bar{\psi} H D$	$H^6 D^2,$ $\psi \bar{\psi} H^4 D,$ $\psi^2 \bar{\psi}^2 H^2$	$\bar{\psi}^2 H^5$
	4			$X_L^2 X_R^2,$ $X_L X_R H^2 D^2,$ $H^4 D^4,$ $X_L X_R \psi \bar{\psi} D,$ $X_R \psi^2 H D^2,$ $X_L \bar{\psi}^2 H D^2,$ $\psi \bar{\psi} H^2 D^3,$ $\psi^2 \bar{\psi}^2 D^2$	$X_R H^4 D^2,$ $X_R^2 \psi^2 H,$ $X_R \psi \bar{\psi} H^2 D,$ $\bar{\psi}^2 H^3 D^2,$ $X_R \psi^2 \bar{\psi}^2,$ $\psi \bar{\psi}^3 H D$	$X_R^2 H^4,$ $X_R \bar{\psi}^2 H^3,$ $\bar{\psi}^4 H^2$
	2				$X_R^2 H^2 D^2,$ $X_R^2 \psi \bar{\psi} D,$ $X_R \bar{\psi}^2 H D^2,$ $\bar{\psi}^4 D^2$	$X_R^3 H^2,$ $X_R^2 \bar{\psi}^2 H,$ $X_R \bar{\psi}^4$
	0					X_R^4
		0	2	4	6	8

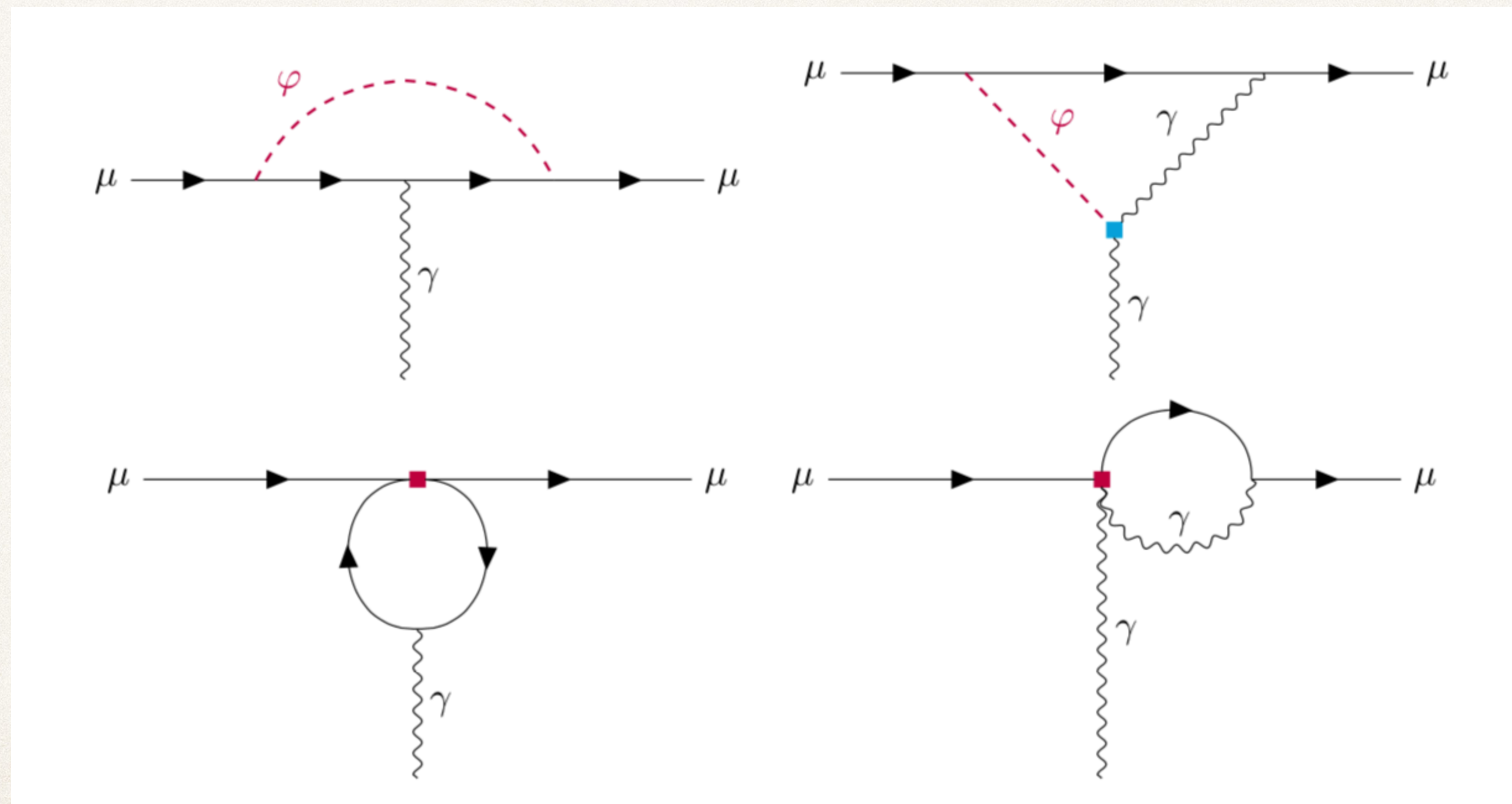
w

Muon $g - 2$

- ❖ $d = 8$ effects can be parametrically different from $d = 6$

UV theory w/ heavy
Higgs φ

SMEFT



(SM Higgs lines not drawn)

$$\psi^4, \quad d = 6$$

$$\psi^2 X^2 H, \quad d = 8$$

(vector leptoquark instead
generates $\psi^4 X$)

Non-standard neutrino interactions

- ❖ At $d = 6$ all $(\bar{\nu}\gamma_\mu\nu)(\bar{f}\gamma^\mu f)$ operators are experimentally constrained by $(\bar{e}\gamma_\mu e)(\bar{f}\gamma^\mu f)$ operators
- ❖ $\psi^4 H^2$ operators allow for independent $\nu^2 f^2$ ops. at low-energy

$d = 6$ correlations broken at $d = 8$

- ❖ Lepton universality violation - no $d = 6$ SMEFT contribution to LEFT operator $(\bar{\tau}_L \gamma_\mu \nu_{L\tau})(\bar{c}_R \gamma^\mu b_R)$
- ❖ W, Z, γ dipole moments - only 2 of 3 are independent at $d = 6$
- ❖ Triple gauge couplings
 - ❖ $X^3 H^2 \rightarrow \lambda_Z \neq \lambda_\gamma$
 - ❖ $XH^4 D^2 \rightarrow g_1^V, \kappa_V \not\propto C_{HWB}$
- ❖ Higgs measurements - $\psi^2 H^5$ breaks correlation between Yukawa contribution to single and double Higgs production

Multi-boson processes

- ❖ Quartic gauge couplings - $X^4, H^4 D^4, X^2 H^2 D^2$
- ❖ Light-by-light scattering - X^4
- ❖ Neutral triple gauge couplings - $X^2 H^2 D^2$
- ❖ $\psi\bar{\psi} \rightarrow V_L V_L$ from $\psi^2 H^2 D^3$ can dominate over $\psi^2 H^2 D$
- ❖ $\psi\bar{\psi} \rightarrow V_T Z_L$ from $\psi^2 X H D^2$ can dominate over C_{HWB}

More $d = 8$ physics

- ❖ Radiative FCNC decays or lepton flavor violating processes from $\psi^2 X^2 H$
e.g. 1803.00313, 2103.07212
- ❖ Helicity violating scattering e.g. $e_L e_R \rightarrow e_L e_L$ from $\psi^2 HD$
- ❖ Novel angular observables - 2003.11615
- ❖ Testing positivity at colliders e.g. $e^+ e^- \rightarrow \gamma\gamma$ - 2011.03055
- ❖ Neutron EDM: $G^3 \widetilde{G}$ can dominate over $G^2 \widetilde{G}$