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?


C.W.Murphy '21
$t \to cg\gamma$
$\mu A \to eA$
$\psi\bar{\psi} \to V_T Z_L$
$\psi\bar{\psi} \to V_L V_L$
Neutron EDM
Non-standard neutrino interactions
$e_L e_R \to e_L e_L$
$e^+e^- \to \gamma\gamma$
Angular observables in Drell-Yan
U
EWPD
S, T
Dimension-8 SMEFT Physics
Positivity Bounds
Light-by-Light scattering
parametrically new contributions to $g-2$
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
$pp \to W^\pm h$

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}

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

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, $Dy_{1-3} = 0$

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

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

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

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

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

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

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

CM - JHEP 10 (2020) 174 - 2005.00059

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}

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

$$y_1 = (D\bar{l})_{a,(\dot{a}\dot{c})} e_{\dot{d}} H B_{(cd)} \epsilon^{ac} \epsilon^{\dot{a}\dot{d}},$$
$$y_2 = \bar{l}_{\dot{c}} (De)_{a,(\dot{a}\dot{d})} H B_{(cd)} \epsilon^{ac} \epsilon^{\dot{a}\dot{c}},$$
$$y_3 = \bar{l}_{\dot{c}} e_{\dot{d}} (DH)_{a,\dot{a}} B_{(cd)} \tfrac{1}{2} \epsilon^{ac} (\epsilon^{\dot{a}\dot{c}} + \epsilon^{\dot{a}\dot{d}}).$$

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Repeated Fields & Flavor Representations

- Method based on Fonseca 1907.12584
- Example field content: q^3lB

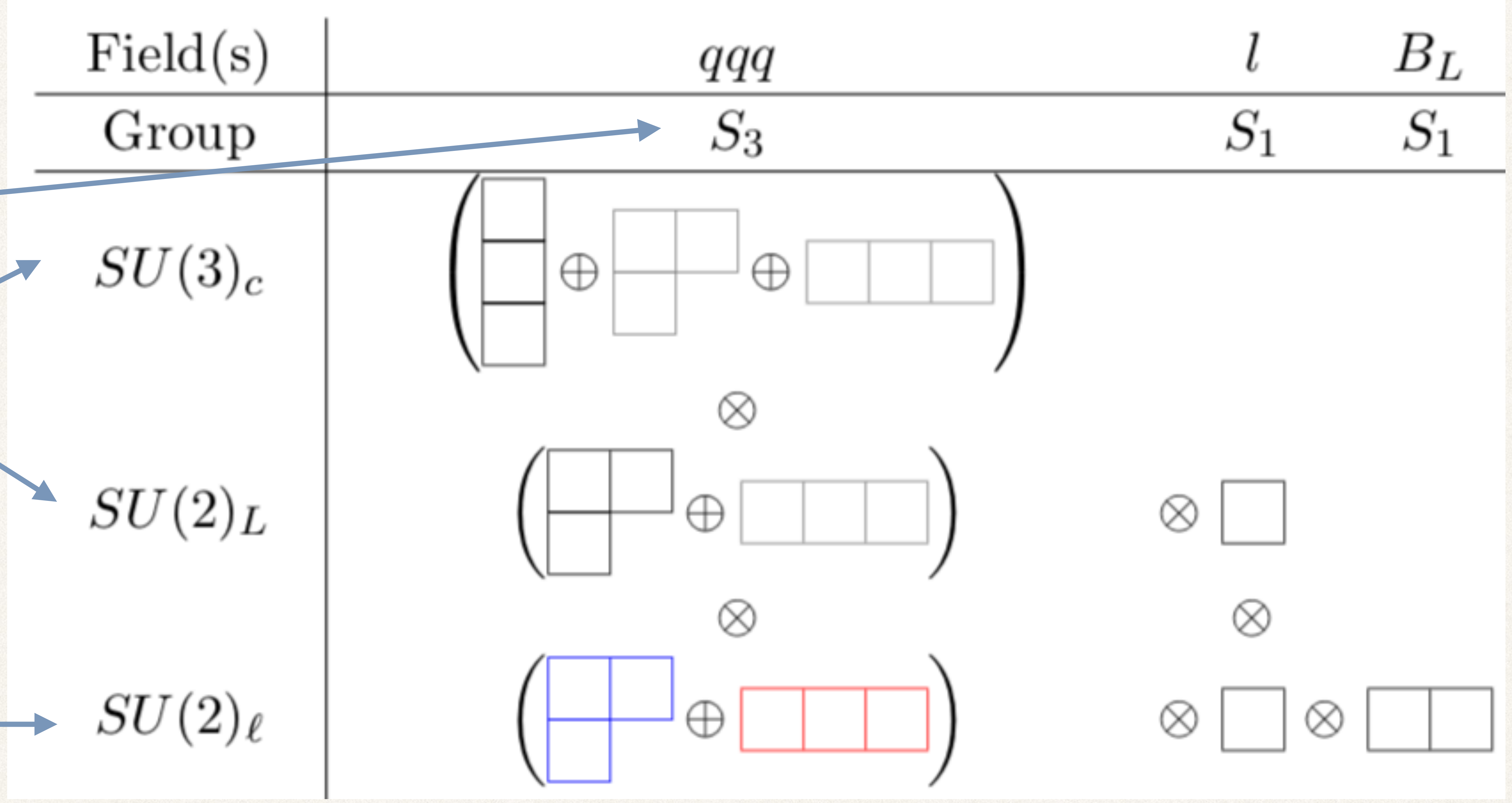
(this example by **CM**)

Repeated Fields & Flavor Reps.

permutation group of m objects, S_m

gauge

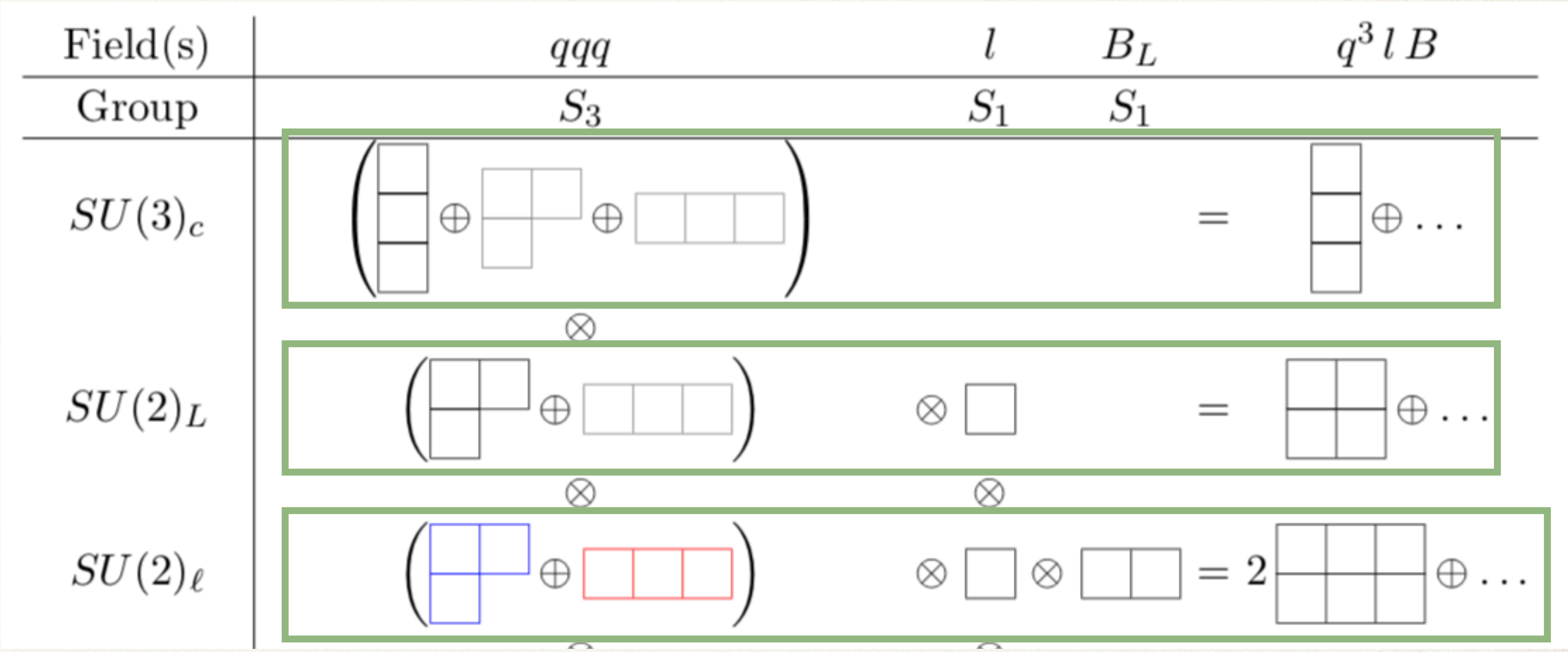
Lorentz



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

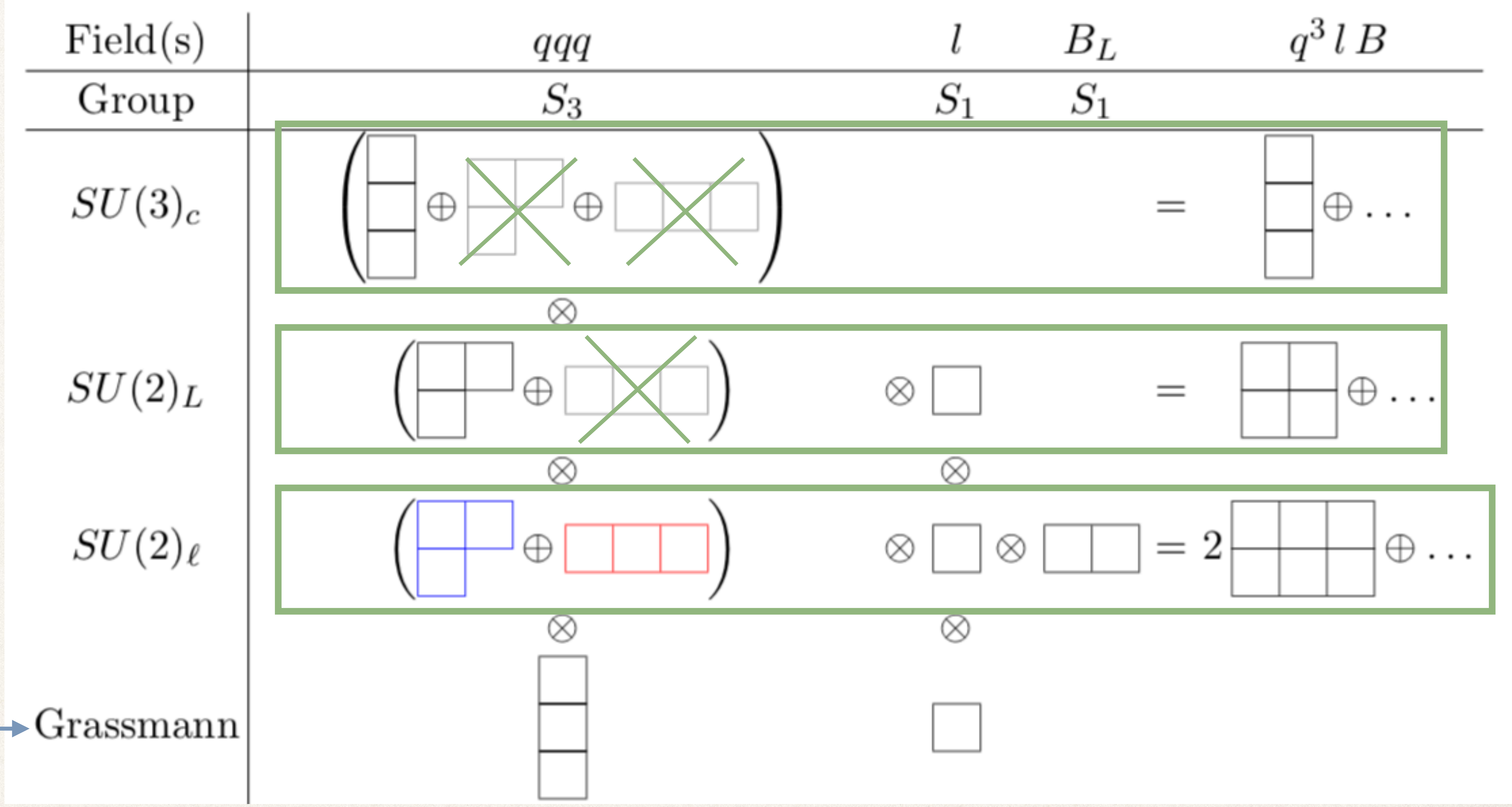
Repeated Fields & Flavor Reps.

- Multiply rows together to get valid operator contractions



Repeated Fields & Flavor Reps.

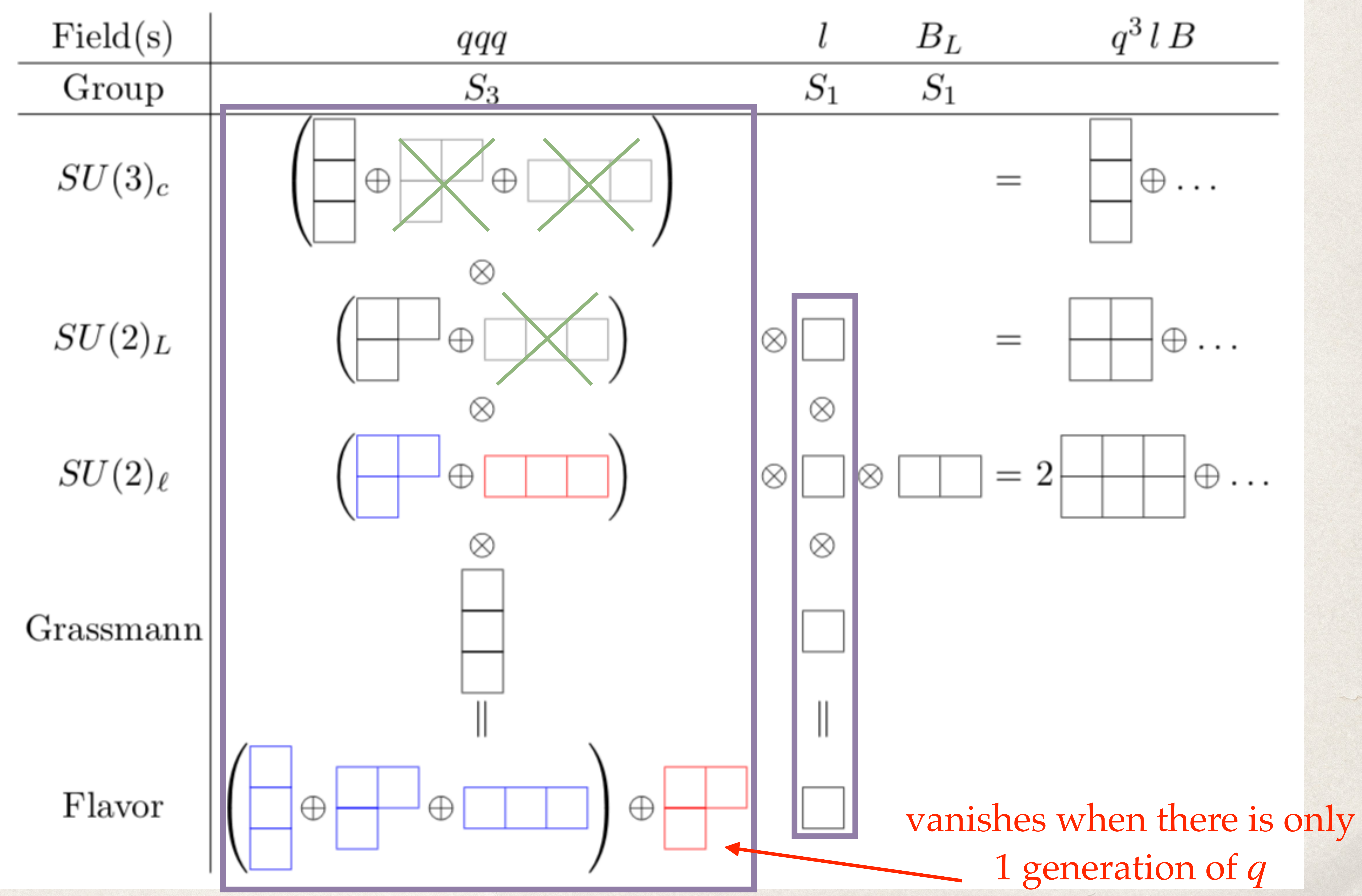
- Multiply rows together to get valid operator contractions



enforce Bose or Fermi sym. →

Repeated Field & Flavor Reps.

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



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": $\Delta\mathscr{L} = \sum_{p,r,s,t} C_{prst}^{ee} Q_{prst}^{ee}$

  flavor indices

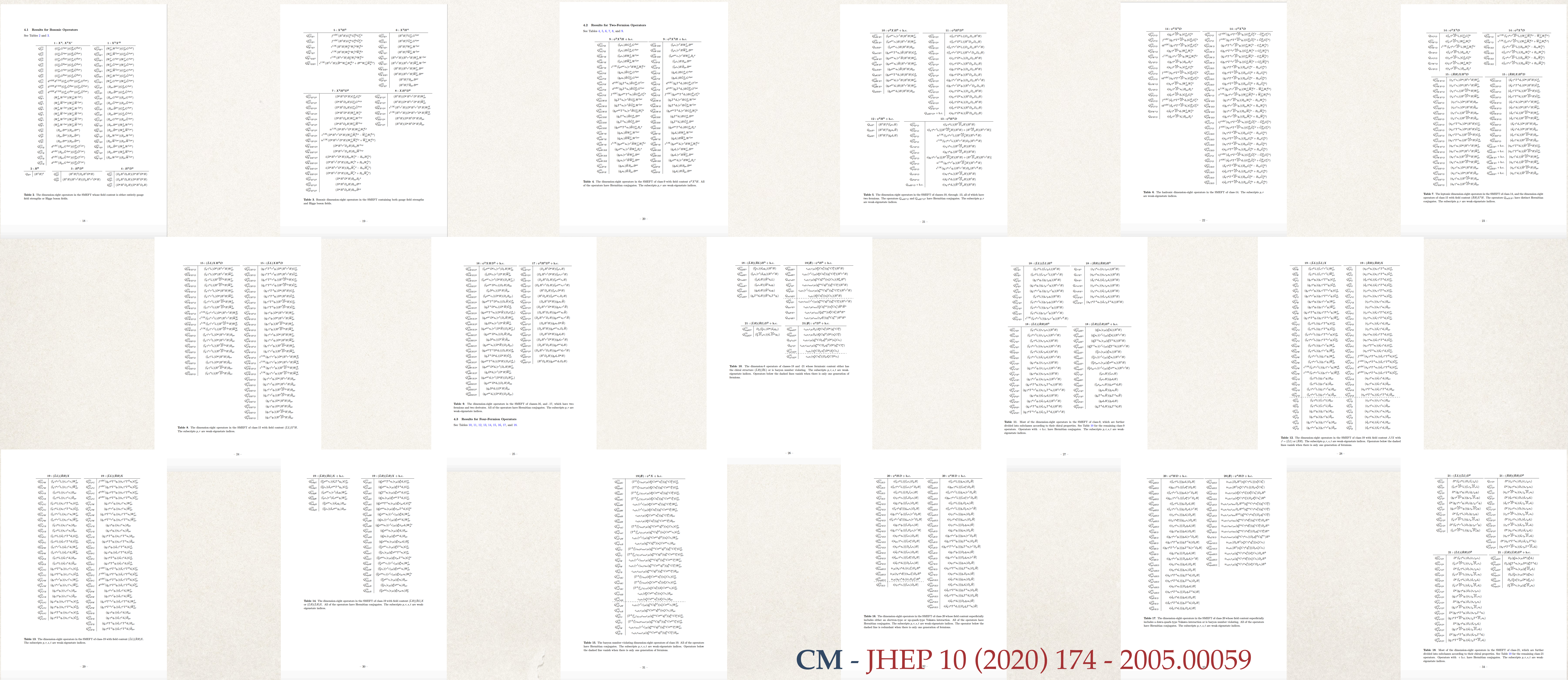
- What should be included in the sum?…

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

The result is 17 pages long…



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Low-Energy EFT below the Electroweak Scale

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

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 <u>mostly</u> straightforward…

Dimension-8 Operators in LEFT

- …new types of 4-fermion ops. appear w/o $SU(2)_L$ gauge invariance
- $N_{\text{ops.}} = 21144\,|^{\Delta L=0}_{\Delta B=0} + 5442\,|^{\Delta L=2}_{\Delta B=0} + 4536\,|^{\Delta L=1}_{\Delta B=1} + 3888\,|^{\Delta L=-1}_{\Delta B=1} + 48\,|^{\Delta L=4}_{\Delta B=0}$
  $= 35058 \quad \text{with} \quad n_u = 2, n_d = n_e = n_\nu = 3$

$n \to p e^- \bar{\nu}$ $\quad 0\nu 2\beta$ $\quad p \to e^+ + \pi^0$ $\quad n \to e^- + \pi^+$ $\quad 0\nu 4\beta$

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 $d = 9$)

Result only 16 pages long this time…

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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”

$\bar{w}$ \ w	0	2	4	6
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

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

$\bar{w}$					
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

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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

EWPD (T parameter)

double Higgs production

Model	$\mathbf{c_H}$	$\mathbf{c_6}\lambda_{\mathbf{SM}}$	$\mathbf{c_T}$	$\mathbf{c_f}$
Real Singlet w/ explicit $\not{Z}_2$	$\tan^2\alpha$	$\tan^2\alpha\left(\lambda_\alpha - \frac{m_2}{v}\tan\alpha\right)$	0	0
Real Singlet w/ spontaneous $\not{Z}_2$	$\tan^2\alpha$	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	$\frac{24\tan^2\beta\, m_A^4}{7m_H^2 v^2}$	0	0
Quartet$_3$	0	$\frac{8\tan^2\beta\, m_A^4}{3m_H^2 v^2}$	0	0

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Matching: Dimension-6 Operators

single Higgs production → c_H, c_f

double Higgs production → c_H, $c_6\lambda_{SM}$, c_f

EWPD (T parameter) → c_T

Model	c_H	$c_6\lambda_{SM}$	c_T	c_f
Real Singlet w/ explicit $\not{Z}_2$	$\tan^2\alpha$	$\tan^2\alpha\left(\lambda_\alpha - \frac{m_2}{v}\tan\alpha\right)$	0	0
Real Singlet w/ spontaneous $\not{Z}_2$	$\tan^2\alpha$	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	$\frac{24\tan^2\beta\, m_A^4}{7m_H^2 v^2}$	0	0
Quartet_3	0	$\frac{8\tan^2\beta\, m_A^4}{3m_H^2 v^2}$	0	0

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

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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)

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

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

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

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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	$\mathbf{c_H}$	$\mathbf{c_6 \lambda_{SM}}$	$\mathbf{c_T}$	$\mathbf{c_f}$
Real Singlet w/ explicit $\not{Z}_2$	$\tan^2\alpha$	$\tan^2\alpha\left(\lambda_\alpha - \frac{m_2}{v}\tan\alpha\right)$	0	0
Real Singlet w/ spontaneous $\not{Z}_2$	$\tan^2\alpha$	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	$\frac{24\tan^2\beta\, m_A^4}{7 m_H^2 v^2}$	$\frac{24\tan^2\beta\, m_A^4}{7 m_H^4}$	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

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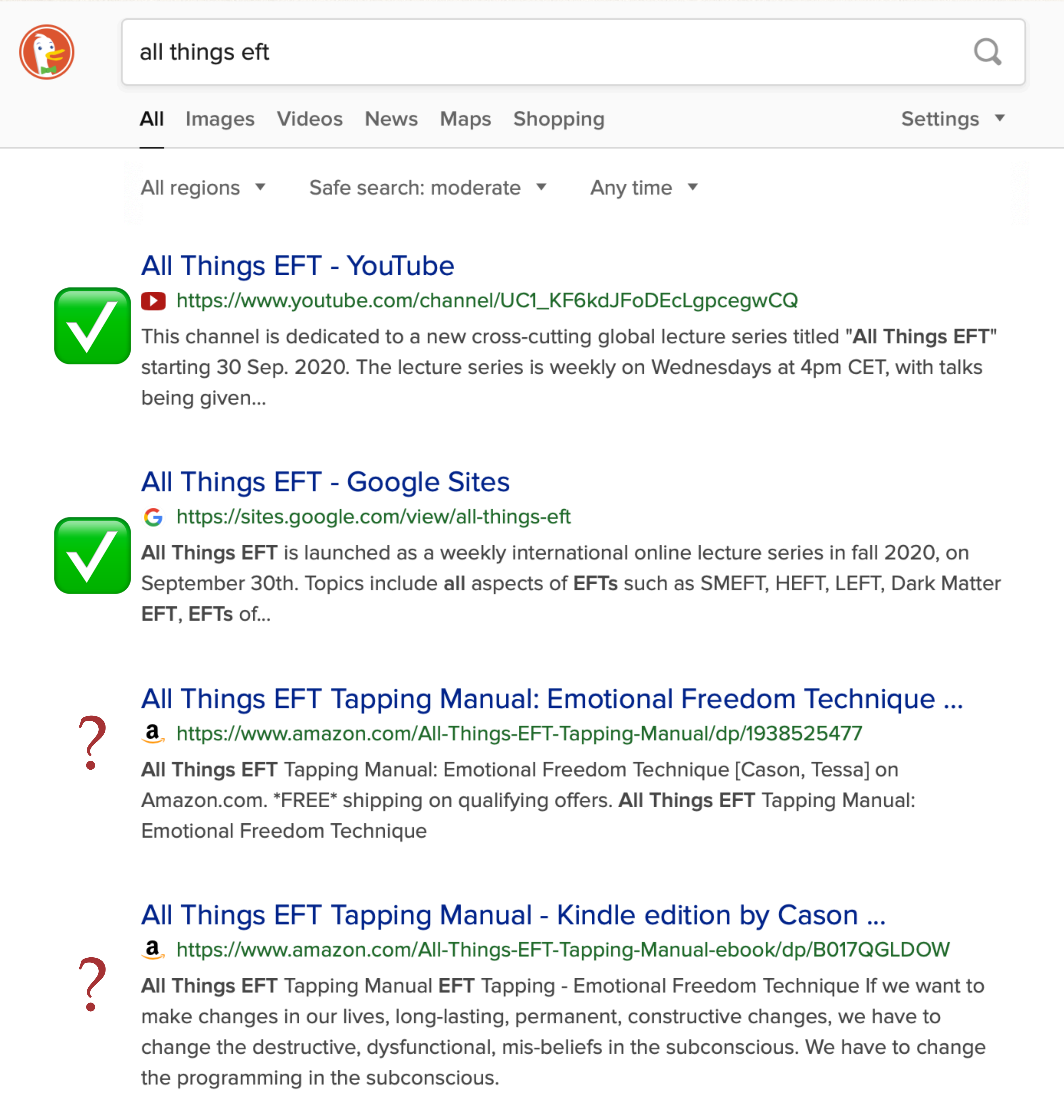
Summary

- 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

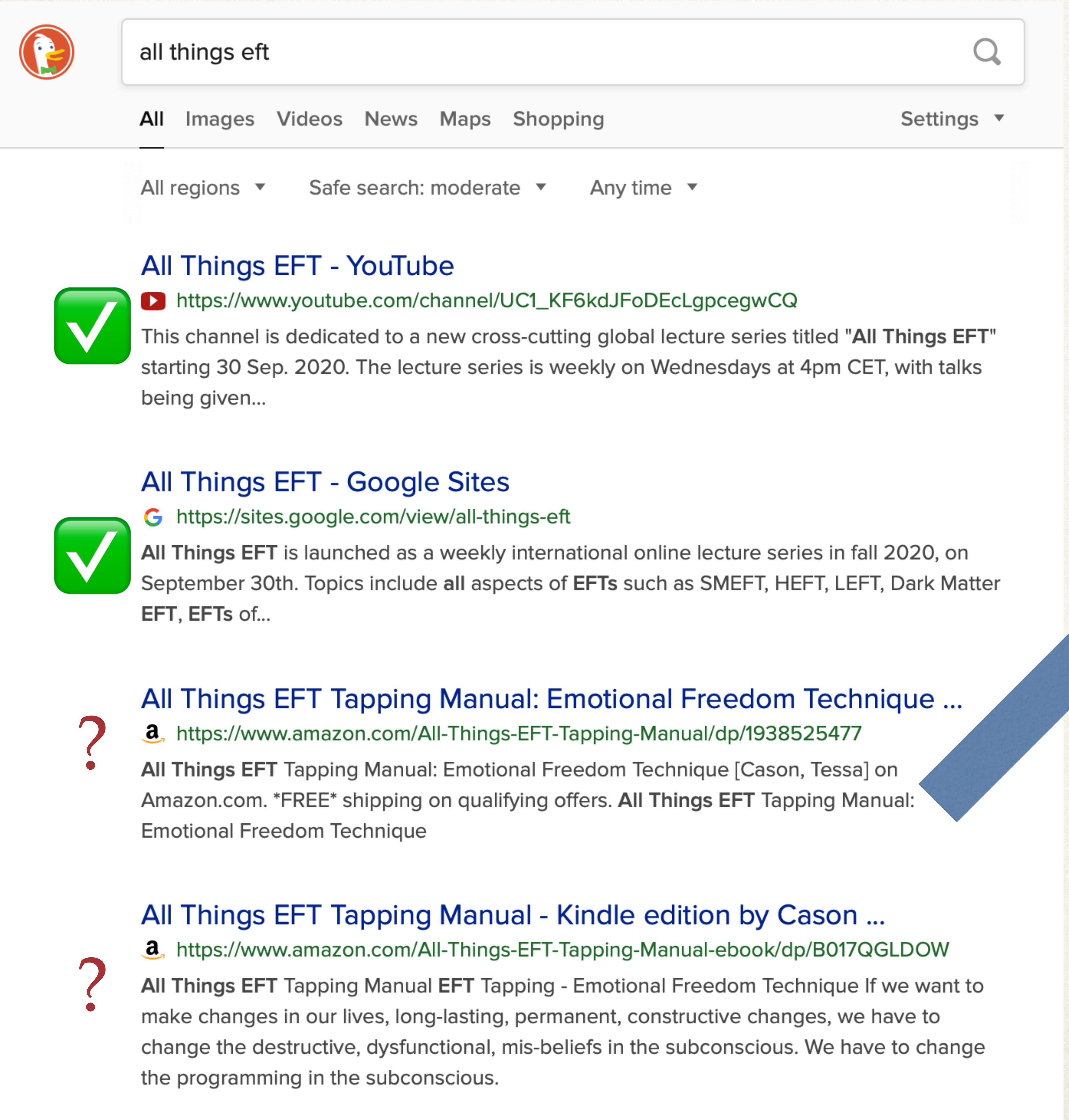
Thanks!

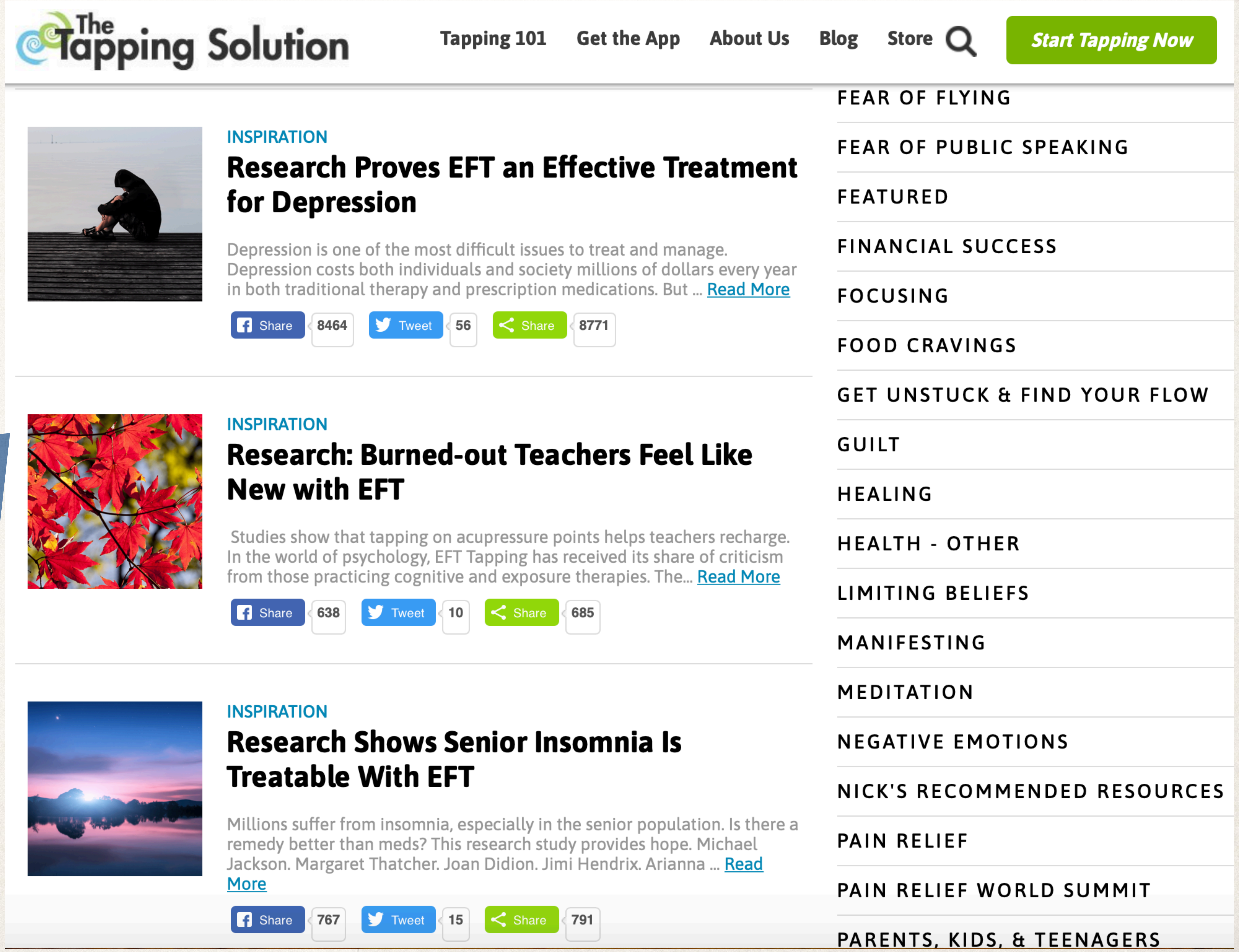
All Things EFT search engine optimization



Improvement from October!

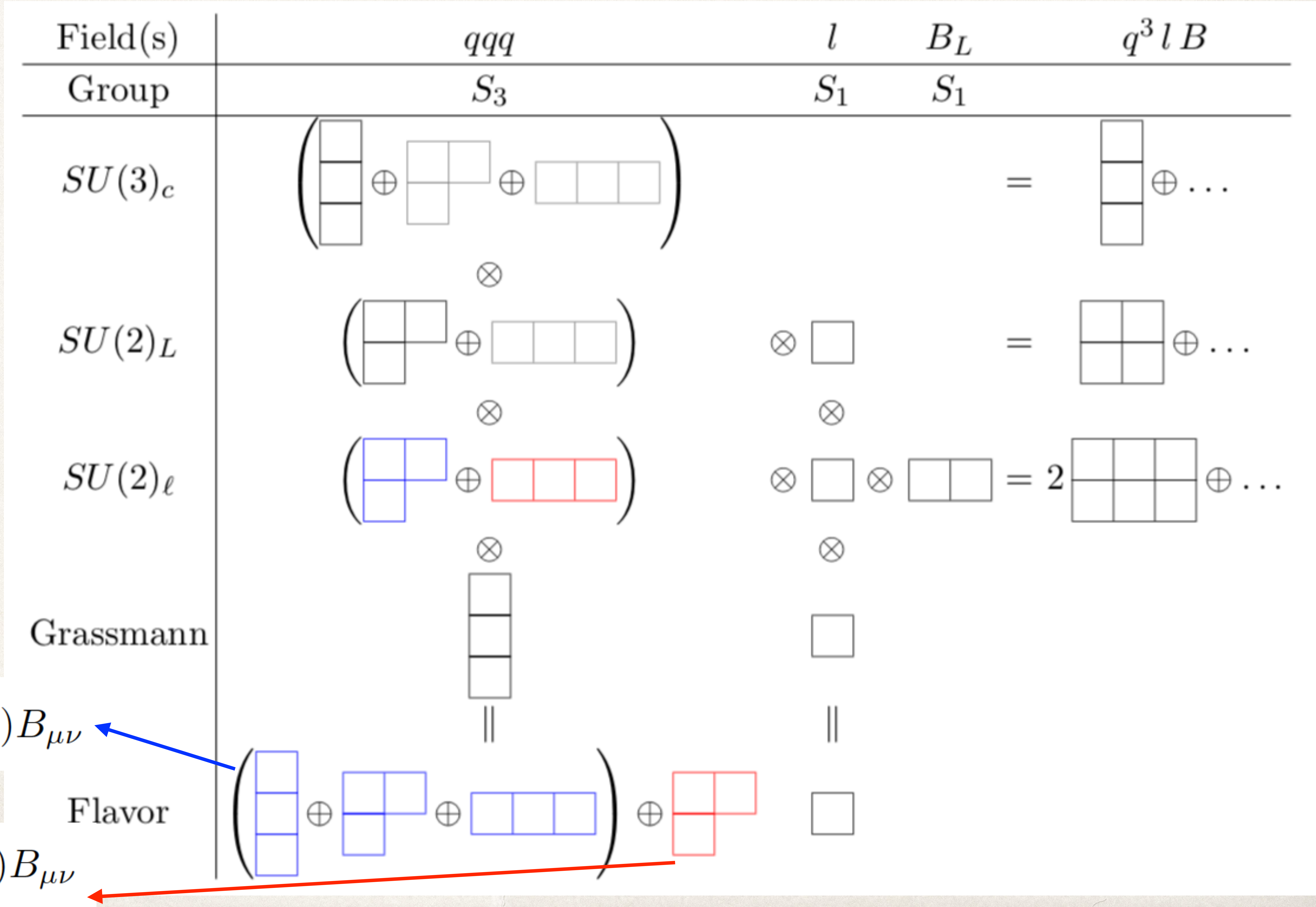
EFT disambiguation





Repeated Fields & Flavor Reps.

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



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

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

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 $Q^{(1)}_{q^3 lB}$ from previous slide and $Q^{(3)}_{q^3 lB} = \epsilon_{\alpha\beta\gamma}\epsilon_{mj}\epsilon_{kn}(q_p^{m\alpha} C q_r^{j\beta})(q_s^{k\gamma} C \sigma^{\mu\nu} l_t^n) B_{\mu\nu}$
  - $-Q^{(3)}_{\substack{q^3 lB\\ prst}} = Q^{(1)}_{\substack{q^3 lB\\ prst}} + Q^{(1)}_{\substack{q^3 lB\\ rpst}}$
  - $p \leftrightarrow r$ symmetry of $Q^{(3)}_{q^3 lB}$ doesn't allow for the antisymmetric $\{1,1,1\}$ rep. of S_3
  - whereas $Q^{(1)}_{\substack{q^3 lB\\ prst}} + Q^{(1)}_{\substack{q^3 lB\\ rpst}} = Q^{(1)}_{\substack{q^3 lB\\ sprt}} + Q^{(1)}_{\substack{q^3 lB\\ srpt}}$ allows for all 3 flavor representations

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

$\overline{w}$ \ w	0	2	4	6	8
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

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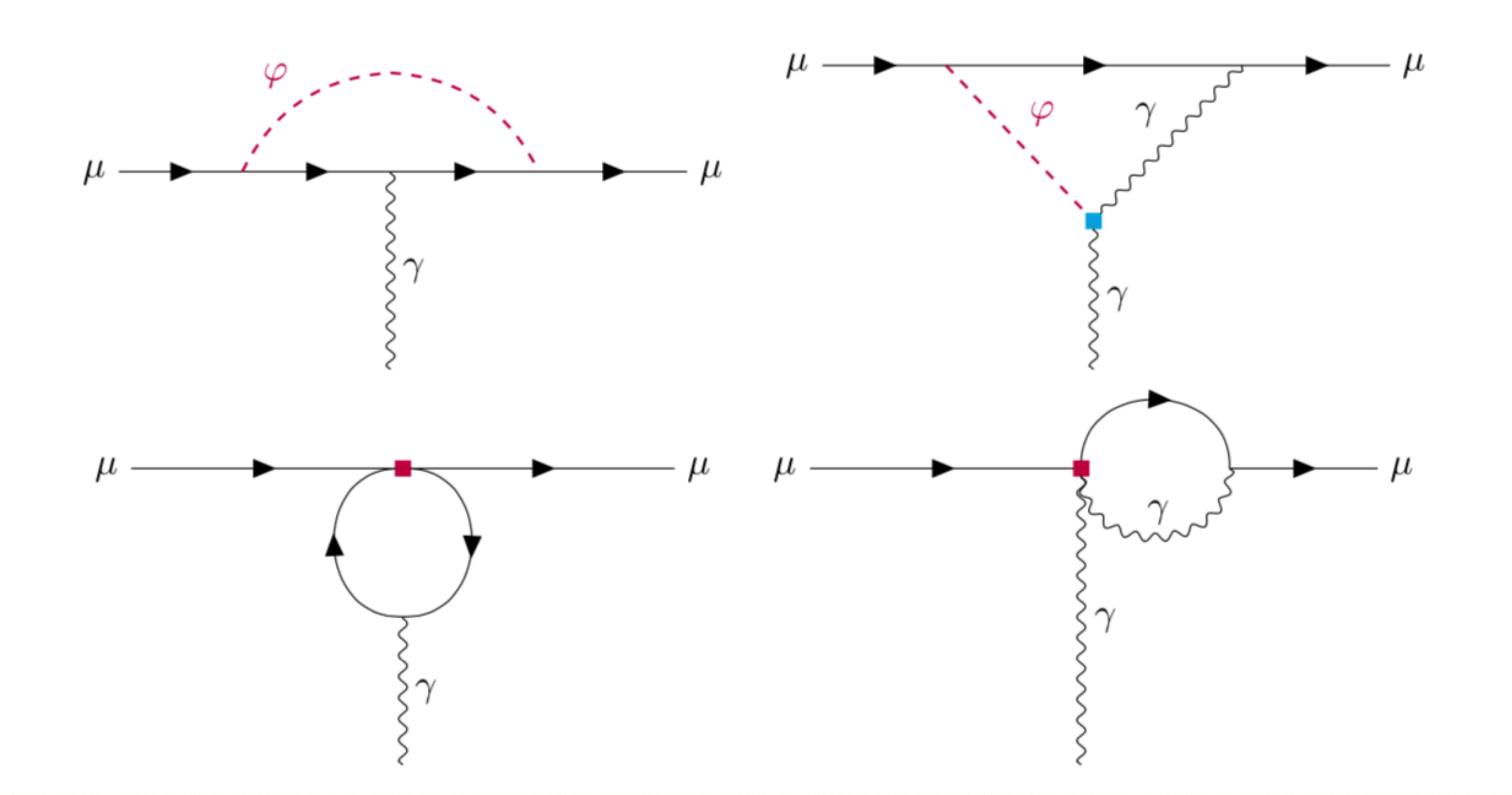
Muon $g - 2$

- $d = 8$ 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
  - $X^3H^2 \to \lambda_Z \neq \lambda_\gamma$
  - $XH^4D^2 \to g_1^V, \kappa_V \not\propto C_{HWB}$
- Higgs measurements - $\psi^2 H^5$ breaks correlation between Yukawa contribution to single and double Higgs production

Multi-boson processes

- Quartic gauge couplings - $X^4, H^4D^4, X^2H^2D^2$
- Light-by-light scattering - X^4
- Neutral triple gauge couplings - $X^2H^2D^2$
- $\psi\bar{\psi} \to V_L V_L$ from $\psi^2 H^2 D^3$ can dominate over $\psi^2 H^2 D$
- $\psi\bar{\psi} \to V_T Z_L$ 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. $e_L e_R \to e_L e_L$ from $\psi^2 HD$
- Novel angular observables - 2003.11615
- Testing positivity at colliders e.g. $e^+ e^- \to \gamma\gamma$ - 2011.03055
- Neutron EDM: $G^3 \widetilde{G}$ can dominate over $G^2 \widetilde{G}$