Institute of Theoretical Physics
Chinese Academy of Sciences

通向新物理的有效途径
Effective Pathway to New Physics

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Outline

- EFT: top-down vs bottom-up approach
- Amplitude Basis construction for EFT operators

ITP-CAS group

Hao-Lin Li, Zhe Ren, Jing Shu, Ming-Lei Xiao, **JHY**, Yu-Hui Zheng, 2005.00008, PRD
Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **JHY**, Yu-Hui Zheng, 2007.07899, PRD
Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **JHY**, Yu-Hui Zheng, 2012.09188, JHEP
Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **JHY**, Yu-Hui Zheng, 2105.09329, JHEP
Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **JHY**, Yu-Hui Zheng, 2201.04639, JHEP

- Complete UV resonances from bottom-up approach

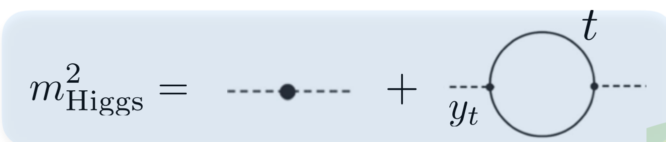
Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **JHY**, 2204.03660
Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **JHY**, 2205.xxxxx
Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **JHY**, 2206.xxxxx

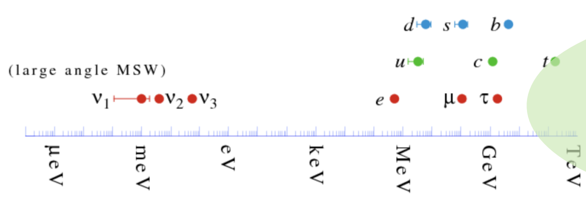
- Summary and outlook

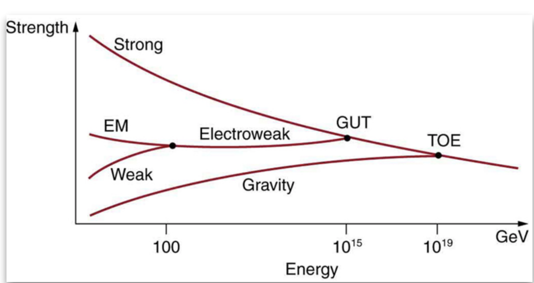
New Physics (NP) Models

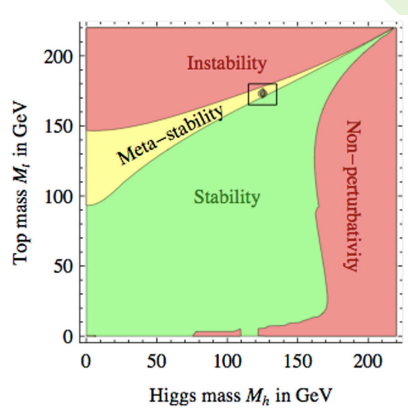
theoretical motivation

experimental challenges









New Physics

Higgs mass

Flavor Hierarchy

Gauge Unification

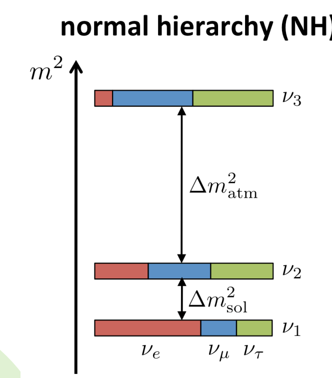
Vacuum Stability

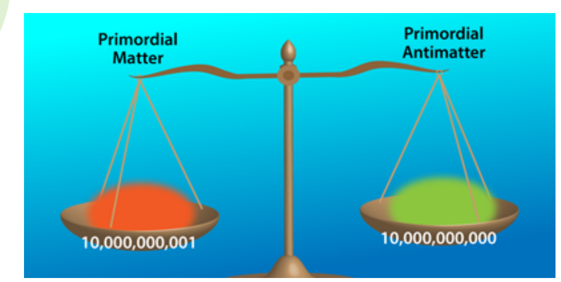
Inflation

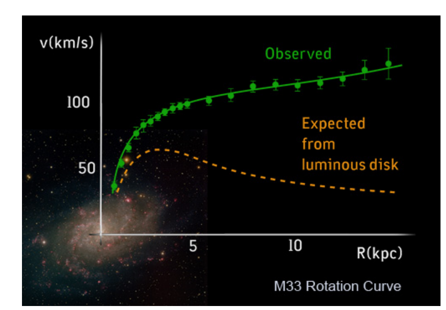
Dark matter

Baryon Asymmetry

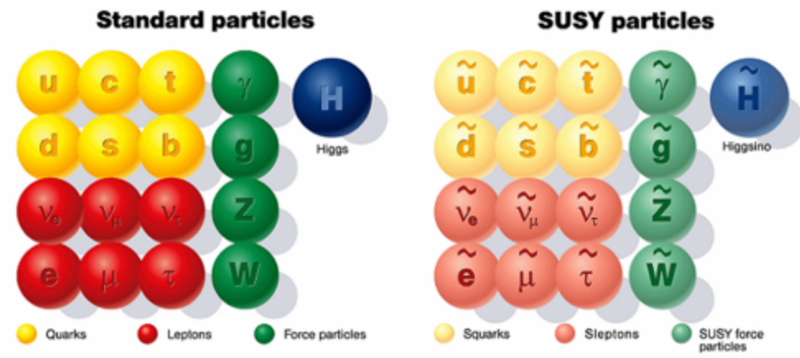
Neutrino



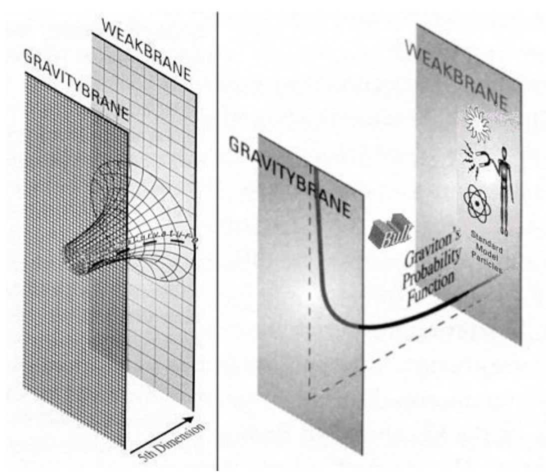




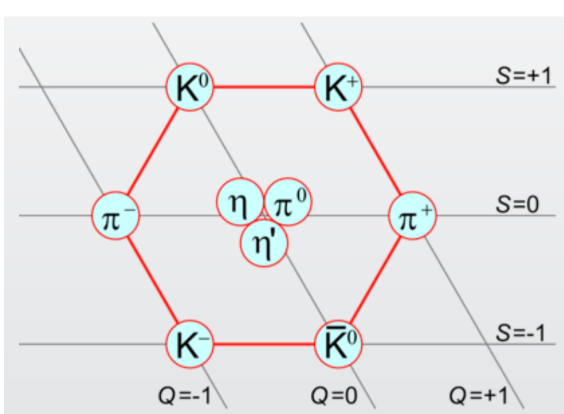
NP Motivated Simplified Model



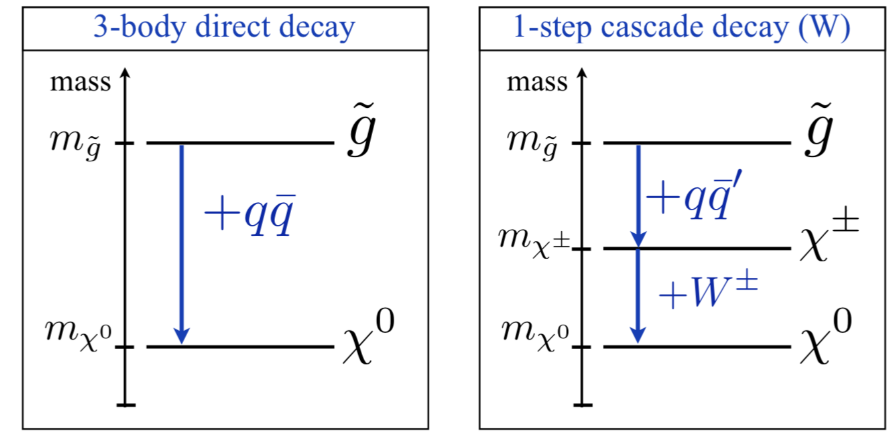
SUSY

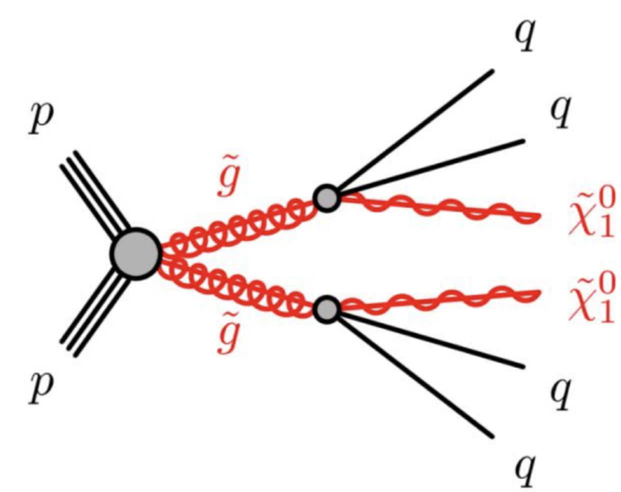


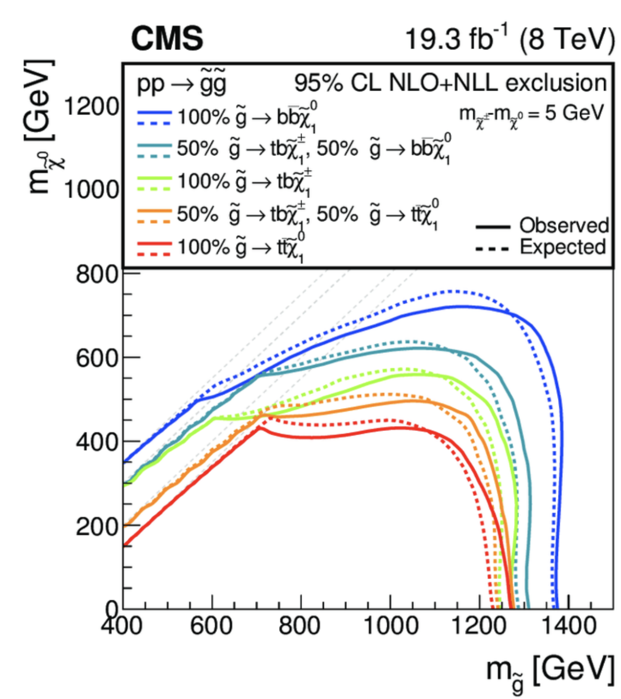
Extra Dimension



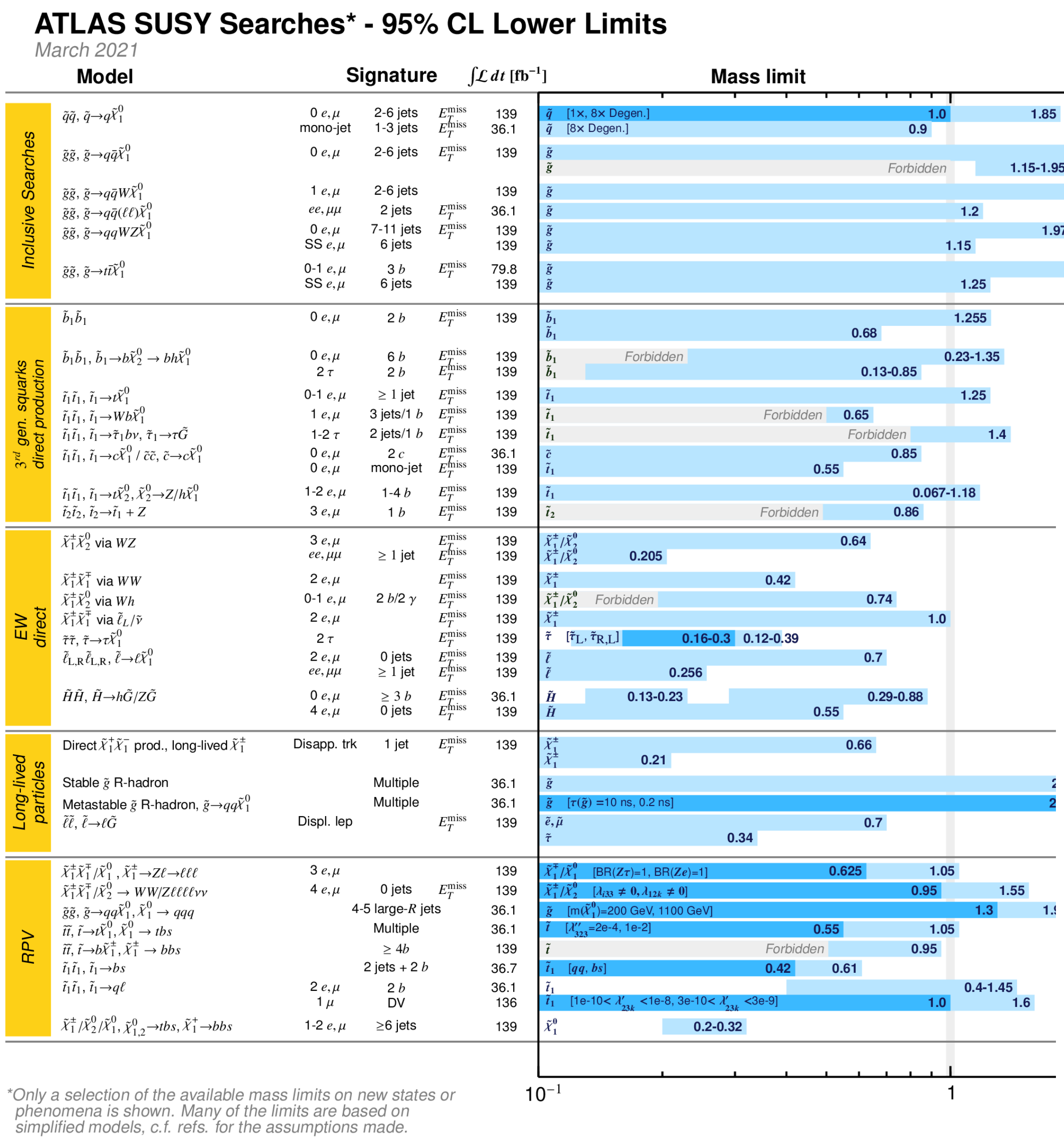
Composite Dynamics

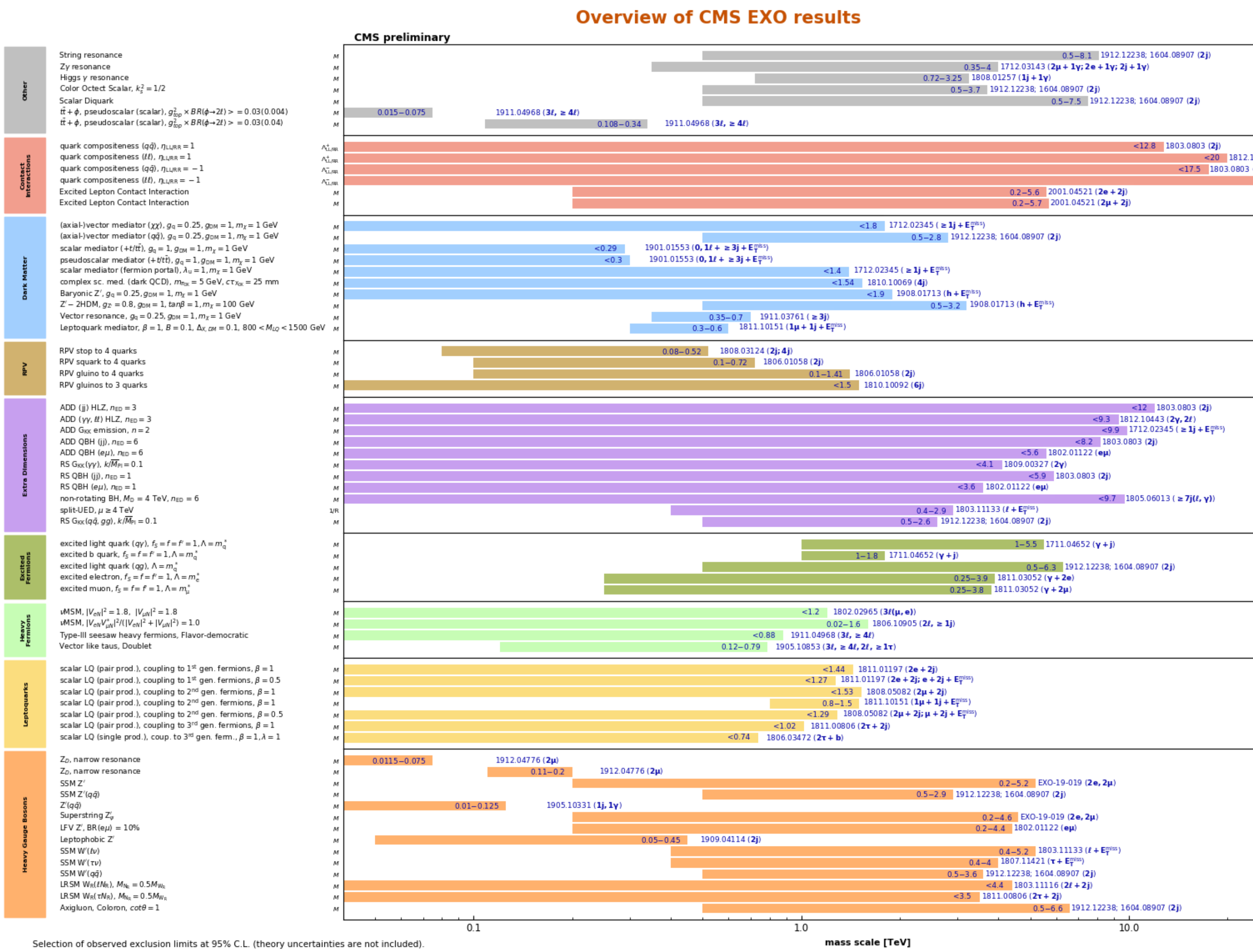






New Physics @ LHC



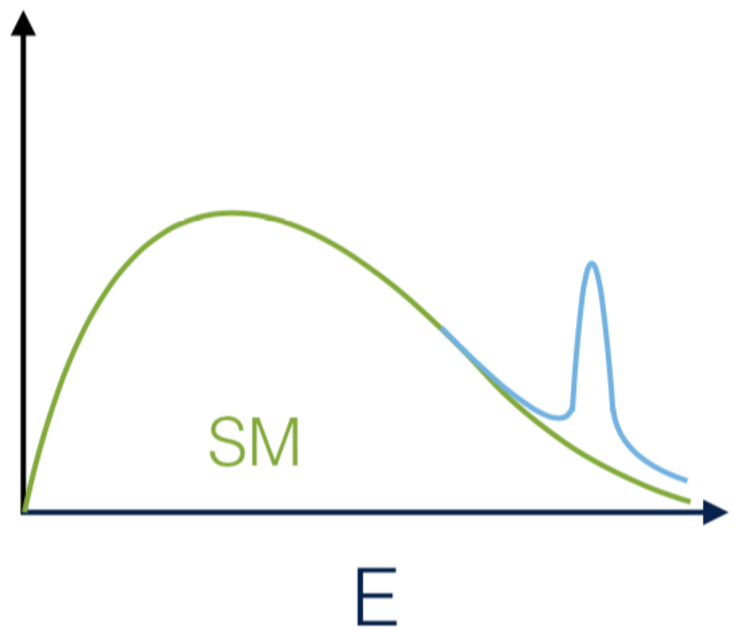


Jiang-Ha

Paradigm Shift

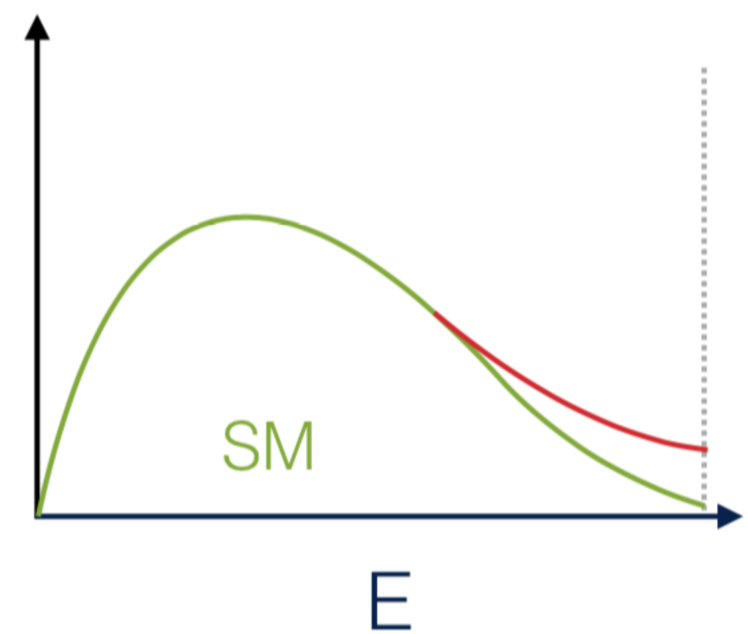
New physics beyond the LHC threshold: paradigm shift for BSM searches

Direct signature



resonance bump hunting at the LHC

Indirect searches



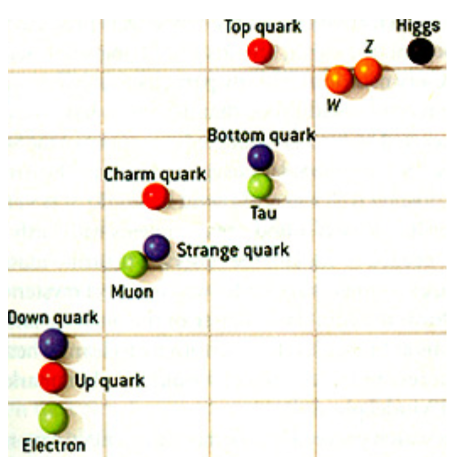
distribution tail deviation at the LHC

Top-Down EFT

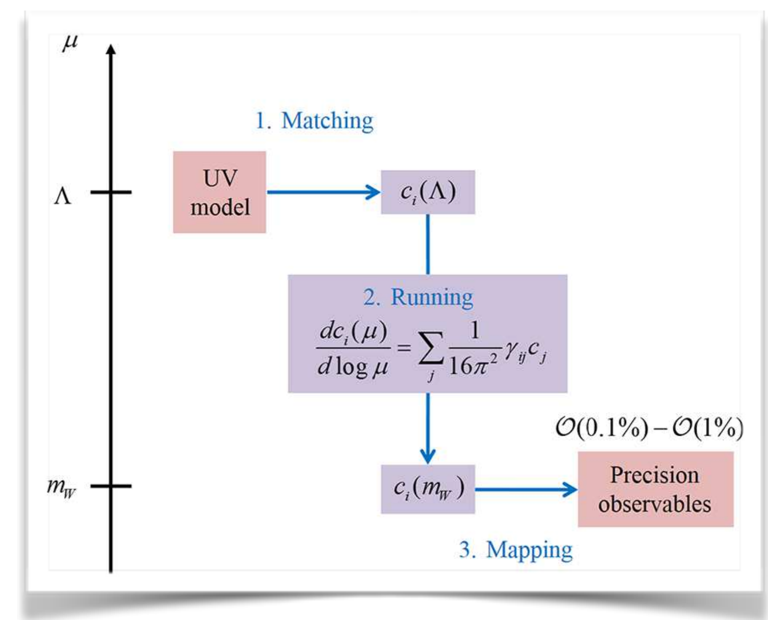
Given new physics models, integrate out heavy particles and match to SMEFT

New Physics Models

Integrate out and matching/running



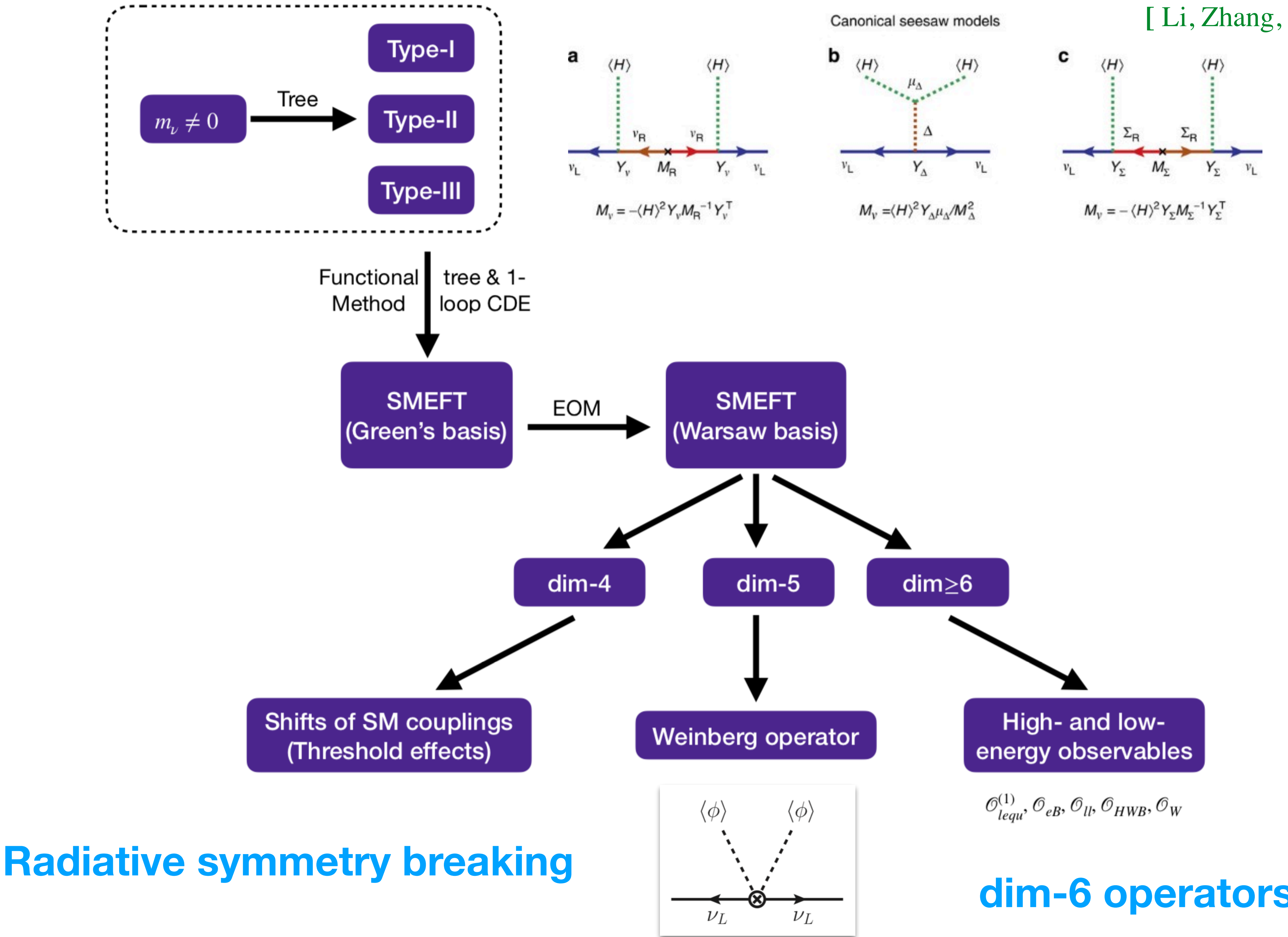
EFT Operators



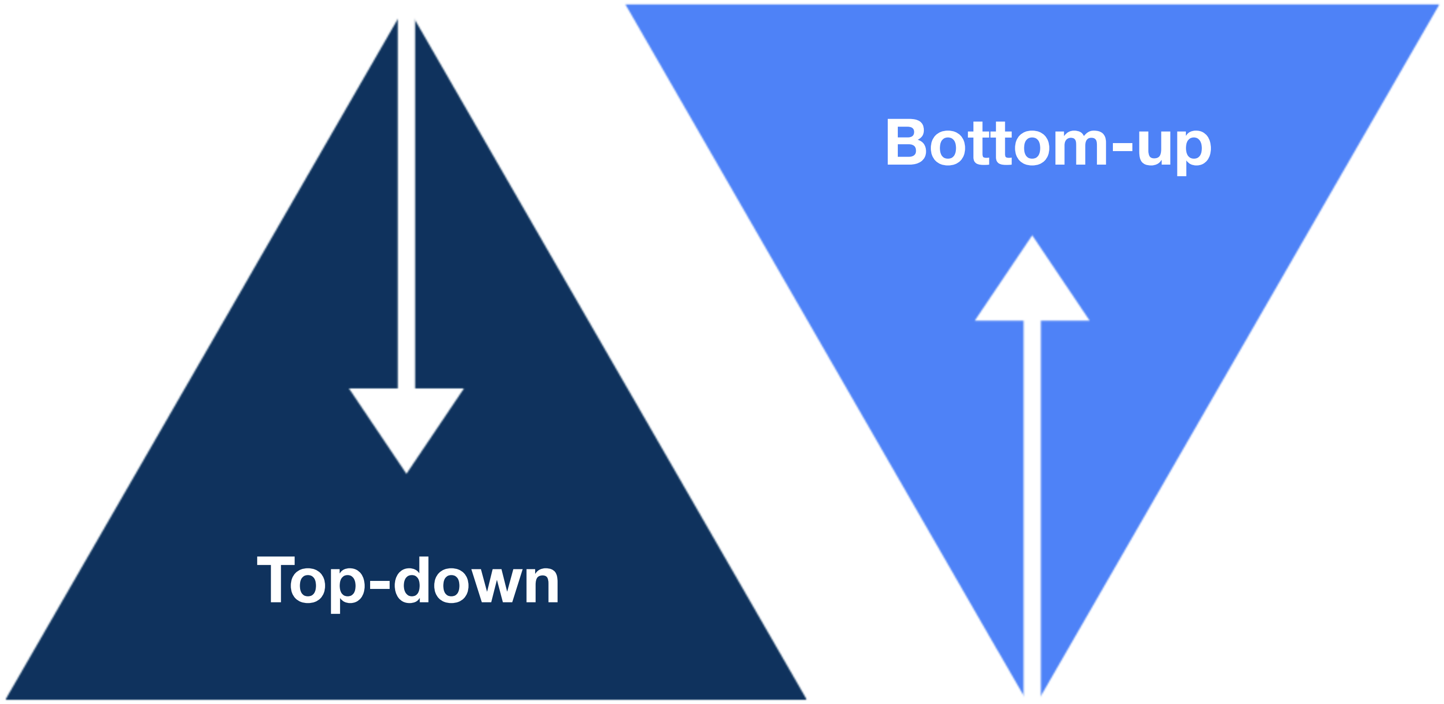
Decoupling theorem

Canonical Seesaw Models

[Du, Li, JH**Yu**, 2201.04646]
[Li, Zhang, Zhou, 2021,2022]

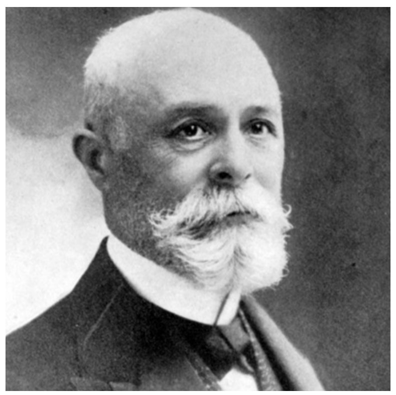


Is the top-down EFT the natural way to do EFT?



History of Weak Theory

Looking back to the past, we did not know the UV theory ahead

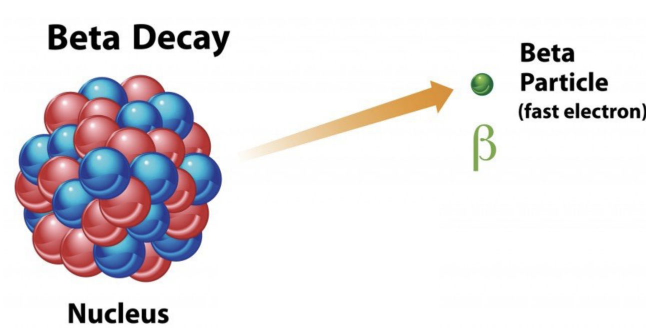


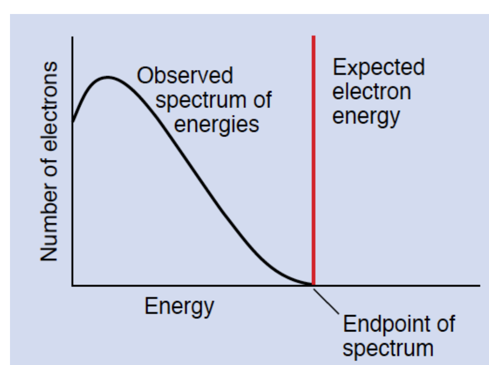
Becquerel
1986

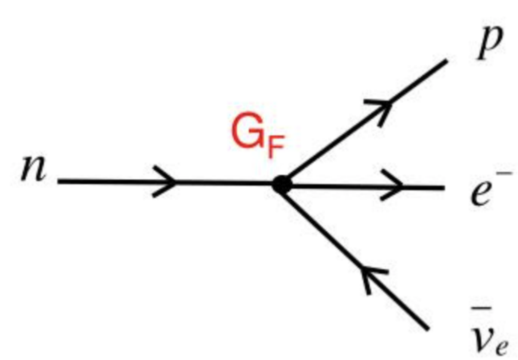
Pauli
1933

Fermi
1934

Gamov-Teller 1936
Fierz 1937







$$\mathcal{L}_i = \sum_{i=1}^{5} g_i \{\bar{\psi}_1 \mathcal{O}^i \psi_2\} \{\bar{\psi}_3 \mathcal{O}_i \psi_4\}$$

$$\mathcal{O}_i = (\mathbf{1},\ \gamma_\mu,\ \sigma_{\mu\nu},\ i\gamma_5\gamma_\mu,\ \text{or}\ \gamma_5)$$

$$M_{fi} = G_F \left[\overline{\psi_n}\gamma^\mu \psi_p\right] \left[\overline{\psi_e}\gamma^\mu \psi_\nu\right]$$

vector current to
Fermi(V/S),
GT(A/T), P

Four-fermi EFT

Four-Fermi EFT

With parity violation, Lee and Yang wrote the most general 4-fermi operators

Lee-Yang 1956
Wu 1956

$$\vec{\sigma}_{\rm Co} \cdot \vec{p}_e$$

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

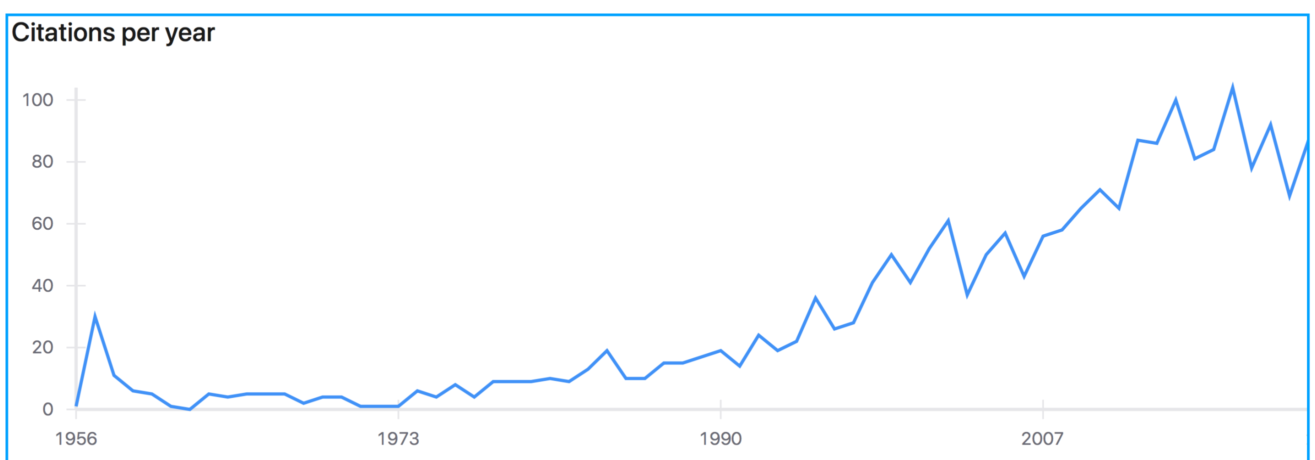
AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

If parity is not conserved in β decay, the most general form of Hamiltonian can be written as

$$\begin{aligned} H_{\rm int} = & (\psi_p^\dagger \gamma_4 \psi_n)(C_S \psi_e^\dagger \gamma_4 \psi_\nu + C_S' \psi_e^\dagger \gamma_4 \gamma_5 \psi_\nu) \\ & + (\psi_p^\dagger \gamma_4 \gamma_\mu \psi_n)(C_V \psi_e^\dagger \gamma_4 \gamma_\mu \psi_\nu + C_V' \psi_e^\dagger \gamma_4 \gamma_\mu \gamma_5 \psi_\nu) \\ & + \tfrac{1}{2}(\psi_p^\dagger \gamma_4 \sigma_{\lambda\mu} \psi_n)(C_T \psi_e^\dagger \gamma_4 \sigma_{\lambda\mu} \psi_\nu \\ & + C_T' \psi_e^\dagger \gamma_4 \sigma_{\lambda\mu} \gamma_5 \psi_\nu) + (\psi_p^\dagger \gamma_4 \gamma_\mu \gamma_5 \psi_n) \\ & \times (-C_A \psi_e^\dagger \gamma_4 \gamma_\mu \gamma_5 \psi_\nu - C_A' \psi_e^\dagger \gamma_4 \gamma_\mu \psi_\nu) \\ & + (\psi_p^\dagger \gamma_4 \gamma_5 \psi_n)(C_P \psi_e^\dagger \gamma_4 \gamma_5 \psi_\nu + C_P' \psi_e^\dagger \gamma_4 \psi_\nu), \end{aligned} \quad \text{(A.1)}$$

Complete charge current LEFT operators



Comprehensive analysis of beta decays
within and beyond the Standard Model

[Falkowski, et.al 2021]

energies. The general EFT Lagrangian describing these interactions at the leading order was written more than 60 years ago by Lee and Yang [6]:

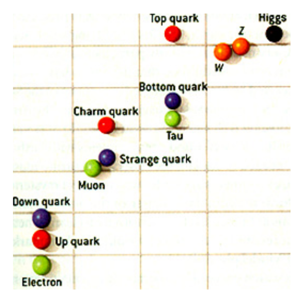
$$\begin{aligned} \mathcal{L}_{\rm Lee-Yang} = & -\bar{p}\gamma^\mu n \left(C_V \bar{e}\gamma_\mu \nu - C_V' \bar{e}\gamma_\mu\gamma_5 \nu\right) + \bar{p}\gamma^\mu\gamma_5 n \left(C_A \bar{e}\gamma_\mu\gamma_5 \nu - C_A' \bar{e}\gamma_\mu \nu\right) \\ & - \bar{p} n \left(C_S \bar{e}\nu - C_S' \bar{e}\gamma_5 \nu\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu} n \left(C_T \bar{e}\sigma_{\mu\nu}\nu - C_T' \bar{e}\sigma_{\mu\nu}\gamma_5 \nu\right) \\ & - \bar{p}\gamma_5 n \left(C_P \bar{e}\gamma_5 \nu - C_P' \bar{e}\nu\right) + \text{h.c.} \end{aligned} \quad (1.1)$$

Bottom-up Approach

PV Lesson: start from the complete bottom-up operators

?

UV unknown



EFT Operators

[Weinberg 1933 - 2021]

a folk theorem: "if one writes down the most general possible Lagrangian, including *all* terms consistent with assumed symmetry principles, and then calculates matrix elements with this Lagrangian to any given order of perturbation theory, the result will simply be the most general possible S-matrix consistent with perturbative unitarity, analyticity, cluster decomposition, and the assumed symmetry properties."

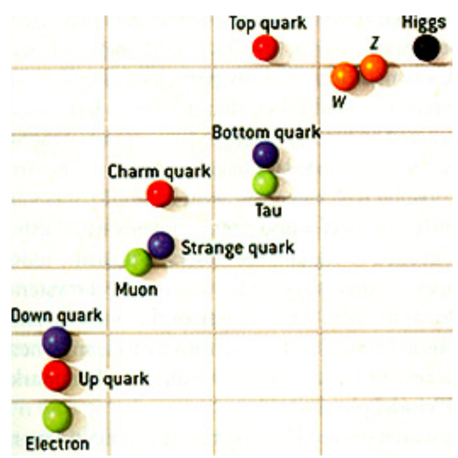
Weinberg's Folk theorem, 1979

SMEFT

Standard model effective field theory (SMEFT)

UV model unspecified

LHC probing scale



SMEFT

Most general Lagrangian with Lorentz and SM gauge symmetry

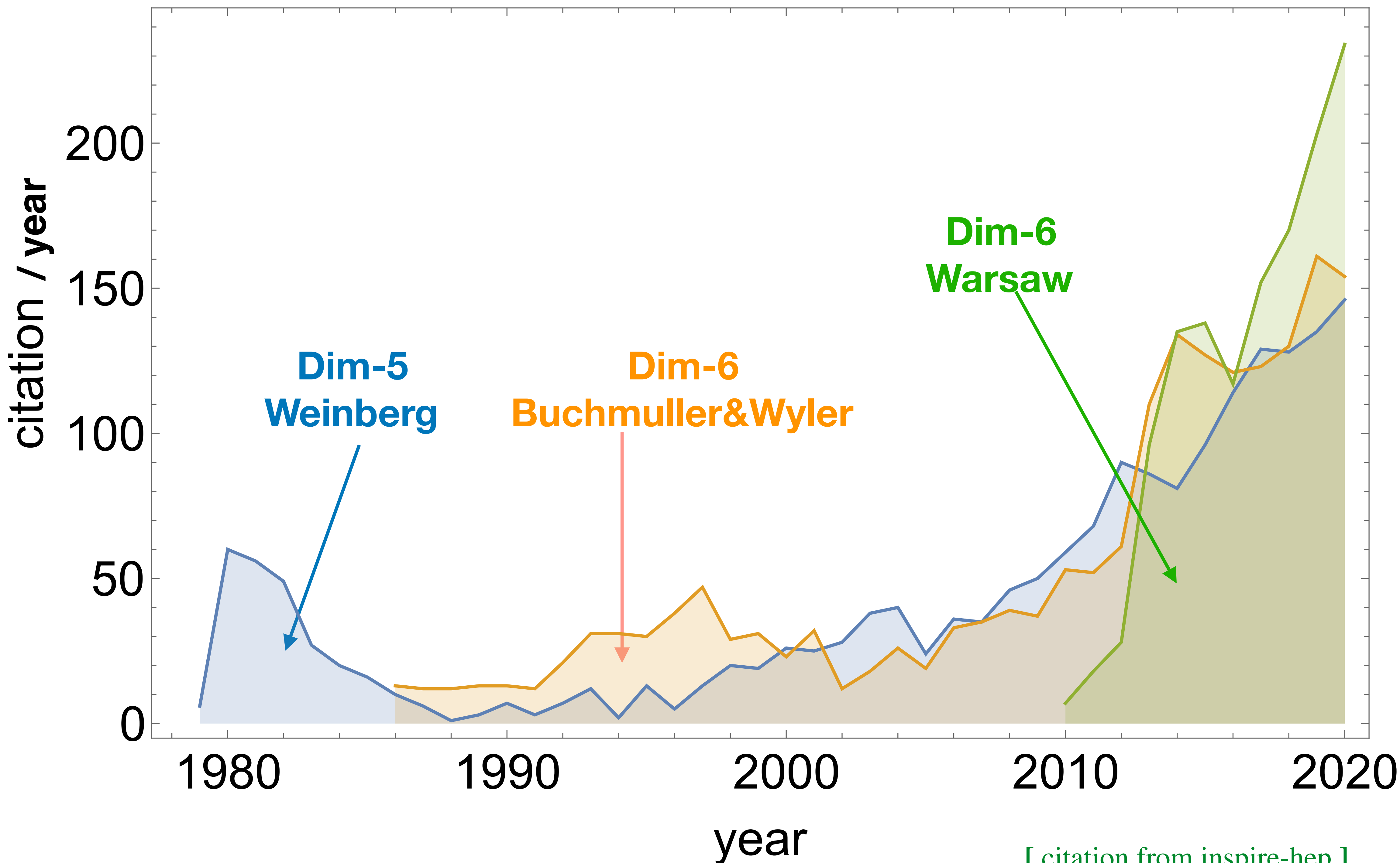
$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \ldots$$

power counting: canonical dim.

SMEFT provides systematic parametrization of

… all possible Lorentz inv. new physics!

SMEFT Operators



[citation from inspire-hep]

SMEFT Dim-6 Operators

Why completing dim-6 took more than 25 years?

tedious and prone-to-error

$$O_\varphi=\tfrac{1}{3}(\varphi^\dagger\varphi)^3, \qquad O_G=f_{ABC}G_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu},$$
$$O_{\partial\varphi}=\tfrac{1}{2}\partial_\mu(\varphi^\dagger\varphi)\,\partial^\mu(\varphi^\dagger\varphi). \qquad O_{\tilde G}=f_{ABC}\tilde G_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu},$$
$$O_{e\varphi}=(\varphi^\dagger\varphi)(\bar\ell e\varphi), \qquad O_W=\varepsilon_{IJK}W_\mu^{I\nu}W_\nu^{J\lambda}W_\lambda^{K\mu},$$
$$O_{u\varphi}=(\varphi^\dagger\varphi)(\bar q u\tilde\varphi), \qquad O_{\tilde W}=\varepsilon_{IJK}\tilde W_\mu^{I\nu}W_\nu^{J\lambda}W_\lambda^{K\mu}.$$
$$O_{d\varphi}=(\varphi^\dagger\varphi)(\bar q d\varphi),$$
$$O_{\varphi G}=\tfrac{1}{2}(\varphi^\dagger\varphi)G^A_{\mu\nu}G^{A\mu\nu}, \qquad O_{\varphi\tilde G}=(\varphi^\dagger\varphi)\tilde G^A_{\mu\nu}G^{A\mu\nu},$$
$$O_{\varphi W}=\tfrac{1}{2}(\varphi^\dagger\varphi)W^I_{\mu\nu}W^{I\mu\nu}, \qquad O_{\varphi\tilde W}=(\varphi^\dagger\varphi)\tilde W^I_{\mu\nu}W^{I\mu\nu},$$
$$O_{\varphi B}=\tfrac{1}{2}(\varphi^\dagger\varphi)B_{\mu\nu}B^{\mu\nu}, \qquad O_{\varphi\tilde B}=(\varphi^\dagger\varphi)\tilde B_{\mu\nu}B^{\mu\nu},$$
$$O_{WB}=(\varphi^\dagger\tau^I\varphi)W^I_{\mu\nu}B^{\mu\nu}, \qquad O_{\tilde WB}=(\varphi^\dagger\tau^I\varphi)\tilde W^I_{\mu\nu}B^{\mu\nu},$$
$$O_\varphi^{(1)}=(\varphi^\dagger\varphi)(D_\mu\varphi^\dagger D^\mu\varphi), \qquad O_\varphi^{(3)}=(\varphi^\dagger D^\mu\varphi)(D_\mu\varphi^\dagger\varphi).$$

$$O_{\ell W}=i\bar\ell\tau^I\gamma_\mu D_\nu\ell W^{I\mu\nu}, \qquad O_{\ell B}=i\bar\ell\gamma_\mu D_\nu\ell B^{\mu\nu},$$
$$O_{eB}=i\bar e\gamma_\mu D_\nu e B^{\mu\nu},$$
$$O_{qG}=i\bar q\lambda^A\gamma_\mu D_\nu q G^{A\mu\nu},$$
$$O_{qW}=i\bar q\tau^I\gamma_\mu D_\nu q W^{I\mu\nu}, \qquad O_{qB}=i\bar q\gamma_\mu D_\nu q B^{\mu\nu},$$
$$O_{uG}=i\bar u\lambda^A\gamma_\mu D_\nu u G^{A\mu\nu},$$
$$O_{uB}=i\bar u\gamma_\mu D_\nu u B^{\mu\nu},$$
$$O_{dG}=i\bar d\lambda^A\gamma_\mu D_\nu d G^{A\mu\nu},$$
$$O_{dB}=i\bar d\gamma_\mu D_\nu d B^{\mu\nu}.$$

80

[Buchmuller, Wyler, 1986]

$$O_{D_e}=(\bar\ell D_\mu e)D^\mu\varphi, \qquad O_{\bar D_e}=(D_\mu\bar\ell e)D^\mu\varphi, \qquad O^{(1)}_{\varphi\ell}=i(\varphi^\dagger D_\mu\varphi)(\bar\ell\gamma^\mu\ell),$$
$$O_{Du}=(\bar q D_\mu u)D^\mu\tilde\varphi, \qquad O_{\bar Du}=(D_\mu\bar q u)D^\mu\tilde\varphi, \qquad O^{(3)}_{\varphi\ell}=i(\varphi^\dagger D_\mu\tau^I\varphi)(\bar\ell\gamma^\mu\tau^I\ell),$$
$$O_{Dd}=(\bar q D_\mu d)D^\mu\varphi, \qquad O_{\bar Dd}=(D_\mu\bar q d)D^\mu\varphi, \qquad O_{\varphi e}=i(\varphi^\dagger D_\mu\varphi)(\bar e\gamma^\mu e),$$
$$O_{eW}=(\bar\ell\sigma^{\mu\nu}\tau^I e)\varphi W^I_{\mu\nu}, \qquad O_{eB}=(\bar\ell\sigma^{\mu\nu}e)\varphi B_{\mu\nu}, \qquad O^{(1)}_{\varphi q}=i(\varphi^\dagger D_\mu\varphi)(\bar q\gamma^\mu q),$$
$$O_{uG}=(\bar q\sigma^{\mu\nu}\lambda^A u)\tilde\varphi G^A_{\mu\nu}, \qquad O^{(3)}_{\varphi q}=i(\varphi^\dagger D_\mu\tau^I\varphi)(\bar q\gamma^\mu\tau^I q),$$
$$O_{uW}=(\bar q\sigma^{\mu\nu}\tau^I u)\tilde\varphi W^I_{\mu\nu}, \qquad O_{uB}=(\bar q\sigma^{\mu\nu}u)\tilde\varphi B_{\mu\nu}, \qquad O_{\varphi_u}=i(\varphi^\dagger D_\mu\varphi)(\bar u\gamma^\mu u),$$
$$O_{dG}=(\bar q\sigma^{\mu\nu}\lambda^A d)\varphi G^A_{\mu\nu}, \qquad O_{\varphi_d}=i(\varphi^\dagger D_\mu\varphi)(\bar d\gamma^\mu d),$$
$$O_{dW}=(\bar q\sigma^{\mu\nu}\tau^I d)\varphi W^I_{\mu\nu}, \qquad O_{dW}=(\bar q\sigma^{\mu\nu}d)\varphi B_{\mu\nu}. \qquad O_{\varphi\varphi}=i(\varphi^\dagger\varepsilon D_\mu\varphi)(\bar u\gamma^\mu d).$$

$$O^{(1)}_{\ell\ell}=\tfrac{1}{2}(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell), \qquad O^{(3)}_{\ell\ell}=\tfrac{1}{2}(\bar\ell\gamma_\mu\tau^I\ell)(\bar\ell\gamma^\mu\tau^I\ell),$$
$$O^{(1,1)}_{qq}=\tfrac{1}{2}(\bar q\gamma_\mu q)(\bar q\gamma^\mu q), \qquad O^{(8,1)}_{qq}=\tfrac{1}{2}(\bar q\gamma_\mu\lambda^A q)(\bar q\gamma^\mu\lambda^A q),$$
$$O^{(1,3)}_{qq}=\tfrac{1}{2}(\bar q\gamma_\mu\tau^I q)(\bar q\gamma^\mu\tau^I q), \qquad O^{(8,3)}_{qq}=\tfrac{1}{2}(\bar q\gamma_\mu\lambda^A\tau^I q)(\bar q\gamma^\mu\lambda^A\tau^I q),$$
$$O^{(1)}_{\ell q}=(\bar\ell\gamma_\mu\ell)(\bar q\gamma^\mu q), \qquad O^{(3)}_{\ell q}=(\bar\ell\gamma_\mu\tau^I\ell)(\bar q\gamma^\mu\tau^I q).$$

$$O_{ee}=\tfrac{1}{2}(\bar e\gamma_\mu e)(\bar e\gamma^\mu e), \qquad O_{\ell e}=(\bar\ell e)(\bar e\ell),$$
$$O^{(1)}_{uu}=\tfrac{1}{2}(\bar u\gamma_\mu u)(\bar u\gamma^\mu u), \qquad O^{(8)}_{uu}=\tfrac{1}{2}(\bar u\gamma_\mu\lambda^A u)(\bar u\gamma^\mu\lambda^A u), \qquad O_{\ell u}=(\bar\ell u)(\bar u\ell),$$
$$O^{(1)}_{dd}=\tfrac{1}{2}(\bar d\gamma_\mu d)(\bar d\gamma^\mu d), \qquad O^{(8)}_{dd}=\tfrac{1}{2}(\bar d\gamma_\mu\lambda^A d)(\bar d\gamma^\mu\lambda^A d), \qquad O_{\ell d}=(\bar\ell d)(\bar d\ell),$$
$$O_{eu}=(\bar e\gamma_\mu e)(\bar u\gamma^\mu u), \qquad O_{qe}=(\bar q e)(\bar e q),$$
$$O_{ed}=(\bar e\gamma_\mu e)(\bar d\gamma^\mu d), \qquad O^{(1)}_{qu}=(\bar q u)(\bar u q),$$
$$O^{(1)}_{ud}=(\bar u\gamma_\mu u)(\bar d\gamma^\mu d), \qquad O^{(8)}_{ud}=(\bar u\gamma_\mu\lambda^A u)(\bar d\gamma^\mu\lambda^A d). \qquad O^{(1)}_{qd}=(\bar q d)(\bar d q),$$
$$O_{qde}=(\bar\ell e)(\bar d q).$$

$$O^{(1)}_{qq}=(\bar q u)(\bar q d), \quad O^{(8)}_{qq}=(\bar q\lambda^A u)(\bar q\lambda^A d), \quad O_{\ell q}=(\bar\ell e)(\bar q u). \quad O^{(8)}_{qu}=(\bar q\lambda^A u)(\bar u\lambda^A q), \quad O^{(8)}_{qd}=(\bar q\lambda^A d)(\bar d\lambda^A q),$$

Equation of motion (Field redefinition)

$$(D^\mu D_\mu\varphi)^j = m^2\varphi^j - \lambda(\varphi^\dagger\varphi)\varphi^j - \bar e\,\Gamma_e^\dagger l^j + \varepsilon_{jk}\bar q^k\,\Gamma_u u - \bar d\,\Gamma_d^\dagger q^j$$

$$i\not{D}l = \Gamma_e e\varphi, \qquad i\not{D}e = \Gamma_e^\dagger\varphi^\dagger l, \qquad i\not{D}q = \Gamma_u u\tilde\varphi + \Gamma_d d\varphi, \qquad i\not{D}u = \Gamma_u^\dagger\tilde\varphi^\dagger q,$$

$$(D^\rho W_{\rho\mu})^I = \frac{g}{2}\left(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi + \bar l\gamma_\mu\tau^I l + \bar q\gamma_\mu\tau^I q\right),$$

Covariant derivative commutator

$$[D_\rho, D_\alpha] \sim X_{\rho\alpha}$$

Bianchi identity

$$D_{[\rho}X_{\mu\nu]} = 0$$

Integration by part (total derivatives)

$$(D^n\varphi)^\dagger(D^m\varphi) = -(D^{n+1}\varphi)^\dagger(D^{m-1}\varphi) + \partial\left[(D^n\varphi)^\dagger(D^{m-1}\varphi)\right]$$

Fierz identity

$$T^A_{\alpha\beta}T^A_{\kappa\lambda} = \frac{1}{2}\delta_{\alpha\lambda}\delta_{\kappa\beta} - \frac{1}{6}\delta_{\alpha\beta}\delta_{\kappa\lambda}$$

$$\tau^I_{jk}\tau^I_{mn} = 2\delta_{jn}\delta_{mk} - \delta_{jk}\delta_{mn}$$

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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	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}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi$		$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)$		$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I$		$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi$		$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

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

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

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

80-1-16-5+1 = 59

Main Difficulties

How about higher dimensional operators?

difficult to write down explicit form of operators

Derivatives

$BWHH^\dagger D^2$

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$$(D^2H^\dagger)HB_{L\mu\nu}W_L^{\mu\nu},\ (D^\mu D_\nu H^\dagger)HB_{L\mu\rho}W_L^{\nu\rho},\ (D_\nu D^\mu H^\dagger)HB_{L\mu\rho}W_L^{\nu\rho},\ (D_\mu H^\dagger)(D^\mu H)B_{L\nu\rho}W_L^{\nu\rho},$$
$$(D_\mu H^\dagger)(D^\nu H)B_{L\nu\rho}W_L^{\mu\rho},\ (D^\nu H^\dagger)(D_\mu H)B_{L\nu\rho}W_L^{\mu\rho},\ (D_\mu H^\dagger)H(D^\mu B_{L\nu\rho})W_L^{\nu\rho},\ (D_\mu H^\dagger)H(D^\nu B_{L\nu\rho})W_L^{\mu\rho},$$
$$(D^\nu H^\dagger)H(D_\mu B_{L\nu\rho})W_L^{\mu\rho},\ (D_\mu H^\dagger)HB_{L\nu\rho}(D^\mu W_L^{\nu\rho}),\ (D_\mu H^\dagger)HB_{L\nu\rho}(D^\nu W_L^{\mu\rho}),\ (D^\nu H^\dagger)HB_{L\nu\rho}(D_\mu W_L^{\mu\rho}),$$
$$H^\dagger(D^2H)B_{L\mu\nu}W_L^{\mu\nu},\ H^\dagger(D^\mu D_\nu H)B_{L\mu\rho}W_L^{\nu\rho},\ H^\dagger(D_\nu D^\mu H)B_{L\mu\rho}W_L^{\nu\rho},\ H^\dagger(D^\mu H)(D_\mu B_{L\nu\rho})W_L^{\nu\rho},$$
$$H^\dagger(D^\nu H)(D_\mu B_{L\nu\rho})W_L^{\mu\rho},\ H^\dagger(D_\mu H)(D^\nu B_{L\nu\rho})W_L^{\mu\rho},\ H^\dagger(D^\mu H)B_{L\nu\rho}(D_\mu W_L^{\nu\rho}),\ H^\dagger(D^\nu H)B_{L\nu\rho}(D_\mu W_L^{\mu\rho}),$$
$$H^\dagger(D_\mu H)B_{L\nu\rho}(D^\nu W_L^{\mu\rho}),\ H^\dagger H(D^2B_{L\mu\nu})W_L^{\mu\nu},\ H^\dagger H(D^\mu D_\nu B_{L\mu\rho})W_L^{\nu\rho},\ H^\dagger H(D_\nu D^\mu B_{L\mu\rho})W_L^{\nu\rho},$$
$$H^\dagger H(D^\mu B_{L\nu\rho})(D_\mu W_L^{\nu\rho}),\ H^\dagger H(D^\nu B_{L\nu\rho})(D_\mu W_L^{\mu\rho}),\ H^\dagger H(D_\mu B_{L\nu\rho})(D^\nu W_L^{\mu\rho}),\ H^\dagger HB_{L\mu\nu}(D^2W_L^{\mu\nu}),$$
$$H^\dagger HB_{L\mu\rho}(D^\mu D_\nu W_L^{\nu\rho}),\ H^\dagger HB_{L\mu\rho}(D_\nu D^\mu W_L^{\nu\rho}). \tag{14}$$

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Which 2 should be picked up?

Repeated fields

$QQQL$

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$$Q^{qqq\ell}_{prst} = C^{prst} \begin{matrix} \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}(L_{pi}Q_{raj})(Q_{sbk}Q_{tcl}) \\ \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}(L_{pi}Q_{sbk})(Q_{raj}Q_{tcl}) \\ \epsilon^{abc}\epsilon^{ij}\epsilon^{kl}(L_{pi}Q_{sbk})(Q_{raj}Q_{tcl}) \\ \epsilon^{abc}\epsilon^{ij}\epsilon^{kl}(L_{pi}Q_{raj})(Q_{sbk}Q_{tcl}) \end{matrix} \qquad p,r,s,t = 1,2,3$$

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What flavor relations should be imposed?

Operator as Spinor Tensor

Operator has more symmetries than what we expect

SO(3,1)	SL(2,C) $SU(2)_l \times SU(2)_r$	Spinor-helicity
ϕ	$\phi \in (0,0)$	
ψ	$\psi_\alpha \in (1/2, 0)$ $\psi^\dagger_{\dot\alpha} \in (0, 1/2)$,	λ_α
$F_{\mu\nu}$ →	$F_{L\alpha\beta} = \frac{i}{2} F_{\mu\nu}\sigma^{\mu\nu}_{\alpha\beta} \in (1,0)$ $F_{R\dot\alpha\dot\beta} = -\frac{i}{2} F_{\mu\nu}\bar\sigma^{\mu\nu}_{\dot\alpha\dot\beta} \in (0,1)$.	$\lambda_\alpha \lambda_\beta$
$R_{\mu\nu\rho\sigma}$	$\mathcal{C}_{\alpha\beta\gamma\delta} = C_{\mu\nu\rho\sigma}\sigma^{\mu\nu}_{\alpha\beta}\sigma^{\rho\sigma}_{\gamma\delta} \in (2,0)$	$\lambda_\alpha\lambda_\beta\lambda_\gamma\lambda_\delta$
D_μ	$D_{\alpha\dot\alpha} = D_\mu \sigma^\mu_{\alpha\dot\alpha} \in (1/2, 1/2)$.	$\lambda_\alpha \tilde\lambda_{\dot\alpha}$

Operator with explicit spinor indices

$$W_{\mu\lambda}\left(e_{cp}\sigma^{\nu\lambda}D^\mu L_r\right) D_\nu H^\dagger \quad \longrightarrow \quad F_1^{\alpha\beta}\psi_2^\gamma (D\psi_3)_{\alpha\beta\dot\alpha} (D\phi_4)_\gamma{}^{\dot\alpha}$$

$$\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_2\alpha_4}\epsilon^{\dot\alpha_3\dot\alpha_4} F_1^{\alpha_1^2}\psi_2^{\alpha_2}(D\psi_3)^{\alpha_3^2}_{\dot\alpha_3}(D\phi_4)^{\alpha_4}_{\dot\alpha_4}$$

Easier to find more symmetries of the operator with spinor indices

Operator as Spinor Tensor

Modern view: operator as Young tensor and on-shell amplitude, with spin-statistics

Operator

$$W_{\mu\lambda}\left(e_{cp}\sigma^{\nu\lambda}D^{\mu}L_r\right)D_\nu H^\dagger$$

Spinor Tensor → **Symmetrize indices**

$$\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_2\alpha_4}\epsilon^{\dot\alpha_3\dot\alpha_4}F_1^{\alpha_1^2}\psi_2^{\alpha_2}\left(D\psi_3\right)^{\alpha_3^2}_{\dot\alpha_3}\left(D\phi_4\right)^{\alpha_4}_{\dot\alpha_4}$$

$$(D\psi)_{\alpha\beta\dot\alpha} = -\frac{1}{2}\epsilon_{\alpha\beta}(\not{D}\psi)_{\dot\alpha} + \frac{1}{2}(D\psi)_{(\alpha\beta)\dot\alpha}$$

$$\left(\frac{1}{2},\frac{1}{2}\right)\otimes\left(\frac{1}{2},0\right) = \left(0,\frac{1}{2}\right)\oplus\left(1,\frac{1}{2}\right)$$

$$(D^2\phi)_{\alpha\beta\dot\alpha\dot\beta} = \frac{1}{2}\epsilon_{\alpha\beta}\epsilon_{\dot\alpha\dot\beta}D^\mu D_\mu\phi - \frac{i}{4}\epsilon_{\dot\alpha\dot\beta}\sigma^{\mu\nu}_{\alpha\beta}[D_\mu, D_\nu]\phi - \frac{i}{4}\epsilon_{\alpha\beta}\bar\sigma^{\mu\nu}_{\dot\alpha\dot\beta}[D_\mu, D_\nu]\phi + \frac{1}{4}(D^2\phi)_{(\alpha\beta)(\dot\alpha\dot\beta)}$$

$\left(\frac{1}{2},\frac{1}{2}\right)\times\left(\frac{1}{2},\frac{1}{2}\right)$ **(0,0)** **(1,0)** **(0,1)** **(1,1)**

Operator as Spinor Tensor

Modern view: operator as Young tensor and on-shell amplitude, with spin-statistics

Operator

$$W_{\mu\lambda}\left(e_{cp}\sigma^{\nu\lambda}D^{\mu}L_r\right)D_{\nu}H^{\dagger}$$

Spinor Tensor → **Symmetrize indices**

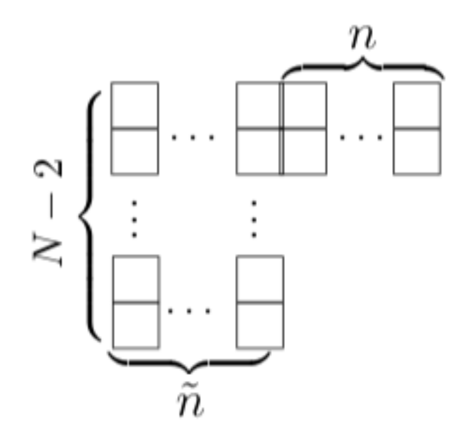
$$\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_2\alpha_4}\epsilon^{\dot\alpha_3\dot\alpha_4}F_1^{\alpha_1^2}\psi_2^{\alpha_2}\left(D\psi_3\right)^{\alpha_3^2}_{\dot\alpha_3}\left(D\phi_4\right)^{\alpha_4}_{\dot\alpha_4}$$

$$(D\psi)_{\alpha\beta\dot\alpha} = -\frac{1}{2}\epsilon_{\alpha\beta}(\not{D}\psi)_{\dot\alpha} + \frac{1}{2}(D\psi)_{(\alpha\beta)\dot\alpha}$$

SL(2,C) x SU(N)

$$\epsilon^{\alpha_i\alpha_j} \to \sum_{k,l}\mathcal{U}^i_k\mathcal{U}^j_l\epsilon^{\alpha_k\alpha_l}, \quad \tilde\epsilon_{\dot\alpha_i\dot\alpha_j} \to \sum_{k,l}\mathcal{U}^{\dagger k}_{\ i}\mathcal{U}^{\dagger l}_{\ j}\tilde\epsilon_{\dot\alpha_k\dot\alpha_l}.$$

$$\mathcal{O} = (\epsilon^{\alpha_i\alpha_j})^n(\tilde\epsilon_{\dot\alpha_i\dot\alpha_j})^{\tilde n}\prod_{i=1}^{N}(D^{r_i-|h_i|}\Phi_i)^{\dot\alpha_i^{r_i+h_i}}_{\alpha_i^{r_i-h_i}}$$



Operator as Spinor Tensor

Modern view: operator as Young tensor and on-shell amplitude, with spin-statistics

Operator

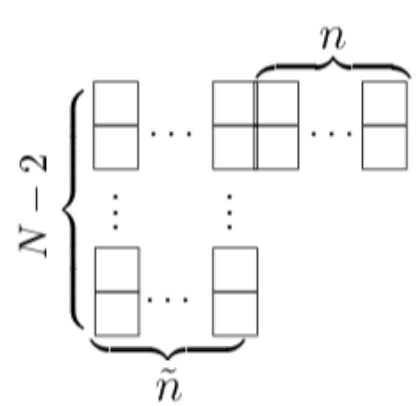
$$W_{\mu\lambda}\left(e_{cp}\sigma^{\nu\lambda}D^{\mu}L_r\right)D_{\nu}H^{\dagger}$$

Spinor Tensor → **Symmetrize indices**

$$\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_2\alpha_4}\epsilon^{\dot\alpha_3\dot\alpha_4}F_1^{\alpha_1^2}\psi_2^{\alpha_2}\left(D\psi_3\right)^{\alpha_3^2}_{\dot\alpha_3}\left(D\phi_4\right)^{\alpha_4}_{\dot\alpha_4}$$

$$(D\psi)_{\alpha\beta\dot\alpha} = -\frac{1}{2}\epsilon_{\alpha\beta}(\not{D}\psi)_{\dot\alpha} + \frac{1}{2}(D\psi)_{(\alpha\beta)\dot\alpha}$$

SL(2,C) x SU(N)



$$\{\overbrace{1,\dots,1}^{\#1},\overbrace{2,\dots,2}^{\#2},\dots,\overbrace{N,\dots,N}^{\#N}\}$$

$$\#i = \tilde{n} - 2h_i$$

SSYT = Amplitude

1	1	1	2
2	3	3	4

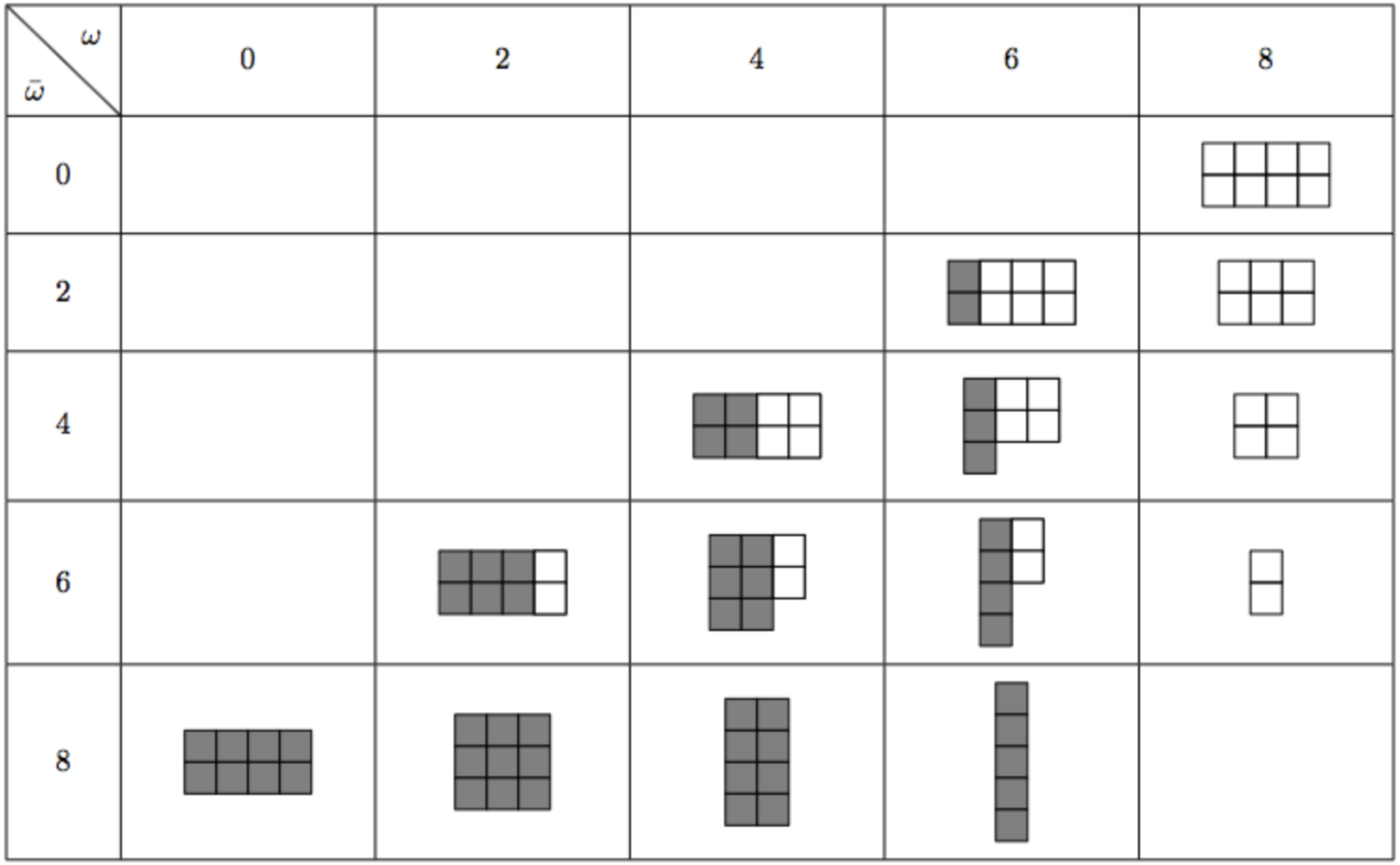
$\langle 13\rangle\langle 13\rangle\langle 24\rangle[34]$

1	1	1	3
2	2	3	4

$\langle 12\rangle\langle 13\rangle\langle 34\rangle[34]$

Operator as Spinor Tensor

Dim-8 operators: 993 (44807) operators for 1 (3) generations



Unified construction of Lorentz & gauge structures by Young Tableau

$$\left(\begin{array}{|c|c|c|c|}\hline 1&1&1&2\\\hline 2&3&3&4\\\hline\end{array} + \begin{array}{|c|c|c|c|}\hline 1&1&1&3\\\hline 2&2&3&4\\\hline\end{array} \right)\times \begin{array}{|c|c|}\hline i&j\\\hline k&l\\\hline\end{array} = \boxed{(\tau^I)^i_j W^I_{\mu\nu}\left(e_{\mathbb{C}p} D^\mu L_{ri}\right) D^\nu H^{\dagger j}} + \boxed{(\tau^I)^i_j W^I_{\mu\lambda}\left(e_{\mathbb{C}p}\sigma^{\nu\lambda}L_{ri}\right) D^\mu D_\nu H^{\dagger j}}$$

Operator as Spinor Tensor

Young tensor method (No need EOM&IBP)

$\boxed{BWHH^\dagger D^2}$ $\#1=3, \#2=3, \#3=1, \#4=1$

1	1	1	3
2	2	2	4

1	1	1	2
2	2	3	4

2

$$\tilde{\epsilon}_{\dot\alpha_3\dot\alpha_4}\epsilon^{\alpha_1\alpha_2}\epsilon^{\alpha_1\alpha_2}\epsilon^{\alpha_3\alpha_4} \qquad \tilde{\epsilon}_{\dot\alpha_3\dot\alpha_4}\epsilon^{\alpha_1\alpha_2}\epsilon^{\alpha_1\alpha_3}\epsilon^{\alpha_2\alpha_4}$$

$$B_L{}^{\alpha\beta}W_{L\alpha\beta}\,(DH^\dagger)^\gamma{}_{\dot\alpha}\,(DH)_\gamma{}^{\dot\alpha}, \qquad B_L{}^{\alpha\beta}W_{L\alpha}{}^\gamma\,(DH^\dagger)_{\beta\dot\alpha}\,(DH)_\gamma{}^{\dot\alpha}$$

$$\langle 13\rangle\langle 13\rangle\langle 24\rangle[34] \qquad \langle 12\rangle\langle 13\rangle\langle 34\rangle[34]$$

All Things EFT…seminar series

EFT Operator Bases for Standard Model and Beyond

报告时间：2021-06-09

报告人：于江浩

https://www.koushare.com/video/videodetail/12645

Traditional method

$\boxed{BWHH^\dagger D^2}$

[Hays, Martin, Sanz, Setford, 2018]

$$(D^2H^\dagger)HB_{L\mu\nu}W_L^{\mu\nu},\ (D^\mu D_\nu H^\dagger)HB_{L\mu\rho}W_L^{\nu\rho},\ (D_\nu D^\mu H^\dagger)HB_{L\mu\rho}W_L^{\nu\rho},\ (D_\mu H^\dagger)(D^\mu H)B_{L\nu\rho}W_L^{\nu\rho},$$
$$(D_\mu H^\dagger)(D^\nu H)B_{L\nu\rho}W_L^{\mu\rho},\ (D^\nu H^\dagger)(D_\mu H)B_{L\nu\rho}W_L^{\mu\rho},\ (D_\mu H^\dagger)H(D^\mu B_{L\nu\rho})W_L^{\nu\rho},\ (D_\mu H^\dagger)H(D^\nu B_{L\nu\rho})W_L^{\mu\rho},$$
$$(D^\nu H^\dagger)H(D_\mu B_{L\nu\rho})W_L^{\mu\rho},\ (D_\mu H^\dagger)HB_{L\nu\rho}(D^\mu W_L^{\nu\rho}),\ (D_\mu H^\dagger)HB_{L\nu\rho}(D^\nu W_L^{\mu\rho}),\ (D^\nu H^\dagger)HB_{L\nu\rho}(D_\mu W_L^{\mu\rho}),$$
$$H^\dagger(D^2H)B_{L\mu\nu}W_L^{\mu\nu},\ H^\dagger(D^\mu D_\nu H)B_{L\mu\rho}W_L^{\nu\rho},\ H^\dagger(D_\nu D^\mu H)B_{L\mu\rho}W_L^{\nu\rho},\ H^\dagger(D^\mu H)(D_\mu B_{L\nu\rho})W_L^{\nu\rho},$$
$$H^\dagger(D^\nu H)(D_\mu B_{L\nu\rho})W_L^{\mu\rho},\ H^\dagger(D_\mu H)(D^\nu B_{L\nu\rho})W_L^{\mu\rho},\ H^\dagger(D^\mu H)B_{L\nu\rho}(D_\mu W_L^{\nu\rho}),\ H^\dagger(D^\nu H)B_{L\nu\rho}(D_\mu W_L^{\mu\rho}),$$
$$H^\dagger(D_\mu H)B_{L\nu\rho}(D^\nu W_L^{\mu\rho}),\ H^\dagger H(D^2B_{L\mu\nu})W_L^{\mu\nu},\ H^\dagger H(D^\mu D_\nu B_{L\mu\rho})W_L^{\nu\rho},\ H^\dagger H(D_\nu D^\mu B_{L\mu\rho})W_L^{\nu\rho},$$
$$H^\dagger H(D^\mu B_{L\nu\rho})(D_\mu W_L^{\nu\rho}),\ H^\dagger H(D^\nu B_{L\nu\rho})(D_\mu W_L^{\mu\rho}),\ H^\dagger H(D_\mu B_{L\nu\rho})(D^\nu W_L^{\mu\rho}),\ H^\dagger HB_{L\mu\nu}(D^2W_L^{\mu\nu}),$$
$$H^\dagger HB_{L\mu\rho}(D^\mu D_\nu W_L^{\nu\rho}),\ H^\dagger HB_{L\mu\rho}(D_\nu D^\mu W_L^{\nu\rho}). \tag{14}$$

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EOM

$$(DH^\dagger)_{\alpha\dot\alpha}(DH)_{\beta\dot\beta}B_{L\{\gamma\delta\}}W_{L\{\xi\eta\}}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$(DH^\dagger)_{\alpha\dot\alpha}(DH)_{\beta\dot\beta}B_{L\{\gamma\delta\}}W_{L\{\xi\eta\}}\,\tfrac{1}{2}\epsilon^{\dot\alpha\dot\beta}\epsilon^{\delta\xi}(\epsilon^{\alpha\gamma}\epsilon^{\beta\eta}+\epsilon^{\beta\gamma}\epsilon^{\alpha\eta})$$
$$(DH^\dagger)_{\alpha\dot\alpha}\,H\,(DB_L)_{\{\beta\gamma\delta\},\dot\beta}W_{L\{\xi\eta\}}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$(DH^\dagger)_{\alpha\dot\alpha}\,H\,B_{L\{\xi\eta\}}(DW_L)_{\{\beta\gamma\delta\},\dot\beta}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$H^\dagger\,(DH)_{\alpha\dot\alpha}\,(DB_L)_{\{\beta\gamma\delta\},\dot\beta}W_{L\{\xi\eta\}}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$H^\dagger\,(DH)_{\alpha\dot\alpha}\,B_{L\{\xi\eta\}}(DW_L)_{\{\beta\gamma\delta\},\dot\beta}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$H^\dagger H\,(DB_L)_{\{\alpha\beta\gamma\},\dot\alpha}(DW_L)_{\{\xi\eta\delta\},\dot\beta}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\xi}\epsilon^{\beta\eta}\epsilon^{\gamma\delta}$$

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IBP

$$B_L{}^{\alpha\beta}W_{L\alpha\beta}\,(DH^\dagger)^\gamma{}_{\dot\alpha}\,(DH)_\gamma{}^{\dot\alpha}$$
$$B_L{}^{\alpha\beta}W_{L\alpha}{}^\gamma\,(DH^\dagger)_{\beta\dot\alpha}\,(DH)_\gamma{}^{\dot\alpha}$$

2

Repeated Fields with Flavor

Another difficulty to write down the independent EFT operators

B-violating	
Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

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$$Q_{prst}^{qqq\ell\,(1)} = -(Q_{prst}^{qqq\ell} + Q_{rpst}^{qqq\ell})$$

$$Q_{prst}^{qqq\ell\,(3)} = -(Q_{prst}^{qqq\ell} - Q_{rpst}^{qqq\ell})$$

[Grzadkowski, et.al. v3 2017]

B-violating	
Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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[Alonso, Chang, Jenkins, Manohar, Shotwell 2014]

$$Q_{prst}^{qqq\ell} + Q_{rpst}^{qqq\ell} = Q_{sprt}^{qqq\ell} + Q_{srpt}^{qqq\ell}$$

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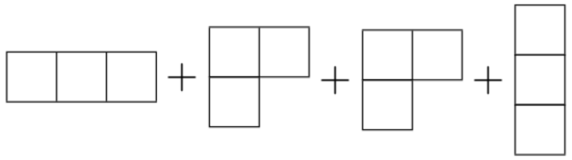
Flavor relations not easy task!

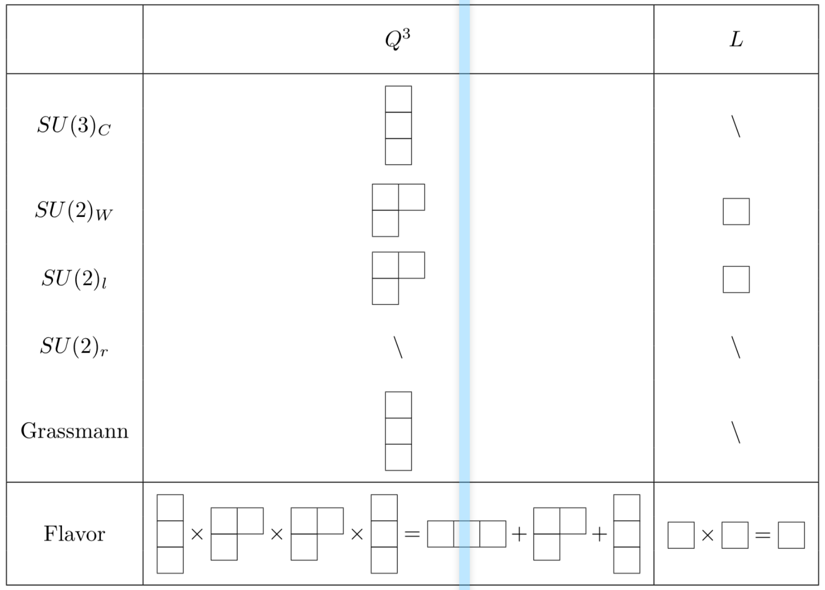
Flavor Symmetry

According to Schur-Weyl theorem, flavor tensor decomposed via S(nf) symmetry

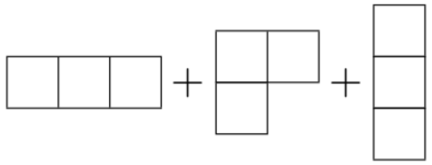
$$O_{qqql}^{p,rst}\epsilon^{abc}\epsilon_{ji}\epsilon_{km}[(q_r^{aj})^T C q_s^{bk}][(q_t^{cm})^T C l_p^i]$$

S_3 :

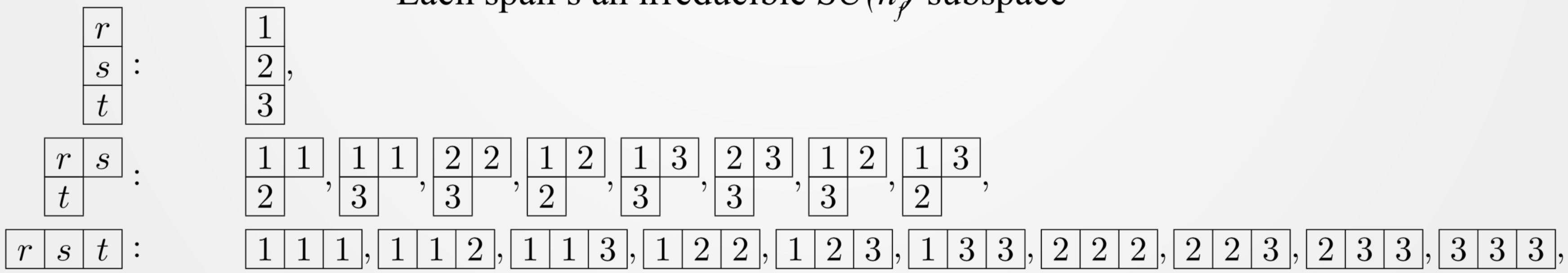




$SU(n_f)$:



Each span's an irreducible $SU(n_f)$ subspace



19 x 3 = 57

Operator: y-basis, f-basis

For QQQL, the Young tableau for Lorentz and gauge structure give the y-basis

$$\left(\begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 & 4 \\ \hline\end{array} + \begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 & 4 \\ \hline\end{array}\right) \times \begin{array}{|c|}\hline a \\ \hline b \\ \hline c \\ \hline\end{array} \times \left(\begin{array}{|c|c|}\hline i & j \\ \hline k & l \\ \hline\end{array} + \begin{array}{|c|c|}\hline i & k \\ \hline j & l \\ \hline\end{array}\right) =$$

$$\mathcal{M} = (L_{pi}Q_{raj})(Q_{sbk}Q_{tcl}),$$
$$(L_{pi}Q_{sbk})(Q_{raj}Q_{tcl})$$

$$T_G = \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}, \ \epsilon^{abc}\epsilon^{ij}\epsilon^{kl}$$

$$O_1 = \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}(L_{pi}Q_{raj})(Q_{sbk}Q_{tcl})$$
$$O_2 = \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}(L_{pi}Q_{sbk})(Q_{raj}Q_{tcl})$$
$$O_3 = \epsilon^{abc}\epsilon^{ij}\epsilon^{kl}(L_{pi}Q_{sbk})(Q_{raj}Q_{tcl})$$
$$O_4 = \epsilon^{abc}\epsilon^{ij}\epsilon^{kl}(L_{pi}Q_{raj})(Q_{sbk}Q_{tcl})$$

Y-Basis = Young tensor basis

EFT operator should be viewed as flavor tensor in the SU(nf) group

Sn symmetry for repeated field

p-basis $\qquad \mathcal{K}^{py}_{ji} \qquad$ y-basis

$$\begin{pmatrix} O^{\square\square\square\square,1} \\ O^{\square\square\square/\square,1} \\ O^{\square\square/\square\square,2} \\ O^{\square\square/\square/\square,1} \end{pmatrix} = \begin{pmatrix} -1 & 2 & 2 & -1 \\ 2 & -1 & -1 & 2 \\ -1 & -1 & 2 & -1 \\ -1 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} O_1 \\ O_2 \\ O_3 \\ O_4 \end{pmatrix}$$

not SU(nf) symmetry for nf flavor

$O^{\square\square/\square\square,1}$ $O^{\square\square/\square\square,2}$ span the same $SU(n_f)$ space.

$$\mathcal{O}^{(p')}_{LQ^3,1} \quad \mathcal{Y}\left[\begin{array}{|c|c|c|}\hline r & s & t \\ \hline\end{array}\right] \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}\,(L_{pi}Q_{raj})\,(Q_{sbk}Q_{tcl})$$
$$\mathcal{O}^{(p')}_{LQ^3,2} \quad \mathcal{Y}\left[\begin{array}{|c|c|}\hline r & s \\ \hline t \\ \cline{1-1}\end{array}\right] \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}\,(L_{pi}Q_{raj})\,(Q_{sbk}Q_{tcl})$$
$$\mathcal{O}^{(p')}_{LQ^3,3} \quad \mathcal{Y}\left[\begin{array}{|c|}\hline r \\ \hline s \\ \hline t \\ \hline\end{array}\right] \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}\,(L_{pi}Q_{raj})\,(Q_{sbk}Q_{tcl})$$

Final expression: f-basis!!!

SMEFT Operators

Dimension-5

$$\epsilon_{ij}\epsilon_{mn}(L^iCL^m)H^jH^n$$

[Weinberg, 1979]

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Dimension-6

Φ^6 and Φ^4D^2	$\psi^2\Phi^3$	X^3
$O_\Phi = (\Phi^\dagger\Phi)^3$	$O_{l\Phi} = (\Phi^\dagger\Phi)(\bar{L}_i l_j\Phi)$	$O_G = -f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$O_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$O_{u\Phi} = (\Phi^\dagger\Phi)(\bar{Q}_i u_j\Phi^c)$	$O_{\widetilde{G}} = -f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$O_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$O_{d\Phi} = (\Phi^\dagger\Phi)(\bar{Q}_i d_j\Phi)$	$O_W = -\epsilon^{abc}W_\mu^{a\nu}W_\nu^{b\rho}W_\rho^{c\mu}$
		$O_{\widetilde{W}} = -\epsilon^{abc}\widetilde{W}_\mu^{a\nu}W_\nu^{b\rho}W_\rho^{c\mu}$

$X^2\Phi^2$	ψ^2X
$O_{\Phi G} = (\Phi^\dagger\Phi)G^A_{\mu\nu}G^{A\mu\nu}$	O_{uG}
$O_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi)\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	O_{dG}
$O_{\Phi W} = (\Phi^\dagger\Phi)W^a_{\mu\nu}W^{a\mu\nu}$	O_{lW}
$O_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}^a_{\mu\nu}W^{a\mu\nu}$	O_{uW}
$O_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	O_{dW}
$O_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu}$	O_{lB}
$O_{\Phi WB} = -(\Phi^\dagger\tau^a\Phi)W^a_{\mu\nu}B^{\mu\nu}$	O_{uB}
$O_{\Phi\widetilde{W}B} = -(\Phi^\dagger\tau^a\Phi)\widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	O_{dB}

$(\bar{L}L)(\bar{L}L)$	$(\bar{R}R)(\bar{R}R)$	$(\bar{L}L)(\bar{R}R)$
$O_{LL} = (\bar{L}_i\gamma_\mu L_j)(\bar{L}_k\gamma^\mu L_l)$	$O_{ll} = (\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	$O_{Ll} = (\bar{L}_i\gamma_\mu L_j)(\bar{l}_k\gamma^\mu l_l)$
$O^{(1)}_{QQ} = (\bar{Q}_i\gamma_\mu Q_j)(\bar{Q}_k\gamma^\mu Q_l)$	$O_{uu} = (\bar{u}_i\gamma_\mu u_j)(\bar{u}_k\gamma^\mu u_l)$	$O_{Lu} = (\bar{L}_i\gamma_\mu L_j)(\bar{u}_k\gamma^\mu u_l)$
$O^{(3)}_{QQ} = (\bar{Q}_i\gamma_\mu\tau^a Q_j)(\bar{Q}_k\gamma^\mu\tau^a Q_l)$	$O_{dd} = (\bar{d}_i\gamma_\mu d_j)(\bar{d}_k\gamma^\mu d_l)$	$O_{Ld} = (\bar{L}_i\gamma_\mu L_j)(\bar{d}_k\gamma^\mu d_l)$
$O^{(1)}_{LQ} = (\bar{L}_i\gamma_\mu L_j)(\bar{Q}_k\gamma^\mu Q_l)$	$O_{lu} = (\bar{l}_i\gamma_\mu l_j)(\bar{u}_k\gamma^\mu u_l)$	$O_{Ql} = (\bar{Q}_i\gamma_\mu Q_j)(\bar{l}_k\gamma^\mu l_l)$
$O^{(3)}_{LQ} = (\bar{L}_i\gamma_\mu\tau^a L_j)(\bar{Q}_k\gamma^\mu\tau^a Q_l)$	$O_{ld} = (\bar{l}_i\gamma_\mu l_j)(\bar{d}_k\gamma^\mu d_l)$	$O^{(1)}_{Qu} = (\bar{Q}_i\gamma_\mu Q_j)(\bar{u}_k\gamma^\mu u_l)$
	$O^{(1)}_{ud} = (\bar{u}_i\gamma_\mu u_j)(\bar{d}_k\gamma^\mu d_l)$	$O^{(8)}_{Qu} = \left(\bar{Q}_i\gamma_\mu\frac{\lambda^A}{2}Q_j\right)\left(\bar{u}_k\gamma^\mu\frac{\lambda^A}{2}u_l\right)$
	$O^{(8)}_{ud} = \left(\bar{u}_i\gamma_\mu\frac{\lambda^A}{2}u_j\right)\left(\bar{d}_k\gamma^\mu\frac{\lambda^A}{2}d_l\right)$	$O^{(1)}_{Qd} = (\bar{Q}_i\gamma_\mu Q_j)(\bar{d}_k\gamma^\mu d_l)$
		$O^{(8)}_{Qd} = \left(\bar{Q}_i\gamma_\mu\frac{\lambda^A}{2}Q_j\right)\left(\bar{d}_k\gamma^\mu\frac{\lambda^A}{2}d_l\right)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	B-violating
$O_{LldQ} = (\bar{L}^\sigma_i l_j)(\bar{d}_k Q^\sigma_l)$	$O_{duQ} = \epsilon^{\alpha\beta\gamma}\epsilon_{\sigma\tau}\left[(d^\alpha_i)^TCu^\beta_j\right]\left[(Q^{\gamma\sigma}_k)^TCL^\tau_l\right]$
$O^{(1)}_{QuQd} = (\bar{Q}^\sigma_i u_j)\epsilon_{\sigma\tau}(\bar{Q}^\tau_k d_l)$	$O_{QQu} = \epsilon^{\alpha\beta\gamma}\epsilon_{\sigma\tau}\left[(Q^{\alpha\sigma}_i)^TCQ^{\beta\tau}_j\right]\left[(u^\gamma_k)^TCl_l\right]$
$O^{(8)}_{QuQd} = \left(\bar{Q}^\sigma_i\frac{\lambda^A}{2}u_j\right)\epsilon_{\sigma\tau}\left(\bar{Q}^\tau_k\frac{\lambda^A}{2}d_l\right)$	$O_{QQQ} = \epsilon^{\alpha\beta\gamma}\epsilon_{\sigma\tau}\epsilon_{\sigma'\tau'}\left[(Q^{\alpha\sigma}_i)^TCQ^{\beta\tau}_j\right]\left[(Q^{\gamma\sigma'}_k)^TCL^{\tau'}_l\right]$
$O^{(1)}_{LlQu} = (\bar{L}^\sigma_i l_j)\epsilon_{\sigma\tau}(\bar{Q}^\tau_k u_l)$	$O_{duu} = \epsilon^{\alpha\beta\gamma}\left[(d^\alpha_i)^TCu^\beta_j\right]\left[(u^\gamma_k)^TCl_l\right]$
$O^{(3)}_{LlQu} = (\bar{L}^\sigma_i\sigma_{\mu\nu}l_j)\epsilon_{\sigma\tau}(\bar{Q}^\tau_k\sigma^{\mu\nu}u_l)$	

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[Buchmuller, Wyler, 1986] [Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

Dimension-7

$1: \psi^2XH^2 + \text{h.c.}$

$Q_{l^2WH^2}$	$\epsilon_{mn}(\tau^I\epsilon)_{jk}(l^m_pCi\sigma^{\mu\nu}l^j_r)H^nH^kW^I_{\mu\nu}$
$Q_{l^2BH^2}$	$\epsilon_{mn}\epsilon_{jk}(l^m_pCi\sigma^{\mu\nu}l^j_r)H^nH^kB_{\mu\nu}$

$2: \psi^2H^4 + \text{h.c.}$

$Q_{l^2H^4}$	$\epsilon_{mn}\epsilon_{jk}(l^m_pCl^j_r)H^nH^k(H^\dagger H)$

$3(B): \psi^4H + \text{h.c.}$

Q_{l^3eH}	$\epsilon_{jk}\epsilon_{mn}(\bar{e}_pl^j_r)(l^k_sCl^m_t)H^n$
Q_{leudH}	$\epsilon_{jk}(\bar{d}_pl^j_r)(u_sCe_t)H^k$
$Q^{(1)}_{l^2qdH}$	$\epsilon_{jk}\epsilon_{mn}(\bar{d}_pl^j_r)(q^k_sCl^m_t)H^n$
$Q^{(2)}_{l^2qdH}$	$\epsilon_{jm}\epsilon_{kn}(\bar{d}_pl^j_r)(q^k_sCl^m_t)H^n$
Q_{l^2quH}	$\epsilon_{jk}(\bar{q}^m_pu_r)(l_{sm}Cl^j_t)H^k$

$3(\not{B}): \psi^4H + \text{h.c.}$

Q_{lud^2H}	$\epsilon_{\alpha\beta\gamma}(\bar{l}_pd^\alpha_r)(u^\beta_sCd^\gamma_t)\widetilde{H}$
Q_{lq^2dH}	$\epsilon_{\alpha\beta\gamma}\epsilon_{jk}(\bar{l}^m_pd^\alpha_r)(q^\beta_{sm}Cq^{j\gamma}_t)\widetilde{H}^k$
Q_{ld^3H}	$\epsilon_{\alpha\beta\gamma}(\bar{l}_pd^\alpha_r)(d^\beta_sCd^\gamma_t)H$
Q_{eqd^2H}	$\epsilon_{\alpha\beta\gamma}\epsilon_{jk}(\bar{e}_pq^{j\alpha}_r)(d^\beta_sCd^\gamma_t)\widetilde{H}^k$

$4: \psi^2H^3D + \text{h.c.}$

Q_{leH^3D}	$\epsilon_{mn}\epsilon_{jk}(l^m_pC\gamma^\mu e_r)H^nH^jiD_\mu H^k$

$5(B): \psi^4D + \text{h.c.}$

Q_{l^2udD}	$\epsilon_{jk}(\bar{d}_p\gamma^\mu u_r)(l^j_sCiD_\mu l^k_t)$

$6: \psi^2H^2D^2 + \text{h.c.}$

$Q^{(1)}_{l^2H^2D^2}$	$\epsilon_{jk}\epsilon_{mn}(l^j_pCD^\mu l^k_r)H^m(D_\mu H^n)$
$Q^{(2)}_{l^2H^2D^2}$	$\epsilon_{jm}\epsilon_{kn}(l^j_pCD^\mu l^k_r)H^m(D_\mu H^n)$

$5(\not{B}): \psi^4D + \text{h.c.}$

Q_{lqd^2D}	$\epsilon_{\alpha\beta\gamma}(\bar{l}_p\gamma^\mu q^\alpha_r)(d^\beta_sCiD_\mu d^\gamma_t)$
Q_{ed^3D}	$\epsilon_{\alpha\beta\gamma}(\bar{e}_p\gamma^\mu d^\alpha_r)(d^\beta_sCiD_\mu d^\gamma_t)$

[Lehman, 2014]
[Henning, Lu, Melia, Murayama, 2015]
[Liao, Ma, 2016]

Dimension-8

[Li, Ren, Shu, Xiao, **Yu**, Zheng, **2020**]

[Murphy, 2020]

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N	$(n,\tilde{n})$	Subclasses	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$	$\mathcal{N}_{\text{operator}}$	Equations
4	(4, 0)	$F_L^4 + h.c.$	14	26	26	(4.19)
	(3, 1)	$F_L^2\psi\psi^\dagger D + h.c.$	22	22	$22n_f^2$	(4.51)
		$\psi^4D^2 + h.c.$	$4+\underline{4}$	$18+\underline{14}$	$12n_f^4+\underline{n_f^3(5n_f-1)}$	(4.75, 4.78, 4.80)
		$F_L\psi^2\phi D^2 + h.c.$	16	32	$32n_f^2$	(4.44)
		$F_L^2\phi^2D^2 + h.c.$	8	12	12	(4.14)
	(2, 2)	$F_L^2F_R^2$	14	17	17	(4.19)
		$F_LF_R\psi\psi^\dagger D$	27	35	$35n_f^2$	(4.50, 4.51)
		$\psi^2\psi^{\dagger2}D^2$	$17+\underline{4}$	$54+\underline{8}$	$\frac{1}{2}n_f^2(75n_f^2+11)+\underline{6n_f^4}$	(4.74, 4.79-4.81)
		$F_R\psi^2\phi D^2 + h.c.$	16	16	$16n_f^2$	(4.44)
		$F_LF_R\phi^2D^2$	5	6	6	(4.14)
		$\psi\psi^\dagger\phi^2D^3$	7	16	$16n_f^2$	(4.31, 4.32)
		ϕ^4D^4	1	3	3	(4.8)
5	(3, 0)	$F_L\psi^4 + h.c.$	$12+\underline{10}$	$66+\underline{54}$	$42n_f^4+\underline{2n_f^3(9n_f+1)}$	(4.86, 4.88, 4.89, 4.91)
		$F_L^2\psi^2\phi + h.c.$	32	60	$60n_f^2$	(4.47, 4.48)
		$F_L^3\phi^2 + h.c.$	6	6	6	(4.16)
	(2, 1)	$F_L\psi^2\psi^{\dagger2} + h.c.$	$84+\underline{24}$	$172+\underline{32}$	$2n_f^2(59n_f^2-2)+\underline{24n_f^4}$	(4.84-4.85), (4.88-4.92)
		$F_R^2\psi^2\phi + h.c.$	32	36	$36n_f^2$	(4.47, 4.48)
		$\psi^3\psi^\dagger\phi D + h.c.$	$32+\underline{14}$	$180+\underline{56}$	$n_f^3(135n_f-1)+\underline{n_f^3(29n_f+3)}$	(4.66, 4.69-4.72)
		$F_L\psi\psi^\dagger\phi^2D + h.c.$	38	92	$92n_f^2$	(4.39, 4.40)
		$\psi^2\phi^3D^2 + h.c.$	6	36	$36n_f^2$	(4.28)
		$F_L\phi^4D^2 + h.c.$	4	6	6	(4.10)
6	(2, 0)	$\psi^4\phi^2 + h.c.$	$12+\underline{4}$	$48+\underline{18}$	$5(5n_f^4+n_f^2)+\underline{\frac{2}{3}(8n_f^4+n_f^2)}$	(4.55, 4.59, 4.62, 4.64)
		$F_L\psi^2\phi^3 + h.c.$	16	22	$22n_f^2$	(4.36)
		$F_L^2\phi^4 + h.c.$	8	10	10	(4.12)
	(1, 1)	$\psi^2\psi^{\dagger2}\phi^2$	$23+\underline{10}$	$57+\underline{14}$	$n_f^2(42n_f^2+n_f+2)+\underline{3n_f^3(3n_f-1)}$	(4.54, 4.55, 4.59-4.63)
		$\psi\psi^\dagger\phi^4D$	7	13	$13n_f^2$	(4.24, 4.25)
		ϕ^6D^2	1	2	2	(4.8)
7	(1, 0)	$\psi^2\phi^5 + h.c.$	6	6	$6n_f^2$	(4.21)
8	(0, 0)	ϕ^8	1	1	1	(4.8)
Total		48	$471+\underline{70}$	$1070+\underline{196}$	$993(n_f=1)$, $44807(n_f=3)$	

Dimension-9

[Li, Ren, Xiao, **Yu**, Zheng, **2020**]

[Liao, Ma, 2020]

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$	$\mathcal{N}_{\text{operator}}$	Equations
4	(3, 2)	$\psi^3\psi^\dagger D^3 + h.c.$	$0+4+2+0$	10	$\frac{2}{3}n_f^2(7n_f^2-1)$	(5.50)(5.51)
		$\psi^2\phi^2D^4 + h.c.$	$0+0+2+0$	6	$3n_f(n_f+1)$	(5.21)
5	(3, 1)	$F_L\psi^3\psi^\dagger D + h.c.$	$0+10+6+0$	72	$32n_f^4$	(5.59)(5.60)
		$\psi^4\phi D^2 + h.c.$	$0+4+4+0$	100	$40n_f^4$	(5.45-5.48)
		$F_L\psi^2\phi^2D^2 + h.c.$	$0+0+4+0$	34	$17n_f^2-n_f$	(5.28)(5.29)
	(2, 2)	$F_R\psi^3\psi^\dagger D + h.c.$	$0+10+6+0$	54	$4n_f^3(6n_f+1)$	(5.59)(5.60)
		$\psi^2\psi^{\dagger2}\phi D^2$	$0+4+4+0$	84	$n_f^3(49n_f+1)$	(5.45-5.48)
		$F_R\psi^2\phi^2D^2 + h.c.$	$0+0+4+0$	20	$2n_f(5n_f-1)$	(5.28)(5.29)
		$\psi\psi^\dagger\phi^3D^3$	$0+0+2+0$	6	$6n_f^2$	(5.19)
6	(3, 0)	$\psi^6 + h.c.$	$2+4+6+0$	116	$\frac{1}{24}n_f^2(415n_f^4+53n_f^3+59n_f^2+139n_f+6)$	(5.63-5.70)
		$F_L\psi^4\phi + h.c.$	$0+12+10+0$	102	$2n_f^3(21n_f+1)$	(5.54-5.56)
		$F_L^2\psi^2\phi^2 + h.c.$	$0+0+8+0$	20	$2n_f(5n_f+2)$	(5.32)
	(2, 1)	$\psi^4\psi^{\dagger2} + h.c.$	$4+26+20+4$	244	$\frac{1}{6}n_f^3(382n_f^3-9n_f^2+2n_f+21)$	(5.63-5.69)
		$F_L\psi^2\psi^{\dagger2}\phi + h.c.$	$0+24+24+0$	92	$52n_f^4$	(5.54-5.56)
		$F_L^2\psi^{\dagger2}\phi^2 + h.c.$	$0+0+8+0$	12	$2n_f(3n_f+2)$	(5.32)
		$\psi^3\psi^\dagger\phi^2D + h.c.$	$0+12+18+0$	186	$\frac{2}{3}n_f^2(146n_f^2+1)$	(5.39-5.42)
		$F_L\psi\psi^\dagger\phi^3D + h.c.$	$0+0+8+0$	12	$12n_f^2$	(5.25)
		$\psi^2\phi^4D^2 + h.c.$	$0+0+4+0$	24	$2n_f(6n_f+1)$	(5.17)
7	(2, 0)	$\psi^4\phi^3 + h.c.$	$0+6+6+0$	32	$\frac{4}{3}n_f^2(10n_f^2-1)$	(5.35-5.37)
		$F_L\psi^2\phi^4 + h.c.$	$0+0+4+0$	8	$2n_f(2n_f-1)$	(5.23)
	(1, 1)	$\psi^2\psi^{\dagger2}\phi^3$	$0+6+10+0$	24	$14n_f^4$	(5.35-5.37)
		$\psi\psi^\dagger\phi^5D$	$0+0+2+0$	2	$2n_f^2$	(5.12)
8	(1, 0)	$\psi^2\phi^6 + h.c.$	$0+0+2+0$	2	$n_f^2+n_f$	(5.9)
Total		42	6+122+164+4	1262	$8+204+348+0$ $(n_f=1)$ $2862+42234+44874+486$ $(n_f=3)$	

LEFT Operators

Dimension-5

Dim-5 operators

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$
3	$(2,0)$	$F_{\rm L}\psi_{\rm L}{}^2 + h.c.$	$10+0+2+0$

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Dimension-6

Dim-6 operators

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
3	$(3,0)$	$F_{\rm L}^3 + h.c.$	$2+0+0+0$	2
4	$(2,0)$	$\psi_{\rm L}^4 + h.c.$	$14+12+8+2$	78
	$(1,1)$	$\psi_{\rm L}^2\psi_{\rm R}^2$	$40+20+12+0$	84
Total		5	$56+32+20+2$	164

[Jenkins, Manohar, Stoffer, 2017]

120

Dimension-7

Dim-7 operators

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	$(3,0)$	$F_{\rm L}^2\psi_{\rm L}^2 + h.c.$	$16+0+4+0$	32
	$(2,1)$	$F_{\rm L}^2\psi_{\rm R}^2 + h.c.$	$16+0+4+0$	24
		$\psi_{\rm L}^3\psi_{\rm R}D + h.c.$	$50+32+22+$	
Total		6	$82+32+30+$	

166

[Liao, Ma, Wang, 2020]

Dimension-8

[Li, Ren, Xiao, **Yu**, Zheng, 2020]

[Murphy, 2020]

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N	$(n,\tilde{n})$	Subclasses	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$	$\mathcal{N}_{\text{operator}}$	Equations
4	$(4,0)$	$F_{\rm L}^4 + h.c.$	14	26	26	(4.19)
	$(3,1)$	$F_{\rm L}^2\psi\psi^\dagger D + h.c.$	22	22	$22n_f^2$	(4.51)
		$\psi^4 D^2 + h.c.$	$4\underline{+4}$	$18\underline{+14}$	$12n_f^4\underline{+n_f^3(5n_f-1)}$	(4.75, 4.78, 4.80)
		$F_{\rm L}\psi^2\phi D^2 + h.c.$	16	32	$32n_f^2$	(4.44)
		$F_{\rm L}^2\phi^2 D^2 + h.c.$	8	12	12	(4.14)
	$(2,2)$	$F_{\rm L}^2 F_{\rm R}^2$	14	17	17	(4.19)
		$F_{\rm L}F_{\rm R}\psi\psi^\dagger D$	27	35	$35n_f^2$	(4.50, 4.51)
		$\psi^2\psi^{\dagger 2}D^2$	$17\underline{+4}$	$54\underline{+8}$	$\frac{1}{2}n_f^2(75n_f^2+11)\underline{+6n_f^4}$	(4.74, 4.79-4.81)
		$F_{\rm R}\psi^2\phi D^2 + h.c.$	16	16	$16n_f^2$	(4.44)
		$F_{\rm L}F_{\rm R}\phi^2 D^2$	5	6	6	(4.14)
		$\psi\psi^\dagger\phi^2 D^3$	7	16	$16n_f^2$	(4.31, 4.32)
		$\phi^4 D^4$	1	3	3	(4.8)
5	$(3,0)$	$F_{\rm L}\psi^4 + h.c.$	$12\underline{+10}$	$66\underline{+54}$	$42n_f^4\underline{+2n_f^3(9n_f+1)}$	(4.86, 4.88, 4.89, 4.91)
		$F_{\rm L}^2\psi^2\phi + h.c.$	32	60	$60n_f^2$	(4.47, 4.48)
		$F_{\rm L}^3\phi^2 + h.c.$	6	6	6	(4.16)
	$(2,1)$	$F_{\rm L}\psi^2\psi^{\dagger 2} + h.c.$	$84\underline{+24}$	$172\underline{+32}$	$2n_f^2(59n_f^2-2)\underline{+24n_f^4}$	(4.84-4.85), (4.88-4.92)
		$F_{\rm R}^2\psi^2\phi + h.c.$	32	36	$36n_f^2$	(4.47, 4.48)
		$\psi^3\psi^\dagger\phi D + h.c.$	$32\underline{+14}$	$180\underline{+56}$	$n_f^3(135n_f-1)\underline{+n_f^3(29n_f+3)}$	(4.66, 4.69-4.72)
		$F_{\rm L}\psi\psi^\dagger\phi^2 D + h.c.$	38	92	$92n_f^2$	(4.39, 4.40)
		$\psi^2\phi^3 D^2 + h.c.$	6	36	$36n_f^2$	(4.28)
		$F_{\rm L}\phi^4 D^2 + h.c.$	4	6	6	(4.10)
6	$(2,0)$	$\psi^4\phi^2 + h.c.$	$12\underline{+4}$	$48\underline{+18}$	$5(5n_f^4+n_f^2)\underline{+\frac{2}{3}(8n_f^4+n_f^2)}$	(4.55, 4.59, 4.62, 4.64)
		$F_{\rm L}\psi^2\phi^3 + h.c.$	16	22	$22n_f^2$	(4.36)
		$F_{\rm L}^2\phi^4 + h.c.$	8	10	10	(4.12)
	$(1,1)$	$\psi^2\psi^{\dagger 2}\phi^2$	$23\underline{+10}$	$57\underline{+14}$	$n_f^2(42n_f^2+n_f+2)\underline{+3n_f^3(3n_f-1)}$	(4.54, 4.55, 4.59-4.63)
		$\psi\psi^\dagger\phi^4 D$	7	13	$13n_f^2$	(4.24, 4.25)
		$\phi^6 D^2$	1	2	2	(4.8)
7	$(1,0)$	$\psi^2\phi^5 + h.c.$	6	6	$6n_f^2$	(4.21)
8	$(0,0)$	ϕ^8	1	1	1	(4.8)
Total		48	$471\underline{+70}$	$1070\underline{+196}$	$993(n_f=1)$, $44807(n_f=3)$	

Dimension-9

[Li, Ren, Xiao, **Yu**, Zheng, 2020]

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N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$	$\mathcal{N}_{\text{operator}}$	Equations
4	$(3,2)$	$\psi^3\psi^\dagger D^3 + h.c.$	$0+4+2+0$	10	$\frac{2}{3}n_f^2(7n_f^2-1)$	(5.50)(5.51)
		$\psi^2\phi^2 D^4 + h.c.$	$0+0+2+0$	6	$3n_f(n_f+1)$	(5.21)
5	$(3,1)$	$F_{\rm L}\psi^3\psi^\dagger D + h.c.$	$0+10+6+0$	72	$32n_f^4$	(5.59)(5.60)
		$\psi^4\phi D^2 + h.c.$	$0+4+4+0$	100	$40n_f^4$	(5.45-5.48)
		$F_{\rm L}\psi^2\phi^2 D^2 + h.c.$	$0+0+4+0$	34	$17n_f^2-n_f$	(5.28)(5.29)
	$(2,2)$	$F_{\rm R}\psi^3\psi^\dagger D + h.c.$	$0+10+6+0$	54	$4n_f^3(6n_f+1)$	(5.59)(5.60)
		$\psi^2\psi^{\dagger 2}\phi D^2$	$0+4+4+0$	84	$n_f^3(49n_f+1)$	(5.45-5.48)
		$F_{\rm R}\psi^2\phi^2 D^2 + h.c.$	$0+0+4+0$	20	$2n_f(5n_f-1)$	(5.28)(5.29)
		$\psi\psi^\dagger\phi^3 D^3$	$0+0+2+0$	6	$6n_f^2$	(5.19)
6	$(3,0)$	$\psi^6 + h.c.$	$2+4+6+0$	116	$\frac{1}{24}n_f^2(415n_f^4+53n_f^3+59n_f^2+139n_f+6)$	(5.63-5.70)
		$F_{\rm L}\psi^4\phi + h.c.$	$0+12+10+0$	102	$2n_f^3(21n_f+1)$	(5.54-5.56)
		$F_{\rm L}^2\psi^2\phi^2 + h.c.$	$0+0+8+0$	20	$2n_f(5n_f+2)$	(5.32)
	$(2,1)$	$\psi^4\psi^{\dagger 2} + h.c.$	$4+26+20+4$	244	$\frac{1}{6}n_f^3(382n_f^3-9n_f^2+2n_f+21)$	(5.63-5.69)
		$F_{\rm L}\psi^2\psi^{\dagger 2}\phi + h.c.$	$0+24+24+0$	92	$52n_f^4$	(5.54-5.56)
		$F_{\rm L}^2\psi^{\dagger 2}\phi^2 + h.c.$	$0+0+8+0$	12	$2n_f(3n_f+2)$	(5.32)
		$\psi^3\psi^\dagger\phi^2 D + h.c.$	$0+12+18+0$	186	$\frac{2}{3}n_f^2(146n_f^2+1)$	(5.39-5.42)
		$F_{\rm L}\psi\psi^\dagger\phi^3 D + h.c.$	$0+0+8+0$	12	$12n_f^2$	(5.25)
		$\psi^2\phi^4 D^2 + h.c.$	$0+0+4+0$	24	$2n_f(6n_f+1)$	(5.17)
7	$(2,0)$	$\psi^4\phi^3 + h.c.$	$0+6+6+0$	32	$\frac{4}{3}n_f^2(10n_f^2-1)$	(5.35-5.37)
		$F_{\rm L}\psi^2\phi^4 + h.c.$	$0+0+4+0$	8	$2n_f(2n_f-1)$	(5.23)
	$(1,1)$	$\psi^2\psi^{\dagger 2}\phi^3$	$0+6+10+0$	24	$14n_f^4$	(5.35-5.37)
		$\psi\psi^\dagger\phi^5 D$	$0+0+2+0$	2	$2n_f^2$	(5.12)
8	$(1,0)$	$\psi^2\phi^6 + h.c.$	$0+0+2+0$	2	$n_f^2+n_f$	(5.9)
Total		42	6+122+164+4	1262	$8+204+348+0\ (n_f=1)$ $2862+42234+44874+486\ (n_f=3)$	

vSMEFT and vLEFT

Dimension-5

Dim-5 operatc

N	$(n, \tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
3	$(2,0)$	$F_L\psi^2 + h.c.$	$0+0+2+0$	2
4	$(1,0)$	$\psi^2\phi^2 + h.c.$	$0+0+2+0$	2
Total		4	$0+0+4+0$	4

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Dimension-6

Dim-6 operatc

N	$(n, \tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	$(2,0)$	$\psi^4 + h.c.$	$4+2+0+2$	14
		$F_L\psi^2\phi + h.c.$	$4+0+0+0$	4
	$(1,1)$	$\psi^2\psi^{\dagger 2}$	$10+2+0+0$	12
		$\psi\psi^\dagger\phi^2 D$	$3+0+0+0$	3
5	$(1,0)$	$\psi^2\phi^3 + h.c.$	$2+0+0+0$	2
Total		8	$23+4+0+2$	35

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[Aguila, Bar-Shalom, Soni, Wudka, 2009]

Dimension-7

Dim-7 operato

N	$(n, \tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	$(3,0)$	$F_L^2\psi^2 + h.c.$	$0+0+6+0$	6
	$(2,1)$	$F_L^2\psi^{\dagger 2} + h.c.$	$0+0+6+0$	6
		$\psi^3\psi^\dagger D + h.c.$	$0+4+20+0$	24
		$F_L\psi\psi^\dagger\phi D + h.c.$	$0+0+8+0$	8
		$\psi^2\phi^2 D^2 + h.c.$	$0+0+4+0$	6
5	$(2,0)$	$\psi^4\phi + h.c.$	$0+2+10+0$	24
		$F_L\psi^2\phi^2 + h.c.$	$0+0+6+0$	6
	$(1,1)$	$\psi^2\psi^{\dagger 2}\phi$	$0+4+22+0$	30
		$\psi\psi^\dagger\phi^3 D$	$0+0+2+0$	4
6	$(1,0)$	$\psi^2\phi^4 + h.c.$	$0+0+2+0$	2
Total		18	$0+10+86+0$	116

[Bhattacharya, Wudka, 2016]

[Liao, Ma, 2017]

Dimension-8

[Li, Ren, Xiao, **Yu**, Zheng, 2021]

N	$(n, \tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	$(3,1)$	$\psi^4 D^2 + h.c.$	$4+0+2+2$	22
		$F_L\psi^2\phi D^2 + h.c.$	$4+0+0+0$	8
	$(2,2)$	$F_L F_R\psi\psi^\dagger D$	$3+0+0+0$	3
		$\psi^2\psi^{\dagger 2} D^2$	$10+2+0+0$	24
		$F_R\psi^2\phi D^2 + h.c.$	$4+0+0+0$	4
		$\psi\psi^\dagger\phi^2 D^3$	$3+0+0+0$	4
5	$(3,0)$	$F_L\psi^4 + h.c.$	$10+4+0+2$	50
		${F_L}^2\psi^2\phi + h.c.$	$8+0+0+0$	12
	$(2,1)$	$F_L\psi^2\psi^{\dagger 2} + h.c.$	$42+12+0+0$	58
		${F_L}^2\psi^{\dagger 2}\phi + h.c.$	$8+0+0+0$	8
		$\psi^3\psi^\dagger\phi D + h.c.$	$24+6+0+2$	108
		$F_L\psi\psi^\dagger\phi^2 D + h.c.$	$12+0+0+0$	16
		$\psi^2\phi^3 D^2 + h.c.$	$2+0+0+0$	12
6	$(2,0)$	$\psi^4\phi^2 + h.c.$	$8+2+0+2$	30
		$F_L\psi^2\phi^3 + h.c.$	$4+0+0+0$	6
	$(1,1)$	$\psi^2\psi^{\dagger 2}\phi^2$	$16+4+0+2$	28
		$\psi\psi^\dagger\phi^4 D$	$3+0+0+0$	3
7	$(1,0)$	$\psi^2\phi^5 + h.c.$	$2+0+0+0$	2
Total		31	$167+30+2+10$	398

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Dimension-9

[Li, Ren, Xiao, **Yu**, Zheng, 2021]

N	$(n, \tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	$(4,1)$	${F_L}^2\psi^2 D^2 + h.c.$	$0+6+0+0$	12
	$(3,2)$	$F_L F_R\psi^2 D^2 + h.c.$	$0+6+0+0$	6
		${F_L}^2\psi^{\dagger 2} D^2 + h.c.$	$0+6+0+0$	6
		$\psi^3\psi^\dagger D^3 + h.c.$	$4+20+0+0$	46
		$F_L\psi\psi^\dagger\phi D^3 + h.c.$	$0+8+0+0$	16
		$\psi^2\phi^2 D^4 + h.c.$	$0+4+0+0$	8
5	$(4,0)$	${F_L}^3\psi^2 + h.c.$	$0+10+0+0$	16
	$(3,1)$	${F_L}^3\psi^{\dagger 2} + h.c.$	$0+4+0+0$	4
		$F_L\psi^3\psi^\dagger D + h.c.$	$10+42+0+0$	222
		${F_L}^2\psi\psi^\dagger\phi D + h.c.$	$0+16+0+0$	32
		$\psi^4\phi D^2 + h.c.$	$2+10+0+0$	120
		$F_L\psi^2\phi^2 D^2 + h.c.$	$0+8+0+0$	42
	$(2,2)$	$F_L {F_R}^2\psi^2 + h.c.$	$0+12+0+0$	12
		$F_R\psi^3\psi^\dagger D + h.c.$	$10+42+0+0$	166
		$F_L F_R\psi\psi^\dagger\phi D$	$0+10+0+0$	24
		$\psi^2\psi^{\dagger 2}\phi D^2$	$4+22+0+0$	210
		$F_R\psi^2\phi^2 D^2 + h.c.$	$0+8+0+0$	24
		$\psi\psi^\dagger\phi^3 D^3$	$0+2+0+0$	20
6	$(3,0)$	$\psi^6 + h.c.$	$6+10+6+2$	130
		$F_L\psi^4\phi + h.c.$	$6+26+0+0$	110
		${F_L}^2\psi^2\phi^2 + h.c.$	$0+12+0+0$	18
	$(2,1)$	$\psi^4\psi^{\dagger 2} + h.c.$	$40+106+14+0$	474
		$F_L\psi^2\psi^{\dagger 2}\phi + h.c.$	$24+116+0+0$	176
		${F_L}^2\psi^{\dagger 2}\phi^2 + h.c.$	$0+10+0+0$	10
		$\psi^3\psi^\dagger\phi^2 D + h.c.$	$10+44+0+0$	268
		$F_L\psi\psi^\dagger\phi^3 D + h.c.$	$0+8+0+0$	32
		$\psi^2\phi^4 D^2 + h.c.$	$0+4+0+0$	20
7	$(2,0)$	$\psi^4\phi^3 + h.c.$	$2+12+0+0$	28
		$F_L\psi^2\phi^4 + h.c.$	$0+6+0+0$	6
	$(1,1)$	$\psi^2\psi^{\dagger 2}\phi^3$	$4+22+0+0$	34
		$\psi\psi^\dagger\phi^5 D$	$0+2+0+0$	4

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Mathematica Code: ABC4EFT

Amplitude Basis Construction for Effective Field Theory

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Welcome to the HEPForge Project: ABC4EFT

This is the website for the Mathematica package: Amplitude Basis Construction for Effective Field Theories (ABC4EFT).

Package

This package has the following features:

- It provides a general procedure to construct the independent and complete operator bases for generic Lorentz invariant effective field theory, given any kind of gauge symmetry and field content, up to any mass dimension.
- Various operator bases have been systematically constructed to emphasize different aspects: operator independence (y-basis), flavor relation (p-basis) and conserved quantum number (j-basis).
- It provides a systematic way to convert any operator into our on-shell amplitude basis and the basis conversion can be easily done.

Authors

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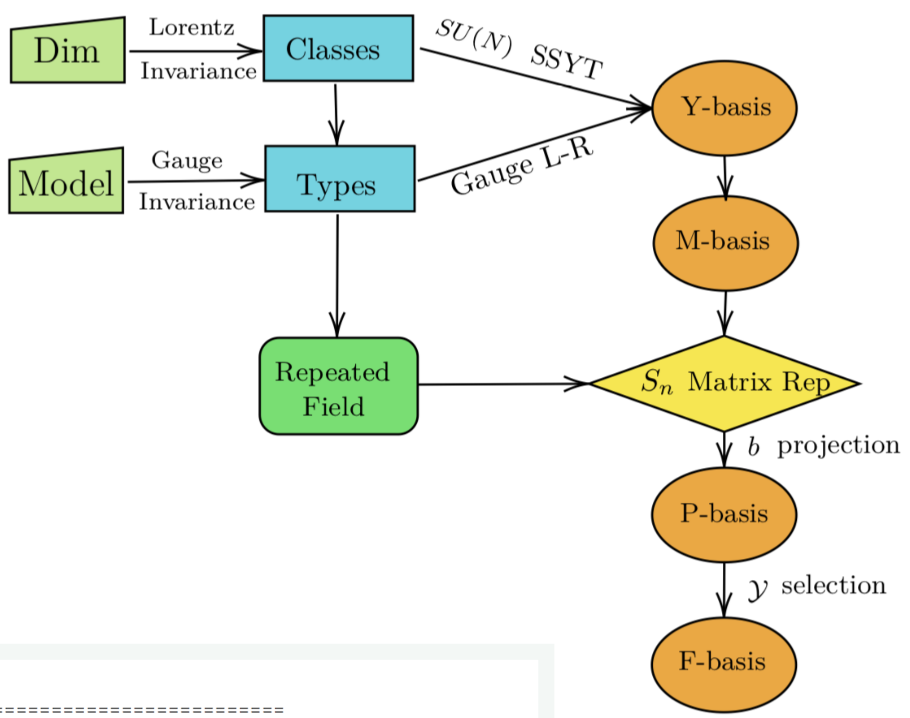
https://abc4eft.hepforge.org/

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<< ABC4EFT

=========================
ABC4EFT 1.0.0
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A Mathematica Package for
Amplitude Basis Construction for Effective Field Theories

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The package is available at hepforge
For the latest version, see the GitHub
If you use this package in your research,
Please cite: arXiv: 2201.04639, 2005.00008, 2007.07899
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4-Fermi EFT: From Beta to NSI

Energy

UV models

many models …..

[Du, Li, Tang, Vihonen, **Yu, 2021**]

[Du, Li, Tang, Vihonen, **Yu, 2022**]

TeV scale

Standard model EFT

$$(\bar{l}^j_\alpha e_\beta)\epsilon_{jk}(\bar{q}^k_s u_t),\quad (\bar{l}^j_\alpha \sigma_{\mu\nu} e_\beta)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t),\quad (\bar{l}^j_\alpha e_\beta)(\bar{d}_s q_{tj}),\quad (\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(\bar{q}_s \gamma_\mu \tau^I q_t)$$

$$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_\alpha \tau^I \gamma^\mu l_\beta),\quad (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r),\quad (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu d_r)$$

$$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_2 \tau^I \gamma^\mu l_2),\quad (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_1 \tau^I \gamma^\mu l_1),\quad (\bar{l}_2 \gamma^\mu l_1)(\bar{l}_1 \gamma_\mu l_2),\quad (\bar{l}_1 \gamma^\mu l_2)(\bar{l}_2 \gamma_\mu l_1)$$

EW scale

Low energy EFT

$$\{[\epsilon_{L(R)}(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i \gamma^\mu P_{L(R)} d_j)\,(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta)\,,$$
$$[\epsilon_{S(P)}(\mu)]^{ij}_{\alpha\beta}(\bar{u}_i \mathbf{1}(\gamma_5) d_j)\,(\bar{\ell}_\alpha P_L \nu_\beta)\,,$$
$$[\epsilon_T(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i \sigma^{\mu\nu} P_L d_j)\,(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta)\}$$

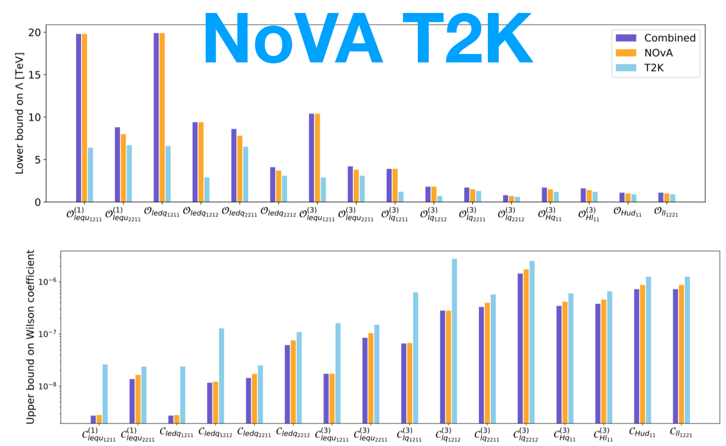
Λ_{QCD}

Chiral Lagrangian

$$[\epsilon_{L(R)}]^{ij}_{\alpha\beta},\ [\epsilon_{S(P)}]^{ij}_{\alpha\beta},\ [\epsilon_T]^{ij}_{\alpha\beta}$$

MeV scale

NoVA T2K



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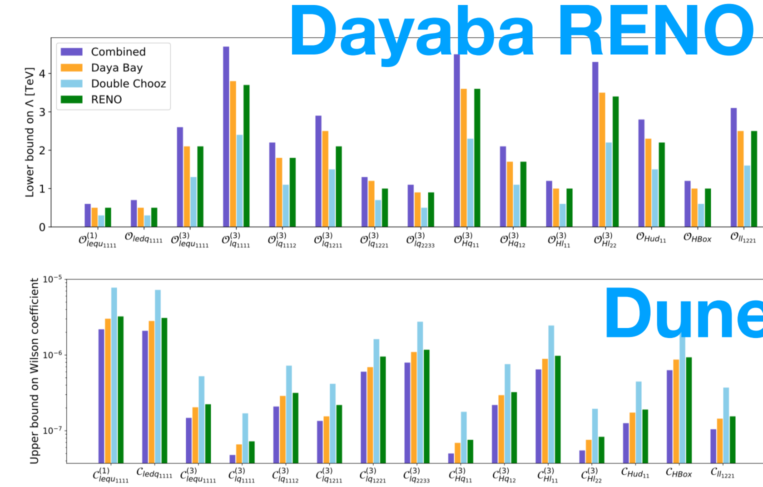
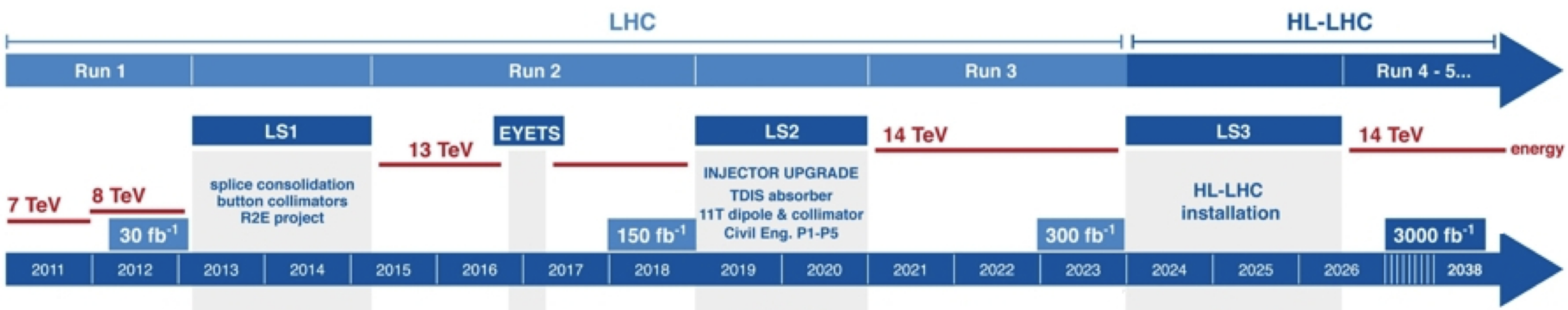
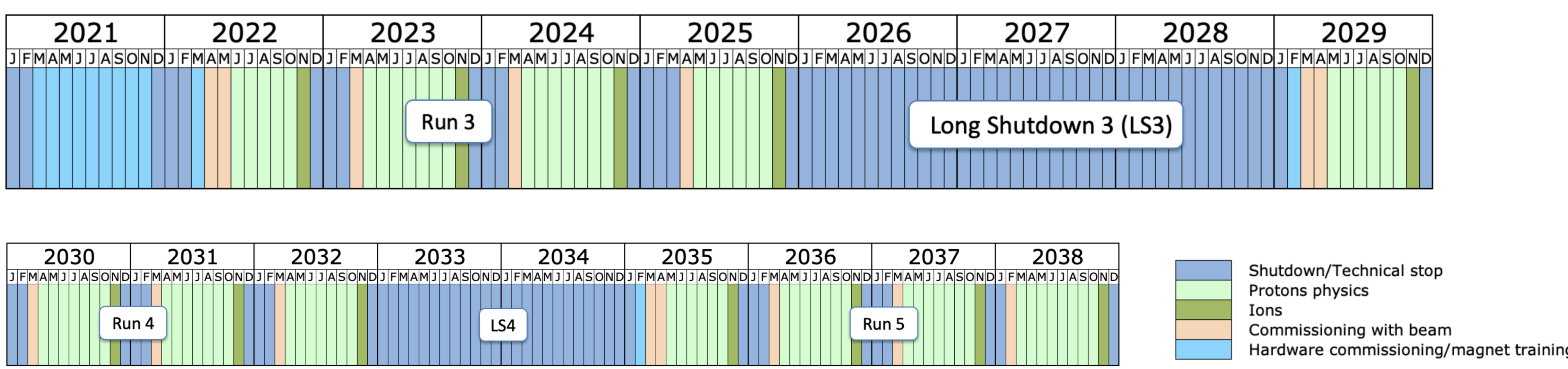


LHC Run III

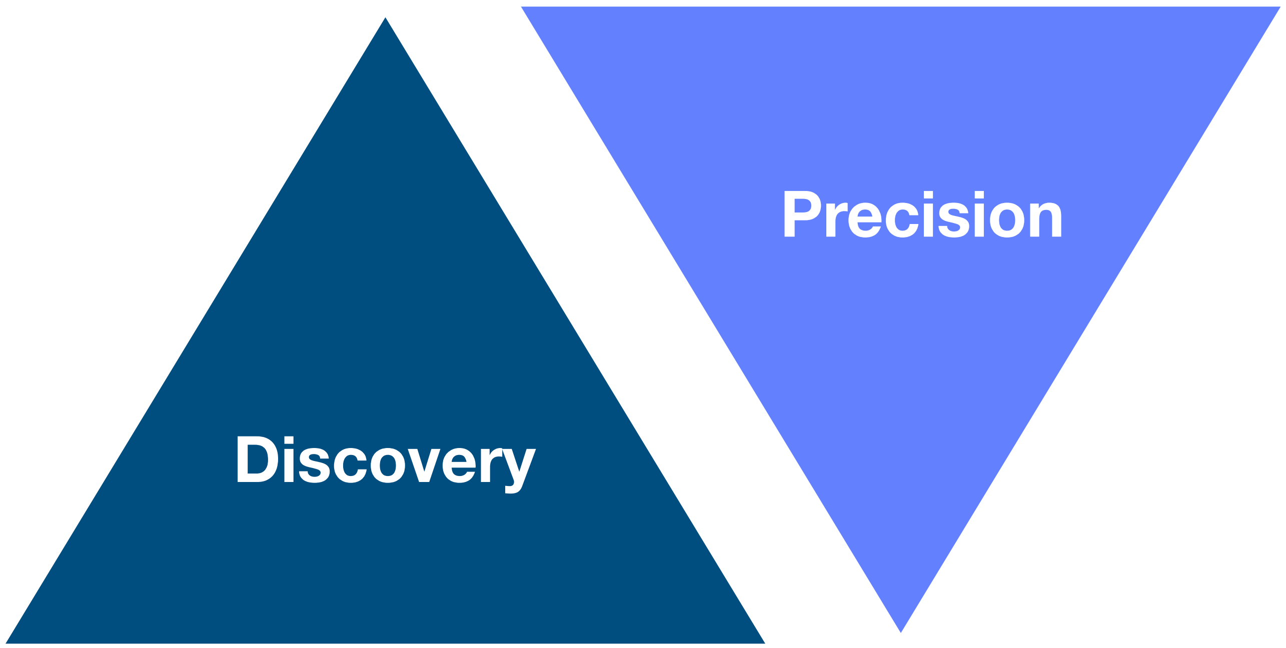
ATLAS/CMS starts to explore the EFT operators systematically in near future



"Precise measurements of these quantities can be interpreted in the context of Effective Field Theories (EFT) and give us a hint as to where new physics could lie". EFTs is a useful tool, allowing to parametrize the effect of new physics lying at higher energy scales in terms of deviations from the SM measurements. "There is a growing interest by the LHC experiments to collect these precise measurements and put them in a common framework that allows to extract the most information out of the collected data".



Is the bottom-up EFT operators our final goal?



Weak Theory at 1957

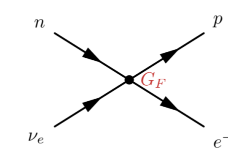
S-T?

1953 6He beta decay

V-A?

Bad high energy behavior

$$\nu_e + n \to p + e^-$$



$$\sigma = \frac{G_F^2 s}{\pi}$$

$m_W <$ 大约 300 GeV.

[Lee, 1961]

If parity is not conserved in β decay, the most general form of Hamiltonian can be written as

$$\begin{aligned} H_{\rm int} = & (\psi_p^\dagger\gamma_4\psi_n)(C_S\psi_e^\dagger\gamma_4\psi_\nu + C_S'\psi_e^\dagger\gamma_4\gamma_5\psi_\nu) \\ & + (\psi_p^\dagger\gamma_4\gamma_\mu\psi_n)(C_V\psi_e^\dagger\gamma_4\gamma_\mu\psi_\nu + C_V'\psi_e^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu) \\ & + \tfrac{1}{2}(\psi_p^\dagger\gamma_4\sigma_{\lambda\mu}\psi_n)(C_T\psi_e^\dagger\gamma_4\sigma_{\lambda\mu}\psi_\nu \\ & + C_T'\psi_e^\dagger\gamma_4\sigma_{\lambda\mu}\gamma_5\psi_\nu) + (\psi_p^\dagger\gamma_4\gamma_\mu\gamma_5\psi_n) \\ & \times(-C_A\psi_e^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu - C_A'\psi_e^\dagger\gamma_4\gamma_\mu\psi_\nu) \\ & + (\psi_p^\dagger\gamma_4\gamma_5\psi_n)(C_P\psi_e^\dagger\gamma_4\gamma_5\psi_\nu + C_P'\psi_e^\dagger\gamma_4\psi_\nu), \qquad \text{(A.1)} \end{aligned}$$

LEFT

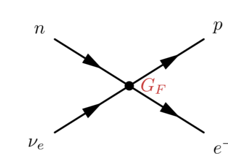
Weak Theory at 1957

Type	Form	Components	"Boson Spin"	
♦ SCALAR	$\overline{\psi}\phi$	1	0	$+$
♦ PSEUDOSCALAR	$\overline{\psi}\gamma^5\phi$	1	0	-
♦ VECTOR	$\overline{\psi}\gamma^\mu\phi$	4	1	(+,-,-,-)
♦ AXIAL VECTOR	$\overline{\psi}\gamma^\mu\gamma^5\phi$	4	1	(+,+,+,+)
♦ TENSOR	$\overline{\psi}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)\phi$	6	2	

Need to know complete UV

Bad high energy behavior

$$\nu_e + n \to p + e^-$$



$$\sigma = \frac{G_F^2 s}{\pi}$$

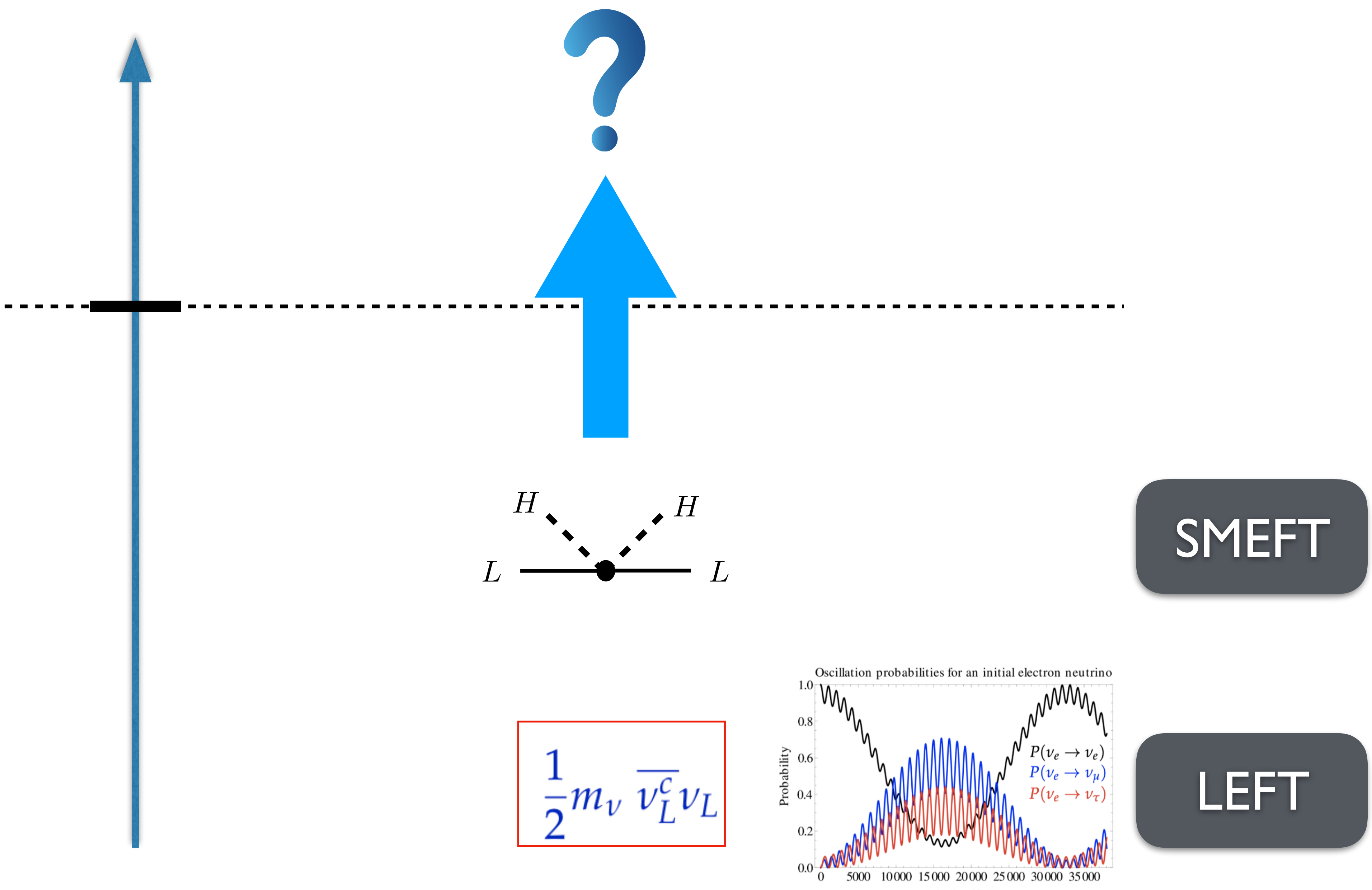
If parity is not conserved in β decay, the most general form of Hamiltonian can be written as

$$\begin{aligned} H_{\rm int} = & (\psi_p^\dagger\gamma_4\psi_n)(C_S\psi_e^\dagger\gamma_4\psi_\nu + C_S'\psi_e^\dagger\gamma_4\gamma_5\psi_\nu) \\ & + (\psi_p^\dagger\gamma_4\gamma_\mu\psi_n)(C_V\psi_e^\dagger\gamma_4\gamma_\mu\psi_\nu + C_V'\psi_e^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu) \\ & + \tfrac{1}{2}(\psi_p^\dagger\gamma_4\sigma_{\lambda\mu}\psi_n)(C_T\psi_e^\dagger\gamma_4\sigma_{\lambda\mu}\psi_\nu \\ & + C_T'\psi_e^\dagger\gamma_4\sigma_{\lambda\mu}\gamma_5\psi_\nu) + (\psi_p^\dagger\gamma_4\gamma_\mu\gamma_5\psi_n) \\ & \times (-C_A\psi_e^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu - C_A'\psi_e^\dagger\gamma_4\gamma_\mu\psi_\nu) \\ & + (\psi_p^\dagger\gamma_4\gamma_5\psi_n)(C_P\psi_e^\dagger\gamma_4\gamma_5\psi_\nu + C_P'\psi_e^\dagger\gamma_4\psi_\nu), \quad (A.1) \end{aligned}$$

LEFT

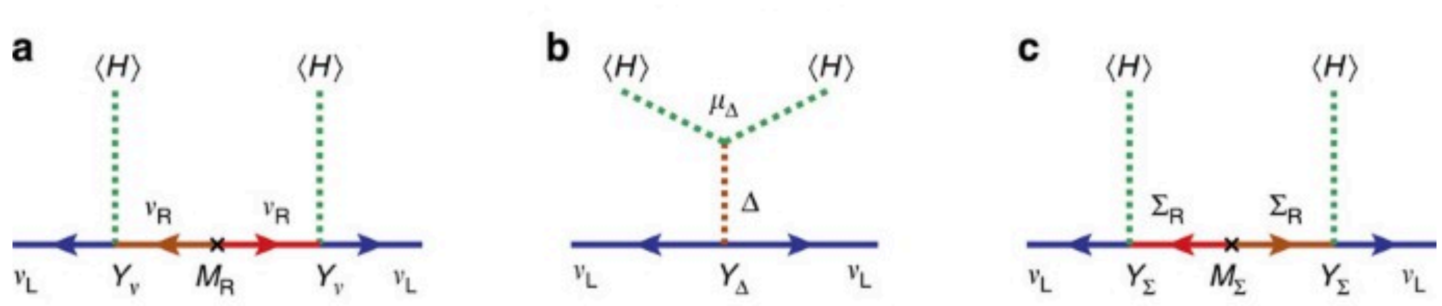
Similar Story: Neutrino Masses

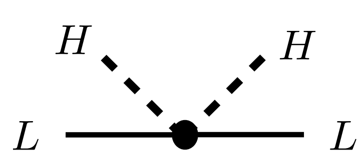
Nowadays, the first evidence of new physics is the neutrino masses



Neutrino Masses

The top-down approach is well-known, how about the bottom-up way?





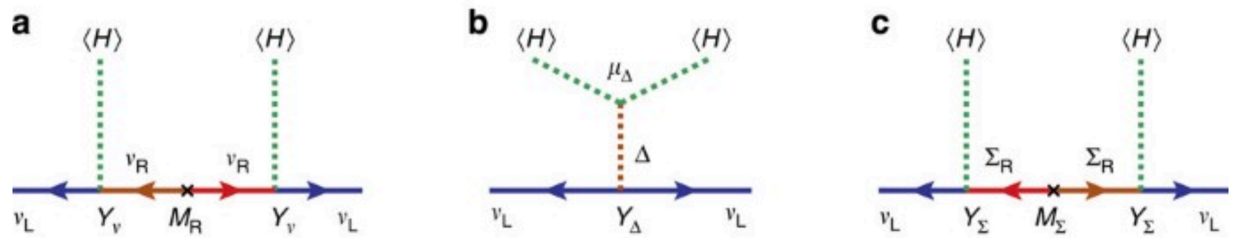
SMEFT

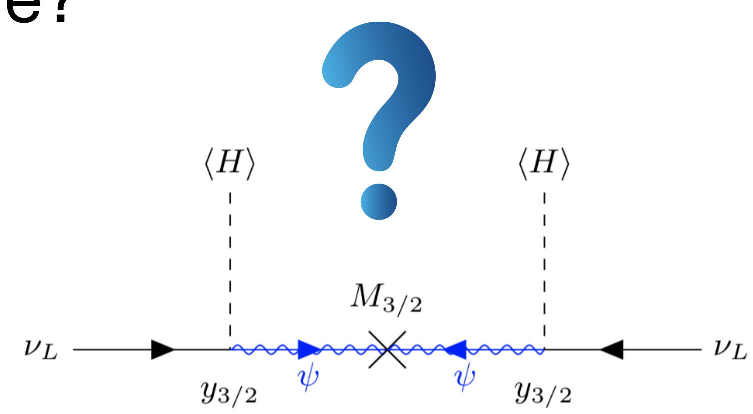
$$\frac{1}{2} m_\nu \, \overline{\nu_L^c} \nu_L$$

LEFT

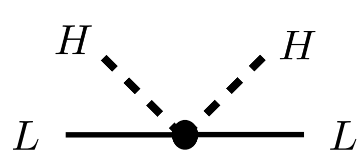
Type-3/2 Seesaw?

Whether additional seesaw (type-3/2 seesaw) is possible?





[Demir, Karahan, Sargm, 2021]

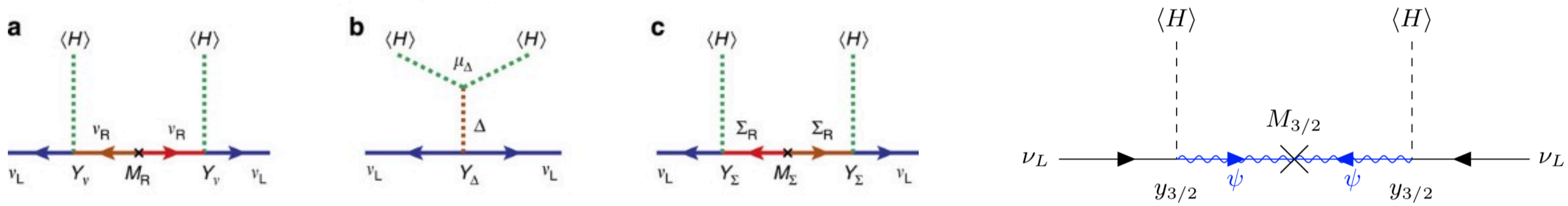


SMEFT

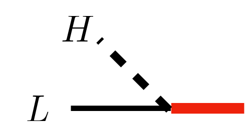
$$\frac{1}{2} m_\nu \, \overline{\nu_L^c} \nu_L$$

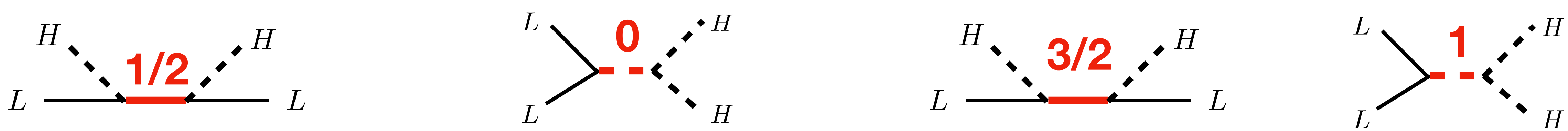
LEFT

Bottom-Up Approach?

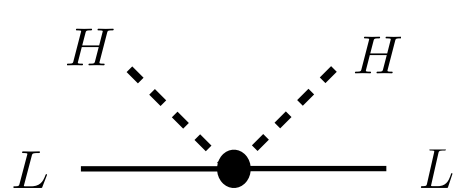


Impose gauge conservation for each vertex





Select UV topology with certain spin

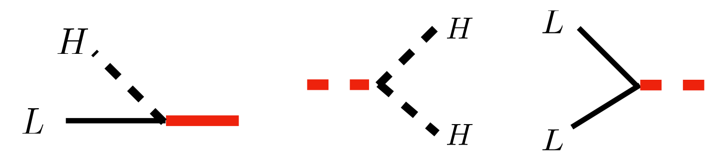


Angular momentum conservation not imposed!

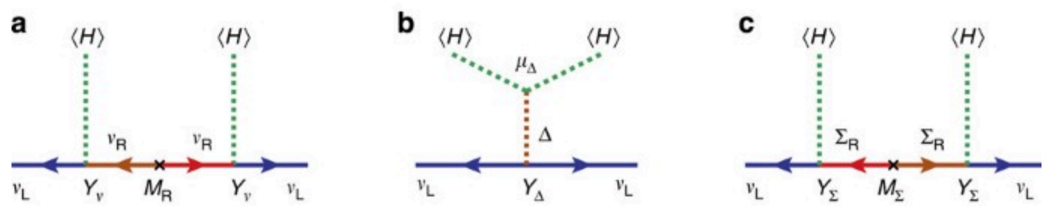
Cannot write 3/2-UV Lag for HHLL

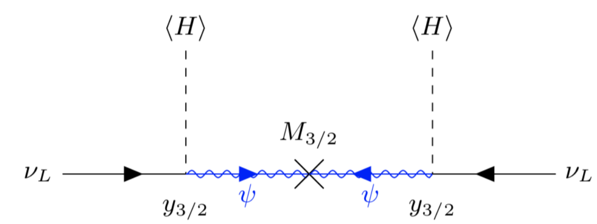
Bottom-Up Approach?

Essentially the top-down approach



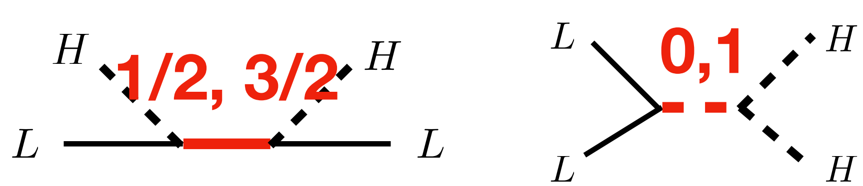
Assume UV spin/gauge/interaction @ **vertex** level



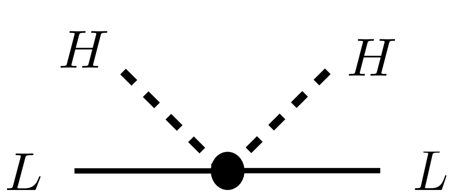


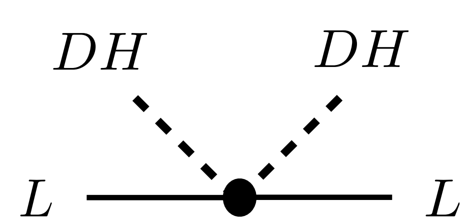
Impose gauge conservation at vertex level

Validation: matching



Select UV topology with fixed spin





Angular Momentum Conservation

Angular momentum conservation for **space-time symmetry** at **operator** level

SO(3) tensor rep

$$\mathbf{J}^2|J,M\rangle = J(J+1)|J,M\rangle$$

$$\mathbf{L}^2\langle\theta,\phi|l,m\rangle = -\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial}{\partial\phi}\right]Y_l^m(\theta,\phi)$$
$$= l(l+1)Y_l^m(\theta,\phi)$$

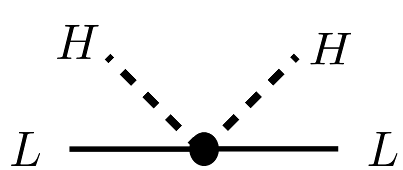
Poincare spinor rep

$$\mathbf{W}^2|P,J,M\rangle = -P^2 J(J+1)|P,J,M\rangle$$

$$\mathbf{W}^2 = \frac{s}{8}\sum_{i,j=1}^{N}\Big(\langle i,\partial_j\rangle\langle j,\partial_i\rangle + [i,\partial_j][j,\partial_i]\Big) - \frac{1}{4}\sum_{i,j,k,l}[i,j]\langle j,\partial_k\rangle\langle k,l\rangle[l,\partial_i]$$

$$\mathbf{W}^2\langle p_L,h_L;p_H,h_H|P,J,J_z\rangle = -P^2 J(J+1)\langle p_L,h_L;p_H,h_H|P,J,J_z\rangle$$

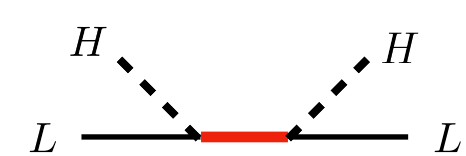
Acting W2 to amplitude/operator gives rise to the spin of UV particle



$$\mathcal{B}^y = \langle 12\rangle$$

$$\langle p_L,h_L;p_H,h_H|p'_L,h'_L;p'_H,h'_H\rangle$$

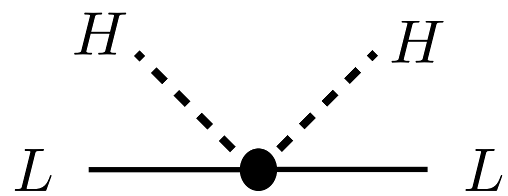
$$W^2_{\{1,3\}}\mathcal{B}^y = -\frac{3}{4}s_{13}\langle 12\rangle$$



$$= -s\sum_J J(J+1)\mathcal{O}^{\mathrm{J}}$$

Acting on whole operator, no need UV vertex info

Poincare Casimir: Spin-1/2&0



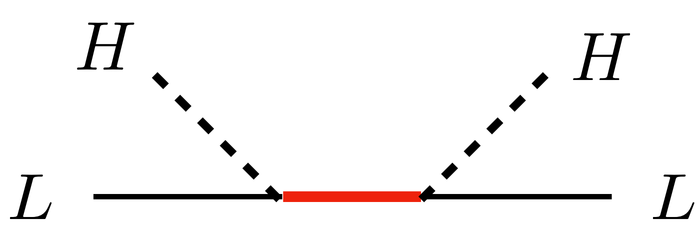
$\mathcal{O}^S = (HL)(HL)$

$\mathcal{B}^y = \langle 12 \rangle$

$$\mathbf{W}^2 \mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$

$LH \to LH$ channel

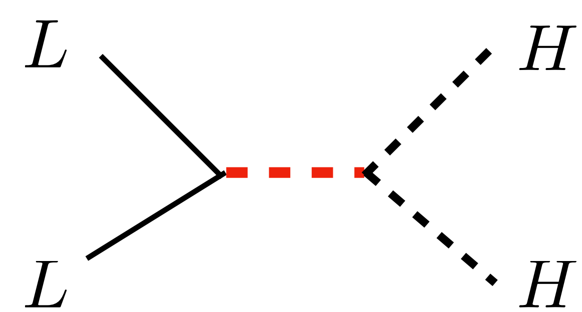
$W^2_{\{1,3\}}\mathcal{B}^y = -\frac{3}{4} s_{13} \langle 12 \rangle$



$J = \frac{1}{2}$

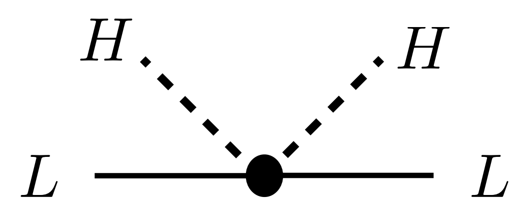
$LL \to HH$ channel

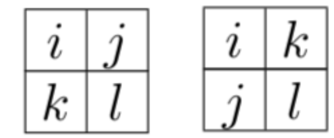
$W^2_{\{1,2\}}\mathcal{B}^y = 0$



$J = 0$

Gauge Casimir: singlet&triplet





$$\mathcal{B}_1^R = \epsilon^{ik}\epsilon^{jl}$$
$$\mathcal{B}_2^R = \epsilon^{ij}\epsilon^{kl}$$

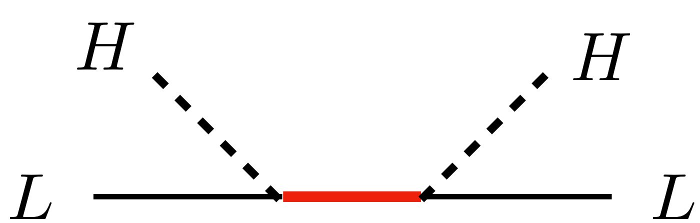
$$\mathbf{C}^2\mathcal{B}^R = r(r+1)\mathcal{B}^R$$

$LH \to LH$ channel

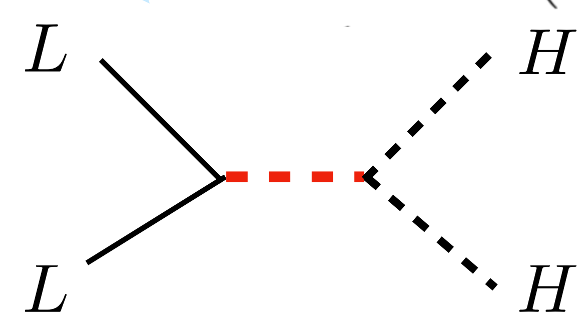
$$C_{21,3}\mathcal{B}^m = \begin{pmatrix} 0 & 0 \\ -1 & 2 \end{pmatrix}\mathcal{B}^m$$

$LL \to HH$ channel

$$C_{21,3}\mathcal{B}^m = \begin{pmatrix} 0 & 0 \\ -1 & 2 \end{pmatrix}\mathcal{B}^m$$



$$\mathcal{B}^{\mathbf{R}} = \begin{cases} \epsilon^{ik}\epsilon^{jl} & \mathbf{R} = 1 \\ \epsilon^{ik}\epsilon^{jl} - 2\epsilon^{ij}\epsilon^{kl} & \mathbf{R} = 3 \end{cases}$$



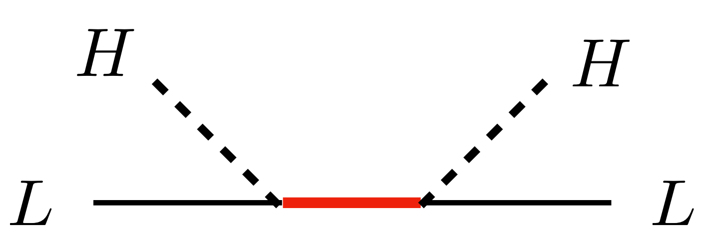
Complete Tree Seesaw Proved!

$$\mathcal{O}^S = (HL)(HL)$$

$$\mathbf{W}^2\mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$

$LH \to LH$ channel

$$W^2_{\{1,3\}}\mathcal{B}^y = -\frac{3}{4}s_{13}\langle 12\rangle$$



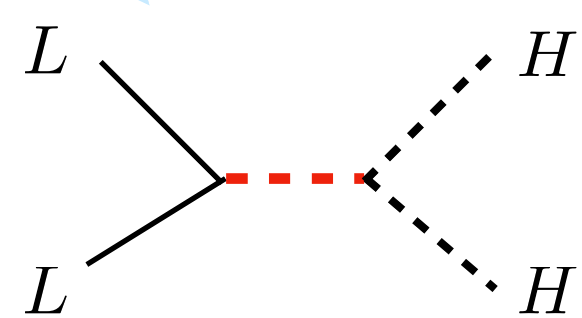
$J = \frac{1}{2}$

Type-I and III: SU(2) **single** and **triplet**

j-basis	Model
$\mathcal{O}^{(1/2,\mathbf{1})}_{HL\to HL} = \mathcal{O}^S + \mathcal{O}^A$	type I
$\mathcal{O}^{(1/2,\mathbf{3})}_{HL\to HL} = \mathcal{O}^S - 3\mathcal{O}^A$	type III

$LL \to HH$ channel

$$W^2_{\{1,2\}}\mathcal{B}^y = 0$$



$J = 0$

Type-II: SU(2) **triplet**, or singlet (excluded by repeated field)

j-basis	Model
$\mathcal{O}^{(0,\mathbf{1})}_{HH\to LL} = \mathcal{O}^A$	N/A
$\mathcal{O}^{(0,\mathbf{3})}_{HH\to LL} = \mathcal{O}^S$	type II

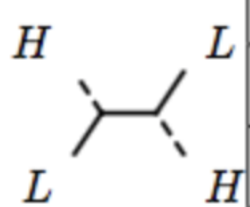
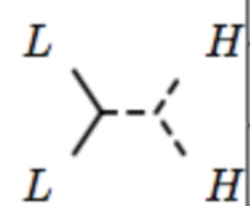
$$\mathcal{O}^S = (HL)(HL), \quad \mathcal{O}^A = (HH)(LL)$$

LLHHDD UV Resonances

$$\mathbf{W}^2\mathcal{B}^{\mathrm{y}} = -s\mathcal{W}.\mathcal{B}^{\mathrm{y}} \xrightarrow[\mathcal{K}.\mathcal{W}.\mathcal{K}^{-1}=\mathrm{diag}\{J(J+1)\}]{\mathcal{B}^{\mathrm{j}}=\mathcal{K}.\mathcal{B}^{\mathrm{y}}} \mathbf{W}^2_{\mathrm{initial/final}}\mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$

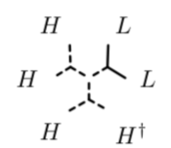
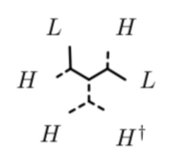
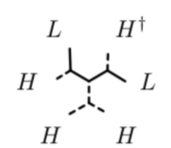
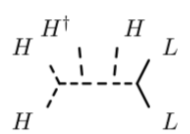
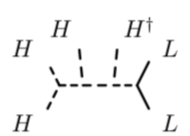
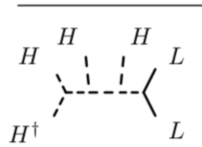
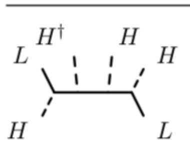
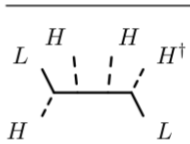
$$\mathcal{B}^y_{\psi^2\phi^2D^2} = \begin{pmatrix} s_{34}\langle 12\rangle \\ [34]\langle 13\rangle\langle 24\rangle \end{pmatrix} \qquad W^2_{\{1,3\}}\mathcal{B}^y = s_{24}\begin{pmatrix} -\frac{15}{4} & 2 \\ 0 & -\frac{3}{4} \end{pmatrix}\mathcal{B}^y \qquad \Rightarrow \mathcal{B}^j = \begin{cases} 3s_{34}\langle 12\rangle + 2[34]\langle 13\rangle\langle 24\rangle & J=\frac{3}{2} \\ \langle 13\rangle\langle 24\rangle & J=\frac{1}{2} \end{cases}$$

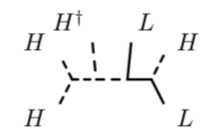
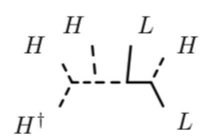
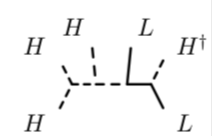
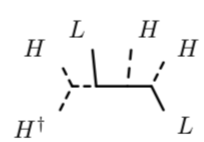
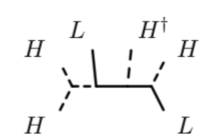
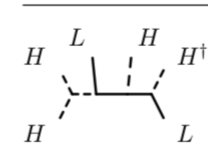
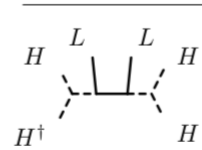
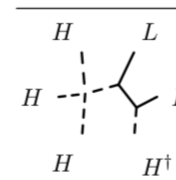
7 UV resonances

Topology	j-basis	Quantum numbers $\{J,\mathbf{R},Y\}$
	$\mathcal{B}_{\{13\},1} = 3\mathcal{B}^p_1 + 6\mathcal{B}^p_2 - 9\mathcal{B}^p_3 - 2\mathcal{B}^p_4,$	$\{\frac{3}{2},3,0\}$
	$\mathcal{B}_{\{13\},2} = 3\mathcal{B}^p_2 - \mathcal{B}^p_4,$	$\{\frac{1}{2},3,0\}$
	$\mathcal{B}_{\{13\},3} = -3\mathcal{B}^p_1 + 2\mathcal{B}^p_2 - 3\mathcal{B}^p_3 + 2\mathcal{B}^p_4,$	$\{\frac{3}{2},1,0\}$
	$\mathcal{B}_{\{13\},4} = \mathcal{B}^p_2 + \mathcal{B}^p_4.$	$\{\frac{1}{2},1,0\}$
	$\mathcal{B}_{\{12\},1} = 2\mathcal{B}^p_1 - 4\mathcal{B}^p_4,$	$\{1,3,-1\}$
	$\mathcal{B}_{\{12\}} = -2\mathcal{B}^p_1,$	$\{0,3,-1\}$
	$\mathcal{B}_{\{12\}} = 4\mathcal{B}^p_2 - 2\mathcal{B}^p_3,$	$\{1,1,-1\}$
	$\mathcal{B}_{\{12\}} = 2\mathcal{B}^p_3.$	$\{0,1,-1\}$ N/A

Genuine dim-7 Seesaw

Tree-level seesaw at dim-7: among 19 topologies, one genuine dim-7 seesaw

Topology	j-basis	Quantum numbers $\{J, \mathbf{R}, Y\}$
	$\mathcal{O}_{\{12\|34\|56\},1} = 2\mathcal{O}_1^p - 4\mathcal{O}_2^p,$	$\{0,3,-1\},\{0,3,1\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|34\|56\},2} = 2\mathcal{O}_2^p + 4\mathcal{O}_3^p,$	$\{0,3,-1\},\{0,1,1\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|34\|56\},3} = 12\mathcal{O}_4^p,$	$\{0,1,-1\},\{0,3,1\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|34\|56\},4} = 4\mathcal{O}_1^p + 4\mathcal{O}_2^p,$	$\{0,3,-1\},\{0,3,1\},\{0,1,0\}$
	$\mathcal{O}_{\{12\|34\|56\},5} = 2\mathcal{O}_4^p + 4\mathcal{O}_5^p.$	$\{0,1,-1\},\{0,1,1\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|24\|56\},1} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|24\|56\},2} = -\mathcal{O}_1^p + 3\mathcal{O}_2^p + 2\mathcal{O}_3^p + 3\mathcal{O}_4^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},1,0\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|24\|56\},3} = -\mathcal{O}_1^p + \mathcal{O}_2^p - 2\mathcal{O}_3^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|24\|56\},4} = -\mathcal{O}_1^p - \mathcal{O}_2^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|24\|56\},5} = \mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},1,0\},\{0,1,0\}$
	$\mathcal{O}_{\{16\|23\|45\},1} = 2\mathcal{O}_1^p - 2\mathcal{O}_2^p - 2\mathcal{O}_3^p + 6\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|23\|45\},2} = -2\mathcal{O}_1^p - \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},1,0\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|23\|45\},3} = 3\mathcal{O}_2^p + 3\mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|23\|45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,1,1\}$
	$\mathcal{O}_{\{16\|23\|45\},5} = \mathcal{O}_2^p - \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p.$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},1,0\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|125\|34\},1} = \mathcal{O}_1^p + 4\mathcal{O}_2^p,$	$\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|125\|34\},2} = -8\mathcal{O}_1^p + 4\mathcal{O}_2^p,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|125\|34\},3} = -12\mathcal{O}_4^p,$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|125\|34\},4} = -2\mathcal{O}_2^p - 4\mathcal{O}_3^p,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|125\|34\},5} = -2\mathcal{O}_4^p - 4\mathcal{O}_5^p.$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|126\|34\},1} = 3\mathcal{O}_1^p,$	$\{0,3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|126\|34\},2} = 12\mathcal{O}_2^p,$	$\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|126\|34\},3} = -12\mathcal{O}_4^p,$	$\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|126\|34\},4} = -2\mathcal{O}_2^p - 4\mathcal{O}_3^p,$	$\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|126\|34\},5} = -2\mathcal{O}_4^p - 4\mathcal{O}_5^p.$	$\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|124\|36\},1} = -\mathcal{O}_1^p - 4\mathcal{O}_3^p,$	$\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|124\|36\},2} = 2\mathcal{O}_1^p + 6\mathcal{O}_2^p + 2\mathcal{O}_3^p,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|124\|36\},3} = -6\mathcal{O}_4^p - 6\mathcal{O}_5^p,$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|124\|36\},4} = -2\mathcal{O}_1^p + 2\mathcal{O}_2^p + 2\mathcal{O}_3^p,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{12\|124\|36\},5} = -2\mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|135\|24\},1} = \mathcal{O}_1^p - 2\mathcal{O}_3^p - 6\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{13\|135\|24\},2} = -\mathcal{O}_1^p - 3\mathcal{O}_2^p - 4\mathcal{O}_3^p + 9\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{13\|135\|24\},3} = \mathcal{O}_1^p - \mathcal{O}_2^p + 2\mathcal{O}_3^p + 3\mathcal{O}_4^p,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{13\|135\|24\},4} = \mathcal{O}_1^p - 3\mathcal{O}_2^p - 2\mathcal{O}_3^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$
	$\mathcal{O}_{\{13\|135\|24\},5} = \mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$
	$\mathcal{O}_{\{16\|146\|23\},1} = -2\mathcal{O}_1^p + 4\mathcal{O}_3^p - 12\mathcal{O}_5^p,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{16\|146\|23\},2} = 2\mathcal{O}_1^p - 3\mathcal{O}_2^p - \mathcal{O}_3^p + 9\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{16\|146\|23\},3} = 3\mathcal{O}_2^p + 3\mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{16\|146\|23\},4} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p - 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$
	$\mathcal{O}_{\{16\|146\|23\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p - \mathcal{O}_4^p + \mathcal{O}_5^p,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$

	$\mathcal{O}_{\{13\|123\|45\},1} = \mathcal{O}_1^p - 4\mathcal{O}_2^p - 4\mathcal{O}_3^p,$	$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|123\|45\},2} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p - 9\mathcal{O}_4^p - 9\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|123\|45\},3} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|123\|45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{13\|123\|45\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p.$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{13\|123\|46\},1} = \mathcal{O}_1^p - 4\mathcal{O}_2^p - 4\mathcal{O}_3^p,$	$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|123\|46\},2} = \mathcal{O}_1^p + 2\mathcal{O}_2^p - \mathcal{O}_3^p - 9\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|123\|46\},3} = -\mathcal{O}_1^p - 2\mathcal{O}_2^p + \mathcal{O}_3^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|123\|46\},4} = -\mathcal{O}_1^p - \mathcal{O}_3^p + 6\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|123\|46\},5} = -\mathcal{O}_1^p - \mathcal{O}_3^p - 2\mathcal{O}_4^p - \mathcal{O}_5^p.$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{16\|126\|34\},1} = 6\mathcal{O}_1^p,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|126\|34\},2} = -3\mathcal{O}_2^p + 9\mathcal{O}_4^p,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|126\|34\},3} = -3\mathcal{O}_2^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|126\|34\},4} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|126\|34\},5} = \mathcal{O}_2^p + 2\mathcal{O}_3^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{23\|235\|46\},1} = \mathcal{O}_1^p - 2\mathcal{O}_3^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{23\|235\|46\},2} = \mathcal{O}_1^p - 6\mathcal{O}_2^p - 5\mathcal{O}_3^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{23\|235\|46\},3} = \mathcal{O}_1^p + 2\mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{23\|235\|46\},4} = -\mathcal{O}_1^p - \mathcal{O}_3^p - 6\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{23\|235\|46\},5} = -\mathcal{O}_1^p - \mathcal{O}_3^p + 2\mathcal{O}_4^p + \mathcal{O}_5^p.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|136\|45\},1} = \mathcal{O}_1^p + 2\mathcal{O}_2^p + 2\mathcal{O}_3^p - 6\mathcal{O}_4^p - 6\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|136\|45\},2} = 2\mathcal{O}_1^p - 5\mathcal{O}_2^p - 5\mathcal{O}_3^p - 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|136\|45\},3} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|136\|45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{13\|136\|45\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{16\|156\|34\},1} = 2\mathcal{O}_1^p - 4\mathcal{O}_2^p + 12\mathcal{O}_4^p,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|156\|34\},2} = 4\mathcal{O}_1^p + \mathcal{O}_2^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|156\|34\},3} = -3\mathcal{O}_2^p - 3\mathcal{O}_4^p,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|156\|34\},4} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{16\|156\|34\},5} = \mathcal{O}_2^p + 2\mathcal{O}_3^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{34\|134\|56\},1} = -\mathcal{O}_1^p + 2\mathcal{O}_2^p + 6\mathcal{O}_4^p,$	$\{0,3,1\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{34\|134\|56\},2} = 4\mathcal{O}_1^p - 8\mathcal{O}_2^p + 12\mathcal{O}_4^p,$	$\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{34\|134\|56\},3} = 2\mathcal{O}_2^p + 4\mathcal{O}_3^p,$	$\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{34\|134\|56\},4} = -4\mathcal{O}_1^p - 4\mathcal{O}_2^p,$	$\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{34\|134\|56\},5} = 2\mathcal{O}_4^p + 4\mathcal{O}_5^p.$	$\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{16\|126\|,1} = 6\mathcal{O}_1^p,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\}$
	$\mathcal{O}_{\{16\|126\},2,3} = \begin{pmatrix} \mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_4^p + 3\mathcal{O}_5^p \\ -2\mathcal{O}_2^p - \mathcal{O}_3^p + 6\mathcal{O}_4^p + 3\mathcal{O}_5^p \end{pmatrix},$	$\{\frac{1}{2},3,-1\},\{0,2,-\frac{3}{2}\}$
	$\mathcal{O}_{\{16\|126\},4,5} = \begin{pmatrix} -\mathcal{O}_2^p - 2\mathcal{O}_3^p - \mathcal{O}_4^p - 2\mathcal{O}_5^p \\ -2\mathcal{O}_2^p - \mathcal{O}_3^p - 2\mathcal{O}_4^p - \mathcal{O}_5^p \end{pmatrix}.$	$\{\frac{1}{2},1,-1\},\{0,2,-\frac{3}{2}\}$

$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\}$
$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\}$
$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\}$
$\{0,3,-1\},\{0,4,-\frac{1}{2}\}$
$\{0,3,-1\},\{0,2,-\frac{1}{2}\}$
$\{0,1,-1\},\{0,2,-\frac{1}{2}\}$
$\{0,3,-1\},\{0,4,-\frac{3}{2}\}$
$\{0,3,-1\},\{0,2,-\frac{3}{2}\}$
$\{0,1,-1\},\{0,2,-\frac{3}{2}\}$

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[Bonnet, Hernandez, Ota, Winter, 2009]

[Babu, Nandi, Tavartkiladze, 2009]

Complete Dim-6 UV Resonances

Scalar	
$(SU(3)_c, SU(2)_2, U(1)_y)$	
$S1\ (\mathbf{1},\mathbf{1},0)$	$B_L{}^2HH^\dagger$ $D^2H^2H^{\dagger2}$ $d_{\mathbb{C}}HH^{\dagger2}Q[(F11),(F8)]$ $e_{\mathbb{C}}HH^{\dagger2}L[(F3),(F2)]$ $G_L{}^2HH^\dagger$ $H^2H^\dagger Qu_{\mathbb{C}}[(S4),(F11),(F9)]$ $HH^\dagger W_L{}^2$ $H^3H^{\dagger3}[(S6),(S2),(S5),(S4,S6),(S2,S4),(S4,S5),(S4)]$ $e_{\mathbb{C}}HH^{\dagger2}L$ $d_{\mathbb{C}}HH^{\dagger2}Q$ $H^2H^\dagger Qu_{\mathbb{C}}$
$S2\ (\mathbf{1},\mathbf{1},1)$	$d_{\mathbb{C}}HH^{\dagger2}Q[(S4),(F10),(F9)]$ $e_{\mathbb{C}}HH^{\dagger2}L[(S4),(F4),(F1)]$ $H^2H^\dagger Qu_{\mathbb{C}}[(F8),(F12)]$ $L^2L^{\dagger2}$ $H^3H^{\dagger3}[(S4),(S5),(S5,S6),(S1),(S4,S5),(S1,S4),(S5,S6),(S4,S6)]$
$S3\ (\mathbf{1},\mathbf{1},2)$	$e_{\mathbb{C}}{}^2e_{\mathbb{C}}^{\dagger2}$
$S4\ (\mathbf{1},\mathbf{2},\frac{1}{2})$	$d_{\mathbb{C}}^\dagger e_{\mathbb{C}}LQ^\dagger$ $d_{\mathbb{C}}HH^{\dagger2}Q[(S6),(S2)]$ $e_{\mathbb{C}}HH^{\dagger2}L[(S6),(S2)]$ $H^2H^\dagger Qu_{\mathbb{C}}$ $H^2H^\dagger Qu_{\mathbb{C}}[(S5),(S1)]$ $QQ^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $H^3H^{\dagger3}[(S6),(S2),(S5,S6),(S2,S5),(S1,S6),(S1,S2),(S2,S6),(S5),(S1,S5),(S1)]$
$S5\ (\mathbf{1},\mathbf{3},0)$	$B_LHH^\dagger W_L$ $D^2H^2H^{\dagger2}$ $d_{\mathbb{C}}HH^{\dagger2}Q[(F11),(F13)]$ $e_{\mathbb{C}}HH^{\dagger2}L[(F3),(F6)]$ $H^2H^\dagger Qu_{\mathbb{C}}[(S4),(F11),(F14)]$ $HH^\dagger W_L{}^2$ $H^3H^{\dagger3}[(S7),(S6),(S2,S6),(S1),($ … $e_{\mathbb{C}}HH^{\dagger2}L$ $d_{\mathbb{C}}$ …
$S6\ (\mathbf{1},\mathbf{3},1)$	$d_{\mathbb{C}}HH^{\dagger2}Q[(S4),(F10),(F14$ … $H^2H^\dagger Qu_{\mathbb{C}}[(F1$ … $H^3H^{\dagger3}[(S7),(S4),(S$ … $,(S5,S7),(S4,S5),($ …
$S7\ (\mathbf{1},\mathbf{4},\frac{1}{2})$	$H^3H^{\dagger3}[(S$ …
$S8\ (\mathbf{1},\mathbf{4},\frac{3}{2})$	H^3 …
$S9\ (\mathbf{3},\mathbf{1},-\frac{4}{3})$	
$S10\ (\mathbf{3},\mathbf{1},-\frac{1}{3})$	$Q^2Q^{\dagger2}$ $e_{\mathbb{C}}LQu_{\mathbb{C}}$ …
$S11\ (\mathbf{3},\mathbf{1},\frac{2}{3})$	
$S12\ (\mathbf{3},\mathbf{2},\frac{1}{6})$	d …
$S13\ (\mathbf{3},\mathbf{2},\frac{7}{6})$	L …
$S14\ (\mathbf{3},\mathbf{3},-\frac{1}{3})$	
$S15\ (\mathbf{6},\mathbf{1},-\frac{2}{3})$	
$S16\ (\mathbf{6},\mathbf{1},\frac{1}{3})$	$d_{\mathbb{C}}Q^2u$ …
$S17\ (\mathbf{6},\mathbf{1},\frac{4}{3})$	
$S18\ (\mathbf{6},\mathbf{3},\frac{1}{3})$	
$S19\ (\mathbf{8},\mathbf{2},\frac{1}{2})$	Q …

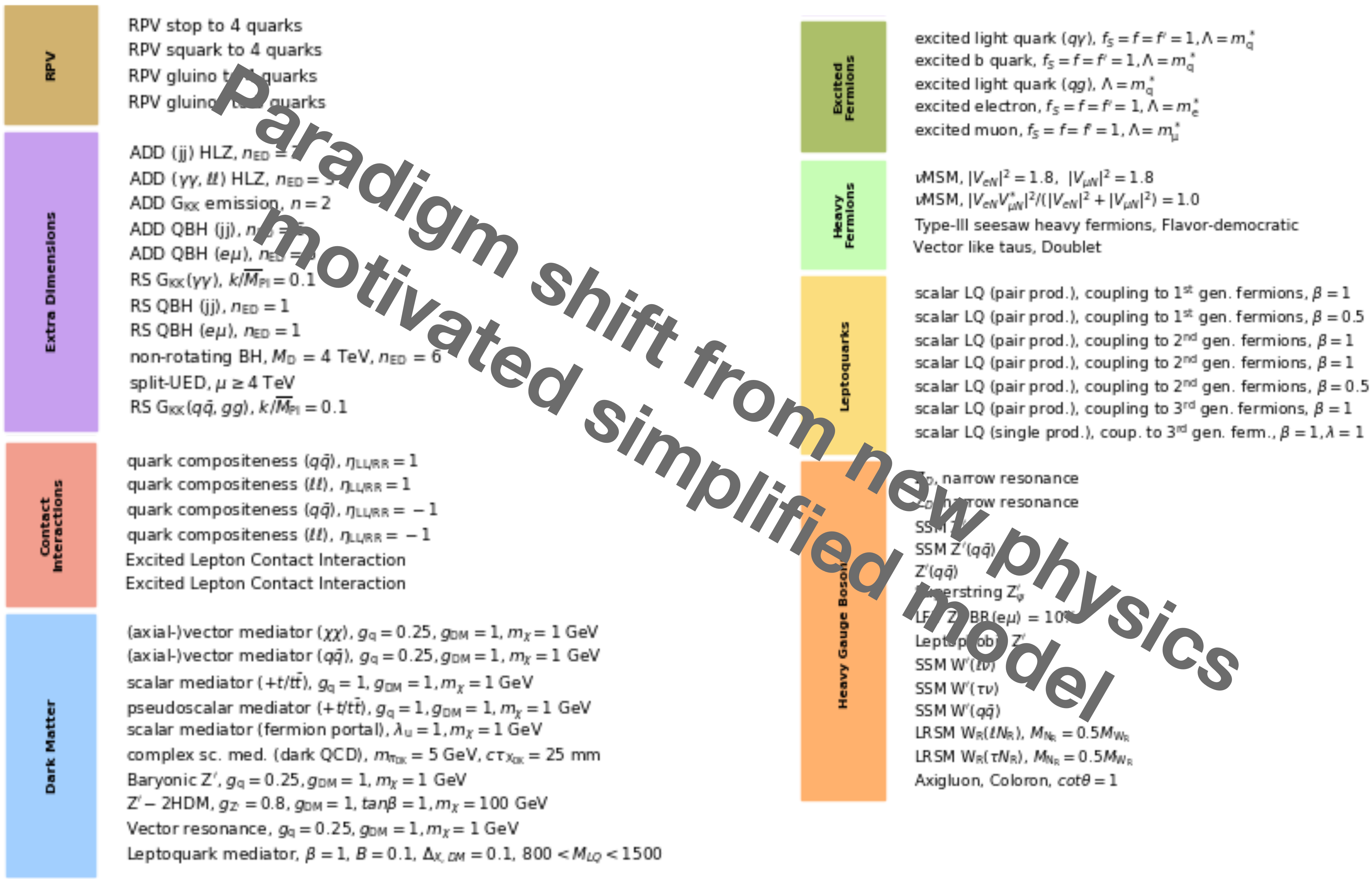
Fermion	
$(SU(3)_c, SU(2)_2, U(1)_y)$	
$F1\ (\mathbf{1},\mathbf{1},0)$	$DHH^\dagger LL^\dagger$ $e_{\mathbb{C}}HH^{\dagger2}L[(F3),$ …
$F2\ (\mathbf{1},\mathbf{1},1)$	$B_Le_{\mathbb{C}}H^\dagger L$ $DHH^\dagger LL^\dagger$ $e_{\mathbb{C}}HH$ … $e_{\mathbb{C}}HH^{\dagger2}L$
$F3\ (\mathbf{1},\mathbf{2},\frac{1}{2})$	$B_Le_{\mathbb{C}}H^\dagger L$ $e_{\mathbb{C}}HH^{\dagger2}L[(F5),(F1),$ …
$F4\ (\mathbf{1},\mathbf{2},\frac{3}{2})$	$De_{\mathbb{C}}e_{\mathbb{C}}^\dagger HH^\dagger$ $e_{\mathbb{C}}HH^{\dagger2}L[(F6),(F2),$ …
$F5\ (\mathbf{1},\mathbf{3},0)$	$DHH^\dagger LL^\dagger$ $e_{\mathbb{C}}HH^{\dagger2}L[(F3),$ …
$F6\ (\mathbf{1},\mathbf{3},1)$	$e_{\mathbb{C}}H^\dagger LW_L$ $e_{\mathbb{C}}HH^{\dagger2}L[(F$ …
$F8\ (\mathbf{3},\mathbf{1},-\frac{1}{3})$	$B_Ld_{\mathbb{C}}H^\dagger Q$ $d_{\mathbb{C}}G_LH^\dagger Q$ $DHH^\dagger QQ^\dagger$ d … $Q[(F10),(F11),(S1)]$
$F9\ (\mathbf{3},\mathbf{1},\frac{2}{3})$	$DHH^\dagger QQ^\dagger$ $B_LHQu_{\mathbb{C}}$ $G_LHQu_{\mathbb{C}}$ $d_{\mathbb{C}}HH^{\dagger2}Q[(F11),(S2)]$ $H^2H^\dagger Qu_{\mathbb{C}}$
$F10\ (\mathbf{3},\mathbf{2},-\frac{5}{6})$	$Dd_{\mathbb{C}}d_{\mathbb{C}}^\dagger HH^\dagger$ $d_{\mathbb{C}}HH^{\dagger2}Q[(F13),(F8),(S6),(S2)]$ $d_{\mathbb{C}}HH^{\dagger2}Q$
$F11\ (\mathbf{3},\mathbf{2},\frac{1}{6})$	$B_Ld_{\mathbb{C}}H^\dagger Q$ $B_LHQu_{\mathbb{C}}$ $G_LHQu_{\mathbb{C}}$ $DHH^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HH^{\dagger2}Q[(F14),(F9),(F13),(F8),(S5),(S1)]$ $H^2H^\dagger Qu_{\mathbb{C}}[(F14),(F9),(F13),(F8),(S5),(S1)]$
$F12\ (\mathbf{3},\mathbf{2},\frac{7}{6})$	$DHH^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $H^2H^\dagger Qu_{\mathbb{C}}[(F14),(F9),(S6),(S2)]$ $H^2H^\dagger Qu_{\mathbb{C}}$
$F13\ (\mathbf{3},\mathbf{3},-\frac{1}{3})$	$d_{\mathbb{C}}H^\dagger QW_L$ $d_{\mathbb{C}}HH^{\dagger2}Q[(F10),(F11),(S5)]$ H …
$F14\ (\mathbf{3},\mathbf{3},\frac{2}{3})$	$HQu_{\mathbb{C}}W_L$ $d_{\mathbb{C}}HH^{\dagger2}Q[(F11),(S6)]$ $H^2H^\dagger Q$ …

Vector	
$(SU(3)_c, SU(2)_2, U(1)_y)$	
$V1\ (\mathbf{1},\mathbf{1},0)$	$d_{\mathbb{C}}{}^2d_{\mathbb{C}}^{\dagger2}$ $d_{\mathbb{C}}d_{\mathbb{C}}^\dagger e_{\mathbb{C}}e_{\mathbb{C}}^\dagger$ $e_{\mathbb{C}}{}^2e_{\mathbb{C}}^{\dagger2}$ $Dd_{\mathbb{C}}d_{\mathbb{C}}^\dagger HH^\dagger$ $De_{\mathbb{C}}e_{\mathbb{C}}^\dagger HH^\dagger$ $D^2H^2H^{\dagger2}$ $d_{\mathbb{C}}d_{\mathbb{C}}^\dagger LL^\dagger$ $e_{\mathbb{C}}e_{\mathbb{C}}^\dagger LL^\dagger$ $DHH^\dagger LL^\dagger$ $L^2L^{\dagger2}$ $d_{\mathbb{C}}d_{\mathbb{C}}^\dagger QQ^\dagger$ $e_{\mathbb{C}}e_{\mathbb{C}}^\dagger QQ^\dagger$ $DHH^\dagger QQ^\dagger$ $LL^\dagger QQ^\dagger$ $Q^2Q^{\dagger2}$ $d_{\mathbb{C}}d_{\mathbb{C}}^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $e_{\mathbb{C}}e_{\mathbb{C}}^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $DHH^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $LL^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $QQ^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HH^{\dagger2}Q$ $e_{\mathbb{C}}HH^{\dagger2}L$ $H^2H^\dagger Qu_{\mathbb{C}}$ $e_{\mathbb{C}}HH^{\dagger2}L$ $d_{\mathbb{C}}HH^{\dagger2}Q$ $H^2H^\dagger Qu_{\mathbb{C}}$
$V2\ (\mathbf{1},\mathbf{1},1)$	$D^2H^2H^{\dagger2}$ $Dd_{\mathbb{C}}H^{\dagger2}u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}d_{\mathbb{C}}^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $e_{\mathbb{C}}HH^{\dagger2}L$ $d_{\mathbb{C}}HH^{\dagger2}Q$ $H^2H^\dagger Qu_{\mathbb{C}}$ $d_{\mathbb{C}}HH^{\dagger2}Q$
$V3\ (\mathbf{1},\mathbf{2},\frac{3}{2})$	$e_{\mathbb{C}}e_{\mathbb{C}}^\dagger LL^\dagger$
$V4\ (\mathbf{1},\mathbf{3},0)$	$D^2H^2H^{\dagger2}$ $DHH^\dagger LL^\dagger$ $L^2L^{\dagger2}$ $DHH^\dagger QQ^\dagger$ $LL^\dagger QQ^\dagger$ $Q^2Q^{\dagger2}$ $e_{\mathbb{C}}HH^{\dagger2}L$ $d_{\mathbb{C}}HH^{\dagger2}Q$ $H^2H^\dagger Qu_{\mathbb{C}}$ $e_{\mathbb{C}}HH^{\dagger2}L$
$V5\ (\mathbf{3},\mathbf{1},\frac{2}{3})$	$d_{\mathbb{C}}^\dagger e_{\mathbb{C}}LQ^\dagger$
$V6\ (\mathbf{3},\mathbf{1},\frac{5}{3})$	$e_{\mathbb{C}}e_{\mathbb{C}}^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$
$V7\ (\mathbf{3},\mathbf{2},-\frac{5}{6})$	$d_{\mathbb{C}}d_{\mathbb{C}}^\dagger LL^\dagger$ $d_{\mathbb{C}}^\dagger e_{\mathbb{C}}LQ^\dagger$ $e_{\mathbb{C}}e_{\mathbb{C}}^\dagger QQ^\dagger$ $d_{\mathbb{C}}L^\dagger Q^\dagger u_{\mathbb{C}}$ $e_{\mathbb{C}}Q^{\dagger2}u_{\mathbb{C}}$ $QQ^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$
$V8\ (\mathbf{3},\mathbf{2},\frac{1}{6})$	$d_{\mathbb{C}}d_{\mathbb{C}}^\dagger QQ^\dagger$ $d_{\mathbb{C}}L^\dagger Q^\dagger u_{\mathbb{C}}$ $LL^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$
$V9\ (\mathbf{3},\mathbf{3},\frac{2}{3})$	$LL^\dagger QQ^\dagger$
$V10\ (\mathbf{6},\mathbf{2},-\frac{1}{6})$	$d_{\mathbb{C}}d_{\mathbb{C}}^\dagger QQ^\dagger$
$V11\ (\mathbf{6},\mathbf{2},\frac{5}{6})$	$QQ^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$
$V12\ (\mathbf{8},\mathbf{1},0)$	$d_{\mathbb{C}}{}^2d_{\mathbb{C}}^{\dagger2}$ $d_{\mathbb{C}}d_{\mathbb{C}}^\dagger QQ^\dagger$ $Q^2Q^{\dagger2}$ $d_{\mathbb{C}}d_{\mathbb{C}}^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $QQ^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ $u_{\mathbb{C}}{}^2u_{\mathbb{C}}^{\dagger2}$
$V13\ (\mathbf{8},\mathbf{1},1)$	$d_{\mathbb{C}}d_{\mathbb{C}}^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$
$V14\ (\mathbf{8},\mathbf{3},0)$	$Q^2Q^{\dagger2}$

[de Blas, Criado, Perez-Victoria, Santiago, 2017]

New LHC searches!

EFT Motivated Simplified Model



Paradigm shift from new physics motivated simplified model

Complete Dim-7 UV Resonances

Scalar	
$(SU(3)_c, SU(2)_2, U(1)_y)$	
$S1\ (\mathbf{1},\mathbf{1},0)$	$H^3H^\dagger L^2[(S6),(S2),(F5),(F1),(S4,S6),(S2,S4),$ $(S4,F5),(S4,F1),(F3,F5),(F1,F3),(S6,F3),(S2,F3)]$
$S2\ (\mathbf{1},\mathbf{1},1)$	$D^2H^2L^2$ $e_{\mathbb{C}}HL^3[(S4),(F4),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S4),(F10),(F9)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(F8),(F12)]$ $De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(F1),(F3),(V3)]$ $H^3H^\dagger L^2[(F1,F3),(S5,S6),(S1),(F5,F6),(F1,F2),(S4,S6),$ $(S4),(S5,S6),(S5),(S4,S5),(S1,S4),(S4,F5),(S4,F1),(F3,F5)$ $,(S5,F6),(S5,F2),(F3,F6),(F2,F3),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$
$S4\ (\mathbf{1},\mathbf{2},\frac{1}{2})$	$H^3H^\dagger L^2[(S6),(S2,S6),(S2),(S5,S6),(S2,S5),(S1,S6),(S1,S2),$ $(S6,F5),(S6,F1),(S2,F5),(S2,F1),(S5,F5),(S5,F1),(S1,F5),(S1,F1)]$
$S5\ (\mathbf{1},\mathbf{3},0)$	$H^3H^\dagger L^2[(S6),(S2,S6),(F5)$ $(S2,S4),(S7,F5),(S4,F5),$ $(F1,F3),(S6,F7),$
$S6\ (\mathbf{1},\mathbf{3},1)$	$D^2H^2L^2$ $e_{\mathbb{C}}HL^3[(S4),(F4),(F$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4$ $De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(F5),(F3),($ $H^3H^\dagger L^2[(F3,F5),(S5),(S1),(S2,$ $(S7),(S4),(S2,S4),(S8),(S5),(S2,S5),(S$ $(S4,F1),(F5,F7),(F1,F3),(S8,F6),$ $,(F2,F3),(S5,F7),$ $H^2L^2W_L$ B_L $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}H$
$S7\ (\mathbf{1},\mathbf{4},\frac{1}{2})$	$H^3H^\dagger L^2[(S6),(S5,S$
$S8\ (\mathbf{1},\mathbf{4},\frac{3}{2})$	$H^3H^\dagger L^2[(S$
$S10\ (\mathbf{3},\mathbf{1},-\frac{1}{3})$	$d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S12),(F10),(F1)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S12),(F10),(F1)]$
$S11\ (\mathbf{3},\mathbf{1},\frac{2}{3})$	$d_{\mathbb{C}}{}^3H^\dagger L[(S12),(F11),(F2)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(F11$
$S12\ (\mathbf{3},\mathbf{2},\frac{1}{6})$	$d_{\mathbb{C}}{}^3H^\dagger L[(S11),(F11)]$ $d_{\mathbb{C}}{}^2$ $d_{\mathbb{C}}HL^2Q[(S10),(S14),(F5),(F1),(F14)$
$S13\ (\mathbf{3},\mathbf{2},\frac{7}{6})$	$d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S11),(F10)]$
$S14\ (\mathbf{3},\mathbf{3},-\frac{1}{3})$	$d_{\mathbb{C}}HL^2Q[(S12),(F10),(F5)]$

Vector	
$(SU(3)_c, SU(2)_2, U(1)_y)$	
$V2\ (\mathbf{1},\mathbf{1},1)$	$Dd_{\mathbb{C}}L^2u_{\mathbb{C}}^\dagger$ $D^2H^2L^2$ $De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(F1),(V3),(F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$
$V3\ (\mathbf{1},\mathbf{2},\frac{3}{2})$	$De_{\mathbb{C}}H^{\dagger 3}L^\dagger$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(F10),(F12)]$ $De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(V2),(V5),(S6),(S2)]$
$V5\ (\mathbf{1},\mathbf{3},1)$	$D^2H^2L^2$ $De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(F3),(V3),(F5)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$
$V5\ (\mathbf{3},\mathbf{1},\frac{2}{3})$	$Dd_{\mathbb{C}}{}^3e_{\mathbb{C}}^\dagger$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(F1),(V8),(F12)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(F1),(V8),(F12)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(V8),(F10),(F8)]$
$V8\ (\mathbf{3},\mathbf{2},\frac{1}{6})$	$Dd_{\mathbb{C}}L^2u_{\mathbb{C}}^\dagger$ $Dd_{\mathbb{C}}{}^2LQ^\dagger$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(F5),(F1),(V9),(V5),(F13),(F8)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(F5),(F1),(V9),(V5),(F13),(F8)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(V5),(F10),(F3)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(V5),(F10),(F3)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$
$V9\ (\mathbf{3},\mathbf{3},\frac{2}{3})$	$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(F5),(V8),(F12)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(V8),(F10),(F13)]$

Fermion	
$(SU(3)_c, SU(2)_2, U(1)_y)$	
$F1\ (\mathbf{1},\mathbf{1},0)$	$D^2H^2L^2$ $e_{\mathbb{C}}HL^3[(S4),(S2)]$ $d_{\mathbb{C}}HL^2Q[(S4),(S10),(S12)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(V5),(V8)]$ $De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(S2),(F3),(V2)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S11),(S10)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(V5)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(S10),(V8)]$ $H^2L^2W_L[(F5)]$ $H^3H^\dagger L^2[(S2,F3),(S5,F5),(S1),(S6,F6),(S2,F2),(F3,F5),$ $(F3),(S4,S6),(S2,S4),(S6,F3),(S4,S5),(S1,S4),(F3,F6),$ $(F2,F3),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$
$F2\ (\mathbf{1},\mathbf{1},1)$	$d_{\mathbb{C}}{}^3H^\dagger L[(S11)]$ $H^3H^\dagger L^2[(S6,F5),(S2,F1),(F3,F5),$ $(F1,F3),(S5,S6),(S2,S5),(S6,F3),(S2,F3)]$
$F3\ (\mathbf{1},\mathbf{2},\frac{1}{2})$	$De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(F5),(F1),(S6),(S2),(V2),(V5)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S12),(V8)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(V8),(S11)]$
$F4\ (\mathbf{1},\mathbf{2},\frac{3}{2})$	$e_{\mathbb{C}}HL^3[(S6),(S2)]$
$F5\ (\mathbf{1},\mathbf{3},0)$	$e_{\mathbb{C}}HL^3[(S4),(S6)]$ $d_{\mathbb{C}}HL^2Q[(S4),(S12),(S14)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(V9),(V8)]$ $D^2H^2L^2$ $De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(S6),(F3),(V5)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(S14),(V8)]$ $H^2L^2W_L[(F7),(F1)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$
$F6\ (\mathbf{1},\mathbf{3},1)$	$H^3H^\dagger L^2[(S6,F5),(S6,F1),(S2,F5),(F5,F7),(F3,F5),$ $(F1,F3),(S6,S8),(S5,S6),(S2,S5),(S6,F7),(S6,F3),(S2,F3)]$
$F7\ (\mathbf{1},\mathbf{4},\frac{1}{2})$	$H^2L^2W_L[(F5),(S6)]$ $H^3H^\dagger L^2[(F5),(S6,F5),(F5,F6),(S6,F6),(S5,F5),(S5,S6)]$
$F8\ (\mathbf{3},\mathbf{1},-\frac{1}{3})$	$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S2),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(V8),(S12),(V5)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(V5),(S11)]$
$F9\ (\mathbf{3},\mathbf{1},\frac{2}{3})$	$d_{\mathbb{C}}HL^2Q[(S12),(S2)]$
$F10\ (\mathbf{3},\mathbf{2},-\frac{5}{6})$	$d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S12),(S10),(S13)]$ $d_{\mathbb{C}}HL^2Q[(S10),(S6),(S$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(V3),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(S10),(S14),$
$F11\ (\mathbf{3},\mathbf{2},\frac{1}{6})$	$d_{\mathbb{C}}{}^3H^\dagger L[(S11),(S12)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S11),(S12)]$
$F12\ (\mathbf{3},\mathbf{2},\frac{7}{6})$	$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(S2),(V9),(V5)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(V5),(S12),(V3)]$
$F13\ (\mathbf{3},\mathbf{3},-\frac{1}{3})$	$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(V8),(S12),(V9)]$
$F14\ (\mathbf{3},\mathbf{3},\frac{2}{3})$	$d_{\mathbb{C}}HL^2Q[(S12),(S6)]$

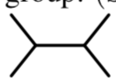
More LHC searches!

Complete Dim-8 UV Resonances

Type: $D^4H^2H^{\dagger 2}$

$$\mathcal{O}_1^f = \tfrac{1}{4}\mathcal{Y}[\square\square_H]\mathcal{Y}[\square\square_{H^\dagger}]H_iH_j(D_\mu D_\nu H^{\dagger i})(D^\mu D^\nu H^{\dagger j}),$$
$$\mathcal{O}_2^f = \tfrac{1}{4}\mathcal{Y}[\square\square_H]\mathcal{Y}[\square\square_{H^\dagger}]H^{\dagger i}H_i(D_\mu D_\nu H_j)(D^\mu D^\nu H^{\dagger j}),$$
$$\mathcal{O}_3^f = \tfrac{1}{4}\mathcal{Y}[\square\square_H]\mathcal{Y}[\square\square_{H^\dagger}]H_i(D_\mu H_j)(D_\nu H^{\dagger i})(D^\mu D^\nu H^{\dagger j}).$$

group: $(\mathrm{Spin}, SU(3)_c, SU(2)_w, U(1)_y)$



	group	
	$\{H_1, H_2\}, \{H^\dagger{}_3, H^\dagger{}_4\}$	
*	$(2,1,3,1)$	$-8\mathcal{O}_1^f - 48\mathcal{O}_2^f - 48\mathcal{O}_3^f$
	$(0,1,3,1)$	$8\mathcal{O}_1^f$
	$(1,1,1,1)$	$8\mathcal{O}_1^f + 16\mathcal{O}_3^f$
	$\{H_1, H^\dagger{}_3\}, \{H_2, H^\dagger{}_4\}$	
*	$(2,1,3,0)$	$16\mathcal{O}_1^f - 4\mathcal{O}_2^f + 56\mathcal{O}_3^f$
	$(1,1,3,0)$	$8\mathcal{O}_1^f - 4\mathcal{O}_2^f + 8\mathcal{O}_3^f$
	$(0,1,3,0)$	$8\mathcal{O}_1^f + 4\mathcal{O}_2^f + 16\mathcal{O}_3^f$
*	$(2,1,1,0)$	$-24\mathcal{O}_1^f - 4\mathcal{O}_2^f - 24\mathcal{O}_3^f$
	$(1,1,1,0)$	$-4\mathcal{O}_2^f - 8\mathcal{O}_3^f$
	$(0,1,1,0)$	$4\mathcal{O}_2^f$

In the forward limit, a twice-subtracted dispersion relation

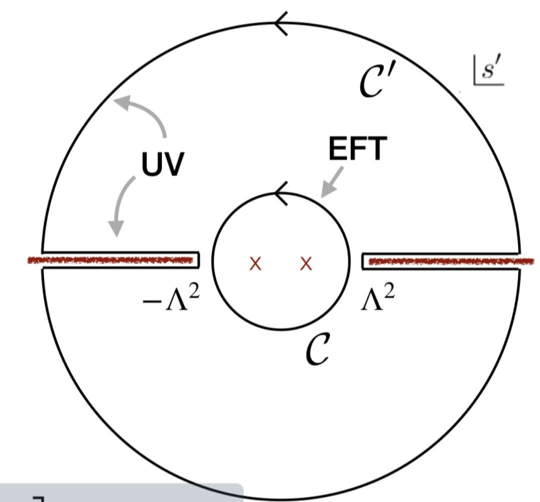
$$\mathcal{M}^{ijkl} = \frac{1}{2\pi}\int_{(\epsilon\Lambda)^2}^{\infty}\frac{ds}{s^3}\sum_X\left[\mathbf{M}_{ij\to X}\mathbf{M}^*_{kl\to X} + (j \leftrightarrow l)\right]$$

Particle	Spin	Charge/irrep	Interaction	ER	$\vec{c}$	$\vec{c}^{(6)}$
$\mathcal{B}_1$	1	1_1	$g\mathcal{B}_1^{\mu\dagger}(H^T\epsilon\overleftrightarrow{D}_\mu H) + h.c.$	✓	$8(1,0,-1)$	$2(-1,2)$
Ξ_1	0	3_1	$gM\Xi_1^{I\dagger}(H^T\epsilon\tau^I H) + h.c.$	✗	$8(0,1,0)$	$2(1,2)$
$\mathcal{S}$	0	$1_0(S)$	$gM\mathcal{S}(H^\dagger H)$	✓	$2(0,0,1)$	$-\frac{1}{2}(1,0)$
$\mathcal{B}$	1	$1_0(A)$	$g\mathcal{B}^\mu(H^\dagger\overleftrightarrow{D}_\mu H)$	✓	$2(-1,1,0)$	$-\frac{1}{2}(1,4)$
Ξ_0	0	$3_0(S)$	$gM\Xi_0^I(H^\dagger\tau^I H)$	✗	$2(2,0,-1)$	$\frac{1}{2}(1,-4)$
$\mathcal{W}$	1	$3_0(A)$	$g\mathcal{W}^{\mu I}(H^\dagger\tau^I\overleftrightarrow{D}_\mu H)$	✗	$2(1,1,-2)$	$-\frac{3}{2}(1,0)$

Analyticity in complex s plane (fixed t)

$$A(s,t) = \frac{1}{2\pi i}\oint_{\mathcal{C}} ds' \frac{A(s',t)}{s'-s}$$

Cauchy's integral formula



Fixed t dispersion relation

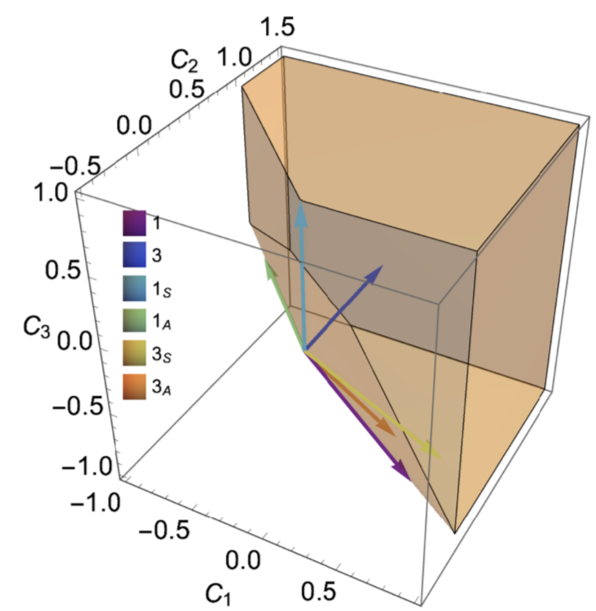
$$A(s,t) \sim \int_{\Lambda^2}^{\infty}\frac{d\mu}{\pi\mu^2}\left[\frac{s^2}{\mu-s} + \frac{u^2}{\mu-u}\right]\mathrm{Im}\,A(\mu,t)$$

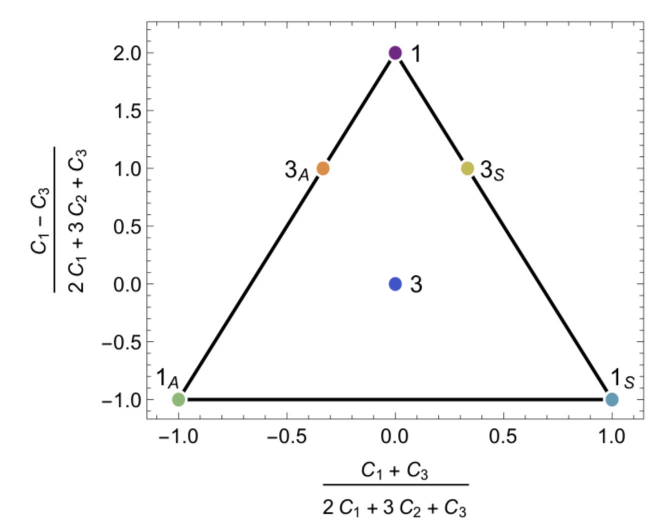
$\mu > \Lambda^2$

EFT amplitude **IR ~ UV connection** UV full amplitude

$$\mathrm{Disc}A_{ij\to kl}(s) = A_{ij\to kl}(s) - A_{kl\to ij}(s)^* = i\sum_X M_{ij\to X}(s)M_{kl\to X}(s)^*$$

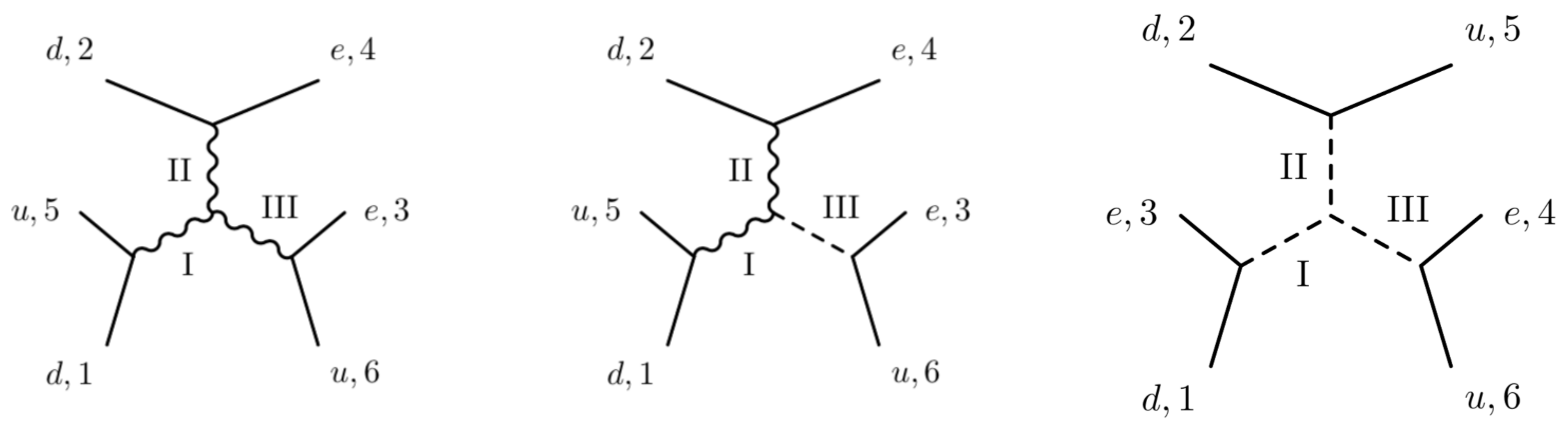
S.Y. Zhou





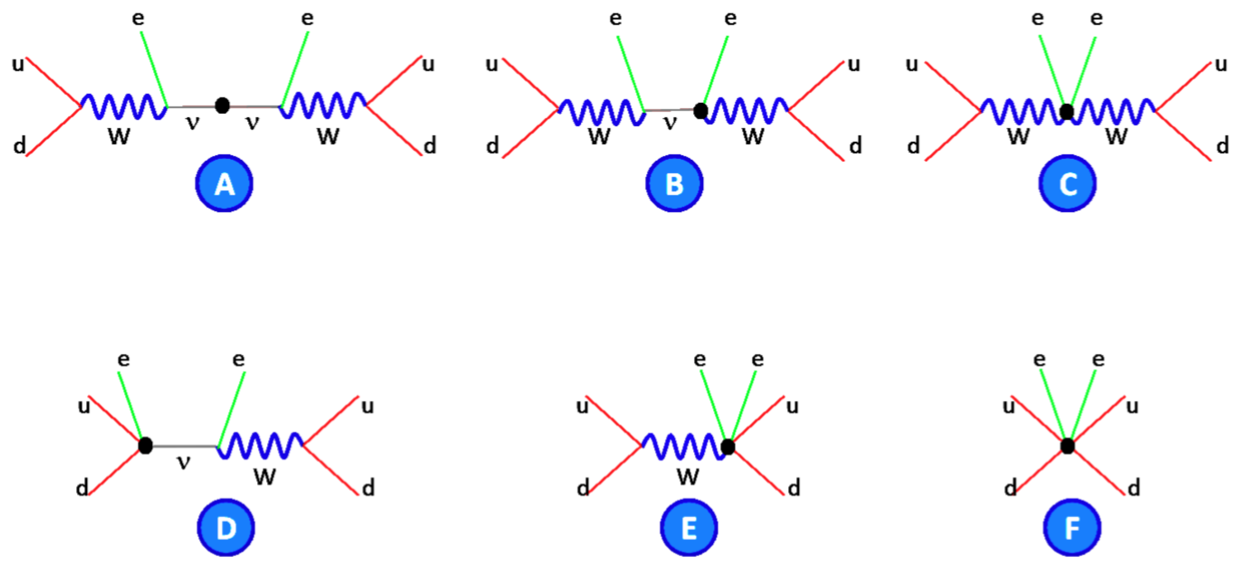
[Cen Zhang, 2021]

Dim-9: 0vbb

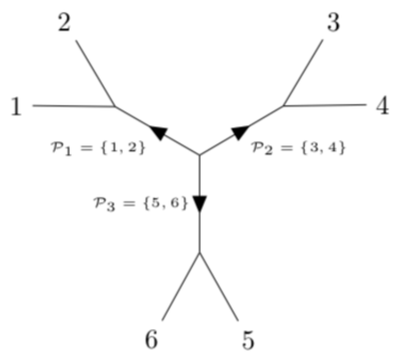


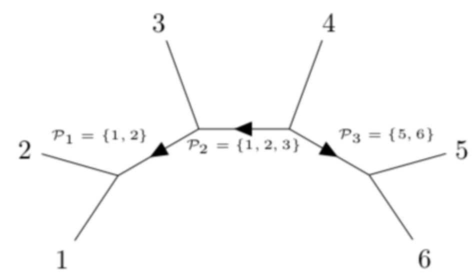
[Bonnet, Hirsch, Ota, Winter, 2012]

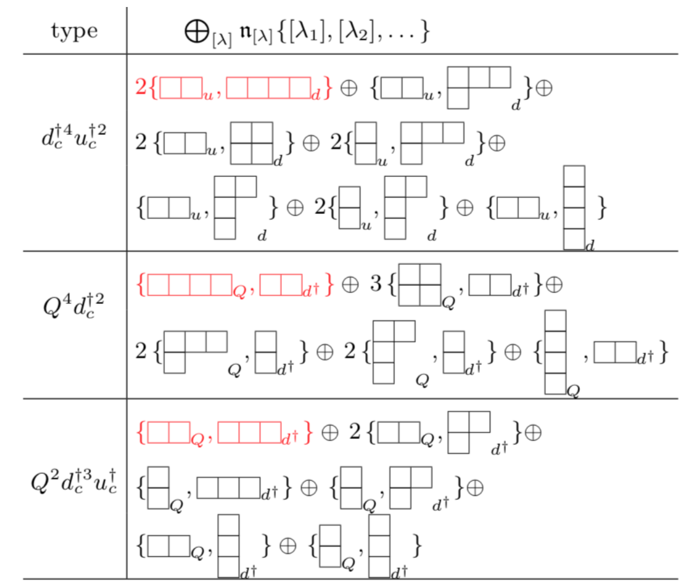
$$\mathbf{W}^2\mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$



Dim-9: n-nbar oscillation



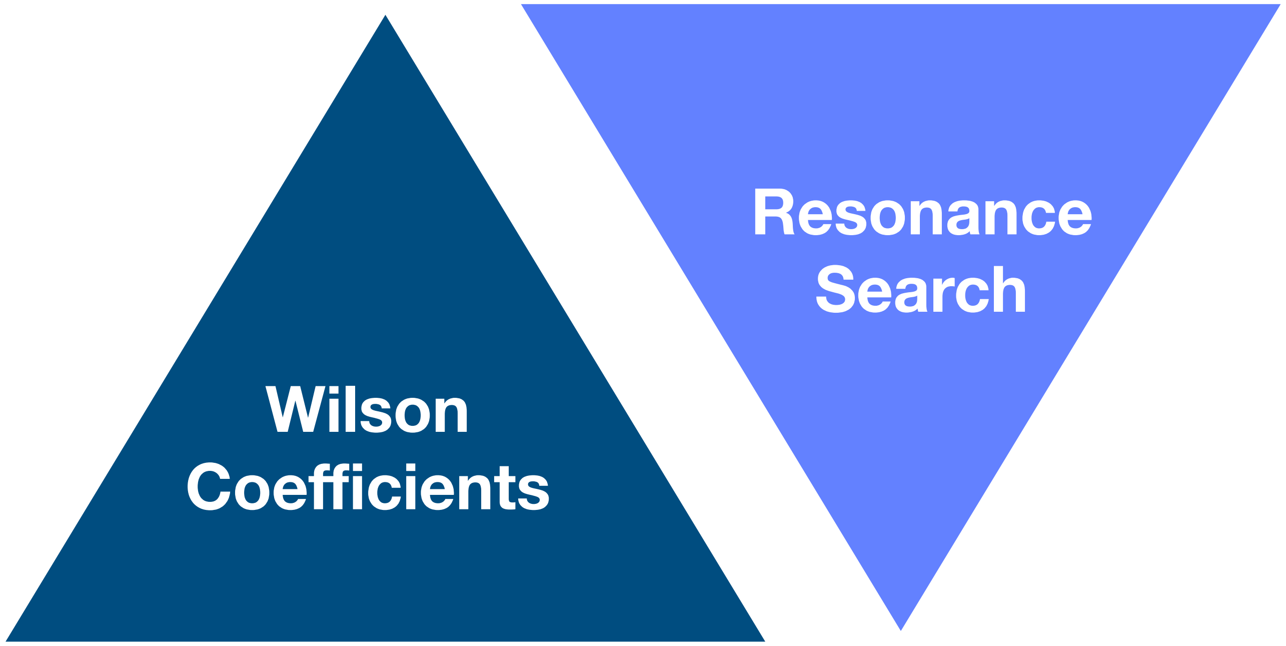




$(\mathbf{r}_i, J_i)$	$(1,1,1)$	$(0,1,1)$	$(1,0,1)$	$(1,1,0)$	$(0,0,0)$
$(\mathbf{6},\mathbf{6},\mathbf{6})$	0	$3\mathcal{O}_1 + 8\mathcal{O}_2$	0	0	$\mathcal{O}_1 - 8\mathcal{O}_2$ [Babu, Mohapatra, Nasri, 2006]
$(\mathbf{6},\bar{\mathbf{3}},\bar{\mathbf{3}})$	0	$\mathcal{O}_2$	0	0	$\mathcal{O}_2$
$(\bar{\mathbf{3}},\mathbf{6},\bar{\mathbf{3}})$	$3\mathcal{O}_1 + 8\mathcal{O}_2$	0	$\mathcal{O}_1 - 8\mathcal{O}_2$	$3\mathcal{O}_1 + 8\mathcal{O}_2$	0
$(\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{6})$	$3\mathcal{O}_1 + 8\mathcal{O}_2$	0	$3\mathcal{O}_1 + 8\mathcal{O}_2$	$\mathcal{O}_1 - 8\mathcal{O}_2$	0
$(\bar{\mathbf{3}},\bar{\mathbf{3}},\bar{\mathbf{3}})$	$-3\mathcal{O}_1 + 8\mathcal{O}_2$	0	$3\mathcal{O}_1 + 8\mathcal{O}_2$	$3\mathcal{O}_1 + 8\mathcal{O}_2$	0

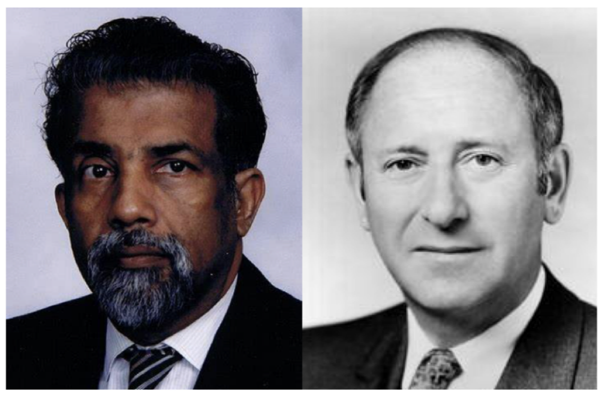
$$\mathcal{O}_1^{\mathrm{p}} = \epsilon^{ace}\epsilon^{bdf}(d_{Ra}d_{Rb})(d_{Rc}d_{Rd})(u_{Re}u_{Rf}),$$
$$\mathcal{O}_2^{\mathrm{p}} = \epsilon^{acd}\epsilon^{bef}(d_{Ra}d_{Rb})(d_{Rc}u_{Re})(d_{Rd}u_{Rf}).$$

Is EFT an effective pathway to new physics?



V-A Theory and W-boson

With universal couplings (correlation), the correct UV resonances are picked up



Marshak, Sudarshan
1957

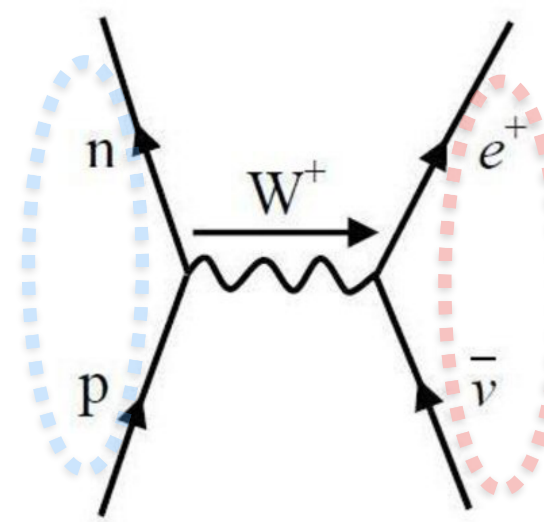
Gell-mann, Feynman
1957

Lee-Yang
1960

$$\frac{G_F}{\sqrt{2}} g_{\mu\nu}[\overline{\psi}\gamma^\mu(1-\gamma^5)\psi][\overline{\psi}\gamma^\nu(1-\gamma^5)\psi]$$

- (i) muon decay: $g_{e\mu}$
  $\mu^- \to \nu_\mu e^- \bar{\nu}_e$
- (ii) neutron decay : g_{ud}
  $n \to p e^- \bar{\nu}_e \ (d \to u e^- \bar{\nu}_e)$
- (ii) kaon decay: g_{us}
  $K^- \to \pi^0 e^- \bar{\nu}_e \ (s \to u e^- \bar{\nu}_e)$

Universal weak couplings

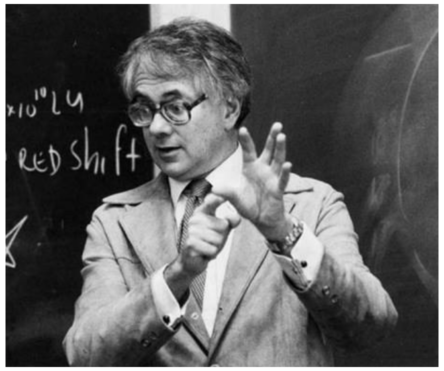


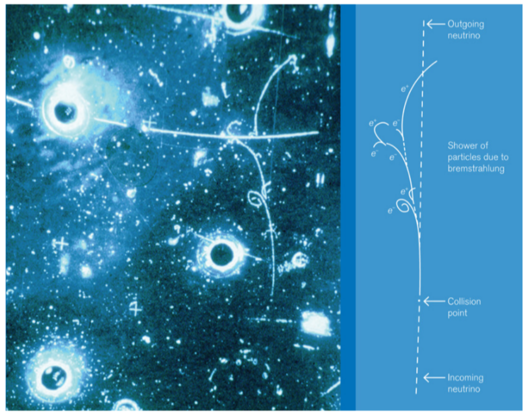
Strong isospin (gauge SU2)

Weak isospin?

Electroweak Standard Model

Lagrangian universal couplings (operator correlation) are the key to the UV model!




Schwinger 1957

Glashow 1961

Weinberg-Salam 1967

CERN Bubble Chamber 1973

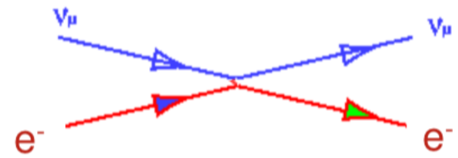
Nobel prize 1979

Electroweak unification?

Both E&W display universality

Both E&W known to be vectorial

$\nu_\mu\, e^- \to \nu_\mu\, e^-$

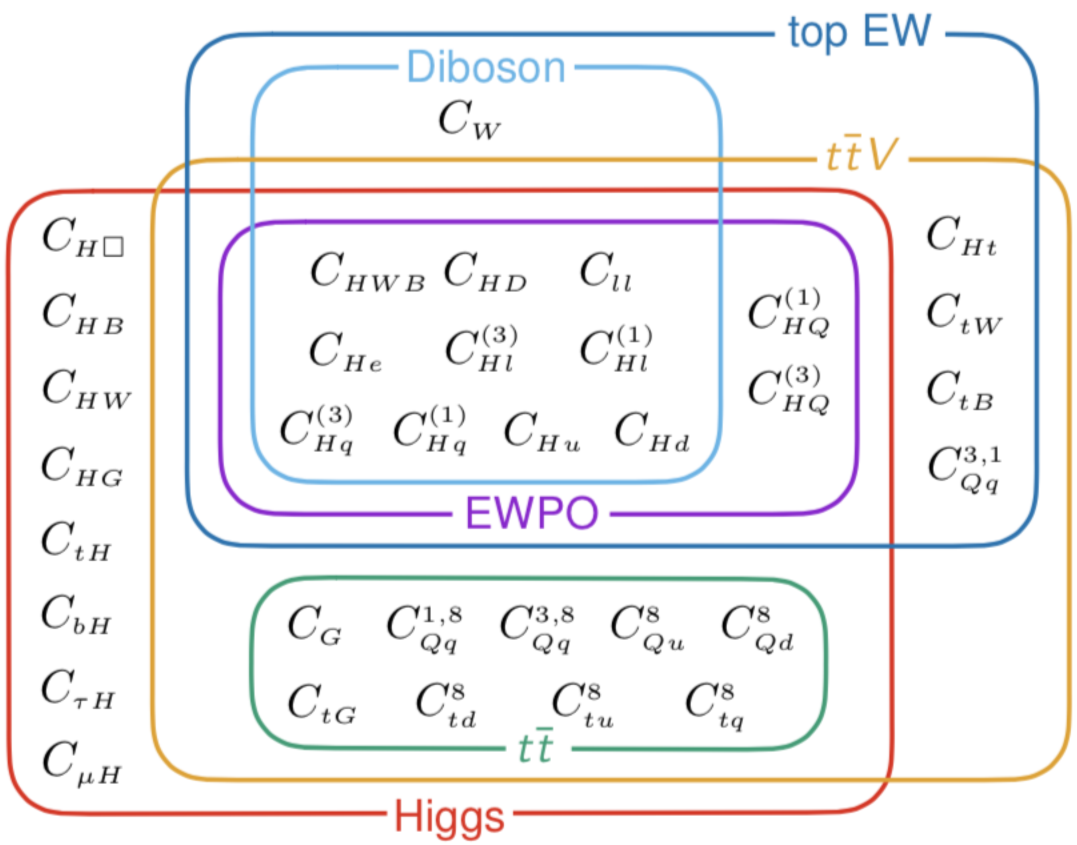


Neutral current EFT operator

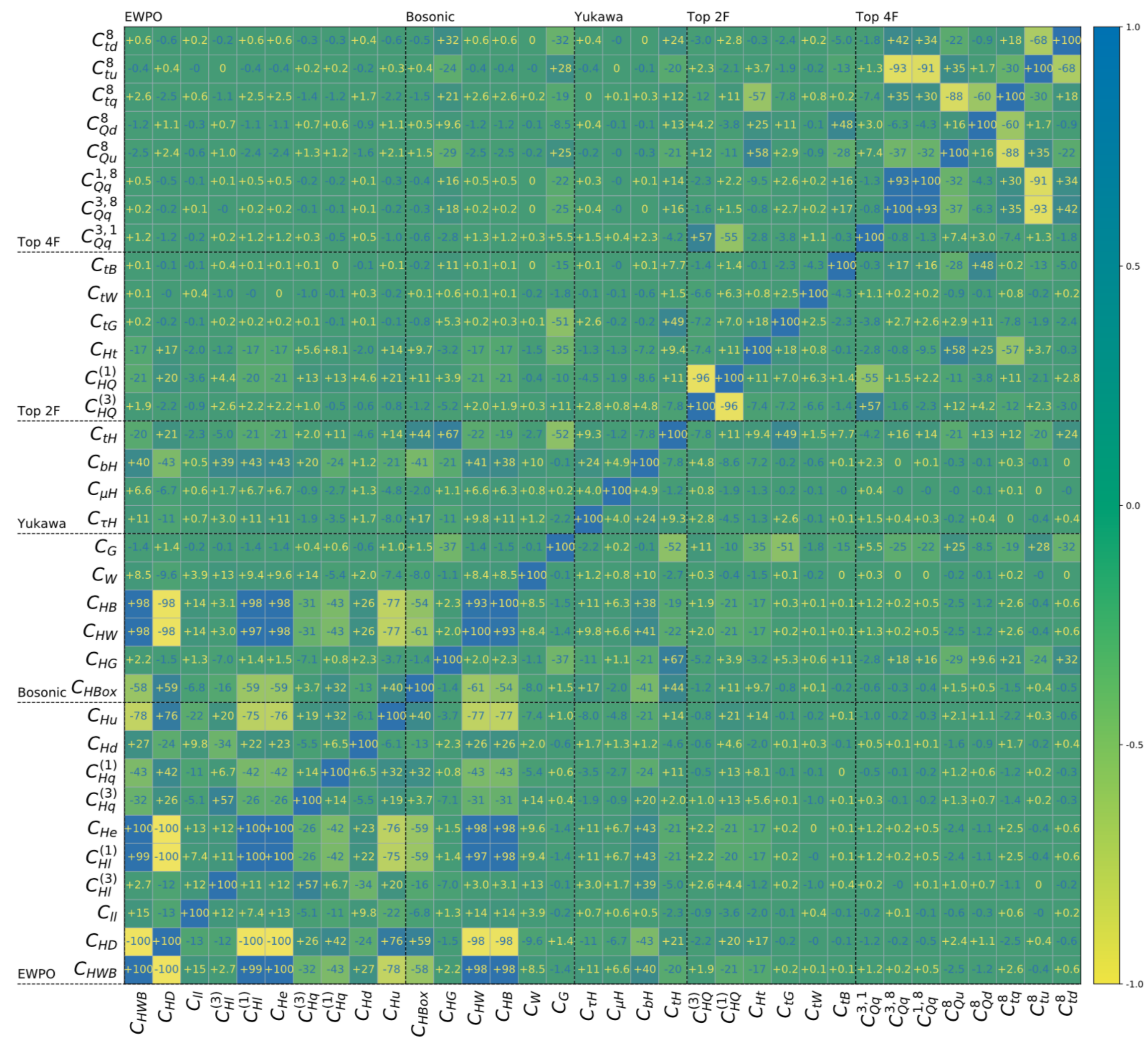
No resonance observed yet

SMEFT Operator Correlation

SMEFT operators parametrize all possible Lorentz-invariant new physics effects



[Ellis, et.al 2020]



Unfortunately there are only limits on the effective operators

SMEFT Operator Correlation

Effective Operator

Kinematics

$$\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)+C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

Various possible UVs

Symmetry

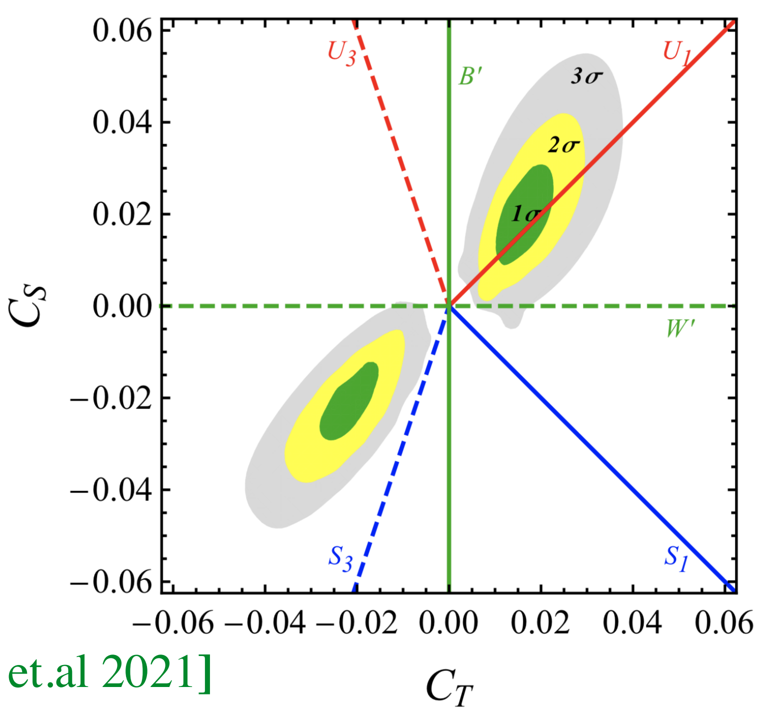
$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S^L_{1/2}),\ LR\,(S^R_{1/2})$	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}^L_{1/2}),\ \overline{LR}\,(\tilde{S}^{\bar{L}}_{1/2})$	0
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}^R_0)$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S^L_0),\ RR\,(S^R_0),\ \overline{RR}\,(S^{\bar{R}}_0)$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}^{\bar{R}}_0)$	-2
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V^L_{1/2}),\ LR\,(V^R_{1/2})$	-2
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}^L_{1/2}),\ \overline{LR}\,(\tilde{V}^{\bar{R}}_{1/2})$	-2
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}^R_0)$	0
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	$LL\,(V^L_0),\ RR\,(V^R_0),\ \overline{RR}\,(V^{\bar{R}}_0)$	0
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	$\overline{RR}\,(\bar{V}^{\bar{R}}_0)$	0

$$R_K = 0.846^{+0.060\,+0.016}_{-0.054\,-0.014}\,, \quad \text{for}\ \ 1.1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2\,,$$

$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03\,, & \text{for } 0.045\,\text{GeV}^2 < q^2 < 1.1\,\text{GeV}^2\,, \\ 0.69^{+0.11}_{-0.07} \pm 0.05\,, & \text{for } 1.1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2\,, \end{cases}$$

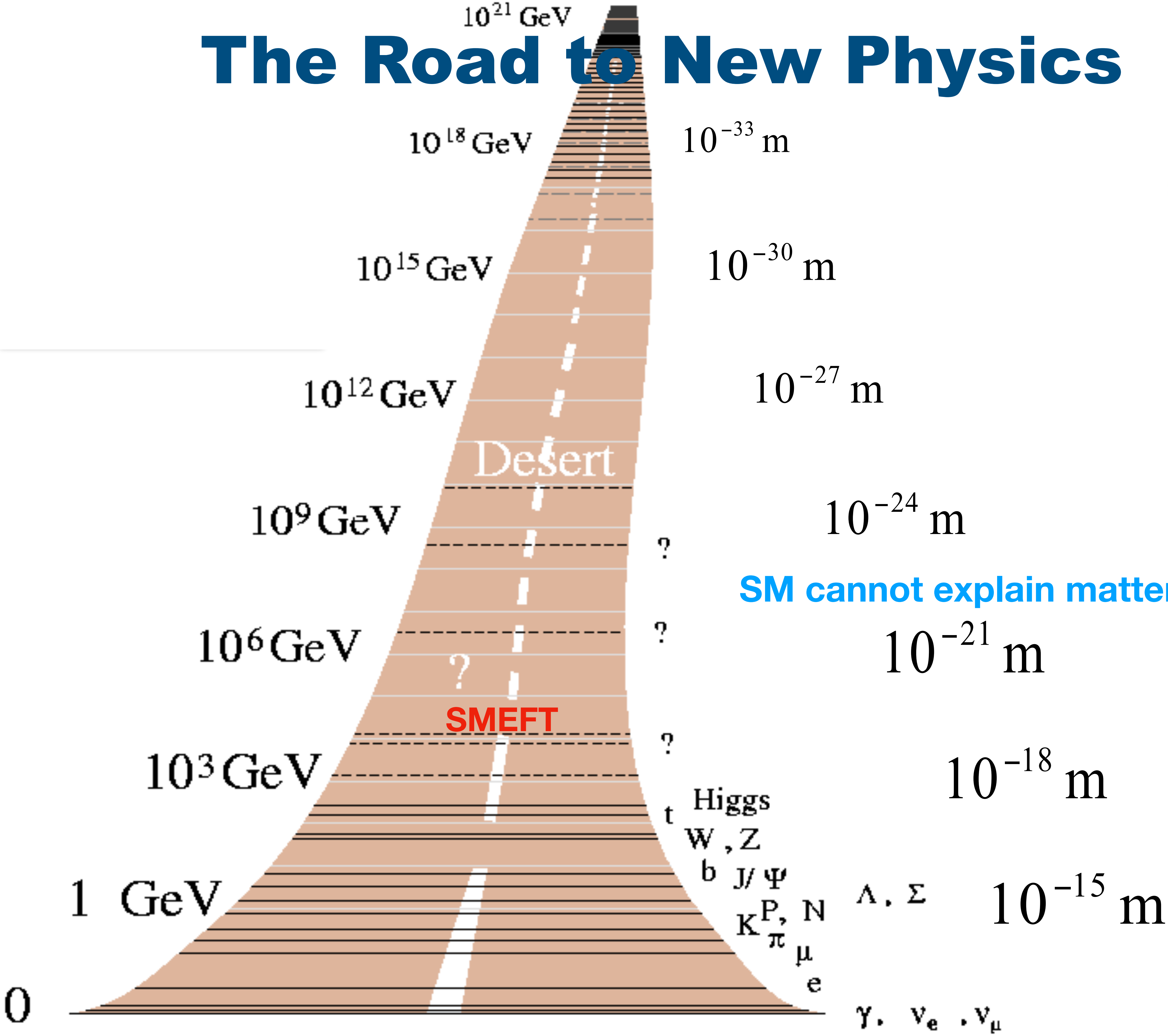
Wilson Coefficient Correlation

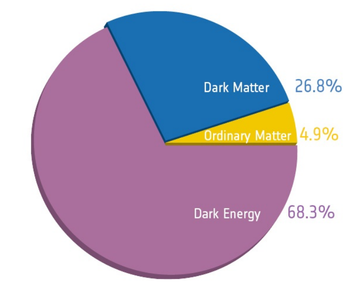
Dynamics



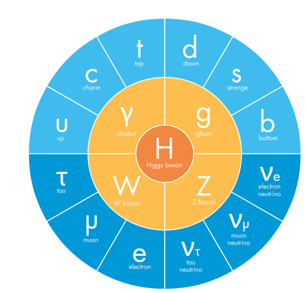
[Cornella, et.al 2021]

The Road to New Physics





SM cannot explain matter, DM, DE!



Remark: A Bigger Picture

Effective operator has more symmetries than what we expected

Conformal symmetry

Spinor representation

$$[D, P_\mu] = -iP_\mu,$$
$$[D, K_\mu] = iK_\mu,$$
$$[K_\mu, P_\nu] = 2i(\eta_{\mu\nu}D + M_{\mu\nu}),$$
$$[M_{\mu\nu}, K_\rho] = i(\eta_{\mu\rho}K_\nu - \eta_{\nu\rho}K_\mu),$$

$$P^{\alpha\dot\alpha} = \sum_i \lambda_i^\alpha \tilde\lambda_i^{\dot\alpha} \qquad -iD = n + \frac{1}{2}\sum_i \left(\lambda_i^\alpha \partial_{i\alpha} + \tilde\lambda_i^{\dot\alpha}\bar\partial_{i\dot\alpha}\right),$$
$$K_{\alpha\dot\alpha} = -4\sum \partial_{i\alpha}\bar\partial_{i\dot\alpha} \qquad -iM_{\alpha\beta} = \sum_i \lambda_{i\alpha}\partial_{i\beta} + \lambda_{i\beta}\partial_{i\alpha},$$
$$W_{\alpha\dot\alpha} = \frac{i}{2}\left(P_{\alpha\dot\beta}\bar M^{\dot\beta}{}_{\dot\alpha} - M_\alpha{}^\beta P_{\beta\dot\alpha}\right) \qquad -i\bar M_{\dot\alpha\dot\beta} = \sum_i \tilde\lambda_{i\dot\alpha}\bar\partial_{i\dot\beta} + \tilde\lambda_{i\dot\beta}\bar\partial_{i\dot\alpha}.$$

Special conformal K — **Amplitude-basis**

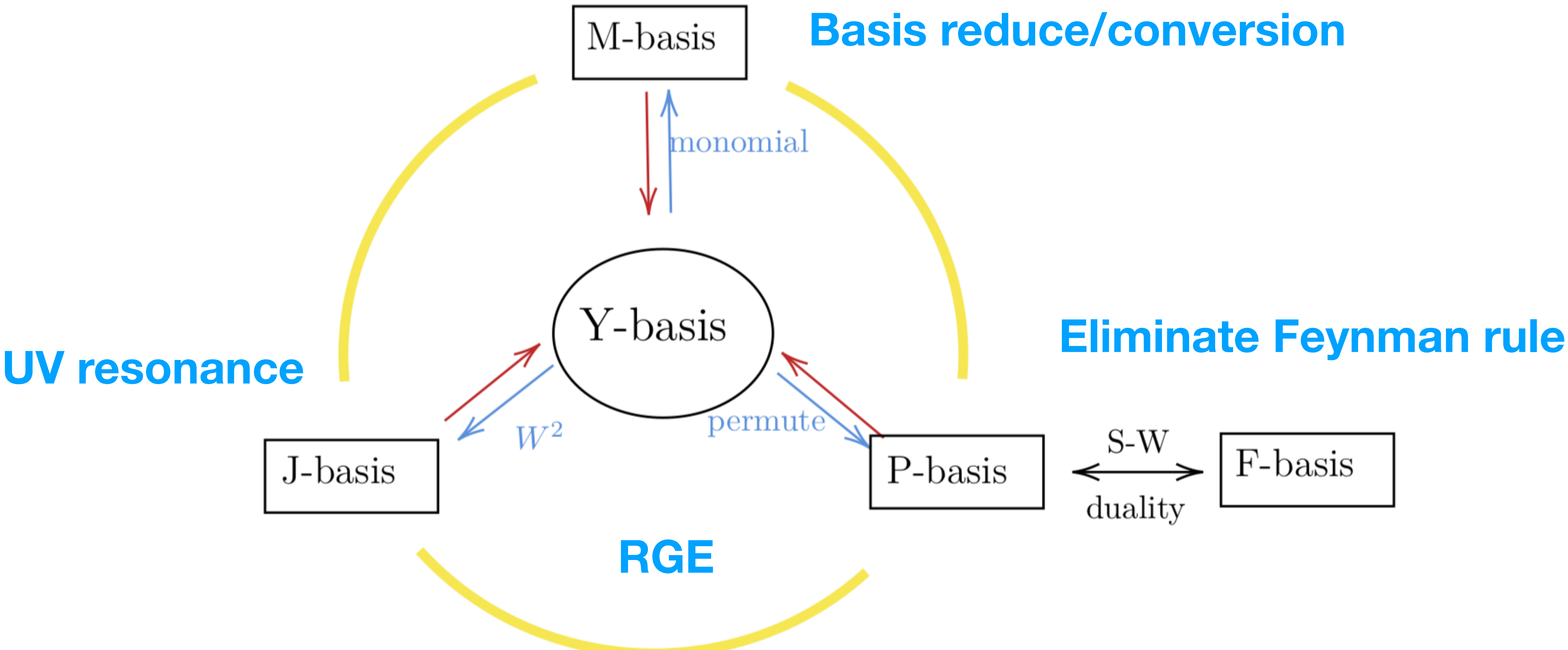
Pauli-Lubanski W — **UV resonances**

Dilatation D — **Anomalous dim**

(Global) symmetry determines interaction (operator)!

Why Young Tensor Basis?

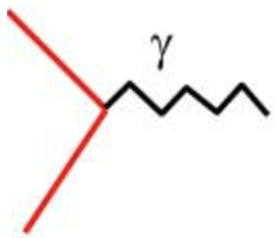
Young Tensor basis exhibits the space-time symmetry of underlying S-matrix



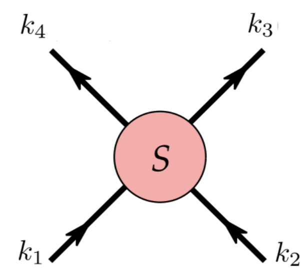
example of “(global) symmetry determines interaction”

Deja Vu: Open door for future?!?

From local symmetry to asymptotic global symmetry, and back



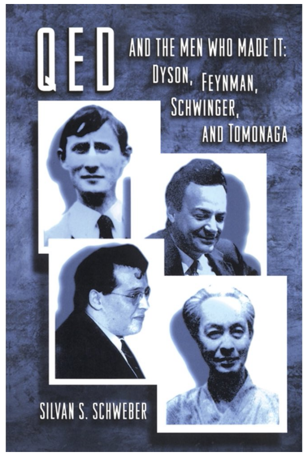
QED



S-matrix, bootstrap

Weinberg:
Why it fails?

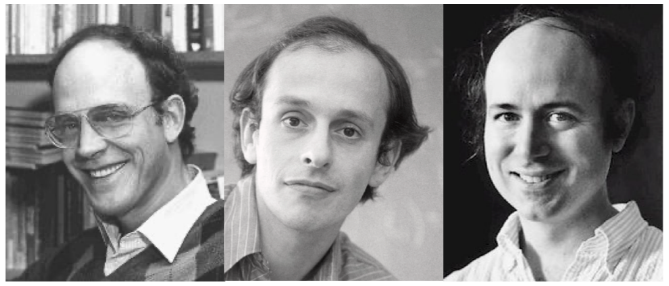
QCD



$$
\begin{aligned}
\mathcal{L}_4 = {} & L_1 \langle D_\mu U^\dagger D^\mu U\rangle^2 + L_2 \langle D_\mu U^\dagger D_\nu U\rangle \langle D^\mu U^\dagger D^\nu U\rangle \\
& + L_3 \langle D_\mu U^\dagger D^\mu U D_\nu U^\dagger D^\nu U\rangle + L_4 \langle D_\mu U^\dagger D^\mu U\rangle \langle U^\dagger \chi + \chi \dagger U\rangle \\
& + L_5 \langle D_\mu U^\dagger D^\mu U \left(U^\dagger \chi + \chi^\dagger U\right)\rangle + L_6 \langle U^\dagger \chi + \chi^\dagger U\rangle^2 \\
& + L_7 \langle U^\dagger \chi - \chi^\dagger U\rangle^2 + L_8 \langle \chi^\dagger U \chi^\dagger U + U^\dagger \chi U^\dagger \chi\rangle \\
& - i L_9 \langle F_R^{\mu\nu} D_\mu U D_\nu U^\dagger + F_L^{\mu\nu} D_\mu U^\dagger D_\nu U\rangle + L_{10} \langle U^\dagger F_R^{\mu\nu} U F_{L\mu\nu}\rangle
\end{aligned}
$$

Dynamics: xPT

i	$L_i^r(M_\rho) \times 10^3$	Source	Γ_i
1	1.0 ± 0.1	K_{e4}, $\pi\pi \to \pi\pi$	3/32
2	1.6 ± 0.2	K_{e4}, $\pi\pi \to \pi\pi$	3/16
3	-3.8 ± 0.3	K_{e4}, $\pi\pi \to \pi\pi$	0
4	0.0 ± 0.3	Zweig rule	1/8
5	1.2 ± 0.1	F_K/F_π	3/8
6	0.0 ± 0.4	Zweig rule	11/144
7	-0.3 ± 0.2	GMO, $L_{5,8}$	0
8	0.5 ± 0.2	$M_{K^0} - M_{K^+}$, L_5, $(m_s - \hat{m})/(m_d - m_u)$	5/48
9	6.9 ± 0.7	$\langle r^2\rangle_V^\pi$	1/4
10	-5.2 ± 0.17	$\tau \to \nu_\tau + \text{hadrons}$, $\pi \to e\nu\gamma$	−1/4



Standard Model

effective operator
UV resonances

new physics

Dynamics:
correlation

Summary

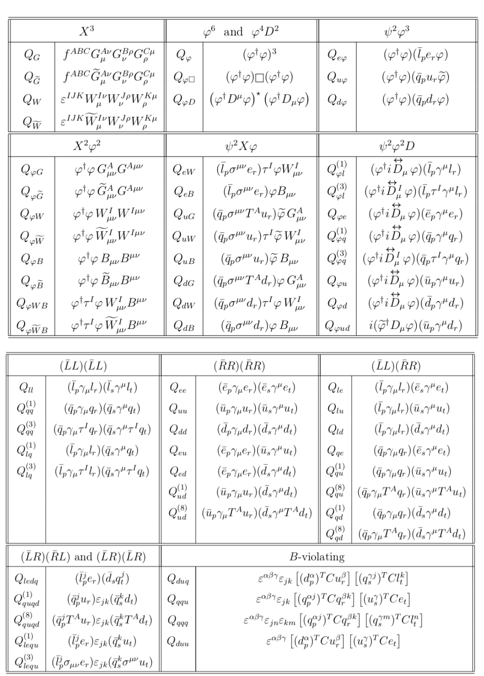
Take home message 1: paradigm shift in new physics

Bottom-up EFT provides a clear pathway to new physics step by step

Take home message 2: symmetry determines interaction

From Warsaw dim-6 to any-dim Young tensor basis and UVs systematically

Warsaw basis → Young Tensor Basis → Complete UVs

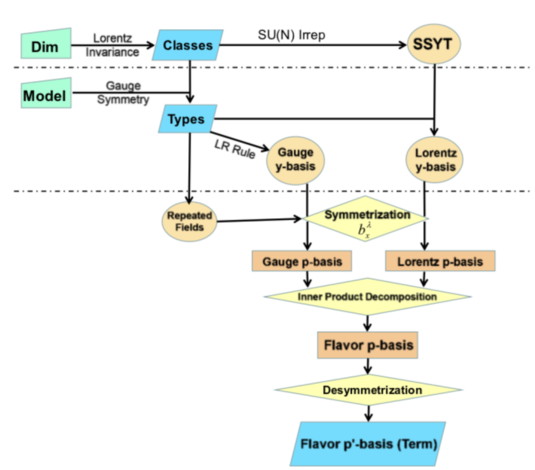


X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r\varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r\widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	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}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	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}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

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

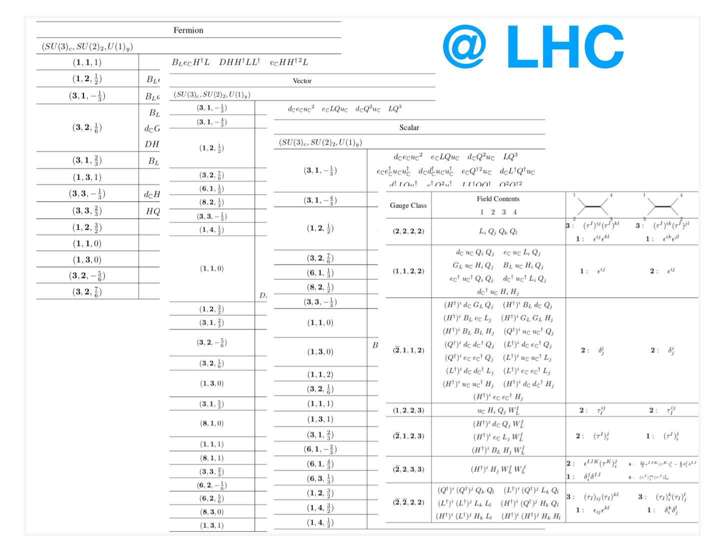
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q^{(1)}_{quqd}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k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

Any operator to any mass dimension



Complete UV resonances

@ LHC



Thanks for your attention!

Backup Slides

Literatures on SMEFT

The SMEFT approach

Precision era @LHC with all experimental data consistent wit[h]
the use of:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \dots$$

describing any UV physics at $\Lambda \gg v$

Bases

d=5: Weinberg PRL43(1979)1566
d=6: Buchmller,Wyler Nucl.Phys.B268(1986)621
Grzadkowski et al 1008.4884
d=7: Lehman 1410.4193, Henning,Lu,Melia,Murayama 1512.0343
d=8: Li,Ren,Shu,Xiao,Yu,Zheng 2005.00008
Murphy 2005.00059
d=9: Li,Ren,Xiao,Yu,Zheng 2007.07899, Liao,Ma 2007.08125

Anomalous dimensions (d=6)

Alonso,Jenkins,Manohar,Trott 1308.2627,1310.4838,1312.2014
Grojean,Jenkins,Manohar,Trott1301.2588
Alonso,Chang,Jenkins,Manohar,Shotwell 1405.0486
Miro,Ingoldby,Riembau 2005.06983
Baratella,Fernandez,Pomarol 2005.07129,2010.13809

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis

- # parameters known for all orders
- complete bases up to $d = 9$

5: Weinberg PRL43(1979)1566
6: Buchmller,Wyler Nucl.Phys.B268(1986)621, Grzadkowski et al 1008.4884
7: Lehman 1410.4193, Henning,Lu,Melia,Murayama 1512.0343
8: Li,Ren,Shu,Xiao,Yu,Zheng 2005.00008, Murphy 2005.00059
9: Li,Ren,Xiao,Yu,Zheng 2007.07899, Liao,Ma 2007.08125

Notations for this Talk

$\psi_\alpha \in (1/2, 0), \quad \psi^\dagger_{\dot\alpha} \in (0, 1/2),$ $\qquad H_i \in (0,0)\,, \quad H^{\dagger i} \in (0,0)\,,$

$F_{\mathrm{L}\alpha\beta} = \frac{i}{2} F_{\mu\nu}\sigma^{\mu\nu}_{\alpha\beta} \in (1,0), \quad F_{\mathrm{R}\dot\alpha\dot\beta} = -\frac{i}{2} F_{\mu\nu}\bar\sigma^{\mu\nu}_{\dot\alpha\dot\beta} \in (0,1).$ $\qquad X^{\mu\nu}_{L,R} = \frac{1}{2}(X^{\mu\nu} \mp i\widetilde{X}^{\mu\nu})$

$$h = j_r - j_l$$

Fields	$SU(2)_l \times SU(2)_r$	h	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	Flavor
$G^A_{\mathrm{L}\alpha\beta}$	$(1,0)$	-1	$\mathbf{8}$	$\mathbf{1}$	0	1
$W^I_{\mathrm{L}\alpha\beta}$	$(1,0)$	-1	$\mathbf{1}$	$\mathbf{3}$	0	1
$B_{\mathrm{L}\alpha\beta}$	$(1,0)$	-1	$\mathbf{1}$	$\mathbf{1}$	0	1
$L_{\alpha i}$	$(\frac{1}{2},0)$	$-1/2$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	n_f
$e_{\mathrm{c}\alpha}$	$(\frac{1}{2},0)$	$-1/2$	$\mathbf{1}$	$\mathbf{1}$	1	n_f
$Q_{\alpha a i}$	$(\frac{1}{2},0)$	$-1/2$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	n_f
$u^a_{\mathrm{c}\alpha}$	$(\frac{1}{2},0)$	$-1/2$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	n_f
$d^a_{\mathrm{c}\alpha}$	$(\frac{1}{2},0)$	$-1/2$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	n_f
H_i	$(0,0)$	0	$\mathbf{1}$	$\mathbf{2}$	$1/2$	1

Hermitian conjugate $\qquad (F_{\mathrm{L}\alpha\beta})^\dagger = F_{\mathrm{R}\dot\alpha\dot\beta}$

$H^\dagger$ (and $L^\dagger, Q^\dagger$) as a 2 of $SU(2)$ $\quad \epsilon^{ij} H^\dagger_i H_j. \quad H^\dagger_{\bar 2} = \epsilon H^\dagger_2$ $\qquad e_R = e^\dagger_C, u_R = u^\dagger_C, d_R = d^\dagger_C$

$\tilde H = \epsilon H^\dagger$

Fierz and Schouten Identities

$$\Psi = \begin{pmatrix} \xi_\alpha \\ \chi^{\dagger\dot{\alpha}} \end{pmatrix}, \quad \bar{\Psi} = \Psi^\dagger \gamma^0 = \left(\chi^\alpha, \ \xi^\dagger_{\dot{\alpha}}\right)$$

$$u_{\mathbb{C}} \sigma^\mu u^\dagger_{\mathbb{C}} = \bar{u}\gamma^\mu u, \quad e_{\mathbb{C}} L = \bar{e}\, l, \quad u^\dagger_{\mathbb{C}} d^\dagger_{\mathbb{C}} = u^T C d\,.$$

Fierz identity

$$\begin{pmatrix} \delta_{ij}\delta_{kl} \\ (\gamma^\mu)_{ij}(\gamma_\mu)_{kl} \\ \frac{1}{2}(\sigma^{\mu\nu})_{ij}(\sigma_{\mu\nu})_{kl} \\ (\gamma^\mu\gamma_5)_{ij}(\gamma_\mu\gamma_5)_{kl} \\ (\gamma_5)_{ij}(\gamma_5)_{kl} \end{pmatrix} = \begin{pmatrix} 1/4 & 1/4 & 1/4 & -1/4 & 1/4 \\ 1 & -1/2 & 0 & -1/2 & -1 \\ 3/2 & 0 & -1/2 & 0 & 3/2 \\ -1 & -1/2 & 0 & -1/2 & 1 \\ 1/4 & -1/4 & 1/4 & 1/4 & 1/4 \end{pmatrix} \begin{pmatrix} \delta_{il}\delta_{kj} \\ (\gamma^\mu)_{il}(\gamma_\mu)_{kj} \\ \frac{1}{2}(\sigma^{\mu\nu})_{il}(\sigma_{\mu\nu})_{kj} \\ (\gamma^\mu\gamma_5)_{il}(\gamma_\mu\gamma_5)_{kj} \\ (\gamma_5)_{il}(\gamma_5)_{kj} \end{pmatrix}$$

SO(3,1) trace part

Schouten identity

$$g_{\mu\nu}\sigma^\mu_{\alpha\dot{\alpha}}\sigma^\nu_{\beta\dot{\beta}} = 2\epsilon_{\alpha\beta}\epsilon_{\dot{\alpha}\dot{\beta}},$$
$$\epsilon^{\alpha\beta}\delta^\gamma_\kappa + \epsilon^{\beta\gamma}\delta^\alpha_\kappa + \epsilon^{\gamma\alpha}\delta^\beta_\kappa = 0.$$
$$\tilde{\epsilon}_{\dot{\alpha}\dot{\beta}}\delta^{\dot{\kappa}}_{\dot{\gamma}} + \tilde{\epsilon}_{\dot{\beta}\dot{\gamma}}\delta^{\dot{\kappa}}_{\dot{\alpha}} + \tilde{\epsilon}_{\dot{\gamma}\dot{\alpha}}\delta^{\dot{\kappa}}_{\dot{\beta}} = 0$$

$$|i\rangle\langle jk\rangle + |j\rangle\langle ki\rangle + |k\rangle\langle ij\rangle = 0\,.$$

$$\langle ri\rangle\langle jk\rangle + \langle rj\rangle\langle ki\rangle + \langle rk\rangle\langle ij\rangle = 0\,.$$

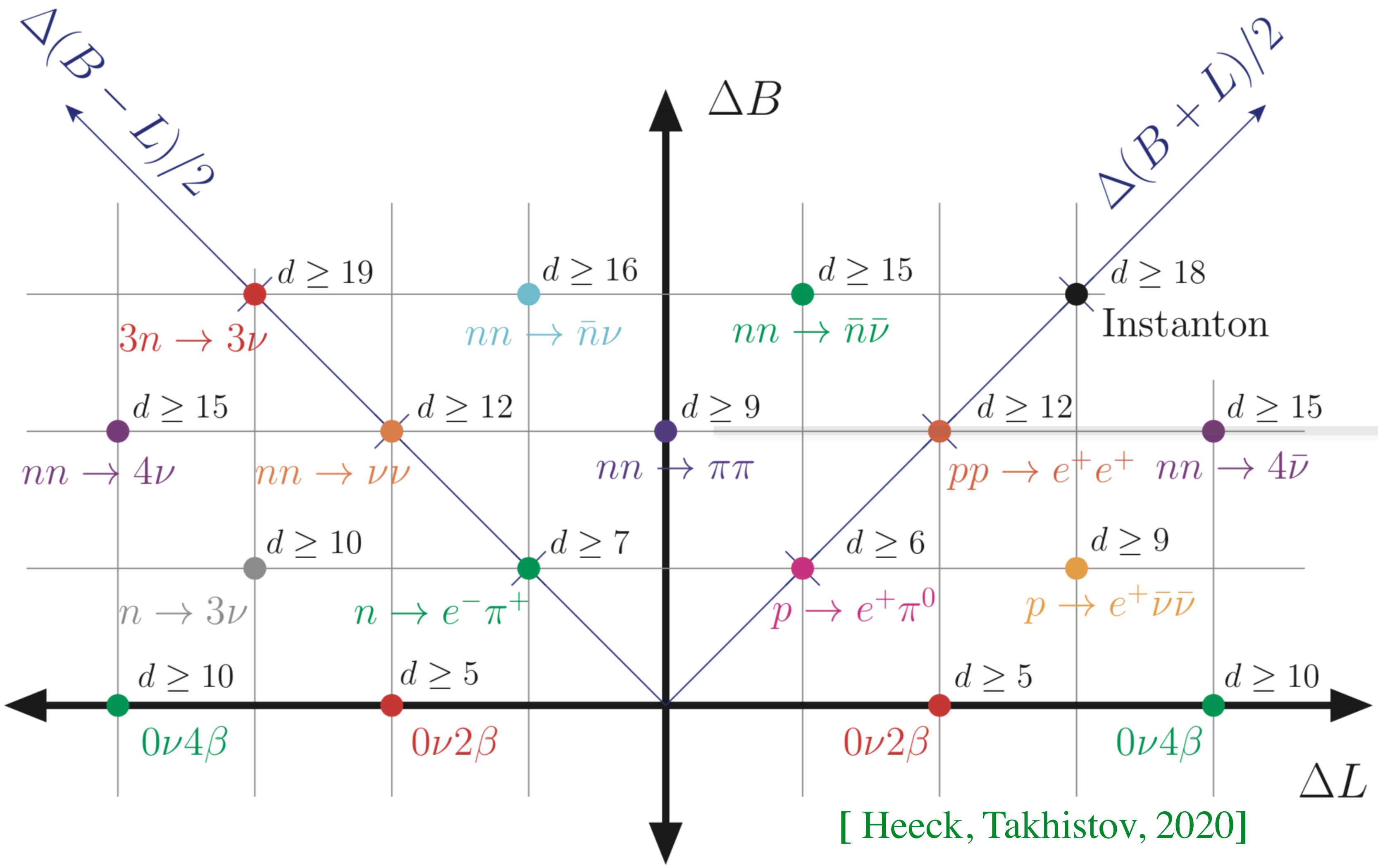
$$(\bar{d}l)(\bar{l}d) = -\frac{1}{4}(\bar{d}d)(\bar{l}l) - \frac{1}{4}(\bar{d}\gamma^\mu d)(\bar{l}\gamma_\mu l) - \frac{1}{8}(\bar{d}\sigma^{\mu\nu}d)(\bar{l}\sigma_{\mu\nu}l) + \frac{1}{4}(\bar{d}\gamma^\mu\gamma_5 d)(\bar{l}\gamma_\mu\gamma_5 l) - \frac{1}{4}(\bar{d}\gamma_5 d)(\bar{l}\gamma_5 l)$$
$$= -\frac{1}{2}(\bar{d}\gamma^\mu d)(\bar{l}\gamma_\mu l)\,, \qquad ($$

$$(\bar{l}C\bar{q})(lCq) = -\frac{1}{4}(\bar{l}l)(\bar{q}q) + \frac{1}{4}(\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q) + \frac{1}{8}(\bar{l}\sigma^{\mu\nu}l)(\bar{q}\sigma_{\mu\nu}q) + \frac{1}{4}(\bar{l}\gamma^\mu\gamma_5 l)(\bar{q}\gamma_\mu\gamma_5 q) - \frac{1}{4}(\bar{l}\gamma_5 l)(\bar{q}\gamma_5 q)$$
$$= \frac{1}{2}(\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q)\,. \qquad ($$

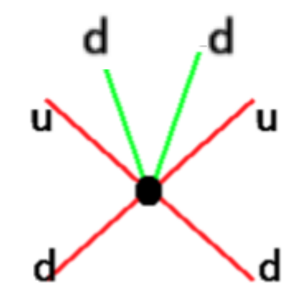
Higher Dim Operators

new physics without new particle: neutrino masses and baryon asymmetry

B and L violation



n-nbar oscillation



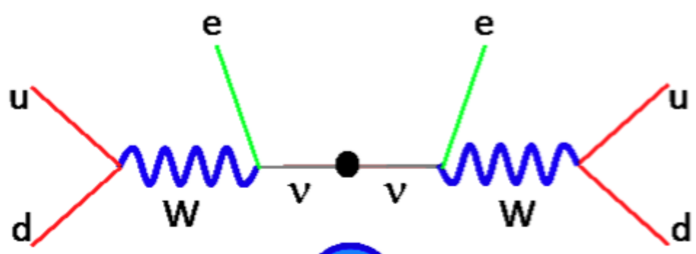
Dim-9

dim-8: neutral triple gauge couplings

SMEFT Operators

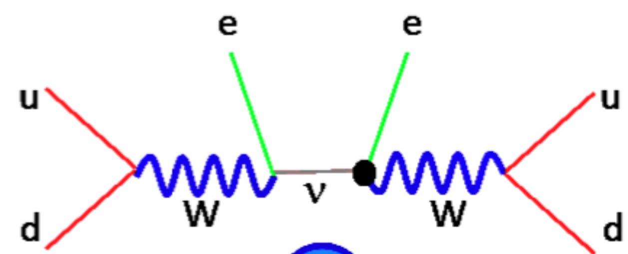
Very different types of operators contribute to the same process

$e_R = e_C^\dagger, u_R = u_C^\dagger, d_R = d_C^\dagger$



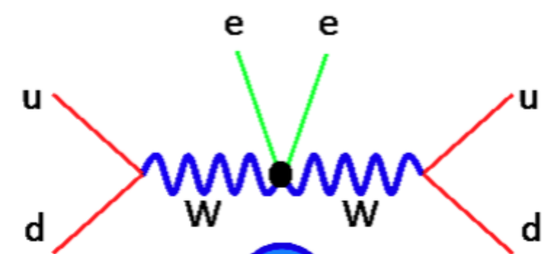
A **Dim-5**

$H^2 L^2$ $H^3 H^\dagger L^2$



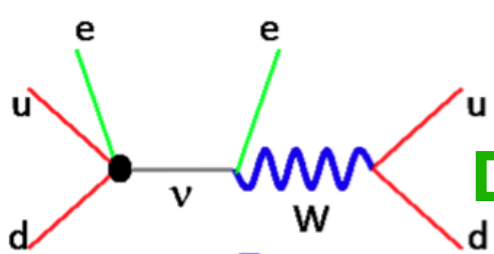
B **Dim-7**

$D\, ec\, H^{\dagger 3} L^\dagger$ $H^{\dagger 2} L^{\dagger 2} WR$



C **Dim-9**

$D^2 H^{\dagger 2} L^{\dagger 2}$ $D^2 H^{\dagger 2} L^{\dagger 2} WL$

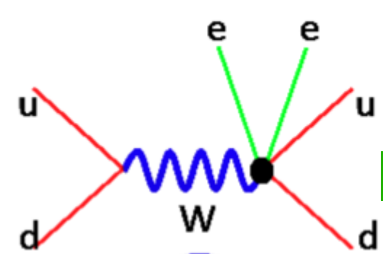


Dim-7

D

$dc^\dagger H^\dagger L^{\dagger 2} Q^\dagger$

$D\, dc^\dagger L^{\dagger 2} uc$

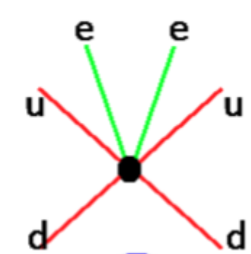


Dim-9

E

$D\, dc^\dagger L^{\dagger 2} uc$

$dc^\dagger\, ec\, H^\dagger L^\dagger\, uc\, WL$



Dim-9

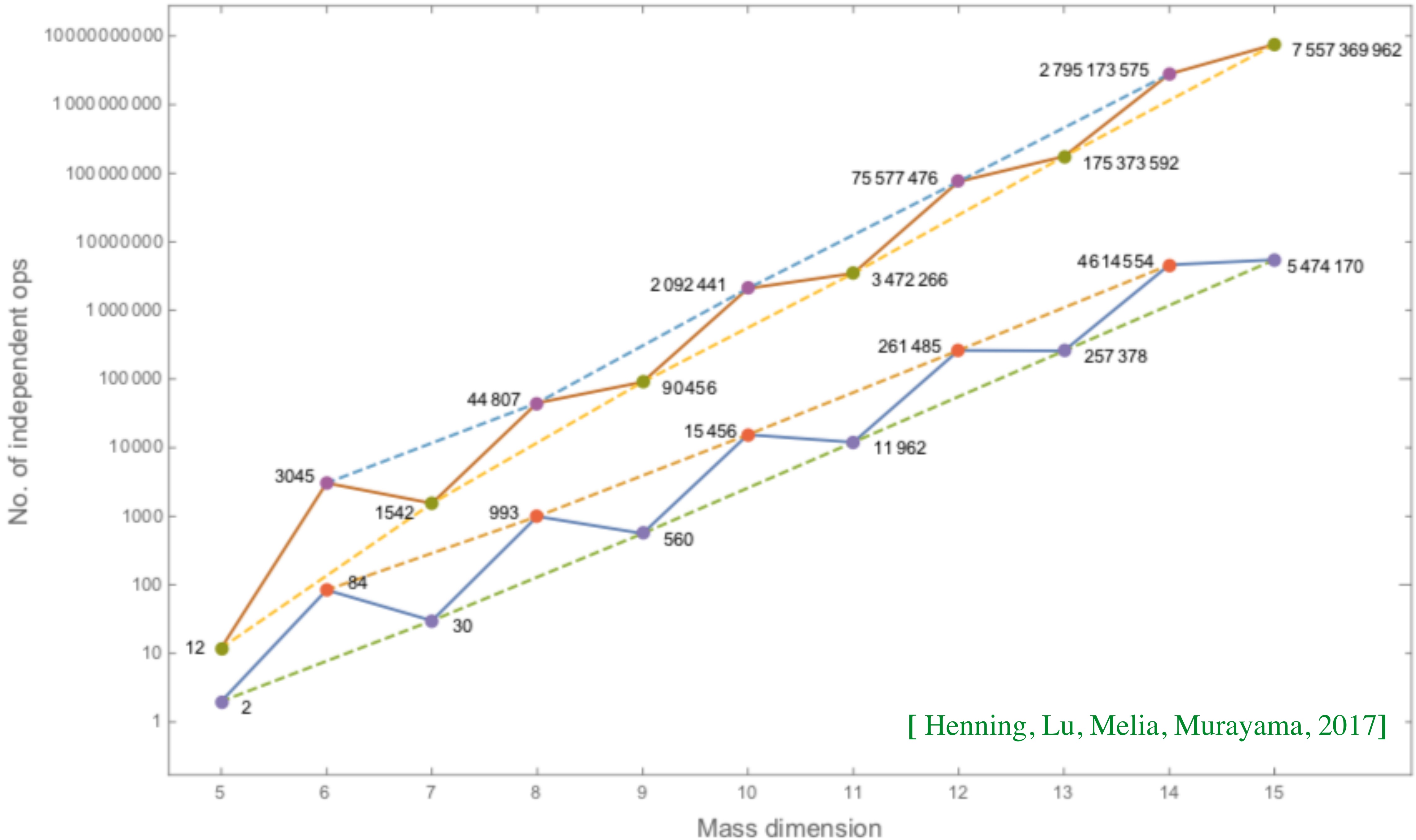
F

$dc^2 L^2 Q^2$, $dc^2 dc^\dagger L^2 uc^\dagger$, $dc\, L^2 uc\, uc^{\dagger 2}$, $dc^2 ec^\dagger L\, Q\, uc^\dagger$,

$dc^{\dagger 2} ec^2 uc^2$, $dc\, L^2 Q\, Q^\dagger uc^\dagger$, $dc^\dagger ec\, L^\dagger Q\, uc^2$, $L^{\dagger 2} Q^2 uc^2$

Need write down complete set of operators up to dim-9

SMEFT Operators



Also [Lehman, Martin 2015]

Operator as Spinor Tensor

Each field belongs to Lorentz irrep:

SO(3,1)	SL(2,C) $SU(2)_l \times SU(2)_r$	Spinor-helicity
ϕ	$\phi \in (0,0)$	
ψ	$\psi_\alpha \in (1/2,0)$ $\psi^\dagger_{\dot\alpha} \in (0,1/2),$	λ_α
$F_{\mu\nu}$ →	$F_{\mathrm{L}\alpha\beta} = \frac{i}{2} F_{\mu\nu}\sigma^{\mu\nu}_{\alpha\beta} \in (1,0)$ $F_{\mathrm{R}\dot\alpha\dot\beta} = -\frac{i}{2} F_{\mu\nu}\bar\sigma^{\mu\nu}_{\dot\alpha\dot\beta} \in (0,1).$	$\lambda_\alpha\lambda_\beta$
$R_{\mu\nu\rho\sigma}$	$\mathcal{C}_{\alpha\beta\gamma\delta} = C_{\mu\nu\rho\sigma}\sigma^{\mu\nu}_{\alpha\beta}\sigma^{\rho\sigma}_{\gamma\delta} \in (2,0)$	$\lambda_\alpha\lambda_\beta\lambda_\gamma\lambda_\delta$
D_μ	$D_{\alpha\dot\alpha} = D_\mu \sigma^\mu_{\alpha\dot\alpha} \in (1/2,1/2),$	$\lambda_\alpha\tilde\lambda_{\dot\alpha}$

Operator with explicit spinor indices

$$W_{\mu\lambda}\left(e_{cp}\sigma^{\nu\lambda}D^\mu L_r\right)D_\nu H^\dagger \quad \rightarrow \quad F_1^{\alpha\beta}\psi_2^\gamma\,(D\psi_3)_{\alpha\beta\dot\alpha}\,(D\phi_4)_\gamma{}^{\dot\alpha}$$

$$\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_2\alpha_4}\epsilon^{\dot\alpha_3\dot\alpha_4}F_1^{\alpha_1^2}\psi_2^{\alpha_2}\,(D\psi_3)^{\alpha_3^2}_{\dot\alpha_3}\,(D\phi_4)^{\alpha_4}_{\dot\alpha_4}$$

Easier to find more symmetries of the operator with spinor indices

Equation of Motion

For fields with derivatives, symmetric and antisymmetric indices:

$$(D\psi)_{\alpha\beta\dot{\alpha}} = -\frac{1}{2}\epsilon_{\alpha\beta}(\not{D}\psi)_{\dot{\alpha}} + \frac{1}{2}(D\psi)_{(\alpha\beta)\dot{\alpha}}$$

$$\left(\tfrac{1}{2},\tfrac{1}{2}\right)\otimes\left(\tfrac{1}{2},0\right) = \left(0,\tfrac{1}{2}\right)\oplus\left(1,\tfrac{1}{2}\right)$$

$\left(\frac{1}{2},\frac{1}{2}\right)\times\left(\frac{1}{2},0\right)$ **(0,1/2)** **(1,1/2)**

$$(D^2\phi)_{\alpha\beta\dot{\alpha}\dot{\beta}} = \frac{1}{2}\epsilon_{\alpha\beta}\epsilon_{\dot{\alpha}\dot{\beta}}D^\mu D_\mu\phi - \frac{i}{4}\epsilon_{\dot{\alpha}\dot{\beta}}\sigma^{\mu\nu}_{\alpha\beta}[D_\mu, D_\nu]\phi - \frac{i}{4}\epsilon_{\alpha\beta}\bar{\sigma}^{\mu\nu}_{\dot{\alpha}\dot{\beta}}[D_\mu, D_\nu]\phi + \frac{1}{4}(D^2\phi)_{(\alpha\beta)(\dot{\alpha}\dot{\beta})}$$

$\left(\frac{1}{2},\frac{1}{2}\right)\times\left(\frac{1}{2},\frac{1}{2}\right)$ **(0,0)** **(1,0)** **(0,1)** **(1,1)**

Only take the **symmetric indices** part for field with derivatives

EOM, covariant derivative commutator, Bianchi identity all removed

$$D^w\Psi \in \left(j_l + \frac{w}{2}, j_r + \frac{w}{2}\right) \oplus \text{~~lower weights~~}$$

with totally symmetric spinor indices

[Similar treatment: EOM removed by taking highest weight rep.]

Also [Lehman, Martin 2016]

Spinor Tensor Transformation

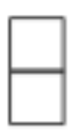
Any operator can be written with totally symmetric spinor indices:

$$\mathcal{O} = (\epsilon^{\alpha_i\alpha_j})^n(\tilde{\epsilon}_{\dot{\alpha}_i\dot{\alpha}_j})^{\tilde{n}}\prod_{i=1}^{N}(D^{r_i-|h_i|}\Phi_i)^{\dot{\alpha}_i^{r_i+h_i}}_{\alpha_i^{r_i-h_i}}$$

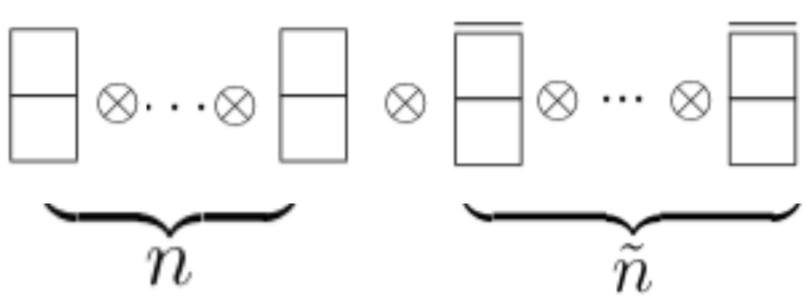
$$\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_2\alpha_4}\tilde{\epsilon}^{\dot{\alpha}_3\dot{\alpha}_4}F_1^{\alpha_1^2}\psi_2^{\alpha_2}(D\psi_3)^{\alpha_3^2}_{\dot{\alpha}_3}(D\phi_4)^{\alpha_4}_{\dot{\alpha}_4} \qquad F_1^{\alpha\beta}\psi_2^{\gamma}(D\psi_3)_{\alpha\beta\dot{\alpha}}(D\phi_4)_{\gamma}{}^{\dot{\alpha}}$$

Epsilon tensor transformations under SL(2,C) x SU(N)

$$\epsilon^{\alpha_i\alpha_j} \to \sum_{k,l}\mathcal{U}^i_k\mathcal{U}^j_l\epsilon^{\alpha_k\alpha_l}, \quad \tilde{\epsilon}_{\dot{\alpha}_i\dot{\alpha}_j} \to \sum_{k,l}\mathcal{U}^{\dagger k}_{\ i}\mathcal{U}^{\dagger l}_{\ j}\tilde{\epsilon}_{\dot{\alpha}_k\dot{\alpha}_l}. \qquad i,j,k,l = 1 \text{ to } N$$

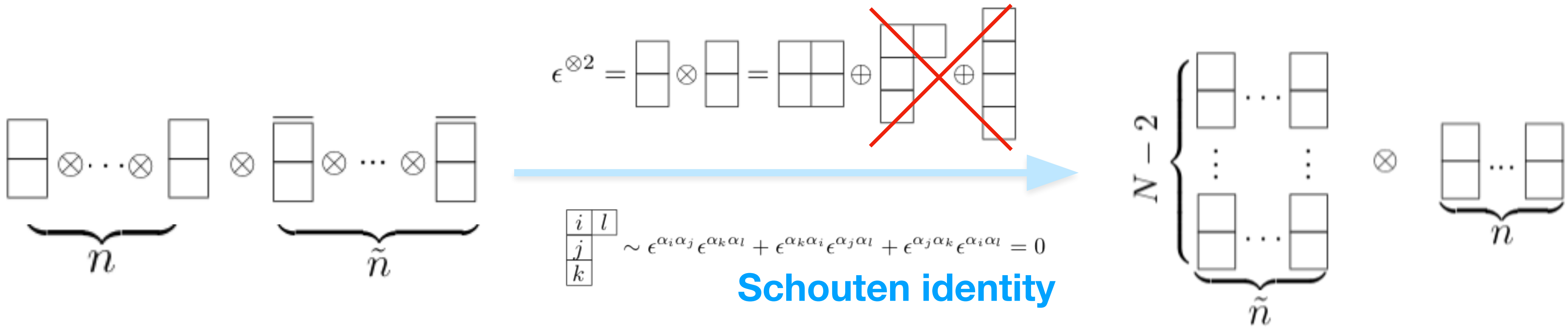
 $= [1^2]$  $= [1^{N-2}]$

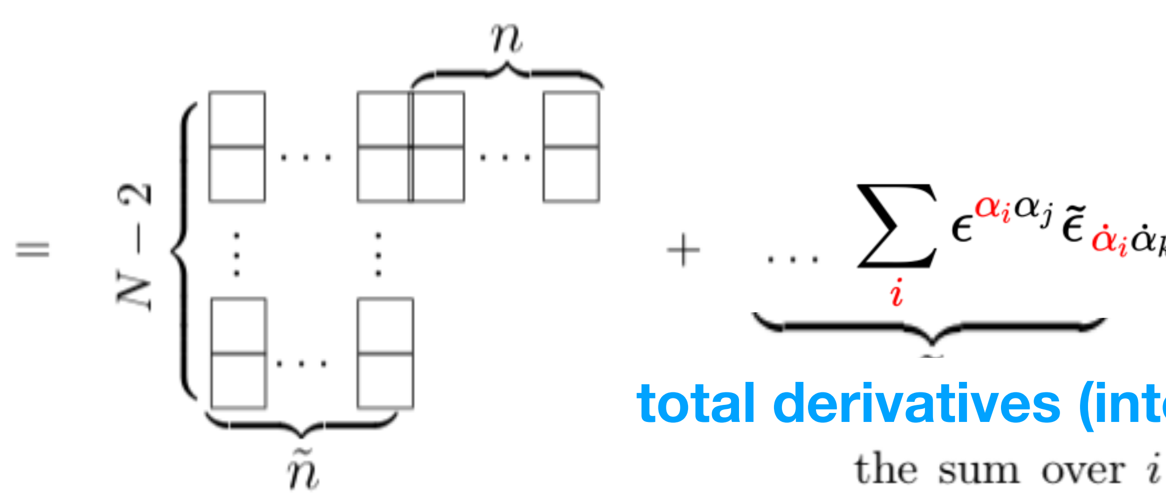
$\epsilon^{\alpha_i\alpha_j}$ $\qquad \mathcal{E}^{ijk_1,\ldots,k_{N-2}}\ \tilde{\epsilon}_{\dot{\alpha}_i\dot{\alpha}_j}$



= Irrep ⊕ ... ⊕ Irrep

Integration-by-part





total derivatives (integration by part)

the sum over i means a total derivative

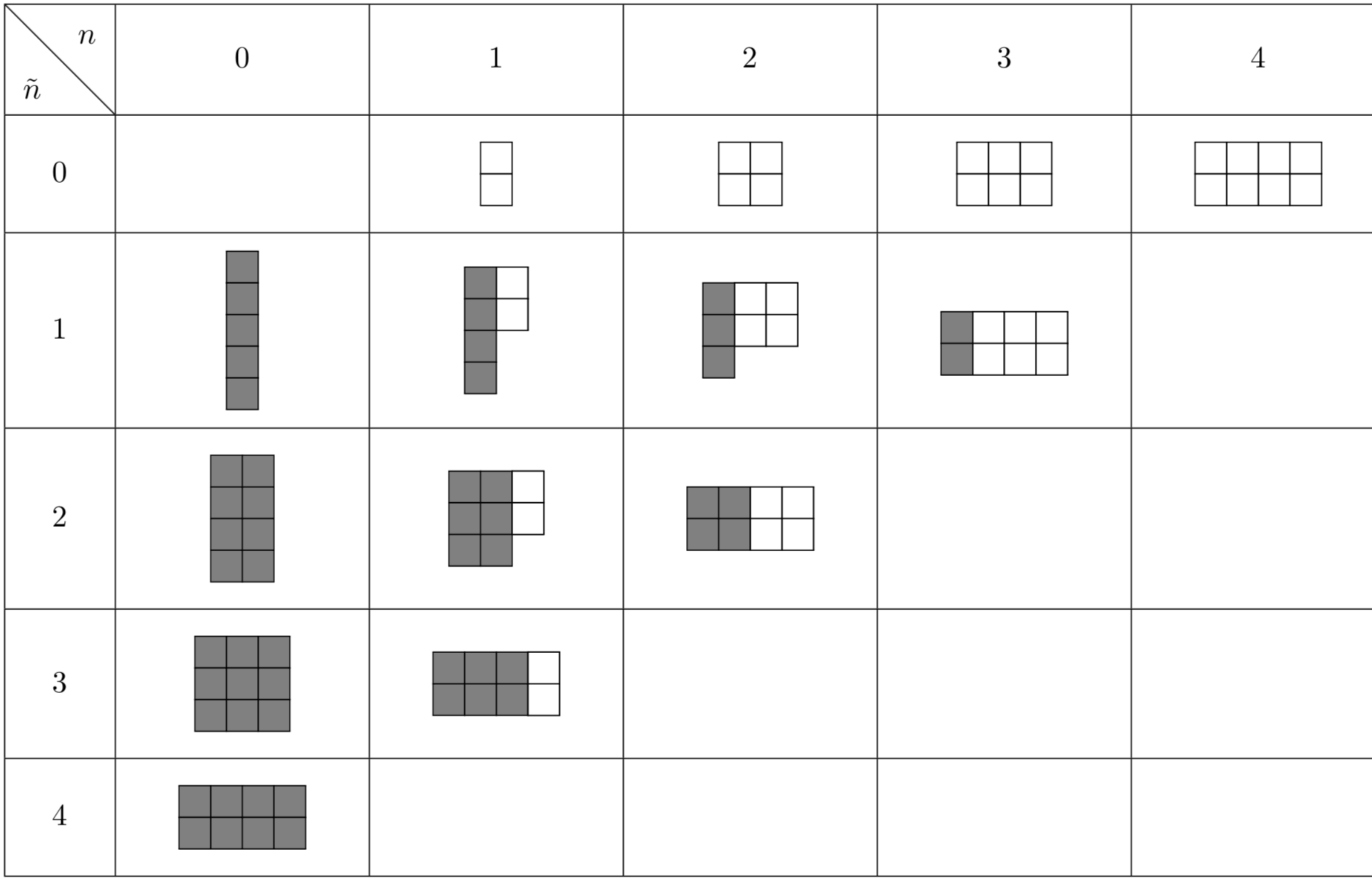
We obtain Young diagram using epsilon tensor transformation

[Such Young diagram also obtained from conformal K harmonics]

Also [Henning, Melia, 2019]

Young Diagrams

Dim-8 operators: 993 (44807) operators for 1 (3) generations



Young Diagrams

Dim-8 operators: 993 (44807) operators for 1 (3) generations

N = 7, N = 6, N = 5, N = 4

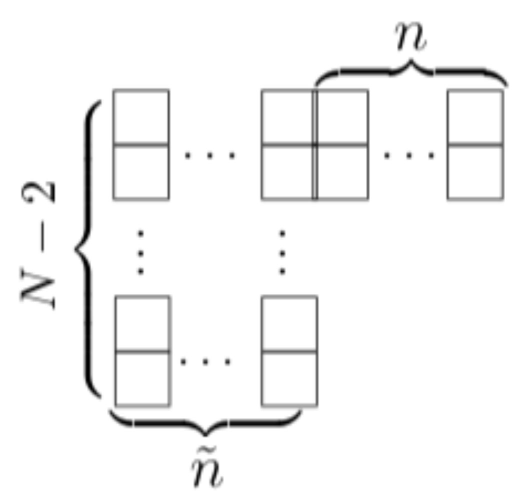
$\bar{n}$ \ n	0	1	2	3	4
0	ϕ^8	$\psi^2\phi^5$	$\psi^4\phi^2$, $F_{\rm L}\psi^2\phi^3$, $F_{\rm L}^2\phi^4$	$F_{\rm L}\psi^4$, $F_{\rm L}^2\psi^2\phi$, $F_{\rm L}^3\phi^2$	$F_{\rm L}^4$
1	$\psi^{\dagger 2}\phi^5$	$\psi^{\dagger 2}\psi^2\phi^2$, $\psi^\dagger\psi\phi^4 D$, $\phi^6 D^2$	$F_{\rm L}\psi^{\dagger 2}\psi^2$, $F_{\rm L}^2\psi^{\dagger 2}\phi$, $\psi^\dagger\psi^3\phi D$, $F_{\rm L}\psi^\dagger\psi\phi^2 D$, $\psi^2\phi^3 D^2$, $F_{\rm L}\phi^4 D^2$	$F_{\rm L}^2\psi^\dagger\psi D$, $\psi^4 D^2$, $F_{\rm L}\psi^2\phi D^2$, $F_{\rm L}^2\phi^2 D^2$	
2	$\psi^{\dagger 4}\phi^2$, $F_{\rm R}\psi^{\dagger 2}\phi^3$, $F_{\rm R}^2\phi^4$	$F_{\rm R}\psi^{\dagger 2}\psi^2$, $F_{\rm R}^2\psi^2\phi$, $\psi^{\dagger 3}\psi\phi D$, $F_{\rm R}\psi^\dagger\psi\phi^2 D$, $\psi^{\dagger 2}\phi^3 D^2$, $F_{\rm R}\phi^4 D^2$	$F_{\rm R}^2 F_{\rm L}^2$, $F_{\rm R}F_{\rm L}\psi^\dagger\psi D$, $\psi^{\dagger 2}\psi^2 D^2$, $F_{\rm R}\psi^2\phi D^2$, $F_{\rm L}\psi^{\dagger 2}\phi D^2$, $F_{\rm R}F_{\rm L}\phi^2 D^2$, $\phi^4 D^4$, $\psi^\dagger\psi\phi^2 D^3$		
3	$F_{\rm R}\psi^{\dagger 4}$, $F_{\rm R}^2\psi^{\dagger 2}\phi$, $F_{\rm R}^3\phi^2$	$F_{\rm R}^2\psi^\dagger\psi D$, $\psi^{\dagger 4}D^2$, $F_{\rm R}\psi^{\dagger 2}\phi D^2$, $F_{\rm R}^2\phi^2 D^2$			
4	$F_{\rm R}^4$				

Lorentz Structure

We invent a Young diagram filling procedure to obtain independent Lorentz

Semi-standard Young tableau (SSYT)

$Y_{N,n,\tilde{n}} =$



$$\{\overbrace{1,\ldots,1}^{\#1},\overbrace{2,\ldots,2}^{\#2},\ldots,\overbrace{N,\ldots,N}^{\#N}\}$$

$$\#i = \tilde{n} - 2h_i$$

Semi-standard Young tableau forms a **independent and complete basis** for a type

$(\tilde{n} = 1, n = 3)$

$F^2\bar{\psi}\psi D,\ \psi^4 D^2,$
$F\psi^2\phi D^2,\ F^2\phi^2 D^2$

$\#1 = 3, \#2 = \#3 = 2, \#4 = 1.$

1	1	1	2
2	3	3	4

1	1	1	3
2	2	3	4

$$F_{L1}^{\alpha\beta}\psi_2^{\gamma}\,(D\psi_3)_{\alpha\beta\dot{\alpha}}\,(D\phi_4)_{\gamma}{}^{\dot{\alpha}}$$

$$F_{L1}^{\alpha\beta}\psi_{2\alpha}\,(D\psi_3)_{\beta}{}^{\gamma}{}_{\dot{\alpha}}\,(D\phi_4)_{\gamma}{}^{\dot{\alpha}}$$

$\#1 = 3,\ \#2 = 3,\ \#3 = 1 \text{ and } \#4 = 1$

1	1	1	3
2	2	2	4

1	1	1	2
2	2	3	4

$$F_{L1}{}^{\alpha\beta}F_{L2\alpha\beta}(D\phi_3)^{\gamma}{}_{\dot{\alpha}}(D\phi_4)_{\gamma}{}^{\dot{\alpha}}$$

$$F_{L1}{}^{\alpha\beta}F_{L2\alpha}{}^{\gamma}(D\phi_3)_{\beta\dot{\alpha}}(D\phi_4)_{\gamma}{}^{\dot{\alpha}}$$

Different Operator Bases

Effective operators can be written in different bases, even redundant basis

Buchmuller&Wyler:

$$\mathcal{O}_{\partial H} = \frac{1}{2} D_\mu (H^\dagger H) D^\mu (H^\dagger H), \quad \mathcal{O}_H^{(1)} = (H^\dagger H)(D_\mu H^\dagger D^\mu H), \quad \mathcal{O}_H^{(2)} = (H^\dagger D^\mu H)(D_\mu H^\dagger H).$$

Warsaw:

$$\mathcal{O}_{H\Box} = (H^\dagger H) \Box (H^\dagger H), \quad \mathcal{O}_{HD} = \left(H^\dagger D_\mu H\right)^\dagger \left(H^\dagger D^\mu H\right).$$

SILH:

$$\mathcal{O}_{SILH}^{(1)} = D^\mu (H^\dagger H) D_\mu (H^\dagger H), \quad \mathcal{O}_{SILH}^{(2)} = (H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}_\mu H),$$

Amplitude-basis (ITP-basis)

$\mathcal{O}^{(p)}_{H^2 H^{\dagger 2} D^2,1}$	$H_i H_j (D_\mu D_\nu H^{\dagger i})(D^\mu D^\nu H^{\dagger j})$
$\mathcal{O}^{(p)}_{H^2 H^{\dagger 2} D^2,2}$	$H_i H^{\dagger i} (D_\mu D_\nu H_j)(D^\mu D^\nu H^{\dagger j})$
$\mathcal{O}^{(p)}_{H^2 H^{\dagger 2} D^2,3}$	$H_i (D_\mu H_j)(D_\nu H^{\dagger i})(D^\mu D^\nu H^{\dagger j})$

traditional-basis (Murphy)

$\mathcal{O}^{(1)}_{H^4}$	$(D_\mu H^{\dagger i} D_\nu H_i)(D^\nu H^{\dagger j} D^\mu H_j)$
$\mathcal{O}^{(2)}_{H^4}$	$(D_\mu H^{\dagger i} D_\nu H_i)(D^\mu H^{\dagger j} D^\nu H_j)$
$\mathcal{O}^{(3)}_{H^4}$	$(D^\mu H^{\dagger i} D_\mu H_i)(D^\nu H^{\dagger j} D_\nu H_j)$

How to perform the basis conversion? (useful for CDE, etc)

Basis conversion can be easily done in our amplitude basis

On-shell Amplitude Basis

Any operator (non-SSYT) can be converted to the SSYT basis systematically

Our on-shell amplitude basis = SSYT basis

$$\begin{pmatrix} \mathcal{O}_{\partial H} \\ \mathcal{O}_H^{(1)} \\ \mathcal{O}_H^{(2)} \end{pmatrix} = \begin{pmatrix} -\frac{1}{2} & 0 \\ \frac{1}{2} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \mathcal{O}_{H\Box} \\ \mathcal{O}_{HD} \end{pmatrix}$$

Warsaw

$$\begin{pmatrix} \mathcal{O}_{SILH}^{(1)} \\ \mathcal{O}_{SILH}^{(2)} \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 1 & -2 \end{pmatrix} \begin{pmatrix} \mathcal{O}_{H\Box} \\ \mathcal{O}_{HD} \end{pmatrix}$$

SILH **Warsaw**

Reduce any operators to our ITP-basis

$D^2LL^\dagger QQ^\dagger$	
$\mathcal{O}^{(1)}$	$(D_\mu L_{pi} D^\mu Q_{raj})(L_s^{\dagger i} Q_t^{\dagger aj})$
$\mathcal{O}^{(2)}$	$(D_\mu L_{pi} D^\mu Q_{raj})(L_s^{\dagger j} Q_t^{\dagger ai})$
$\mathcal{O}^{(3)}$	$(D_\mu L_{pi} Q_{raj})(D^\mu L_s^{\dagger i} Q_t^{\dagger aj})$
$\mathcal{O}^{(4)}$	$(D_\mu L_{pi} Q_{raj})(D^\mu L_s^{\dagger j} Q_t^{\dagger ai})$
$\mathcal{O}^{(5)}$	$(D_\mu L_{pi} D_\nu Q_{raj})(L_s^{\dagger i} \bar\sigma^{\mu\nu} Q_t^{\dagger aj})$
$\mathcal{O}^{(6)}$	$(D_\mu L_{pi} D_\nu Q_{raj})(L_s^{\dagger j} \bar\sigma^{\mu\nu} Q_t^{\dagger ai})$
$\mathcal{O}^{(7)}$	$(D^\nu L_{pi} \sigma_\mu L_s^{\dagger i})(D^\mu Q_{raj} \sigma_\nu Q_t^{\dagger aj})$
$\mathcal{O}^{(8)}$	$(D^\nu L_{pi} \sigma_\mu Q_t^{\dagger aj})(D^\mu Q_{raj} \sigma_\nu L_s^{\dagger i})$
$\mathcal{O}^{(9)}$	$(D^\mu L_{pi} \sigma_\mu L_s^{\dagger i})(D^\nu Q_{raj} \sigma_\nu Q_t^{\dagger aj})$.

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\frac{1}{2} & \frac{1}{2} & 0 & 0 \\ 0 & 0 & -\frac{1}{2} & \frac{1}{2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & -1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

M-basis	
$\mathcal{O}_1^{(m)}$	$(L_{pi} Q_{raj})(D_\mu L_s^{\dagger i} D^\mu Q_t^{\dagger aj})$
$\mathcal{O}_2^{(m)}$	$(L_{pi} \sigma_{\mu\nu} Q_{raj})(D^\mu L_s^{\dagger i} D^\nu Q_t^{\dagger aj})$
$\mathcal{O}_3^{(m)}$	$(L_{pi} Q_{raj})(D_\mu L_s^{\dagger j} D^\mu Q_t^{\dagger ai})$
$\mathcal{O}_4^{(m)}$	$(L_{pi} \sigma_{\mu\nu} Q_{raj})(D^\mu L_s^{\dagger j} D^\nu Q_t^{\dagger ai})$

Gauge Structure

Gauge structure (internal sym) is easier than Lorentz structure (spacetime sym)

Dim-6 four fermion B-conserving operators: 25

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Buchmuller&Wyler wrote 29: 5 redundant operators (Fierz) + 1 missing

$$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{l}_s\tau^I\gamma^\mu l_t) = 2Q_{ll}^{ptsr} - Q_{ll}^{prst}$$

Fierz identity for SU(N):

$$\sum_a (T_a)_{ij}(T_a)_{kl} = \delta_{il}\delta_{kj} - \frac{1}{N}\delta_{ij}\delta_{kl}$$

U(N) trace relation

Gauge Young Tensor

How to obtain independent and complete gauge structure systematically?

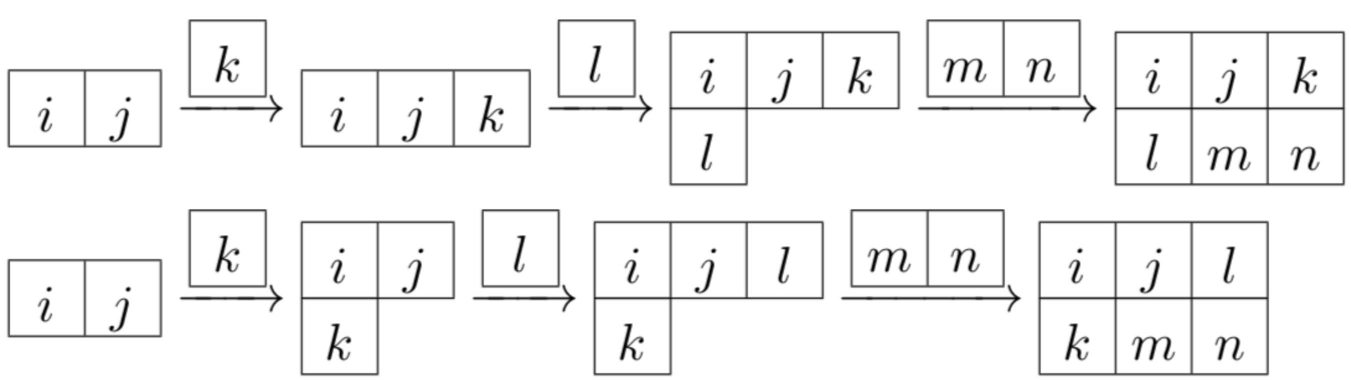
g-2 dim 8 operator

$$\boxed{(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}} \xrightarrow{\text{Add } H^\dagger H} W e_{\mathbb{C}} L H H^{\dagger 2} \quad \boxed{(\tau^I)^k_j W^I_{\mu\nu} (e_{\mathbb{C}p}\sigma^{\mu\nu} L_{rk}) H^{\dagger j} (H^\dagger H)}$$

?

We invent Littlewood-Richardson method at Young tableau level

$\tau^I{}_{ij} W^I$: $\boxed{i\,|\,j}$, L_k: $\boxed{k}$, H_l: $\boxed{l}$, $H^\dagger_m H^\dagger_n$: $\boxed{m\,|\,n}$



$\epsilon^{il}\epsilon^{jm}\epsilon^{kn} \qquad W^I L_k H^{\dagger k} (H^\dagger \tau H)$

$\epsilon^{ik}\epsilon^{jm}\epsilon^{ln} \qquad (\tau^I)^k_j W^I L_k H^{\dagger j} (H^\dagger H)$

Find another g-2 dim 8 operator: $\boxed{W^I_{\mu\nu} (e_{\mathbb{C}p}\sigma^{\mu\nu} L_{ri}) H^{\dagger i} (H^\dagger \tau^I H)}$

Schur-Weyl Theorem

Three 1/2-particle with 3 flavors:

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$

SU(3)	Tableau	Fillings	S3
SU(3) 1-d irrrep	r / s / t :	1/2/3,	S3 1-dim irrrep [111]
SU(3) 8-d irrrep	$r\ s$ / t :	1 1/2, 1 1/3, 2 2/3, 1 2/2, 1 3/3, 2 3/3, 1 2/3, 1 3/2,	S3 2-dim irrrep [21]
SU(3) 10-d irrrep	$r\ s\ t$:	1 1 1, 1 1 2, 1 1 3, 1 2 2, 1 2 3, 1 3 3, 2 2 2, 2 2 3, 2 3 3, 3 3 3,	S3 1-dim irrrep [3]

$$|1\rangle\ |2\rangle\ |3\rangle\ |4\rangle\ |5\rangle\ |6\rangle\ |7\rangle\ |8\rangle$$

$$|1'\rangle\ |2'\rangle\ |3'\rangle\ |4'\rangle\ |5'\rangle\ |6'\rangle\ |7'\rangle\ |8'\rangle$$

SU(3) 8-dim irrrep

S3 2-dim irrrep [2 1]

Schur-Weyl theorem:

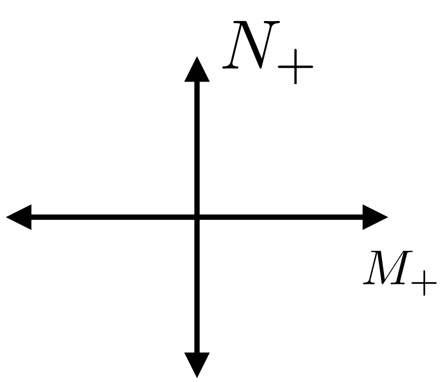
$$\underbrace{(\{1\} \otimes (1)) \otimes (\{1\} \otimes (1)) \otimes \cdots \otimes (\{1\} \otimes (1))}_{N \text{ factors}} = \sum_{\lambda \vdash N} \{\lambda\} \otimes (\lambda)$$

Lorentz/Poincare/Conformal

SO(3,1)

$$\tfrac{1}{2}M^{\mu\nu}M_{\mu\nu} = \mathbf{J}^2 - \mathbf{K}^2\,,$$
$$\tfrac{1}{2}\epsilon^{\mu\nu\sigma\tau}M_{\mu\nu}M_{\sigma\tau} = -\mathbf{J}\cdot\mathbf{K}\,,$$

$$M_i = \tfrac{1}{2}(J_i + iK_i)\,,$$
$$N_i = \tfrac{1}{2}(J_i - iK_i)\,,$$



Fields

$(0,0), (1/2,0), (0,1/2),$
$(1/2,1/2), (1,0), (0,1)$

$$K_i = -i\frac{1}{2}\sigma_i, \qquad J_i = iK_i = \frac{1}{2}\sigma_i.$$

Poincare

Semidirect product of a semisimple (Lorentz) and an Abelian group (translations)

$$P^2 = P_\mu P^\mu$$
$$W^2 = W_\mu W^\mu$$

$$W_\mu = \epsilon_{\mu\nu\sigma\tau}M^{\nu\sigma}P^\tau$$

$$W_0 = \mathbf{P}\cdot\mathbf{J}\,,$$
$$\mathbf{W} = P_0\,\mathbf{J} - \mathbf{P}\times\mathbf{K}\,.$$

P invariant subgroup:

$$[w_0, w_\pm] = \pm m w_\pm$$
$$[w_+, w_-] = 2m w_0$$

States

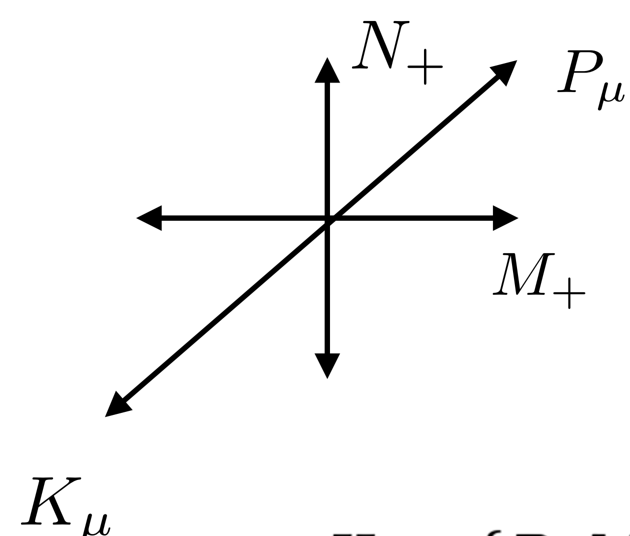
$|m, \mathbf{p}, j, \sigma\rangle$

SO(4,2)

3 casimirs

$$\tfrac{1}{2}M^{\mu\nu}M_{\mu\nu} + D(D-d) - P^\mu K_\mu$$

$$E_+ = \{P_\mu, M_+, N_+\} \qquad E_- = \{K_\mu, M_-, N_-\}$$



$$H_0 = \{D, M_3, N_3\}$$

(Δ, ℓ_1, ℓ_2)

$$P_\mu : (\Delta, \ell) \to \left(\Delta + 1, \ell \otimes \left(\frac{1}{2}, \frac{1}{2}\right)\right)$$
$$\ell = (\ell_1, \ell_2)$$

J-Basis Operators

J-Basis is flavor blind basis, not independent if repeated fields

$$\mathcal{A}^{(6)}(H_{1,i}, H_3^{\dagger,k} \to H_{2,j}, H_4^{\dagger,l}) = \sum_{J,\mathbf{r}} C^{J,\mathbf{r}} \mathcal{B}^J T^{\mathbf{r}}$$

$\phi^4 D^2$

$$\mathcal{B}^{\mathrm{y}} = \begin{cases} s_{12} \\ s_{13} \end{cases}$$

$$\mathbf{W}_{(1,3)}{}^2 \mathcal{B}^{\mathrm{y}} = -s_{13} \begin{pmatrix} 2 & 1 \\ 0 & 0 \end{pmatrix} . \mathcal{B}^{\mathrm{y}}$$

$$\Rightarrow \mathcal{B}^{\mathrm{j}} = \begin{cases} s_{13} & J=0 \\ s_{12} - s_{14} & J=1 \end{cases}$$

Lorentz j-basis (partial waves)	Gauge j-basis
$\mathcal{B}^{J=0} = s_{13}/\Lambda^2$	$T^{\mathbf{r}=\mathbf{1}} = \delta_i^k \delta_j^l$
$\mathcal{B}^{J=1} = (s_{12} - s_{14})/\Lambda^2$	$T^{\mathbf{r}=\mathbf{3}} = (\tau^I)_i^k (\tau^I)_j^l$

$$\mathcal{B}^{\mathrm{j}} = \mathcal{K}.\mathcal{B}^{\mathrm{y}}$$

$$C^{J,\mathbf{r}} \to C^{\mathrm{j}} = (\mathcal{K}^{\mathrm{pj}})^{\intercal}.C^{\mathrm{p}}$$

$$\mathcal{K}^{\mathrm{pj}} = \mathcal{K}^{\mathrm{py}}.(\mathcal{K}^{\mathrm{jy}})^{-1}$$

$$\underbrace{\begin{pmatrix} C^{0,\mathbf{1}} \\ C^{0,\mathbf{3}} \\ C^{1,\mathbf{1}} \\ C^{1,\mathbf{3}} \end{pmatrix}}_{C^{\mathrm{j}}} = \underbrace{\begin{pmatrix} 3 & 0 \\ -1 & 1 \\ -1 & -1 \\ -1 & 0 \end{pmatrix}}_{(\mathcal{K}^{\mathrm{pj}})^{\intercal}} . \underbrace{\begin{pmatrix} C_{H\Box} \\ C_{HD} \end{pmatrix}}_{C^{\mathrm{p}} \text{ in the Warsaw basis}}$$

$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$

$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$