# Effective Field Pathway to New Physics

## 有效场论观点下的新物理

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# Outline

Apologize for wasting your time if you have heard this talk!

- Why, What and How EFT?
- Higher Dim Operator Bases

  [ Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2201.04639 ]

  [ Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2012.09188 ]

  [ Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2007.07899 ]

  [ Hao-Lin Li, Jing Shu, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2005.00008 ]
- EFTs at Broken Phase

  [ Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2206.07722 ]

  [ Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2210.14939 ]

  [ Hao Sun, Yi-Ning Wang, **J.H.Yu**, in préparation ]
- UV Completion of EFT Operators

  [ Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2204.03660 ]

  [ Xu-Xiang Li, Zhe Ren, **J.H.Yu,** in preparation ]

  [ Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, in preparation ]
- Summary

# Why, What and How EFT?

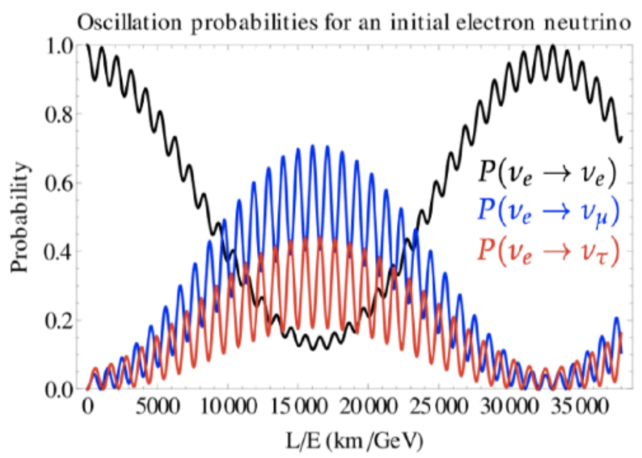
# Why New Physics?

There are experimental challenges in the standard model and theoretical motivation for new physics

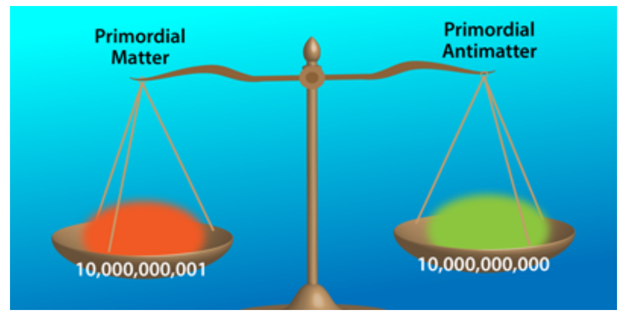
experimental challenges

theoretical motivation

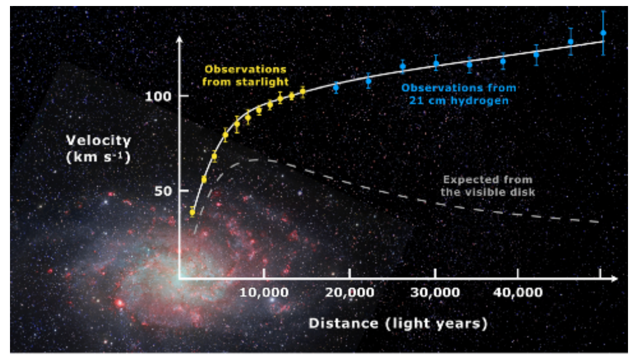
## Neutrino masses



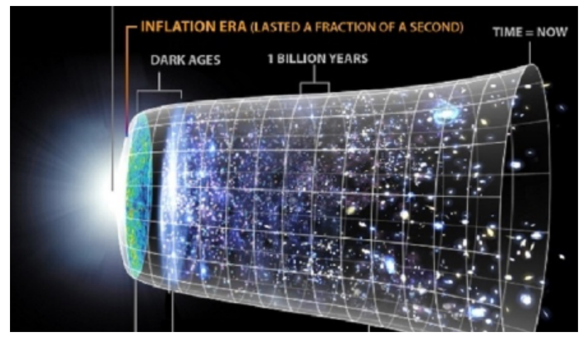

## Baryon asymmetry

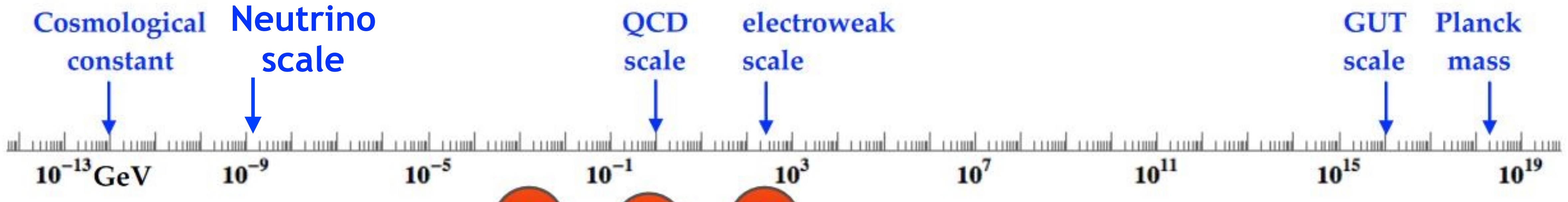


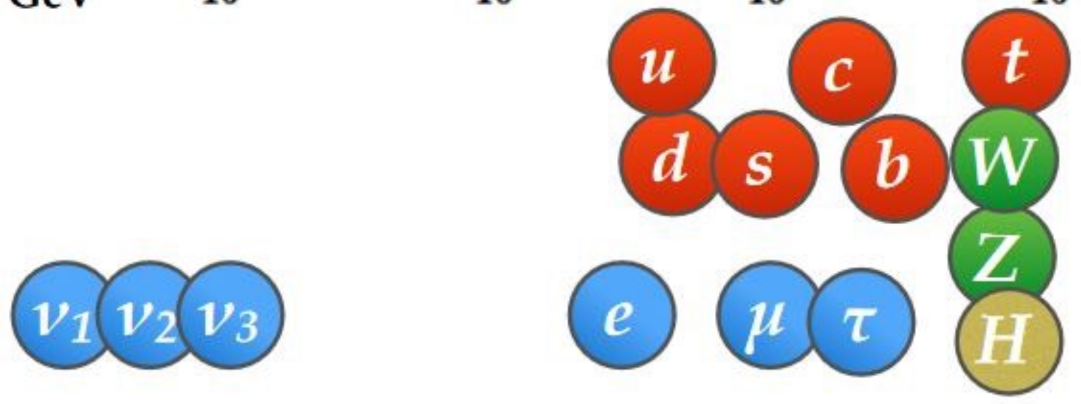

## Dark matter

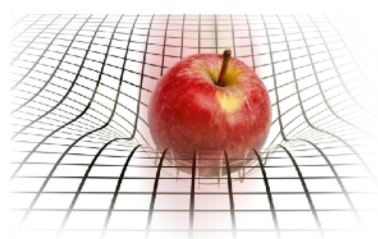



## Inflation



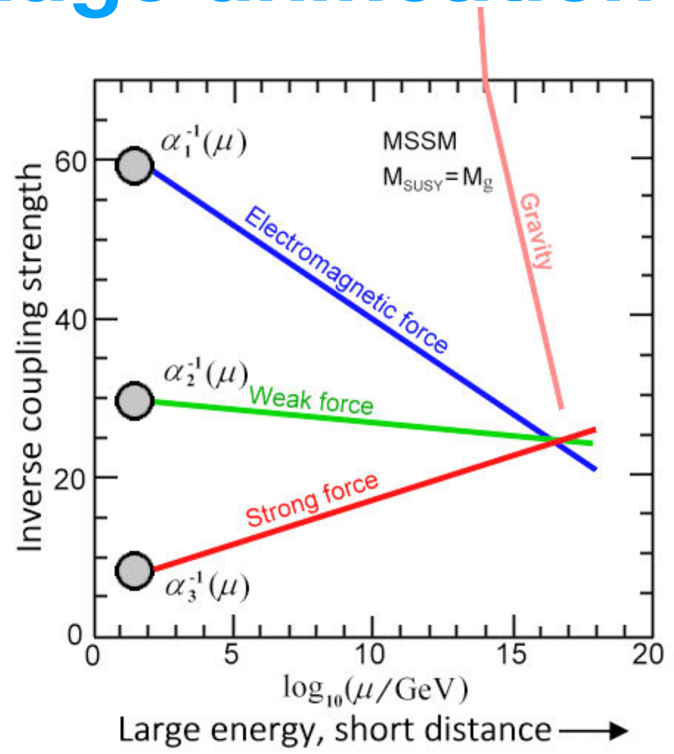



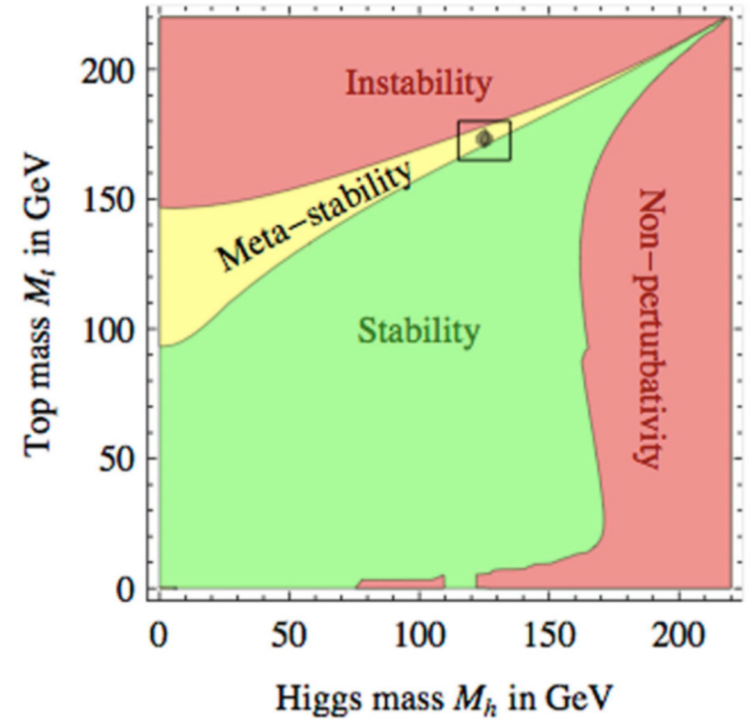
## Fermion flavor hierarchy

## Higgs hierarchy problem

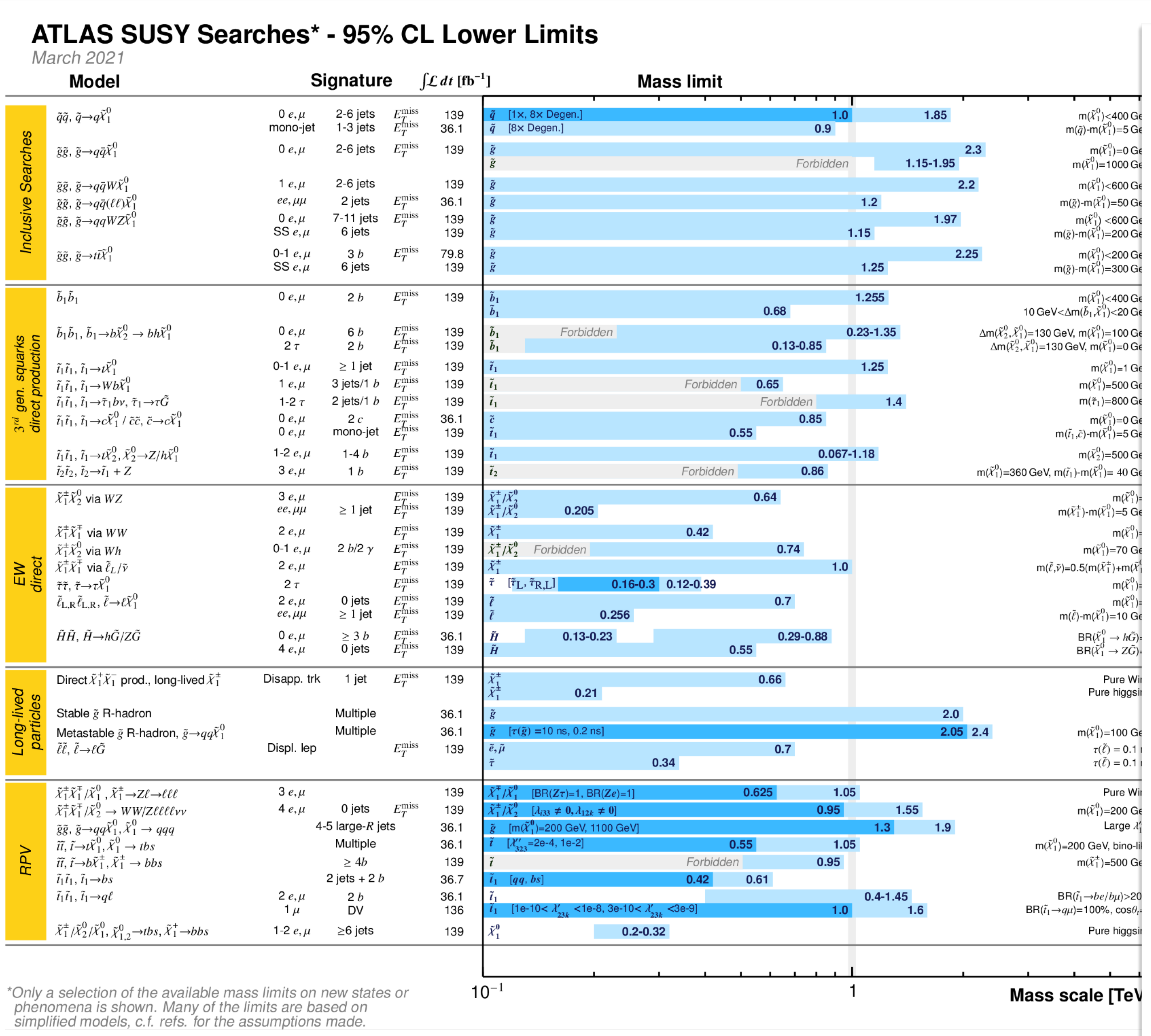
## Gauge unification

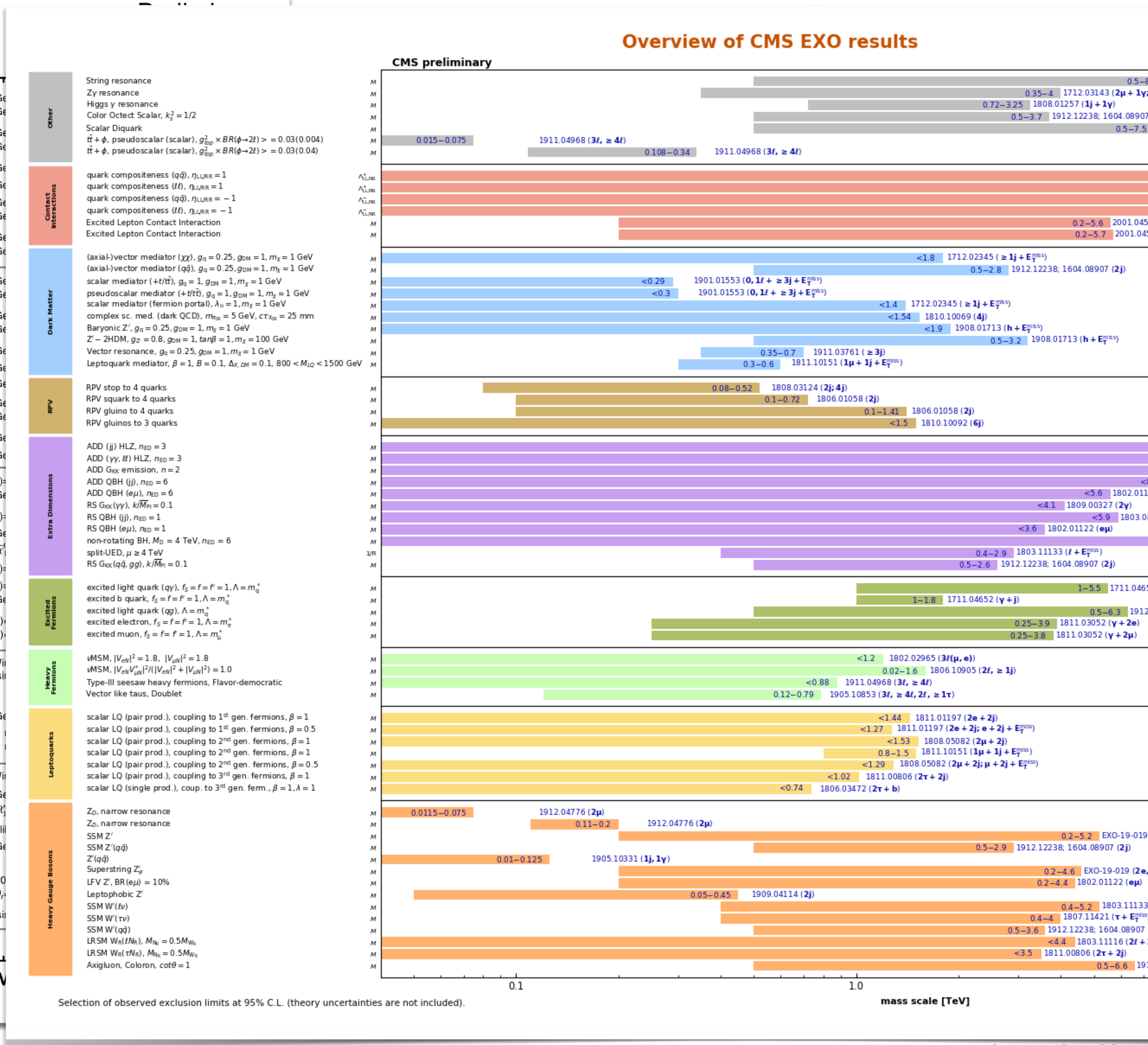



## Vacuum stability



# Where New Physics?

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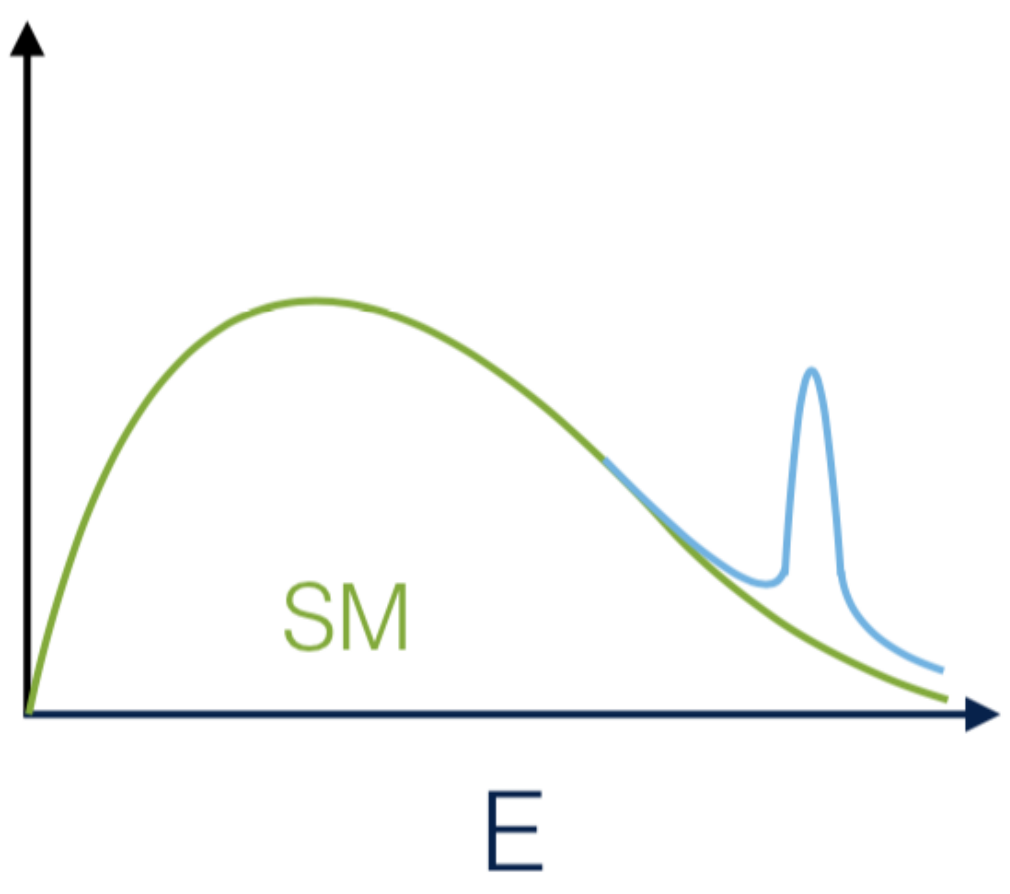
# Paradigm Shift

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

2) New physics hidden at the LHC searches: light particles below 1 GeV   **axion, dark photon, sterile neutrino, etc**

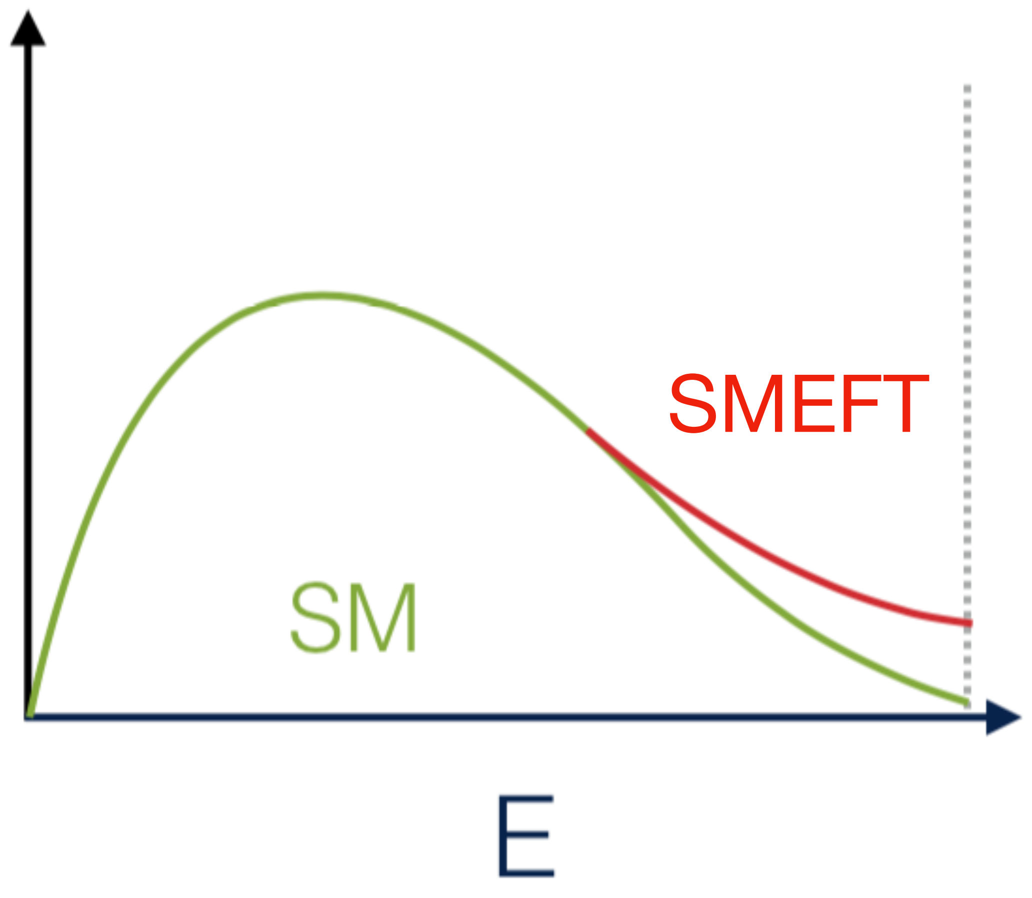
**Direct searches**




**Experiments**: Resonance bump hunting at the LHC

**Theories**: New physics model building

**Precision measurements**




**Experiments**: deviation from SM at the LHC

**Theories**: Effective field theory (EFT) description

**EFT provides evidence of new physics**

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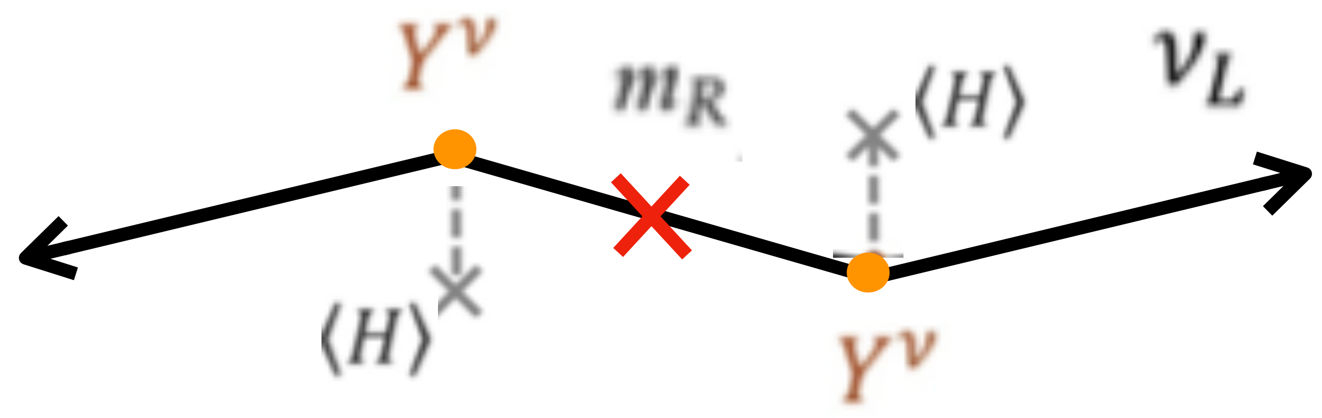
# EFT Description of New Physics

The existence of neutrino masses is the first evidence of new physics beyond standard model (BSM)

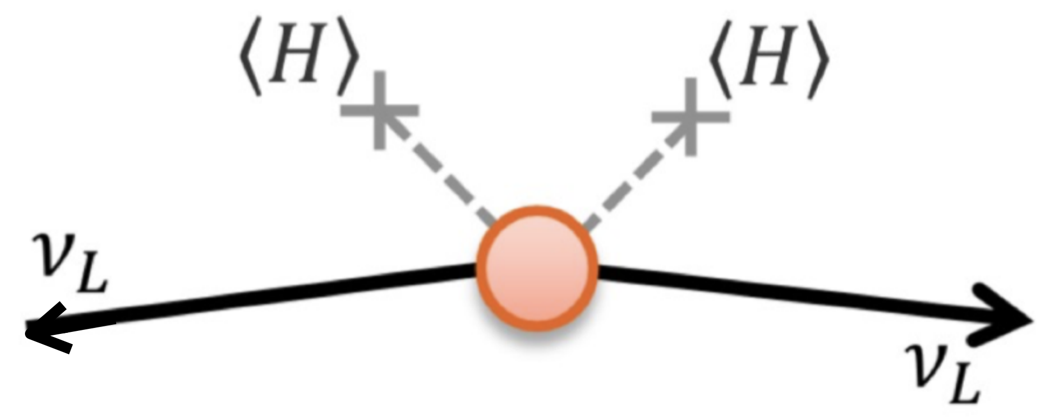
**Beyond the current experimental searches**




for Majorana neutrino

$$m_\nu = \frac{(Y^\nu v_{\rm EW})^2}{m_R}$$

**Measurements of neutrino oscillation**




$$\frac{c_{ij}}{\Lambda}(L_i H)(L_j H) + \mathrm{h.c.}$$

**[ Weinberg, 1979 ]**

$$\to c_{ij}\frac{\mathrm{v}^2}{\Lambda}\nu_i \nu_j + \mathrm{h.c.}$$

**“… the effective field theory point of view had predicted the neutrino masses”**

**[ Weinberg, 2021 ]**

# Effective Field Theory

Standard model is viewed as the leading renormalizable terms of a more general effective field theory

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \ldots$$

[ Weinberg, 1980 ]

Standard Model

Weinberg Operator

$$\frac{c_{ij}}{\Lambda}(L_i H)(L_j H) + \text{h.c.}$$

**Scale separation**: series expansion can be performed and truncated

**Crucial difference between model and EFT**

**Decoupling theorem**: EFT does not depend on details of UV scale

**Provide modern understanding of renormalization**

**DOF**

**SM fields**


**Symmetry**

**SM gauge and Lorentz symmetry**

**Power Counting**

**Canonical dimension**

**Standard Model Effective Field Theory (SMEFT) provides systematic parameterization of all possible Lorentz-inv. new physics**



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# Dim-6 Operators

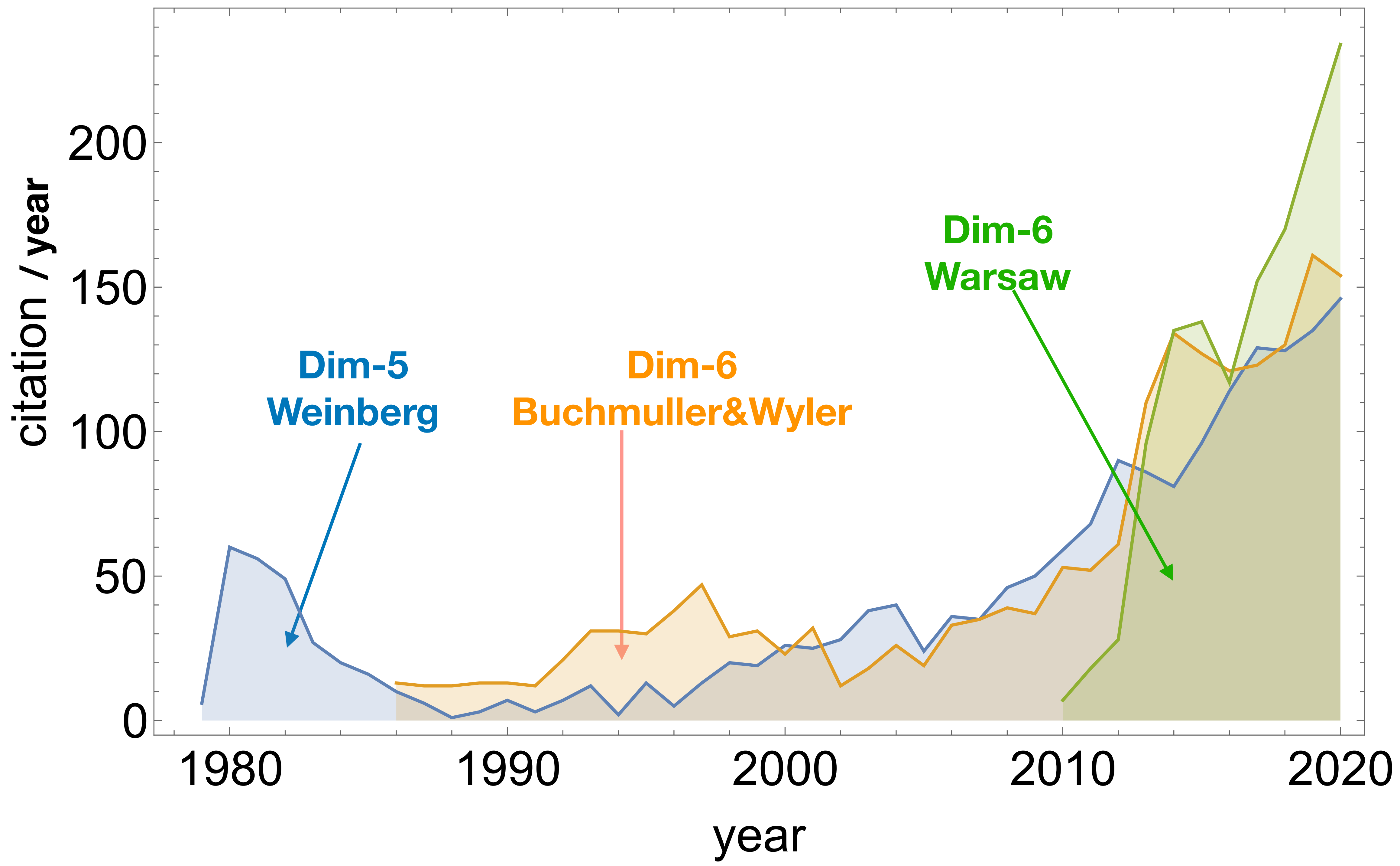
Dimension-6 operators parametrize new physics effects at low energy, electroweak precision, and Higgs boson physics, etc

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \dots$$

[ Buchmuller and Wyler, 1986 ]

**One important task of LHC run-3 : dim-6 operator Wilson coefficients**

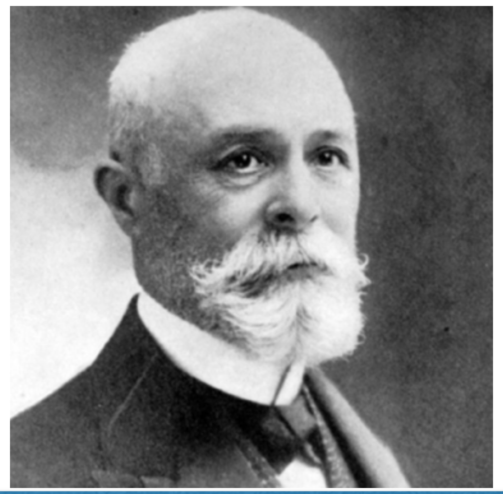
[ Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010 ]




**Why complete and independent dimension-6 operator basis?**

# Why Complete and Independent Operators?

First example of EFT: four fermion theory (dim-6)



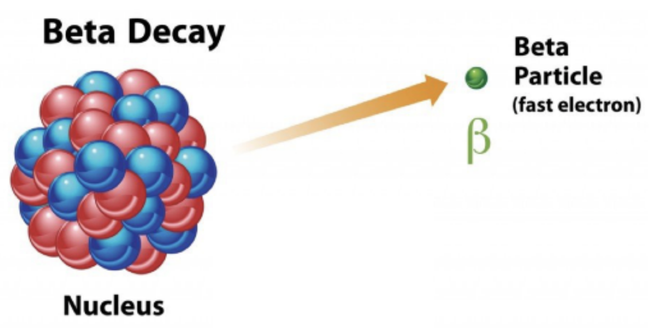
Becquerel
1896

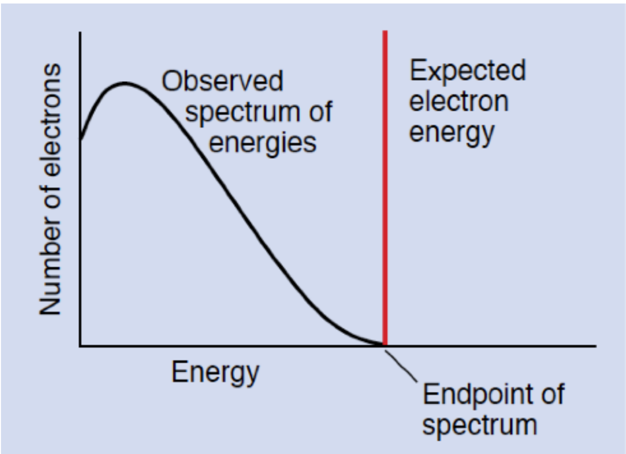
Pauli
1933

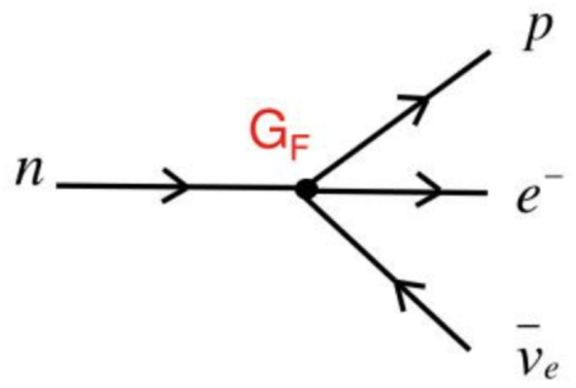
Fermi
1934

Gamov-Teller 1936
Fierz 1937

Lee-Yang 1956
Wu 1956




$$M_{fi} = G_F \left[\bar{\psi}_n \gamma^\mu \psi_p\right] \left[\bar{\psi}_e \gamma^\mu \psi_\nu\right]$$

Four-fermi operator

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

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

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

**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*

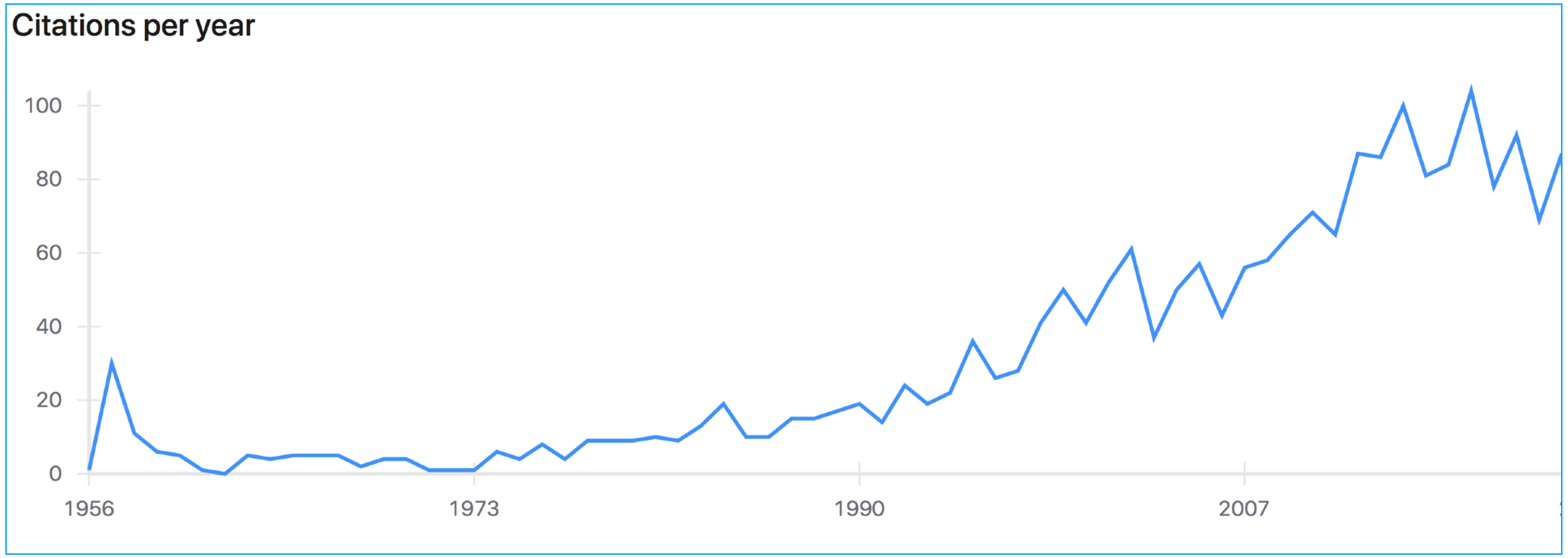
(Received June 22, 1956)

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

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

# Why Complete and Independent Operators?

Lee and Yang: complete four-Fermion charge current low energy EFT operator basis




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]:

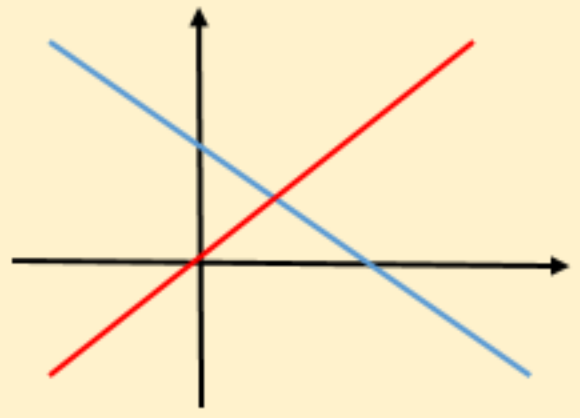
$$\begin{aligned}\mathcal{L}_{\text{Lee-Yang}} = & -\bar{p}\gamma^{\mu}n\left(C_V\bar{e}\gamma_{\mu}\nu - C'_V\bar{e}\gamma_{\mu}\gamma_5\nu\right) + \bar{p}\gamma^{\mu}\gamma_5 n\left(C_A\bar{e}\gamma_{\mu}\gamma_5\nu - C'_A\bar{e}\gamma_{\mu}\nu\right)\\ & - \bar{p}n\left(C_S\bar{e}\nu - C'_S\bar{e}\gamma_5\nu\right)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

How about over-complete basis?

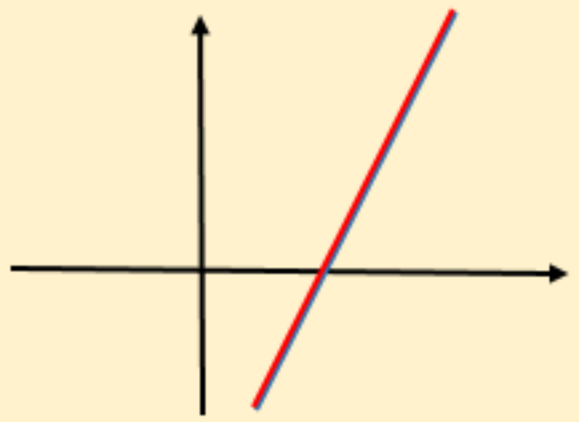
**Cannot uniquely determine Wilson coefficients (WC) for dependent operators**

Example from four-fermion EFT: Fierz identity

$$\left(\bar{u}_1\Gamma^A u_2\right)\left(\bar{u}_3\Gamma^B u_4\right) = \sum_{C,D} C^{AB}_{CD}\left(\bar{u}_1\Gamma^C u_4\right)\left(\bar{u}_3\Gamma^D u_2\right)$$



Consistent Independent
One Solution
Intersect at 1 point



Consistent Dependent
Infinite solutions
Same Line

# Dim-6 Operators

**[ Buchmuller and Wyler, 1986 ]**

$O_\varphi = \frac{1}{3}(\varphi^\dagger\varphi)^3$, $O_{\partial\varphi} = \frac{1}{2}\partial_\mu(\varphi^\dagger\varphi)\,\partial^\mu(\varphi^\dagger\varphi)$.

$O_{e\varphi} = (\varphi^\dagger\varphi)(\bar{\ell}e\varphi)$, $O_{u\varphi} = (\varphi^\dagger\varphi)(\bar{q}u\tilde{\varphi})$, $O_{d\varphi} = (\varphi^\dagger\varphi)(\bar{q}d\varphi)$,

$O_G = f_{ABC}G_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu}$, $O_{\tilde{G}} = f_{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu}$, $O_W = \varepsilon_{IJK}W_\mu^{I\nu}W_\nu^{J\lambda}W_\lambda^{K\mu}$, $O_{\tilde{W}} = \varepsilon_{IJK}\tilde{W}_\mu^{I\nu}W_\nu^{J\lambda}W_\lambda^{K\mu}$.

$O_{\ell B} = i\bar{\ell}\gamma_\mu D_\nu \ell B^{\mu\nu}$, $O_{qB} = i\bar{q}\gamma_\mu D_\nu q B^{\mu\nu}$,

$O_{\varphi G} = \frac{1}{2}(\varphi^\dagger\varphi)G_{\mu\nu}^A G^{A\mu\nu}$, $O_{\varphi\tilde{G}} = (\varphi^\dagger\varphi)\tilde{G}_{\mu\nu}^A G^{A\mu\nu}$,

$O_{\varphi W} = \frac{1}{2}(\varphi^\dagger\varphi)W_{\mu\nu}^I W^{I\mu\nu}$, $O_{\varphi\tilde{W}} = (\varphi^\dagger\varphi)\tilde{W}_{\mu\nu}^I W^{I\mu\nu}$,

$O_{\varphi B} = \frac{1}{2}(\varphi^\dagger\varphi)B_{\mu\nu}B^{\mu\nu}$, $O_{\varphi\tilde{B}} = (\varphi^\dagger\varphi)\tilde{B}_{\mu\nu}B^{\mu\nu}$,

$O_{WB} = (\varphi^\dagger\tau^I\varphi)W_{\mu\nu}^I B^{\mu\nu}$, $O_{\tilde{W}B} = (\varphi^\dagger\tau^I\varphi)\tilde{W}_{\mu\nu}^I B^{\mu\nu}$,

$O_\varphi^{(1)} = (\varphi^\dagger\varphi)(D_\mu\varphi^\dagger D^\mu\varphi)$, $O_\varphi^{(3)} = (\varphi^\dagger D^\mu\varphi)(D_\mu\varphi^\dagger\varphi)$.

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

$O_{\varphi\ell}^{(1)} = i(\varphi^\dagger D_\mu\varphi)(\bar{\ell}\gamma^\mu\ell)$,
$O_{\varphi\ell}^{(3)} = i(\varphi^\dagger D_\mu\tau^I\varphi)(\bar{\ell}\gamma^\mu\tau^I\ell)$,
$O_{\varphi e} = i(\varphi^\dagger D_\mu\varphi)(\bar{e}\gamma^\mu e)$,
$O_{\varphi q}^{(1)} = i(\varphi^\dagger D_\mu\varphi)(\bar{q}\gamma^\mu q)$,
$O_{\varphi q}^{(3)} = i(\varphi^\dagger D_\mu\tau^I\varphi)(\bar{q}\gamma^\mu\tau^I q)$,
$O_{\varphi_u} = i(\varphi^\dagger D_\mu\varphi)(\bar{u}\gamma^\mu u)$,
$O_{\varphi_d} = i(\varphi^\dagger D_\mu\varphi)(\bar{d}\gamma^\mu d)$,

$O_{D_e} = (\bar{\ell}D_\mu e)D^\mu\varphi$, $O_{\bar{D}_e} = (D_\mu\bar{\ell}e)D^\mu\varphi$, $\varepsilon D_\mu\varphi)(\bar{u}\gamma^\mu d)$.

$O_{Du} = (\bar{q}D_\mu u)D^\mu\tilde{\varphi}$, $O_{\bar{D}u} = (D_\mu\bar{q}u)D^\mu\tilde{\varphi}$,

$O_{Dd} = (\bar{q}D_\mu d)D^\mu\varphi$, $O_{\bar{D}d} = (D_\mu\bar{q}d)D^\mu\varphi$,

$O_{eW} = (\bar{\ell}\sigma^{\mu\nu}\tau^I e)\varphi W_{\mu\nu}^I$, $O_{eB} = (\bar{\ell}\sigma^{\mu\nu}e)\varphi B_{\mu\nu}$,

$O_{uG} = (\bar{q}\sigma^{\mu\nu}\lambda^A u)\tilde{\varphi}G_{\mu\nu}^A$,

$O_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\varphi}W_{\mu\nu}^I$, $O_{uB} = (\bar{q}\sigma^{\mu\nu}u)\tilde{\varphi}B_{\mu\nu}$,

$O_{dG} = (\bar{q}\sigma^{\mu\nu}\lambda^A d)\varphi G_{\mu\nu}^A$,

$O_{dW} = (\bar{q}\sigma^{\mu\nu}\tau^I d)\varphi W_{\mu\nu}^I$, $O_{dW} = (\bar{q}\sigma^{\mu\nu}d)\varphi B_{\mu\nu}$.

$O_{\ell\ell}^{(1)} = \frac{1}{2}(\bar{\ell}\gamma_\mu\ell)(\bar{\ell}\gamma^\mu\ell)$, $O_{\ell\ell}^{(3)} = \frac{1}{2}(\bar{\ell}\gamma_\mu\tau^I\ell)(\bar{\ell}\gamma^\mu\tau^I\ell)$,

$O_{qq}^{(1,1)} = \frac{1}{2}(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$, $O_{qq}^{(8,1)} = \frac{1}{2}(\bar{q}\gamma_\mu\lambda^A q)(\bar{q}\gamma^\mu\lambda^A q)$,

$O_{qq}^{(1,3)} = \frac{1}{2}(\bar{q}\gamma_\mu\tau^I q)(\bar{q}\gamma^\mu\tau^I q)$, $O_{qq}^{(8,3)} = \frac{1}{2}(\bar{q}\gamma_\mu\lambda^A\tau^I q)(\bar{q}\gamma^\mu\lambda^A\tau^I q)$,

$O_{\ell q}^{(1)} = (\bar{\ell}\gamma_\mu\ell)(\bar{q}\gamma^\mu q)$, $O_{\ell q}^{(3)} = (\bar{\ell}\gamma_\mu\tau^I\ell)(\bar{q}\gamma^\mu\tau^I q)$.

$O_{ee} = \frac{1}{2}(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)$,

$O_{uu}^{(1)} = \frac{1}{2}(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$, $O_{uu}^{(8)} = \frac{1}{2}(\bar{u}\gamma_\mu\lambda^A u)(\bar{u}\gamma^\mu\lambda^A u)$,

$O_{dd}^{(1)} = \frac{1}{2}(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$, $O_{dd}^{(8)} = \frac{1}{2}(\bar{d}\gamma_\mu\lambda^A d)(\bar{d}\gamma^\mu\lambda^A d)$,

$O_{eu} = (\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$,

$O_{ed} = (\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$,

$O_{ud}^{(1)} = (\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$, $O_{ud}^{(8)} = (\bar{u}\gamma_\mu\lambda^A u)(\bar{d}\gamma^\mu\lambda^A d)$.

$O_{\ell e} = (\bar{\ell}e)(\bar{e}\ell)$,
$O_{\ell u} = (\bar{\ell}u)(\bar{u}\ell)$,
$O_{\ell d} = (\bar{\ell}d)(\bar{d}\ell)$,
$O_{qe} = (\bar{q}e)(\bar{e}q)$,
$O_{qu}^{(1)} = (\bar{q}u)(\bar{u}q)$,
$O_{qd}^{(1)} = (\bar{q}d)(\bar{d}q)$,
$O_{qde} = (\bar{\ell}e)(\bar{d}q)$.

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

$O_{qu}^{(8)} = (\bar{q}\lambda^A u)(\bar{u}\lambda^A q)$,
$O_{qd}^{(8)} = (\bar{q}\lambda^A d)(\bar{d}\lambda^A q)$,

## Equation of motion (field redefinition)

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

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

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

## Covariant derivative commutator

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

80 → 59

## 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

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

$$\tau_{jk}^I\tau_{mn}^I = 2\delta_{jn}\delta_{mk} - \delta_{jk}\delta_{mn}$$

**80-1-16-5+1 = 59**

**[ Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010 ]**

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$ |
| $Q_{\widetilde{G}}$ | $f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$ |
| $Q_W$ | $\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | | | | |

| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
|---|---|---|---|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde{G}}$ | $\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\,G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde{W}}$ | $\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\,W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$ | $Q_{uB}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\,B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde{B}}$ | $\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$ | $Q_{dG}$ | $(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\,G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\,W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde{W}B}$ | $\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\,B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$ |

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

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



Jiang-Hao Yu (ITP-CAS)

# Higher Dimensional Operator Bases

[ Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2201.04639 ]

[ Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2012.09188 ]

[ Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2007.07899 ]

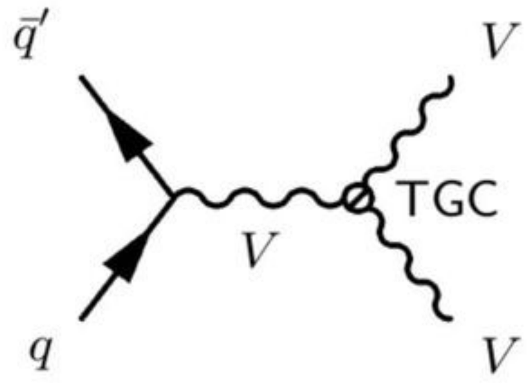
[ Hao-Lin Li, Jing Shu, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2005.00008 ]

# Why Higher Dim Operators?

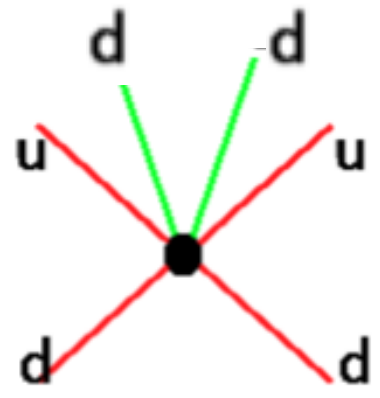
According to power counting rules, typically the higher dim operators are suppressed

$$|\mathcal{A}|^2 \sim \left| A_{\rm SM} + \frac{A_{\rm dim-6}}{\Lambda^2} + \frac{A_{\rm dim-8}}{\Lambda^4} + \ldots \right|^2 \sim |A_{\rm SM}|^2 + \frac{2}{\Lambda^2} A_{\rm dim-6} A^*_{\rm SM} + \frac{1}{\Lambda^4} |A_{\rm dim-6}|^2 + \frac{2}{\Lambda^4} A_{\rm dim-8} A^*_{\rm SM}$$

**Leading operator at higher dim**



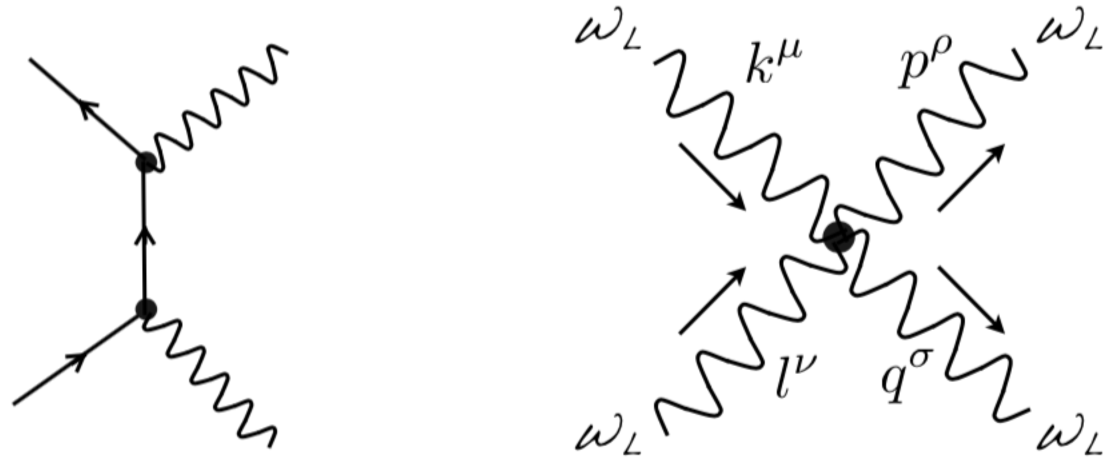

**nTGC at dim-8**




**Neutron-antineutron Oscillation at dim-9**

**Neutrinoless double beta decay**

**New effects at higher dim**




**Derivative couplings Important at high energy**

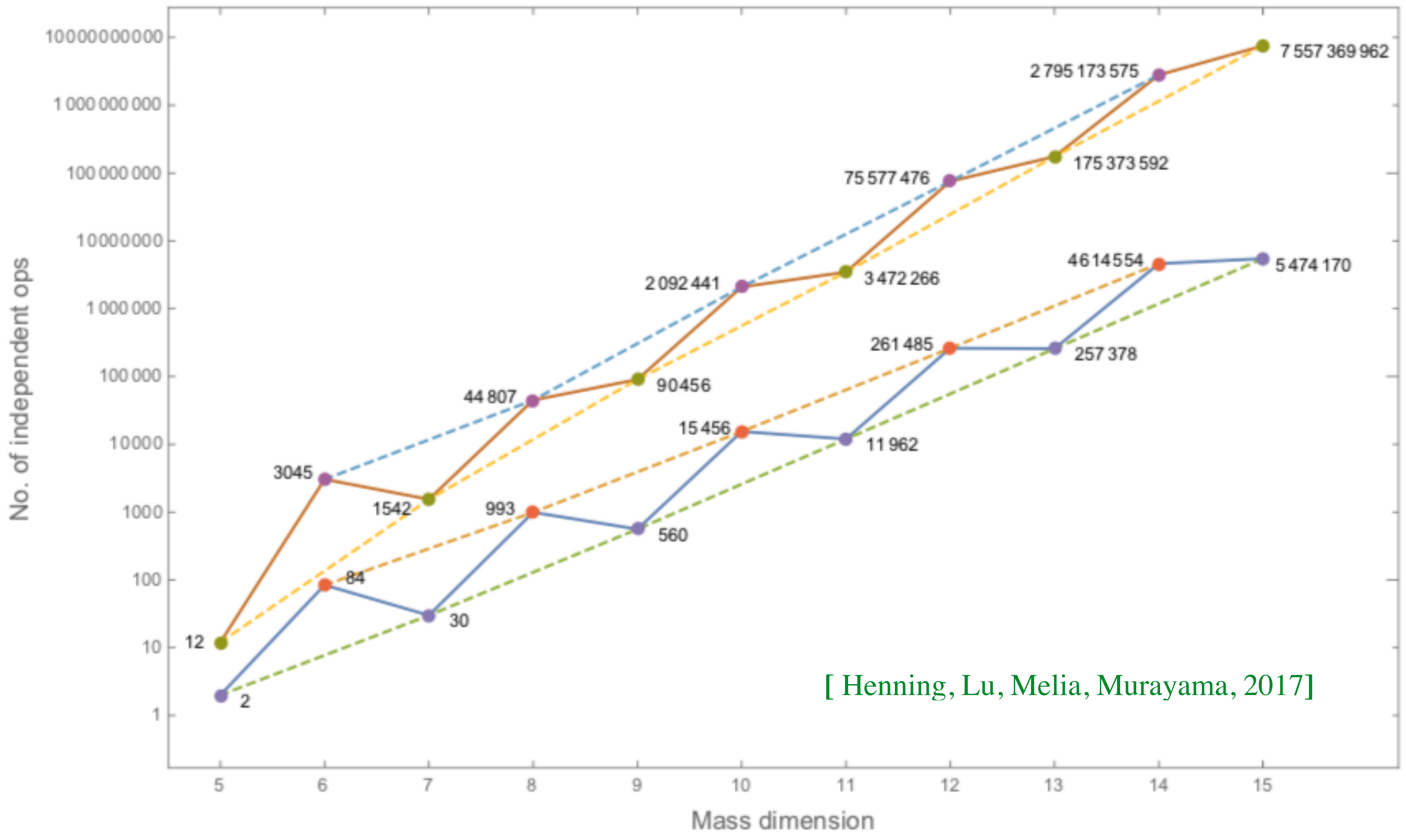
**Correlations among different dim**



Jiang-Hao Yu (ITP-CAS)

# Moore’s Law on EFT Operators

Number of EFT operators grows very fast for higher dim

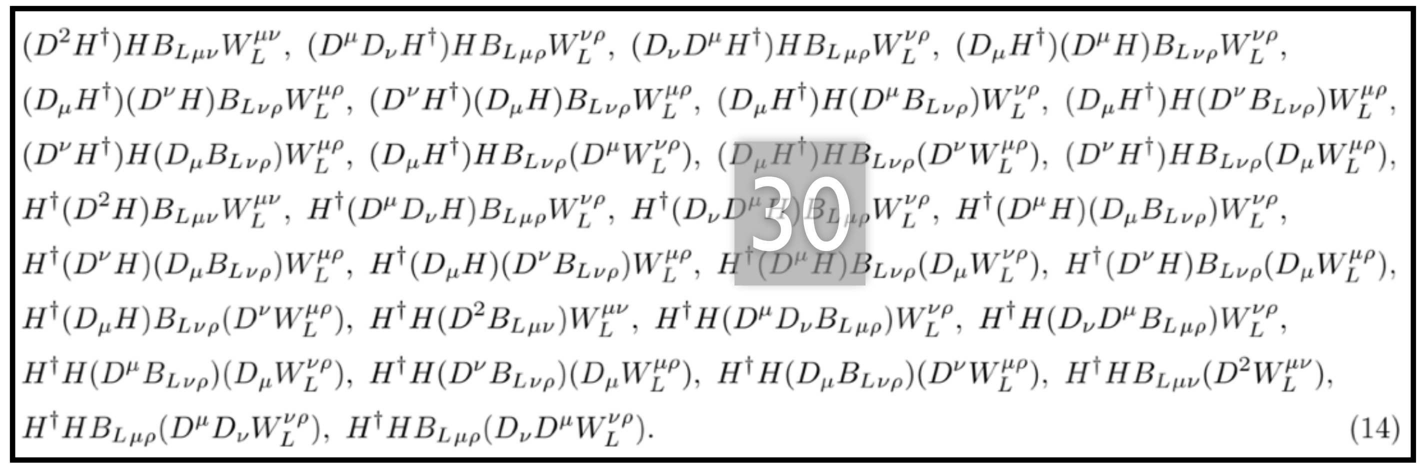



[ Henning, Lu, Melia, Murayama, 2017]

**Derivatives**

$BWHH^\dagger D^2$

2

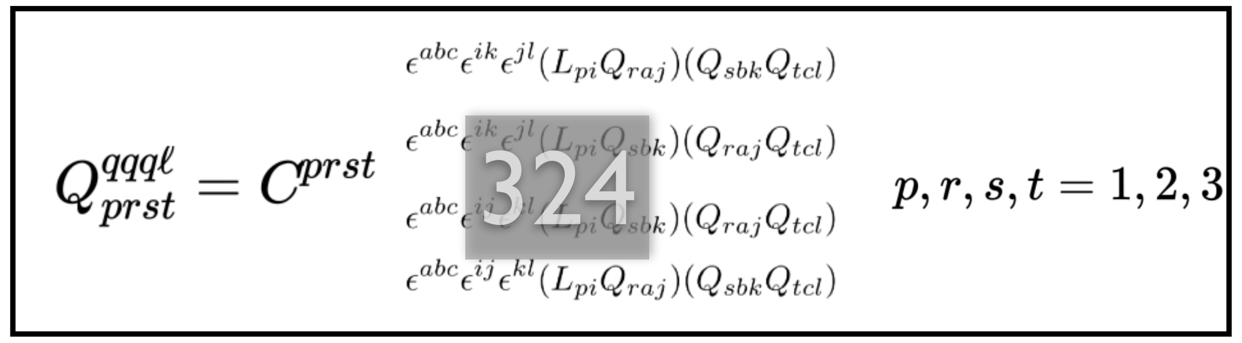



**Which 2 should be picked up?**

**Repeated fields**

$QQQL$

57




**What flavor relations should be imposed?**

# Symmetry of EFT Operators

Operator has more symmetries than what we expected

**Field as irreducible rep of Lorentz group** | **Field transforming under Little group of Poincare**

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

**Building blocks in spinor-helicity form**

$$D^{r_i}\phi_i \Leftrightarrow \lambda_i^{r_i}\tilde\lambda^{i,r_i},$$

$$D^{r_i-1/2}\psi_i^{(\dagger)} \Leftrightarrow \lambda_i^{r_i\pm 1/2}\tilde\lambda^{i,r_i\mp 1/2},$$

$$D^{r_i-1}F_{\mathrm{L/R}\,i} \Leftrightarrow \lambda_i^{r_i\pm 1}\tilde\lambda^{i,r_i\mp 1},$$

$$D^{r_i-2}C_{\mathrm{L/R}\,i} \Leftrightarrow \lambda_i^{r_i\pm 2}\tilde\lambda^{i,r_i\mp 2},$$

On-shell operator

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

$$F_{\mathrm{L}1}{}^{\alpha\beta}F_{\mathrm{L}2\alpha\beta}(D\phi_3)^{\gamma}{}_{\dot\alpha}(D\phi_4)_{\gamma}{}^{\dot\alpha}$$

$\mathcal{M} \to e^{ih_i\varphi}\mathcal{M}$

$\lambda_i \to e^{-i\varphi/2}\lambda_i, \quad \tilde\lambda^i \to e^{i\varphi/2}\tilde\lambda^i.$

$$(\epsilon^{\alpha_i\alpha_j})^{\otimes n}(\tilde\epsilon_{\dot\alpha_i\dot\alpha_j})^{\otimes\tilde n}\prod_{i=1}^{N}\lambda_i^{r_i-h_i}\tilde\lambda^{i,r_i+h_i}$$

$\langle ij\rangle = \epsilon^{\beta\alpha}\lambda_{i\alpha}\lambda_{j\beta}$

$[ij] = \tilde\lambda_{i\dot\alpha}\tilde\epsilon^{\dot\alpha\dot\beta}\tilde\lambda_{j\dot\beta}$

**On-shell Brackets**

$\langle 12\rangle^2\langle 34\rangle[34]$

**EOM and CDC**

$D^2\phi_i \Leftrightarrow p_i^2 = 0$

$[D_\mu, D_\nu] \Leftrightarrow [p_\mu, p_\nu] = 0$

# Operator as Spinor Young Tensor

[ Li, Ren, Xiao, **Yu**, Zheng, 2201.04639 ]
[ Li, Ren, Xiao, **Yu**, Zheng, 2012.09188 ]
[ Li, Ren, Xiao, **Yu**, Zheng, 2007.07899 ]
[ Li, Ren, Shu, Xiao, **Yu**, Zheng, 2005.00008 ]

**Operator**

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

↓

**Spinor Tensor** → **Symmetrize indices**

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

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

$$D_{[\alpha\dot{\alpha}}\Psi_{\beta]} = D_{\mu}\sigma^{\mu}_{[\alpha\dot{\alpha}}\Psi_{\beta]} = -\epsilon_{\alpha\beta}(D_{\mu}\sigma^{\mu}\psi)_{\dot{\alpha}},$$

$$D_{[\alpha\dot{\alpha}}F_{\mathrm{L}\beta]\gamma} = \frac{i}{2}D_{\mu}F_{\mathrm{L}\nu\rho}\sigma^{\mu}_{[\alpha\dot{\alpha}}\sigma^{\nu\rho}_{\beta]\gamma} = i D^{\mu}F_{\mathrm{L}\mu\nu}\epsilon_{\alpha\beta}\sigma^{\nu}_{\gamma\dot{\alpha}},$$

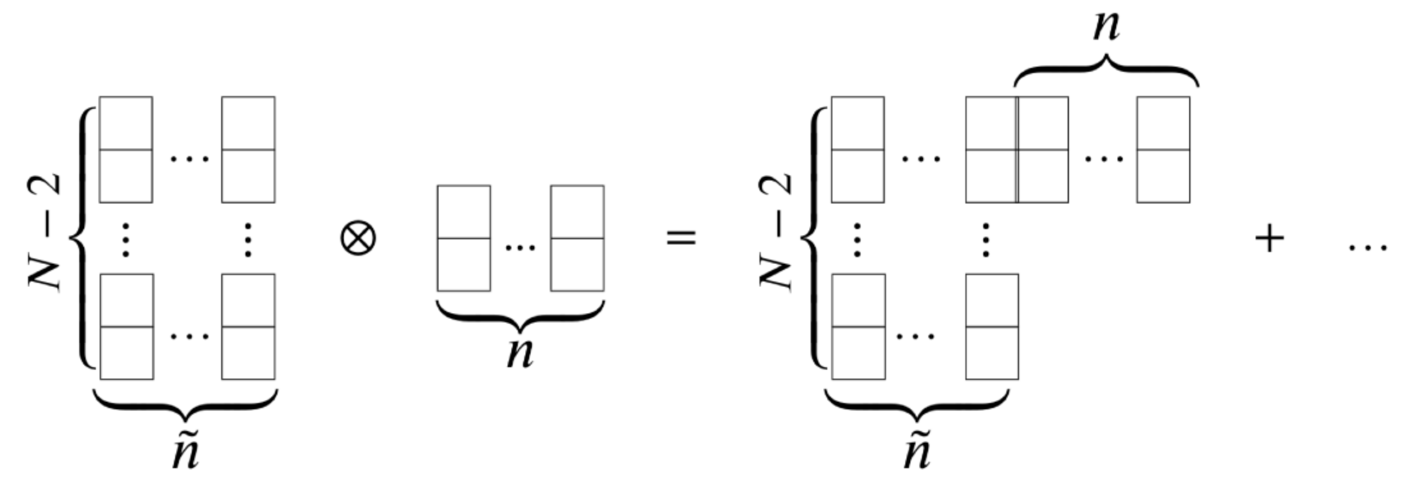
$$(D\psi)_{\alpha\beta\dot{\alpha}} = -\frac{1}{2}\epsilon_{\alpha\beta}(\not{D}\psi)_{\dot{\alpha}} + \frac{1}{2}(D\psi)_{(\alpha\beta)\dot{\alpha}}$$

↓

**SL(2,C) x SU(N)**

$$\lambda_i \to \sum_j U_i^j\lambda_j, \quad \tilde{\lambda}^i \to \sum_k U^{\dagger i}{}_k\tilde{\lambda}^k,$$

$$(\epsilon^{\alpha_i\alpha_j})^{\otimes n}(\tilde{\epsilon}_{\dot{\alpha}_i\dot{\alpha}_j})^{\otimes\tilde{n}}\prod_{i=1}^{N}\lambda_i^{r_i-h_i}\tilde{\lambda}^{i,r_i+h_i}$$




| $i$ |
|---|
| $j$ |

$\Leftrightarrow \langle ij\rangle$

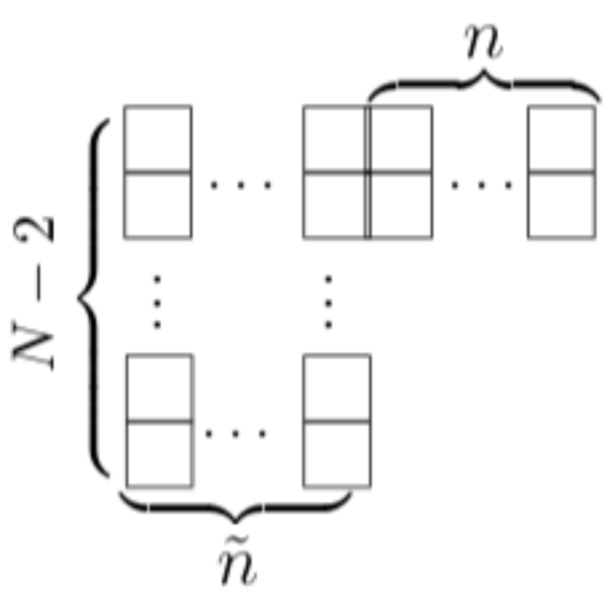
**Momentum conservation**

$$\delta^{(4)}\left(\sum_{i=1}^{N}\lambda_i\tilde{\lambda}_i\right)$$

$$\sum_i\lambda_i\tilde{\lambda}^i \to \sum_i\sum_j\sum_k U_i^j U^{\dagger i}{}_k\lambda_j\tilde{\lambda}^k = \sum_j\lambda_j\tilde{\lambda}^j$$

↓

**SSYT** → **On-shell Amplitude**




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

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

| | | | |
|---|---|---|---|
| 1 | 1 | 1 | 2 |
| 2 | 3 | 3 | 4 |

$\langle 13\rangle\langle 13\rangle\langle 24\rangle[34]$ $\quad F_{\mathrm{L}1}^{\alpha\beta}\psi_2^{\gamma}(D\psi_3)_{\alpha\beta\dot{\alpha}}(D\phi_4)_{\gamma}{}^{\dot{\alpha}}$

| | | | |
|---|---|---|---|
| 1 | 1 | 1 | 3 |
| 2 | 2 | 3 | 4 |

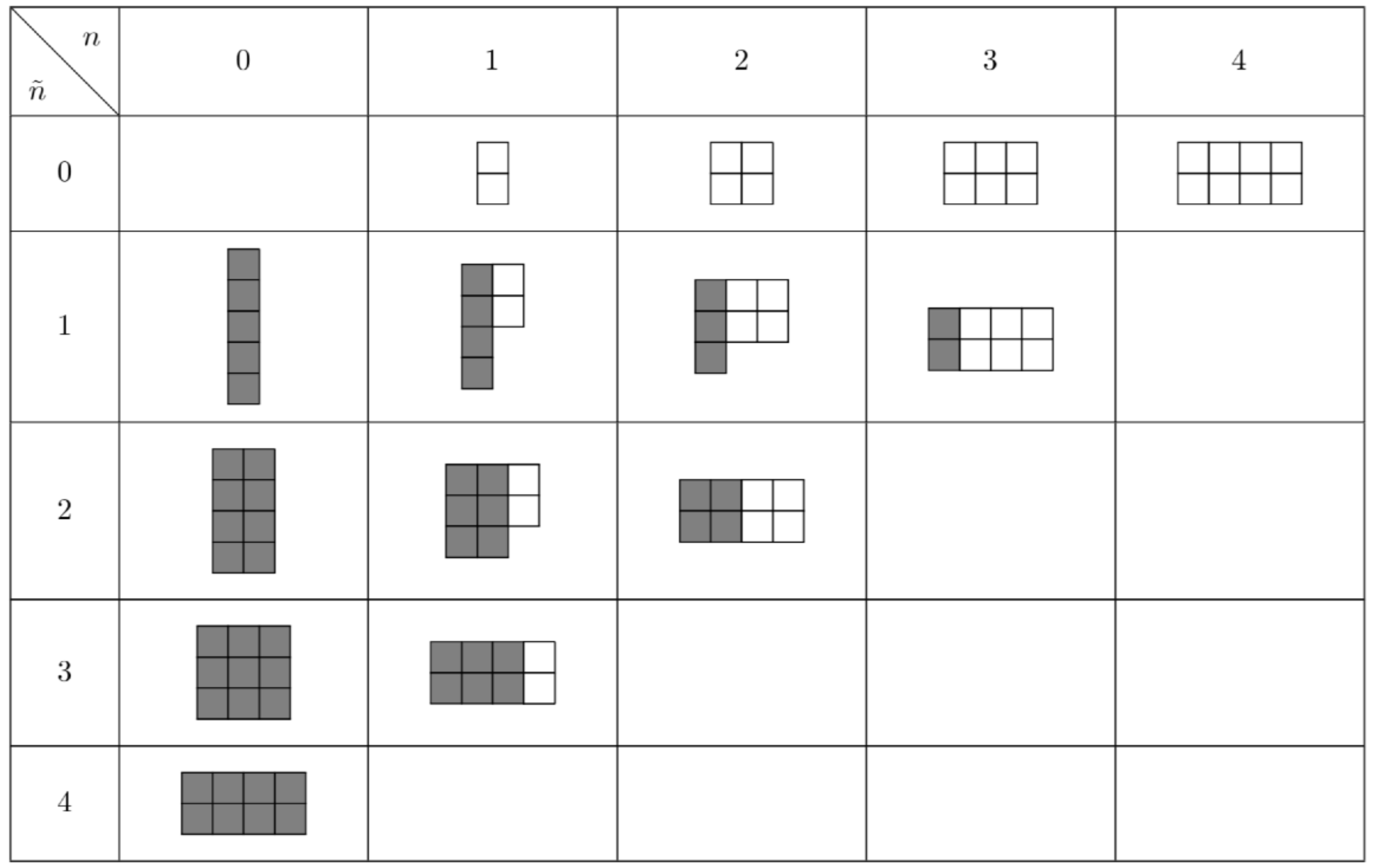
$\langle 12\rangle\langle 13\rangle\langle 34\rangle[34]$ $\quad F_{\mathrm{L}1}^{\alpha\beta}\psi_{2\alpha}(D\psi_3)_{\beta}{}^{\gamma}{}_{\dot{\alpha}}(D\phi_4)_{\gamma}{}^{\dot{\alpha}}$

**On-shell Amplitude correspondence**

# Procedure and Comparison

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

**Step-1**




| $n$ / $\tilde{n}$ | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 0 | $\phi^8$ | $\psi^2\phi^5$ | $\psi^4\phi^2$, $F_L\psi^2\phi^3$, $F_L^2\phi^4$ | $F_L\psi^4$, $F_L^2\psi^2\phi$, $F_L^3\phi^2$ | $F_L^4$ |
| 1 | $\psi^{\dagger 2}\phi^5$ | $\psi^{\dagger 2}\psi^2\phi^2$, $\psi^\dagger\psi\phi^4 D$, $\phi^6 D^2$ | $F_L\psi^{\dagger 2}\psi^2$, $F_L^2\psi^{\dagger 2}\phi$, $\psi^\dagger\psi^3\phi D$, $F_L\psi^\dagger\psi\phi^2 D$, $\psi^2\phi^3 D^2$, $F_L\phi^4 D^2$ | $F_L^2\psi^\dagger\psi D$, $\psi^4 D^2$, $F_L\psi^2\phi D^2$, $F_L^2\phi^2 D^2$ | |
| 2 | $\psi^{\dagger 4}\phi^2$, $F_R\psi^{\dagger 2}\phi^3$, $F_R^2\phi^4$ | $F_R\psi^{\dagger 2}\psi^2$, $F_R^2\psi^2\phi$, $\psi^{\dagger 3}\psi\phi D$, $F_R\psi^\dagger\psi\phi^2 D$, $\psi^{\dagger 2}\phi^3 D^2$, $F_R\phi^4 D^2$ | $F_R^2 F_L^2$, $F_R F_L\psi^\dagger\psi D$, $\psi^{\dagger 2}\psi^2 D^2$, $F_R\psi^2\phi D^2$, $F_L\psi^{\dagger 2}\phi D^2$, $F_R F_L\phi^2 D^2$, $\phi^4 D^4$, $\psi^\dagger\psi\phi^2 D^3$ | | |
| 3 | $F_R\psi^{\dagger 4}$, $F_R^2\psi^{\dagger 2}\phi$, $F_R^3\phi^2$ | $F_R^2\psi^\dagger\psi D$, $\psi^{\dagger 4} D^2$, $F_R\psi^{\dagger 2}\phi D^2$, $F_R^2\phi^2 D^2$ | | | |
| 4 | $F_R^4$ | | | | |

**Step-2**

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

**Step-3**

| | | | |
|---|---|---|---|
| 1 | 1 | 1 | 3 |
| 2 | 2 | 2 | 4 |

↓

| | | | |
|---|---|---|---|
| 1 | 1 | 1 | 2 |
| 2 | 2 | 3 | 4 |

2

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

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

## Traditional method

[ Hays, Martin, Sanz, Setford, 2018]

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

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

30

EOM

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

7

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

# SMEFT Operator Bases up to Dim-9

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \cdots$$

## Standard Model Effective Field Theory

**SU(3) x SU(2) x U(1) gauge symmetry**

- Dim-5: [Weinberg, 1979]
- Dim-6: [Buchmuller, Wyler, 1986]; [Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]
- Dim-7: [Lehman, 2014]; [ Henning, Lu, Melia, Murayama, 2015]; [Liao, Ma, 2016]
- Dim-8: [ Li, Ren, Shu, Xiao, **Yu**, Zheng, **2020**]; [Murphy, 2020]
- Dim-9: [ Li, Ren, Xiao, **Yu**, Zheng, **2020**]; [Liao, Ma, 2020]

## Low Energy Effective Field Theory

**SU(3) x U(1) gauge symmetry**

- Dim-5: [Dirac, 1932 ]
- Dim-6: [ Fermi, 1934 ]; [ Lee, Yang, 1956 ]; [Jenkins, Manohar, Stoffer, 2017]
- Dim-7: [Liao, Ma, Wang, 2020]; [ Li, Ren, Xiao, **Yu**, Zheng, 2020]
- Dim-8: [ Li, Ren, Xiao, **Yu**, Zheng, 2020]; [Murphy, 2020]
- Dim-9: [ Li, Ren, Xiao, **Yu**, Zheng, 2020]



Jiang-Hao Yu (ITP-CAS)

# Operator Bases for Generic EFT up to All Order

## Amplitude Basis Construction for Effective Field Theory

[ Li, Ren, Xiao, **Yu**, Zheng, 2201.04639 ]

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### Welcome to the HEPForge Project: ABC4EFT

**This is the website for the Mathematica package: Amplitude Basis Construction for Effective Field Th**

#### Package

**This package has the following features:**

- It provides a general procedure to construct the independent and complete operator bases for generic L invariant effective field theory, given any kind of gauge symmetry and field content, up to any mass dim
- 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 cor can be easily done.

#### Authors

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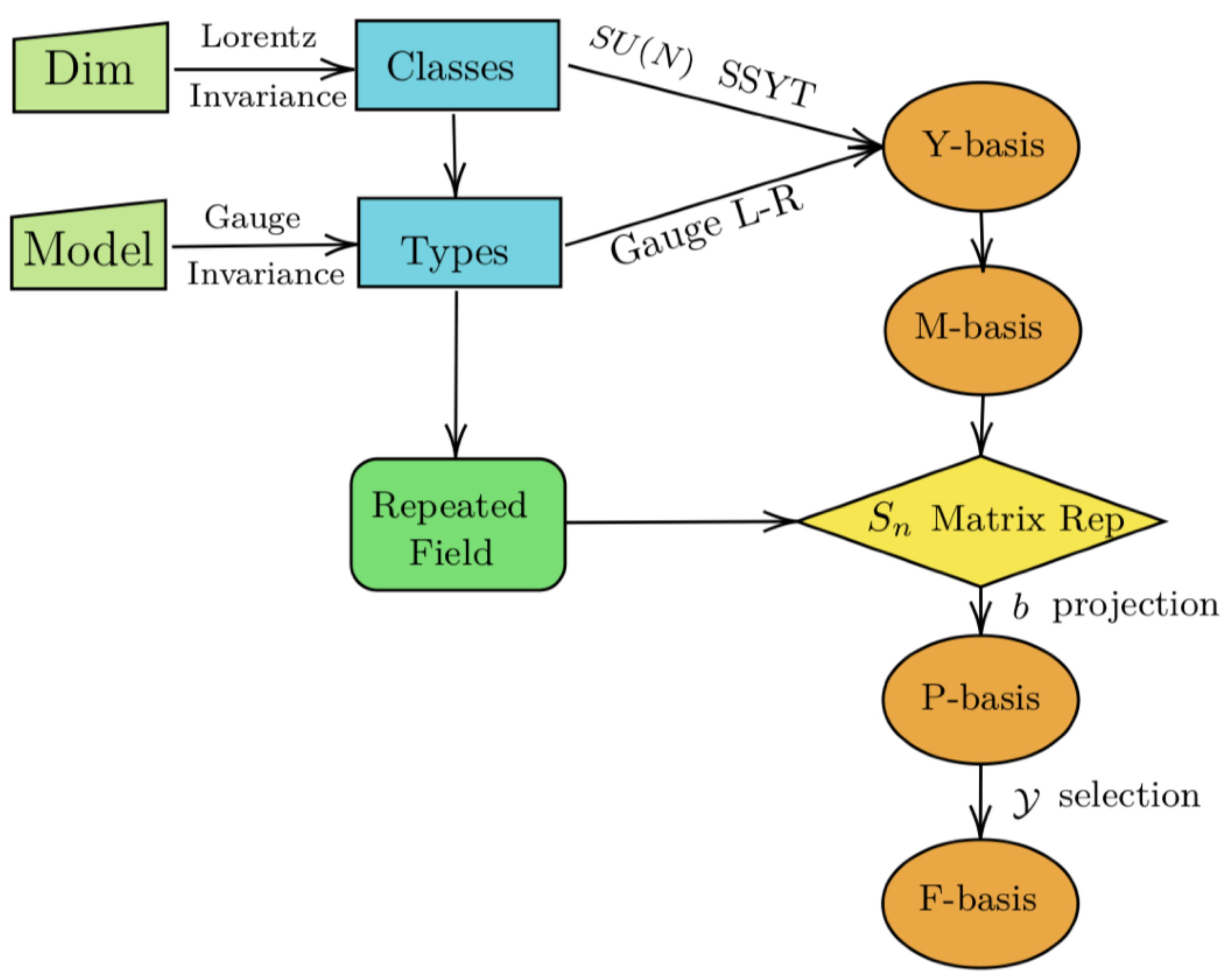



**Fully Automatic**

**Dark matter EFT**
**Sterile neutrino EFT**
**Gravity EFT**
**Axion EFT**
**…**

**https://abc4eft.hepforge.org/**

# EFTs at Broken Phase

[ Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2206.07722 ]

[ Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2206.07722 ]

[ Hao Sun, Yi-Ning Wang, **J.H.Yu**, in préparation ]

# EFTs at Broken Phase

Standard Model Effective Field Theory → (Matching / Running) → Low Energy Effective Field Theory

**approximate custodial symmetry**
**SU(2) x SU(2)**

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix} \to g_L \, \Sigma \, g_R^\dagger$$

$$\langle \Sigma \rangle = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix} \neq 0$$

**approximate chiral symmetry**
**SU(3) x SU(3)**

$$\mathbf{q}_L \to g_L \, \mathbf{q}_L \,, \quad \mathbf{q}_R \to g_R \, \mathbf{q}_R \,,$$

$$\langle 0 | (\bar{\mathbf{q}}_L \mathbf{q}_R + \bar{\mathbf{q}}_R \mathbf{q}_L) | 0 \rangle \neq 0$$

Electroweak Chiral Lagrangian

$$\Phi \equiv \frac{1}{\sqrt{2}} \vec{\sigma} \cdot \vec{\varphi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \varphi^0 & \varphi^+ \\ \varphi^- & -\frac{1}{\sqrt{2}} \varphi^0 \end{pmatrix}$$

SM fields and Goldstone

QCD Chiral Lagrangian

$$\Phi \equiv \frac{\vec{\lambda}}{\sqrt{2}} \vec{\phi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}} \eta \end{pmatrix}$$

meson and baryon

**SM Fermion masses from Higgs VEV**

**Baryon masses around cutoff scale from Trace anomaly**

# Goldstone EFT and Power Counting

Construct generic EFT for Goldstone at IR broken phase

PHYSICAL REVIEW VOLUME 166, NUMBER 5 25 FEBRUARY 1968

**Nonlinear Realizations of Chiral Symmetry***

STEVEN WEINBERG†
*Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts*

(Received 25 September 1967)

**Shift symmetry:**

$$\pi \to \pi + \epsilon + \cdots$$

**Goldstone mode is a fluctuation around the background in the direction of broken generator**

Gapless mode | Weakly coupled at IR | Non-linear transform under G/H

**No interaction at long-wave limit**

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{p^2} + \mathscr{L}_{p^3} + \mathscr{L}_{p^4} + \mathscr{L}_{p^5} + \mathscr{L}_{p^6} + \ldots$$

$$\frac{f^2}{4}\langle D_\mu \mathbf{U}^\dagger D^\mu \mathbf{U}\rangle$$

**Power counting: Derivative expansion**

$$\Pi_{\hat{a}} \to \Pi_{\hat{a}}^{(g_{\mathcal{H}})} = \left(e^{i\,\alpha_a t_\pi{}^a}\right)_{\hat{a}}^{\ \hat{b}} \Pi_{\hat{b}}$$

$$\Pi_{\hat{a}} \to \Pi^{(g_{\mathcal{G}/\mathcal{H}})}{}_{\hat{a}} = \Pi_{\hat{a}} + \frac{f}{\sqrt{2}}\alpha_{\hat{\alpha}} + \mathcal{O}\left(\alpha\frac{\Pi^2}{f} + \alpha\frac{\Pi^3}{f^2}\ldots\right)$$

$$U[\Pi] = e^{i\frac{\sqrt{2}}{f}\Pi_{\hat{a}}(x)\widehat{T}^{\hat{a}}}$$

$$g\cdot U[\Pi] = U[\Pi^{(g)}]\cdot h[\Pi;\, g] \qquad h[\Pi;\, g] = e^{i\,\zeta_a[\Pi;g]T^a}$$

**Coset Construction**

[Callan, Coleman, Wess, Zumino, 1969]

# CCWZ Chiral Lagrangian

Define the nonlinear Goldstone matrix

[Callan, Coleman, Wess, Zumino, 1969]

$$\Omega(\Pi) \equiv \exp\left[\frac{i}{2f}\Pi(x)\right] \to \Omega(\Pi^{(\mathfrak{g})}) = \mathfrak{g}\Omega(\Pi)\mathfrak{h}^{-1}(\Pi;\mathfrak{g})$$

**CCWZ Coset**

$$-i\Omega^\dagger\partial_\mu\Omega = d_\mu^{\hat{a}}T^{\hat{a}} + E_\mu^a T^a \equiv d_\mu + E_\mu$$

$$d_\mu \to \mathfrak{h} d_\mu \mathfrak{h}^{-1}, \quad E_\mu \to \mathfrak{h}E_\mu\mathfrak{h}^{-1} - ih\partial_\mu\mathfrak{h}^{-1}$$

$$\partial_\mu \to D_\mu = \partial_\mu + iA_\mu$$
$$A_\mu = A_\mu^{\hat{a}}T^{\hat{a}} + A_\mu^a T^a$$

Building block

$$d_\mu(\Pi), \quad E_{\mu\nu}(\Pi) \quad \nabla_\mu \equiv \partial_\mu + iE_\mu$$
$$f_{\mu\nu} = \Omega^\dagger F_{\mu\nu}\Omega = f_{\mu\nu}^{-\hat{a}}T^{\hat{a}} + f_{\mu\nu}^{+a}T^a$$

$$E_{\mu\nu} = -i[u_\mu, u_\nu] + f_{\mu\nu}^+$$
$$d_\mu = u_\mu$$

$$[T_{\hat{a}}, T_{\hat{b}}] \propto T_c$$

**Symmetric Coset**

$$\Omega \to \mathfrak{g}\Omega\mathfrak{h}^{-1}, \quad \Omega \to \mathfrak{h}\Omega\mathfrak{g}_{\mathcal{R}}^{-1}$$

$$U \equiv \Omega^2 \to \mathfrak{g}\,U\mathfrak{g}_{\mathcal{R}}^{-1}$$

$$D_\mu U \equiv \partial_\mu U + iA_\mu U - iUA_\mu^{(R)}$$
$$A_\mu^{(R)} \equiv A_\mu^a T^a - A_\mu^{\hat{a}}T^{\hat{a}}$$

Building block

$$u_\mu = i\Omega(D_\mu U)^\dagger\Omega \qquad D_\mu$$
$$f_{\mu\nu}^\pm = \frac{1}{2}\left(f_{\mu\nu} \pm f_{\mu\nu}^{(R)}\right) = \Omega^\dagger F_{\mu\nu}\Omega \pm F_{\mu\nu}^{(R)}$$

$$\Omega(\Pi) \equiv \begin{bmatrix} u(\Pi) & 0 \\ 0 & u^\dagger(\Pi) \end{bmatrix} \qquad u \to \sqrt{\mathfrak{g}_L U \mathfrak{g}_R^\dagger} = \mathfrak{g}_L u\mathfrak{h}^{-1} = \mathfrak{h}^{-1}u\mathfrak{g}_R$$

$$U(\Pi) \equiv u^2(\Pi) \longrightarrow \mathfrak{g}_L \mathbf{U}(\Pi)\mathfrak{g}_R^\dagger$$

**QCD Chiral Lag**

$$u_\mu \to \mathfrak{h}\,u_\mu\,\mathfrak{h}^{-1}$$

$$u_\mu = \mathrm{i}\left[u^\dagger(\partial_\mu - \mathrm{i}r_\mu)u - u(\partial_\mu - \mathrm{i}l_\mu)u^\dagger\right]$$

$$\chi_\pm = u^\dagger\chi u^\dagger \pm u\chi^\dagger u\,,$$
$$f_{\mu\nu}^\pm = uf_{\mu\nu}^{\mathrm{L}}u^\dagger \pm u^\dagger f_{\mu\nu}^{\mathrm{R}}u\,,$$

**EW Chiral Lag**

$$\mathbf{V}_\mu \to \mathfrak{g}_L\,\mathbf{V}\,\mathfrak{g}_L^{-1}$$

$$\mathbf{V}_\mu(x) = i\mathbf{U}(x)D_\mu\mathbf{U}(x)^\dagger$$

$$\mathbf{T} = \mathbf{U}\mathcal{T}_R\mathbf{U}^\dagger \longrightarrow \mathfrak{g}_L\mathbf{T}\mathfrak{g}_L^\dagger \qquad \hat{W}_{\mu\nu} \longrightarrow \mathfrak{g}_L\hat{W}_{\mu\nu}\mathfrak{g}_L^\dagger$$

$$\mathbf{Y} = \mathbf{U}\mathcal{Y}_R\mathbf{U}^\dagger \longrightarrow \mathfrak{g}_L\mathbf{Y}\mathfrak{g}_L^\dagger \qquad \hat{B}_{\mu\nu} \longrightarrow \mathfrak{g}_R\hat{B}_{\mu\nu}\mathfrak{g}_R^\dagger$$

# Adler Zero Condition for Goldstone Boson

**Chiral symmetry (PCAC)**

$$\alpha \to \beta \quad \xleftrightarrow{\text{At low energy}} \quad \alpha + n_1\pi \to \beta + n_2\pi$$

Goldberger-Trieman, Callan-Trieman, Adler-Weisberger, etc

**Adler Zero condition** [ Adler, 1965 ]

$$T(\alpha + \phi(p), \beta) = -\frac{p_\mu}{F} R^\mu(p) \xrightarrow{p \to 0} 0$$

**Amplitude (soft limit of external leg s)**

$$\mathcal{A}(1,\ldots,N,s) \xrightarrow{p_s \to 0} \begin{cases} \left(S^{(0)}(s) + S^{(\mathrm{sub})}(s)\right)\mathcal{A}(1,\ldots,N) \\ \mathcal{O}(p_s^\sigma) \quad \text{for Goldstone Boson} \end{cases}$$

$\{-1/2, -1/2, 1, 0, 0\}$

$$\begin{array}{|c|c|c|c|}\hline 1&1&1&4\\ \hline 2&2&2&5\\ \hline 4&5 \\ \cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\ \hline 2&2&5&5\\ \hline 4&4 \\ \cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\ \hline 2&2&4&4\\ \hline 5&5 \\ \cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\ \hline 2&2&4&5\\ \hline 4&5 \\ \cline{1-2}\end{array},$$

**Expand the soft-limit amplitude into the SSYT basis**

**Put constraints on the SSYT basis**

$$\mathcal{B}_i^{(N)}(p_\pi \to 0) = \sum_{l=1}^{d_N} \mathcal{K}_{il} \mathcal{B}_l^{(N)}$$

$$\begin{array}{|c|c|c|c|}\hline 1&1&1&4\\ \hline 2&2&2&5\\ \hline 4&5 \\ \cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\ \hline 2&2&4&5\\ \hline 4&5 \\ \cline{1-2}\end{array},$$

[ Sun, Xiao, **Yu**, 2210.14939 ]
[ Sun, Xiao, **Yu**, 2206.07722 ]
[ Low, Shu, Xiao, Zheng, 2022]

custodial/chiral symmetry breaking: spurion

# Chiral Lagrangian for QCD and EW Theory

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{p^2} + \mathscr{L}_{p^3} + \mathscr{L}_{p^4} + \mathscr{L}_{p^5} + \mathscr{L}_{p^6} + \ldots$$

**ChPT and Chiral EFT**

LO Lagrangian
[ Weinberg, 1979 ]

Pure mesonic
[ Gasser, Leutwyler, 1984, 1985 ]
[ Fearing, Scherer 1994 ]
[ Bijnens, Colangelo, Ecker, 1999 ]
[ Jiang, Ge, Wang, 2014 ]
[ Bijnens, Hermansson, Wang, 2018 ]

nucleon-meson
[ Krause, 1990 ]
[ Ecker, 1994 ]
[ Fettes, Meisner, Mojzis, Steininger, 2000 ]
[ Oller, Verbeni, Prades, 2006 ]
[ Frink, Meisner, 2006 ]
[ Jiang, Chen, Liu, 2017 ]

nucleon-nucleon
[ Weinberg 1990 ]
[ van Kolck, Ordonez, 1992 ]
[ Petschauer, Kaiser, 2013 ]
[ Petschauer, Haidenbauer, Kaiser, Meisner, Weise, 2020 ]

[ Sun, Wang, **Yu**, in préparation ]

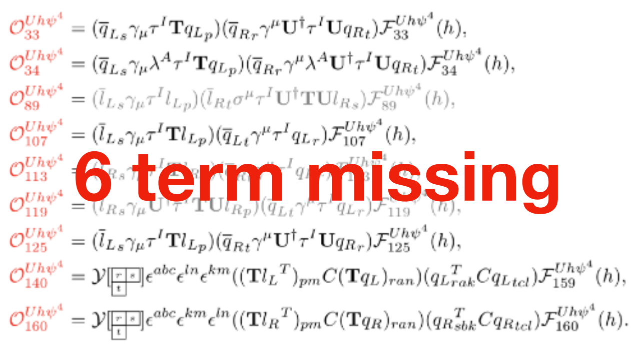
**EW Chiral Lagrangian = HEFT**

LO Lagrangian
[ Weinberg, 1979 ]

NLO bosonic
[ Appelquist, Bernard, 1980 ]
[ Longhitano, 1980, 1981 ]
[ Feruglio, 1993 ]

NLO 2-fermion
[ Buchalla, Cata, Krause, 2014 ]

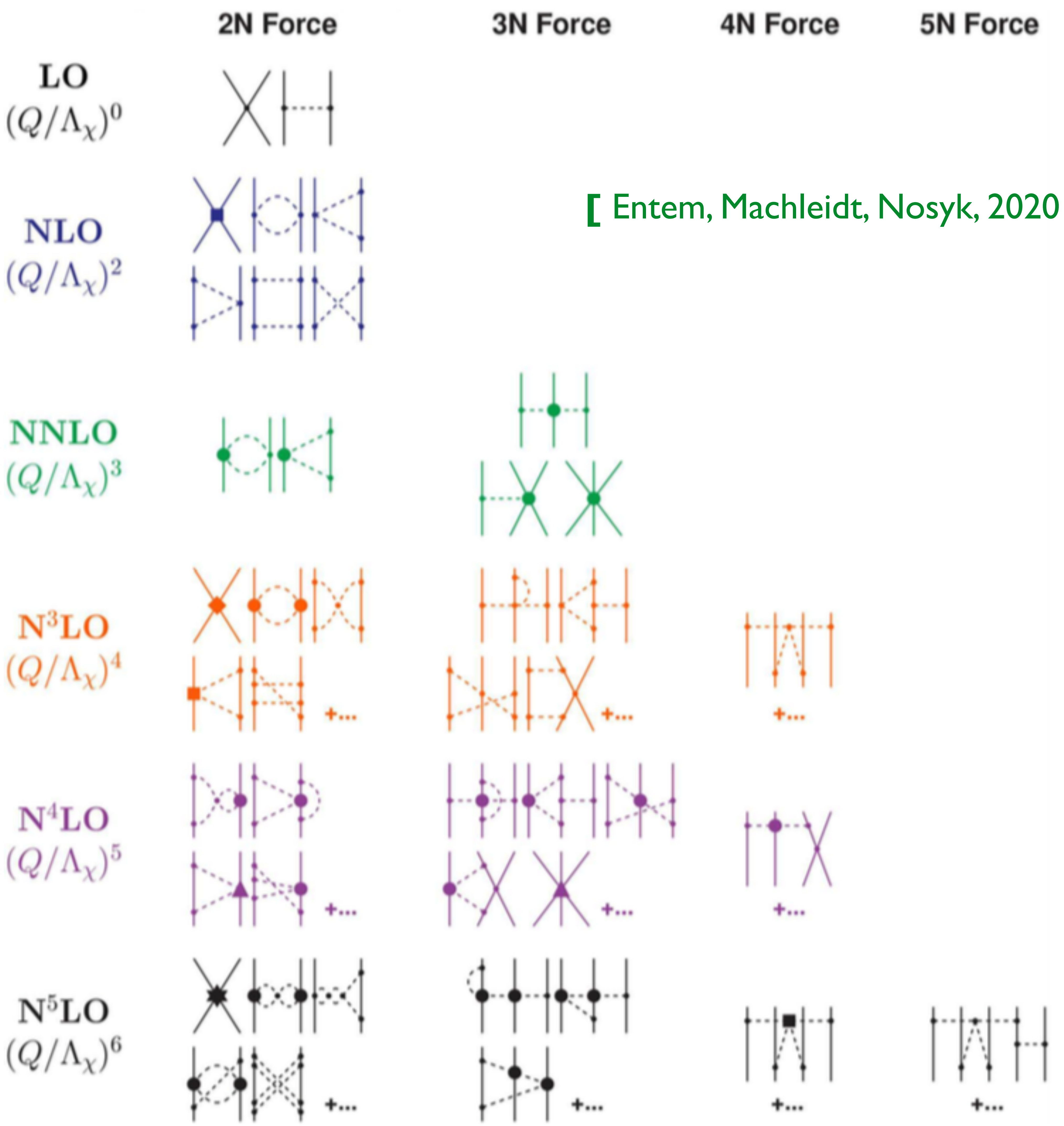
NLO 4-fermion
[ Buchalla, Cata, Krause, 2014 ]
[ Pich, Rosell, Santos, Sanz-Cillero, 2015, 2018 ]
[ Sun, Xiao, **Yu**, 2206.07722 ]




NNLO Basis
[ Sun, Xiao, **Yu**, 2210.14939 ]

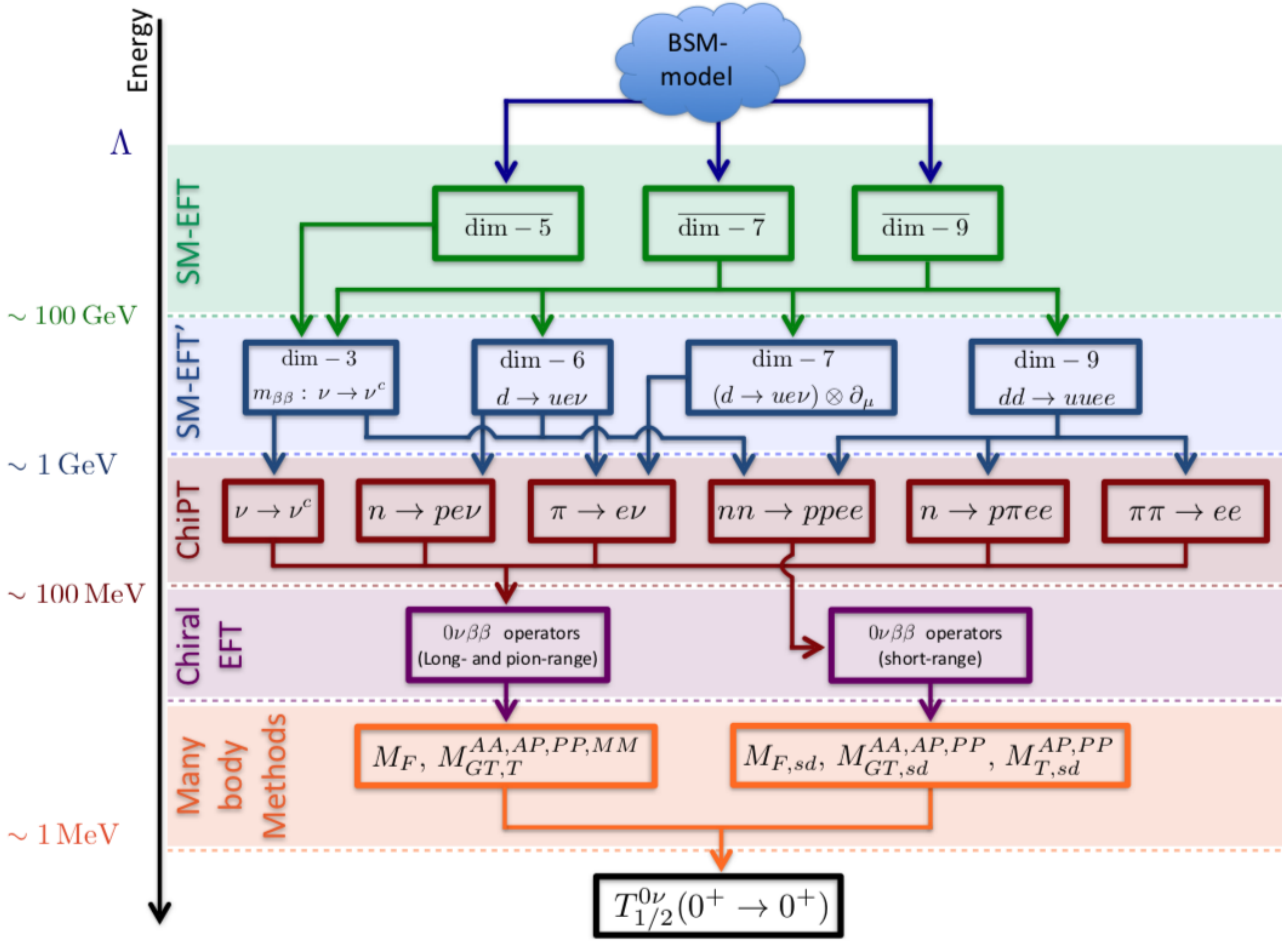
# Why Higher Order Chiral Lagrangian?

Ab initio nuclear force




[ Entem, Machleidt, Nosyk, 2020 ]

Higher order chiral perturbation

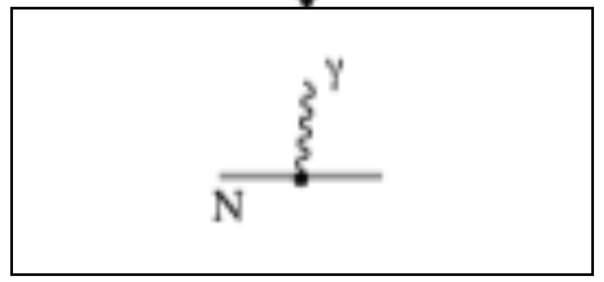


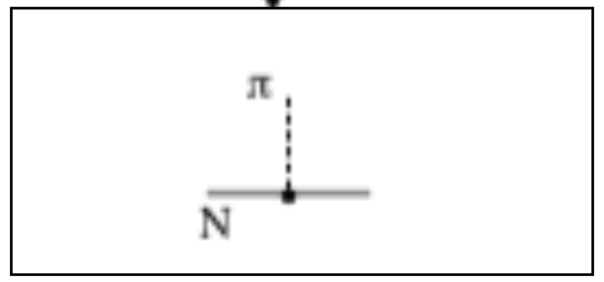

[ Cirigliano, Dekens, de Vries, Graesser, Mereghetti, 2017]

# Chiral Nuclear Force

**Meson Exchange Model**

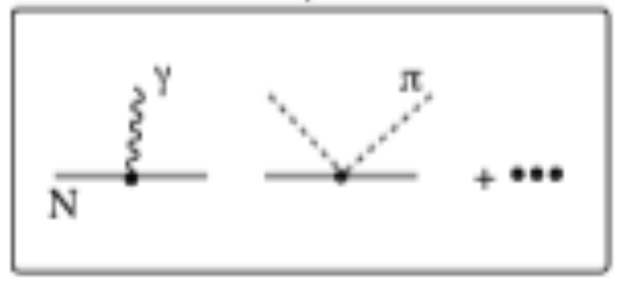
$$\mathcal{L}_\sigma = \overline{N_L}\, i\not{D}\, N_L + \overline{N_R}\, i\not{D}\, N_R - g\overline{N_R}\,\Sigma\, N_L - g\overline{N_L}\,\Sigma^\dagger\, N_R$$

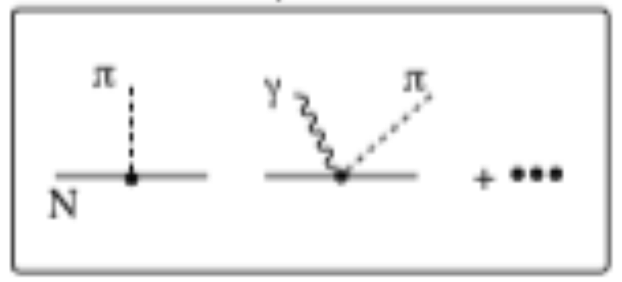



**Chiral EFT**

$$\mathcal{L}^{(1)}_{\pi N} = \bar{\psi}\left(i\not{D} - m_N + \tfrac{1}{2} g_A \gamma_\mu \gamma_5 u^\mu\right)\psi$$

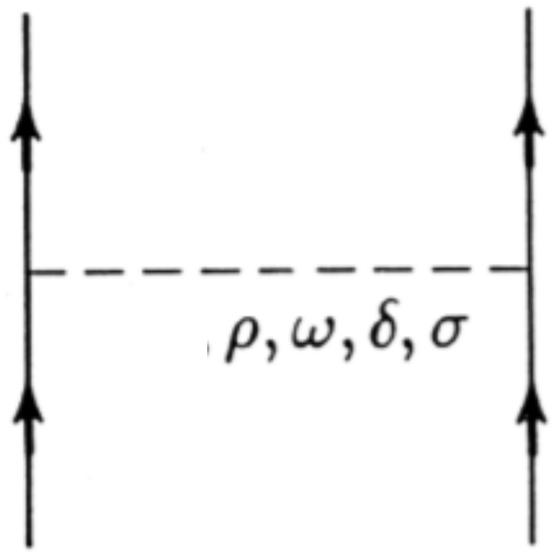


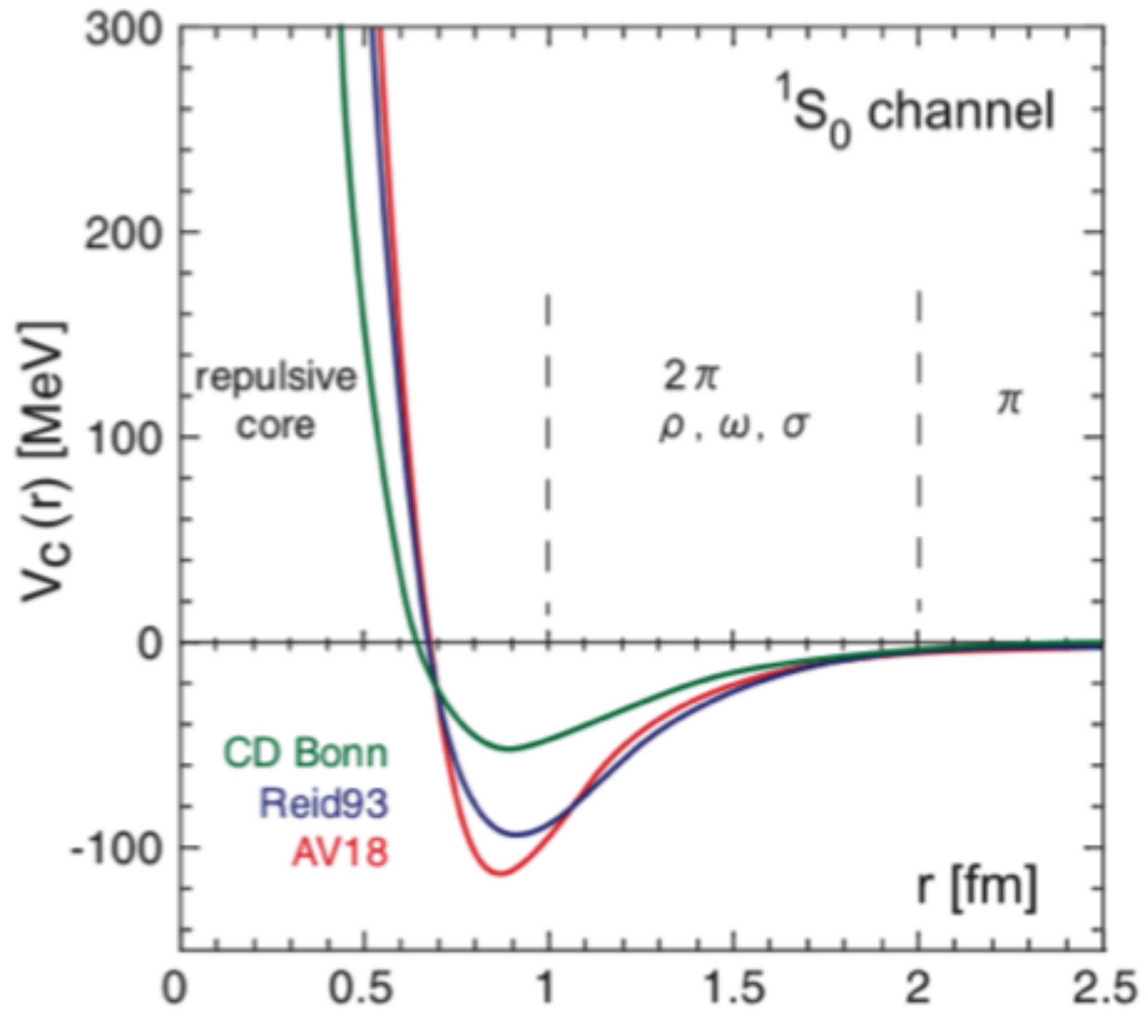



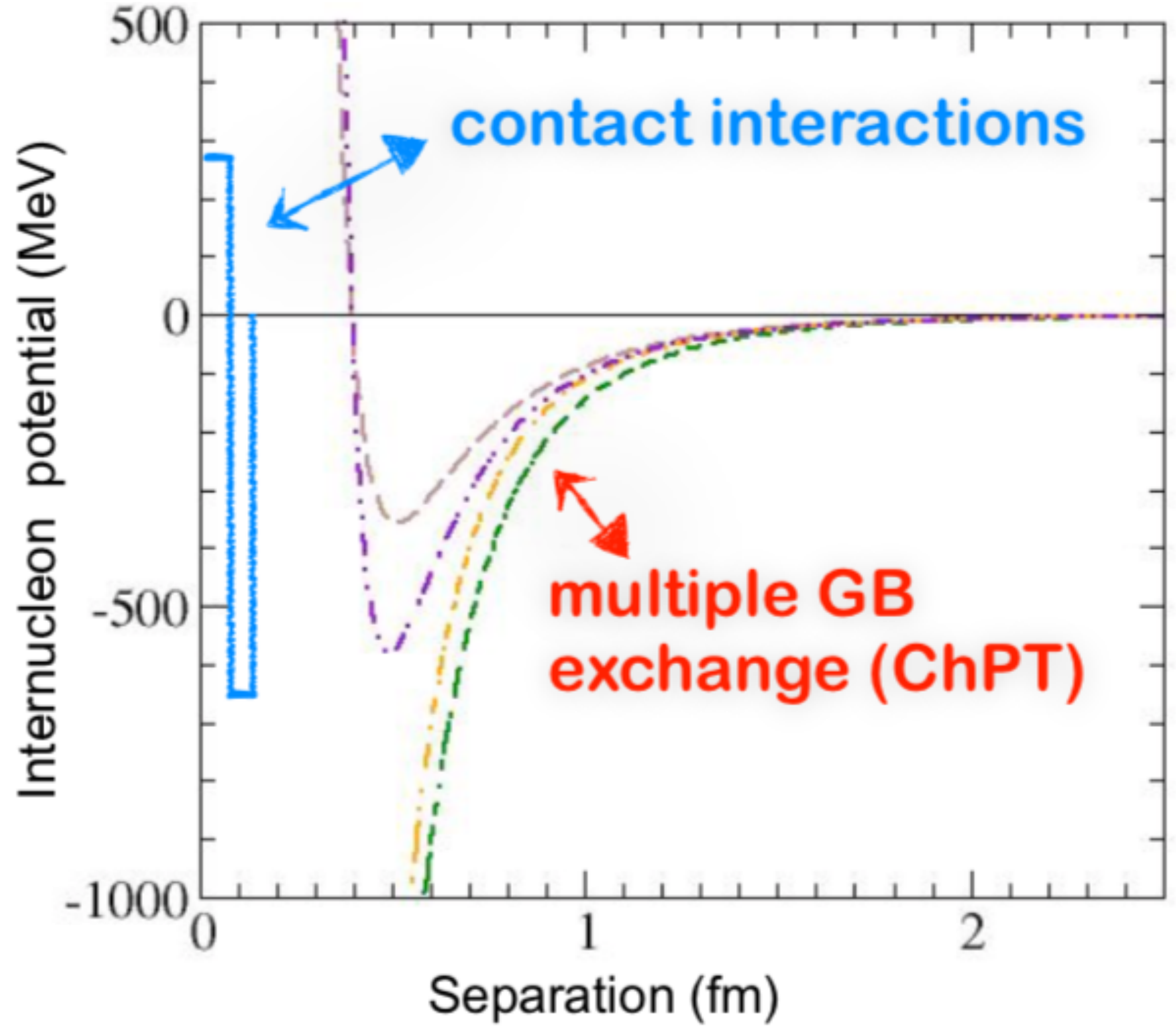

$$M_N g_A(0) = F_\pi\, g_{\pi NN}$$

$$g_A \simeq 1.27,\ g_{\pi NN} \simeq 13.40$$

**Goldberger-Treiman Relation**



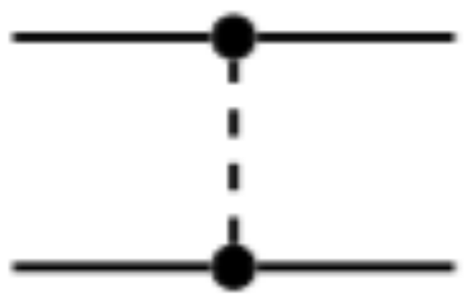




$$\mathcal{L} = N^\dagger\left(i\partial_0 + \frac{\vec{\nabla}^2}{2m_N}\right)N - \frac{1}{2}C_S(N^\dagger N)^2 - \frac{1}{2}C_T(N^\dagger\vec{\sigma}N)^2 + \underbrace{\ldots}_{\text{terms with} \geq 2 \text{ derivatives}}$$

# Chiral effective field theory

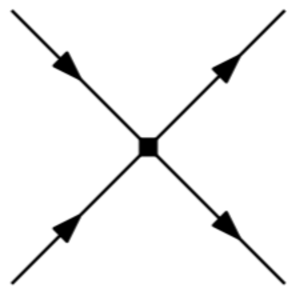
Weinberg power counting $$\mu = 2 + 2\ell - r + \sum_i V_i\left(d_i + \frac{1}{2}n_i - 2\right)$$

[ Weinberg, 1990 ]



Dim = 2(1-2+2/2) = 0

$$V_{1\pi} = -\left(\frac{g_A}{2F_\pi}\right)^2 \frac{\vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}}{q^2+M_\pi^2}\,\vec{\tau}_1\cdot\vec{\tau}_2 \sim \mathcal{O}(1)$$

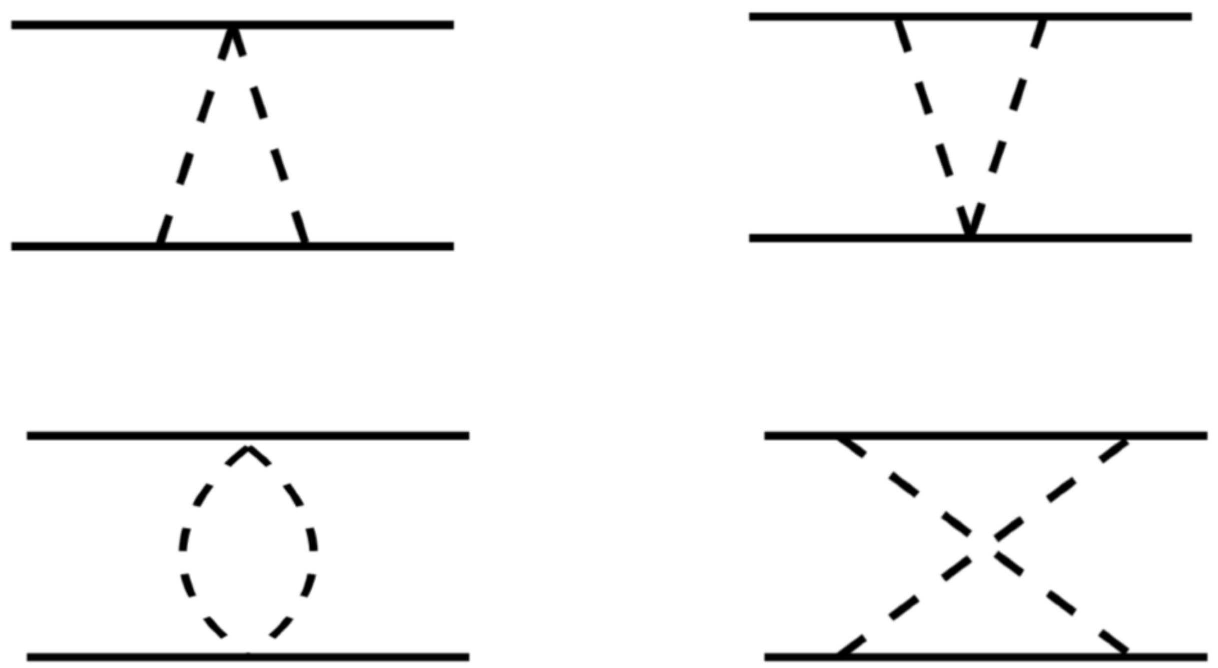


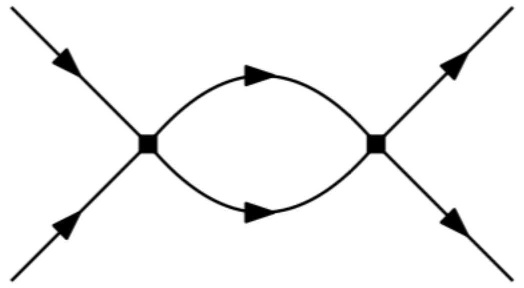
= (0-2+4/2) = 0

$-C_0$

Irreducible

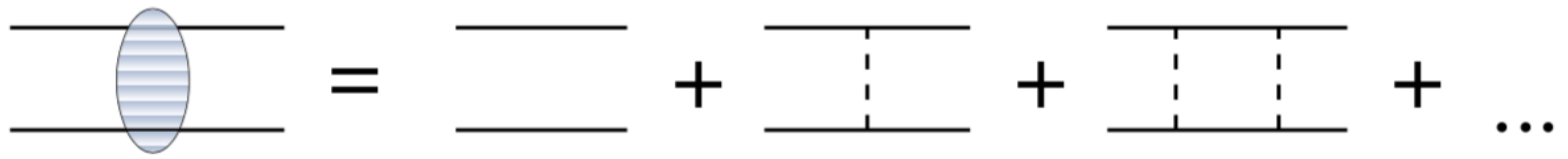
Dim = 2+2-2+2(1-2+2/2) = 2

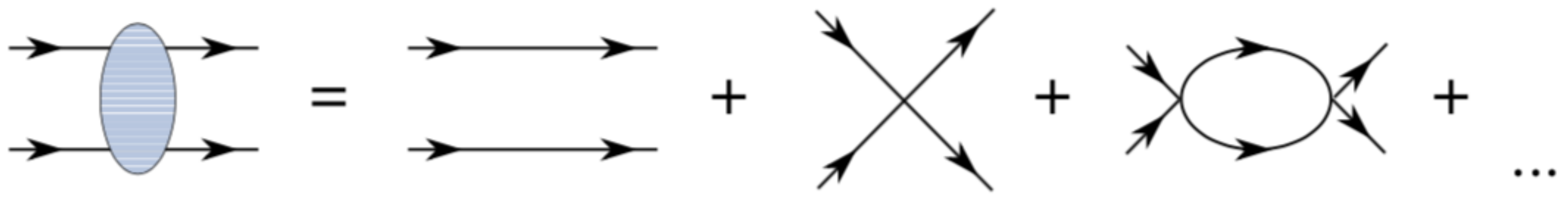




Pinch singularity

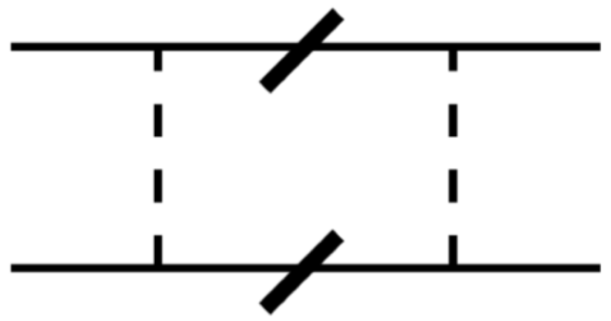
$$\frac{Q^5}{4\pi M}\times C_0\left(\frac{M}{Q^2}\right)\left(\frac{M}{Q^2}\right)C_0 \sim C_0^2\frac{MQ}{4\pi}$$





Unnatural scattering length

Reducible 2PI



$$\sim\left(\frac{g_A}{F_\pi}\right)^2\frac{Q}{\Lambda_{NN}} \qquad \Lambda_{NN} = \frac{4\pi F_\pi^2}{g_A^2 m_N} \sim f_\pi$$

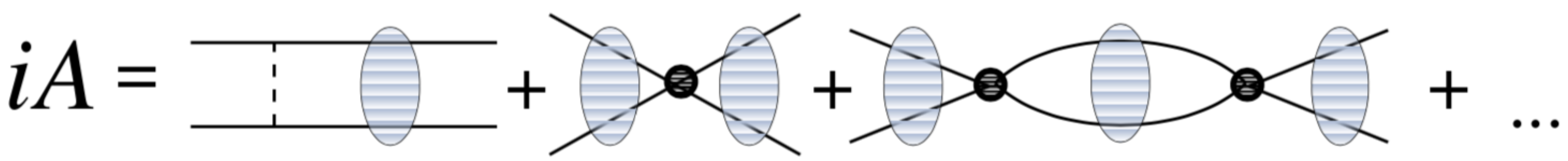
# Chiral EFT operators

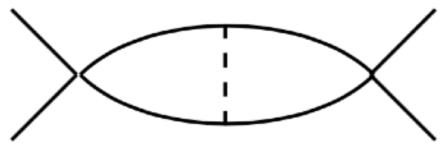
- **Weinberg:** $C_0^R \sim \mathcal{O}(1)$ $\quad V^{\rm LO}_{\rm Weinberg} \sim \mathcal{O}(1), \quad V^{\rm NLO}_{\rm Weinberg} \sim \mathcal{O}(p^2)$
  $\mu \sim \mathcal{O}(1)$ $\quad C_2^R \sim \mathcal{O}(1)$ $\quad$ [i.e. scaling of $C_{2n}$ according to NDA ($\sim$ O(1))]

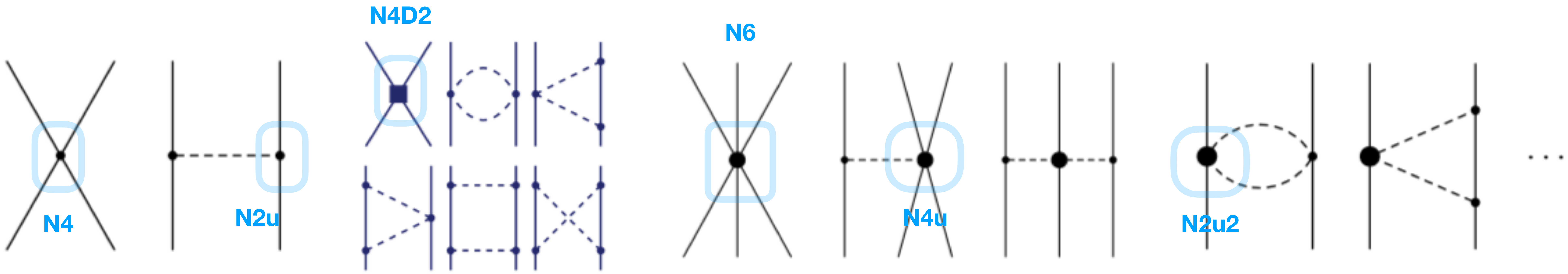
  [ Weinberg, 1990 ]

- **KSW:** $C_0^R \sim \mathcal{O}(p^{-1})$ $\quad V^{\rm LO}_{\rm KSW} \sim \mathcal{O}(p^{-1}), \quad V^{\rm NLO}_{\rm KSW} \sim \mathcal{O}(1)$
  $\mu \sim \mathcal{O}(p)$ $\quad C_2^R \sim \mathcal{O}(p^{-2})$ $\quad$ [i.e. scaling of $C_{2n}$ as $C_{2n} \sim O(p^{-1-n})$]

  [ Kaplan, Savage, Wise, 1998 ]






[ Petschauer, Haidenbauer, Kaiser, Meisner, Weise, 2020 ]

$$\langle \bar{B}B\bar{B}B \rangle\,,\ \langle \bar{B}\bar{B}BB \rangle\,,\ \langle \bar{B}B \rangle\langle \bar{B}B \rangle\,,\ \langle \bar{B}\bar{B} \rangle\langle BB \rangle\,,$$
$$\langle \bar{B}\chi B\bar{B}B \rangle\,,\ \langle \bar{B}B\chi\bar{B}B \rangle\,,\ \langle \bar{B}\chi B \rangle\langle \bar{B}B \rangle\,,\ \ldots$$

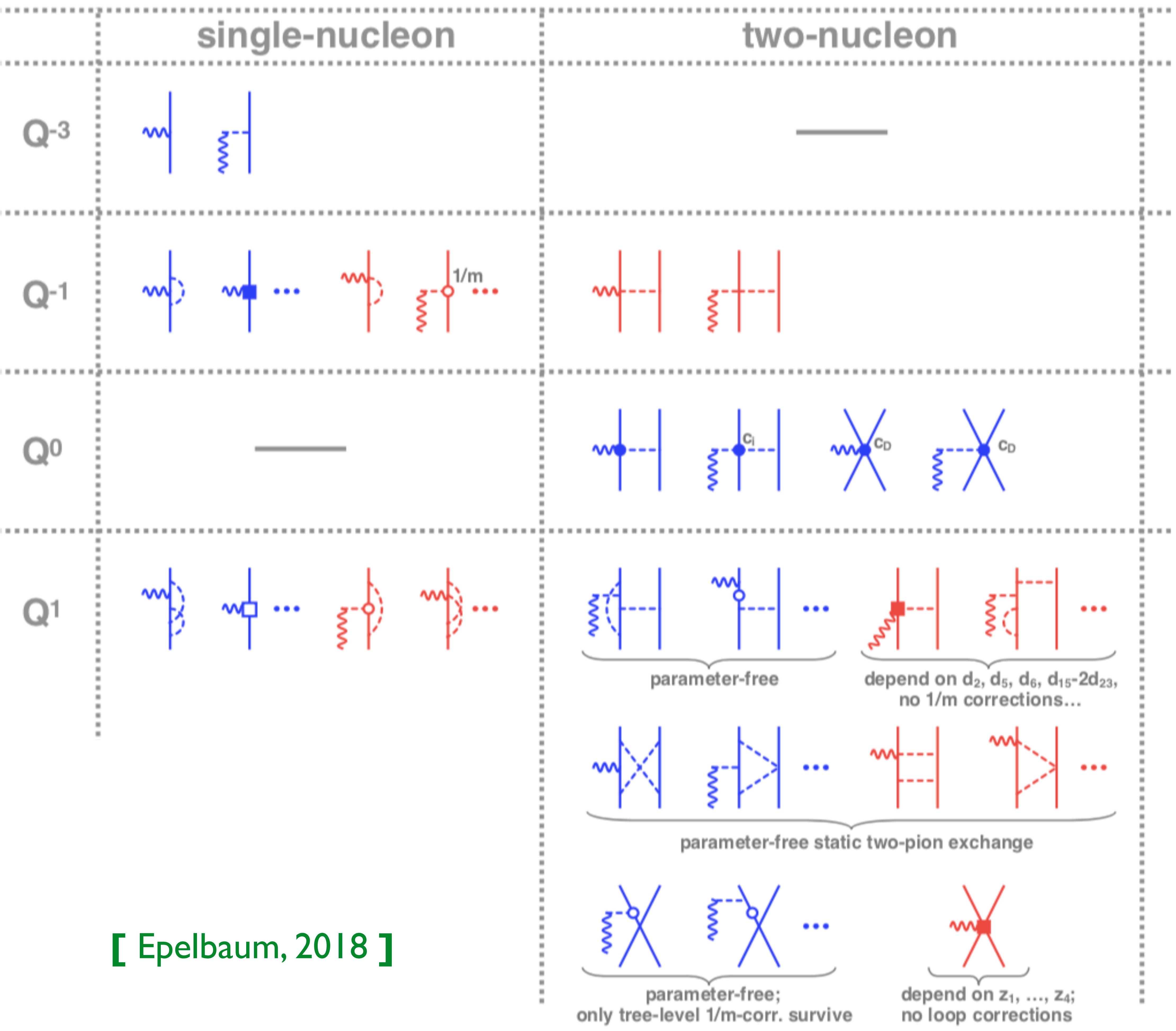
[ Petschauer, Kaiser, 2013 ]

$$\langle \bar{B}\bar{B}\bar{B}BBB \rangle\,, \langle \bar{B}\bar{B}B\bar{B}BB \rangle\,, \langle \bar{B}\bar{B}BB\bar{B}B \rangle\,,$$
$$\langle \bar{B}B\bar{B}B\bar{B}B \rangle\,, \langle \bar{B}\bar{B}BB \rangle\langle \bar{B}B \rangle\,, \langle \bar{B}B\bar{B}B \rangle\langle \bar{B}B \rangle\,,$$
$$\langle \bar{B}\bar{B}\bar{B}B \rangle\langle BB \rangle\,, \langle \bar{B}\bar{B}\bar{B} \rangle\langle BBB \rangle\,, \langle \bar{B}\bar{B}B \rangle\langle B\bar{B}B \rangle\,,$$
$$\langle \bar{B}B \rangle\langle \bar{B}B \rangle\langle \bar{B}B \rangle\,, \langle \bar{B}\bar{B} \rangle\langle \bar{B}B \rangle\langle BB \rangle\,,$$

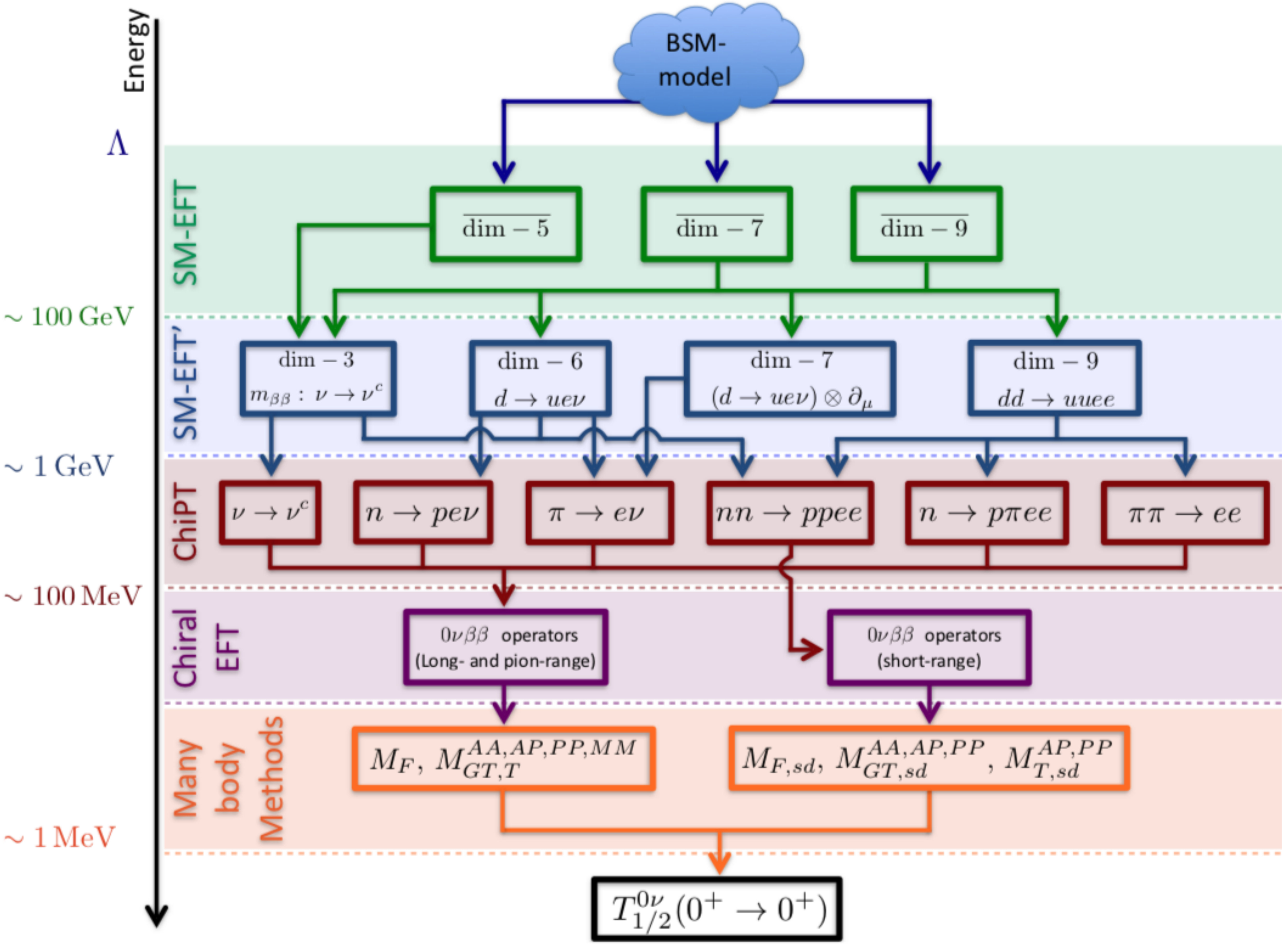
[ Sun, Wang, **Yu**, in préparation ]

# Nuclear Weak Currents

Explore the nuclear weak currents (EDM, 0vbb, etc) in chiral EFT




[ Epelbaum, 2018 ]




[ Cirigliano, Dekens, de Vries, Graesser, Mereghetti, 2017]

# UV Completion of EFT Operators

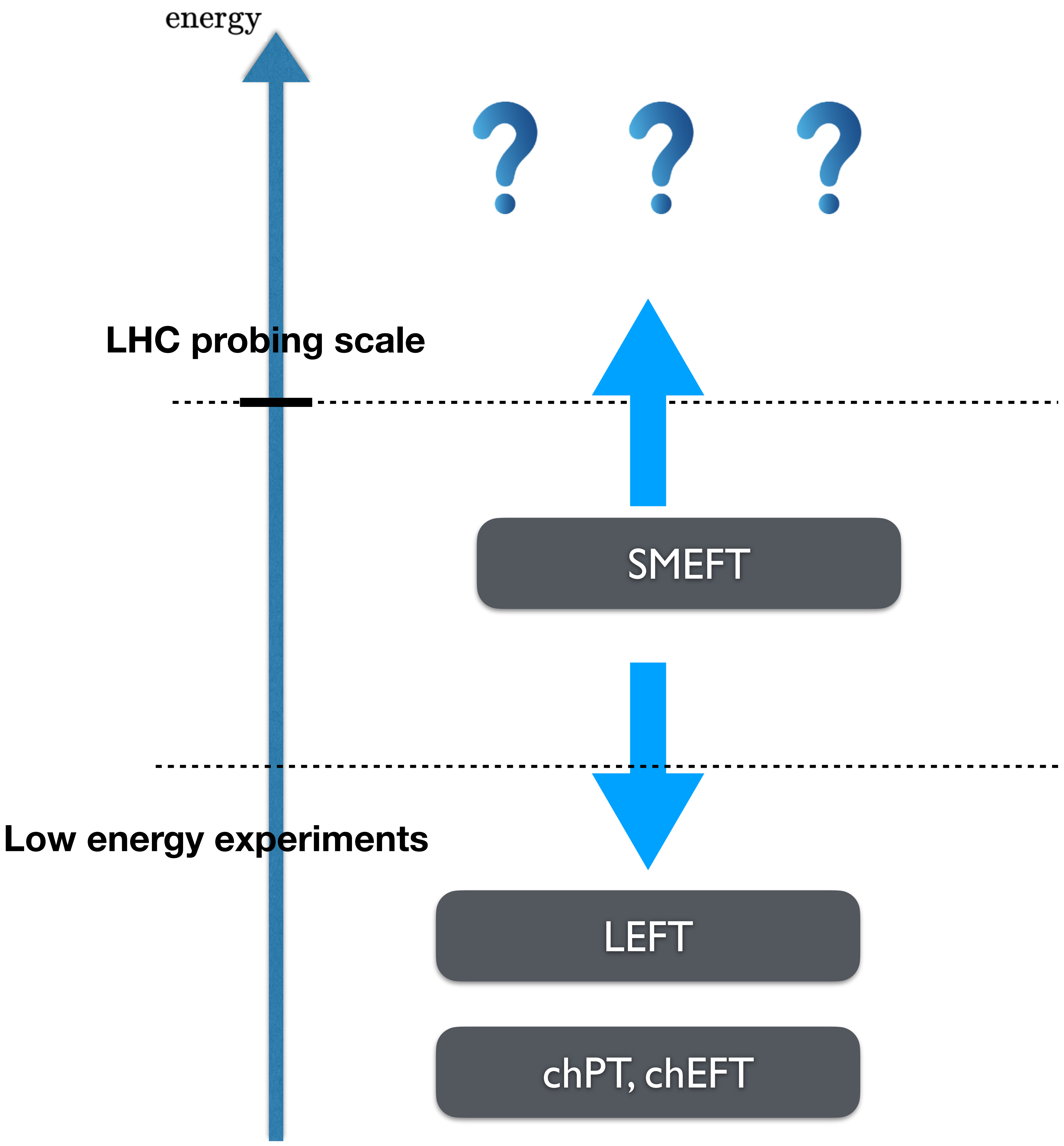
[ Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2204.03660 ]

[ Xu-Xiang Li, Zhe Ren, **J.H.Yu,** in preparation ]

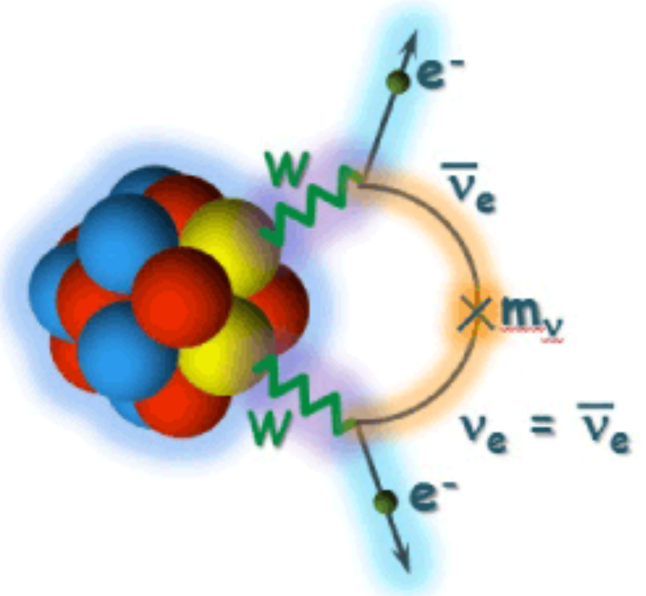
[ Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, in preparation ]

# EFT Inverse Problem

After writing down the effective operators, what is the next step?




$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \dots$$

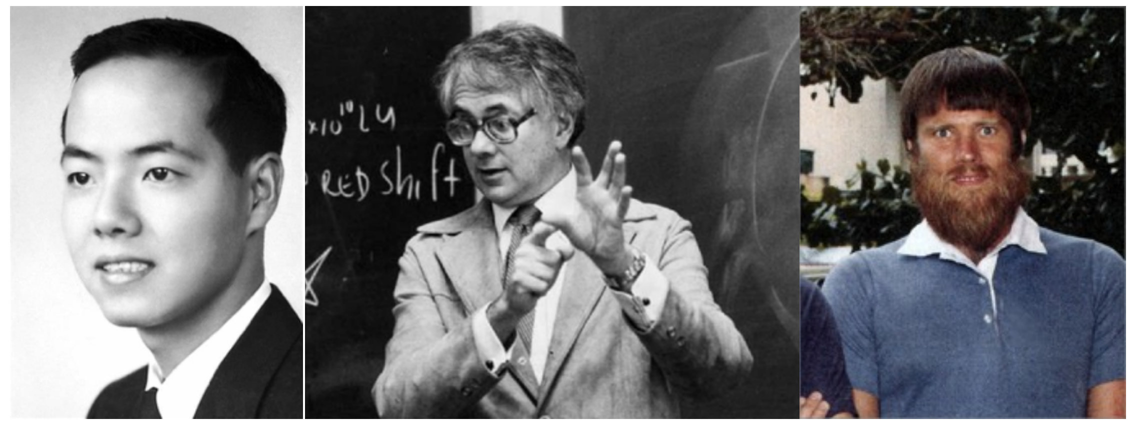





Jiang-Hao Yu (ITP-CAS)

# Lesson from Four-fermion EFT

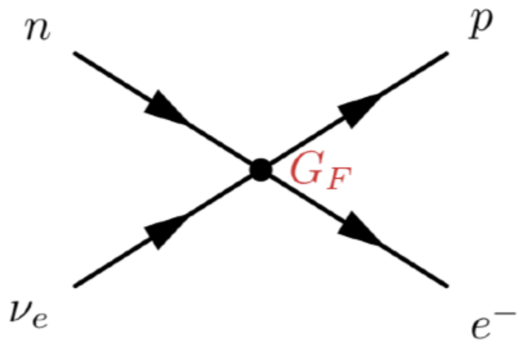
Glashow-Weinberg-Salam
1961 1967



Lee-Georgi-Glashow
1960 1972

**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 ]

**V-A**

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

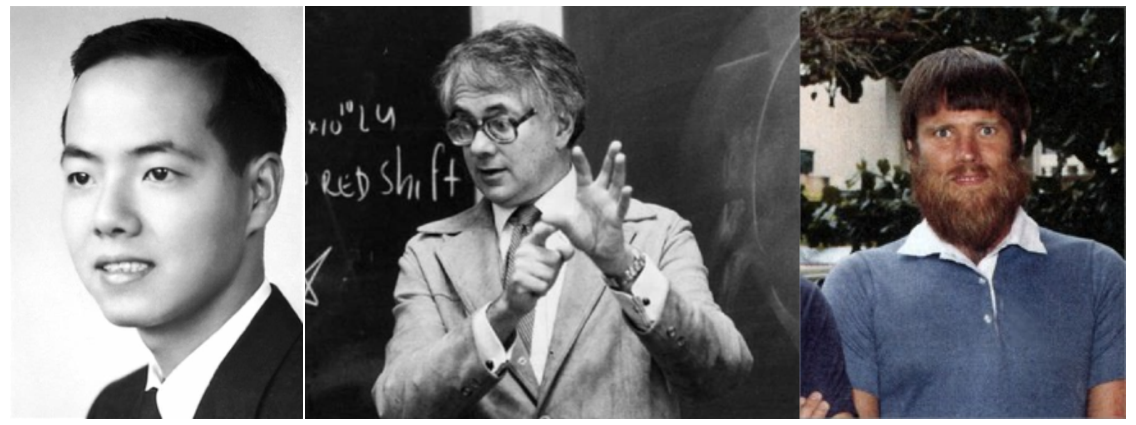
$$\begin{aligned} H_{\rm int} = & (\psi_p^\dagger \gamma_4 \psi_n)(C_S \psi_e^\dagger \gamma_4 \psi_\nu + C_S' \psi_e^\dagger \gamma_4 \gamma_5 \psi_\nu) \\ & + (\psi_p^\dagger \gamma_4 \gamma_\mu \psi_n)(C_V \psi_e^\dagger \gamma_4 \gamma_\mu \psi_\nu + C_V' \psi_e^\dagger \gamma_4 \gamma_\mu \gamma_5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

LEFT

# Lesson from Four-fermion EFT


Nobel prize
1979

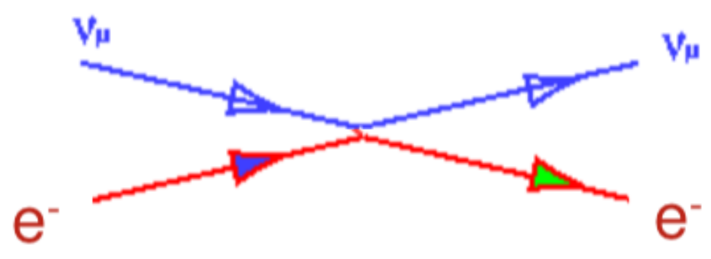
Glashow-Weinberg-Salam
1961 1967

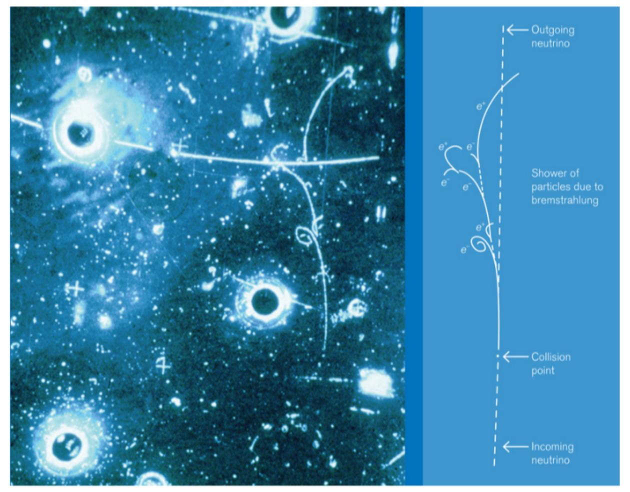


Lee-Georgi-Glashow
1960 1972

**Nobel Prize before W/Z discovery**

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



CERN Bubble Chamber
1973

**Effective interaction detected!**

**V-A**

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

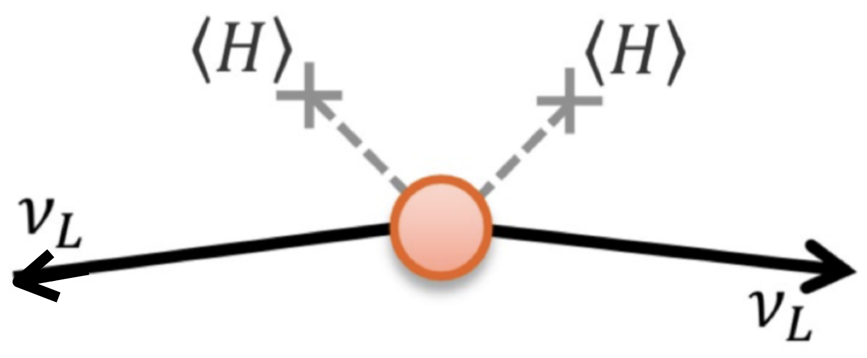
$$\begin{aligned} H_{\text{int}} = & (\psi_p^\dagger \gamma_4 \psi_n)(C_S \psi_e^\dagger \gamma_4 \psi_\nu + C_S' \psi_e^\dagger \gamma_4 \gamma_5 \psi_\nu) \\ & + (\psi_p^\dagger \gamma_4 \gamma_\mu \psi_n)(C_V \psi_e^\dagger \gamma_4 \gamma_\mu \psi_\nu + C_V' \psi_e^\dagger \gamma_4 \gamma_\mu \gamma_5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

LEFT

# Similar Story: Neutrino Masses

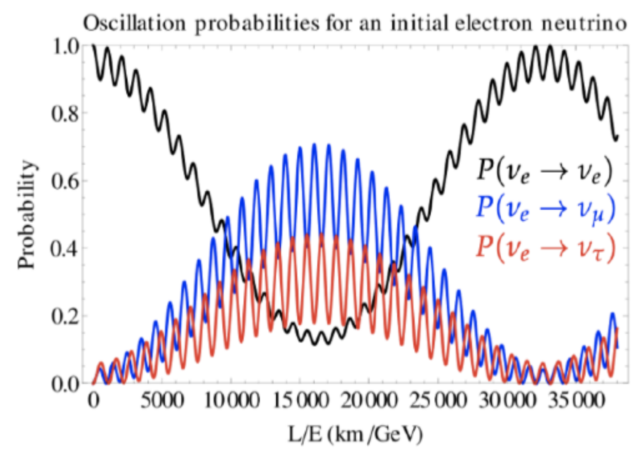
The existence of neutrino masses is the first evidence of new physics beyond standard model

?




SMEFT

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




LEFT



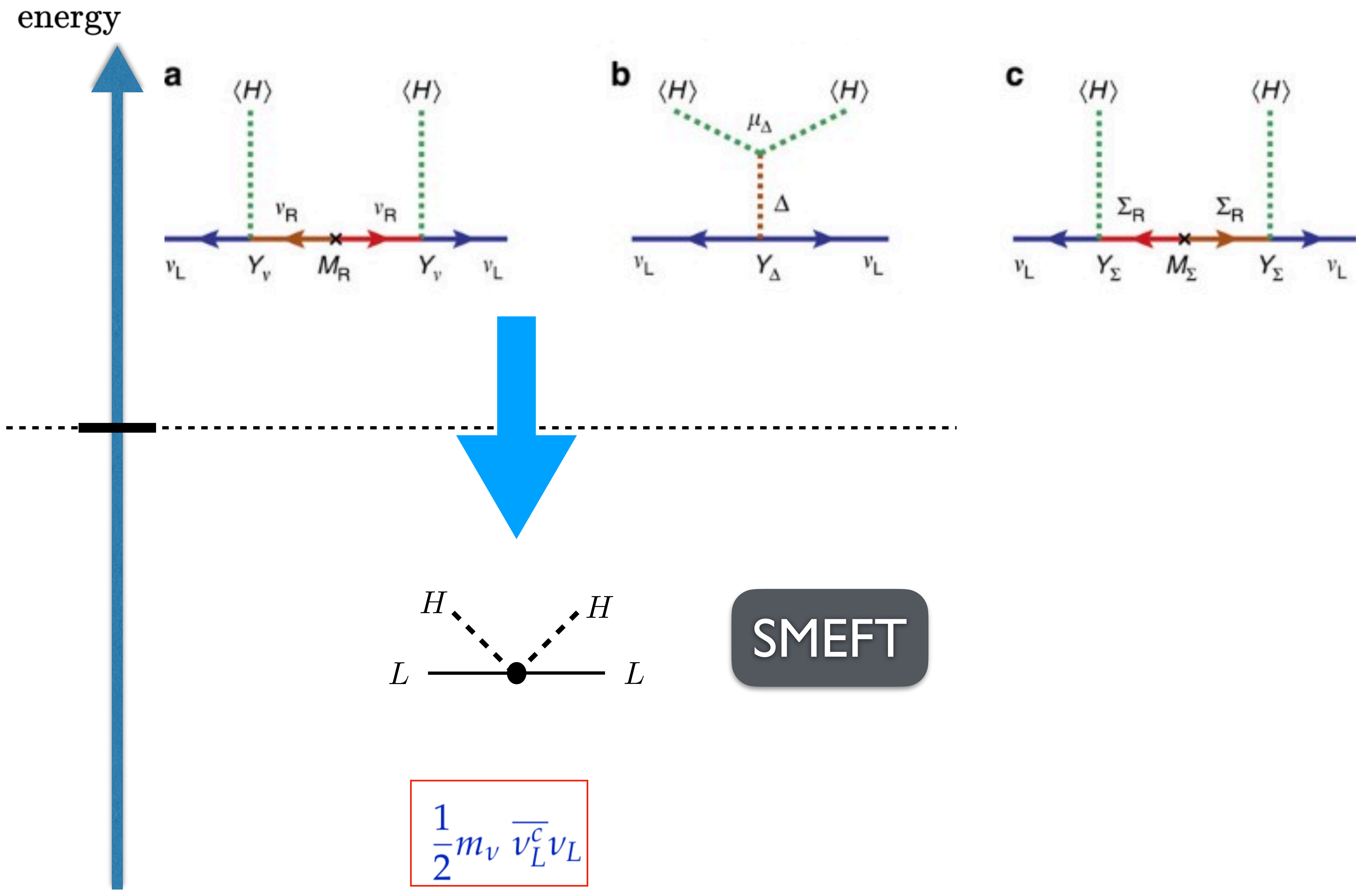
Jiang-Hao Yu (ITP-CAS)

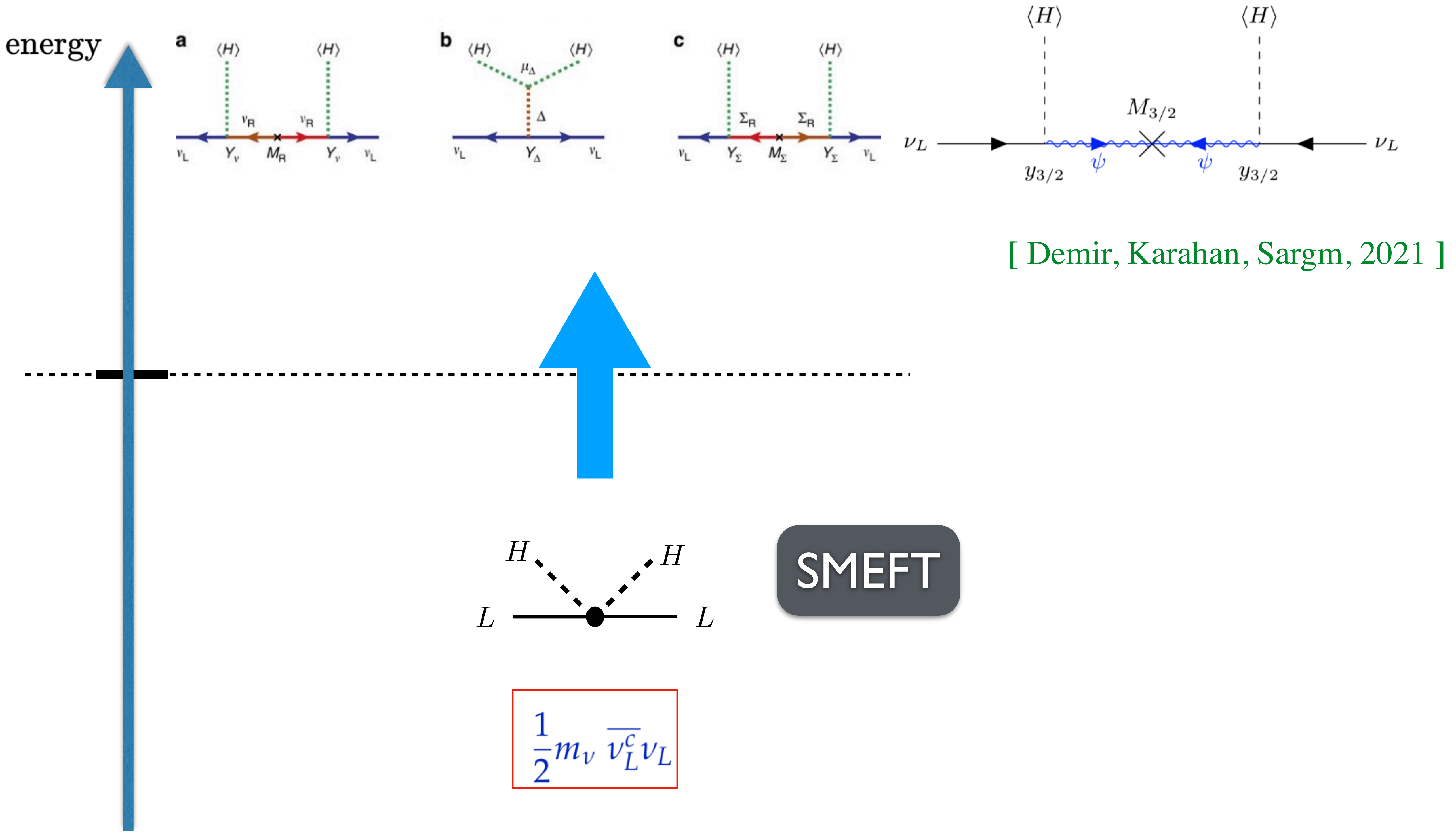
# Seesaw Tree UVs

**Top-down Approach**

**Bottom-up Approach**

[ Yanagida 1979, Gell-Mann, Ramond, Slansky1979, Mahapatra, Senjanovic, 1980 ]
[ Schecheter, Walle, 1980, Cheng, Li 1980, Magg and Wetterich 1980 ]
[ Foot, Lew, He, Joshi 1989 ]



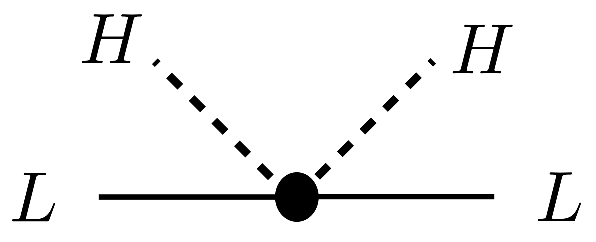




**Consider Angular momentum conservation**

# Pauli-Lubanski Casimir

Weinberg operator as on-shell amplitude

$$\mathcal{O}^S = (HL)(HL) \qquad \mathcal{B}^y = \langle 12 \rangle$$



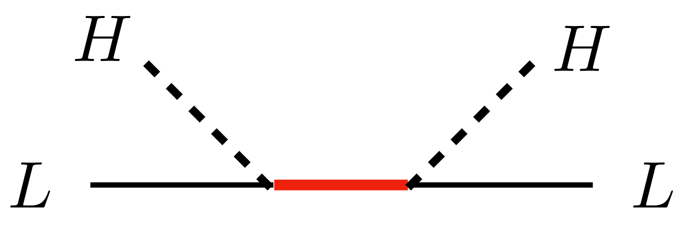

$$\langle p_L, h_L; p_H, h_H | p'_L, h'_L; p'_H, h'_H \rangle$$

[ Li, Ni, Xiao, **Yu**, 2204.03660 ]

**Acting on the Pauli-Lubanski Casimir, obtain the eigenvalues on spin!**

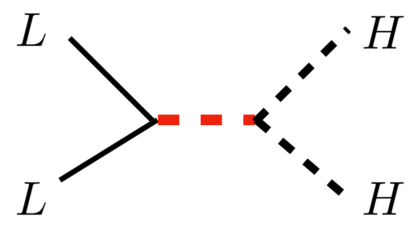
$$\mathbf{W}^2 \langle p_L, h_L; p_H, h_H | P, J, J_z \rangle = -P^2 J(J+1) \langle p_L, h_L; p_H, h_H | P, J, J_z \rangle \quad = -s \sum_J J(J+1) \mathcal{O}^{\mathrm{J}}$$

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




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

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




$$J = 0$$

**Acting on the SU(2) Casimir, obtain the eigenvalues on gauge!**

| i | j |
|---|---|
| k | l |

| i | k |
|---|---|
| j | l |

$$\mathcal{B}^R_1 = \epsilon^{ik}\epsilon^{jl} \qquad \mathcal{B}^R_2 = \epsilon^{ij}\epsilon^{kl}$$

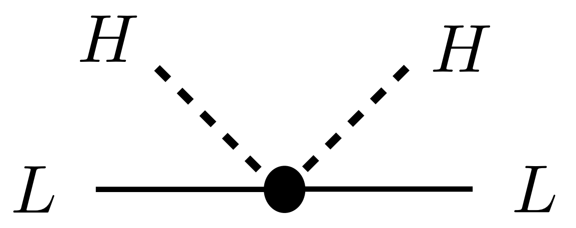
$$\mathbf{C}^2 \mathcal{B}^R = r(r+1) \mathcal{B}^R$$

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

# Only 3 Types of Seesaw at Dim-5

## Generalized partial wave analysis for Poincare/Gauge Casimir

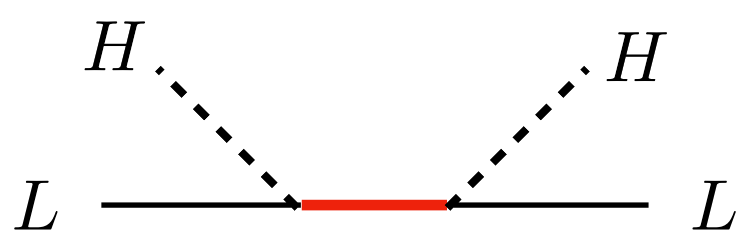
[ Li, Ni, Xiao, **Yu**, 2204.03660 ]



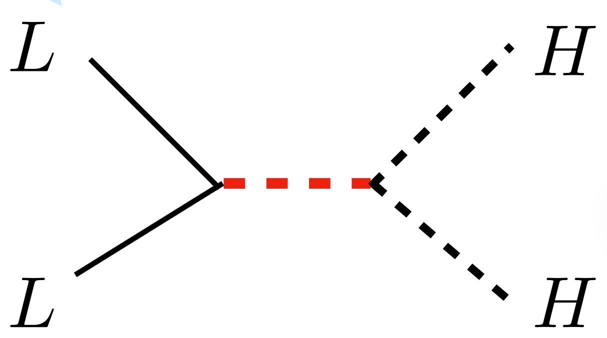

$$\mathbf{W}^2 \mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$

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

$LL \to HH$ channel $\quad W^2_{\{1,2\}}\mathcal{B}^y = 0$




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




$J = 0$

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

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

| 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 |

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

| 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 |

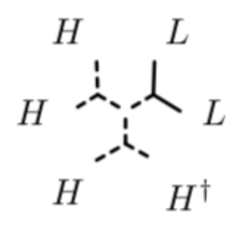
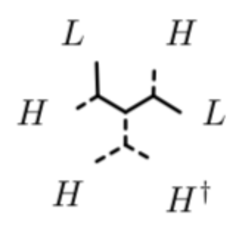
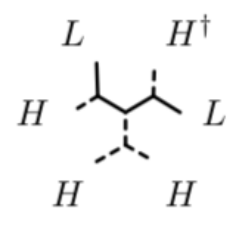
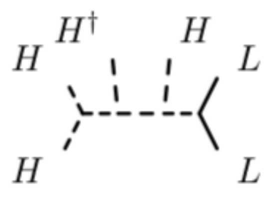
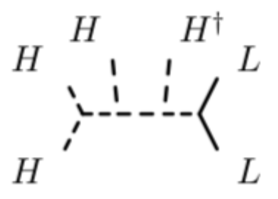
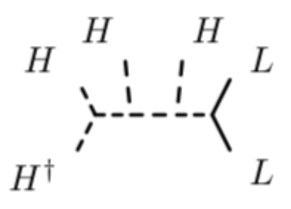
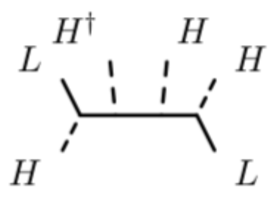
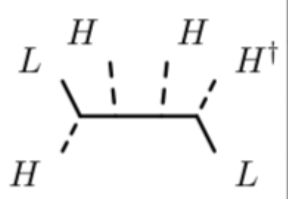
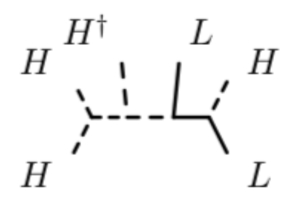
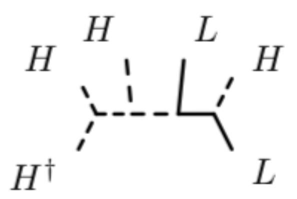
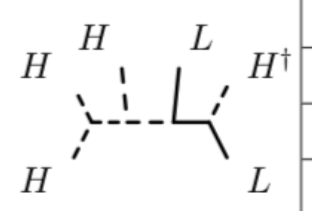
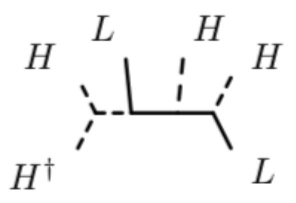
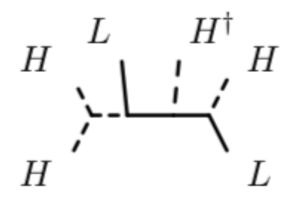
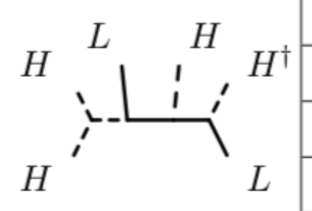
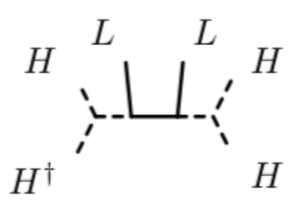
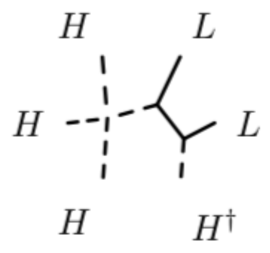
## Dim-7 Operators

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

# Dim-7 Tree-level Seesaw

59 UV tree-level models, 19 topologies, one genuine dim-7 seesaw

[ Li, Ni, Xiao, **Yu**, 2204.03660 ]

| Topology | j-basis | Quantum numbers $\{J, \mathbf{R}, Y\}$ |
|---|---|---|
|   | $\mathcal{O}_{\{12\|34\|56\},1} = 2\mathcal{O}_1^p - 4\mathcal{O}_2^p,$ | $\{0,3,-1\},\{0,3,1\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|34\|56\},2} = 2\mathcal{O}_2^p + 4\mathcal{O}_3^p,$ | $\{0,3,-1\},\{0,1,1\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|34\|56\},3} = 12\mathcal{O}_4^p,$ | $\{0,1,-1\},\{0,3,1\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|34\|56\},4} = 4\mathcal{O}_1^p + 4\mathcal{O}_2^p,$ | $\{0,3,-1\},\{0,3,1\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{12\|34\|56\},5} = 2\mathcal{O}_4^p + 4\mathcal{O}_5^p.$ | $\{0,1,-1\},\{0,1,1\},\{0,1,0\}$ |
|   | $\mathcal{O}_{\{13\|24\|56\},1} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|24\|56\},2} = -\mathcal{O}_1^p + 3\mathcal{O}_2^p + 2\mathcal{O}_3^p + 3\mathcal{O}_4^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},1,0\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|24\|56\},3} = -\mathcal{O}_1^p + \mathcal{O}_2^p - 2\mathcal{O}_3^p - 3\mathcal{O}_4^p,$ | $\{\frac{1}{2},1,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|24\|56\},4} = -\mathcal{O}_1^p - \mathcal{O}_2^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{13\|24\|56\},5} = \mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$ | $\{\frac{1}{2},1,0\},\{\frac{1}{2},1,0\},\{0,1,0\}$ |
|   | $\mathcal{O}_{\{16\|23\|45\},1} = 2\mathcal{O}_1^p - 2\mathcal{O}_2^p - 2\mathcal{O}_3^p + 6\mathcal{O}_4^p + 6\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|23\|45\},2} = -2\mathcal{O}_1^p - \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},1,0\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|23\|45\},3} = 3\mathcal{O}_2^p + 3\mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|23\|45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{16\|23\|45\},5} = \mathcal{O}_2^p - \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p.$ | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},1,0\},\{0,1,1\}$ |
|   | $\mathcal{O}_{\{12\|125\|34\},1} = \mathcal{O}_1^p + 4\mathcal{O}_2^p,$ | $\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|125\|34\},2} = -8\mathcal{O}_1^p + 4\mathcal{O}_2^p,$ | $\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|125\|34\},3} = -12\mathcal{O}_4^p,$ | $\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|125\|34\},4} = -2\mathcal{O}_2^p - 4\mathcal{O}_3^p,$ | $\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{12\|125\|34\},5} = -2\mathcal{O}_4^p - 4\mathcal{O}_5^p.$ | $\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$ |
|   | $\mathcal{O}_{\{12\|126\|34\},1} = 3\mathcal{O}_1^p,$ | $\{0,3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|126\|34\},2} = 12\mathcal{O}_2^p,$ | $\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|126\|34\},3} = -12\mathcal{O}_4^p,$ | $\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|126\|34\},4} = -2\mathcal{O}_2^p - 4\mathcal{O}_3^p,$ | $\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{12\|126\|34\},5} = -2\mathcal{O}_4^p - 4\mathcal{O}_5^p.$ | $\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$ |
|   | $\mathcal{O}_{\{12\|124\|36\},1} = -\mathcal{O}_1^p - 4\mathcal{O}_3^p,$ | $\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|124\|36\},2} = 2\mathcal{O}_1^p + 6\mathcal{O}_2^p + 2\mathcal{O}_3^p,$ | $\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|124\|36\},3} = -6\mathcal{O}_4^p - 6\mathcal{O}_5^p,$ | $\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|124\|36\},4} = -2\mathcal{O}_1^p + 2\mathcal{O}_2^p + 2\mathcal{O}_3^p,$ | $\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{12\|124\|36\},5} = -2\mathcal{O}_4^p + 2\mathcal{O}_5^p.$ | $\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$ |
|   | $\mathcal{O}_{\{13\|135\|24\},1} = \mathcal{O}_1^p - 2\mathcal{O}_3^p - 6\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{13\|135\|24\},2} = -\mathcal{O}_1^p - 3\mathcal{O}_2^p - 4\mathcal{O}_3^p + 9\mathcal{O}_4^p + 6\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{13\|135\|24\},3} = \mathcal{O}_1^p - \mathcal{O}_2^p + 2\mathcal{O}_3^p + 3\mathcal{O}_4^p,$ | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{13\|135\|24\},4} = \mathcal{O}_1^p - 3\mathcal{O}_2^p - 2\mathcal{O}_3^p - 3\mathcal{O}_4^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$ |
| | $\mathcal{O}_{\{13\|135\|24\},5} = \mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$ | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$ |
|   | $\mathcal{O}_{\{16\|146\|23\},1} = -2\mathcal{O}_1^p + 4\mathcal{O}_3^p - 12\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{16\|146\|23\},2} = 2\mathcal{O}_1^p - 3\mathcal{O}_2^p - \mathcal{O}_3^p + 9\mathcal{O}_4^p + 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{16\|146\|23\},3} = 3\mathcal{O}_2^p + 3\mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{16\|146\|23\},4} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p - 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$ |
| | $\mathcal{O}_{\{16\|146\|23\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p - \mathcal{O}_4^p + \mathcal{O}_5^p,$ | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$ |
|   | $\mathcal{O}_{\{13\|123\|45\},1} = \mathcal{O}_1^p - 4\mathcal{O}_2^p - 4\mathcal{O}_3^p,$ | $\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|123\|45\},2} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p - 9\mathcal{O}_4^p - 9\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|123\|45\},3} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|123\|45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{13\|123\|45\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p.$ | $\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$ |
|   | $\mathcal{O}_{\{13\|123\|46\},1} = \mathcal{O}_1^p - 4\mathcal{O}_2^p - 4\mathcal{O}_3^p,$ | $\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|123\|46\},2} = \mathcal{O}_1^p + 2\mathcal{O}_2^p - \mathcal{O}_3^p - 9\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|123\|46\},3} = -\mathcal{O}_1^p - 2\mathcal{O}_2^p + \mathcal{O}_3^p - 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|123\|46\},4} = -\mathcal{O}_1^p - \mathcal{O}_3^p + 6\mathcal{O}_4^p + 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{13\|123\|46\},5} = -\mathcal{O}_1^p - \mathcal{O}_3^p - 2\mathcal{O}_4^p - \mathcal{O}_5^p.$ | $\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$ |
|   | $\mathcal{O}_{\{16\|126\|34\},1} = 6\mathcal{O}_1^p,$ | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|126\|34\},2} = -3\mathcal{O}_2^p + 9\mathcal{O}_4^p,$ | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|126\|34\},3} = -3\mathcal{O}_2^p - 3\mathcal{O}_4^p,$ | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|126\|34\},4} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|126\|34\},5} = \mathcal{O}_2^p + 2\mathcal{O}_3^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$ | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
|   | $\mathcal{O}_{\{23\|235\|46\},1} = \mathcal{O}_1^p - 2\mathcal{O}_3^p + 6\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{23\|235\|46\},2} = \mathcal{O}_1^p - 6\mathcal{O}_2^p - 5\mathcal{O}_3^p - 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{23\|235\|46\},3} = \mathcal{O}_1^p + 2\mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{23\|235\|46\},4} = -\mathcal{O}_1^p - \mathcal{O}_3^p - 6\mathcal{O}_4^p - 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{23\|235\|46\},5} = -\mathcal{O}_1^p - \mathcal{O}_3^p + 2\mathcal{O}_4^p + \mathcal{O}_5^p.$ | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$ |
|   | $\mathcal{O}_{\{13\|136\|45\},1} = \mathcal{O}_1^p + 2\mathcal{O}_2^p + 2\mathcal{O}_3^p - 6\mathcal{O}_4^p - 6\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|136\|45\},2} = 2\mathcal{O}_1^p - 5\mathcal{O}_2^p - 5\mathcal{O}_3^p - 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|136\|45\},3} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|136\|45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p - 3\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{13\|136\|45\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p.$ | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$ |
|   | $\mathcal{O}_{\{16\|156\|34\},1} = 2\mathcal{O}_1^p - 4\mathcal{O}_2^p + 12\mathcal{O}_4^p,$ | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|156\|34\},2} = 4\mathcal{O}_1^p + \mathcal{O}_2^p - 3\mathcal{O}_4^p,$ | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|156\|34\},3} = -3\mathcal{O}_2^p - 3\mathcal{O}_4^p,$ | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|156\|34\},4} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p,$ | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{16\|156\|34\},5} = \mathcal{O}_2^p + 2\mathcal{O}_3^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p.$ | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$ |
|   | $\mathcal{O}_{\{34\|134\|56\},1} = -\mathcal{O}_1^p + 2\mathcal{O}_2^p + 6\mathcal{O}_4^p,$ | $\{0,3,1\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{34\|134\|56\},2} = 4\mathcal{O}_1^p - 8\mathcal{O}_2^p + 12\mathcal{O}_4^p,$ | $\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{34\|134\|56\},3} = 2\mathcal{O}_2^p + 4\mathcal{O}_3^p,$ | $\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{34\|134\|56\},4} = -4\mathcal{O}_1^p - 4\mathcal{O}_2^p,$ | $\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{34\|134\|56\},5} = 2\mathcal{O}_4^p + 4\mathcal{O}_5^p.$ | $\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$ |
|   | $\mathcal{O}_{\{16\|126\},1} = 6\mathcal{O}_1^p,$ | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\}$ |
| | $\mathcal{O}_{\{16\|126\},2,3} = \begin{pmatrix} \mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_4^p + 3\mathcal{O}_5^p \\ -2\mathcal{O}_2^p - \mathcal{O}_3^p + 6\mathcal{O}_4^p + 3\mathcal{O}_5^p \end{pmatrix},$ | $\{\frac{1}{2},3,-1\},\{0,2,-\frac{3}{2}\}$ |
| | $\mathcal{O}_{\{16\|126\},4,5} = \begin{pmatrix} -\mathcal{O}_2^p - 2\mathcal{O}_3^p - \mathcal{O}_4^p - 2\mathcal{O}_5^p \\ -2\mathcal{O}_2^p - \mathcal{O}_3^p - 2\mathcal{O}_4^p - \mathcal{O}_5^p \end{pmatrix}.$ | $\{\frac{1}{2},1,-1\},\{0,2,-\frac{3}{2}\}$ |

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[ Bonnet, Hernandez, Ota, Winter, 2009]

# Complete dim-7 Tree UVs

[ Li, Ni, Xiao, **Yu**, 2204.03660 ]

| $(\mathrm{SU}(3)_c, \mathrm{SU}(2)_2, \mathrm{U}(1)_y)$ | Scalar |
|---|---|
| $S1\ (\mathbf{1},\mathbf{1},0)$ | $H^3H^\dagger L^2[(S6),(F5),(F1),(S4,S6),$<br>$(S4,F5),(S4,F1),(F3,F5),(F1,F3),(S6,F3)]$ |
| $S2\ (\mathbf{1},\mathbf{1},1)$ | $e_{\mathbb{C}}HL^3[(S4),(F4),(F1)]\quad d_{\mathbb{C}}HL^2Q[(S4),(F10),(F9)]$<br>$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(F8),(F12)]\quad De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(F1),(F3),(V3)]$ |
| $S4\ \left(\mathbf{1},\mathbf{2},\frac{1}{2}\right)$ | $e_{\mathbb{C}}HL^3[(S6),(S2),(F5),(F1)]\quad d_{\mathbb{C}}HL^2Q[(S6),(S2),(F5),(F1)]$<br>$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(S2),(F5),(F1)]\quad H^3H^\dagger L^2[(S6),(F5),(F1),(S5,S6),(S1,S6),$<br>$(S6,F5),(S6,F1),(S5,F5),(S5,F1),(S1,F5),(S1,F1)]$ |
| $S5\ (\mathbf{1},\mathbf{3},0)$ | $H^3H^\dagger L^2[(S6),(F1,F5),(S6,S7),(S4,S6),(S7,F5),$<br>$(S4,F5),(S4,F1),(F5,F7),(F3,F5),(F1,F3),(S6,F7),(S6,F3)]$ |
| $S6\ (\mathbf{1},\mathbf{3},1)$ | $D^2H^2L^2\quad e_{\mathbb{C}}HL^3[(S4),(F4),(F5)]\quad d_{\mathbb{C}}HL^2Q[(S4),(F10),(F14)]$<br>$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(F13),(F12)]$<br>$De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(F5),(F3),(V3)]\quad H^2L^2W_L[(F7)]$<br>$H^3H^\dagger L^2[(S4),(S8),(S7),(S5),(S1),(F5,F6),(F1,F6),$<br>$(S5,S7),(S4,S5),(S1,S4),(S7,F5),(S4,F5),(S4,F1),(F5,F7),(F3,F5),$<br>$(F1,F3),(S8,F6),(F6,F7),(F3,F6),(S5,F7),(S5,F3),(S1,F3)]$<br>$H^2L^2W_L\quad B_LH^2L^2\quad e_{\mathbb{C}}HL^3$<br>$HL^2Q^\dagger u_{\mathbb{C}}^\dagger\quad d_{\mathbb{C}}HL^2Q\quad De_{\mathbb{C}}^\dagger H^3L$ |
| $S7\ \left(\mathbf{1},\mathbf{4},\frac{1}{2}\right)$ | $H^3H^\dagger L^2[(S6),(F5),(S5,S6),(S6,F5),(S5,F5)]$ |
| $S8\ \left(\mathbf{1},\mathbf{4},\frac{3}{2}\right)$ | $H^3H^\dagger L^2[(S6),(F6),(S6,F6)]$ |
| $S10\ \left(\mathbf{3},\mathbf{1},-\frac{1}{3}\right)$ | ${d_{\mathbb{C}}}^2HLu_{\mathbb{C}}[(S12),(F10),(F1)]\quad d_{\mathbb{C}}HL^2Q[(S12),(F10),(F1)]$<br>$d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S12),(F10),(F1)]\quad d_{\mathbb{C}}HLQ^{\dagger 2}[(S12),(F10),(F1)]$ |
| $S11\ \left(\mathbf{3},\mathbf{1},\frac{2}{3}\right)$ | ${d_{\mathbb{C}}}^3H^\dagger L[(S12),(F11),(F2)]\quad {d_{\mathbb{C}}}^2HLu_{\mathbb{C}}[(F11),(S13),(F1)]\quad {d_{\mathbb{C}}}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(S13),(F3),(F8)]$ |
| $S12\ \left(\mathbf{3},\mathbf{2},\frac{1}{6}\right)$ | ${d_{\mathbb{C}}}^3H^\dagger L[(S11),(F11)]\quad {d_{\mathbb{C}}}^2HLu_{\mathbb{C}}[(F11),(S10),(F10)]$<br>$d_{\mathbb{C}}HL^2Q[(S10),(S14),(F5),(F1),(F14),(F9)]\quad d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(F3),(F12)]$ |
| $S13\ \left(\mathbf{3},\mathbf{2},\frac{7}{6}\right)$ | ${d_{\mathbb{C}}}^2HLu_{\mathbb{C}}[(S11),(F10)]\quad {d_{\mathbb{C}}}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(S11),(F10)]$ |
| $S14\ \left(\mathbf{3},\mathbf{3},-\frac{1}{3}\right)$ | $d_{\mathbb{C}}HL^2Q[(S12),(F10),(F5)]\quad d_{\mathbb{C}}HLQ^{\dagger 2}[(S12),(F10),(F5)]$ |

| $(\mathrm{SU}(3)_c, \mathrm{SU}(2)_2, \mathrm{U}(1)_y)$ | Fermion |
|---|---|
| $F1\ (\mathbf{1},\mathbf{1},0)$ | $D^2H^2L^2\quad e_{\mathbb{C}}HL^3[(S4),(S2)]\quad d_{\mathbb{C}}HL^2Q[(S4),(S10),(S12)]$<br>$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(V5),(V8)]\quad De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(F3),(V2)]$<br>${d_{\mathbb{C}}}^2HLu_{\mathbb{C}}[(S11),(S10)]\quad d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(V5)]\quad d_{\mathbb{C}}HLQ^{\dagger 2}[(S10),(V8)]$<br>$H^2L^2W_L[(F5)]$<br>$H^3H^\dagger L^2[(S4),(S5,F5),(S1),(S6,F6),(F3,F5),(F3),(F3,F6),$<br>$(S4,S6),(S6,F3),(S4,S5),(S1,S4),(S5,F3),(S1,F3)]$<br>$H^2L^2W_L\quad B_LH^2L^2\quad e_{\mathbb{C}}HL^3$<br>$HL^2Q^\dagger u_{\mathbb{C}}^\dagger\quad d_{\mathbb{C}}HL^2Q\quad De_{\mathbb{C}}^\dagger H^3L$ |
| $F2\ (\mathbf{1},\mathbf{1},1)$ | ${d_{\mathbb{C}}}^3H^\dagger L[(S11)]$ |
| $F3\ \left(\mathbf{1},\mathbf{2},\frac{1}{2}\right)$ | $De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(F5),(F1),(S6),(V2)]\quad d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S12),(V8)]$<br>${d_{\mathbb{C}}}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(V8),(S11)]\quad H^3H^\dagger L^2[(F5),(F1,F5),(F1),(F5,F6),(F1,F6),(S6,F5),$<br>$(S6,F1),(S5,F5),(S5,F1),(S1,F5),(S1,F1),(S6,F6),(S5,S6),(S1,S6)]$ |
| $F4\ \left(\mathbf{1},\mathbf{2},\frac{3}{2}\right)$ | $e_{\mathbb{C}}HL^3[(S6),(S2)]$ |
| $F5\ (\mathbf{1},\mathbf{3},0)$ | $e_{\mathbb{C}}HL^3[(S4),(S6)]\quad d_{\mathbb{C}}HL^2Q[(S4),(S12),(S14)]\quad HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(V9),(V8)]$<br>$D^2H^2L^2\quad De_{\mathbb{C}}H^{\dagger 3}L^\dagger[(S6),(F3),(V5)]\quad d_{\mathbb{C}}HLQ^{\dagger 2}[(S14),(V8)]$<br>$H^2L^2W_L[(F7),(F1)]\ H^3H^\dagger L^2[(S4),(S7),(S5,F1),(S1),(S6,F6),(F7),(F3),(F1,F3),$<br>$(F6,F7),(F3,F6),(S6,S7),(S4,S6),(S6,F7),(S6,F3),(S5,S7),$<br>$(S4,S5),(S1,S4),(S5,F7),(S5,F3),(S1,F3)]$<br>$H^2L^2W_L\quad B_LH^2L^2\quad e_{\mathbb{C}}HL^3$<br>$HL^2Q^\dagger u_{\mathbb{C}}^\dagger\quad d_{\mathbb{C}}HL^2Q\quad De_{\mathbb{C}}^\dagger H^3L$ |
| $F6\ (\mathbf{1},\mathbf{3},1)$ | $H^3H^\dagger L^2[(S8),(S6,F5),(S6,F1),(F5,F7),(F3,F5),(F1,F3),(S6,S8),(S6,F7),(S6,F3)]$ |
| $F7\ \left(\mathbf{1},\mathbf{4},\frac{1}{2}\right)$ | $H^2L^2W_L[(F5),(S6)]\quad H^3H^\dagger L^2[(F5),(S6,F5),(F5,F6),(S6,F6),(S5,F5),(S5,S6)]$ |
| $F8\ \left(\mathbf{3},\mathbf{1},-\frac{1}{3}\right)$ | $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S2),(V8)]\quad d_{\mathbb{C}}HLQ^{\dagger 2}[(V8),(S12),(V5)]\quad {d_{\mathbb{C}}}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(V5),(S11)]$ |
| $F9\ \left(\mathbf{3},\mathbf{1},\frac{2}{3}\right)$ | $d_{\mathbb{C}}HL^2Q[(S12),(S2)]$ |
| $F10\ \left(\mathbf{3},\mathbf{2},-\frac{5}{6}\right)$ | ${d_{\mathbb{C}}}^2HLu_{\mathbb{C}}[(S12),(S10),(S13)]\quad d_{\mathbb{C}}HL^2Q[(S10),(S6),(S2),(S14)]$<br>$d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(V3),(V8)]\quad d_{\mathbb{C}}HLQ^{\dagger 2}[(S10),(S14),(V9),(V5)]$ |
| $F11\ \left(\mathbf{3},\mathbf{2},\frac{1}{6}\right)$ | ${d_{\mathbb{C}}}^3H^\dagger L[(S11),(S12)]\quad {d_{\mathbb{C}}}^2HLu_{\mathbb{C}}[(S11),(S12)]$ |
| $F12\ \left(\mathbf{3},\mathbf{2},\frac{7}{6}\right)$ | $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(S2),(V9),(V5)]\quad d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(V5),(S12),(V3)]$ |
| $F13\ \left(\mathbf{3},\mathbf{3},-\frac{1}{3}\right)$ | $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(V8)]\quad d_{\mathbb{C}}HLQ^{\dagger 2}[(V8),(S12),(V9)]$ |
| $F14\ \left(\mathbf{3},\mathbf{3},\frac{2}{3}\right)$ | $d_{\mathbb{C}}HL^2Q[(S12),(S6)]$ |

# Complete Dim-6 Tree UVs

[ Li, Ni, Xiao, **Yu**, 2204.03660 ]

| Scalar | |
|---|---|
| $(SU(3)_c, SU(2)_2, U(1)_y)$ | |
| $S1\ (\mathbf{1},\mathbf{1},0)$ | $B_L{}^2HH^\dagger$ $D^2H^2H^{\dagger 2}$ $d_{\mathbb{C}}HH^{\dagger 2}Q[(F11),(F8)]$ $e_{\mathbb{C}}HH^{\dagger 2}L[(F3),(F2)]$ <br> $G_L{}^2HH^\dagger$ $H^2H^\dagger Qu_{\mathbb{C}}[(S4),(F11),(F9)]$ $HH^\dagger W_L{}^2$ <br> $H^3H^{\dagger 3}[(S6),(S2),(S5),(S4,S6),(S2,S4),(S4,S5),(S4)]$ <br> $e_{\mathbb{C}}HH^{\dagger 2}L$ $d_{\mathbb{C}}HH^{\dagger 2}Q$ $H^2H^\dagger Qu_{\mathbb{C}}$ |
| $S2\ (\mathbf{1},\mathbf{1},1)$ | $d_{\mathbb{C}}HH^{\dagger 2}Q[(S4),(F10),(F9)]$ $e_{\mathbb{C}}HH^{\dagger 2}L[(S4),(F4),(F1)]$ <br> $H^2H^\dagger Qu_{\mathbb{C}}[(F8),(F12)]$ $L^2L^{\dagger 2}$ <br> $H^3H^{\dagger 3}[(S4),(S5),(S5,S6),(S1),(S4,S5),(S1,S4),(S5,S6),(S4,S6)]$ |
| $S3\ (\mathbf{1},\mathbf{1},2)$ | $e_{\mathbb{C}}{}^2e_{\mathbb{C}}^{\dagger 2}$ |
| $S4\ (\mathbf{1},\mathbf{2},\frac{1}{2})$ | $d_{\mathbb{C}}^\dagger e_{\mathbb{C}}LQ^\dagger$ $d_{\mathbb{C}}HH^{\dagger 2}Q[(S6),(S2)]$ $e_{\mathbb{C}}HH^{\dagger 2}L[(S6),(S2)]$ <br> $H^2H^\dagger Qu_{\mathbb{C}}$ $H^2H^\dagger Qu_{\mathbb{C}}[(S5),(S1)]$ $QQ^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ <br> $H^3H^{\dagger 3}[(S6),(S2),(S5,S6),(S2,S5),$ <br> $(S1,S6),(S1,S2),(S2,S6),(S5),(S1,S5),(S1)]$ |
| $S5\ (\mathbf{1},\mathbf{3},0)$ | $B_LHH^\dagger W_L$ $D^2H^2H^{\dagger 2}$ $d_{\mathbb{C}}HH^{\dagger 2}Q[(F11),(F13)]$ <br> $e_{\mathbb{C}}HH^{\dagger 2}L[(F3),(F6)]$ $H^2H^\dagger Qu_{\mathbb{C}}[(S4),(F11),(F14)]$ $HH^\dagger W_L{}^2$ <br> $H^3H^{\dagger 3}[(S7),(S6),(S2,S6),(S1),(S6,S7),(S4,S6),(S2,S4),(S4),(S1,S4)]$ <br> $e_{\mathbb{C}}HH^{\dagger 2}L$ $d_{\mathbb{C}}HH^{\dagger 2}Q$ $H^2H^\dagger Qu_{\mathbb{C}}$ |
| $S6\ (\mathbf{1},\mathbf{3},1)$ | $d_{\mathbb{C}}HH^{\dagger 2}Q[(S4),(F10),(F14)]$ $e_{\mathbb{C}}HH^{\dagger 2}L[(S4),(F4),(F5)]$ <br> $H^2H^\dagger Qu_{\mathbb{C}}[(F13),(F12)]$ $L^2L^{\dagger 2}$ <br> $H^3H^{\dagger 3}[(S7),(S4),(S8),(S5),(S5),(S1),(S2,S5)$ <br> $,(S5,S7),(S4,S5),(S1,S4),(S2,S5),(S2,S4)]$ |
| $S7\ (\mathbf{1},\mathbf{4},\frac{1}{2})$ | $H^3H^{\dagger 3}$ <br> $H^3H^{\dagger 3}[(S6),(S5),(S5,S6)]$ |
| $S8\ (\mathbf{1},\mathbf{4},\frac{3}{2})$ | $H^3H^{\dagger 3}$ <br> $H^3H^{\dagger 3}[(S6)]$ |
| $S9\ (\mathbf{3},\mathbf{1},-\frac{4}{3})$ | $u_{\mathbb{C}}{}^2u_{\mathbb{C}}^{\dagger 2}$ |
| $S10\ (\mathbf{3},\mathbf{1},-\frac{1}{3})$ | $Q^2Q^{\dagger 2}$ $e_{\mathbb{C}}LQu_{\mathbb{C}}$ $e_{\mathbb{C}}Q^{\dagger 2}u_{\mathbb{C}}$ $e_{\mathbb{C}}e_{\mathbb{C}}^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ |
| $S11\ (\mathbf{3},\mathbf{1},\frac{2}{3})$ | $d_{\mathbb{C}}{}^2d_{\mathbb{C}}^{\dagger 2}$ |
| $S12\ (\mathbf{3},\mathbf{2},\frac{1}{6})$ | $d_{\mathbb{C}}d_{\mathbb{C}}^\dagger LL^\dagger$ |
| $S13\ (\mathbf{3},\mathbf{2},\frac{7}{6})$ | $LL^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ |
| $S14\ (\mathbf{3},\mathbf{3},-\frac{1}{3})$ | $Q^2Q^{\dagger 2}$ |
| $S15\ (\mathbf{6},\mathbf{1},-\frac{2}{3})$ | $d_{\mathbb{C}}{}^2d_{\mathbb{C}}^{\dagger 2}$ |
| $S16\ (\mathbf{6},\mathbf{1},\frac{1}{3})$ | $d_{\mathbb{C}}Q^2u_{\mathbb{C}}$ $d_{\mathbb{C}}d_{\mathbb{C}}^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ |
| $S17\ (\mathbf{6},\mathbf{1},\frac{4}{3})$ | $u_{\mathbb{C}}{}^2u_{\mathbb{C}}^{\dagger 2}$ |
| $S18\ (\mathbf{6},\mathbf{3},\frac{1}{3})$ | $Q^2Q^{\dagger 2}$ |
| $S19\ (\mathbf{8},\mathbf{2},\frac{1}{2})$ | $QQ^\dagger u_{\mathbb{C}}u_{\mathbb{C}}^\dagger$ |

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

New LHC searches!

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

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

# Complete Dim-8 Tree UVs

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

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

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

In the forward limit, a twice-subtracted dispersion relation

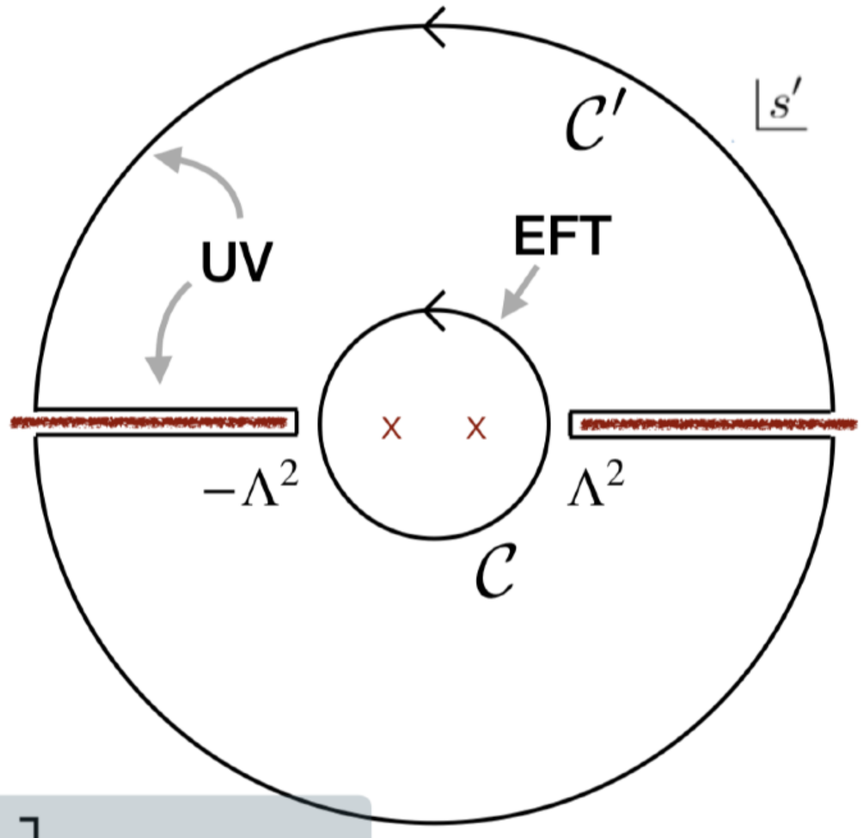
$$\mathcal{M}^{ijkl} = \frac{1}{2\pi}\int_{(\epsilon\Lambda)^2}^{\infty}\frac{ds}{s^3}\sum_X[\mathbf{M}_{ij\to X}\mathbf{M}^*_{kl\to X} + (j\leftrightarrow l)]$$

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



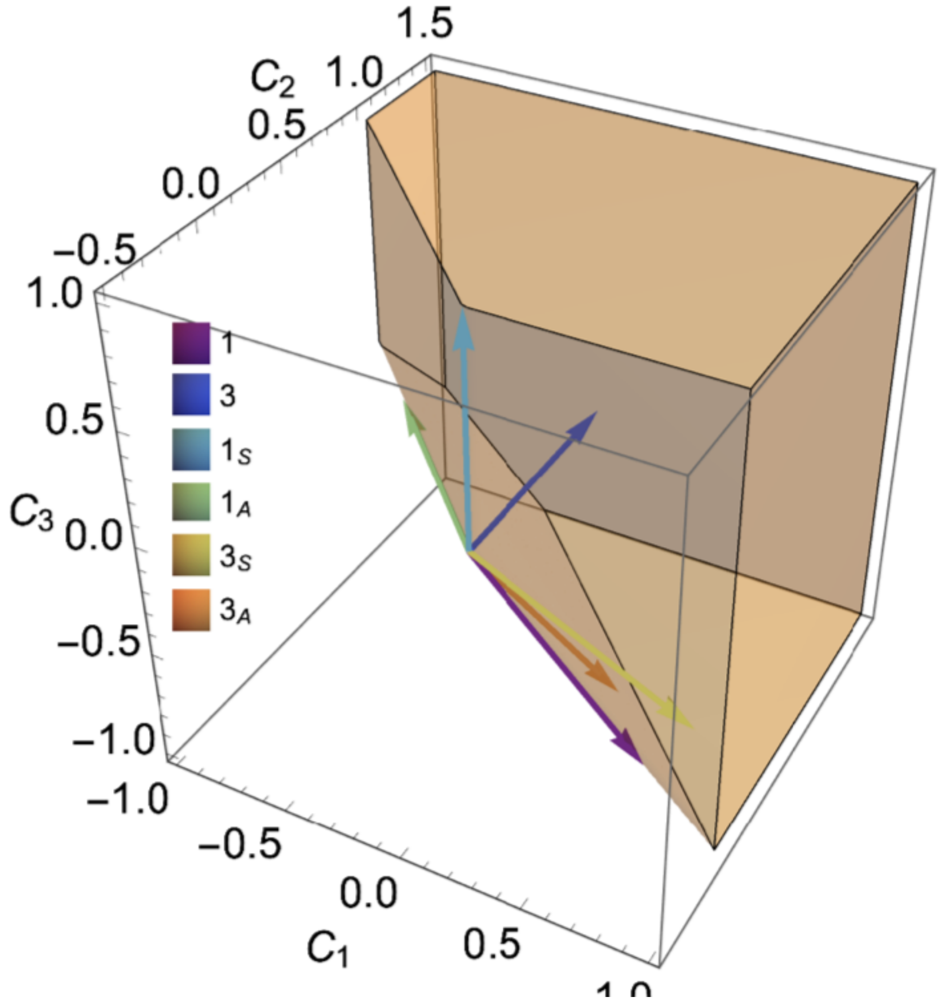

**Fixed $t$ dispersion relation**

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

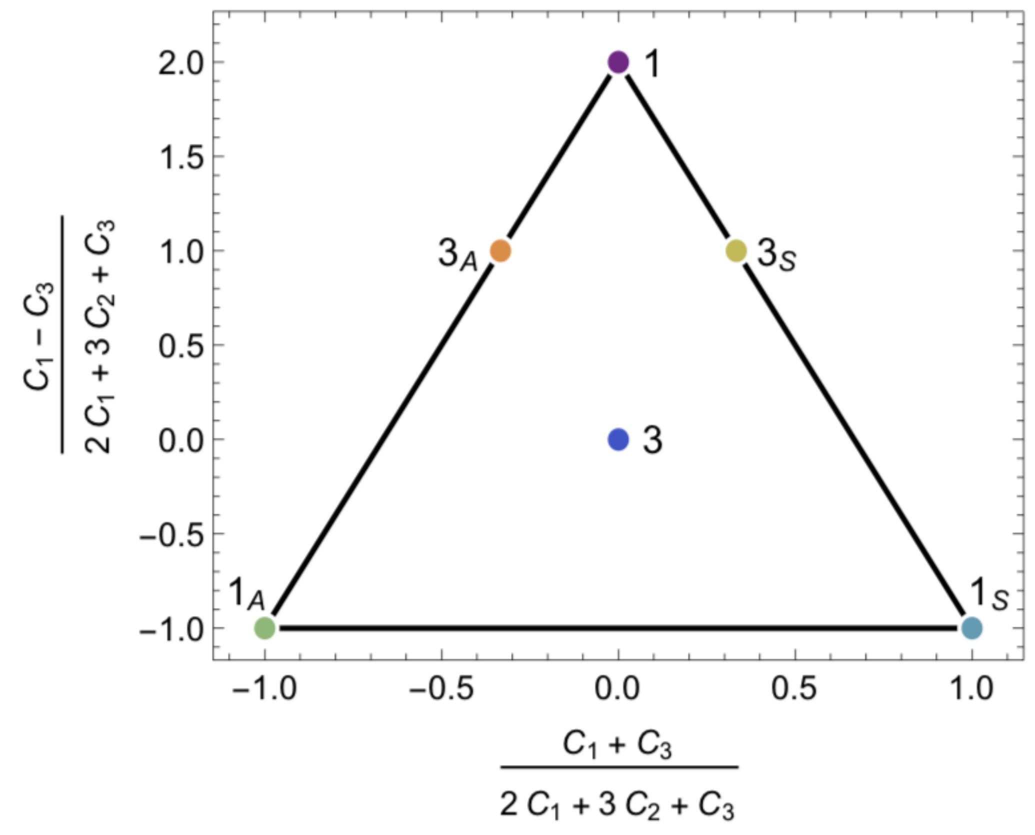
$\mu > \Lambda^2$

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

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




[ Cen Zhang, S-Y Zhou ]

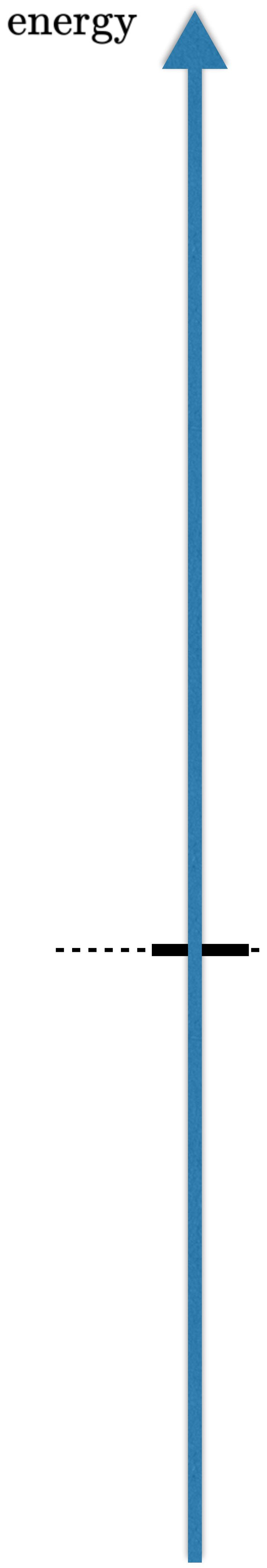


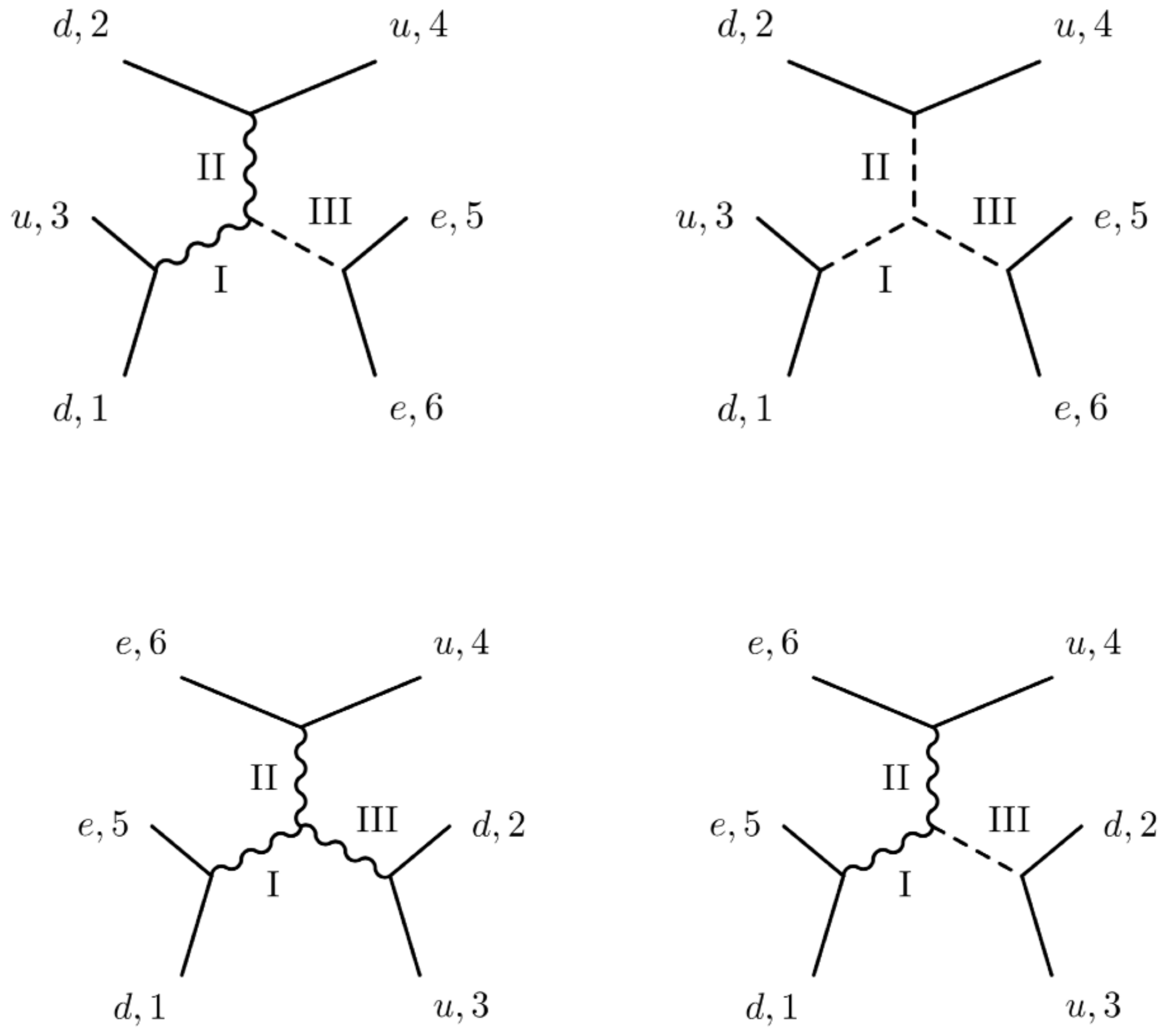



Jiang-Hao Yu (ITP-CAS)

# Complete Dim-9 UV for 0vbb

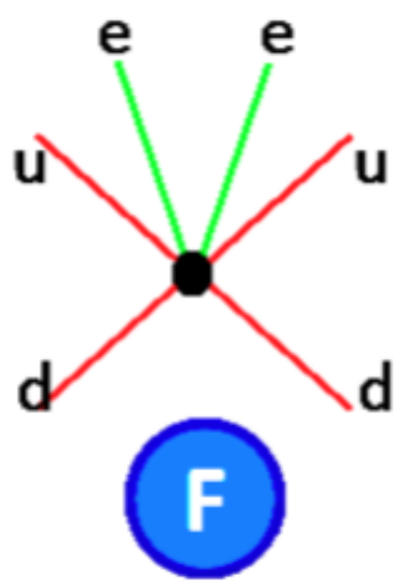
[ Li, Ni, Xiao, **Yu**, in preparation ]




| $(\mathbf{r}_i, J_i)$ | $(1,1,0)$ | $(0,0,0)$ |
|---|---|---|
| $(\mathbf{8}_2, \mathbf{8}_2, \mathbf{1}_3)$ | $\frac{4}{3}\mathcal{O}_1 + 2\mathcal{O}_2$ | $-\frac{2}{3}\mathcal{O}_2$ |
| $(\mathbf{8}_2, \mathbf{8}_2, \mathbf{1}_1)$ | $-2\mathcal{O}_2$ | $\frac{4}{3}\mathcal{O}_1 + \frac{2}{3}\mathcal{O}_2$ |
| $(\mathbf{1}_2, \mathbf{1}_2, \mathbf{1}_3)$ | $-4\mathcal{O}_1 - 6\mathcal{O}_2$ | $2\mathcal{O}_2$ |
| $(\mathbf{1}_2, \mathbf{1}_2, \mathbf{1}_1)$ | $6\mathcal{O}_2$ | $-4\mathcal{O}_1 - 2\mathcal{O}_2$ |

| $(\mathbf{r}_i, J_i)$ | $(1,1,1)$ | $(1,1,0)$ |
|---|---|---|
| $(\mathbf{3}_3, \mathbf{8}_2, \bar{\mathbf{3}}_2)$ | $-\frac{8}{3}\mathcal{O}_1$ | $\frac{4}{3}\mathcal{O}_1 + \frac{8}{3}\mathcal{O}_2$ |
| $(\mathbf{3}_1, \mathbf{8}_2, \bar{\mathbf{3}}_2)$ | $-\frac{8}{3}\mathcal{O}_1$ | $0$ |
| $(\mathbf{3}_3, \mathbf{1}_2, \bar{\mathbf{3}}_2)$ | $-\frac{8}{3}\mathcal{O}_1$ | $\frac{4}{3}\mathcal{O}_1 + \frac{8}{3}\mathcal{O}_2$ |
| $(\mathbf{3}_1, \mathbf{1}_2, \bar{\mathbf{3}}_2)$ | $-\frac{8}{3}\mathcal{O}_1$ | $0$ |



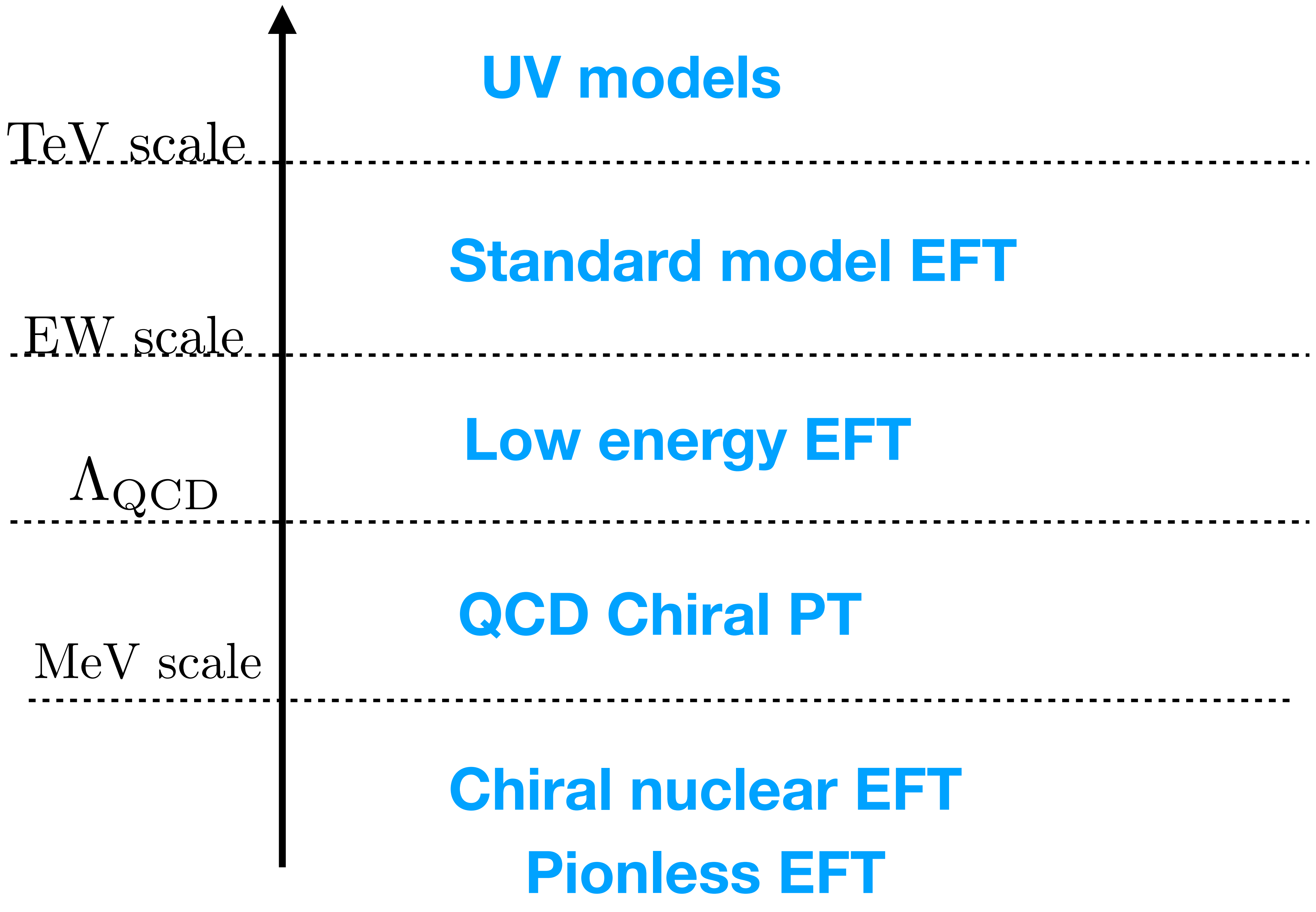

$$\mathcal{O}_1 = \tfrac{1}{4}({L^\dagger}_u{}^j {L^\dagger}_v{}^i)(Q_{pai}Q_{rbj})({u_{cs}}^b {u_{ct}}^a)$$

$$\mathcal{O}_2 = -\tfrac{1}{4}({L^\dagger}_u{}^j {L^\dagger}_v{}^i)(Q_{pai}{u_{cs}}^b)(Q_{rbj}{uc_t}^a).$$

# Summary

- EFT provides most general parametrization of new physics at different scales

**Large Log avoided**




Based on fields, symmetry, and power counting

Construct operator bases in each levels of EFTs using spinor Young tensor

**Can also be applied to axion, dark photon, sterile neutrino, dark matter, gravity EFTs**

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[ Huayang Song, Hao Sun, **J.H.Yu**, 2305.16770 ]

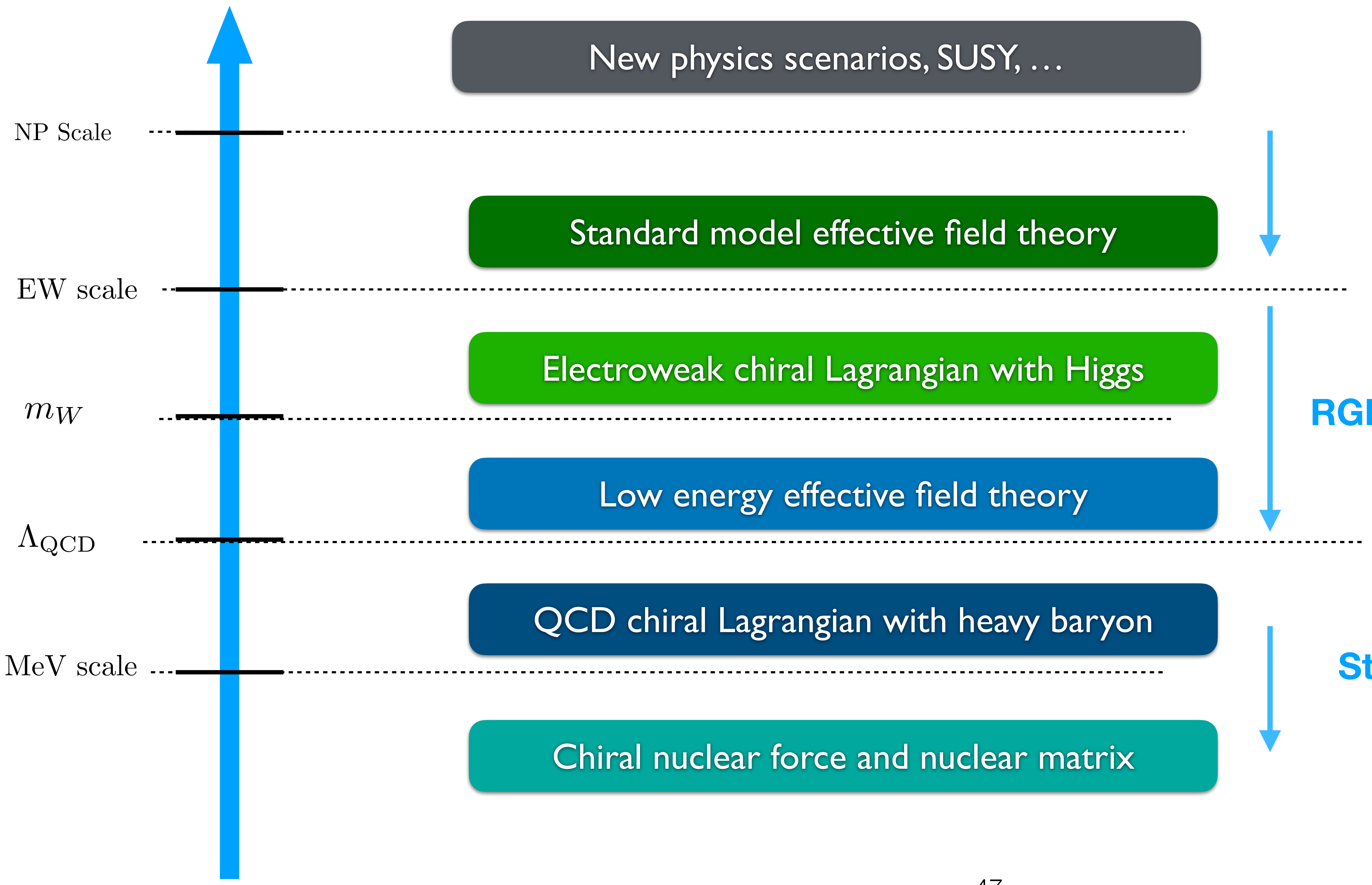
[ Huayang Song, Hao Sun, **J.H.Yu**, 2306.05999 ]

- The complete UVs can be explored via Casimir projection

# Thanks for your attention!

# Tower of effective field theories

To avoid large log among scales, it is natural to consider matching and running procedures among EFTs




**RGE running effects not so small**

**EFT framework!**

**Strong coupling region**

**chiral expansion is perturbative!**