Effective Field Pathway to New Physics

有效场论观点下的新物理

Jiang-Hao Yu (于江浩)

Institute of Theoretical Physics, Chinese Academy of Sciences

FIND CPV workshop @ USTC

08-26, 2023

Outline

- Why EFT and How CPV in EFT?
- SMEFT and LEFT Operators

[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

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

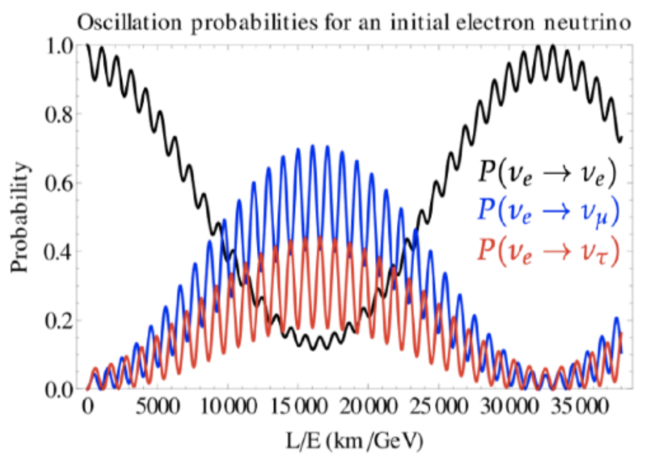
Why EFT and How CPV in EFT?

Why New Physics?

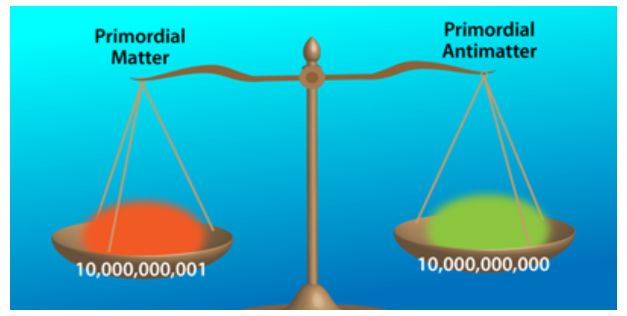
There are experimental challenges in the standard model and theoretical motivation for new physics

experimental challenges

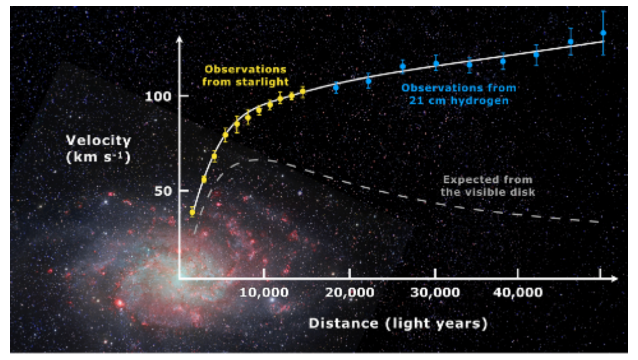
Neutrino masses



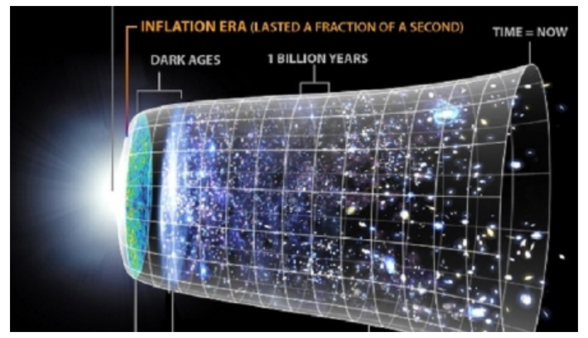
Baryon asymmetry



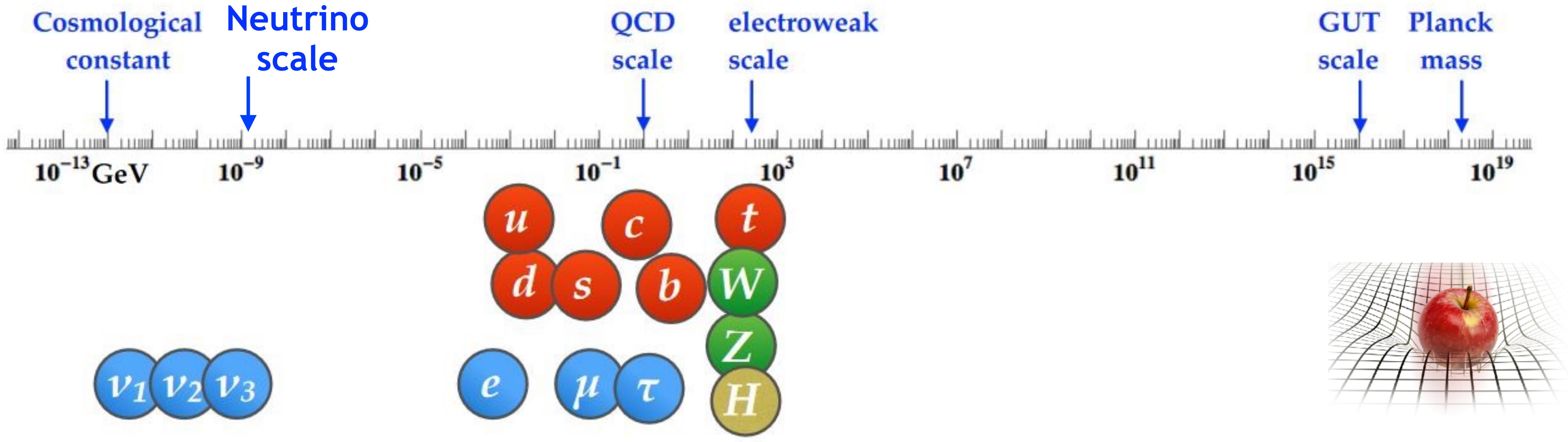
Dark matter



Inflation



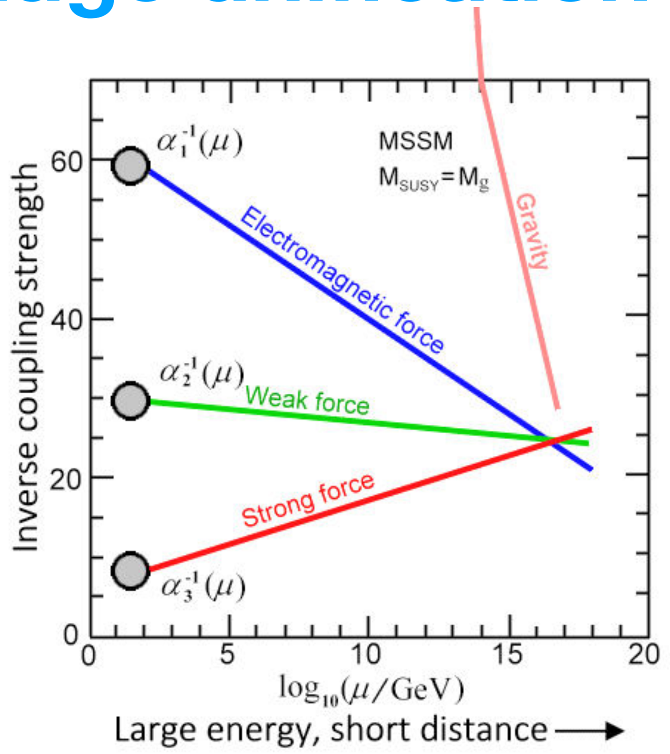
theoretical motivation



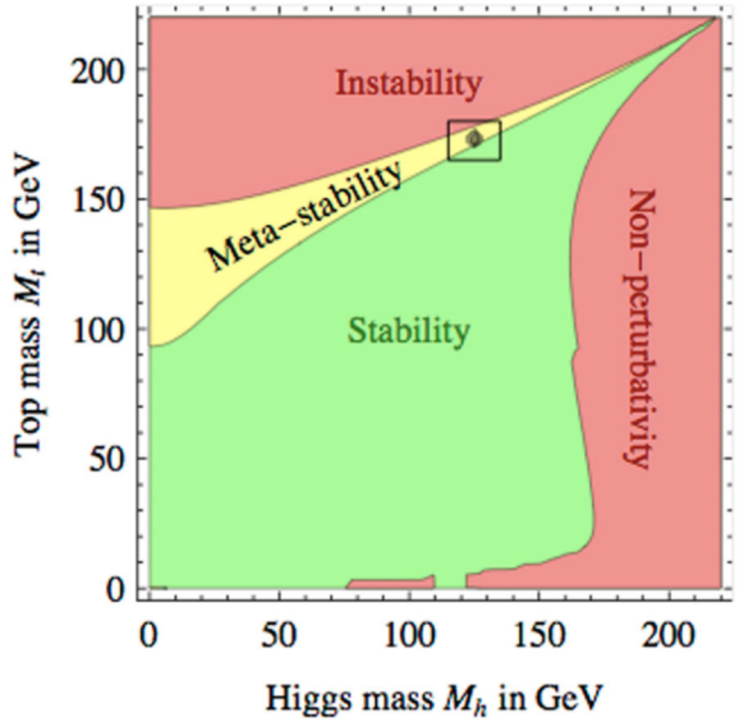
Fermion flavor hierarchy

Higgs hierarchy problem

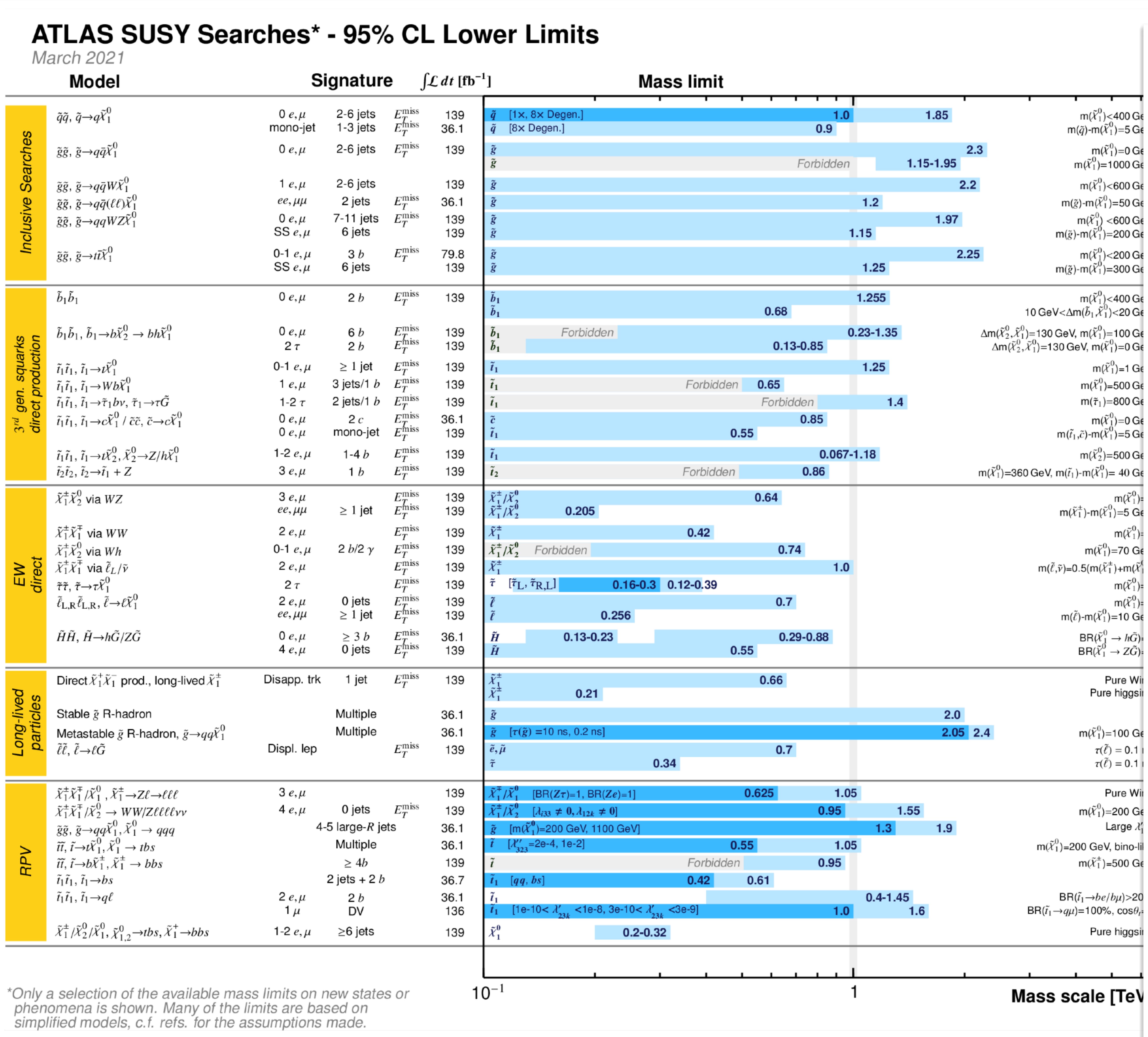
Gauge unification

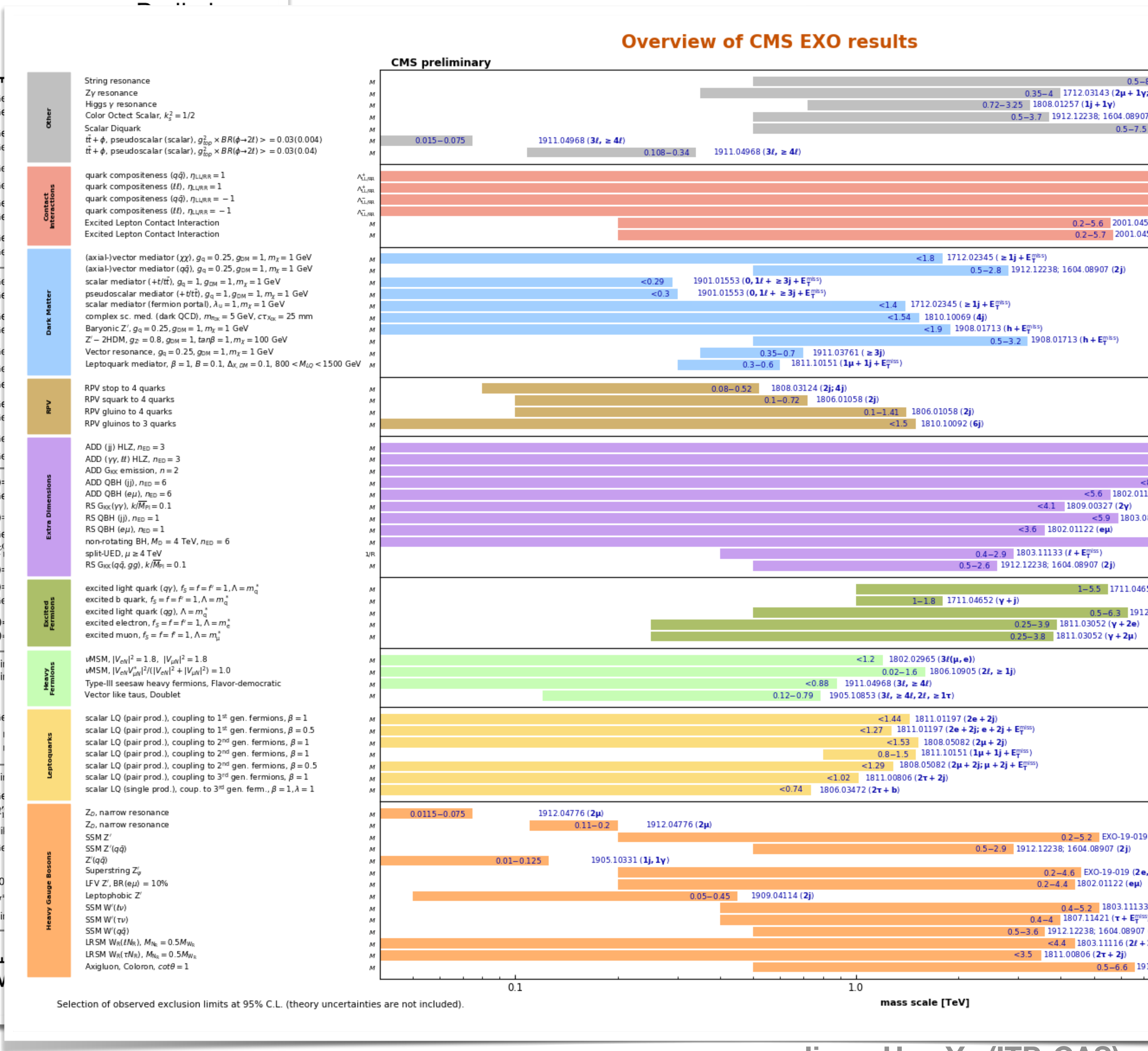


Vacuum stability



Where New Physics?





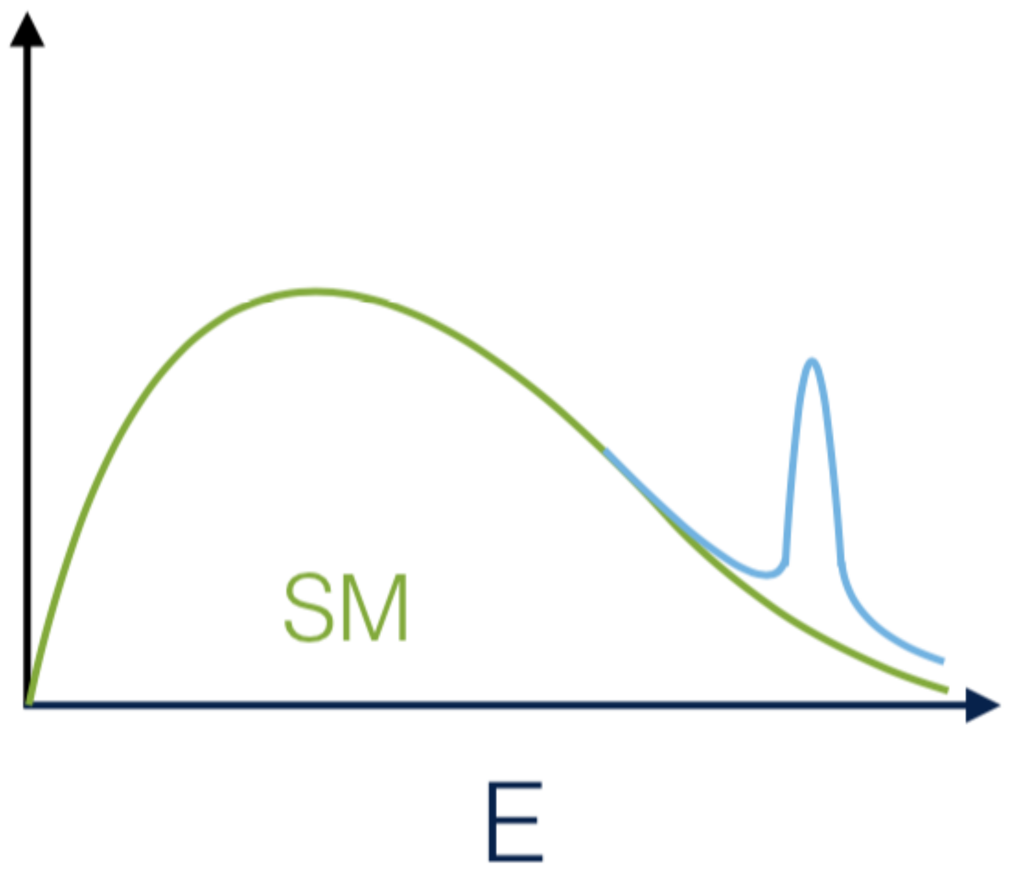
Jiang-Hao Yu (ITP-CAS)

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**

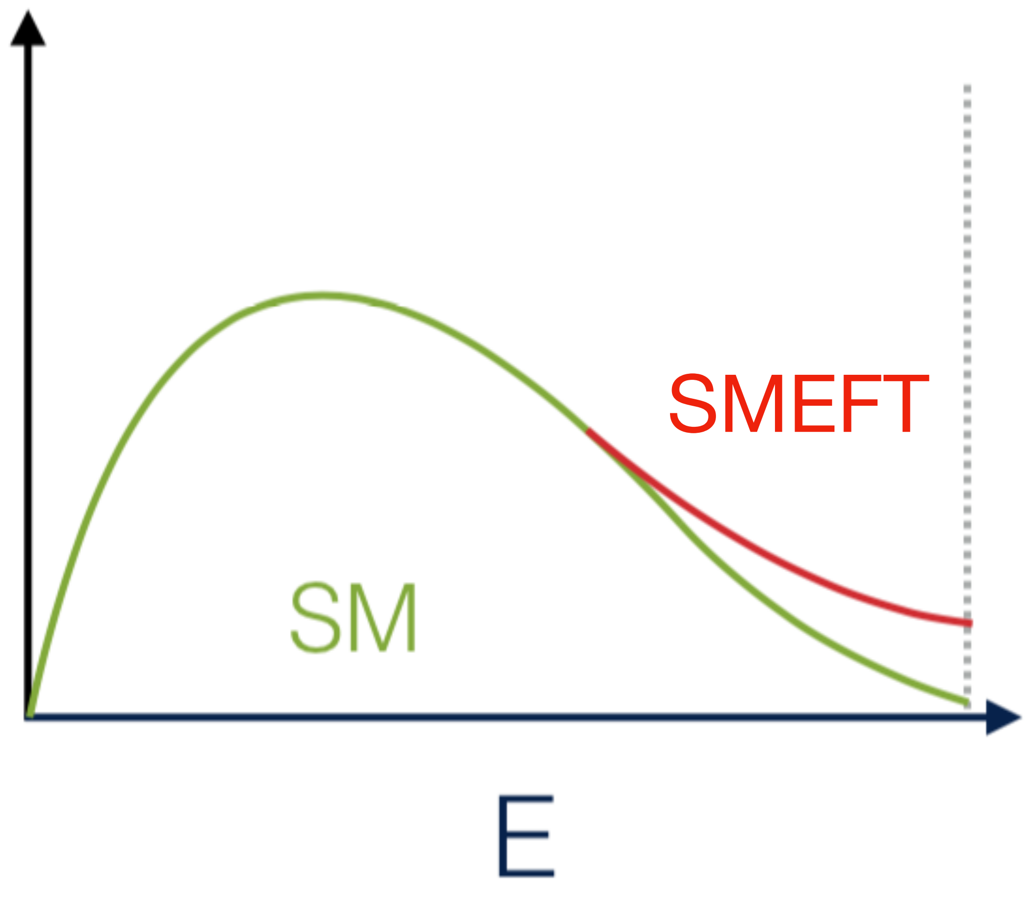
Direct searches



Experiments: Resonance bump hunting at the LHC

Theories: New physics model building

Precision measurements



Experiments: deviation from SM at the LHC

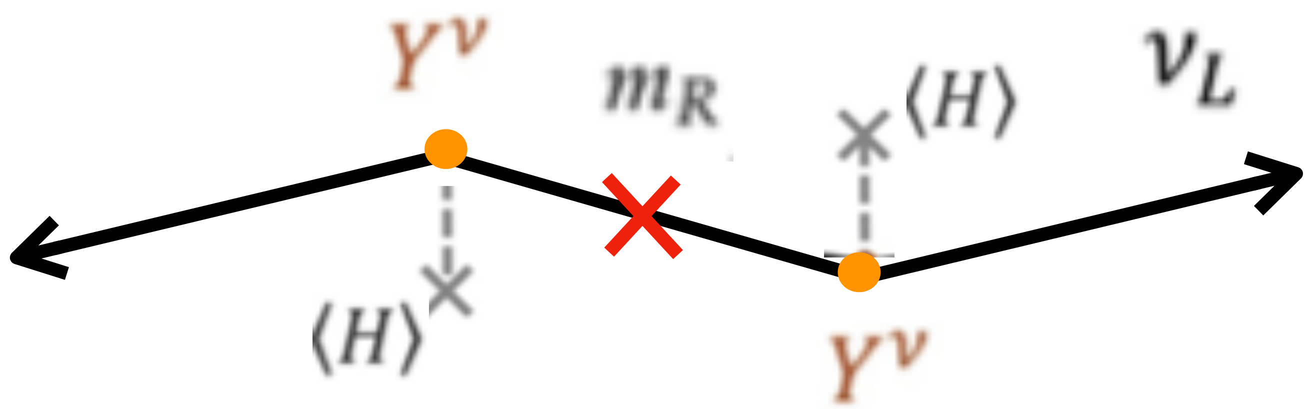
Theories: Effective field theory (EFT) description

EFT provides evidence of new physics

EFT Description of New Physics

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

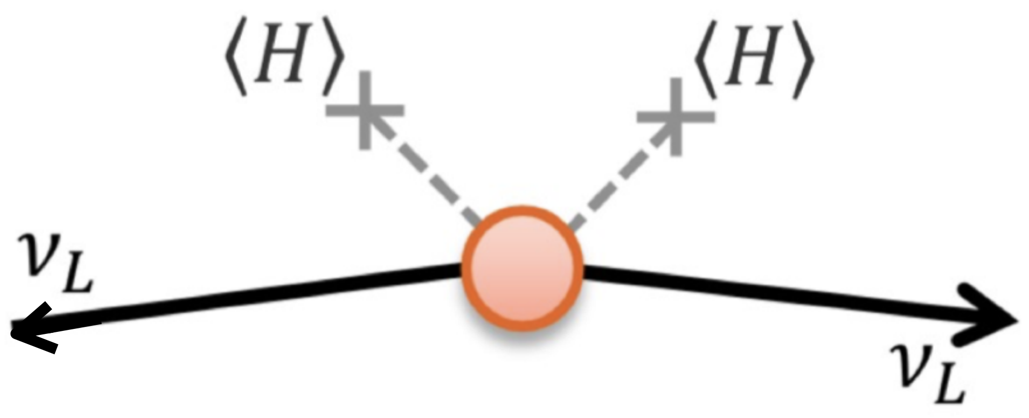
Beyond the current experimental searches



for Majorana neutrino

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

Measurements of neutrino oscillation



$$\frac{c_{ij}}{\Lambda}(L_iH)(L_jH) + \mathrm{h.c.}$$

[Weinberg, 1979]

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

2 Majorana CP phase (neutrino-antineutrino oscillation)

"… 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

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

[Weinberg, 1980]

Standard Model

Weinberg Operator

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

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

Dim-6 Operators

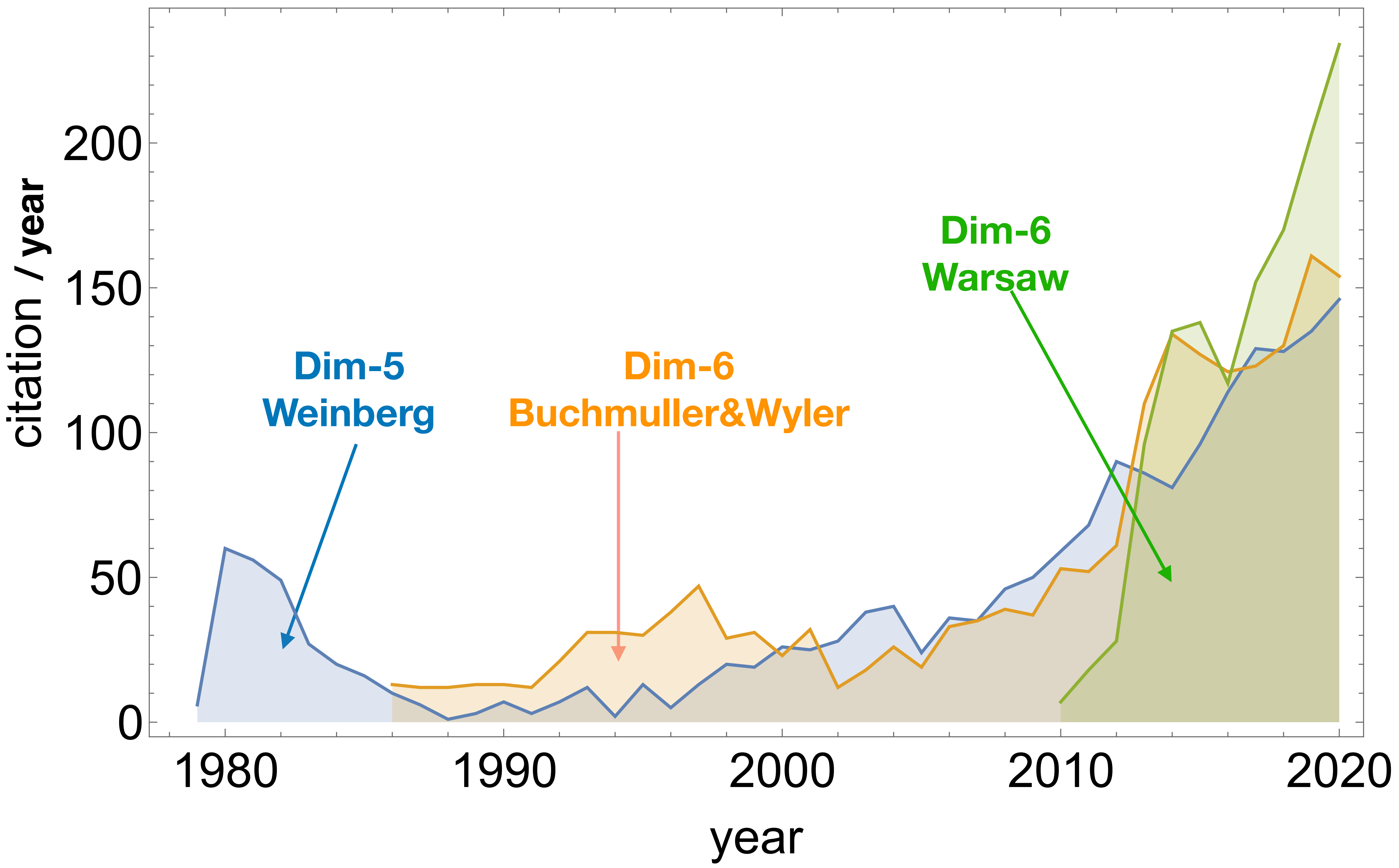
Dimension-6 operators parametrize new physics effects at low energy, electroweak precision, and Higgs boson physics, etc

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

[Buchmuller and Wyler, 1986]

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

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



CPV in Dim-6 Operators

There are total 2 (dim-4, theta) + 2 (dim-5, Majorana) + 705 (dim-6) order parameters of CPV!

6 boson operators

$$\phi^2 X^2 \rightarrow \quad \mathcal{Q}_{H\tilde{G}} : (H^\dagger H)(\tilde{G}^A_{\mu\nu} G^{A\mu\nu}), \quad \mathcal{Q}_{H\tilde{W}} : (H^\dagger H)(\tilde{W}^I_{\mu\nu} W^{I\mu\nu}),$$

$$\mathcal{Q}_{H\tilde{B}} : (H^\dagger H)(\tilde{B}_{\mu\nu} B^{\mu\nu}), \quad \mathcal{Q}_{H\tilde{W}B} : (H^\dagger \tau^I H)(\tilde{W}^I_{\mu\nu} B^{\mu\nu}),$$

$$X^3 \rightarrow \quad \mathcal{Q}_{\tilde{G}} : f^{ABC} \tilde{G}^{A\mu}_{\nu} G^{B\nu}_{\rho} G^{C\rho}_{\mu}, \quad \mathcal{Q}_{\tilde{W}} : \varepsilon^{IJK} \tilde{W}^{I\mu}_{\nu} W^{J\nu}_{\rho} W^{K\rho}_{\mu}.$$

φ^6 and $\varphi^4 D^2$

	Type of op.	# of ops	# real	# im.	inv. under $U(1)_{L_i} - U(1)_{L_j}$ # real	# im.
bilinears	Yukawa	3	27	27	21	21
	Dipoles	8	72	72	60	60
	current-current	8	51	30	42	21
	all bilinears	19	150	129	123	102
4-Fermi	LLLL	5	171	126	99	54
	RRRR	7	255	195	186	126
	LLRR	8	360	288	246	174
	LRRL	1	81	81	27	27
	LRLR	4	324	324	216	216
	all 4-Fermi	25	1191	1014	774	597
	all		1341	1143	897	699

[Bonnefoy, Gendy, Grojean, Ruderman 2022]

Higgs CPV

Modified Yukawas	Q_{eH}	$(H^\dagger H)(\bar{L}_i e_j H) + \text{h.c.}$
	Q_{uH}	$(H^\dagger H)(\bar{Q}_i u_j \widetilde{H}) + \text{h.c.}$
	Q_{dH}	$(H^\dagger H)(\bar{Q}_i d_j H) + \text{h.c.}$
Dipole	Q_{eW}	$(\bar{L}_i \sigma^{\mu\nu} e_j)\tau^I H W^I_{\mu\nu} + \text{h.c.}$
	Q_{eB}	$(\bar{L}_i \sigma^{\mu\nu} e_j) H B_{\mu\nu} + \text{h.c.}$
	Q_{uG}	$(\bar{Q}_i \sigma^{\mu\nu} T^A u_j)\widetilde{H} G^A_{\mu\nu} + \text{h.c.}$
	Q_{uW}	$(\bar{Q}_i \sigma^{\mu\nu} u_j)\tau^I \widetilde{H} W^I_{\mu\nu} + \text{h.c.}$
	Q_{uB}	$(\bar{Q}_i \sigma^{\mu\nu} u_j)\widetilde{H} B_{\mu\nu} + \text{h.c.}$
	Q_{dG}	$(\bar{Q}_i \sigma^{\mu\nu} T^A d_j) H G^A_{\mu\nu} + \text{h.c.}$
	Q_{dW}	$(\bar{Q}_i \sigma^{\mu\nu} d_j)\tau^I H W^I_{\mu\nu} + \text{h.c.}$
	Q_{dB}	$(\bar{Q}_i \sigma^{\mu\nu} d_j) H B_{\mu\nu} + \text{h.c.}$
Current-current	$Q^{(1)}_{HL}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}_i \gamma^\mu L_j)$
	$Q^{(3)}_{HL}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{L}_i \tau^I \gamma^\mu L_j)$
	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_i \gamma^\mu e_j)$
	$Q^{(1)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}_i \gamma^\mu Q_j)$
	$Q^{(3)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}_i \tau^I \gamma^\mu Q_j)$
	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_i \gamma^\mu u_j)$
	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_i \gamma^\mu d_j)$
	Q_{Hud}	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_i \gamma^\mu d_j) + \text{h.c.}$

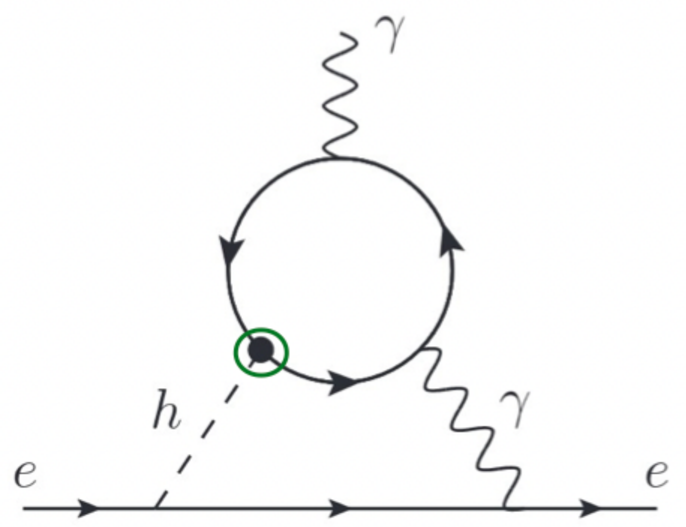
EDM

Meson mixing/Decay

LLLL	Q_{LL}	$(\bar{L}_i\gamma_\mu L_j)(\bar{L}_k\gamma^\mu L_l)$
	$Q^{(1)}_{QQ}$	$(\bar{Q}_i\gamma_\mu Q_j)(\bar{Q}_k\gamma^\mu Q_l)$
	$Q^{(3)}_{QQ}$	$(\bar{Q}_i\gamma_\mu\tau^I Q_j)(\bar{Q}_k\gamma^\mu\tau^I Q_l)$
	$Q^{(1)}_{LQ}$	$(\bar{L}_i\gamma_\mu L_j)(\bar{Q}_k\gamma^\mu Q_l)$
	$Q^{(3)}_{LQ}$	$(\bar{L}_i\gamma_\mu\tau^I L_j)(\bar{Q}_k\gamma^\mu\tau^I Q_l)$
RRRR	Q_{ee}	$(\bar{e}_i\gamma_\mu e_j)(\bar{e}_k\gamma^\mu e_l)$
	Q_{uu}	$(\bar{u}_i\gamma_\mu u_j)(\bar{u}_k\gamma^\mu u_l)$
	Q_{dd}	$(\bar{d}_i\gamma_\mu d_j)(\bar{d}_k\gamma^\mu d_l)$
	Q_{eu}	$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$
	Q_{ed}	$(\bar{e}_i\gamma_\mu e_j)(\bar{d}_k\gamma^\mu d_l)$
	$Q^{(1)}_{ud}$	$(\bar{u}_i\gamma_\mu u_j)(\bar{d}_k\gamma^\mu d_l)$
	$Q^{(8)}_{ud}$	$(\bar{u}_i\gamma_\mu T^A u_j)(\bar{d}_k\gamma^\mu T^A d_l)$
LLRR	Q_{Le}	$(\bar{L}_i\gamma_\mu L_j)(\bar{e}_k\gamma^\mu e_l)$
	Q_{Lu}	$(\bar{L}_i\gamma_\mu L_j)(\bar{u}_k\gamma^\mu u_l)$
	Q_{Ld}	$(\bar{L}_i\gamma_\mu L_j)(\bar{d}_k\gamma^\mu d_l)$
	Q_{Qe}	$(\bar{Q}_i\gamma_\mu Q_j)(\bar{e}_k\gamma^\mu e_l)$
	$Q^{(1)}_{Qu}$	$(\bar{Q}_i\gamma_\mu Q_j)(\bar{u}_k\gamma^\mu u_l)$
	$Q^{(8)}_{Qu}$	$(\bar{Q}_i\gamma_\mu T^A Q_j)(\bar{u}_k\gamma^\mu T^A u_l)$
	$Q^{(1)}_{Qd}$	$(\bar{Q}_i\gamma_\mu Q_j)(\bar{d}_k\gamma^\mu d_l)$
	$Q^{(8)}_{Qd}$	$(\bar{Q}_i\gamma_\mu T^A Q_j)(\bar{d}_k\gamma^\mu T^A d_l)$
LRRL	Q_{LedQ}	$(\bar{L}^a_i e_j)(\bar{d}_k Q_{la}) + \text{h.c.}$
LRLR	$Q^{(1)}_{QuQd}$	$(\bar{Q}^a_i u_j)\epsilon_{ab}(\bar{Q}^b_k d_l) + \text{h.c.}$
	$Q^{(8)}_{QuQd}$	$(\bar{Q}^a_i T^A u_j)\epsilon_{ab}(\bar{Q}^b_k T^A d_l) + \text{h.c.}$
	$Q^{(1)}_{LeQu}$	$(\bar{L}^a_i e_j)\epsilon_{ab}(\bar{Q}^b_k u_l) + \text{h.c.}$
	$Q^{(3)}_{LeQu}$	$(\bar{L}^a_i \sigma_{\mu\nu} e_j)\epsilon_{ab}(\bar{Q}^k_s \sigma^{\mu\nu} u_t) + \text{h.c.}$

CPV Invariants

Only identify these complex parameters not enough, since it can always be rotated away (re-phasing)



$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}_4} + \frac{C_{uH}}{\Lambda^2}|H|^2\overline{Q}_L u_R \tilde{H} + \mathrm{h.c.}$$

$$\frac{d_e}{e} = -\frac{1}{48\pi^2}\frac{v m_e m_u}{m_h^2}\frac{\mathrm{Im}(C_{uH})}{\Lambda^2}F_1\left(\frac{m_u^2}{m_h^2},0\right)$$

$$u_R \to e^{-i\arg(C_{uH})}u_R$$

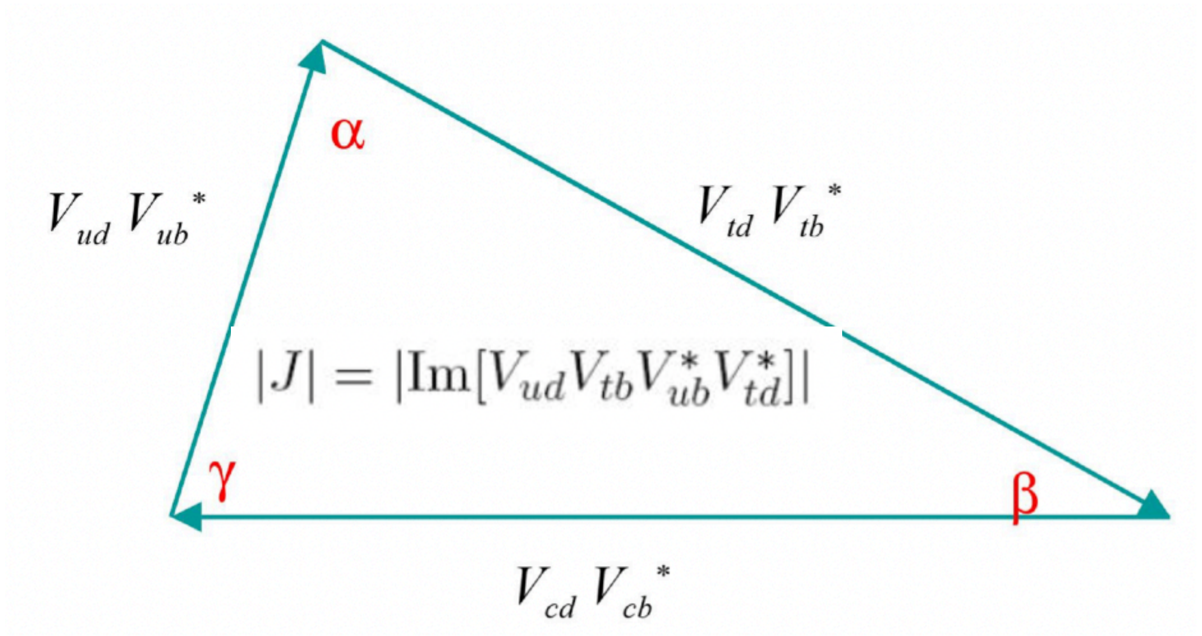
$$\mathcal{L} \supset -m_u\overline{u}_L u_R - m_u^*\overline{u}_R u_L + \frac{v^2 C_{uH}}{\sqrt{2}\Lambda^2}\overline{u}_L u_R h + \frac{v^2 C_{uH}^*}{\sqrt{2}\Lambda^2}\overline{u}_R u_L h$$

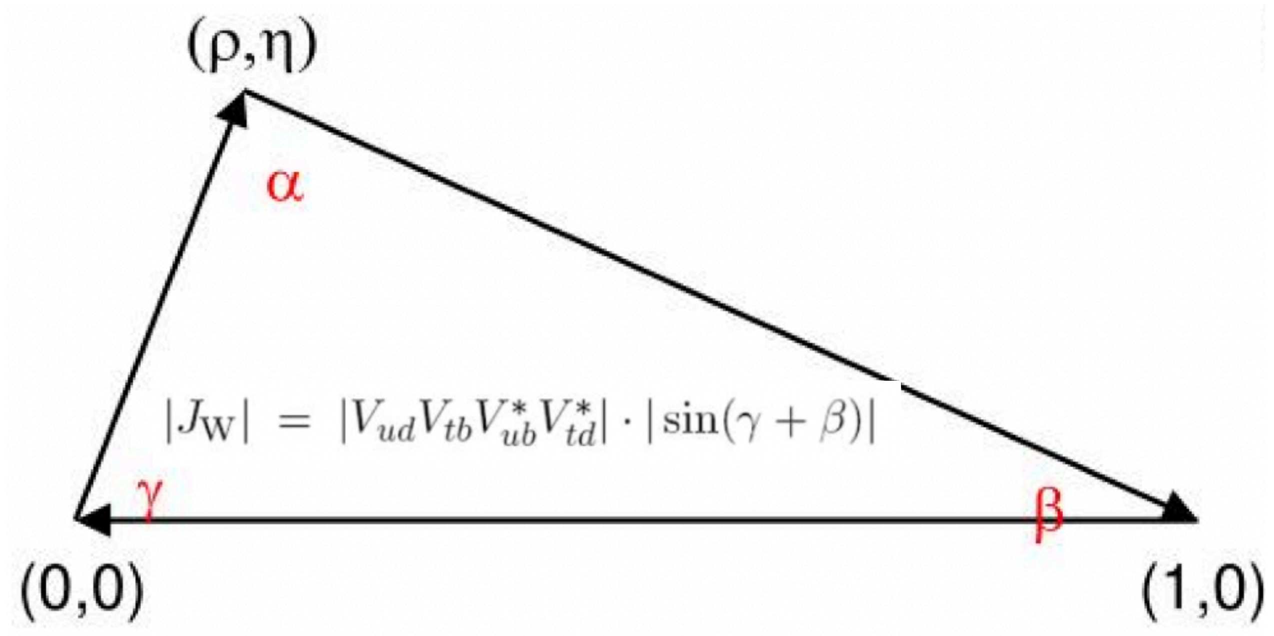
$$\frac{d_e}{e} = -\frac{1}{48\pi^2}\frac{v m_e}{m_h^2}\frac{\mathrm{Im}(m_u^* C_{uH})}{\Lambda^2}F_1\left(\frac{|m_u|^2}{m_h^2},0\right)$$

Real quark mass assumed on left

Need to identify CPV invariant quantities in exp observable

Different parametrization, the same invariants in SM





$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{q}\left(i\not{D} - m_q e^{i\theta_q\gamma_5}\right)q - \frac{1}{4}G^{a\,\mu\nu}G^a_{\mu\nu} + \theta\frac{g_s^2}{32\pi^2}G^{a\,\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$\bar{\theta} = \theta + \mathrm{Arg\,Det}\,Y_U Y_D$$

Large Jarlskog, small strong phase

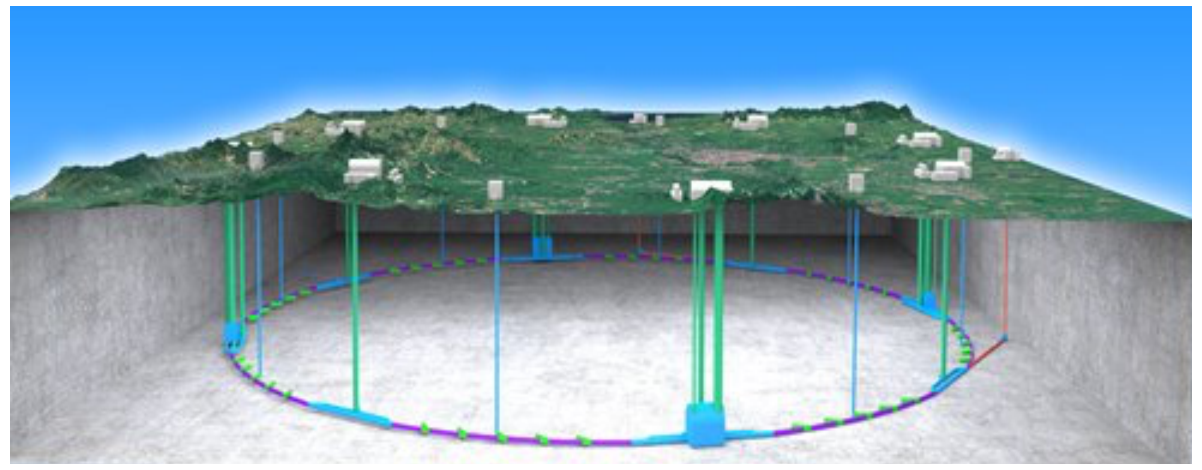
Jiang-Hao Yu (ITP-CAS)

CPV at different Scales

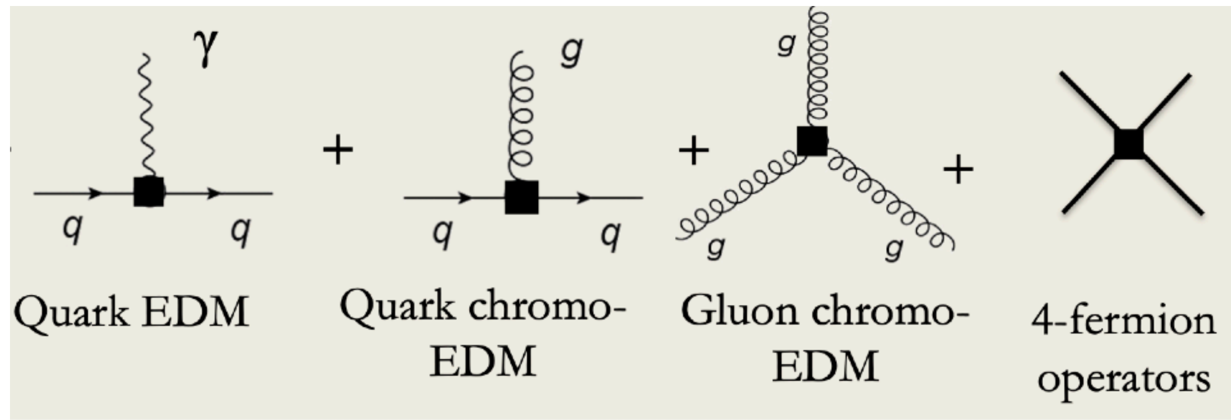
Various experiments to probe CPV effective operators

TeV scale

EW scale

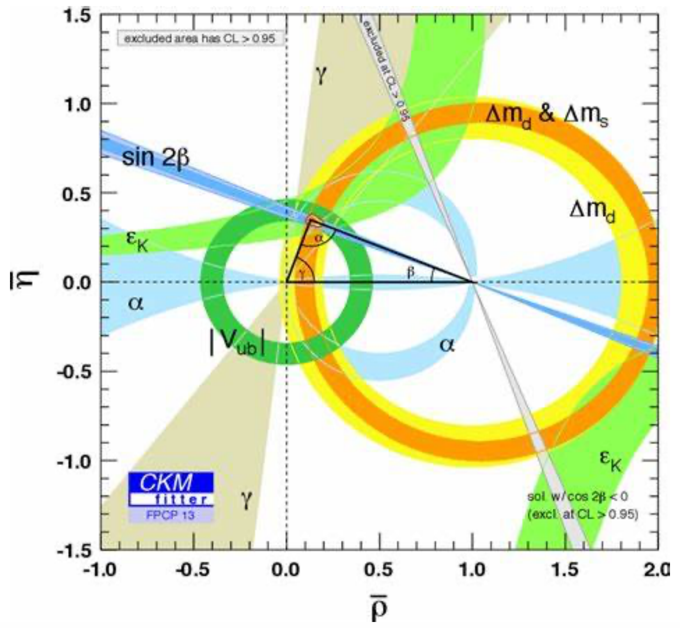


Top, Higgs, diboson @ Collider



m_W

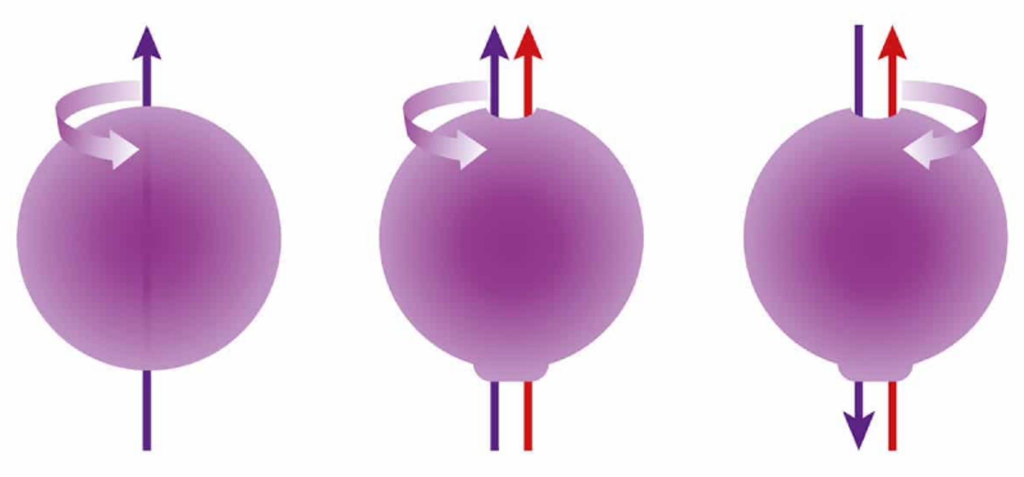
Λ_{QCD}



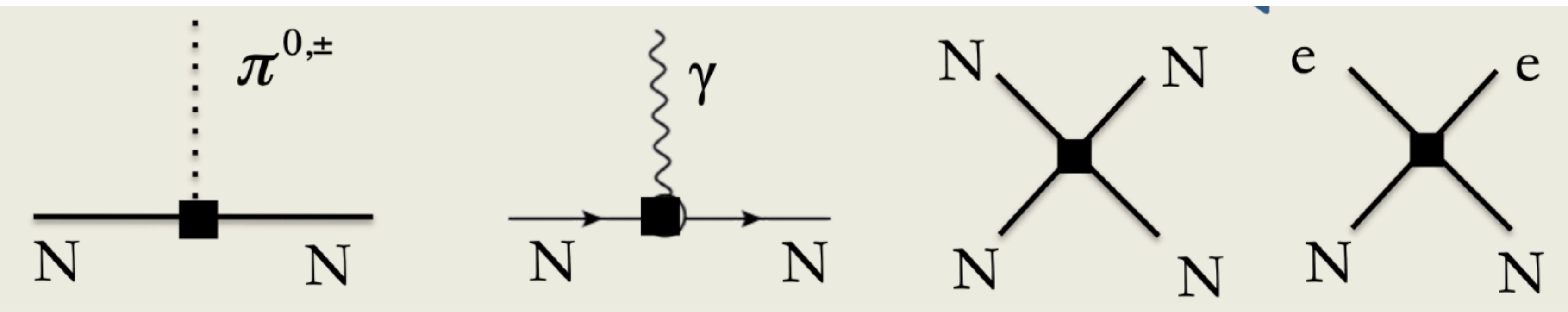
b/charm/kaon Flavor physics

MeV scale

Nucleus



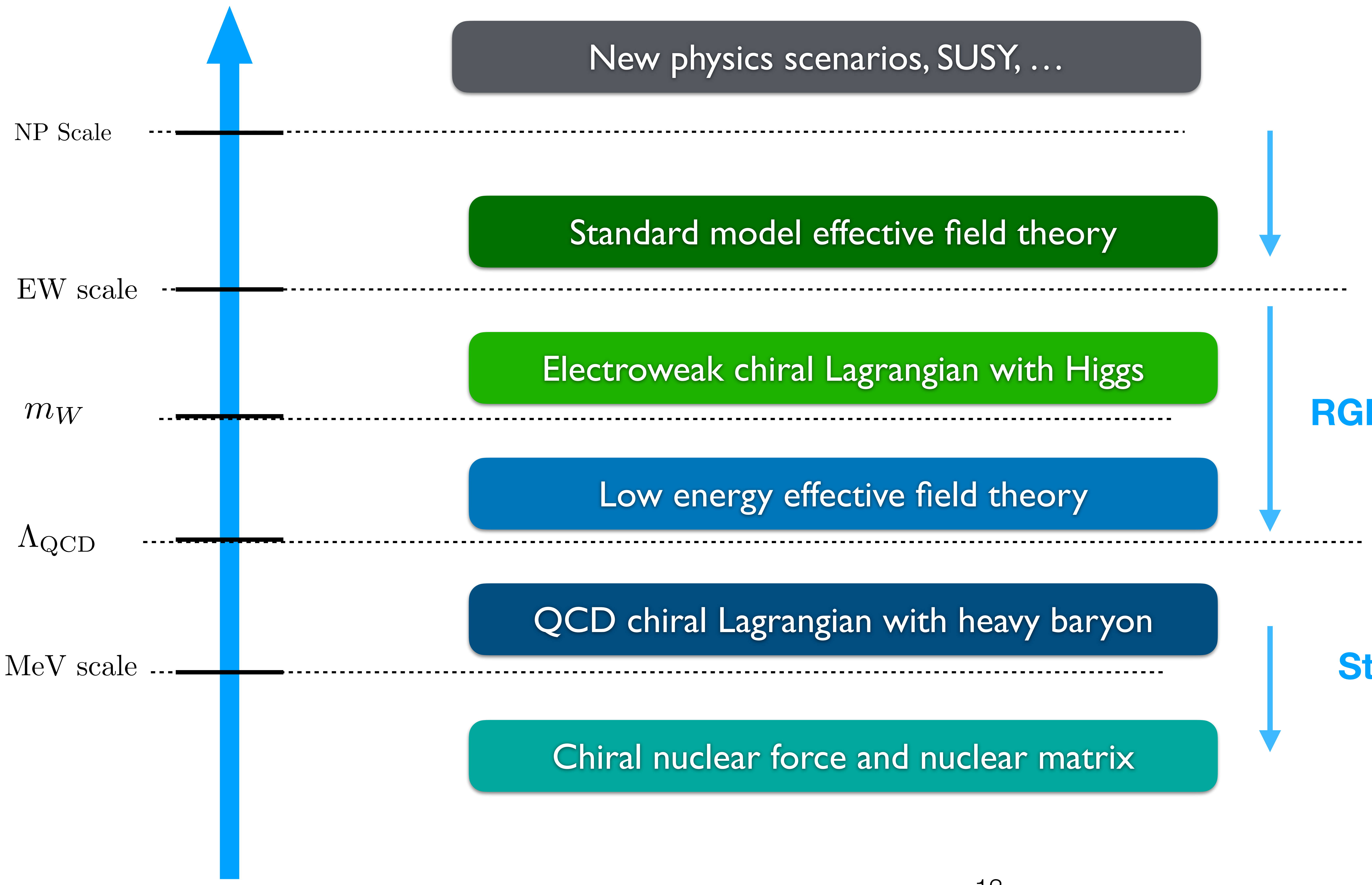
EDM



Jiang-Hao Yu (ITP-CAS)

Tower of effective field theories

To investigate various CPV experiments, it is natural to consider different EFTs to avoid large Logs



RGE running effects not so small

EFT framework!

Strong coupling region

chiral expansion is perturbative!

CPV and Higher Dim Operators

Precision EDM starts to be sensitive to dimension-8 operators

$$|d_e| < 1.1 \cdot 10^{-29}\,\mathrm{e \cdot cm}$$

Dim-6, one-loop

$$\frac{d_e}{e} \simeq \left(\frac{g^2}{16\pi^2}\right) \frac{m_e}{\Lambda^2}$$

1 PeV

Dim-6, two-loop

$$\frac{d_e}{e} \simeq \left(\frac{g^2}{16\pi^2}\right)^2 \frac{m_e}{\Lambda^2}$$

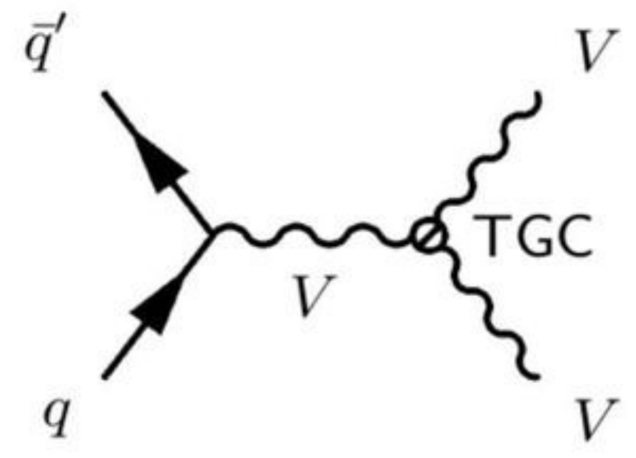
2.5 TeV

Dim-8. One-loop

$$\frac{d_e}{e} \simeq \frac{g^2}{16\pi^2} \frac{m_e m_W^2}{\Lambda^4}$$

2 TeV

For certain processes, the leading CPV operators are at dimension-8



CPV nTGC at dim-8

$$\mathcal{O}_{\tilde{B}W} = iH^\dagger \tilde{B}_{\mu\nu} W^{\mu\rho}\{D_\rho, D^\nu\}H,$$

Even higher dimensions

[Akdag, Kubis, Wirzba 2023]

Decay	Mesonic operator	Lowest order	Current measurement	Theoretical estimate
$\eta^{(\prime)} \to \pi^0\pi^+\pi^-$	$i\,\eta^{(\prime)}\partial^\mu\pi^0(\pi^+\partial_\mu\pi^- - \pi^-\partial_\mu\pi^+)$	$p^2\,(\delta^0)$	$g_2 = -9.3(4.5)\cdot 10^3/\mathrm{TeV}^2$ [121]	$\lvert g_2\rvert \sim 3\cdot 10^{-4}\,\mathrm{TeV}^2/\Lambda^4$
$\eta' \to \eta\pi^+\pi^-$	$i\,\eta'\partial^\mu\eta(\pi^+\partial_\mu\pi^- - \pi^-\partial_\mu\pi^+)$	$p^2\,(\delta^1)$	$g_1 = 0.7(1.0)\cdot 10^6/\mathrm{TeV}^2$ [121]	$\lvert g_1\rvert \sim 3\cdot 10^{-4}\,\mathrm{TeV}^2/\Lambda^4$
$\eta^{(\prime)} \to \pi^0\gamma^*$	$\partial_\mu\eta^{(\prime)}\,\partial_\nu\pi^0 F^{\mu\nu}$	$p^4\,(\delta^2)$	–	–
$\eta' \to \eta\gamma^*$	$\partial_\mu\eta'\,\partial_\nu\eta F^{\mu\nu}$	$p^4\,(\delta^2)$	–	–
$\eta \to \pi^0 e^+e^-$	$\eta\partial_\mu\pi^0\,\bar{e}\gamma^\mu e$	$p^2\,(\delta^1)$	$\mathrm{BR} < 7.5\cdot 10^{-6}$ [113]	$\mathrm{BR} \sim 7\cdot 10^{-27}\,\mathrm{TeV}^8/\Lambda^8$
$\eta \to \pi^0\mu^+\mu^-$	$\eta\partial_\mu\pi^0\,\bar{\mu}\gamma^\mu\mu$	$p^2\,(\delta^1)$	$\mathrm{BR} < 5\cdot 10^{-6}$ [115]	$\mathrm{BR} \sim 2\cdot 10^{-27}\,\mathrm{TeV}^8/\Lambda^8$
$\eta' \to \pi^0 e^+e^-$	$\eta'\partial_\mu\pi^0\,\bar{e}\gamma^\mu e$	$p^2\,(\delta^1)$	$\mathrm{BR} < 1.4\cdot 10^{-3}$ [114]	$\mathrm{BR} \sim 9\cdot 10^{-28}\,\mathrm{TeV}^8/\Lambda^8$
$\eta' \to \pi^0\mu^+\mu^-$	$\eta'\partial_\mu\pi^0\,\bar{\mu}\gamma^\mu\mu$	$p^2\,(\delta^1)$	$\mathrm{BR} < 6\cdot 10^{-5}$ [115]	$\mathrm{BR} \sim 6\cdot 10^{-28}\,\mathrm{TeV}^8/\Lambda^8$
$\eta' \to \eta e^+e^-$	$\eta'\partial_\mu\eta\,\bar{e}\gamma^\mu e$	$p^2\,(\delta^1)$	$\mathrm{BR} < 2.4\cdot 10^{-3}$ [114]	$\mathrm{BR} \sim 9\cdot 10^{-29}\,\mathrm{TeV}^8/\Lambda^8$
$\eta' \to \eta\mu^+\mu^-$	$\eta'\partial_\mu\eta\,\bar{\mu}\gamma^\mu\mu$	$p^2\,(\delta^1)$	$\mathrm{BR} < 1.5\cdot 10^{-5}$ [115]	$\mathrm{BR} \sim 3\cdot 10^{-29}\,\mathrm{TeV}^8/\Lambda^8$
$\eta \to \pi^+\pi^-\gamma$	$\epsilon_{\alpha\beta\mu\nu}\,\eta(\partial^\nu\pi^+\partial^\rho\partial^\mu\pi^- + \partial^\nu\pi^-\partial^\rho\partial^\mu\pi^+)\partial_\rho F^{\alpha\beta}$	$p^6\,(\delta^2)$	$A_{LR} = 0.009(4)$ [81]	$\lvert A_{LR}\rvert \sim 5\cdot 10^{-16}\,\mathrm{TeV}^4/\Lambda^4$
$\eta' \to \pi^+\pi^-\gamma$	$\epsilon_{\alpha\beta\mu\nu}\,\eta'(\partial^\nu\pi^+\partial^\rho\partial^\mu\pi^- + \partial^\nu\pi^-\partial^\rho\partial^\mu\pi^+)\partial_\rho F^{\alpha\beta}$	$p^6\,(\delta^2)$	$A_{LR} = 0.03(4)$ [81]	$\lvert A_{LR}\rvert \sim 1\cdot 10^{-14}\,\mathrm{TeV}^4/\Lambda^4$
$\eta \to \pi^0\pi^0\gamma$	$\epsilon_{\alpha\beta\mu\nu}\,\eta(\partial^\nu\pi^0\partial^\rho\partial^\mu\pi^0 + \partial^\nu\pi^0\partial^\rho\partial^\mu\pi^0)\partial_\rho F^{\alpha\beta}$	$p^6\,(\delta^3)$	$\mathrm{BR} < 5\cdot 10^{-4}$ [119]	$\mathrm{BR} \sim 1\cdot 10^{-29}\,\mathrm{TeV}^8/\Lambda^8$
$\eta' \to \pi^0\pi^0\gamma$	$\epsilon_{\alpha\beta\mu\nu}\,\eta'(\partial^\nu\pi^0\partial^\rho\partial^\mu\pi^0 + \partial^\nu\pi^0\partial^\rho\partial^\mu\pi^0)\partial_\rho F^{\alpha\beta}$	$p^6\,(\delta^3)$	–	$\mathrm{BR} \sim 2\cdot 10^{-28}\,\mathrm{TeV}^8/\Lambda^8$
$\eta' \to \eta\pi^0\gamma$	$\epsilon_{\alpha\beta\mu\nu}\,\eta'\partial^\mu\eta\partial^\nu\pi^0 F^{\alpha\beta}$	$p^4\,(\delta^3)$	–	$\mathrm{BR} \sim 2\cdot 10^{-28}\,\mathrm{TeV}^8/\Lambda^8$
$\eta' \to \eta\pi^0\pi^0\gamma$	$\eta'\partial_\mu\eta\pi^0\partial_\nu\pi^0 F^{\mu\nu}$	$p^4\,(\delta^2)$	–	$\mathrm{BR} \sim 2\cdot 10^{-32}\,\mathrm{TeV}^8/\Lambda^8$
$\eta \to 3\pi^0\gamma$	$\partial_\mu\eta\partial_\nu\pi^0\partial_\alpha\pi^0\pi^0\partial^\alpha F^{\mu\nu}$	$p^6\,(\delta^3)$	$\mathrm{BR} < 6\cdot 10^{-5}$ [119]	$\mathrm{BR} \sim 1\cdot 10^{-35}\,\mathrm{TeV}^8/\Lambda^8$
$\eta' \to 3\gamma$	$\epsilon^{\mu\nu\rho\sigma}\partial_\alpha\eta'(\partial^\gamma F^{\alpha\beta})(\partial_\gamma\partial_\beta F_{\rho\sigma})F_{\mu\nu}$	$p^{10}\,(\delta^4)$	$\mathrm{BR} < 1\cdot 10^{-4}$ [109]	$\mathrm{BR} \sim 3\cdot 10^{-35}\,\mathrm{TeV}^8/\Lambda^8$

SMEFT and LEFT Operators

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

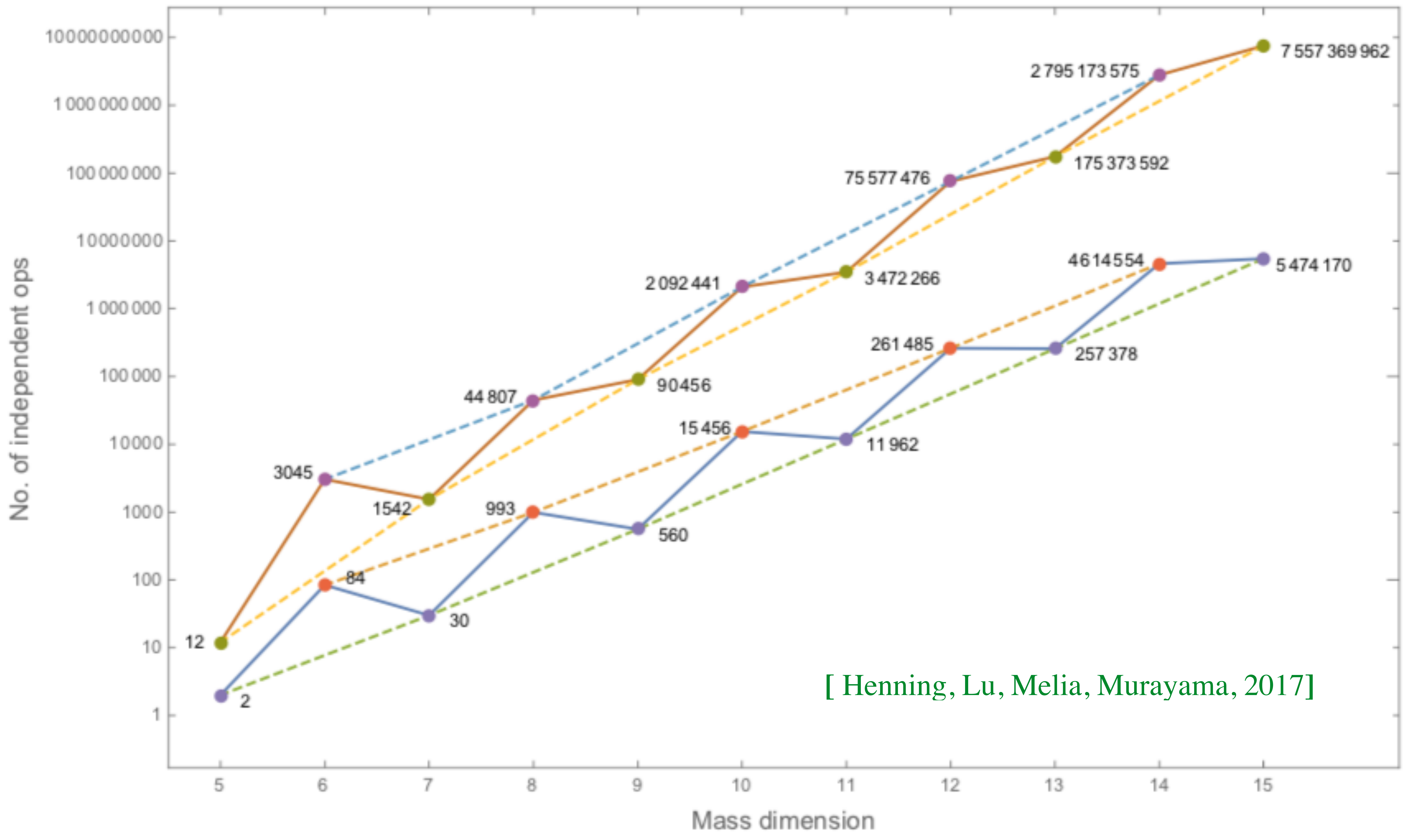
[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2012.09188]

[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]

Moore's Law on EFT Operators

Number of EFT operators grows very fast for higher dim



Derivatives

$BWHH^\dagger D^2$

2

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

30

Which 2 should be picked up?

Repeated fields

$QQQL$

57

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

324

What flavor relations should be imposed?

Jiang-Hao Yu (ITP-CAS)

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	Building blocks in spinor-helicity form
ϕ	$\phi \in (0,0)$		$D^{r_i}\phi_i \Leftrightarrow \lambda_i^{r_i}\tilde{\lambda}^{i,r_i}$,
ψ	$\psi_\alpha \in (1/2,0)$ $\psi^\dagger_{\dot\alpha} \in (0,1/2)$,	λ_α	$D^{r_i-1/2}\psi_i^{(\dagger)} \Leftrightarrow \lambda_i^{r_i\pm 1/2}\tilde{\lambda}^{i,r_i\mp 1/2}$,
$F_{\mu\nu}$	$F_{L\alpha\beta} = \frac{i}{2}F_{\mu\nu}\sigma^{\mu\nu}_{\alpha\beta} \in (1,0)$ $F_{R\dot\alpha\dot\beta} = -\frac{i}{2}F_{\mu\nu}\bar\sigma^{\mu\nu}_{\dot\alpha\dot\beta} \in (0,1)$.	$\lambda_\alpha\lambda_\beta$	$D^{r_i-1}F_{L/R\,i} \Leftrightarrow \lambda_i^{r_i\pm 1}\tilde{\lambda}^{i,r_i\mp 1}$,
$R_{\mu\nu\rho\sigma}$	$C_{\alpha\beta\gamma\delta} = C_{\mu\nu\rho\sigma}\sigma^{\mu\nu}_{\alpha\beta}\sigma^{\rho\sigma}_{\gamma\delta} \in (2,0)$	$\lambda_\alpha\lambda_\beta\lambda_\gamma\lambda_\delta$	$D^{r_i-2}C_{L/R\,i} \Leftrightarrow \lambda_i^{r_i\pm 2}\tilde{\lambda}^{i,r_i\mp 2}$,
D_μ	$D_{\alpha\dot\alpha} = D_\mu\sigma^\mu_{\alpha\dot\alpha} \in (1/2,1/2)$.	$\lambda_\alpha\tilde\lambda_{\dot\alpha}$	

On-shell operator

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

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

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

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

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

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

On-shell Brackets

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

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

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**

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

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

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

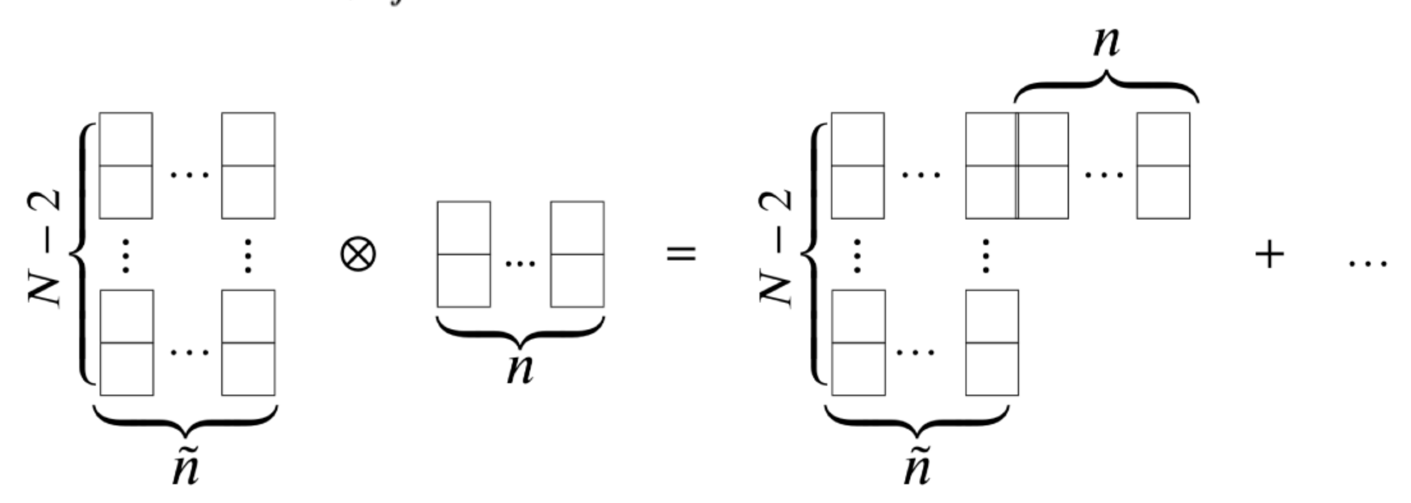
$$D_{[\alpha\dot{\alpha}}F_{\mathrm{L}\beta]\gamma} = \frac{i}{2}D_\mu F_{\mathrm{L}\nu\rho}\sigma^\mu_{[\alpha\dot{\alpha}}\sigma^{\nu\rho}_{\beta]\gamma} = iD^\mu F_{\mathrm{L}\mu\nu}\epsilon_{\alpha\beta}\sigma^\nu_{\gamma\dot{\alpha}},$$

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

SL(2,C) x SU(N)

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

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

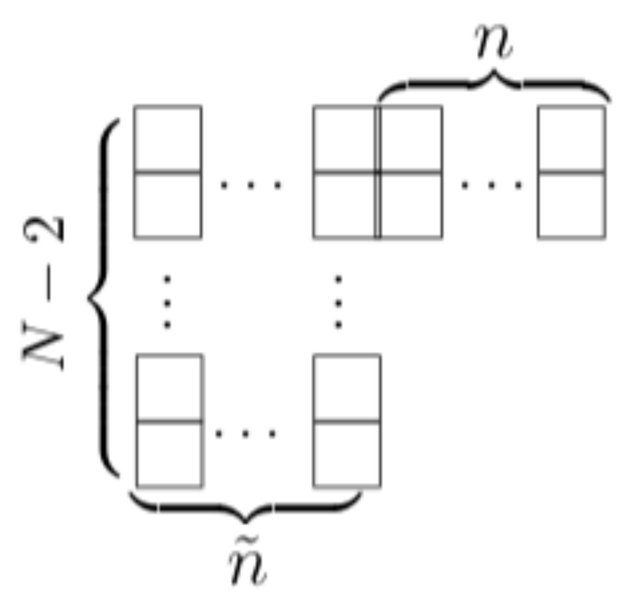


Momentum conservation

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

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

SSYT



$$\begin{array}{|c|}\hline i\\\hline j\\\hline\end{array} \Leftrightarrow \langle ij\rangle$$

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

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

→ **On-shell Amplitude**

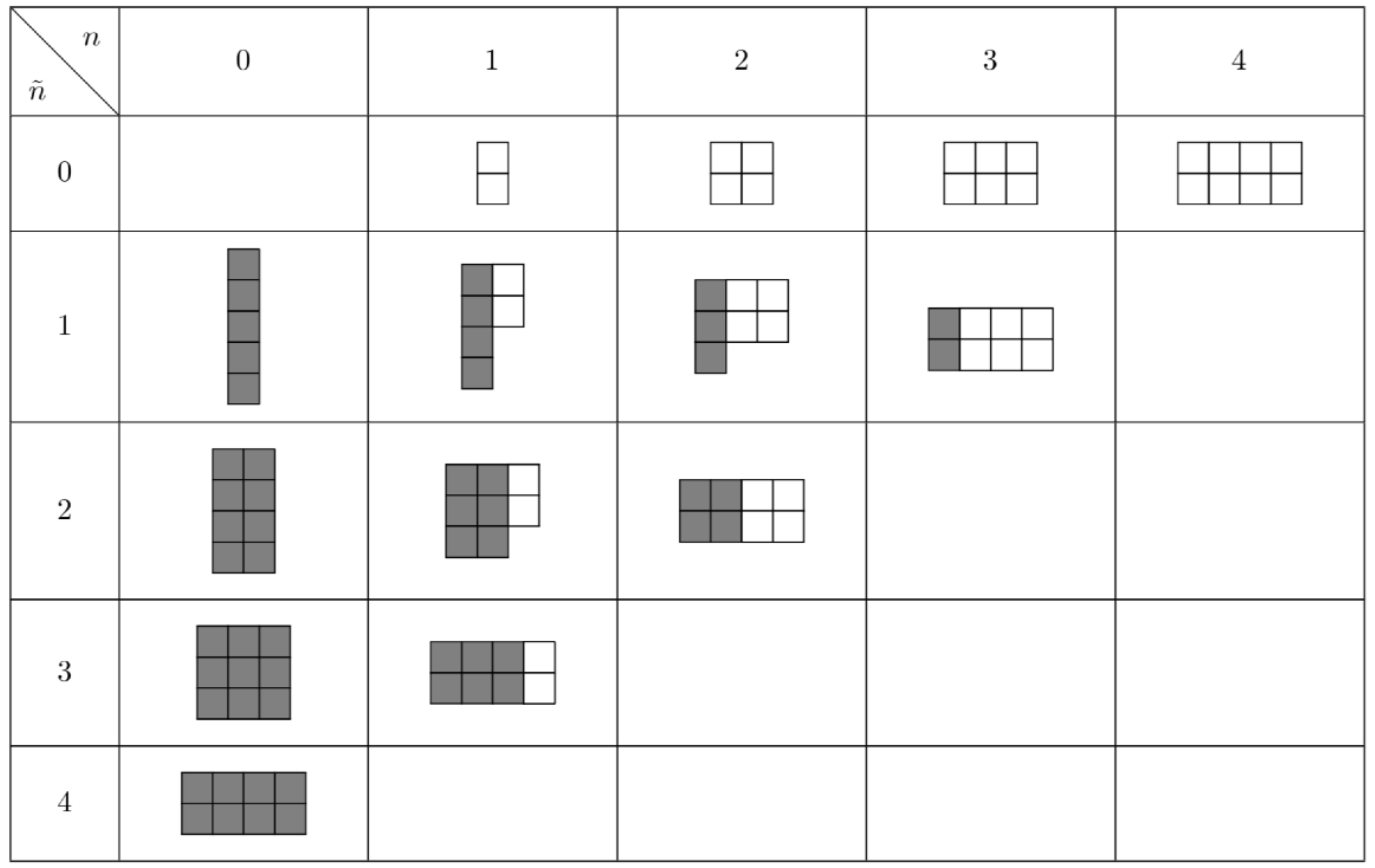
1 1 1 2	2 3 3 4	$\langle 13\rangle\langle 13\rangle\langle 24\rangle[34]$	$F_{\mathrm{L}1}^{\alpha\beta}\psi_2^{\gamma}(D\psi_3)_{\alpha\beta\dot{\alpha}}(D\phi_4)_{\gamma}{}^{\dot{\alpha}}$		
1 1 1 3	2 2 3 4	$\langle 12\rangle\langle 13\rangle\langle 34\rangle[34]$	$F_{\mathrm{L}1}^{\alpha\beta}\psi_{2\alpha}(D\psi_3)_\beta{}^\gamma{}_{\dot{\alpha}}(D\phi_4)_\gamma{}^{\dot{\alpha}}$		

On-shell Amplitude correspondence

Procedure and Comparison

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

Step-1



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

Step-2

$BWHH^\dagger D^2$ $\quad \#1 = 3, \#2 = 3, \#3 = 1, \#4 = 1$

Step-3

1	1	1	3
2	2	2	4

1	1	1	2
2	2	3	4

2

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

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

Traditional method

[Hays, Martin, Sanz, Setford, 2018]

$BWHH^\dagger D^2$

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

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

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

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]

Classifying Operators by CP

Parity and charge conjugation are the outer automorphism of the Lorentz and internal symmetry

$$SO(4) \rtimes \{1, \mathcal{P}\} = O(4) = SO(4) \sqcup O_-(4)$$

$$I \rtimes \{1, \mathcal{C}\} = I \sqcup I_-.$$

Hilbert series

$$\mathcal{H}^{C^\pm P^\pm}(D,\phi) \equiv \int_G d\mu(g) \left(\sum_{C^\pm P^\pm} \frac{\mathrm{PE}(\phi \chi_{R_\phi}(D, g_{\{C^\pm P^\pm\}}))}{P(D, g_{\{C^\pm P^\pm\}}))} \right)$$

CP-odd

Rephasing

$$U(3)^5 = U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_e$$

Yukawa

$$U(1)_B \quad U(1)_e \times U(1)_\mu \times U(1)_\tau$$

SU(2) Theta

$$U(1)_{B-L} \times U(1)_{\mu-e} \times U(1)_{\tau-\mu}$$

Group Branch	$SO(4)$		$O_-(4)$
integral variable	$a_+ = a = (a_1, a_2)$		$a_- = a_1$
reparametrization	$\bar{a}_+ = a$		$\bar{a}_- = (a_1, 1)$
Haar measure	$d\mu_{SO(4)}(a)$		$d\mu_{Sp(2)}(a_-)$
Group Branch	$U(1)$		$U_-(1)$
integral variable	$x_+ = x$		$x_- = x$
reparametrization	$\bar{x}_+ = x$		$\bar{x}_- = x$
Haar measure	$d\mu_{U(1)}(x)$		$d\mu_{U(1)}(x)$
Group Branch	$SU(2)$		$SU_-(2)$
integral variable	$y_+ = y$		$y_- = y$
reparametrization	$\bar{y}_+ = y$		$\bar{y}_- = y$
Haar measure	$d\mu_{SU(2)}(y)$		$d\mu_{SU(2)}(y)$
Group Branch	$SU(N)$	$SU_-(N=2k)$	$SU_-(N=2k+1)$
integral variable	$z = (z_1, ..., z_N)$	$z_- = (z_1, ..., z_k)$	$z_- = (z_1, ..., z_k)$
reparametrization	$\bar{z}_+ = z$	$\bar{z}_- = (\sqrt{z_1}, ..., \sqrt{z_k}, 1/\sqrt{z_k}, ..., 1/\sqrt{z_1})$	$\bar{z}_- = (\sqrt{z_1}, ..., \sqrt{z_k}, 1, 1/\sqrt{z_k}, ..., 1/\sqrt{z_1})$
Haar measure	$d\mu_{SU(N)}(z)$	$d\mu_{SO(2k+1)}(z_-)$	$d\mu_{Sp(2k)}(z_-)$

[Hao Sun, Yi-Ning Wang, **J.H.Yu**, 2211.11598]

[Kondo, Murayama, Okabe, 2212.02413]

Results

N_f	Dimension=	5	6	7	8
1	CP-odd	1	27	15	430
1	CP-violating	0	23	0	381
3	CP-odd	6	1422	771	22016
3	CP-violating	0	705	0	11777

CP Invariants

Build the CP invariant from building blocks from Young tensor method above

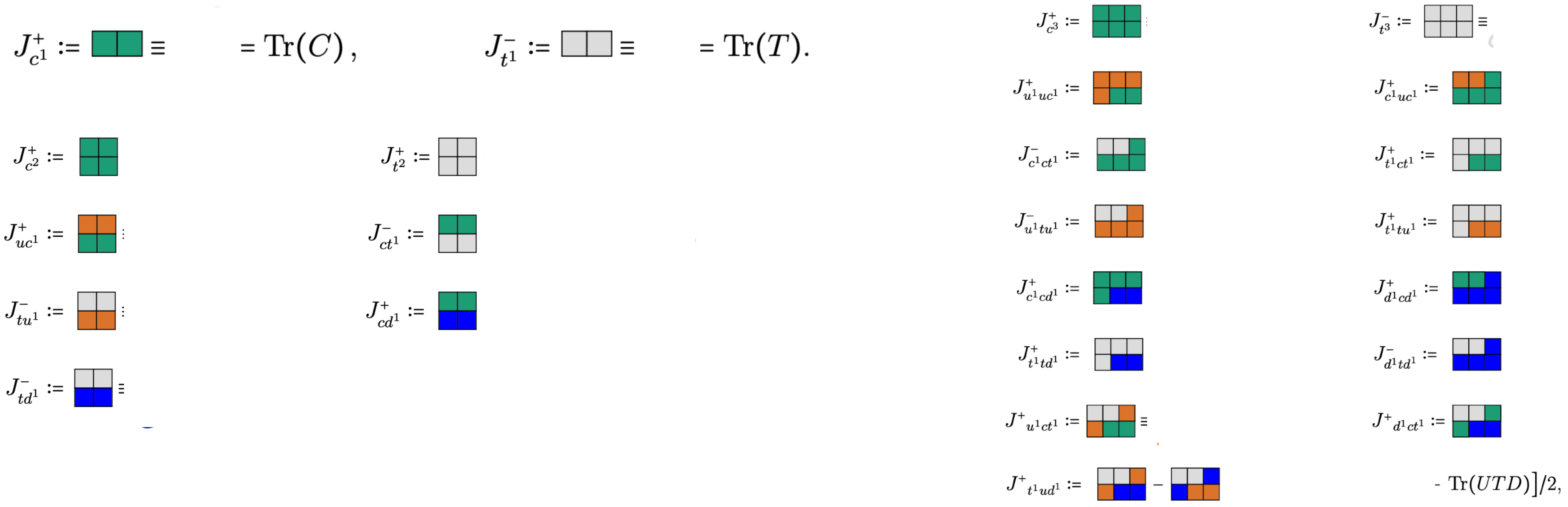
$$\mathcal{L} \supset Y_u \overline{Q}_{\mathrm{L},i} \widetilde{H}\, u_{\mathrm{R},j} + \frac{C^{(2n)}_{HQu}}{\Lambda^{2n-4}} |H|^{2n-4} \overline{Q}_{\mathrm{L},i} \widetilde{H}\, u_{\mathrm{R},j} + Y_d \overline{Q}_{\mathrm{L},i}\, H\, d_{\mathrm{R},j} + \mathrm{h.c.}$$

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

Building blocks $U \equiv Y_u Y_u^\dagger$ and $D \equiv Y_d Y_d^\dagger$ $\quad C_u = C^{(2n)} Y_u^\dagger$ and $C_u^\dagger = Y_u C^{(2n)\dagger}$

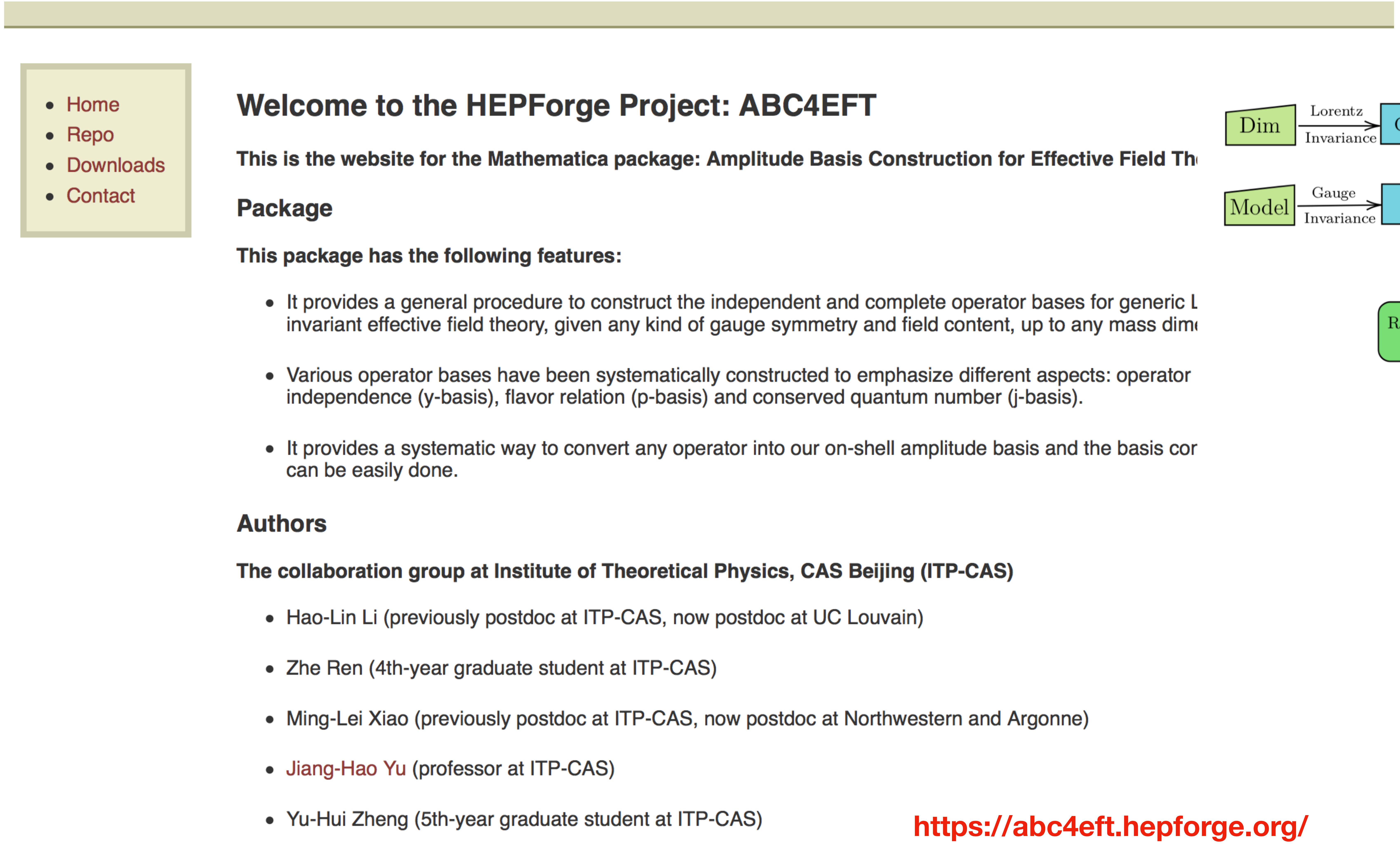
$$U \to U(3)_Q\, U\, U(3)_Q^\dagger, \qquad D \to U(3)_Q\, D\, U(3)_Q^\dagger$$

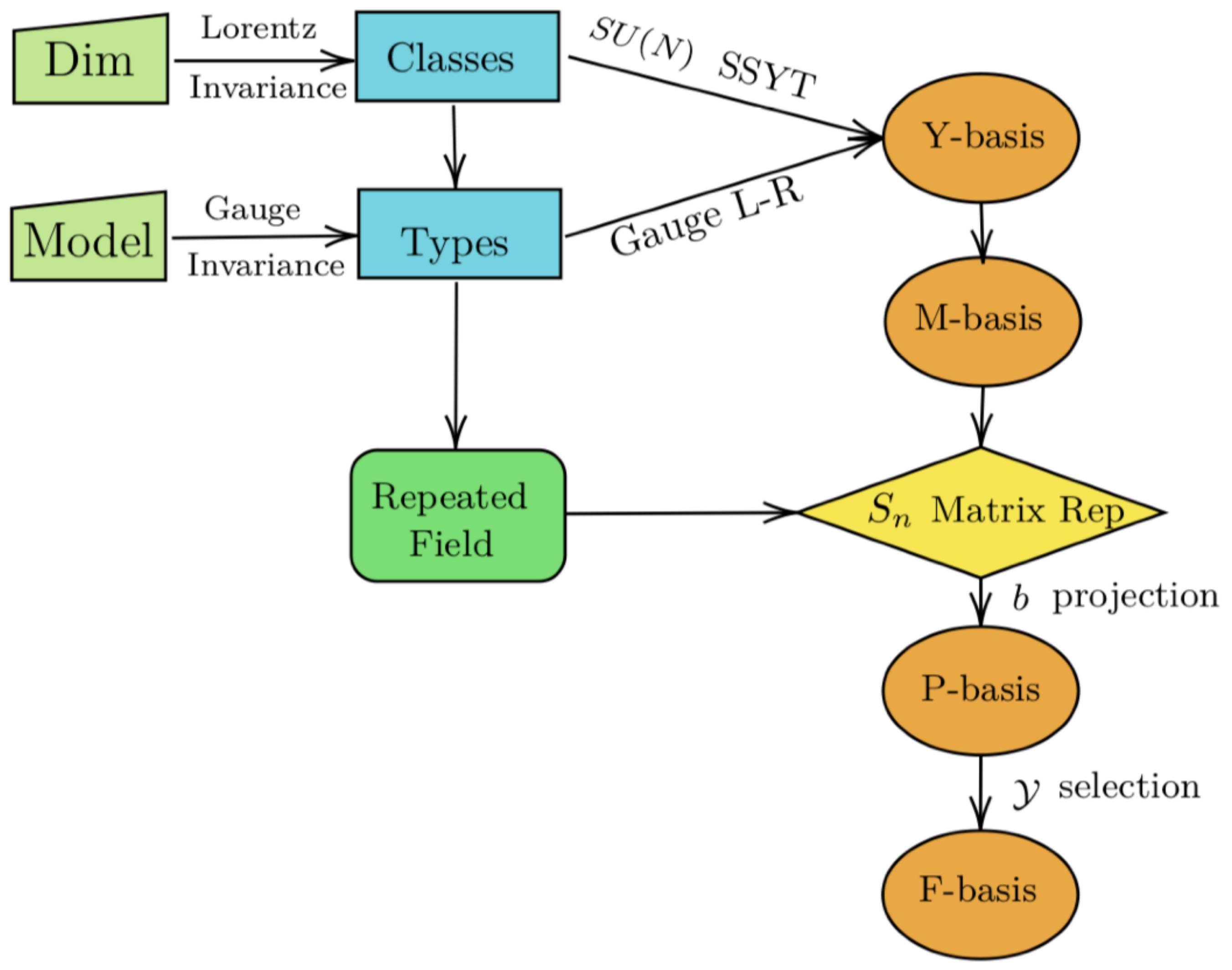
$$C = \frac{C_u + C_u^\dagger}{2}, \qquad T = \frac{C_u - C_u^\dagger}{2}.$$



Operator Bases for Generic EFT up to All Order

Amplitude Basis Construction for Effective Field Theory [Li, Ren, Xiao, **Yu**, Zheng, 2201.04639]





https://abc4eft.hepforge.org/

Fully Automatic

Dark matter EFT
Sterile neutrino EFT
Gravity EFT
Axion EFT
...

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

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

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

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

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

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

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

Power counting: Derivative expansion

Coset Construction

[Callan, Coleman, Wess, Zumino, 1969]

CCWZ Chiral Lagrangian

Define the nonlinear Goldstone matrix

[Callan, Coleman, Wess, Zumino, 1969]

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

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

CCWZ Coset

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

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

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

Building block

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

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

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

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

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

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

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)

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

$$\{-1/2, -1/2, 1, 0, 0\} \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&4\\\hline 2&2&2&5\\\hline 4&5\\\cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\\hline 2&2&5&5\\\hline 4&4\\\cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\\hline 2&2&4&4\\\hline 5&5\\\cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\\hline 2&2&4&5\\\hline 4&5\\\cline{1-2}\end{array},$$

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

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

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]

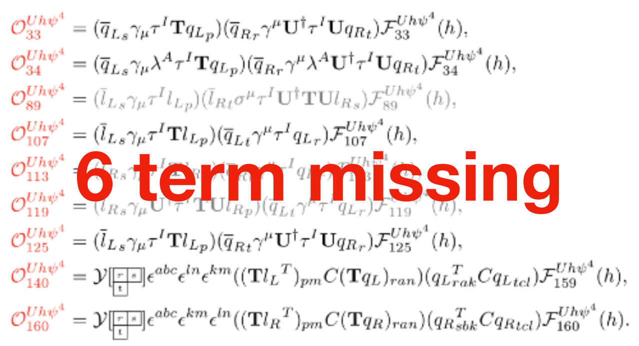
EW Chiral Lagrangian = HEFT

LO Lagrangian [Weinberg, 1979]

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

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

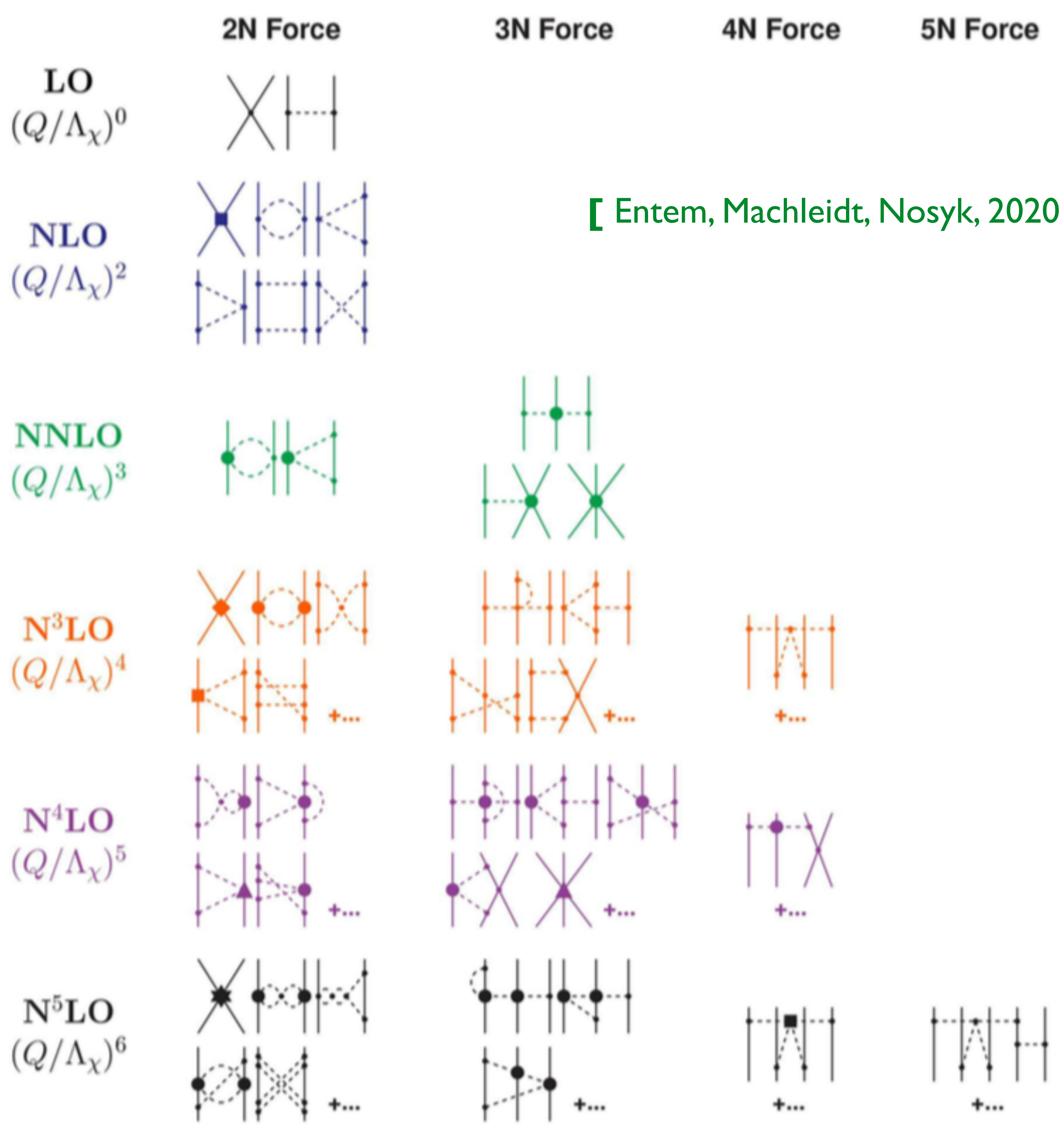
NLO 4-fermion
- [Buchalla, Cata, Krause, 2014]
- [Pich, Rosell, Santos, Sanz-Cillero, 2015, 2018]
- [Sun, Xiao, **Yu**, 2206.07722]



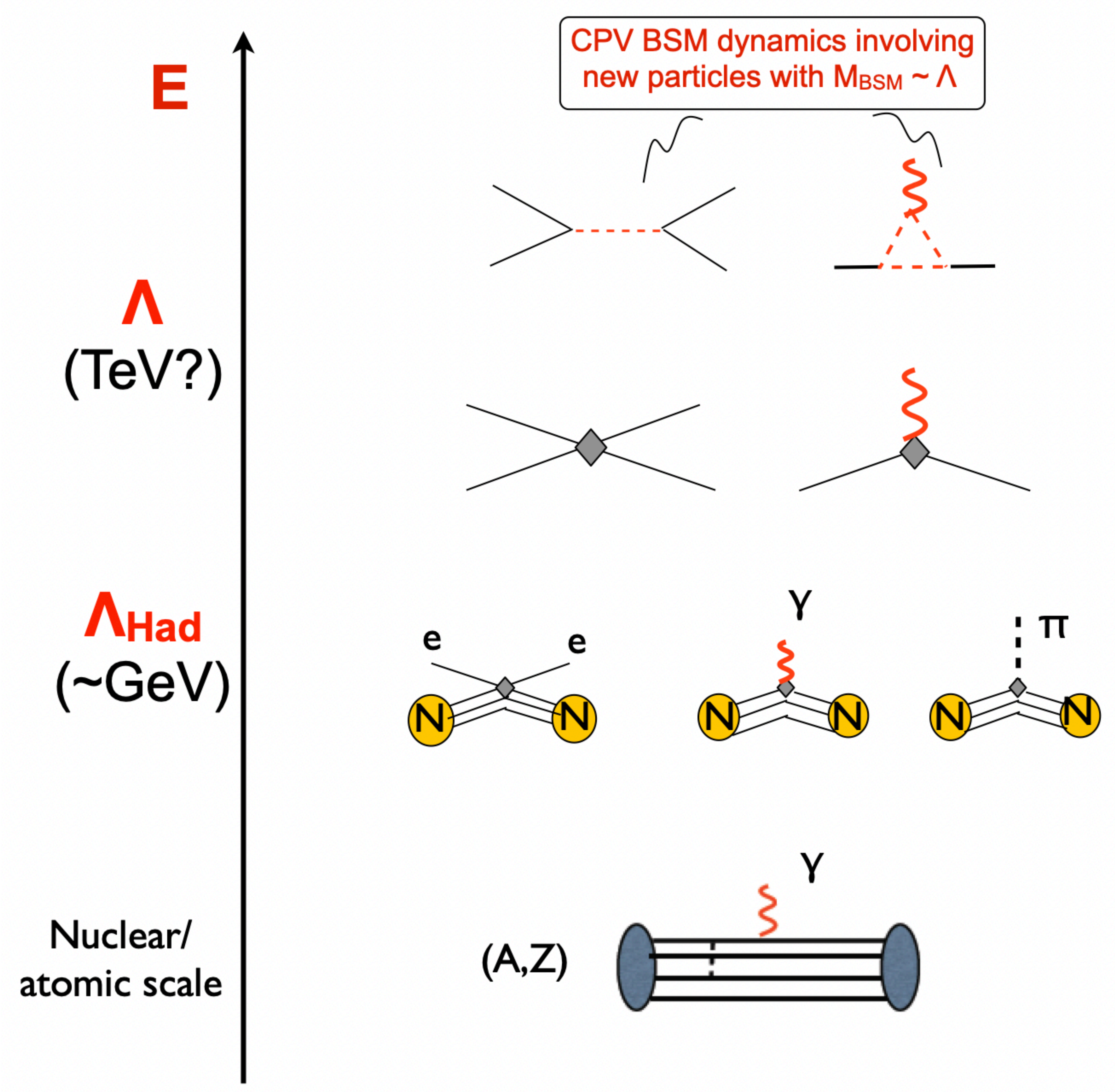
NNLO Basis [Sun, Xiao, **Yu**, 2210.14939]

Why Higher Order Chiral Lagrangian?

Ab initio nuclear force



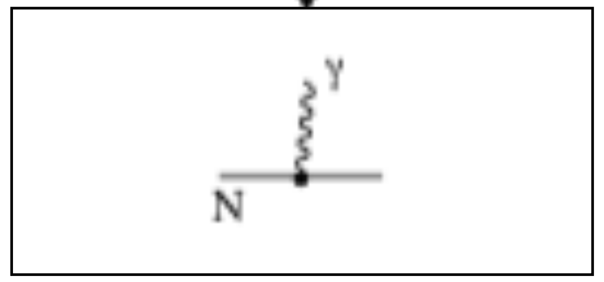
[Entem, Machleidt, Nosyk, 2020]

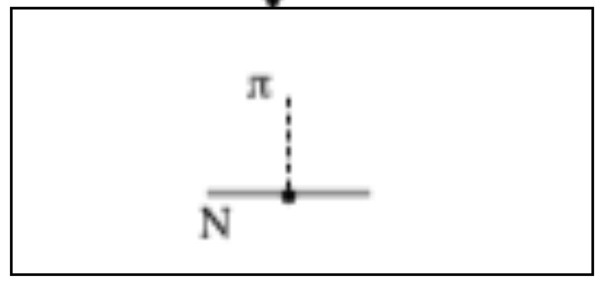


Chiral Nuclear Force

Meson Exchange Model

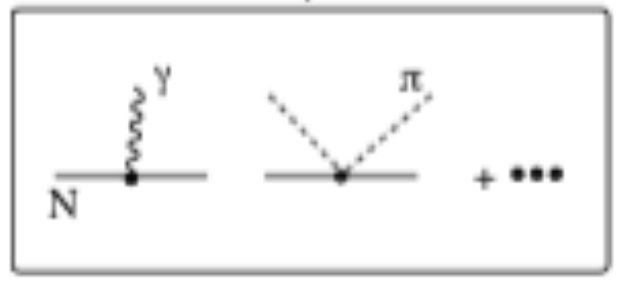
$$\mathcal{L}_\sigma = \overline{N_L}\, i\not{D}\, N_L + \overline{N_R}\, i\not{D}\, N_R - g\overline{N_R}\,\Sigma\, N_L - g\overline{N_L}\,\Sigma^\dagger\, N_R$$

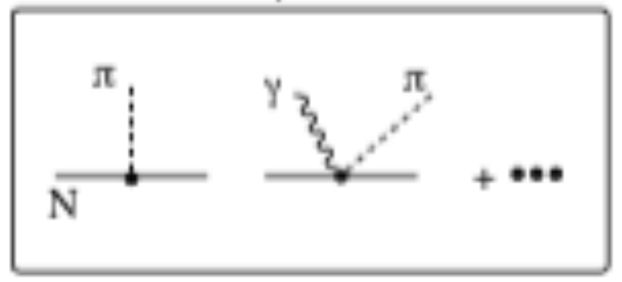




Chiral EFT

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

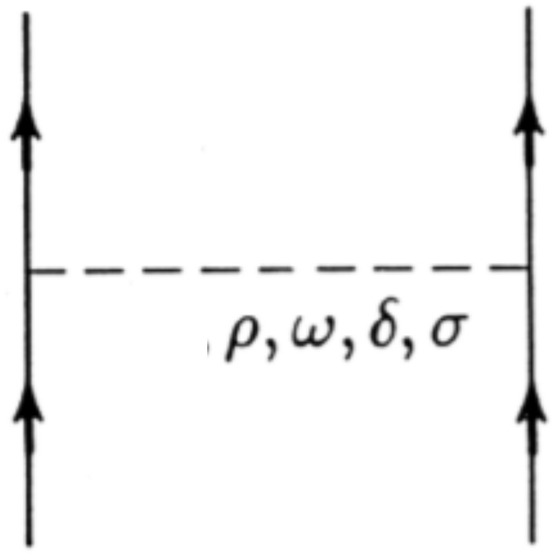


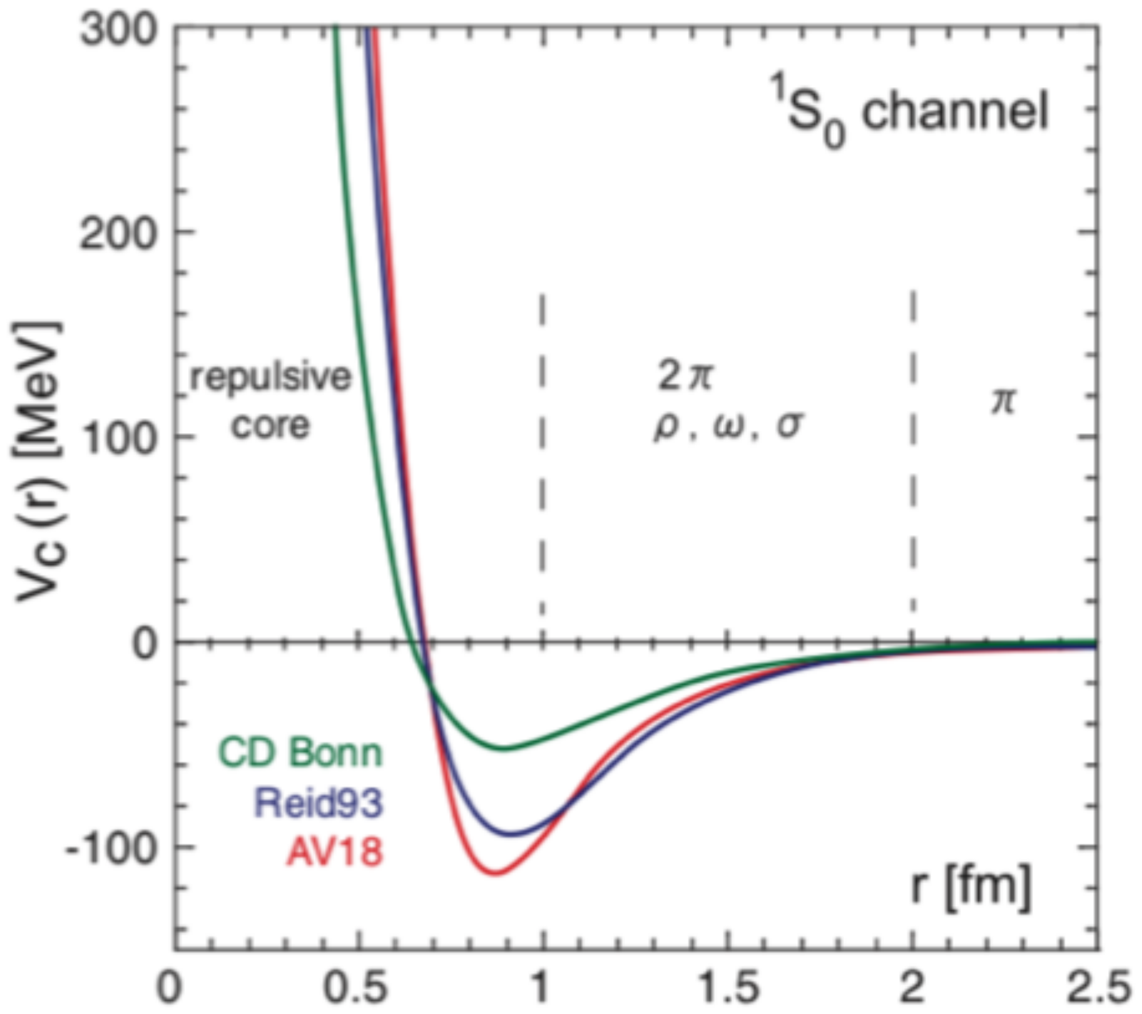


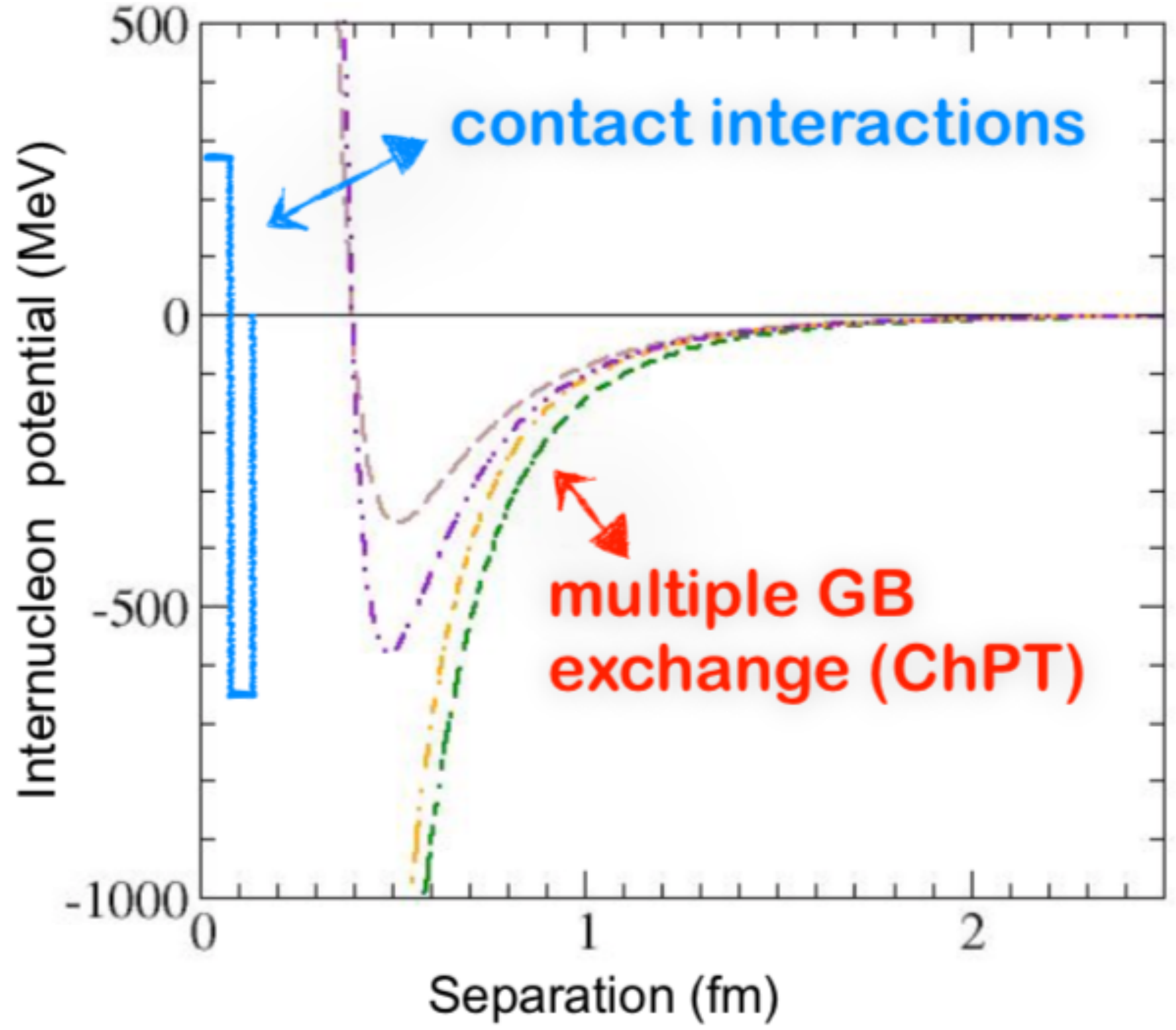
$$M_N g_A(0) = F_\pi\, g_{\pi NN}$$

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

Goldberger-Treiman Relation





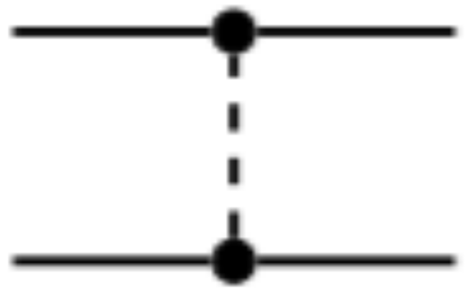


$$\mathcal{L} = N^\dagger\left(i\partial_0 + \frac{\vec{\nabla}^2}{2m_N}\right)N - \frac{1}{2}C_S(N^\dagger N)^2 - \frac{1}{2}C_T(N^\dagger\vec{\sigma}N)^2 + \underbrace{\ldots}_{\text{terms with} \geq 2 \text{ derivatives}}$$

Chiral effective field theory

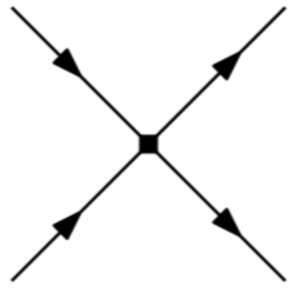
Weinberg power counting $\mu = 2 + 2\ell - r + \sum_i V_i\left(d_i + \frac{1}{2}n_i - 2\right)$

[Weinberg, 1990]



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

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

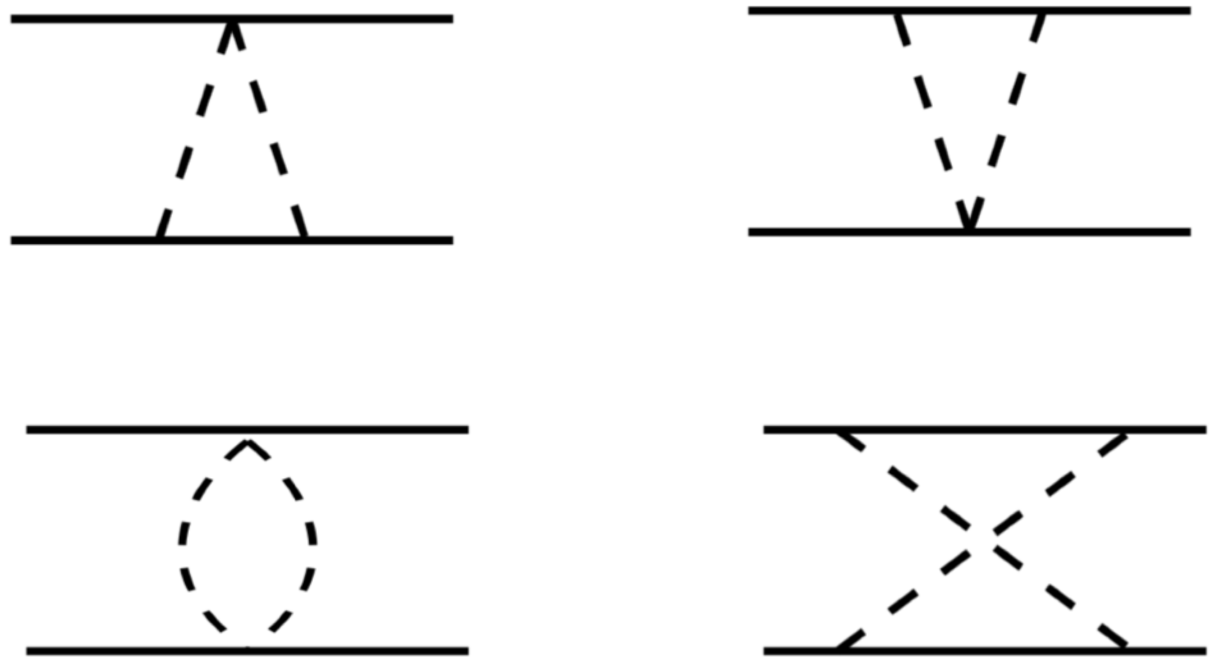


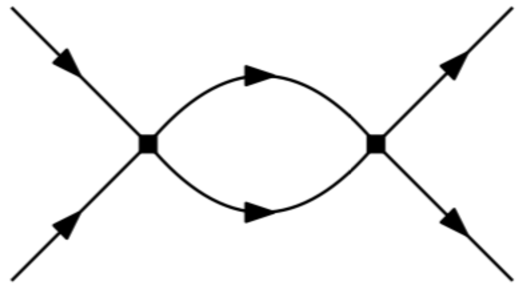
= (0-2+4/2) = 0

$-C_0$

Irreducible

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

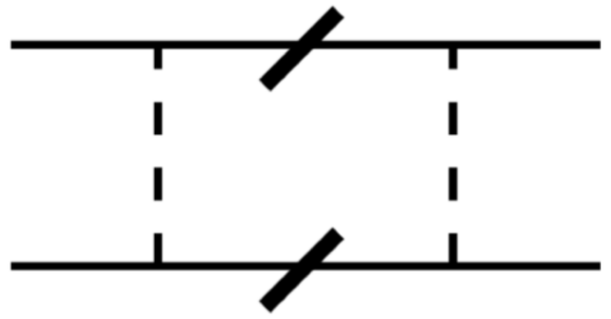




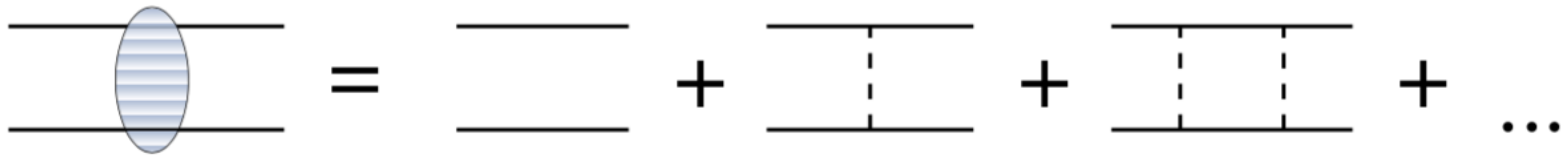
Pinch singularity

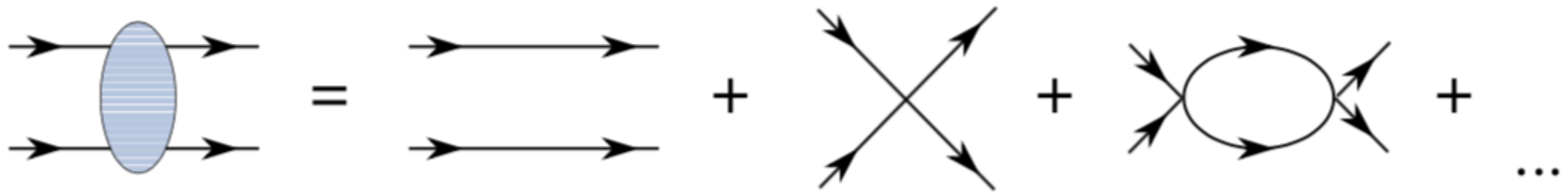
$$\frac{Q^5}{4\pi M} \times C_0\left(\frac{M}{Q^2}\right)\left(\frac{M}{Q^2}\right)C_0 \sim C_0^2\frac{MQ}{4\pi}$$

Reducible 2PI



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





Unnatural scattering length

Chiral EFT operators

- **Weinberg:** $C_0^{\mathrm{R}} \sim \mathcal{O}(1)$ $\quad V^{\mathrm{LO}}_{\mathrm{Weinberg}} \sim \mathcal{O}(1)$, $\quad V^{\mathrm{NLO}}_{\mathrm{Weinberg}} \sim \mathcal{O}(p^2)$

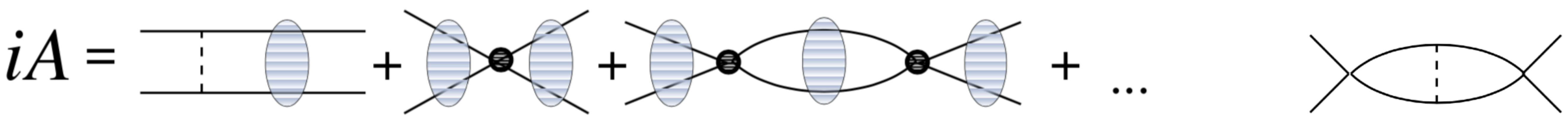
  $\mu \sim \mathcal{O}(1)$ $\quad C_2^{\mathrm{R}} \sim \mathcal{O}(1)$ $\quad$ [i.e. scaling of C_{2n} according to NDA (~ O(1))]

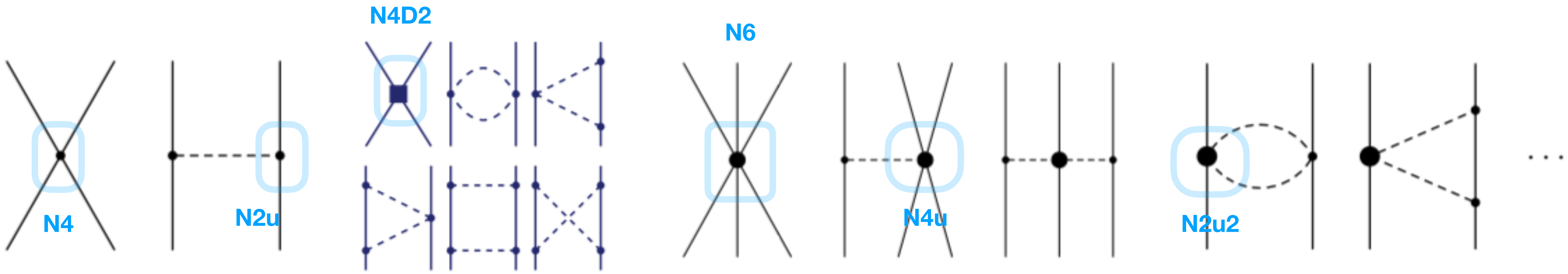
  [Weinberg, 1990]

- **KSW:** $C_0^{\mathrm{R}} \sim \mathcal{O}(p^{-1})$ $\quad V^{\mathrm{LO}}_{\mathrm{KSW}} \sim \mathcal{O}(p^{-1})$, $\quad V^{\mathrm{NLO}}_{\mathrm{KSW}} \sim \mathcal{O}(1)$

  $\mu \sim \mathcal{O}(p)$ $\quad C_2^{\mathrm{R}} \sim \mathcal{O}(p^{-2})$ $\quad$ [i.e. scaling of C_{2n} as $C_{2n} \sim O(p^{-1-n})$]

  [Kaplan, Savage, Wise, 1998]





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

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

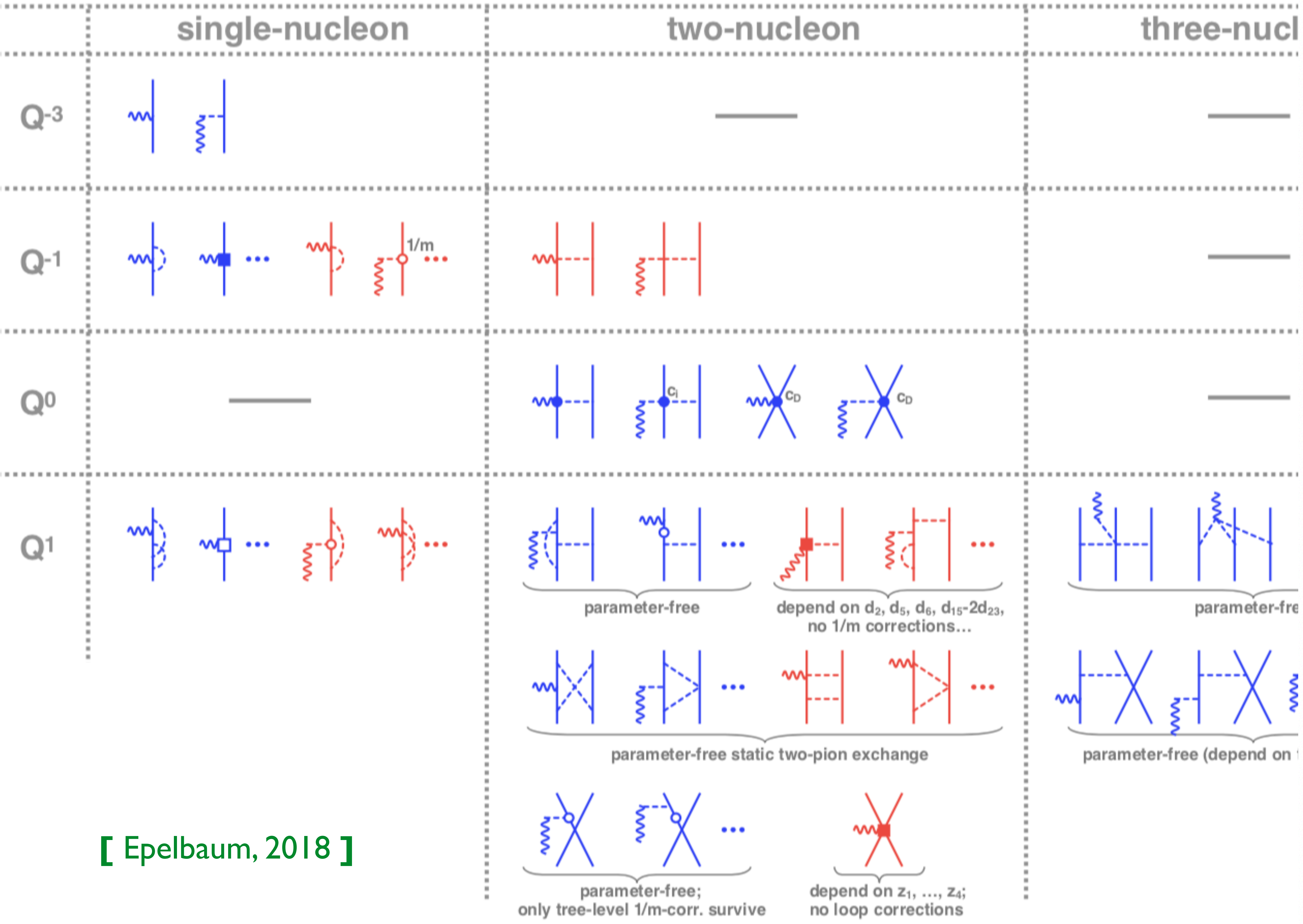
[Petschauer, Kaiser, 2013]

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

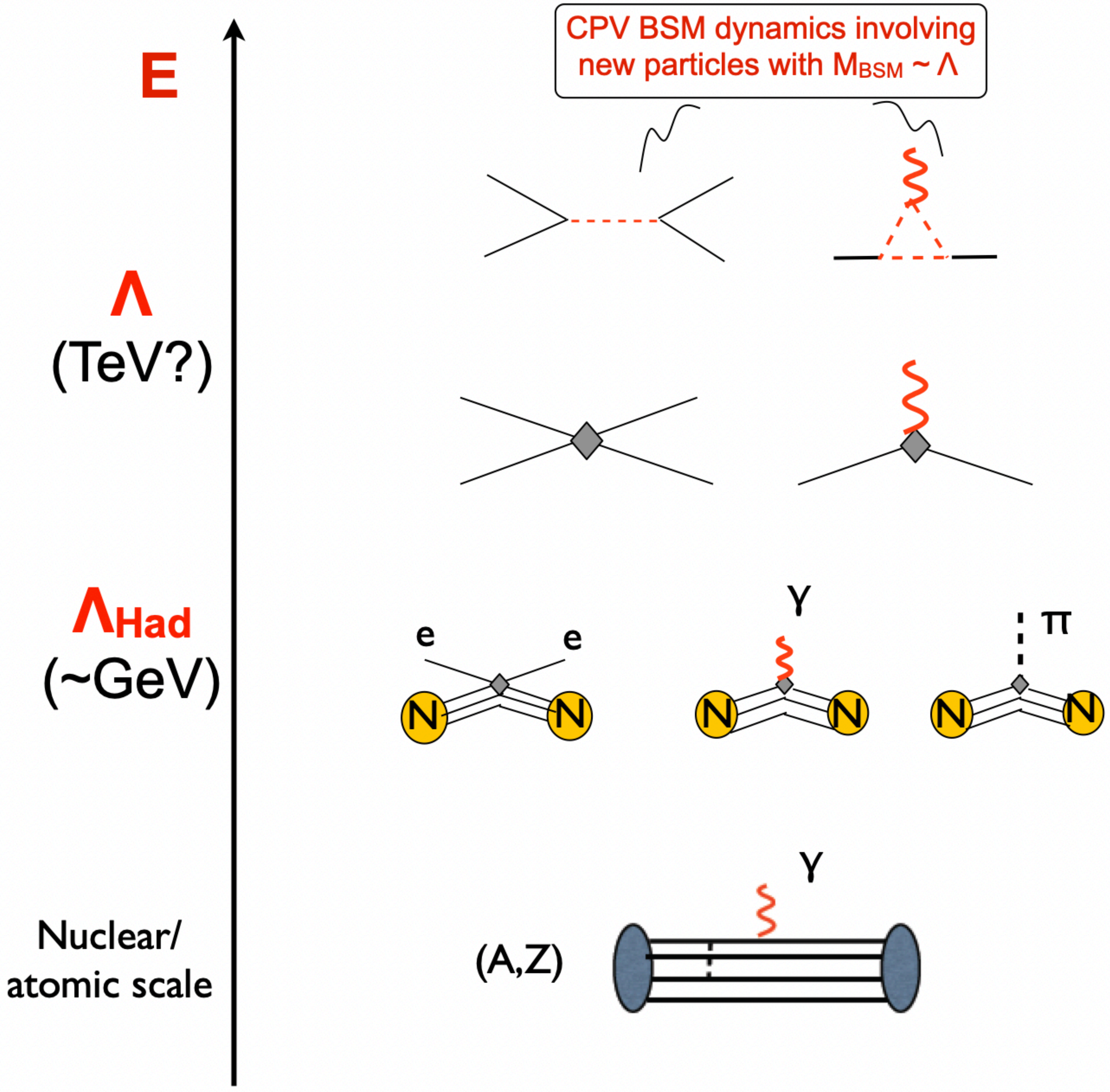
[Sun, Wang, **Yu**, in préparation]

Nuclear Weak Currents

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



[Epelbaum, 2018]



UV Completion of EFT Operators

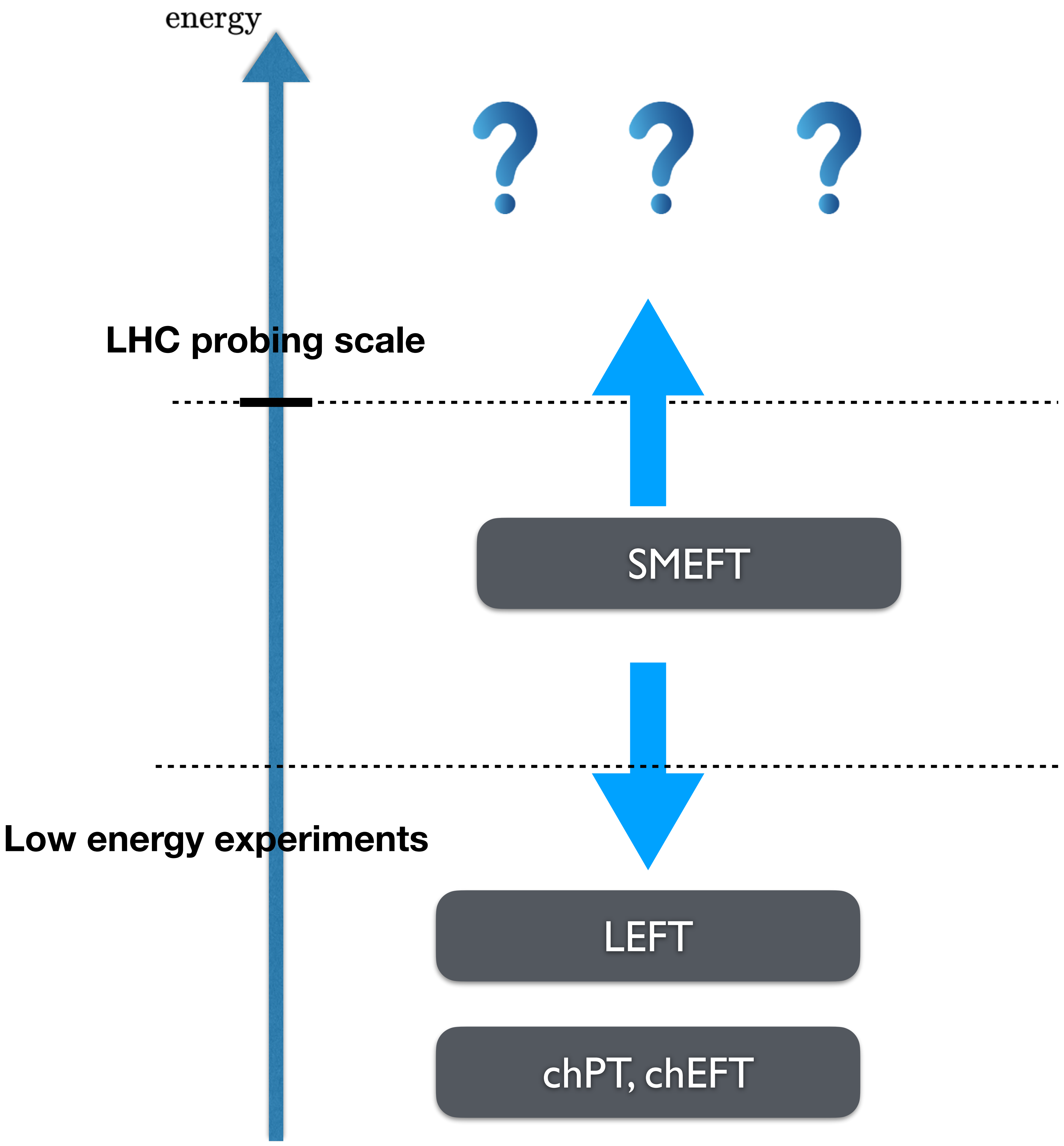
[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2204.03660]

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

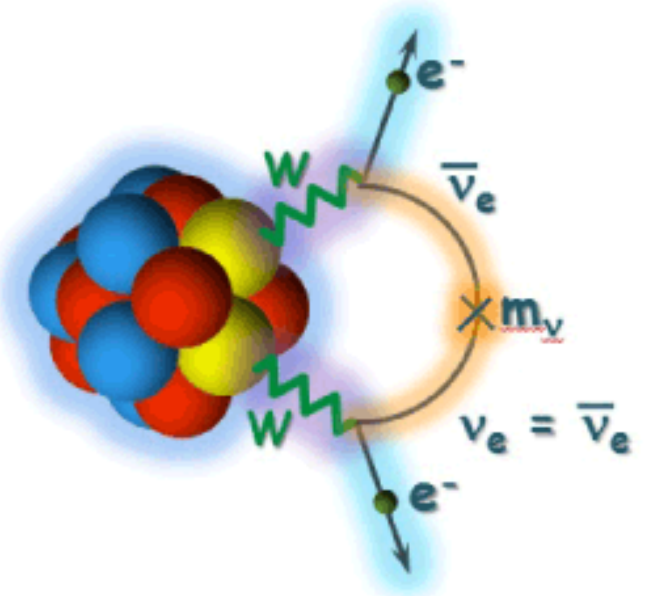
[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, in preparation]

EFT Inverse Problem

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

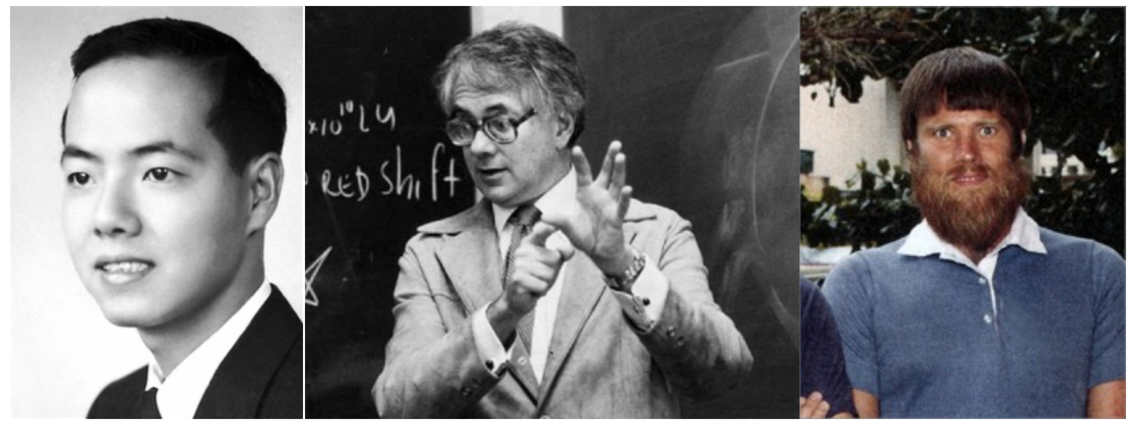


$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \dots$$



Lesson from Four-fermion EFT

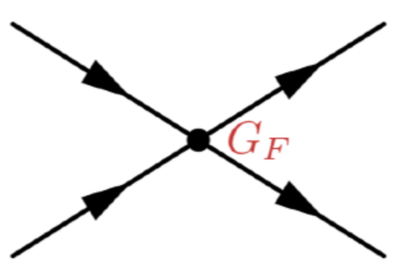
Glashow-Weinberg-Salam
1961 1967



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 β decay, the most general form of Hamiltonian can be written as

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

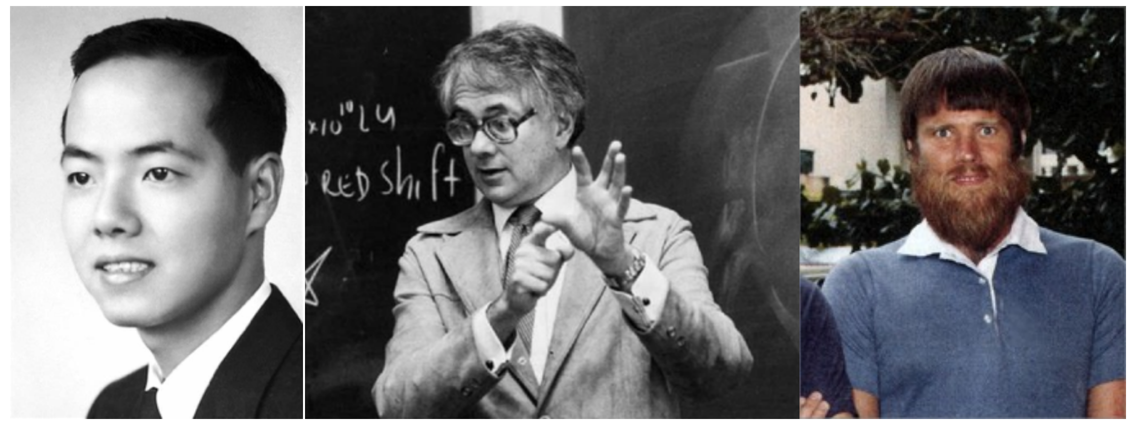
LEFT

Lesson from Four-fermion EFT

Nobel prize
1979

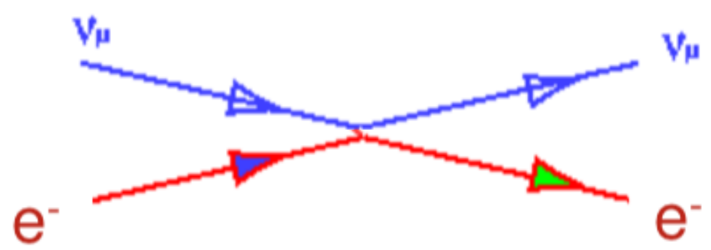
Nobel Prize before W/Z discovery

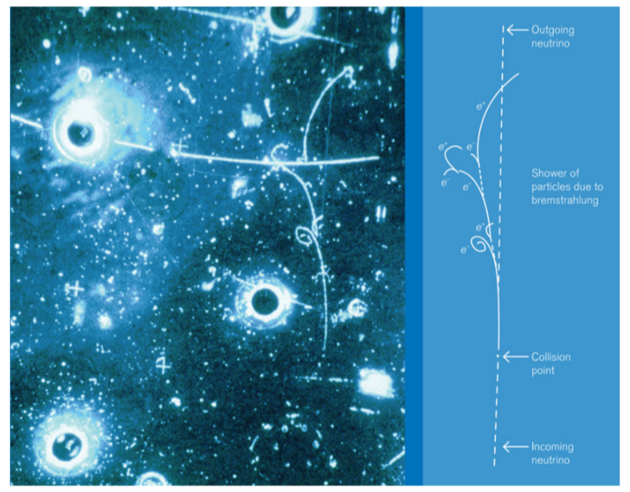
Glashow-Weinberg-Salam
1961 1967



Lee-Georgi-Glashow
1960 1972

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





CERN Bubble Chamber
1973

Effective interaction detected!

V-A

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

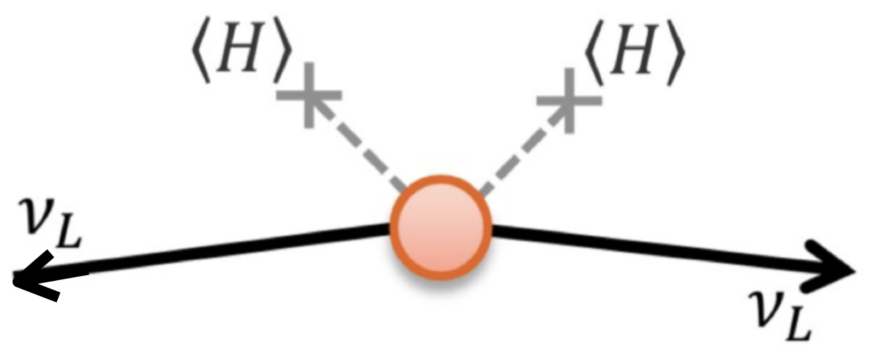
$$
\begin{aligned}
H_{\text{int}} = & (\psi_p^\dagger\gamma_4\psi_n)(C_S\psi_e^\dagger\gamma_4\psi_\nu + C_S'\psi_e^\dagger\gamma_4\gamma_5\psi_\nu) \\
& + (\psi_p^\dagger\gamma_4\gamma_\mu\psi_n)(C_V\psi_e^\dagger\gamma_4\gamma_\mu\psi_\nu + C_V'\psi_e^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu) \\
&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

LEFT

Similar Story: Neutrino Masses

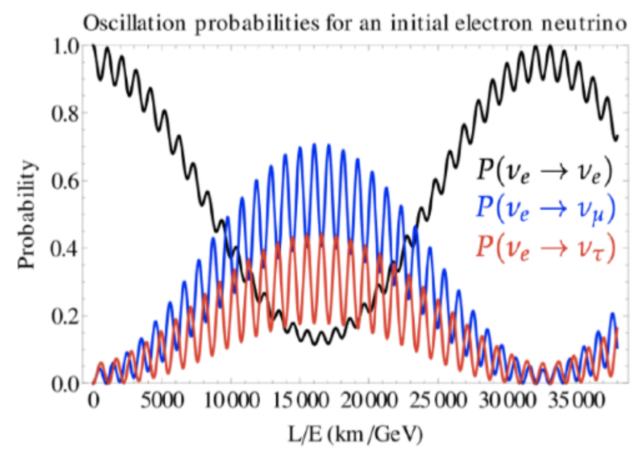
The existence of neutrino masses is the first evidence of new physics beyond standard model

?



SMEFT

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



LEFT

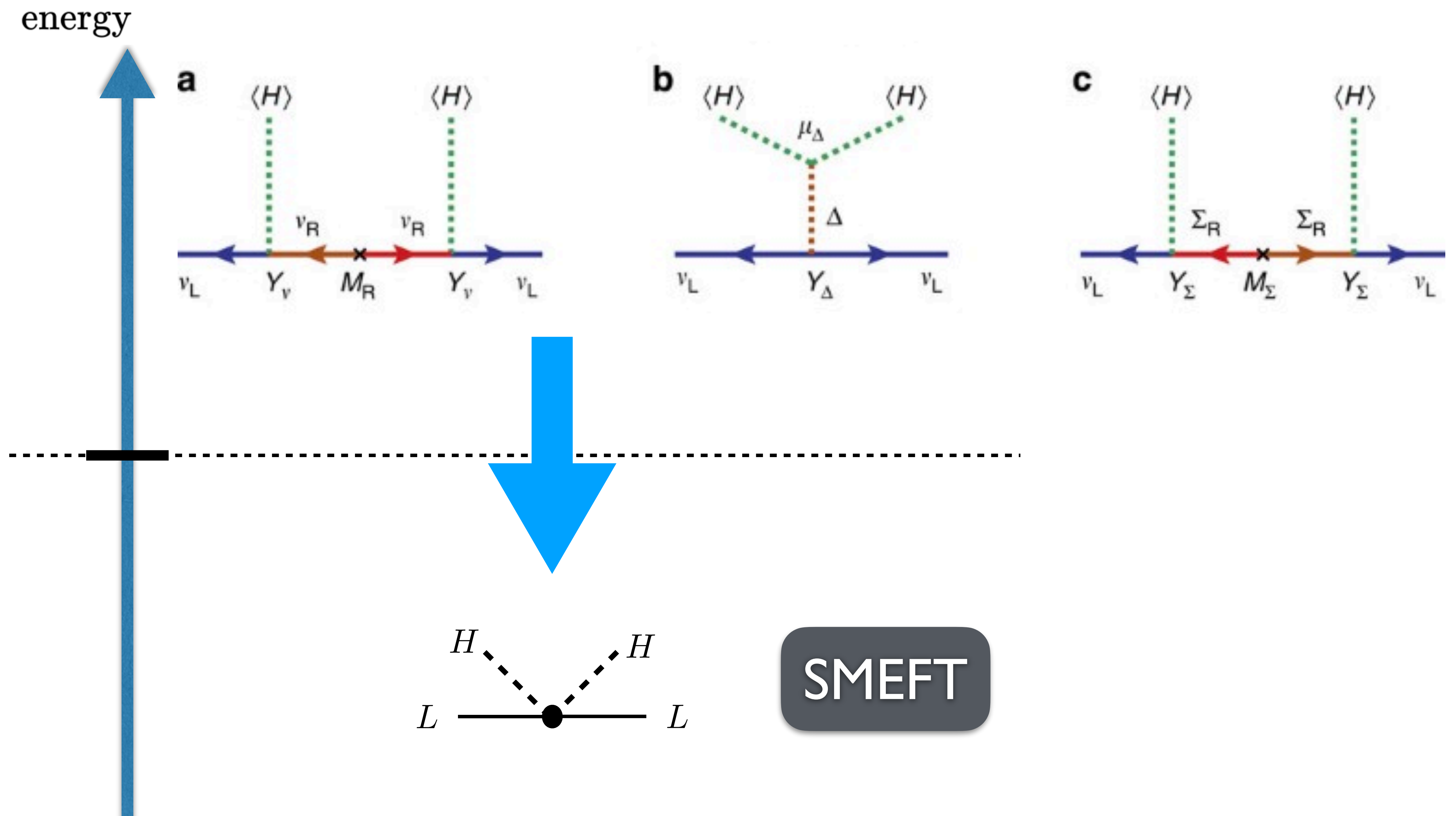
Seesaw Tree UVs

Top-down Approach

[Yanagida 1979, Gell-Mann, Ramond, Slansky1979, Mahapatra, Senjanovic, 1980]

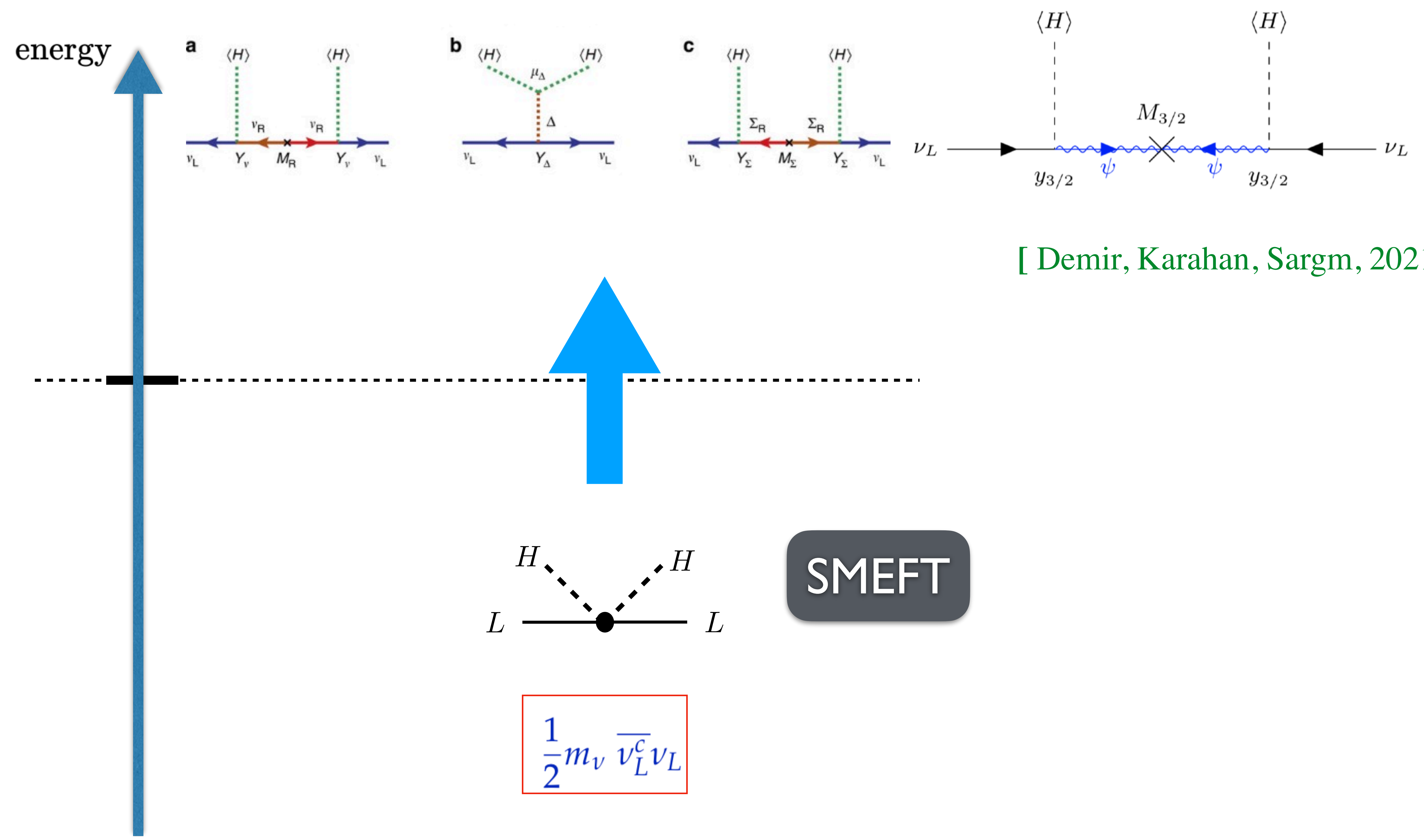
[Schecheter, Walle, 1980, Cheng, Li 1980, Magg and Wetterich 1980]

[Foot, Lew, He, Joshi 1989]



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

Bottom-up Approach



[Demir, Karahan, Sargm, 2021]

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

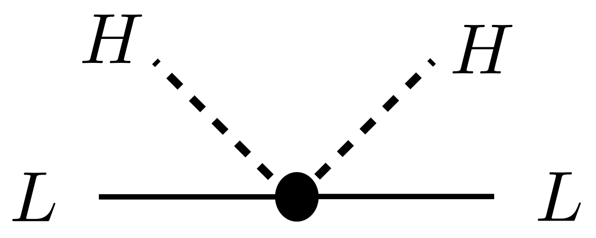
Consider Angular momentum conservation

Pauli-Lubanski Casimir

Weinberg operator as on-shell amplitude

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

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



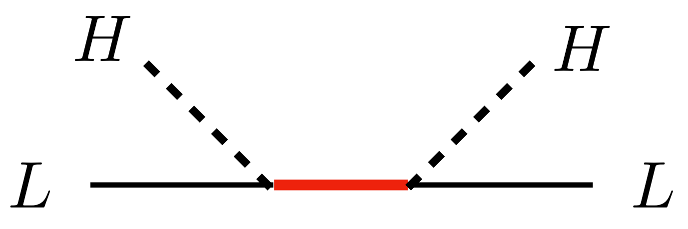
$$\langle p_L, h_L; p_H, h_H | p'_L, h'_L; p'_H, h'_H \rangle$$

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

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

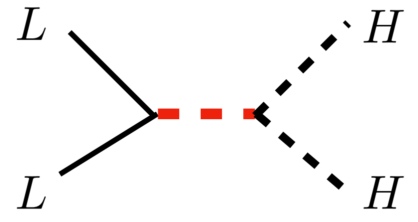
$$\mathbf{W}^2 \langle p_L, h_L; p_H, h_H | P, J, J_z \rangle = -P^2 J(J+1) \langle p_L, h_L; p_H, h_H | P, J, J_z \rangle \quad = -s \sum_J J(J+1) \mathcal{O}^{\mathrm{J}}$$

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



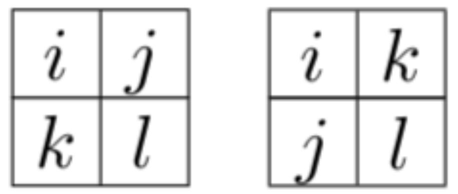
$$J = \frac{1}{2}$$

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



$$J = 0$$

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



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

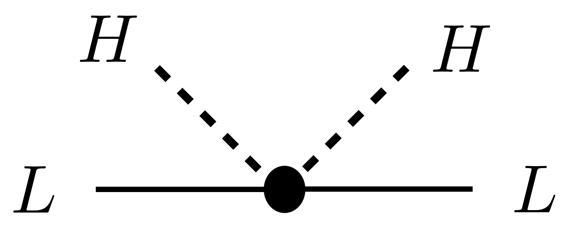
$$\mathbf{C}^2 \mathcal{B}^R = r(r+1) \mathcal{B}^R$$

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

Only 3 Types of Seesaw at Dim-5

Generalized partial wave analysis for Poincare/Gauge Casimir

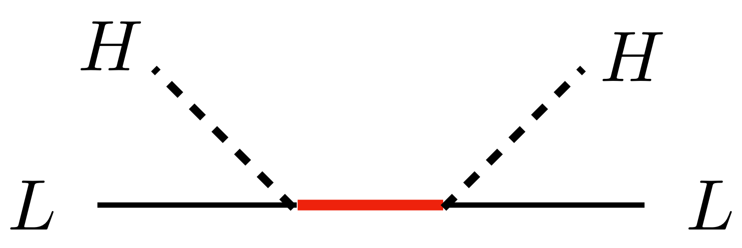
[Li, Ni, Xiao, **Yu**, 2204.03660]



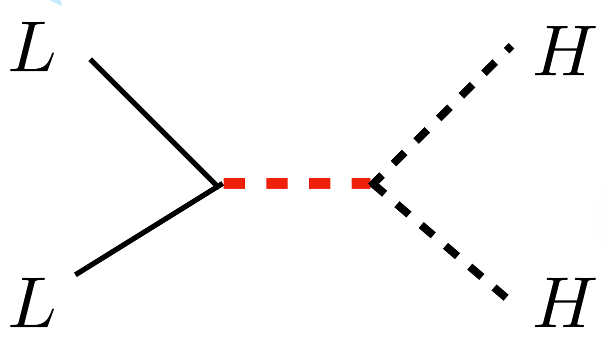
$$\mathbf{W}^2 \mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$

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

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



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



$J = 0$

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

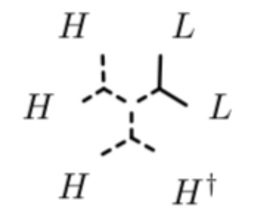
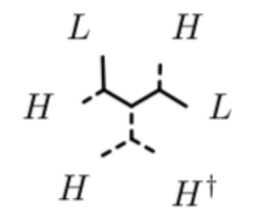
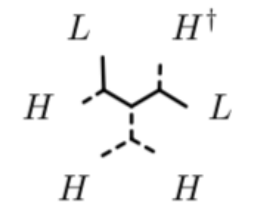
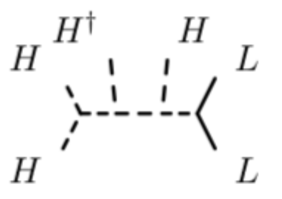
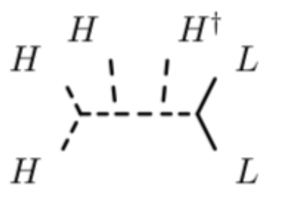
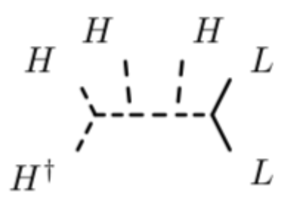
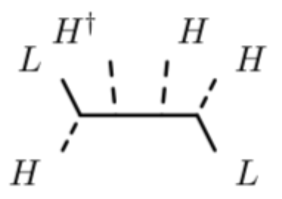
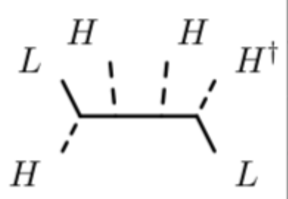
Dim-7 Operators

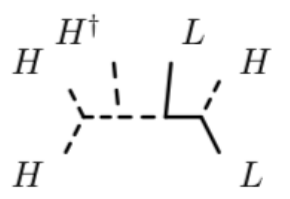
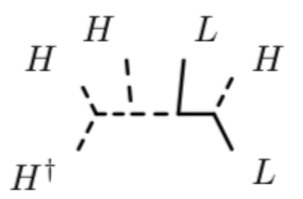
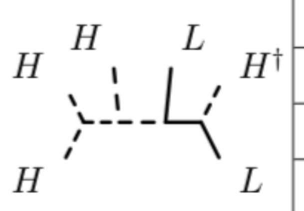
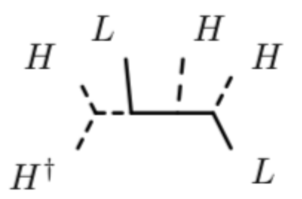
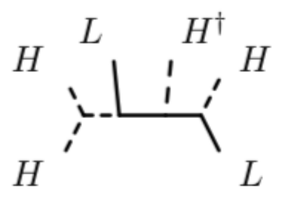
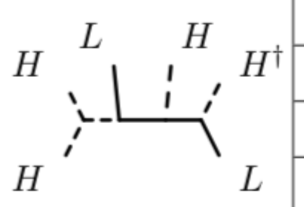
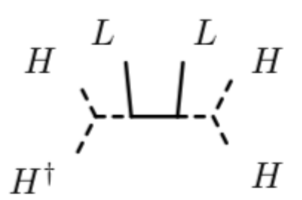
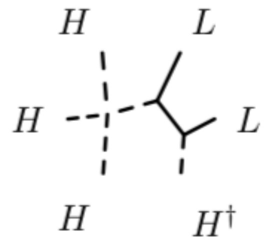
$$\mathcal{B}^y_{\psi^2\phi^2 D^2} = \begin{pmatrix} s_{34}\langle 12\rangle \\ [34]\langle 13\rangle\langle 24\rangle \end{pmatrix} \qquad W^2_{\{1,3\}}\mathcal{B}^y = s_{24}\begin{pmatrix} -\frac{15}{4} & 2 \\ 0 & -\frac{3}{4} \end{pmatrix}\mathcal{B}^y \qquad \Rightarrow \mathcal{B}^j = \begin{cases}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

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 $\{J, \mathbf{R}, Y\}$
	$\mathcal{O}_{\{12\vert 34\vert 56\},1} = 2\mathcal{O}^p_1 - 4\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,3,1\},\{0,3,0\}$
	$\mathcal{O}_{\{12\vert 34\vert 56\},2} = 2\mathcal{O}^p_2 + 4\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,1,1\},\{0,3,0\}$
	$\mathcal{O}_{\{12\vert 34\vert 56\},3} = 12\mathcal{O}^p_4,$	$\{0,1,-1\},\{0,3,1\},\{0,3,0\}$
	$\mathcal{O}_{\{12\vert 34\vert 56\},4} = 4\mathcal{O}^p_1 + 4\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,3,1\},\{0,1,0\}$
	$\mathcal{O}_{\{12\vert 34\vert 56\},5} = 2\mathcal{O}^p_4 + 4\mathcal{O}^p_5.$	$\{0,1,-1\},\{0,1,1\},\{0,1,0\}$
	$\mathcal{O}_{\{13\vert 24\vert 56\},1} = -\mathcal{O}^p_2 - 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$
	$\mathcal{O}_{\{13\vert 24\vert 56\},2} = -\mathcal{O}^p_1 + 3\mathcal{O}^p_2 + 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},1,0\},\{0,3,0\}$
	$\mathcal{O}_{\{13\vert 24\vert 56\},3} = -\mathcal{O}^p_1 + \mathcal{O}^p_2 - 2\mathcal{O}^p_3 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$
	$\mathcal{O}_{\{13\vert 24\vert 56\},4} = -\mathcal{O}^p_1 - \mathcal{O}^p_2 + 3\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,1,0\}$
	$\mathcal{O}_{\{13\vert 24\vert 56\},5} = \mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},1,0\},\{0,1,0\}$
	$\mathcal{O}_{\{16\vert 23\vert 45\},1} = 2\mathcal{O}^p_1 - 2\mathcal{O}^p_2 - 2\mathcal{O}^p_3 + 6\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 23\vert 45\},2} = -2\mathcal{O}^p_1 - \mathcal{O}^p_2 - \mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},1,0\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 23\vert 45\},3} = 3\mathcal{O}^p_2 + 3\mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 23\vert 45\},4} = \mathcal{O}^p_2 - \mathcal{O}^p_3 - 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,1,1\}$
	$\mathcal{O}_{\{16\vert 23\vert 45\},5} = \mathcal{O}^p_2 - \mathcal{O}^p_3 + \mathcal{O}^p_4 - \mathcal{O}^p_5.$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},1,0\},\{0,1,1\}$
	$\mathcal{O}_{\{12\vert 125\vert 34\},1} = \mathcal{O}^p_1 + 4\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\vert 125\vert 34\},2} = -8\mathcal{O}^p_1 + 4\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\vert 125\vert 34\},3} = -12\mathcal{O}^p_4,$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\vert 125\vert 34\},4} = -2\mathcal{O}^p_2 - 4\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\vert 125\vert 34\},5} = -2\mathcal{O}^p_4 - 4\mathcal{O}^p_5.$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\vert 126\vert 34\},1} = 3\mathcal{O}^p_1,$	$\{0,3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\vert 126\vert 34\},2} = 12\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\vert 126\vert 34\},3} = -12\mathcal{O}^p_4,$	$\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\vert 126\vert 34\},4} = -2\mathcal{O}^p_2 - 4\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\vert 126\vert 34\},5} = -2\mathcal{O}^p_4 - 4\mathcal{O}^p_5.$	$\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\vert 124\vert 36\},1} = -\mathcal{O}^p_1 - 4\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{12\vert 124\vert 36\},2} = 2\mathcal{O}^p_1 + 6\mathcal{O}^p_2 + 2\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{12\vert 124\vert 36\},3} = -6\mathcal{O}^p_4 - 6\mathcal{O}^p_5,$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{12\vert 124\vert 36\},4} = -2\mathcal{O}^p_1 + 2\mathcal{O}^p_2 + 2\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{12\vert 124\vert 36\},5} = -2\mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{13\vert 135\vert 24\},1} = \mathcal{O}^p_1 - 2\mathcal{O}^p_3 - 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{13\vert 135\vert 24\},2} = -\mathcal{O}^p_1 - 3\mathcal{O}^p_2 - 4\mathcal{O}^p_3 + 9\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{13\vert 135\vert 24\},3} = \mathcal{O}^p_1 - \mathcal{O}^p_2 + 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{13\vert 135\vert 24\},4} = \mathcal{O}^p_1 - 3\mathcal{O}^p_2 - 2\mathcal{O}^p_3 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$
	$\mathcal{O}_{\{13\vert 135\vert 24\},5} = \mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$
	$\mathcal{O}_{\{16\vert 146\vert 23\},1} = -2\mathcal{O}^p_1 + 4\mathcal{O}^p_3 - 12\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{16\vert 146\vert 23\},2} = 2\mathcal{O}^p_1 - 3\mathcal{O}^p_2 - \mathcal{O}^p_3 + 9\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{16\vert 146\vert 23\},3} = 3\mathcal{O}^p_2 + 3\mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{16\vert 146\vert 23\},4} = 2\mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_3 - 3\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$
	$\mathcal{O}_{\{16\vert 146\vert 23\},5} = -\mathcal{O}^p_2 + \mathcal{O}^p_3 - \mathcal{O}^p_4 + \mathcal{O}^p_5,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$

	$\mathcal{O}_{\{13\vert 123\vert 45\},1} = \mathcal{O}^p_1 - 4\mathcal{O}^p_2 - 4\mathcal{O}^p_3,$	$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\vert 123\vert 45\},2} = 2\mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_3 - 9\mathcal{O}^p_4 - 9\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\vert 123\vert 45\},3} = 2\mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\vert 123\vert 45\},4} = \mathcal{O}^p_2 - \mathcal{O}^p_3 + 3\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{13\vert 123\vert 45\},5} = -\mathcal{O}^p_2 + \mathcal{O}^p_3 + \mathcal{O}^p_4 - \mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{13\vert 123\vert 46\},1} = \mathcal{O}^p_1 - 4\mathcal{O}^p_2 - 4\mathcal{O}^p_3,$	$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{13\vert 123\vert 46\},2} = \mathcal{O}^p_1 + 2\mathcal{O}^p_2 - \mathcal{O}^p_3 - 9\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{13\vert 123\vert 46\},3} = -\mathcal{O}^p_1 - 2\mathcal{O}^p_2 + \mathcal{O}^p_3 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{13\vert 123\vert 46\},4} = -\mathcal{O}^p_1 - \mathcal{O}^p_3 + 6\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{13\vert 123\vert 46\},5} = -\mathcal{O}^p_1 - \mathcal{O}^p_3 - 2\mathcal{O}^p_4 - \mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{16\vert 126\vert 34\},1} = 6\mathcal{O}^p_1,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 126\vert 34\},2} = -3\mathcal{O}^p_2 + 9\mathcal{O}^p_4,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 126\vert 34\},3} = -3\mathcal{O}^p_2 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 126\vert 34\},4} = -\mathcal{O}^p_2 - 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 126\vert 34\},5} = \mathcal{O}^p_2 + 2\mathcal{O}^p_3 + \mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{23\vert 235\vert 46\},1} = \mathcal{O}^p_1 - 2\mathcal{O}^p_3 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{23\vert 235\vert 46\},2} = \mathcal{O}^p_1 - 6\mathcal{O}^p_2 - 5\mathcal{O}^p_3 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{23\vert 235\vert 46\},3} = \mathcal{O}^p_1 + 2\mathcal{O}^p_2 - \mathcal{O}^p_3 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{23\vert 235\vert 46\},4} = -\mathcal{O}^p_1 - \mathcal{O}^p_3 - 6\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{23\vert 235\vert 46\},5} = -\mathcal{O}^p_1 - \mathcal{O}^p_3 + 2\mathcal{O}^p_4 + \mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{13\vert 136\vert 45\},1} = \mathcal{O}^p_1 + 2\mathcal{O}^p_2 + 2\mathcal{O}^p_3 - 6\mathcal{O}^p_4 - 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\vert 136\vert 45\},2} = 2\mathcal{O}^p_1 - 5\mathcal{O}^p_2 - 5\mathcal{O}^p_3 - 3\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\vert 136\vert 45\},3} = 2\mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\vert 136\vert 45\},4} = \mathcal{O}^p_2 - \mathcal{O}^p_3 + 3\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{13\vert 136\vert 45\},5} = -\mathcal{O}^p_2 + \mathcal{O}^p_3 + \mathcal{O}^p_4 - \mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{16\vert 156\vert 34\},1} = 2\mathcal{O}^p_1 - 4\mathcal{O}^p_2 + 12\mathcal{O}^p_4,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 156\vert 34\},2} = 4\mathcal{O}^p_1 + \mathcal{O}^p_2 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 156\vert 34\},3} = -3\mathcal{O}^p_2 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\vert 156\vert 34\},4} = -\mathcal{O}^p_2 - 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{16\vert 156\vert 34\},5} = \mathcal{O}^p_2 + 2\mathcal{O}^p_3 + \mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{34\vert 134\vert 56\},1} = -\mathcal{O}^p_1 + 2\mathcal{O}^p_2 + 6\mathcal{O}^p_4,$	$\{0,3,1\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{34\vert 134\vert 56\},2} = 4\mathcal{O}^p_1 - 8\mathcal{O}^p_2 + 12\mathcal{O}^p_4,$	$\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{34\vert 134\vert 56\},3} = 2\mathcal{O}^p_2 + 4\mathcal{O}^p_3,$	$\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{34\vert 134\vert 56\},4} = -4\mathcal{O}^p_1 - 4\mathcal{O}^p_2,$	$\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{34\vert 134\vert 56\},5} = 2\mathcal{O}^p_4 + 4\mathcal{O}^p_5.$	$\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{16\vert 126\},1} = 6\mathcal{O}^p_1,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\}$
	$\mathcal{O}_{\{16\vert 126\},2,3} = \begin{pmatrix} \mathcal{O}^p_2 - \mathcal{O}^p_3 - 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5 \\ -2\mathcal{O}^p_2 - \mathcal{O}^p_3 + 6\mathcal{O}^p_4 + 3\mathcal{O}^p_5 \end{pmatrix},$	$\{\frac{1}{2},3,-1\},\{0,2,-\frac{3}{2}\}$
	$\mathcal{O}_{\{16\vert 126\},4,5} = \begin{pmatrix} -\mathcal{O}^p_2 - 2\mathcal{O}^p_3 - \mathcal{O}^p_4 - 2\mathcal{O}^p_5 \\ -2\mathcal{O}^p_2 - \mathcal{O}^p_3 - 2\mathcal{O}^p_4 - \mathcal{O}^p_5 \end{pmatrix}.$	$\{\frac{1}{2},1,-1\},\{0,2,-\frac{3}{2}\}$

34/59

[Bonnet, Hernandez, Ota, Winter, 2009]

Complete dim-7 Tree UVs

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

Scalar $(\mathrm{SU}(3)_c, \mathrm{SU}(2)_2, \mathrm{U}(1)_y)$	
$S1\ (\mathbf{1},\mathbf{1},0)$	$H^3H^\dagger L^2[(S6),(F5),(F1),(S4,S6),(S4,F5),(S4,F1),(F3,F5),(F1,F3),(S6,F3)]$
$S2\ (\mathbf{1},\mathbf{1},1)$	$e_{\mathbb{C}}HL^3[(S4),(F4),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S4),(F10),(F9)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(F8),(F12)]$ $De_{\mathbb{C}}H^{\dagger3}L^\dagger[(F1),(F3),(V3)]$
$S4\ (\mathbf{1},\mathbf{2},\frac{1}{2})$	$e_{\mathbb{C}}HL^3[(S6),(S2),(F5),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S6),(S2),(F5),(F1)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(S2),(F5),(F1)]$ $H^3H^\dagger L^2[(S6),(F5),(F1),(S5,S6),(S1,S6),(S6,F5),(S6,F1),(S5,F5),(S5,F1),(S1,F5),(S1,F1)]$
$S5\ (\mathbf{1},\mathbf{3},0)$	$H^3H^\dagger L^2[(S6),(F1,F5),(S6,S7),(S4,S6),(S7,F5),(S4,F5),(S4,F1),(F5,F7),(F3,F5),(F1,F3),(S6,F7),(S6,F3)]$
$S6\ (\mathbf{1},\mathbf{3},1)$	$D^2H^2L^2$ $e_{\mathbb{C}}HL^3[(S4),(F4),(F5)]$ $d_{\mathbb{C}}HL^2Q[(S4),(F10),(F14)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(F13),(F12)]$ $De_{\mathbb{C}}H^{\dagger3}L^\dagger[(F5),(F3),(V3)]$ $H^2L^2W_L[(F7)]$ $H^3H^\dagger L^2[(S4),(S8),(S7),(S5),(S1),(F5,F6),(F1,F6),(S5,S7),(S4,S5),(S1,S4),(S7,F5),(S4,F5),(S4,F1),(F5,F7),(F3,F5),(F1,F3),(S8,F6),(F6,F7),(F3,F6),(S5,F7),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$
$S7\ (\mathbf{1},\mathbf{4},\frac{1}{2})$	$H^3H^\dagger L^2[(S6),(F5),(S5,S6),(S6,F5),(S5,F5)]$
$S8\ (\mathbf{1},\mathbf{4},\frac{3}{2})$	$H^3H^\dagger L^2[(S6),(F6),(S6,F6)]$
$S10\ (\mathbf{3},\mathbf{1},-\frac{1}{3})$	$d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S12),(F10),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S12),(F10),(F1)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S12),(F10),(F1)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S12),(F10),(F1)]$
$S11\ (\mathbf{3},\mathbf{1},\frac{2}{3})$	$d_{\mathbb{C}}{}^3H^\dagger L[(S12),(F11),(F2)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(F11),(S13),(F1)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(S13),(F3),(F8)]$
$S12\ (\mathbf{3},\mathbf{2},\frac{1}{6})$	$d_{\mathbb{C}}{}^3H^\dagger L[(S11),(F11)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(F11),(S10),(F10)]$ $d_{\mathbb{C}}HL^2Q[(S10),(S14),(F5),(F1),(F14),(F9)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(F3),(F12)]$
$S13\ (\mathbf{3},\mathbf{2},\frac{7}{6})$	$d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S11),(F10)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(S11),(F10)]$
$S14\ (\mathbf{3},\mathbf{3},-\frac{1}{3})$	$d_{\mathbb{C}}HL^2Q[(S12),(F10),(F5)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S12),(F10),(F5)]$

Fermion $(\mathrm{SU}(3)_c, \mathrm{SU}(2)_2, \mathrm{U}(1)_y)$	
$F1\ (\mathbf{1},\mathbf{1},0)$	$D^2H^2L^2$ $e_{\mathbb{C}}HL^3[(S4),(S2)]$ $d_{\mathbb{C}}HL^2Q[(S4),(S10),(S12)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(V5),(V8)]$ $De_{\mathbb{C}}H^{\dagger3}L^\dagger[(F3),(V2)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S11),(S10)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(V5)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S10),(V8)]$ $H^2L^2W_L[(F5)]$ $H^3H^\dagger L^2[(S4),(S5,F5),(S1),(S6,F6),(F3,F5),(F3),(F3,F6),(S4,S6),(S6,F3),(S4,S5),(S1,S4),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$
$F2\ (\mathbf{1},\mathbf{1},1)$	$d_{\mathbb{C}}{}^3H^\dagger L[(S11)]$
$F3\ (\mathbf{1},\mathbf{2},\frac{1}{2})$	$De_{\mathbb{C}}H^{\dagger3}L^\dagger[(F5),(F1),(S6),(V2)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S12),(V8)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(V8),(S11)]$ $H^3H^\dagger L^2[(F5),(F1,F5),(F1),(F5,F6),(F1,F6),(S6,F5),(S6,F1),(S5,F5),(S5,F1),(S1,F5),(S1,F1),(S6,F6),(S5,S6),(S1,S6)]$
$F4\ (\mathbf{1},\mathbf{2},\frac{3}{2})$	$e_{\mathbb{C}}HL^3[(S6),(S2)]$
$F5\ (\mathbf{1},\mathbf{3},0)$	$e_{\mathbb{C}}HL^3[(S4),(S6)]$ $d_{\mathbb{C}}HL^2Q[(S4),(S12),(S14)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(V9),(V8)]$ $D^2H^2L^2$ $De_{\mathbb{C}}H^{\dagger3}L^\dagger[(S6),(F3),(V5)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S14),(V8)]$ $H^2L^2W_L[(F7),(F1)]$ $H^3H^\dagger L^2[(S4),(S7),(S5,F1),(S1),(S6,F6),(F7),(F3),(F1,F3),(F6,F7),(F3,F6),(S6,S7),(S4,S6),(S6,F7),(S6,F3),(S5,S7),(S4,S5),(S1,S4),(S5,F7),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$
$F6\ (\mathbf{1},\mathbf{3},1)$	$H^3H^\dagger L^2[(S8),(S6,F5),(S6,F1),(F5,F7),(F3,F5),(F1,F3),(S6,S8),(S6,F7),(S6,F3)]$
$F7\ (\mathbf{1},\mathbf{4},\frac{1}{2})$	$H^2L^2W_L[(F5),(S6)]$ $H^3H^\dagger L^2[(F5),(S6,F5),(F5,F6),(S6,F6),(S5,F5),(S5,S6)]$
$F8\ (\mathbf{3},\mathbf{1},-\frac{1}{3})$	$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S2),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(V8),(S12),(V5)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(V5),(S11)]$
$F9\ (\mathbf{3},\mathbf{1},\frac{2}{3})$	$d_{\mathbb{C}}HL^2Q[(S12),(S2)]$
$F10\ (\mathbf{3},\mathbf{2},-\frac{5}{6})$	$d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S12),(S10),(S13)]$ $d_{\mathbb{C}}HL^2Q[(S10),(S6),(S2),(S14)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(V3),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S10),(S14),(V9),(V5)]$
$F11\ (\mathbf{3},\mathbf{2},\frac{1}{6})$	$d_{\mathbb{C}}{}^3H^\dagger L[(S11),(S12)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S11),(S12)]$
$F12\ (\mathbf{3},\mathbf{2},\frac{7}{6})$	$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(S2),(V9),(V5)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(V5),(S12),(V3)]$
$F13\ (\mathbf{3},\mathbf{3},-\frac{1}{3})$	$HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(V8),(S12),(V9)]$
$F14\ (\mathbf{3},\mathbf{3},\frac{2}{3})$	$d_{\mathbb{C}}HL^2Q[(S12),(S6)]$

Complete Dim-6 Tree UVs

[Xu-Xiang Li, Zhe Ren, **J.H.Yu,** 2307.10380]

Propose new way of searching new physics

LHC search these 47 resonances!

which covers all dim-6 NP scenarios

19 Scalars

Notation	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{1})_1$	$(\mathbf{1},\mathbf{1})_2$	$(\mathbf{1},\mathbf{2})_{\frac{1}{2}}$	$(\mathbf{1},\mathbf{3})_0$	$(\mathbf{1},\mathbf{3})_1$	$(\mathbf{1},\mathbf{4})_{\frac{1}{2}}$	$(\mathbf{1},\mathbf{4})_{\frac{3}{2}}$
Notation	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}		
Name	ω_4	ω_1	ω_2	Π_1	Π_7	ζ		
Irrep	$(\mathbf{3},\mathbf{1})_{-\frac{4}{3}}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}$		
Notation	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}			
Name	Ω_2	Ω_1	Ω_4	Υ_1	Φ			
Irrep	$(\mathbf{6},\mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{6},\mathbf{1})_{\frac{1}{3}}$	$(\mathbf{6},\mathbf{1})_{\frac{4}{3}}$	$(\mathbf{6},\mathbf{3})_{\frac{1}{3}}$	$(\mathbf{8},\mathbf{2})_{\frac{1}{2}}$			

14 Fermions

Notation	F_1	F_2	F_3	F_4	F_5	F_6	F_7
Name	N	E^c	Δ_1^c	Δ_3^c	Σ	Σ_1^c	
Irrep	$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{1})_1$	$(\mathbf{1},\mathbf{2})_{\frac{1}{2}}$	$(\mathbf{1},\mathbf{2})_{\frac{3}{2}}$	$(\mathbf{1},\mathbf{3})_0$	$(\mathbf{1},\mathbf{3})_1$	$(\mathbf{1},\mathbf{4})_{\frac{1}{2}}$
Notation	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}	F_{14}
Name	D	U	Q_5	Q_1	Q_7	T_1	T_2
Irrep	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}$	$(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$

14 Vectors

Notation	V_1	V_2	V_3	V_4	V_5	V_6	V_7
Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{L}_3^\dagger$	$\mathcal{W}$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_5$
Irrep	$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{1})_1$	$(\mathbf{1},\mathbf{2})_{\frac{3}{2}}$	$(\mathbf{1},\mathbf{3})_0$	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{\frac{5}{3}}$	$(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$
Notation	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}
Name	$\mathcal{Q}_1$	$\mathcal{X}$	$\mathcal{Y}_1^\dagger$	$\mathcal{Y}_5^\dagger$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$
Irrep	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$(\mathbf{6},\mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{6},\mathbf{2})_{\frac{5}{6}}$	$(\mathbf{8},\mathbf{1})_0$	$(\mathbf{8},\mathbf{1})_1$	$(\mathbf{8},\mathbf{3})_0$

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}	F_{14}
$\mathcal{O}_{eH}$		✓	✓	✓	✓	✓								
$\mathcal{O}_{uH}$									✓		✓	✓	✓	✓
$\mathcal{O}_{dH}$								✓		✓	✓		✓	✓
$\mathcal{O}_{Hl}^{(1)}$	✓	✓			✓	✓								
$\mathcal{O}_{Hl}^{(3)}$	✓	✓			✓	✓								
$\mathcal{O}_{He}$			✓	✓										
$\mathcal{O}_{Hq}^{(1)}$								✓	✓				✓	✓
$\mathcal{O}_{Hq}^{(3)}$								✓	✓				✓	✓
$\mathcal{O}_{Hu}$											✓	✓		
$\mathcal{O}_{Hd}$										✓	✓			
$\mathcal{O}_{Hud}$											✓			

Complete Dim-6 Tree UVs

[Xu-Xiang Li, Zhe Ren, **J.H.Yu,** 2307.10380]

Different final states

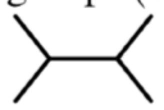
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}
$\mathcal{O}_H$	✓			✓	✓	✓	✓	✓											
$\mathcal{O}_{H\Box}$	✓				✓	✓													
$\mathcal{O}_{HD}$					✓	✓													
$\mathcal{O}_{eH}$	*			✓	✓	✓													
$\mathcal{O}_{uH}$	*			✓	✓	✓													
$\mathcal{O}_{dH}$	*			✓	✓	✓													
$\mathcal{O}_{ll}$		✓				✓													
$\mathcal{O}_{qq}^{(1)}$										✓				✓		✓		✓	
$\mathcal{O}_{qq}^{(3)}$										✓				✓		✓		✓	
$\mathcal{O}_{lq}^{(1)}$										✓				✓					
$\mathcal{O}_{lq}^{(3)}$										✓				✓					
$\mathcal{O}_{ee}$			✓																
$\mathcal{O}_{uu}$									✓								✓		
$\mathcal{O}_{dd}$											✓				✓				
$\mathcal{O}_{eu}$										✓									
$\mathcal{O}_{ed}$									✓										
$\mathcal{O}_{ud}^{(1)}$										✓						✓			
$\mathcal{O}_{ud}^{(8)}$										✓						✓			
$\mathcal{O}_{le}$				✓															
$\mathcal{O}_{lu}$													✓						
$\mathcal{O}_{ld}$												✓							
$\mathcal{O}_{qe}$													✓						
$\mathcal{O}_{qu}^{(1)}$				✓															✓
$\mathcal{O}_{qu}^{(8)}$				✓															✓
$\mathcal{O}_{qd}^{(1)}$				✓															✓
$\mathcal{O}_{qd}^{(8)}$				✓															✓
$\mathcal{O}_{ledq}$				✓															
$\mathcal{O}_{quqd}^{(1)}$				✓						✓						✓			
$\mathcal{O}_{quqd}^{(8)}$										✓						✓			✓
$\mathcal{O}_{lequ}^{(1)}$				✓						✓			✓						
$\mathcal{O}_{lequ}^{(3)}$										✓			✓						
$\mathcal{O}_{duq}$										✓									
$\mathcal{O}_{qqu}$										✓									
$\mathcal{O}_{qqq}$										✓				✓					
$\mathcal{O}_{duu}$									✓	✓									

	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}
$\mathcal{O}_H$		✓		✓										
$\mathcal{O}_{H\Box}$	✓	✓		✓										
$\mathcal{O}_{HD}$	✓	✓		✓										
$\mathcal{O}_{eH}$	✓	✓		✓										
$\mathcal{O}_{uH}$	✓	✓		✓										
$\mathcal{O}_{dH}$	✓	✓		✓										
$\mathcal{O}_{Hl}^{(1)}$	✓													
$\mathcal{O}_{Hl}^{(3)}$				✓										
$\mathcal{O}_{He}$	✓													
$\mathcal{O}_{Hq}^{(1)}$	✓													
$\mathcal{O}_{Hq}^{(3)}$				✓										
$\mathcal{O}_{Hu}$	✓													
$\mathcal{O}_{Hd}$	✓													
$\mathcal{O}_{Hud}$		✓												
$\mathcal{O}_{ll}$	✓			✓										
$\mathcal{O}_{qq}^{(1)}$	✓											✓		✓
$\mathcal{O}_{qq}^{(3)}$				✓								✓		✓
$\mathcal{O}_{lq}^{(1)}$	✓				✓				✓					
$\mathcal{O}_{lq}^{(3)}$				✓	✓				✓					
$\mathcal{O}_{ee}$	✓													
$\mathcal{O}_{uu}$	✓											✓		
$\mathcal{O}_{dd}$	✓											✓		
$\mathcal{O}_{eu}$	✓					✓								
$\mathcal{O}_{ed}$	✓				✓									
$\mathcal{O}_{ud}^{(1)}$	✓	✓											✓	
$\mathcal{O}_{ud}^{(8)}$		✓										✓	✓	
$\mathcal{O}_{le}$	✓		✓											
$\mathcal{O}_{lu}$	✓							✓						
$\mathcal{O}_{ld}$	✓						✓							
$\mathcal{O}_{qe}$	✓						✓							
$\mathcal{O}_{qu}^{(1)}$	✓						✓				✓			
$\mathcal{O}_{qu}^{(8)}$							✓				✓	✓		
$\mathcal{O}_{qd}^{(1)}$	✓							✓		✓				
$\mathcal{O}_{qd}^{(8)}$								✓		✓		✓		
$\mathcal{O}_{ledq}$					✓		✓							
$\mathcal{O}_{duq}$							✓	✓						
$\mathcal{O}_{qqu}$							✓							

Complete Dim-8 Tree UVs

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

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

group: (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

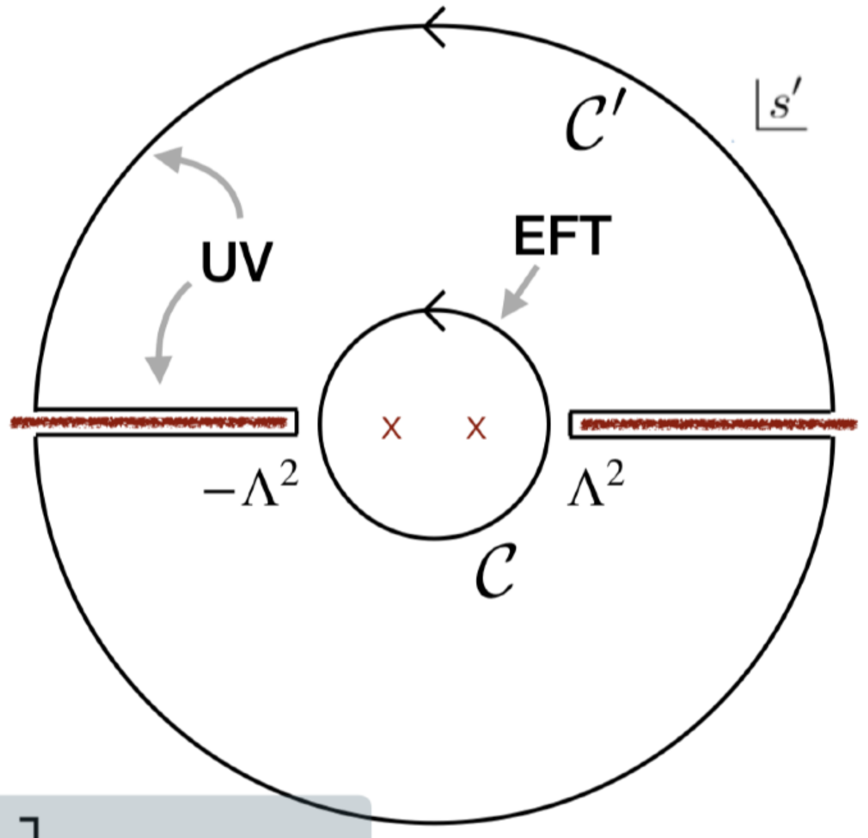
$$\mathcal{M}^{ijkl} = \frac{1}{2\pi}\int_{(\epsilon\Lambda)^2}^{\infty}\frac{ds}{s^3}\sum_X\left[\mathbf{M}_{ij\to X}\mathbf{M}^*_{kl\to X} + (j\leftrightarrow l)\right]$$

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

Analyticity in complex s plane (fixed t)

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

Cauchy's integral formula



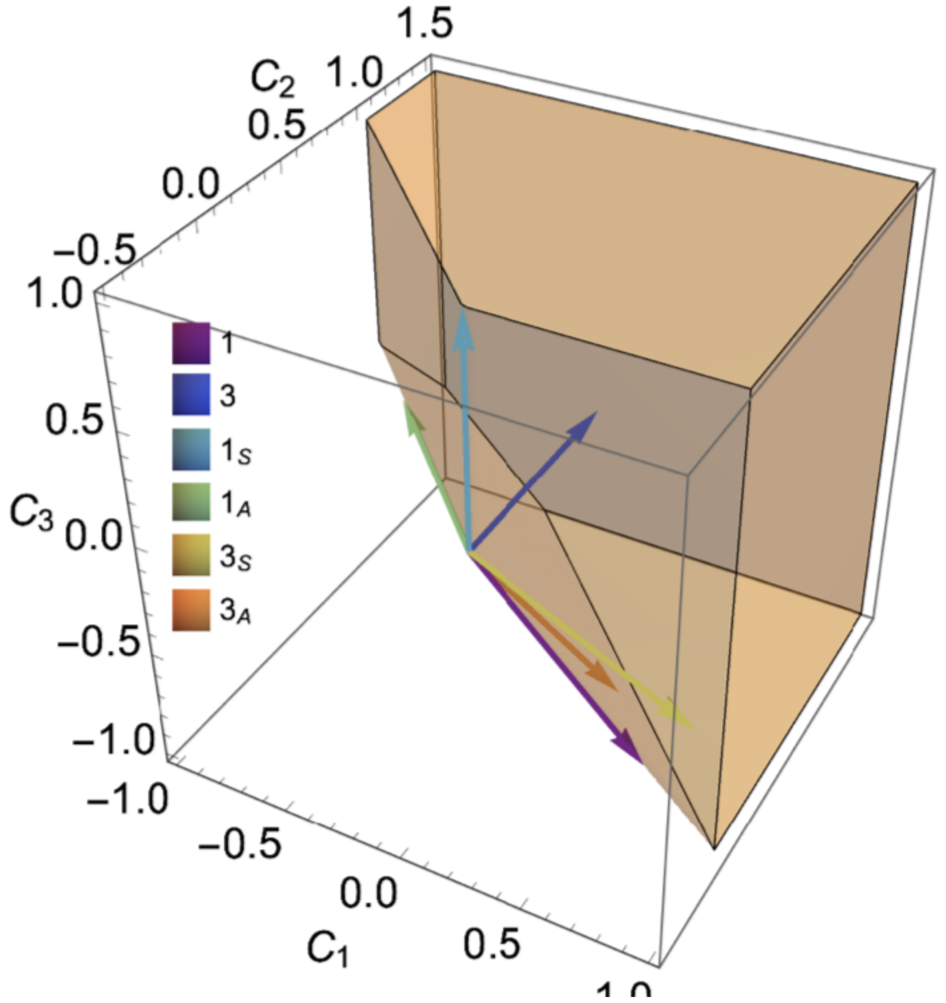
Fixed t dispersion relation

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

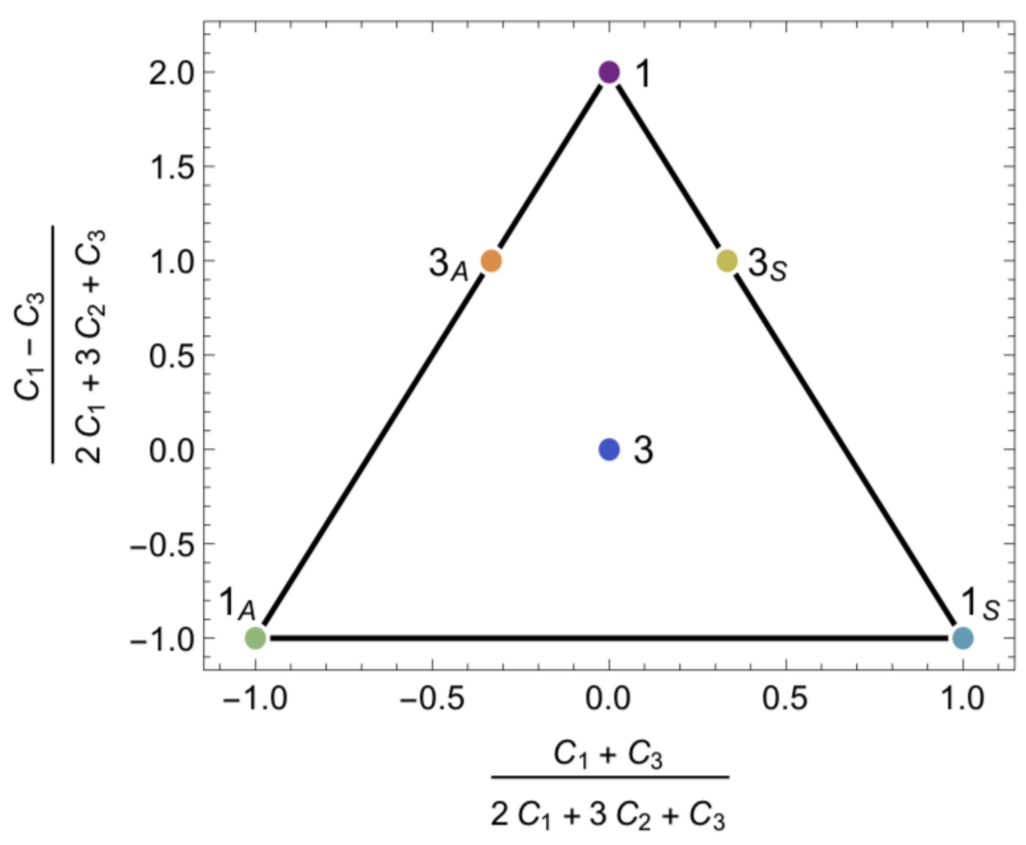
$\mu > \Lambda^2$

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

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

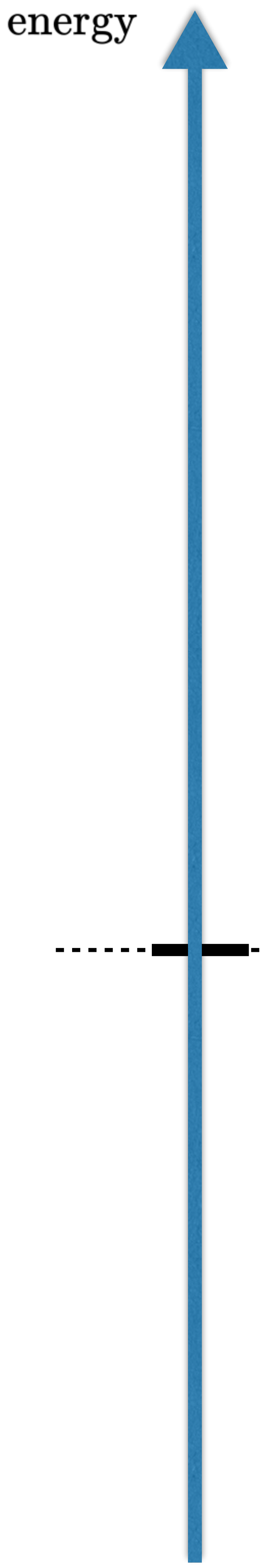


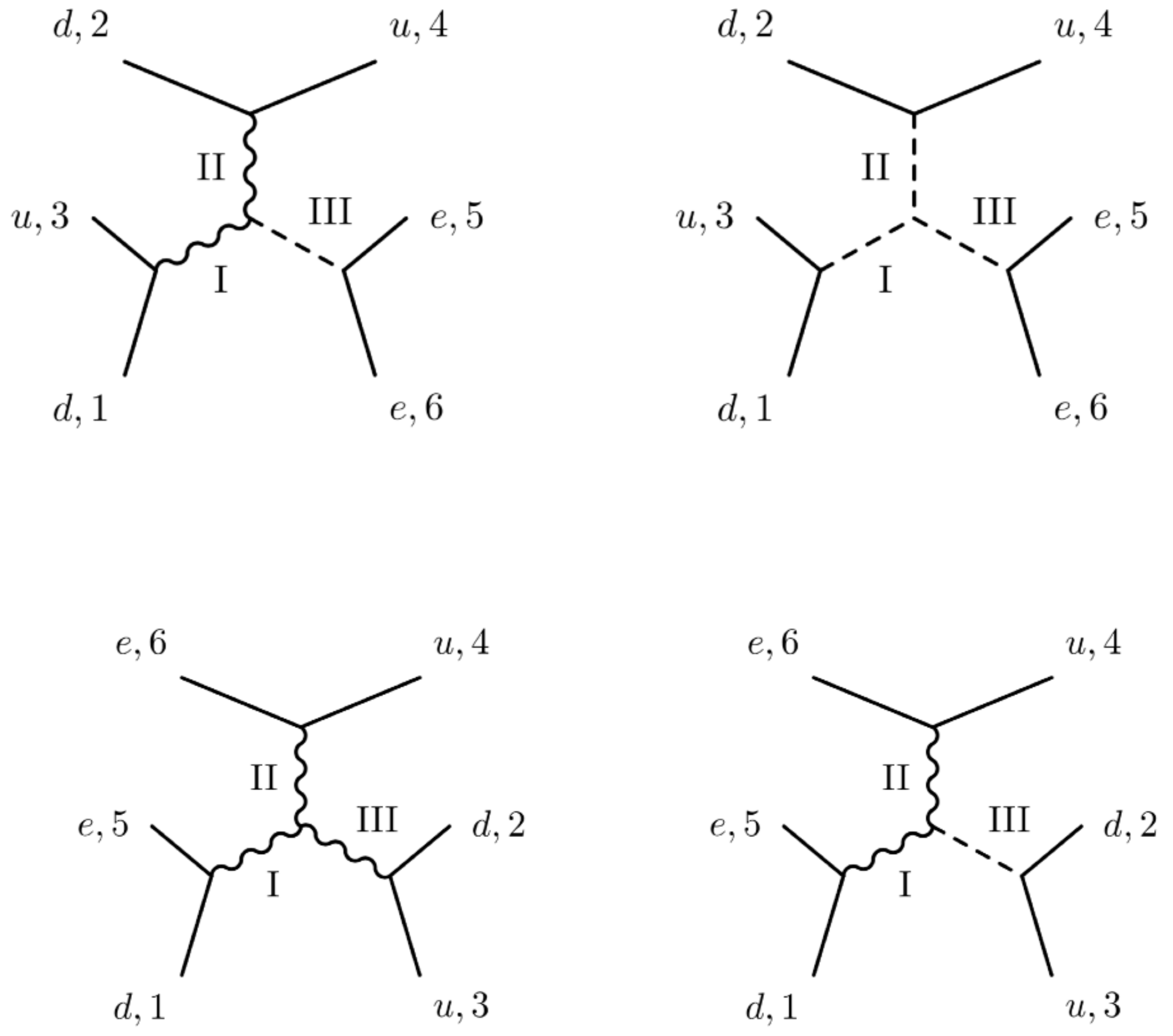
[Cen Zhang, S-Y Zhou]



Complete Dim-9 UV for 0vbb

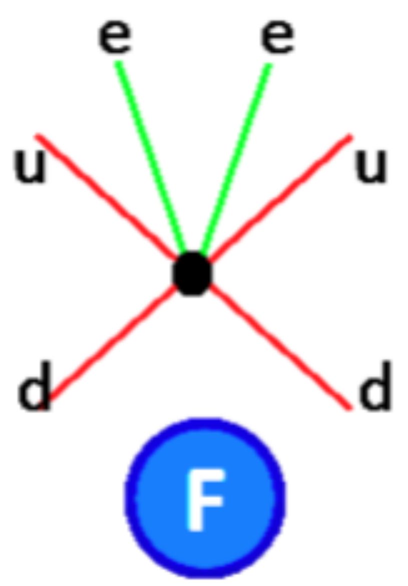
[Li, Ni, Xiao, **Yu**, in preparation]





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

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



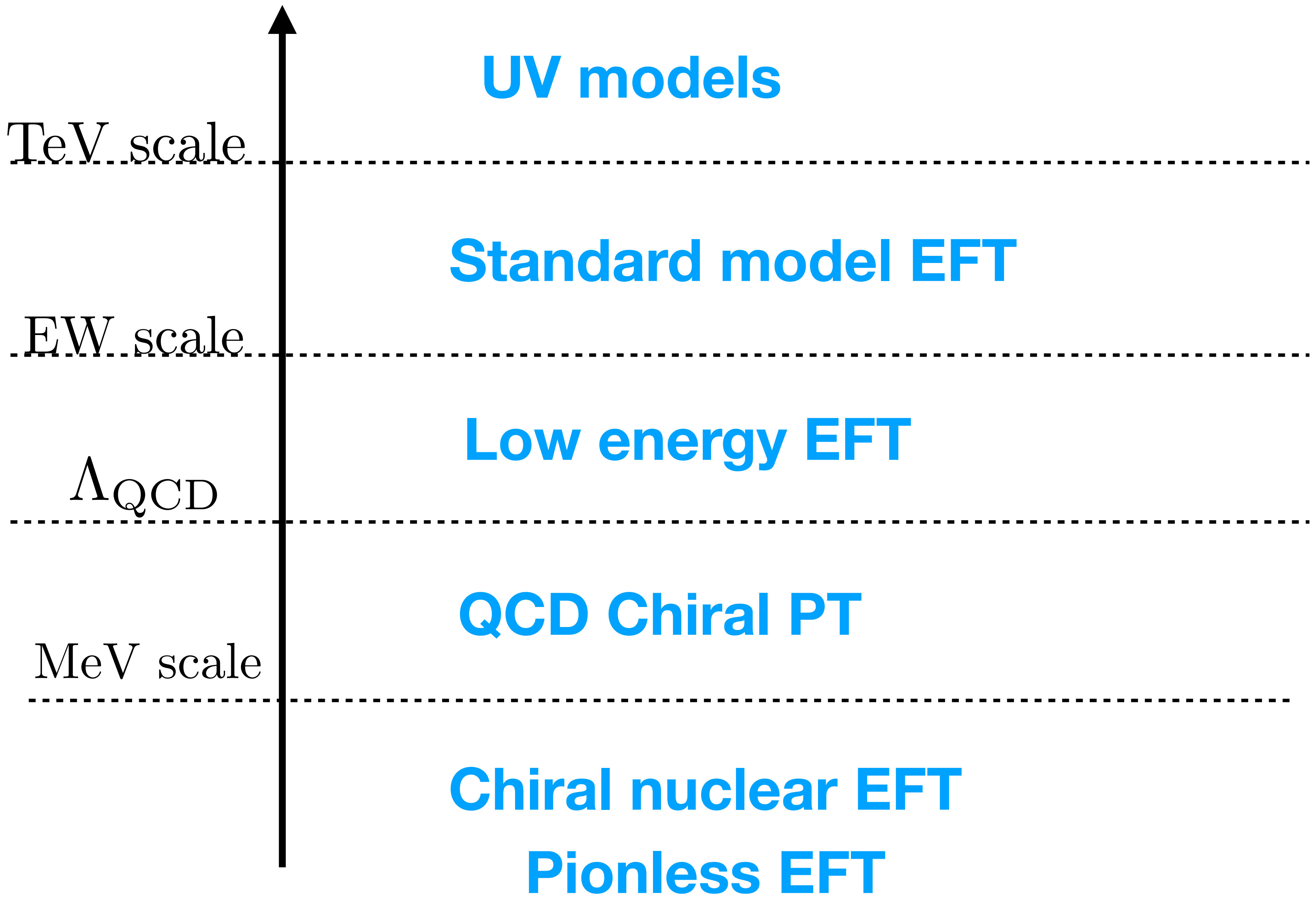
$$\mathcal{O}_1 = \frac{1}{4}(L^{\dagger}{}_u{}^j L^{\dagger}{}_v{}^i)(Q_{pai}Q_{rbj})(u_{cs}{}^b u_{ct}{}^a)$$

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

Summary

- EFT provides most general parametrization of new physics (CPV) 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

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2305.10481]

[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!