



Institute of Theoretical Physics
Chinese Academy of Sciences



清华大学
Tsinghua University

通向新物理的有效途径

SMEFT and HEFT

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第十六届TeV物理工作组学术研讨会
暨邝宇平院士学术思想研讨会

Nov 10, 2022 @ 清华大学

Outline

- Which EFT for New Physics
- Operator Basis Construction for Any EFT
- Complete UV Resonances from EFT
- Summary

Apologize for not covering EFT phenomenologies ...

Such as b-physics, collider physics, low energy, etc

[See talks by Jibo He, Qiang Li, Gang Li, Bin Yan, Fa Peng Huang, Shun Zhou]

Which EFT for New Physics

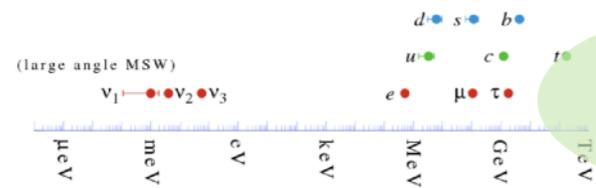
Why New Physics?

theoretical motivation

experimental challenges

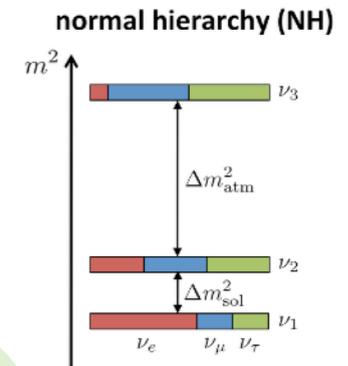
$$m_{\text{Higgs}}^2 = \dots + y_t \text{ (loop diagram with } t \text{ quark)}$$

Higgs mass

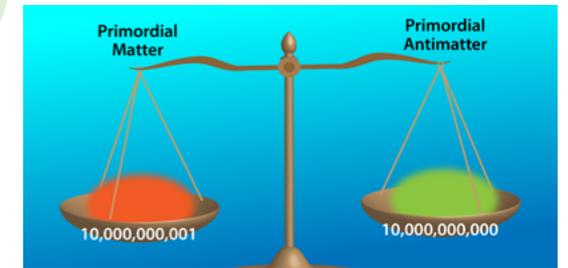


Flavor Hierarchy

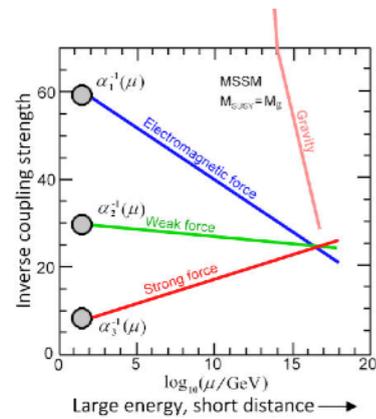
Neutrino



Baryon Asymmetry

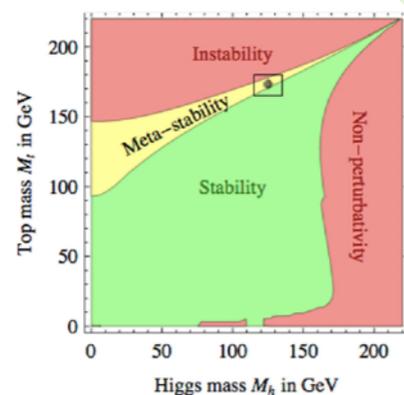


Dark matter

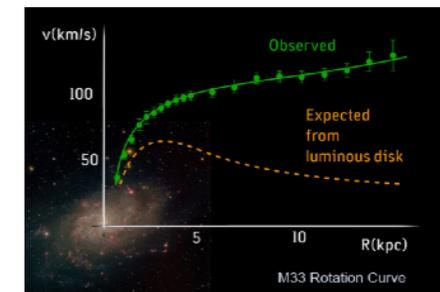
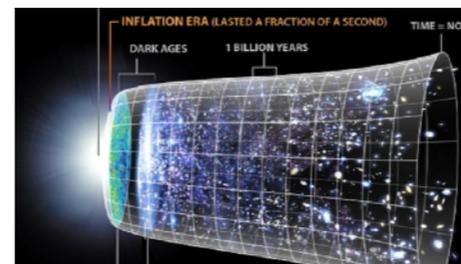


Gauge Unification

Vacuum Stability



Inflation



What New Physics?

Naturalness	Baryon asymmetry	Neutrino Mass	Dark Matter	Gauge Unification
MSSM	Higgs Singlet	Type-I seesaw	Higgs portal DM	U(1) extensions
NMSSM	Higgs Doublet	Type-II seesaw	Minimal DM	G221
Little Higgs	Higgs Triplet	Type-III seesaw	Singlet-doublet dark matter	G331
Composite Higgs	Type-I seesaw	Inert doublet	Scalar Portal DM	Pati-Salam
Randall-Sundrum	Vector Fermion	Leptoquark	Fermion Portal	SU(5) GUT
Twin Higgs	4th gen. quark		Z-prime Portal	SO(10) GUT
Minimal neutral naturalness			Hidden U(N)	
Trigonometric Higgs				

Some models address several problems together

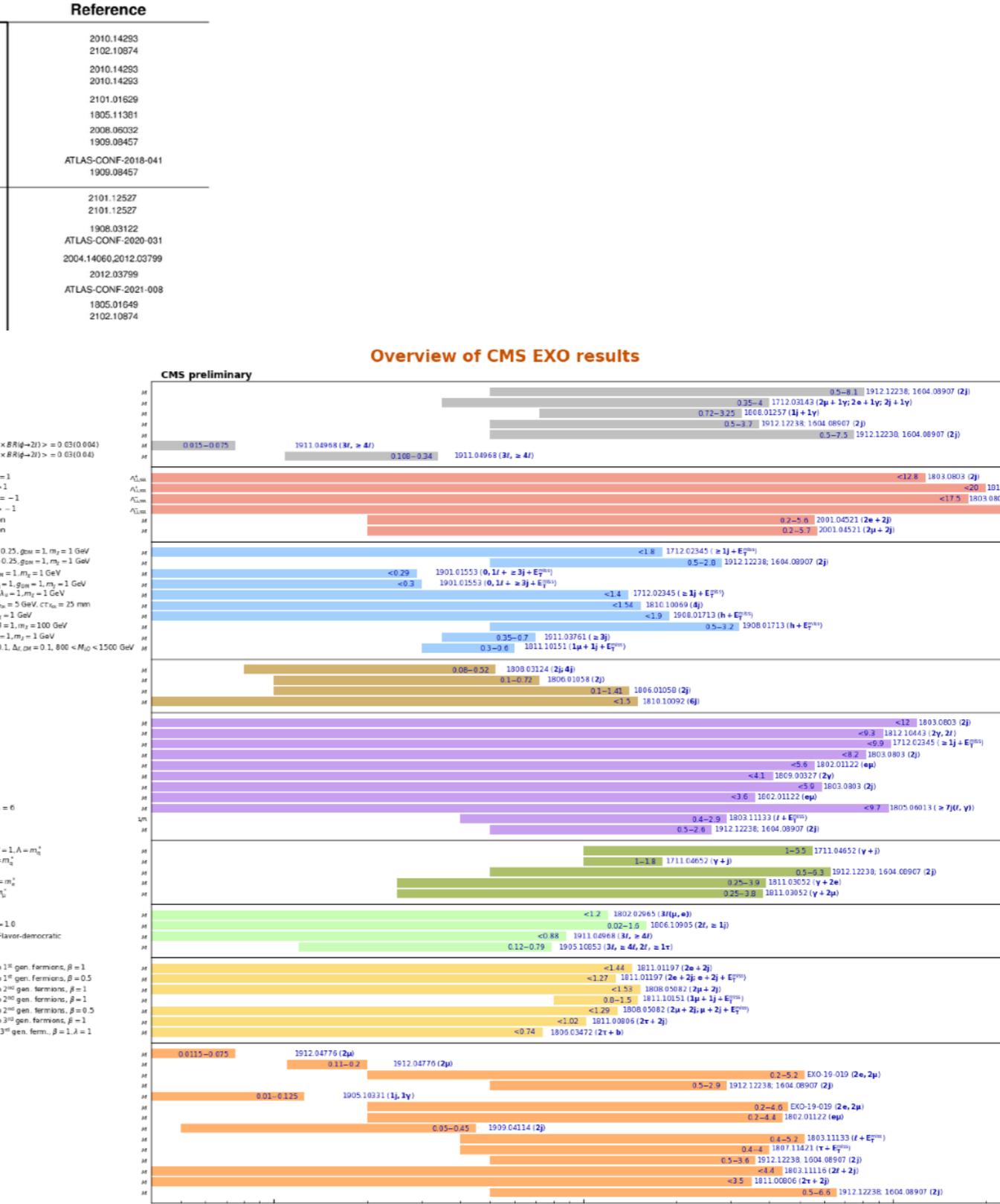
Apologize if not including your favorite model ...

Where New Physics?

ATLAS SUSY Searches* - 95% CL Lower Limits
March 2021

ATLAS Preliminary
 $\sqrt{s} = 13$ TeV

Model	Signature	$\int \mathcal{L} dt$ [fb $^{-1}$]	Mass limit	Reference					
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, μ mono-jet	E_T^{miss} E_T^{miss}	139 36.1	\tilde{q} [1x, 8x Degen] \tilde{q} [8x Degen]	1.0 0.9	1.85	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	2010.14293 2102.10874
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, μ	2-6 jets E_T^{miss}	139	\tilde{g}	Forbidden	2.3	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{g}) = 1000$ GeV	2010.14293 2010.14293
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, μ	2-6 jets	E_T^{miss}	139	\tilde{g}	2.2	$m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	0 e, μ	2 jets	E_T^{miss}	36.1	\tilde{g}	1.2	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50$ GeV	1805.11361
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, μ	7-11 jets	E_T^{miss}	139	\tilde{g}	1.97	$m(\tilde{\chi}_1^0) < 600$ GeV	2008.06032
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	SS e, μ	6 jets	E_T^{miss}	139	\tilde{g}	1.15	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets	E_T^{miss} E_T^{miss}	79.8 139	\tilde{g} \tilde{g}	2.25 1.25	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	ATLAS-CONF-2018-041 1909.08457
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ	2 b	E_T^{miss}	139	\tilde{b}_1	1.255	$m(\tilde{\chi}_1^0) < 400$ GeV 10 GeV $< \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow b\tilde{h}\tilde{\chi}_1^0$	0 e, μ	6 b	E_T^{miss}	139	\tilde{b}_1	Forbidden	0.23-1.35	1908.03122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ	≥ 1 jet	E_T^{miss}	139	\tilde{t}_1	1.25	$\Delta m(\tilde{t}_1^+, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{t}_2^+, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ	3 jets/1 b	E_T^{miss}	139	\tilde{t}_1	Forbidden	0.65	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau_1 b\tilde{\chi}_1^0, \tilde{t}_1 \rightarrow \tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	139	\tilde{t}_1	Forbidden	1.4	2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{\chi}_1^0, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ	2 c	E_T^{miss}	36.1	\tilde{t}_1	0.85	$m(\tilde{\chi}_1^0) = 1$ GeV	ATLAS-CONF-2021-008
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{\chi}_1^0, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ	mono-jet	E_T^{miss}	139	\tilde{t}_1	0.55	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 2102.10874
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 e, μ	1-4 b	E_T^{miss}	139	\tilde{t}_1	0.067-1.18	-	-	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ	1 b	E_T^{miss}	139	\tilde{t}_2	Forbidden	0.86	-	
EW direct	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via WZ	3 e, μ	≥ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	0.64	-	-
	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$ via WW	2 e, μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$	0.42	-	-
	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$ via Wh	0-1 e, μ	2 $h/2 \gamma$	E_T^{miss}	139	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$	Forbidden	0.74	-
	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$ via $\tilde{t}_L/\tilde{\nu}$	2 e, μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^+$	1.0	-	-
	$\tilde{t}_L, \tilde{t}_L \rightarrow t\tilde{\chi}_1^0$	2 τ	0 jets	E_T^{miss}	139	\tilde{t}_L	0.16-0.3	0.12-0.39	-
$\tilde{t}_L, \tilde{t}_L \rightarrow t\tilde{\chi}_1^0$	2 e, μ	≥ 1 jet	E_T^{miss}	139	\tilde{t}_L	0.256	0.7	-	
$\tilde{t}_L, \tilde{t}_L \rightarrow t\tilde{\chi}_1^0$	0 e, μ	0 jets	E_T^{miss}	139	\tilde{t}_L	0.13-0.23	0.29-0.88	-	
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	4 e, μ	$\geq 3 b$ 0 jets	E_T^{miss} E_T^{miss}	36.1 139	\tilde{H} \tilde{H}	0.55	-	-	
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}_1^\pm$	0.21	0.66	-
	Stable \tilde{g} R-hadron	Multiple	Multiple	E_T^{miss}	36.1	\tilde{g}	-	-	-
RPV	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Displ. lep	Multiple	E_T^{miss}	139	\tilde{g}	0.34	0.7	-
	$\tilde{\chi}_1^+ \tilde{\chi}_1^+ / \tilde{\chi}_1^+ \tilde{\chi}_1^0 \rightarrow Z\ell\ell$	3 e, μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^+ \tilde{\chi}_1^+ / \tilde{\chi}_1^+ \tilde{\chi}_1^0$	0.625	1.05	-
	$\tilde{\chi}_1^+ \tilde{\chi}_1^+ / \tilde{\chi}_1^+ \tilde{\chi}_1^0 \rightarrow WWZZ\ell\ell\nu\nu$	4 e, μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^+ \tilde{\chi}_1^+ / \tilde{\chi}_1^+ \tilde{\chi}_1^0$	0.95	1.55	-
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}q$	4-5 large-R jets	Multiple	E_T^{miss}	36.1	\tilde{g}	1.3	1.1	-
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}s$	$\geq 4b$	Multiple	E_T^{miss}	139	\tilde{t}_1	0.55	1.05	-

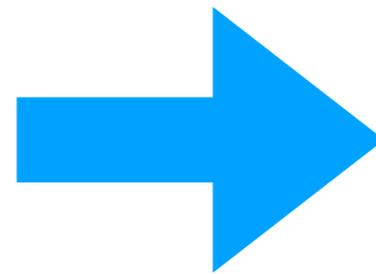
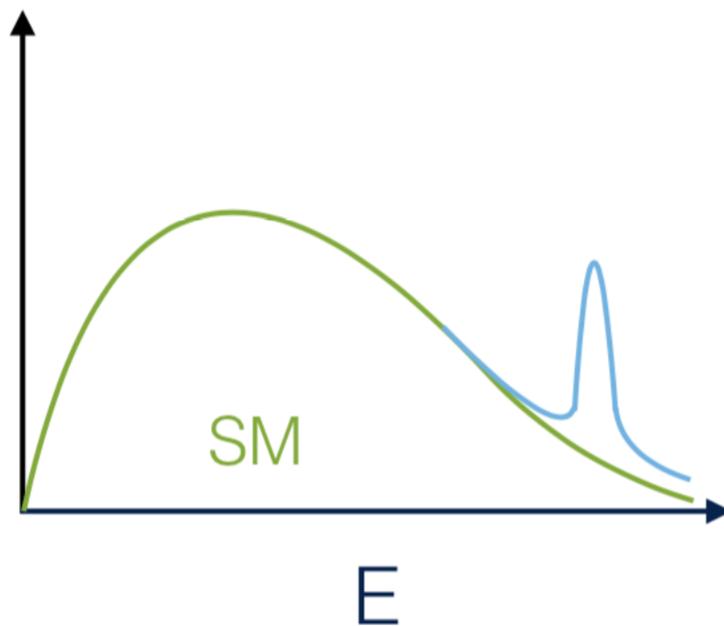


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

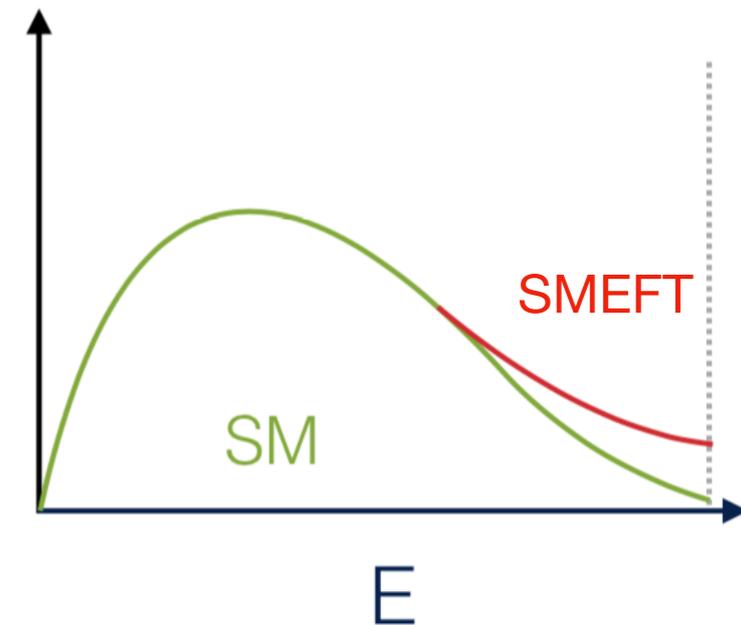
Paradigm Shift

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

Direct signature



Indirect searches



resonance bump hunting at the LHC

distribution (xsection) deviation at the LHC

Model building

Effective operator description

Effective Lagrangian

2005/12/18 First TeV Physics Working Group Meeting

[Prof. Y.-P. Kuang's slides]

SUSY (轻 Higgs) TC (无 Higgs) top seesaw (重 Higgs) extra dim. (无 Higgs) little Higgs (轻 Higgs) ...



自然界=?

研究 无遗漏的普遍探测。若 LHC 未发现新粒子，更需要这种研究。

探测已发现粒子的 有效拉氏量系数 (有效相互作用)



●有轻 Higgs 的情况:

需要测量其 反常耦合

●无轻 Higgs 的情况:

需测量 电弱手征拉氏量 的各系数

Which EFT for New Physics?

Before the Higgs discovery ...

Weak dynamics @ EW scale

SM, SUSY, etc

**Standard Model EFT
(SMEFT)**

Strong dynamics @ EW scale

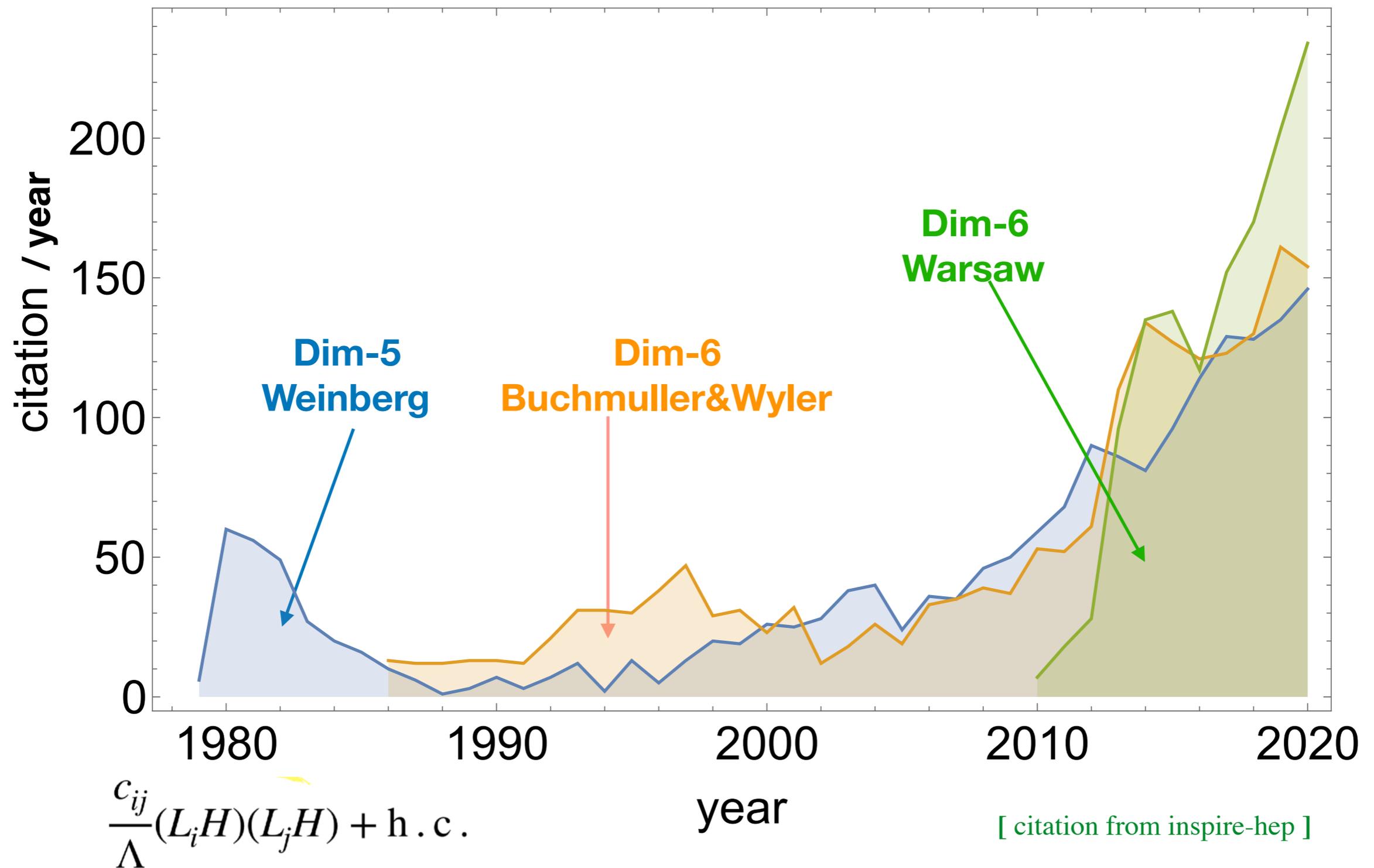
Technicolor, etc

Electroweak Chiral Lagrangian



SMEFT

After the Higgs discovery ...



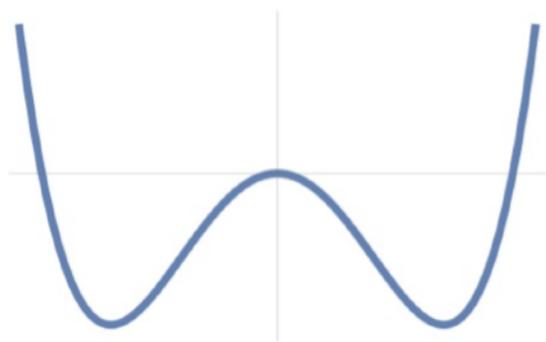
Higgs EFT

Next mission: what is the nature of Higgs Boson!

Classify Higgs nature in four categories:

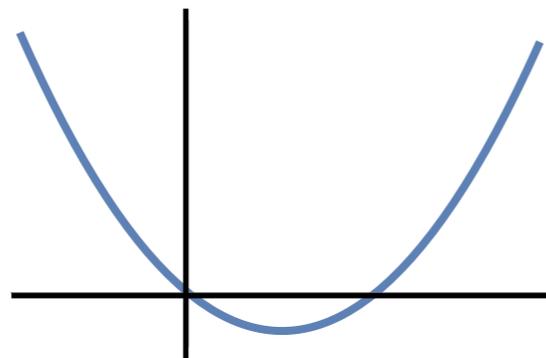
[Agrawal, Saha, Xu, **Yu**, Yuan, 1907.02078]

Landau-Ginzburg Higgs



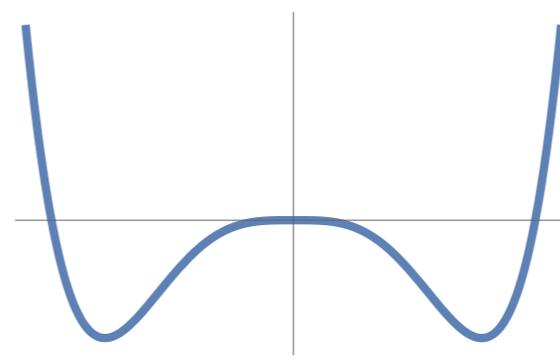
$$V(\phi) = -m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

Tadpole-induced Higgs



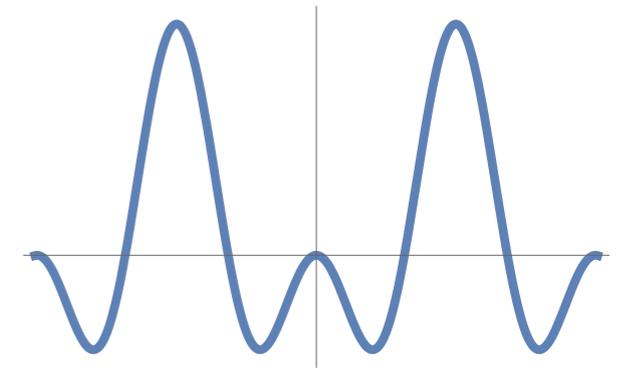
$$V(\phi) = -\mu^3 \sqrt{\phi^\dagger \phi} + m^2 \phi^\dagger \phi$$

Coleman Weinberg Higgs



$$V(\phi) = \lambda (\phi^\dagger \phi)^2 + \epsilon (\phi^\dagger \phi)^2 \log \frac{\phi^\dagger \phi}{\mu^2}$$

Pseudo-Goldstone Higgs



$$V(\phi) = -a \sin^2(\phi/f) + b \sin^4(\phi/f)$$

Fundamental
particle

Partial Fundamental
(condensate)

Conformal particle

Composite particle

Not all of these scenarios can be described in SMEFT

Need electroweak chiral Lagrangian with light Higgs (HEFT)

Also [Falkowski, Rattazzi 2019]

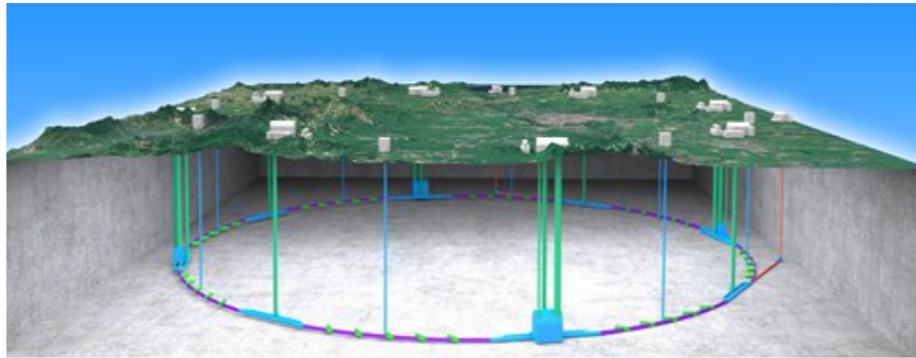
[Cohen, Craig, Lu, Sutherland, 2021]

[Gomez-Ambrosio, etc, 2022]

Low Energy Probe of HEP

Energy frontiers for searching new physics

high energy, high cost!



TeV scale

EW scale

m_W

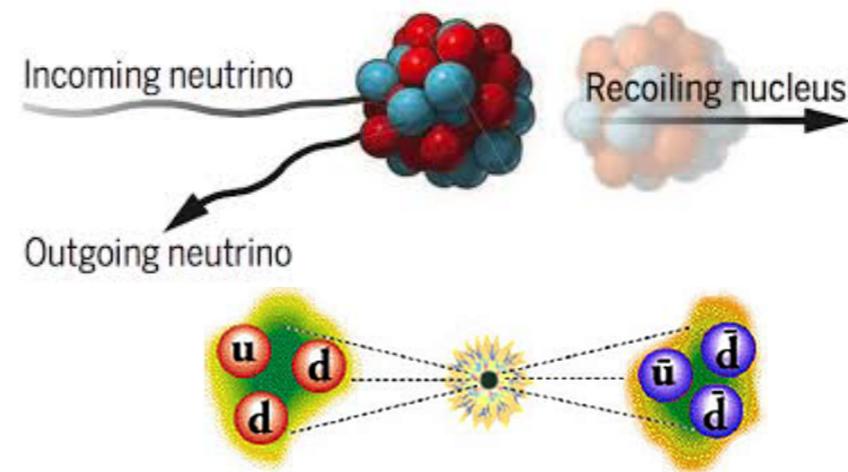
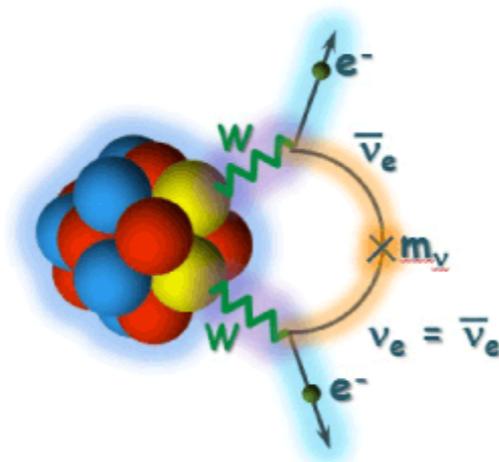
Λ_{QCD}

MeV scale

Nucleus

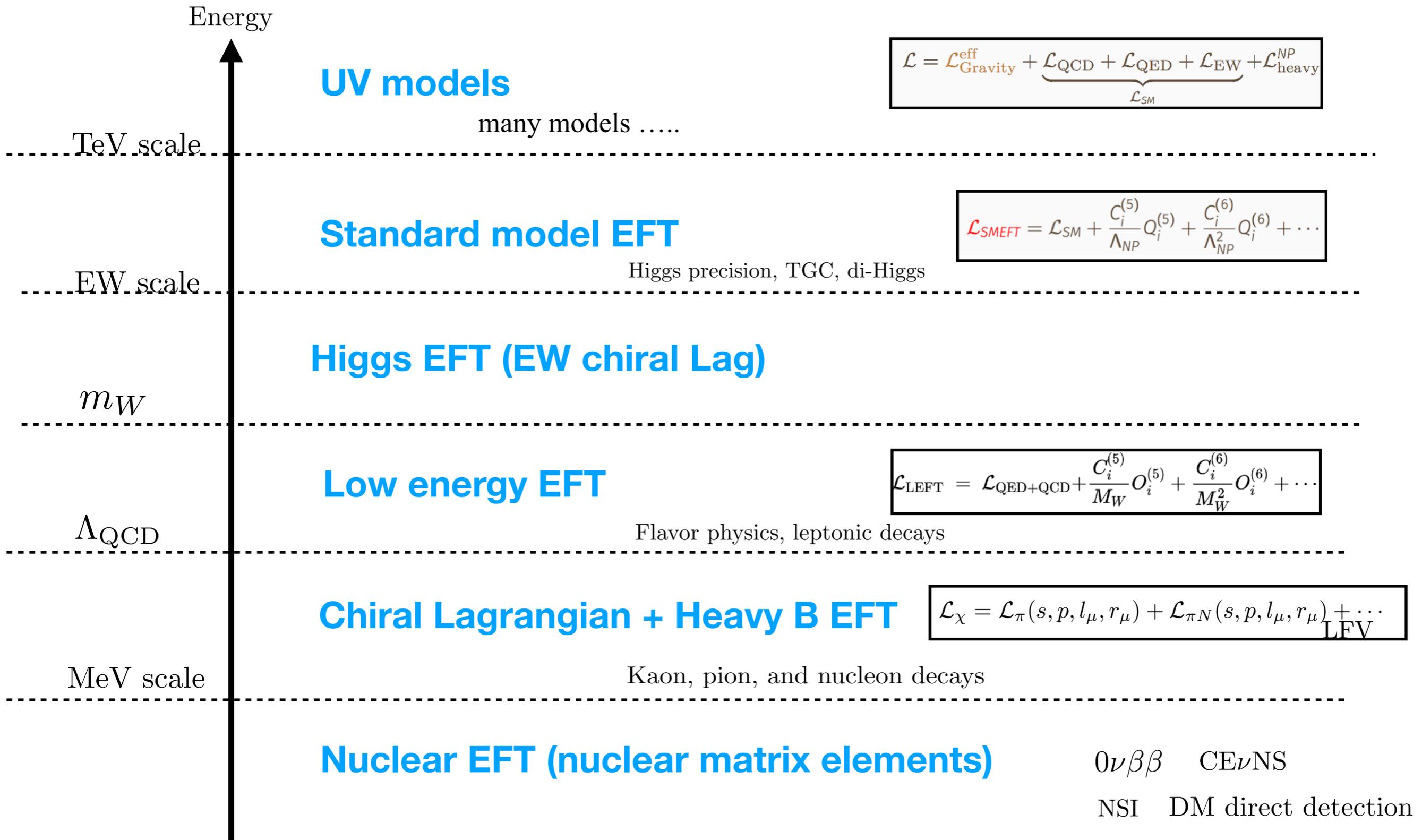
Low energy probe of high energy physics

high intensity, low cost!

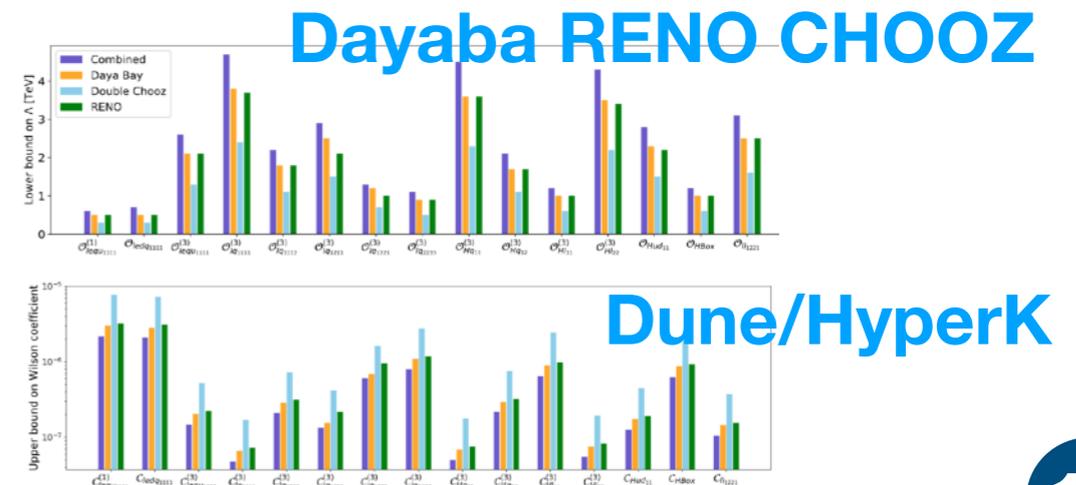
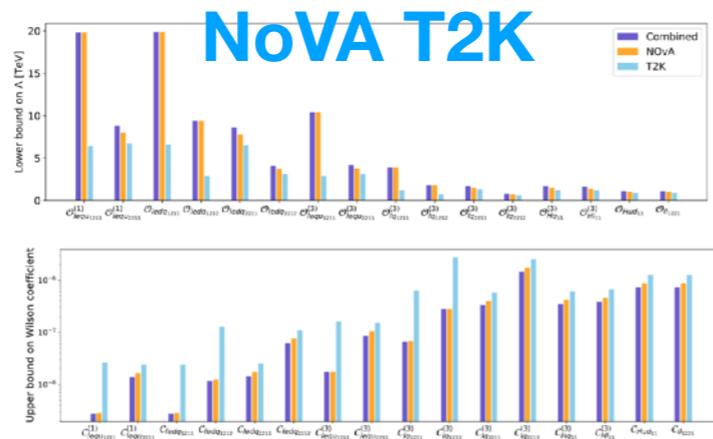
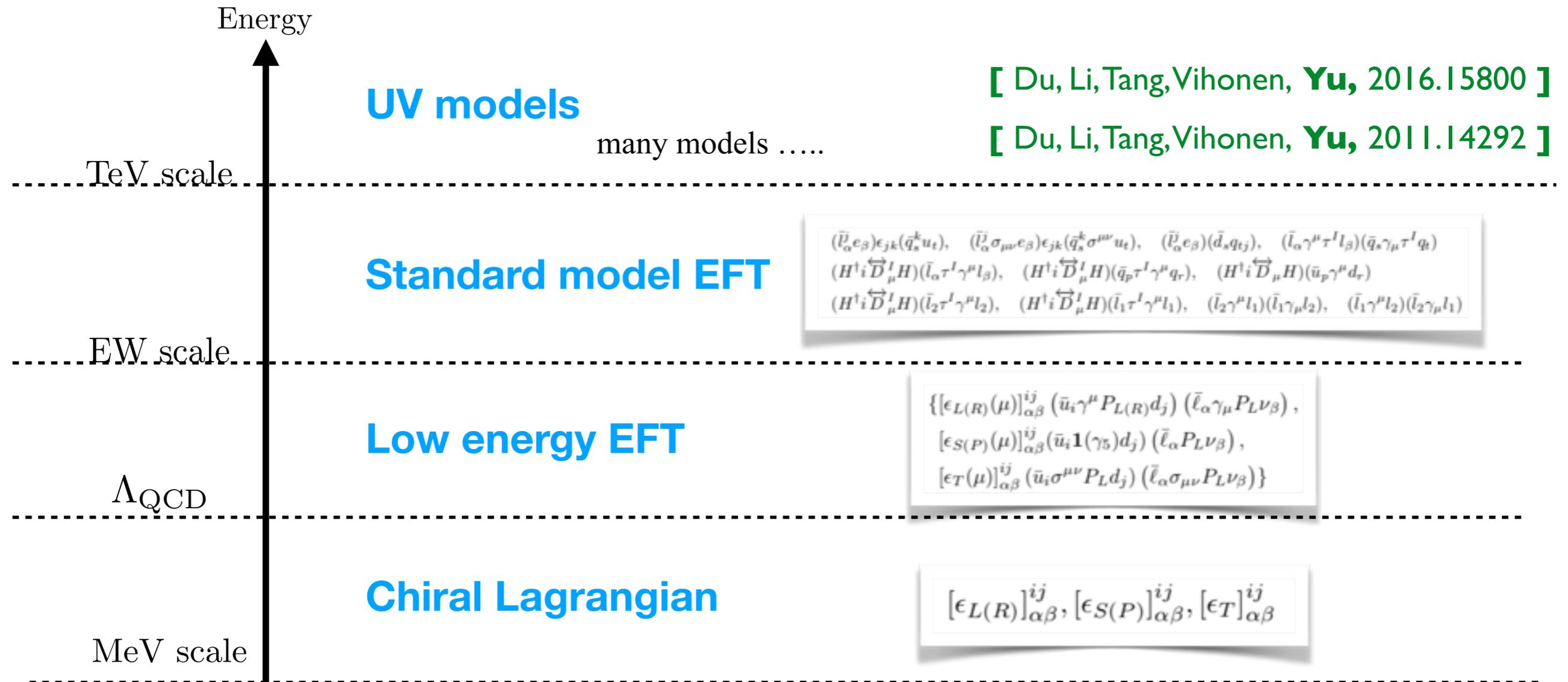


Also light new physics

EFT Ladder



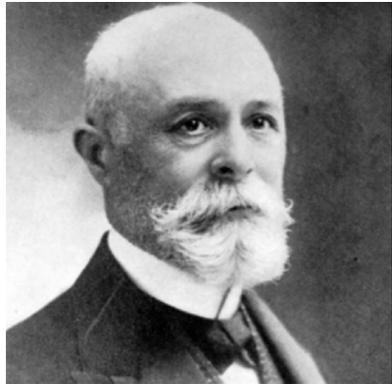
4-Fermi EFT: From Beta to NSI



Operator Basis Construction

History of Weak Theory

First effective Lagrangian: 4-fermion theory



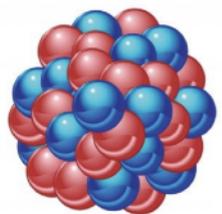
Becquerel
1896

Pauli
1933

Fermi
1934

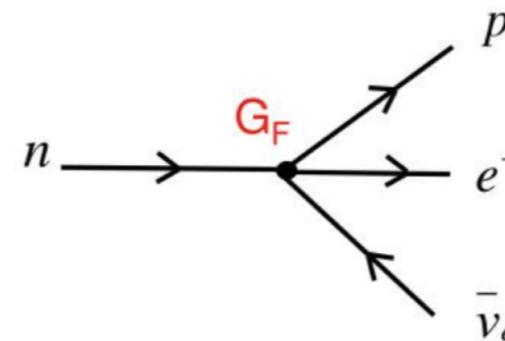
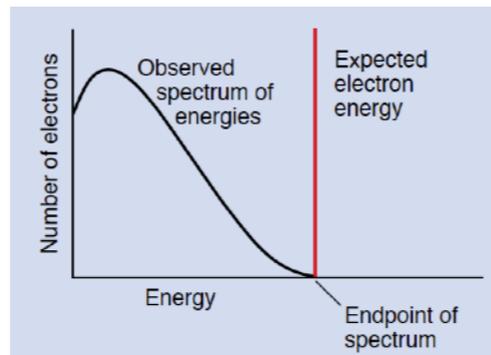
Gamov-Teller 1936
Fierz 1937

Beta Decay



Nucleus

Beta Particle
(fast electron)
 β



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

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

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

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

Four-fermi EFT

Four-Fermi EFT

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



Lee-Yang 1956
Wu 1956

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

Question of Parity Conservation in Weak Interactions*

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

AND

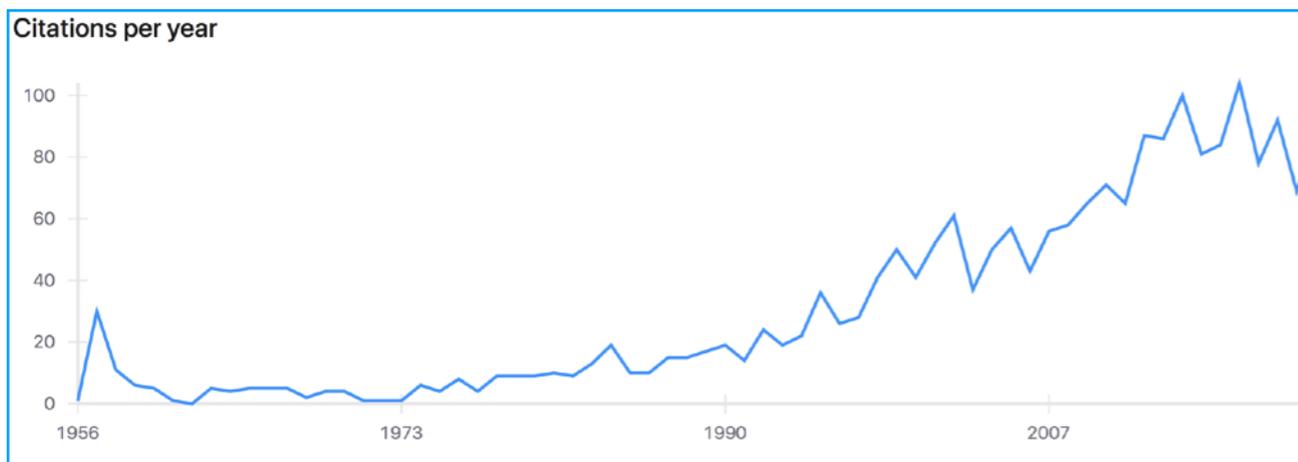
C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

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

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

Complete charge current LEFT operators



Comprehensive analysis of beta decays within and beyond the Standard Model

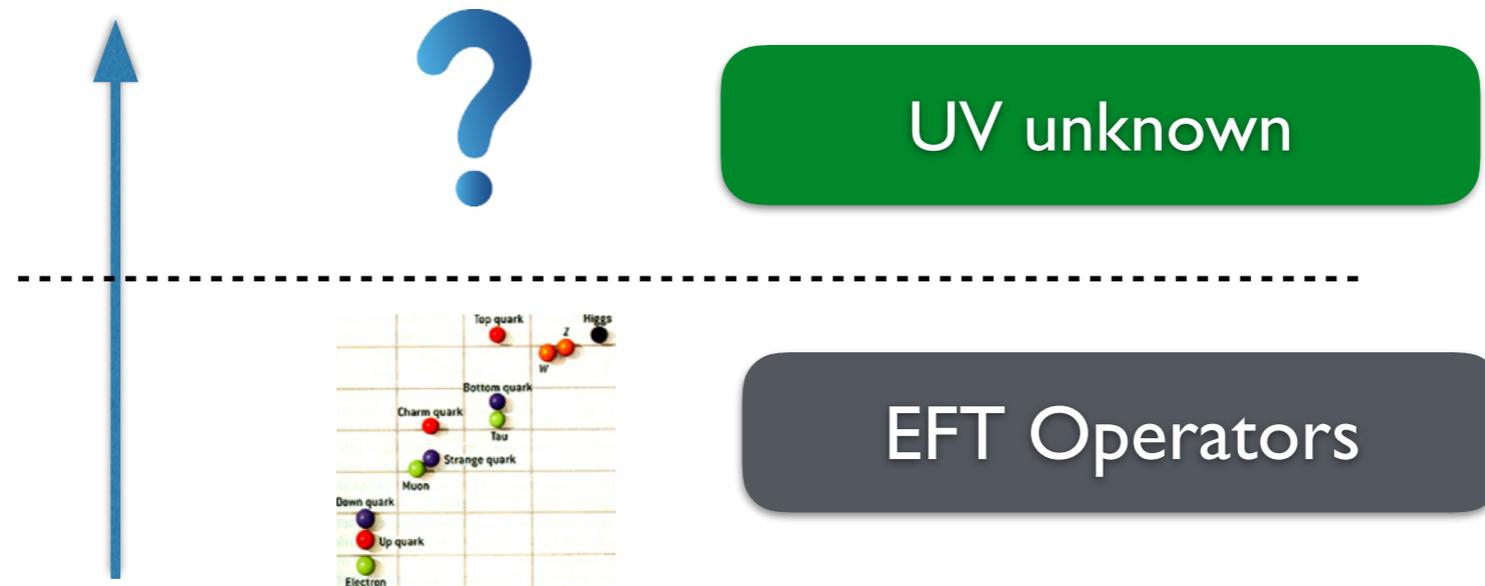
[Falkowski, et.al 2021]

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

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

Weinberg's Folk Theorem

Start from the complete and independent operators



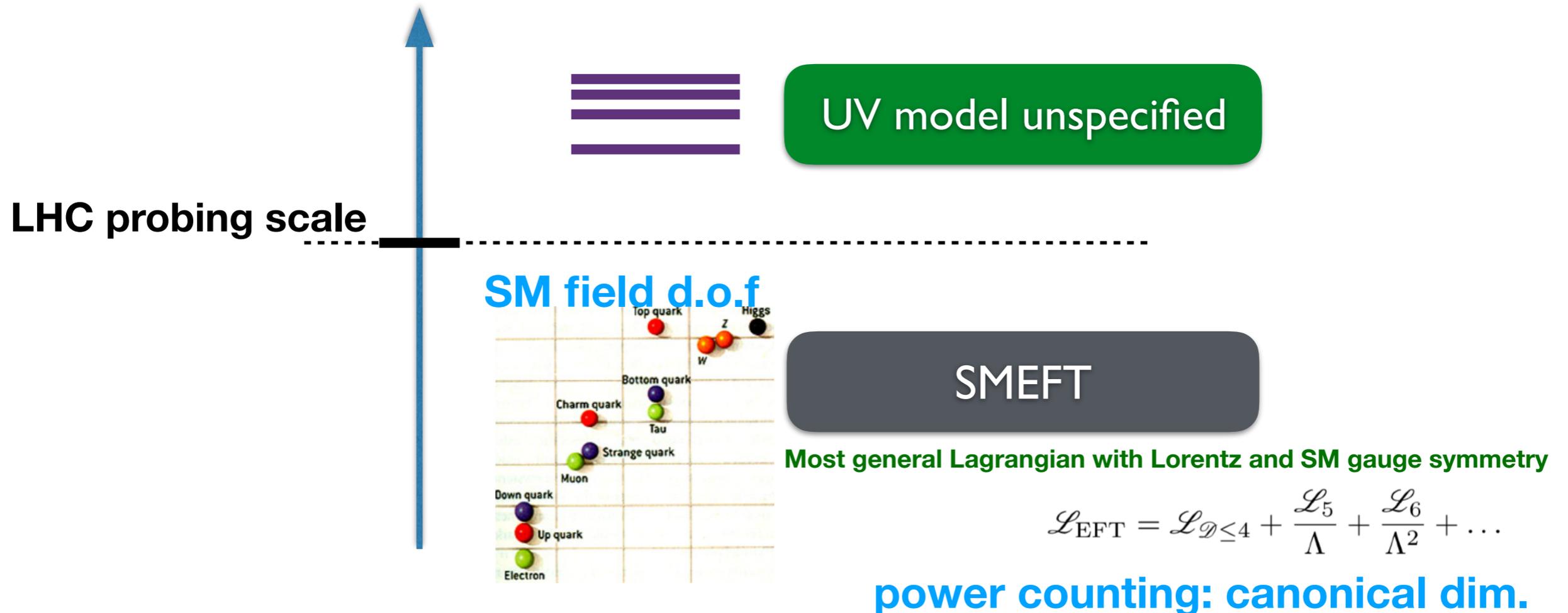
[Weinberg 1933 - 2021]

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

Weinberg's Folk theorem, 1979

SMEFT

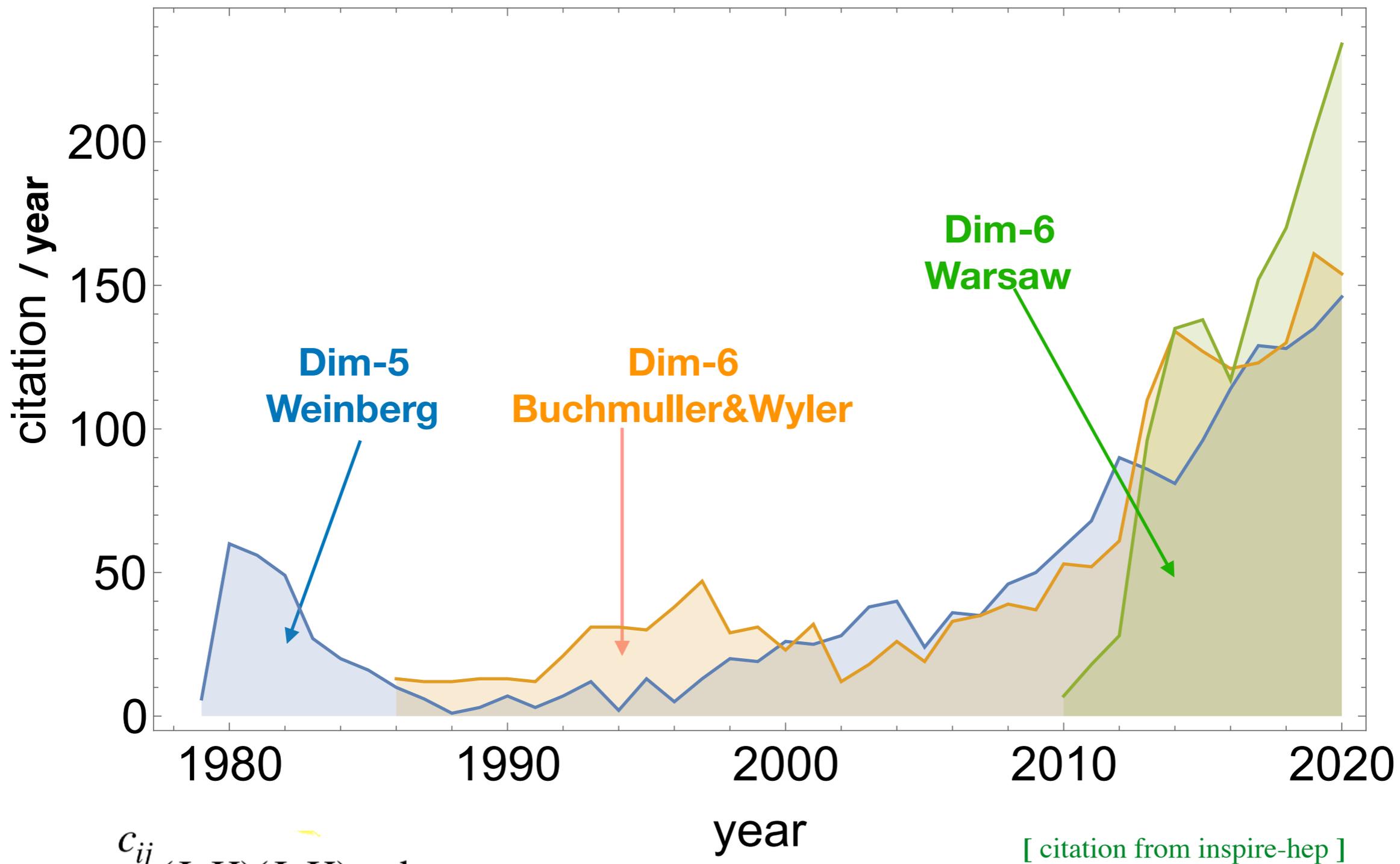
Standard model effective field theory (SMEFT)



SMEFT provides systematic parametrization of

... all possible Lorentz inv. new physics!

SMEFT Operators



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

Dim-6 Operators

Why completing dim-6 took more than 25 years?

tedious and prone-to-error

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

Equation of motion (Field redefinition)

$$\begin{aligned}
 (D^\mu D_\mu \varphi)^j &= m^2 \varphi^j - \lambda (\varphi^\dagger \varphi) \varphi^j - \bar{e} \Gamma_e^\dagger l^j + \varepsilon_{jk} \bar{q}^k \Gamma_u u - \bar{d} \Gamma_d^\dagger q^j \\
 i\not{D}l &= \Gamma_e e \varphi, & i\not{D}e &= \Gamma_e^\dagger \varphi^\dagger l, & i\not{D}q &= \Gamma_u u \tilde{\varphi} + \Gamma_d d \varphi, & i\not{D}u &= \Gamma_u^\dagger \tilde{\varphi}^\dagger q, \\
 (D^\rho W_{\rho\mu})^I &= \frac{g}{2} (\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi + \bar{l} \gamma_\mu \tau^I l + \bar{q} \gamma_\mu \tau^I q),
 \end{aligned}$$

Covariant derivative commutator

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

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

Integration by part (total derivatives)

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

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

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

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

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[Buchmuller, Wyler, 1986]

$$\begin{aligned}
 O_{D_\nu} &= (\bar{\ell} D_\mu e) D^\mu \varphi, & O_{D_\nu} &= (D_\mu \bar{\ell} e) D^\mu \varphi, & O_{\varphi\ell}^{(1)} &= i(\varphi^\dagger D_\mu \varphi)(\bar{\ell} \gamma^\mu \ell), \\
 O_{D_u} &= (\bar{q} D_\mu u) D^\mu \varphi, & O_{D_u} &= (D_\mu \bar{q} u) D^\mu \varphi, & O_{\varphi\ell}^{(3)} &= i(\varphi^\dagger D_\mu \tau^I \varphi)(\bar{\ell} \gamma^\mu \tau^I \ell), \\
 O_{D_d} &= (\bar{q} D_\mu d) D^\mu \varphi, & O_{D_d} &= (D_\mu \bar{q} d) D^\mu \varphi, & O_{\varphi e} &= i(\varphi^\dagger D_\mu \varphi)(\bar{e} \gamma^\mu e), \\
 O_{eW} &= (\bar{\ell} \sigma^{\mu\nu} \tau^I e) \varphi W_{\mu\nu}^I, & O_{eB} &= (\bar{\ell} \sigma^{\mu\nu} e) \varphi B_{\mu\nu}, & O_{\varphi q}^{(1)} &= i(\varphi^\dagger D_\mu \varphi)(\bar{q} \gamma^\mu q), \\
 O_{uG} &= (\bar{q} \sigma^{\mu\nu} \lambda^A u) \varphi G_{\mu\nu}^A, & & & O_{\varphi q}^{(3)} &= i(\varphi^\dagger D_\mu \tau^I \varphi)(\bar{q} \gamma^\mu \tau^I q), \\
 O_{uW} &= (\bar{q} \sigma^{\mu\nu} \tau^I u) \varphi W_{\mu\nu}^I, & O_{uB} &= (\bar{q} \sigma^{\mu\nu} u) \varphi B_{\mu\nu}, & O_{\varphi u} &= i(\varphi^\dagger D_\mu \varphi)(\bar{u} \gamma^\mu u), \\
 O_{dG} &= (\bar{q} \sigma^{\mu\nu} \lambda^A d) \varphi G_{\mu\nu}^A, & & & O_{\varphi d} &= i(\varphi^\dagger D_\mu \varphi)(\bar{d} \gamma^\mu d), \\
 O_{dW} &= (\bar{q} \sigma^{\mu\nu} \tau^I d) \varphi W_{\mu\nu}^I, & O_{dB} &= (\bar{q} \sigma^{\mu\nu} d) \varphi B_{\mu\nu}, & O_{\varphi\varphi} &= i(\varphi^\dagger \varepsilon D_\mu \varphi)(\bar{u} \gamma^\mu d).
 \end{aligned}$$

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

$$\begin{aligned}
 O_{ee} &= \frac{1}{2}(\bar{e} \gamma_\mu e)(\bar{e} \gamma^\mu e), & O_{\ell e} &= (\bar{\ell} e)(\bar{e} \ell), & O_{\ell q}^{(1)} &= (\bar{q} u)(\bar{q} d), \\
 O_{uu}^{(1)} &= \frac{1}{2}(\bar{u} \gamma_\mu u)(\bar{u} \gamma^\mu u), & O_{\ell u} &= (\bar{\ell} u)(\bar{u} \ell), & O_{\varphi q}^{(8)} &= (\bar{q} \lambda^A u)(\bar{q} \lambda^A d), \\
 O_{dd}^{(1)} &= \frac{1}{2}(\bar{d} \gamma_\mu d)(\bar{d} \gamma^\mu d), & O_{\ell d} &= (\bar{\ell} d)(\bar{d} \ell), & O_{\ell q} &= (\bar{\ell} e)(\bar{q} u), \\
 O_{eu} &= (\bar{e} \gamma_\mu e)(\bar{u} \gamma^\mu u), & O_{qe} &= (\bar{q} e)(\bar{e} q), & O_{qu}^{(8)} &= (\bar{q} \lambda^A u)(\bar{u} \lambda^A q), \\
 O_{ed} &= (\bar{e} \gamma_\mu e)(\bar{d} \gamma^\mu d), & O_{qu}^{(1)} &= (\bar{q} u)(\bar{u} q), & O_{qd}^{(8)} &= (\bar{q} \lambda^A d)(\bar{d} \lambda^A q), \\
 O_{ud}^{(1)} &= (\bar{u} \gamma_\mu u)(\bar{d} \gamma^\mu d), & O_{qd}^{(1)} &= (\bar{q} d)(\bar{d} q), & & \\
 O_{ud}^{(8)} &= (\bar{u} \gamma_\mu \lambda^A u)(\bar{d} \gamma^\mu \lambda^A d), & O_{qe} &= (\bar{q} e)(\bar{e} q), & & \\
 & & O_{de} &= (\bar{d} e)(\bar{e} d), & &
 \end{aligned}$$

80-1-16-5+1 = 59

X ³		φ ⁶ and φ ⁴ D ²		ψ ² φ ³	
Q _G	f ^{ABC} G _μ ^{Aν} G _ν ^{Bρ} G _ρ ^{Cμ}	Q _φ	(φ [†] φ) ³	Q _{eφ}	(φ [†] φ)($\bar{\ell}_p e_r \varphi$)
Q _{̃G}	f ^{ABC} ̃G _μ ^{Aν} G _ν ^{Bρ} G _ρ ^{Cμ}	Q _{φ□}	(φ [†] φ)□(φ [†] φ)	Q _{uφ}	(φ [†] φ)($\bar{q}_p u_r \tilde{\varphi}$)
Q _W	ε ^{IJK} W _μ ^{Iν} W _ν ^{Jρ} W _ρ ^{Kμ}	Q _{φD}	(φ [†] D ^μ φ) [†] (φ [†] D _μ φ)	Q _{dφ}	(φ [†] φ)($\bar{q}_p d_r \varphi$)
Q _{̃W}	ε ^{IJK} ̃W _μ ^{Iν} W _ν ^{Jρ} W _ρ ^{Kμ}				
X ² φ ²		ψ ² Xφ		ψ ² φ ² D	
Q _{φG}	φ [†] φ G _{μν}^A G^{Aμν}}	Q _{eW}	($\bar{\ell}_p \sigma^{\mu\nu} e_r$)τ ^I φ W _{μν}^I}	Q _{̃φℓ}^{(1)}}	(φ [†] i $\overleftrightarrow{D}_\mu^I$ φ)($\bar{\ell}_p \gamma^\mu l_r$)
Q _{φ̃G}	φ [†] φ ̃G _{μν}^A G^{Aμν}}	Q _{eB}	($\bar{\ell}_p \sigma^{\mu\nu} e_r$)φ B _{μν}}	Q _{̃φℓ}^{(3)}}	(φ [†] i $\overleftrightarrow{D}_\mu^I$ φ)($\bar{\ell}_p \tau^I \gamma^\mu l_r$)
Q _{φW}	φ [†] φ W _{μν}^I W^{Iμν}}	Q _{uG}	($\bar{q}_p \sigma^{\mu\nu} T^A u_r$)φ G _{μν}^A}	Q _{̃φe}	(φ [†] i $\overleftrightarrow{D}_\mu^I$ φ)($\bar{e}_p \gamma^\mu e_r$)
Q _{φ̃W}	φ [†] φ ̃W _{μν}^I W^{Iμν}}	Q _{uW}	($\bar{q}_p \sigma^{\mu\nu} u_r$)τ ^I φ W _{μν}^I}	Q _{̃φq}^{(1)}}	(φ [†] i $\overleftrightarrow{D}_\mu^I$ φ)($\bar{q}_p \gamma^\mu q_r$)
Q _{φB}	φ [†] φ B _{μν} B^{μν}}	Q _{uB}	($\bar{q}_p \sigma^{\mu\nu} u_r$)φ B _{μν}}	Q _{̃φq}^{(3)}}	(φ [†] i $\overleftrightarrow{D}_\mu^I$ φ)($\bar{q}_p \tau^I \gamma^\mu q_r$)
Q _{φ̃B}	φ [†] φ ̃B _{μν} B^{μν}}	Q _{dG}	($\bar{q}_p \sigma^{\mu\nu} T^A d_r$)φ G _{μν}^A}	Q _{̃φq}^{(1)}}	(φ [†] i $\overleftrightarrow{D}_\mu^I$ φ)($\bar{u}_p \gamma^\mu u_r$)
Q _{φWB}	φ [†] τ ^I φ W _{μν}^I B^{μν}}	Q _{dW}	($\bar{q}_p \sigma^{\mu\nu} d_r$)τ ^I φ W _{μν}^I}	Q _{̃φq}^{(3)}}	(φ [†] i $\overleftrightarrow{D}_\mu^I$ φ)($\bar{d}_p \gamma^\mu d_r$)
Q _{φ̃WB}	φ [†] τ ^I φ ̃W _{μν}^I B^{μν}}	Q _{dB}	($\bar{q}_p \sigma^{\mu\nu} d_r$)φ B _{μν}}	Q _{̃φq}^{(1)}}	i(φ [†] D _μ φ)($\bar{u}_p \gamma^\mu d_r$)
(LL)(LL)		(RR)(RR)		(LL)(RR)	
Q _{ll}	($\bar{\ell}_p \gamma_\mu l_r$)($\bar{\ell}_s \gamma^\mu l_t$)	Q _{ee}	($\bar{e}_p \gamma_\mu e_r$)($\bar{e}_s \gamma^\mu e_t$)	Q _{le}	($\bar{\ell}_p \gamma_\mu l_r$)($\bar{e}_s \gamma^\mu e_t$)
Q _{ll}^{(1)}}	($\bar{q}_p \gamma_\mu q_r$)($\bar{q}_s \gamma^\mu q_t$)	Q _{uu}	($\bar{u}_p \gamma_\mu u_r$)($\bar{u}_s \gamma^\mu u_t$)	Q _{lu}	($\bar{\ell}_p \gamma_\mu l_r$)($\bar{u}_s \gamma^\mu u_t$)
Q _{ll}^{(3)}}	($\bar{q}_p \gamma_\mu \tau^I q_r$)($\bar{q}_s \gamma^\mu \tau^I q_t$)	Q _{dd}	($\bar{d}_p \gamma_\mu d_r$)($\bar{d}_s \gamma^\mu d_t$)	Q _{ld}	($\bar{\ell}_p \gamma_\mu l_r$)($\bar{d}_s \gamma^\mu d_t$)
Q _{ll}^{(1)}}	($\bar{\ell}_p \gamma_\mu l_r$)($\bar{q}_s \gamma^\mu q_t$)	Q _{eu}	($\bar{e}_p \gamma_\mu e_r$)($\bar{u}_s \gamma^\mu u_t$)	Q _{le}	($\bar{q}_p \gamma_\mu q_r$)($\bar{e}_s \gamma^\mu e_t$)
Q _{ll}^{(3)}}	($\bar{\ell}_p \gamma_\mu \tau^I l_r$)($\bar{q}_s \gamma^\mu \tau^I q_t$)	Q _{ed}	($\bar{e}_p \gamma_\mu e_r$)($\bar{d}_s \gamma^\mu d_t$)	Q _{lu}^{(1)}}	($\bar{q}_p \gamma_\mu q_r$)($\bar{u}_s \gamma^\mu u_t$)
		Q _{ud}^{(1)}}	($\bar{u}_p \gamma_\mu u_r$)($\bar{d}_s \gamma^\mu d_t$)	Q _{le}^{(8)}}	($\bar{q}_p \gamma_\mu T^A q_r$)($\bar{u}_s \gamma^\mu T^A u_t$)
		Q _{ud}^{(8)}}	($\bar{u}_p \gamma_\mu T^A u_r$)($\bar{d}_s \gamma^\mu T^A d_t$)	Q _{ld}^{(1)}}	($\bar{q}_p \gamma_\mu q_r$)($\bar{d}_s \gamma^\mu d_t$)
		Q _{ld}^{(8)}}	($\bar{q}_p \gamma_\mu T^A q_r$)($\bar{d}_s \gamma^\mu T^A d_t$)	Q _{ld}^{(8)}}	($\bar{q}_p \gamma_\mu T^A q_r$)($\bar{d}_s \gamma^\mu T^A d_t$)
(LR)(RL) and (LR)(LR)		B-violating			
Q _{le}^{(1)}}	($\bar{\ell}_p e_r$)($\bar{d}_s q_t^I$)	Q _{du}^{(1)}}	ε ^{αβγ} ε _{ijk} [(d _p ^α) ^T C u _r ^β] [(q _s ^γ) ^T C l _t ^δ]		
Q _{qu}^{(1)}}	($\bar{q}_p^I u_r$)ε _{jk} ($\bar{q}_s^k d_t$)	Q _{qu}^{(8)}}	ε ^{αβγ} ε _{ijk} [(q _p ^α) ^T C q _r ^{βk}] [(u _s ^γ) ^T C e _t]		
Q _{qu}^{(8)}}	($\bar{q}_p^I T^A u_r$)ε _{jk} ($\bar{q}_s^k T^A d_t$)	Q _{qu}^{(8)}}	ε ^{αβγ} ε _{ijk} [(q _p ^α) ^T C q _r ^{βk}] [(q _s ^γ) ^T C l _t ^δ]		
Q _{le}^{(1)}}	($\bar{\ell}_p^I e_r$)ε _{jk} ($\bar{q}_s^k u_t$)	Q _{du}^{(8)}}	ε ^{αβγ} [(d _p ^α) ^T C u _r ^β] [(u _s ^γ) ^T C e _t]		
Q _{le}^{(8)}}	($\bar{\ell}_p^I \sigma_{\mu\nu} e_r$)ε _{jk} ($\bar{q}_s^k \sigma^{\mu\nu} u_t$)				

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

Operator as Spinor Tensor

Operator has more symmetries than what we expected

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

Operator with explicit spinor indices

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

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

Easier to find more symmetries of the operator with spinor indices

Operator as Spinor Tensor

Modern view: operator as contact on-shell amplitude (same S-matrix/ field redefinition)

Operator

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

Spinor Tensor

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

Symmetrize indices

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

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

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

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

(0,0)

(1,0)

(0,1)

(1,1)

No need EOM/CDC

[Li, Ren, Shu, Xiao, **Yu**, Zheng, 2005.00008]

[Li, Ren, Xiao, **Yu**, Zheng, 2007.07899]

[Li, Ren, Xiao, **Yu**, Zheng, 2012.09188]

[Li, Ren, Xiao, **Yu**, Zheng, 2105.09323]

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

[Sun, Xiao, **Yu**, 2206.07722]

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

[Ren, **Yu**, 2211.01420]

Operator as Spinor Tensor

Modern view: operator as contact on-shell amplitude (momentum conservation)

[Li, Ren, Shu, Xiao, **Yu**, Zheng, 2005.00008]

[Li, Ren, Xiao, **Yu**, Zheng, 2007.07899]

[Li, Ren, Xiao, **Yu**, Zheng, 2012.09188]

[Li, Ren, Xiao, **Yu**, Zheng, 2105.09323]

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

[Sun, Xiao, **Yu**, 2206.07722]

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

[Ren, **Yu**, 2211.01420]

Operator

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

Spinor Tensor

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

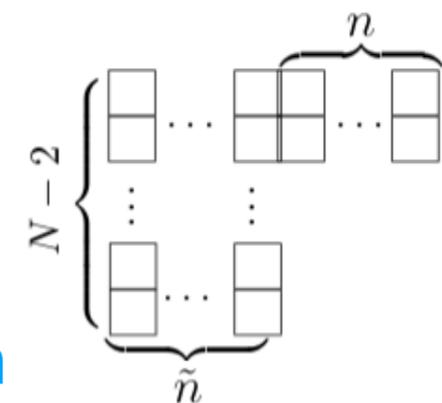
Symmetrize indices

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

SL(2,C) x SU(N)

$$\epsilon^{\alpha_i\alpha_j} \rightarrow \sum_{k,l} U_k^i U_l^j \epsilon^{\alpha_k\alpha_l}, \quad \tilde{\epsilon}_{\dot{\alpha}_i\dot{\alpha}_j} \rightarrow \sum_{k,l} U_i^{\dagger k} U_j^{\dagger l} \tilde{\epsilon}_{\dot{\alpha}_k\dot{\alpha}_l}$$

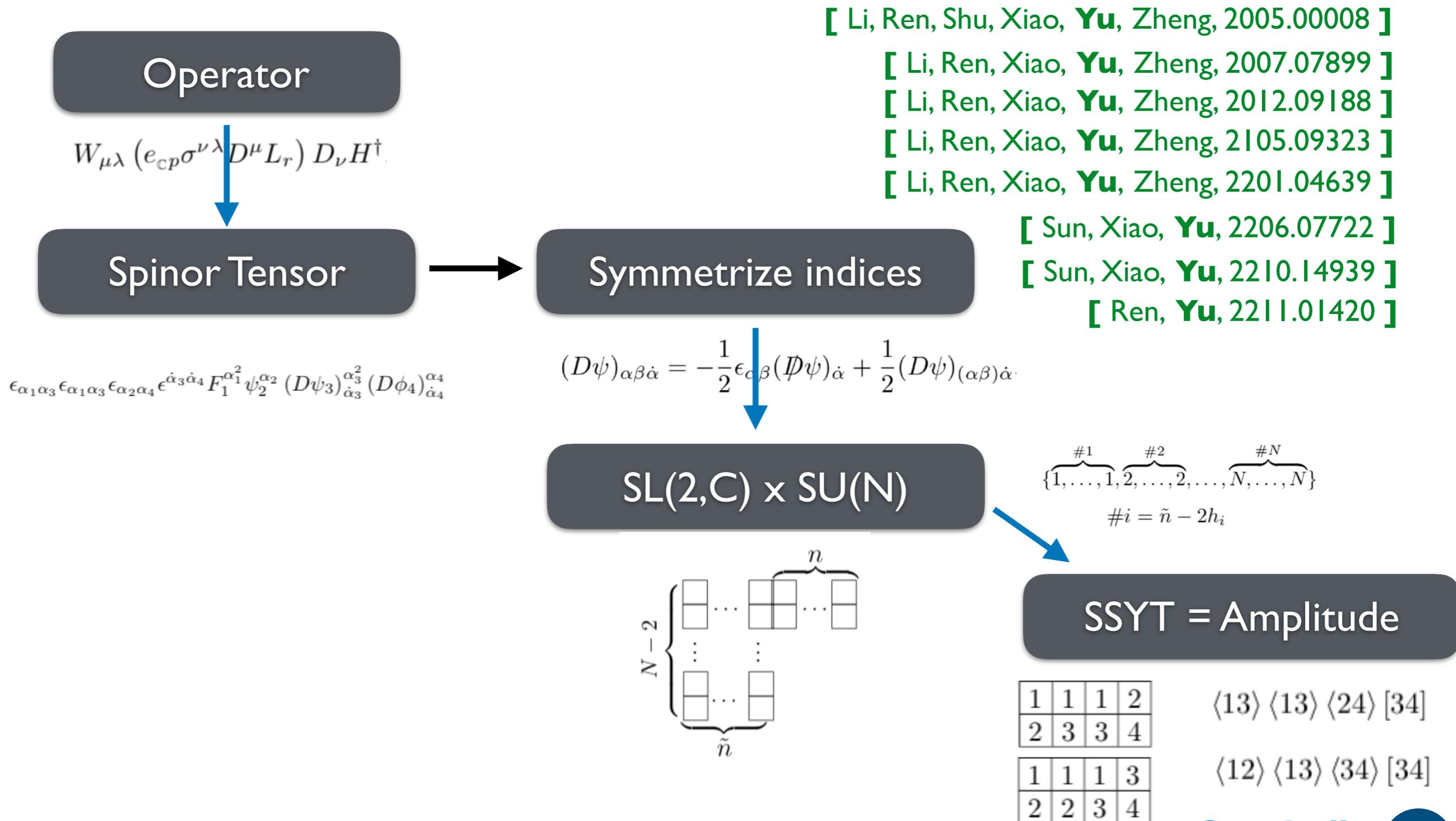
$$\mathcal{O} = (\epsilon^{\alpha_i\alpha_j})^n (\tilde{\epsilon}_{\dot{\alpha}_i\dot{\alpha}_j})^{\tilde{n}} \prod_{i=1}^N (D^{r_i-|h_i|} \Phi_i)^{\dot{\alpha}_i^{r_i+h_i} \alpha_i^{r_i-h_i}}$$



No need IBP/Schouten

Operator as Spinor Tensor

Modern view: operator as contact on-shell amplitude (one-to-one correspondence)



[Li, Ren, Shu, Xiao, **Yu**, Zheng, 2005.00008]

[Li, Ren, Xiao, **Yu**, Zheng, 2007.07899]

[Li, Ren, Xiao, **Yu**, Zheng, 2012.09188]

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

[Ren, **Yu**, 2211.01420]

Operator as Spinor Tensor

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

$\bar{\omega} \backslash \omega$	0	2	4	6	8
0					
2					
4					
6					
8					

Unified construction of Lorentz & gauge structures by Young Tableau

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

Complete Operator Basis

SSYT Filling forms a linear basis, which guarantees all operators found

semi-standard Young tableau (SSYT)

$$Y_{N,n,\tilde{n}} = \left\{ \begin{array}{c} \underbrace{\left[\begin{array}{c} \square \cdots \square \square \cdots \square \\ \square \cdots \square \end{array} \right]}_n \\ \vdots \\ \underbrace{\left[\begin{array}{c} \square \cdots \square \\ \square \cdots \square \end{array} \right]}_{\tilde{n}} \end{array} \right\}_{N-2}$$

$$\{ \underbrace{1, \dots, 1}_{\#1}, \underbrace{2, \dots, 2}_{\#2}, \dots \}$$

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

Basis $\left\{ \begin{array}{l} \text{YT method guarantees independence!} \\ \text{Filling all SSYT guarantees completeness!} \end{array} \right.$

Can be cross-checked using the Lorentz/Poincare characters

Schur theorem: orthonormal with Haar measure integral $\int d\mu_G(g) \chi_{\mathbf{R}}(g) \chi_{\mathbf{R}'}^*(g) = \delta_{\mathbf{R}\mathbf{R}'}$.

$$\mathcal{H}(\phi_{\mathbf{R}}, \dots, \varphi_{\mathbf{R}'}) = \int d\mu_G \text{PE}[\phi_{\mathbf{R}}, \dots, \varphi_{\mathbf{R}'}].$$

Molien-Weyl formula

Equivalently not using Young tensor, but using the off-shell formalism

$$|i_{\hat{d}_i}\rangle \langle i_{\hat{d}_i}| = - \sum_{j=1, j \neq i}^N |j_{\hat{d}_j+1}\rangle \langle j_{\hat{d}_j+1}|$$

[Ren, Yu, 2211.01420]

$$\langle i_{x_i} l_{x_l} \rangle \langle j_{x_j} k_{x_k} \rangle = - \langle i_{x_i} j_{x_j} \rangle \langle k_{x_k} l_{x_l} \rangle + \langle i_{x_i} k_{x_k} \rangle \langle j_{x_j} l_{x_l} \rangle;$$

Operator as Spinor Tensor

Young tensor method

$$BWHH^\dagger D^2$$

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

1	1	1	3
2	2	2	4

1	1	1	2
2	2	3	4

$$\tilde{\epsilon}_{\dot{\alpha}_3 \dot{\alpha}_4} \epsilon^{\alpha_1 \alpha_2} \epsilon^{\alpha_1 \alpha_2} \epsilon^{\alpha_3 \alpha_4}$$

2

$$\tilde{\epsilon}_{\dot{\alpha}_3 \dot{\alpha}_4} \epsilon^{\alpha_1 \alpha_2} \epsilon^{\alpha_1 \alpha_3} \epsilon^{\alpha_2 \alpha_4}$$

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

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

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

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

No need to

First list over-complete and remove redundancy

Details refer to All things EFT seminar

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

Jiang-Hao Yu (ITP-CAS)

Traditional method

$$BWHH^\dagger D^2$$

[Hays, Martin, Sanz, Setford, 2018]

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

EOM

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

IBP

$$\begin{aligned} & B_L^{\alpha\beta} W_{L\alpha\beta} (DH^\dagger)^\gamma{}_{\dot{\alpha}} (DH)_\gamma{}^{\dot{\alpha}} \\ & B_L^{\alpha\beta} W_{L\alpha}{}^\gamma (DH^\dagger)_{\beta\dot{\alpha}} (DH)_\gamma{}^{\dot{\alpha}} \end{aligned}$$

SMEFT

Field d.o.f: all SM fields

Symmetry: SU3 x SU2 x U1

Power counting: canonical dimension

$$\mathcal{L}_{\text{SM}} \quad \frac{c_{ij}}{\Lambda}(L_i H)(L_j H) \quad \frac{c}{\Lambda^2} \mathcal{O}_6 \quad \frac{c}{\Lambda^3} \mathcal{O}_7 \quad \frac{c}{\Lambda^4} \mathcal{O}_8 \quad \frac{c}{\Lambda^5} \mathcal{O}_9$$

[Weinberg, 1967]

[Weinberg, 1979]

Dim-6

Dim-8

[Buchmuller, Wyler, 1986]

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

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

[Murphy, 2020]

Dim-7

[Lehman, 2014]

[Henning, Lu, Melia, Murayama, 2015]

[Liao, Ma, 2016]

Dim-9

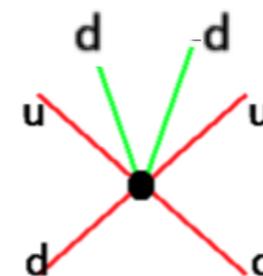
[Li, Ren, Xiao, **Yu**, Zheng, 2020]

[Liao, Ma, 2020]

RGE

[Jenkins, Manohar, Trott 2014]

[Liao, Ma, 2016]



n-nbar oscillation

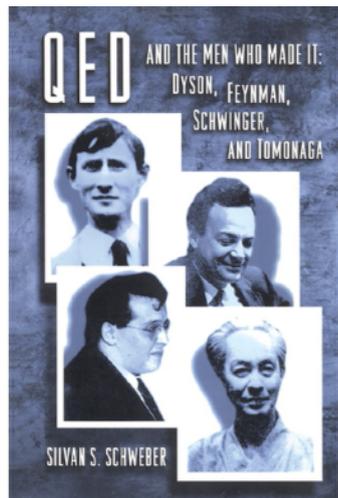
Dim-9

Low Energy EFT

Fields: SM fields except Higgs, top, W, Z

Symmetry: SU3 x U1

Power counting: canonical dimension



Dim-6

[Fermi, 1934]

[Lee, Yang, 1956]

[Jenkins, Manohar, Stoffer, 2017]

Dim-8

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

[Murphy, 2020]

Dim-7

[Liao, Ma, Wang, 2020]

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

Dim-9

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

RGE

[Jenkins, Manohar, Stoffer 2017]

[Jin, Ren, Yang 2021]

EFTs in Broken Phase

Standard model EFT

SU3 x SU2 x U1

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{C_i^{(5)}}{\Lambda_{NP}} Q_i^{(5)} + \frac{C_i^{(6)}}{\Lambda_{NP}^2} Q_i^{(6)} + \dots$$

Matching



Running

Low energy EFT

SU3 x U1

$$\mathcal{L}_{LEFT} = \mathcal{L}_{QED+QCD} + \frac{C_i^{(5)}}{M_W} O_i^{(5)} + \frac{C_i^{(6)}}{M_W^2} O_i^{(6)} + \dots$$

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

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

$$(g_L, g_R) \in \mathbf{SU}(2) \times \mathbf{SU}(2)$$

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

The vacuum is not invariant (SSB)

EW 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

approximate chiral symmetry
SU(2) x SU(2)

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

$$(g_L, g_R) \in \mathbf{SU}(2) \times \mathbf{SU}(2)$$

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

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

Chiral Lagrangian

Define the Goldstone matrix, which transform nonlinearly under G

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

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

CCWZ Coset

[Callan, Coleman, Wess, Zumino, 1969]

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

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

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

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

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

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

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

Building block

$$u_\mu = i\Omega(D_\mu U)^\dagger \Omega \quad D_\mu$$

$$f_{\mu\nu}^\pm = \frac{1}{2} (f_{\mu\nu} \pm f_{\mu\nu}^{(R)}) = \Omega^\dagger F_{\mu\nu} \Omega \pm F_{\mu\nu}^{(R)}$$

Chiral Lag for QCD and EW

$$\Omega(\Pi) \equiv \begin{bmatrix} u^{(\Pi)} & 0 \\ 0 & u^\dagger(\Pi) \end{bmatrix} \quad u \rightarrow \sqrt{g_L U g_R^\dagger} = g_L u h^{-1} = h^{-1} u g_R$$

$$U(\Pi) \equiv u^2(\Pi) \longrightarrow g_L \mathbf{U}(\Pi) g_R^\dagger$$

QCD Chiral Lag

$$u_\mu \rightarrow h u_\mu h^{-1}$$

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

$$\chi_\pm = u^\dagger \chi u^\dagger \pm u \chi^\dagger u,$$

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

$$B \rightarrow h B h^{-1}$$

$$D_\mu A = \partial_\mu A + [\Gamma_\mu, A]$$

$$[D_\mu, D_\nu] A = \frac{1}{4} [[u_\mu, u_\nu], A] - \frac{i}{2} [f_{\mu\nu}^+, A]$$

$$\Gamma_\mu = \frac{1}{2} \left[u^\dagger (\partial_\mu - i r_\mu) u + u (\partial_\mu - i l_\mu) u^\dagger \right]$$

$$\Gamma^{\mu\nu} = \nabla^\mu \Gamma^\nu - \nabla^\nu \Gamma^\mu - [\Gamma^\mu, \Gamma^\nu] = \frac{1}{4} [u^\mu, u^\nu] - \frac{i}{2} f_+^{\mu\nu}$$

EW Chiral Lag

$$\mathbf{V}_\mu \rightarrow g_L \mathbf{V} g_L^{-1}$$

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

$$\hat{W}_{\mu\nu} \longrightarrow g_L \hat{W}_{\mu\nu} g_L^\dagger$$

$$\hat{B}_{\mu\nu} \longrightarrow g_R \hat{B}_{\mu\nu} g_R^\dagger$$

$$\psi_L \longrightarrow g_L \psi_L$$

$$\mathbf{U} \psi_R \longrightarrow g_L \mathbf{U} \psi_R$$

$$\mathbf{T} = \mathbf{U} \mathcal{T}_R \mathbf{U}^\dagger \longrightarrow g_L \mathbf{T} g_L^\dagger$$

$$\mathbf{Y} = \mathbf{U} \mathcal{Y}_R \mathbf{U}^\dagger \longrightarrow g_L \mathbf{Y} g_L^\dagger$$

Higgs EFT



LO and NLO boson **2012**

LO Lagrangian

[Weinberg, 1979]

NLO Bosonic Lagrangian

[Appelquist, Bernard, 1980]

[Longhitano, 1980, 1981]

[Feruglio, 1993]

[Wang, Wang, 2006]

EWChL with light Higgs

NLO fermion sector

NLO Fermionic Lagrangian

[Buchalla, Cata, Krause, 2014]

[Pich, Rosell, Santos, Sanz-Cillero, 2015, 2018]

2020

Higgs EFT

Full NLO and NNLO

Complete NLO Lagrangian (p4)

237 (8595) operators for one (three)

[Sun, Xiao, Yu, 2206.07722]

$$\begin{aligned}
 \mathcal{O}_{33}^{Uh\psi^4} &= (\bar{q}_{Ls}\gamma_\mu\tau^I\mathbf{T}q_{Lp})(\bar{q}_{Rr}\gamma^\mu\mathbf{U}^\dagger\tau^I\mathbf{U}q_{Rt})\mathcal{F}_{33}^{Uh\psi^4}(h), \\
 \mathcal{O}_{34}^{Uh\psi^4} &= (\bar{q}_{Ls}\gamma_\mu\lambda^A\tau^I\mathbf{T}q_{Lp})(\bar{q}_{Rr}\gamma^\mu\lambda^A\mathbf{U}^\dagger\tau^I\mathbf{U}q_{Rt})\mathcal{F}_{34}^{Uh\psi^4}(h), \\
 \mathcal{O}_{89}^{Uh\psi^4} &= (\bar{l}_{Ls}\gamma_\mu\tau^I l_{Ls})(\bar{l}_{Rt}\sigma^{\mu\nu}\tau^I\mathbf{U}^\dagger\mathbf{T}\mathbf{U}l_{Rt})\mathcal{F}_{89}^{Uh\psi^4}(h), \\
 \mathcal{O}_{107}^{Uh\psi^4} &= (\bar{l}_{Ls}\gamma_\mu\tau^I\mathbf{T}l_{Ls})(\bar{l}_{Rt}\sigma^{\mu\nu}\tau^I\mathbf{U}^\dagger\mathbf{T}\mathbf{U}l_{Rt})\mathcal{F}_{107}^{Uh\psi^4}(h), \\
 \mathcal{O}_{113}^{Uh\psi^4} &= (\bar{l}_{Rt}\gamma_\mu\tau^I\mathbf{T}l_{Rp})(\bar{q}_{Rr}\gamma^\mu\tau^I q_{Rr})\mathcal{F}_{113}^{Uh\psi^4}(h), \\
 \mathcal{O}_{119}^{Uh\psi^4} &= (\bar{l}_{Rt}\gamma_\mu\mathbf{U}^\dagger\tau^I\mathbf{T}\mathbf{U}l_{Rp})(\bar{q}_{Lr}\gamma^\mu\tau^I q_{Lr})\mathcal{F}_{119}^{Uh\psi^4}(h), \\
 \mathcal{O}_{125}^{Uh\psi^4} &= (\bar{l}_{Ls}\gamma_\mu\tau^I\mathbf{T}l_{Lp})(\bar{q}_{Rr}\gamma^\mu\mathbf{U}^\dagger\tau^I\mathbf{U}q_{Rr})\mathcal{F}_{125}^{Uh\psi^4}(h), \\
 \mathcal{O}_{140}^{Uh\psi^4} &= \mathcal{Y}[\square] \epsilon^{abc}\epsilon^{ln}\epsilon^{km}((\mathbf{T}l_{Lr}^T)_{pm}C(\mathbf{T}q_{Lr})_{ran})(q_{Lrak}^T C q_{Lcl})\mathcal{F}_{140}^{Uh\psi^4}(h), \\
 \mathcal{O}_{160}^{Uh\psi^4} &= \mathcal{Y}[\square] \epsilon^{abc}\epsilon^{km}\epsilon^{ln}((\mathbf{T}l_{Rr}^T)_{pm}C(\mathbf{T}q_{Rr})_{ran})(q_{Rsbk}^T C q_{Rcl})\mathcal{F}_{160}^{Uh\psi^4}(h).
 \end{aligned}$$

6 term missing

Complete NNLO Lagrangian (p5, p6)

11506(1927574) NNLO operators with flavor number 1(3).

p6 terms for the first time [Sun, Xiao, Yu, 2110.14939]

Adler Zero Condition

The amplitude in the soft limit of an external leg s

[Adler, 1965]
[Low, 2014]

$$\mathcal{A}(1, \dots, N, s) \xrightarrow{p_s \rightarrow 0} \begin{cases} (S^{(0)}(s) + S^{(\text{sub})}(s)) \mathcal{A}(1, \dots, N) \\ \mathcal{O}(p_s^\sigma) & \text{for Goldstone Boson} \end{cases}$$

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

1	1	1	4
2	2	2	5
4	5		

1	1	1	2
2	2	5	5
4	4		

1	1	1	2
2	2	4	4
5	5		

1	1	1	2
2	2	4	5
4	5		

Expand the soft-limit amplitude into the SSYT basis

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

Put constraints on the SSYT basis

1	1	1	4
2	2	2	5
4	5		

1	1	1	2
2	2	4	5
4	5		

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

Spurion Technique

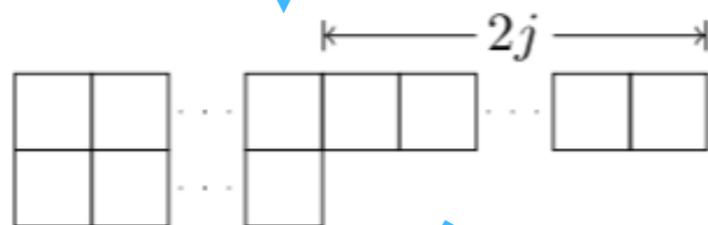
The SU(2) spurion is introduced to parametrize the custodial symmetry breaking

$$t_i \in \mathbf{2} \sim \square$$

$$\epsilon_{ij} t^j \in \bar{\mathbf{2}} \sim \square$$

$$t^I \tau_i^{Ik} \epsilon_{kj} \in \mathbf{3} \sim \square \square$$

Littlewood-Richarson rules



$$\mathbf{T}^I \tau^{Ik} \epsilon_{kj} \in \boxed{i} \boxed{j},$$

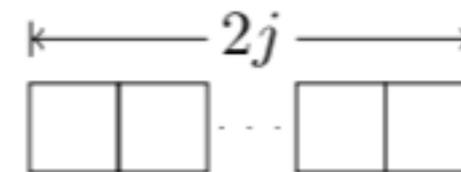
$$\mathbf{T}^{\{I_1 \dots I_j\}} \in \text{spin } j$$

$$\mathbf{T}^I \mathbf{T}^J = \mathbf{T}^2 \delta^{IJ} + \mathbf{T}^{[I} \mathbf{T}^{J]} + \mathbf{T}^{(I} \mathbf{T}^{J)},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1} + \mathbf{3} + \mathbf{5}.$$

$$\epsilon^{IJK} \mathbf{T}^I \mathbf{T}^J \mathbf{T}^K$$

Symmetric highest weight



Gauge Singlet

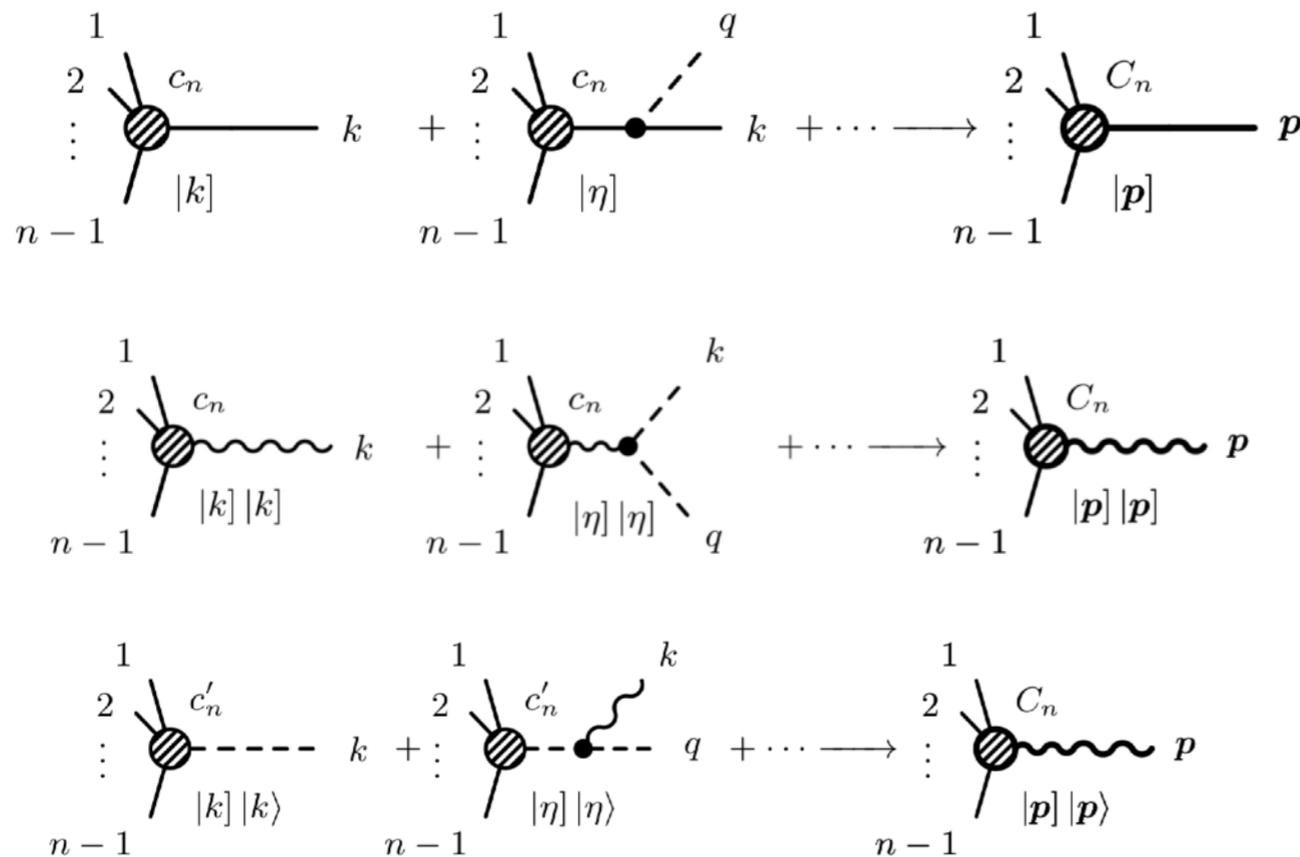
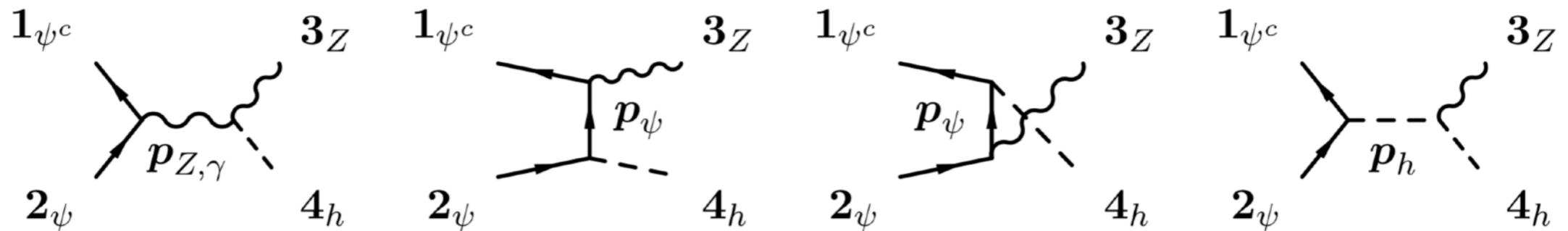
$$SU(2) \sim \square \square \dots \square$$

[Sun, Xiao, Yu, 2210.14939]

[Sun, Xiao, Yu, 2206.07722]

Massive Amplitude from HEFT

HEFT (broken phase EFT) also describes the on-shell massive amplitudes



Massive EFT On-shell Amplitude

[Shadmi, Weiss, 2018]

[Ma, Shu, Xiao, 2019]

[Durieux, Kitahara, Shadmi, Weiss, 2019]

[Falkowski, Machado, 2019]

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

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

[Li, Shu, Xiao, Yu, 2020]

[Durieux, Kitahara, Machado, Shadmi, Weiss, 2020]

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

[Balkin, Durieux, Kitahara, Shadmi, Weiss, 2021]

[De Angelis, 2022]

[Dong, Ma, Shu, Zheng, 2022]

Mathematica Code: ABC4EFT

Amplitude Basis Construction for Effective Field Theory

Automatic Basis Conversion for Effective Field Theory

Welcome to the HEPForge Project: ABC4EFT

This is the website for the Mathematica package: Amplitude Basis Constr

Package

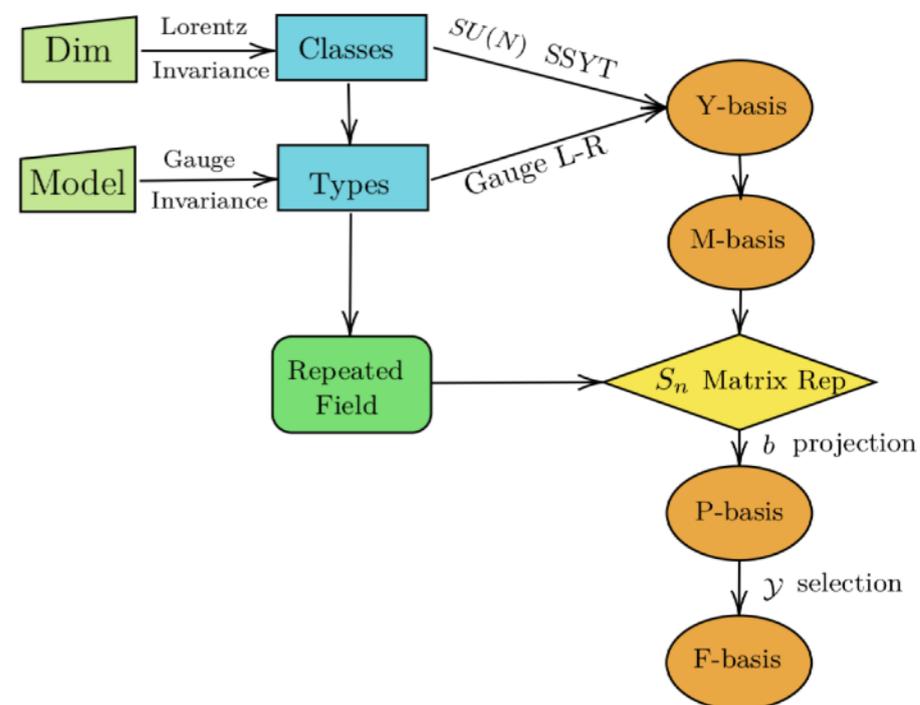
This package has the following features:

- It provides a general procedure to construct the independent and complete invariant effective field theory, given any kind of gauge symmetry and field
- Various operator bases have been systematically constructed to emphasize independence (y-basis), flavor relation (p-basis) and conserved quantum
- It provides a systematic way to convert any operator into our on-shell am \mathcal{M} can be easily done.

Authors

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Fully Automatic

Dark matter EFT

Sterile neutrino EFT

Gravity EFT

Axion EFT

<https://abc4eft.hepforge.org/>

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

Jiang-Hao Yu (ITP-CAS)

...

Complete UV Resonances from EFT

Top-Down EFTs

For a given UV model

Predict Wilson coeff. for each EFT

TeV scale

Running

Standard model EFT

Higgs precision, TGC, di-Higgs

EW scale

Matching

Higgs EFT (EW chiral Lag)

m_W

Running

Low energy EFT

Flavor physics, leptonic decays

Λ_{QCD}

Matching

Chiral Lagrangian + Heavy B EFT

Kaon, pion, and nucleon decays

MeV scale

Nuclear EFT (nuclear matrix elements)

$0\nu\beta\beta$ CE ν NS

NSI DM direct detection

To-Down: Matching to Chiral Lag

2005/12/18 First TeV Physics Working Group Meeting

★ 已发展新非微扰方法, 由 QCD 计算出 0^- 介子有效拉氏量的系数。

★ 准备用此方法研究一些非微扰的新物理模型, 例如:

- * technicolor
- * walking technicolor
- * topcolor-assisted technicolor
- * top quark seesaw
- * little Higgs
- * Higgsless model
- *

以便在实验测得各 $g_{HVV}^{(i)}$ 、 α_i 后来判断哪类模型能反映自然界。

[Prof. Y.-P. Kuang's slides]

[Wang]

Derivation of Electroweak Chiral Lagrangian from One Family Technicolor Model #19

Hong-Hao Zhang (Zhongshan U.), Kai-Xi Feng (Zhongshan U.), Shao-Zhou Jiang (Tsinghua U., Beijing), Qing Wang (Tsinghua U., Beijing) (Apr, 2009)

Published in: *Mod.Phys.Lett.A* 24 (2009) 693-702 • e-Print: 0904.1794 [hep-ph]

pdf DOI cite claim reference search 1 citation

Electroweak Chiral Lagrangian for a Hypercharge-universal Topcolor Model #20

Jun-Yi Lang (Tsinghua U., Beijing), Shao-Zhou Jiang (Tsinghua U., Beijing), Qing Wang (Tsinghua U., Beijing) (Jan, 2009)

Published in: *Phys.Lett.B* 673 (2009) 63-67 • e-Print: 0901.3837 [hep-ph]

pdf DOI cite claim reference search 3 citations

Electroweak Chiral Lagrangian from Natural Topcolor-assisted Technicolor Model #21

Jun-Yi Lang (Tsinghua U., Beijing), Shao-Zhou Jiang (Tsinghua U., Beijing), Qing Wang (Tsinghua U., Beijing) (Nov, 2008)

Published in: *Phys.Rev.D* 79 (2009) 015002 • e-Print: 0811.0086 [hep-ph]

pdf DOI cite claim reference search 5 citations

Electroweak chiral Lagrangian for left-right symmetric models #26

Ying Zhang (Tsinghua U., Beijing), Shun-Zhi Wang (Tsinghua U., Beijing), Feng-Jun Ge (Tsinghua U., Beijing), Qing Wang (Tsinghua U., Beijing) (Apr, 2007)

Published in: *Phys.Lett.B* 653 (2007) 259-266 • e-Print: 0704.2172 [hep-ph]

pdf DOI cite claim reference search 12 citations

Electroweak Chiral Lagrangian for W-prime Boson #22

Shun-Zhi Wang (Tsinghua U., Beijing), Shao-Zhou Jiang (Tsinghua U., Beijing), Feng-Jun Ge (Tsinghua U., Beijing), Qing Wang (Tsinghua U., Beijing) (May, 2008)

Published in: *JHEP* 06 (2008) 107 • e-Print: 0805.0643 [hep-ph]

pdf DOI cite claim reference search 7 citations

Stueckelberg Mechanism and Chiral Lagrangian for Z-prime Boson #23

Ying Zhang (Xian Jiaotong U. and Tsinghua U., Beijing), Shun-Zhi Wang (Tsinghua U., Beijing), Qing Wang (Tsinghua U., Beijing) (Mar, 2008)

Published in: *JHEP* 03 (2008) 047 • e-Print: 0803.1275 [hep-ph]

pdf DOI cite claim reference search 15 citations

Electroweak chiral Lagrangian for left-right symmetric models: The matter sector #24

Shun-Zhi Wang (Tsinghua U., Beijing), Feng-Jun Ge (Tsinghua U., Beijing), Qing Wang (Tsinghua U., Beijing) (2008)

Published in: *Phys.Lett.B* 662 (2008) 375-382

DOI cite claim reference search 5 citations

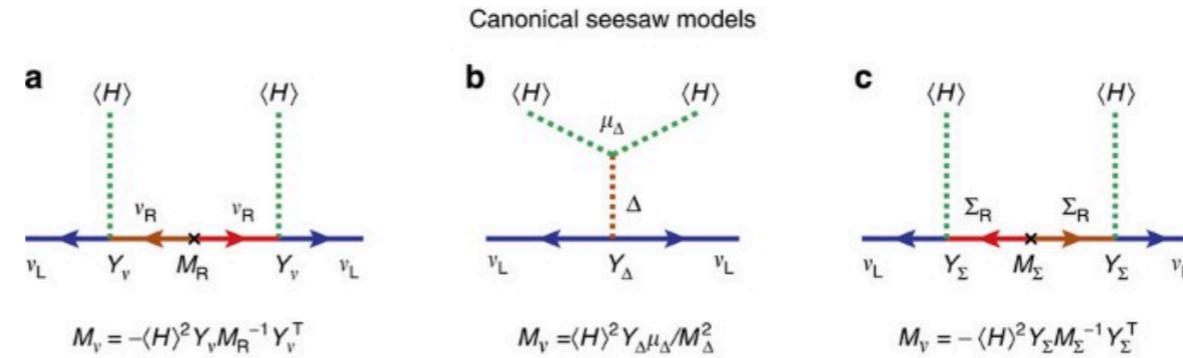
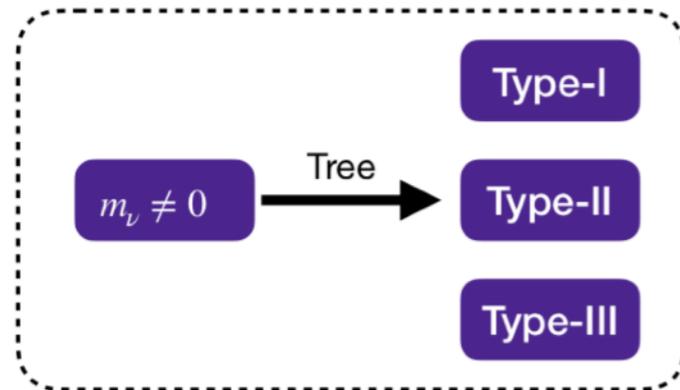
Dynamical Computation on Coefficients of Electroweak Chiral Lagrangian from One-doublet and Topcolor-assisted Technicolor Models #25

Hong-Hao Zhang (Tsinghua U., Beijing), Shao-Zhou Jiang (Tsinghua U., Beijing), Qing Wang (Tsinghua U., Beijing) (May, 2007)

Published in: *Phys.Rev.D* 77 (2008) 055003 • e-Print: 0705.0115 [hep-ph]

pdf DOI cite claim reference search 7 citations

Top-Down: Matching to SMEFT



Functional Method
tree & 1-loop CDE

SMEFT
(Green's basis)

EOM

SMEFT
(Warsaw basis)

Covariant Derivative Expansion Method

- [Du, Li, Yu, 2201.04646]
- [Zhang, Zhou, 2107.12133]
- [Li, Zhang, Zhou, 2201.05082]

[Liao, Ma, 2210.04270]

dim-4

dim-5

dim ≥ 6

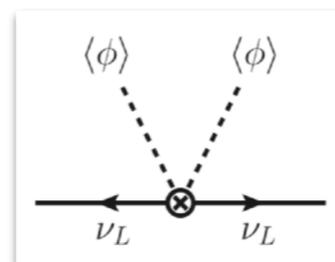
Shifts of SM couplings
(Threshold effects)

Weinberg operator

High- and low-energy observables

$$\mathcal{O}_{lequ}^{(1)}, \mathcal{O}_{eB}, \mathcal{O}_{ll}, \mathcal{O}_{HWB}, \mathcal{O}_W$$

Radiative symmetry breaking

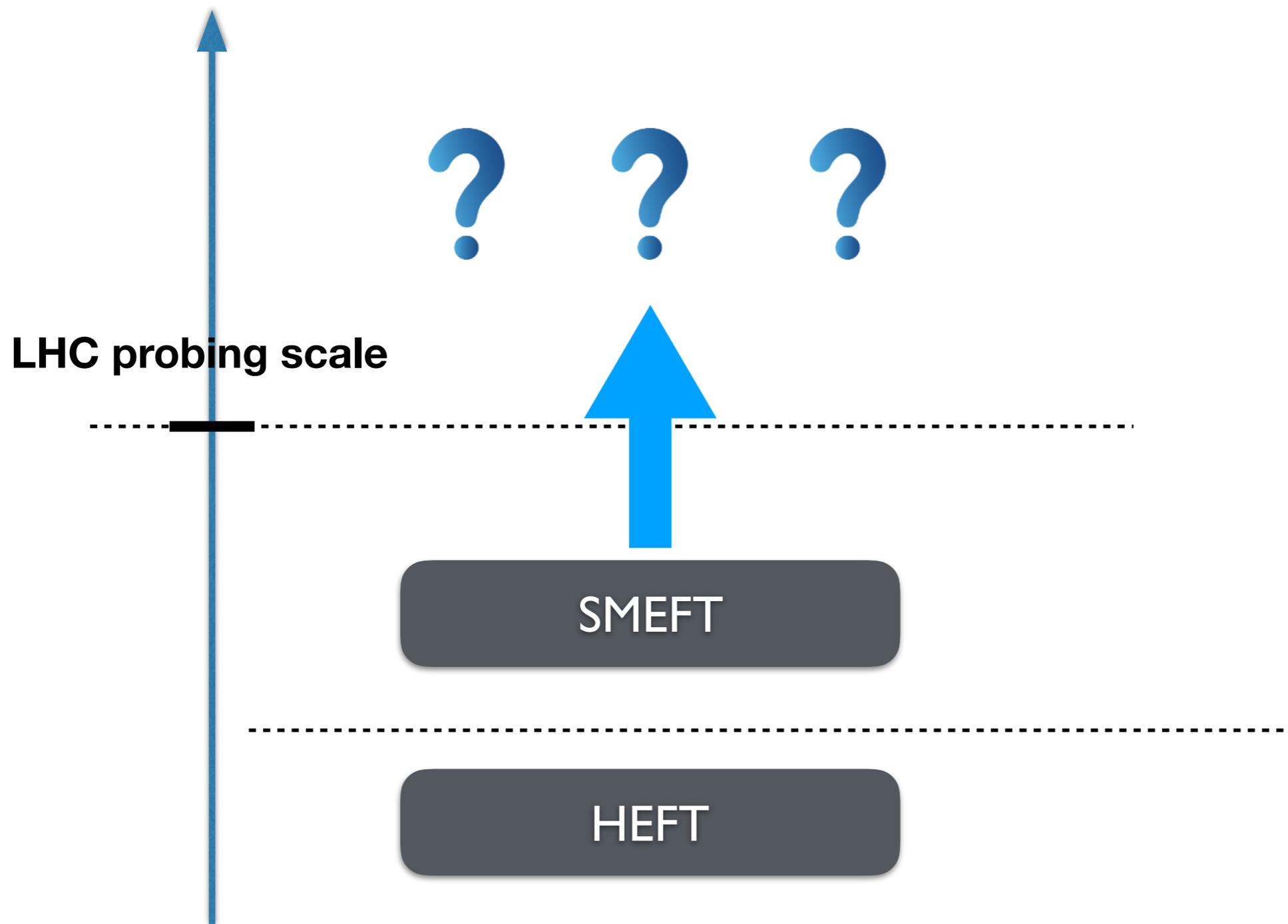


dim-6 operators

Bottom-Up EFT

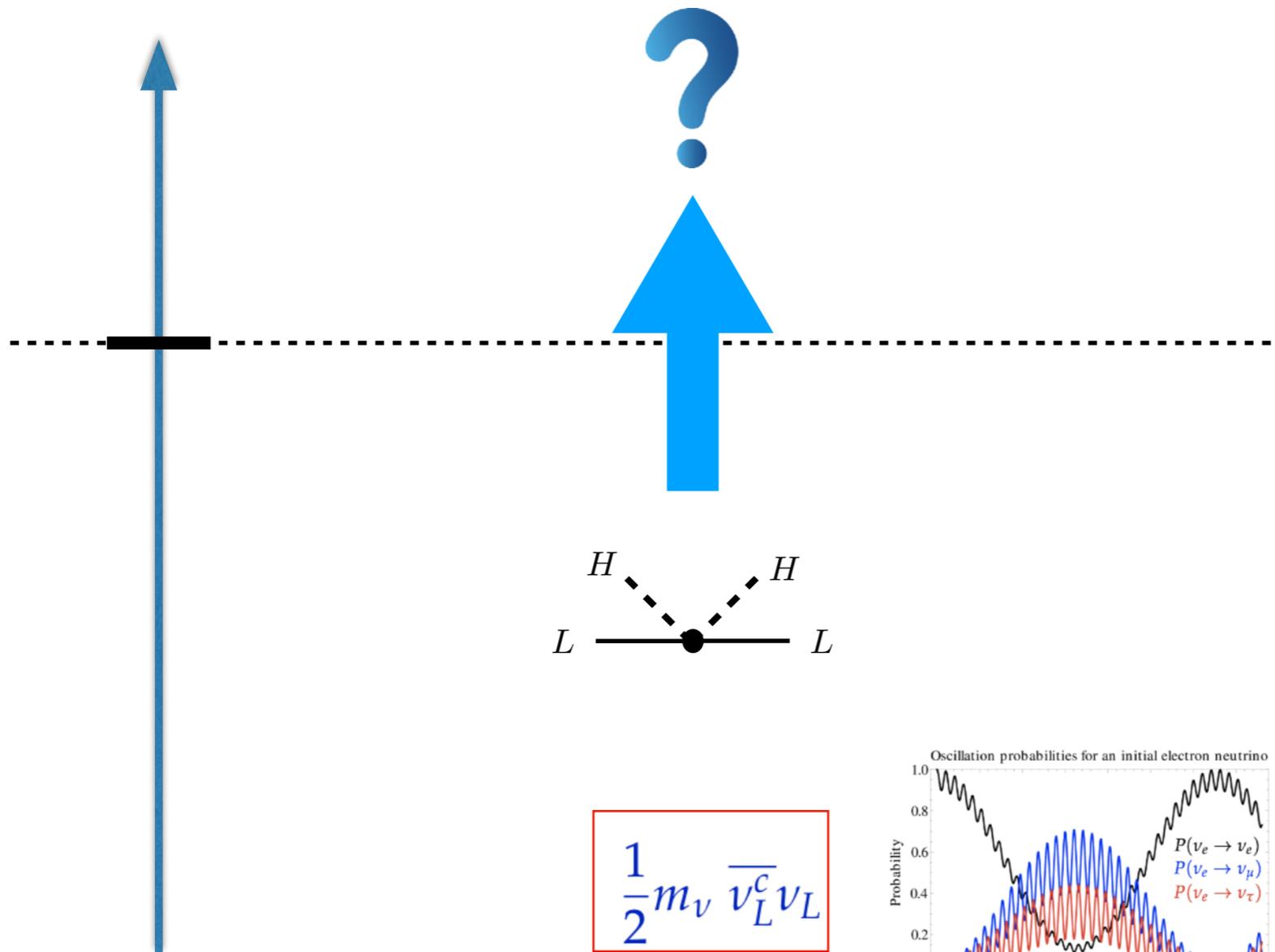
Given the effective operators, what kinds of UV for such operators?

SMEFT Inverse Problem!



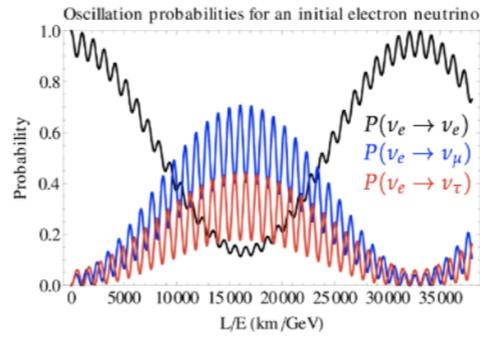
Neutrino Masses

The first evidence of new physics is the neutrino masses



SMEFT

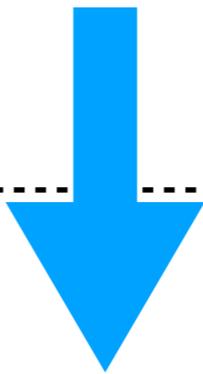
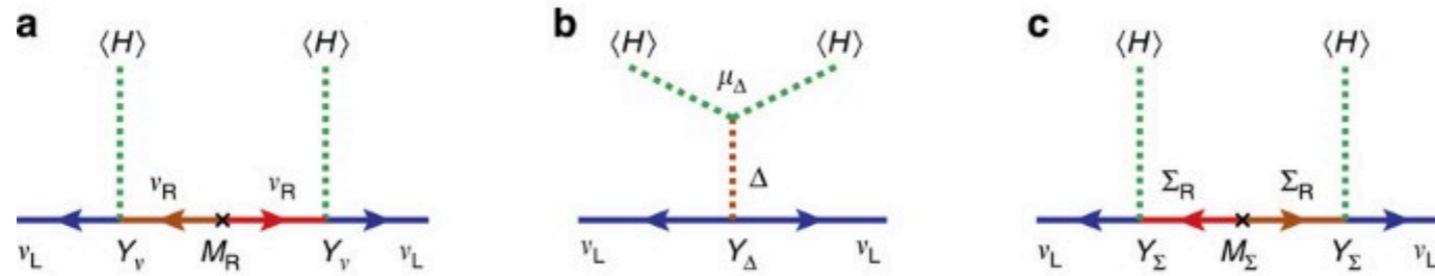
LEFT



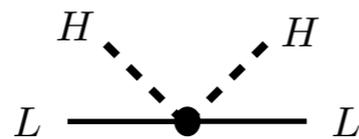
$$\frac{1}{2} m_\nu \bar{\nu}_L^c \nu_L$$

Neutrino Masses

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



[See Shun Zhou's talk]

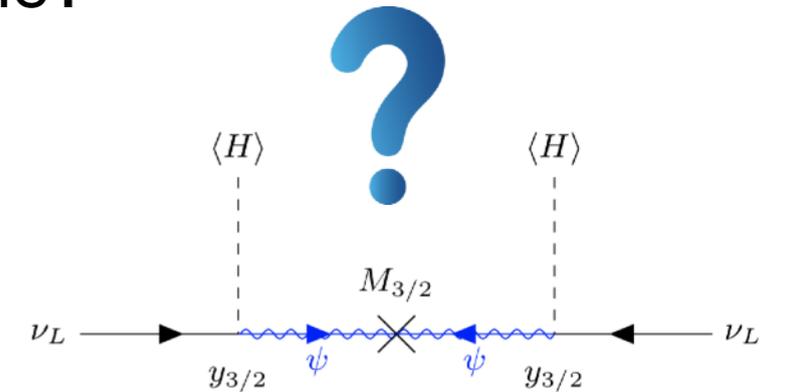
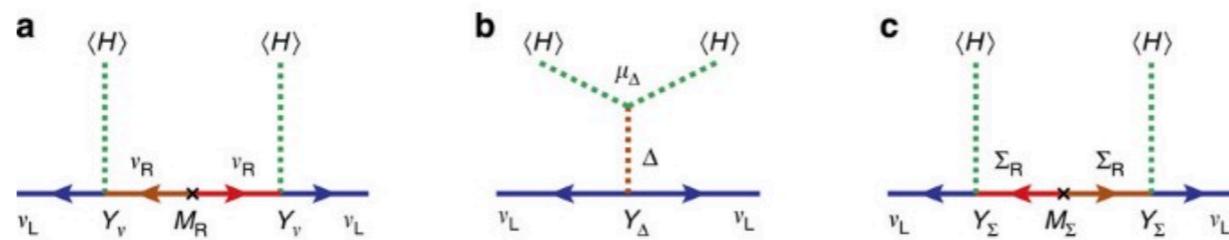


SMEFT

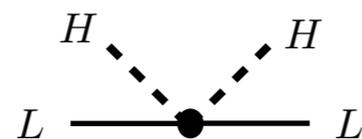
$$\frac{1}{2} m_\nu \bar{\nu}_L^c \nu_L$$

Bottom-up: Type-3/2 Seesaw?

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



[Demir, Karahan, Sargm, 2021]



SMEFT

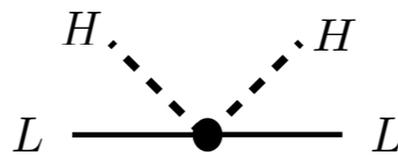
Angular momentum conservation not imposed!

Angular Momentum Conservation

Angular momentum conservation for **space-time Poincare symmetry**

Operator as the on-shell amplitude

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



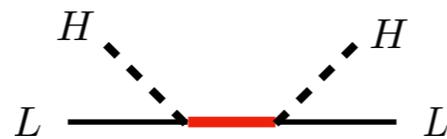
$$\langle p_L, h_L; p_H, h_H | p'_L, h'_L; p'_H, h'_H \rangle$$

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

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

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

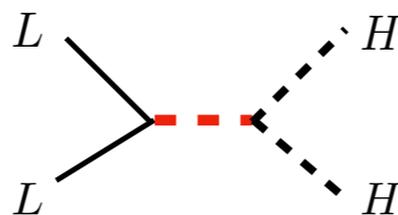
$$W_{\{1,3\}}^2 \mathcal{B}^y = -\frac{3}{4} s_{13} \langle 12 \rangle$$



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

[Li, Ni, Xiao, Yu, 2204.03660]

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



$$J = 0$$

Complete Tree-level Seesaw!

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

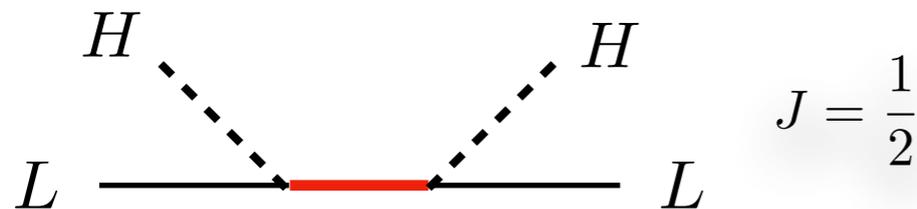
[Li, Ni, Xiao, Yu, 2204.03660]

Generalized partial wave analysis for Poincare/Gauge Casimir

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

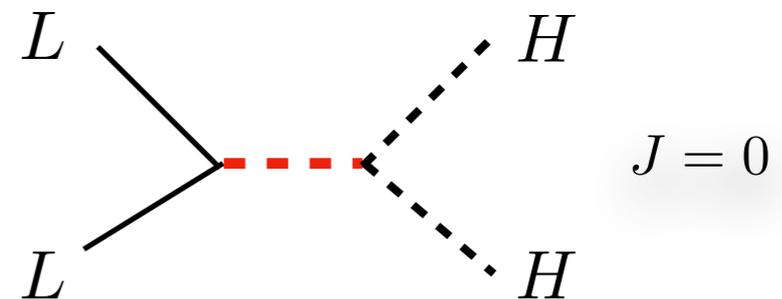
$LH \rightarrow LH$ channel

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



$LL \rightarrow HH$ channel

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



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

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

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

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

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

Complete Dim-6 UV Resonances

[Li, Ni, Xiao, Yu, 2204.03660]

Scalar		Fermion		Vector	
$(SU(3)_c, SU(2)_2, U(1)_y)$		$(SU(3)_c, SU(2)_2, U(1)_y)$		$(SU(3)_c, SU(2)_2, U(1)_y)$	
S1 (1, 1, 0)	$B_L^2 HH^\dagger$ $D^2 H^2 H^{\dagger 2}$ $d_C HH^{\dagger 2} Q[(F11), (F8)]$ $e_C HH^{\dagger 2} L[(F3), (F2)]$ $G_L^2 HH^\dagger$ $H^2 H^\dagger Q u_C[(S4), (F11), (F9)]$ $HH^\dagger W_L^2$ $H^3 H^{\dagger 3}[(S6), (S2), (S5), (S4, S6), (S2, S4), (S4, S5), (S4)]$ $e_C HH^{\dagger 2} L$ $d_C HH^{\dagger 2} Q$ $H^2 H^\dagger Q u_C$	F1 (1, 1, 0)	$DHH^\dagger LL^\dagger$ $e_C HH^{\dagger 2} L[(F3),$	V1 (1, 1, 0)	$d_C^2 d_C^{\dagger 2}$ $d_C d_C^\dagger e_C e_C^\dagger$ $e_C^2 e_C^{\dagger 2}$ $D d_C d_C^\dagger HH^\dagger$ $De_C e_C^\dagger HH^\dagger$ $D^2 H^2 H^{\dagger 2}$ $d_C d_C^\dagger LL^\dagger$ $e_C e_C^\dagger LL^\dagger$ $DHH^\dagger LL^\dagger$ $L^2 L^{\dagger 2}$ $d_C d_C^\dagger QQ^\dagger$ $e_C e_C^\dagger QQ^\dagger$ $DHH^\dagger QQ^\dagger$ $LL^\dagger QQ^\dagger$ $Q^2 Q^{\dagger 2}$ $d_C d_C^\dagger u_C u_C^\dagger$ $e_C e_C^\dagger u_C u_C^\dagger$ $DHH^\dagger u_C u_C^\dagger$ $LL^\dagger u_C u_C^\dagger$ $QQ^\dagger u_C u_C^\dagger$ $d_C HH^{\dagger 2} Q$ $e_C HH^{\dagger 2} L$ $H^2 H^\dagger Q u_C$ $e_C HH^{\dagger 2} L$ $d_C HH^{\dagger 2} Q$ $H^2 H^\dagger Q u_C$
S2 (1, 1, 1)	$d_C HH^{\dagger 2} Q[(S4), (F10), (F9)]$ $e_C HH^{\dagger 2} L[(S4), (F4), (F1)]$ $H^2 H^\dagger Q u_C[(F8), (F12)]$ $L^2 L^{\dagger 2}$ $H^3 H^{\dagger 3}[(S4), (S5), (S5, S6), (S1), (S4, S5), (S1, S4), (S5, S6), (S4, S6)]$	F2 (1, 1, 1)	$B_L e_C H^\dagger L$ $DHH^\dagger LL^\dagger$ $e_C HH^{\dagger 2} L$	V2 (1, 1, 1)	$D^2 H^2 H^{\dagger 2}$ $D d_C H^{\dagger 2} u_C^\dagger$ $d_C d_C^\dagger u_C u_C^\dagger$ $e_C HH^{\dagger 2} L$ $d_C HH^{\dagger 2} Q$ $H^2 H^\dagger Q u_C$ $d_C HH^{\dagger 2} Q$
S3 (1, 1, 2)	$e_C^2 e_C^{\dagger 2}$	F3 (1, 2, 1/2)	$B_L e_C H^\dagger L$ $e_C HH^{\dagger 2} L[(F5), (F1),$	V3 (1, 2, 3/2)	$e_C e_C^\dagger LL^\dagger$
S4 (1, 2, 1/2)	$d_C^\dagger e_C L Q^\dagger$ $d_C HH^{\dagger 2} Q[(S6), (S2)]$ $e_C HH^{\dagger 2} L[(S6), (S2)]$ $H^2 H^\dagger Q u_C$ $H^2 H^\dagger Q u_C[(S5), (S1)]$ $Q Q^\dagger u_C u_C^\dagger$ $H^3 H^{\dagger 3}[(S6), (S2), (S5, S6), (S2, S5),$ $(S1, S6), (S1, S2), (S2, S6), (S5), (S1, S5), (S1)]$	F4 (1, 2, 3/2)	$De_C e_C^\dagger HH^\dagger$ $e_C HH^{\dagger 2} L[(F6), (F2),$	V4 (1, 3, 0)	$D^2 H^2 H^{\dagger 2}$ $DHH^\dagger LL^\dagger$ $L^2 L^{\dagger 2}$ $DHH^\dagger QQ^\dagger$ $LL^\dagger QQ^\dagger$ $Q^2 Q^{\dagger 2}$ $e_C HH^{\dagger 2} L$ $d_C HH^{\dagger 2} Q$ $H^2 H^\dagger Q u_C$ $e_C HH^{\dagger 2} L$
S5 (1, 3, 0)	$B_L HH^\dagger W_L$ $D^2 H^2 H^{\dagger 2}$ $d_C HH^{\dagger 2} Q[(F11), (F13)]$ $e_C HH^{\dagger 2} L[(F3), (F6)]$ $H^2 H^\dagger Q u_C[(S4), (F11), (F14)]$ $HH^\dagger W_L^2$ $H^3 H^{\dagger 3}[(S7), (S6), (S2, S6), (S1), (S5, S7), (S4, S5), (S4, S6), (S5, S7), (S4, S5), (S4, S6)]$ $e_C HH^{\dagger 2} L$ $d_C HH^{\dagger 2} Q$	F5 (1, 3, 0)	$DHH^\dagger LL^\dagger$ $e_C HH^{\dagger 2} L[(F3),$	V5 (3, 1, 2/3)	$d_C^\dagger e_C L Q^\dagger$
S6 (1, 3, 1)	$d_C HH^{\dagger 2} Q[(S4), (F10), (F14)]$ $H^2 H^\dagger Q u_C[(F14), (F9), (F13), (F8), (S5), (S1)]$ $H^3 H^{\dagger 3}[(S7), (S4), (S5), (S5, S7), (S4, S5), (S4, S6), (S5, S7), (S4, S5), (S4, S6)]$	F6 (1, 3, 1)	$e_C H^\dagger L W_L$ $e_C HH^{\dagger 2} L[(F$	V6 (3, 1, 5/3)	$e_C e_C^\dagger u_C u_C^\dagger$
S7 (1, 4, 1/2)	$H^3 H^{\dagger 3}[(S7), (S4), (S5), (S5, S7), (S4, S5), (S4, S6), (S5, S7), (S4, S5), (S4, S6)]$	F7 (3, 1, 0)	$B_L d_C H^\dagger Q$ $d_C G_L H^\dagger Q$ $DHH^\dagger QQ^\dagger$ $d_C d_C^\dagger u_C u_C^\dagger$	V7 (3, 2, -5/6)	$d_C d_C^\dagger LL^\dagger$ $d_C^\dagger e_C L Q^\dagger$ $e_C e_C^\dagger QQ^\dagger$ $d_C L^\dagger Q^\dagger u_C$ $e_C Q^{\dagger 2} u_C$ $Q Q^\dagger u_C u_C^\dagger$
S8 (1, 4, 3/2)	H^3	F8 (3, 1, -1/3)	$DHH^\dagger QQ^\dagger$ $B_L H Q u_C$ $G_L H Q u_C$ $d_C HH^{\dagger 2} Q[(F11), (S2)]$ $H^2 H^\dagger Q u_C$	V8 (3, 2, 1/6)	$d_C d_C^\dagger QQ^\dagger$ $d_C L^\dagger Q^\dagger u_C$ $LL^\dagger u_C u_C^\dagger$
S9 (3, 1, -4/3)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$	F9 (3, 1, 2/3)	$D d_C d_C^\dagger HH^\dagger$ $d_C HH^{\dagger 2} Q[(F13), (F8), (S6), (S2)]$ $d_C HH^{\dagger 2} Q$	V9 (3, 3, 2/3)	$LL^\dagger QQ^\dagger$
S10 (3, 1, -1/3)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$	F10 (3, 2, -5/6)	$B_L d_C H^\dagger Q$ $B_L H Q u_C$ $G_L H Q u_C$ $DHH^\dagger u_C u_C^\dagger$ $d_C HH^{\dagger 2} Q[(F14), (F9), (F13), (F8), (S5), (S1)]$ $H^2 H^\dagger Q u_C[(F14), (F9), (F13), (F8), (S5), (S1)]$	V10 (6, 2, -1/6)	$d_C d_C^\dagger QQ^\dagger$
S11 (3, 1, 2/3)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$	F11 (3, 2, 1/6)	$DHH^\dagger u_C u_C^\dagger$ $H^2 H^\dagger Q u_C[(F14), (F9), (S6), (S2)]$ $H^2 H^\dagger Q u_C$	V11 (6, 2, 5/6)	$Q Q^\dagger u_C u_C^\dagger$
S12 (3, 2, 1/6)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$	F12 (3, 2, 7/6)	$d_C H^\dagger Q W_L$ $d_C HH^{\dagger 2} Q[(F10), (F11), (S5)]$ $H^2 H^\dagger Q u_C[(F14), (F9), (S6), (S2)]$	V12 (8, 1, 0)	$d_C^2 d_C^{\dagger 2}$ $d_C d_C^\dagger QQ^\dagger$ $Q^2 Q^{\dagger 2}$ $d_C d_C^\dagger u_C u_C^\dagger$ $Q Q^\dagger u_C u_C^\dagger$ $u_C^2 u_C^{\dagger 2}$
S13 (3, 2, 7/6)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$	F13 (3, 3, -1/3)	$H Q u_C W_L$ $d_C HH^{\dagger 2} Q[(F11), (S6)]$ $H^2 H^\dagger Q u_C$	V13 (8, 1, 1)	$d_C d_C^\dagger u_C u_C^\dagger$
S14 (3, 3, -1/3)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$	F14 (3, 3, 2/3)	$H Q u_C W_L$ $d_C HH^{\dagger 2} Q[(F11), (S6)]$ $H^2 H^\dagger Q u_C$	V14 (8, 3, 0)	$Q^2 Q^{\dagger 2}$
S15 (6, 1, -2/3)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$				
S16 (6, 1, 1/3)	$d_C Q^2 u$				
S17 (6, 1, 4/3)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$				
S18 (6, 3, 1/3)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$				
S19 (8, 2, 1/2)	$Q^2 Q^{\dagger 2}$ $e_C L Q u_C$				

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

New LHC searches!

Complete Dim-7 UV Resonances

Scalar		Fermion		Vector	
$(SU(3)_c, SU(2)_2, U(1)_y)$		$(SU(3)_c, SU(2)_2, U(1)_y)$		$(SU(3)_c, SU(2)_2, U(1)_y)$	
S1 (1, 1, 0)	$H^3 H^\dagger L^2[(S6), (S2), (F5), (F1), (S4, S6), (S2, S4), (S4, F5), (S4, F1), (F3, F5), (F1, F3), (S6, F3), (S2, F3)]$			V2 (1, 1, 1)	$Dd_c L^2 u_c^\dagger$ $D^2 H^2 L^2$ $De_c H^{\dagger 3} L^\dagger[(F1), (V3), (F3)]$ $H^2 L^2 W_L$ $B_L H^2 L^2$ $e_c HL^3$ $HL^2 Q^\dagger u_c^\dagger$ $d_c HL^2 Q$ $De_c^\dagger H^3 L$ $HL^2 Q^\dagger u_c^\dagger$ $d_c HL^2 Q$
S2 (1, 1, 1)	$D^2 H^2 L^2$ $e_c HL^3[(S4), (F4), (F1)]$ $d_c HL^2 Q[(S4), (F10), (F9)]$ $HL^2 Q^\dagger u_c^\dagger[(S4), (F8), (F12)]$ $De_c H^{\dagger 3} L^\dagger[(F1), (F3), (V3)]$ $H^3 H^\dagger L^2[(F1, F3), (S5, S6), (S1), (F5, F6), (F1, F2), (S4, S6), (S4), (S5, S6), (S5), (S4, S5), (S1, S4), (S4, F5), (S4, F1), (F3, F5), (S5, F6), (S5, F2), (F3, F6), (F2, F3), (S5, F3), (S1, F3)]$ $H^2 L^2 W_L$ $B_L H^2 L^2$ $e_c HL^3$ $HL^2 Q^\dagger u_c^\dagger$ $d_c HL^2 Q$ $De_c^\dagger H^3 L$			V3 (1, 2, 3/2)	$De_c H^{\dagger 3} L^\dagger$ $d_c e_c^\dagger H L u_c^\dagger[(F10), (F12)]$ $De_c H^{\dagger 3} L^\dagger[(V2), (V5), (S6), (S2)]$
S4 (1, 2, 1/2)	$H^3 H^\dagger L^2[(S6), (S2, S6), (S2), (S5, S6), (S2, S5), (S1, S6), (S1, S2), (S6, F5), (S6, F1), (S2, F5), (S2, F1), (S5, F5), (S5, F1), (S1, F5), (S1, F1)]$			V5 (1, 3, 1)	$D^2 H^2 L^2$ $De_c H^{\dagger 3} L^\dagger[(F3), (V3), (F5)]$ $H^2 L^2 W_L$ $B_L H^2 L^2$ $e_c HL^3$ $HL^2 Q^\dagger u_c^\dagger$ $d_c HL^2 Q$ $De_c^\dagger H^3 L$
S5 (1, 3, 0)	$H^3 H^\dagger L^2[(S6), (S2, S6), (F5), (S2, S4), (S7, F5), (S4, F5), (F1, F3), (S6, F7), (S1, S2), (S5, S6), (S2, S5), (S1, S6), (S1, S2), (S6, F5), (S6, F1), (S2, F5), (S2, F1), (S5, F5), (S5, F1), (S1, F5), (S1, F1)]$			V5 (3, 1, 2/3)	$Dd_c^3 e_c^\dagger$ $HL^2 Q^\dagger u_c^\dagger[(F1), (V8), (F12)]$ $d_c e_c^\dagger H L u_c^\dagger[(F1), (V8), (F12)]$ $d_c HL Q^{\dagger 2}[(V8), (F10), (F8)]$
S6 (1, 3, 1)	$D^2 H^2 L^2$ $e_c HL^3[(S4), (F4), (F1)]$ $d_c HL^2 Q[(S4), (F10), (F9)]$ $HL^2 Q^\dagger u_c^\dagger[(S4), (F8), (F12)]$ $De_c H^{\dagger 3} L^\dagger[(F5), (F3), (V3)]$ $H^3 H^\dagger L^2[(F3, F5), (S5), (S1), (S2, S7), (S4), (S2, S4), (S8), (S5), (S2, S5), (S2, S4), (S4, F1), (F5, F7), (F1, F3), (S8, F6), (F2, F3), (S5, F7)]$ $H^2 L^2 W_L$ $B_L H^2 L^2$ $e_c HL^3$ $HL^2 Q^\dagger u_c^\dagger$ $d_c HL^2 Q$	F1 (1, 1, 0)	$D^2 H^2 L^2$ $e_c HL^3[(S4), (S2)]$ $d_c HL^2 Q[(S4), (S10), (S12)]$ $HL^2 Q^\dagger u_c^\dagger[(S4), (V5), (V8)]$ $De_c H^{\dagger 3} L^\dagger[(S2), (F3), (V2)]$ $d_c^2 HL u_c[(S11), (S10)]$ $d_c e_c^\dagger H L u_c^\dagger[(S10), (V5)]$ $d_c HL Q^{\dagger 2}[(S10), (V8)]$ $H^2 L^2 W_L[(F5)]$ $H^3 H^\dagger L^2[(S2, F3), (S5, F5), (S1), (S6, F6), (S2, F2), (F3, F5), (F3), (S4, S6), (S2, S4), (S6, F3), (S4, S5), (S1, S4), (F3, F6), (F2, F3), (S5, F3), (S1, F3)]$ $H^2 L^2 W_L$ $B_L H^2 L^2$ $e_c HL^3$ $HL^2 Q^\dagger u_c^\dagger$ $d_c HL^2 Q$ $De_c^\dagger H^3 L$		
S7 (1, 4, 1/2)	$H^3 H^\dagger L^2[(S6), (S5, S6), (S2, S4), (S7, F5), (S4, F5), (F1, F3), (S6, F7), (S1, S2), (S5, S6), (S2, S5), (S1, S6), (S1, S2), (S6, F5), (S6, F1), (S2, F5), (S2, F1), (S5, F5), (S5, F1), (S1, F5), (S1, F1)]$	F2 (1, 1, 1)	$d_c^3 H^\dagger L[(S11)]$ $H^3 H^\dagger L^2[(S6, F5), (S2, F1), (F3, F5), (F1, F3), (S5, S6), (S2, S5), (S6, F3), (S2, F3)]$		
S8 (1, 4, 3/2)	$H^3 H^\dagger L^2[(S6), (S5, S6), (S2, S4), (S7, F5), (S4, F5), (F1, F3), (S6, F7), (S1, S2), (S5, S6), (S2, S5), (S1, S6), (S1, S2), (S6, F5), (S6, F1), (S2, F5), (S2, F1), (S5, F5), (S5, F1), (S1, F5), (S1, F1)]$	F3 (1, 2, 1/2)	$De_c H^{\dagger 3} L^\dagger[(F5), (F1), (S6), (S2), (V2), (V5)]$ $d_c e_c^\dagger H L u_c^\dagger[(S12), (V8)]$ $d_c^2 e_c^\dagger H Q^\dagger[(V8), (S11)]$		
S10 (3, 1, -1/3)	$d_c^2 HL u_c[(S12), (F10), (F1)]$ $d_c e_c^\dagger H L u_c^\dagger[(S12), (F10), (F1)]$	F4 (1, 2, 3/2)	$e_c HL^3[(S6), (S2)]$		
S11 (3, 1, 2/3)	$d_c^3 H^\dagger L[(S12), (F11), (F2)]$ $d_c^2 HL u_c[(F11), (S12), (F10), (F1)]$	F5 (1, 3, 0)	$e_c HL^3[(S4), (S6)]$ $d_c HL^2 Q[(S4), (S12), (S14)]$ $HL^2 Q^\dagger u_c^\dagger[(S4), (V9), (V8)]$ $D^2 H^2 L^2$ $De_c H^{\dagger 3} L^\dagger[(S6), (F3), (V5)]$ $d_c HL Q^{\dagger 2}[(S14), (V8)]$ $H^2 L^2 W_L[(F7), (F1)]$ $H^2 L^2 W_L$ $B_L H^2 L^2$ $e_c HL^3$ $HL^2 Q^\dagger u_c^\dagger$ $d_c HL^2 Q$ $De_c^\dagger H^3 L$		
S12 (3, 2, 1/6)	$d_c^3 H^\dagger L[(S11), (F11)]$ $d_c^2 HL^2 Q[(S10), (S14), (F5), (F1), (F14)]$	F6 (1, 3, 1)	$H^3 H^\dagger L^2[(S6, F5), (S6, F1), (S2, F5), (F5, F7), (F3, F5), (F1, F3), (S6, S8), (S5, S6), (S2, S5), (S6, F7), (S6, F3), (S2, F3)]$		
S13 (3, 2, 7/6)	$d_c^2 HL u_c[(S11), (F10)]$	F7 (1, 4, 1/2)	$H^2 L^2 W_L[(F5), (S6)]$ $H^3 H^\dagger L^2[(F5), (S6, F5), (F5, F6), (S6, F6), (S5, F5), (S5, S6)]$		
S14 (3, 3, -1/3)	$d_c HL^2 Q[(S12), (F10), (F5)]$	F8 (3, 1, -1/3)	$HL^2 Q^\dagger u_c^\dagger[(S2), (V8)]$ $d_c HL Q^{\dagger 2}[(V8), (S12), (V5)]$ $d_c^2 e_c^\dagger H Q^\dagger[(V5), (S11)]$		
		F9 (3, 1, 2/3)	$d_c HL^2 Q[(S12), (S2)]$		
		F10 (3, 2, -5/6)	$d_c^2 HL u_c[(S12), (S10), (S13)]$ $d_c HL^2 Q[(S10), (S6), (S13)]$ $d_c e_c^\dagger H L u_c^\dagger[(S10), (V3), (V8)]$ $d_c HL Q^{\dagger 2}[(S10), (S14), (S12), (S14), (F5), (F1), (F14)]$		
		F11 (3, 2, 1/6)	$d_c^3 H^\dagger L[(S11), (S12)]$ $d_c^2 HL u_c[(S11), (S12)]$		
		F12 (3, 2, 7/6)	$HL^2 Q^\dagger u_c^\dagger[(S6), (S2), (V9), (V5)]$ $d_c e_c^\dagger H L u_c^\dagger[(V5), (S12), (V3)]$		
		F13 (3, 3, -1/3)	$HL^2 Q^\dagger u_c^\dagger[(S6), (V8)]$ $d_c HL Q^{\dagger 2}[(V8), (S12), (V9)]$		
		F14 (3, 3, 2/3)	$d_c HL^2 Q[(S12), (S6)]$		

[Li, Ni, Xiao, Yu, 2204.03660]

More LHC searches!

Complete Dim-8 UV Resonances

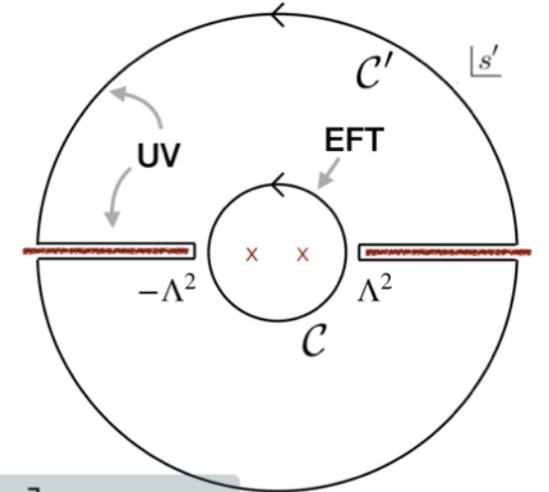
[Li, Ni, Xiao, Yu, in preparation]

Type: $D^4 H^2 H^{\dagger 2}$	group: (Spin, $SU(3)_c, SU(2)_w, U(1)_y$)	
$\mathcal{O}_1^f = \frac{1}{4} \mathcal{Y}[\square]_H \mathcal{Y}[\square]_{H^\dagger} H_i H_j (D_\mu D_\nu H^{\dagger i})(D^\mu D^\nu H^{\dagger j}),$	$\{H_1, H_2\}, \{H^\dagger_3, H^\dagger_4\}$	
$\mathcal{O}_2^f = \frac{1}{4} \mathcal{Y}[\square]_H \mathcal{Y}[\square]_{H^\dagger} H^\dagger_i H_i (D_\mu D_\nu H_j)(D^\mu D^\nu H^{\dagger j}),$		
$\mathcal{O}_3^f = \frac{1}{4} \mathcal{Y}[\square]_H \mathcal{Y}[\square]_{H^\dagger} H_i (D_\mu H_j)(D_\nu H^{\dagger i})(D^\mu D^\nu H^{\dagger j}).$		
*	(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)	$4\mathcal{O}_2^f$

Analyticity in complex s plane (fixed t)

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

Cauchy's integral formula



Fixed t dispersion relation

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

EFT amplitude

IR ~ UV connection

UV full amplitude

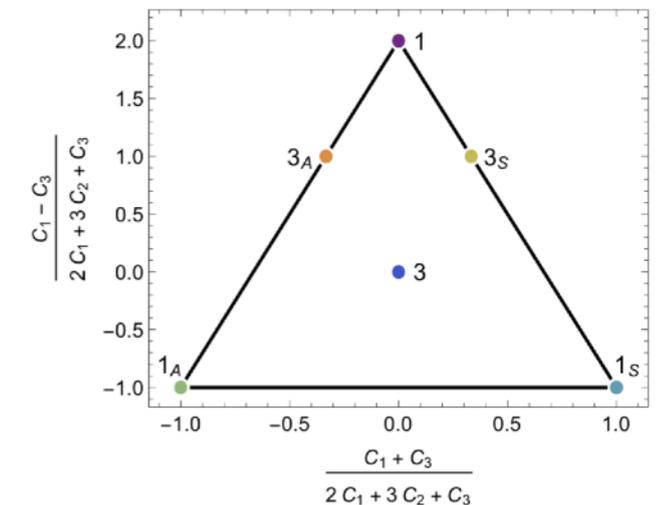
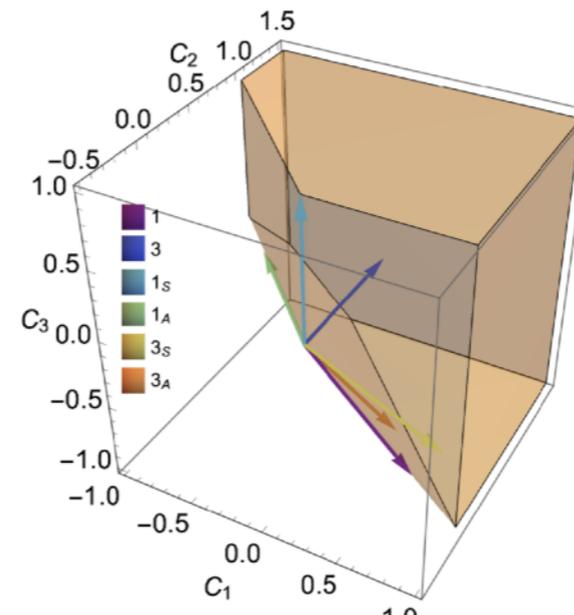
$$\text{Disc} A_{ij \rightarrow kl}(s) = A_{ij \rightarrow kl}(s) - A_{kl \rightarrow ij}(s)^* = i \sum_X M_{ij \rightarrow X}(s) M_{kl \rightarrow X}(s)^*$$

In the forward limit, a twice-subtracted dispersion relation

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

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

[Cen Zhang, S-Y Zhou]



Unbiased Search for NP @ LHC

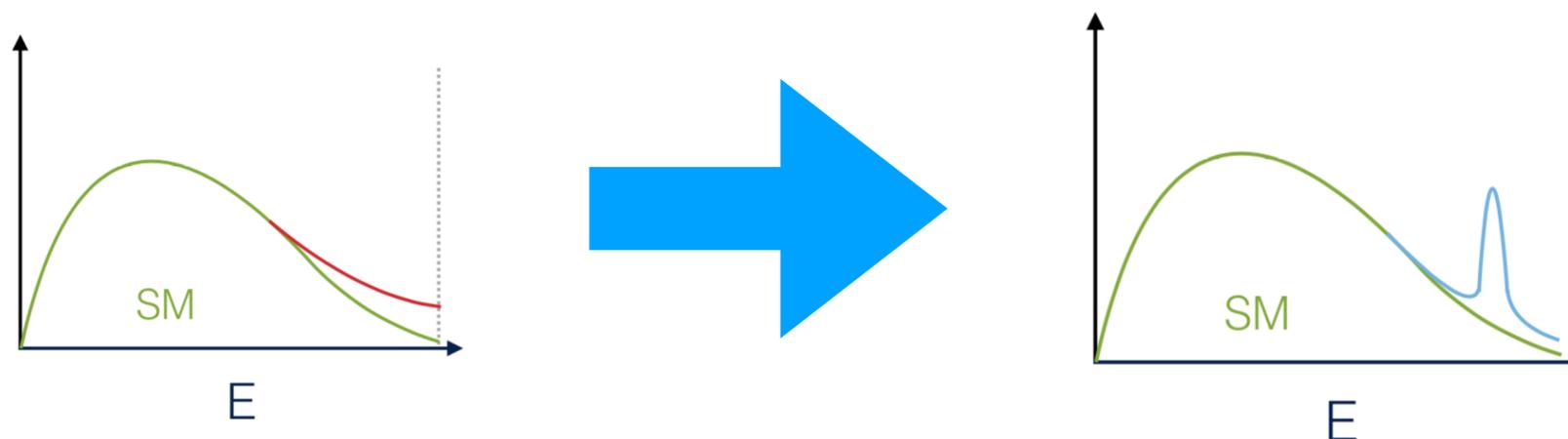
Instead of searching new physics model by model ...

There are infinite models (even simplified model) in the market

Search new physics operator by operator!

There are finite operators in certain mass dimension

Un-biased search for experimentalists



At dimension 6, only 19 scalars, 14 fermions, 14 vector bosons

Summary

1. paradigm shift in new physics searches

Bottom-up EFT provides a clear pathway to new physics

2. New way of constructing complete EFT operators and its UV
SMEFT, LEFT, Higgs EFT, QCD chiral Lag, gravity, etc

Which EFT?

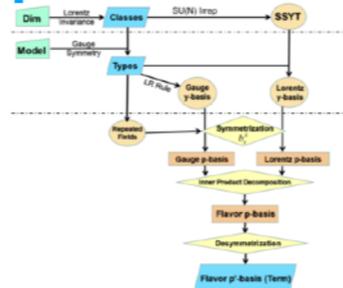
Complete Operators

Complete UVs

Nature of Higgs boson



Any operator to any dimension



Partial wave for

UV resonances

3. Given EFT Lagrangians, calculate/measure Wilson coeff.

Application of EFT to various scales: collider, flavor, low energy

LHC Run3 are starting to explore EFT operators systematically

$$\mathcal{L}_{eff}(W, Z, \varphi) = \sum_{i=0}^{14} \mathcal{L}^{(i)} = \sum_{i=0}^{14} \alpha_i \mathcal{O}(W, Z, \varphi) \equiv \sum_{i=0}^{14} \frac{\ell_i}{16\pi^2} \mathcal{O}(W, Z, \varphi),$$

★ 已分析 LHC 和 LC 上测量各 α_i 的所有灵敏过程。Monte Carlo 模拟

祝邝老师：生日快乐，身体健康，万事如意!



北京大学

硕士研究生学位论文

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感谢邝宇平院士的教诲，他的言行、思想对我有着十分重要的影响。“善歌者使人继其声，善教者使人继其志。”邝老师精彩的课程及其老当益壮的精神让我坚定了做TeV物理的信念，并为此不懈努力。我也永难忘记无数次的请教、讨论，并对此永远感激不尽。

**粒子物理前沿课程：
(2006年笔记)**

**对称性自发破缺、量子反常、有效势
QCD手征拉氏量、动力学自发破缺
电弱手征理论、等价定理、标准模型精确检验
超出标准模型的新物理 (technicolor ...)**

Thanks for your attention!