Institute of Theoretical Physics
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Chiral Effective Field Theories

For Strong and Weak Dynamics

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HAPOF 强子物理在线论坛

04-24, 2024

Outline

- Overview on chiral symmetry
- QCD chiral perturbation theory

[Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2405.15047]

[Xuan-He Li, Hao Sun, Feng-Jie Tang, **J.H.Yu**, 2404.14152]

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

- Electroweak chiral Lagrangian

[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**, 2211.11598]

- Nuclear chiral effective theory

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

[Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, in préparation]

- Axion effective field theory

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

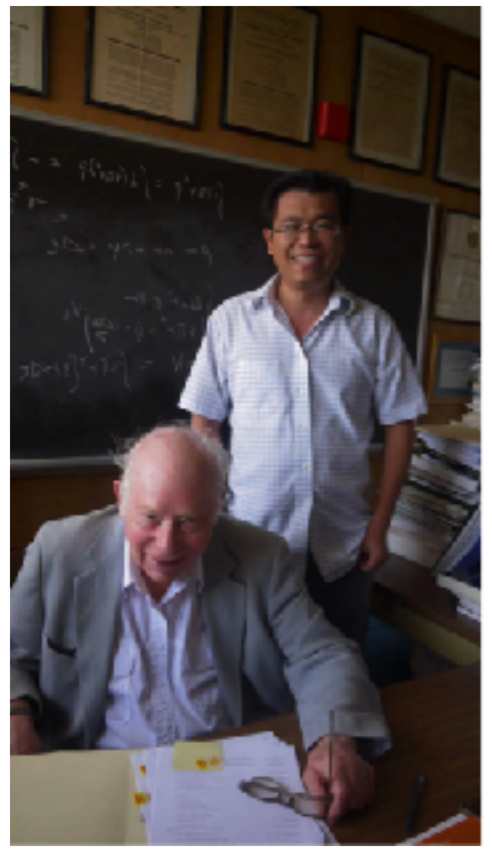
[Huayang Song, Hao Sun, **J.H.Yu**, 2306.05999]

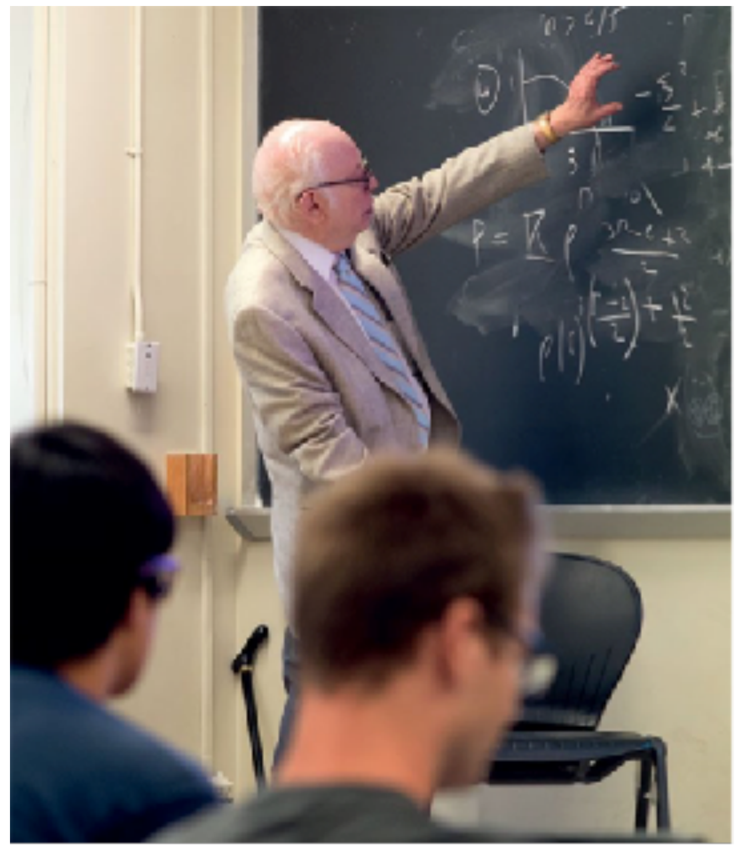
[Hao Sun, **J.H.Yu**, in preparation]

- Summary

Outline

- This talk is dedicated to the memory of Steven Weinberg (1933 - 2021)





[Weinberg 1933.5.3 - 2021.7.23]

- Review chiral Lagrangian at various scales: QCD, electroweak, TeV, nuclei scale

Physica 96A (1979) 327–340 © North-Holland Publishing Co.

PHENOMENOLOGICAL LAGRANGIANS*

STEVEN WEINBERG

Lyman Laboratory of Physics, Harvard University

A MODEL OF LEPTONS*

Steven Weinberg†

Laboratory for Nuclear Science and Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)

Nuclear forces from chiral lagrangians

Steven Weinberg [1]

Theory Group, Department of Physics, University of Texas, Austin, TX 78712, USA

Received 14 August 1990

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)

VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

A New Light Boson?

Steven Weinberg

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

EFFECTIVE CHIRAL LAGRANGIANS FOR NUCLEON–PION INTERACTIONS AND NUCLEAR FORCES

Steven WEINBERG*

Theory Group, Department of Physics, University of Texas, Austin, TX 78712, USA

Received 2 April 1991

Outline

Among 15 top-cited papers, 7 are relevant to chiral symmetry, 5 relevant to effective field theory

311 results | cite all   Citation Summary   Most Cited

A Model of Leptons #1
Steven Weinberg (MIT, LNS) (Nov, 1967)
Published in: *Phys.Rev.Lett.* 19 (1967) 1264-1266
links DOI cite claim   reference search   14,151 citations

The Cosmological Constant Problem
Steven Weinberg (Texas U.) (May, 1988)
Published in: *Rev.Mod.Phys.* 61 (1989) 1-23
DOI cite claim

A New Light Boson?
Steven Weinberg (Harvard U.) (Dec, 1977)
Published in: *Phys.Rev.Lett.* 40 (1978) 223-226
pdf DOI cite claim

Phenomenological Lagrangians
Steven Weinberg (Harvard U. and Harvard-Smithsonian Ctr. Astrophys.) (O
Published in: *Physica A* 96 (1979) 1-2, 327-340 • Contribution to: Sympos
Occasion of his 60th Birthday, 327-340
DOI cite claim

Implications of Dynamical Symmetry Breaking
Steven Weinberg (Harvard U.) (Sep, 1975)
Published in: *Phys.Rev.D* 13 (1976) 974-996, *Phys.Rev.D* 19 (1979) 1277-
DOI cite claim

Broken Symmetries
Jeffrey Goldstone (Cambridge U.), Abdus Salam (Imperial Coll., London), Steven W
1962)
Published in: *Phys.Rev.* 127 (1962) 965-970
DOI cite claim

Baryon and Lepton Nonconserving Processes
Steven Weinberg (Harvard U.) (1979)
Published in: *Phys.Rev.Lett.* 43 (1979) 1566-1570
pdf DOI cite claim

Natural Conservation Laws for Neutral Currents
Sheldon L. Glashow (Harvard U.), Steven Weinberg (Harvard U.) (Aug, 1976)
Published in: *Phys.Rev.D* 15 (1977) 1958
pdf DOI cite claim

Hierarchy of Interactions in Unified Gauge Theories
H. Georgi (Harvard U.), Helen R. Quinn (Harvard U.), Steven Weinberg (Harvard U.)
Published in: *Phys.Rev.Lett.* 33 (1974) 451-454
DOI cite claim

Pion scattering lengths #10
Steven Weinberg (UC, Berkeley) (Jun, 1966)
Published in: *Phys.Rev.Lett.* 17 (1966) 616-621
DOI cite claim   reference search   1,808 citations

Supergravity as the Messenger of Supersymmetry Breaking #11
Lawrence J. Hall (UC, Berkeley), Joseph D. Lykken (Texas U.), Steven Weinberg (Texas U.) (1983)
Published in: *Phys.Rev.D* 27 (1983) 2359-2378
DOI cite claim   reference search   1,629 citations

Cosmological Lower Bound on Heavy Neutrino Masses #12
Benjamin W. Lee (Fermilab), Steven Weinberg (Stanford U., Phys. Dept.) (May, 1977)
Published in: *Phys.Rev.Lett.* 39 (1977) 165-168
pdf links DOI cite claim   reference search   1,566 citations

Gauge and Global Symmetries at High Temperature #13
Steven Weinberg (Harvard U.) (Mar, 1974)
Published in: *Phys.Rev.D* 9 (1974) 3357-3378
DOI cite claim   reference search   1,554 citations

Nuclear forces from chiral Lagrangians #14
Steven Weinberg (Texas U.) (Oct 9, 1990)
Published in: *Phys.Lett.B* 251 (1990) 288-292
DOI cite claim   reference search   1,551 citations

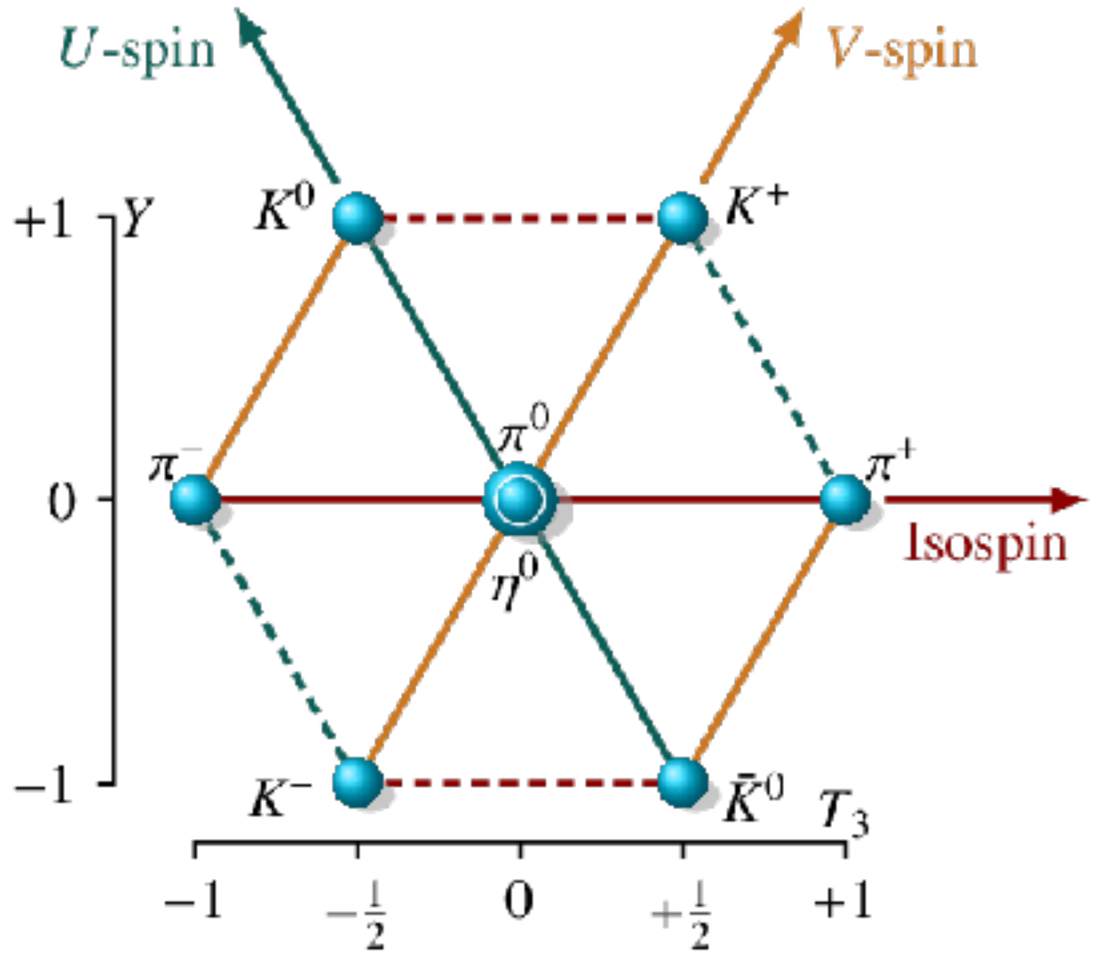
Effective chiral Lagrangians for nucleon - pion interactions and nuclear forces #15
Steven Weinberg (Texas U.) (Apr 1, 1991)
Published in: *Nucl.Phys.B* 363 (1991) 3-18
pdf DOI cite claim   reference search   1,465 citations

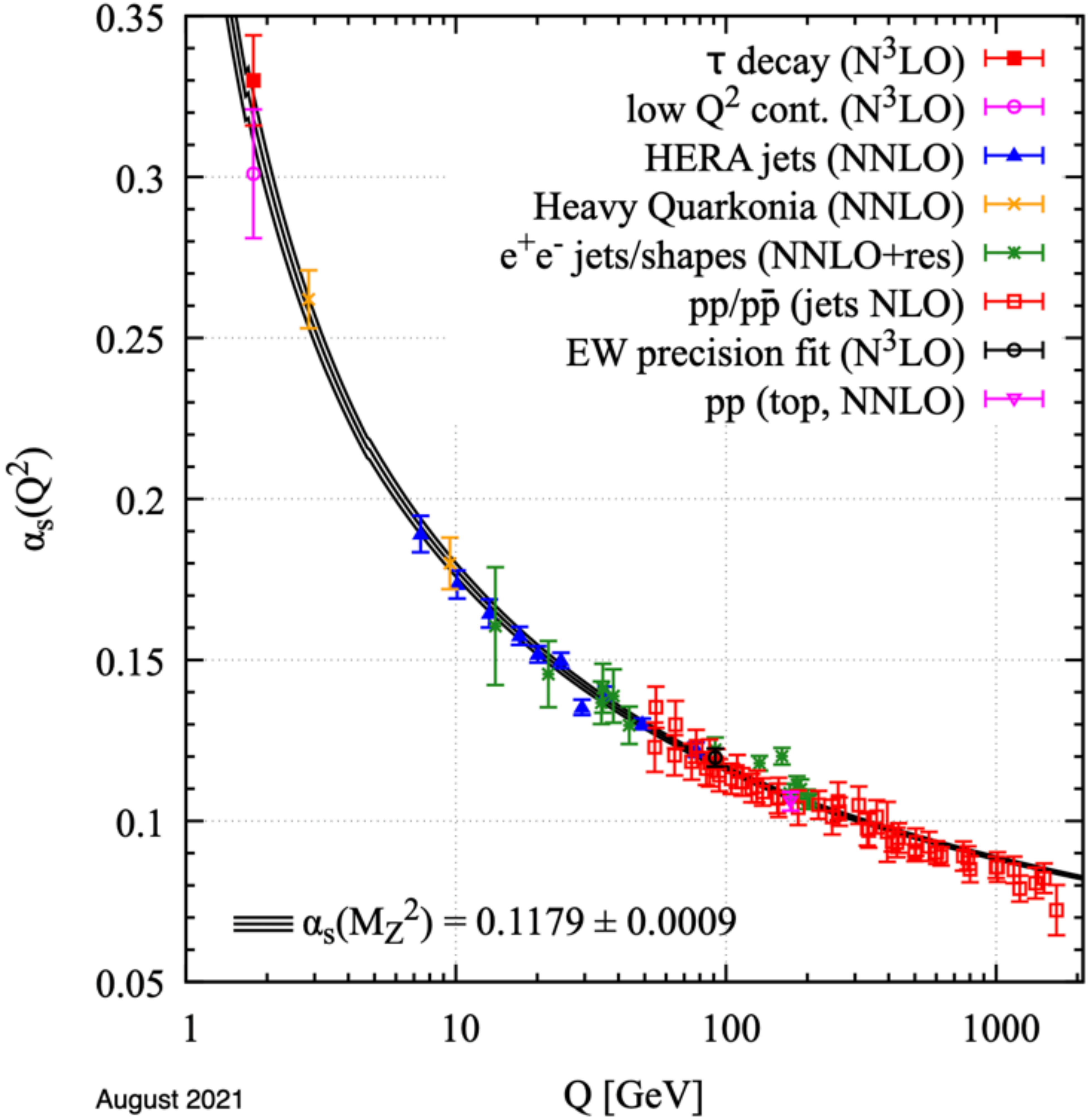
Overview on Chiral Symmetry

QCD at high and low scales

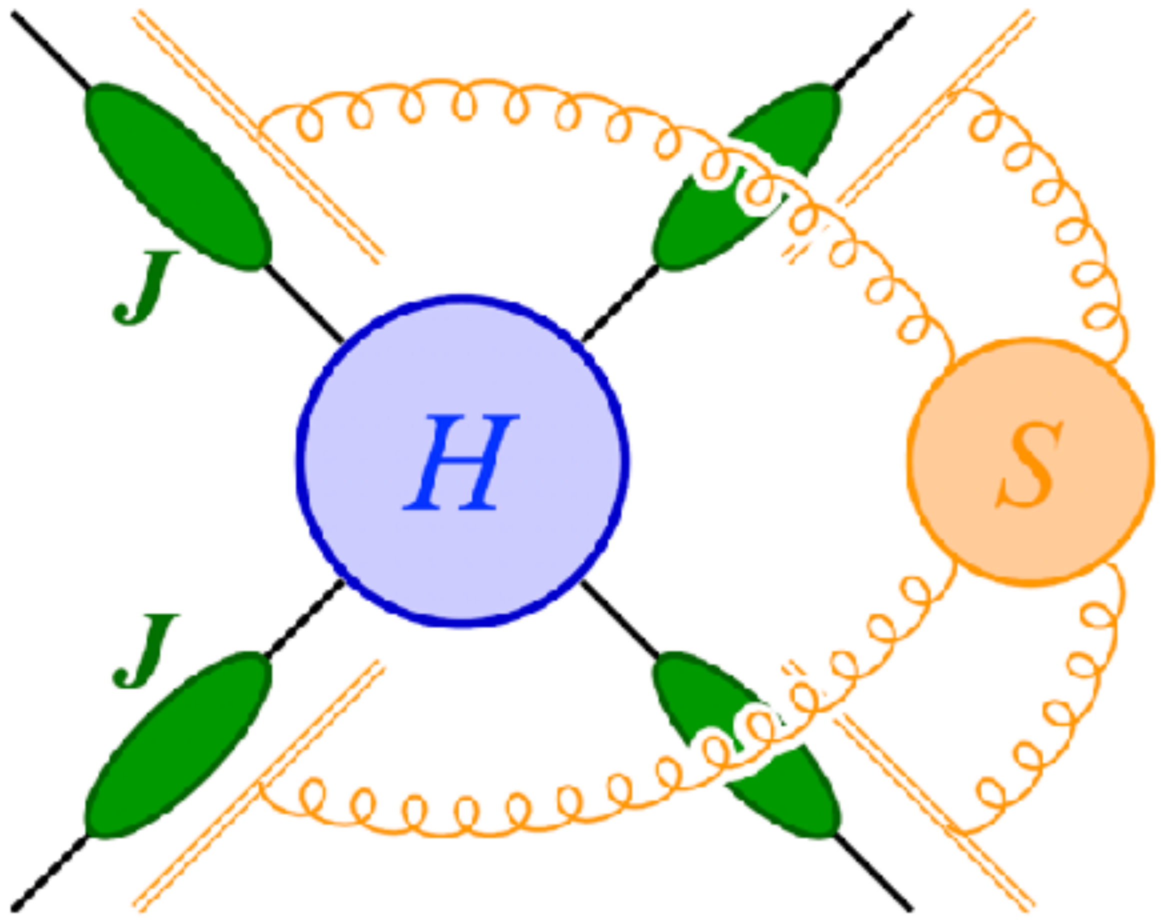
Perturbative QCD vs non-perturbative QCD

Symmetry





Factorization



Symmetries in QCD

$$\mathcal{L}_{\rm QCD} = \sum_q \bar{q}(i\not{D} - m_q e^{i\theta_q})q - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$$

Scale symmetry

$$x^\mu \to \lambda x^\mu,$$

$$\psi_q(x) \to \lambda^{3/2}\psi_q(\lambda x), \quad A_\mu^a(x) \to \lambda A_\mu^a(\lambda x)$$

Anomalous: trace anomaly

$$\partial_\mu S^\mu = \Theta_\mu^\mu = -\frac{\beta}{2g_s} F_{\mu\nu}^{(a)} F^{(a)\mu\nu} + \sum_q m_q \bar{\psi}_q \psi_q$$

$$m_N \bar{u}(\mathbf{p}) u(\mathbf{p}) = \langle N(\mathbf{p}) | \theta_\mu^\mu | N(\mathbf{p}) \rangle$$
$$= \left\langle N(\mathbf{p}) \middle| \frac{\beta_{\rm QCD}}{2g_3} F_{\mu\nu}^a F_a^{\mu\nu} + \sum_q m_q \bar{q} q \middle| N(\mathbf{p}) \right\rangle$$

90% proton mass from gluon dynamics

Chiral symmetry

U(3) x U(3)

$$\psi_q \to e^{i\alpha}\psi_q$$ Baryon number

$$\psi_q \to e^{i\alpha\gamma_5}\psi_q$$ U(1)A

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix} \to U \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

Gell-mann SU(3)

Anomalous: axial anomaly

$$\partial^\mu J_{5\mu}^{(0)}(x) = \frac{3\alpha_s}{4\pi} F_{\mu\nu}^a \tilde{F}_a^{\mu\nu} + \sum_q m_q \bar{q}\gamma_5 q$$

$$\mathcal{L}_{\rm det} = (-1)^{N_f} K^{-5} \langle \bar{u}_L u_R \rangle \left\langle \bar{d}_L d_R \right\rangle \langle \bar{s}_L s_R \rangle e^{i2\theta_{\eta'}} \sim \Lambda_{\rm QCD}^2 \, \eta'^2$$

Eta-prime mass from instanton dynamics

Although anomalies, still approximate SU(3) x SU(3) symmetry for $\Lambda_{\rm QCD} \gg m_q$

Chiral Symmetry

Enlarged SU(3) x SU(3) symmetry for small quark masses

$$q_L \equiv \begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix} \mapsto L\, q_L \equiv \exp\left(-i\epsilon_L^a \frac{\lambda^a}{2}\right) q_L$$

$$q_R \equiv \begin{pmatrix} u_R \\ d_R \\ s_R \end{pmatrix} \mapsto R\, q_L \equiv \exp\left(-i\epsilon_R^a \frac{\lambda^a}{2}\right) q_R$$

$$V_\mu^a = R_\mu^a + L_\mu^a = \bar{q}\gamma_\mu \frac{\lambda^a}{2} q$$

$$A_\mu^a = R_\mu^a - L_\mu^a = \bar{q}\gamma_\mu\gamma_5 \frac{\lambda^a}{2} q$$

$Q_1^V, \ldots, Q_8^V$ (vector currents)

$Q_1^A, \ldots, Q_8^A$ (axial currents)

Wigner-Weyl realization

$Q_V^a|0\rangle = 0 \qquad Q_A^a|0\rangle = 0$

Vacuum is symmetric

$\langle 0|\bar{q}_R q_L|0\rangle = 0$

Nambu-Goldstone realization

$Q_V^a|0\rangle = 0 \qquad Q_A^a|0\rangle \neq 0$

Quark condensation breaks chiral vacuum

$\langle 0|\bar{q}_R q_L|0\rangle \neq 0$

Vafa-Witten Theorem

Parity doubling for hadron spectra

Gell-man SU(3)

Goldstone Theorem

$$H_0 Q_i^A|0\rangle = Q_i^A H_0|0\rangle = 0$$

$$E = 0: \quad Q_1^A|0\rangle, \ldots, Q_8^A|0\rangle$$

Pion, K, eta are identified as
8 Goldstone modes

Lagrangian for low energy pion

Most general scalar Lagrangian

Current algebra, PCAC, sigma model, NJL model …

$$\mathcal{L}_\pi = \frac{1}{2}\partial_\mu\pi^a\partial^\mu\pi^a + b_0\pi^a\pi^a$$ quadratic in pion fields

$$+ b_1(\pi^a\pi^a)^2 + \ldots$$ quartic, no derivative

$$+ c_1(\partial_\mu\pi^a\pi^a)^2 + c_2(\partial_\mu\pi^a\partial^\mu\pi^a)(\pi^b\pi^b) + \ldots$$ quartic, two derivatives

$$+ \ldots$$ quartic, four derivatives, …

Chiral symmetry

Flavor symmetry relates matrix elements of multiplets

$\alpha \to \beta$ ⟷ (At low energy) $\alpha + n_1\pi \to \beta + n_2\pi$

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

Adler Zero condition

$b_k = 0$ for $k = 1, \ldots$

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

Chiral Ward Identity

$c_1 = -c_2$

PCAC relation

$$c_1 = -c_2 = \frac{1}{6f^2}$$

$$\langle 0|\, j^a_{5\mu}(x)\, |\pi^b(p)\rangle = \delta^{ab}\, ip_\mu F e^{-ip\cdot x}$$

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*

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(Received 25 September 1967)

Shift symmetry:

$$\pi \longrightarrow \pi + \epsilon + \cdots$$

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

Gapless mode

Weakly coupled at IR

Non-linear transform under G/H

No interaction at long-wave limit

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

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

Power counting: Derivative expansion

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

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

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

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

Coset Construction

[Callan, Coleman, Wess, Zumino, 1969]

CCWZ Chiral Lagrangian

Define the nonlinear Goldstone matrix

[Callan, Coleman, Wess, Zumino, 1969]

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

CCWZ Coset

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

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

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

Building block

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

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

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

Symmetric Coset

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

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

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

Building block

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

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

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

QCD Chiral Lag

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

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

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

EW Chiral Lag

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

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

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

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

QCD Chiral Perturbation Theory

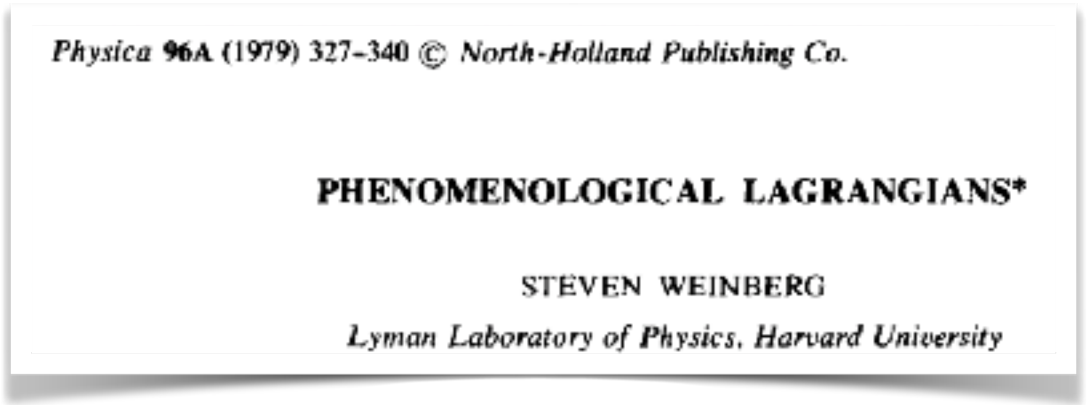
[Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2405.15047]

[Xuan-He Li, Hao Sun, Feng-Jie Tang, **J.H.Yu**, 2404.14152]

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

Weinberg's Folk Theorem

Weinberg developed a systematic procedure on effective Lagrangian in 1979


Physica 96A (1979) 327–340 © North-Holland Publishing Co.

PHENOMENOLOGICAL LAGRANGIANS*

STEVEN WEINBERG

Lyman Laboratory of Physics, Harvard University

[Weinberg 1933 - 2021]

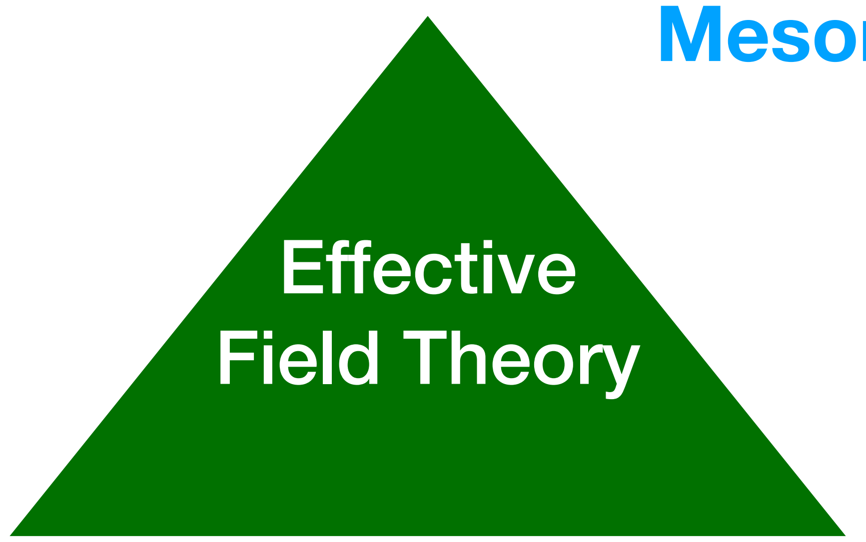
Weinberg's Folk theorem

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."

$$\mathcal{L}_2 = \frac{F^2}{4}\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) + \frac{F^2}{4}\mathrm{Tr}\left(\chi U^\dagger + U\chi^\dagger\right)$$

Proper Degree of freedom

Meson and baryon, external source



Global and local symmetry

SU(2) x SU(2) / SU(2)

Power Counting scheme

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_2 + \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

Naive Dimension Analysis (NDA)

Weinberg power counting on amplitude and NDA for LEC

$p^2/(4\pi f)^2$

$T =$ 

$$\mathcal{L}_0 = \frac{f^2}{4}\mathrm{Tr}\,\partial U^\dagger \partial U = \mathrm{Tr}\,\partial\pi\partial\pi + \frac{1}{3f^2}\mathrm{Tr}[\partial\boldsymbol{\pi}, \boldsymbol{\pi}]^2 + \ldots$$

$$\mathcal{L}_{2,4\pi} \simeq \frac{p^2\pi^4}{f^2} \qquad 2\text{ x } \mathcal{L}_{2,4\pi} \simeq \frac{p^4\pi^4}{f^4}\int\frac{d^4k}{(2\pi)^4}\frac{1}{(k^2)^2} \qquad \mathcal{L}_{4,4\pi}$$

$$\simeq \frac{p^4\pi^4}{f^4}\frac{1}{(4\pi)^2}\log(\Lambda^2_{\chi SB}/\kappa^2) \qquad \frac{f^2}{\Lambda^2_{\chi SB}}\mathrm{tr}(\partial^\mu\Sigma\partial^\nu\Sigma^\dagger\partial_\mu\Sigma\partial_\nu\Sigma^\dagger)$$

Curved field space

Loop factor

$$\mathcal{L} = \Lambda^2 f^2\left[\frac{1}{4\Lambda^2}\mathrm{Tr}\,\partial_\mu U^\dagger\partial^\mu U + \frac{1}{\Lambda^4}\left(\mathrm{Tr}\left(\partial_\mu U^\dagger\partial^\mu U\right)\right)^2 + \cdots\right]$$

$$\Lambda \sim 4\pi f_\pi \qquad \frac{f^2}{\Lambda^2_{\chi SB}} \gtrsim \frac{1}{(4\pi)^2}$$

Up to given order, only finite # of LEC are needed to renormalize the EFT

NDA

$$f^2\Lambda^2\left[\frac{\partial}{\Lambda}\right]^{N_p}\left[\frac{\phi}{f}\right]^{N_\phi}\left[\frac{A}{f}\right]^{N_A}\left[\frac{\psi}{f\sqrt{\Lambda}}\right]^{N_\psi}\left[\frac{g}{4\pi}\right]^{N_g}\left[\frac{y}{4\pi}\right]^{N_y}\left[\frac{\lambda}{16\pi^2}\right]^{N_\lambda}$$

Weinberg PC

$$D = 2 + 2N = 2 + 2\left(L + \sum_d \frac{d-2}{2}V_d\right)$$

V_d = # vertices with d derivatives

I = # internal lines

L = # loops

Building Blocks

Two kinds of parametrizations $\mathcal{G} = SU(2)_L \times SU(2)_R \rightarrow \mathcal{H} = SU(2)_V$ $\mathcal{L} = \mathcal{L}^0_{\rm QCD} + \bar{q}\gamma^\mu(v_\mu + \gamma_5 a_\mu)q - \bar{q}(s - i\gamma_5 p)q$

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

Symmetric coset

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

External source

$$\chi = 2B_0(s + ip)$$

$$f^R_{\mu\nu} \equiv \partial_\mu r_\nu - \partial_\nu r_\mu - i[r_\mu, r_\nu]$$
$$f^L_{\mu\nu} \equiv \partial_\mu l_\nu - \partial_\nu l_\mu - i[l_\mu, l_\nu]$$

Covariant derivative and chiral connection

$$D_\mu X \equiv \partial_\mu X - i r_\mu X + i X\, l_\mu$$

$$U, D_\mu, \chi, f^L_{\mu\nu} U, U f^R_{\mu\nu}$$

Transform under H $X \rightarrow h\, X\, h^\dagger$

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

$$u_\mu \rightarrow \mathfrak{h}\, u_\mu\, \mathfrak{h}^{-1} \qquad B \rightarrow \mathfrak{h}\, B\, \mathfrak{h}^{-1}$$

External source

$$\chi_\pm = u^\dagger \chi u^\dagger \pm u \chi^\dagger u\,,$$
$$f^\pm_{\mu\nu} = u f^{\rm L}_{\mu\nu} u^\dagger \pm u^\dagger f^{\rm R}_{\mu\nu} u\,,$$

Covariant derivative and chiral connection

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

$$[D_\mu, D_\nu]\, A = \frac{1}{4}\left[\left[u_\mu, u_\nu\right], A\right] - \frac{\mathrm{i}}{2}\left[f^+_{\mu\nu}, A\right]$$

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

$$u_\mu, D_\mu, \chi^\pm, f^\pm$$

Redundancies

Equation of motion (field redefinition)

$$D^\mu u_\mu = 0\,, \qquad i\gamma^\mu D_\mu N = (M - \frac{g_A}{2}\gamma^5\gamma^\mu u_\mu)N\,, \qquad -iD_\mu \overline{N}\gamma_\mu = \overline{N}(M - \frac{g_A}{2}\gamma^5\gamma^\mu u_\mu)\,.$$

$$(\overline{N}D^\mu u_\mu \Gamma N) \to 0\,,$$
$$(\overline{N}\gamma^\mu \overleftrightarrow{D}_\mu N) \to (\overline{N}(M - \frac{g_A}{2}\gamma^5\gamma^\mu u_\mu)N)\,,$$
$$(\overline{N}\gamma^5\gamma^\mu \overleftrightarrow{D}_\mu N) \to (\overline{N}\gamma^5(M - \frac{g_A}{2}\gamma^5\gamma^\mu u_\mu)N)\,,$$

Integration by part (momentum conservation)

$$D^{\mu_1}D^{\mu_2}\ldots D^{\mu_n}(\overline{N}\Gamma\Pi N) \to (\overline{N}\Gamma D^{\mu_1}D^{\mu_2}\ldots D^{\mu_n}\Pi N)\,,$$

Ferz identity (Schouten identity)

$$(\overline{N}^\alpha \Gamma_{1\alpha\beta}N^\lambda)(\overline{N}^\rho \Gamma_{2\rho\lambda}N^\beta) \to (\overline{N}^\alpha \Gamma_{3\alpha\beta}N^\beta)(\overline{N}^\rho \Gamma_{4\rho\lambda}N^\lambda)\,,$$

$$(\overline{N}^i \Gamma_1 \tau^I{}_{il} N^l)(\overline{N}^k \Gamma_2 \tau^I{}_{kj} N^j) \to (\overline{N}^i \Gamma_1 N_j)(\overline{N}^j \Gamma_2 N_i) - (\overline{N}^i \Gamma_1 N_i)(\overline{N}^j \Gamma_2 N_j)\,.$$

Cayley-Hamilton relation (trace basis)

$$\begin{aligned}&-\langle AD\rangle\langle BC\rangle - \langle AC\rangle\langle BD\rangle - \langle AB\rangle\langle CD\rangle \\ &+\langle ABCD\rangle + \langle ACBD\rangle + \langle ABDC\rangle + \langle ACDB\rangle + \langle ADBC\rangle + \langle ADCB\rangle \\ &= 0\,,\end{aligned}$$

$$\begin{aligned}&T_1 = \langle AC\rangle\langle BD\rangle\,, \quad T_2 = \langle AB\rangle\langle CD\rangle\,, \\ &T_3 = \langle ABCD\rangle\,, \quad T_4 = \langle ABDC\rangle\,, \quad T_5 = \langle ACBD\rangle \\ &T_6 = \langle ACDB\rangle\,, \quad T_7 = \langle ADBC\rangle\,, \quad T_8 = \langle ADCB\rangle\,.\end{aligned}$$

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

$$(\psi_1\psi_2)(D^\mu F_{R3}^{\nu\lambda})(D_\mu F_{R4\nu\lambda})$$

$$D^{r_i}\phi_i \Leftrightarrow \lambda_i^{r_i}\tilde\lambda^{i,r_i}, \qquad D^{r_i-1}F_{\mathrm{L/R}\,i} \Leftrightarrow \lambda_i^{r_i\pm1}\tilde\lambda^{i,r_i\mp1},$$

$$D^{r_i-1/2}\psi_i^{(\dagger)} \Leftrightarrow \lambda_i^{r_i\pm1/2}\tilde\lambda^{i,r_i\mp1/2},$$

Spinor Tensor → **Symmetrize indices**

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

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

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

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

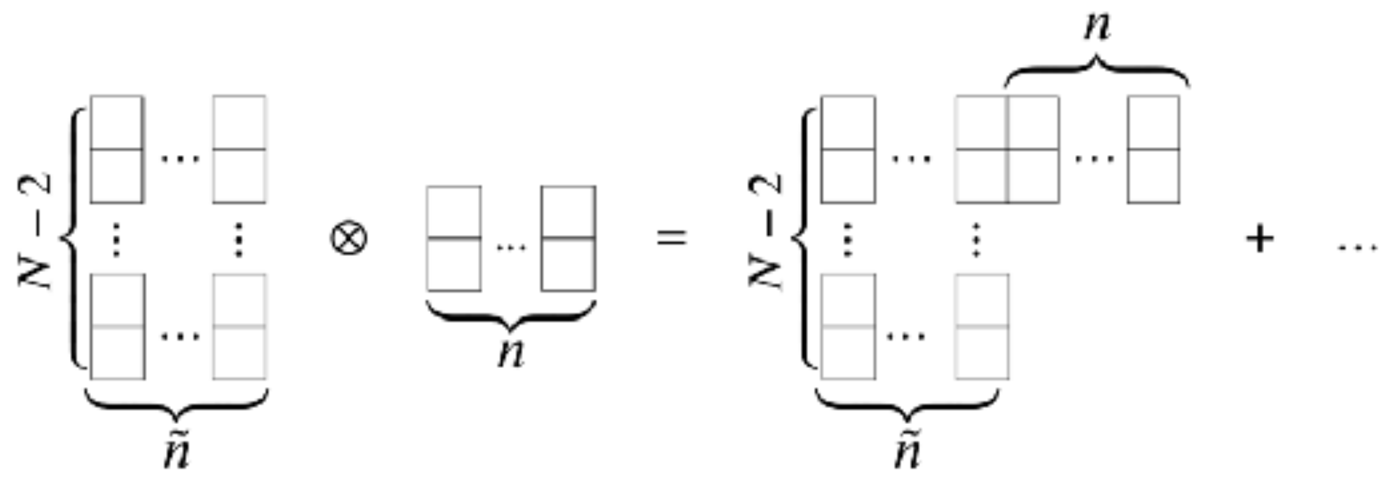
$$(D\psi)_{\alpha\beta\dot\alpha} = -\frac{1}{2}\epsilon_{\alpha\beta}(\not{D}\psi)_{\dot\alpha} + \frac{1}{2}(D\psi)_{(\alpha\beta)\dot\alpha}$$

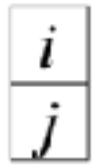
↓

SL(2,C) x SU(N)

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

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





$\Leftrightarrow \langle ij\rangle$

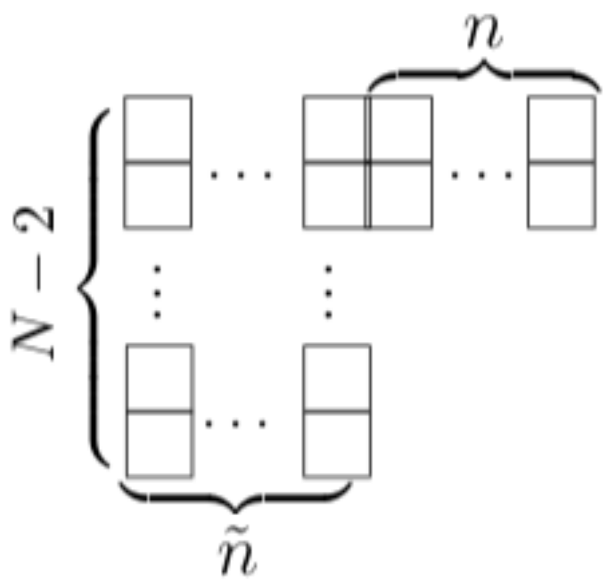
Momentum conservation

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

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

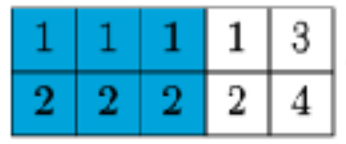
↓

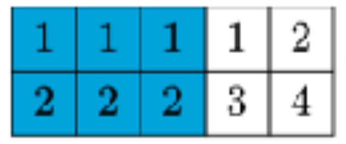
SSYT → **On-shell Amplitude**



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

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

$\mathcal{B}_1 =$  $\sim [34]^2\langle12\rangle\langle34\rangle = (\psi_1\psi_2)(D^\mu F_{R3}^{\nu\lambda})(D_\mu F_{R4\nu\lambda})$,

$\mathcal{B}_2 =$  $\sim [34]^2\langle13\rangle\langle24\rangle = (\psi_1\sigma^{\rho\lambda}\psi_2)(D_\lambda F_{R3}^{\mu\nu})(D_\rho F_{R4\mu\nu})$,

On-shell Amplitude correspondence

Adler Zero Condition for Goldstone Boson

Chiral symmetry (PCAC)

$\alpha \to \beta$ ⟷ (At low energy) $\alpha + n_1\pi \to \beta + n_2\pi$

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)

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

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

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

Expand the soft-limit amplitude into the SSYT basis

Put constraints on the SSYT basis

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

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

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

Chiral symmetry breaking: spurion technique

Chiral Lagrangian for QCD and beyond

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

Pure Meson sector

p2 order — [Weinberg, 1979]

p4 order — [Gasser, Leutwyler, 1984, 1985]; [Fearing, Scherer 1994]

p6 orde — [Bijnens, Colangelo, Ecker, 1999]; [Jiang, Ge, Wang, 2014] CP-odd

p8 orde — [Bijnens, Hermansson, Wang, 2018]

[Li, Sun, Tang, **J.H.Yu**, 2404.14152] CP-odd

Meson-Baryon sector

SU(2) p3 — [Krause, 1990]; [Ecker, 1994]

SU(2) p4 — [Fettes, Meisner, Mojzis, Steininger, 2000]

p3 order — [Oller, Verbeni, Prades, 2006]; [Frink, Meisner, 2006]

p4 order — [Jiang, Chen, Liu, 2017]

p5 order — [Song, Sun, **J.H.Yu**, 2405.15047]

Classifying Operators by CP

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

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

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

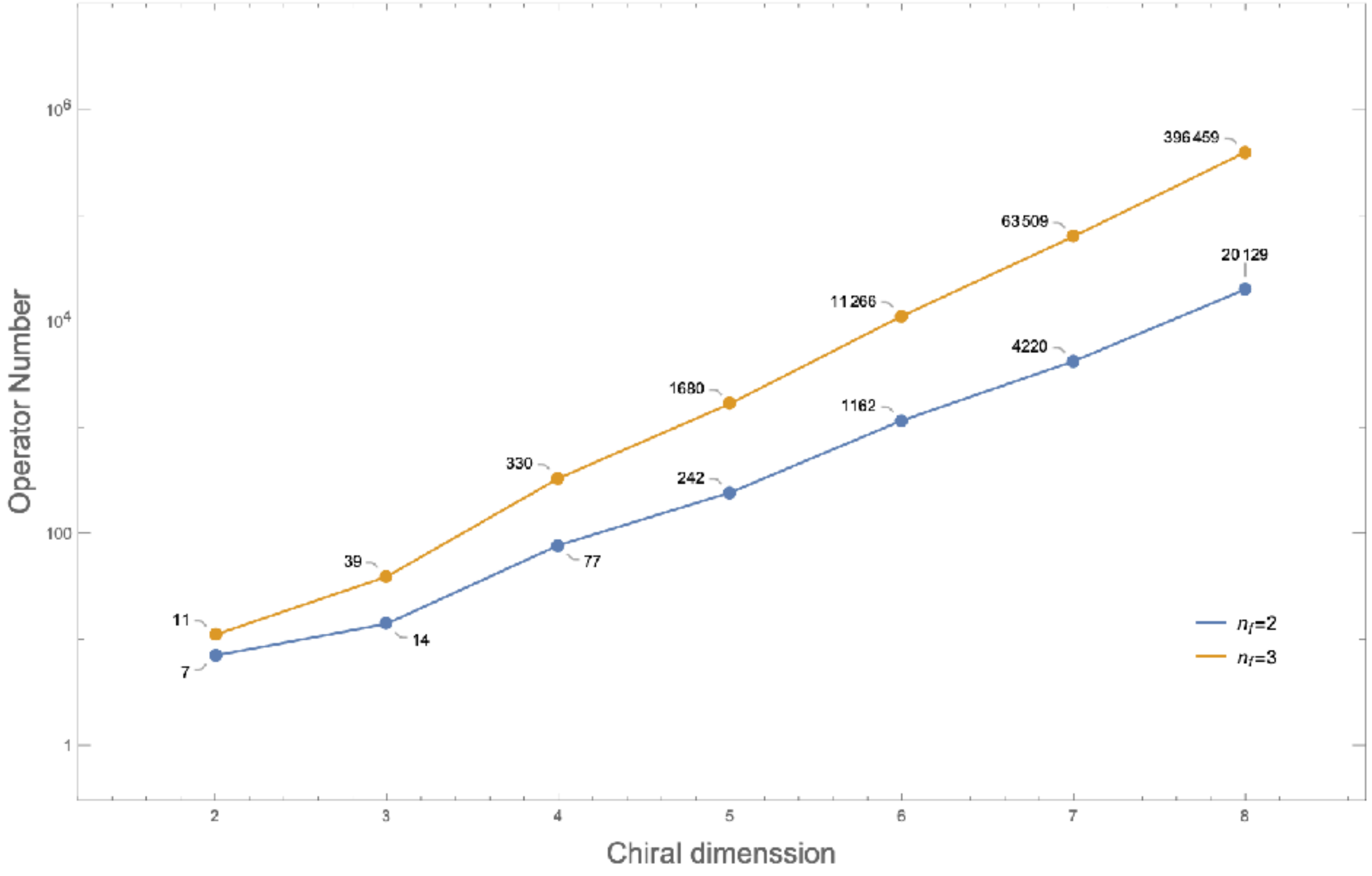
[Hao Sun, Yi-Ning Wang, **J.H.Yu**, 2211.11598]

[Sun, Wang, **Yu**, in préparation]

Hilbert series

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

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



Operator Bases for Generic EFT up to All Order

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

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Welcome to the HEPForge Project: ABC4EFT

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

Package

This package has the following features:

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

Authors

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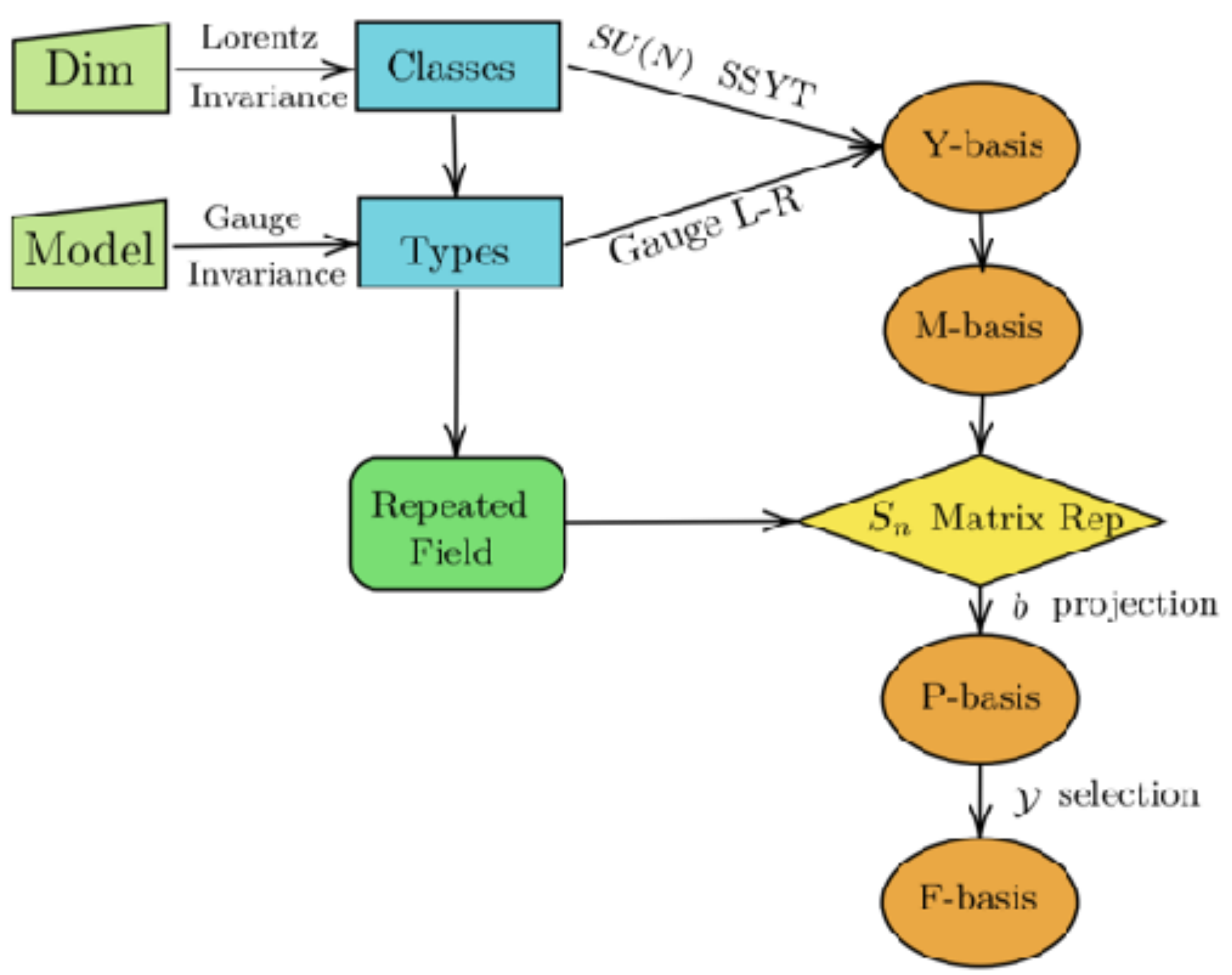
- Jiang-Hao Yu (professor at ITP-CAS)
- Yu-Hui Zheng (5th-year graduate student at ITP-CAS)

https://abc4eft.hepforge.org/



Fully Automatic

- Standard model EFT
- Low energy EFT
- Dark matter EFT
- Sterile neutrino EFT
- Gravity EFT
- Axion EFT
- ...

Electroweak Chiral Lagrangian

[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**, 2211.11598]

[Fordi, Schmitz, **J.H.Yu,** 2010]

[**J.H.Yu,** 2016, 2017]

[Li, Xu, **J.H.Yu**, Zhu**,** 2019]

[Xu, **J.H.Yu**, Zhu**,** 2020]

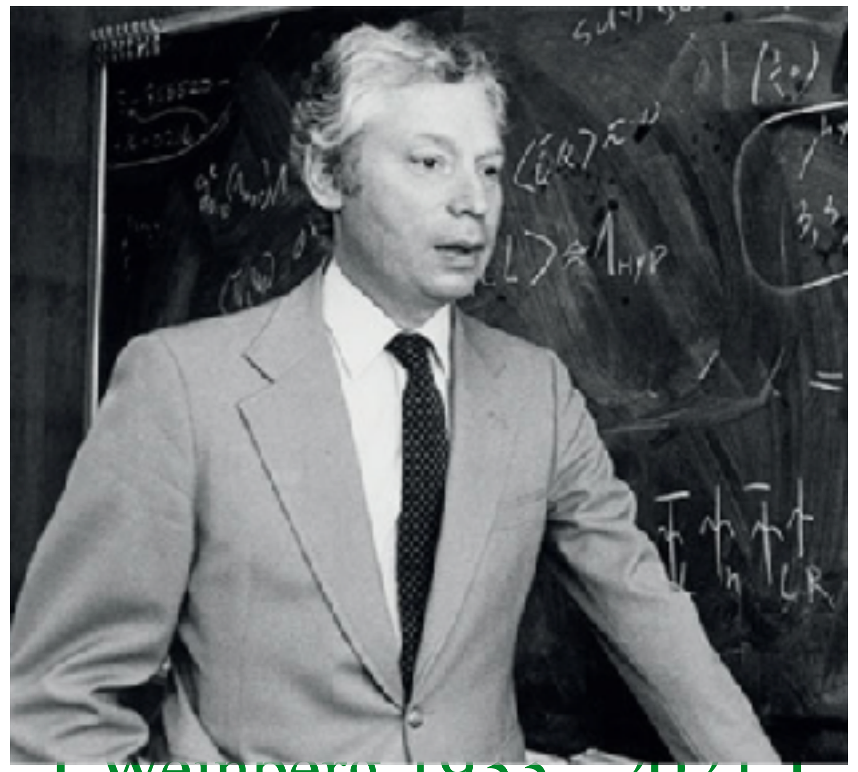
[Qi, **J.H.Yu**, Zhu**,** 2020]

Weinberg's Standard Model

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Electroweak unification inspired by QCD chiral dynamics



[Weinberg 1933 - 2021]

My starting point in 1967 was the old aim, going back to Yang and Mills, of developing a gauge theory of the strong interactions, based on the symmetry group $SU(2) \times SU(2)$

Then it suddenly occurred to me that this was a perfectly good sort of theory, but I was applying it to the wrong kind of interaction. The right place to apply these ideas was not to the strong interactions, but to the weak and electromagnetic interactions.

Weinberg 2004

$SU(2)_L \otimes SU(2)_R \to SU(2)_{L+R}$ **Symmetry**

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}}(v+H)U(\vec{\varphi})\begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger D^\mu \Phi - \lambda\left(|\Phi|^2 - \frac{v^2}{2}\right)^2$$

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix} \equiv \frac{1}{\sqrt{2}}(v+H)U(\vec{\varphi})$$

$$\mathcal{L}_\Phi = \frac{1}{2}\mathrm{Tr}\left[(D^\mu\Sigma)^\dagger D_\mu \Sigma\right] - \frac{\lambda}{4}\left(\mathrm{Tr}\left[\Sigma^\dagger\Sigma\right] - v^2\right)^2$$

Gell-mann-Levi model

$$\mathcal{L}_\Phi = \frac{v^2}{4}\left(1+\frac{h}{v}\right)^2 \langle D_\mu \mathbf{U}^\dagger D^\mu \mathbf{U}\rangle + \frac{1}{2}\left(\partial_\mu h \partial^\mu h - m_h^2 h^2\right) - \frac{m_h^2}{2v}h^3 - \frac{m_h^2}{8v^2}h^4$$

Custodial symmetry:

$$\mathcal{L}_2 = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu U^\dagger D^\mu U\right) \xrightarrow{U=1} \mathcal{L}_2 = M_W^2 W_\mu^\dagger W^\mu + \frac{1}{2}M_Z^2 Z_\mu Z^\mu$$

$$\mathrm{M_W} = \mathrm{M_Z}\cos\theta_W = \frac{1}{2}\mathrm{g\,v}$$

Electroweak chiral Lagrangian

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)

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

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

Electroweak Chiral Lagrangian

QCD Chiral Lagrangian

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

SM fields and Goldstone

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

meson and baryon

SM Fermion masses from Higgs VEV

Baryon masses around cutoff scale from Trace anomaly

Ingredients of electroweak chiral Lagrangian

Three ingredients: field, symmetry and power counting

building blocks	spinor-helicity	Lorentz group	$SU(2)_L$	$SU(3)_C$	d_χ
L_L	$L_{L\alpha}$	$(\frac{1}{2},0)$	Fundamental	Singlet	1
L_R	${L_R}^{\dot\alpha}$	$(0,\frac{1}{2})$	Fundamental	Singlet	1
Q_L	$Q_{L\alpha}$	$(\frac{1}{2},0)$	Fundamental	Fundamental	1
Q_R	${Q_R}^{\dot\alpha}$	$(0,\frac{1}{2})$	Fundamental	Fundamental	1
W_L	${W_L}^I_{\alpha\beta}\tau^I$	$(1,0)$	Adjoint	Singlet	2
W_R	${W_R}^{I\dot\alpha\dot\beta}\tau^I$	$(0,1)$	Adjoint	Singlet	2
G_L	$G_{L\alpha\beta}$	$(1,0)$	Singlet	Adjoint	2
G_R	${G_R}^{\dot\alpha\dot\beta}$	$(0,1)$	Singlet	Adjoint	2
B_L	$B_{L\alpha\beta}$	$(1,0)$	Singlet	Singlet	2
B_R	${B_R}^{\dot\alpha\dot\beta}$	$(0,1)$	Singlet	Singlet	2
$\mathbf{V}^\mu \sim D^\mu\Pi$	$(D\phi^I)_{\dot\alpha\beta}\tau^I$	$(\frac{1}{2},\frac{1}{2})$	Adjoint	Singlet	1
D^μ	$D_{\alpha\dot\beta}$	$(\frac{1}{2},\frac{1}{2})$	Singlet	Singlet	1
$\mathbf{T}$	$\mathbf{T}^T\tau^I$	$(0,0)$	Adjoint	Singlet	0

$$u_\mu = iu\,(D_\mu U)^\dagger\, u = -iu^\dagger D_\mu U u^\dagger \longrightarrow \mathfrak{g}_{\mathcal{H}} u_\mu \mathfrak{g}_{\mathcal{H}}^\dagger$$
$$f_\pm^{\mu\nu} = u^\dagger \hat{W}^{\mu\nu} u \pm u\hat{B}^{\mu\nu}u^\dagger \longrightarrow \mathfrak{g}_{\mathcal{H}} f_\pm^{\mu\nu} \mathfrak{g}_{\mathcal{H}}^\dagger$$
$$\mathcal{T} = u\mathcal{T}_R u^\dagger \longrightarrow \mathfrak{g}_{\mathcal{H}} \mathcal{T} \mathfrak{g}_{\mathcal{H}}^\dagger$$
$$u^\dagger \psi_L \longrightarrow \mathfrak{g}_{\mathcal{H}} u^\dagger \psi_L$$
$$u\psi_R \longrightarrow \mathfrak{g}_{\mathcal{H}} u\psi_R$$
$$\mathcal{Y} = u\mathcal{Y}_R u^\dagger \longrightarrow \mathfrak{g}_{\mathcal{H}} \mathcal{Y} \mathfrak{g}_{\mathcal{H}}^\dagger$$

$$\mathbf{V}_\mu(x) = i\mathbf{U}(x)D_\mu \mathbf{U}(x)^\dagger, \longrightarrow \mathfrak{g}_L \mathbf{V}_\mu \mathfrak{g}_L^\dagger$$
$$\hat{W}_{\mu\nu} \longrightarrow \mathfrak{g}_L \hat{W}_{\mu\nu} \mathfrak{g}_L^\dagger$$
$$\hat{B}_{\mu\nu} \longrightarrow \hat{B}_{\mu\nu}$$
$$\mathbf{T} = \mathbf{U}\mathcal{T}_R\mathbf{U}^\dagger \longrightarrow \mathfrak{g}_L \mathbf{T} \mathfrak{g}_L^\dagger$$
$$\psi_L \longrightarrow \mathfrak{g}_L \psi_L$$
$$\mathbf{U}\psi_R \longrightarrow \mathfrak{g}_L \mathbf{U}\psi_R$$
$$\mathbf{Y} = \mathbf{U}\mathcal{Y}_R\mathbf{U}^\dagger \longrightarrow \mathfrak{g}_L \mathbf{Y} \mathfrak{g}_L^\dagger$$

Chiral dimension (NDA)

$$d_\chi = d_i + k_i + \frac{F_i}{2} + V_i = 2L_i + 2.$$

$$\frac{p^2}{16\pi^2 \mathbf{v}^2} \sim \frac{g^2}{(4\pi)^2}, \frac{y^2}{(4\pi)^2}, \frac{\lambda}{(4\pi)^2} \ll 1\,.$$

Jiang-Hao Yu (ITP-CAS)

Spurion Technique

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

$$\tau^{K}{}^{i}_{l}\tau^{M}{}^{k}_{j}\epsilon^{IJM}\mathbf{T}^{J}\mathbf{T}^{K}W_{L}{}^{I}{}_{\mu\nu}(L_{Lp_i}\sigma_{\lambda}{}^{\nu}L^{\dagger}_{Rr}{}^{j})(Q_{Lsak}\sigma^{\mu\lambda}Q^{\dagger}_{Rt}{}^{al})$$
$$\tau^{J}{}^{k}_{l}\mathbf{T}^{I}\mathbf{T}^{J}W_{L}{}^{I}{}_{\mu\nu}(L_{Lp_i}\sigma^{\mu\nu}L^{\dagger}_{Rr}{}^{i})(Q_{Lsak}Q^{\dagger}_{Rt}{}^{al})$$

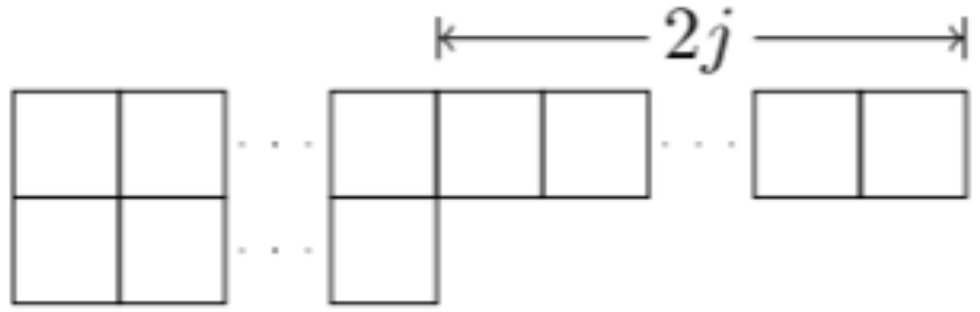
$$t_i \in \mathbf{2} \sim \square$$
$$\epsilon_{ij}t^j \in \bar{\mathbf{2}} \sim \square$$
$$t^I\tau_i^{Ik}\epsilon_{kj} \in \mathbf{3} \sim \square\square$$

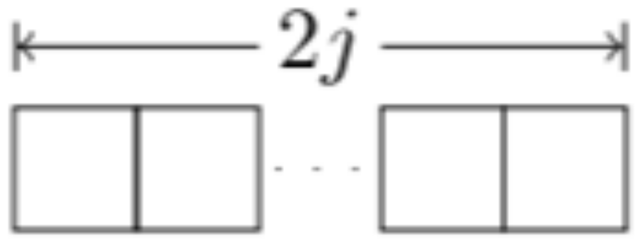
$$\mathbf{T}^{I}\tau^{Ik}{}_{i}\epsilon_{kj} \in \boxed{i\,|\,j}\,,$$
$$\mathbf{T}^{\{I_1}\ldots\mathbf{T}^{I_j\}} \in \text{spin } j$$
$$\begin{array}{ccccccccc} \mathbf{T}^I\mathbf{T}^J & = & \mathbf{T}^2\delta^{IJ} & + & \mathbf{T}^{[I}\mathbf{T}^{J]} & + & \mathbf{T}^{(I}\mathbf{T}^{J)}, \\ \mathbf{3}\otimes\mathbf{3} & = & \mathbf{1} & + & \mathbf{3} & + & \mathbf{5}. \end{array}$$

Littlewood-Richarson rules

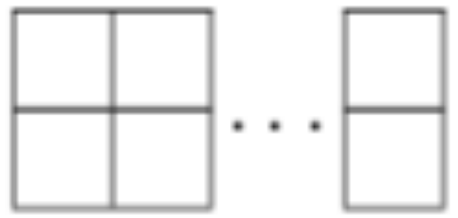
Symmetric highest weight

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





Gauge Singlet

$SU(2) \sim$ 

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

Results at LO/NLO/NNLO

Compared with literatures, new 6 (9) operators found at NLO

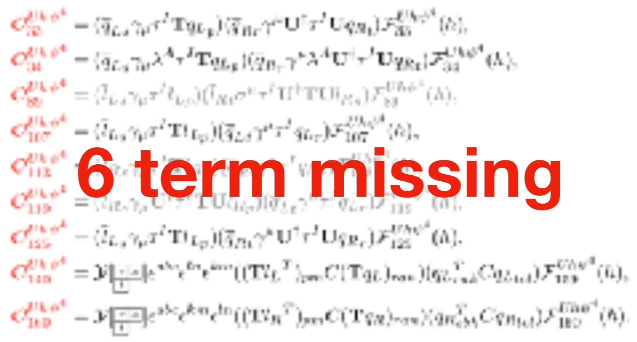
$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{p^2} + \mathscr{L}_{p^3} + \mathscr{L}_{p^4} + \mathscr{L}_{p^5} + \mathscr{L}_{p^6} + \ldots$$

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]

Classes	$\mathcal{N}_{\rm type}$	$\mathcal{N}_{\rm term}$	$\mathcal{N}_{\rm operator}$
UhD^4	$3+6+0+0$	15	15
X^2Uh	$6+4+0+0$	10	10
$XUhD^2$	$2+6+0+0$	8	8
X^3	$4+2+0+0$	6	6
ψ^2UhD	$4+8+0+0$	13(16)	$13{n_f}^2 \quad (16{n_f}^2)$
ψ^2UhD^2	$6+10+0+0$	60(80)	$60{n_f}^2 \quad (80{n_f}^2)$
ψ^2UhX	$7+7+0+0$	22(28)	$22{n_f}^2 \quad (28{n_f}^2)$
ψ^4	$12+24+4+8$	117(160)	$\frac{1}{4}{n_f}^2(31-6n_f+335{n_f}^2) \quad ({n_f}^2(9-2n_f+125{n_f}^2))$
Total	123	261(313)	$\frac{335{n_f}^4}{4}-\frac{3{n_f}^3}{2}+\frac{411{n_f}^2}{4}+39 \quad (39+133{n_f}^2-2{n_f}^2-2{n_f}^3+125{n_f}^4)$ $\mathcal{N}_{\rm operatrs}(n_f=1)=224(295), \quad \mathcal{N}_{\rm operatrs}(n_f=3)=7704(11307)$

$$\mathcal{O}_{33}^{Uh\psi^4} = (\bar{q}_{L_s}\gamma_\mu\tau^I\mathbf{T}q_{L_p})(\bar{q}_{R_r}\gamma^\mu\mathbf{U}^\dagger\tau^I\mathbf{U}q_{R_t})\mathcal{F}_{33}^{Uh\psi^4}(h),$$
$$\mathcal{O}_{34}^{Uh\psi^4} = (\bar{q}_{L_s}\gamma_\mu\lambda^A\tau^I\mathbf{T}q_{L_p})(\bar{q}_{R_r}\gamma^\mu\lambda^A\mathbf{U}^\dagger\tau^I\mathbf{U}q_{R_t})\mathcal{F}_{34}^{Uh\psi^4}(h),$$
$$\mathcal{O}_{89}^{Uh\psi^4} = (\bar{l}_{L_s}\gamma_\mu\tau^I l_{L_p})(\bar{l}_{R_t}\sigma^\mu\tau^I\mathbf{U}^\dagger\mathbf{T}\mathbf{U}l_{R_s})\mathcal{F}_{89}^{Uh\psi^4}(h),$$
$$\mathcal{O}_{107}^{Uh\psi^4} = (\bar{l}_{L_s}\gamma_\mu\tau^I\mathbf{T}l_{L_p})(\bar{q}_{L_t}\gamma^\mu\tau^I q_{L_r})\mathcal{F}_{107}^{Uh\psi^4}(h),$$
$$\mathcal{O}_{113}^{Uh\psi^4} = (\bar{l}_{R_s}\gamma_\mu\tau^I\mathbf{T}l_{R_p})(\bar{q}_{R_t}\gamma^\mu\tau^I q_{R_r})\mathcal{F}_{113}^{Uh\psi^4}(h),$$
$$\mathcal{O}_{119}^{Uh\psi^4} = (\bar{l}_{R_s}\gamma_\mu\mathbf{U}^\dagger\tau^I\mathbf{T}\mathbf{U}l_{R_p})(\bar{q}_{L_t}\gamma^\mu\tau^I q_{L_r})\mathcal{F}_{119}^{Uh\psi^4}(h),$$
$$\mathcal{O}_{125}^{Uh\psi^4} = (\bar{l}_{L_s}\gamma_\mu\tau^I\mathbf{T}l_{L_p})(\bar{q}_{R_t}\gamma^\mu\mathbf{U}^\dagger\tau^I\mathbf{U}q_{R_r})\mathcal{F}_{125}^{Uh\psi^4}(h),$$
$$\mathcal{O}_{140}^{Uh\psi^4} = \mathcal{Y}\left[\begin{smallmatrix} r & s \\ t & \end{smallmatrix}\right]\epsilon^{abc}\epsilon^{ln}\epsilon^{km}((\mathbf{T}{l_L}^T)_{pm}C(\mathbf{T}q_L)_{ran})(q_{L_{rak}}^T C q_{L_{tcl}})\mathcal{F}_{159}^{Uh\psi^4}(h),$$
$$\mathcal{O}_{160}^{Uh\psi^4} = \mathcal{Y}\left[\begin{smallmatrix} r & s \\ t & \end{smallmatrix}\right]\epsilon^{abc}\epsilon^{km}\epsilon^{ln}((\mathbf{T}{l_R}^T)_{pm}C(\mathbf{T}q_R)_{ran})(q_{R_{sbk}}^T C q_{R_{tcl}})\mathcal{F}_{160}^{Uh\psi^4}(h).$$

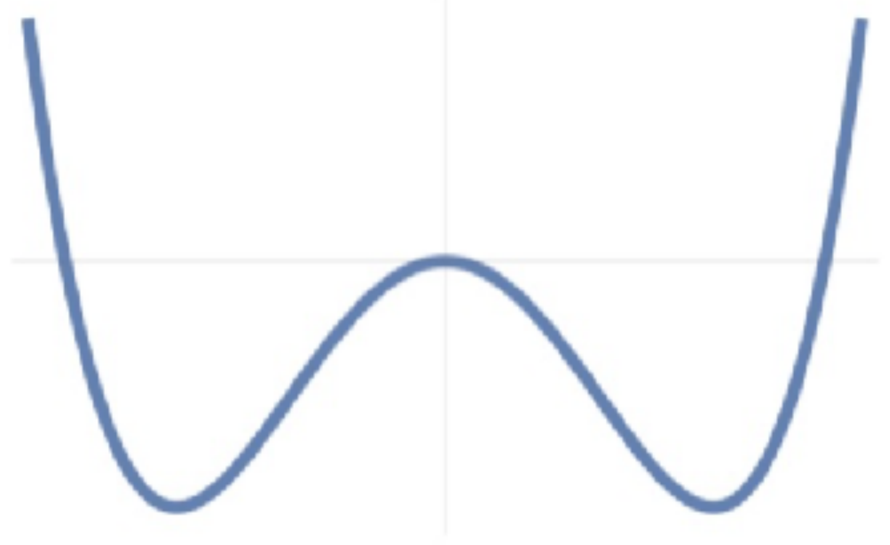
Which EFT? SMEFT or HEFT

Does the SMEFT cover all kinds of new physics scenarios?

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

Depending on nature of the Higgs boson and decoupling feature of new particle

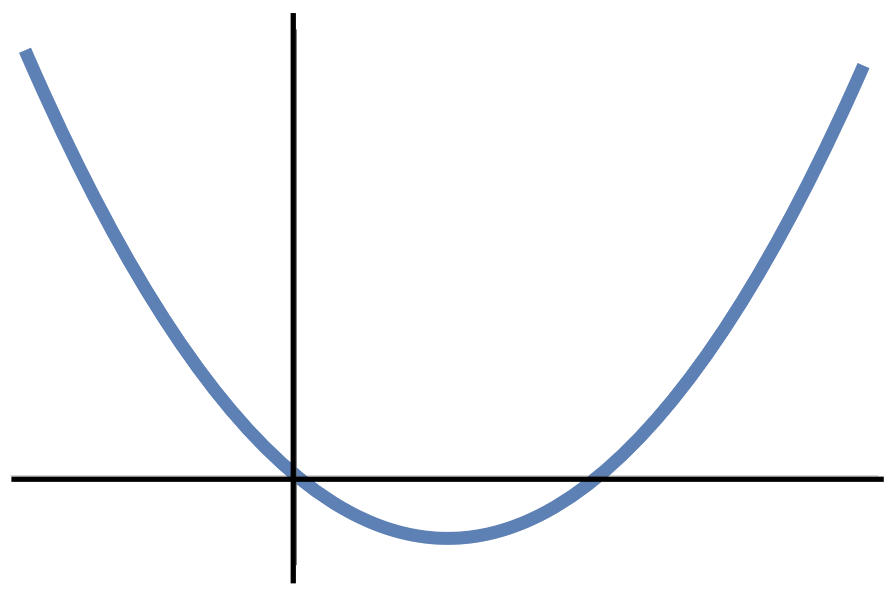
Landau-Ginzburg Higgs



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

Fundamental particle

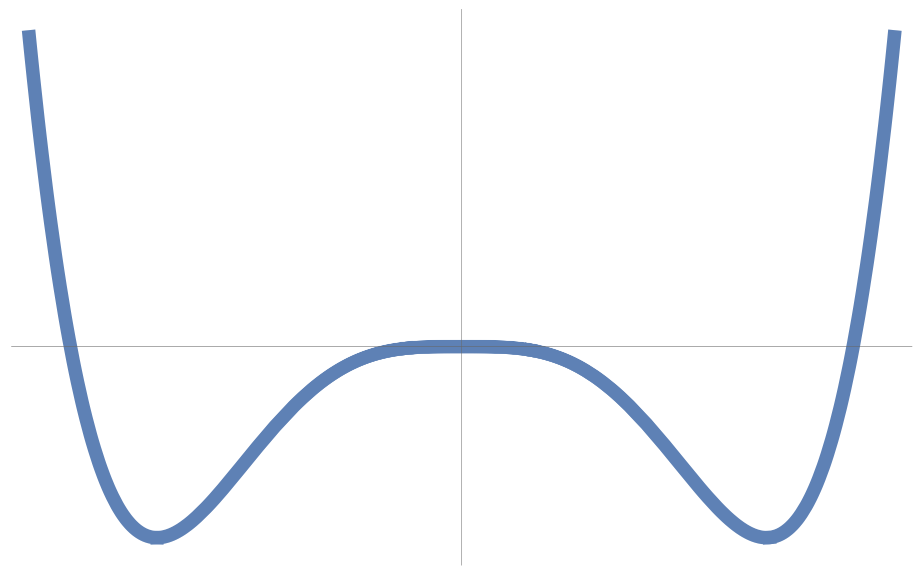
Tadpole-induced Higgs



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

Partial Fundamental (condensate)

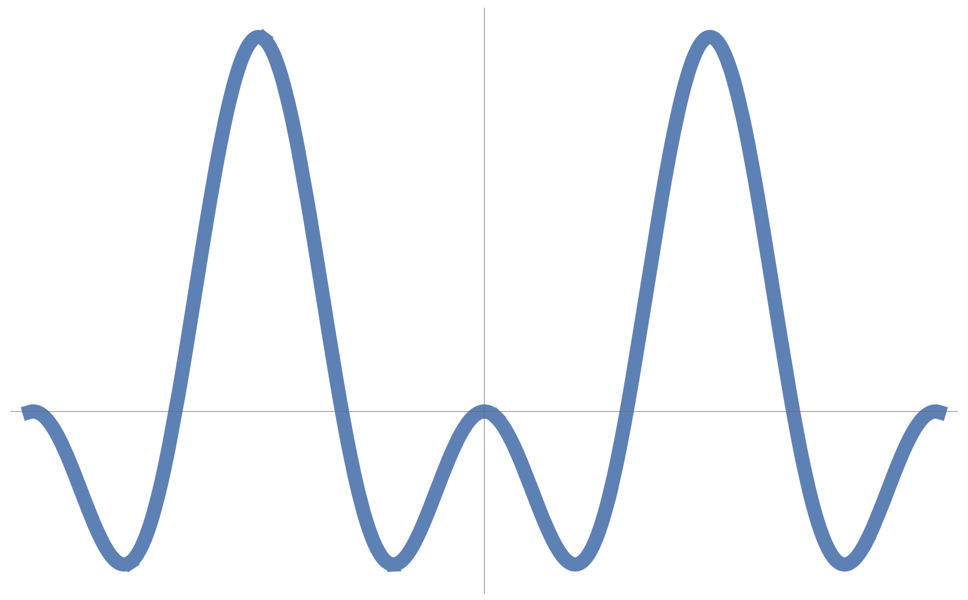
Coleman Weinberg Higgs



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

Conformal particle

Pseudo-Goldstone Higgs



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

Composite particle

Also [Falkowski, Rattazzi 2019]

[Cohen, Craig, Lu, Sutherland, 2021]

Nature of the Higgs Boson

Before the Higgs discovery, and after …

What is dynamics at EW scale?

Weak dynamics @ EW scale

SM, SUSY, etc

Strong dynamics @ EW scale

Technicolor, etc

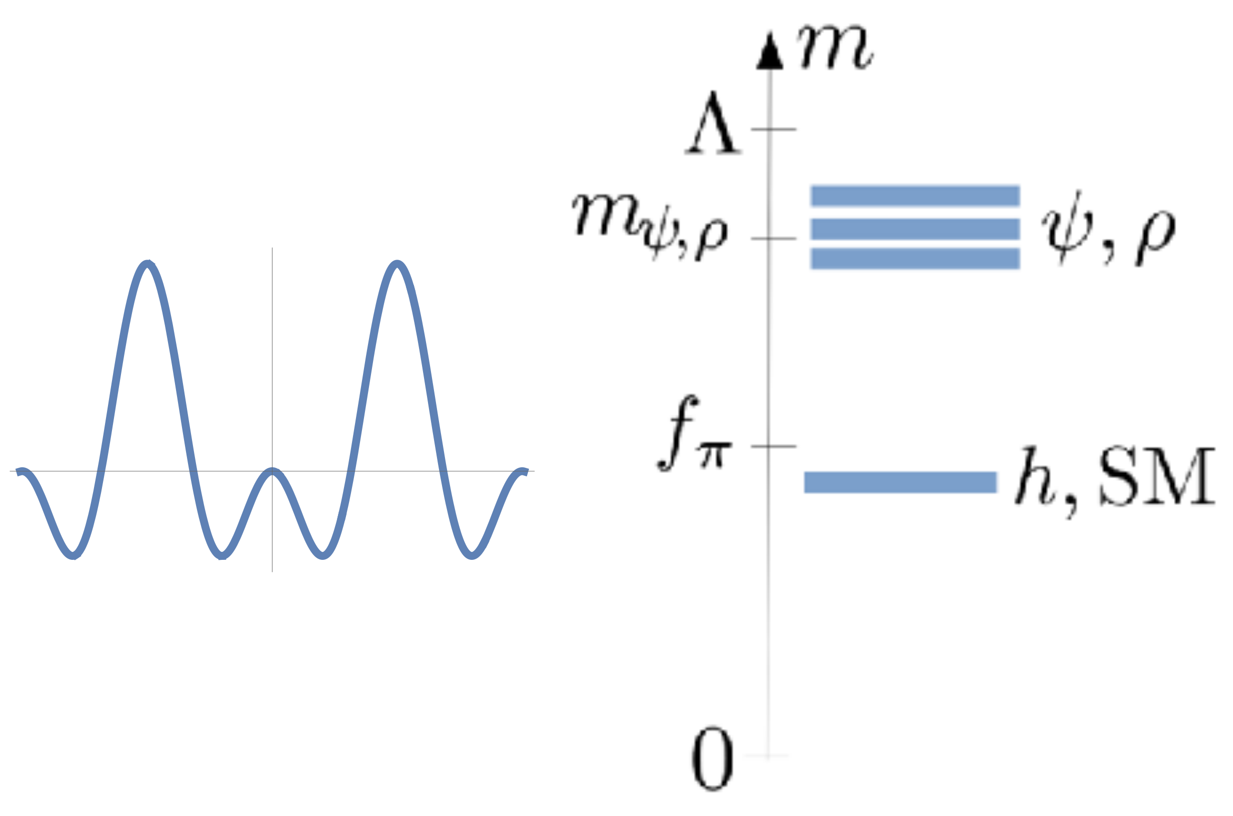
What is dynamics at TeV scale?

Fundamental

weak dynamics at TeV

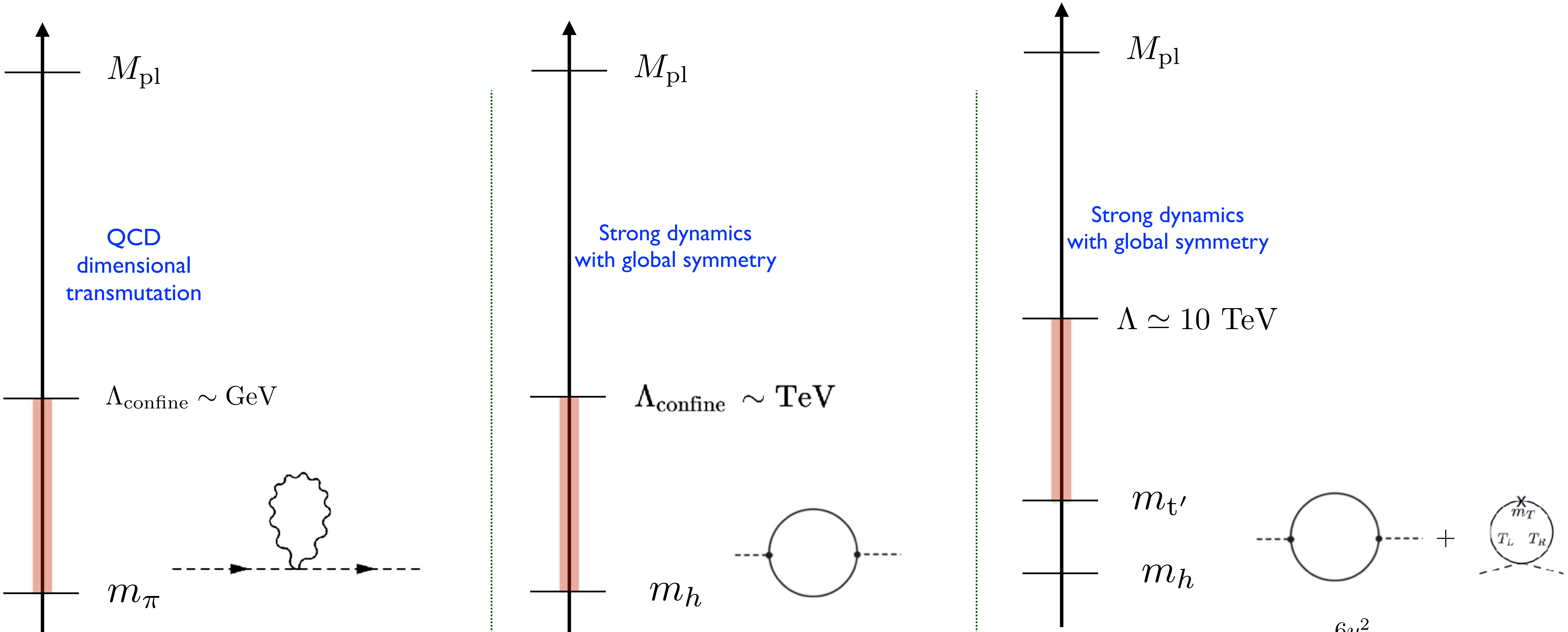
Composite

strong dynamics at TeV



Higgs as Goldstone Boson

From QCD to composite Higgs to little Higgs



$M^2_{\pi^+} - M^2_{\pi^0} = \frac{3e^2}{16\pi^2}\Lambda^2$ $\quad \frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} = \frac{G_F^2 f_K^2}{6\pi^2} \sin^2\theta_c \, \Lambda^2$

$\Lambda < 850~{\rm MeV}$ Rho meson!

$m^2 = -\frac{6y_t^2}{16\pi^2}\Lambda^2$

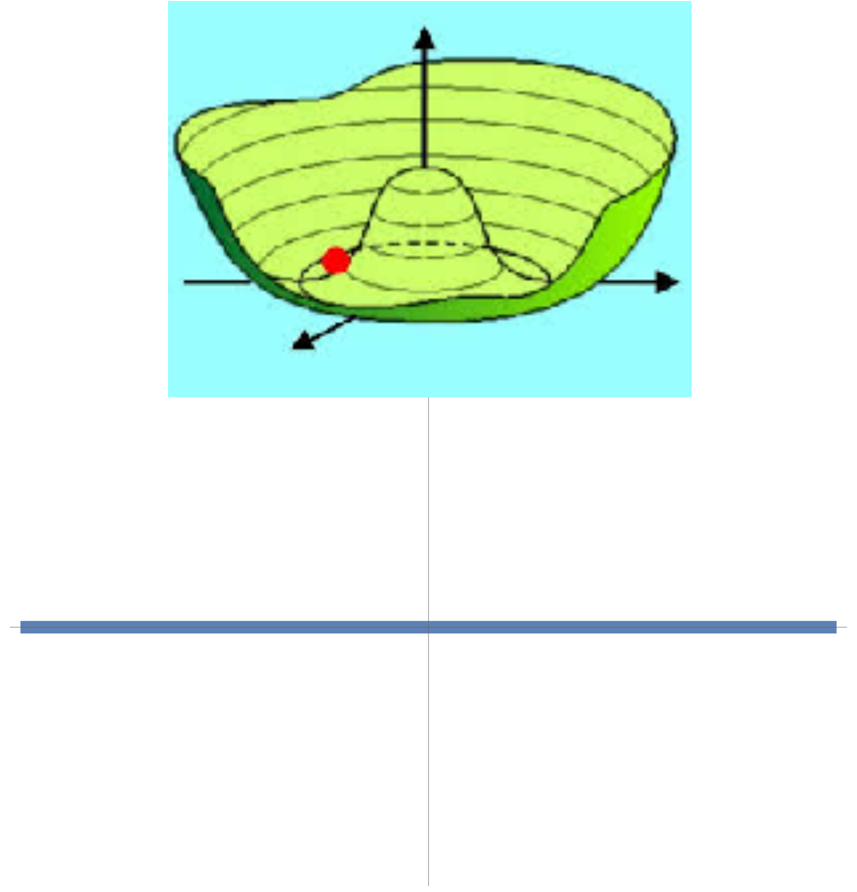
$\Lambda < 500~{\rm GeV}$ Ruled out!

$m^2 \sim \frac{6y_t^2}{16\pi^2} m_{t'}^2$

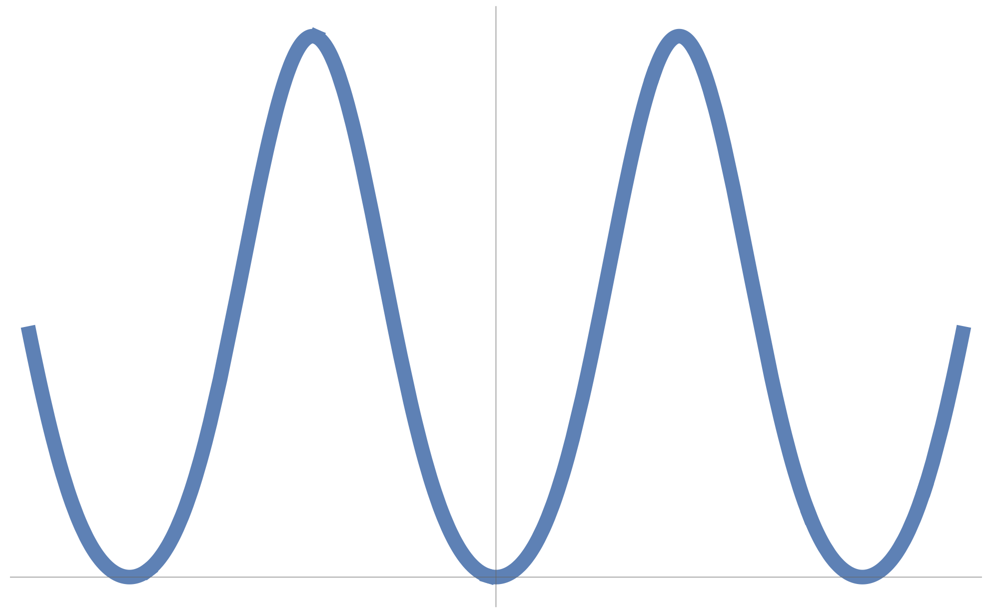
T-prime!

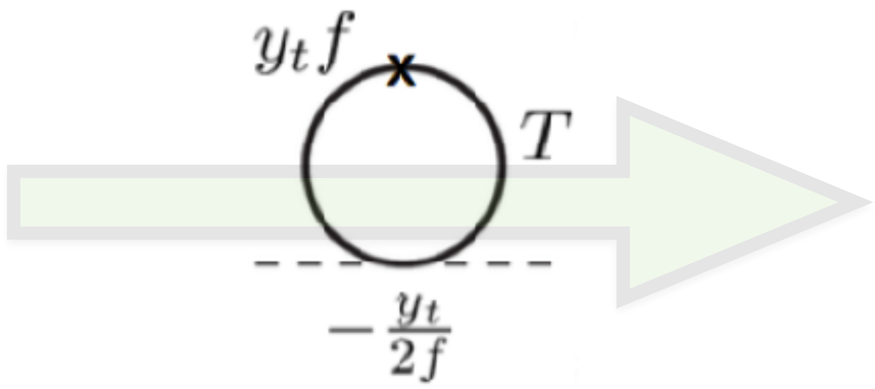
Vacuum misalignment

There is no vacuum for pion, how to obtain the Higgs vacuum?

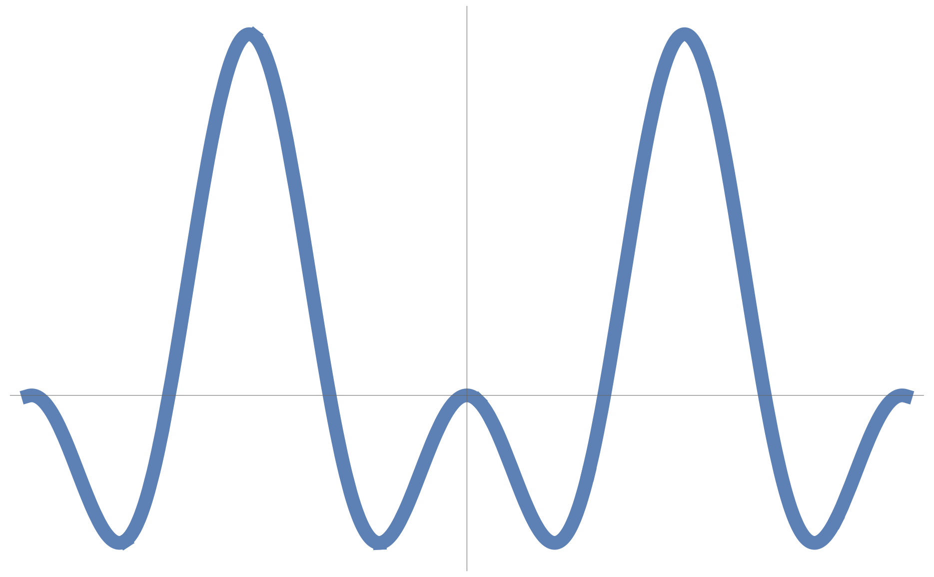


Higgs potential with only boson sector



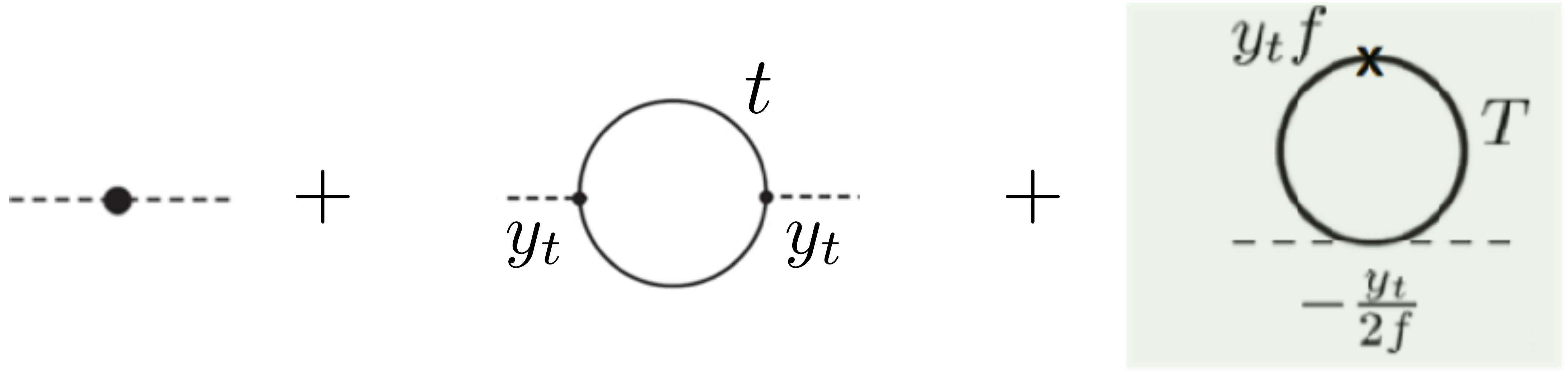


EW symmetry breaking



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

$-(100\ \mathrm{GeV})^2 =$



$$= (m^0)^2 + \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + 6y_t^2\right) + \frac{6y_t^2}{16\pi^2} m_{t'}^2 \log\frac{\Lambda^2}{m_{t'}^2}$$

Model Buildings

G/H coset and fermion assignment with symmetries

Little Higgs (2000) | Composite Higgs (2004) | Neutral Naturalness (2015)

fundamental top partner | partial composite top partner | Colorless top partner

Littlest Higgs

[Arkani-hamed, et.al. 2000]

Minimal Composite Higgs

[Agashe, Contino, Pomarol 2004]

[Foadi, Schmidt, **Yu, 2010**]

Collective symmetry breaking

LR Z2 Higgs

[Li, Xu, **Yu**, Zhu, **2019**]

LR symmetry

[Chacko, Goh, Harnik 2006]

Mirror Twin Higgs

[**Yu, 2016**]

Minimal neutral naturalness

[Xu, **Yu**, Zhu, **2018**]

Z2/SU(6) symmetry

Composite Higgs
[Agashe, Contino, Pomarol 2004]

Minimal Neutral Naturalness
[Xu, **Yu**, Zhu, **2018**]

Twin Higgs
[Chacko, Goh, Harnik 2006]

$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{SU(2)\times SU(2)}\ (\mathbf{r}_{SU(2)\times U(1)})$
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SO(6)	SO(5)	✓	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	✓	6	$\mathbf{6} = 2 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(8)	SO(7)	✓	7	$\mathbf{7} = 3 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SU(4) × U(1)	SU(3) × U(1)		7	$\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3 \cdot \mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$
SO(7)	G_2	✓*	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(9)	SO(8)	✓	8	$\mathbf{8} = 2 \cdot (\mathbf{2}, \mathbf{2})$
SU(4)	$[SU(2)]^2 \times U(1)$	✓*	8	$(\mathbf{2}, \mathbf{2})_{\pm 2} = 2 \cdot (\mathbf{2}, \mathbf{2})$
$[SU(3)]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$
Sp(6)	Sp(4) × SU(2)	✓	8	$(\mathbf{4}, \mathbf{2}) = 2 \cdot (\mathbf{2}, \mathbf{2})$
SU(5)	SU(4) × U(1)	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2 \cdot (\mathbf{2}, \mathbf{2})$
$[SO(5)]^2$	SO(5)	✓*	10	$\mathbf{10} = (\mathbf{1}, \mathbf{3}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	SO(5) × U(1)	✓*	10	$\mathbf{10}_0 = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$[SU(2)]^3$	✓*	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \cdot (\mathbf{2}, \mathbf{2})$
SU(5)	SO(5)	✓*	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$
SU(6)	Sp(6)	✓*	14	$\mathbf{14} = 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{3}) + 3 \cdot (\mathbf{1}, \mathbf{1})$
$[SO(6)]^2$	SO(6)	✓*	15	$\mathbf{15} = (\mathbf{1}, \mathbf{1}) + 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3})$
SO(9)	SO(5) × SO(4)	✓*	20	$(\mathbf{5}, \mathbf{4}) = (\mathbf{2}, \mathbf{2}) + (\mathbf{1} + \mathbf{3}, \mathbf{1} + \mathbf{3})$

[Csaki, et. al, 2015]

Effective Field Theory for Composite Higgs

m_ρ

G/H with composite states

Integrate out heavy composite states

$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{SU(2)\times SU(2)}$ $(\mathbf{r}_{SU(2)\times U(1)})$
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	✓	6	$\mathbf{6} = 2\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(8)	SO(7)	✓	7	$\mathbf{7} = 3\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SU(4) × U(1)	SU(3) × U(1)		7	$\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3\cdot\mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$
SO(7)	G_2	✓*	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(9)	SO(8)	✓	8	$\mathbf{8} = 2\cdot(\mathbf{2},\mathbf{2})$
SU(4)	$[SU(2)]^2$ × U(1)	✓*	8	$(\mathbf{2},\mathbf{2})_{\pm 2} = 2\cdot(\mathbf{2},\mathbf{2})$
$[SU(3)]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$
Sp(6)	Sp(4) × SU(2)	✓	8	$(\mathbf{4},\mathbf{2}) = 2\cdot(\mathbf{2},\mathbf{2})$
SU(5)	SU(4) × U(1)	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2\cdot(\mathbf{2},\mathbf{2})$
$[SO(5)]^2$	SO(5)	✓*	10	$\mathbf{10} = (\mathbf{1},\mathbf{3}) + (\mathbf{3},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × U(1)	✓*	10	$\mathbf{10}_0 = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	$[SU(2)]^3$	✓*	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\cdot(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	✓*	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$
SU(6)	Sp(6)	✓*	14	$\mathbf{14} = 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{3}) + 3\cdot(\mathbf{1},\mathbf{1})$
$[SO(6)]^2$	SO(6)	✓*	15	$\mathbf{15} = (\mathbf{1},\mathbf{1}) + 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3})$
SO(9)	SO(5) × SO(4)	✓*	20	$(\mathbf{5},\mathbf{4}) = (\mathbf{2},\mathbf{2}) + (\mathbf{1}+\mathbf{3},\mathbf{1}+\mathbf{3})$

G/H

f

Integrate out heavy PNGB other than the Higgs

triplet, doublet
usually heavy

If all other PNGB heavy

SO(5)/SO(4) EFT

If one light PNGB (singlet)

SO(6)/SO(5) EFT

If one light PNGB (multiplet)

….

EW chiral Lagrangian

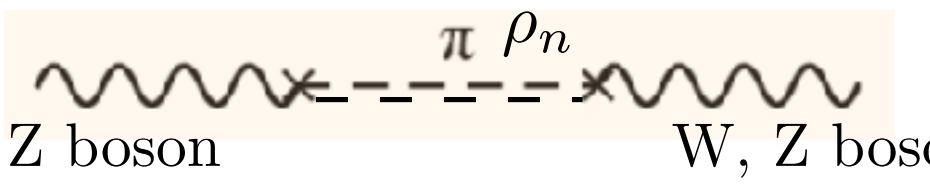
[Qi, **Yu**, Zhu, **2019**]

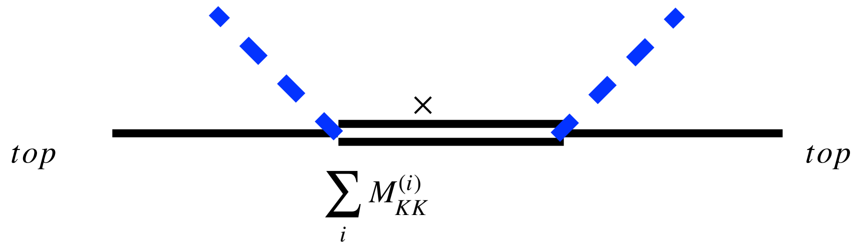
Effective Lagrangian

Composite Higgs | Left-Right Z2 | Twin Higgs | Minimal NN

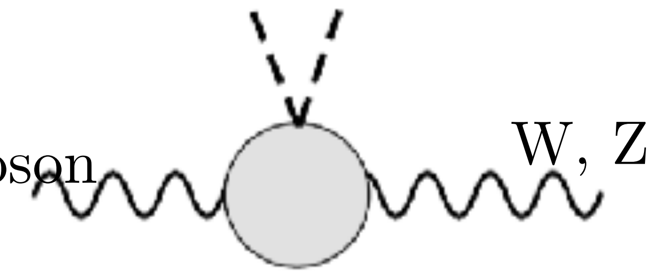
[Li, Xu, **Yu**, Zhu, **2019**]

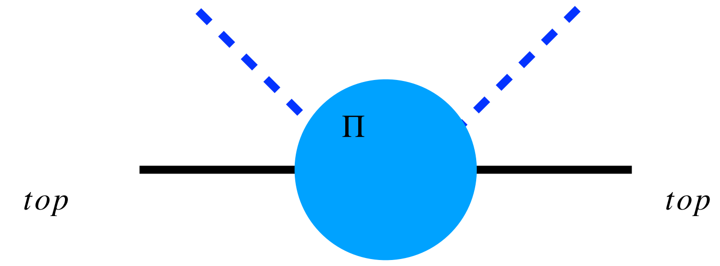
$$\mathcal{L} \supset \frac{1}{2}(P_T)^{\mu\nu}\left(\Pi_0(q^2)\mathrm{Tr}(A_\mu A_\nu) + \Pi_1(q^2)\Sigma A_\mu A_\nu \Sigma^T\right)$$





Heavy composite states





Generalized Lagrangian

$$\mathcal{L}_{\rm eff} = \bar{t}_L \not{p}\Pi_{t_L}(p^2)t_L + \bar{t}_R\not{p}\Pi_{t_R}(p^2)t_R - \left(\bar{t}_L\Pi_{t_Lt_R}(p^2)t_R + \text{h.c.}\right)$$

$$c_g = v\frac{\partial}{\partial\langle h\rangle}\left[\frac{1}{2}\log\Pi_{t_Lt_R}(0)\right] \qquad c_t = v\frac{\partial}{\partial\langle h\rangle}\log\Pi_{t_Lt_R}(0)$$

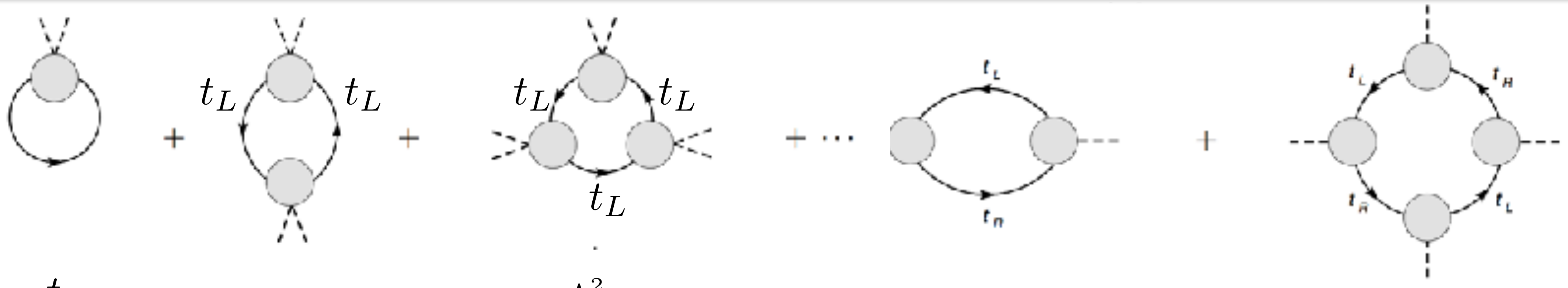
$$c_{gghh} = -v^2\frac{\partial^2}{\partial\langle h\rangle^2}\left[\frac{1}{2}\log\Pi_{t_Lt_R}(0)\right] \qquad c_{tthh} = \frac{v^2}{2}\frac{1}{m_t}\frac{\partial^2\Pi_{t_Lt_R}(0)}{\partial\langle h\rangle^2}$$

Composite Higgs | Left-Right Z2 | Twin Higgs | Minimal NN

$$\mathcal{L}_{\rm eff} = \bar{t}_L \not{p}\Pi_{t_L}(p^2)t_L + \bar{t}_R\not{p}\Pi_{t_R}(p^2)t_R - \left(\bar{t}_L\Pi_{t_Lt_R}(p^2)t_R + \text{h.c.}\right)$$

$$\Pi_{t_L}(-Q^2) = \Pi_{0t_L}(-Q^2) + \Pi_{1t_L}(-Q^2)\,s_h^2 + \Pi_{2t_L}(-Q^2)\,s_h^4 + \cdots$$

Coleman-Weinberg effective potential

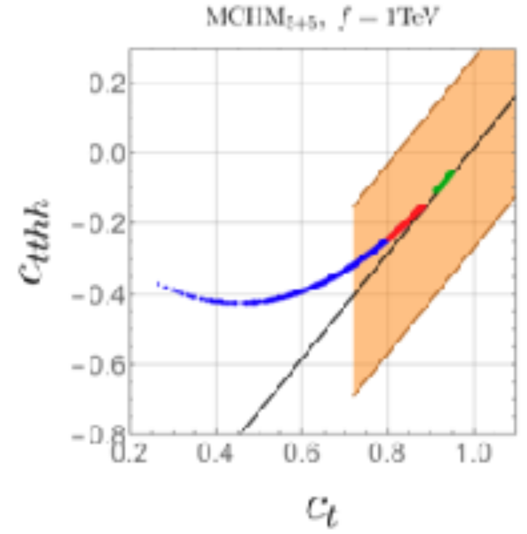


$$V(h) = -\frac{2N_c}{16\pi^2}\int_0^{\Lambda^2} dQ^2 Q^2 \log[\Pi_{t_L}\Pi_{t_R}\cdot Q^2 + \Pi^2_{t_Lt_R}]$$

$$= -\gamma_f s_h^2 + \beta_f s_h^4 + \cdots$$

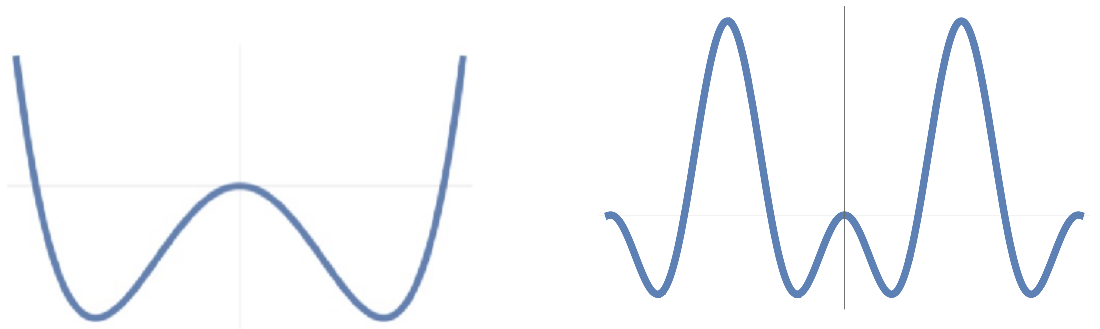
EW Chiral Lagrangian

Higgs nonlinearity



[Li, Xu, **Yu**, Zhu, **2019**]

Shape of Higgs potential



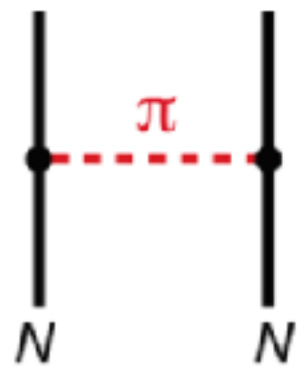
[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]

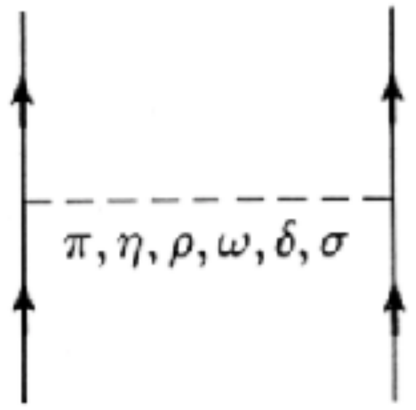
Nuclear Chiral Effective Theory

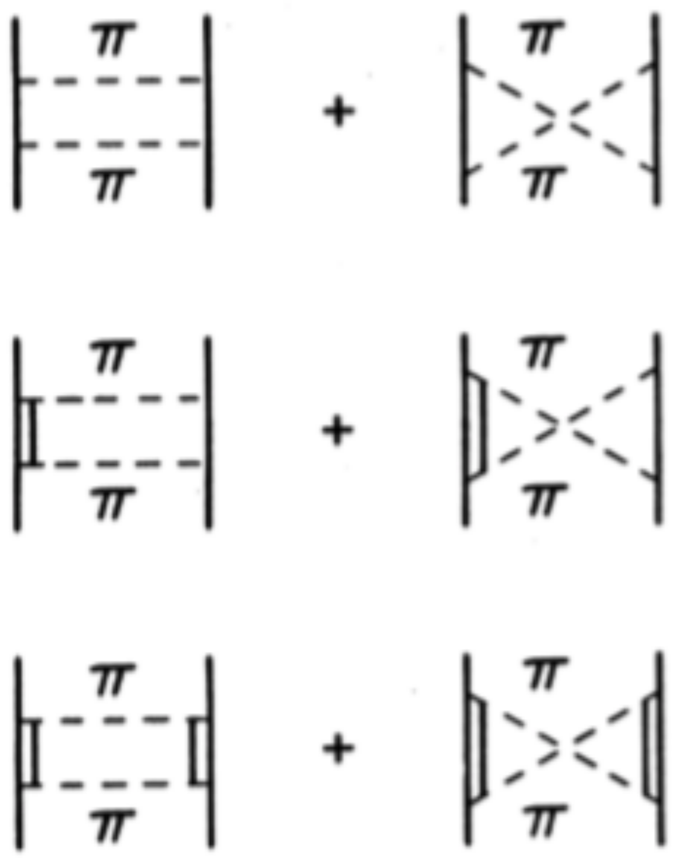
[Hao Sun, Yi-Ning Wang, **J.H.Yu**, in préparation]

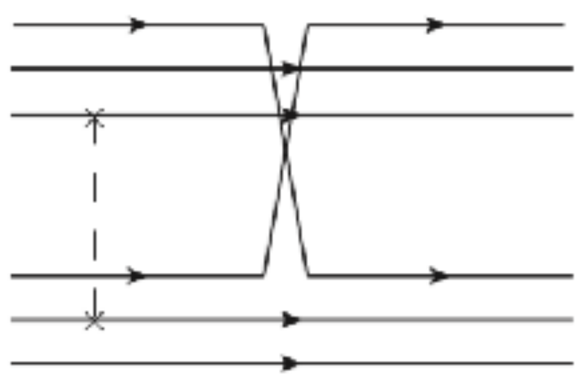
[Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, in préparation]

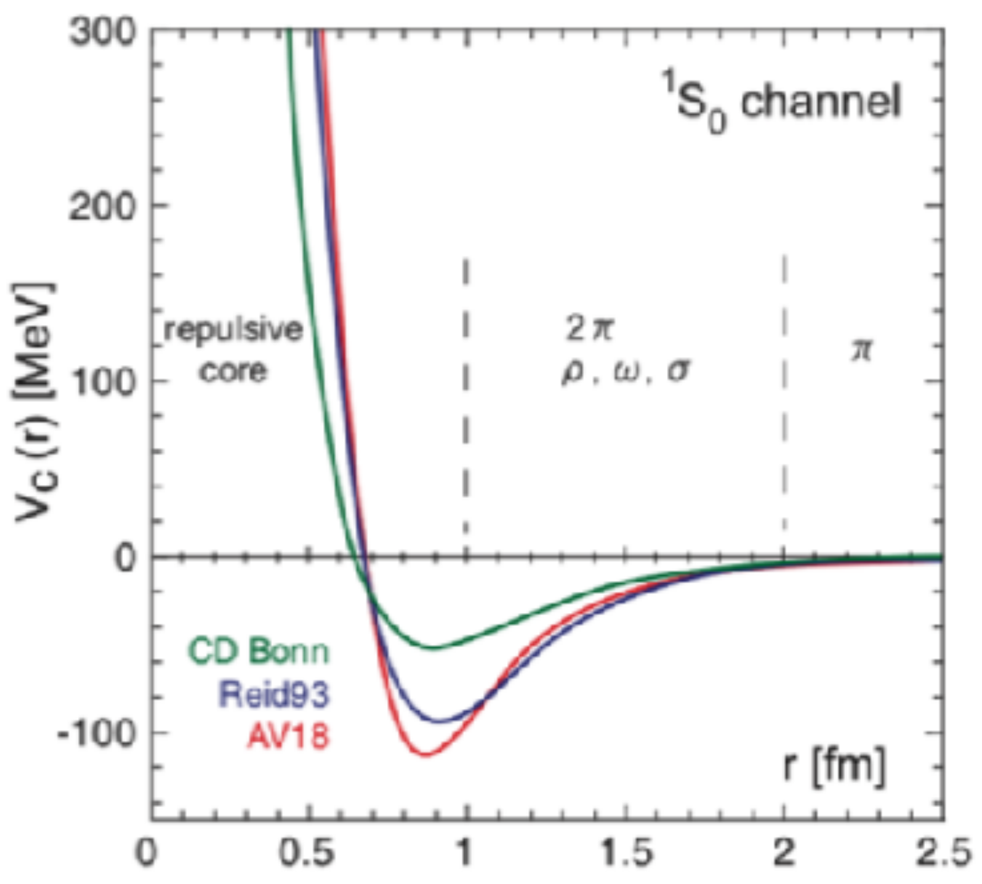
Historical overview on nuclear force

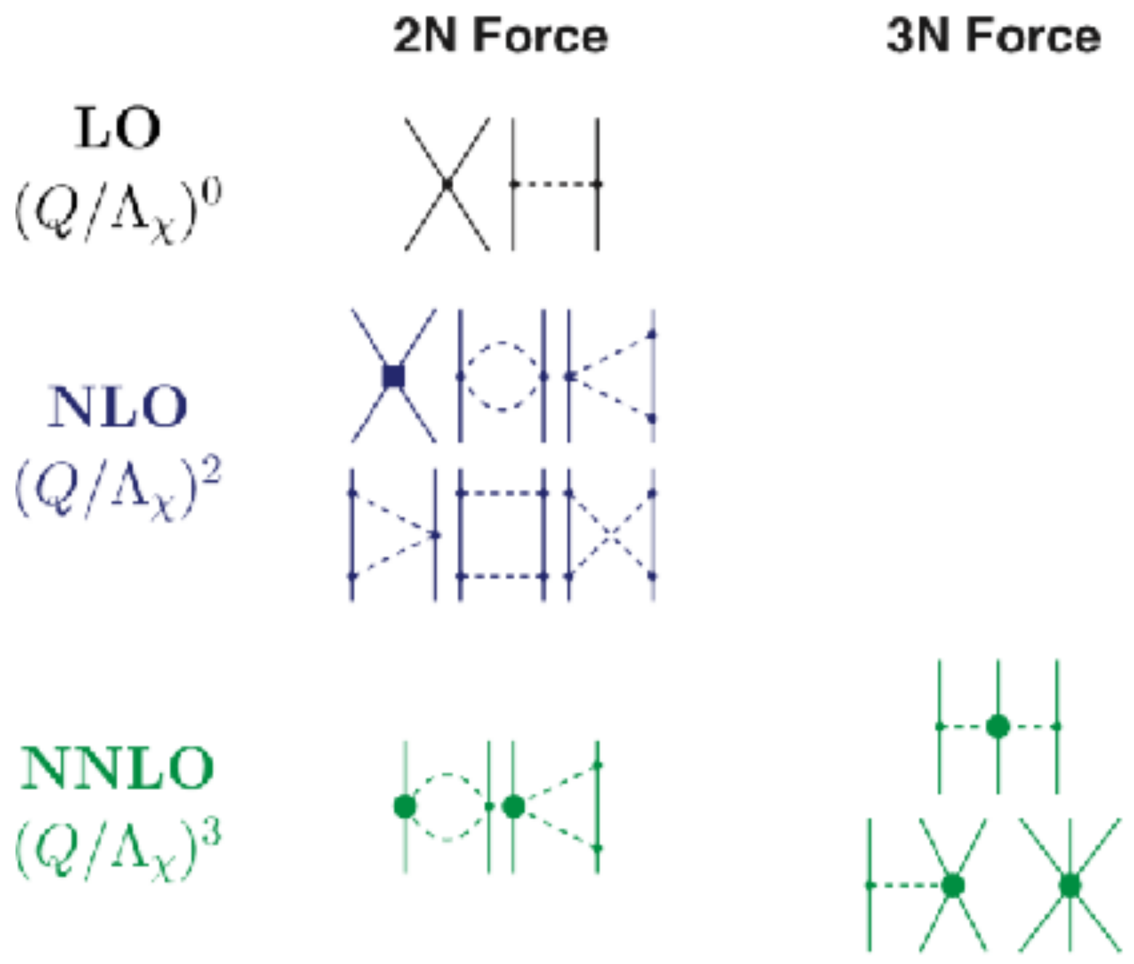












Yukawa Pion Theory
1935

One-Boson Exchange Model
1936 - 1960

Two-Pion Exchange
1950 - 1980

N-N from quark/chiral-bag model
1970 - 1980

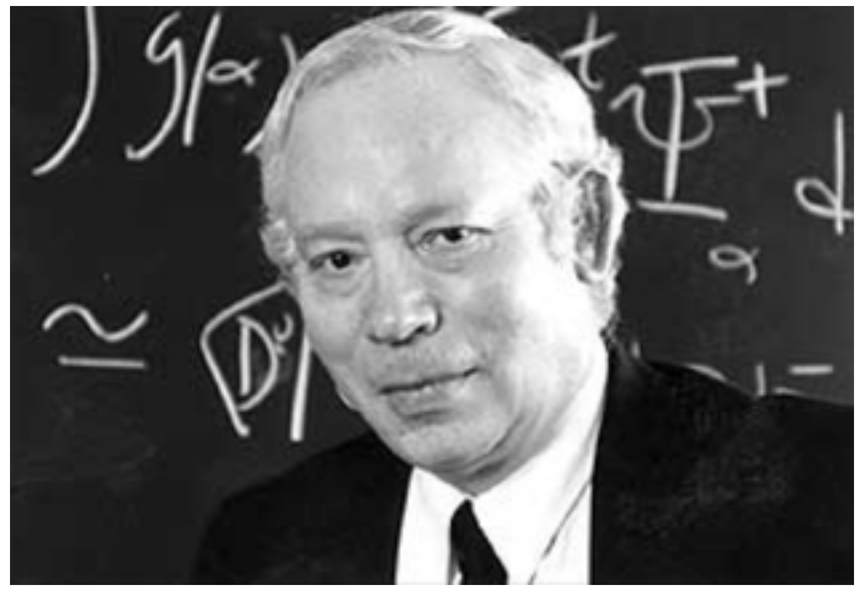
High precision potential
1990 -

Weinberg nuclear chiral EFT
1990 -

Proca, Kemmer, Moller, Rosenfeld and Schwinger, Pauli, …

Taketani, Nakamura Sasaki, Bruckner, Watson, …

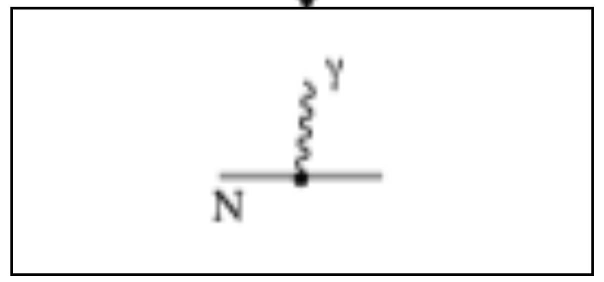
AV18, CD Bonn, Nijm, Reid93 …

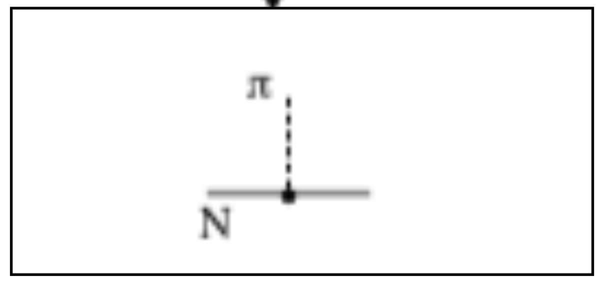


Why chiral nuclear force?

Meson Exchange Model

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





$$+\frac{1}{4}\langle\partial_\mu\Sigma\partial^\mu\Sigma\rangle - \frac{\lambda}{16}\left(\langle\Sigma^\dagger\Sigma\rangle - 2v^2\right)^2$$

$$\Sigma = (v+S)U(\varphi)$$

$$\psi_L = uN_L, \quad \psi_R = u^\dagger N_R, \quad U = u^2$$

$$\mathcal{L} = \frac{v^2}{4}\left(1+\frac{S}{v}\right)^2\langle u_\mu u^\mu\rangle$$

$$+\bar\psi i(\not\partial + \not\Gamma)\psi + \frac{1}{2}\bar\psi\,\not u\gamma_5\,\psi - g(v+S)\bar\psi\psi$$

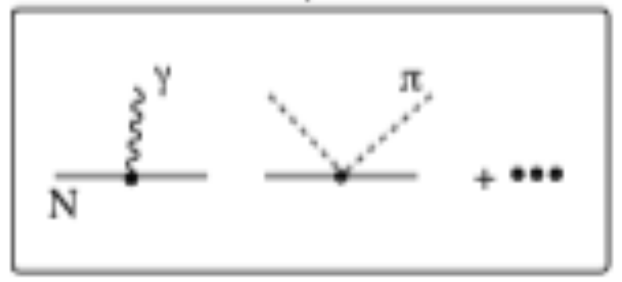
$g_{\pi NN} \simeq 13.40$

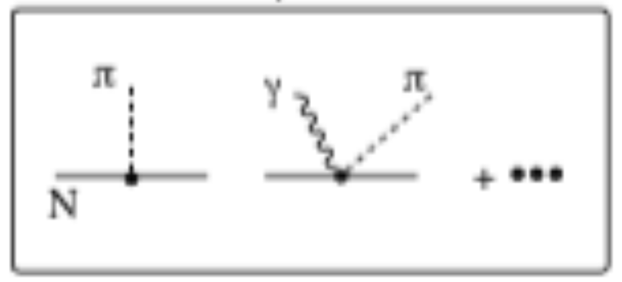
$$g_A = 1 \qquad m_N = gv \equiv g_{\pi NN}F_\pi$$

Modeling only

Chiral EFT

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





$$D_\mu \equiv \partial_\mu + u^\dagger\partial_\mu u + u\partial_\mu u^\dagger = \partial_\mu + \frac{i}{2F^2}\tau\cdot\pi\times\partial_\mu\pi + \mathcal{O}(\pi^4)$$

Chiral Ward Identity

$$< p(p')|\partial^\mu j^A_{5\mu}|n(p) > = \bar u_p(p')\left(q g_A(q^2) + q^2 h_A(q^2)\right)\gamma_5 u_n(p)$$

$$= \frac{M_\pi^2 F_\pi}{M_\pi^2 - q^2}g_{\pi NN}\bar u_p(p')\gamma_5 u_n(p)$$

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

$g_A \simeq 1.27$

Goldberger-Treiman Relation

Perturbative derivative expansion

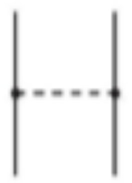
Chiral Nuclear Force

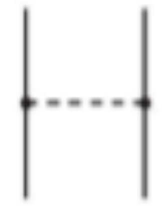
Meson Exchange Model | **Chiral EFT**

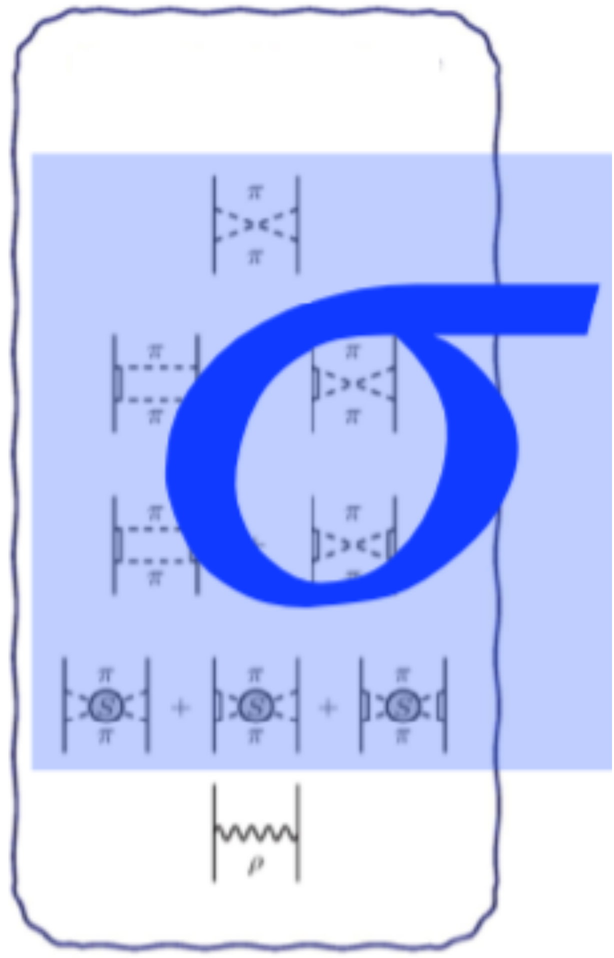
$$\mathcal{L}_\sigma = \overline{N_L}\, i\not{D}\, N_L + \overline{N_R}\, i\not{D}\, N_R - g\overline{N_R}\,\Sigma\, N_L - g\overline{N_L}\,\Sigma^\dagger\, N_R$$

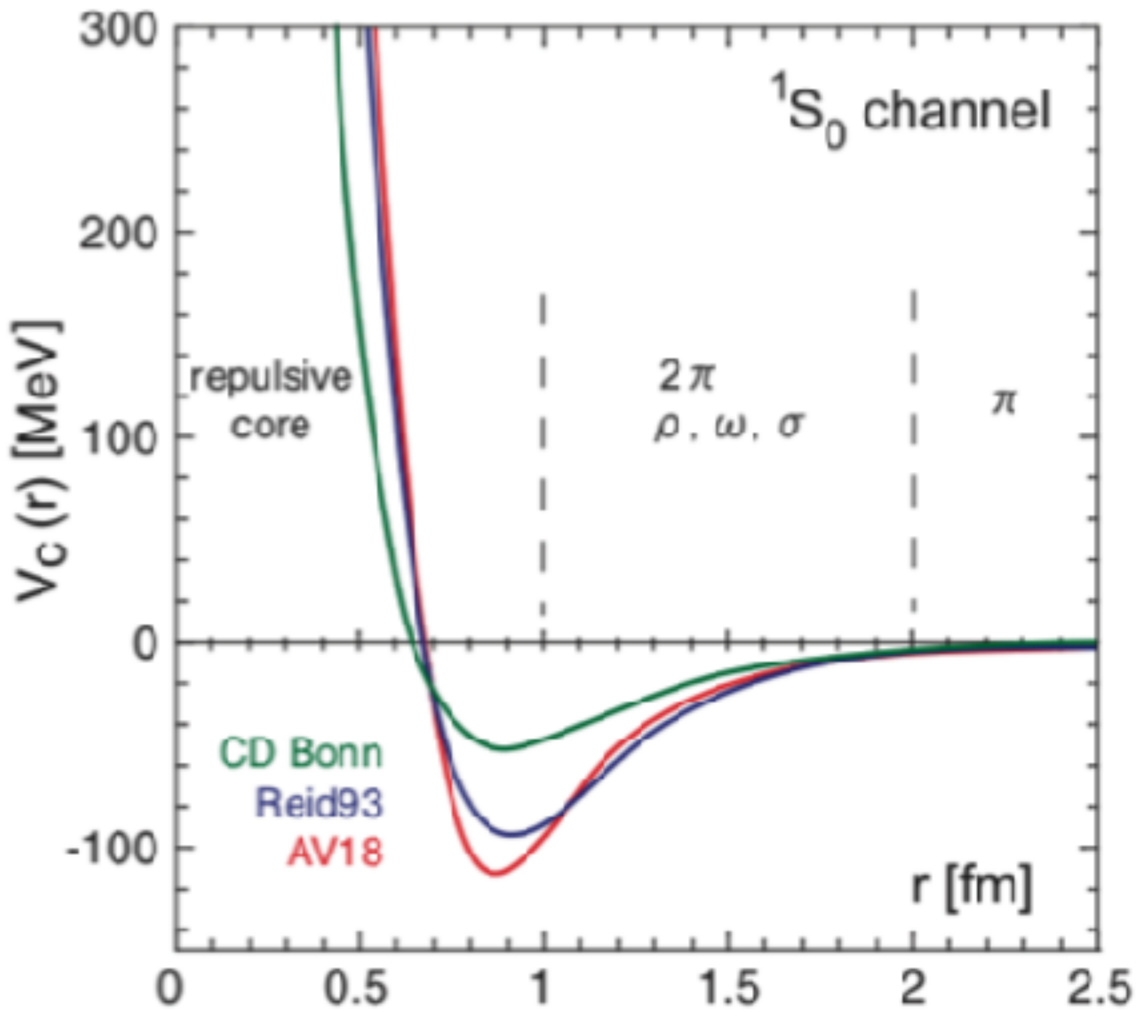
$$\mathcal{L}^{(1)}_{\pi N} = \bar{\psi}\left(i\not{D} - m_N + \tfrac{1}{2} g_A \gamma_\mu \gamma_5 u^\mu\right)\psi$$

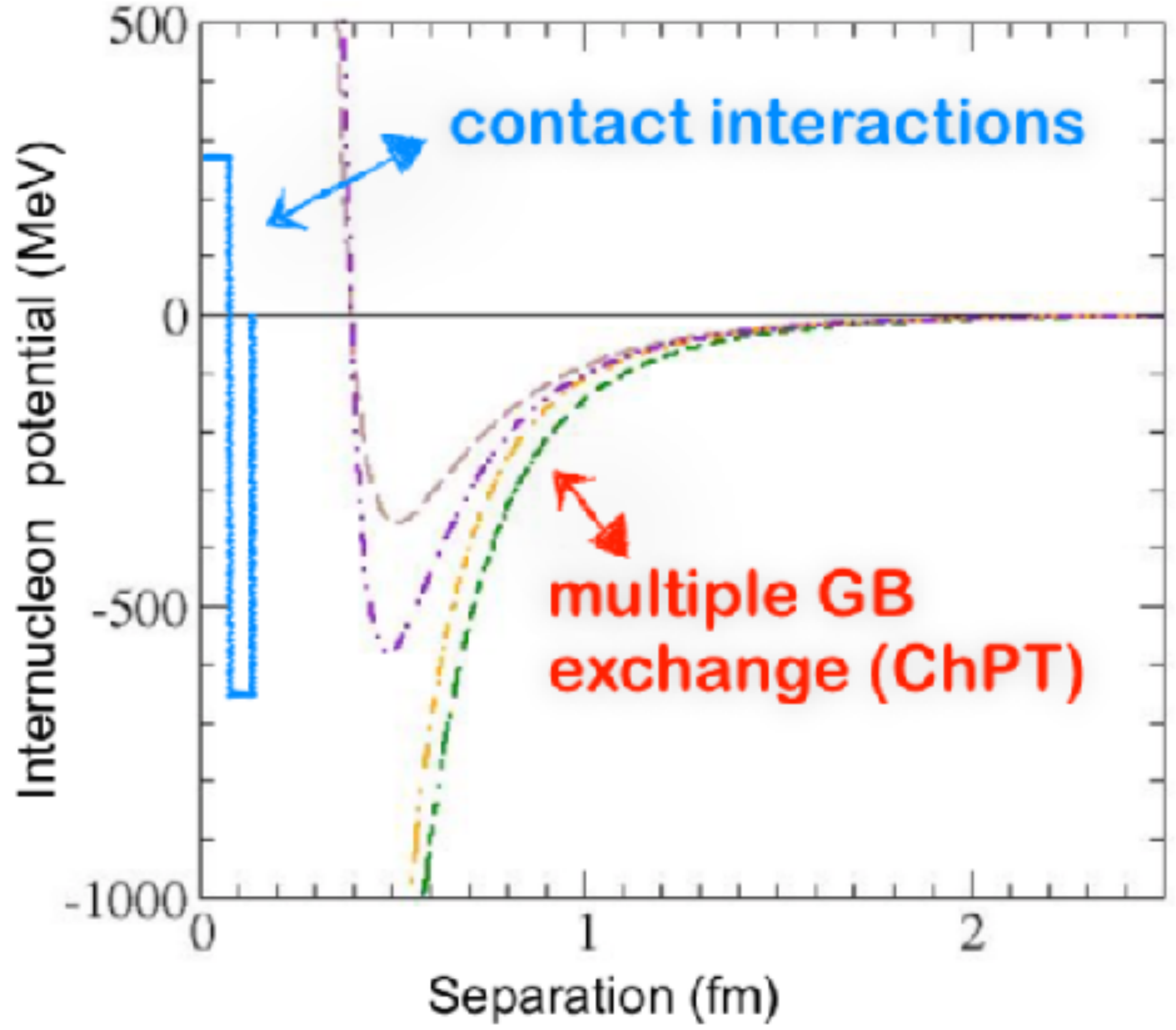
$$V(\mathbf{r}) = \left\{C_c + C_\sigma \sigma_1 \cdot \sigma_2 + C_T\left(1 + \frac{3}{m_\alpha r} + \frac{3}{(m_\alpha r)^2}\right) S_{12}(\hat{r}) + C_{SL}\left(\frac{1}{m_\alpha r} + \frac{1}{(m_\alpha r)^2}\right)\mathbf{L}\cdot\mathbf{S}\right\}\frac{e^{-m_\alpha r}}{m_\alpha r}\quad (1,\ \tau_1 \cdot \tau_2)$$

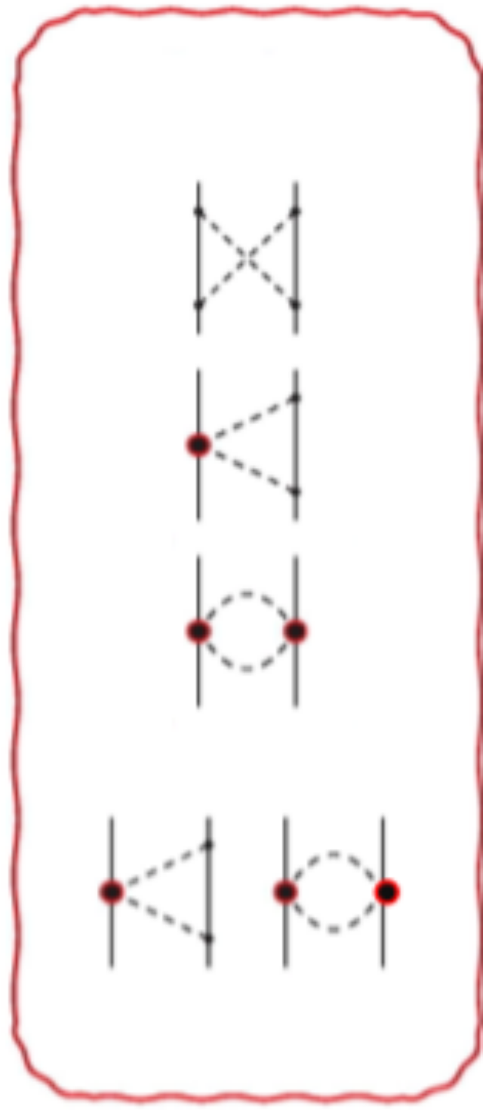








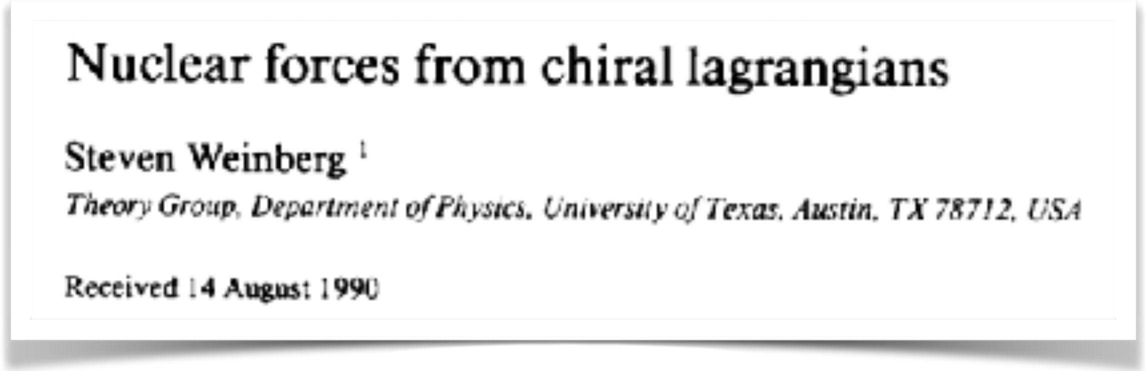




Repulsive central

CAS)

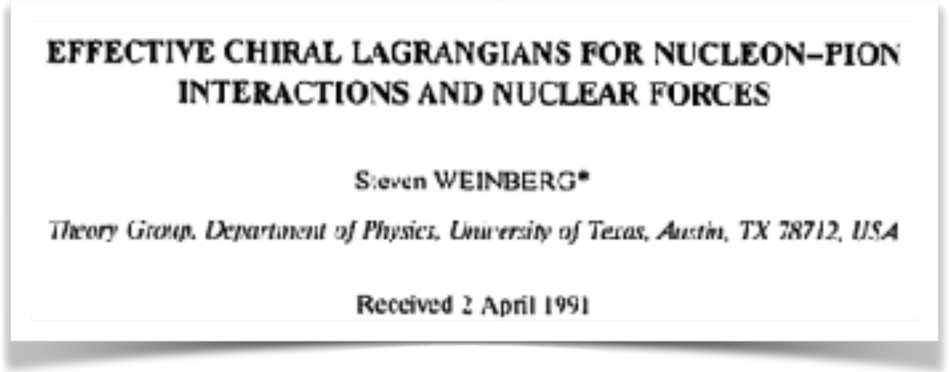
Weinberg's nuclear force


Nuclear forces from chiral lagrangians

Steven Weinberg [1]

Theory Group, Department of Physics, University of Texas, Austin, TX 78712, USA

Received 14 August 1990


EFFECTIVE CHIRAL LAGRANGIANS FOR NUCLEON–PION INTERACTIONS AND NUCLEAR FORCES

Steven WEINBERG*

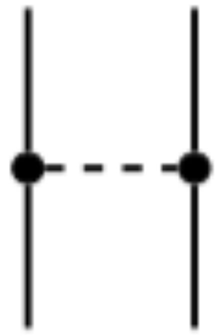
Theory Group, Department of Physics, University of Texas, Austin, TX 78712, USA

Received 2 April 1991

Hard-core nucleon-nucleon interaction

[Weinberg 1933 - 2021]

Weinberg power counting $$D = 2 - A + 2L + \sum_d V_d \left(d - 2 + \frac{f}{2} \right)$$

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

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

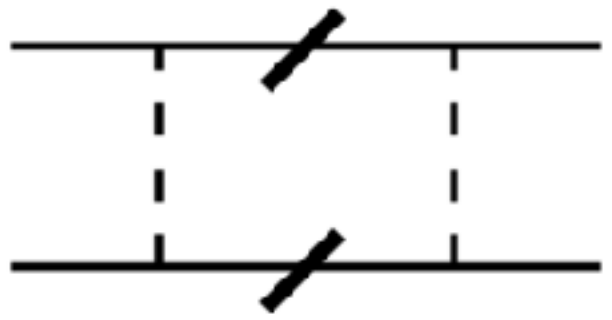
It had taken me a decade to realize that four divided by two is two. This sort of interaction is just the kind of hard-core nucleon-nucleon interaction that nuclear physicists had always known would be needed to understand nuclear forces. But now we had a rationale for it.

Weinberg 2021

2PI Diagrams


Nuclear potential from Irre. 2PI only

2PR Diagrams



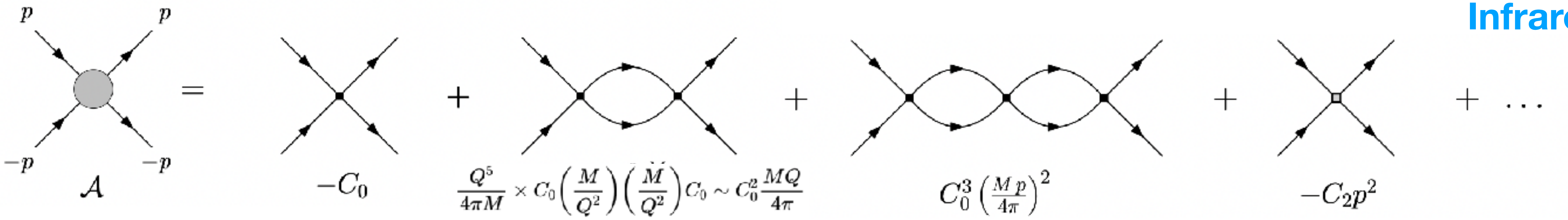
Breakdown in perturbation theory = nuclear bound states

Resumed by Schrodinger equation

Pionless effective field theory

At low energy, the NN contact interaction shows non-perturbative nature (nuclei bound states)

Infrared enhancement!



Effective Range Expansion

$$\sigma_{tot} \to 4\pi a^2 \text{ as } p \to 0.$$

$$\mathcal{A} = \frac{4\pi}{M}\frac{1}{p\cot\delta - ip} \qquad p\cot\delta = -\frac{1}{a} + \frac{1}{2}r_0 p^2 + \cdots = -\frac{1}{a} + \frac{1}{2}\Lambda^2\sum_{n=0}^{\infty} r_n\left(\frac{p^2}{\Lambda^2}\right)^n$$

$$1/m_\pi \approx 1.4 \text{ fm} \qquad a_0 \approx -23.7 \text{ fm}$$

Natural scattering length $|a| \lesssim 1/\Lambda$

Weinberg, 1991

Expansion converge up to $p \sim \Lambda$

$$\mathcal{A} = -\frac{4\pi a}{M}\left[1 - iap + \left(\frac{1}{2}ar_0 - a^2\right)p^2 + O(p^3/\Lambda^3)\right]$$

$$= \sum_{n=0}^{\infty}\mathcal{A}_n \qquad \mathcal{A}_n \sim \mathcal{O}(p^n)$$

$\mathcal{O}(p^0)$ $\quad C_0 \sim 4\pi a/M$ **Irrelevant**

Unnatural scattering length $|a| \gg 1/\Lambda$

Kaplan, Savage, Wise 1998

Expansion breaking when $p \sim 1/|a|$, far below Λ. keep ap to all orders

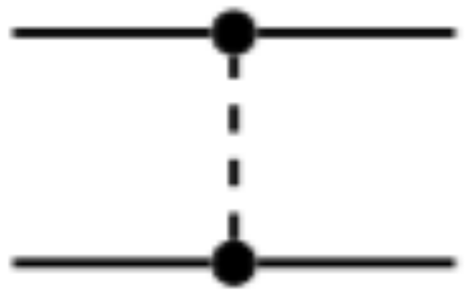
$$\mathcal{A} = -\frac{4\pi}{M}\frac{1}{(1/a + ip)}\left[1 + \frac{r_0/2}{(1/a+ip)}p^2 + \frac{(r_0/2)^2}{(1/a+ip)^2}p^4 + \ldots\right]$$

$$= \mathcal{A}_{-1} + \sum_{n=0}^{\infty}\mathcal{A}_n \qquad \mathcal{A}_n \sim \mathcal{O}(p^n)$$

$\mathcal{O}(p^{-1})$ $\quad C_0 \sim 4\pi/MQ$ **Relevant**

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]

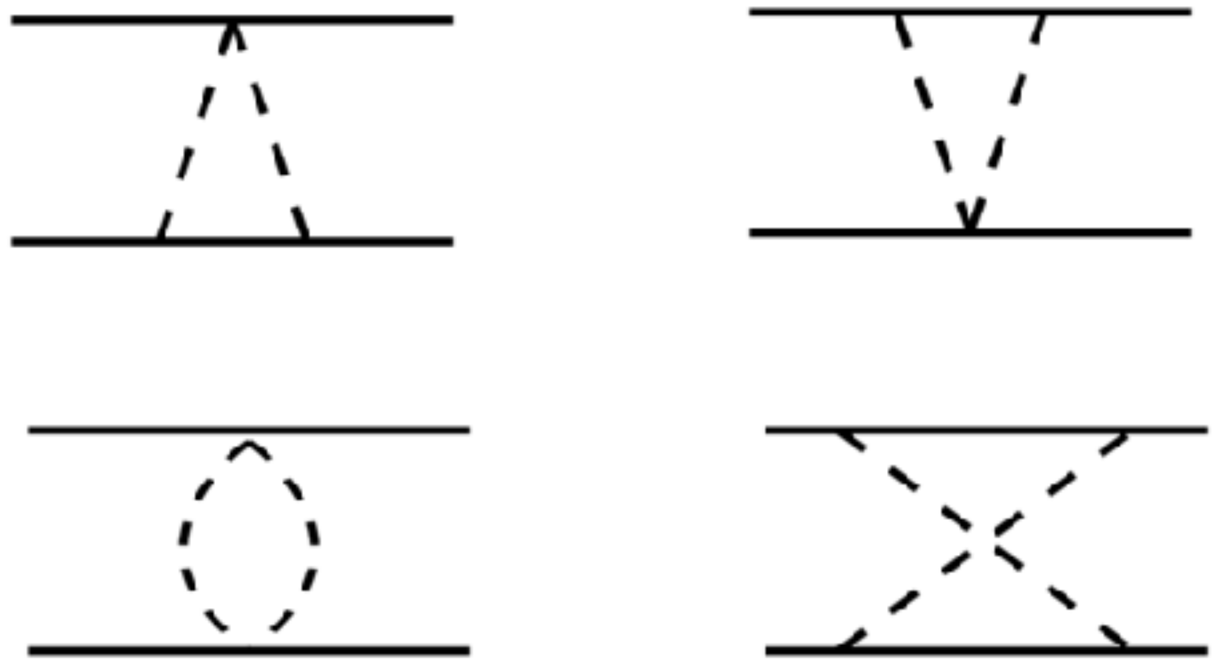


Dim = 2(1-2+2/2) = 0

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

Irreducible

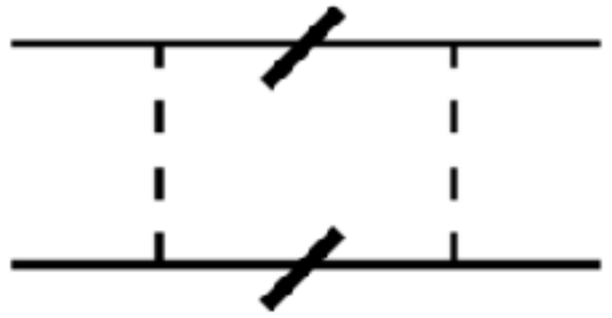
Dim = 2+2-2+2(1-2+2/2) = 2



1. calculate nuclear potential from irreducible diagrams

pinch diagrams subtracted

2PR Diagrams



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

$$I \sim \int \frac{d^d q}{(2\pi)^d} \frac{1}{q^0 + i\epsilon} \frac{1}{-q^0 + i\epsilon} \frac{1}{(q+k)^2 + i\epsilon} \frac{1}{(q-k)^2 + i\epsilon}$$

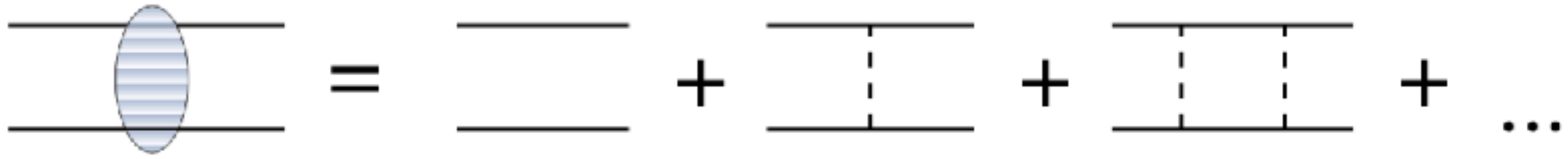
nucleon pole ↓ **Pinch singularity**

$$I \sim \int \frac{d^d q}{(2\pi)^d} \frac{1}{q^0 - \frac{\vec{p}^2 - \vec{q}^2}{2M} - i\epsilon} \frac{1}{-q^0 + \frac{\vec{p}^2 - \vec{q}^2}{2M} + i\epsilon} \frac{1}{(q+p)^2 + i\epsilon} \frac{1}{(q-p)^2 + i\epsilon}$$

$$\frac{Q^3}{16\pi^2}(2\pi) \frac{2M_N}{\vec{p}^2 - \vec{q}^2 + i\epsilon}$$

mN enhancement $\frac{g_A^2 Q^2}{f_\pi^2 (Q^2 + m_\pi^2)} \times \frac{m_N Q}{4\pi} \times \frac{g_A^2 Q^2}{f_\pi^2 (Q^2 + m_\pi^2)}$

2. Truncated nuclear potential is iterated to all order



Solve Schrodinger equation

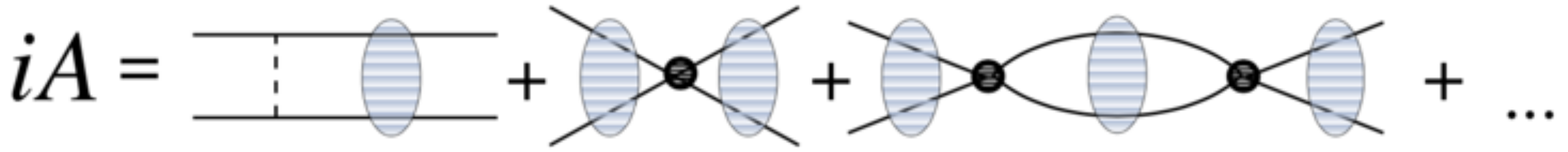
Power counting schemes

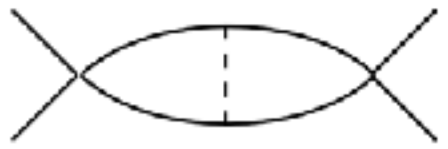
Complicated due to non-perturbative natures and renormalization problems

Weinberg Scheme

$V^{\rm LO}_{\rm Weinberg} \sim \mathcal{O}(1), \quad V^{\rm NLO}_{\rm Weinberg} \sim \mathcal{O}(p^2)$

[i.e. scaling of C_{2n} according to NDA (~ O(1))]





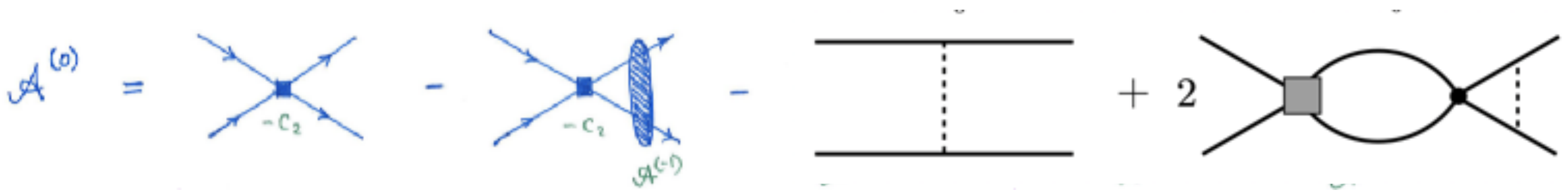
Renormalization problem!

KSW Scheme

$V^{\rm LO}_{\rm KSW} \sim \mathcal{O}(p^{-1}), \quad V^{\rm NLO}_{\rm KSW} \sim \mathcal{O}(1)$

[i.e. scaling of C_{2n} as $C_{2n} \sim O(p^{-1-n})$]

Pion are perturbative



Converge problem!

Modified Weinberg

[Nogga, Timmermans, van Kolck, 2005]

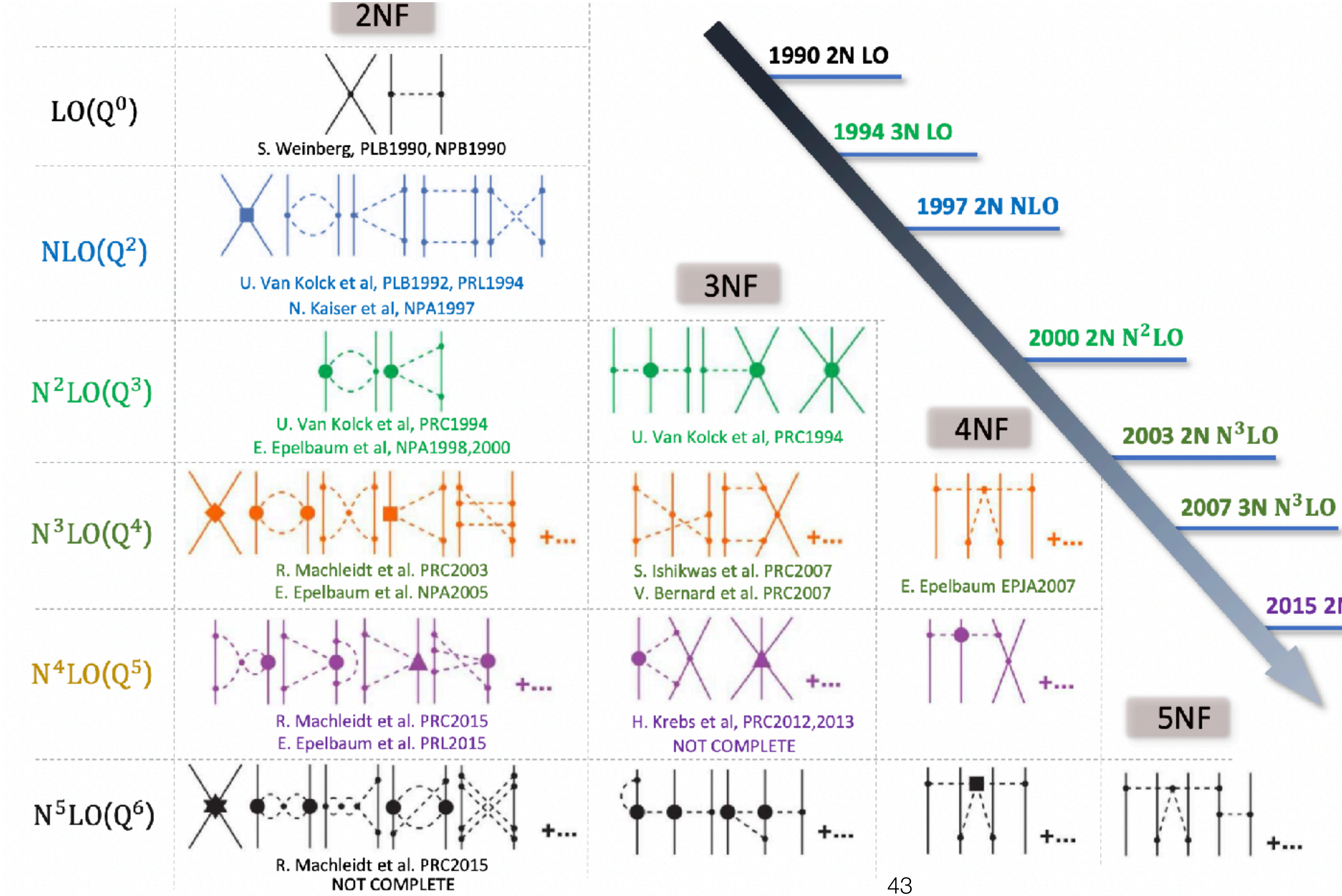
[Epelbaum, Gegelia, 2012]

[S. Wu, B. W. Long, 2019]

$$V^{\rm WPC}_{\rm LO}(\mathbf{p},\mathbf{p}') = \frac{g_A^2}{4f_\pi^2}\tau_1\cdot\tau_2\frac{(\sigma_1\cdot\mathbf{q})(\sigma_2\cdot\mathbf{q})}{m_\pi^2+\mathbf{q}^2} + \tilde{C}_{^1S_0} + \tilde{C}_{^3S_1} \longrightarrow V^{\rm MWPC}_{\rm LO}(\mathbf{p},\mathbf{p}') = V^{\rm WPC}_{\rm LO}(\mathbf{p},\mathbf{p}') + (\tilde{C}_{^3P_0} + \tilde{C}_{^3P_2})pp'$$

Solve both but why?

High precision nuclear force



[from L. S. Geng's slides]

Weinberg scheme

[Entem, Machleidt, Nosyk, 2020]

NN and 3N Operators

Nucleon-nucleon sector

3 nucleon sector

LO

[Weinberg 1990] [Weinberg 1991]

[van Kolck, Ordonez, 1992]

NLO

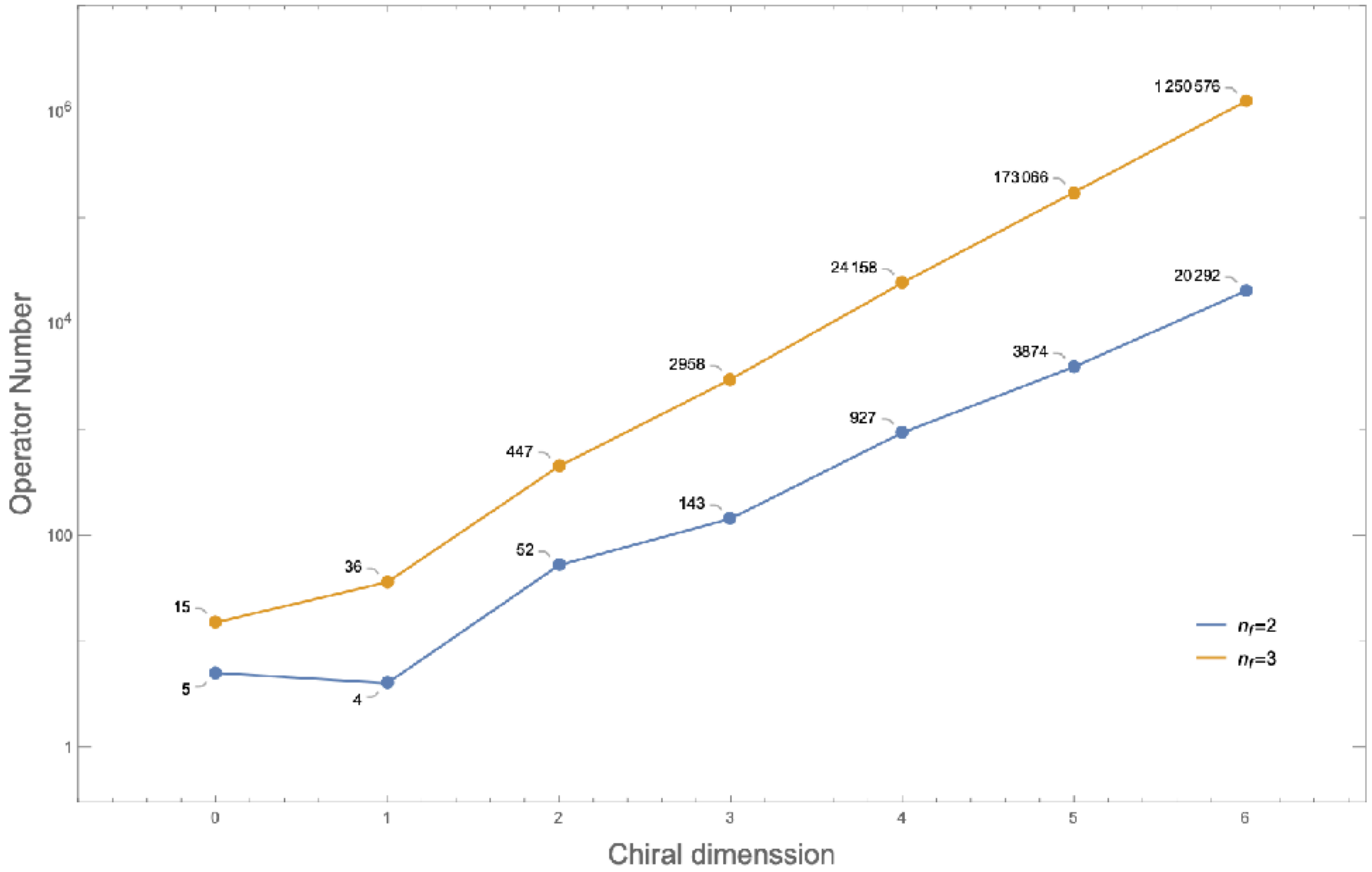
[Girlanda, Pastore, Schiavilla, Viviani, 2010]

[Petschauer, Kaiser, 2013] [Xiao, Geng, Ren, 2019]

NNLO

[Petschauer, Haidenbauer, Kaiser, Meisner, Weise, 2016]

[Nasoni, Filandri, Girlanda, 2023]

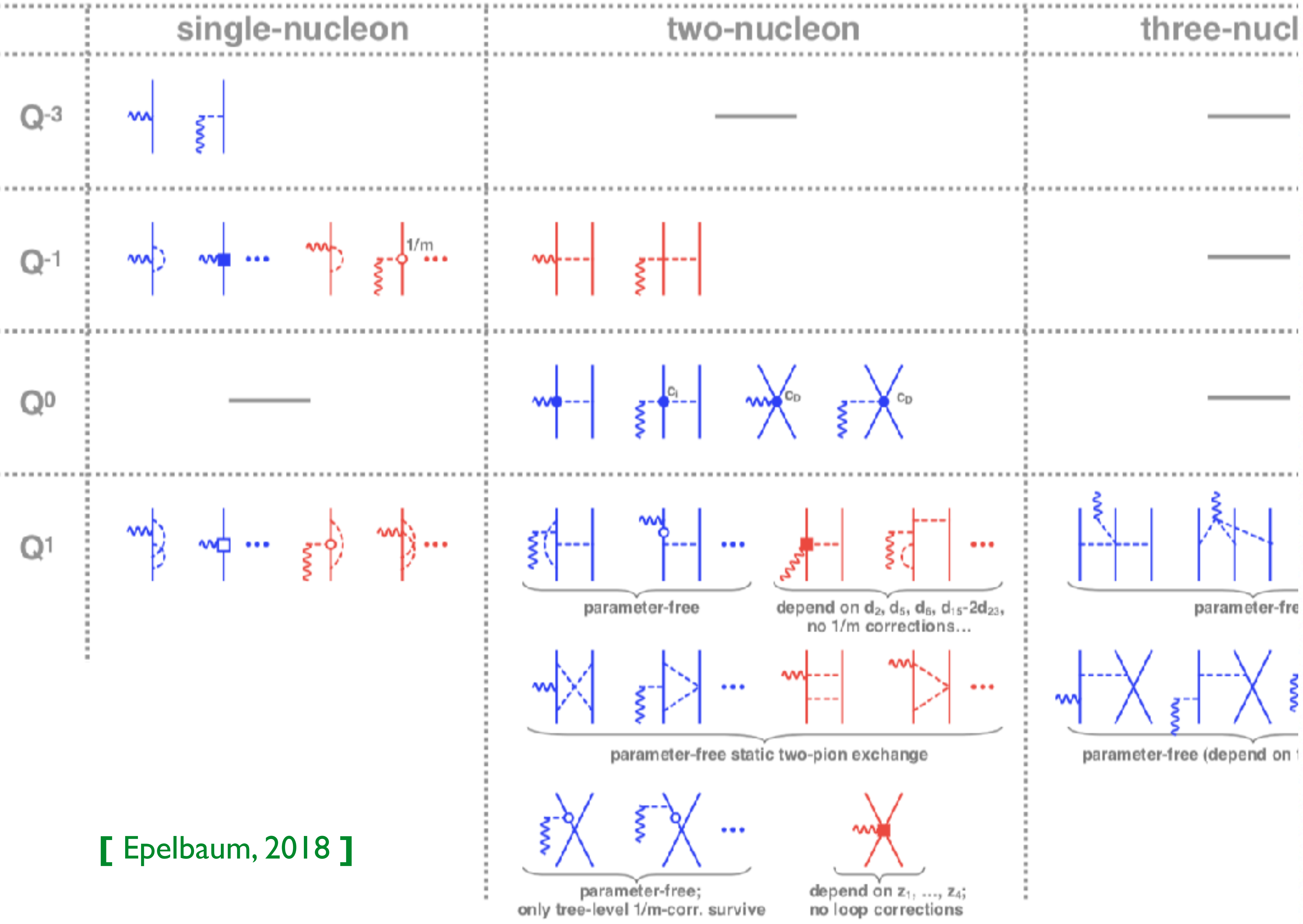


In order to obtain the most general contact Lagrangian in flavor SU(3), we follow the same procedure as used for the four-baryon contact terms in Ref. [47]. Generalizing these construction rules straightforwardly to six-baryon contact terms, we end up with a (largely) overcomplete set of terms for the leading covariant Lagrangian:

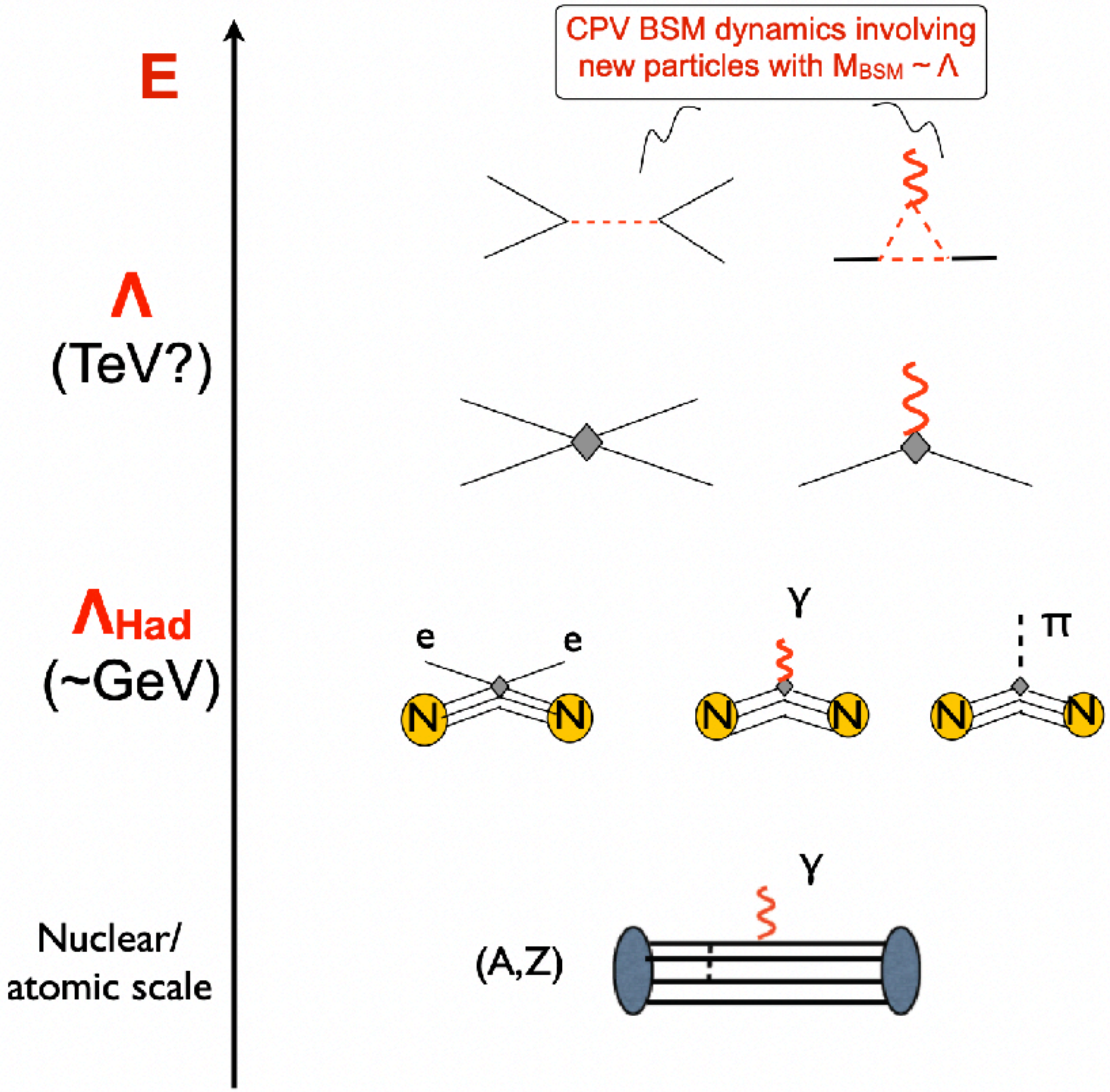
[Sun, Wang, **Yu**, in préparation]

Nuclear Weak Currents

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

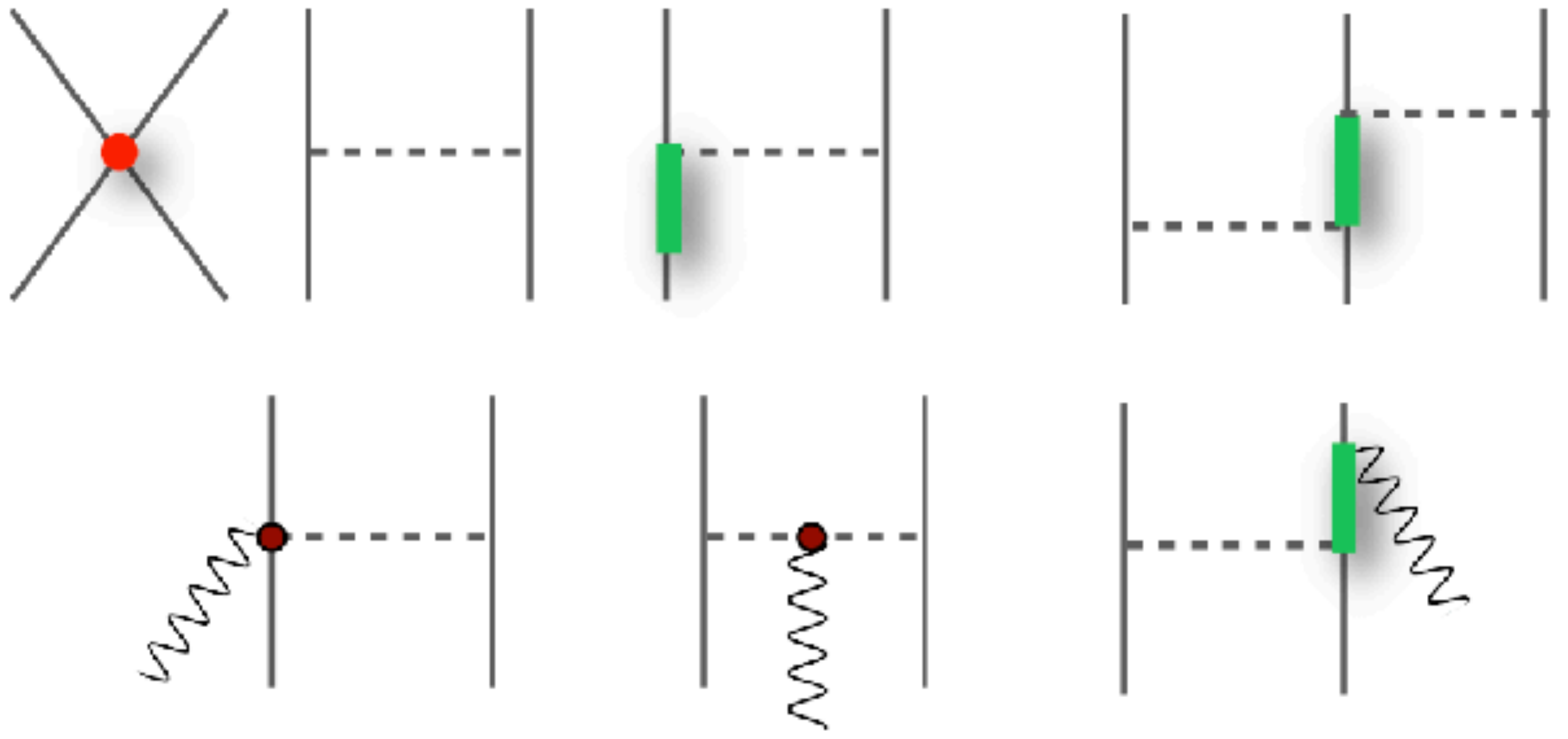


[Epelbaum, 2018]



Ab initio nuclear structure

Effective Hamiltonians and consistent currents



Accurate nuclear many-body methods

$$H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

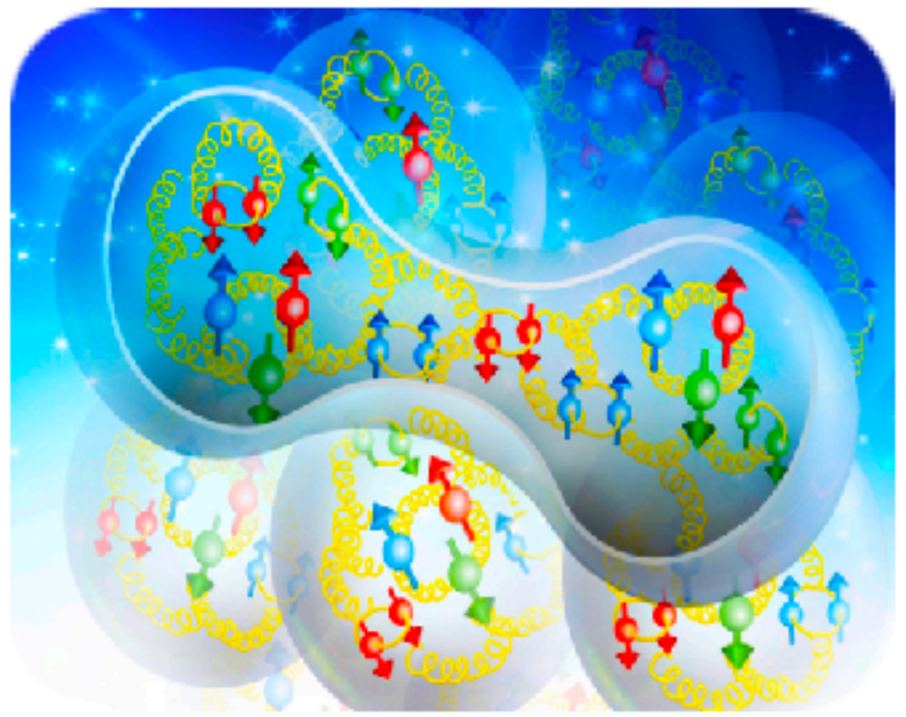
$$J_{mn} = \langle\Psi_m|J|\Psi_n\rangle$$

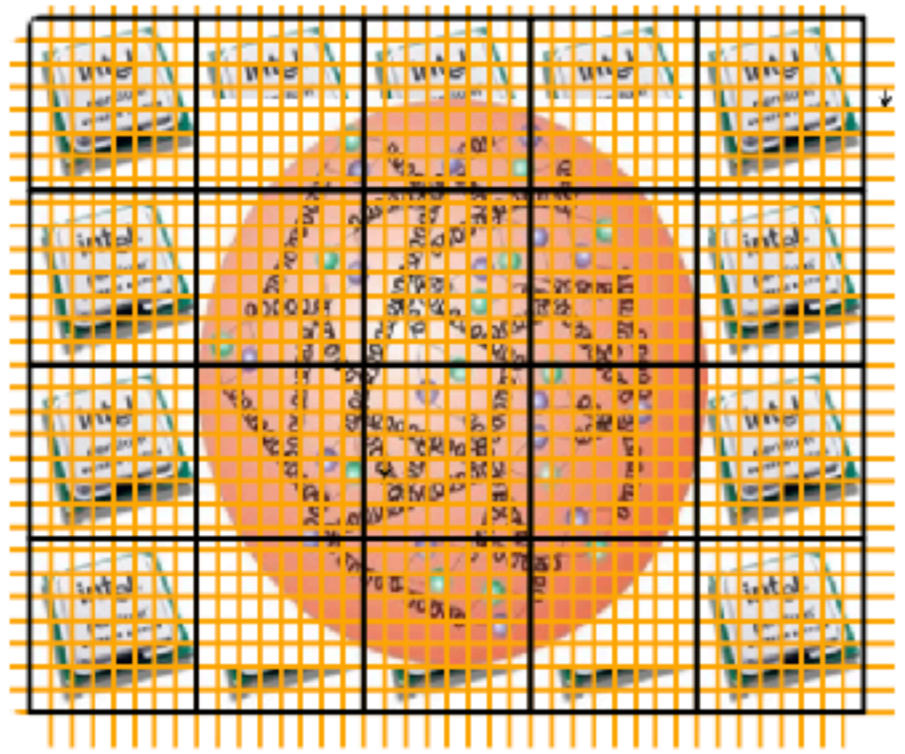
many-body theory

exact	QMC, NCSM, ...
approximate	CC, IMSRG, MBPT, SCGF, ...
phenomenological	SM, DFT, ...

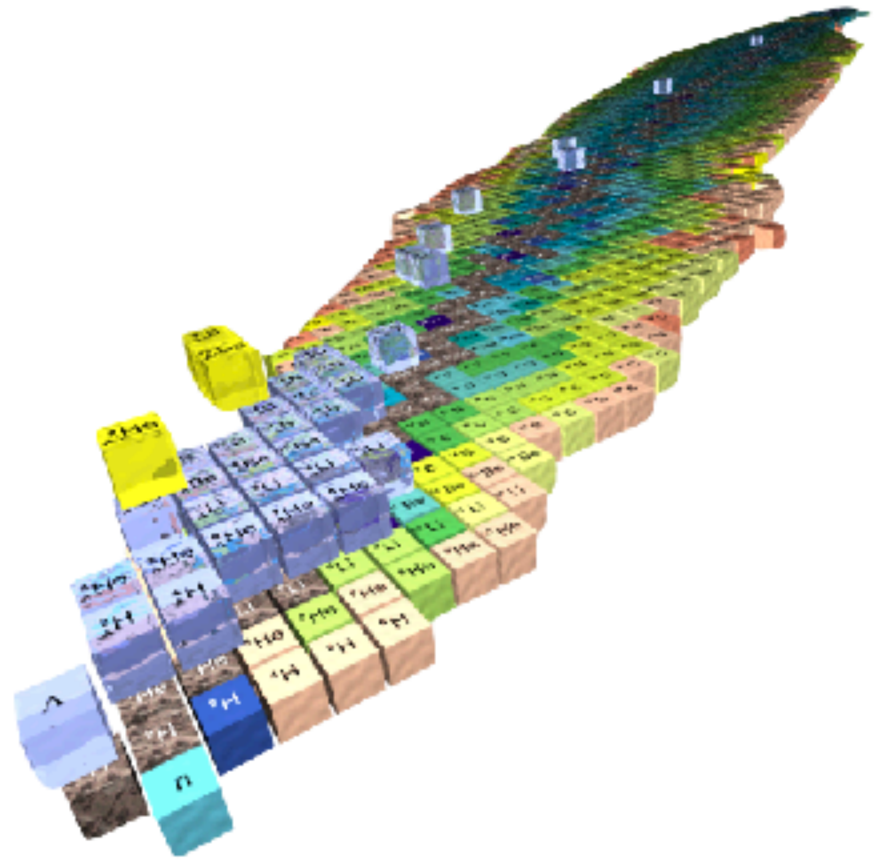
renormalization group
(SRG, Okubo-Lee-Suzuki, ...)

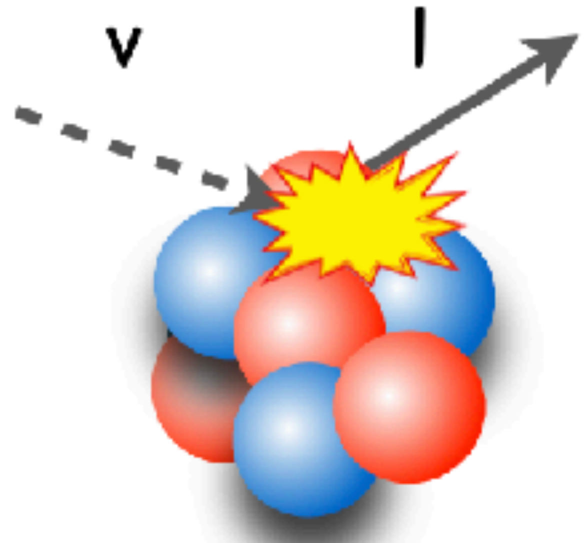
Quantum Chromodynamcs





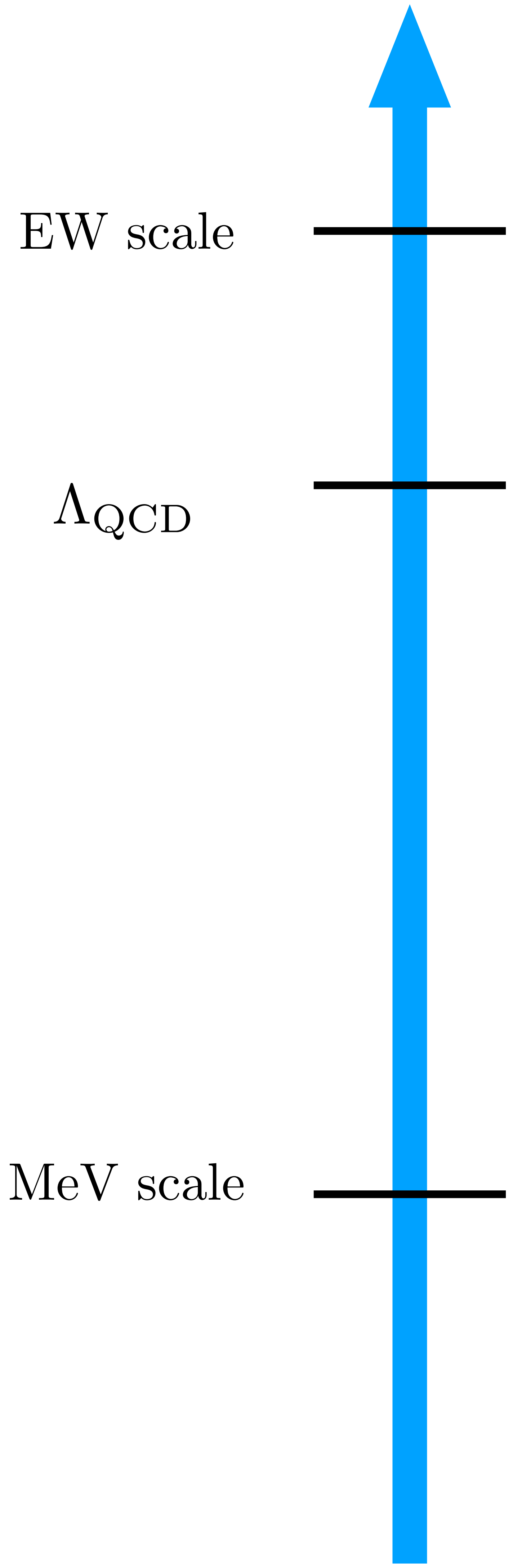
Nuclei and electroweak interactions





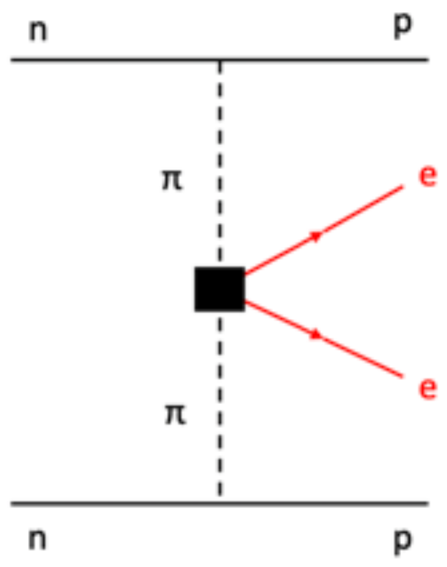
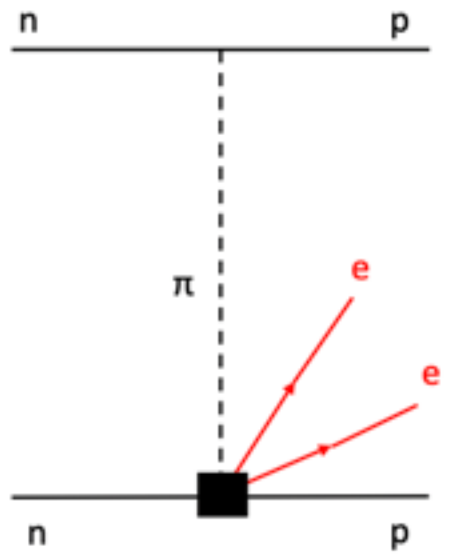
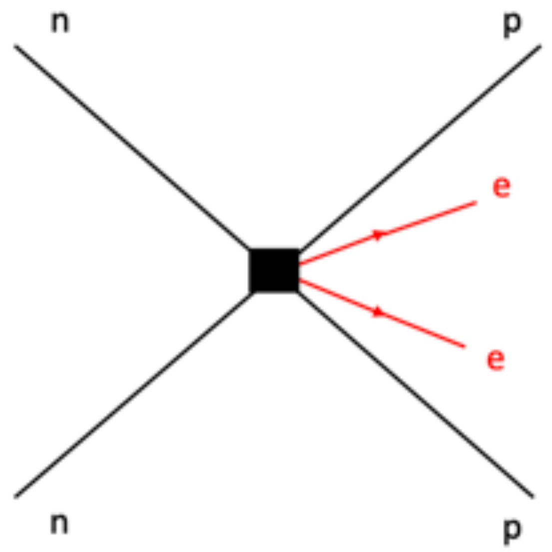
Neutrinoless double beta decay

Operators at different level



Standard model effective field theory up to dim-9

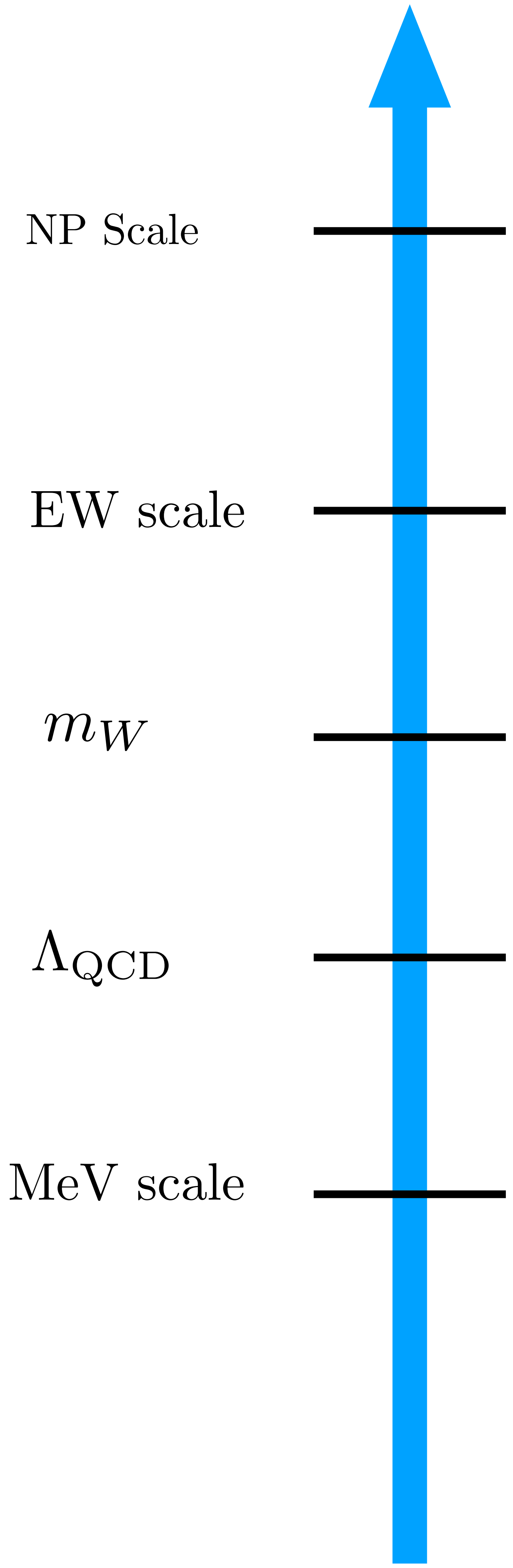
Low energy effective field theory up to dim-9

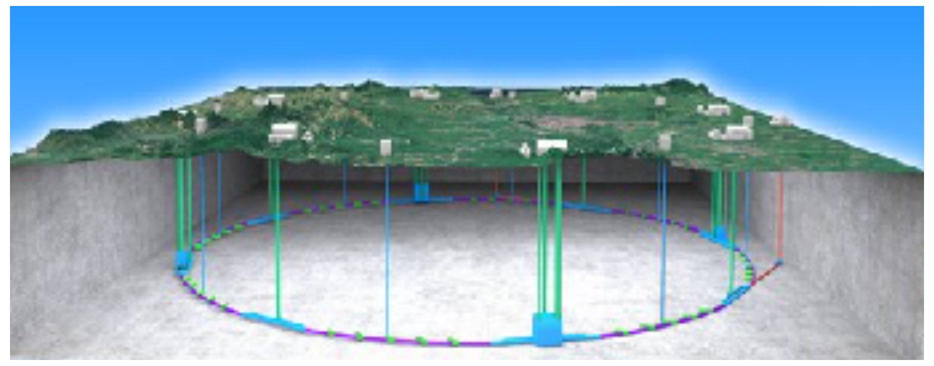
Pure meson with lepton source	Meson-nucleon with lepton source	Nucleon-nucleon with lepton source
		

Jiang-Hao Yu (ITP-CAS)

Low energy probe of high energy physics

weak currents of nuclear processes (intensity frontier)



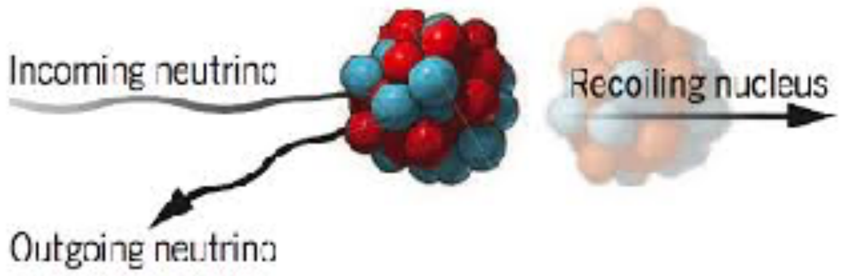


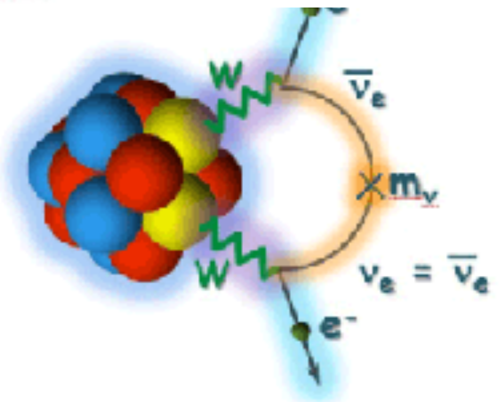
Energy frontier

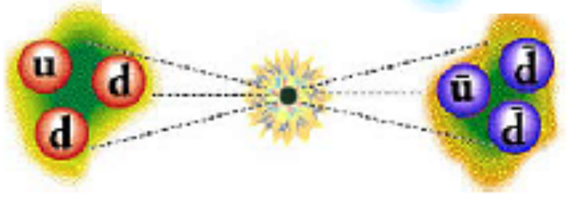
high energy, high cost!

Intensity frontier

high intensity, low cost!







Flavor physics: pion, kaon, bottom, …

Rare process: cLFV, mu-e conversion, …

Neutrino physics: NSI, CEvNS, 0vbb, …

Axion Effective Field Theory

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

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

[Hao Sun, **J.H.Yu**, in preparation]

U(1)A Problem

Where is the 9th Goldstone boson? Eta-prime?

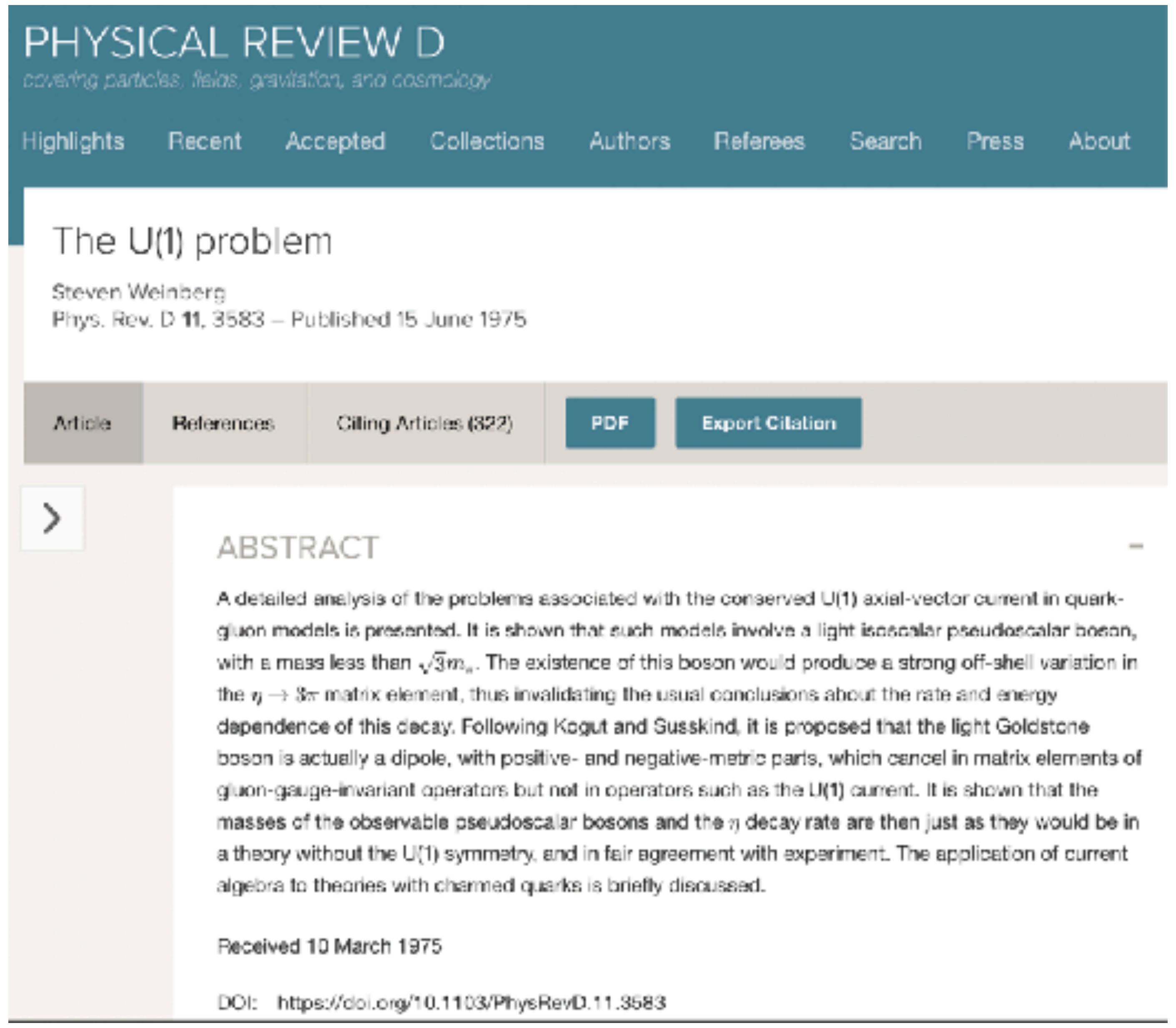
$$U(F)\times U(F)\equiv SU(F)_V\times SU(F)_A\times U(1)_V\times U(1)_A$$

↓ **Chiral condensate**

$$SU(F)_V\times U(1)_V$$

Quark mass ↓ $U(1)_{\rm EM}\subset SU(F)_V$

$$U(1)^F$$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The U(1) problem

Steven Weinberg
Phys. Rev. D 11, 3583 – Published 15 June 1975

Article References Citing Articles (822) PDF Export Citation

ABSTRACT

A detailed analysis of the problems associated with the conserved U(1) axial-vector current in quark-gluon models is presented. It is shown that such models involve a light isoscalar pseudoscalar boson, with a mass less than $\sqrt{3}m_\pi$. The existence of this boson would produce a strong off-shell variation in the $\eta\to 3\pi$ matrix element, thus invalidating the usual conclusions about the rate and energy dependence of this decay. Following Kogut and Susskind, it is proposed that the light Goldstone boson is actually a dipole, with positive- and negative-metric parts, which cancel in matrix elements of gluon-gauge-invariant operators but not in operators such as the U(1) current. It is shown that the masses of the observable pseudoscalar bosons and the η decay rate are then just as they would be in a theory without the U(1) symmetry, and in fair agreement with experiment. The application of current algebra to theories with charmed quarks is briefly discussed.

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Under the chiral transformation, path integral measure changes and the Lagrangian becomes

$$\psi\to e^{i\alpha}\psi,\quad \psi\to e^{i\beta\gamma_5}\psi\qquad \psi_{\rm L}\to e^{i(\alpha-\beta)}\psi_{\rm L},\quad \psi_{\rm R}\to e^{i(\alpha+\beta)}\psi_{\rm R}\qquad \alpha=0\qquad \mathcal{L}\to\mathcal{L}+\beta\frac{g^2}{32\pi}\varepsilon^{\mu\nu\alpha\beta}F^a_{\mu\nu}F^a_{\alpha\beta}$$

Chiral Anomaly

$\mathrm{U(1)}^2_{\rm QED}\times \mathrm{U(1)}_{\pi^0}$

$\mathrm{U(1)}^2_{\rm QED}\times \mathrm{U(1)}_A$

$\mathrm{U(1)}_{\pi^0}\subset SU(F)_A$

$$\partial^\mu J^a_{A\mu}=N_c\frac{e^2}{16\pi^2}\mathrm{tr}\left(\frac{\sigma^a}{2}Q^2\right)F^{\mu\nu}\tilde F_{\mu\nu}$$

Total derivative absorbed to current

U(1)A Anomaly

$\mathrm{SU(3)}^2_{\rm color}\times \mathrm{SU}(F)_A$

$\mathrm{SU(3)}^2_{\rm color}\times \mathrm{U(1)}_A$

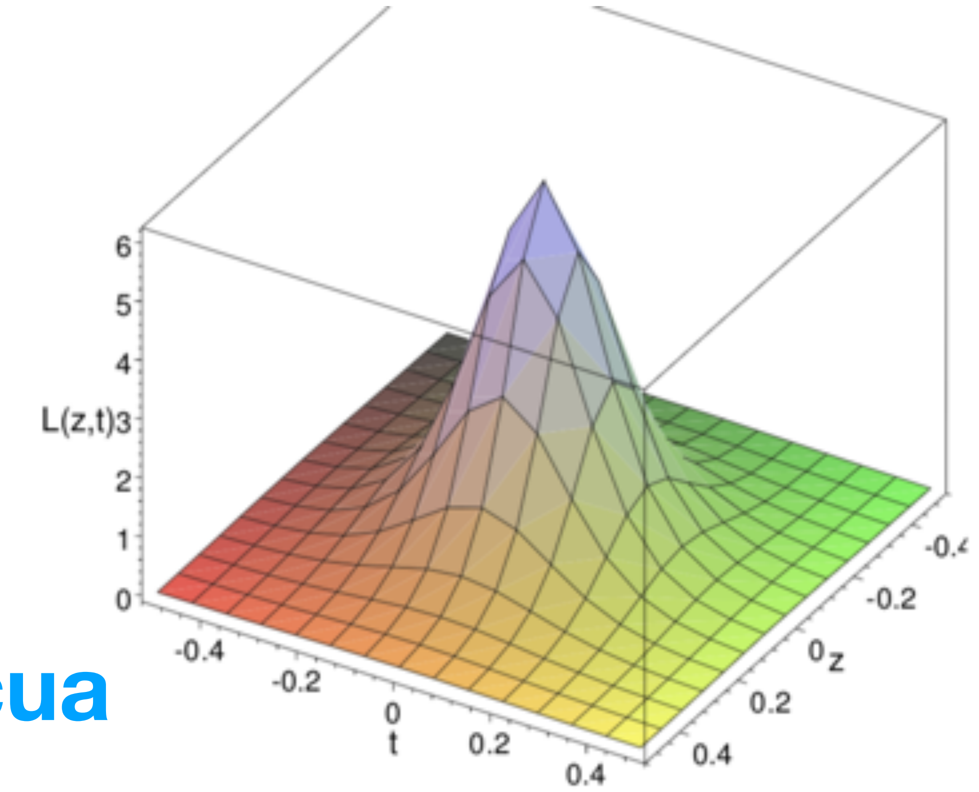
$$\partial^\mu J_{5\mu}=-iN_f\frac{g^2}{16\pi^2}G^a_{\mu\nu}\tilde G^a_{\mu\nu}$$

Non-vanishing total derivative due to instanton

Instanton and 't Hooft Lagrangian

Under the QCD vacuum $|\theta\rangle = e^{-in\theta}|n\rangle$ the Lagrangian becomes

$$\mathcal{L}_{A,\psi} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{\psi}_i(\mathrm{i}\not{D} - M_{ij})\psi_j + \theta\frac{g^2}{32\pi^2}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$



What is an instanton?

Configuration localized in Euclidean space and time

Tunnelling between different vacua

Integrating out instanton induces the following fermion path integral

$$\int DA^{(\nu)}D\psi D\bar{\psi}\left[\exp\left(-S_{A,\psi} - J\bar{\psi}\psi\right)\right] \Leftrightarrow e^{-8\pi^2/g^2}\int D\psi D\bar{\psi}\left[\exp\left(-S_{0,\psi} - J\bar{\psi}\psi\right)\right]\cdot\det\left[\bar{\psi}_R(x)\psi_L(x)\right]$$

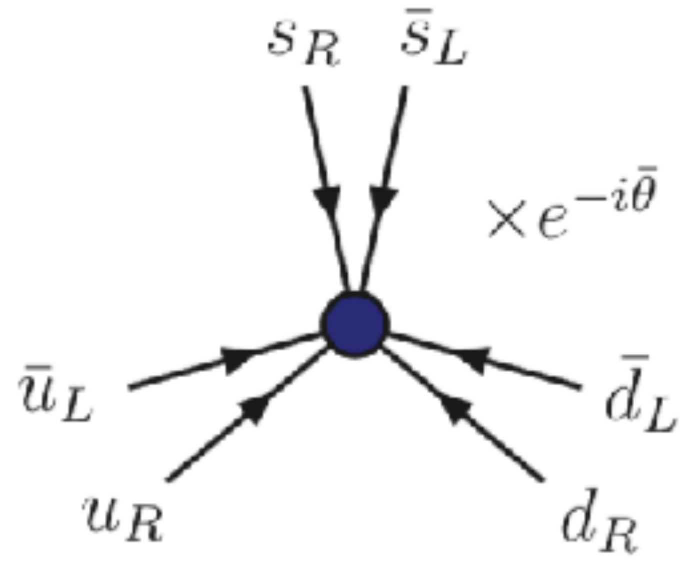
Fermion integral in an instanton bg **Fermion integral without gauge bg, but determinant**

Sum over all (anti-)instantons, obtain the 't Hooft effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \kappa\left[\mathrm{e}^{\mathrm{i}\theta}\det\psi_{\mathrm{L}}(x)\bar{\psi}_{\mathrm{R}}(x) + \mathrm{e}^{-\mathrm{i}\theta}\det\psi_{\mathrm{R}}(x)\bar{\psi}_{\mathrm{L}}(x)\right]$$

$$\psi_{\mathrm{L}} \to \mathrm{e}^{+\mathrm{i}\beta}\psi_{\mathrm{L}}, \quad \psi_{\mathrm{R}} \to \mathrm{e}^{-\mathrm{i}\beta}\psi_{\mathrm{R}}$$

$$\theta \to \theta + 2N_f\beta$$



Jiang-Hao Yu (ITP-CAS)

Spurion Transformation

The U(1)A relevant Lagrangian

$$\mathcal{L} \supset -\sum_{j=1}^{N_f} \bar{\psi}_j m_j \mathrm{e}^{\mathrm{i}\alpha_j \gamma^5} \psi_j + \frac{1}{16\pi^2} \theta \, \mathrm{tr} \, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$\bar{\psi}_i \left(m_i e^{\mathrm{i}\alpha_i \gamma^5} \right) \psi_i = \bar{\psi}_{i\mathrm{R}} \left(m_i e^{-\mathrm{i}\alpha_i} \right) \psi_{i\mathrm{L}} + \bar{\psi}_{i\mathrm{L}} \left(m_i e^{\mathrm{i}\alpha_i} \right) \psi_{i\mathrm{R}}$$

Chiral transformation

$$\psi \to \mathrm{e}^{\mathrm{i}\beta\gamma_5} \psi \qquad \psi_\mathrm{L} \to \mathrm{e}^{+\mathrm{i}\beta} \psi_\mathrm{L}$$
$$\bar{\psi} \to \bar{\psi} \mathrm{e}^{\mathrm{i}\beta\gamma_5} \qquad \psi_\mathrm{R} \to \mathrm{e}^{-\mathrm{i}\beta} \psi_\mathrm{R}$$

+

Spurion transformation

$$m_j \mathrm{e}^{\mathrm{i}\alpha_j \gamma^5} \to m_j \mathrm{e}^{\mathrm{i}(\alpha_j - 2\beta)\gamma^5}$$
$$\theta \to \theta - 2N_f \beta$$

Choose the phase $\beta = \alpha/2$ **making the Dirac mass phase real, obtain the rephasing invariant**

$$\theta \to \theta + \sum_i \alpha_i = \theta + \mathrm{Arg} \det M \equiv \bar{\theta}$$

If $\arg \det M = 0$, θ phase can always be rotated away

Massless u quark

Theta phase induces physical effects!

Chiral Lagrangian

Chiral Lagrangian for SU(3)L x SU(3)R x U(1)A, invariant under spurion transformation

$$\theta \to \theta + 2N_f\alpha$$

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[(\partial_\mu U)^\dagger \partial^\mu U\right] + a\Lambda f_\pi^2(\mathrm{Tr}[M_Q U] + \text{ h.c. }) + b\Lambda^2 f_\pi^2\left(e^{i\theta}\det U + \text{ h.c. }\right)$$

$$U(x) \equiv e^{i\eta'} e^{i\pi^a T^a}$$

$$-2b\Lambda^2 f_\pi^2 \cos\left(\theta - N_f\eta'\right)$$

$$\eta' = \frac{\theta + 2k\pi}{N_f}$$

$$U(x) \simeq e^{i\frac{\theta}{N_f}} e^{i\pi^a T^a}$$

$$M_Q = e^{i\theta_q} m_q$$

$$V_\pi = -a\Lambda f_\pi^2 e^{i\bar\theta/N_f}\,\mathrm{Tr}\left(m_q e^{i\pi^a T^a}\right) + \text{ h.c.}$$

$$-2a\Lambda f_\pi^2 \sum_{i=1}^{N_f} m_i \cos\left(\frac{\bar\theta}{N_f} + t_i^j \pi^j\right)$$

$$V_2 = -2a\Lambda f_\pi^2\left[m_u \cos\left(\frac{\bar\theta}{2} + \pi^0\right) + m_d\cos\left(\frac{\bar\theta}{2} - \pi^0\right)\right]$$

$$V_{\min} = -2|a|\Lambda f_\pi^2 \sqrt{m_u^2 + m_d^2 + 2m_u m_d \cos\bar\theta}$$

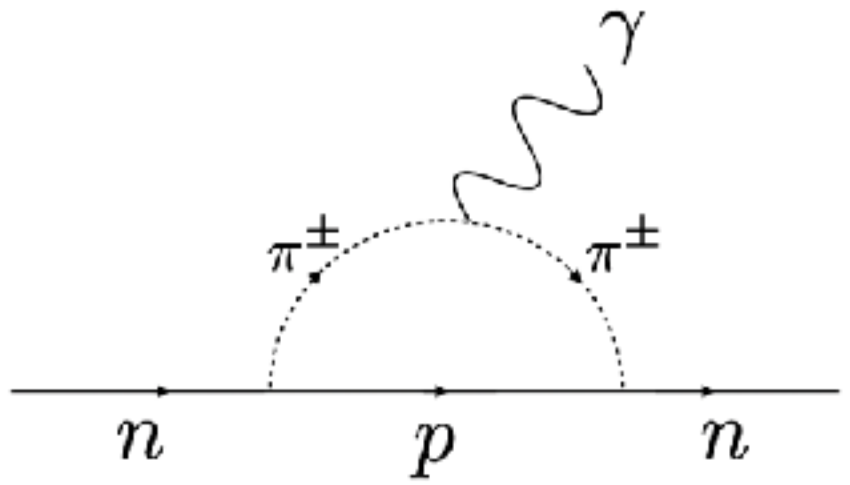
EDM in Chiral Lagrangian

Pion-Nucleon Lagrangian

$$\mathcal{L} = -m_N N U^\dagger N^c - c_1 N M N^c - c_2 N U^\dagger M^\dagger U^\dagger N^c - \frac{i}{2}(g_A - 1)\left[N^\dagger \sigma^\mu U \partial_\mu U^\dagger N + N^{c,\dagger} \sigma^\mu U^\dagger \partial_\mu U N^c\right]$$

CP-violating

$$\mathcal{L} = -\bar{\theta}\frac{c_+\mu}{f_\pi}\pi^a N \tau^a N^c - i\frac{g_A m_N}{f_\pi}\pi^a N \tau^a N^c, \qquad \mu = \frac{m_u m_d}{m_u + m_d}. \qquad c_+ = c_1 + c_2 \approx 1.7$$



$$\approx \frac{e\bar{\theta} g_A c_+ \mu \log\frac{\Lambda^2}{m_\pi^2}}{4\pi^2 f_\pi^2}\epsilon^*_\mu(q)\bar{u}(p')\gamma^{\mu\nu}q_\nu i\gamma_5 u(p)$$

$$d_n = \frac{e\bar{\theta} g_A c_+ \mu}{8\pi^2 f_\pi^2}\log\frac{\Lambda^2}{m_\pi^2} \sim 3\times 10^{-16}\,\bar{\theta}\,\mathrm{e\ cm}.$$

Massless up quark	Axion	P/CP symmetry

rotate away theta

$$q \to e^{i\gamma_5\alpha}q \quad \longrightarrow \quad \begin{cases}\theta_q \to \theta_q + 2\alpha \\ \theta \to \theta + 2\alpha\end{cases}$$

η' is the axion

Ruled out!

IR:

θ is relaxed in the infrared.

Peccei-Quinn (axion),

m_u=0 (eta prime)*

sensitive to UV symmetry-breaking

UV:

θ=0 is a BC assoc. P/CP.

Preserved in IR via β_θ << 1 in SM

Nelson-Barr, Parity models

little IR trace

sensitive to new BSM phases,

how P/CP are broken

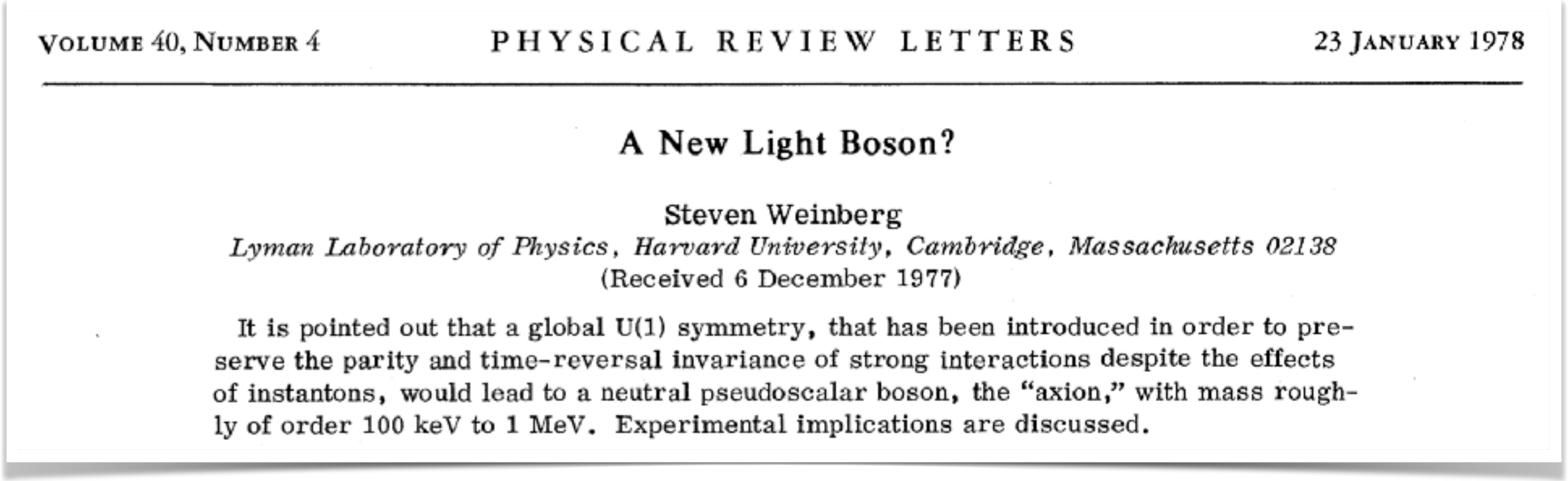
Jiang-Hao Yu (ITP-CAS)

PQ Symmetry and Axion

The U(1)A symmetry for chiral quarks

$$\partial^\mu J_{5\mu} = -iN_f \frac{g^2}{16\pi^2} G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$

Induces Theta phase and eta-prime



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A New Light Boson?

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(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

Theta becomes dynamical dof by introducing additional U(1)PQ

U(1)PQ axion particle

1.Goldstone of global U(1)PQ breaking

2. U(1)PQ are anomalous under QCD

$$\partial^\mu J^{\mathrm{PQ}}_\mu = N_{\mathrm{PQ}} \frac{g_s^2}{16\pi^2} G\tilde{G} + E_{PQ}\frac{e^2}{16\pi^2} F\tilde{F}$$

[Weinberg 1933 - 2021]

Under PQ symmetry, again the spurion analysis

$$a \to a + \varphi\, f_a, \quad \theta \to \theta - N_{\mathrm{PQ}}\varphi$$

$$\mathcal{L} \supset \left(N_{PQ}\frac{a}{f_a} + \theta\right)\frac{1}{16\pi^2} G\tilde{G}$$

KSVZ and DFSZ Axion

Consider UV setup, the PQ transformation with the spurion

KSVZ: SM are PQ neutral

$$\sigma \to e^{i\alpha}\sigma$$
$$(Q, Q^c) \to e^{-i\alpha/2}(Q, Q^c)$$

DFSZ: SM are PQ charged

$$\sigma \to e^{i\alpha}\sigma$$
$$H_{u,d} \to e^{-i\alpha}H_{u,d}$$
$$\psi_{\rm SM} \to e^{i\alpha/2}\psi_{\rm SM}$$

Spurion transformation

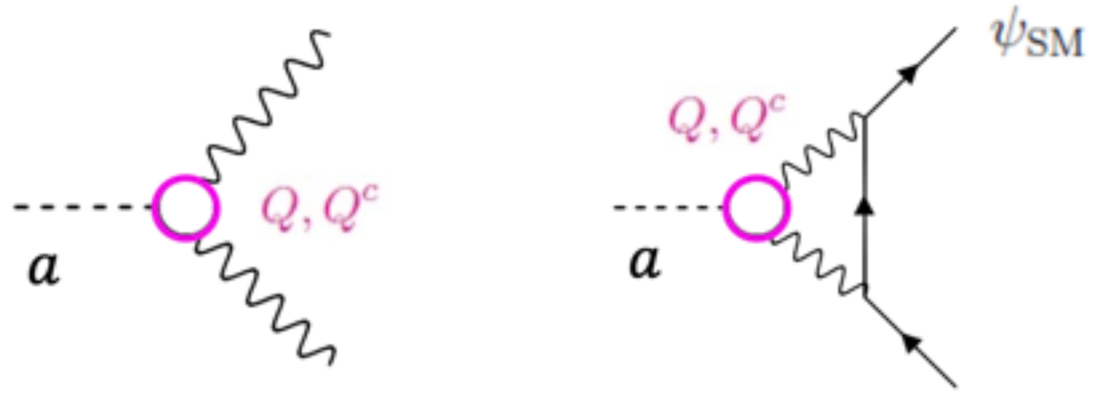
$$a \to a + \alpha f_a$$
$$\theta \to \theta - N_{PQ}\,\alpha$$

$$\mathcal{L}_{\rm KSVZ} \supset -m_Q \bar{\mathcal{Q}}_L \mathcal{Q}_R e^{ia/v_a} + \text{h.c.}$$

$$\mathcal{Q}_L \to e^{i\frac{a}{2v_a}}\mathcal{Q}_L, \qquad \mathcal{Q}_R \to e^{-i\frac{a}{2v_a}}\mathcal{Q}_R$$

$$\delta\mathcal{L}_{\rm KSVZ} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{\alpha}{8\pi}\frac{E}{N}\frac{a}{f_a}F\tilde{F}$$

Integrate out Q
No kinetic term



$$\mathcal{L}_{\text{DFSZ-I}} \supset -m_U \bar{u}_L u_R e^{i\mathcal{X}_{H_u}\frac{a}{v_a}} - m_D \bar{d}_L d_R e^{i\mathcal{X}_{H_d}\frac{a}{v_a}} - m_E \bar{e}_L e_R e^{i\mathcal{X}_{H_d}\frac{a}{v_a}} + \text{h.c.}$$

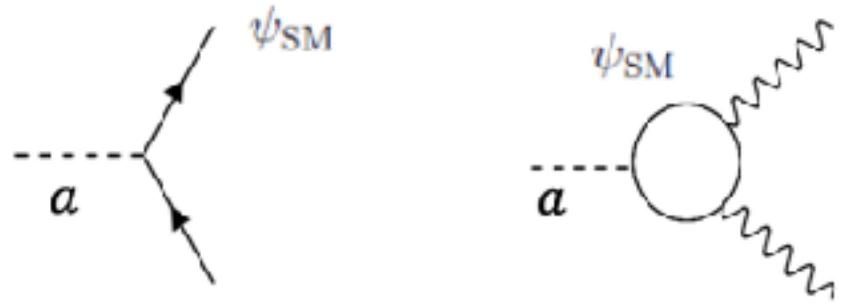
$$u \to e^{-i\gamma_5 \mathcal{X}_{H_u}\frac{a}{2v_a}}u, \quad d \to e^{-i\gamma_5 \mathcal{X}_{H_d}\frac{a}{2v_a}}d, \quad e \to e^{-i\gamma_5 \mathcal{X}_{H_d}\frac{a}{2v_a}}e$$

$$\delta\mathcal{L}_{\rm DFSZ-I} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{\alpha}{8\pi}\left(\frac{E}{N}\right)\frac{a}{f_a}F\tilde{F}$$

$$\delta(\bar{u}i\partial\!\!\!/ u) = \mathcal{X}_{H_u}\frac{\partial_\mu a}{2v_a}\bar{u}\gamma^\mu\gamma_5 u$$
$$\delta(\bar{d}i\partial\!\!\!/ d) = \mathcal{X}_{H_d}\frac{\partial_\mu a}{2v_a}\bar{d}\gamma^\mu\gamma_5 d$$

With shift symmetry

$$\frac{\partial_\mu a}{2f_a}\bar{q}c_q^0\gamma^\mu\gamma_5 q$$



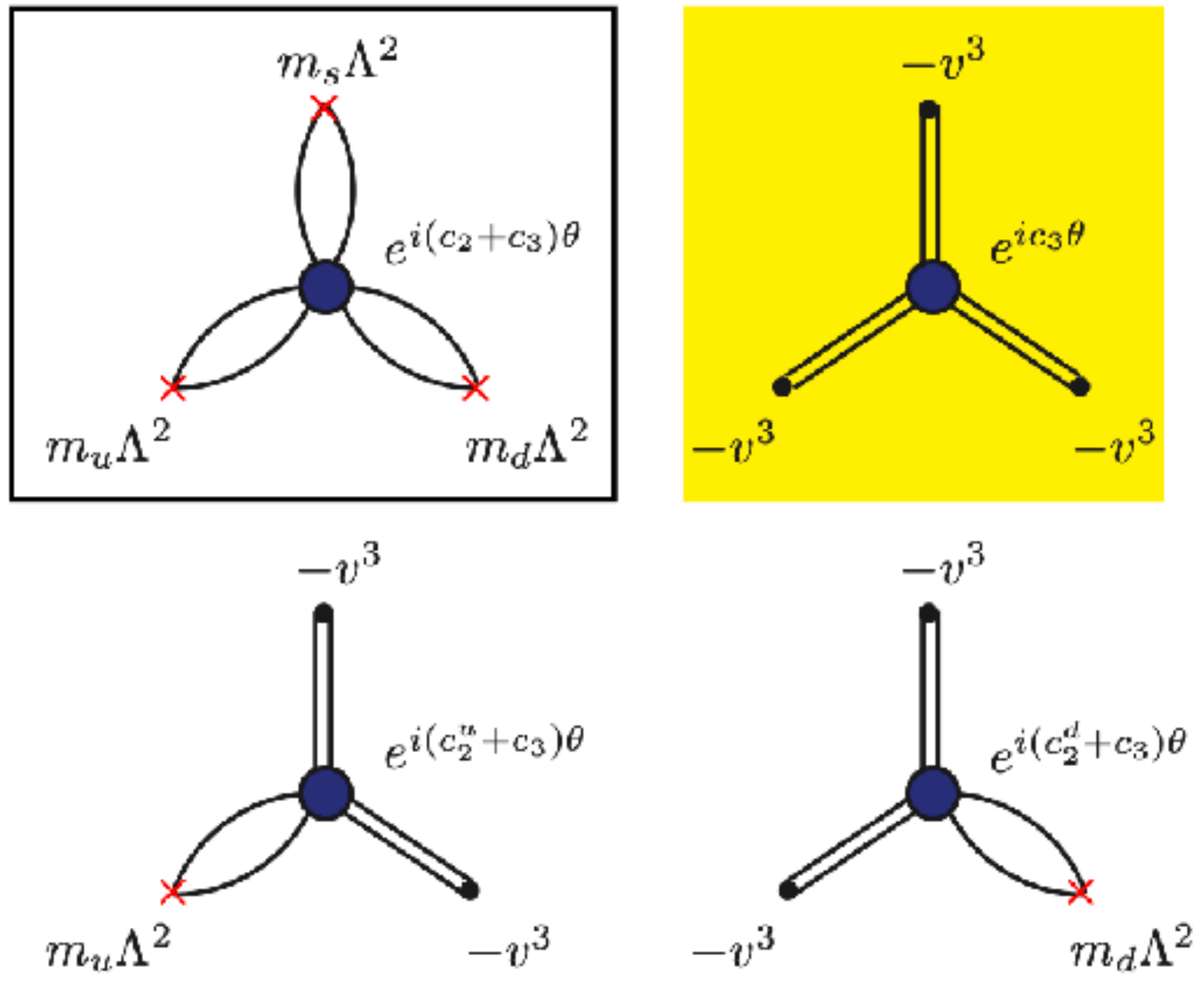
Instanton Analysis

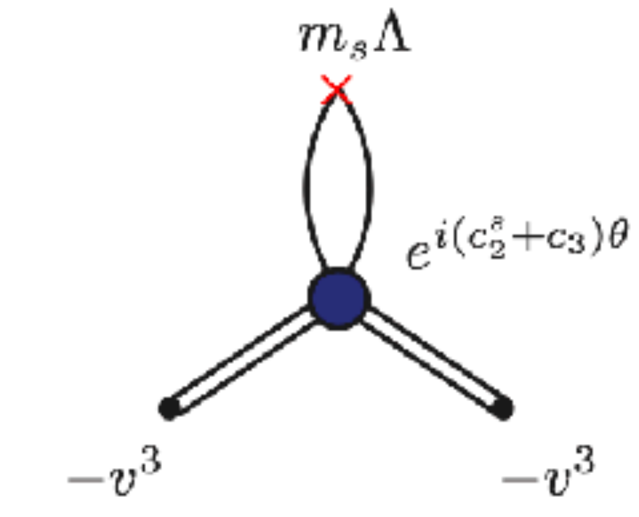
Below scale f, take Georgi-Kaplan-Randall basis (only axion transform under U(1)PQ, other invariant)

$$\frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\partial_\mu a}{f_a}\left[ic_\phi(\phi^* D^\mu \phi - \phi D^\mu \phi^*) + c_\psi \bar{\psi}\bar{\sigma}^\mu \psi\right] + c_A \frac{g_A^2}{32\pi^2}\frac{a(x)}{f_a} F^{A\mu\nu}\tilde{F}^A_{\mu\nu}.$$

$$F^A_{\mu\nu} = (G^\alpha_{\mu\nu}, W^i_{\mu\nu}, B_{\mu\nu})$$

Instanton diagrams, where a is a spurion of the theta parameter





$+ \quad \mathcal{O}(m^2\Lambda^4 v^3)$

$\times e^{-i\bar{\theta}-N_{PQ}a/f}$

$$\mathcal{L}_{\rm det} = -2^{-1} i c_3\theta (-1)^{N_f} \frac{e^{-ic_3\theta}}{K^{3N_f-4}} {\rm Det}(q_R \bar{q}_L) + {\rm h.c.}$$

$$\mathcal{L}_{\rm det} = (-1)^{N_f} K^{-5}\left(\langle \bar{u}_L u_R\rangle\langle \bar{d}_L d_R\rangle\langle \bar{s}_L s_R\rangle e^{i(2\theta_{\eta'}-c_3\theta)} + \cdots + \text{flavor singlet constraint}\right) + {\rm h.c}$$

$$\mathcal{L} = -m_u\langle \bar{u}_L u_R\rangle e^{i[(\theta_\pi+\theta_{\eta'})+c_2^u\theta]} - m_d\langle \bar{d}_L d_R\rangle e^{i[(-\theta_\pi+\theta_{\eta'})+c_2^d\theta]} + {\rm h.c.}$$

$$\begin{aligned} V \ = \ & m_u v^3 \cos(\theta_\pi + \theta_{\eta'}) + m_d v^3 \cos(-\theta_\pi + \theta_{\eta'}) + \frac{v^9}{K^5}\cos\left(2\theta_{\eta'} - (c_2^u + c_2^d + c_3)\theta\right) \\ & + m_u \frac{\Lambda_u^2 v^6}{K^5}\cos\left(-\theta_\pi + \theta_{\eta'} - (c_2^u + c_2^d + c_3)\theta\right) + m_d \frac{\Lambda_d^2 v^6}{K^5}\cos\left(\theta_\pi + \theta_{\eta'} - (c_2^u + c_2^d + c_3)\theta\right) \end{aligned}$$

Chiral Lagrangian with Axion

Chiral Lagrangian for SU(3)L x SU(3)R x U(1)A again + axion currents

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[(\partial_\mu U)^\dagger \partial^\mu U\right] + a\Lambda f_\pi^2(\mathrm{Tr}[M_Q U] + \text{ h.c. }) + b\Lambda^2 f_\pi^2\left(e^{i\theta + iN_{PQ}a/f}\det U + \text{ h.c. }\right) + \frac{\partial^\mu a}{2f_a}\frac{1}{2}\mathrm{Tr}[c_q\sigma^a]J_\mu^a$$

$$J_\mu^a = \frac{i}{2}f_\pi^2\,\mathrm{Tr}\left[\sigma^a\left(UD_\mu U^\dagger - U^\dagger D_\mu U\right)\right]$$

$$V_k\left(\eta', a, \pi^j\right) = -2\alpha\Lambda^2 f_\pi^2\sum_{i=1}^{N_f}\frac{m_i}{\Lambda}\cos\left(\eta' + \theta_q + t_i^j\pi^j\right) - 2b\Lambda^2 f_\pi^2\cos(\theta - N_f\eta' + N_{\mathrm{PQ}}a)$$

$$\eta' = \frac{\theta + N_{\mathrm{PQ}}\,a}{N_f}$$

$$V_a = -2\alpha\Lambda^2 f_\pi^2\sum_{i=1}^{F}\frac{m_i}{\Lambda}\cos\left(\frac{\bar\theta + aN_{\mathrm{PQ}}}{N_f} + t_i^j\pi^j\right)$$

$$\langle a\rangle = -\frac{\bar\theta}{N_{\mathrm{PQ}}}, \quad \langle\pi^i\rangle = 0 \qquad a\Lambda^2 f_\pi^2\sum_{i=1}^{F}\frac{m_i}{\Lambda}\left(\frac{aN_{\mathrm{PQ}}}{F} + t_i^j\pi^j\right)^2$$

$$V(a) = -m_\pi^2 f_\pi^2\sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$

$$m_a^2 = 2\alpha\Lambda N_{\mathrm{PQ}}^2\frac{f_\pi^2}{f_a^2}\frac{m_u m_d}{m_u + m_d} = N_{\mathrm{PQ}}^2 m_\pi^2\frac{f_\pi^2}{f_a^2}\frac{m_u m_d}{(m_u+m_d)^2}$$

Depending on quark mass

Axion EFT Operators

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

Adler zero conditions for axion

$$\mathcal{A}_3[aVV] = C_{aVV}\frac{i}{f_a}(\langle \mathbf{12}\rangle^2 - [\mathbf{12}]^2)$$

$$\mathcal{A}_3[af\bar{f}] = C_{af\bar{f}}\frac{im_f}{f_a}(\langle \mathbf{12}\rangle - [\mathbf{12}])$$

$(\mathbf{1}^{\frac{1}{2}}, \mathbf{2}^{\frac{1}{2}}, \mathbf{3}^0)$	$\langle \mathbf{12}\rangle$	$[\mathbf{12}]$
$(-\frac{1}{2}, -\frac{1}{2}, 0)$	$\langle 12\rangle$	–
$(+\frac{1}{2}, +\frac{1}{2}, 0)$	–	$[12]$

Parity: $c_1\,(\langle 12\rangle - [12])$

$$c_1\frac{m_f}{gv}\partial_\mu\phi\bar{\psi}\gamma^\mu\gamma_5\psi$$

$$\mathcal{L}_{\rm int} = -\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{g_{\phi N}}{2m_N}\partial_\mu\phi(\bar{N}\gamma^\mu\gamma_5 N) + \frac{g_{\phi e}}{2m_e}\partial_\mu\phi(\bar{e}\gamma^\mu\gamma_5 e) - \frac{i}{2}g_d\phi\bar{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu}$$

Class	Type	Real	F	Axion	Majoron
$F_L^2\phi$	$B_L^2 s$	$sB_{L\mu\nu}B_L{}^{\mu\nu}$		$\not\checkmark$	
	$W_L^2 s$	$sW_L{}^I{}_{\mu\nu}W_L{}^{I\mu\nu}$		$\not\checkmark$	
	$G_L^2 s$	$sG_L{}^A{}_{\mu\nu}G_L{}^{A\mu\nu}$		$\not\checkmark$	
$\psi^2\phi^2$	$e_cH^\dagger Ls$	$sH^{\dagger i}(e_{cp}L_{ri})$		$\not\checkmark$	
	$d_cH^\dagger Qs$	$sH^{\dagger i}(d_{cp}{}^aQ_{rai})$		$\not\checkmark$	
	HQu_cs	$\epsilon^{ij}sH_j(Q_{pai}u_{cr}{}^a)$		$\not\checkmark$	
$D^2\phi^4$	$D^2HH^\dagger s^2$	$(D_\mu s)(D^\mu s)H_iH^{\dagger i}$		✓	
$DF_L\phi\psi\bar{\psi}$	$DB_Lu_cu_c^\dagger s$	$(D_\nu s)B_L{}^{\mu\nu}(u_{cp}{}^a\sigma_\mu u^\dagger_{cra})$		✓	
	$DB_LQQ^\dagger s$	$(D_\nu s)B_L{}^{\mu\nu}(Q_{pai}\sigma_\mu Q^\dagger{}_r{}^{ai})$		✓	
$Dd_cL^2u_c^\dagger s$		$\epsilon^{ij}(D^\mu s)(d_{cp}{}^aL_{ri})(L_{sj}\sigma_\mu u^\dagger_{cta})$	$\mathcal{Y}[\boxed{r}\boxed{s}]$	✓	✓

Axion - Nucleon chiral Lagrangian

Majoron, Goldstone for LNV, leading order at dim-8

$$\mathcal{L}_N = \bar{N}v^\mu\partial_\mu N + 2g_A\frac{c_u - c_d}{2}\frac{\partial_\mu a}{2f_a}\bar{N}S^\mu\sigma^3 N + 2g_0^{ud}\frac{c_u + c_d}{2}\frac{\partial_\mu a}{2f_a}\bar{N}S^\mu N + \ldots$$

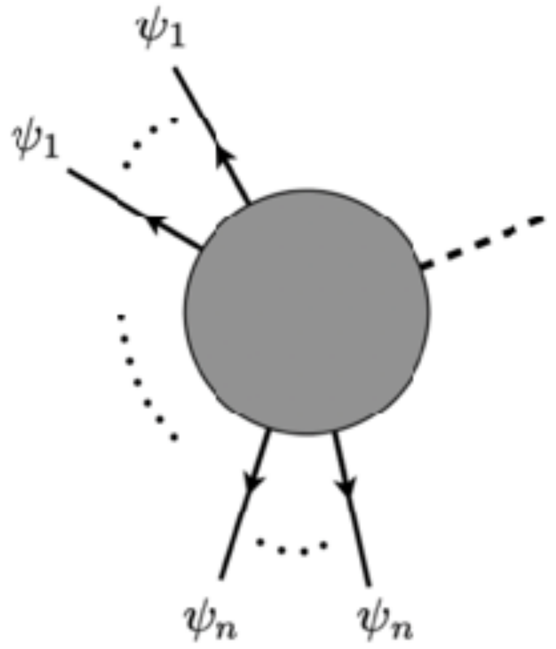
Explicit PQ Breaking

Axion becomes pseudo-Goldstone due to explicit PQ breaking

Instanton effects

't Hooft eff. Lag

$$\mathcal{L}_{\rm eff} = K\left(\prod_{i=1}^{N_f}\det\left(\bar{q}_L^i q_R^i\right)\right) e^{-i\frac{a}{f_a}}$$



$$\bar{u}_L u_R \approx |\langle \bar{u}_L u_R\rangle| \exp\left(i(\theta_{\pi^0}+\theta_{\eta'})\right)$$
$$\bar{d}_L d_R \approx |\langle \bar{d}_L d_R\rangle| \exp\left(i(-\theta_{\pi^0}+\theta_{\eta'})\right)$$
$$\bar{s}_L s_R \approx |\langle \bar{s}_L s_R\rangle| \exp\left(i\theta_{\eta'}\right)$$

spurion analysis

$$V(a) = m_\pi^2 f_\pi^2 \cos\left(\frac{a}{f_a}\right)$$

UV breaking gravity

Axion quality problem

$$V \sim \epsilon^2\Phi^2 + \frac{\Phi^n}{M_{\rm pl}^{n-4}}$$

$$V \sim \epsilon^2 f_a^2 \cos\left(\frac{a}{f_a}+\phi\right)$$

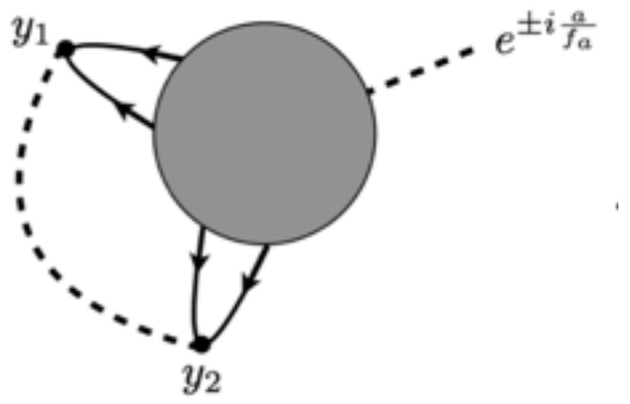
$$V \sim \frac{f_a^n}{M_{\rm pl}^{n-4}} \cos\left(\frac{a}{f_a}+\phi_n\right)$$

Enhanced symmetry

1. Discrete gauge
2. Composite dynamics
3. Extra dimension

SM Yukawa

CKM phase



$$\theta_{\rm eff}^{\rm SM} \sim \frac{G_F^2}{m_c^2} J_{\rm CKM} f_\pi^4 \Lambda_\chi^2 \sim 10^{-19}$$

Flavor connection

flavion

axiflavon

Majoron-axion

Small Instanton effects

Increase axion mass

$$V(a) = m_\pi^2 f_\pi^2 \cos\left(\frac{a}{f_a}\right) + \sum \Lambda_i^4 \cos\left(\frac{n_i a}{f_a}+\alpha_i\right)$$

$$\frac{\delta m_a^2}{m_a^2} = \frac{\Lambda_i^4}{m_\pi^2 f_\pi^2}$$

Heavy axion

New QCD

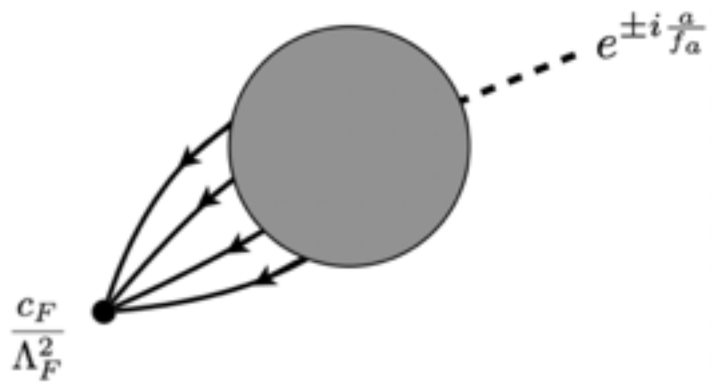
Partially broken

$$\theta_{\rm eff} = \alpha_i \frac{\delta m_a^2}{m_a^2}$$

Multi-axion

CPV Effective Operators

Higher dim Op



$$\left\langle 0\left|\mathcal{T}\left(F\tilde{F}(x)\right)\mathcal{O}_{\rm CPV}(0)\right|0\right\rangle$$

CPV Op

$$\theta_{\rm eff}^{\rm BSM} \sim \left(\frac{\Lambda_\chi}{\Lambda_{\rm BSM}}\right)^2 \sim 10^{-10}\left(\frac{100{\rm TeV}}{\Lambda_{\rm BSM}}\right)^2$$

New CPV effects

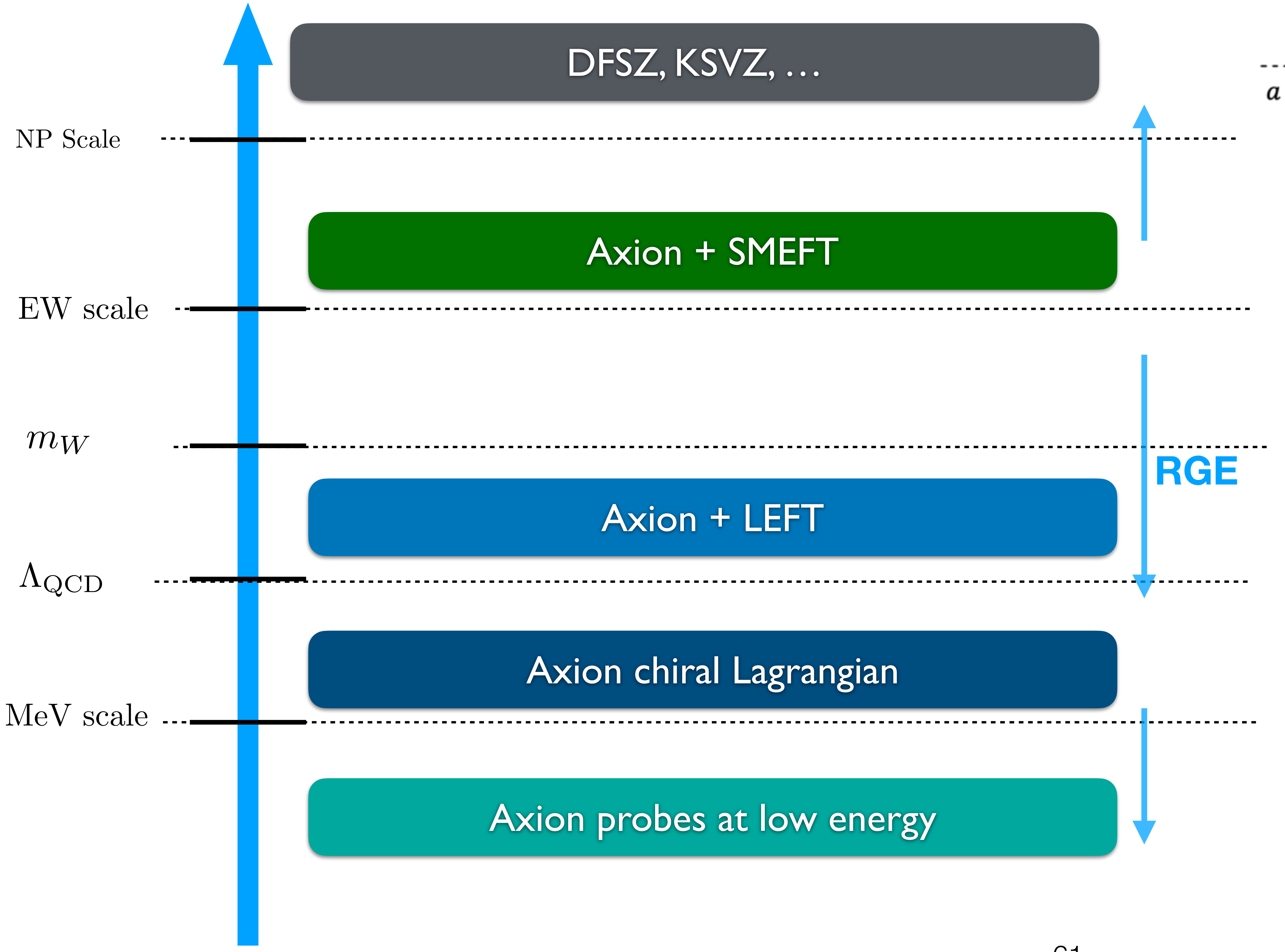
[Hu, Jiang, Li, Xiao, **Yu**, 2009.01452]

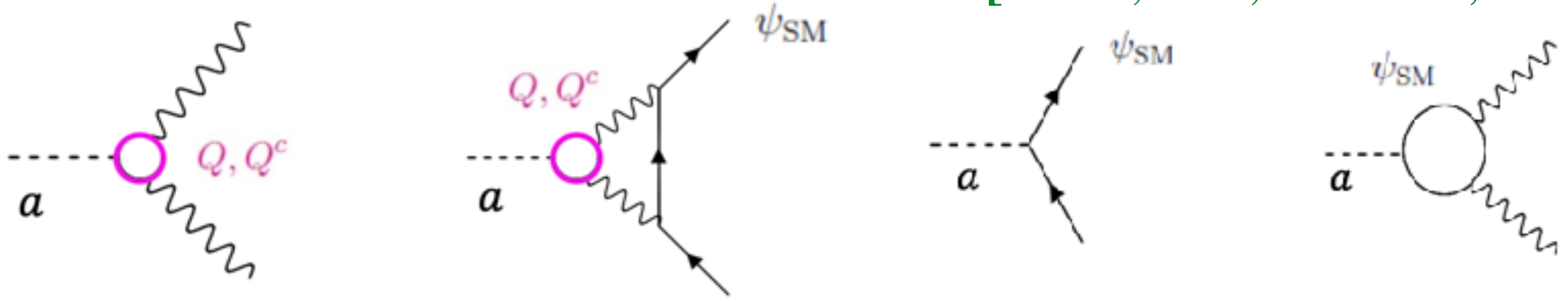
[Sun, Wang, **Yu**, in progress]

Axion effective field theories

[Georgi, Kaplan, Randall, 1986]
[Bauer, Neubert, Renner, Schäuble, Thamm, 2021]
[Dekens, de Vries, Shain, 2022]
[Di Luzio, Levati, Paradisi, 2023]
[Vonk, Guo, Meissner, 2021]

From high scale models to low scale descriptions





$$\frac{\partial_\mu a}{2f_a}\left(\sum_\psi c_\psi \bar\psi\gamma^\mu\psi + \sum_\phi c_\phi \phi^\dagger i\partial_\mu\phi\right) + \frac{a}{f_a}\sum_V c_V \frac{g_V^2}{32\pi^2} F_V^{\mu\nu}\tilde F_{V\mu\nu}$$

$$c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde G^{\mu\nu,a} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f}W^A_{\mu\nu}\tilde W^{\mu\nu,A} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f}B_{\mu\nu}\tilde B^{\mu\nu}.$$

$$\frac{\partial^\mu a}{f}\sum_F \bar\psi_F \mathbf{c}_F\gamma_\mu\psi_F + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde G^{\mu\nu,a} + c_{\gamma\gamma}\frac{\alpha_1}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde F^{\mu\nu}.$$

$$\mathcal{L}_a^{\chi\rm PT} = \frac{f_\pi^2}{4}\left[\mathrm{Tr}\left((D^\mu U)^\dagger D^\mu U\right) + 2B_0\,\mathrm{Tr}\left(UM_a^\dagger + M_a U^\dagger\right)\right] + \frac{\partial^\mu a}{2f_a}\frac{1}{2}\mathrm{Tr}\left[c_q\sigma^a\right]J^a_\mu$$

$$J^a_\mu = \frac{i}{2}f_\pi^2\,\mathrm{Tr}\left[\sigma^a(UD_\mu U^\dagger - U^\dagger D_\mu U)\right] \qquad D_\mu U = \partial_\mu U + ieA_\mu[Q,U]$$

$$\mathcal{L}_{\rm ALP}^{\rm QCD} = \frac{\partial_\mu\phi}{\Lambda}\left[2\,\mathrm{Tr}(Y_V T_a)\,(j^\mu_{V,a})_{\rm B} + \frac{1}{N}\mathrm{Tr}(Y_V)\,(j^\mu_V)'_{\rm B} + 2\,\mathrm{Tr}(Y_A T_a)\,(j^\mu_{A,a})_{\rm B} + \frac{1}{N}\mathrm{Tr}(Y_A)\,(j^\mu_A)'_{\rm B}\right]$$

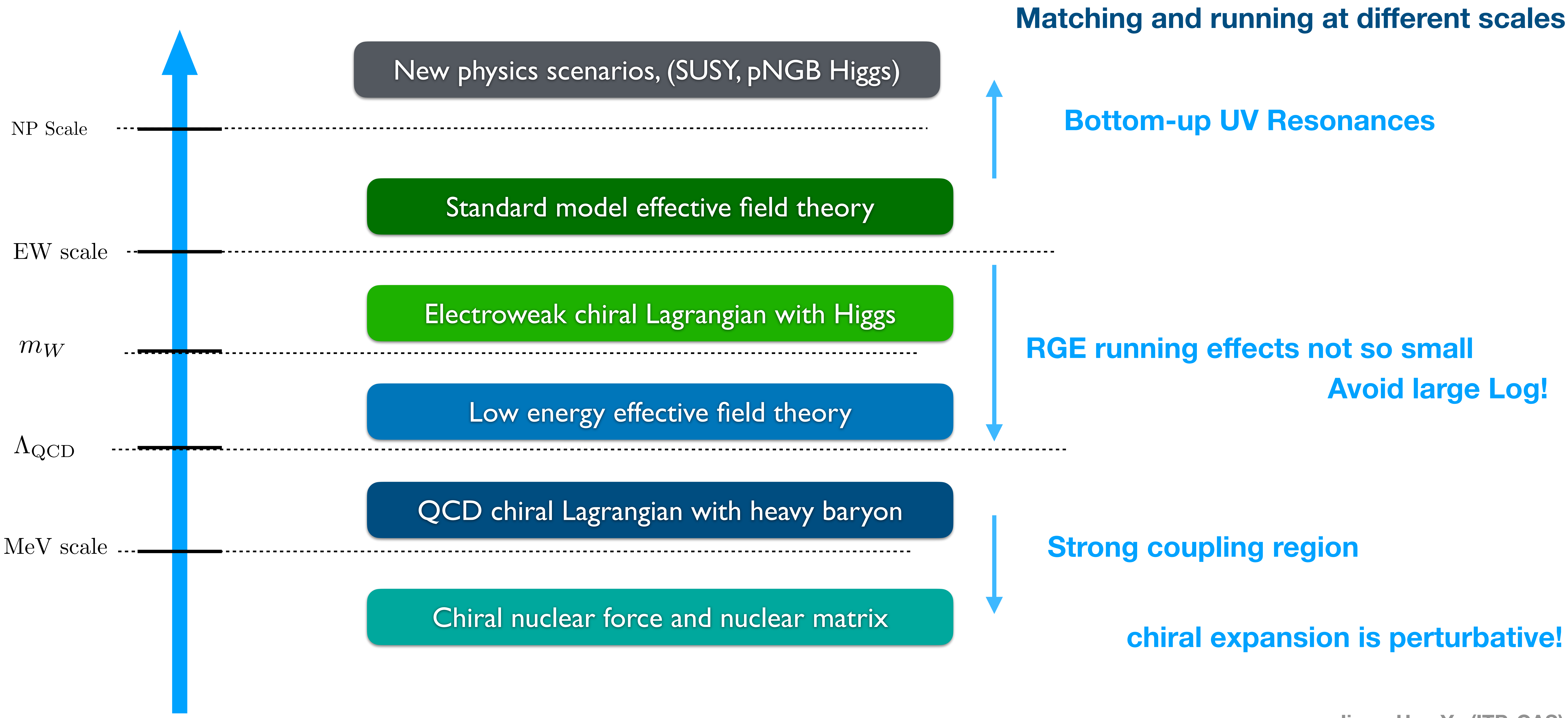
$$(j_A^{a,\mu})_{\rm N} = \frac{1}{2}\bar N_v\gamma^\mu\left[\xi T^a\xi^\dagger - \xi^\dagger T^a\xi\right]N_v + \frac{g_A}{2}\bar N_v\gamma^\mu\gamma_5\left[\xi T^a\xi^\dagger + \xi^\dagger T^a\xi\right]N_v\,,$$
$$(j_V^{a,\mu})_{\rm N} = -\frac{1}{2}\bar N_v\gamma^\mu\left[\xi T^a\xi^\dagger + \xi^\dagger T^a\xi\right]N_v - \frac{g_A}{2}\bar N_v\gamma^\mu\gamma_5\left[\xi T^a\xi^\dagger - \xi^\dagger T^a\xi\right]N_v\,,$$
$$(j_A^{\mu})_{\rm N} = \frac{1}{2}\bar N_v\gamma^\mu\left[\xi\xi^\dagger - \xi^\dagger\xi\right]N_v + \frac{g_A}{2}\bar N_v\gamma^\mu\gamma_5\left[\xi\xi^\dagger + \xi^\dagger\xi\right]N_v\,,$$
$$(j_V^{\mu})_{\rm N} = -\frac{1}{2}\bar N_v\gamma^\mu\left[\xi\xi^\dagger + \xi^\dagger\xi\right]N_v - \frac{g_A}{2}\bar N_v\gamma^\mu\gamma_5\left[\xi\xi^\dagger - \xi^\dagger\xi\right]N_v\,.$$

TP-CAS)

Summary

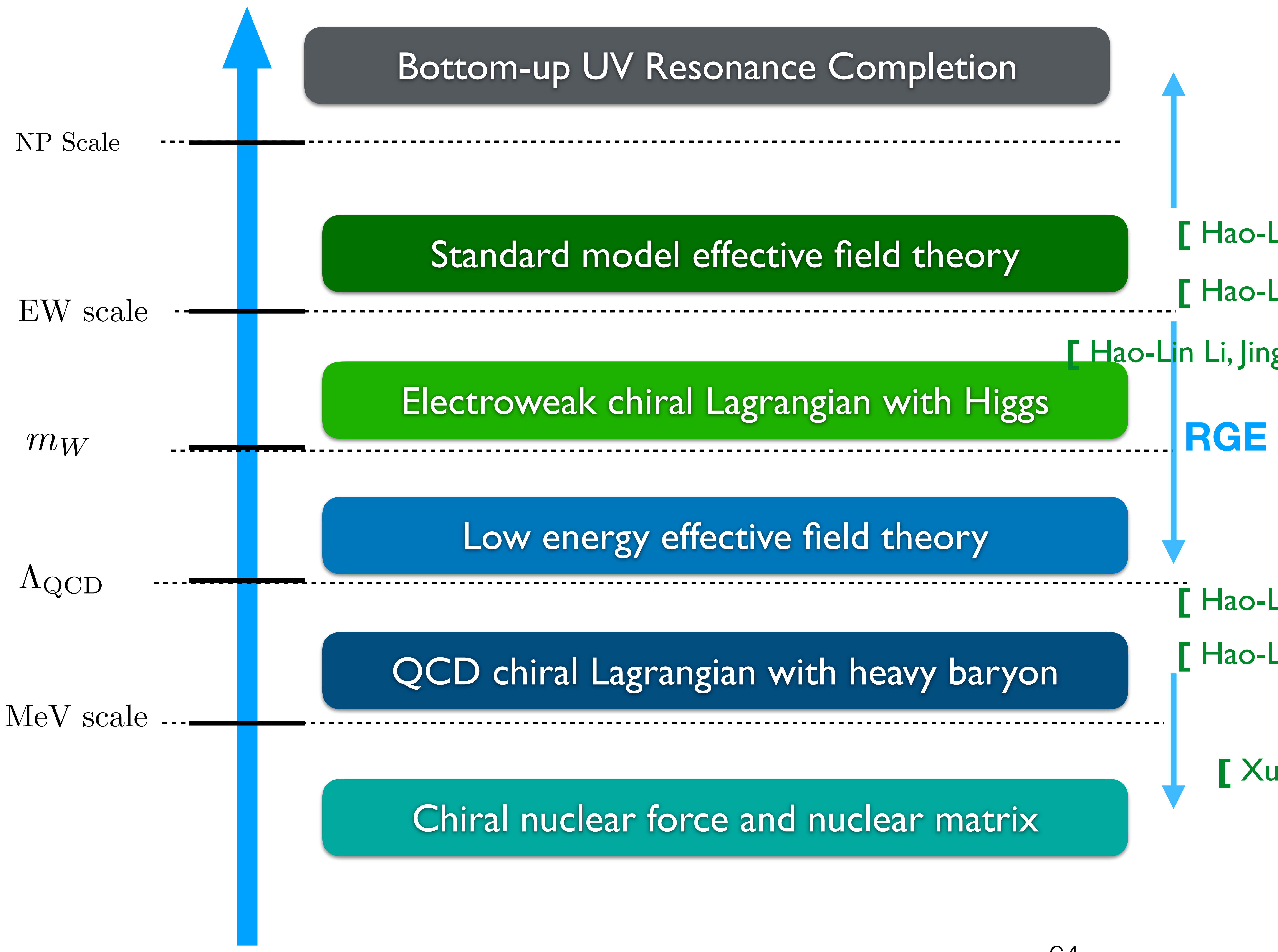
Summary

- Revisit tower of EFTs based on Young tensor and Adler zero/spurion technique



Tower of effective field theories

Five years (2019 - 2023) on reorganizing effective field theories among several scales



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Thanks for your attention!