Institute of Theoretical Physics
Chinese Academy of Sciences

Chiral Effective Field Theories

~~For Strong and Weak Dynamics~~

Jiang-Hao Yu (于江浩)

Institute of Theoretical Physics, Chinese Academy of Sciences

第三届高能物理理论与实验融合发展研讨会

11-02, 2024 @ 大连

Institute of Theoretical Physics
Chinese Academy of Sciences

Chiral Effective Field Theories
For Precision Neutrino Physics

Jiang-Hao Yu (于江浩)

Institute of Theoretical Physics, Chinese Academy of Sciences

第三届高能物理理论与实验融合发展研讨会

11-02, 2024 @ 大连

Outline

- **EFT description for neutrino physics**

- **Chiral Lagrangian matched from quark operators**

[Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2404.15047]

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

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

[Gang Li, Chuan-Qiang Song, **J.H.Yu**, in preparation]

- **Nuclear weak current from chiral EFT**

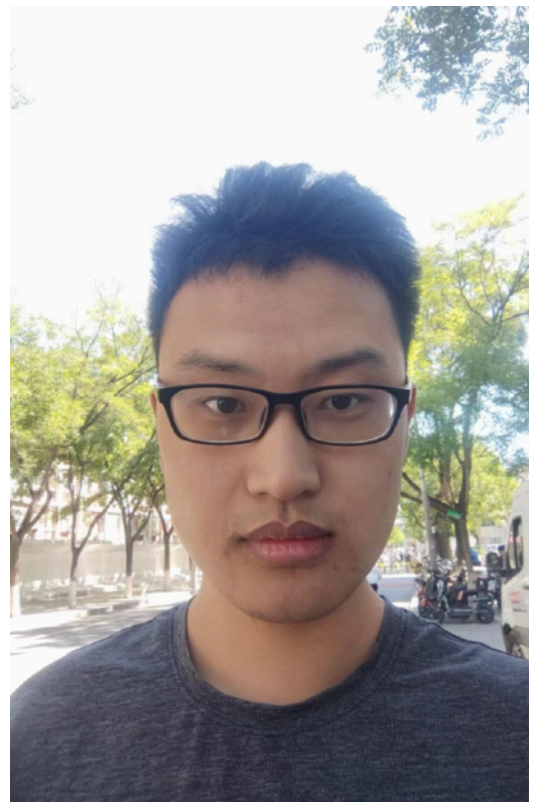
[Hao Sun, Yi-Ning Wang, **J.H.Yu**, in préparation]

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

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

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

- **Summary**



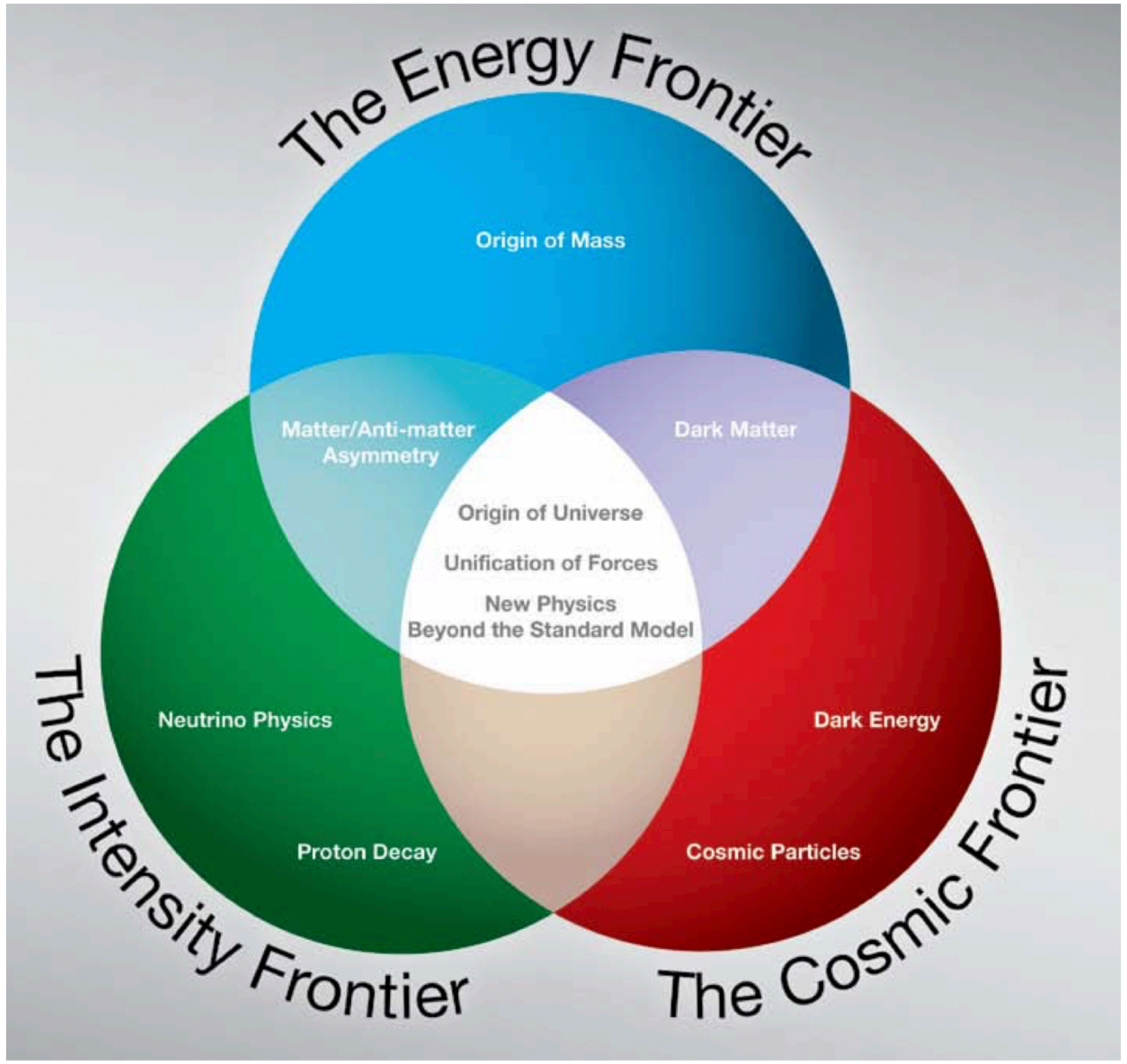
Hao Sun

EFT description for Neutrino Physics

Paradigm Shift 2013 - 2023

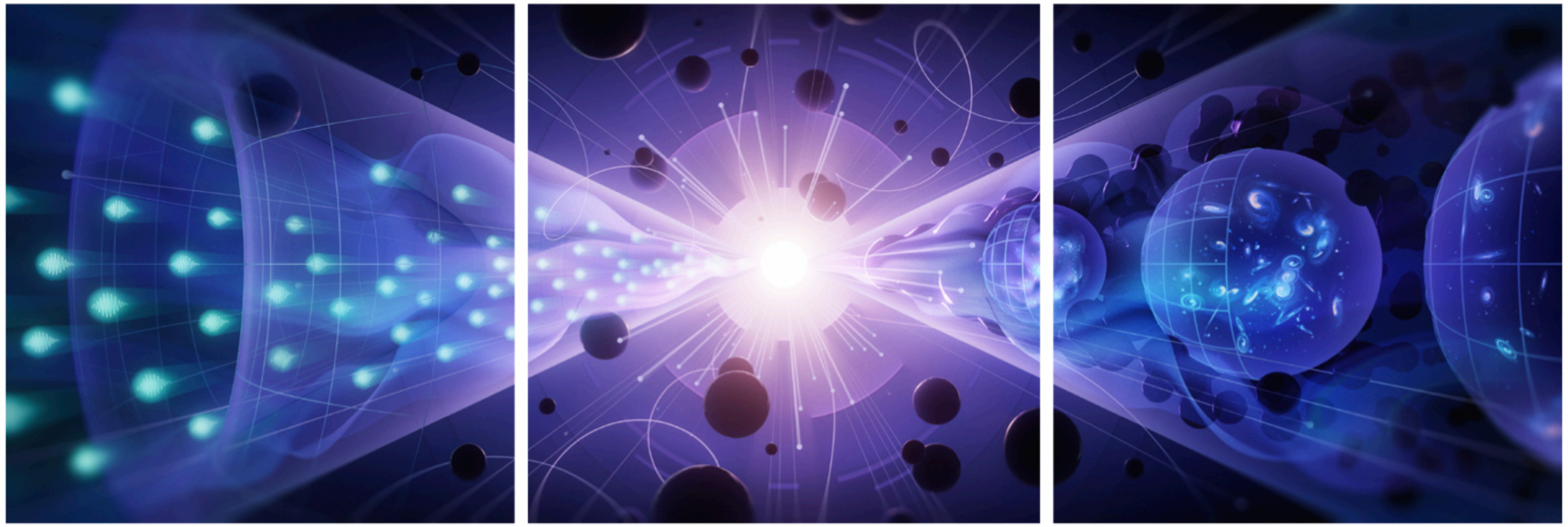
2013

The Particle Physics Project Prioritization Panel (P5) Report



2023

The Particle Physics Project Prioritization Panel (P5) Report



Decipher the Quantum Realm

- Elucidate the Mysteries of Neutrinos
- Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

- Search for Direct Evidence of New Particles
- Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

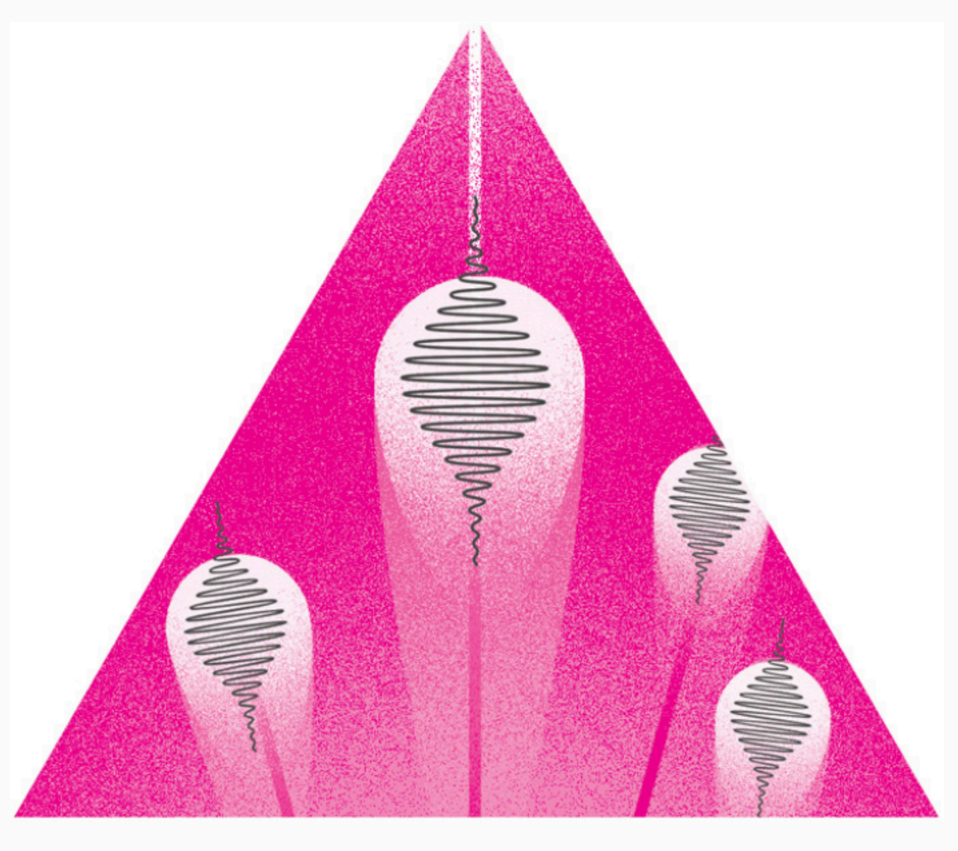
- Determine the Nature of Dark Matter
- Understand What Drives Cosmic Evolution

Roadmap of neutrino physics

2023 P5 Report

Neutrino oscillation

Normal or Inverted hierarchy
CPV phase
Octant



Nature of neutrino

Absolute neutrino masses
Dirac or Majorana nature
Lepton number violation
Majorana CPV phase

Beyond standard neutrino

Non-unitarity
Light sterile neutrino
Non-standard neutrino interactions
Portal to dark sector

Jiang-Hao Yu (ITP-CAS)

Roadmap of neutrino physics

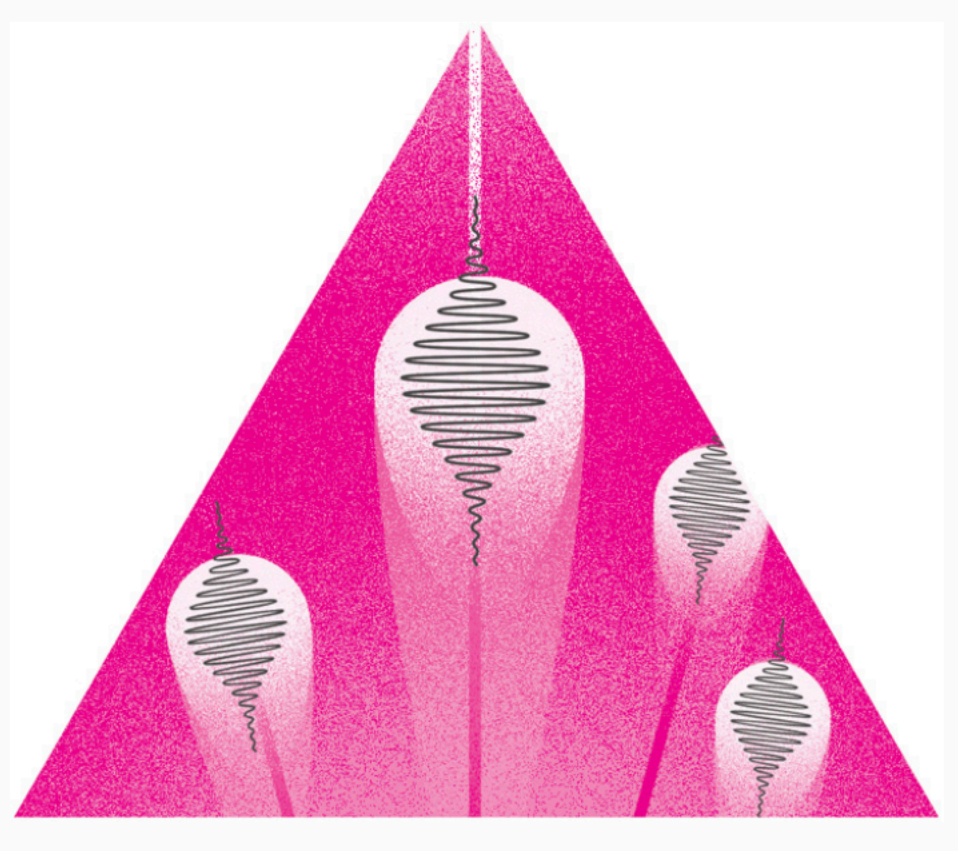
2023 P5 Report

Neutrino oscillation

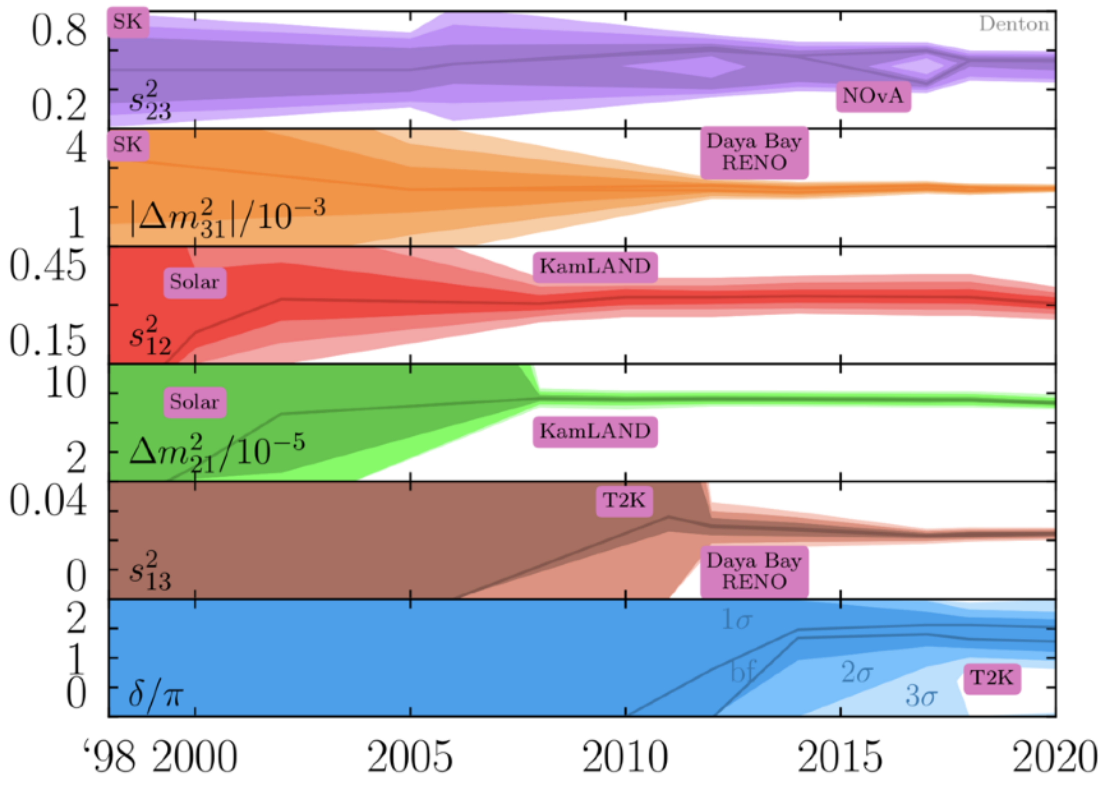
Normal or Inverted hierarchy

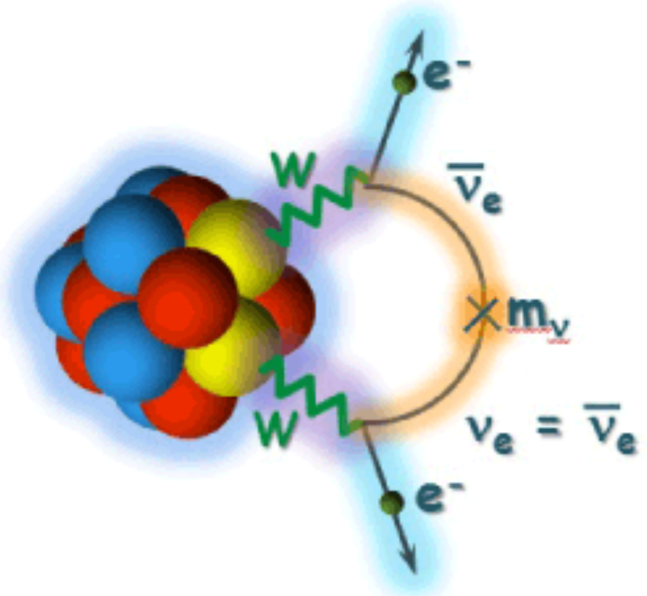
CPV phase

Octant



Precision neutrino measurements





Nature of neutrino

Absolute neutrino masses

Dirac or Majorana nature

Lepton number violation

Majorana CPV phase

Neutrinoless double beta decay

Beyond standard neutrino

Non-unitarity

Light sterile neutrino

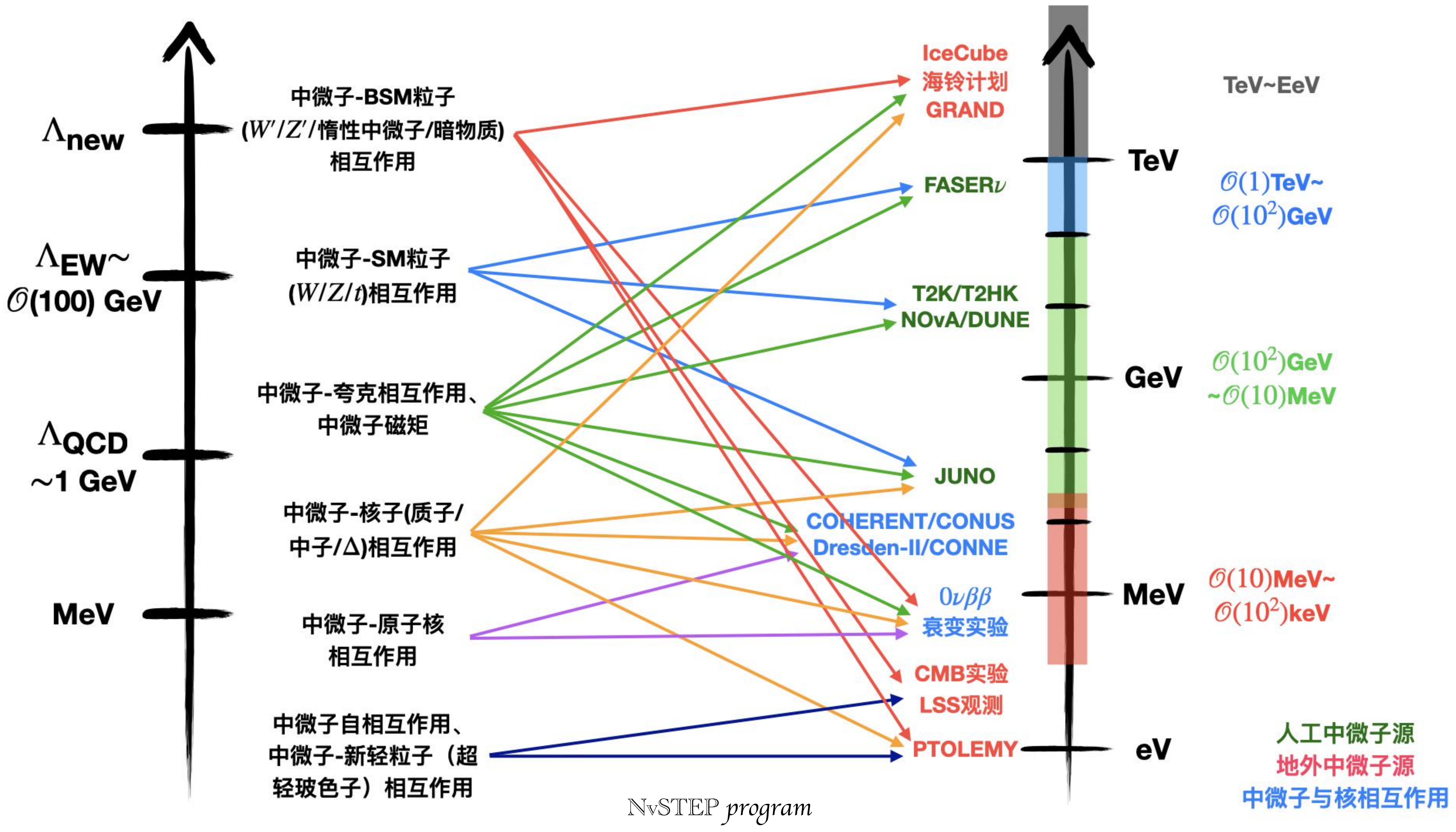
Non-standard neutrino interactions

Portal to dark sector

Probe at different scales

Neutrino at different scales

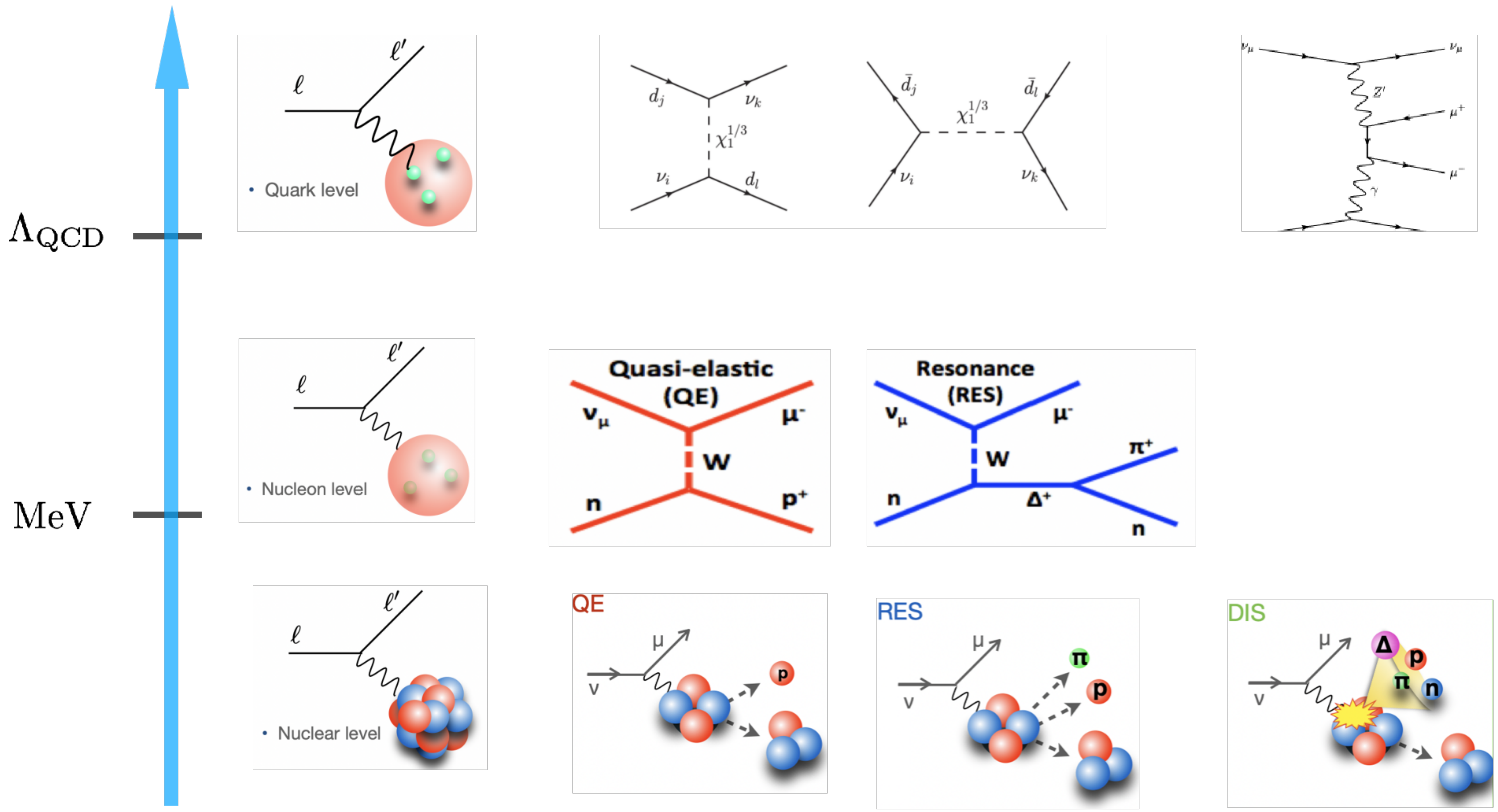
All of these involve in neutrino interactions at different scales



Jiang-Hao Yu (ITP-CAS)

Neutrino at hadronic and nuclear scales

Neutrino at quark level is well understood, but complicated at hadronic and nuclear levels

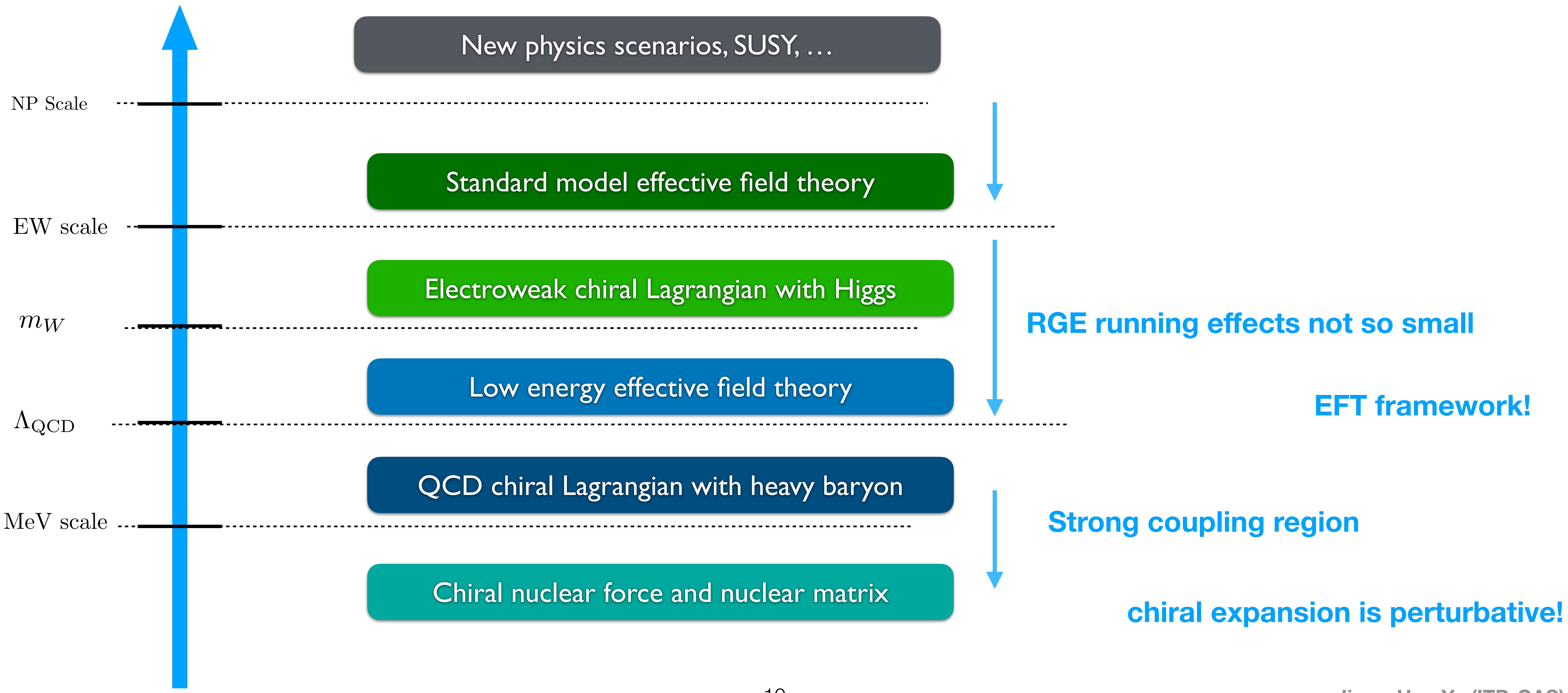


EFTs at quark level: SMEFT, LEFT

EFTs at low energy scales?

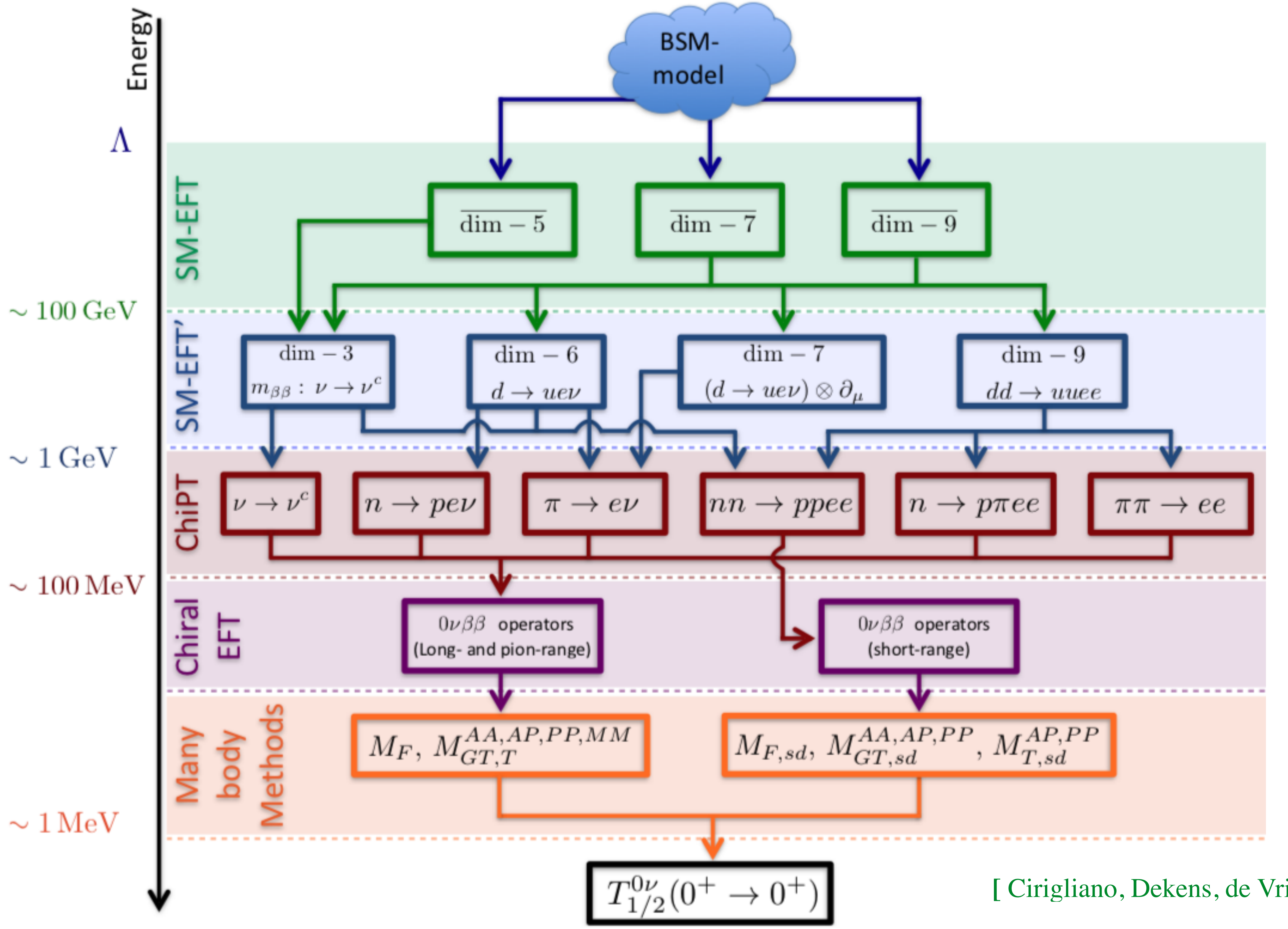
Tower of Effective Field Theories

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



Jiang-Hao Yu (ITP-CAS)

Neutrinoless double beta decay (0vbb)



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

Chiral Lagrangian for Nν at Hadronic scale

[Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2404.15047]

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

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

[Gang Li, Chuan-Qiang Song, **J.H.Yu**, in preparation]

QCD at quark and hadronic scales

Perturbative QCD vs non-perturbative QCD

Symmetry

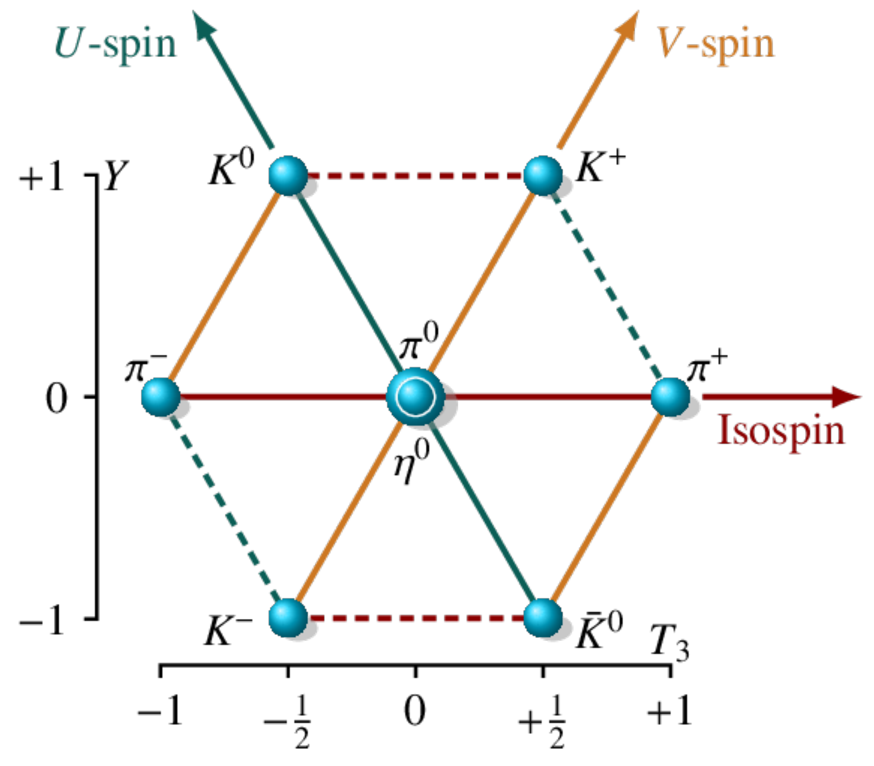
SU(3) x SU(3)

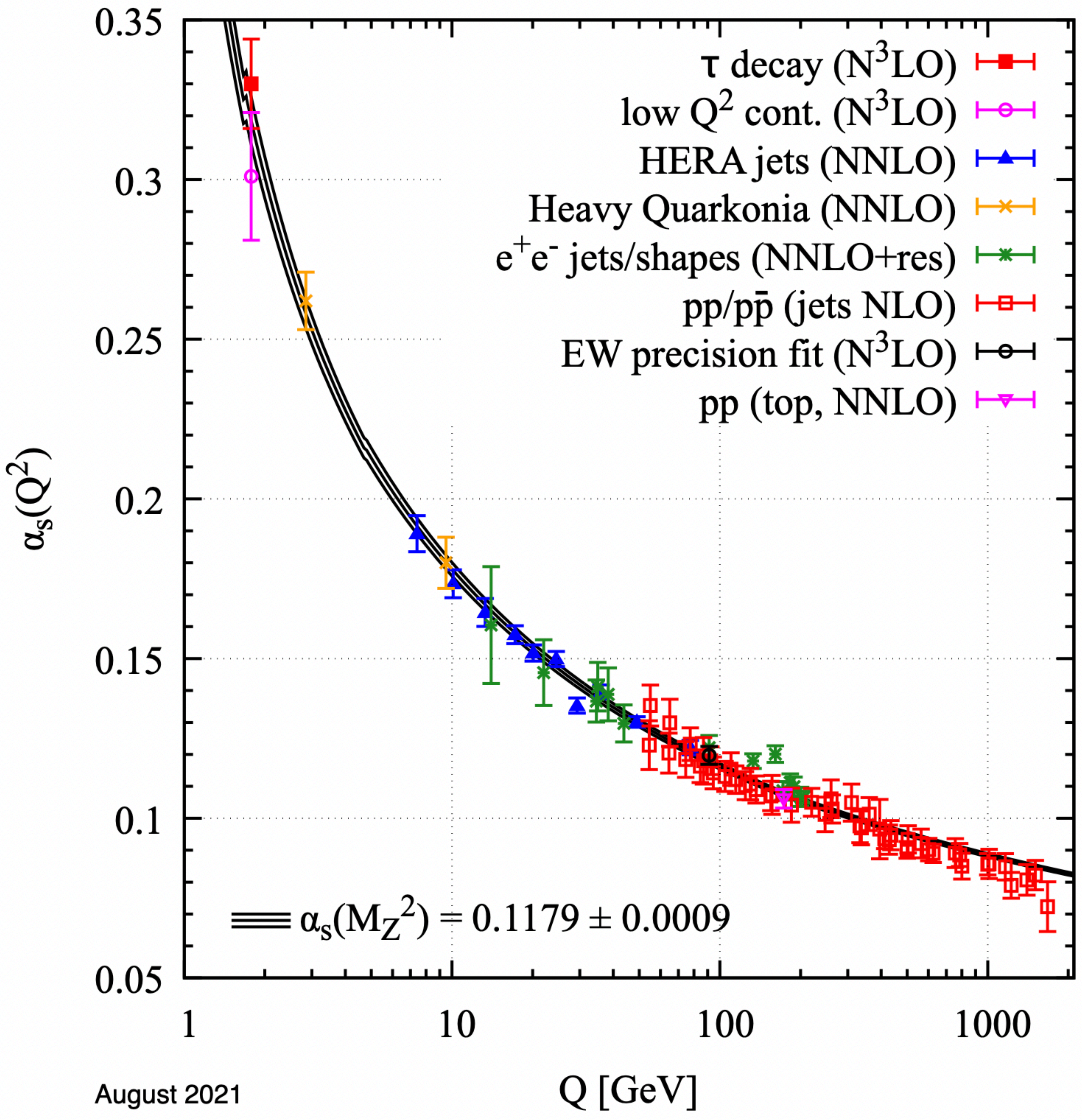
$$q_L \equiv \begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix} \mapsto L\, q_L \equiv \exp\left(-i\epsilon_L^a \frac{\lambda^a}{2}\right) q_L$$

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

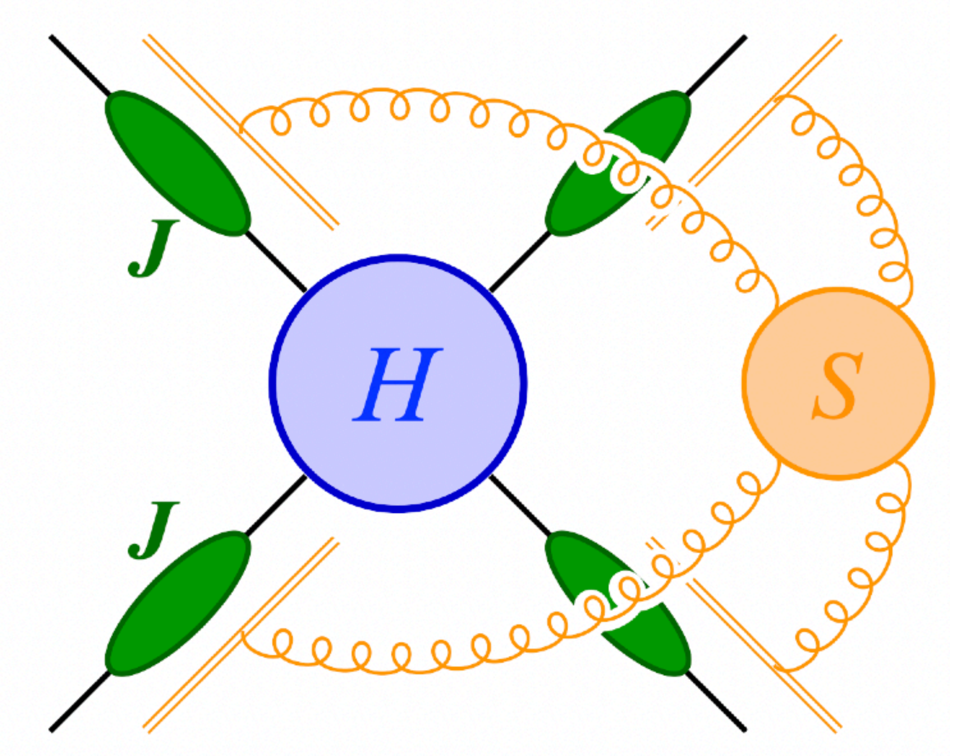
$$\langle 0 | \bar{q}_R q_L | 0 \rangle \neq 0$$

SU(3) x SU(3)/SU(3)





Factorization



gluon gluon scattering

Chiral Lagrangian

Effective Lagrangian for Pion and nucleon with power counting rules

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

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

$$\overline{N}(i\gamma^\mu D_\mu - M + \frac{g_A}{2}\gamma^5\gamma^\mu u_\mu)N$$

Power counting: Derivative expansion

How to implement electroweak physics at hadronic scales?

External source method

$$\mathcal{L} = \mathcal{L}^0_{\rm QCD} + \bar{q}\gamma^\mu[\nu_\mu + \gamma_5 a_\mu]q - \bar{q}[s - i\gamma_5 p]q$$

$$\nu^\mu \to \bar{e}\gamma^\mu e\,, \quad a^\mu \to \bar{e}\gamma^5\gamma^\mu e\,, \quad s \to \bar{e}e\,, \quad p \to \bar{e}\gamma^5 e$$

$\Lambda_{\rm QCD}$

$$\langle u_\mu u^\mu\rangle\langle\Sigma_+\rangle \qquad \langle f_+{}^{\mu\nu}[u_\mu, u_\nu]\rangle \qquad \langle u^\mu[D_\mu f_{+\nu\lambda}, f_-{}^{\nu\lambda}]\rangle \qquad \langle D_\mu f_+{}^{\mu\nu}[u_\nu, \Sigma_-]\rangle$$

Higher dim quark operators

Quark level EFT (LEFT) has been constructed up to dimension 9

$(\bar{q}\overleftrightarrow{\partial}^\mu q)(\bar{e}\gamma_\mu e)$ $\quad$ $(\bar{q}\overleftrightarrow{\partial}^\mu \gamma^\nu q)(\bar{e}\overleftrightarrow{\partial}_\mu \gamma_\nu e)$

$(\bar{q}\gamma^\mu\gamma^5 q)(\bar{q}\gamma^\nu q)(\bar{e}\sigma_{\mu\nu}e)$ $\quad$ $(\bar{q}\gamma^\mu\gamma^5 q)(\bar{e}\sigma^{\nu\rho}e)(\bar{e}\sigma_{\mu\nu}\partial_\rho e)$

[Li, Ren, Xiao, **J.H.Yu**, Zheng, 2012.09188]

Introduce new external sources, such as tensor, and higher sources?

External sources replaced by lepton currents

[Liao, Ma, Wang, 1909.06272]

Need many SU(3) x SU(3) LECs

$SU(3)_L \times SU(3)_R$
$(\mathbf{6},\bar{\mathbf{6}}) \oplus (\mathbf{6},\mathbf{3}) \oplus (\bar{\mathbf{3}},\bar{\mathbf{6}}) \oplus (\bar{\mathbf{3}},\mathbf{3})$
$(\bar{\mathbf{6}},\mathbf{6}) \oplus (\mathbf{3},\mathbf{6}) \oplus (\bar{\mathbf{6}},\bar{\mathbf{3}}) \oplus (\mathbf{3},\bar{\mathbf{3}})$
$(\mathbf{27},\mathbf{1}) \oplus (\mathbf{10},\mathbf{1}) \oplus (\overline{\mathbf{10}},\mathbf{1}) \oplus 4\times(\mathbf{8},\mathbf{1}) \oplus 2\times(\mathbf{1},\mathbf{1})$
$(\mathbf{1},\mathbf{27}) \oplus (\mathbf{1},\mathbf{10}) \oplus (\mathbf{1},\overline{\mathbf{10}}) \oplus 4\times(\mathbf{1},\mathbf{8}) \oplus 2\times(\mathbf{1},\mathbf{1})$
$(\mathbf{8},\mathbf{8}) \oplus (\mathbf{1},\mathbf{8}) \oplus (\mathbf{8},\mathbf{1}) \oplus (\mathbf{1},\mathbf{1})$
$(\mathbf{15},\bar{\mathbf{3}}) \oplus (\bar{\mathbf{6}},\bar{\mathbf{3}}) \oplus (\bar{\mathbf{3}},\bar{\mathbf{3}}) \oplus (\mathbf{3},\bar{\mathbf{3}})$
$(\overline{\mathbf{15}},\mathbf{3}) \oplus (\mathbf{6},\mathbf{3}) \oplus (\bar{\mathbf{3}},\mathbf{3}) \oplus (\mathbf{3},\mathbf{3})$
$(\mathbf{3},\overline{\mathbf{15}}) \oplus (\mathbf{3},\mathbf{6}) \oplus (\mathbf{3},\bar{\mathbf{3}}) \oplus (\mathbf{3},\mathbf{3})$
$(\bar{\mathbf{3}},\mathbf{15}) \oplus (\bar{\mathbf{3}},\bar{\mathbf{6}}) \oplus (\bar{\mathbf{3}},\bar{\mathbf{3}}) \oplus (\bar{\mathbf{3}},\mathbf{3})$

Notation	Quark operator	chiral irrep	Hadronic operator
$\mathcal{O}_{udus}^{LLLL,S/P}$ (✓)	$(\overline{u_L}\gamma^\mu d_L)[\overline{u_L}\gamma_\mu s_L](j/j_5)$	$\mathbf{27}_L \times \mathbf{1}_R$	$\frac{5}{12}g_{27\times 1}F_0^4(\Sigma i\partial_\mu\Sigma^\dagger)_2^1(\Sigma i\partial^\mu\Sigma^\dagger)_3^1$
$\mathcal{O}_{udus}^{RRRR,S/P}$ (P)	$(\overline{u_R}\gamma^\mu d_R)[\overline{u_R}\gamma_\mu s_R](j/j_5)$	$\mathbf{1}_L \times \mathbf{27}_R$	$\frac{5}{12}g_{1\times 27}F_0^4(\Sigma^\dagger i\partial_\mu\Sigma)_2^1(\Sigma^\dagger i\partial^\mu\Sigma)_3^1$
$\mathcal{O}_{udus}^{LRLR,S/P}$ (✓)	$(\overline{u_L}d_R)[\overline{u_L}s_R](j/j_5)$	$\bar{\mathbf{6}}_L \times \mathbf{6}_R$	$-g^a_{\bar{6}\times 6}\frac{F_0^4}{4}(\Sigma^\dagger)_2^1(\Sigma^\dagger)_3^1$
$\tilde{\mathcal{O}}_{udus}^{LRLR,S/P}$ (✓)	$(\overline{u_L}d_R][\overline{u_L}s_R)(j/j_5)$	$\bar{\mathbf{6}}_L \times \mathbf{6}_R$	$-g^b_{\bar{6}\times 6}\frac{F_0^4}{4}(\Sigma^\dagger)_2^1(\Sigma^\dagger)_3^1$
$\mathcal{O}_{udus}^{RLRL,S/P}$ (P)	$(\overline{u_R}d_L)[\overline{u_R}s_L](j/j_5)$	$\mathbf{6}_L \times \bar{\mathbf{6}}_R$	$-g^a_{6\times\bar{6}}\frac{F_0^4}{4}(\Sigma)_2^1(\Sigma)_3^1$
$\tilde{\mathcal{O}}_{udus}^{RLRL,S/P}$ (P)	$(\overline{u_R}d_L][\overline{u_R}s_L)(j/j_5)$	$\mathbf{6}_L \times \bar{\mathbf{6}}_R$	$-g^b_{6\times\bar{6}}\frac{F_0^4}{4}(\Sigma)_2^1(\Sigma)_3^1$
$\mathcal{O}_{udus}^{LRLL,A}$ (✓)	$(\overline{u_L}d_R)[\overline{u_L}\gamma^\mu s_L]j_{\mu 5}$	$\overline{\mathbf{15}}_L \times \mathbf{3}_R$	$-g^a_{\overline{15}\times 3}\frac{F_0^4}{4}(\Sigma i\partial_\mu\Sigma^\dagger)_3^1(\Sigma^\dagger)_2^1$
$\tilde{\mathcal{O}}_{udus}^{LRLL,A}$ (✓)	$(\overline{u_L}d_R][\overline{u_L}\gamma^\mu s_L)j_{\mu 5}$	$\overline{\mathbf{15}}_L \times \mathbf{3}_R$	$-g^b_{\overline{15}\times 3}\frac{F_0^4}{4}(\Sigma i\partial_\mu\Sigma^\dagger)_3^1(\Sigma^\dagger)_2^1$
$\mathcal{O}_{usud}^{LRLL,A}$ (✓)	$(\overline{u_L}s_R)[\overline{u_L}\gamma^\mu d_L]j_{\mu 5}$	$\overline{\mathbf{15}}_L \times \mathbf{3}_R$	$-g^c_{\overline{15}\times 3}\frac{F_0^4}{4}(\Sigma i\partial_\mu\Sigma^\dagger)_2^1(\Sigma^\dagger)_3^1$
$\tilde{\mathcal{O}}_{usud}^{LRLL,A}$ (✓)	$(\overline{u_L}s_R][\overline{u_L}\gamma^\mu d_L)j_{\mu 5}$	$\overline{\mathbf{15}}_L \times \mathbf{3}_R$	$-g^d_{\overline{15}\times 3}\frac{F_0^4}{4}(\Sigma i\partial_\mu\Sigma^\dagger)_2^1(\Sigma^\dagger)_3^1$
$\mathcal{O}_{udus}^{RLRR,A}$ (P)	$(\overline{u_R}d_L)[\overline{u_R}\gamma^\mu s_R]j_{\mu 5}$	$\mathbf{3}_L \times \overline{\mathbf{15}}_R$	$-g^a_{3\times\overline{15}}\frac{F_0^4}{4}(\Sigma^\dagger i\partial_\mu\Sigma)_3^1(\Sigma)_2^1$
$\tilde{\mathcal{O}}_{udus}^{RLRR,A}$ (P)	$(\overline{u_R}d_L][\overline{u_R}\gamma^\mu s_R)j_{\mu 5}$	$\mathbf{3}_L \times \overline{\mathbf{15}}_R$	$-g^b_{3\times\overline{15}}\frac{F_0^4}{4}(\Sigma^\dagger i\partial_\mu\Sigma)_3^1(\Sigma)_2^1$
$\mathcal{O}_{usud}^{RLRR,A}$ (P)	$(\overline{u_R}s_L)[\overline{u_R}\gamma^\mu d_R]j_{\mu 5}$	$\mathbf{3}_L \times \overline{\mathbf{15}}_R$	$-g^c_{3\times\overline{15}}\frac{F_0^4}{4}(\Sigma^\dagger i\partial_\mu\Sigma)_2^1(\Sigma)_3^1$
$\tilde{\mathcal{O}}_{usud}^{RLRR,A}$ (P)	$(\overline{u_R}s_L][\overline{u_R}\gamma^\mu d_R)j_{\mu 5}$	$\mathbf{3}_L \times \overline{\mathbf{15}}_R$	$-g^d_{3\times\overline{15}}\frac{F_0^4}{4}(\Sigma^\dagger i\partial_\mu\Sigma)_2^1(\Sigma)_3^1$
$\mathcal{O}_{udus+}^{LRRR,A}$ (✓)	$\frac{1}{2}\left[(\overline{u_L}d_R)[\overline{u_R}\gamma^\mu s_R]+d\leftrightarrow s\right]j_{\mu 5}$	$\bar{\mathbf{3}}_L \times \mathbf{15}_R$	$g^a_{\bar{3}\times 15}\frac{F_0^4}{4}\left[(\Sigma^\dagger)_2^1(\Sigma^\dagger i\partial_\mu\Sigma)_3^1+(\Sigma^\dagger)_3^1(\Sigma^\dagger i\partial_\mu\Sigma)_2^1\right]$
$\tilde{\mathcal{O}}_{udus+}^{LRRR,A}$ (✓)	$\frac{1}{2}\left[(\overline{u_L}d_R][\overline{u_R}\gamma^\mu s_R)+d\leftrightarrow s\right]j_{\mu 5}$	$\bar{\mathbf{3}}_L \times \mathbf{15}_R$	$g^b_{\bar{3}\times 15}\frac{F_0^4}{4}\left[(\Sigma^\dagger)_2^1(\Sigma^\dagger i\partial_\mu\Sigma)_3^1+(\Sigma^\dagger)_3^1(\Sigma^\dagger i\partial_\mu\Sigma)_2^1\right]$
$\mathcal{O}_{udus-}^{LRRR,A}$ (✓)	$\frac{1}{2}\left[(\overline{u_L}d_R)[\overline{u_R}\gamma^\mu s_R]-d\leftrightarrow s\right]j_{\mu 5}$	$\bar{\mathbf{3}}_L \times \bar{\mathbf{6}}_R$	$g^a_{\bar{3}\times\bar{6}}\frac{F_0^4}{4}\left[(\Sigma^\dagger)_2^1(\Sigma^\dagger i\partial_\mu\Sigma)_3^1-(\Sigma^\dagger)_3^1(\Sigma^\dagger i\partial_\mu\Sigma)_2^1\right]$
$\tilde{\mathcal{O}}_{udus-}^{LRRR,A}$ (✓)	$\frac{1}{2}\left[(\overline{u_L}d_R][\overline{u_R}\gamma^\mu s_R)-d\leftrightarrow s\right]j_{\mu 5}$	$\bar{\mathbf{3}}_L \times \bar{\mathbf{6}}_R$	$g^b_{\bar{3}\times\bar{6}}\frac{F_0^4}{4}\left[(\Sigma^\dagger)_2^1(\Sigma^\dagger i\partial_\mu\Sigma)_3^1-(\Sigma^\dagger)_3^1(\Sigma^\dagger i\partial_\mu\Sigma)_2^1\right]$
$\mathcal{O}_{udus+}^{RLLL,A}$ (P)	$\frac{1}{2}\left[(\overline{u_R}d_L)[\overline{u_L}\gamma^\mu s_L]+d\leftrightarrow s\right]j_{\mu 5}$	$\mathbf{15}_L \times \bar{\mathbf{3}}_R$	$g^a_{15\times\bar{3}}\frac{F_0^4}{4}\left[(\Sigma)_2^1(\Sigma i\partial_\mu\Sigma^\dagger)_3^1+(\Sigma)_3^1(\Sigma i\partial_\mu\Sigma^\dagger)_2^1\right]$
$\tilde{\mathcal{O}}_{udus+}^{RLLL,A}$ (P)	$\frac{1}{2}\left[(\overline{u_R}d_L][\overline{u_L}\gamma^\mu s_L)+d\leftrightarrow s\right]j_{\mu 5}$	$\mathbf{15}_L \times \bar{\mathbf{3}}_R$	$g^b_{15\times\bar{3}}\frac{F_0^4}{4}\left[(\Sigma)_2^1(\Sigma i\partial_\mu\Sigma^\dagger)_3^1+(\Sigma)_3^1(\Sigma i\partial_\mu\Sigma^\dagger)_2^1\right]$
$\mathcal{O}_{udus-}^{RLLL,A}$ (P)	$\frac{1}{2}\left[(\overline{u_R}d_L)[\overline{u_L}\gamma^\mu s_L]-d\leftrightarrow s\right]j_{\mu 5}$	$\bar{\mathbf{6}}_L \times \bar{\mathbf{3}}_R$	$g^a_{\bar{6}\times\bar{3}}\frac{F_0^4}{4}\left[(\Sigma)_2^1(\Sigma i\partial_\mu\Sigma^\dagger)_3^1-(\Sigma)_3^1(\Sigma i\partial_\mu\Sigma^\dagger)_2^1\right]$
$\tilde{\mathcal{O}}_{udus-}^{RLLL,A}$ (P)	$\frac{1}{2}\left[(\overline{u_R}d_L][\overline{u_L}\gamma^\mu s_L)-d\leftrightarrow s\right]j_{\mu 5}$	$\bar{\mathbf{6}}_L \times \bar{\mathbf{3}}_R$	$g^b_{\bar{6}\times\bar{3}}\frac{F_0^4}{4}\left[(\Sigma)_2^1(\Sigma i\partial_\mu\Sigma^\dagger)_3^1-(\Sigma)_3^1(\Sigma i\partial_\mu\Sigma^\dagger)_2^1\right]$
$\mathcal{O}_{udus}^{LRRL,S/P}$ (✓)	$(\overline{u_L}d_R)[\overline{u_R}s_L](j/j_5)$	$\mathbf{8}_L \times \mathbf{8}_R$	$g^a_{8\times 8}\frac{F_0^4}{4}(\Sigma^\dagger)_2^1(\Sigma)_3^1$
$\tilde{\mathcal{O}}_{udus}^{LRRL,S/P}$ (✓)	$(\overline{u_L}d_R][\overline{u_R}s_L)(j/j_5)$	$\mathbf{8}_L \times \mathbf{8}_R$	$g^b_{8\times 8}\frac{F_0^4}{4}(\Sigma^\dagger)_2^1(\Sigma)_3^1$
$\mathcal{O}_{usud}^{LRRL,S/P}$ (P)	$(\overline{u_L}s_R)[\overline{u_R}d_L](j/j_5)$	$\mathbf{8}_L \times \mathbf{8}_R$	$g^c_{8\times 8}\frac{F_0^4}{4}(\Sigma^\dagger)_3^1(\Sigma)_2^1$
$\tilde{\mathcal{O}}_{usud}^{LRRL,S/P}$ (P)	$(\overline{u_L}s_R][\overline{u_R}d_L)(j/j_5)$	$\mathbf{8}_L \times \mathbf{8}_R$	$g^d_{8\times 8}\frac{F_0^4}{4}(\Sigma^\dagger)_3^1(\Sigma)_2^1$

LEFT with spurion

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

Reformulate the quark level LEFT in terms of SU(3)V symmetry

$$(\bar{\mathbf{3}}_L, \mathbf{3}_L) \oplus (\mathbf{3}_R, \bar{\mathbf{3}}_R) \to \mathbf{1}^+ + \mathbf{1}^- + \mathbf{8}^+ + \mathbf{8}^- :$$

$$(\bar{q}_L \Gamma q_L) \oplus (\bar{q}_R \Gamma q_R) = (\bar{q}\Gamma q)_{\mathbf{1}} + (\bar{q}\Gamma\gamma^5 q)_{\mathbf{1}} + (\bar{q}\Gamma q)_{\mathbf{8}} + (\bar{q}\Gamma\gamma^5 q)_{\mathbf{8}}\,;$$

$$[(\bar{\mathbf{3}}_L, \mathbf{3}_R) \oplus (\mathbf{3}_L, \bar{\mathbf{3}}_R)] \otimes [(\bar{\mathbf{3}}_L, \mathbf{3}_R) \oplus (\mathbf{3}_L, \bar{\mathbf{3}}_R)]$$

$$\to (\mathbf{1}^+ + \mathbf{1}^- + \mathbf{8}^+ + \mathbf{8}^-) \otimes (\mathbf{1}^+ + \mathbf{1}^- + \mathbf{8}^+ + \mathbf{8}^-)$$

$$= 2\times\mathbf{1}^+ + 2\times\mathbf{1}^- + 4\times\mathbf{8}^+ + 4\times\mathbf{8}^- + 2\times(\mathbf{8}\times\mathbf{8})^+ + 2\times(\mathbf{8}\times\mathbf{8})^-$$

Introduce single spurion T as flavor octet

$$\mathbf{T}^0 \to span\{\mathbf{t}^5, \mathbf{t}^6, \mathbf{t}^7, \mathbf{t}^8\}$$
$$\mathbf{T}^+ \to span\{\mathbf{t}^2, \mathbf{t}^4\}$$
$$\mathbf{T}^- \to span\{\mathbf{t}^1, \mathbf{t}^3\}\,.$$

Building blocks and SU(3)V, CP transformation

$$\begin{pmatrix} q_L \\ q_R \\ \mathbf{T} \\ e_L \\ e_R \\ \nu_L \\ F_{\mu\nu} \end{pmatrix} \to \begin{pmatrix} Vq_L \\ Vq_R \\ V\mathbf{T}V^\dagger \\ e_L \\ e_R \\ \nu_L \\ F_{\mu\nu} \end{pmatrix}, \quad V \in SU(3)_V$$

$C+P+:$

$$\mathcal{O}_1^{(8)} = F_{\mu\rho}F_\nu^\rho(\bar{q}\mathbf{T}^0\gamma^\mu \overleftrightarrow{\partial}^\nu q) + h.c.\,,$$
$$\mathcal{O}_3^{(8)} = F_{\mu\nu}j_T^{0\mu\nu}(\bar{q}\mathbf{T}^0 q) + h.c.\,,$$
$$\mathcal{O}_5^{(8)} = F_{\mu\nu}j_T^{+\mu\nu}(\bar{q}\mathbf{T}^0 q) + h.c.\,,$$
$$\mathcal{O}_7^{(8)} = (\partial^2 j_S^0)(\bar{q}q)\,,$$
$$\mathcal{O}_9^{(8)} = j_{TL}^{0\mu\nu}(\bar{q}\mathbf{T}^0\gamma_\mu \overleftrightarrow{\partial}_\nu q) + h.c.\,,$$
$$\mathcal{O}_{11}^{(8)} = j_{TL}^{+\mu\nu}(\bar{q}\mathbf{T}^-\gamma_\mu \overleftrightarrow{\partial}_\nu q) + h.c.\,,$$

$C+P-:$

$$\mathcal{O}_{12}^{(8)} = F_{\mu\nu}j_V^{0\mu}(\bar{q}\mathbf{T}^0\gamma^5\gamma^\nu q) + h.c.\,,$$
$$\mathcal{O}_{14}^{(8)} = F_{\mu\nu}j_V^{+\mu}(\bar{q}\mathbf{T}^-\gamma^5\gamma^\nu q) + h.c.\,,$$
$$\mathcal{O}_{16}^{(8)} = F_{\mu\nu}j_T^{0\mu\nu}(\bar{q}i\gamma^5 q) + h.c.\,,$$
$$\mathcal{O}_{18}^{(8)} = (\partial^2 j_S^0)(\bar{q}\mathbf{T}^0 i\gamma^5 q) + h.c.\,,$$
$$\mathcal{O}_{20}^{(8)} = (\partial^2 j_S^+)(\bar{q}\mathbf{T}^- i\gamma^5 q) + h.c.\,,$$
$$\mathcal{O}_{22}^{(8)} = (\partial^2 j_V^0)(\bar{q}\gamma^5\gamma_\mu q)\,,$$

$C-P+:$

$$\mathcal{O}_{24}^{(8)} = F_{\mu\nu}j_V^{0\mu}(\bar{q}\mathbf{T}^0\gamma^\nu q) + h.c.\,,$$
$$\mathcal{O}_{26}^{(8)} = F_{\mu\nu}j_V^{+\mu}(\bar{q}\mathbf{T}^-\gamma^\nu q) + h.c.\,,$$
$$\mathcal{O}_{28}^{(8)} = F_{\mu\nu}j_S^0(\bar{q}\sigma^{\mu\nu} q)\,,$$
$$\mathcal{O}_{30}^{(8)} = F_\nu^\rho j_T^{0\mu\nu}(\bar{q}\mathbf{T}^0\sigma_{\mu\rho} q) + h.c.\,,$$
$$\mathcal{O}_{32}^{(8)} = F_\nu^\rho j_T^{+\mu\nu}(\bar{q}\mathbf{T}^-\sigma_{\mu\rho} q) + h.c.\,,$$
$$\mathcal{O}_{34}^{(8)} = (\partial^2 j_V^0)(\bar{q}\gamma_\mu q)\,,$$
$$\mathcal{O}_{36}^{(8)} = j_{VL}^{0\mu}(\bar{q}\mathbf{T}^0 \overleftrightarrow{\partial}_\mu q) + h.c.\,,$$
$$\mathcal{O}_{38}^{(8)} = j_{VL}^{+\mu}(\bar{q}\mathbf{T}^- \overleftrightarrow{\partial}_\mu q) + h.c.\,,$$

$C-P-:$

$$\mathcal{O}_{39}^{(8)} = F_{\mu\rho}F_\nu^\rho(\bar{q}\mathbf{T}^0\gamma^5\gamma^\mu \overleftrightarrow{\partial}^\nu q) + h.c.\,,$$
$$\mathcal{O}_{41}^{(8)} = j_{TL}^{0\mu\nu}(\bar{q}\mathbf{T}^0\gamma^5\gamma_\mu \overleftrightarrow{\partial}_\nu q) + h.c.\,,$$
$$\mathcal{O}_{43}^{(8)} = j_{TL}^{+\mu\nu}(\bar{q}\mathbf{T}^-\gamma^5\gamma_\mu \overleftrightarrow{\partial}_\nu q) + h.c.\,,$$
$$\mathcal{O}_{45}^{(8)} = j_{VL}^{0\mu}(\bar{q}\gamma^5 \overleftrightarrow{\partial}_\mu q)\,,$$

$C+P+:$

$$\mathcal{O}_{47}^{(8)} = (\bar{q}q)\partial^2(\bar{q}q)\,,$$
$$\mathcal{O}_{49}^{(8)} = (\bar{q}\mathbf{T}_1 q)\partial^2(\bar{q}\mathbf{T}_2 q)\,,$$
$$\mathcal{O}_{51}^{(8)} = (\bar{q}i\gamma^5 q)\partial^2(\bar{q}\mathbf{T}^0 i\gamma^5 q)\,,$$
$$\mathcal{O}_{53}^{(8)} = (\bar{q}\gamma^\mu q)\partial^2(\bar{q}\gamma_\mu q)\,,$$
$$\mathcal{O}_{55}^{(8)} = (\bar{q}\mathbf{T}_1\gamma^\mu q)\partial^2(\bar{q}\mathbf{T}_2\gamma_\mu q)\,,$$
$$\mathcal{O}_{57}^{(8)} = (\bar{q}\gamma^5\gamma^\mu q)\partial^2(\bar{q}\mathbf{T}^0\gamma^5\gamma_\mu q)\,,$$
$$\mathcal{O}_{59}^{(8)} = (\bar{q}\overleftrightarrow{\partial}^\mu q)(\bar{q}\overleftrightarrow{\partial}_\mu q)\,,$$
$$\mathcal{O}_{61}^{(8)} = (\bar{q}\mathbf{T}_1\overleftrightarrow{\partial}^\mu q)(\bar{q}\mathbf{T}_2\overleftrightarrow{\partial}_\mu q)\,,$$
$$\mathcal{O}_{63}^{(8)} = (\bar{q}i\gamma^5\overleftrightarrow{\partial}^\mu q)(\bar{q}\mathbf{T}^0 i\gamma^5\overleftrightarrow{\partial}_\mu q)\,,$$
$$\mathcal{O}_{65}^{(8)} = (\bar{q}\gamma^\mu\overleftrightarrow{\partial}^\nu q)(\bar{q}\gamma_\mu\overleftrightarrow{\partial}_\nu q)\,,$$
$$\mathcal{O}_{67}^{(8)} = (\bar{q}\mathbf{T}_1\gamma^\mu\overleftrightarrow{\partial}^\nu q)(\bar{q}\mathbf{T}_2\gamma_\mu\overleftrightarrow{\partial}_\nu q)\,,$$
$$\mathcal{O}_{69}^{(8)} = (\bar{q}\gamma^5\gamma^\mu\overleftrightarrow{\partial}^\nu q)(\bar{q}\mathbf{T}^0\gamma^5\gamma_\mu\overleftrightarrow{\partial}_\nu q)\,,$$

$C+P-:$

$$\mathcal{O}_{71}^{(8)} = (\bar{q}q)\partial^2(\bar{q}i\gamma^5 q)\,,$$
$$\mathcal{O}_{73}^{(8)} = (\bar{q}\mathbf{T}^0 q)\partial^2(\bar{q}i\gamma^5 q)\,,$$
$$\mathcal{O}_{75}^{(8)} = (\bar{q}\mathbf{T}_2 q)\partial^2(\bar{q}\mathbf{T}_1 i\gamma^5 q)\,,$$
$$\mathcal{O}_{77}^{(8)} = (\bar{q}\overleftrightarrow{\partial}^\mu q)(\bar{q}\mathbf{T}^0 i\gamma^5\overleftrightarrow{\partial}_\mu q)\,,$$
$$\mathcal{O}_{79}^{(8)} = (\bar{q}\mathbf{T}_1\overleftrightarrow{\partial}^\mu q)(\bar{q}\mathbf{T}_2 i\gamma^5\overleftrightarrow{\partial}_\mu q)\,,$$

Chiral Lagrangian with spurion

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

External sources

$$\chi = 2B(s+ip)\,,$$
$$f^R_{\mu\nu} = \partial_\mu r_\nu - \partial_\nu r_\mu - i[r_\mu, r_\nu]\,, \quad r_\mu = v_\mu + a_\mu\,,$$
$$f^L_{\mu\nu} = \partial_\mu l_\nu - \partial_\nu l_\mu - i[l_\mu, l_\nu]\,, \quad l_\mu = v_\mu - a_\mu\,,$$

u-parameterization	U-parameterization
Bosonic building blocks	
$u_\mu \to h u_\mu h^{-1}$	$V_\mu \to g_R V_\mu g_R^{-1}$
$f_{+\mu\nu} \to h f_{+\mu\nu} h^{-1}$	$f^L_{\mu\nu} \to g_L f^L_{\mu\nu} g_L^{-1}$
$f_{-\mu\nu} \to h f_{-\mu\nu} h^{-1}$	$f^R_{\mu\nu} \to g_R f^R_{\mu\nu} g_R^{-1}$
$\Sigma_+ \to h \Sigma_+ h^{-1}$	$\chi \to g_L \chi g_R^{-1}$
$\Sigma_- \to h \Sigma_- h^{-1}$	$\chi^\dagger \to g_R \chi^\dagger g_L^{-1}$

Spurion technique

$$\Sigma_\pm = u^\dagger \mathbf{T} u^\dagger \pm u \mathbf{T}^\dagger u\,,$$
$$Q_\pm = u^\dagger \mathbf{T} u \pm u \mathbf{T}^\dagger u^\dagger\,.$$

$$\begin{pmatrix} u_\mu \\ \Sigma_- \\ \Sigma_+ \\ Q_- \\ Q_+ \\ B \\ e_R \\ e_L \\ \nu_L \\ F_{\mu\nu} \end{pmatrix} \to \begin{pmatrix} V u_\mu V^\dagger \\ V\Sigma_- V^\dagger \\ V\Sigma_+ V^\dagger \\ VQ_- V^\dagger \\ VQ_+ V^\dagger \\ VBV^\dagger \\ e_R \\ e_L \\ \nu_L \\ F_{\mu\nu} \end{pmatrix}, \quad V \in SU(3)_V$$

Lepton currents

Pure meson p8 chiral Lagrangian with external sources

[Song, Sun, **J.H.Yu**, 2404.15047]

Nucleon-meson p5 chiral Lagrangian with external sources

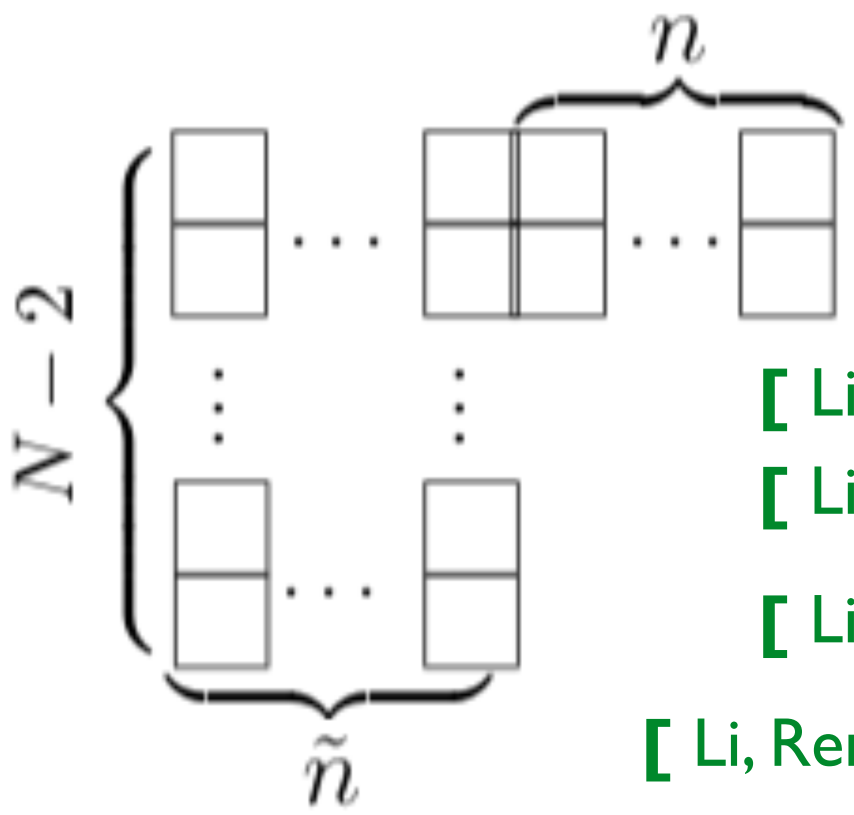
[Li, Sun, Tang, **J.H.Yu**, 2404.14152]

Easy to match: T and lepton currents

Systematic construction

Several techniques are utilized

On-shell construction



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

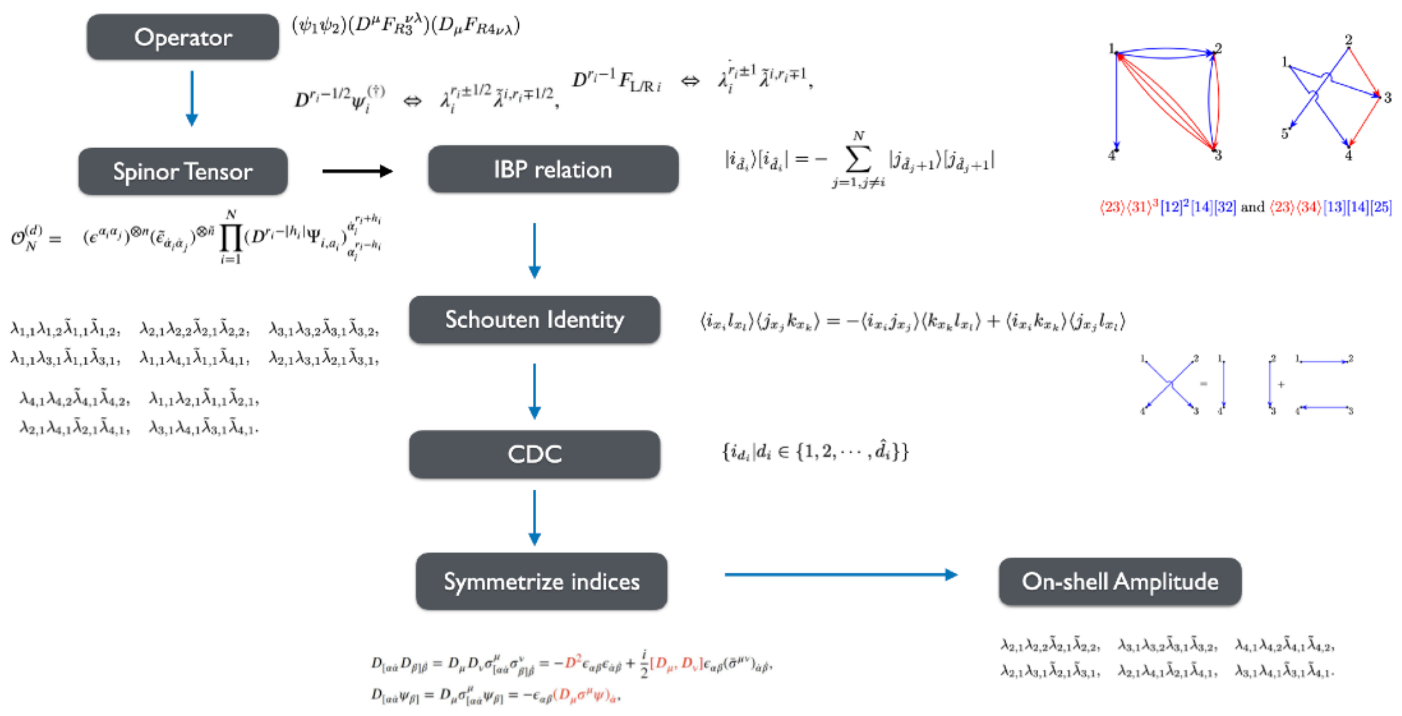
[Li, Ren, Xiao, **Yu**, Zheng, 2012.09188]

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

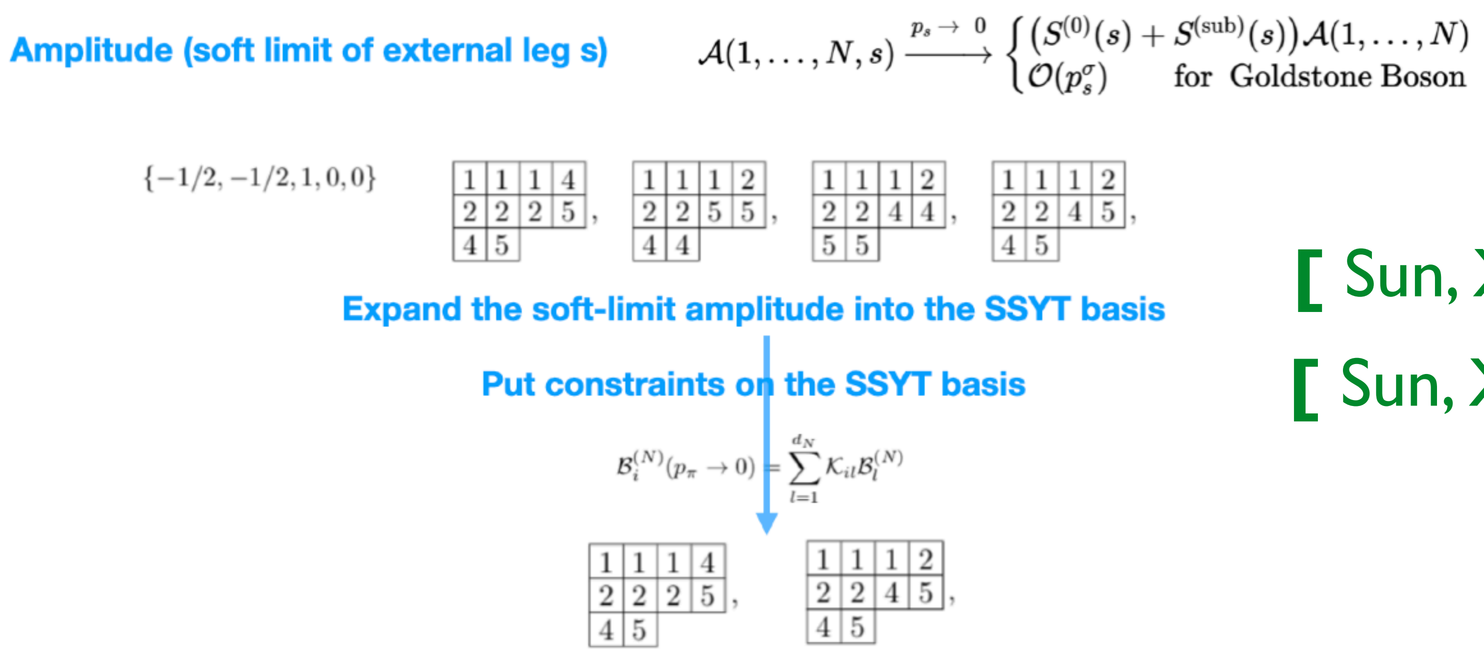
[Li, Ren, Shu, Xiao, **Yu**, Zheng, 2005.00008]

Off-shell construction

[Zhe, Ren, **Yu**, 2211.01420]



Adler zero for Pion

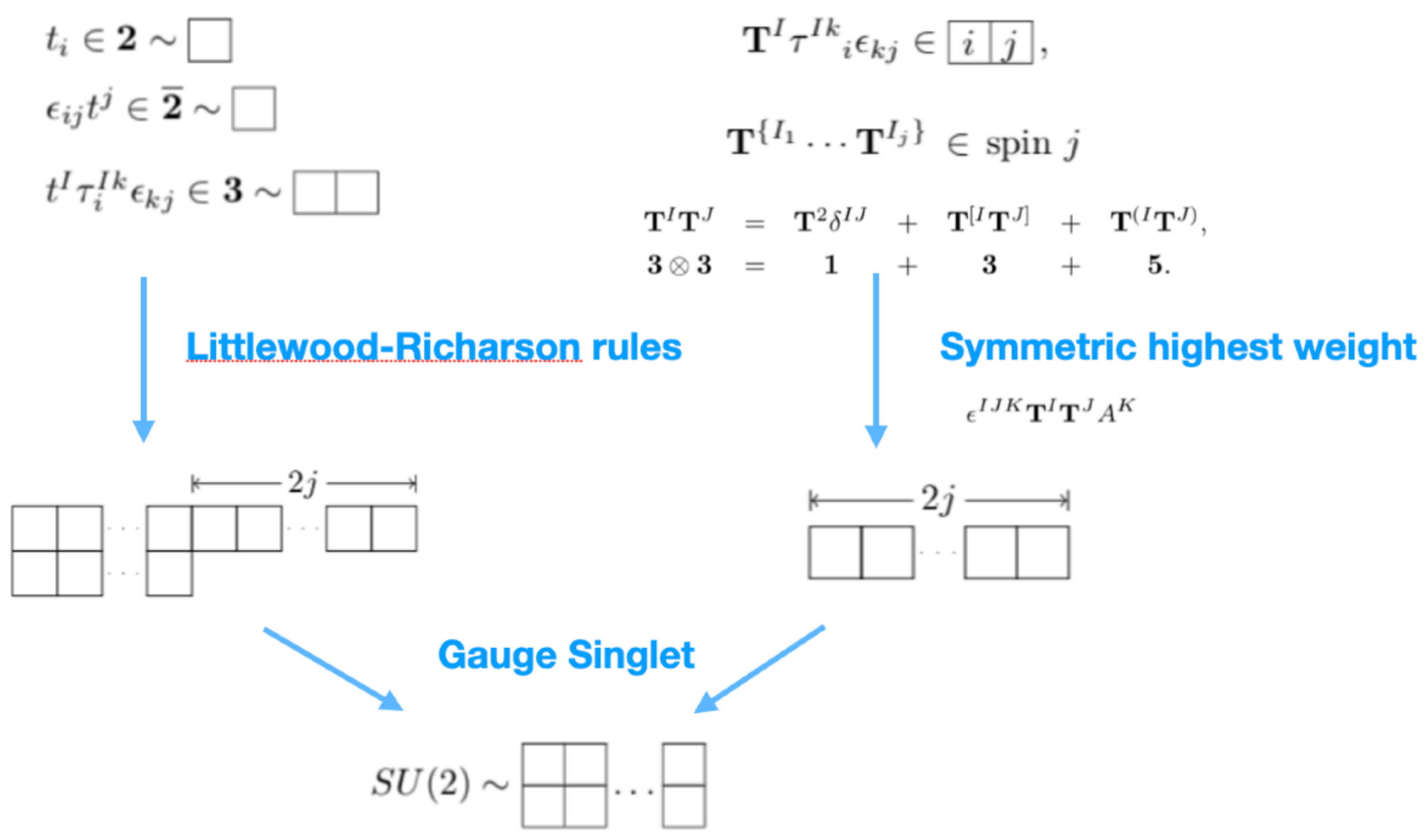


[Sun, Xiao, **Yu**, 2210.14939]

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

Spurion technique

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



Matching: external source vs spurion

$$\mathcal{L} = \mathcal{L}^0_{\text{QCD}} + \bar{q}\gamma^\mu[\nu_\mu + \gamma_5 a_\mu]q - \bar{q}[s - i\gamma_5 p]q$$

$$\nu^\mu \to \bar{e}\gamma^\mu e\,, \quad a^\mu \to \bar{e}\gamma^5\gamma^\mu e\,, \quad s \to \bar{e}e\,, \quad p \to \bar{e}\gamma^5 e$$

Λ_{QCD}

$$\langle u_\mu u^\mu\rangle\langle\Sigma_+\rangle \qquad \langle f_+{}^{\mu\nu}[u_\mu, u_\nu]\rangle \qquad \langle u^\mu[D_\mu f_{+\nu\lambda}, f_-{}^{\nu\lambda}]\rangle \qquad \langle D_\mu f_+{}^{\mu\nu}[u_\nu, \Sigma_-]\rangle$$

Find same lepton structure, and same T spurion, and matching

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

$$(\bar{q}\overleftrightarrow{\partial}^\mu \mathbf{T} q)(\bar{e}_L\gamma_\mu e_L)\,,$$
$$(\bar{q}\overleftrightarrow{\partial}^\mu \mathbf{T} q)(\bar{e}_R\gamma_\mu e_R)\,,$$
$$(\bar{q}\gamma^5\overleftrightarrow{\partial}^\mu \mathbf{T} q)(\bar{e}_L\gamma_\mu e_L)\,,$$
$$(\bar{q}\gamma^5\overleftrightarrow{\partial}^\mu \mathbf{T} q)(\bar{e}_R\gamma_\mu e_R)\,.$$

$$\frac{\Lambda^4_{\text{EW}}}{16\pi^2}\left[\frac{\Lambda_\chi}{\Lambda_{\text{EW}}}\right]^{N_p+2N_F+\frac{3}{2}N_\psi}\left[\frac{\partial}{\Lambda_\chi}\right]^{N_p}\left[\frac{F}{\Lambda_\chi^2}\right]^{N_F}\left[\frac{\psi}{\sqrt{\Lambda_\chi}f}\right]^{N_\psi}$$

Λ_{QCD}

$$\left[\frac{\Lambda_\chi}{\Lambda_{\text{EW}}}\right]^{\mathcal{D}}\left(f^2\Lambda_\chi^2\left[\frac{\partial}{\Lambda_\chi}\right]^{N_p}\left[\frac{F}{\Lambda_\chi^2}\right]^{N_F}\left[\frac{\psi}{\sqrt{\Lambda_\chi}f}\right]^{N_\psi}\right)$$

$$\langle\Sigma_+[u_\nu, D^\nu u_\mu]\rangle(\bar{e}_L\gamma^\mu e_L)\,, \quad \langle[\Sigma_-, u_\mu]u^\nu u_\nu\rangle(\bar{e}_L\gamma^\mu e_L)$$

$$\langle\bar{B}\gamma^\mu\Sigma_+ B\rangle(\bar{e}_L\gamma_\mu e_L)\,, \quad \langle\bar{B}\gamma^\mu B\Sigma_+\rangle(\bar{e}_L\gamma_\mu e_L)\,, \quad \langle\bar{B}\gamma^\mu B\rangle\langle\Sigma_+\rangle(\bar{e}_L\gamma_\mu e_L)\,.$$

Reformulate using SU(3) x SU(3)

$$\bar{q}_L \to \xi^\dagger\,, q_L \to \xi\,, \bar{q}_R \to \xi\,, q_R \to \xi^\dagger\,, \xi = \exp\left(\frac{i\Pi}{\sqrt{2}f}\right)\,,$$
$$\bar{q}_L \to D^\mu\xi^\dagger\,, q_L \to D^\mu\xi\,, \bar{q}_R \to D^\mu\xi\,, q_R \to D^\mu\xi^\dagger\,,$$

[Gang Li, Chuan-Qiang Song, **J.H.Yu**, in preparation]

Chiral Nuclear Force for Nν at Nuclear scale

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

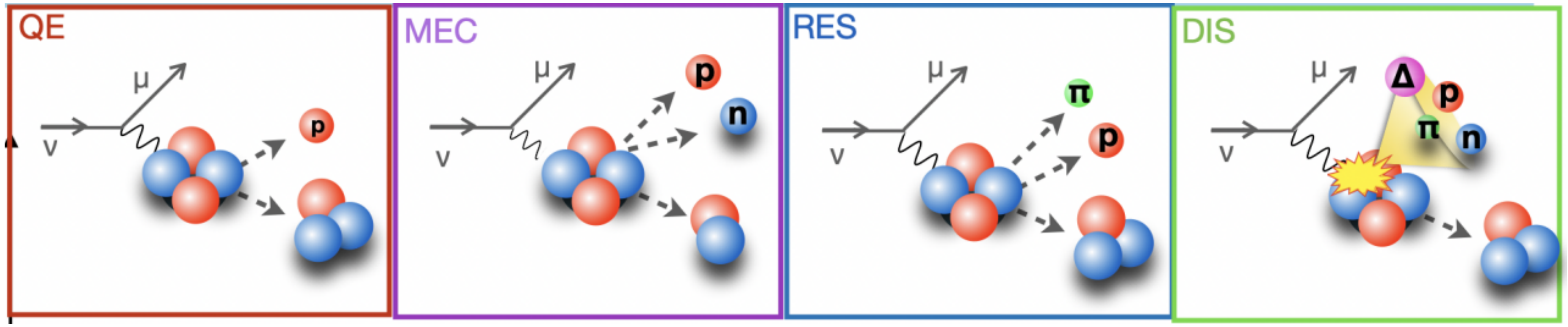
[Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, in préparation]

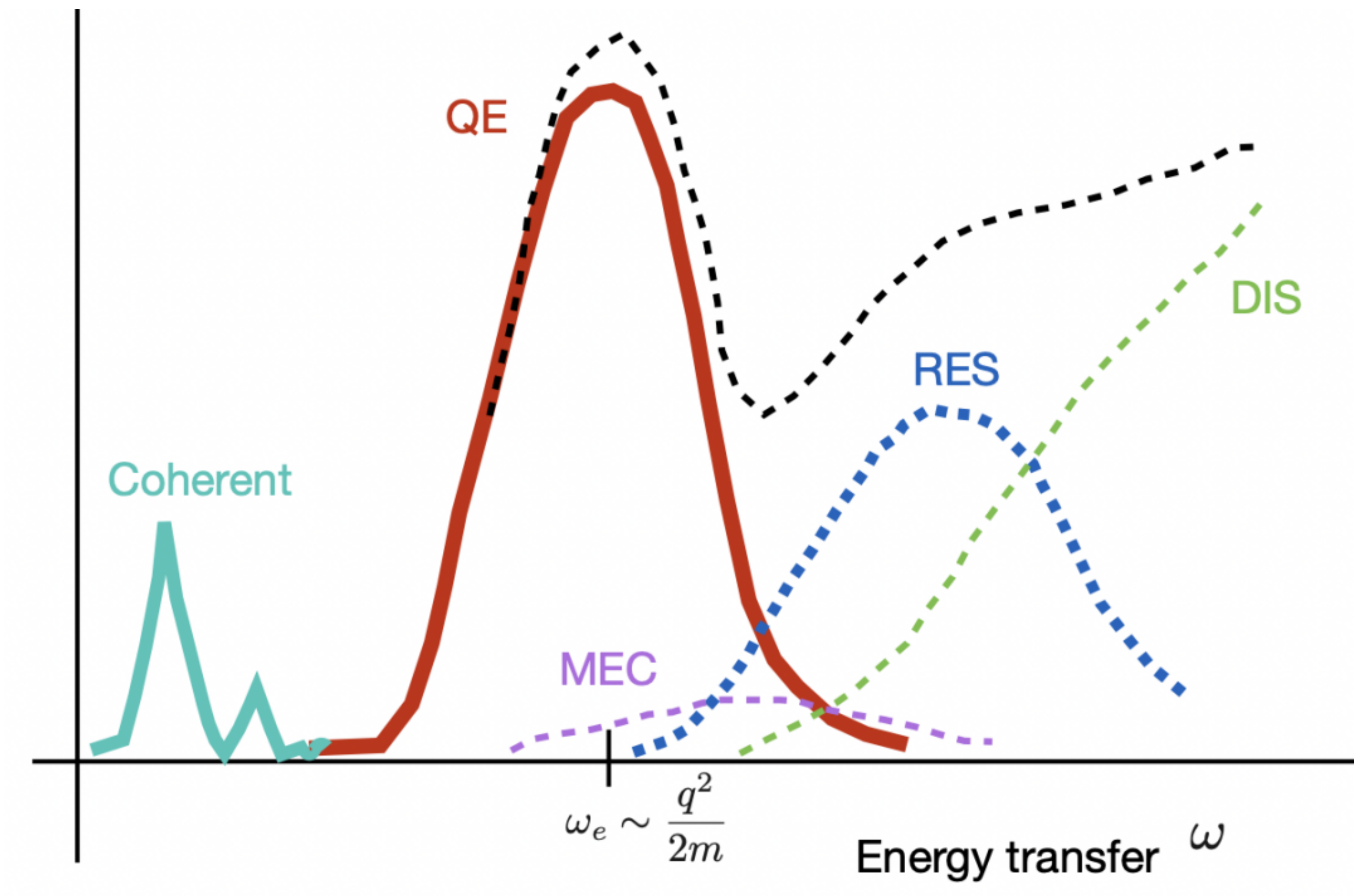
[Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, in préparation]

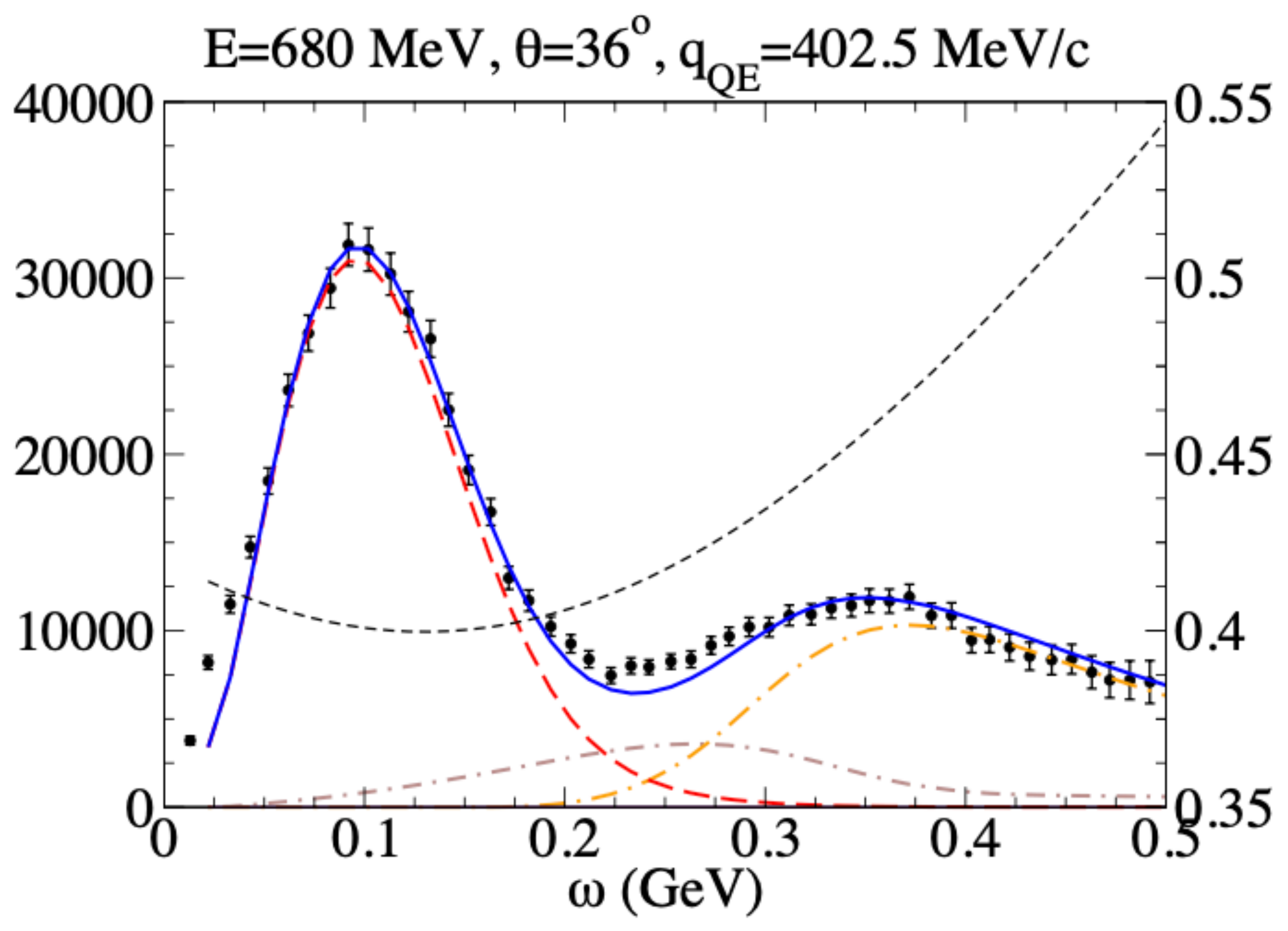
[Chuan-Qiang Song, Hao Sun, **J.H.Yu**, In preparation]

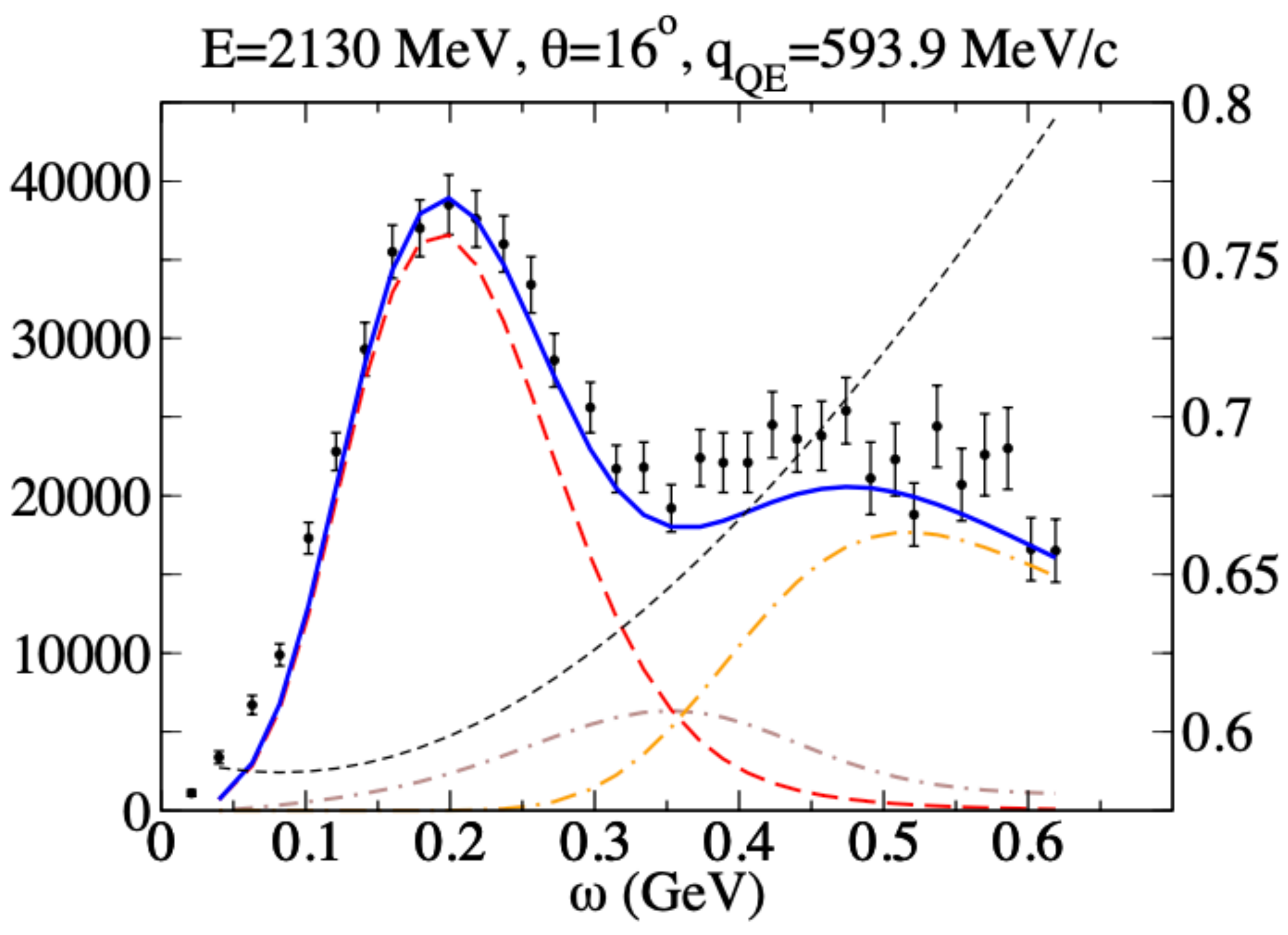
Electroweak processes at nuclear scale

Many body nuclear effects could be important



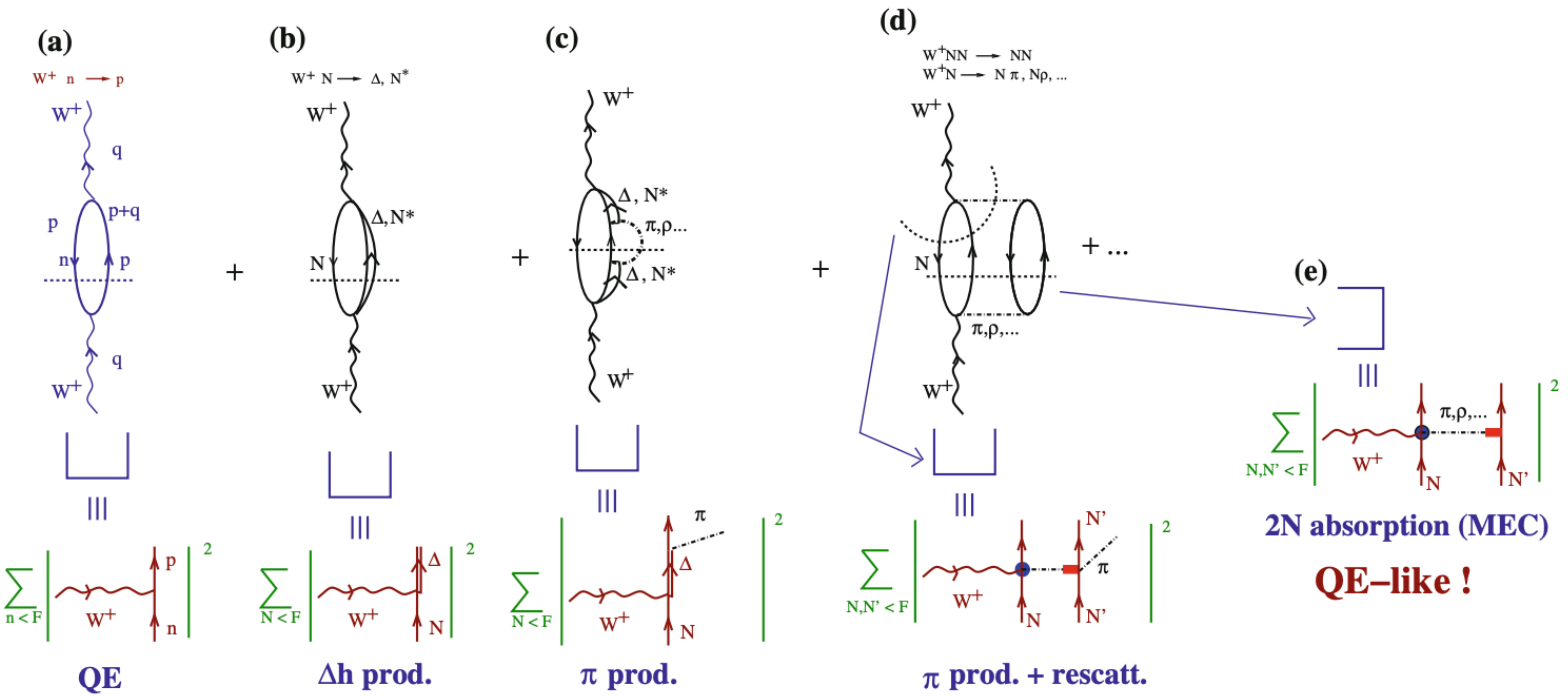






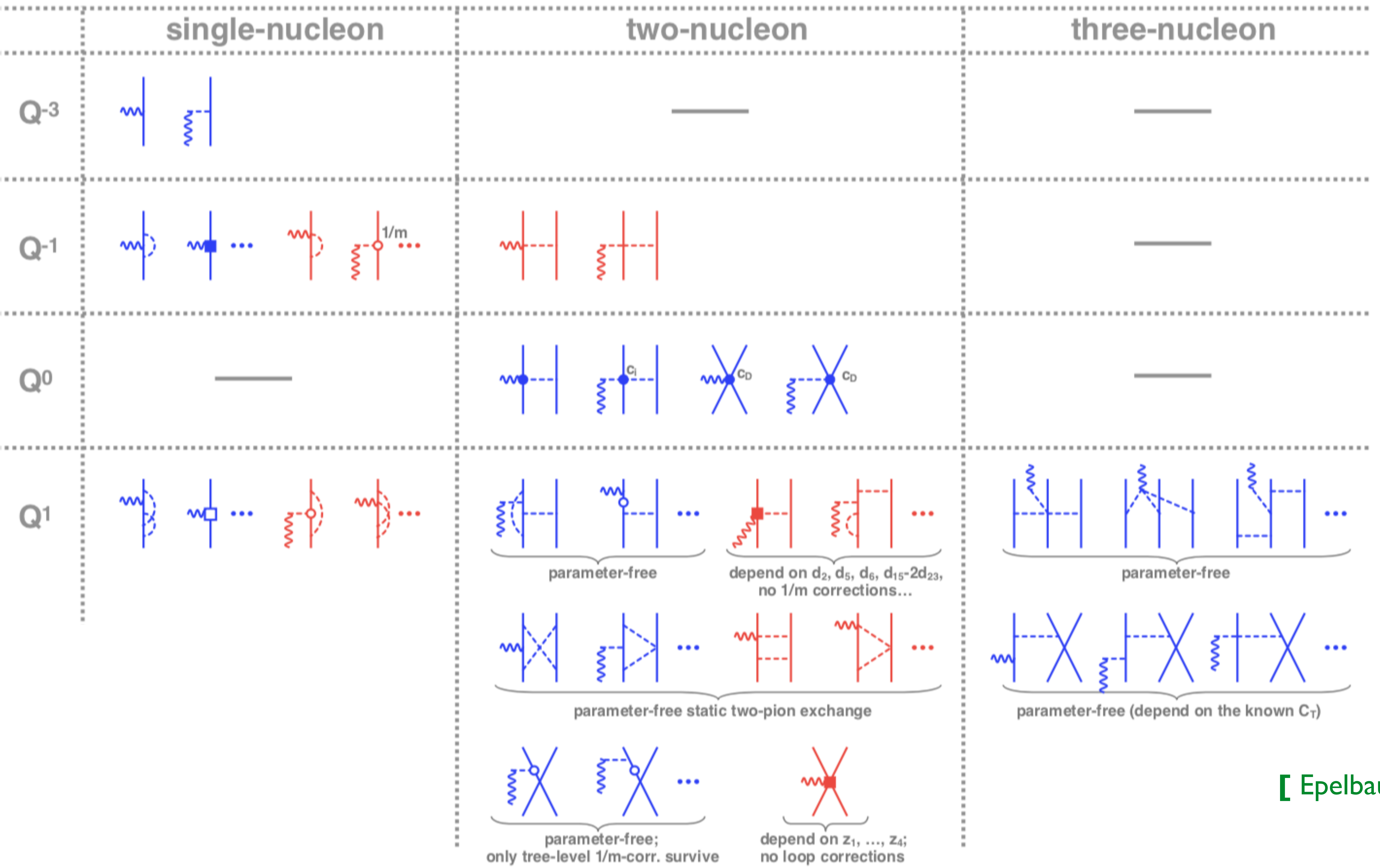
Electroweak processes at nuclear scale

Many body nuclear effects in nuclear physics and particle physics community



Electroweak processes at nuclear scale

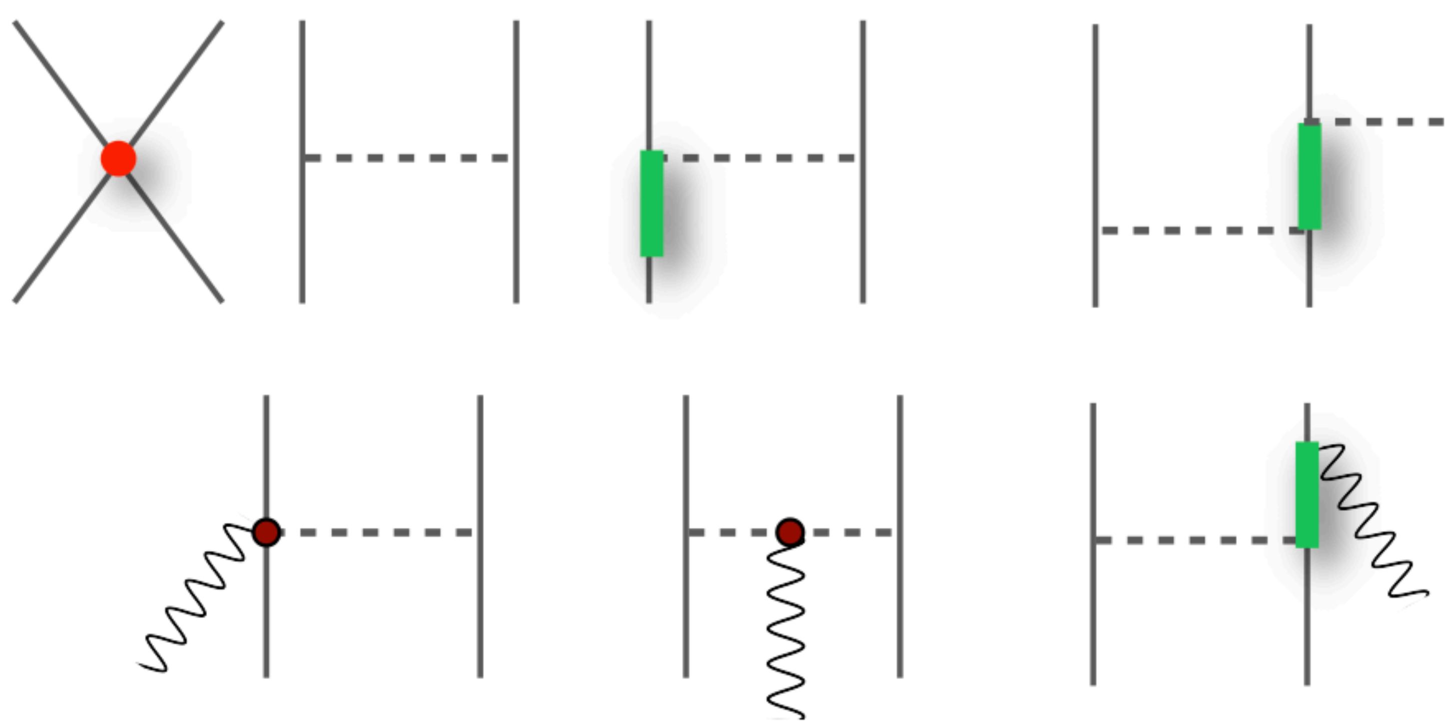
Nuclear potential with external currents



[Epelbaum, 2018]

Ab initio nuclear structure

Effective Hamiltonians and consistent currents

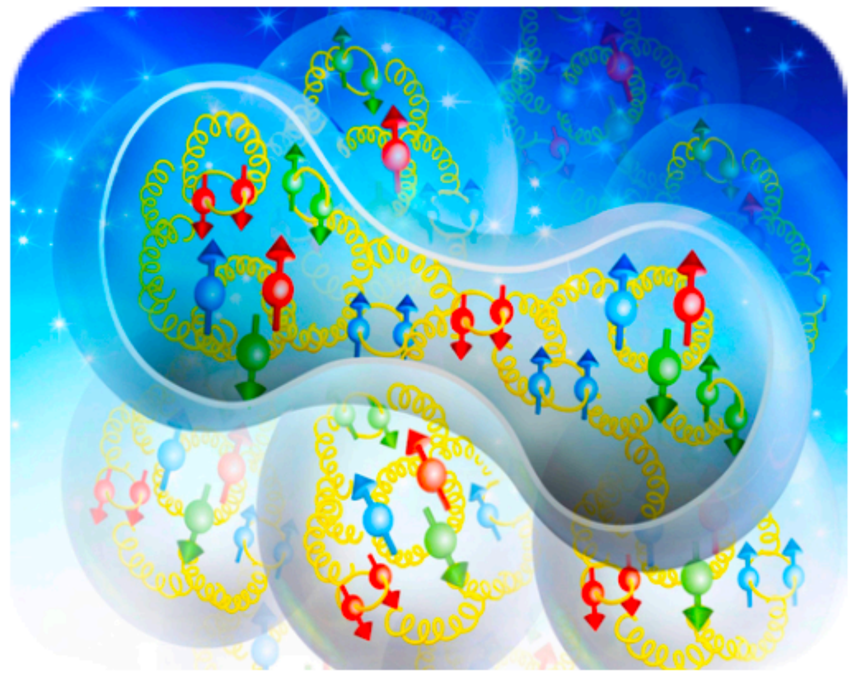


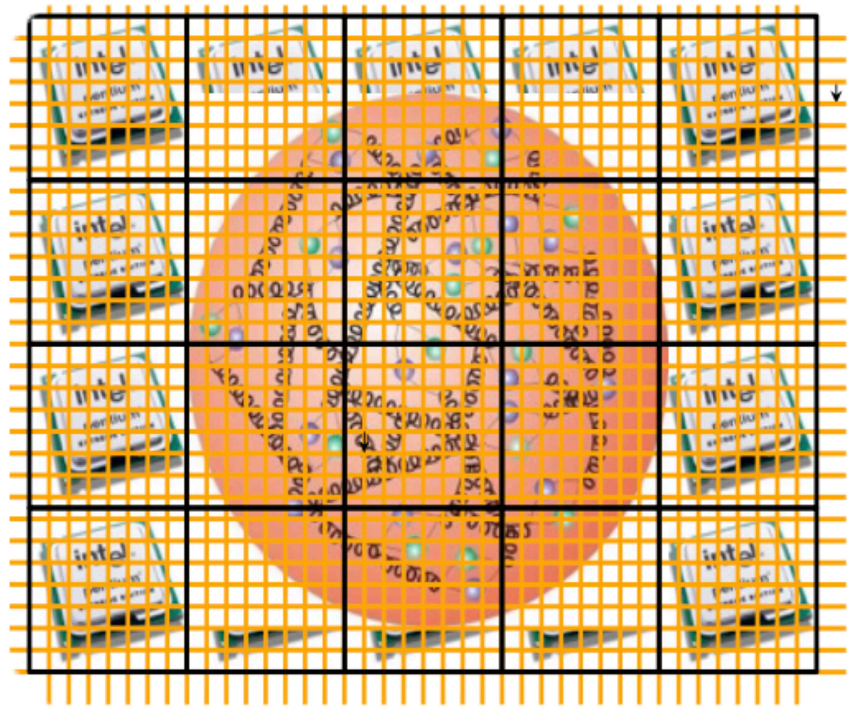
Accurate nuclear many-body methods

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

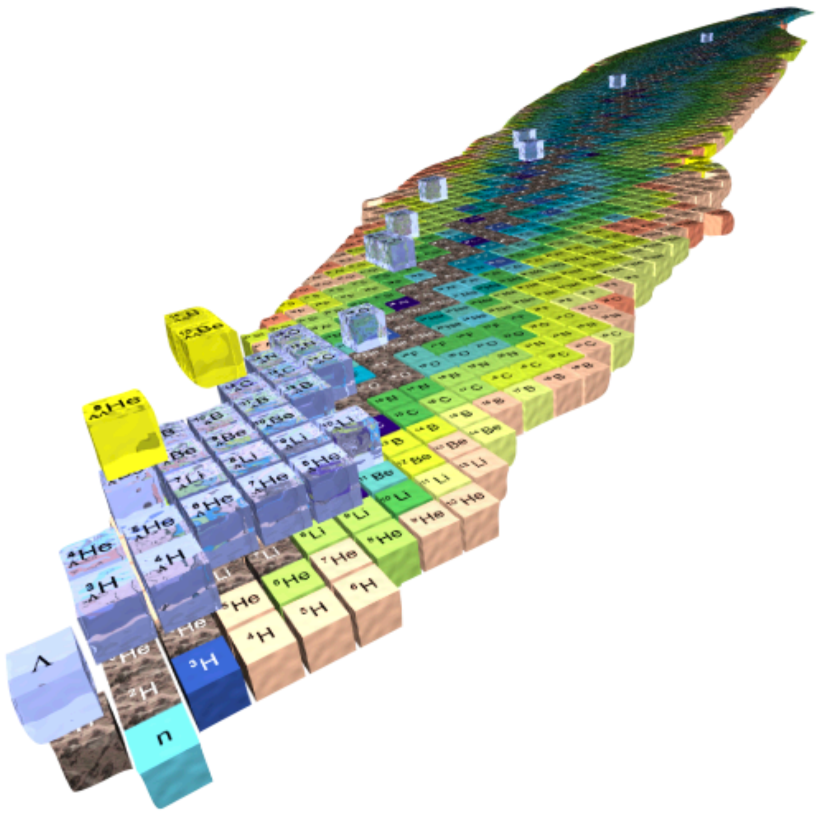
$$J_{mn} = \langle\Psi_m|J|\Psi_n\rangle$$

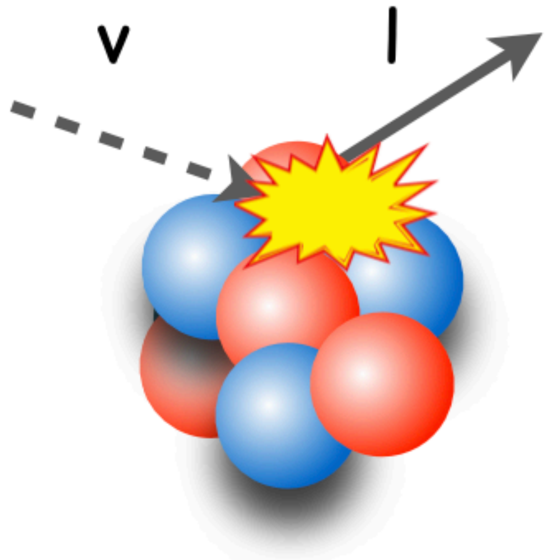
Quantum Chromodynamcs



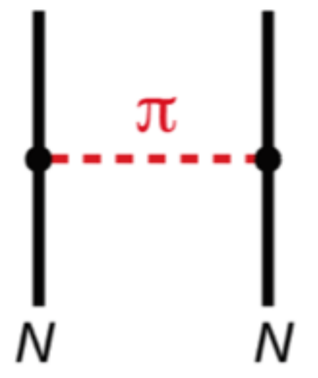


Nuclei and electroweak interactions

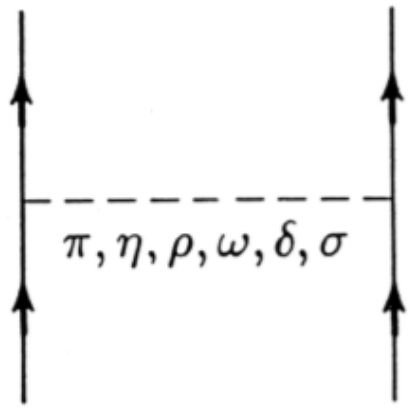




Nuclear force

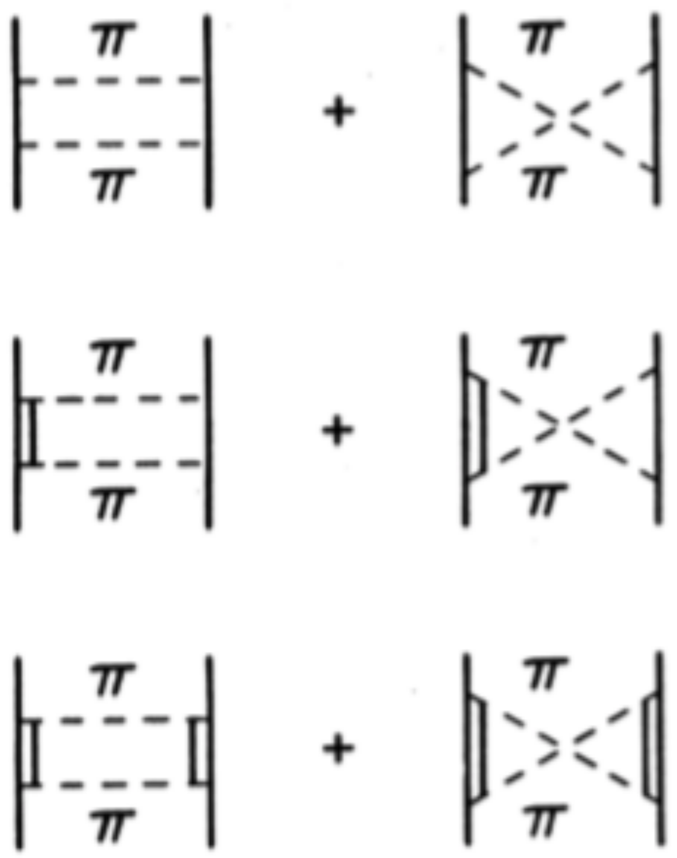


Yukawa Pion Theory
1935



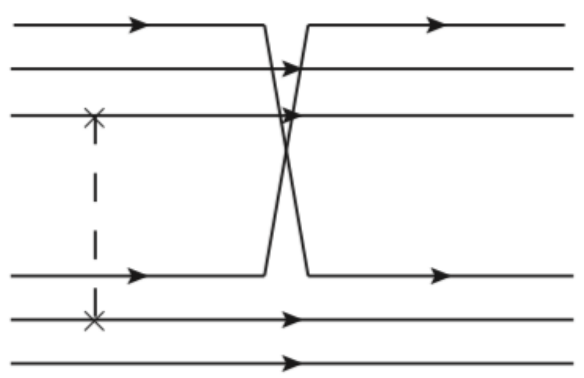
One-Boson Exchange Model
1936 - 1960

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

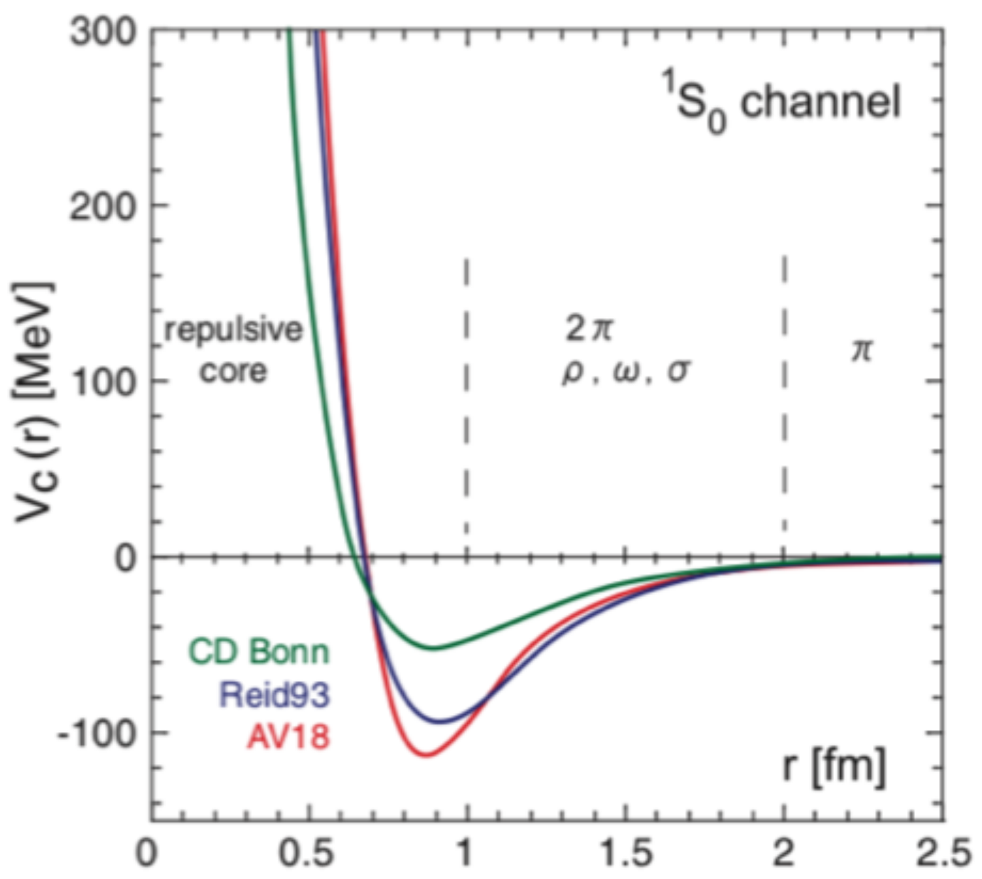


Two-Pion Exchange
1950 - 1980

Taketani, Nakamura Sasaki, Bruckner, Watson, …

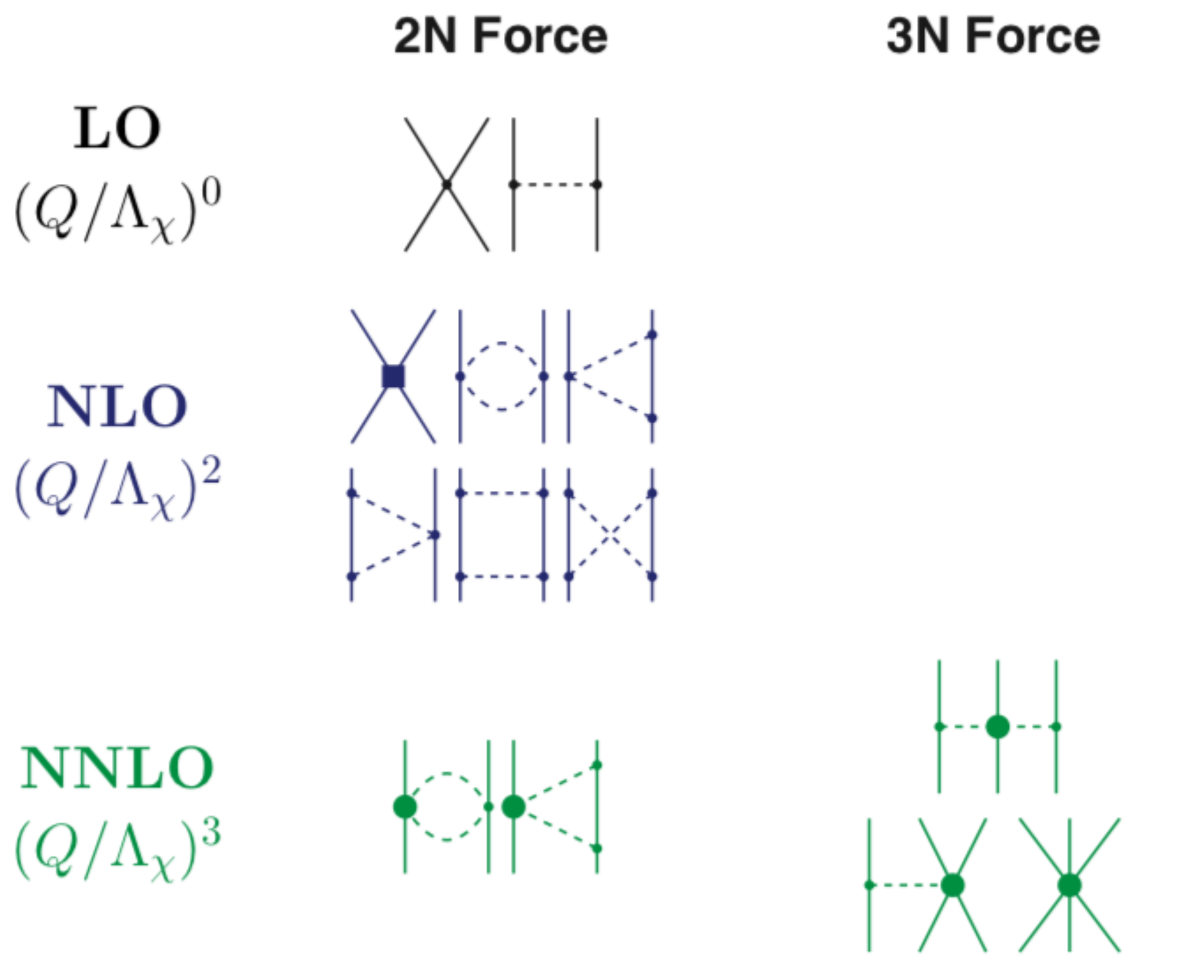


N-N from quark/chiral-bag model
1970 - 1980

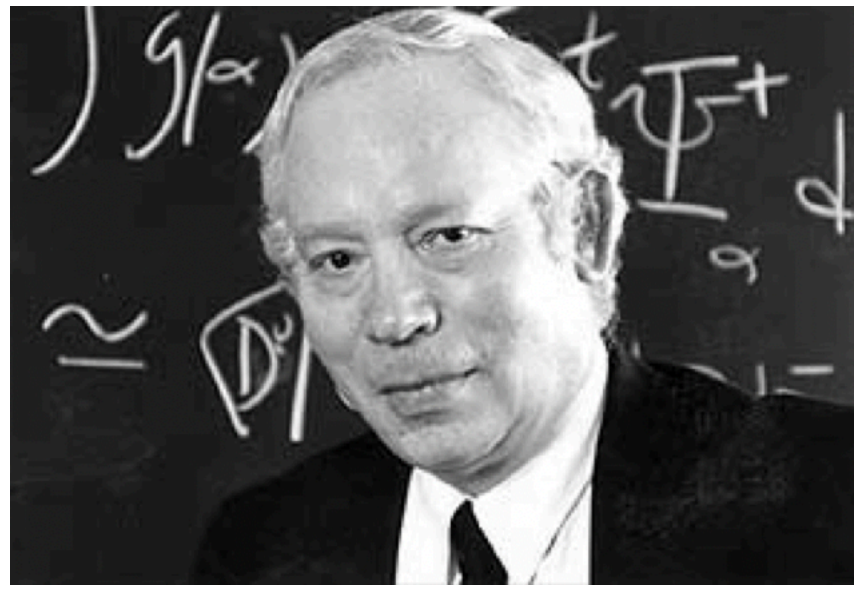


High precision potential
1990 -

AV18, CD Bonn, Nijm, Reid93 …



Weinberg nuclear chiral EFT
1990 -



Chiral nuclear force

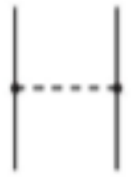
Meson Exchange Model

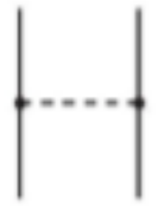
$$\mathcal{L}_\sigma = \overline{N_L}\, i\not{D}\, N_L + \overline{N_R}\, i\not{D}\, N_R - g\overline{N_R}\, \Sigma\, N_L - g\overline{N_L}\, \Sigma^\dagger\, N_R$$

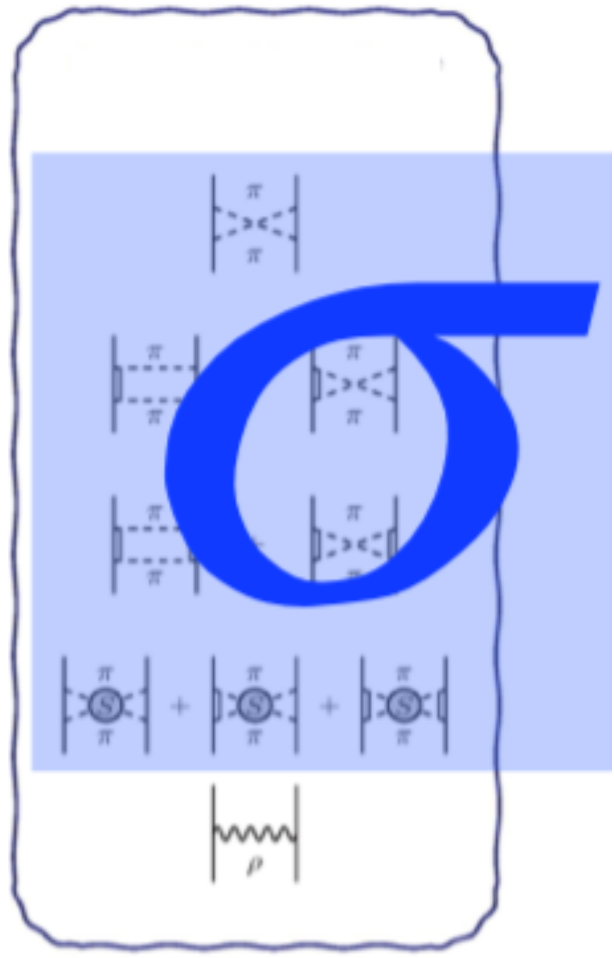
Chiral EFT

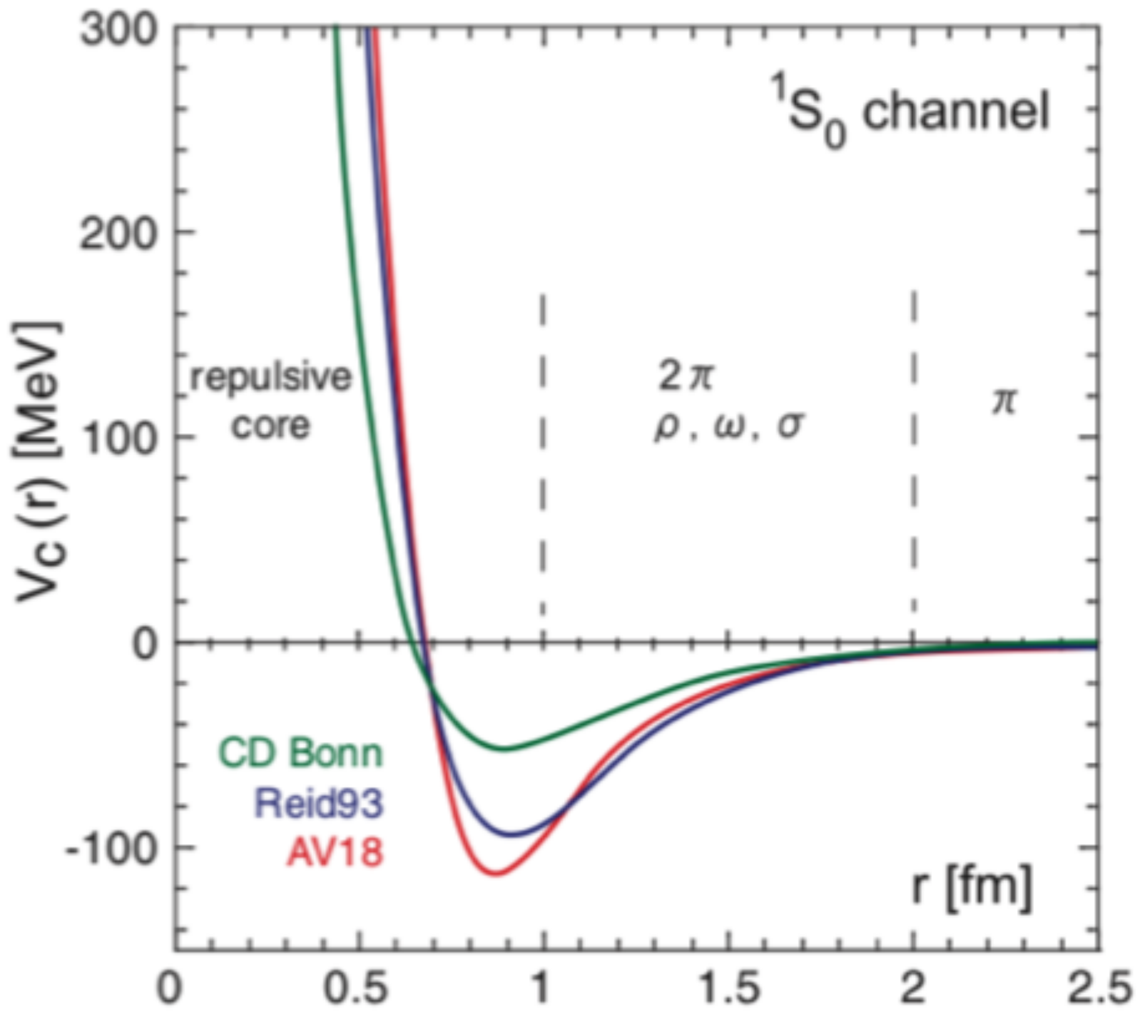
$$\mathcal{L}^{(1)}_{\pi N} = \bar{\psi}\left(i\not{D} - m_N + \tfrac{1}{2} g_A \gamma_\mu \gamma_5 u^\mu\right)\psi$$

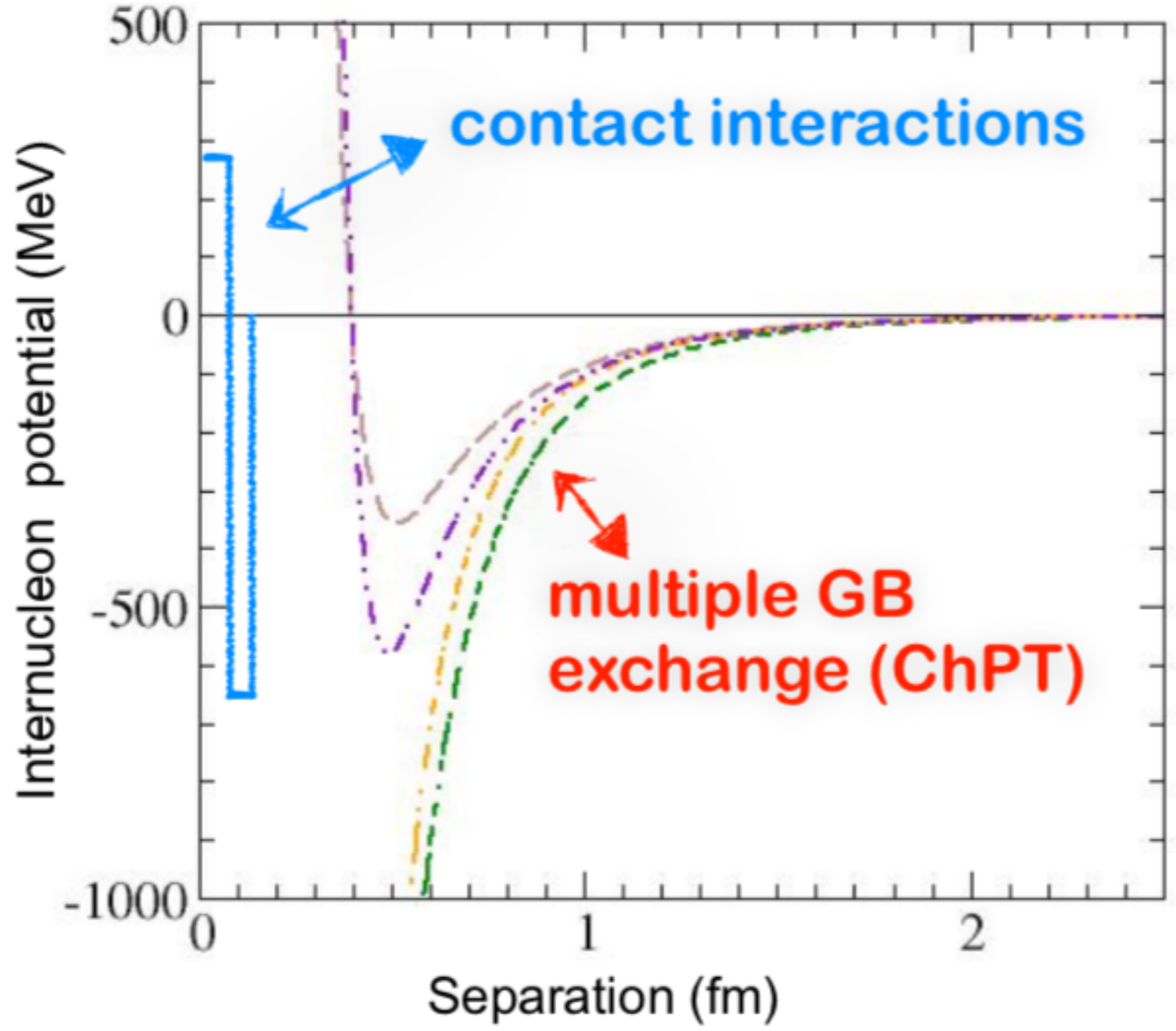
$$V(\mathbf{r}) = \left\{ C_c + C_\sigma \sigma_1 \cdot \sigma_2 + C_T \left(1 + \frac{3}{m_\alpha r} + \frac{3}{(m_\alpha r)^2}\right) S_{12}(\hat{r}) + C_{SL}\left(\frac{1}{m_\alpha r} + \frac{1}{(m_\alpha r)^2}\right) \mathbf{L}\cdot\mathbf{S} \right\} \frac{e^{-m_\alpha r}}{m_\alpha r} \quad (1,\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

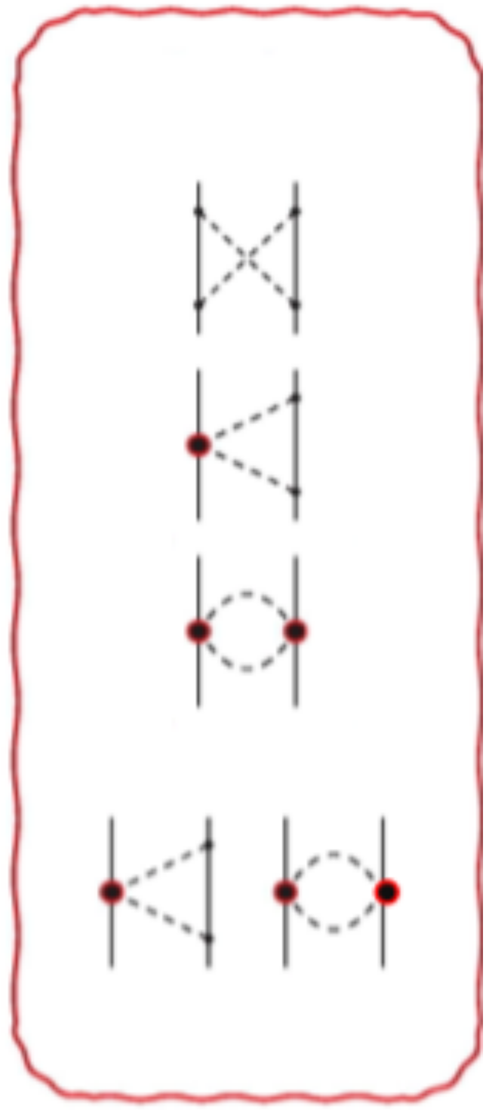










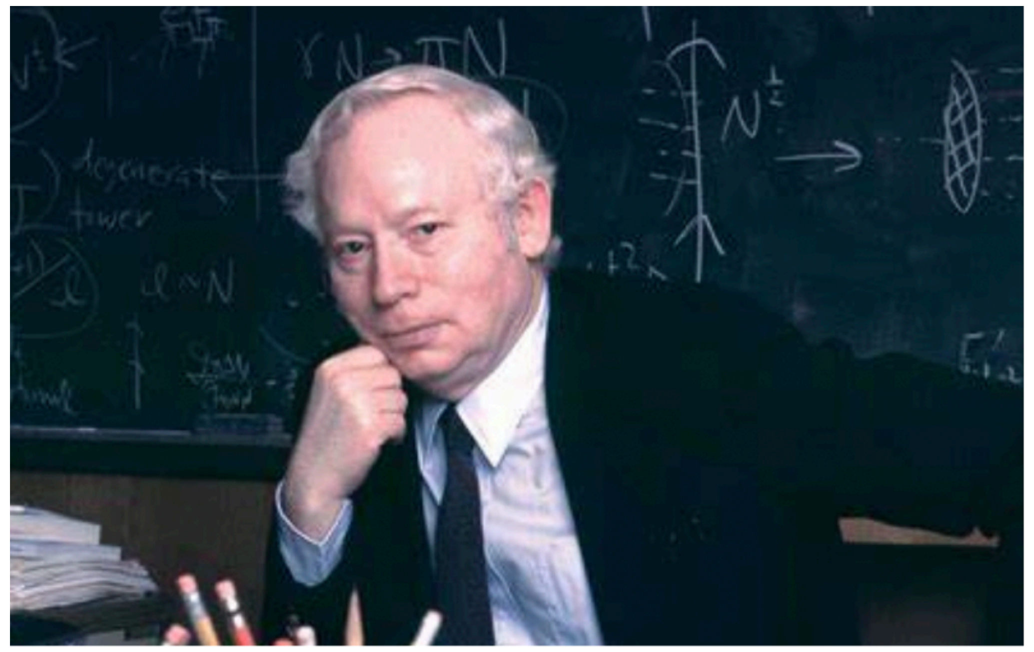


Repulsive central

CAS)

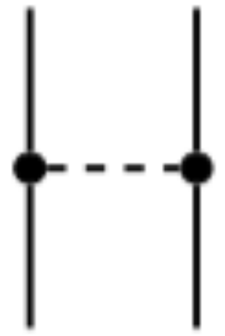
Weinberg's nuclear force

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

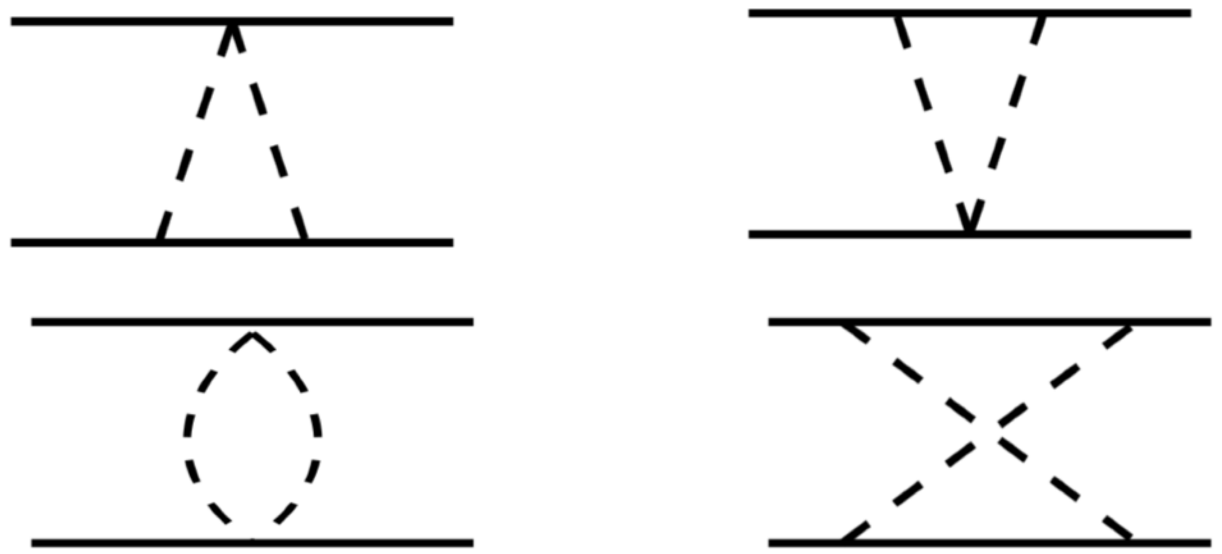
= (0-2+4/2) = 0

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

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.

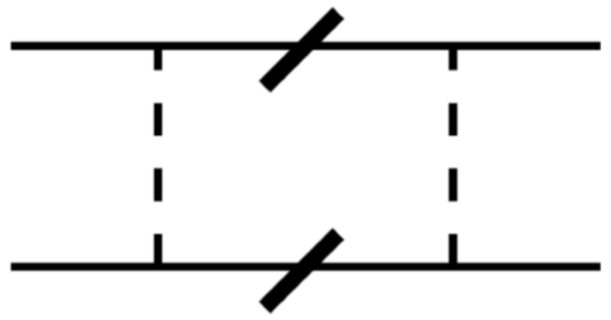
Weinberg 2021

2PI Diagrams



Nuclear potential from Irre. 2PI only

2PR Diagrams

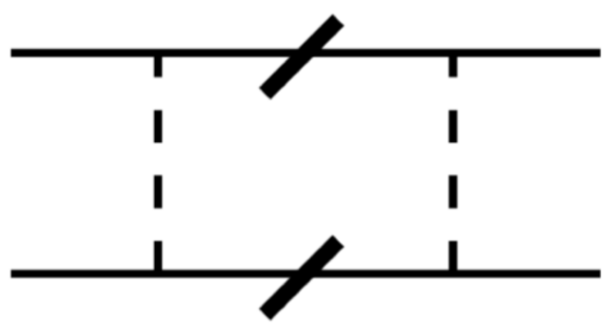


Breakdown in perturbation theory = nuclear bound states

Chiral effective field theory

Chiral EFT with Pion

[Weinberg, 1990]



$$\sim \left(\frac{g_A}{F_\pi}\right)^2 \frac{Q}{\Lambda_{NN}}$$

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

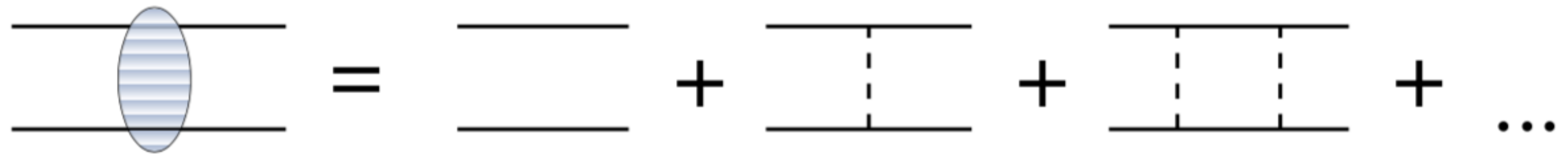
Pinch singularity

Infrared enhancement!

1. calculate nuclear potential from irreducible diagrams

pinch diagrams subtracted

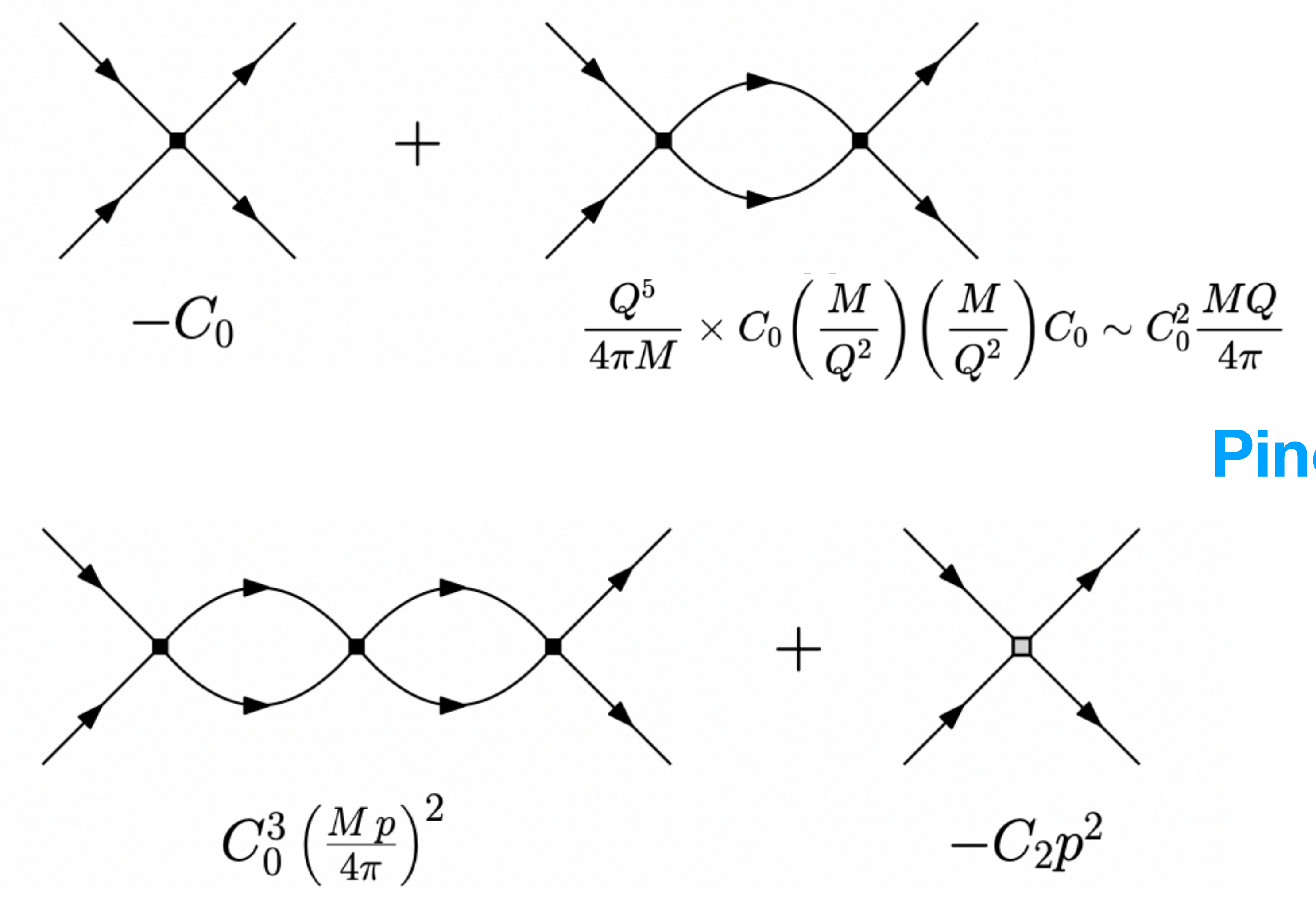
2. Truncated nuclear potential is iterated to all order



Solve Schrodinger equation

Pionless EFT

Kaplan, Savage, Wise 1998



Pinch singularity

$\sigma_{tot} \to 4\pi a^2$ as $p \to 0$. $\quad a_0 \approx -23.7$ fm $\quad 1/m_\pi \approx 1.4$ fm

a. Natural scattering length

$$\mathcal{A} = -\frac{4\pi a}{M}\left[1 - iap + \left(\frac{1}{2}ar_0 - a^2\right)p^2 + O(p^3/\Lambda^3)\right] \qquad C_0 \sim 4\pi a/M$$

Irrelevant

b. Unnatural scattering length

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

$C_0 \sim 4\pi/MQ$

Relevant

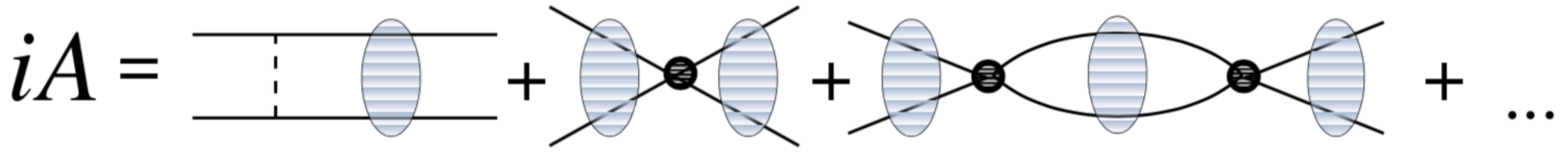
Power counting schemes

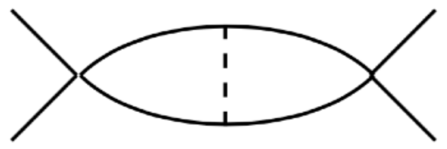
Complicated due to non-perturbative natures and renormalization problems

Weinberg Scheme

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

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





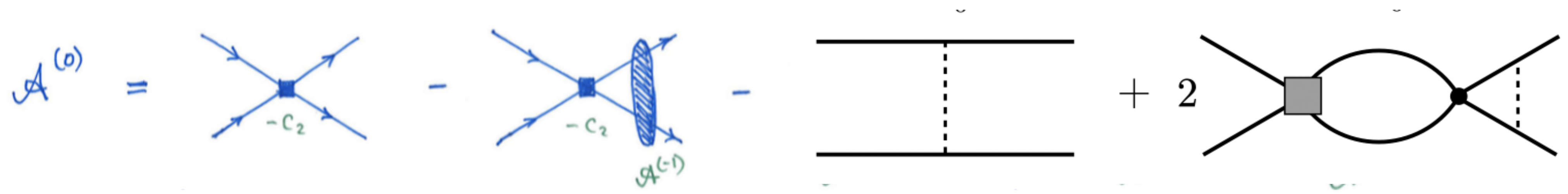
Renormalization problem!

KSW Scheme

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

[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]

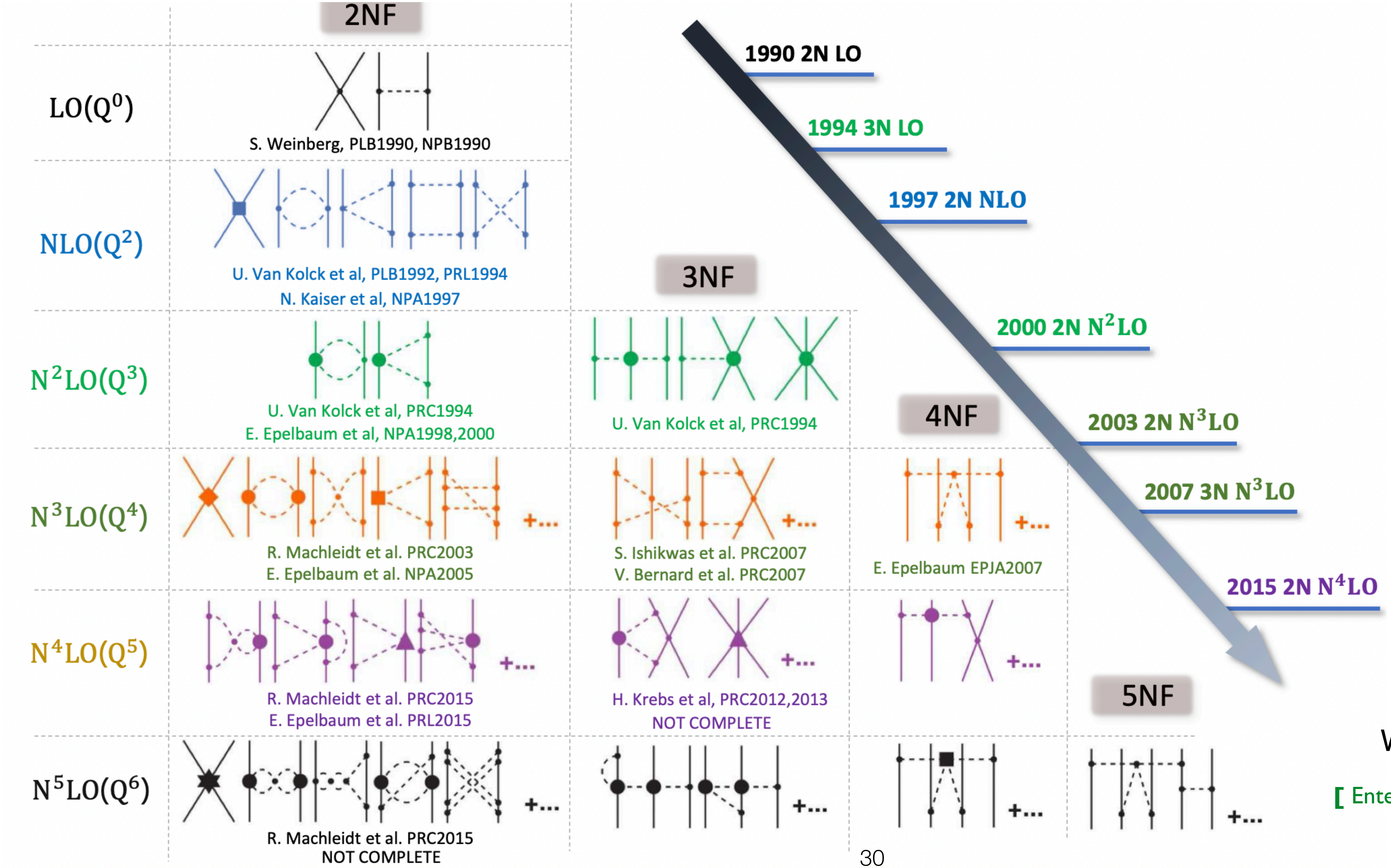
[Epelbaum, Gegelia, 2012]

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

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

Solve both but why?

High precision nuclear force



Weinberg scheme

[Entem, Machleidt, Nosyk, 2020]

Non-relativistic operators

[Li, Wang, **J.H.Yu**, in préparation]

Operator

$$O = \epsilon^n \prod_{n_k}^{n_E}\prod_{n_l}^{n_B} N^\dagger (\nabla^{\omega_k} E_{n_k})(\nabla^{\omega_l} B_{n_l})\nabla^{\omega_j} N$$

$$(N^\dagger \sigma \cdot \overrightarrow{\nabla} N)(N^\dagger \sigma \cdot \overleftarrow{\nabla} N)$$

↓

Spin Relation → **EOM and CDC**

$$[s^I, s^J] = \sqrt{-1}\varepsilon^{IJK} s^K$$

↓

Schouten Identity

$$\nabla_{kj} \equiv \epsilon_{ki}\nabla_I(\sigma^I)^i_j. \quad + \langle ri\rangle\langle jk\rangle + \langle rj\rangle\langle ki\rangle = 0,$$

↓

IBP

$$i(\nabla \times \vec{E})^i = Tr[\sigma^i\sigma^j\sigma^k]\nabla^j E^k = Tr[\sigma^i\sigma^k\sigma^j]\nabla^j E^k$$

↓

SU(2) YD → **On-shell Amplitude**

i_1	j_3	i_2	k_2
j_3	i_3	k_2	i_4

$$\epsilon^{i_1j_3}\epsilon^{j_3i_3}\epsilon^{i_2k_2}\epsilon^{k_2i_4} \sim \langle i_1j_3\rangle\langle j_3i_3\rangle\langle i_2k_2\rangle\langle k_2i_4\rangle$$

$$\Psi(x) = e^{-imv\cdot x}\Big[\underbrace{e^{imv\cdot x}P_v^+\Psi(x)}_{\equiv\mathcal{N}_v(x)} + \underbrace{e^{imv\cdot x}P_v^-\Psi(x)}_{\equiv\mathcal{H}_v(x)}\Big]$$

Non-linearized Lorentz symmetry

$$SO(3,1)/SO(3)$$

$$v^\mu = L(\vec{\eta}(v))v_0^\mu \qquad L(\vec{\eta}) = e^{i\vec{\eta}\cdot\vec{K}}$$

Missing Goldstone

$$\left.\begin{matrix}|v_0, 0, \sigma\rangle \\ |v_0, \vec{k}\rangle\end{matrix}\right\} \longrightarrow |v_0, \vec{k}, \sigma\rangle.$$

NN and 3N operators

Nucleon-nucleon sector

3 nucleon sector

LO

[Weinberg 1990] [Weinberg 1991]

[van Kolck, Ordonez, 1992]

NLO

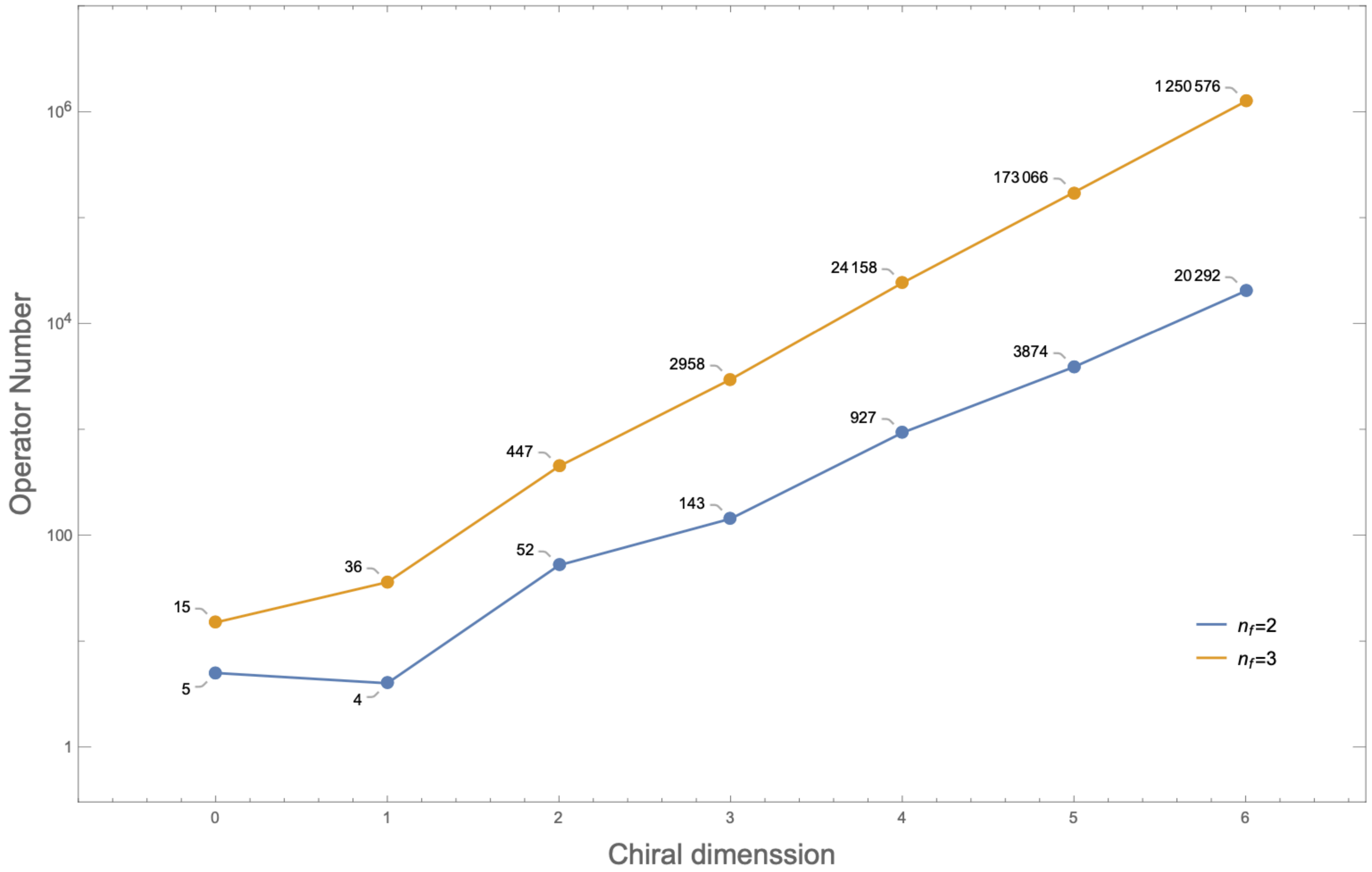
[Girlanda, Pastore, Schiavilla, Viviani, 2010]

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

NNLO

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

[Nasoni, Filandri, Girlanda, 2023]



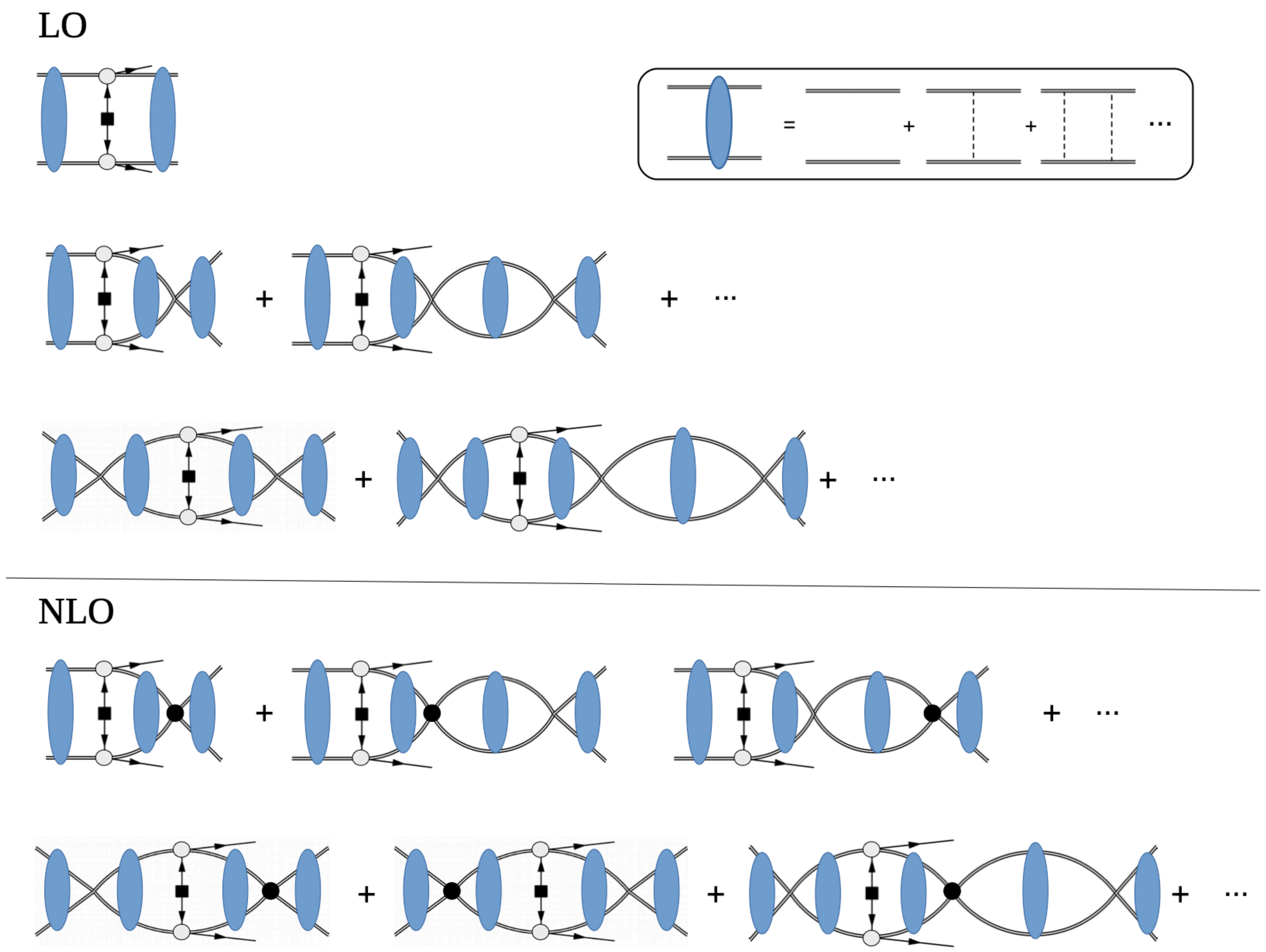
In order to obtain the most general contact Lagrangian in flavor SU(3), we follow the same procedure as used for the four-baryon contact terms in Ref. [47]. Generalizing these construction rules straightforwardly to six-baryon contact terms, we end up with a (largely) overcomplete set of terms for the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

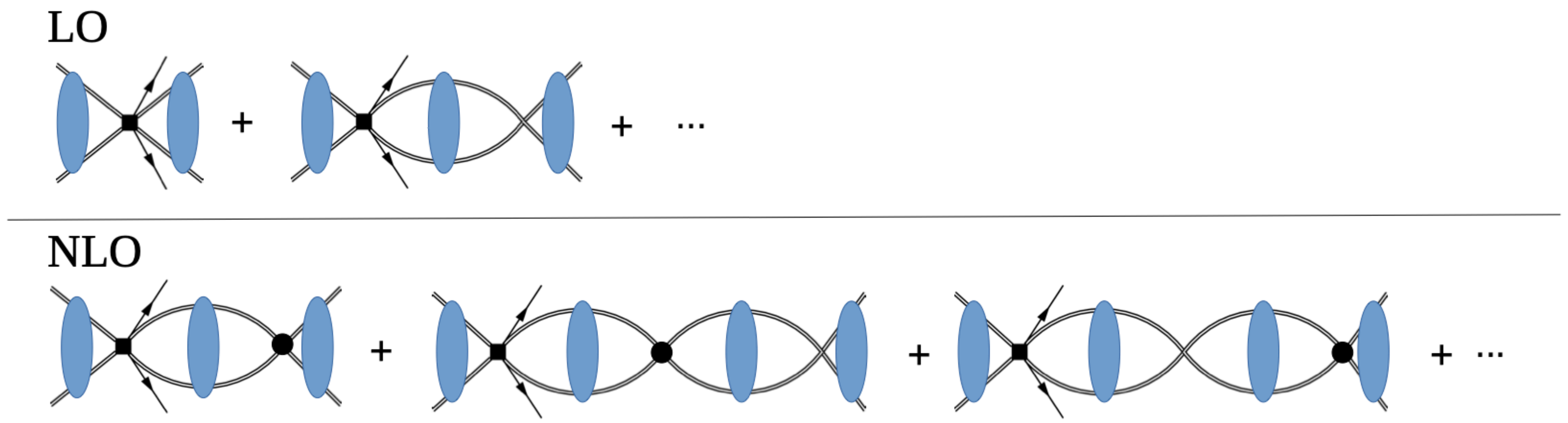
[Sun, Wang, **Yu**, in préparation]

[Li, Wang, **Yu**, in préparation]

Nuclear many body effects for 0vbb

Long-range and short-range weak currents



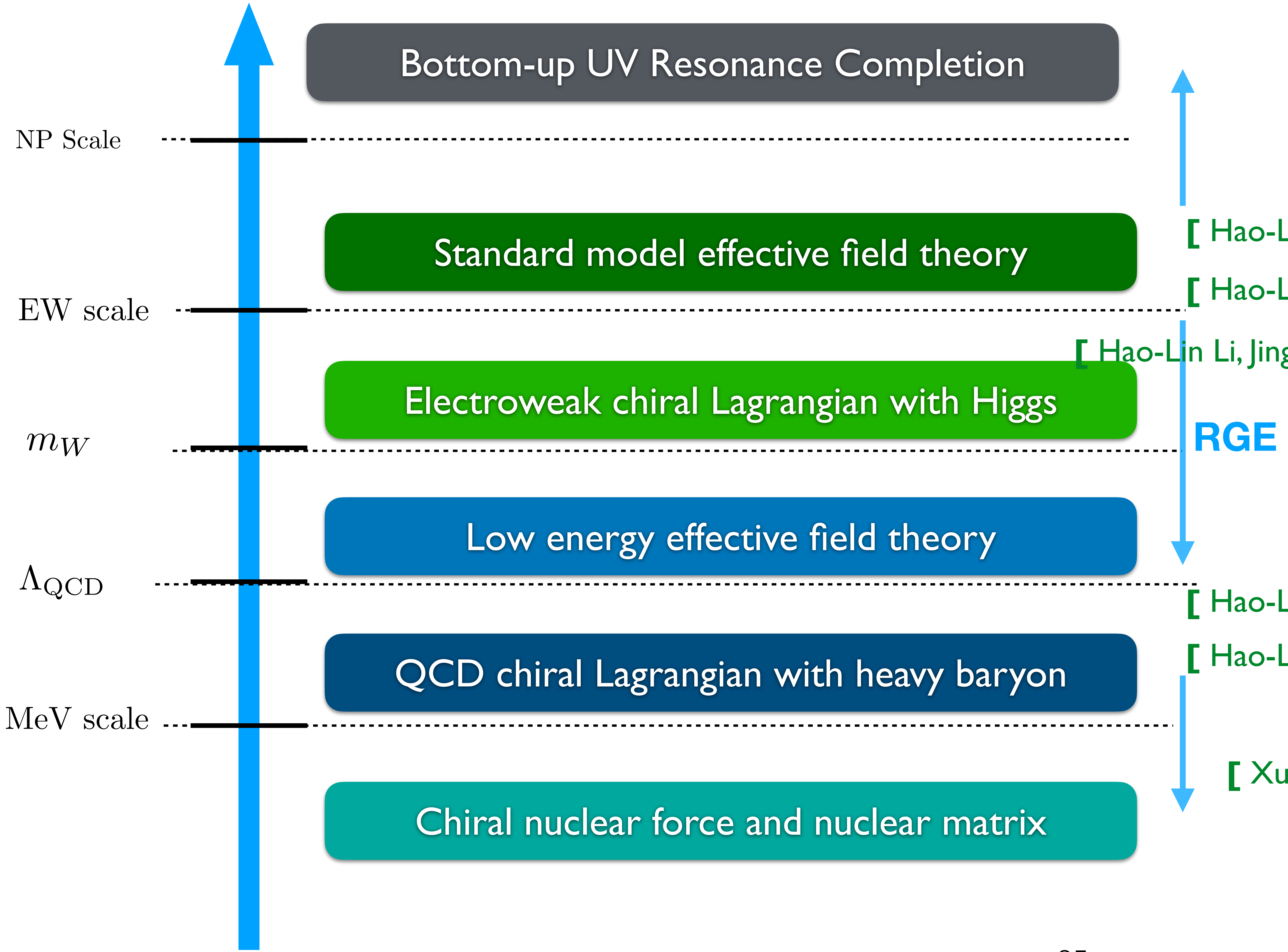


[Cirigliano, Dekens, de Vries, Graesser, Mereghetti, 2019]

Summary

Tower of effective field theories

From 2019 (6 years) on reorganizing effective field theories among several scales



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

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

[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2306.15933]

[Yong Du, Xu-Xiang Li, **J.H.Yu,** 2201.04646]

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

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

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

[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]

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

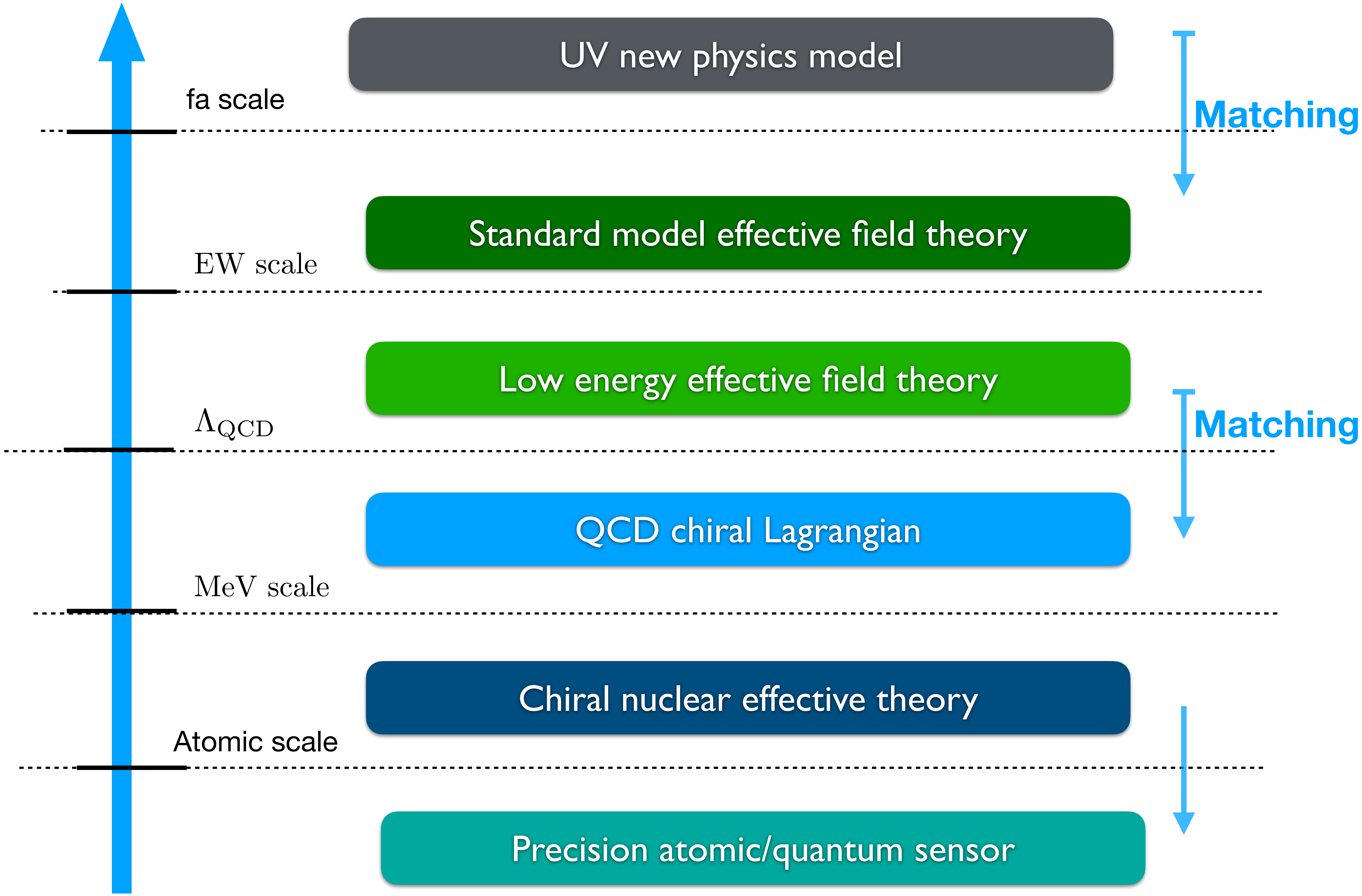
[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2105.09329]

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

[Xuan-He Li, Chuan-Qiang Song, Hao Sun, **J.H.Yu**, in préparation]

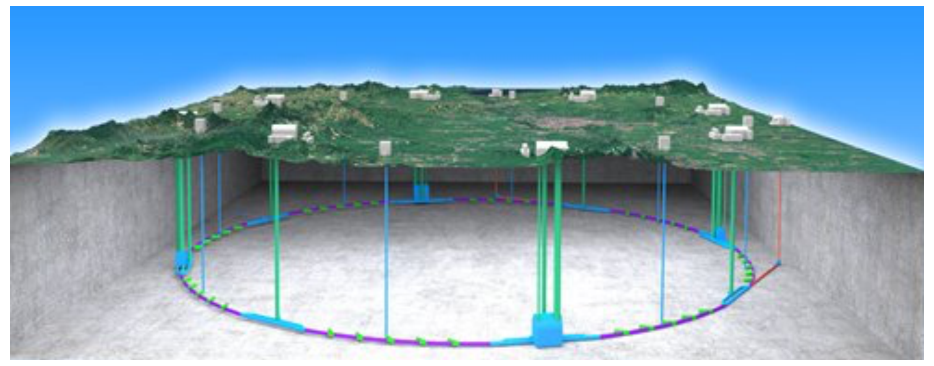
[Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, in préparation]

Application to neutrino physics



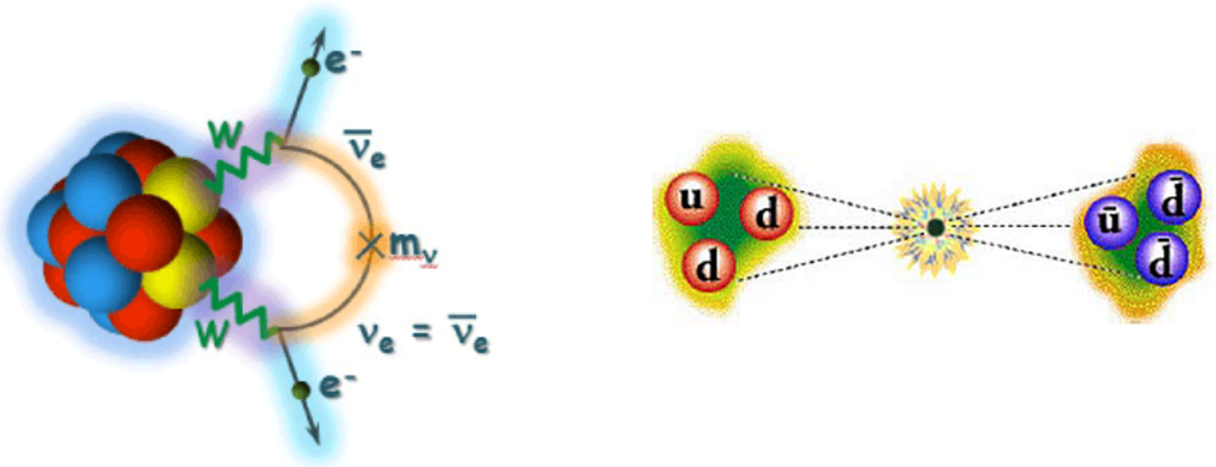
Energy frontier

high energy, high cost!



Intensity frontier

high intensity, low cost!



Jiang-Hao Yu (ITP-CAS)

Thanks for your attention!