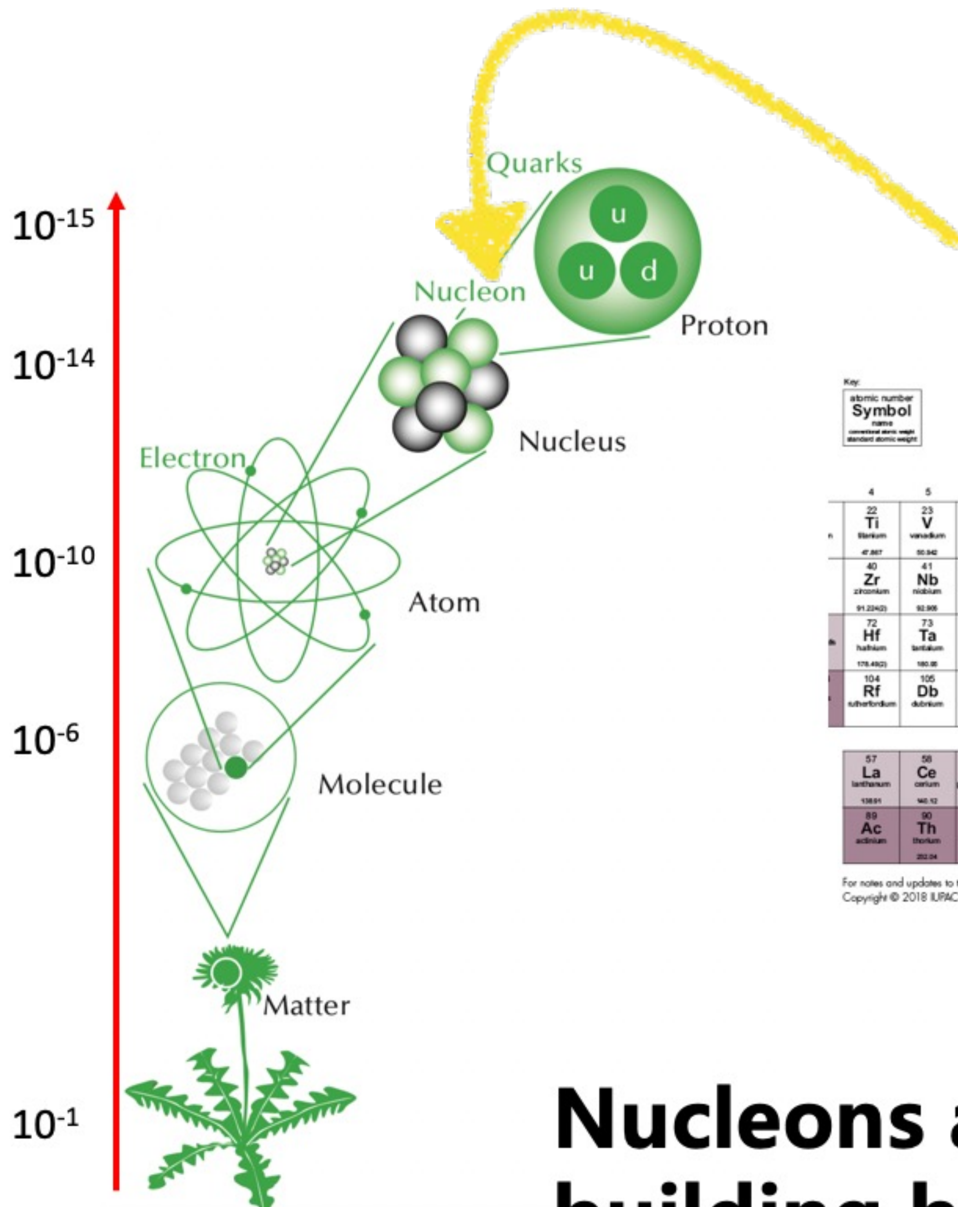
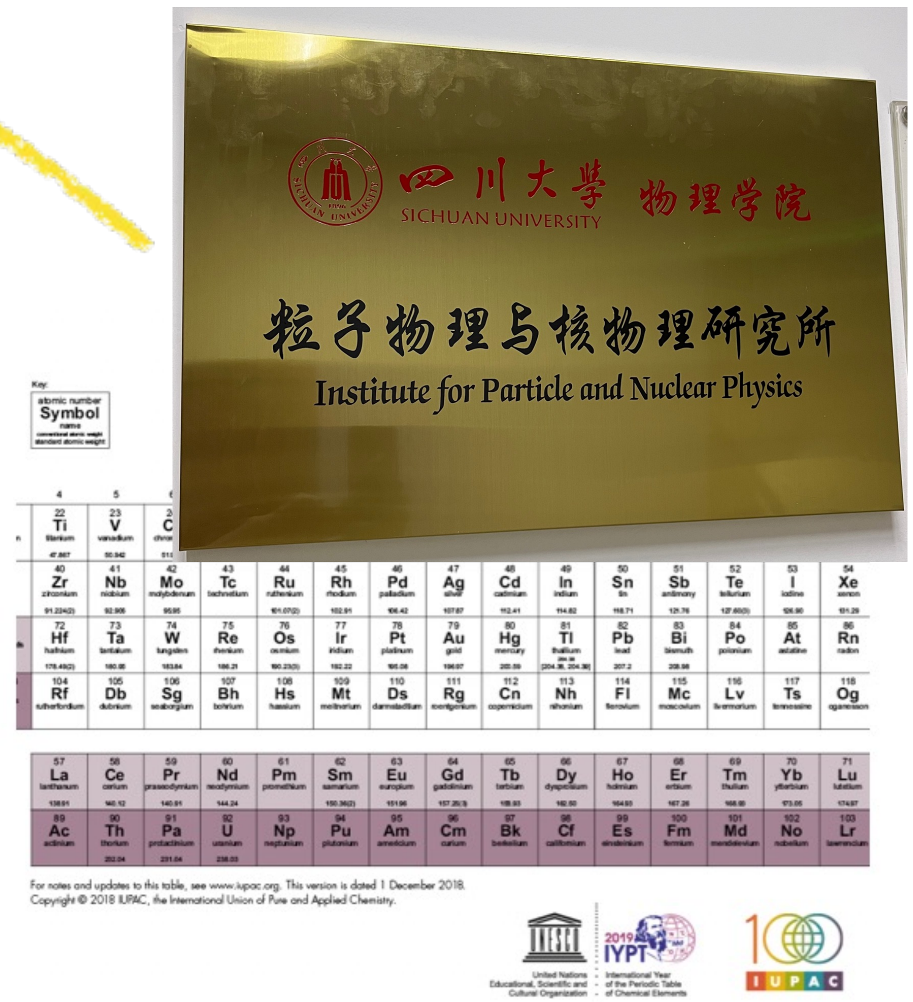
Nuclear weak currents from chiral effective field

龙炳蔚
Bingwei Long

四川大學
SICHUAN UNIVERSITY

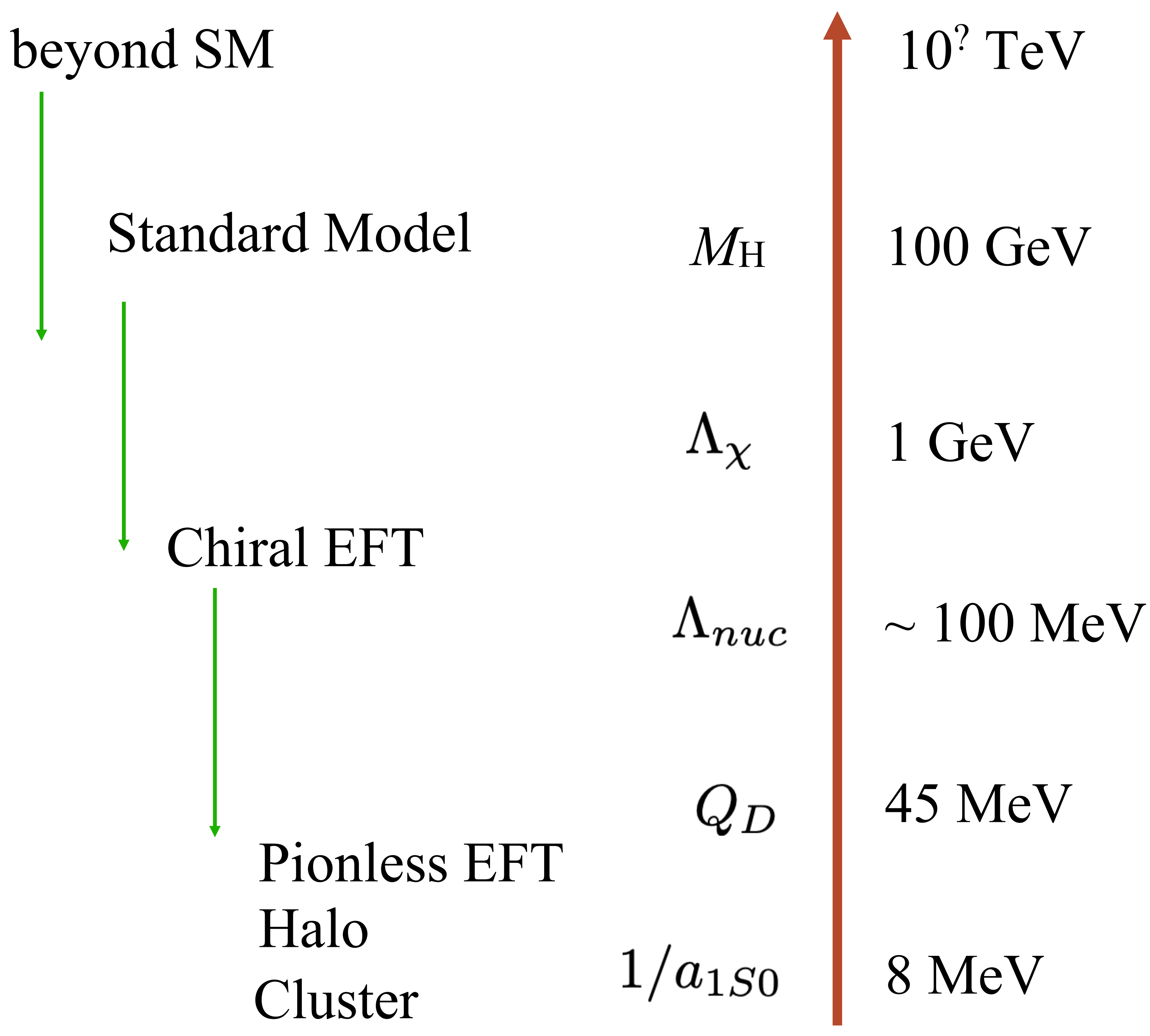
粒子物理与核物理结合，大有可为



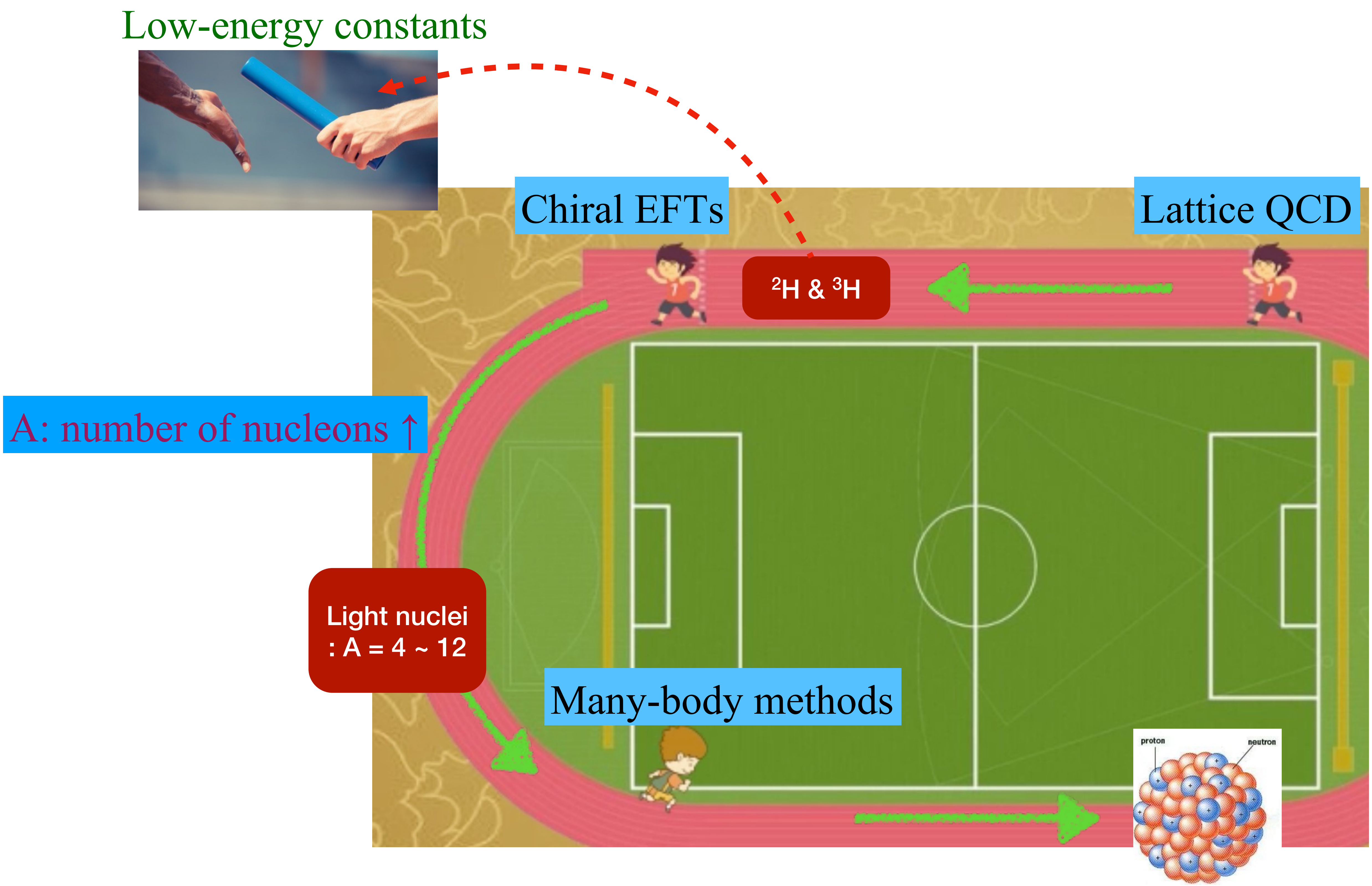


Nucleons are the essential building blocks of Matter!

Hierarchy of EFTs



Relay: from quarks & gluons to Uranium



EFT is a strategy

- Predictive power is w/ the SM (QCD)
- If EFTs have many LECs, so be it
- Job of EFTs:
    - where LECs lie;
    - *not* the values of LECs

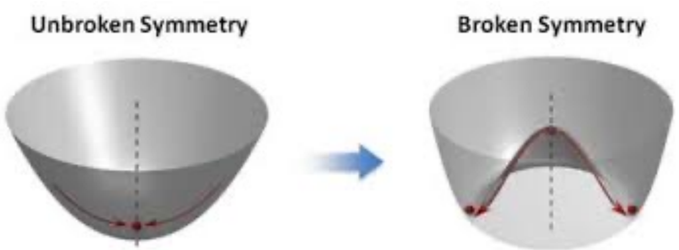
QCD —> Chiral Lagrangian

External sources: v, a, s, ps

$$\mathcal{L}_{QCD} = \bar{q}_R i\gamma_\mu D^\mu q_R + \bar{q}_L i\gamma_\mu D^\mu q_L - \frac{1}{4}G^a_{\mu\nu}G^{a\,\mu\nu} + \bar{q}\gamma^\mu(v_\mu + \gamma_5 a_\mu)q - \bar{q}(s - i\gamma_5 p_s)q$$

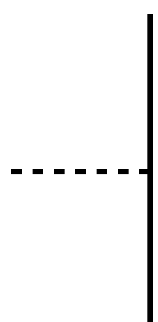
$$r_\mu = v_\mu + a_\mu = -eQA_\mu\,,$$
$$l_\mu = v_\mu - a_\mu = -eQA_\mu - \frac{g}{\sqrt{2}}(W^\dagger_\mu T_+ + h.c)\,,$$
$$s = \mathcal{M} \equiv \mathrm{diag}(m_q, m_q)\,,$$
$$p_s = 0\,.$$

Incomplete!

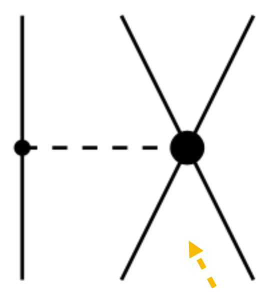


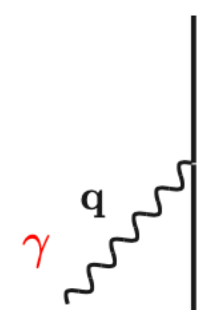
nonlinear realization
CCWZ; Weinberg; ...

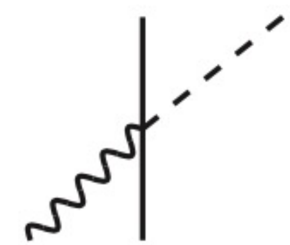
Nucleonic operators



$$-\frac{g_A}{2f_\pi}N^\dagger\tau_a\vec{\sigma}\cdot\vec{\nabla}\pi_a N$$
$$\vec{a}_a$$

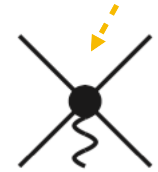






$H_{\gamma\pi NN}$

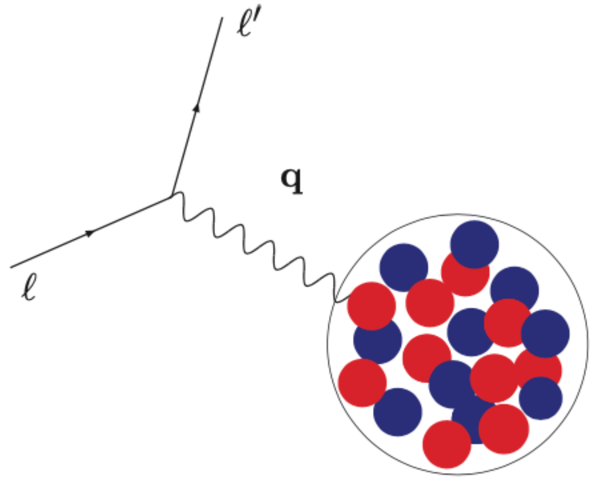
C_D

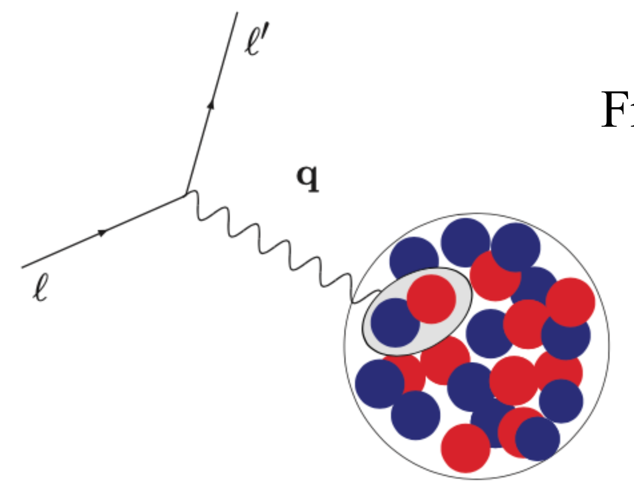


+ . . .

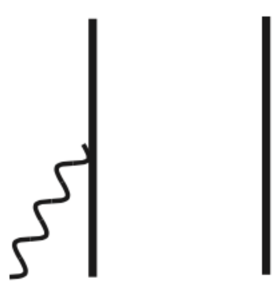
1N and 2N currents

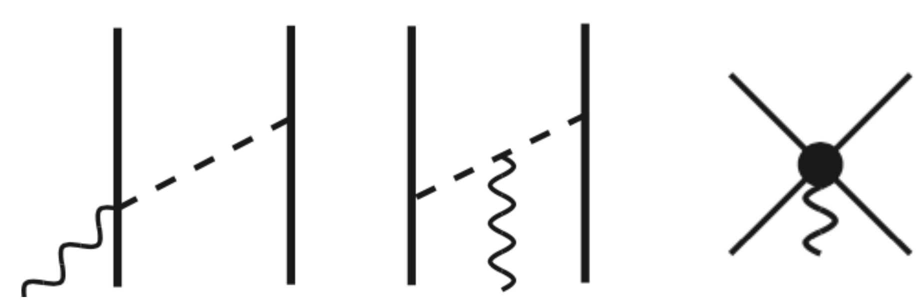
- NN correlations may be enhanced by long-distance scale of NN correlations





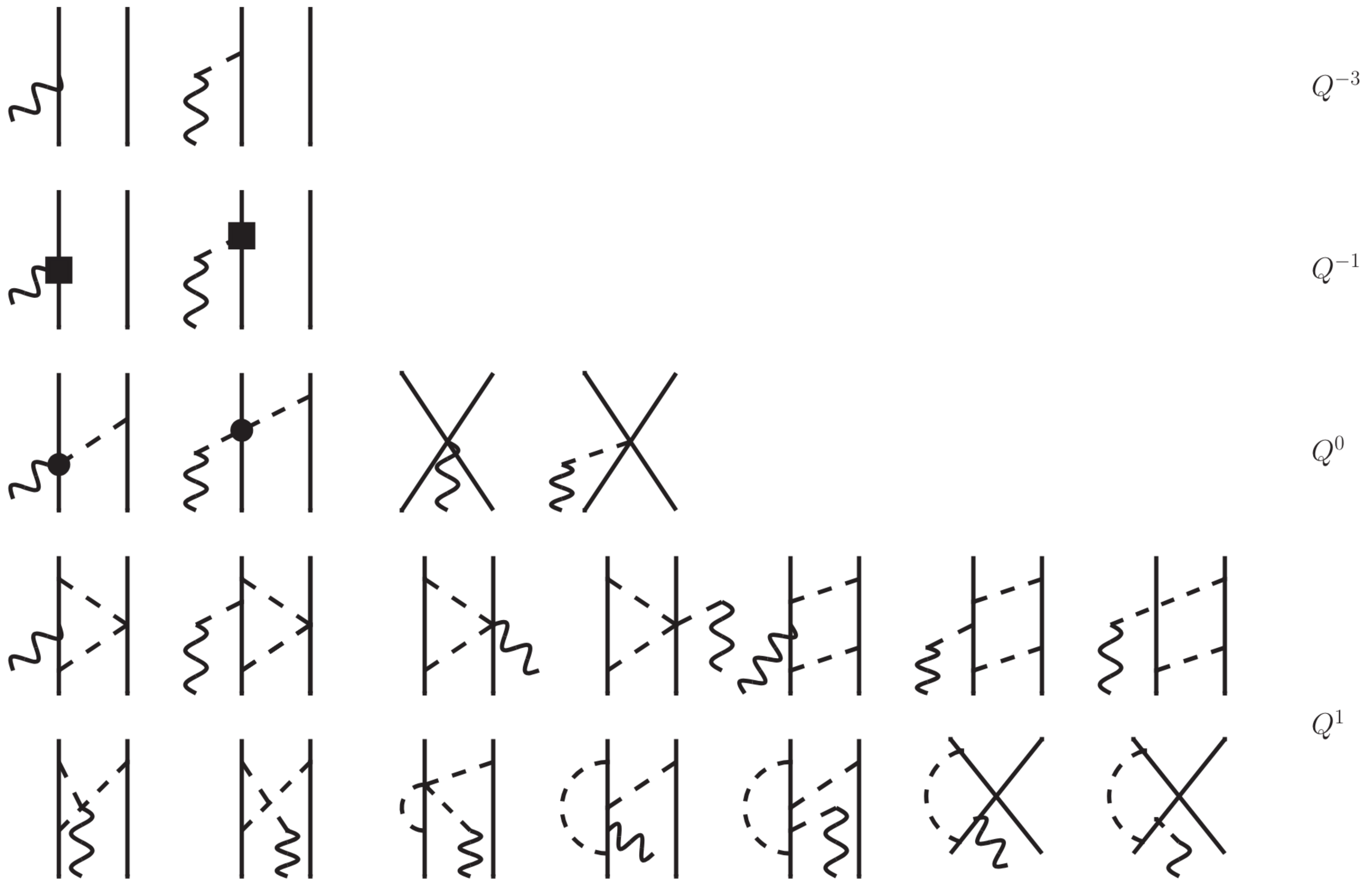
From Pastore’s talk





Axial current diagrams

From Girlanda's talk



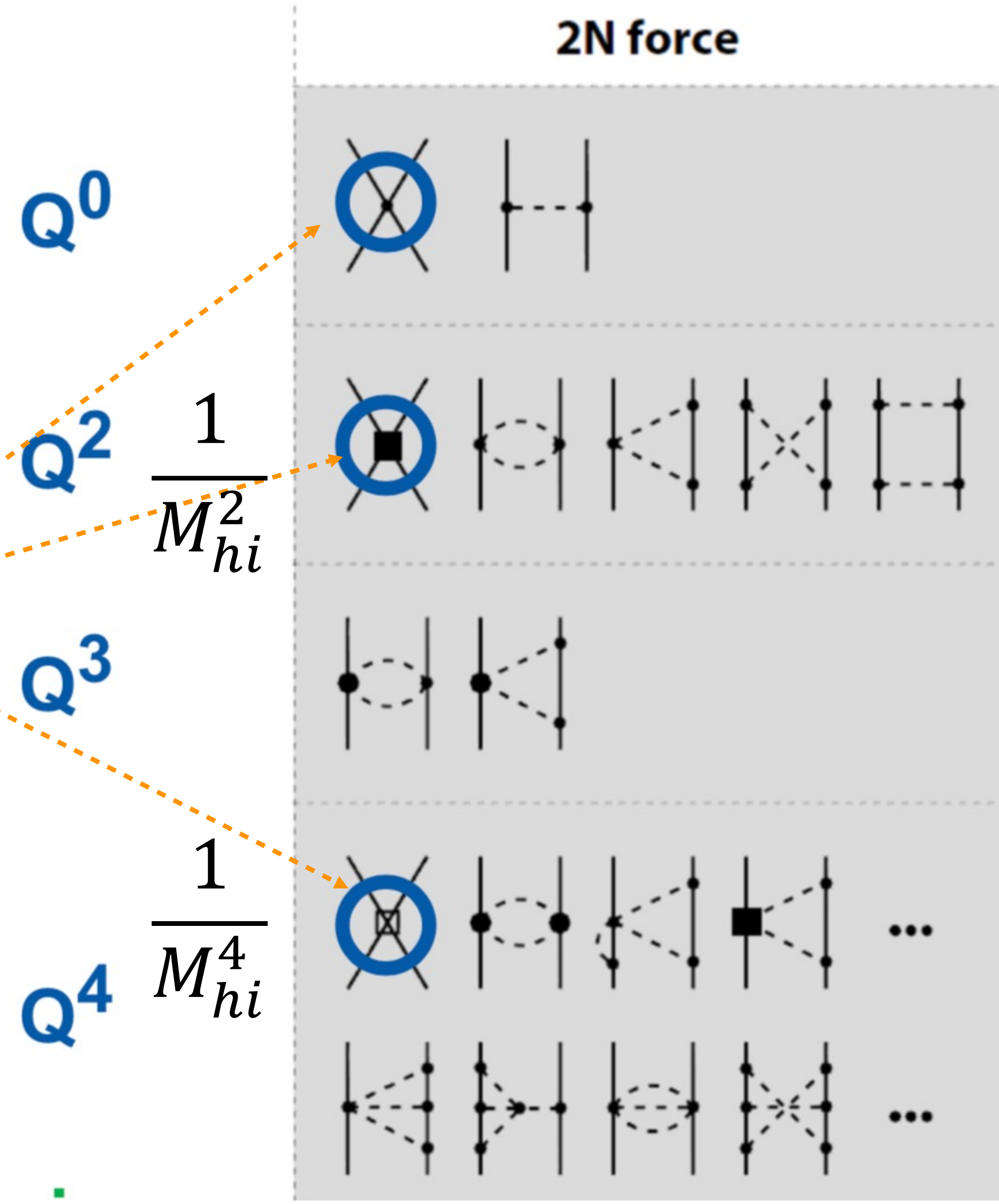
Riska & Schiavilla, arxiv:1603.01253

Krebs, arxiv:2008.00974

NN potentials from ChEFT

- Contact forces are doing heavy lifting

24 contact terms
in NDA up to Q^4



NDA = naive dim. analysis

van Kolck et al. since ’92

Entem & Machleidt since ’03

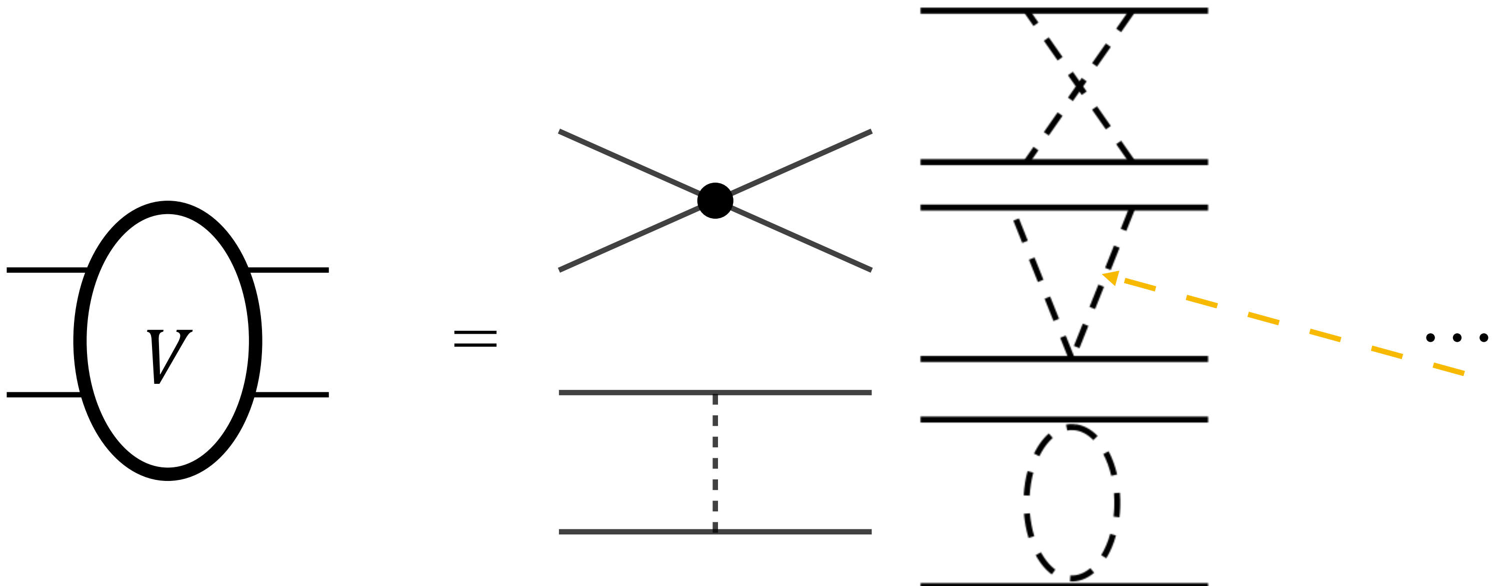
Epelbaum et al. since ’99

Pastore, Piarulli, et al. since ’09

…

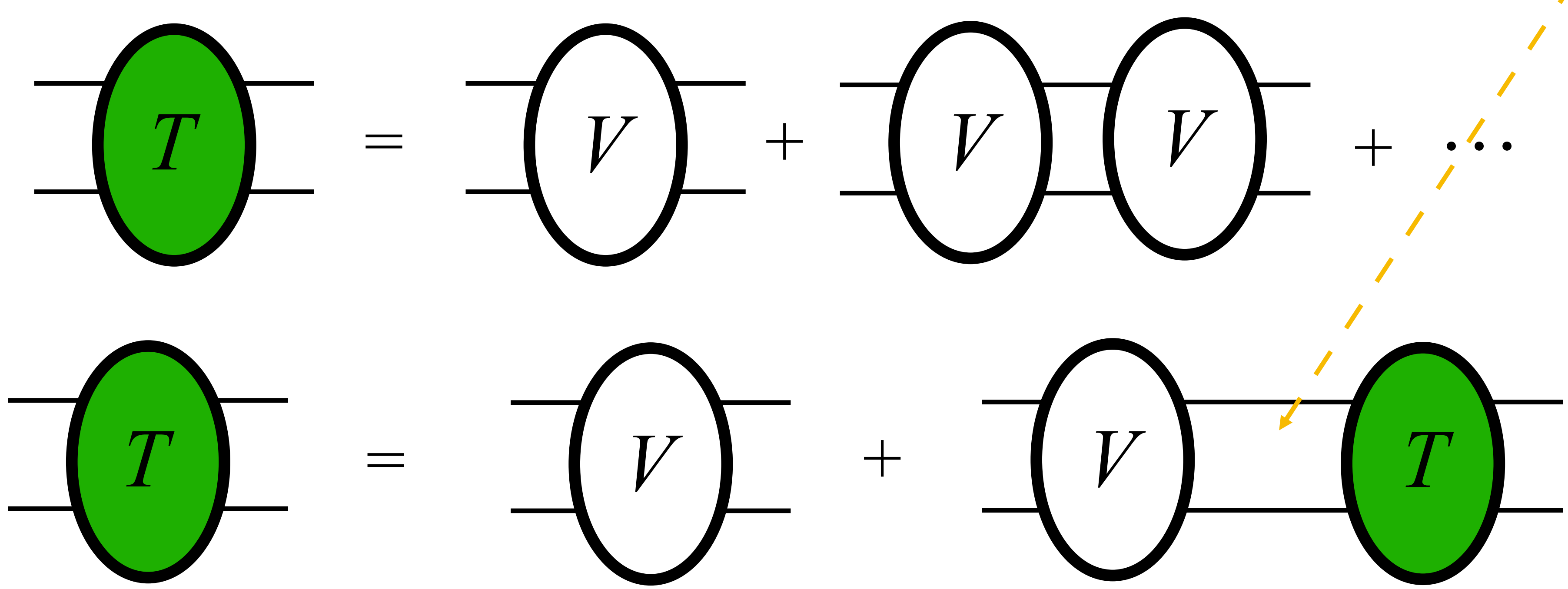
From potential to amplitude

- "*NN* Potential": two-nucleon irreducible diagrams



Λ: UV cutoff

- Lippmann-Schwinger eqn (equivalent to Schrodinger eqn)



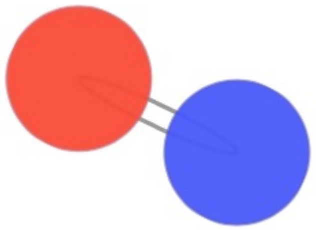
Few-body methods

- Equivalent to Schrodinger eqn
- Precise numerical solutions

Easy

- Two-body: NN, N-cluster, cluster-cluster

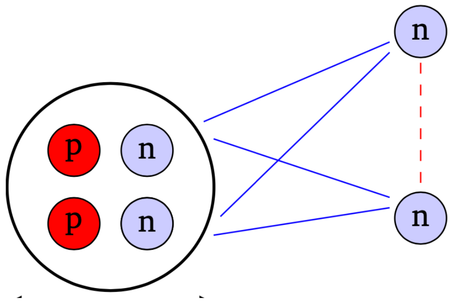
  Lippmann-Schwinger equation



Medium

- Three-body: NNN, 2n-cluster, 3alpha, …

  Faddeev equation



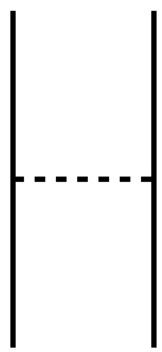
Hard

- Four-body: NNNN, 3n-alpha …

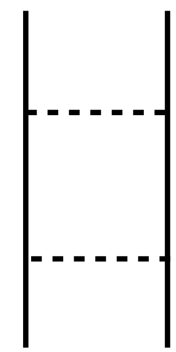
  Faddeev/Yakubowski equation

Strength of one-pion-exchange

$Q \sim m_\pi$



$$\sim \frac{1}{f_\pi^2}\frac{Q^2}{m_\pi^2+Q^2} \sim \frac{1}{f_\pi^2}$$



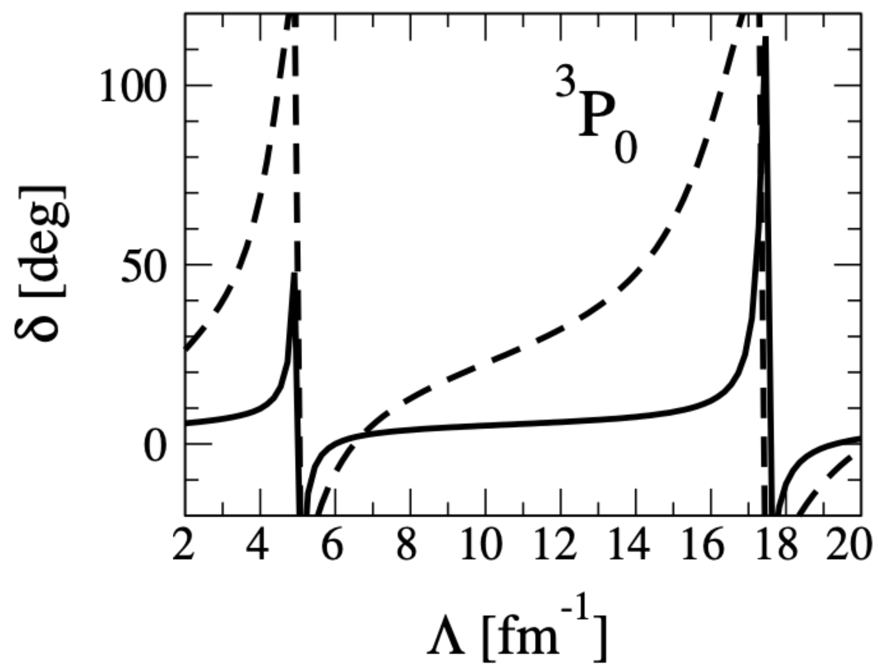
$$\sim \frac{1}{f_\pi^2}\frac{m_N}{4\pi f_\pi}\frac{Q}{a_l f_\pi}$$

- Strength of OPE ~ $a_l f_\pi$
- $a_l \sim 1$ for small l, $a_l \gg 1$ for large l
- $a_l f_\pi$ may have impact on contacts through renormalization
- coexistence of $a_l f_\pi$ and M_{hi} makes NDA no longer reliable

Renormalizing singular attraction

Nogga, Timmerman & van Kolck (2005)

Phase shifts vs. Λ



Solid: Tlab = 10 MeV, dashed: 50 MeV

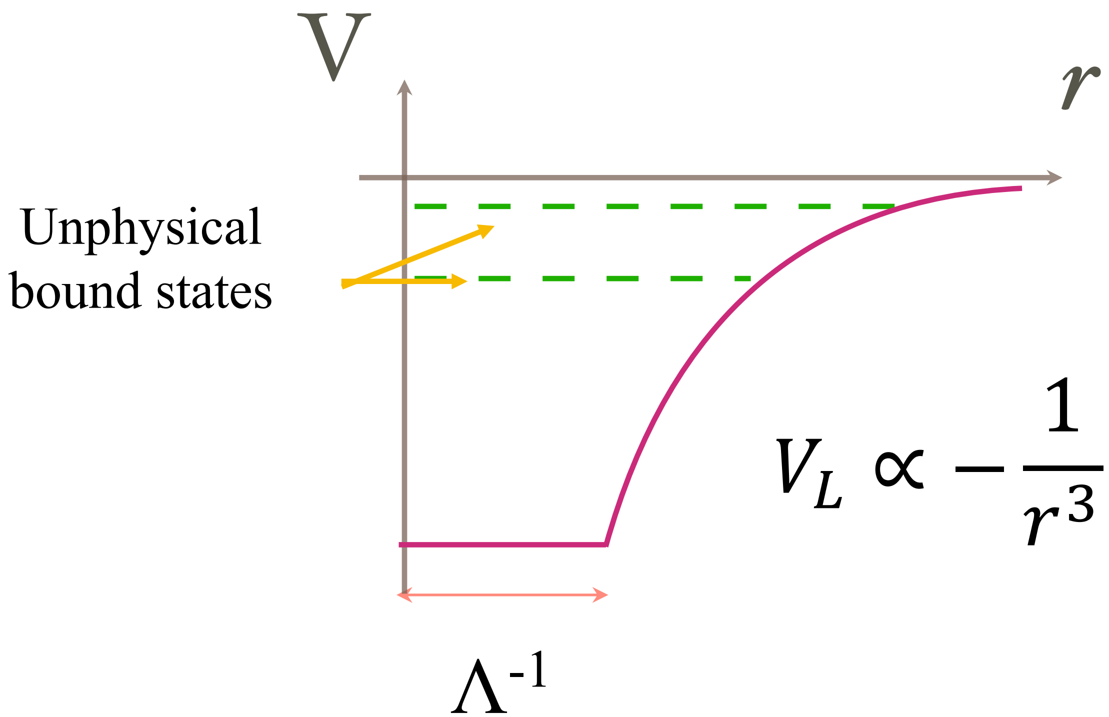
Naive dimensional analysis (NDA)

$$C_{3P0}\vec{p}\cdot\vec{p}' \sim \frac{Q^2}{m_{hi}^2}$$

N2LO

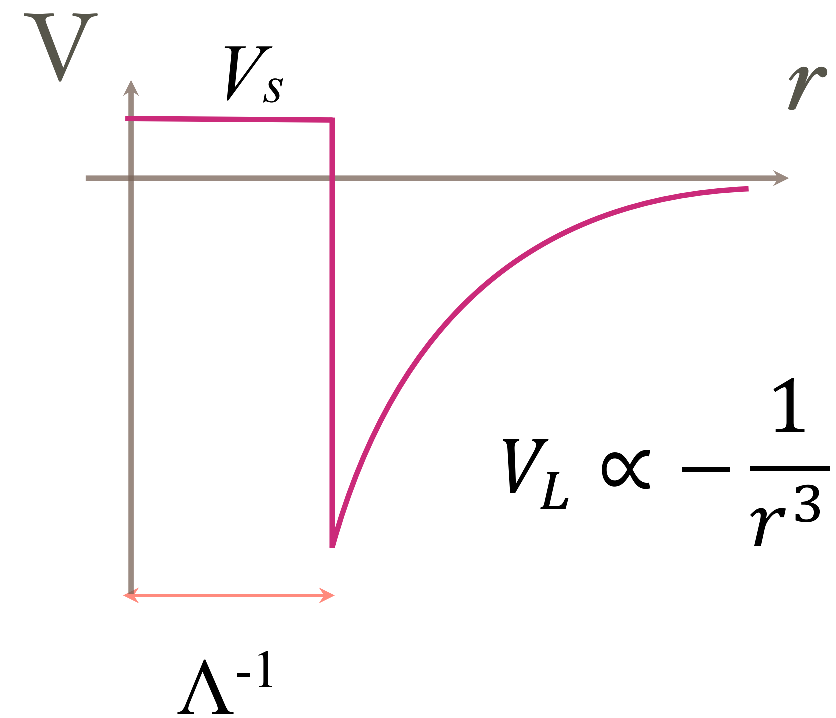
Renormalizing singular attraction

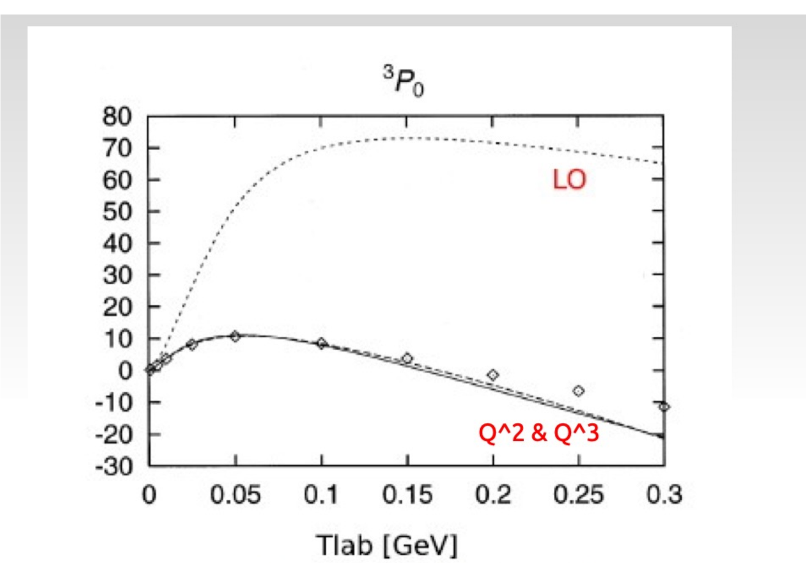
Beane et al ('01)
Pavon Valderrama & Ruiz Arriola ('05 ~ '07)
Nogga et al ('05)



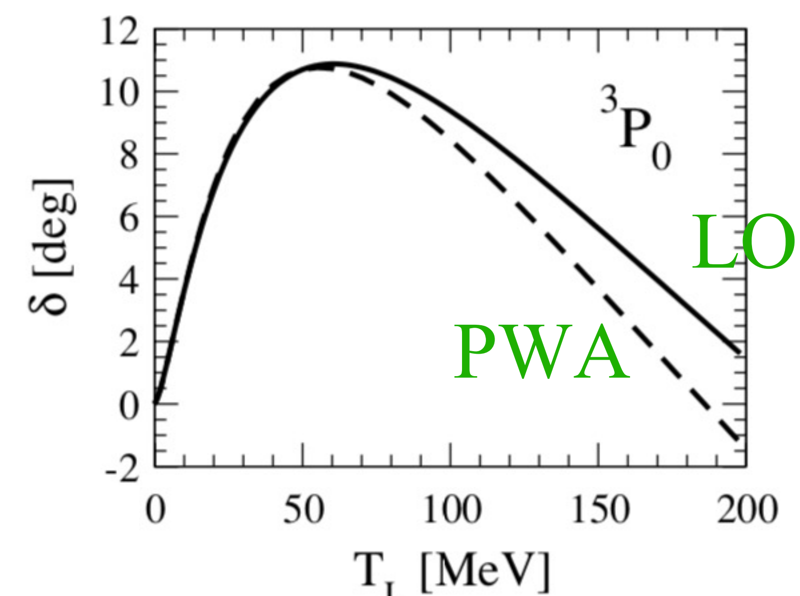
Modify PC

$\Longrightarrow$





Epelgaum et at, NPA 671, 295



Nogga et al ('05)

RG as diagnostic tool for PC

- The cutoff dependence of vth order must be of v+1 order or smaller

$$\frac{\Lambda}{T^{(\nu)}(Q,\Lambda)}\frac{dT^{(\nu)}(Q,\Lambda)}{d\Lambda} = \mathcal{O}\left(\frac{Q^{\nu+1}}{M_{hi}^{\nu}\Lambda}\right)$$

- A consistent power counting (PC) must be a solution to RGE

  Modify PC if necessary!

	NDA	RG inv.
$C_{3P0}\vec{p}\cdot\vec{p}'$	NNLO	LO

Modified power counting for chiral nuclear forces

Nogga et al. ’05

BwL & Yang ’11, ’12

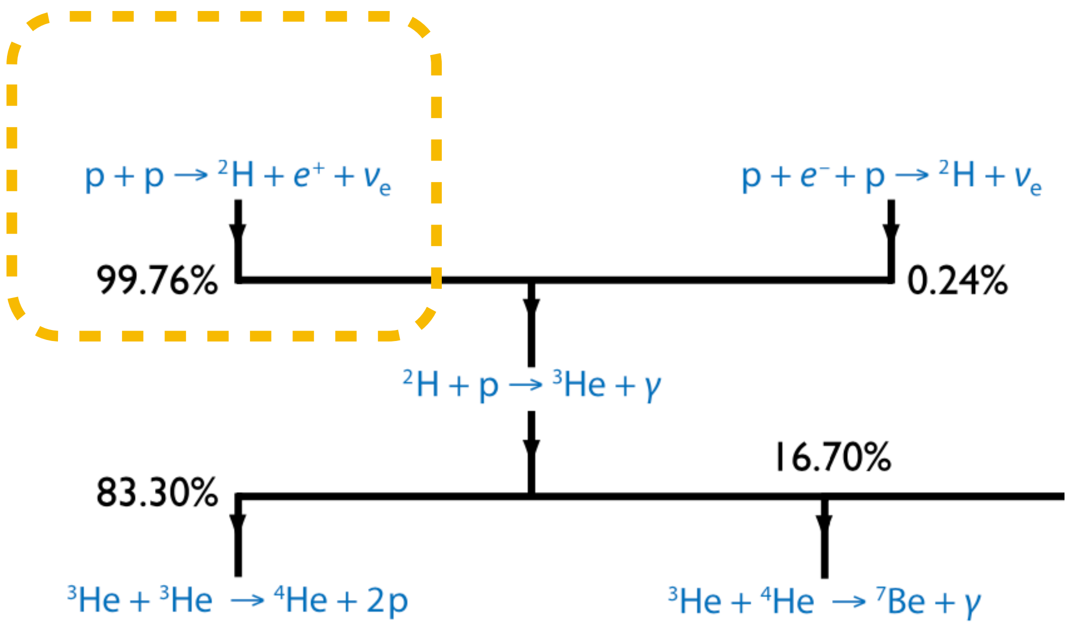
Wu & BwL ’19

- PC varies for different partial waves
- LO : (C + OPE) for 1S0, 3S1, 3P0

(perturbative OPE for most waves)

- NLO : Q^2 C.T. for 1S0; OPE for 1P1, 3P1, 3P2…
- N2LO: (Q^4 C.T. + TPE) for 1S0; (Q^2 C.T. + TPE) for 3S1-3D1 and 3P0
- N3LO: ….

PP fusion



Park, Kubodera, Min & Rho ’98

Marcucci, Schiavilla, Viviani ’13

Acharya et al, ’16

Valderrama & Phillips, ’15

$$\langle \psi_d^M | A_-^i | \psi_{pp} \rangle = \delta_{Mi} \sqrt{\frac{32\pi}{\gamma^3}} g_A C_0 \Lambda_R(p)$$

$$\vec{A}_-^{(0)}(\vec{p}\,', \vec{p}\,) = -g_A \sum_i \vec{\sigma}_i \tau_{i,-}$$

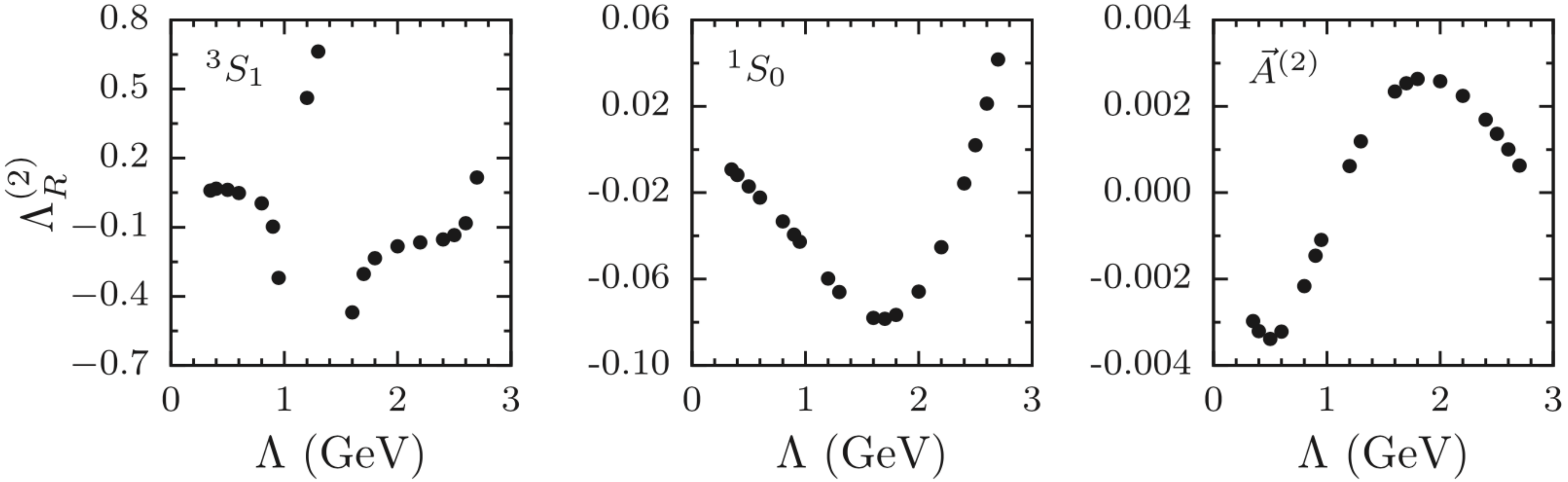
$$\vec{A}_-^{(2)}(\vec{p}\,', \vec{p}\,) = \frac{g_A}{2m_N^2} \sum_i [\vec{K}^2 \vec{\sigma}_i - (\vec{\sigma}_i \cdot \vec{K})\vec{K}] \tau_{i,-}$$

- Two-body currents accounting for a few percents, an
- Promoted from N3LO to N2LO

Liu, Peng, Lyu & BwL ’22

$$\vec{A}_{\rm ct}(\vec{p}\,', \vec{p}\,) = \hat{d}_R\, \vec{\sigma}_1 \times \vec{\sigma}_2 (\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)_-$$

N2LO vs cutoff

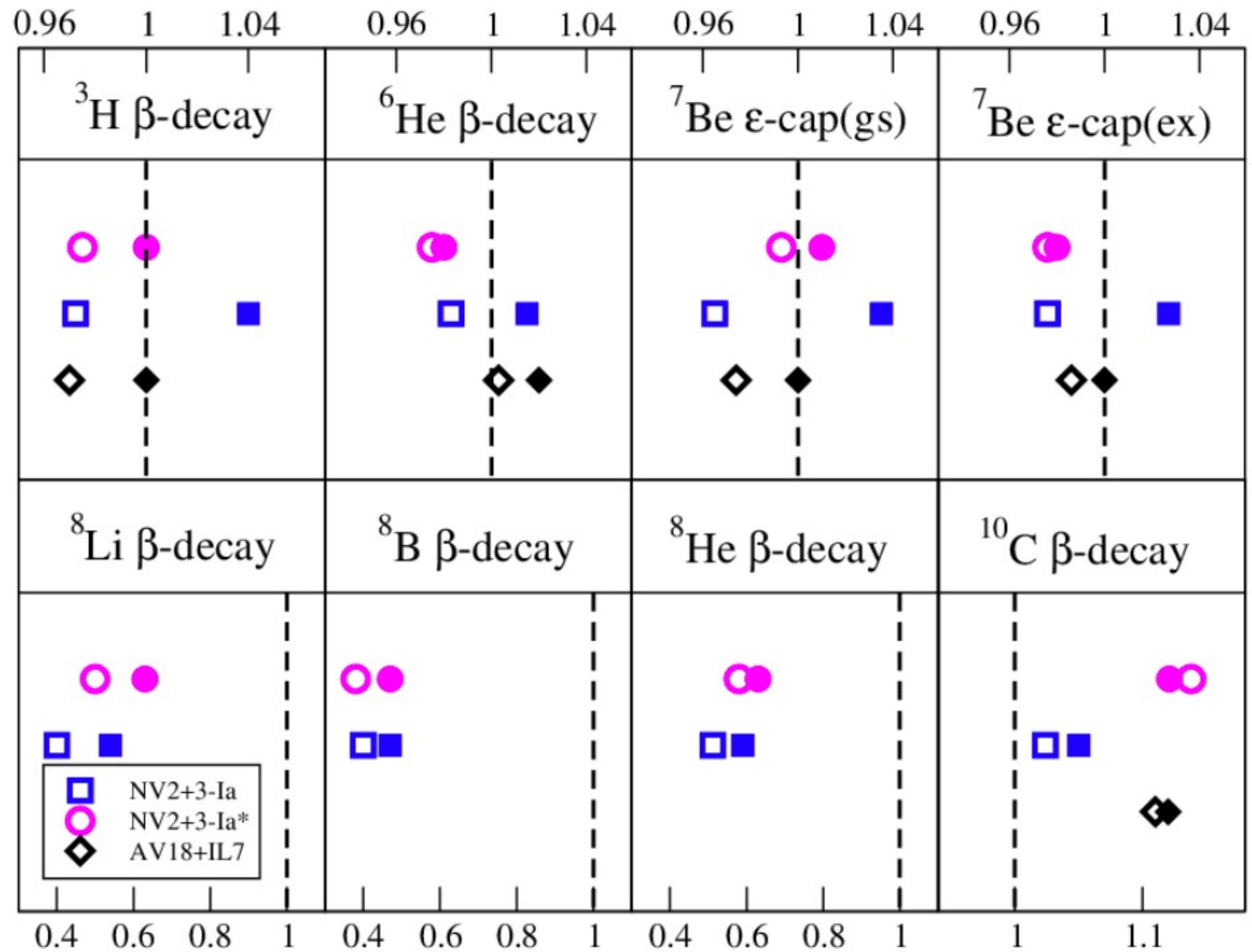


Beta decays by QMC

Baroni et al. '18

LO — empty

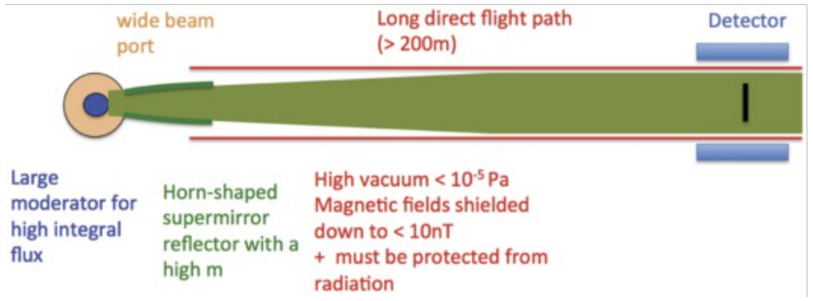
N3LO — filled



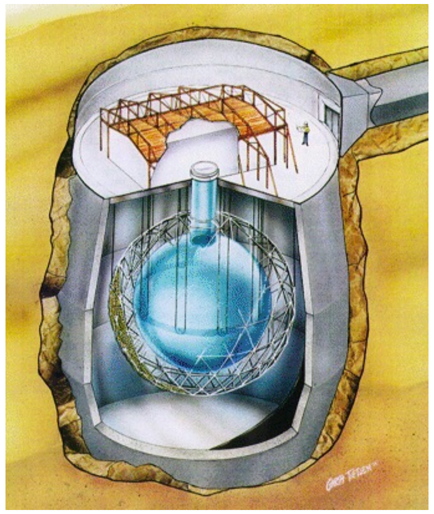
- One-body dominates for most nuclei
- gA quenching no longer an issue once many-body solvers improve
- For some nuclei, high-order corrections do not go right direction

Neutron-antineutron oscillation

- Some BSM models favor baryon-number violation $|\Delta B| = 2$
- Can explain baryon asymmetry of universe
- Stable nuclei become "unstable"
- Can we relate $\tau_{n\text{-}nbar}$ to Γ_d ?
- EFT helps disentangle different B-violating physics

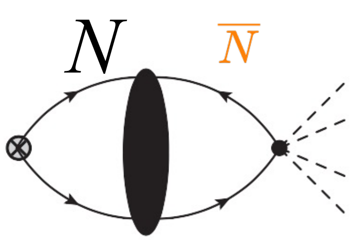


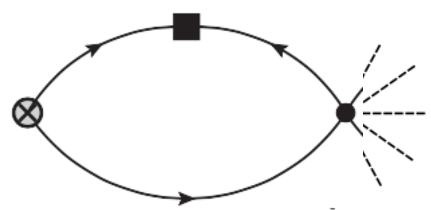
In vacuum (European spallation source)



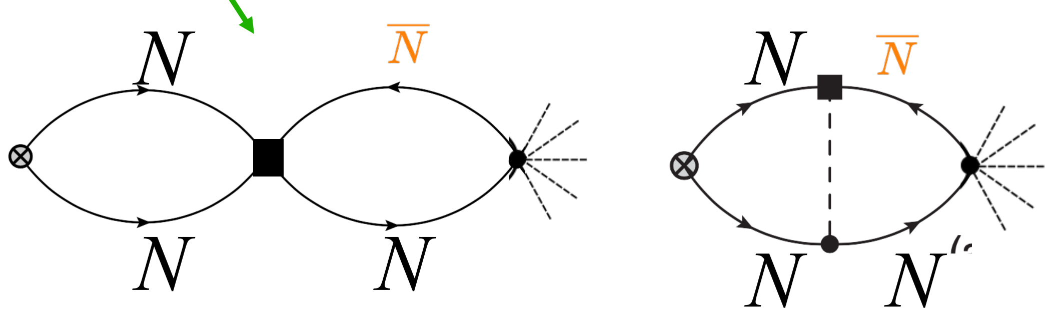
Limit on deuteron lifetime (SNO)

$NN \rightarrow NNbar$





1-body



2-body

Uncertainty

$$R_d \equiv \Gamma_d^{-1}/\tau_{n\bar{n}}^2$$

$$R_d = -\left[\frac{m_N}{\kappa}\mathrm{Im}a_{\bar{n}p}(1 + 0.40 + 0.20 - 0.13 \pm 0.4)\right]^{-1}$$
$$= (1.1 \pm 0.3) \times 10^{22}\ \mathrm{s}^{-1}.$$

Oosterhof, BwL, et al. PRL 122,17

Summary

- QCD Lag + chiral symmetry + external
  —> chiral Lagrangian w/ vector and axial vector sources

- Pion-exchange potentials and currents have been calculated to N4LO or higher

- Two-body currents may be enhanced due to nucleon-nucleon correlations at long distances

- Few-nucleon systems are testbeds for understanding of chiral forces and currents