SOME LANDMARKS ON THE SCENIC ROUTE FROM BEYOND THE STANDARD MODEL TO HADRONS AND NUCLEI

FONDAZIONE BRUNO KESSLER

ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

Bira van Kolck

cnrs

THE UNIVERSITY OF ARIZONA

Outline

warning: only glimpses!

- ☐ The scenic road
- ☐ The horizon
- ☐ A peek over the hill
- ☐ The green valley
- ☐ Through the hadronic/nuclear lens
- ☐ An example: NDBD, *B-L*, and bosons
- ☐ Conclusion

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2024 PROGRAMME OF ACTIVITIES

FEBRUARY

5-9.2 alpha_S(2024): Workshop on Precision Measurements of the Strong Coupling Constant
D. D'ENTERRIA (CERN), S. KLUTH (MPP), G. ZANDERIGHI (MPP)

12-16.2 New Jet Quenching Tools to Explore Equilibrium and Non-Equilibrium Dynamics in Heavy-Ion Collisions
A. SADOFYEV (LIP), C. ANDRES (LIP), J. BARATA (BNL), C. SALGADO (IGFAE)

26.2-1.2 Inaugural Workshop on Nuclear Astrochemistry
N. MASON (University of Kent), D. BEMMERER (HZDR), E. MASHA (HZDR), D. MIFSUD (Atomki)

MARCH

04-08.2 EDMs: Complementary Experiments and Theory Connections
S. DEGENKOLB (Heidelberg University), P. SCHMIDT-WELLENBURG (Paul Scherrer Institute), G. Pignol (LPSC), J. DE VRIES (University of Amsterdam), R. BERGER (Philipps-Universität Marburg)

APRIL

15-19.4 Bridging Scales: At the Crossroads among Renormalisation Group, Multi-Scale Modelling, and Deep Learning
R. MENICHETTI (University of Trento), F. PEDERIVA (University of Trento), R. POTESTIO (University of Trento), A. ROGGERO (University of Trento)

22-26.4 The Physics of Strongly Interacting Matter: Neutron Stars, Cold Atomic Gases and Related Systems
A. SCHWENK (TU Darmstadt), F. FERLAINO (University of Innsbruck), C. PETHICK (Niels Bohr Institute), A. WATTS (University of Amsterdam)

MAY

7-10.5 Quantum Science Generation 2024
D. DE BERNARDIS (INO-CNR), V. PANIZZA (University of Trento), L. VESPUCCI (University of Trento), A. BALDAZZI (University of Trento), V. AMITRANO (University of Trento), C. BENAVIDES-RIVEROS (INO-CNR), A. BERTI (INO-CNR), A. NARDIN (University of Trento)

13-17.5 SPICE: Strange Hadrons as a Precision Tool for Strongly InteraCting SystEms
J. POCHODZALLA (University of Mainz), C. CURCEANU (INFN-LNF), B. DOENIGUS (University of Frankfurt), L. FABBIETTI (TU Munich), S. NAKAMURA (University of Tokyo), F. SAKUMA (RIKEN), I. VIDANA (INFN Catania)

20-24.5 Beyond-Eikonal Methods in High-Energy Scattering
J. JALILIAN-MARIAN (Baruch College), A. CZAJKA (NCBJ), Y. KOVCHEGOV (Ohio State University)

27-31.5 Machine Learning and the Renormalization Group
J. URBAN (MIT), D. HACKETT (Fermilab), A. HASENFRATZ (University of Colorado Boulder), J. PAWLOWSKI (Heidelberg University), B. LUCINI (Swansea University)

JUNE

3-7.6 A Modern Odyssey: Quantum Gravity meets Quantum Collapse at Atomic and Nuclear Physics Energy Scales in the Cosmic Silence
C. CURCEANU (INFN-LNF), A. BASSI (University and INFN Trieste), L. BAUDIS (University of Zurich), A. MARCIANO (Fudan University China), K. PISCICCHIA (CREF & Centro Ricerche Enrico Fermi), L. DIOSI (Wigner, University of Budapest)

10-14.6 Diffraction and Gluon Saturation at the LHC and the EIC
C. ROYON (University of Kansas), M. HENTSCHINSKI (Universidad de las Americas Puebla), A. SABIO VERA (Universidad Autonoma de Madrid), S. SCHLICHTING (University of Bielefeld), A. DESHPANDE (Stony Brook University)

17-21.6 Towards a Consistent Approach for Nuclear Structure and Reaction: Microscopic Optical Potentials
C. BARBIERI (University of Milan), C. ELSTER (Ohio University), C. HEBBORN (FRIB), A. OBERTELLI (TU Darmstadt)

JUY

1-5.7 New Opportunities and Challenges in Nuclear Physics with High Power Lasers
C.J. YANG (ELI-NP), K. SPOHR (ELI-NP), P. TOMOSSINI (ELI-NP), Y. FUKADA (Kansai Photon Science Institute), V. HORNY (ELI-NP), L. GIZZI (INO), D. DOMENICO (ELI-NP)

8-12.7 Synergies between LHC and EIC for Quarkonium Physics
F. CELIBERTO (Universidad de Alcalà), C. VAN HULSE (Universidad de Alcalà), J.P. LANSBERG (CNRS), D. KIKOLA (Warsaw University of Technology), D. BOER (University of Groningen), E. GONZALES-FERREIRO (IGFAE), C. FLORE (University of Turin)

15.7-2.8 DTP/TALENT: Training in Advanced Low Energy Nuclear Theory: Nuclear Theory for Astrophysics
A. ARCONES (TU Darmstadt & GSI), B. GIACOMAZZO (University of Milano-Bicocca), J. PIEKAREWICZ (Florida State University)

AUGUST

5-9.8 Towards Improved Hadron Tomography with Hard Exclusive Reactions
M. BOER (Virgina Tech), A. CAMSONNE (Jlab), J. WAGNER (NCBJ)

19-23.8 The Nuclear Interaction: Post-Modern Developments
R. TIMMERMANS (University of Groningen), J. McGOVERN (University of Manchester), M. PIARULLI (Washington University), U. VAN KOLCK (IJClab Orsay)

SEPTEMBER

9-13.9 New Developments in Studies of the QCD Phase Diagram
H. DING (Central China Normal University), F. KARSCH (University of Bielefeld), M.P.LOMBARDO (INFN Florence), P. PETRECZKY (BNL)

16-20.9 Spin and Quantum Features of QCD Plasma
F. BECATTINI (University and INFN Florence), X. HUANG (Fudan University), D. RISCHKE (Goethe University Frankfurt), Y. YIN (CAS)

30.9-4.10 KAMPAI - Kaonic, Antiprotonic, Muonic, Pionic and "onia" exotic Atoms: Interchanging Knowledge
A. SCORDO (INFN Frascati), P. INDELICATO (Laboratoire Kastler Brossel), J. OBERTOVA (Czech Technical University, Prague), C. CURCEANU (INFN-LNF), A. KNECHT (PSI), M. SKURZOK (Jagiellonian University of Krakow), T. HASHIMOTO (JAEA)

OCTOBER

14-25.10 Measuring Neutrino Interactions for Next-Generation Oscillation Experiments
S. DOLAN (CERN), C. WILKINSON (LBNL), C. WRET (University of Oxford), L. PICKERING (Rutherford Appleton Laboratory)

NOVEMBER

4-8.11 Universal Themes in Bose-Einstein Condensation
J. CARUSOTTO (INO-CNR BEC Center), T. GIAMARCHI (University of Geneva), G. FERRARI (University of Trento), D. SNOKE (University of Pittsburgh), P. LITTLEWOOD (University of Chicago), F. M. MARCHETTI (UAM), N. PROUKAKIS (University of Newcastle)

DECEMBER

02-06.12 Penetrating Probes of Hot High-mu_B matter: Theory Meets Experiment
E. SCOMPARIN (INFN Turin), T. GALATYUK (TU Darmstadt), M.P. Lombardo (INFN Florence), R. RAPP (Texas A&M University), G. USAI (University Cagliari)

The ECT* is part of the Fondazione Bruno Kessler. The Centre is funded by the Autonomous Province of Trento, funding agencies of EU Member and Associated states, and by INFN-TIFPA and has the supportof the Department of Physics of the University of Trento. The Interim Director of ECT* is Prof. Gert Aarts (ECT* and Swansea University).
For information: staff@ectstaff.eu | www.ectstar.eu

Wikipedia

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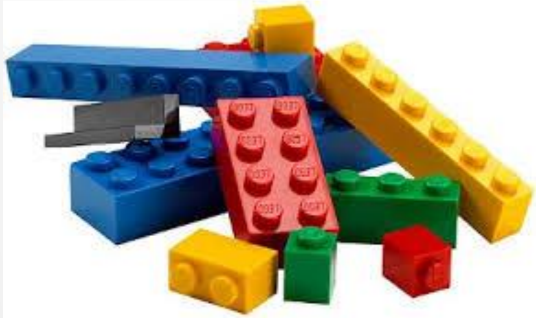
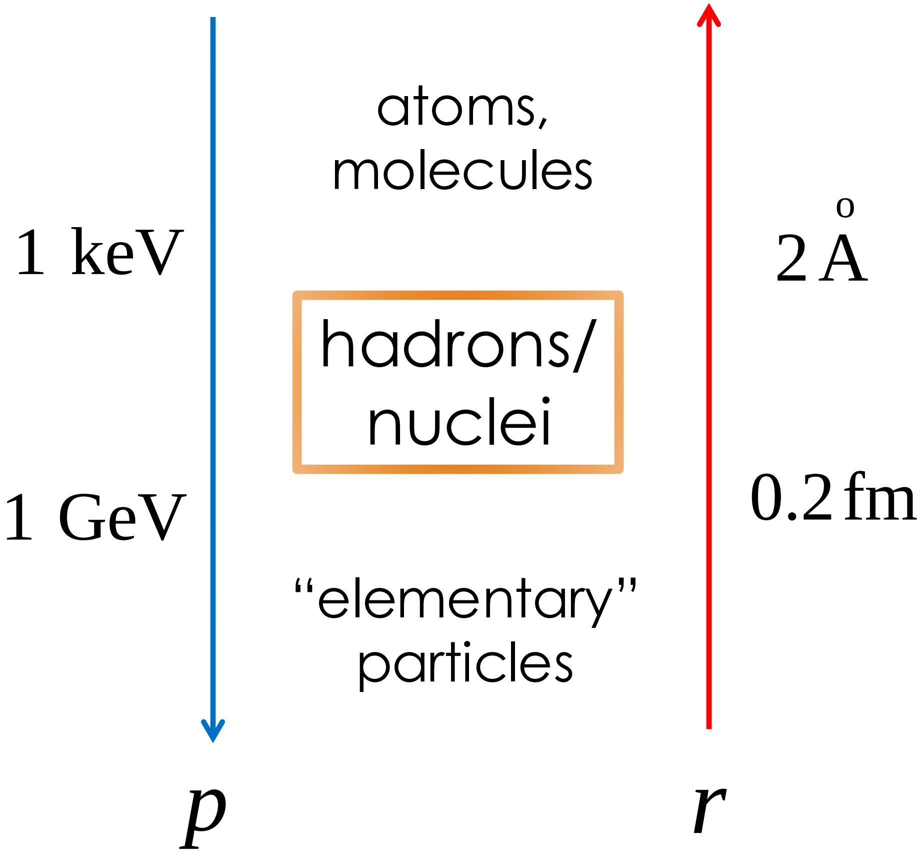
Ideal for
CRC
activities!

The scenic route

"reduction":
what are the
building blocks?





atoms,
molecules

1 keV

$2\,\text{Å}$

hadrons/
nuclei

1 GeV

$0.2\,\text{fm}$

"elementary"
particles

p

r

"emergence":
how do the building
blocks fit together?

$$pr : 1$$

uncertainty principle

Heisenberg '27

Here: $h = 1, c = 1$

$$[m] = [E] = [p] = [r]^{-1} = [t]^{-1}$$

Framework: Effective Field Theory

“Folk Theorem”

Weinberg ‘79

The quantum field theory generated by the most general Lagrangian with some assumed symmetries will produce the most general S matrix incorporating quantum mechanics, Lorentz invariance, unitarity, cluster decomposition and those symmetries, with no further physical content.

independence from high-momentum/short-distance *details*

regulator = infinite series of interactions, with constrained coefficients

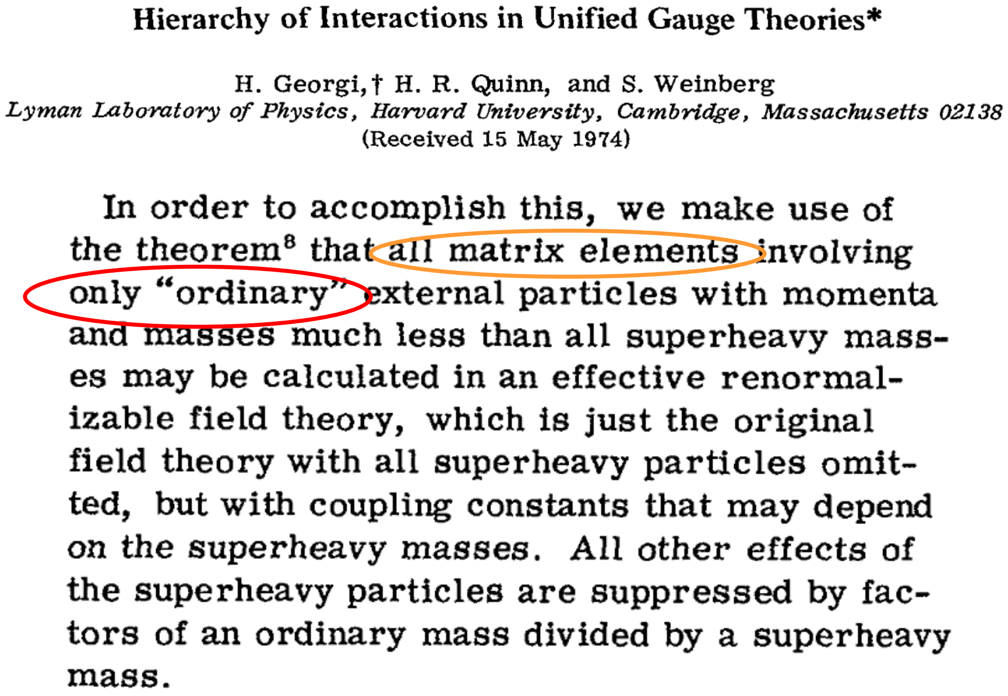
NOT
most general

⇒ renormalization

“Nonrenormalizable theories are as renormalizable as renormalizable theories”
(S. Weinberg, many times)

Standard Model as an EFT

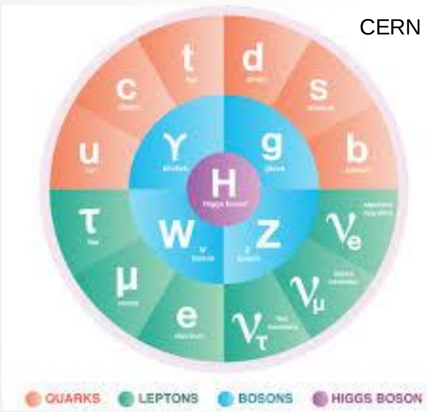
¿ neutrino masses, galaxy rotations and lensing, matter-antimatter asymmetry
unnaturalness, many parameters, non-unified group structure, general relativity, *etc.* ?



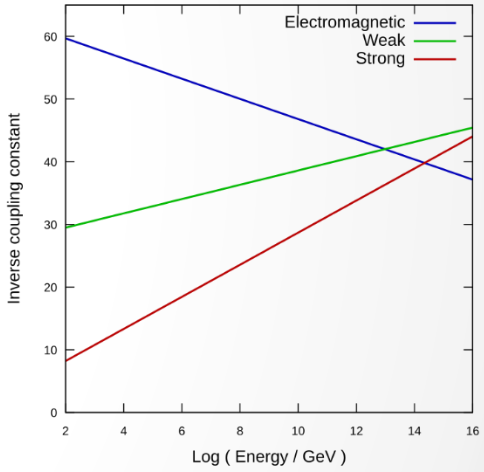
Hierarchy of Interactions in Unified Gauge Theories*

H. Georgi,† H. R. Quinn, and S. Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 15 May 1974)

In order to accomplish this, we make use of the theorem[8] that all matrix elements involving only "ordinary" external particles with momenta and masses much less than all superheavy masses may be calculated in an effective renormalizable field theory, which is just the original field theory with all superheavy particles omitted, but with coupling constants that may depend on the superheavy masses. All other effects of the superheavy particles are suppressed by factors of an ordinary mass divided by a superheavy mass.



CERN



Victor Balcus/Creative Commons

"extraordinary" light particles?

dark matter, right-handed neutrinos, axions,
additional gauge bosons, X17…

higher-dimensional operators

violation of accidental symmetries,
small corrections to nonzero quantities

The Way of EFT

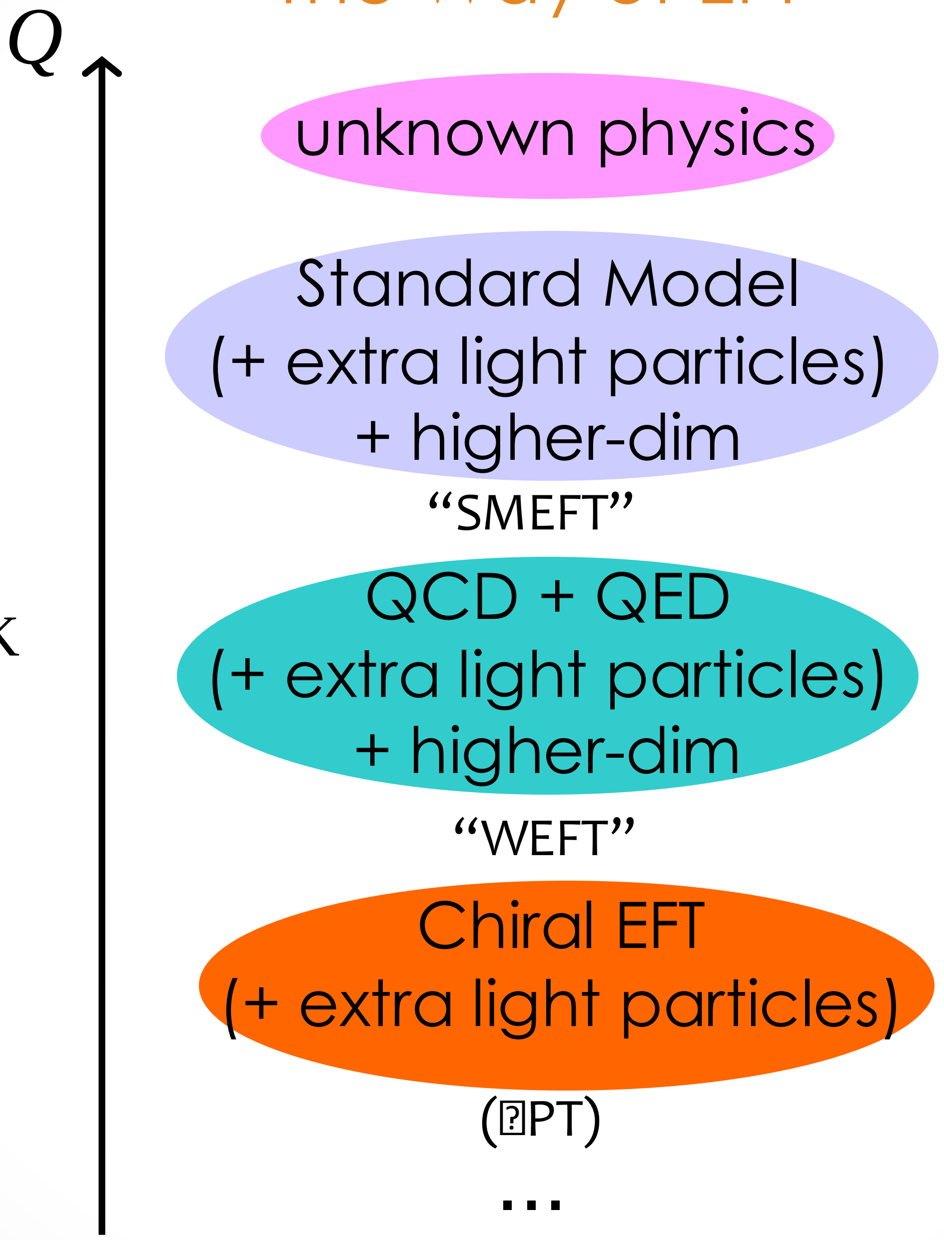
$M_{\not{L}}$: ?

$M_{\rm EW}$: v, m_Z, m_W
: 100 GeV

$M_{\rm QCD}$: $m_N, m_\rho, 4\pi f_\pi, \ldots$
: 1 GeV

$M_{\rm nuc}$: $f_\pi, 1/r_{NN}, m_\pi, \ldots$
: 100 MeV

...



unknown physics

Standard Model
(+ extra light particles)
+ higher-dim

“SMEFT”

QCD + QED
(+ extra light particles)
+ higher-dim

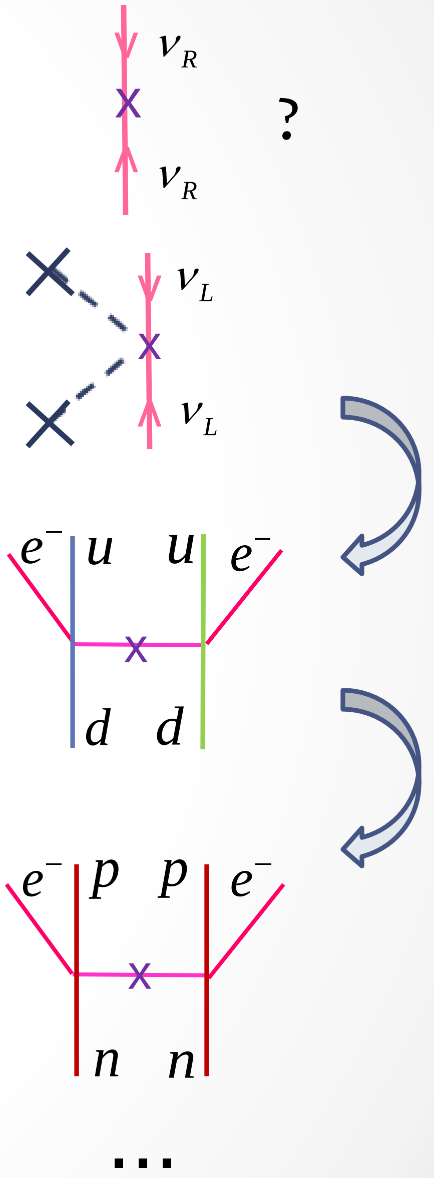
“WEFT”

Chiral EFT
(+ extra light particles)

(χPT)

...

example



run
RG

match
with
lattice,
...

$Q \sim M_{\mathrm{EW}}$

The horizon

$$\mathcal{L}_{\mathrm{SMEFT}} = \boxed{\mathcal{L}_{\mathrm{SM}}} + \mathcal{L}_{\mathrm{dim}=5} + \mathcal{L}_{\mathrm{dim}=6} + \ldots + \mathcal{L}_{\mathrm{dim}=9} + \ldots$$

Weinberg '67
Salam '68
…
Weinberg '79

Rao + Shrock '82
…
Weinberg '79'80
Wilczek + Zee '79
Abbott + Wise '80
…

B-L accidental sym

$|\Delta L| = 2$

$\not{P}, \not{T}$

$|\Delta B| = |\Delta L| = 1$

$|\Delta B| = 2$

HADRON STRUCTURE

NUCLEAR STRUCTURE

$nn \to ppee$

neutrinoless double-beta decay

nucleon electric dipole moments

light-nuclear EDMs

proton decay

neutron-antineutron oscillations

nuclear decay

“Background”: STRONG INTERACTIONS

corrections to running of weak mixing angle
single-beta decay properties
neutrino properties
muon properties
muonic atoms
…

QC(+E)D (LITE)

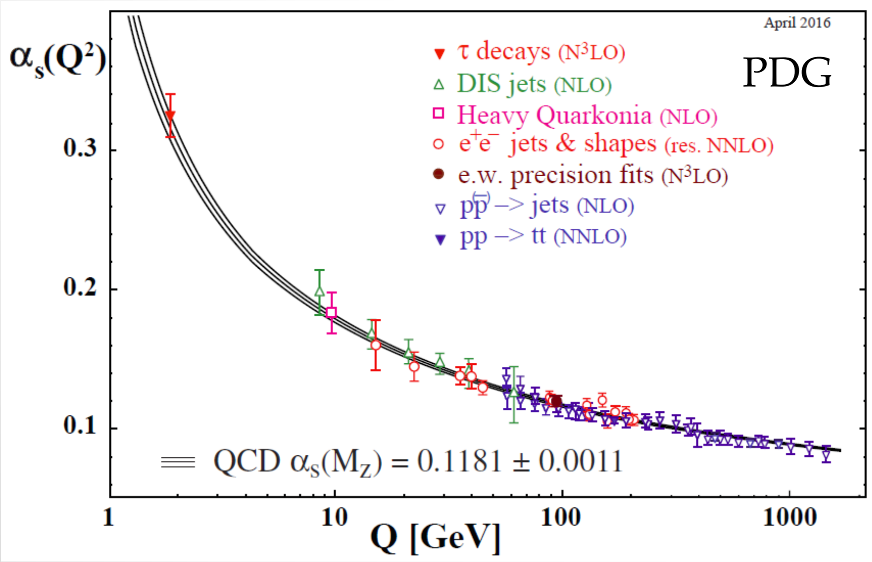
d.o.f.s quarks: $q=\begin{pmatrix}u\\ d\end{pmatrix}$ gluons: G^{a}_{μ} (+ photon)

symmetries SO(3,1) global, $\mathrm{SU(3)_c}$ $(+\mathrm{U(1)_{em}})$ gauge

$Q = M_{\mathrm{EW}}$

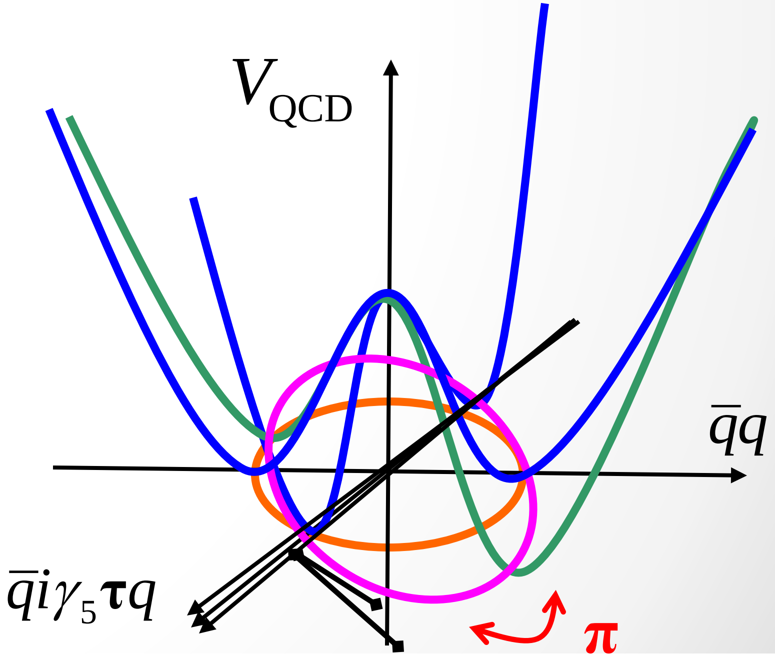
Basic
mass scales

$$\mathrm{L}_{\mathrm{QCD}} = \underbrace{\bar q\left(i\not\partial + g_s \not G\right)q - \frac{1}{2}\mathrm{Tr}\,G^{\mu\nu}G_{\mu\nu}}_{M_{\mathrm{QCD}} \,:\, m_N, m_\rho, 4\pi f_\pi, \mathrm{K} \,:\, 1\,\mathrm{GeV}} + \underbrace{\bar m\,\bar q\left(1-\varepsilon\tau_3\right)q}_{m_\pi \,:\, \sqrt{\bar m M_{\mathrm{QCD}}}\,;\, 140\,\mathrm{MeV}} + \mathrm{K}$$



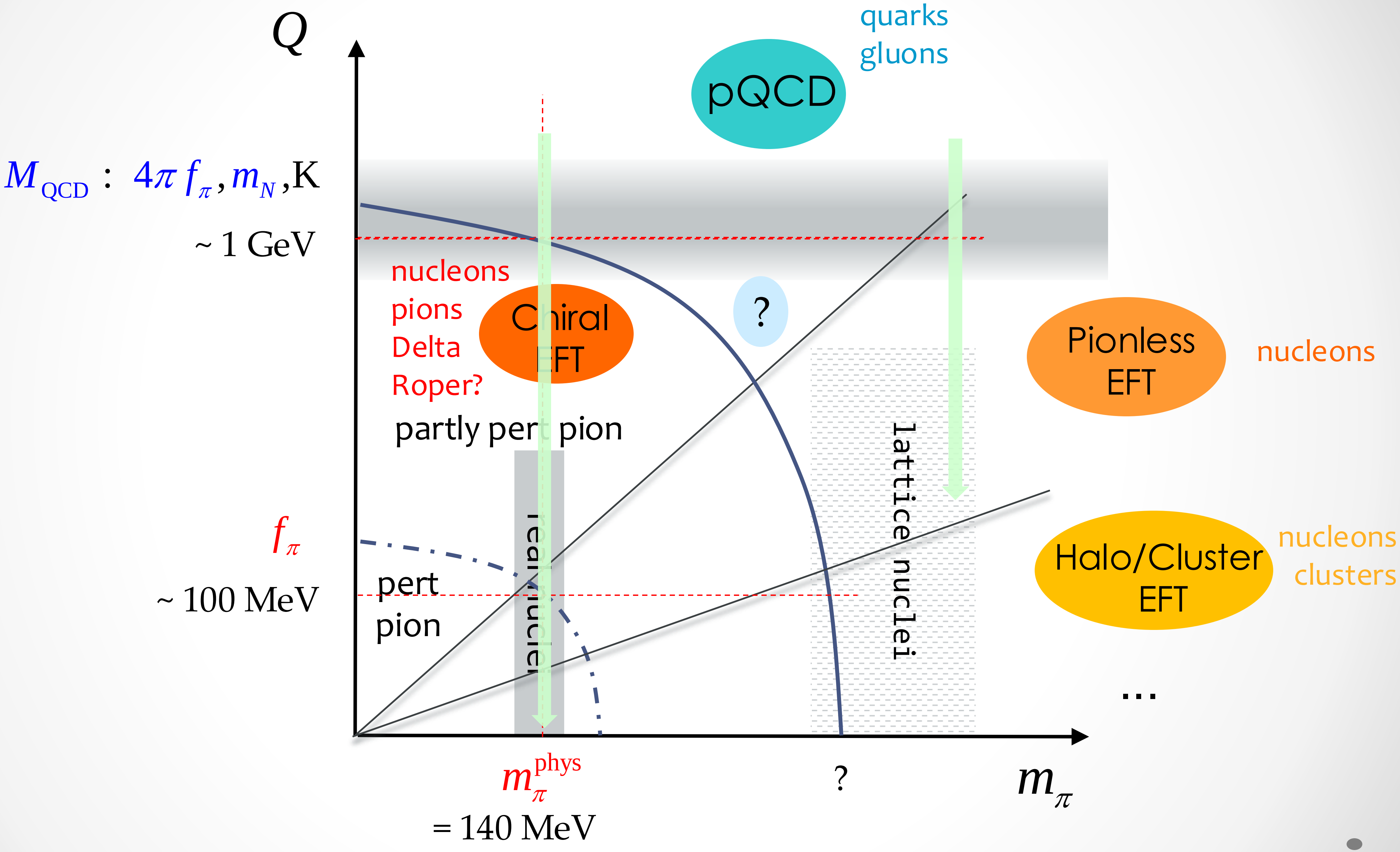
Gross + Wilczek '73
Politzer '73
…

Nambu '64
…



$$f_\pi \,:\, M_{\mathrm{QCD}}/4\pi + \mathrm{O}(\bar m)\,;\; 100\,\mathrm{MeV}$$

Hadronic/Nuclear EFT Landscape



Q

M_{QCD} : $4\pi f_\pi, m_N, \ldots$

~ 1 GeV

f_π

~ 100 MeV

pQCD

quarks
gluons

nucleons
pions
Delta
Roper?

Chiral EFT

partly pert pion

pert
pion

real nuclei

?

lattice nuclei

Pionless EFT

nucleons

Halo/Cluster EFT

nucleons
clusters

…

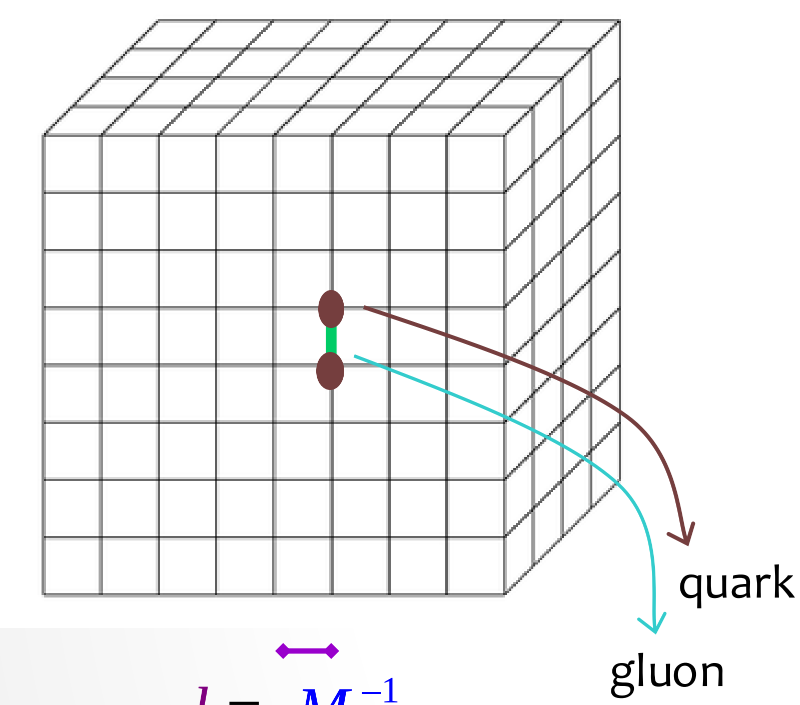
m_π^{phys}
= 140 MeV

?

m_π

Lattice QCD

Wilson ’75
…



$l = M_{QCD}^{-1}$

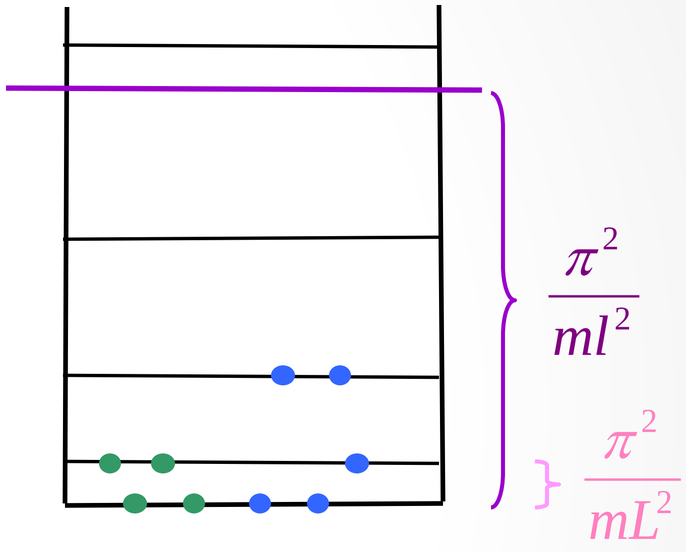
$L ? \; m_\pi^{-1}$

difficulty:
large enough lattices

path integral
with
Monte Carlo

$$\boxed{\begin{array}{l} \Lambda : 1/l \\ \lambda : 1/L \end{array}}$$

lattice “model space”

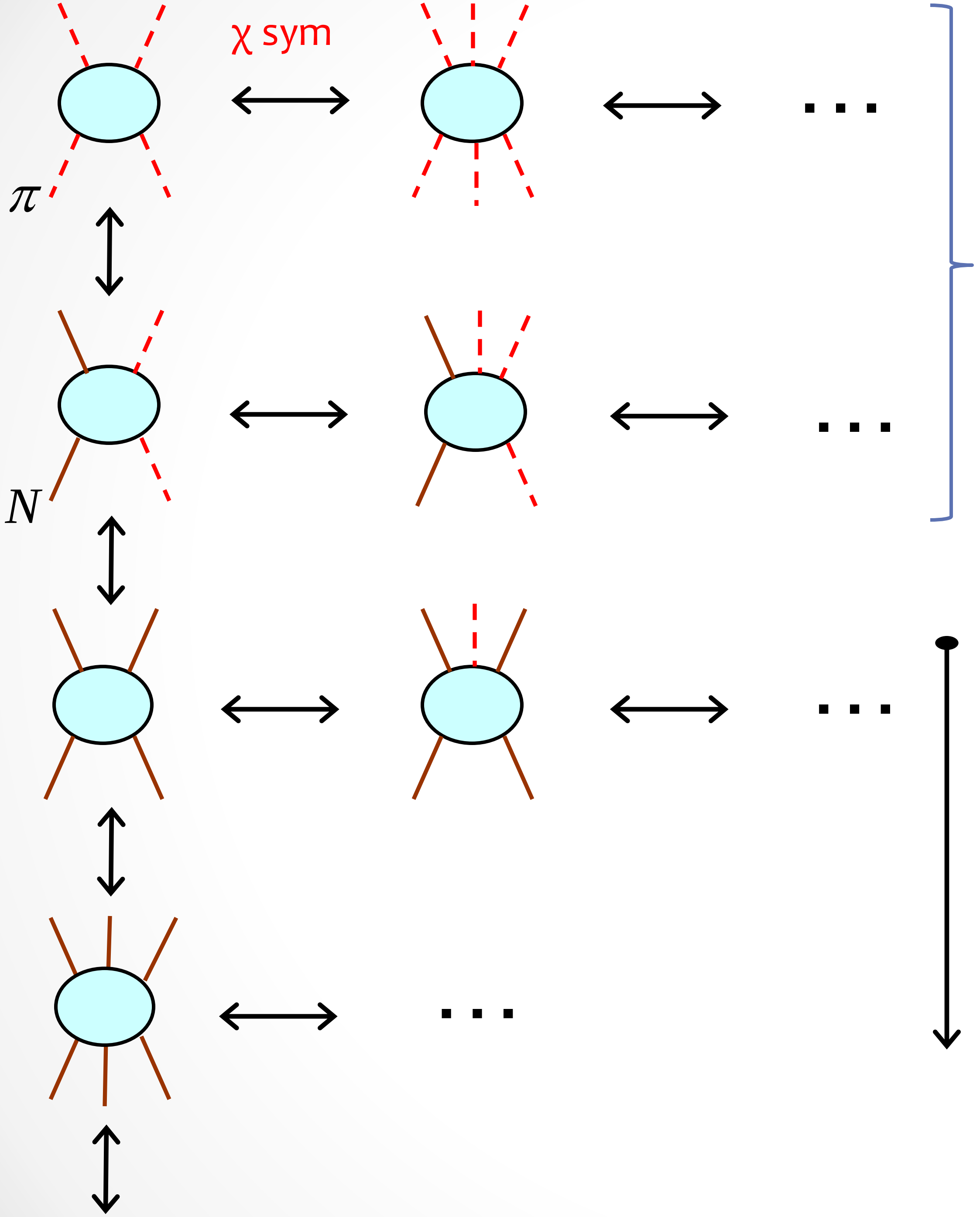


$$\cot\delta(E) = \frac{4}{\sqrt{mEl}}\left[\frac{\pi l}{L}\sum_{\mathbf{n}}^{|\mathbf{n}|<L/l}\frac{1}{(2\pi\mathbf{n})^2 - mEL^2} - 1\right]$$

Lüscher ‘91

fix:
large pion masses,
small number of nucleons

Chiral EFT



Weinberg ’79
Gasser + Leutwyler ’84
…

Chiral Perturbation Theory

Gasser, Sainio + Švarc ’87
Bernard, Kaiser + Meißner ‘90
Jenkins + Manohar ’91
…

Weinberg ’90
Rho ’91
Weinberg ’91
Ordóñez + vK ’92
Weinberg ‘92
vK ’94
…

Non-perturbative
at leading order!

(Distorted-wave)
perturbation theory
at subleading orders

Pionless EFT
- integrate out pions
- different power counting

vK '97
Bedaque + vK '97
…

Halo/Cluster EFT
- integrate in tight nucleon clusters
- different power counting

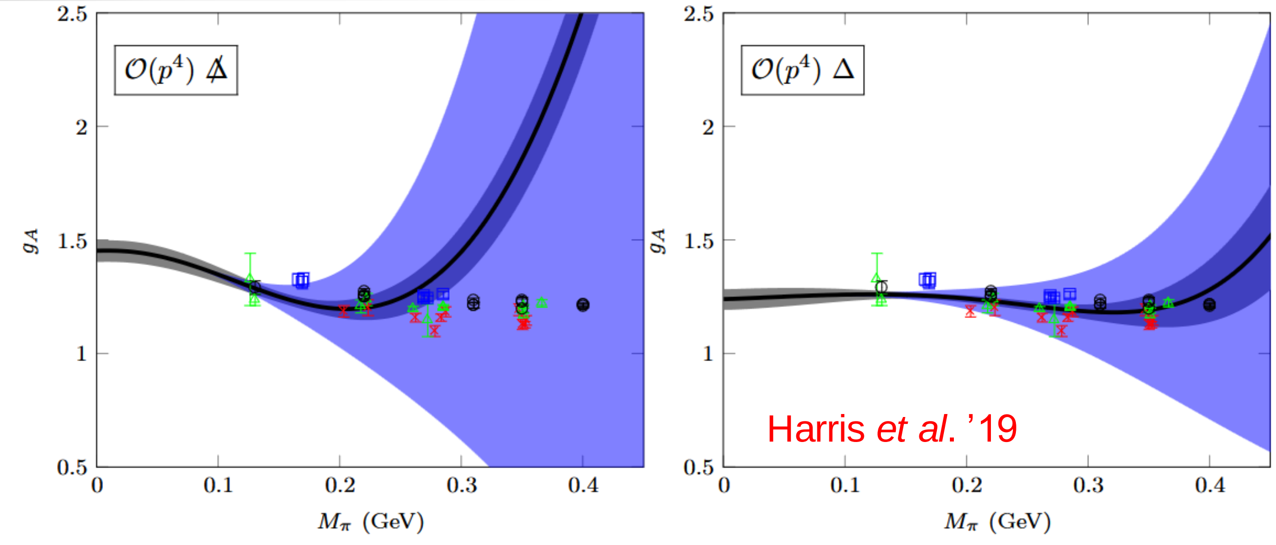
Bertulani, Hammer + vK '02
Bedaque, Hammer + vK '03
…

⋮

adapted to lower energies (shallow nuclei, low-energy reactions)
but no explicit constraints from chiral symmetry

A peek over the hill

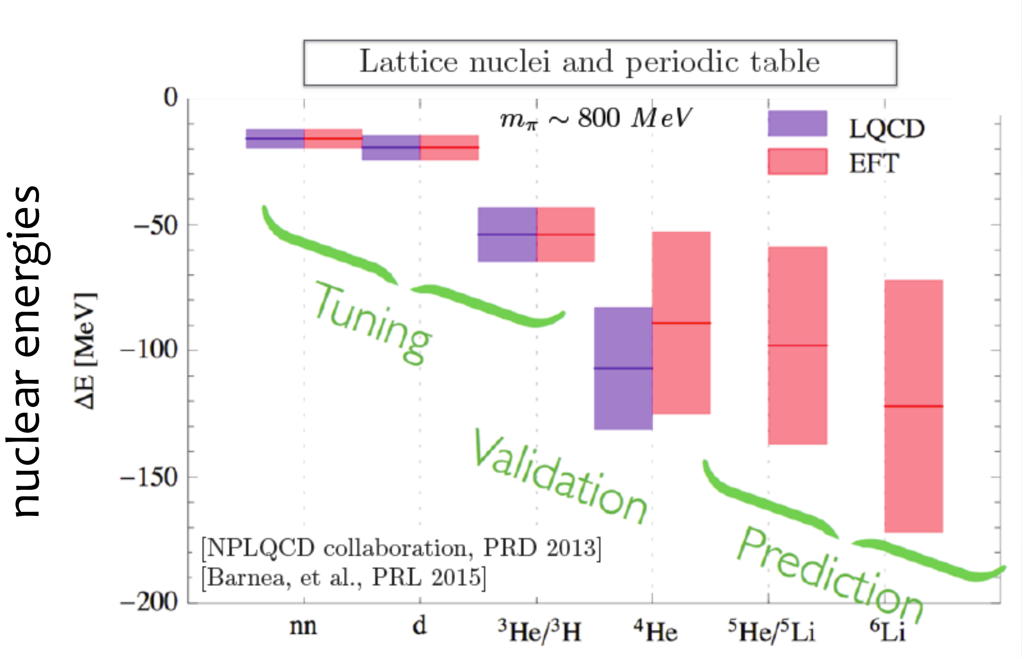
Alvarado + Alvarez-Ruso, *Phys. Rev. D* **105** (2022) 074001



Harris *et al.* '19

Barnea *et al.*'15

...



nuclear energies

Tuning

Validation

Prediction

Z. Davoudi

Chiral EFT with Delta

Pascalutsa + Phillips '02

...

LO Pionless EFT

but LQCD data under scrutiny

The green valley

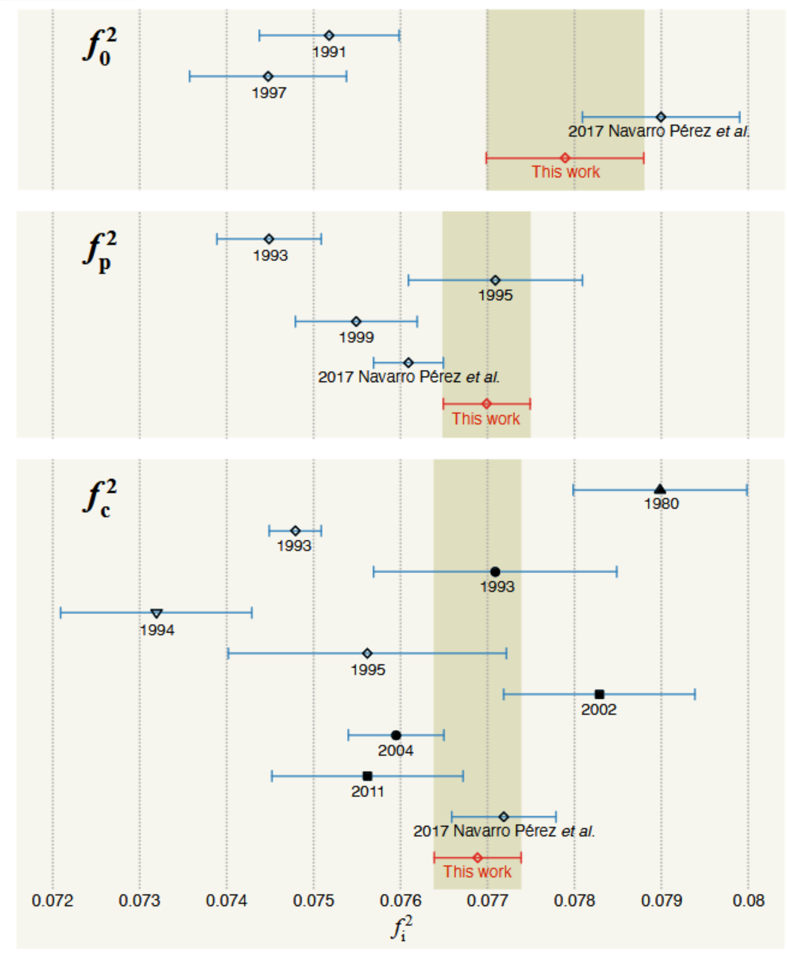
$$f = \frac{g_A m_{\pi^+} d}{4\sqrt{\pi}\, f_\pi}$$

pion-nucleon couplings

average neutral pion

neutral pion -proton

charged pion

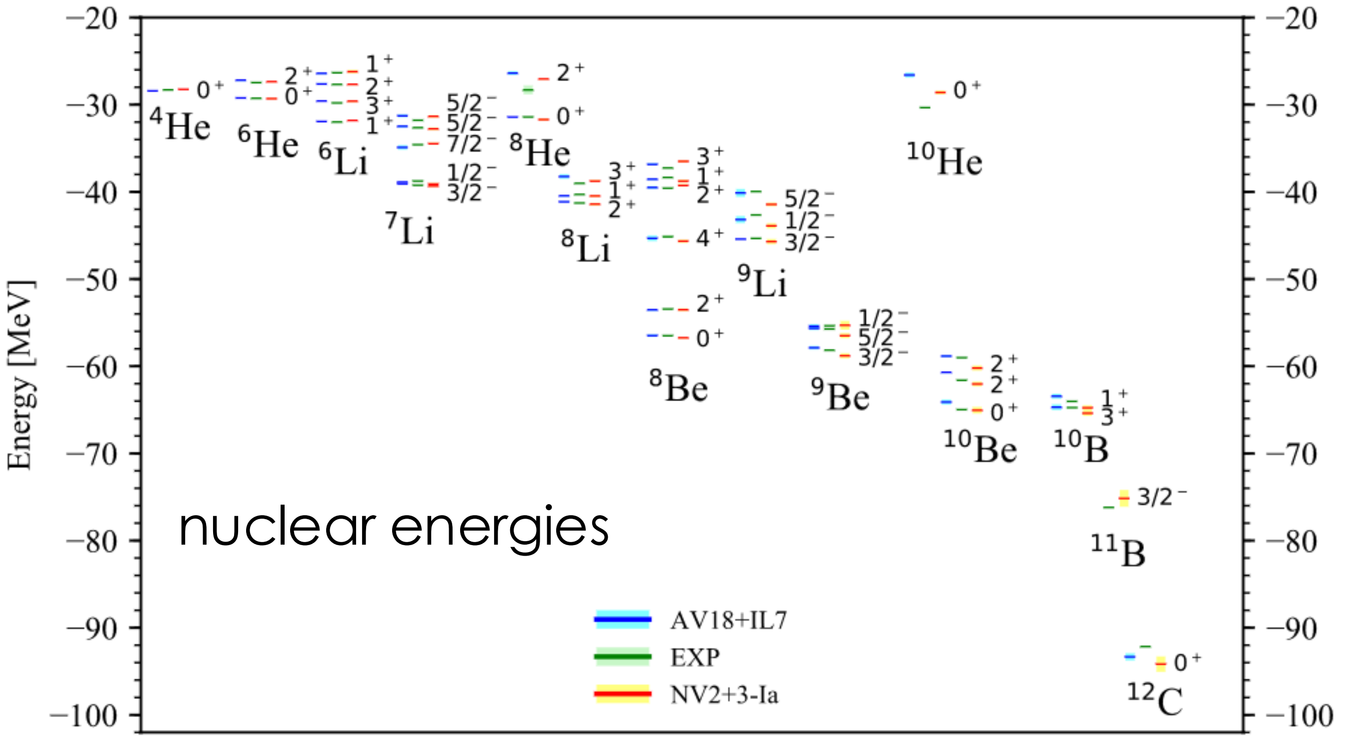


filled: πN

empty: NN

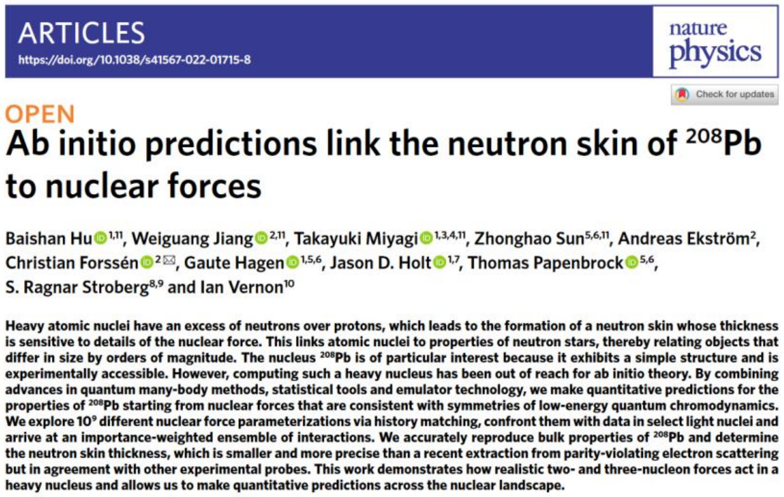
Reinert, Krebs + Epelbaum, *Phys. Rev. Lett.* **126** (2021) 092501

Piarulli *et al.*, *Phys. Rev. Lett.* **120** (2018) 052503



nuclear energies

Resumming some subleading corrections


ARTICLES

https://doi.org/10.1038/s41567-022-01715-8

nature physics

Check for updates

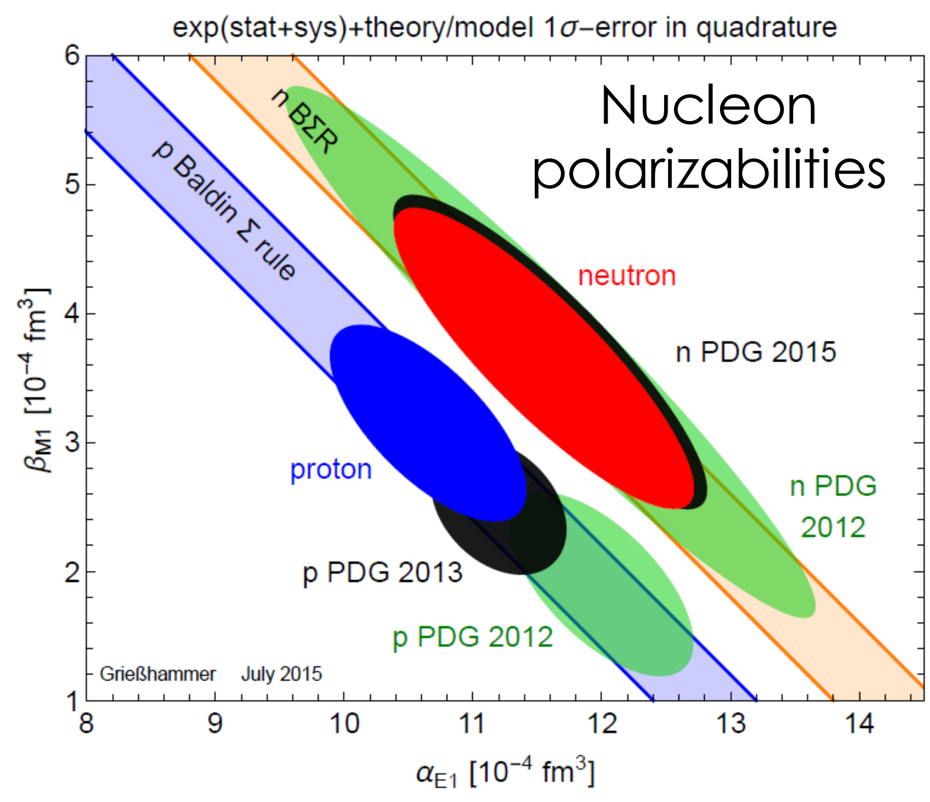
OPEN

Ab initio predictions link the neutron skin of ^{208}Pb to nuclear forces

Baishan Hu[1,11], Weiguang Jiang[2,11], Takayuki Miyagi[1,3,4,11], Zhonghao Sun[5,6,11], Andreas Ekström[2], Christian Forssén[2]✉, Gaute Hagen[1,5,6], Jason D. Holt[1,7], Thomas Papenbrock[5,6], S. Ragnar Stroberg[8,9] and Ian Vernon[10]

Heavy atomic nuclei have an excess of neutrons over protons, which leads to the formation of a neutron skin whose thickness is sensitive to details of the nuclear force. This links atomic nuclei to properties of neutron stars, thereby relating objects that differ in size by orders of magnitude. The nucleus ^{208}Pb is of particular interest because it exhibits a simple structure and is experimentally accessible. However, computing such a heavy nucleus has been out of reach for ab initio theory. By combining advances in quantum many-body methods, statistical tools and emulator technology, we make quantitative predictions for the properties of ^{208}Pb starting from nuclear forces that are consistent with symmetries of low-energy quantum chromodynamics. We explore 10^9 different nuclear force parameterizations via history matching, confront them with data in select light nuclei and arrive at an importance-weighted ensemble of interactions. We accurately reproduce bulk properties of ^{208}Pb and determine the neutron skin thickness, which is smaller and more precise than a recent extraction from parity-violating electron scattering but in agreement with other experimental probes. This work demonstrates how realistic two- and three-nucleon forces act in a heavy nucleus and allows us to make quantitative predictions across the nuclear landscape.

… including currents



Grießhammer, McGovern, Phillips,
arXiV: 1509.09177

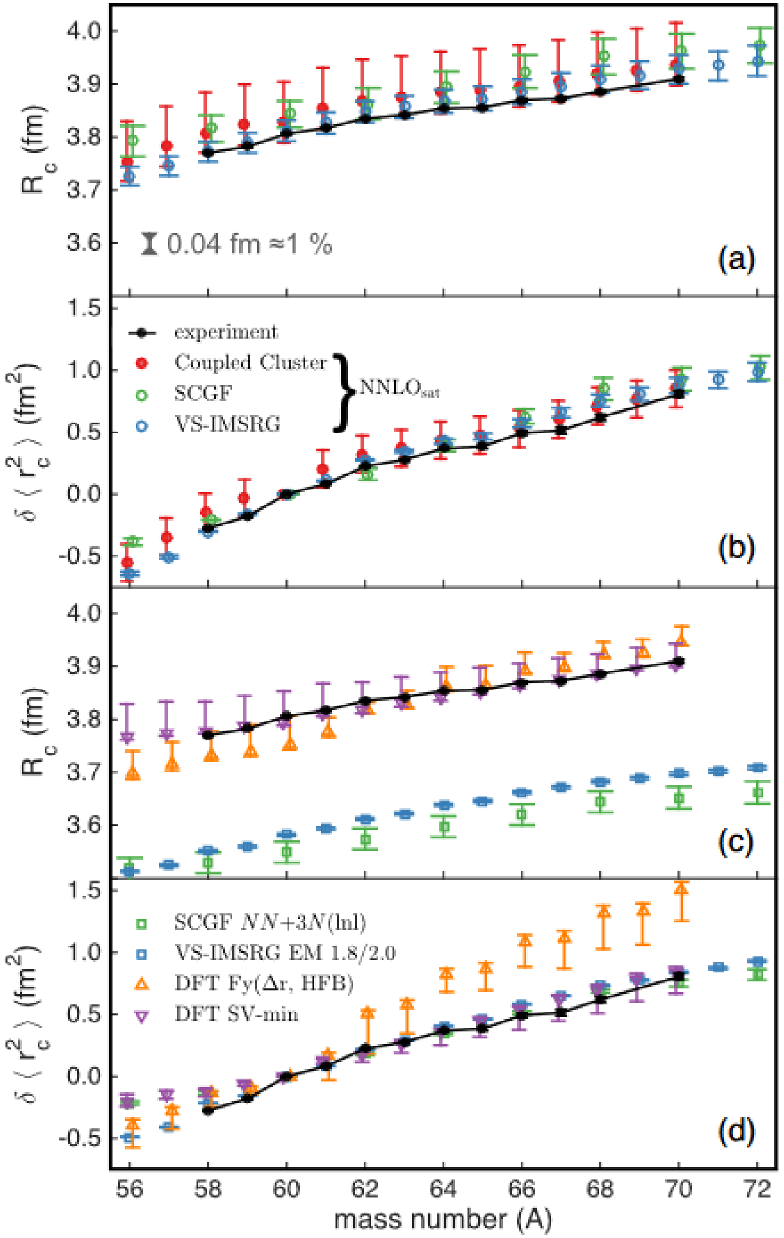
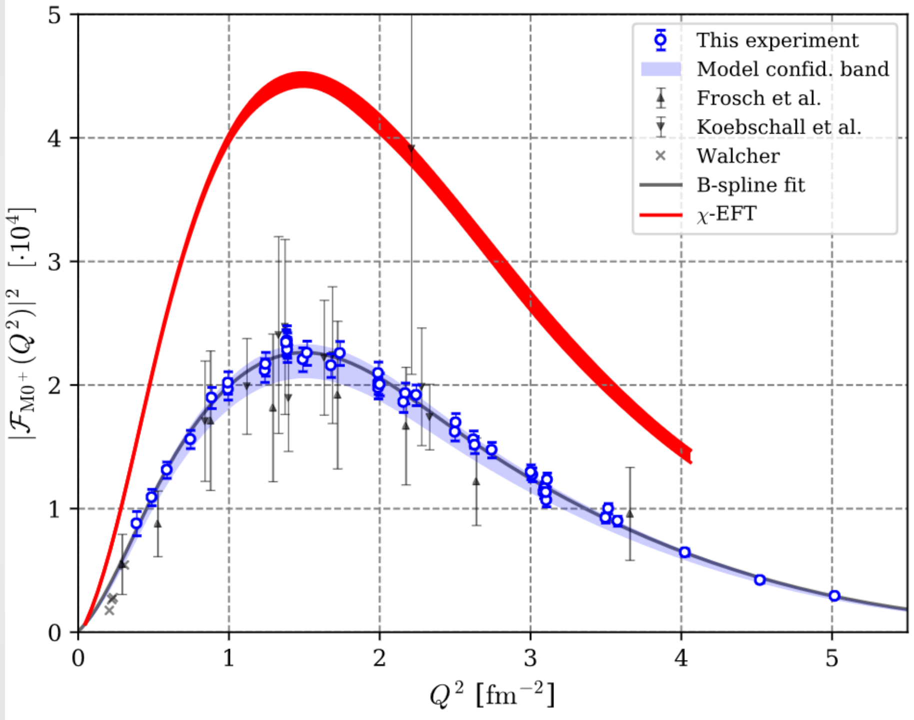


FIG. 2. Nuclear charge radii R_c (a,c) and differentials $\delta\langle r_c^2\rangle^{60,A}$ (b,d) of Ni isotopes with respect to ^{60}Ni as reference. Experimental data are compared to theoretical results. See text for details.

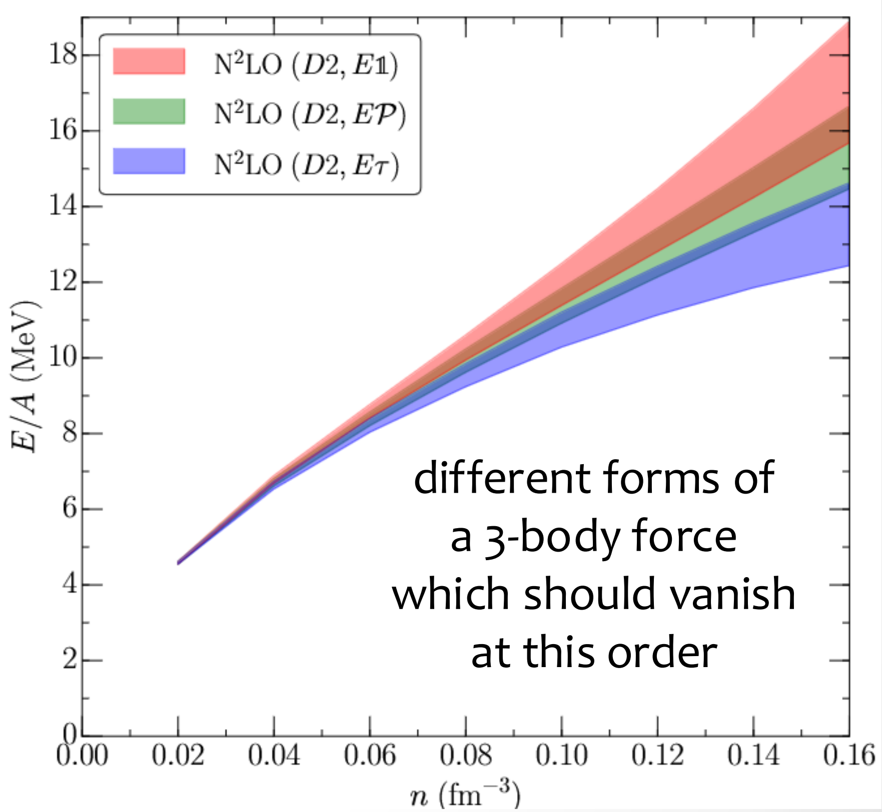
Malbrunot-Ettanauer *et al.*, *Phys. Rev. Lett.* **128** (2022) 022502

alpha-particle
transition monopole form factor



Kegel *et al*., *Phys. Rev. Lett.* **130** (2023) 152052

neutron matter
equation of state

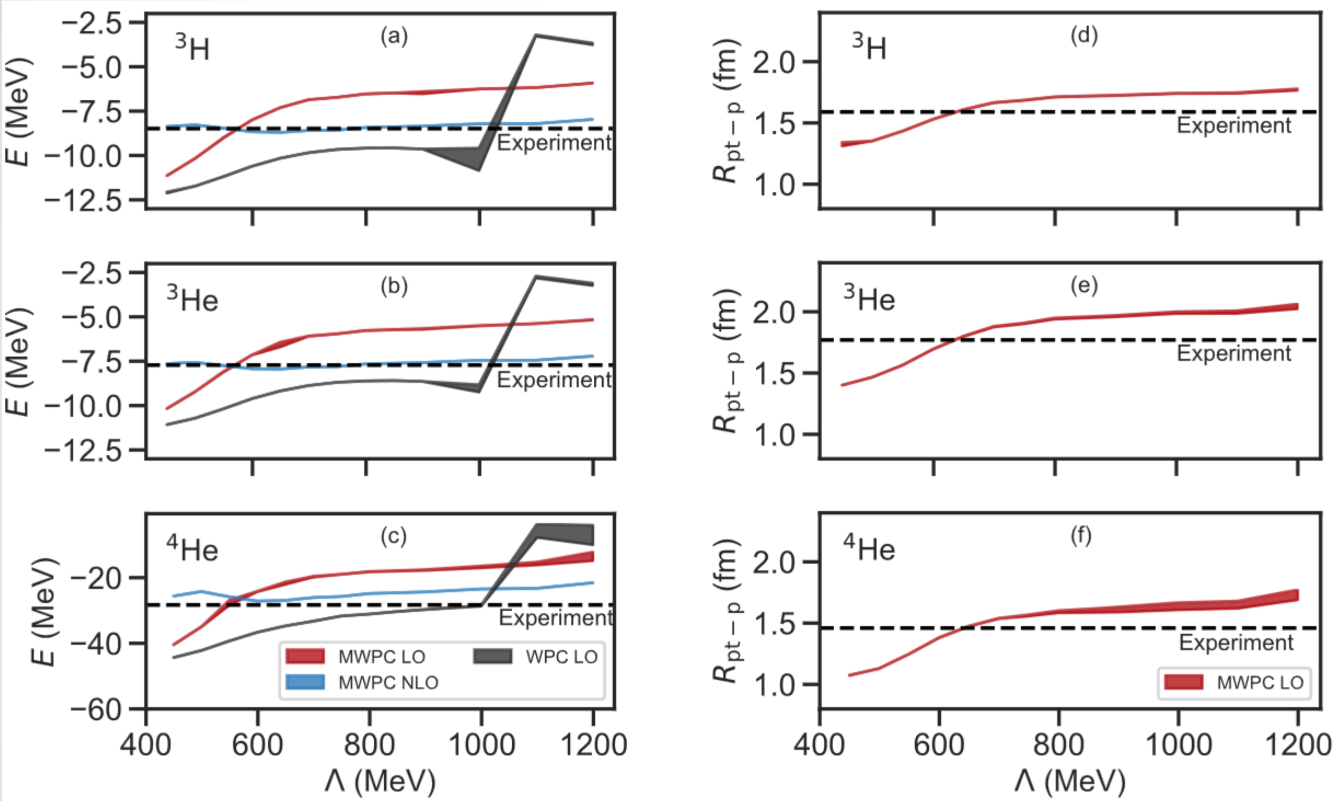


different forms of
a 3-body force
which should vanish
at this order

Lynn *et al*., *Phys. Rev. Lett.* **116** (2016) 062501

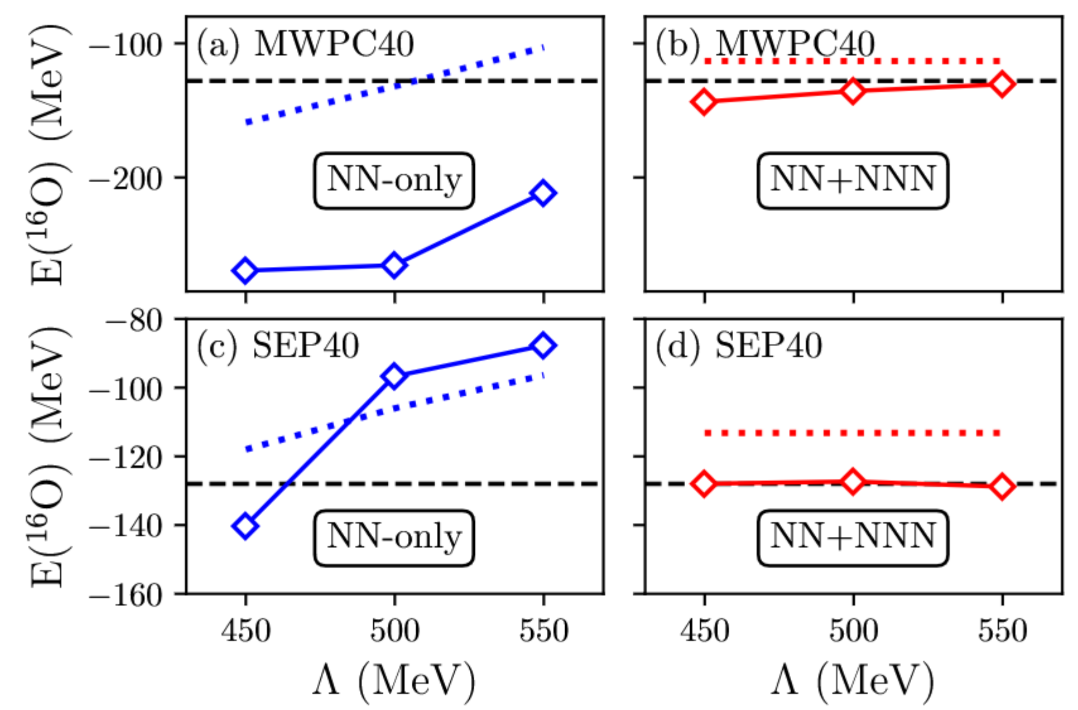
regulator dependence
= model dependence

corrected power counting



Yang, Ekström, Forssén + Hagen, *Phys. Rev. C* **103** (2021) 054304

LO



Yang et al., *Eur. Phys. J. A* **59** (2023) 233

Through the hadronic/nuclear lens: nuclear scattering as a tool

dark matter scattering off
deuterons and alpha particles

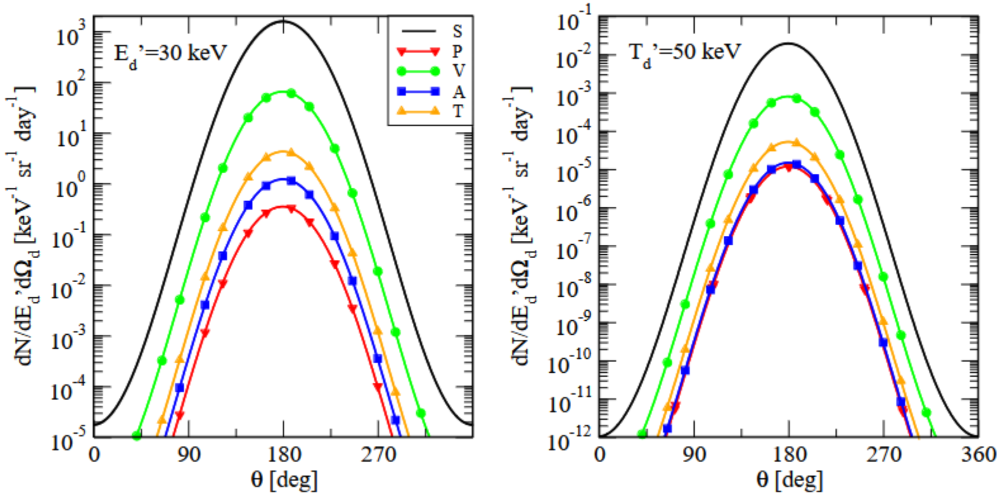


FIG. 3. (color online) The number of scattered deuterons per day as function of the angle between $\boldsymbol{V}$ and $\boldsymbol{P}'_d$ by a 100 ton of deuterium, per unit of energy (keV) and solid angle (sr). For all cases we have taken $M_\chi = 10$ GeV and $C_+^X = 10^{-4}$ for the sake of comparison. The left (right) panel reports the number of events for scattered deuterons of recoil energy 30 (50) keV. All the results are presented as (very narrow) bands (see the main text for more detail).

Chiral
EFT

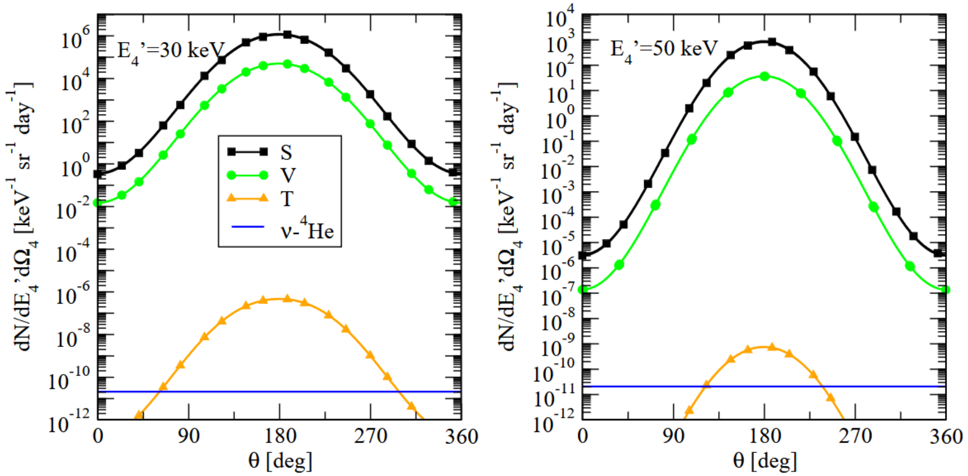


FIG. 7. (color online) The same as Fig. 3 but for ^{4}He. The horizontal blue lines denote the number of scattered ^{4}He per day due to the bac

WIMP-nucleon contact interactions

Filandri + Viviani, *Phys. Rev. C* **110** (2024) 034002

Through the hadronic/nuclear lens: chiral symmetry as a filter

De Vries, Timmermans,
Mereghetti + vK '11
Mereghetti *et al.*'11
De Vries *et al.*'11
...

Chiral EFT

$\not{P}, \not{T}$ sources

electric dipole moments

$Q: f_\pi$		θ term	qEDM	qCEDM	gCEDM, PSC	LRC
$^1\mathrm{H}$	d_p/d_n	$O(1)$	$O(1)$	$O(1)$	$O(1)$	$O(1)$
$^2\mathrm{H}$	d_d/d_n	$O(1)$	$O(1)$	$O\left(\frac{M_{\mathrm{QCD}}^2}{Q^2}\right)$	$O(1)$	$O\left(\frac{M_{\mathrm{QCD}}^2}{Q^2}\right)$
$^3\mathrm{He}$	d_h/d_n	$O\left(\frac{M_{\mathrm{QCD}}^2}{Q^2}\right)$	$O(1)$	$O\left(\frac{M_{\mathrm{QCD}}^2}{Q^2}\right)$	$O(1)$	$O\left(\frac{M_{\mathrm{QCD}}^2}{Q^2}\right)$
$^3\mathrm{H}$	d_t/d_h	$O(1)$	$O(1)$	$O(1)$	$O(1)$	$O(1)$

+ specific relations

Farley *et al.* '04
...

e.g.

$$\begin{cases} d_h + d_t \;;\; 0.84\left(d_n + d_p\right) & \text{qEDM and } \theta \text{ term} \\ d_h - d_t \;;\; 0.94\left(d_n - d_p\right) & \text{qEDM} \\ d_h + d_t \;;\; 3d_d & \text{qCEDM and LRC} \end{cases}$$

storage-ring measurements
could teach us about sources!

0ν2ß decay: an example

unless
B-L
exact

$$\mathrm{L}_{\mathrm{dim}=5} \to \left\{ \begin{array}{l} \text{Majorana neutrino mass} \\ {}^{A}Z \to {}^{A}(Z+2) + 2e^{-} \end{array} \right.$$

$$|\Delta L| = 2$$

$$m_\nu : 0.1\,\mathrm{eV} \Rightarrow M_{\not{L}} : c_5 \cdot 10^{15}\ \mathrm{GeV}$$

$$c_5 = \mathrm{O}(4\pi\alpha)$$

naïve
dim analysis

comparable to GUT scale!

coincidence?

$$\left(T_{1/2}^{(0\nu 2\beta)}\right)^{-1} \propto \left|M^{(0\nu)}\right|^2 \left|m_{\beta\beta}\right|^2$$

e.g. Haxton + Stephenson '84

nuclear matrix element

effective Majorana mass

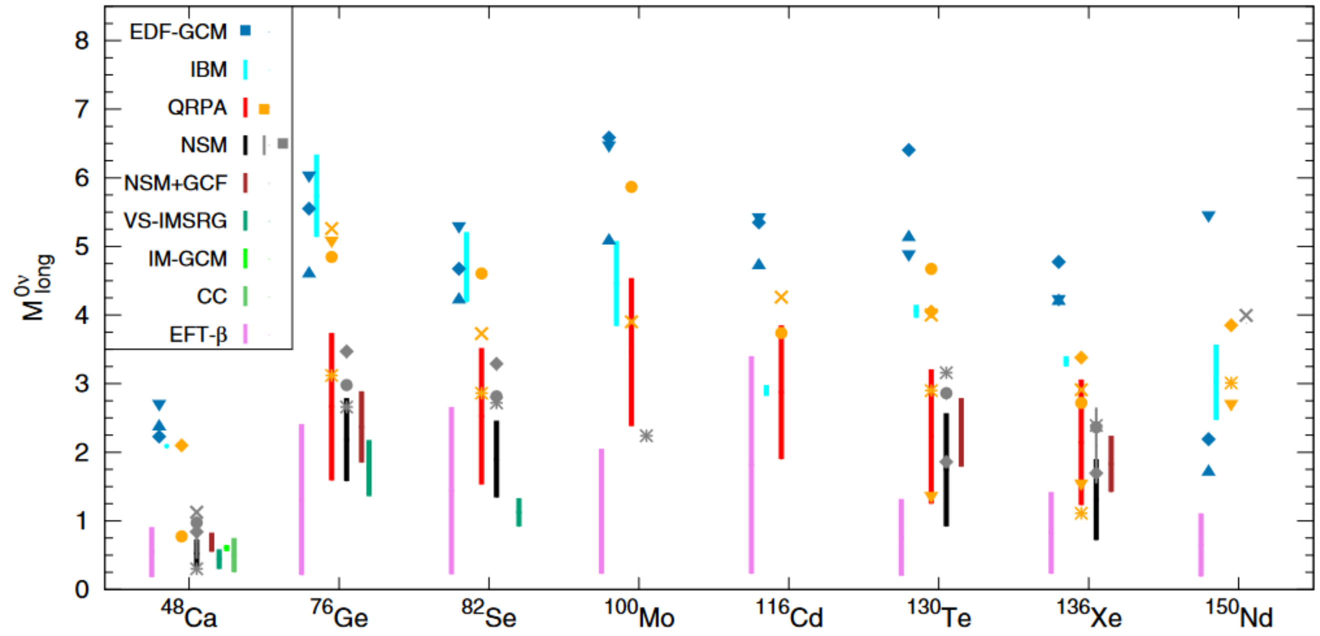
$$m_{\beta\beta} \equiv \sum_{i=1}^{n} U_{ei}^2\, m_{\nu i}$$

$$\left\{ \begin{array}{l} c_{ij} \equiv \cos\theta_{ij} \\ s_{ij} \equiv \sin\theta_{ij} \end{array} \right.$$

Majorana phases

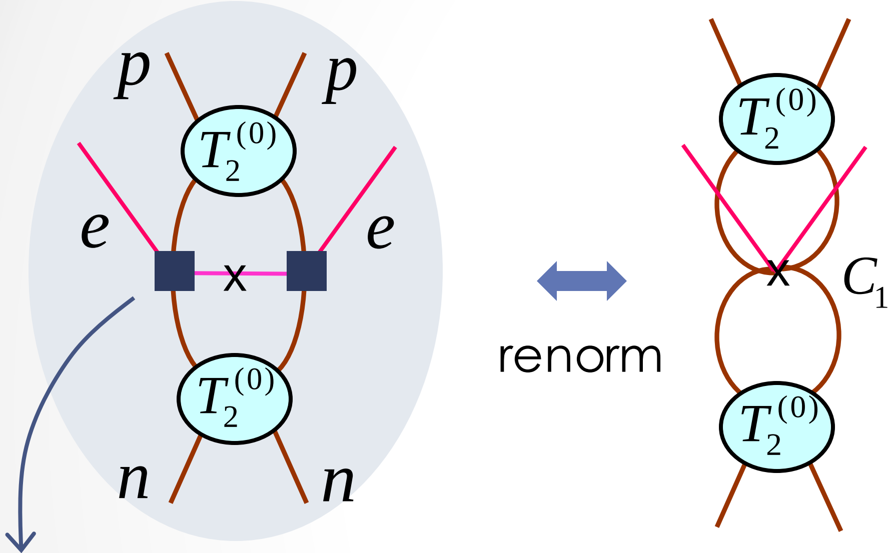
Dirac phase

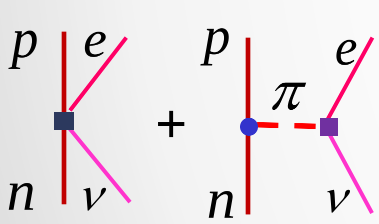
$$m_{\beta\beta} = m_{\nu 1}\, c_{12}^2 c_{13}^2 + m_{\nu 2}\, s_{12}^2 c_{13}^2\, e^{i\alpha_{21}} + m_{\nu 3}\, s_{13}^2\, e^{i(\alpha_{31} - 2\delta)}$$



Gómez-Cadenas *et al.*, *Riv. Nuovo Cim.* **46** (2023) 619

$Q = M_{\mathrm{QCD}}$



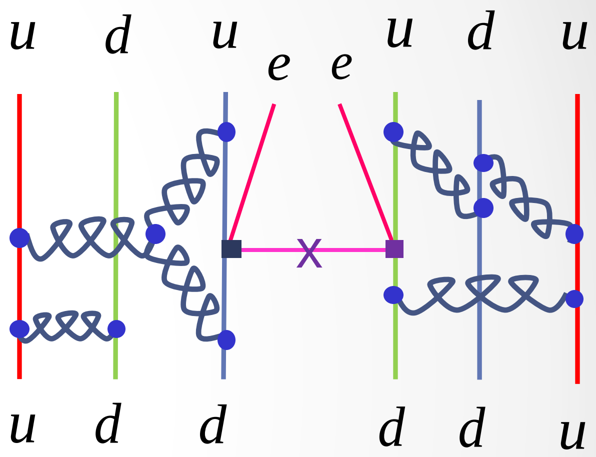


$$\propto \int d^3 l_1 \int d^3 l_2 \, \frac{m_N}{l_1^2} \, \frac{m_N}{l_2^2} \, \frac{1}{(l_1 - l_2)^2} \propto m_N^2 \ln \Lambda$$

bad news:
unknown
LO parameter

Cirigliano, Dekens, De Vries, Graesser,
Mereghetti, Pastore + vK '18
Cirigliano, Dekens, De Vries, Graesser,
Mereghetti, Pastore, Piarulli, vK + Wiringa '19

$Q : M_{\mathrm{QCD}}$



calculable with lattice QCD

Davoudi + Kadan '21
Davoudi *et al.* (NPLQCD Collab) '24

$C_1 \propto \langle pp | \frac{1}{q^2} | nn \rangle$ same as electromagnetism for $I = 2$

$$\Rightarrow \quad \mathcal{L}_{\chi\mathrm{EFT}} = \mathrm{K} + \frac{e^2}{8}(C_1 + C_2)\left[N^\dagger \tau_3 N\, N^\dagger \tau_3 N - \frac{1}{3} N^\dagger \boldsymbol{\tau} N \cdot N^\dagger \boldsymbol{\tau} N\right]$$

$$+ 2 G_F^2\, m_{\beta\beta}\, C_1 \left[V_{ud}^2\, \bar{e}_L C \bar{e}_L^T\; N^\dagger \tau^+ N\, N^\dagger \tau^+ N + \mathrm{H.c.}\right]$$

$$+ \boxed{\mathrm{K}}$$

charge-independence
breaking in *NN*

multi-pion E&M interactions
can in principle separate $C_{1,2}$

Wu, Fleming, Mereghetti + vK,
in preparation

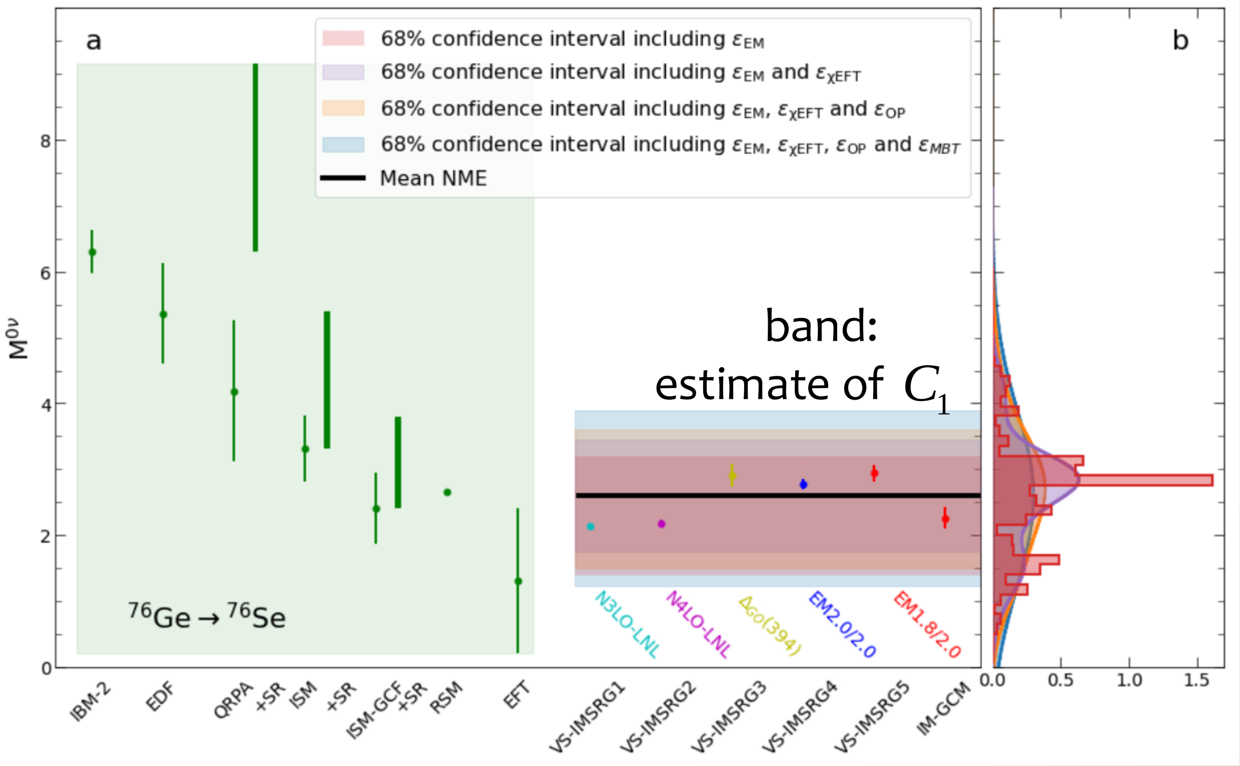
cf. pion-nucleus scattering

…

Tsaran + Vanderhaeghen '24

…

phenomenological models *ab initio* from chiral pots



band:
estimate of C_1

Belley *et al.*, *Phys. Rev. Lett.* **132** (2024) 182502

if
B-*L*
(nearly)
exact

$L_{\mathrm{dim}=6} \to$

nucleon decay into antilepton

$U(1)_{B-L}$ gauge ?

Davidson '79
Marshak + Mohapatra '80

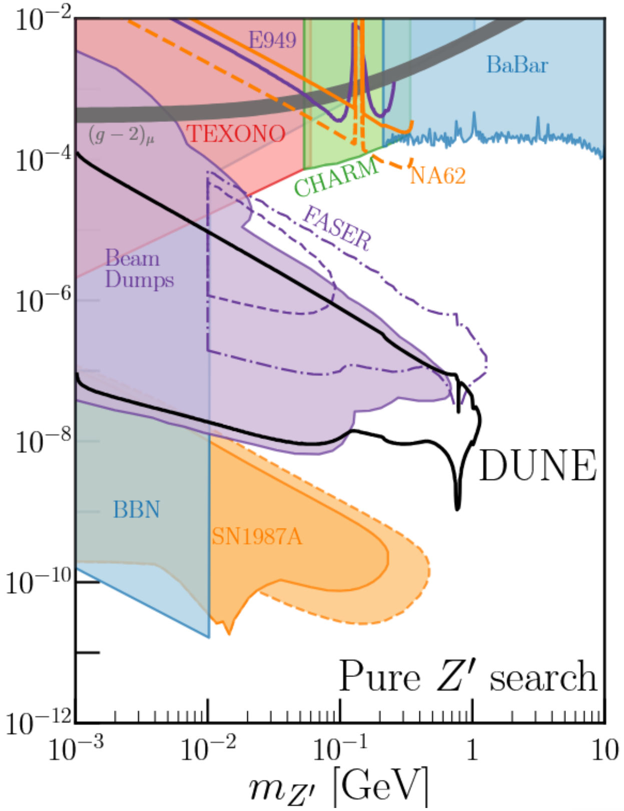
⇓

anomaly cancelation → three right-handed neutrinos

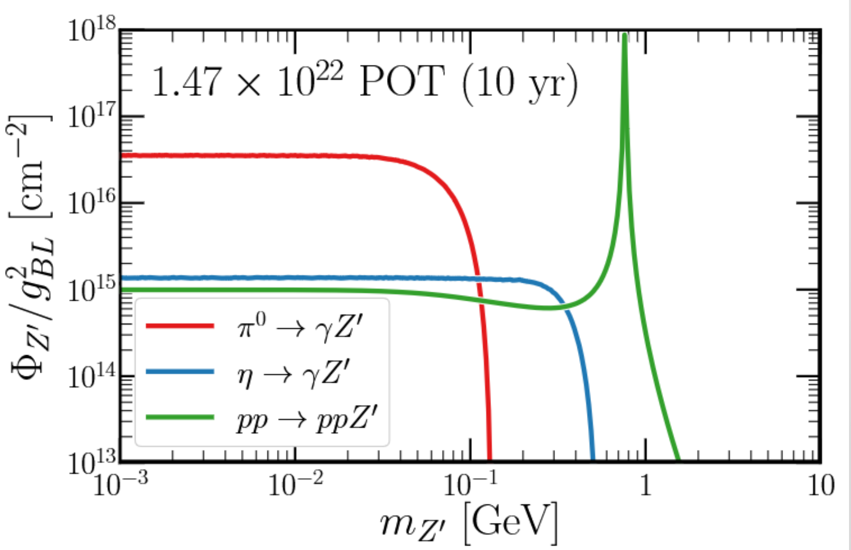
light *Z*' gauge boson

nuclear effects subleading

Oosterhof, De Vries, Timmermans + vK '21



Bhupal Dev, Dutta, Mohapatra + Zhang,
JHEP **07** (2021) 166



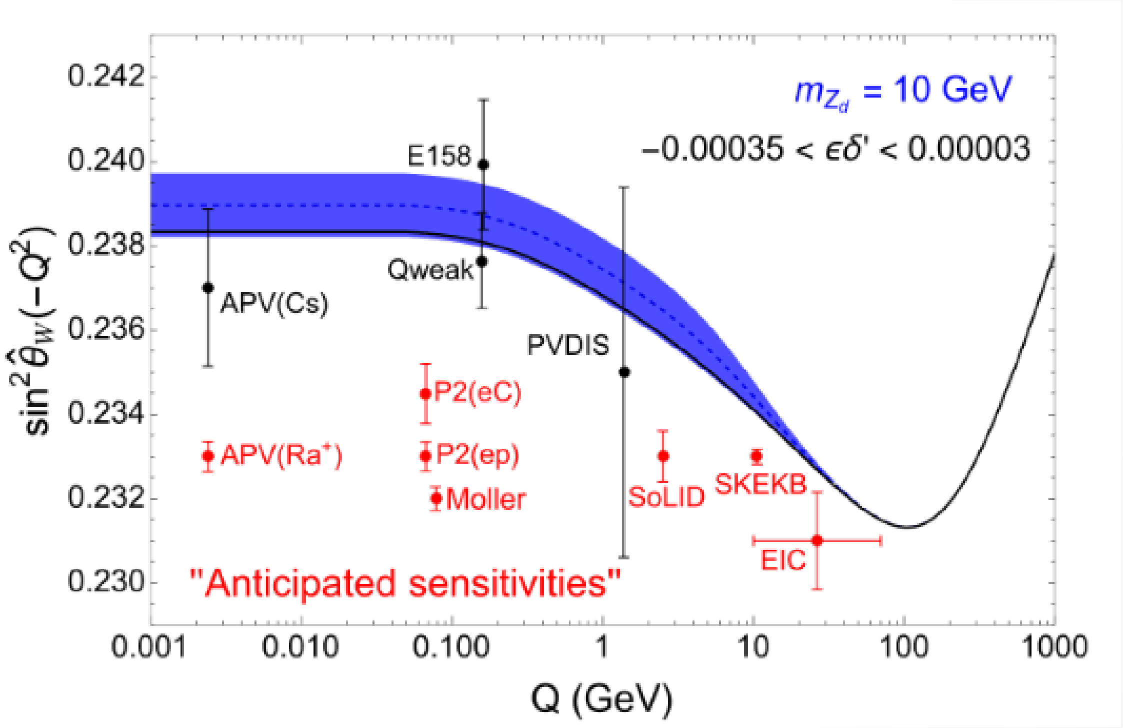
$U(1)_d$ gauge

light Z_d gauge boson

More generally, coupling to hypercharge: mixing with Z, γ

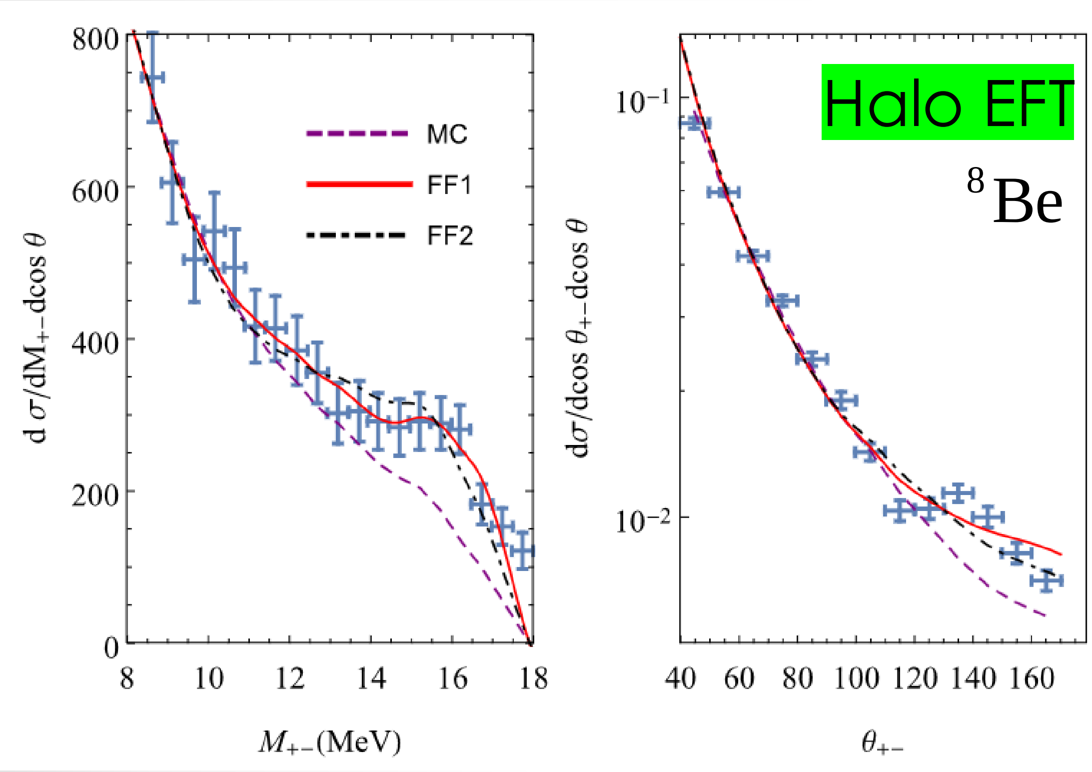
Holdom '86

…



Davoudiasl *et al.*, *Phys. Rev. D* **108** (2023) 115018

Miller + Zhang, *Phys. Lett. B* **773** (2017) 159



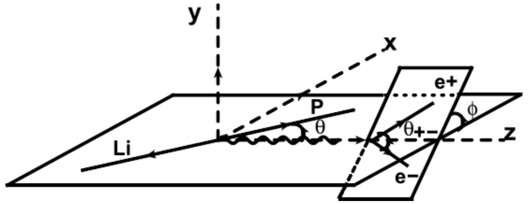
Halo EFT

^{8}Be

pair invariant mass

form-factor scale

~ 10 fm

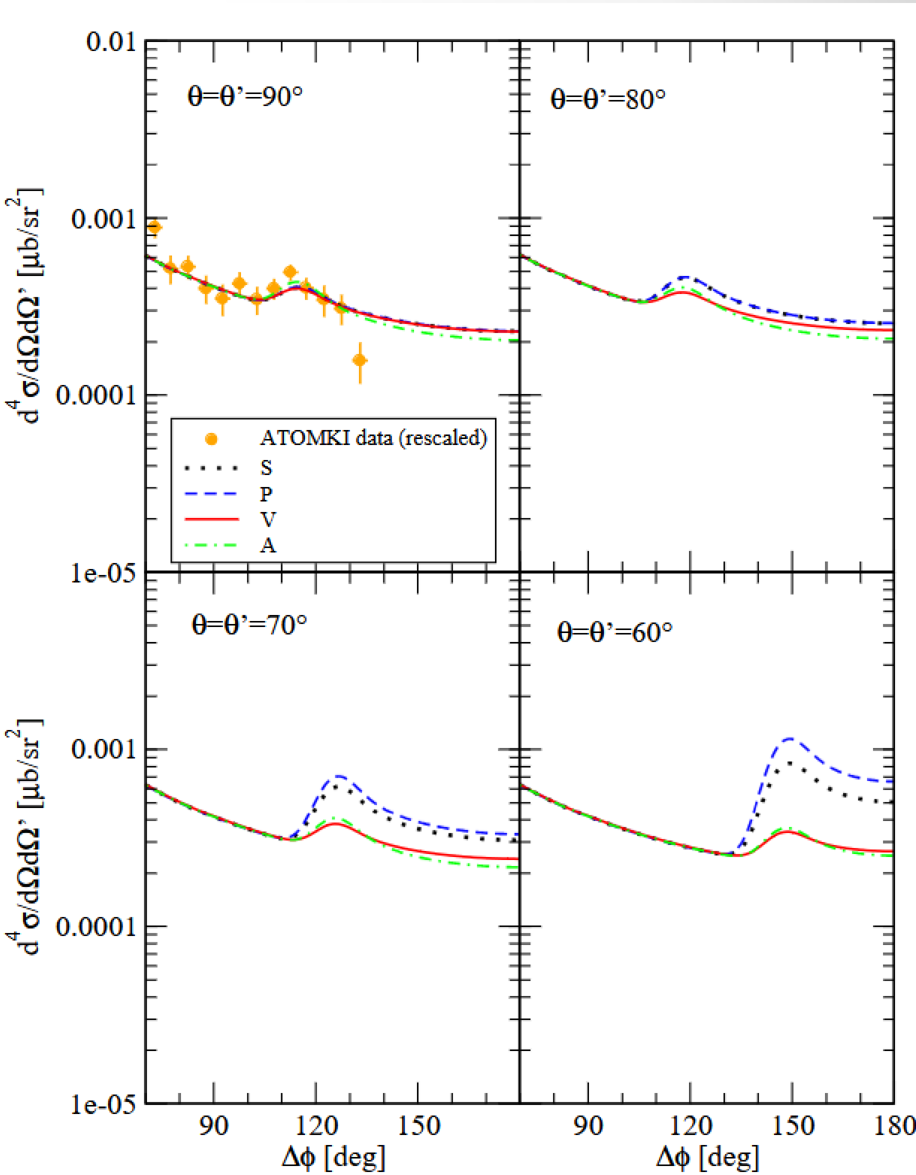


X17

^{4}He

Chiral EFT

Viviani, Filandri, *et al.*,
Phys. Rev. C **105** (2022) 014001



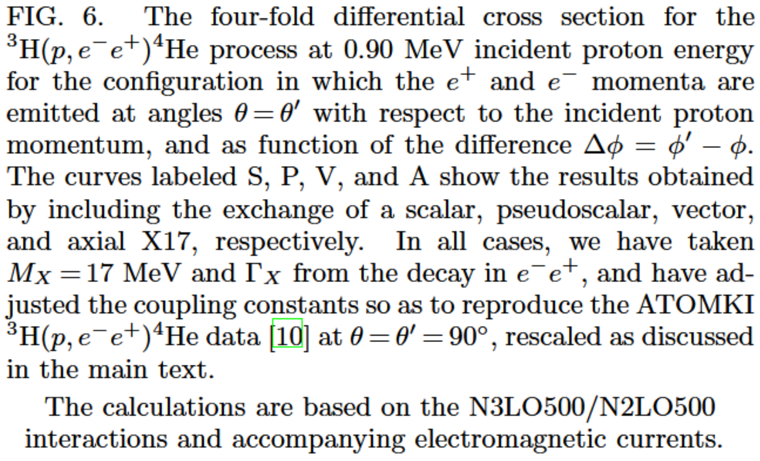
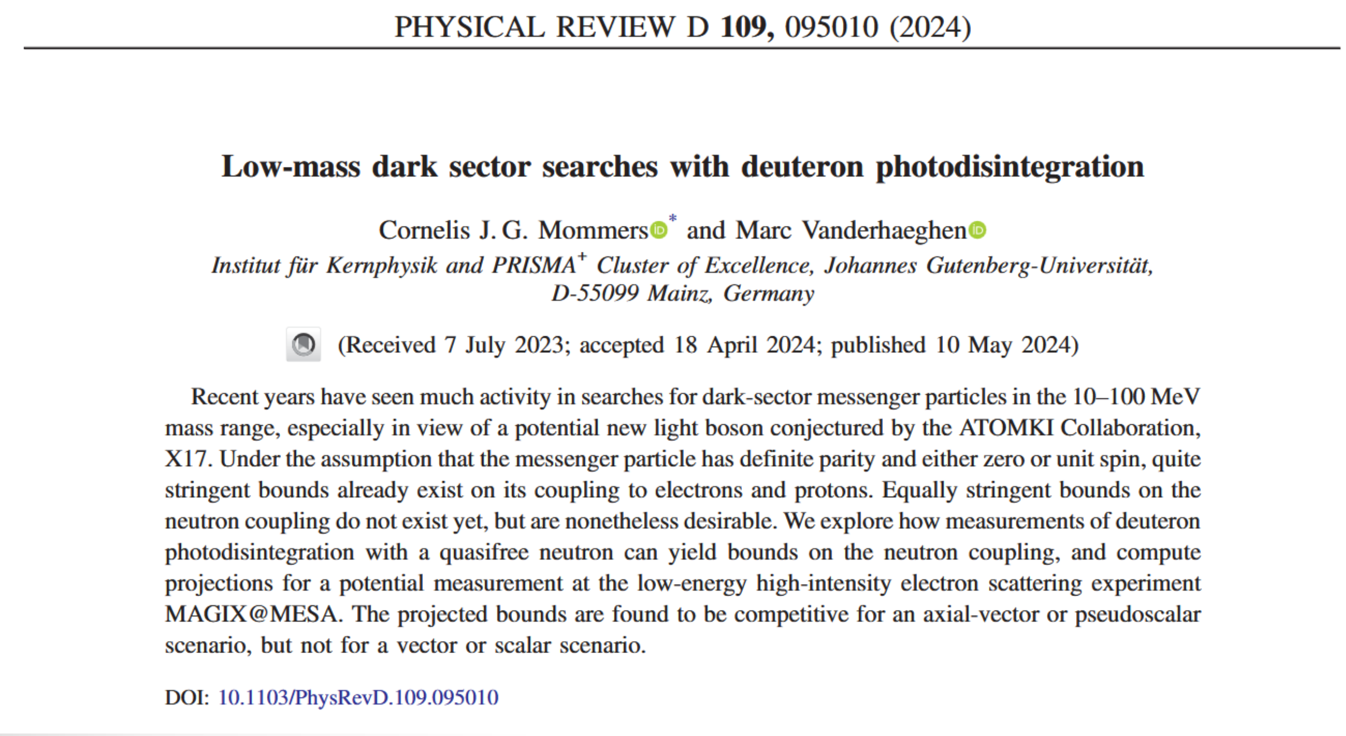


FIG. 6. The four-fold differential cross section for the ^{3}H$(p,e^-e^+)^4$He process at 0.90 MeV incident proton energy for the configuration in which the e^+ and e^- momenta are emitted at angles $\theta=\theta'$ with respect to the incident proton momentum, and as function of the difference $\Delta\phi=\phi'-\phi$. The curves labeled S, P, V, and A show the results obtained by including the exchange of a scalar, pseudoscalar, vector, and axial X17, respectively. In all cases, we have taken $M_X=17$ MeV and Γ_X from the decay in e^-e^+, and have adjusted the coupling constants so as to reproduce the ATOMKI ^{3}H$(p,e^-e^+)^4$He data [10] at $\theta=\theta'=90°$, rescaled as discussed in the main text.

The calculations are based on the N3LO500/N2LO500 interactions and accompanying electromagnetic currents.



PHYSICAL REVIEW D **109,** 095010 (2024)

Low-mass dark sector searches with deuteron photodisintegration

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(Received 7 July 2023; accepted 18 April 2024; published 10 May 2024)

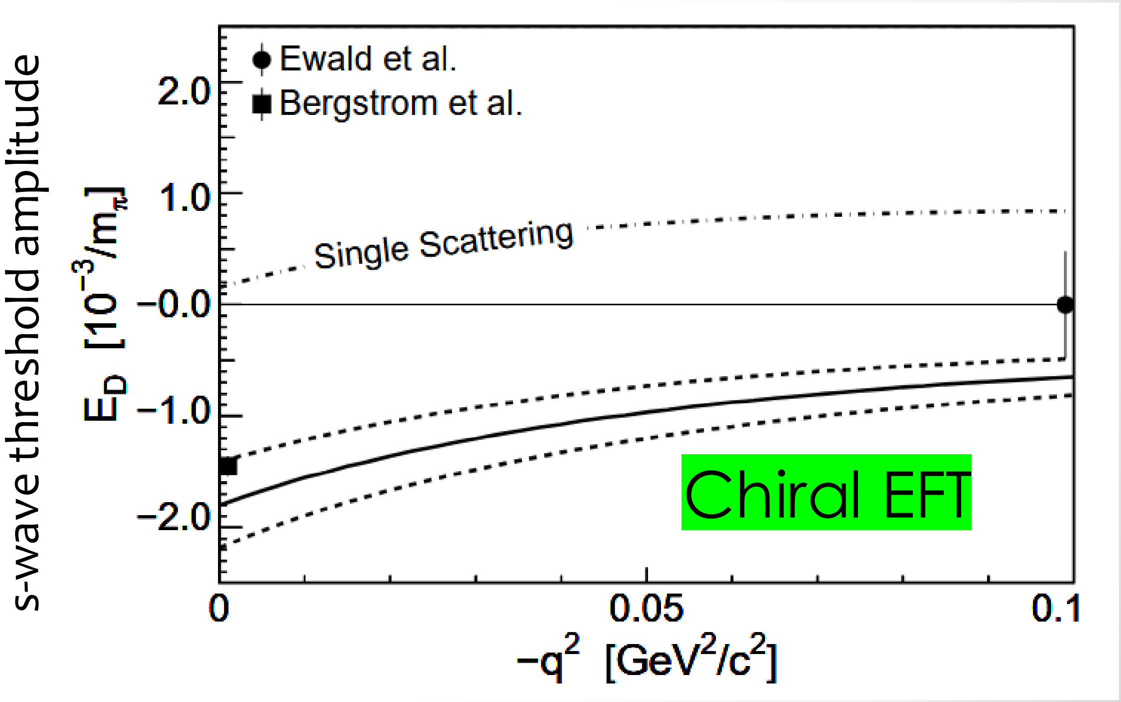
Recent years have seen much activity in searches for dark-sector messenger particles in the 10–100 MeV mass range, especially in view of a potential new light boson conjectured by the ATOMKI Collaboration, X17. Under the assumption that the messenger particle has definite parity and either zero or unit spin, quite stringent bounds already exist on its coupling to electrons and protons. Equally stringent bounds on the neutron coupling do not exist yet, but are nonetheless desirable. We explore how measurements of deuteron photodisintegration with a quasifree neutron can yield bounds on the neutron coupling, and compute projections for a potential measurement at the low-energy high-intensity electron scattering experiment MAGIX@MESA. The projected bounds are found to be competitive for an axial-vector or pseudoscalar scenario, but not for a vector or scalar scenario.

DOI: 10.1103/PhysRevD.109.095010

could be tackled
with Chiral EFT?

Beane, Lee + vK' 95
Beane *et al.* '97
Bernard, Krebs + Meissner '00
...

cf. neutral-pion electroproduction
on the deuteron



Ewald et al., *Phys. Lett. B* **499** (2001) 238

Conclusion

EFT: a way to track SM and BSM interactions across scales

SM and BSM treated consistently in hadronic/nuclear EFTs matched to LQCD

Hadrons/nuclei: a tool to separate BSM interactions

B-L physics: a special opportunity

Much work to be done to account for the BSM zoo!