Chiral Structure of Few-Nucleon Systems

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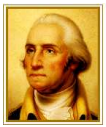
D. R. Phillips: Chiral Dynamics with πs, Ns and Δs	Done.
hg: Chiral Structure of Few-Nucleon Systems	Now.
H. Weller: Probing Chiral Dynamics with Photons	Next.



THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON DC

Unified description of Nuclear Physics, rooted in QCD.
Unique signatures of Chiral Physics & few-N forces.
Reliable high-accuracy predictions and extractions
of nucleonic and nuclear properties.

CNS
Center for Nuclear Studies

My apologies for omissons, mis-representations and mistakes.

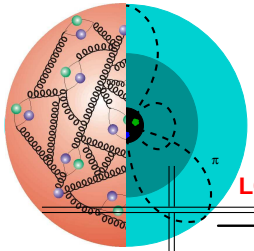
(a) Few-Nucleon Interactions in χEFT

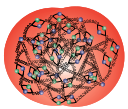
Weinberg, Ordóñez/Ray/van Kolck, Friar/Coon, Kaiser/Brockmann/Weise, Epelbaum/Glöckle/Meißner, Entem/Machleidt, Kaiser, Higa/Robilotta, Epelbaum, ...

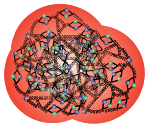
$\frac{\text{typ. momentum}}{\text{breakdown scale}} \ll 1$

Long-Range: correct symmetries and IR degrees of freedom: **Chiral Dynamics**

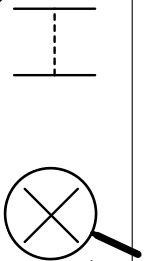
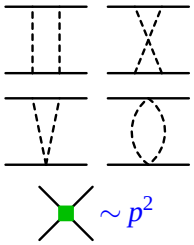
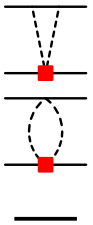
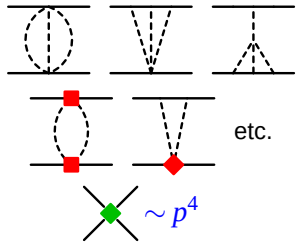
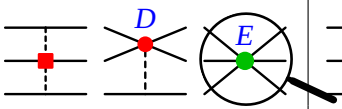
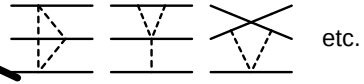
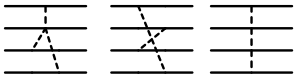
Short-Range: symmetries constrain contact-ints to simplify UV: **Minimal parameter-set**





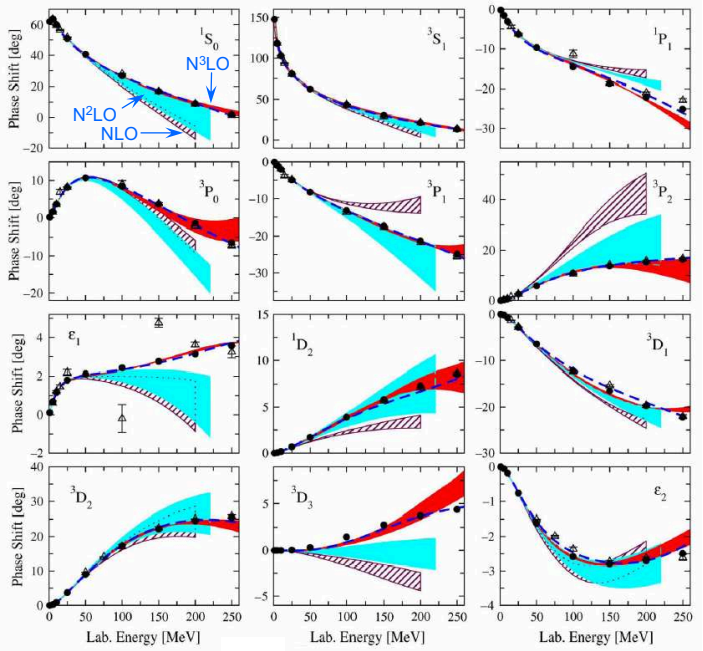


Hierarchy: 2NF-effects $\gg$ 3NF-effects $\gg$ 4NF-effects

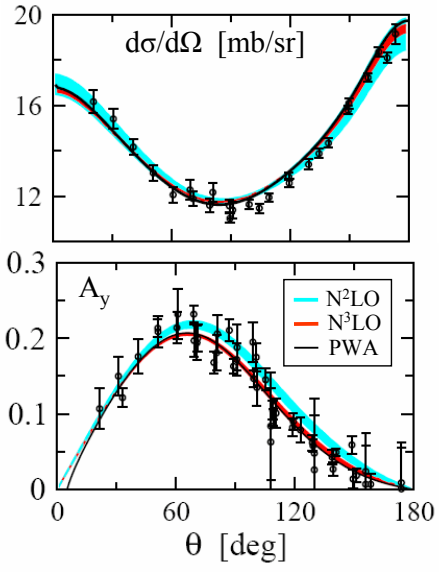
	LO	NLO	N^{2}LO	N^{3}LO
$2N$ ints	 2 parameter	 $\sim p^2$ +7 parameter	 +0 parameter	 etc. $\sim p^4$ +15 = 24 param.
$3N$ ints			 2 parameter	 parameter-free, in progress
$4N$ ints				 etc. parameter-free

Entem/Machleidt 2003, Epelbaum/Glöckle/Meißner 2005

Neutron-proton phase shifts up to N^{3}LO



np scattering at 50 MeV



Bands estimate higher-order effects.

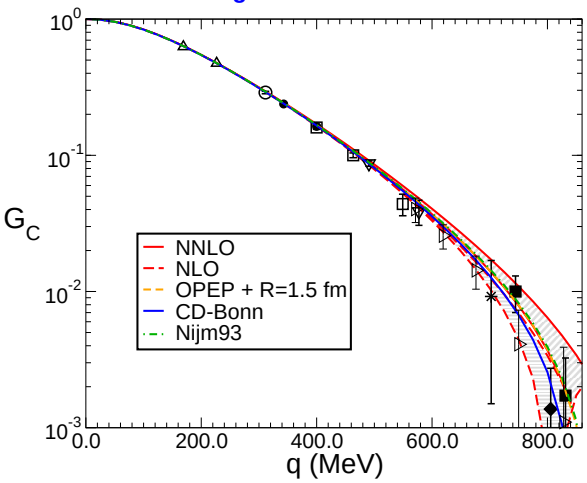
	LO	NLO	N^{2}LO	N^{3}LO	AV 18
# of parameters	2	+7	+0	+15 = 24	~ 40
χ^2/d.o.f in np		36.2	10.1	1.10	1.04

Future: High-accuracy deuteron physics, Dynamical $\Delta(1232)$, P, weak, iso-spin breaking, $T = \frac{3}{2}$ 3NFs,...

(c) Test: Deuteron Form-Factors

Phillips 2003-06

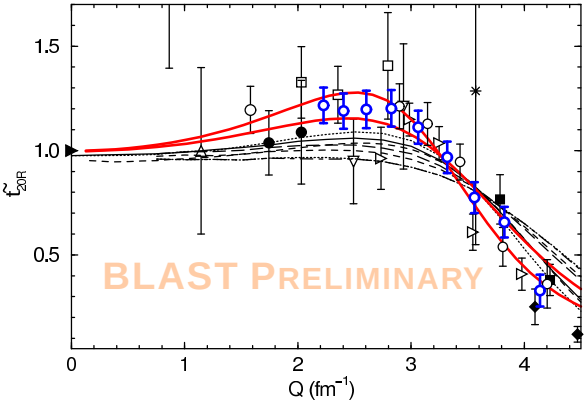
Charge Form-Factor



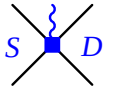
Bands estimate higher-order effects.

Measure for Quadrupole Form-Factor: $\tilde{t}_{20R} \sim \dfrac{t_{20}}{Q^2}$

BLAST, normalised at $Q = \{1.88; 2.05\}\ \mathrm{fm}^{-1}$.



χEFT: one C.T. at N^{3}LO



by quadrupole moment

Future: *Experiment:*

JLab to resolve $A(Q^2)$-discrepancy Saclay vs. MAMI

Normalisation of t_{20}

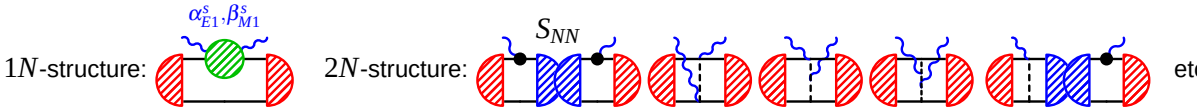
Theory:

Breakup $(e, e'N)$, more nuclei

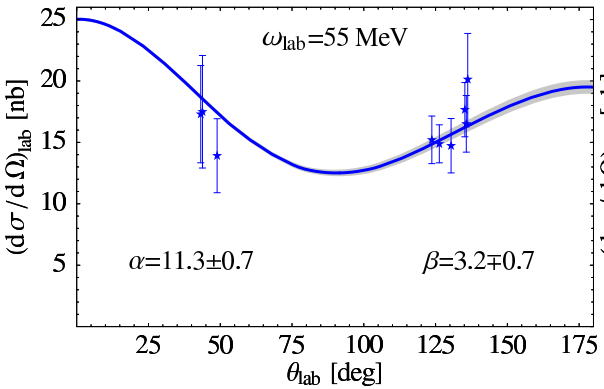
Higher orders

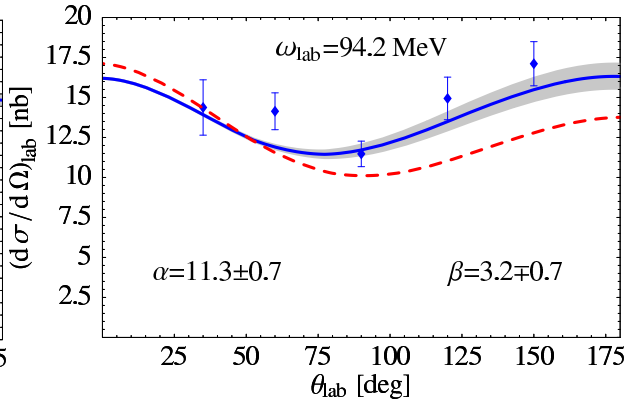
(d) Nuclei as Neutron Targets: Compton Scattering

Beane/Malheiro/McGovern/Phillips/van Kolck 2001-04, hg/Hemmert/Hildebrandt/Phillips 2004-05



All data below 100 MeV: Illinois ○, Lund ⋆, Saskatoon ◆ — $N\pi$ only — $N\pi + \Delta$ + stat. error





Nucleon $[10^{-4}\ \text{fm}^3]$: $\bar{\alpha}^s = 11.3 \pm 0.7_{\rm stat} \pm 0.6_\Sigma \pm 1_{\rm theory}$ $\bar{\beta}^s = 3.2 \mp 0.7_{\rm stat} \pm 0.6_\Sigma \pm 1_{\rm theory}$

Proton hg/...2003: $\bar{\alpha}^p = 11.0 \pm 1.4_{\rm stat} \pm 0.4_\Sigma \pm 1_{\rm theory}$ $\bar{\beta}^p = 2.8 \mp 1.4_{\rm stat} \pm 0.4_\Sigma \pm 1_{\rm theory}$

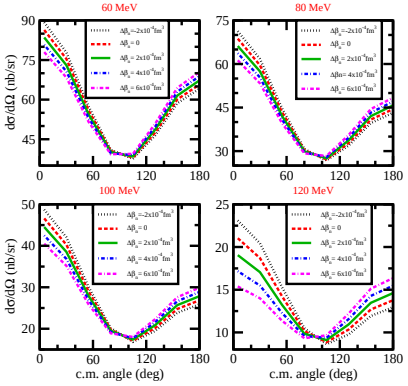
previous ranges nucleon: $[6 \ldots 18]$ $[-4 \ldots 9]$

$\Longrightarrow$ **neutron $\approx$ proton polarisabilities, Δ important.** as predicted by χEFT.

(e) Future of Compton Scattering

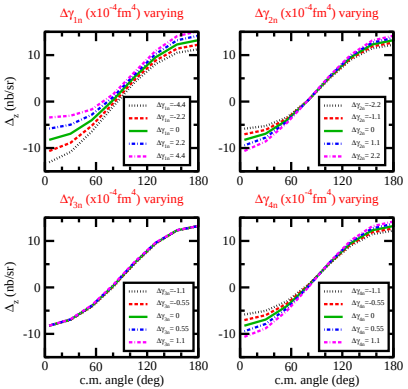
Compton on ^{3}He

Choudhury/Phillips/Nogga 2006



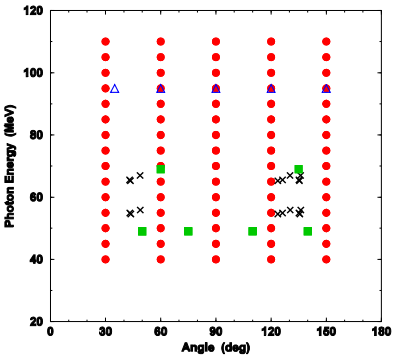
Spin-Pols from ^{3}He

Choudhury/Phillips/Nogga 2006



d Compton at MAXlab

ongoing



Theory:

Inelastic, N^{2}LO, resonance region: Δ-resummation;

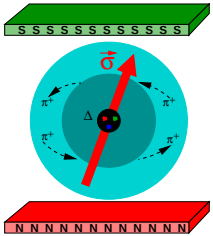
ω- and Q^2-dependence;...

Short-distance origin of C.T.s $\delta\bar{\alpha},\ \delta\bar{\beta}$.

Experiment:

Call for data answered by MAXlab, HIγS,...:

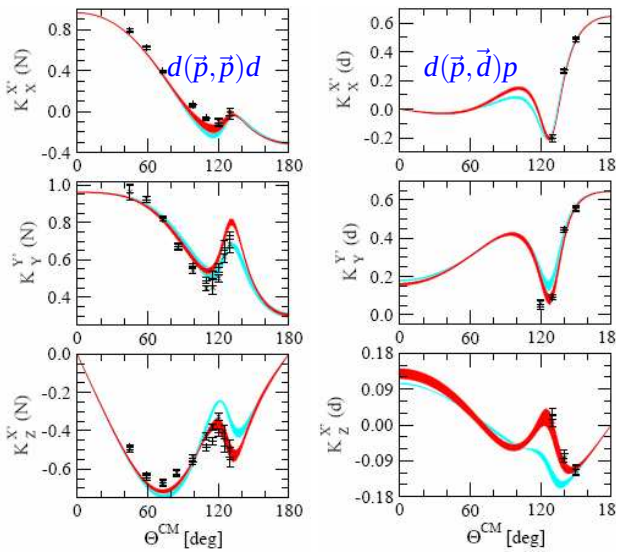
precision experiments on p, d, ^{3}H, ^{3}He polarised



$n-p$ pion cloud difference, response of nucleon-spin constituents: spin-pols

(f) Data and Few-Nucleon χEFT: Examples for $N > 2$

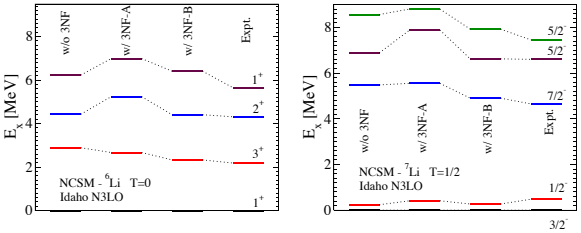
Polarisation transfer coeffs., $E_p = 22.7$ MeV



Epelbaum/Glöckle/Gołak/Meißner/Witała, data: Krakow 2006

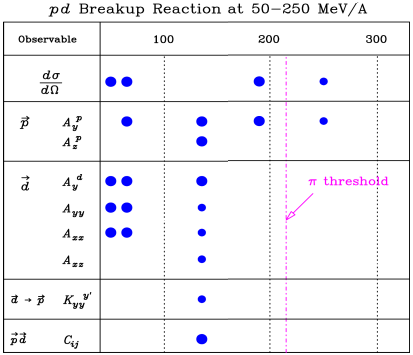
Bands estimate higher-order effects.

Light Nuclei



NCSM Nogga/Navrátil/Barrett/Vary 2006

Coverage Problem Example

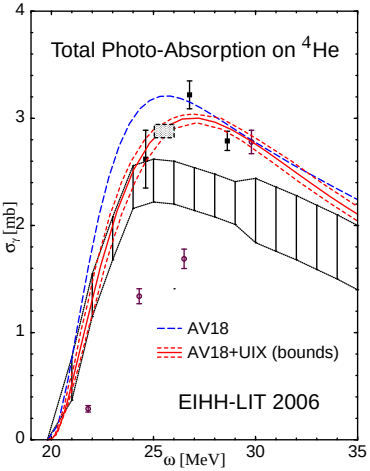


The more nucleons, the less data. $\Longrightarrow$ More experiments also at low energies! $\rightarrow$ Tandem@TUNL,...

(g) Few-Nucleon χEFT: A Merger of Opportunities

$A \geq 4$: Merge χEFT with well-developed but sophisticated numerical techniques.

Several new collaborations explore this, for example:



$\longrightarrow$ HIγS, MAXlab proposals

NCSM Navrátil, Nogga, Stetcu, Barrett, Vary, van Kolck, ...

Spectra, radii, halo-nuclei,...

EIHH-Lorentz-Integral-Transform Leidemann/Orlandini/hg/...

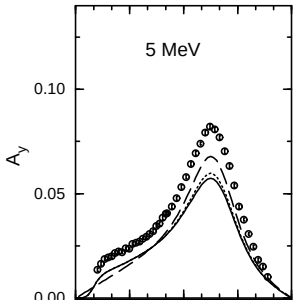
Preferred inclusive reactions $A \leq 8$

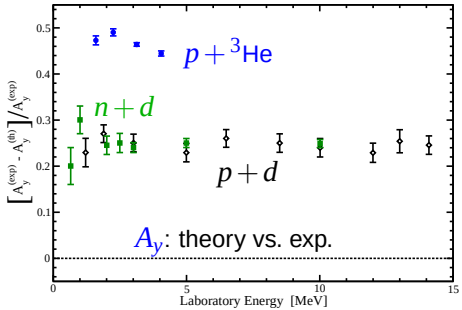
Resonating Group Model Hofmann/hg/...

Preferred exclusive reactions $A \leq 16$

χEFT on the Lattice D. Lee/Th. Schäfer/Borasoy/Epelbaum/Krebs/Meißner

Simulate χEFT of nuclei and nuclear matter





Tandem@TUNL 2006

(h) Error-Bars for Nuclear Physics

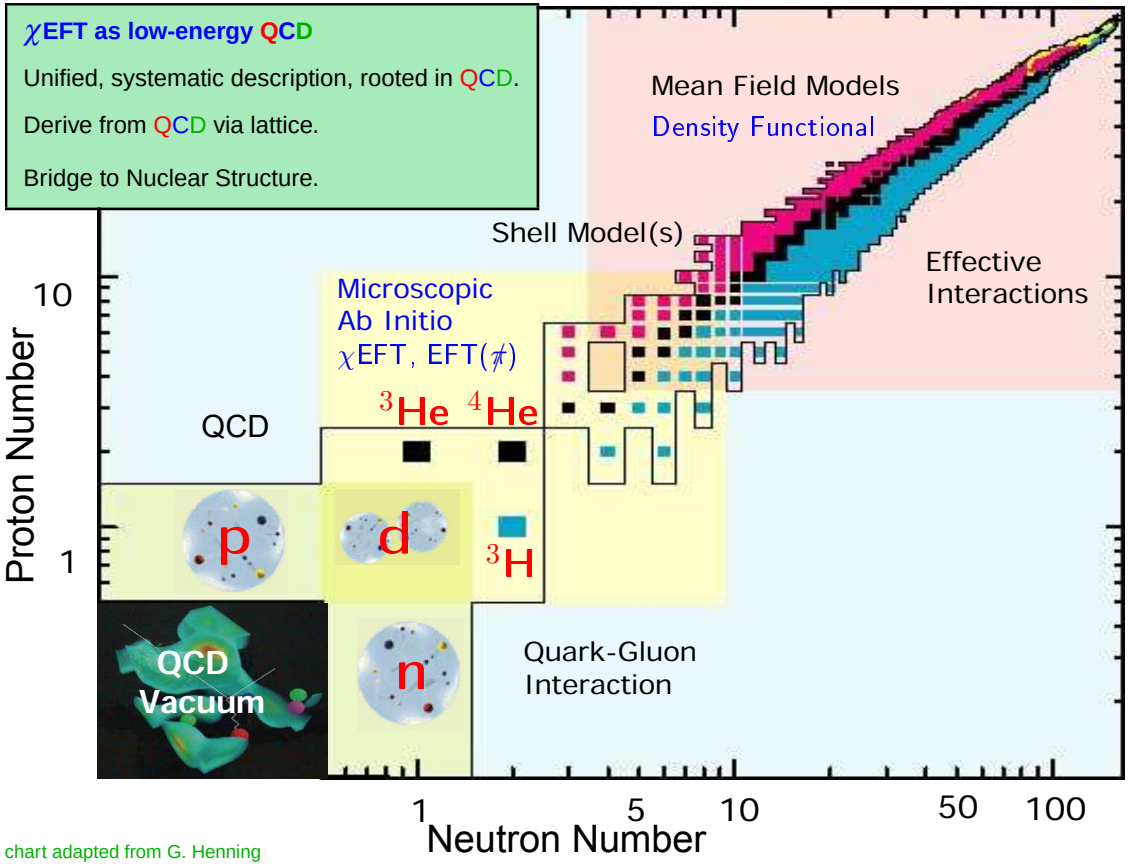


chart adapted from G. Henning

(h) Error-Bars for Nuclear Physics

χEFT as low-energy QCD

Unified, systematic description, rooted in QCD.

Derive from QCD via lattice.

Bridge to Nuclear Structure.

Quantitative studies of few-N systems

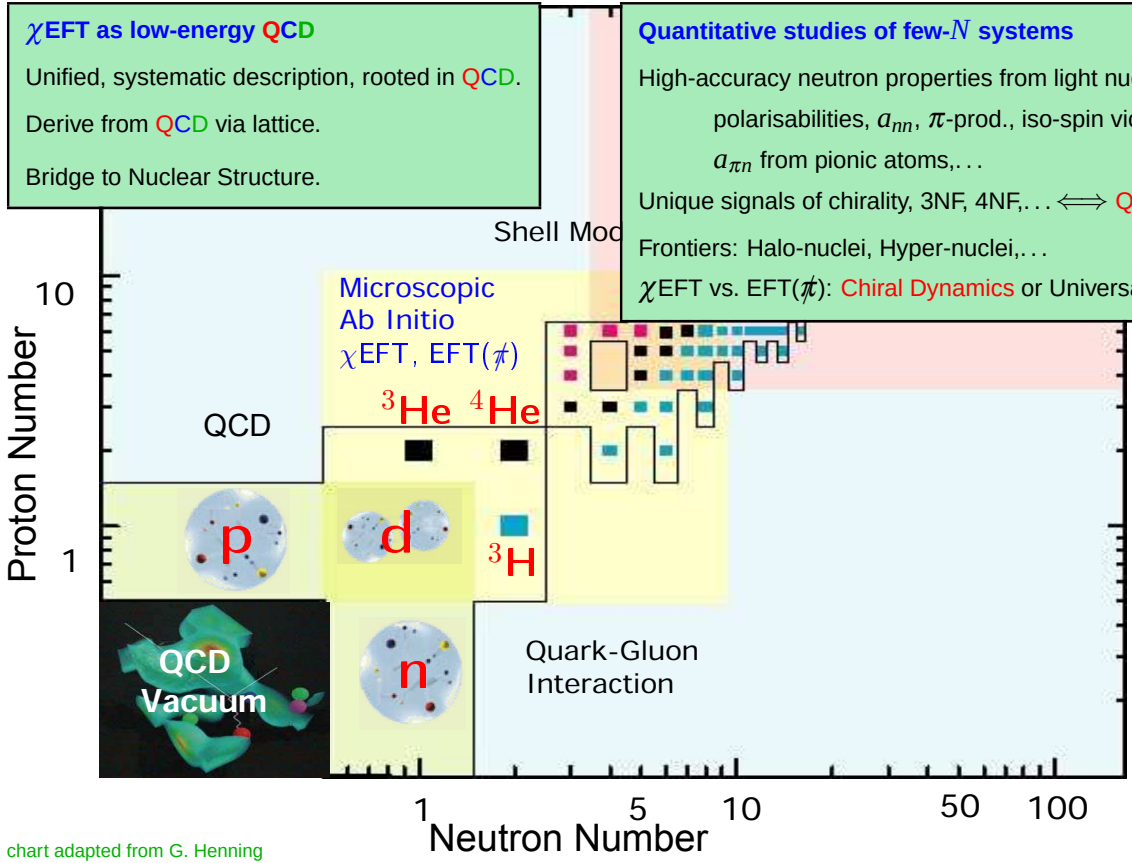
High-accuracy neutron properties from light nuclei:

polarisabilities, a_{nn}, π-prod., iso-spin violation, $a_{\pi n}$ from pionic atoms,...

Unique signals of chirality, 3NF, 4NF,... $\Longleftrightarrow$ QCD

Frontiers: Halo-nuclei, Hyper-nuclei,...

χEFT vs. EFT($\not\pi$): Chiral Dynamics or Universality?



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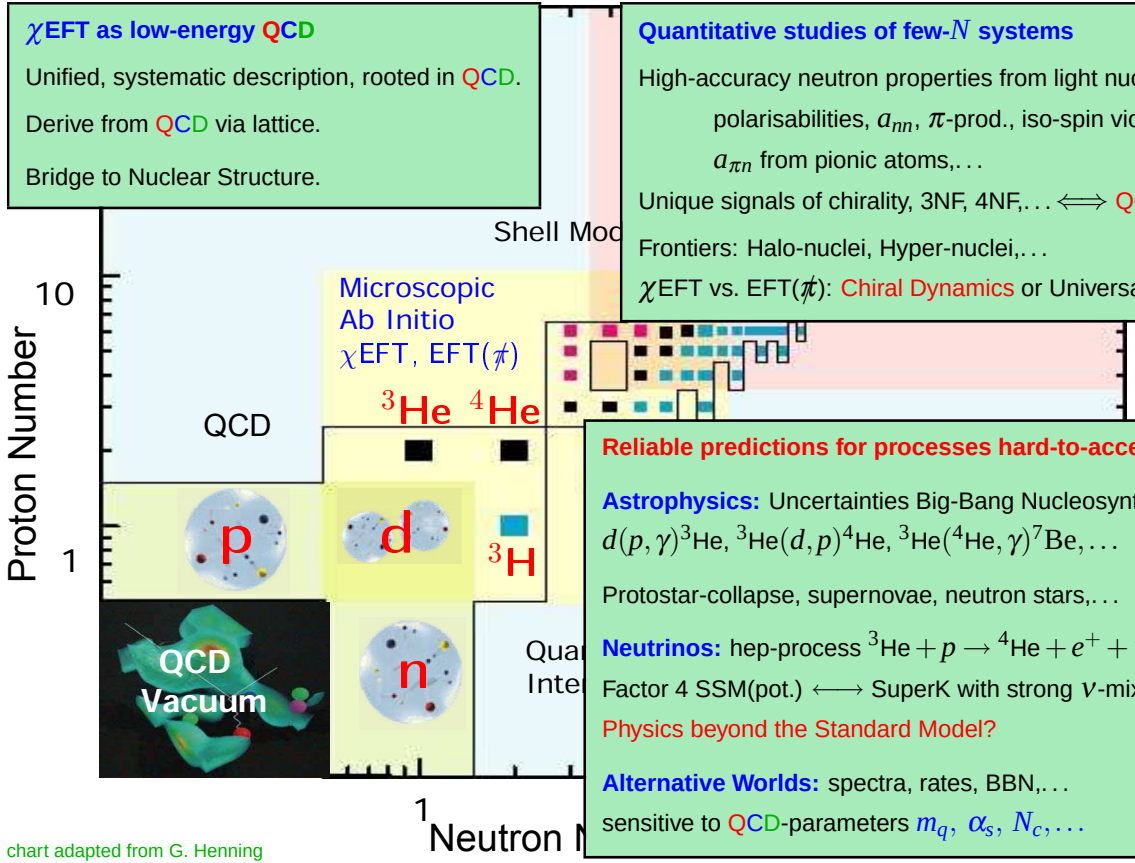


Reliable predictions for processes hard-to-access:

Astrophysics: Uncertainties Big-Bang Nucleosynthesis: $d(p,\gamma)^3$He, ^{3}He$(d,p)^4$He, ^{3}He$(^4$He$,\gamma)^7$Be,...

Protostar-collapse, supernovae, neutron stars,...

Neutrinos: hep-process $^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

Factor 4 SSM(pot.) $\longleftrightarrow$ SuperK with strong ν-mixing

Physics beyond the Standard Model?

Alternative Worlds: spectra, rates, BBN,...

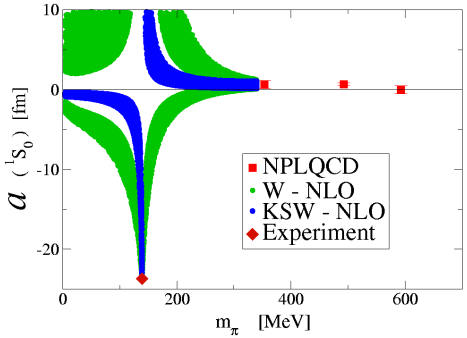
sensitive to QCD-parameters m_q, α_s, N_c,...

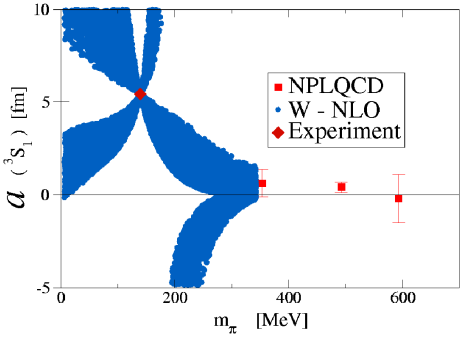
chart adapted from G. Henning

(i) χEFT, Few-N Interactions and QCD Lattice Simulations

χEFT: long-range correlations well understood, short-distance QCD encoded in minimal parameter-set.

$\Longrightarrow$ χEFT for extrapolation in $m_q \propto m_\pi^2, \ldots$, volume, lattice-spacing.





m_π-dependence of NN-scatt. lengths from MILC-lattices (unquenched)

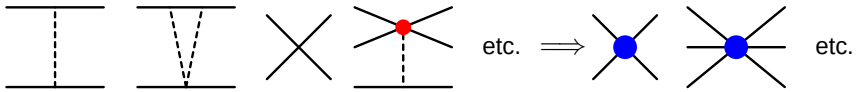
NPLQCD 2006

Future: Fully dynamical simulations utilising χEFT for long-range part.

- Verify NN-potential from first principles — cf. Ishii/Aoki/Hatsuda 2006 (quenched)
- Fix parameters hard to determine experimentally: weak int.'s, πNN- & YN-couplings... — cf. Chicago meeting
- Explain fine-tuning of NN-scattering lengths, origin of few-N int.'s
- Implications of QCD-parameter changes on Nuclear Physics, BBN etc. — e.g. Kneller/McLaughlin 2003

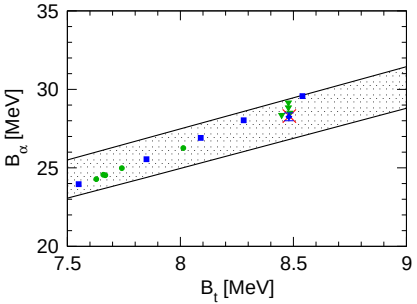
(j) χEFT at Very Low Energies: EFT($\not\pi$)

Very low momenta $\ll m_\pi \Longrightarrow$ only contact ints between nucleons: "systematised Eff. Range Expansion"



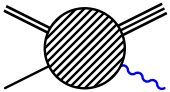
EFT($\not\pi$): Universal aspects of systems with large scattering lengths.

^{3}H– ^{4}He binding energy correlation



Platter/Hammer/Meißner 2004

$nd \to t\gamma$ at thermal energies



pot. models (different short-dist.) $[0.48 \ldots 0.63]$ mb

Kievsky/Schiavilla/Viviani + Marucci/Rosati

experiment Jurney 1982 $[0.508 \pm 0.015]$ mb

N^{2}LO EFT($\not\pi$) Sadeghi/Bayegan/hg 2006 $[0.503 \pm 0.003]$ mb

EFT($\not\pi$) input: scatt. lengthes, eff. ranges of $2N$, $3N$ S-waves, thermal $np \to d\gamma$.

No new parameter, no new 3NF.

Differentiate between Universality and signals of Chiral Symmetry!

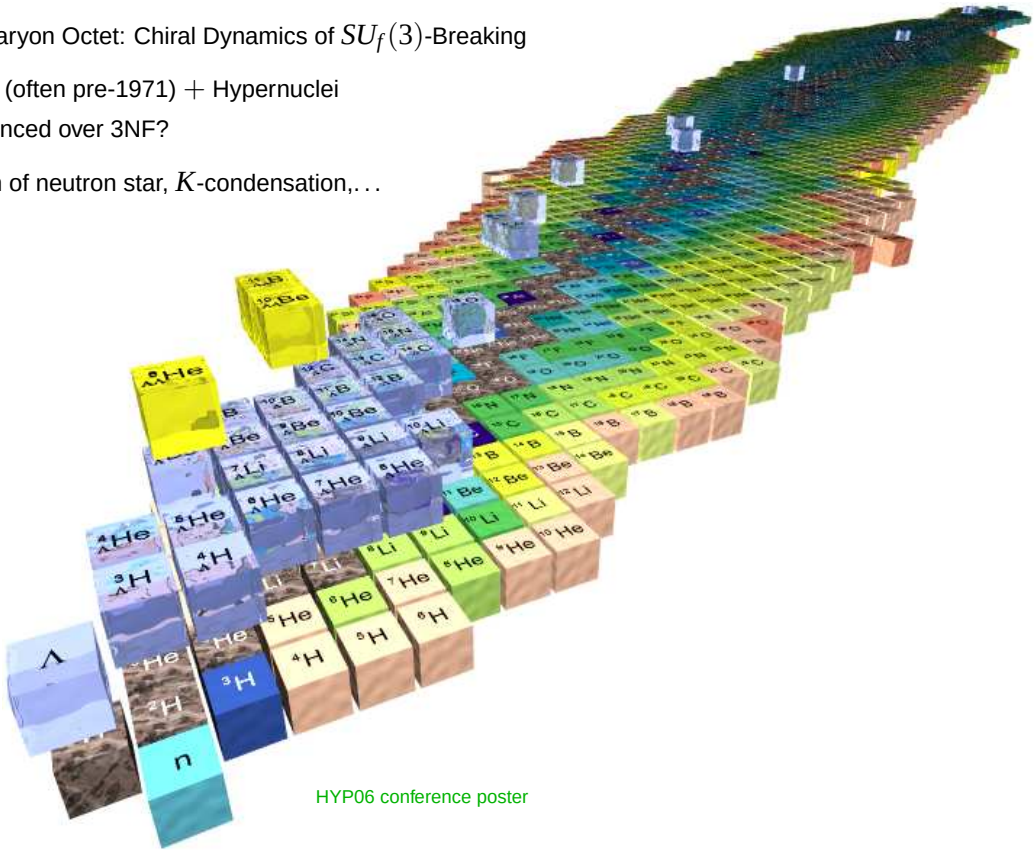
(k) Hypernuclei: “Third Axis” of the Nuclear Chart

Strangeness & Baryon Octet: Chiral Dynamics of $SU_f(3)$-Breaking

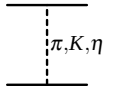
Only 35 YN data (often pre-1971) $+$ Hypernuclei

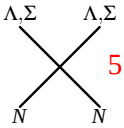
YNN, YYN enhanced over 3NF?

$\Longrightarrow$ Composition of neutron star, K-condensation,...



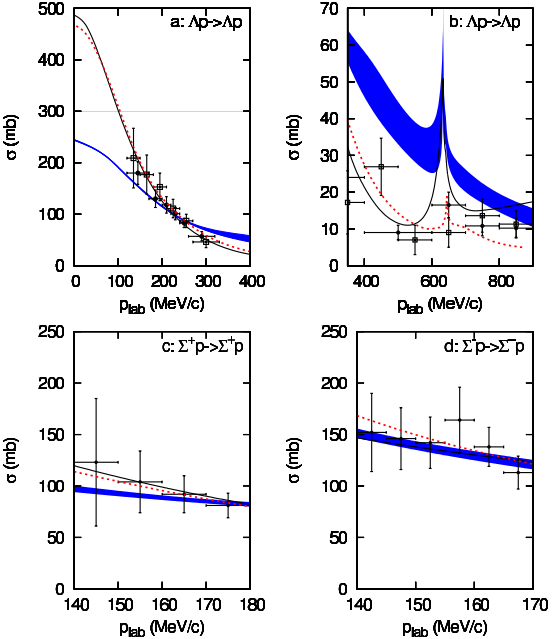
(k) Hypernuclei: “Third Axis” of the Nuclear Chart

LO χEFT for YN: 

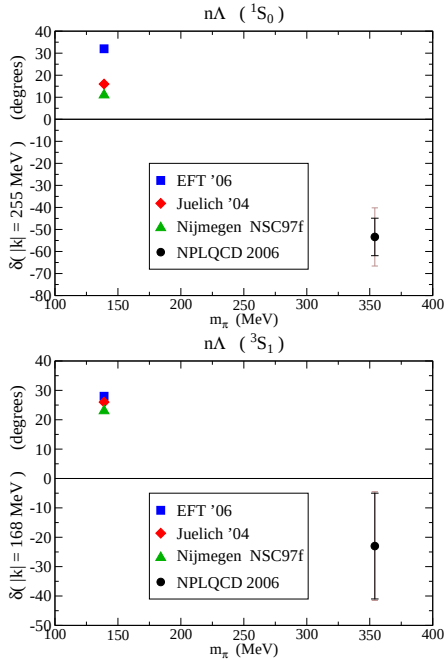


5 parameter

Polinder/Haidenbauer/Meißner 2006



Phase-Shifts from lattice using EFT NPLQCD 2006



$B(^3_\Lambda\mathrm{H}) = 2.35 \pm 0.01$ MeV χEFT

$B(^3_\Lambda\mathrm{H}) = 2.35 \pm 0.05$ MeV exp

Determine unknowns from lattice, feed into χEFT, predict.

(I) Conclusions

χEFT as low-energy QCD

Unified, systematic description, rooted in QCD.

Derive from QCD via lattice.

Bridge to Nuclear Structure.

Quantitative studies of few-N systems

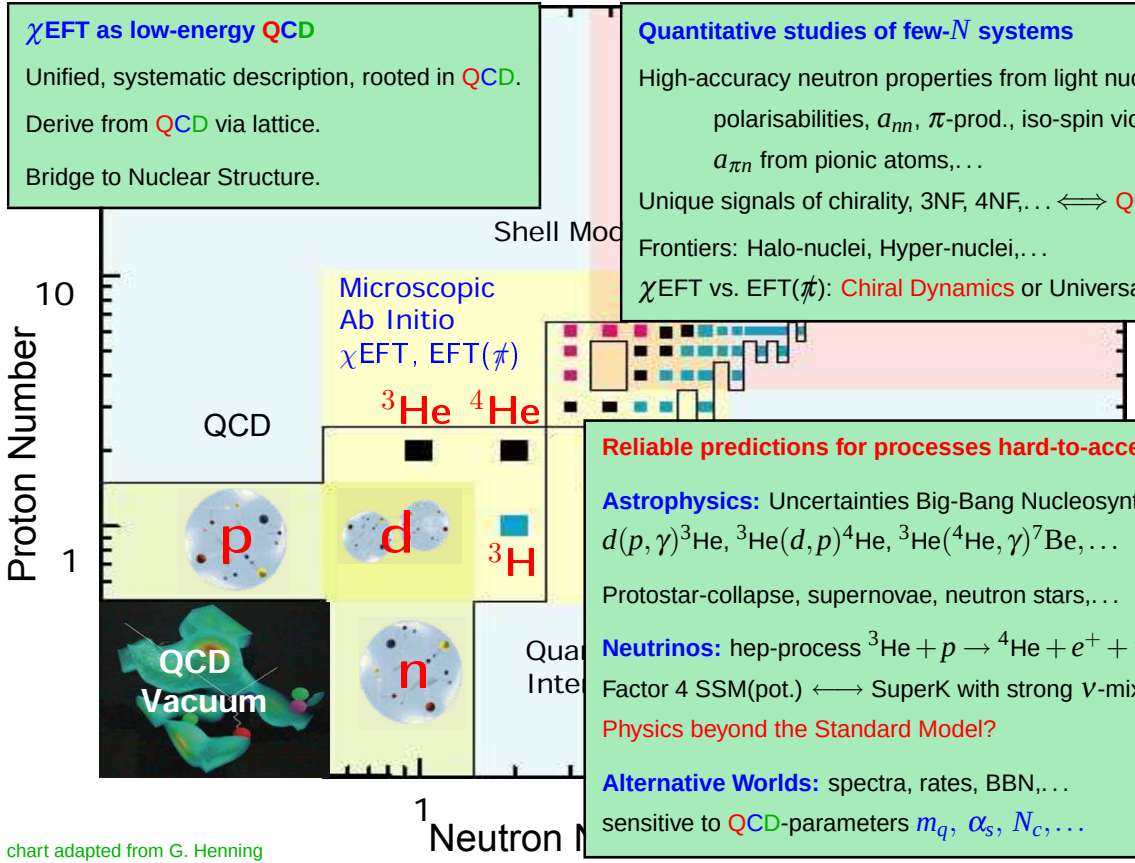
High-accuracy neutron properties from light nuclei:

polarisabilities, a_{nn}, π-prod., iso-spin violation, $a_{\pi n}$ from pionic atoms,...

Unique signals of chirality, 3NF, 4NF,... $\Longleftrightarrow$ QCD

Frontiers: Halo-nuclei, Hyper-nuclei,...

χEFT vs. EFT($\not\pi$): Chiral Dynamics or Universality?



Reliable predictions for processes hard-to-access:

Astrophysics: Uncertainties Big-Bang Nucleosynthesis: $d(p,\gamma)^3$He, ^{3}He$(d,p)^4$He, ^{3}He$(^4$He$,\gamma)^7$Be,...

Protostar-collapse, supernovae, neutron stars,...

Neutrinos: hep-process $^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

Factor 4 SSM(pot.) $\longleftrightarrow$ SuperK with strong ν-mixing

Physics beyond the Standard Model?

Alternative Worlds: spectra, rates, BBN,...

sensitive to QCD-parameters m_q, α_s, N_c,...

chart adapted from G. Henning