II. Diagrammar and Effective Field Theories

10. Effective Field Theories: Introduction

A Biased View

References: [Lepage; AH I.11.8; see me for more...]
**The EFT Tenet**

Weinberg 1979

Short-distance physics doesn’t have to be right for a good calculation, because a low-energy process cannot probe details of the high-energy structure.

Refined by Weinberg 1979 (Wilson 1967):

**Effective Field Theories**: method for multiple, separate scales:

Identify those **degrees of freedom and symmetries** which are **appropriate to resolve the relevant Physics** at the scale of interest.

Turn into **systematic approximation** of real world, allowing for **estimate of theoretical uncertainties involved**.
Serious Theorists Have Error Bars

Scientific Method:
Quantitative results with corridor of theoretical uncertainties for falsifiable predictions.

PHYSICAL REVIEW A 83, 040001 (2011)

Editorial: Uncertainty Estimates

The purpose of this Editorial is to discuss the importance of including uncertainty estimates in papers involving theoretical calculations of physical quantities.

It is not unusual for manuscripts on theoretical work to be submitted without uncertainty estimates for numerical results. In contrast, papers presenting the results of laboratory measurements would usually not be considered acceptable for publication in Physical Review A without a detailed discussion of the uncertainties involved in the measurements. For example, a graphical presentation of data is always accompanied by error bars for the data points. The determination of these error bars is often the most difficult part of the measurement. Without them, it is impossible to tell whether or not bumps and irregularities in the data are real physical effects, or artifacts of the measurement. Even papers reporting the observation of entirely new phenomena need to contain enough information to convince the reader that the effect being reported is real. The standards become much more rigorous for papers claiming high accuracy.

The question is to what extent can the same high standards be applied to papers reporting the results of theoretical calculations. It is all too often the case that the numerical results are presented without uncertainty estimates. Authors sometimes say that it is difficult to arrive at error estimates. Should this be considered an adequate reason for omitting them? In order to answer this question, we need to consider the goals and objectives of the theoretical (or computational) work being done. Theoretical papers can be broadly classified as follows:

Also Special Issue J. Phys. G (Feb 2015):
“Enhancing the Interaction between Nuclear Experiment & Theory through Information & Statistics”
Serious Theorists Have Error Bars

**Scientific Method:**
Quantitative results with corridor of theoretical uncertainties for *falsifiable predictions.*

physical effects not included in the calculation from the beginning, such as electron correlation and relativistic corrections. It is of course never possible to state precisely what the error is without in fact doing a larger calculation and obtaining the higher accuracy. However, the same is true for the uncertainties in experimental data. **The aim is to estimate the uncertainty, not to state the exact amount of the error or provide a rigorous bound.**

There are many cases where it is indeed not practical to give a meaningful error estimate for a theoretical calculation; for example, in scattering processes involving complex systems. The comparison with experiment itself provides a test of our theoretical understanding. However, there is a broad class of papers where estimates of theoretical uncertainties can and should be made. Papers presenting the results of theoretical calculations are expected to include uncertainty estimates for the calculations whenever practicable, and especially under the following circumstances:

1. If the authors claim high accuracy, or improvements on the accuracy of previous work.
2. If the primary motivation for the paper is to make comparisons with present or future high precision experimental measurements.
3. If the primary motivation is to provide interpolations or extrapolations of known experimental measurements.

These guidelines have been used on a case-by-case basis for the past two years. Authors have adapted well to this, resulting in papers of greater interest and significance for our readers.

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PACS number(s): 01.30.Ww

Also **Special Issue J. Phys. G (Feb 2015):**

“Enhancing the Interaction between Nuclear Experiment & Theory through Information & Statistics”
Ingredients:

Separation of scales by breakdown-scale $\tilde{\Lambda}_{\text{EFT}}$:

- high momenta $q_{\text{high}} \gtrsim \tilde{\Lambda}_{\text{EFT}} \rightarrow$ simplify complicated/unknown UV into local LECs.
- low momenta $q_{\text{low}} \ll \tilde{\Lambda}_{\text{EFT}}$

Effective (relevant) degrees of freedom $\rightarrow$ correct IR-Physics

Symmetries at low scales constrain interactions. Lorentz, gauge, ...
### Ingredients:

Separation of scales by breakdown-scale $\Lambda_{\text{EFT}}$:

- **High momenta** $q_{\text{high}} \gtrsim \Lambda_{\text{EFT}}$ → simplify complicated/unknown UV into local LECs.
- **Low momenta** $q_{\text{low}} \ll \Lambda_{\text{EFT}}$

Effective (relevant) degrees of freedom → correct IR-Physics

Symmetries at low scales constrain interactions. Lorentz, gauge, . . .

### Recipe:

Write down most general Lagrangean permitted by ingredients. → infinitely many terms

Order in small expansion parameter

$$Q = \frac{\text{typ. low momenta } q_{\text{low}}}{\text{breakdown scale } \Lambda_{\text{EFT}}} = \frac{1/(\text{resolution } \lambda)}{1/(\text{target size } R)} \ll 1:$$

→ low-$q$ expansion of $\mathcal{L}$: Estimate importance of LECs & graphs before explicit calculation by **Naïve Dimensional Analysis & Naturalness Assumption**.

Determine LECs at desired accuracy from underlying theory or (simple) low-mom. observables.

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**Graduate Nuclear and Particle Physics II, Spring 2015**

H. W. Grießhammer, INS, George Washington University II.10.3
Ingredients:

Separation of scales by breakdown-scale $\bar{\Lambda}_{\text{EFT}}$:

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Symmetries at low scales constrain interactions. Lorentz, gauge, \ldots

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$\rightarrow$ low-$q$ expansion of $\mathcal{L}$: Estimate importance of LECs & graphs before explicit calculation by Naïve Dimensional Analysis & Naturalness Assumption.

Determine LECs at desired accuracy from underlying theory or (simple) low-mom. observables.

Result:

Model-independent, universal, systematic, unique: Predictions with estimate of uncertainties.

Finite accuracy with minimal number of parameters at each order. \textit{“Space from Improvement”}
Example: Why the Sky Is Blue
EFT at Non-Relativistic Energies

Non-relativistic reduction: $p_{\text{typ.}} \sim q \ll M$ also inside loops.

$\Rightarrow$ Isolate kinetic energy $T = p_0 - M$ of free non-relativistic boson (spin “trivial” extension):

$$\mathcal{L} = \Phi^\dagger \left[ (T - M)^2 - \vec{p}^2 - M^2 \right] \Phi = \left( \sqrt{2M} \Phi^\dagger \right) \left[ T - \frac{\vec{p}^2}{2M} - \frac{\vec{p}^4}{8M^3} + \ldots \right] \left( \sqrt{2M} \Phi \right)$$

relative $O(Q^2)$

$\Rightarrow$ Treat higher orders as perturbation: $\times -i \frac{\vec{p}^4}{8M^3}$

$\Rightarrow$ Propagator $\frac{i}{T - \frac{\vec{p}^2}{2M} + i\varepsilon}$ has only one pole: $T = \frac{\vec{p}^2}{2M} - i\varepsilon > 0 \Rightarrow$ no anti-particle in loop.
EFT at Non-Relativistic Energies

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$\implies$ Propagator $\frac{i}{T - \frac{\vec{p}^2}{2M} + i\epsilon}$ has only one pole: $T = \frac{\vec{p}^2}{2M} - i\epsilon > 0 \implies$ no anti-particle in loop.$\checkmark$

Do loops change the picture? No!: Lorentz invariance (symmetry) fixes size of BPHZ CTs!

$\implies$ nucleons: $\mathcal{L}_N = N^\dagger \left[ T - \frac{\vec{p}^2}{2M} - \frac{\vec{p}^4}{8M^3} + \ldots \right] N$; spin by Pauli spinors $N = \left( \uparrow \downarrow \right)$.

$\implies$ Use non-relativistic QM for few-$N$ bound states from potentials: Schrödinger eq.,…
[...], you’re not really making any assumption that could be wrong, unless of course Lorentz invariance or quantum mechanics or cluster decomposition is wrong, [...]

[...] As long as you let it be the most general possible Lagrangian consistent with the symmetries of the theory, you’re simply writing down the most general theory you could possibly write down.

[Steven Weinberg: *What is quantum field theory, and what did we think it is?* [hep-th/9702027]]

“I know of no proof, but I am sure it’s true. That’s why it’s called a »folk theorem«.” [Weinberg, Chiral Dynamics 2009 (Bern)]

“EFT = Symmetries + Parameterisation of Ignorance”???

**WHAT CAN POSSIBLY GO WRONG??**
Serve With Caution:

Check assumptions:
- \( p_{\text{typ.}} \uparrow \Lambda_{\text{EFT}} \implies Q \ll 1 \)?
  
  “EFTs carry seed of their own destruction.”
  
  [D. R. Phillips]

- No separation/jungle of scales? e.g. \( N^* \) at 2 GeV

- Wrong constituents/degrees of freedom?
  new d.o.f. e.g. QED at 100 GeV without \( W, Z \)
  change of d.o.f. over phase transition
    e.g. \( N, \pi \rightarrow \text{quarks, gluons} \)

- Nature does not have assumed symmetry?
  e.g. impose Parity in weak interactions

Check Quantitatively Predicted Convergence Pattern:
- Order by order smaller corrections.
- Order by order less cut-off/RScheme dependence.

Falsifiability: Convergence to Nature tests assumptions. – After theoretical uncertainties determined.
Using Cut-Offs to Your Advantage.

Observable $\mathcal{O}(k)$ at momentum $k$, order $Q^n$ in EFT, cut-off $\Lambda$:

$$\mathcal{O}_n(k; \Lambda) = \sum_i^n \left( \frac{k, p_{\text{typ.}}}{\bar{\Lambda}_{\text{EFT}}} \right)^i \mathcal{O}_i + C(\Lambda) \left( \frac{k, p_{\text{typ.}}}{\bar{\Lambda}_{\text{EFT}}} \right)^{n+1}$$

renormalised, $\Lambda$-indep. residual $\Lambda$-dependence

$\implies$ Difference of any two cut-offs:

$$\frac{\mathcal{O}_n(k; \Lambda_1) - \mathcal{O}_n(k; \Lambda_2)}{\mathcal{O}_n(k; \Lambda_1)} = \left( \frac{k, p_{\text{typ.}}}{\bar{\Lambda}_{\text{EFT}}} \right)^{n+1} \times \frac{C(\Lambda_1) - C(\Lambda_2)}{C(\Lambda_1)}$$

Breakdown scale $\bar{\Lambda}_{\text{EFT}}$ & order $n$ by double-ln plot of “derivative of observable w. r. t. cut-off”.

**Complication:** Several intrinsic low-energy scales in few-N EFT:

scattering momentum $k$, inverse $NN$ scatt. lengths $\gamma(3S_1) \approx 45 \text{ MeV}$, $\gamma(1S_0) \approx 8 \text{ MeV}, \ldots$
II. Diagrammar and Effective Field Theories

11. Nuclear Effective Field Theories

Biased Applications

References: [see me for more...]
One- and Few-Nucleon Physics

Nucleon & Few-N System is gateway to understand microscopic nuclear structure from QCD.
Only nucleons: Expand in $Q = \frac{1}{(\text{deuteron size})} \approx \frac{1}{(\text{NN scatt. length } a \approx 4 \text{ fm})} \approx \frac{1}{\frac{1}{\rho_0} \approx 1/m_\pi \approx 1 \text{ fm}} \approx \frac{1}{[3 \ldots 5]}$

2-Body Sector: most general interactions: $-iC_0$, $ip^2C_2$, $ip^4C_4$, ...

LO ($\lesssim 30\%$): $C_0 \propto \frac{1}{a + ik}$ scattering lengths $a$

NLO ($\lesssim 10\%$): $k^2C_2 \propto \frac{1}{a + ik} \frac{1}{2} \frac{1}{\rho_0} \propto \frac{1}{a + ik}$ effective ranges $\rho_0 \approx \frac{1}{m_\pi}$

3-Body Sector: All interactions permitted by symmetries $\implies$ 3-body interactions

$H_0 (N^+N)^3: \quad \frac{H_0}{k^2H_2} (N^+N)^3: \quad \frac{k^2H_2}{\text{ etc.}}$

How important? $\iff$ Which observables most sensitive?
(b) EFT($\pi$): Pion-less Nuclear Physics

**Only nucleons:** Expand in $Q = \frac{1}{(\text{deuteron size})} ≈ \frac{1}{(\text{NN scatt. length } a ≈ 4 \text{ fm})} \approx \frac{1}{\frac{1}{\text{nucleon size } ρ_0 ≈ 1/m_π ≈ 1 \text{ fm}}}$

\[ \approx \frac{1}{3 \ldots 5} \]

**2-Body Sector:** most general interactions:

\[ -iC_0 \quad , \quad ip^2C_2 \quad , \quad ip^4C_4 \quad , \quad \ldots \]

**LO ($\lesssim 30\%$):**

\[ C_0 \quad = \quad \frac{1}{a + ik} \]

**NLO ($\lesssim 10\%$):**

\[ \frac{k^2C_2}{a + ik} \sim \frac{1}{a + ik} \frac{k^2ρ_0}{2} \frac{1}{a + ik} \]

**3-Body Sector:** All interactions permitted by symmetries \[ ⇒ 3\text{-body interactions} \]

\[ H_0 (N^†N)^3 \quad , \quad k^2 H_2 (N^†N)^3 \quad , \quad \text{etc.} \]

**How important?** \[ ⇐⇒ \] **Which observables most sensitive?**
Cutoff Dependence and $3N$ Interactions in EFT($\pi\hdots$)

Cutoff-Dependence of the Triton ($^3$H) Binding Energy

without $3N$ interaction $H_0$.

after $H_0$ fixed to $Nd$ scatt. length.

LO and NLO ($\lesssim 10\%$ accuracy): One free parameter $H_0$: $Nd$ scattering length.

N2LO and N3LO ($\lesssim 1\%$ accuracy): One more free parameter $H_2$: triton or $^3$He binding energy.
Settling a Power Counting Controversy in the $3N$ System

Does momentum-dependent $3NI$ $H_2$ enter at $N^2\text{LO}$ $\gamma/g\ldots2002-4$ or higher Platter/Phillips 2006?

- $k \ll \gamma$, other scales $\Rightarrow$ plateau obscures slope
- Cutoff dependence decreases with order
- $\gamma, \ldots \ll k \ll \Lambda_\pi$ $\Rightarrow$ extract slope

$$1 - \frac{k \cot \delta(\mu = 200 \text{ MeV})}{k \cot \delta(\mu = \infty)} \sim \left( \frac{k, p_{\text{typ.}}}{\Lambda_\pi} \right)^{n+1} Q^{n+1}$$

<table>
<thead>
<tr>
<th></th>
<th>LO</th>
<th>NLO</th>
<th>$N^2\text{LO}$</th>
<th>$N^2\text{LO}$ without $H_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>fitted</td>
<td>$\sim 1.9$</td>
<td>$2.9$</td>
<td>$4.8$</td>
<td>$3.1$</td>
</tr>
<tr>
<td>predicted</td>
<td>$2$</td>
<td>$3$</td>
<td>$4$</td>
<td>$4!!!$</td>
</tr>
</tbody>
</table>

$\Rightarrow$ Fit to $k \in [70; 100 \ldots 130]$ MeV $\gg \gamma, \ldots$ : $H_2$ is $N^2\text{LO}$; re-confirmed by Ji/Phillips/Platter 2012

Slope Confirms Power Counting; Estimates $\Lambda_\pi \approx 140$ MeV; Determines Mom.-Dep. Uncertainties.
EFT(\phi) Predicts Triton Radiative Capture $n^2H \rightarrow ^3H \gamma$

Important process to gauge theory accuracy of Big Bang Nucleosynthesis:

A Problem Solved: $nd \rightarrow t\gamma$ at thermal energies: $E_n = 0.0253$ eV

$\begin{align*}
0.0253 \text{ eV} & \quad 8.3 \text{ MeV} \\
\text{AV14 + UU} & \quad \text{no } \Delta(1232) \\
\text{AV18 + UIX} & \quad \text{pert. } \Delta \\
\text{AV18 + UIX gauge-inv} & \quad \text{full } \Delta \\
\text{exp } \text{EFT(\phi)} & \quad \text{+3N-currents}
\end{align*}$

$\text{experiment Jurey 1982} \quad [0.508 \pm 0.015] \text{ mb}$

$\text{N}^2\text{LO EFT(\phi)} \quad [0.503 \pm 0.003] \text{ mb} \quad = [0.485 + 0.011 + 0.007] \text{ mb}$

- Prediction: No new 3BFs up to $N^3\text{LO}$. $H_0, H_2$ fixed by $B_3, a_3$.

Traditional models: problem with gauge invariance, consistency.

$\iff$ EFT manifestly gauge-invariant.
(c) Larger Energy Range: Chiral Effective Field Theory

**Degrees of freedom** $\pi, N, \Delta(1232) +$ **symmetries**: Chiral SSB, gauge, iso-spin, ...

$\implies$ **Chiral Effective Field Theory** $\chi$EFT $\equiv$ low-energy QCD

\[ \mathcal{L} = (D_\mu \pi^a)(D^\mu \pi^a) - m_\pi^2 \pi^a \pi^a + \cdots + N^\dagger [i D_0 + \frac{\bar{D}^2}{2M} + \frac{8A}{2f_\pi} \vec{\sigma} \cdot \bar{D} \pi + \cdots] N + C_0^\chi (N^\dagger N)^2 + \cdots \]

**Pion:** scalar QED + more  ;  **Nucleon:** $p_{\text{typ}} \ll M \implies$ non-relativistic Pauli spinor & isospinor $\begin{pmatrix} p \\ n \end{pmatrix}$

\[ N \quad \bar{q} \quad \pi^a \quad \frac{gA}{2f_\pi} \begin{pmatrix} \tau^a \\ \vec{\sigma} \cdot \bar{q} \end{pmatrix} N \text{ isospin} \& \text{spin} \]

gauge $p_\mu \rightarrow p_\mu + eA_\mu$.

"Kroll-Rudermann term":

\[ \sim - \frac{iQ_\pi gA}{2f_\pi} \vec{\sigma} \cdot \bar{\epsilon} \]

Expand in $\delta = \frac{M_\Delta - M_N}{\Lambda_\chi} \approx 1 \text{ GeV} \approx \sqrt{\frac{m_\pi}{\Lambda_\chi}} = \frac{p_{\text{typ}}}{\Lambda_\chi} \approx \frac{2}{5} \ll 1$ (numerical fact) [Pascalutsa/Phillips 2002]
(d) Nucleon Polarisabilities

Example: induced electric dipole radiation from harmonically bound charge, damping $\Gamma$ Lorentz/Drude 1900/1905

\[
\vec{d}_{\text{ind}}(\omega) = \frac{q^2}{m} \frac{1}{\omega_0^2 - \omega^2 - i\Gamma \omega} \vec{E}_{\text{in}}(\omega)
\]

\[
=: 4\pi \alpha_{E1}(\omega)
\]

\[
\mathcal{L}_{\text{pol}} = 2\pi \left[ \alpha_{E1}(\omega) \vec{E}^2 + \beta_{M1}(\omega) \vec{B}^2 + \ldots \right]
\]

electric, magnetic scalar dipole
"displaced volume" [$10^{-3}$ fm$^3$]

\[\implies\text{Clean, perturbative probe of } \Delta(1232) \text{ properties, nucleon spin-constituents,}
\]
\[
\chi \text{iral symmetry of pion-cloud & its breaking (proton-neutron difference).}
\]

- fundamental properties of nucleon
- $\beta_{M1}^p - \beta_{M1}^n$ in elmag. p-n mass split $M_\gamma^p - M_\gamma^n \approx [1.1 \pm 0.5]$ MeV
  \[\text{Gasser/Leutwyler 1975; Walker-Loud/\ldots 2012}\]
- $2\gamma$ contribution to Lamb shift in muonic H ($\beta_{M1}$), proton radius

A top priority for US Nuclear Physics: 12 approved/running experiments: MAMI, HI$\gamma$S, MAXlab.
All Contributions to $N^4$LO

$covariant$ with $vertex$ corrections

$\delta \alpha, \delta \beta$ fit

$e^2 \delta^0$ LO

$e^2 \delta^2 N^2$LO

$e^2 \delta^3 N^3$LO

$e^2 \delta^4 N^4$LO

Unknowns: $\delta \alpha, \delta \beta \Longleftrightarrow \alpha_{E1}, \beta_{M1}, \gamma N\Delta$ strengths $b_1(M1), b_2(E2)$
Fit Discussion: Parameters and Uncertainties

$\Sigma$-rule

LO (no fit)

NLO (free)

NLO (Baldin)

N2LO (free)

N2LO (Baldin)

$1\sigma$-contours (statistical error)

Consistent with Baldin $\Sigma$ Rule

$$\alpha_{E1} + \beta_{M1} = \frac{1}{2\pi^2} \int_{v_0}^{\infty} dv \sigma(\gamma p \rightarrow X) \frac{v^2}{\nu^2}$$

$$= 13.8 \pm 0.4 \text{ [Olmos de Leon 2001]}$$

Estimate Residual Theory Uncertainty from convergence pattern:

$$\delta = \frac{M_\Delta - M_N}{\Lambda_\chi} \approx 1 \text{ GeV} \approx \sqrt{\frac{m_\pi}{\Lambda_\chi}} \approx \frac{2}{5} \ll 1$$

$$\implies \delta^2 \approx \frac{1}{6} \text{ of LO} \rightarrow \text{NLO change}$$

$$\Delta(\alpha - \beta)(\text{LO} \rightarrow \text{N^2LO}) = 3.5$$

$$\implies \text{for individual } \alpha_{E1}^p, \beta_{M1}^p:$$

$$\pm 3.5 \times \frac{1}{6} \times \frac{1}{2} = \pm 0.3_{\text{th}}$$

N$^2$LO proton $10.65 \pm 0.4_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.3_{\text{th}}$

$$113.2/135$$
neutron \approx \text{proton polarisabilities; exp. error dominates.}

Downie, Feldman, . . . spokespersons of Compton efforts at HIγS, MAMI, . . .
At present, only neutron simulations available.

Lattice has $m_\pi > m_\pi^{\text{phys}} \implies$ expansion parameter relative uncertainty $\delta^2 = \frac{m_\pi}{\Lambda_\chi}$ increases with $m_\pi \uparrow$.

$\implies$ Assign $\Delta \alpha_{E1}(m_\pi) = \text{th. error at } m_\pi^{\text{phys}} (\pm 0.3) \times \frac{m_\pi}{m_\pi^{\text{phys}}}$.

$\sim 4 \text{ fm}$

neutron electric polarisability

GW's lattice group: [Alexandru/Lee/Freeman/Lujan/...]

Only GW has Compton experiment, low-energy theory and lattice under one roof.
Neutron Polarisabilities and Nuclear Binding

Need model-independent, systematic subtraction of binding effects. \( \Rightarrow \) \( \chi \) EFT: reliable uncertainties.

- **Nucleon structure**: neutron & proton polarisabilities:

  \( \chi \) EFT, Disp. Rel.: p-n difference is small \( \text{hg/Pasquini}/\ldots\text{2005} \)

- **Parameter-free one-nucleon contributions**:

- **Parameter-free charged meson-exchange currents** dictated in \( \chi \) EFT by gauge & chiral symmetry:

  \( \sum \) partial waves

Test charged-pion component of NN force.

**Started**: above \( \pi \)-threshold

\( \Delta \) in chiral NN pot.

exp.: MAXlab, HI\( \gamma \)S,\ldots

Rescattering pivotal for Thomson limit.

Only we have tools to extract neutron values from deuteron, \( ^3 \text{He} \),\ldots \( \Rightarrow \) Experiments like us.
Polarised Deuteron-Proton Scattering

Bands estimate theoretical uncertainties by higher-order effects.
Starting on Light Nuclei

**Error-Bars for Nuclear Physics!**

$\chi$EFT is low-energy QCD

Unified, systematic description, rooted in QCD.
Universally parameterise short-range int's.
Bridge from (lattice) QCD to Nuclear Structure.

**Mean Field Models**

Density Functional

**Shell Model(s)**

**Reliable predictions & extractions** for light nuclei:
neutron properties, iso-spin & P-violation, . . .
Unique signals of chirality, 3NF, 4NF, . . . $\leftrightarrow$ QCD

**Need accurate data:** Fix parameters, test theory!

**Reliable predictions for processes hard-to-access:**

**Astro- & Neutrino-Physics:** supernovae, Big Bang, . . .

**Beyond the Standard Model:** low-energy precision

**Alternative Worlds:** vary $m_q$, $\alpha_s$, $N_c$, . . .

[chart adapted from G. Henning]
What holds the nucleus together?

1953

In the past quarter century physicists have devoted a huge amount of experimentation and mental labor to this problem – probably more man-hours than have been given to any other scientific question in the history of mankind. […]

The glue that holds the nucleus together must be a kind of force utterly different from any we yet know.

[Hans A. Bethe: “What holds the nucleus together?”,
Scientific American 189 (1953), no. 2, p. 58]
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2007

Effective Field Theory

Effective field theories provide a powerful framework for solving physical problems that are characterized by a natural separation of distance scales. They are particularly important tools in QCD, where the relevant degrees of freedom are quarks and gluons at short distances and hadrons and nuclei at longer distances. Indeed, at energies below the proton mass, the most notable features of QCD are the confinement of quarks and the spontaneous breaking of QCD’s chiral symmetry. Chiral perturbation theory is an effective field theory that incorporates both; when applied to mesons it is a mature theory. Perhaps the most striking advances in chiral effective field theory have come in its application to few-nucleon systems. This has yielded precise results for nucleon-nucleon forces and also produced consistent three-nucleon forces. This opens the way for precision analyses of…

Next: III. Scattering Theory of Hadrons

Prof. Doring

Familiarise yourself with: […]