Effective Field Theories

http://www.becher.itp.unibe.ch/eft/

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Tools for QFT computations

Expansion in the interaction strength: perturbation theory

Expansion in scale ratios: Effective Field Theories

Numerical methods: lattice simulations

Toy models: solvable models SUSY theories AdS/CFT

Benefits of EFTs

- Expansion in scale ratios simplifies computations
- Factorization of physics at different energy scales
  - Separate perturbative from non-perturbative physics
  - Dimensional analysis
  - Perturbation theory works. (It cannot be applied in multi-scale problems due to large logarithms.)
- Symmetries
  - emergent: heavy-quark symmetry
  - approximate: chiral symmetry
- General framework also for cases where the full theory is not known, or cannot be used for computations

Wilsonian vs. Continuum EFT

- Wilsonian EFT integrates out high-energy physics above some cutoff exactly, using path integral
  - top down approach, difficult in practice
  - works with hard cutoffs
  - provides physical picture of renormalization
- Continuum EFT
  - write down the most general low energy $\mathcal{L}_{\text{eff}}$
  - determine coefficients of terms in $\mathcal{L}_{\text{eff}}$ by matching
  - usually: dimensional regularization instead of hard cutoff

Traditional low energy EFTs

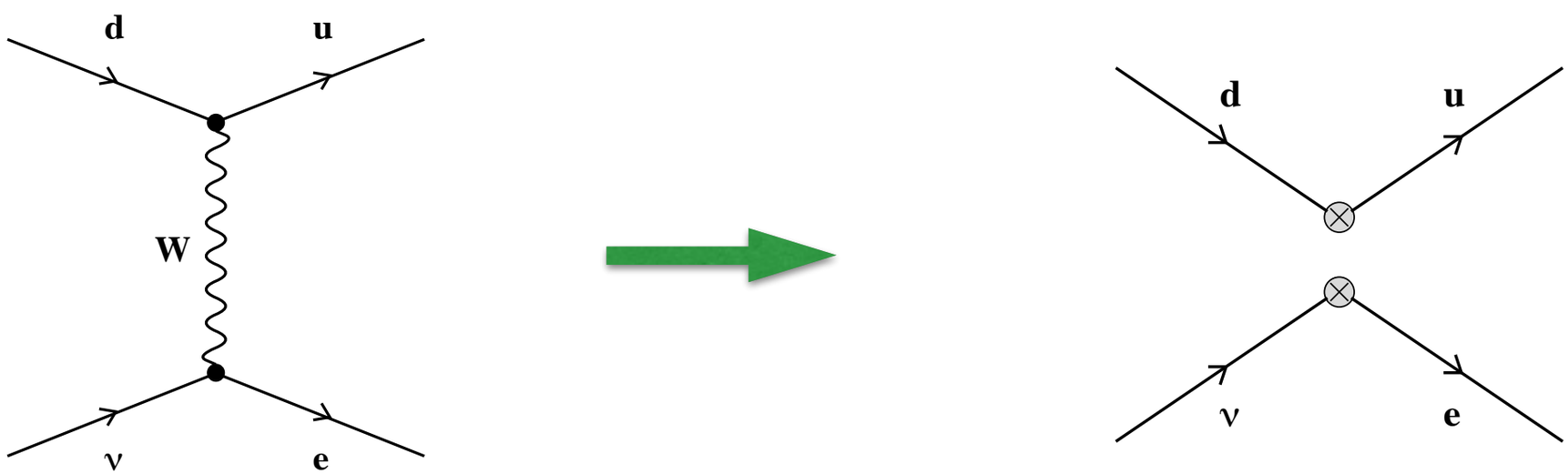
The effective theory is a standard relativistic quantum field theory, but includes non-renormalizable operators.

- higher-dim operators suppressed at low energies
- renormalizable up to a given power

Typically, such EFTs are obtained after integrating out heavy particles.

- Effective Lagrangian depends on light fields
- Higher-dim operators are induced from integrating out heavy degrees of freedom

Fermi theory



$$\frac{1}{p^2 - M_W^2} \longrightarrow \frac{1}{-M_W^2}\left(1 + \frac{p^2}{M_W^2} + \dots\right)$$

A tower of EFTS

effective theory	full theory	energy scale Λ	fields in L_{eff}
Fermi theory (QED+QCD+eff. weak)	SM	$M_W \approx 80$ GeV	l, ν, q, g, γ

A tower of EFTS

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Fermi theory (QED+QCD+eff. weak)	SM	$M_W \approx 80$ GeV	l, ν, q, g, γ
CHPT + QED	QCD + QED + eff. weak	$m_\rho \approx 1$ GeV	π, K, γ,…

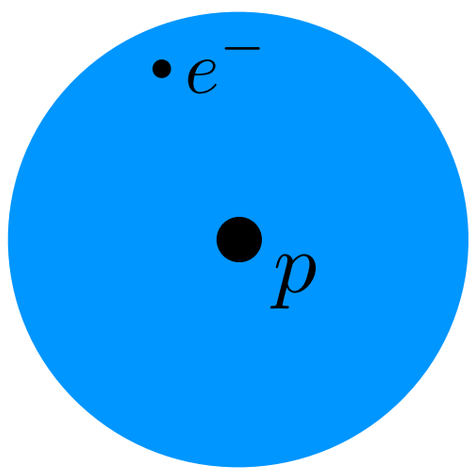
A tower of EFTS

effective theory	full theory	energy scale Λ	fields in L_{eff}
SM	?	Λ_{new} = ?	l, ν, q, g, γ, H, W, Z
Fermi theory (QED+QCD+eff. weak)	SM	$M_W \approx 80$ GeV	l, ν, q, g, γ
CHPT + QED	QCD + QED + eff. weak	$m_\rho \approx 1$ GeV	p, n, π, K, γ,…

Modern EFTs: e.g. NRQED

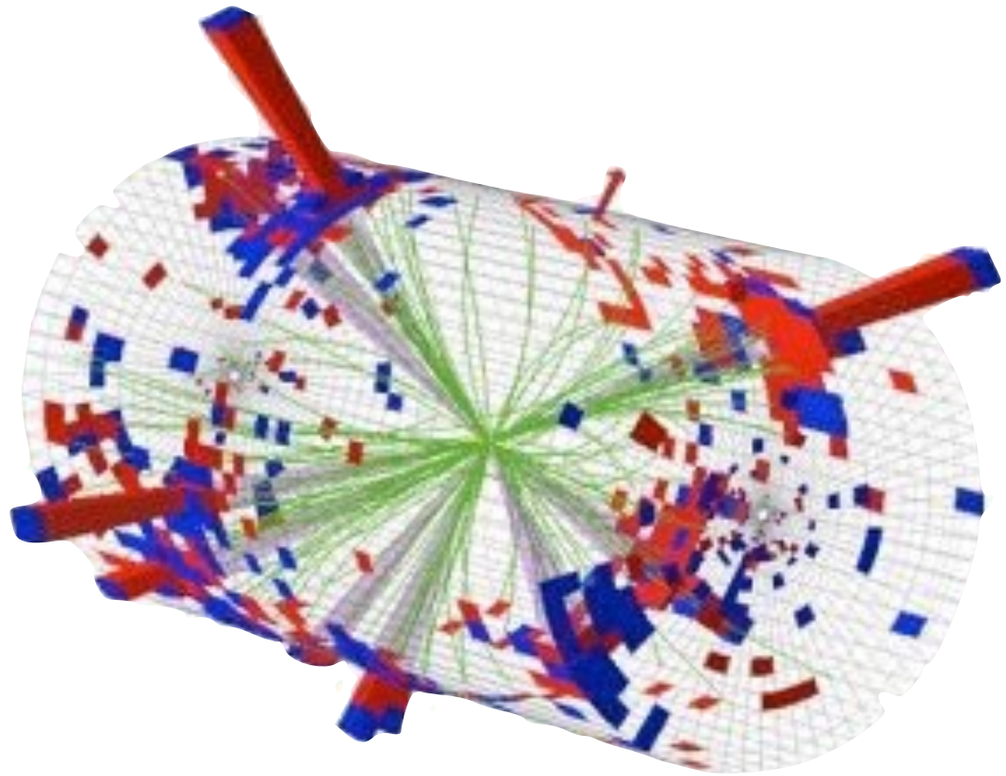
Many examples of scale hierarchies in QFT in which the low-energy part does not consist of light particles with low momentum.

e.g. non-relativistic problems $E_{\rm kin} \ll |\vec{p}| \ll m$



- Cannot simply integrate out e^- or p.
- Different components of the momentum scale differently

Jet physics at the LHC



Many scale hierarchies!

$$\sqrt{s} \gg p_{\rm Jet}^T \gg M_{\rm Jet} \gg E_{\rm out} \gg m_{\rm proton} \sim \Lambda_{\rm QCD}$$

→ Soft-Collinear Effective Theory (SCET)

Modern complications

- EFT is tailored to physics at hand: reference vectors,…
- Particles may be described by several fields (modes)
  - Two kinds of photon fields in NRQED: soft and ultra-soft
  - Various types of soft and collinear particles in SCET
- Not all momentum components are small: non-localities along the directions of large momenta
  - parton-distribution functions
  - Coulomb potential

Outline

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Effective Field Theories

This lecture provides an introduction to the framework of low energy effective field theories. After developing the basic concepts, the method is used to analyze the electromagnetic, weak and strong interactions at low energies. The course is intended for graduate students and master students, who have taken a first course in quantum field theory.

This lecture was first given in the spring semester 2010, and is currently offered again, with somewhat different selection of topics. The lecture notes are linked below. They are also available as a single file (180 pages, 12.4MB), which however does not contain the figures.

- Outline and some references

1. Introduction
2. The Wilsonian effective action
    1. Integrating out high-energy modes
    2. Classification of operators
    3. Renormalization group
3. Continuum effective theory
    1. Tree-level matching calculations
    2. Field redefinitions
    3. Matching at higher orders
    4. Power counting
    5. Renormalization group improved perturbation theory
4. The Standard Model at low energies
    1. Euler Heisenberg Theory
    2. Decoupling of heavy flavors (Figures: running coupling, anomalous magnetic moment)
    3. Effective weak Hamiltonian (Fermi Theory)
    4. Chiral Perturbation Theory
        1. Chiral symmetry
        2. Transformation properties of Goldstone bosons
        3. Effective Lagrangian
        4. Applications (figures)
5. Non-relativistic theories
    1. Heavy-Quark Effective Theory (HQET)
        1. Connection to quantum mechanics
        2. Applications of HQET (figures)
    2. Non-relativistic QCD and QED
6. Energetic particles and jet physics
    1. Asymptotic expansions and the method of regions
    2. Soft-Collinear Effective Theory

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Appendices

A. Loop integrals in dimensional regularization
B. Feynman rules for derivative couplings
C. QCD Lagrangian and Feynman rules