SCET: EFTs for precision jet & hadronic physics

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What can I cover in 3 1-hr lectures + discussion?

I Intro to EFTs

- overview of SCET
- Fermi theory
- HQET
- SCET

II SCET Lagrangian

- label & residual momenta
- momentum bins & dim reg.

- $SCET_I$ Lagrangian
- collinear Wilson lines
- BPS field redefinition
- soft Wilson lines

III Factorization & Resummation using SCET

- 2-jet matching
- DIS 1-jettiness / thrust
- jet, beam & soft functions
- large logs
- RG Evolution

Discussion ?

General References:

Google "Iain Stewart SCET lectures"

QCD ⟷ SCET comparisons / dictionaries
CL & G. Sterman hep-ph/0611061
+ Almeida, Ellis, Sung & Walsh 1401.4460

A. Manohar Intro to EFTs 1804.05863

→ invention of SCET
hep-ph/0005275 Bauer Fleming Luke
0011336 B, F, Pirjol, Stewart
0107001 BS
0109045 BPS

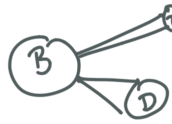
Lecture 1 : Intro to EFTs and SCET — Mon. Aug 5, 2019

What is SCET?
↓
Soft Collinear Effective Theory

- an EFT of QCD applicable to processes with energetic, light-like degrees of freedom

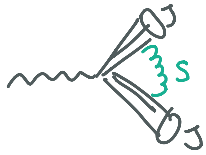
$E \gg m$ (collinear) e.g. jets  $m_J^2 \ll E_J^2$

E_J

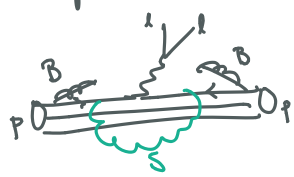
light hadrons  $m_\pi^2 \ll E_\pi^2$

that exchange/radiate soft wide-angle radiation

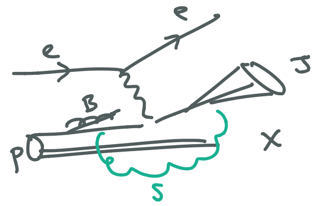
e.g.



$e^+e^- \to$ jets



$pp \to \ell^+\ell^- X$



$ep \to e' X$

- invented 2000–2002... mainly B physics → 2000's jet physics ... → 2010's heavy-ion physics ... 2020's
  - TMD
  - small-x
  - EW / dark matter
  - ⋮

- EFT organization of many concepts / tools in QCD factorization
  - power expansion in $\lambda \sim \frac{m}{E}, \frac{q_T}{Q}$
  - factorized modes for soft and collinear dofs separated in virtuality or rapidity scales
  - systematic organization of power corrections
  - RG evolution to sum large logs
  - identify universal nonperturbative effects in terms of field theory matrix elements

- Can do all these in "direct" QCD but often easier in EFT

e.g. SCET ⇒ N^3LL resummations
jet & TMD physics at subleading power
rigorous proofs of universal NP corrections
new approaches to jet substructure, NGLs, TMDs, small x, heavy ions...

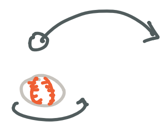
So … what is an EFT?

A1: Every theory is an EFT.

A2: Field theory containing

- dofs accessible kinematically at relevant energy/distance scales
- operators in $\mathcal{L}$ up to power/dimension needed for desired accuracy

  e.g. 1 particle Newtonian mechanics for baseball
  but need seams to describe curveball

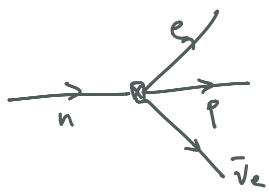


- symmetries known to be obeyed experimentally or from "full theory"
- regularization/renormalization scheme (e.g. DR)
- EFT does not have to be renormalizable! can have UV cutoff Λ_{UV}

  $\to$ EFT does not have to be renormalizable!

<u>Example 1</u>: Fermi theory

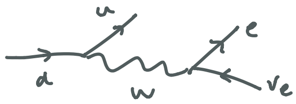
β decay:



$$\mathcal{L}_{EFT} = \sum_{ij} \frac{c_{ij}}{\Lambda_W^2} \bar{p}\Gamma_i n \; \bar{e}\Gamma_j \nu_e \quad + \text{h.c.}$$

Γ_i, Γ_j can be $\in \{ \underset{S}{1}, \underset{P}{\gamma_5}, \underset{V}{\gamma_\mu}, \underset{A}{\gamma_\mu\gamma_5}, \underset{T}{\sigma_{\mu\nu}} = \frac{i}{2}[\gamma_\mu,\gamma_\nu] \}$ $\qquad 16\times 16$

Now know full theory: SM



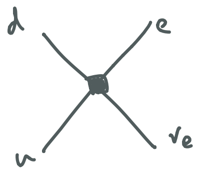
$$\mathcal{A} = \frac{g^2}{8} V_{ud} \frac{i}{k^2 - M_W^2} \bar{u}\gamma_\mu(1-\gamma_5) d \; \bar{e}\gamma^\mu(1-\gamma_5)\nu_e$$

$\downarrow$ for $k \ll M_W$

$$-\frac{i}{M_W^2}\left(1 + \frac{k^2}{M_W^2} - \frac{1}{2}\left(\frac{k^2}{M_W^2}\right)^2 + \cdots\right)$$

$\downarrow$

at leading order generates "effective operator"



$$\hat{\mathcal{O}} = \bar{u}\gamma_\mu(1-\gamma_5) d \; \bar{e}\gamma^\mu(1-\gamma_5) e$$

$\downarrow$

$\boxed{\text{"V–A"}}$ also known experimentally in Fermi th.

(still need NP matrix els. in p, n)

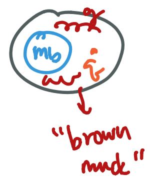
$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} V_{ud} \hat{\mathcal{O}}$$ with the SM prediction $\boxed{\frac{G_F}{\sqrt{2}} = \frac{g^2}{2M_W^2}}$

In this type of EFT, we "integrate out" a heavy particle(s) $\Rightarrow$ also SMEFT.

In the type we shall consider, we integrate out only large momentum modes of some given particle (e.g. HQET, NRQCD, SCET)

Example 2: HQET (Heavy Quark Effective Theory)

consider B meson



$P_Q = m_Q v + k$; $k \ll m_Q$; $v = (1, \vec{0})$ in B rest frame

Goal: "integrate out" m_Q fluctuations while leaving $k \sim \Lambda_{QCD}$ fluctuations in EFT

what do we expect in $\mathcal{L}_{HQET}$?

heavy quark propagator

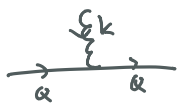
$$\frac{i(\not{P}_Q + m_Q)}{P_Q^2 - m_Q^2 + i\epsilon} = i \, \frac{m_Q \not{v} + \cancel{\not{k}} + m_Q}{\cancel{m_Q^2} + 2 m_Q v\cdot k + \cancel{k^2} - \cancel{m_Q^2} + i\epsilon}$$

small   small

$$= i \, \frac{1+\not{v}}{2 v\cdot k + i\epsilon} \rightarrow \text{indep. of } m_Q!$$

$\boxed{\text{flavor symmetry}}$ $c \leftrightarrow b$

gluon vertex



$$\sim \frac{1+\not{v}}{2}\gamma_\mu \frac{1+\not{v}}{2} = \frac{1+\not{v}}{2}\Big(\underbrace{\frac{1-\not{v}}{2}}_{0}\gamma_\mu + v_\mu\Big) = \frac{1+\not{v}}{2} v_\mu \frac{1+\not{v}}{2}$$

$\Rightarrow \gamma_\mu \longrightarrow v_\mu$ in HQET $\Rightarrow$ $\boxed{\text{spin symmetry}}$ e.g. $B \leftrightarrow B^*$

heavy quark symmetry: relates e.g. $B \to D e \nu$ to $D^* e \nu$ decay rates

corrections suppressed by $\frac{1}{m_Q}$.

$\Rightarrow$ even though we know the full theory (QCD), HQET makes approx. symmetries manifest and simplifies many calculations.

To construct $\mathcal{L}_{HQET}$:

Step 1: heavy quark field $\psi(x) = e^{-i m_Q v\cdot x}\,\psi_v(x)$: pulls out large momentum phase

$\hookrightarrow$ velocity "label"

Step 2: separate "large" & "small" spinor components:

$$\psi_v = h_v + H_v$$

$$h_v = \frac{1+\not{v}}{2}\psi_v \qquad H_v = \frac{1-\not{v}}{2}\psi_v$$

Step 3: plug in to $\mathcal{L}_{QCD}$:

$$\mathcal{L} = \bar{\psi}(i\not{D} - m_Q)\psi$$

$$= \bar{\psi}_v \, e^{i m_Q v\cdot x} (i\not{D} - m_Q) \, e^{-i m_Q v\cdot x}\psi_v$$

$$= \bar{\psi}_v (i\not{D} + m_Q\not{v} - m_Q)\psi_v$$

use $(1-\not{v})h_v = 0$
$(1-\not{v})H_v = 2H_v$

$$= (\bar h_v + \bar H_v)\,[\,i\slashed{D} h_v + (i\slashed{D} - 2m_Q) H_v\,]$$

use $\frac{1+\slashed{v}}{2}\, i\slashed{D}\, \frac{1+\slashed{v}}{2} = \frac{1+\slashed{v}}{2}\, iv\cdot D$

$$= \bar h_v\, iv\cdot D\, h_v - \bar H_v (iv\cdot D + 2m_Q) H_v$$
$$+ \bar h_v\, i\slashed{D}_\perp H_v + \bar H_v\, i\slashed{D}_\perp h_v$$

where $X_\perp^\mu = X^\mu - X\cdot v\, v^\mu$

step 4: H_v is like a "heavy" particle w/ mass $2m_Q$

$\Rightarrow$ integrate out using EOM $(iv\cdot D + 2m_Q) H_v = i\slashed{D}_\perp h_v$

$$\Rightarrow \mathcal{L} = \bar h_v \left(iv\cdot D + i\slashed{D}_\perp \frac{1}{iv\cdot D + 2m_Q} i\slashed{D}_\perp \right) h_v$$

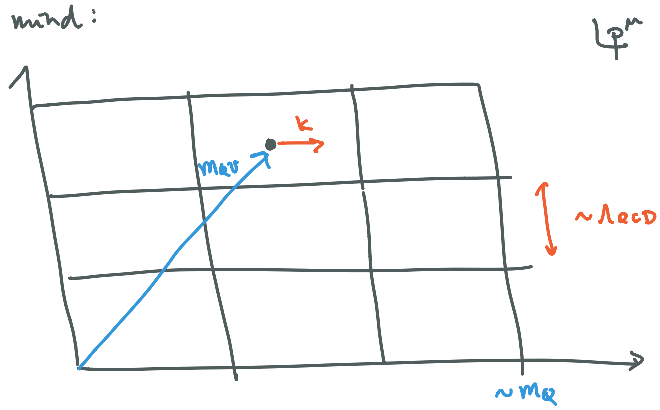
$$= \bar h_v \Big(iv\cdot D - \frac{1}{2m_Q} \slashed{D}_\perp \slashed{D}_\perp + \underbrace{\cdots}_{\sim \frac{1}{m_Q^2}} \Big) h_v$$

$$= \bar h_v \Big(\underbrace{iv\cdot D}_{\mathcal{O}(1)} \underbrace{- \frac{D_\perp^2}{2m_Q} - g\frac{\sigma^{\mu\nu} G_{\mu\nu}}{4m_Q}}_{\mathcal{O}(\frac{1}{m_Q})} + \cdots \Big) h_v$$

$\mathcal{O}(1)$: reproduces leading order HQET Feynman rules

$\mathcal{O}(\frac{1}{m_Q})$: breaks spin-flavor symmetry

Picture to have in mind:



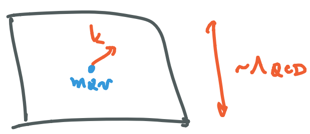
Note: RPI (Reparameterization Invariance)

HQET invariant under

$v \to v + \frac{\epsilon}{m_Q}$

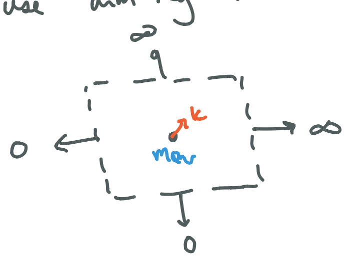
$k \to k - \epsilon$

HQET lives in the box:



defined w/ a regulator: cutoff intuitive but bad for Lorentz/gauge invariance

use dim reg & scale boundaries away:



$\mathcal{L}_{HQET}$ accurately reproduces $\mathcal{L}_{QCD}$ in the box (IR)

but not for large $k \gg \Lambda_{QCD}$

and "wrong" UV structure as $k \to \infty$

$\Downarrow$

fixed by matching & renormalization

$\downarrow$

actually useful for RGE to resum logs.