Status of Jet Physics

...actually more an introduction to SCET

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Outline

• Introduction
• Jet theory from separation of quantum modes
• Soft-Collinear Effective Theory (SCET)
• Anatomy of the SCET method
• Applications
• Extensions of the basic SCET setup
Jets

Jet: cluster of energetic hadrons leaving tracks and energy deposits in the detectors.

Most common object arising in high energy collisions and heavy particle decays
Jets

**Aim:** Precise (conceptual and) quantitative understanding of jet properties in the framework of QCD.

**In order to achieve:**

- Disentangle details of physics of the underlying hard reactions (QCD, Higgs, decays of new physics particles, …)
- Test our understanding of QCD and our tools to describe it quantitatively

**Characteristics of jets:**

- Represent very rich dynamical objects
- Can behave like unambiguous “particles” or quantum objects, that are defined by the measurement prescription, depending on what question we ask.
- Contain perturbative physics are different energy scales as well as non-perturbative effects. Portion depends on which observables we consider.
Monte-Carlo event generators:

- Separation/factorization of dynamical effects from different energy scales.
  - Hard interactions
  - Parton evolution to higher multiplicities
  - Hadronization
  - Secondary interactions

The workhorse for all experimental analyses.

- Full description of all aspects down to all properties of the individual final state hadrons
- Extremely versatile
Previous Talks

Applications:

• V+jet production: tests of MCs with NLO hard MEs
  important for assigning precision in BSM searches
  
  Vieri Candelise

• High-$p_T$ jet measurements: $\alpha_s$ and PDF determinations
  
  Nuno Anjos

• Jets as tools to learn about diffraction
  
  Grzegori Gach

• Jets in SUSY searches
  
  Sascha Caron

• Jets in DM decays
  
  Henso Abreu

• Jets in heavy ion collisions
  
  Thomas Trainor
Active areas or research to improve Monte Carlos:

- $N^k\text{LO}$ ($k=1,2$) partonic calculations
- Merging of parton shower and NLO partonic calculations
- Improvements/examinations of parton showers
- Test of models for secondary interactions (e.g. UE)

Adam Kardos
Marek Schönherr
Stefan Kluth
Wei Yang Wang

Brickwall problems that cannot be addressed in that way:

- Parton showers do not have more than LL precision
- Strong model component (hadronization, UE model, …)
- Limited theoretical precision for many subtle aspects
- What is the theory precision of tuning?
- Monte-Carlo: more model OR more first principles QCD?

What is the meaning of the QCD parameters in the Monte-Carlo?

$\alpha_s$, $m_{\text{top}}$, …

We also have to go different ways, and describe jets with first principles QCD.
Jets from Mode Separation

\[ E_{\text{jet}} \gg m_{\text{jet}} \gg E_{\text{soft particles}} \]

- Jet as multi-scale quantum system
- Separate quantum modes that live in separated areas of phase space
- Different quark and gluon fields for each separated sector in phase space
- Lagrangian formulation

Effective Field Theory Approach

Soft-Collinear-Effective Theory (SCET)

15 years ago: EFT approach invented to describe jets in B decays, for which EFTs are the only known theory approach

Until 5 years ago: EFT approach only reproduced many collider physics results already known before from the classic pQCD approach to jets.

Today: EFT approach addresses problems not addressed before …
Basic idea of mode separation

First developed for single jet problems in B-physics.

Bauer, Fleming, Pirjol, Stewart
2000-2001

We talk about a jet if: \( m_X^2 \lesssim Q \Lambda_{QCD} \)

Light-cone coordinates:

\[
\begin{align*}
 n^\mu &= (1, 0, 0, -1) \\
 \bar{n}^\mu &= (1, 0, 0, 1)
\end{align*}
\]

\[
\begin{align*}
 p^\mu &= p^+ \frac{\bar{n}^\mu}{2} + p^- \frac{n^\mu}{2} + p_\perp \\
 &= (p^+, p^-, p_\perp)
\end{align*}
\]

\[
\begin{align*}
 p^+ &= n.p = p_0 + p_3 \\
 p^- &= \bar{n}.p = p_0 - p_3
\end{align*}
\]
Basic idea of mode separation

First developed for single jet problems in B-physics.

B → X_s γ
E_γ → E_{γ}^{max}

jet invariant mass

Q = m_b

Bauer, Fleming, Pirjol, Stewart
2000-2001

Separation of modes:

Q^2 ≫ m_X^2 ≫ \frac{m_X^4}{Q^2} ≲ \Lambda_{QCD}^2

SCET 1

m_X^2 \sim Q \Lambda

\lambda = \sqrt{\frac{\Lambda}{Q}}

<table>
<thead>
<tr>
<th>modes</th>
<th>p^\mu = (+, -, \perp)</th>
<th>p^2</th>
<th>fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>collinear</td>
<td>Q(\lambda^2, 1, \lambda)</td>
<td>Q^2 \lambda^2</td>
<td>\xi_n, A_\mu^n</td>
</tr>
<tr>
<td>usoft</td>
<td>Q(\lambda^2, \lambda^2, \lambda^2)</td>
<td>Q^2 \lambda^4</td>
<td>q_{us}, A_\mu^{us}</td>
</tr>
</tbody>
</table>
Jets from Mode Separation

**Soft-Collinear Effective Theory:**

- Doing jet physics using the concept of mode and scale separation at the Lagrangian and operator level
  - Feynman rules
  - Systematic power counting
- Lagrangian level access to jet physics problems.
- IR-log resummation (soft+collinear) through UV-renormalization.
- Approach to access power corrections and subleading twist terms, double counting issues at operator level.
- Leads to results theoretically equivalent to classic pQCD wherever dedicated results have been derived in both approaches.

Differences in the way how results are implemented in applications (subleading).

Some problems appear harder / easier in either approach.
Consider simple example: \( e^+ e^- \rightarrow 2 \text{jets} \)

\( q = E_{\text{cm}} \) (massless quarks)

SCET 1

\[ m_X^2 \sim Q \Lambda \]

\[ \lambda = \sqrt{\frac{\Lambda}{Q}} \]

The physical measurement fixed the relevant setup of the quantum modes!
Effective Lagrangian

Collinear Lagrangian:

\[ \mathcal{L}_{\text{QCD}} = \bar{\psi} i\slashed{D} \psi \quad \psi = \xi n_i + \chi \bar{n}_i \]

\[ \mathcal{L}_{c,n} = \bar{\xi}_n \left( i\bar{n}.D_{us} + i\slashed{D}_{c,\perp} \frac{1}{i\bar{n}.D_{c}} i\slashed{D}_{c,\perp} \right) \frac{\bar{n}}{2} \xi_n \]

\[ iD_{us}^\mu = i\partial^\mu + gA_{us}^\mu \]

Effective Lagrangian: (leading in \( \lambda \))

\[ \mathcal{L}_{\text{SCET}} = \sum_{\text{jets } i} \mathcal{L}_{c,n_i}(\xi_{n_i}, A_{n_i}^\mu) + \mathcal{L}_s(q_{us}, A_{us}^\mu) \]
Effective Lagrangian

Effective jet currents: (dijet production in $e^+e^-$)

\[ \mathcal{J}^\mu(\omega, \bar{\omega}) = \bar{\chi}_{n,\omega}(0) \Gamma^\mu \chi_{\bar{n},\bar{\omega}}(0) \]

jet field

\[ \chi_{n,\omega}(0) = (W^\dagger \xi_n)(0) \]

n-collinear Wilson line

\[ W_n(0) = P \exp \left( ig \int_0^\infty ds \bar{n}.A_n(s\bar{n}) \right) \]

Jet fields are gauge invariant under collinear gauge transformations.

Complete gauge invariance in connection with all soft processes.

Explains the existence of jets + soft radiation between jets!
Factorization at Operator Level

Factorization:

\[ \mathcal{L}_{c,n} = \bar{\xi}_n i n \cdot D_{us} \frac{\bar{n}}{2} \xi_n \]

Soft field redefinition: soft-collinear decoupling

\[ \xi_n \rightarrow Y_n \xi_n, \quad A_n^\mu \rightarrow Y_n A_n^\mu Y_n^\dagger \]

\[ Y_n(x) = \bar{P} \exp \left( -ig \int_0^\infty ds \, n \cdot A_{us}(ns + x) \right) \]

\[ \mathcal{L}_{c,n} = \bar{\xi}_n i n \cdot \partial_{us} \frac{\bar{n}}{2} \xi_n \]

Factorization:

\[ |X\rangle \rightarrow |X_n X_n X_{\bar{n}} X_{us}\rangle = |X_n\rangle \otimes |X_n\rangle \otimes |X_{us}\rangle \]

\[ \mathcal{J}_\mu(\omega, \bar{\omega}) \rightarrow \bar{\chi}_{n,\omega}(0) Y_n^\dagger Y_{\bar{n}} \Gamma^\mu \chi_{\bar{n}, \bar{\omega}}(0) \]

soft-collinear decoupling

at the operator level
Anatomy of SCET Predictions

Singular Cross section (SCET 1)

\[
\left( \frac{d\sigma}{d\tau} \right)_{\text{sing}} \sim \sigma_0 H(Q, \mu_Q) U_H(Q, \mu_Q, \mu_s) \int d\ell d\ell' U_J(Q\tau - \ell - \ell', \mu_Q, \mu_s) J_T(Q\ell', \mu_j) S_T(\ell - \Delta, \mu_s)
\]

Convolution

\[ \lambda \sim \tau \]
Anatomy of SCET Predictions

Matrix element terms (fixed-order)

$$\left(\frac{d\sigma}{d\tau}\right)_{\text{sing, part}} \sim \sigma_0 H(Q, \mu_Q) U_H(Q, \mu_Q, \mu_s) \int d\ell d\ell' U_J(Q \tau - \ell - \ell', \mu_Q, \mu_s) J_T(Q \ell', \mu_j) S_T(\ell - \Delta, \mu_s)$$

Hard function

Each factor gauge invariant!

Soft function

Jet function

$$J_n(Q r_n^+, \mu) = \frac{-1}{8\pi N_c Q} \text{Disc} \int d^4 \vec{x} \, e^{i r_n \cdot x} \langle 0| T \bar{\chi}_n, Q(0) \tilde{\vec{p}} \chi_n(x) |0 \rangle$$

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Anatomy of SCET Predictions

Summation of large logarithms (RG-summation, SCET 1)

\[
\left( \frac{d\sigma}{d\tau} \right)_{\text{sing}} \sim \sigma_0 H(Q, \mu_Q) U_H(Q, \mu_Q, \mu_s) \int d\ell d\ell' U_J(Q_\tau - \ell - \ell', \mu_Q, \mu_s) J_T(Q\ell', \mu_j) S_T(\ell - \Delta, \mu_s)
\]

2-jet production current

\[
\mu \frac{d}{d\mu} H_Q(Q, \mu) = \gamma_{HQ}(Q, \mu) H_Q(Q, \mu)
\]

\[
\gamma_{HQ}(Q, \mu) = \Gamma_{H_Q}[\alpha_s] \ln \left( \frac{\mu^2}{Q^2} \right) + \gamma_{H_Q}[\alpha_s]
\]

NNNLL summations possible!
More powerful, but less general than CEASAR/ARES!

→ Heather McAslan

Jet function evolution

\[
\mu \frac{d}{d\mu} J(y, \mu) = \gamma_J(y, \mu) J(y, \mu) = \left[ 2\Gamma^{\text{cusp}}(\alpha_s) \ln(iy\mu^2 e^{\gamma_E}) + \gamma_J(\alpha_s) \right] J(y, \mu)
\]
Anatomy of SCET Predictions

Summation of large logarithms (RG-summation, SCET 1)

\[ \left( \frac{d\sigma}{d\tau} \right)_{\text{sing \ part}} \sim \sigma_0 H(Q, \mu_Q) U_H(Q, \mu_Q, \mu_s) \int d\ell d\ell' U_J(Q\tau - \ell - \ell', \mu_Q, \mu_s) J_T(Q\ell', \mu_j) S_T(\ell - \Delta, \mu_s) \]

\[ \frac{1}{\sigma} \frac{d\sigma}{d\tau} \]

scales become equal for multijet region

profile functions

\[ \mu_J(\tau) \propto \tau^{1/2} \]

\[ R(\tau) \sim \mu_S(\tau) \]
Anatomy of SCET Predictions

Combination for hadron level prediction

\[
\left( \frac{d\sigma}{d\tau} \right) = \int d\ell \left[ \left( \frac{d\sigma}{d\tau} \right)_{\text{part}}^{\text{sing}} \left( \tau - \frac{\ell}{Q} \right) + \left( \frac{d\sigma}{d\tau} \right)_{\text{part}}^{\text{nonsing}} \left( \tau - \frac{\ell}{Q} \right) \right] S^{\text{mod}}(\ell)
\]

- Fixed-order minus terms already resummed
- Soft matrix element model function

\[
\hat{F}(k)
\]

- \(\hat{F}^{(0)}(k)\)
- \(\hat{F}^{(1)}(k)\)
- \(\hat{F}^{(2)}(k)\)
- \(\hat{F}^{(3)}(k)\)
- \(\hat{F}^{(4)}(k)\)

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Application of SCET 1

Can be applied to global jet shape variables, not sensitive to transverse momenta: e.g. $e^+e^-$ eventshapes

$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

C-parameter

$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i| |\vec{p}_j| \sin^2 \theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$$

Analyses at NNNLL + $O(\alpha^2)$ fixed order using tail data (all available $Q>25$ GeV)

Becher, Schwartz (partonic resummation)

Full analysis incl. nonpert. effects:

Abbate, Fickinger, AHH, Mateu, Stewart (thrust)

AHH, Kolodrubetz, Mateu, Stewart (C-para)
Strong Coupling Determination

\[ \alpha_s(M_Z) = 0.1135 \pm 0.001 \]

Strong coupling from jets smaller than world average (basically lattice).
Further Developments (small selection)

Extension of massless SCET-1 to massive quarks: Pietrulewicz, AHH, Jemos, Mateu

Variable Flavor Number scheme for final state jets (can be combined with PDF)

For arbitrary masses and full log resummation in any kinematic regime.
Further Developments (small selection)

Upcoming: Measurement of MC top quark mass from NNLL + $O(\alpha_s)$ calculation from eventshapes (2-jettiness)

Butenschön, Dehnadi, AHH, Mateu, Stewart

$\overline{m}_t(\overline{m}_t) = 160$ GeV

Theory uncertainty (top)

MSR mass

(/preliminary)
Further Developments (small selection)

Upcoming: Measurement of MC top quark mass from NNLL + O(α_s) calculation from eventshapes

Butenschöne, Dehnadi, AHH, Mateu, Stewart

(preliminary)
Further Developments (small selection)

Different types of SCET (examples)

Actually all different EFTs, but they are all part of the SCET method.

For example: DIS for $x \to 1$

AHH, Pietrulewicz, Samitz

Fixes flaws in previous factorization proofs by Becher, Neubert and Fleming, Zang.
Further Developments (small selection)

Summation of non-global logarithms (NGLs)

NGLs arise in non-global jet observables (only radiation in limited regions included)

Add more and more measurements to resolve increasing number of soft subjets located at the jet boundary, where the NGLs are generated. Resummation of NGL by usual RG methods.

Larkoski, Moult, Neill
Further Developments (small selection)

Summation of non-global logarithms (NGLs)

NGLs arise in non-global jet observables (only radiation in limited regions included)

Problem is actually a jet substructure problem which is also an active subject in the SCET community.

\[
\frac{d\sigma}{dA dB} = H_{n\bar{n}} J_n(A) \otimes \tilde{J}_{\bar{n}}(B) \otimes S_{n\bar{n}}(A, B)
\]

Observable wanted

\[
\frac{d\sigma}{d\epsilon_2^{(\alpha)} d\epsilon_2^{(\beta)} d\epsilon_3^{(\beta)} dB} = H_{n\bar{n}} H_{n\bar{n}} \epsilon_2^{(\alpha)} \epsilon_2^{(\beta)} J_{n\bar{n}}(e_3^{(\beta)}) \otimes S_{n\bar{n}s}(e_3^{(\beta)}) \otimes S_{n\bar{n}s}(e_3^{(\beta)} ; B) \otimes J_{n}(e_3^{(\beta)}) \otimes \tilde{J}_{\bar{n}}(B)
\]

Sum logs here

marginalize

Larkoski, Moult, Neill
Conclusions

- Monte-Carlo event generator description of jets is and will be the working horse of jet physics
- Versatility of the MCs represents a brickwall for the conceptual/theoretical precision of parton showers beyond LO/LL order
- Soft-Collinear Effective Theory: aimed at making internal dynamics of jets accessible to pQCD and factorization in a systematically improvable matter
- Lagrangian formulation of SCET is its strength (e.g. bookkeeping, all log summation related to renormalization and RG-evolution)
- Crucial aspect of SCET: finding the relevant quantum modes for a particular measurement → factorization → calculations (FO+logs)
- SCET allows for high precision computations
- SCET allows for very complicated mode setups to solve previously hard problems