Collider physics with SCET

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Collider Physics

Many different scales in collider processes

- $E_{\text{c.m.}}$
- $p_T$ of jets
- Jet masses $M_J$
- Energy of soft radiation,
- Hadron masses: $m_p$

Effective field theories are the standard tool to analyze multi-scale problems in quantum field theory.
Soft-Collinear Effective Theory

Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke et al. 2002; ...

Implements structure of soft and collinear interactions on the Lagrangian level:

- Soft and collinear fields with definite interactions and power counting.
- Theory contains non-localities associated with large light-like momenta.

Provides efficient formalism to

- (re-)derive factorization theorems
- perform resummations of logarithmically enhanced contributions to all orders

\[ d\sigma \sim H(\{s_{ij}\}, \mu) \prod_i J_i(M_i^2, \mu) \otimes S(\{\Lambda_{ij}^2\}, \mu) \]
Diagrammatic Factorization

The simple structure of soft and collinear emissions forms the basis of the classic factorization proofs, which were obtained by analyzing Feynman diagrams.

Collins, Soper, Sterman, ...

Advantages of the the SCET approach:

• Simpler to exploit gauge invariance on the Lagrangian level
• Operator definitions for the soft and collinear contributions
• Resummation with renormalization group
• Can include power corrections

Collins and Soper ‘81
Timeline of the talk

The classical period

- Threshold (aka soft-gluon) resummation

The dark age

- Transverse momentum resummation and the collinear anomaly

Modern times

- Resummations for jet physics:
  - jet vetoes, jet shapes, jet charge, ...
Threshold resummation
Threshold resummation

Resum higher-order perturbative terms near the partonic threshold

- often, this gives the bulk of the perturbative corrections
- region enhanced by the fall-off of the PDFs

SCET methods well developed

- based on RG evolution in momentum space

recently combined with Coulomb resummation for top production.
**Theory vs. ATLAS data**

$W^+ + W^-$ (LHC, 7 TeV, 31 pb$^{-1}$)

- NLO
- $N^3LL_p + NLO$

PDF uncertainties

Becher, Lorentzen Schwarz ’12
\( \bar{t}t \) production, soft and Coulomb resummation

**Figure 10**: Comparison of theory to data. The dashed blue lines indicate PDF uncertainties, while the solid red lines show the central values. The TOPIXS result (red) is compared to the D0 experimental result (black). The spread of the central-value predictions obtained from different PDF sets is also shown.

**Legend**
- **Tevatron**
  - Experimental result: D0
  - Theoretical result: TOPIXS

**Notes**
- Beneke, Falgari, Klein, and Schwinn ’11
- TOPIXS: Beneke, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan ’12

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As pointed out in the introduction, measurements of top-quark pair production at the Tevatron, where the inclusion of the exact NNLO result for the dominant gg production, in [20] it has been shown that NNLL corrections beyond NLO can be very large, up to 15\% for higher masses, becoming much smaller than the error of the most recent experimental cross sections. This is particularly true for higher masses, becoming much smaller than the error of the most recent experimental cross sections.

Theoretical predictions are compatible with the error estimate of the individual NNPDF2.1 [24] and ABM11 [25] NNLO PDF sets are remarkably close to the experimental values provided by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NNPDF2.1 still show a good agreement with each other by D0 and CDF. At the LHC, MSTW2008, CT10 and NN.pdf
\[ \nu, W \text{ and } Z \text{ production at large } p_T \]

\[ t\bar{t} \text{ production, soft and Coulomb resummation} \]

\[ t\bar{t} \text{ production} \]

cross section

FB asymmetry

\[ \sqrt{s} = 1.96 \text{ TeV} \]

\[ d\sigma / dM_{tt} \text{ [fb/GeV]} \]

\[ M_{tt} \text{ [GeV]} \]

\[ A_{FB} \]

Ahrens, Ferroglia, Neubert, Pecjak and Yang '11
\( \bar{t} \bar{t} \) production, soft and Coulomb resummation

\[ \alpha_s W^2 \] production

SUSY: squark, gluino and slepton production

K-factor for \( \tilde{s}, \tilde{g} \)

K-factor for \( \tilde{\ell} \)

Falgari, Schwinn, Wever ’12

Broggio, Neubert and Vernazza ’12
Transverse momentum resummation and the collinear anomaly
Standard factorization (SCET$_t$)

Three correlated scales

• Hard scale $Q$
• Collinear Scale $P$
• Soft scale $P^2/Q$

Soft matrix element depends in large scale $Q$

\[ d\sigma = H \cdot J \otimes J \otimes S \]

\[ \ln^2 \frac{Q^2}{P^2} = \frac{1}{2} \ln^2 \frac{Q^2}{\mu^2} - \ln^2 \frac{P^2}{\mu^2} + \frac{1}{2} \ln^2 \frac{P^4/Q^2}{\mu^2} \]

Sudakov double logarithm
Anomalous factorization (SCET_{II})

Standard (ultra-)soft modes do not contribute to observables sensitive transverse momentum.

\[ P_T^{\text{ultra-soft}} \sim P_T^2/Q \ll P_T \]

**Puzzle:** The cross section can only be \( \mu \) independent, if also the low-energy part is \( Q \) dependent.

\[
\ln^2 \frac{Q^2}{P_T^2} = \ln^2 \frac{Q^2}{\mu^2} - \ln^2 \frac{P_T^2}{\mu^2} + ?
\]

Unregularized light-cone singularities in SCET diagrams.
Anomalous factorization (SCET$_{\|}$)

Standard (ultra-)soft modes do not contribute to observables sensitive transverse momentum.

$$P_{T}^{\text{ultra-soft}} \sim P_{T}^{2}/Q \ll P_{T}$$

Resolution: $Q$ dependence arises from a collinear factorization anomaly in the effective theory

$$\ln^{2} \frac{Q^{2}}{P_{T}^{2}} = \ln^{2} \frac{Q^{2}}{\mu^{2}} - \ln^{2} \frac{P_{T}^{2}}{\mu^{2}} - 2 \ln \frac{P_{T}^{2}}{\mu^{2}} \ln \frac{Q^{2}}{P_{T}^{2}}$$

TB, Neubert ’10
Analytic phase-space regularization

EFT phase-space integrals suffer from rapidity divergences not regularized dimensionally. Regularize with

$$\int d^d k \, \delta(k^2) \, \theta(k^0) \quad \Rightarrow \quad \int d^d k \, \left(\frac{\nu_+}{k_+}\right)^\alpha \delta(k^2) \, \theta(k^0)$$

Divergences in $\alpha$ cancel when the different sectors of SCET are combined, but anomalous $Q$-dependence remains

- Consistency conditions yield all-order form of $Q$-dependence

  Chiu, Golf, Kelley and Manohar ’07; TB, Neubert ’10

Alternative: “Rapidity renormalization group” based on regularization of Wilson lines Chiu, Jain, Neill, Rothstein ’12
Drell-Yan production at small $q_T$

Classical two-scale process for which the resummation of Sudakov logs $\sim \alpha_s^n \ln^{2n}(M/q_T)$ is essential.

First achieved in Collins, Soper and Sterman (CSS) ’84

Obtain factorization theorem based on collinear anomaly.

\[
\frac{d\sigma}{dq_T} \sim H(M) \int d^2 x_T e^{-i q_T \cdot x_T} \left[ I(x_T) \otimes \phi \right] \left[ I(x_T) \otimes \phi \right] (M^2 x_T^2)^{-F_{qq}(x_T)}
\]

beam functions
anomalous $M$ dependence is a pure power in $x_T$ space

Matches onto CSS. Derive three-loop coefficient $A^{(3)}$, last unknown ingredient for NNLL accuracy in CSS formula.
Z-boson production at Tevatron

TB, Neubert, Wilhelm ’11

• First complete calculation of Z-boson and Higgs production at NNLL+NLO

Figure 7: Comparison with Tevatron Run I data from CDF, with and without long-distance corrections. The lower panels show the deviation from the default theoretical prediction.

In Figure 7, we compare again to the CDF data [26] and plot the theoretical prediction for \( \Lambda_{NP} = 0 \) and \( \Lambda_{NP} = 0.6 \text{ GeV} \). In the lower panels, we give the ratio of the experimental and theoretical results to our default prediction. Including a non-perturbative shift, a good description of the data is achieved over the entire \( q_T \) range. In Figure 8, we repeat the same comparison for the Tevatron Run II results from DØ [31, 32] and for the LHC result of the ATLAS collaboration [33]. Since this data is not finely binned in the peak region, it difficult to draw firm conclusions on the necessity for long-distance corrections. However, in both cases, the first data bin is below the prediction without including a long-distance correction.

The systematic experimental uncertainties which affect the low \( q_T \) experimental results are substantial, because it is highly sensitive to lepton transverse momentum resolution. Recently, two new variables \( a_T \) and \( \phi^* \eta \) were introduced, which probe the same physics but have reduced sensitivity to the momentum resolution [34, 35]. DØ has now performed a very precise measurement of the variable \( \phi^* \eta \) [36]. It would be interesting to include the lepton decay in our results and to study these variables. In the traditional framework, resummed results for these quantities were presented recently in [37, 38].

The region of larger \( q_T \gtrsim 20 \text{ GeV} \) is not affected by long-distance corrections and should be described well by fixed-order perturbation theory. In this region the data lies somewhat above the prediction, in particular for the case of the ATLAS results. A comparison to the existing fixed-order results is given in Figure 9. The red bands correspond to the \( O(\alpha_s^2) \) fixed-order result for the spectrum, which is the highest order currently known.

The hadronic parameter: 

\[ \Lambda_{NP} = 0 \]

\[ \Lambda_{NP} = 0.6 \text{ GeV} \]
Z-boson production at the LHC

Figure 8: Comparison to Tevatron Run II and ATLAS data, with and without long-distance corrections. The lower panels show the deviation from the default theoretical prediction.

- Spectrum has remarkable properties for $q_T \rightarrow 0$ TB, Neubert, Wilhelm ’11
Factorization

Factorization at low $q_T$ proceeds in two steps

1.) Use $q_T \ll M_Z$ to factorize cross section

\[
\mathcal{B}_{q/N_1} \times H(Q^2, \mu) \times \mathcal{B}_{\bar{q}/N_2}
\]

“hard function” $\times$ “transverse PDF” $\times$ “transverse PDF”

2.) Use $\Lambda_{QCD} \ll q_T$ to factorize

\[
\mathcal{B}_{i/N}(\xi, x_T^2, \mu) = \sum_j \int_{\xi}^1 \frac{dz}{z} \mathcal{I}_{i\rightarrow j}(z, x_T^2, \mu) \phi_{j/N}(\xi/z, \mu) + \mathcal{O}(\Lambda_{QCD}^2 x_T^2)
\]

“transverse PDF” $=$ “matching coefficient” $\times$ “standard PDF”
Transverse PDFs

Regularization of transverse PDFs is delicate. Using phase-space regularized definition TB, Bell ’12

\[ \mathcal{B}_{q/N_1}(z, x_T^2) = \frac{1}{2\pi} \int_{-\infty}^{\infty} dt \, e^{-izt\vec{n} \cdot \vec{p}} \sum_{X, \text{reg.}} \frac{\eta_{\alpha\beta}}{2} \langle N_1(p) | \bar{\chi}_\alpha(t\vec{n} + x_\perp) | X \rangle \langle X | \chi_\beta(0) | N_1(p) \rangle \]

matching from to standard PDFs has now been computed at the two-loop level. Gehrmann, Lübbert, Yang 1209.0682

- First two-loop computation for transverse PDFs!

Individual PDFs suffer from divergences in analytic regulator but the product of PDFs is well defined and the regulator can be removed.

Anomalous Q-dependence

\[ \left[ \mathcal{B}_{q/N_1}(z_1, x_T^2, \mu) \mathcal{B}_{\bar{q}/N_2}(z_2, x_T^2, \mu) \right] Q^2 = \left( \frac{x_T^2 Q^2}{4e^{-2\gamma_E}} \right) -F_{q\bar{q}}(x_T^2, \mu) \mathcal{B}_{q/N_1}(z_1, x_T^2, \mu) \mathcal{B}_{\bar{q}/N_2}(z_2, x_T^2, \mu) \]

for more discussion on TMPDFs, see Ignazio Scimemi’s talk
Jet broadening

\[ B_T = \frac{1}{2Q} \sum_i |p_i^\perp| = \frac{1}{2Q} \sum_i |p_i \times \vec{n}_T| \]

- Event shape which measures transverse momentum inside jet. Measured precisely at LEP.
- Large logs at small \( B_T \). NLL resummation was known Dokshitzer et al. ’98
- Jet recoils against soft radiation: All-order factorization theorem based on collinear anomaly. TB, Bell Neubert ’11; Chiu, Jain, Neill, Rothstein ’11.
Broadening distributions

- Have extended resummation to NNLL accuracy with two-loop computation of collinear anomaly. TB, Bell 1210.0580
- Results will be used for precise determination of $\alpha_s$ from experimental data. Consistency check on $\alpha_s$ extraction from $N^3LL+NNLO$ prediction of thrust. Abbate et al. ’10
Two-loop anomaly exponent

\[ d^B_2(z) = C_A \left\{ -\frac{1}{9} \frac{z^2}{9} h_1(z) + \frac{67 + 2z^2}{9} h_2(z) - 8 h_3(z) + 32 S_{1,2} \left( -\frac{z_-}{z_+} \right) - 8 \text{Li}_3 \left( -\frac{z_-}{z_+} \right) \right. \]

\[ + 8 S_{1,2}(-w) - 24 \text{Li}_3(-w) - 24 S_{1,2}(1-w) + 8 \text{Li}_3(1-w) + 24 S_{1,2} \left( \frac{1-w}{2} \right) \]

\[ - 8 \text{Li}_3 \left( \frac{1-w}{2} \right) - 8 \left( 3 \ln z_+ + 4 \ln 2 \right) \text{Li}_2 \left( -\frac{z_-}{z_+} \right) + 8 \ln \left( (1+w)w^3 \right) \text{Li}_2(-w) \]

\[ - 8 \ln 2 \text{Li}_2 \left( \frac{1-w}{2} \right) + 4 \ln \frac{w}{2} \ln^2 z_+ + 12 \ln^2 w \ln(4z_+) - \frac{16}{3} \ln^3(2z_+) \]

\[ + \frac{11}{3} \ln^2 z_+ + 16 \ln 2 \ln \frac{w}{4} \ln z_+ + \left( 24 \ln^2 2 + \frac{67}{9} \right) \ln z_+ + 4 \ln^2 2 \ln \frac{w^4}{2} \]

\[ + \pi^2 \ln 2 + \frac{290}{27} - 18 \zeta_3 - \frac{2}{9} z^2 - \frac{2w(32 - z^2)}{9} \ln \left( \frac{1+w}{w} \right) - \frac{w(65 + 2z^2)}{9} \right}\]

\[ + T_F n_f \left\{ \frac{2(1+z^2)}{9} h_1(z) - \frac{2(13 + 2z^2)}{9} h_2(z) - \frac{4}{3} \ln z_+ - \frac{20}{9} \ln z_+ + \frac{4}{9} z^2 - \frac{82}{27} \right\} \]

\[ + \frac{4w(5 - z^2)}{9} \ln \left( \frac{1+w}{w} \right) + \frac{2w(11+2z^2)}{9} \right\}, \]

where \( w = \sqrt{1+z^2} \) and \( z_\pm = (w \pm 1)/4 \).

\( h_1(z) \) and \( h_2(z) \) and \( h_3(z) \) are elliptic integrals.
Verify that we obtain the right logarithmic terms at $O(\alpha_s^2)$ and $O(\alpha_s^3)$ by comparing with fixed-order results at small broadening.
Jet observables
Jet physics

Most hadron collider physics is discussed in terms of jet observables. Many examples of multi-scale problems

- Jet veto

- enhance Higgs signal, ...

- Small $p_T$, small jet radius $R$, small jet mass, ...

- Jet substructure

- distinguish $W$ or top jets from QCD jets
Jet veto in Higgs production

Analysis is done in jet bins, since background is very different when Higgs is produced in association with jets.

Need precise predictions for $H + n$ jets, in particular for the 0-jet bin, i.e. the cross section with a jet veto:

$$p_{T}^{\text{Jet}} < p_{T}^{\text{Veto}} \sim 15-30 \text{ GeV}$$
All-order factorization for jet veto

\[
\frac{d\sigma(p_T^{\text{veto}})}{dy} = \sigma_0(\mu) C_t^2(m_t^2, \mu) |C_S(-m_H^2, \mu)|^2 \left( \frac{m_H}{p_T^{\text{veto}}} \right)^{-2F_{gg}(p_T^{\text{veto}}, \mu)} \times \sum_{i,j} I_{g\leftarrow i}(p_T^{\text{veto}}, \mu) \otimes \phi_i/P(\mu) I_{g\leftarrow j}(p_T^{\text{veto}}, \mu) \otimes \phi_j/P(\mu)
\]

All NNLL ingredients known, except two-loop anomaly. Can be extracted from NNLL results of Banfi, Salam and Zanderighi ‘12;

- Have verified their result, with computation in SCET. TB, Rothen, Neubert, in preparation.
- Detailed phenomenological analysis under way.
Resummations for $N$-jet processes

• **The good:** hard anomalous dimensions for NNLL resummations of arbitrary $N$-jet processes known. T.B., Neubert ’09

• **the bad:** many observables suffer from non-global logarithms Dasgupta and Salam ’01 in soft functions

• several explicit computations of such logs, but so far no way to resum them. Kelley et al. ’11, Hornig et al. ’11

• **and the ugly:** phase-space constraints from traditional jet algorithms induce complicated clustering algorithms at each order. Kelley, Walsh, Zuberi ’12

→ Will likely need to **switch to simpler observables**, such as $N$-jettiness Stewart, Tackmann, Waalewijn ’10 to reach higher-log accuracy.
\( N \)-jettiness

Stewart, Tackmann, Waalewijn ’10

\[ \tau_N = \frac{2}{Q^2} \sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots, q_N \cdot p_k\} \]

- Similar to \( e^+e^- \) event shape \( \tau=1-T \), but \( N \) different axes, instead of single thrust axis.
- Vanishes, if all particles move along the \( N \) axes.
Consider only particles inside single jet.

\( \tau_{21} = \tau_2 / \tau_1 \) can be used to distinguish boosted W-jets from QCD jets.

\( \tau_{32} \) for boosted top jets (with generalized \( \tau_N \) def.)

ATLAS ’12 has measured \( \tau_{21} \) and \( \tau_{32} \).
Recycling thrust

Feige, Schwartz, Stewart and Thaler ’12

- Obtain $\tau_{21} = \tau_2/\tau_1$ subjet-tiness distribution of highly boosted $Z$-decays from $e^+e^-$ thrust distribution.

- Can correct $\tau_{21}$ for contamination from rest of the event (ISR/UE) at large $Q$. 

Jet properties

• Fragmentation inside jet Procura Stewart ’10; Jain, Procura, Waalewijn ’11, ’12; Procura, Waalewijn ’11, ’12

• Jet charge Krohn, Lin, Schwartz, Waalewijn ’12; Waalewijn ’12

• distinguish quark from anti-quark and gluon jets

• Jet quenching D’Eramo, Hong Liu, Krishna Rajagopal ’11 ’12; Ovanesyan, Vitev ’11; Benzke, Brambilla, Escobedo, Vairo ’12

→ Michael Benzke’s talk
Summary

• Soft collinear effective theory is an efficient tool to derive factorization theorems and perform resummations

• Many collider physics applications: $W$, $Z$, $\gamma$, $t$, $H$ production, event shapes, jet properties, ...

• in several cases SCET has pushed the limits of what has been achieved with traditional methods

• Focus is now on jet processes at hadron colliders

• Lots of new results, but also still many interesting open questions
Extra slides
Infrared protection at very small $q_T$

TB, Neubert, Wilhelm: 1109.6027 (JHEP)

A careful analysis reveals that the spectrum $d\sigma/dq_T$ is **short-distance dominated** (but genuinely non-perturbative) all the way down to zero transverse momentum

The appropriate choice of $\mu$ eliminating large logarithms from the Bessel integrals is:

$$\mu \sim \max(q_T, q_\ast) \quad \text{with:} \quad q_\ast \approx M \exp \left( -\frac{2\pi}{(4C_F/A + \beta_0) \alpha_s(M)} \right)$$

- minimal scale $\mu = q_\ast$ corresponds to $\eta = 1$

$\Rightarrow$ yields **1.9 GeV** for Z production, and **7.7 GeV** for Higgs production

Scale $q_\ast$ controls the size of **long-distance hadronic corrections**, which are sizable for Z production but very small for Higgs production
Infrared protection at very small $q_T$

Dedicated analysis of $q_T \to 0$ limit yields:

$$\frac{d\sigma}{dq_T^2} \sim \frac{N}{\sqrt{\alpha_s}} e^{-\#/\alpha_s} (1 + c_1 \alpha_s + \ldots)$$

• expression has an essential singularity at $\alpha_s = 0$ (zero convergence radius)

Essential features of the spectrum are non-perturbative (but short-distance dominated)

Parisi, Petronzio 1979; Collins, Soper, Sterman 1985; Ellis, Veseli 1998

TB, Neubert, Wilhelm: 1109.6027 (JHEP)
Higgs-boson production at LHC

- Higgs $q_T$ spectrum is predicted with similar accuracy, only that long-distance hadronic corrections are much smaller in this case.