Effective field theory methods for the LHC

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Puzzle of the inclusive Higgs cross section

The simplest hadron collider process, yet very large corrections ...

Higgs cross sections working group (2012)

→ see talks by S. Dittmaier & R. Boughezal

Harlander, Kilgore (2002); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003)
Outline: Production of EW bosons W, Z, H (+ jets)

- Motivation and introduction
- Conventional factorization theorems
- “Anomalous” factorization theorems
- Summary
Complexities of hadron collider processes

- **Multi-scale problems**, typically involving several hierarchical scales and often complicated kinematics
- Presence of **soft and collinear singularities** leads to large Sudakov double logarithms
- Separation of **short and long-distance contributions** is subtle; cannot be performed using a conventional OPE
- Due to **light-like nature** of these processes, any field-theory description must be intrinsically **non-local**

QCD factorization theorems:

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

operators containing **Wilson lines**
Philosophy of effective field theory

• Separate contributions associated with different mass scales, turning a multi-scale problem into a series of single-scale problems
• Evaluate each contribution at its natural scale, leading to improved perturbative behavior
• Use the renormalization group to evolve contributions to an arbitrary factorization scale, thereby exponentiating (resumming) large corrections

When this can be done consistently large K-factors do not arise, since no large perturbative corrections are left unexponentiated!
Scale separation in collider physics

**Soft-collinear effective theory (SCET):** systematic framework to study collider problems by describing collinear and soft particles by effective quark and gluon fields with well-defined interactions and power counting

- **factorization** of short- and long-distance contributions follows from structure of $\mathcal{L}_{\text{eff}}$ (caveat: “collinear anomaly”)
- **gauge invariance** implemented at Lagrangian level
- **operator definitions** of jet and soft functions
- **resummation** of Sudakov logarithms is accomplished by solving RG equations

Elegant method for (re-)deriving **factorization theorems** in collider and heavy-flavor physics and resumming large perturbative corrections

Often allows for improved control over nonperturbative **long-distance effects**
Conventional factorization theorems

Drell-Yan processes near threshold
- W/Z production
- Higgs production in gluon fusion
- slepton pair production

Pair production of heavy particles
- top-quark pair production
- boosted tops
- squark and gluino pair production

Threshold production of W/Z/H+jet

Becher, MN: 0605050 (PRL); + Xu: 0710.0680 (JHEP)
Ahrens, Becher, MN, Yang: 0809.4283 (EPJC), 1008.3162 (PLB)
Broggio, MN, Vernazza: 1111.6624 (JHEP)

Ahrens, Ferroglia, MN, Pecjak, Yang: 1003.5827 (JHEP), 1103.0550 (JHEP), 1105.5824 (PLB), 1106.6051 (PRD); Beneke, Falgari, Klein, Schwinn: 1109.1536 (NPB)
Ferroglia, Pecjak, Yang: 1205.3662 (PRD), 1306.1537 (JHEP); + Marzani: 1310.3836 (JHEP)

Broggio, Ferroglia, MN, Vernazza, Yang: 1304.2411 (JHEP), 1312.4540 (JHEP); Beneke et al.: 1312.0837
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Becher, Bell, Lorentzen, Marti: 1309.3245 (JHEP)
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Conventional factorization theorems

Jet substructure
- boosted event shapes
- jet charge
- energy correlation functions

Soft radiation at hadron colliders
- matching fully differential NNLO predictions with parton showers
- factorization analysis of soft hadronic activity underlying primary hard interaction (ISR, multiple parton interactions, underlying event, …)

→ topics for the QCD session

- Feige, Schwartz, Stewart, Thaler: 1204.3898 (PRL)
- Waalewijn: 1209.3019 (PRD)
- Larkoski, Salam, Thaler: 1305.0007 (JHEP)
- Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi: 1311.0286
- Stewart, Tackmann, Waalewijn: 1405.6722

and many more papers …
Factorization of three correlated scales

Generic factorization theorem:

\[ d\sigma = H J \otimes J \otimes S \]
Drell-Yan processes near threshold

In Drell-Yan processes \( pp \rightarrow V + X \) \((V = \gamma, Z, W, H)\) near the partonic threshold, where \( z = \frac{M_V^2}{\hat{s}} \rightarrow 1 \), the collinear functions are standard parton distribution functions (PDFs):

\[
d\sigma = H \phi \otimes \phi \otimes S
\]

Hence large Sudakov logarithms can be resummed by evolving the hard function \( H \) and PDFs to the characteristic soft scale, using the RGE:

\[
\mu^2 \frac{d}{d \mu^2} H(Q, \mu) = \left[ C_{q/g} \gamma_{\text{cusp}}(\alpha_s) \ln \frac{|Q^2|}{\mu^2} + 2 \gamma_{q/g}(\alpha_s) \right] H(Q, \mu)
\]

SCET factorization theorem is equivalent to standard QCD factorization theorem by Sterman (1987) and Catani, Trentadue (1989).

Drell-Yan processes near threshold

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  d\sigma = H \phi \otimes \phi \otimes S
\]

SCET resummation approach is equivalent to standard soft-gluon resummation in QCD with **one important twist**:

- hard function for time-like processes \( q\bar{q} \to W, Z \) and \( gg \to H \) is naturally evaluated at \( \mu^2 \sim Q^2 = -m_H^2 \)

- EFT evolution then **automatically resums** a class of large perturbative corrections \( \sim (N_c\alpha_s\pi)^n \) and **significantly improves the convergence** of the perturbative expansion!

Higgs production in gluon fusion @ N^3LL+NNLO


- perturbative expansion after resummation **converges** very well
- scale uncertainties are **reduced** order by order
- prediction at N^3LL+NNLO is about **15% higher** than fixed-order NNLO, accounting for most of the ~16% enhancement expected from preliminary NNNLO calculations → see talk by S. Dittmaier
- remaining uncertainty dominated by **PDFs**:

```
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<th>m_H [GeV]</th>
<th>LHC (14 TeV)</th>
<th>LHC (14 TeV)</th>
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<td>57.9^{+1.6+4.4}_{-0.3-4.2}</td>
<td>58.8^{+1.7+3.1}_{-0.4-3.5}</td>
<td>60.3^{+1.8+3.9}_{-0.7-3.9}</td>
</tr>
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<td>125</td>
<td>50.4^{+1.4+3.8}_{-0.3-3.6}</td>
<td>51.1^{+1.4+2.6}_{-0.3-3.0}</td>
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<td>47.8^{+1.3+2.5}_{-0.3-2.7}</td>
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</tr>
</tbody>
</table>
```

→ public code RGHiggs available at: [http://projects.hepforge.org/rghiggs](http://projects.hepforge.org/rghiggs)
Pair-production of heavy colored particles

Formula

$$d\sigma = H \phi \otimes \phi \otimes S$$

still valid, but hard and soft functions now depend on several kinematic variables and are matrices in color space

For top-quark pair production near threshold:

$$\frac{d^2\sigma}{dMd\cos\theta} = \frac{8\pi\beta_t}{3sM} \sum_{i,j} \int_\tau^1 \frac{dz}{z} f_{ij}(\tau/z, \mu_f) C_{ij}(z, M, m_t, \cos\theta, \mu_f)$$

with: → see talks by A. Ferroglia & S. Moch

$$C_{ij}(z, M, m_t, \cos\theta, \mu_f) = \text{Tr} \left[ H_{ij}(M, m_t, \cos\theta, \mu_f) S_{ij}(\sqrt{s}(1-z), m_t, \cos\theta, \mu_f) \right] + \mathcal{O}(1-z)$$

Pair-production of heavy colored particles

**Anomalous dimensions** needed for threshold resummation are matrices in color space and depend on kinematic variables as well

- for resummation at NNLL order, they are known for an **arbitrary collider process**, involving any number of massless or massive external particles:

\[
\Gamma(p, m, \mu) = \sum_{(i,j)} \frac{T_i \cdot T_j}{2} \gamma_{\text{cusp}}(\alpha_s) \ln \frac{\mu^2}{-s_{ij}} + \sum_i \gamma_i(\alpha_s)
\]

\[
- \sum_{(I,J)} \frac{T_I \cdot T_J}{2} \gamma_{\text{cusp}}(\beta_{IJ}, \alpha_s) + \sum_I \gamma^I(\alpha_s) + \sum_{I,J} T_I \cdot T_J \gamma_{\text{cusp}}(\alpha_s) \ln \frac{m_I \mu}{-s_{IJ}}
\]

\[
+ \sum_{(I,J,K)} \epsilon_{IJK} T^a_I T^b_J T^c_K F_1(\beta_{IJ}, \beta_{JK}, \beta_{KI})
\]

\[
+ \sum_{(I,J)} \sum_k \epsilon_{IJK} T^a_I T^b_J T^c_K f_2(\beta_{IJ}, \ln \frac{-\sigma_{JK} v_J \cdot p_k}{-\sigma_{IK} v_I \cdot p_k}) + \mathcal{O}(\alpha_s^3)
\]

- deep connection to **IR singularities of scattering amplitudes** in non-abelian gauge theories

Becher, MN (2009); Gardi, Magnea (2009);
Mitov, Sterman, Sung (2009); Ferroglia, MN, Pecjak, Yang (2009)
Top-quark pair production @ NNLL+NLO

Arbitrary differential distributions (of the top-quark pair and of individual top quarks) can be resummed near threshold:

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

\[ \frac{d\sigma}{dM} \] [fb/GeV]

\[ \langle M \rangle \approx 445 \text{ GeV for the Tevatron and } 375 \text{ GeV for the LHC} \]

\[ \theta \] [degree]

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

\[ \langle \sigma \rangle \] [fb/GeV]

\[ \sigma_{\text{approx NNLO}} \] [fb/GeV]

\[ \sigma_{\text{NLO+NNLL}} \] [fb/GeV]

\[ \sigma_{\text{NLO}} \] [fb/GeV]

\[ \frac{d\sigma}{dp_T} \] [fb/GeV]

→ update and comparison with new Tevatron and LHC data in preparation
**Top-quark pair production @ NNLL+NLO**


**Arbitrary differential distributions** (of the top-quark pair and of individual top quarks) can be resummed near threshold:

![Graphs showing differential distributions](image)

- \( \sigma / dM \) [fb/GeV] for the invariant mass \( M \) [GeV], with CDF data and NLO+NLL predictions. The peak in the cross section is evident.

- \( A_{\text{FB}}(M_{tt}) \) as a function of the invariant mass \( M_{tt} \) [GeV], comparing NLO and NLO+NNLL predictions.

→ update and comparison with new Tevatron and LHC data in preparation
**Boosted tops:** for $M \gg 2m_t$ (or $p_t^\perp \gg m_t$) a more complicated factorization theorem was derived, which resums logarithms of $(1 - z)$ and $M/m_t$ (or $p_t^\perp/m_t$).

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**Figure 1:** Invariant mass distribution at the LHC with $\sqrt{s} = 7$ TeV (upper panel) and $\sqrt{s} = 14$ TeV (lower panel).

The remaining difference between approximation C and the exact result for the total cross section at NNLO is due to corrections to the coefficient $\tilde{c}^{(2)}_{ij}$ away from the $m_t$ limit, as well as on-singular terms as $z \to 1$. However, because the total cross section is dominated by values of $M$ where corrections in $m_t^2/M^2$ can be significant, our analysis does not allow us to distinguish the relative importance of the two.

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Ferroglia, Pecjak, Yang (2012, 2013); + Marzani (2013)

→ see talk by A. Ferroglia
Threshold production of $W/Z/H + \text{jet} @ N^3\text{LL+NLO}$

Extended factorization formula

$$d\sigma = H \phi \otimes \phi \otimes S \otimes J$$

holds for associated production of a high-$p_T$ boson with a jet, in the limit where the extra radiation is such that $m_X^2 \to 0$

Main features of the prediction:

- first resummation of a 3-jet observable at $N^3\text{LL+NLO}$
- threshold terms expected to give good approximation to exact NNLO result

\[ \hat{s} \frac{d\hat{\sigma}}{d\hat{u} \, dt} = \hat{\sigma}_{ab}^{(0)}(\hat{u}, \hat{t}, \mu) \, \hat{H}_{ab}(\hat{u}, \hat{t}, \mu) \int dk \, J_c(m_X^2 - 2E_Jk, \mu) \, S_{ab}(k, \mu) \]

Becher, Schwartz (2009); + Lorentzen (2011, 2012)
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Becher, Bell, Lorentzen, Marti (2013)
Becher @ SCET2014
“Anomalous” factorization theorems

Electroweak Sudakov resummation

Transverse momentum spectra

- W/Z production
- $x_\perp$-dependent PDFs
- Higgs production
- Top-pair production

Exclusive production in jet bins

- Higgs production with jet veto
- Jet veto for off-shell Higgs
- W/Z/H + jet production
- SCET and small-x physics (BFKL)

Becher, MN: 1007.4005 (EPJC); + Wilhelm: 1109.6027 (JHEP)

Gehrmann, Lübbert, Yang: 1209.0682 (PRL), 1403.6451

Chiu, Jain, Neill, Rothstein: 1202.0814 (JHEP); Becher, MN, Wilhelm: 1212.2621 (JHEP)

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Banfi, Salam, Zanderighi: 1203.5773 (JHEP); + Monni: 1206.4998 (PRL); Becher, MN: 1205.3806 (JHEP); + Rothen: 1307.0025 (JHEP); Stewart, Tackmann, Walsh, Zuberi: 1307.1808; Alioli, Walsh: 1311.5234 (JHEP)

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Fleming: 1404.5672; Stewart @ SCET 2014
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Fleming: 1404.5672; Stewart @ SCET 2014
“Anomalous” factorization of two scales

- For observables sensitive to transverse momentum, standard (ultra-)soft modes do not contribute

- How to factorize?

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

\[
\text{hard} \quad \text{collinear}
\]
“Anomalous” factorization of two scales

• **Anomaly** of classical SCET Lagrangian provides another source of **large rapidity logarithms**

Becher, MN (2010); Chiu, Jain, Neill, Rothstein (2011, 2012)

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\frac{1}{2} \ln^2 \frac{Q^2}{P^2} = \frac{1}{2} \ln^2 \frac{Q^2}{\mu^2} - \frac{1}{2} \ln^2 \frac{P^2}{\mu^2} - \ln \frac{P^2}{\mu^2} \ln \frac{Q^2}{P^2}
\]

large rapidity range

virtuality

\( Q \)

\( \mu \)

\( P = \lambda Q \)
Transverse momentum spectra of W/Z/h

Transverse momentum distributions in Drell-Yan processes $pp \rightarrow V + X$ with $V=W/Z/H$ require resummation of large logarithms

**SCET factorization formula** (with $\xi_{1,2} = e^{\pm y} M/\sqrt{s}$):

$$\frac{d^2\sigma}{dq_T^2\,dy} = \sum_{i,j} H_{ij}(-M^2, \mu) \int d^2x_\perp e^{-iq_\perp \cdot x_\perp} \left( \frac{x_T^2 M^2}{4e^{-2\gamma_E}} \right)^{-F_{qq}(x_T^2, \mu)} \times B_{i/N_1}(\xi_1, x_T^2, \mu) B_{j/N_2}(\xi_2, x_T^2, \mu) + \mathcal{O}\left( \frac{q_T^2}{M^2} \right)$$

- **two sources** of large Sudakov logarithms $\sim \alpha_s^n \ln^{2n}(M/q_T)$
- **collinear beam functions** describe the transverse structure of the proton:
  $$B_{i/N}(\xi, x_T^2, \mu) = \sum_j \int^1_\xi \frac{dz}{z} I_{i\leftarrow j}(z, x_T^2, \mu) \phi_{j/N}(\xi/z, \mu) + \mathcal{O}(\Lambda_{QCD}^2 x_T^2)$$

- factorization formula provides **consistent definition of transverse-position dependent PDFs**, which has been checked to 2-loop order!

Becher, MN (2010)

Stewart, Tackmann, Waalewijn (2009)

Gehrmann, Lübbert, Yang (2012, 2014)
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$$\frac{d^2 \sigma}{dq_T^2 \, dy} = \sum_{i,j} H_{ij}(-M^2, \mu) \int d^2 x_\perp \, e^{-i q_\perp \cdot x_\perp} \left( \frac{x_T^2 M^2}{4 e^{-2\gamma_E}} \right)^{-F_{qq}(x_T^2, \mu)}$$

$$\times B_{i/N_1}(\xi_1, x_T^2, \mu) B_{j/N_2}(\xi_2, x_T^2, \mu) + \mathcal{O}\left( \frac{q_T^2}{M^2} \right)$$

SCET factorization theorem is equivalent to standard QCD factorization theorem by Collins, Soper, Sterman (1984), however:

- could derive last missing ingredient (coefficient $A_3$) needed for NNLL resummation from a 2-loop calculation (anomaly equation)  
  Becher, MN (2010)
- obtain model-independent prediction for the leading, logarithmically enhanced long-distance correction to the spectrum:
  
  $$F_{ij}(x_T^2) \rightarrow F_{ij}(x_T^2) + \Lambda_{NP}^2 x_T^2$$

  Becher, Bell (2013)

where universal parameter $\Lambda_{NP}^2$ only depends on the color representation
Z-boson production @ NNLL+NLO

First complete calculation of Z-boson production at this order:

→ upgrade to NNLL+NNLO and improved treatment of long-distance corrections is possible (work in progress)

→ public code CuTe available at: [http://cute.hepforge.org](http://cute.hepforge.org)
Higgs production with jet veto

Higgs search in $h \rightarrow WW^*$ channel is done in jet bins, since background is very different if Higgs is produced in association with jets.

Need precise cross-section predictions for Higgs + $n$ jets, in particular for $n=0$ bin (jet veto), where $p_T^{\text{jet}} < p_T^{\text{veto}} \sim 20 - 30 \text{ GeV}$.
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Higgs production with jet veto

**SCET factorization theorem** for jet-veto cross section, valid for $R = \mathcal{O}(1)$:

$$
\frac{d\sigma(p_T^{\text{veto}})}{dy} = H(-m_H^2, \mu) \left( \frac{m_H}{p_T^{\text{veto}}} \right)^{-2F_{gg}(p_T^{\text{veto}}, R, \mu)} B_{g/p}(\xi_1, p_T^{\text{veto}}, R, \mu) B_{g/p}(\xi_2, p_T^{\text{veto}}, R, \mu)
$$

Becher, MN (2012); + Rothen (2013)

- sequential jet recombination algorithms ($k_T$, anti-$k_T$, C/A) clusters soft and collinear radiation separately, as long as $R$ is not parametrically large
Higgs production with jet veto

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\]

- sequential jet recombination algorithms (\( k_T \), anti-\( k_T \), C/A) **clusters soft and collinear radiation separately**, as long as \( R \) is not parametrically large
- results in **simple factorization formula**
- anomalous exponent and beam functions depend on jet radius \( R \)

Banfi, Monni, Salam, Zanderighi (2012)

Becher, MN (2012); + Rothen (2013)
Higgs jet-veto cross section @ N^{3}LL_{p}+NNLO

Accurate predictions with similar accuracy available from different groups:

- important impact of higher-order effects ($R$-dependent terms)
- predicting the cross section rather than the veto efficiency has advantage of being directly related to experimental measurements

Banfi, Monni, Salam, Zanderighi (2012)  
Becher, MN, Rothen (2013)

\[ \sqrt{s} = 8 \text{ TeV} \]
\[ m_{H} = 125 \text{ GeV} \]
Higgs jet-veto cross section @ N^3LL_p+NNLO

Accurate predictions with similar accuracy available from different groups:

- Becher, MN, Rothen (2013)
- Stewart, Tackmann, Walsh, Zuberi (2013)

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- predicting the cross section rather than the veto efficiency has advantage of being directly related to experimental measurements
Higgs jet-veto cross section @ N$^3$LL$_p$+NNLO

Accurate predictions with similar accuracy available from different groups:

- subtracting the jet-veto cross section from the total inclusive cross section one obtains the cross section for Higgs + (≥1 jet) production

[see also: Boughezal, Liu, Petriello, Tackmann, Walsh (2013)]
Exclusive Higgs + jet production @ NLL’+NLO

SCET factorization theorem for H+1-jet cross section valid to NLL’ accuracy:

\[
\frac{d\sigma_{\text{NLL}'}}{d\Phi_H d\Phi_J} = \frac{1}{2\hat{s}} (2\pi)^4 \delta^4 (q_a + q_b - q_J - q_H) \sum_{a,b} \int dx_a dx_b \mathcal{F}(\Phi_H, \Phi_J) \times \sum_{\text{spin}} \sum_{\text{color}} \text{Tr}(H \cdot S) \mathcal{I}_{a,i_a j_a} \otimes f_{j_a}(x_a) \mathcal{I}_{b,i_b j_b} \otimes f_{j_b}(x_b) J_J(R)
\]

- derivation of factorization formula far more non-trivial
- formula no longer holds in higher orders, where non-global logarithms arise and should be resummed


Liu, Petriello: (2013)
Conclusions

SCET provides efficient tools for addressing difficult collider-physics problems: factorization and resummation.

Many applications exist for Drell-Yan processes (production of Z, W, H, sleptons) and (s)top-quark pair production, both in threshold limit and for transverse momentum spectra.

Jet observables (so far W/Z/H + n jets with n=0,1) are currently being considered by several goups.

In some cases, SCET methods have pushed the limits of what has been accomplished using traditional techniques.