Precision Predictions for Higgs and Top-Quark Pair Production at Hadron Colliders

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& Ruprecht Karls University Heidelberg

ICHEP 2010
Paris - 23 July 2010
Based on:

- **IR singularities of scattering amplitudes in non-abelian gauge theories**
  
  Thomas Becher, MN: 0901.0722 (PRL), 0903.1126 (JHEP), 0904.1021 (PRD)
  Andrea Ferroglia, Ben Pecjak, MN, Li Lin Yang: 0907.4791 (PRL), 0908.3676 (JHEP)

- **Threshold resummation for Higgs production**
  
  Valentin Ahrens, Thomas Becher, MN, Li Lin Yang: 0808.3008 (PRD), 0809.4283 (EPJC)
  & update for this conference!

- **Threshold resummation for top-pair production**
  
  Andrea Ferroglia, Ben Pecjak, MN, Li Lin Yang: 0912.3375 (PLB) & 1003.5827 (JHEP)
A tale of many scales

- Collider processes characterized by many scales: \( s, s_{ij}, M_i, \Lambda_{\text{QCD}}, \ldots \)
- Large Sudakov logarithms arise, which need to be resummed (e.g. parton showers, mass effects, aspects of underlying event)
- Effective field theories provide modern, elegant approach to this problem based on scale separation (factorization theorems) and RG evolution (resummation)
**Soft-collinear factorization**

Sen 1983; Kidonakis, Oderda, Sterman 1998

- Factorize cross section:

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

- Define components in terms of field theory objects in SCET

- Resum large Sudakov logarithms directly in momentum space using RG equations
Soft-collinear effective theory (SCET)

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

✧ Two-step matching procedure:

✧ Integrate out hard modes, describe collinear and soft modes by fields in SCET

✧ Integrate out collinear modes (if perturbative) and match onto a theory of Wilson lines

\[
\Lambda_{ij}^2 = \frac{M_i^4}{s_{ij}} \quad \text{soft} \\
\]

\[
M_i^2 \quad \text{collinear} \\
\]

\[
s_{ij} \quad \text{hard} \\
\]
Anomalous dimension to two loops

- General result for arbitrary processes:
  \[
  \Gamma(p, m, \mu) = \sum_{(i,j)} \frac{T_i \cdot T_j}{2} \gamma_{\text{cusp}}(\alpha_s) \ln \frac{\mu^2}{-s_{ij}} + \sum_i \gamma^i(\alpha_s)
  \]
  \[
  - \sum_{(I,J)} \frac{T_I \cdot T_J}{2} \gamma_{\text{cusp}}(\beta_{IJ}, \alpha_s) + \sum I \gamma^I(\alpha_s) + \sum_{I,J} T_I \cdot T_J \gamma_{\text{cusp}}(\alpha_s) \ln \frac{m_I \mu}{-s_{IJ}}
  \]
  \[
  + \sum_{(I,J,K)} i f^{abc} T_I^a T_J^b T_K^c F_1(\beta_{IJ}, \beta_{JK}, \beta_{KI})
  \]
  \[
  + \sum_{(I,J)} \sum_k i f^{abc} T_I^a T_J^b T_k^c f_2(\beta_{IJ}, \ln \frac{-\sigma_{Jk} v_J \cdot p_k}{-\sigma_{IK} v_I \cdot p_k}) + O(\alpha_s^3).
  \]

- Generalizes structure found for massless case
- Novel three-parton terms appear at two loops

Becher, MN 2009 (see also: Gardi, Magnea 2009)
Mitov, Sterman, Sung 2009; Becher, MN 2009
Ferroglia, MN, Pecjak, Yang 2009
EFT-based predictions for Higgs production at Tevatron and LHC

Ahrens, Becher, MN, Yang 2008 & update for ICHEP 2010
Large higher-order corrections

- **Corrections are large:**
  70% at NLO + 30% at NNLO
  [130% and 80% if PDFs and $\alpha_s$ are held fixed]

- Only $C_{gg}$ contains leading singular terms, which give
  90% of NLO and 94% of NNLO correction

- Contributions of $C_{qg}$ and $C_{qq}$
  are small: -1% and -8% of the NLO correction

Harlander, Kilgore 2002; Anastasiou, Melnikov 2002
Ravindran, Smith, van Neerven 2003
Effective theory analysis

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

When this is done consistently, large K-factors should not arise, since no large perturbative corrections are left unexponentiated!
Cross section predictions

For MRST2004 PDFs \[52\], the $K$-factors after resummation are somewhat larger, $K \approx 1.3$ for the LHC, see \[18\].
Update for ICHEP 2010

- Consider lower LHC energies (\(\sqrt{s}=7, 10\text{ TeV}\))
- Include electroweak radiative corrections, some of which were obtained after our paper
  \footnotetext{Actis, Passarino, Sturm, Uccirati 2008 & 2009}
  \footnotetext{Anastasiou, Boughezal, Petriello 2009}
- Include (as before) QCD corrections with NNNLL resummation (also large kinematical corrections specific for time-like processes) matched onto NNLO fixed-order results
Update for ICHEP 2010
Ahrens, Becher, MN, Yang 2010 (to appear)

Cross section predictions after resummation:

![Graphs showing cross sections at Tevatron and LHC for √s = 1.96 TeV, 7 TeV, 10 TeV, and 14 TeV.](image)
Update for ICHEP 2010
Ahrens, Becher, MN, Yang 2010 (to appear)

- State-of-the-art predictions (most precise to date) using MSTW2008NNLO PDFs:

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>Tevatron</th>
<th>LHC (7 TeV)</th>
<th>LHC (10 TeV)</th>
<th>LHC (14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>1.213±0.031+0.070−0.007−0.075</td>
<td>18.17±0.53+0.46−0.14−0.57</td>
<td>33.6±1.0+0.8−0.2−1.0</td>
<td>57.8±1.6+1.4−0.3−1.8</td>
</tr>
<tr>
<td>120</td>
<td>1.072±0.026+0.064−0.006−0.069</td>
<td>16.72±0.48+0.43−0.13−0.53</td>
<td>31.2±0.9+0.7−0.2−1.0</td>
<td>53.9±1.3+1.3−0.3−1.7</td>
</tr>
<tr>
<td>125</td>
<td>0.950±0.022+0.059−0.005−0.063</td>
<td>15.43±0.44+0.40−0.12−0.49</td>
<td>29.0±0.8+0.7−0.2−0.9</td>
<td>50.4±1.4+1.2−0.3−1.5</td>
</tr>
<tr>
<td>130</td>
<td>0.845±0.019+0.054−0.004−0.058</td>
<td>14.28±0.40+0.37−0.11−0.46</td>
<td>27.0±0.7+0.6−0.2−0.8</td>
<td>47.2±1.3+1.1−0.3−1.5</td>
</tr>
<tr>
<td>135</td>
<td>0.754±0.016+0.050−0.004−0.045</td>
<td>13.25±0.36+0.35−0.10−0.45</td>
<td>25.2±0.7+0.6−0.2−0.8</td>
<td>44.4±1.2+1.0−0.3−1.4</td>
</tr>
<tr>
<td>140</td>
<td>0.679±0.014+0.046−0.003−0.049</td>
<td>12.33±0.33+0.33−0.09−0.40</td>
<td>23.6±0.6+0.6−0.2−0.7</td>
<td>41.8±1.1+1.0−0.3−1.3</td>
</tr>
<tr>
<td>145</td>
<td>0.605±0.012+0.043−0.003−0.045</td>
<td>11.49±0.31+0.32−0.09−0.37</td>
<td>22.2±0.6+0.5−0.1−0.7</td>
<td>39.4±1.0+0.9−0.2−1.2</td>
</tr>
<tr>
<td>150</td>
<td>0.544±0.010+0.040−0.002−0.042</td>
<td>10.74±0.28+0.30−0.08−0.35</td>
<td>20.8±0.5+0.5−0.1−0.6</td>
<td>37.2±1.0+0.9−0.2−1.1</td>
</tr>
<tr>
<td>155</td>
<td>0.491±0.009+0.037−0.002−0.039</td>
<td>10.05±0.26+0.29−0.07−0.33</td>
<td>19.6±0.5+0.5−0.1−0.6</td>
<td>35.2±0.9+0.8−0.2−1.0</td>
</tr>
<tr>
<td>160</td>
<td>0.440±0.008+0.034−0.002−0.036</td>
<td>9.36±0.24+0.27−0.07−0.31</td>
<td>18.4±0.5+0.5−0.1−0.6</td>
<td>33.2±0.8+0.8−0.2−1.0</td>
</tr>
<tr>
<td>165</td>
<td>0.387±0.006+0.031−0.002−0.032</td>
<td>8.54±0.22+0.25−0.06−0.29</td>
<td>16.9±0.4+0.4−0.1−0.5</td>
<td>30.6±0.8+0.7−0.2−0.9</td>
</tr>
<tr>
<td>170</td>
<td>0.346±0.005+0.028−0.002−0.026</td>
<td>7.92±0.20+0.24−0.05−0.27</td>
<td>15.8±0.4+0.4−0.1−0.5</td>
<td>28.7±0.7+0.7−0.2−0.8</td>
</tr>
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<td>175</td>
<td>0.312±0.005+0.026−0.001−0.027</td>
<td>7.41±0.18+0.23−0.05−0.26</td>
<td>14.8±0.4+0.4−0.1−0.5</td>
<td>27.1±0.7+0.6−0.2−0.8</td>
</tr>
<tr>
<td>180</td>
<td>0.282±0.004+0.024−0.001−0.025</td>
<td>6.94±0.17+0.22−0.05−0.24</td>
<td>14.0±0.3+0.3−0.1−0.4</td>
<td>25.7±0.6+0.6−0.2−0.8</td>
</tr>
<tr>
<td>185</td>
<td>0.253±0.003+0.022−0.001−0.023</td>
<td>6.45±0.16+0.21−0.04−0.23</td>
<td>13.1±0.3+0.3−0.1−0.4</td>
<td>24.1±0.6+0.6−0.1−0.7</td>
</tr>
<tr>
<td>190</td>
<td>0.228±0.003+0.020−0.001−0.021</td>
<td>6.03±0.14+0.20−0.05−0.22</td>
<td>12.3±0.3+0.3−0.1−0.4</td>
<td>22.8±0.6+0.5−0.1−0.7</td>
</tr>
<tr>
<td>195</td>
<td>0.208±0.002+0.019−0.001−0.020</td>
<td>5.68±0.13+0.19−0.04−0.21</td>
<td>11.6±0.3+0.3−0.1−0.4</td>
<td>21.7±0.5+0.5−0.1−0.6</td>
</tr>
<tr>
<td>200</td>
<td>0.189±0.002+0.018−0.001−0.019</td>
<td>5.37±0.13+0.18−0.04−0.20</td>
<td>11.0±0.3+0.3−0.1−0.3</td>
<td>20.7±0.5+0.5−0.1−0.6</td>
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</table>

scale uncertainty PDF uncertainty
State-of-the-art predictions (most precise to date) using CTEQ6.6 PDFs:

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<tbody>
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<td>$1.200^{+0.030+0.068}_{-0.006-0.068}$</td>
<td>$18.23^{+0.54+0.52}_{-0.13-0.63}$</td>
<td>$34.0^{+1.0+1.1}_{-0.2-1.3}$</td>
<td>$58.9^{+1.7+2.1}_{-0.4-2.5}$</td>
</tr>
<tr>
<td>120</td>
<td>$1.060^{+0.026+0.064}_{-0.005-0.063}$</td>
<td>$16.76^{+0.48+0.47}_{-0.12-0.56}$</td>
<td>$31.5^{+0.9+1.0}_{-0.2-1.2}$</td>
<td>$54.8^{+1.3+1.9}_{-0.3-2.3}$</td>
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<td>125</td>
<td>$0.940^{+0.022+0.061}_{-0.004-0.059}$</td>
<td>$15.46^{+0.44+0.43}_{-0.11-0.51}$</td>
<td>$29.2^{+0.8+0.9}_{-0.2-1.1}$</td>
<td>$51.2^{+1.4+1.7}_{-0.3-2.1}$</td>
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<td>$13.25^{+0.37+0.36}_{-0.10-0.42}$</td>
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<td>$0.669^{+0.014+0.052}_{-0.003-0.049}$</td>
<td>$12.31^{+0.34+0.33}_{-0.08-0.38}$</td>
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<td>150</td>
<td>$0.541^{+0.010+0.047}_{-0.002-0.043}$</td>
<td>$10.71^{+0.29+0.28}_{-0.07-0.32}$</td>
<td>$20.9^{+0.6+0.6}_{-0.1-0.7}$</td>
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<td>155</td>
<td>$0.488^{+0.009+0.044}_{-0.002-0.041}$</td>
<td>$10.02^{+0.26+0.26}_{-0.07-0.30}$</td>
<td>$19.7^{+0.5+0.5}_{-0.1-0.6}$</td>
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<td>$0.312^{+0.005+0.034}_{-0.001-0.031}$</td>
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<td>180</td>
<td>$0.282^{+0.004+0.030}_{-0.000-0.029}$</td>
<td>$6.90^{+0.17+0.18}_{-0.05-0.21}$</td>
<td>$14.0^{+0.3+0.4}_{-0.1-0.4}$</td>
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<td>$0.209^{+0.002+0.027}_{-0.001-0.024}$</td>
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<td>200</td>
<td>$0.191^{+0.002+0.025}_{-0.001-0.022}$</td>
<td>$5.32^{+0.12+0.15}_{-0.03-0.16}$</td>
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</table>
EFT-based predictions for top-pair production at Tevatron and LHC

Ahrens, Ferroglia, MN, Pecjak, Yang 2009 & 2010
State of the art

- Fixed-order NLO calculations:
  - total cross section
    - Nason, Dawson, Ellis 1988
    - Beenakker et al. 1989
  - differential
    - Nason, Dawson, Ellis 1989
    - Mangano, Nason, Ridolfi 1992
    - Frixione, Mangano, Nason, Ridolfi 1995

- Fixed-order NNLO calculations:
  - none exist! (but several pieces available)
  - “leading terms” (enhanced near threshold) for total cross section
    - Beneke, Falgari, Schwinn 2009
    - Czakon, Mitov, Sterman 2009
    - Ahrens, Ferroglia, MN, Pecjak, Yang 2010
  - “leading terms” for distributions
    - Ahrens, Ferroglia, MN, Pecjak, Yang 2009
State of the art

- Threshold resummation at NLL:
  - total cross section
  - distributions

- Resummation at NNLL+NLO matching:
  - total cross section
  - distributions

References:
Bonciani, Catani, Mangano, Nason 1998
Berger, Contopanagos 1995
Kidonakis, Laenen, Moch, Vogt 2001
Kidonakis, Vogt 2003; Banfi, Laenen 2005
Beneke, Falgari, Schwinn 2009
Czakon, Mitov, Sterman 2009
Ahrens, Ferroglia, MN, Pecjak, Yang 2010
Dominance of threshold terms

- Fixed-order results for invariant mass distribution at Tevatron and LHC:
  - Leading singular terms near partonic threshold give dominant contributions even at low and moderate $M$ values.

- Leading singular terms near partonic threshold $z = M^2/\hat{s} \to 1$ give dominant contributions even at low and moderate $M$ values.
Invariant mass distributions

- Fixed-order vs. resummed PT (matched to NLO):

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

\[ \sqrt{s} = 7 \text{ TeV} \]

Tevatron

LHC
Comparison with CDF data

✧ Overlay (not a fit!) for $m_t=173.1$ GeV:
Features of inv. mass distribution

- Spectrum predictions in \( \overline{\text{MS}} \) scheme, obtained with \( \overline{m}_t(\overline{m}_t) = 164.0 \text{ GeV} \):

- Improved convergence

see also: Langenfeld, Moch, Uwer 2009
Velocity distribution

 Transform to relative 3-velocity of top quarks in $t\bar{t}$ rest frame: 
 \[ \beta_t = \sqrt{1 - \frac{4m_t^2}{M^2}} \]

- Top quarks are relativistic, $\beta_t \sim 0.4-0.9$
Total cross section

- Usually, resummation is done around absolute threshold at $\hat{s}=4m_t^2$ (non-relativistic top quarks)
- Mixed Coulomb and soft gluon singularities arise for $\beta = \sqrt{1 - 4m_t^2/\hat{s}} \to 0$
- Obtain partial NNLO results based on small-$\beta$ expansion
  Moch, Uwer 2008; Beneke et al. 2009
- But this covers only a tiny portion of phase space!
Total cross section

- Fact that \( \beta \geq \beta_t \) and shape of \( \beta_t \) distribution imply that small-\( \beta \) region is unimportant for the total cross section
- In our approach, soft gluon effects are resummed also far above absolute threshold
- Different systematics & more accurate results!

![Graph showing distribution of \( d\sigma/d\beta_t \) at different energy scales showing comparable results for NLO and NLL]

\[ \frac{d\sigma}{d\beta_t} = \frac{2m_t\beta_t}{\sqrt{s}}(1 - \beta_t^2)^{3/2} \frac{d\sigma}{dM}. \]
Total cross section

Comparison of different approximations to NLO corrections (including parton luminosities):
✦ our approximation lies much closer to NLO result than small-\(\beta\) approximation
✦ reproduces fine details of the curves
✦ improvement over traditional PIM curve
## Total cross section

- **Detailed predictions for total cross sections:**

<table>
<thead>
<tr>
<th>Cross section (pb)</th>
<th>Tevatron</th>
<th>LHC (7 TeV)</th>
<th>LHC (10 TeV)</th>
<th>LHC (14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{LO}} )</td>
<td>( 4.49^{+1.71+0.24}_{-1.15-0.19} )</td>
<td>( 84^{+29+4}_{-20-5} )</td>
<td>( 217^{+70+10}_{-49-11} )</td>
<td>( 495^{+148+19}_{-107-24} )</td>
</tr>
<tr>
<td>( \sigma_{\text{NLL}} )</td>
<td>( 5.07^{+0.37+0.28}_{-0.36-0.18} )</td>
<td>( 112^{+18+5}_{-14-5} )</td>
<td>( 276^{+47+10}_{-37-11} )</td>
<td>( 598^{+108+19}_{-94-19} )</td>
</tr>
<tr>
<td>( \sigma_{\text{NLO}, \text{leading}} )</td>
<td>( 5.49^{+0.78+0.31}_{-0.78-0.20} )</td>
<td>( 134^{+16+7}_{-17-7} )</td>
<td>( 341^{+34+14}_{-38-14} )</td>
<td>( 761^{+64+25}_{-75-26} )</td>
</tr>
<tr>
<td>( \sigma_{\text{NLO}} )</td>
<td>( 5.79^{+0.79+0.33}_{-0.80-0.22} )</td>
<td>( 133^{+21+7}_{-19-7} )</td>
<td>( 341^{+50+14}_{-46-15} )</td>
<td>( 761^{+105+26}_{-101-27} )</td>
</tr>
<tr>
<td>( \sigma_{\text{NLO+NNLL}} )</td>
<td>( 6.30^{+0.19+0.31}_{-0.19-0.23} )</td>
<td>( 149^{+7+8}_{-7-8} )</td>
<td>( 373^{+17+16}_{-15-16} )</td>
<td>( 821^{+40+24}_{-42-31} )</td>
</tr>
<tr>
<td>( \sigma_{\text{NNLO, approx (scheme A)}} )</td>
<td>( 6.14^{+0.49+0.31}_{-0.53-0.23} )</td>
<td>( 146^{+13+8}_{-12-8} )</td>
<td>( 369^{+34+16}_{-30-16} )</td>
<td>( 821^{+71+27}_{-65-29} )</td>
</tr>
<tr>
<td>( \sigma_{\text{NNLO, approx (scheme B)}} )</td>
<td>( 6.05^{+0.43+0.31}_{-0.50-0.23} )</td>
<td>( 139^{+9+7}_{-9-7} )</td>
<td>( 349^{+23+15}_{-23-15} )</td>
<td>( 773^{+47+25}_{-50-27} )</td>
</tr>
</tbody>
</table>

- **Scale uncertainty**
- **PDF uncertainty**

- **Singular terms dominate NLO corrections**
- **Resummation stabilizes scale dependence**
**Total cross section**

- **Small-β expansion misses important NLO effects**

<table>
<thead>
<tr>
<th>Cross section (pb)</th>
<th>Tevatron</th>
<th>LHC (7 TeV)</th>
<th>LHC (10 TeV)</th>
<th>LHC (14 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{NLO})</td>
<td>5.79±0.79±0.33</td>
<td>133±21±7</td>
<td>341±50±14</td>
<td>761±105±26</td>
</tr>
<tr>
<td>(\sigma_{NLO, \text{leading}})</td>
<td>5.49±0.78±0.31</td>
<td>134±16±7</td>
<td>341±34±14</td>
<td>761±64±25</td>
</tr>
<tr>
<td>(\sigma_{NLO, \beta-\text{exp. v1}})</td>
<td>8.22±0.54±0.49</td>
<td>157±12±8</td>
<td>395±24±14</td>
<td>877±49±29</td>
</tr>
<tr>
<td>(\sigma_{NLO, \beta-\text{exp. v2}})</td>
<td>6.59±0.96±0.38</td>
<td>151±15±8</td>
<td>386±30±15</td>
<td>863±49±29</td>
</tr>
<tr>
<td>(\sigma_{NLO+NNLL})</td>
<td>6.30±0.19±0.31</td>
<td>149±7±8</td>
<td>373±17±16</td>
<td>821±40±24</td>
</tr>
<tr>
<td>(\sigma_{NNLO, \beta-\text{exp. v1}})</td>
<td>7.37±0.01±0.39</td>
<td>156±2±8</td>
<td>392±4±16</td>
<td>865±5±29</td>
</tr>
<tr>
<td>(\sigma_{NNLO, \beta-\text{exp.+potential v1}})</td>
<td>7.30±0.01±0.39</td>
<td>158±3±8</td>
<td>398±7±16</td>
<td>880±12±29</td>
</tr>
<tr>
<td>(\sigma_{NNLO, \beta-\text{exp. v2}})</td>
<td>6.98±0.17±0.37</td>
<td>156±2±8</td>
<td>394±2±16</td>
<td>871±0±29</td>
</tr>
<tr>
<td>(\sigma_{NNLO, \beta-\text{exp.+potential v2}})</td>
<td>6.95±0.16±0.36</td>
<td>159±3±8</td>
<td>401±6±17</td>
<td>888±7±30</td>
</tr>
</tbody>
</table>

- **Likely that this remains true at NNLO**

- ![scale uncertainty](image1.png)
- ![PDF uncertainty](image2.png)
Conclusions

✦ Effective field theory provides efficient tools for addressing difficult collider-physics problems
✦ Systematic “derivation” of factorization theorems (known ones and ones to be discovered) and simple, transparent resummation techniques
✦ Detailed applications exist for Drell-Yan, Higgs, and top-quark pair production
✦ Longer-term goal is to understand resummation at NNLL+NLO order for jet processes, such as $pp \rightarrow n \text{jets} + V$ (with $n \leq 3$, $V=\gamma, Z, W$)