Potential improvements to the fitting of the $\alpha_s$ through means of soft drop

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Boosted particles

- LHC energy much larger than heavy particle masses
- Massive particles predominately produced boosted ($p_T \gg m$)
- Harder to distinguish from QCD jets
Non-perturbative contributions

Many effects cannot be described by perturbation theory:

- Hadronization effects
- Multi-parton interactions
- Pile-up
Jet substructure

- Many jet substructure techniques developed; Grooming and Tagging
- Created with the purpose of distinguishing signal from background
- Removes soft wide-angle radiation
- Can also help reduce non-perturbative corrections
Main technique we will deal with is soft drop:

\[ \min \left( p_{T,1}, p_{T,2} \right) \frac{p_{T,1} + p_{T,2}}{z_c \left( \frac{\Delta R_{12}}{R} \right)^\beta} \]

or at \( e^+e^- \) colliders:

\[ \min \left[ E_i, E_j \right] \frac{E_i + E_j}{z_{cut} \left( 1 - \cos \theta_{ij} \right)^{\beta/2}} \]

Makes use of Cambridge/Aachen clustering.

[Dokshitzer, Leder, Moretti, Webber; '97][Wobisch, Wengler; '99]

Reduces to modified Mass Drop Tagger (mMDT) for \( \beta = 0 \)

[Dasgupta, Fregoso, Marzani, Salam; '13]
1) Decluster the last step
2) Check the soft drop condition for this splitting
3) If it fails drop the softest and repeat
4) If it passes finish the grooming
Full Soft drop

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Need for resummation

For boosted jets, great separation of scales $p_T \gg m$ leads to large logarithms:

$$\log \left( \frac{m_J^2}{p_T^2 R^2} \right)$$

Large logarithms need to be resummed.
Analytic computations

Pythia8, parton

Analytic

[1] [Larkoski, Marzani, Soyez, Thaler; '14]
Reduction in NP corrections

[LaRkoski, Marzani, Soyez, Thaler; '14]
Further computations

- Computation of soft drop using SCET at NNLL accuracy approximated for $e_2^{(2)} \ll z_{cut}$ [Frye, Larkoski, Schwartz, Yan; '16]

- Calculation in dQCD including finite $z_{cut}$ effects [Marzani, Schunk, Soyez; '17]

- Including jet radius resummation in SCET [Kang, Lee, Liu, Ringer; '18]

- Good agreement to experiments [CMS;'17] [ATLAS;'17]

- Application to top quark mass measurements [Hoang, Mantry, Pathak, Stewart;'17]

- And $\alpha_s$ measurements at LHC [Les Houches;'18] and $e^+e^-$ [Baron, Marzani, VT; '18] ← This talk
Computation at NNLL accuracy

- Computation of soft drop using SCET at NNLL accuracy
  
  \[\text{[Frye, Larkoski, Schwartz, Yan; '16]}\]

- Approximated for \(e_2^{(2)} \ll z_{\text{cut}}\)

\[\]
Finite $z_{\text{cut}}$ effects

Continued calculation in dQCD including finite $z_{\text{cut}}$ effects

[Marzani, Schunk, Soyez; '17]:

Percent level corrections for $z_{\text{cut}} = 0.1$, but can be larger for other values
The importance of $\alpha_s$

- Jet physics of great importance to the LHC
- Higher order perturbative corrections shown to be important scale with higher powers of $\alpha_s$
- Higgs boson production scales as $\alpha_s^2$

An accurate measurement of $\alpha_s$ is necessary for precession LHC measurements
Jet Physics  The strong coupling constant \( \alpha_s \) thrust measurement

\[ \tau \text{-decays lattice structure functions } e^+e^- \text{jets & shapes} \]

hadron collider
electroweak precision fits

[Particle Data Group; 16]

April 2016
NP contributions

[Abbate, Fickinger, Hoang, Mateu, Stewart; 10]
Jet Physics  The strong coupling constant  SD thrust

**Thrust**

\[ \tau = 1 - T = \min_{\vec{n}} \left( 1 - \frac{\sum_i |\vec{n} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|} \right) \]

Minimize for thrust axis \( \vec{n} \)

[Abbate, Fickinger, Hoang, Mateu, Stewart; 10]
Hemisphere jets at an $e^+e^-$ collider $\rightarrow$ Different soft drop condition:

$$\frac{\min [E_i, E_j]}{E_i + E_j} > z_{\text{cut}} (1 - \cos \theta_{ij})^{\beta/2}$$

\[\begin{array}{c}
\text{(LO)} (e^+e^- \rightarrow q\bar{q} + X) \\
\text{Q = M}_Z \\
\beta = 0, z_{\text{cut}} = 0.1
\end{array}\]
Alternative definition

- Separation into two jets at the hand of thrust axis pre-softdrop
- After softdrop each hemisphere will have its own axis
- Each thrust axis is the jet axis

\[ T_{SD}' = \frac{\sum_{i \in H^L_{SD}} |\vec{n}_L \cdot \vec{p}_i|}{\sum_{i \in E_{SD}} |\vec{p}_i|} + \frac{\sum_{i \in H^R_{SD}} |\vec{n}_R \cdot \vec{p}_i|}{\sum_{i \in E_{SD}} |\vec{p}_i|} \]
MC studies

\[ \tau \frac{d\sigma}{d\tau} (e^+ e^- \rightarrow q\bar{q} + X) \]

- \text{Pythia}
- \text{Sherpa}
- \text{Herwig}

\[ Q = M_Z \]

\[ \beta = 0, \quad z_{cut} = 0.1 \]

Non-perturbative corrections above 10% around \( \tau \approx 0.07 \)
Non-perturbative corrections above 10% around $\tau \approx 0.001$
Reduction in non-perturbative corrections.
Different values of $\beta$ do not offer improvement
Smaller values of $z_{\text{cut}}$ offer more data in the relevant region with only a slight increase in non-perturbative corrections.

**[Baron, Marzani, VT; ’18]**

\[
\tau \frac{d\sigma}{d\tau} (e^+ e^- \rightarrow q\bar{q} + X)
\]

\[
\left( \frac{d\sigma}{d\tau} \right)_{\text{Hadron}} / \left( \frac{d\sigma}{d\tau} \right)_{\text{Parton}}, (e^+ e^- \rightarrow q\bar{q} + X)
\]
Additional calculation for contributions where $\tau \sim z_{\text{cut}}$ at NLL' accuracy:

$$\frac{\alpha_s}{\pi} C_F (\beta + 2) \text{Li}_2 \left[ \frac{1}{2} \left( \frac{2\tau}{z_{\text{cut}}} \right)^{\frac{2}{\beta+2}} \right]$$

Can be neglected for $\tau \ll z_{\text{cut}}$, but offers a constant contribution near the transition point $\tau = z_{\text{cut}}/2$.

Additional corrections for the end-point of the resummation and expansion.
Resummation results

- Expansion offers a good approximation for fixed order
- Transition corrections are important for thrust
Alternative observables

Other observables allow for a reduction in transition point effects.
Conclusions

- Soft drop can help reduce dependence on non-perturbative corrections for thrust
- Could help break degeneracy between non-perturbative contributions and $\alpha_s$ in fit
- Significant transition point effects that will need to be taken into account at NNLL accuracy
- Other observables could reduce the transition point effects
## Summary

### Conclusions

- Soft drop can help reduce dependence on non-perturbative corrections for thrust
- Could help break degeneracy between non-perturbative contributions and $\alpha_s$ in fit
- Significant transition point effects that will need to be taken into account at NNLL accuracy
- Other observables could reduce the transition point effects

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Thank you for your attention
Recent comparison to LHC data:

CMS Preliminary

2.3 fb$^{-1}$ (13 TeV)

900 < $p_T$ < 1000 GeV

<table>
<thead>
<tr>
<th>Normalized cross section</th>
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<tr>
<td>Data</td>
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<tr>
<td>Stat. Unc.</td>
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<tr>
<td>Pythia8</td>
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<tr>
<td>HERWIG++</td>
</tr>
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<td>POWHEG + PYTHIA8</td>
</tr>
</tbody>
</table>

Frye et al
Marzani et al

CMS Preliminary (13 TeV) -12.3 fb $< 1000$ GeV

T $> 600$ GeV

R=0.8, $p_t$ anti-$k_T$, $z_{cut} = 0.1$

Soft drop, $\beta = 2$

Data
Pythia 8.1
Sherpa 2.1
Herwig++ 2.7
LO+NNLL, large NP effects
LO+NNLL
NLO+NLL+NP

ATLAS
\[13 \text{ TeV, 32.9 fb}^{-1}\]

Good agreement with Data

[CMS;'17]  [ATLAS;'17]
Factorization for $\tau \ll z_{\text{cut}} \ll 1$ [Frye, Larkoski, Schwartz, Yan; '16]:

$$\frac{d\sigma}{d\tau} = H(Q) S_G(z_{\text{cut}}, \beta) [S_C(\tau, z_{\text{cut}}, \beta) \otimes J(\tau)]^2$$

Computed in Laplace space and inverted leading to:

$$\Sigma(\tau) = \left[1 + \left(\frac{\alpha_s}{\pi}\right) C^{(1)} + \cdots\right] \exp\left[\frac{1}{\alpha_s} g_1(-\lambda\tau, \lambda z_{\text{cut}}) + g_2(-\lambda\tau, \lambda z_{\text{cut}}) + \cdots\right]$$

for $\lambda_x = \alpha_s b_0 \log x$ and confirmed using dQCD.

With matching:

$$\tau \frac{d\sigma^{\text{LO+NLL}'}}{d\tau} = \tau \frac{d\sigma^{\text{LO}}}{d\tau} + \left[\tau \frac{d\sigma^{\text{NLL}'}}{d\tau} - \tau \frac{d\sigma^{\text{NLL}'|\text{LO}}}{d\tau}\right]$$
End point corrections

Modification of the logarithm:

\[ \log (x_L \tau) \rightarrow -\log \left( \frac{1}{x_L \tau} - \frac{1}{x_L \tau_{\text{max}}} + 1 \right) \]

Additional contribution:

\[ \tau \frac{d\sigma_{\text{exp}}}{d\tau} = \frac{\alpha_s}{\pi} \left[ \frac{1}{2} G_{12} \log \bar{\tau} + G_{11} \left( 1 - \frac{\tau}{\tau_{\text{max}}} \right) \right] \]

Leads to resummation:

\[ \tau \frac{d\sigma_{\text{res}}}{d\tau} = \left( F' (\log \bar{\tau}) - \frac{\tau}{\tau_{\text{max}}} \frac{\alpha_s}{\pi} G_{11} \right) C \exp \left[ F (\log \bar{\tau}) - \frac{\tau}{\tau_{\text{max}}} \frac{\alpha_s}{\pi} G_{11} \log \bar{\tau} \right] \]
\[ \tau \frac{d\sigma_{\text{res}}}{d\tau} = \left( F' \left( \log \bar{\tau} \right) - \frac{\tau}{\tau_{\text{max}}} \frac{\alpha_s}{\pi} G_{11} \right) C \exp \left[ F \left( \log \bar{\tau} \right) - \frac{\tau}{\tau_{\text{max}}} \frac{\alpha_s}{\pi} G_{11} \log \bar{\tau} \right] \]

In order to treat both sides of the transition point the same:

\[ \tau \frac{d\sigma_{\text{res}}}{d\tau} = \left( F' \left( \log \bar{\tau}, \log z_{\text{cut}} \right) - \frac{\tau}{\tau_{\text{max}}} \left( G_{11}^{(SD)} + S'_0 \right) \right) \]

\[ C^{(SD)} \left( \frac{2\tau}{z_{\text{cut}}} \right) \exp \left[ F \left( \log \bar{\tau}, \log z_{\text{cut}} \right) \right] \]

\[ \times \prod_K \exp \left[ \frac{\tau}{\tau_{\text{max}}} \frac{G_{11}^{(K)}}{p_K} \left( -p_K^{(\bar{N})} \log \bar{\tau} + p_K^{(z_{\text{cut}})} \log \left( x_L \frac{z_{\text{cut}}}{2} \right) \right) \right] \]
Resummation results

\[ \frac{\tau}{\sigma_0} \frac{d\sigma}{d\tau}(e^+e^- \rightarrow q\bar{q} + X) \]

\[ Q = m_Z \]

\[ z_{\text{cut}} = 0.05, \beta = 0 \]

[Baron, Marzani, VT; '18]

Soft drop Thrust 31 V. Theeuwes
Transition point methods

\[ \frac{e_2^{(2)}}{e_2^{(2)}} \frac{d\sigma}{d\epsilon_2} (e^+ e^- \rightarrow q\bar{q} + X) \]

For this observable matching can take into account bulk of the effect.
$R$ dependence

Other observables allow for a reduction in transition point effects.