Transverse Momentum Resummation for single top quark production at the LHC

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In collaboration with Qing-Hong Cao, Peng Sun, C.-P. Yuan and Feng Yuan, arxiv:1801.09656
Single top-quark production

- Top quark can be produced singly at LHC via electroweak interactions, including t-channel, s-channel, and associated production.

- Inclusive cross sections

- t-channel (pp or p+p)

- tW (pp or p+p)

- s-channel (pp)

- s-channel (p+p)

- Probing EW coupling (V_{tb})

- Polarized top-quark production

- Test of heavy-quark scheme

- Constraining parton distributions

- Measuring top-quark mass

- Sensitive to various new physics

From Jun Gao
State of the art: single top quark production

NLO:
PRD66(2002)054024
P. Falgari, P. Mellor and A. Signer, PRD82(2010)054028
R. Schwienhorst, C. P. Yuan, C. Mueller and Q. H. Cao, PRD83(2011)034019
J. M. Campbell, R. Frederix, F. Maltoni, and F. Tramontano, PRL102(2009)182003

Soft-gluon resummation: (threshold)
J. Wang, C.S. Li, H.X. Zhu, and J,J, Zhang, arxiv:10010.4509
N. Kidonakis, 2011-2016
J. Wang, C.S. Li, and H. X. Zhu, PRD87(2013)no.3, 034030
Alekhin, Moch, Thier, 2016

Matching with Parton Shower:
S.Alioli, P. Nason, C. Oleari and E. Re, JHEP09(2009)111
S.Frederix, E. Re and P. Torrielli, JHEP 09 (2013)130

NNLO:
M. Brucherseifer, F. Caola and K. Melnikov, PLB736(2014)58-63

Apologize if missing your works!
Kinematic distribution and resummation

**Single top quark events @ LHC**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta(j)</td>
</tr>
<tr>
<td>$m(\ell vb)$</td>
<td>top-quark mass reconstructed from the charged lepton, neutrino and $b$-quark jet</td>
</tr>
<tr>
<td>$m(jb)$</td>
<td>invariant mass of the tagged ($b$) and light quark jet ($j$)</td>
</tr>
<tr>
<td>$m_T(W)$</td>
<td>transverse mass of the reconstructed $W$ boson</td>
</tr>
<tr>
<td>$m(\ell b)$</td>
<td>invariant mass of the lepton ($\ell$) and the tagged jet ($b$)</td>
</tr>
<tr>
<td>$\eta(\ell b)$</td>
<td>pseudorapidity of the reconstructed $W$-boson</td>
</tr>
<tr>
<td>$\cos \Theta(\ell, J_{\ell b\text{r.f.}})$</td>
<td>cosine of the angle $\theta$ between the charged lepton and the light quark (untagged) jet ($j$) in the rest frame of the reconstructed top quark</td>
</tr>
<tr>
<td>$H_T(l, \text{jets}, E_T^{\text{miss}})$</td>
<td>scalar sum of the transverse momenta of the jets, the charged lepton and the missing transverse momentum</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>transverse missing momentum</td>
</tr>
<tr>
<td>$\Delta R(\ell vb, \ell)$</td>
<td>$\Delta R$ of the reconstructed top quark and the charged lepton</td>
</tr>
<tr>
<td>$p_T(\ell\nu)$</td>
<td>transverse momentum of the reconstructed $W$-boson</td>
</tr>
<tr>
<td>$\eta(\ell vb)$</td>
<td>pseudorapidity of the reconstructed top quark</td>
</tr>
<tr>
<td>$\eta(b)$</td>
<td>pseudorapidity of the $b$-quark jet ($b$)</td>
</tr>
<tr>
<td>$p_T(\ell vb)$</td>
<td>transverse momentum of the reconstructed top quark</td>
</tr>
</tbody>
</table>

Detection efficiency of the events, after imposing the needed kinematic cuts

Resum large $\log \frac{O^2}{q_{\perp}^2}$ to improve the kinematic distribution

Better understanding and further improvements on the theory are needed

Experimental uncertainty is around 12%
CSS Formalism (For Drell-Yan-like processes)

The large logs will be resummed into the exponential form factor:

\[ W(Q, b) = e^{- \int_{1/b}^{Q} \frac{d\mu}{\mu} \left( \ln \frac{Q}{\mu} A + B \right)} C \otimes f_1 C \otimes f_2 \]


Only for initial state soft gluon resummation

- Dotted: Pert (\( \alpha_s \))
- Dot-dashed: Pert (\( \alpha_s^2 \))
- Dashed: CSS (1,1,1)
- Solid: CSS (2,2,1)
Single top quark vs. Drell-Yan process

A. Final states carry color, Soft gluon radiation from final state will contribute

B. Jet algorithm will enter into the calculations as well

Only out of the cone radiation contributions to the imbalance between the top quark and jet system

C. Color coherence effects between the initial and final states are important (t-channel)
Color coherence effects

\[ T = \ln \frac{-\hat{t}}{\hat{s}} + \ln \frac{-\hat{t} - m_t^2}{\hat{s} - m_t^2} \]

Blue: \(|y_j| < 4.5\)
Red: \(|y_j| < 4.5\), turn off the color coherence factor \(T\)
Black: \(3 < |y_j| < 4.5\)
Green: \(3 < |y_j| < 4.5\), turn off the color coherence factor \(T\)

Subleading logs in this process would be enhanced in the jet forward region \(|\hat{t}| \to 0\)
Finite bottom quark mass

S-ACOT scheme:

J. C. Collins, PRD58,094002(1998)

A. Belyaev, P.M. Nadolsky and C.-P. Yuan, JHEP04,004(2006)
Monte-Carlo Approach (Pythia)
Parton showers

Backward Radiation
(Initial State Radiation)

Kinematics of the radiated gluon, controlled by 
Sudakov form factor with some arbitrary cut-off. 
( In contrast to perform integration in impact parameter space, i.e., b space. )
Compared to Pythia

The resummation prediction is different from Pythia when $3 < |y_J| < 4.5$

Color coherence factor plays an important role

$$\begin{align*}
\hat{s} &= \left( p_{q'} + p_b \right)^2 \\
\hat{t} &= \left( p_{q'} - p_q \right)^2 \\
T &= \ln \frac{\hat{t}}{\hat{s}} + \ln \left( \frac{\hat{t} - m_t^2}{\hat{s} - m_t^2} \right)
\end{align*}$$
Phenomenological results

Resummation scale:

\[ H_T \equiv \sqrt{m_t^2 + P_{J\perp}^2} + P_J. \]

Black: resummation calculation
Green: leading order matrix element with parton showers by Pythia

| \[|y_J| < 4.5\] |
|---|
| \[3 < |y_J| < 4.5\] |

Blue: Asymptotic part; Red: NLO calculation; Orange: Y-piece

<table>
<thead>
<tr>
<th>[p p \to t + \text{jet}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[\mu = H_T]</td>
</tr>
<tr>
<td>[P_{J\perp} &gt; 30 \text{ GeV}]</td>
</tr>
<tr>
<td>[3 &lt;</td>
</tr>
</tbody>
</table>
$\sqrt{S} = 13$ TeV
$pp \rightarrow t + jet$
$\mu = H_T, \ |y_J| < 4.5$
$P_{J\perp} > 30$ GeV, $|y_t| < 3$

Only depends on the jet and top quark moving directions, not their energies
Kinematic acceptance

| $\phi^*$ | $|y_J| < 4.5$ | $< 0.05$ | $< 0.1$ | $< 0.15$ | $< 0.2$ | $< 0.25$ | $< 0.3$ |
|---------|-------------|---------|---------|---------|---------|---------|---------|
| Res     | 48%        | 68%     | 79%     | 86%     | 91%     | 94%     | 94%     |
| PYTHIA  | 46%        | 68%     | 81%     | 88%     | 93%     | 96%     | 96%     |
| 3 < $|y_J|$ < 4.5 | 54%    | 72%     | 83%     | 89%     | 93%     | 96%     | 96%     |
| Res     | 46%        | 68%     | 80%     | 87%     | 92%     | 96%     | 96%     |
| PYTHIA  | 46%        | 68%     | 80%     | 87%     | 92%     | 96%     | 96%     |

The difference between Res and Pythia: 3% – 8%

Experimental uncertainty is around 12%
Summary:

Soft gluon resummation are important for the single top quark production.

Color coherence effects:

The difference between Res and Pythia: 3% – 8%

Thank you!
Backup
Resummation Formalism

\[
\frac{d^4 \sigma}{dy_t dy_J dP_{J \perp}^2 d^2 q_{\perp}} = \sum_{ab} \left[ \int \frac{d^2 \vec{b}}{(2\pi)^2} e^{-i\vec{q} \cdot \vec{b}} W_{ab \to tJ}(x_1, x_2, b) + Y_{ab \to tJ} \right]
\]

\[
W_{ab \to tJ}(x_1, x_2, b) = x_1 f_a(x_1, \mu_F = b_0/b_*) x_2 f_b(x_2, \mu_F = b_0/b_*) e^{-S_{Sud}(Q^2, \mu_{Res}, b_*)} e^{-F_{NP}(Q^2, b)}
\]

\[
\times \text{Tr} \left[ H_{ab \to tJ}(\mu_{Res}) \exp\left[ -\int_{b_0/b_*}^{\mu_{Res}} \frac{d\mu}{\mu} \gamma_s^s \right] S_{ab \to tJ}(b_0/b_*) \exp\left[ -\int_{b_0/b_*}^{\mu_{Res}} \frac{d\mu}{\mu} \gamma_s^s \right] \right]
\]

\[
S_{Sud}(Q^2, \mu_R, b_*) = \int_{b_0^2/b_*^2}^{\mu^2_R} \frac{d\mu^2}{\mu^2} \left[ \ln \left( \frac{Q^2}{\mu^2} \right) A + B + D_1 \ln \frac{Q^2 - m_t^2}{P_{J\perp}^2 R^2} + D_2 \ln \frac{Q^2 - m_t^2}{m_t^2} \right]
\]

\[
F_{NP}(Q^2, b) = g_1 b^2 + g_2 \ln \frac{Q}{Q_0} \ln \frac{b}{b_*}; \quad b_* = b / \sqrt{1 + b^2 / b_{\text{max}}^2}
\]

From final state radiation

\[
A = C_F \frac{\alpha_s}{\pi} , \quad B = -2C_F \frac{\alpha_s}{\pi} , \quad D_1 = D_2 = C_F \frac{\alpha_s}{2\pi}
\]
Resummation Formalism

\[
\frac{d^4 \sigma}{dy_t dy_J dP_{J\perp}^2 d^2 q_\perp} = \sum_{ab} \left[ \int \frac{d^2 \vec{b}}{(2\pi)^2} e^{-i\vec{q_\perp} \cdot \vec{b}} W_{ab \to tJ}(x_1, x_2, \vec{b}) + Y_{ab \to tJ} \right]
\]

**Color Space**

\[C_{1kl}^{ij} = \delta_{ik} \delta_{jl}, \quad C_{2kl}^{ij} = T_{ik}^{a'} T_{jl}^{a'}\]

\[\hat{s} = (p_{q'} + p_b)^2 \quad \hat{u} = (p_{q'} - p_t)^2 \quad \hat{t} = (p_{q'} - p_q)^2\]
Subleading logs in this process would be enhanced in the jet forward region $|\hat{t}| \to 0$
Finite bottom quark mass

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\[ \sqrt{S} = 13 \text{ TeV} \]

\[ pp \rightarrow t+\text{jet} \]

\[ \mu = H_T, P_{J_L} > 30 \text{ GeV} \]

\[ |y_J| < 4.5, |y_t| < 3 \]

\[ m_b \neq 0 \]

\[ m_b = 0 \]

\[ \frac{d\sigma}{dq_{\perp}} \text{[pb/GeV]} \]

\[ q_{\perp}[\text{GeV}] \]

\[ C_{b/g}^{(1)}(x, b, m_b, \mu_F) = T_R x (1 - x) b m_b K_1(b m_b) \]

\[ + P_{q/g}^{(1)}(x) \left[ K_0(b m_b) - \theta(\mu_F - m_b) \ln \left( \frac{\mu_F}{m_b} \right) \right] \]

\[ \lim_{b m_b \to 0} C_{b/g}^{(1)}(x, b, m_b, \mu_F) = T_R x (1 - x) - \ln \left( \frac{\mu_F b}{b_0} \right) P_{q/g}^{(1)}(x). \]
Finite bottom quark mass

\[ m_b \neq 0 \]

\[ m_b = 0 \]

S. Berge, P. M. Nadolsky and F. I. Olness, PRD73,013002(2006)
Pseudorapidity distribution of the leading-jet

CT14LO PDF is used in the Pythia prediction