Towards Precision Top Quark Measurements in $e^+e^-$ Collisions at Linear Colliders

Naomi van der Kolk,
On behalf of the CLICdp collaboration and the ILC Physics Study
Why study the top quark at a linear lepton collider?

- Top quarks have been exclusively studied at hadron colliders
- Clean experimental environment in $e^+e^-$ allows to measure all decay modes with a high resolution and low background
- Top quark production through the electroweak process has no competing QCD production, leading to high theoretical precision
- Top mass can be measured in theoretically well defined mass schemes in a threshold scan ($\sim 350$ GeV)
- Top quark as a tool for BSM physics; precision measurement of the top EW couplings ($>> 350$ GeV) aided by polarisable beams
- Beam polarisation enhances sensitivity
Future Linear Lepton Colliders

- Two machines proposed: ILC and CLIC
  - Japan considers hosting the ILC, CLIC is an option for a future facility at CERN
  - Linear lepton colliders can reach energies substantially above the top quark production threshold extending sensitivity for New Physics searches

<table>
<thead>
<tr>
<th>Energy [GeV]</th>
<th>250</th>
<th>350</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Luminosity [ab^{-1}]</td>
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<td>0.2</td>
<td>4</td>
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<tr>
<td>arXiv:1506.07830</td>
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<table>
<thead>
<tr>
<th>Energy [GeV]</th>
<th>380</th>
<th>350</th>
<th>1500</th>
<th>3000</th>
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<td>0.1</td>
<td>1.5</td>
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<td>arXiv:1608.07537</td>
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</table>
Top quark properties

- Top quark properties (mass, width, Yukawa coupling) are an important ingredient in the Standard Model.
- Energy scan around the top pair production threshold provides the most accurate measurement of the top mass.
- Production cross section is affected by top quark properties and QCD: mass, width, Yukawa coupling, strong coupling constant.
- Theoretical uncertainties on par with experimental errors -> QCD scale uncertainties in cross section calculation.
- Uncertainty on top quark mass (ILC):
  - Statistical (10 points, total 100 fb\(^{-1}\)) \(\sim 20\) MeV (+\sim 10% for CLIC)
  - Experimental systematic uncertainty \(\sim 40\) MeV
  - Theoretical systematic uncertainty: NNNLO QCD scale variations 40 MeV + parametric \(\alpha_s\) 35 MeV (current WA)
  - Total: 40 - 75 MeV

Frank Simon
@ LC top 2017
Top quark properties

- Simultaneous extraction of top quark properties: 2D template fits of e.g. mass and width
- Increase in uncertainties due to correlations in the 2D fit
- Improvement expected by including differential observables (top momentum, forward-backward asymmetry, ...)

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- 1D mass resolution (assuming def. $\Gamma_t$)
  - $18$ MeV
- 1D width resolution (assuming def. $m_t$)
  - $43$ MeV
- Extension of 2D $1\sigma$ contour:
  - $m_t +39-35$ MeV
  - $\Gamma_t +109-90$ MeV
  - correlation $0.26$
Top quark properties

- Direct measurement of the top mass in the continuum, complementary to the threshold measurement, over a large range of production energies -> probe running of the top mass
- The ttbar production cross section depends on centre of mass energy and $m_{\text{top}}$
- Use radiative events:
  - $e^+e^- \rightarrow \text{ttbar} + \gamma_{\text{ISR}}$
    In the presence of ISR the cross section is sensitive to the energy of the ISR photon
  - $e^+e^- \rightarrow \text{ttbar} + g_{\text{FSR}}$
    In the presence of FSR the gluon energy spectrum is sensitive to $m_{\text{top}}$
- ISR channel more sensitive to $m_{\text{top}}$ near the production threshold, FSR channel sensitive over a large energy range
- Particle level study results are very promising, full simulations study in progress

<table>
<thead>
<tr>
<th>$E$ (GeV)</th>
<th>Luminosity (fb-1)</th>
<th>$\Delta m_t$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>500</td>
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</tr>
<tr>
<td>500</td>
<td>4000</td>
<td>101</td>
</tr>
<tr>
<td>1000</td>
<td>3500</td>
<td>388</td>
</tr>
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</table>

Pablo Gomis @ LC top 2017
Rare top decays

- In the Standard Model FCNC top decays are highly suppressed $B(t \rightarrow c\gamma, t \rightarrow cZ, t \rightarrow cg, t \rightarrow cH) \sim 10^{-12}$ to $10^{-14}$
- Observing such decays directly points to New Physics, in many BSM models branching ratios are increased to the $10^{-2}$ to $10^{-4}$ level
- Two decay channels being studied at the moment; $t \rightarrow cH$ and $t \rightarrow c\gamma$ in full simulations in 2DHM (III) model
- Main effort into selecting signal events w.r.t the standard top decays, background rejection relies heavily on flavour tagging
- Determine exclusion limits (95% C.L.) on the branching ratio of these channels
FCNC Limits

- Competitive limits for FCNC top decays
  - \( t \rightarrow cH \)
    - Expected limits from HL-LHC (ATLAS) on \( B(t \rightarrow qH) \sim 2 \times 10^{-4} \)
    - Limit for CLIC 500 fb\(^{-1}\) at 380 GeV
      - Fully hadronic \( B(t \rightarrow cH) \times B(H \rightarrow bb) = 1.4 \times 10^{-4} \)
      - Semi-leptonic Work in Progress \( B(t \rightarrow cH) \times B(H \rightarrow bb) = 3.9 \times 10^{-4} \)
  - \( t \rightarrow c\gamma \)
    - Currently most stringent limit from CMS: \( B(t \rightarrow c\gamma) < 1.7 \times 10^{-3} \)
    - Expected limits at HL-LHC \( B(t \rightarrow c\gamma) < 3.4 \times 10^{-4} \sim 2.0 \times 10^{-4} \) for 3 ab\(^{-1}\) at 14 TeV
    - Limit for CLIC 500 fb\(^{-1}\) at 380 GeV Work in Progress \( B(t \rightarrow c\gamma) \sim 2 \times 10^{-4} \)

Filip Żarnecki and Naomi van der Kolk
@ LC top 2017

arXiv:1511.03951
CMS-DP-2016-064
Top quark ideal tool to find BSM physics: precision measurement of EW couplings allow to find/exclude new physics

Polarisation at lepton colliders provides additional sensitivity

Observables: cross section and forward-backward asymmetry

Global fit at 2 energy points provides low uncertainty for top quark couplings

Sensitivity to New Physics scales much better than at HL-LHC from ttZ couplings

EW couplings (CP-conserving)

Michael Russell @ LC top 2017

Martín Perelló @ LC top 2017
EW couplings (CP-violating)

- CP-violating effects manifest in top spin correlations
- Due to short top lifetime, spin information propagates to the daughter particles
- Extract CP-violating form factors from asymmetries sensitive to CP-violating effects
- Asymmetries extracted from lepton 4-vector in semi-leptonic decay channel
EW couplings (@ high energy)

- Developing methods to measure asymmetries at high energy
- Reconstruction of boosted top within “fat” jets, where standard reconstruction techniques do not work
  - B-tagging may not be feasible as decay products are very close to each other
- Tag tops by identifying prongy structure within a “fat” jet; looking at various techniques - parsing jet substructure and multivariate analysis using jet substructure variables such as ‘subjettiness’, angular relations, etc.
- Forward-backward asymmetry at 1.4 TeV
  Work in Progress
  ~0.01 for -80% electron polarisation and
  ~0.01 - 0.02 for +80% electron polarisation

The three subjets after top tagging are shaded separately

Rickard Ström
@ LC top 2017

CLICdp preliminary
Conclusion

- Lepton colliders allow to study top quark properties with high precision
- Beam polarisation in linear lepton colliders enhances the physics reach and sensitivity to BSM models
- Threshold scan around top pair production threshold provides the most accurate top mass measurement in a well defined theoretical mass scheme
  - MSbar mass precision ~ 50 MeV
    hadron colliders ~ 1 GeV dominated by theory uncertainties
- Precision measurements at lepton colliders of EW couplings allow a far superior sensitivity to BSM models
  - Form factor precision at the % level,
    ~order of magnitude better than HL-LHC
Thank you for your attention
CLIC baseline staging scenario

• Full programme will span 22 years

• 5 to 7 years at each energy stage

• 2 year upgrade periods between stages

• Luminosity ramp up for each energy stage

• Assume CLIC will operate for the equivalent of 125 days \( (1.08 \times 10^7 \text{ s}) \) per year at 100% efficiency

<table>
<thead>
<tr>
<th>Stage</th>
<th>( \sqrt{s} ) (GeV)</th>
<th>( \mathcal{L}_{\text{int}} ) (fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>100</td>
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<tr>
<td>2</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

Figure 19: Overview of the CLIC layout at \( p \Sigma = 3 \text{ TeV} \).

Year  0  5  10  15  20

Luminosity per year [fb\(^{-1}\)]

0  5  10  15  20

0.38 TeV  1.5 TeV  3 TeV

Luminosity per year [fb\(^{-1}\)]

0  5  10  15  20

0.38 TeV  1.5 TeV  3 TeV

Integrated luminosity [fb\(^{-1}\)]
ILC Running Scenario

- Standard running scenario H20 assuming 20 years of operation
- The actual running scenario will depend on physics outcomes from LHC and ILC
- Guarantees the fully independent profiling of the Higgs boson

ILC running scenarios: arXiv: 1506.07830

Table 7: Scenario H-20: Sequence of energy stages and their real-time conditions.

<table>
<thead>
<tr>
<th>Energy Stage</th>
<th>√s [GeV]</th>
<th>∫L dt [fb⁻¹]</th>
<th>L_peak [fb⁻¹/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics run</td>
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<td>500</td>
<td>288</td>
</tr>
<tr>
<td>Physics run</td>
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<td>200</td>
<td>160</td>
</tr>
<tr>
<td>Physics run</td>
<td>250</td>
<td>500</td>
<td>240</td>
</tr>
<tr>
<td>Shutdown</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physics run</td>
<td>500</td>
<td>3500</td>
<td>576</td>
</tr>
<tr>
<td>Physics run</td>
<td>250</td>
<td>1500</td>
<td>480</td>
</tr>
</tbody>
</table>

ILC, Scenario H-20
- ECM = 250 GeV
- ECM = 350 GeV
- ECM = 500 GeV

4 Time Development of Physics Results

In this section we present some examples of how important physics results evolve in time for the three scenarios presented above. All plots in this section are preliminary since not all analyses involved have been finished yet, so that some measurements are extrapolated, e.g. from other center-of-mass energies.

4.1 Higgs couplings to fermions and gauge bosons
**CLIC @ 380 GeV**

- **Higgs Physics**
  - Dominant Higgsstrahlung process provides model independent measurement of the coupling $g_{HZZ}$ to a precision of 0.8%
  - Together with WW fusion process gives access to total decay width and the coupling $g_{HWW}$
  - Higgs mass to a precision of $\sim 100$ MeV
  - Best precision on cross-section around 350 GeV, precision of all Higgs couplings is limited by this uncertainty

- **Top Physics**
  - Top mass to a precision of $\sim 50$ MeV from threshold scan around 350 GeV
  - Precision at the percent level on top form factors, above production threshold the boost helps accurate reconstruction
  - BSM in top sector best near the maximum cross-section at 420 GeV

- **380 GeV favourable for both Higgs and Top physics studies, supplemented with a top threshold scan around 350 GeV**

- **Accelerator**
  - Length: 11.4 km
  - Accelerating gradient: 72 MV/m
  - 1 drive beam complex
CLIC @ 1.5 and 3 TeV

- **Higgs Physics**
  - WW-fusion and ZZ-fusion processes dominant
  - ~1% precision on the Higgs couplings to fermions and bosons
  - Higgs mass to ~32 MeV through H → bb, ~24 MeV with polarisation (1.5 + 3 TeV)
  - Top yukawa coupling through Higgs e⁺e⁻ → ttH 4-5% statistical accuracy (with 80% electron polarisation)
  - Higgs self coupling through e⁺e⁻ → HH gives access to the coupling λ to 10% precision (1.5 + 3 TeV)

- **BSM physics**
  - Direct searches: e.g. SUSY particle masses with 1% accuracy up to approximately half the centre of mass energy
  - Indirect searches: deviations from SM predictions in Higgs and Top properties, or search for Z' via e⁺e⁻ → μμ
  - Top sector: less statistical accuracy but improved reconstruction through boost and increased relative BSM contributions

- **Accelerator**
  - 3 TeV maximum envisaged energy
  - 1.5 TeV maximum energy for 1 drive beam complex
  - Length: 29.0 / 50.1 km
  - Accelerating gradient: 72 and 100 MV/m

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*EPS-HEP 2017 - Towards Precision Top Quark Measurements in e+e- Collisions - N. van der Kolk*
ILC Physics Program

- $e^+e^-$ collider offers a well defined initial state, absence of strong interaction background, controlled and calculable electroweak background
- High precision tests of the Standard Model over a wide energy range to detect the onset of New Physics
- Main focus on Higgs and top quark, W and Z
- Machine settings can be “tailored” for specific processes: $E_{cm}$ and beam polarisation (enhance cross section, remove background)

ILC physics program: arXiv:1506.05992
Figure 9: The heavy dots display the shifts in the left- and right-handed top quark couplings to the $Z$ boson predicted in a variety of models with composite Higgs bosons, from Ref. [41]. The ellipses show the 68% confidence regions for these couplings expected from the LHC [36, 43] and the ILC [42].

Violating interactions of the top quark [44, 45], which provide the driving force in one class of models of the cosmic matter-antimatter asymmetry.

**New Particles**

In addition to searches for new particles and forces through the precision study of the Higgs boson and the top quark, the ILC will carry out direct searches for new particles outside the Standard Model. The LHC has already carried out a broad program of searches for new particles, setting upper limits on masses higher than $10^{16}$ GeV. Still, it is possible that new particles are being produced at the LHC and yet are not visible to the experiments there. Such particles do not appear only in artificial examples but even in some of the best-motivated scenarios for new physics. We will review some specific models of this type below. At the ILC, we can use the advantages of $e^+e^-$ collisions to discover or definitively exclude these particles.

A new capability that the ILC will make available is the ability to polarize the colliding electron and positron beams. We have already discussed the use of beam polarization in studies of the Higgs boson and the top quark. For studies of an unknown...
Top Mass Uncertainties - Status

- A number of studies in Tesla, ILC, CLIC contexts: Expected statistical uncertainty **20 - 30 MeV** (for 100 fb⁻¹)

<table>
<thead>
<tr>
<th>error source</th>
<th>$\Delta m_t^{PS}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>stat. error (200 fb⁻¹)</td>
<td>13</td>
</tr>
<tr>
<td>theory (NNNLO scale variations, PS scheme)</td>
<td>40</td>
</tr>
<tr>
<td>parametric ($\alpha_s$, current WA)</td>
<td>35</td>
</tr>
<tr>
<td>non-resonant contributions (such as single top)</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>residual background / selection efficiency</td>
<td>10 – 20</td>
</tr>
<tr>
<td>luminosity spectrum uncertainty</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>beam energy uncertainty</td>
<td>&lt; 17</td>
</tr>
<tr>
<td>combined theory &amp; parametric</td>
<td>30 – 50</td>
</tr>
<tr>
<td>combined experimental &amp; backgrounds</td>
<td>25 – 50</td>
</tr>
<tr>
<td>total (stat. + syst.)</td>
<td>40 – 75</td>
</tr>
</tbody>
</table>

The Basics for all Studies presented today

- Experimental details:
  - Based on CLIC / ILC top threshold study (EPJ C73, 2530 (2013)):
    - CLIC_ILD Detector model
    - Threshold simulated using efficiency & backgrounds from full simulations, signal scaled according to theory input
    - Assuming ILC TDR luminosity spectrum
  - Theory input:
      - Including NNNLO Higgs effects, NLO non-resonant EW contributions, NLO QED
    - Using the **PS Mass Scheme** as the “native” scheme of the calculation, also using MSbar and 1S schemes to explore scheme dependence

Thanks to Martin Beneke, Andreas Meyer, Jan Piclum for help and fruitful discussions!
m_t can be measured by counting the ttbar events produced for a certain s' (i.e. ISR energy photon, which can be measured with high precision)

Our observable $B(m_t, \zeta_{s'})$ is the differential cross section of the ttbar production as a function of $\zeta_{s'} = \sqrt{s'}$

The observable is more sensitive to m_t near the top production threshold, and the dependence diminishes as $\zeta_{s'}$ grows

P. Gomis (Pablo.Gomis@ific.uv.es) @ Workshop on Top physics at the Linear Collider 2017 - 07/06/2017
We construct the observable as in the ISR case: \( B(m_t, \zeta_{s'}) \) is the differential cross section of the \( tt\bar{t} + g_{FSR} \) production as a function of \( \zeta_{s'} \), where \( s' \) is the \( tt\bar{t} \) center of mass energy after FSR emission.

In the case of the FSR the curves are very sensitive to the mass over all the interval, instead of only in the threshold (as was in the ISR study).
PARTON LEVEL STUDY: PROCEDURE

- A study to test the potential of the observable was produced using Pythia 8.1: no detector effects or backgrounds are considered.

- $e^-e^+ \rightarrow t\bar{t}$bar unpolarized events with ISR and FSR were produced at parton level.

- From the energy spectrum of the ISR/FSR bosons we obtained the observable curves for ISR and FSR.

- For the study we produced reference curves (with high statistics) and datasets (for certain luminosities).

- A template fit of $N$ (~100 - 500) datasets to the reference curves was performed in order to estimate the observable’s sensitivity.

P. Gomis (Pablo.Gomis@ific.uv.es) @ Workshop on Top physics at the Linear Collider 2017 - 07/06/2017
**Top quark couplings**

**Objective:** to study the potential of a global fit in the top EW sector.

**Form-factors**
\[
\Gamma_{\mu X}(k^2, q, \bar{q}) = ie \left\{ \gamma_{\mu} \left( F_{1V}^{X}(k^2) + \gamma_5 F_{1A}^{X}(k^2) \right) - \frac{\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^{\nu} \left( iF_{2V}^{X}(k^2) + \gamma_5 F_{2A}^{X}(k^2) \right) \right\}
\]

**CP Conserving**

**Effective Field Theory**
\[
\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}(\Lambda^{-4})
\]

**Wtb vertex**

**Contact interactions**

**Z/γ tt vertices**

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Martín Perelló, IFIC 3 TopLC 2017 - CERN - 08/06/17
Change of basis

Transformation between effective operators and form-factors:

\[
\begin{align*}
F_1^V - F_1^{Z,SM} &= \frac{1}{2} \left( C_{\varphi Q}^{(3)} - C_{\varphi Q}^{(1)} - C_{\varphi t} \right) \frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2} C_{\varphi q}^V \frac{m_t^2}{\Lambda^2 s_W c_W} \\
F_1^A - F_1^{Z,SM} &= \frac{1}{2} \left( -C_{\varphi Q}^{(3)} + C_{\varphi Q}^{(1)} - C_{\varphi t} \right) \frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2} C_{\varphi q}^A \frac{m_t^2}{\Lambda^2 s_W c_W} \\
F_2^Z &= \left( \text{Re}\{C_{tw}\} c_w^2 - \text{Re}\{C_{tB}\} s_w^2 \right) \frac{4m_t^2}{\Lambda^2 s_W c_W} = \text{Re}\{C_{uZ}\} \frac{4m_t^2}{\Lambda^2} \\
F_2^V &= \left( \text{Re}\{C_{tw}\} + \text{Re}\{C_{tB}\} \right) \frac{4m_t^2}{\Lambda^2} = \text{Re}\{C_{uA}\} \frac{4m_t^2}{\Lambda^2} \\
[F_2^Z, F_2^V] &\propto [\text{Im}\{C_{tw}\}, \text{Im}\{C_{tB}\}]
\end{align*}
\]

Conversion to V/A - V basis in contact interactions:

\[
\begin{align*}
C_{\ell q}^V &= C_{\ell u} + C_{\ell q}^{(1)} - C_{\ell q}^{(3)} \\
C_{\ell q}^A &= C_{\ell u} - C_{\ell q}^{(1)} + C_{\ell q}^{(3)} \\
C_{\ell q}^V &= C_{\ell u} + C_{\ell q} \\
C_{\ell q}^A &= C_{\ell u} - C_{\ell q}
\end{align*}
\]
Optimal CP-odd observables

- CP-odd observables are defined with the four momenta available in $t\bar{t}$ semi-leptonic decay channel

$$O^{Re}_+ = (\hat{q}_X \times \hat{q}^*_+) \cdot \hat{p}_+,$$

$$O^{Im}_+ = -\left[1 + \left(\frac{\sqrt{s}}{2m_t} - 1\right)(\hat{q}_X \cdot \hat{p}_+)^2\right]\hat{q}^*_+ \cdot \hat{q}_X + \frac{\sqrt{s}}{2m_t} \hat{q}_X \cdot \hat{p}_+ \hat{q}^*_+ \cdot \hat{p}_+$$

- The way to extract the CP-violating form factor is to construct asymmetries sensitive to CP-violation effects

$$A^{Re}_+ = \langle O^{Re}_+ \rangle - \langle O^{Re}_- \rangle = c_\gamma(s) \text{Re} F^\gamma_{2A} + c_Z(s) \text{Re} F^Z_{2A}$$

$$A^{Im}_+ = \langle O^{Im}_+ \rangle - \langle O^{Im}_- \rangle = \bar{c}_\gamma(s) \text{Im} F^\gamma_{2A} + \bar{c}_Z(s) \text{Im} F^Z_{2A}$$

$$A^{Re,L}_\gamma, Z \quad A^{Re,L}_\gamma, Z \quad A^{Im,R}_\gamma, Z \quad A^{Im,R}_\gamma, Z$$
Lepton colliders

• provide complementary probe of $ttZ$ coupling

• lower energy, but much better precision

  $N^3LO$ QCD, per-mille scale variation, no PDFs, low background

• ideal environment for looking for non-resonant new physics

  that’s precisely what an EFT is after all!
ILC500 constraints

see also Aguilar-Saavedra, Fiolhais, Onofre: 1206.1033

factor 100-1000x improvement over LHC 3 ab$^{-1}$

Global constraints weaker

But typically overly conservative when matched to UV model
Top tagging

- Top tagging is a powerful method to identify top quarks, in particular for boosted tops where the jet decay structure is complex (collimated collections of particles that look like single jets).

- Method 1: Following the method from Kaplan et al.
  - DOI: 10.1103/PhysRevLett.101.142001
  - Distinguish boosted top jets from light-quark and gluon jets using jet substructure:
  - Parsing jet cluster (Isolate events with three-four hard, nearby subjets)
  - Imposing kinematic constraints (exploit 3-body kinematics of top decay)

- Method 2: Multivariate classifier (BDT) with jet multiplicity, subjettiness, etc.
Method 1: Top tagging algorithm

1) PFO objects are clustered into jets of size $R$ (large jet) - any algorithm
   - Iteratively merge 4-vector pairs with closest $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ until $\Delta R < R$

2) Iteratively decluster each resulting jet (reversing each step in the jet clustering) to search for subjets
   - Split into two parts, reject softest if $\frac{p_T^{\text{subj}}}{p_T^{\text{jet}}} < \delta_p$
   - Declustering continues on the harder object until:
     - Both subjets are harder than $p_T^{\text{jet}} \cdot \delta_p$ ✔
     - Both subjets are too close $|\Delta \eta| + |\Delta \phi| < \delta_r$ ✗
     - Both subjets are softer than $p_T^{\text{jet}} \cdot \delta_p$ ✗

3) If an original jet declusters into two subjets - step 2 is repeated on those subjets
   - Results in 1 (original jet), 2, 3, or 4 (additional soft gluon emission) subjets

4) Additional kinematic cuts

Rickard Ström - rickard.stroem@cern.ch
Method 2: BDT event classification

- A top tagger using multivariate techniques and jet substructure to identify semileptonic tt decays and single top events
- Example jet substructure variables used:
  - Jet multiplicity (number of objects within fat-jet)
- Angular relations (relative angles between subjet pairs, identifies forced splitting)