Top Quark Physics at FCC-ee

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IPM

FCC Week 2016, Rome
Introduction to top quark
Motivations
Top quark mass
Top EW couplings
Rare Top quark decays
Summary and conclusions
Top quark

✧ Top quark lifetime: $\tau \approx 4 \times 10^{-25} \text{s}$, very short life time due to its large mass.

✧ Such a short lifetime is corresponding to a decay width of $\Gamma_t = \frac{\hbar c}{c \tau} \approx 1.4 \text{ GeV}$.

✧ Comparing $\Gamma_t$ with typical hadronization scale $\Lambda_{QCD} \approx 250 \text{ MeV}$:

► Top quark decays before hadronization
► Top is a “free” quark
► no bound states [i.e. no toponium, top mesons/baryons]

✧ Spin/polarization passed on to decay products ➔ direct access to quark spin properties

After the top quark discovery, the main focus is on measurement of the top quark properties as they are sensitivity to new physics beyond the SM:

- Top quark mass
- Precise measurements of the couplings to photon/Z-boson
- Top FCNC decays
- Top Yukawa coupling
...

FCC-Rome
Motivations for Top quark studies

Radiative corrections connect $m_W$, $m_t$, and $m_H$ ...
Both top quark and Higgs boson are contributing to 1-loop $W/Z$ propagators:

Assuming $\alpha$, $G_F$ and $M_Z$ as inputs, $M_{W}^{2}$ at 1-loop is given by:

$$M_{W}^{2} = \frac{\pi \alpha}{\sqrt{2} G_F \sin^2 \theta_W} \frac{1}{1 - \Delta r(m_t, M_H)}$$

$$\Delta r(m_t, M_H) \simeq c_t m_t^2 + c_H \ln \left( \frac{M_H^2}{M_Z^2} \right) + \cdots$$

The presence of a new physics with EW couplings would change this picture!
Motivations: Top mass in flavor physics

- In the SM, the rare decay $B_s \rightarrow \mu^+\mu^-$ proceeds through box and triangle diagrams involving top quark, W, ... exchange:

\[
\begin{align*}
\text{BR}(B_s \rightarrow \mu^+\mu^-) &= (3.33 \pm 0.24) \times 10^{-9} \left(\frac{M_t}{173.34 \text{ GeV}}\right)^{3.06} \\
\text{- New physics models can contribute significantly in this process.} \\
\text{- This decay has been observed in a combined analysis by the CMS and LHCb experiments.}
\end{align*}
\]

- The mass differences of the $B_{s,d}^0 - B_{s,d}^{0\bar{s}}$ systems in the SM.

- The branching ratio for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the SM.

Motivations for Top quark studies

As the top quark is the heaviest SM particle, its Yukawa coupling is sizeable ($y_t \sim \sqrt{2} \frac{m_t}{v} \sim 1$) and plays a crucial role in determining the predictions of the SM theory very short distances. A precise determination of $m_{\text{top}}$ is crucial to check for the Stability of the electroweak vacuum:

The quartic Higgs boson coupling in the high-energy regime implies that the instability scale most critically depends on the Higgs and top masses.

A small change in $m_{\text{top}}$ can drastically modify our conclusions regarding vacuum stability.

JHEP 1208 (2012) 098
Top Mass @ FCC-ee
Top quark mass from the threshold scan

- There is a resembling resonant behavior around the threshold due to the QCD bound state effects.

- Threshold shape of the top pair cross section:
  - strongly depends on the mass & width of the top quark → precise measurement of $m_{\text{top}}, \Gamma_t$ (and consequently $V_{tb}$)
  - receives contributions from the strong coupling constant ($\alpha_S$) and from the top quark Yukawa coupling. Both affect the interaction of the top pair in the final state and the overall magnitude of the cross section.

There are studies where multi-parameter fits to cross-section at threshold (and other distribution) are used to obtain $m_{\text{top}}, \Gamma_t$ and $\alpha_S$.

Horiguchi et al., arXiv:1310.0563 ; Martinez, Miquel, EPJ C27, 49 (2003); Seidel, Simon, Tesar, Poss, EPJ C73 (2013);
The threshold shape is also affected by luminosity spectrum and ISR. They lead to:

- an overall reduction of the ttbar effective cross section (as they shift a fraction of the luminosity below the threshold energy)
- broadening of the threshold turn-on because of the tail at low-energy & the width of the main luminosity peak.

As can be seen, at the FCC-ee:

- an enhancement of the steepness of the threshold profile
- larger absolute value of the ttbar effective cross section

With 100fb$^{-1}$ and an ILD/CLIC like detector: $16\text{MeV@FCCee}$
Uncertainties

- $\alpha_S$: the systematic uncertainty due to strong coupling constant on $m_t$ is 2.7 MeV per $10^{-4}$ uncertainty of $\alpha_S$. It is notable that:
  
  - The beam energy: need to be known to a fraction of MeV (precise measurement of $Z$, $W$ mass and energy/momentum conservation $\rightarrow$ statistical precision on $E_{beam}$ of around 1MeV)
  
  - New development in theory uncertainty in conversion of $1S \rightarrow \overline{MS}$ much reduced:

<table>
<thead>
<tr>
<th>Relating $1S$ and $PS$ masses to $\overline{MS}$ mass:</th>
</tr>
</thead>
<tbody>
<tr>
<td>#loops</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4 (x1.03)</td>
</tr>
</tbody>
</table>

(Hoang, Stahlhofen)

- Theoretical uncertainty on the calculation of the threshold top pair cross section $\rightarrow$ 8-14 MeV (1D-2D fit).

Top quark mass measurement using the threshold scan is going to be studied with new FCC-ee software.
$Z\bar{t}t\bar{t}$ and $\gamma \bar{t}t\bar{t}$ couplings @ FCC-ee

and the study by N. Foppiani, T. Pajero, et al, presented in the FCC-ee Workshop - February 2nd, 2016
https://indico.cern.ch/event/469561/session/1/contribution/20/attachments/1221484/1828346/nicolo_foppiani_top_couplings.pdf
Several SM extensions of the SM such as extra dimensions and composite Higgs models lead to sizable deviations in the couplings of $t\bar{t}V$, $V = Z, \gamma$ (JHEP 08 (2015), arXiv:1403.2893 …)

At the FCC-ee, the $t\bar{t}V$ ($V = \gamma, Z$) couplings could be probed directly through the top pair production process. The most general Lorentz-invariant vertex function describing the interaction of a neutral vector boson $V$ with two on-shell top quarks can be written:

$$\Gamma_{t\bar{t}V}^{\mu} = \frac{g}{2} \left[ \gamma^{\mu} \left( A_{V} + \delta A_{V} \right) - \gamma_{5} ( B_{V} + \delta B_{V} ) \right] + \frac{(p_{t} - p_{\bar{t}})^{\mu}}{2m_{t}} (\delta C_{V} - \delta D_{V} \gamma_{5})$$

At tree level in the SM, $\delta A_{V} = \delta B_{V} = \delta C_{V} = \delta D_{V} = 0$

The energy and the angular distributions of the decay products, in particular, the charged lepton and the $b$-quark,… are powerful tools to disentangle and access different components of the $t\bar{t}Z$ and $t\bar{t}\gamma$.
The differential production cross section $d^2\sigma/d\cos\theta dx_f$ for $e^+e^- \rightarrow t\bar{t} \rightarrow b\bar{b}q\bar{q}'\ell\nu_\ell$ ($\ell = e, \mu$) is given by:

$$\Gamma_\mu^{\nu} = \frac{g}{2} \left[ \gamma^\mu \left\{ (A_V + \delta A_V) - \gamma_5 (B_V + \delta B_V) \right\} + \frac{(p_t - p_{\ell})^\mu}{2m_t} \left( \delta C_V - \delta D_V \gamma_5 \right) \right]$$

Reduced charged lepton energy:

$$x_f \equiv \frac{2E_f}{m_t} \sqrt{\frac{1 - \beta}{1 + \beta}} \quad \beta(\equiv \sqrt{1 - 4m_t^2/s})$$

Top EW couplings

- After performing a likelihood fit of the anomalous couplings to the double differential cross section with conservative assumptions on lepton identification, b-tagging efficiencies, and lepton angular and momentum resolutions, the estimated precisions are at the order of: $10^{-3}, 10^{-2}$

- The double-differential cross section is statistically optimal at the FCC-ee at the energy of 365 GeV to probe the Ztt couplings.

- We do not need the beam polarization as it is compensated by the large integrated luminosity.

- Not necessary for high energy runs above the threshold.
A full simulation study

The Top EW couplings have been probed including signal and the backgrounds assuming a similar performance of the FCC-ee detector to CLIC/ILD detector.

Reduced charged lepton energy and angular distributions after the cuts

The analytical results have been proven with full detector simulation considering signal and backgrounds.

<table>
<thead>
<tr>
<th>Good agreement with the predictions in Arxiv 1503.01325</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Whizard full simulation</strong></td>
</tr>
<tr>
<td>$\sigma(\delta A_Z)$</td>
</tr>
<tr>
<td>$\sigma(\delta B_Z)$</td>
</tr>
</tbody>
</table>

Assumptions in arXiv:1503.1325

- selection efficiency $\approx 0.5$
- complete rejection of the background
- included also the fully leptonic final state analysis in its estimates
The large hierarchy between the masses of the first two and the third generation of SM quarks could point out an intrinsic difference between the nature of these particles and suggest that the top quark plays a special role in the underlying mechanisms of EWSB.

While this problem is not addressed in the SM, new physics (NP) scenarios such as Composite Higgs models (CHMs) provide a solution to this puzzle.

Within CHM framework, the Higgs is assumed to be a bound state of a new strongly interacting sector and the mass hierarchy between the SM fermions is addressed by postulating a sizable mixing of the third generation of quarks with the strong sector to which the Higgs belongs.

Compositeness of the Higgs can bring compositeness of the top quark and the prediction of new particles: vector-like tops $T$ (needed to give a finite and calculable theory of the Higgs mass), new vector resonances $Z', W'$ (contributing to the EW top axial and vector-axial coupling modification).

S. De Curtis et al, more details can be found in talk by Stefania: https://indico.cern.ch/event/438866/session/14/contribution/143
New physics sensitivity

In CHM, the Z-t-t coupling is modified from: mixing between top and extra fermions (partial compositeness), mixing between Z and Z’s.

Typical deviations of the $Zt_L t_L$ and $Zt_R t_R$ couplings for various NP models (purple points) and for the 4D-CHM (black points) together with the sensitivity expected at LHC-13 with 300 and 3000/fb, outer and inner red lines, from ILC-500, blue dashed lines, and FCC-ee green lines.

The precision of FCC-ee on $\delta A_\gamma$ provides a sensitivity to the Z’s of CHMs with masses up to 4 TeV.

See talk by Stefania:
https://indico.cern.ch/event/438866/session/14/contribution/143
Top quark rare decays: FCNC

Based on the analysis done by S. Biswas, F. Margaroli, B. Mele and H. Khanpour, S. Khatibi, M. Khatiri, M. Mohammadi
Flavor Changing Neutral Current (FCNC): SM & BSM

- Flavor-changing neutral current (FCNC) interactions: Transition from a quark with flavor-X and charge-Q to another quark of flavor-Y but with the same charge-Q.

For example: \(b \rightarrow s \gamma\), \(t \rightarrow u \gamma\), \(t \rightarrow uZ\) …

- FCNC are forbidden at tree level and only allowed via higher order corrections such as penguin diagrams and strongly suppressed: due to GIM mechanism and smallness of the related CKM matrix elements.

- Top decays through FCNC are enhanced in many models beyond the SM.

- The enhancement mechanism depends on the model. It can be done via weaker GIM cancellation by new particles in loop corrections.

### SM Predictions

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>2HDM (FV)</th>
<th>MSSM</th>
<th>ED: RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Br(t \rightarrow c\gamma))</td>
<td>(\mathcal{O}(10^{-11}))</td>
<td>(\mathcal{O}(10^{-13}))</td>
<td></td>
</tr>
<tr>
<td>(Br(t \rightarrow cZ))</td>
<td>(\mathcal{O}(10^{-13}))</td>
<td>(\mathcal{O}(10^{-13}))</td>
<td></td>
</tr>
<tr>
<td>(Br(t \rightarrow cg))</td>
<td>(\leq 10^{-7})</td>
<td>(\leq 10^{-8})</td>
<td>(\leq 10^{-9})</td>
</tr>
<tr>
<td>(Br(t \rightarrow Z+c))</td>
<td>(\leq 10^{-6})</td>
<td>(\leq 10^{-6})</td>
<td>(\leq 10^{-5})</td>
</tr>
<tr>
<td>(Br(t \rightarrow g+c))</td>
<td>(\leq 10^{-4})</td>
<td>(\leq 10^{-7})</td>
<td>(\leq 10^{-10})</td>
</tr>
</tbody>
</table>


arXiv:1311.2028
The anomalous FCNC couplings of a top quark with a photon and Z boson can be written in a model independent way using an effective Lagrangian approach.

\[ \mathcal{L}_{\text{eff}} = \sum_{q=u,c} \left[ e \lambda_{tq} \bar{t}(\lambda^\nu - \lambda^a \gamma^5) \frac{i\sigma_{\mu\nu} q^\nu}{m_t} q A^\mu \\
+ \frac{g_W}{2c_W} \kappa_{tq} \bar{t}(\kappa^\nu - \kappa^a \gamma^5) \frac{i\sigma_{\mu\nu} q^\nu}{m_t} q Z^\mu \nu \\
+ \frac{g_W}{2c_W} X_{tq} \bar{t} \gamma_\mu (x^L P_L + x^R P_R) q Z^\mu \right] + \text{h.c.} , \]

The anomalous FCNC interactions tqγ and tqZ lead to production of a top quark in association with a light quark in electron-positron collisions @ center-of-mass energies of 240 and 350 GeV.

There are two analyses

- semi-leptonic top decay: \( t \rightarrow Wb \rightarrow l+\nu+b \) with \( l = e, \mu \).

- full hadronic top decay: \( t \rightarrow Wb \rightarrow j+j+bjet \)
In order to perform the simulation, the following tools/methods have been used:

- The FCNC eff. Lagrangian prepared and implemented into the MadGraph5_aMC@NLO using the FeynRules package.

- PYTHIA has been used for showering and hadronization.

- Detector simulation is performed based on an ILD inspired detector using Delphes.

- Jets are reconstructed using the anti-$k_t$ algorithm for the semi-leptonic analysis and Iterative Cone algorithm for the full-hadronic channel.

In the semi-leptonic analysis the background processes are:

- $e^++e^-\rightarrow Wjj\rightarrow lvjj$ (the main background)
- $e^++e^-\rightarrow t+t\bar{t}\rightarrow lvjjjj$ (center-of-mass energy above $t\bar{t}$ threshold)
- $e^++e^-\rightarrow Zll\rightarrow jll$

In the full hadronic analysis the backgrounds are:

- $e^++e^-\rightarrow Wjj\rightarrow jjjj$
- there are other 4-jets backgrounds, negligible …
Reconstructed Top quark mass distribution for the semi-leptonic and full hadronic channels
**Exclusion limits at 95% CL**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>240, 100 fb$^{-1}$</th>
<th>240, 10 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full hadronic channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{Br}(t\to q\gamma)$</td>
<td></td>
<td>1.43x10$^{-4}$</td>
<td>3.17x10$^{-5}$</td>
</tr>
<tr>
<td>$\text{Br}(t\to qZ)(\sigma_{\mu\nu})$</td>
<td></td>
<td>1.86x10$^{-4}$</td>
<td>4.12x10$^{-5}$</td>
</tr>
<tr>
<td>$\text{Br}(t\to qZ)(\gamma_{\mu})$</td>
<td></td>
<td>3.78x10$^{-4}$</td>
<td>8.22x10$^{-5}$</td>
</tr>
<tr>
<td><strong>Semi-leptonic channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{Br}(t\to q\gamma)$</td>
<td></td>
<td>2.01x10$^{-5}$</td>
<td>9.86x10$^{-6}$</td>
</tr>
<tr>
<td>$\text{Br}(t\to qZ)(\sigma_{\mu\nu})$</td>
<td></td>
<td>2.44x10$^{-5}$</td>
<td>1.41x10$^{-5}$</td>
</tr>
<tr>
<td>$\text{Br}(t\to qZ)(\gamma_{\mu})$</td>
<td></td>
<td>5.02x10$^{-5}$</td>
<td>5.27x10$^{-5}$</td>
</tr>
</tbody>
</table>

S.Biswa, F.Margaroli, B. Mele; More details can be found in talk by B. Mele: http://indico.cern.ch/event/438866/session/10/contribution/254/attachments/1256224/1854541/FCCW_Mele.pdf

Comparison with the LHC experiments

All are preliminary results $\Rightarrow$ efforts are going to be done for combination and optimization.
Summary & Conclusions

- Precise measurement in top quark physics sector is a promising way to search for physics beyond the SM.

- Due to very high luminosity and run at different center-of-mass energies, FCC-ee provides an excellent chance for very precise measurement of the top quark properties and achieve a high sensitivity to physics BSM.

- The top quark mass with a statistical accuracy of order of 10 MeV and a total uncertainty of $\Delta m_t \leq 100$ MeV can be extracted from the threshold scan.

- Width, CKM matrix element $V_{tb}$, and $y_t$ can be measured with a very good accuracy at the FCC-ee.

- The top EW couplings of $ttZ$ and $tt\gamma$ couplings can be measured to $< 1\%$.

- The rare FCNC top quark decays are accessible at FCC-ee down to the order of $10^{-5,6}$, where the indirect new physics can show up.

- Detailed studies to assess the nominal center of mass energy, statistics and running conditions for the complete Top Physics program is in progress.

FCC-ee top quark working group: http://tlep.web.cern.ch/content/wg4-exp

Acknowledgement: Many thanks to FCC-ee top-quark conveners and to the conference organizers
Backup slides
Top Mass from Reconstruction

-Above threshold: $m_t$ from invariant mass of decay products.

-The current world average, based on standard reconstruction methods, has an uncertainty $\approx 700$ MeV, with a recent CMS measurement yielding $\approx 500$ MeV.

-suffers from being correlated with the real pole mass which brings significant theoretical uncertainties.

-Alternatives methods such as $t\bar{t}$ cross section, $m_{lb}$, endpoint, $J/\psi (m_{3\ell})$, b-jet energy, leptonic observables, would reach a better uncertainty.

At CLIC, for $\sqrt{s} = 500$ GeV and $L = 100$ fb$^{-1}$:

Using PYTHIA for signal and backgrounds $e^+e^- \rightarrow WW/ZZ$; and WHIZARD for other backgrounds.

An uncertainty of 80 MeV in a combined channel is reachable.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$m_{\text{top}}$</th>
<th>$\Delta m_{\text{top}}$</th>
<th>$\Gamma_{\text{top}}$</th>
<th>$\Delta \Gamma_{\text{top}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>fully-hadronic</td>
<td>174.049</td>
<td>0.099</td>
<td>1.47</td>
<td>0.27</td>
</tr>
<tr>
<td>semi-leptonic</td>
<td>174.293</td>
<td>0.137</td>
<td>1.70</td>
<td>0.40</td>
</tr>
<tr>
<td>combined</td>
<td>174.133</td>
<td>0.080</td>
<td>1.55</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Top mass theory

Pole mass is not adequate; 1S and potential-subtracted are suitable threshold masses

\[ m_{1S} = \frac{1}{2} \{ m [\Upsilon(1S)_{tt}] \} \; ; \; m_{PS}(\mu_F) = m_{\text{pole}} - \frac{1}{2} \int_{|q|<\mu_F} \frac{d^3q}{(2\pi)^3} \tilde{V}(q) \]

Relating 1S and PS masses to \( \overline{\text{MS}} \) mass:

4-loop impact: 44 MeV (PS), 8 MeV (1S)

Overall uncertainty on \( \overline{\text{MS}} \) mass conversion:

23 MeV (PS); 7 MeV (1S)
LHC projections for the top quark mass

Perspectives on top mass measurement at the LHC (Snowmass, EPJ’14, to be updated)

Conventional methods:

$$\Delta m_t \simeq 600-700 \text{ MeV} \ (0.3-0.4\%)$$

<table>
<thead>
<tr>
<th>CM Energy</th>
<th>Sites</th>
<th>Projections</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td></td>
<td>14 TeV</td>
</tr>
<tr>
<td>167 pb</td>
<td>951 fb</td>
<td></td>
</tr>
<tr>
<td>5 fb$^{-1}$</td>
<td>100 fb$^{-1}$</td>
<td>300 fb$^{-1}$</td>
</tr>
<tr>
<td>Pileup</td>
<td>9.3</td>
<td>19</td>
</tr>
<tr>
<td>Syst. (GeV)</td>
<td>0.95</td>
<td>0.7</td>
</tr>
<tr>
<td>Stat. (GeV)</td>
<td>0.43</td>
<td>0.04</td>
</tr>
<tr>
<td>Total</td>
<td>1.04</td>
<td>0.7</td>
</tr>
<tr>
<td>Total (%)</td>
<td>0.6</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Endpoint method:

$$\Delta m_t \simeq 500-1000 \text{ MeV} \ (0.3-0.6\%)$$

$J/\psi$ method ($m_{J/\psi \ell}$ or $m_{3\ell}$)

$$\Delta m_t \simeq 600-2300 \text{ MeV} \ (0.4-1.3\%)$$

<table>
<thead>
<tr>
<th>CM Energy</th>
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<tbody>
<tr>
<td>7 TeV</td>
<td></td>
<td>14 TeV</td>
</tr>
<tr>
<td>167 pb</td>
<td>951 fb</td>
<td></td>
</tr>
<tr>
<td>5 fb$^{-1}$</td>
<td>100 fb$^{-1}$</td>
<td>300 fb$^{-1}$</td>
</tr>
<tr>
<td>Syst. (GeV)</td>
<td>1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Stat. (GeV)</td>
<td>0.90</td>
<td>0.10</td>
</tr>
<tr>
<td>Total</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Total (%)</td>
<td>1.2</td>
<td>0.6</td>
</tr>
</tbody>
</table>

$J/\psi$ method ($m_{J/\psi \ell}$ or $m_{3\ell}$)

$$\Delta m_t \simeq 600-2300 \text{ MeV} \ (0.4-1.3\%)$$

<table>
<thead>
<tr>
<th>CM Energy</th>
<th>Sites</th>
<th>Projections</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td></td>
<td>14 TeV</td>
</tr>
<tr>
<td>240 pb</td>
<td>951 pb</td>
<td>5522 pb</td>
</tr>
<tr>
<td>20 fb$^{-1}$</td>
<td>100 fb$^{-1}$</td>
<td>300 fb$^{-1}$</td>
</tr>
<tr>
<td>Theory (GeV)</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td>Stat. (GeV)</td>
<td>7.00</td>
<td>1.8</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>2.3</td>
</tr>
<tr>
<td>Total (%)</td>
<td>-</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Other method for top mass

There are other methods proposed in ILC studies to extract the top quark mass:


- simultaneous fit of observables ($\sigma t_t$, $A_{FB}$ and $p_{@max}$) sensitive to $m_{top}$, $\Gamma_{top}$ and $\lambda_{top}$

- Results simply scaled to the FCCee case (no beamstrahlung bkg and higher luminosity)

<table>
<thead>
<tr>
<th>Lumi / 5 years</th>
<th># top pairs</th>
<th>$\Delta m_{top}$</th>
<th>$\Delta \Gamma_{top}$</th>
<th>$\Delta \lambda_{top}/\lambda_{top}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLEP 4x800 fb$^{-1}$</td>
<td>$\sim$ 1,000,000</td>
<td>10 MeV</td>
<td>12 MeV</td>
<td>13%</td>
</tr>
<tr>
<td>ILC 350 fb$^{-1}$</td>
<td>100,000</td>
<td>30 MeV</td>
<td>35 MeV</td>
<td>40%</td>
</tr>
</tbody>
</table>
Top EW couplings: full simulation study

Simulation characteristics:

- Samples generated using WHIZARD v57, at the center-of-mass energy of 365 GeV with no polarization for the beams.
- Marlin particle flow reconstruction algorithm
- Similar performance of the FCC-ee detector to CLIC/ILD detector is assumed.

- Background processes: & their cross sections:

  - $\bar{b}qq' b\nu$  \( \sigma = 290.5 \text{fb} \)
  - $qq' l\nu_l$  \( \sigma = 6400 \text{fb} \)
  - $qq' l\bar{l}$  \( \sigma = 1900 \text{fb} \)
  - $qqqq$  \( \sigma = 5900 \text{fb} \)
  - $qq\nu\nu$  \( \sigma = 365 \text{fb} \)
  - $HZ$  \( \sigma = 110 \text{fb} \)
Top EW couplings: Background rejection

- max b-tag > 0.85 → rejecting events with a similar signature without b-jet, like qqlν final state
- Hadronic Mass in range 130 GeV ÷ 300 GeV → rejecting events with ZZ and WW → four jets.
- Missing Energy in range 20 GeV ÷ 140 GeV → rejecting events with Z → invisible in the final state
- Top and W mass constraint: \( \chi^2 < 15 \) → Rejecting the events with a similar signature to the signal, from ZZ, WW and HZ decays
Top EW couplings: Signal and background distributions after cuts

**Reduced Energy distribution after cuts (muons)**

- **Number of events / 0.04**
  - **0**: 10^4
  - **1**: 10^3
  - **0.1**: 10^2
  - **1**: 10

  **Reduced Energy**
  - 0.1 to 0.2
  - 0.2 to 0.3
  - 0.3 to 0.4
  - 0.4 to 0.5
  - 0.5 to 0.6
  - 0.6 to 0.7
  - 0.7 to 0.8
  - 0.8 to 0.9
  - 0.9 to 1

- **Red**: background
- **Light Blue**: signal

**Angular distribution after cuts (muons)**

- **Number of events / 0.08**
  - **0**: 10^4
  - **1**: 10^3
  - **0.1**: 10^2
  - **1**: 10

  **Cosθ**
  - -1 to -0.8
  - -0.8 to -0.6
  - -0.6 to -0.4
  - -0.4 to -0.2
  - -0.2 to 0
  - 0 to 0.2
  - 0.2 to 0.4
  - 0.4 to 0.6
  - 0.6 to 0.8
  - 0.8 to 1

- **Red**: background
- **Light Blue**: signal

**Results:**

<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Muons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Efficiency</strong></td>
<td>48%</td>
<td>56%</td>
</tr>
<tr>
<td><strong>Purity</strong></td>
<td>99%</td>
<td>99%</td>
</tr>
</tbody>
</table>

**efficiency** = \( \frac{\text{signal selected}}{\text{signal generated}} \)

**purity** = \( \frac{\text{signal selected}}{\text{selected events}} \)

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