Top/QCD at the Linear Collider: Experimental Aspects

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Loopfest
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Outline

• Top Quark Physics
  – Measurements at threshold
  – Measurements above threshold

• QCD
  – Precision measurement of $\alpha_s$
  – $Q^2$ evolution
## Machine Parameters

<table>
<thead>
<tr>
<th></th>
<th>TESLA(500)</th>
<th>TESLA(800)</th>
<th>NLC(500)</th>
<th>NLC(1000)</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E (GeV)</strong></td>
<td>500</td>
<td>800</td>
<td>500</td>
<td>1000</td>
<td>2000</td>
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<tr>
<td><strong>Lum. x 1E33</strong></td>
<td>31</td>
<td>5</td>
<td>20</td>
<td>34</td>
<td>0.1</td>
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<tr>
<td><strong>Rep rate (Hz)</strong></td>
<td>5</td>
<td>3</td>
<td>120</td>
<td>120</td>
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<tr>
<td><strong>Bunches/pulse</strong></td>
<td>2820</td>
<td>4500</td>
<td>190</td>
<td>190</td>
<td>—</td>
</tr>
<tr>
<td><strong>Bunch sep (ns)</strong></td>
<td>337</td>
<td>189</td>
<td>1.4</td>
<td>1.4</td>
<td>396</td>
</tr>
<tr>
<td><strong>σ(x) at i.p.</strong></td>
<td>553 nm</td>
<td>391 nm</td>
<td>245 nm</td>
<td>190 nm</td>
<td>30 μm</td>
</tr>
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<td><strong>σ(y) at i.p.</strong></td>
<td>5 nm</td>
<td>2 nm</td>
<td>2.7 nm</td>
<td>2.1</td>
<td>30 μm</td>
</tr>
<tr>
<td><strong>σ(z) at i.p.</strong></td>
<td>0.4 mm</td>
<td>0.3 mm</td>
<td>110 nm</td>
<td>110 nm</td>
<td>30 cm</td>
</tr>
<tr>
<td><strong>δB(%)</strong></td>
<td>3.3</td>
<td>4.7</td>
<td>4.7</td>
<td>10.2</td>
<td>0</td>
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<tr>
<td><strong>P(e−) (%)</strong></td>
<td>80–90</td>
<td>80–90</td>
<td>80–90</td>
<td>80–90</td>
<td>—</td>
</tr>
<tr>
<td><strong>P(e+) (%)</strong></td>
<td>60</td>
<td>60</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Top Production at the LC

- $\sigma_{tt} \approx 0.6$ pb at $\sqrt{s} = 500$ GeV

- $\Rightarrow$ 200,000 $tt$ pairs / year at TESLA design luminosity.

- Why "do top"?
  - $\Gamma_t \sim 1.3$ GeV $>> \Lambda_{QCD}$, so top decays before hadronization: Unique opportunity to observe the weak interactions of a bare quark.
  - $m_t, \Gamma_t, g_{tth}$ etc. are precision EWK parameters.
  - Possible role in EWSB dynamics
Top Quark Threshold

Large top width provides IR cutoff, so can use pQCD to compute threshold cross section. Convergence is sensitive to mass definition used: pole and kinematic masses not IR-safe.

Best results come from using the 1S mass definition ($\frac{1}{2}$ the mass of the lowest $tt$ bound state, evaluated in the limit $\Gamma_t \to 0$) combined with a velocity resummation.

Also, reduces previous large correlation between $m_t$ and $\alpha_s$. 

Hoang, Manohar, Stewart, Teubner, hep-ph/0107144
Machine Effects on Top Threshold Lineshape

Note: can reduce beamstrahlung at cost of luminosity: optimization issue for experimentalists.
Threshold Measurements

Recent analysis by R. Miquel, M. Martinez (Chicago LCWS ’02):

- Assume 300 fb$^{-1}$ and 9 scan points plus one well below threshold for background determination.
- Use the cross section and, in addition, the observables $A_{FB}$ and $P_{peak}$.
Threshold Results

• **Mass:** $\Delta m_t = 16$ MeV, $\Delta \alpha_S = 0.0011$
  
  – Using cross section only: $\Delta m_t = 24$ MeV, $\Delta \alpha_S = 0.0017$.
  
  – $\Gamma_t, g_{tth}$ fixed at SM values; assume $m_h = 120$ GeV, $\alpha_s(M_Z) = 0.120$.
  
  – Theory error: $\sim 100$ MeV.

• **Width:** allow to vary in a 3–parameter fit.
  
  – $\Delta \Gamma_t = 32$ MeV, $\Delta m_t = 18$ MeV, $\Delta \alpha_S = 0.0015$
  
  – 2% exp. uncertainty on width
Top–Higgs Yukawa Coupling at Threshold

- Small effect in all observables, diminishes rapidly for $m_h > 120$ GeV
- If all other parameters fixed (best–case scenario), find $\Delta g_{\text{th}}/g_{\text{th}} = +17\%–24\%
- Fit $m_t$, $\Gamma_t$, $g_{\text{th}}$ simultaneously with 0.001 constraint on $\alpha_s$:
  $\Delta g_{\text{th}}/g_{\text{th}} = +33\%–57\%$
  (with correlations up to 85%) Also $\Delta m_t = 30$ MeV, $\Delta \Gamma_t = 33$ MeV.
- $\Rightarrow$This measurement looks hard.
Loopfest Wish List for Top Threshold

- Measurements may be dominated by theory systematics.
- Much progress in recent years on threshold cross section. How much more can calculation be improved? Better quantification of systematics?
- Improved calculations of other threshold observables (NLL calculations currently used for $A_{FB}$, $P_{peak}$, e.g.)
ttH production and the Top Yukawa Coupling

- $e^+e^- \rightarrow ttH \rightarrow WbWb \; bb$

- Very complicated final state:
  - Up to 8 jets
  - 4 b's
  - Many kinematic constraints

- Tiny cross section (~2 fb), with backgrounds ~3 orders of magnitude higher.

- Interfering backgrounds from EWK (ttZ), QCD ($g \rightarrow bb$)

- Non-interfering backgrounds
  - Dominantly $e^+e^- \rightarrow tt$
  - Formally smaller number of partons, but can enter the selection due to hard gluon radiation, detector effects, and their very large cross sections
ttH Analysis Strategy (Juste, Merino)

- **Lots of luminosity**: 1 ab\(^{-1}\) at 500 GeV

- **Loose preselection on semileptonic final states (9 event variables)**
  - Retains \(\sim 45\%\) of signal while reducing bkgds by 2–3 orders of magnitude.
  - Still have only \(\sim 36\) signal events, \(\sim 3800\) bkgd events, about half of which are tt.

- **Then apply multivariate analysis to remaining events. Neural net that uses the 9 preselection variables plus 14 more.**
ttH Preselection
ttH Sensitivity

- For the semileptonic channel, $L=1 \text{ ab}^{-1}$, $m_H=120$, find

$$\left( \frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} \right)_{\text{stat}} \approx 0.33$$

- Only $N \approx 11$ signal events, $\sim 54$ background events survive.

- Assuming $\sqrt{2}$ improvement from fully hadronic channel,

$$\left( \frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}} \right)_{\text{stat}} \approx 0.23$$

- NB: $K$–factors not used for signal or bkgd processes. Know $K \approx 1.5$ for $t\bar{t}H @ 500$ GeV (Dawson and Reina; Dittmaier et al.); would improve sensitivity by 22%. $K$–factors for backgrounds?

- Factor of 3–4 improvement at $\sqrt{s} = 800$ GeV.
Top Production/Decay Form Factors

General neutral–current couplings:

\[ \Gamma_{t\bar{t}Y,Z}^\mu = ie \left\{ \gamma^\mu \left[ F_{1V}^{Y,Z} + F_{1A}^{Y,Z} \gamma^5 \right] + \frac{i \sigma^{\mu\nu} q_\nu}{2m_t} \left[ F_{2V}^{Y,Z} + F_{2A}^{Y,Z} \gamma^5 \right] \right\} \]

SM: only \( F_{1V}^{Y}, F_{1V}^{Z}, F_{1A}^{Z} \) are nonzero.

\( F_{2V} \Rightarrow \) weak magnetic dipole moment \((\neq 0\) in some strong EWSB models)  
\( F_{2A} \Rightarrow \) weak electric dipole moment, violates CP. \((\neq 0\) in some SUSY models)

General charged–current couplings:

\[ \Gamma_{tbW}^\mu = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^\mu \left[ F_{1L}^L P_L + F_{1R}^L P_R \right] + \frac{i \sigma^{\mu\nu} q_\nu}{2m_t} \left[ F_{2L}^L P_L + F_{2R}^L P_R \right] \right\} \]

SM: only \( F_{1L}^1 \) is nonzero.
Information about the form factors is encoded in the helicity angles:

- Charge of lepton tags $t$ or $\bar{t}$
- Can also use charge of $b$–tagged jet ($\varepsilon$=57%, purity = 83%)
- Four–momentum of the leptonic $t$–quark from the opposite hadronically–decaying top.

Analysis strategy (M. Iwasaki, 2002): assume 100 fb$^{-1}$ at $\sqrt{s} = 500$ GeV

- Force 4–jet final state using JADE clustering algorithm ($\varepsilon = 60\%$)
- Cut on 2–jet invariant mass ($W$ identification) and 3–jet mass (top ID) (50%)
- $b$–tag using SLD–esque algorithm ZVTOP. (67%)
Reconstructed Helicity Angles and Results

Axial form factors from maximum likelihood analysis:

\[ F_{1A}^\gamma \approx 0.05 \]
\[ F_{1A}^Z \approx 0.01 \]
\[ F_{2A}^\gamma \approx 0.04 \]
\[ F_{2A}^Z \approx 0.01 \]

Vector form factors from L–R asymmetry (200 fb\(^{-1}\)):

- \( F_{1V}^\gamma \approx 0.05 \)
- \( F_{1V}^Z \approx 0.01 \)
- \( F_{2V}^\gamma \approx 0.04 \)
- \( F_{2V}^Z \approx 0.01 \)

68% C.L. sensitivities
Top Quark Strong Moments

- Top may play a role in new strong interactions, which can modify top couplings through higher-dimension operators.
- Simplest, CP-conserving form:
  \[ L = g_s t T_a \left( \gamma_\mu + \frac{i}{2m_t} \sigma_{\mu\nu}(\kappa - i\tilde{\kappa}\gamma_5)q^\nu \right) t G_\mu^a \]
  - \( \kappa, \tilde{\kappa} \) both zero in SM.

Affects energy spectrum and angular distribution of hard gluon radiation above threshold.

\[ \sqrt{s} = 1 \text{ TeV} \]

100 fb\(^{-1}\)

200 fb\(^{-1}\)
Precision Measurement of $\alpha_s$

• Why?
  – RG extrapolation of the gauge couplings constrains / tests physics at the GUT scale. Currently limited by ~few percent uncertainty on $\alpha_s$.
  – Measure $Q^2$–dependence over wide range to test QCD or reveal new physics.

• Main technique: event shape observables
  – E.g. thrust, sphericity, jet masses, jet rates...
  – Fit each observable to a pQCD prediction, allowing $\alpha_s$ to vary.
  – Statistical uncertainties currently ~0.001, experimental systematics at level of ~0.001–0.004.
Theory Uncertainty Dominates

Points: measured values with exp. errors

Gray bands: theory uncertainty

P. N. Burrows, hep-ex/9612008
Ratio Method (GigaZ)

- Measure inclusive ratios $\frac{\Gamma_Z^{\text{had}}}{\Gamma_Z^{\text{lept}}}$, $\frac{\Gamma_{\tau}^{\text{had}}}{\Gamma_{\tau}^{\text{lept}}}$, which depend on $\alpha_s$ through radiative corrections.

- LEP data (16M Z’s): $\Delta \alpha_s = \pm 2.5\% \text{ (stat.)} \pm 1\% \text{ (exp. syst.)}$

- GigaZ: $\Delta \alpha_s = \pm 0.4\% \text{ (stat.)}$

- Theory uncertainties controversial: 1–2%, maybe as high as 5%.

- If theory uncertainties clarified/improved, this could be a competitive $\sim 1\%$–level measurement.
\( \alpha_s \) Wish List

- **What we have:**
  - 5 partons at tree level
  - 4 partons at one loop
  - parts of 3 parton amplitudes at 2 loops
  - Ratio method calculated to NNLO

- **What we need for a 1\% measurement:**
  - Full NNLO calculation of jet rates!
  - For ratio method, need NNNLO calculation, as well as NLO(?) EWK corrections.
  - This is left as an exercise...
Q² Evolution of $\alpha_s$

• For the preceding measurements, we normalize to $\alpha_s(M_Z^2)$, using the QCD $\beta$–function to connect measurements at different scales.

• But want to test this running explicitly, since the $\beta$–function itself is an important prediction of QCD.

• Linear collider is well–suited to high–precision measurements under similar experimental conditions over a large lever arm in Q².
Measurement of $Q^2$ Evolution

- LC at $\sqrt{s}=91, 500, 1000$ GeV
- Use jet rates/shapes at all energies, and ratio technique at Z pole.
- Assume 1% theory uncertainty.

Resulting improvement in extrapolation to GUT scale with 1% measurement:
Conclusions

• Top and QCD illustrate many of the challenges and rewards of the LC physics program.

• At the same time, they only scratch the surface of the physics we hope to do there!

• We need calculations and theories worthy of the machine and detectors we are going to build.

• For the LC physics program to reach its potential, your help is essential!