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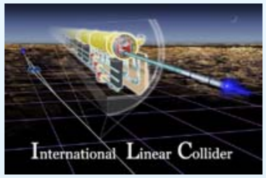
Top Precision Physics at the ILC

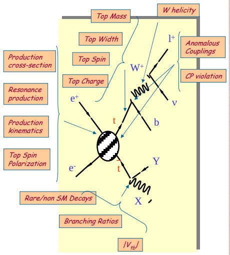


One of the most urgent problems in HEP is to identify the mechanism of Electroweak Symmetry Breaking (EWSB) and mass generation, in which the top quark may play a special role. The future International e^+e^- Linear Collider (ILC) shows the promise of fully outlining the top quark profile with unprecedented precision, which should prove crucial to point to the relevant energy scales and to possible extensions of the Standard Model (SM).

Motivation

The Tevatron/LHC will provide first incisive tests of SM top physics. The LHC has a large potential for discovery of New Physics effects: e.g. heavy tt resonances, rare decays, etc. High precision measurements in the top sector will be needed to provide hints on the correct underlying theory.

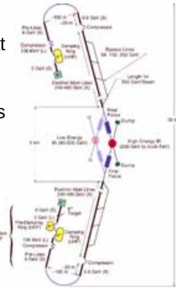
Experimentation at e^+e^- colliders has a number of features that make them particularly well suited for this task: well defined initial state, precise theoretical calculations, low backgrounds and excellent experimental accuracy.



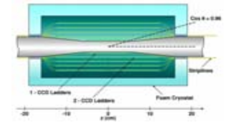
Baseline Machine and Detector

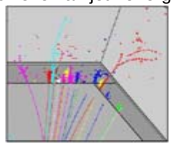
Baseline Machine

- $(\sqrt{s})_{max}$= 500 GeV but can operate at any $\sqrt{s}$ in the range 200-500 GeV
- 500 fb^{-1} in first 4 years of running
- Possibility of energy scans at any $\sqrt{s}$ in whole energy range
- Possibility to go down to the Z peak for calibration
- Beam energy precision < 0.1%
- $P(e^-)\geq 80\%$ in whole energy range
- 2 interaction regions

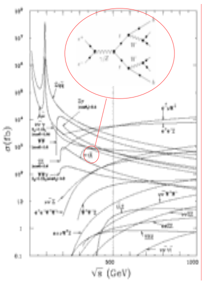


A high resolution detector is being designed, based on the experience from LEP/SLD and R&D for the LHC. It features excellent vertexing (5 layer pixel detector with 3 μm point resolution) and tracking ($\Delta(1/p_T)\leq 5\times10^{-5}$ GeV^{-1}). Combined with a highly granular and hermetic calorimeter, a particle flow algorithm could possibly achieve a jet energy resolution of ~30%/$\sqrt{E}$.



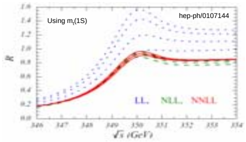


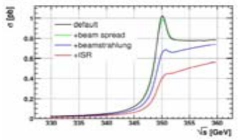
Top Quark Production in e^+e^- Collisions



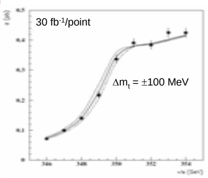
In an e^+e^- collider, top quarks are dominantly produced in pairs via the electroweak interaction (γ/Z exchange). At $\sqrt{s}$=500 GeV, the top quark pair production cross section is ~0.6 pb. Assuming the baseline instantaneous luminosity of 2×10^{34} $cm^{-2}s^{-1}$ this translates into ~120k events per year. The relatively low cross sections of the main backgrounds ($Z/\gamma^*\to qq$ and W^+W^-), together with the distinct signature of tt events, allow to effectively perform top quark measurements in an almost background free environment.

Near threshold ($\sqrt{s}$~350 GeV), top quarks are produced essentially at rest and interact with each other via Coulombic gluon exchange. The large top quark width (Γ_t~1.5 GeV) makes the top quark decay before hadronization effects or toponium bound states have time to develop. The remnants of the S-wave toponium resonances induce a fast rise of σ_{tt} near threshold, which is very sensitive to m_t, Γ_t and α_s. Other threshold observables, such as the top p_T spectrum or A_{FB} are mostly sensitive to Γ_t and α_s. The existence of very precise theoretical predictions (via the use of special threshold mass definitions, e.g. 1S mass, and velocity resummation techniques) opens the possibility of unprecedented accuracy in the measurement of m_t, Γ_t and α_s. The tt lineshape is severely distorted by Bremsstrahlung and Beamstrahlung (beam-beam) effects, which must be precisely estimated.



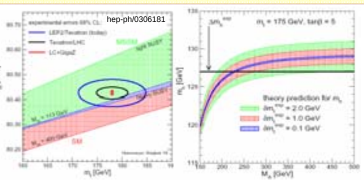


m_t and Γ_t from a Threshold Scan



The strategy is to perform a scan in $\sqrt{s}$ around the threshold region and compare measurement of various observables to theoretical predictions as a function of m_t, Γ_t and α_s. For a 10 point scan with 30 fb^{-1}/point, assuming $(\Delta\sigma_{tt}/\sigma_{tt})_{theo}$~3% and considering all three threshold observables (σ_{tt}, peak of top p_T spectrum and A_{FB}), the following experimental precision can be achieved: Δm_t(1S)=19 MeV, $\Delta\alpha_s$=0.0012, $\Delta\Gamma_t$=32 MeV.

Since the relationship between the 1S mass and the more standard $\overline{MS}$ mass is very well known theoretically, an ultimate uncertainty on m_t of ≤ 100 MeV appears feasible. It is important to point out that such precision is only possible because this measurement, in contrast with direct reconstruction techniques at hadron colliders, is based on a color-singlet system.

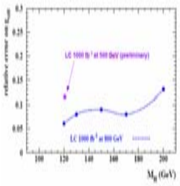


The top quark mass is a crucial ingredient for EW precision analyses at the quantum level. A measurement of m_t to ≤100 MeV will be needed to fully exploit the LHC and ILC precision on Higgs measurements.

Top-Higgs Yukawa Coupling

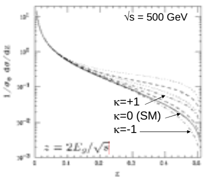
The top-Higgs Yukawa coupling is the largest coupling of the Higgs boson to fermions (g_{ttH} ~ 0.7 vs g_{bbH} ~ 0.02). Its precise measurement is very important since it may provide clues on the EWSB dynamics.

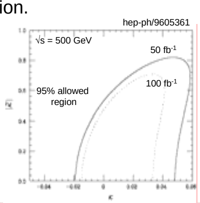
It can be determined via the cross section measurement for ttH. The low σ_{ttH} (e.g. ~2.5 fb at $\sqrt{s}$=800 GeV for m_H=120 GeV) and huge backgrounds require high luminosity. The signature is spectacular, with 8 jets or one lepton and 6 or 8 jets.



Top-Gluon Coupling

The g-t-t coupling can be affected by strong dipole moments related to New Physics: the chromo-magnetic dipole moment (κ) is CP-conserving whereas the chromo-electric dipole moment ($\tilde{\kappa}$) is CP-violating. The main observable is the energy spectrum of extra jets radiated off either top quark in top quark pair production.

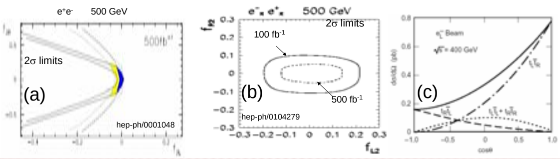




Top Couplings to Weak Gauge Bosons (W,Z,γ)

Since the W and Z bosons acquire mass as a result of the EWSB mechanism, in which the top quark could possibly play a key role, the precise measurement of top quark interactions to weak gauge bosons is extremely interesting. The use of polarized beams is an extremely powerful tool for this task.

Within the SM, the W-t-b interaction is of the V-A type. The Tevatron/LHC will have probed a V+A interaction to the percent level. The ILC can in addition explore tensor-like couplings to the 5-10% level via the measurement of asymmetries in top quark pair production (Fig. a) or the single top quark production rate (Fig. b).



The $e^+e^-\to Z/\gamma^*\to tt$ process is very sensitive to Z/γ-t-t couplings. In order to disentangle the effect of different couplings and to increase the sensitivity, the use of beam polarization is crucial. Both, inclusive polarization observables (e.g. A_{LR}, $\sigma(e^-_{L/R}e^+\to tt)$) and differential distributions (Fig. c) can be used. Typical precision reaches the percent level (see Table).

Tesla TDR

Form factor	SM value	$\sqrt{s}$ = 500 GeV	
L=300 fb^{-1}		$p=0$	$p=-0.8$
F^Z_{1V}	1		0.019
F^Z_{1A}	1		0.016
$F^{\gamma,Z}_{2V}=(g-2)^{\gamma,Z}_t$	0	0.015	0.011
$\mathrm{Re}\,F^{\gamma}_{2A}$	0	0.035	0.007
$\mathrm{Re}\,d^{\gamma}_t$ $[10^{-19}$ e cm$]$	0	20	4
$\mathrm{Re}\,F^Z_{2A}$	0	0.012	0.008
$\mathrm{Re}\,d^Z_t$ $[10^{-19}$ e cm$]$	0	7	5
$\mathrm{Im}\,F^{\gamma}_{2A}$	0	0.010	0.008
$\mathrm{Im}\,F^Z_{2A}$	0	0.055	0.010