Top quark physics and QCD

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Contents

- Top quark physics: Overview
- Progress since the TDR
- QCD
- Polarization issues
- Conclusions

Top quark physics: Overview

Unique features of the top quark and physics questions

- Heaviest fundamental particle observed: $m_t = 174.3 \pm 5.1$ GeV
  Top quark interactions are still relatively unknown.
- New interactions may reveal through non-standard top decays, e.g. into spartic-les , charged Higgs,. . .
- Top quark: good probe of electroweak symmetry breaking mechanism.
  Top Yukawa coupling as predicted by the SM?
- $\Gamma_t^{SM} \approx 1.5$ GeV $\gg \Lambda_{QCD}$: no hadronization effects.
- TESLA provides large number of $t\bar{t}$ pairs: $\sim$ 300 000 for $\int \mathcal{L} \sim 300$ fb^{-1}

Top quark: unique probe of fundamental interactions at very high energy scales

Top quark physics: Overview

Threshold scan: $v \sim \alpha_s \sim 0.1 \ll 1 \Rightarrow t\bar{t}$ system is non-relativistic, provides a testing ground for (NR)QCD. In particular, we hope to achieve:

- a determination of m_t with unmatched precision
- a precise measurement of the top width Γ_t
- a competitive measurement of α_s
- a constraint on the top Yukawa coupling λ_t

Analysing $e^+e^- \to t\bar{t} \to \ldots$ at threshold and **in the continuum** will allow for high-precision measurements of form factors like

- Z charges of the top (needs polarization of e^-)
- magnetic dipole moments $(g-2)_t^{\gamma,Z}$
- electric and weak dipole moments of the top (non-SM CP violation)
- non-standard tWb couplings (i.e. $(V+A)$) in top quark decays

Top quark physics: Overview

Why do we want to know m_t very precisely?

Example: Standard Model consistency check:

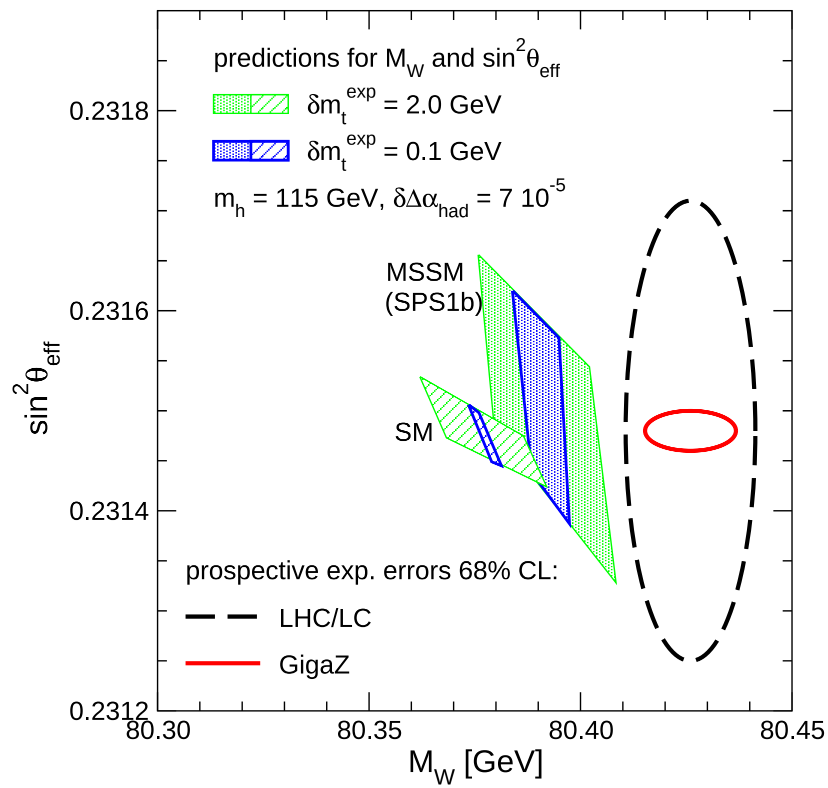


Fig. : S.Heinemeyer, S.Kraml, W.Porod, G.Weiglein [hep-ph/0304mmm]

Progress since the TDR

Threshold studies

Update of $t\bar{t}$ threshold scan simulation (M. Martinez, R. Miquel [hep-ph/0207315]). New features:

- Three observables: cross section, momentum distribution, forward-backward asymmetry.
- Multiparameter fit up to 4 parameters: m_t, α_s, Γ_t, λ_t.
- Inclusion of some systematic uncertainties

Question: What experimental accuracy may be finally achieved?
Input:

- $\int \mathcal{L} = 300\ \mathrm{fb}^{-1}$, equally distributed in 9+1 scan points
- Assume theoretical uncertainty $\Delta\sigma/\sigma = 3\%$ (see below).

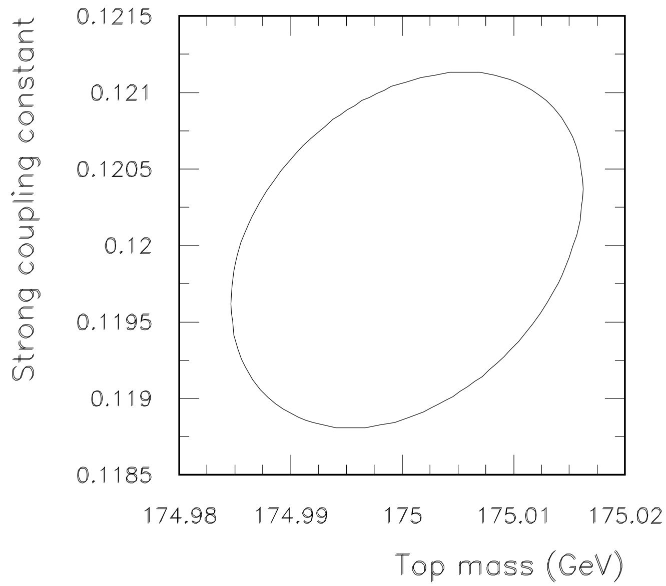
Progress since the TDR

Two-parameter fit $(m_t,\ \alpha_s)$:

- Most sensitivity on m_t in threshold position (using ‘1S’ mass definition)
- α_s mainly from cross section above threshold

Results:

$\Delta m_t^{1S} = 16\ \mathrm{MeV}, \qquad \Delta\alpha_s = 0.0012.$



Progress since the TDR

Size of **top width** Γ_t determines how pronounced 1S resonance is.

Three-parameter fit $(m_t,\ \alpha_s,\ \Gamma_t)$**:**

$$\Delta m_t^{1S} = 19\ \mathrm{MeV}, \qquad \Delta\alpha_s = 0.0012, \qquad \Delta\Gamma_t = 32\ \mathrm{MeV}.$$

Improvement on $\Delta\Gamma_t$ w.r.t. earlier studies factor $\sim$ 9. Due to:

- higher integrated luminosity
- better selection efficiency
- sharper beam spectrum
- better scanning strategy when using 1S mass.

Progress since the TDR

Sensitivity to **top Yukawa coupling** not very large. Assume 1% systematic errors (including theory errors).

Four-parameter fit $(m_t,\ \alpha_s,\ \Gamma_t,\ \lambda_t)$**;** $M_H = 120\ \mathrm{GeV}$**:**

$$\Delta m_t^{1S} = 31\ \mathrm{MeV}, \qquad \Delta\alpha_s = 0.001\ (\mathrm{constr.}), \qquad \Delta\Gamma_t = 34\ \mathrm{MeV}, \qquad \Delta\lambda_t/\lambda_t =^{+0.35}_{-0.65}\,.$$

$\Rightarrow$ Top-Yukawa coupling from threshold scan: challenging task!

Better method: $t\bar{t}H$ production (cf. talk by K. Desch).

Note: Theoretical uncertainties in relating the 1S mass to the $\overline{\mathrm{MS}}$ mass (which we want to know!) are presently $\sim$ 100-200 MeV.

Progress since the TDR

Theoretical developments

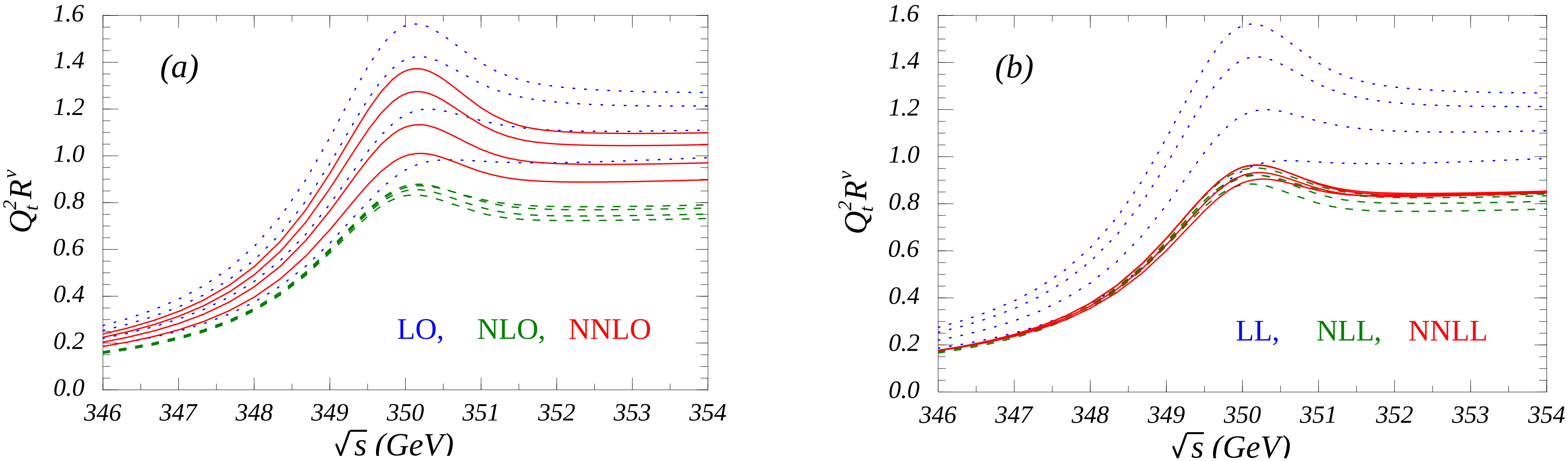
Status of spring 2001: Several groups calculated threshold cross section at NNLO. Corrections were found to be large. Pole mass: threshold location unstable, large correlation between m_t and α_s.

- Location of threshold is stabilized by using so-called threshold masses. Also m_t, α_s-correlation largely reduced.
- Height of the cross section suffers from large theoretical uncertainty $\sim 20-30\%$.

Recently:

- Hoang, Manohar, Stewart, Teubner performed a summation of QCD logarithms (almost complete) at NNLL. Theoretical error obtained from scale variation $\sim 3\%$.
- Progress towards calculating the threshold cross section at NNNLO has been achieved (Kniehl, Penin, Smirnov, Steinhauser).

Progress since the TDR



Figs. : Hoang, Manohar, Stewart, Teubner [hep-ph/0107144]

Progress since the TDR

Future work:

- Further scrutinizing theoretical uncertainties
- Inclusion of electroweak effects beyond leading order
- Improvement of predictions for momentum distribution and A_{FB}
- . . .

Top threshold studies have reached a very high level of sophistication. Further improvements are possible and under way.

Progress since the TDR

Continuum production and decay

Activity since spring 2001 (Theory):

- Electroweak corrections to $e^+e^- \longrightarrow t\bar{t}$: Calculations by several groups have been compared in detail, with very good numerical agreement. The package `topfit` is publicly available (`http://www-zeuthen.desy.de/∼riemann/`).
- New generators for $e^+e^- \longrightarrow$ 6 fermions: `eett6f` (Kolodziej) and `LUSIFER` (Dittmaier, Roth). These programs allow to study in particular the non-resonant background to $t\bar{t}$ production and decay.
- Single top production at $e^+e^-, e\gamma, \gamma\gamma$ (Boos, Dubinin, Pukhov, Sachwitz, Schreiber): High sensitivity on V_{tb} ($\sim$ 1%) and anomalous Wtb couplings in $e^+\gamma \longrightarrow t\bar{b}\bar{\nu}_e$. ($\Leftarrow$ very recently, QCD corrections have been computed (Kühn, Sturm, Uwer)).
- SUSY-QCD corrections to production and decay of polarized top quarks (A.B.,M. Maniatis): Leptonic decay width and lepton energy spectrum may be modified at the percent level. Only tiny impact on top polarization observables.

Progress since the TDR

Continuum production and decay: New simulations:

- Top mass measurement in the continuum (Chekanov, Morgunov [hep-ex/0301014]):

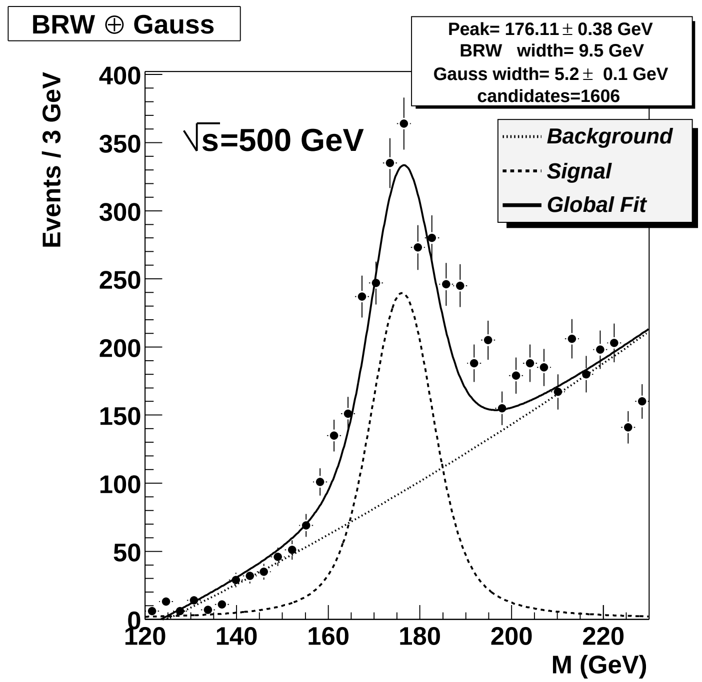
• Consider $e^+e^- \longrightarrow t\bar{t} \longrightarrow 6$ jets including QCD background.

• Use exclusive jet algorithm and energy-momentum conservation to group all particles into jets and reconstruct top quarks.

• Statistical uncertainty of peak position ('kinematical top mass'): 100 MeV for $\int \mathcal{L} = 300\ \mathrm{fb}^{-1}$.

• Experimental systematic errors not yet studied.

• News at this meeting: Also semileptonic top decays have been studied.



M : invariant mass of 3-jet clusters.

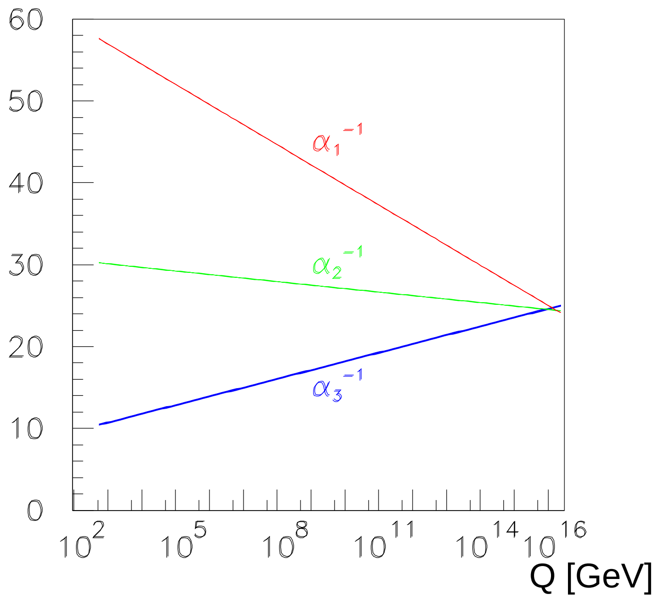
Primal goal:
Measure α_s as precisely as possible! Current accuracy: $\Delta\alpha_s(M_Z) \sim 0.003$.
Aim:

$$\boxed{\Delta\alpha_s(M_Z) \lesssim 0.001}$$

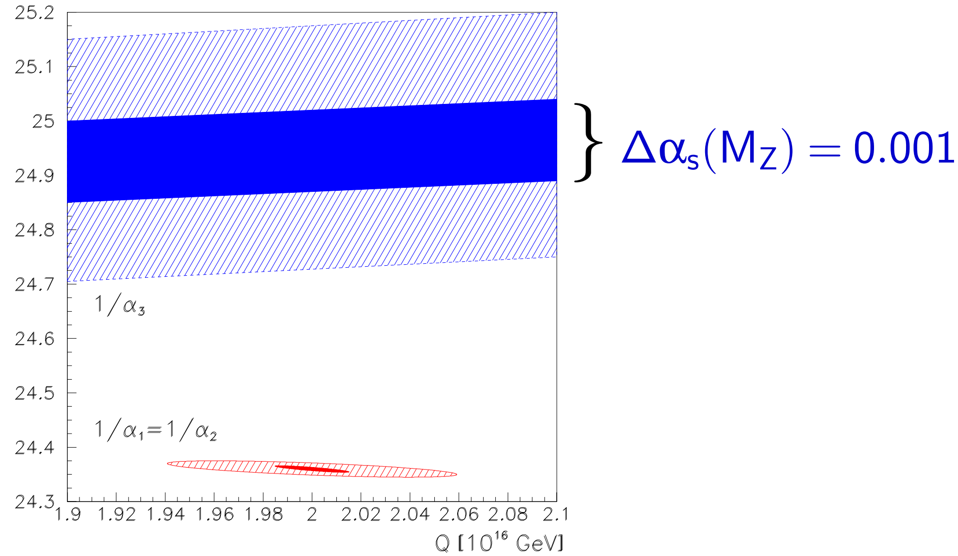
Why is such an accuracy of importance?

- **All** predictions of pQCD are directly affected, in particular multi-jet cross sections at higher orders.
- Extrapolating $\alpha_s(Q)$ to very high scales to test the hypothesis of **Grand Unification** needs precise initial conditions.

QCD



Running of inverse gauge couplings



Determination of unification point

Figure taken from Blair, Porod, Zerwas, hep-ph/0210058.

QCD

Recent developments

- Determination of α_s at Giga-Z (M. Winter, LC-PHSM-2001-016):
  Giga-Z versus LEP: ~ 100 times larger data sample, better detector performance $\Rightarrow$ experimental systematic errors may shrink by a factor 3-5. No theory errors included!

Variable	$R_l = \Gamma_h/\Gamma_l$	σ_0^l	σ_0^h	Γ_Z	combined
$\frac{\Delta\alpha_s(M_Z)}{0.001}$	0.6-0.8	0.9-1.4	2.7-4.4	~ 2	0.5-0.7

- Determination of α_s from event shapes:
  Bottleneck: Theoretical predictions currently available only to NLO $O(\alpha_s^2) \Rightarrow \Delta^{\text{theory}}\alpha_s(M_Z) = 0.005$. **Significant progress** in calculating $e^+e^- \to 3\,\text{jets}$ at NNLO within the last 2 years. Theory error estimated to shrink by factor 3-5 at NNLO.

Polarization issues

Polarization will be an asset for both top and QCD studies. Examples:

Non-standard t-decays

Polarization of both beams helps to determine, e.g., the handedness of the Yukawa coupling in $t \longrightarrow H^+b$. Sensitivity on FCN couplings $Z(\gamma)tq$ is increased.

Form factors

Sensitivity is increased, e.g.:

Form factor	SM value	$\sqrt{s}$ = 500 GeV		$\sqrt{s}$ = 800 GeV	
		$p = 0$	$p = -0.8$	$p = 0$	$p = -0.8$
$F_{2V}^{\gamma,Z} = (g-2)^{\gamma,Z}{}_t$	0	0.015	0.011	0.011	0.008
$\mathrm{Re}\, d_t^\gamma$ [10^{-19} e cm]	0	20	4	8	2

Background reduction

Example: $e^+e^- \longrightarrow$ jets. Background from $e^+e^- \longrightarrow W^+W^- \longrightarrow$ hadrons reduced for e^-_R, and further reduced by e^+_L.

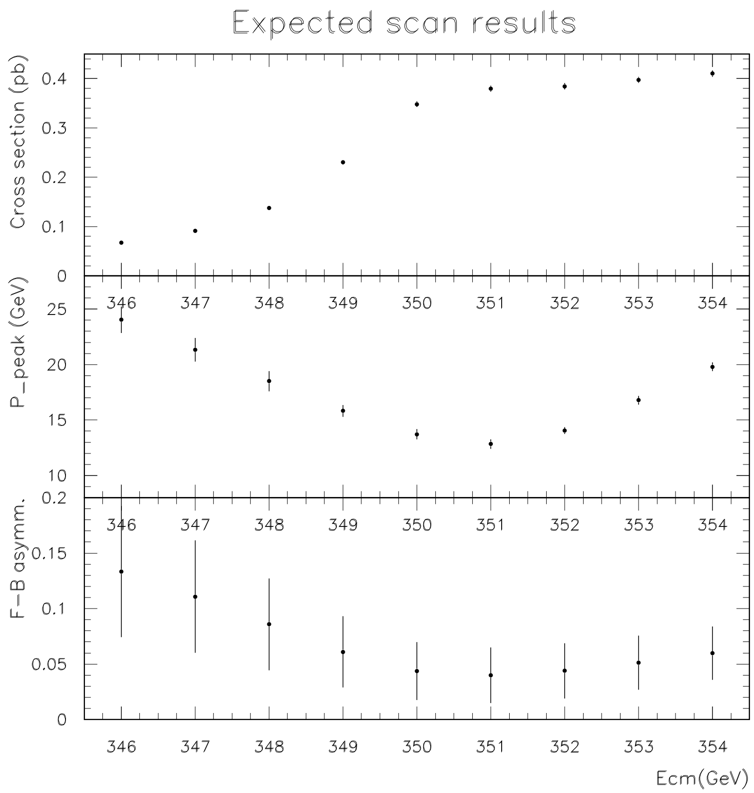
Conclusions

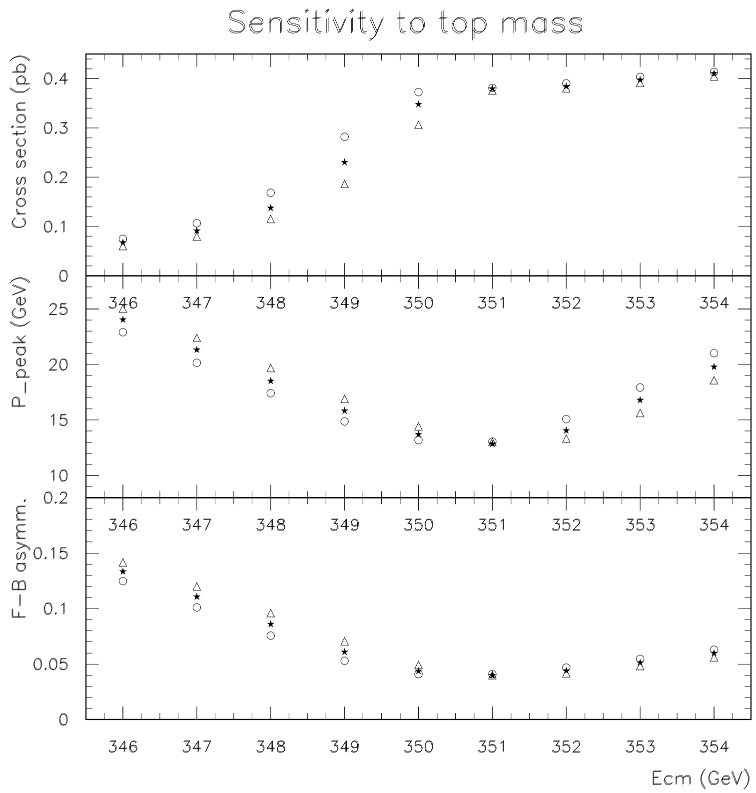
TESLA will be an excellent facility to study in detail the physics of top quarks and strong interaction phenomena.

Some tasks for the future

- Refine even further theoretical understanding of $t\bar{t}$ threshold cross section and relations between different top mass definitions.
- Include realistic $d\mathcal{L}/dE$ in threshold scan simulation.
- Perform simulations of top quark form factor determination at the detector level.
- Reduce theoretical error of event shape variables to achieve $\Delta\alpha_s = 0.001$.

Progress since the TDR





Figs. : M.Martinez, R.Miquel [hep-ph/0207315]

Markers : $\Delta m_t = 200$ MeV

Top quark physics: Overview

Form factor	SM value	$\sqrt{s}$ = 500 GeV		$\sqrt{s}$ = 800 GeV	
		p = 0	p = – 0.8	p = 0	p = – 0.8
F_{1V}^Z	1		0.019		
F_{1A}^Z	1		0.016		
$F_{2V}^{\gamma,Z} = (g-2)^{\gamma,Z}{}_t$	0	0.015	0.011	0.011	0.008
Re F_{2A}^{γ}	0	0.035	0.007	0.015	0.004
Re d_t^{γ} [10^{-19} e cm]	0	20	4	8	2
Re F_{2A}^Z	0	0.012	0.008	0.008	0.007
Re d_t^Z [10^{-19} e cm]	0	7	5	5	4
Im F_{2A}^{γ}	0	0.010	0.008	0.006	0.005
Im F_{2A}^Z	0	0.055	0.010	0.037	0.007
F_{1R}^W	0	0.030	0.012		
ImF_{2R}^W	0	0.025	0.010		

1 s.d. statistical sensitivities to form factors in $t\bar{t}$ production and in $t \longrightarrow Wb$ decays. (Table taken from the TDR.)