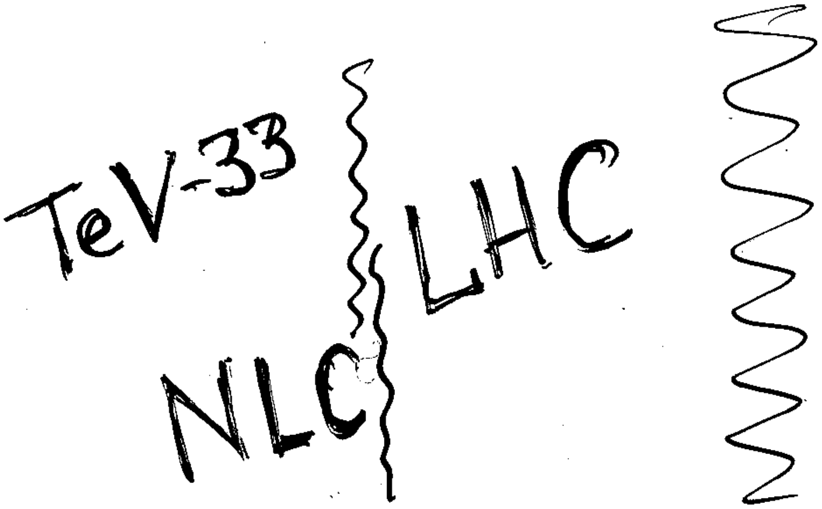
ALC

Approximately
Linear
Collider

VLHC

→


TeV-33
LHC
NLC

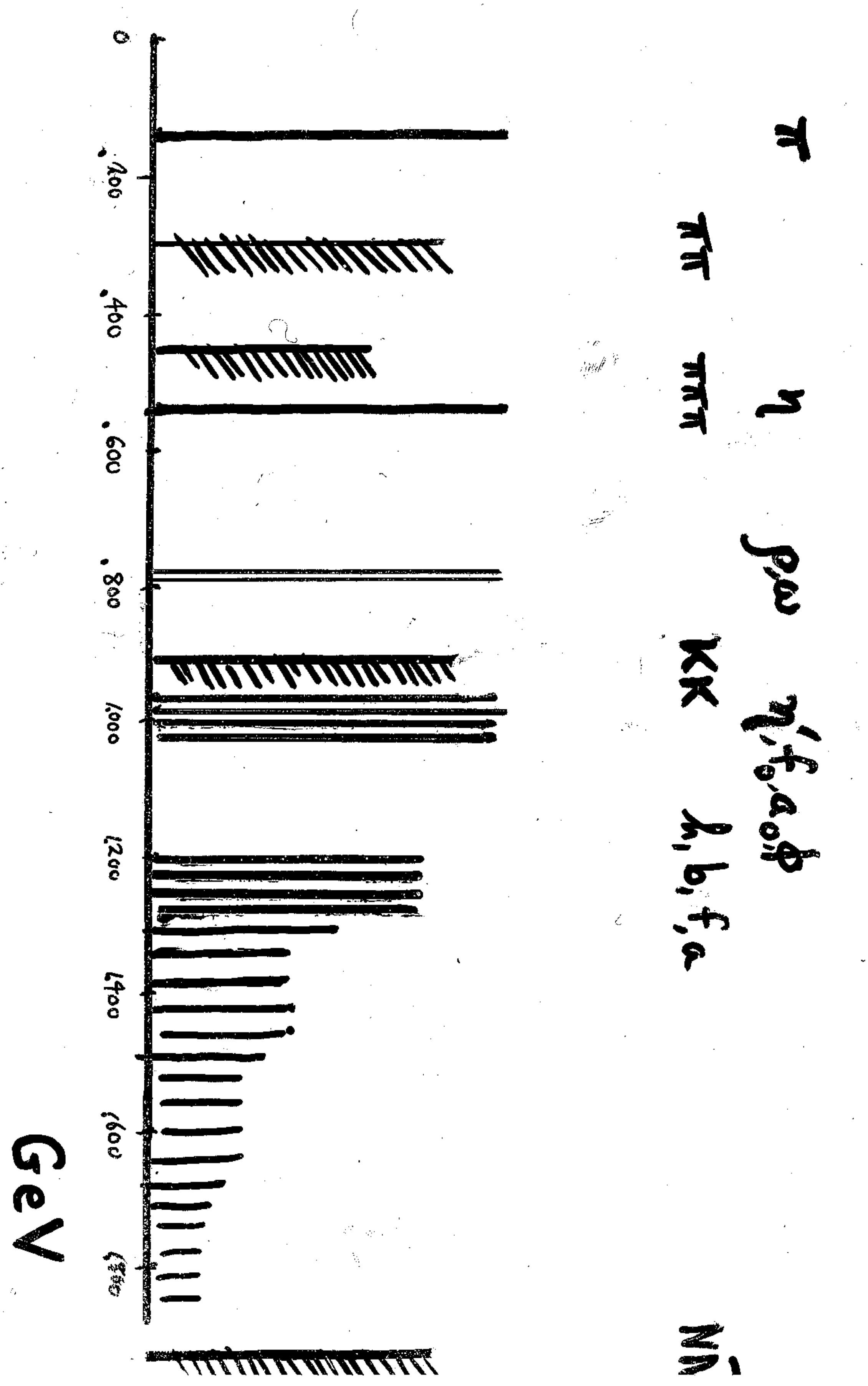
SUSY: h^0 (Zh^0) (Wh^0) A^0, H^0 $\hat{g}\hat{g}$; $\hat{g}\hat{\chi}$; $\underset{t}{\hat{q}}$ $\hat{\ell}$ TeV

$\longleftarrow$ All SUSY partners $\longrightarrow$

SUSY Breaking Scale $\longrightarrow$

Techni: $\tilde{\pi}$ $(\tilde{\rho}, \tilde{\omega})$ multiscale TC $\tilde{\eta}$ $\tilde{\rho}$ $\tilde{\omega}$ $\bar{Q}Q$ Techniquarks Colorons? ETCons? TeV

$\xrightarrow[\text{ETC}]{Z'}$


0
.200
.400
.600
.800
1000
1200
1400
1600
1800
GeV
π
ππ
πππ
η
ρω
KK
η', f₀, a₀, φ
h, b, f, a
NN̄

Role of a High-Energy e^+e^- Synchrotron:

- First stop on path to a VLHC:
  1. May allow the argument to be made for large tunnel **now** rather than apres LHC;
  2. Amortization of tunnel costs extends over century;
  3. Program may be cost competitive with LC; Advantageous?
  4. Part of Advanced Accelerator R & D → we must examine all possibilities; possible new concepts?
- 5-point e^+e^- Physics Program:
  1. Giga-Z: $> 10^9$ Z bosons → improve measurements of most EW parameters by order of magnitude. (**Do we need polarization for** $\sin^2\theta_W$ **from** A_{LR}**?**)
  2. Continuum fermion pair production.
  3. W mass from W threshold studies.
  4. Higgs: "Bj process" $e^+e^- \to Z^* \to Z + H$
  5. Top quark threshold: $e^+e^- \to \gamma^*, Z^* \to t\bar{t}$
- Enlarged Physics Program Potential:
  1. Is $e + \gamma$ Feasible? $\gamma\gamma$?
  2. Is $e + p$(Tevatron) Feasible? Desireable?
  3. Future: Is $e + p$(VLHC) Feasible? Desireable?

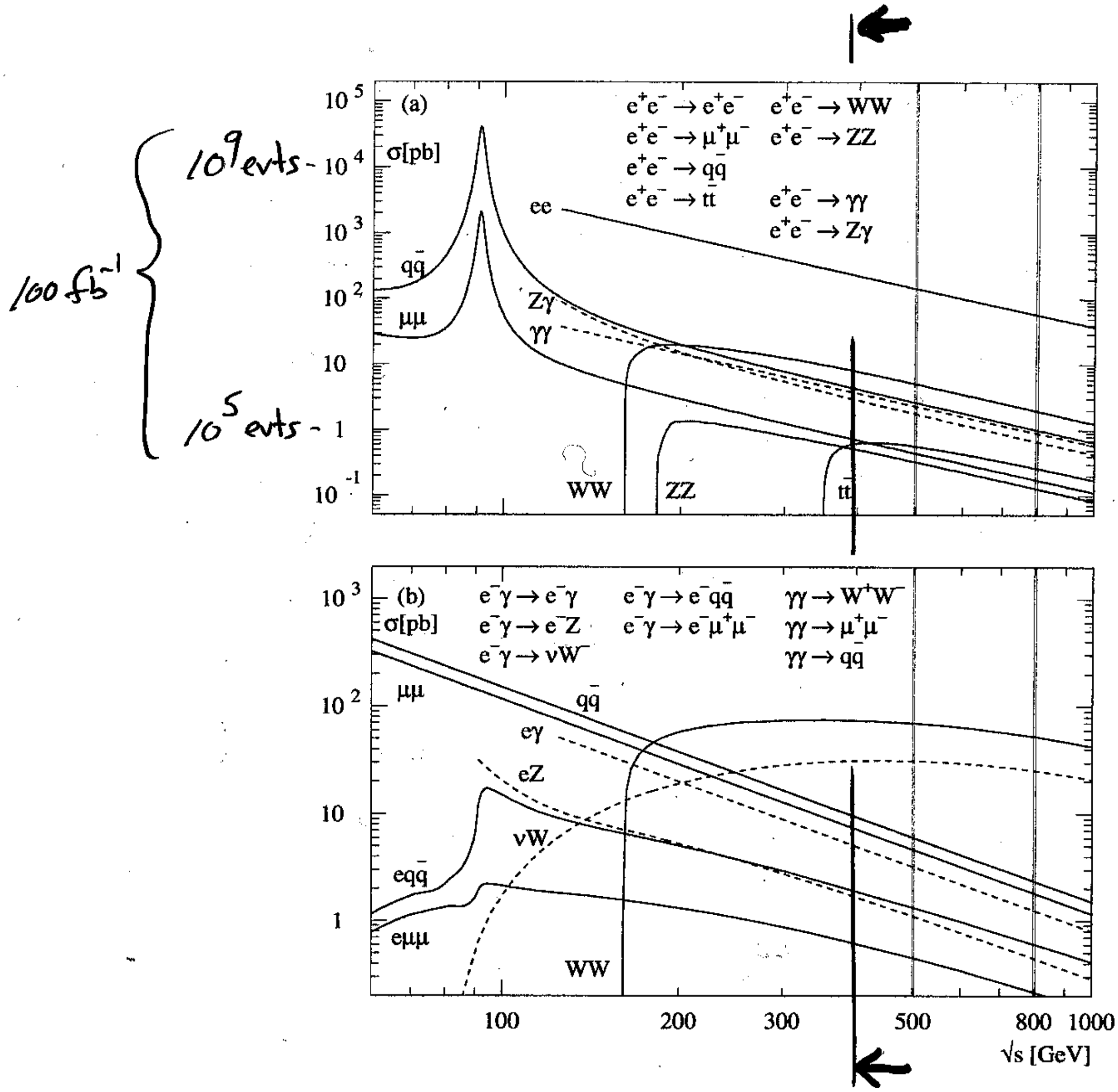


Figure 1: (a) The basic processes of the Standard Model: e^+e^- annihilation to pairs of fermions and gauge bosons. The cross sections are given for polar angles between $10^0 < \theta < 170^0$ in the final state. (b) Elastic/inelastic Compton scattering and $\gamma\gamma$ reactions. $\sqrt{s}$ is the invariant $e\gamma$ and $\gamma\gamma$ energy. The polar angle of the final state particles is restricted as in (a); in addition, the invariant $\mu^+\mu^-$ and $q\bar{q}$ masses in the inelastic Compton processes are restricted to $M_{inv} > 50$ GeV. (from Murayama and Peskin)

Probing Beyond the Standard Model:

- The Higgs vacuum expectation value in lowest order is:

$$\sqrt{2\sqrt{2}G_F}^{\,-1} = v_0 = 175 \;\; GeV$$

- Parameterize "oblique" radiative corrections with two VEV's; $v_W(q^2)$ and $v_Z(q^2)$ parameterized by S and T of Peskin & Takeuchi:

$$\begin{aligned} v_W^2(q^2) &= v_0^2 + \frac{S}{8\pi}q^2 + \frac{\alpha T}{2}v_0^2 \\ v_Z^2(q^2) &= v_0^2 + \frac{S}{8\pi}q^2 - \frac{\alpha T}{2}v_0^2 \end{aligned}$$

- Two running couplings: $g_1(q^2)$ and $g_2(q^2)$ or equivalently:

$$4\pi\alpha = \frac{g_1^2(q^2)g_2^2(q^2)}{g_1^2(q^2)+g_2^2(q^2)} \qquad \sin^2(\theta_W) = \frac{g_1^2(q^2)}{g_1^2(q^2)+g_2^2(q^2)}$$

- Input all the observables:

  1. $\alpha(0)^{-1}$
  2. $G_F = 1/2\sqrt{2}\; v_W^2(0)$
  3. $\sin^2\theta_W(M_Z) = \frac{g_1^2(M_Z)}{g_1^2(M_Z)+g_2^2(M_Z)}$
  4. $M_W^2 = \frac{1}{2}g_2^2(M_W)\; v_W^2(M_W)$
  5. $M_Z^2 = \frac{1}{2}(g_1^2(M_Z)+g_2^2(M_Z))\; v_Z^2(M_Z)$
  6. Forward Backward asymmetry of charm → $\sin^2\theta_W(M_Z)$
  7. Polarization asymmetry of electron → $\sin^2\theta_W(M_Z)$
  8. .... etc.

The Physics Questions of 2001:

1. What is the mechanism responsible for Electroweak Symmetry Breaking? (What makes $\sqrt{2\sqrt{2}G_F}^{-1} = 175$ GeV?)
    (a) Is it a fundamental Higgs Boson?
        - Is it the Standard Model? How?
        - Is there Supersymmetry? Where?

    (b) Is Higgs a composite object?
        - What is it made of? $t\bar{t}$?
        - Where are the requisite new strong interactions?

2. What is the mechanism responsible for the generation of the quark and lepton masses, and CKM mixing angles, and CP-violation?
    - If it's supersymmetry, is this question answerable below M_{Planck}?
    - If it's new strong dynamics, is the top quark special?

3. All mechanisms beyond the Standard Model imply new physics. Where is it?
    - If it's supersymmetry, where are the superpartners?
    - If it's new strong dynamics, where are the pseudo-Nambu-Goldstone bosons? New gauge fields?

4. What will be the interesting questions when we know what breaks Electroweak Symmetry?

Obtain the S-T Error Ellipse:

- All observables are functions of $g_1(q^2)$, $g_2(q^2)$, and S and T with the previous parameterization (equivalently, $\alpha(q^2)$, $\sin^2(\theta)$ and S and T).
- Use established theory (QED) to evolve $\alpha(q^2)$ from $q^2 = 0$ to $q^2 = M_W^2$ or $q^2 = M_Z^2$.
- S and T are viewed as "small" parameters, and represent a linearized fit accomodating unknown new physics.
- S and T have calculable contributions from known Standard Model parameters, e.g. m_t, M_W, m_H, etc.
- Choose coordinates so $S = T = 0$ corresponds to Standard Model with $m_H = 100$ GeV.
- Combine all known data to obtain the S-T error ellipse.
- S and T have contributions from unknown new physics e.g., m_χ in the Top Seesaw Model, or $N_{generations}$ in Technicolor models. Thus, we can overlay the theoretiucal values of S and T from putative new physics.
- Higgs is light in the Standard Model, or perturbative extensions (e.g. supersymmetry) but may be as heavy as ~ 1 TeV in nonstandard extensions involving new strong interactions.

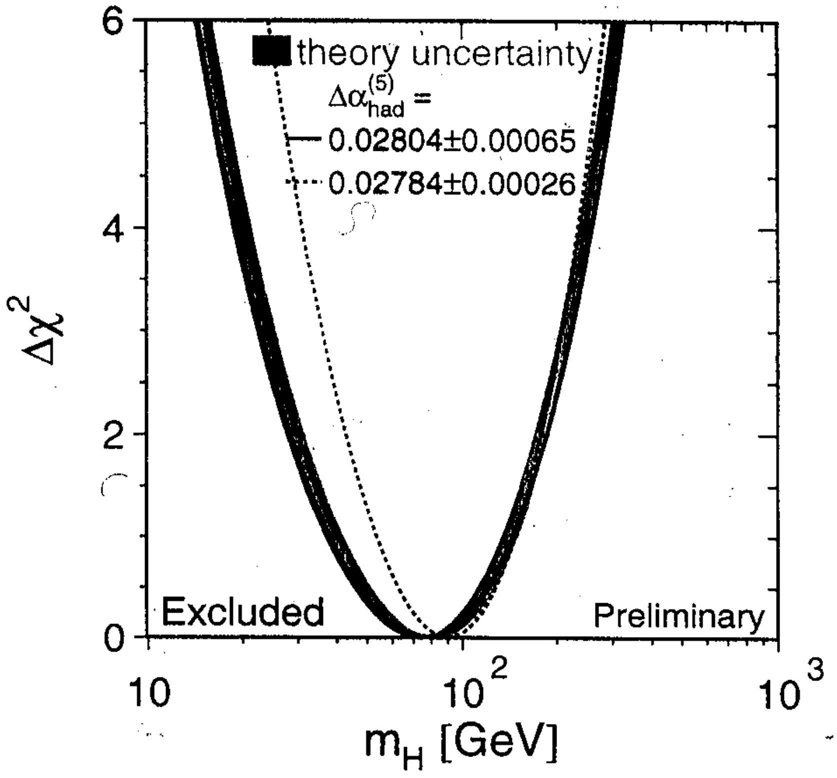
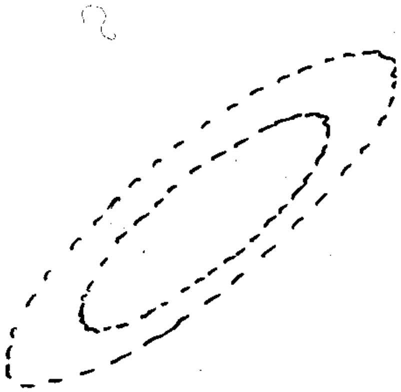


Figure 3: $\Delta\chi^2$ of the fit as a function of the Higgs-mass



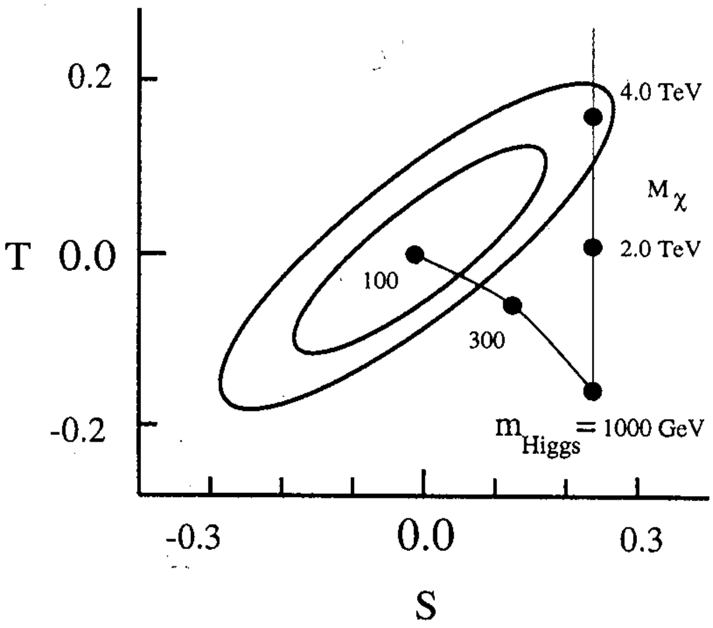
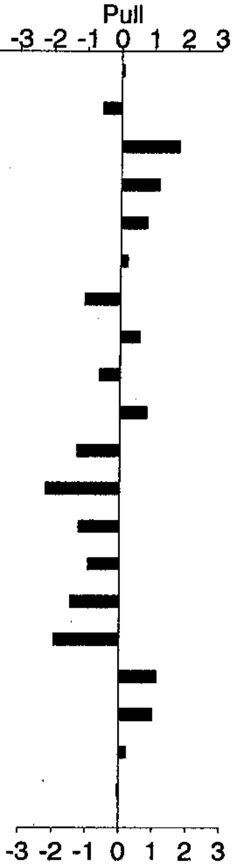


Figure 2: The $1-2\ \sigma$ S-T error ellipses, superimposing the Standard Model with $m_t = 175$ GeV, showing Higgs masses from 100 GeV through 1000 GeV. For the case of the Top Seesaw model, $m_H \approx 1$ TeV and we show the S-T dependence upon the heavy χ-quark mass. Current data is therefore consistent with a ~ 1 TeV Higgs, and $M_\chi \approx 4.0$ TeV. S-T plot from M. Swartz, 1999.

Stanford 1999

	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.08
Γ_Z [GeV]	2.4944 ± 0.0024	-.56
σ^0_{hadr} [nb]	41.544 ± 0.037	1.75
R_e	20.768 ± 0.024	1.16
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.80
A_e	0.1483 ± 0.0051	.21
A_τ	0.1425 ± 0.0044	-1.07
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.60
m_W [GeV]	80.350 ± 0.056	-.62
R_b	0.21642 ± 0.00073	.81
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0988 ± 0.0020	-2.20
$A^{0,c}_{fb}$	0.0692 ± 0.0037	-1.23
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.46
$\sin^2\theta^{lept}_{eff}$	0.23099 ± 0.00026	-1.95
$\sin^2\theta_W$	0.2255 ± 0.0021	1.13
m_W [GeV]	80.448 ± 0.062	1.02
m_t [GeV]	174.3 ± 5.1	.22
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.05



Best fit values for the SM parameters (as of October, 2000, from Langacker):

$$
\begin{aligned}
M_H &= 86^{+48}_{-32}\ \text{GeV}, \\
m_t &= 174.2 \pm 4.4\ \text{GeV}, \\
\alpha_s &= 0.1195 \pm 0.0028, \\
\hat{s}^2_Z &= 0.23107 \pm 0.00016, \\
\Delta\alpha^{(5)}_{\text{had}}(M_Z) &= 0.02778 \pm 0.00020
\end{aligned}
$$

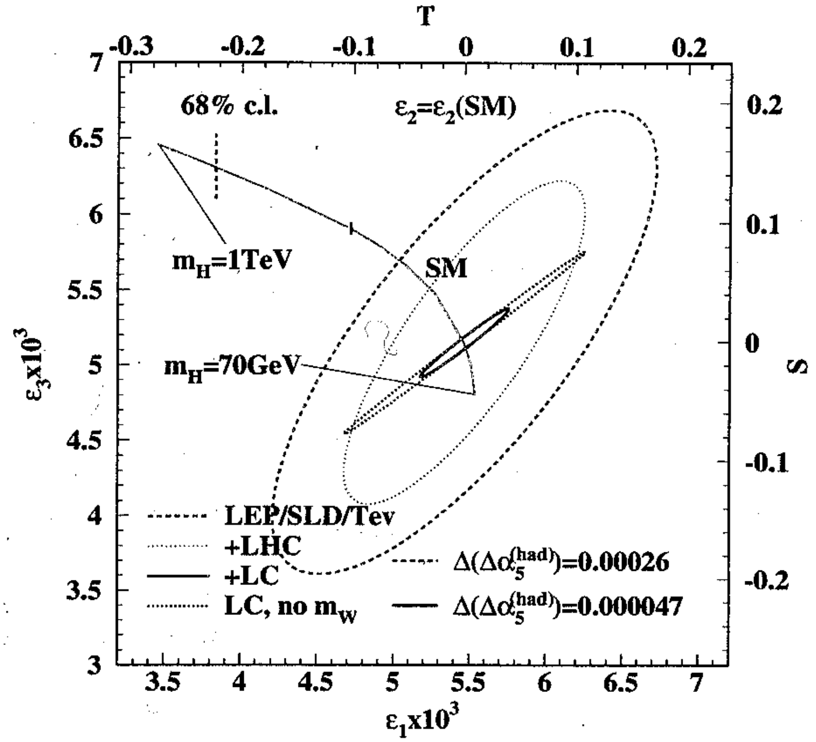


Figure 5: Allowed regions in the $\varepsilon_1 - \varepsilon_3$ (S-T) planes for various assumptions compared to the Standard Model prediction. Also shown is the uncertainty in the prediction due to $\alpha(M_Z)$. (Monig)

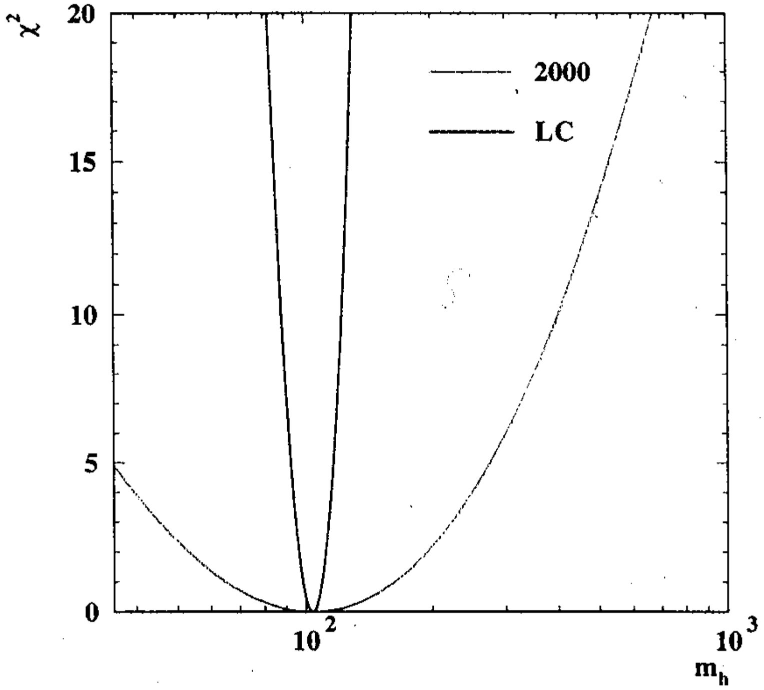


Figure 4: $\Delta\chi^2$ as a function of M_H for the present and the Giga-Z data.

GIGA-Z

$> 10^9$ Collected Z decays.

Significant component of Giga-Z requires electron and positron polarization for left-right asymmetry precise determination of $\sin^2\theta_W$

"Polarization is essential" ???

- Left-right asymmetry, $A_{LR} \equiv 2(1-4\sin^2\theta_{\rm eff})/(1+(1-4\sin^2\theta_{\rm eff})^2)$, measured to high precision, $\delta A_{LR} \approx \pm 10^{-4}$ (both electrons and positrons polarized longitudinally).
- From A_{LR} the mixing angle measured to precision:

$$\delta\sin^2\theta_{\rm eff} \approx \pm 1\times 10^{-5}, \qquad \text{(current: } \pm 2.6\times 10^{-4} \qquad (0.1)$$

- Polarization as high as 99.44% if both beams are up to 90%, (optimistic; theoretical maximum ~ 93%.
- TESLA is being designed to operate on top of the Z boson resonance (adding bypass to the main beam line).
- High luminosity, $L = 3\times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, $e^+e^- \to Z$ cross section, $\sigma_Z \approx 30$ nb, hence $\sim 10^9$ Z events can be generated in three operational years of 10^7s. ergo: **GIGA-Z**.
- $\sim 10^9$ Z events implies improvement in high precision electroweak physics.

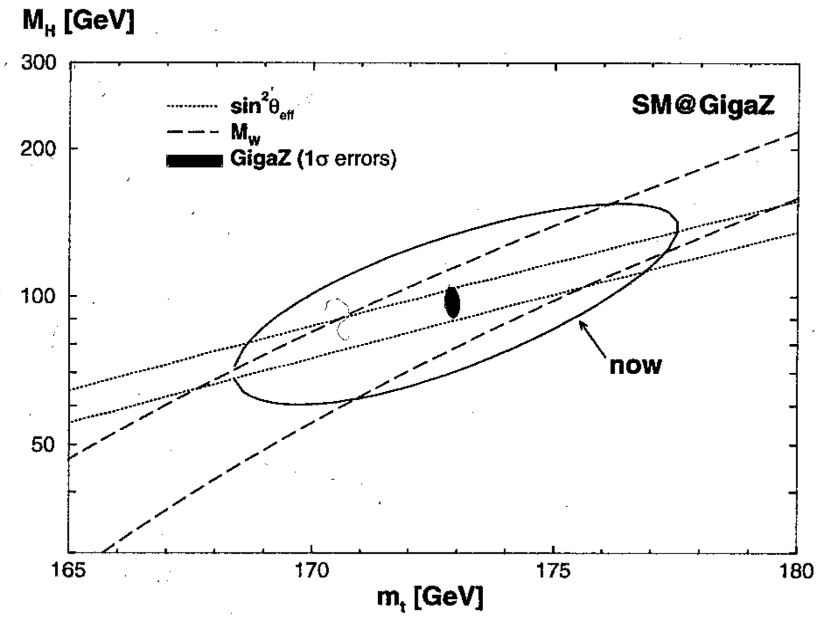


Figure 6: 1σ allowed regions in the m_{top}-M_H plane taking into account the current measurements and the anticipated GigaZ precisions for $\sin^2\theta_{\rm eff}, M_W, \Gamma_Z, R_l, R_q$ and m_{top}.

Giga-Z *sans* polarization?

Many things to do which *do not involve polarization* and offer complementary information on M_H, and α_s.

Are there possible advantages of improved beam energy resolution in a circular e^+e^- machine?

- Total Z width to precision: $\delta\Gamma_Z = \pm 1$ MeV at LC: **can this be improved in Synchrotron with smaller δE?**
- Hadronic/leptonic partial Z widths determined to precision: $\delta R_\ell / R_\ell = \pm 0.05\%$ (vs. $\delta R_l / R_l = \pm 0.25\%$ currently);
- Ratio of the $b\bar{b}$/hadronic partial widths to precision $\delta R_b = \pm 1.4 \times 10^{-4}$ (vs. $\delta R_b / R_b = \pm 0.3\%$ currently);
- R_ℓ implies precise α_s; helps control m_{top} QCD effects; Giga-Z allows precision: $\delta\alpha_s \approx \pm 0.001$, currently ± 0.003 implies smaller uncertainty in δm_{top}, and top QCD effects.
- Expect to determine $\sin^2\theta_W$ to a precision of order $\pm 10^{-4}$ from other Z-pole measurements without polarization.
- The 2 MeV error on M_Z induces error of 0.000014 on $\sin^2\theta$ and, if the beam energy is calibrated relative to the Z-mass 1 on M_W. "**Unless a new circular collider for Z-pole running is built, where it is easier to measure the absolute energy scale, this error limits even further improvement.** - K. Monig hep-ex/0101005."

- Equivalent Uncertainty in $\sin^2\theta$ or M_W:
  - Homework (easy):

$$\sin^2\theta_W = \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_W^2}\left(1+\frac{SM_W^2}{8\pi v_0^2}\right)$$

$$\sin^2\theta_W\cos^2\theta_W = \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_Z^2}\left(1+\frac{SM_Z^2}{8\pi v_0^2}+\alpha T\right)$$

$$\frac{1}{\alpha(M_z)} = 128.89 \pm 0.02 \text{ smallest } \leftrightarrow \pm 0.1 \text{ largest}$$

  - Assume fixed $\sin^2\theta_W$, G_F, S, T: $\delta\frac{\alpha(M_Z)}{M_W^2}=0$,

$$\delta M_W = \pm 6\ MeV \text{ smallest } \leftrightarrow \pm\ 30\ MeV \text{ largest}$$

  - Assume fixed M_Z, G_F, S, T: $\delta\frac{\alpha(M_Z)}{\sin^2\theta\cos^2\theta}=0$;

$$\delta\sin^2\theta = \pm 3\times 10^{-5} \text{ smallest } \leftrightarrow 1.5\times 10^{-4} \text{ largest}$$

- **How much improvement can we expect in precision determination of $\Delta\alpha^{(5)}_{\text{had}}(M_Z)$?** Need better than 1% remeasurement of $R(q^2)$ from ρ through Υ. How? Systematics? Theory?

- Skeptic: The BES uncertainty is the limitation. Hence Giga-Z is overkill; 10^8 Z's is sufficient. Synchrotron comes within a factor of 3 of this limiting uncertainty in $\sin^2\theta$.

How useful is a Giga-Z–*avec*–polarization determination of $\sin^2\theta$ to $1/10^5$ in practice???

To be useful, the precision of $\sin^2\theta$ must be matched by comparable precision in $\alpha(M_Z)$.

- *Largest theory uncertainty is hadronic contribution to running of* $\alpha(\mu)$ from precisely known value $\alpha^{-1}(0) \sim 137.036$ to M_Z; expect: $\alpha^{-1}(M_Z) \sim \hat{\alpha}^{-1}(M_Z) + 0.99 \sim 129$. ($\hat{\alpha}$ refers to the $\overline{MS}$ scheme.) (Related uncertainty in the hadronic contribution to the $g-2$ of the muon).
- Define $\Delta\alpha$ by

$$\alpha(M_Z^2) = \frac{\alpha(0)}{1-\Delta\alpha}. \tag{0.2}$$

then,

$$\Delta\alpha = \Delta\alpha_\ell + \Delta\alpha_t + \Delta\alpha^{(5)}_{\rm had} \sim 0.031497 - 0.000070 + \Delta\alpha^{(5)}_{\rm had}.$$

- $\Delta\alpha^{(5)}_{\rm had}$ unreliable from light quark QCD contribution: Dispersion integral over $R_{\rm had}$ Significant uncertainties/discrepancies in the low energy data.
- Uncertainty in $\Delta\alpha^{(5)}_{\rm had}(M_Z)$ defined as $\delta^2\alpha$, then:

$$\delta\left(\frac{1}{\alpha}\right) = \frac{\delta^2\alpha}{\alpha}$$

$$\frac{1}{\alpha(M_z)} = 128.89 \pm 0.02 \text{ smallest } \leftrightarrow \pm 0.1 \text{ largest}$$

	Author(s)	Result	Comment
	Martin & Zeppenfeld	0.02744 ± 0.00036	PQCD for $\sqrt{s} > 3$ GeV
	Eidelman & Jegerlehner	0.02803 ± 0.00065	PQCD for $\sqrt{s} > 40$ GeV
	Geshkenbein & Morgunov	0.02780 ± 0.00006	$\mathcal{O}(\alpha_s)$ resonance model
	Burkhardt & Pietrzyk	0.0280 ± 0.0007	PQCD for $\sqrt{s} > 40$ GeV
	Swartz	0.02754 ± 0.00046	use of fitting function
	Alemany, Davier, Höcker	0.02816 ± 0.00062	includes τ decay data
	Krasnikov & Rodenberg	0.02737 ± 0.00039	PQCD for $\sqrt{s} > 2.3$ GeV
	Davier & Höcker	0.02784 ± 0.00022	PQCD for $\sqrt{s} > 1.8$ GeV
→	Kühn & Steinhauser	0.02778 ± 0.00016	complete $\mathcal{O}(\alpha_s^2)$
→	*Erler*	0.02779 ± 0.00020	converted from $\overline{\text{MS}}$ scheme
→	Davier & Höcker	0.02770 ± 0.00015	use of QCD sum rules
	Groote *et al.*	0.02787 ± 0.00032	use of QCD sum rules
	Jegerlehner	0.02778 ± 0.00024	converted from MOM
→	Martin, Outhwaite, Ryskin	0.02741 ± 0.00019	includes new BES data
	Pietrzyk	0.02755 ± 0.00046	details not published

Table 1: Recent evaluations of $\Delta\alpha^{(5)}_{\text{had}}(M_Z)$ (adjusted to $\alpha_s(M_Z) = 0.120$).

- **The GIGA-Z proposed determination of $\sin^2\theta$ has a precision three times smaller than the equivalent precision coming from the best claimed analysis of $\Delta\alpha^{(5)}_{\text{had}}(M_Z)$!**
- **The proposed determination of $\sin^2\theta$ has a precision one order of magnitude smaller than the equivalent precision coming from the average of analyses of $\Delta\alpha^{(5)}_{\text{had}}(M_Z)$!**
- **Can matching precision in $\Delta\alpha^{(5)}_{\text{had}}(M_Z)$ be acheived?** (Cornell?
- **The proposed determination of $\sin^2\theta$ without polarization has of order the equivalent precision coming from the average of analyses of $\Delta\alpha^{(5)}_{\text{had}}(M_Z)$!**
- **Can better precision in $\sin^2\theta$ without or with some polarization be acheived?**

Increase Energy to W W Threshold

- → 10^6 W bosons can be generated at optimal energy point, $\sqrt{s} \sim 162$ GeV, for measuring M_W. 100 fb^{-1}
- 3×10^6 W bosons at the energy of maximal cross section. 100 fb^{-1}
- $e^+e^- \to W^+W^-$ mediated by (i) t–channel ν_e exchange, (ii) s–channel γ and Z exchanges.
- Polarization: Large fraction of forward events by the t–channel ν_e-exchange. Right-handed electrons, switches this off.
- Polarization: s–channel exchange switched off at high energy for right-handed electrons.
- Single W production generated reactions $e^+e^- \to e^+\nu_e W^-$ and $e^+e^- \to \bar{\nu}_e e^- W^+$. [Weizsäcker–Williams photon, $e \to e\gamma$, and subsequent $\gamma e^- \to W^-\nu_e$ and $e^+\gamma \to \bar{\nu}_e W^+$. e^- and e^+ beams must both be polarized in right/left state to suppress this background reaction.
- **How important is polarization in W threshold physics?** Polarized e^- and e^+ beams provides control. Different mechanisms can be switched on and off by selecting different polarizations. Rates backgrounds can be reduced.

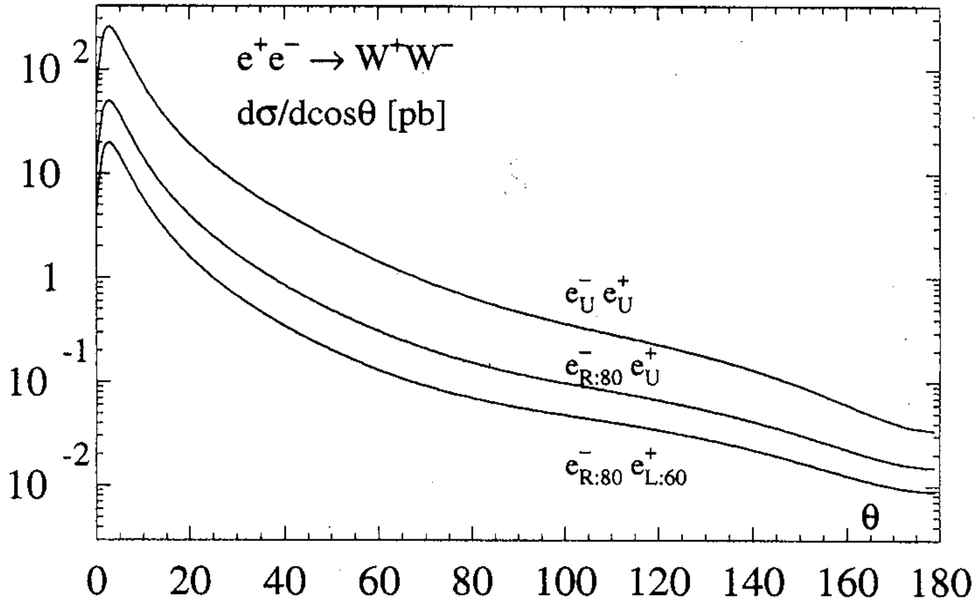


Figure 7: *The effect of beam polarization on the cross section for the production of* W^+W^- *pairs. U denotes unpolarized electron and positron beams, R:80 denotes 80% right-handedly polarized electron beams, and L:60 denotes 60% left-handedly polarized positron beams.*

WW Threshold Scanning *sans* Polarization?

- Measure W mass in e^+e^- operating near the WW threshold with high luminosity. Scan threshold region near $\sqrt{s} =$ 161 GeV, where sensitivity to the W mass is maximal. Uncertainty on the beam energy is essential issue. At LC use high-precision analyses of $Z\gamma$ and ZZ events, to $< 10\ MeV$, and the uncertainty in measurement of cross section to below one percent, accuracy

  $$\delta M_W \approx 15\text{MeV}$$ (Peskin + Murayama)

  should be achievable at LC.

- Comparable accuracy by reconstructing W bosons in mixed lepton/jet WW final states. Final error on the W mass expected below $\delta M_W \sim 15$ MeV for integrated luminosity of 50 to 100 fb^{-1} at $\sqrt{s} \sim 350$ and 500 GeV. Measurement can be performed in parallel to other experimental analyses.

- Optimistically: W boson mass measured to precision:

  $$\delta M_W \approx \pm 6 \text{ MeV}.$$ (Rowson, Mönig)

- **Does the synchrotron offer an advantage here due to small δE?**

Continuum $f\bar{f}$ Production (QCD)

- Fermion pair production in $e^+e^- \to f\bar{f}$. mediated by s–channel γ and Z exchanges. (except Bhabha process which can also be generated by t–channel γ and Z exchanges). Cross sections, apart from the Bhabha process, vary between 1.0 and 10 pb at $\sqrt{s} = 400$ GeV, corresponding to 10^5 to 10^6 events for an integrated luminosity of $\int \mathcal{L} = 100$ fb^{-1}.
- Dynamical impact of beam polarization on fermion-pair production through annihilation is negligible.
- $e^+e^- \to \gamma^*/Z^* \to q\bar{q}$, $q\bar{q}g$ ... provides a high-energy source of clean quark and gluon jets. Topics of include the study of multijet topologies, the energy increase of charged multiplicity, particle momentum spectra and scaling violations, angular ordering effects, hadronization phenomenology (power corrections), etc.
- Asymptotic freedom has been tested in many observables measured at e^+e^- colliders and other accelerators between a minimum Q^2 of order 4 GeV^2 up to 4×10^4 GeV^2, ranging from the τ lifetime to multi-jet distributions in Z decays. Range of Q^2 can be extended at e^+e^- by an order of magnitude to a value $Q^2 \sim 6.4 \times 10^5$ GeV^2.
- $e + p$ **Option**: $Q^2 \sim 1.6 \times 10^6$ GeV^2 in the $e + p$ mode with Tevatron and $Q^2 \sim 1.6 \times 10^8$ GeV^2 with 100 TeV VLHC!

- Sensitive observable in e^+e^- is 2, 3, 4, ... jets ratios. Asymptotic freedom linearity, modified slightly by higher order corrections.

- Error in determination of the QCD coupling at $\sqrt{s} = 500$ GeV expected to be $\delta\alpha_s(M_Z^2) \simeq 0.005$, matching error from the analysis of the top excitation curve at threshold. If theory can be improved, the error on α_s can be reduced significantly.

- Two-Photon Physics is also rich (e.g., charm excitation in deep-inelastic $\gamma\gamma$ physics).

- Møller scattering $e^-e^- \to e^-e^-$ and Bhabhah $e^+e^- \to e^+e^-$ at high energies provide limits on electron compositeness. Four-electron contact interactions:

$$\mathcal{L}_C = \frac{2\pi}{\Lambda_c^2}\bar{e}_L\gamma_\mu e_L \cdot \bar{e}_L\gamma_\mu e_L$$

  (strength of the interaction set to $g_*^2/4\pi = 1$). Møller scattering is superior to Bhabha scattering in this context, consequence of bigger cross-section in the central rapidity region. Polarization that can be achieved for electron beams, gives Møller scattering another advantage. Bound on electron compositeness can be set to

$$\Lambda_c \approx 100 \text{ TeV} \Rightarrow R_e \; 10^{-18}\text{cm}$$

  for $\int \mathcal{L} \sim 100$ fb^{-1} if polarized electrons are used.

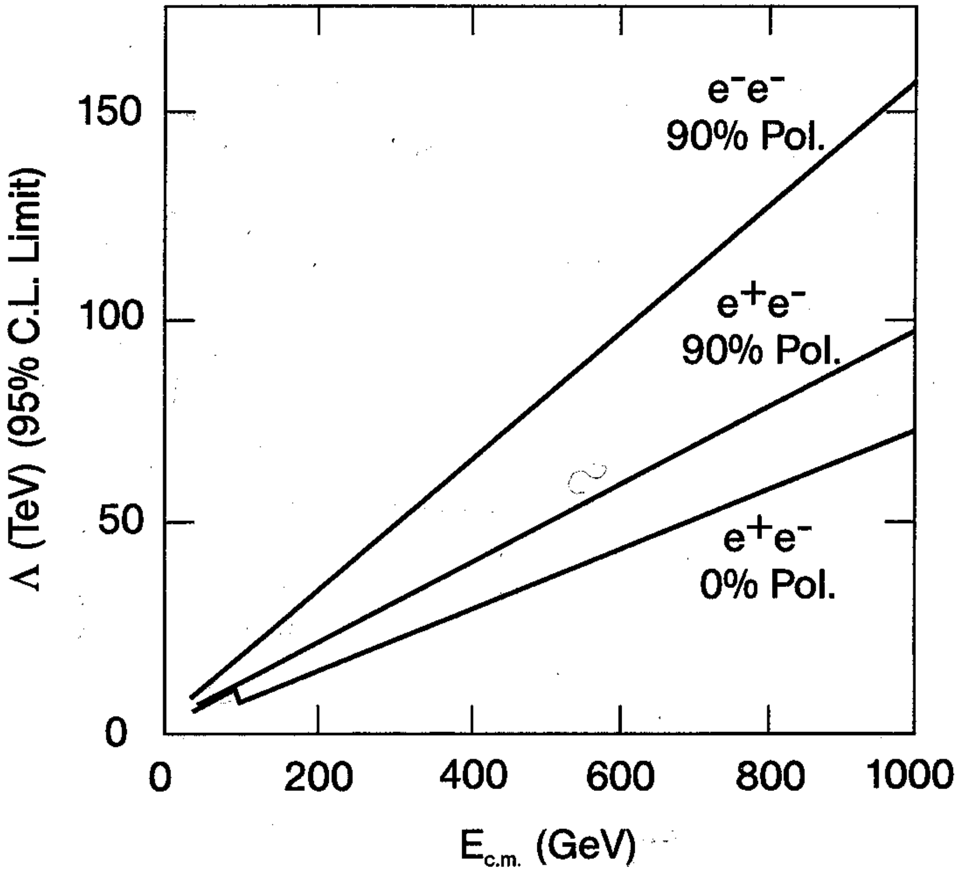


Figure 8: *Bounds on the compositeness scale of electrons, extracted from large angle Møller scattering* $e^-e^- \to e^-e^-$*. At* $\sqrt{s} = 1$ *TeV the integrated luminosity is assumed to be* $\int = 80\text{fb}^{-1}$.

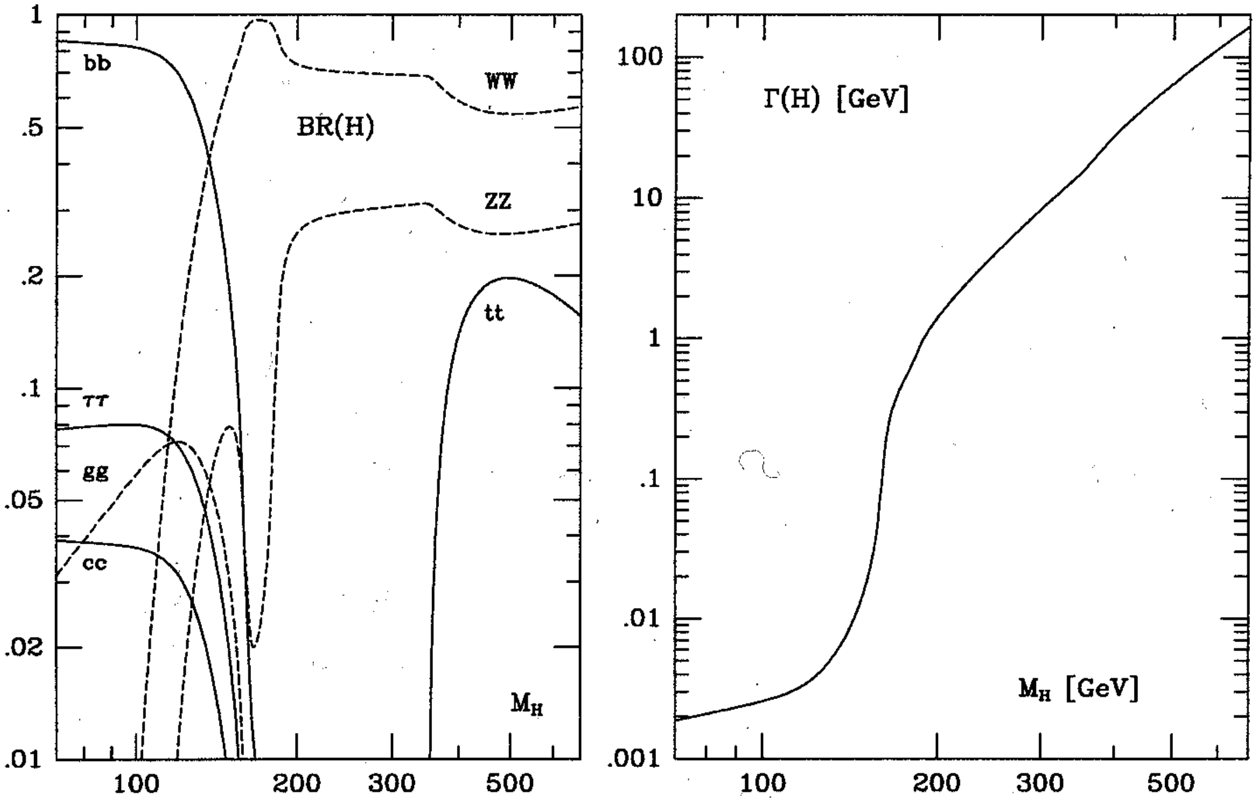
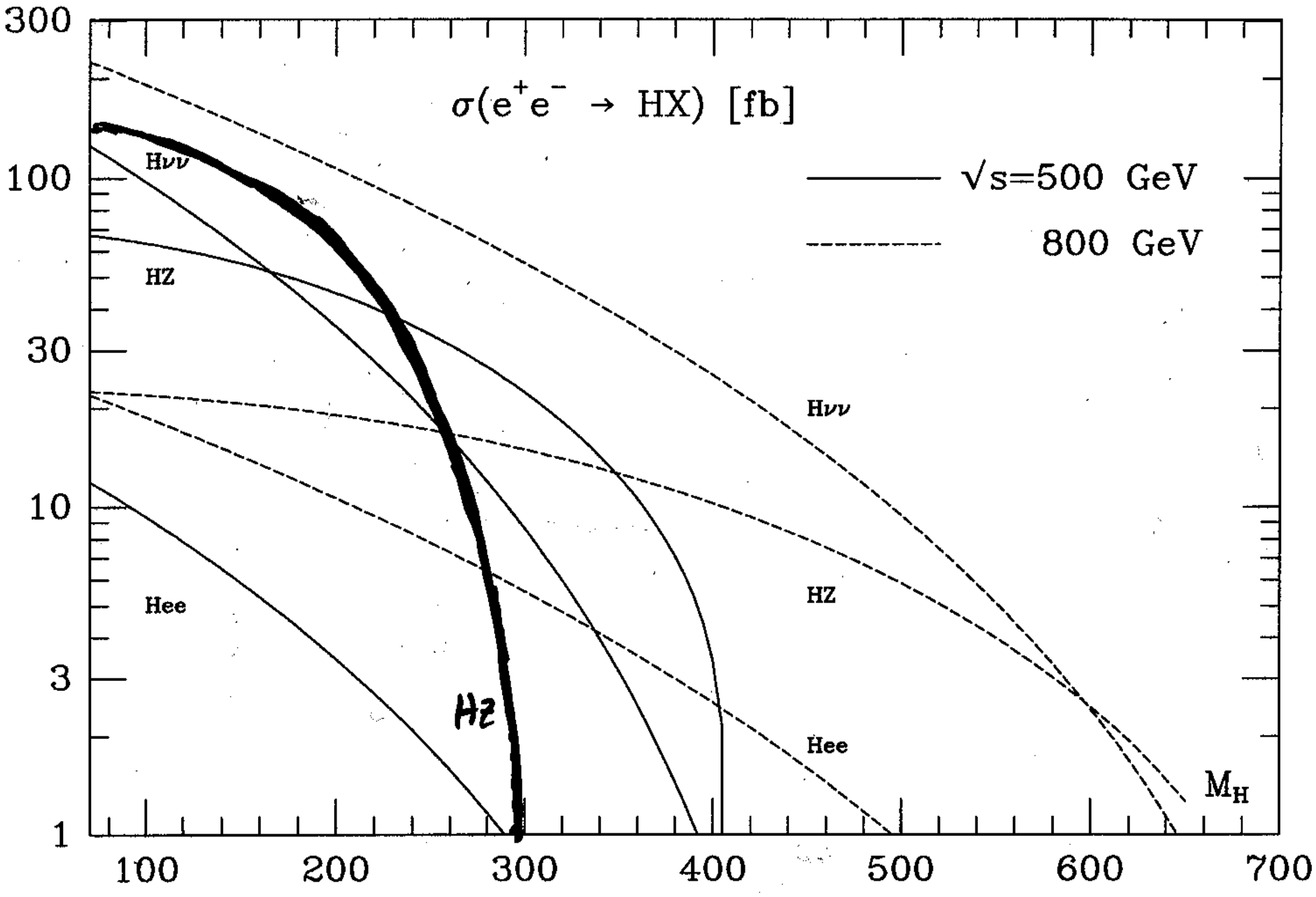


Figure 9: *Branching ratios of the main decay modes of the SM Higgs boson and total decay width.*



(guess) H+Z @ √s: 400

Figure 10: *The cross section for the production of SM Higgs bosons in Higgs-strahlung* $e^+e^- \to ZH$ *and* WW/ZZ *fusion* $e^+e^- \to \bar{\nu}\nu/e^+e^-H$*; solid curves:* $\sqrt{s} = 500$ *GeV, dashed curves:* $\sqrt{s} = 800$ *GeV.*

Exploitation of the Higgs Boson

- The SM Higgs boson can be discovered at the Tevatron in the region above LEP2, up to ~ 140 to ~ 180 GeV exploiting $p\bar{p} \to W + H$ and $p\bar{p} \to t + \bar{t} + H$, assuming ~ 15 fb^{-1} to ~ 60 fb^{-1} integrated luminosity.
- The SM Higgs boson can be discovered at the LHC up to the canonical upper limit of $M_H \sim 800$ GeV. In the theoretically preferred intermediate mass range below the ZZ decay threshold, the experimental search is difficult.
- A variety of channels can be exploited to search for Higgs particles:

$$\begin{aligned} e^+e^- &\xrightarrow{WW} \bar{\nu}_e \nu_e H \\ e^+e^- &\xrightarrow{ZZ} e^+e^- H \\ e^+e^- &\xrightarrow{Z^*} ZH \end{aligned}$$

Signatures clear and backgrounds almost negligible. In the HZ recoil-mass techniques can be used in final states with leptonic Z decays, or the Higgs particle may be reconstructed in $Hb\bar{b}, WW$ directly. WW fusion process requires the reconstruction of the Higgs.

- Reconstruction of Higgs potential?

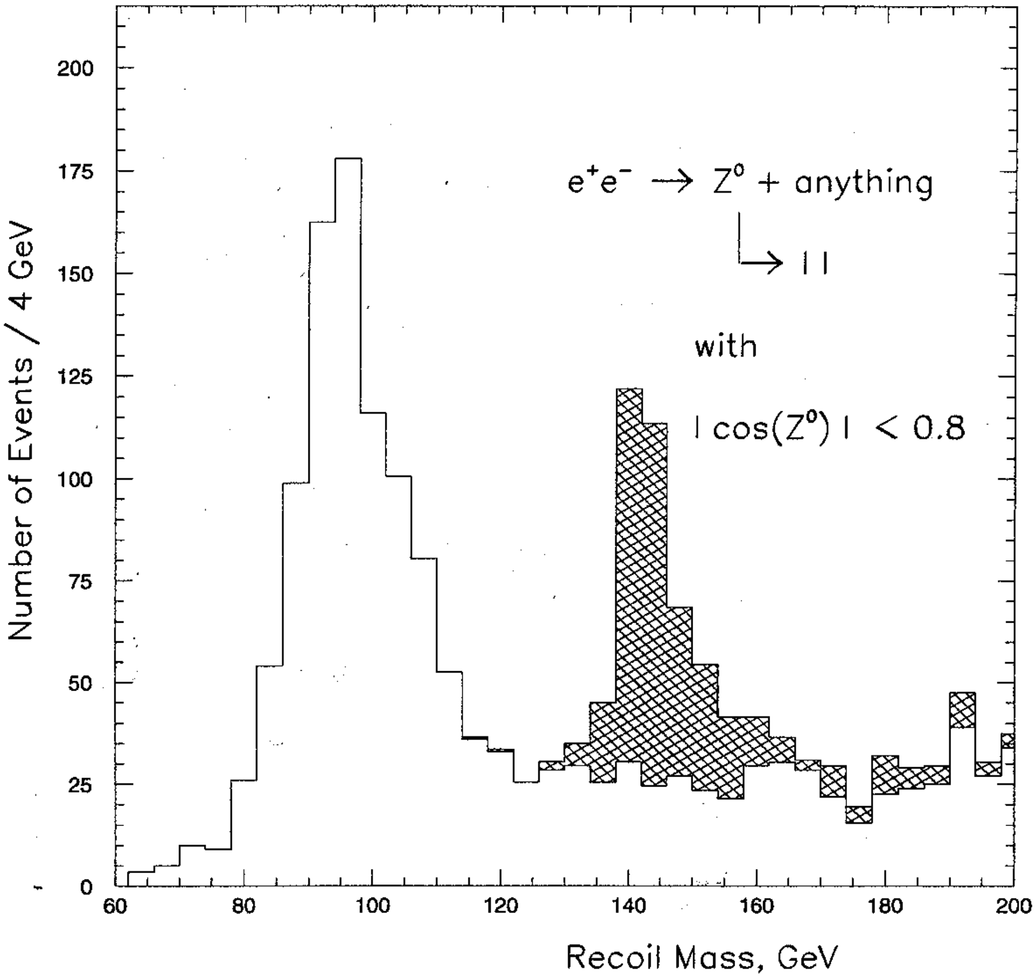


Figure 11: *Dilepton recoil mass analysis of Higgs-strahlung* $e^+e^- \to ZH \to l^+l^-$+anything *in the intermediate Higgs mass range for* M_H = 140 *GeV. The c.m. energy is* $\sqrt{s}$=*360 GeV and the integrated luminosity* $\int \mathcal{L}$ =*50* fb^{-1}.

Higgs Boson

- Mass of the Higgs determined precisely: (i) Exploit kinematical constraints in four-jet topology; (ii) $\tau\bar{\tau}q\bar{q}$ final state (iii) leptonic Z channels in HZ events. For $\int\mathcal{L} = 50$ fb^{-1}, $\sqrt{s} =$ 500 GeV, precision of ±180 MeV can be reached **Murayama and Peskin, Annl. Rev. Nucl. Part. Sci. 46 (1996) 533.**

- Γ_H, determination depends upon Higgs mass; can be determined through entire mass range if results from LHC, e^+e^-, *and optional* $\gamma\gamma$ can be combined.

- The angular distribution of the Z/H bosons in the $Z + H$ process is sensitive to the *spin and parity* of the Higgs.

- Higgs couplings to massive gauge bosons can be determined from the production cross-section with an accuracy of ±3 %, the HZZ coupling in the $H + Z$ process; HWW coupling in the WW fusion process.

- Higgs couplings to fermions, loop effects in $H \to gg, \gamma\gamma$ (mediated by top quark loops) must be exploited, or use the branching ratios $H \to b\bar{b}, c\bar{c}, \tau^+\tau^-$ in the lower part of the intermediate mass range; latter provide a *direct* determination of the Higgs Yukawa couplings to these fermions.

- Higher Energy: Yukawa coupling Higgs boson to the top quark in the range $M_H \leq 120$ GeV can be measured directly in the bremsstrahlung process $e^+e^- \to t\bar{t}H$.

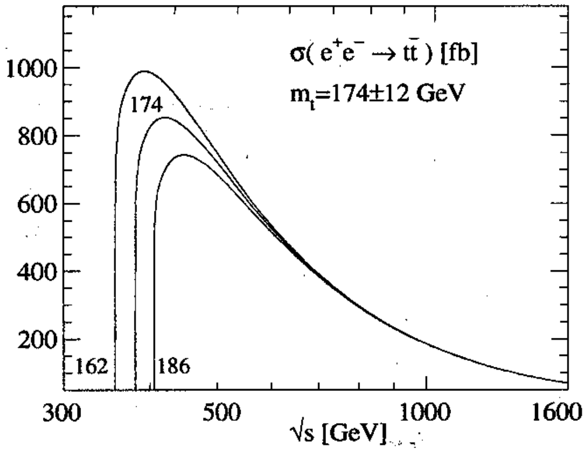


Figure 12: *The cross section for the production of top-quark pairs in the continuum as a function of the total energy for three representative(a) values of the top mass.*

Increase Energy to $t\,\bar{t}$ Threshold

- Main production mechanism for top quarks in e^+e^- collisions is the annihilation channel:

$$e^+e^- \xrightarrow{\gamma,Z} t\bar{t}$$

- σ of the order of 1 pb → top quarks produced at large rates in a clean environment at e^+e^- linear colliders, 10^5 pairs for 100 fb^{-1}.
- Helicities of tops determined from decay distribution of jets and leptons in $t \to b + W^+ \to b + f\bar{f}'$.
- The form factors of the top quark in the electromagnetic and the weak neutral currents, the Pauli–Dirac form factors $F_1^{\gamma,Z}$ and $F_2^{\gamma,Z}$, the axial form factor F_A^Z and the $\mathcal{CP}$ violating form factors $D_A^{\gamma,Z}$, can be measured accurately. ($F_1^{\gamma,Z}$ and F_A^Z are unity (*modulo* radiative corrections); $F_2^{\gamma,Z}$ and $D_A^{\gamma,Z}$ vanish in the Standard Model). Anomalous values could be a consequence of electroweak symmetry breaking in non-standard scenarios or of composite quark structures; Deviations typically grow with the c.m. energy.
- Can we see new physics in this channel associated with $\langle \bar{t}t \rangle$ models? Top Seesaw?

$$\sim m_t \frac{F^{\mu\nu}\,\bar{t}\sigma_{\mu\nu}t}{\Lambda^2}$$

Static Parameters of the top quark which can be determined only in e^+e^- Colliders

- *Z charges of the top quark.* The form factors F_1^Z, F_A^Z, or likewise the vectorial and axial Z charges of the top quark, $v_t = +1 - \frac{8}{3}\sin^2\theta_w$ and $a_t = +1$, determined from the $t\bar{t}$ production cross section.
- *Magnetic dipole moments of the top quark.* If electrons are left-handed, top quarks are produced preferentially left-handed in forward direction. Backward direction sensitive to small anomalous magnetic moment of the top quark. The anomalous magnetic moments can be bounded to about 5% by measuring the angular dependence of the t quark cross section.
- *Electric dipole moment of the top quark* generated by exotic $\mathcal{CP}$ violating interactions. Non-zero values can be detected through non-vanishing of $\mathcal{CP}$–odd momentum tensors such as $T_{ij} \sim (q_+ - q_-)_i(q_+ \times q_-)_j$ or $A \sim p_+ \cdot (q_+ \times q_-)$, ($p_+$, $q_\pm$ are unit momentum vectors of the initial e^+ and of the W–decay leptons). Sensitivity of $d_t^{\gamma,Z} < 10^{-18}$ e cm can for $\sim$ 20fb^{-1} with polarization.
- Detailed simulations at predict sensitivity to the top mass and QCD coupling, from excitation curve and t momentum spectrum combined:

$$\begin{aligned} \delta m_t &\approx 120 \text{ MeV} \\ \delta\alpha_s &\approx 0.003 \qquad \text{for } 50 \text{ fb}^{-1} \end{aligned}$$

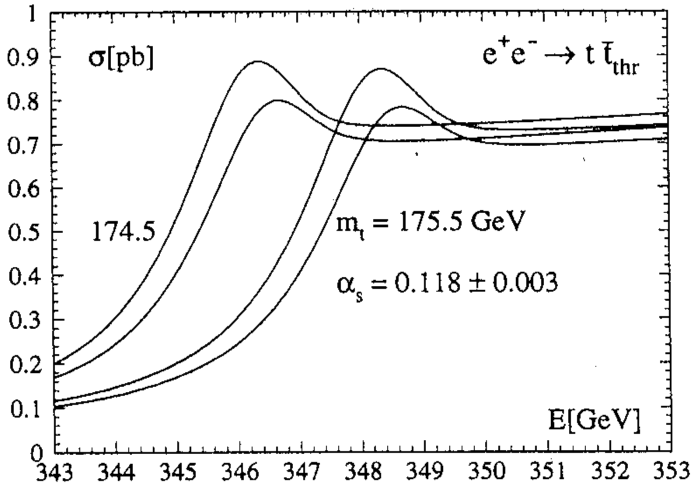


Figure 13: *The cross section for the production of top quarks near the threshold. Demonstrated is the sensitivity of the cross section to the value of the top mass and the QCD coupling (normalized at the Z mass).*

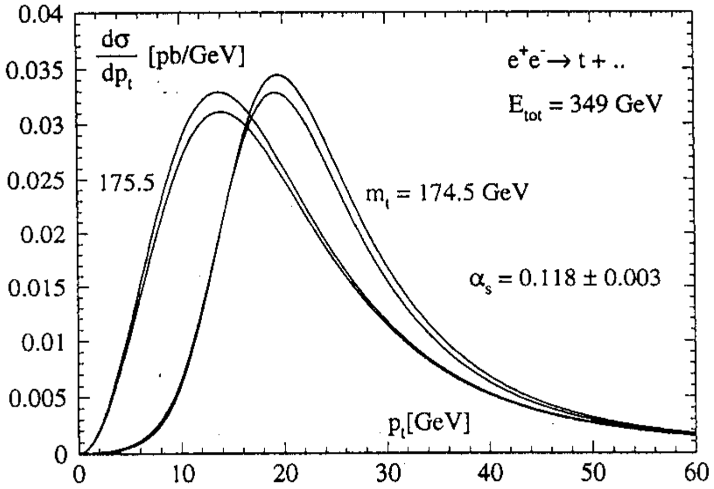


Figure 14: *The momentum spectrum of the top quarks near the threshold for a fixed total c.m. energy. The momentum depends strongly on the top mass, yet less on the QCD coupling.*

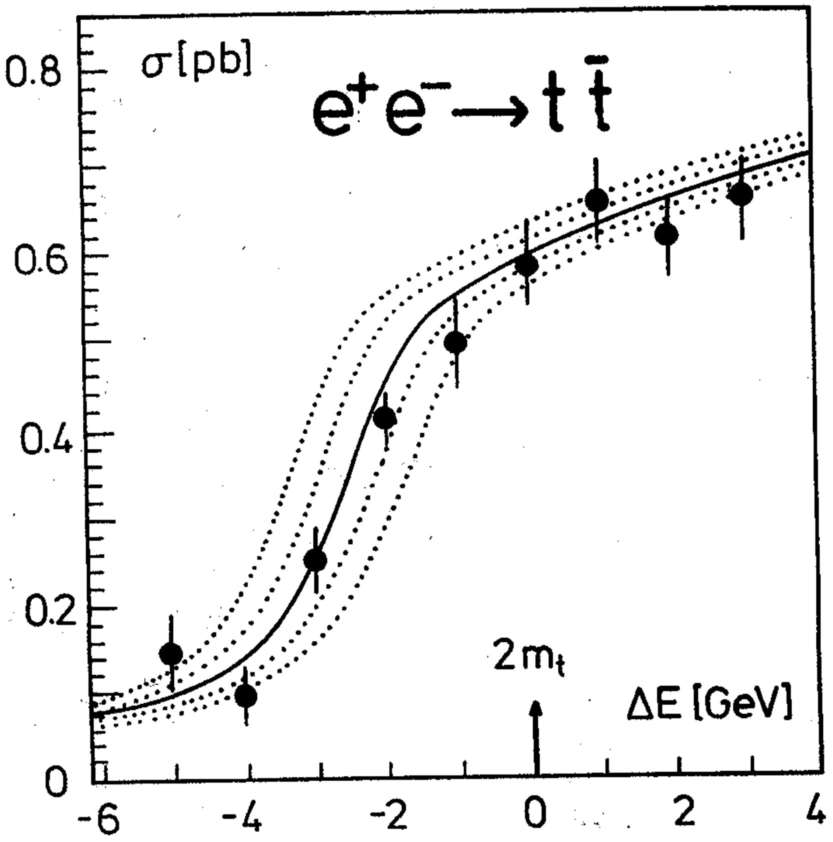


Figure 15: *Excitation curve of the top quarks including initial-state radiation and beamstrahlung. The errors of the data points correspond to an integrated luminosity of* $\int \mathcal{L} =$ *50* fb^{-1} *in toto. The dotted curves indicate shifts of the top mass by 200 and 400 MeV.*

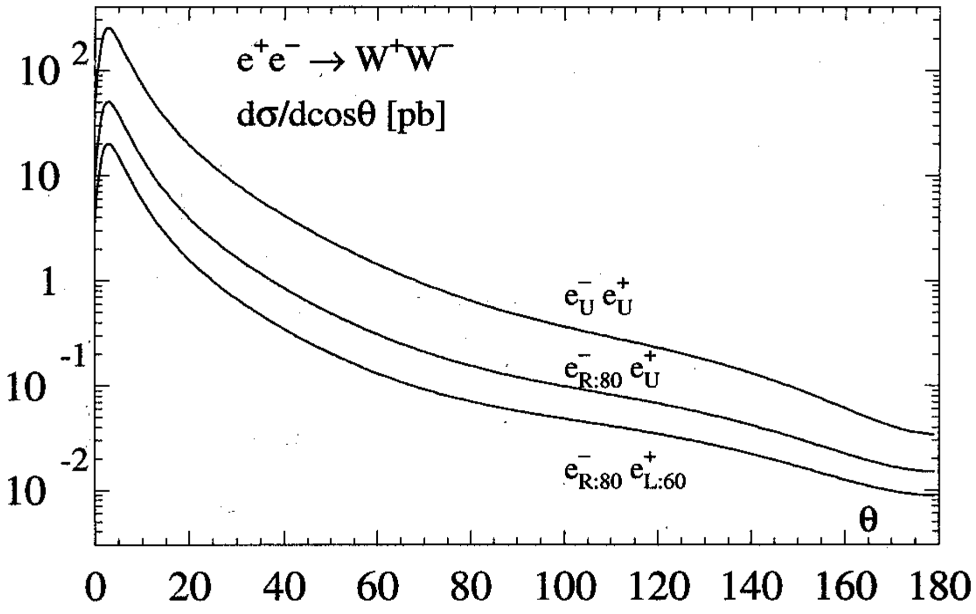


Figure 7: *The effect of beam polarization on the cross section for the production of* W^+W^- *pairs. U denotes unpolarized electron and positron beams, R:80 denotes 80% right-handedly polarized electron beams, and L:60 denotes 60% left-handedly polarized positron beams.*

WW Threshold Scanning *sans* Polarization?

- Measure W mass in e^+e^- operating near the WW threshold with high luminosity. Scan threshold region near $\sqrt{s} =$ 161 GeV, where sensitivity to the W mass is maximal. Uncertainty on the beam energy is essential issue. At LC use high-precision analyses of $Z\gamma$ and ZZ events, to $< 10\ MeV$, and the uncertainty in measurement of cross section to below one percent, accuracy

$$\delta M_W \approx 15\text{MeV}$$

should be achievable at LC.

- Comparable accuracy by reconstructing W bosons in mixed lepton/jet WW final states. Final error on the W mass expected below $\delta M_W \sim 15$ MeV for integrated luminosity of 50 to 100 fb^{-1} at $\sqrt{s} \sim 350$ and 500 GeV. Measurement can be performed in parallel to other experimental analyses.

- Optimistically: W boson mass measured to precision:

$$\delta M_W \approx \pm 6\ \text{MeV}.$$

- **Does the synchrotron offer an advantage here due to small δE?**

Conclusions

- The case for an e^+e^- synchrotron seems weakened if we have little or no polarization.
- **However,** the inherent physics limitations on the utility of polarization-based measurements, e.g., $\delta^2\alpha(M_Z)$, may weaken the case **for** polarization.
- A rich physics case exists for $> 10^9$ Z's without polarization (IMO).
- It is important to understand if there are **inherent advantages in the synchotron to beam energy resolution,** and the consequences for the physics program. There may be novel opportunites, e.g., δM_Z, $\delta\Gamma_Z$, etc.
- New opportunites, such as $e+p$, to $Q^2 >> 10^6$ strengthen the case.
- As a first stage of the VLHC the ALC program offers a wide range of excellent physics topics.