Physics with Electron-Positron Linear Colliders

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Manchester University
30/6/99 IoP Future Initiatives meeting (Birmingham)

Most of the material is drawn from :

DESY/ECFA Conceptual Design Report (DESY1997-048)

and SLAC ZDR (SLAC-Report-485)

See also proceedings from Saariselska 91, Waikoloa 93, Morioka 95 and Sitges 99.

and http://www/slac.stanford.edu/~mpeskin/LC/#biblio

http://www.desy.de/conferences/ecfa-desy-lc98.html

Physics Motivation for New Colliders

- Discovery of new particles and understanding of their interactions
  - High Precision Measurements of physics related to Standard Model particles
    - top quark
    - Higgs boson and the Higgs mechanism
    - Electro-weak gauge bosons (W, Z) and QCD
  - Explore physics beyond the Standard Model
    - super-symmetry
    - strongly interacting EW sector
    - novel space-time phenomena, GUTs, compositeness

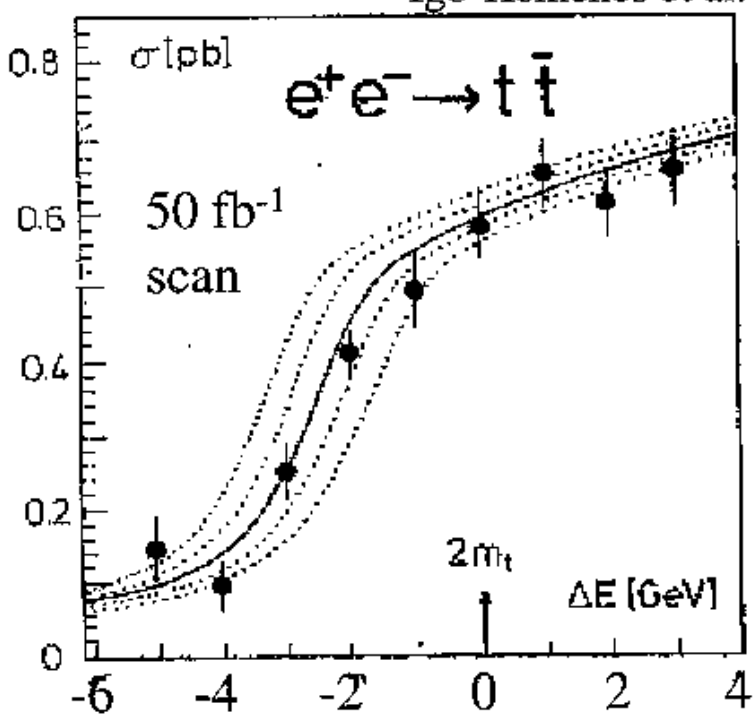
Outline

- Top quark
  - Mass
  - Decays
- Higgs
  - Comprehensive understanding
    - Discovery
    - Cross-section
    - Mass and Width
    - BR's
    - J^{PC}
    - top-Higgs Yukawa coupling
    - Higgs self-coupling
- Precision physics
  - A_{LR} (Z pole)
  - Γ_h/Γ_l (Z pole)
  - M_W (W threshold)
  - WW couplings (high E)
- New Physics
  - Strong EWSB
    - WW re-scattering
  - Weak EWSB
    - Super-symmetry : measure masses and couplings precisely with threshold scans and polarisation

Top Mass Measurement

Top quark mass can be determined most accurately at threshold :

Igo-Kemenes et al.



Tevatron, LHC expect errors around 2000 MeV

Expected experimental accuracy on m_{top} (1s) for 50 fb^{-1} is 50 MeV

Estimated theoretical uncertainty ≈ 40 MeV

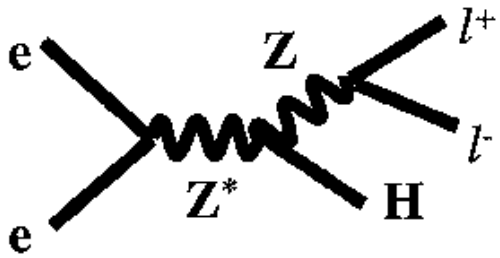
Δm_{top} (1s) < 100 MeV

Further improvement needs better theory.

Higgs Discovery

Maybe at LEP2 or Tevatron or LHC

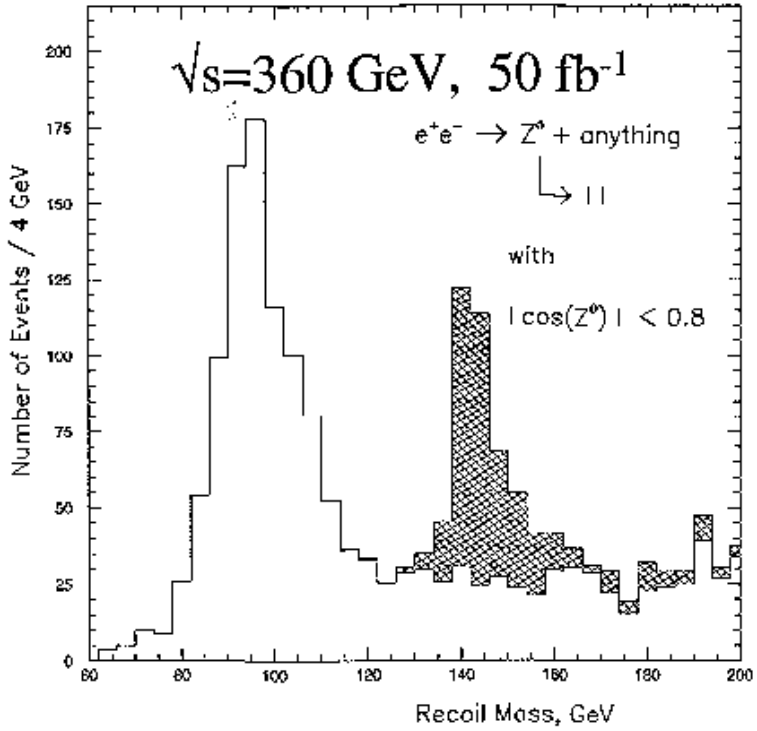
At LC : (6% of Z decays)



Higgs mass measured from di-lepton recoil mass :

Linear collider can find the Higgs no matter how it decays. Even invisibly !

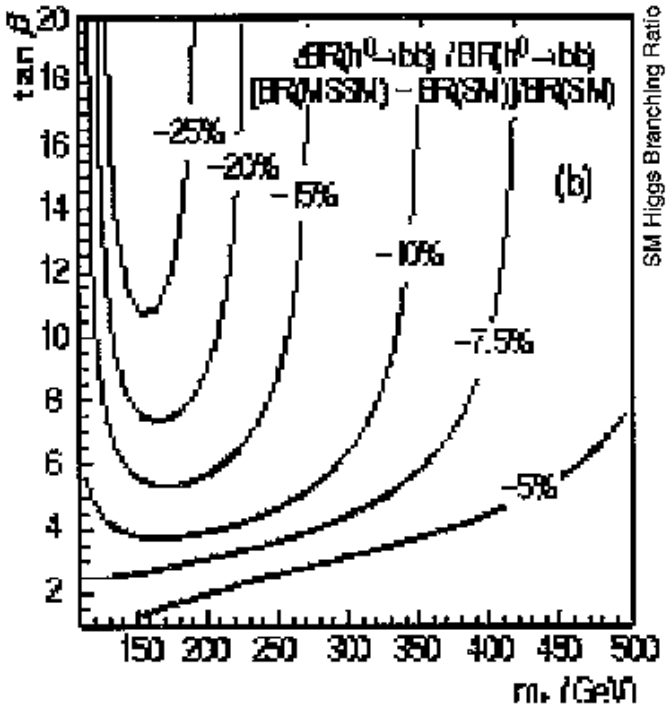
Schreiber et al.



Branching ratio measurements follow

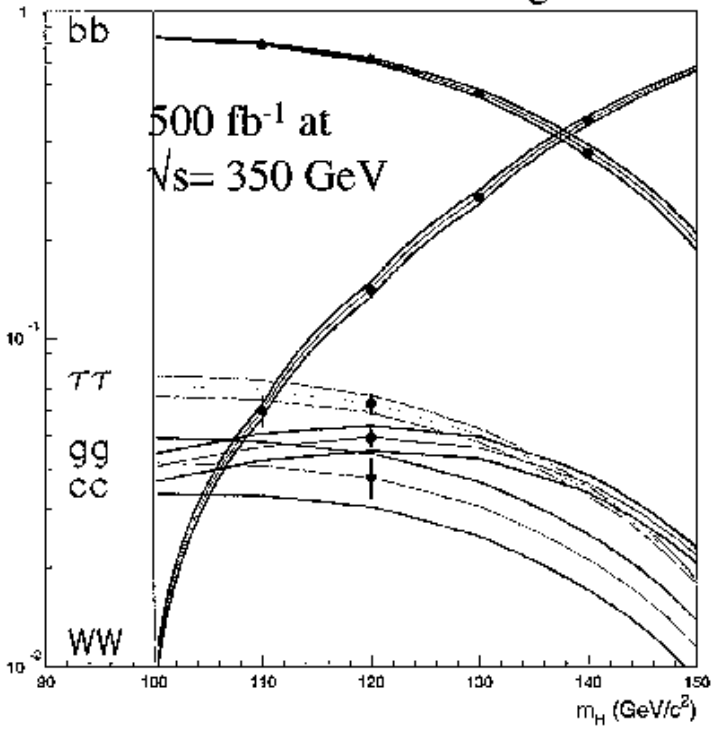
Higgs BRs

Contours of difference in bb fraction for SM/MSSM Higgs



Measure BR's for all decay modes:

Battaglia et al.



ΔB/B for m_H=120 GeV

bb 4%

WW 5%

ττ 6%

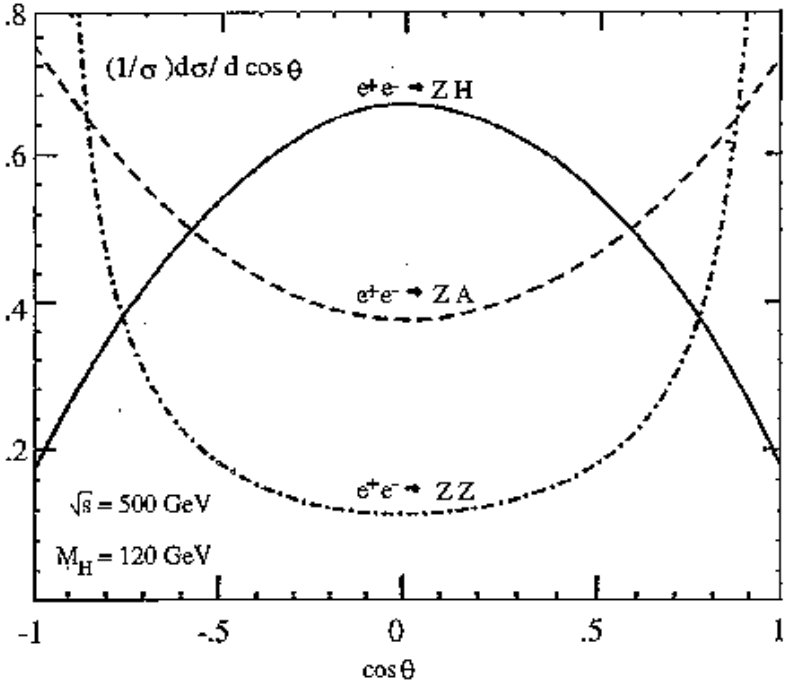
gg 8%

cc 15%

(γγ 15%)

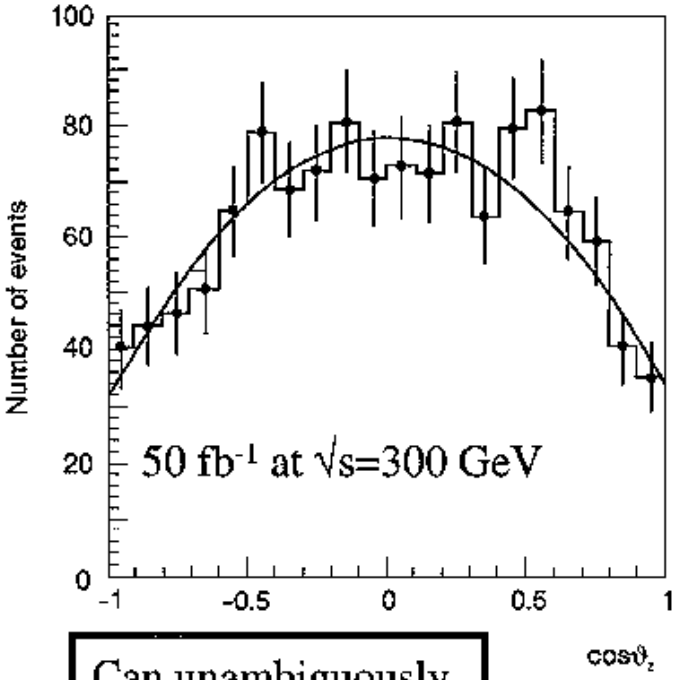
Higgs Spin and Parity

Can be determined from the angular distribution of the decay products and the production angle of the associated Z:



Difficult to do at the LHC

Janot



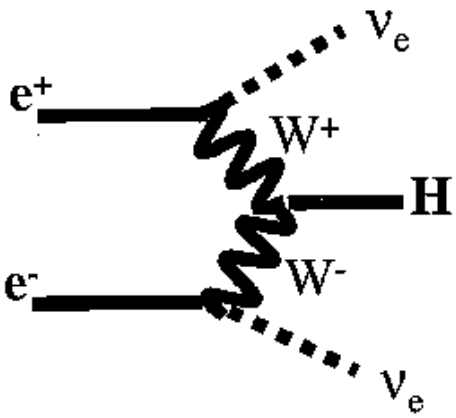
Can unambiguously show that $J^P=0^+$

Higgs Width

Γ_{tot} can be derived in two independent ways :

1. From $\gamma\gamma$ collisions, can measure $\Gamma_{\gamma\gamma}$ (photon collider or maybe even $e^+e^- \rightarrow e^+e^- H$)

2. From WW fusion, can measure Γ_{WW}



$$\Gamma_{tot} = \Gamma_{\gamma\gamma} / BR_{\gamma\gamma} = \Gamma_{WW} / BR_{WW}$$

Errors on BR dominate (especially for $\gamma\gamma$), so best precision expected from WW :

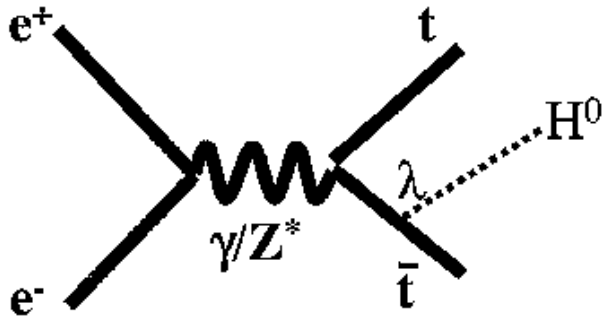
Total width can be determined to better than 10% (typically 3%) for Higgs masses exceeding 110 GeV.

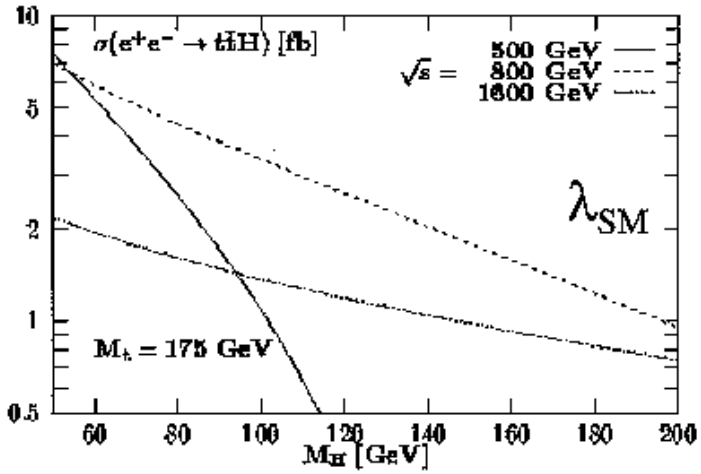
Top Yukawa Coupling to Higgs

The top quark mass is large : 175 GeV ! (while m_π= 140 MeV)

SM explanation of large top mass is a huge Yukawa coupling, λ

Test by measuring Higgs radiation in top-pair events :





(LHC precision ≈ 20% but only for light Higgs)

Signature : W W b $\bar{b}$ b $\bar{b}$

Background (t $\bar{t}$):W W b $\bar{b}$

For 800 GeV and high lumi (1000 fb^{-1}) can measure λ to 5%

Higgs Self-Coupling

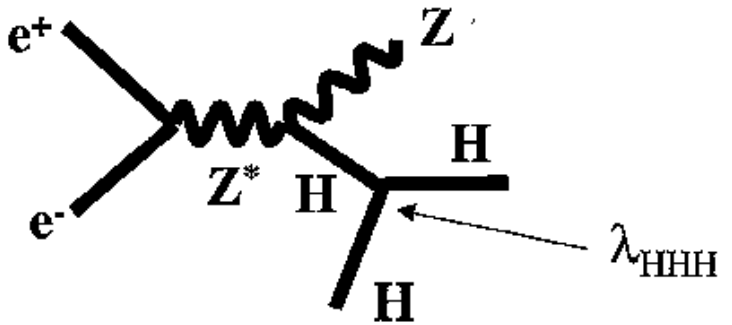
Experimentally, probe the Higgs potential :

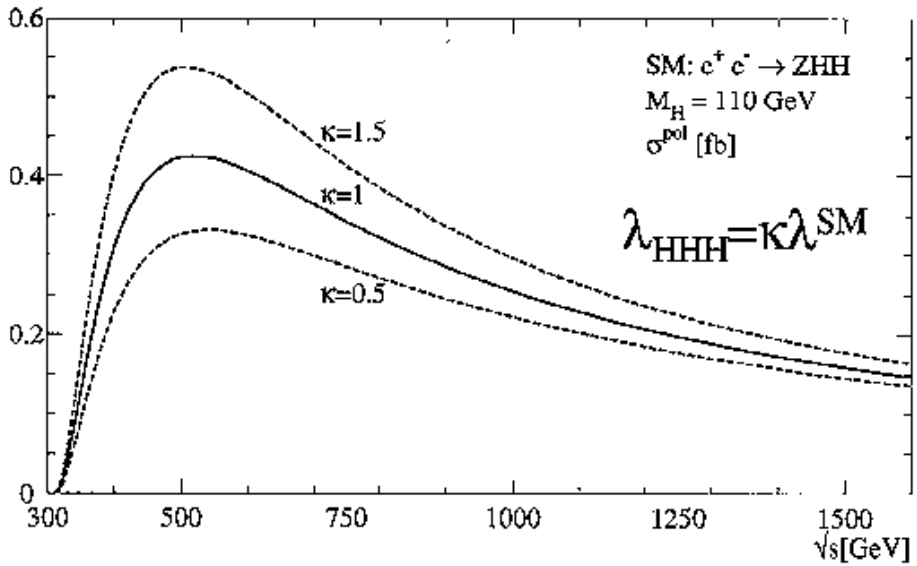
$$V = \mu^2\phi^2 + \lambda\phi^4$$

SM has explicit relation between the Higgs self-coupling λ and its mass.

$$M_H^2 = \frac{\sqrt{2}}{G_F}\lambda$$

Test it !





With 1000 fb^{-1}, few hundred events : measure to ≈ 20%

Precision physics (Z-pole observables)

TESLA design : L = 5.6×10^{33} at the Z^0 with polarisable e- and e+

Equivalent to 4 Giga-Z's , 6×10^8 B's , 2.5×10^8 e,μ,τ's (per year)

Just some of the possible physics applications are :

Improve on $\sin^2\theta_W$ using A_{LR}

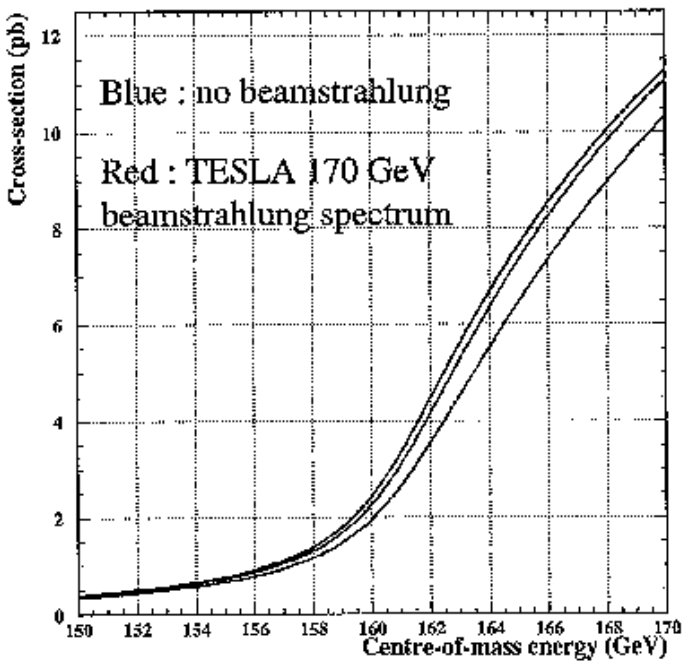
Expected statistical precision : $\Delta A_{LR} = 4 \times 10^{-5} \sqrt{\frac{10}{N_Z}}$

Systematics from E_{beam}, beam-strahlung => 10^{-4} on A_{LR} (Moenig)
equivalent to $\Delta \sin^2\theta_W$ of 10^{-5}

Improve on Γ_{had}/Γ_l (Measure ratio of hadron to lepton cross-section). Potentially an order of magnitude improvement in α_S...
Error of 0.5% on α_S feasible (match theory error)

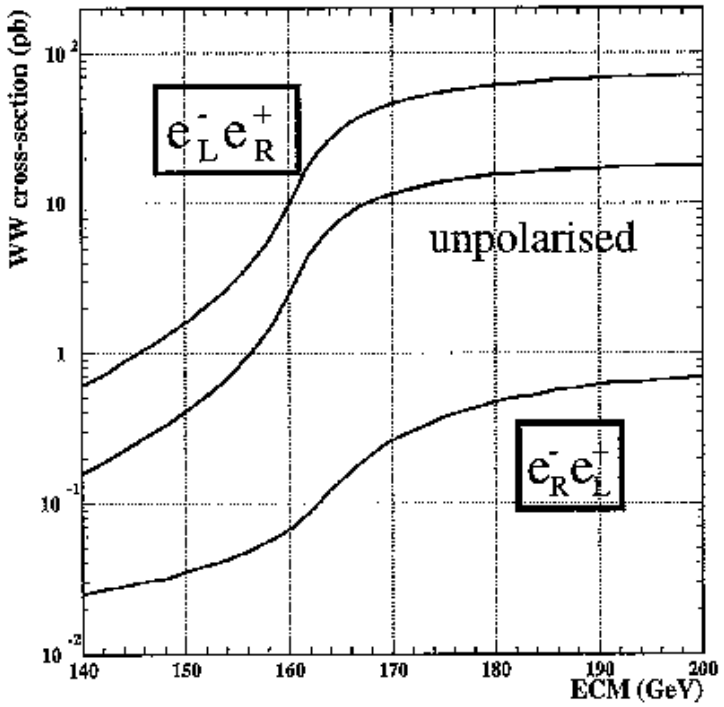
M_W (W threshold scan)

Beam-strahlung : not a big effect



Use Z mass for E-calibration

Use Polarisation to increase the signal AND measure the background

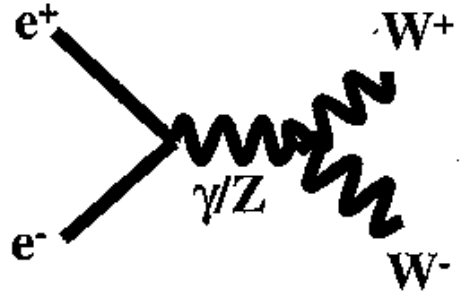


100 fb^{-1} (1 year with TESLA) gives ΔM_W of 6 MeV

GWW

WW couplings (high E)

Measure WWγ and WWZ couplings :



Full reconstruction of W production and decay (as at LEP2)

Example (least constrained)

Precision on $\Delta\kappa_\gamma$: 0.0002 (Burgard)

Anomalous couplings expected to be suppressed by factors of order $\frac{M_W^2}{\Lambda^2}$

Other machines : LEP2 (now) 0.09

LEP2 (soon) 0.05

LHC 0.02

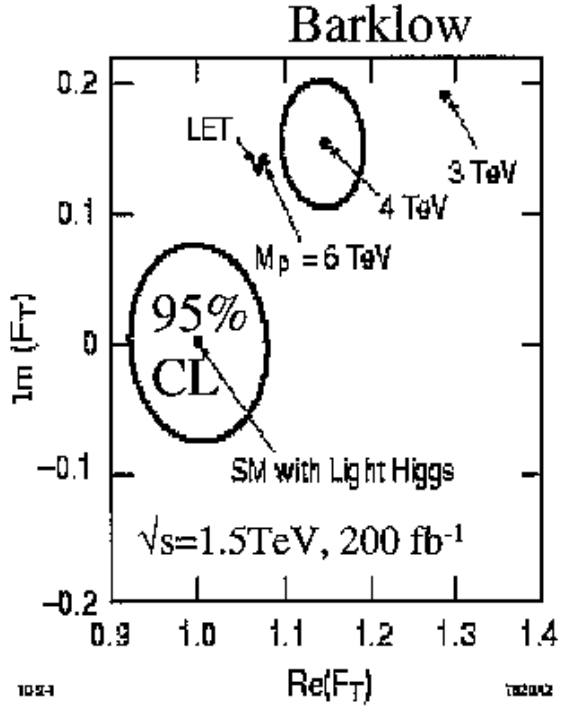
So, precision measurements of W-pairs will probe to much higher energy scales than at the LHC

New Physics : Strong EWSB

If there is no Higgs, expect WW TGC couplings to deviate from the SM.

Strong EW symmetry breaking can lead to eg. techni-rho resonances affecting the $W_L W_L \rightarrow W_L W_L$ channel and the WW cross-section

Resonances with mass of order 5 TeV are observable this way (LHC sensitivity around 1.5 TeV)

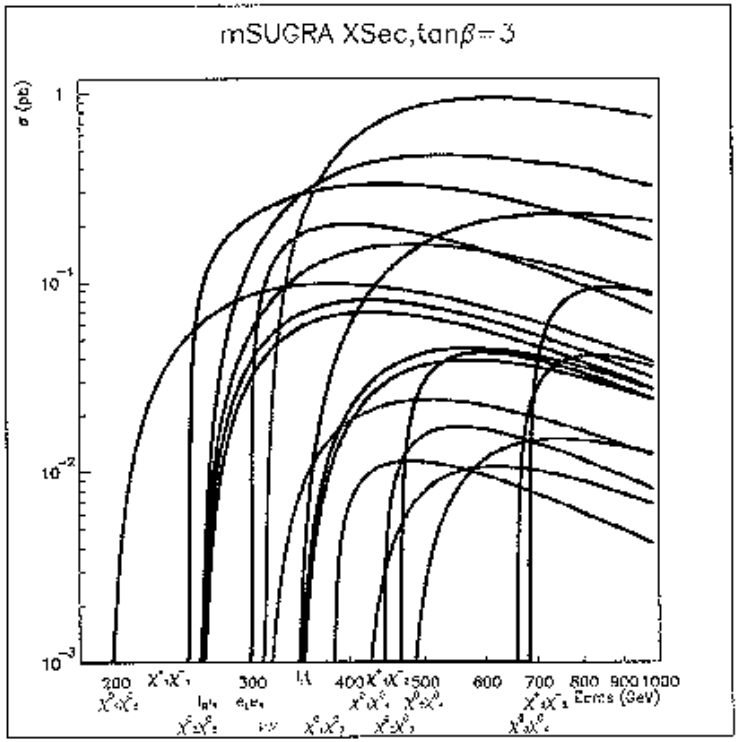


(F_T is WW rescattering coefficient)

Need either $\sqrt{s}$=1.5 TeV (200 fb^{-1}) or 1 TeV (2000 fb^{-1}) to test definitively whether the Higgs sector is strongly or weakly interacting for non-resonant case. (Barklow 92)

New Physics : Weak EWSB

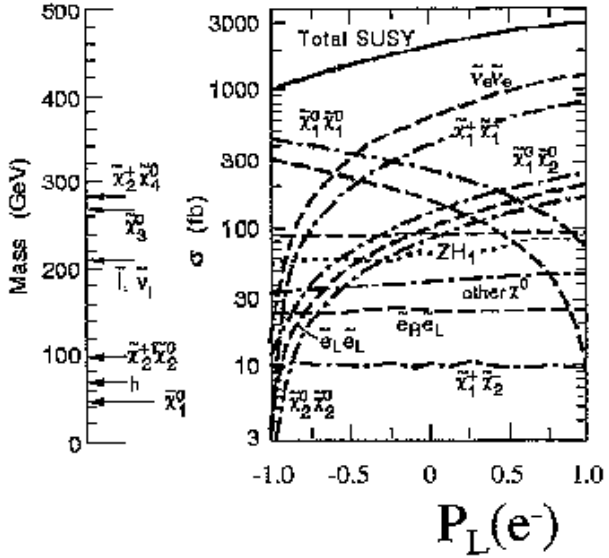
If Supersymmetry exists, then many new particles accessible to a LC :



The LC offers the opportunity for comprehensive measurements of them in a systematic way :

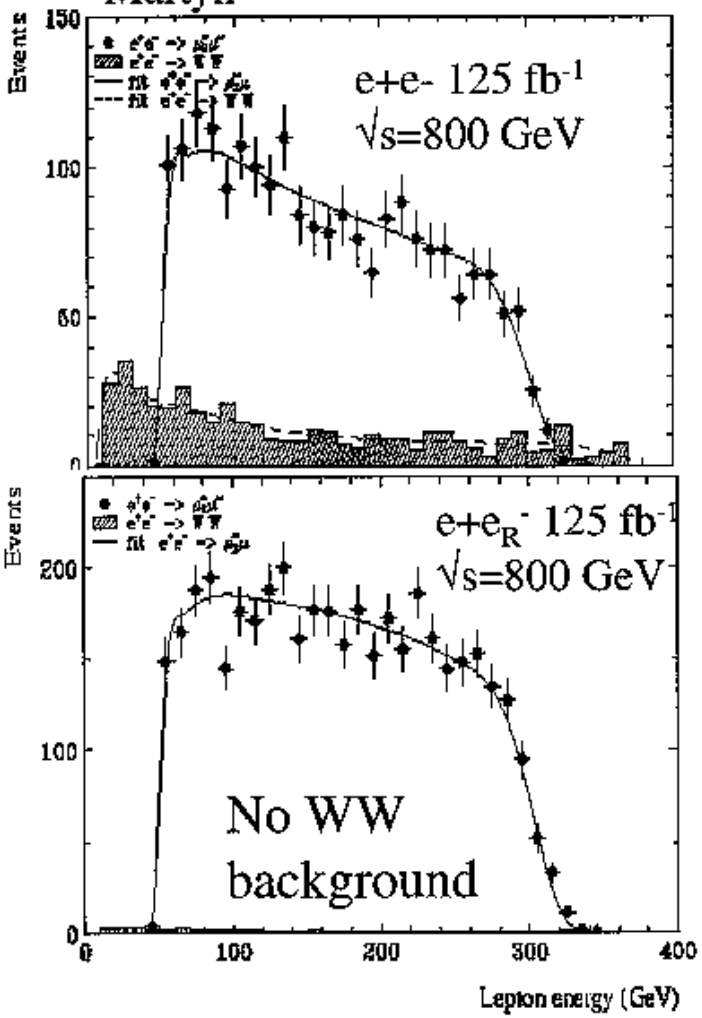
Masses : from kinematics and threshold scans

Couplings : using beam polarisation

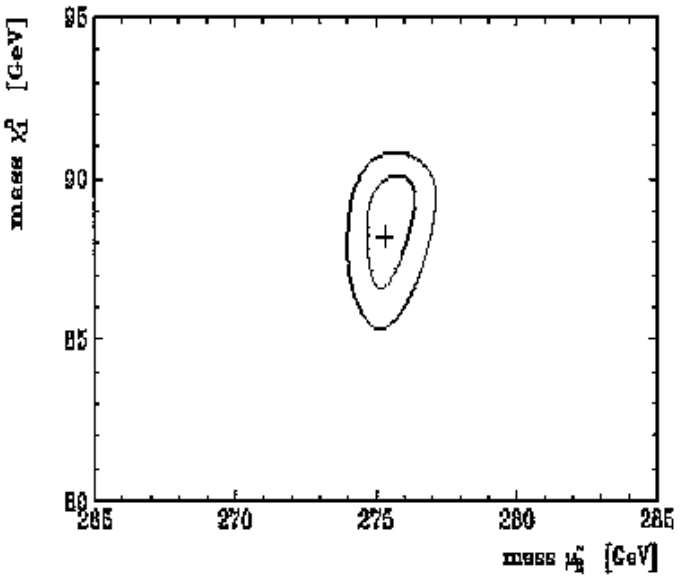


SuSy Measurements

Martyn



Example : Smuon Pair Production



With polarised e- can measure

smuon mass to 0.8 GeV

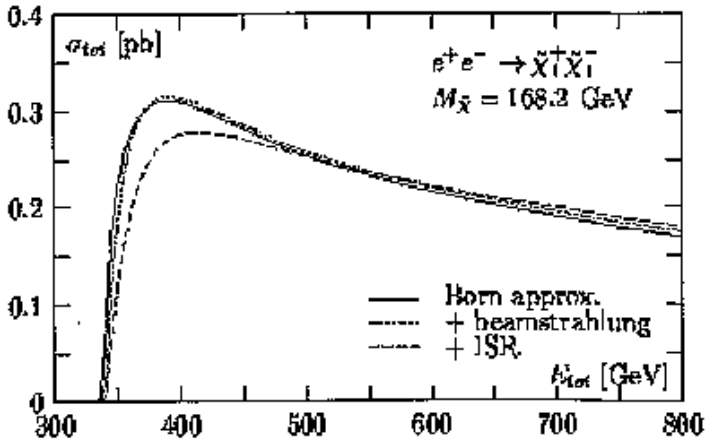
neutralino mass to 1.7 GeV

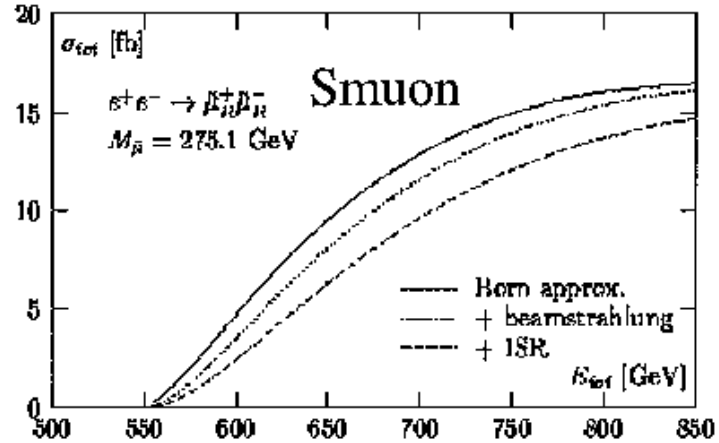
Threshold Scans

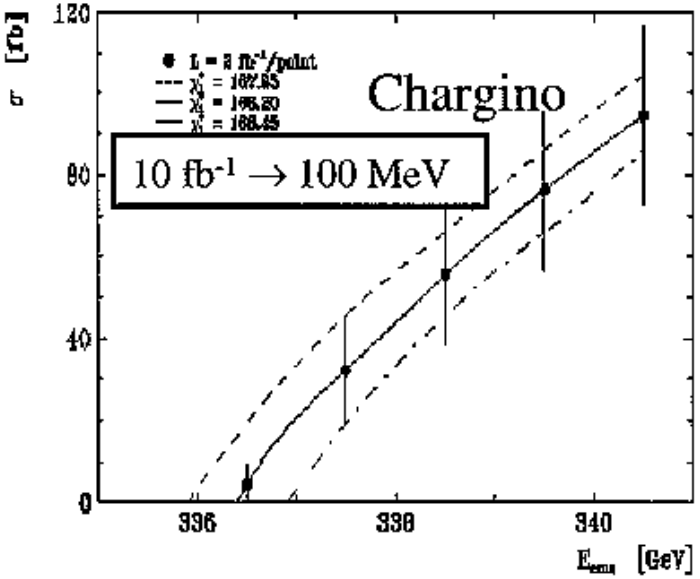
Slepton mass can be measured more accurately at threshold (β^3/s though)

Measure smuon mass to 300 MeV (100 fb^{-1})

Most accurate for β/s rise. Eg. selectrons in e-e- !, or charginos in e+e-.







Particle mixings

Many SUSY particles are mixed states :
neutralinos, charginos, stop, sbottom, stau.

Beam polarisation is essential to unravel this.

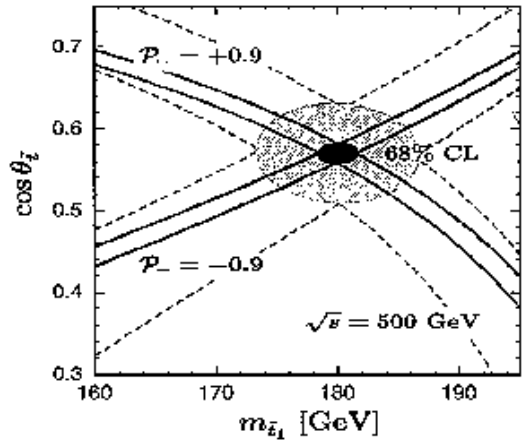
Example : Measure stop-pair production cross-section for left and right-handed electrons :

Extract mass and mixing angle

Kraml et al.
Determination of MSSM parameters with polarized e^- beams

— high lumi —

$m_{\tilde{t}_1} = 180$ GeV, $\cos\theta_{\tilde{t}} = 0.57$



$\mathcal{L} = 300$ fb^{-1}: we ESTIMATE errors

$\mathcal{P}_- = -0.9$ ... $\sigma(\tilde{t}_1\bar{\tilde{t}}_1) = 61.2 \pm 1.5$ fb

$\mathcal{P}_- = +0.9$ ... $\sigma(\tilde{t}_1\bar{\tilde{t}}_1) = 57.1 \pm 1.4$ fb

SUSY-QCD corrections taken into account

$\Rightarrow \quad m_{\tilde{t}_1} = 180 \pm 1.65$ GeV, $\cos\theta_{\tilde{t}} = 0.57 \pm 0.012$

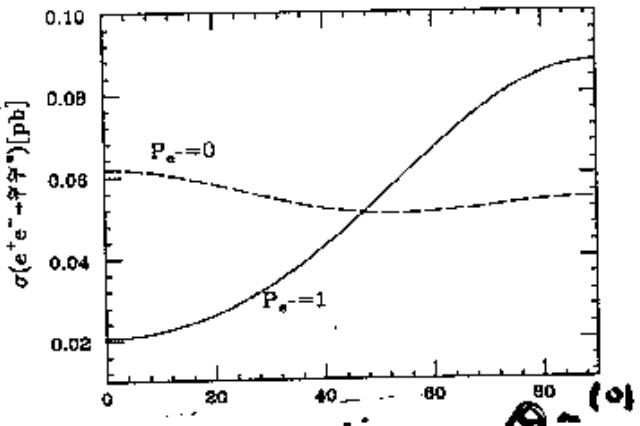
$\tilde{\tau}$ PHYSICS

$e^+e^- \to \tilde{\tau}_1^+ \tilde{\tau}_1^-$

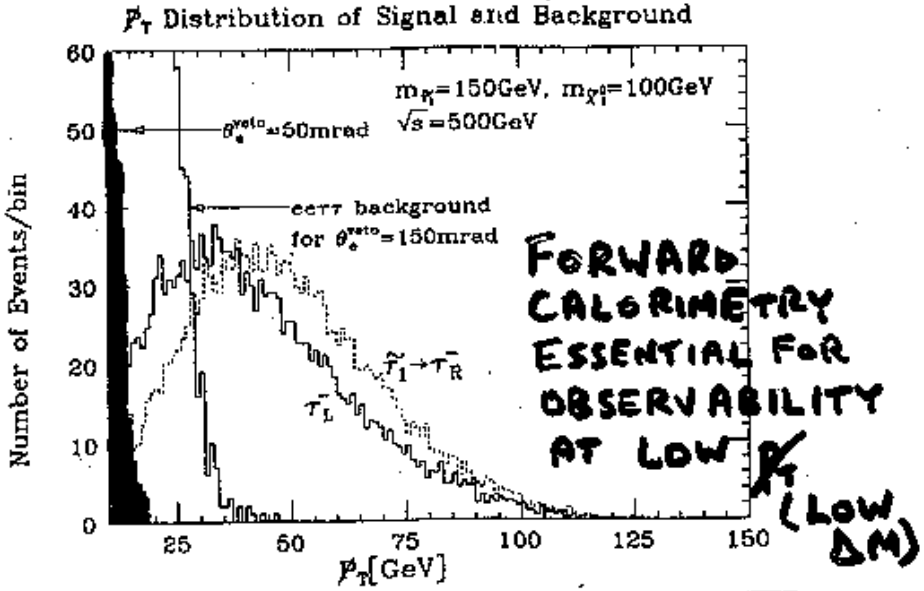
$\tilde{\tau}_1 \to \tau \tilde{\chi}_1^0$

$$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta_{\tilde{\tau}} & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{\tau}_L \\ \tau_R \end{pmatrix}$$

$\sigma_{\tilde{\tau}_1\tilde{\tau}_1}$ (pb)



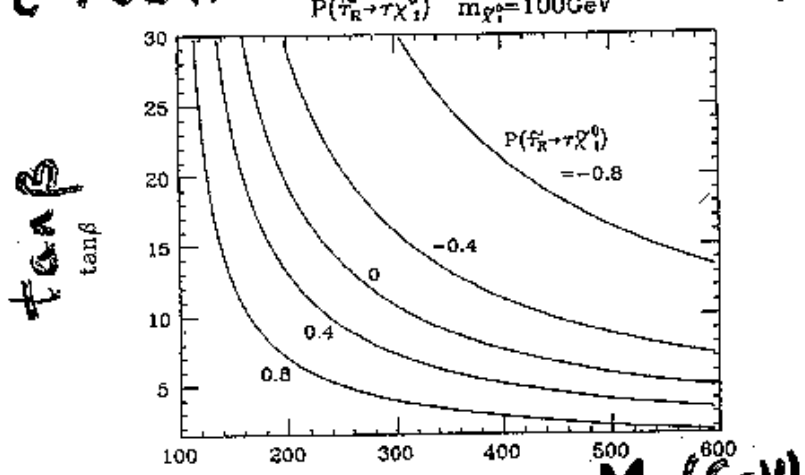
$\theta_{\tilde{\tau}}$

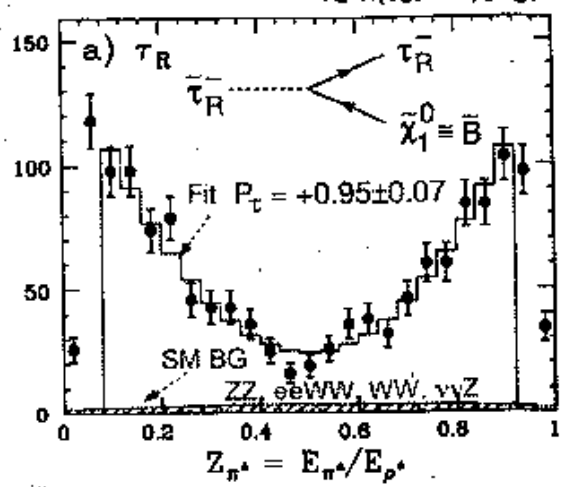


FORWARD CALORIMETRY ESSENTIAL FOR OBSERVABILITY AT LOW P_T (LOW ΔM)

τ POLN. IN $\tilde{\tau} \to \tau \tilde{\chi}_1^0$ DECAY

Tsukamoto et al.





SPIN ANALYSE $\tilde{\tau}^+ \to \rho^+ \nu_\tau$ DECAY TO MEASURE P_τ (DEPENDS ON $\tilde{\chi}^0$ MIXING)

What can be learned about SuSy ?

- With definitive measurements of SuSy particles : can test the theory
  - Establish supersymmetry breaking mechanism ?
  - Gauge unification ?
  - Sfermion Universality ?
  - Is R-parity a conserved quantum number ?
  - Is observed SuSy and Higgs phenomenology consistent ?
  - What particles are missing ?
  - Is there a viable dark matter particle with appropriate mass and couplings ?
  - Can physics near the Planck scale be calculated ?
- The LC will excel in providing the measurements needed to answer these sort of questions (if SuSy exists ...)

Conclusions

- The linear collider has a broad and rich physics programme
- "Dream-machine" for Higgs and Susy
- Ideal laboratory for comprehensively exploring and understanding the mass range from 100 GeV to 1 TeV
- LC Advantages : Diagnose what is going on :
  - Well-defined kinematics
  - Highly Polarised e- and e+
  - High Luminosity (5xLHC) with feasible technology
  - No pile-up, no trigger, no decay backgrounds, 4π detector
  - Adjustable energy (90-160-250-350-500-750-1000 GeV)
  - Other modes : e-e-, $e\gamma$, $\gamma\gamma$
- Let's play a leading role in making it a reality.