Experimental Aspects of LC Physics (SM, GigaZ, WW)

Graham W. Wilson
University of Kansas

May 9th 2002

Workshop on Radiative Corrections for Linear Collider Physics

Brookhaven

Outline

- Present status of theoretical calculations as seen by existing e^+e^- experiment (LEP2).
- Linear collider – accelerator, detector, determination of initial conditions.
  - This may well benefit from theoretical input (hard radiative corrections – not loops so much!)
- Physics program of Giga-Z, WW threshold, 2f measurements at high energy.

Orientation of the talk

- I'll be relatively brief on "selling" the physics that may be possible at a LC particularly one capable of high lumi at low energy
  - Why. a) you are familiar with many of the arguments.
  - b) As an experimentalist who has worked at LEP2, it is not just the far-off possible data from a LC which challenges current theoretical calculation and modelling of Standard Model processes.
  - So I think part of my job is to highlight areas which are very relevant to the success of a LC program where theoretical work will be badly needed.

Theoretical Uncertainties at LEP2

Already with 2 fb^{-1} (not 1000 fb^{-1}) , theory is hard pushed to keep up with experiment even for 2f observables ! (LEP2 should have been a statistics limited exercise)

M. Kobel et al. hep-ph/0007180, report on precision calculations for LEP2 physics

Table 35: Comparison of the typical theoretical uncertainties with the typical experimental precision tags

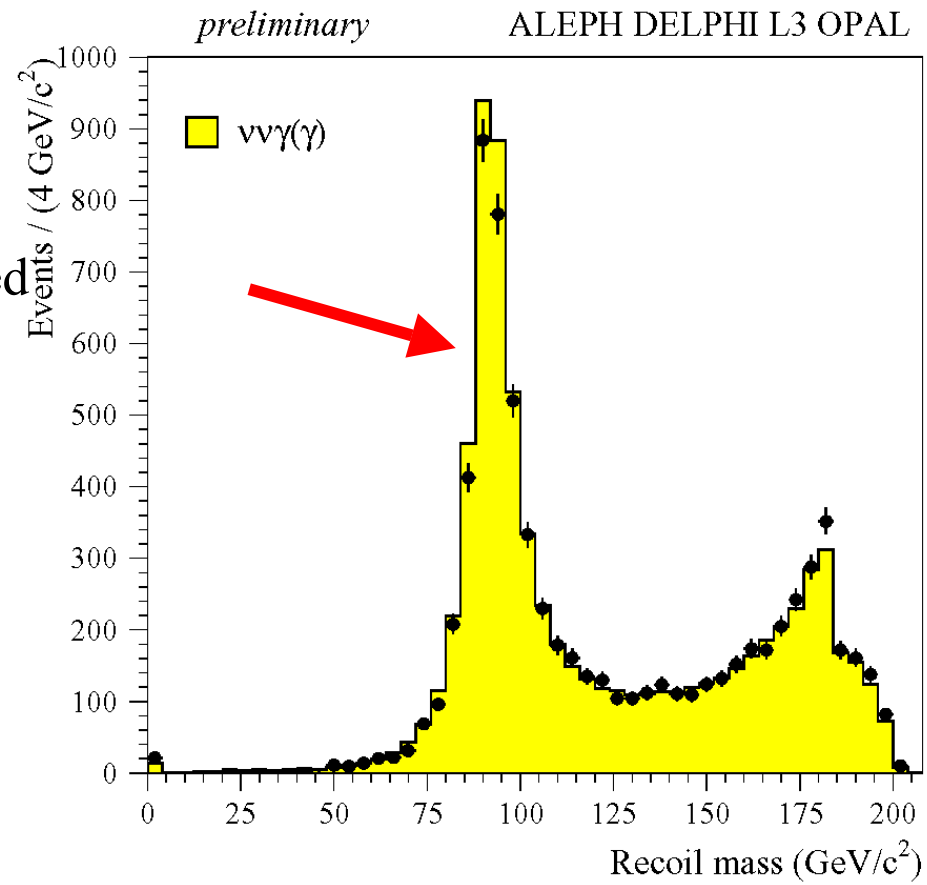
class of observables	theoretical uncertainty	experimental precision tag
$e^+e^- \to q\bar{q}(\gamma)$	0.26 %	0.1 % -0.2 %
$e^+e^- \to \mu^+\mu^-(\gamma)$	0.4 %	0.4 % -0.5 %
$e^+e^- \to \tau^+\tau^-(\gamma)$	0.4 %	0.4 % -0.6 %
$e^+e^- \to e^+e^-(\gamma)$ (endcap)	0.5 %	0.13 %
$e^+e^- \to e^+e^-(\gamma)$ (barrel)	2.0 %	0.21 %
$e^+e^- \to e^+e^-\gamma$	3 %	1.5 %
$e^+e^- \to l^+l^-\gamma$	1 %	1.5 %
$e^+e^- \to \nu\bar{\nu}\gamma$	4 %	0.5 %

Example : Single photon "anomaly" at LEP2

$e^+e^- \rightarrow \gamma + E_T^{miss}$

Many fewer events observed in radiative return peak than predicted by KORALZ.

Is this exptl uncertainty, theory uncertainty (or new physics) ?

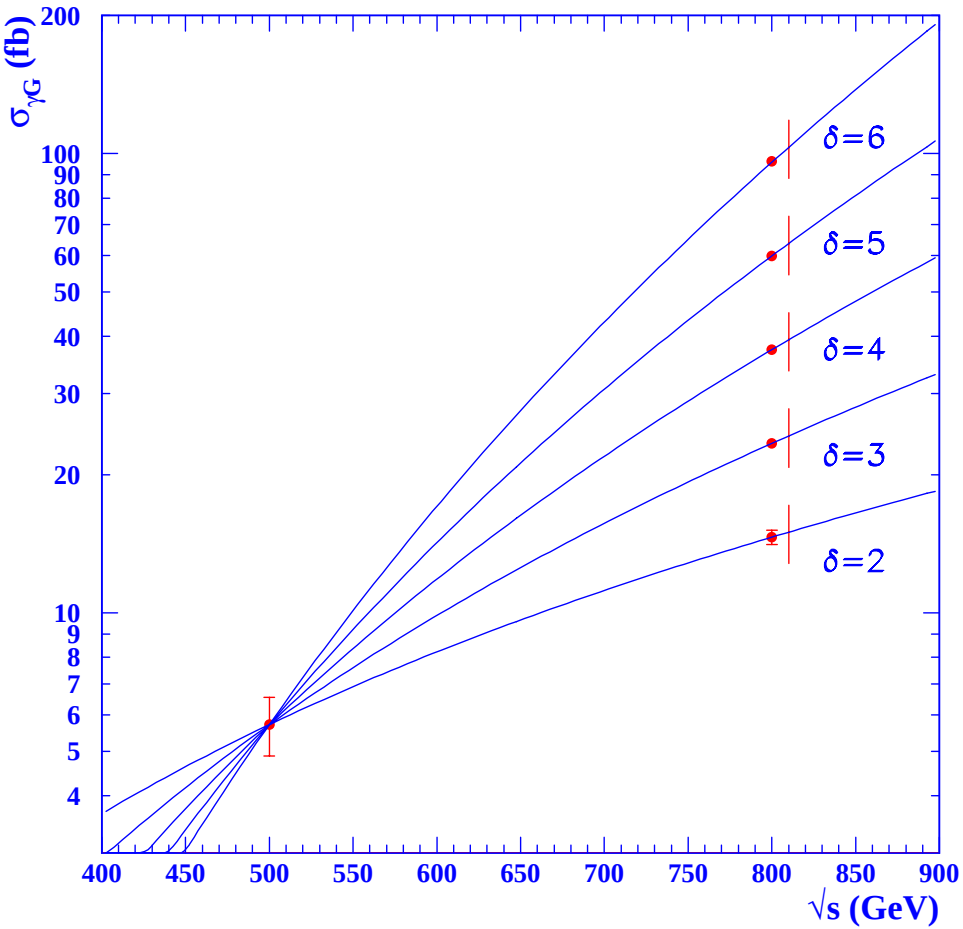


New calculations by Was et al – KK2f – looks to have several sources of error under better control BUT lack of independent cross-checks makes the authors of the apparently state-of-the-art code queasy about quoting theoretical errors smaller than 2% on the INCLUSIVE cross-section

Measuring the number of extra dimensions ??

This study assumed a total exptl + theory syst error of 0.3 % (geometric mean of plausible 0.1% - 1% range)

LEP2 search reach limited by theory error on SM XS



Equivalent to M_D=5.0±0.04 TeV (δ=2)

γG cross-section has power-law dependence on δ with √s

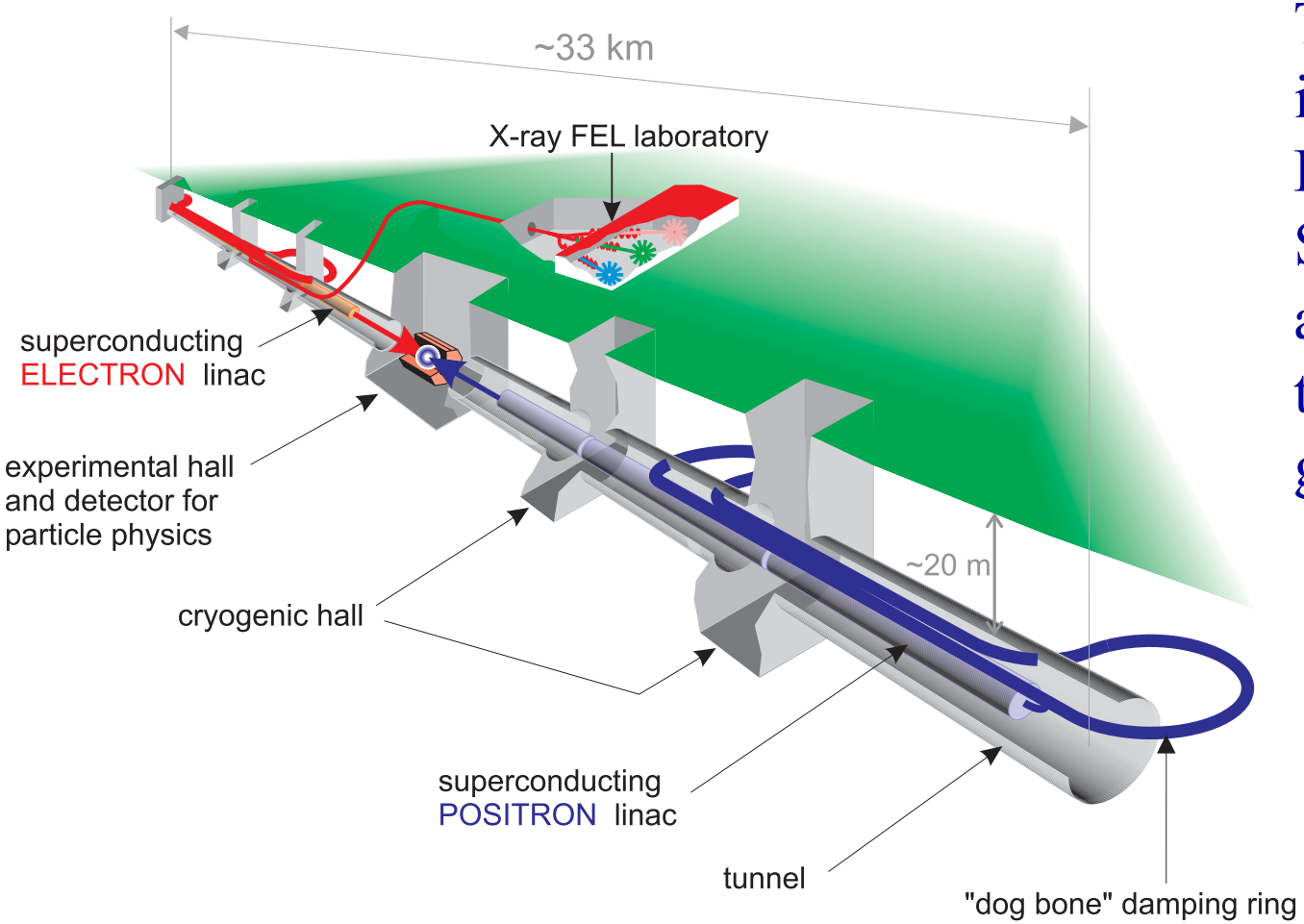
With 0.5ab^{-1} at 500 GeV and 1 ab^{-1} at 800 GeV, can determine δ at 99% CL for σ_{500} as low as that for M_D=5.1 TeV (δ=2)

Single photons :

20th century - measure N_ν

21st century - measure δ ! (and M_D)

e^+e^- Linear Colliders



Three major initiatives at DESY (TESLA), SLAC (NLC) and KEK (JLC) to develop a next generation LC

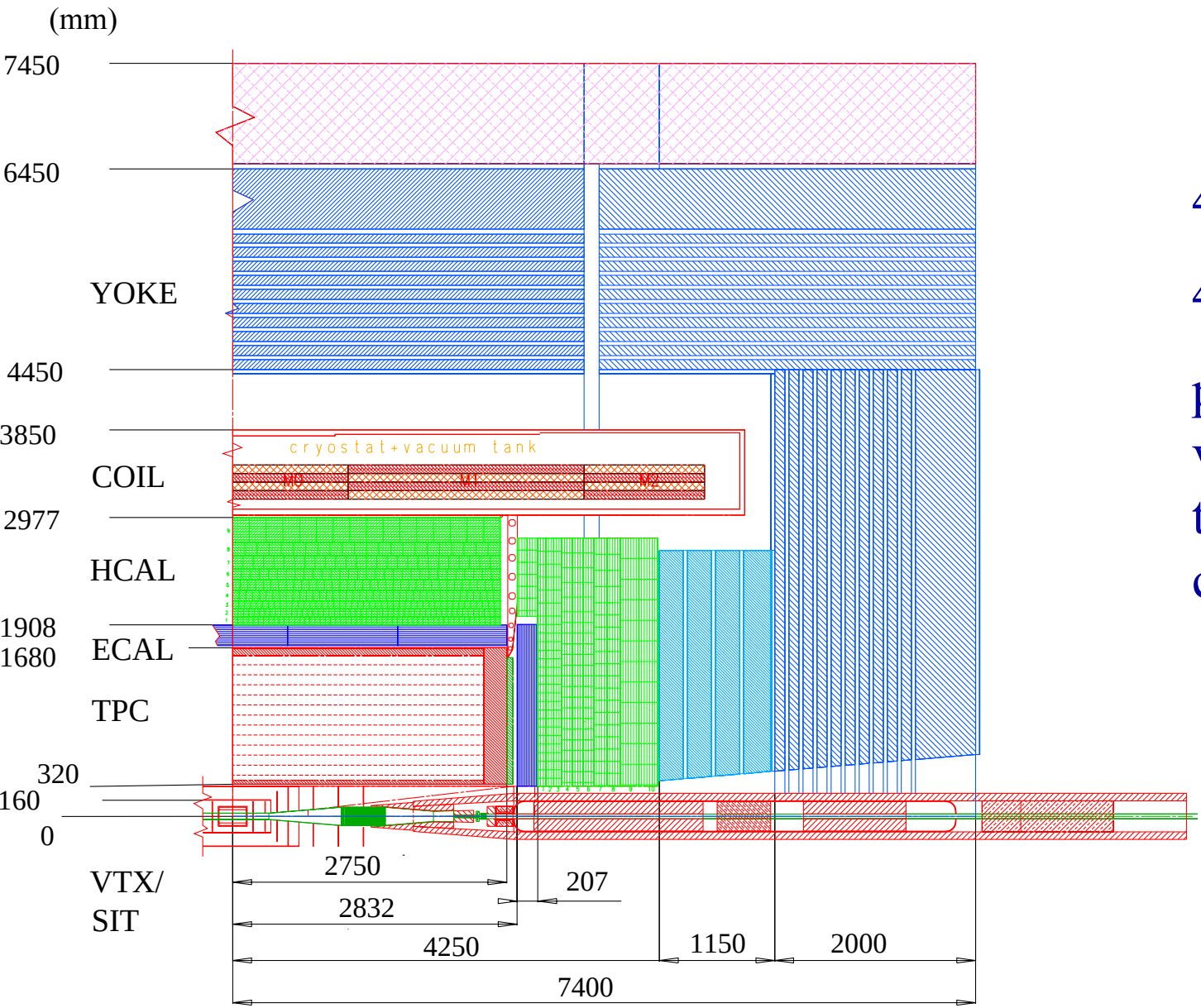
Some differences for experiment from technology choice – but should not be so important for theorists

HEPAP (US), ECFA (Europe), ACFA (Asia) have recommended expeditious construction of a LC as an international project as the next major initiative in HEP

Accelerator Parameters

- LEP/SLD
  - e^+e^-, 0.09-0.2 TeV, last millenium, 0.5 fb^{-1}/expt
- Tevatron run II
  - p pbar 2 TeV, now-2008 2-15-30 fb^{-1}
- LHC
  - p p 14 TeV , starts ~ 2007, 100 fb^{-1} /year/expt
- Linear Collider (LC)
  - e^+e^-, e^-e^-, $e^-\gamma$, $\gamma\gamma$. $\sqrt{s}$ =0.09- 1 TeV. Proposed. Data by 2012 ? Polarised e^- (80-90%). Polarised e^+ possible (< 60%).
  - 300 fb^{-1}/year at 0.5 TeV

TESLA Detector



4π detector

4T solenoid

precision vertexing, tracking and calorimetry

Using linear colliders for physics

Eg. TESLA 5 10^{33} @ 100 GeV. 5 10^{34} @ 800 GeV.

Longitudinal Polarisation for e^- (80%) and e^+ (60% - TESLA)

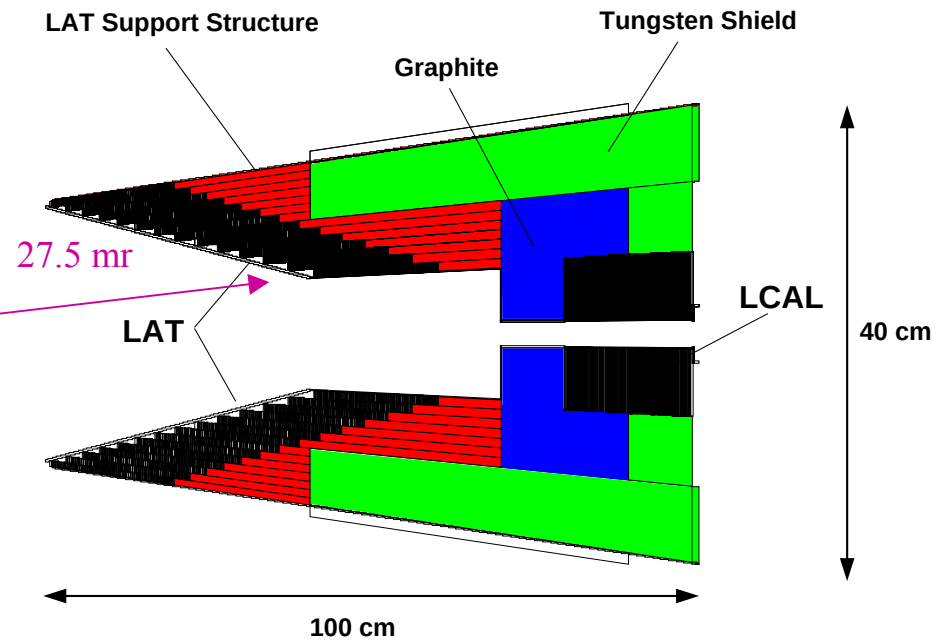
Can adjust √s. Can also choose to do physics with e^+e^-, e^-e^-,$e\gamma$,$\gamma\gamma$.

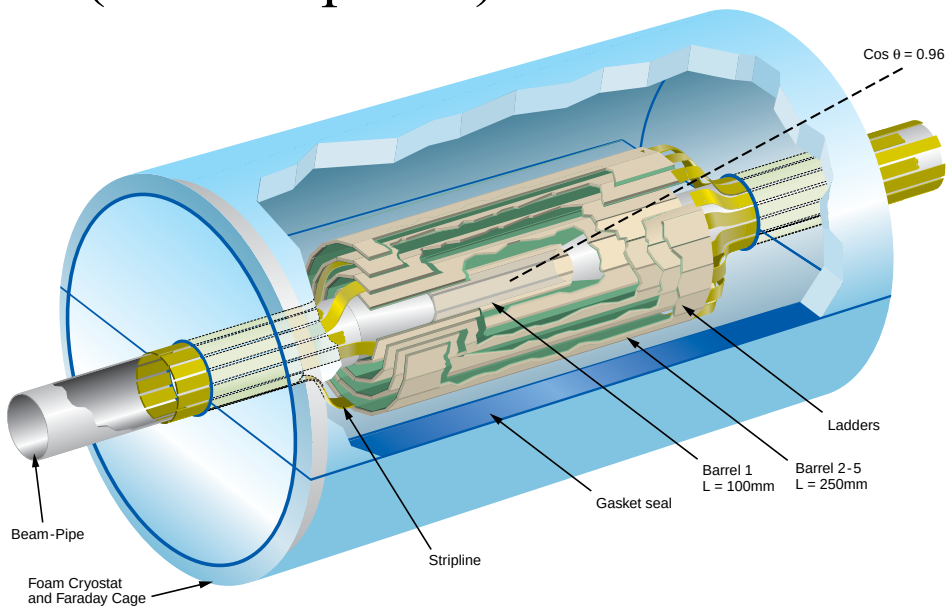
(Excellent physics diagnostic capability)

Hermetic EM calorimetry down to 27.5 mrad

SLD style vertex detector for excellent b,c, τ tagging.

(CCD or pixels)





5.1: *Design of the forward angle calorimeters. The sampling calorimeters (LAT*

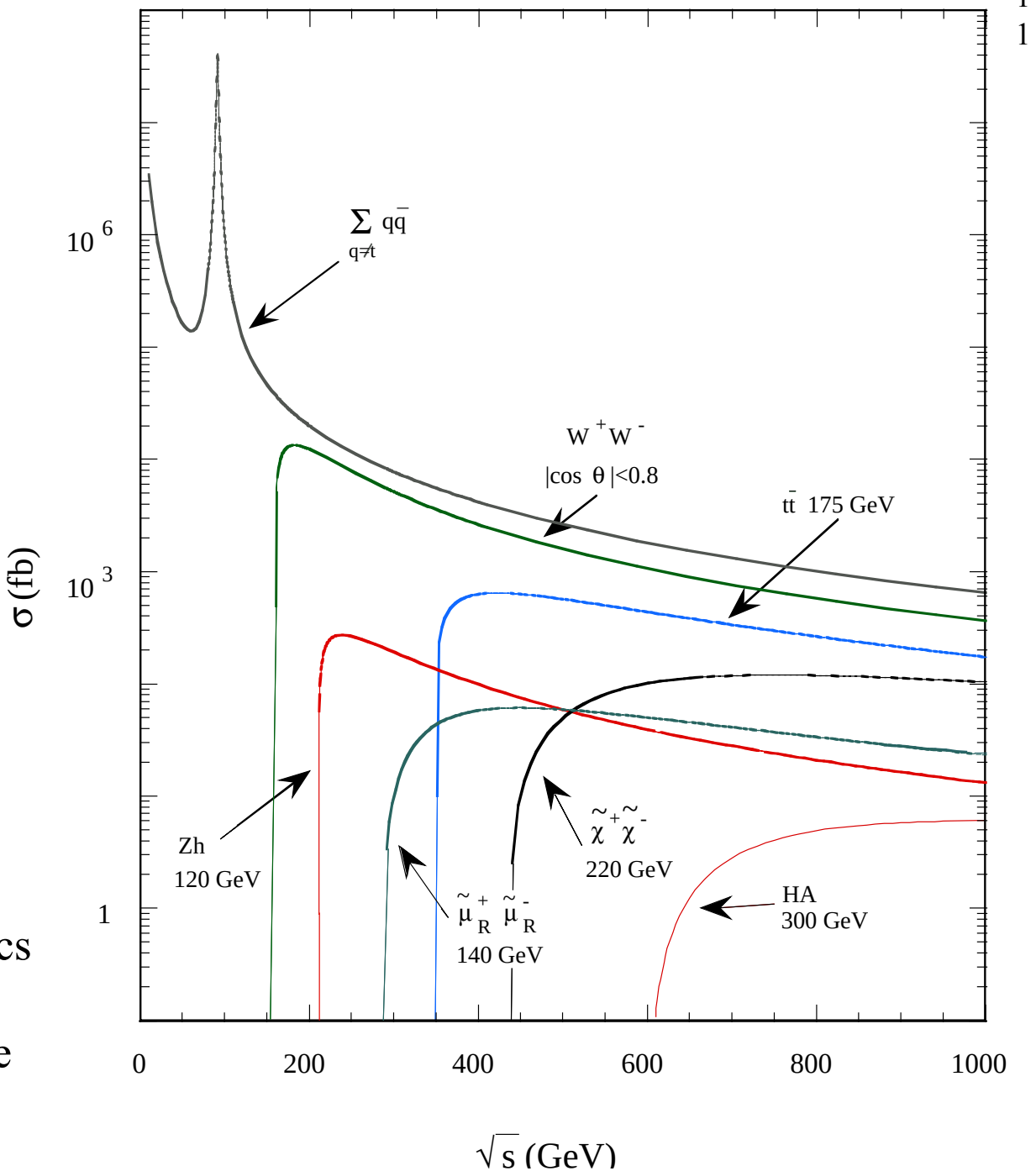
e^+e^- Cross-sections

At 500 GeV,

$L \approx 300\ fb^{-1} / 10^7 s$ year

Statistical errors in the 0.1% range achievable in 3 years with σ=1 pb

Not trivial for experiment to achieve 0.1% type systematics BUT not at all impossible especially for the detector we are designing



Low Energy Running

- Note that an accelerator designed for initial operation at $\sqrt{s}$ = 500 GeV and extendable to around 1 TeV, will not necessarily take any substantial data-set at the Z or WW threshold.
  - Comprehensive Higgs program
  - And hopefully, exploration of the new physics will be the top priorities
- These running possibilities are "options" which depending on the physics du jour may or may not be attractive
  - But we should strive to keep the accelerator design compatible with them.

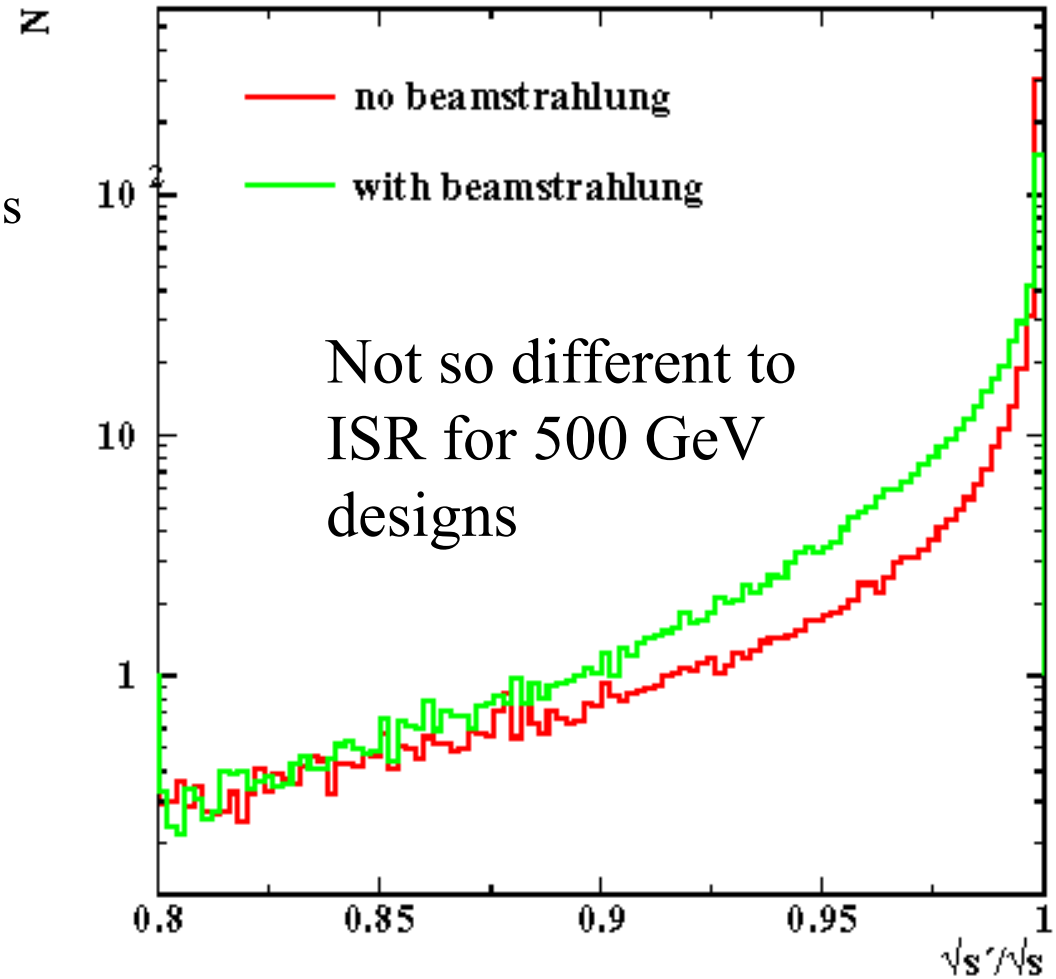
Linear colliders vs synchrotrons

Three significant accelerator challenges to the physics program:

(i) Beamstrahlung leads to degradation of luminosity spectrum – accelerator dependent

(ii) Precise absolute beam energy determination

(iii) Development of novel polarised e^+ source

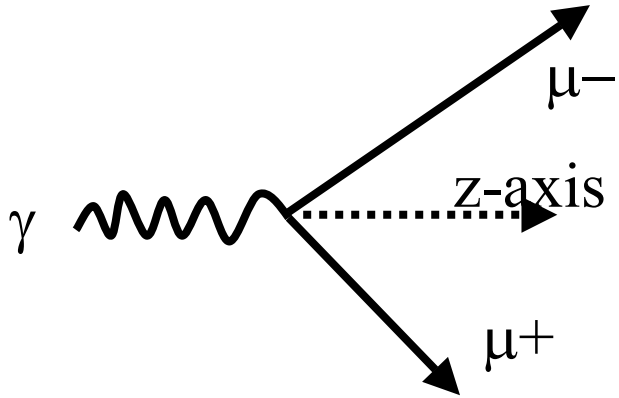


(No free lunch with a factor of 100 in L, a factor of 5 in E, and polarised beam(s) compared to LEP2)

Initial State Diagnosis

- Compared to traditional e^+e^- colliders, the linear collider environment imposes a different approach to determining the initial state.
  - This is key to doing really good physics, and needs theoretical effort.
    - Some of these channels are not even under good enough theoretical control at LEP2 !
- Luminosity spectrum measurement ($dL / d\sqrt{s}$) . This is likely to just be a RELATIVE measurement. Need to measure the beamsstrahlung which is convolved with radiated photons (mainly ISR).
  - Favoured method : s' algorithm angular measurement in Bhabha scattering at moderate (10°) angle (not well controlled theoretically at LEP2 ….) Study shows 5×10^{-5} precision from 3 fb^{-1} given precise forward tracker on relative CM energy.
- Centre-of-mass energy determination (calibration of the above abscissa - $\sqrt{s}$)
  - Precision Moeller spectrometer ?
  - In situ - use Z (γ) ? with $Z \rightarrow \mu\mu$. Can potentially use e^+e^- with similar precision.
- ABSOLUTE luminosity measurement.
  - Which channel : low-angle Bhabhas ?? (maybe not appropriate – background).
  - $e^+e^- \rightarrow \gamma\gamma$ is attractive experimentally – but SM calculations / MC not available with sufficient sophistication even for LEP1.
- Polarisation measurement
  - Best approach may be in situ with "Blondel scheme" (if polarised positrons available)

CM Energy from Radiative Returns

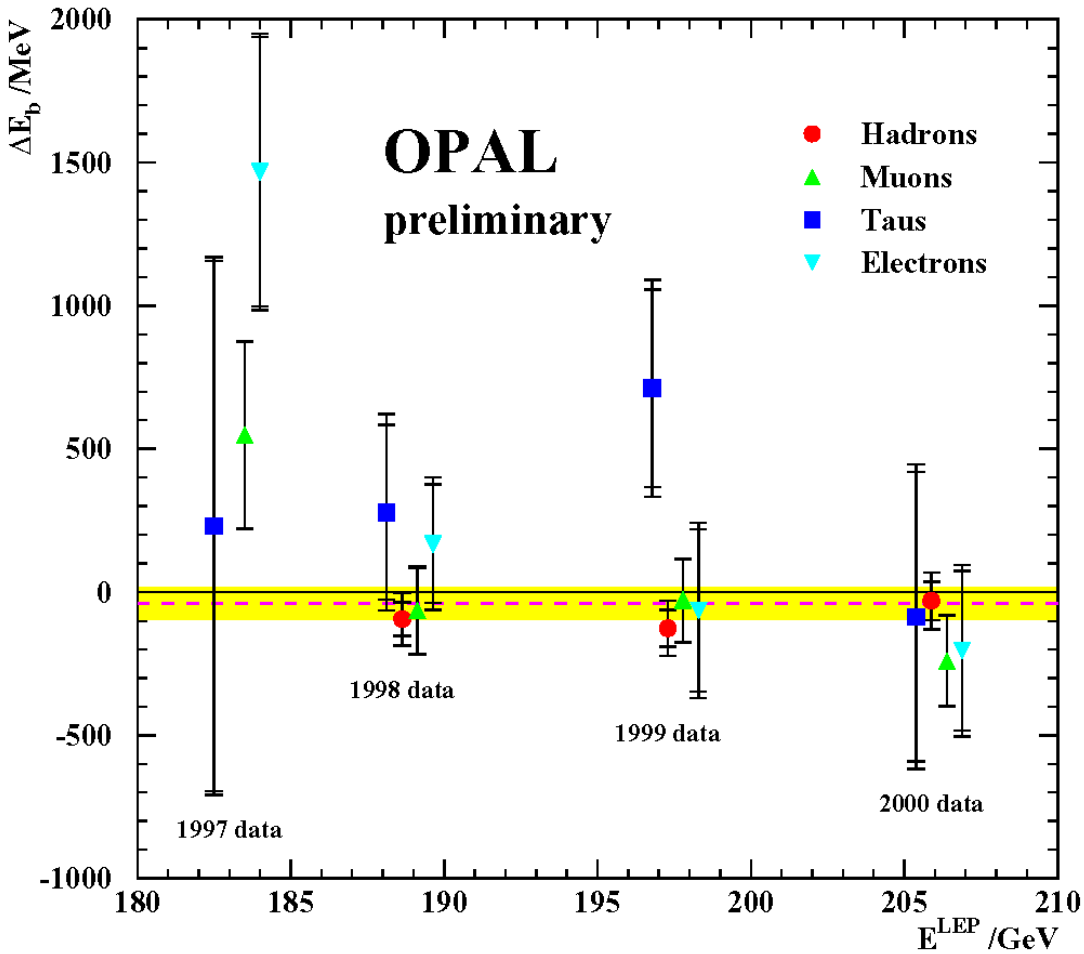


- Idea : Use $e^+e^- \rightarrow Z\,(\gamma)$ events.
- Best case $Z \rightarrow \mu\,\mu$.
  - In the low pT and zero mass for the photons limit, the muons will be back-to-back in the transverse plane, and the measured polar angles of the two muons can be related to the di-lepton mass scaled to √s using the usual s' algorithm)

$m_{ll}^2/s = 1 - 2\,|\sin(\theta_1 + \theta_2)| \,/\, \{|(\sin(\theta_1+\theta_2)| + \sin\theta_1 + \sin\theta_2\}$

Experimentally all we need to do is measure the polar angles with small systematic precision, and this measured quantity should tell us √s since we know m_Z.

Does it work ?



Main experimental requirement : systematic error on theta measurement < desired fractional error in E_{beam}.

Seems to : at least for OPAL

Note that the muons have the smallest experimental systematic error.

Hadrons don't offer the potential of reaching precisions at the few 10^{-5} level as needed for example for m_W

Prospects for improved EW measurements at high energy colliders

- Top mass (now to 5 GeV)
  - Tevatron run II (1.5 GeV)
  - LHC (1 GeV)
  - LC (< 0.1 GeV)

U. Baur et al, hep-ph/0202001 gives an extensive review including more details on Tevatron and LHC

- W mass (WA – 33 MeV (dominated by LEP))
  - Tevatron – 20 MeV
  - LHC - 15 MeV
  - LC - 6 MeV
- $\sin^2\theta_{eff}$ precision of 1.3 10^{-5} from A_{LR} at LC.

So, in particular with A_{LR} and m_{top} the LC would provide precision an order of magnitude better than otherwise achievable

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 : $\Delta A_{LR} = 4 \times 10^{-5} \sqrt{\frac{10^9}{N_Z}}$

Systematics from E_{beam}, beam-strahlung => 10^{-4} on A_{LR} (Moenig) equivalent to $\Delta \sin^2\theta_W$ of 1.3×10^{-5} and a factor of 20 improvement over SLD !!

Improve on $\Gamma_{had}/\Gamma_{l.}$ (Measure ratio of hadron to lepton cross-section). Potentially factor of 4 improvement in world average α_S...
Error of 0.5% on α_S feasible (match theory error)

Projected errors on Electro-weak quantities

	Now	LC with runs at Mz, 2Mw
• $\sin^2\theta^l_{eff}$	1.7×10^{-4}	1.3×10^{-5}
• M_Z	2.1 MeV	2.1 MeV
• α_S	0.0027	0.0009
• N_ν	0.008	0.004
• M_W	36 MeV	6 MeV

"Blondel" Scheme

$$\sigma = \sigma_u [1 - P^+ P^- + A_{LR} (P^+ - P^-)]$$

If polarised positrons are available can measure four polarised cross-sections : σ_{+-}, σ_{-+}, σ_{--}, σ_{++}.

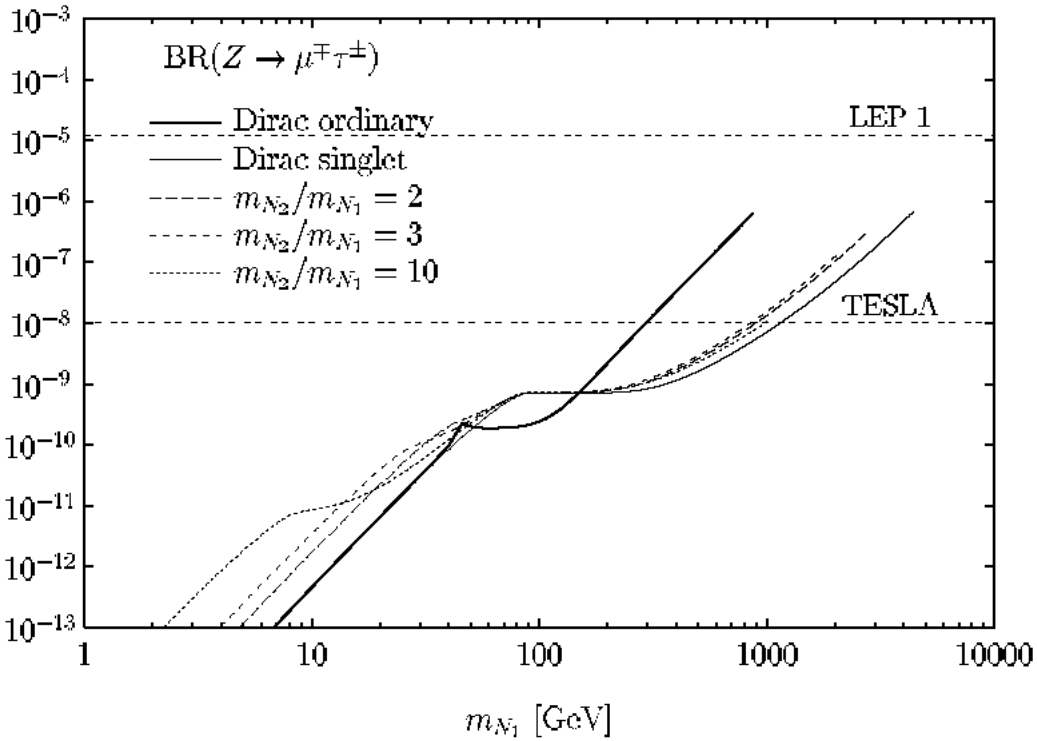
If the absolute polarisation values for electron bunches with opposing helicity states are equal, and likewise for the positrons, the measurement does not rely on ABSOLUTE polarisation measurements : (4 equations, 4 unknowns, σ_u, P^+, P^-, A_{LR}).

If polarised e^+ cannot be achieved, precision on A_{LR} would degrade by a factor of 4 assuming absolute polarisation measurements to 0.25%.

Rare Z decays

4×10^9 Z decays per year. Can look for rare decays of the Z. Eg. $Z \to \gamma\gamma\gamma$ or $Z \to \mu\tau$

T. Riemann et al

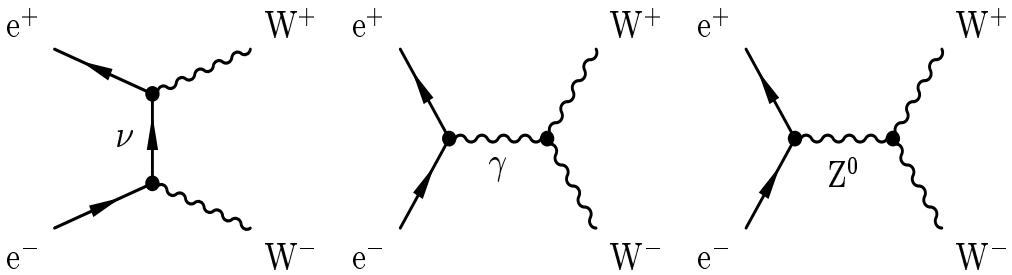


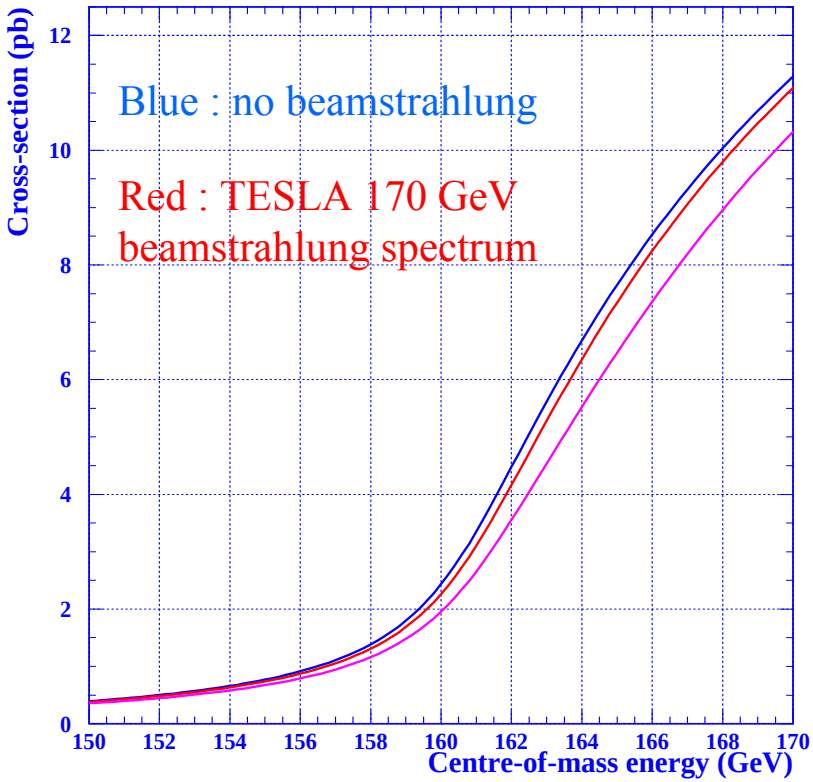
(Actually, I never bothered publishing a LEP1 search for $Z \to \gamma\gamma\gamma$ because it was systematics limited by theoretical calculation of QED background ….)

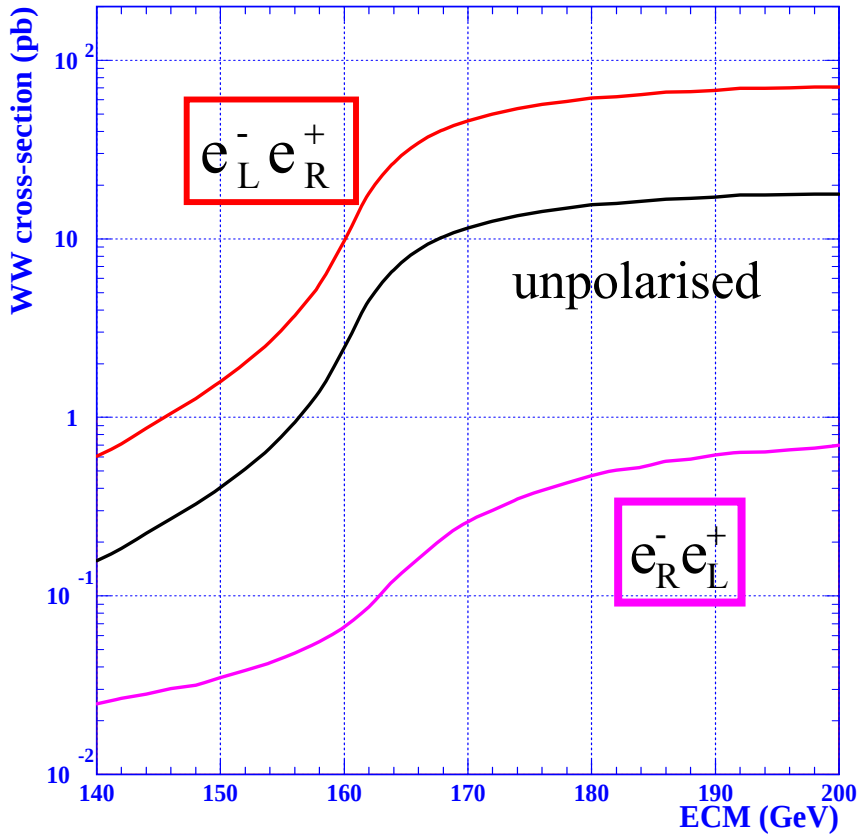
Superb momentum resolution reduces the $\tau\tau$ background.

M_W (W threshold scan)

NB Need precision √s absolute calibration before embarking on such a scan







Use Polarisation to increase the signal AND measure the background

Beam-strahlung : not a big effect

M_W Measurement

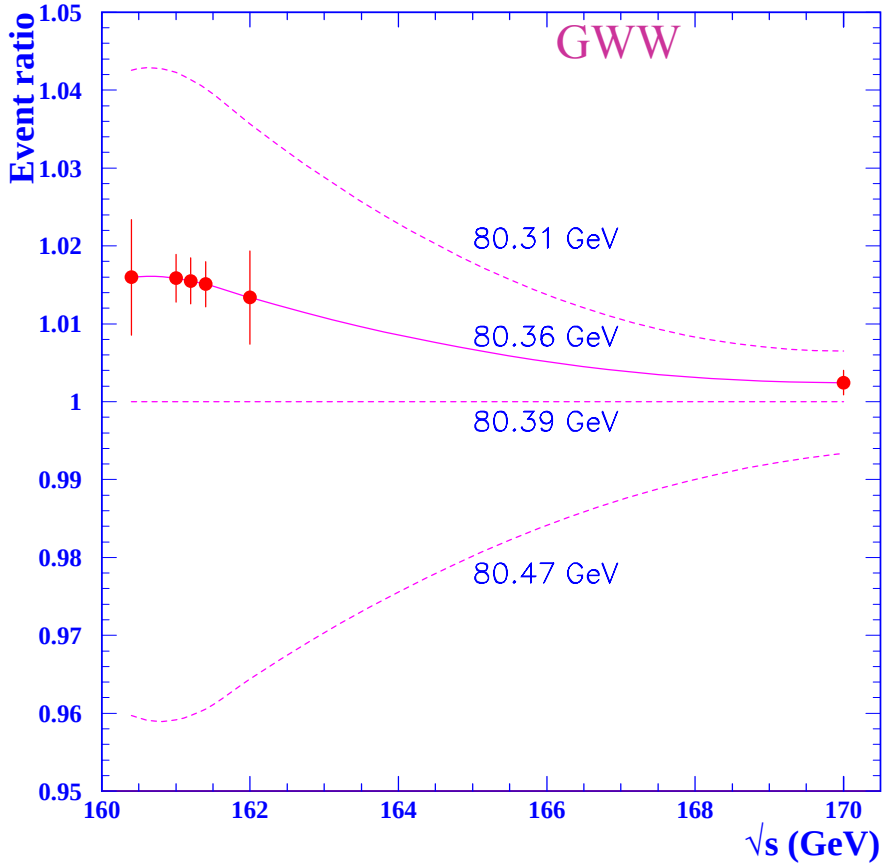
Use Z mass for E-calibration

By taking a data-set with appropriate data fractions with each beam helicity combination :

Can measure the **polarisation** in situ using Z γ events.

Can measure the **background** from the data.

Experimentally robust – in principle don't even need to know the absolute efficiency.



LEP2 : 35 MeV

TeV II : 20 MeV LHC : 15 MeV

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

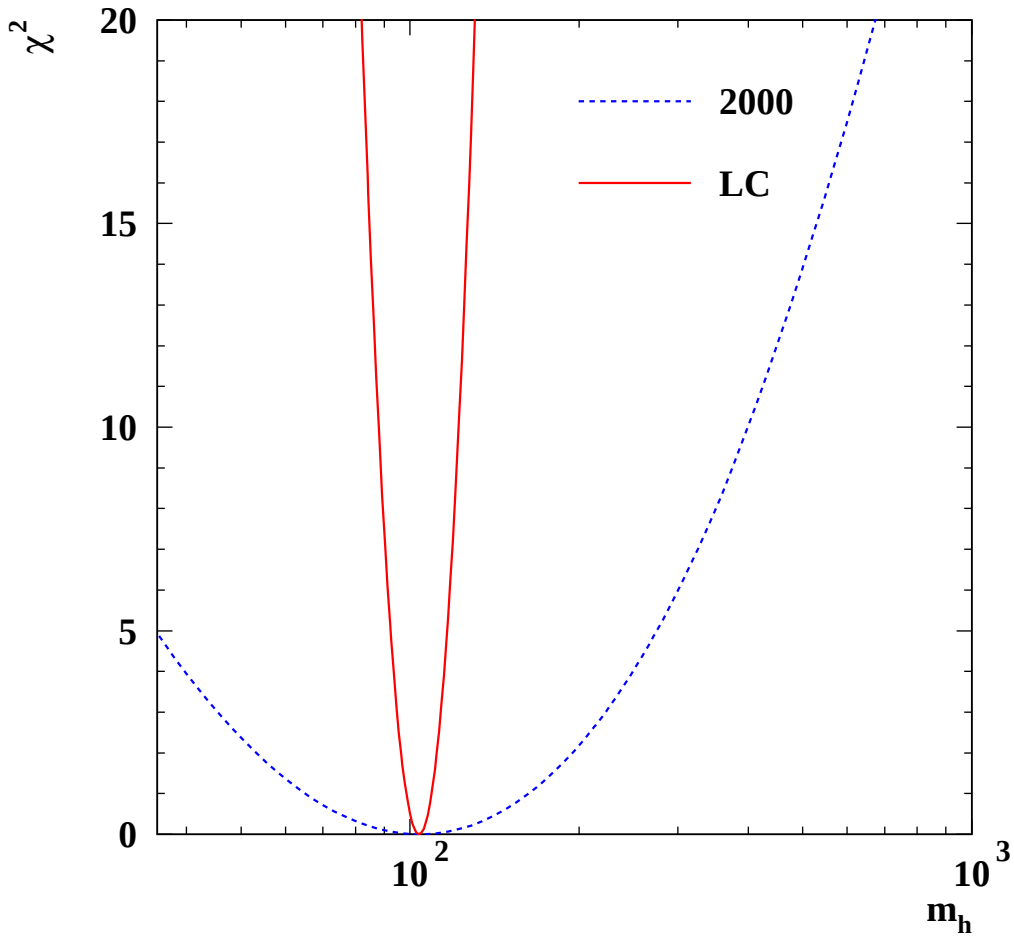
This challenges theory

Why "Giga-Z" precision ?

Can measure the Higgs mass indirectly with 7% precision

It could be that the "new physics" observable at LHC and a LC is 1 SM-like Higgs boson and nothing else.

Is its mass consistent with the electroweak data ?



Note : To take advantage of many of these improvements in experimental precision, will require major advances in theoretical calculations. Work has started in this direction.

Devil's advocate example

In general 2HDM, can potentially have a light Higgs with **negligible** ZZh coupling while the heavier states ($A, H^0, H^{\pm}$) are much heavier.

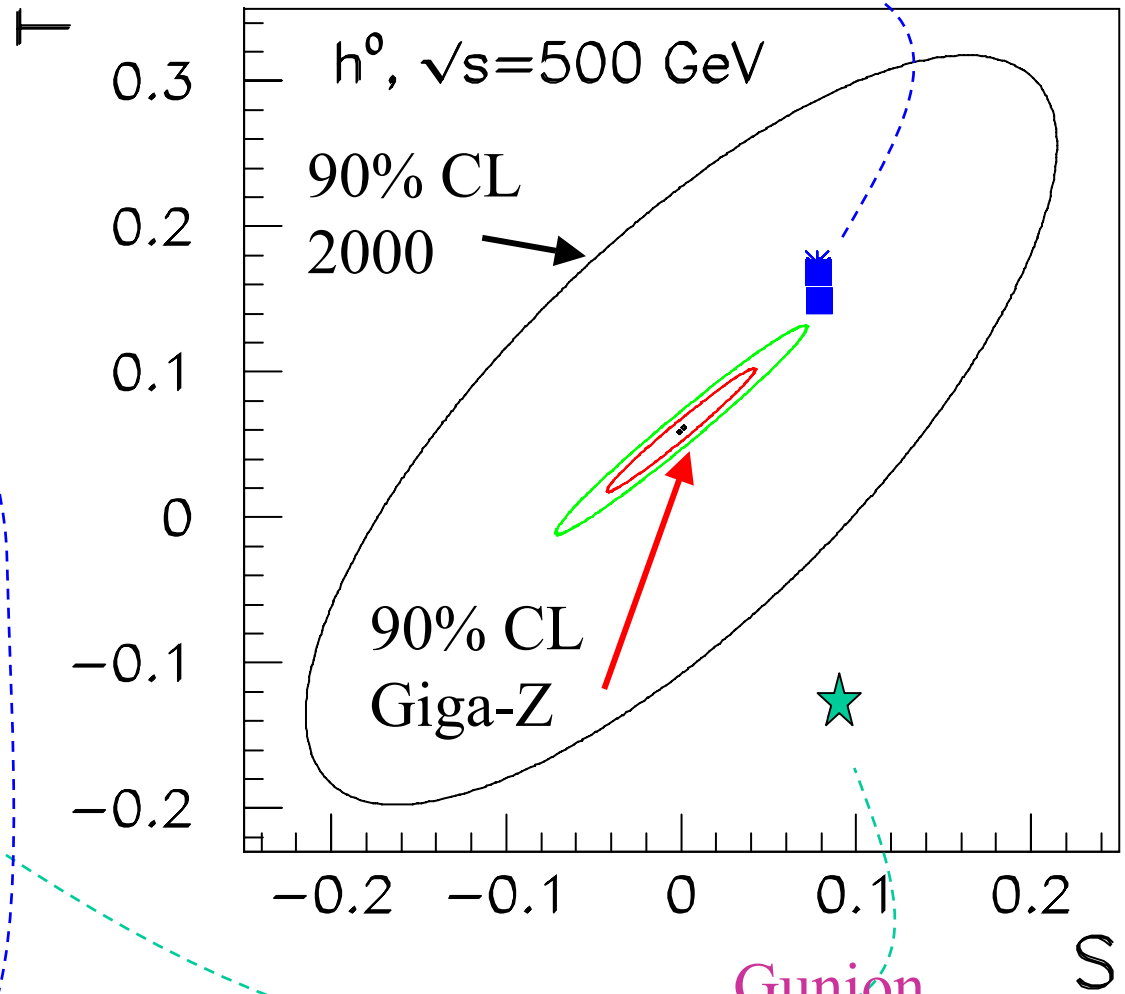
e.g. no higgs directly observable at a 500 GeV LC.

Can this precision EW data distinguish between :

i) SM Higgs with mass beyond kinematic limit

ii) 2HDM light Higgs with suppressed ZZh coupling

S,T parameters of Peskin, Takeuchi



YES !

Gunion

2-fermion observables

Interaction with V and A couplings fully specified if one measures :

- σ_{tot}
- A_{FB}
- A_{LR}
- A_{FB}^{pol}

Applies to a Z'.

See S. Riemann LC-TH-2001-007

Following slide based on these assumptions on systematic errors

Case A.

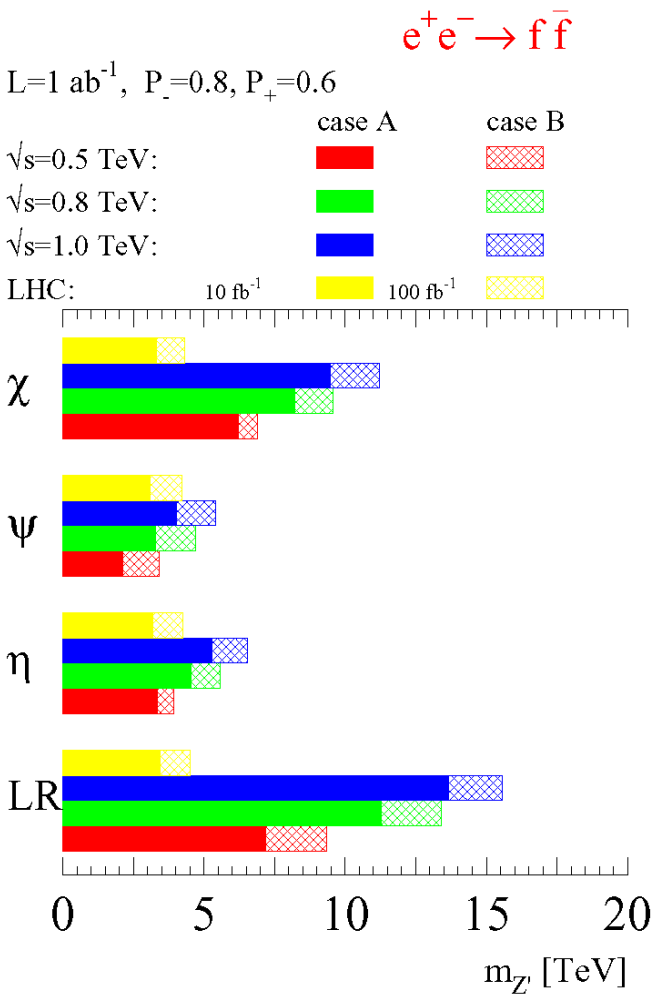
$\Delta P = 1\%$, $\Delta L = 0.5\%$, $\Delta E_l = 0.5\%$ $\Delta E_h = 0.5\%$

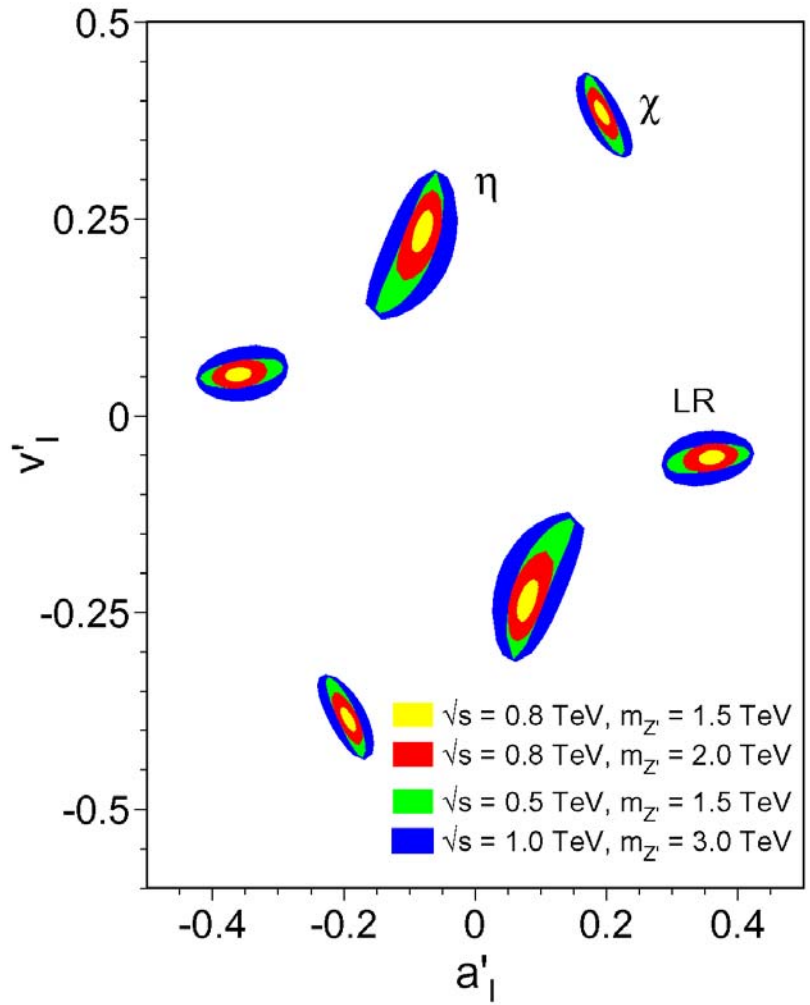
Case B.

$\Delta P = 0.5\%$, $\Delta L = 0.2\%$, $\Delta E_l = 0.1\%$ $\Delta E_h = 0.1\%$

Z'

Mass reach – depends on achievable experimental and theoretical systematic errors





Concluding remarks

The linear collider has the potential for order of magnitude improvement on several key electro-weak observables.

- This is a challenge for the accelerator, experiment and especially theoretical calculations

There are several opportunities particularly in the top, WW and 2f sectors for people with your skills and insight to make profound advances in the way things are calculated.

Remember experimentalists need tools (particularly MC) which they can use.

Beware ! It may well get tested by experiment in the not so far future.