Physics at a Linear Collider

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CERN
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Plan

Day 1: Introduction - Projects – Detectors

Day 2: Higgs Physics

Day 3: New Particles (SUSY, Extra Dimensions, New Gauge Bosons)

Day 4: Precision SM (Top Quark, Gauge Bosons, Return to Z)

Day 5: Synergy of ILC and LHC

Preliminaries

Focus will be on experimental possibilities + studies with detector simulation

Huge theoretical effort in the past decade will probably not be covered as it should – apologies!

I’m happy to answer questions at any time – we don’t have to rush!

Any selection of topics is biased – in these lectures as well…

Suggested reading

A few good sources of recent information:

The TESLA TDR, Part III+IV: `http://tesla.desy.de/new_pages/TDR_CD/start.html`

Snowmass ‘Orange Book’: `http://www.slac.stanford.edu/grp/th/LCBook/`

ACFA JLC report: `http://acfahep.kek.jp/acfareport/`

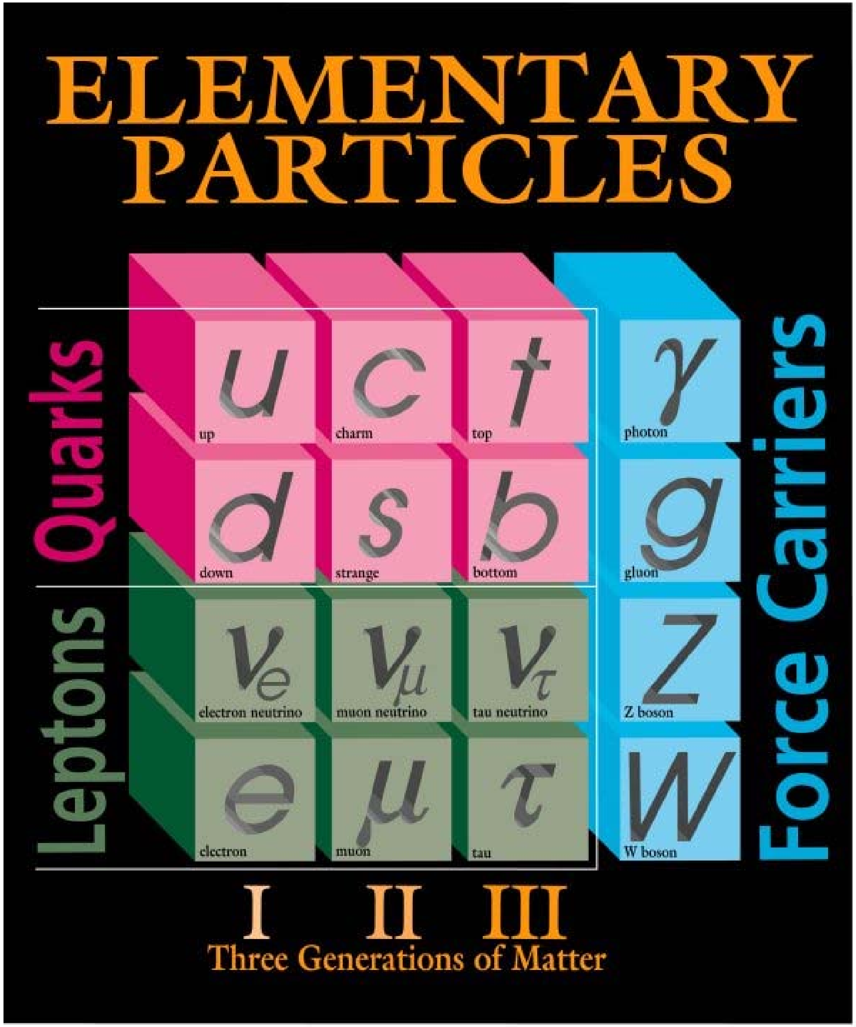
LHC/LC study group report: `hep-ph/0410364+http://www.ippp.dur.ac.uk/~georg/lhclc/`

CLIC physics report: `CERN-2004-005`

LCWS Paris 2004: `http://polywww.in2p3.fr/actualites/congres/lcws2004/`

“Linear Collider Physics in the new Millenium” , World Scientific, to appear in June 2005

In a nutshell: why do we need a Linear Collider?



Fermilab 95-759

- Standard Model is extremely successful
- Experimental discovery of all of its matter constituents and force carriers
- Simple common approach to describe all (relevant) forces: gauge principle
- Self-consistent at the level of quantum corrections

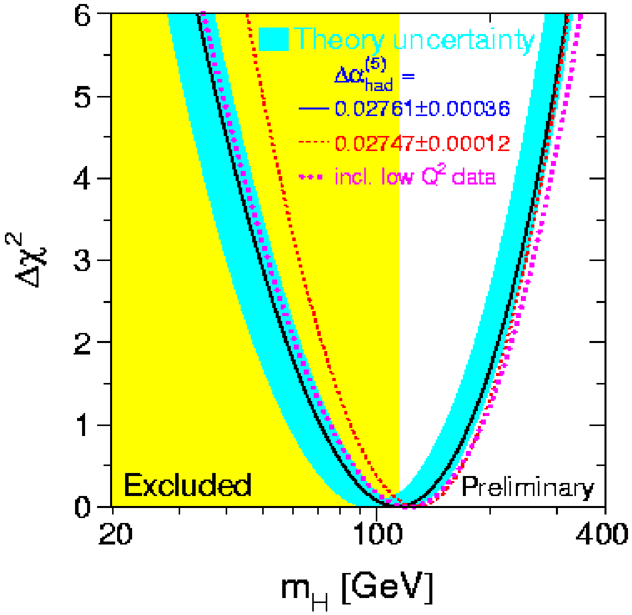
1. Introduction

In a nutshell: why do we need a Linear Collider?

1st "but":

The SM's suggestion how to break electro-weak symmetry is not verified

Higgs mechanism (i.e. the SM approach) is a viable solution and evidence is compelling:



Experimental challenge #1:

Find this Higgs (or its relatives) or exclude it!

something in the loops mimics a light Higgs
or it is a light Higgs…

In a nutshell: why do we need a Linear Collider?

2nd 'but':

Even if we find a light Higgs:
why is it so light?

If there are no new phenomena which protect radiative corrections to the Higgs mass, it will receive un-naturally large (quadratic) corrections:

$m_H = m_{bare} - \delta m \approx (200 \text{ GeV})$

$\delta m \sim \Lambda^2$ m_{bare} and δm are both $o(\Lambda^2)$ but almost equal!

'fine tuning'

We know this since so long that some of us are even willing to accept it (e.g. split SUSY, later…)

Nevertheless, there are very good ideas how to protect the Higgs mass

Experimental challenge #2:

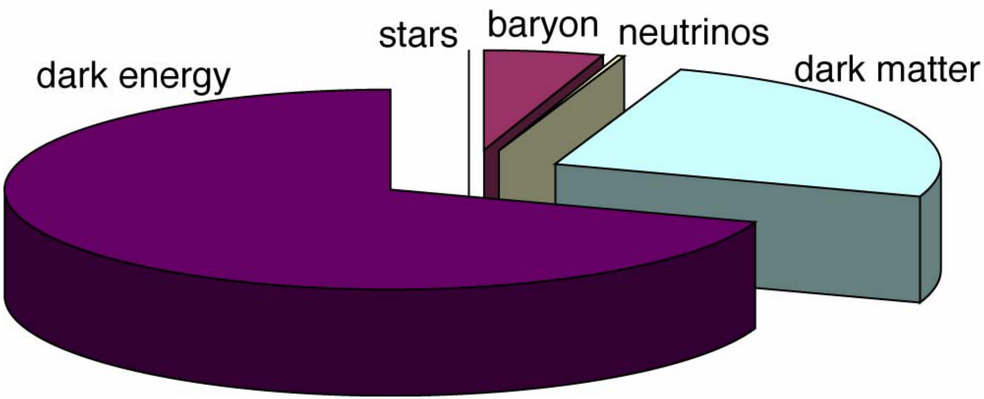
Find out what protects the Higgs mass at the TeV scale

1. Introduction

In a nutshell: why do we need a Linear Collider?

3rd ‘but’:

Our beloved SM contains only a tiny fraction of what’s in our universe today!
(how embarrassing)



The Universe:

5% SM matter

25% dark matter

70% dark energy

Experimental challenge #3:

What is the microscopic nature of dark matter (and dark energy?)

In a nutshell: why do we need a Linear Collider?

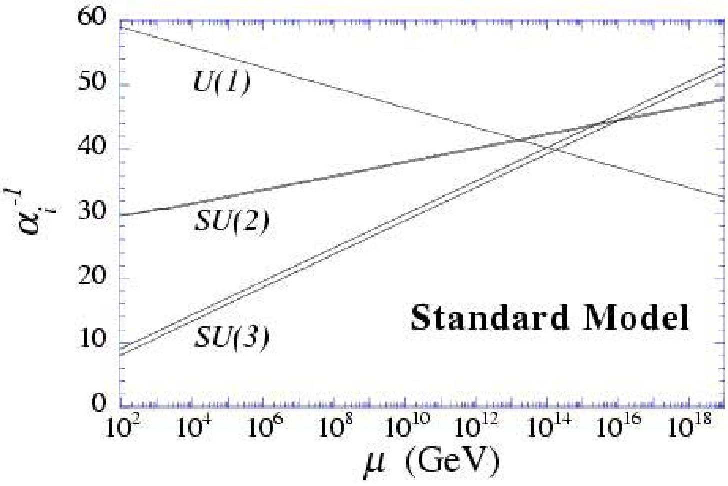
4th ‘but’:

We would probably not be happy with the answers to ‘but’s 1-3 unless they tell us something about physics at even higher energy scales!

a) unification of forces
b) connection between families (flavour physics)

We do have hints to very high scale physics

a) unification of forces ?



b) heavy neutrinos ?

$$m_N = \frac{m_D}{m_\nu^2} \approx \frac{1\mathrm{GeV}^2}{10^{-2}\,\mathrm{eV}^2} = 10^{11}\,\mathrm{GeV}\,??$$

Experimental challenge #4:

If Nature is kind to give a line of sight to high-scale physics use a precision telescope to look at it

In a nutshell: why do we need a Linear Collider?

The SM was to a large extent established at (hadron+lepton) colliders

The road ahead of us will need a broader set of exp. techniques:

- neutrino physics (from space + from accelerators/reactors)
- astro(particle)physics experiments (CMB, cosmic rays, …)
- ultra-high precision at low energy (rare decays, g-2, …)

- but of course again colliders!

Which energy?

The TeV scale looks very interesting!

Why? →

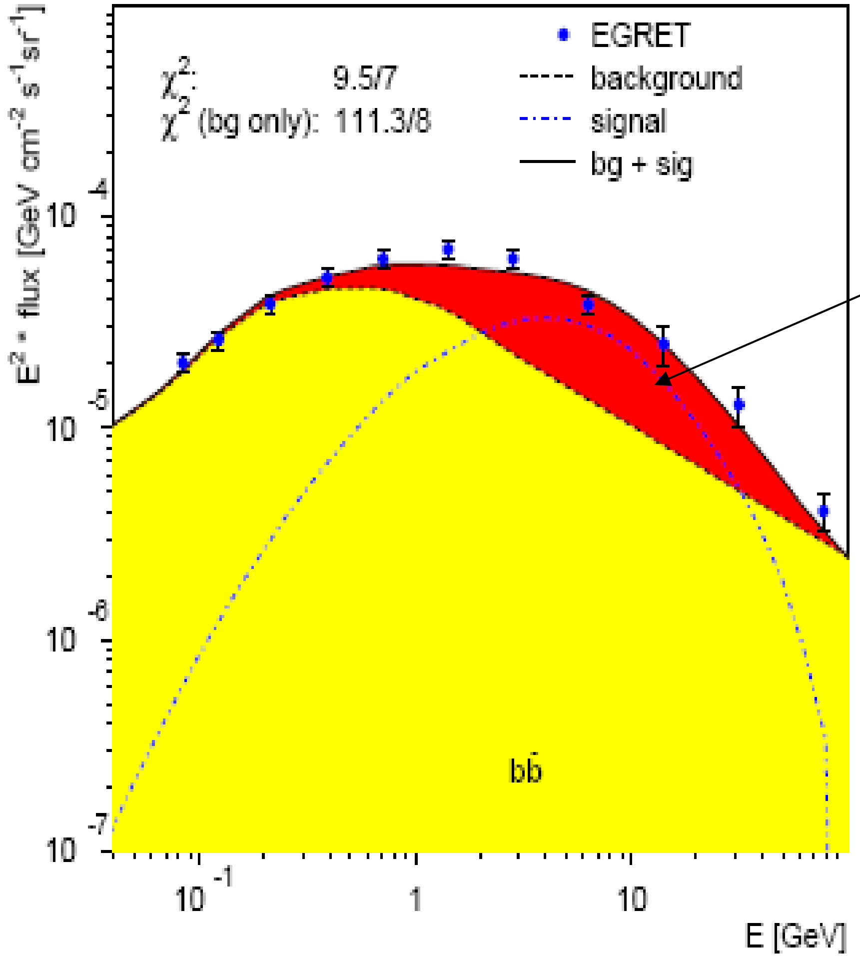
In a nutshell: why do we need a Linear Collider?

Why is the TeV scale interesting?

1. SM without Higgs violates unitarity (in $W_L W_L \rightarrow W_L W_L$) at 1.3 TeV!
   (something must happen!)
2. Higgs field vacuum expectation value v = 246 GeV
3. Evidence for light Higgs
4. Dark Matter consistent with (sub) TeV-scale WIMP (e.g. SUSY-LSP)
5. $2m_{top}$ = 350 GeV
6. Diffuse x-ray spectra (from EGRET) consistent with 50-100 GeV WIMP

In a nutshell: why do we need a Linear Collider?

W. de Boer et al, hep-ph/0408166



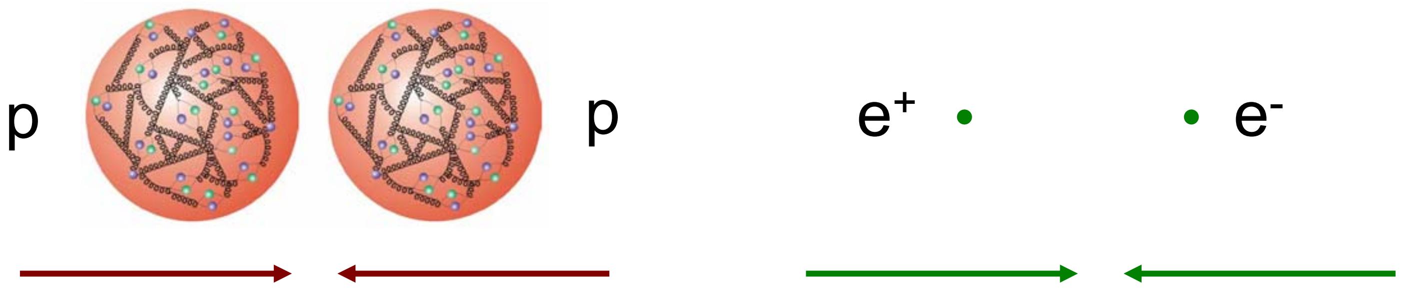
red: excess γ's from WIMP χ^0_1 annihilation

for mSugra model with
$m_{1/2} \cong 180$ GeV
$m_0 \cong 1400$ GeV

In a nutshell: why do we need a Linear Collider?

All of this so far could have been a speech to build the LHC

Why an electron positron LC then?



- easier to reach high energies
- p = composite particle
  unknown c.m.s. of initial system
  parasitic collisions
- p = strongly interacting
  huge SM backgrounds
  not possible to reconstruct all f.st.
  need highly selective trigger

- difficult to reach high energies (synchrotron radiation)
- e = pointlike particle
  c.m.s. = lab system
  can use kinematic constraints
- e = electro-weakly interacting
  low SM backgrounds
  can reconstruct all final states
  no trigger needed!

1. Introduction

In a nutshell: why do we need a Linear Collider?

Physics case worked out in much detail over the past decade and well documented (TESLA TDR, Snowmass report, ACFA study etc.)

Whatever LHC will find, ILC will have a lot to say!

‘What’ depends on LHC findings:

1. If there is a ‘light’ Higgs (consistent with prec.EW)
   ⇨ verify the Higgs mechanism is at work in all elements

2. If there is a ‘heavy’ Higgs (inconsistent with prec.EW)
   ⇨ verify the Higgs mechanism is at work in all elements
   ⇨ find out why prec. EW data are inconsistent

3. 1./2. + new states (SUSY, XD, little H, Z’, …)
   ⇨ precise spectroscopy of the new states

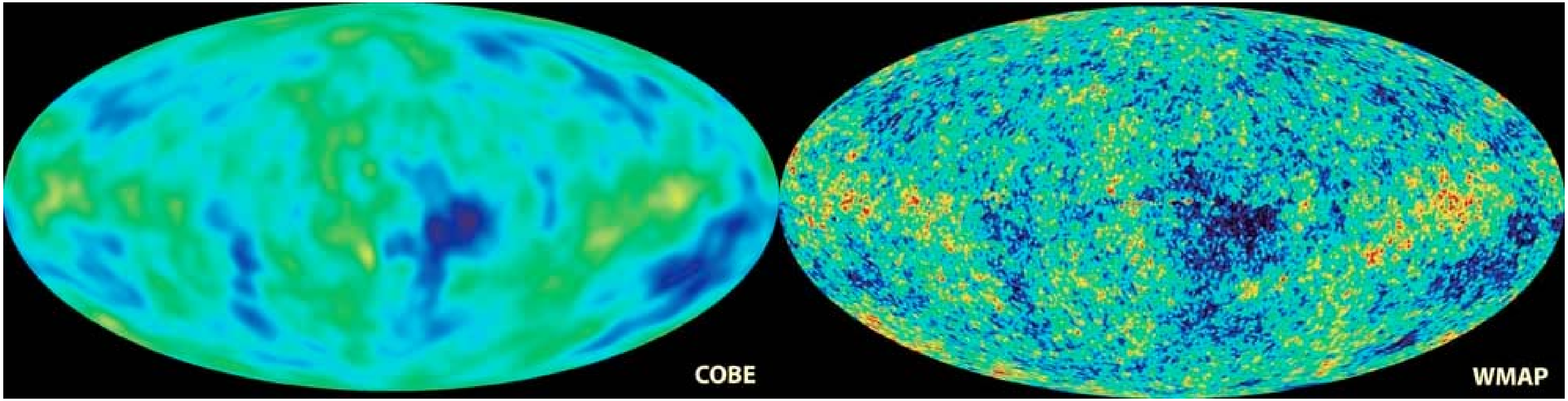
4. No Higgs, no new states (inconsistent with prec.EW)
   ⇨ find out why prec. EW data are inconsistent
   ⇨ look for threshold effects of strong EWSB

In a nutshell: why do we need a Linear Collider?

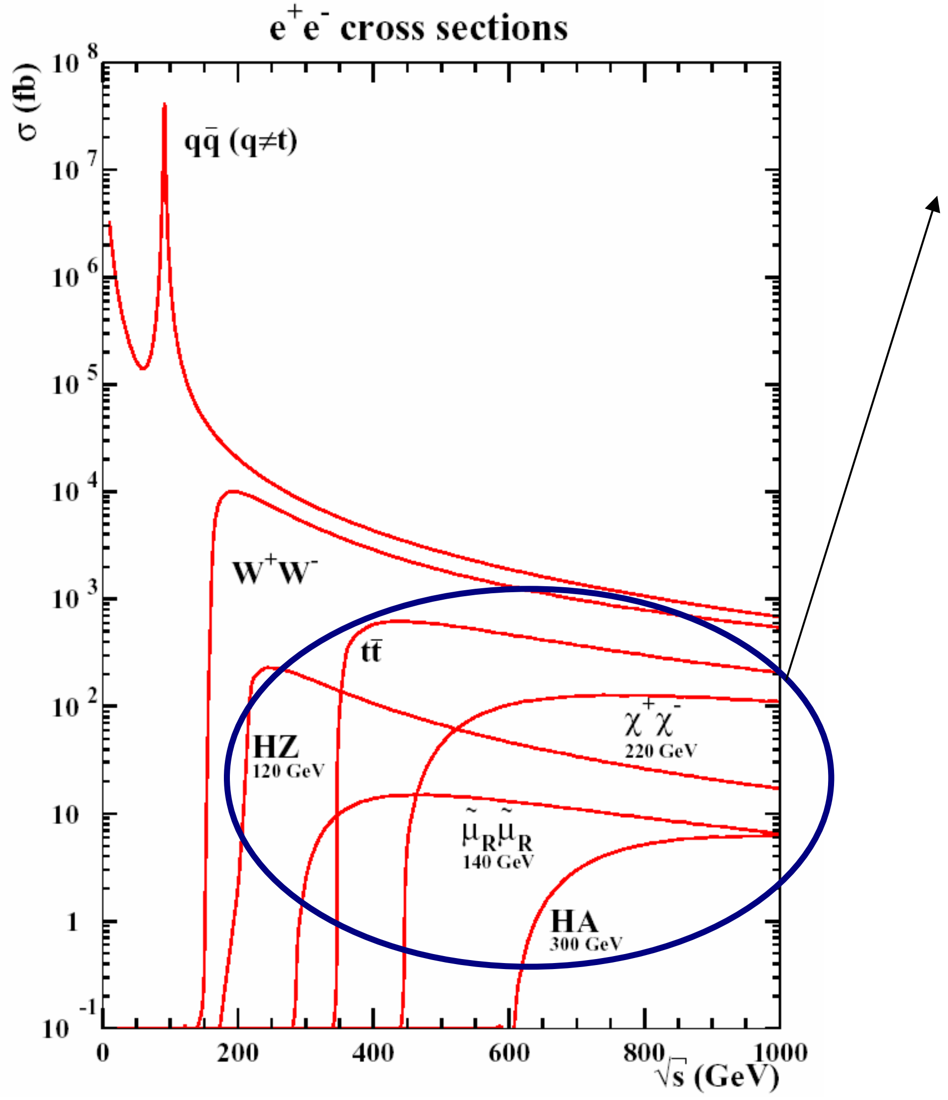
Electron positron colliders allow for

1. Discovery of the unexpected
2. Precision measurements of new + ‘old’ physics

Higher precision can give discoveries:



In a nutshell: why do we need a Linear Collider?



Interesting new processes often only smaller by 0-2 orders of magnitude

But 1/s suppression calls for very high luminosity (1000-10000 x LEP!)

In a nutshell: why do we need a Linear Collider?

Typical event rates in a 500 fb^{-1} sample

event type	o(# events)	√s (GeV)
HZ (m_h=120 GeV)	10^5	300
tt	3.5 10^5	350
W^+W^-	10^6	500
Z	10^9	91
$\tilde{\mu}\tilde{\mu}$ (m=140 GeV)	10^4	400
$\chi^+\chi^-$ (m=220 GeV)	5 10^4	600
ttH (m_h=120 GeV)	10^3	800
HHZ (m_h=120 GeV)	10^2	500

Many processes with o(%) or better statistical precision
Match this precision with a high-resolution detector

1.2 Projects

In the rest of these lectures, I will give an overview topic-by-topic how the precision of linear electron-positron colliders may help to

- understand the discoveries at the LHC ahead of us
- guide us even if there should be 'nothing' at the LHC

But first, let's look at the projects

1. The International Linear Collider (ILC)
   - 90 – 1000 GeV
   - based on superconducting technology (ITRP, Aug04)
   - matured technical design

main focus
of this week

2. Compact Linear Collider (CLIC)
   - 3000 (5000) GeV
   - normal-conducting cavities
   - two-beam acceleration
   - R&D at CERN

will mention
occasionally

1.2 Projects

The International Linear Collider (ILC)
planned for 2015, overlaps with LHC.

Parameters defined by ILCSC scope-panel

`http://www.fnal.gov/directorate/icfa/LC_parameters.pdf`

Baseline	$\sqrt{s}$ = 200-500 GeV, integrated Luminosity 500 fb^{-1} over first 4 years 80% electron polarisation 2 interaction regions with easy switching
Upgrade	Anticipate $\sqrt{s} \rightarrow$ 1 TeV, $\int L$ = 1 ab^{-1} over 4 years
Options	e^-e^- collisions, 50% positron polarisation, “GigaZ”; high L at Z and at WW threshold, Laser backscatter for $\gamma\gamma$ and γe collisions, Doubled L at 500 GeV.

Choice among options to be guided by physics needs.

Technology Choice:

International Technology Recommendation Panel in August 04 recommended
‘that the ILC be based on superconducting RF technology’

ILCSC + ICFA unanimously accepted the recommendation

First workshop on global ILC design
at KEK, Nov 13-15.

Goal:

Technical Design
in 2007

Use exisiting TDRs (TESLA,NLC,GLC)
as input!

First ILC Workshop

Towards an International Design of a Linear Collider

November 13th (Sat) through 15th (Mon), 2004

KEK, High Energy Accelerator Research Organization
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Program Committee:
Kaoru Yokoya (KEK), Hitoshi Hayano (KEK), Kenji Saito (KEK), David Burke (SLAC), Steve Holmes (FNAL), Gerald Dugan (Cornell), Nick Walker (DESY), Jean-Pierre Delahaye (CERN), Olivier Napoli (CEA/Saclay)

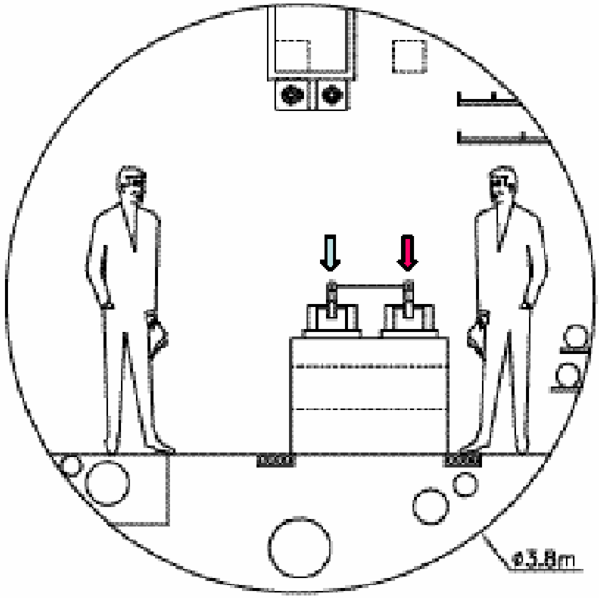
Local Organizing Committee:
Yoji Totsuka (KEK)(Chair), Fumihiko Takasaki (KEK)(Deputy-chair), Junji Urakawa (KEK), Kiyoshi Kubo (KEK), Shigeru Kuroda (KEK), Nobuhiro Terunuma (KEK), Toshiyasu Higo (KEK), Tsunehiko Omori (KEK), Toshiaki Tauchi (KEK), Akiya Miyamoto (KEK), Masao Kuriki (KEK), Kiyosumi Tsuchiya (KEK), Shuichi Noguchi (KEK), Eiji Kako (KEK)

International Advisory Committee:
Robert Aymar (CERN), Albrecht Wagner (DESY), Michael Witherell (FNAL), Yoji Totsuka (KEK), Jonathan Dorfan (SLAC), Won Namkung (PAL), Brian Foster (Oxford), Maury Tigner (Cornell), Hesheng Chen (IHEP), Alexander Skrinsky (BINP), Carlos Garcia Canal (UNLP), Sachio Komamiya (Tokyo), Paul Grannis (SUNY)

http://lcdev.kek.jp/ILCWS/

Compact Linear Collider (CLIC)

CLIC tunnel cross-section



Very compact (30 GHz, 150 MV/m),

Short (0.5/3 TeV => 10/33 km)

⬇ **Main beam**: 0.009 to 1.5 TeV

beam pulse: 1 A pulse in 102 ns

⇩ **Drive beam**: 2 to 0.2 GeV

beam pulse: 150 A in 130 ns

Active R&D by CLIC collaboration to validate concept by the time LHC results available

CLIC challenges:

-- 172/150 MV/m (without/with beam)

-- Generation and control of drive beam

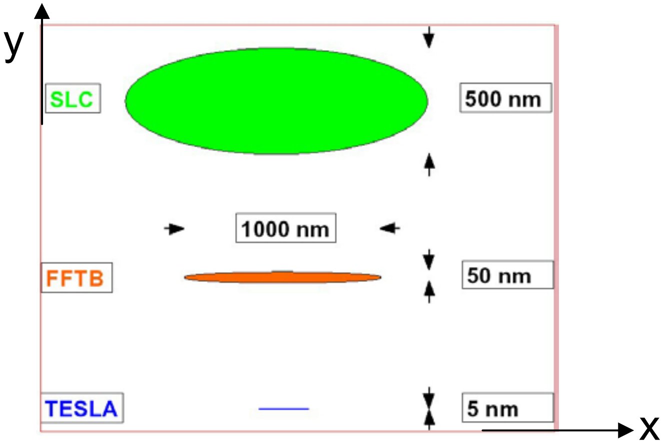
-- Demonstration: needs big unit

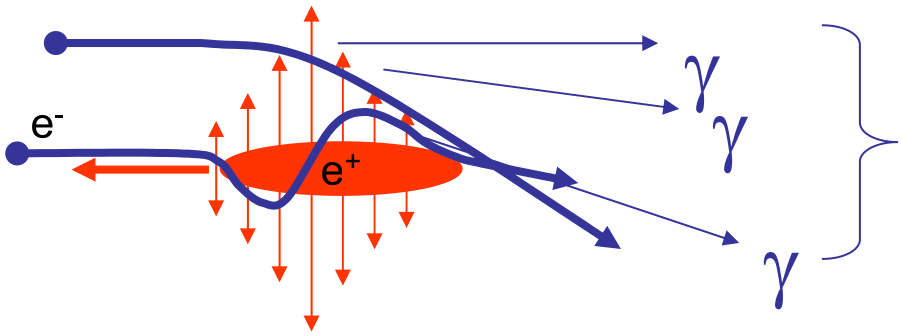
1. Introduction

1.2 Projects

This is not LEP (nor SLC)!

- Beamstrahlung
- Bunch Crossing Rate





hard γ's radiated by intense electric field
= Beamstrahlung

RMS Energy Loss:

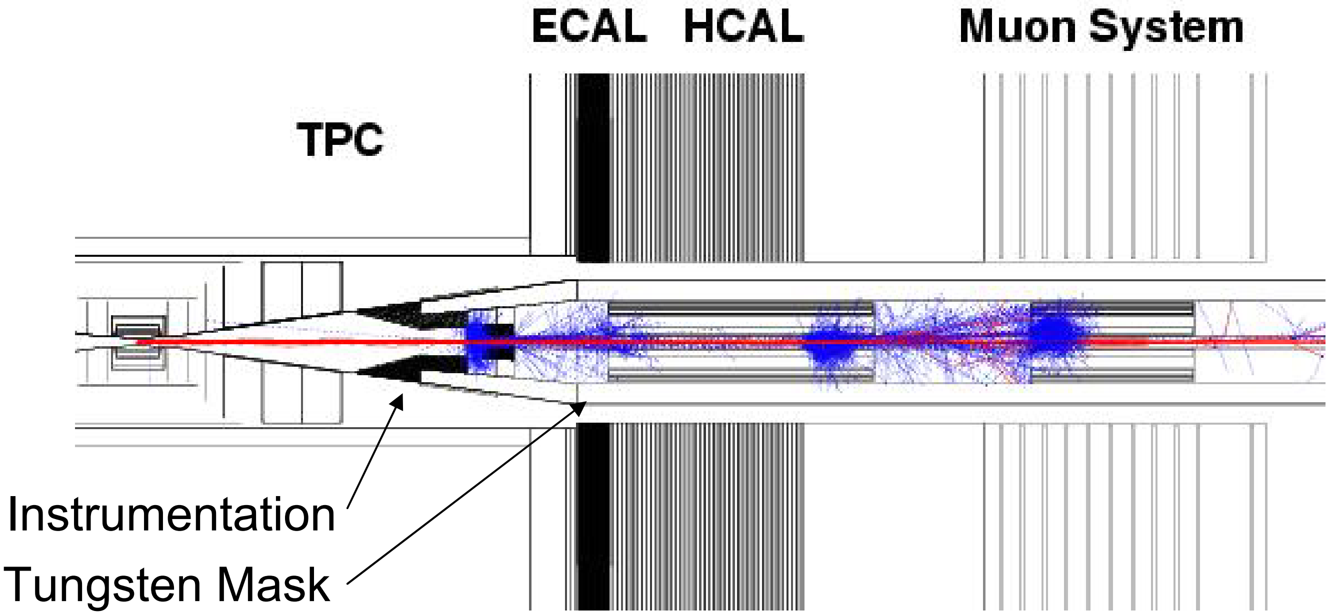
$$\delta_{BS} = \frac{\Delta E}{E} \propto \frac{E_{cm}}{\sigma_z}\left(\frac{N}{\sigma_x^* + \sigma_y^*}\right)^2$$

Minimize while keeping $\sigma_x^* \sigma_y^*$ (luminosity!) constant by chosing flat beams ($\sigma_x^* \gg \sigma_y^*$)

Beamstrahlung creates:

6×10^{10} photons/BX (1.3-1.5 photon/electron)
140000 e^+e^- pairs
secondary particles from $\gamma\gamma \rightarrow$ hadrons

Photons and most of pairs vanish in beampipe but need to shield detector from backscattered secondaries!

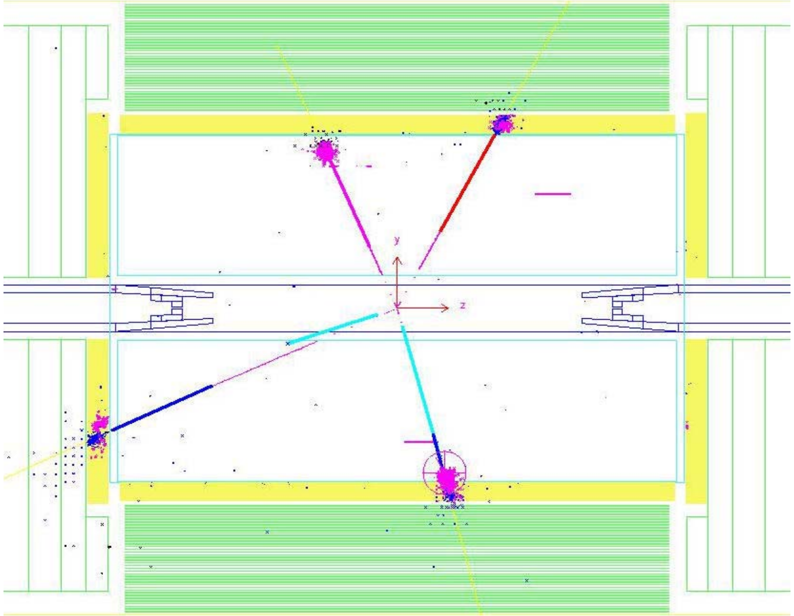


1. Introduction

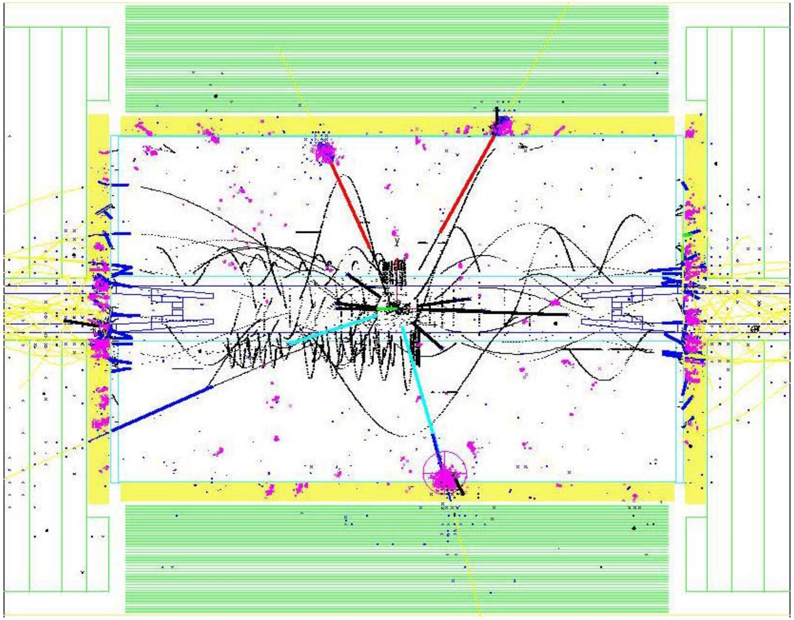
1.2 Projects

Important to have detector readout/time-stamp fast enough not to pile-up $\gamma\gamma \rightarrow$ hadrons events from beamstrahlung

HZ → ττee event (no background)



Same event + ~60 BX pileup

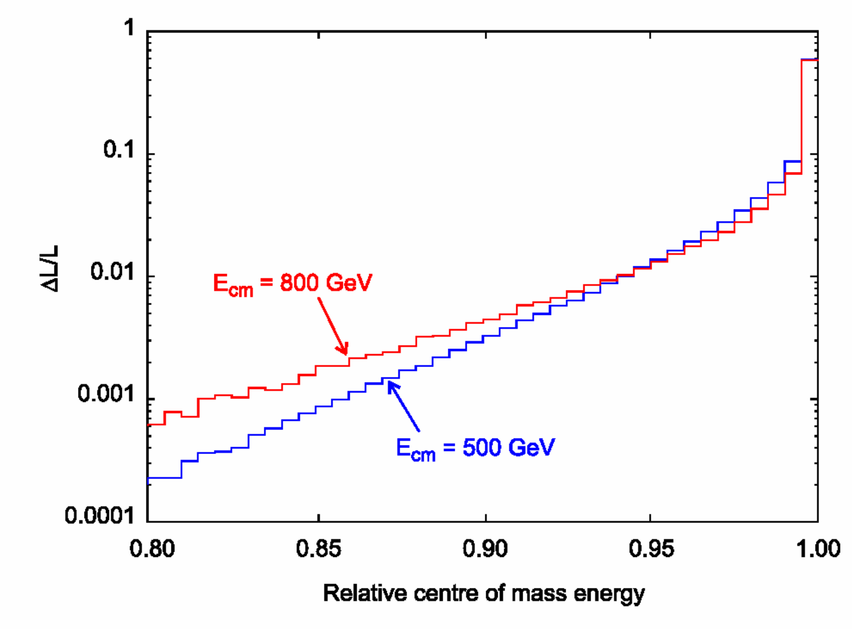


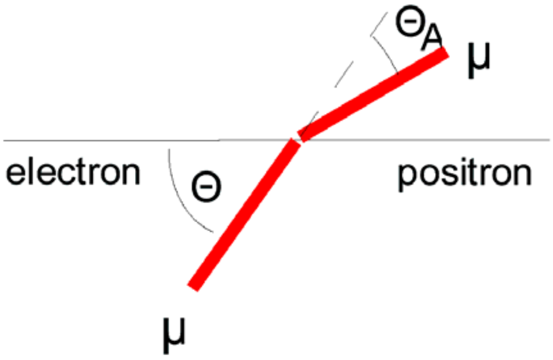
Δt (ILC) = 330 ns
Δt (CLIC) = 0.7 ns

1. Introduction

1.2 Projects

Beamstrahlung reduces the collision energy on average by 1.5% at 500 GeV
90% of the events have >95% of nominal collision energy





$$\Theta_A = \frac{\Delta p \sin \Theta}{p_{beam}}$$

- Effect needs to be taken into account in physics studies
- Spectrum needs to be monitored countinously during data taking
  → use acollinearity of Bhabha-events, μ-pairs

1.2 Projects

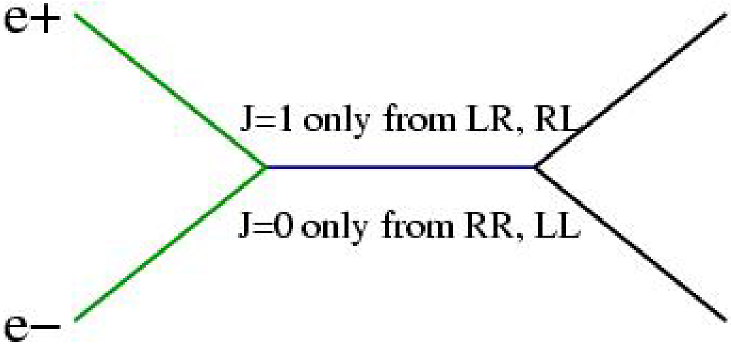
Polarisation is a very important tool to disentangle structure of new physics and to suppress backgrounds

e^- Polarisation: expect 90% (polarised source, proven at SLC)

e^+ Polarisation: expect ~50-60% (creates polarized photons in helical undulator of high-energy e^- beam, convert photons in thin target)

Benefit from polarisation

1. s-channel:



SM: J=1 (gamma, Z)

BSM: might be J=0

Electron polarisation selects ‘correct’ helicity for positrons

⇨ e^- Polarisation sufficient to select the ‘signal’ state

But: Positron polarisation helps in increasing:

a) Effective Luminosity

b) Effective Polarisation

1. Introduction

1.2 Projects

Effective Polarsation: $(\#LR - \#RL)/(\#LR + \#RL) = (P^{e-} - P^{e+})/(1 - P^{e-}P^{e+})$

Effective Luminosity: $(\#LR + \#RL)/(\#all) = 0.5 \times (1 - P^{e-}P^{e+})$

Fraction of collisions:

P	RL	LR	RR	LL	Effective Polarisation	Effective Lumi
$P(e^-) = 0$ $P(e^+) = 0$	0.25	0.25	0.25	0.25	0.	x 0.5
$P(e^-) = -1$ $P(e^+) = 0$	0.	0.50	0.	0.50	1.	x 0.5
$P(e^-) = -0.8$ $P(e^+) = 0.$	0.05	0.45	0.05	0.45	0.8	x 0.5
$P(e^+) = -0.8$ $P(e^-) = +0.6$	0.1x0.2= 0.02	0.9x0.8= 0.72	0.1x0.8= 0.08	0.9x0.2= 0.18	0.95	x 0.74

wanted!

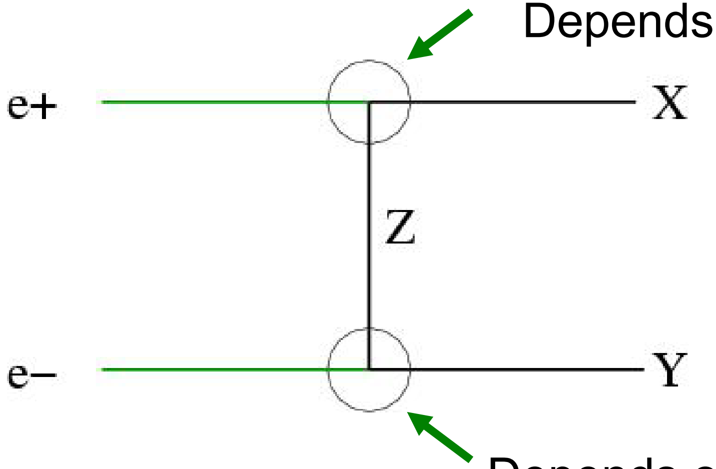
unwanted!

1. Introduction

1.2 Projects

Benefit from polarisation

2. t-channel:

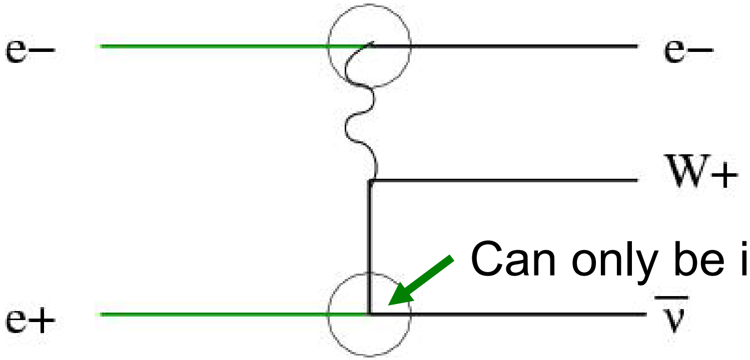


Depends only on $P(e^+)$

Depends only on $P(e^-)$

e^+ and e^- polarisation are 'functionally' different!

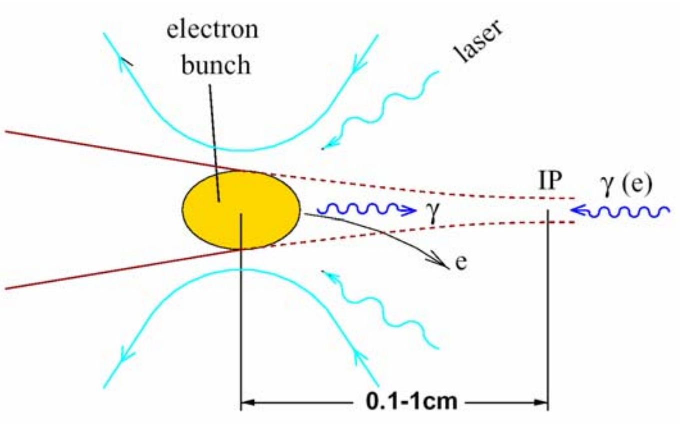
Famous SM example single W production:



Can only be influenced with $P(e^-)$

Photon Collider

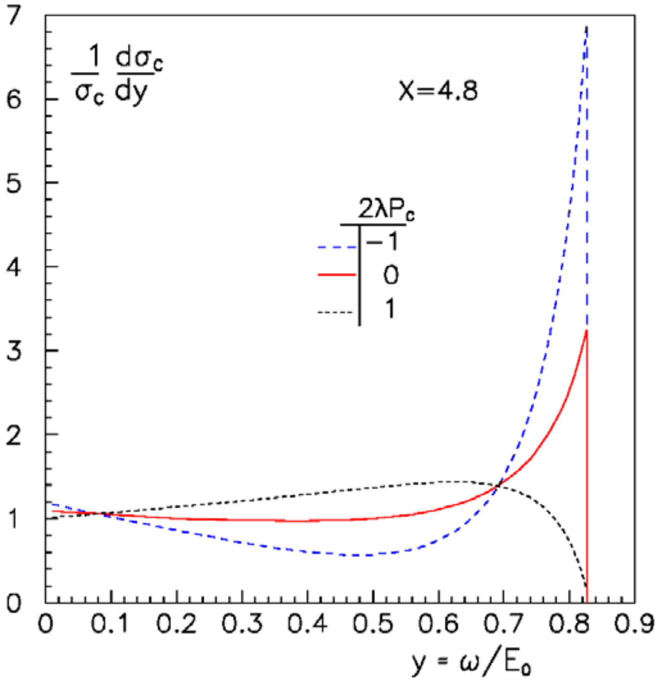
High energetic photons from Compton backscatter of laserlight



$$E_\gamma^{max} = \frac{x}{x+1} E_e \qquad x = \frac{E_e E_{laser}}{m_e^2}$$

keep x<4.8 to avoid $\gamma\gamma \rightarrow e^+e^-$

$$\Rightarrow E_\gamma^{max} \approx 0.8 E_e$$



Photon spectrum depends on laser- and beam-polarization

Need crossing angle to separate outgoing photon beam

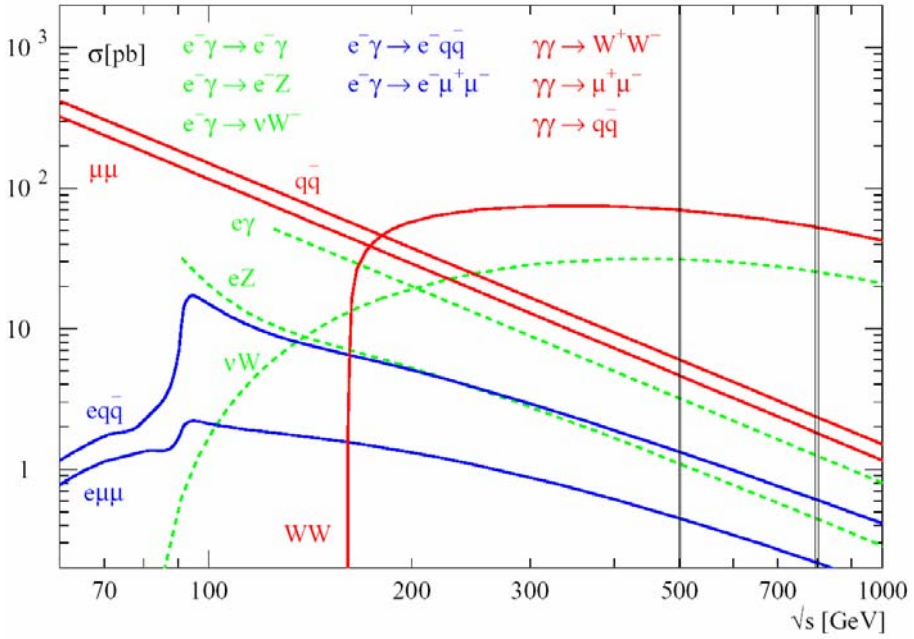
Photon Collider

Choice of $\gamma\gamma$ option depends on physics at LHC and e^+e^-

Advantages:
- Large WW cross section (TGC's)
- clean separation of Z from γ couplings
- s-channel $\gamma\gamma \rightarrow$ Higgs production
- potentially larger mass reach for heavy SUSY Higgs production

Further options:
- e^-e^- collisions
  (e.g. for some SUSY processes, see later)
  but factor ~7 lower lumi
  (anti-pinch effect)

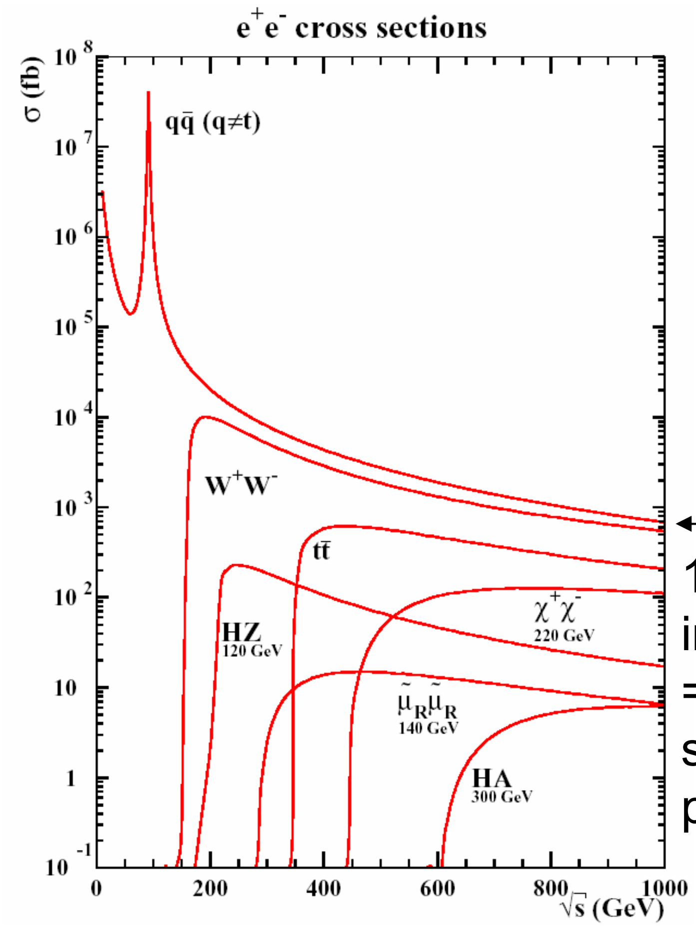
- $e\gamma$ collisions



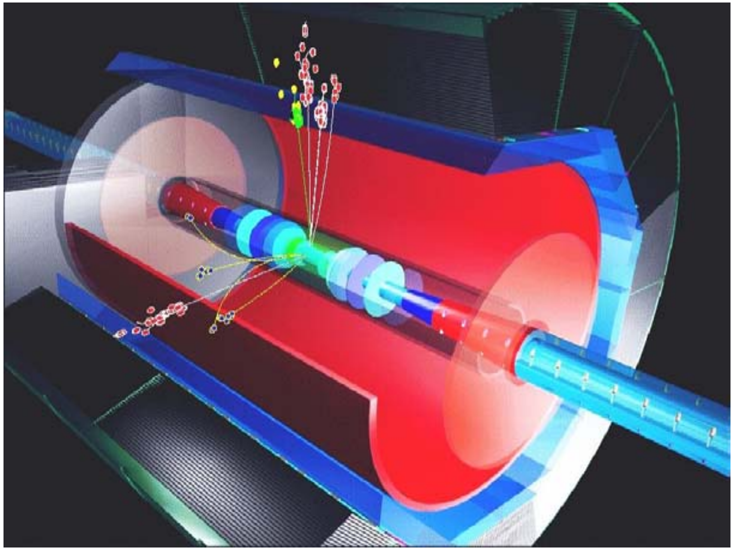
1. Introduction

1.3 Detectors

High Luminosity and clean environment call for a ultra-high precision detector!
Important sub-detectors are challenging (and different from LHC det's)



10^6 events
in 1 ab^{-1}
= $o(^0/_{00})$
statistical
precision

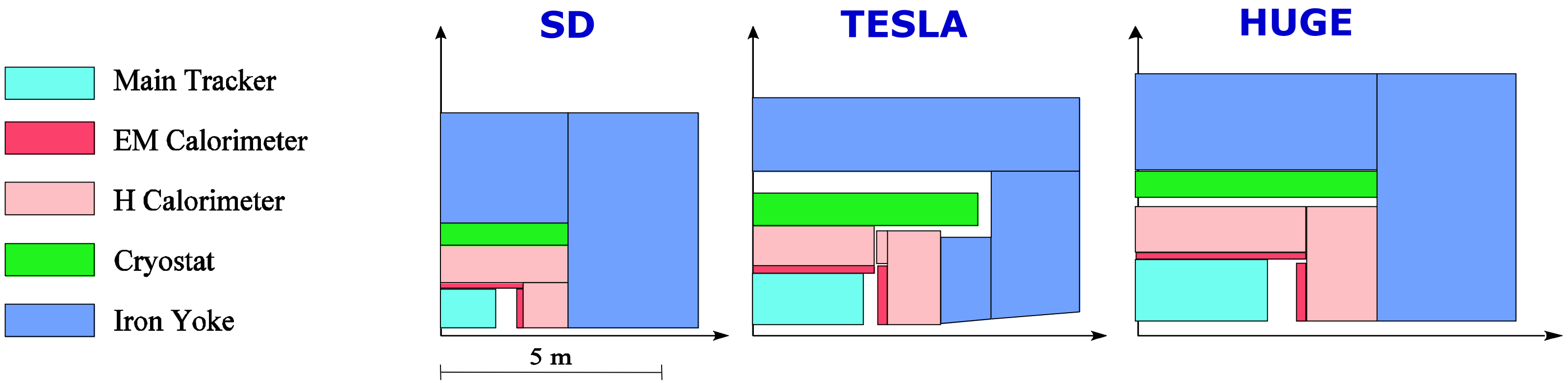


Challenges:

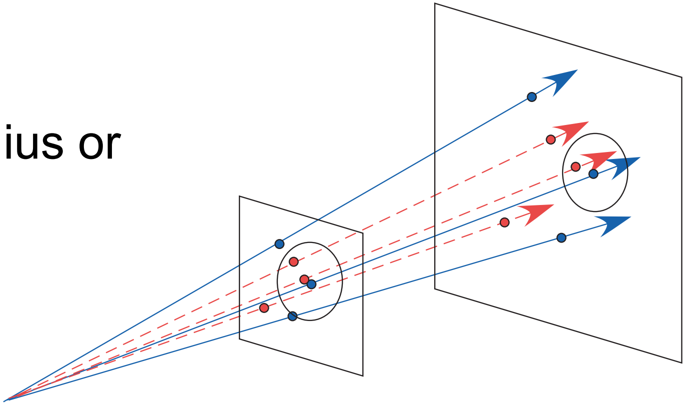
'Particle flow' paradigm
Excellent momentum resolution
Precision vertexing

1. Introduction | 1.3 Detectors

2-3 global concepts are emerging



Main design issues
- Si or gaseous tracking ?
- Si/W ECAL (1x1cm) at small-medium radius or coarser Sc/W ECAL at larger radius ?



Particle separation at Calo surface:

$B \times L^2 / R_{\mathrm{Moliere}}$

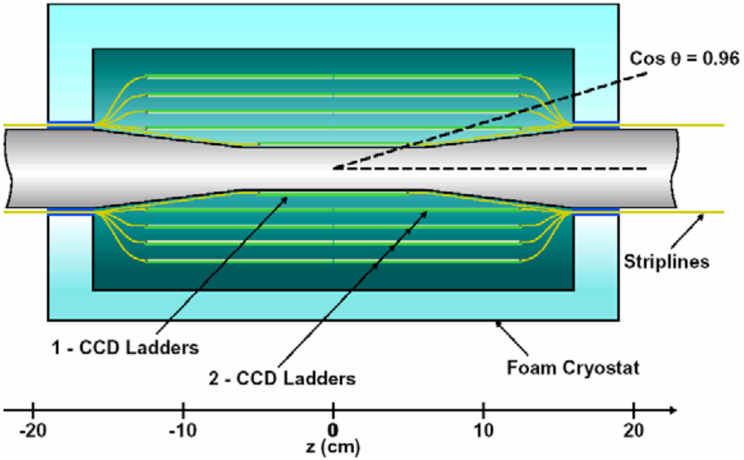
Those are open concepts not collaborations!
Many sub-detector R&D items in common

Vertex-Detector

High resolution pixel detector, 5 layers, innermost layer at r=1.2cm

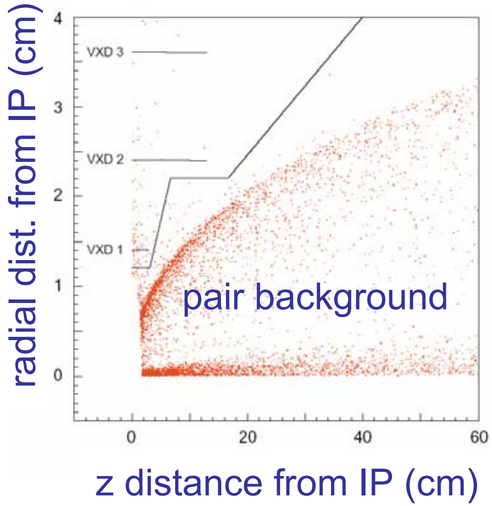
Driving physics:

- Flavour tag (b/c) for Higgs BR's
- τ lifetime tag
- improve momentum resolution+ pattern recognition for main tracker



R&D ongoing in various directions:

- CCDs
- CMOS pixels
- DEPFET
- SoI Pixels

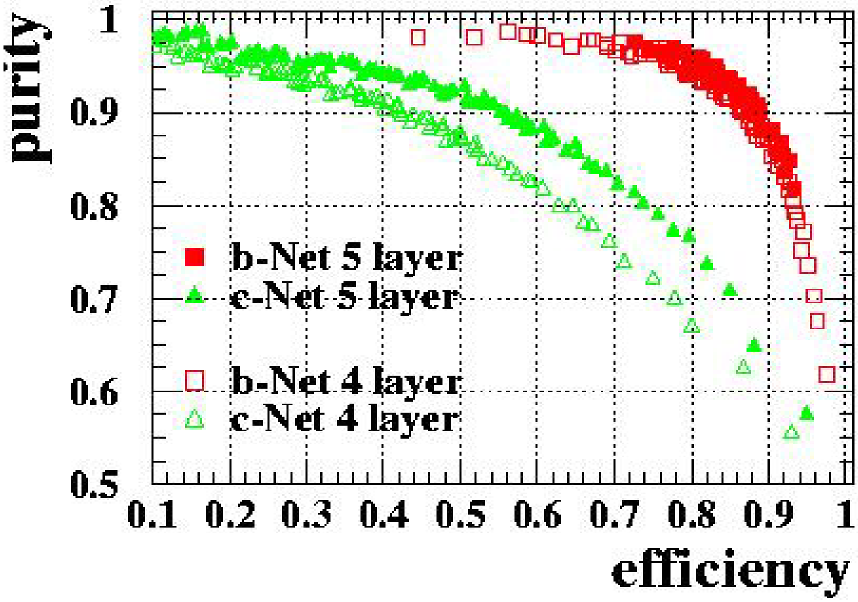


Critical issues:

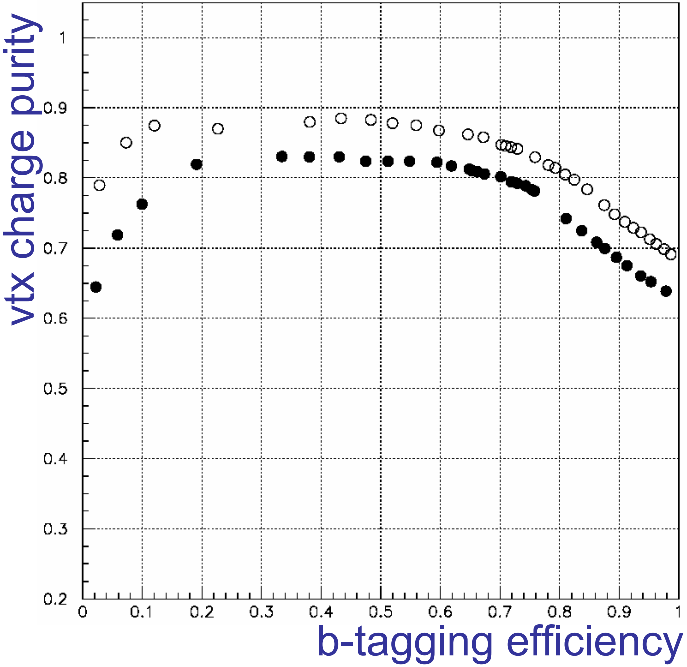
- fast (column parallel) readout
- beamstrahlung pairs (high B-Field (4T) helps)
- ultra-thin detectors (0.1%X_0/layer)
- power consumption/cooling (material)

Performance:

b/c jets from Z decays:



vertex charge reconstruction



1. Introduction | 1.3 Detectors | Main tracker

Gaseous tracker (TPC, Jet chamber) or Silicon tracker

Driving physics:

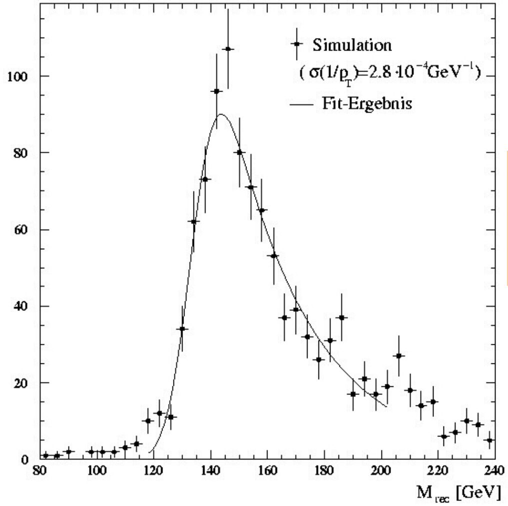
1. Excellent momentum resolution, e.g. for Z→μμ (Higgs recoil mass)

   momentum resolution:
   $\Delta(1/p) = 7 \times 10^{-5}/\text{GeV}$ (1/10xLEP)

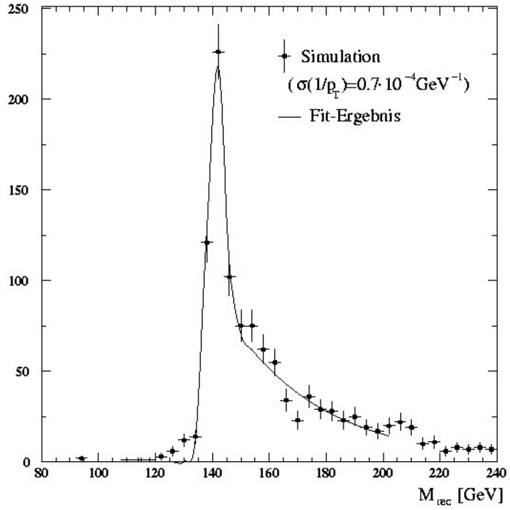
   ➪ $\Delta M(\mu\mu) < 0.1\ \Gamma_Z$
   ➪ ΔM_H dominated by beamstrahlung

2. Robust and efficient charged track reconstruction for particle-flow jet reconstruction

Z recoil mass



a la LEP



a la ILC

1. Introduction | 1.3 Detectors | Particle Flow

Ideally would like to treat quarks as any fermion ⇨ optimize jet energy res.

Method: particle flow paradigm
= most exclusive reconstruction of charged and neutral particles in a jet
⇨ Use tracking detectors to measure energy of charged particles
(65% of the typical jet energy)

- ⇨ EM calorimeter for photons (25%)
- ⇨ EM and Had calorimeter for neutral hadrons (10%)

$$E_{\text{jet}} = E_{\text{charged}} + E_{\text{photons}} + E_{\text{neut. had.}}$$

$$\sigma^2_{E\text{jet}} = \sigma^2_{E\text{charged}} + \sigma^2_{E\text{photons}} + \sigma^2_{E\text{neut.had.}} + \sigma^2_{\text{confusion}}$$

$$\sigma^2_{\text{Ejet}} \approx (0.14)^2 \left(\text{E}_{\text{jet}} \cdot \text{GeV}\right) + \sigma^2_{\text{confusion}} \overset{!}{\approx} (0.3)^2 \left(\text{E}_{\text{jet}} \cdot \text{GeV}\right)$$

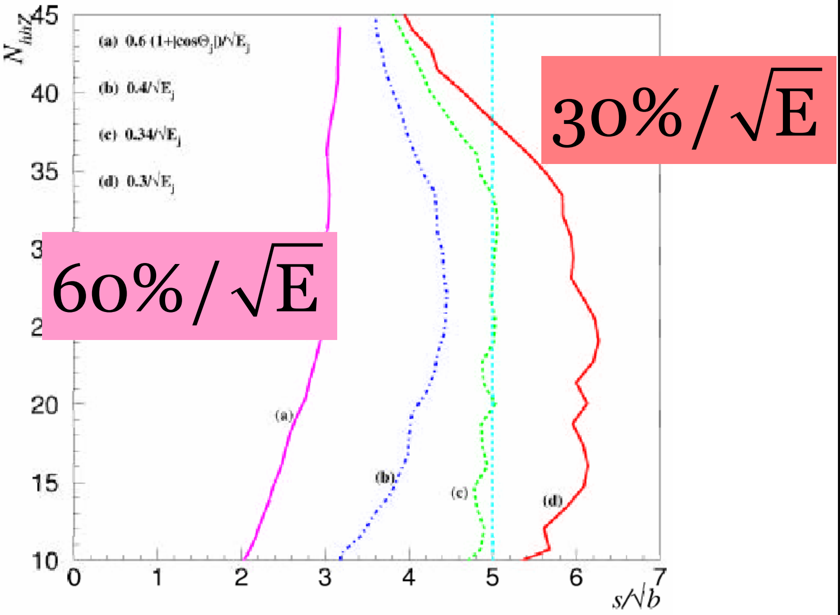
$\sigma^2_{\text{confusion}}$ is the largest contribution!

Particle Flow

To reduce confusion in the calorimeters:

- Have large B field and large calorimeter inner radius
  - to separate the particles
- Use materials with small Moliere radius
  - to reduce shower overlap
- Finely segment calorimeters (in 3D)
  - to allow separation of neighbouring showers
- Place calorimeters inside coil, no cracks
- Develop smart algorithms

Significance of HHZ signal for 500fb^{-1} :



$30\%/\sqrt{E}$

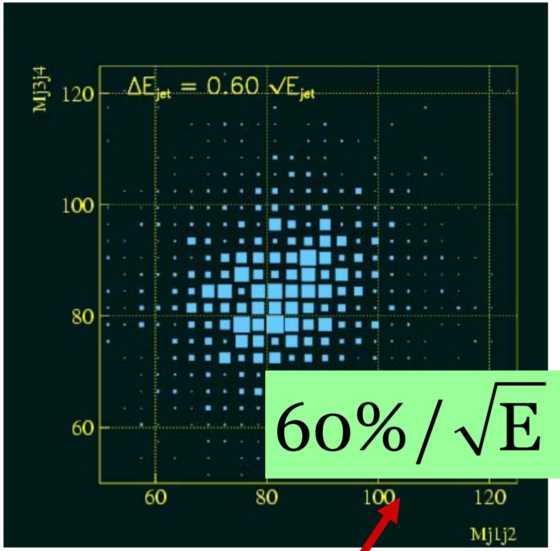
$60\%/\sqrt{E}$

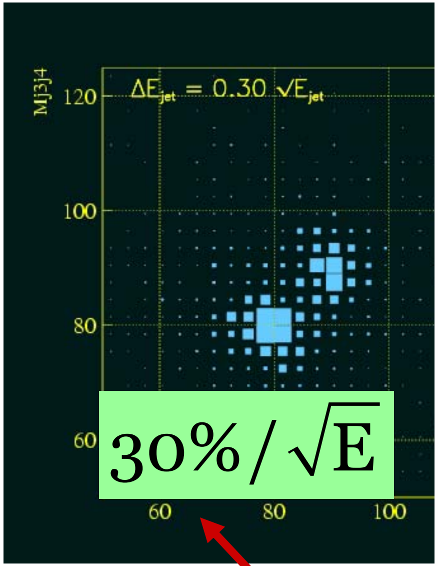
Particle Flow

Di-jet mass resolution

distinguish W and Z in their
hadronic decay modes:

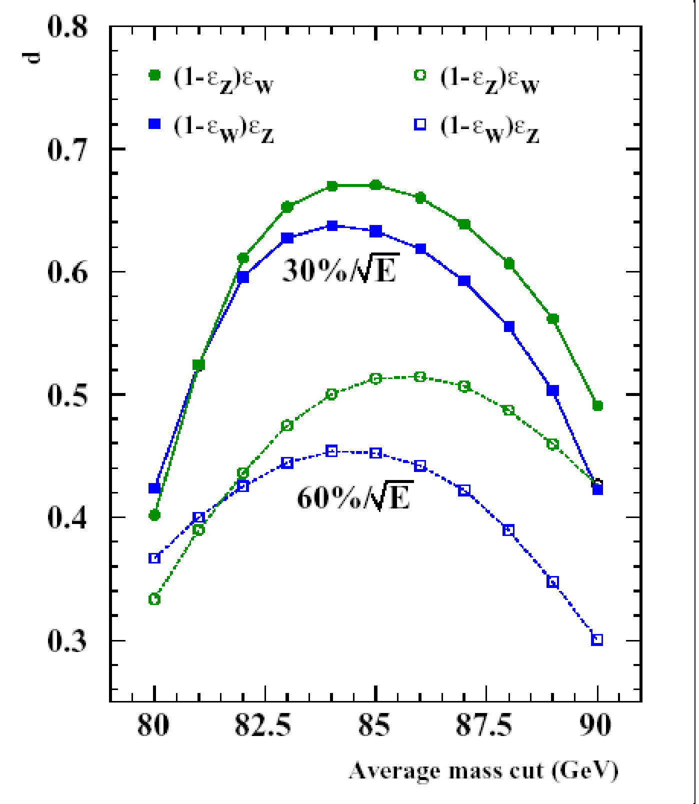
$$e^+e^- \to WW\,\nu\bar{\nu} \quad , \quad e^+e^- \to ZZ\,\nu\bar{\nu}$$





LEP-like resolution

LC goal



Dilution factor vs cut:
integrated luminosity equivalent

1. Introduction

Summary of Day 1

- Standard Model is successful enough to show us that we are not on a completely wrong path
- Very likely for new phenomena to appear at the TeV energy scale Those can be studied at high-energy colliders
- The TeV linear collider (ILC) will study these new phenomena in much more depth than the LHC
- CLIC may continue these studies up into the multi-TeV region
- Experimentation at a Linear Collider is more demanding than at LEP/SLC
- Experimental effects of beamstrahlung have to be taken into account
- A high-resolution detector with small systematics is needed to match the statistical precision offered by the high luminosity