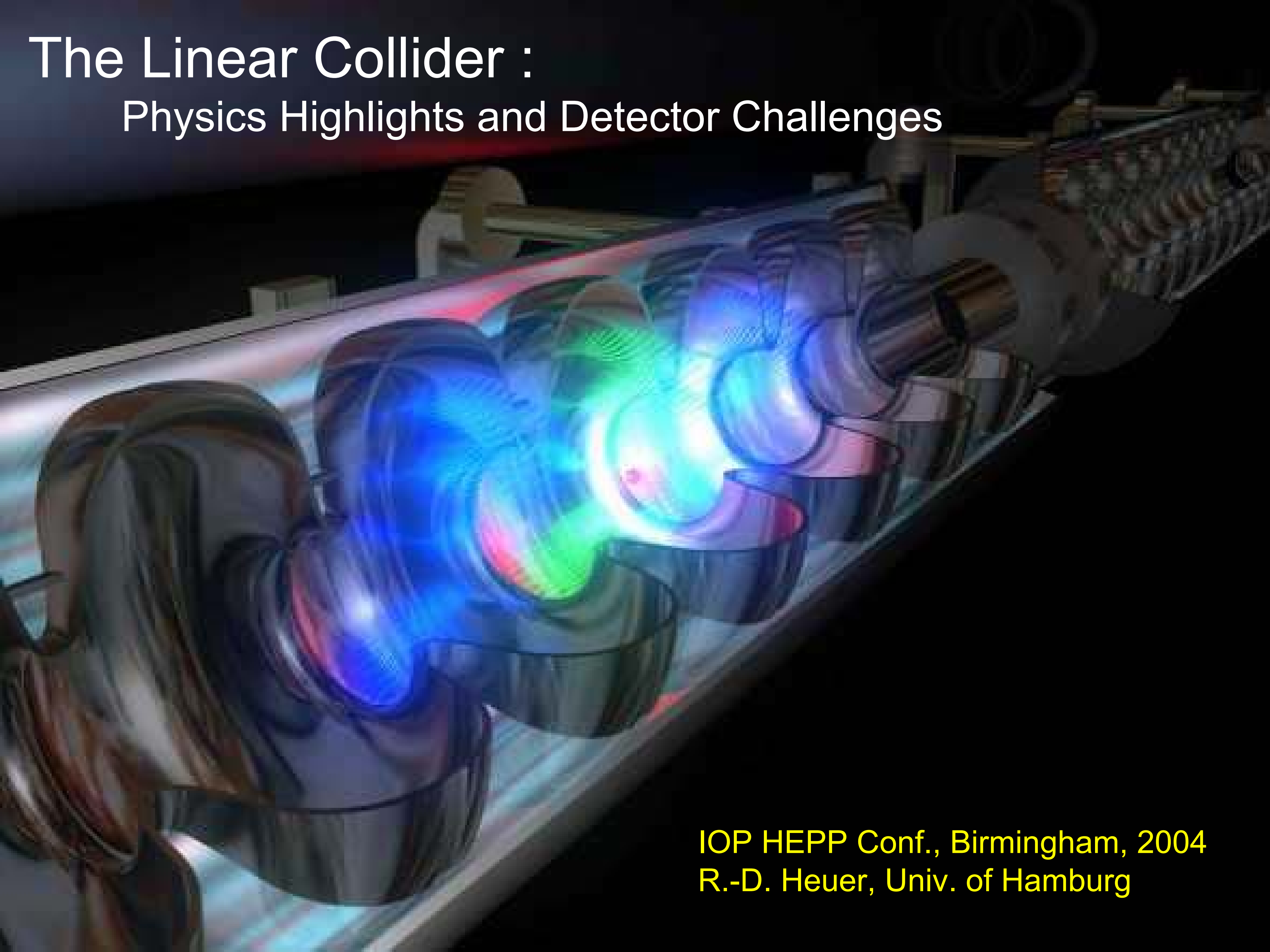
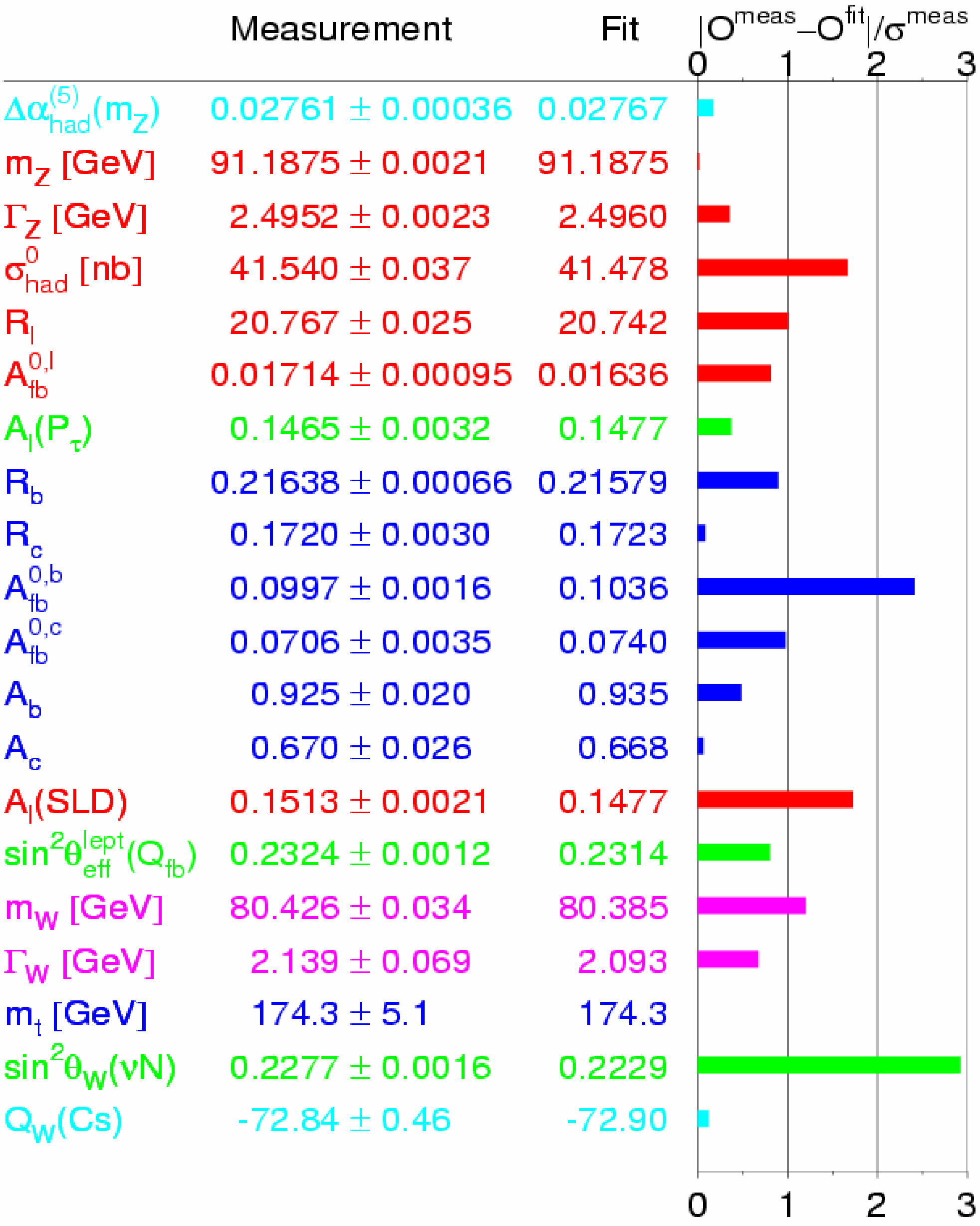


The Linear Collider :

Physics Highlights and Detector Challenges

IOP HEPP Conf., Birmingham, 2004
R.-D. Heuer, Univ. of Hamburg

Summer 2003



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1036
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
$Q_W(Cs)$	-72.84 ± 0.46	-72.90

(LEP/SLC/Tevatron...)

Standard Model today enormously successful:

- tested at quantum level
- (sub)permille accuracy

But:
many key questions open

- origin of electroweak symmetry breaking
- unification of forces
- extra space dimensions
- origin of dark matter/energy
- ….

The next steps at the energy frontier

There are two distinct and complementary strategies
for gaining new understanding of matter, space and time
at future particle accelerators

HIGH ENERGY

direct discovery of new phenomena
i.e. accelerators operating at the energy scale of the new particle

HIGH PRECISION

interference of new physics at high energies through the precision measurement of phenomena at lower scales

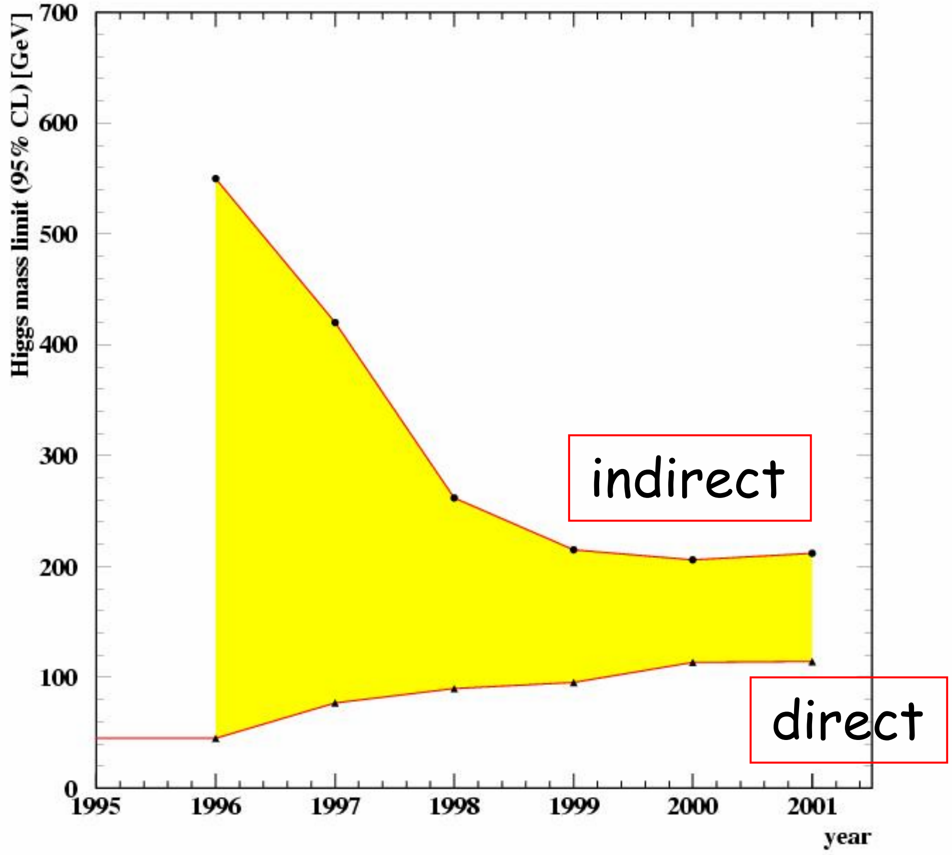
Both strategies have worked well together
→ much more complete understanding than from either one alone

prime example: LEP / Tevatron

The next steps

We know enough now to predict with great certainty that fundamental new understanding of how forces are related, and the way that mass is given to all particles, will be found with the LHC and a Linear Collider operating at an energy of at least 500 GeV upgradeable to about 1000 GeV.

Experimental limits on the Higgs boson mass



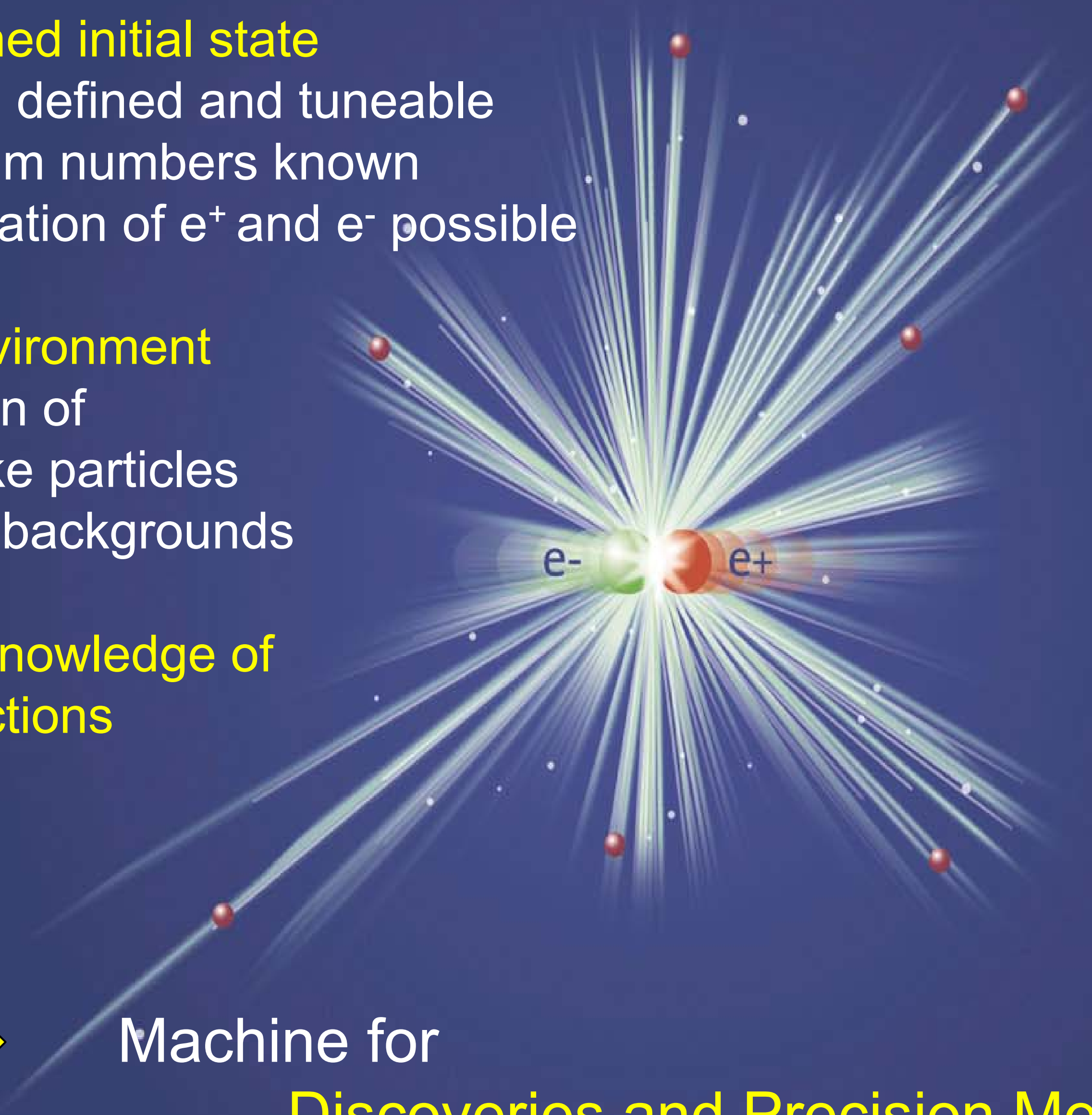
M_H between 114 and ~210 GeV

Electron-Positron Linear Collider offers

- well defined initial state
  - $\sqrt{s}$ well defined and tuneable
  - quantum numbers known
  - polarisation of e^+ and e^- possible

- clean environment
  - collision of
  - pointlike particles
  - → low backgrounds

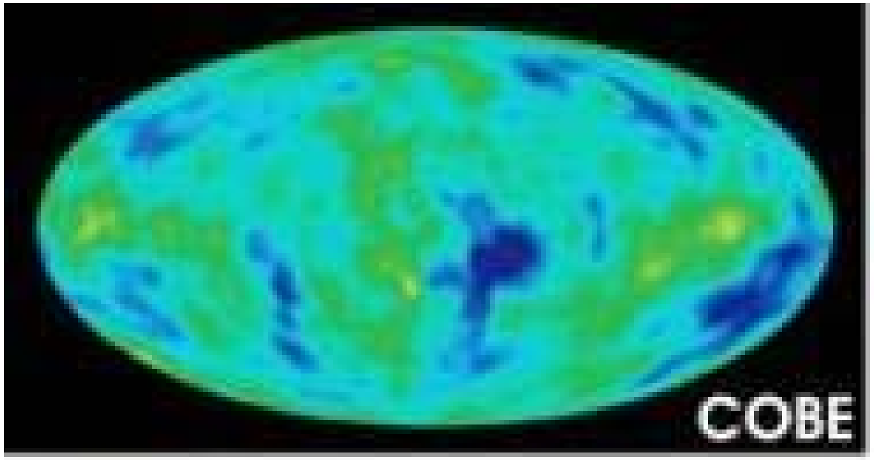
- precise knowledge of cross sections

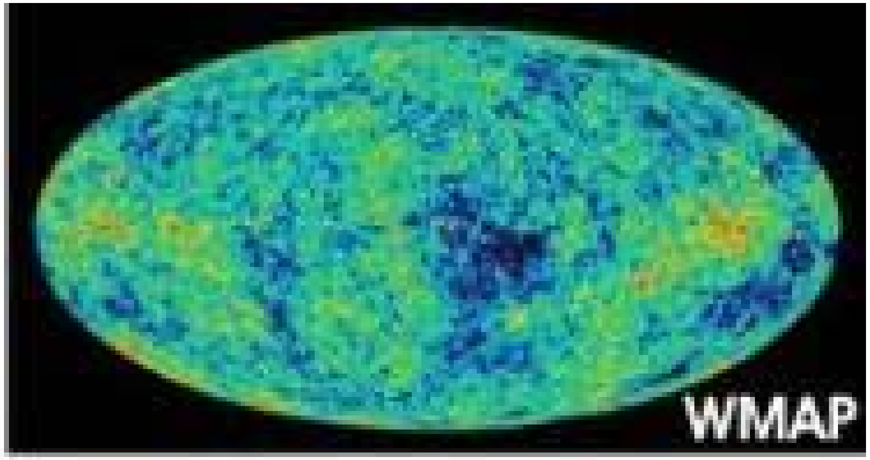


⇒ Machine for

Discoveries and Precision Measurements

An Analogy: What precision does for you ...



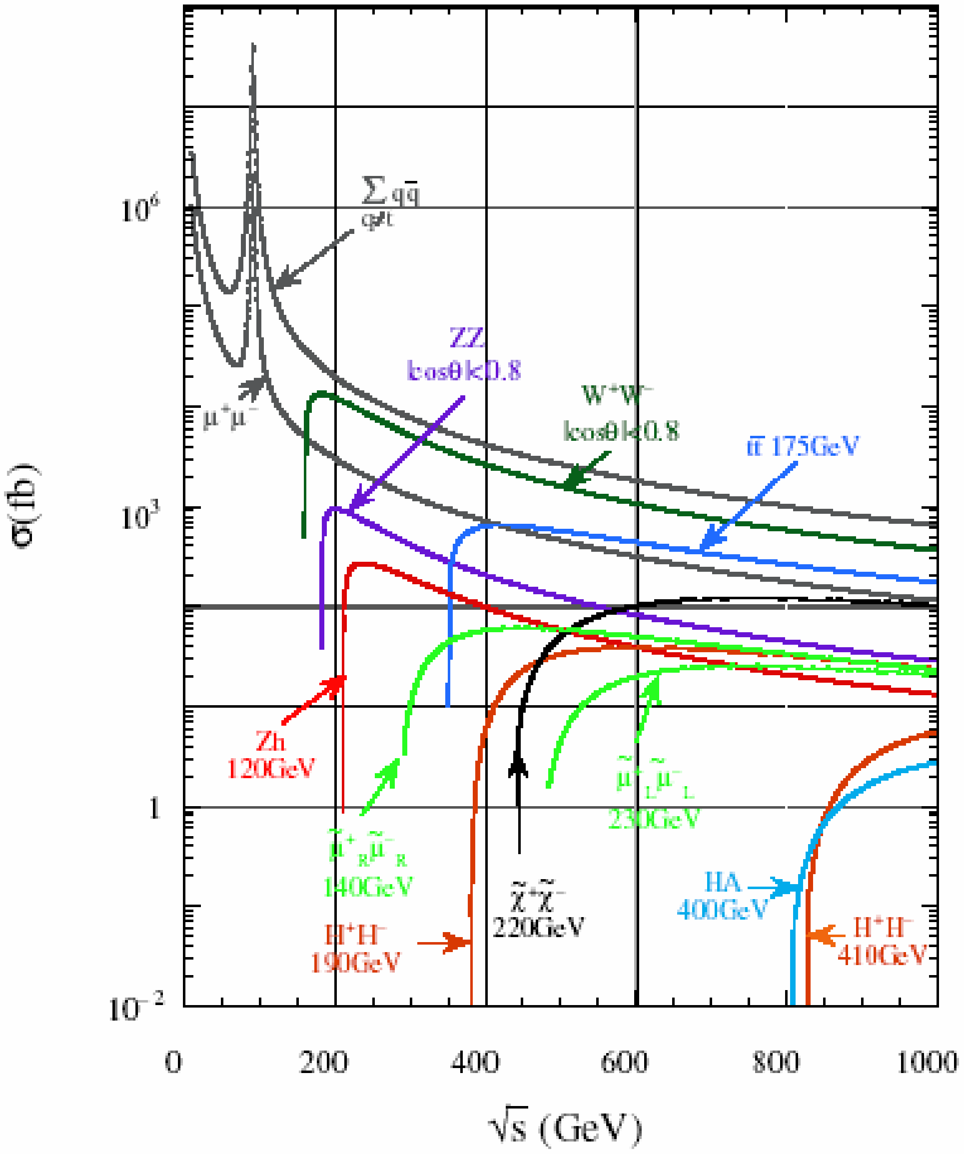


Physics Goal

Comprehensive and high precision coverage of energy range from M_Z to ~ 1 TeV

Physics Highlights

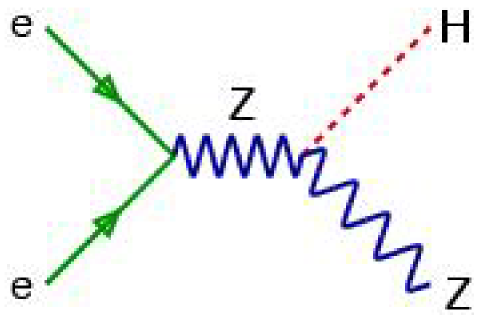
- Higgs Mechanism
- Supersymmetry
- Strong Electroweak Symmetry Breaking
- Extra Dimensions
- Precision Measurements at lower energies
-
-

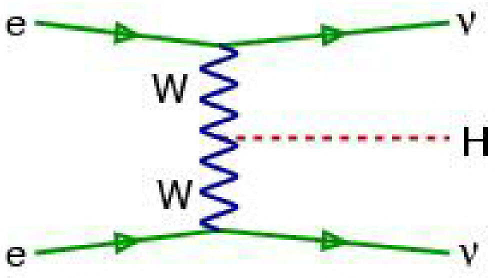


cross sections few *fb* to few *pb*
high lumi → *O*(10,000) HZ/yr

Precision physics of Higgs bosons

Dominant production processes at LC:





Task at the LC:

establish Higgs mechanism responsible for the origin of mass

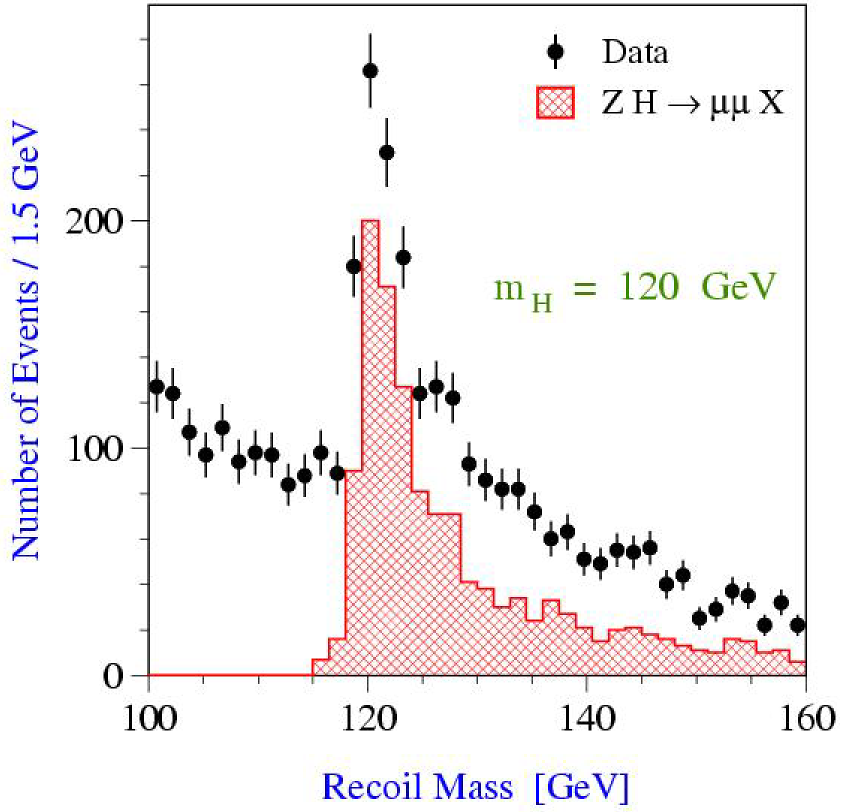
i.e. precision measurement of

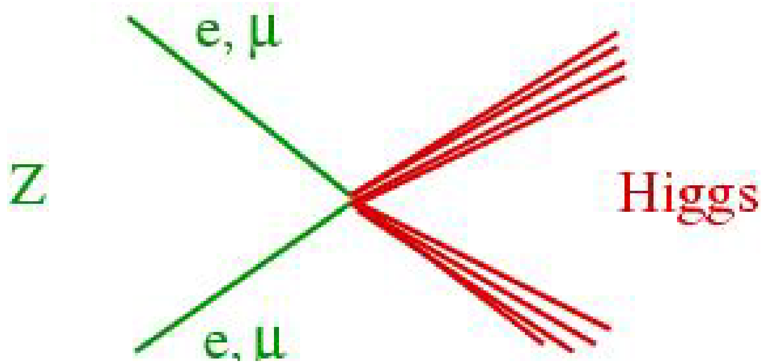
- mass(es) LHC, LC
- couplings (LHC), LC
- self-coupling (potential) LC

Precision physics of Higgs bosons

Recoil mass spectrum

ee -> HZ with Z -> l^+l^-





$\Delta\sigma \sim 3\%$

model independent measurement

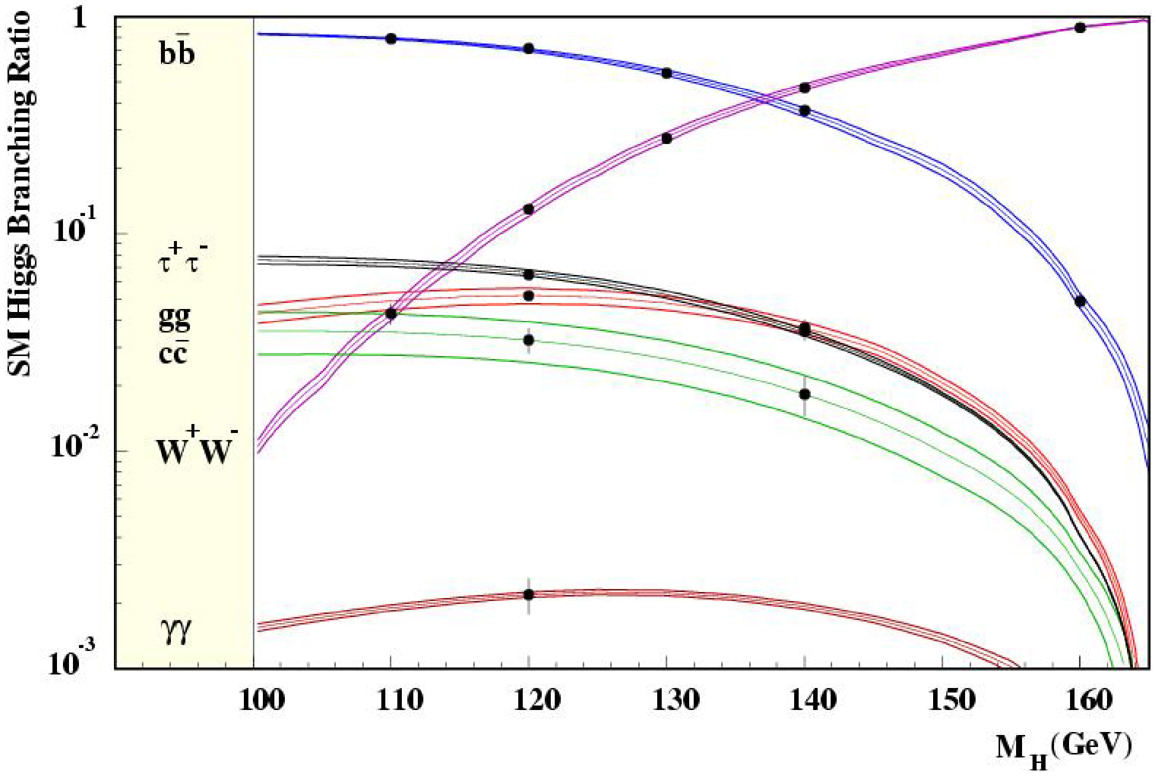
$\Delta m \sim 50$ MeV

sub-permille precision

Detector Challenge: tracking / momentum resolution

Precision physics of Higgs bosons

Higgs field responsible for particle masses
→ couplings proportional to masses



Precision analysis
of Higgs decays

ΔBR/BR

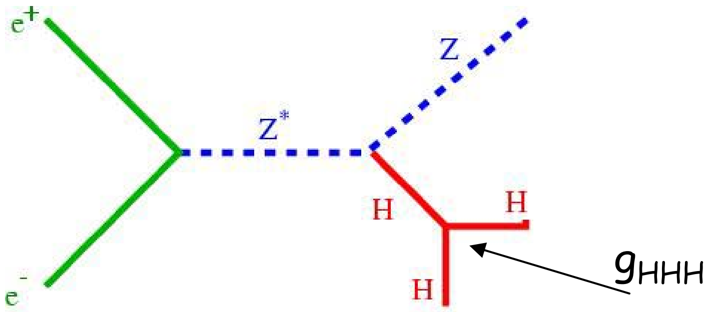
bb	2.4%
cc	8.3%
gg	5.5%
tt	6.0%
gg	23.0%
WW	5.4%

For 500 fb^{-1}
M_H = 120 GeV

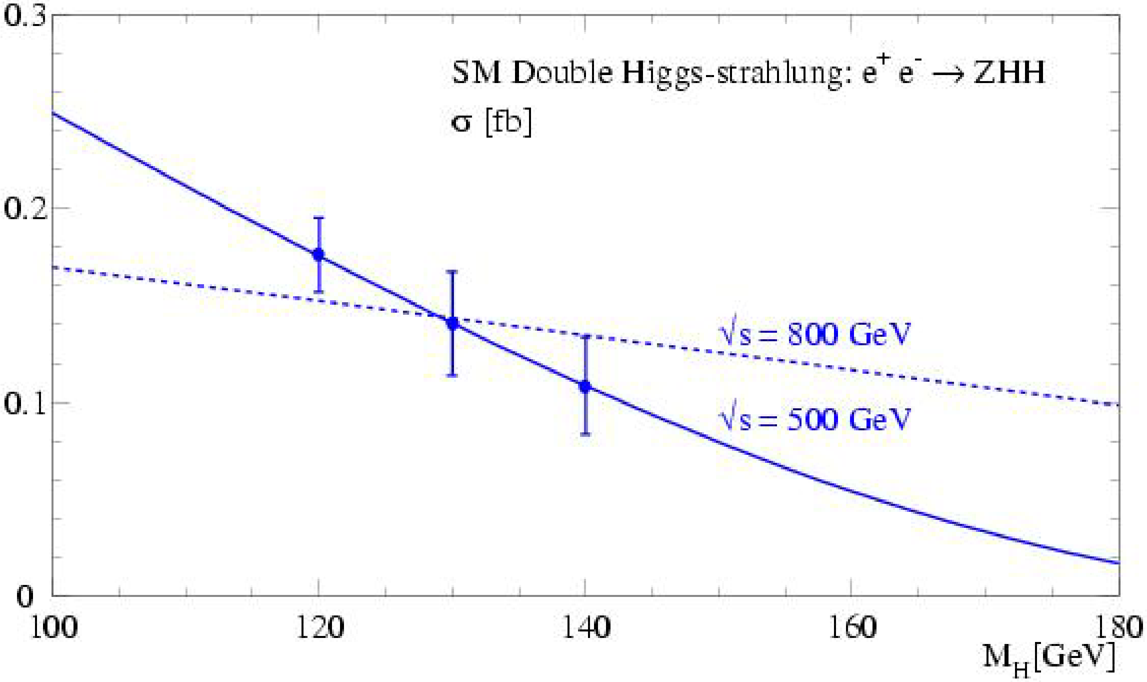
Precision high enough to distinguish SM Higgs from e.g. MSSM Higgs

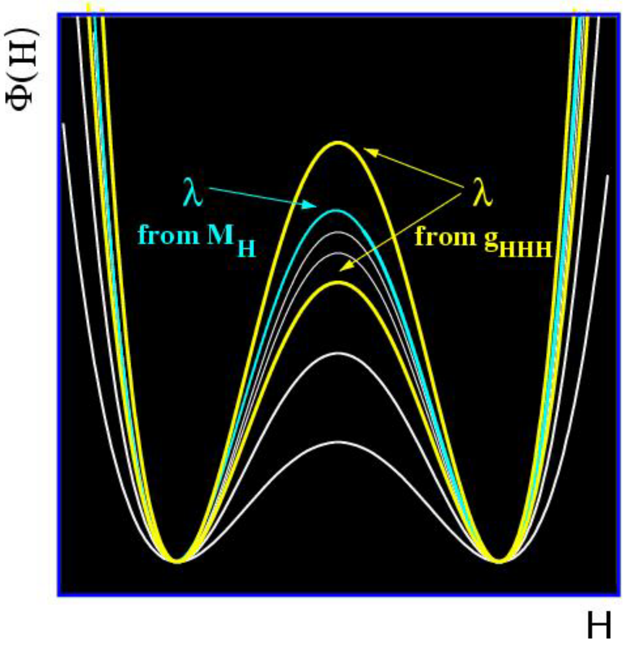
Detector Challenge: vertexing / secondary vertices (charm!)

Reconstruction of the Higgs-potential



$\Phi(H)=\lambda v^2H^2 + \lambda vH^3 + 1/4\lambda H^4$
SM: $g_{HHH} = 6\lambda v$, fixed by M_H





$\Delta\lambda/\lambda \cong 20\%$

($1\ ab^{-1}$)

↓

LC Challenge: luminosity

Detector Challenge: particle flow (Calorimetry)

Precision physics of Higgs bosons

Conclusion

precision measurements at the Linear Collider
together with the results from LHC
are crucial to establish the Higgs mechanism
responsible for the origin of mass and for revealing
the character of the Higgs boson

if the electroweak symmetry is broken in a more
complicated way then foreseen in the Standard Model
the LC measurements strongly constrain the
alternative model

Supersymmetry

- best motivated extension of SM
  grand unification – connection to gravity – light Higgs – $\sin^2\Theta_W$
  dark matter candidate – ….

- mass spectrum depends on the unknown breaking scheme

- LC task for SUSY

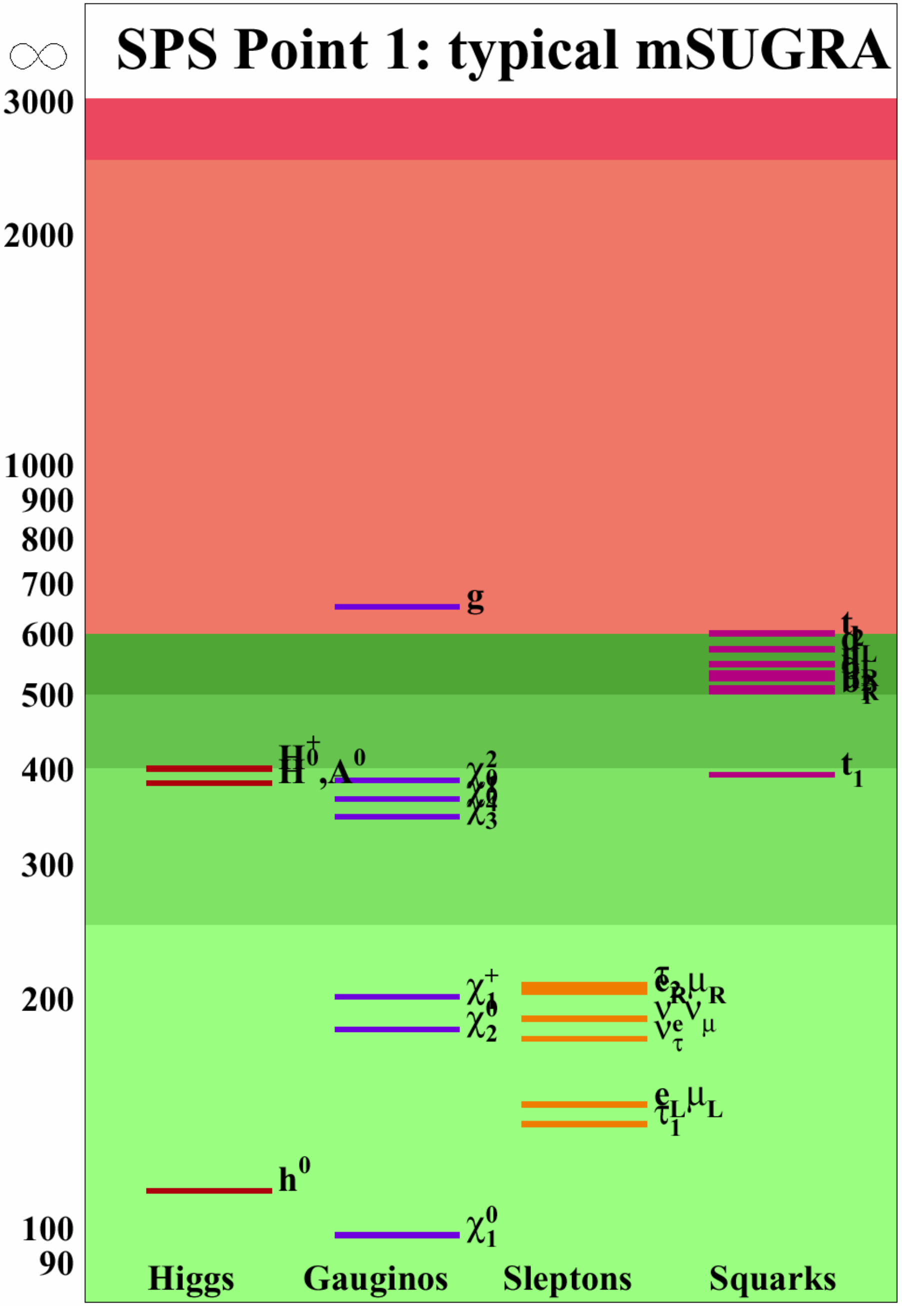
  reconstruction of kinematically accessible sparticle spectrum
  i.e. measure sparticle properties (masses, Xsections, spin-parity)

  extract fundamental parameters (mass parameters, mixings, couplings) at the weak scale

  input to cosmology: precision on Dark Matter (few %)
  well matching precision of cosmology (Planck)

  extrapolate to GUT scale using RGEs
  → *determine underlying supersymmetric model*

Supersymmetry



Mass spectra depend on choice of models and parameters...

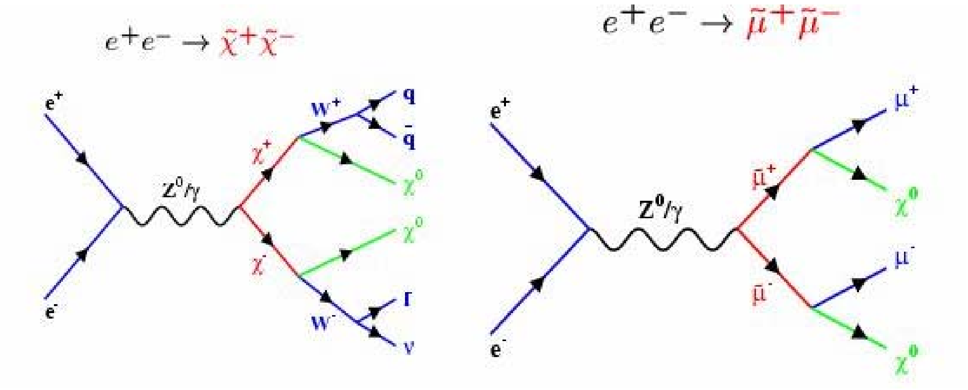
well measureable at LHC

precise spectroscopy at the Linear Collider

no well motivated model without sparticles within LC reach

at least to my knowledge...

Supersymmetry

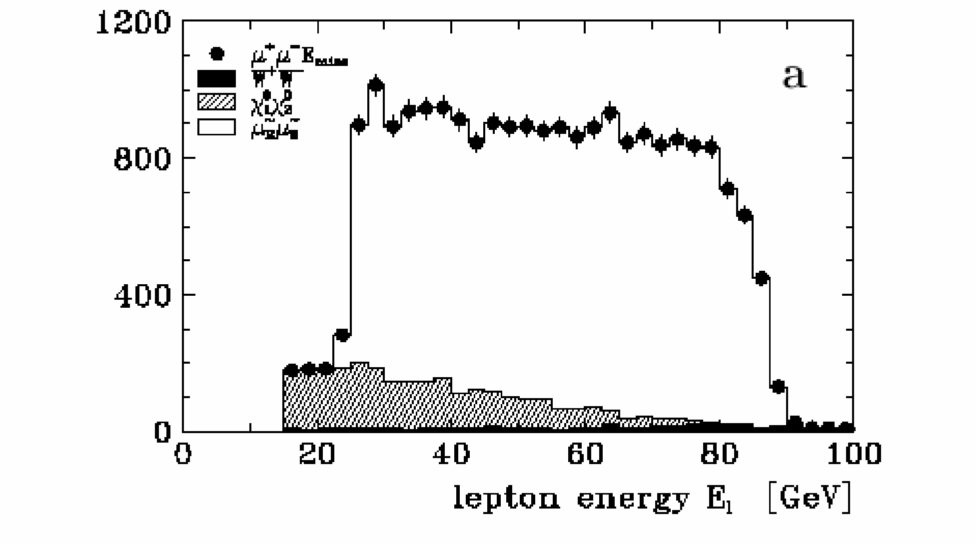


Measurement of sparticle masses

Experimental signature: missing energy

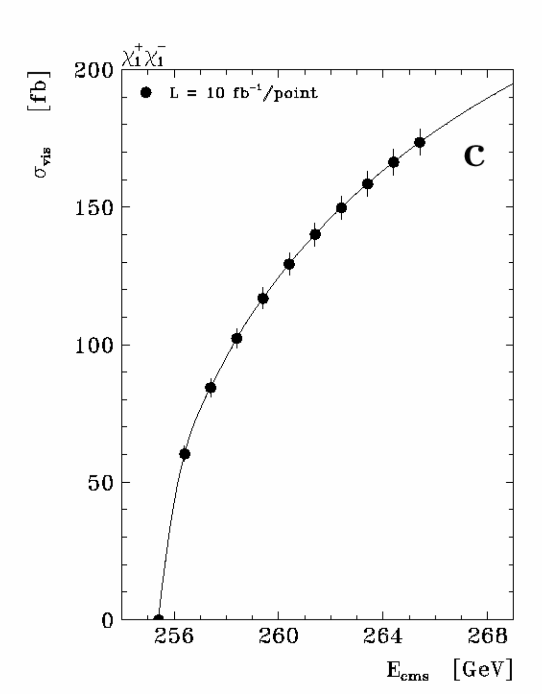
ex: Sleptons

lepton energy spectrum in continuum



ex: Charginos

threshold scan

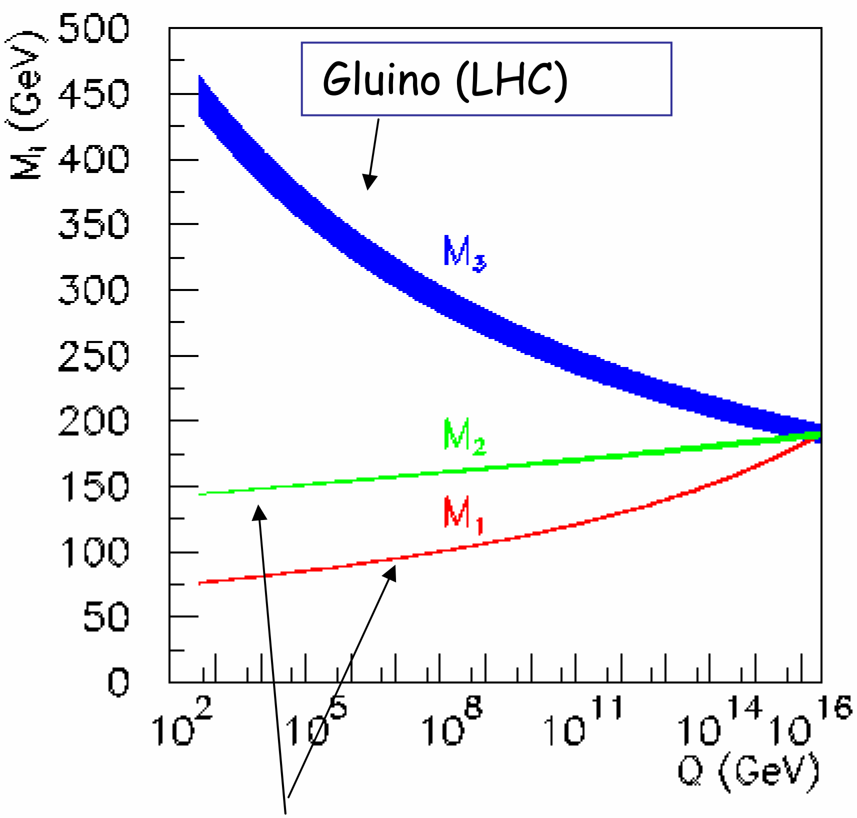


achievable accuracy: $\delta m/m \sim 10^{-3}$

→ precision on DM: few%

Supersymmetry

Extrapolation to GUT scale



Gluino (LHC)

SUSY partners of
electroweak bosons and Higgs

Extrapolation of SUSY parameters from weak to GUT scale (here: within mSUGRA)

Gauge couplings unify at high energies,

Gaugino masses unify at same scale

Precision provided by LC for slepton, charginos and neutralinos will allow to test if masses unify at same scale as forces

Supersymmetry

Conclusions

The Linear Collider will be a unique tool
for high precision measurements:

- model independent determination of SUSY parameters
- input to cosmology
- determination of SUSY breaking mechanism
- extrapolation to GUT scale possible

but what if ……

No Higgs boson(s) found….

→ divergent $W_L\ W_L \to W_L\ W_L$ amplitude in SM at $\Lambda^2 = o\left(\frac{4\pi\sqrt{2}}{G_F}\right) \approx (1.2TeV)^2$

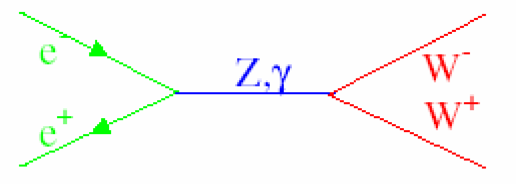
→ SM becomes inconsistent unless a new strong QCD-like interaction sets on

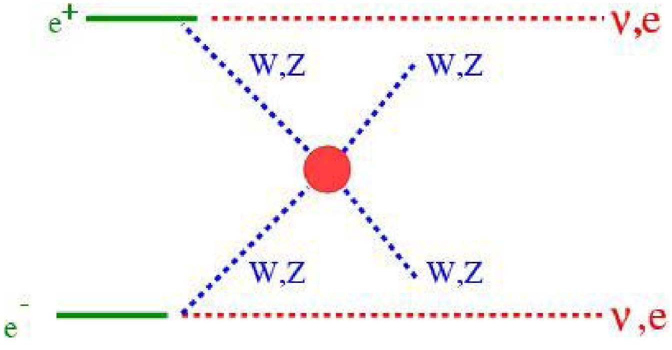
→ Goldstone bosons ("Pions") = W states ("technicolor")

→ no(?) calculable theory until today in agreement with precision data

Experimental consequences: *deviations in*

triple gauge couplings *quartic gauge couplings:*





LC (800 GeV): sensitivity to energy scale Λ:
triple gauge couplings: ~ 8 TeV
quartic gauge couplings: ~ 3 TeV

⇨ *complete threshold region covered*

Detector Challenge: particle flow (Calorimetry)

Precision electroweak tests

high luminosity running at the Z-pole

Giga Z (10^9 Z/year) ≈ 1000 x “LEP” in 3 months

with e^- and e^+ polarisation

$\Delta \sin\Theta_W = 0.000013$

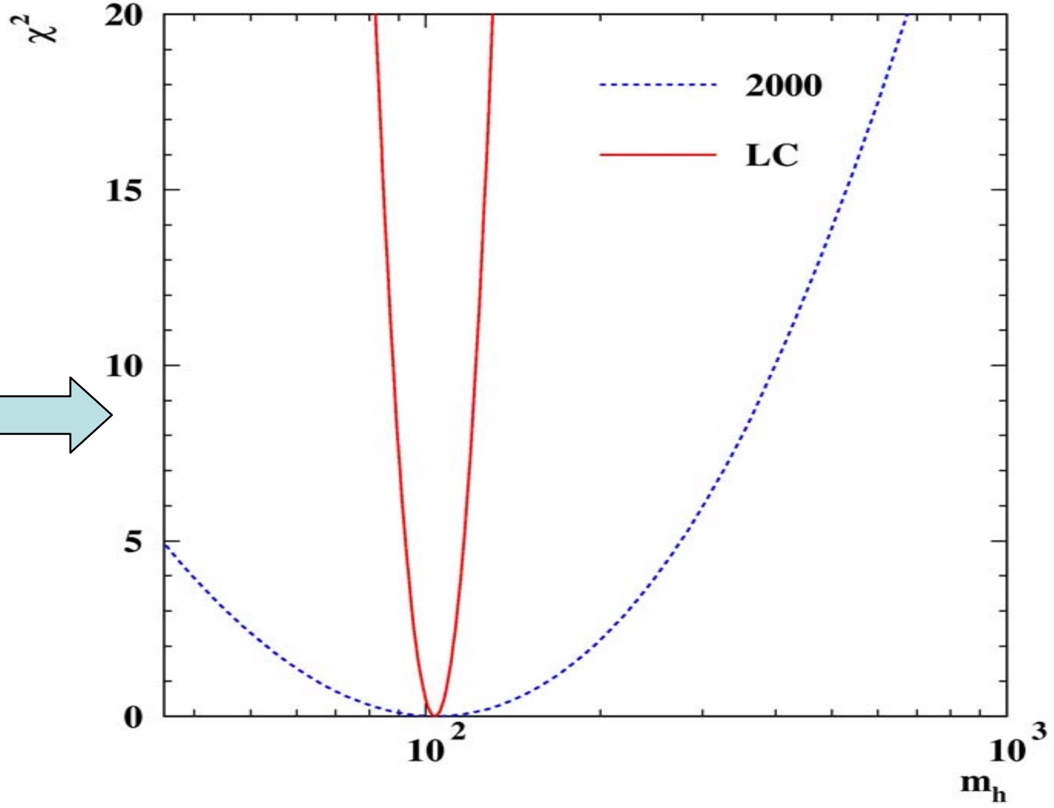
together with

$\Delta M_W = 7$ MeV

(threshold scan)

And

$\Delta M_{top} = 100$ MeV



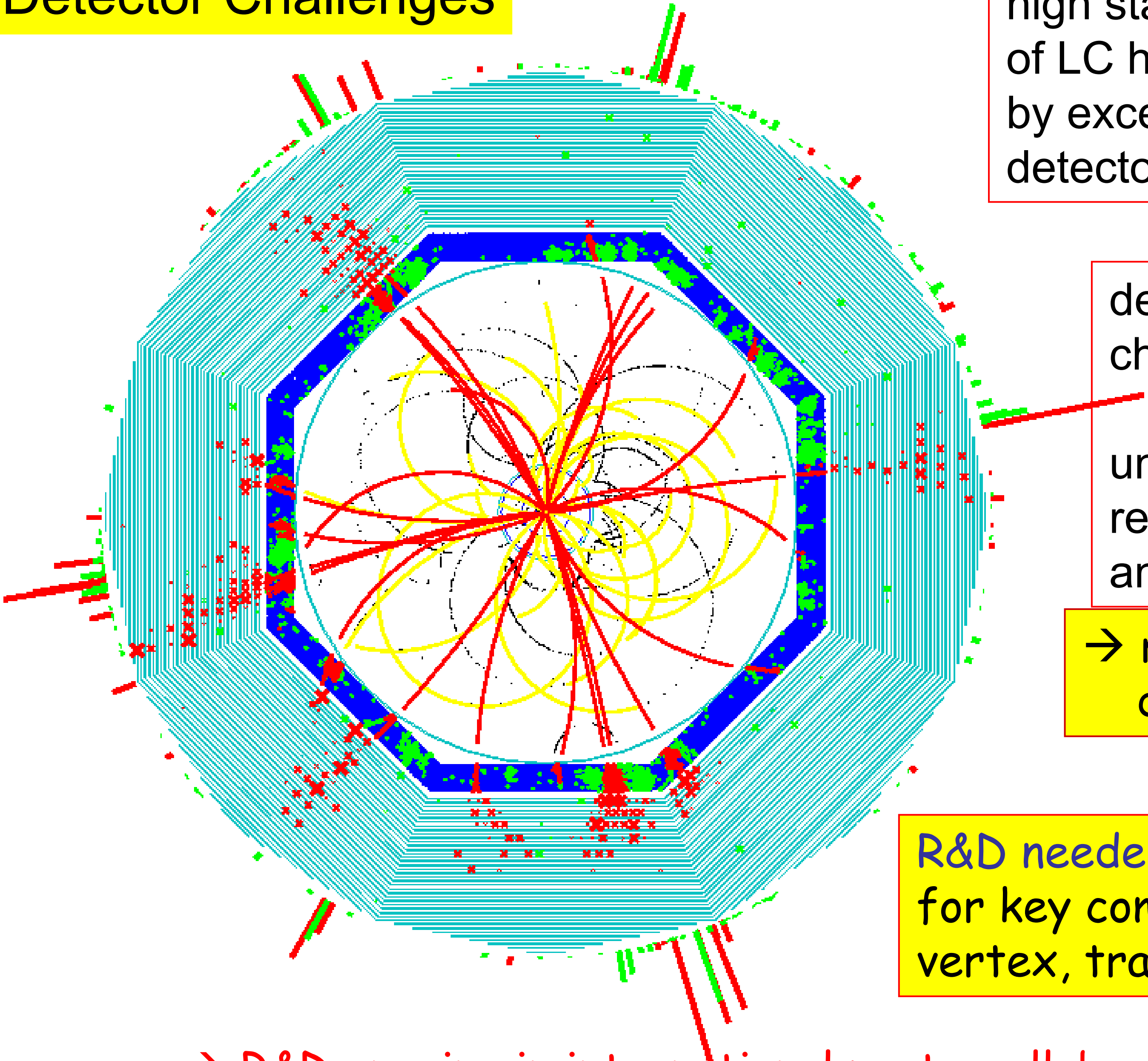
Physics Conclusion

LC with $\sqrt{s} \leq 1$ TeV and high luminosity allows

- most stringent test of electroweak Standard Model
- to establish Higgs mechanism in its essential elements
- to explore SUSY sector with high accuracy, model independent
- extrapolations beyond kinematically accessible region
- ….

World-wide consensus on physics case:
http://sbhep1.physics.sunysb.edu/~grannis/lc_consensus.html

Detector Challenges



high statistical power
of LC has to be met
by excellent
detector performance

detector design
challenging:

unprecedented
resolution
and systematics

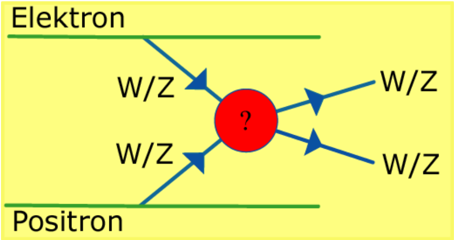
→ requirements
different from LHC

R&D needed now
for key components:
vertex, tracking, calorimeter

→ R&D ongoing in international proto-collaborations

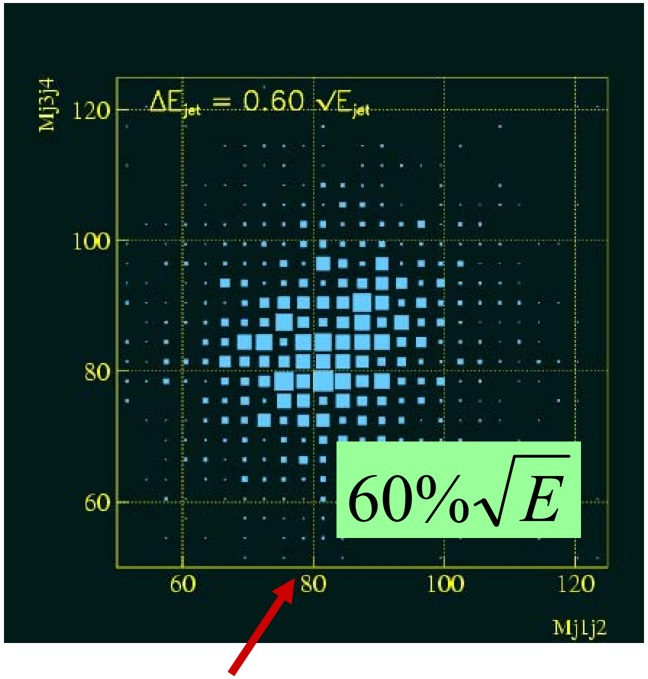
Detector Challenges: Particle Flow

Ex: strong electroweak symmetry breaking

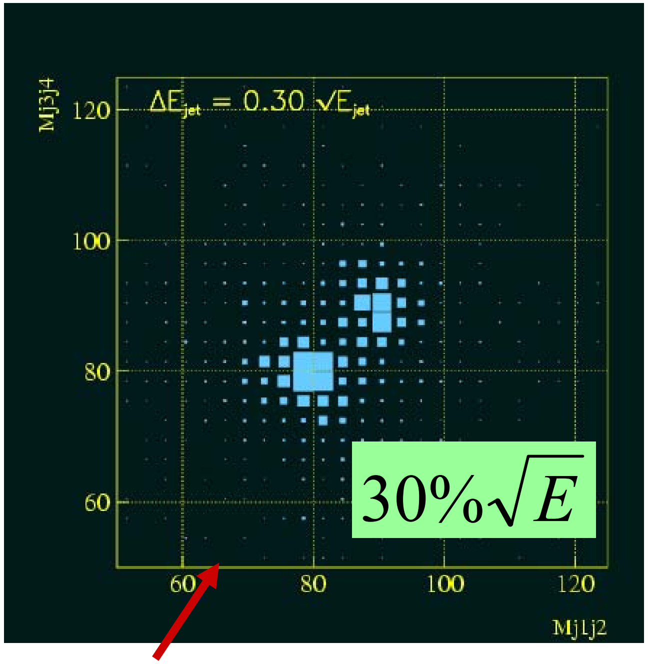


→ distinguish W and Z in their hadronic decay modes

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



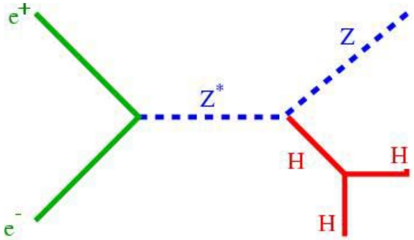
LEP-like resolution

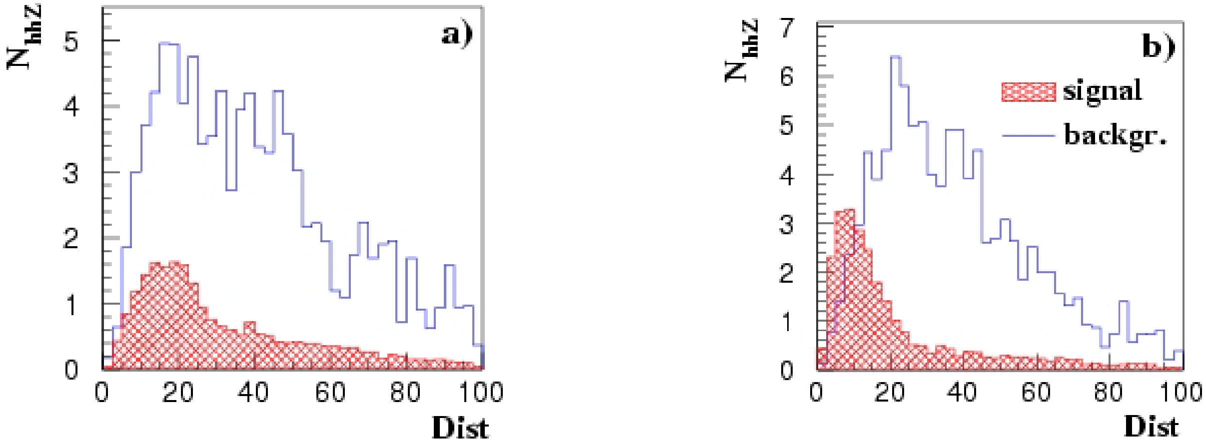


LC goal

Detector Challenges: Particle Flow

ex: Triple Higgs coupling

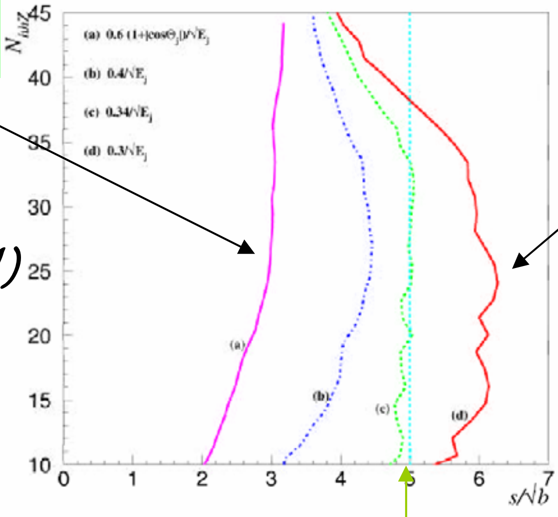




Reconstruct observable from 3 di-jet masses:

high resolution mandatory

$60\%\sqrt{E}$



$30\%\sqrt{E}$

N_{ev} (1ab-1)

$s/\sqrt{B}$

5 sigma

Detector Challenges: Particle Flow

for best jet energy and di-jet mass resolution need

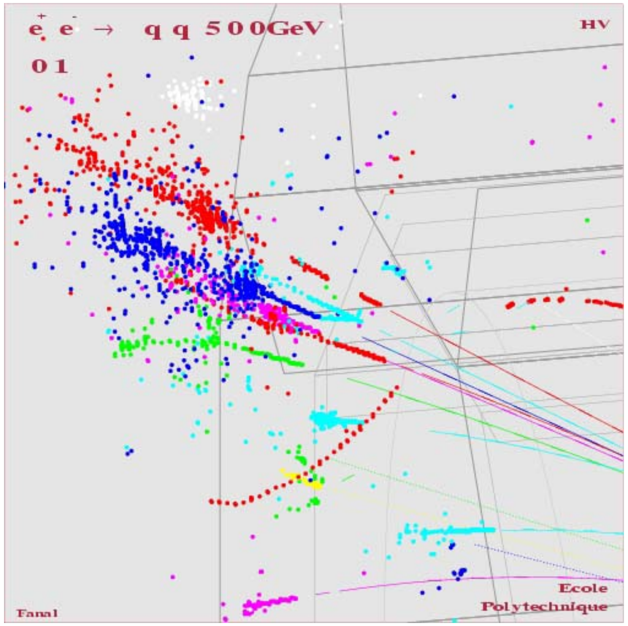
- tracking detectors to measure energy of charged particles (65% of the typical jet energy)
- EM calorimeter for photons (25%)
- EM and HAD calorimeter for neutral hadrons (10%)

particle flow goal

reconstruction of all individual charged and neutral particles

need

- excellent directional and energy resolution
- excellent 3D-separation (also in calorimeter)



Detector Challenges: Calorimeter

Calorimeter and Particle Flow algorithm represent formidable challenges

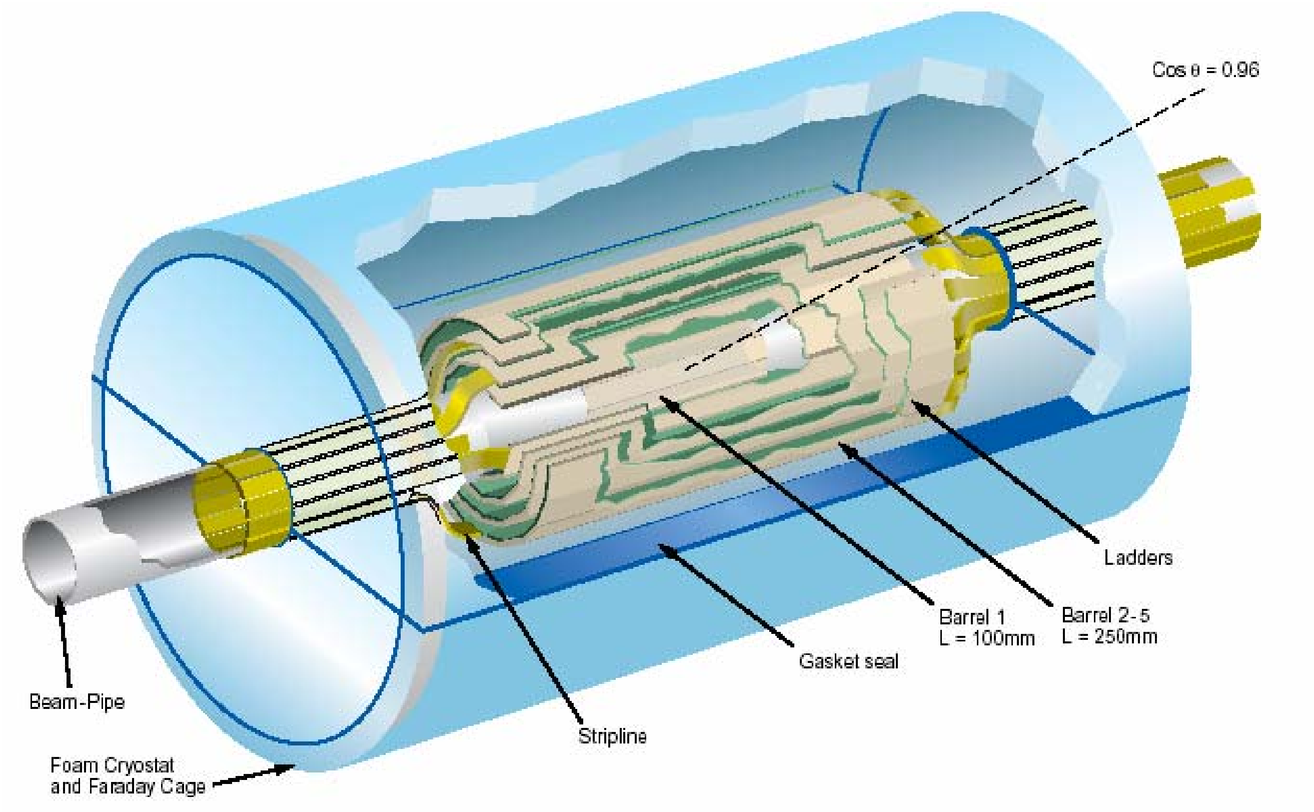
Present technologies under study:
EM calorimeter: SiW
HAD calorimeter: scintillating tiles (‘analog’)
RPC, GEM, tiles (‘digital’)

addressed by a world-wide R&D effort

partly organized in (open) proto-collaborations,

e.g. CALICE: 164 Physicists, 26 Institutes, 9 Countries in 3 Regions
strong participation by UK groups in the ECAL:
Birmingham - Cambridge - Imperial College London
Manchester - University College London - RAL

Detector Challenges: Vertex detector



Universally agreed (almost):

~ 5 layers (inner layer radius 12-15 mm, with 3-hit coverage to cosΘ = 0.96)

pixel size at most 20 mm square

< 0.1% X_0 per layer for minimal mult scatt and γ conversions

Detector Challenge: Vertex detector

- Aggressive requirements from precision vertexing
  → monolithic silicon pixel sensors like CCDs, MAPS and DEPFET

- addressed by a world-wide R&D effort, organized in regional collaborations (e.g. LCFI in UK) but world-wide interactions

- important areas of R&D:
  - requirement for untriggered DAQ system
    need multiple readout (~ 20 frames) during TESLA bunch train of duration 1 ms [At NLC, it is still OK to read in 8 ms between trains]
    → column parallel concept (CPCCD),
    successfully prototyped by LCFI collaboration
  - concerns regarding beam-related RF pickup
    initiated a re-think for all technologies
    → concept of in-situ storage of signal charge.
    to be implemented into CPCCD by LCFI

Detector Challenges: Summary

- detector requirements different from LHC

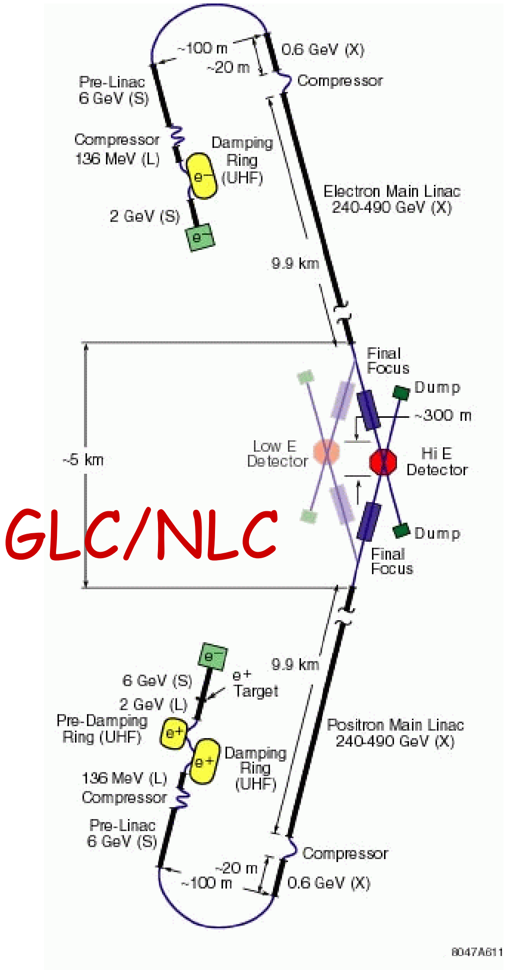
- need to achieve unprecedented resolution
  and systematics

- detector R&D ongoing in international proto-collaborations

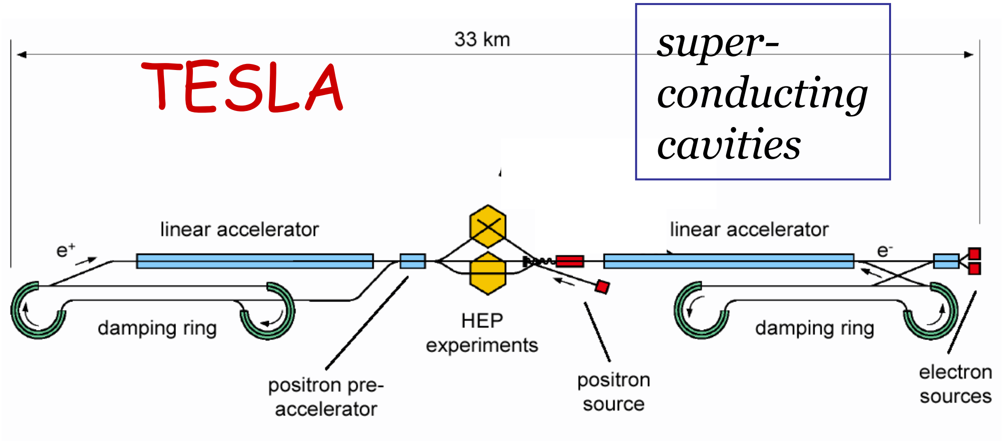
  e.g. SI-Vertexing and -tracking
  LC-TPC
  CALICE
  Forward Region

  addressing R&D issues globally, not regionally
  LC technology independent

Steps towards realisation



normal-conducting cavities



super-conducting cavities

- Technology choice **2004**
- Concurrent running with the LHC:
  - ready for approval **2007+**
  - start commissioning **2015**

Summary + Outlook

- Linear Electron Positron Collider in the range 500-1000 GeV has excellent scientific potential
- Worldwide consensus: LC next large HEP project – soon
- Detector R&D necessary and under way internationally
- HEP community wants to build the LC as truly global project – choice of technology by end 2004
- Activities on political level started – Think global