Collider Physics Conference 2004

Future Colliders

- Science
- Technology
- Strategy

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DESY and Hamburg University

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Introductory Comments

Where do we stand and where do we go in particle physics?

-> Guido Altarelli

I will focus on one of the vital questions of the coming years:

Why, how and when do we build the next e+e- collider?

I will therefore not discuss issues like *muon colliders* or a *very large hadron collider*, nor issues of generic R&D in new acceleration technologies

The future of particle physics is strongly linked to our ability to promote and build a LC in a timely fashion.

The Development of Accelerators

Towards highest energies

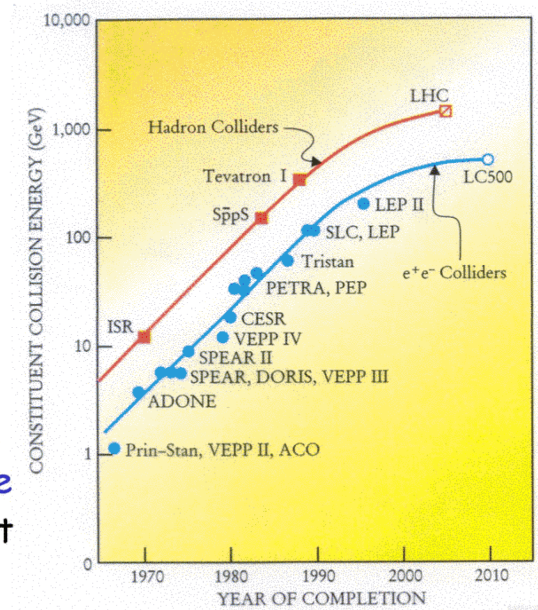
Hadron Colliders

- LHC under construction at CERN

Towards precision measurements

Electron-Positron Collider

- e.g. GLC, NLC, TESLA



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Physics and experience teach us that we need these different tools to answer the open questions and that they complement each other

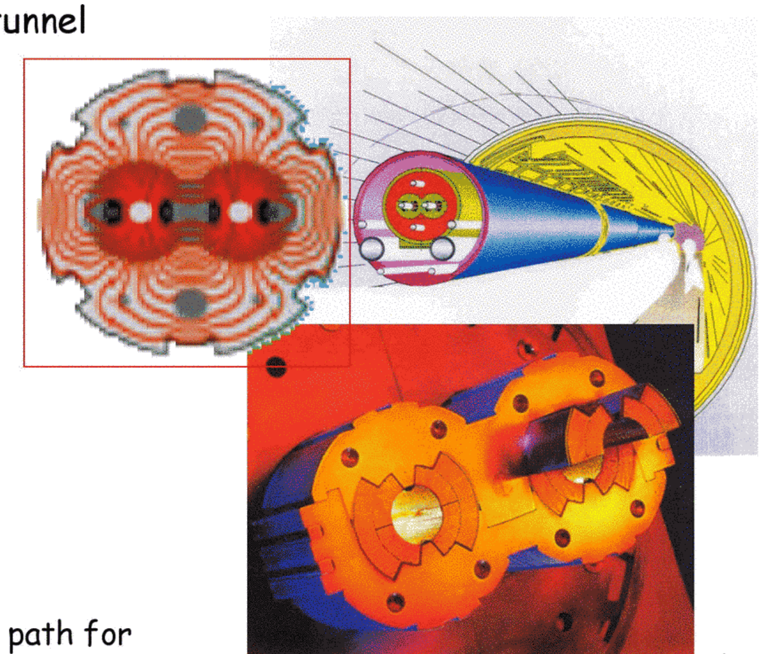
Need to push accelerator R&D

The Large Hadron Collider

proton-proton collider, under construction in the LEP tunnel

(27 km circumference)

first luminosity in 2007



Parameters:

E_{beam} = 7 TeV

Field = 8.33 T

L = 10^{34} cm^{-2} s^{-1}

The most probable upgrade path for the LHC is the SLHC (*10 Lumi)

The Scientific Case for a LC

Understanding Matter, Energy, Space and Time : The Case for the e^+e^- Linear Collider

A world-wide consensus has formed for a baseline LC project in which *positrons* collide with *electrons* at energies up to 500 GeV, with *luminosity* above 10^{34} $cm^{-2}s^{-1}$.

The energy should be upgradable to about 1 TeV.

Above this firm baseline, several options are envisioned whose priority will depend upon the nature of the discoveries made at the LHC and in the initial LC operation.

The consensus document has been signed by > 2000 scientists from all around the world.
http://www-flc.desy.de/lcsurvey/

Substantial overlap in running with LHC recommended

Relation of Hadron Collider and Linear Collider

1. Since the LC will start after the start of LHC, it must add significant amount of information

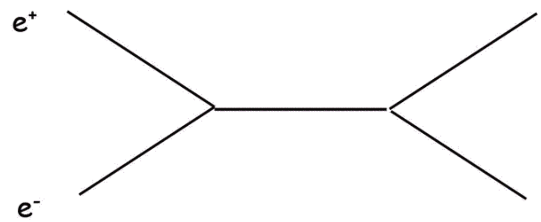
2. Neither LC nor HC's can draw the whole picture alone. A LC will add new discoveries and precision of LC is a key asset for a better understanding of the underlying physics.

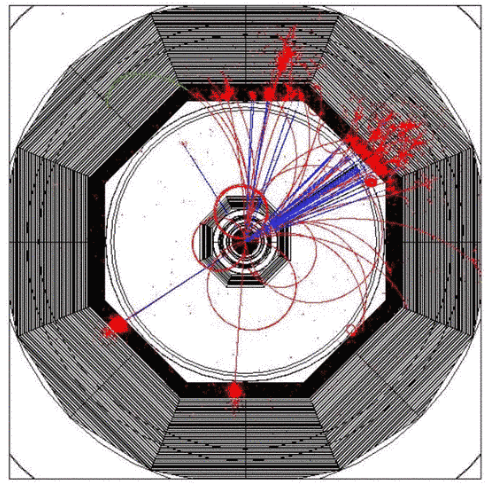
3. There are probably pieces which can only be explored by the LHC due to the higher mass reach. Joint interpretation of the results will improve the overall picture

4. Overlapping running of both machines will further increase the potential of both machines and might be mandatory, depending on the physics scenario realized

The Power of $e^+ e^-$ Colliders

- well defined production process, simple kinematics
- precise knowledge of quantum numbers in initial state
- precise (<%) knowledge of the cross sections
- polarisation of e^- and e^+ beams possible
- energy and momentum of all partons known
- energy of system can be varied
- low background





HZ -> q q μ μ

Discovery by precision measurements

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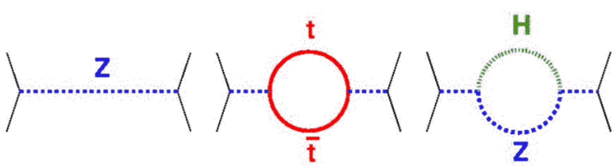
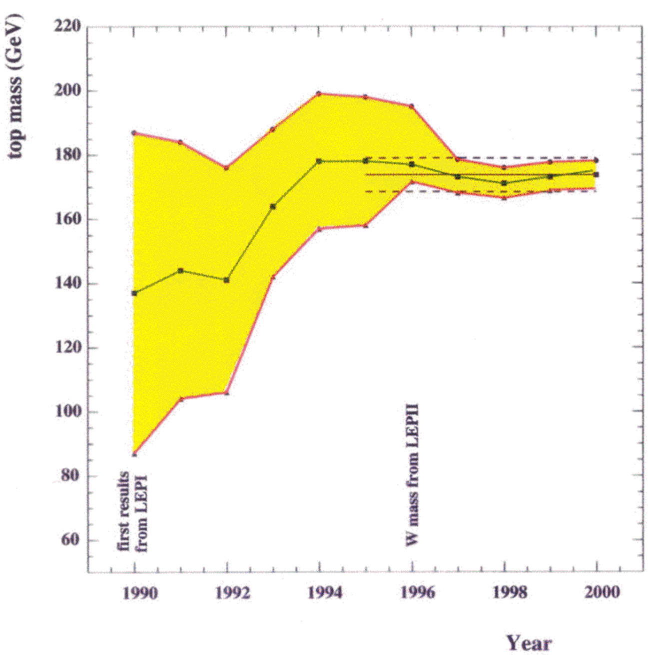
Testing Quantum Fluctuations





Indirect determination of the top mass

possible due to

- precision measurements
- known higher order electroweak corrections

$$\propto \left(\frac{M_t}{M_W}\right)^2, \ln\left(\frac{M_h}{M_W}\right)$$

Test of the SM at the level of quantum fluctuations

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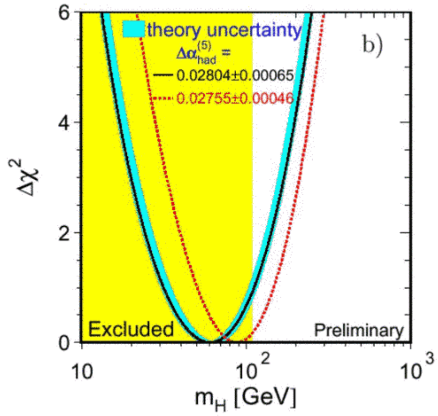
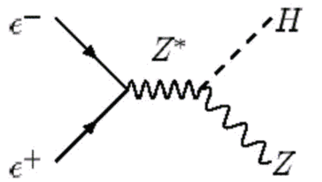
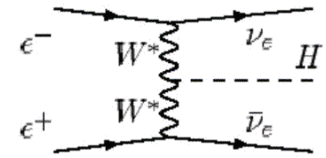
The Higgs: Key to Understanding Mass



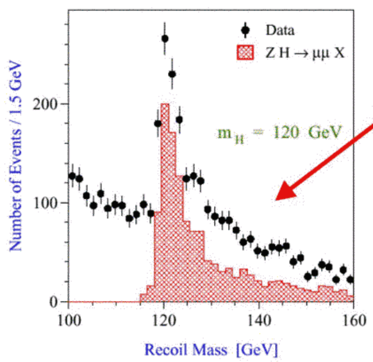




from precision tests of the SM we deduce:

114 < m(H) < ~200 GeV (95 % CL)

New input on m_{top} from Tevatron is important



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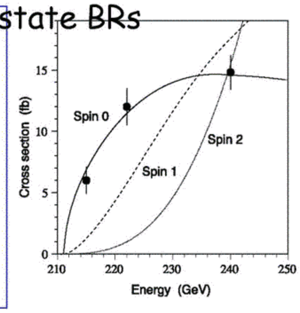
Detection independent of final state BRs

A Linear Collider measures:

- mass
- Spin, CP
- lifetime
- Couplings/branching ratios

= test the mechanism of mass generation



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Higgs Branching Ratios

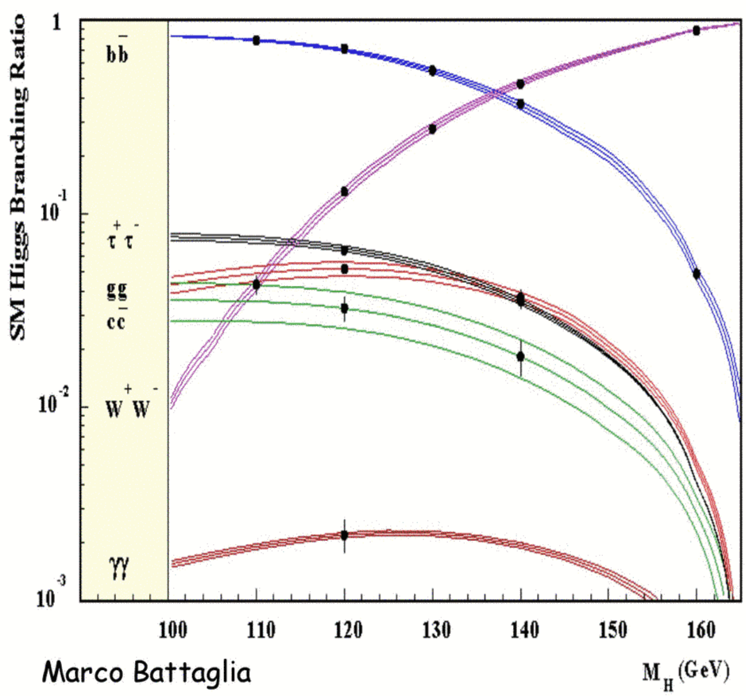
Branching ratios measure the Higgs coupling to fermions,

a test of the Higgs mechanism

accuracy a few %

500 fb-1

at 350 GeV



Marco Battaglia

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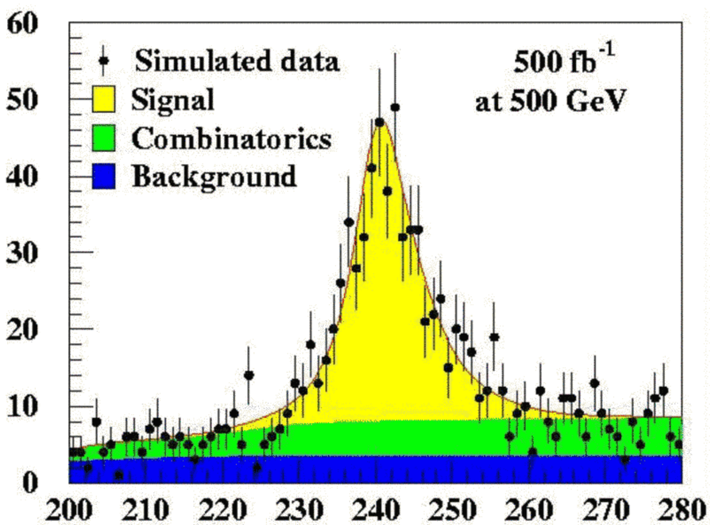
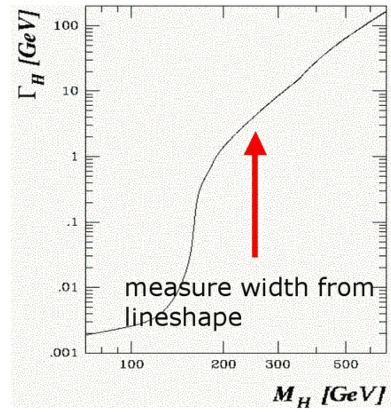
Physics: Higgs Bosons

also heavier SM-like Higgs boson accessible...

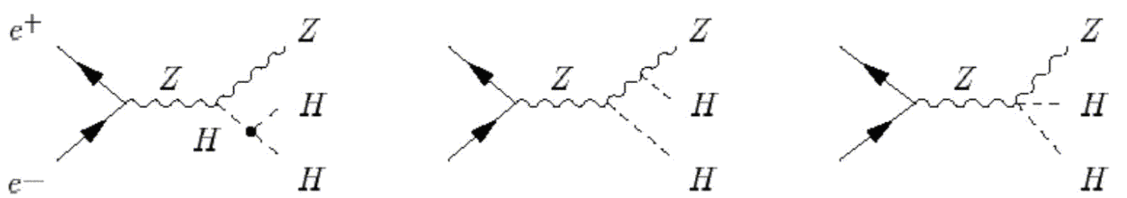




measure BR's (WW,ZZ) at the % level

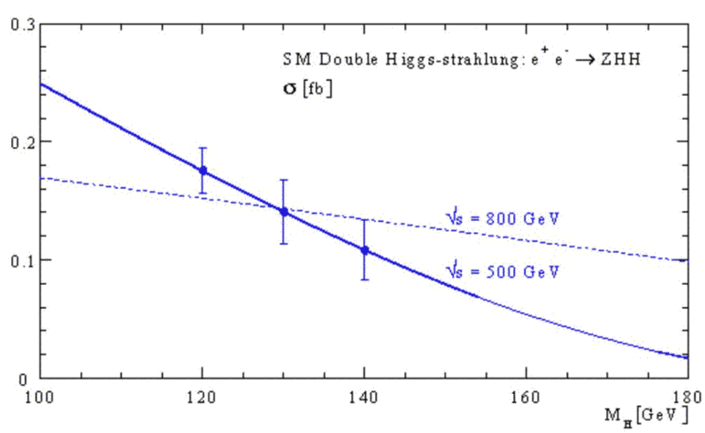
total width at 10% level

The Higgs Potential

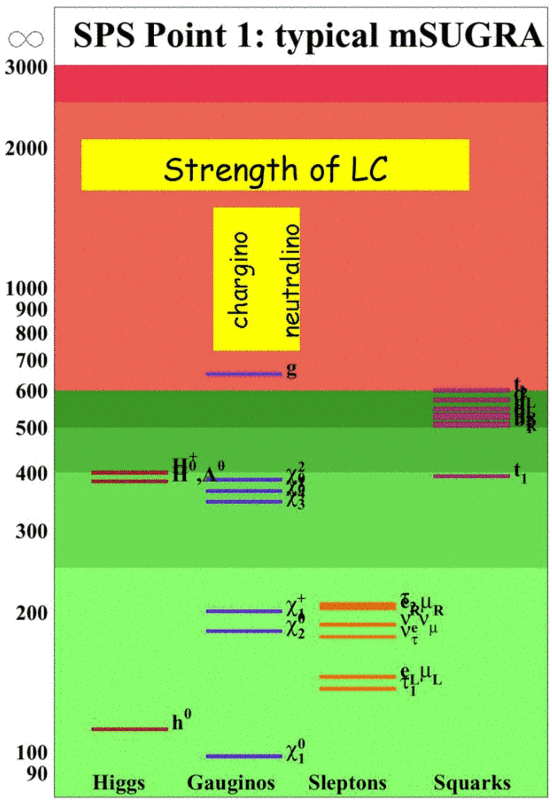


Cross section for double Higgs-strahlung

error bars correspond to 1000 fb-1



tri-linear Higgs coupling λ_{HHH} can be measure to 22 %



Discoveries beyond the SM

Extrapolation of present measurements to high energies (10^{16} GeV) fails in simple SM and suggests new physics in the 100 – 1000 GeV scale

The most favoured possibility:

Supersymmetry

A Linear Collider can measure supersymmetric particles:

- masses
- quantum numbers
- lifetimes
- decays

Mass spectra depend on SUSY parameters...

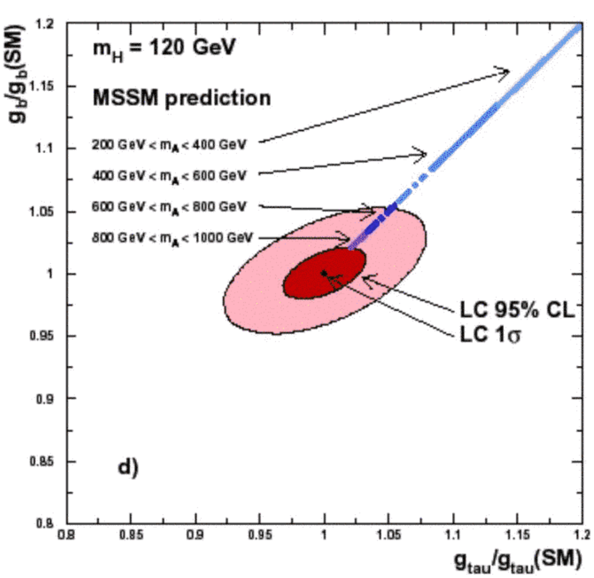
The key to understanding SUSY is to see a few of these states

Higgs Couplings

Discovery by precision, e.g.

Precise measurement of Higgs BRs probes non-SM nature of Higgs:

Is Higgs SM or MSSM?



Global fit to measured cross sections and BRs yields

Higgs couplings,

e.g. g(Hbb) and g(Hττ)

500 fb-1

m(H) = 120 GeV

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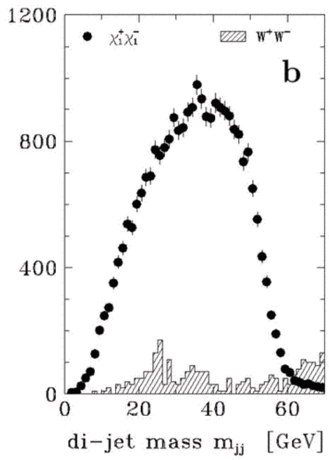
Charginos

Produced in pairs

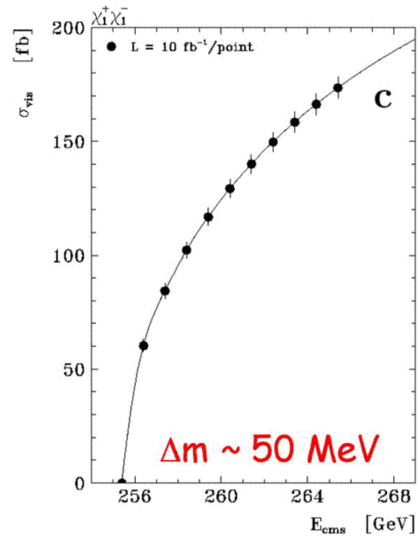
$$e_L^- e_R^+ \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^+ \rightarrow l^\pm \nu \tilde{\chi}_1^0 q\bar{q}' \tilde{\chi}_1^0$$

Easy detection
through their decays



350 GeV

160 fb^{-1}



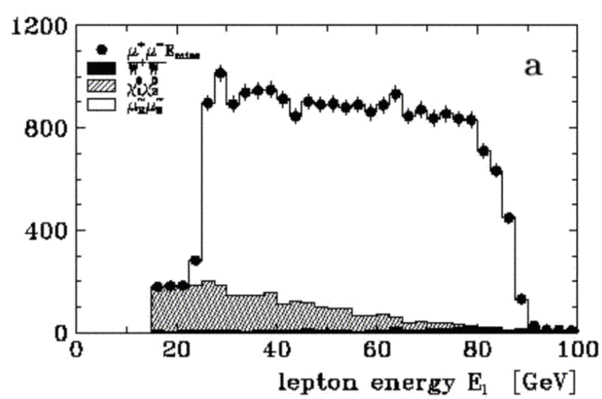
Cross section rises as $\sigma_{\chi\chi} \propto \beta$

Shape of X-section -> spin

Sleptons

Production and decay of
smuons:
$e_R^- e_L^+ \rightarrow \tilde{\mu}_R \tilde{\mu}_R \rightarrow \mu^- \tilde{\chi}_1^0 \mu^+ \tilde{\chi}_1^0$

160 fb-1



Energy spectrum of muons

Mass errors (MeV):

	smuon	χ_1^0
end points:	300	300
threshold:	90	70

LC: masses, couplings of colourless part of spectrum with high precision

HC: coloured sparticles

Cascade Decays

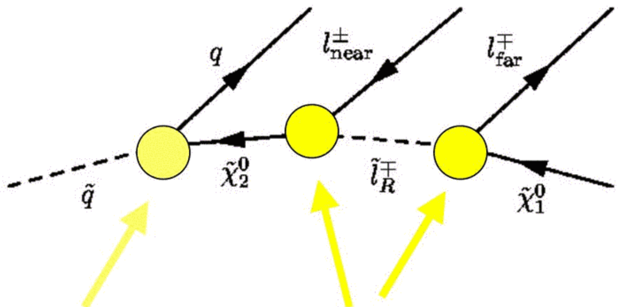
Cascade decays of squarks: if heavy, only accessible at LHC.

Hard to measure properties, if BR's of lower members of decay chain unknown.

F.Paige

A.Parker
D.Tovey

Example:

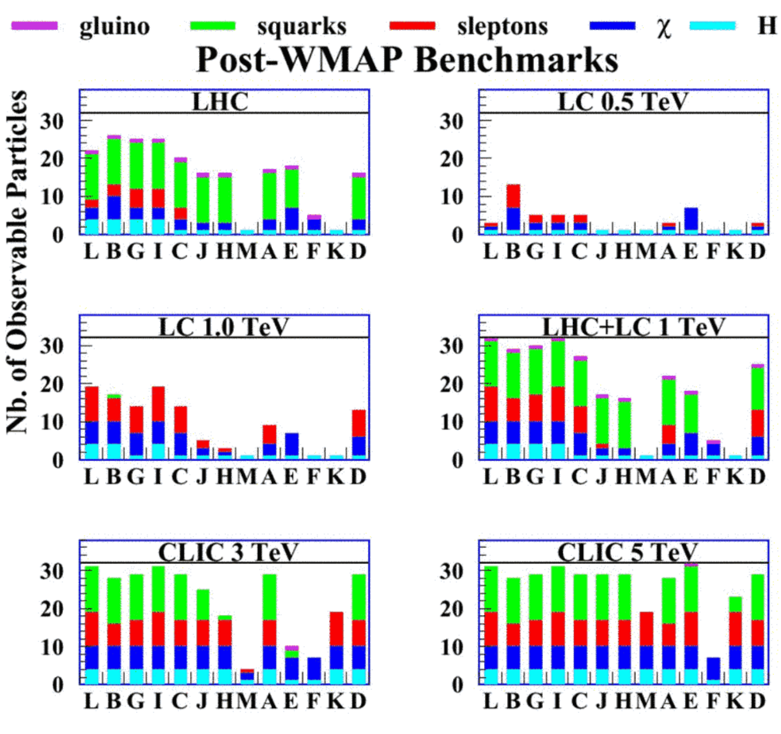


only accessible at LHC   if these are known from LC

Different final states have different acceptance corrections
Can be combined if relative BR's are known

J. Ellis at al., hep-ph/0306219

Discovery vs Energy



"Numbers of MSSM particles detectable at various accelerators in benchmark scenarios.

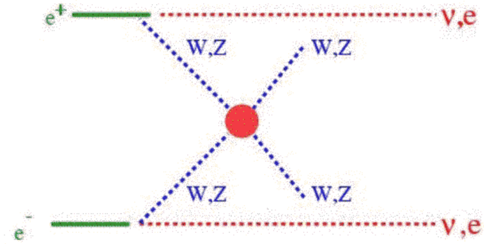
Capabilities of the LHC and of LCs are largely complementary.

Mass and coupling measurements at LC usually much cleaner, more precise than at HC, where it is not known how to distinguish the light squark flavours."

No Higgs boson(s) found....

$W_L W_L$ scattering:

Standard Model mathematically inconsistent unless new physics at about 1.3 TeV

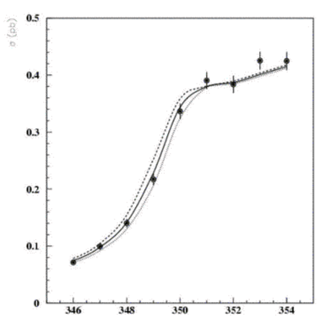


Experimental consequence: New strong interaction measurable in triple and quartic gauge boson couplings

Sensitivity at a TeV Linear Collider: ~ 8 TeV (TGC)
~ 3 TeV (QGC)

	E (GeV)	L (fb-1)	M (1.6 TeV)	No res
LC	500	300	16 σ	3 σ
LHC	14000	100	6 σ	5 σ

Ultrahigh Precision for SM Processes



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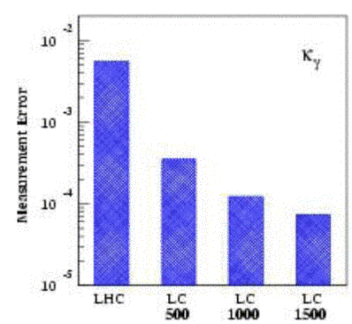
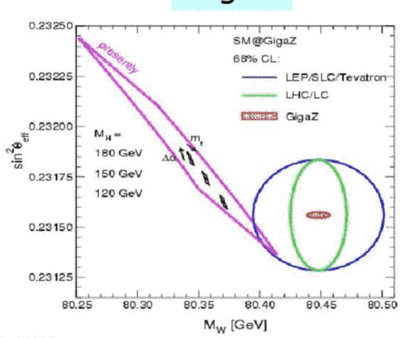
TGC's

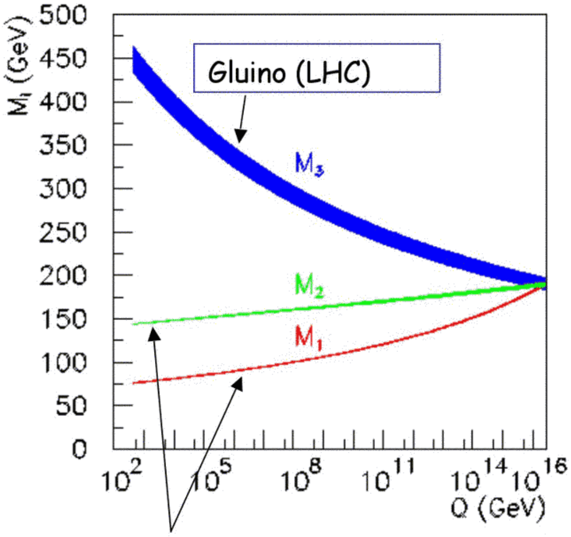


GigaZ



Test of Unification

MSSM:
105 parameters: some from HC, some from LC



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

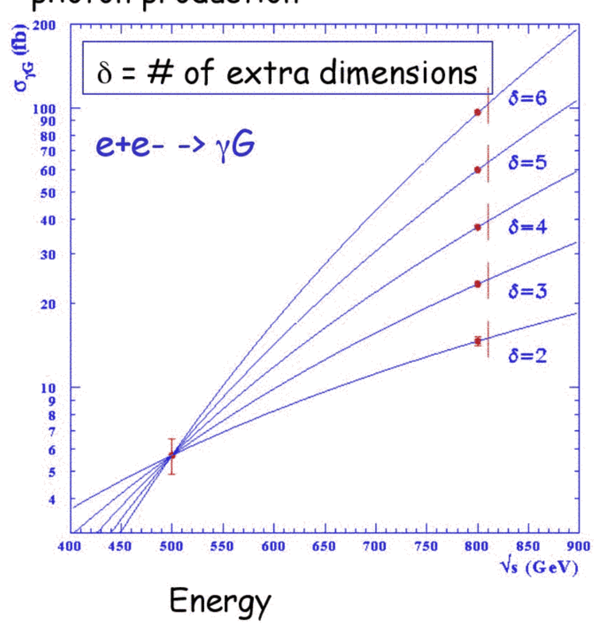
Gauge couplings unify at high energies,

Gaugino masses unify at same scale

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

Extra Spatial Dimensions

cross section for anomalous single photon production



•In how many dimensions do we live?

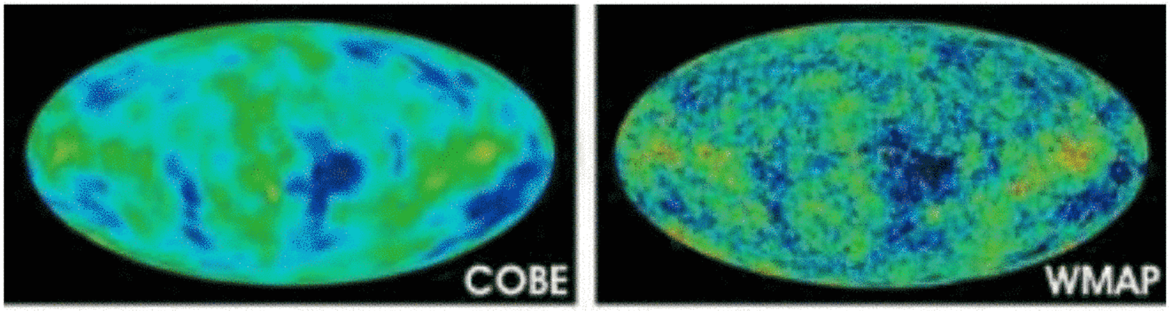
Emission of gravitons into extra dimensions

+ emission of γ or a jet

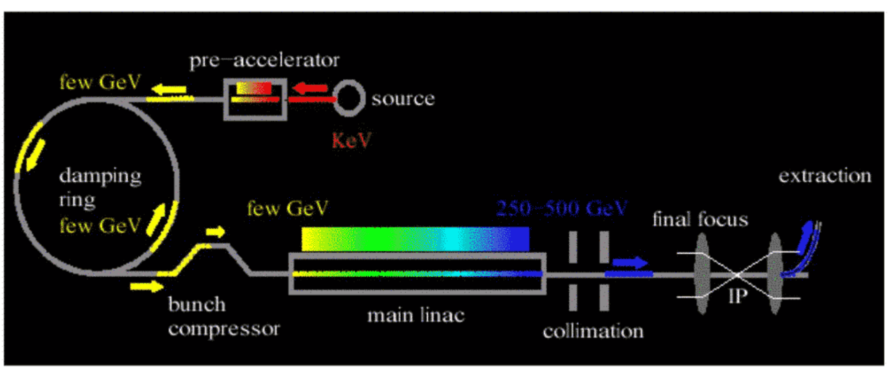
measurement of cross sections at different energies allows to determine number and scale of extra dimensions

(500 fb-1 at 500 GeV,

An Analogy: What precision does for you ...



e+e- Colliders: The Challenges



For E > 200 GeV need to build linear colliders

Proof of principle: SLC

The challenges:

Luminosity: high charge density (10^{10}), > 10,000 bunches/s

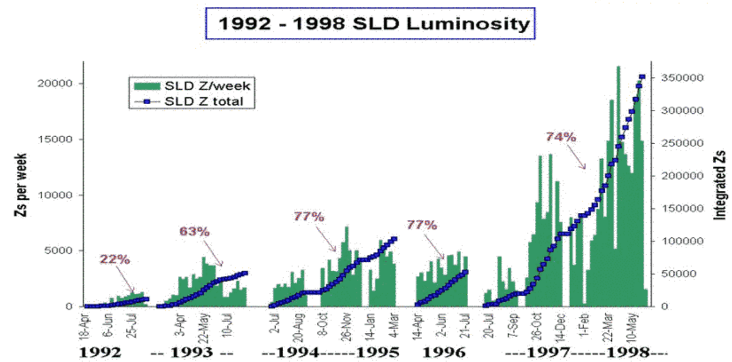
very small vertical emittance (damping rings, linac)

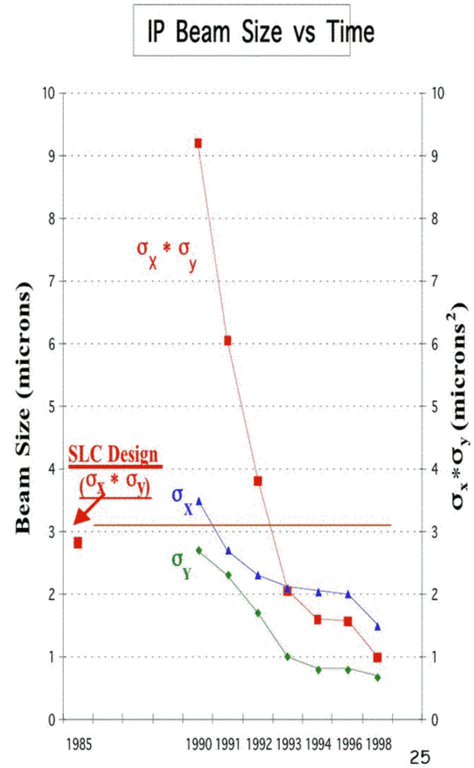
tiny beam size (5*500 nm) (final focus)

Energy: high accelerating gradient (> 25 MV/m, 500 - 1000 GeV)

To meet these challenges: A lot of R&D on LC's world-wide

Lessons from the SLC





New Territory in Accelerator Design and Operation

- Sophisticated on-line modeling of non-linear physics.
- Techniques expanded from *trajectory* to *emittance* corrections, and from hands-on to fully automated control.

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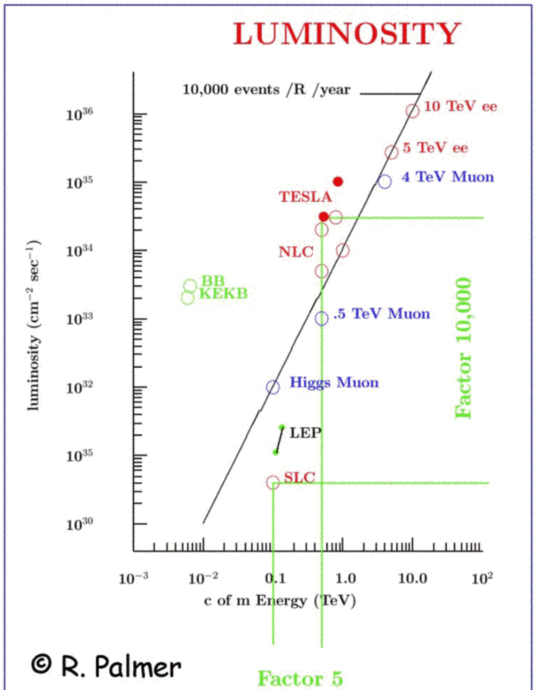
The Challenges



© R. Palmer

Main challenges for the TeV LC compared to SLC:

- Luminosity
- Energy

	SLC	TESLA	
Energy E_{cm}	100	500 (→ ~1000)	GeV
Beam Power	0.04	~10	MW
Spot size IP	500 (~50§)	~5	nm
Luminosity	$3 \cdot 10^{-4}$	3	10^{34} cm^{-2} s^{-1}

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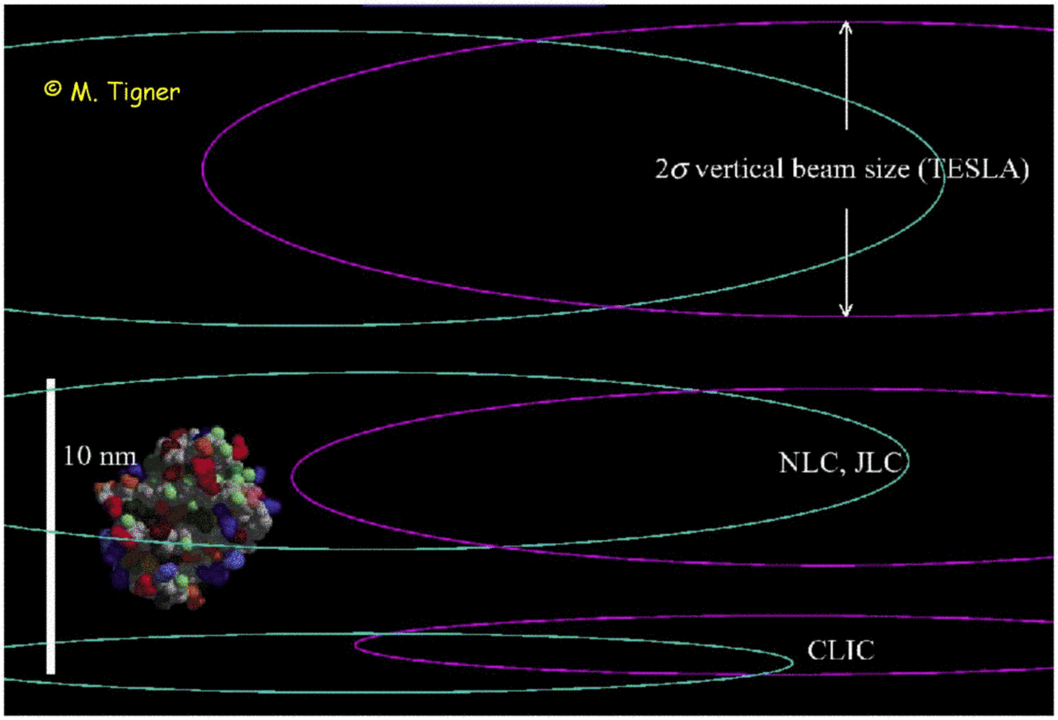
Beam Sizes



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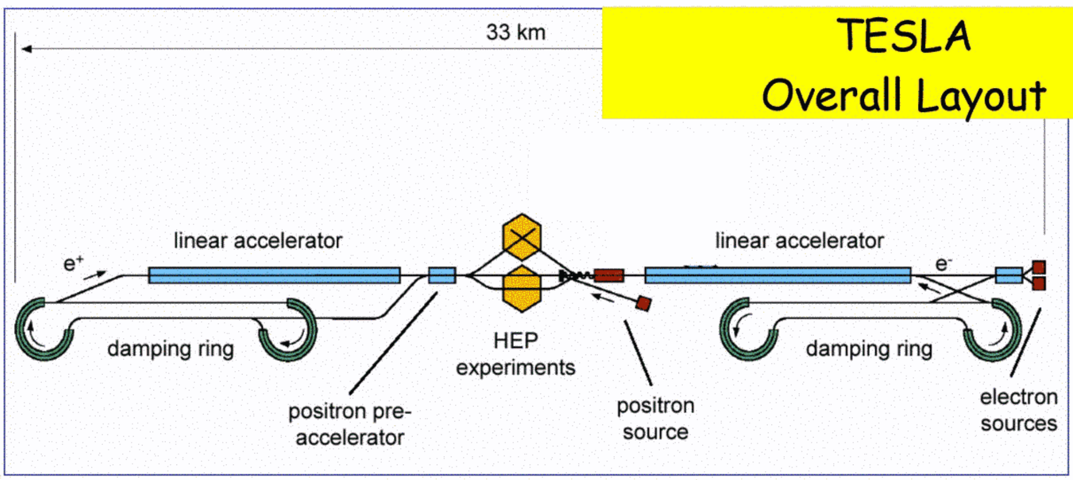
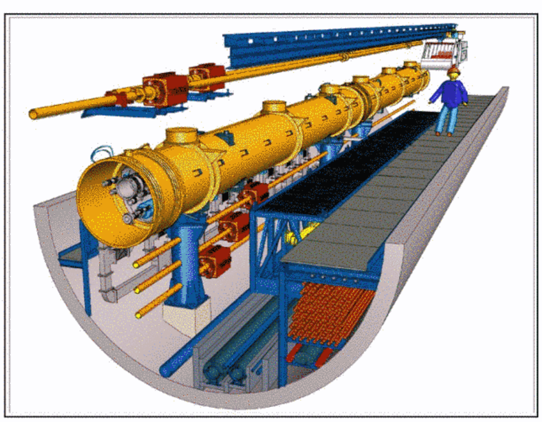
TESLA Overall Layout





Superconducting RF, 1.3 GHz

Loaded gradient up to 35 MV/m

For site length 33 km: E_{cm} = 800 GeV

The Technical Design Report incl. cost was published in March 2001

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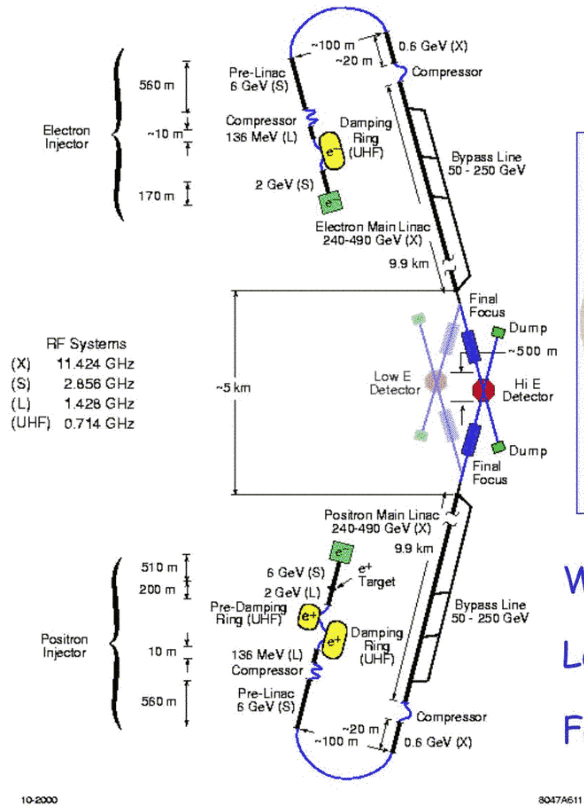
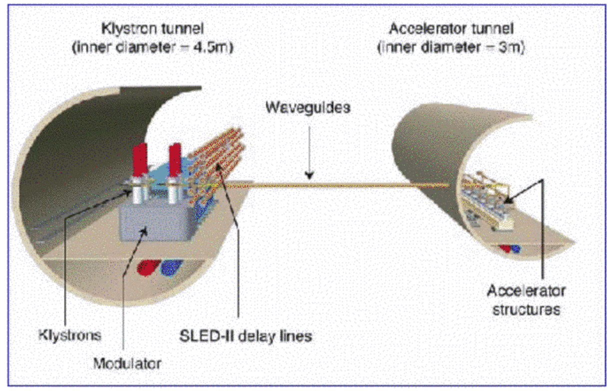
(GLC)/NLC Overall Layout



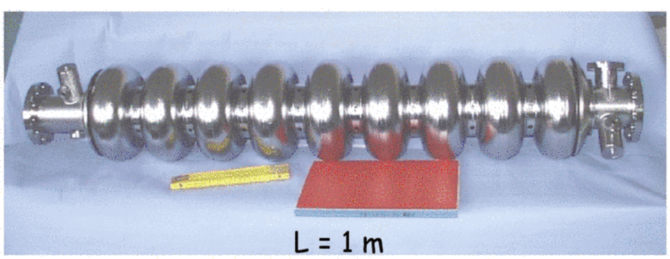


Warm RF, 11.4 GHz

Loaded gradient 50 MV/m

For site length 33 km: E_{cm} = 1.-1.3 TeV

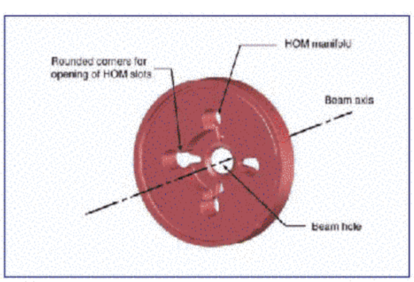
Accelerating Structures



TESLA: 9-cell L-band

Pure Niobium cell

Iris diameter: 70 mm



GLC/NLC: DDS structure, X-band

Copper cell

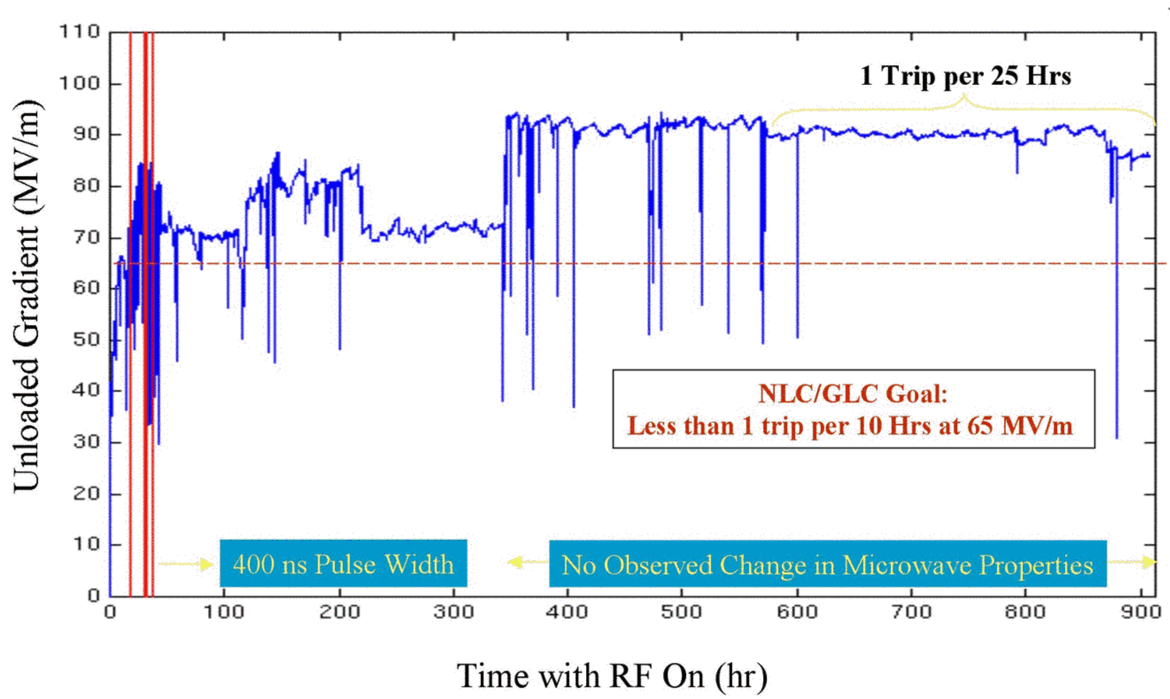
Iris diamater : 9 mm

Key Challenges for High Gradient Normal Conducting Cavities

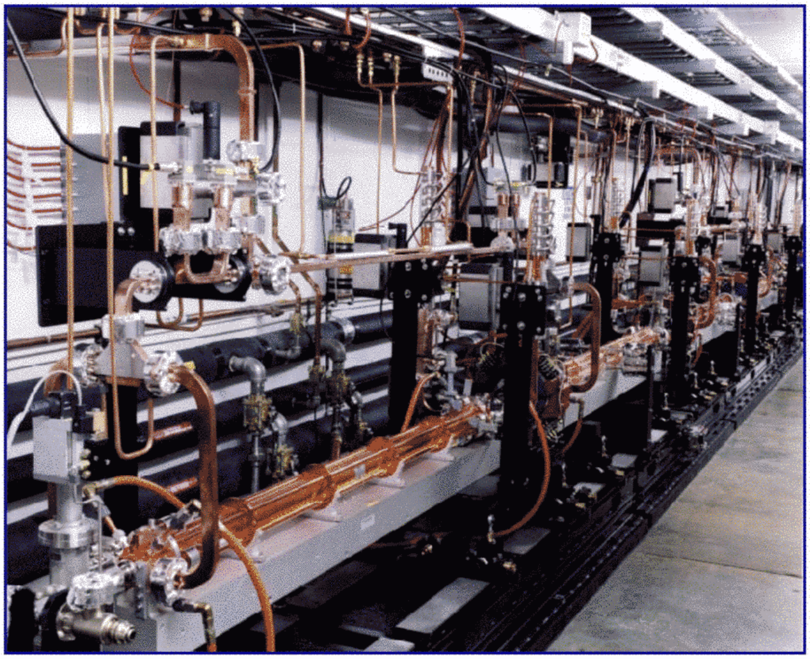
• Extensive R&D on X-band cavities at SLAC and KEK have yielded a substantial number of 1.8 m structures capable of gradients in the 40-45 MV/m range.
• Efforts to push to higher gradients have required careful attention to minimize the stored energy (through reduced group velocity) and limit regions of high pulsed heating, while maintaining acceptable transverse impedance.
• The latest prototype 60 cm structure has demonstrated close to the required breakdown performance at 65 MV/m.
• 8 similar structures will be made and tested to demonstrate performance of the basic main linac rf unit.

M. Tigner LC2003

Test Structure Run History



The NLC Test Accelerator



The NLCTA with 1.8 m accelerator structures (ca 1997).

Demonstrated of X-Band concept, wakefield control, beam loading compensation

Accelerating gradient limited to < 40 MV/m (loaded)

Key Challenges for High Gradient L-band Superconducting Cavities

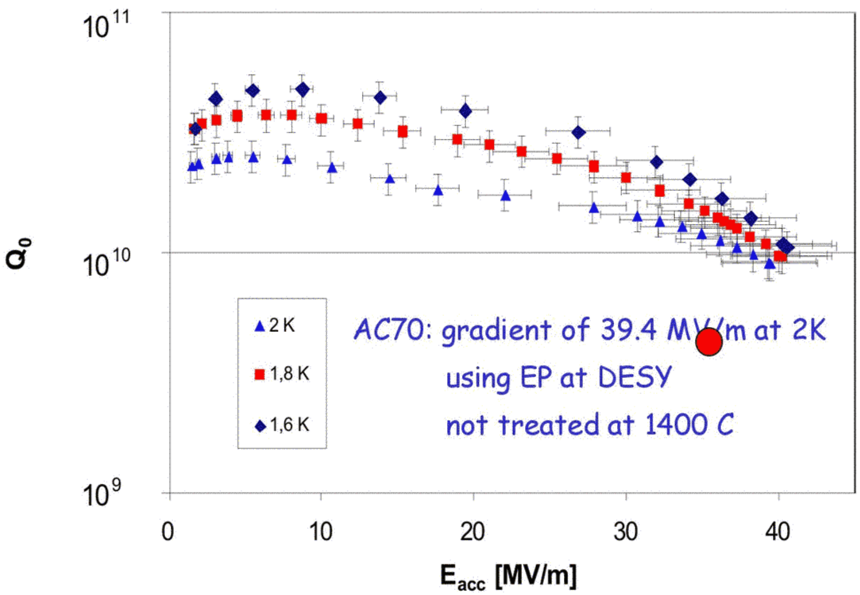
- Extensive R&D at DESY, KEK and Cornell over the past decade, in
  - cavity design (to reduce peak magnetic fields),
  - Nb material specification,
  - cavity fabrication, cleaning and processing techniques

has led to the production of a substantial number of L-band cavities capable of gradients in excess of 24 MV/m.

- The latest development in cavity processing (electropolishing) has yielded a “fully-dressed” 9-cell cavity capable of exceeding 35 MV/m
- More such cavities need to be made, to demonstrate the reproducibility of the process, and tested for dark current performance.

M. Tigner LC2003

High Gradients in EP nine-cell Cavities



High gradients is a high priority item at DESY and in TESLA collab.

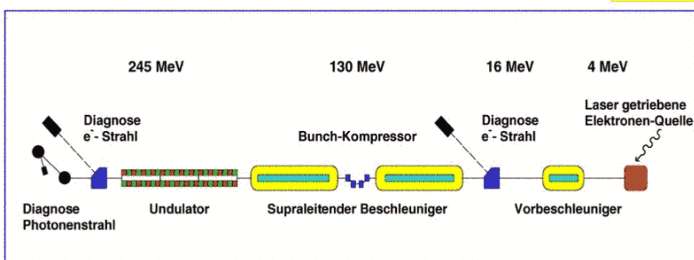
Test of 1/8th of a TESLA cryomodule at 5 Hz, 500 μs fill, 800μs flat-top

->35 MV/m

with no interruption related to cavity-coupler-klystron for more than 1000 hours

No field emission

The TESLA Test Facility



Construction of a prototype accelerator:

Tasks:

Test of all components

Operation for > 13 000 h

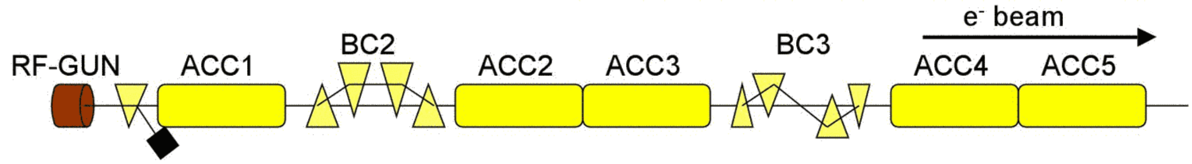
Proof of laser

Base for costing

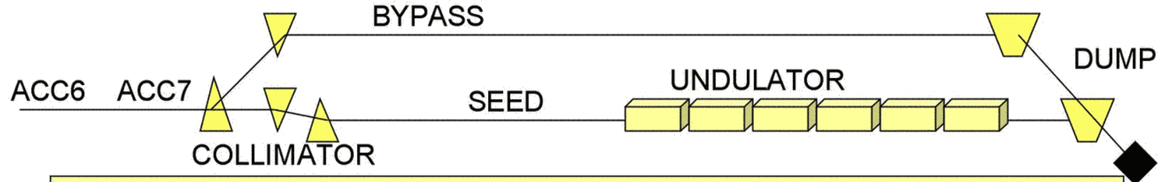
Conclusion:

The technical readiness has been demonstrated

TTF2 Installation



• a new RF Gun	
• a new injector concept	Injector 3
• three new accelerator modules and later this year another two	ACC3 to ACC5 (3*, 4, 5) ACC1 and ACC2 (2*, 1*)
• another bunch compressor	BC3



• new beamlines	more than 150 m
• a new collimator concept	transv. and energy collim.
• a long undulator	6 modules, 30 m
• a long bypass and a spectrometer line	

Future e+e- colliders

NLC and SC type LC are not last e+e- accelerators for which R&D is being done:

CLIC: New acceleration principle:

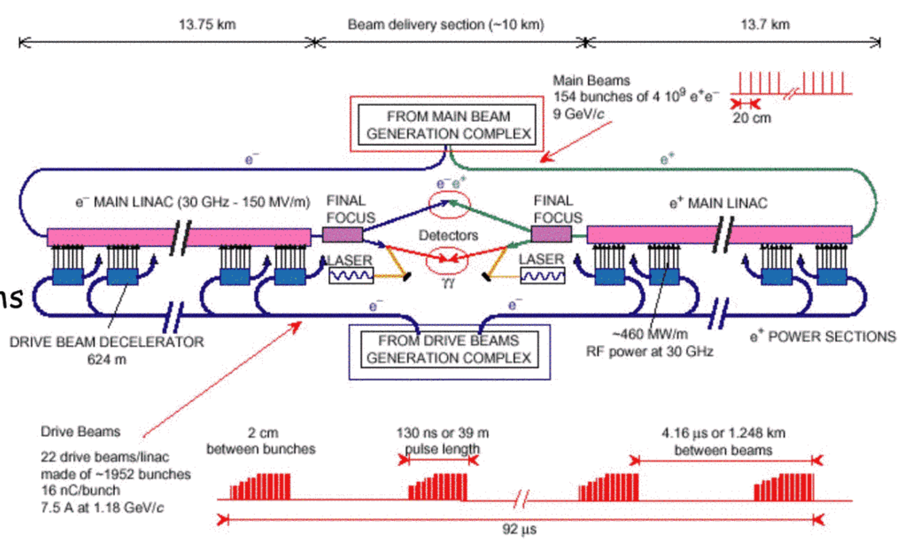
Two-Beam Accelerator

E= 3 TeV

L=10^{35}

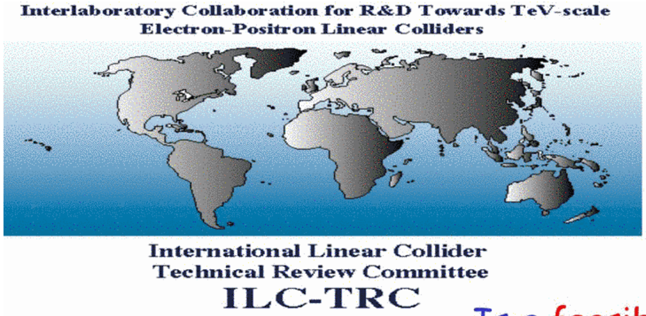
22 drive beams

70 GeV each



g=150 MV/m

f= 30 GHz



R1: R&D Needed for a Feasibility Demonstration

Review defines and ranks R&D needed for choosing technology

Is a feasibility demonstration required?

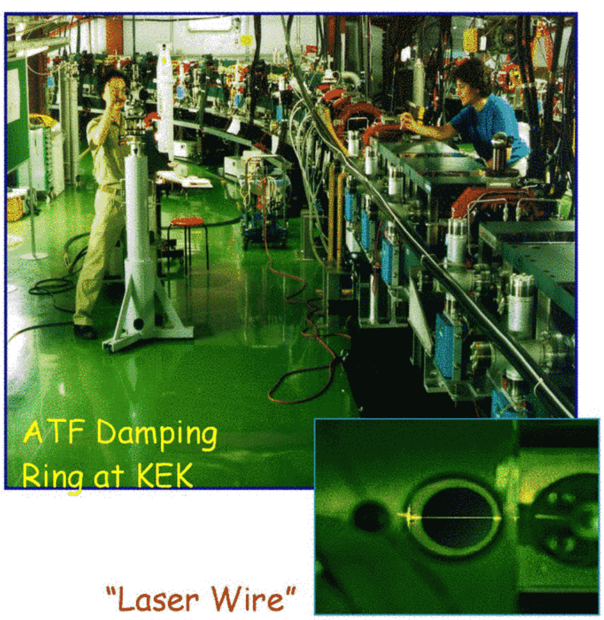
Score Card

	Modulators	Klystrons	RF Distribution	Accelerator Structures
TESLA	No	No	No	No (500 GeV) Yes (800 GeV)
NLC/JLC-X	No	No	Yes	Yes
JLC-C	No	No	Yes	Yes
CLIC	Yes	Yes	Yes	Yes

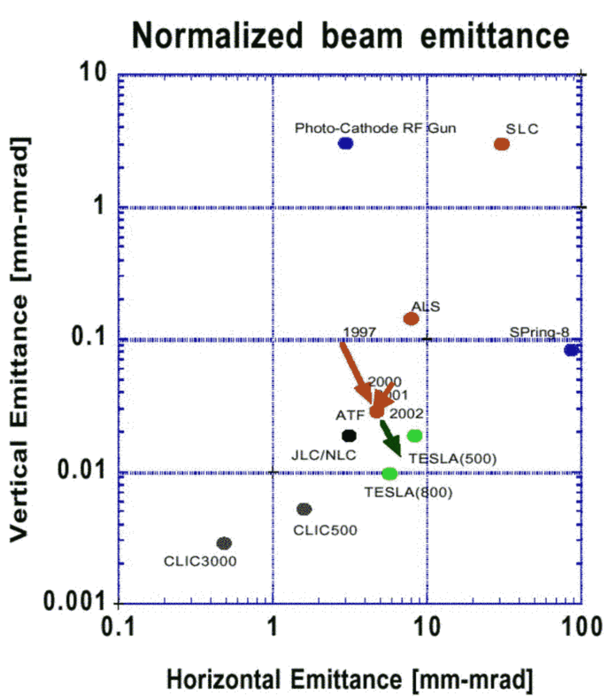
In addition, system aspects like uptime, reliability etc. are of utmost importance to meet the challenges of a LC

Damping Ring

Low emittance



"Laser Wire"



Strategy : What has Happened since 2001?

- ACFA, ECFA, HEPAP scientific recommendations (2001)
- TESLA TDR in March 2001
- OECD Global Science Forum (2002 and continuing)
- German Science Council recommendations (Nov 2002)
- JLC Road Map in February 2003
- German Government decision
- International Technical Review (2003)
- ILCSC and regional steering groups
- Discussion among funding agencies
- Discussion in CERN Council about CERNs role in a LC
- WGs on organisational matters
- GAN workshops
- US 20 year outlook

Political Situation

US

Near-Term

1	FES	ITER
2	ASCR	UltraScale Scientific Computing Capability
Tie for 3	HEP	Joint Dark Energy Mission
	BES	Linac Coherent Light Source
	BER	Protein Production and Tags
	NP	Rare Isotope Accelerator
Tie for 7	BER	Characterization and Imaging
	NP	CEBAF Upgrade
	ASCR	Esnet Upgrade
	ASCR	NERSC Upgrade
	BES	Transmission Electron Achromatic Microscope
12	HEP	BTeV

Mid-Term

13	HEP	Linear Collider
Tie for 14	BER	Analysis and Modeling of Cellular Systems
	BES	SNS 2-4 MW Upgrade
	BES	SNS Second Target Station
	BER	Whole Proteome Analysis
Tie for 18	NP	Double Beta Decay Underground Detector
	FES	Next Step Spherical Tokamak
	NP	RHIC II

Mid Term Readiness for construction

Germany: „The government is the first one to have announced to be principally committed to participating in the project. "

UK: Substantial increase in R&D sending for LCs

Technology Choice

The International Linear Collider Steering Committee (ILCSC) has selected twelve members of the International Technology Recommendation Panel (ITRP):

Asia:	Europe:	North America:
G.S. Lee	J-E Augustin	J. Bagger
A. Masaike	G. Bellettini	B. Barish (Chair)
K. Oide	G. Kalmus	P. Grannis
H. Sugawara	V. Soergel	N. Holtkamp

First meeting end of January at RAL

Recommendation of one technology (NLC or TESLA) before end of 2004

Next Milestones towards a Global Linear Collider

2004 Selection of Collider Technology (warm or cold) and setting up of an international project team with branches in America, Asia and Europe

Continuation of discussion between funding agencies

Further studies of organisation structures

2005 Start of work of project teams (‚Pre GLC')

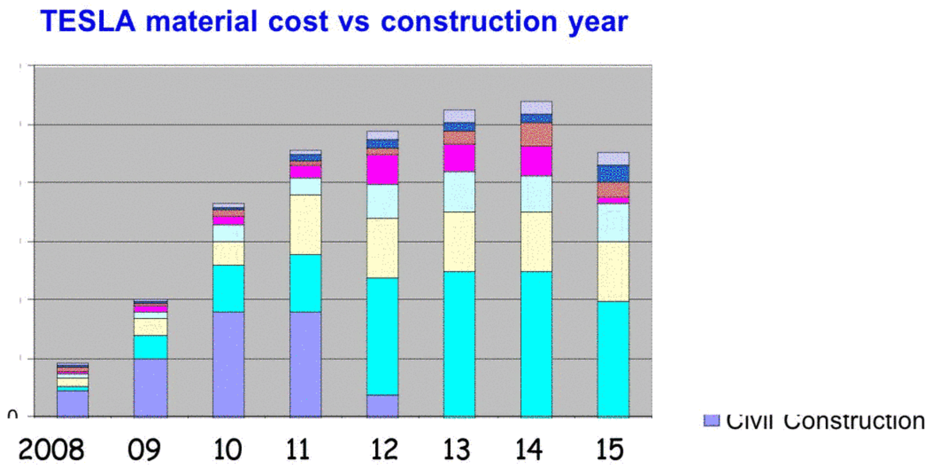
2006 Completion of the project layout including costing

2007 Decision in principle by governments to go ahead with LC

2015 Start of commissioning

An exercise.....

Spending Profile for TESLA

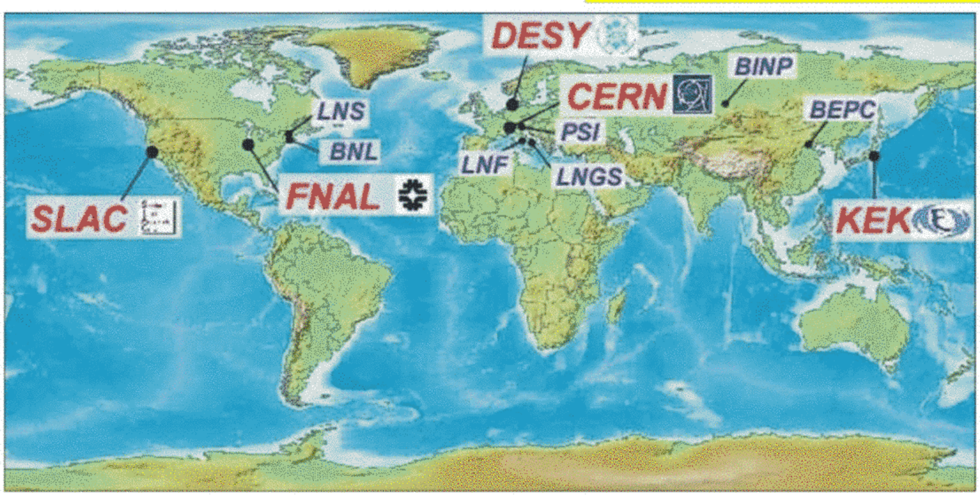


This is assuming a construction time of 8 years.

By parallel manufacturing of components this construction time can be shortened to ~ 6 years

-> matches turn on and first results of LHC before major spending starts

The Accelerator Labs Today



$Sp\bar{p}S$	CERN	1981	$p\bar{p}$	500 GeV
LEP	CERN	1989-2000	e^+e^-	100/200 GeV
HERA	DESY	1992	$e^\pm p$	300 GeV
TEVATRON	FNAL	1987	$p\bar{p}$	≈2000 GeV

... and B-factories at SLAC and KEK

How to Realise Big Accelerator Projects?

Global Accelerator Network

- Collaboration of interested accelerator laboratories and institutes world-wide with the goal to build, operate and utilise large new accelerators
- Follows major detector collaboration in particle physics
- Partners contribute through components or subsystems
- Facility is common property
- Responsibility, cost are shared
- Remote operation
- Project of limited duration (~ 25 years)

Examples from science:

ALMA, ITER

Examples from industry:

Airbus

Feasibility studies at SLAC and DESY:

positive

Summary 1

- Before the start of the LHC new information will come in from Tevatron and HERA. This will help sharpen our knowledge and predictions for high energies
- The next generation of accelerators (LHC and LC) will lead to a disproportionate increase in our knowledge
- The scientific case for the LC is as strong as ever. The complementarity with LHC is strong, so is the discovery potential of the LC
- Broad support and enthusiasm in community (consensus paper, YPPs, ..) must be maintained in the interest of the future
- The results from LHC and LC will tell us what the next energy scale beyond the TeV scale is
- Due to the long lead, construction and exploitation time HEP needs to develop a "world strategy" for the future accelerators

Summary 2

- Concerning the LC, need to continue to impress politicians by steady progress (technical decision, joint global design, self-organisation,..)
- Strength of field lies in ability to form consensus. We should be careful to maintain it.
- We need to keep cost of the project within meaningful boundaries, e.g. LHC, ITER. This can be done.
- We need to present a time line which allows politicians to react and us to keep the momentum going.
- Choice of site will be entirely in the hands of politics (see present ITER negotiations). Need to adapt to this
- 2015 is a realistic target date for commissioning of the LC. It also allows for input from the LHC before the big money is spent. To reach this the target we have to keep going at full