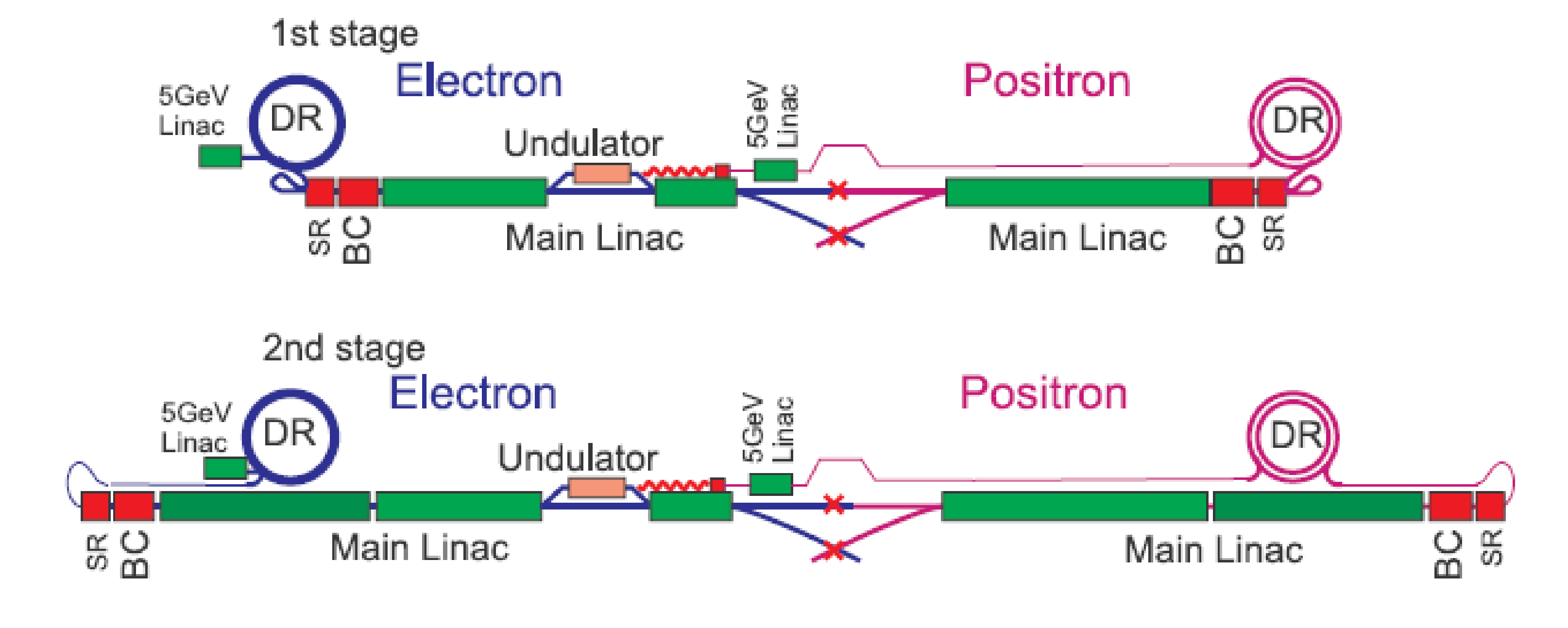
Precision Physics at the International Linear Collider



Loops and Legs,
Eisenach, April 26,2006

R.-D. Heuer, Univ. Hamburg/DESY

Precision Physics at the International Linear Collider

Introduction

Physics Examples

Detector Challenges

Project Status

Loops and Legs,
Eisenach, April 26,2006

R.-D. Heuer, Univ. Hamburg/DESY

Tests of the Standard Model

Status spring 2005

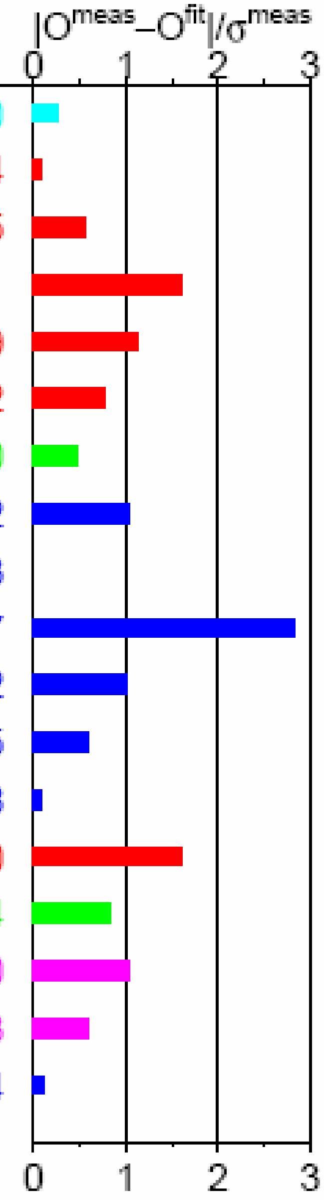
Precision measurements
1990-2003

(LEP,SLD,Tevatron, NuTeV,…)

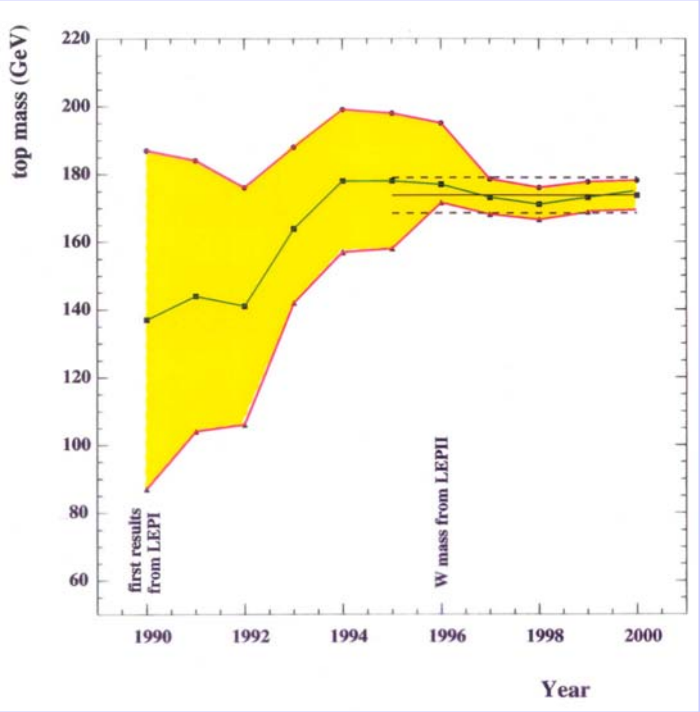
Standard Model tested to permille level

Precise and quantitative description of subatomic physics

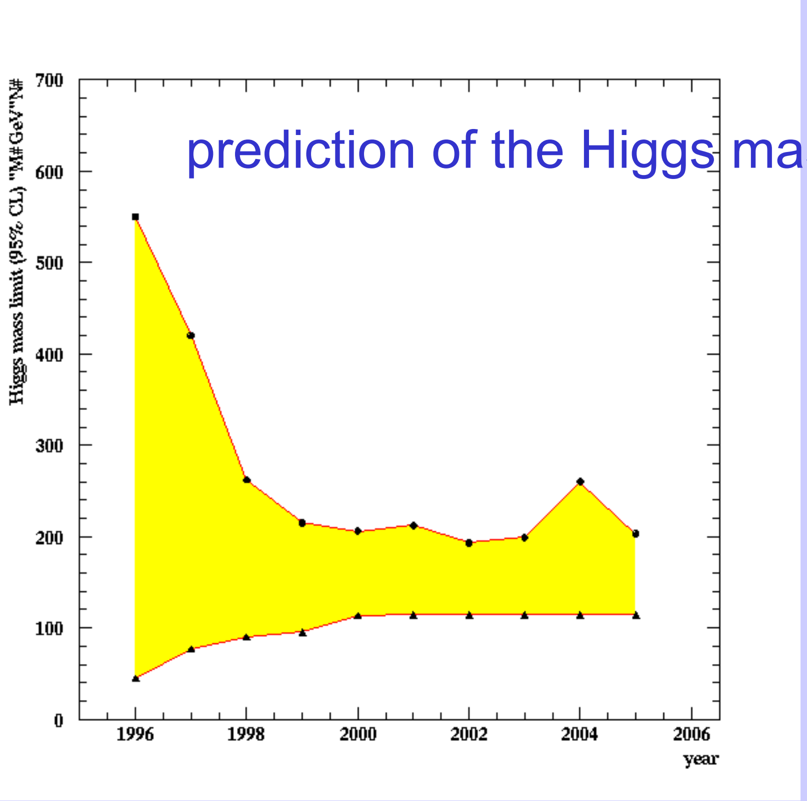
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02770
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.390
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.4



indirect determination of the top mass



prediction of the Higgs mass



possible due to

- precision measurements
- **known higher order electroweak corrections**

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

Key Questions of Particle Physics

origin of mass/matter or
origin of electroweak symmetry breaking

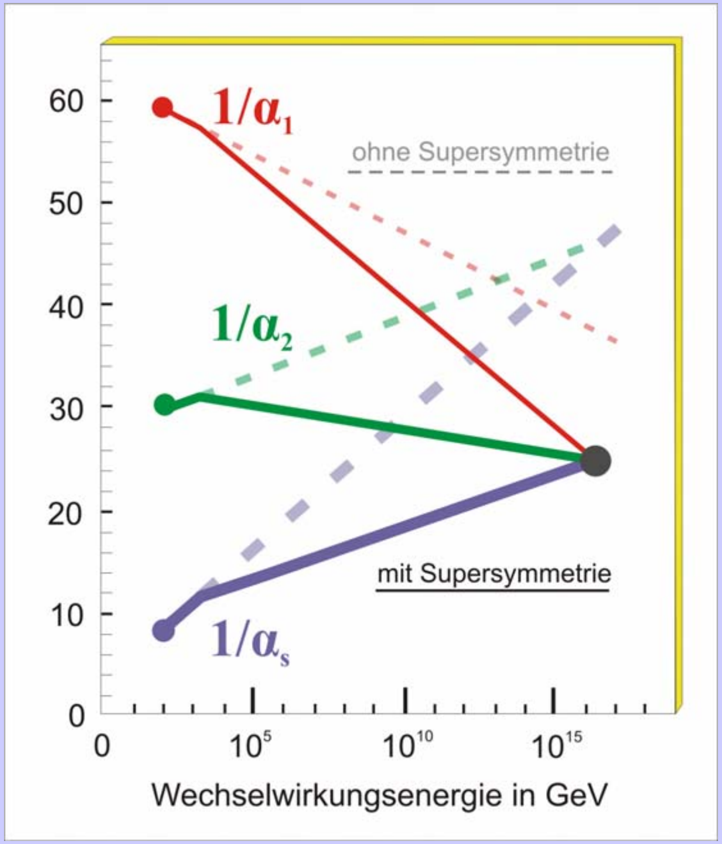
unification of forces

fundamental symmetry of forces and matter

unification of quantum physics and general relativity

structure of space-time

dark matter / dark energy



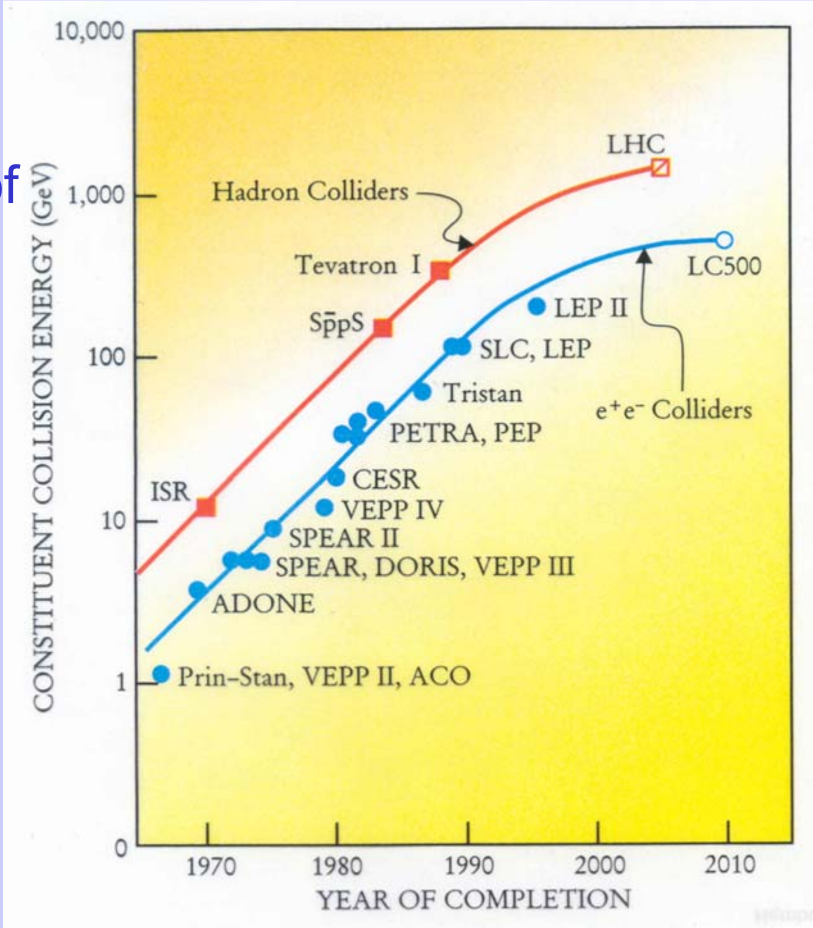
The next steps at the Energy Frontier

How to get the experimental answers?

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

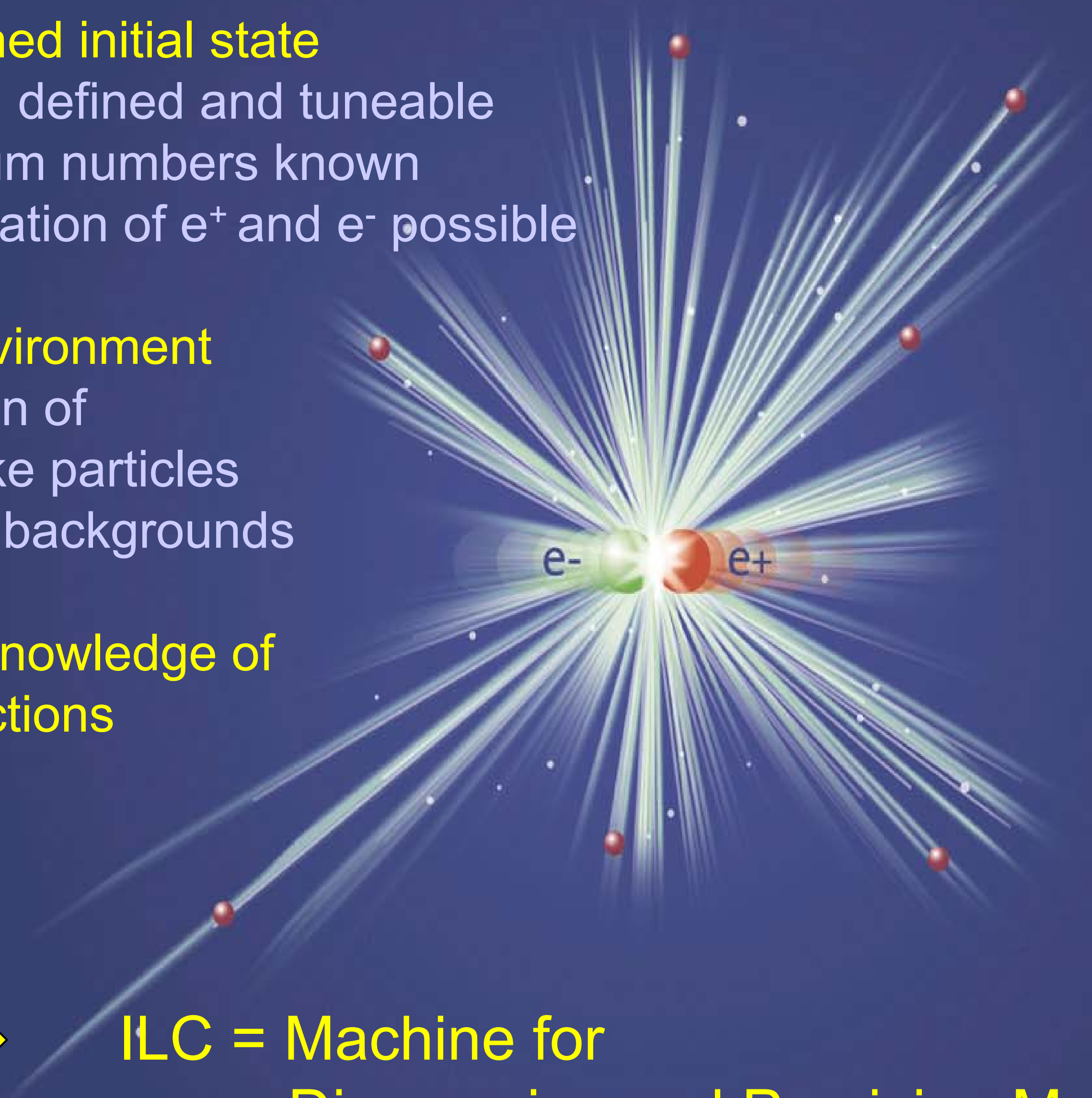


The power of an Electron-Positron Linear Collider

- **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**



options:
e^-e^-, $e\gamma$, $\gamma\gamma$

⇒ ILC = Machine for Discoveries and Precision Measurements

The Role of the ILC

Explore new Physics through high precision at high energy

microscopic

$$e^+e^- \rightarrow X_{new}(+Y_{SM})$$

telescopic

$$e^+e^- \rightarrow SM$$

Study the properties of new particles (cross sections, BR's, quantum numbers)

Study known SM processes to look for tiny deviations through virtual effects (needs **ultimate precision** of measurements and **theoretical predictions**)

→precision measurements will allow
-- distinction of different physics scenarios
-- extrapolation to higher energies

The ILC Physics Case
or
Relation of Hadron Collider and Linear Collider

1. Since the ILC will start after the start of LHC, it must add significant amount of information. This is the case!
   (see e.g. TESLA TDR, Snowmass report, ACFA study etc.)

2. Neither ILC nor HC's can draw the whole picture alone. An ILC will
   - add new discoveries and
   - precision of ILC will be essential for a better understanding of the underlying physics (see e.g. LHC/ILC report Phys.Rept. 426(2006)47)

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

International Linear Collider Parameters
global consensus (Sept. 2003)

(1) baseline machine

200 GeV < $\sqrt{s}$ < 500 GeV

integrated luminosity ~ 500 fb^{-1} in 4 years

electron polarisation ~ 80%

(2) energy upgrade

to $\sqrt{s}$ ~ 1 TeV

integrated luminosity ~ 1 ab^{-1} in 3 years

(3) options

positron polarisation of ~ 50%

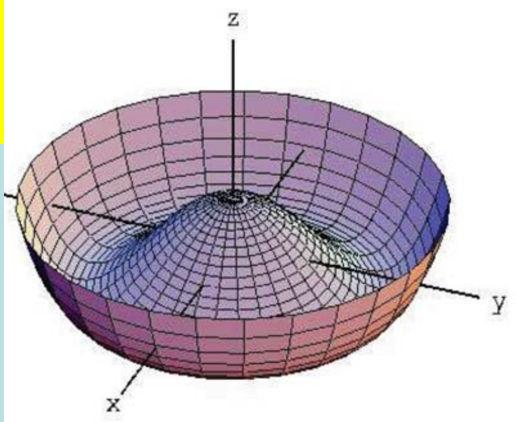
high luminosity running at M_Z and W-pair threshold

e^-e^-, $e\gamma$, $\gamma\gamma$ collisions

(4) concurrent running with LHC desired

! Times quoted for data taking cover only part of program !

Physics Examples



Electroweak Symmetry Breaking

- Higgs mechanism
- no Higgs scenarios

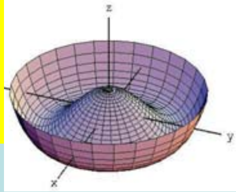
Supersymmetry

- unification of forces
- dark matter

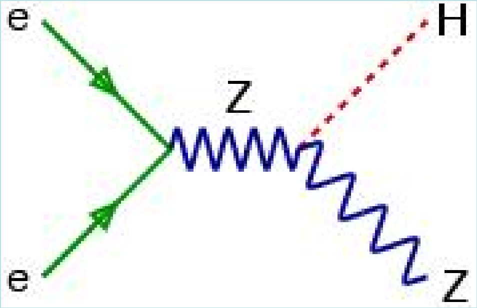
Precision tests of the Standard Model

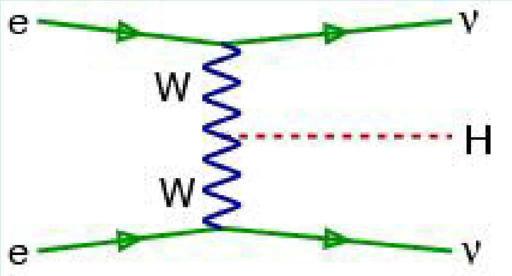
- top quark properties
- high luminosity running at the Z-pole

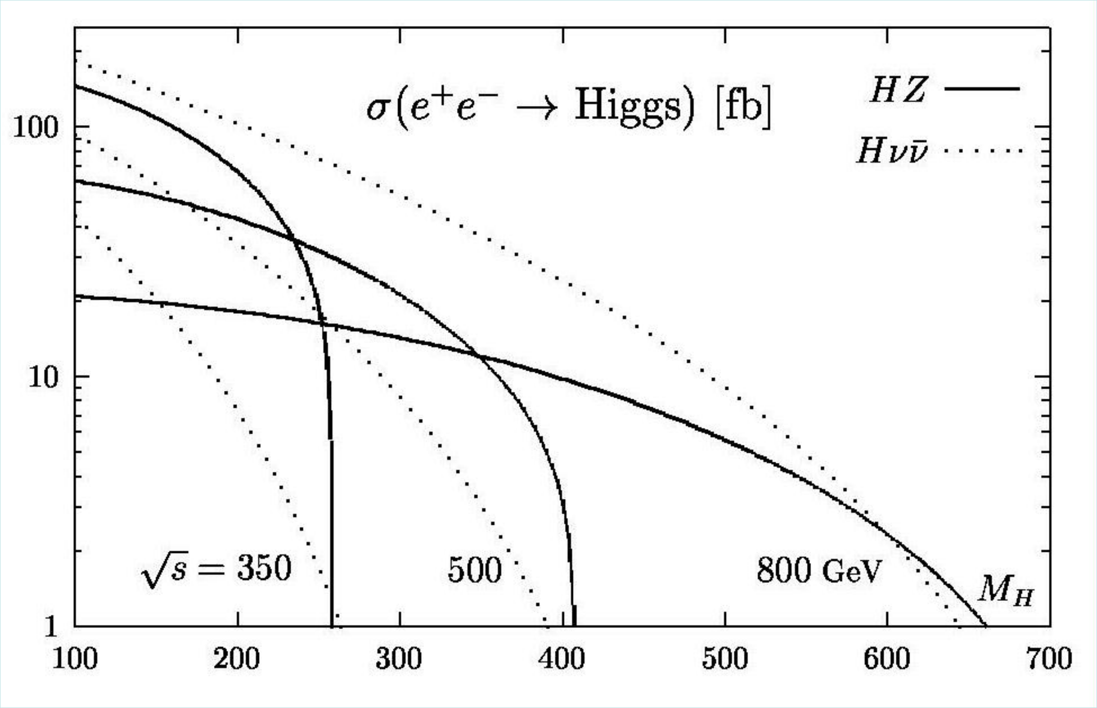
The Higgs: Key to Understanding Mass



Dominant production processes at ILC:





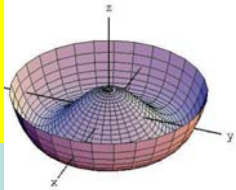


Task at the ILC:

- determine properties of the Higgs-boson
- establish Higgs mechanism responsible for the origin of mass

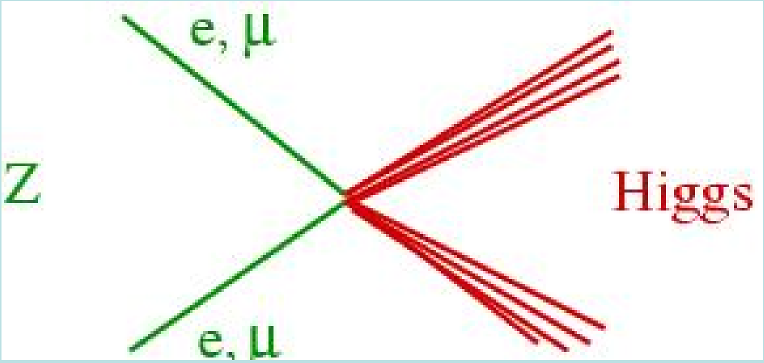
. . . together with LHC

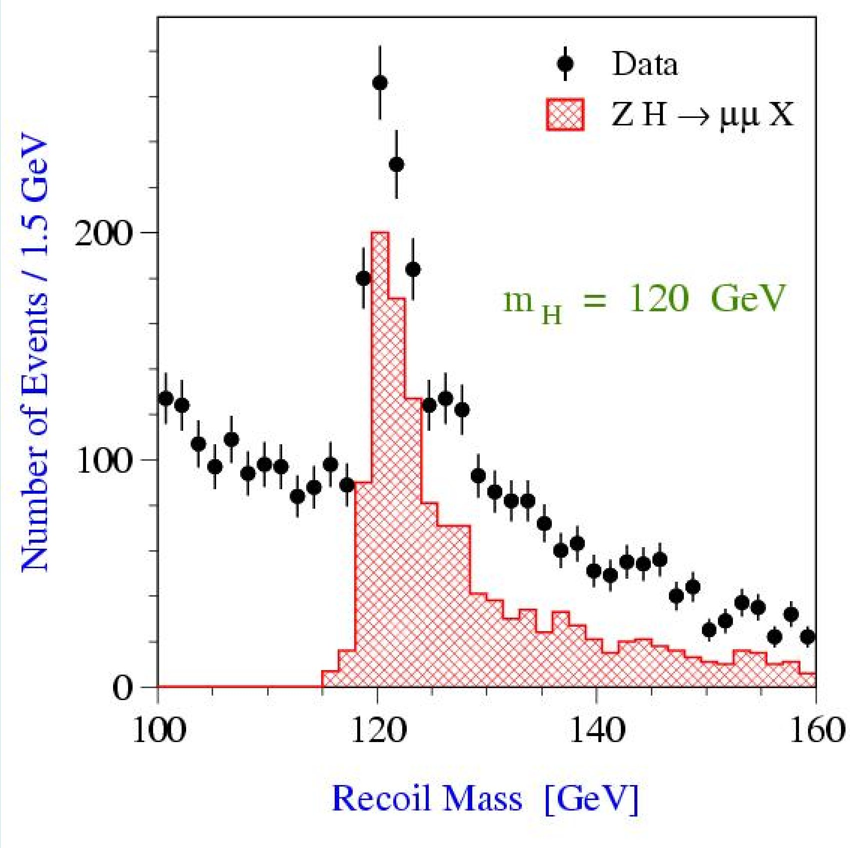
The Higgs: Key to Understanding Mass



Recoil mass spectrum

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





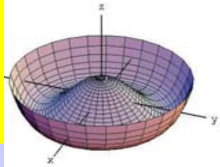
$\Delta\sigma \sim 3\%$

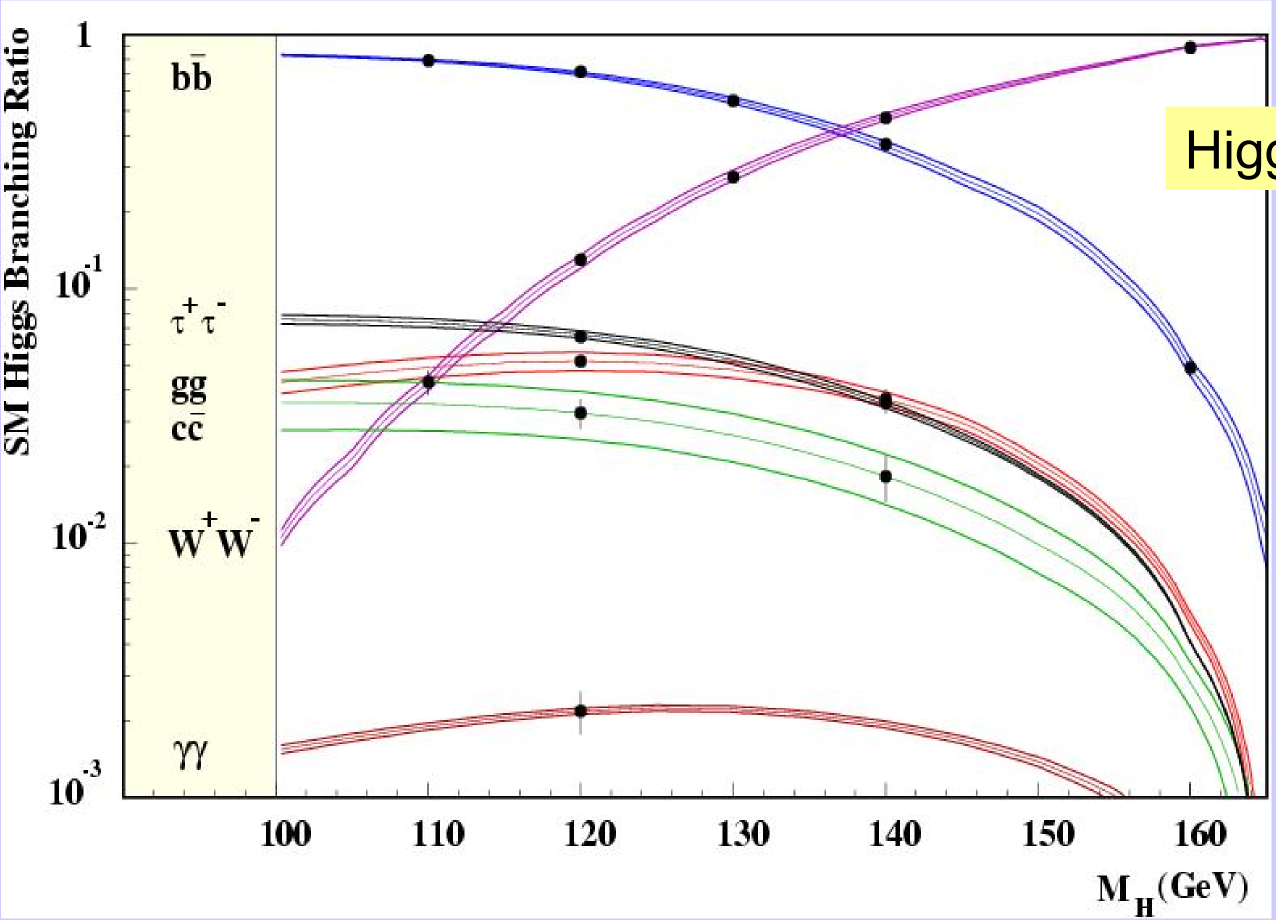
model independent measurement

$\Delta m \sim 50$ MeV

sub-permille precision

The Higgs: Key to Understanding Mass

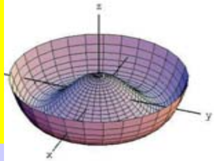




Higgs branching ratios

Model-independent measurements at %-level possible

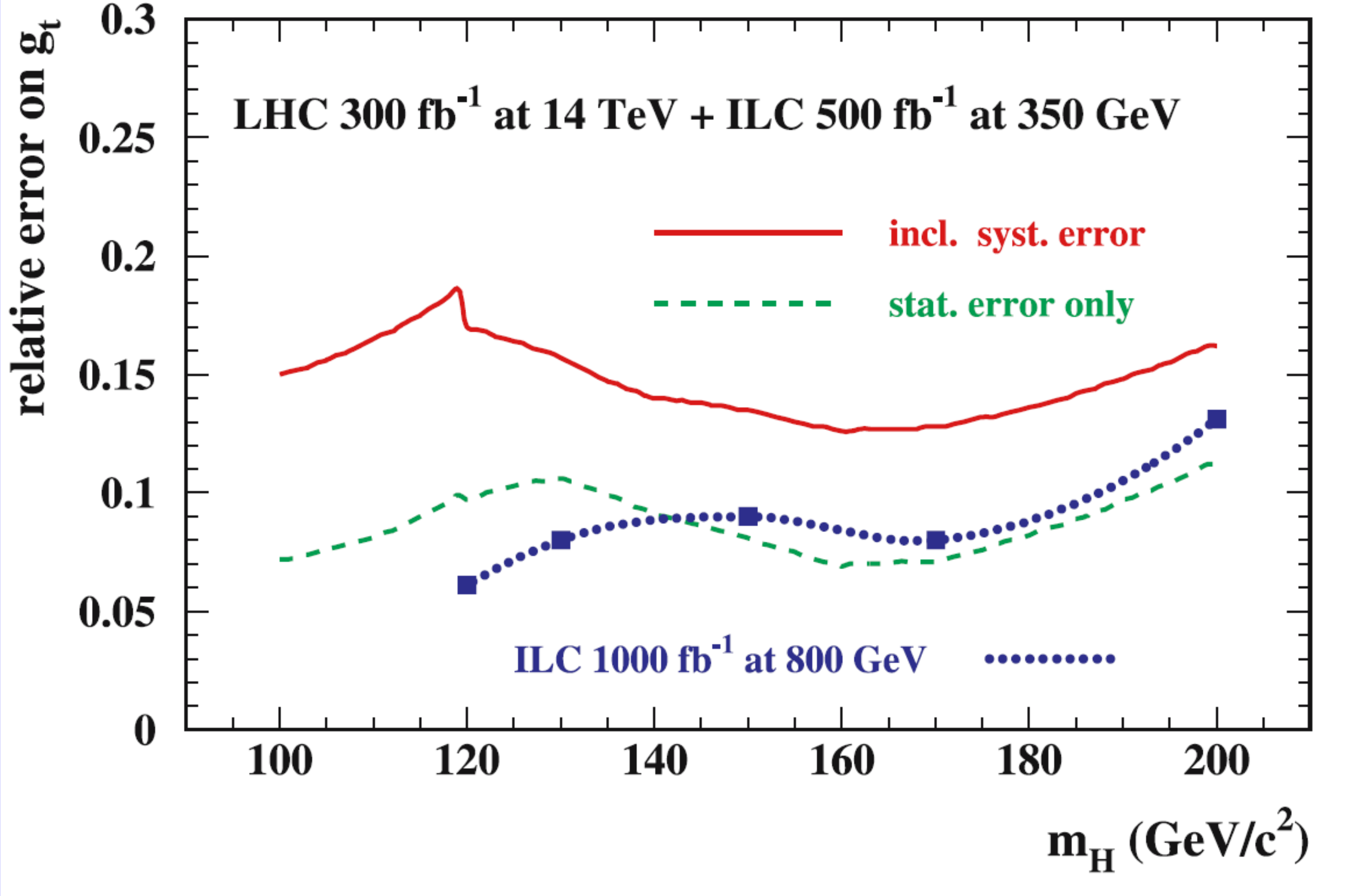
Example: Top Yukawa Coupling



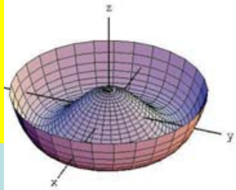
LHC sensitive to top Yukawa coupling of light Higgs through tth production.

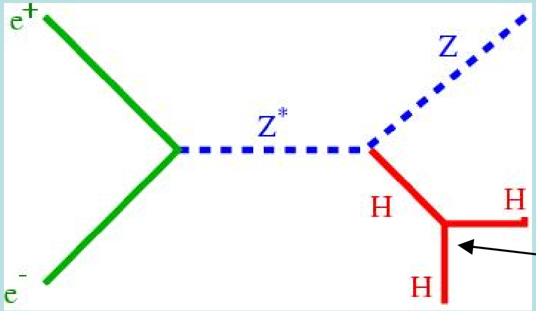
ILC500 BR measurement (h→bb and h→WW) turns rate measurement into an absolute coupling measurement

ILC direct measurement only at high energy (> 800 GeV)



The Higgs: Key to Understanding Mass

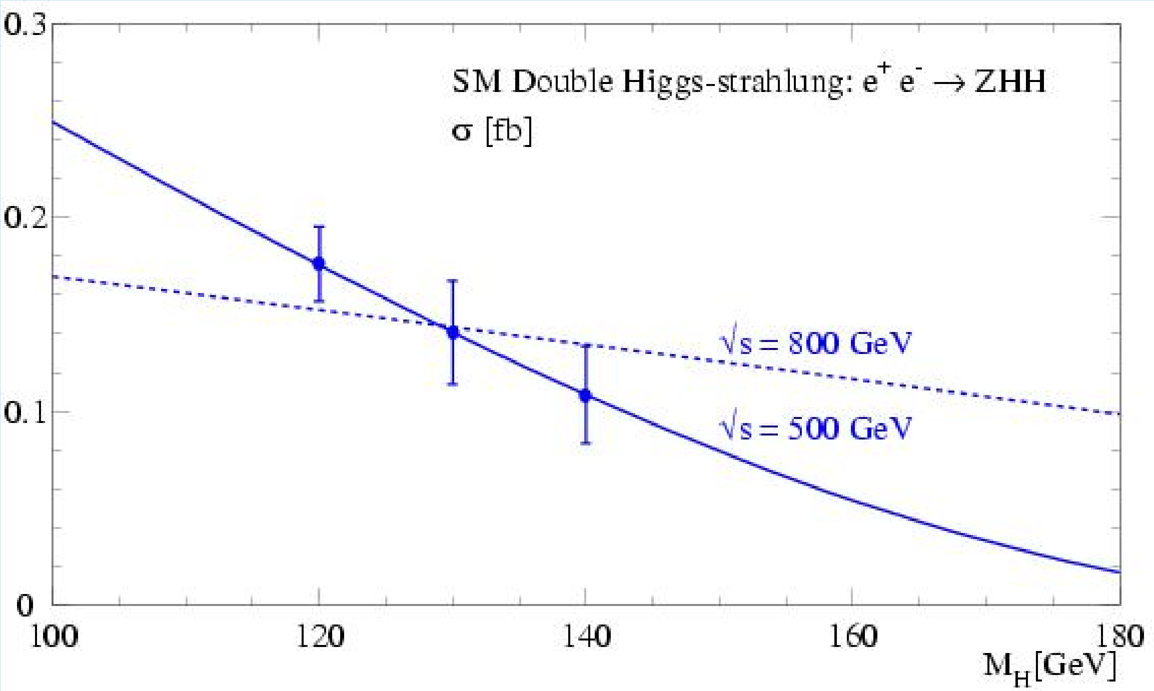


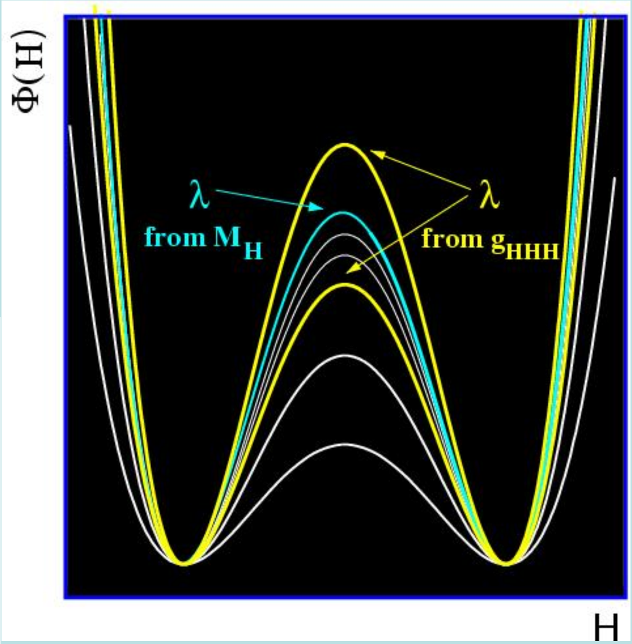


g_{HHH}

Higgs self coupling

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

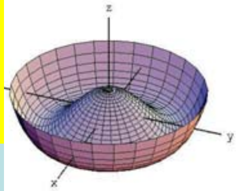




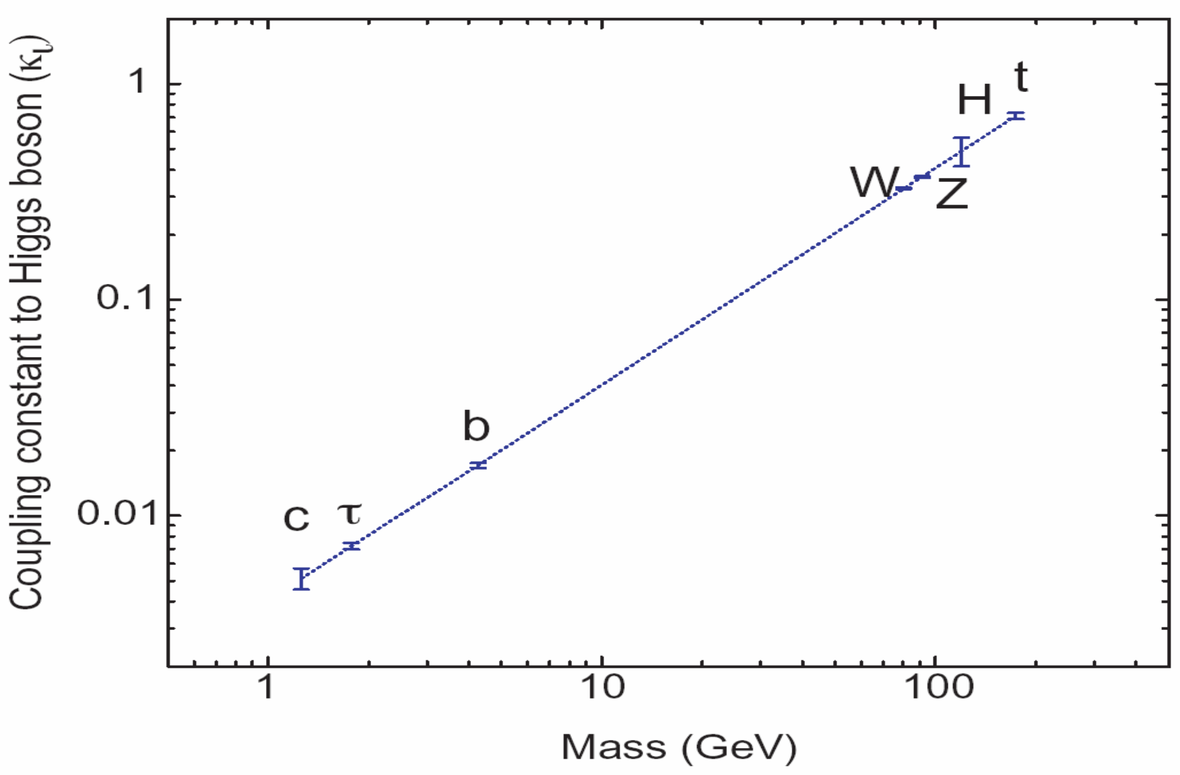
$\Delta\lambda/\lambda \approx 15\ \%$

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

The Higgs: Key to Understanding Mass



Testing the Yukawa couplings…

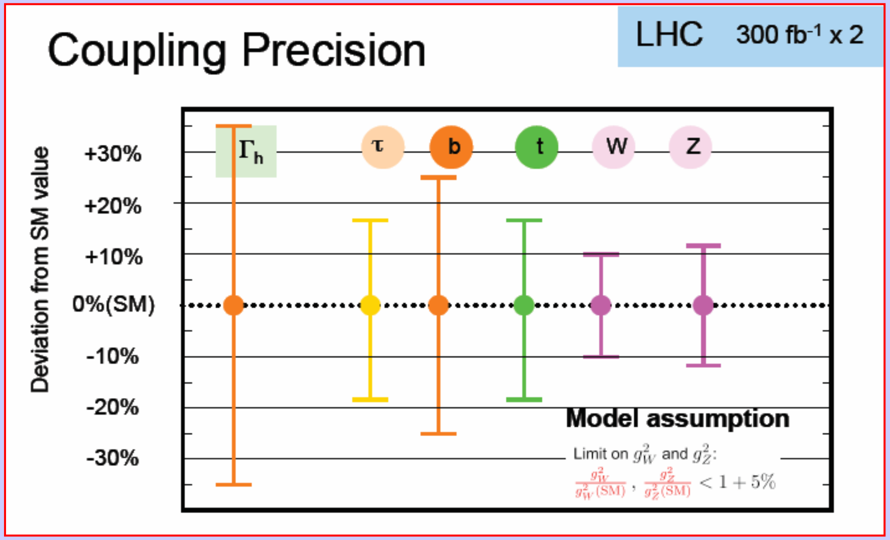


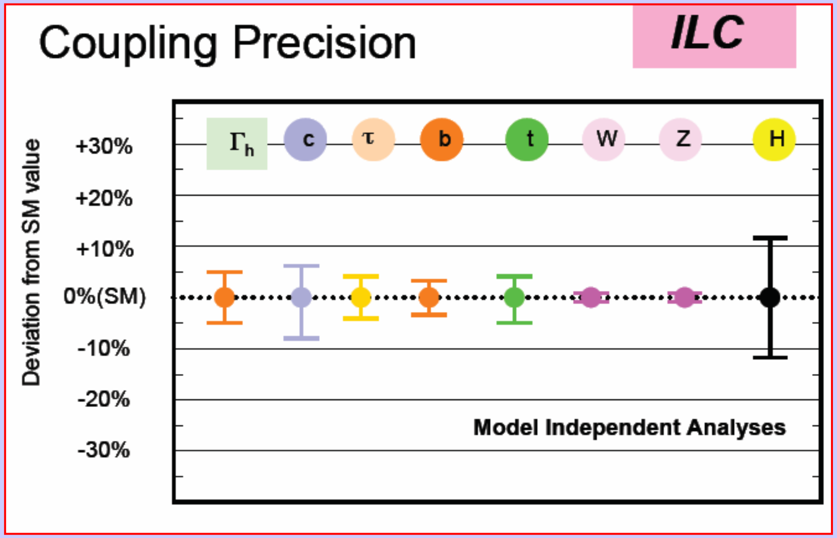
Precision
~ % level

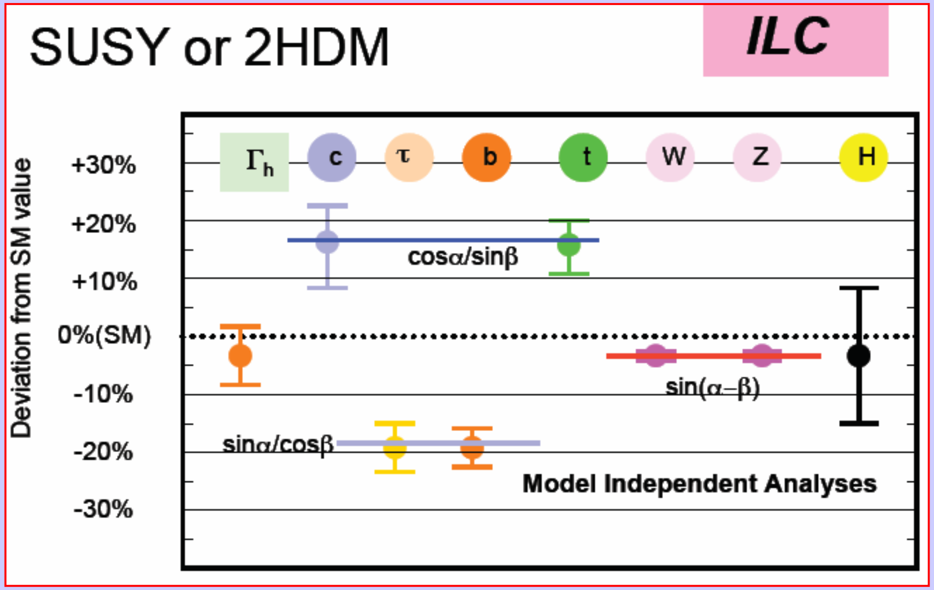
…through the measurement of absolute BRs:

$$\mathrm{BR}(\mathrm{H} \to \mathrm{X}) = \frac{\left[\sigma(\mathrm{HZ}) \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{X})\right]^{\mathrm{meas}}}{\sigma(\mathrm{HZ})^{\mathrm{meas}}}$$

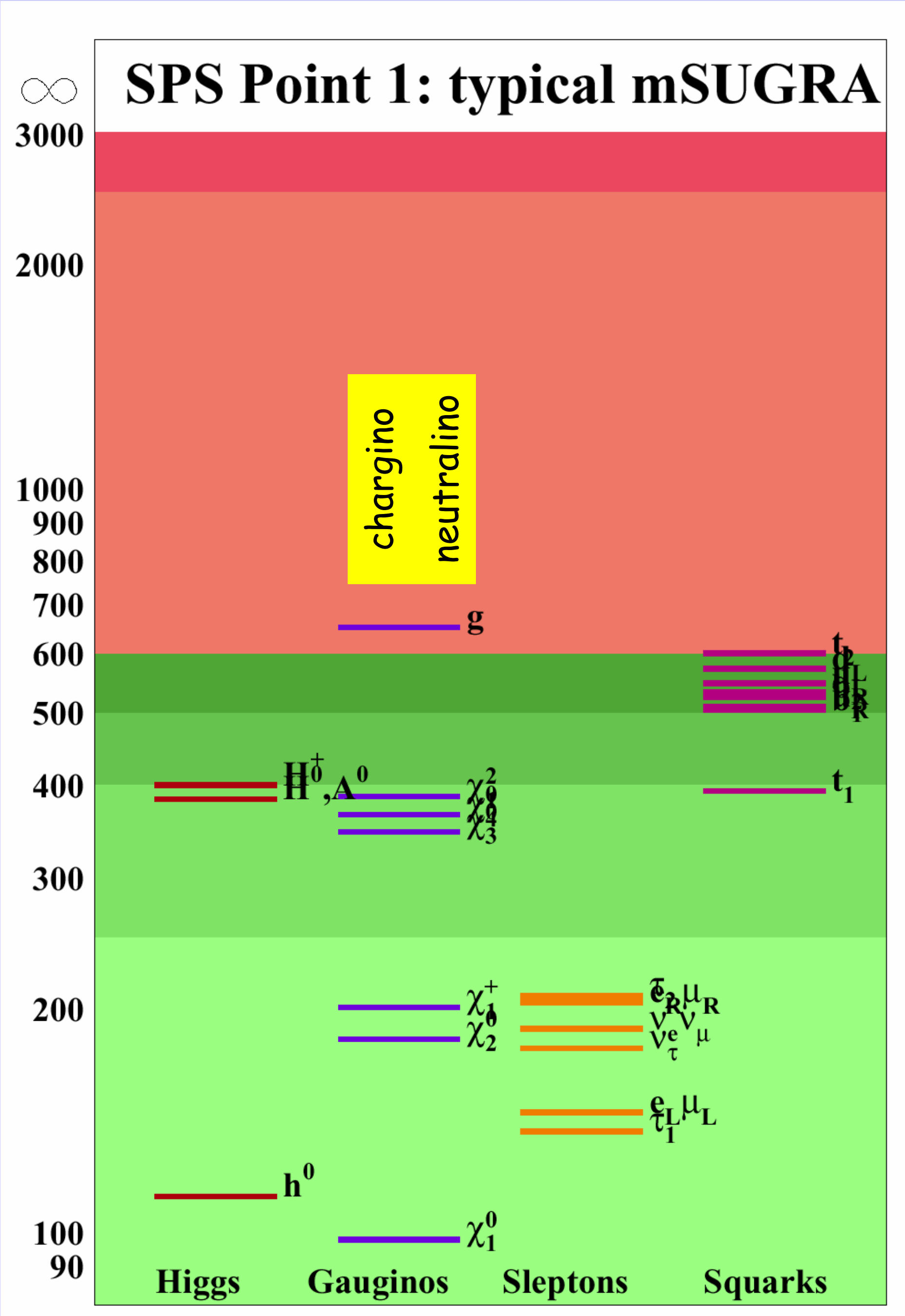
e.g. Coupling Precision and New Physics







Yamashita



Supersymmetry

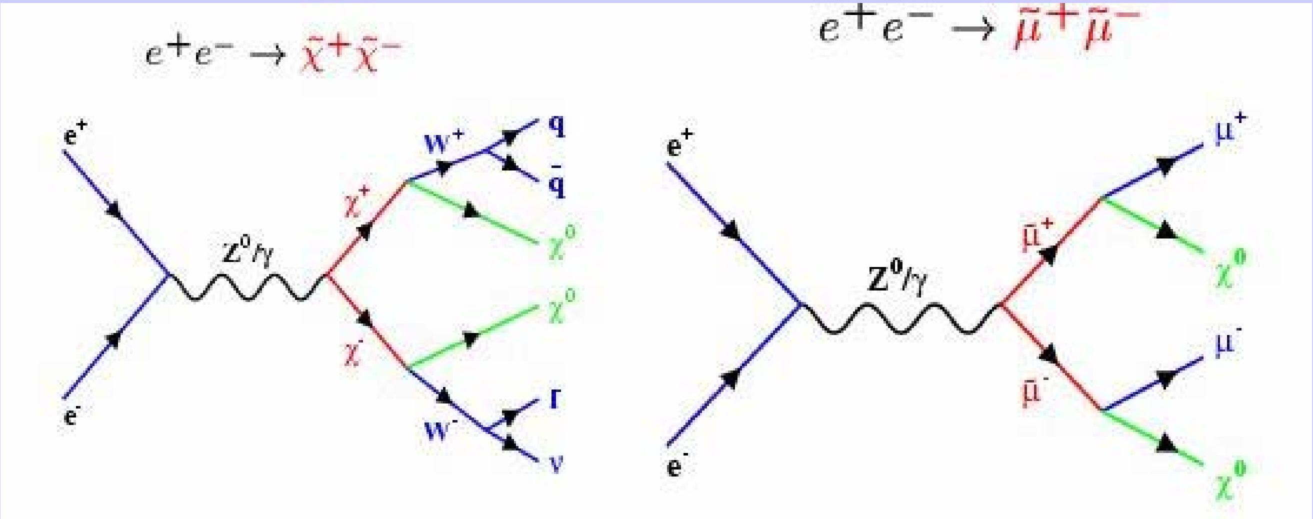
Mass spectra depend on choice of parameters...

Huge research area at **ILC:**

- measure sparticle properties (**masses,** cross sections, J^{PC} , **coupling strength, chirality, mixing**) with high precision
- use these + **LHC** to **determine underlying SUSY model** and **SUSY breaking mechanism**
- **extrapolate to GUT scale** using RGEs to determine **SUSY GUT mechanism**

Supersymmetry

Production and decay of supersymmetric particles at **e⁺e⁻ colliders (ILC)**



charginos

s-muons

Lightest supersymmetric particle stable in most models

→ candidate for dark matter

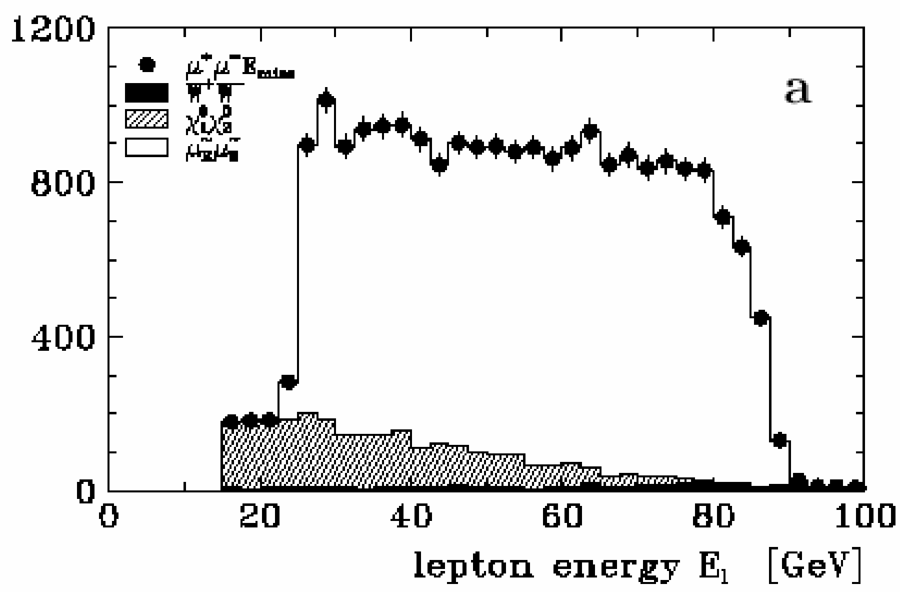
Experimental signature: missing energy

Supersymmetry

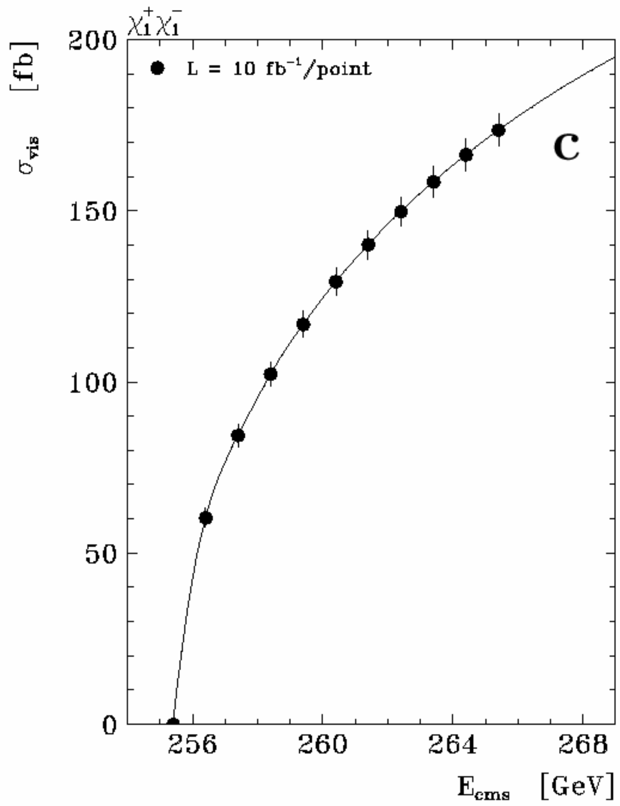
Measurement of sparticle masses

ex: Sleptons

lepton energy spectrum in continuum



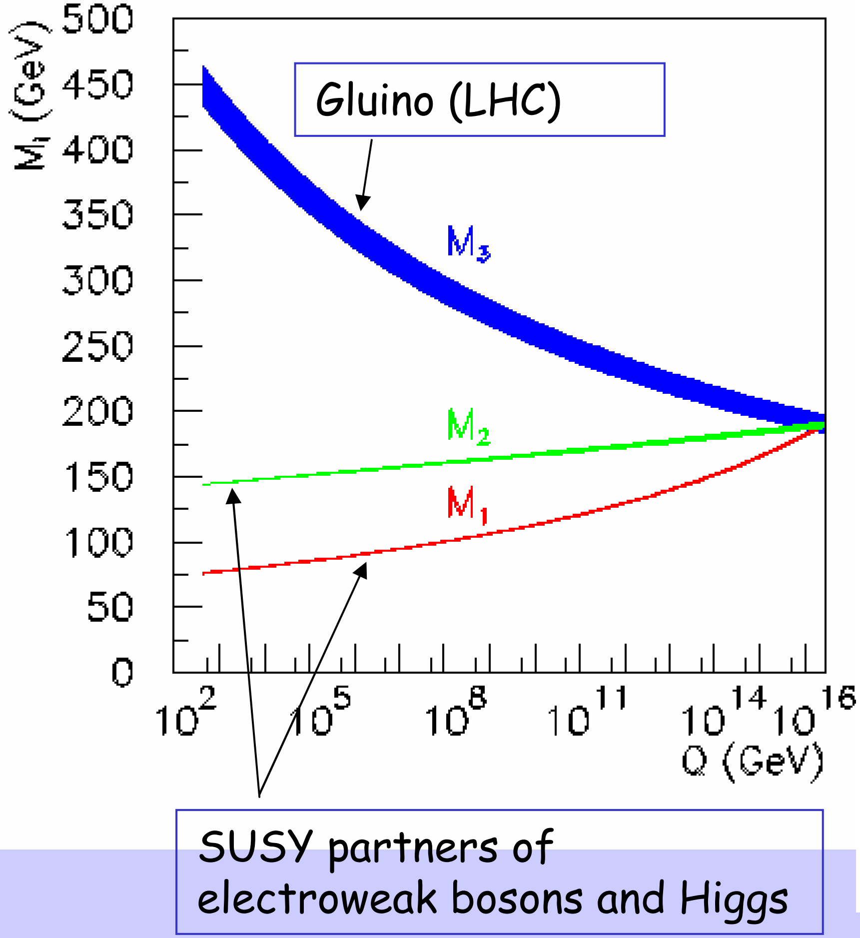
ex: Charginos threshold scan



achievable accuracy:

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

Test of Unification



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

Gauge couplings unify at high energies,

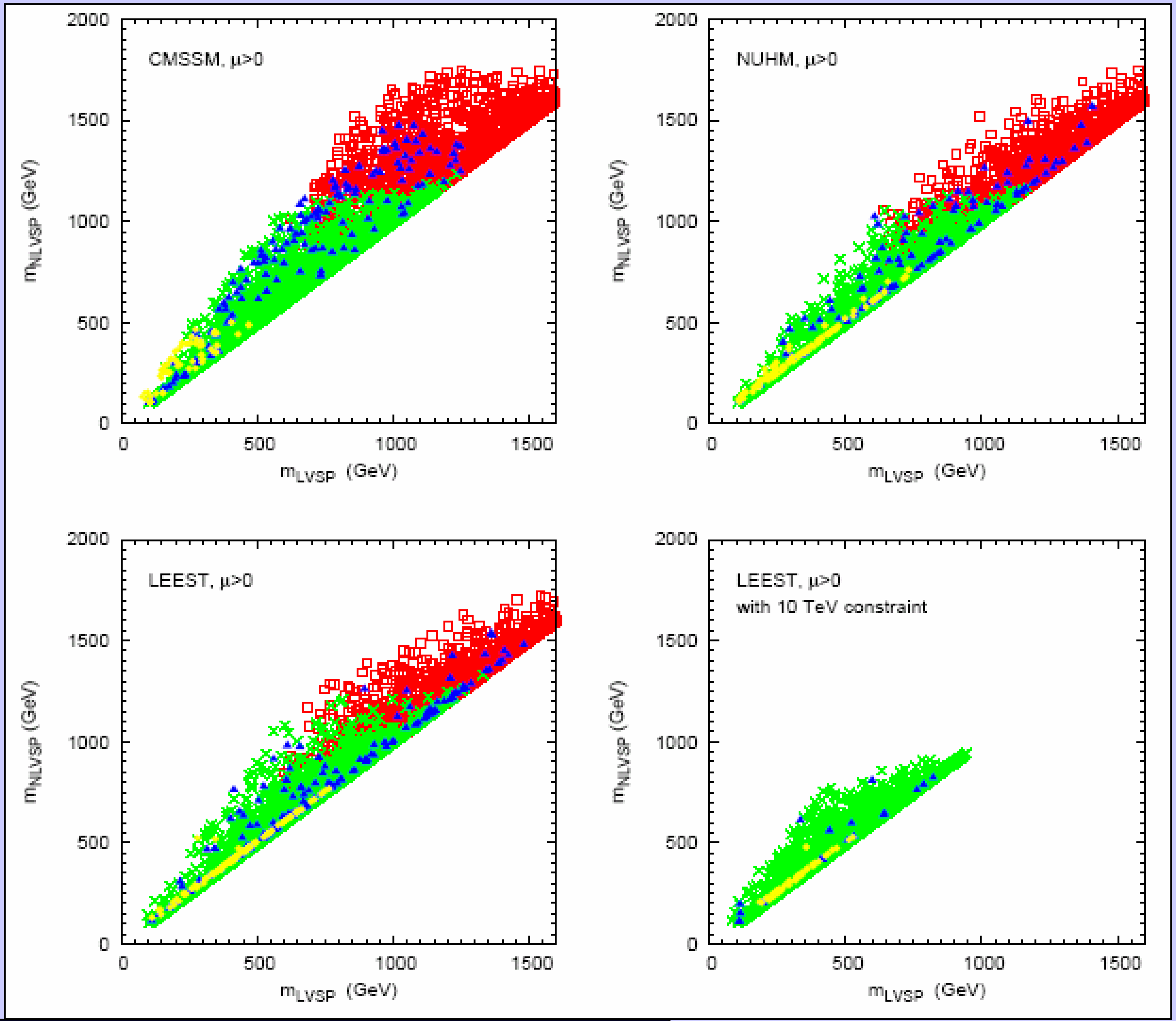
Gaugino masses unify at same scale

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

BUT

Sparticles may not be very light

↑ Second lightest visible sparticle

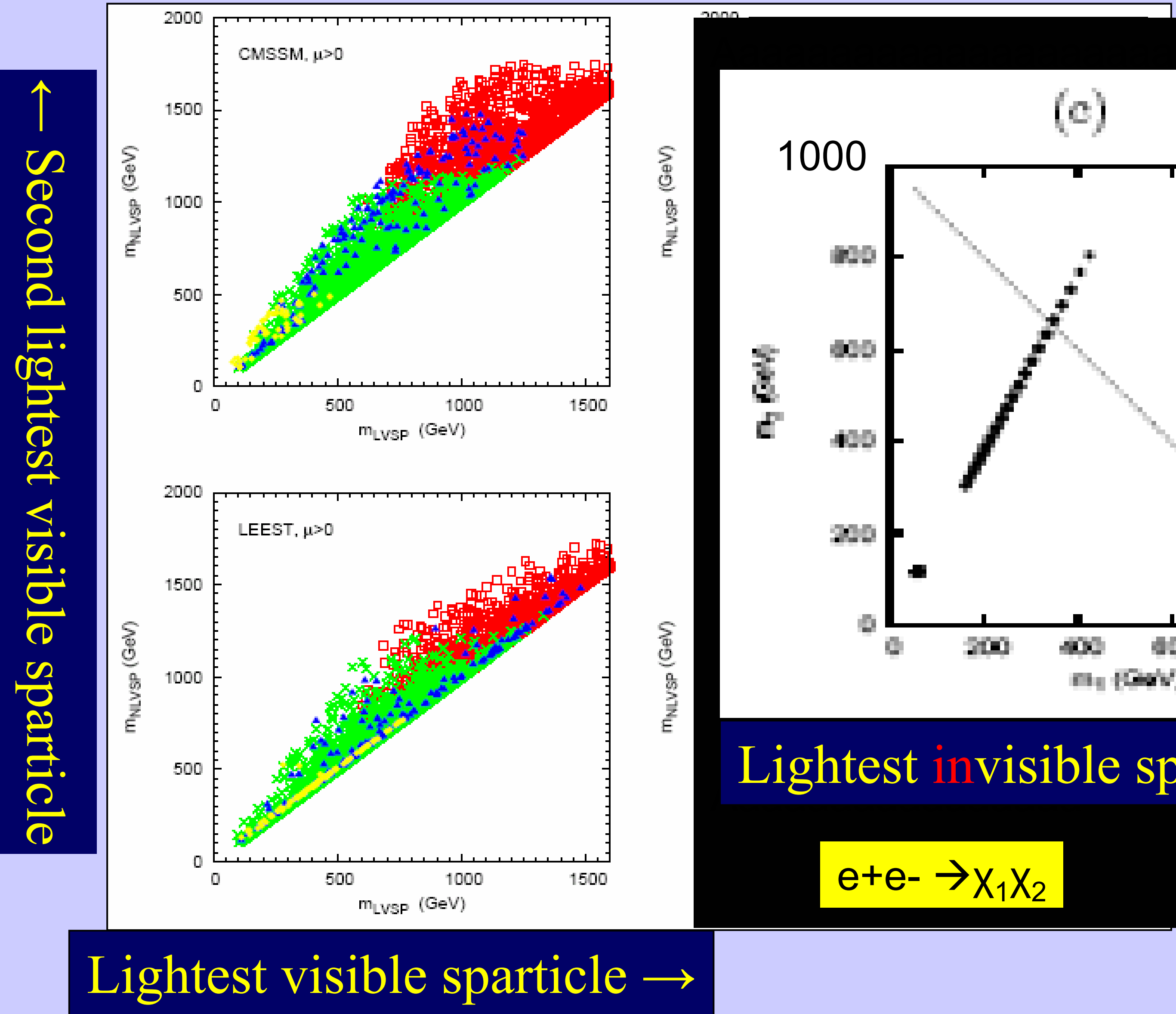


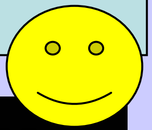
Lightest visible sparticle →

JE + Olive + Santoso + Spanos

BUT

LSP light in most cases





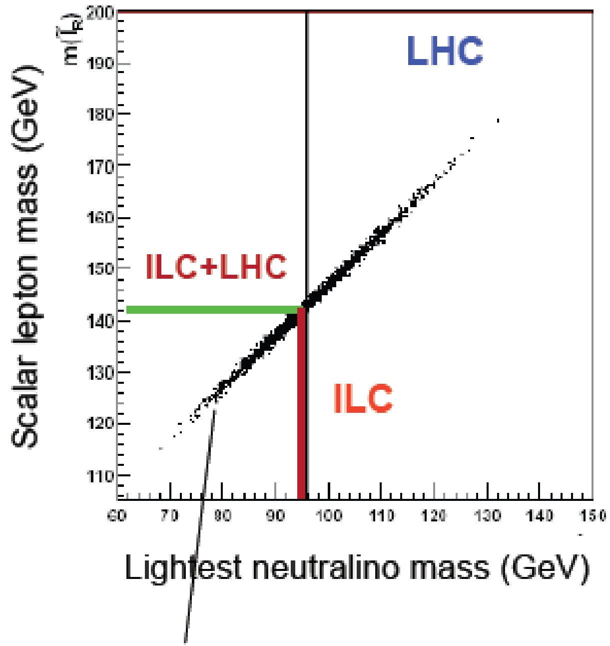
$e^+e^- \rightarrow \chi_1\chi_2$

Kalinowski

Using the $M(\chi^0_1)$ from ILC

300 fb^{-1}@LHC
ΔM values in GeV

	LHC	LHC+LC (0.2%)
$\Delta m_{\tilde{\chi}^0_1}$	4.8	0.19 (ILC input)
$\Delta m_{\tilde{l}_R}$	4.8	0.34
$\Delta m_{\tilde{\chi}^0_2}$	4.7	0.24
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{b}_1}$	13.2	10.5

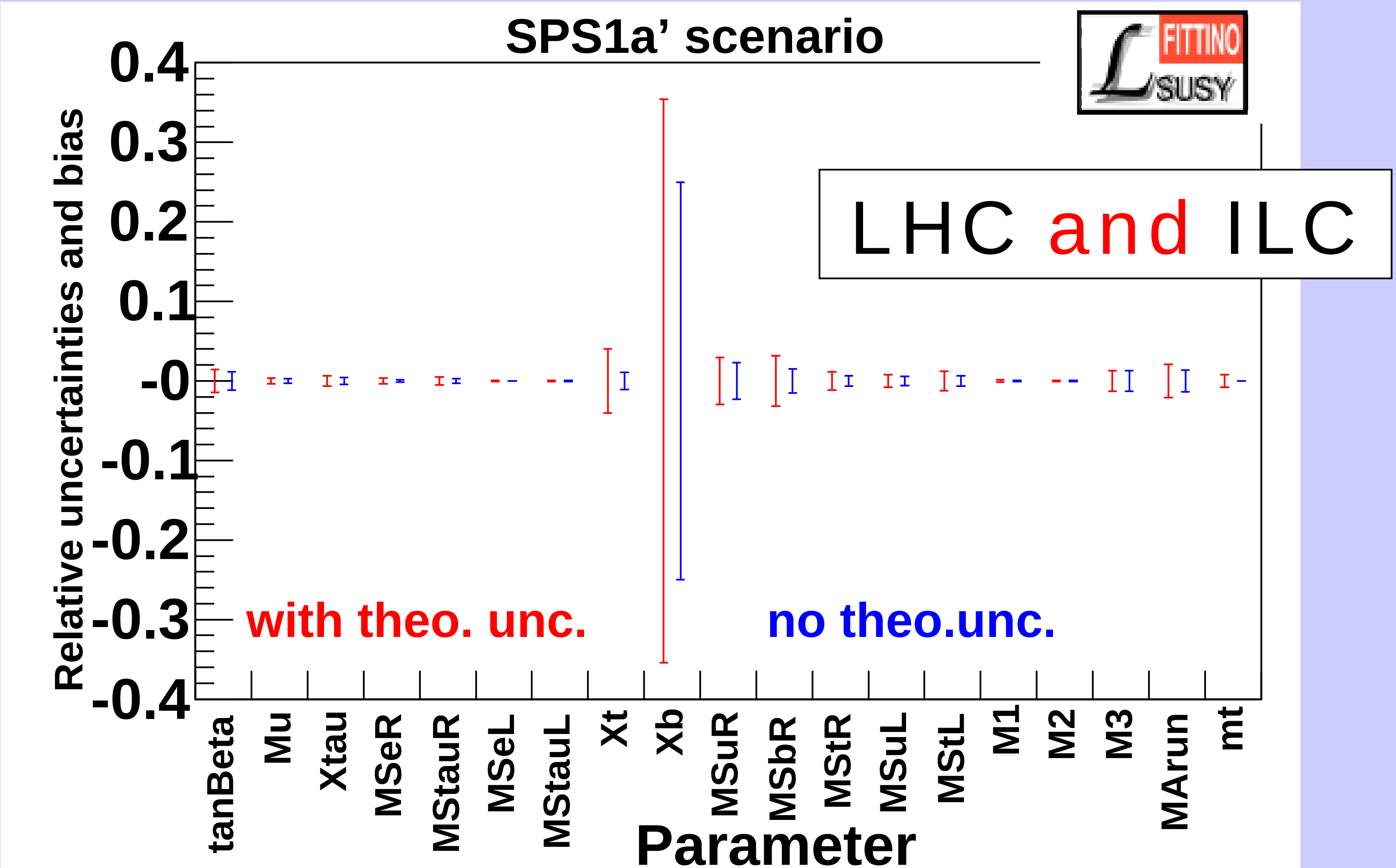


Significant improvements **even if only $m(\chi^0)$ is measured at ILC**

Strong correlation at LHC

An input from ILC resolve this correlation

MSSM parameters from global fit



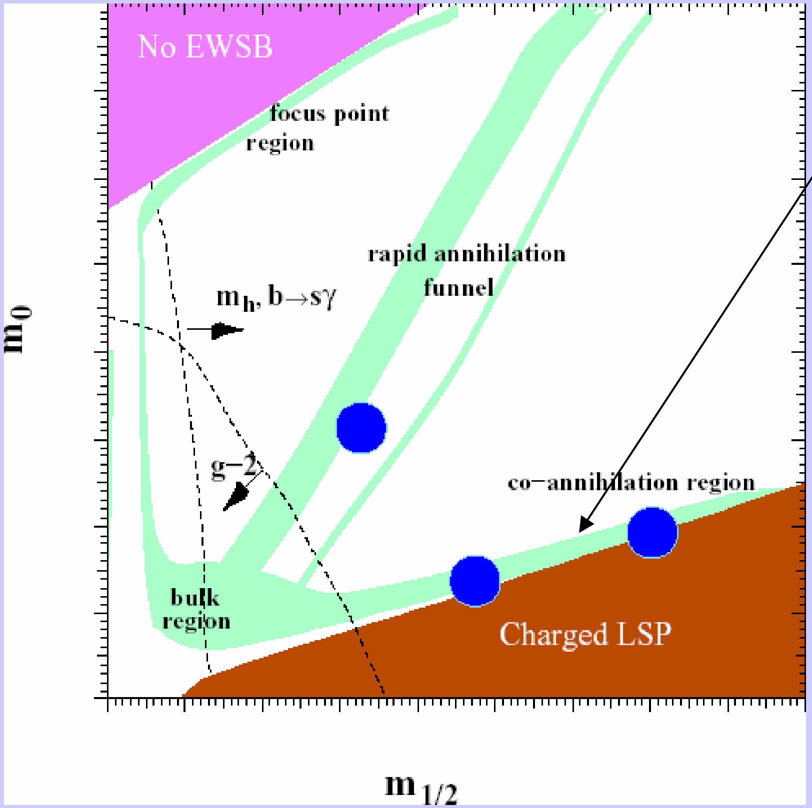
→ only possible with information from BOTH colliders

Dark Matter

If SUSY LSP responsible for Cold Dark Matter, need accelerators to show that its properties are consistent with CMB data

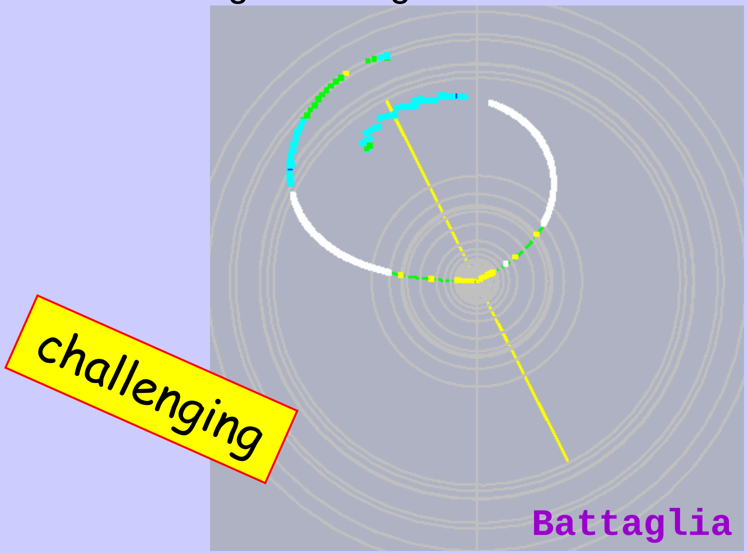
- Future precision on Ωh^2 ~ 2% (Planck) –> match this precision!

- WMAP points to certain difficult regions in parameter space:



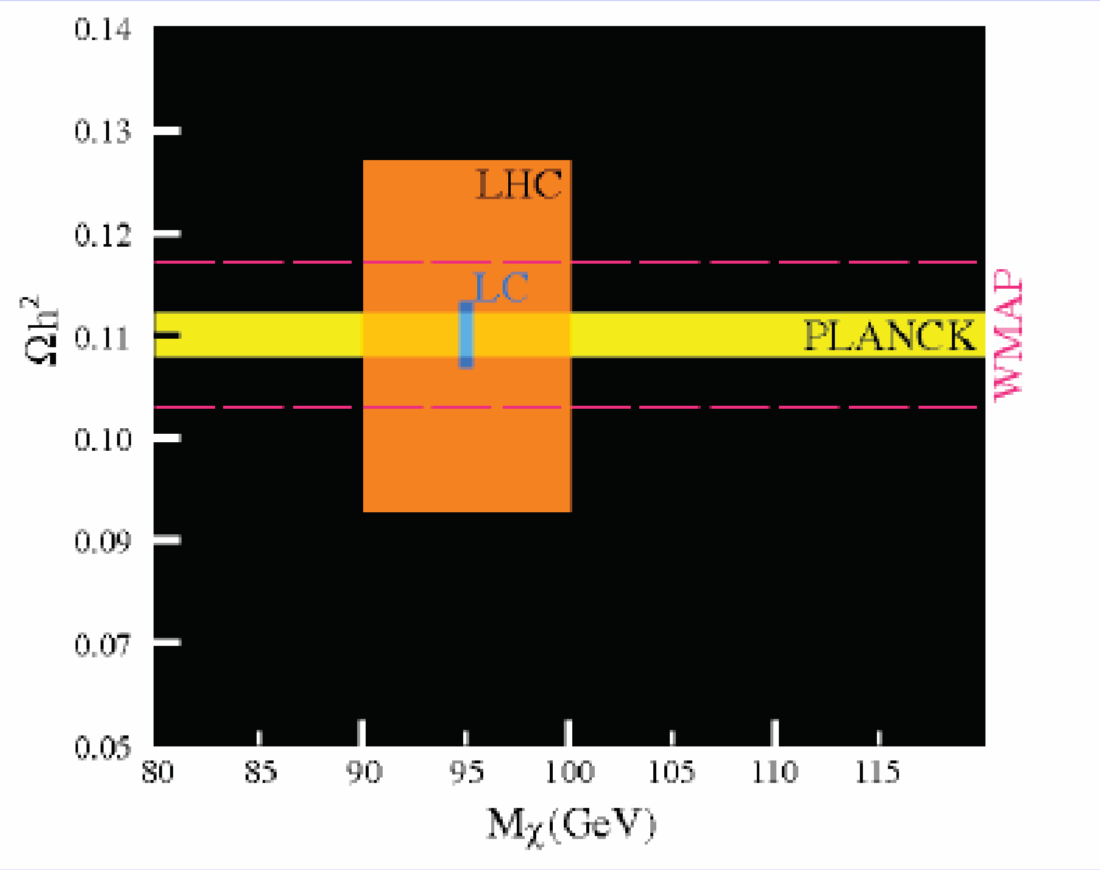
small $\Delta M = M_{\tilde{\ell}} - M_{\chi_1^0}$

e.g. smuon pair production at 1TeV
only two very soft muons!
need to fight backgrounds



Dark Matter and SUSY

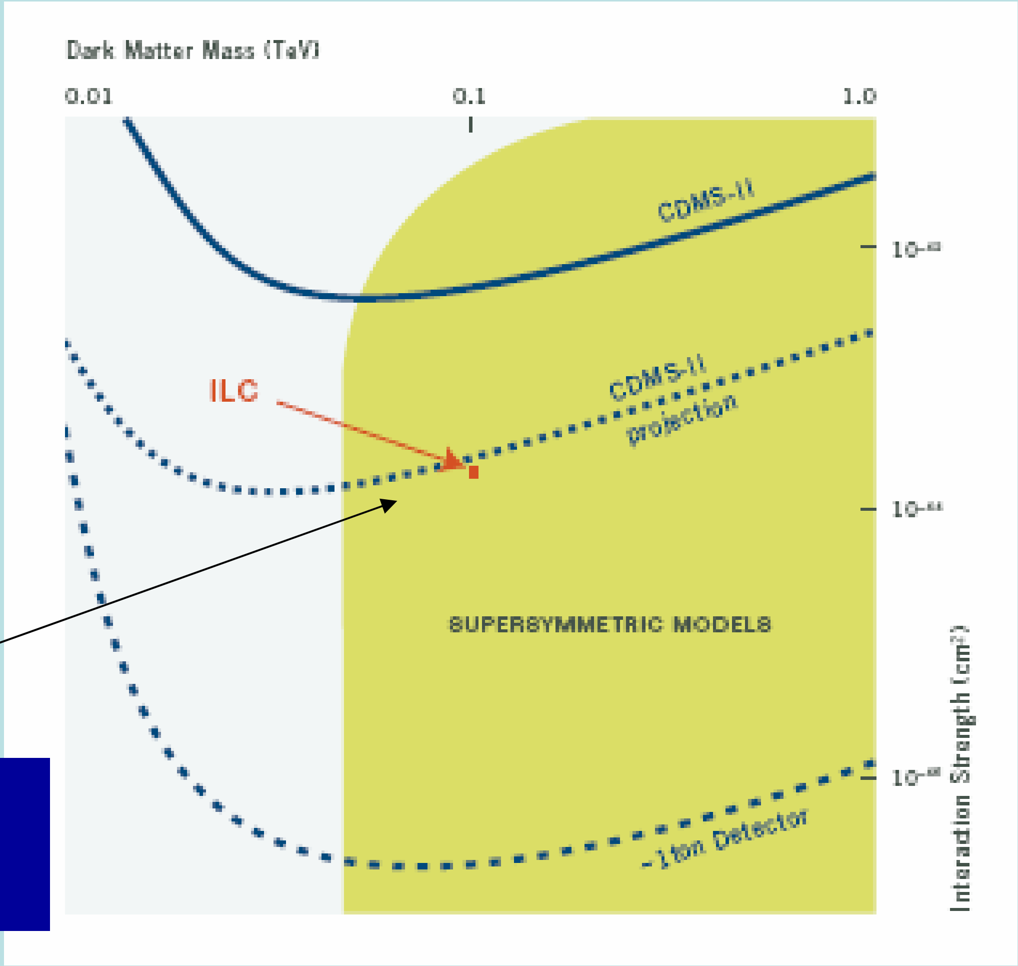
- is Dark Matter linked to the LSP?



'WMAP'	7 %
LHC	~15 %
'Planck'	~2 %
ILC	~3 %

a match between collider and astrophysical measurements would provide overwhelming evidence that the observed particle(s) is dark matter

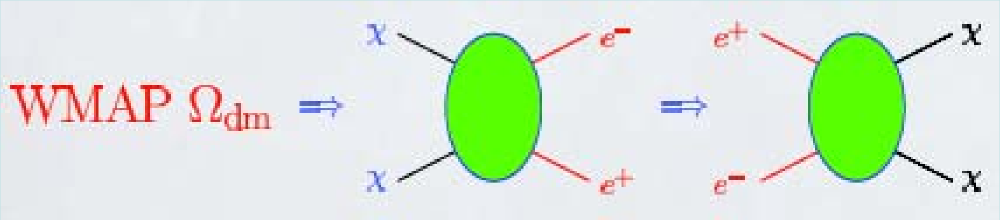
Comparison with expectations from direct searches



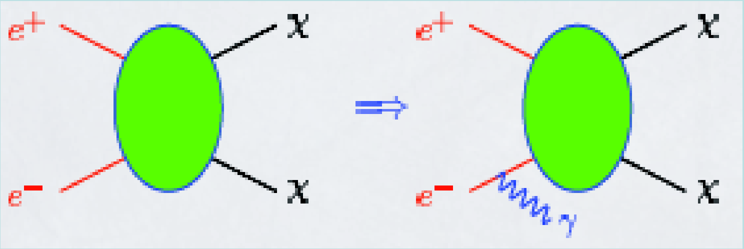
constrain mass and interaction strength

Model independent WIMP search

- consider pair production **$e^+e^- \to \chi_1\chi_1$**



- **χ invisible**
- **use photon radiated off e^+ or e^-**



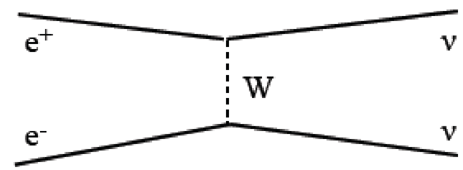
- Ω_{dm} => σ (**$e^+e^- \to \chi\chi\gamma$**) ≈ 0.1 .... 10 fb
  ~ 50....5000 events / 4 years ILC
  [A.Birkedal et al hep-ph/0403004]
- **not trivial,**

  main background: $e^+e^- \to \nu\nu$ (+γ)

  reduction through appropriate choice of beam polarisation

How does Polarisation help?

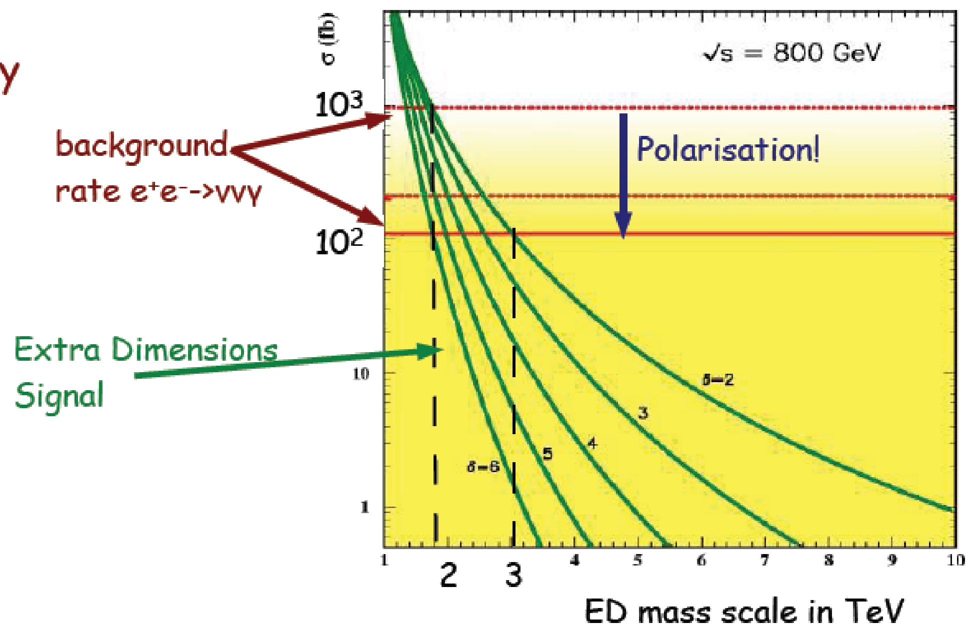
Polarisation reduces main background source: $e^+e^- \to \nu\nu\gamma$



=> heavy reduction of background
with $P(e^-) > 0$
& $P(e^+) < 0$

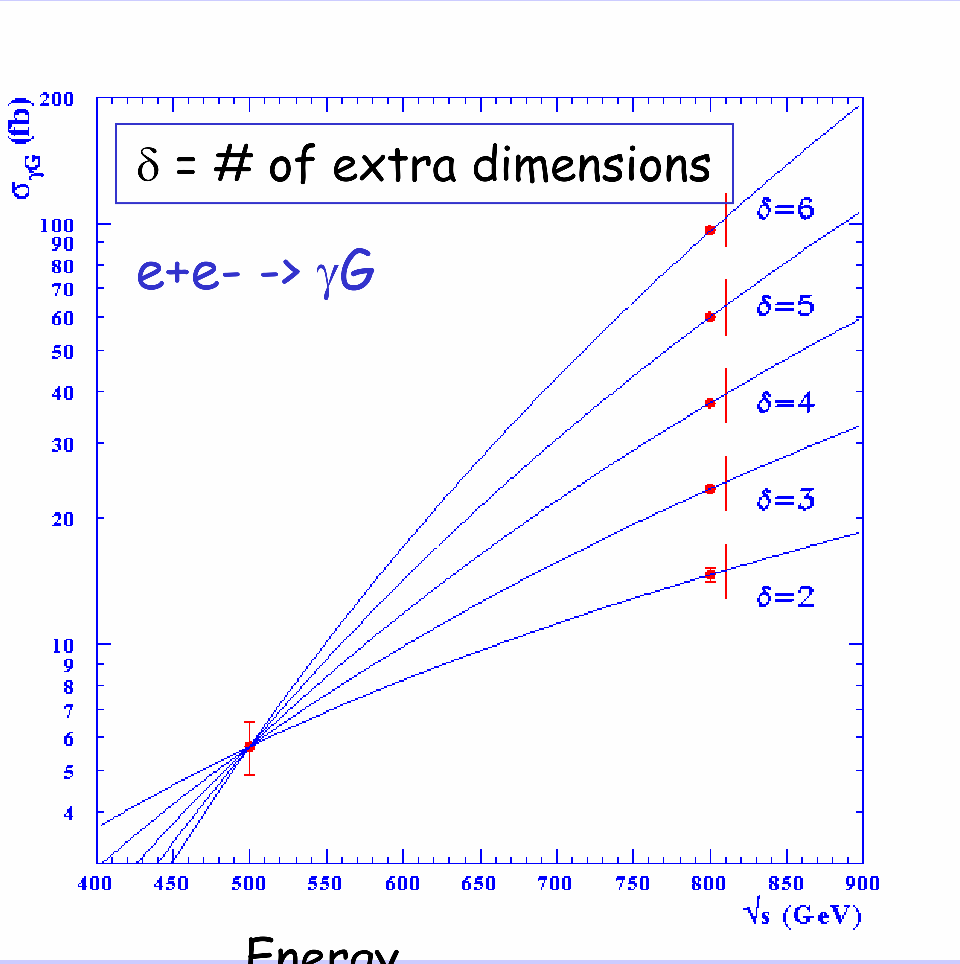
Example: Extra Dimensions $e^+e^- \to \gamma G$ [TESLA-TDR]

precision of polarimetry important:
- sensitivity to signal
- ~ uncertainty of background expectation
- ~ uncertainty of polarisation!



Extra Spatial Dimensions

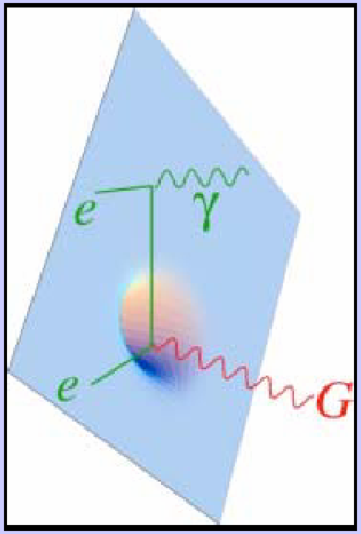
cross section for anomalous single photon production



Energy

•In how many dimensions do we live?

Emission of gravitons into extra dimensions



+ emission of G (or one jet)

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

No Higgs boson(s) found….

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

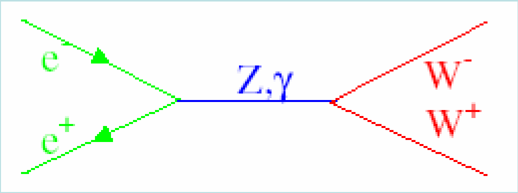
→ SM becomes inconsistent unless a new strong QCD-like interaction sets on

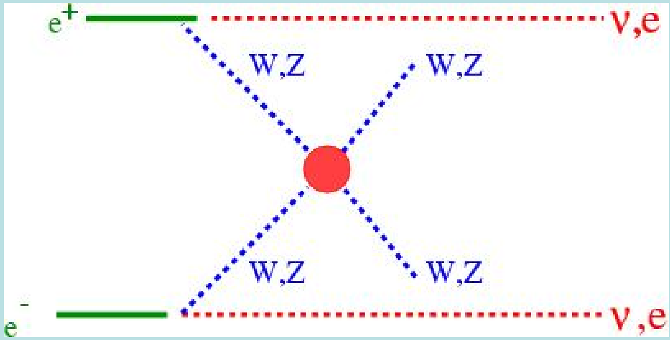
→ Goldstone bosons ("Pions") = W states ("technicolor")

→ no calculable theory until today in agreement with precision data

Experimental consequences: *deviations in*

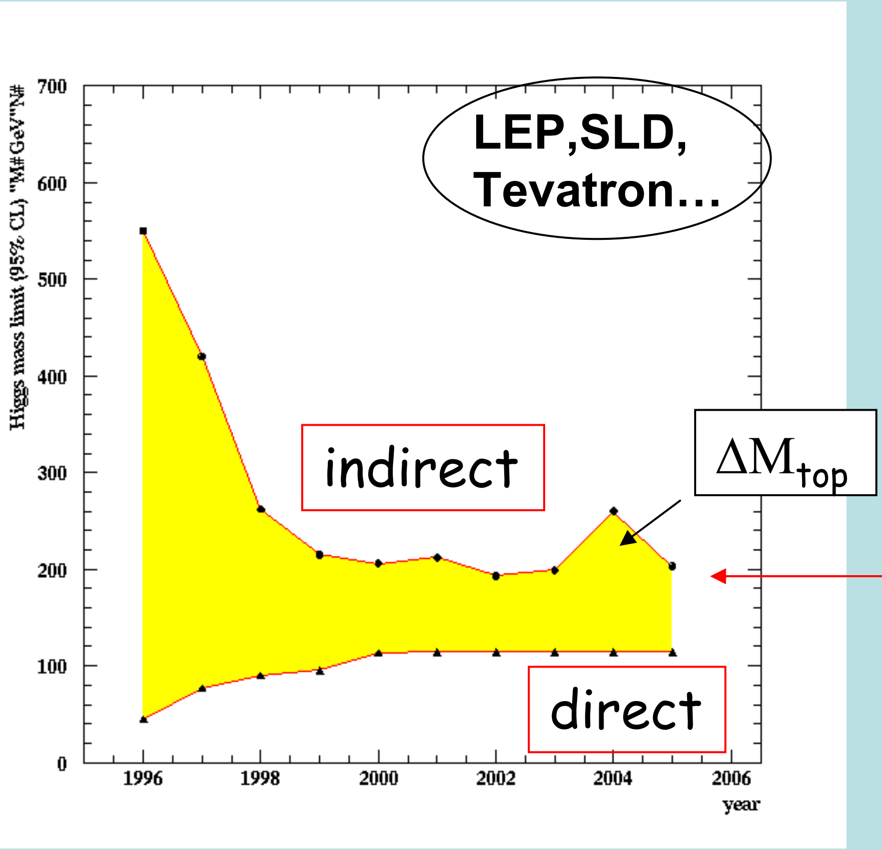
triple gauge couplings *quartic gauge couplings:*





ILC (800 GeV): sensitivity to energy scale Λ:
triple gauge couplings: ~ 8 TeV
quartic gauge couplings: ~ 3 TeV ⇨ *complete threshold region covered*

Precision electroweak tests



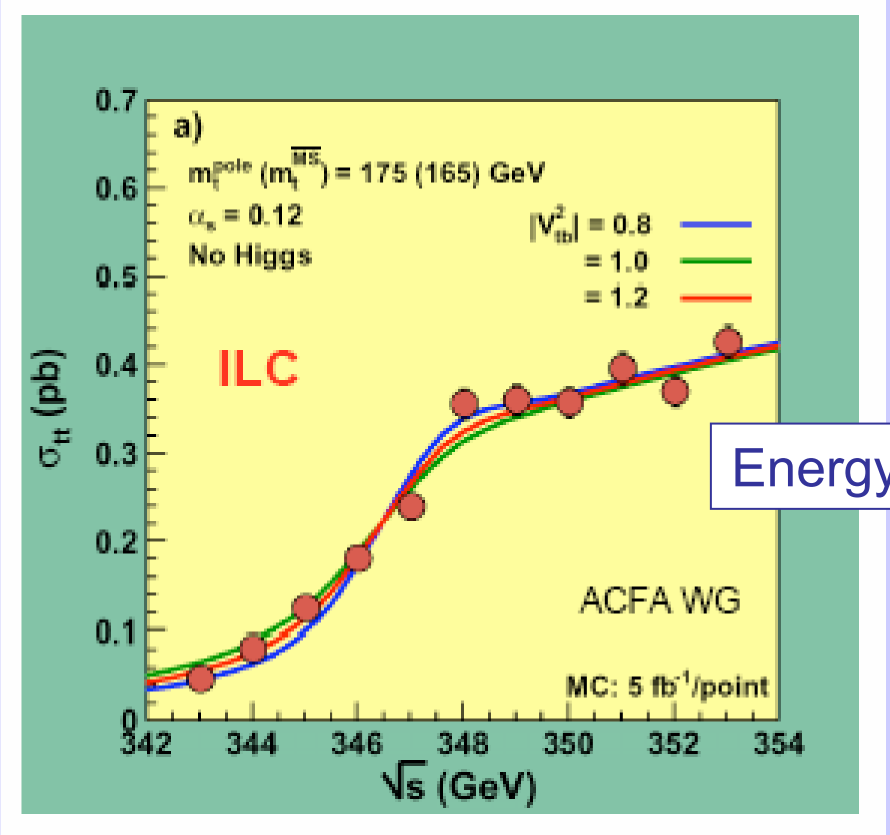
the top-quark is playing a key role in precision tests…..

remember the indirect determination of the mass of the Higgs

Precision electroweak tests

As the heaviest quark, the top-quark could play a key role in the understanding of flavour physics…..

…requires precise determination of its properties….

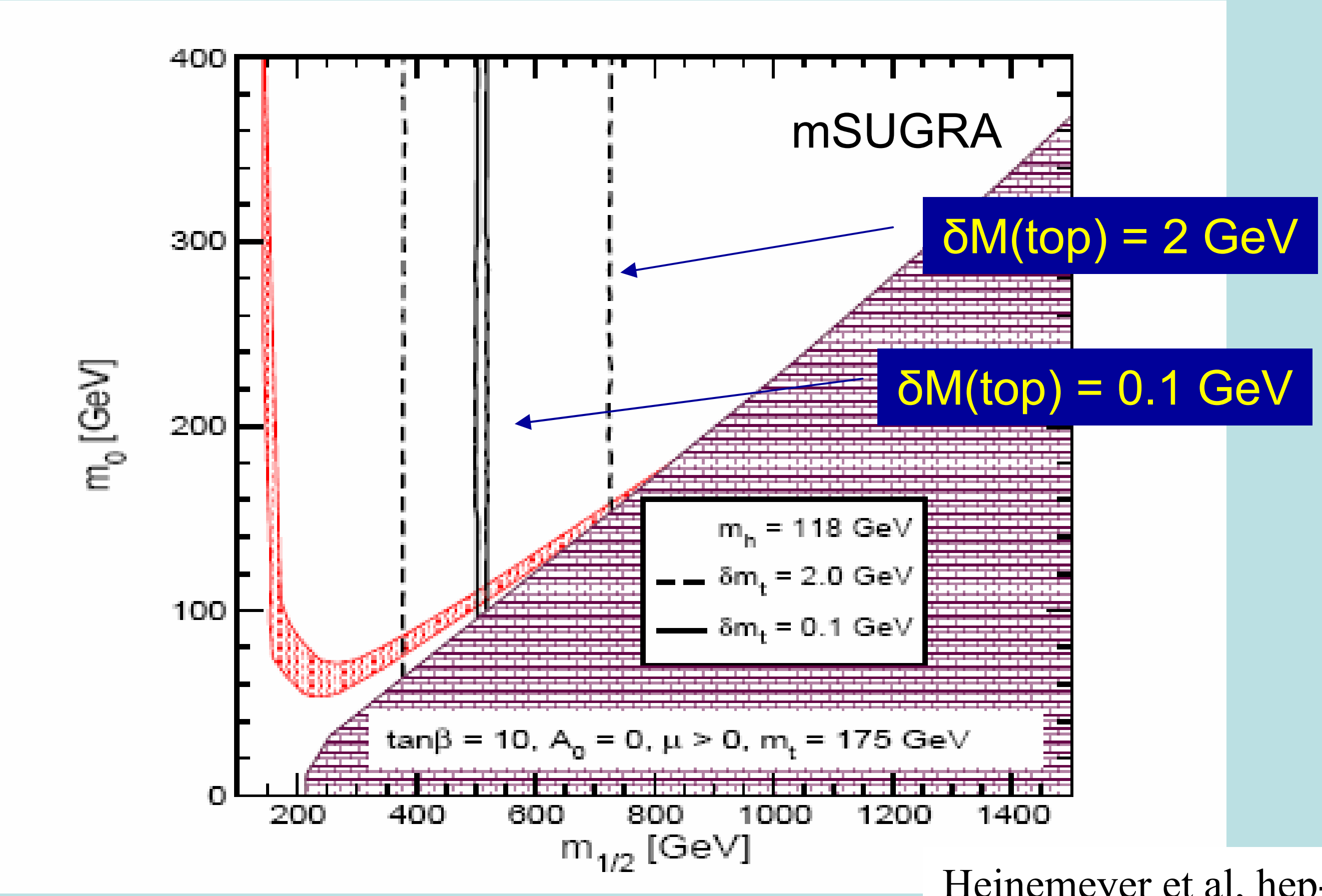


Energy scan of top-quark threshold

$\Delta M_{top} \approx 100$ MeV

limited by theory

Precision electroweak tests



Heinemeyer et al, hep-ph/0306181

→ constrain allowed parameter space

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

$\Delta \sin\Theta_W = 0.000013$

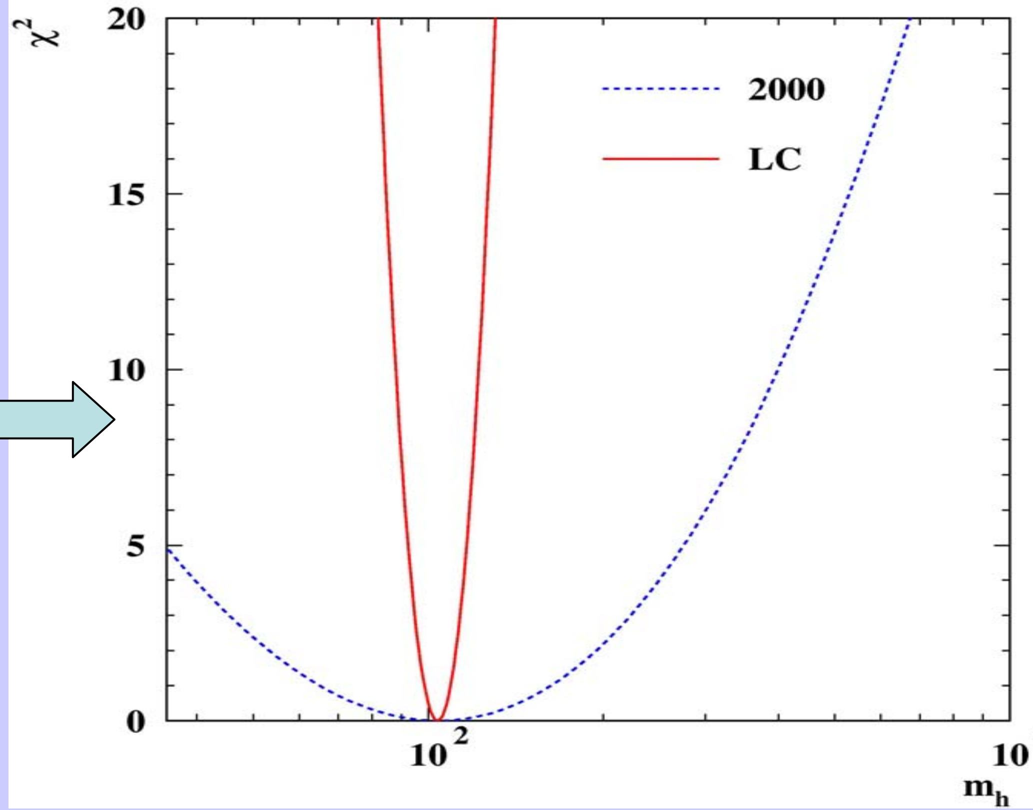
together with

$\Delta M_W = 7$ MeV

(threshold scan)

and

$\Delta M_{top} = 100$ MeV



The ILC physics case

0. Top quark at threshold

1. 'Light' Higgs (consistent with precision EW)
   ⇨ verify the Higgs mechanism is at work in all elements

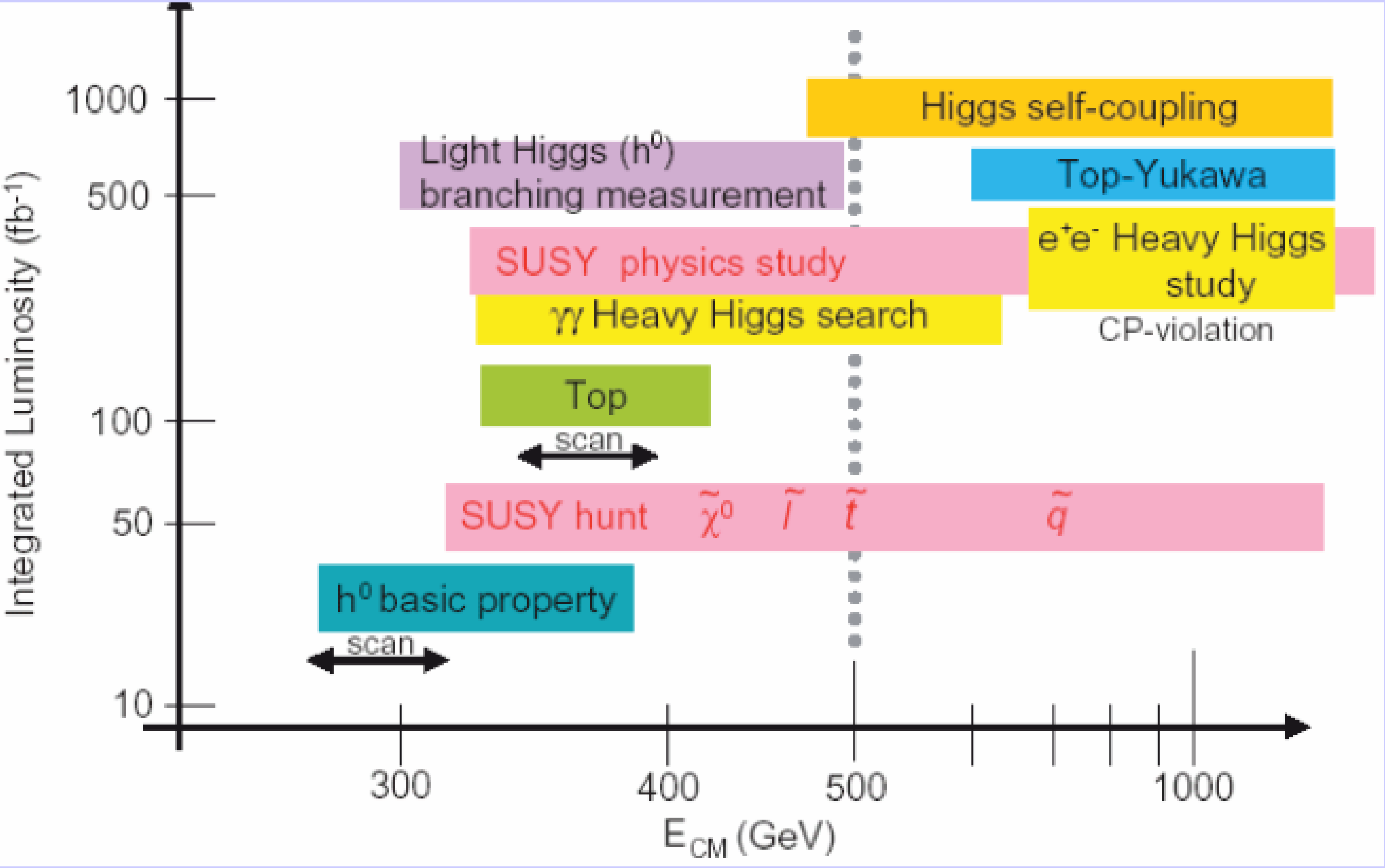
2. 'Heavy' Higgs (inconsistent with precision EW)
   ⇨ verify the Higgs mechanism is at work in all elements
   ⇨ find out why prec. EW data are inconsistent

3. 1./2. + new states (SUSY, XD, little H, Z', ...)
   ⇨ precise spectroscopy of the new states
   ⇨ precision measurements of couplings of SM&new states
   properties of new particles above kinematic limit

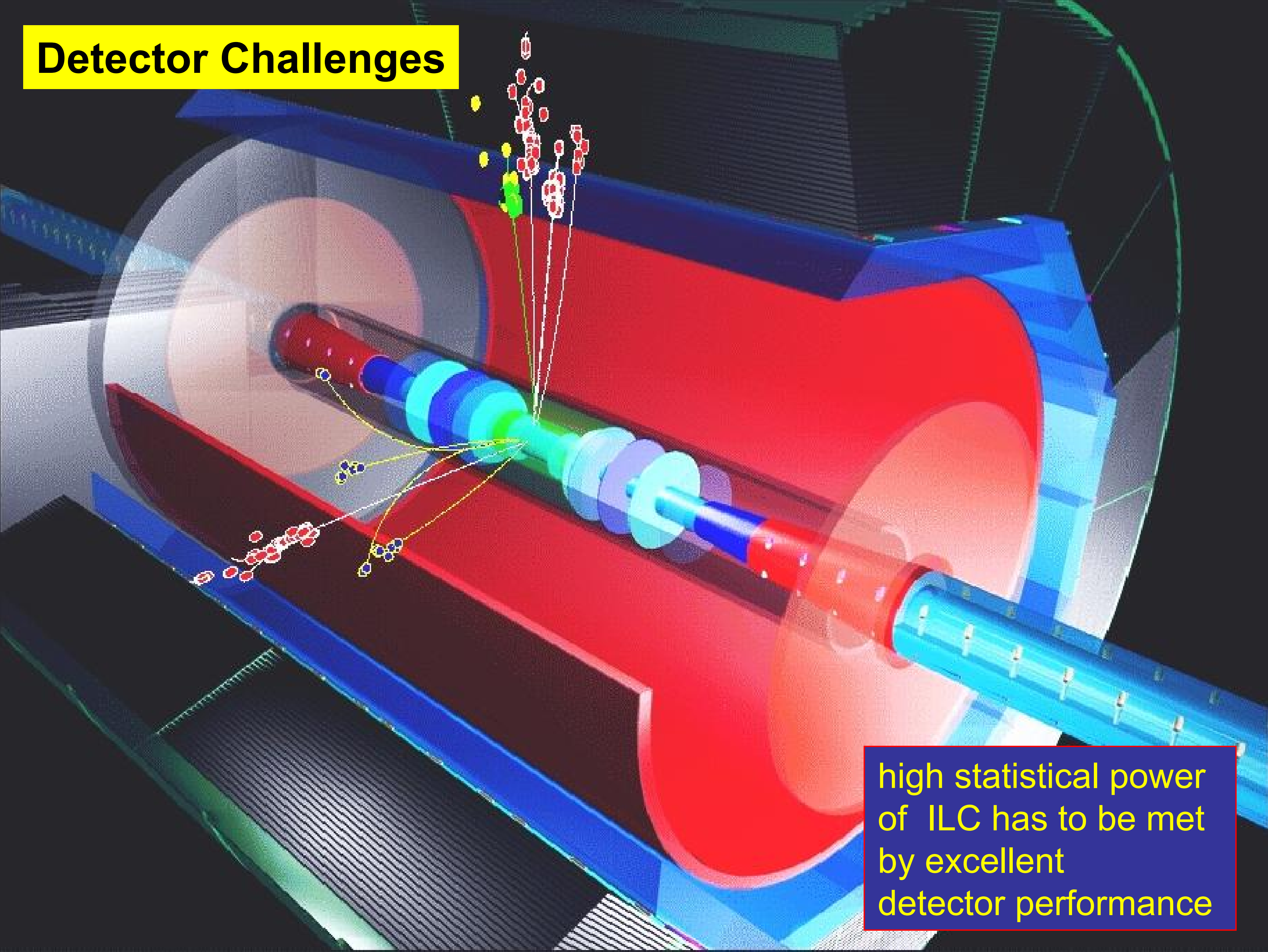
4. No Higgs, no new states (inconsistent with precision EW)
   ⇨ find out why precision EW data are inconsistent
   ⇨ look for threshold effects of strong/delayed EWSB

Early LHC data likely to guide the direction → choice of ILC options
LHC + ILC data analysed together → synergy!

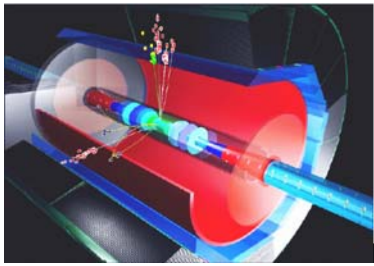
Intermezzo: ILC Physics Reach



Detector Challenges

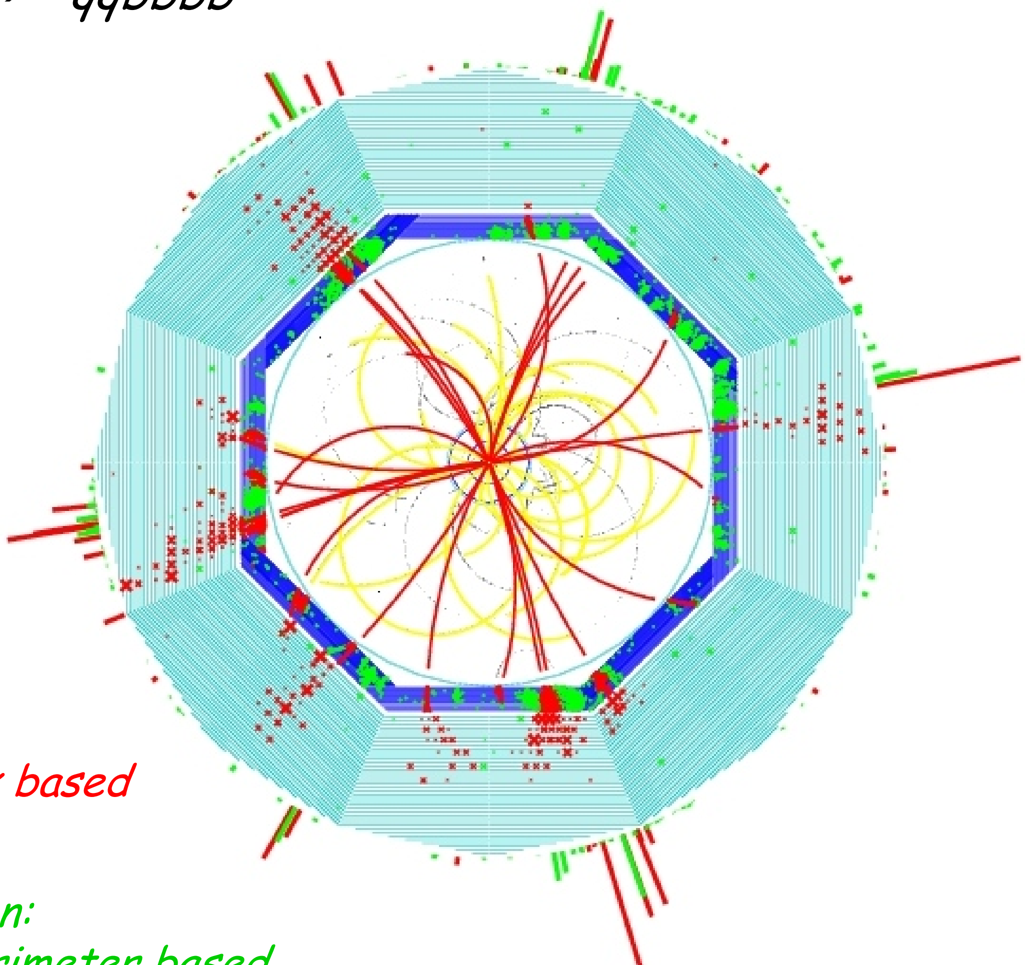


high statistical power of ILC has to be met by excellent detector performance



Detector challenges: calorimeter

ZHH → qqbbbb



red: track based

green: calorimeter based

High precision measurements demand new approach to the reconstruction:

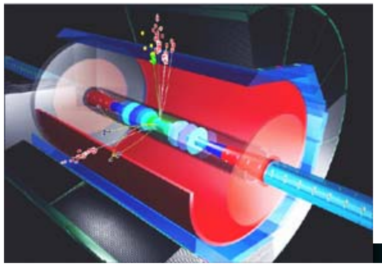
- particle flow (i.e. reconstruction of ALL individual particles)

this requires

- unprecedented granularity

in three dimensions

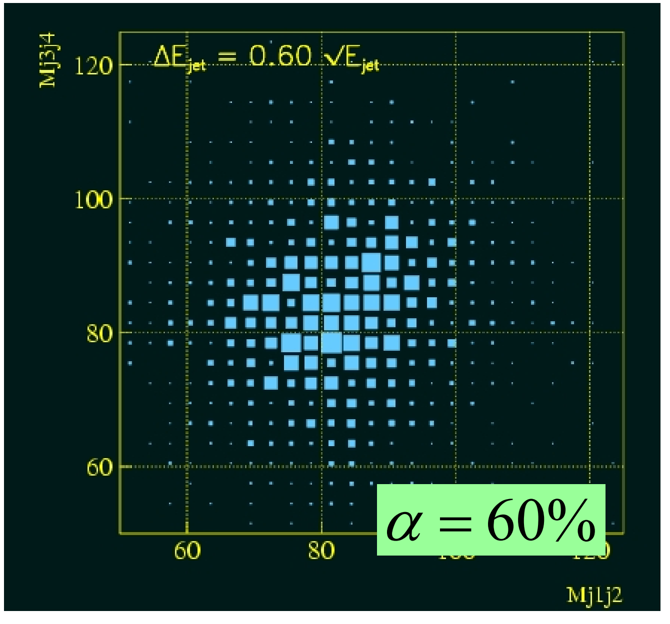
R&D needed now for key components



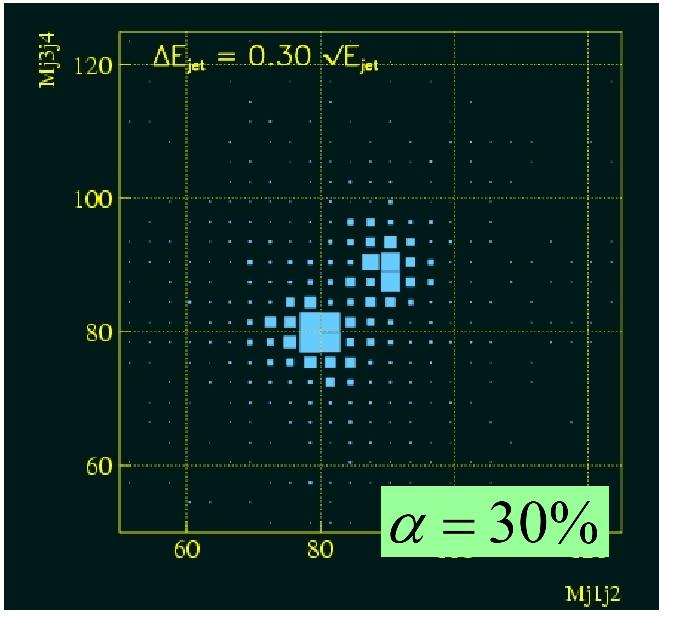
Jet energy resolution

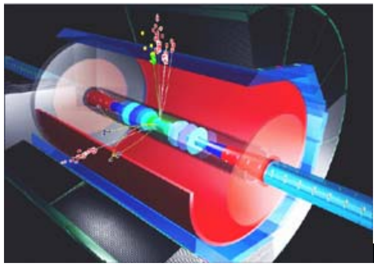
- Dijet masses in WWvv, ZZvv events (no kinematic fit possible):
- Challenge: separate W and Z in their hadronic decay mode

LEP-like detector



LC design goal

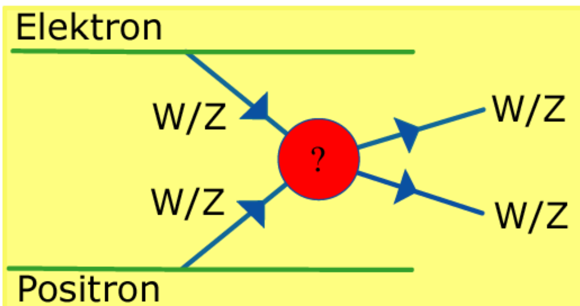




WW/ZZ separation

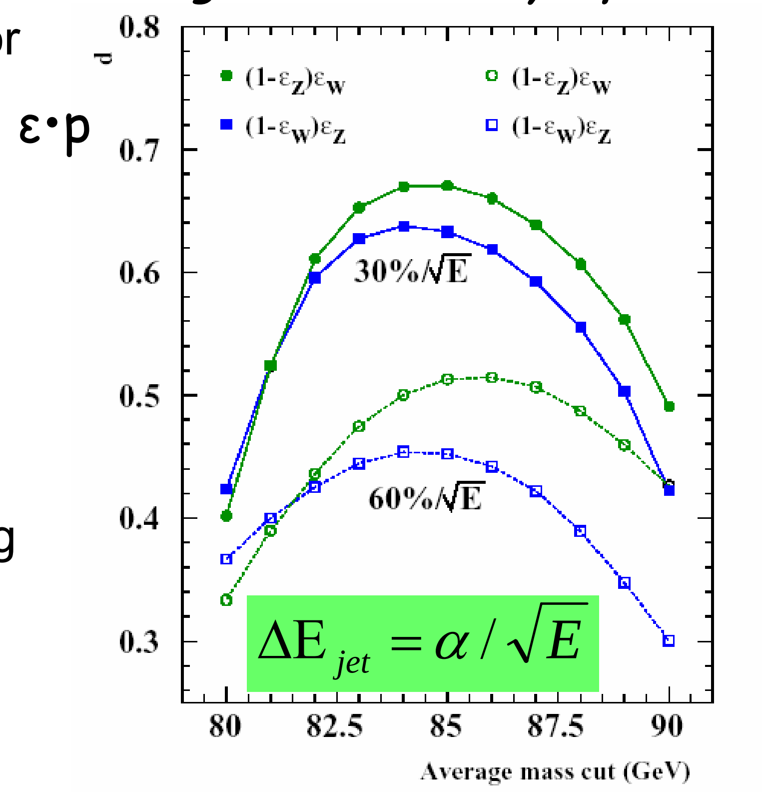
No Higgs scenario:

- WW scattering violates unitarity at ~1.2TeV, or new forces show up

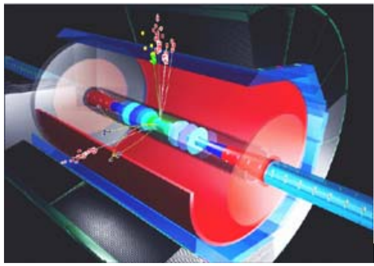


- access EWSB mechanism from WW scattering
- analyze ee→WWνν and ee→ZZνν channels
- need to separate ZZ background
- no kinematic fit possible due to the neutrinos

Dilution factor vs cut:
integrated luminosity equivalent

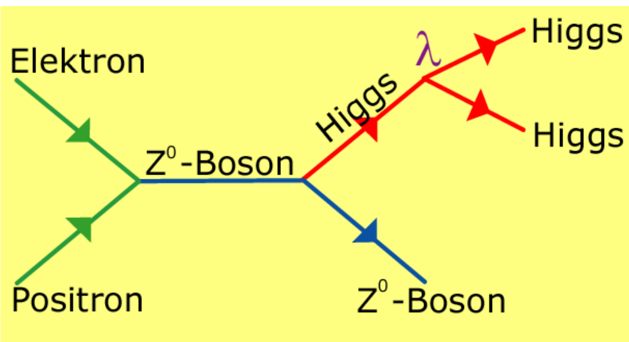


➔ Larger ε•p for α=30% is equivalent to a gain of ~ factor 2 in luminosity



Higgs potential / self coupling

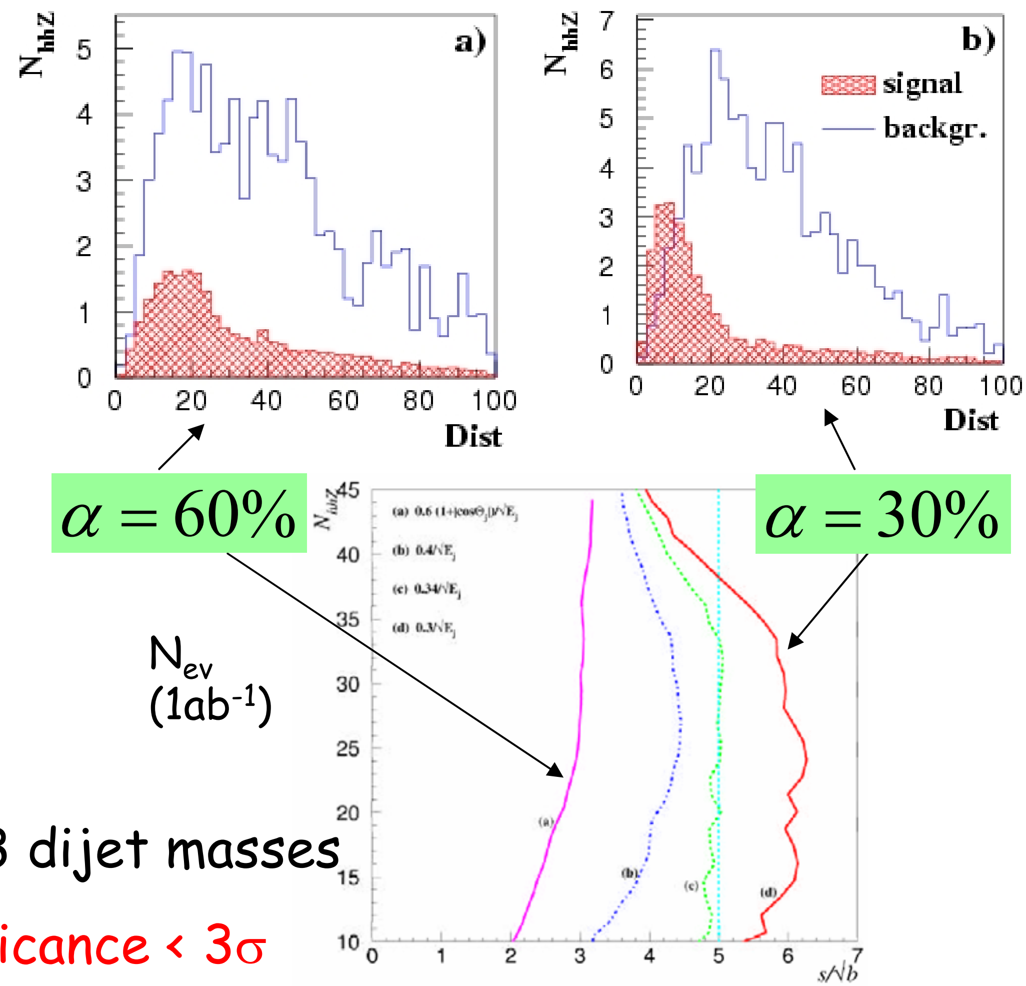
- **Is** the Higgs the Higgs?
- Check $\lambda = M^2_H / 2v^2$

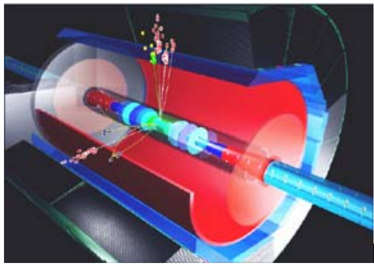


ee→ ZHH → 6 jets

- few tens of events
- reconstruct observable from 3 dijet masses

➔with LEP-like detector significance < 3σ

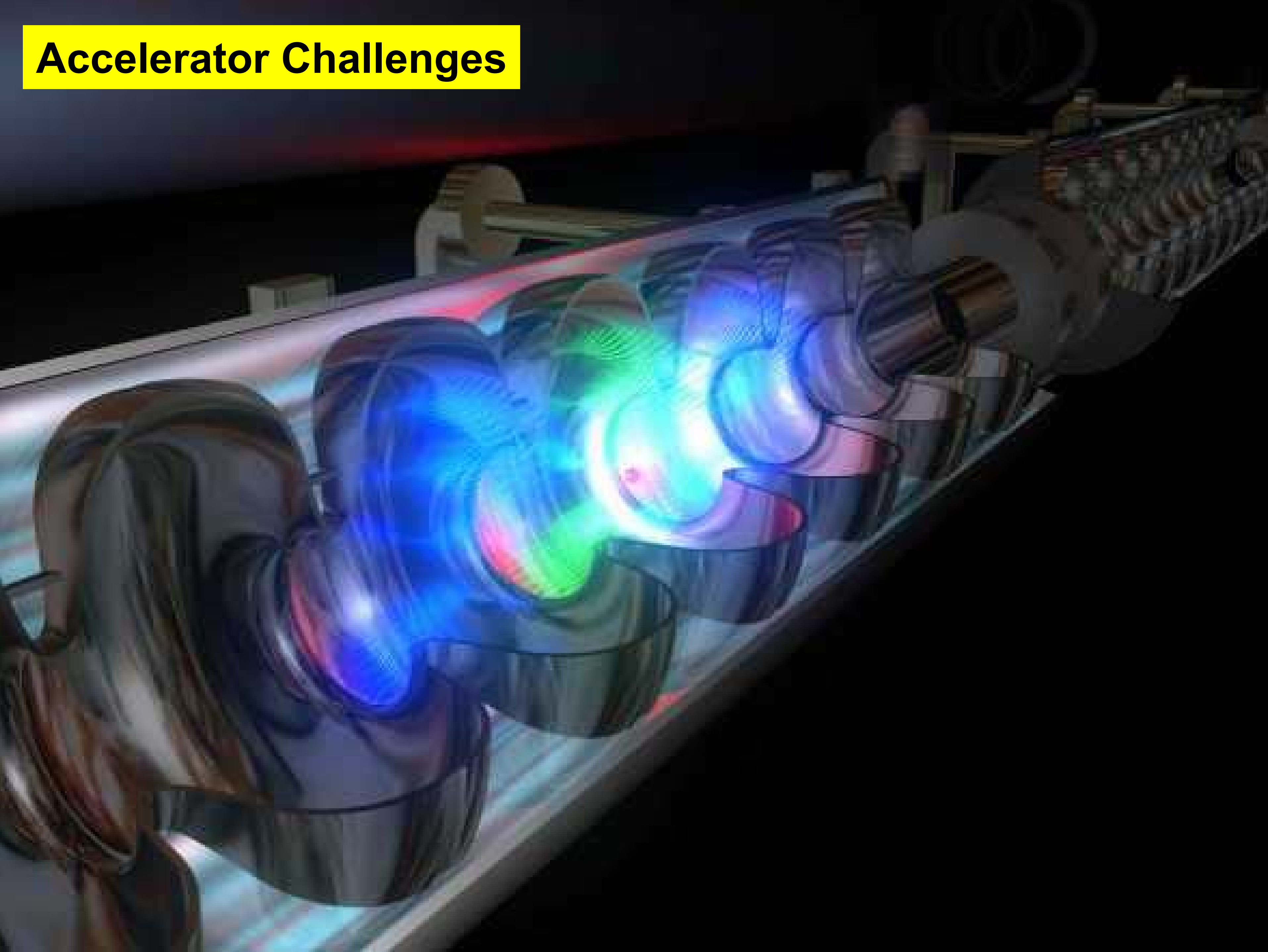




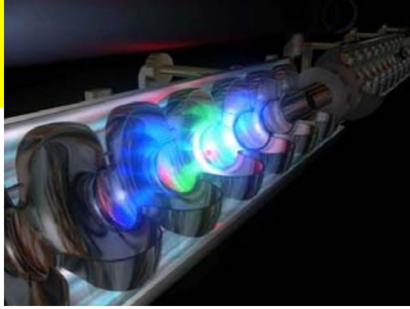
Detector Intermezzo

- The linear collider physics represents a formidable challenge for the detector (vertexing – tracking – calorimetry)
- met by a world-wide R&D effort, internationally coordinated (international subdetector collaborations)
- An interesting test beam period is ahead of us, to sharpen our views e.g. on imaging calorimetry and particle flow algorithms
- work on overall optimized detector concepts going on

Accelerator Challenges



Accelerator 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 foc.)

Energy:

- high accelerating gradient

In comparision to SLC the ILC has the following properties:

	SLC	ILC		factor
Energy E_{cm}	100	500 ($\rightarrow$ ~1000)	GeV	5-10
Beam Power	0.04	~10	MW	250
Spot size IP	500	~5	nm	100
Luminosity	$3 \cdot 10^{-4}$	3	10^{34} cm^{-2} s^{-1}	10,000

Status of the ILC

- TESLA was the catalyst that in the last three years has moved the ILC forwards very rapidly.
- There will only be one machine like this in the world – so it is essential that world-wide agreement be obtained. This has been in place for ~3 years.
- ECFA report:

  "..the realisation, in as timely a fashion as possible, of a world-wide collaboration to construct a high-luminosity e^+e^- linear collider with an energy range up to at least 400 GeV as the next accelerator project in particle physics; decisions concerning the chosen technology and the construction site for such a machine should be made soon"
- HEPAP report:

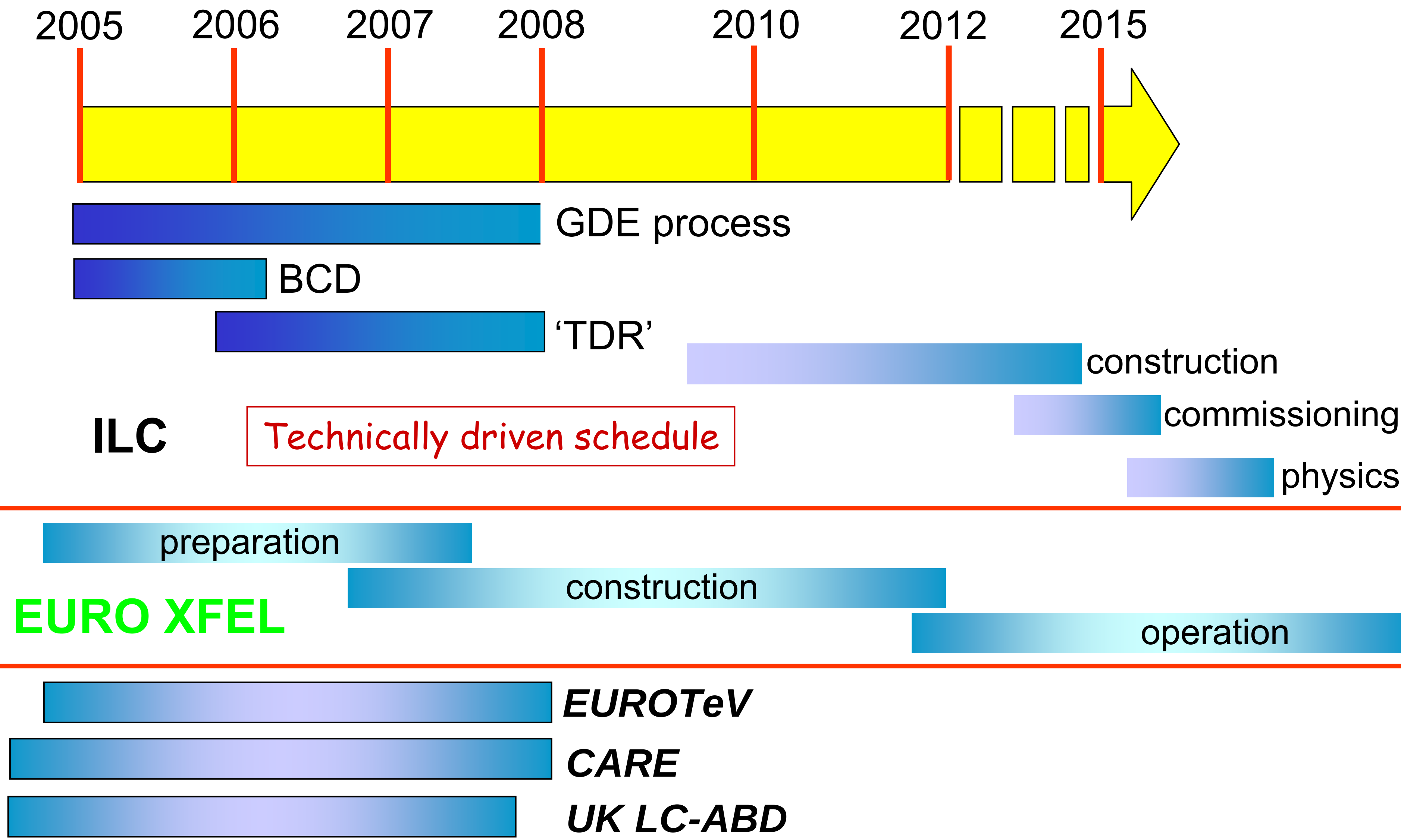
  "We recommend that the highest priority of the U.S. program be a high-energy, high-luminosity, electron-positron linear collider, wherever it is built in the world.... We recommend that the United States prepare to bid to host the linear collider, in a facility that is international from the inception."
- ACFA:

  "ACFA urges the Japanese Government to arrange a preparatory budget for KEK to pursue an engineering design of the collider, to study site and civil engineering, as well as to investigate the process for the globalization."

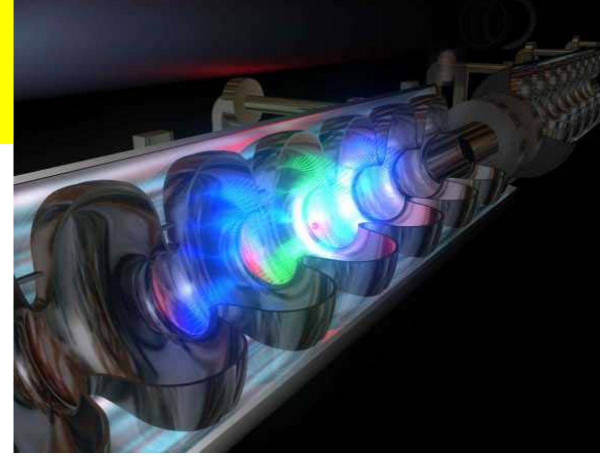
Status of the ILC

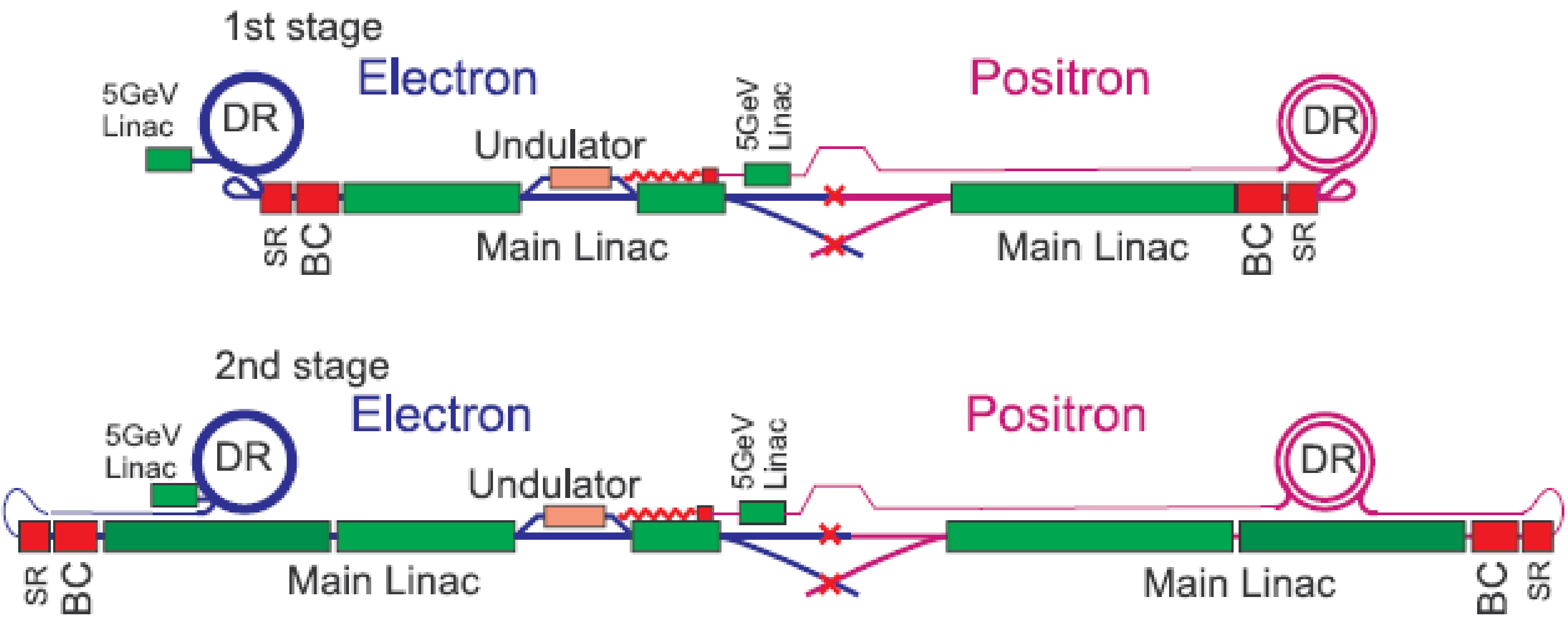
- In August 2004, group of "Wise Men", chaired by B. Barish, chose the "cold", superconducting, RF technology over the competing "warm" X-band RF.
- Despite the fact that both US and Asian research had been in warm technology, both regions accepted the decision and united behind cold technology; 18 months on, transition is now complete.
- ICFA moved ahead quickly to appoint a Global Design Effort (GDE) to transform the technology decision into a full Technical Design Report, capable of being presented to world governments for a decision to construct.
- B. Barish appointed as GDE director, with three regional directors:
  BF (Europe), F. Takasaki (Asia), G. Dugan (Americas)

Project Timelines



BCD layout




1st stage
Electron
Positron
5GeV
Linac
DR
Undulator
5GeV
Linac
DR
SR
BC
Main Linac
Main Linac
BC
SR
2nd stage
Electron
Positron
5GeV
Linac
DR
Undulator
5GeV
Linac
DR
SR
BC
Main Linac
Main Linac
BC
SR

Summary

- The scientific case for a Linear Collider is strong and convincing, a broad consensus exists on importance and timing w.r.t. the LHC
- ILC and LHC offer a complementary view of Nature at the energy frontier
- Detector technologies to do the physics at the ILC are being developed
- The SC technology for the ILC is well developed
- 2015 is the target date for commissioning. To reach this we have to keep going at full speed. At present, community is keeping timeline. . .
- Politicians are following the process (technical decision, joint global design, self-organisation,..)

The ILC provides an exciting and promising future for discoveries and for understanding the universe and its origin