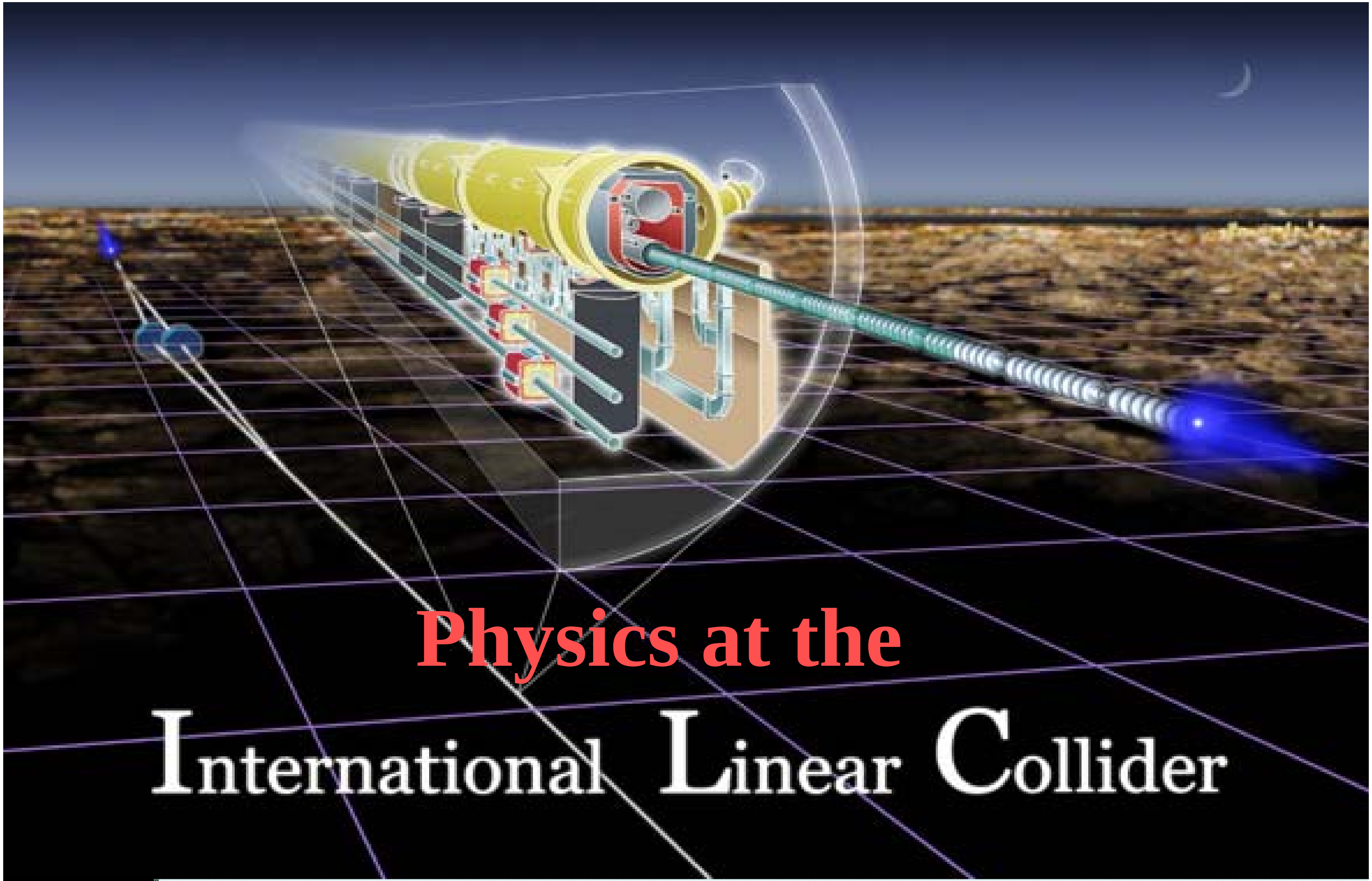


Physics at the International Linear Collider

Ariane Frey, MPI für Physik

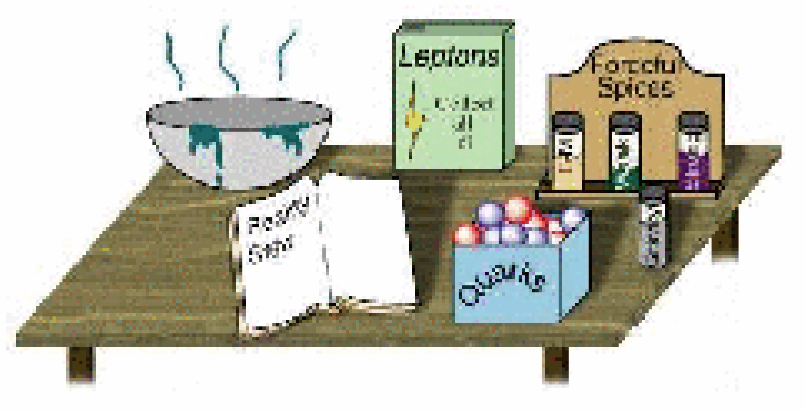
1st IMPRS Block Course

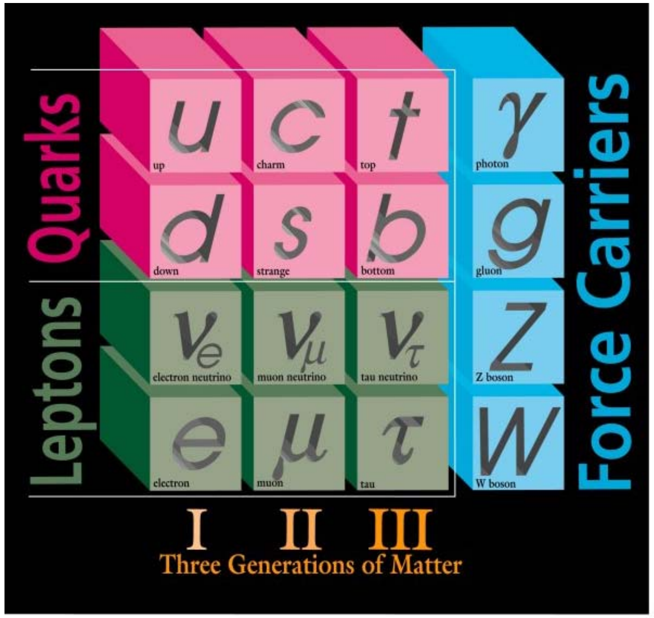
October 19th, 2005

Overview

1. Motivation
2. ILC Project
3. Detector concepts
4. Selected physics topics
    - Higgs
    - SUSY (only touching)
    - Large extra dimensions
    - Precision Measurements
        - Strong EW Symmetry Breaking
        - New Gauge Bosons (Z')
5. Summary (LHC/ILC)

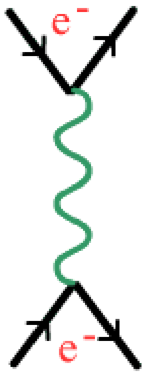
Success of the Standard Model





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

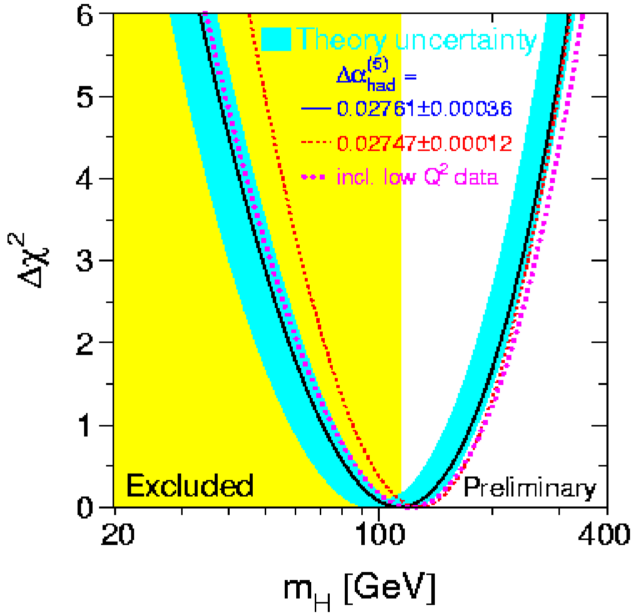


However ......

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…

Open questions

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:

'fine tuning'

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

SuperSymmetry, Extra Dimensions, new forces, or ??

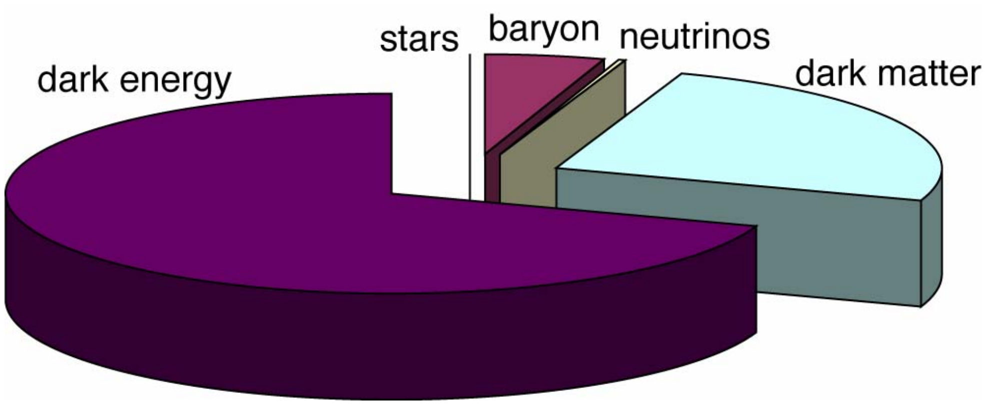
Experimental challenge #2:

Find out what protects the
Higgs mass at the TeV scale

Open questions

3rd 'but':

Our beloved SM contains only a tiny fraction of what's in our universe today!



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?)

Open questions

4th 'but':

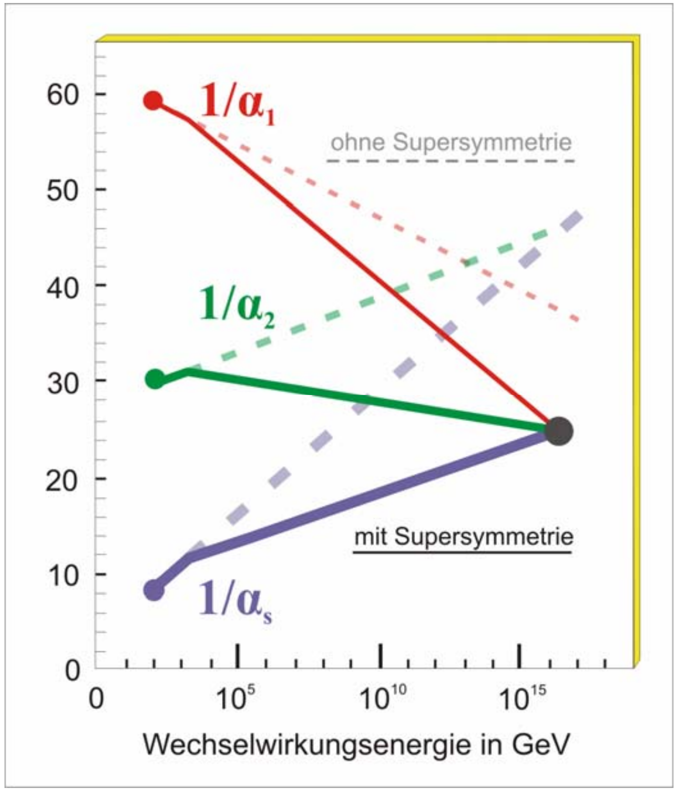
We would probably not be happy with the answers to 'but's 1-3 unless they tell us something about physics at even higher energy scales!

a) unification of forces ?
b) connection between families
(flavour physics, hierarchy problem)

SUSY ? New forces ?

Experimental challenge #4:

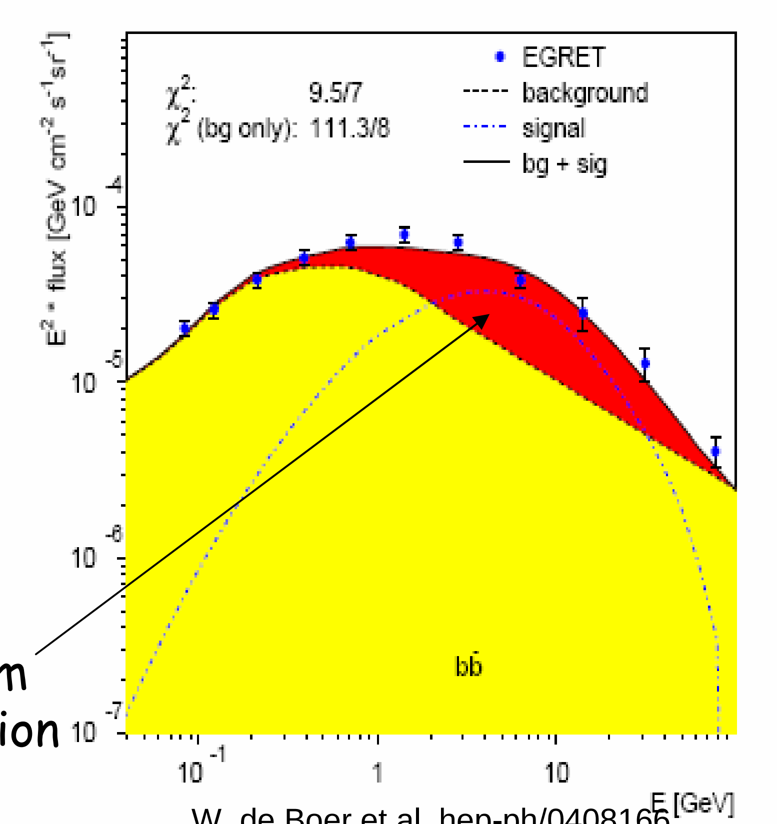
If Nature is kind to give a line of sight to high-scale physics use a precision telescope to look at it



Terascale Physics

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. Evidence for light Higgs
3. $2 * M_{top} = 350$ GeV
4. Dark Matter consistent with
   (sub) TeV-scale WIMP (e.g. SUSY-LSP)
5. Diffuse x-ray spectra (from EGRET)
   consistent with 50-100 GeV WIMP



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

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

Why an e^+e^- Collider ?

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

Why an electron positron collider then?

- Easier to reach high energies
- p = composite particle:
  unknown √s of IS partons,
  no polarization of IS partons,
  parasitic collisions
- p = strongly interacting:
  huge SM backgrounds,
  highly selective trigger needed,
  radiation hard detectors needed

- Difficult to reach high energies (synchrotron radiation)
- e = pointlike particle:
  known and tunable √s of IS particles,
  polarization of IS particles possible,
  kinematic contraints can be used
- e = electroweakly interacting
  low SM backgrounds,
  no trigger needed,
  detector design driven by precision

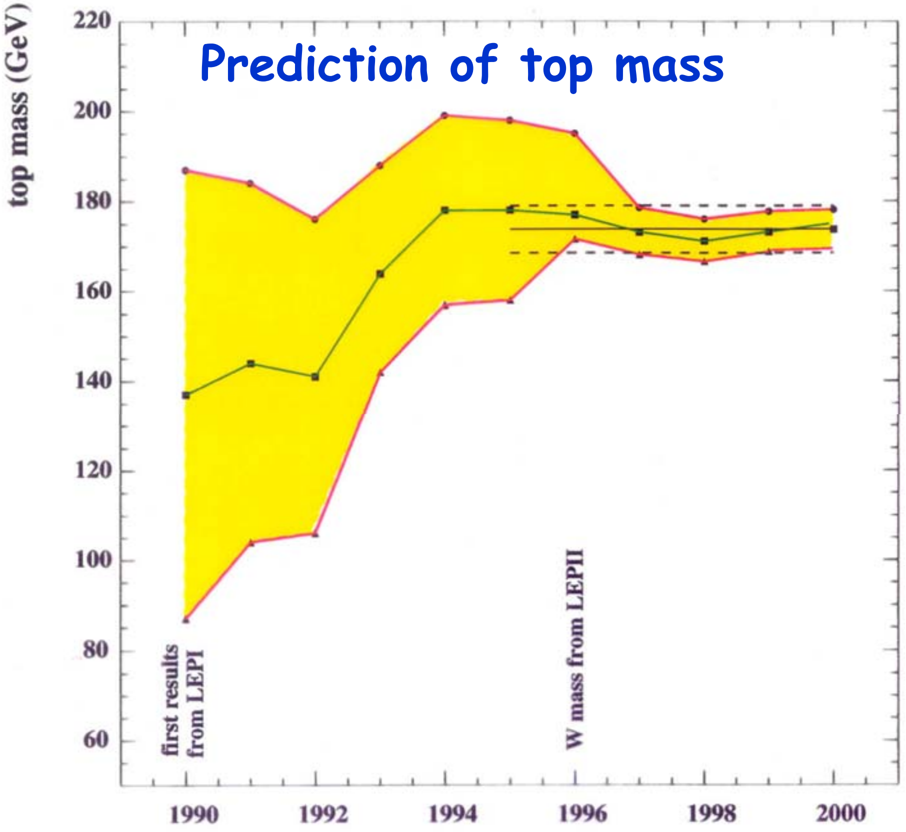
Why an e^+e^- Collider ?

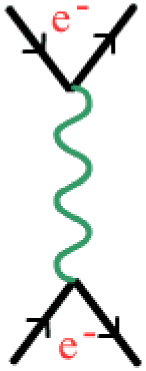
Electron positron colliders allow for

1. Discovery of the unexpected $e^+e^- \to X_{new}(+Y_{SM})$
2. Precision measurements of new + ‘old’ physics

$e^+e^- \to SM$

telescopic





Why an e^+e^- Collider ?

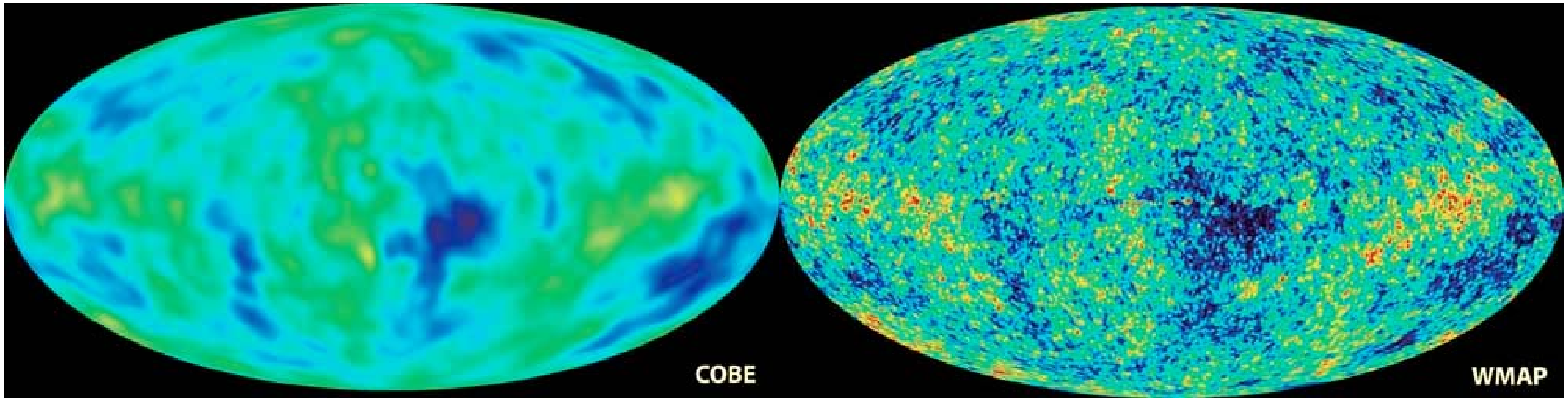
Electron positron colliders allow for

1. Discovery of the unexpected $e^+e^- \to X_{new}(+Y_{SM})$
2. Precision measurements of new + ‘old’ physics

$$e^+e^- \to SM$$

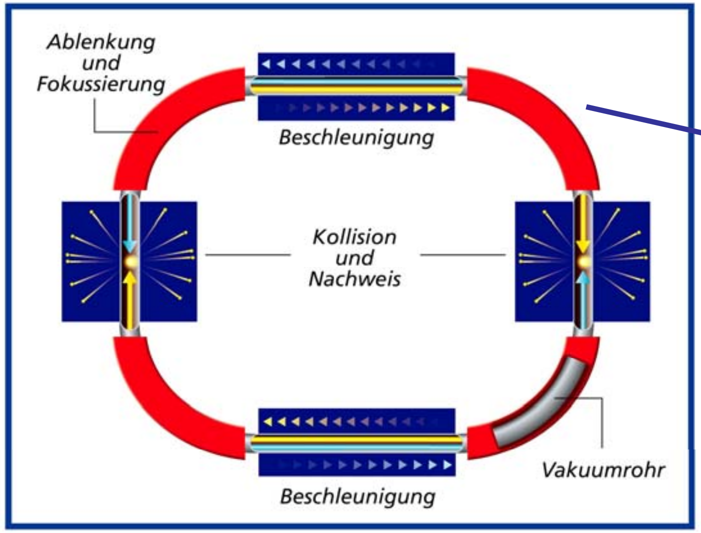
telescopic

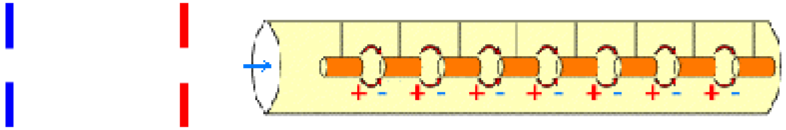
Higher precision can give discoveries:



Why a LINEAR Collider ?

Storage rings:

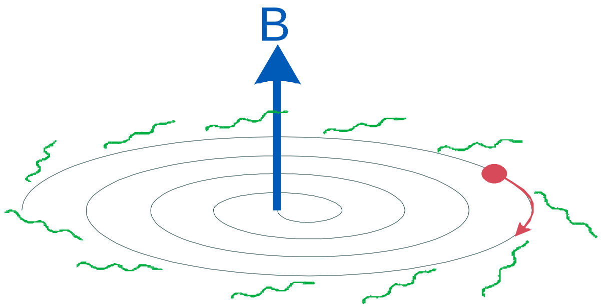




Size and energy determined by

- bending magnet strength
- accelerating gradient

Synchrotron Radiation from
an electron in a magnetic field:



Energy loss per turn of a machine
with an average bending radius ρ :

$$\Delta E \propto 1/\rho \, (E/m)^4$$

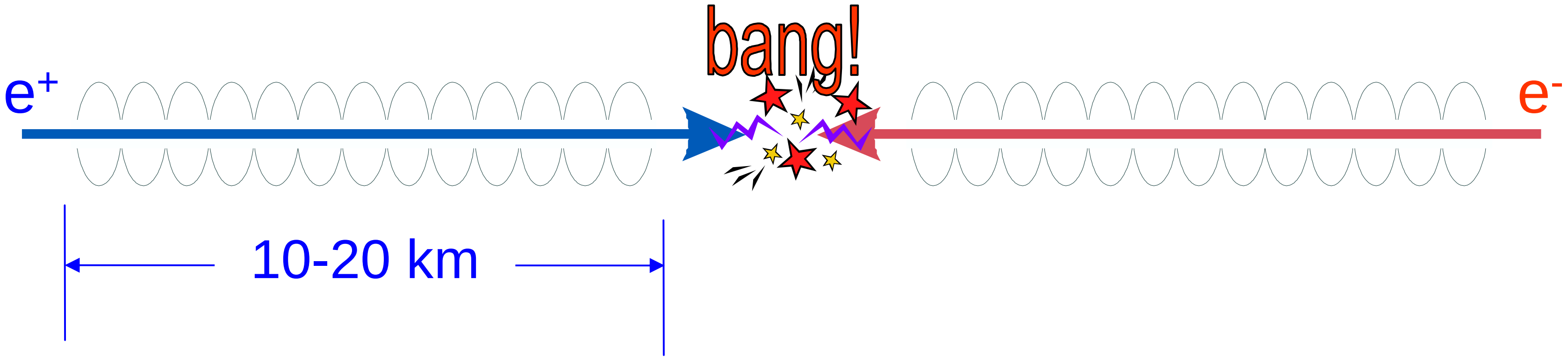
($\Delta E = 8.85 \times 10^{-5}\ E^4/\rho$ MeV per turn
for electrons, *E in GeV, ρ in km*)

Energy loss must be
replaced by the RF system

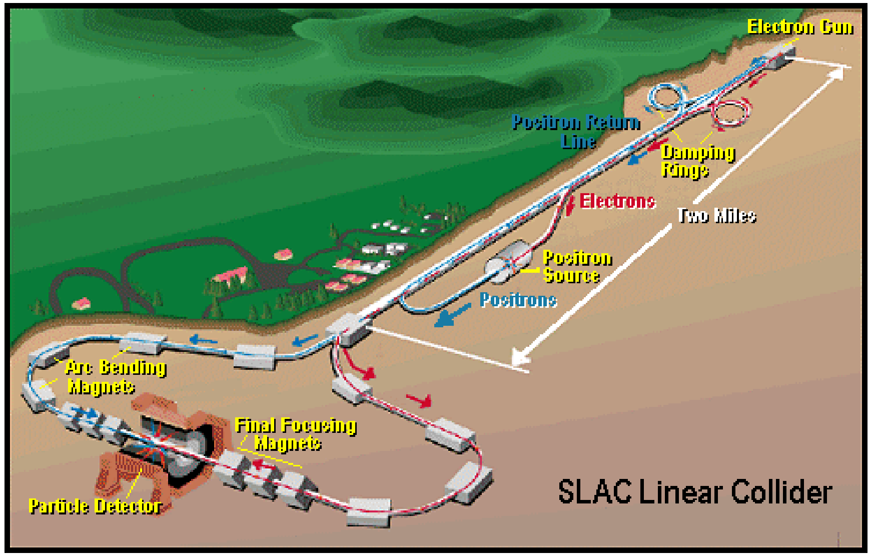
e^+e^- storage rings beyond LEP-II ??

		LEP-II	**Super-LEP**	**Hyper-LEP**
E_{cm}	GeV	200	500	2000
L	km	27	200	3200
ΔE	GeV	1.5	12	240
$\$_{tot}$	10^9 SF	2	15	240

Linear Collider



- long *linac* constructed of many RF accelerating structures
- typical gradients range from 25–60 MV/m
- single shot
- One working machine
  SLC at SLAC
  ← proof of principle



The International Linear Collider

Strong consensus in the HEP community that the next machine after the LHC should be a linear e^+e^- collider in the energy range 500-1000 GeV.

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

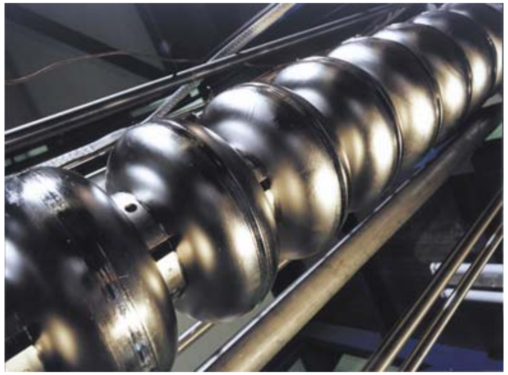
Baseline	$\sqrt{s} = 200\text{-}500$ GeV, integrated Luminosity 500 fb^{-1} in 4 years electron polarisation ~ 80%
Upgrade	Anticipate $\sqrt{s} \to 1$ TeV, $\int L = 1\ ab^{-1}$ in 3 years
Options	positron polarisation ~ 50% high L at Z and at WW threshold (“GigaZ”) e^-e^-, $\gamma\gamma$ and γe collisions

Choice among options to be guided by physics needs.

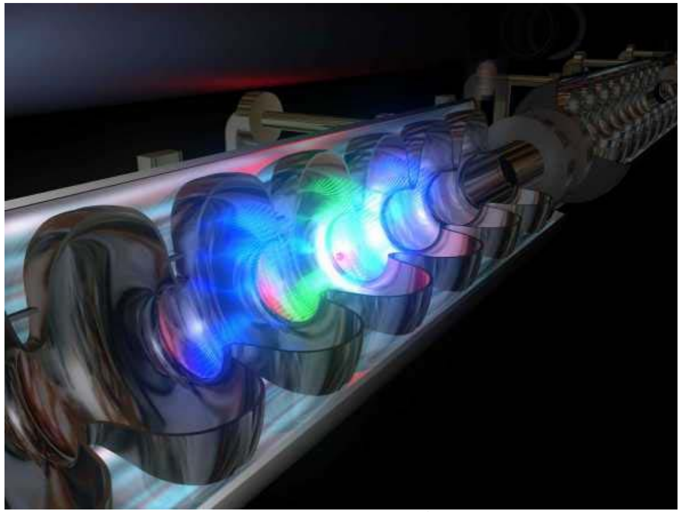
ILC Technology Decision

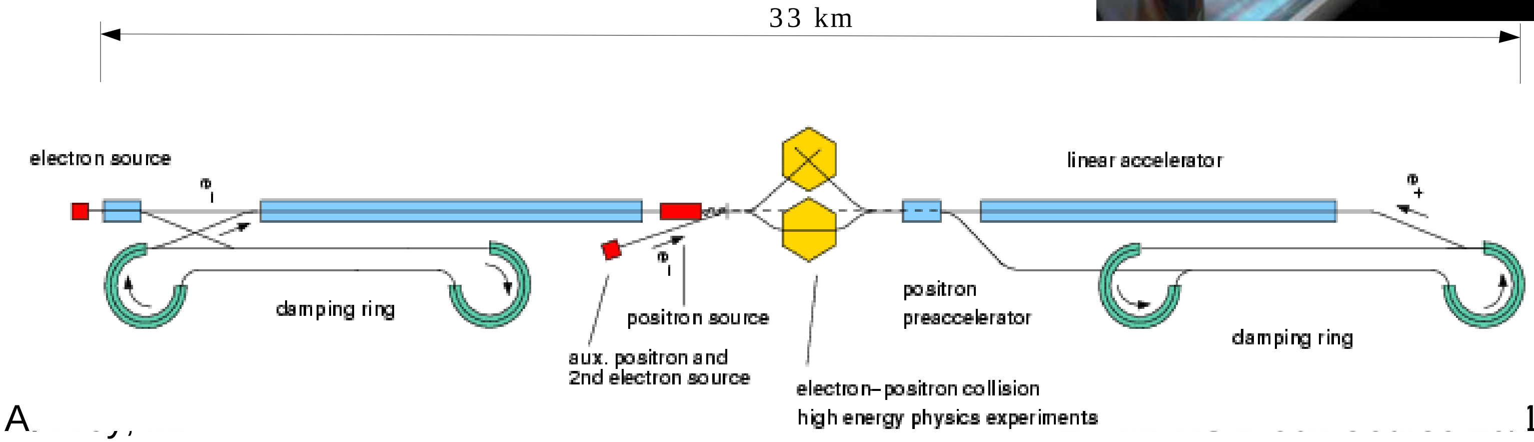
Two competing technologies:
normal conducting vs superconducting accelerating cavities

International Technology Review Panel recommended in August 2004
COLD superconducting technology (à la TESLA)

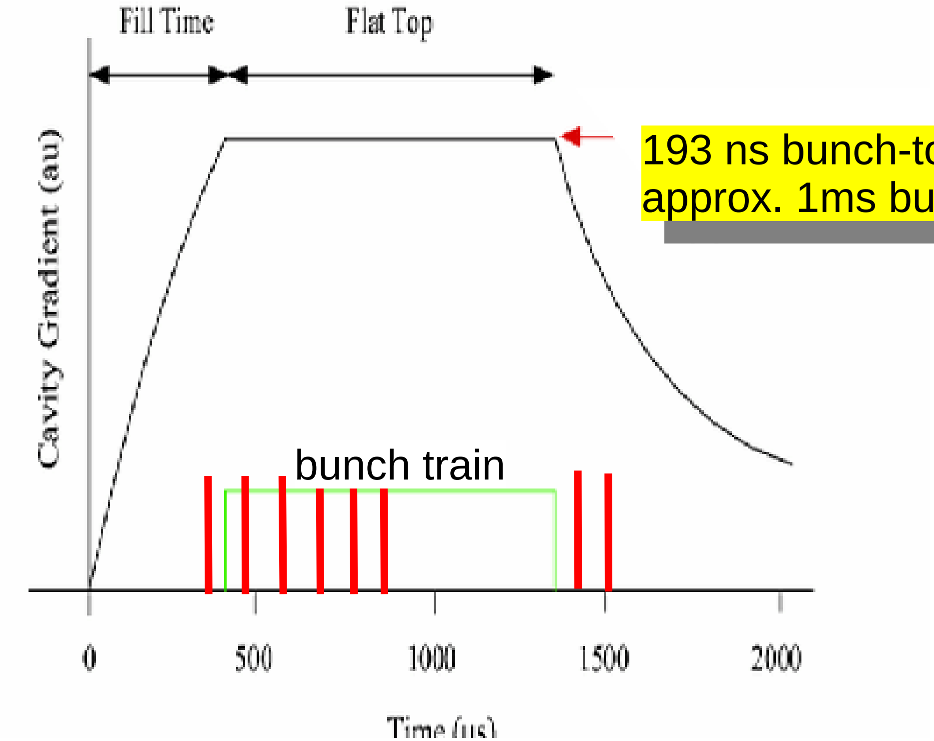


Niobium
resonator





Beam structure



193 ns bunch-to-bunch
approx. 1ms bunch train

Target Luminosity: **few 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$**

$$\sigma \times L = \text{Event rate}$$

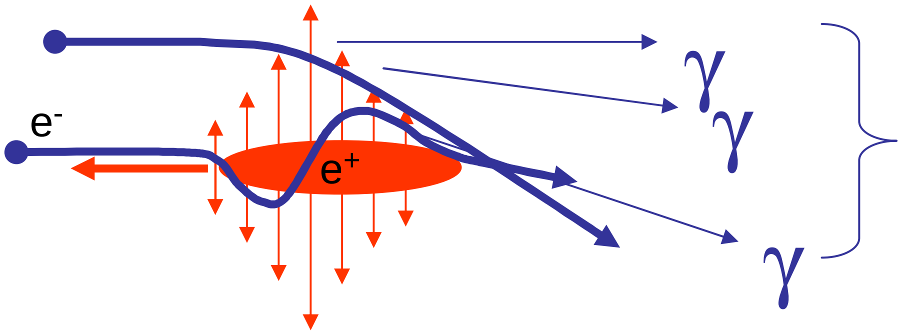
$$L \propto N_1 \cdot N_2 / A$$

$$\sigma_x^* \sigma_y^*$$

Beamstrahlung

This is not LEP (nor SLC)!

- Beamstrahlung

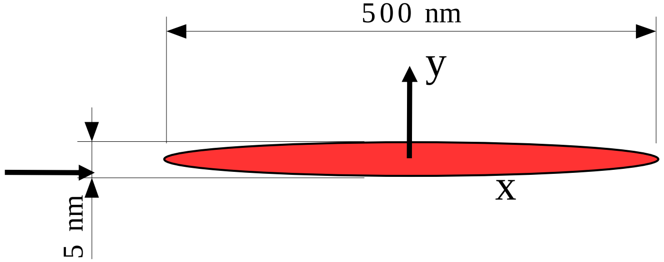


hard γ's radiated by intense electric field = Beamstrahlung

RMS Energy Loss:

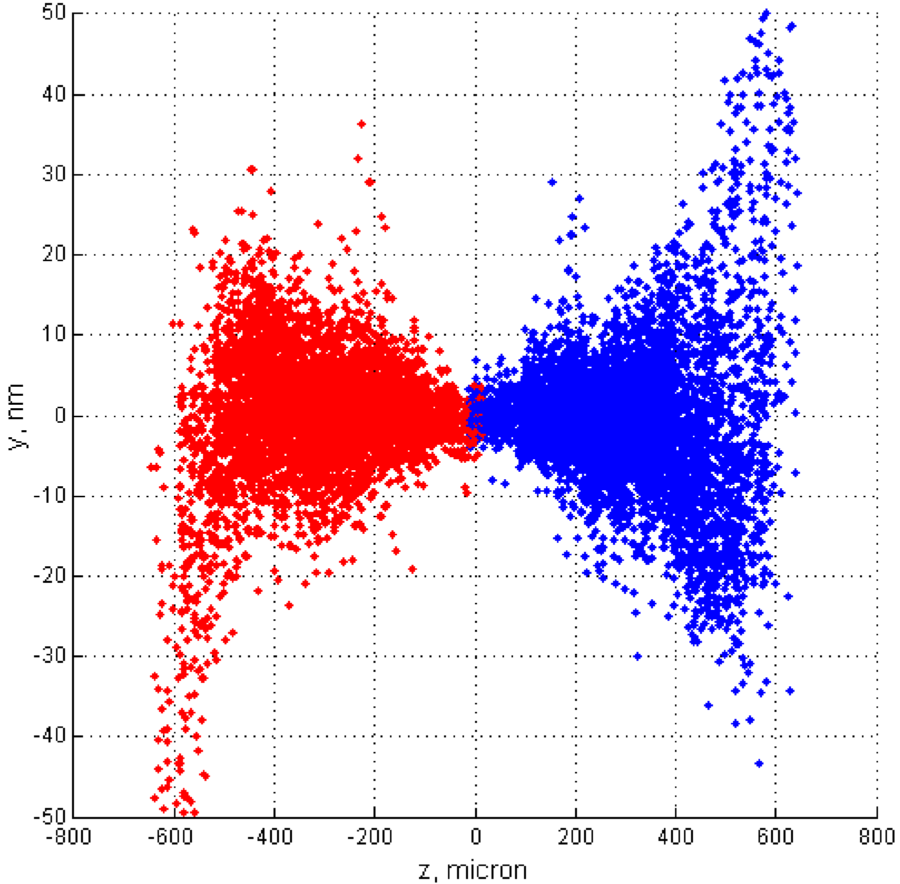
$$\delta_{BS} = \frac{\Delta E}{E} \propto \frac{E_{cm}}{\sigma_z}\left(\frac{N}{\sigma_x^* + \sigma_y^*}\right)^2$$

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



Bunch crossings

Simulation of two LC bunches (NLC) as they meet each other



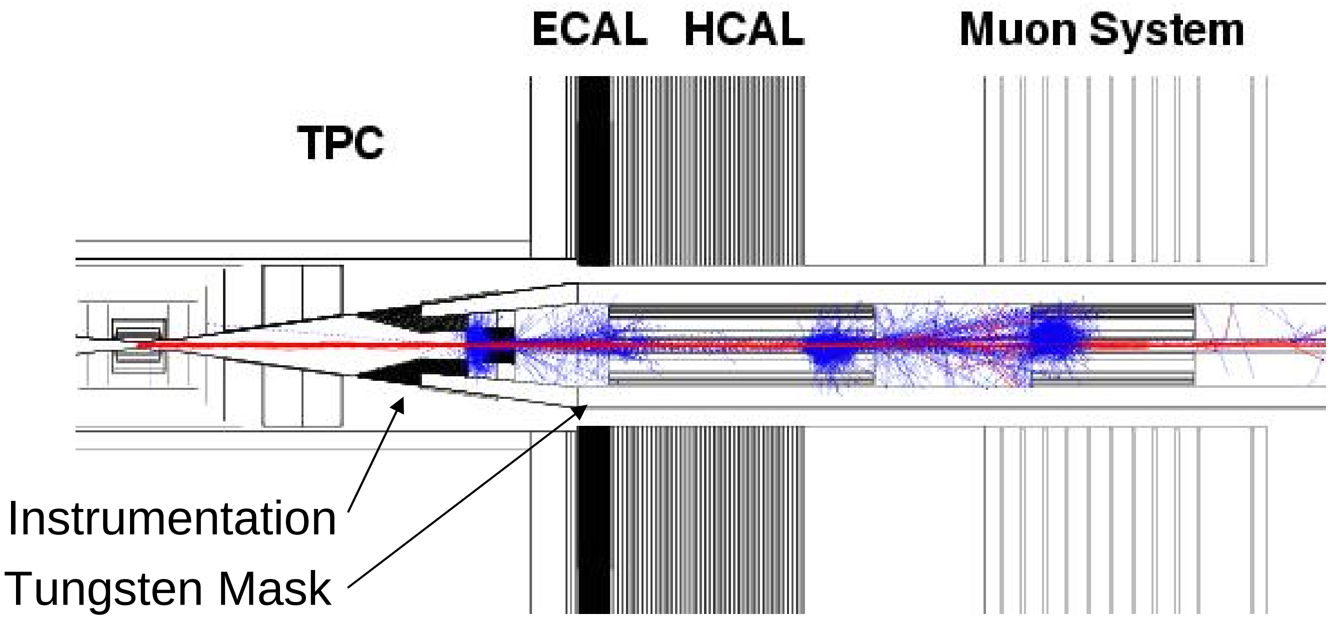
Andrei Sergey, SLAC

Background from Beamstrahlung

Beamstrahlung creates:

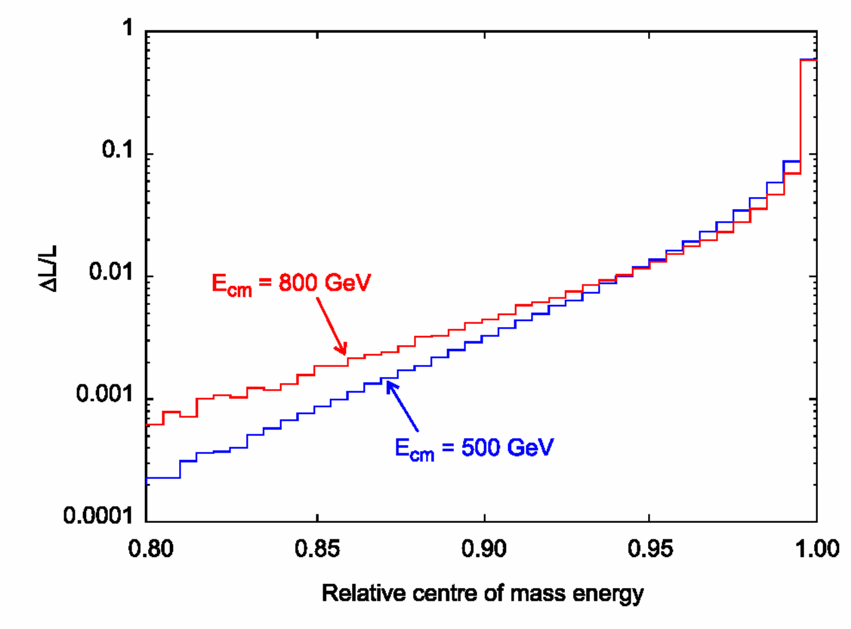
6 x 10^{10} photons/BX (1.3-1.5 photon/electron)
140000 e^+e^- pairs
secondary particles from $\gamma\gamma \rightarrow$ hadrons

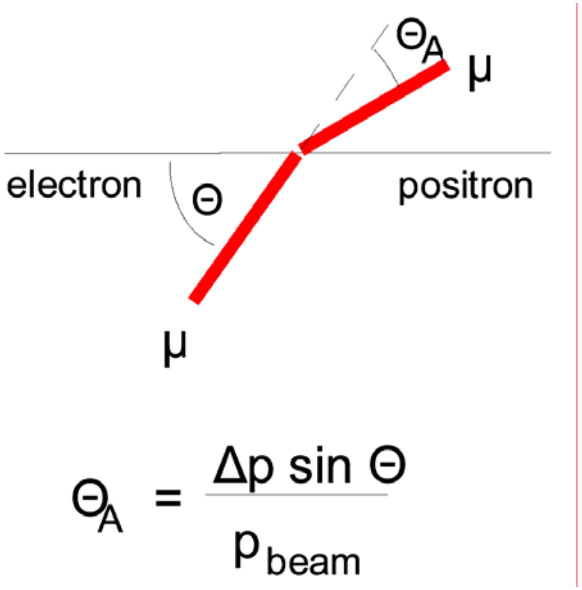
Photons and most of pairs vanish in beampipe but need to shield detector from backscattered secondaries!



Background from Beamstrahlung

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



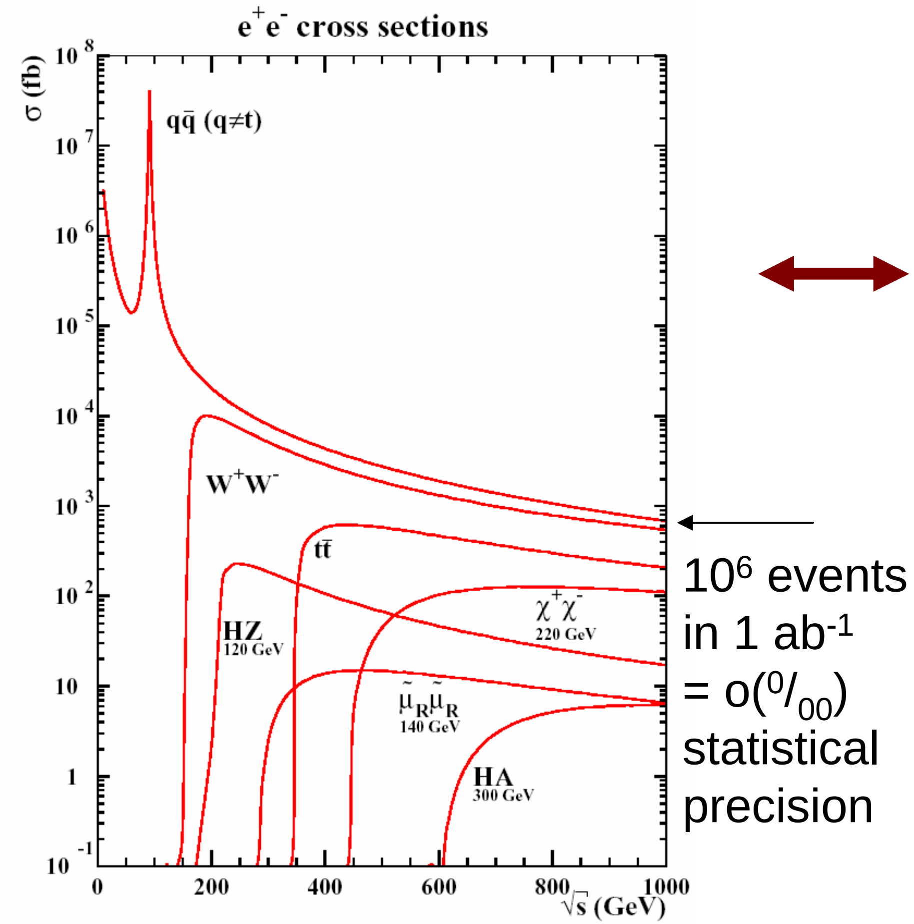


$$\Theta_A = \frac{\Delta p \sin \Theta}{p_{beam}}$$

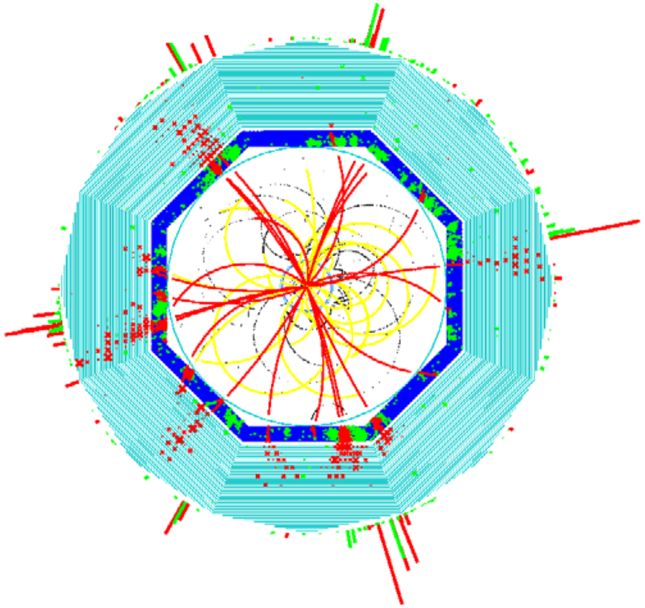
- Effect needs to be taken into account in physics studies
- Spectrum needs to be monitored countinously during data taking
  → use acollinearity of Bhabha-events, μ-pairs

Detectors for the ILC

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

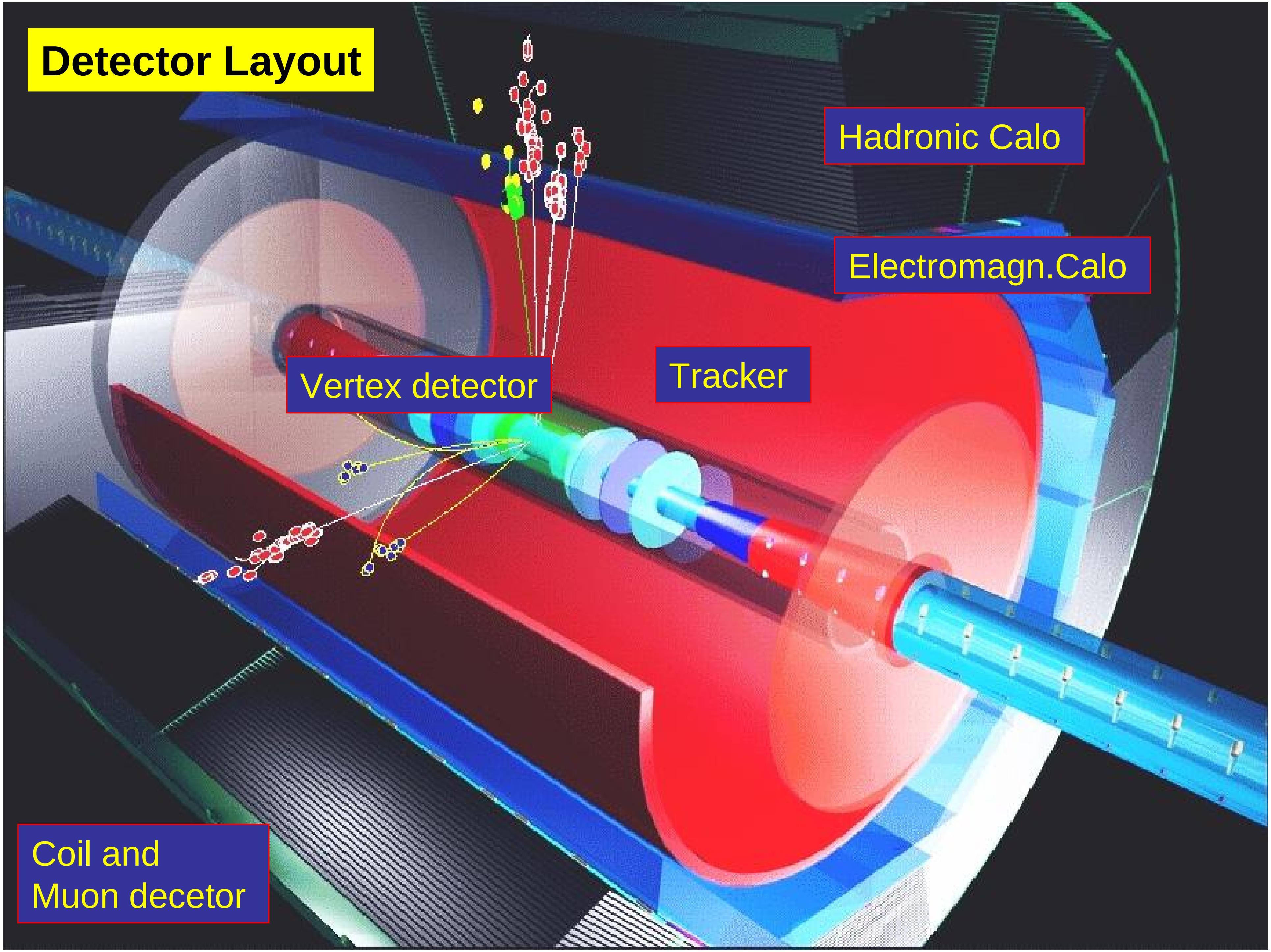


10^6 events in 1 ab^{-1} = o($^0/_{00}$) statistical precision



Challenges:
‘Particle flow’ paradigm
Excellent momentum resolution
Precision vertexing

Detector Layout



Hadronic Calo

Electromagn.Calo

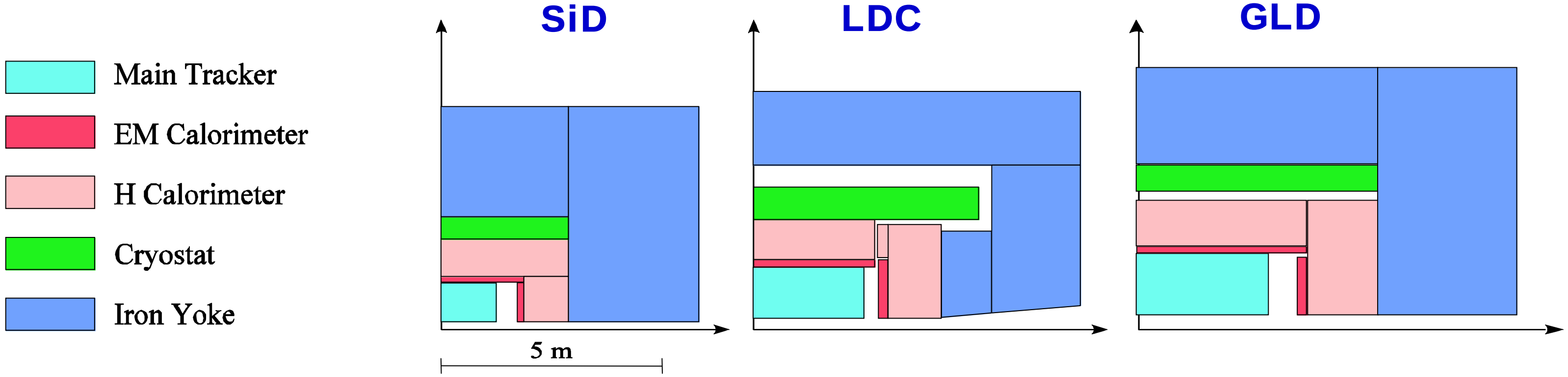
Vertex detector

Tracker

Coil and
Muon decetor

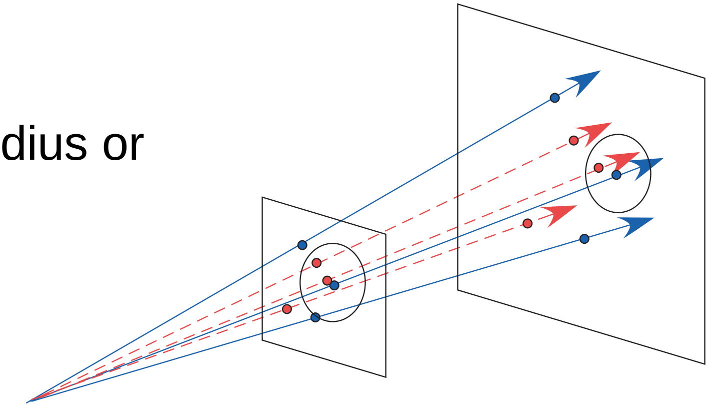
Detector concepts

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:

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

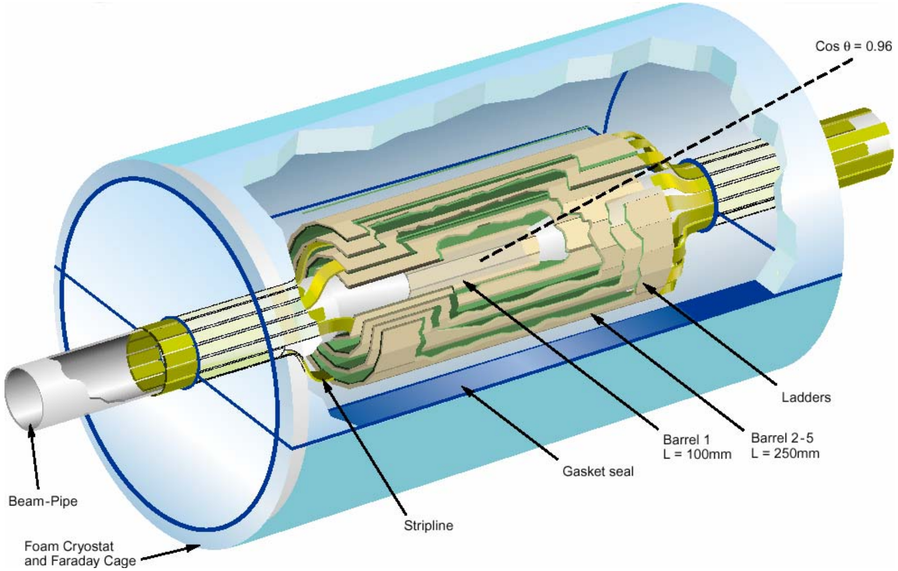
Those are open concepts not collaborations!
Many sub-detector R&D items in common

Vertex Detector

High resolution pixel detector, 5 layers, innermost layer at r=1.5cm

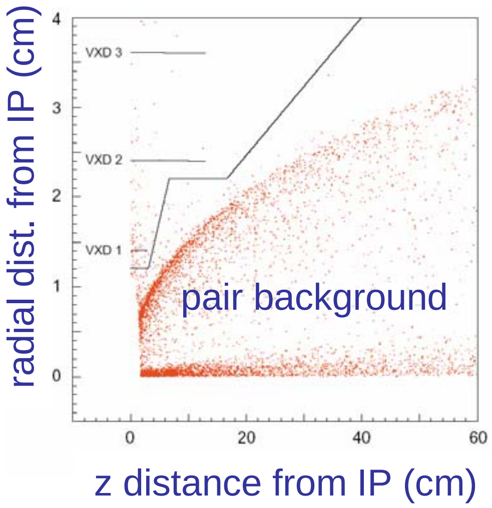
Driving physics:

- 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)

Main tracker

Gaseous tracker (TPC, Jet chamber) or Silicon tracker ??

Driving physics:

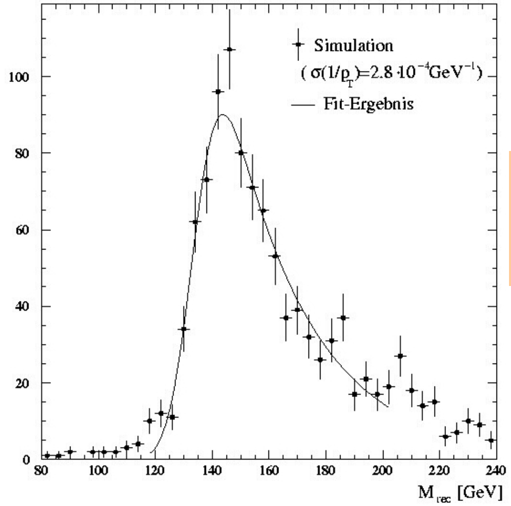
1. Excellent momentum resolution, e.g. for Z→μμ (Higgs recoil mass)

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

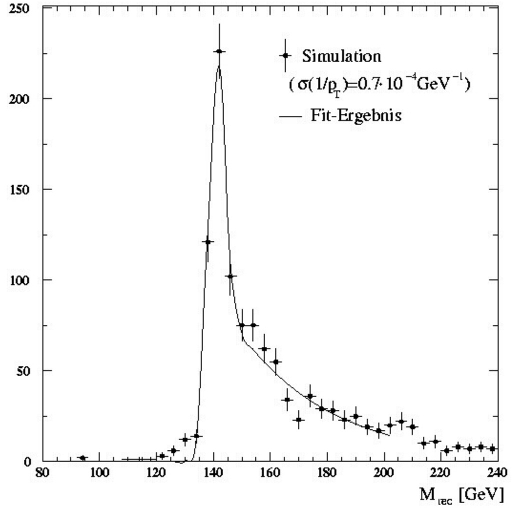
   ➪ $\Delta M(\mu\mu) < 0.1\ \Gamma_Z$
   ➪ ΔM_H dominated by beamstrahlung

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

Z recoil mass



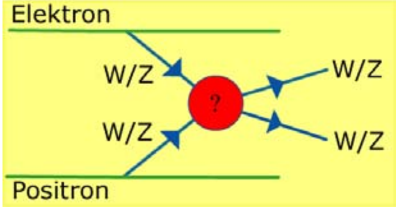
a la LEP



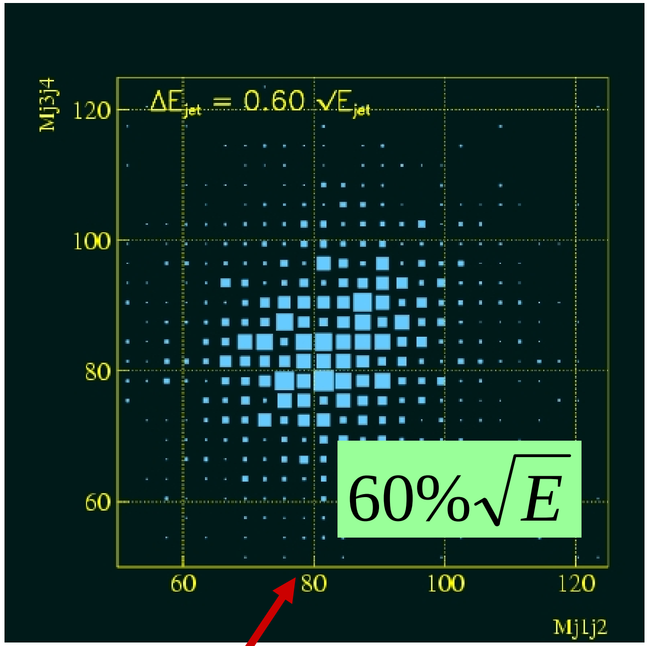
a la ILC

Di-Jet Mass Resolution

Excellent resolution needed to distinguish W and Z in their hadronic decay modes

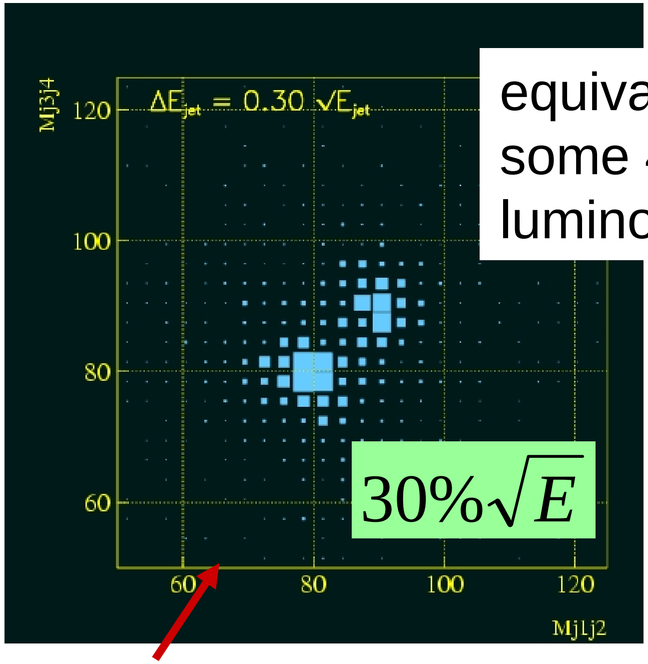


$$e^+e^- \rightarrow WW\nu\bar{\nu} \quad , \; e^+e^- \rightarrow ZZ\nu\bar{\nu}$$



$60\%\sqrt{E}$

LEP-like resolution



$30\%\sqrt{E}$

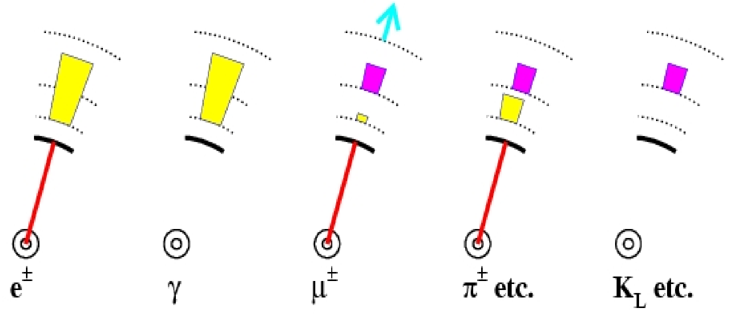
equivalent to some 40% luminosity gain

LC goal

Jet Energy Resolution ⇒ 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%)

$$\boxed{\begin{aligned} E_{\text{jet}} &= E_{\text{charged}} + E_{\text{photons}} + E_{\text{neut. had.}} \\ \sigma^2_{E\text{jet}} &= \sigma^2_{E\text{charged}} + \sigma^2_{E\text{photons}} + \sigma^2_{E\text{neut.had.}} + \sigma^2_{\text{confusion}} \end{aligned}}$$

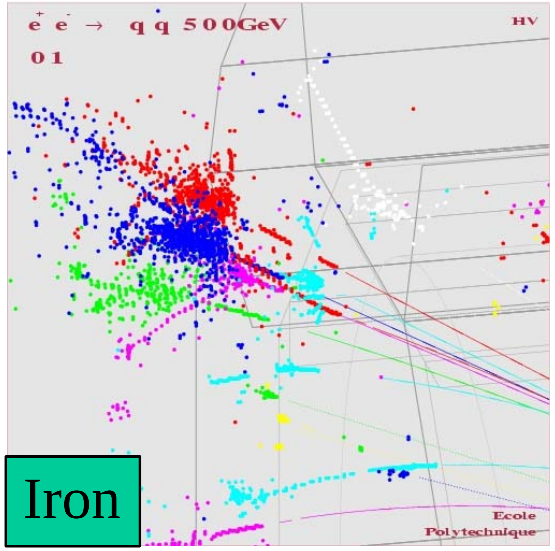
$$\sigma^2_{\text{Ejet}} \approx (0.14)^2 \left(\text{E}_{\text{jet}} \cdot \text{GeV}\right) + \sigma^2_{\text{confusion}} \overset{!}{\approx} (0.3)^2 \left(\text{E}_{\text{jet}} \cdot \text{GeV}\right)$$

↑ largest contribution!

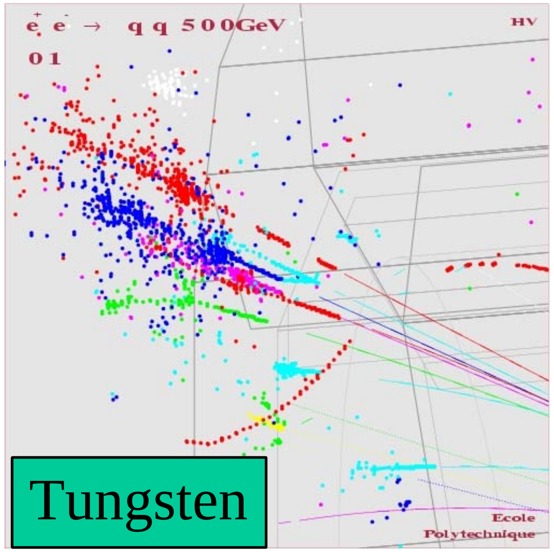
Particle Flow

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



Iron: $X_0/\lambda_I = 1.8\text{cm}/17\text{cm} \sim 0.1$



Tungsten: $X_0/\lambda_I = 0.35\text{cm}/9.6\text{cm} \sim 0.04$

Interim Summary

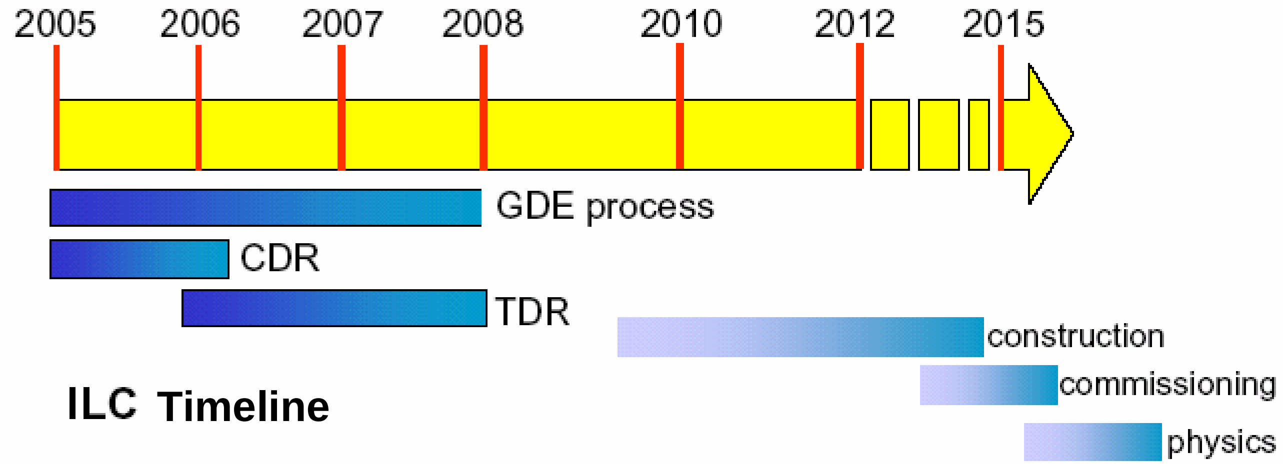
- Standard Model is successful enough to show us that we are not on a completely wrong path.

- Very likely for new phenomena to appear at the TeV energy scale. Those can be studied at high-energy colliders.

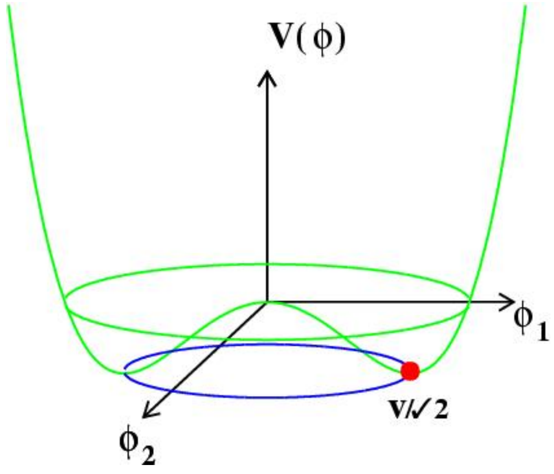
- The TeV linear collider (ILC) will study these new phenomena in more depth than the LHC.

- Experimentation at a Linear Collider is more demanding than at LEP/SLC.

- A high-resolution detector with small systematics is needed to match the statistical precision offered by the high luminosity.



The Physics Case - Higgs

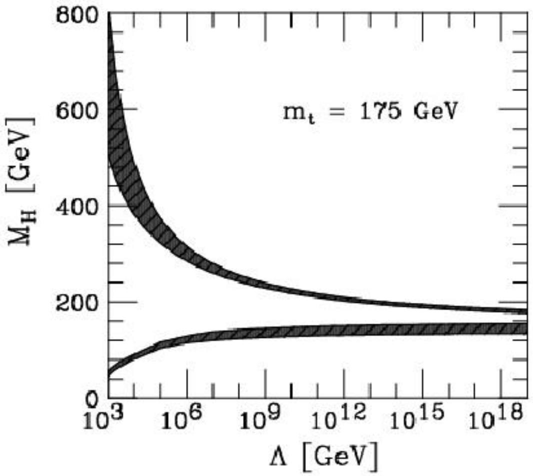


“Mexican hat-Potential”

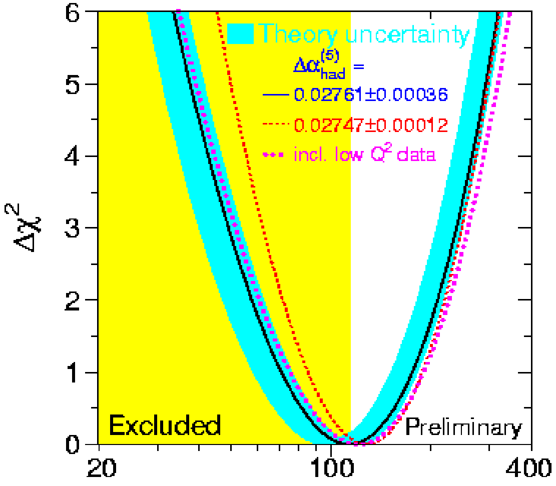
$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

most simple case: Φ =complex doublet of weak isospin (=SM)

but this is a pure guess
many more possibilities, e.g.:
2 doublets (minimal SUSY), triplets,...



The Higgs boson is probably “light”!



Theory:

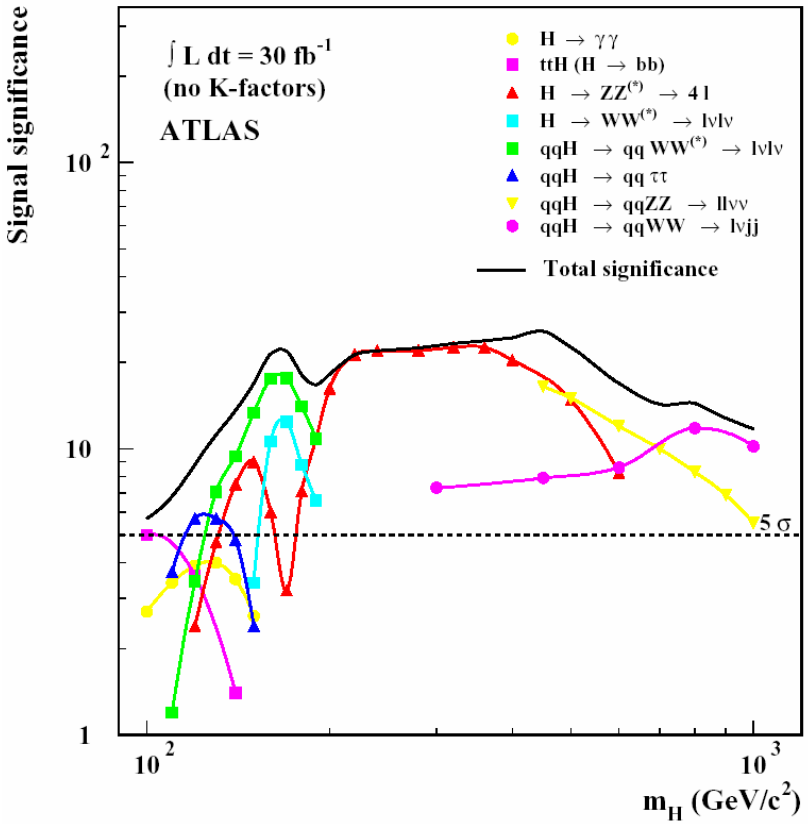
Upper bound: perturbativity ($\lambda<1$)
Lower bound: vacuum stability
Models: minimal SUSY: m<135 GeV
GUT’s : m<180 GeV

Experiment:

Precision measurements
(LEP, SLC, TeVatron)

m<250 GeV (95% CL) within SM

Higgs discovery at LHC



SM-like Higgs discovery
with 30 fb^{-1} in one experiment
guaranteed

Light Higgs most challenging
Fusion channels help a lot

Unusual decay modes
(invisible, purely hadronic)
more complicated

First measurements of Higgs properties possible:

- Mass: 0.1 – 0.4%
- Production rates: 10-20%
- Ratios of couplings: W/Z, W/t, W/t: 10-20%
- model-independent measurements of absolute couplings impossible

Higgs - Task of a Linear Collider

After the discovery of a Higgs boson, the key task of ILC is to
establish the Higgs mechanism in all elements
as being responsible for EW symmetry breaking

Precision Measurements must comprise:

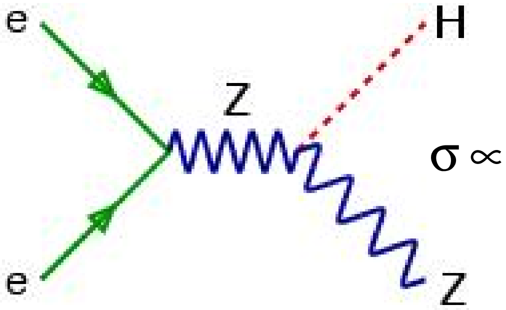
- Mass
- Total Width
- Quantum numbers J^{PC} (Spin 0, CP-even?)
- Higgs-Fermion couplings (~ mass ?)
- Higgs-Gauge-Boson couplings (W/Z masses)
- Higgs self coupling (spontaneous symmetry breaking)

Measurements should be precise enough to distinguish between different models (e.g. SM/MSSM, effects from extra-dimensions, …)

Aim at model-independence!

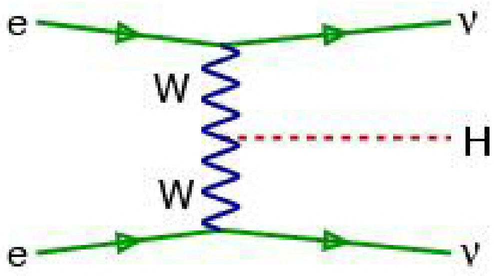
Higgs Production

Dominant production processes at LC:



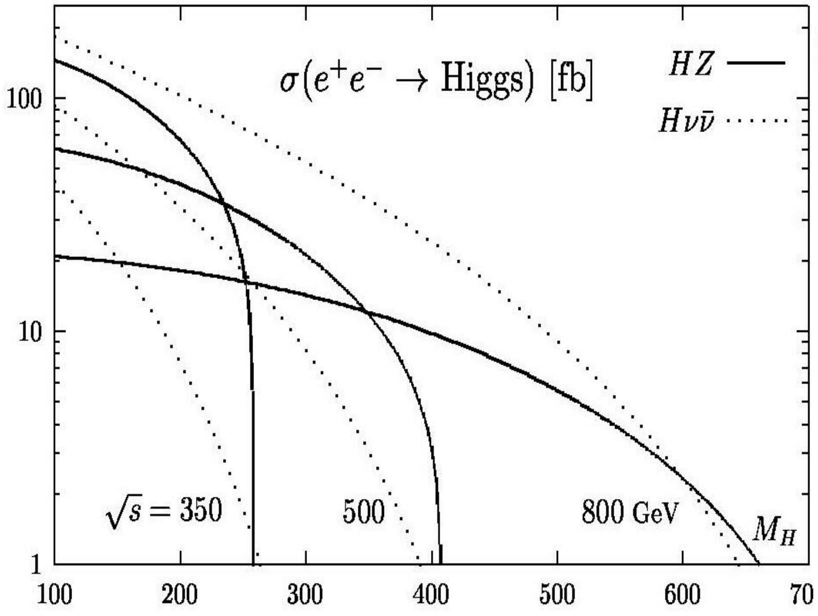
$\sigma \propto \sim 1/s$

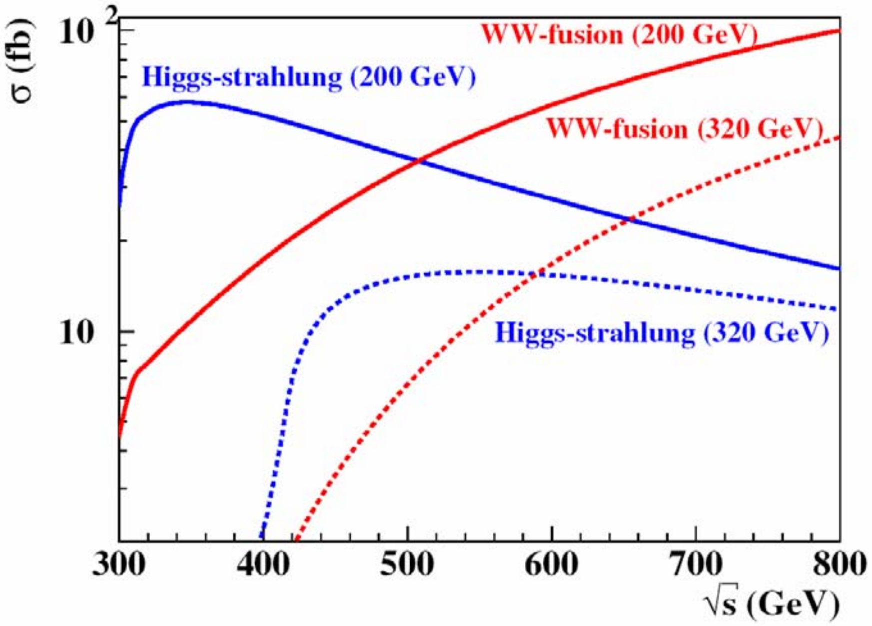
Higgs-strahlung

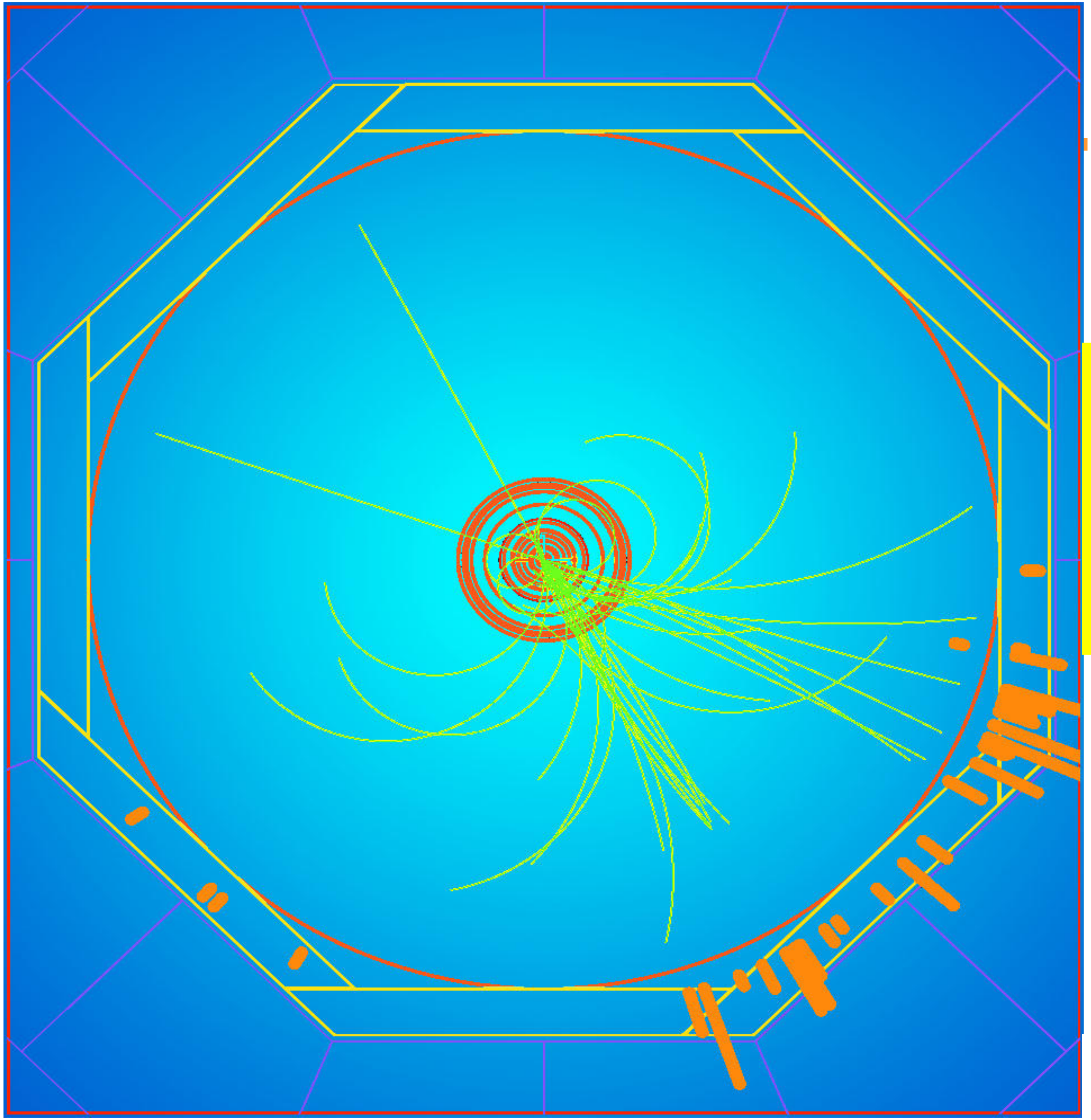


$\sigma \propto \sim \ln s$

WW fusion

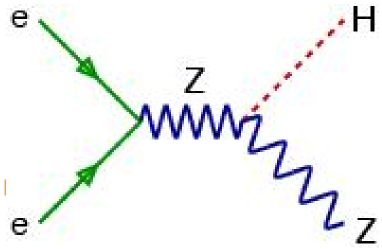






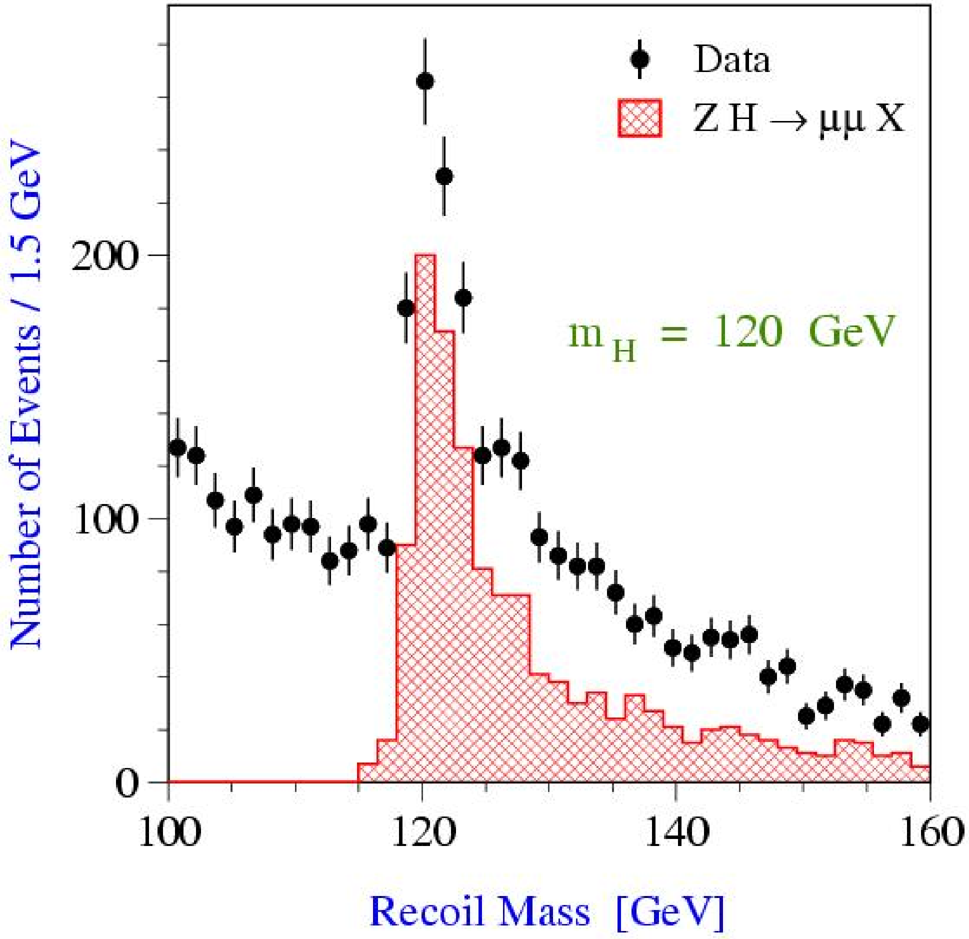
Higgs-strahlung

ee -> HZ
Z -> l l
H -> qq

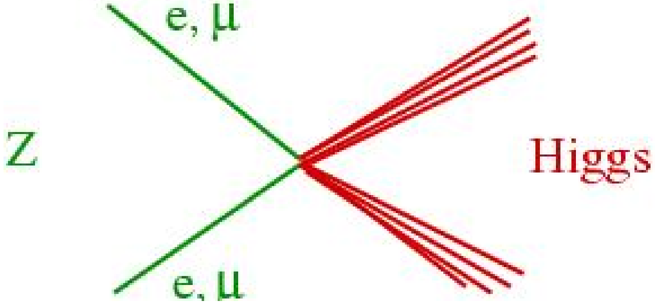


Model-independent observation

Anchor of LC Higgs physics:



- select di-lepton events consistent with Z→ee/μμ



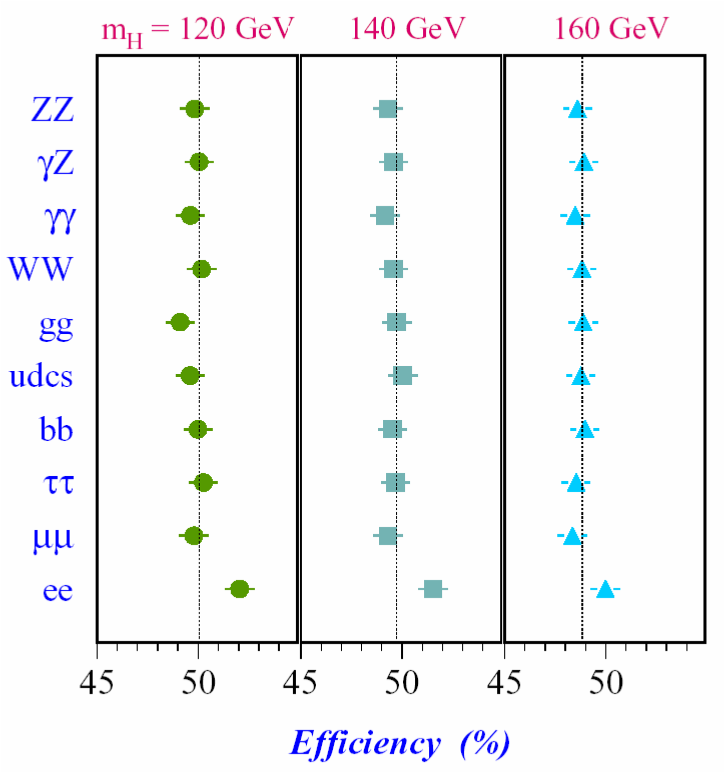
- calculate recoil mass:

$$m_H^2 = (p_{\ell\ell} - p_{\text{initial}})^2$$

model independent,
decay-mode independent
measurement!

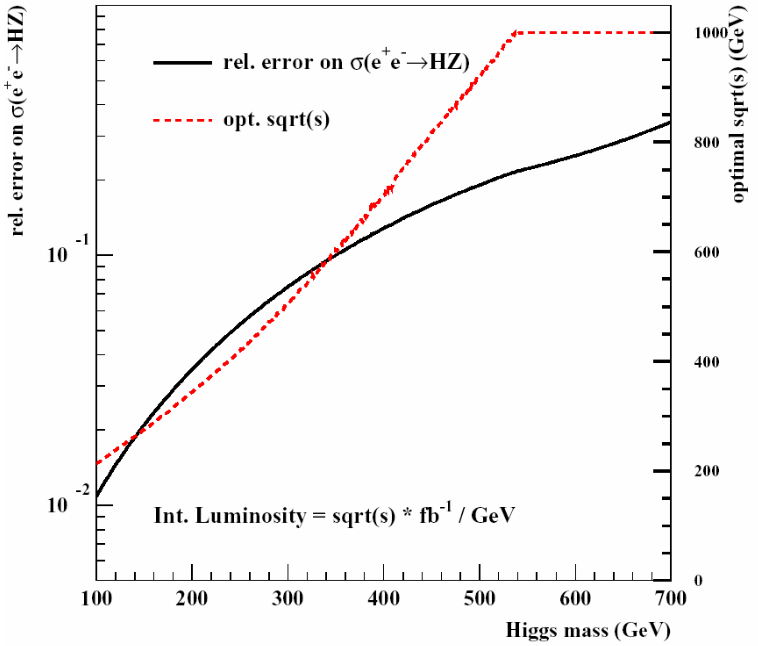
Model-independent observation

efficiency is ~independent of decay mode:



small differences can be corrected with MC

works over the whole range of possible Higgs masses:

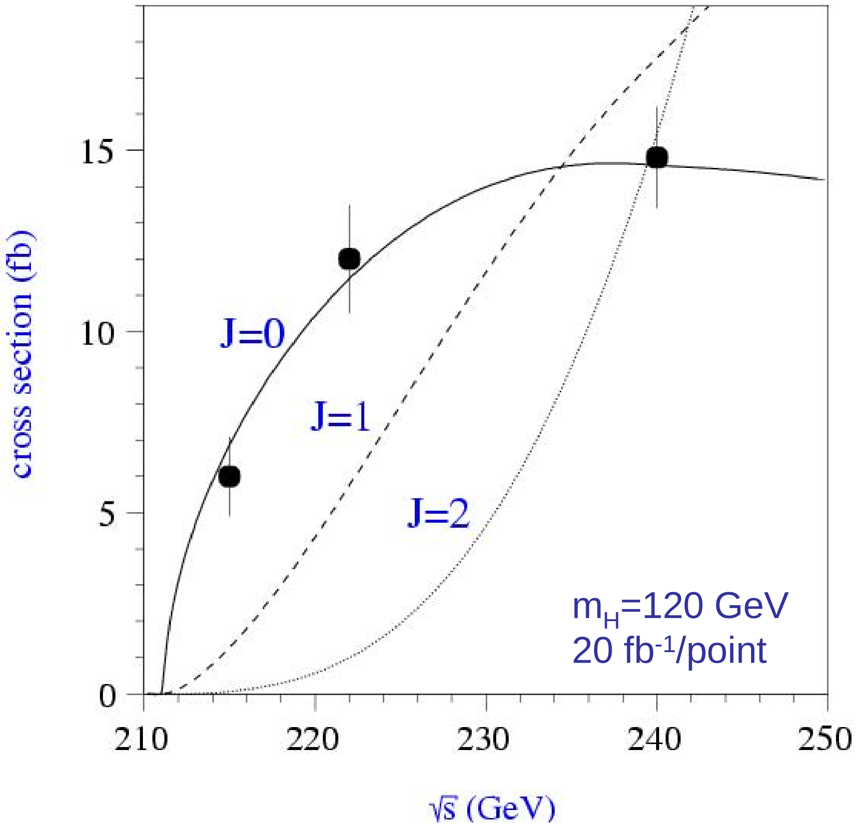


precision on σ(HZ):
1-3% for m_H<200 GeV
3-20% for m_H<500 GeV

Higgs Quantum Numbers

Is it a Higgs boson ?

Rise of cross section near threshold is sensitive to Higgs Spin



for J=0: rise ~ β

for J>0: rise ~ β^k ,k>1

(some cases for J=2 are also ~β but can be distinguished from J=0 through angular distributions)

also:

observation of $H \rightarrow \gamma\gamma$ or $\gamma\gamma \rightarrow H$ rule out J=1 and require C = +

Measurement of the Higgs Mass

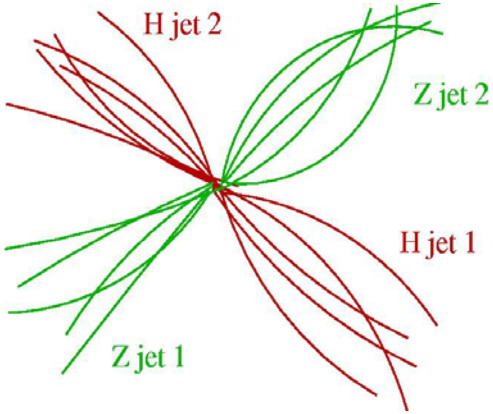
Model-independent HZ analysis only uses a fraction of the events ($Z \to ll$)

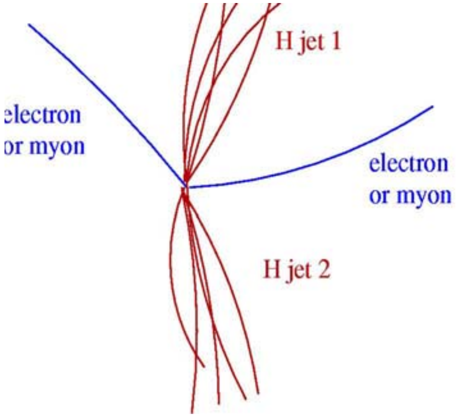
For a precise mass determination further statistics can be gained if hadronic Z-decays are used.

For mass measurement, explicit Higgs final states (e.g. $H \to bb$) may be used

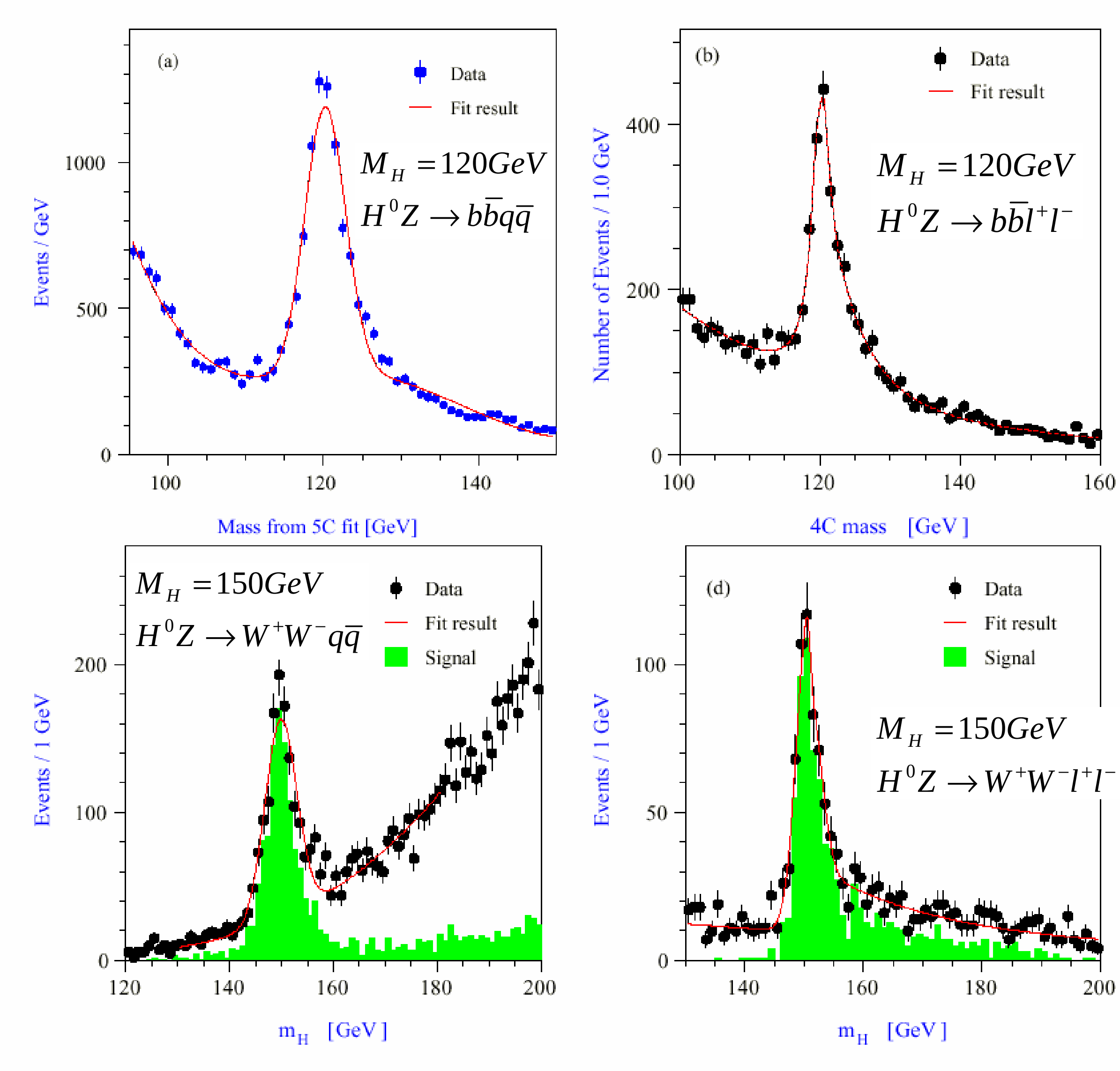
Highest sensitivity to Higgs mass comes from purely hadronic events

Kinematic fits improve the mass resolution





Higgs Mass



M_H (GeV)	Channel	δM_H (MeV)
120	$\ell\ell qq$	± 70
120	$qqbb$	± 50
120	Combined	± 40
150	$\ell\ell$ Recoil	± 90
150	$qqWW$	± 130
150	Combined	± 70
180	$\ell\ell$ Recoil	± 100
180	$qqWW$	± 150
180	Combined	± 80

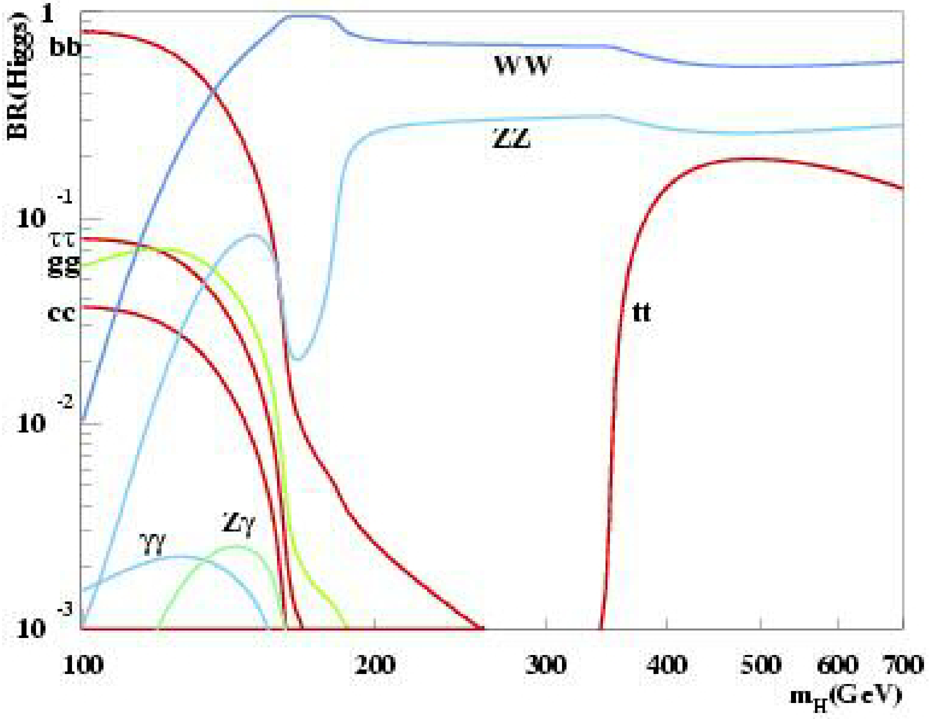
sub-permille precision

500 fb^{-1} @ $\sqrt{s}$ = 350 GeV

Higgs Branching Ratios

Higgs Branching ratios best to study Higgs Yukawa couplings for a light H

Crucial test: $\Gamma(H\rightarrow ff) \sim m_f$?



At ILC measurement of >absolute< BR's is possible, because of decay-mode independent g_{HZZ} measurement:

$$\mathrm{BR}(\mathrm{H}\rightarrow \mathrm{X}) = \frac{[\sigma(\mathrm{HZ})\times\mathrm{BR}(\mathrm{H}\rightarrow \mathrm{X})]^{\mathrm{meas}}}{\sigma(\mathrm{HZ})^{\mathrm{meas}}}$$

Higgs Branching Ratios

Most challenging: disentangle the hadronic Higgs decays

H→bb H→cc H→gg

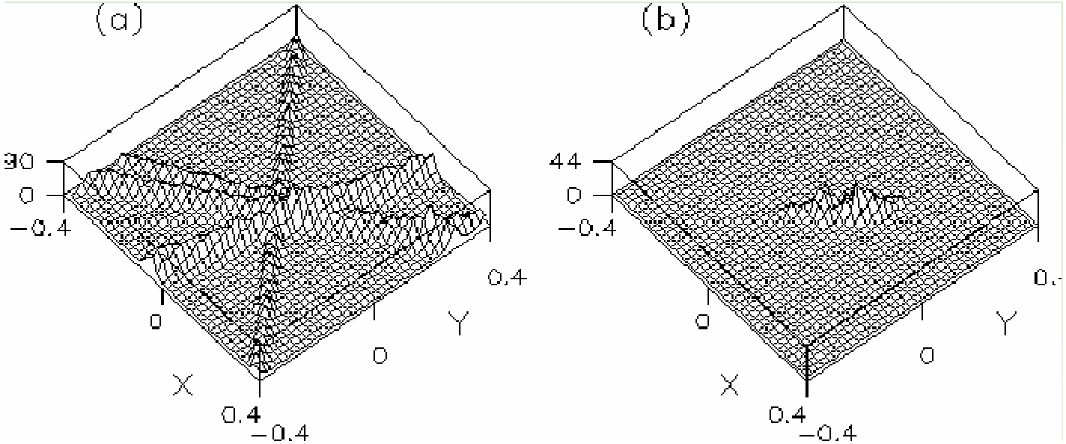
H→bb	68.2%
H→cc	3.0 %
H→gg	6.7 %

for m_H=120 GeV

Need sophisticated flavour tagging:
Vertex reconstruction using ZVTOP algorithm (SLD)

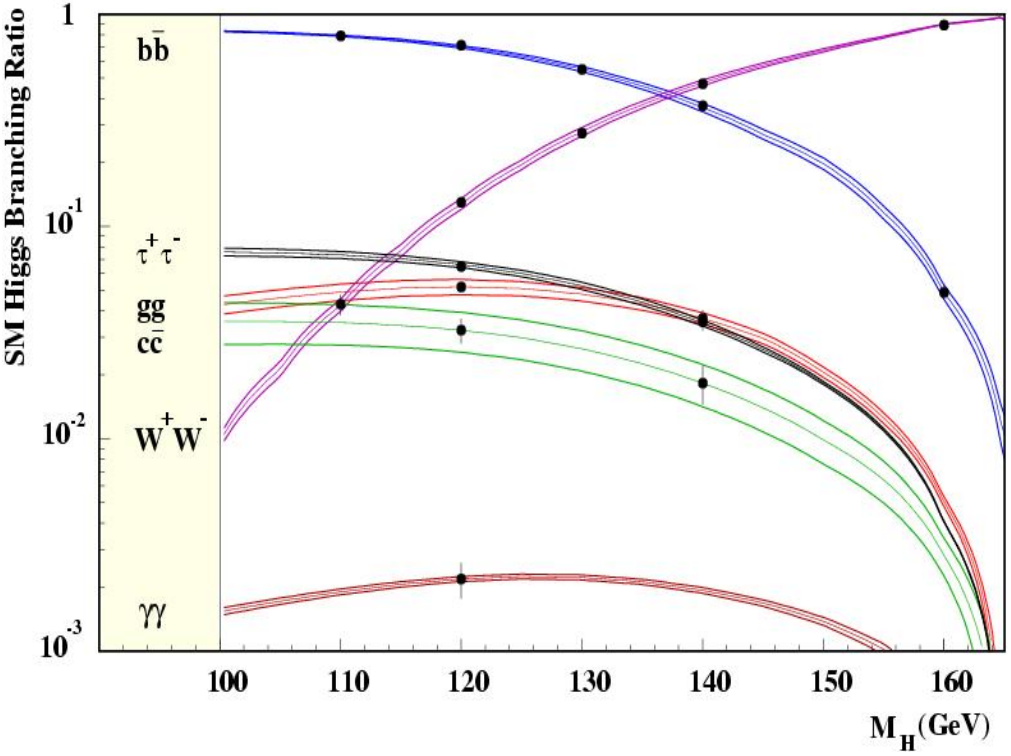
Tracks interpreted as 3D probability tubes

Vertices = overlapping tubes



After vertex reconstruction, use ANN's with vertex+track information to obtain b- and c-likeness for each jet

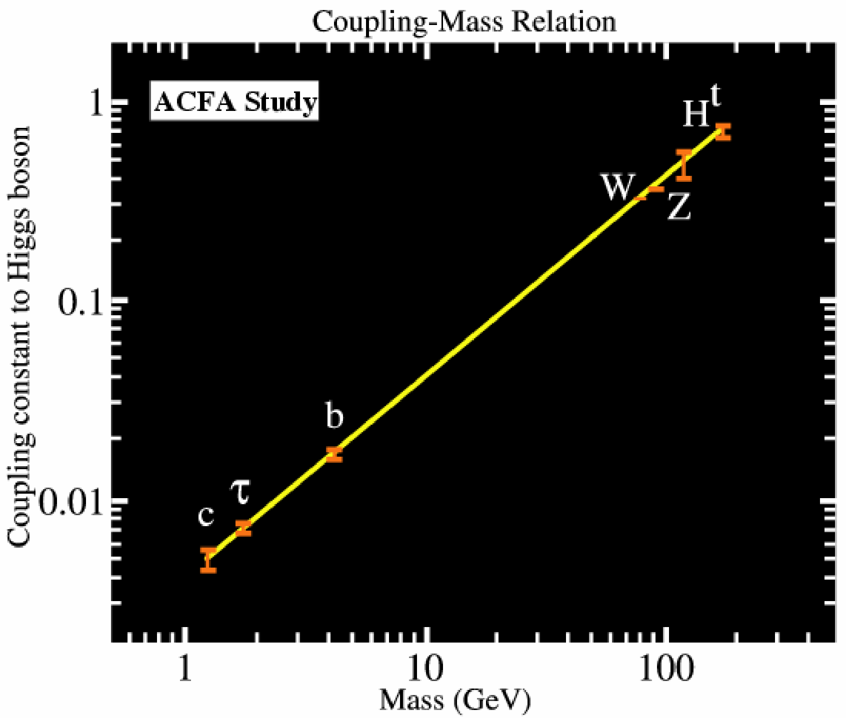
Higgs Branching Ratios



ΔBR/BR

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

For 500 fb-1
MH = 120 GeV



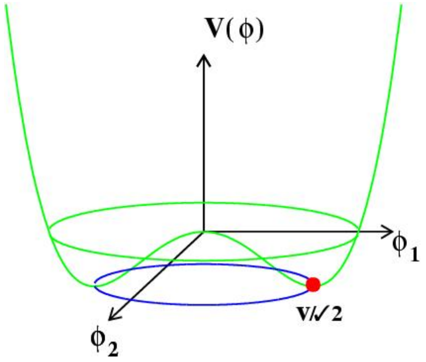
A. Frey, MPI

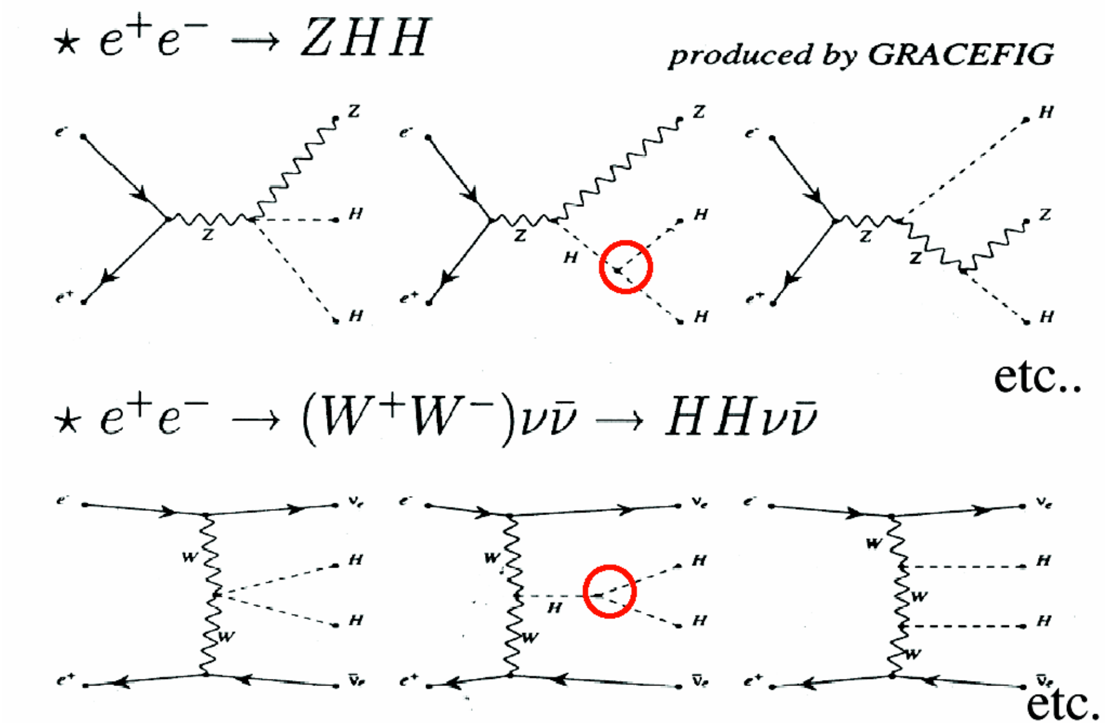
Higgs Self Coupling

Higgs self-coupling (‘the holy grail’):

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

→ essential test of the mechanism of spontaneous symmetry breaking




$\star\ e^+e^- \longrightarrow ZHH$

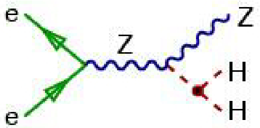
produced by GRACEFIG

etc..

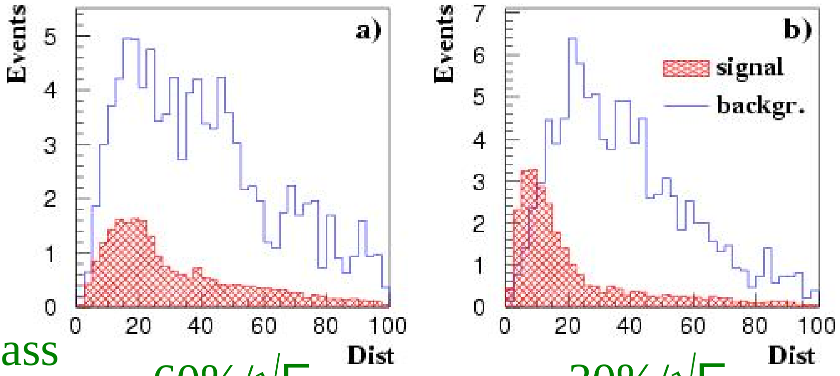
$\star\ e^+e^- \longrightarrow (W^+W^-)\nu\bar{\nu} \longrightarrow HH\nu\bar{\nu}$

etc.

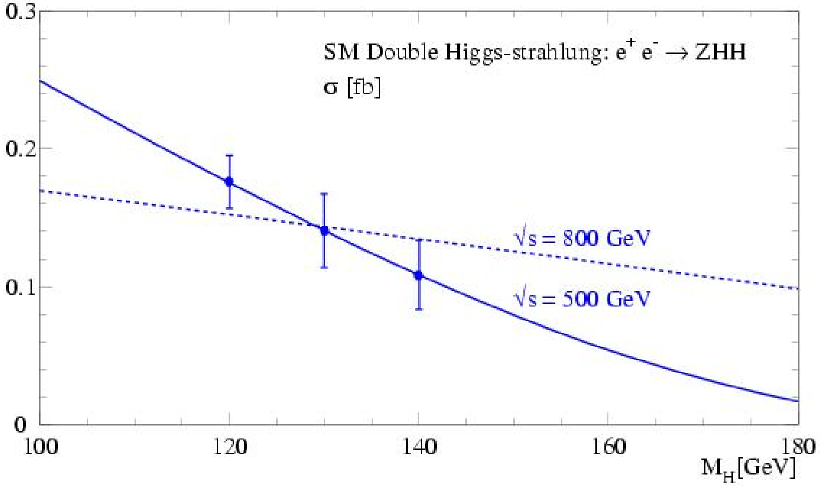
Measurement of Higgs self coupling



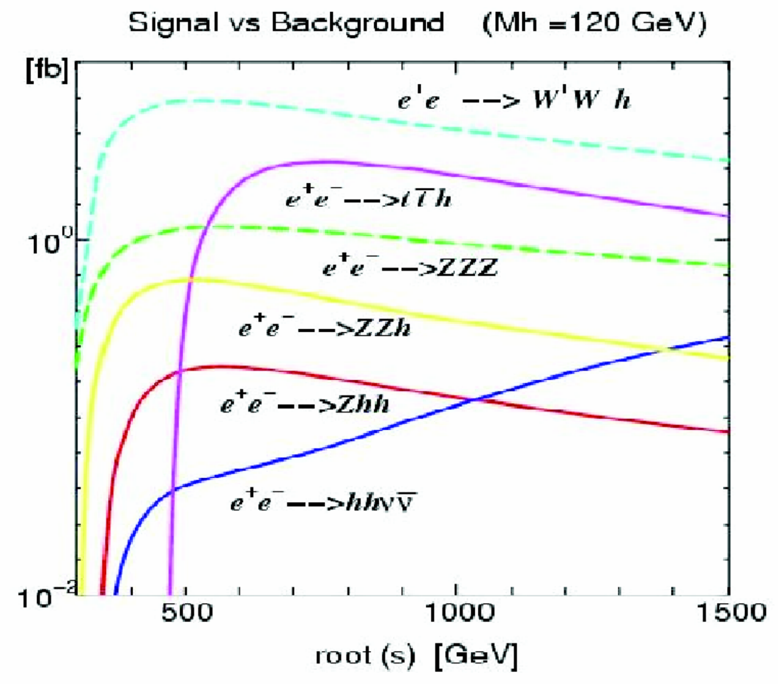
Tiny cross section
Complicated multi-jet final state
→ detector design: energy flow



jet mass resolution: 60%/√E 30%/√E



Difficult backgrounds



Need highest luminosity
Precision for 1 ab^{-1} :

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

A. Frey, MPI

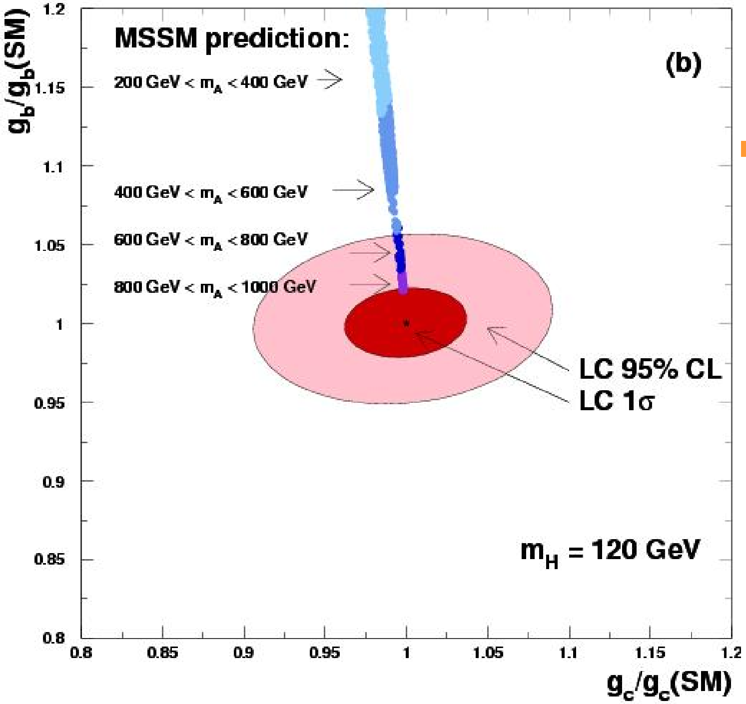
1st IMPRS Block Course 19/10/2005

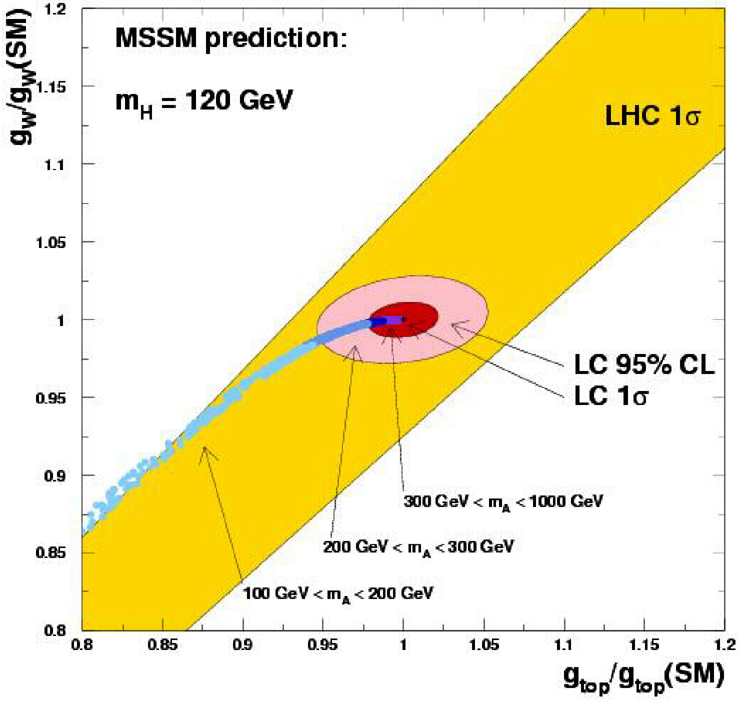
Higgs - Global Fits

Interpretation of branching ratio
and
cross section measurements
in global fits (HFITTER)

Coupling	$M_H = 120\,\mathrm{GeV}$	$140\,\mathrm{GeV}$
g_{HWW}	$\pm\, 0.012$	$\pm\, 0.020$
g_{HZZ}	$\pm\, 0.012$	$\pm\, 0.013$
g_{Htt}	$\pm\, 0.030$	$\pm\, 0.061$
g_{Hbb}	$\pm\, 0.022$	$\pm\, 0.022$
g_{Hcc}	$\pm\, 0.037$	$\pm\, 0.102$
$g_{H\tau\tau}$	$\pm\, 0.033$	$\pm\, 0.048$
g_{HWW}/g_{HZZ}	$\pm\, 0.017$	$\pm\, 0.024$
g_{Htt}/g_{HWW}	$\pm\, 0.029$	$\pm\, 0.052$
g_{Hbb}/g_{HWW}	$\pm\, 0.012$	$\pm\, 0.022$
$g_{H\tau\tau}/g_{HWW}$	$\pm\, 0.033$	$\pm\, 0.041$
g_{Htt}/g_{Hbb}	$\pm\, 0.026$	$\pm\, 0.057$
g_{Hcc}/g_{Hbb}	$\pm\, 0.041$	$\pm\, 0.100$
$g_{H\tau\tau}/g_{Hbb}$	$\pm\, 0.027$	$\pm\, 0.042$

%-level accuracy – sensitivity beyond SM





SUSY Higgs Bosons

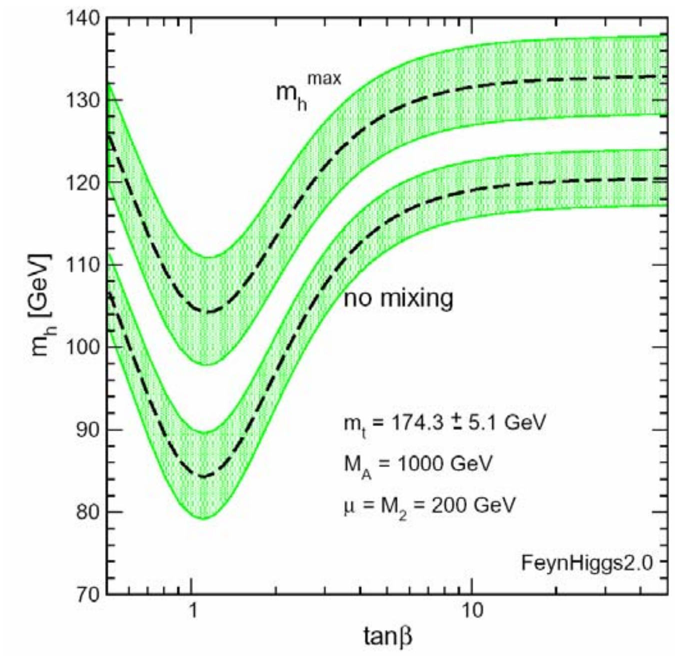
In MSSM two complex Higgs doublet fields needed

(cancellation of triangle anomalies)

Minimal possibility: two doublets (weak isospin ±1)

→ 5 physical Higgs bosons:

h,H	neutral, CP-even
A	neutral, CP-odd
$H^\pm$	charged

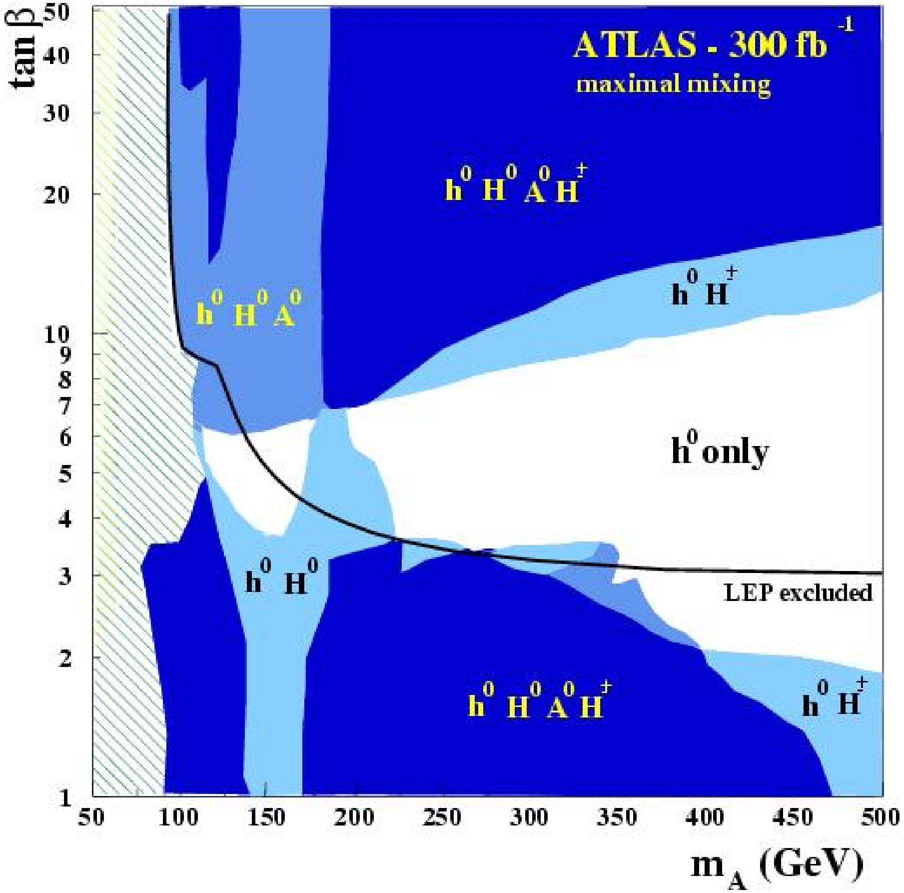


Masses at tree-level predicted as function of m_A and tanβ
but large rad. corrections (top, stop)

$m_h < 135$ GeV

SUSY Higgs at LHC

To prove the structure of the Higgs sector, the heavier Higgs bosons have to be observed either directly or through loop-effects.
Direct observation difficult in part of parameter space at LHC

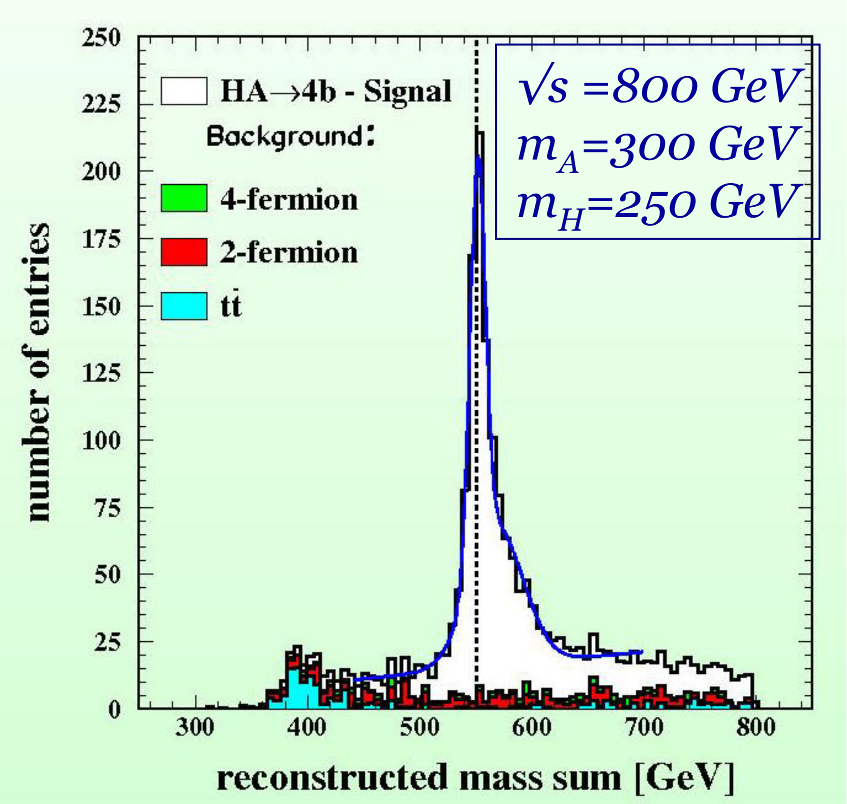


What’s possible at a Linear Collider?

SUSY Higgs Bosons

Very clear signal in HA → bbbb
100 – 1000 MeV mass precision due to kinematic fit
drawback: pair production → mass reach ~ √s / 2

Example for m_H=250 GeV / m_A=300 GeV at √s = 800 GeV:



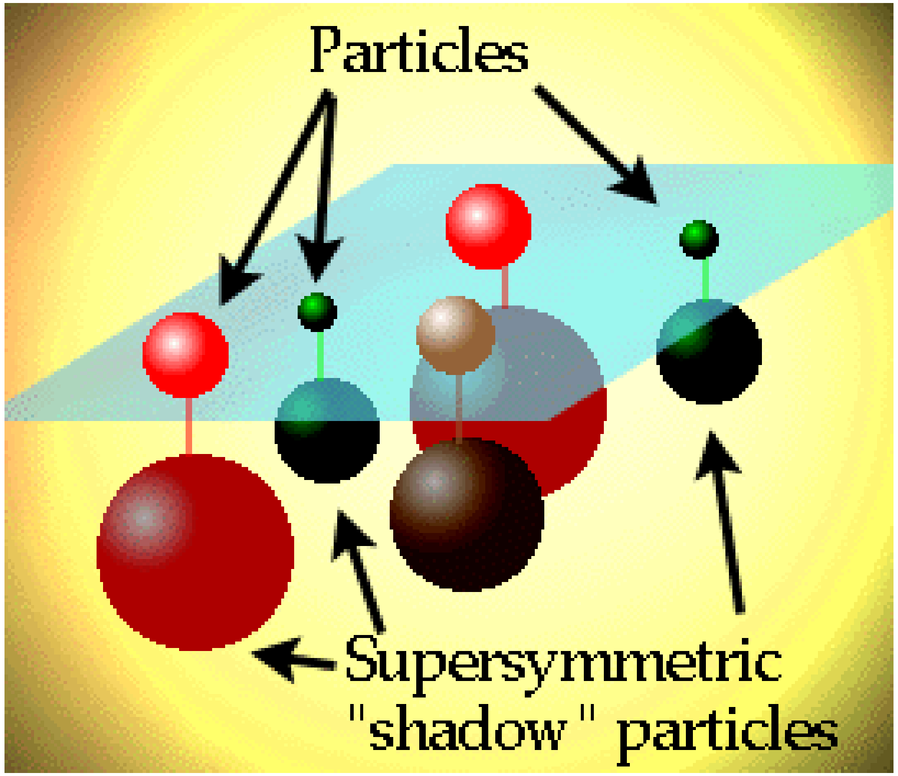
Reach extended into
the LHC wedge region

Higgs Summary

- Higgs mechanism (still) the only completely calculable model of electro-weak symmetry breaking
- Intriguing hints for light Higgs boson from experiment + theory
- LHC will find a SM-like Higgs if it's there
- ILC will be able to pin down the properties of the light Higgs at the quantum level and test details of the model
- Heavy SUSY Higgses can be seen if $m<\sqrt{s_{ee}}/2$ or $m<\sqrt{s_{\gamma\gamma}}$

Supersymmetry

SUSY is one of the most attractive extensions to the SM!



Simple Idea:

Symmetry between
Bosons and Fermions

↪ each SM particle has a SUSY partner with same Quantum numbers and Spin differing by ½.

But where are the SUSY Partners? Must be heavy

SUSY must be broken!

Why is it so attractive, then?

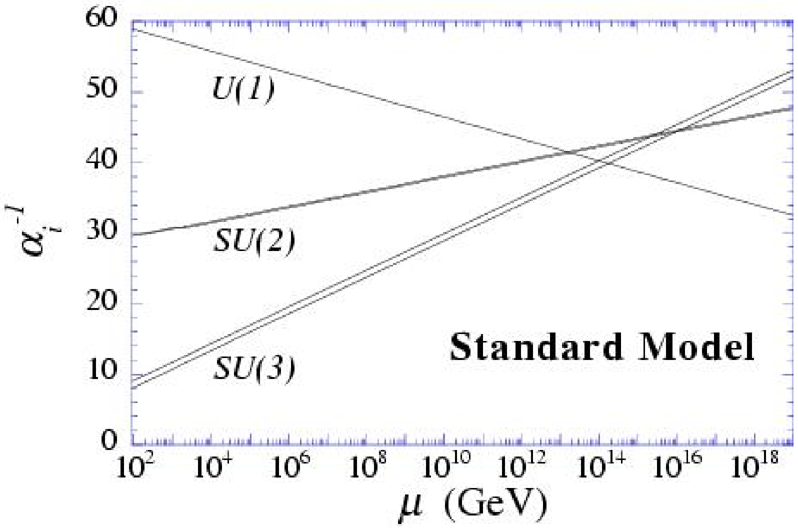
Supersymmetry

1. It solves the Hierarchy problem:

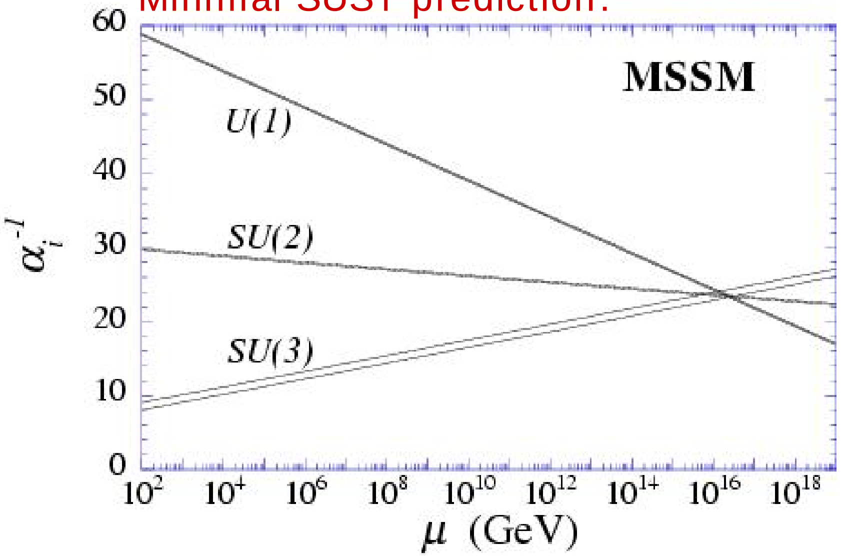
The divergency in the Higgs mass corrections is cancelled exactly for unbroken SUSY.

If it is not broken too heavily (i.e. if the SUSY partners are at <~ 1 TeV), there is no fine tuning necessary.

2. It shows a path to Grand unification:



Minimal SUSY prediction:



(requires light (< TeV) partners of EW gauge bosons)

Supersymmetry

3. Cold Dark Matter:

The lightest SUSY partner particle might well be stable and is an excellent candidate for the observed cold dark matter

4. Link to Gravity:

SUSY offers the theoretical link to incorporate gravity. Most string models are supersymmetric.

5. Light Higgs Boson:

SUSY predicts a light (< 135 GeV) Higgs boson as favoured by electro-weak precision data from LEP and Tevatron.

Sparticle Spectrum

SM particle		J	superpartner		J
leptons	$\ell,\ \nu_\ell$	$\frac{1}{2}$	sleptons	$\tilde{\ell},\ \tilde{\nu}_\ell$	0
quarks	q	$\frac{1}{2}$	squarks	$\tilde{q}$	0
gluon	g	1	gluino	$\tilde{g}$	$\frac{1}{2}$
bosons	γ, Z, W	1	charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\frac{1}{2}$
Higgs	$h, H, H^\pm, A$	0	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	$\frac{1}{2}$

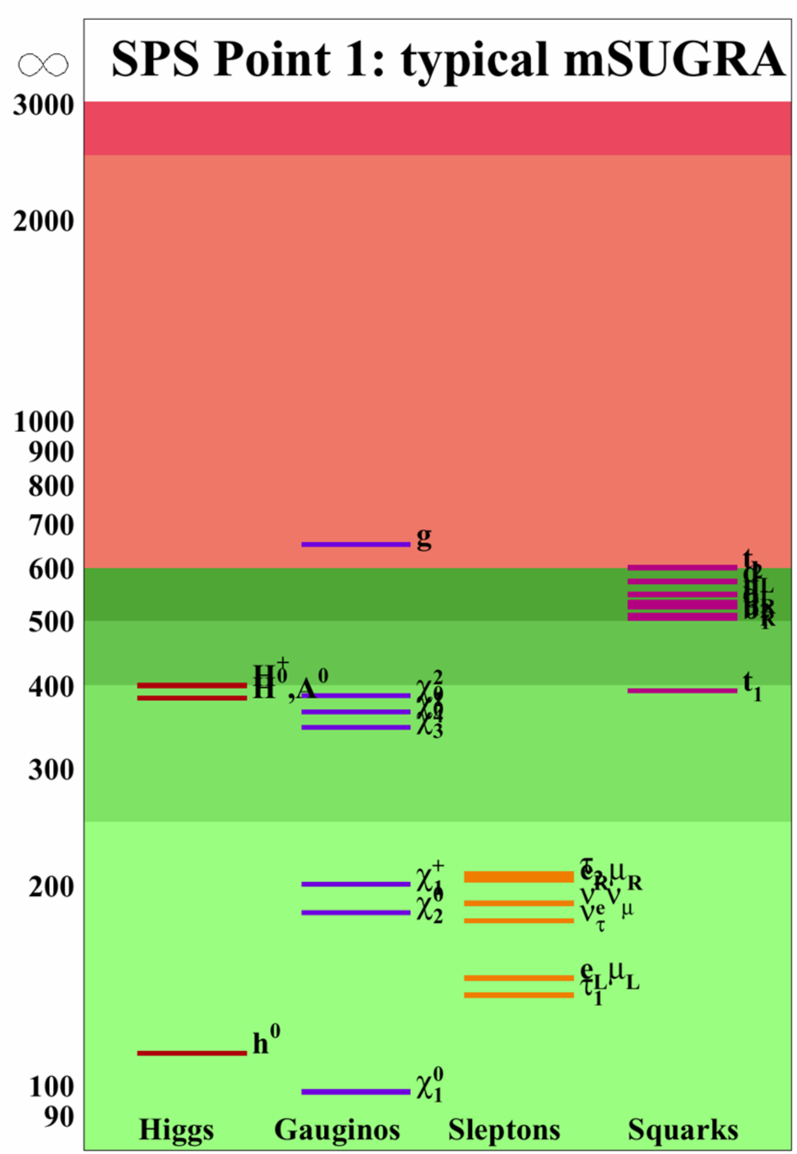
lightest supersymmetric particle stable $\mathrm{LSP} = \tilde{\chi}_1^0$

The minimal supersymmetric model (MSSM) has 105 new parameters

Most of them arise from our ignorance about the way SUSY is broken

Explicit models of SUSY breaking typically only have few parameters
e.g., mSUGRA: tanβ, $m_{1/2}$, m_0, A_0, sgn(μ)

Typical SUSY spectrum

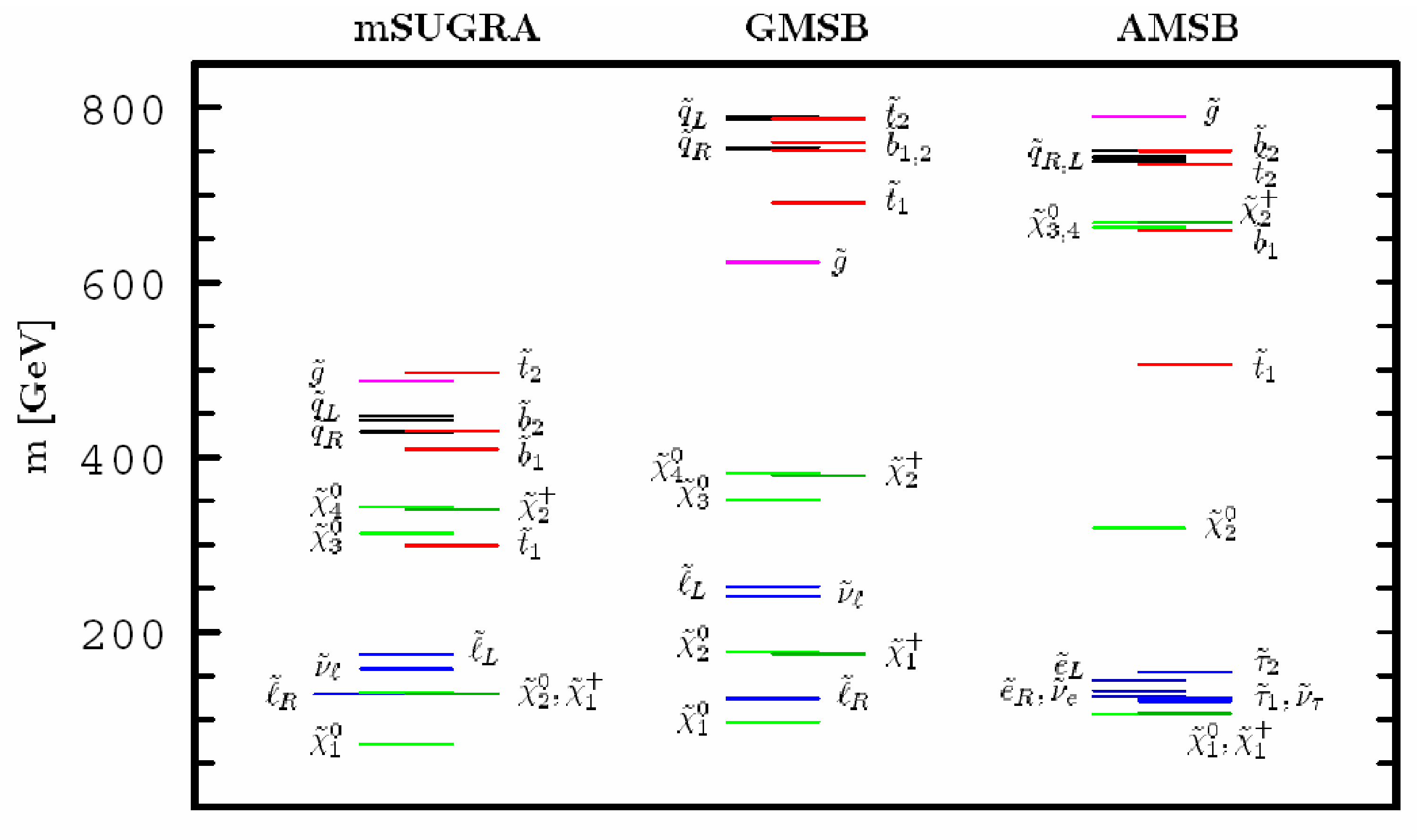


well measurable at LHC

precise spectroscopy at LC

Supersymmetry - Task of LC

different SUSY breaking mechanisms yield different spectra:



Supersymmetry - Task of the LC

After discovery, the task is to reveal the underlying theory of SUSY breaking. The LC can do this by precision measurements of the masses and properties of the accessible part of the spectrum

- is it really SUSY?

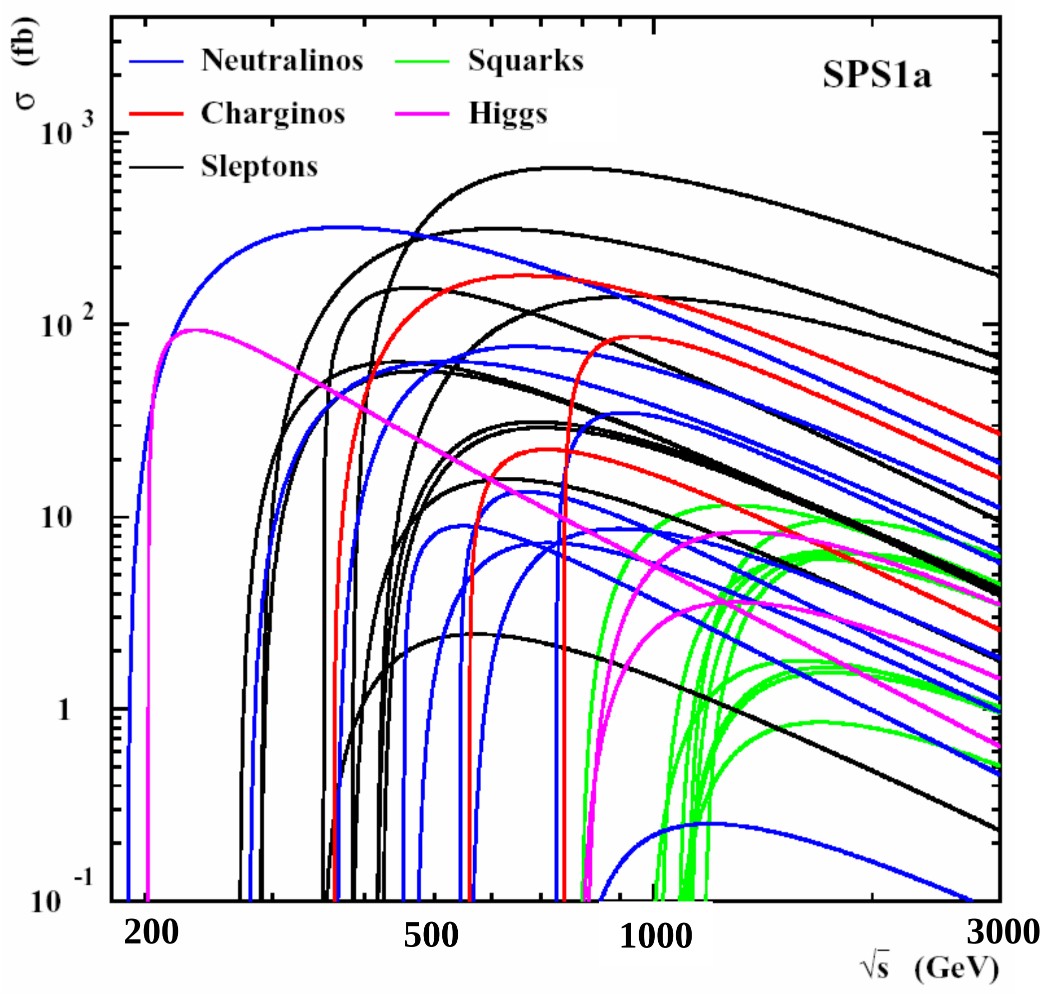
- how is it realized?
  (particle content) MSSM, NMSSM, …

- how is it broken?
  measure as many of the >100 LE parameters as possible
  measure them as precisely as possible -> extrapolation to high scale
  (bottom-up approach)

Note: successfully fitting the parameters of a constrained model
to the observations is a necessary but not a sufficient test of
the model.

SUSY Production at ILC

This will be fun…



cross sections in the
10 – 1000 fb range

o(10^3 – 10^5) events

to disentangle this ‘chaos’
the various LC options,
in particular

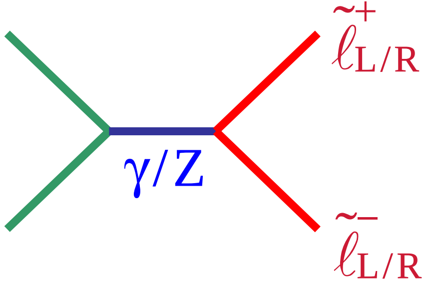
- tunable √s
- tunable beam polarisation

are vital!

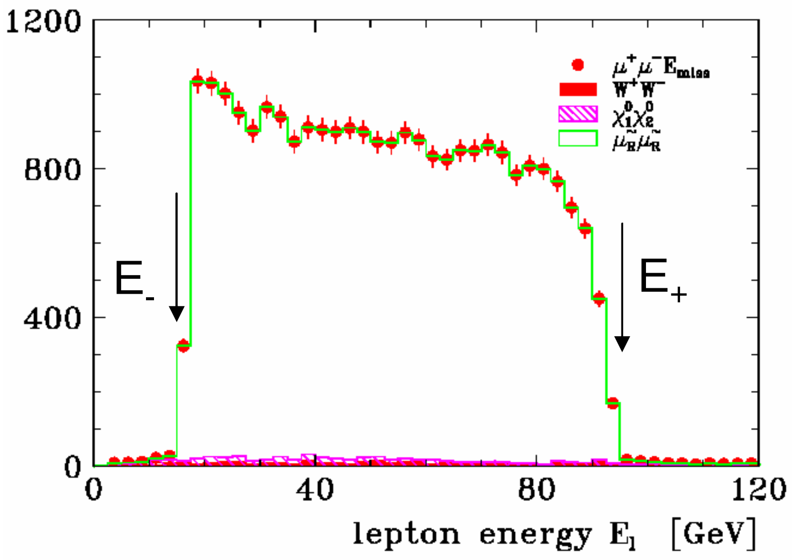
Example: Sleptons

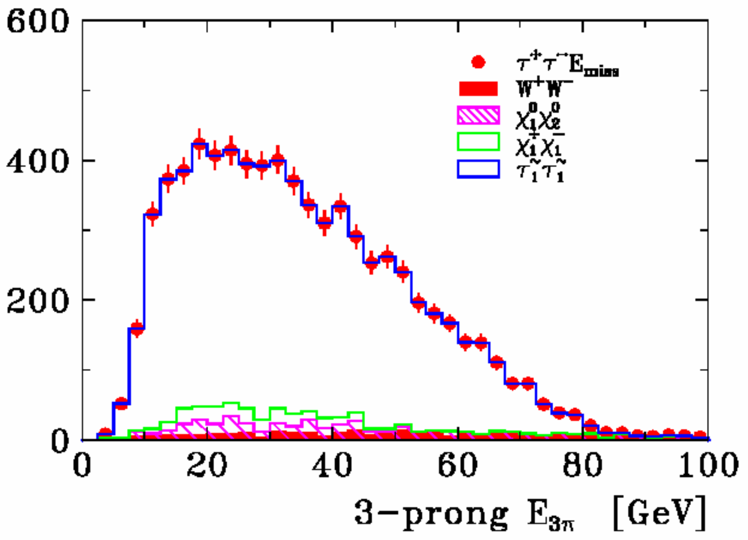
Pair-production

$$\begin{array}{lcl} e^+e^- & \longrightarrow & \tilde{e}_R\tilde{e}_R,\ \tilde{e}_L\tilde{e}_L,\ \tilde{e}_R\tilde{e}_L,\ \tilde{\nu}_e\bar{\tilde{\nu}}_e \\ e^+e^- & \longrightarrow & \tilde{\mu}_R\tilde{\mu}_R,\ \tilde{\mu}_L\tilde{\mu}_L,\ \tilde{\nu}_\mu\bar{\tilde{\nu}}_\mu \\ e^+e^- & \longrightarrow & \tilde{\tau}_1\tilde{\tau}_1,\ \tilde{\tau}_2\tilde{\tau}_2,\ \tilde{\tau}_1\tilde{\tau}_2,\ \tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau \end{array}$$



Examples:





Simple two-body kinematics and beam-constraint allow for mass measurement of both slepton and lightest neutralino

$$\boxed{\begin{aligned} m_{\tilde{l}} &= \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_- E_+} \\ m_{\tilde{\chi}} &= m_{\tilde{l}}\sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}} \end{aligned}}$$

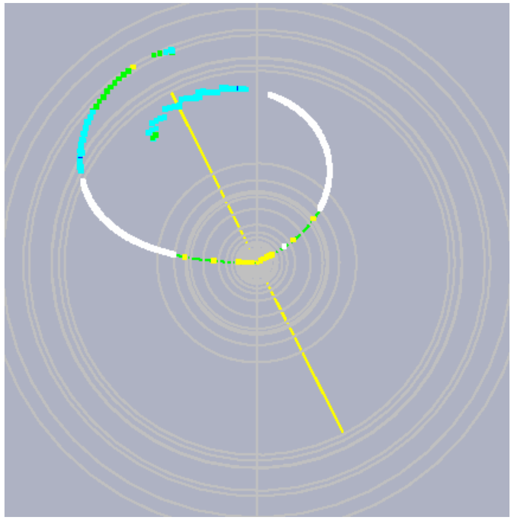
SUSY - Dark Matter

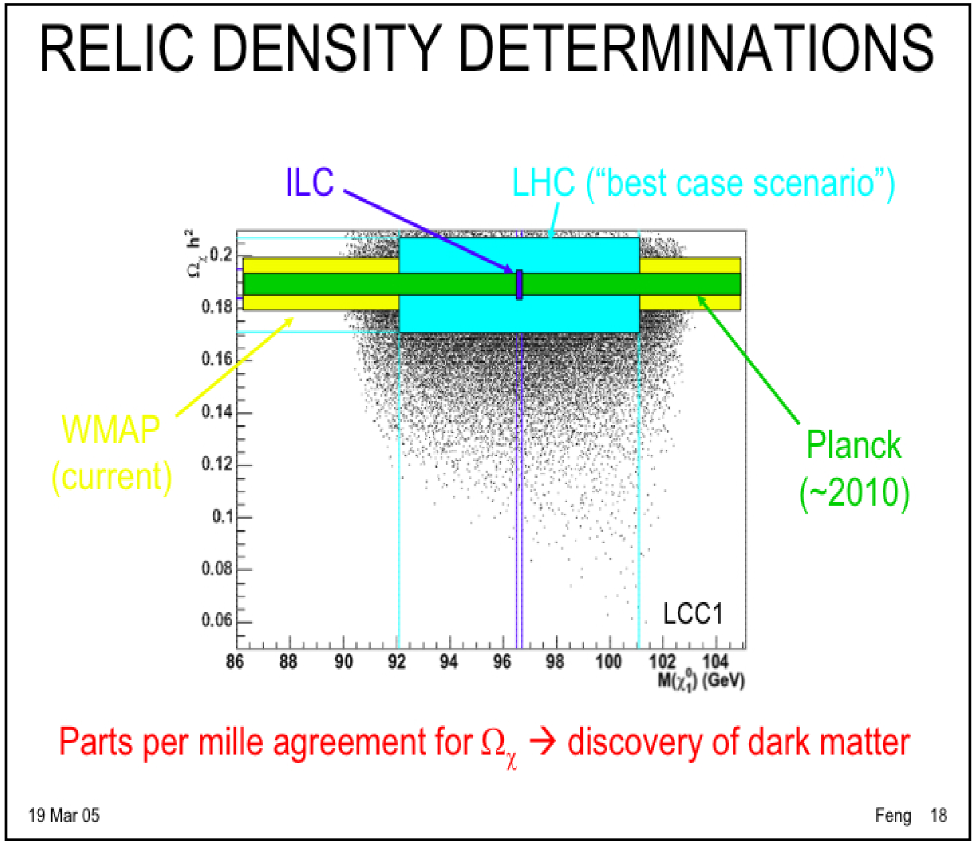
If SUSY LSP responsible for Cold Dark Matter, need accelerators to show that its properties are consistent with CMB data

- 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





RELIC DENSITY DETERMINATIONS

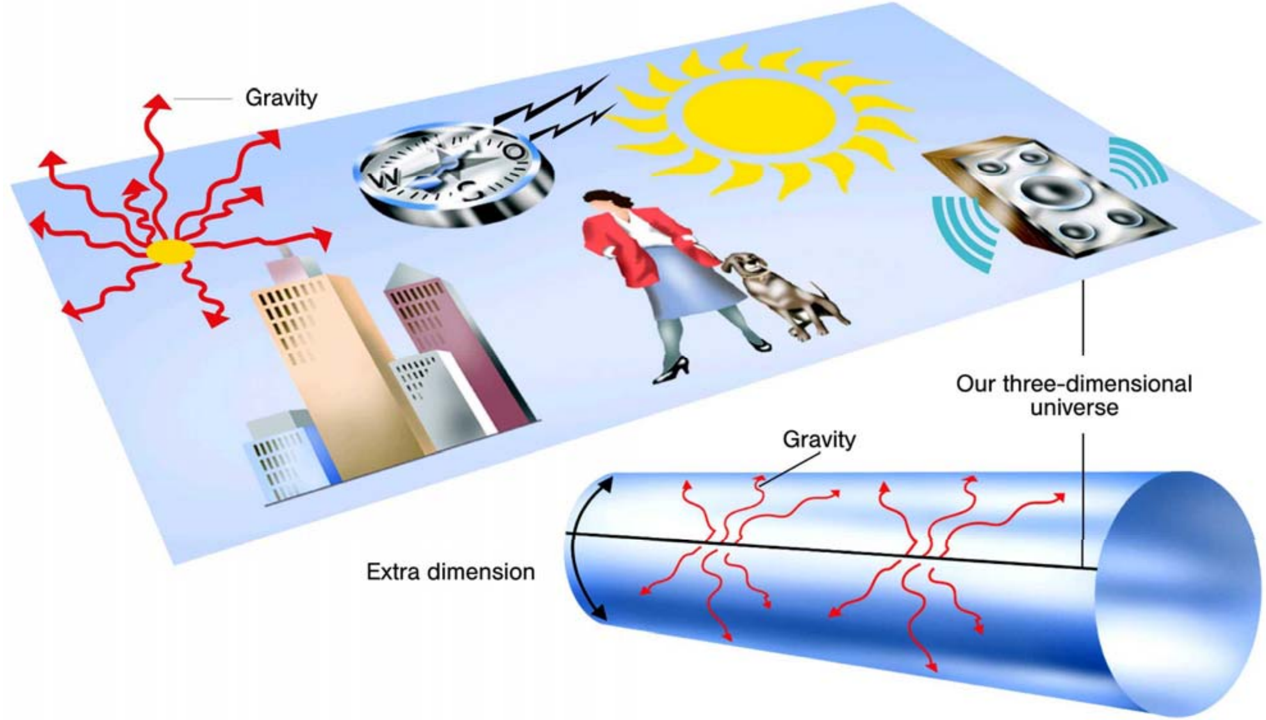
Parts per mille agreement for Ω_χ → discovery of dark matter

19 Mar 05

Feng 18

Extra Dimensions

- Completely alternative approach to solve hierarchy problem: "There is no hierarchy problem"
- Suppose the SM fields live in "normal" 3+1 dim. space
- Gravity lives in 4 + δ dimensions
- δ extra dimensions are curled to a small volume (radius R)



Extra Dimensions

For r < R, gravity follows Newton's law in 4 + δ dimensions:

$$V(r) = \frac{G_S}{r^{\delta+1}}$$

For r > R, gravity follows effectively Newton's law in 4 dimensions, since the “distance” in the extra dimensions does not rise anymore:

$$V(r) = \frac{G_S}{R^\delta r} = \frac{G_N}{r} \text{ with } G_N = \frac{G_S}{R^\delta}$$

The Planck mass $M^2_{Planck} = \hbar c / G_N$ only effectively appears so high at large distances. The true scale of gravity is

$$M_S^2 = \hbar c / G_S = \hbar c R^\delta / G_N$$

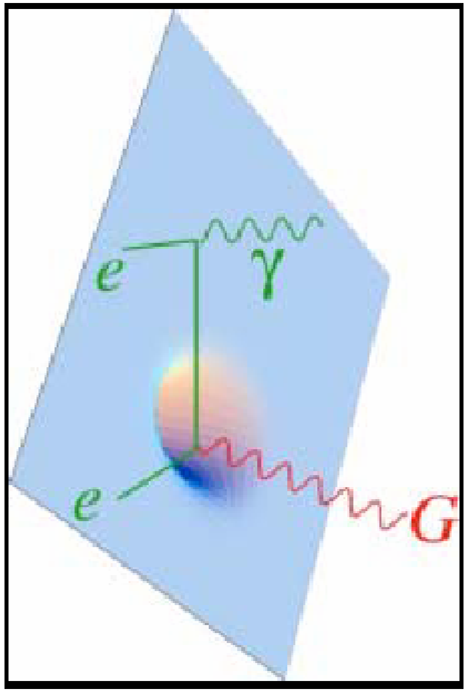
If e. g. R ~ $\mathcal{O}$(100 μm) and δ = 2, one obtains $M_S = o(1\,\mathrm{TeV})$

⇒ Gravity might become visible at TeV-scale colliders!

Extra Dimensions

Extra dimensions provide an explanation for the hierarchy problem

String theory motivates brane models in which our world is confined to a membrane embedded in a higher dimensional space



e.g. large extra dimensions:

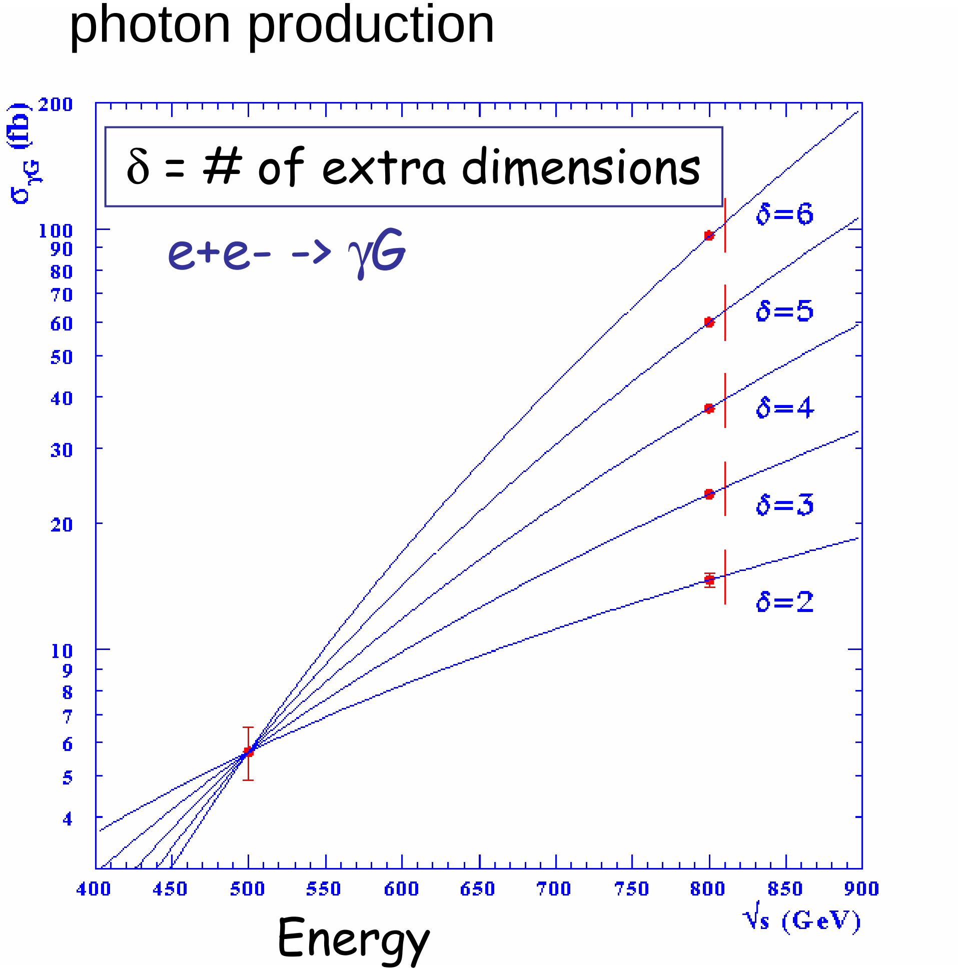
Emission of gravitons into extra dimensions

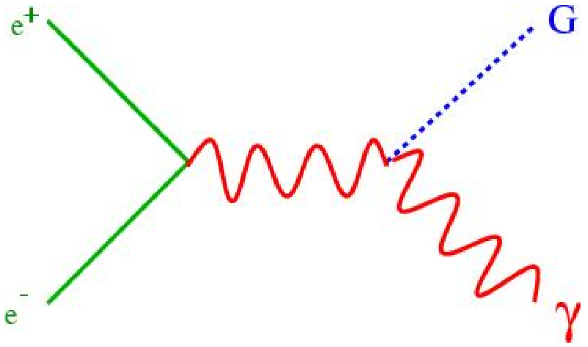
Experimental signature

single photons

Extra Dimensions

cross section for anomalous single photon production



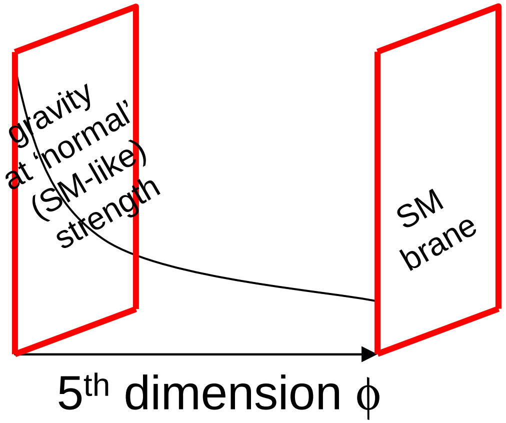


measurement of cross sections at different energies allows to determine number and scale of extra dimensions

(500 fb-1 at 500 GeV,

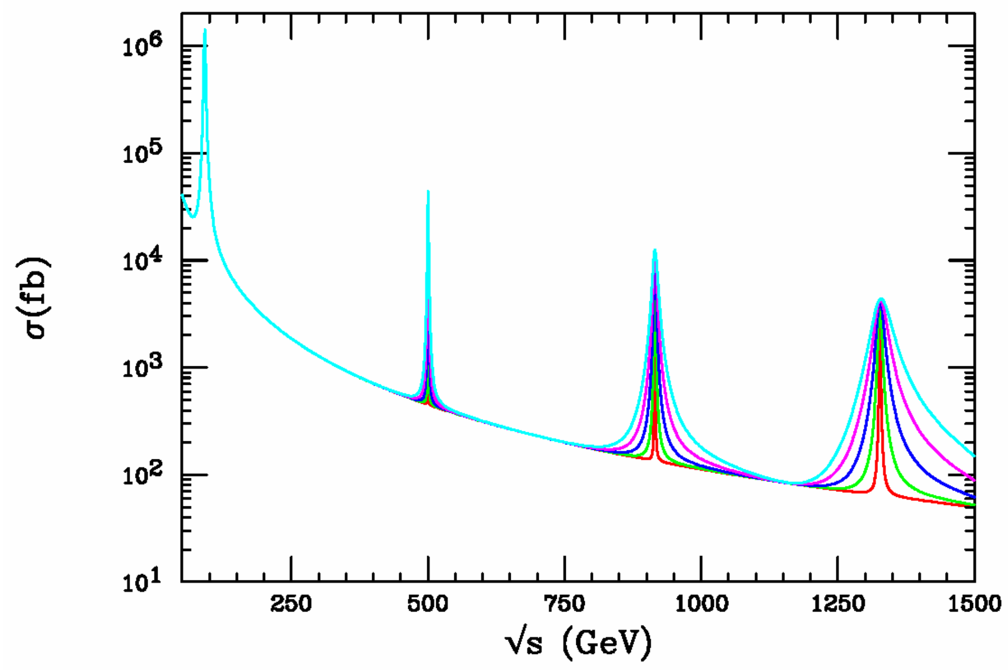
1000 fb-1 at 800 GeV)

Warped Extra Dimensions



gravity appears weak on SM brane (in our world) due to exponentially 'warped' metric in 5th dimension

$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2$$



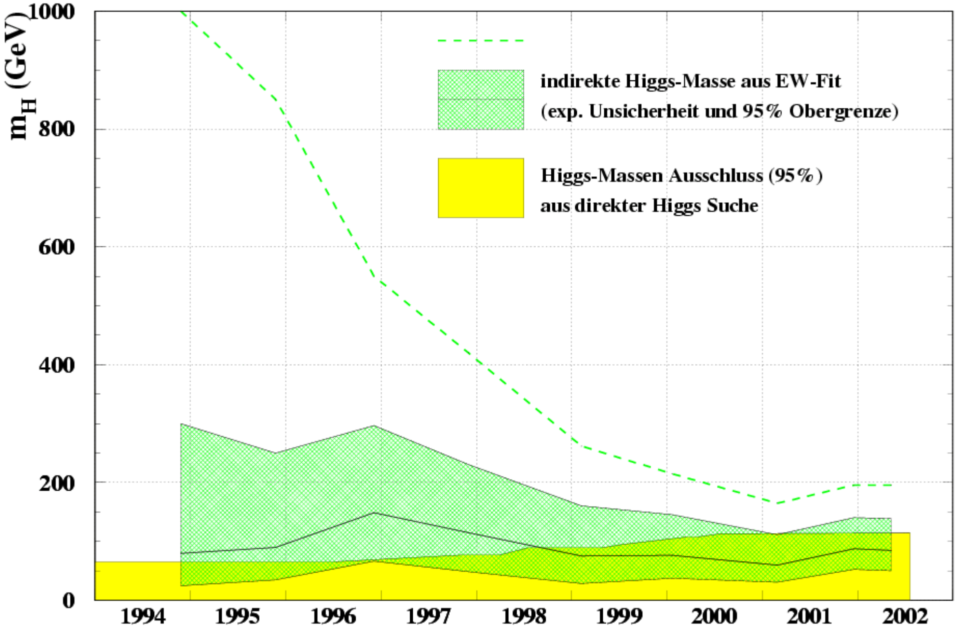
might observe spectacular KK-excitations of the graviton

\+ graviscalar excitations ("Radions") which mix with the Higgs and modify its couplings + mass

Discovery through precision

Precision measurements of SM processes are a telescope to higher scale physics

Example Higgs



- Top quark
- Z‘ and similar vector resonances
- Alternative EWSB
- etc.

If no Higgs boson(s) found….

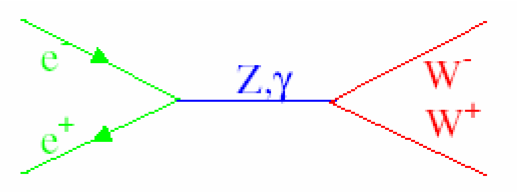
→ divergent $W_L W_L \rightarrow W_L W_L$ amplitude in SM at $\Lambda^2 = o\left(\frac{4\pi\sqrt{2}}{G_F}\right) \approx (1.2 TeV)^2$

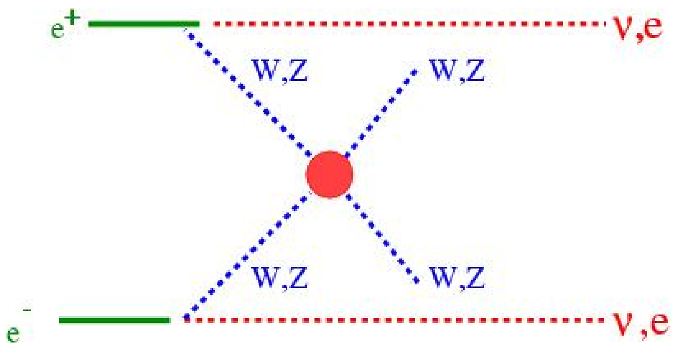
→ SM becomes inconsistent unless a new strong QCD-like interaction sets on

→no calculable theory until today in agreement with precision data

Experimental consequences: *deviations in*

triple gauge couplings *quartic gauge couplings:*





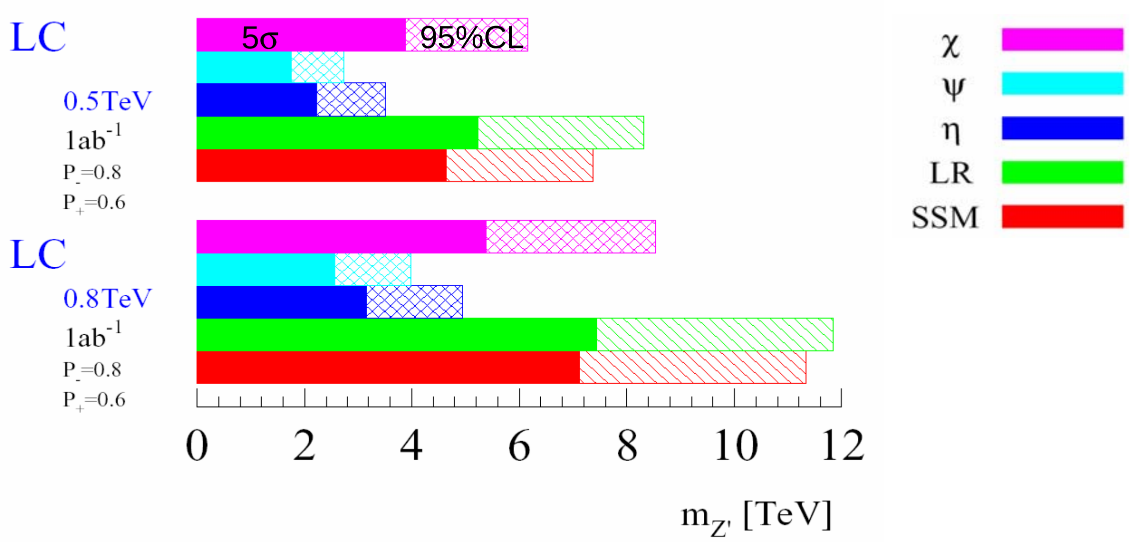
LC (800 GeV): sensitivity to energy scale Λ:
triple gauge couplings: ~ 8 TeV
quartic gauge couplings: ~ 3 TeV ⇨ *complete threshold region covered*

New Gauge Bosons (Z')

Heavy Z' vector boson motivated by TeV scale remnants of
Grand Unified Theories, string theories etc.
Examples: Z' in SO_{10}, E_6

LHC: M(Z') up to ~ 5 TeV

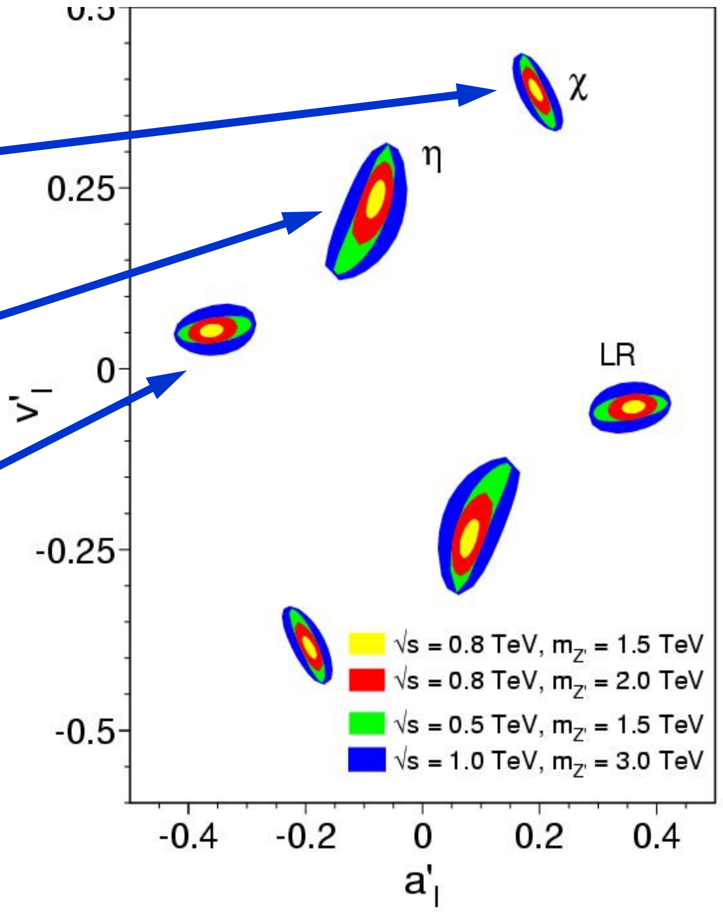
ILC: Unlikely to directly produce a Z' (Tevatron limits approaching 1 TeV)
virtual extension up to 15 TeV measuring its interference with Z,γ exchange
(PETRA could measure Z properties without producing Z's)



New Gauge Bosons (Z’)

If Z’ mass is known (e.g. from LHC) ILC can measure the vector and axial-vector couplings an pin down the nature of the Z’

By measuring at two different √s, ILC can measure both mass and couplings



If here, related to origin of neutrino masses

If here, related to origin of Higgs

If here, Z’ comes from an extra dimension of space

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

Final remarks

We live in exciting times:

- **Expect major discoveries at the TeV scale with LHC and ILC**

- **High energy physics will not be finished with LHC+ILC**
  Active R&D for the multi-TeV regime is vital and necessary now
  CLIC is a promising way to get there

- **ILC technology at hands – if we all work (and talk) together this dream can turn into reality**

- **LHC startup soon – highest priority: let's make this a success**

CLIC

THE COMPACT LINEAR COLLIDER (CLIC) STUDY

Multi TeV e^+e^- collider

up to 3 TeV