P. Grannis – University of Lancaster Dec. 7, 2001

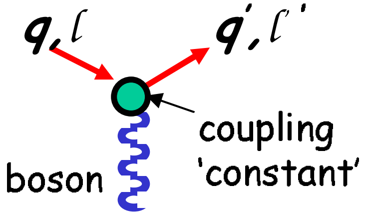
Physics at the e^+e^- Linear Collider

The big questions confronting particle physics :

- What is the origin of symmetry breaking in the electroweak interaction?
  - What gives mass to all particles?
  - What is the new physics at the TeV scale,
  - Is space-time modified? (extra spatial dimensions, new fermionic dimensions)?
  - Is there force unification?
- Where do the quark and lepton flavors come from ?
  - Why are there 3 generations of quarks and leptons?
  - Why is there CP violation? Why the baryon/antibaryon asymmetry in universe?
  - Why fermion mass disparities & mixing patterns (all those arbitrary parameters)?
- What are the unseen elements of the universe ?
  - What is the dark matter & dark energy?
  - Why is the cosmological constant so small ($\neq 0$) and the universe flat ?

Electroweak symmetry breaking

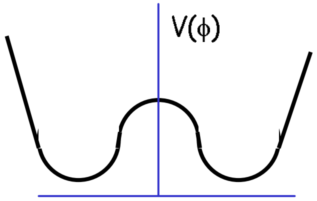
- Fermi observed the similarity between EM and Weak int'ns: postulate the W boson to carry Weak force, but it has to be massive due to short range. Fermi theory violates unitarity in WW scattering.



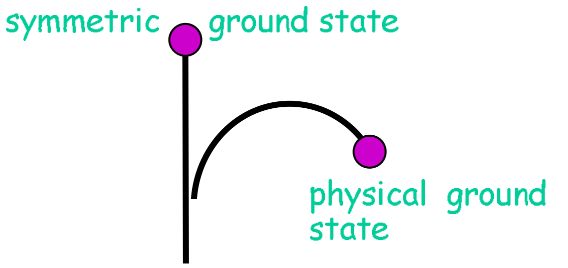
$H = \alpha J_\mu J^\mu$ (Fermi) (α = coupling)

$J_\mu^{EM} = e\,\gamma_\mu\,e + \ldots$; $J_\mu^{Wk} = d\,\gamma_\mu(1-\gamma_5)\,u + e\,\gamma_\mu(1-\gamma_5)\,\nu_e + \ldots$ (V-A chg currrent)

- Yang, Mills, Veltmann, t'Hooft, Glashow, Weinberg, Salam show that local gauge theories based on weak isospin/weak hypercharge can lead to a renormalizable Weak Interaction if there is a massless spin 1 triplet and singlet of gauge bosons ($\omega^{+,0,-}$ and **b**^{0})



- Higgs mechanism: introduce a complex isodoublet of scalar bosons (4 degrees of freedom). The Higgs potential, $V(\phi) = \lambda(\phi^2 - \frac{1}{2} v^2)$, (v = vacuum expectation value = 246 GeV) may have a minimum at away from zero. The spontaneous symmetry breaking to the true ground state allows three of the Higgs degrees of freedom to be absorbed giving longitudinal spin components of massive $W^\pm$ and Z bosons. The remaining degree of freedom emerges as 'the Higgs boson' with non zero Higgs mass, $M_H = 4\,\lambda v^2$. The Yukawa couplings of the Higgs give rise to the fermion (quark and lepton) masses.



classical dynamical symmetry breaking

- The acquisition of masses for W and Z involves a rotation of the underlying massless (ω,**b**) eigenstates; the 'weak mixing angle' $\sin^2\theta_W = (1 - M_W^2/M_Z^2) = 0$ (to lowest order).

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} b^0 \\ \omega^0 \end{pmatrix}$$

Electroweak symmetry breaking

For the unified Electroweak Interaction, the `charges' are electric charge (q), weak isospin (I_W), and weak hypercharge (Y_W).

EW Int'n = SU(2) X U(1)

(with the Strong Int's, Standard Model = SU(3)XSu(2)xU(1))

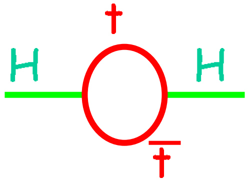
Three parameters specify the EW interaction of leptons and quarks: G_F, M_Z, $\sin^2\theta_W$.

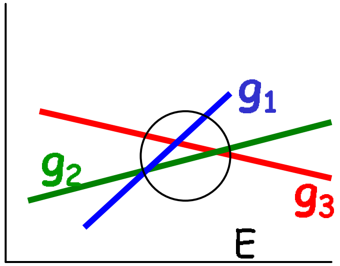
The Higgs boson mass is not predicted: we must measure it experimentally.

In past 20 years, 100's of measurements by experiments at LEP, Tevatron, SLC, HERA, ν interactions have shown that the EW SM agrees with Nature to 0.1% level (including higher order corrections), and predict the Higgs mass to be below 200 GeV.

But we don't think the SM is correct:

- In SM, the Higgs mass gets quantum corrections that should drive it to the Planck or unification scale (the hierarchy problem)
- The Strong coupling and two EW couplings do not unify in the SM:
- There are 26 arbitrary masses, mixing angles, coupling parameters that are completely *ad hoc*.





Finding the Higgs and elucidating the source of EW symmetry breaking is within the reach of experiments in the next several years, and is thus now our highest priority.

Supersymmetry

Supersymmetry offers a popular way to solve the hierarchy problem; if there are near-degenerate pairs of fermions and bosons with otherwise identical properties and couplings, the loop divergences due to fermions and bosons cancel. For example, the partner of the left-handed e^- with spin ½ would be a selectron $\tilde{e}_L^-$ with spin 0. Since we don't observe such a state with m = 0.511 MeV, we know that supersymmetry must be broken.

If there is supersymmetry, there is a new space-time of 'fermionic' dimensions. Supersymmetry occurs in string theories (at the Planck scale).

To make supersymmetry work, need two complex Higgs doublets ϕ_1 and ϕ_2 to give mass separately to up- and down-type fermions. After EWSB giving W/Z masses, 5 Higgs states survive: h^0, H^0 (scalars), A^0 (pseudoscalar) and $H^\pm$ (charged Higgs). The ratio $\langle\phi_1\rangle/\langle\phi_2\rangle$ = tanβ is an unknown parameter (along with masses of fundamental scalars, spin ½ states, etc.)

Some of the Susy zoo:

electron e	→	selectron $\tilde{e}$	(J=0)
muon μ	→	smuon $\tilde{\mu}$	"
quarks q	→	squarks $\tilde{q}$	"
gluons g	→	gluinos $\tilde{g}$	(J= ½)
etc.			

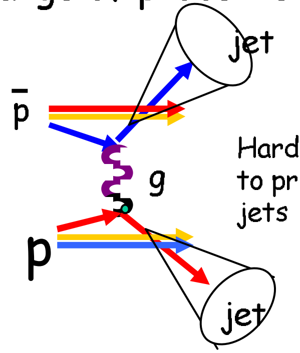
photon γ	→	photino $\tilde{\gamma}$	(J= ½)
Z	→	zino $\tilde{Z}$	"
Higgs ϕ_1	→	Higgsino $\tilde{\phi}_1$	"
Higgs ϕ_2	→	Higgsino $\tilde{\phi}_2$	"
$W^\pm$	→	Wino $\tilde{W}^\pm$	"
$H^\pm$	→	Higgsino $\tilde{H}^\pm$	"

These identical Q# states mix to give physical **neutralino** states χ_i^0 (i=1,4)

These mix to give physical **chargino** states $\chi_i^\pm$(i=1,2)

The tools for the next decade

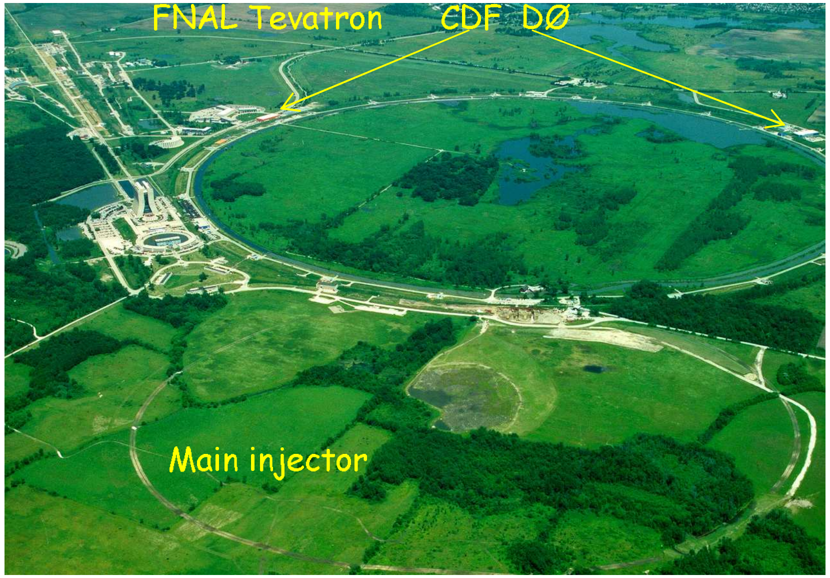
Hadron colliders operate at the highest accessible energies. Incoming protons (antiprotons) contain constituent quarks and gluons (partons) that collide through strong interactions, and produce a wealth of particles. Due to momentum distribution of partons, there is a range of constituent cm energies, so a range of processes are simultaneously accessible.



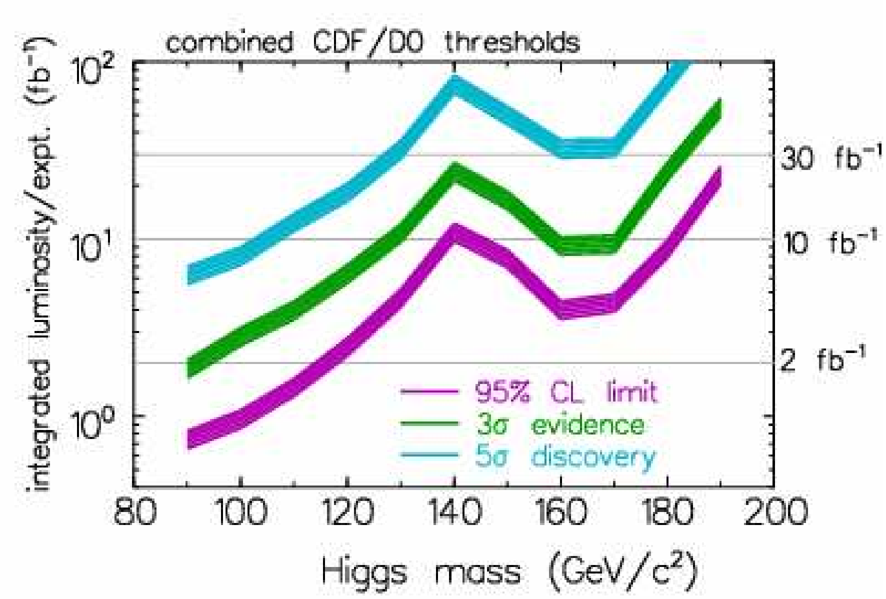
Hard quark scattering to produce final state jets

The drawbacks of hadron are the very large backgrounds due to strong interaction processes, and the lack of knowledge of the initial state parton energy and quantum numbers.

The 2 TeV $p\bar{p}$ Tevatron collider is now operating.

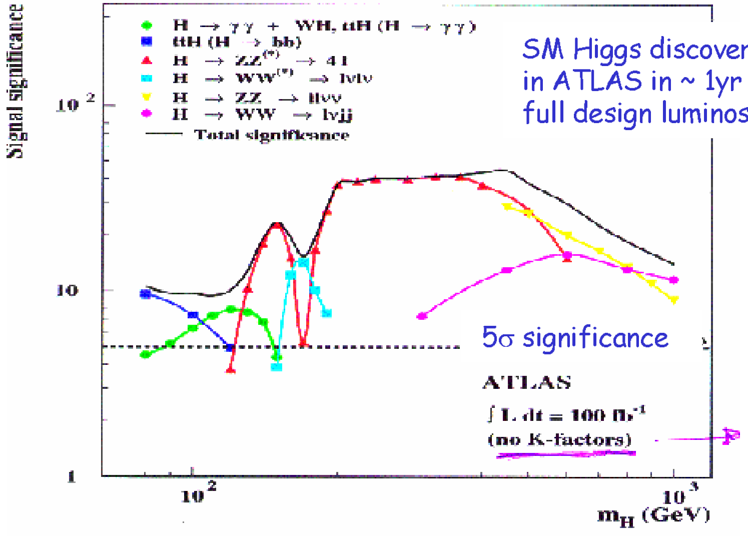


The Tevatron should discover the Higgs boson up with mass up to 180 GeV.



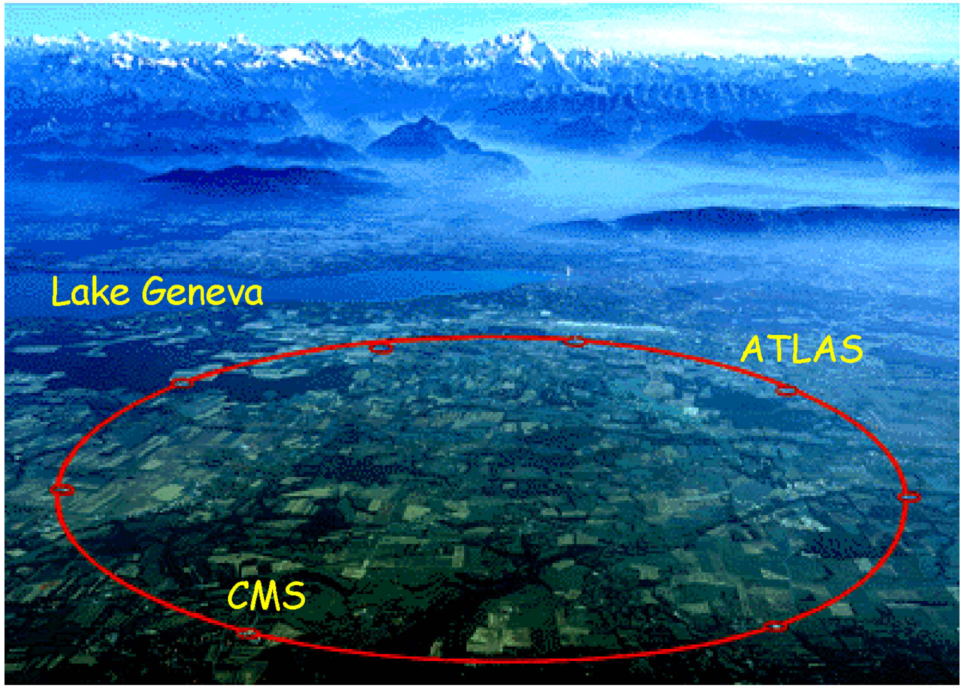
The tools for the next decade

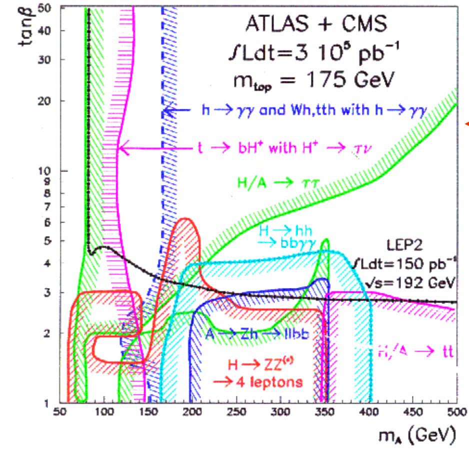
The CERN LHC pp collider will start operation at 14 TeV in ~2007. The two experiments ATLAS and CMS are virtually assured to discover any Higgs (the Higgs makes little sense if $M_H > 1$ TeV).



SM Higgs discovery in ATLAS in ~ 1yr at full design luminosity

5σ significance



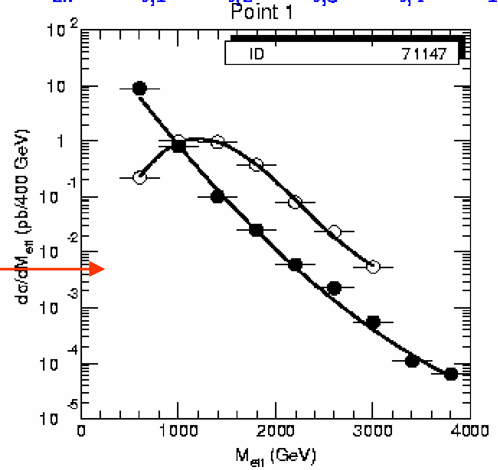


LHC will discover Susy if it exists!

At least one Susy Higgs will be seen, for any Susy parameters chosen.

Very simple effective mass variable reveals the presence of Susy particles over SM backgrounds.

$$M_{\rm eff} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + \not{E}_T$$

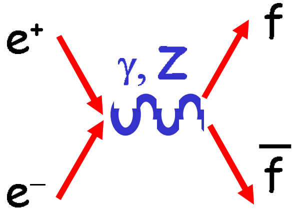


Lepton colliders

Although Tevatron/LHC should make the discoveries, they will not be able to measure the crucial properties of Higgs that tell us what it really is, and cannot make critical Susy measurements to pin down the model or explain Supersymmetry breaking.

Lepton-lepton colliders offer complementary strengths to hadron colliders, and in the past, both have been necessary to fully understand particle properties.

We have had a succession of e^+e^- colliders, through LEP which operated at E_{CM} up to 205 GeV. They produce final state fermion pairs (leptons or quarks) or boson pairs (ZH) via s-channel γ or Z exchange.



The strengths of the lepton colliders are their well defined initial parton energy and quantum numbers ($J^P = 1^-$). The final states of interest are relatively free of backgrounds due to the absence of strong interactions for the leptons.

The electron beams (perhaps positrons) may be polarized, giving more incisive control of reactions. It is possible to Compton backscatter laser light from the e beam giving nearly monochromatic high energy γ's that can be used for $e\gamma$ or $\gamma\gamma$ collisions – useful for special studies.

Circular e^+e^- colliders suffer from synchrotron radiation ($E_{rad} \sim E_e^4$), and probably LEP is the end of the line for such machines. The Stanford Linear Collider (SLC) was the world's first linear e^+e^- collider, operating at $E_{CM} = M_Z$. In the past 10 years, much R&D has been done on new higher energy and higher luminosity linear colliders.

Recently proposals have been made for muon colliders, using very high intensity proton beams creating $\pi \rightarrow \mu\nu$, μ capture, μ cooling (reduction of phase space) and μ acceleration. Much R&D remains, and muon colliders are probably 15 years away (but an adaptation may make a muon storage ring as an intense source of ν somewhat sooner).

Linear ee Colliders

Two competing technologies are becoming available:

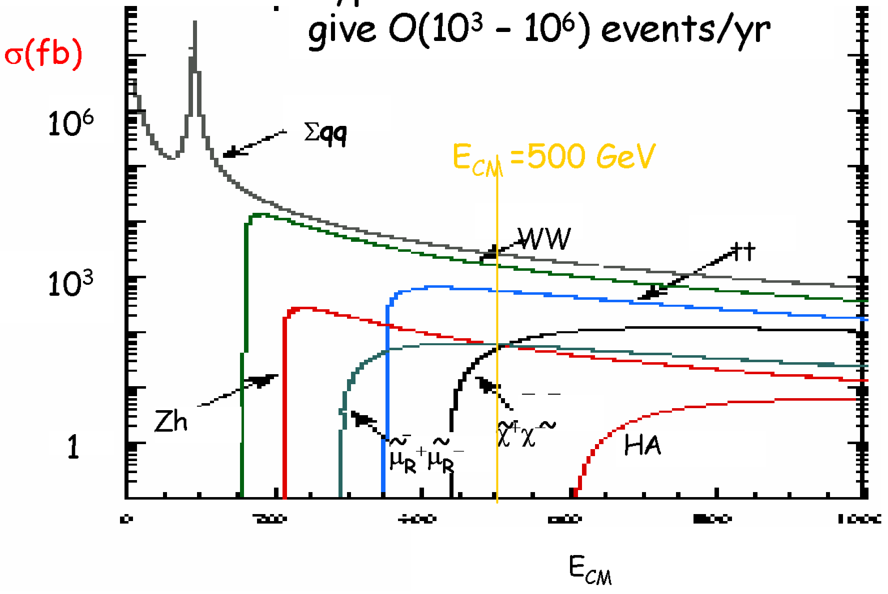
a) Superconducting rf accelerating structures – large aperture, long bunch intervals, easier to stabilize beams. (**TESLA** developed at DESY).

		TESLA	NLC/JLC
$\mathcal{L}_{design}$	(10^{34} $cm^{-2}s^{-1}$)	3.4 → 5.8	2.0 → 3.4
E_{CM}	(GeV)	500 → 800	500 → 1000
Gradient	(MV/m)	23.4 → 35	70
RF freq.	(GHz)	1.3	11.4
Δt_{bunch}	(ns)	337 → 176	1.4

b) Warm copper rf structures, higher gradients (easier to get higher energy), short bunch interval, harder to stabilize beams (**NLC** developed at SLAC and **JLC** developed at KEK/Japan)

Either would have electron polarization ~ 80%; may have positron polarization ~60% Optional $\gamma\gamma$, $e^-\gamma$, e^-e^- collisions at reduced luminosity give special physics capabilities.

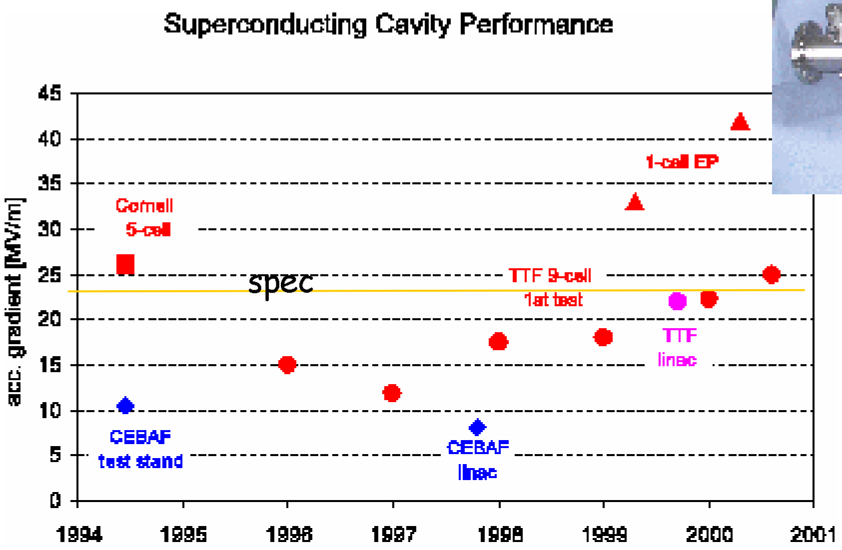
$\mathcal{L}$ = $1\text{x}10^{34}$ $cm^{-2}s^{-1}$ for 10^7 sec. year gives 100 fb^{-1}/year

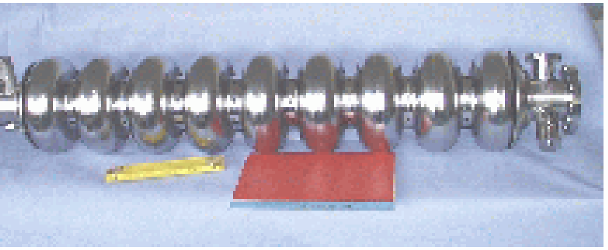


Typical XS of 10 - 10^4 fb give O(10^3 - 10^6) events/yr

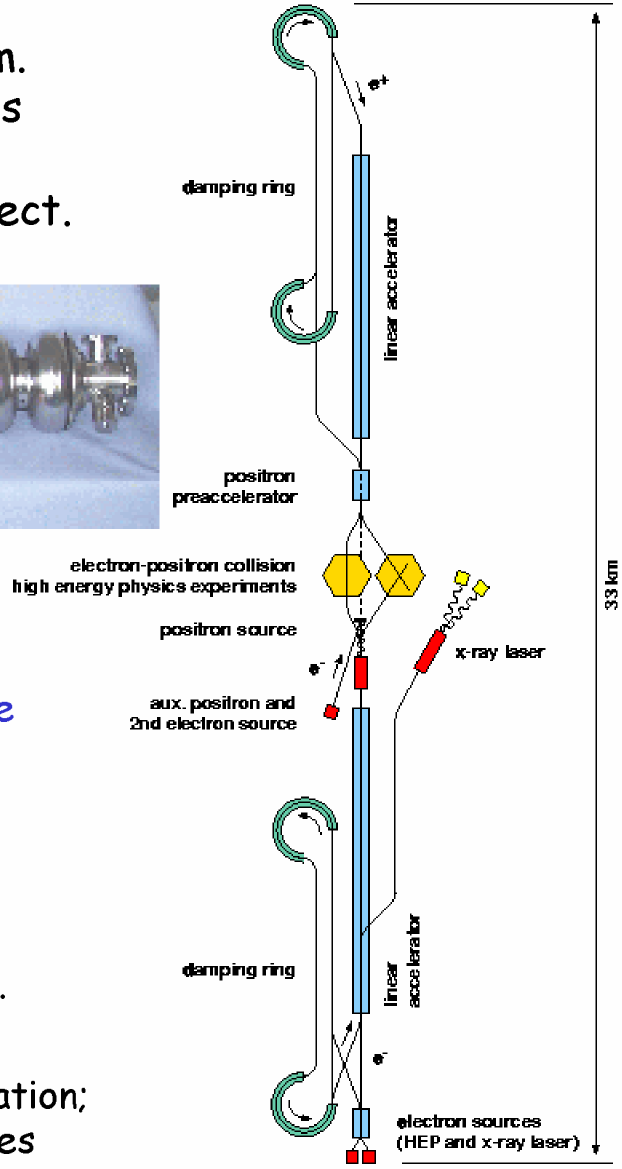
Tesla

TESLA site length = 33 km (15 km linacs). Operates with superconducting RF cavities; design for 500 GeV is 23.4 MV/m. Bunches are separated by 337 ns, allowing for head-on collisions without satellite crossings. An X-ray free electron laser for materials sci., biology, chemistry is an integral part of the project.





Upgrade to 800 GeV by going to 35 MV/m in the constrained length.



Cost: $3.16B (using 0.93 $/Euro). Includes 1 IR, 1 detector ($233M). xFEL added cost is $495M.

Cost in yr 2000 prices; no contingency (HERA was on budget), no escalation; no second detector/IR; exclusive of manpower at collaborating institutes (6933 man-yrs estimated: ~$700M)

NLC/JLC

NLC baseline 2001: 26 km site (2 in CA, 2 in IL). Two 10 km linacs sized for 1 TeV. Fill $\frac{1}{2}$ of linacs for 500 GeV. Final focus, Injector design for 1.5 TeV. Two IRs; 'Hi E' IR with no bend (crossing angle 20 mrad) can work at multi-TeV; 'Lo E IR requires bend; maximum energy 500 GeV (→ 1 TeV?)

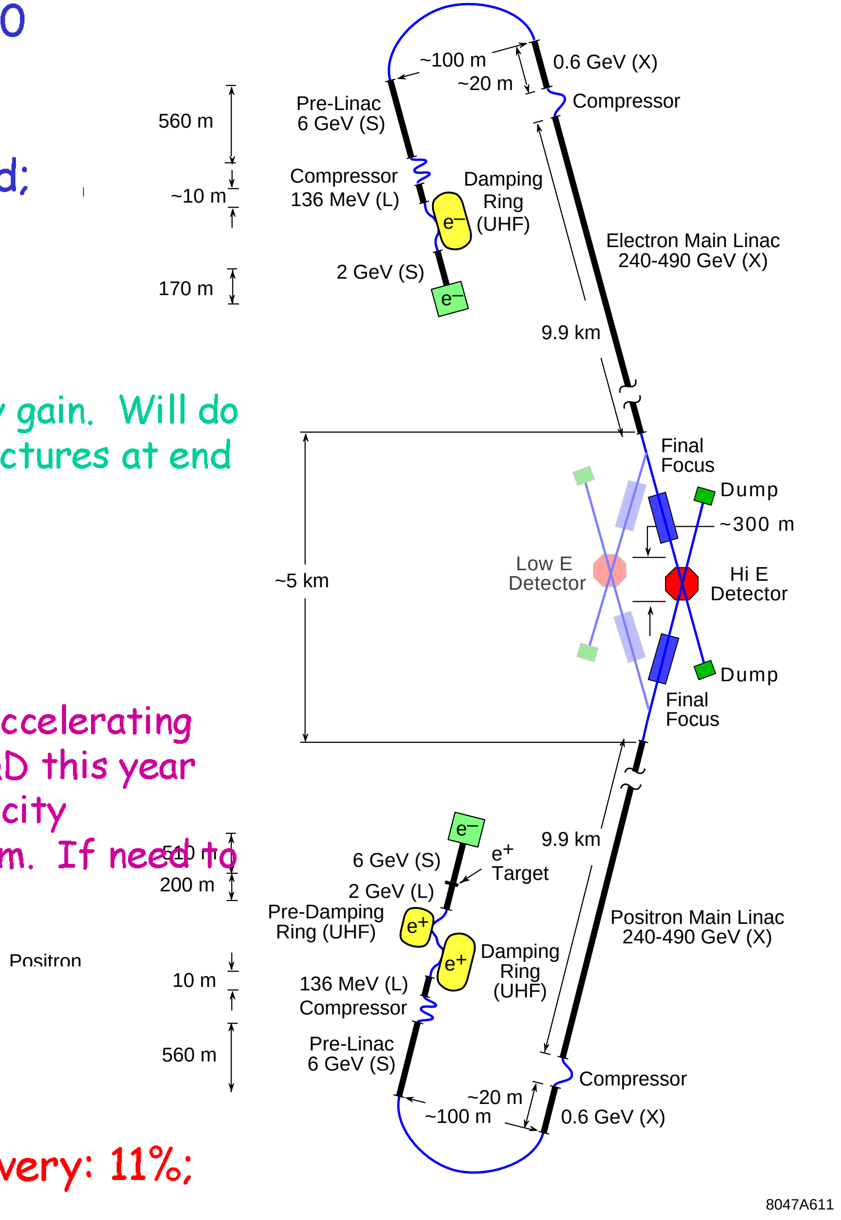
Recent work:

Improved klystrons and SS modulators give x3-4 efficiency gain. Will do full test of modulator, 8 klystrons, set of accelerating structures at end 2003 to demonstrate.

New compact final focus region

rf Structures:

Optimum cost for gradient 70 MV/m but deterioration of accelerating structure surfaces seen (at high group velocity). Active R&D this year has made good progress to fix this. Going to low group velocity travelling wave (or standing wave) seems to cure the problem. If need to reduce to 50 MV/m, cost penalty is 5-10%.



Cost: estimate $3.7B with manpower (no escalation, contingency, detectors).

Injectors: 19%; Linacs: 39%; beam delivery: 11%; global costs: 17%; management/business: 14%

Main LC physics themes

Precision measurements in the past decade (LEP, SLC, Tevatron, ν scattering) indicate the need for something like the Higgs boson below a few 100 GeV.

★ **Study the `Higgs boson' (or its surrogate) and understand what it really is.**

The SM Higgs mechanism is unstable and ugly. We expect some new physics beyond the SM to occur at the TeV scale

★ **Find and explore this new physics sector.**

(Also a rich program of study of the top quark, QCD, precision EW measurements, etc.)

Recent comprehensive physics studies:

⇒ TESLA TDR, DESY 2001 - 011, (Part III - Physics at an e^+e^- Linear Collider)

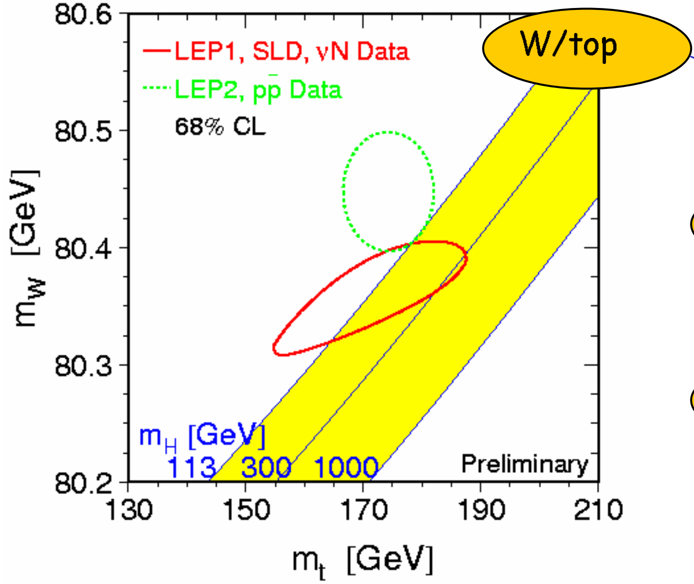
⇒ LC Physics : Resource Book for Snowmass 2001, (hep-ex/0106055, 056, 057, 058)

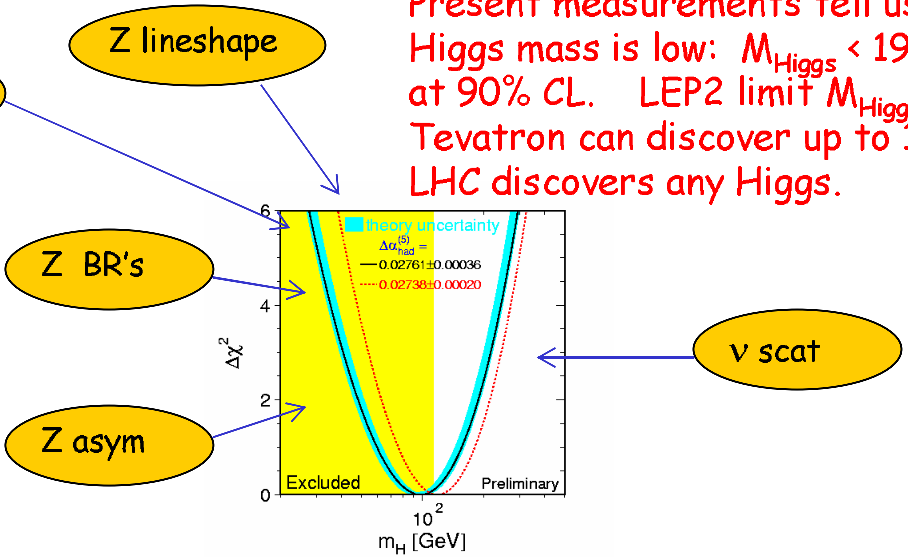
⇒ ACFA Physics Book: http://acfahep.kek.jp

What is the Higgs ??

(Only measurements can tell us !)

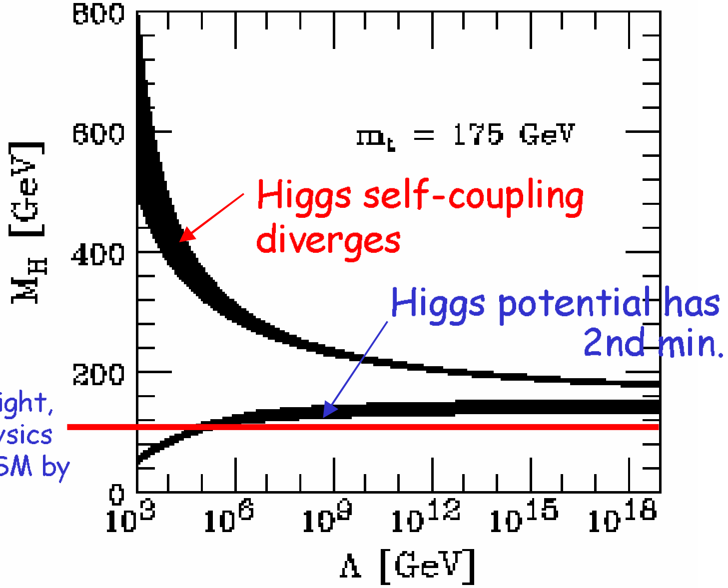
Present measurements tell us the SM Higgs mass is low: $M_{Higgs} < 190$ GeV at 90% CL. LEP2 limit $M_{Higgs} > 113.5$ GeV. Tevatron can discover up to 180 GeV; LHC discovers any Higgs.





LEP2 direct Higgs search – Maximum Likelihood for Higgs signal at m_H = 115.0 GeV with 2.2σ significance (4 experiments)

The SM is not a consistent theory above some scale Λ – either because the Higgs coupling diverges, or because the ground state of the Higgs potential is not stable. Only for a narrow region of Higgs mass between 140 and 180 GeV could the SM be valid up to the Planck scale. So even if we see a 'SM Higgs', it is likely to require some new physics beyond SM somewhere.



If LEP right, need physics beyond SM by 10^6 GeV

Program for Higgs Study

- Find a Higgs boson candidate, and measure its mass (& masses of added Higgs states in SM extensions)

→ Tevatron or LHC should discover Higgs, and measure the mass well (unless Higgs decays dominantly in invisible modes - then the LC finds it).

- Measure **total width**, Γ_{TOT}, and **couplings** to all available fermion pairs and gauge bosons. Are the couplings proportional to mass? Do they conform to the simple SM? or to Susy models? Is there more than 1 Higgs?

→ LHC will not do Γ_{TOT} (or do rather poorly) and only *ratios* of *some* couplings to ~20%. Linear Collider can measure Γ and couplings to ~5%; these are crucial to establish the nature of the Higgs.

- Measure the **quantum numbers** of the Higgs states. For the SM, expect $J^{PC} = 0^{++}$; for Susy, both 0^{++} and 0^{-+}.

→ LHC will not do; Linear Collider will do easily

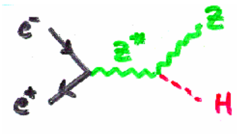
- Explore the **Higgs potential**. The self-couplings lead to multiple Higgs production.

→ LHC will not do; LC can do trilinear coupling, with sufficient luminosity

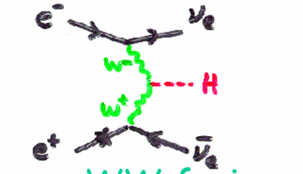
Tevatron/LHC should discover a Higgs candidate;
LC should discover what it really is. **We will likely need both !**

Higgs discovery, mass & gauge couplings

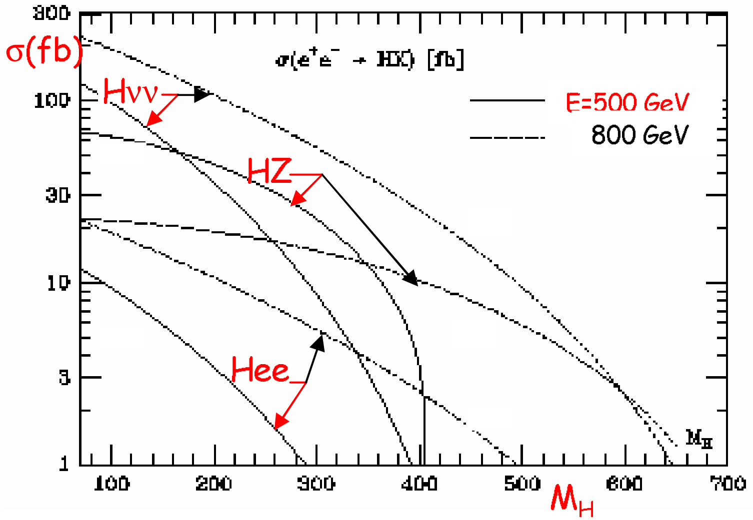
Dominant Higgs production for lower mass Higgs at LC is 'ZH bremsstrahlung'. At higher energy, WW (or ZZ) fusion becomes dominant yielding Hνν (Hee) final state.



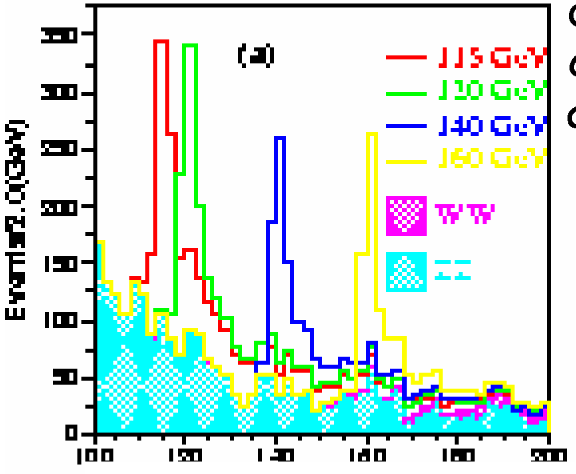
ZH brems



WW fusion



In ZH bremsstrahlung, observing the Z decay products (ee, μμ, qq modes) allows Higgs mass meas. (to 0.1%) and study without bias (even invisible decays of Higgs are possible using the recoil Z). ZH cross section allows determination of (ZZH) coupling and tests if there are more Higgs: →



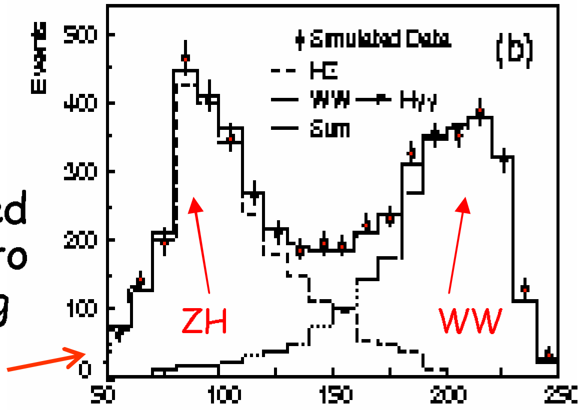
Z recoil mass

Does measured coupling of 1st Higgs saturate the sum rule ?

$$\Sigma g^2_{(hZZ)i} = \underbrace{(M_Z\, g_{EW} / \cos\theta_W)^2}_{\text{known}}$$

Higgs width and Z & W couplings

Measuring WW fusion gives the HWW coupling (exactly predicted in SM). With BR(H→WW), use to determine Γ_{TOT} to few%, testing for unexpected Higgs decays. Can distinguish WW from ZH using jet tags and missing mass.

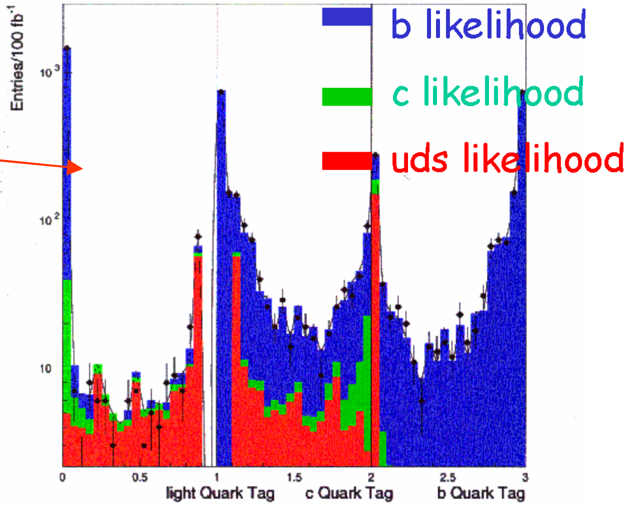


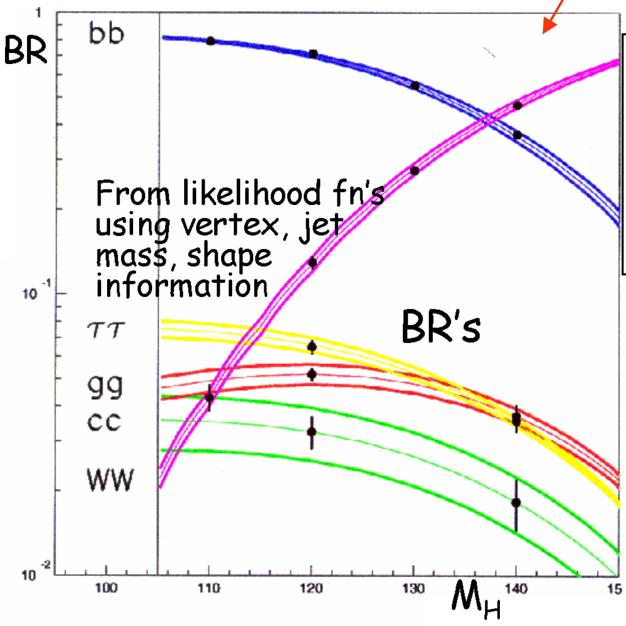
Missing mass

Higgs fermion couplings

We need to determine experimentally that Higgs couplings to fermions are indeed proportional to mass. SM couplings differ from Susy couplings.

Using displaced vertex distance, jet shape, particle energies, define likelihood to distinguish b, c, light quark jets: use jet probabilities to measure BRs into various particles.



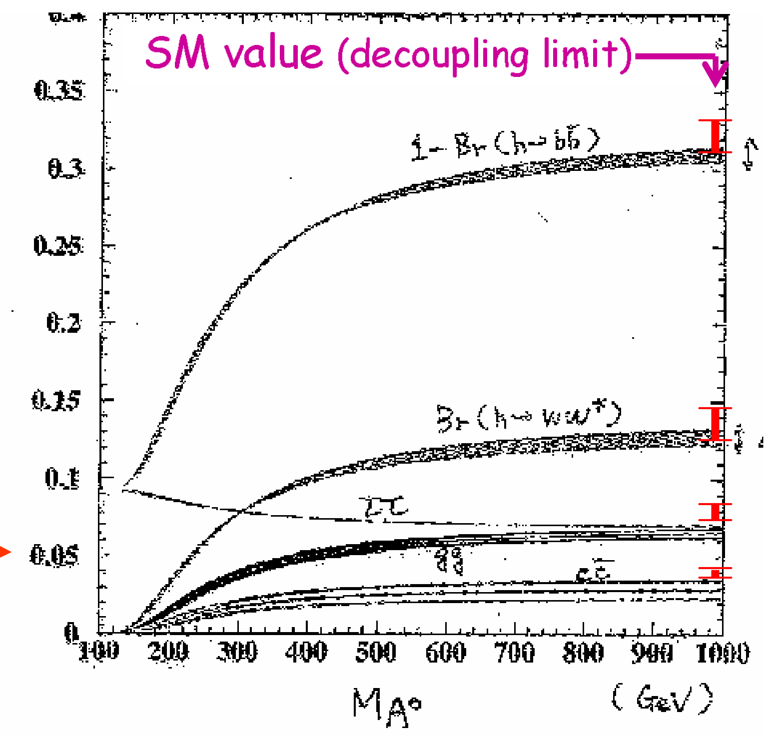


500 fb^{-1} for 300 GeV LC
(M_h = 120 GeV)

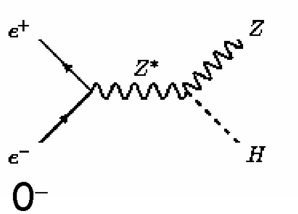
H → bb	2.4%
H → cc	8.3%
H → gg	5.5 %
H → ττ	6.0%
H → WW	5.4%

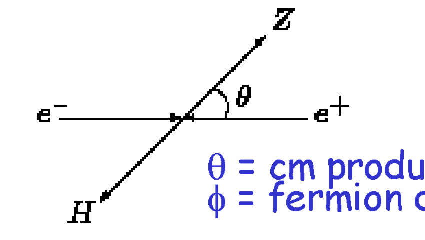
Measurement of these BR's is powerful indicator of new physics, and senses M_A well above E_{CM}.

Susy Higgs BR's must agree with Susy parameters from many other measurements.



Higgs spin parity

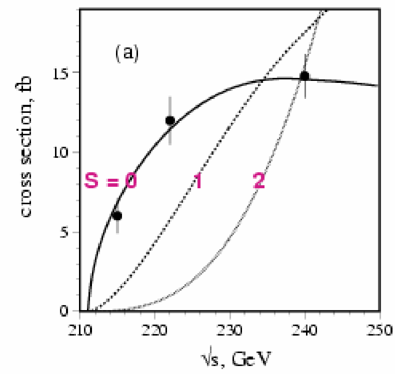




θ = cm production angle;
ϕ = fermion decay angle in Z frame

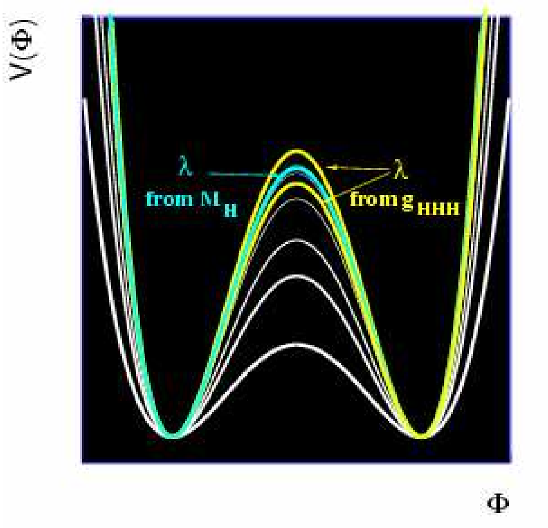
	$J^P = 0^+$	$J^P = 0^-$
$d\sigma/d\cos\theta$	$\sin^2\theta$	$(1 - \sin^2\theta)$
$d\sigma/d\cos\phi$	$\sin^2\phi$	$(1 +/- \cos\phi)^2$

β and angular dependences near threshold permit unambiguous determination of spin-parity →



Higgs self couplings

Measures Higgs potential shape λ, independent of Higgs mass measurement. Determination of λ and M_H gives new constraint on SM.



double Higgs-strahlung: $e^+e^- \rightarrow Zhh$

Study ZHH production and decay to 6 jets (4 b's). Cross section is small; premium on very good jet energy resolution. Can enhance XS with positron polarization.

Inclusion of WW → HH, use of diHiggs mass and angular correlations improves the sensitivity:

$\Delta\lambda/\lambda$ error = 20 – 30% in 1000 fb^{-1}

Physics beyond the Standard Model

There are serious defects of the SM:

- No gauge interaction unification occurs
- Higgs mass is unstable to loop corrections
- Can't explain baryon asymmetry in universe …

Many possible new theories are proposed to cure these ills and embed the SM in a larger framework:

- **Supersymmetry** Susy models come in many variants, with different scales of Susy breaking (supergravity, gauge mediation, anomaly mediation …) Each has a different spectrum of particles, underlying parameters.

- **A new gauge interaction** like QCD with `mesons' at larger masses. (Technicolor/topcolor) These interactions avoid introducing a fundamental scalar. `technipions' play the role of iggs new particles to be observed, and modifications to WW scattering.

- **String-inspired models with some extra dimensions** compactified at millimeter to femtometer scales.

- Something different?

★ **LC must be able to sort out which is at work. Can imagine cases where LHC sees new phenomena, but misunderstands the source.**

Supersymmetry

If Susy is to stabilize the Higgs & gauge boson masses (and give grand unification) it is 'natural' to believe that some Supersymmetric particles will appear at a 500 GeV LC.

The main goal is to measure the underlying model parameters and deduce the character of the supersymmetry, energy scale for Susy breaking. There are ~105 unknown parameters in general Susy model, all of which should be measured, and used to fix the models.

This can be done through measurement of the masses, quantum numbers, branching ratios, asymmetries, CP phases -- and in particular the pattern of mixing of states with similar quantum numbers -- the 2 stops, sbottoms, staus, and the 2 chargino and 4 neutralino states (partners of the γ/Z/W and supersymmetric Higgs states).

Susy may well be the next frontier for flavor physics – study FCNC, CP violation for sparticles, generational patterns, etc.
Susy can provide a dark matter candidate (the lightest neutralino).

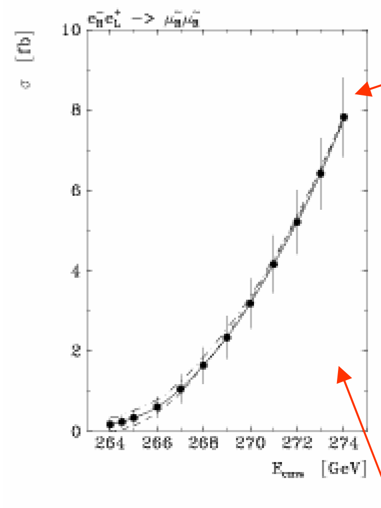
The LHC will discover Susy if it exists.
But disentangling the information on the full mass spectrum, particle quantum no's/couplings and the mixings will be difficult at LHC.

⇒ The **LC can make these crucial measurements**, (e.g. sparticle masses to 0.1 – few % level) benefitting from --

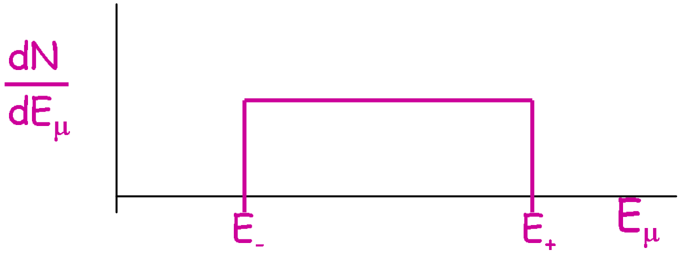
- Polarization of electron (positron?) beam
- Known partonic cm energy
- Known initial state ($J^P = 1^-$)

Making Susy measurements

Consider the illustrative case of $\tilde{\mu}_R$ (partner of right-handed muon) properties. Production occurs via $e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^-$. Production of scalar smuon pairs is p-wave (β^3 threshold behavior)



The two body process yields monoenergetic smuons. The smuon decay is $\tilde{\mu}_R \rightarrow \chi_1^0 \;\mu$ (the lightest neutralino, χ_1^0, is the lightest Susy particle (LSP) and thus stable if R parity ('Susy-ness') is conserved). The decay is isotropic in the smuon rest frame, so in the Lab frame, the energy of the final μ is uniformly distributed between lower and upper limits:



$$E_\pm = 1/2\,(1 \pm \beta\,)\,(1 - m_{\tilde{\mu}}^2/m_\chi^2)\,;$$

$$\beta = \;(s/4m_{\tilde{\mu}}^2 - 1)^{\frac{1}{2}}$$

Measure E_+ , $E_- \rightarrow$ determine $m_{\tilde{\mu}}$ and m_χ . With detector simulation and backgrounds, get % level accuracy.

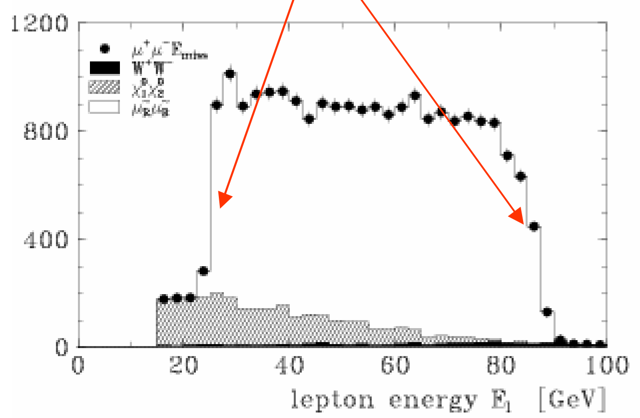
With $\tilde{\mu}_R$, χ_1^0 masses from end points, do a threshold scan to obtain more accurate masses (~ 0.1%).

The threshold β behavior and the angular distribution of μ's determine the quantum numbers of the $\tilde{\mu}$. To verify it is Susy, the smuons should be spin 0 and there should be two (non-degenerate) partners for both left- and right-handed μ.

Supersymmetry predicts that analogous couplings between Susy particles and SM particles are identical. e.g.

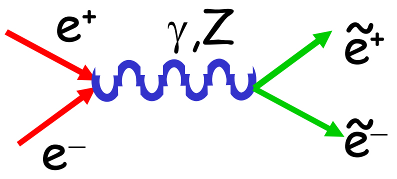
$$g_{\mu\nu W} = g_{\tilde{\mu}\nu\tilde{W}}$$

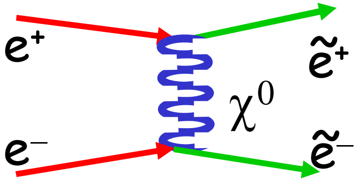
These can also be measured to verify it is Supersymmetry (corrections to these equalities are related for different couplings.



Supersymmetry at the Linear Collider

An example: production of selectron pairs -- have two diagrams; typically the t-channel χ^0 exchange dominates and allows measurement of neutralino couplings (gaugino vs. higgsino) to lepton/slepton. s-channel γ/Z process only for $\tilde{e}_L^+ \tilde{e}_L^-$ and $\tilde{e}_R^+ \tilde{e}_R^-$. Bkgnd WW suppressed for beam e_R^-.

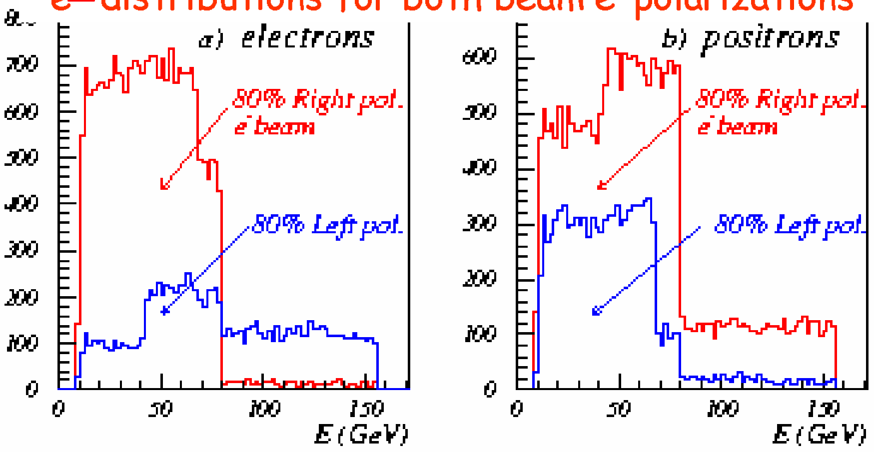




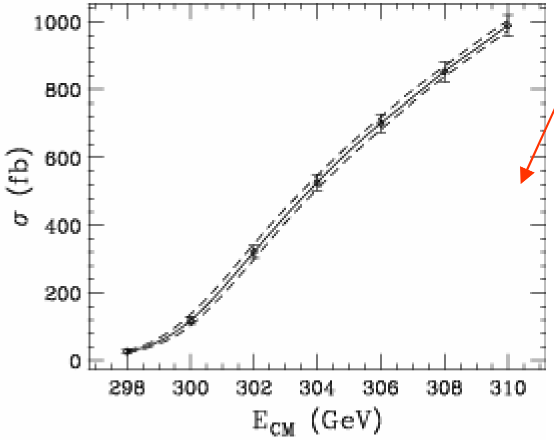
End point measurements for selectrons are more complex as can reach $\tilde{e}_R^+\tilde{e}_R^-$, $\tilde{e}_R^+\tilde{e}_L^-$, $\tilde{e}_L^+\tilde{e}_R^-$, and $\tilde{e}_L^+\tilde{e}_L^-$ states simultaneously.

Upper & lower end points of decay electron energy distribution from $\tilde{e}_{L,R} \longrightarrow e\ \chi_1^0$ gives masses of left and right handed selectrons and neutralino.

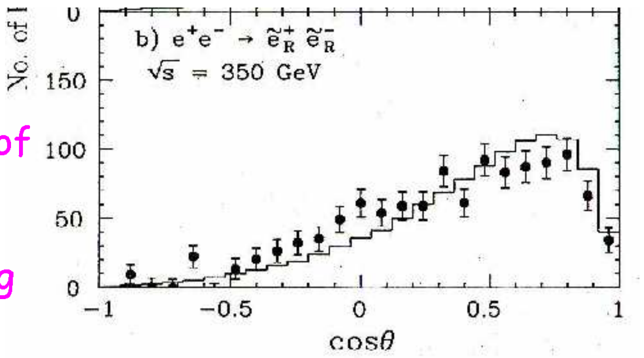
e± distributions for both beam e⁻ polarizations



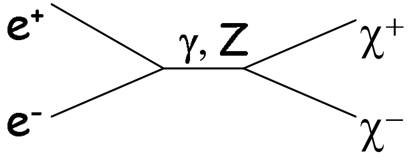
Do scan at threshold for very accurate masses
Here use e⁻e⁻ since this is s-wave (β^1), not p-wave (β^3) as for e⁺e⁻. Can achieve 20 MeV (0.01%).

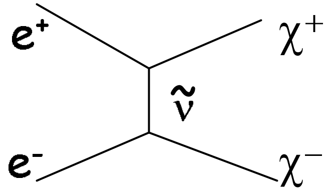


Angular distributions of decay electrons with polarized beams, give quantum numbers, coupling of exchanged $\chi_1^0$and give information on neutralino mixing, hence the underlying Susy mass parameters.



Chargino studies





Masses are again determined from end points in reactions like $e^+ e^- \longrightarrow \chi_1^+ \chi_1^-$, with decays:

$\chi_1^+ \longrightarrow \chi_1^0 W^+$ / $\chi_1^0 \ell \nu$ / $\chi_1^0 q' \bar{q}$

as for previous case (to few %).

The mass values of χ_1^+, χ_2^+ constrain the parameters that govern the mixing of eigenstates ($\tilde{W}^+ \tilde{H}^+$) into physical states (χ_1^+, χ_2^+). M_2 is mass of SU(2) Susy boson; μ is mass of Higgsino.

$$\begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix} = \begin{bmatrix} M_2 & 2m_W\cos\beta \\ 2m_W\sin\beta & \mu \end{bmatrix} \begin{pmatrix} W^+ \\ H^+ \end{pmatrix}$$

$$M^2(\chi_1^+) + M^2(\chi_2^+) = M_2^2 + 2\,M^2(W) + \mu^2$$

$$M(\chi_1^+) \times M(\chi_2^+) = \mu M_2 - M^2(W)\sin(2\beta)$$

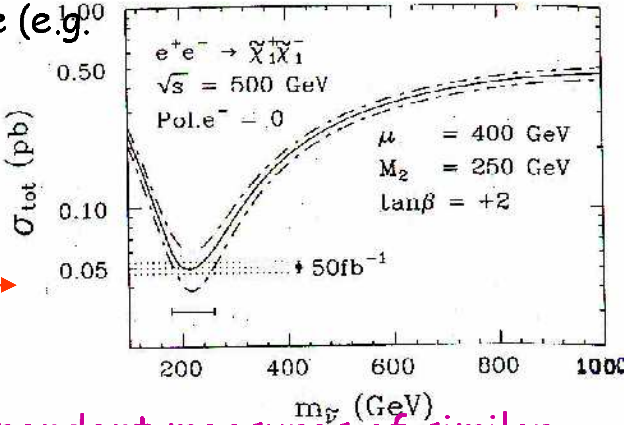
Thresholds for gauginos are β^1 (thus better mass precision than for scalars).

e^- Polarization is again crucial:

$e_R^- e^+ \rightarrow \chi_1^+ \chi_1^-$ removes the t-channel diagram; cross section and A_{FB} give the higgsino/wino content of χ_1^+. Tests of Susy relations are possible (e.g. measure M_W to ~ 23 MeV from purely Susy quantities.)

$e_L^- e^+ \rightarrow \chi_1^+ \chi_1^-$ allows test of SUSY coupling relation $g(\chi^+ \tilde{\nu} e) = g(W^+ \nu e)$

$e_L^- e^+ \rightarrow \chi_1^+ \chi_1^-$ has strong s & t channel interference, sensitive to $m(\tilde{\nu})$ to about 2 E_{CM}. →



Similar studies for neutralino, $\tilde{t}$, $\tilde{\tau}$, $\tilde{\mu}$, production lead to independent measures of similar parameters, neutralino mixing matrix, CP-violating phases and should enable a constrained fit to determine the Susy model.

LC Supersymmetry

The Linear Collider can determine the Susy model, and make progress to understand the high energy supersymmetry breaking scale. To do this, one would like to see the full spectrum of sleptons, gaugino/higgsino states.

Thresholds for selected sparticle pair productions -- at **LHC mSUGRA** model points.

Point reaction	1 GeV	2 GeV	3 GeV	4 GeV	5 GeV	6 GeV
$\chi_1^0\chi_1^0$	**336**	**336**	**90**	**160**	**244**	**92**
$\chi_1^0\chi_2^0$	**494**	**489**	**142**	**228**	**355**	**233**
$\chi_1^+\chi_1^-$	650	642	**192**	**294**	**464**	**304**
$\chi_1^+\chi_2^-$	1089	858	**368**	**462**	750	**459**
$\tilde{e}\tilde{e}/\tilde{\mu}\tilde{\mu}$	920	922	**422**	1620	**396**	**470**
$\tilde{\tau}\tilde{\tau}$	860	850	**412**	1594	**314**	**264**
Z h	**186**	**207**	**160**	**203**	**184**	**203**
Z H/A	1137	828	**466**	950	727	**248**
H^+H^-	2092	1482	756	1724	1276	**364**
$\tilde{q}\tilde{q}$	1882	1896	630	1828	1352	1010

RED: Accessible at e

BLUE: added at 1 TeV

These reference points need updating. New data rules some points out, but the message is still similar

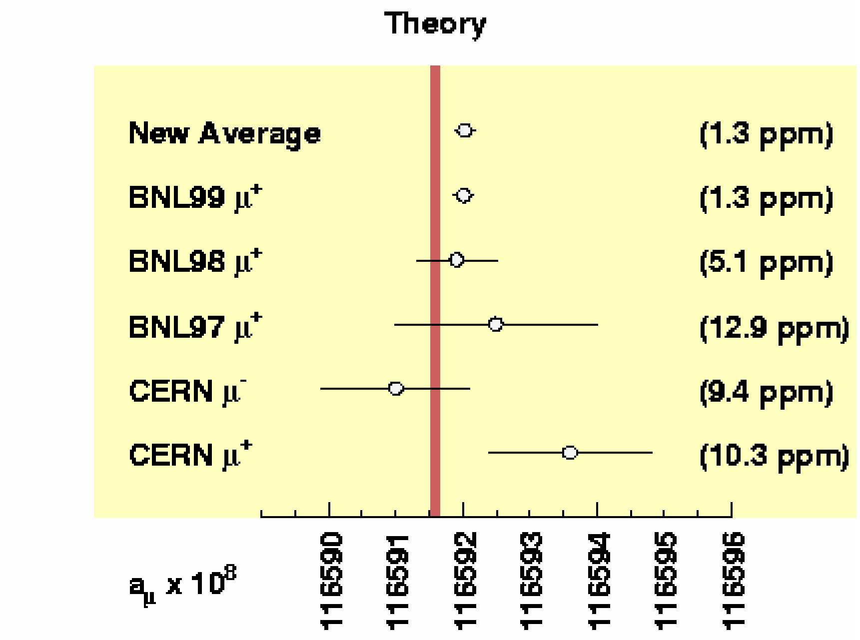
Operation in eγ mode can increase mass reach: e.g. $e^- \gamma \rightarrow \tilde{e}\,\tilde{\chi}_1^0$ need produce only a single $\tilde{e}$.

→ **It is likely that, in the case that supersymmetry exists, one will want upgrades of energy to at least 1 TeV.**

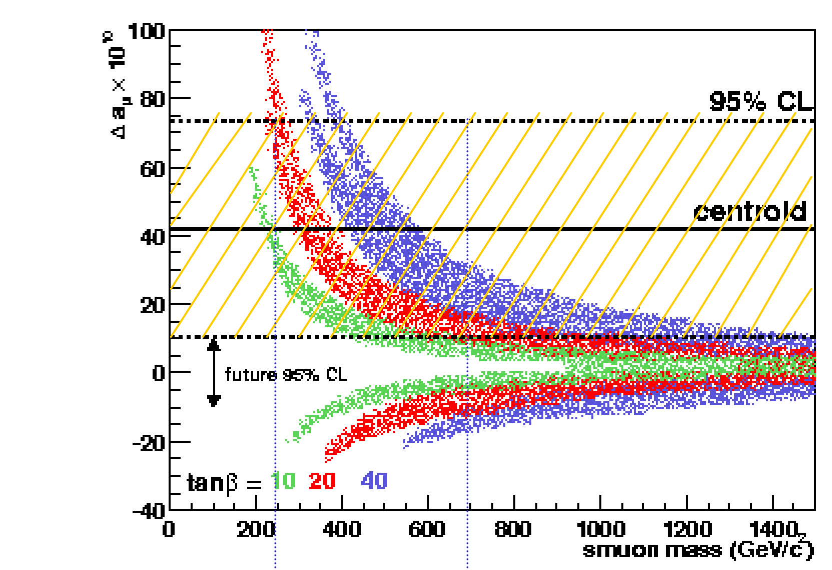
Muon (g-2)

Recent measurement of muon spin precession in BNL experiment gives accurate measurement of (g-2)/2:

$$\boxed{a_\mu^{expt} - a_\mu^{theory} = 42(16)\times10^{-10}}$$



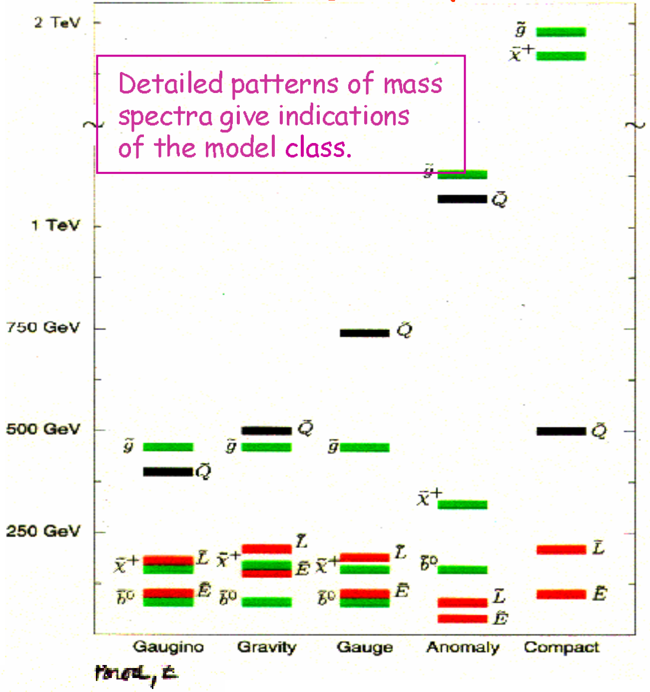
If interpret deviation as sparticles in vacuum polarization loops (smuons and charginos), can set some sparticle mass limits , suggesting relatively light Susy.



favored
mass region

Susy breaking mechanism

The LC complements the LHC. LHC will see those particles coupling to color. But some Higgs & sleptons, lighter gauginos only if present in cascade decays of squarks and gluinos. LC will do sleptons, sneutrinos, gauginos well. Electron polarization is essential for disentangling states and processes at LC.

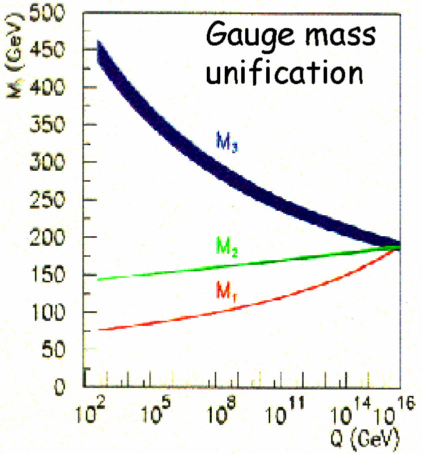


Detailed patterns of mass spectra give indications of the model class.

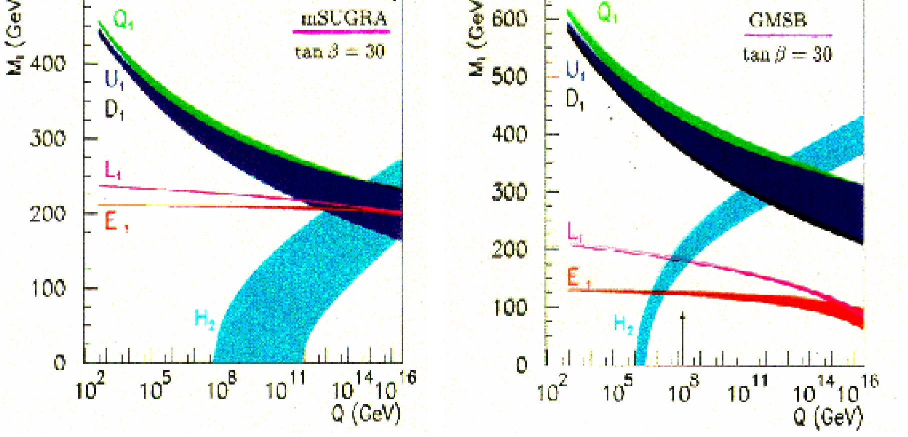
We really want understand the origin of Susy and determine the 105 soft parameters from experiment without assuming the model (mSUGRA, GMSB, anomaly, gaugino … mediation). We want to understand Susy breaking, gain insight into the unification scale and illuminate string theory.

Can use LC and LHC masses, cross sections, as input to RGE evolution of mass parameters, couplings reveal the model class without assumptions.

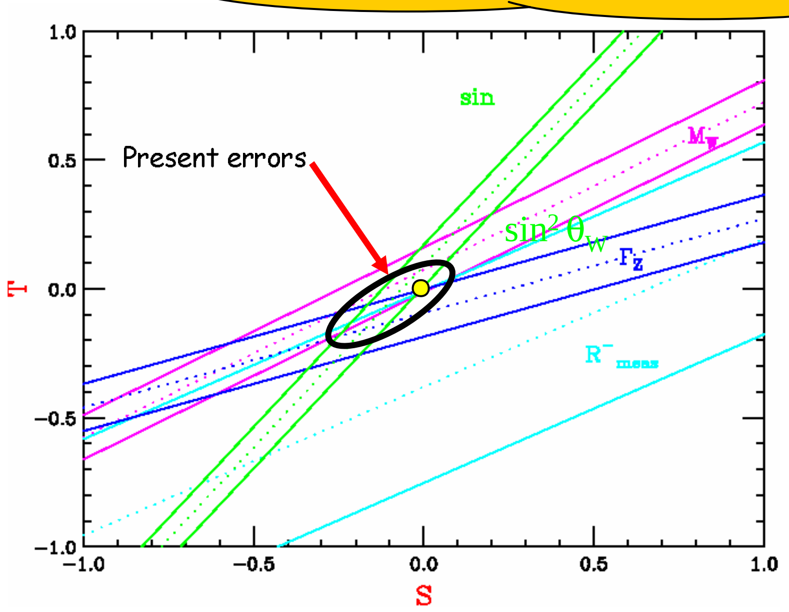
This study for ~ 1000 fb^{-1} LC operation, and LHC meas. of gluinos and squarks, shows unification at Susy breaking scale for mSUGRA, and a dramatically distinct mass parameter patterns for mSUGRA and GMSB.



Quark/lepton mass evolution



Precision studies constrain **ANY** new physics



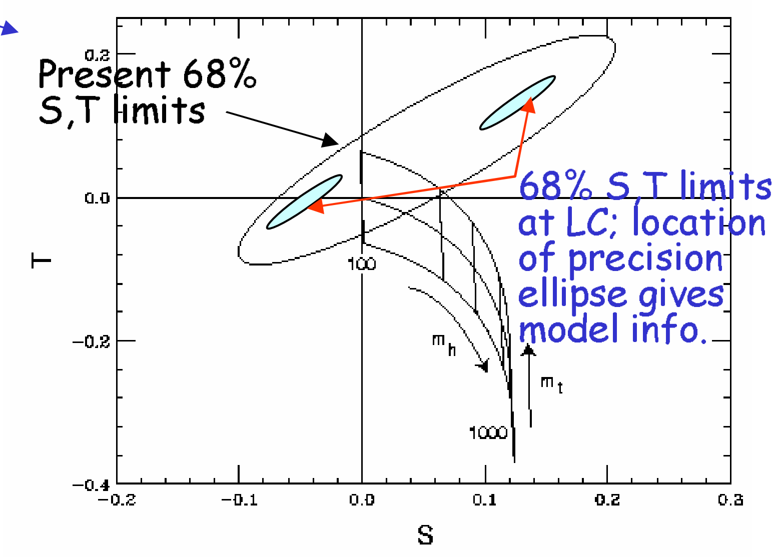
S & T parameters measure vacuum polarization effects on W/Z observables. S for weak isoscalar and T for isotriplet

All EW observables are linear functions of S & T and are presently measured to ±0.1, in agreement with the SM with a light Higgs.

The chevron shows the change in S & T as the Higgs mass increases from 100 to 1000 GeV, given the current top mass constraint. If the Higgs turns out to be heavy (> 200 GeV), we would need some compensating effects from new physics. Need a positive ΔT or negative ΔS. Several classes of models to do this, but it is difficult to evade their observable consequences at LC.

Giga-Z samples at LC (20 fb^{-1}) would improve $\sin^2\theta_W$ by x10 (requires e^+ polarization), WW threshold run improves δM_W to 6 MeV. LC will measure top mass to 200 MeV.

→ **Factor 8 improvement on S,T.**



Present 68% S,T limits

68% S,T limits at LC; location of precision ellipse gives model info.

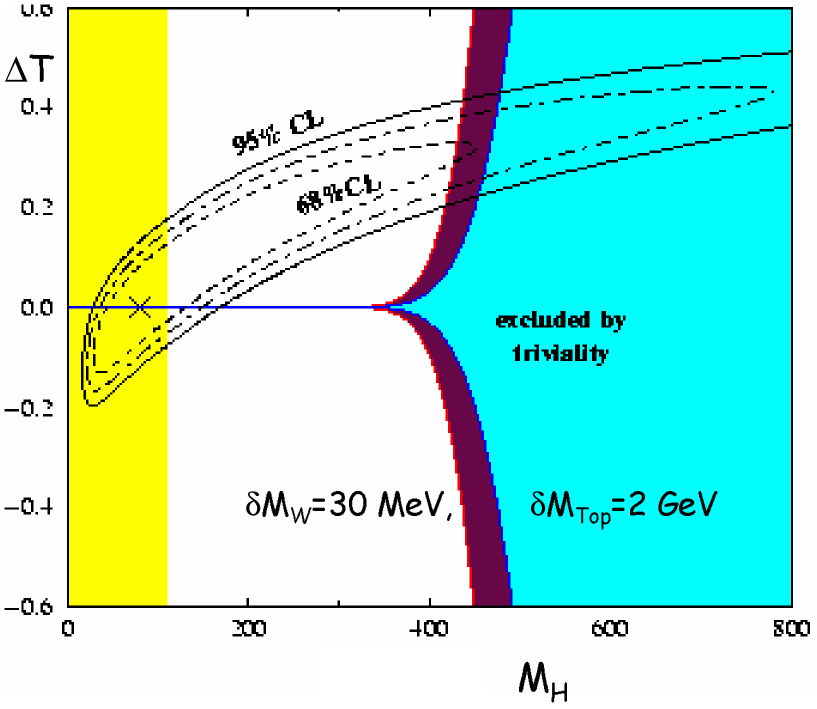
The precision measurement of S & T at a linear collider could be crucial to understand the nature of the new physics, if no Susy.

Strong Coupling Gauge Models

For many people, fundamental scalar fields are unnatural. We do however possess a theory (QCD) in which pseudoscalars (pions) arise as **bound states** of fundamental fermions. 'Strong Coupling' models were originally patterned after QCD (e.g. Technicolor), introducing new 'techni-quarks' at high masses, mimicking QCD color. Some of the 'technipions' could play the role of the Higgs boson, and thus introduce EWSB.

These theories, though appealing a priori, are difficult to make in agreement with recent precision measurements (S&T).

With **Giga Z** precision on EW properties at the LC, a strong coupling composite 'Higgs' should be constrained to < 500 GeV. Such a `Higgs', or other observable consequences of Strong Coupling, should be observable at the LC.

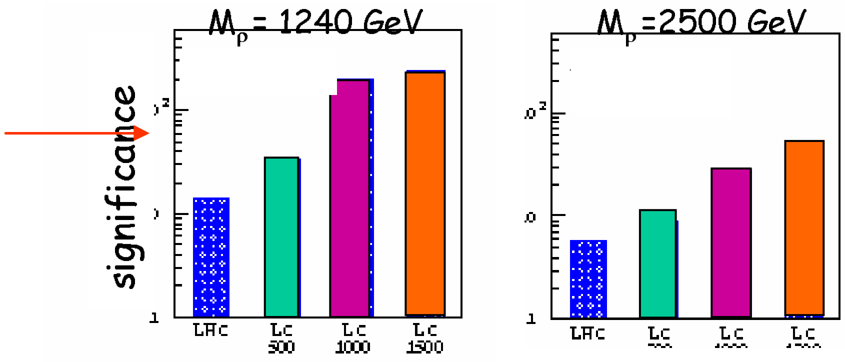


Strong Coupling Gauge Models

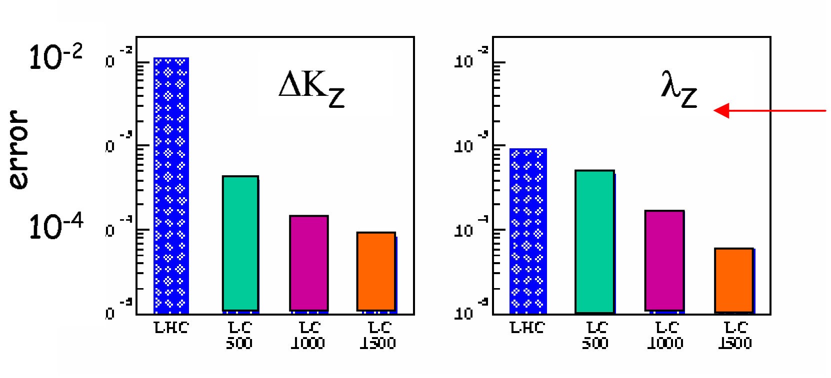
Observing Strong Coupling at LC:

Bound states of the new techniquarks should occur on the TeV scale. Also, since the longitudinal components of W/Z are primordial higgs particles, WW (ZZ) scattering is modified.

Signal significance technirho observation for **LHC** and **LC** at 500, 1000, 1500 GeV



Expect observable modifications to WWγ/WWZ couplings. For the anomalous magnetic moment of the W ($\Delta\kappa_{\gamma,Z}$), LC at 500 GeV has precision 10-20 times better than LHC – in the range expected in Strong Coupling models. $\gamma\gamma \rightarrow$ WW gives orthogonal information of comparable precision.



Errors on WWZ couplings for **LHC** and LC at 500 , 1000 , 1500 GeV.

Discovery reach for Z' at **LC500** is better or comparable to **LHC** for different models; better for **LC1000** by factor ~2.

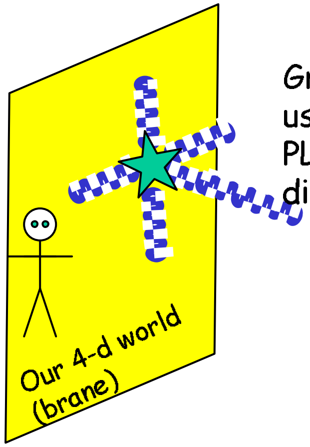
Anomalous top couplings to Z,γ are expected, only observable at LC.

Extra Dimensions

The only known path to a theory of quantum gravity and unification of all forces is string theory, in which extra curled-up spatial dimensions exist.

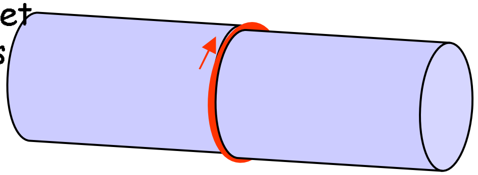
The chief defect of the SM is the hierarchy problem – our failure to understand why the EW scale at O(TeV) is so different from the scale of gravity at O(10^{15} TeV). Supersymmetry and Strong Coupling seek to solve this through new physics at the TeV scale that shields the EW interaction scale from instability.

Another possibility is to modify gravity by postulating extra dimensions in which gravity (or other fields) propagate. There are many possible phenomenologies to distinguish, depending on size of extra dimensions and which fields (gravity, gauge bosons, quarks …) propagate in the bulk.



Gravity propagating in usual 3+1 dim. brane PLUS δ extra (small) bulk dimensions.

Kinetic motion in small extra dimension gives 'particle in a box' set of modes called Kaluza Klein states as seen in 3+1 dimensions. Mass spacing depends on size of extra dimensions.

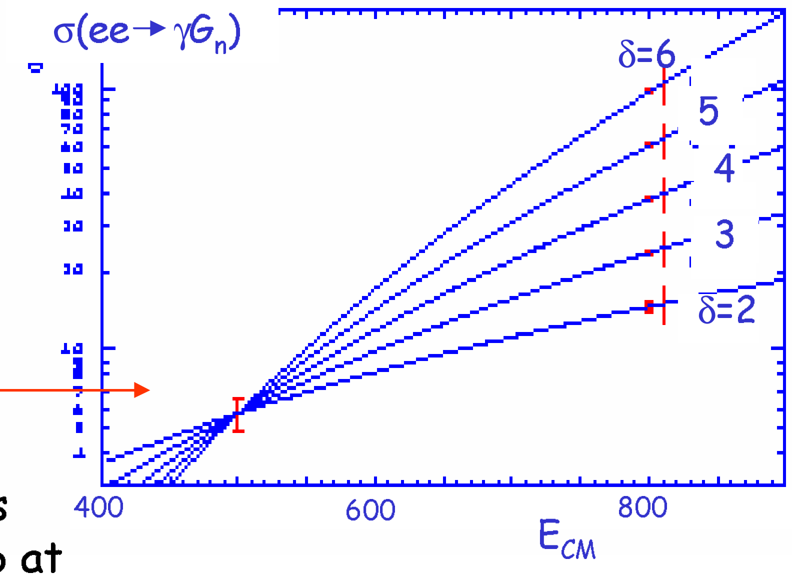


The KK states modify the amplitudes for observable processes, or can be directly observed at high mass.

Extra Dimensions examples

- **'Large' Extra Dimensions (μm scale):**

gravity propagates in 4+δ dimensions with true Planck scale = $M_* \ll M_{Planck}$. Towers of KK states modify $ee \to \gamma/Z$ + unseen G_{KK} rate or angular distributions in $e^+e^- \to f\bar{f}$. LC500 and LHC are comparable in reach for fundamental Planck scale M_*; The E_{CM} dependence at LC gives δ.

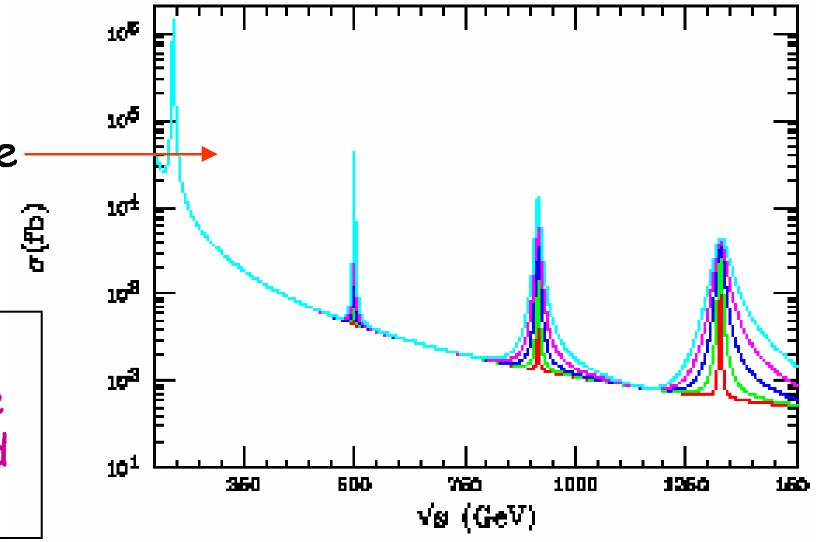


If supersymmetry in the bulk, KK tower of gravitinos modifies $ee \to \tilde{e}\tilde{e}$, sensitive to M_* = 12 TeV for δ = 6 at LC500, using polarized e^-.

Polarized $\gamma\,\gamma \to$ WW process has larger sensitivity to graviton exchange for large ED than e^+e^- or LHC.

- **Warped ED/localized gravity:**

Sensitivity to KK resonances at LC500 is comparable to LHC; LC1000 exceeds LHC.



There are many phenomenological models of Extra Dimensions; LC500 sensitivity is roughly comparable to LHC, but gives complementary information needed to unscramble the character of the model.

Scenarios

Are there physics scenarios for which the LC does not add critical information?

- We have looked at many possible physics situations, including cases where low scale supersymmetry does not exist, or the Higgs is at unexpectedly high mass.
- We do not see a case where the LC cannot find and study the Higgs, though it is possible that one would need a bit than 500 GeV. In the case of $M_H > 200$ GeV, where $H \rightarrow WW$ predominantly (e.g. in Strong Coupling models), one would learn less about the Higgs sector (no fermionic couplings), but still significantly more than LHC.
- If there is Susy, the LC should be the instrument of choice for its study – but going to higher energy ultimately to see all the states would be very desirable.
- If there is no Susy (Strong Coupling or Extra Dimensions), the LC will add information not available from the LHC. In these cases, the Giga-Z option may be crucial, as the constraints from precision measurements on the new physics will be very important. In the most extreme (and unexpected) case of no Higgs and no new physics, the precision measurements will be a critical need.

We have looked at a potential allocation of running time for a physics rich case – 120 GeV Higgs and low mass Susy – asking whether all the energy settings, beam polarizations, beam particles (e^+,e^-,γ) can be accommodated in reasonable time. For 1 ab^{-1}(~ 6 years of operation), we find excellent precision on Higgs parameters (coupling errors at few % level), and find that the accessible Susy particles can be disentangled with masses measured to precisions of ~ (0.1 – few) %.

Realizing a Linear Collider

- **Recent high level studies assessing the priority of future new projects in Europe (ECFA), Asia (ACFA) and the US (HEPAP) all concluded resoundingly that the LC was the highest priority for a next step.**

  - Expect technical proposals and proposals to site a LC from each of the three regions. The TESLA proposal is now before the German Science Ministry, a recommendation expected in 2002.

  - The cost of the LC will be high – multi B$ (estimates differ in assessing manpower costs, upgrades contingency, etc.) No more than one LC in the world !

  - Perhaps the next major step to be taken is a recommendation on the technology for the LC – superconducting TESLA with simpler beam dynamics issues vs. NLC/JLC with better potential for energy upgradability. An international committee charged by ICFA is evaluating the technical merits, comparative costs, and R&D issues – report in late 2002? (but not a decision making body!) We need a method for making this choice in the 2003 – 2004 time frame.

  - The choice of site will be difficult; it will likely be driven by the region that is willing to put up the majority of the funding (~2/3 ?)

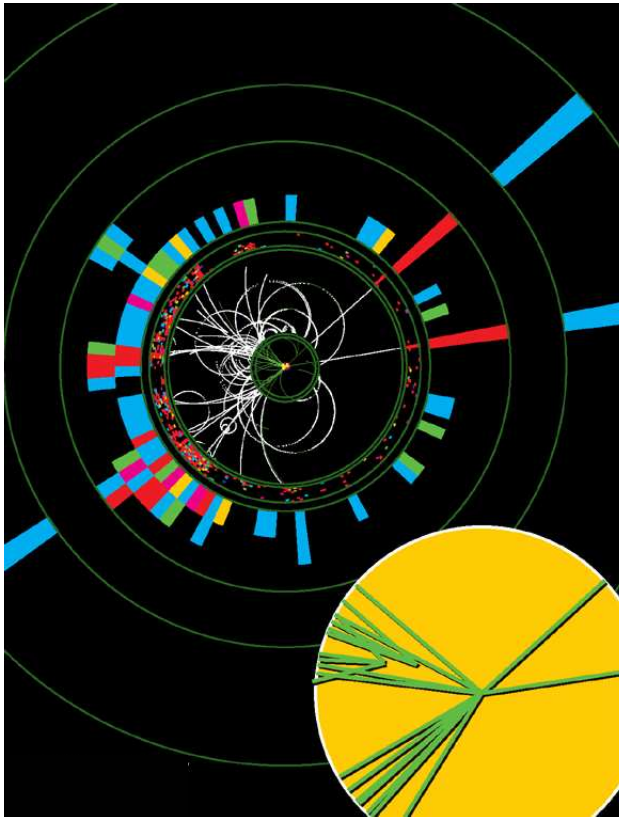
  - To succeed, the LC will have to be international from the start. To maximize the involvement of all regions, and to ensure each region's physics and accelerator community's vitality, there should be assignment of major portions of the project to each region – encompassing design, fabrication, assembly, commissioning and maintenance. The Global Accelerator Network proposal envisions direct remote responsibility for operations across the globe.

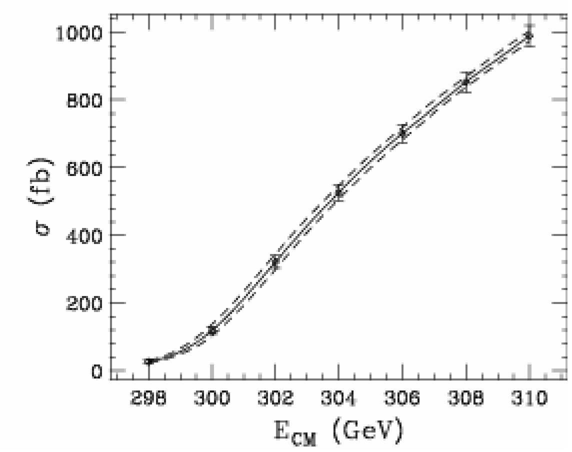
- **Realizing effective international cooperation on a project of this magnitude is a great challenge. HEP has pioneered such collaboration on the smaller scale of large collider detectors in the past. We can help establish the paradigm for future international scientific cooperation.**

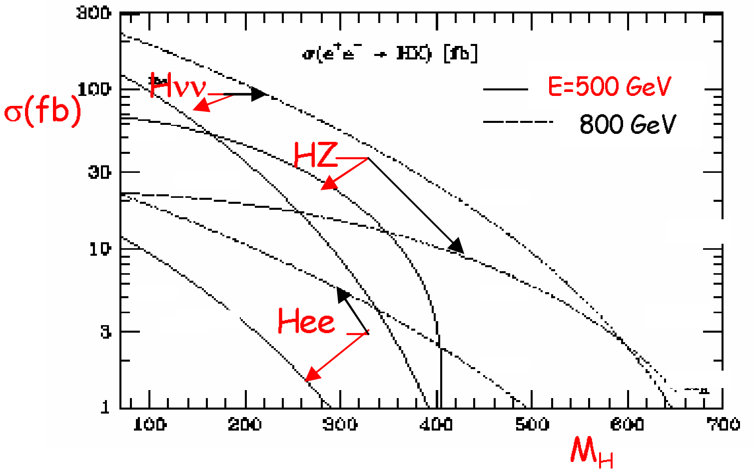
Summary

- A Linear Collider, starting at 500 GeV and expanding to higher energy, will bring crucial understanding of the main questions before our field, significantly beyond that obtained at LHC. It should provide definitive understanding of Electroweak Symmetry Breaking, and may give insights into questions such as dark matter, CP violation & the role of flavor.

- A Linear Collider is technically challenging and expensive it can only be achieved through international cooperation




1000
800
600
400
200
0
σ (fb)
298
300
302
304
306
308
310
E_CM (GeV)


σ(e+e− → HX) [fb]
E=500 GeV
800 GeV
Hνν
HZ
Hee
σ(fb)
300
100
30
10
3
1
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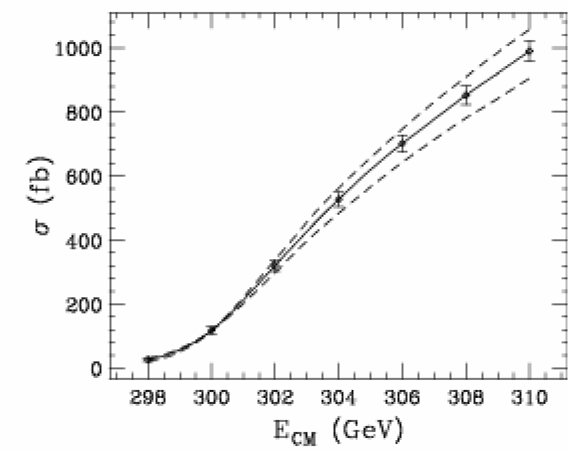
500
600
700
M_H


1000
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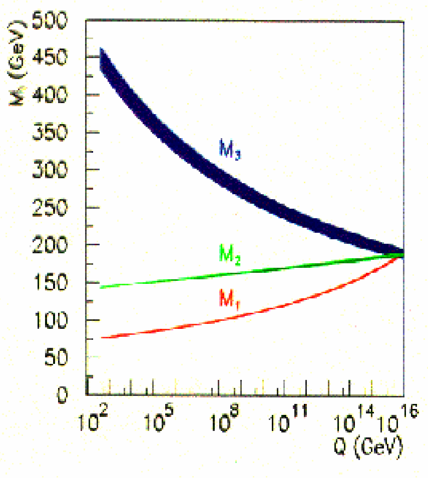
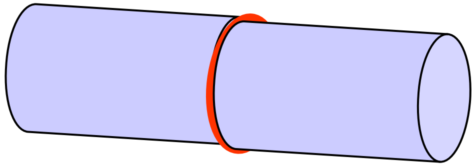
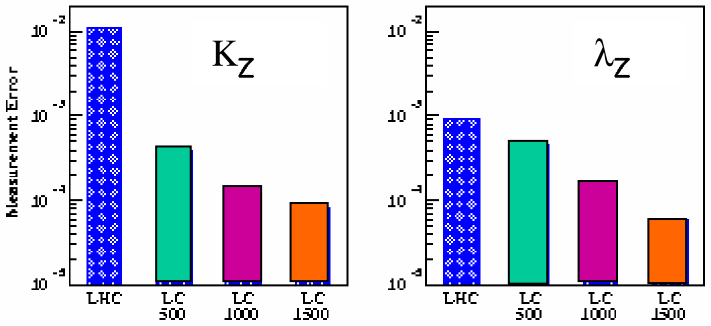
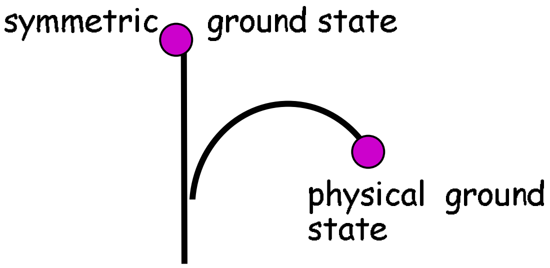
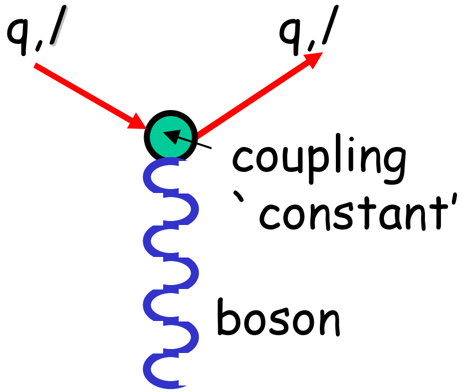
σ (fb)
298
300
302
304
306
308
310
E_CM (GeV)


Mᵢ (GeV)
500
450
400
350
300
250
200
150
100
50
0
10^2
10^5
10^8
10^{11}
10^{14}
10^{16}
Q (GeV)
M_3
M_2
M_1

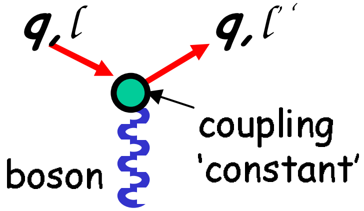


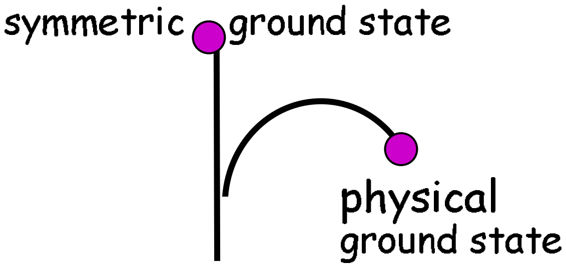

Measurement Error
10^{-2}
10^{-3}
10^{-4}
10^{-5}
K_Z
λ_Z
LHC
LC 500
LC 1000
LC 1500

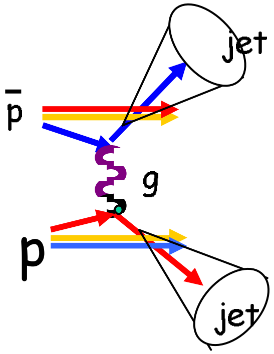


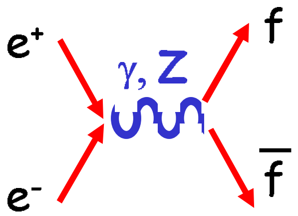


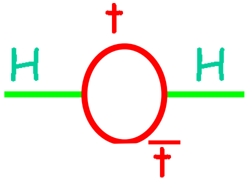
$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} b^0 \\ \omega^0 \end{pmatrix}$$

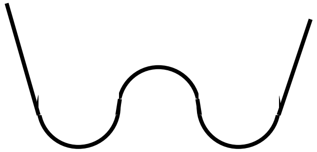


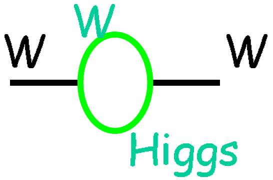


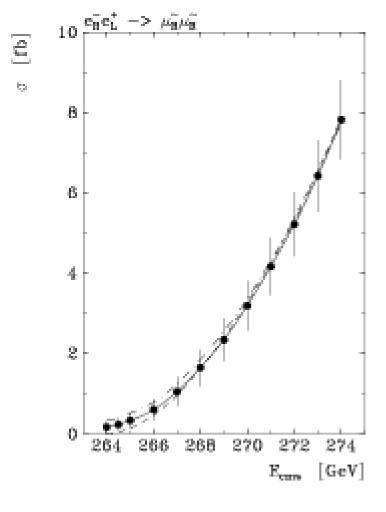

jet
p̄
g
p
jet

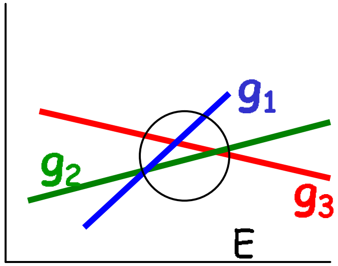

e+
γ, Z
f
e-
f̄

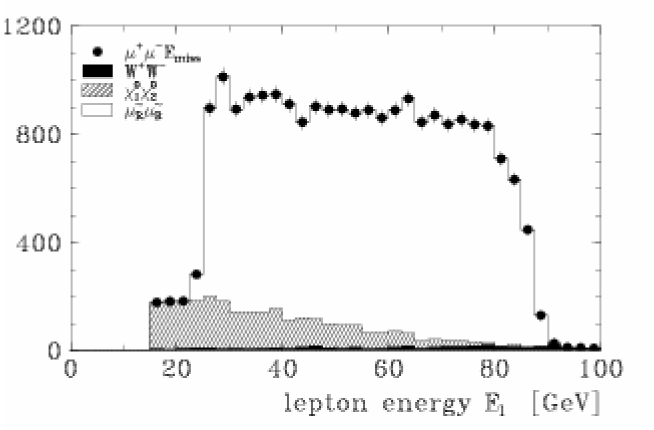

t
H
H
t̄




W
W
W
Higgs


$e^-_R e^+_L \to \tilde{\mu}_R \tilde{\mu}_R$
σ [fb]
0
2
4
6
8
10
264
266
268
270
272
274
E_{cms} [GeV]


g_1
g_2
g_3
E


1200
800
400
0
0
20
40
60
80
100
lepton energy E_l [GeV]
● $\mu^+\mu^- E_{miss}$
W^+W^-
$\chi^0_1\chi^0_2$
$\tilde{\mu}_R\tilde{\mu}_R$