Introduction to Linear Collider Physics

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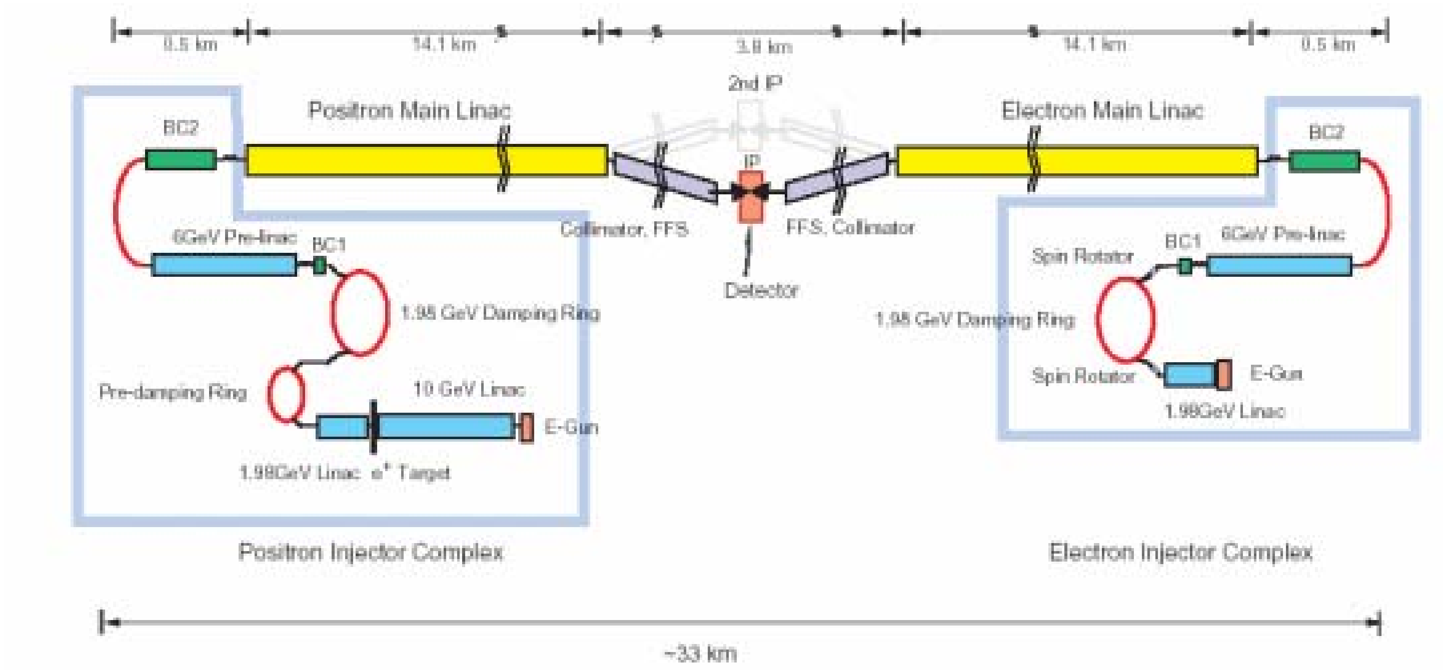
ACFA LC Workshop, TIFR,
Mumbai, December 15, 2003

Linear Collider Project

- Highest energy e+e- collider

  Ecm: up to 500 GeV in 1st stage ,~1TeV in 2nd stage
- Luminosity: above 10^34/cm^2/s,(equivalent to a few x10^4 Higgs bosons /year)
- Concurrent running with LHC



GLC report

Current understanding of particle physics

- The Standard Model

Discovery of gluon, W, and Z bosons

Discovery of three generations of quarks and leptons.

Precise determinations of V-F-F, and V-V-V coupling constants.

CP violation in terms of Kobayashi- Maskawa mechanism

No direct evidence on the Higgs mechanism

Hints of new physics

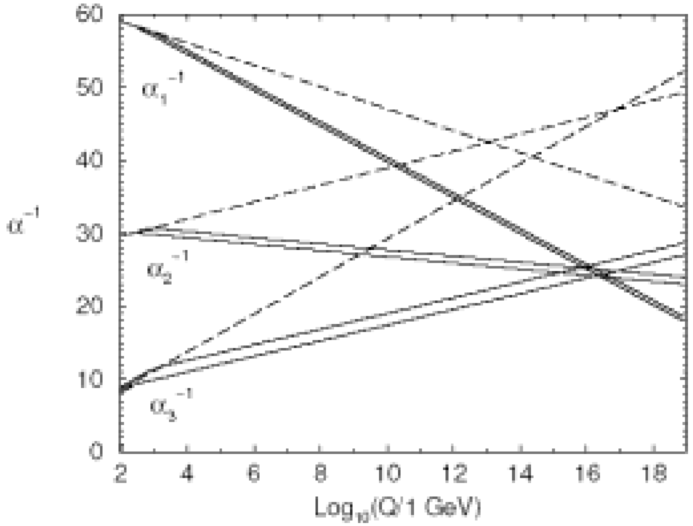
1. Unification ?
Gauge coupling unification in SUSY GUT

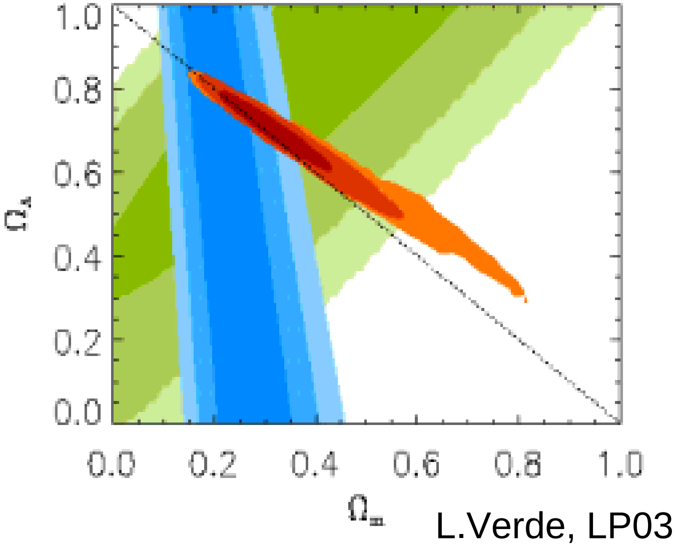
2. Neutrino mass. Seesaw mechanism?

3. Cosmological connection with particle physics

WMAP -> Dark matter candidate?
Baryon number of the Universe-> New source of CP violation?

4. Theoretical arguments
Hierarchy problem, Unification with gravity interaction, Superstring…





L.Verde, LP03

Physics of LC

- Higgs physics (Electroweak symmetry breaking and mass-generation)
- Direct signals of new physics (SUSY, extra-dimensions, …)
- Indirect search for new physics from precision study on gauge bosons, top and other fermion processes.
- “Unexpected” new signals

Advantage of LC experiments

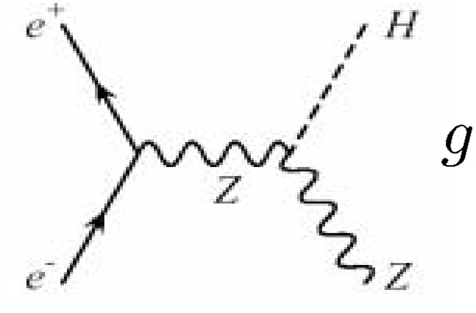
- e+ and e- are elementary particle (well-defined kinematics).
- Less background than LHC experiments.
- Beam polarization, energy scan.
- γ - γ, e- γ, e- e- options, Z pole option.
- Energy extendibility

We should clarify how these features can enhance physics potentials of LC experiments.

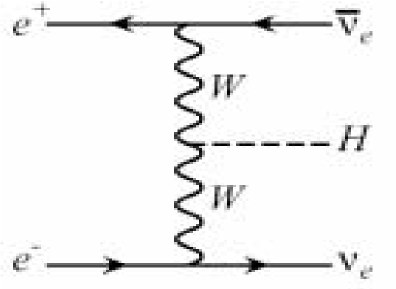
Higgs Physics

- Higgs boson. An important prediction of the modern particle physics.
- Mass-generation of elementary particles

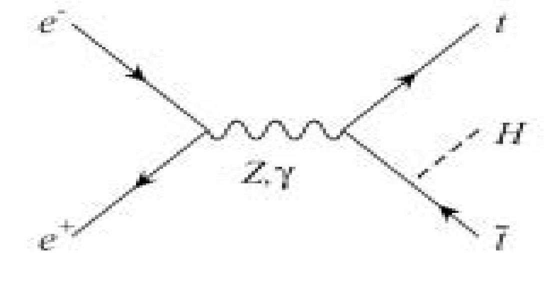
=> Higgs coupling measurements



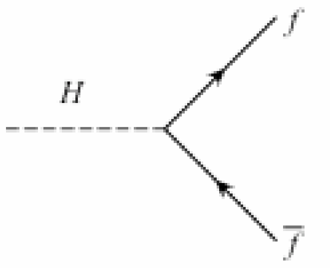
g_{ZZH}



g_{WWH}



$y_{t\bar{t}H}$

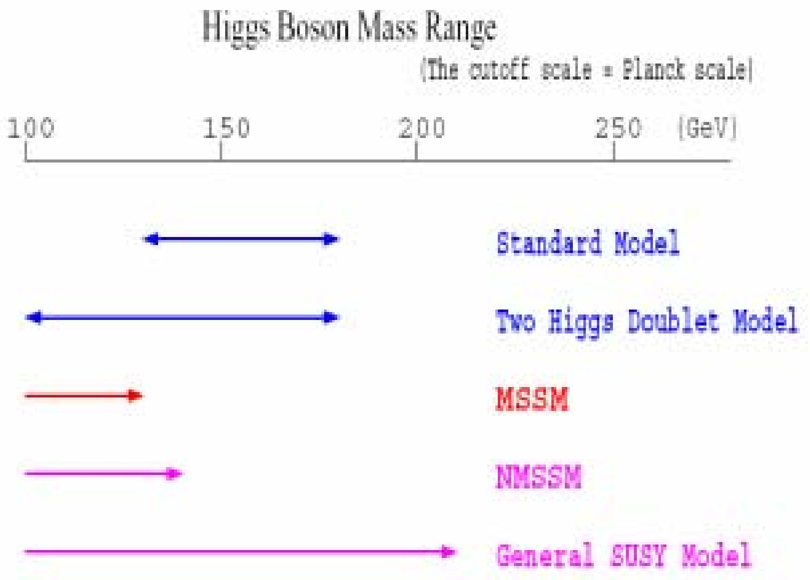


$y_{f\bar{f}H}$

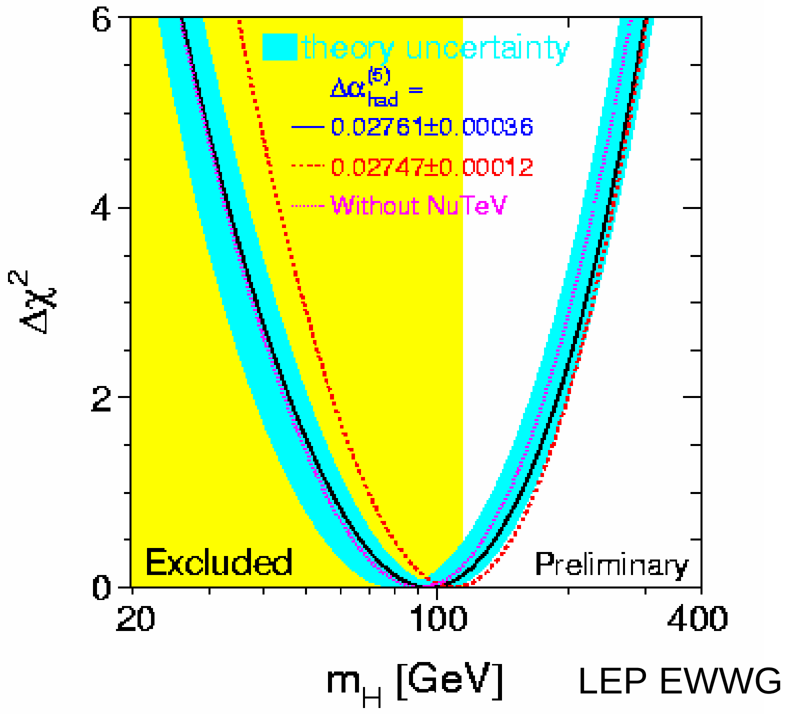
Higgs Boson Mass

The most important parameter : related to the strength of the force responsible for electroweak symmetry breaking.

Unification theory from the Planck scale (SUSY, String theory, etc)
=> a light Higgs boson



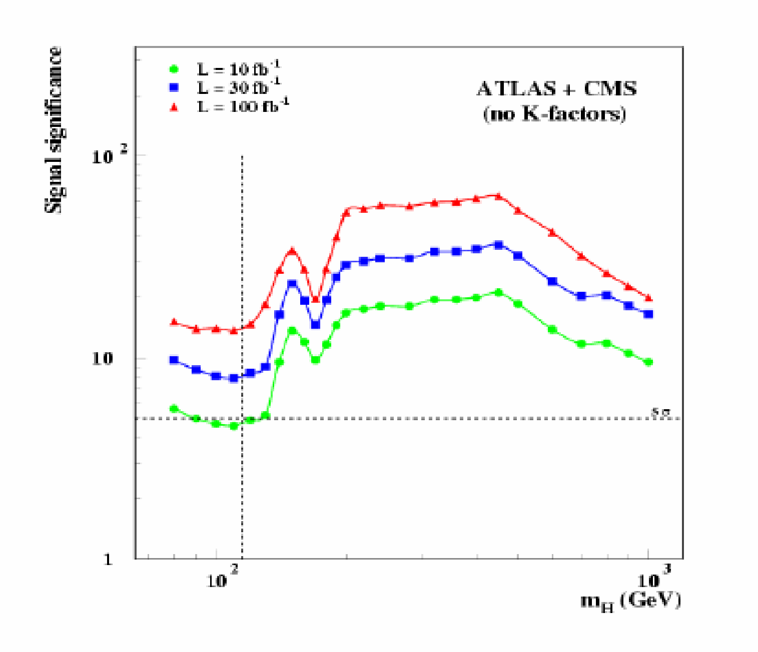
Current bounds on SM Higgs boson mass



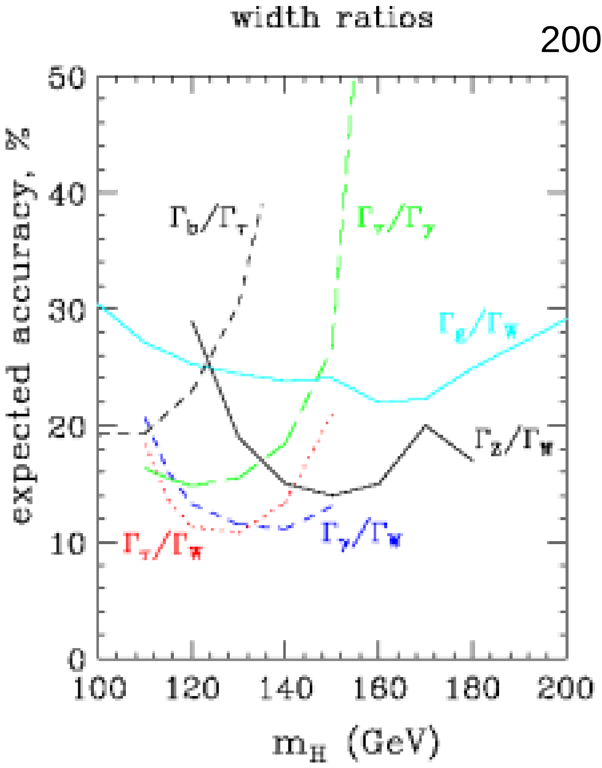
$$114 \text{ GeV} < m_H < 219 \text{ GeV } (95\%\text{CL})$$

Higgs physics at LHC

Discovery of a SM Higgs boson in a whole mass range



Coupling ratio measurements



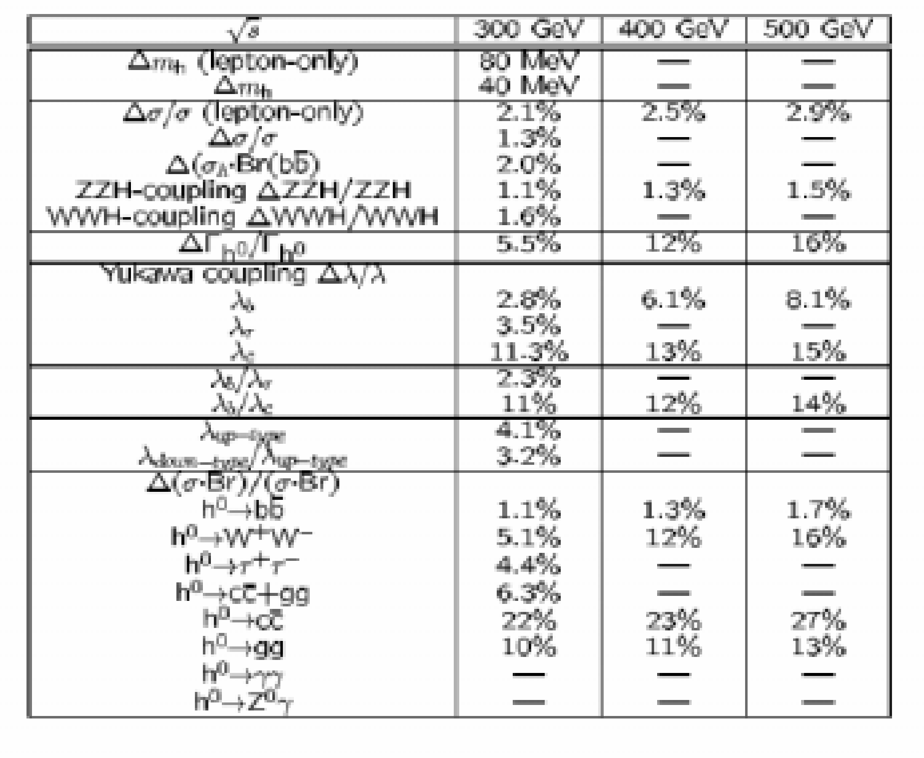
200/fb

Higgs partial width ratio:
a few x 10 %

The Precision Higgs WG of Smowmass 2001

Coupling measurements at LC

Precision of coupling determination
mH=120 GeV, 500/fb



$\sqrt{s}$	300 GeV	400 GeV	500 GeV
Δm_h (lepton-only)	80 MeV	—	—
Δm_h	40 MeV	—	—
$\Delta\sigma/\sigma$ (lepton-only)	2.1%	2.5%	2.9%
$\Delta\sigma/\sigma$	1.3%	—	—
$\Delta(\sigma_h \cdot Br(b\bar{b}))$	2.0%	—	—
ZZH-coupling ΔZZH/ZZH	1.1%	1.3%	1.5%
WWH-coupling ΔWWH/WWH	1.6%	—	—
$\Delta\Gamma_{h^0}/\Gamma_{h^0}$	5.5%	12%	16%
Yukawa coupling $\Delta\lambda/\lambda$			
λ_b	2.8%	6.1%	8.1%
λ_τ	3.5%	—	—
λ_c	11.3%	13%	15%
λ_b/λ_τ	2.3%	—	—
λ_b/λ_c	11%	12%	14%
$\lambda_{up-type}$	4.1%	—	—
$\lambda_{down-type}/\lambda_{up-type}$	3.2%	—	—
$\Delta(\sigma \cdot Br)/(\sigma \cdot Br)$			
$h^0 \to b\bar{b}$	1.1%	1.3%	1.7%
$h^0 \to W^+W^-$	5.1%	12%	16%
$h^0 \to \tau^+\tau^-$	4.4%	—	—
$h^0 \to c\bar{c}+gg$	6.3%	—	—
$h^0 \to c\bar{c}$	22%	23%	27%
$h^0 \to gg$	10%	11%	13%
$h^0 \to \gamma\gamma$	—	—	—
$h^0 \to Z^0\gamma$	—	—	—

A few % level

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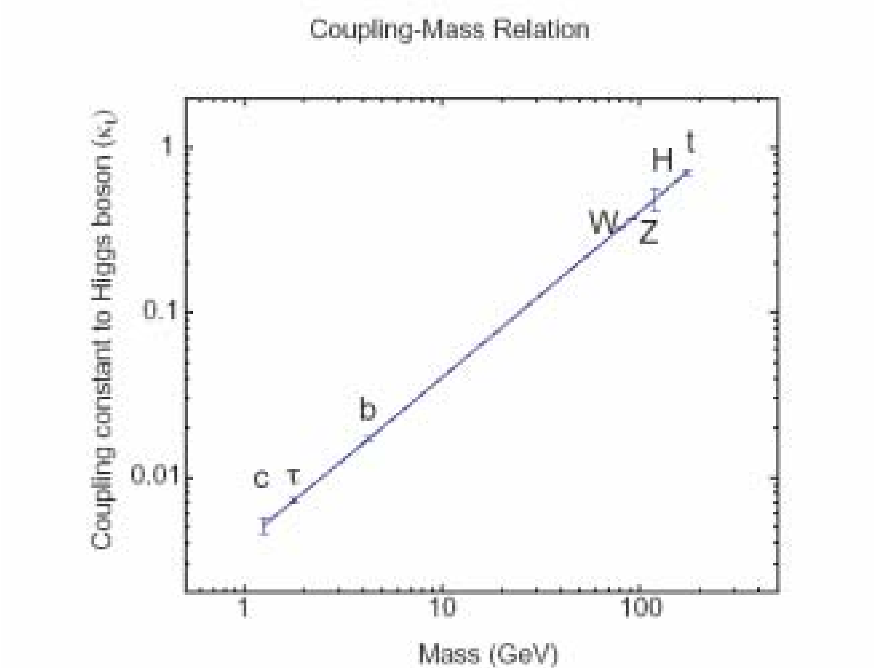

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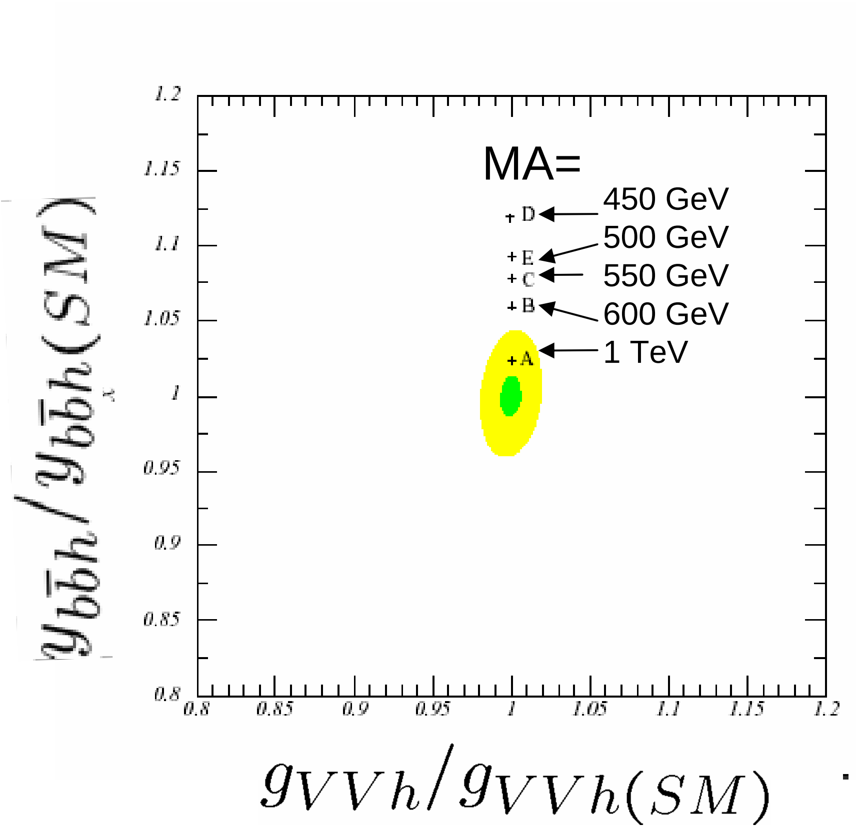
Particle mass

$$m_i = v \times \kappa_i$$

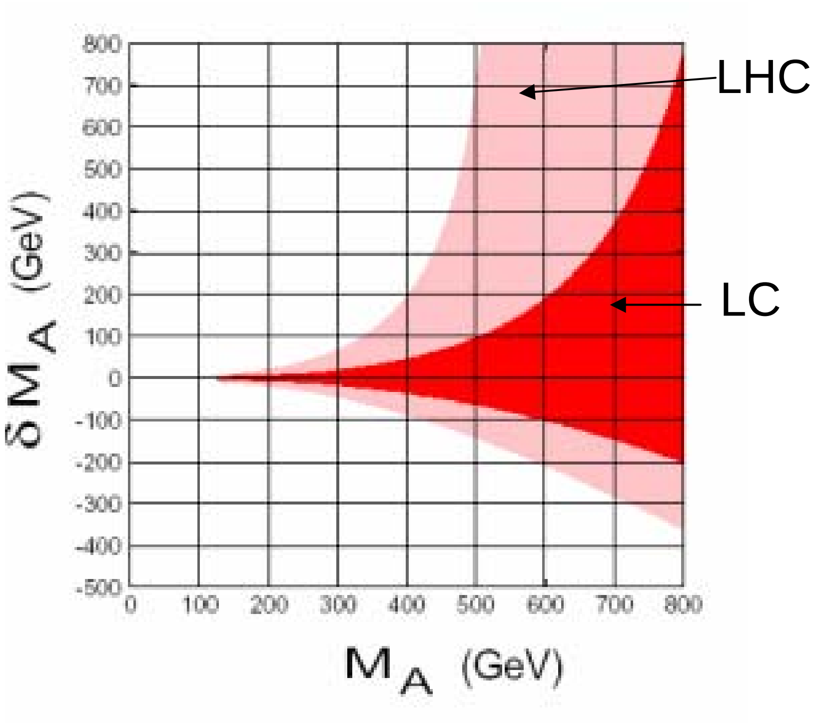
Higgs coupling constant

Implications to MSSM

Indirect determination of the heavy Higgs boson mass (MA)



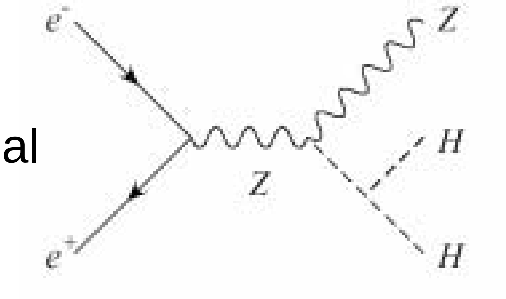
MA=
450 GeV
500 GeV
550 GeV
600 GeV
1 TeV

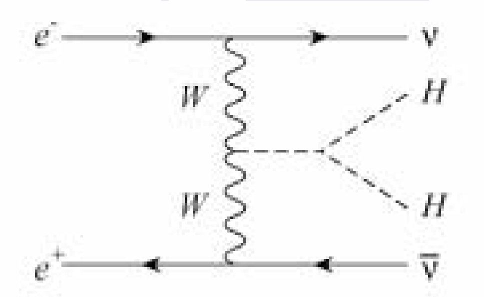


LHC
LC

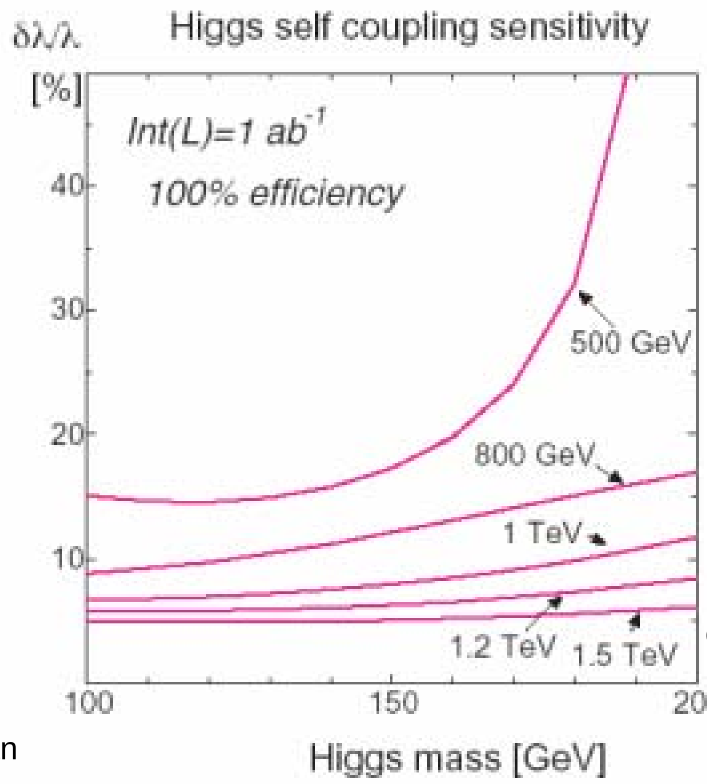
ACFA report

Higgs self coupling constant





- The first access to the Higgs potential
- Need a higher energy for precise determination
- The Higgs potential can receive a large loop correction, for example, in Two Higgs Doublet Model.



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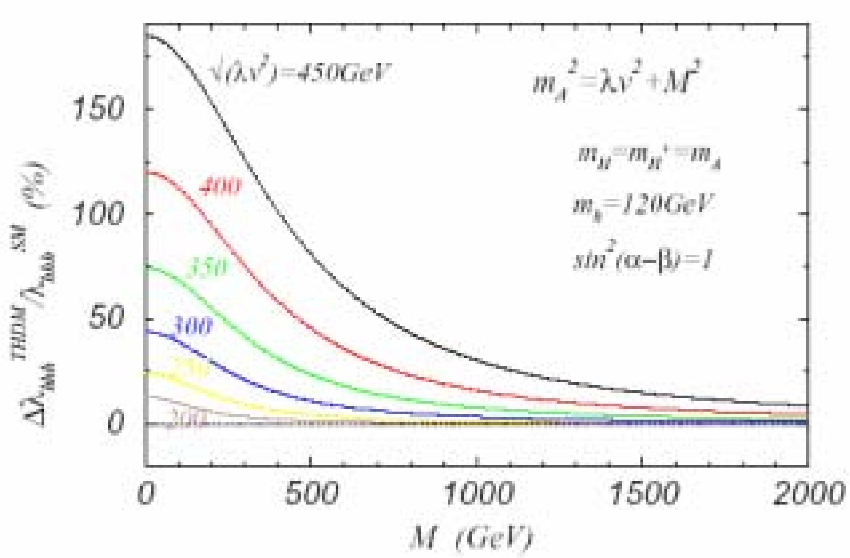
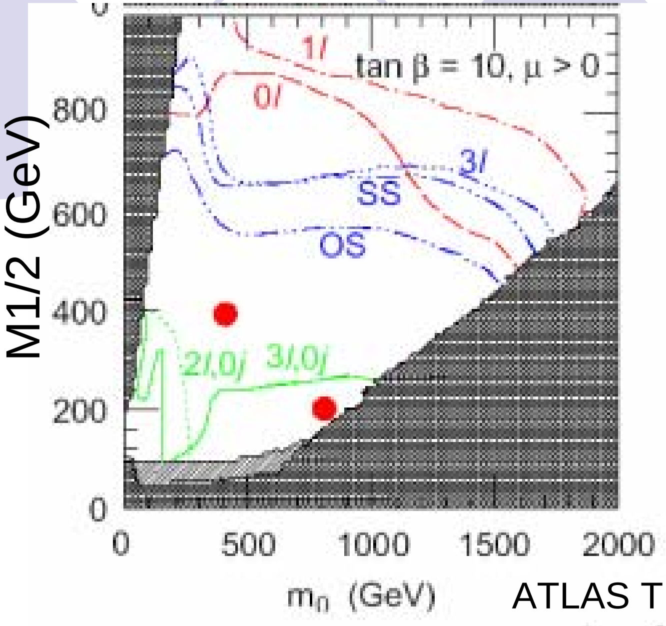


S.Kanemura, S.Kiyoura, Y.Okada, E.Senaha, and C.-P. Yuan

Supersymmetry

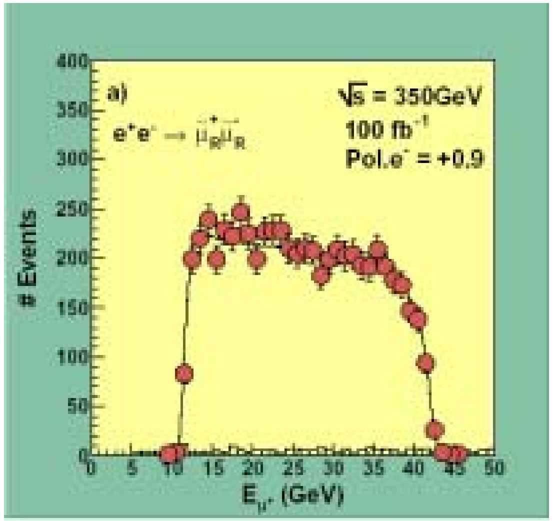
- New concept on space-time.
- LHC can find SUSY if squarks and gluino is less than 2.5TeV through cascade decays.
- LC is an ideal place to study SUSY. A beam polarization and threshold scan are powerful tools.
- Determination of mass and spin of SUSY particles.
- Determination of coupling constants.
- LC is necessary to establish new physics principle.

LHC SUSY search



ATLAS TDR

Smuon pair production in LC



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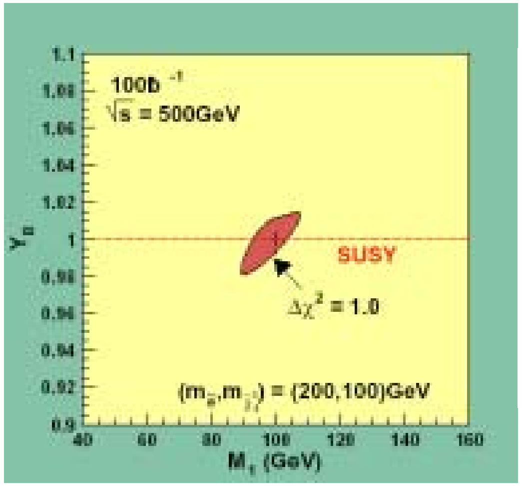
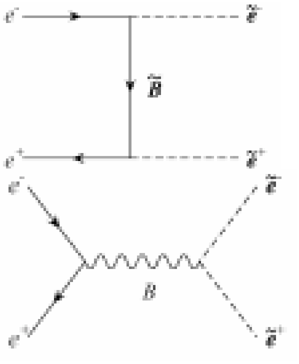
SUSY study at LC

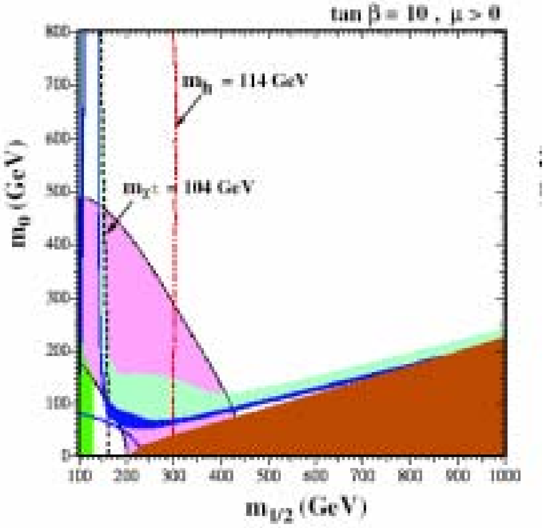
(1) Test of SUSY relation $Y_B = \frac{g_{\tilde{B}\tilde{e}_R e}}{g_{Bee}}$





M.M.Nojiri, K.Fujii, and T.Tsukamoto

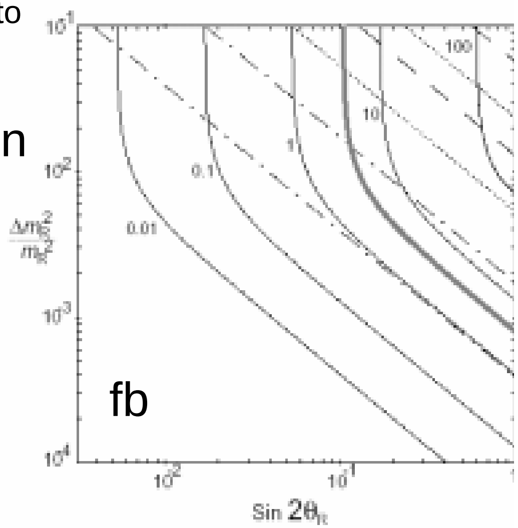
(2) Dark matter candidate: properties of the lightest SUSY particle



J.Ellis,K.A.Olive, Y.Santoso, and V.C.Spanos

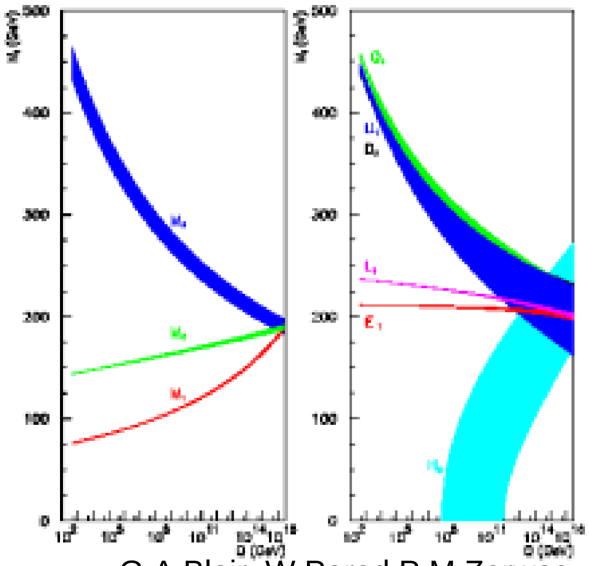
(3) Neutrino oscillation
-> lepton flavor violation
In slepton production

$$\sigma(e^+ e_R^- \to e\mu\chi^0\chi^0)$$



N.Arkani-Hamed, H.Cheng,J.L.Feng, and L.J.Hall

(4) SUSY breaking scenario
& GUT relation (LHC +LC)



G.A.Blair, W.Porod,P.M.Zerwas

SUSY Higgs sector

Two Higgs doublet model

$\tan\beta$ (vacuum angle)

$$m_h = f(m_A, \tan\beta, m_t, m_{\tilde{t}}, \ldots)$$

Determination of tan β from:
mass formula,
heavy Higgs decay branching,
stau decay,
chargino-neutralino sector…

↔

EW gauge interaction

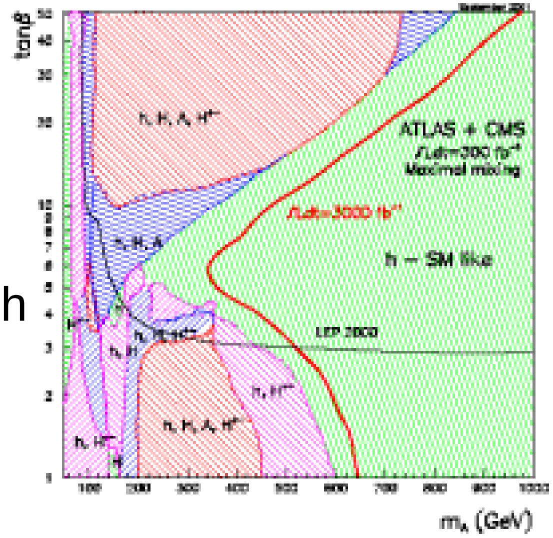
$\sin\theta_W$ (gauge boson mixing angle)

ρ -parameter

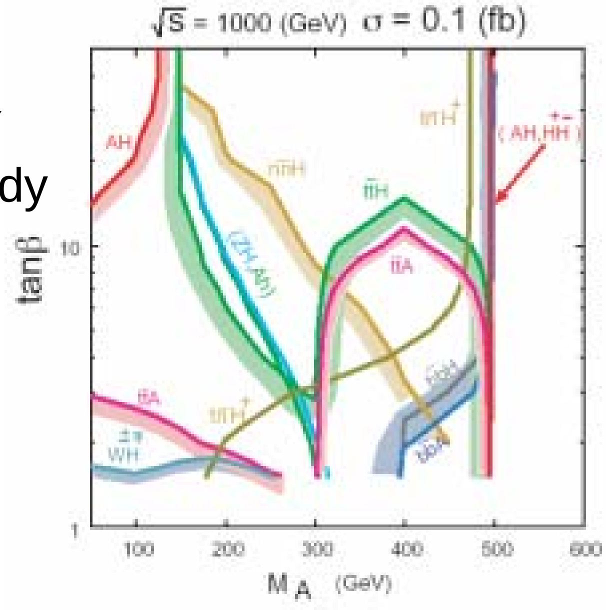
Determination of sin θw from
various EW processes (LEP, SLC).

LHC SUSY

Higgs search



LC SUSY
Higgs study



S.Kiyoura et al, GLC report

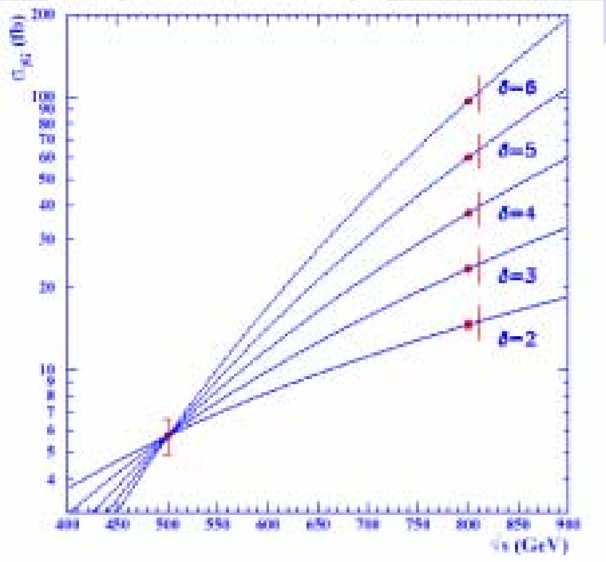
Large extra-dimensions

- An alternative solution to the hierarchy problem.
- A variety of models.
- Spectacular signals are possible at LHC (Black hole production, etc)
- LC is important to clarify what is going on.

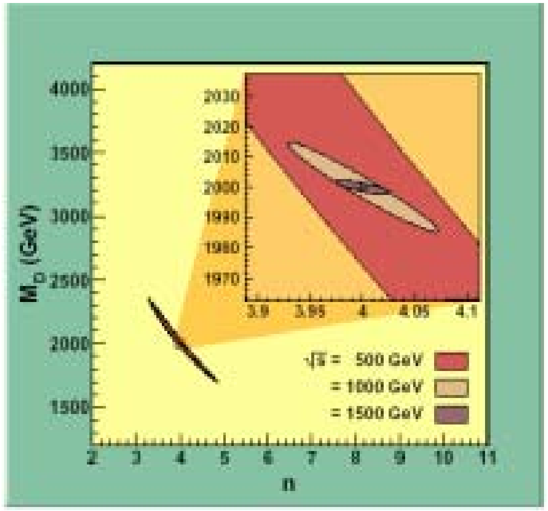
  Size and numbers of extra-dimensions,

  spin 2 property of Kaluza-Klein gravitons.

$$e^+e^- \rightarrow \gamma + graviton$$



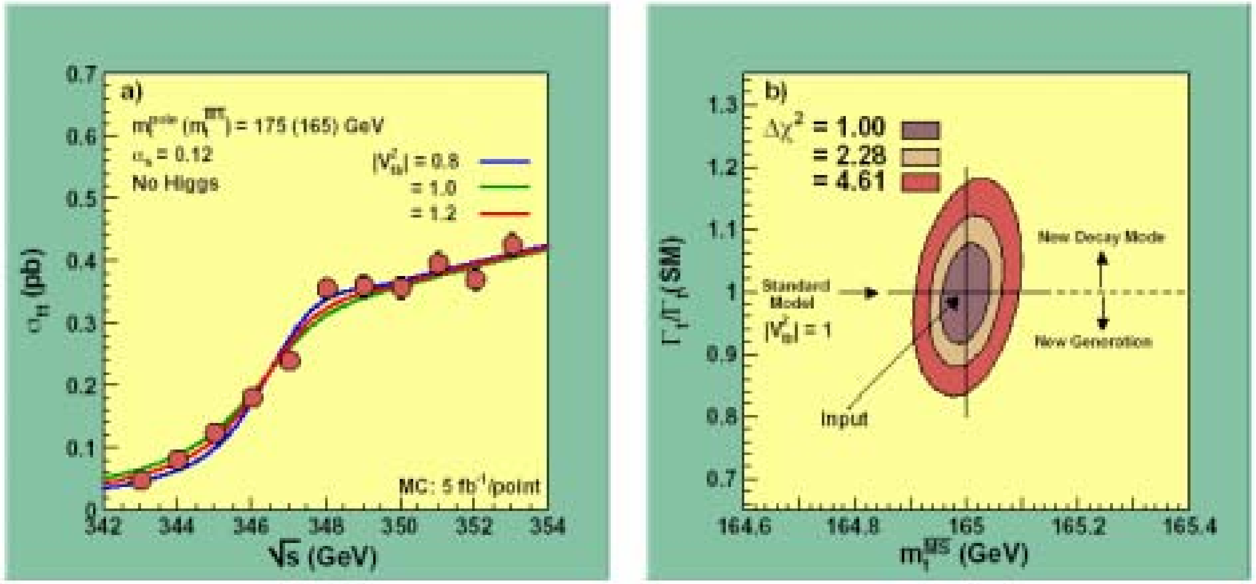
G.W.Wilson



K.Odagiri, GLC report

Top threshold scan

- Top quark is produced only in a hadron machine, unlike other particles.
- The threshold scan at LC improves the top mass measurement and determines the top width.



GLC report

Search for anomalous interactions

- Many new physics scenarios predict indirect effects in various process involving the SM particles.

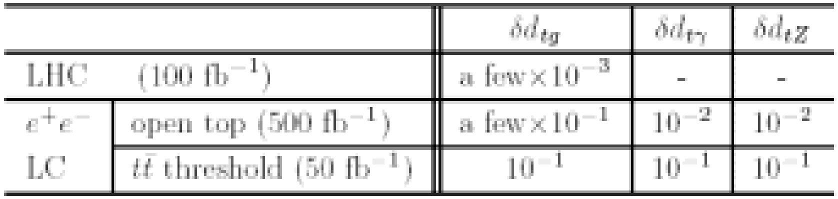
  $e^+e^- -> f\bar{f}, e^+e^- \to WW$ etc.
- Examples:

  Vector resonance in strong int. Higgs sector.

  Extra-gauge bosons in the little Higgs model.

  Contact interaction by K-K graviton exchange.
- High sensitivity at a higher beam energy.

Anomalous Top coupling



		δd_{tg}	$\delta d_{t\gamma}$	δd_{tZ}
LHC	(100 fb^{-1})	a few $\times 10^{-3}$	-	-
e^+e^- LC	open top (500 fb^{-1})	a few $\times 10^{-1}$	10^{-2}	10^{-2}
	$t\bar{t}$ threshold (50 fb^{-1})	10^{-1}	10^{-1}	10^{-1}

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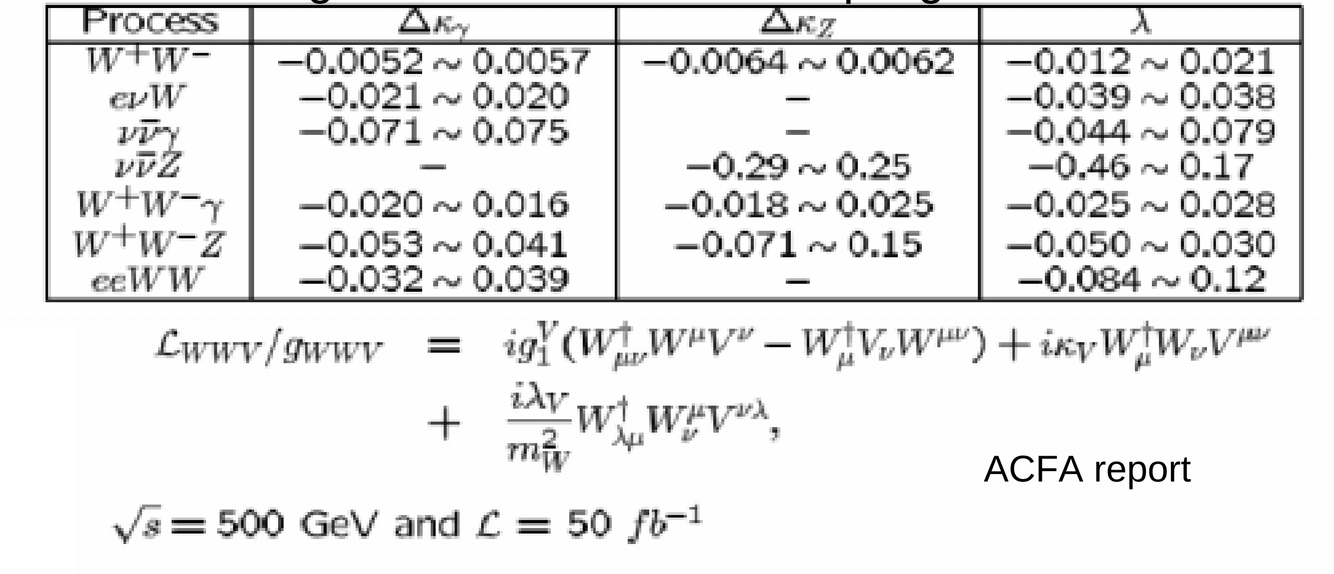
Gauge boson anomalous coupling



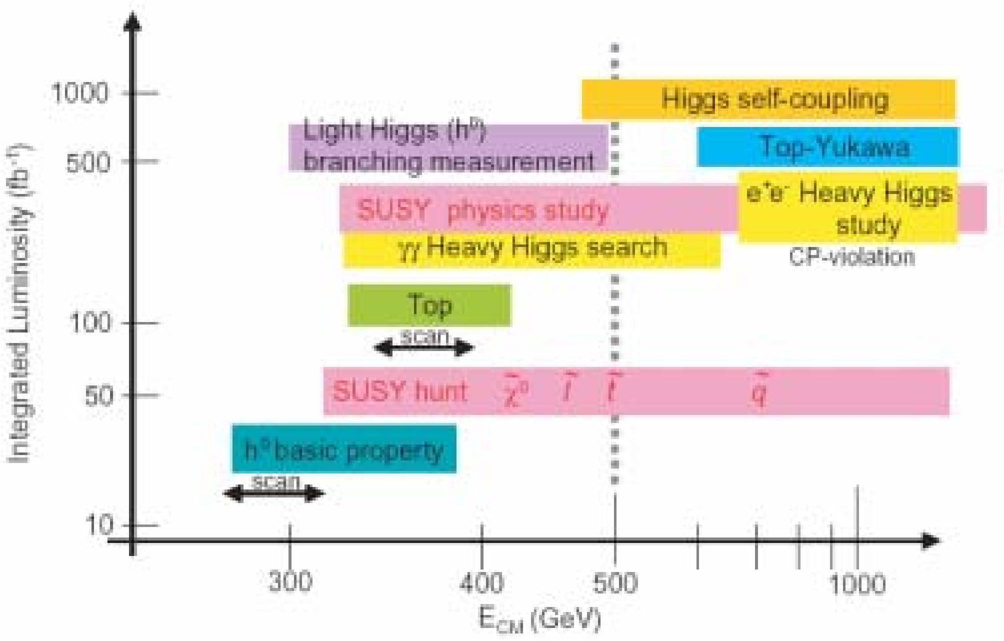
Process	$\Delta\kappa_\gamma$	$\Delta\kappa_Z$	λ
W^+W^-	$-0.0052 \sim 0.0057$	$-0.0064 \sim 0.0062$	$-0.012 \sim 0.021$
$e\nu W$	$-0.021 \sim 0.020$	$-$	$-0.039 \sim 0.038$
$\nu\bar{\nu}\gamma$	$-0.071 \sim 0.075$	$-$	$-0.044 \sim 0.079$
$\nu\bar{\nu}Z$	$-$	$-0.29 \sim 0.25$	$-0.46 \sim 0.17$
$W^+W^-\gamma$	$-0.020 \sim 0.016$	$-0.018 \sim 0.025$	$-0.025 \sim 0.028$
W^+W^-Z	$-0.053 \sim 0.041$	$-0.071 \sim 0.15$	$-0.050 \sim 0.030$
$eeWW$	$-0.032 \sim 0.039$	$-$	$-0.084 \sim 0.12$

$$\mathcal{L}_{WWV}/g_{WWV} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda},$$

$\sqrt{s} = 500$ GeV and $\mathcal{L} = 50\ fb^{-1}$

ACFA report

Summary of LC physics



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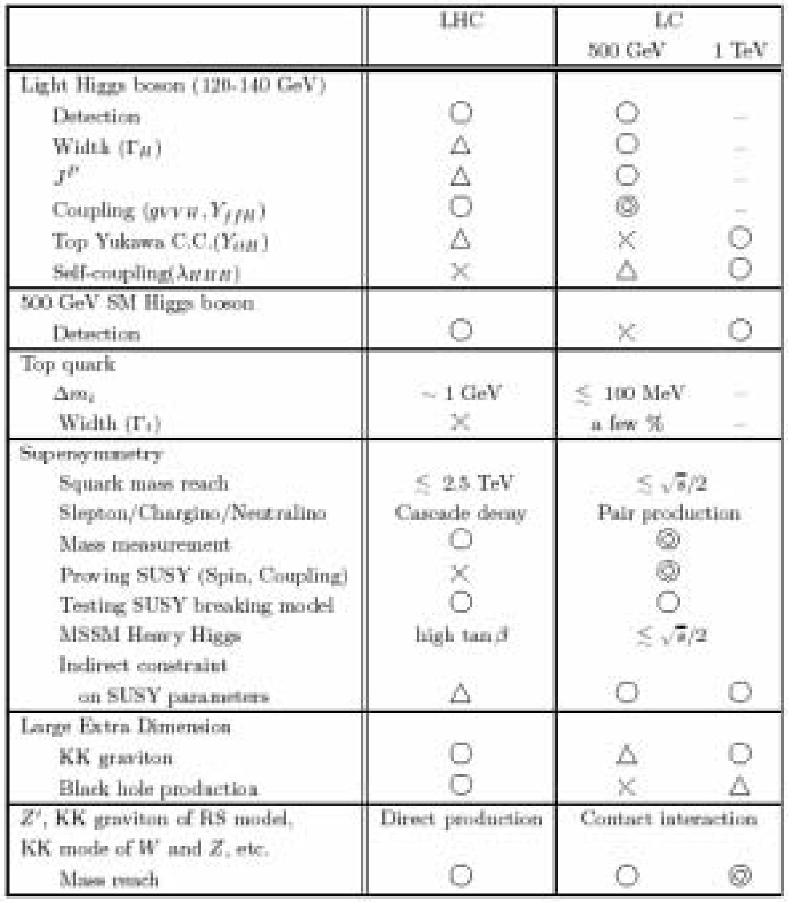
Rich physics programs in the first stage (~ 500 GeV)
Energy should be extended to ~ 1 TeV
in the second stage.

Roles of LHC and LC



	LHC	LC	
		500 GeV	1 TeV
Light Higgs boson (120-140 GeV)			
Detection	○	○	–
Width (Γ_H)	△	○	–
J^P	△	○	–
Coupling (g_{VVH}, Y_{ffH})	○	◎	–
Top Yukawa C.C.(Y_{ttH})	△	×	○
Self-coupling(λ_{HHH})	×	△	○
500 GeV SM Higgs boson			
Detection	○	×	○
Top quark			
Δm_t	~ 1 GeV	$\lesssim$ 100 MeV	–
Width (Γ_t)	×	a few %	–
Supersymmetry			
Squark mass reach	$\lesssim$ 2.5 TeV	$\lesssim \sqrt{s}/2$	
Slepton/Chargino/Neutralino	Cascade decay	Pair production	
Mass measurement	○	◎	
Proving SUSY (Spin, Coupling)	×	◎	
Testing SUSY breaking model	○	○	
MSSM Heavy Higgs	high $\tan\beta$	$\lesssim \sqrt{s}/2$	
Indirect constraint on SUSY parameters	△	○	○
Large Extra Dimension			
KK graviton	○	△	○
Black hole production	○	×	△
Z', KK graviton of RS model, KK mode of W and Z, etc.	Direct production	Contact interaction	
Mass reach	○	○	◎

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Conclusions

- Goals of research at LC are to open a new era of elementary particle physics through critical discoveries which lead to new fundamental principles of Nature.
- Physics case of the LC experiment is very strong.
- In this workshop, we should further clarify:

  role of LC in connection with LHC,
  importance of the energy extension in the 2nd stage,
  requirements to the detector design from physics studies,
  importance of various options of LC experiments,
  role of LC in a grand view of the particle physics and cosmology.