ILC Physics

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Current Status

July 2012: 5σ discovery of “a new particle” at 126 GeV

The particle is, if it is the Higgs boson, consistent with the SM prediction at the quantum level with LEP/SLC precision data

Existence of *h* couplings to

γγ, gg, ZZ, WW, ττ, bb, …

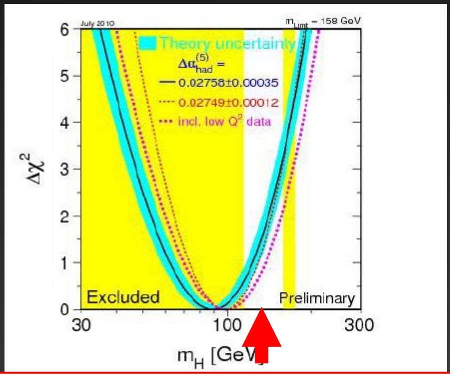
is being confirmed at LHC

The particle seems consistent with the SM Higgs

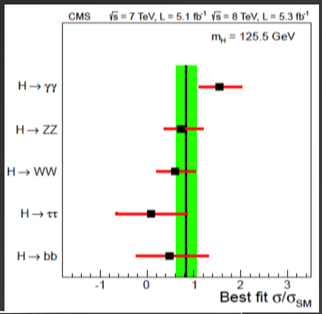
No other new particle has been found yet

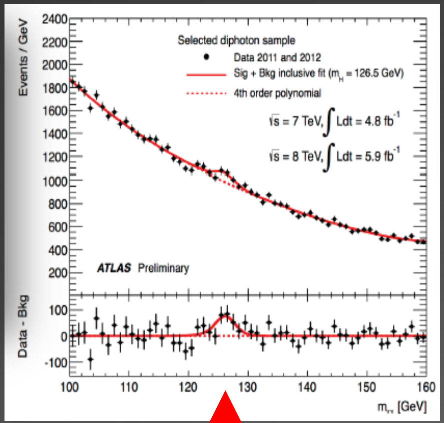
It is a great victory of the standard model!

Yes. Clearly this is not the end of the story



Allowed region by LEP/SLC





New discovery

New Era of High Energy Physics started

Discovery of the new boson at 125 GeV
opened the door to the physics beyond the SM

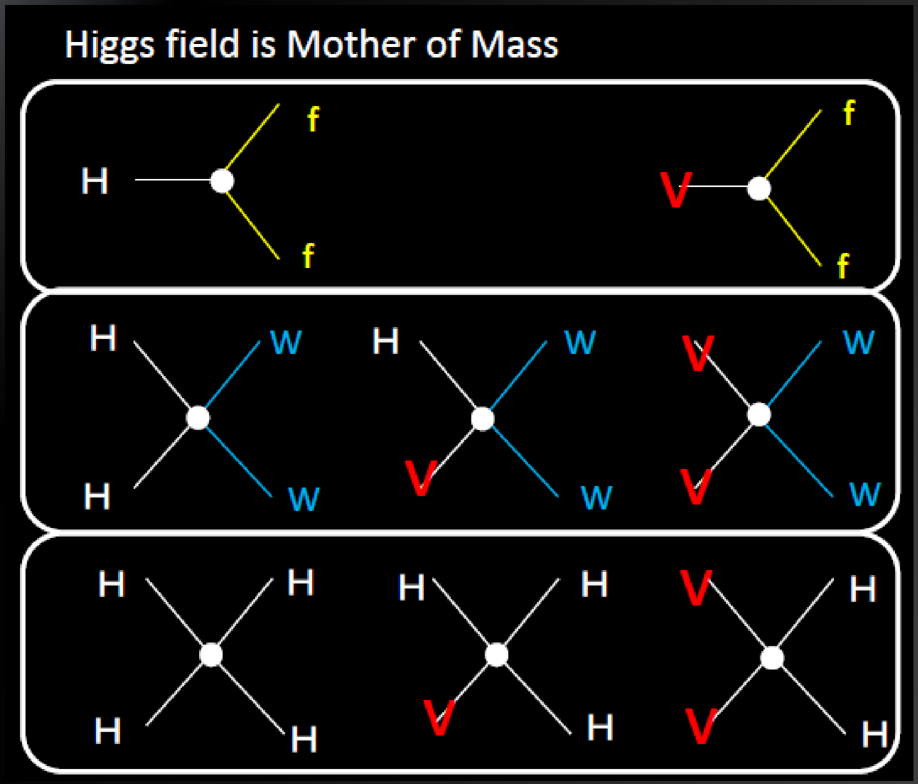
SM particle content has finally been completed
(We can predict the SM prediction accurately
for high energy phenomena)

Direct clue to test the origin of
Electroweak Symmetry Breaking

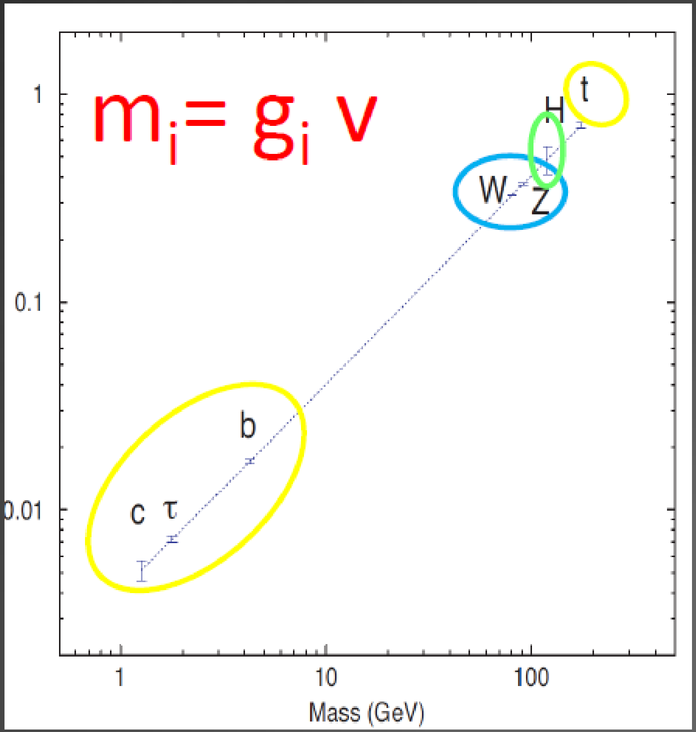
Higgs boson in the Standard Model

- Origin of Mass

SM Higgs sector: only one Higgs doublet gives masses to all particles



Mass-Coupling universality in SM



BSM

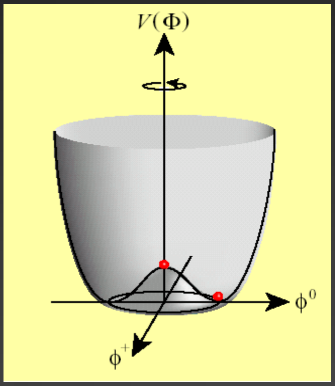
Problem in the SM

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

Higgs Sector:

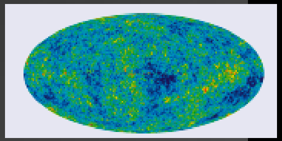
- Minimal/Non-minimal? (No principle)
- Quadratic divergences (Hierarchy Problem)
- Why $\mu^2 < 0$? (EWSB)
- What is the λ coupling? (Dynamics behind)

$$\delta m_H^2 = \frac{\Lambda_{cutoff}^2}{16\pi^2}$$



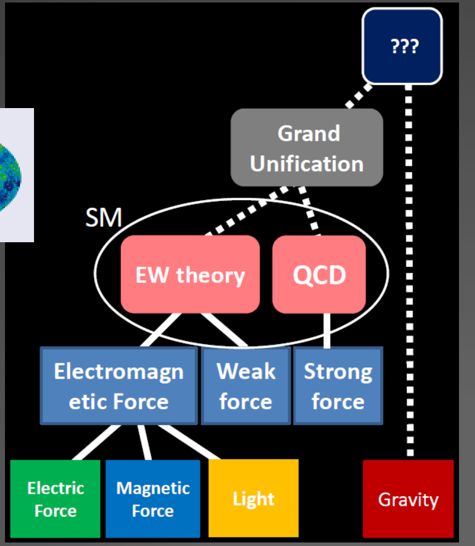
BSM Phenomena (What SM cannot explain):

Dark Matter, Neutrino Mass, Baryogenesis, Inflation …



Unification (we are still on the way):

Charge discretization, Coupling Unification, Flavor, Gravity , ….



SM must be replaced by new physics

At which scale?

Terascale

This is expected to solve Hierarchy Problem
WIMP Hypothesis predicts DM candidate at TeV scale

Minimal or non-minimal?

- No principle for the SM Higgs sector
- Possibility of an extended Higgs sector
- Many new physics models predict specific extended Higgs sectors with extra doublets, singlets, or triplets
- Deviation in SM-like Higgs coupling constants via mixing!

Type2-2HDM (MSSM) Higgs couplings

Φ_1 and $\Phi_2 \Rightarrow h, \; H, \; A^0, H^\pm \oplus$ Goldstone bosons

↑ CPeven ↑ CPodd ↑charged

Higgs mixing

$$\begin{pmatrix}\phi_1\\ \phi_2\end{pmatrix} = \begin{pmatrix}\cos\alpha & -\sin\alpha\\ \sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}H\\ h\end{pmatrix}$$

VEV's: $v_1^2 + v_2^2 = v^2 \simeq (246\ \text{GeV})^2$

$$\tan\beta = \frac{v_2}{v_1}$$

SM		2HDM type2 (MSSM)	
Gauge coupling: $\phi VV \quad (V = Z, W)$	$\Rightarrow$	hVV: $\sin(\beta-\alpha)$,	HVV: $\cos(\beta-\alpha)$
Yukawa coupling: $\phi b\bar{b}$	$\Rightarrow$	$hb\bar{b}$: $\frac{\sin\alpha}{\cos\beta}$,	$Hb\bar{b}$: $\frac{\cos\alpha}{\cos\beta}$
$\phi t\bar{t}$	$\Rightarrow$	$Ht\bar{t}$: $\frac{\sin\alpha}{\sin\beta}$,	$ht\bar{t}$: $\frac{\cos\alpha}{\sin\beta}$

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

Higgs and New Physics

What is the essence of the Higgs field?

Higgs nature	⇔	New Physics scenario
– Elementary Scalar?		**Supersymmetry**
– Composite?		**Dynamical Symetry Breaking**
– Pseudo NG Boson?		**Little Higgs**
– A gauge field in Extra D?		**Gauge-Higgs unification**
– ……		**……**

Each model has a specific Higgs sector

Higgs sector = Window to new physics

Where is it ?

TeV scale? -------------------- Planck Scale?

It must be at the Tera-eV scale

- Hierarchy Problem
  (Be just above EWSB scale!)
  - Λ = 1 TeV mild fine tuning
  - 10 TeV large fine tuning
  - 10^{16} GeV huge fine tuning
- Dark Matter
  - WIMP hypothesis naively indicate

    m_{DM} = 1GeV - 1 TeV

$$\delta m_H^2 = \frac{\Lambda_{cutoff}^2}{16\pi^2}$$

NP candidate
SUSY
Little Higgs
Dynamical
Extra D
……

$$\Omega_{DM} h^2 \simeq \frac{0.1\text{pb} \cdot c}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle \sim (g^2/4\pi)^2/m^2$$

$$\Omega_{DM} h^2 = 0.1 (\text{WMAP})$$

⇩

$$m \sim g^2 \times (1\text{TeV})$$

Terascale!

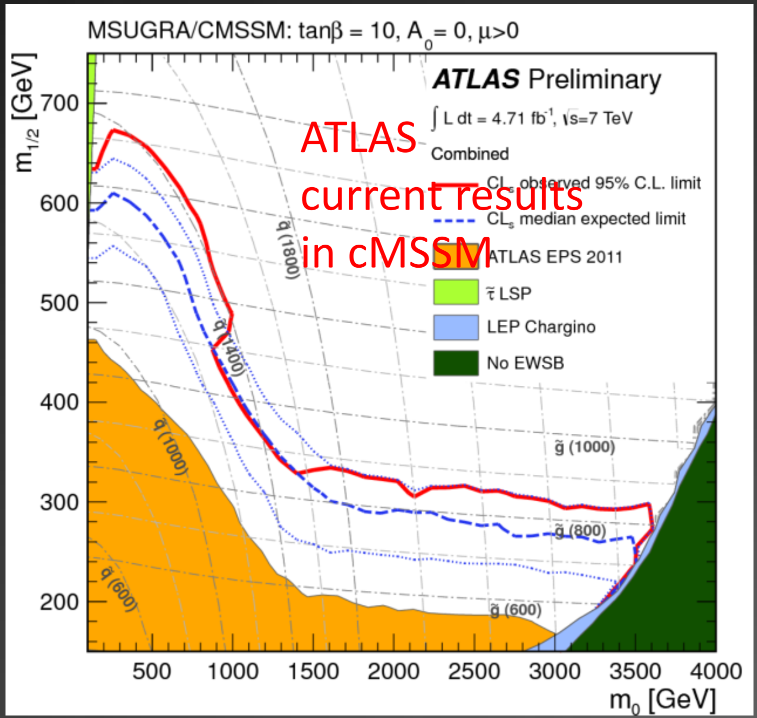
LHC has not found new physics at TeV scale

Gluino, Squarks > 1.6 TeV (cMSSM)

Isn't it at TeV scale?

It would possibly be at TeV scales, but the mass of new particles strongly depends on model

Let us wait for new results from 14 TeV Run at LHC



cMSSM has been in trouble

It is time to give up on the cMSSM.   But what should replace it ?

Here are two options:

1. Find a type of SUSY model in which the mass scale is least constrained by the condition of naturalness.

2. Accept that the theory of electroweak symmetry breaking might involve strong interactions.

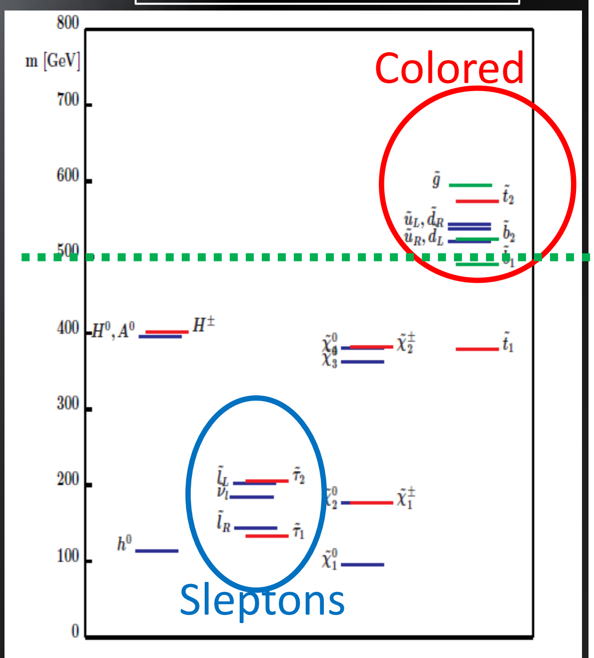
Where do these ideas lead ?

Michael Peskin, Summary Talk at LP11, Aug 2011

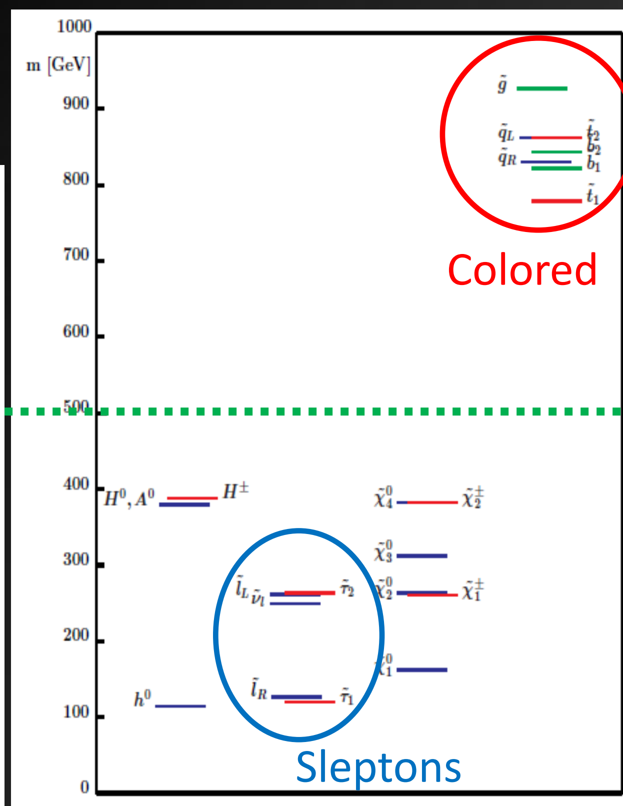
Colored sparticles are constrained from below by LHC

We need mass splitting between the colored sector and the uncolored sector

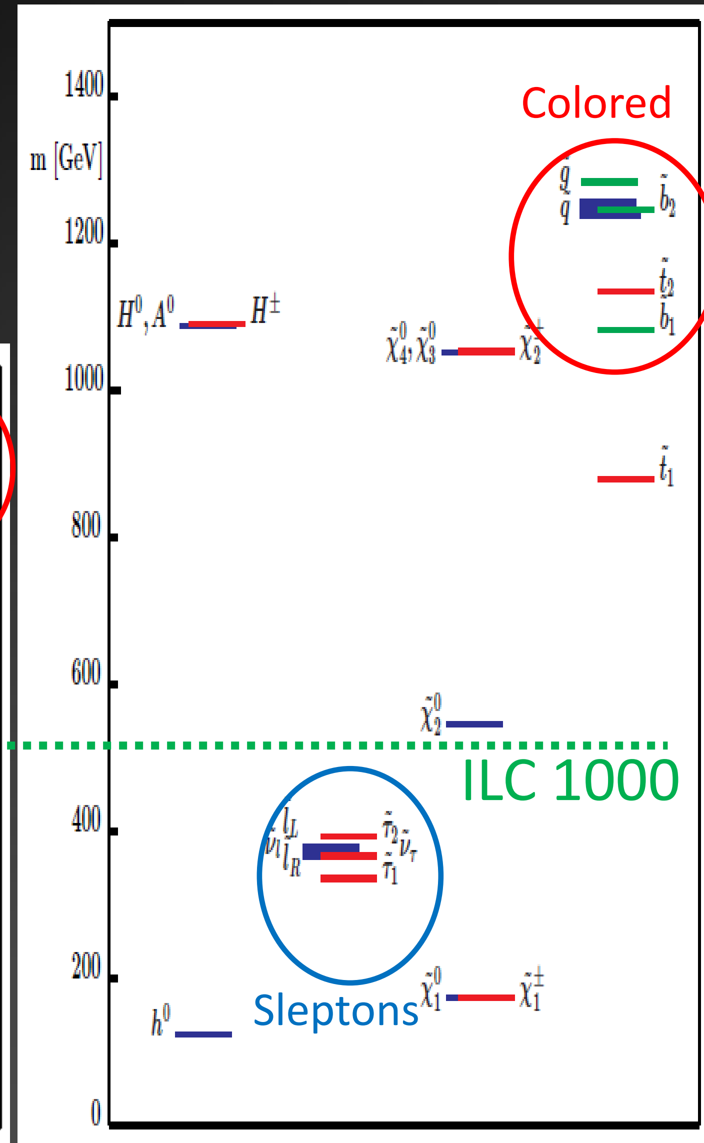
Typical CMSSM scenario



Typical GMSB scenario



Typical AMSB scenario



S. Heinemeyer

Some alternative SUSY scenarios

- Natural SUSY Scenario

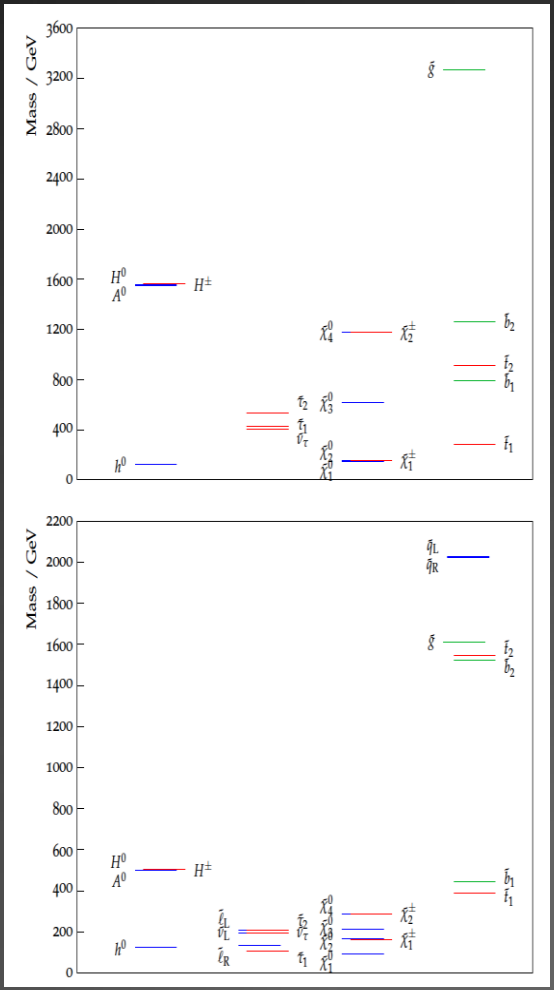
$$\frac{1}{2}m_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2$$

EWSB scale is naturally generated, if all terms are roughly the same size

> SLP: Higgsino like
> 3^{rd} generation squarks and sleptons can be light
> The others are heavier than TeV

- pMSSM (light sleptons)

> NSLP: stau
> Sleptons and chargenos/neutralinos are light



These scenarios are difficult to be tested at LHC but is well tested at ILC

New Physics models

H. Murayama

What is the point?

- The new physics is likely to be at a TeV scale
- But it strongly depends on the model whether the mass is 300 GeV, 1 TeV or even 3 TeV
- This would be a serious situation from the experimental view point, especially in designing future colliders
- We need a good luck for direct detection of new physics at colliders

Solid target is the Higgs sector

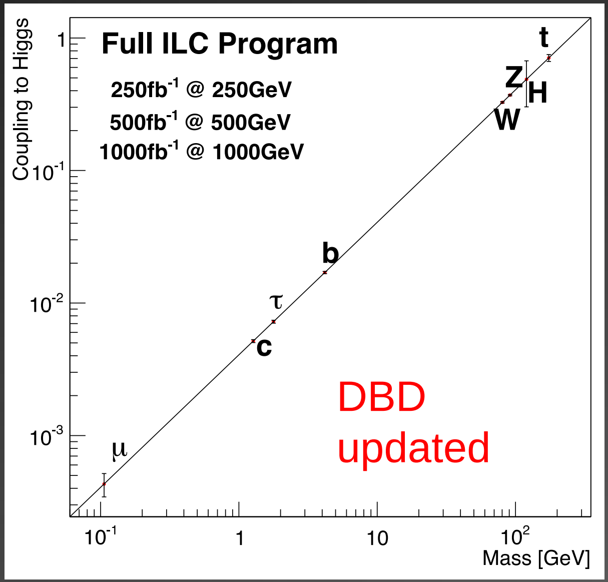
Something was found at 125 GeV

Notice that SM-like ≠ SM !

- Does it really play a role of the origin of mass?

- Minimal/Non-Minimal?

Extra singlets, doublets, triplets…



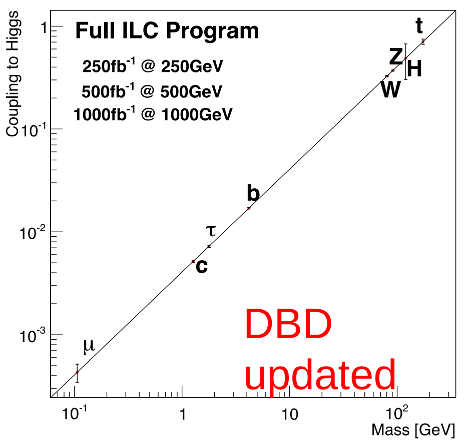
Mass-Coupling Relation

M_h=125GeV ⇒ We can calculate SM predictions exactly.

Deviation ⇒ Non-standard model physics

Solid target is the Higgs sector

Precision measurement of Higgs couplings



1. Coupling with weak bosons: *hZZ, hWW*
   Yukawa couplings : *hbb, htt, hττ, hcc, hμμ*
   Sensitive to mixing with extra Higgses

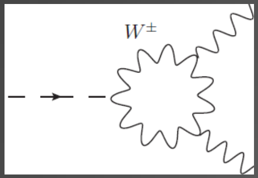
Type of extended Higgs sector can be separated by looking at the pattern of deviations

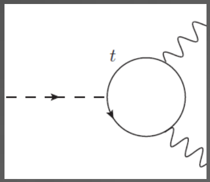
Finger printing of the model

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

2. Loop induced couplings: *hγγ, hgg, (hhh)*
   Sensitive to loop effect of new particels

Mass scale and dynamics of new physics particles may be better extracted





Deviation of $O(v^2/M^2)$
by the decoupling theorem

Fingerprinting of new physics models

Deviation pattern in a set of Higgs coupling depends on each model
→ fingerprinting!

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	10%[a], 100%[b]
LHC 14 TeV, $3\,\mathrm{ab}^{-1}$	8%	10%	15%

R.S.Gupta, H.Rzehak, J.D.Wells arXiv: 1206.3560v1

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{g_{hff}}{g_{h_{SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}.$$

Composite Higgs

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2 & \text{(MCHM4)} \\ 1 - 9\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2 & \text{(MCHM5).} \end{cases}$$

SUSY

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

Higgs as a probe of new physics

To this end, how accurately we have to measure the couplings?

Decoupling Theorem

When new physics scale *M* is large, low energy theory is the SM
Up to m_h^2/M^2 [O(1-10)% for *M*=TeV]

Supersymmetry: $g(\tau)/SM = 1 + 10\% \left(\frac{400\ \text{GeV}}{m_A}\right)^2$

$g(b)/SM = g(\tau)/SM + (1-3)\%$

Little Higgs: $g(g)/SM = 1 + (5-9)\%$

$g(\gamma)/SM = 1 + (5-6)\%$

Composite Higgs: $g(f)/SM = 1 + (3-9)\% \cdot \left(\frac{1\ \text{TeV}}{f}\right)^2$

1. New physics can potentially tweak any Higgs coupling independently of the others.
2. If we cannot reach 5% accuracy, we likely are not in the game.
3. If we are able to reach 1% accuracy, we can be sensitive to new particles at 3 TeV or higher.

The ILC gives new capabilities both for qualitative and quantitative improvement in our understanding of the Higgs boson.

LHC cannot measure couplings so accurately even with 3000fb^{-1}

[M.Peskin]

International Linear Collider

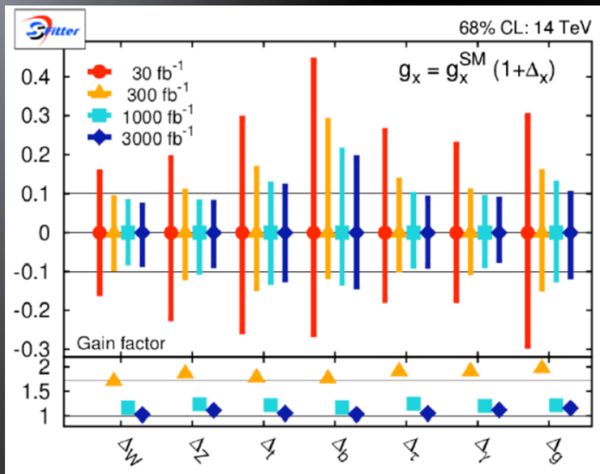
LHC is useful for discovery, but cannot be sufficient for a satisfactory level of precise measurements for finger printing and spectroscopy to determine the model of BSM

Precision Measurement

This is the main reason
why we want ILC !

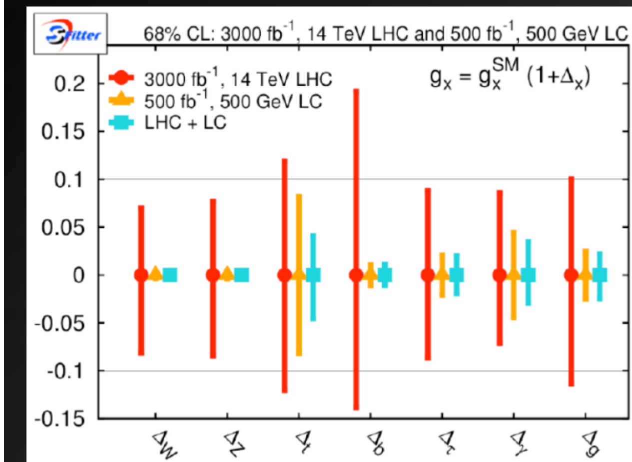
visualize the improvement of ILC over LHC

LHC (30/300/1000/3000 fb^{-1})



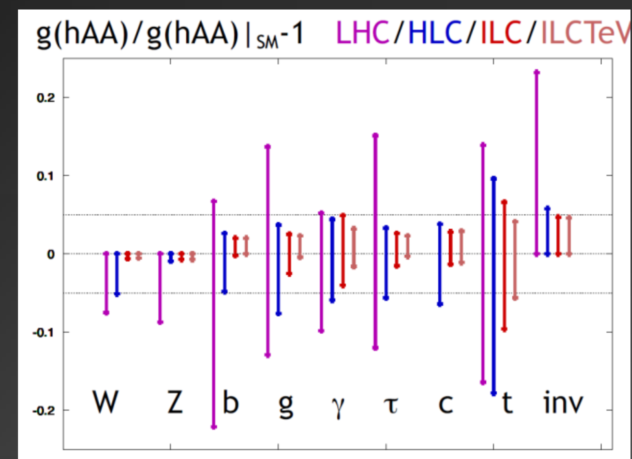
[D. Zerwas]

LHC (3000 fb^{-1}) and LC(500GeV/500fb^{-1})



[D. Zerwas]

LHC (3000 fb^{-1}) and LC(HLC/ILC/ILCTeV)



[M. Peskin]

At LHC, coupling determination starts limited by systematics for 300 fb^{-1}

⇒

No drastic improvement at 3000fb^{-1} ?

LC can measure independently

X-sections $\sigma(e^+e^- \to Zh)$ (250GeV)

$\sigma(e^+e^- \to \nu\nu h)$ (350-500GeV)

$\sigma(e^+e^- \to \nu\nu h)$ (700GeV-TeV)

Branching ratios

Invisible and unexpected *h* decays

hcc, hττ, hhh, htt, hγγ

ILC can measure the Higgs couplings accurately! ⇒ Use to test new physics

International Linear Collider

Advantages of e^+e^- colliders

Cleanliness No huge QCD background, removed pile up, high detector performance

Democracy e^+e^- annihilation produces similar amount of new particle pairs to the SM ones as long as kinematically accessible

Calculability EW interaction only, perturbation works well, Part-per-mil level of theory prediction possible

Detail Controled initial polarization of electron (positron) kinematic information of final states
→ Helicity dependent cross section and decay reconstracted

Target for each energy at ILC

E = 250 GeV

- Higgs factory via $e^+e^- \rightarrow Zh$

E = 350-400GeV

- top threshold (m_t ,$\alpha_{s,}$ Γ_t)
- Higgs via W-fusion (*hWW* coupling determination)
- WW (precision W couplings)
- *hhh* measurement at Photon Collision option

E = 500 GeV

- Precision measurement of all Higgs coupling constants including *hhh* and *htt* couplings
- Higher scale (> 10 TeV) can be proved by $e^+e^- \rightarrow f\,f$
- Direct search for non-colored new particles

E = 1 TeV

- Precision measurements of the *hhh* coupling via W fusion
- Top Yukawa,
- Direct search for colored/non-colored new particles

E = 90-180 GeV (*Giga-Z, Mega-W*)

Total Width and Coupling Extraction

One of the major advantages of the LC

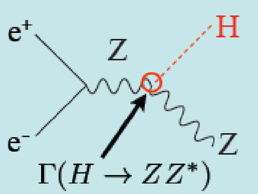
To extract couplings from BRs, we need the total width:

$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

To determine the total width, we need at least one partial width and corresponding BR:

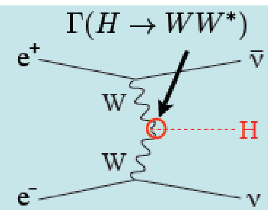
$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

In principle, we can use the A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

BR=O(1%): precision limited by low stat. for H->ZZ* events



$BR(H \to WW^*)$

More advantageous but not easy at low E

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$

$\Delta\Gamma_H/\Gamma_H \simeq 10\%$

Jenny List's talk

9

[Fujii]

[J. List]

Measurement accuracy of Γ^{tot}_H

$$\frac{\Delta\sigma(\text{WW-fusion})}{\sigma(\text{WW-fusion})} \;\&\; \frac{\Delta BR(H \to WW)}{BR(H \to WW)}^{**} \longrightarrow \frac{\Delta\Gamma^{tot}_H}{\Gamma^{tot}_H}$$

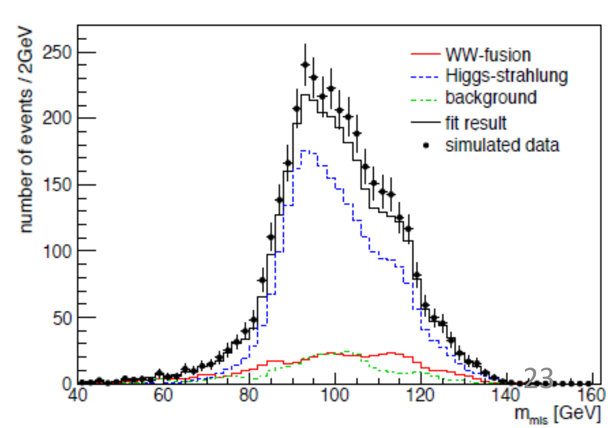
$$\frac{\Delta BR(H \to b\bar{b})}{BR(H \to b\bar{b})} = 3.0\,\%$$

$$\frac{\Delta BR(H \to WW)}{BR(H \to WW)} = 4.6\,\%$$

$$\Delta\Gamma^{tot}_H / \Gamma^{tot}_H = 11.88\,\%$$

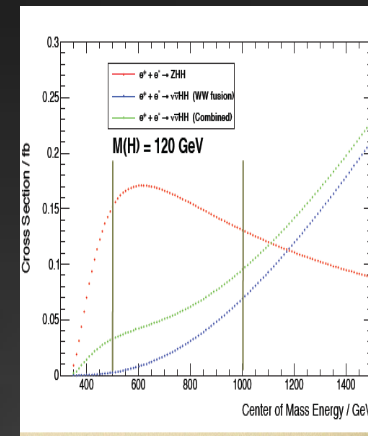
E=250GeV

~ 5-6 % (500GeV)



Higgs Self-Coupling

- 20 % accuracy may be required to test some scenarios of new physics
  - EW baryogenesis
  - Light Higgs but strongly interacting Higgs sector
  - Exotic Higgs sectors (eg: Triplet model)

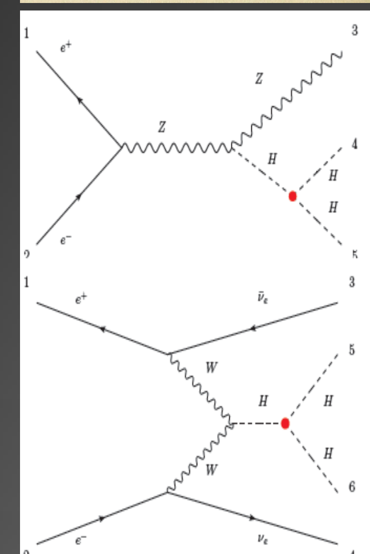


- At LHC 3σ observation at $3000 fb^{-1}$ [J. Yu]
- ILC [0.5 TeV, 1 TeV] [J. Tian]

  m_h = 120 GeV δλ/λ~40% ($500GeV/2fb^{-1}$)

  δλ/λ~17% ($1TeV/2fb^{-1}$)

Zhh production



hhνν production

Expecting 20% or better for m_h=125GeV [K. Fujii et al]

- CLIC [1.4TeV-3TeV] [Lastvicka]

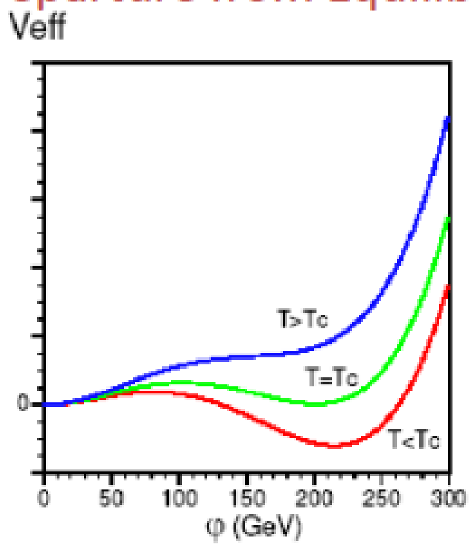
  30 – 35% λ_{HHH} uncertainty @ 1.4 TeV

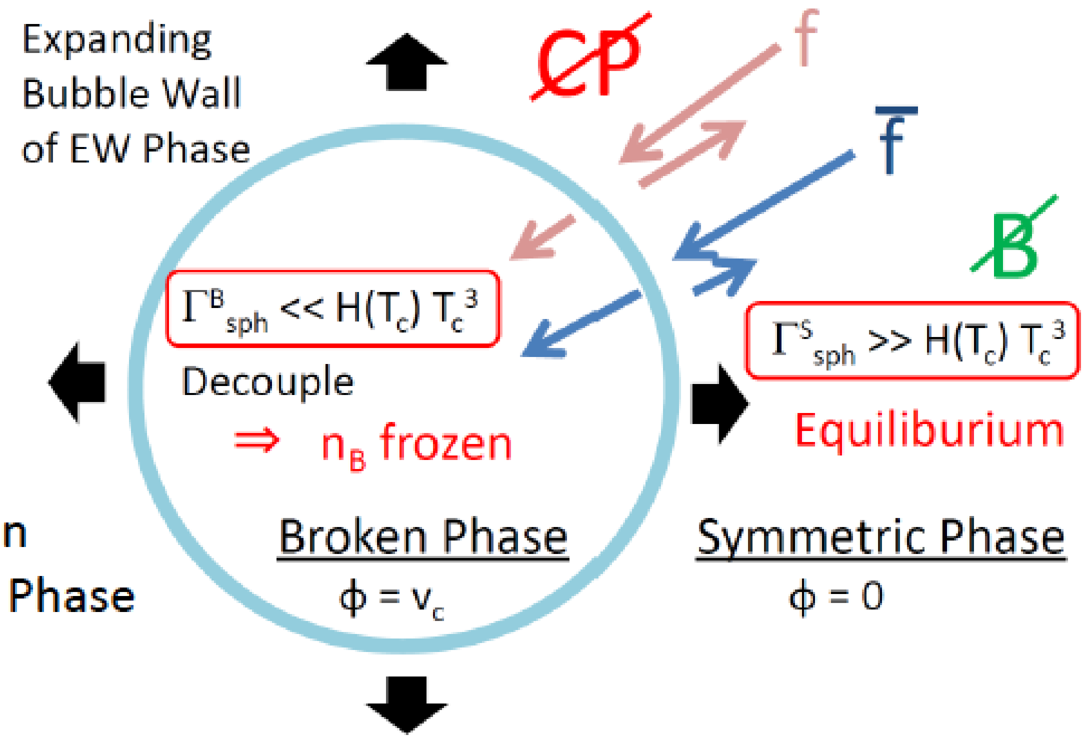
  15 – 20% uncertainty @ 3 TeV

Relation to electroweak baryogenesis

Sakharov's conditions:

- B Violation → Sphaleron transition at high T
- C and CP Violation → CP Phases in extended scalar sector
- Departure from Equilibrium → 1^{st} Order EW Phase Transition





Quick sphaleron decoupling to retain sufficient baryon number in Broken Phase

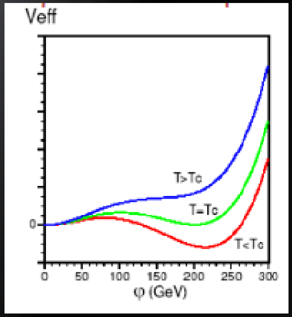
$$\frac{\varphi_c}{T_c} \gtrsim 1$$

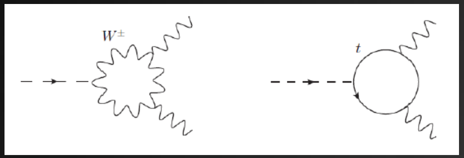
SM must be extended to satisfy this condition

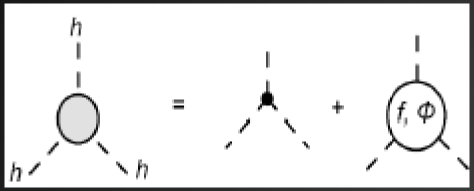
Electroweak Baryogenesis

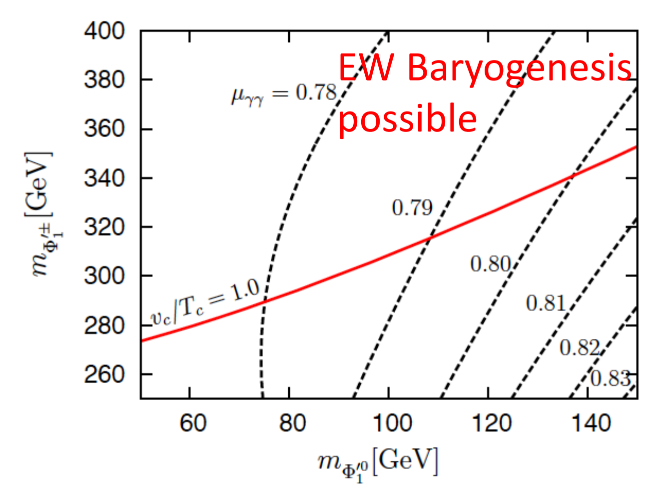
$V(\varphi, T) \Leftrightarrow V(\varphi)$

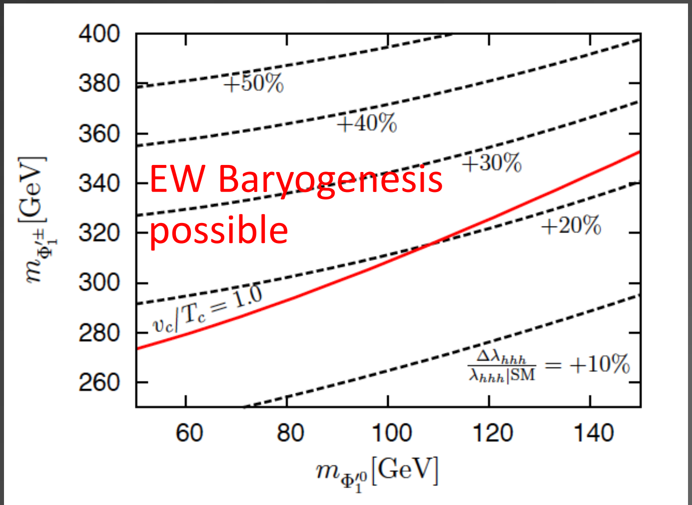
Dynamics to realize 1st Order Phase Transition strong ⇔ Dynamics to make large deviations in hγγ and hhh











About 20% Reduced *hγγ* Coupling

20-30 % Enhanced *hhh* Coupling

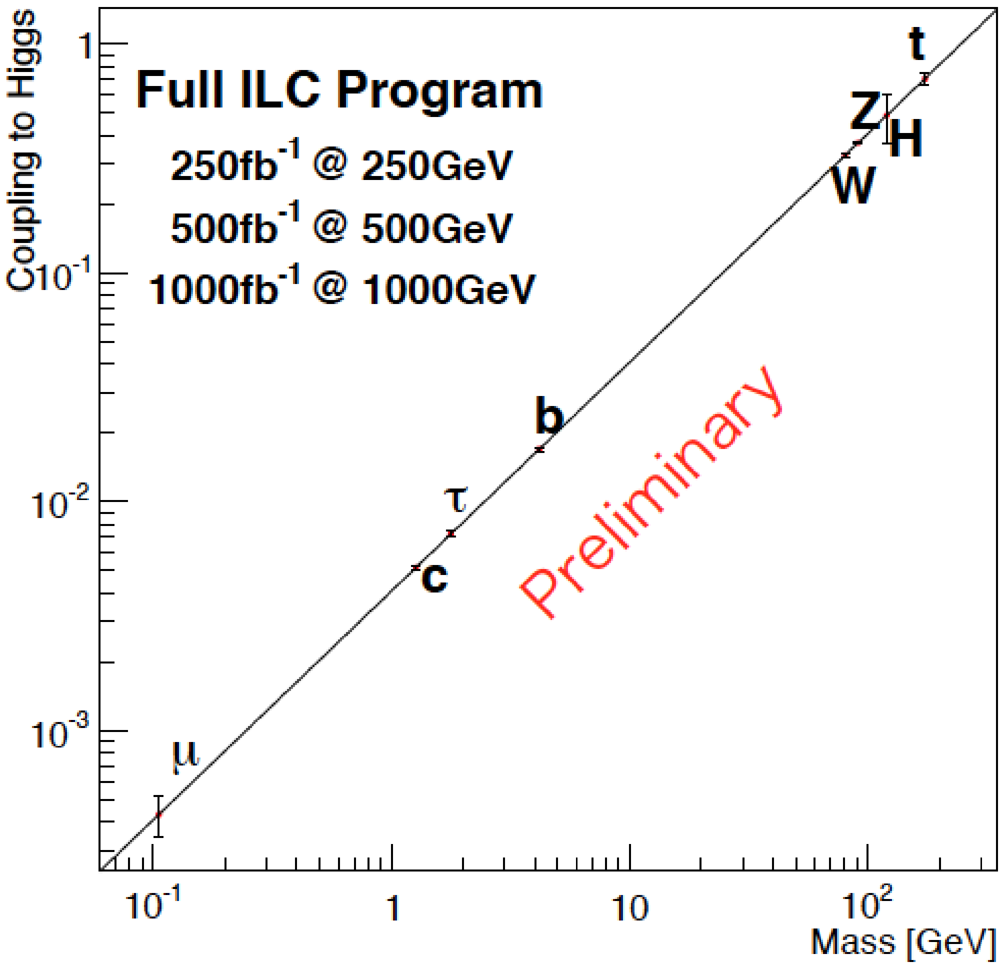
ILC business!

SUSY 4HDM with singlets

Connection between cosmology and collider physics

Mass Coupling Relation

After Nominal Full ILC Program

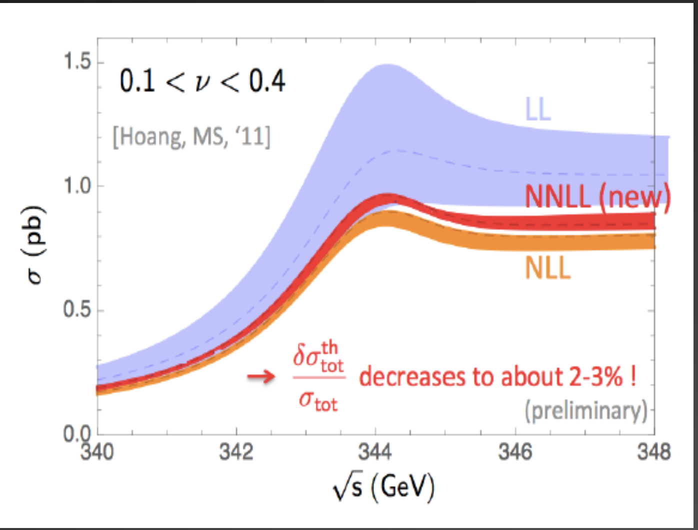


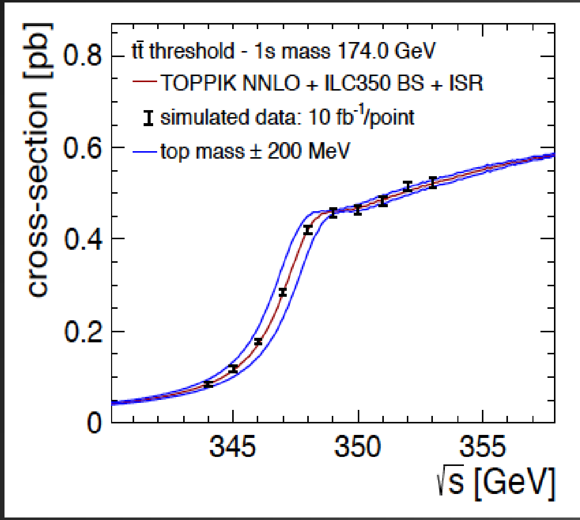
Top pair threshold

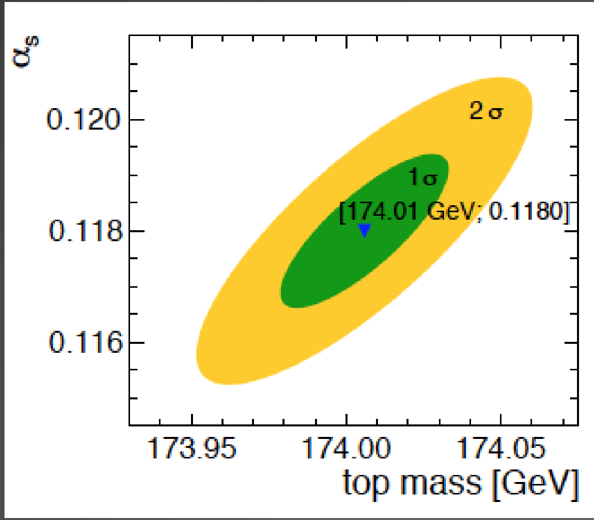
Comparison of higher order QCD calculation and the threshold scan dratisticly improves uncertainties in m_t, α_s, Γ_s

Δm_t = 19 MeV
$\Delta \alpha_s(m_Z)$ = 0.0012
$\Delta \Gamma_t$ = 32 MeV

Such improvement is very important in predicting physics Quantity in new physics models



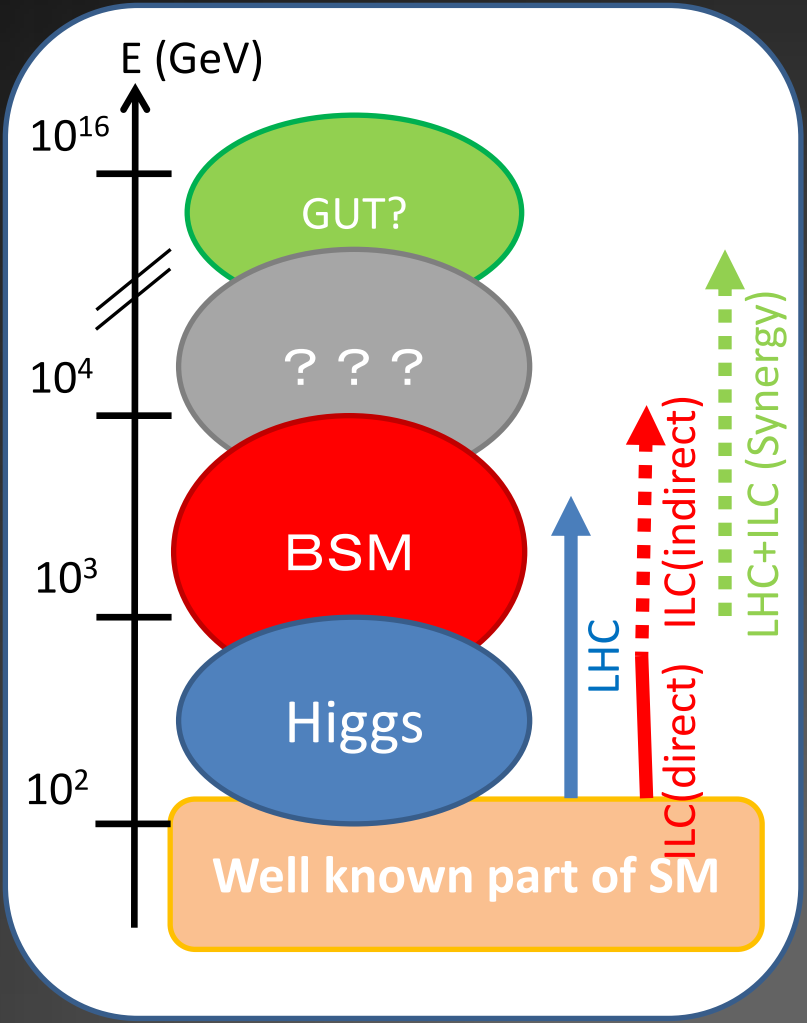




Exploration beyond TeV scale

New physics at much higher than 1 TeV can be indirectly tested at ILC

- Radiative correction to the EW parameters (m_W, $\sin\vartheta_W$, …)
- Anomalous effect on gauge coupling and Yukawa coupling via higher dimensional operators
- Test of a new gauge boson Z'



LHC Direct Search v.s. ILC Precision Measurement

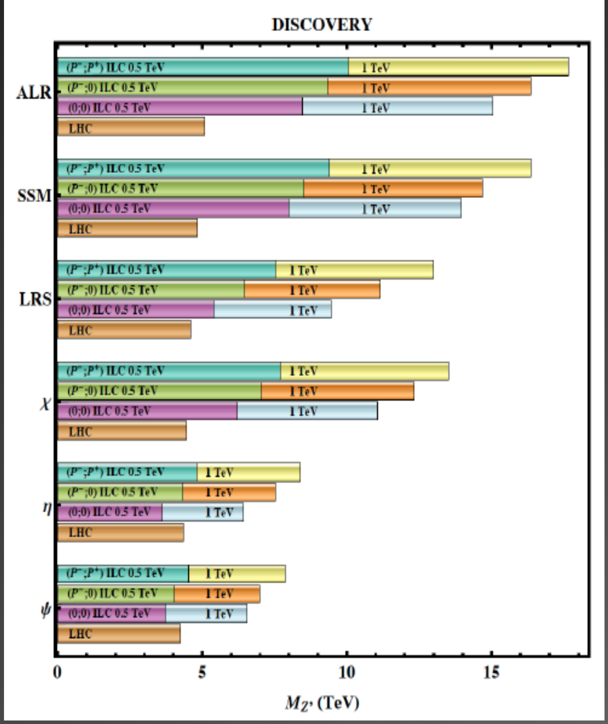
$e^+e^- \rightarrow ff$ as a probe of new hidden gauge symmetry (Z')

Additional gauge boson Z' is Predicted in various new physics models

$e^+e^- \rightarrow Z' \rightarrow ff$

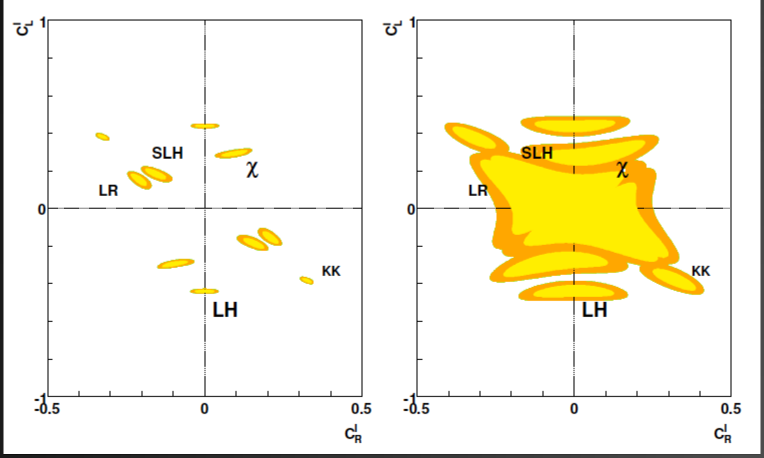
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[A_+(1+\cos\theta)^2 + A_-(1-\cos\theta)^2\right]$$

E > 500 GeV



Typically Z' can be searched up to 10-15 TeV

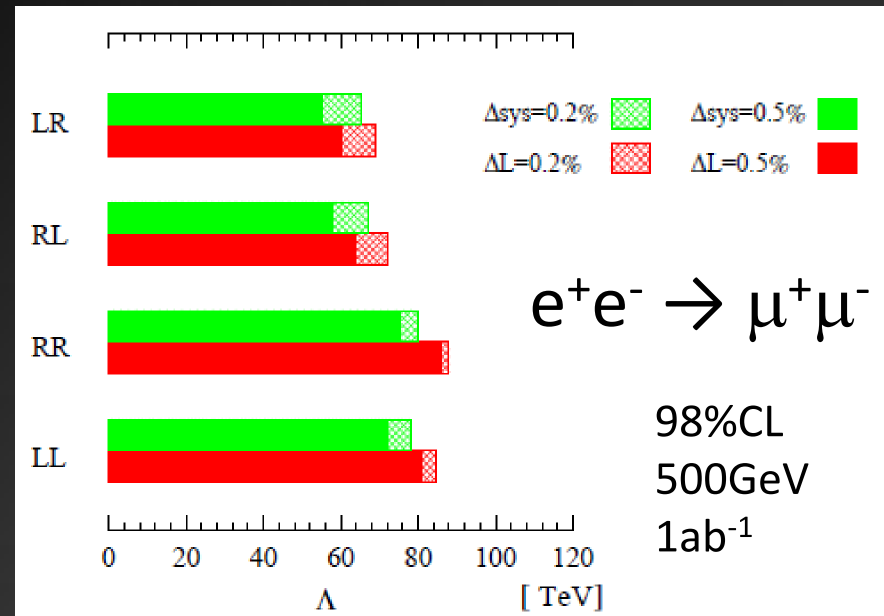
Model discrimination can be possible

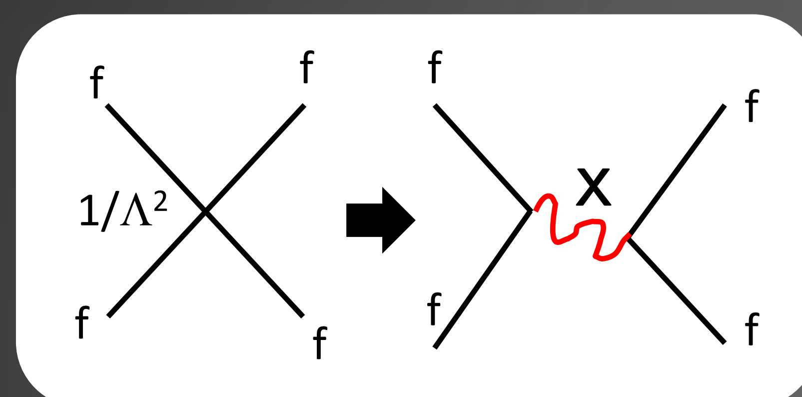


Higher oder operator analysis

- Four Fermi interactions contain information on the new physics scale
- Constraint by precision measurement at ILC
- We can test up to O(100) TeV

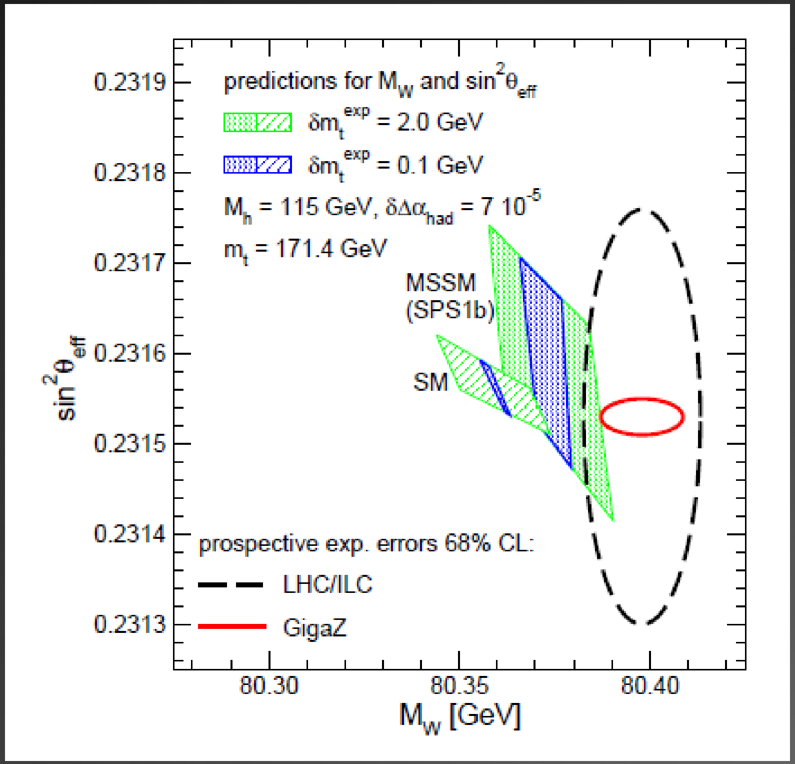
$$\mathcal{L}_{\rm eff} = \sum_{i,j=L,R} \eta_{ij} \frac{4\pi}{\Lambda_{ij}^2} \bar{e}_i \gamma^\mu e_i \cdot \bar{f}_j \gamma_\mu f_j$$





Giga-Z, Mega-W

- EW parameter
- Precision measurement and radiative correction
- Redo LEP experiments at 91 GeV and 160 GeV but with much more luminosity
- Discriminate new physics models



Some alternative SUSY scenarios

- Natural SUSY Scenario

$$\frac{1}{2}m_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2$$

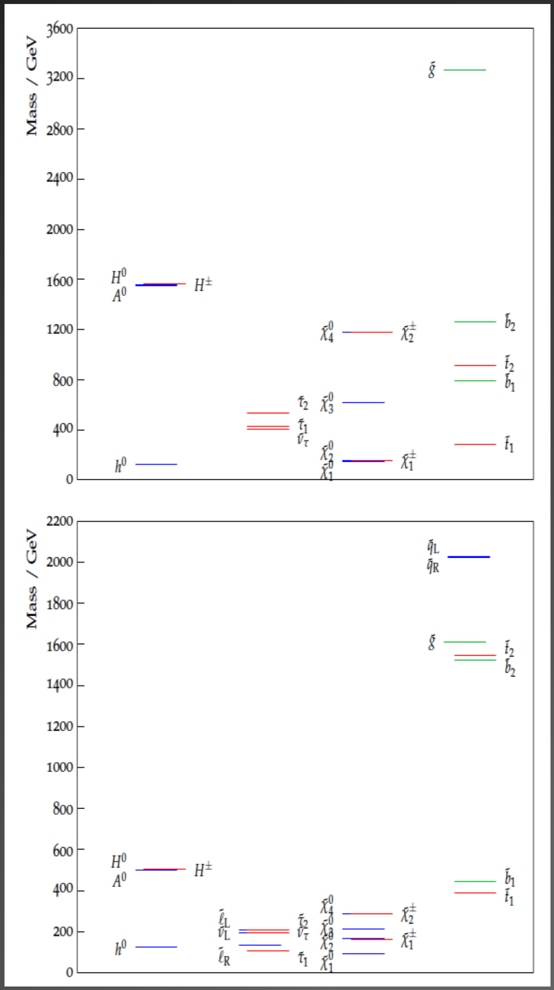
EWSB scale is naturally generated, if all terms are roughly the same size

> SLP: Higgsino like
> 3^{rd} generation squarks and sleptons can be light
> The others are heavier than TeV

- pMSSM (light sleptons)

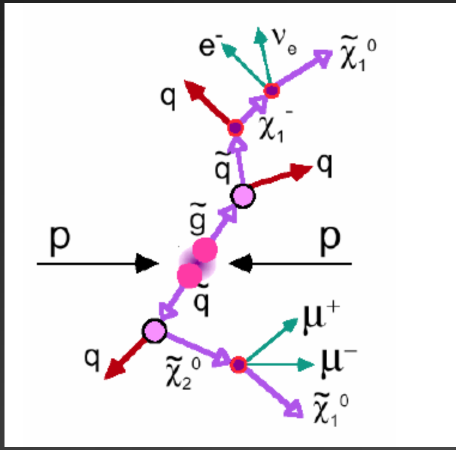
> NSLP: stau
> Sleptons and chargenos/neutralinos are light

These scenarios are difficult to be tested at LHC but is well tested at ILC

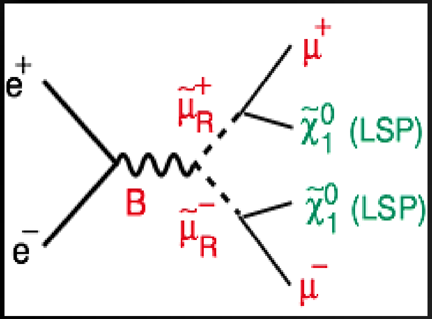


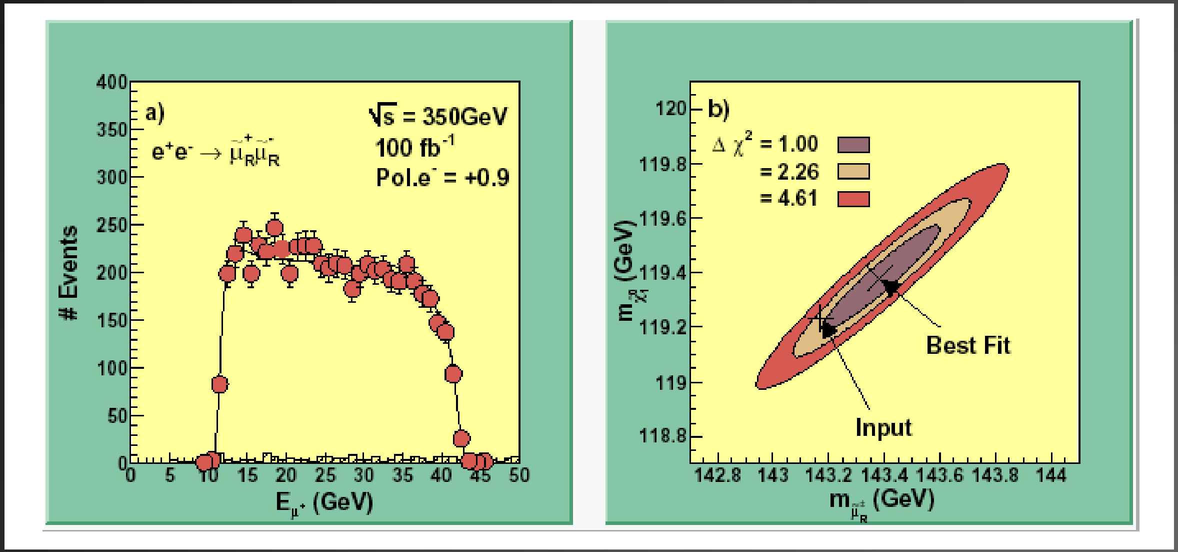
Direct search of SUSY particles

At LHC, sleptons and chargino/neutralino are produced via the cascade decays (Mass differences measured)



At ILC, pair production if kinematically accessible, and mass can be reconstruct at 0.1 % level

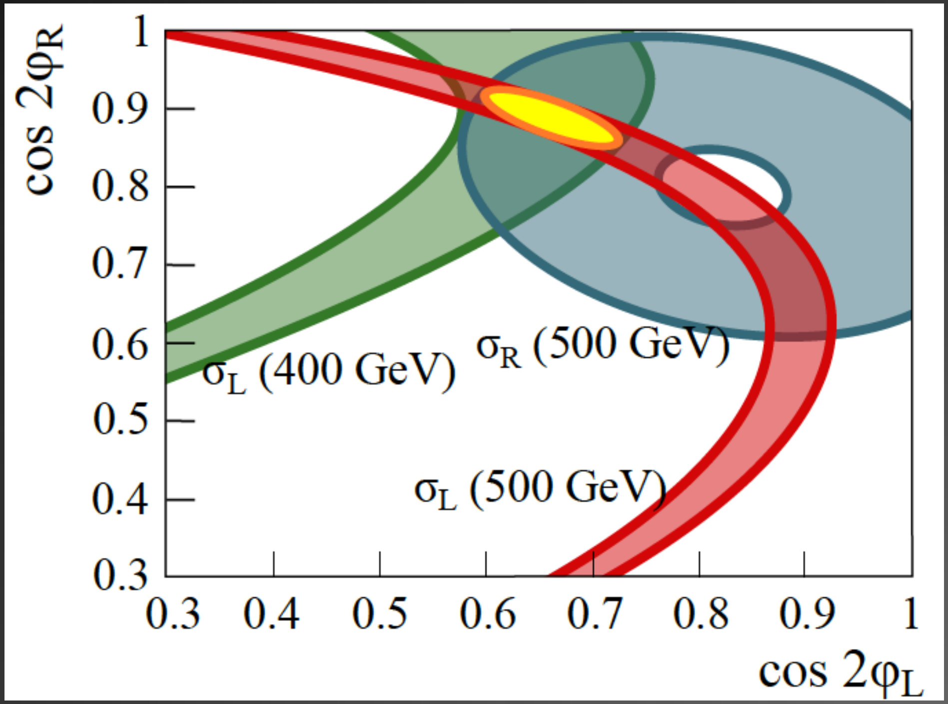




SUSY spectroscopy may be possible

Model parameter determination

Precision measurement of
Polarized cross sections of
chargino pair productions
at different energies
can determine mixing angles
and other parameters



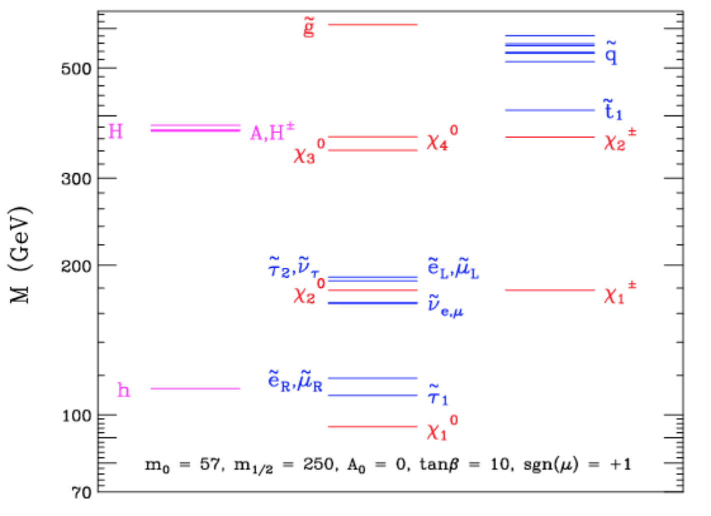
SUSY Dark Matter

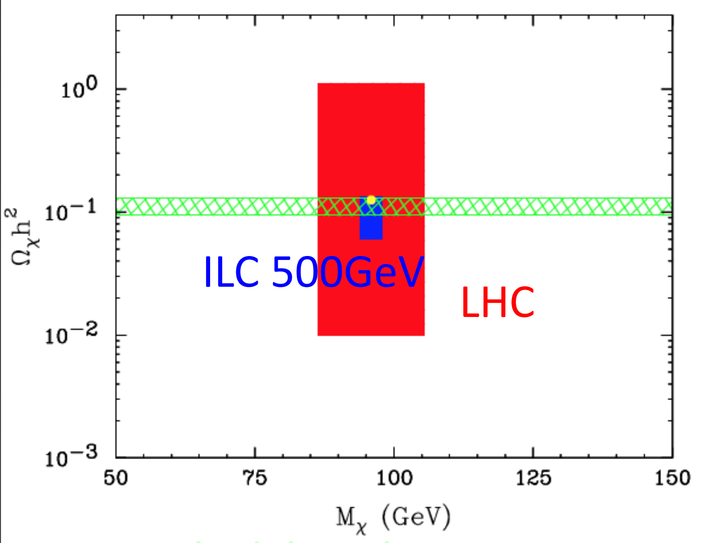
WIMP (Weakly Interacting Massive Particle) Hypothesis:

One of the most attractive scenario for collider Experiments and many TeV new physics models

SUSY models with R-parity naturally contain the WIMP DM candidate
Lightest Superpatner Partcle (LSP)

Other non-SUSY candidates:
Lightest Kalza-Klein particle in UED,
Light vector boson in Little Higgs model with T-parity,
…





Pecision mearurement of the mass and coupling constants at ILC can determine the essence of Dark matter

Birkedal et al. 2005, 2006

Summary

- After July 2012, the world has changed
  - Higgs discovery is not the end of the story
  - The new stage just started
- Higgs Sector (Still being mystery)
  - Origin of Mass? Essence of EWSB? Dynamics of λ coupling?
  - Its shape, dynamics, couplings are related to each scenario of new physics models beyond the SM

Higgs sector = Window to new physics

- New Physics
  - Direct searches (strongly model dependent)
  - Indirect test by fingerprinting from details of *h* couplings, top physics. and other precisely measured quantities (guaranteed physics)

We need LC

Thank you very much