Overview of LC Physics
and Detector Requirements

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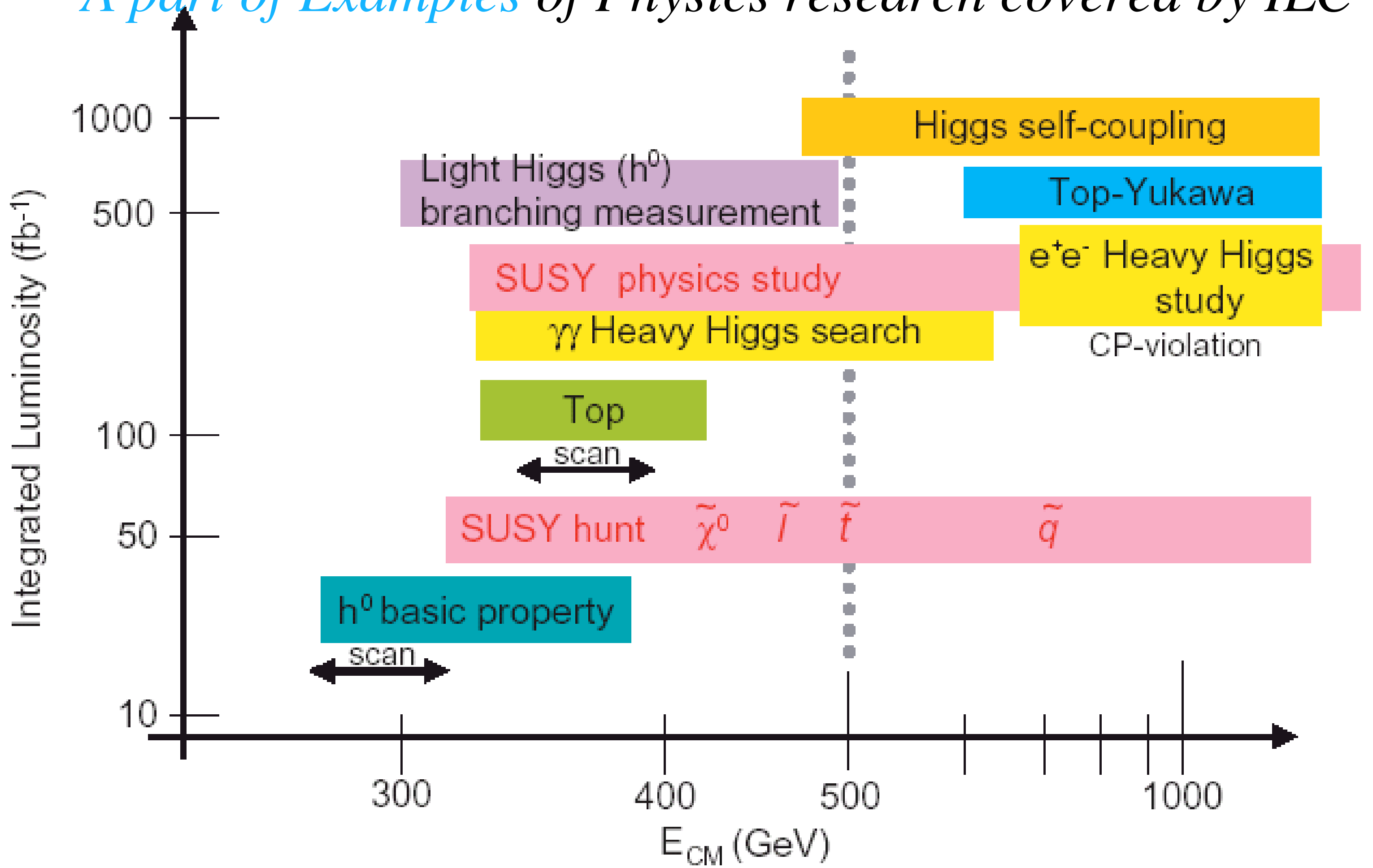
Many materials from

- ACFA LC report (2001)
- TESLA TDR (2001)
- LC physics resource book for Snowmass (2001)
- GLC Project (2003)
- Linear collider report from WWS (2003)
- LHC-LC note (G.Weiglein et al. 2004)
- Response to ITRP questions (2004)
- Many from LHC, LC related workshops
- … … …

Many thanks to all

A part of Examples of Physics research covered by ILC



1^{st} stage: Ecm =210 -500 GeV,
Luminosity = ~ 200 - 500 / fb / year x several years .
2^{nd} stage: Ecm = 1 TeV

Goals of ILC

1. **"Unexpected" new signals**
2. **Electroweak symmetry breaking** and mass-generation
3. Direct signals for **new physics** (SUSY, extra-dimensions, Z'…) and **determine The Physics**
4. **GUT and Planck scale** physics

Murayama LP03

Powerful Tools at ILC

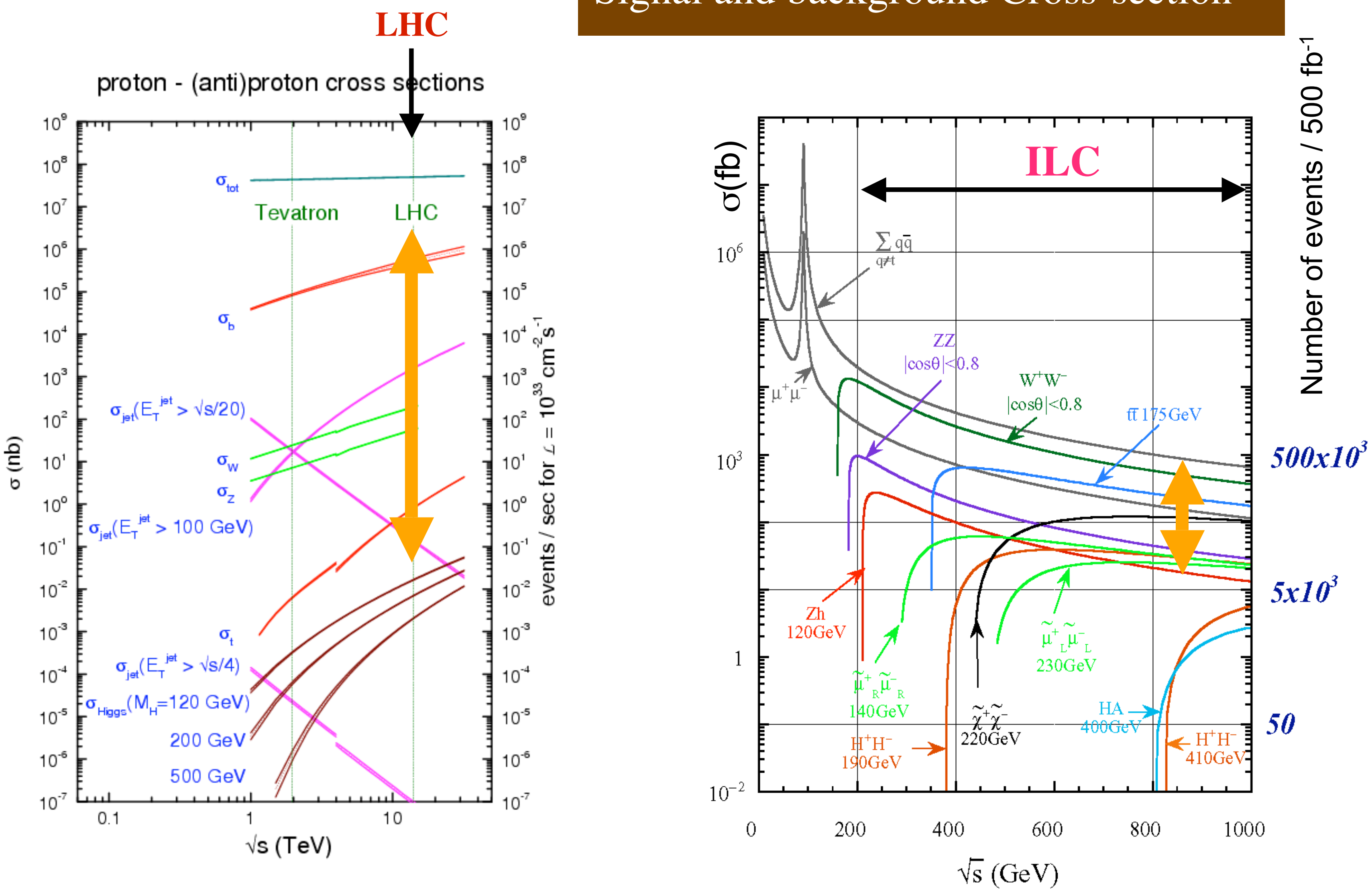
- **Electron/positron collision** (elementary process)
- **High Energy and High Luminosity**
- **Energy scan** (controllable)
- Controllable **beam polarization**
- **Very sensitive detectors** & Trigger free
- Precise **theoretical calculation** (<1%)

→ Precise physics information & long energy reach

LHC gives us a **new** **global (mixed)** picture.

→ ILC gives us **new** dynamic **multi-dimensional total** views.

Signal and background Cross-section



Detector Requirements

The best summarized in World-wide "Linear Collider Detector R&D"

J.Brau, C.Damerell, G.Fisk, Y.Fujii, R.Heuer, H.Park, K.Riles, R.Settles, H.Yamamoto

Complete document is available from

http://blueox.uoregon.edu/~lc/randd.ps (.pdf)

Performance Goal of ILC Detectors

■ VXT

Impact Parameter resolution: $< 5\mu m + 10\mu m / p(GeV) \sin^{-3/2}\theta$

■ Tracker

Momentum resolution: $dp/p < 5 \times 10^{-5} \times p(GeV)$ (central region)
$3 \times 10^{-4} \times p(GeV)$ for forward region

Angular resolution: $d\theta < 2 \times 10^{-5}$ rad (for $|\cos\theta|<0.99$)

■ Jet energy resolution: $dE/E < 0.3 / \sqrt{E(GeV)}$

■ Excellent Hermeticity: down to θ < 5--10 mrad (active mask)

Challenge

In order to accomplish our physics goal at ILC

With respect to detectors at LHC:

■ **Inner VTX layer**	**3--6 times closer to IP**
■ **VTX pixel size**	**1 / 30**
■ **VTX materials**	**1 / 30**
■ **Materials in Tracker**	**1 / 6**
■ **Track mom. resolution**	**1 / 10**
■ **EM cal granularity**	**1 / 200 !!**

Most of physics needs information from all sub-detectors

In most cases, physics sensitivity is determined by
how well the sub-detectors are combined and optimized as a single detector,
rather than how well each sub-detector works.

How to combine and optimize the total performance of detector

"**Detector concept**" is essential

→ **Next 3 talks**

To accomplish the detector optimization and comparison in the most effective way:

Need

- **Common (for ALL "concepts") Physics Benchmarks**
  - Physics models
  - Particle properties (mass..) and decay Br
  - Energy and luminosity points

  Choose different type of event topologies

- **Common sets of Event generators**
- **Common Simulation platform(s) -- simulators/data format**
- **Common archive for Analyses Tools**
- **Common data archive**

Very good starting points: **Snowmas points**, **Le Houche accord**, etc..

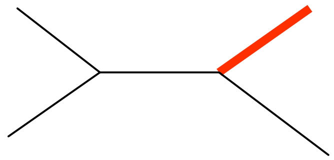
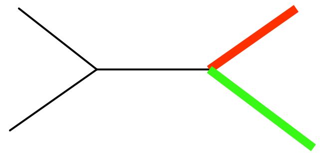
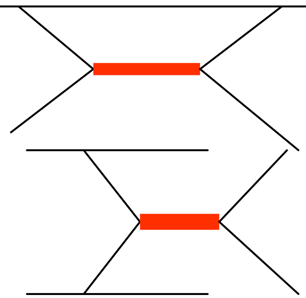
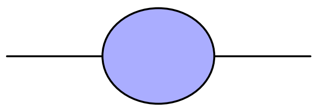
It's time for "Taipei points / scheme" for ILC

Back to ILC physics

Introduction

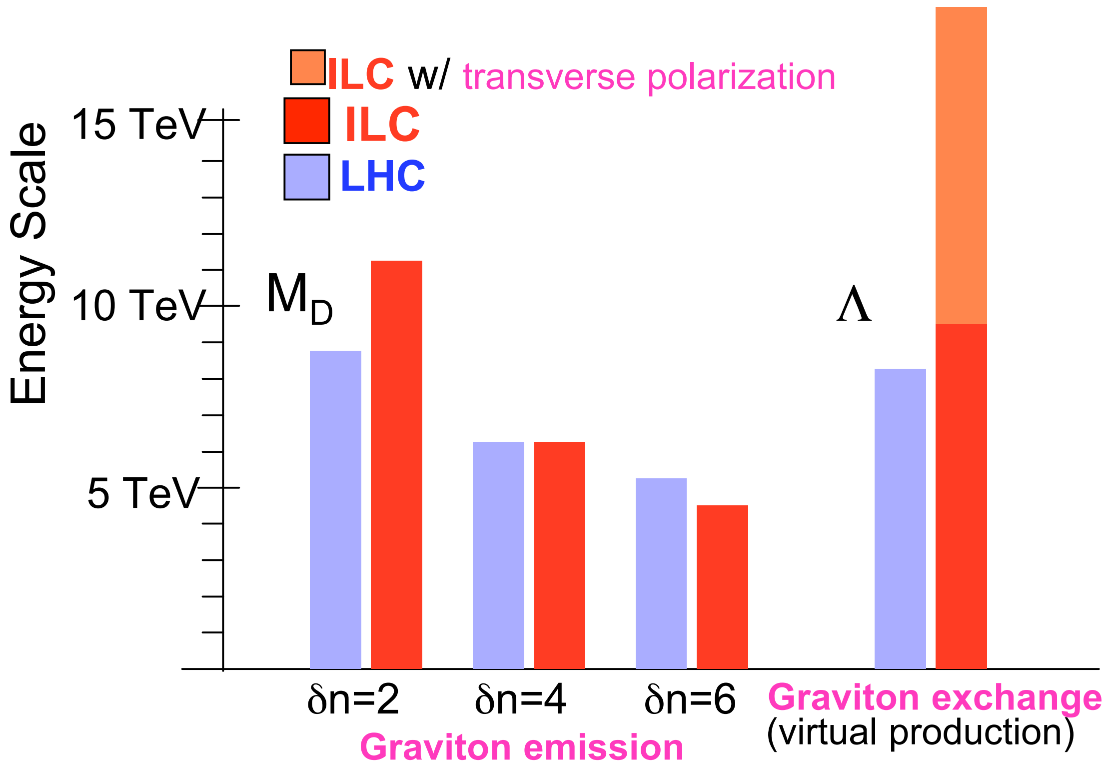
Higgs, SUSY, etc..

Sensitivity, Physics reach and precision

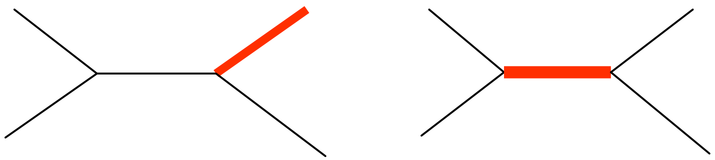
		LHC	ILC
Single production Higgs Extra-Dimension		**~a few TeV** ds/s > 10 %	**~ 1 TeV** **$\delta\sigma/\sigma \sim 1\%$** **$\delta(d\sigma/d\Omega) \sim 1\%$**
Pair production SUSY Heavy Higgs		**~2-3 TeV (colored)**	**~0.5 TeV (any type)** **$\delta\sigma/\sigma \sim 1\ \%$** Energy scan, Beam pol
Intermediate state Extra-Dimension Strong EWSB Z', contact Int.		~several TeV **resonance**	**>10 TeV** $\delta\sigma/\sigma \sim 1\ \%$ Energy scan, Beam pol Coupling, spin
Loop effect		△✕	**A few % level effect**

Examples: Reach and beyond

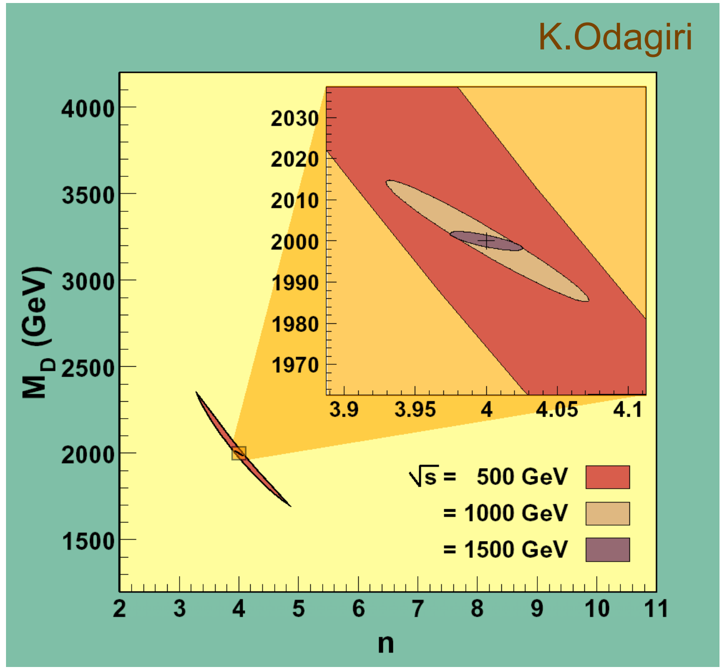
Large Extra Dimension Reach



Numbers are taken
From J.Hewett et al



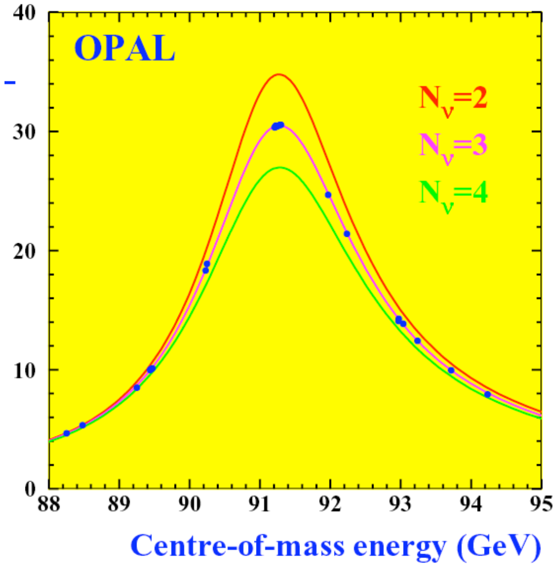
Not only the reach !

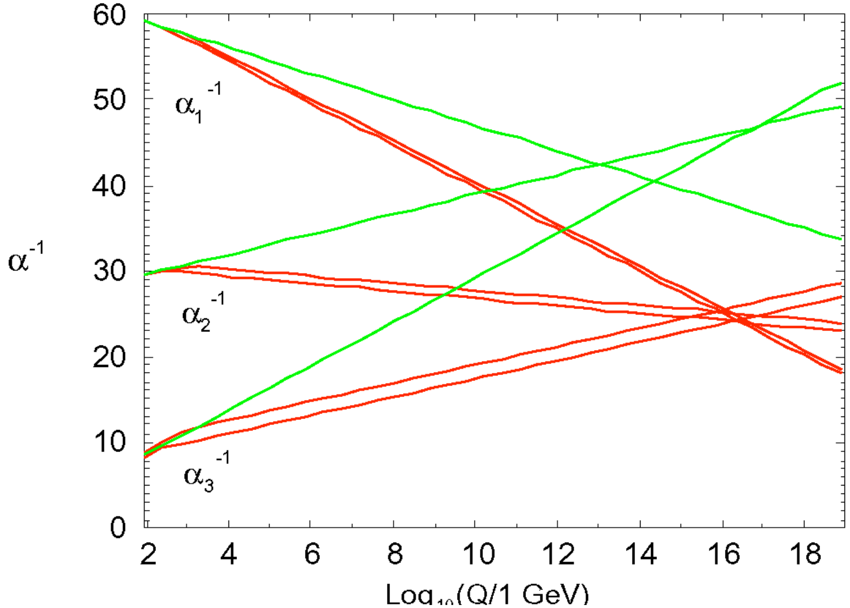


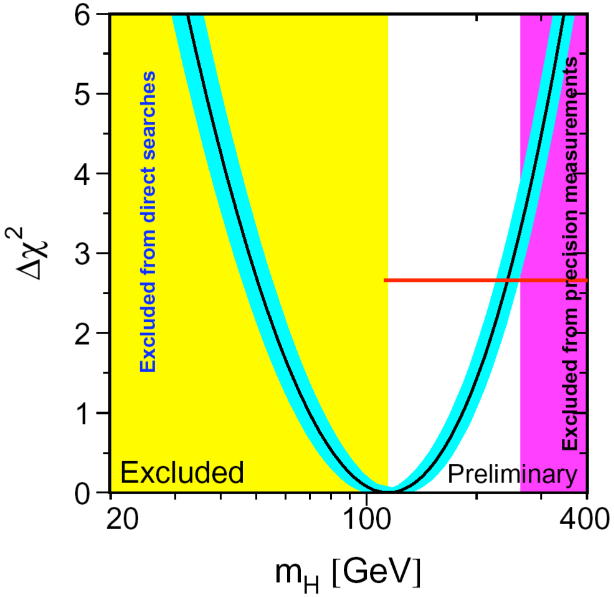
# of extra-dimensional space

The **size and number of the extra-space** to be determined at ILC.

Everyone knows power of Precision







LEP/SLC/Tevatron

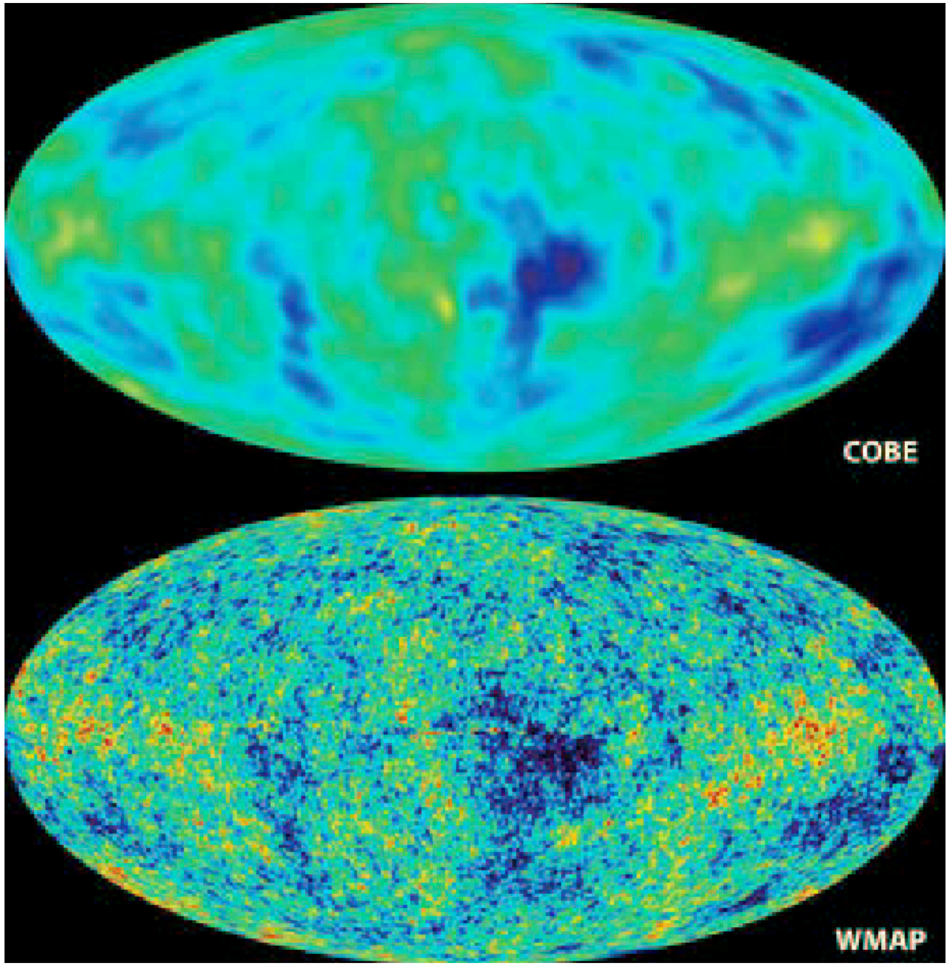
$SU(3)_c$ X $SU(2)_L$ X $U(1)$ Gauge interaction

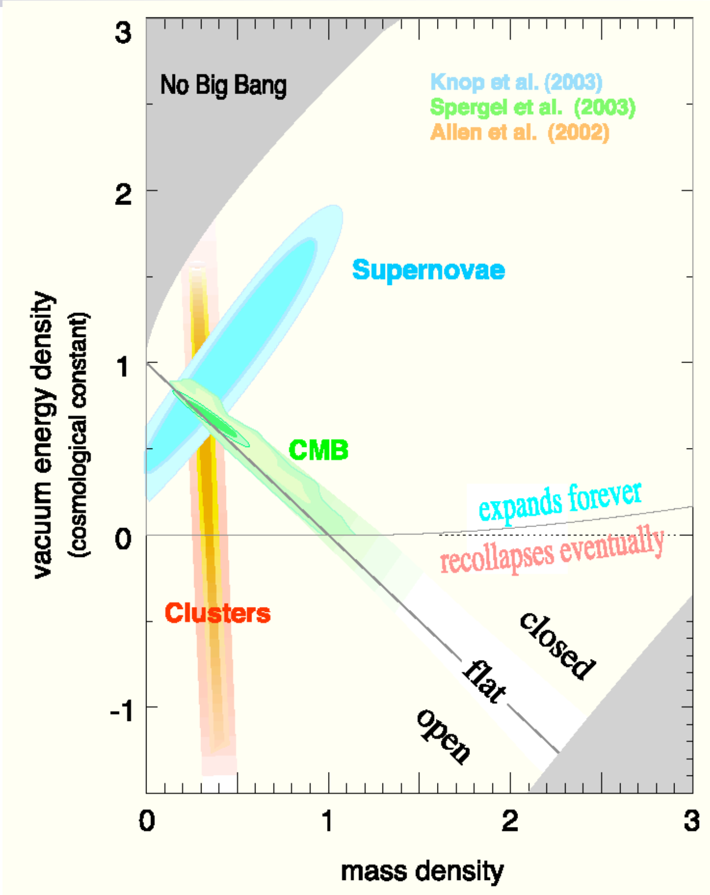
3 generations

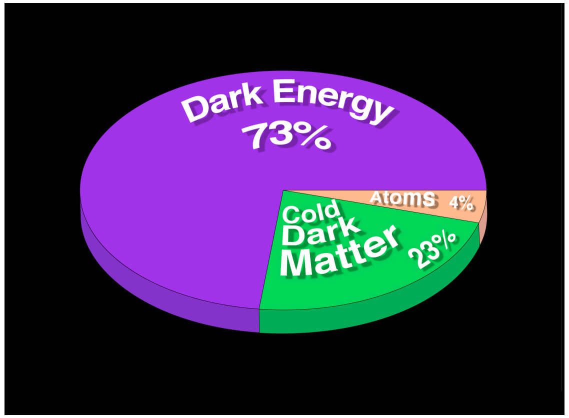
Higgs is light (114-260 GeV for SM Higgs)

SUSY GUT indication

Precision gives us a lot!

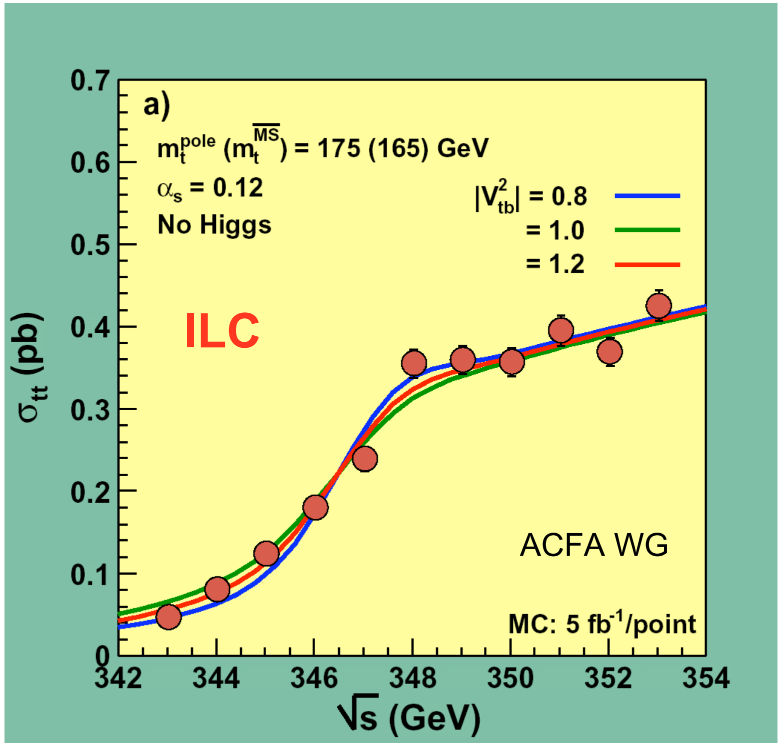


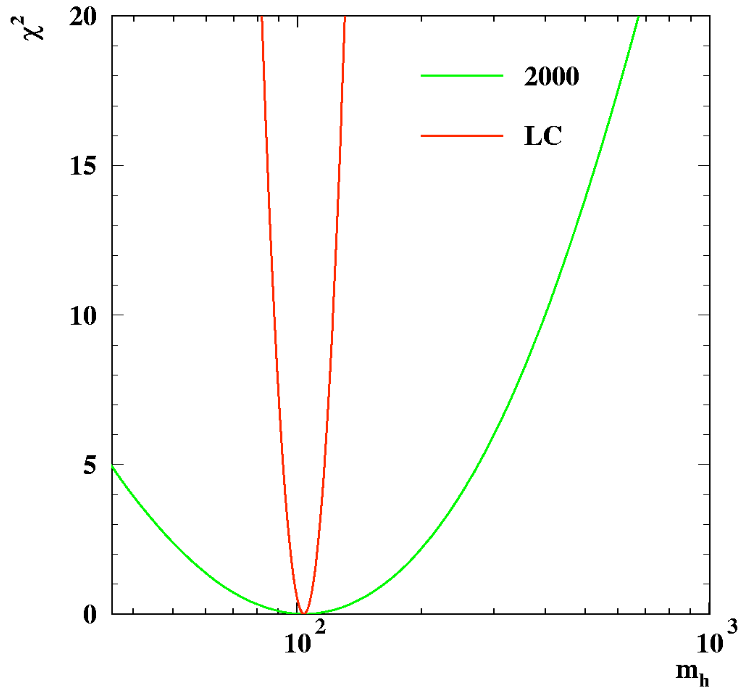




Very High precision at ILC

	δm_W (MeV)	δm_{top} (GeV)	$\delta \sin^2\theta_{eff} \times 10^5$
now	34	3.9	17
TeV Run 2	16	1.4	29
LHC	15	1-2	14-20
ILC(+GigaZ)	7	0.1	1.3





First Step = Higgs

- Higgs is
  - Spin 0 (elementary?) particle
  - very sensitive to Physics between O(100GeV) to GUT/Planck scale
- Structure and coupling of Higgs sector are keys to
  - Origin of mass and spectrum of particle masses
  - Vacuum structure of Universe
  - Physics between O(100GeV) to GUT scale
  - SUSY structure and spectrum
  - Electroweak Baryogenesis

Higgs Mechanism

Coupling-mass relation

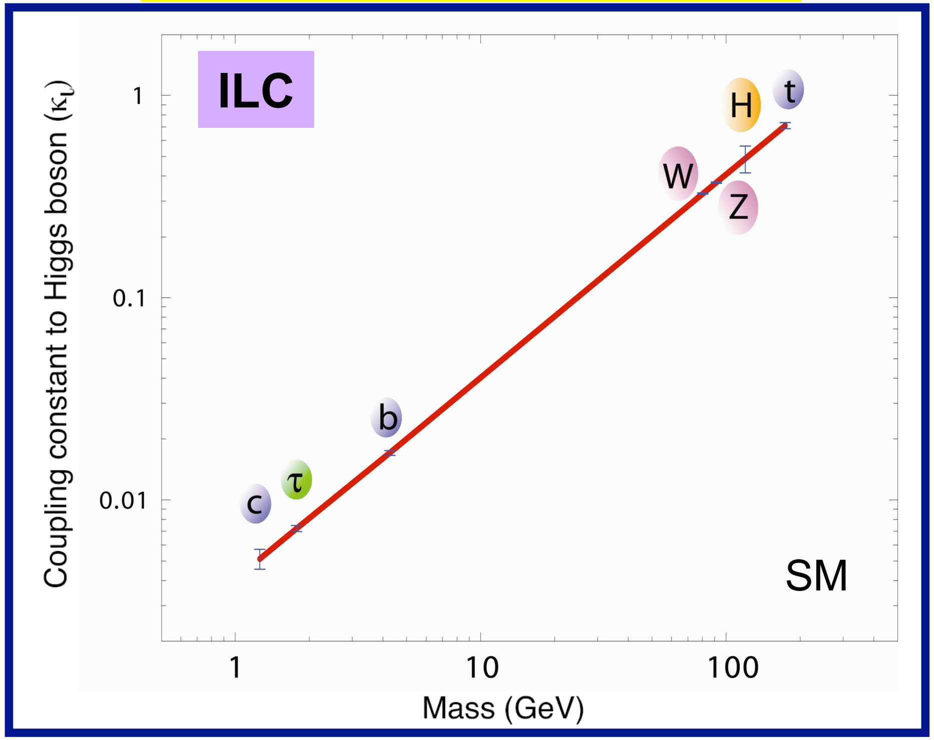
The Higgs vacuum-expectation-value

$$m_i = v \times \kappa_i$$

Particle mass

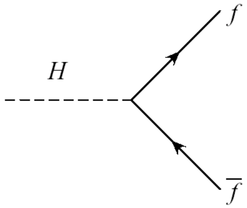
Higgs coupling constant

If one Higgs generate all masses

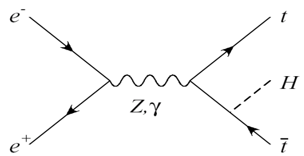


Different pattern If SUSY, Multi-Higgs etc..

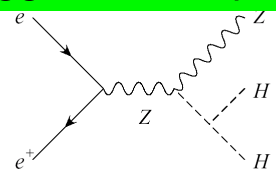
Higgs boson branching ratios



Top Yukawa coupling



Higgs Self-coupling



Mass-generation mechanism

Higgs Sector is unknown

Electroweak fit at LEP/SLC/Tevatron tells
At least one should exist below 300 GeV
which couples to Z and W

Almost NOTHING is known

- NOTHING is known for **Yukawa-coupling**
- NOTHING is known for **self-coupling**

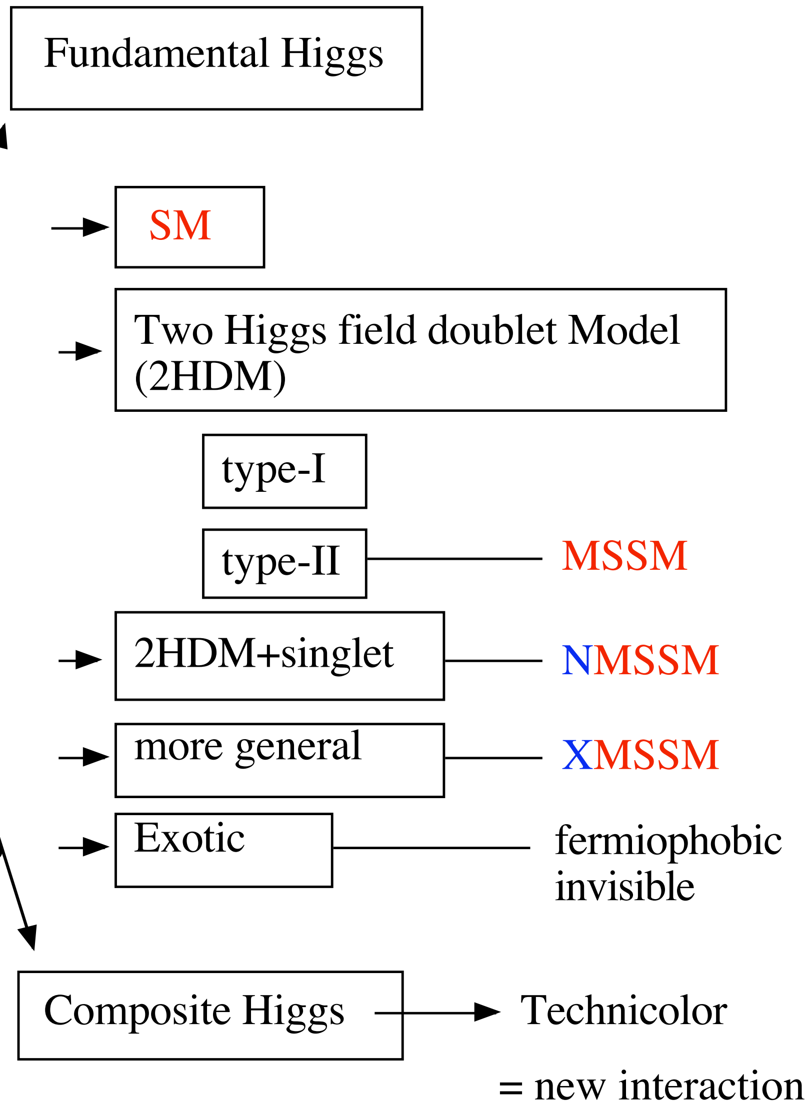
- Single Higgs? Two Higgs field doublets?
- Additional singlet? Triplet?

- SUSY? Extra-dimension?
- **Composite?**
- Type-I? Type-II?

- Why top is so heavy? Special for 3rd generation?

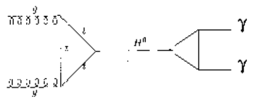
- **CP-violation** in Higgs sector?

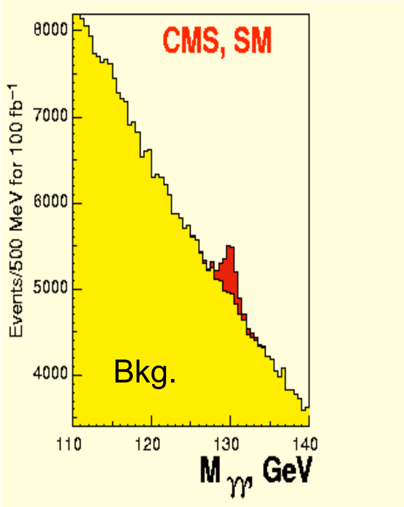
- More exotics?



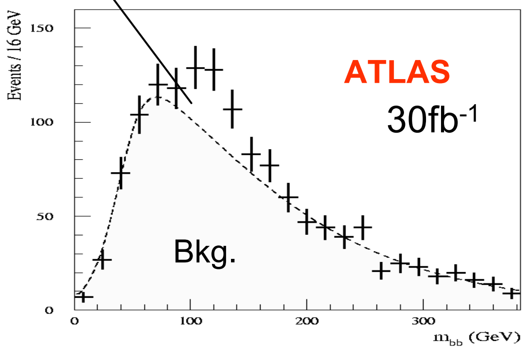
LHC Higgs signal

$H \rightarrow \gamma\gamma$

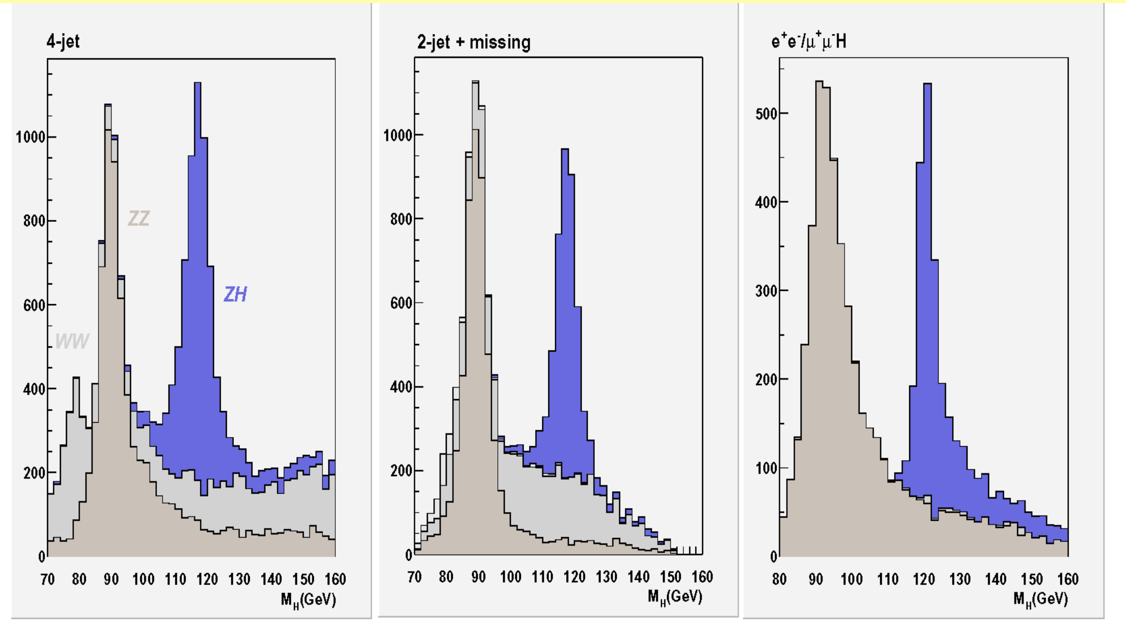


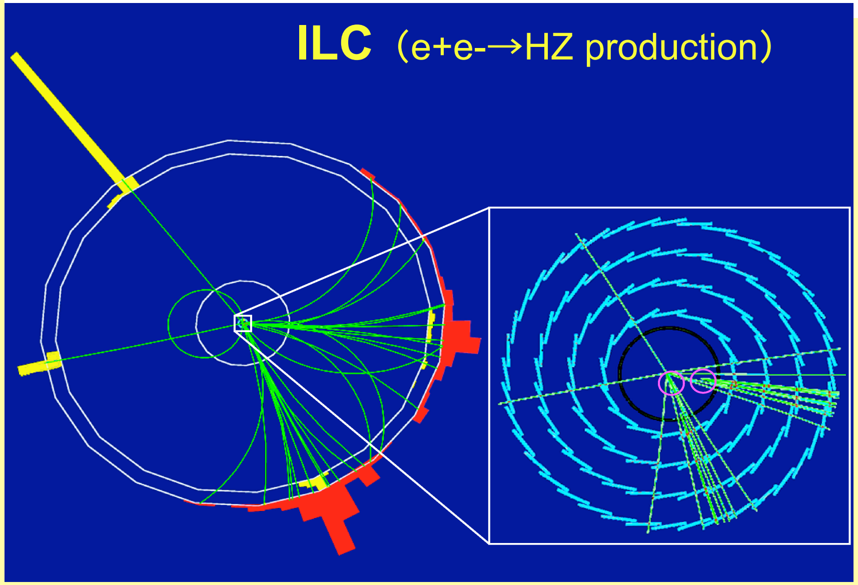


ttH→WbWbbb→lνjjbbbb



ILC Higgs signal

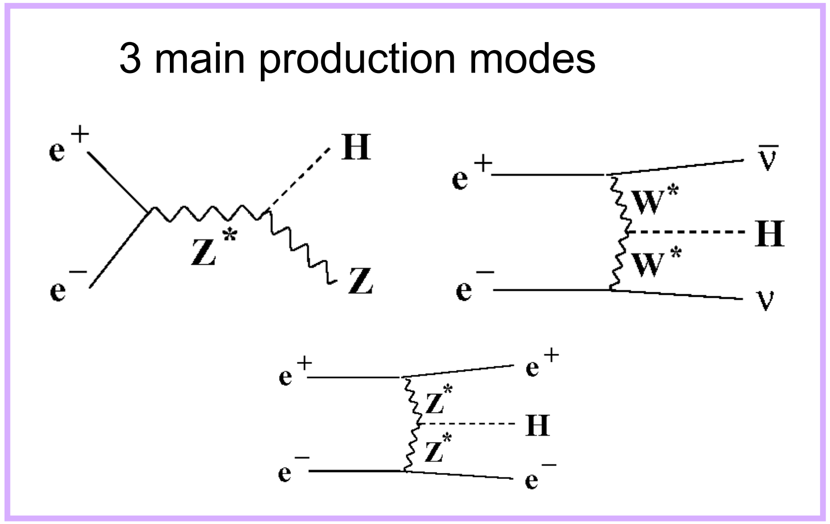


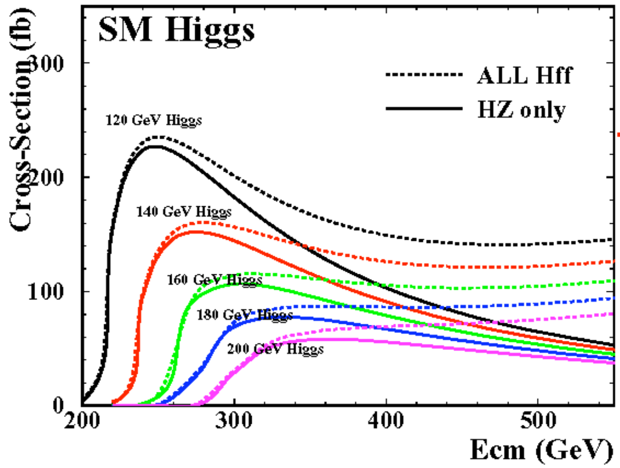


Typical numbers

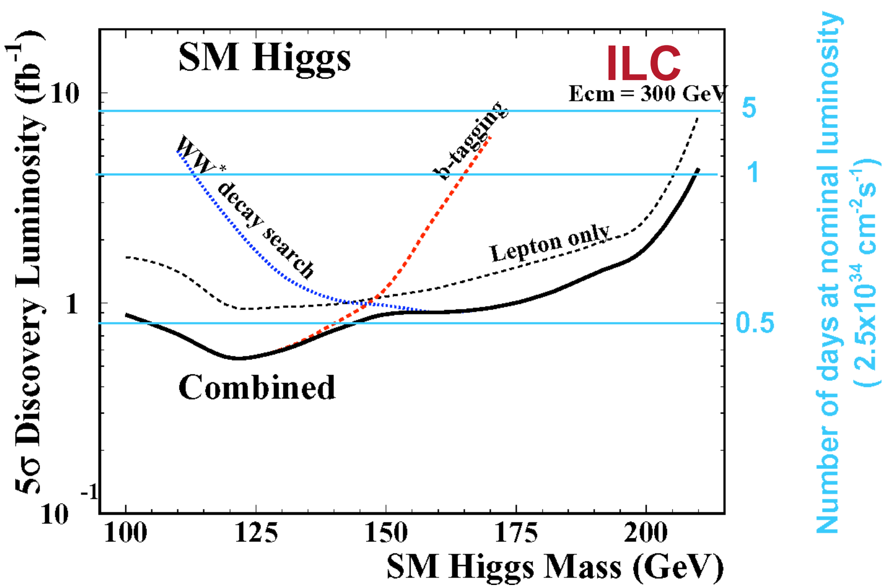
Tagging efficiency
~ 30-50 %

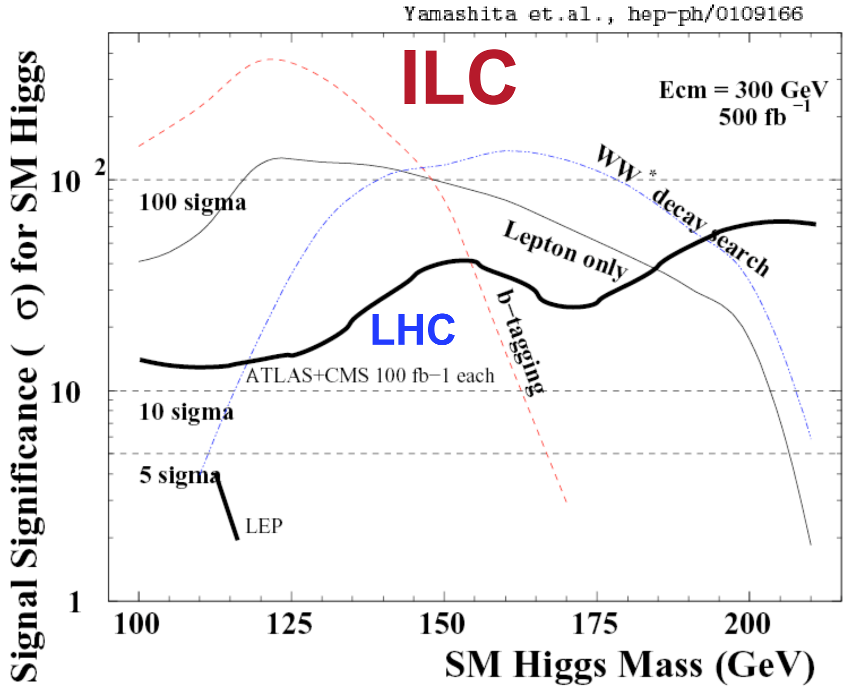
S/N > 1





$>10^5$ Higgs for 500fb^{-1}

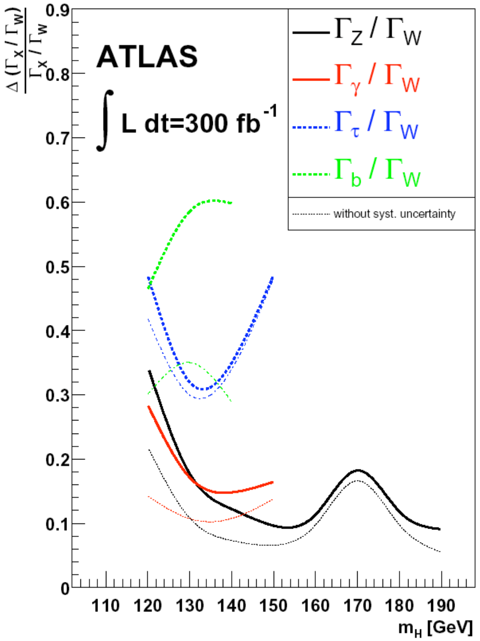




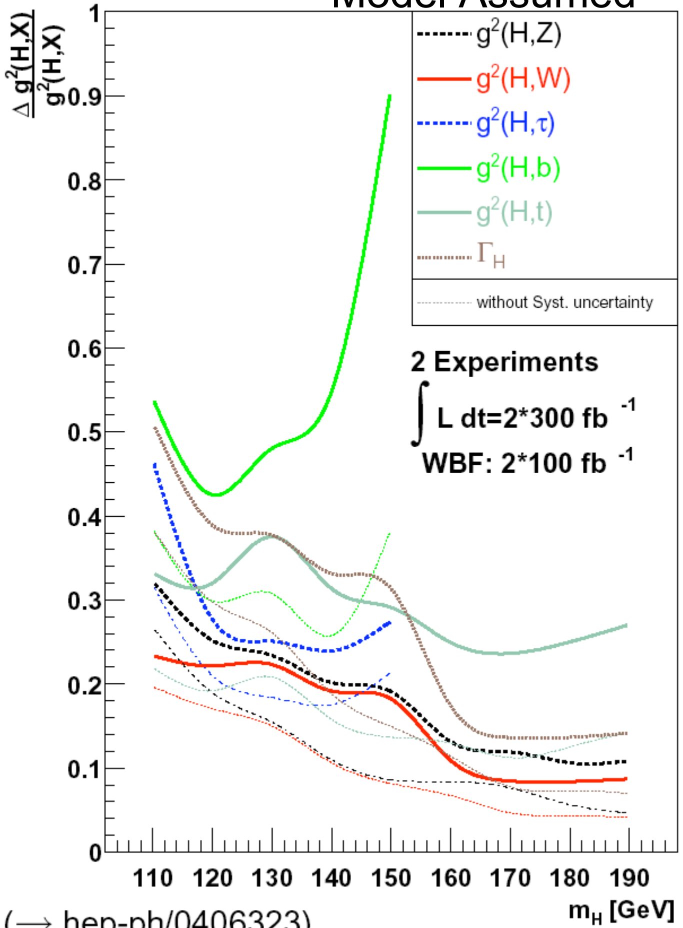
Higgs coupling measurements at LHC

Ratio can be obtained using events with “similar” topology

Michael Duhrssen et al. `04 (hep-ph/0406323)



Model Assumed



(⟶ hep-ph/0406323)

Γ_{tot} is unknown..
Absolute strength is difficult to measure

Using moderate
model assumption

Limit on g_W^2 and g_Z^2:

$$\frac{g_W^2}{g_W^2(\mathrm{SM})}, \frac{g_Z^2}{g_Z^2(\mathrm{SM})} < 1 + 5\%$$

For Mh 115-150 GeV

$\delta\Lambda_\tau / \Lambda_\tau \sim 15\ \%$

$\delta\Lambda_b / \Lambda_b > 20\ \%$

Mainly from ttH process

$\delta\Lambda_{top} / \Lambda_{top} \sim 15\text{–}20\ \%$

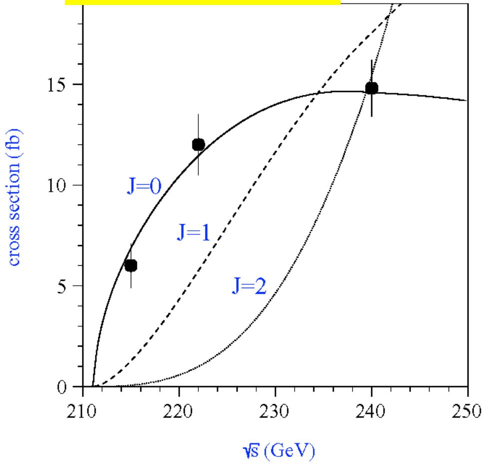
ILC Examples of Higgs *Model Independent* Analyses

Mass & Cross-section measurement
=**Gauge coupling** measurement

$\Gamma_W = f(M_h) \times \sigma$

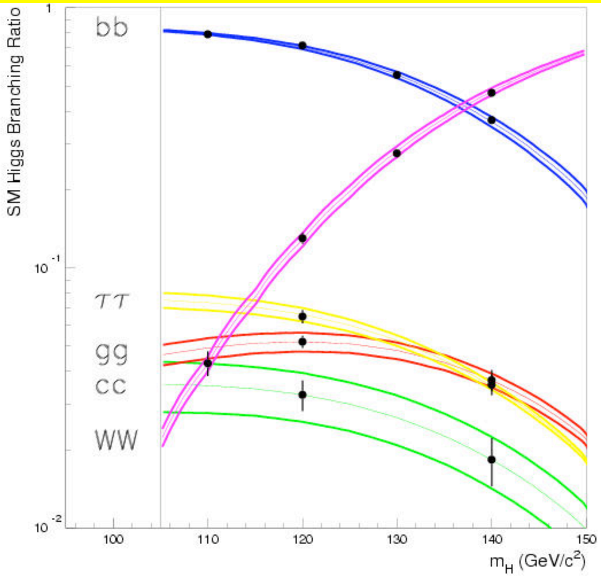
$\delta g/g \sim 1\%$ **$\delta M_h \sim 40$MeV**

Energy scan



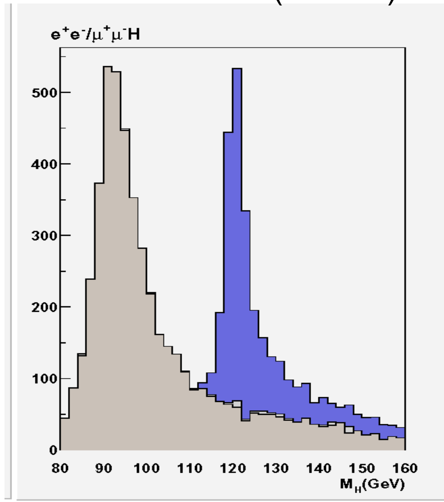
Spin, Parity

Branching ration measurements

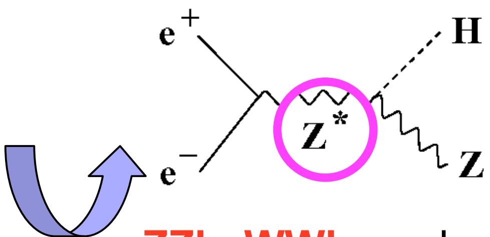


Invisible width

Use Recoil mass(no bias)



Beam polarization



ZZh, WWh production
(selectable)

CP, $SU(2)_L \times U(1)$

Total width measurement

$\Gamma_{tot} = \Gamma_W / \mathbf{Br}(H \to WW)$

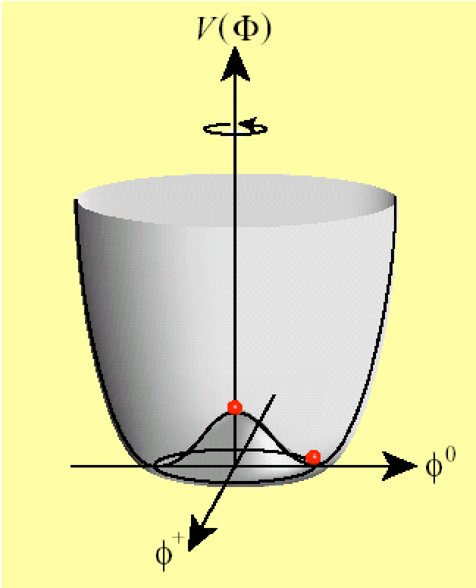
$\delta\Gamma_{tot}/\Gamma_{tot} \sim 5\%$

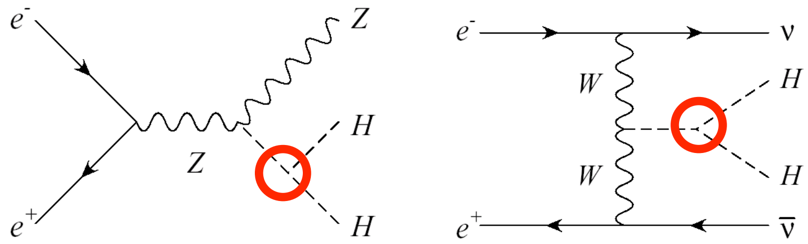
Absolute strength of Yukawa-Coupling determination

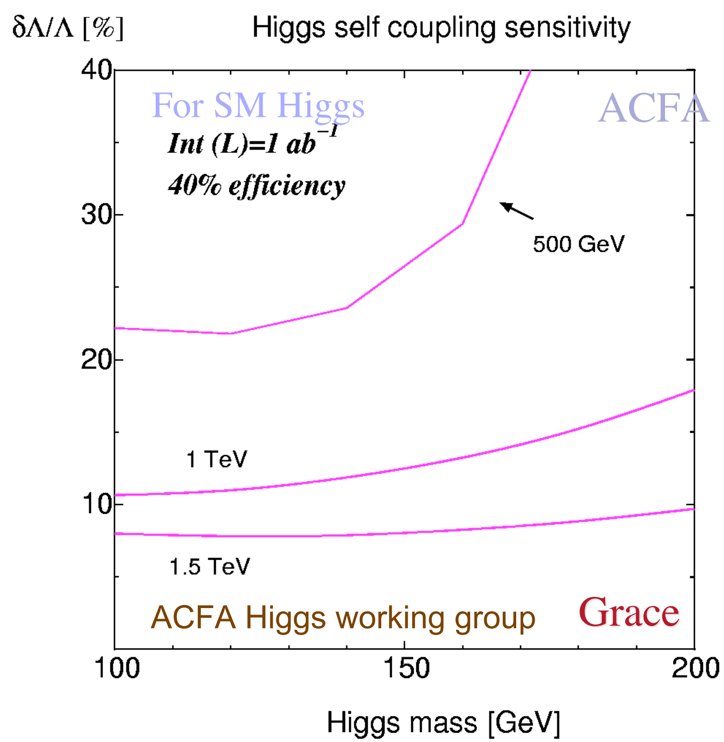
$\Lambda_f^2 = C(M_h) \times \mathbf{Br}(H \to ff) \times \Gamma_{tot}$

$\delta\Lambda_b/\Lambda_b \sim 3\%$, $\delta\Lambda_\tau/\Lambda_\tau \sim 4\%$,
$\delta\Lambda_c/\Lambda_c \sim 8\%$, $\delta\Lambda_U/\Lambda_U \sim 4\%$

Higgs potential = Origin of EW symmetry breaking





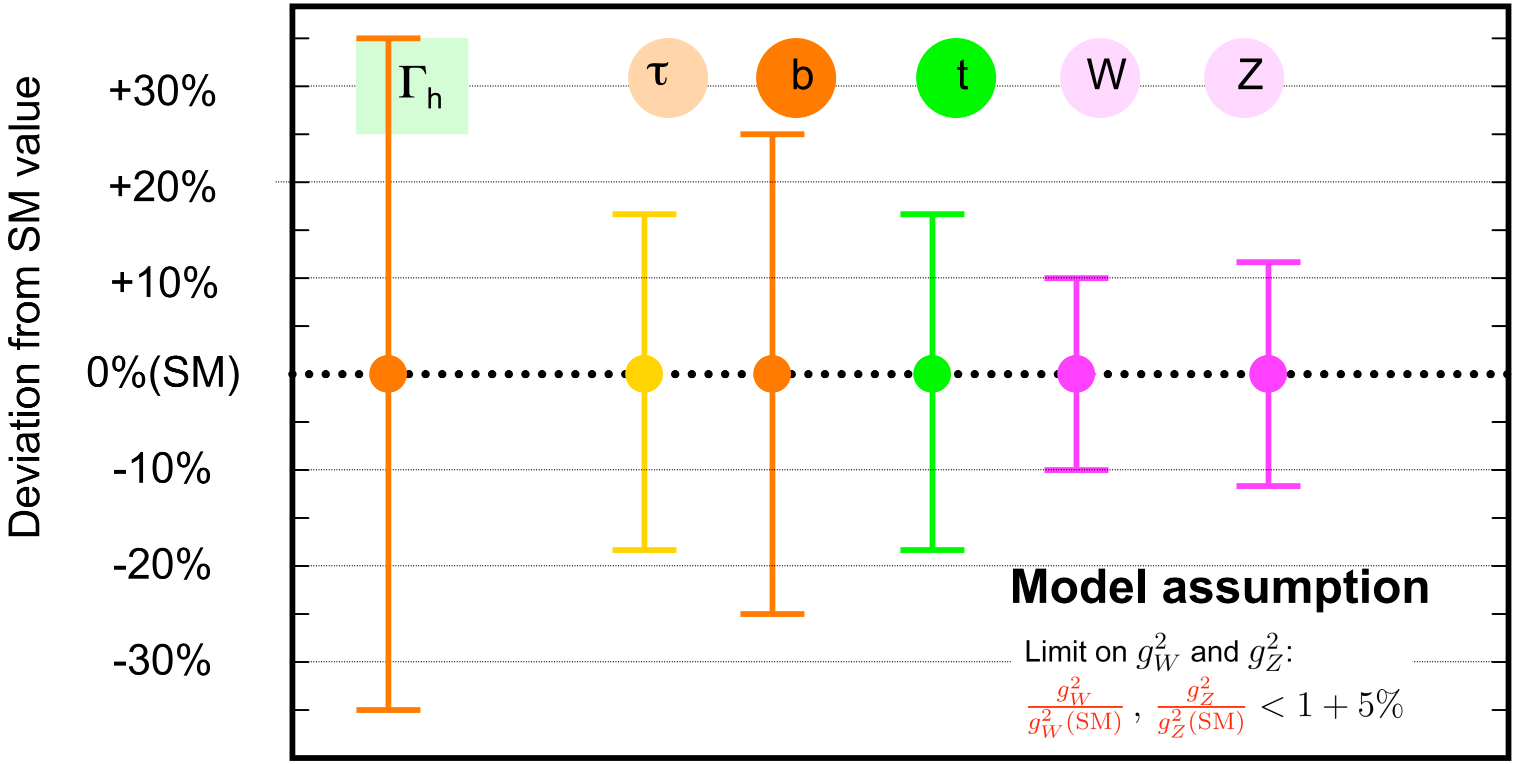


The first access to the Higgs potential through double Higgs-boson production.

$\delta\Lambda/\Lambda \sim 10 - 15$ %

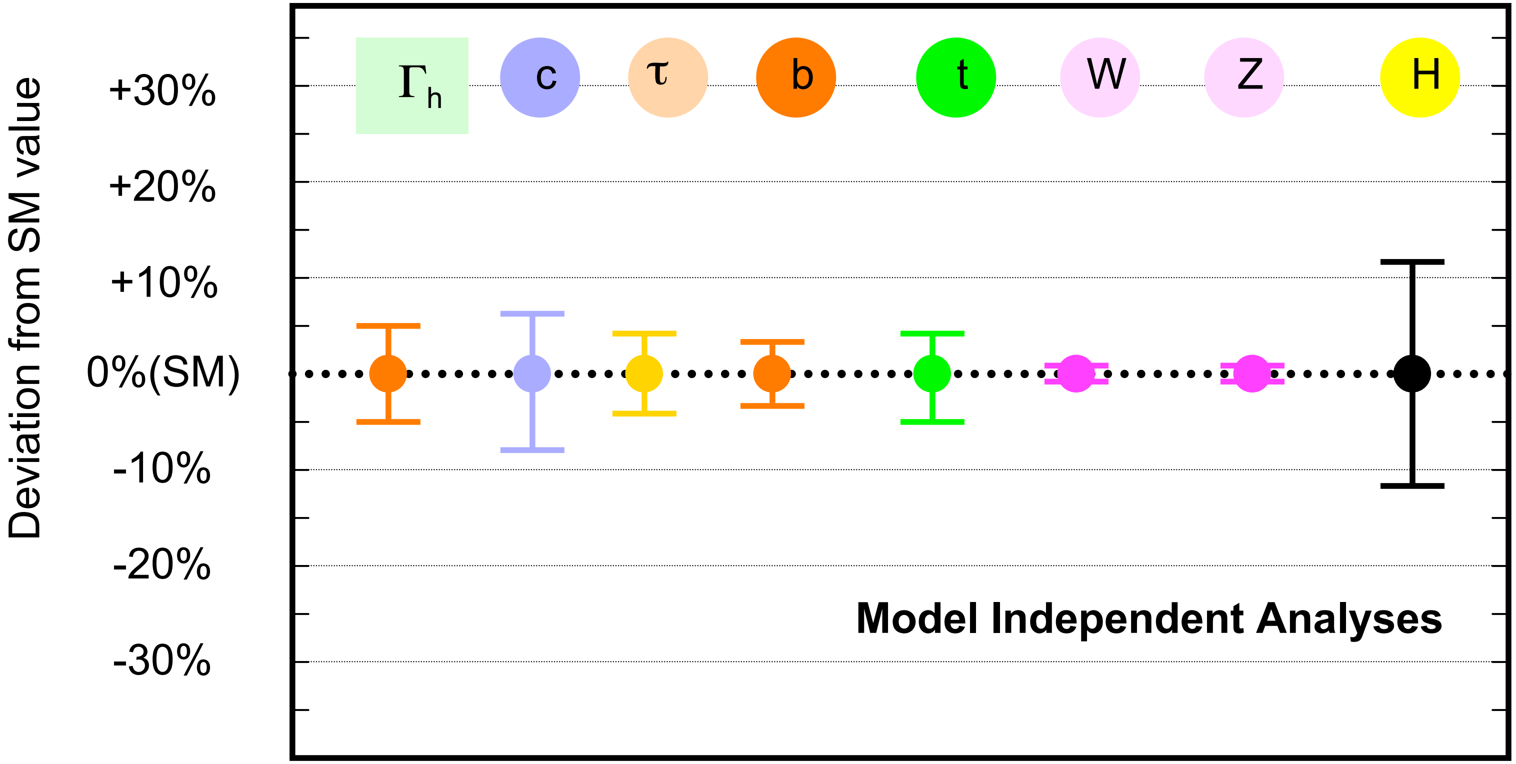
Coupling Precision

LHC 300 fb^{-1} x 2



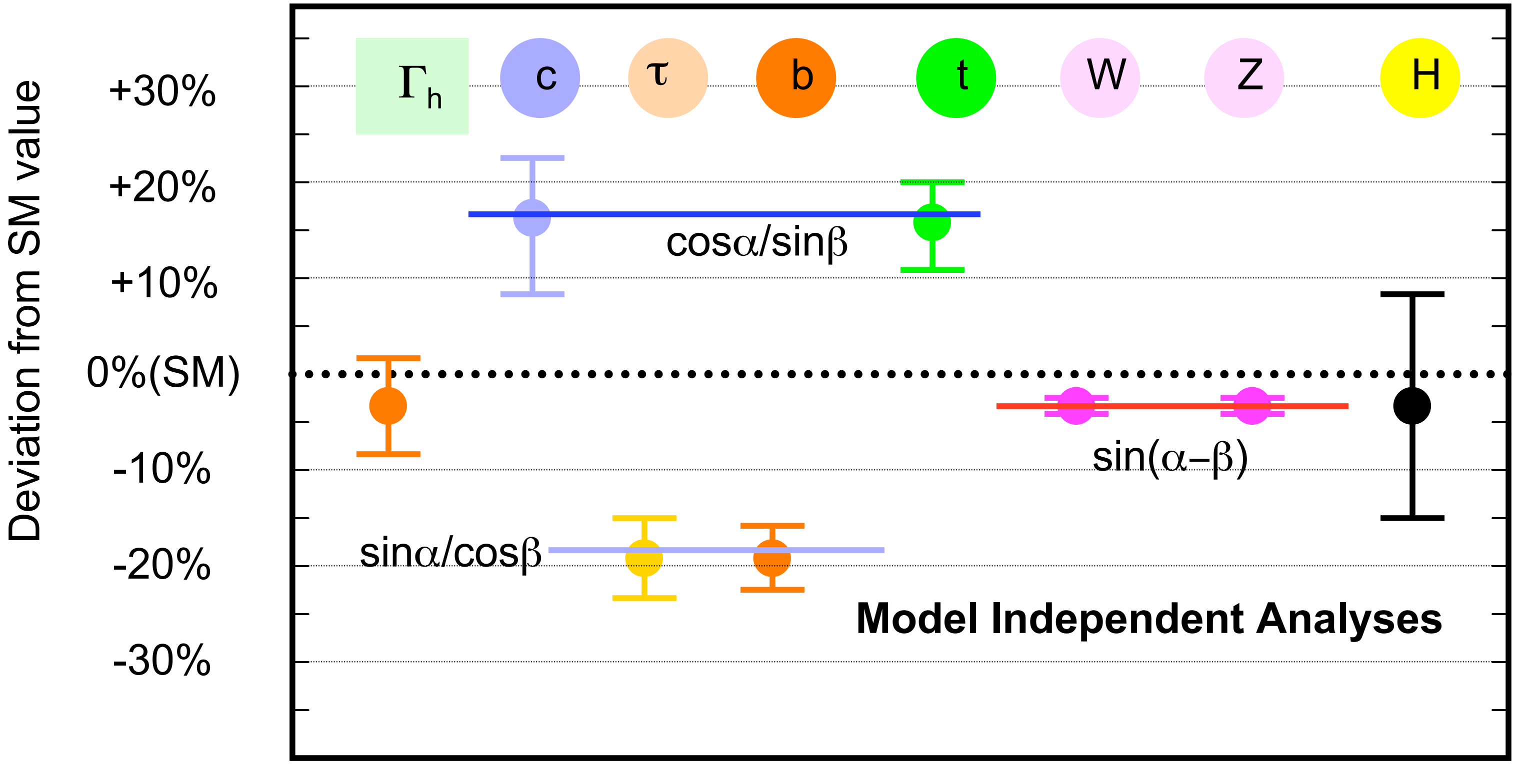
Coupling Precision

ILC



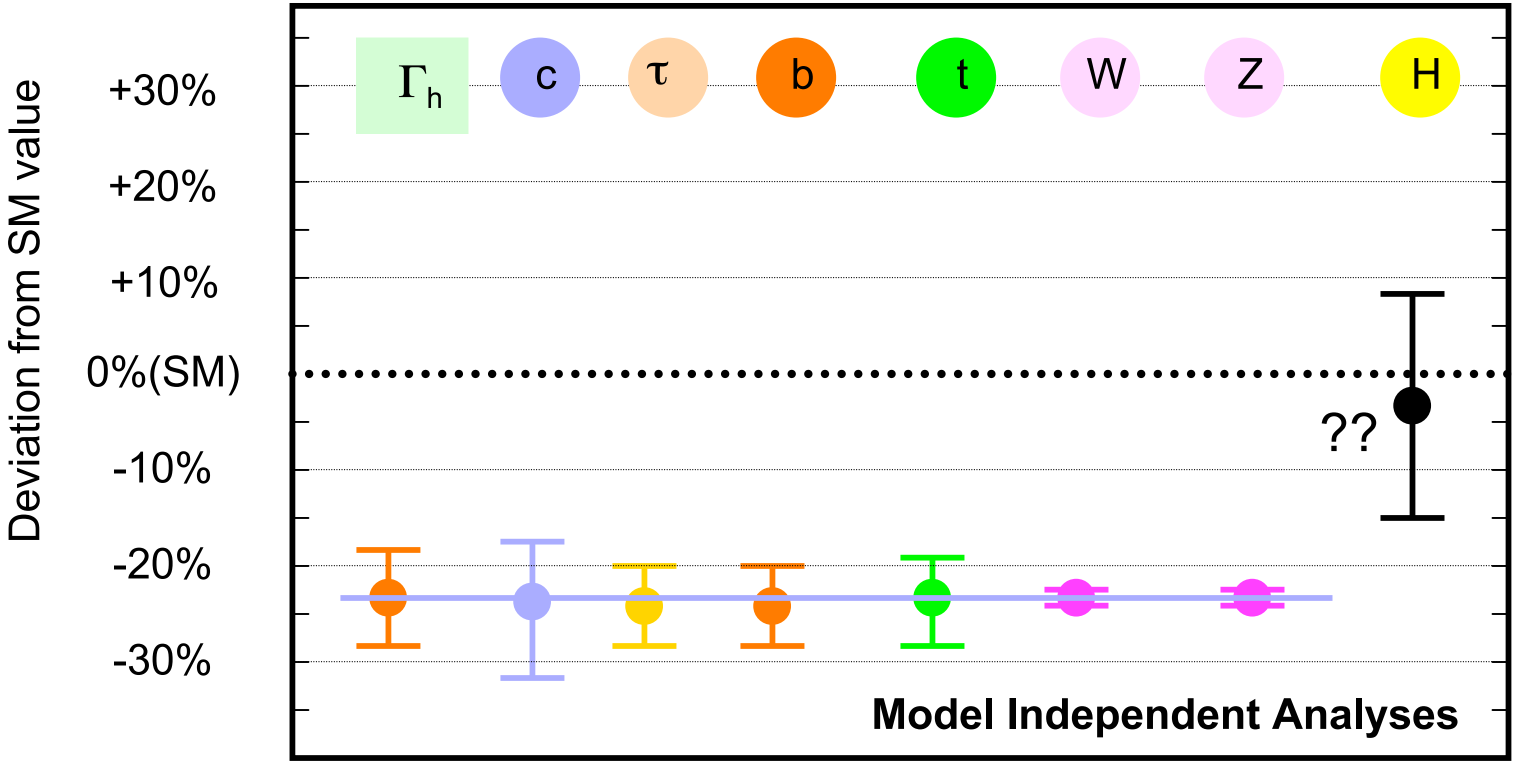
SUSY or 2HDM

ILC



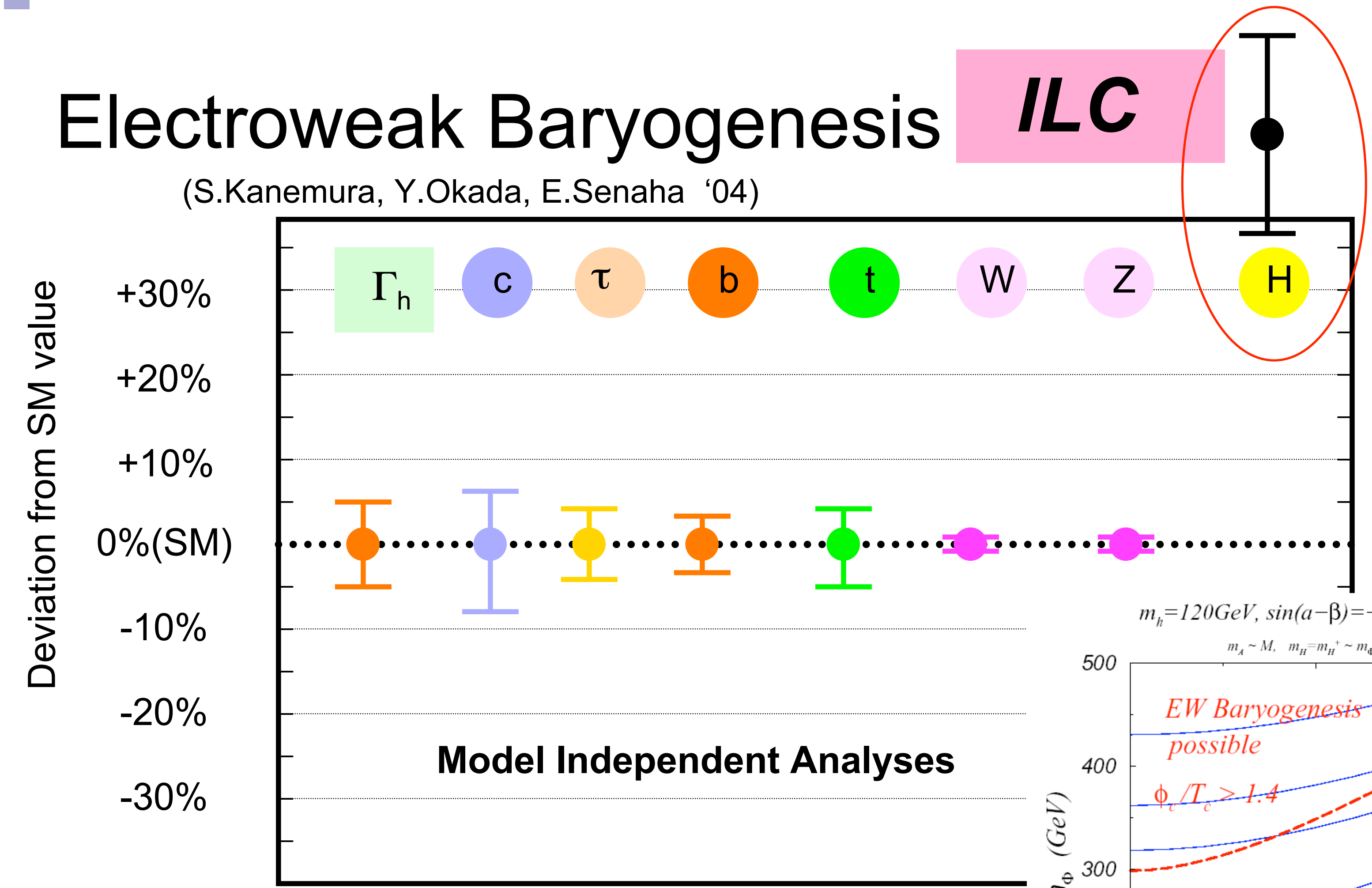
Extra-dimension (radion-Higgs mixing)

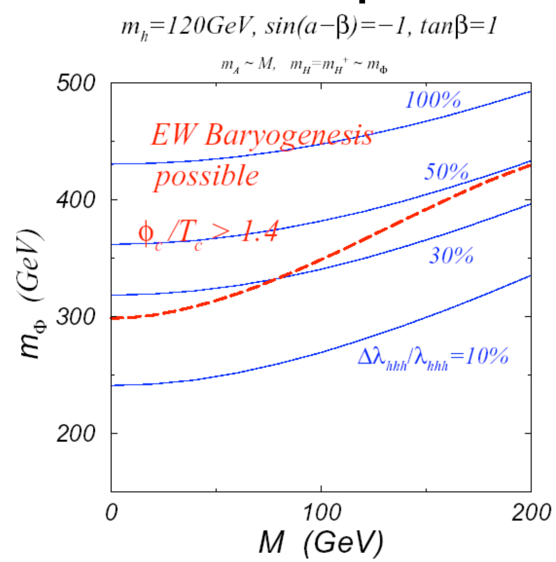
ILC



Electroweak Baryogenesis

(S.Kanemura, Y.Okada, E.Senaha '04)

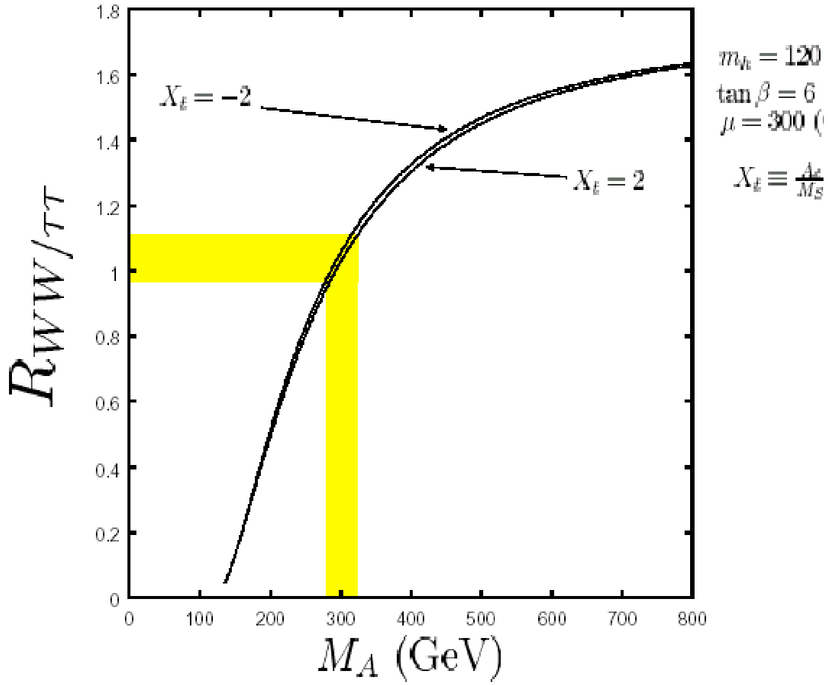




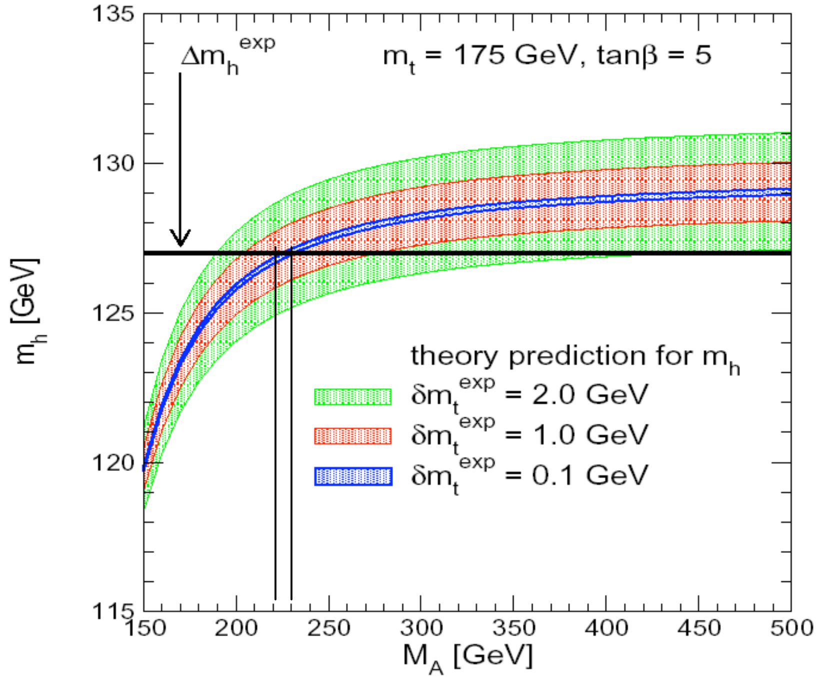
More than one Higgs boson?

$h, H, A, H^{\pm}$ in the Minimal Supersymmetric Standard Model.

$$R_{WW/\tau\tau} \equiv \frac{B(h \to W^{+(*)}W^{-(*)})}{B(h \to \tau^+\tau^-)}$$



Accurate coupling measurements tell us M_A



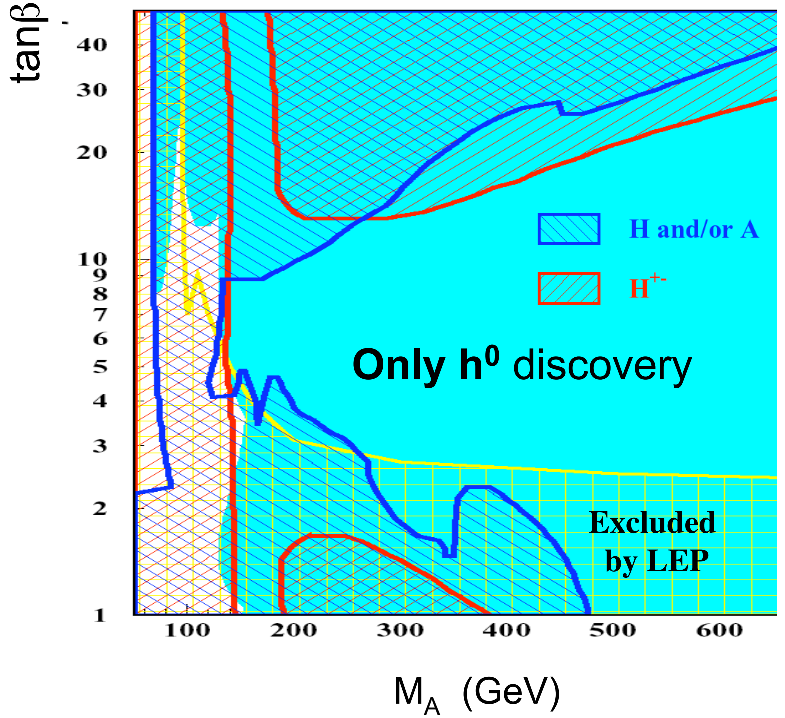
Top mass is also essential

Direct and indirect searches for heavy Higgs bosons at ILC.

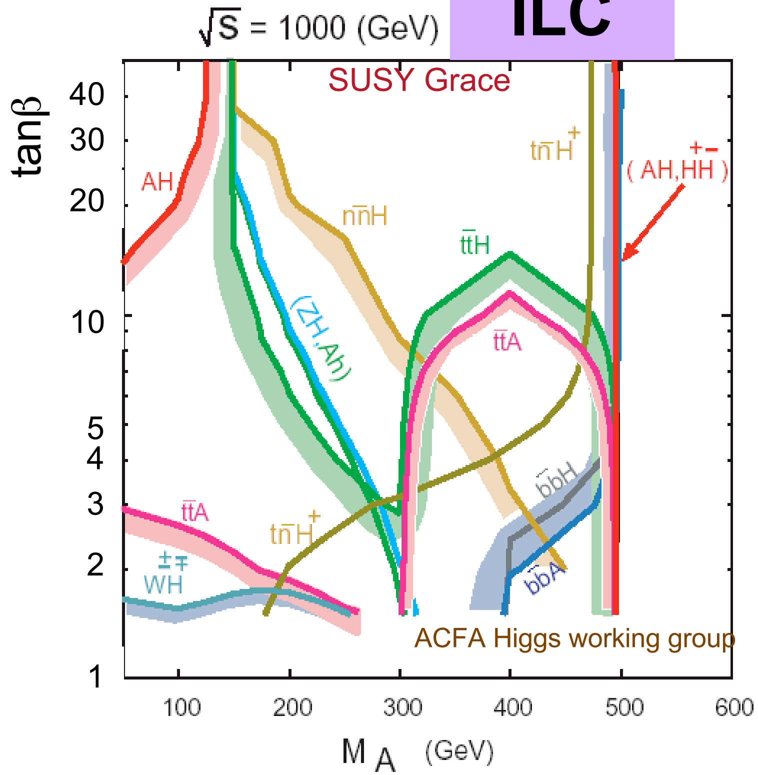
Heavy Higgs (A^0, H^0, H^{+-}) Discovery Reach

LHC

Mhmax scinario



ILC



Discovery reach depends on tanβ and model

Good at large tanβ case

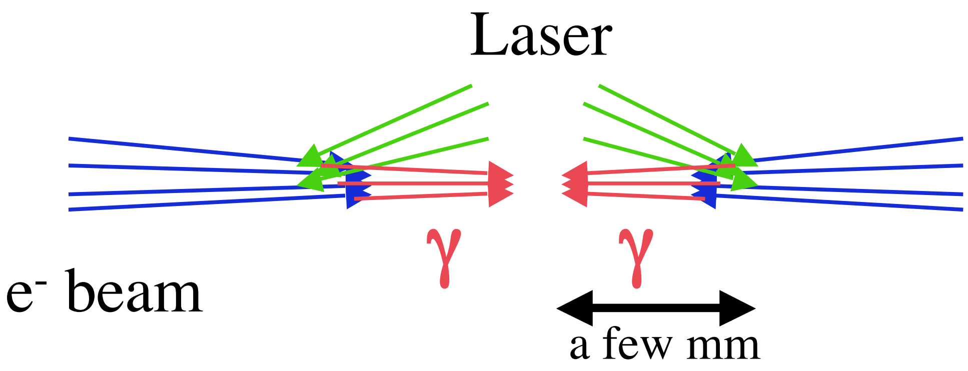
Full discovery in many channels independent of tanβ

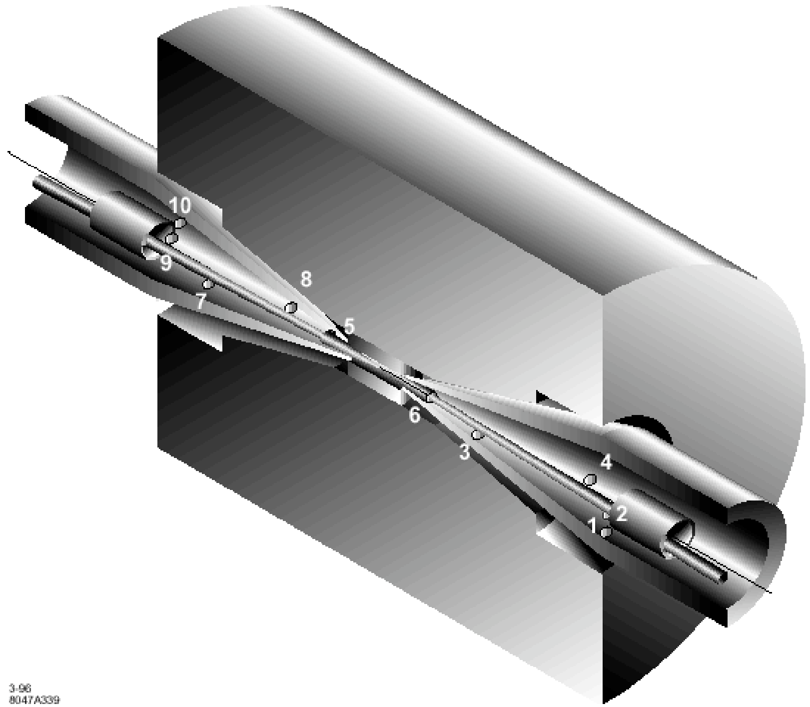
Reach up to ~ beam energy

If measured mass at ILC/LHC ≠ predicted mass by ILC

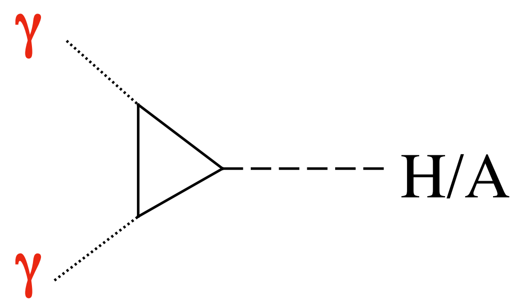
→ **Beyond MSSM, beyond 2HDM !**

Photon-photon collider option at ILC





- **Discovery Mode** for **Heavier Higgs**
- **Discovery reach up to ~800 GeV**
- **CP mixing** in Higgs sector
- Gamma decay width of light Higgs



Super Symmetry

SUSY List

SUSY particles

LHC

ILC

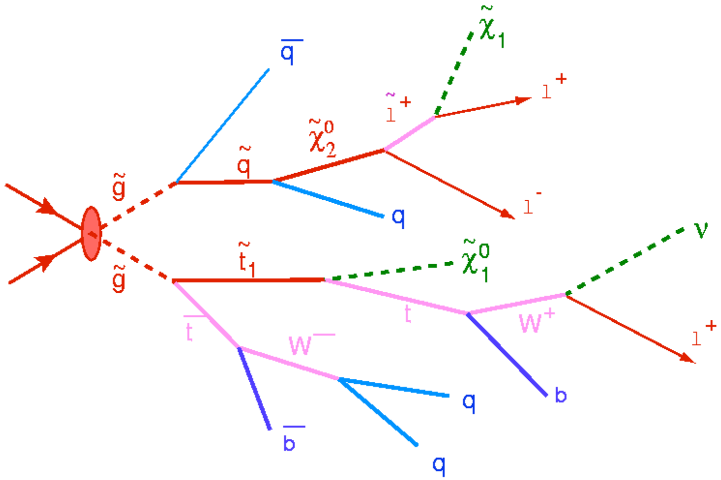
spin	0	1/2	1
Quark family	squark	quark	
	$\begin{pmatrix}\tilde u_L\\ \tilde d_L\end{pmatrix}$ $\begin{pmatrix}\tilde c_L\\ \tilde s_L\end{pmatrix}$ $\begin{pmatrix}\tilde t_L\\ \tilde b_L\end{pmatrix}$	$\begin{pmatrix}u_L\\ d_L\end{pmatrix}$ $\begin{pmatrix}c_L\\ s_L\end{pmatrix}$ $\begin{pmatrix}t_L\\ b_L\end{pmatrix}$	
	$\tilde u_R$ $\tilde c_R$ $\tilde t_R$	u_R c_R t_R	
	$\tilde d_R$ $\tilde s_R$ $\tilde b_R$	d_R s_R b_R	
Lepton family	slepton	lepton	
	$\begin{pmatrix}\tilde\nu_{eL}\\ \tilde e_L\end{pmatrix}$ $\begin{pmatrix}\tilde\nu_{\mu L}\\ \tilde\mu_L\end{pmatrix}$ $\begin{pmatrix}\tilde\nu_{\tau L}\\ \tilde\tau_L\end{pmatrix}$	$\begin{pmatrix}\nu_{eL}\\ e_L\end{pmatrix}$ $\begin{pmatrix}\nu_{\mu L}\\ \mu_L\end{pmatrix}$ $\begin{pmatrix}\nu_{\tau L}\\ \tau_L\end{pmatrix}$	
	$\tilde e_R$ $\tilde\mu_R$ $\tilde\tau_R$	e_R μ_R τ_R	
Higgs particles	Higgs boson	Higgsino	
	$\begin{pmatrix}\phi_1^0\\ \phi_1^-\end{pmatrix}$ $\begin{pmatrix}\phi_2^+\\ \phi_2^0\end{pmatrix}$	$\begin{pmatrix}\tilde\phi_1^0\\ \tilde\phi_1^-\end{pmatrix}$ $\begin{pmatrix}\tilde\phi_2^+\\ \tilde\phi_2^0\end{pmatrix}$	
Gauge particle		Gagino	Gauge boson
		$\tilde\gamma$	γ
		$\tilde Z^0$ $\tilde W^\pm$	Z^0 $W^\pm$
		$\tilde g$	g

$$(\tilde\gamma, \tilde Z^0, \tilde\phi_1^0, \tilde\phi_2^0) \to (\tilde\chi_1^0,\ \tilde\chi_2^0,\ \tilde\chi_3^0,\ \tilde\chi_4^0)$$

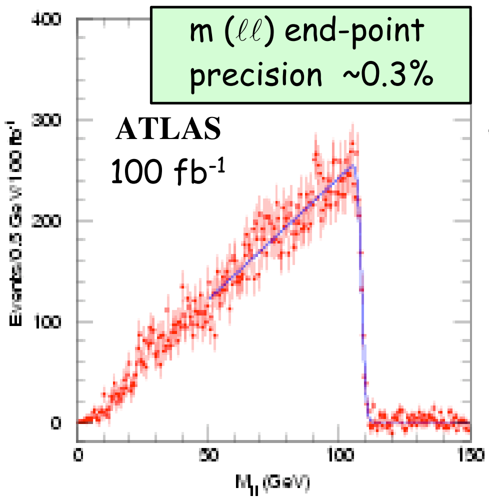
$$(\tilde W^\pm,\ \tilde\phi^\pm) \to (\tilde\chi_1^\pm,\ \tilde\chi_2^\pm)$$

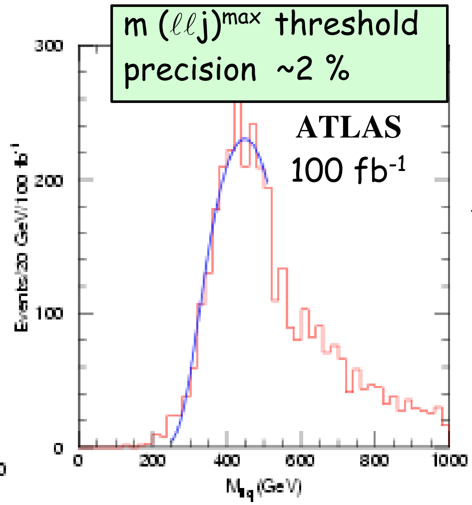
LHC would discover SUSY phenomena quickly by ~2009, however…

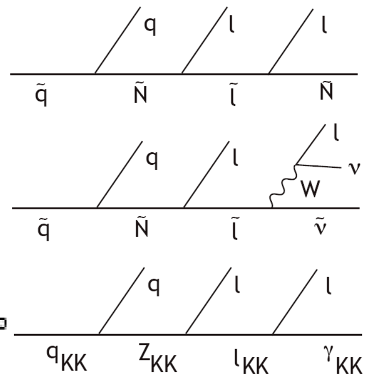
1. Complicated cascade chain
2. Large SM and other **SUSY backgrounds**
3. Model dependence of new physics analyses



multiple hypotheses, distinguished by different spin and energy flows, **difficult to distinguish at LHC**
(M.Peskin, Victoria, 2004)







conventional SUSY

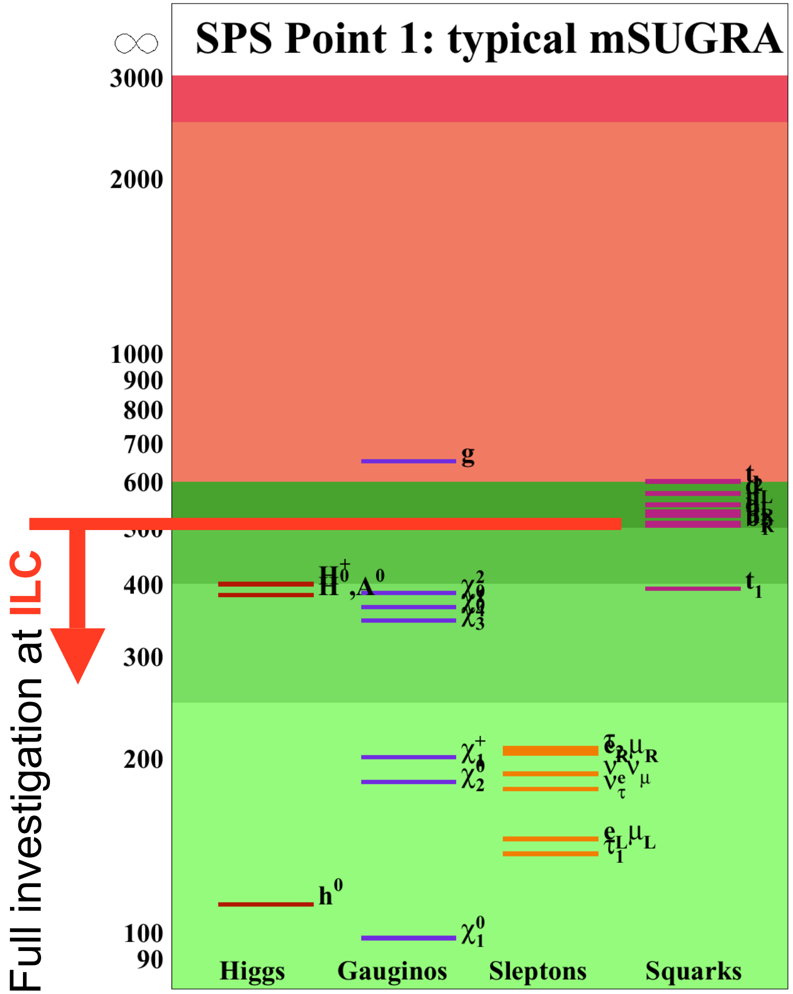
sneutrino LSP (Murayama et al)

'bosonic supersymmetry'
(Cheng, Matchev, Schmaltz)

SUSY at ILC

Huge research area at **ILC**

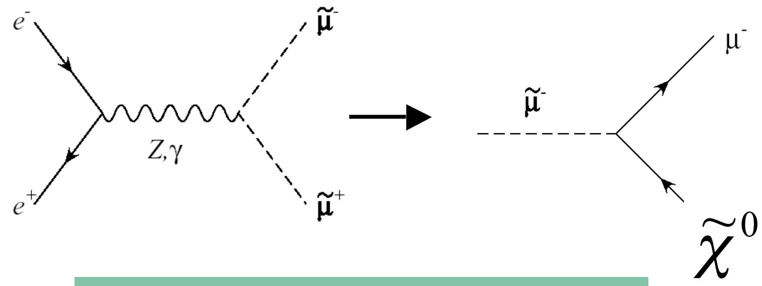
- measure sparticle properties (**masses,** cross sections, J^{PC} , **coupling strength, chirality, mixing**)
- use these + **LHC** to **determine underlying SUSY model** and **SUSY breaking mechanism**
- **extrapolate to GUT scale** using RGEs to detemine **SUSY GUT mechanism**

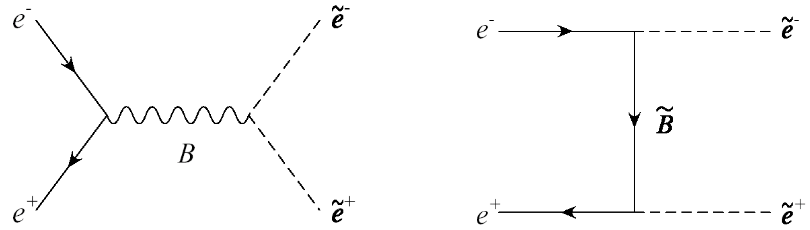


1st step of SUSY at ILC

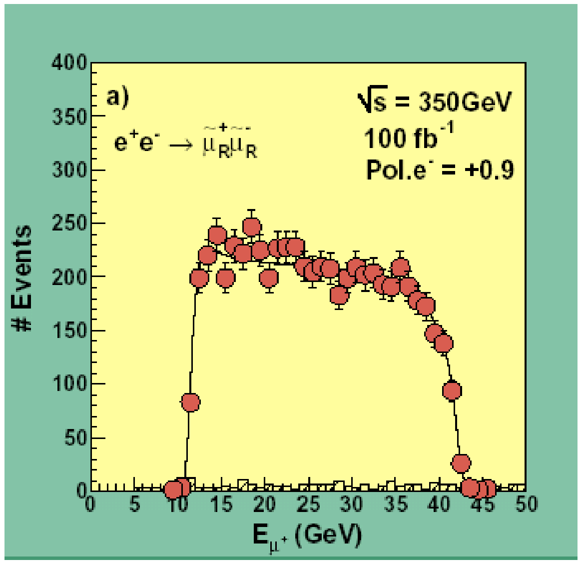
Discovery of SUSY principle

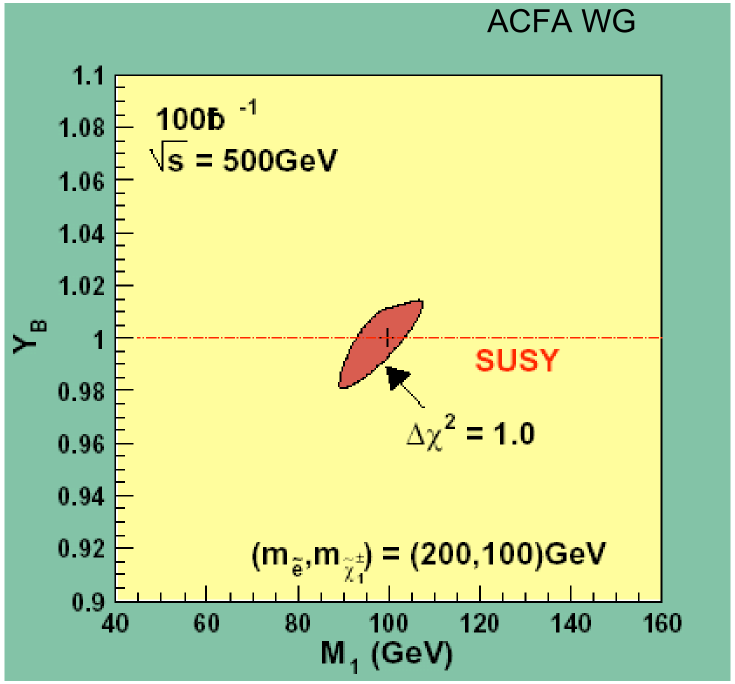
eg.) Smuon production and decay





Selectron production





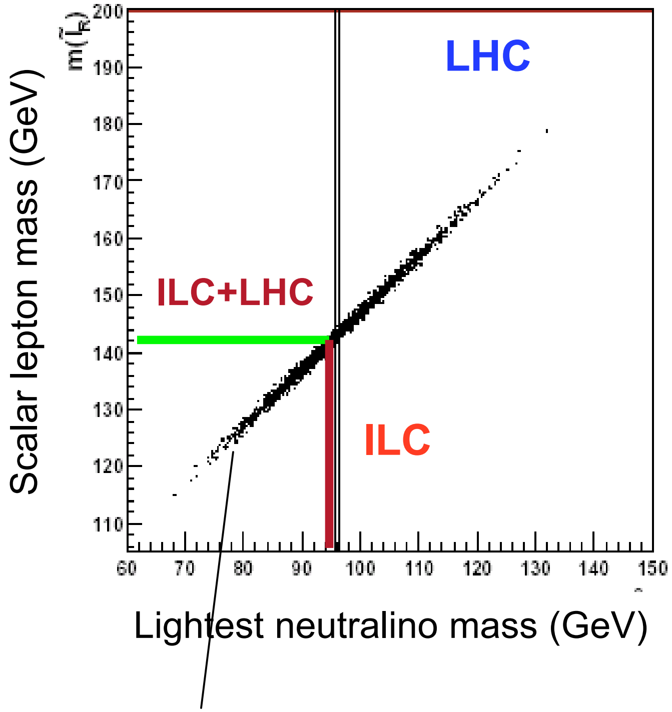
Spin, CP, coupling strength, etc..
precisely measure

Using the M(χ^0_1) from ILC

300 fb^{-1}@LHC
ΔM values in GeV

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

Significant improvements even if only m(χ^0) is measured at ILC



Strong correlation at LHC

An input from ILC resolve this correlation

Pin down physics models

Example 1)

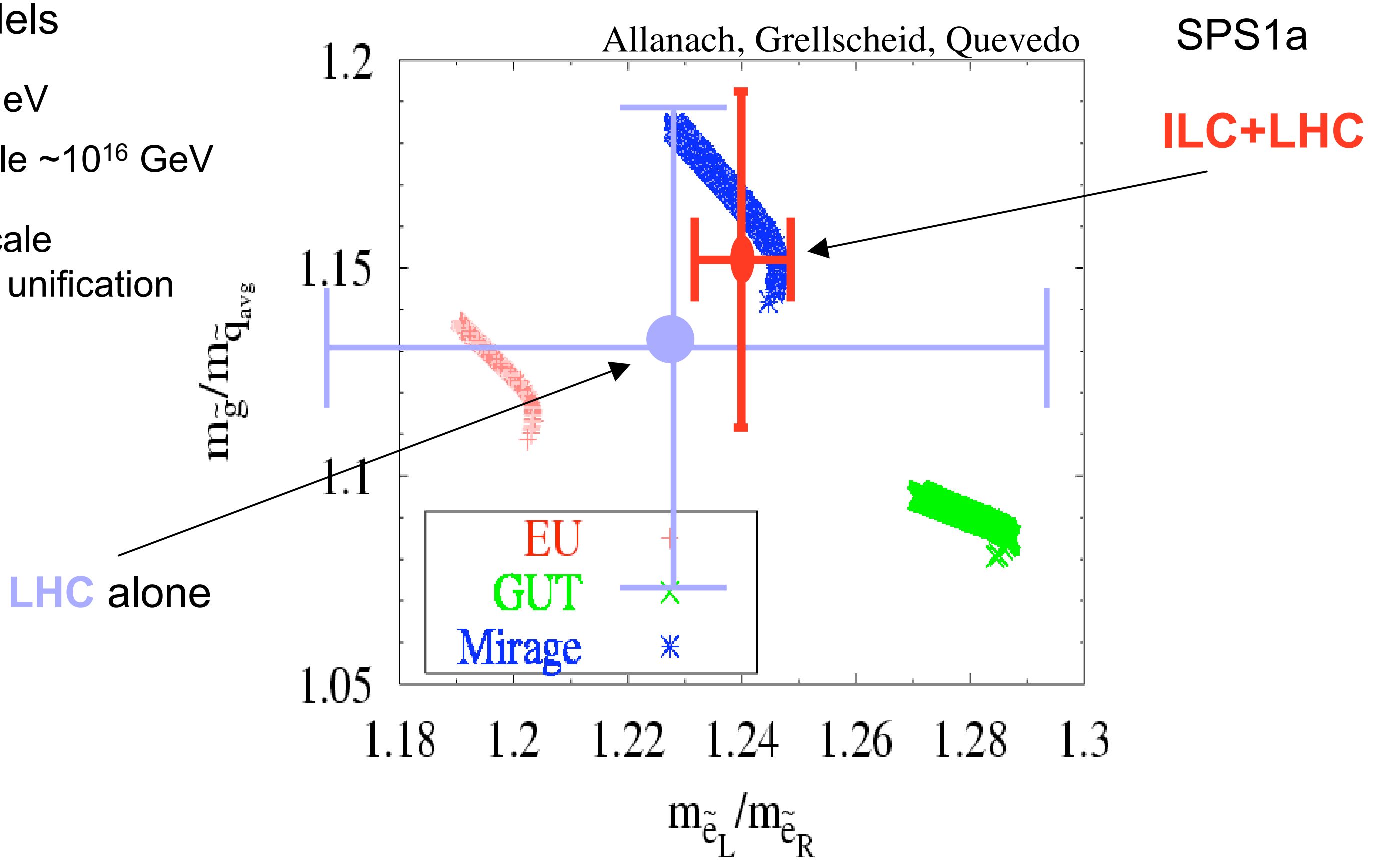
Discrimination between different SUSY-breaking scenarios

Type-I string inspired models

EU: early unification at 10^{11} GeV

GUT: string scale at GUT scale ~10^{16} GeV

Mirage: Intermediate string scale at 10^{11} GeV + Mirage unification



2nd step of SUSY at ILC

Discovery of a new principle GUT

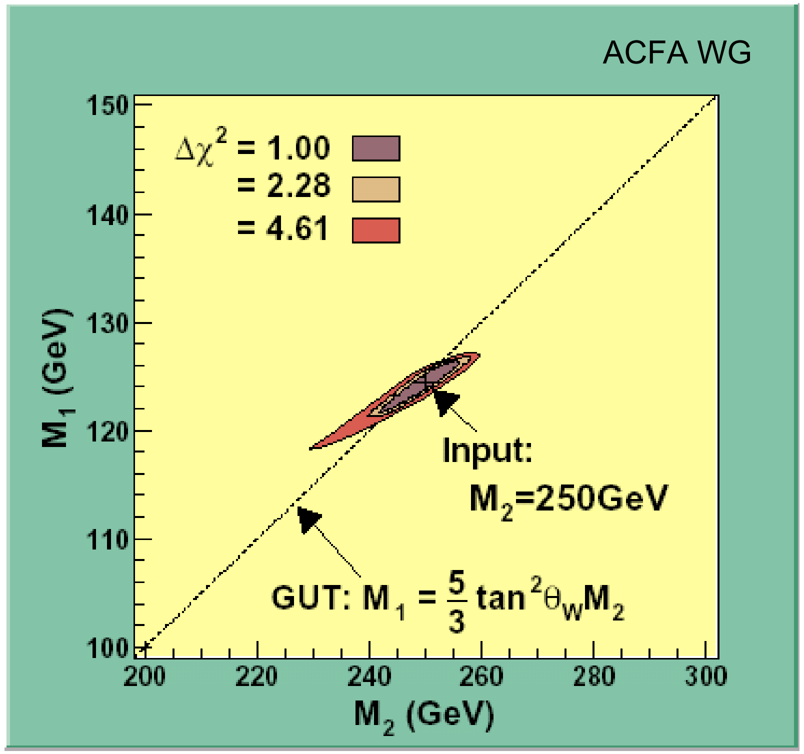
Discovery of M1-M2 gaugino Grand Unification

mass

coupling

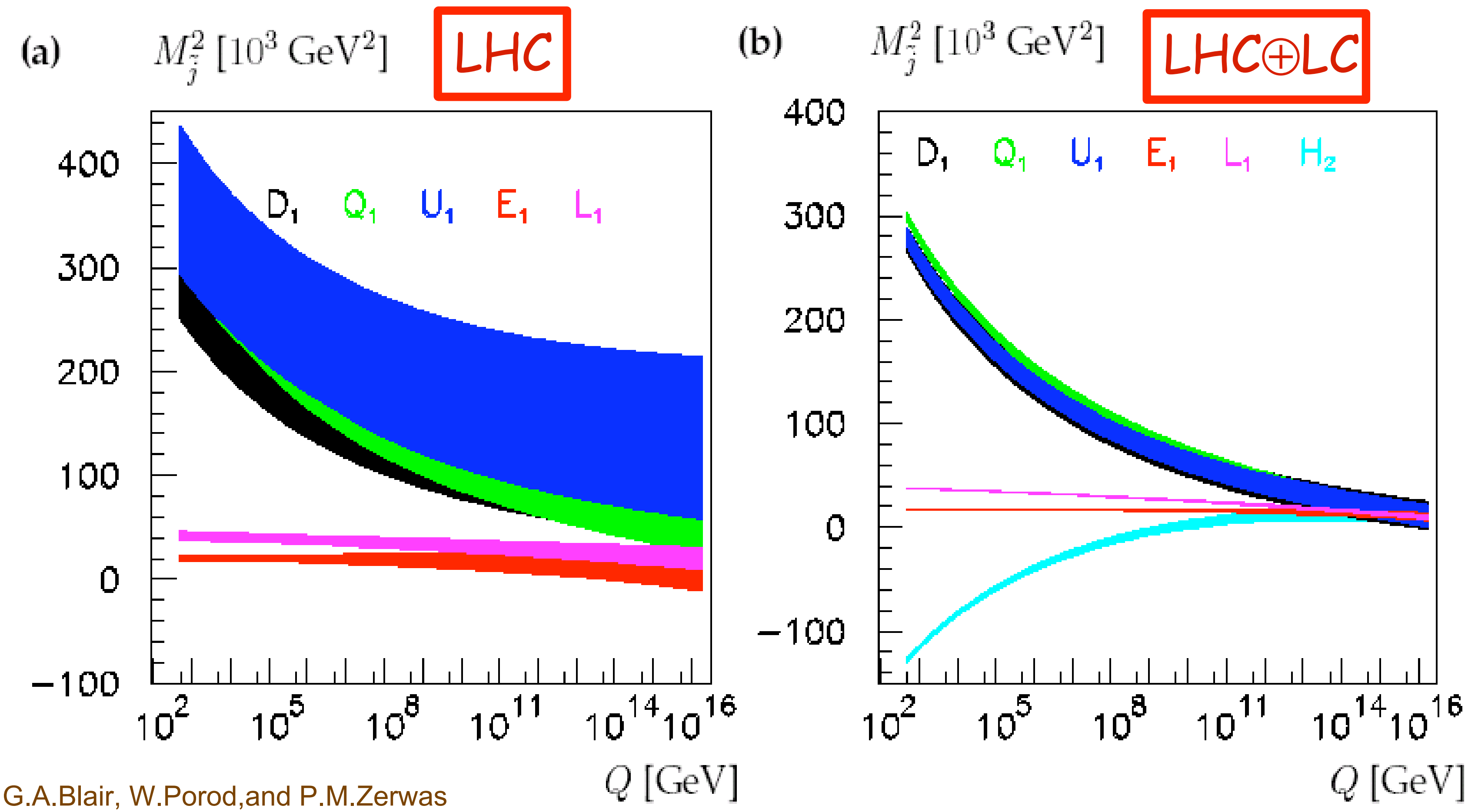
chirality

Mixing



From selectron and chargino productions

Evolution of scalar fermion mass parameters

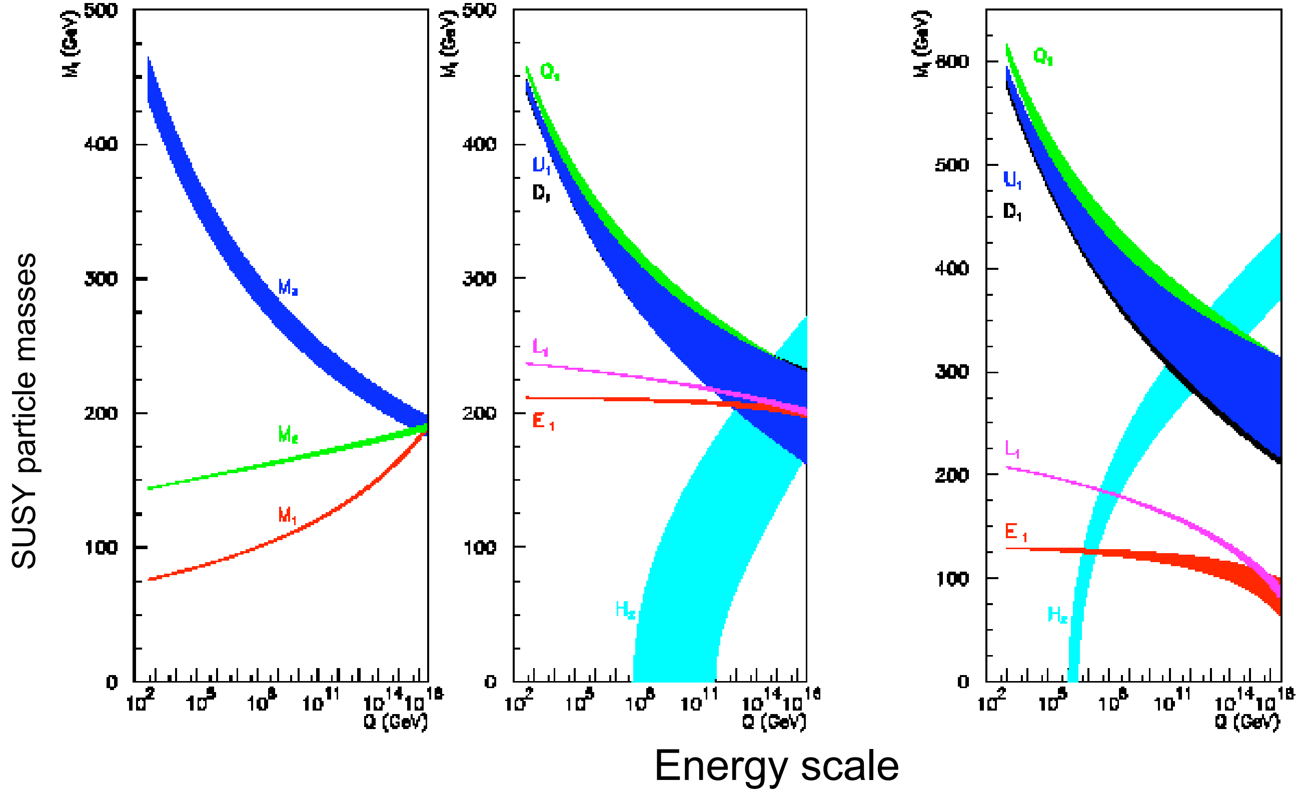


G.A.Blair, W.Porod,and P.M.Zerwas

Determining SUSY breaking mechanism

LHC+ILC
Combined analysis

→ **SUSY breaking** scenario

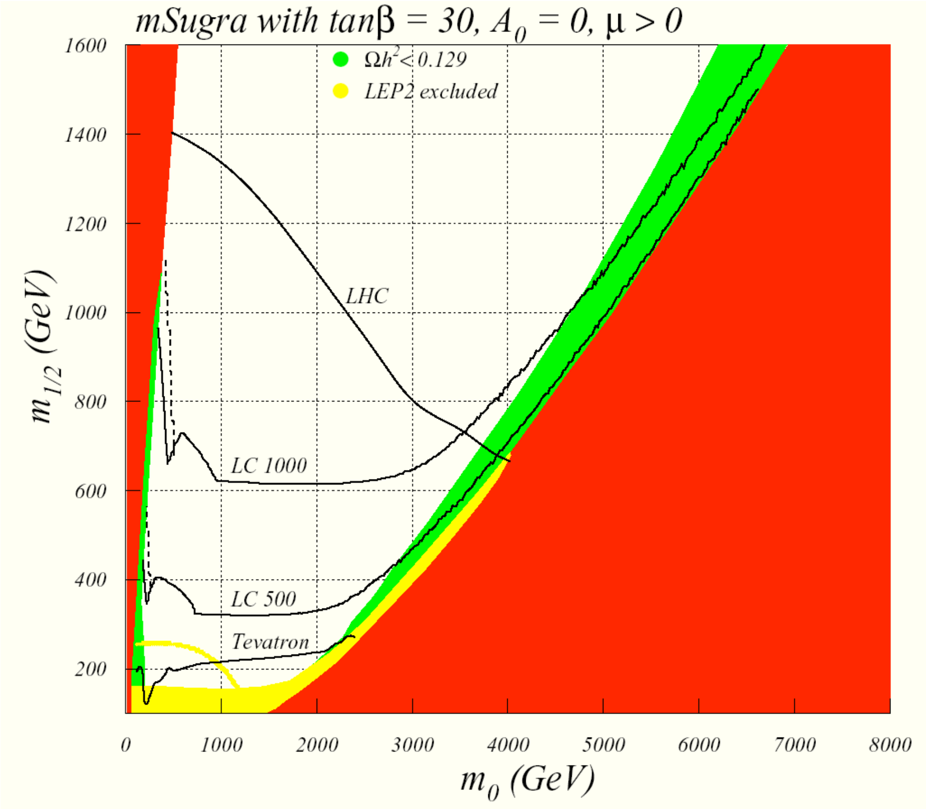


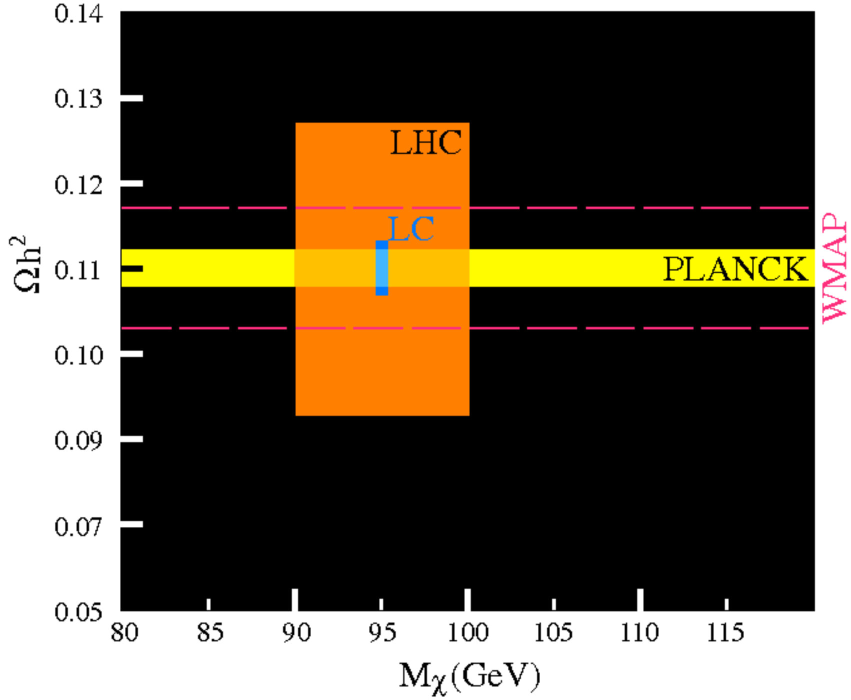
Super Gravity (mSUGRA)

Gauge Mediation

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

Cosmology: Dark Matter = LSP?





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

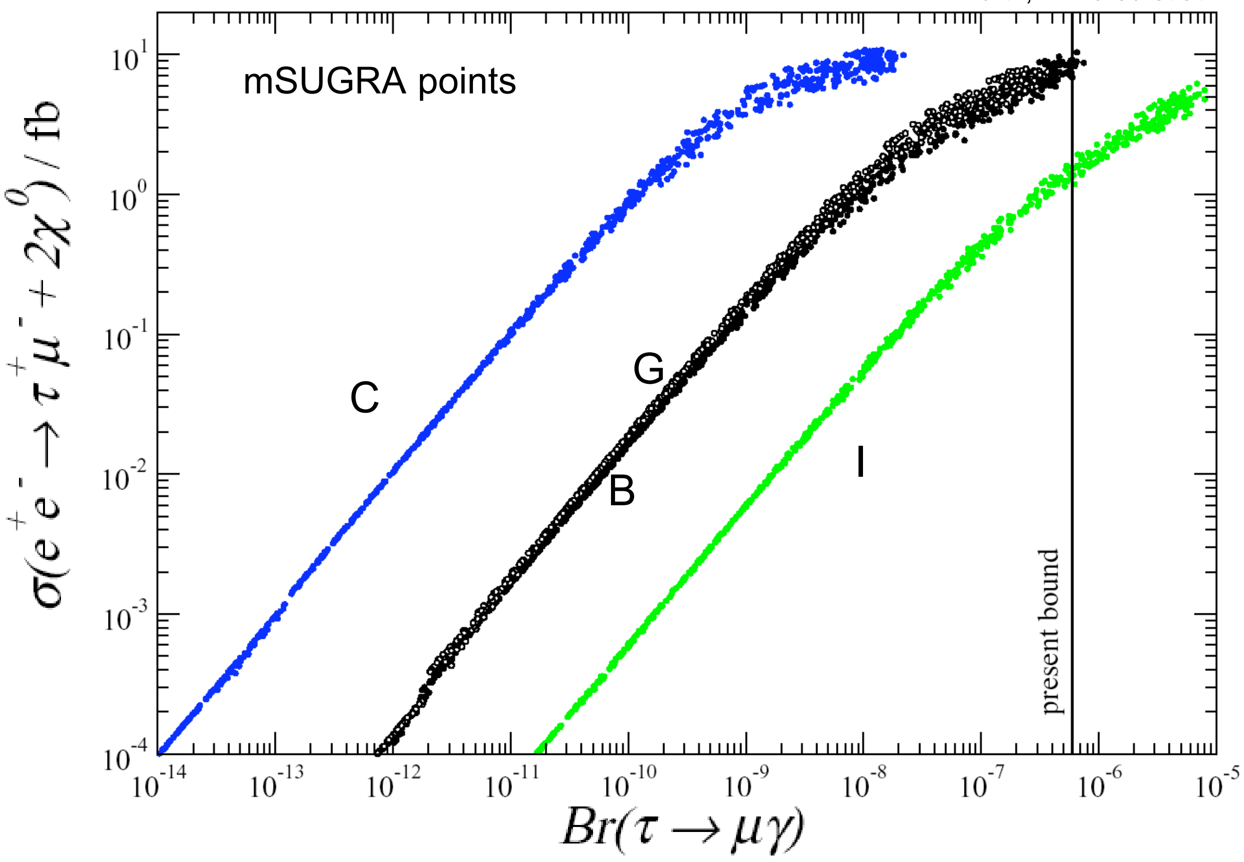
WMAP .094 < Ωh^2 < .128 (2 sigma)

Flavor Violation in SUSY sector

e.g) SUSY-Seesaw model

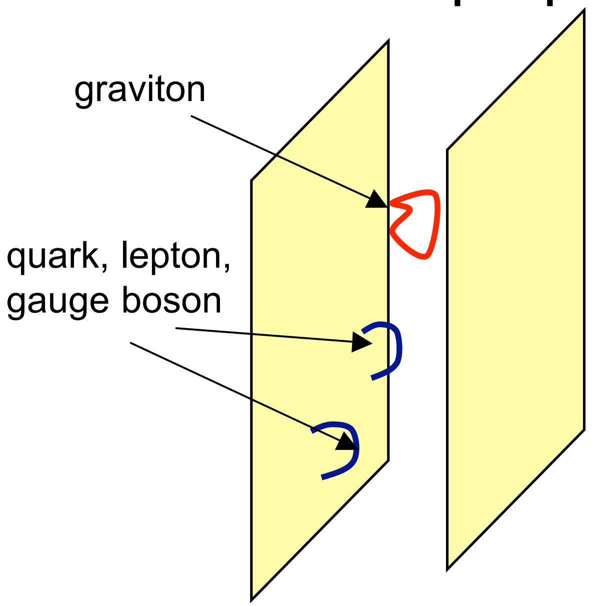
ILC Ecm=800 GeV

T.Hurth, W.Porod et at.



Extra Dimensions

Inspired by superstring theory, a scenario with large extra-dimension is proposed.

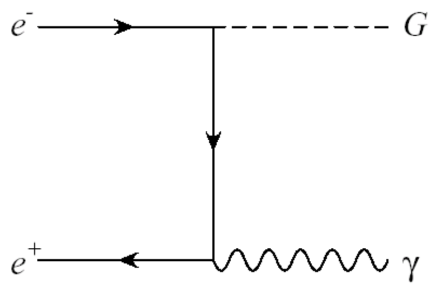


Studio R

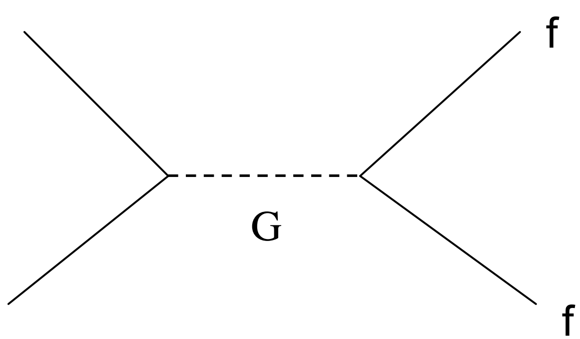
Quarks, leptons, and gauge bosons live in a 3-dimensional wall.
Gravity can propagate in 3+n dimensional space.

Search for extra-space at ILC

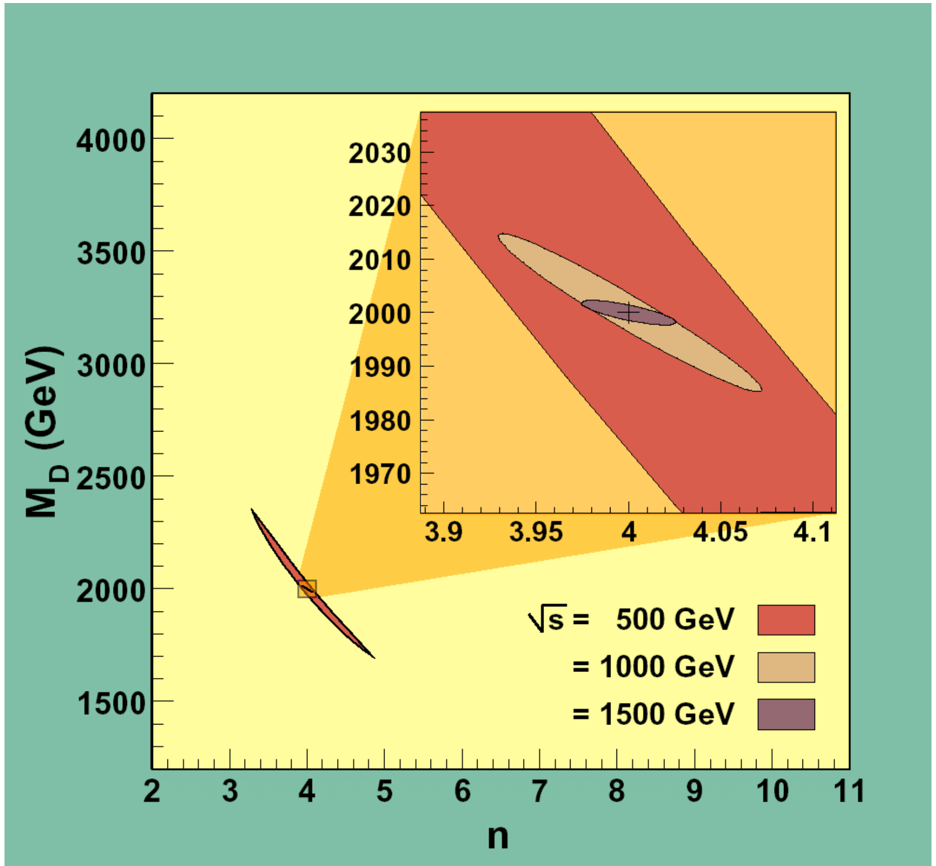
K.Odagiri



Graviton emission to extra-space



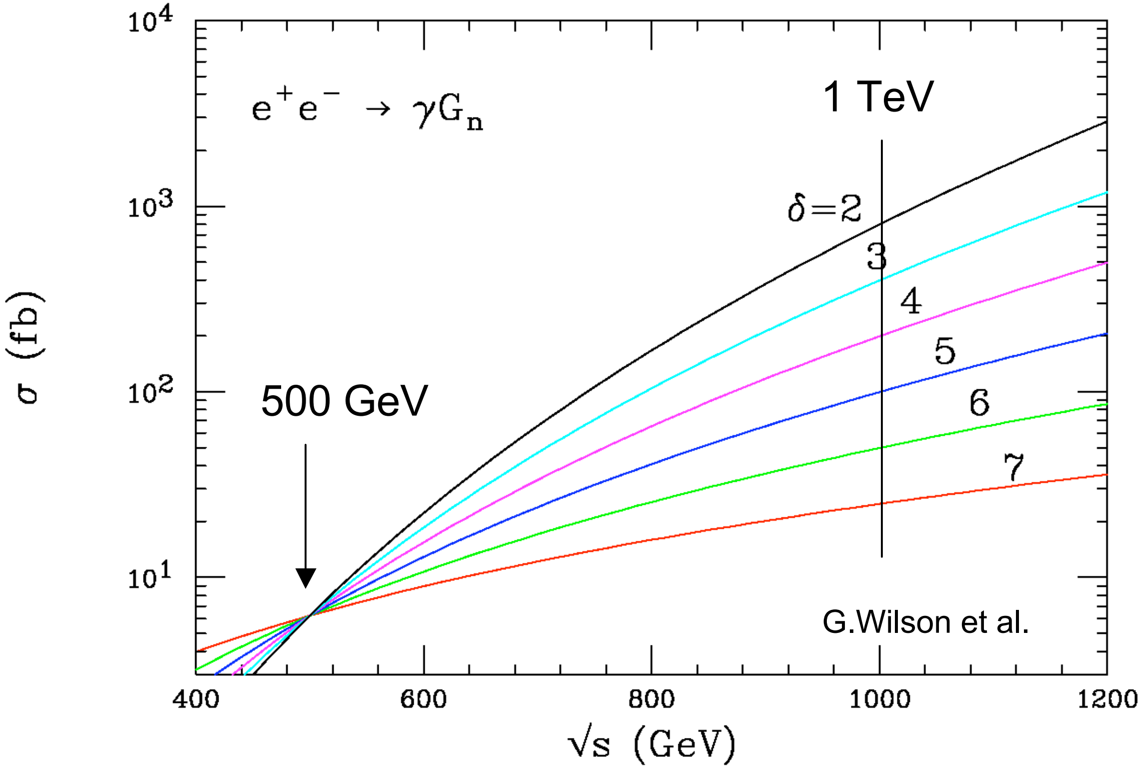
Graviton exchange



# of extra-dimensional space

The **size and number of the extra-space** may be determined at LC.

Number of dimension determination
By two energies at ILC



Murayama LP03

Final Goal of Physics at ILC
together with LHC