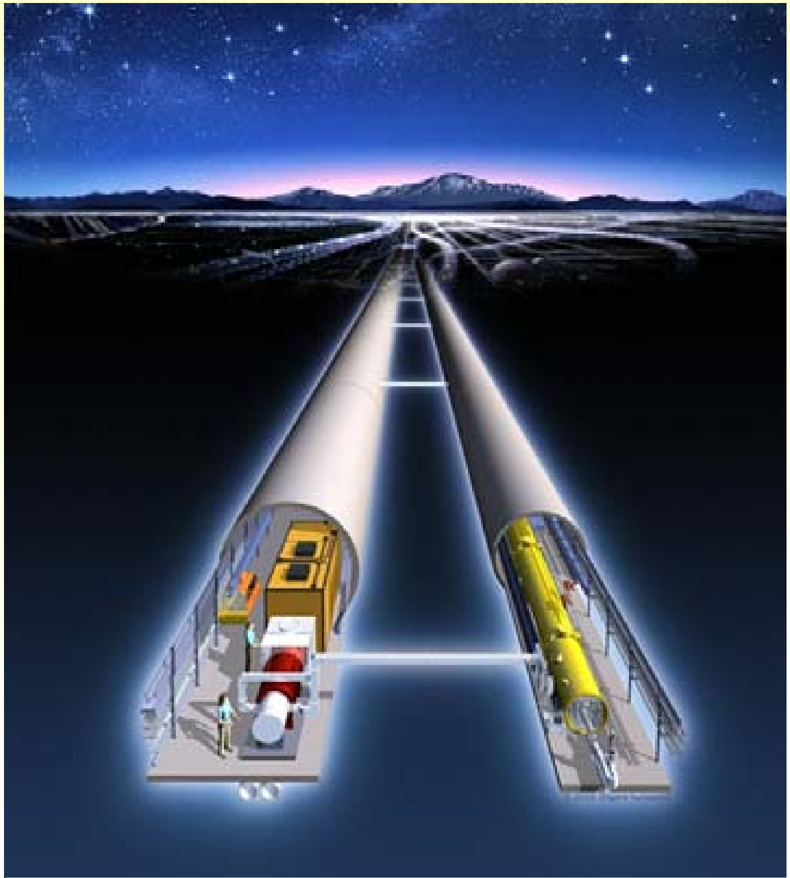
Hadron 07, LNF, 12 October 2007

The Physics Case of ILC

- the ILC project (a few words)
- physics at ILC
- ILC versus LHC



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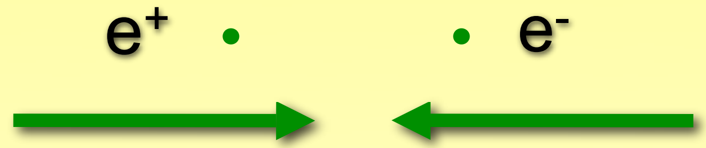
Why a linear collider?



❖ Particle physics colliders to date have all been circular machines (with one exception – SLAC SLC).

❖ Highest energy e^+e^- collider was LEP2: E_{CM}=200 GeV

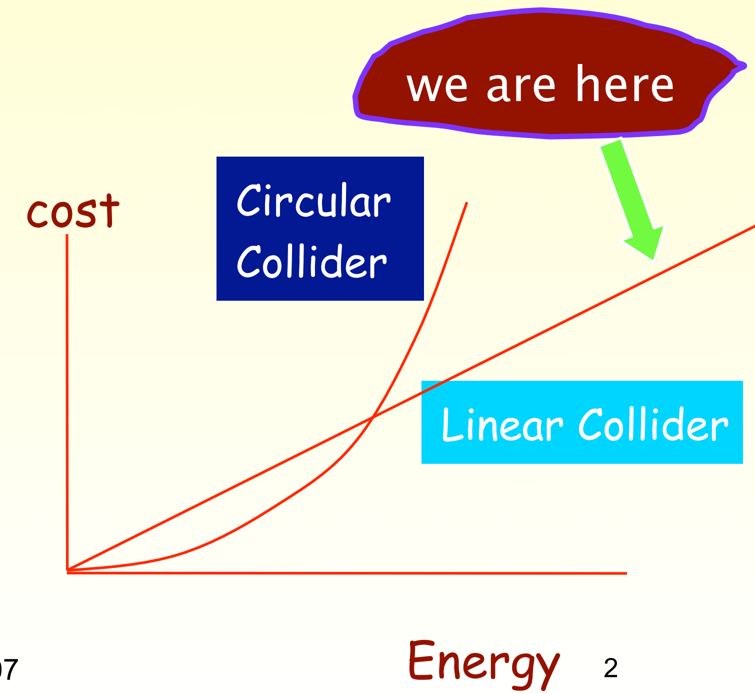
• as energy increases at given radius

$\Delta E \sim E^4/\rho$ (synchrotron radiation)

e.g. LEP ΔE=4 GeV/turn; P~20 MW

• high energy in a circular machine becomes prohibitively expensive – large power or huge tunnels.

• go to long single-pass linacs to reach desired energy.



. . . in 90's DESY, SLAC, KEK involved in different projects

in 2002, ICFA ⇨ ILCSC

Technology decision in 2004 : use superconducting RF (~TESLA)

⇨ the International Linear Collider ILC

the baseline:

- $e^+ e^-$ LC operating from M_Z to 500 GeV, tunable energy !
- e^- polarization (at least 80%)
- at least 500 fb^{-1} in the first 4 years
- upgradable to ~ 1 TeV , 500 fb^{-1} /year

options :

A lot of flexibility !

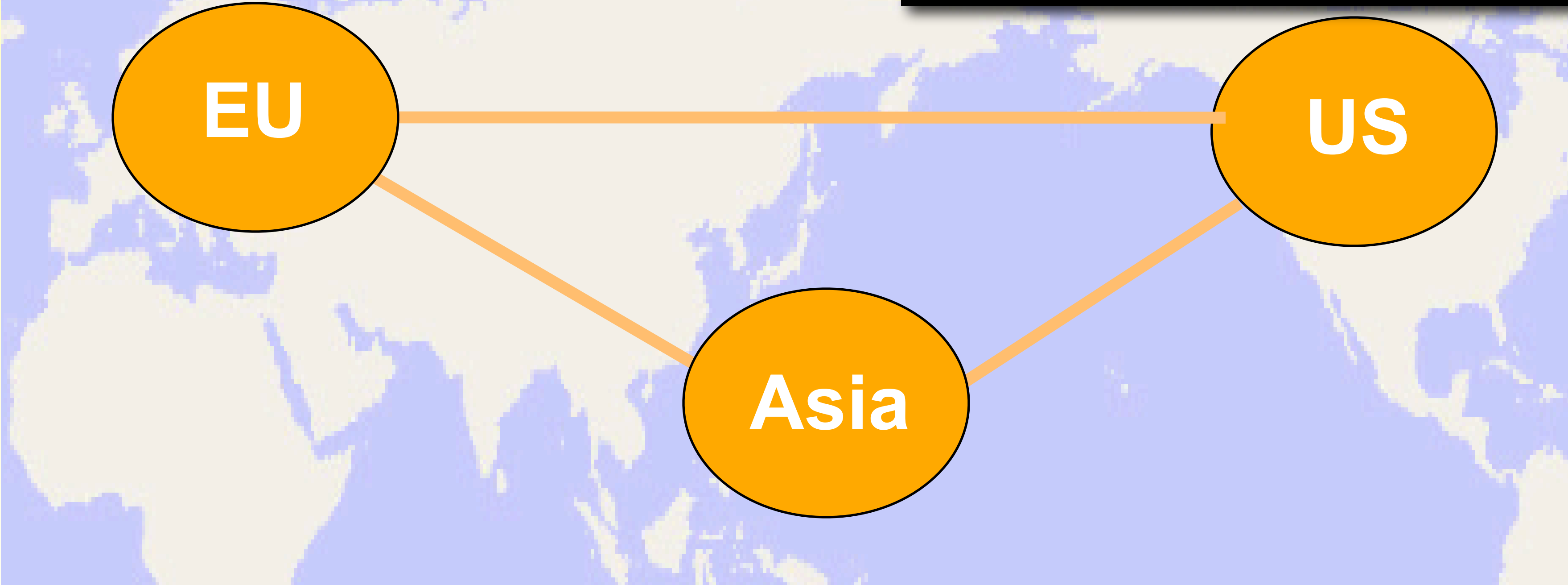
- e^+ polarization , transverse polarization
- GigaZ (high luminosity running at M_Z)
- e-e-, $\gamma\gamma$, $e\gamma$ collisions

⇨ Global Design Effort (GDE) started (2005)

Global Effort on Design / R&D

(none can afford this project alone !)

Present
GDE Membership
Americas 22
Europe 24
Asia 18
About 30 FTEs



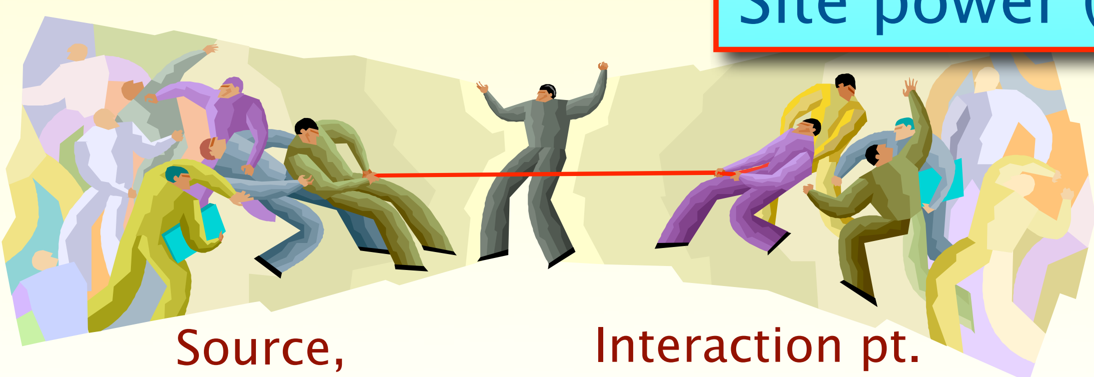
Joint Design, Implementation, Operations, Management
Host Country Provides Conventional Facilities

ILC parameters

Bunch spacing	337 ns
Bunch train length	950 μs
Train rep rate	5 Hz
Beam height at collision	6 nm
Beam width at collision	540 nm
Accel. Gradient	31.5 MV/m
Wall plug effic.	23%
Site power (500 GeV)	140 MW

$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

10^5 annihil.s/sec

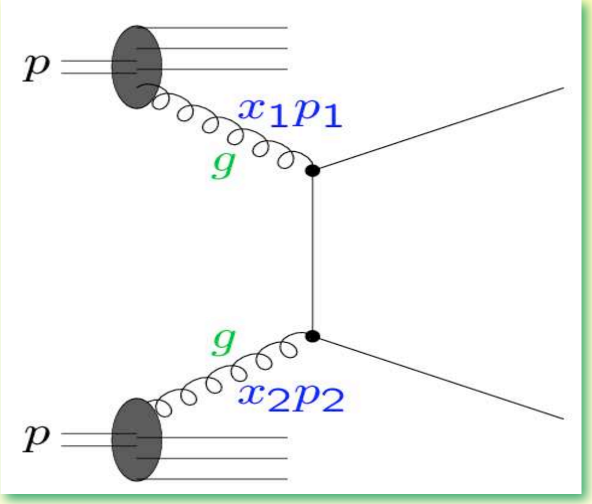


Source, damping ring

Interaction pt. beam extraction

Physics at the LHC and ILC in a nutshell

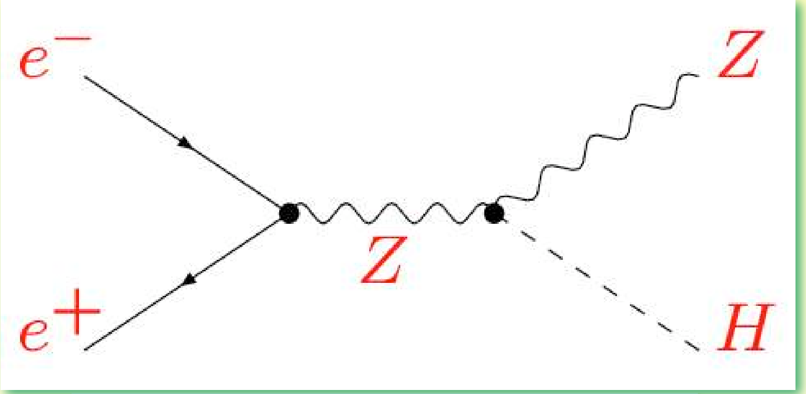
LHC: pp scattering at 14 TeV



Scattering process of proton constituents with energy up to several TeV, strongly interacting

⇒ huge QCD backgrounds, low signal–to–background ratios

ILC: e^+e^- scattering at ≈0.5–1 TeV



Clean exp. environment: well-defined initial state, tunable energy, beam polarization, GigaZ, $\gamma\gamma$, $e\gamma$, e^-e^- options, . . .

⇒ rel. small backgrounds high-precision physics

mainly high-precision physics at ILC !

- *can determine properties of New Discoveries at LHC*
  (cross sections, BR's, Quantum numbers).
- *can detect what is "invisible" at LHC.*
- *can measure radiative EW precision pattern of Standard Model observables with higher precision*

  → *extends new-physics potential (deep into multi-TeV region) even in case of no new particle observed at LHC.*

Intern. Study Groups active in different Physics fields (since many years . . .)

Higgs

Supersymmetry

Beyond the Standard Model

Top / Quantum Chromodynamics

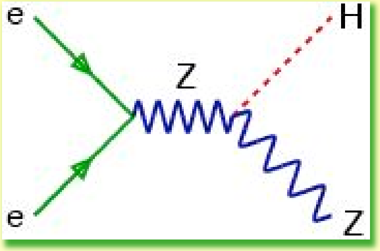
LHC/ILC Connections

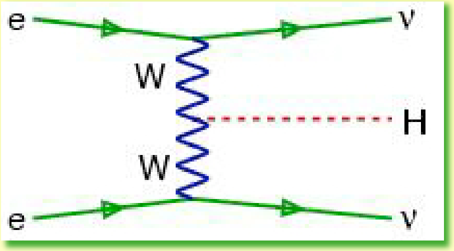
hep-ph/0410364

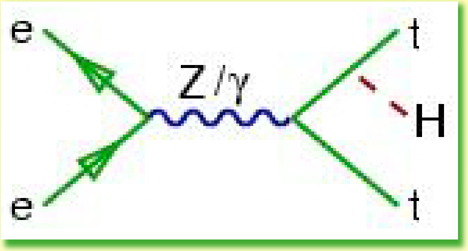
Cosmological Connections

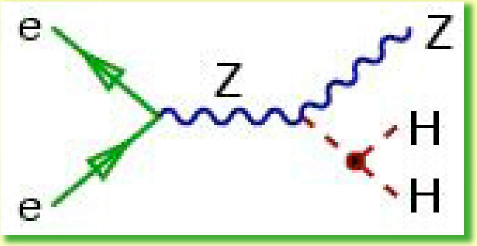
Radiative Corrections (Loopfest)

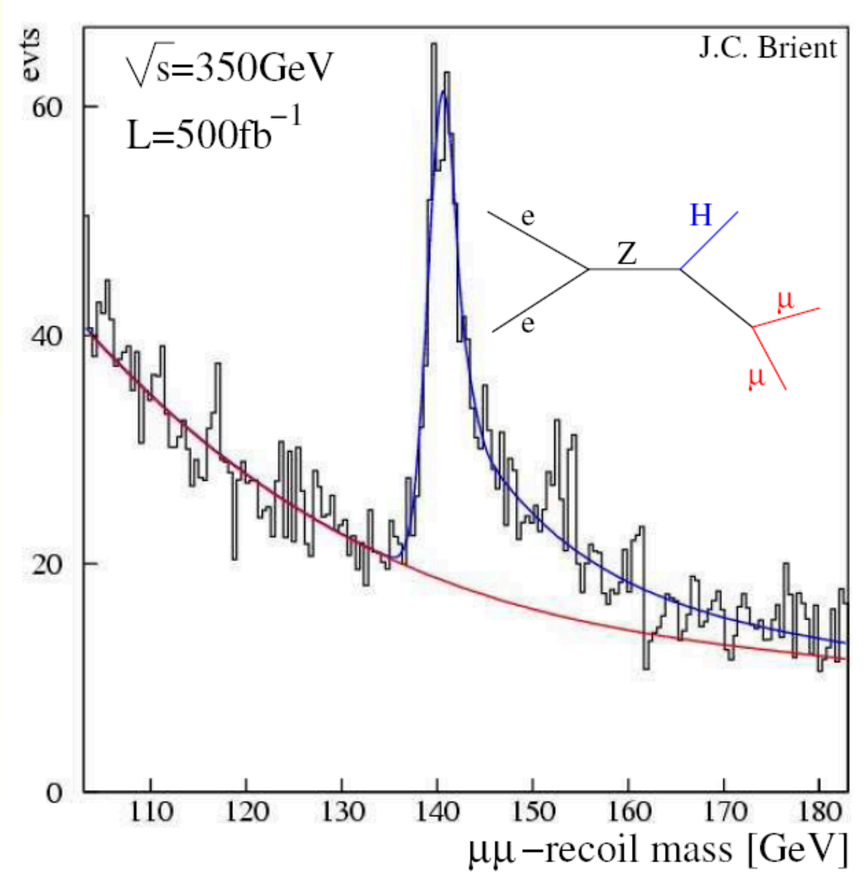
Precision Higgs physics at the ILC







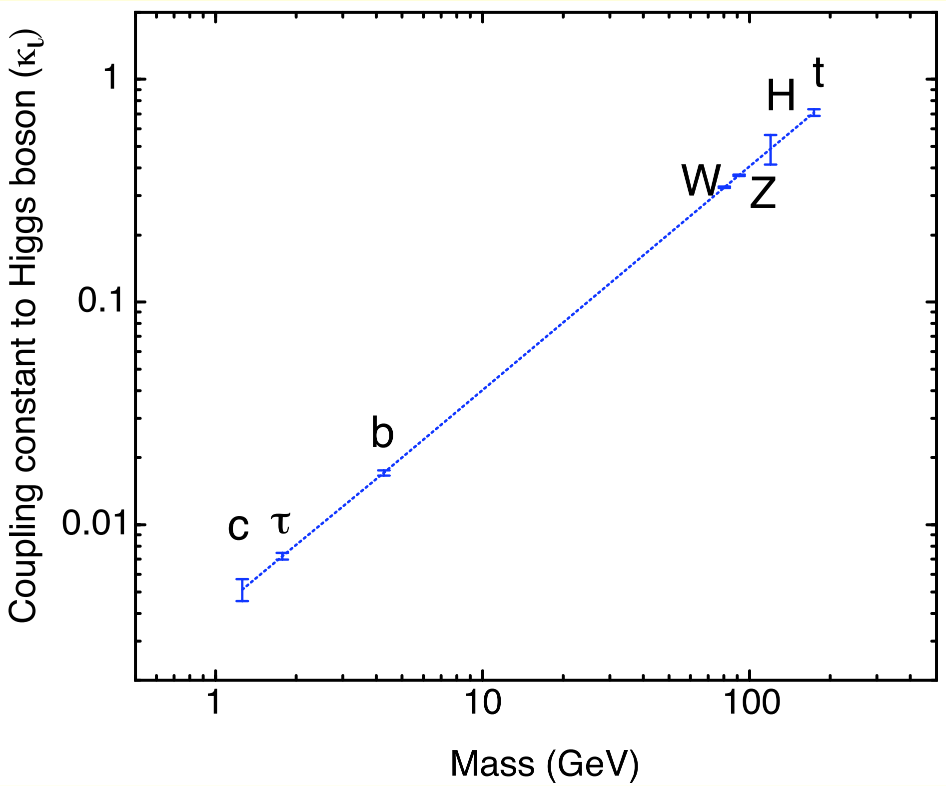




- model-independent observation
- mass
- absolute branching ratios
- total width (mod.indep.)
- spin, *CP*
- top Yukawa coupling
- self coupling

most measurements at the percent level !

Determining Higgs couplings



- in the SM, Higgs couplings are directly proportional to mass. Measuring these couplings is a sensitive test of whether we have only the SM or some extension.

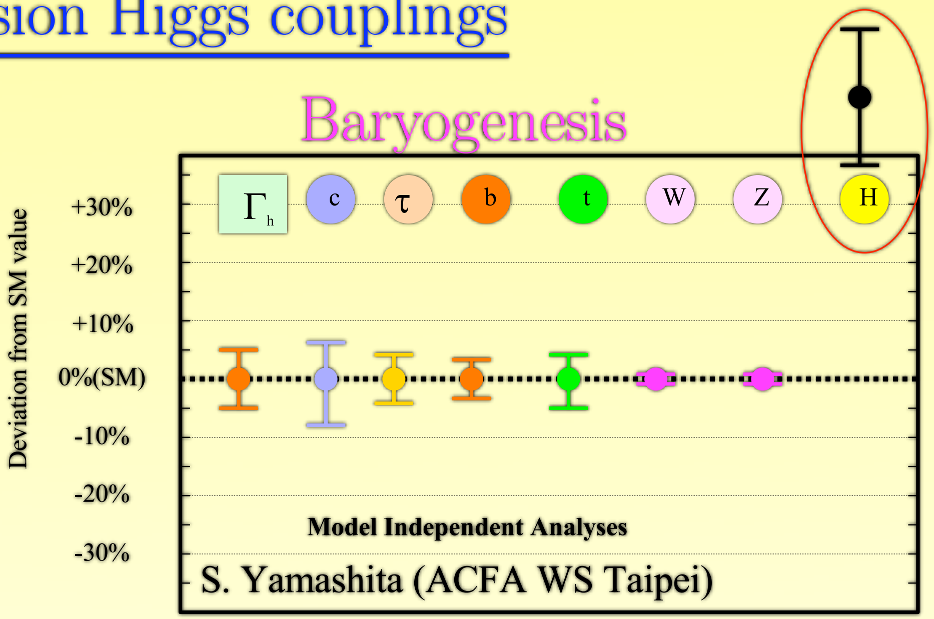
- in the clean environment of the ILC, it is possible to distinguish Higgs decays to b, c, and lighter quarks; e, μ, τ, and W, Z and thus directly measure these couplings.

- this requirement sets one of the key criteria for ILC detectors – a very finely grained Si vertex pixel detector at small radius.

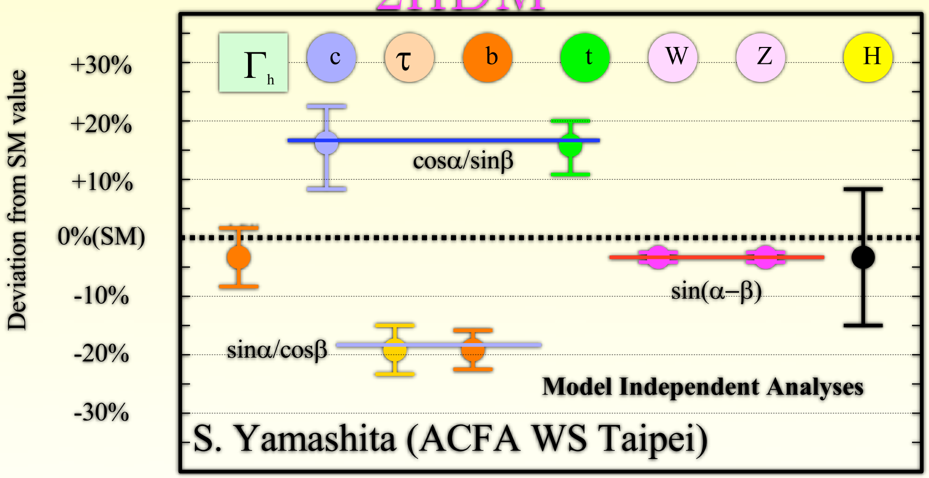
Applications of precision Higgs couplings

Especially the Higgs-coupling measurements are a powerful test of the model that LHC cannot do

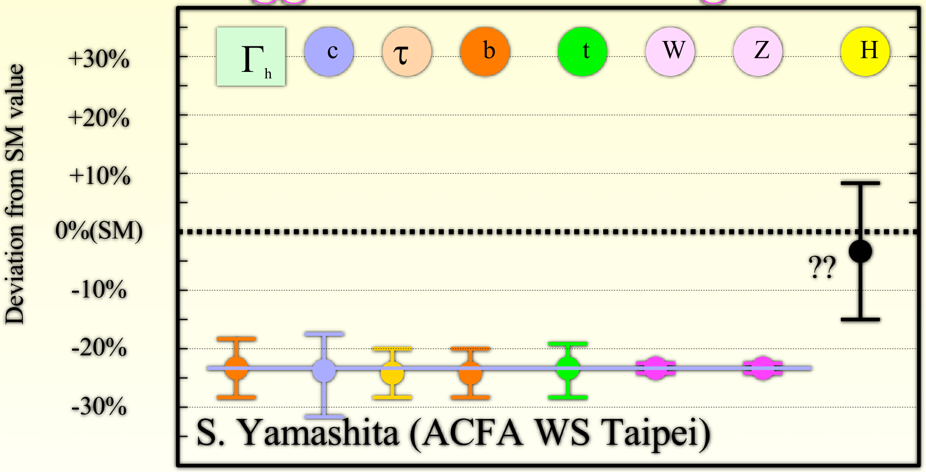
Baryogenesis



2HDM



Higgs-Radion mixing



Higgs coupling determination at LHC $\oplus$ ILC:

LHC can directly determine only ratios of couplings

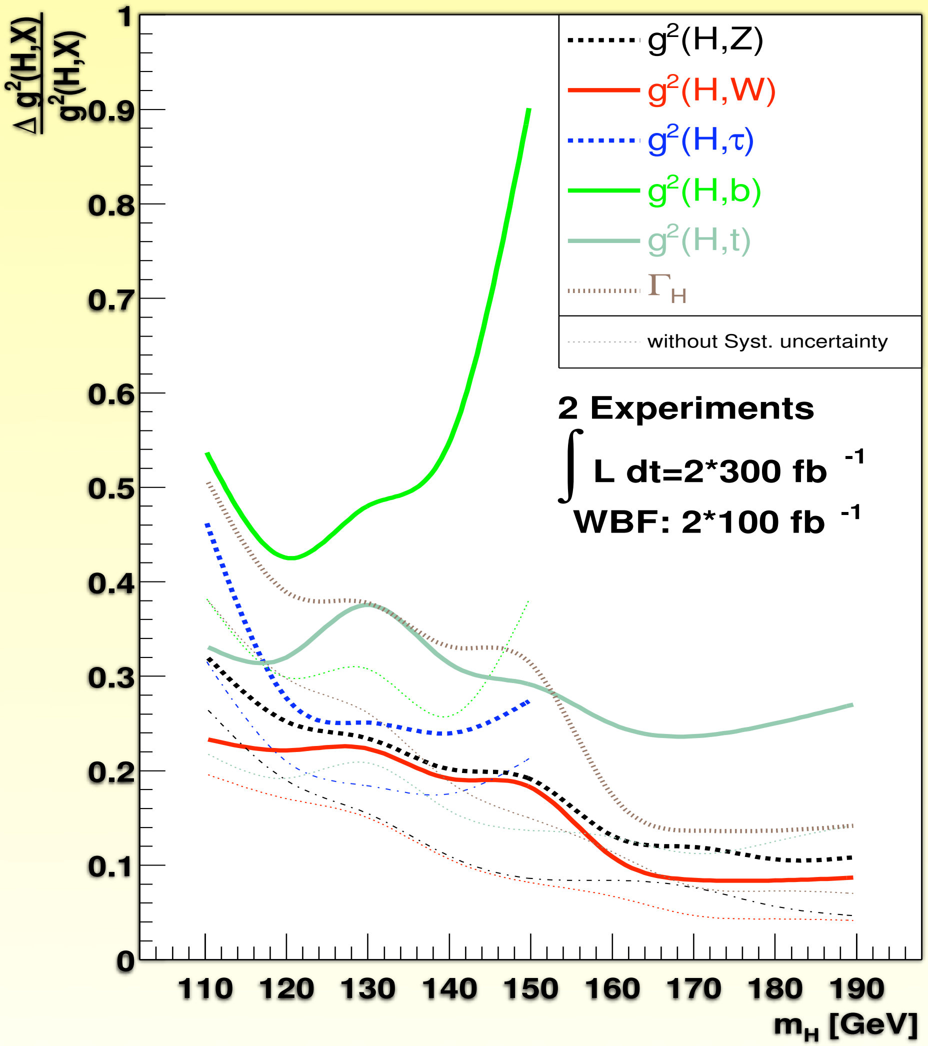
Need additional (mild) theory assumptions to obtain absolute values of the couplings

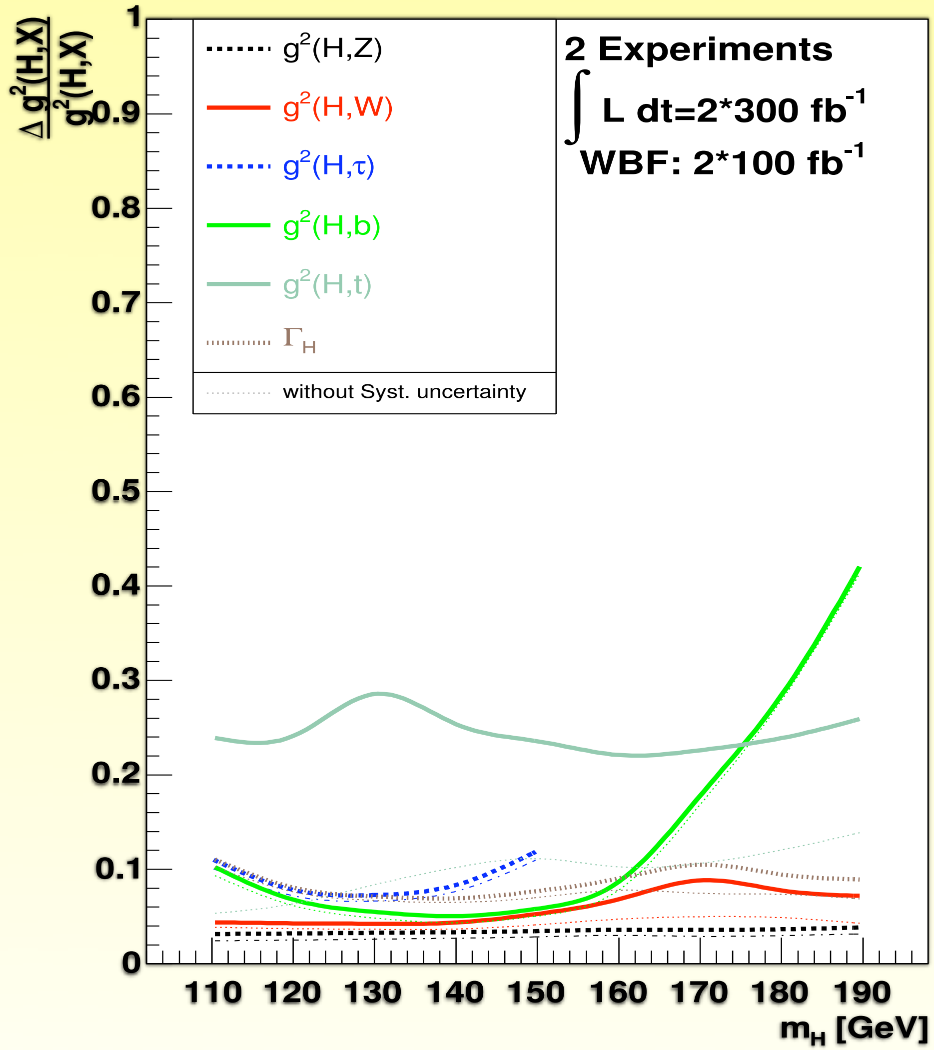
$\Rightarrow$ Use ILC input instead of theory assumption

Fit of Higgs couplings with input from LHC and ILC

$$M_{\rm H},\ \sigma(e^+e^- \to HZ),\ {\rm BR}(H \to b\bar{b}, \tau^+\tau^-, gg, WW^*),$$
$$\sigma(e^+e^- \to \nu\bar{\nu}H) \times {\rm BR}(H \to b\bar{b})$$

Comparison: LHC only vs. LHC $\oplus$ ILC



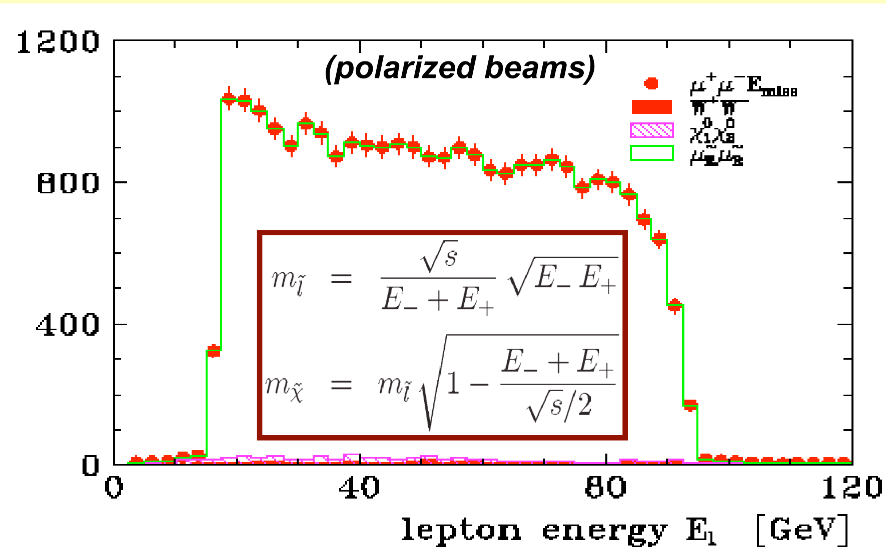


⇒ higher accuracy on $g_{Ht\bar{t}}$ (and also $g_{H\gamma\gamma}$) than for LHC alone (+ theory) and ILC$_{500}$ alone: $\Delta g_{Ht\bar{t}}/g_{Ht\bar{t}} \approx 11$–$14\%$

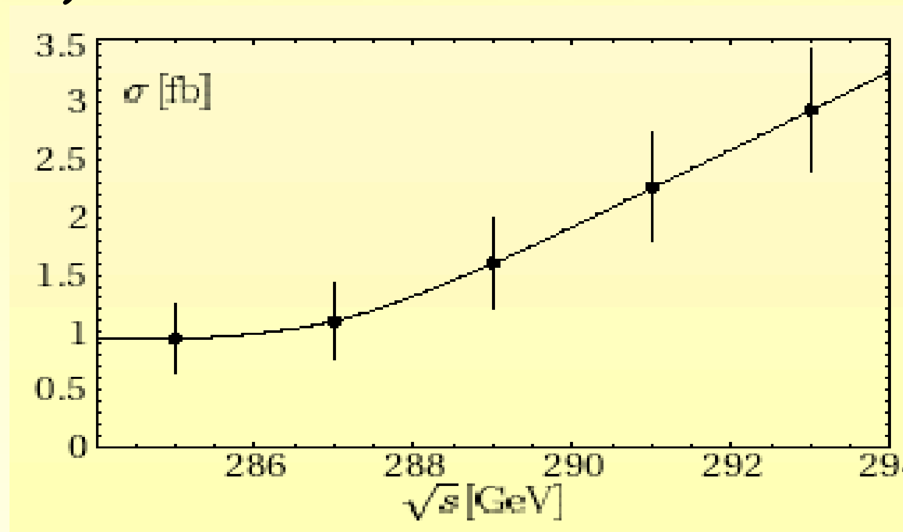
Supersymmetry

Two methods to obtain absolute sparticle <u>masses</u>:

a) in the continuum:



b) at the kinematic threshold:



many more observables than just masses:

- angular distributions, FB-asymmetries
- cross sections
- LR-asymmetries
- ratios of branching ratios

mass precision ‰ - %

→ possibility to determine SUSY parameters without many model assumptions

SUSY masses at LHC vs LHC+ILC :

use of χ_1 from ILC (high precision) in LHC analyses improves mass determination !

	m_{SPS1a}	LHC	ILC	LHC+ILC		m_{SPS1a}	LHC	ILC	LHC+ILC
h	111.6	0.25	0.05	0.05	H	399.6		1.5	1.5
A	399.1		1.5	1.5	$H+$	407.1		1.5	1.5
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{u}_1$	551.0	19.0		16.0	$\tilde{u}_2$	570.8	17.4		9.8
$\tilde{d}_1$	549.9	19.0		16.0	$\tilde{d}_2$	576.4	17.4		9.8
$\tilde{s}_1$	549.9	19.0		16.0	$\tilde{s}_2$	576.4	17.4		9.8
$\tilde{c}_1$	551.0	19.0		16.0	$\tilde{c}_2$	570.8	17.4		9.8
$\tilde{e}_1$	144.9	4.8	0.05	0.05	$\tilde{e}_2$	204.2	5.0	0.2	0.2
$\tilde{\mu}_1$	144.9	4.8	0.2	0.2	$\tilde{\mu}_2$	204.2	5.0	0.5	0.5
$\tilde{\tau}_1$	135.5	6.5	0.3	0.3	$\tilde{\tau}_2$	207.9		1.1	1.1
$\tilde{\nu}_e$	188.2		1.2	1.2					

MSSM parameter determination

LHC only vs. LHC $\oplus$ ILC

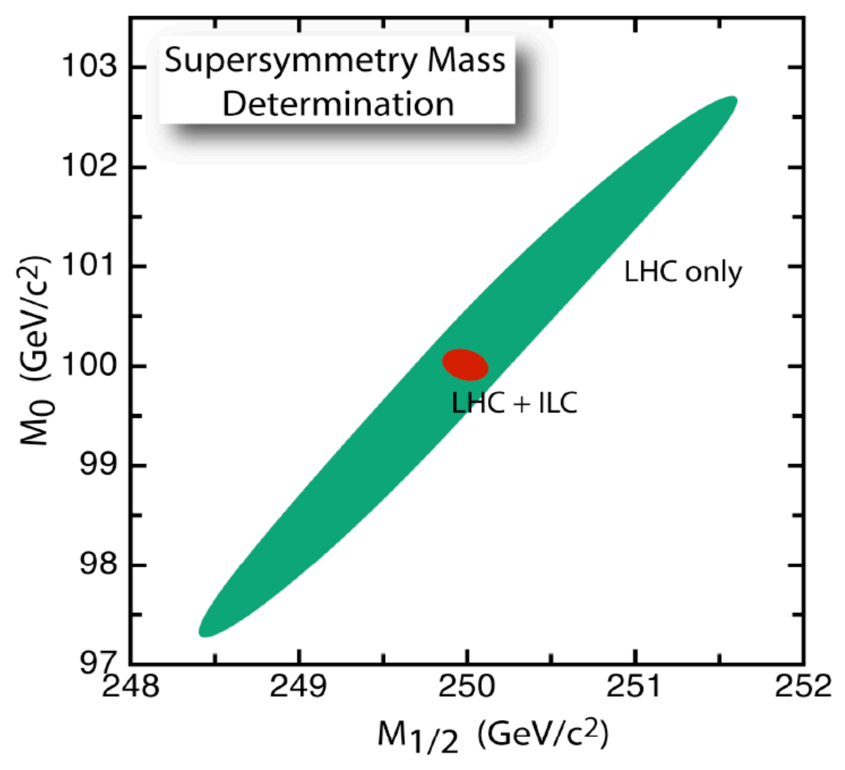
Parameter	"True" value	ILC Fit value	Uncertainty (ILC+LHC)	Uncertainty (LHC only)
$\tan\beta$	10.00	10.00	0.11	6.7
μ	400.4 GeV	400.4 GeV	1.2 GeV	811. GeV
X_τ	-4449. GeV	-4449. GeV	20.GeV	6368. GeV
$M_{\tilde{e}_R}$	115.60 GeV	115.60 GeV	0.27 GeV	39. GeV
$M_{\tilde{\tau}_R}$	109.89 GeV	109.89 GeV	0.41 GeV	1056. GeV
$M_{\tilde{e}_L}$	181.30 GeV	181.30 GeV	0.10 GeV	12.9 GeV
$M_{\tilde{\tau}_L}$	179.54 GeV	179.54 GeV	0.14 GeV	1369. GeV
X_t	-565.7 GeV	-565.7 GeV	3.1 GeV	548. GeV
X_b	-4935. GeV	-4935. GeV	1284. GeV	6703. GeV
$M_{\tilde{u}_R}$	503. GeV	503. GeV	24. GeV	25. GeV
$M_{\tilde{b}_R}$	497. GeV	497. GeV	8. GeV	1269. GeV
$M_{\tilde{t}_R}$	380.9 GeV	380.9 GeV	2.5 GeV	753. GeV
$M_{\tilde{u}_L}$	523. GeV	523. GeV	10. GeV	19. GeV
$M_{\tilde{t}_L}$	467.7 GeV	467.7 GeV	3.1 GeV	424. GeV
M_1	103.27 GeV	103.27 GeV	0.06 GeV	8.0 GeV
M_2	193.45 GeV	193.45 GeV	0.10 GeV	132. GeV
M_3	569. GeV	569. GeV	7. GeV	10.1 GeV
$m_{A run}$	312.0 GeV	311.9 GeV	4.6 GeV	1272. GeV
m_t	178.00 GeV	178.00 GeV	0.050 GeV	0.27 GeV

$\Rightarrow$ most of the Lagrangian parameters can hardly be constrained by LHC data alone

$\Rightarrow$ precise determination of SUSY parameters only possible with LHC $\oplus$ ILC

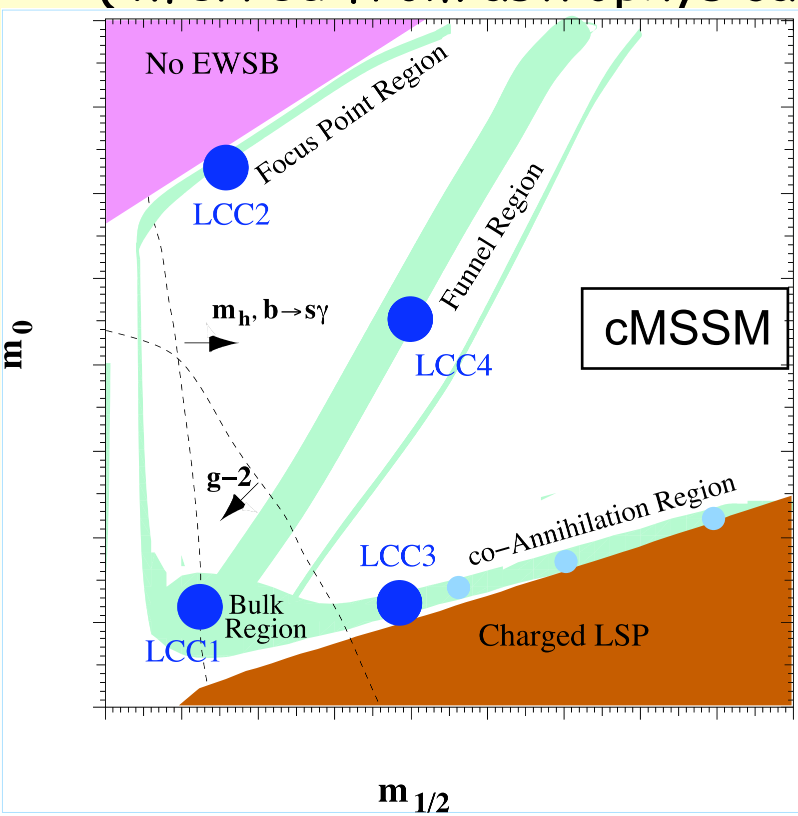
SUSY : ILC + LHC

- **LHC able to measure the parameters at the level %**
- **ILC will improve by a factor 10**
- **LHC+ILC reduces the model dependence**
- **MSSM can be probed at both colliders with sensitivities to different regions of the parameter space**



the Cosmic Connection

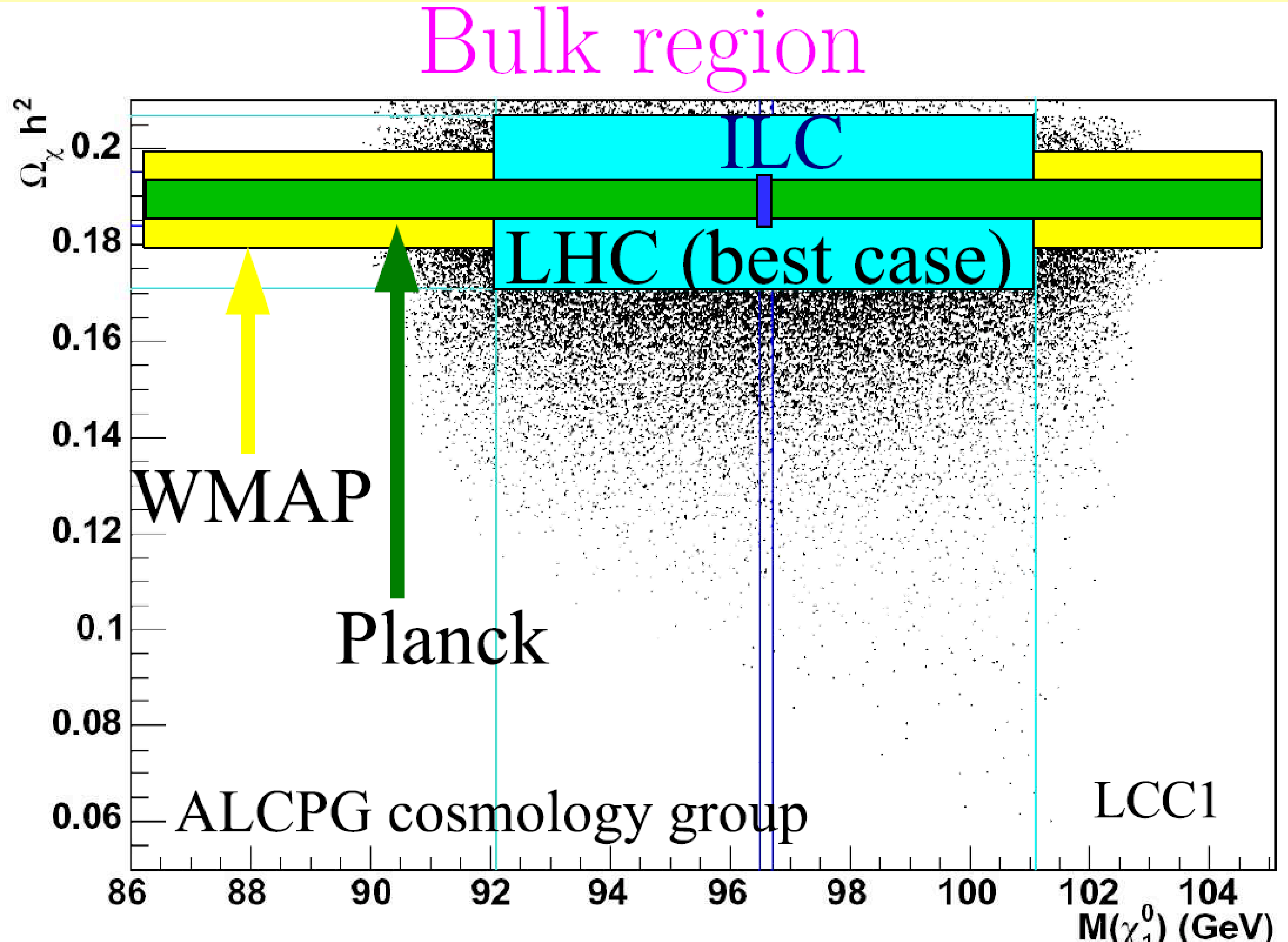
- SUSY provides excellent candidate for dark matter (LSP)
- other models also provide TeV-scale WIMPs
- how well can the properties of the DM-candidates (to be found at accelerators) be compared to the properties of the real DM (inferred from astrophysical measurements) ?



	$\Delta\Omega_{DM}/\Omega_{DM}$	main sensitivity
bulk	3.5%	$\tilde{\chi}_1^0, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_1$
focus	1.9%	$\tilde{\chi}_1^0, \tilde{\chi}_2^0 - \tilde{\chi}_1^0, \tilde{\chi}_3^0 - \tilde{\chi}_1^0, \tilde{\chi}_1^+ - \tilde{\chi}_1^0, \sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$
co-ann.	6.5%	$\tilde{\chi}_1^0, \tilde{\chi}_1^0 - \tilde{\tau}_1$
funnel	3.1%	$A^0, \tilde{\chi}_1^0, \tilde{\tau}_1$

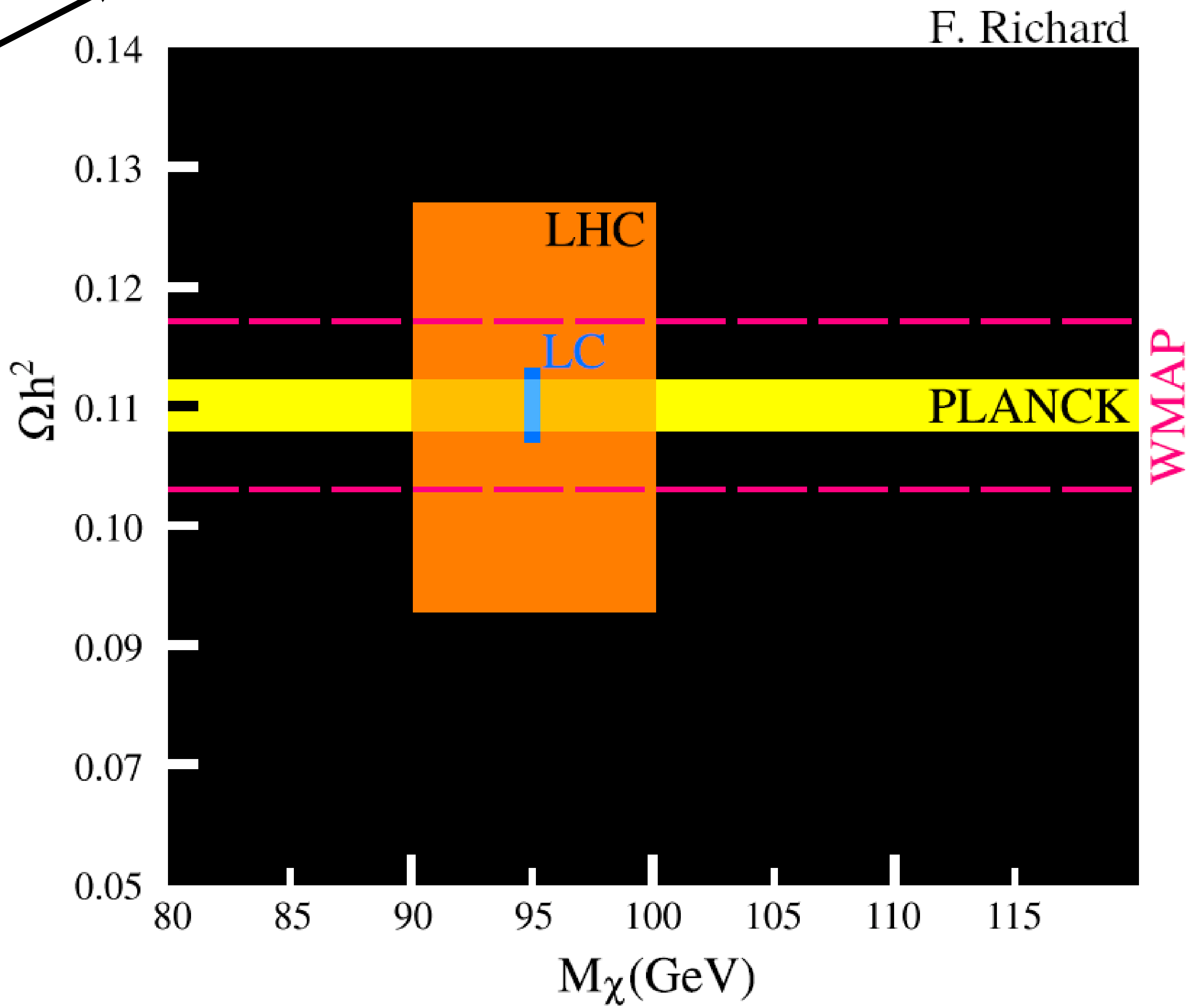
ILC matches precision of future CMB exp !

Dark Matter : is it the Susy LSP ?

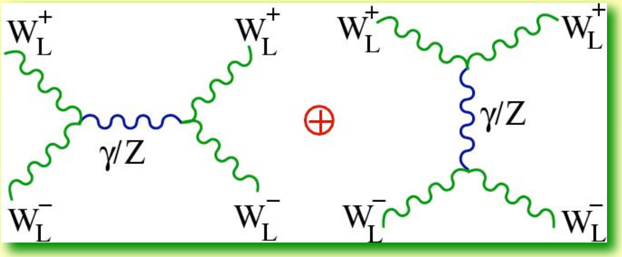


$\tilde{\tau} - \tilde{\chi}_1^0$ coannihilation region

Difficult at LHC



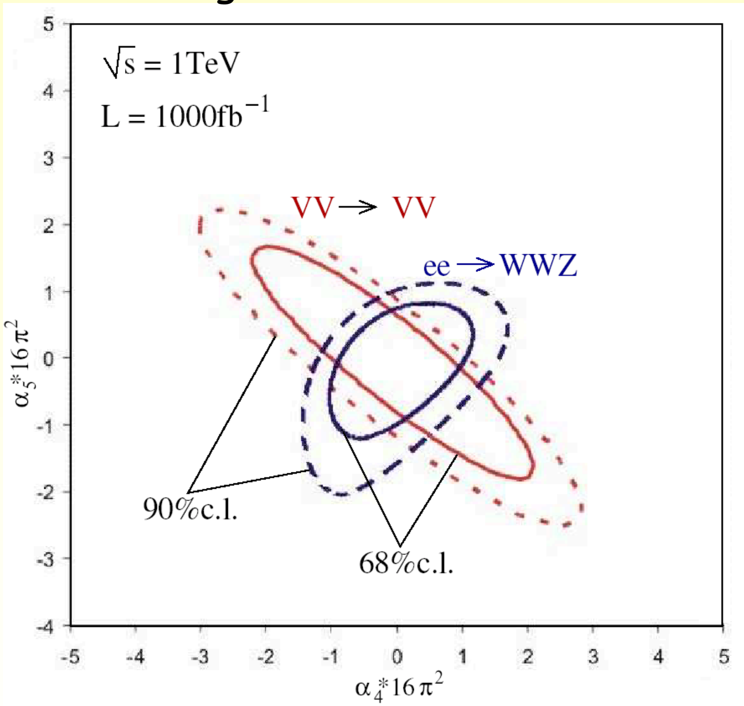
no elementary Higgs ?



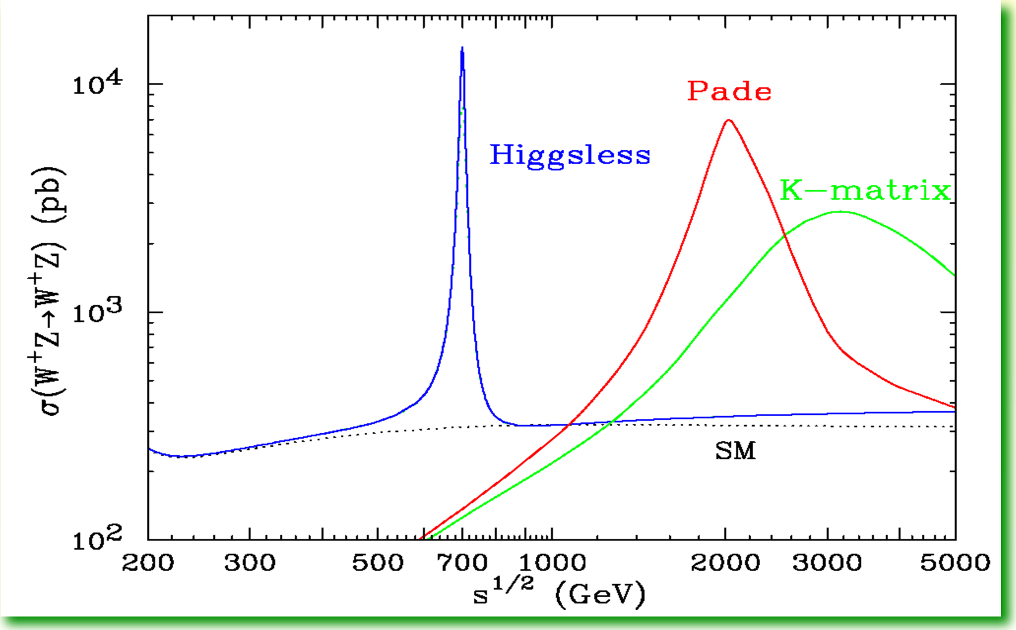
Cross section for vector boson scattering violates unitarity at ~1.2 TeV, if forces remain weak and no new resonances appear

ILC sensitivity deep into multi-TeV region from VB final states !

eff. Lagrangian parameters of strong EWSB:



Higgsless model: new resonance in WZ→WZ



Coupling structure from ILC if resonance seen by LHC

Effective 4-fermion contact interactions

$$\mathcal{L}_{CI} = \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} (\overline{u}_{F,i}\gamma^{\mu} u_{F,i})(\overline{u}_{f,j}\gamma^{\mu} u_{f,j})$$

		LHC Λ [TeV]				LC Λ [TeV]			
model		LL	RR	LR	RL	LL	RR	LR	RL
eeqq:	Λ_+	20.1	20.2	22.1	21.8	64	24	92	22
	Λ_-	33.8	33.7	29.2	29.7	63	35	92	24
$ee\mu\mu$:	Λ_+					90	88	72	72
	Λ_-					90	88	72	72
eeee:	Λ_+					44.9	43.4	52.4	52.4
	Λ_-					43.5	42.1	50.7	50.7

Table 7.1: The 95% sensitivity reaches for a basic choice of contact interactions expected for the LHC [9] ($L_{int} = 100\ fb^{-1}$ at 14 TeV and δL=5%) and the LC [11, 13] ($L_{int} = 1\ ab^{-1}$ at 0.5 TeV and P_{e^-}=0.8, P_{e^+}=0.6).

hep-ph/0410364

What if "unexpected" New Physics ?

LHC: interaction rate of 10^9 events$/s$

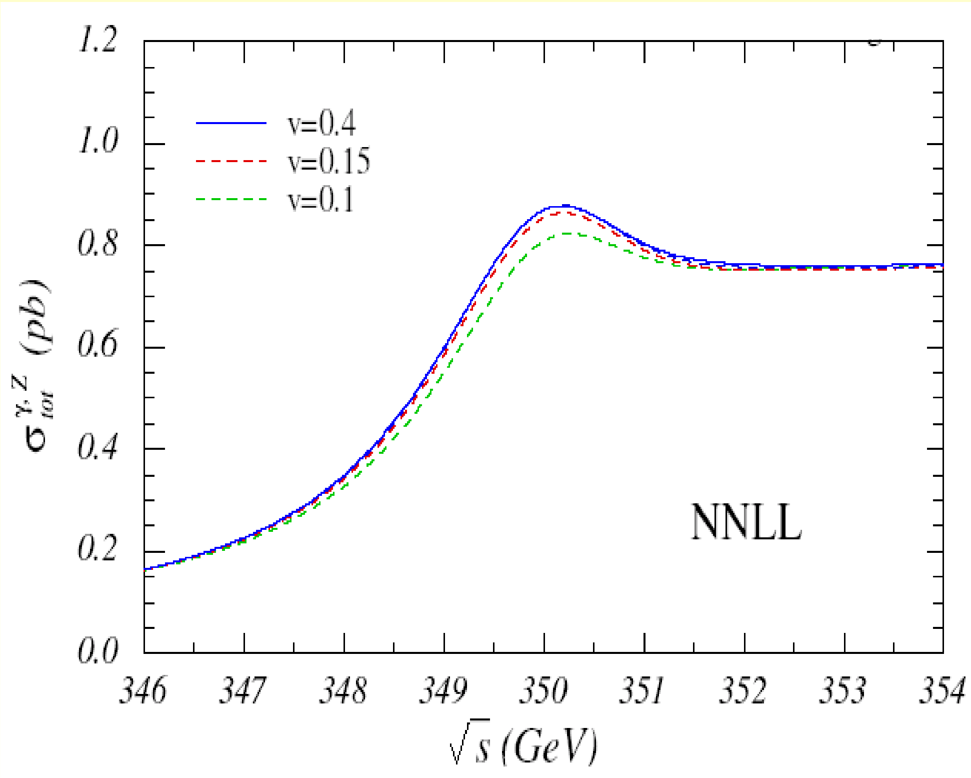
$\Rightarrow$ can trigger on only 1 event in 10^7

ILC: untriggered operation

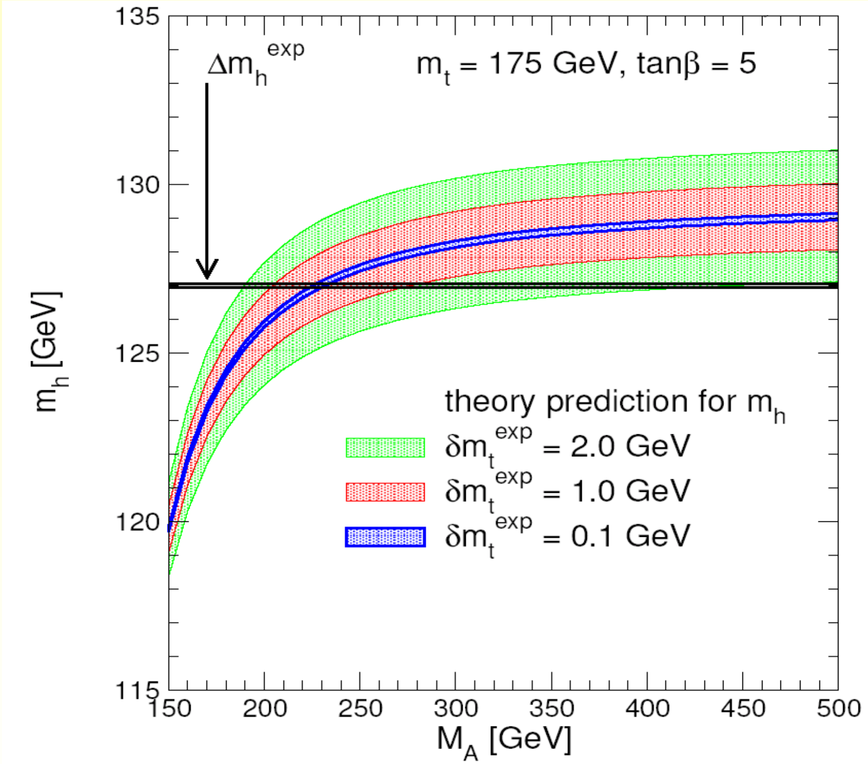
$\Rightarrow$ can find signals of unexpected new physics (direct production $+$ large indirect reach) that manifests itself in events that are not selected by the LHC trigger strategies

top quark physics (it is there for sure !)

• threshold scan provides excellent mass measurement
Theory (NNLL) controls $m_t(\overline{MS})$ to 100 MeV



• precise m_{top} **vital** for
- improved SM fits
- MSSM (m_h prediction)
- DM-density in mSugra
- . . . .



EW precision measurements :

Anticipated experimental precision of $M_W, m_t, sin^2\theta_{eff}, M_H$

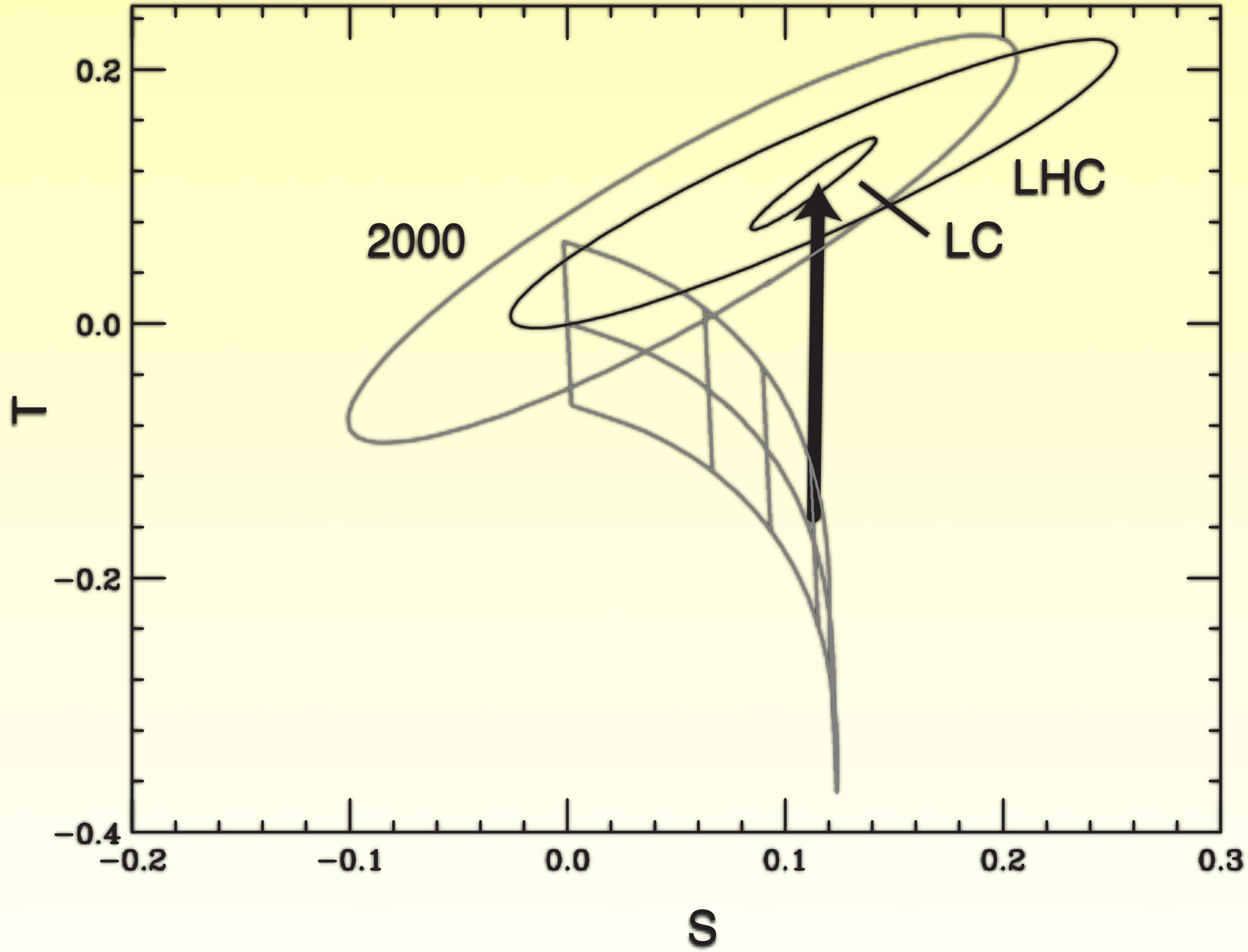
	now	LHC	LC	GigaZ
$\delta \sin\theta_{eff} (\times 10^5)$	17	14–20	(6)	1.3
δM_W [MeV]	30	15	10	7
δm_t [GeV]	2.3	1.0	0.2	0.13
δM_H [MeV]$*$	–	100	50	50

$*$ assuming $M_H = 115$ GeV

from U.Baur *et al.*, hep-ph/0111314

Electroweak precision test

Does m_H agree with electroweak precision expectations?

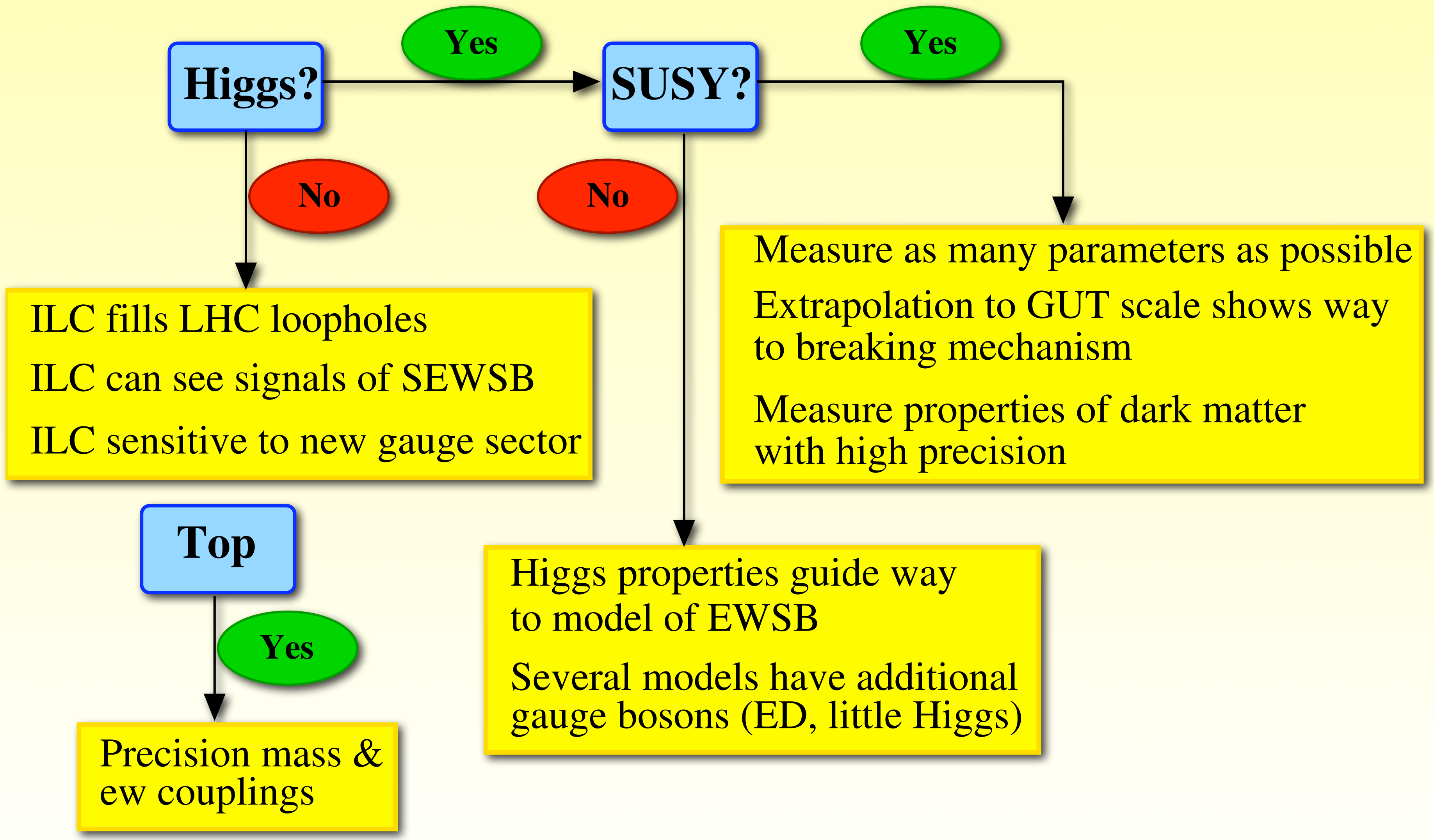


More stringent test of SM.

Gain clues to New Physics if there's a discrepancy

from Peskin & Wells, hep-ph/0101342

Conclusions : ILC crucial in any scenarios !



further reading :

INTERNATIONAL LINEAR COLLIDER

REFERENCE DESIGN REPORT

ILC Global Design Effort and

World Wide Study **AUGUST, 2007**

(Volume 2 - Physics at the ILC)

http://www.linearcollider.org/cms/?pid=1000437