Physics at the International Linear Collider

[Apology for no proper quotation]

Why ILC?

In recent years, all of the highest–energy particle accelerators have been colliding beam facilities

e^+e^-	SLC	90 GeV	1989 – 1998
e^+e^-	LEP	90 – 210 GeV	1989 – 2000
$p\bar{p}$	Tevatron	1.8 – 2 TeV	1988–
pp	LHC	14 TeV	2007–

The ILC would be a successor to LEP and SLC at higher energy. What is it about the results from these colliders that calls for a successor?

Their aim was to make precision tests of the Standard Model of electroweak/strong interactions. This is a Yang–Mills gauge theory with the following ingredients:

Local gauge symmetry: SU(3)×SU(2)×U(1)

Unification of weak and EM interactions

Maximal parity violation

Spontaneous symmetry breaking

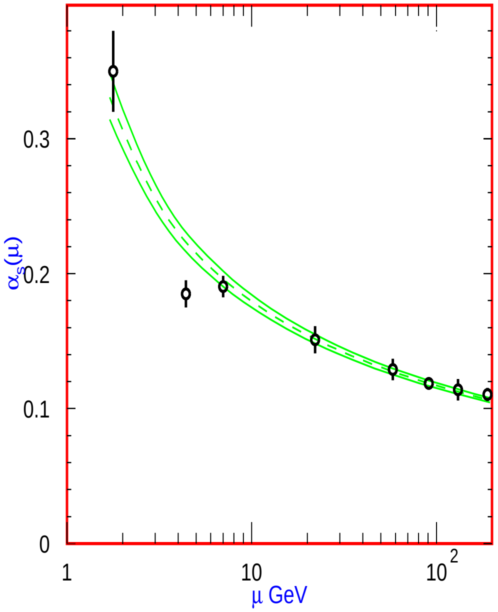
$$g_s^2/4\pi = 1/9,\ g^2/4\pi = 1/30,\ g'^2/4\pi = 1/99, \quad \langle\phi\rangle = v = 246\,\mathrm{GeV}$$

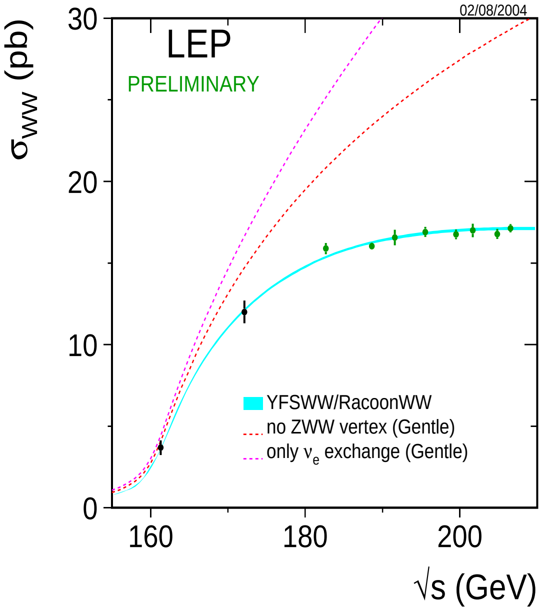
$$m_W = gv/2, \quad m_Z = (g^2 + g'^2)^{1/2} v/2, \quad m_{\gamma,g} = 0; \quad m_f = y_f v/\sqrt{2}$$

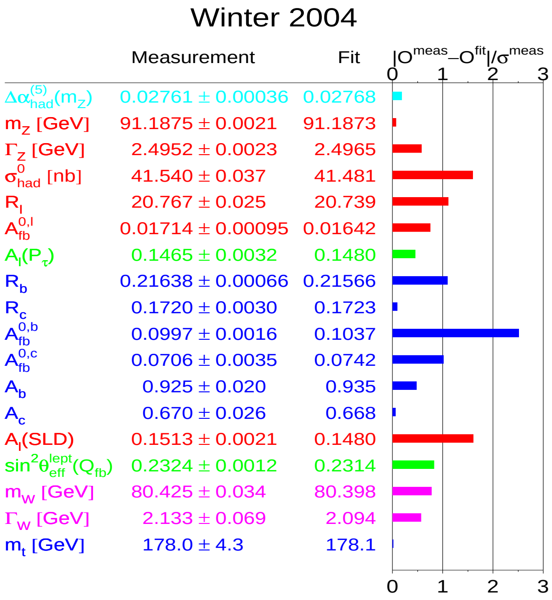
$$Z = c_W W - s_W B, \quad \gamma = s_W W + c_W B \quad \text{with} \quad s_W/c_W = g'/g$$

$$Q = I_3 + Y, \qquad \boxed{Q_Z = I_3 - Q\sin^2\theta_W}$$

Why ILC?

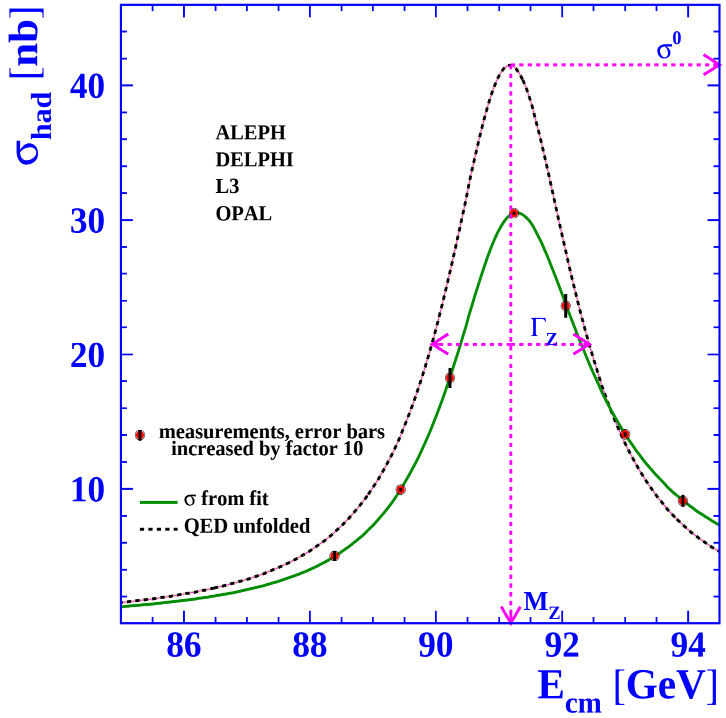






Winter 2004

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1



The theory of the Z resonance line shape is somewhat sophisticated. The EW and strong radiative corrections must be included.

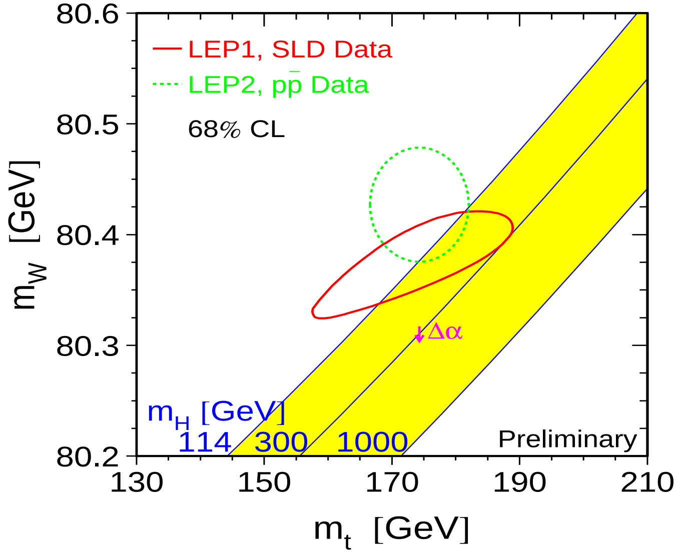
The final result agrees with experiment at the parts–per–mill level.

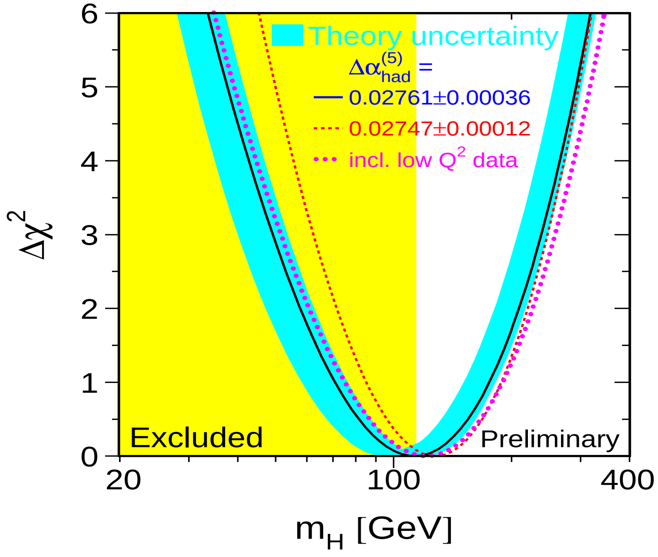
The beautiful experiments leave little room for doubt that EW interactions have a basic gauge symmetry SU(2)×U(1). This brings into focus the next question:

What is the agent that breaks this holy symmetry?

The Standard Model contains no dynamical mechanism for EWSB. It can only be explained by a new fundamental interaction operating at an energy scale of a few hundred GeV. Being ignorant of what the interaction is, physicists propose a descriptive theory by adding a SU(2) scalar doublet, yielding the Higgs boson.

The Higgs boson influences the structure of the W and Z, through the vertex that gives these particles mass. Fitting the electroweak data, we can look for a systematic shift due to a heavy Higgs boson. $\boxed{m_{h_{SM}} < 260 \text{ GeV (95\% c.l.)}}$





The Higgs boson(s) should be discovered at the LHC, if not before. From the LHC, we will also understand whether there are other new particles of comparable mass which produce the physics of electroweak symmetry breaking.

Whatever the outcome of these experiments, the next step is to understand the physics of electroweak symmetry breaking in detail.

To do this, we should apply the powerful experimental methods learned from LEP and SLC to the Higgs boson and the new particles at a few hundred GeV energies.

International Linear Collider

e^+e^- with $E_c \geq 0.5$ TeV and high luminosity
Energy scan $\oplus$ Beam polarization
Sensitive detectors $\oplus$ Precise theoretical predictions

LHC gives us a new global (mixed) picture.
ILC gives us new dynamic multi–dimensional total views.

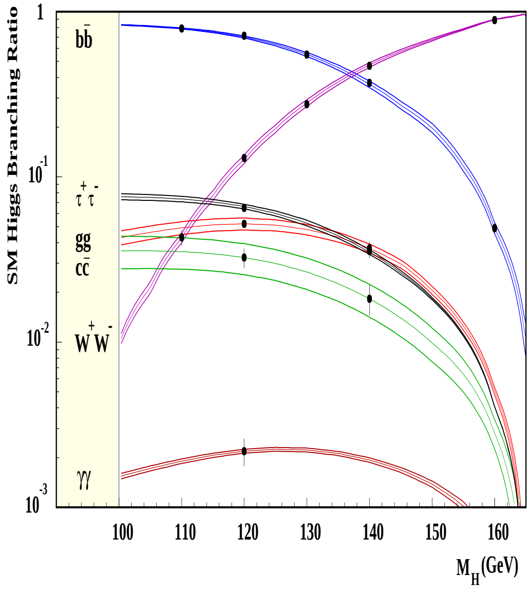
Many materials for ILC physics

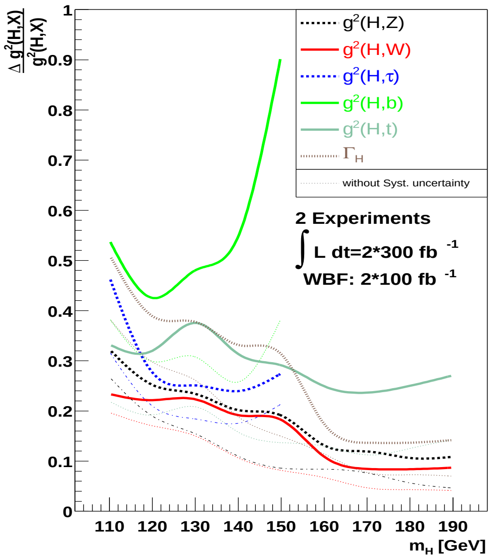
- ACFA LC report (2001)
- TESLA TDR (2001)
- LC resource book for Snowmass (2001)
- GLC project (2003)
- LC report from WWS (2003)
- LHC/LC note (2004)
- Response to ITRP questions (2004)
- Many LHC/LC related workshops
- ...

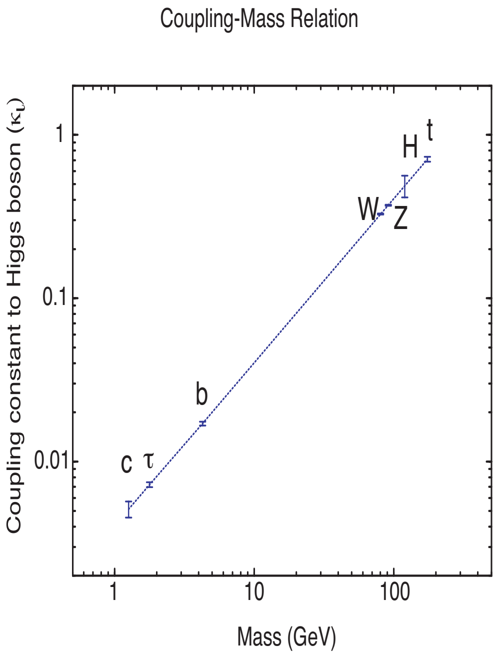
Once a Higgs–like particle is found, ILC can make precision measurements of its basic properties.

If the Higgs boson is the one to give masses to all the SM particles, we need to observe proportionality between mass and coupling.

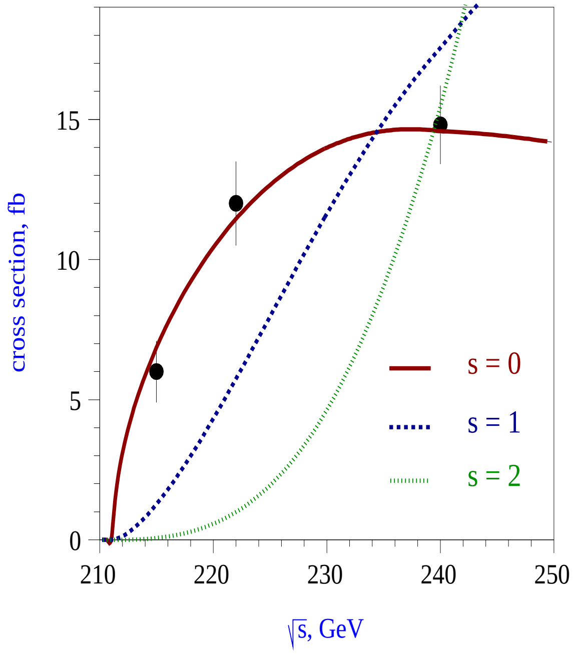
We need to measure Higgs self couplings as well to determine the shape of the Higgs pot and to understand what makes the Higgs boson condense in the vacuum.

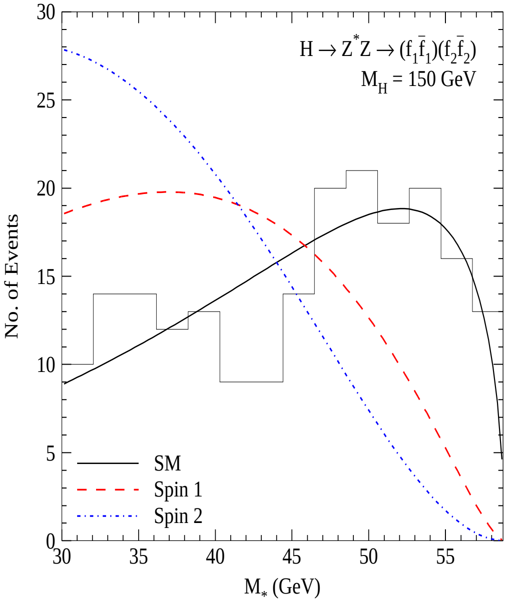


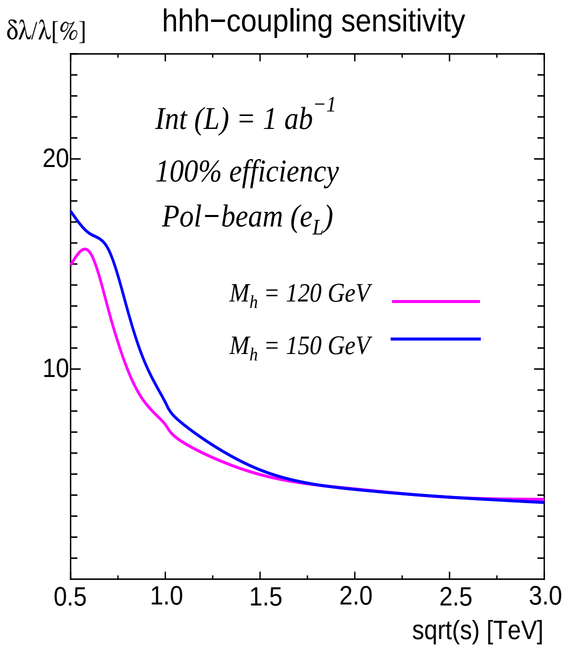




Spin and Self–couplings





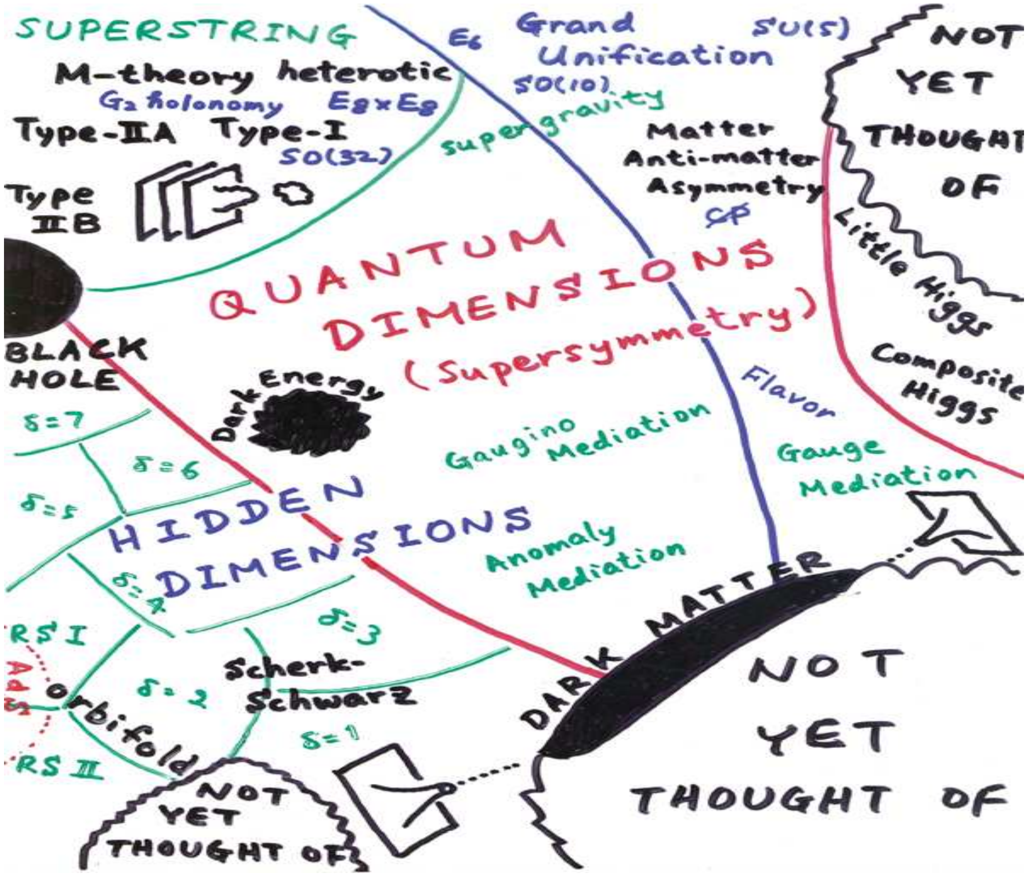


At present, almost NOTHING is known about Higgs sector.
The profile depends on the new physics scenario at the TeV scale.

Too Many BSM Scenarios

TOO many new physics scenarios with extra dimensions and symmetries

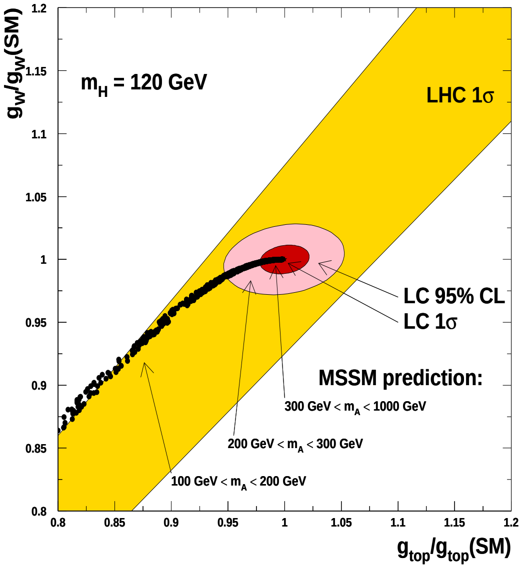
- In the case of high cut–off scale
  - ✠ SUSY (fermionic dimensions): the most well–motivated and studied
  - – ???
- In the case of low cut–off scale
  - ✠ Large extra dimension (bosonic dimensions)
  - – Extra symmetries
    - ∗ Techni–color
    - ∗ Little Higgs
    - ∗ Higgsless
    - ∗ ???
- Hybrids or much wilder thoughts??

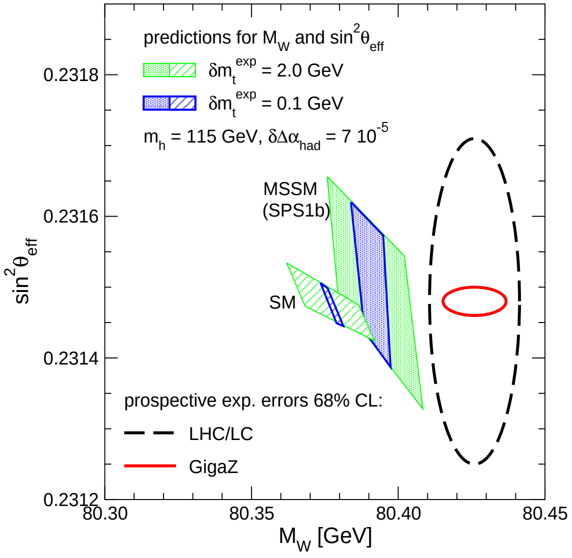


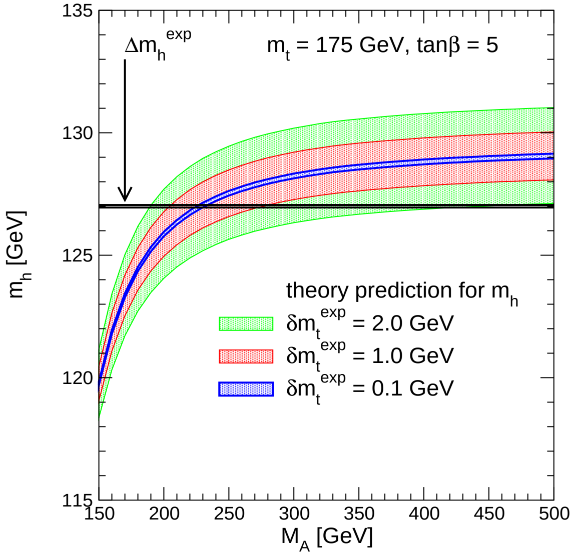
Decisive principles and/or experiments DESPERATELY needed

Precision matters!!

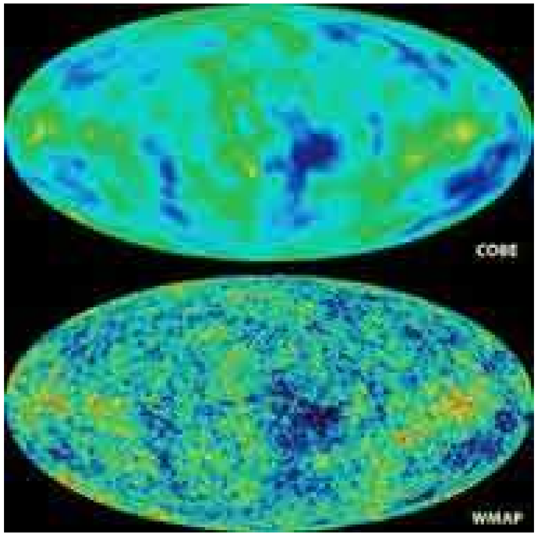
- Single Higgs? Two Higgs doublets? Additional singlets or triplets?
- SUSY or/and extra–dimension? Composite?
- Type–I or II or III Yukawa couplings and flavor mixings?
- Why top is heavy? Special for the 3rd generation?
- CP violation in Higgs sector? ⇒ $\boxed{\gamma\gamma \text{ mode}}$

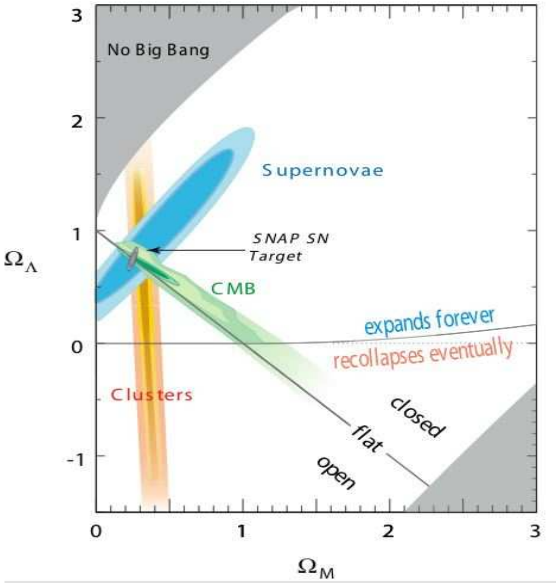


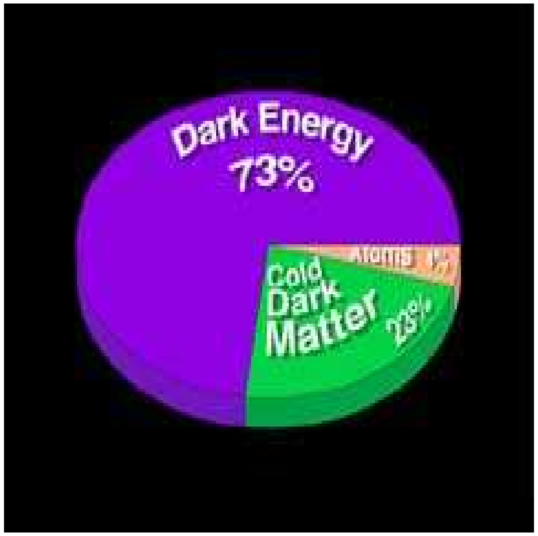




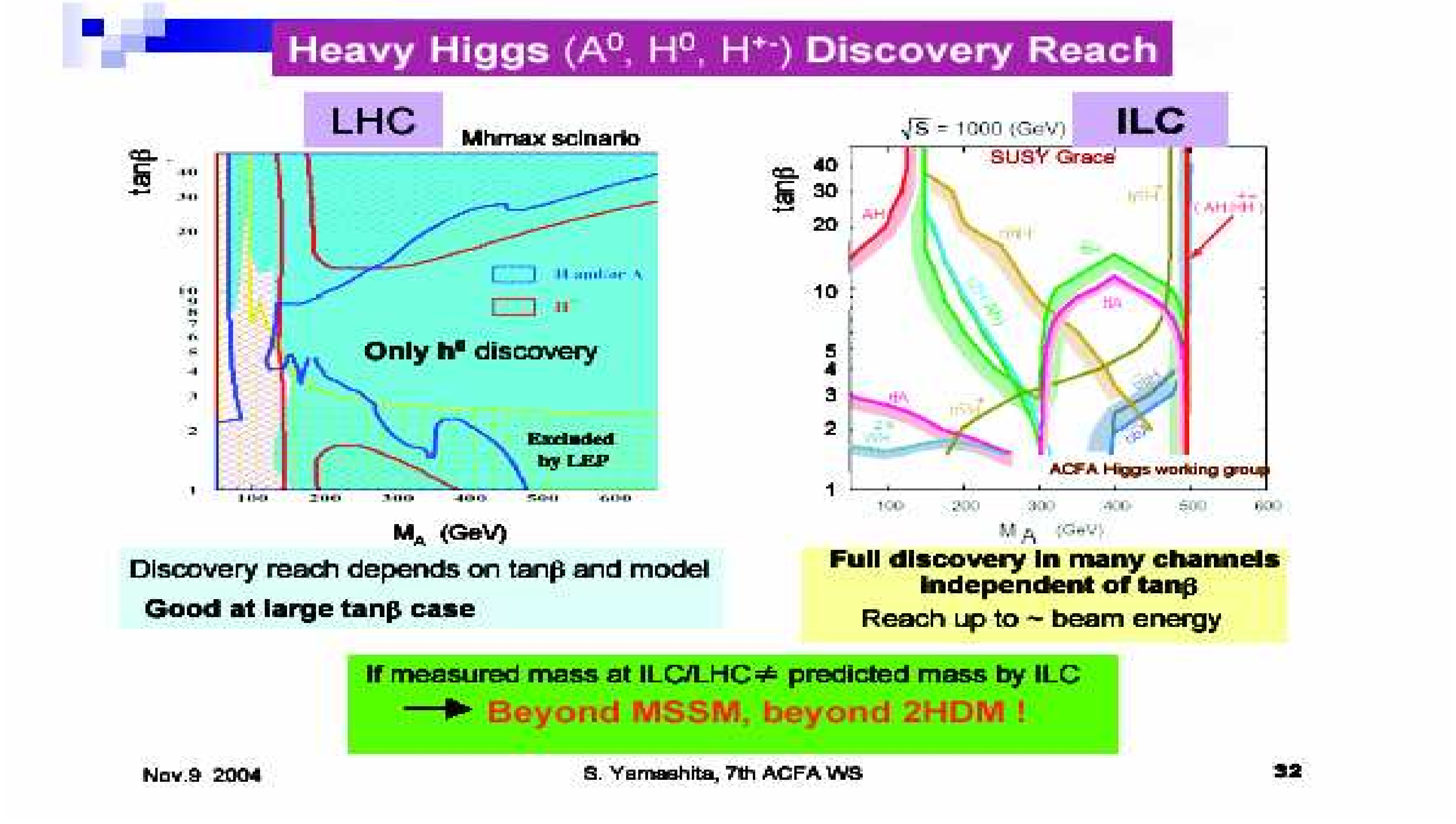
Precision mattered in the Universe as well!!







Model–independent searches!!!



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

LHC

Mhmax scinario

Discovery reach depends on tanβ and model

Good at large tanβ case

ILC

$\sqrt{s}$ = 1000 (GeV)

SUSY Grace

Full discovery in many channels independent of tanβ

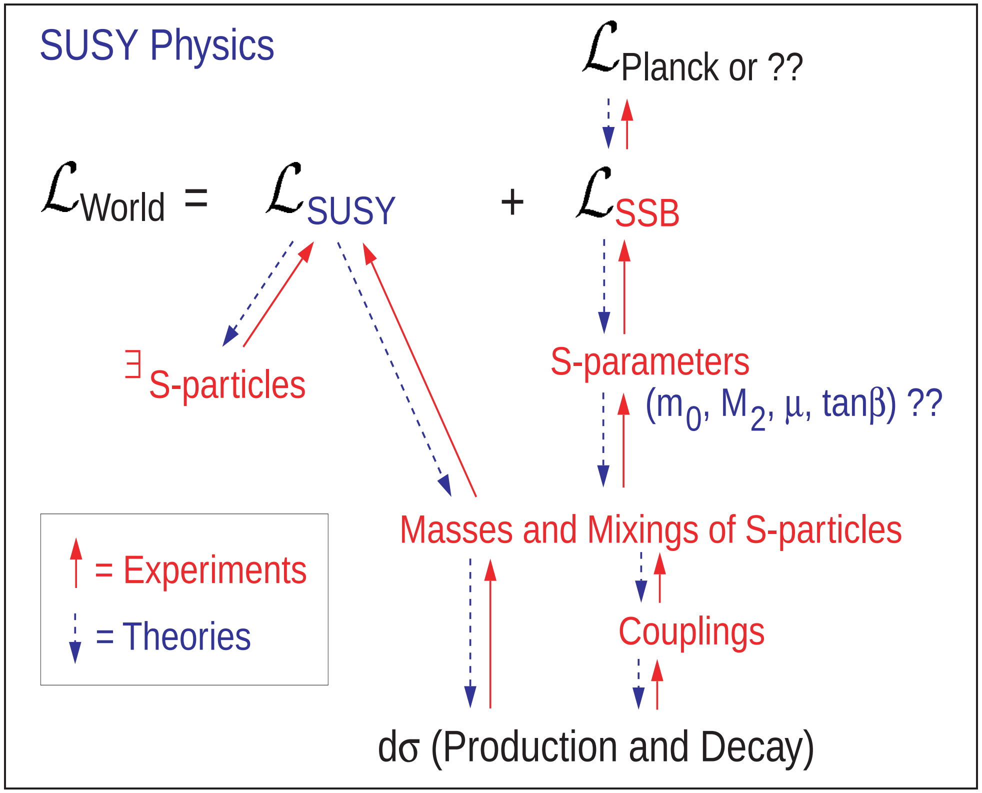
Reach up to ~ beam energy

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

⟶ Beyond MSSM, beyond 2HDM !

Nov.9 2004 S. Yamashita, 7th ACFA WS 32

Supersymmetry at the ILC



Model–independent methods

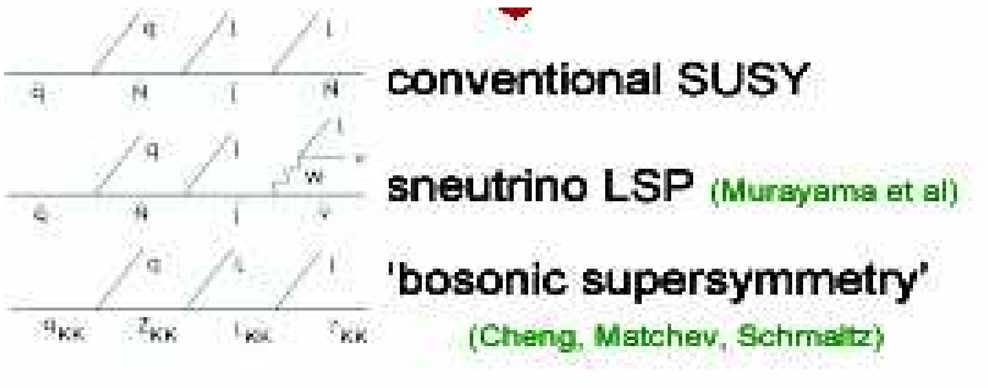
- End–point spectra
- Beam polarizations
- $e^-e^- \oplus \gamma e \oplus \gamma\gamma$ modes

What can be achieved?

- SUSY breaking mechanism
- Grand extrapolation

LHC would discover SUSY phenomena quickly by 2009. However, the measurements at the LHC involve

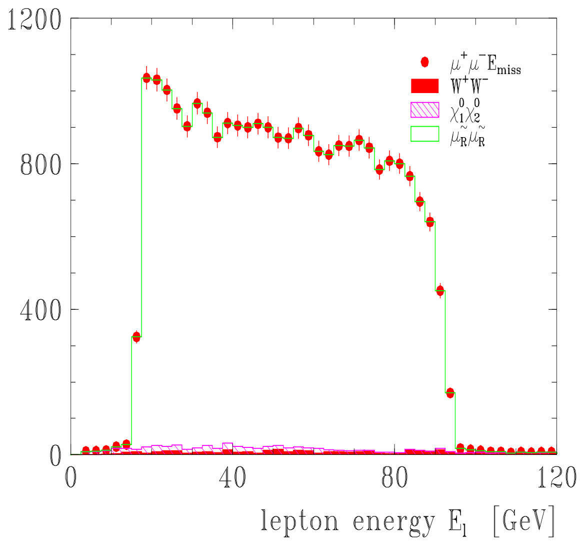
Complicated cascade chains
Large SM and other SUSY backgrounds
Model dependence of new physics analyses

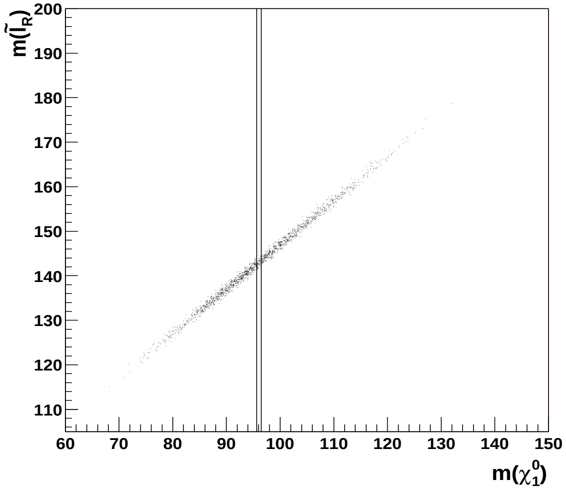


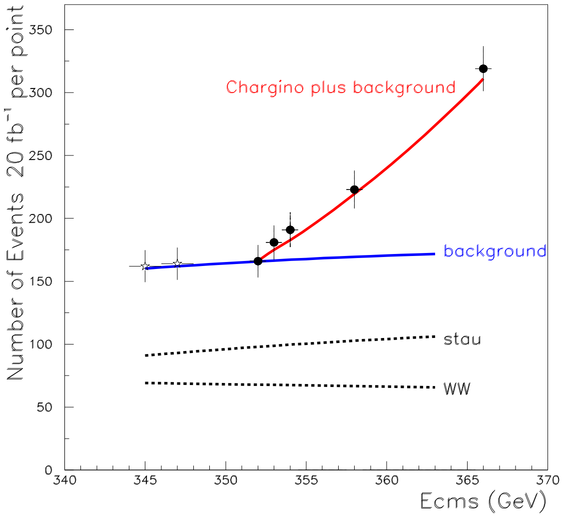
Multiple hypotheses, distinguished by different spins and energy flows, DIFFICULT to distinguish at the LHC due to missing/unfixed energies.

⇓

Model–independent analyses!!







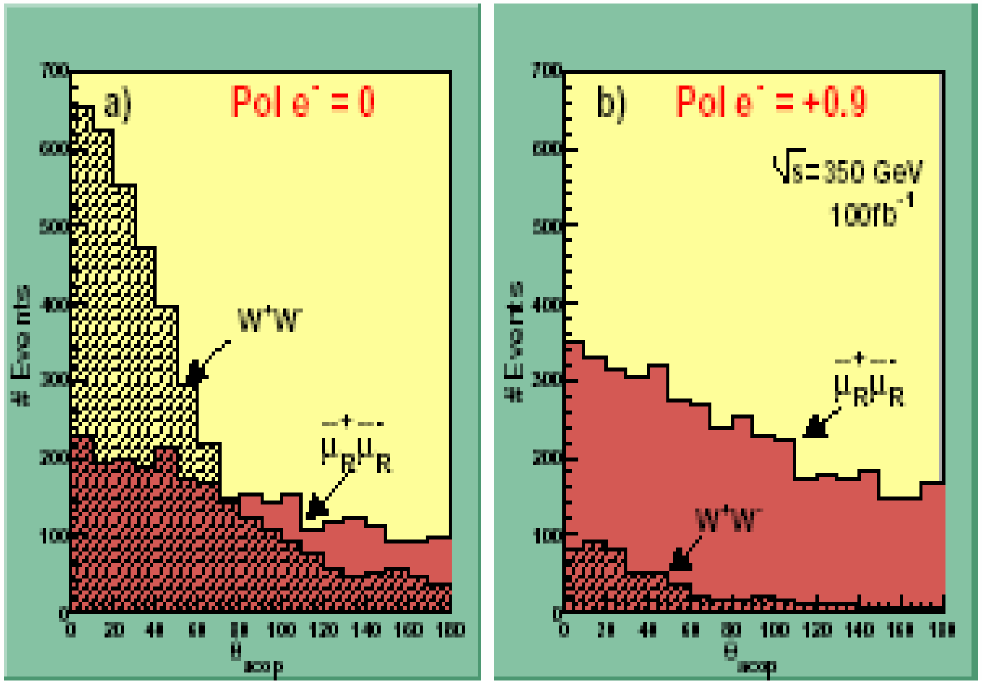
$\Uparrow$

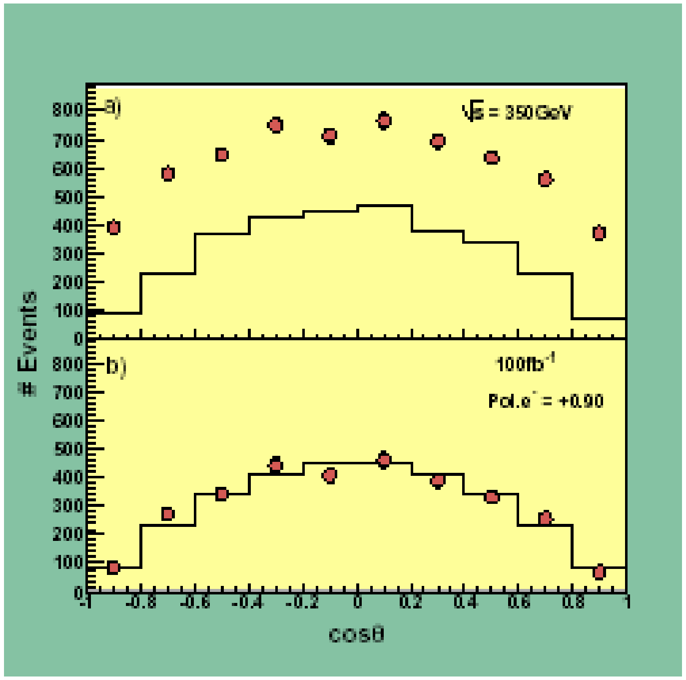
An LHC/LC synergy

The precisely measured LSP mass at the ILC constrains the LHC measurements of sfermion masses.

Beam polarization

Spinless?





SUSY and GUT

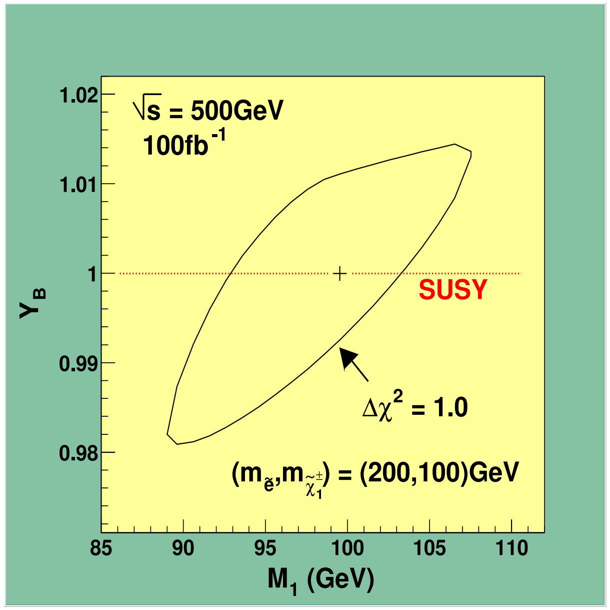
Masses

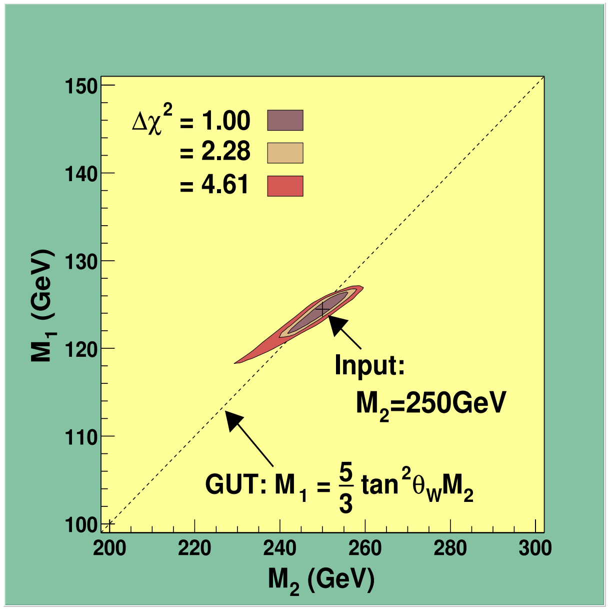
Couplings

Chirality

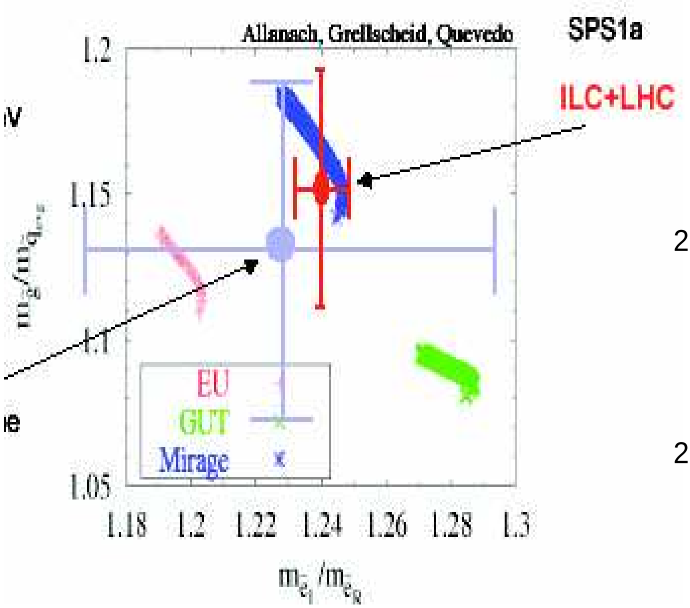
Mixing

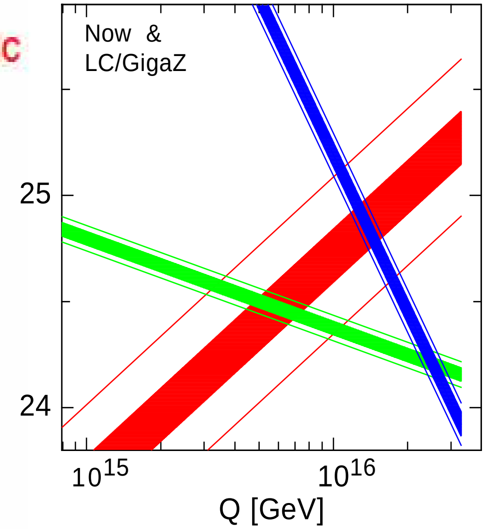
$\Rrightarrow$

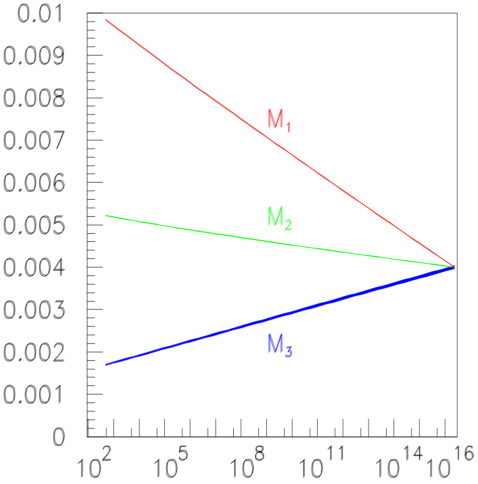




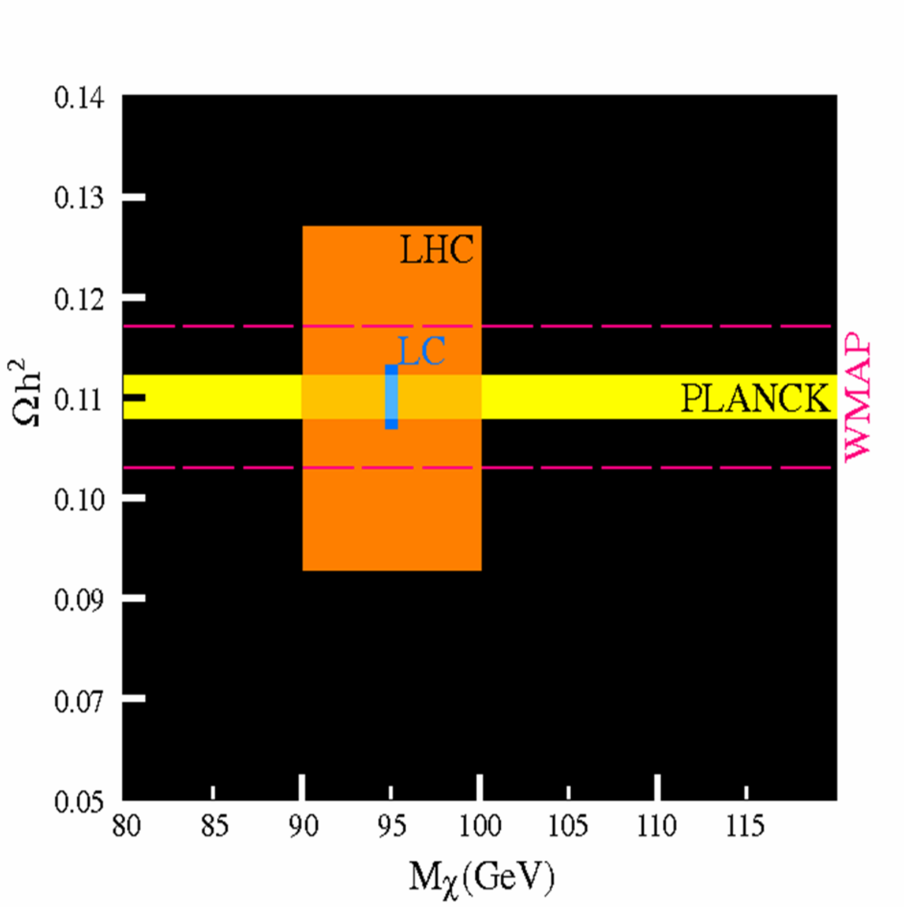
Grand extrapolation







Dark Matter = LSP?



WMAP: $0.094 < \Omega h^2 < 0.128$ (2σ)

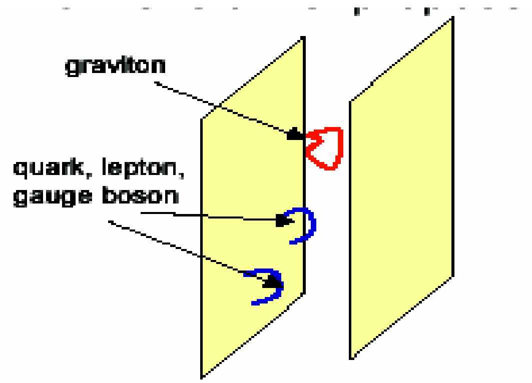
WMAP: 7%

LHC: 15%

Planck: 2%

ILC: 3%

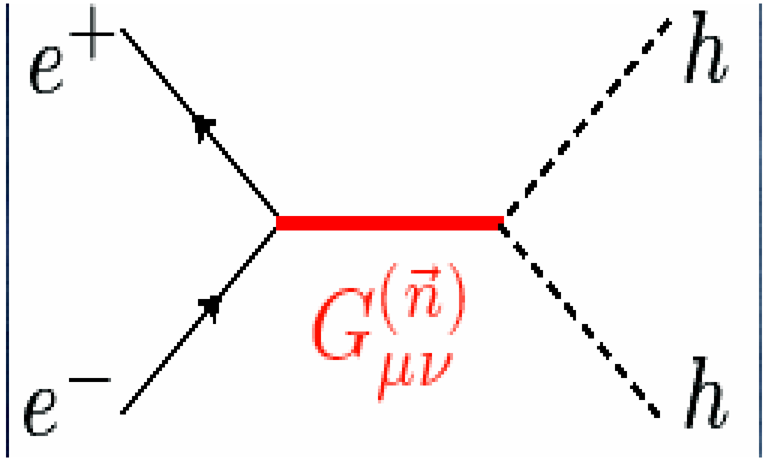
Extra dimensions at the ILC



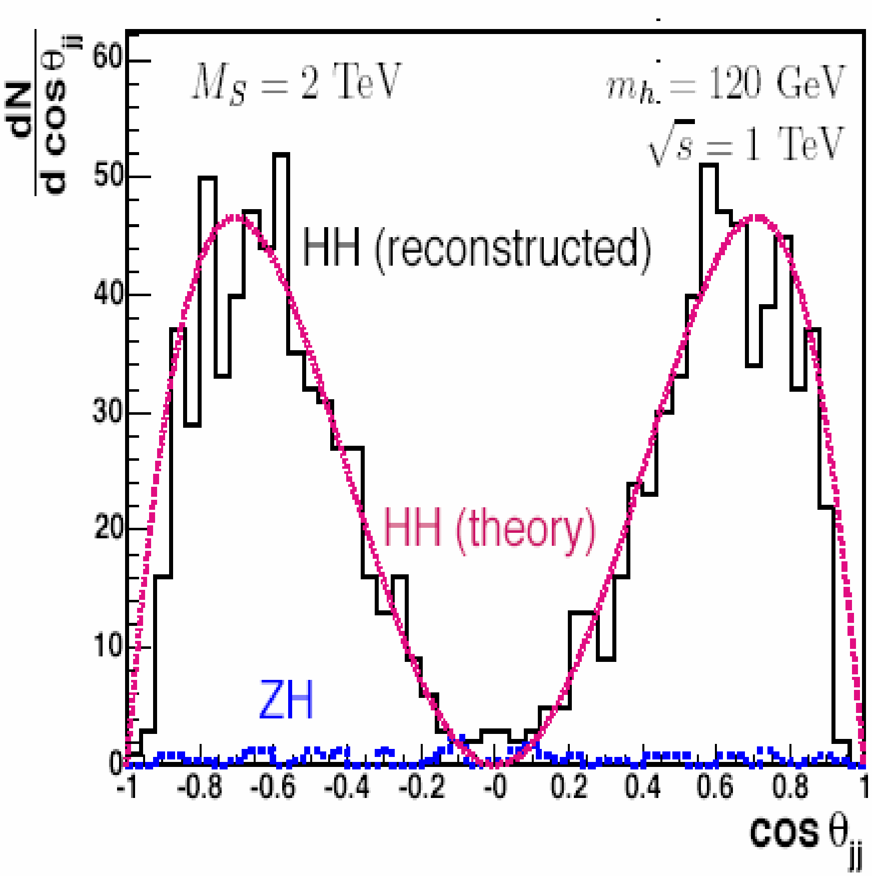
✠ How to tell LED signals from others?

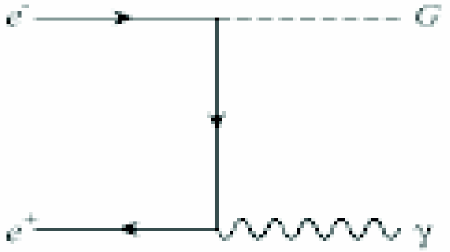
- How to decide nature of extra dimensions?
  - ✠ Size and shape (topology)?
  - – Non–commutative geometry?
- Possible probes
  - ✠ Quantum gravity effects (KK modes)?
  - – Brane excitation (KK modes of SM particles)?
  - – Classical gravity effects (Black holes)?

Impossible in SM

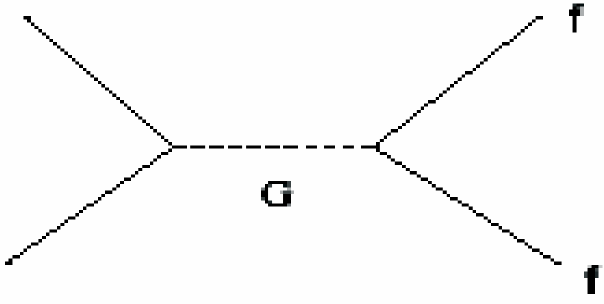


Cleanest way to test J=2

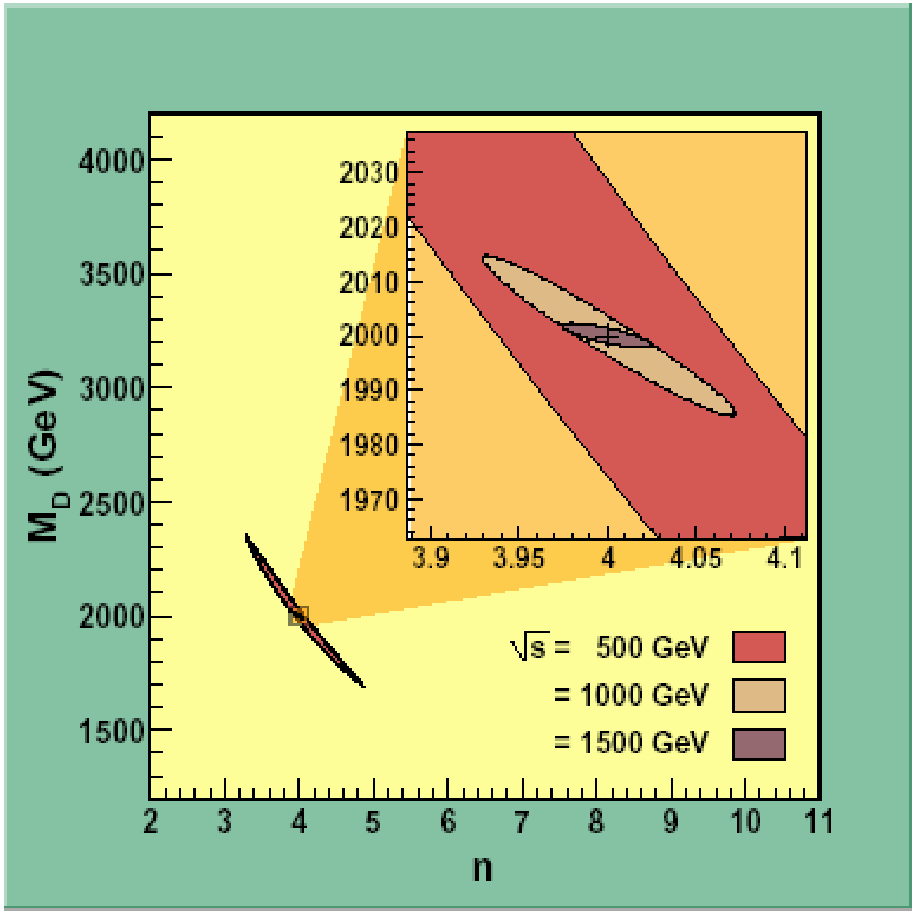




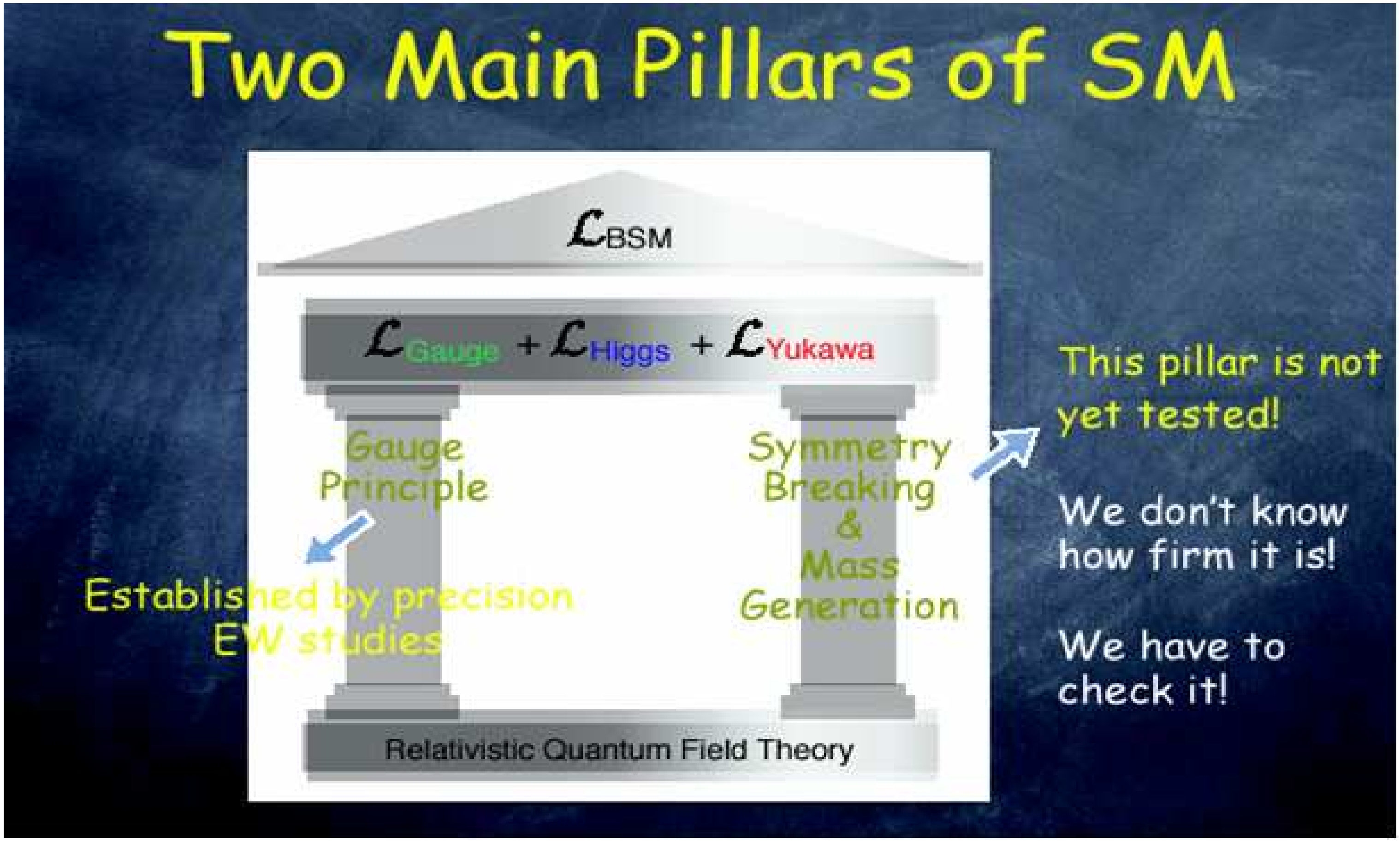
Graviton emission to extra-space



Graviton exchange



Conclusions



Two Main Pillars of SM

Established by precision EW studies

This pillar is not yet tested!

We don't know how firm it is!

We have to check it!

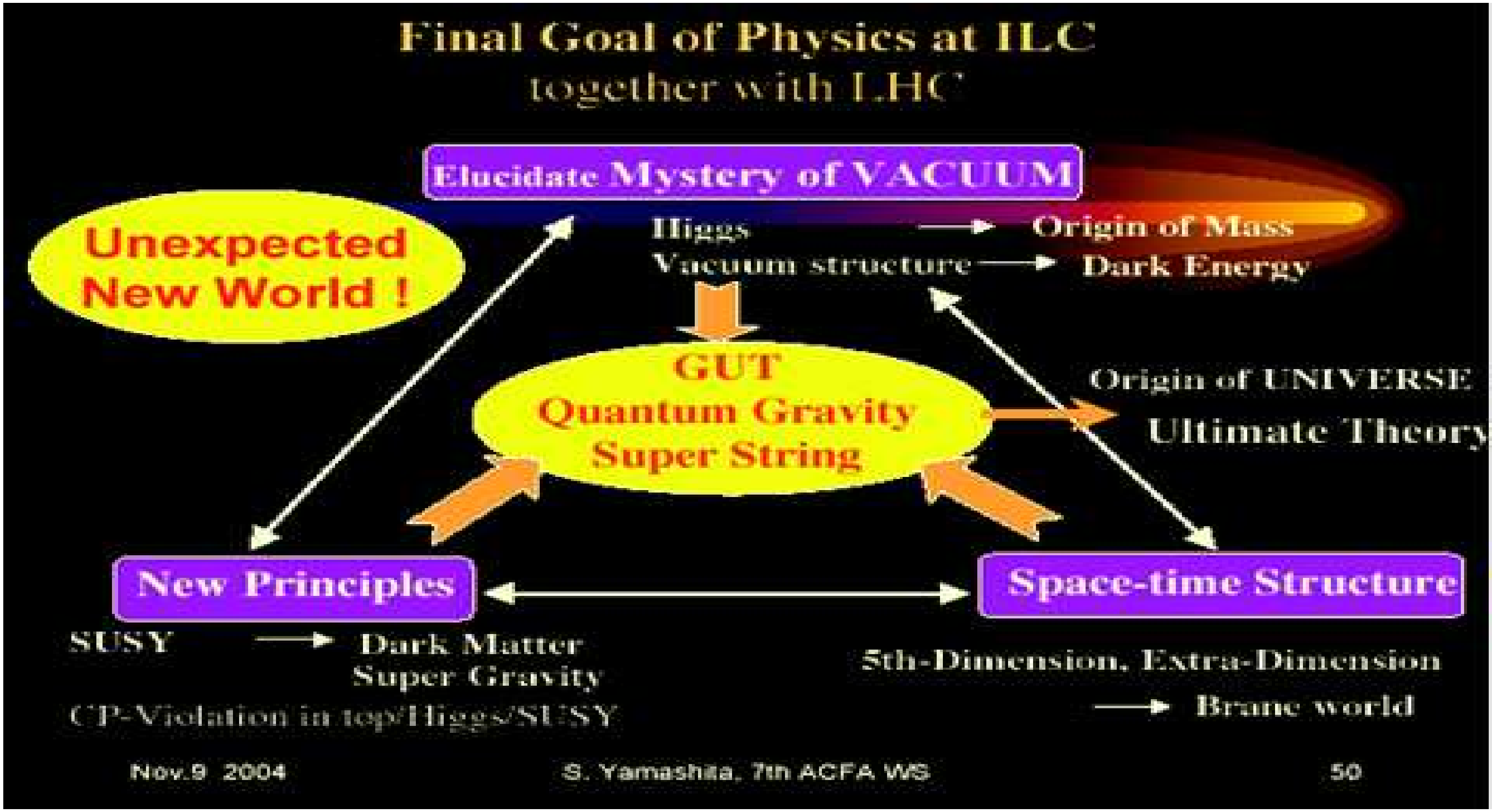
- © The test of the 2nd (right) pillar of the SM - symmetry breaking and mass generation - is the most important and urgent problem to solve.

- © The sub–TeV ILC will be crucial to carry out this mission and hence we need it regardless of the BSM scenarios.

- © To what extent the ILC will be able to explore the BSM depends on its scale and thus luck.

- © If its scale is not too high, ILC [along with LHC $\oplus \cdots$] can do a lot:
  - Precision super–spectroscopy to test SSB mechanism
  - Measurement of size and shape of LED
  - Cosmological $\oplus$ low–high $\oplus$ CP–Baryon connections

- ✠ Certainly, unexpected phenomena are highly expected as history has taught us!



Final Goal of Physics at ILC
together with LHC

Elucidate Mystery of VACUUM

Higgs → Origin of Mass
Vacuum structure → Dark Energy

Unexpected New World !

GUT
Quantum Gravity
Super String

Origin of UNIVERSE
Ultimate Theory

New Principles

SUSY → Dark Matter
Super Gravity
CP-Violation in top/Higgs/SUSY

Space-time Structure

5th-Dimension, Extra-Dimension
→ Brane world

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