9th ACFA ILC Workshop

Physics Session Summary

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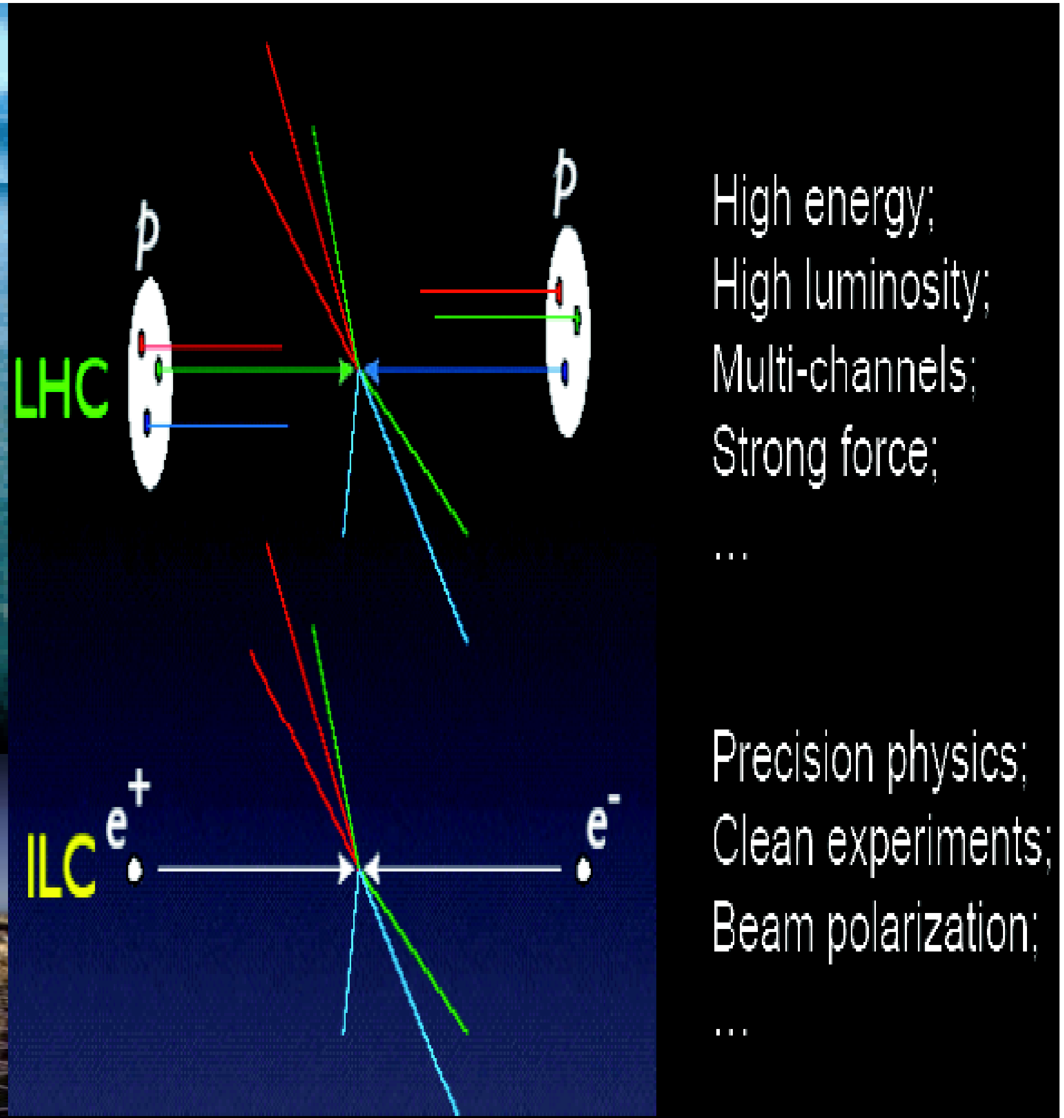
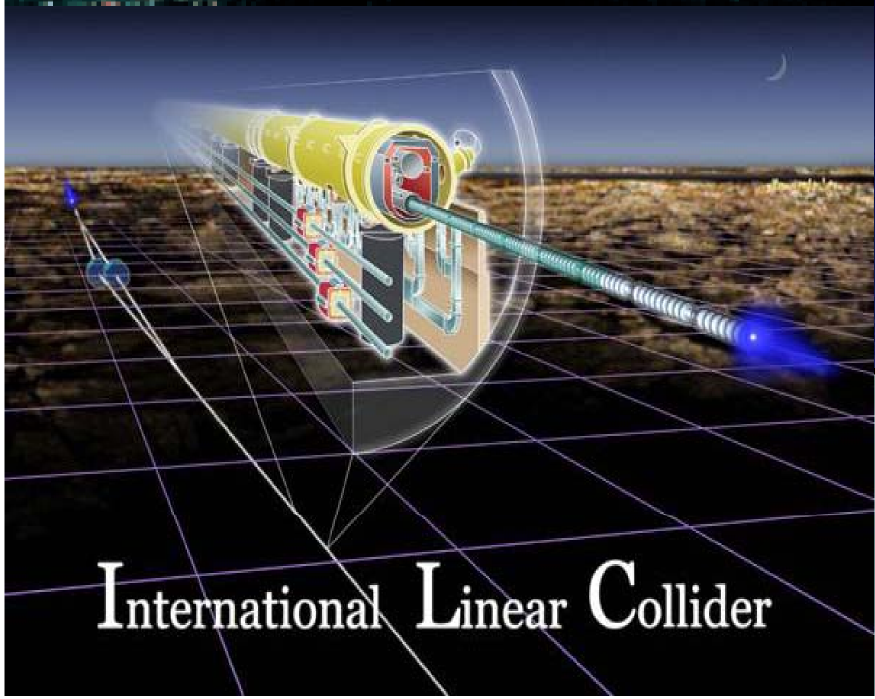
Tsinghua University

Feb. 4-7, 2007, IHEP, Beijing





Consensus:

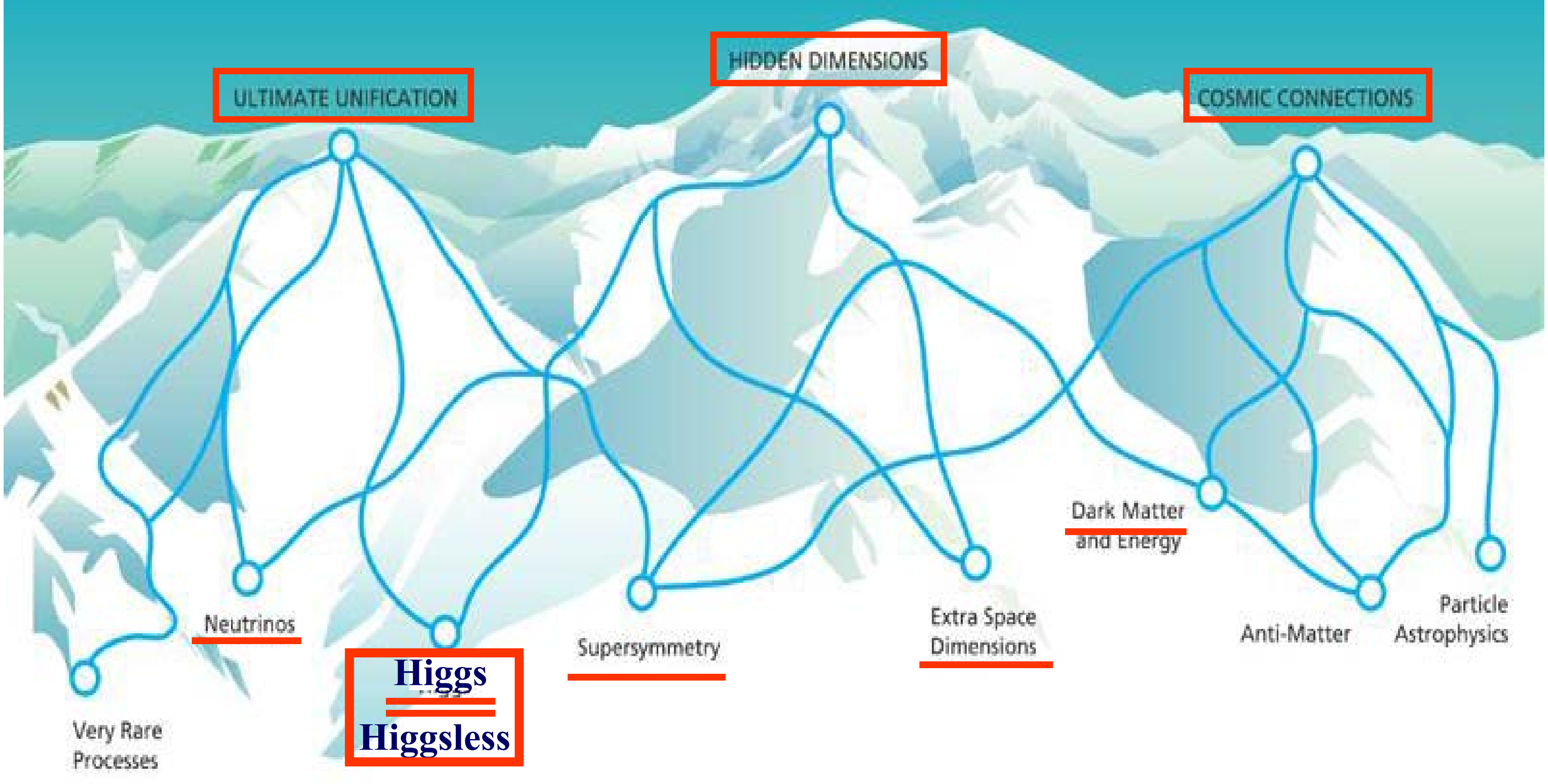
"Future" of ILC strongly depends on What New Phys LHC will discover.

- Zhengguo Zhao, **(Anomalous Gauge Boson Coupling)**
  Diboson Production and Triple Gauge Boson Couplings at TeV Hadron Collider
- Denis Perret-Gallix, **(Calculation Tool: Grace)**
  Simulate with Grace
- Kingman Cheung, **(Higgs: Very Light A^0)**
  Phenomenology of the Light Pseudoscalar Boson in NMSSM
- Eri Asakawa, **(Exotic Higgs-Gauge-Coupling: $H^+W^-Z^0$)**
  Potential for Measuring the $H^+W^-Z^0$ vertex at colliders
- Liang Han, **(NLO EW Corrections)**
  Theoretical Calculation for ILC Precise Measurement
- Jin Min Yang, **(SUSY: Splitting Model)**
  Split Supersymmetry at ILC
- Shou-hua Zhu, **(Exotic Higgs A^0: 0.215GeV)**
  Unique Higgs Boson Signature at Colliders
- Koichi Matsuda, **(Anomalous Higgs Yukawa: ee→vvtt, ee→htt)**
- New Physics Search by Helicity Decomposition of Heavy Fermion Pair-Production from W-boson Fusion at LHC/ILC
- Hideo Itoh, **(SUSY-breaking/brane world: TeV-scale X)**
  Low scale supergravity mediation in brane world scenario
  and hidden sector Phenomenology
- W. Lohmann, **(Higgs: Detector Full simulation/Reconstruction)**
  Study of ee→Zh→llX using full detector simulation and exact reconstruction

Central Physics Issues for LHC & ILC

- **Why TeV Scale ?**
- **What New Physics ?**
- **How to Compute/Observe: Signals vs Bkgnds ?**
- **How does ILC play Complementarity to LHC?**

New Physics at TeV Scale ??
Which is Guaranteed ??



New Physics at TeV Scale ?

- **Hierarchy/Fine-Tuning Problem ?**

  → **Not strong enough !**
- **Unification ?**

  → **Many possible realizations !**
- **Light Higgs ?**

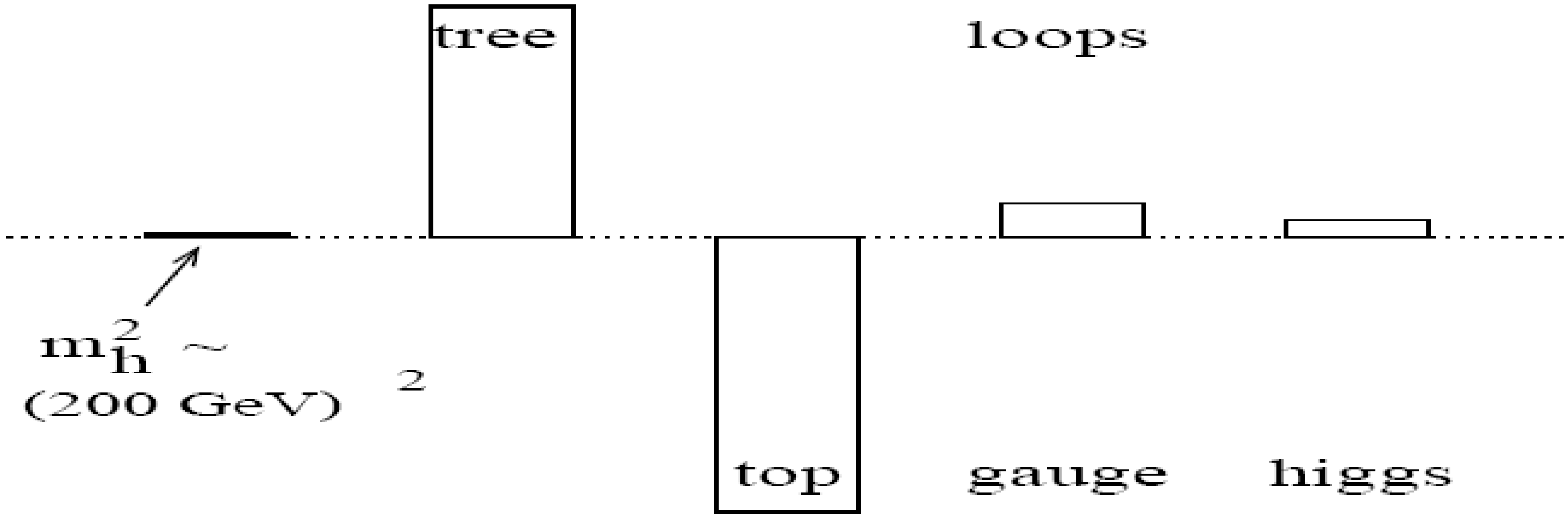
  → **Not enforced by data !**
- **Then,**

  WHAT best justifies TeV Scale? …

Fine-Tuning Problem ?

- **Radiative Corrections to Higgs Mass:**

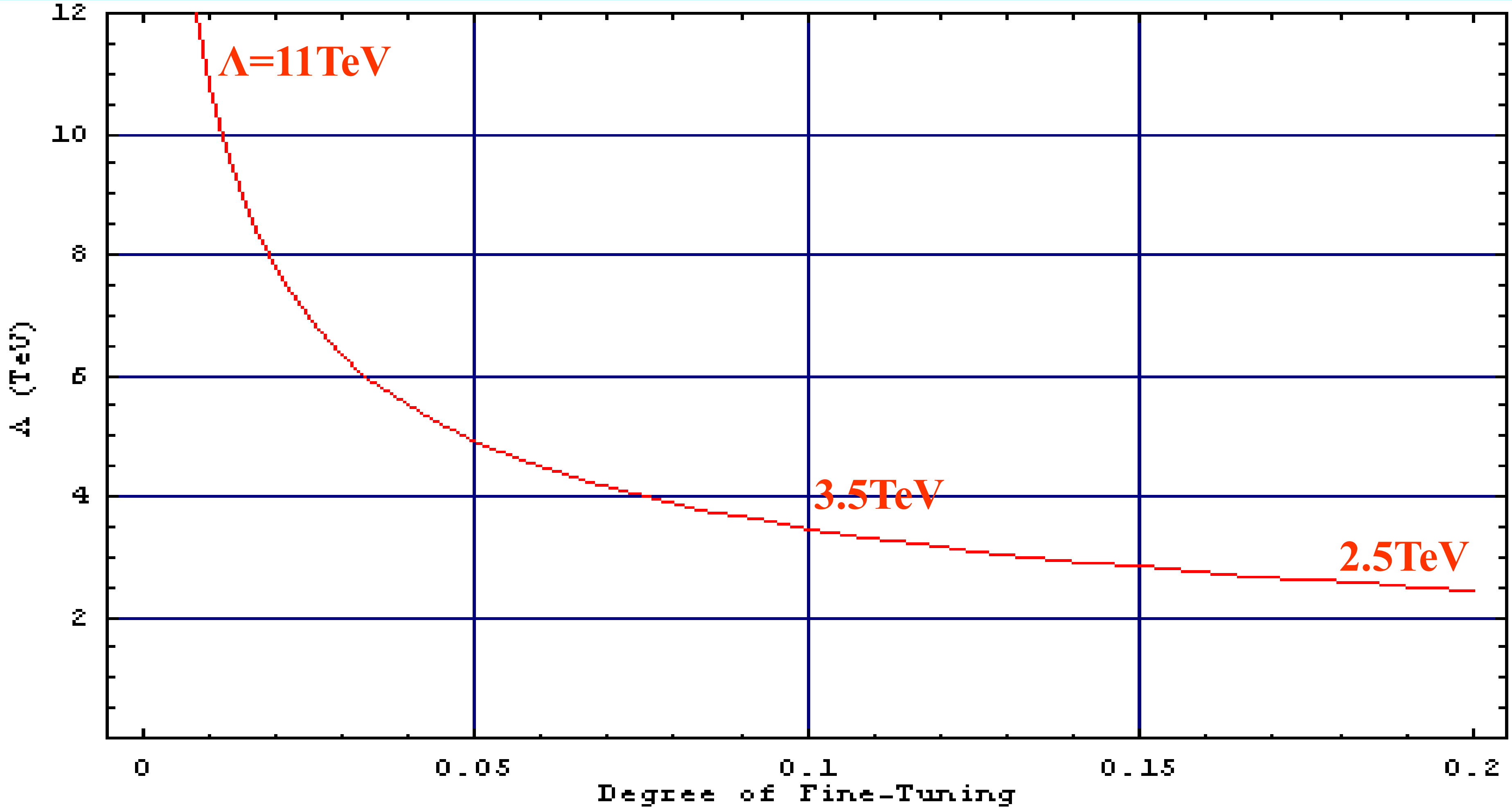
$$(200\,\text{GeV})^2 = M^2_{Ho} + [-(2\,\text{TeV})^2 + (520\,\text{GeV})^2 + (460\,\text{GeV})^2]\left(\frac{\Lambda}{10\,\text{TeV}}\right)^2$$



- **Degree of Fine-Tuning (DFT):**

DFT = $200^2/[|-2000^2+520^2+460^2|*(\Lambda/10\text{TeV})^2]$

Fine-Tuning is a Technical Problem !



Not strong enough for LHC/ILC!

SM Higgs Potential runs into
more serious
Vacuum Energy Problem
even at Tree-Level: (eg, S.Weinberg,1989)

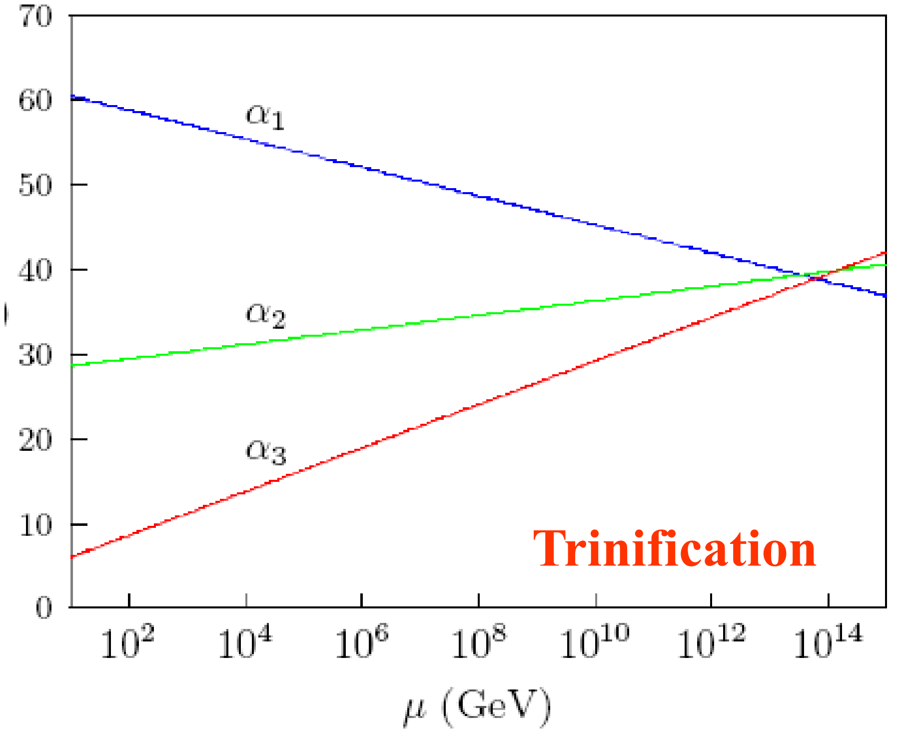
$$\langle\rho\rangle = V_{min} - \lambda v^4/4$$
$$= V_{min} - O(100\text{GeV})^4 == (10^{-4}\text{eV})^4$$

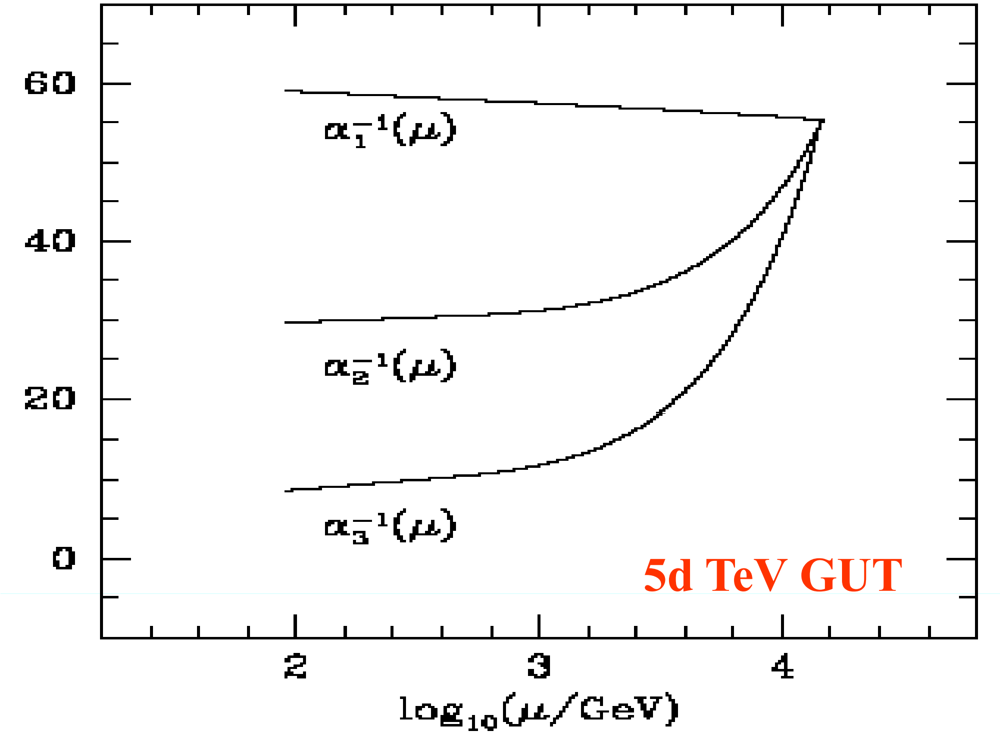
→ **60 Orders of Magnitude Fine-tuning !**

→ **So, Why do we care 1% Tuning at 1-Loop ?!**

Unification without SUSY? → YES.

→Many possible realizations !!!

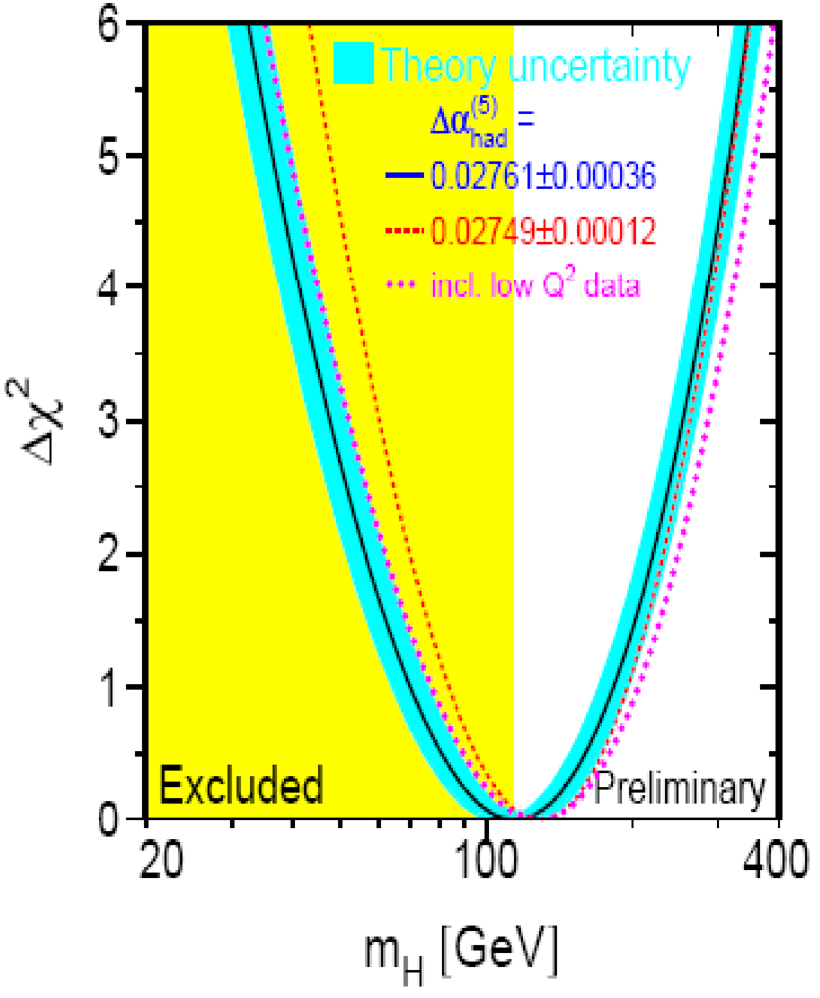




- Trinification with just 6 Higgs doublets (Willenbrock et al, 2003)
- 5d TeV GUT with just 3 real scalars of SU(2)-adjoint (Dienes etal, 1998)
- And more: Efficacious Unification with 2 scalar octocts, 1 triplet scalar, 1 triplet majorana fermiom, which also predicts dark matter, as good as Splitting SUSY (E. Ma, 05), ………

A Misconception:

Light Higgs from Data ?

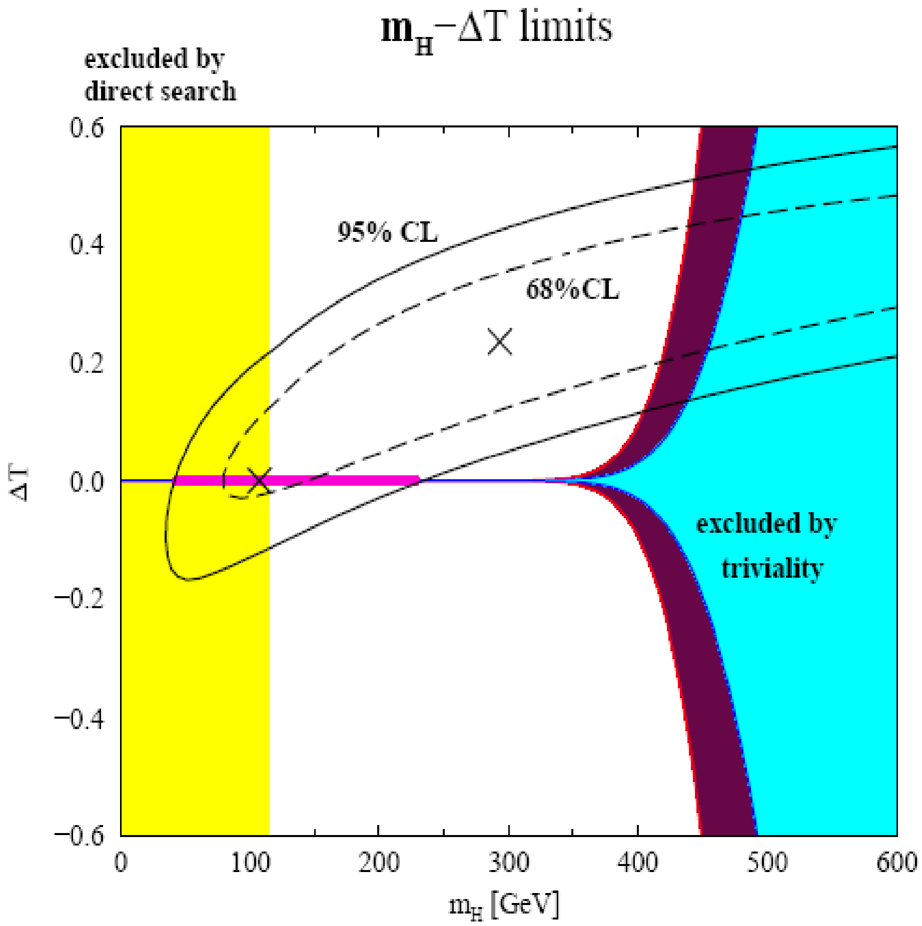


114.4 < M_H < 260GeV (95%CL)

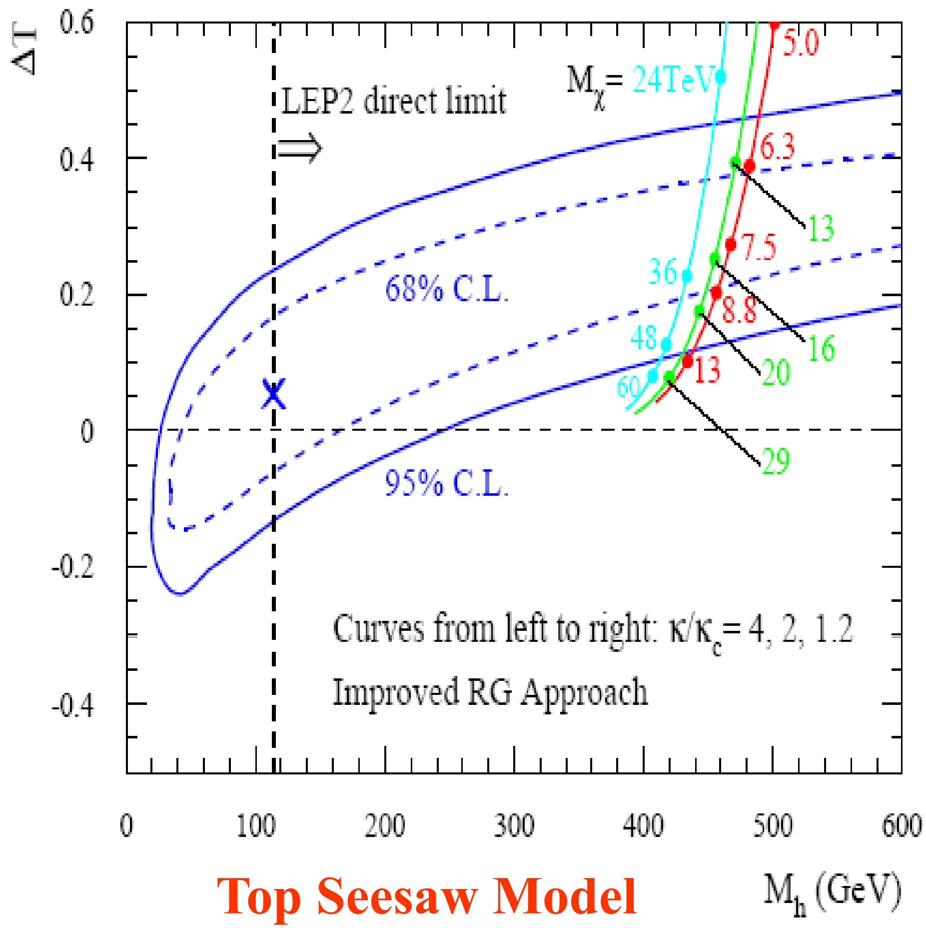
→Could be True
Only If No New Physics &
Higgs was Exactly SM-like!

Heavy Higgs vs Precision Data:
No Problem !

R. S. Chivvukula, Snowmass-2001



H. J. He, Snowmass-2001

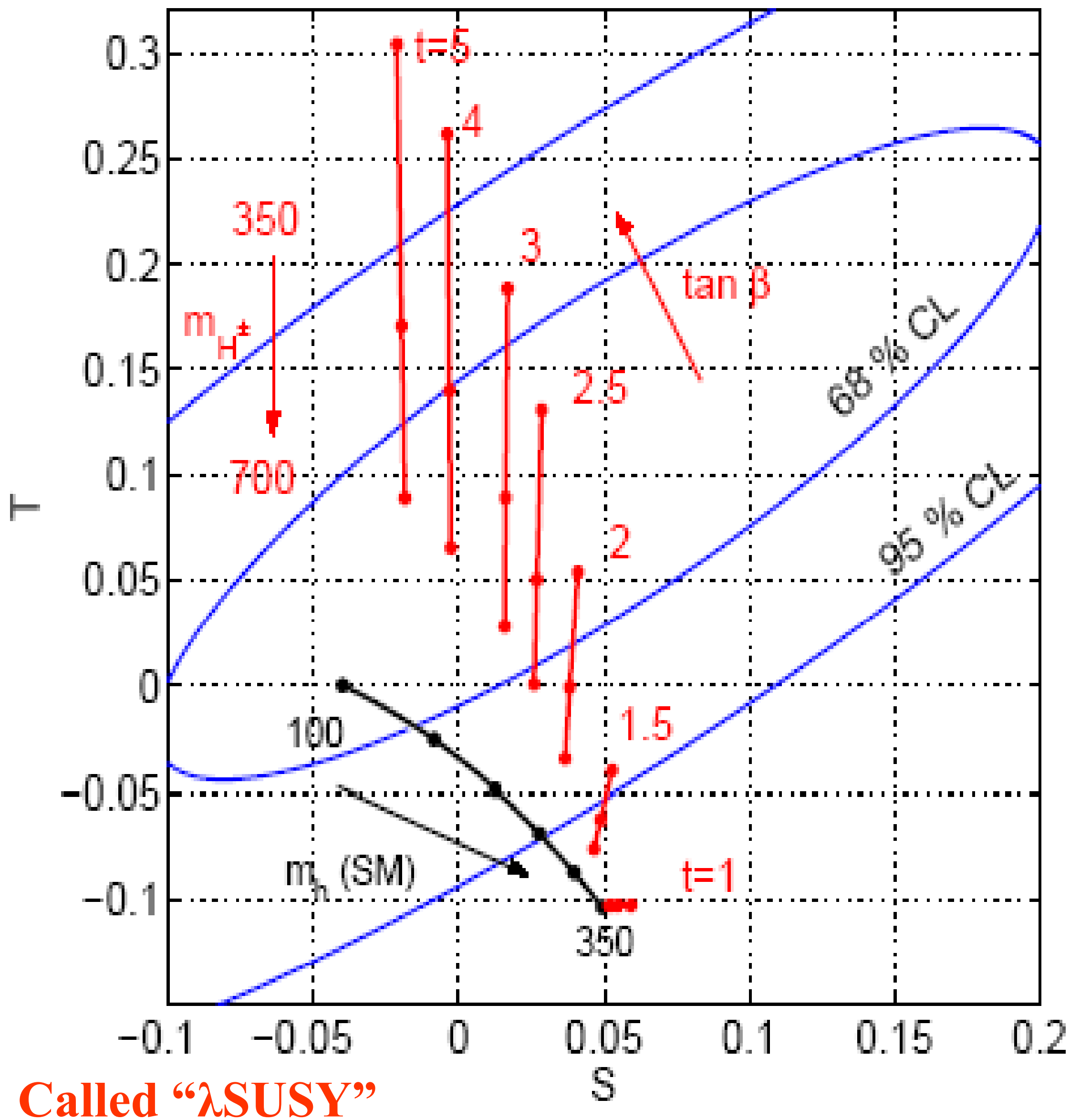


Top Seesaw Model

SUSY with Heavy Higgs: OK…

See Y. Nomura's talk, hep-ph/0607332

- $\lambda S H_1 H_2$ remains **perturbative** up to about **10TeV**
- **M_h is heavy, up to 300GeV**
- **Higgs/Higgsino: 200-700GeV**



Called "λSUSY"

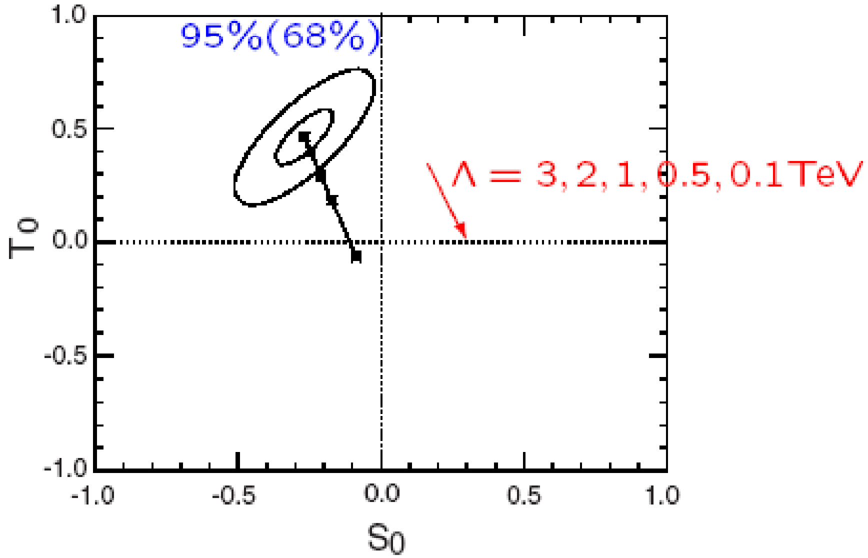
Higgsless SM Fits Precision Data too !

- In the SM, Higgs mass M_H is a Free Parameter.
- In Higgsless SM, M_H is removed, there are only 2 New Inputs needed for a perfect Precision Fit with New Physics (S, T). At scale $\mu = \Lambda$,

$$S_0 = -\left(\frac{4\pi v}{\Lambda}\right)^2 \frac{\ell_1}{\pi}\,, \qquad T_0 = \left(\frac{4\pi v}{\Lambda}\right)^2 \frac{\ell_0}{2\pi c_W^2}\,.$$

Renormalization connects (S_0, T_0) to (S, T) at Z-pole $(\mu = M_Z)$,

$$S = S_0 + \frac{1}{6\pi}\ln\frac{\Lambda}{M_Z}\,, \qquad T = T_0 - \frac{3}{8\pi c_W^2}\ln\frac{\Lambda}{M_Z}\,,$$



J. Bagger et al/PRL99

Lesson for LHC & ILC:

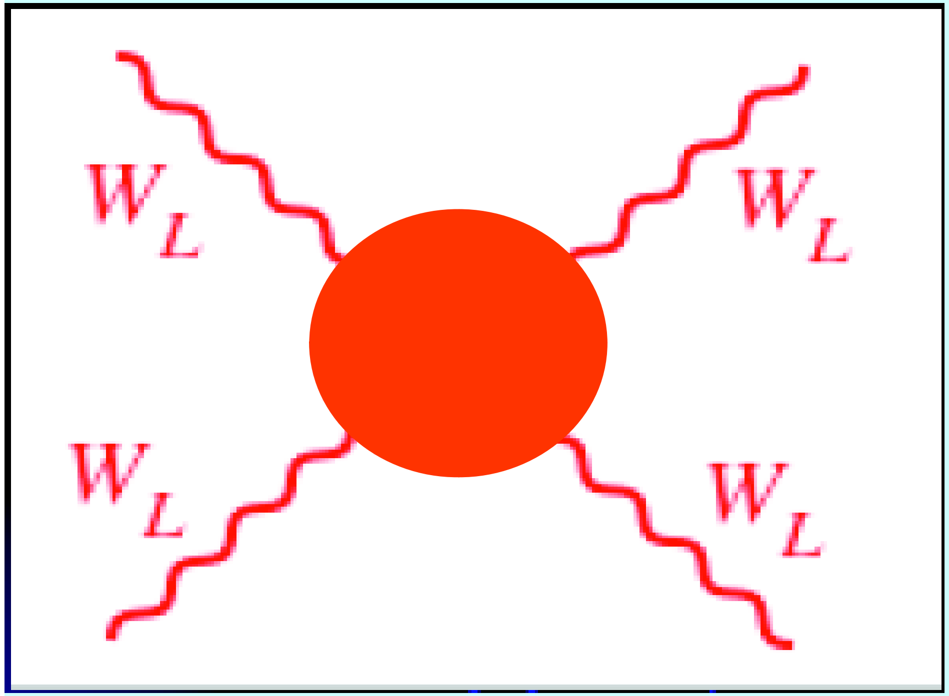
Keep Your Mind Fully Open !!!

The Real Problem with Particle Masses is

Unitarity Violation

in the **High Energy Scattering** !!!!!

Unitarity of $W_L W_L \to W_L W_L$:
Electroweak Symmetry Breaking Scale



$$\Lambda_U = \sqrt{8\pi} v \simeq 1.2\,\text{TeV}$$

TeV Scale for LHC & ILC !!!

→ **Stronger & More Robust than Fine-tuning bound !**

Scales of Fermion Mass Generation

▶ $f\bar{f} \to W_L W_L$ on Dirac Fermion Mass Generation: $\Rightarrow$ **Too high for All Light Fermions !**

(Appelquist & Chanowitz, Phys.Rev.Lett. 1987)

$$\Lambda_U \simeq \frac{8\pi v^2}{\sqrt{2N_c}\, m_f} \simeq (3.5,\ 2\times 10^5;\ 606,\ 2\times 10^6)\ \text{TeV} \quad \text{for } f = (t,\ u;\ \tau,\ e)$$

▶ $\nu_L \nu_L \to W_L W_L$ on Majorana Neutrino Mass Generation:

(Willenbrock et al, Phys.Rev.Lett.2001)

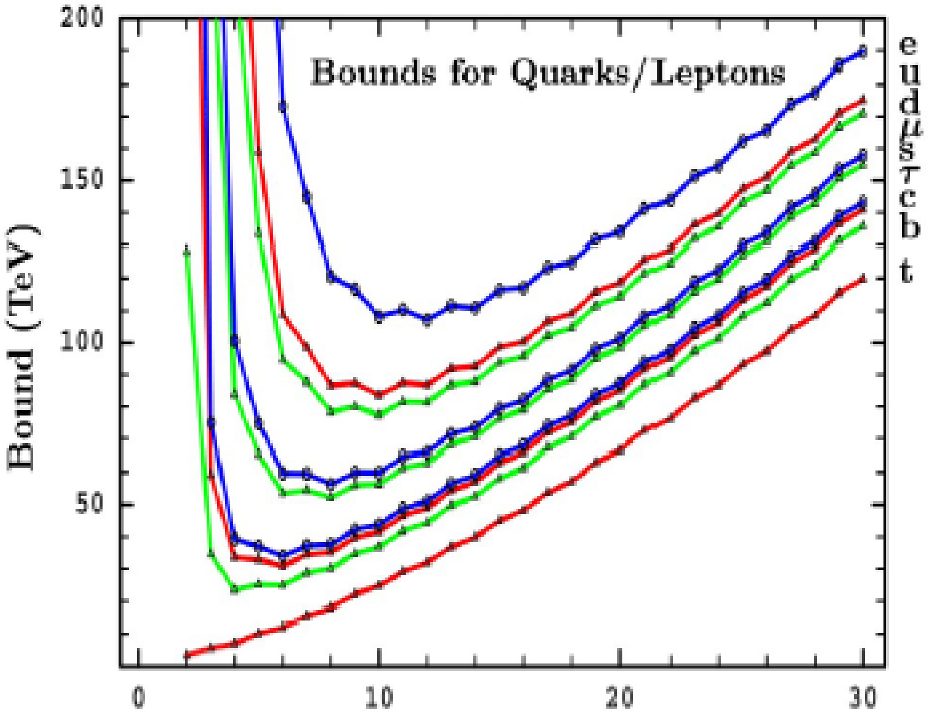
$$\Lambda_U \simeq \frac{2\pi v^2}{m_\nu} \simeq 10^{16}\ \text{GeV} \qquad (m_\nu \simeq 0.05\text{eV})$$

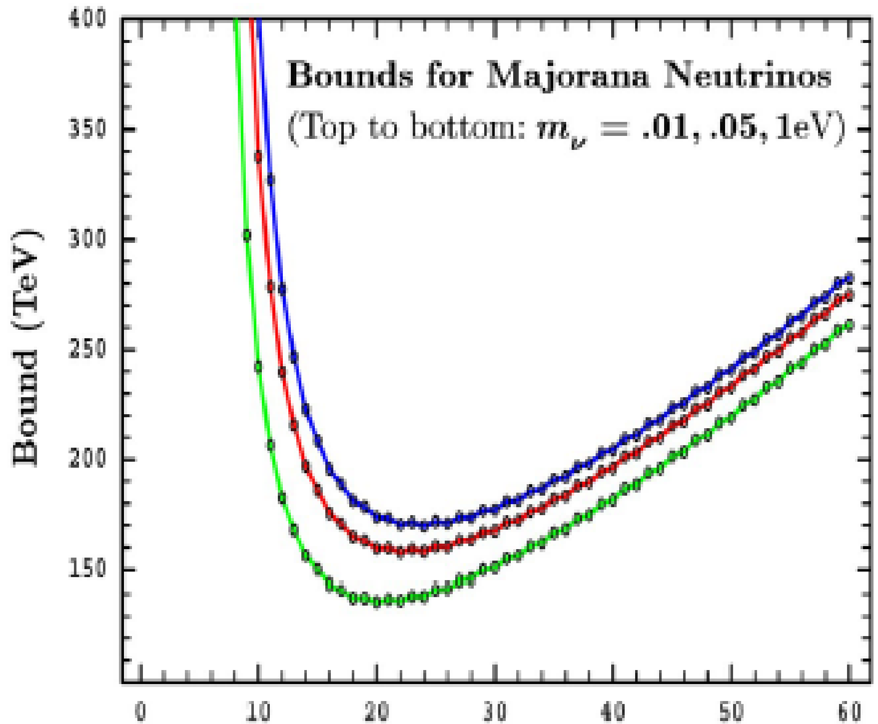
$\Rightarrow$ **Seesaw/GUT Scale – Too High !**

Scales of Mass Generation for Quarks, Leptons, and Majorana Neutrinos

Duane A. Dicus[1] and Hong-Jian He[1,2]
[1]*Center for Particle Physics and Department of Physics, University of Texas at Austin, Texas 78712, USA*
[2]*Center for High Energy Physics, Tsinghua University, Beijing 100084, China*
(Received 10 January 2005; published 8 June 2005)

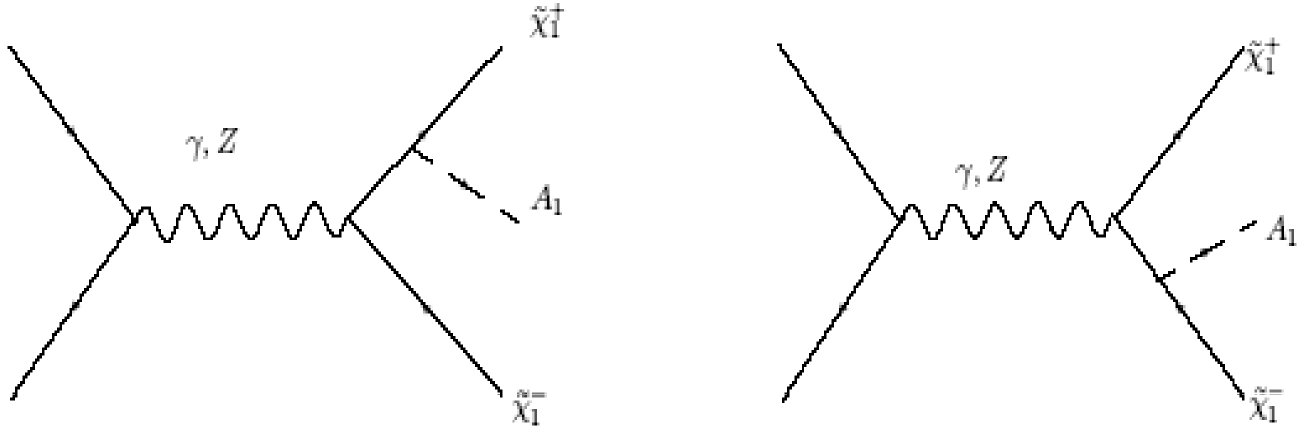
We study $2 \longrightarrow n$ inelastic fermion-(anti)fermion scattering into multiple longitudinal weak gauge bosons and derive *universal* upper bounds on the scales of fermion mass generation by imposing unitarity of the S matrix. We place new upper limits on the scales of fermion mass generation, independent of the electroweak symmetry breaking scale. Strikingly, we find that the strongest $2 \longrightarrow n$ limits fall in a narrow range, 3–170 TeV (with $n = 2$–24), depending on the observed fermion masses.





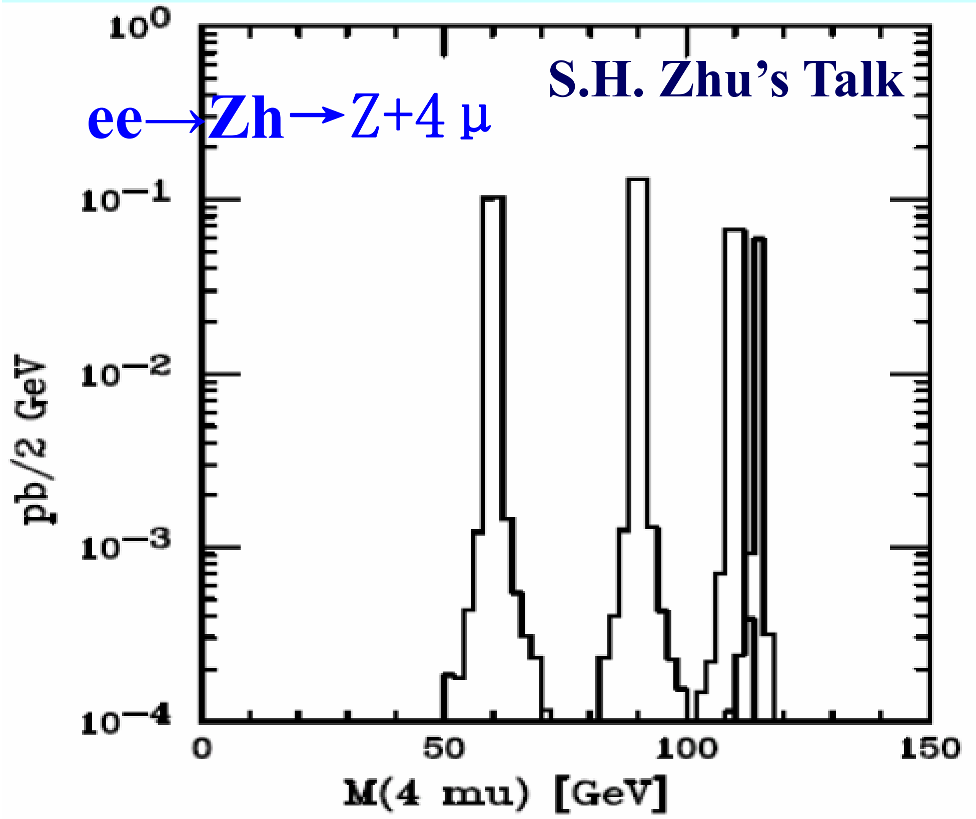
n → **Future: After LHC/ILC !** n

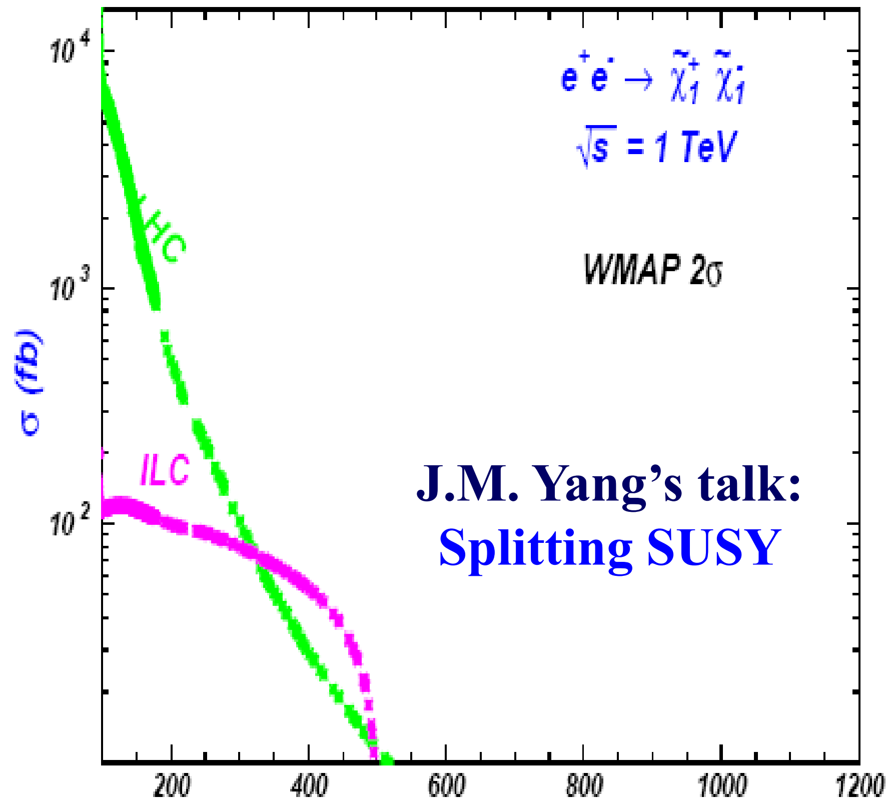
How to Observe ?



K. Cheung's talk:
NMSSM
Large tanβ & v_s

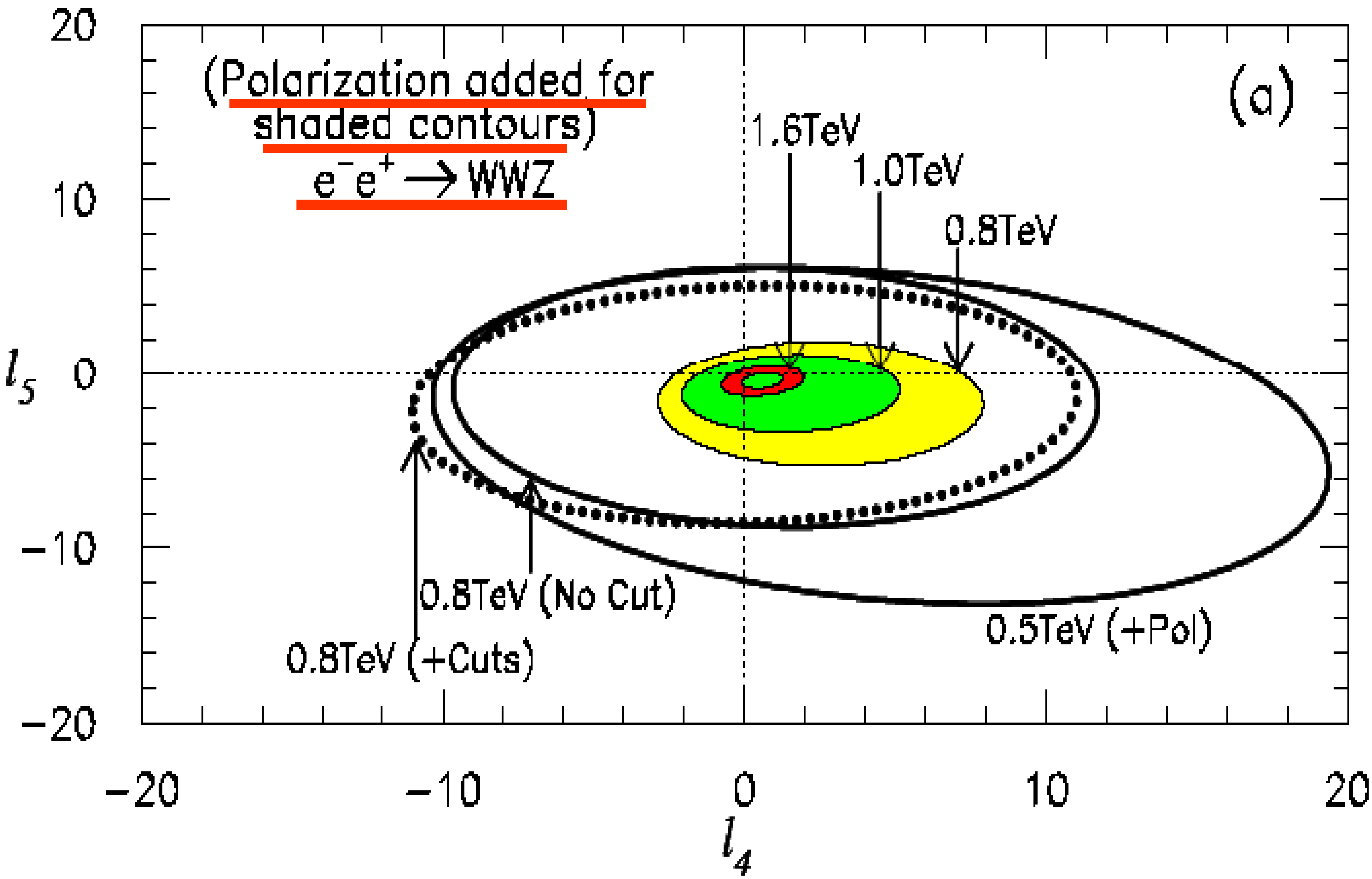
$$\theta_A < 10^{-3}$$





Probing Higgsless Parameters: E vs Polarization

Han, He, Yuan



Higgsless Model: New W' at ILC

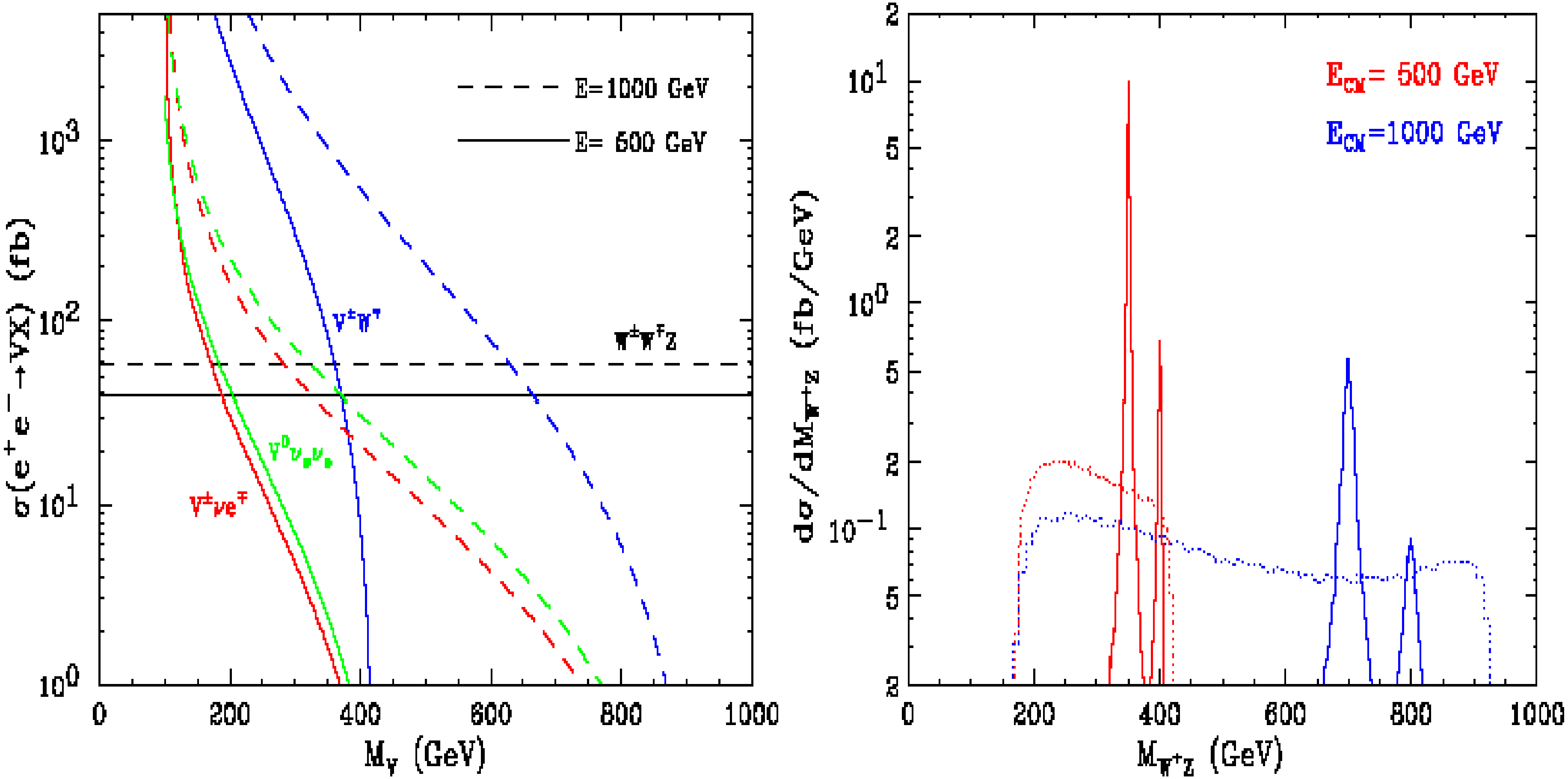


Figure 5: Left: V_1 production cross-sections and the continuum SM background at an e^+e^- lepton collider of center of mass energy 500 GeV (solid) or 1 TeV (dashed). Right: WZ invariant mass distribution for Higgsless signals (solid) and SM background (dotted), at E_{CM} = 500 GeV (red, $M^{\pm} = 350, 400$ GeV) and E_{CM} = 1 TeV (blue, $M^{\pm} = 700, 800$ GeV).

Conclusions

- **Why TeV Scale:** Unitarity of $W_L W_L \to W_L W_L$
  ILC must be upgradeable to 1TeV !

- **What New Physics:** Many Kinds – Keep your Mind Open !!!
  Light Higgs or Heavy Higgs or Higgsless;
  SUSY or Splitting SUSY or SUSY-Less;
  4-Dimension or Extra-d or Deconstruction…

- **How to Compute/Observe at ILC:** Signals vs Bkgnds
  New Channels, Beam polarizations,
  e-e- Mode, Photon-collider, ……

- **ILC plays Complementarity:**
  Precision Test, Loop Effects, ……

Thank You!

Back Up Slides

Higgsless SM vs Precision Data: No Problem !

- The **Most Minimal Model**: (Only S,T are relevant to current data !)

  (*Appelquist/Longhitano, 1980, see review: He, Kuang, Yuan, hep-ph/9704276*

$$\mathcal{L}_{\rm HSM} = \mathcal{L}_{\rm YM} + \mathcal{L}^{(2)} + \mathcal{L}^{(2)\prime} + \sum_{n=1}^{14} \mathcal{L}_n$$

$$\mathcal{L}^{(2)} = \frac{v^2}{4}{\rm Tr}\left[D_\mu U^\dagger D^\mu U\right] \quad \Longrightarrow \quad (M_W,\, M_Z) \neq 0$$

$$\mathcal{L}^{(2)\prime} = \ell_0 \left(\frac{v}{\Lambda}\right)^2 \frac{g'^2 v^2}{4}\left[{\rm Tr}\,(\mathcal{T}\mathcal{V}_\mu)\right]^2 \quad \Longrightarrow \quad \ell_0 = \left(\frac{\Lambda}{4\pi v}\right)^2 2\pi c_{\rm W}^2 T$$

$$\mathcal{L}_1 = \ell_1 \left(\frac{v}{\Lambda}\right)^2 \frac{gg'}{2} B_{\mu\nu}{\rm Tr}\left[\mathcal{T}W^{\mu\nu}\right] \quad \Longrightarrow \quad \ell_1 = -\left(\frac{\Lambda}{4\pi v}\right)^2 \pi S$$

$$\mathcal{L}_4 = \ell_4 \left(\frac{v}{\Lambda}\right)^2 \left[{\rm Tr}\,(\mathcal{V}_\mu \mathcal{V}_\nu)\right]^2$$

$$\mathcal{L}_5 = \ell_5 \left(\frac{v}{\Lambda}\right)^2 \left[{\rm Tr}\,(\mathcal{V}_\mu \mathcal{V}^\mu)\right]^2$$

$$\mathcal{L}_8 = \ell_8 \left(\frac{v}{\Lambda}\right)^2 \frac{g^2}{4}{\rm Tr}\left[\mathcal{T}W^{\mu\nu}\right]^2 \quad \Longrightarrow \quad \ell_8 = -\left(\frac{\Lambda}{4\pi v}\right)^2 \pi U$$

$$\mathcal{L}_n = \cdots\cdots$$

where $U = \exp\left[i\tau^a\pi^a/v\right]$, $\mathcal{V}_\mu \equiv (D_\mu U)U^\dagger$, $\mathcal{T} \equiv U\tau_3 U^\dagger$.

- **Approx custodial** $SU(2)_c$ **enforces:** $\ell_8 \ll \ell_{0,1} \quad \Longrightarrow \quad U \ll S, T$

Nonlinear Realization of SM Gauge Symmetry

- Without assuming Higgs H^0, SM gauge symmetry must be nonlinearly realized, and 3 "eaten" Goldstones $\{\pi^a\}$ are formulated by

$$U = \exp\left[i\pi^a\tau^a/v\right], \qquad (v \simeq 250\text{GeV})$$

- Gauge Boson bare mass terms $M_W^2 W^+W^- + \frac{1}{2}M_Z^2 Z^2$ can be written as dim-2 gauge-invariant operator:

$$\mathcal{L}_{\text{mass}}^{V} = \frac{v^2}{4}\text{Tr}\left|D_\mu U\right|^2,$$

- For Dirac Fermions (Quarks/Leptons) $F = (f,\, f')^T$, the bare mass terms $-m_f\overline{f}f - m_{f'}\overline{f'}f'$ can be written as gauge-invariant dim-3 operator:

$$\mathcal{L}_{\text{mass}}^{f} = -m_f\overline{F_L}U\begin{pmatrix}1\\0\end{pmatrix}f_R - m_{f'}\overline{F_L}U\begin{pmatrix}0\\1\end{pmatrix}f'_R + \text{H.c.}$$

- Light Neutrinos can form bare Majorana Mass term $-\frac{1}{2}m_\nu^{ij}\,\nu_{Li}^T\widehat{C}\nu_{Lj} + \text{H.c.}$ $\Rightarrow$ Gauge-invariant form, with $\Phi = U(0, v/\sqrt{2})^T$, $F_{Lj} = L_j$,

$$\mathcal{L}_{\text{mass}}^{\nu} = -\frac{m_\nu^{ij}}{v^2}L_i^{\alpha T}\widehat{C}L_j^{\beta}\Phi^{\alpha'}\Phi^{\beta'}\epsilon^{\alpha\alpha'}\epsilon^{\beta\beta'} + \text{H.c.}$$

Scales for Mass Generations: Summary

Dicus & He, PRD, PRL.2005

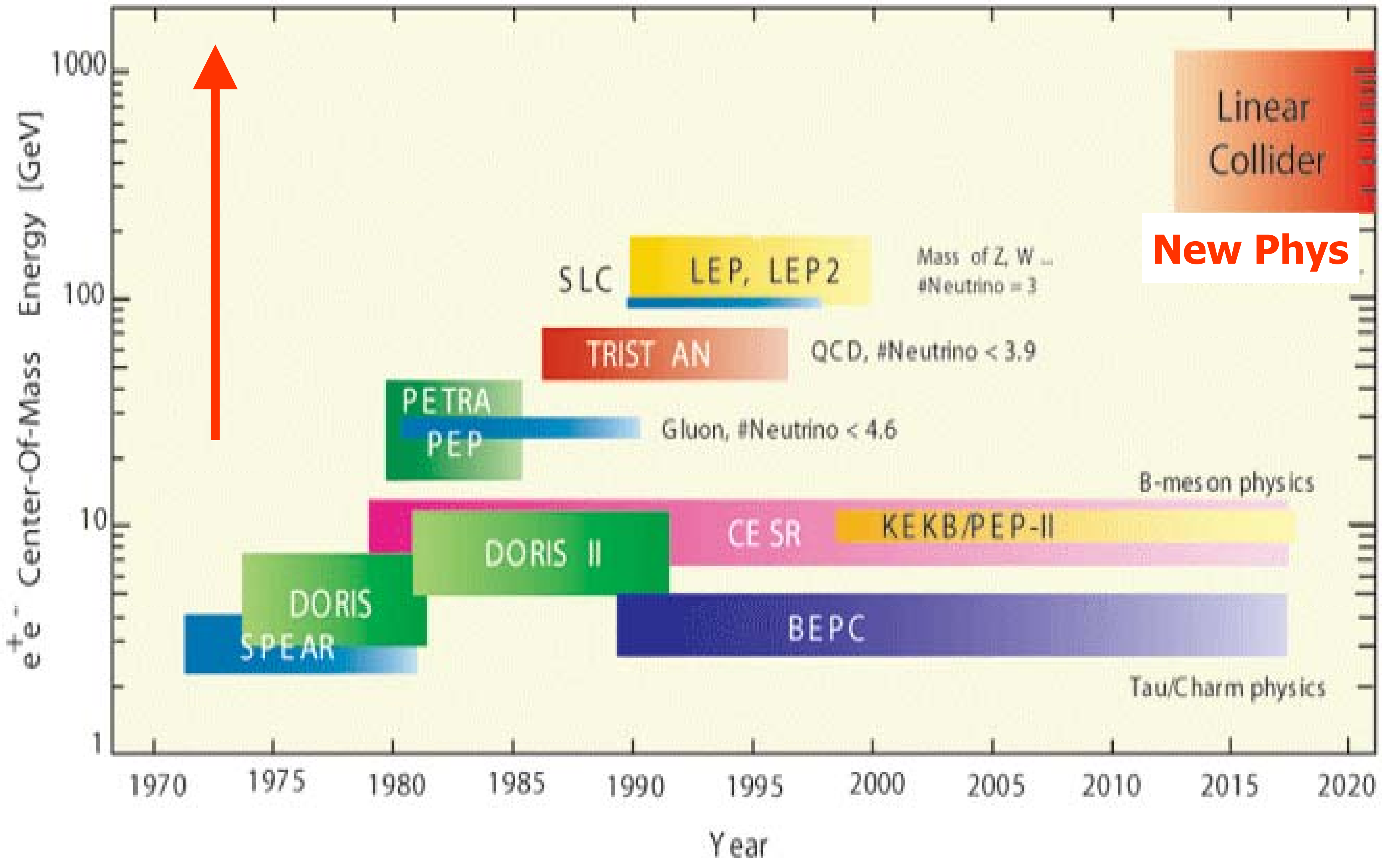
VLHC: http://vlhc.org (50-200TeV)

- Summary of Classic Unitarity Limits $\Lambda_{\rm U}^{\rm old}$ ($n=2$) vs New Unitarity Limits $\Lambda_{\rm U}^{\rm new}$ ($n=n_s$) for Scattering $\xi_1\xi_2 \to n\pi^a\,(nW_L^a)$. ($\xi_1\xi_2 = \pi^{a_1}\pi^{a_2}$, or, $f\bar{f}$, and n_s is # of final state π^a's (W_L^a's) corresponding to best limit $\Lambda_{\rm U}^{\rm new}$.)

$\xi_1\xi_2$	$\pi^{a_1}\pi^{a_2}$	$t\bar{t}$	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$d\bar{d}$	$u\bar{u}$	$\tau^-\tau^+$	$\mu^-\mu^+$	e^-e^+	$\nu\nu$
$\Lambda_{\rm U}^{\rm old}$ (TeV)	1.2	3.5	128	377	6×10^3	10^5	2×10^5	606	10^4	2×10^6	10^{13}
$\Lambda_{\rm U}^{\rm new}$ (TeV)	1.2	3.5	23	31	52	77	84	34	56	107	158
n_s	2	2	4	6	8	10	10	6	8	12	22

★ These limits are Universal & Independent of any detail of the Mechanism of Mass Generation.

The Energy Frontier

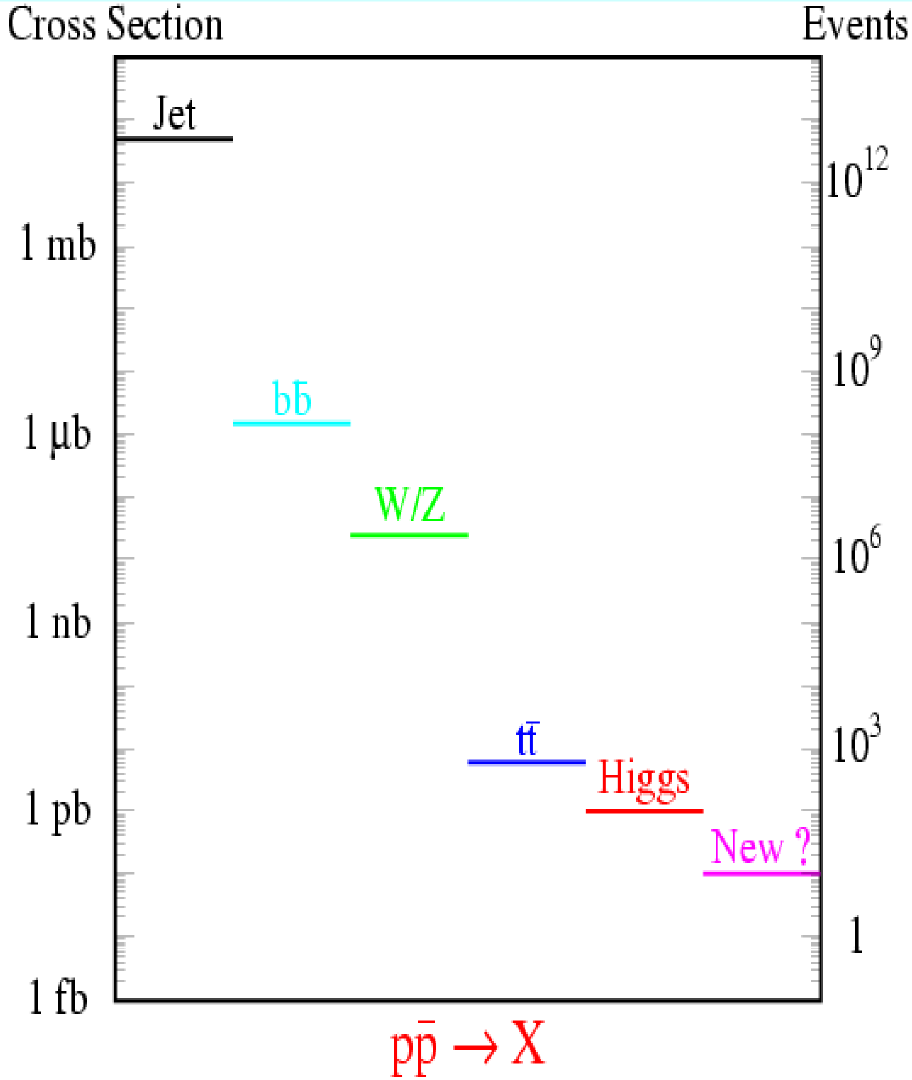


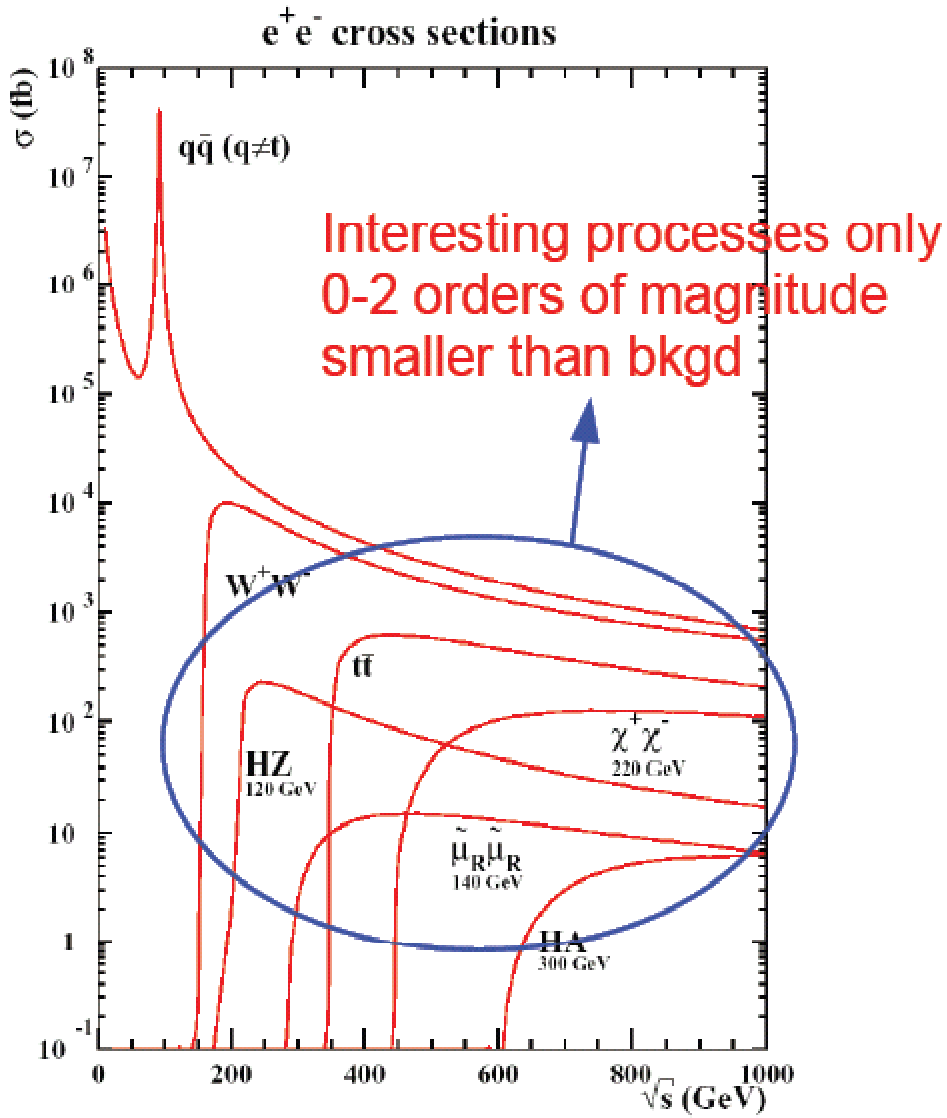
Parameters for the ILC

- E_{cm} adjustable from 200 – 500 GeV
- Luminosity → $\int L dt = 500\ fb^{-1}$ in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%
- The machine must be upgradeable to 1 TeV

LHC

ILC


Cross Section
Events
Jet
1 mb
1 μb
1 nb
1 pb
1 fb
bb̄
W/Z
tt̄
Higgs
New ?
10^12
10^9
10^6
10^3
1
pp̄ → X

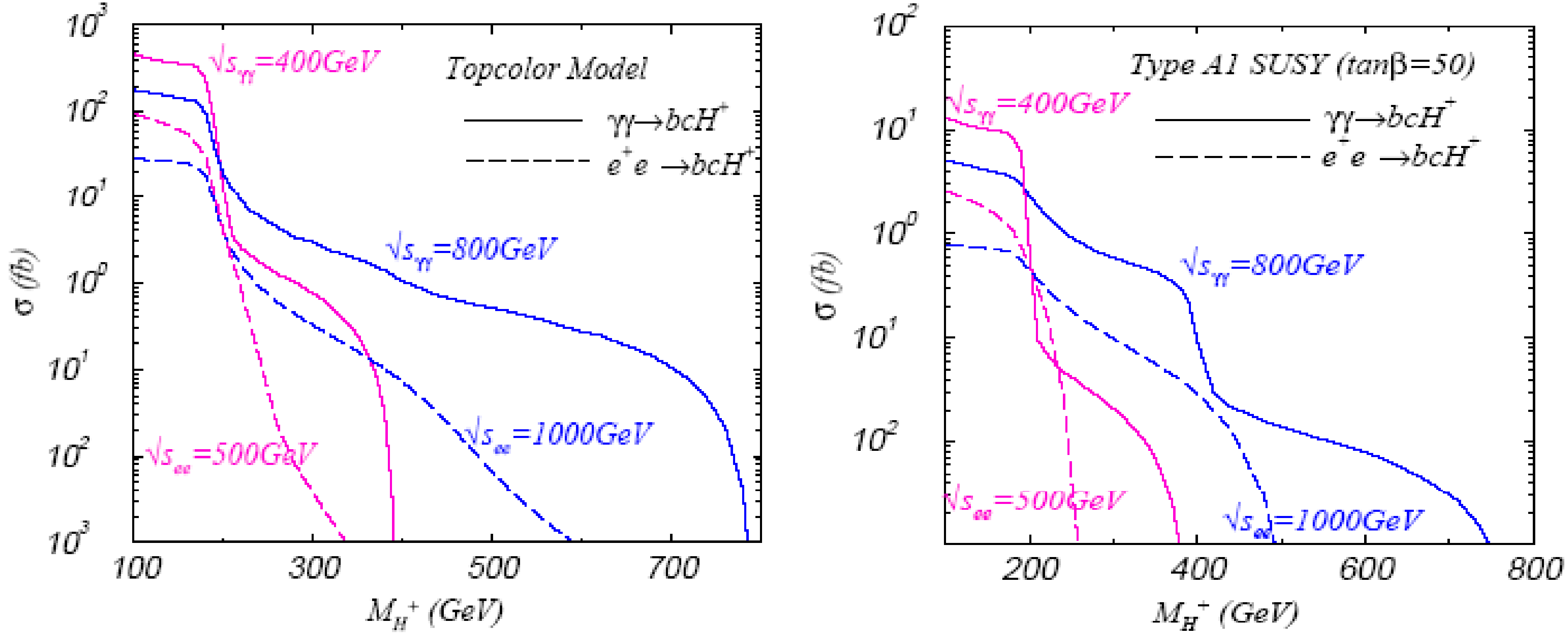

e+e- cross sections
σ (fb)
qq̄ (q≠t)
W+W-
tt̄
HZ
120 GeV
χ+χ-
220 GeV
μ̃Rμ̃R
140 GeV
HA
300 GeV
√s (GeV)
Interesting processes only
0-2 orders of magnitude
smaller than bkgd

Importance of Photon Collider & Polarization
(Charged Higgs Boson Production)

VOLUME 89, NUMBER 10 PHYSICAL REVIEW LETTERS 2 SEPTEMBER 2002

Determining the Chirality of Yukawa Couplings via Single Charged Higgs Boson Production in Polarized Photon Collisions

Hong-Jian He,[1] Shinya Kanemura,[2] and C.-P. Yuan[2]



Different SUSY Breakings and Particle Spectrum:
Need Precision Tests at ILC !