Electroweak Symmetry Breaking Summary Report (theory)

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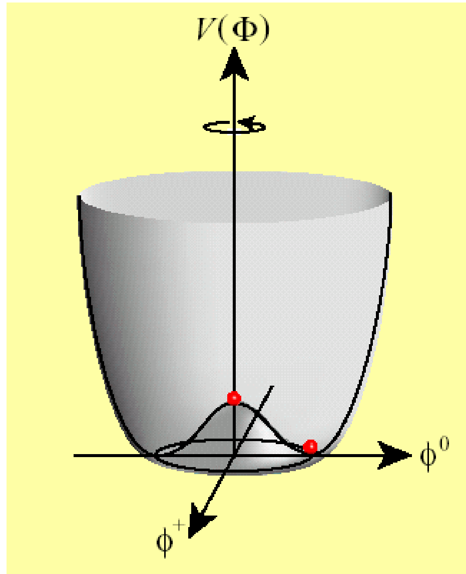
Electroweak symmetry breaking in SM

- Gauge structure: $SU(3)_C \times SU(2)_I \times U(1)_Y$
- EWSB : $SU(2)_I \times U(1)_Y \rightarrow U(1)_{EM}$



A Higgs doublet $\Phi = \begin{bmatrix} w^+ \\ \frac{1}{\sqrt{2}}(H + v + iz^0) \end{bmatrix}$

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4 \quad \langle\Phi\rangle = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}}v \end{bmatrix}$$

$$m_H^2 = \lambda\langle\Phi\rangle^2$$

Light Higgs → Weak coupling
Heavy Higgs → Strong coupling

All masses are given in proportion to a unique VEV

$$\frac{m_W}{g} = \frac{m_b}{f_b} = \frac{m_c}{f_c} = \frac{m_\tau}{f_\tau} = \frac{m_H}{\lambda^{1/2}} = v$$

Not measured

When H is found, the SM is tested by this universarity

In the extended Higgs models, this does not hold

Motivation to extend Higgs sector

- Hierarchy $m_H << m_P$
  - SUSY (MSSM, NMSSM)
  - Dynamical Symmetry Breaking (Technicolor, Little Higgs, ….)
  - Extra D (ADD, RS,….)
- Flavor (Yukawa interaction)
  - md,mu << mb << mt
  - tiny neutrino mass — Zee Model
- Cosmology
  - Baryogenesis — EWBG (Higgs potential)

Features of extended Higgs sectors

- Existence of extra particles
  - Direct search
  - Indirect search
    - If the lightest (SM-like) Higgs is found, its mass, width,cross section, branching ratios are measured precisely.
    - We can test models via (radiative correction + precise data)
- Property
  - Decoupling/non-decoupling?
  - Weakly/strongly coupling?
  - CP property

  We can determine direction of the new physics

Theory contributions

H. Haber

- Precise calculation in Benchmark theories
  - SM — S. Dittmaier
  - MSSM — S. Heinemeyer, H. Eberl
- Effect of extended models from Benchmarks
  - CP phase effect in MSSM, 2HDM — A. Akeroyd, K.Y. Lee
  - NMSSM — D.J. Miller, (J. Gunion)
- Implication to New Physics scenarios
  - Electroweak baryogenesis — Y. Okada
  - Extra dimensions — D. Dominici
  - LFV in Higgs decays — T. Ota
  - Little Higgs — (G. Gunion)

Precise calculations in the benchmark models

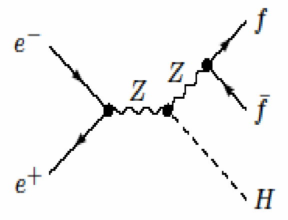
- SM radiarive correction to
  e+e-→ttH , nunuH Dittmaier

- MSSM Higgs decay into a chargino/neutralino pair Eberl

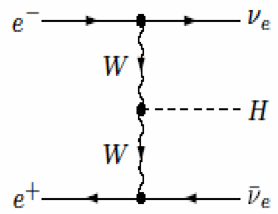
- Highly precise prediction in MSSM Heinemeyer

Dittmaier

ZH production ("Higgs-strahlung")



WW fusion



On the $\mathcal{O}(\alpha)$ correction to $e^+e^- \to \nu\bar{\nu}H$

Improved Born approximation (IBA) for $e^+e^- \to \nu\bar{\nu}H$

IBA includes ISR and heavy-top corrections.

Channel for analyzing the top-quark Yukawa coupling:

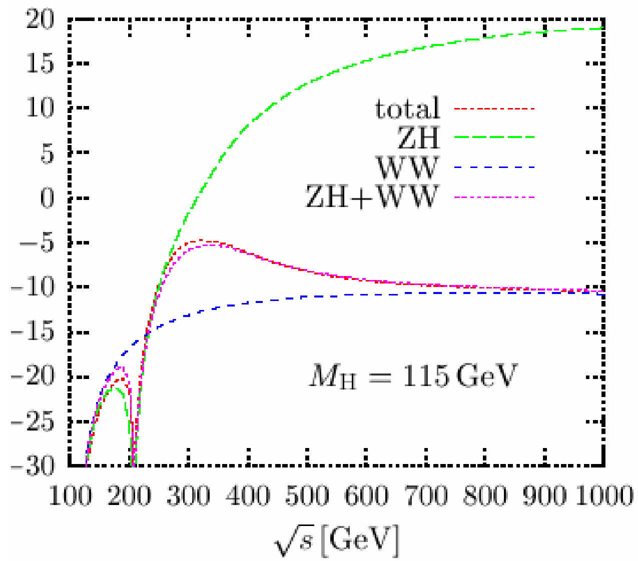
Associated Higgs production: $e^+e^- \to t\bar{t}H$

- ⋄ electroweak corrections typically of $\mathcal{O}(10\%)$
- ⋄ simple approximation for corrections seems unfeasible

⇒ Full calculations needed for LC physics

Relative corrections (G_μ-scheme):

$\frac{\sigma}{\sigma_{tree}} - 1\,[\%]$ Denner, S.D., Roth, Weber '03



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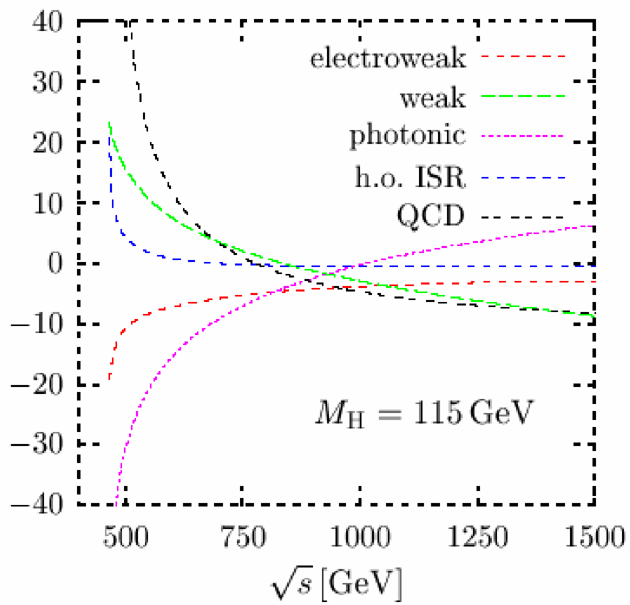


MSSM Higgs decay into a chargino/neutralino pair including full one-loop correction

Eberl

$$H^0 \to \tilde{\chi}_1^+ + \tilde{\chi}_1^- \qquad A^0 \to \tilde{\chi}_1^+ + \tilde{\chi}_1^- \qquad H^0 \to \tilde{\chi}_1^0 + \tilde{\chi}_2^0$$

Two schemes for δ e、 the difference is less than 1%.
Many comparisons with automatical calculation program, …. agree

full correction can go up to $\sim$ 20%.

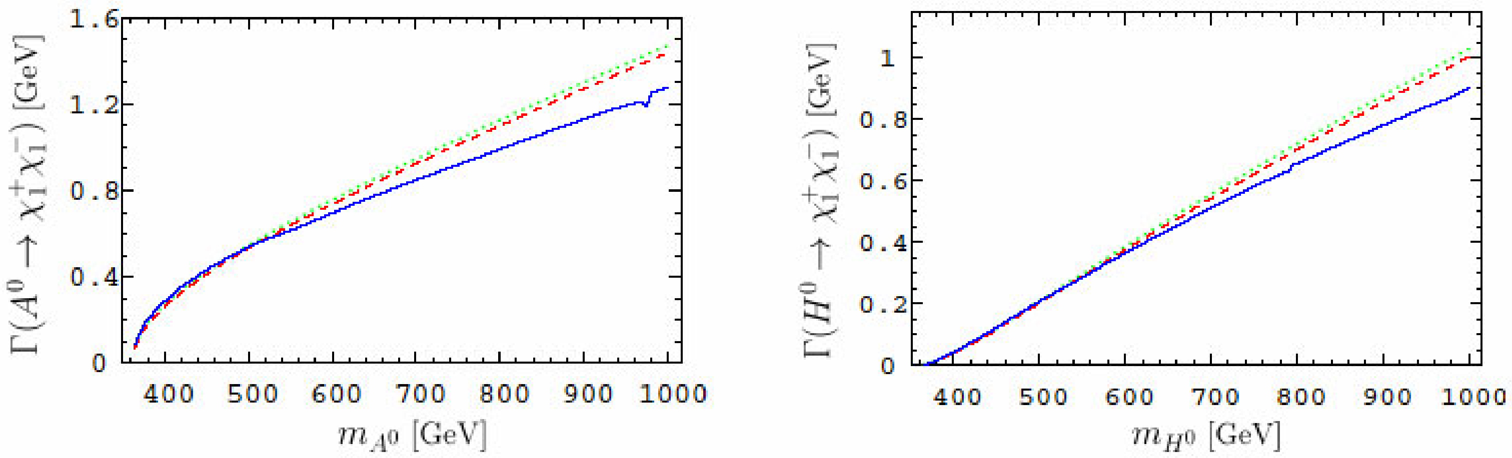


FIGURE : Naive tree-level (dotted), tree-level (dashed) and one-loop corrected (solid) widths in the $\alpha(m_Z)$ schemes for the renormalization of the SU(2) gauge coupling g.

High precision prediction of mh in MSSM

S.Heinemeyer

Intrisic uncertainties (unknown higher-order corrections)

full intrinsic error: (from unknown higher-order corrections)

today: $\Delta m_h^{\text{intr}} \approx 3$ GeV

needed for future: $\Delta m_h^{\text{intr}} \lesssim 0.5 - 0.1$ GeV ... possible:
needed: full two-loop (incl. renormalization), leading three-loop

3B: Parametric uncertainties:

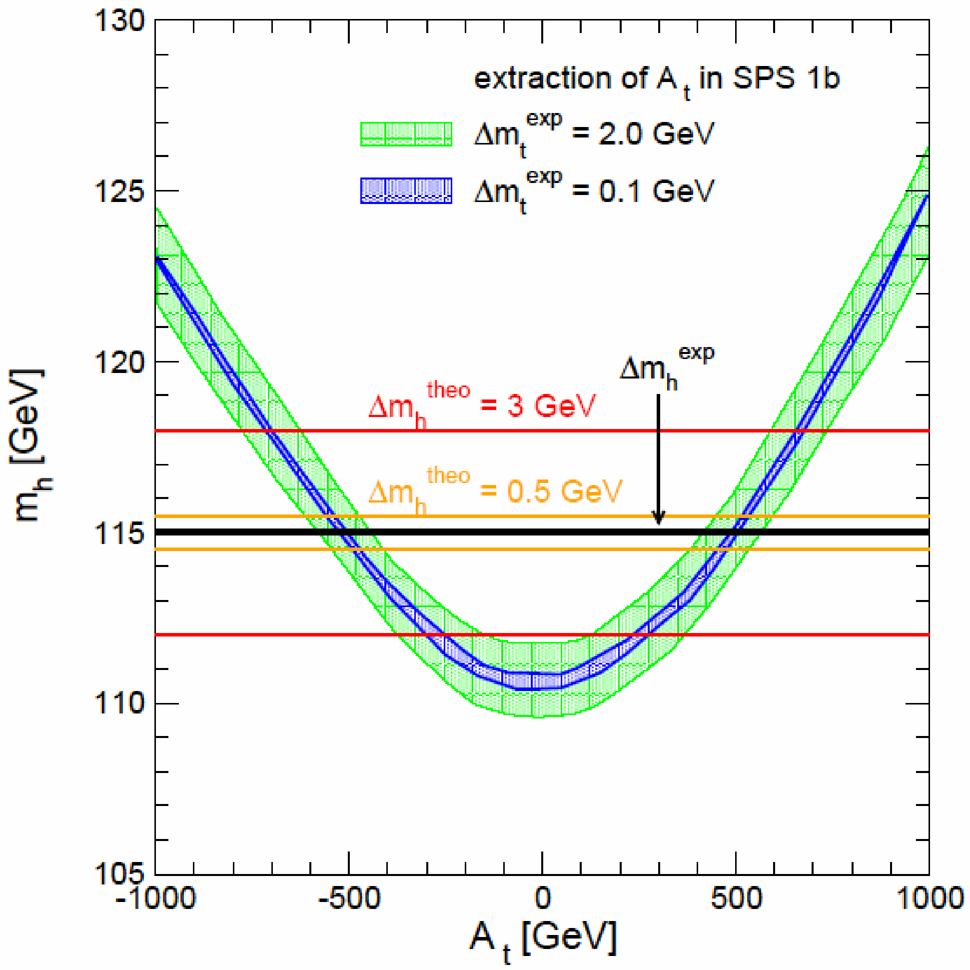
m_t:
today: $\delta m_t^{\text{Tevatron}} \approx 4$ GeV $\Rightarrow \Delta m_h^{m_t} \approx 4$ GeV
future: $\delta m_t^{\text{LC}} \approx 100$ MeV $\Rightarrow \Delta m_h^{m_t} \approx 100$ MeV

Experimental uncertainties:

$\Delta m_h^{\text{exp,LC}} \approx 50$ MeV $\Rightarrow$ very difficult to match

Heinemeyer

Example of effects: m_h prediction as a function of A_t



SPS1b:

$m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$ known,

A_t unknown

$\tan\beta, M_A$ known,

realistic parametric errors assumed

(incl. SUSY exp. errors)

$\Rightarrow$ extraction of A_t possible

$\Rightarrow$ Δm_h^{theo} has to be under control

At can be determined from mh measurement

New Physics contribution to Higgs Phenomenology

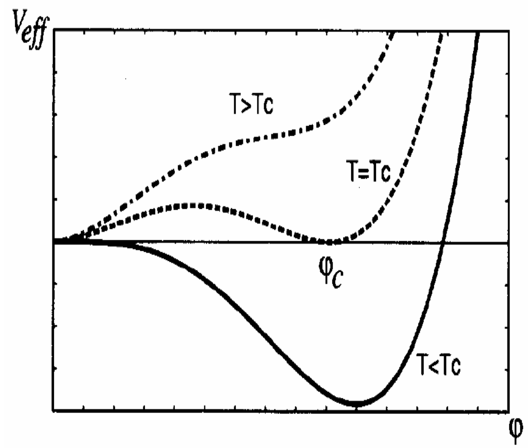
- ADD — Invisible H width — Dominici
- Little Higgs — additional W',t' ($\gamma\gamma \rightarrow H$) — Gunion
- LFV — SUSY + right handed neutrinos — Ota

New Physics from Higgs self-coupling

Y. Okada

By the non-decoupling loop effect of extra Higgs bosons, the renormalized hhh coupling (h: SM like Higgs boson) in the 2HDM can differ from the SM prediction by O(100%)

$$\lambda^{eff}_{hhh}(THDM) = \frac{3m_h^2}{v}\left\{1 + \frac{m_H^4}{12\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_H^2}\right)^3 + \frac{m_A^4}{12\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_A^2}\right)^3 + \frac{m_{H^\pm}^4}{6\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_{H^\pm}^2}\right)^3 - \frac{N_{c_t} m_t^4}{3\pi^2 m_h^2 v^2} + \mathcal{O}\left(\frac{p_i^2 m_\Phi^2}{m_h^2 v^2}, \frac{m_\Phi^2}{v^2}, \frac{p_i^2 m_t^2}{m_h^2 v^2}, \frac{m_t^2}{v^2}\right)\right\}$$



Such large deviation in hhh due to the non-decoupling effect corresponds to the scenario of electroweak baryogenesis

Baryogenesis : C, CP violation — 2HDM

Out of equilibrium — 1st order PT

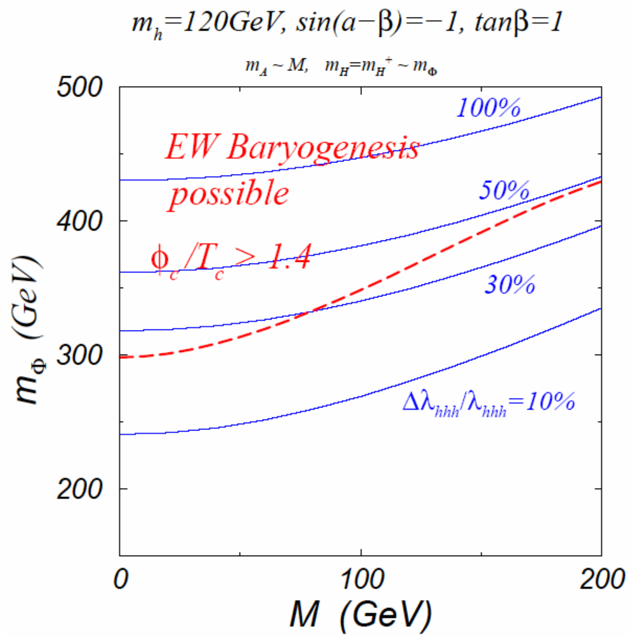
$$V_{eff}[\varphi, T] = D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \dots$$

Sphalelon condition $\frac{\varphi_C}{T_C} = \frac{2E}{\lambda_{T_C}} \gtrsim 1.4$

Cubic term can be easily large due to non-decoupling effect of extra Higgs boson loop

Connection between collider physics and cosmology

$$\boxed{V_{eff}(\phi) \leftrightarrow V_T(\phi, T)}$$



Dominici

ADD model: a model with large ED

In general, we can add

$$S = -\xi \int d^4x \sqrt{g_{ind}} R(g_{ind}) H^\dagger H$$

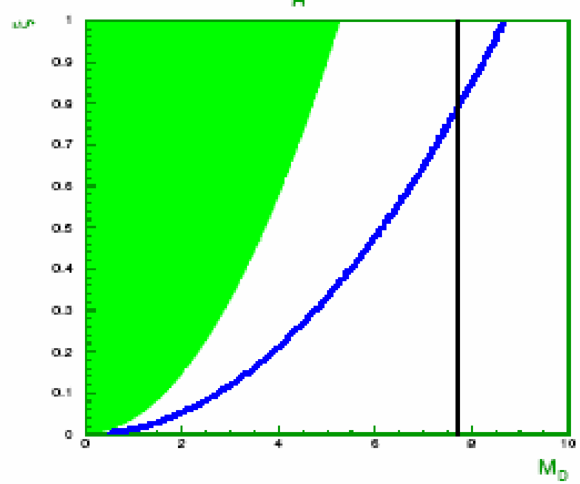
Graviscalar-Higgs kinetic mixing

$$\sigma(WW \to h' + \sum_{\vec{m}>0} s'_{\vec{m}} \to F)$$

$$\simeq \sigma_{SM}(WW \to h \to F) \left[\frac{\Gamma_h}{\Gamma_h + \Gamma_{h \to graviscalar}} \right]$$

- For a light Higgs boson the process $pp \to W^*W^* + X \to$ Higgs, graviscalars + X $\to$ invisible + X will be observable at the 5 σ level at the LHC for the portion of the Higgs-graviscalar mixing (ξ) and D-dimensional Planck mass (M_D) parameter space where channels relying on visible Higgs decays fail to achieve a 5 σ signal.
- Accuracy of $\Delta BR(H \to \text{invisible})/BR(H \to \text{invisible})$ at the e^+e^- LC allows to constrain M_D and ξ parameters for known number of extra dimensions δ.

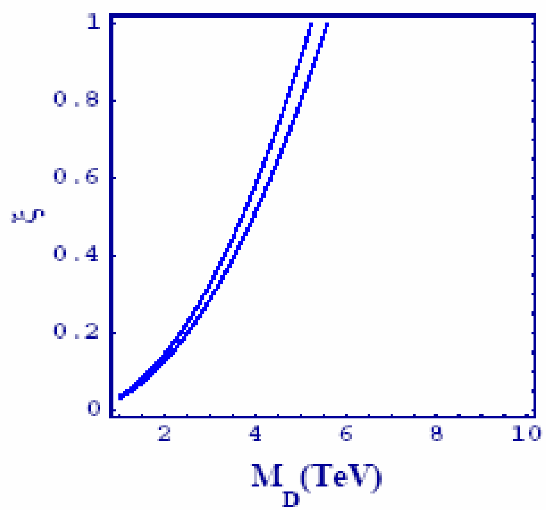
Sensitivity to ADD Γ_{inv} at LHC



jets/γ with missing

Sensitivity to M_D-ξ at LC-500

$\delta = 2$



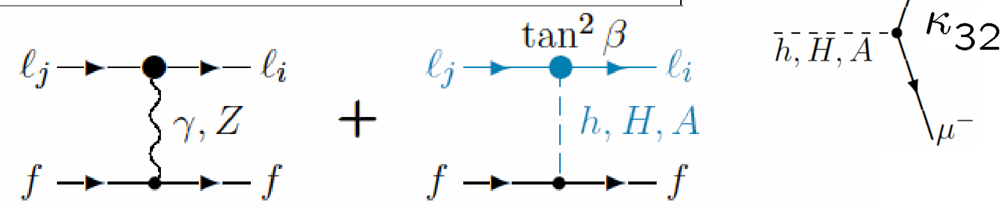
Limits from $e^+e^- \to \gamma + \text{missing energy}$ (Mirabelli, Perelstein, Peskin): $M_D \geq 6.5$ **TeV** ($\delta = 2$)

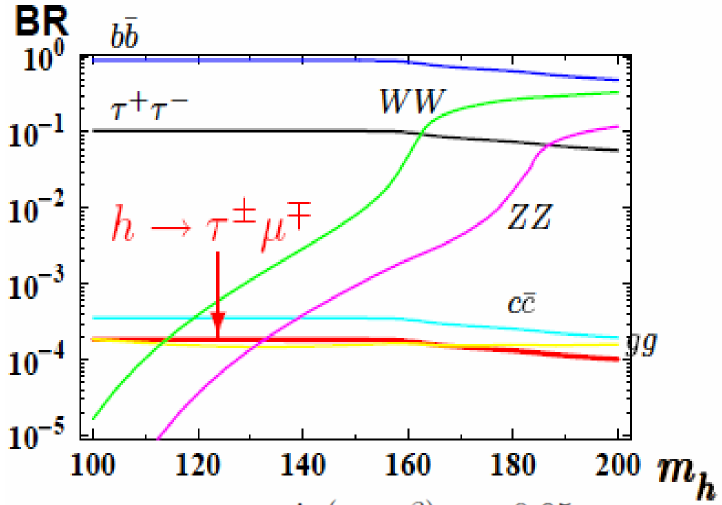
Search for LFV via the Higgs decay

T. Ota

In MSSM with large $\tan\beta$, the Higgs bosons affect *the LFV processes*, such as,

$\tau \to 3\mu$: K.Babu C.Kolda, PRL**89** 241802,
A.Dedes J.Ellis M.Raidal, PLB**549** 159,
$\tau \to \mu\eta$: Sher, PRD**66** 057301,
μ-e conv: R.Kitano M.Koike S.Komine Y.Okada PLB**575** 300.



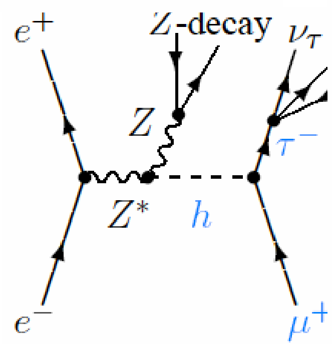


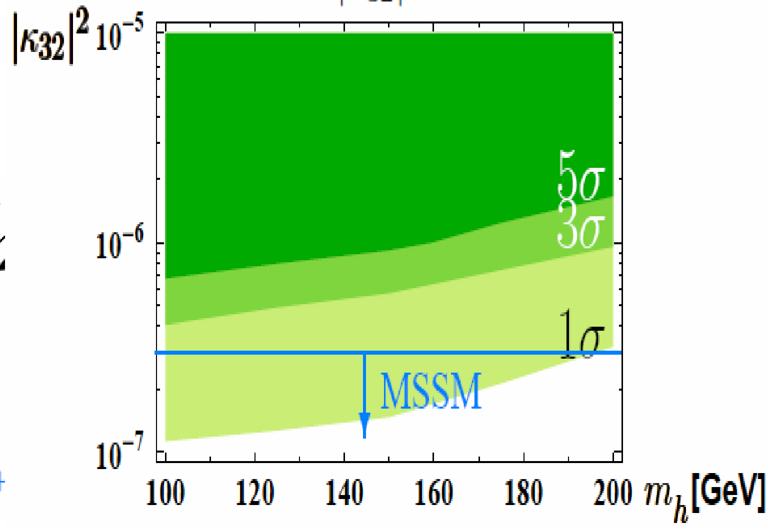
$\sin(\alpha-\beta) = -0.95,$
$\tan\beta = 60,$
$|\kappa_{32}|^2 = 0.3 \times 10^{-6}.$

The bound on $|\kappa_{32}|^2$ from $\tau \to \mu\eta$ (Belle)

$$|\kappa_{32}|^2 < 0.3 \times 10^{-6} \times \left(\frac{m_A}{150[\mathrm{GeV}]}\right)^4 \times \left(\frac{60}{\tan\beta}\right)^6$$

$$\mathrm{Br}(h \to \tau^+ + \mu^-) \simeq \frac{1}{N_c}\frac{m_\tau^2}{m_b^2}\frac{\cos^2(\beta-\alpha)}{\sin^2\alpha\cos^2\beta}|\kappa_{32}|^2$$





LFV Higgs coupling may be measured at LC

Mh=120GeV, L=1ab^-1

The Higgs and neutralino sectors of the NMSSM

D.J. Miller

Next-to-MSSM

solves μ-problem

$$\lambda S H_u H_d \longrightarrow \lambda \langle S \rangle H_u H_d$$

Spectrum like MSSM + 2 extra states

3 scalars:	H_1,	H_2,	H_3
2 pseudoscalars:	A_1,	A_2	
Charged:	$H^\pm$		

$$M_{H_3} \approx M_{H^\pm} \approx M_{A_2}$$

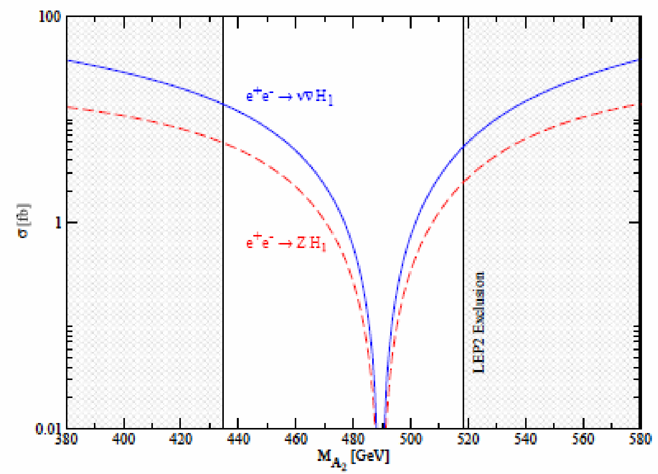
$$M_{H_2}^2 \approx M_Z^2 \cos^2 2\beta$$

$$M_{H_1}^2 \approx \kappa\langle S\rangle[4\kappa\langle S\rangle + A_\kappa] \qquad M_{A_1}^2 \approx -3\kappa\langle S\rangle$$

New bosons have mass depending on $\kappa\langle S\rangle$

Special scenario:
H1, A1 (singlet-like) lightest <100GeV
LEP OK suppressed VVH1 coupling
LHC cannot detect

Lightest Higgs production at a $\sqrt{s} = 500$ GeV e^+e^- Linear Collider



Visible for most of the allowed range

The Neutralino Sector

2 gauginos + 2 higgsinos + "singlino" → 5 neutralinos

In this scenario LSP is singlino!

– end product of all SuSy decay chains.

Singlino LSP!

Distinguishing non-minimal Higgs sectors of precise measurement of a light Higgs bosons

A. Akeroyd

Neutral Higgs boson production and CP violation at LC

K.Y. Lee

2 Higgs doublet models

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 + i a_1 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 + i a_2 \end{pmatrix}$$

CP violation in the Higgs sector

$\Rightarrow$ Scalar-Pseudoscalar mixing

$$M_N^2 = \begin{pmatrix} M_P^2 & M_{SP}^2 \\ M_{PS}^2 & M_S^2 \end{pmatrix} \qquad M_{PS}^2 = v^2 \begin{pmatrix} Im(\lambda_5)\sin\beta + Im(\lambda_6)\cos\beta \\ Im(\lambda_5)\cos\beta + Im(\lambda_7)\sin\beta \end{pmatrix}$$

MSSM	large phase	Akeroyd
THDM	small phase	Lee

Akeroyd

Effective potential technique employed:

$$\lambda_5, \lambda_6, \lambda_7 = f(\mu, A_t, A_b, M_{SUSY} \ldots)$$

Magnitude of scalar-pseudoscalar mixing

Pilaftsis 98, Pilaftsis,Wagner 99, Choi,Lee,Drees 00

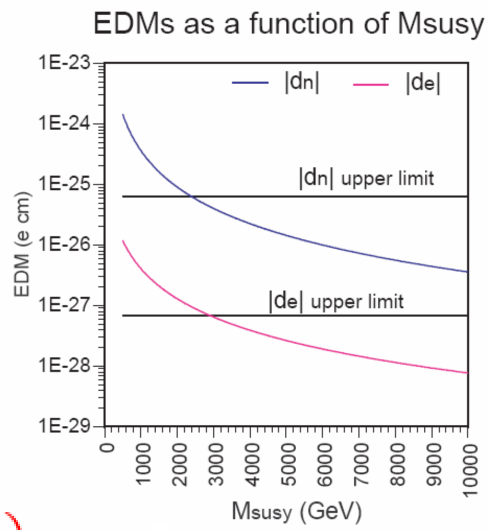
$$M_{PS}^2 = \left(\frac{m_t^4}{v^2}\frac{|\mu||A_t|}{32\pi^2 M_{SUSY}^2}\right)\sin\phi_{CP} \times f(M_{SUSY}, A_t, \mu, \tan\beta)$$

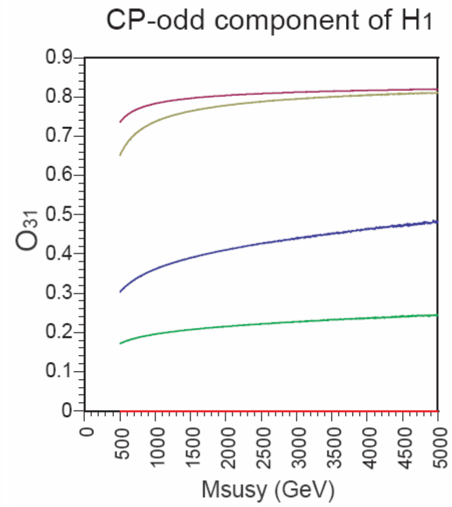
Optimal M_{PS}^2 requires: $\phi_{CP} = arg(A_t\mu)$

- Large $|\mu|/M_{SUSY}$,
- Large $|A_t|/M_{SUSY}$
- moderate to large $\sin\phi_{CP}$

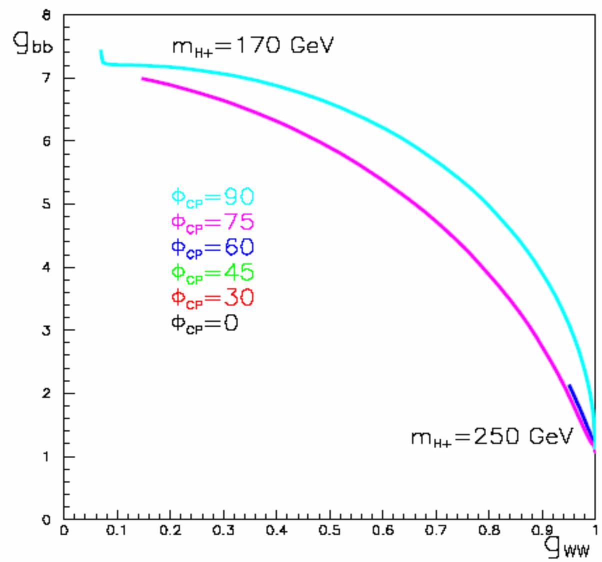
Aim to see if pseudoscalar-scalar mixing can be size-able even if SUSY partices out of range at LHC/Linear Collider

Large $\sin\phi_{CP}$ for $M_{SUSY} = 2000$ GeV





$\sigma(e^+e^- \to H_1 Z)$ can be very suppressed for large ϕ_{CP}



g_{bb} for large $\sin\phi_{CP}$ can be much larger than for $\sin\phi_{CP} = 0$ case

Summary

- To explore Nature of EWSB and its implication to new Physics is the top priority in particle physics.
  - LHC likely will find at least 1 Higgs boson
  - LC, PLC precision measurement → details of model can be studied
- Highly precise calculation in SM, MSSM needed.
  - More loop to utilize the precise data at LC
  - Mass, width, coupling, production rates, ……
- Many new physics scenarios beyond SM, MSSM
  NMSSM,
  THDM(with decoupling or non-decoupling property),
  CP pahses, dynamical EWSB, extraD, little Higgs
  - How distinguish them?
  - Find generic phenomenological features of each scenario
  - Combined analyses of LHC, LC, γ C for each scenarios
- EWSB and Cosmology

S. Dittmaier

S. Heinemeyer, H. Eberl

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D. Dominici

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A lot of subject to do for us.