CP Violation in the Higgs Sector of the BMSSM at Tevatron

Tevatron B physics workshop

KISTI, 2009. 8. 24, 16:10-17:30

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based on work with Seong-A Shim, S. K. Oh

1. **Introduction**
2. **Baryogenesis**
3. **CP violation in the Higgs physics Beyond MSSM**
4. **The Higgs Production of the BMSSM at Tevatron**
5. **Conclusions**

1. Introduction

⊙ **Electromagnetic Interaction: Dirca, Pauli, Heisenberg, Schwinger, Feynman**

⊙ **Weak Interaction: Fermi, Feynman, Gell-Mann**

⊙ **Quantum Chromodynamics: Gross, Politzer, Wilczek**

⊙ **ElectroWeak Theory: Glashow, Weinberg, Salam**

⊙ **Renormalizability of the Standard Model (SM): 't Hooft, Veltman**

⊙ **ElectroWeak Symmetry Breakdown: Higgs (@LHC:?)**

SM Gauge group : $SU(3) \times SU(2) \times U(1)$

Gauge Particles : Photon, Weak Gauge Bosons (W, Z), Gluon

Matter Particles (Fermions): Quark and Lepton

○ **Gauge Theory (Gauge Boson Mass) ⇔ Particle Mass in the SM (?)**

SM Higgs Particle (H): $m_H > 114.5$ GeV (LEP2 Experiments)

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 \ , \quad m_H = \sqrt{2\lambda}v \ , \quad v = 246 \text{ GeV}$$

Higgs Production (e^+e^-, $P\bar{P}$, PP) & Decay ($H \to ff, VV, H^* \to HH$)

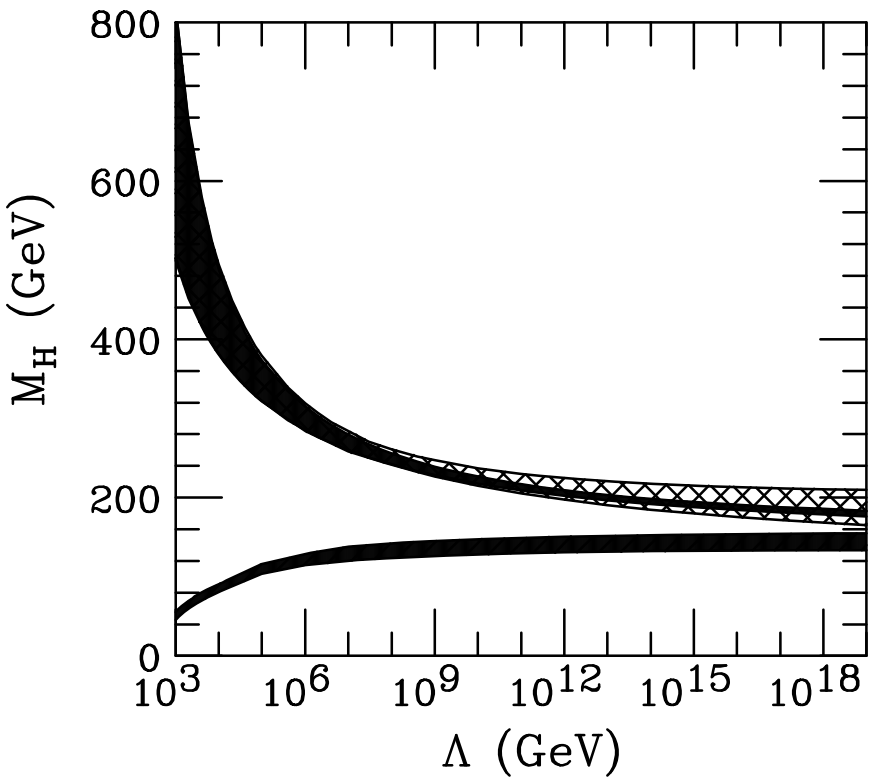
$\lambda > 0$

left: $\mu^2 > 0$

right: $\mu^2 < 0$

◯ **Theoretical Bounds on the SM Higgs boson mass**

⊙ **Hambye and Riesselman, PRD55, 7255 (1997) ⇓**



Triviality Bound

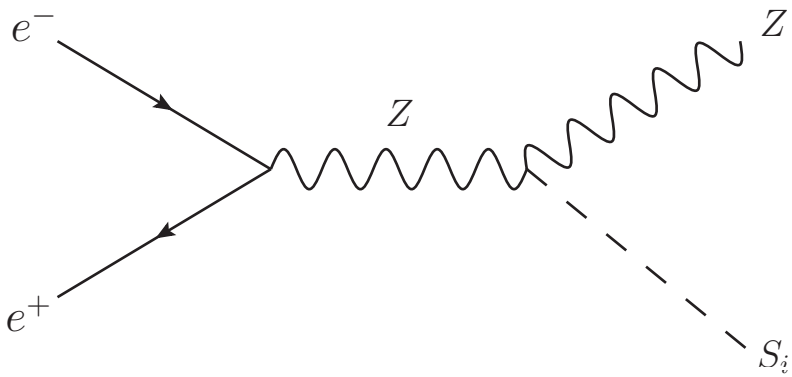
$$\lambda(\Lambda) = \lambda(v) / \left[1 - \frac{3\lambda(v)}{4\pi^2} \log\left(\frac{\Lambda^2}{v^2}\right) \right]$$

Landau Pole: Infinity

Stability Bound

$$\lambda(\Lambda) = \lambda(v) + \frac{1}{16\pi^2}\left[-12h_t^4 + \frac{3}{16}(2g_2^4 + (g_1^2+g_2^2)^2) \right] \log\left(\frac{\Lambda^2}{v^2}\right)$$

Negative λ



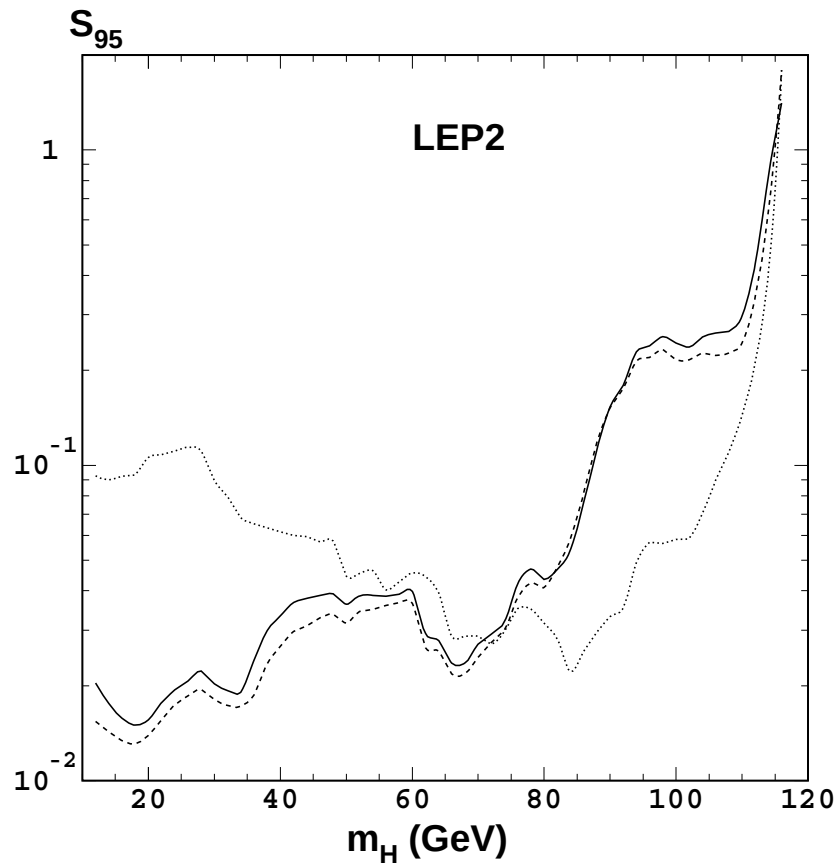
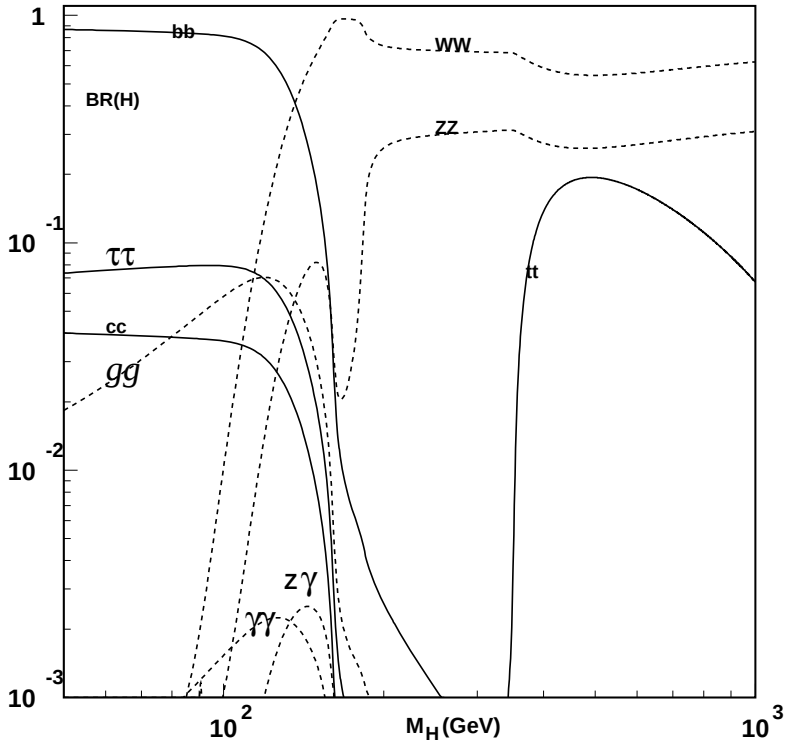
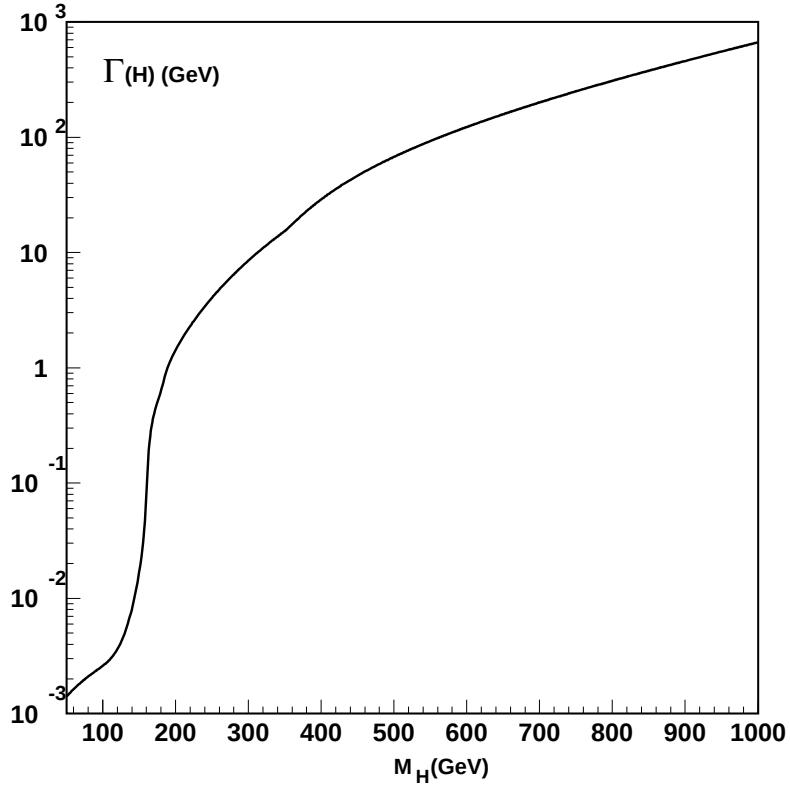
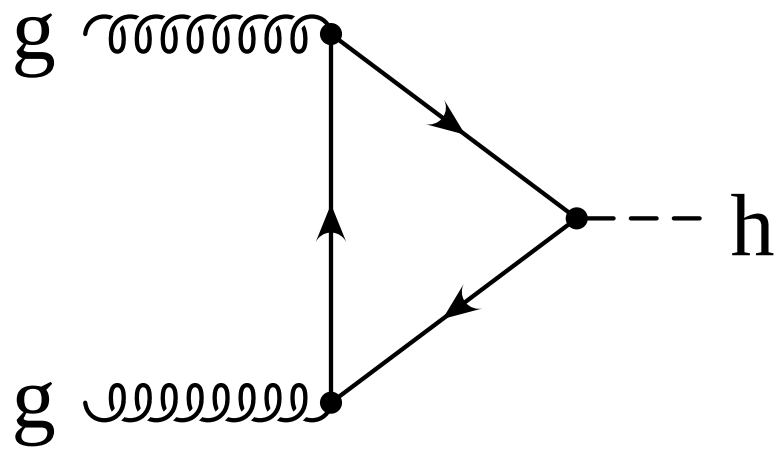


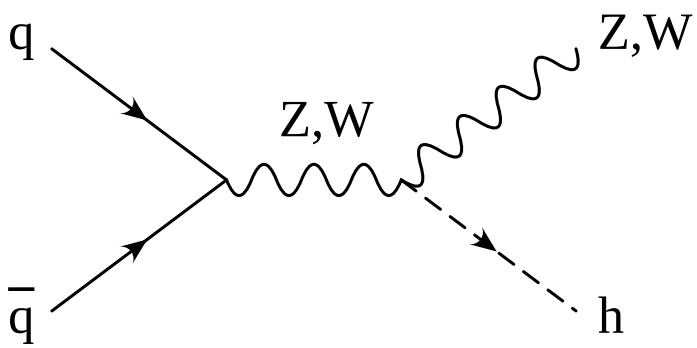
Figure : LEP2: Higgs-strahlung process, LEP constraint: $m_H > 114.5$ GeV

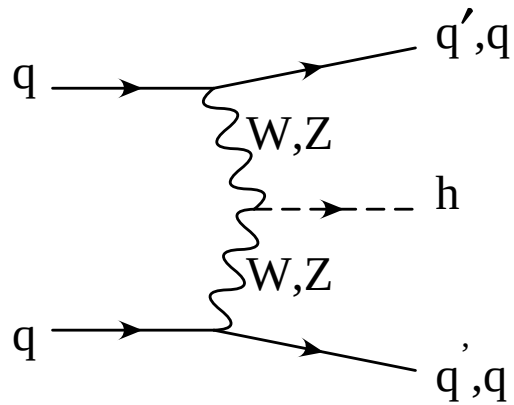

1
10 -1
10 -2
10 -3
bb
WW
BR(H)
ZZ
ττ
tt
cc
gg
Zγ
γγ
10 2
10 3
M H (GeV)


10 3
10 2
10
1
10 -1
10 -2
10 -3
Γ (H) (GeV)
100
200
300
400
500
600
700
800
900
1000
M H (GeV)

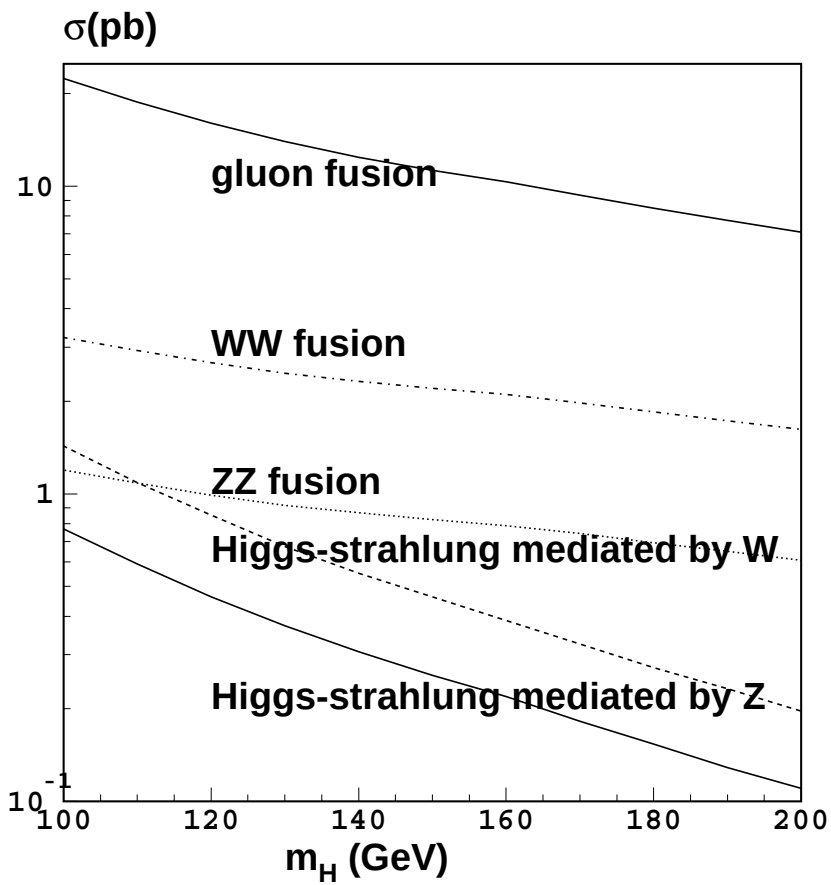
Higgs Production at Hadron Colliders

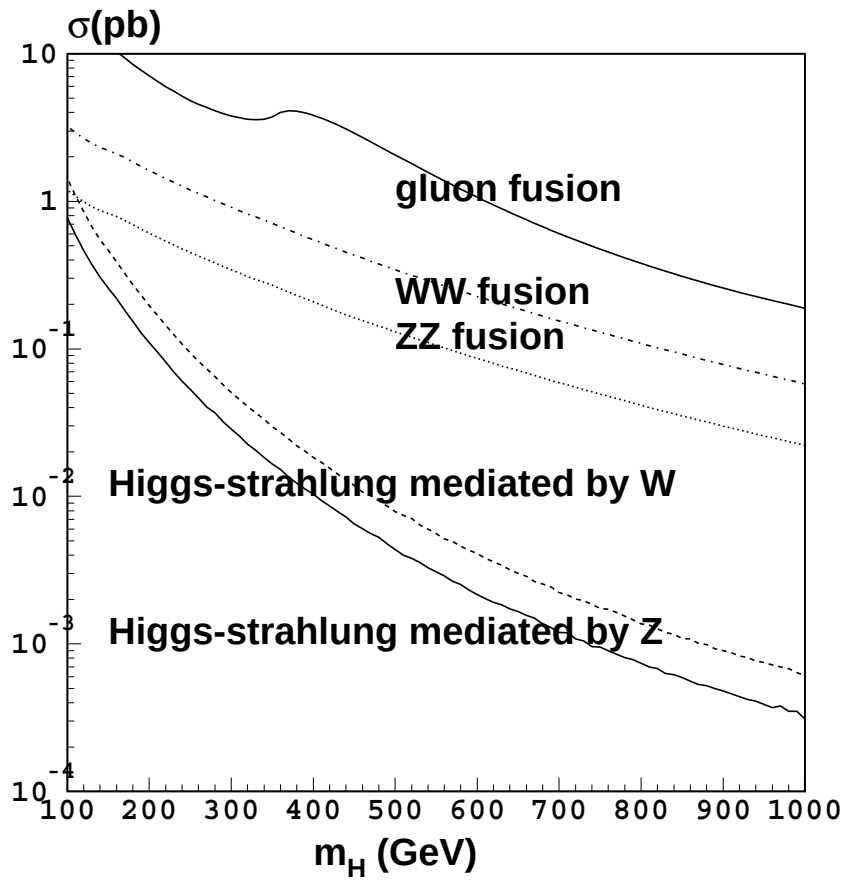




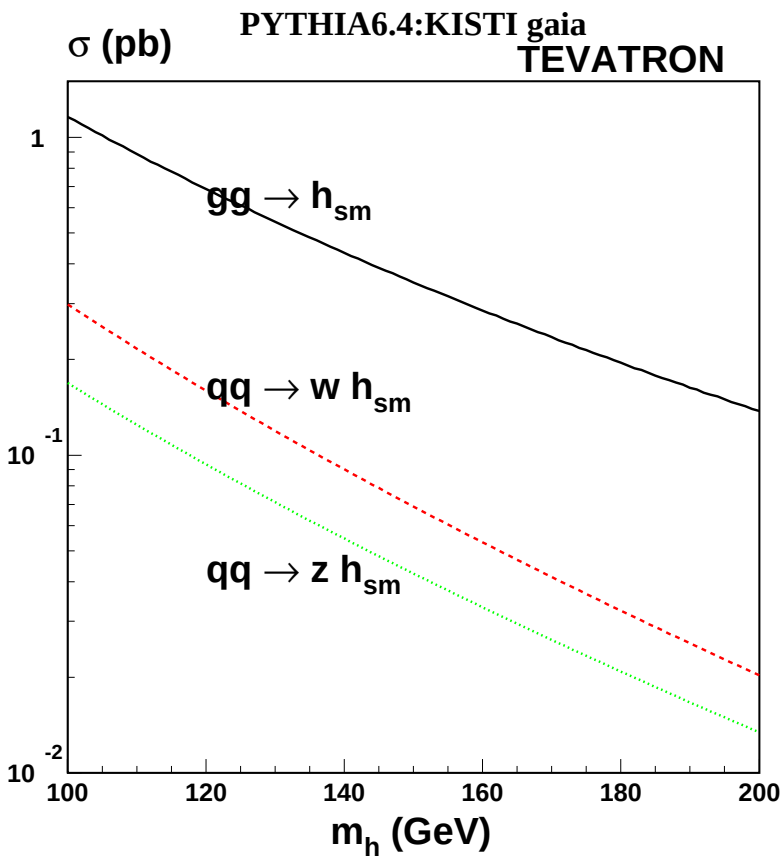


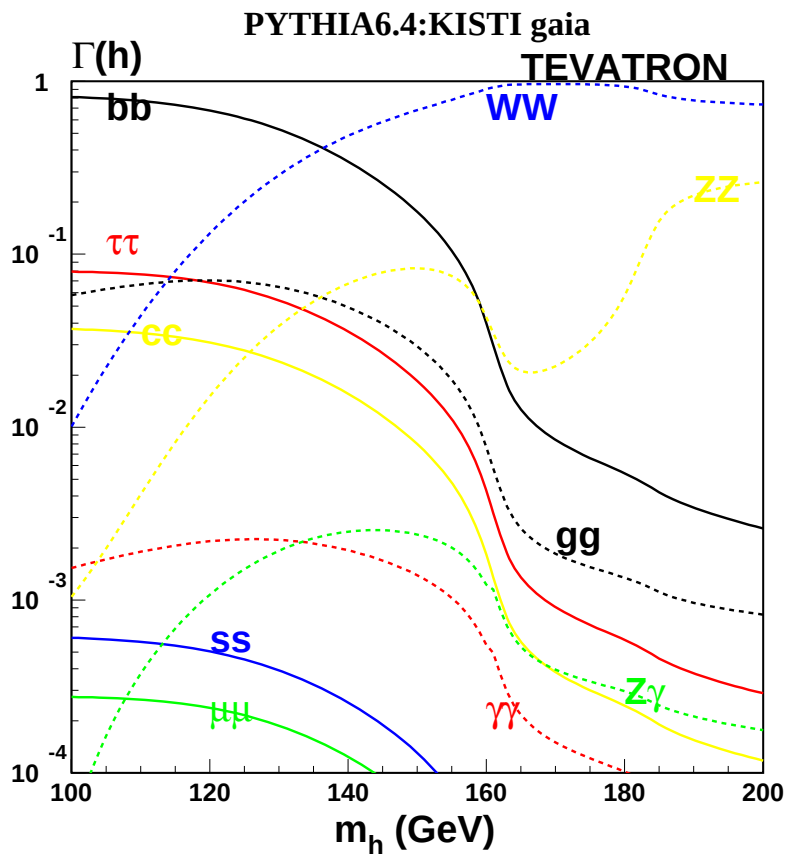
LHC (PYTHIA 6.4: KISTI IBM nobela)





TEVATRON


PYTHIA6.4:KISTI gaia
σ (pb)
TEVATRON
gg → h_sm
qq → w h_sm
qq → z h_sm
1
10^-1
10^-2
100
120
140
160
180
200
m_h (GeV)


PYTHIA6.4:KISTI gaia
Γ(h)
TEVATRON
bb
WW
ZZ
ττ
cc
gg
ss
μμ
γγ
Zγ
1
10^-1
10^-2
10^-3
10^-4
100
120
140
160
180
200
m_h (GeV)

2. Baryogenesis

⊙ On K-meson system, CP Violation: Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, PRL13, 138 (1964).

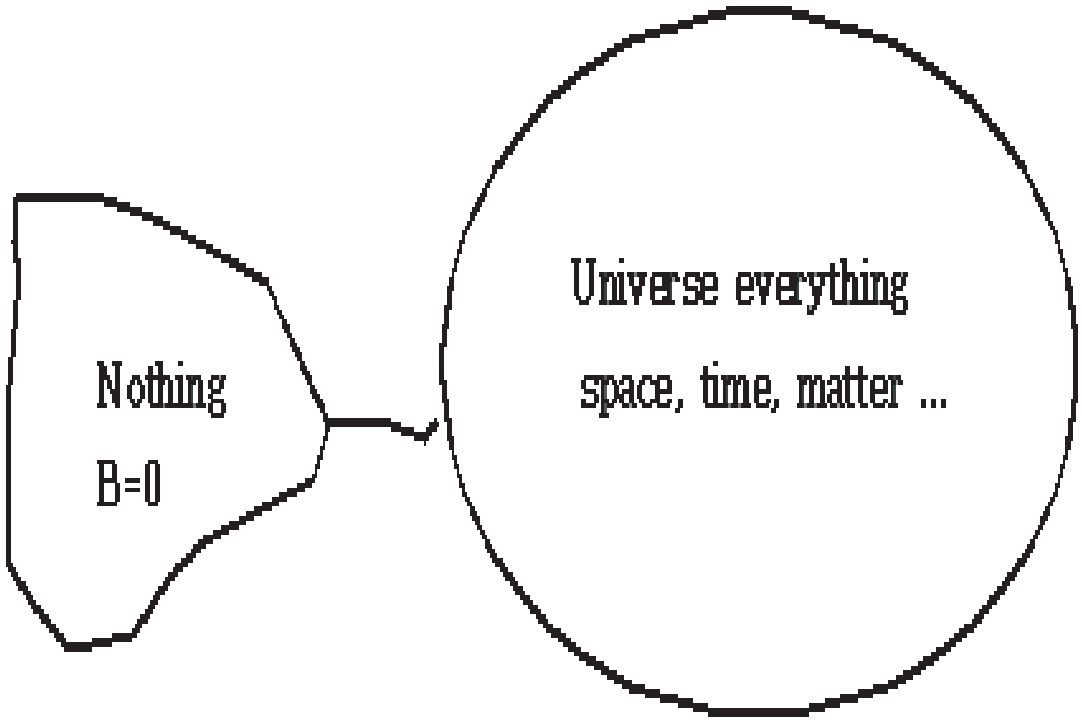
⊙ CP mixing on the Quark Sector, CKM matrix: N. Cabibbo, PRL10, 531 (1963); M. Kobayashi and T. Maskawa, PTP49, 652 (1973).

The SM cannot produce the CP violation large enough to generate the baryon asymmetry by means of complex phase in CKM matrix alone.

⊙ CP mixing on the Higgs Sector: S. Weinberg, PRL37, 657 (1976).

On the extension of the SM Higgs sector, there are the scalar and pseudoscalar Higgs bosons.

CP Mixing: spontaneous CP mixing or Explicit CP mixing


Nothing
B=0
Universe everything
space, time, matter ...

Baryogenesis: Matter-Antimatter Asymmetry of the Universe?.

Locally antimatter area (?) $\rightarrow$ Significant Photon Flux ($\times$)

$\rightarrow$ Baryon Asymmetry of the Universe?

-A. D. Sakharov, JETP Lett. 5, 24 (1967)

(1) The presence of baryon number(B) violation: Axial anomaly

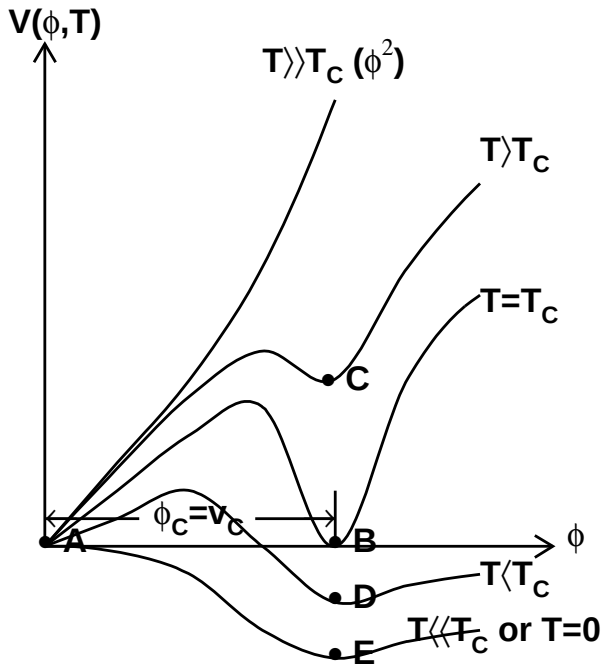
(2) The violation of Both C (Charge Conjugation) and CP:

- C is maximally violated !; $\Gamma(\pi^+ \rightarrow \mu^+ \nu_L) \neq \Gamma(\pi^- \rightarrow \mu^- \bar{\nu}_L) = 0$

- CP Vioaltion: CKM matrix

(3) A departure from thermal equilibrium:

The existence of thermal non-equilibrium during the evolution of Universe $\longrightarrow$ First order phase transition



First order phase transition (Figure)

Potential at $T \neq 0$

1 GeV $= 1.1605 \times 10^{13}$ **K**

$$V = V(\phi, T) = V(\phi, 0) + V_1(\phi, 0) + V_1(\phi, T)$$

Symmetry Restoration at High T

A: Symmetric phase state

B: Broken phase state

◯ **Strongly first order phase transition (Baryon Preserving condition)**

◇ **Sphaleron(Greek for ready to fall) Constraint;** $\phi_C \geq T_C$

◯ **Weakly first order phase transition:** $\phi_C \leq T_C$

ElectroWeak Phase Transition (EWPT) in the Standard Model

$$V(\phi,T) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + V_1(\phi,0) + V_1(\phi,T) \ .$$

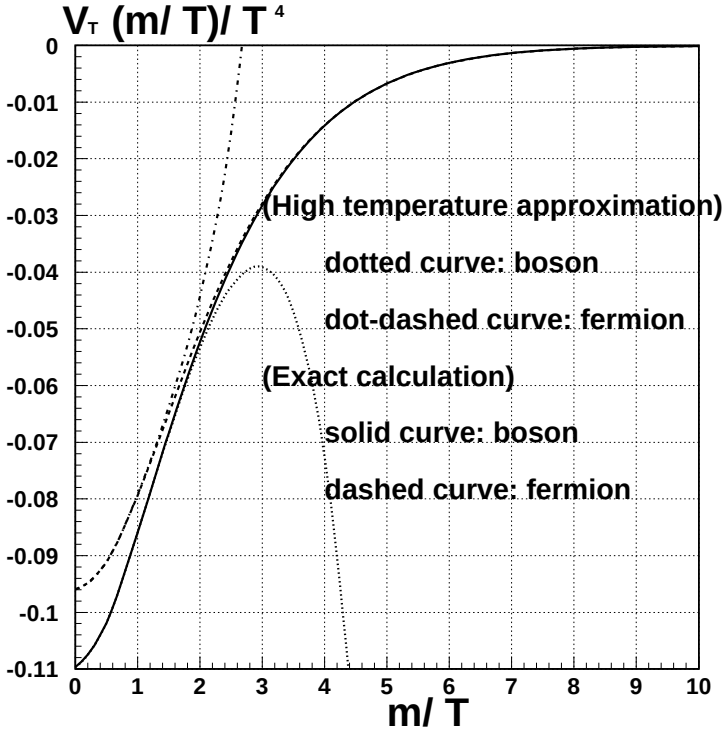
$$V_1(\phi,0) = \sum_i \frac{n_i}{64\pi^2}\left[m_i^4(\phi)\log\left(\frac{m_i^2(\phi)}{m_i^2(v)}\right) - \frac{3}{2}m_i^4(\phi) + 2m_i^2(v)m_i^2(\phi)\right] \ ,$$

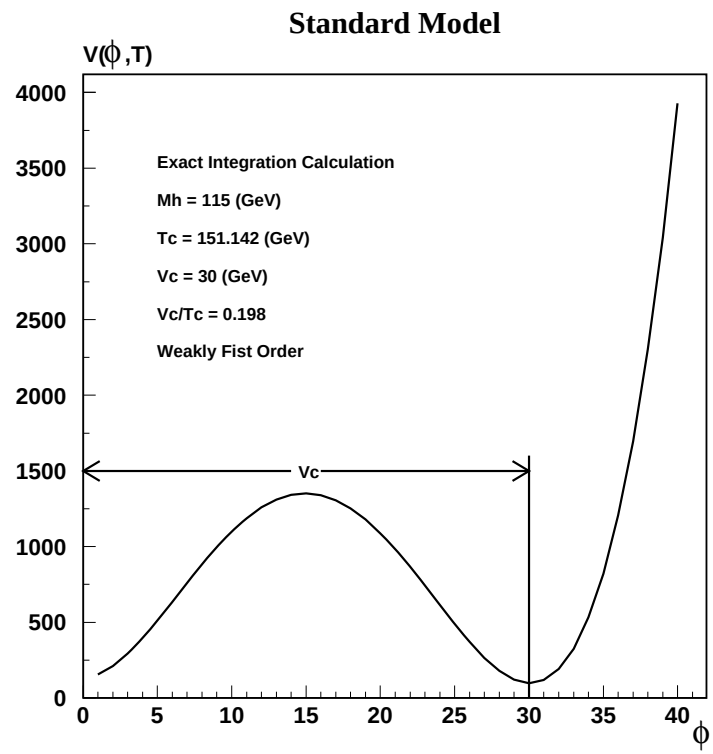
$$V_1(\phi,T) = \sum_i \frac{n_i T^4}{2\pi^2}\int_0^\infty dx \ x^2 \ \log\left[1 \pm \exp\left(-\sqrt{x^2 + m_i^2(\phi)/T^2}\right)\right] \ ,$$

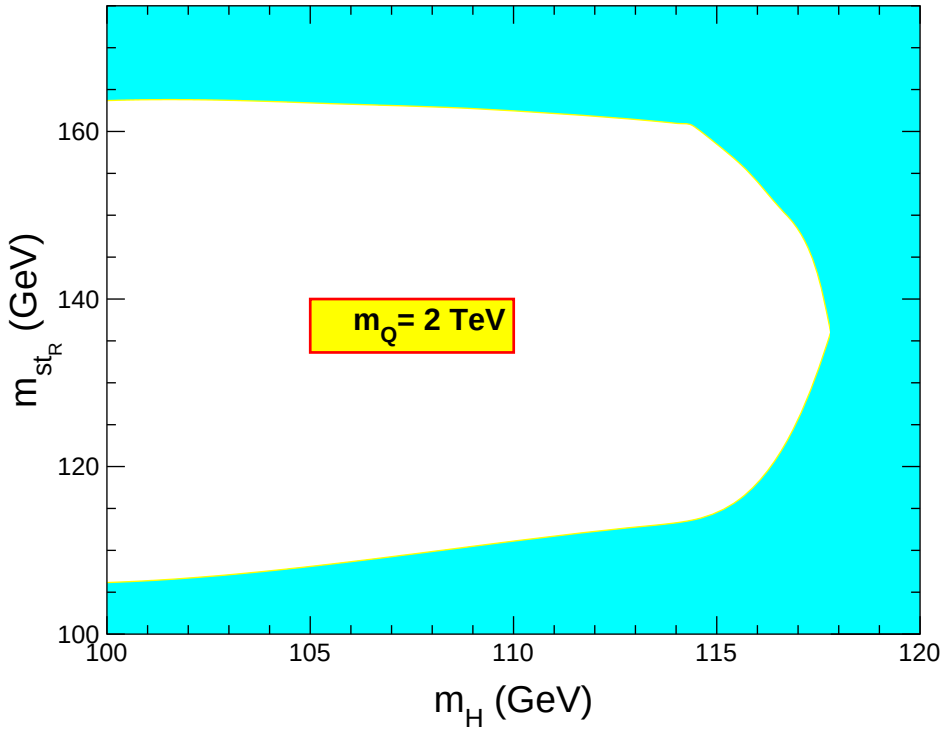
where $i = W, Z, t, \phi, G$**; Boson(**$-$**) and Fermion (**$+$**).**

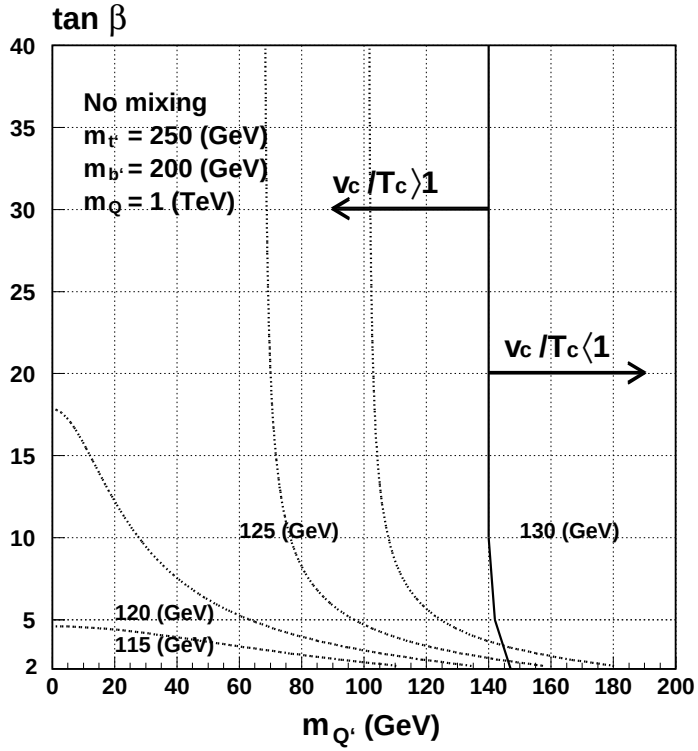
$$\begin{aligned} V_1^{(\text{high } T)}(\phi,T) \ = \ & -n_t\left[\frac{T^2 m_t^2(\phi)}{48} + \frac{m_t^4(\phi)}{64\pi^2}\log\left(\frac{m_t^2(\phi)}{c_f T^2}\right)\right] \\ & + \sum_i n_i\left[\frac{T^2 m_i^2(\phi)}{24} - \frac{T m_i^3(\phi)}{12\pi} - \frac{m_i^4(\phi)}{64\pi^2}\log\left(\frac{m_i^2(\phi)}{c_b T^2}\right)\right] \ . \end{aligned}$$

$\log C_f = 2.64$**,** $\log C_b = 5.41$**: 5 % deviation for** $m_f/T < 1.6$**,** $m_b/T < 2.2$


V_T (m/ T)/ T^4
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.1
-0.11
0 1 2 3 4 5 6 7 8 9 10
m/ T
(High temperature approximation)
dotted curve: boson
dot-dashed curve: fermion
(Exact calculation)
solid curve: boson
dashed curve: fermion


Standard Model
V(ϕ,T)
4000
3500
3000
2500
2000
1500
1000
500
0
0 5 10 15 20 25 30 35 40
ϕ
Exact Integration Calculation
Mh = 115 (GeV)
Tc = 151.142 (GeV)
Vc = 30 (GeV)
Vc/Tc = 0.198
Weakly Fist Order
Vc





EWPT in the MSSM

Left: Electroweak baryogenesis and the Higgs and stop masses, M. Quiros, Nucl. Phys. Proc. Suppl. 101, 401 (2001)

Right: Electroweak phase transition in the MSSM with four generations, S.W. Ham, S.K. Oh, and D. Son, PRD71, 015001 (2005)

3. CP Violation in Higgs Physics Beyond Minimal Supersymmetric Standard Model (BMSSM)

⊙ Possibility of spontaneous CP violation in Higgs physics beyond the minimal supersymmetric standard model, S. W. Ham, Seong-A Shim, S. K. Oh, arXiv:hep-ph/0907.3300 (PRD, September 9, 2009).

⊙ M. Dine, N. Seiberg, and S. Thomas, PRD76, 095004 (2007).

- New Physics Beyond MSSM: The new physics BMSSM lies at an energy scale M, the corrections to the MSSM may be described in terms of higher-dimensional operators.

- The Higgs sector of the simplest version has just two dimension-five operators with the MSSM content, at the energy scale below M.

In the Dine-Seiberg-Thomas model (DSTM),

- Electroweak Baryogenesis (a light stop scenario): K. Blum and Y. Nir, PRD78, 035005 (2008).

- Fine-Tuning Problem: S. Cassel, D. M. Ghilencea, G. G. Ross, arXiv:hep-ph/0903.1115.

- Spontaneous CP violation may take place in the DSTM at the one-loop level, but not at the tree-level, Ham, Shim, Oh (PRD)

- Explicit CP violation may take place in the DSTM at the one-loop level, but not at the tree-level, Ham, Shim, Oh, to appear.

At the tree-level, the general Higgs potential of the DSTM

$$
\begin{aligned}
V_0 \;=\; & m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d - (m_{ud}^2 H_u H_d + \text{H.c.}) + \frac{\lambda_1}{2}(H_u^\dagger H_u)^2 + \frac{\lambda_2}{2}(H_d^\dagger H_d)^2 \\
& + \lambda_3 (H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4 (H_u^\dagger H_u)(H_d^\dagger H_d) \\
& + \left[\frac{\lambda_5}{2}(H_u H_d)^2 + \left\{ \lambda_6 (H_u^\dagger H_u) + \lambda_7 (H_d^\dagger H_d) \right\} H_u H_d + \text{H.c.} \right] \;,
\end{aligned}
$$

$$
\begin{aligned}
& \lambda_1 = \lambda_2 = \frac{1}{4}(g'^2 + g^2), \quad \lambda_3 = \frac{1}{4}(g^2 - g'^2) \;, \\
& \lambda_4 = -\frac{1}{2} g^2 \;, \quad \lambda_5 = 2\epsilon_2 \;, \quad \lambda_6 = \lambda_7 = 2\epsilon_1 \;,
\end{aligned}
$$

where ϵ_1 and ϵ_2 are the coupling coefficients representing the interactions of two dimension-five operators.

The effective potential at one-loop level

$$V_1 = \sum_l \frac{n_l \mathcal{M}_l^4}{64\pi^2} \left[\log \frac{\mathcal{M}_l^2}{\Lambda^2} - \frac{3}{2} \right]$$

After the electroweak symmetry breaking, the top quark mass is given as $m_t = v \sin\beta$ while the stop quark masses are obtained as

$$\begin{aligned} m^2_{\tilde{t}_1,\ \tilde{t}_2} &= \frac{1}{2}(m_Q^2 + m_T^2) + m_t^2 + \frac{1}{4} m_Z^2 \cos 2\beta \mp \sqrt{X_t}\ , \\ X_t &= \left(\frac{1}{2}(m_Q^2 - m_T^2) + \left(\frac{2}{3} m_W^2 - \frac{5}{12} m_Z^2 \right) \cos 2\beta \right)^2 \\ &\quad + m_t^2 \left(A_t^2 + \mu^2 \cot^2\beta - 2\mu A_t \cot\beta\ \cos\varphi \right)\ . \end{aligned}$$

Note the presence of the CP phase φ in the scalar top quark masses.

The minimum condition for the vacuum stability with respect to the CP phase φ yields

$$m_{ud}^2 = 2v^2\left(\epsilon_1 + \epsilon_2 \sin 2\beta \cos\varphi\right) + \frac{3m_t^2 A_t \mu}{16\pi^2 v^2 \sin^2\beta} f(m_{\tilde{t}_1}^2,\ m_{\tilde{t}_2}^2)$$

$$f(m_x^2,\ m_y^2) = \frac{1}{(m_y^2 - m_x^2)}\left[m_x^2 \log\frac{m_x^2}{\Lambda^2} - m_y^2 \log\frac{m_y^2}{\Lambda^2}\right] + 1\ .$$

$$M_{ij} = \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{pmatrix}$$

M_{11}, M_{22}, M_{12} : Elements for Scalar Higgs Bosons

M_{33} : Element for Pseudoscalar Higgs Boson

M_{13}, M_{23} : CP Mixing Elements

$$
\begin{aligned}
M_{ij} &= M^0_{ij} + M^1_{ij} \ , \\
M^0_{11} &= m_Z^2 \cos^2\beta + m_{ud}^2 \tan\beta \cos\varphi + 2\epsilon_1 v^2 (2\cos 2\beta + 1)\tan\beta\cos\varphi \ , \\
M^0_{22} &= m_Z^2 \sin^2\beta + m_{ud}^2 \cot\beta \cos\varphi - 2\epsilon_2 v^2 (2\cos 2\beta - 1)\cot\beta\cos\varphi \ , \\
M^0_{33} &= \frac{m_{ud}^2 \cos\varphi}{\cos\beta\sin\beta} - \frac{2\epsilon_1 v^2 \cos\varphi}{\cos\beta\sin\beta} - 4\epsilon_2 v^2 \cos 2\varphi \ , \\
M^0_{12} &= -m_Z^2 \cos\beta\sin\beta - m_{ud}^2 \cos\varphi + 4\epsilon_1 v^2 \cos\varphi + 2\epsilon_2 v^2 \sin 2\beta \cos 2\varphi \ , \\
M^0_{13} &= m_{ud}^2 \cos\beta\sin\varphi - 6\epsilon_1 v^2 \cos\beta\sin\varphi - \epsilon_2 v^2 (\cos 2\beta + 3)\sin\beta\sin 2\varphi \ , \\
M^0_{23} &= m_{ud}^2 \sin\beta\sin\varphi - 6\epsilon_1 v^2 \sin\beta\sin\varphi + \epsilon_2 v^2 (\cos 2\beta - 3)\cos\beta\sin 2\varphi \ , \\
M^1_{ij} &= \frac{3W_iW_j}{32\pi^2 v^2 (m^2_{\tilde t_2} - m^2_{\tilde t_1})^2}\left(\frac{m^2_{\tilde t_2} + m^2_{\tilde t_1}}{m^2_{\tilde t_1} - m^2_{\tilde t_2}}\log\frac{m^2_{\tilde t_2}}{m^2_{\tilde t_1}} + 2\right) + \frac{3A_iA_j}{32\pi^2 v^2}\log\left(\frac{m^2_{\tilde t_1} m^2_{\tilde t_2}}{\Lambda^4}\right) \\
&\quad + \frac{3(W_iA_j + A_iW_j)}{32\pi^2 v^2}\frac{\log(m^2_{\tilde t_2}/m^2_{\tilde t_1})}{(m^2_{\tilde t_2} - m^2_{\tilde t_1})} + D_{ij}
\end{aligned}
$$

$$
A_1 = \frac{1}{2} m_Z^2 \cos\beta \ , \quad A_2 = \frac{2m_t^2}{\sin\beta} - \frac{1}{2} m_Z^2 \sin\beta \ , \quad A_3 = 0 \ ,
$$

$$
W_1 = \frac{2m_t^2 \mu \Delta_{\tilde t_1}}{\sin\beta} + \cos\beta\Delta_{\tilde t} \ , \quad W_2 = -\frac{2m_t^2 A_t \Delta_{\tilde t_2}}{\sin\beta} - \sin\beta\Delta_{\tilde t} \ , \quad W_3 = \frac{2m_t^2 \mu A_t \sin\varphi}{\sin^2\beta} \ ,
$$

$$
\Delta_{\tilde t_1} = \mu\cot\beta - A_t\cos\varphi \ , \quad \Delta_{\tilde t_2} = \mu\cot\beta\cos\varphi - A_t \ ,
$$

$$\Delta_{\tilde{t}} = \left(\frac{4}{3}m_W^2 - \frac{5}{6}m_Z^2\right)\left(m_Q^2 - m_T^2 + \left(\frac{4}{3}m_W^2 - \frac{5}{6}m_Z^2\right)\cos 2\beta\right)$$

$$\begin{aligned}
D_{33} &= -\frac{3}{16\pi^2 v^2}\left(\frac{m_t^2 \mu A_t \cos\varphi}{\sin^3\beta\cos\beta}\right) f(m_{\tilde{t}_1}^2,\ m_{\tilde{t}_2}^2)\ , \\
D_{11} &= \sin^2\beta D_{33} - \frac{3\cos^2\beta}{16\pi^2 v^2}\left(\frac{4m_W^2}{3} - \frac{5m_Z^2}{6}\right)^2 f(m_{\tilde{t}_1}^2,\ m_{\tilde{t}_2}^2)\ , \\
D_{22} &= \cos^2\beta D_{33} - \frac{3\sin^2\beta}{16\pi^2 v^2}\left(\frac{4m_W^2}{3} - \frac{5m_Z^2}{6}\right)^2 f(m_{\tilde{t}_1}^2,\ m_{\tilde{t}_2}^2) - \frac{3m_t^4}{4\pi^2 v^2\sin^2\beta}\log\left(\frac{m_t^2}{\Lambda^2}\right)\ , \\
D_{12} &= -\cos\beta\sin\beta D_{33} + \frac{3\cos\beta\sin\beta}{16\pi^2 v^2}\left(\frac{4m_W^2}{3} - \frac{5m_Z^2}{6}\right)^2 f(m_{\tilde{t}_1}^2,\ m_{\tilde{t}_2}^2)\ , \\
D_{13} &= -\frac{3}{16\pi^2 v^2}\left(\frac{m_t^2 \mu A_t \sin\varphi}{\tan\beta\sin\beta}\right) f(m_{\tilde{t}_1}^2,\ m_{\tilde{t}_2}^2)\ , \\
D_{23} &= \tan\beta D_{13}
\end{aligned}$$

At the one-loop level, non-zero φ triggers spontaneous CP violation.

⊙ Parameter Space

The distribution of $(m_{h_1}, g^2_{ZZh_1})$ **(stars),**

$(m_{h_2}, g^2_{ZZh_2})$ **(circles),**

and $(m_{h_3}, g^2_{ZZh_3})$ **(crosses),**

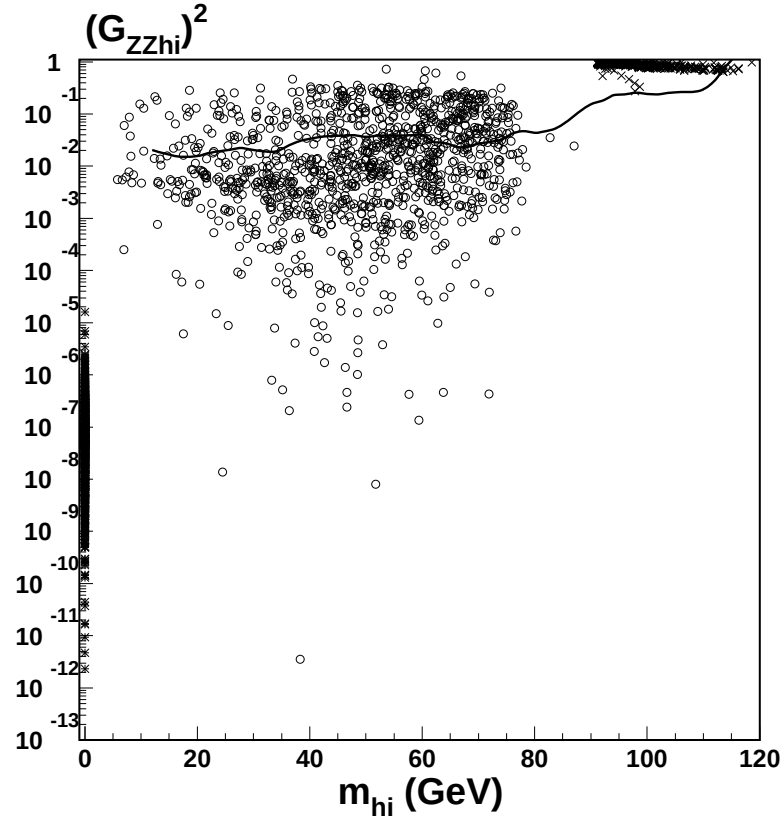
for each of 1145 points

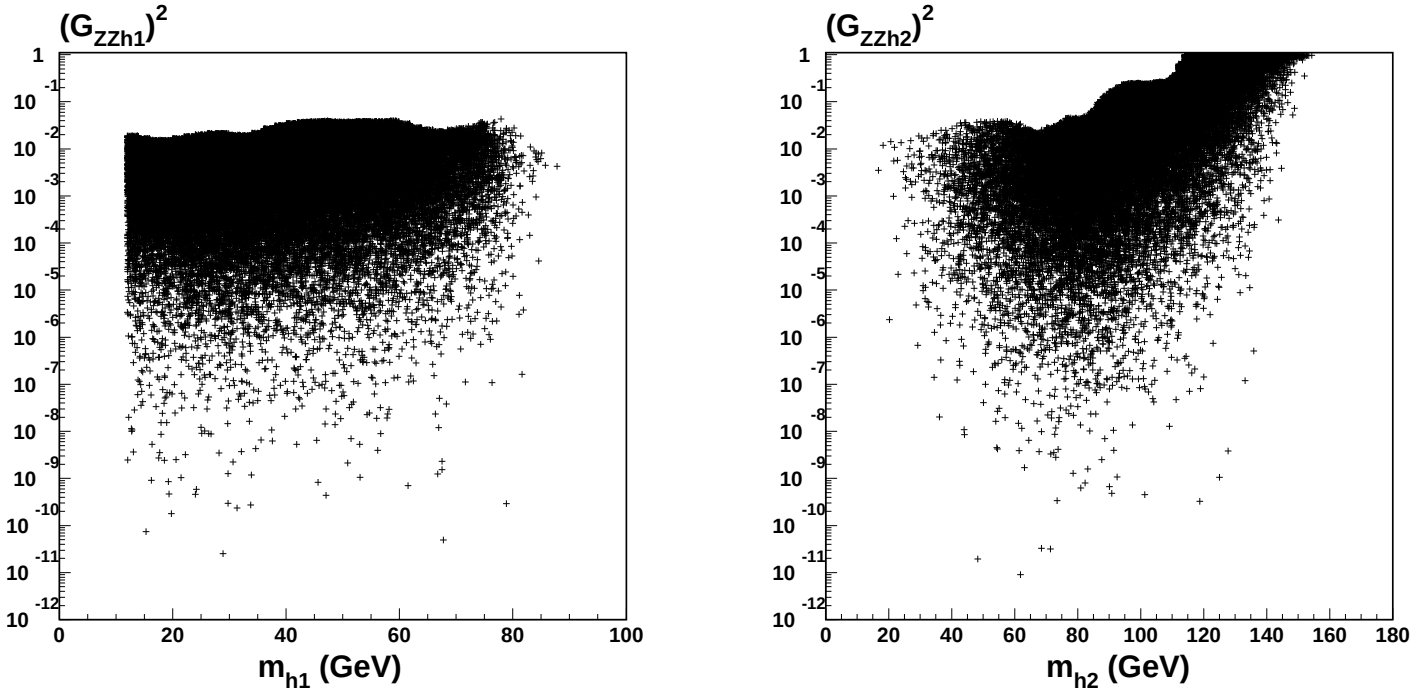
in the parameter region,

defined as $|\varphi| < \pi/2$, $0 < \epsilon_1 < 0.05$,

$0 < \epsilon_2 < 0.05$, **and** $2 < \tan\beta < 30$.

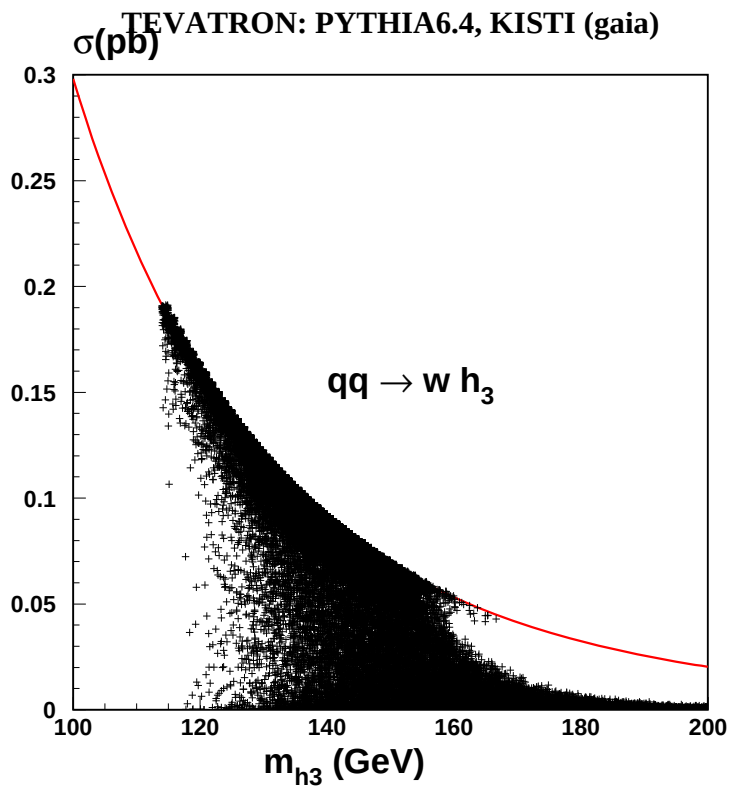
The solid curve: LEP2 Constraint

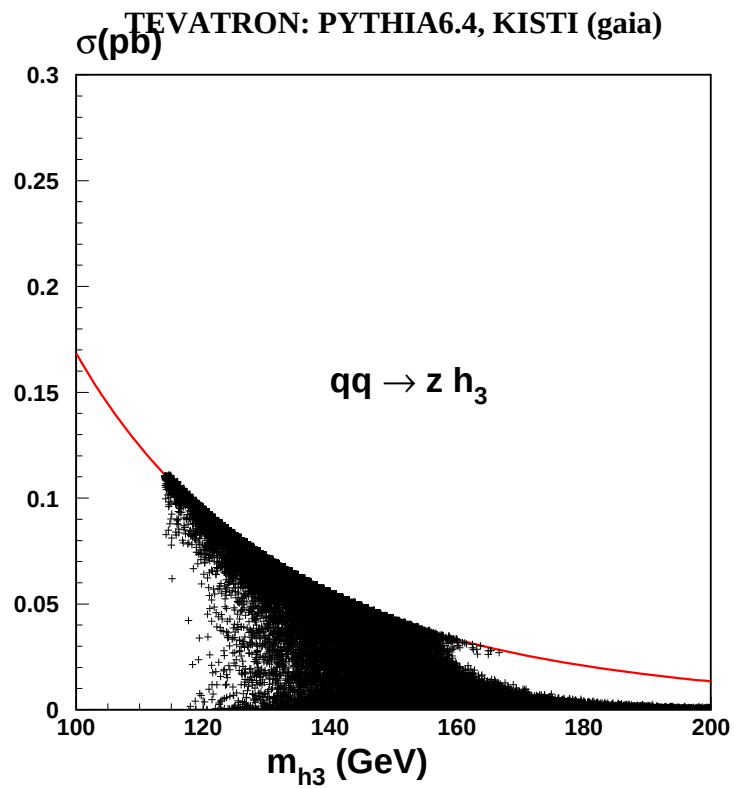




The distribution of $(m_{h_1}, g^2_{ZZh_1})$**, for each of 48914 points in the parameter region, defined as** $|\varphi| < \pi/2$**,** $0 < \epsilon_1 < 0.05$**,** $0 < \epsilon_2 < 0.05$**,** $2 < \tan\beta < 30$**,** $|\mu| < 1000$ **GeV,** $0 < A_t$ (GeV) < 2000**,** $100 < m_Q$ (GeV) < 1000**,** $100 < m_T$ (GeV) < 1000**. The marks are all consistent with the LEP data.**

4. Higgs Production of the BMSSM with spontaneous CP violation at TEVATRON





5. Conclusion

- Spontaneous CP violation take place in the DSTM at the one-loop level, but not at the tree-level.

- We calculated Higgs production of the DSTM with spontaneous CP violation at the TEVATRON via the Higgs-strahlung process.

- The Higgs decay and discovery area is under way for Hadron Colliders.

Thanks a lot