Working Group on the Interplay Between Collider and Flavour Physics

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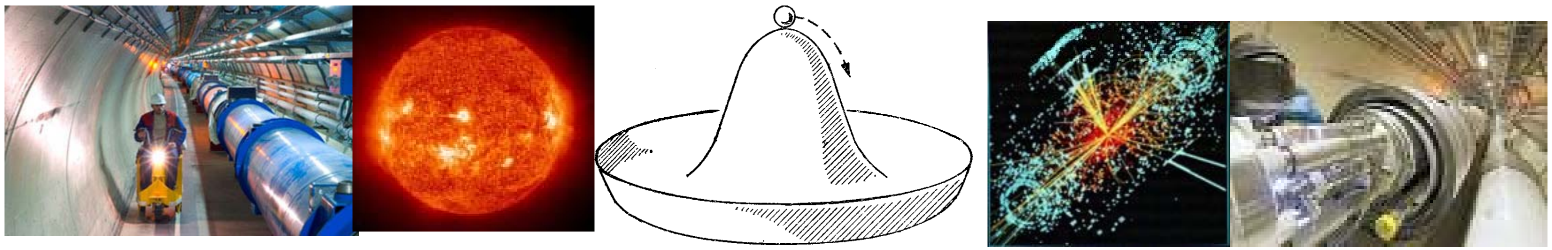
M.N. Dubinin [1], A.I. Sukachev [2]

[1]: Institute of Nuclear Physics, Moscow State University
[2]: Physics Department, Moscow State University

Moscow, Russian Federation

$K^0-\overline{K}^0$, $B^0-\overline{B}^0$ *mixings in the MSSM with explicit CP violation in the Higgs sector*



[1]: mikhail.dubinin@cern.ch; dubinin@theory.sinp.msu.ru
[2]: salex-82@yandex.ru

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Outline

1. **The Model: Charged Higgs boson – how light it could be?**
2. **The System: Calculation of** $\Delta m_K\,, \Delta m_{B_s}\,, \Delta m_{B_d}\,, and\ \varepsilon_K$
3. **Numerical results**
4. **Conclusions**

The Model. 1-1.

- **Scalar sector** – MSSM effective potential (the most generic form):

$$U(\Phi_1,\Phi_2) = -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - \underline{\mu_{12}^2(\Phi_1^\dagger\Phi_2)} - \underline{\underline{\overset{*}{\mu_{12}^2}(\Phi_2^\dagger\Phi_1)}} +$$

$$+\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) +$$

$$+\underline{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2)} + \underline{\underline{\frac{\overset{*}{\lambda_5}}{2}(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1)}} +$$

$$+\underline{\lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)} + \underline{\underline{\overset{*}{\lambda_6}(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1)}} + \underline{\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2)} + \underline{\underline{\overset{*}{\lambda_7}(\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)}}.$$

- **Yukawa sector** – type II:

$$-L_Y^{II} = g_{ij}^{u\,1}\bar{Q}'_{i\,L}\tilde{\Phi}_1 u'_{j\,R} + g_{ij}^{d\,2}\bar{Q}'_{i\,L}\Phi_2 d'_{j\,R} + \text{lept. sec.} + \text{h.c.}$$

- **Radiative corrections** control parameters [1]:
  - **Trilinear universal coupling:** $A_{t,b}$
  - **Higgs superfield mass parameter:** μ
  - **SUSY mass scale:** $M_{\rm SUSY}$
  - **Universal phase:** $\varphi = \arg(\mu A_{t,b})$

Effective potential approach:

[1] – E. N. Akhmetzyanova, M. V. Dolgopolov, and M. N. Dubinin; Phys. Rev. D. 71, P. 075008 (2005).

The Model. 1-2.

h, H, A $\xrightarrow[\| a_{ij}^{CP} \|]{\textbf{CP}}$ h(1), h(2), h(3)

$$m_{H^\pm}^2 = m_W^2 + m_A^2 - \frac{v^2}{2}(\mathrm{Re}\Delta\lambda_5 - \Delta\lambda_4)\,, m_A = m_A(\varphi = 0)$$ [2]

$$\Delta\lambda_4 = -\frac{3\,g_2^2}{32\pi^2}(h_t^2 + h_b^2)\ \ln\left(\frac{M_{\rm SUSY}^2}{m_{\rm top}^2}\right) + \frac{3}{8\pi^2}h_t^2 h_b^2\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_{\rm top}^2}\right) + \frac{1}{2}X_{tb}\right] -$$
$$-\frac{3}{96\pi^2}\frac{|\mu|^2}{M_{\rm SUSY}^2}\left[h_t^4\left(3 - \frac{|A_t|^2}{M_{\rm SUSY}^2}\right) + h_b^4\left(3 - \frac{|A_b|^2}{M_{\rm SUSY}^2}\right)\right] +$$
$$+\frac{3g_2^2\,[h_b^2(|\mu|^2 - |A_b|^2) + h_t^2(|\mu|^2 - |A_t|^2)]}{64\pi^2 M_{\rm SUSY}^2} + \frac{3g_2^4}{64\pi^2}\ \ln\left(\frac{M_{\rm SUSY}^2}{m_{\rm top}^2}\right),$$

$$\Delta\lambda_5 - \frac{3}{96\,\pi^2}\left(h_t^4\left(\frac{\mu A_t}{M_{\rm SUSY}^2}\right)^2 + h_b^4\left(\frac{\mu A_b}{M_{\rm SUSY}^2}\right)^2\right)$$

$$X_{tb} \equiv \frac{|A_t|^2 + |A_b|^2 + 2\mathrm{Re}(A_b^* A_t)}{2M_{\rm SUSY}^2} - \frac{|\mu|^2}{M_{\rm SUSY}^2} - \frac{||\mu|^2 - A_b^* A_t|^2}{6M_{\rm SUSY}^4}$$

The Model. 1-3.

Basic assumptions:

- **CPX scenario [2];** $\mu = 2A_{t,b} = 4M_{SUSY}$, $M_{SUSY} = 500$ GeV
- **Phase universality** $\varphi = \arg(\mu A_b) = \arg(\mu A_t)$.

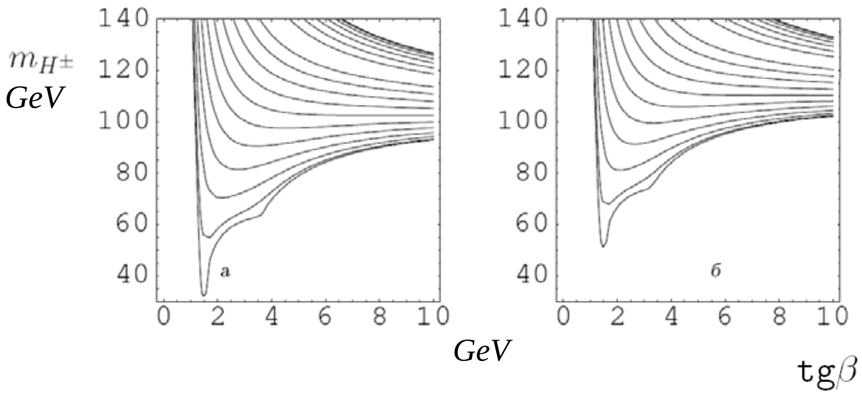
LEP2 limits

SM: $m_h > 114\, GeV$

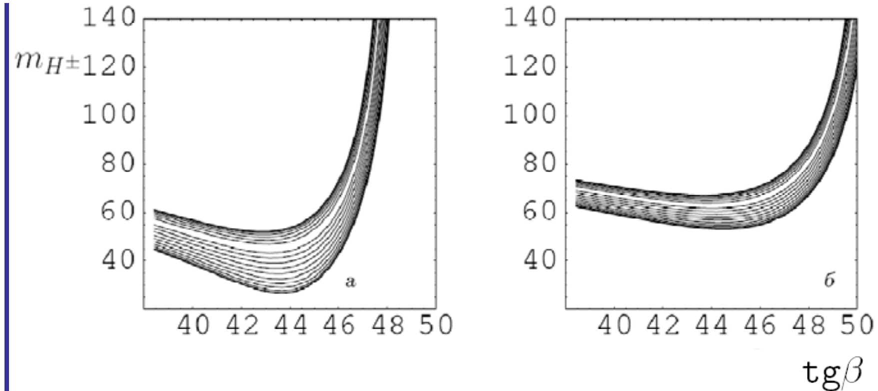
$e^+e^- \to ZH$

MSSM: $m_{H^\pm} > 56\, GeV$

$e^+e^- \to H^+H^-$



Plot 1: Charged Higgs boson in the Model with: (a) $m_{h_1} > 0$, (b) $m_{h_1} = 40\, GeV$ as a function of $tg\,\beta = v_2/v_1$. The sequence of contours is shown for a φ, changing from zero (the lower contour) to 180 degrees (the upper contour) with 10 degree step. CPX-scenario. Below the contour for the certain phase value the lightest neutral Higgs is either not positively defined, or lower than 40 GeV.



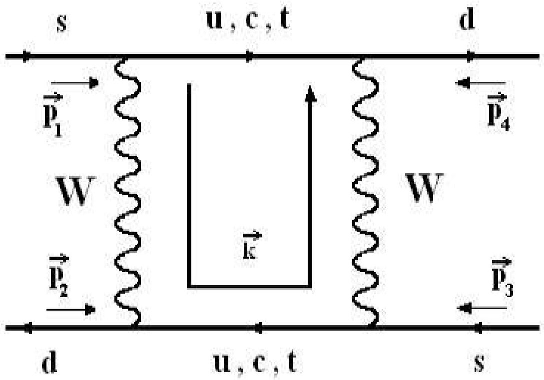
Plot 2: Charged Higgs boson in the Model with: $m_{h_1} \sim 50\, GeV$ at large values of $tg\,\beta$.

(a) $A_{t,b} = 890$ GeV, $\mu = 2000$ GeV

(b) $A_{t,b} = 890$ GeV, $\mu = 1900$ GeV

[2] – M. Carena et. al., Nucl. Phys., B 659, P. 145 (2003);

The System. K-mesons. SM.



1. GIM-mechanism [3], [4]:

$$\Delta m_{LS}^{WW} = \frac{G_F^2 f_K^2 m_K B_K}{6\pi^2} \mathrm{Re}\, A$$

$$|\varepsilon| = \frac{1}{2\sqrt{2}} \frac{\mathrm{Im}\, A}{\mathrm{Re}\, A}$$

$$A = \Big[(V_{cd}^* V_{cs})^2 m_c^2 \eta_1 I(\xi_1) + (V_{td}^* V_{ts})^2 m_t^2 \eta_2 I(\xi_2) + + 2\, V_{td}^* V_{cd}^* V_{ts} V_{cs} \eta_3 \frac{m_c^2 m_t^2}{m_t^2 - m_c^2} \ln \frac{m_t^2}{m_c^2} I(\xi_1, \xi_2, \xi_3) \Big],$$

3. QCD corrections [5]:

$B_K \approx 1.0$

$\eta_1 = 1.3\,(central\ value)$

$\eta_2 = 0.47$

$\eta_3 = 0.57$

2. Inami-Lim-Vysotsky Functions:

$$I(\xi) = \left\{ \frac{\xi^2 - 11\xi + 4}{4(\xi - 1)^2} - \frac{3\xi^2 \ln \xi}{2(1-\xi)^3} \right\}$$

$$I(\xi_1, \xi_2, \xi_3) = \left(\frac{\xi_3}{\ln \xi_3} - \frac{1}{\ln \xi_3} \right) \left(\frac{\ln \xi_1}{(1-\xi_1)^2 (1-\xi_2)^2 (1-\xi_3)} - \frac{\xi_1}{(1-\xi_1)^2(1-\xi_2)^2} + \frac{(2-\xi_2)\xi_2 \ln \xi_1 - (2-\xi_1)\xi_1 \ln \xi_2}{(1-\xi_1)^2(1-\xi_2)^2(1-\xi_3)} + \frac{\xi_1^2(1-\xi_2) - \xi_2^2(1-\xi_1)}{(1-\xi_1)^2(1-\xi_2)^2(1-\xi_3)} \right).$$

$$\xi_1 = \left(\frac{m_c}{m_W}\right)^2$$

$$\xi_2 = \left(\frac{m_t}{m_W}\right)^2$$

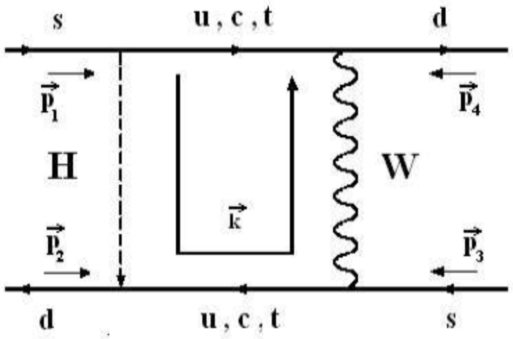
$$\xi_3 = \left(\frac{m_t}{m_c}\right)^2$$

[3] – S.L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, P. 1285 (1970);

[4] – J. Ellis, M.K. Gaillard, and D.V. Nanopoulos, Nucl. Phys. B 109, P 213 (1976);

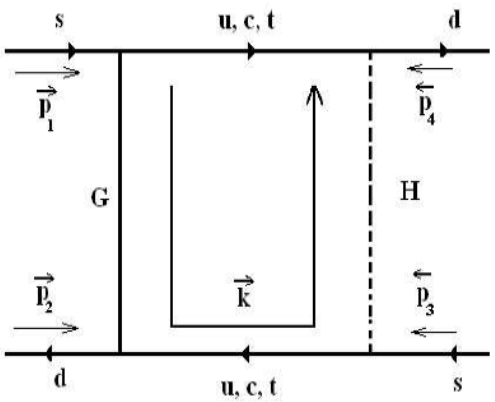
[5] – S. Herrlich, and U. Nierste, Nucl. Phys. B 419, P 292 (1994).

The System. K-mesons. MSSM. HW



$$\Delta m_{LS}^{HW} = \frac{G_F C_H f_K^2 m_K B_K}{48\pi^2 m_W^4} \left((m_s + m_d) m_H^2 \ \mathrm{Re} B_1 + \frac{m_H^2 m_s^2}{\sin 2\beta} \ \mathrm{Re} B_2 \right)$$

$$\begin{aligned} B_1 &= (V_{cd}^* V_{cs})^2 m_c^3 \eta_4 I_{HW-1}(\xi_1, \xi_4, \xi_6) + (V_{td}^* V_{ts})^2 m_t^3 \eta_5 I_{HW-1}(\xi_2, \xi_5, \xi_6) + \\ &\quad + V_{cd}^* V_{td}^* V_{cs} V_{ts} m_c m_t (m_c + m_t) \eta_6 I_{HW-2}(\xi_1, \xi_2, \xi_3, \xi_4, \xi_5, \xi_6), \\ B_2 &= (V_{cd}^* V_{cs})^2 m_c^2 \eta_4 I_{HW-3}(\xi_1, \xi_4, \xi_6) + (V_{td}^* V_{ts})^2 m_t^2 \eta_5 I_{HW-3}(\xi_2, \xi_5, \xi_6) + \\ &\quad + 2 \cdot V_{cd}^* V_{td}^* V_{cs} V_{ts} m_c m_t \eta_6 I_{HW-4}(\xi_1, \xi_2, \xi_3, \xi_4, \xi_5, \xi_6), \end{aligned}$$

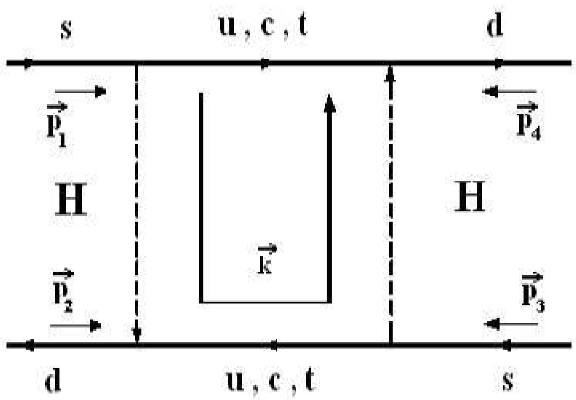


$$\xi_1 = \left(\frac{m_c}{m_W}\right)^2, \ \xi_2 = \left(\frac{m_t}{m_W}\right)^2, \ \xi_3 = \left(\frac{m_t}{m_c}\right)^2$$

$$\xi_4 = \left(\frac{m_c}{m_H}\right)^2, \ \xi_5 = \left(\frac{m_t}{m_H}\right)^2, \ \xi_6 = \left(\frac{m_H}{m_W}\right)^2$$

$C_H(m_{H^\pm}) - G_F$ analogue for MSSM.

The System. K-mesons. MSSM. HH



Assumptions:

1. $k^2 >> p_i^2$

2. $m_u = 0$

$$I^p_{HH-1} = \frac{d^4k \; k^\mu k^\nu m^2_{c,t}}{(k^2+m^2_{c,t})^2(k^2+m^2_H)^2} \sim \frac{1}{k^2}$$

$$I^p_{HH-2} = \frac{d^4k \; k^\mu k^\nu m_c m_t}{(k^2+m^2_c)(k^2+m^2_t)(k^2+m^2_H)^2} \sim \frac{1}{k^2}$$

$$I_{HH-1} = \frac{\xi_{1,2}+\xi_6}{(\xi_{1,2}-\xi_6)^2} - \frac{2\xi_{1,2}\xi_6}{(\xi_{1,2}-\xi_6)^3}\ln\xi_{4,5}$$

$$I_{HH-2} = \frac{\xi_6^3(\xi_1-\xi_2)+\xi_6^2(\xi_2^2-\xi_1^2)+\xi_1^2\xi_6^2\ln\xi_4-\xi_2^2\xi_6^2\ln\xi_5-\xi_1^2\xi_2^2\ln\xi_3}{(\xi_6-\xi_1)^2(\xi_6-\xi_2)^2(\xi_1-\xi_2)} + \frac{\xi_1\xi_2\xi_6(\xi_1-\xi_2+2\xi_2\ln\xi_5-2\xi_1\ln\xi_4)}{(\xi_6-\xi_1)^2(\xi_6-\xi_2)^2(\xi_1-\xi_2)}$$

$$\Delta m^{HH}_{LS} = \frac{f_K^2 m_K B_K m_s^2}{48\pi^2 v^4 m_W^2}\,\mathrm{Re}\,C,$$

$$C = (V^*_{cd}V_{cs})^2 m_c^2\eta_7 I_{HH-1}(\xi_4) + (V^*_{td}V_{ts})^2 m_t^2\eta_8 I_{HH-1}(\xi_5) + \\ + 2\cdot V^*_{cd}V^*_{td}V_{cs}V_{ts}m_c m_t\eta_9 I_{HH-2}(\xi_3,\xi_4,\xi_5).$$

Numerical Results. K-mesons

Table 1: Mass splitting in K-mesons versus charged Higgs mass

$m_{H^\pm}$, GeV	50	100	150	200	250	300	500
$\Delta m_{LS}^{WW} \times 10^{15}$,	2.721 ($\Delta m_{LS}^{exp} = (3.482 \pm 0.013) \times 10^{-15}$,)						
$\Delta m_{LS}^{HW} \times 10^{19}$,	-14.22	-4.44	-2.19	-1.31	-0.87	-0.63	-0.24
$\Delta m_{LS}^{HH} \times 10^{22}$,	61.50	15.79	7.15	4.07	2.63	1.84	0.67

$$V_{LS}^{WW} = G_F^2 \ \mathrm{Im}\, A$$

$$V_{LS}^{HW-1} = \frac{G_F C_H (m_d + m_s) m_H^2}{8 m_W^4} \mathrm{Im}\, B_1$$

$$V_{LS}^{HW-2} = \frac{m_s^2 m_H^2 G_F C_H}{8 m_W^4 \sin 2\beta} \mathrm{Im}\, B_2$$

$$V_{LS}^{HH} = \frac{m_s^2}{v^4 m_W^2} \mathrm{Im}\, C$$

Table 2: Non-direct CP-violation in K-mesons versus charged Higgs mass

$m_{H^\pm}$, GeV	50	100	150	200	250	300	500
$\lvert\varepsilon\rvert_{WW} \times 10^3$	2.0523 ($\varepsilon_{LS}^{exp} = (2.232 \pm 0.007) \times 10^{-3}$)						
$\lvert\varepsilon\rvert_{tot} \times 10^3$	2.0419	2.0472	2.0493	2.0503	2.0509	2.0513	2.0519

$$W_{LS}^{WW} = G_F^2 \cdot \mathrm{Re}\, A,$$

$$W_{LS}^{HW-1} = \frac{G_F C_H (m_d + m_s) m_H^2}{8 m_W^4} \cdot \mathrm{Re}\, B_1,$$

$$W_{LS}^{HW-2} = \frac{G_F C_H m_s^2 m_H^2}{8 m_W^4 \sin 2\beta} \cdot \mathrm{Re}\, B_2,$$

$$W_{LS}^{HH} = \frac{m_s^2}{v^4 m_W^2} \cdot \mathrm{Re}\, C.$$

$$|\varepsilon|_{LS}^{\mathrm{tot}} = \frac{1}{2\sqrt{2}} \frac{V_{LS}^{WW} + V_{LS}^{HW-1} + V_{LS}^{HW-2} + V_{LS}^{HH}}{W_{LS}^{WW} + W_{LS}^{HW-1} + W_{LS}^{HW-2} + W_{LS}^{HH}}$$

Numerical Results. B-mesons

Table 3: Mass splitting in B(s,d)-mesons versus charged Higgs mass

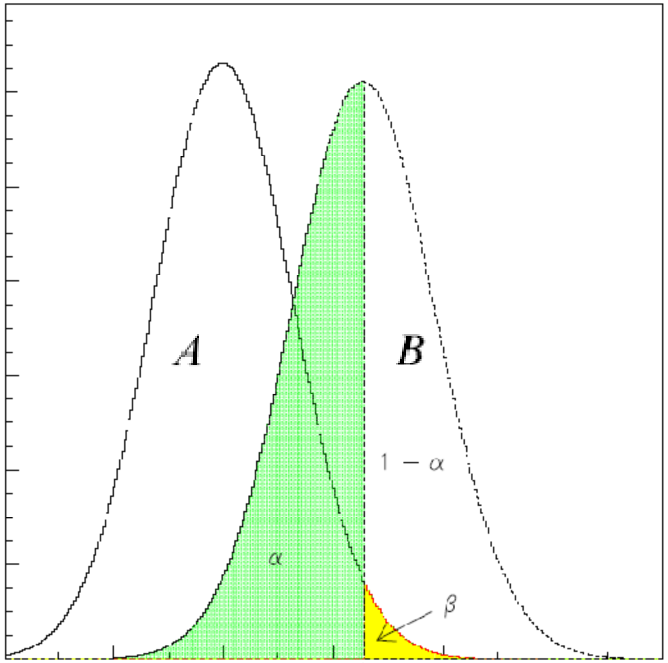
$m_{H^\pm}$ GeV	50	100	150	200	250	300	500
$\Delta m^{WW}_{B_d} \times 10^{13}$	2.11 ($\Delta m^{\rm exp}_{B_d} = (3.33 \pm 0.03) \times 10^{-13}$)						
$\Delta m^{HW}_{B_d} \times 10^{16}$	-17.05	-11.99	-8.70	-6.57	-5.14	-4.13	-2.09
$\Delta m^{HH}_{B_d} \times 10^{17}$	3.97	2.87	2.11	1.59	1.24	0.99	0.47
$\Delta m^{WW}_{B_s} \times 10^{12}$	9.3 ($\Delta m^{\rm exp}_{B_s} = 11.4^{+0.2}_{-0.1} \times 10^{-12}$)						
$\Delta m^{HW}_{B_s} \times 10^{14}$	-8.21	-5.67	-4.08	-3.07	-2.39	-1.92	-0.97
$\Delta m^{HH}_{B_s} \times 10^{15}$	1.83	1.31	0.96	0.72	0.56	0.45	0.21

Table 4: Relative contributions to mass splitting in B(s,d)-mesons

$m_{H^\pm}$ GeV	50	75	100	125	150	175	200
$\Delta m^{WW}_{B_d} \times 10^{13}$	2.11 ($\Delta m^{\rm exp}_{B_d} = (3.33 \pm 0.03) \times 10^{-13}$)						
$\Delta m^{HW}_{B_d} \times 10^{16}$	-17.05	-14.28	-11.99	-10.16	-8.70	-7.57	-6.57
R_{B_d}	0.0081	0.0068	0.0057	0.0048	0.0041	0.0036	0.0031
$\Delta m^{WW}_{B_s} \times 10^{12}$	9.3 ($\Delta m^{\rm exp}_{B_s} = 11.4^{+0.2}_{-0.1} \times 10^{-12}$)						
$\Delta m^{HW}_{B_s} \times 10^{14}$	-8.21	-6.79	-5.67	-4.78	-4.08	-3.54	-3.07
R_{B_s}	0.0088	0.0073	0.0061	0.0051	0.0044	0.0038	0.0033

$$R = |\Delta m^{HW}_{B_{d,s}} / \Delta m^{WW}_{B_{d,s}}|)$$

Numerical Results. Estimations



RESULTS

Experimental accuracy: 0.01×10^{-13} GeV

Statistical significance: 2σ

$$B_s: \quad m_{H^\pm} > 130\ GeV$$

$$B_d: \quad m_{H^\pm} > 120\ GeV$$

S. Bityukov statistical approach is used [6].

1. Hypotheses

H_0 : *new physics is present in Nature*

H_1 : *new physics is absent in Nature*

2. Errors

$$\alpha = P(reject\ H_0|H_0\ is\ true)$$

$$\beta = P(accept\ H_0|H_0\ is\ false)$$

3. Distributions

$$f_0(n) = f(n; \mu_s + \mu_b),$$
$$f_1(n) = f(n; \mu_b).$$

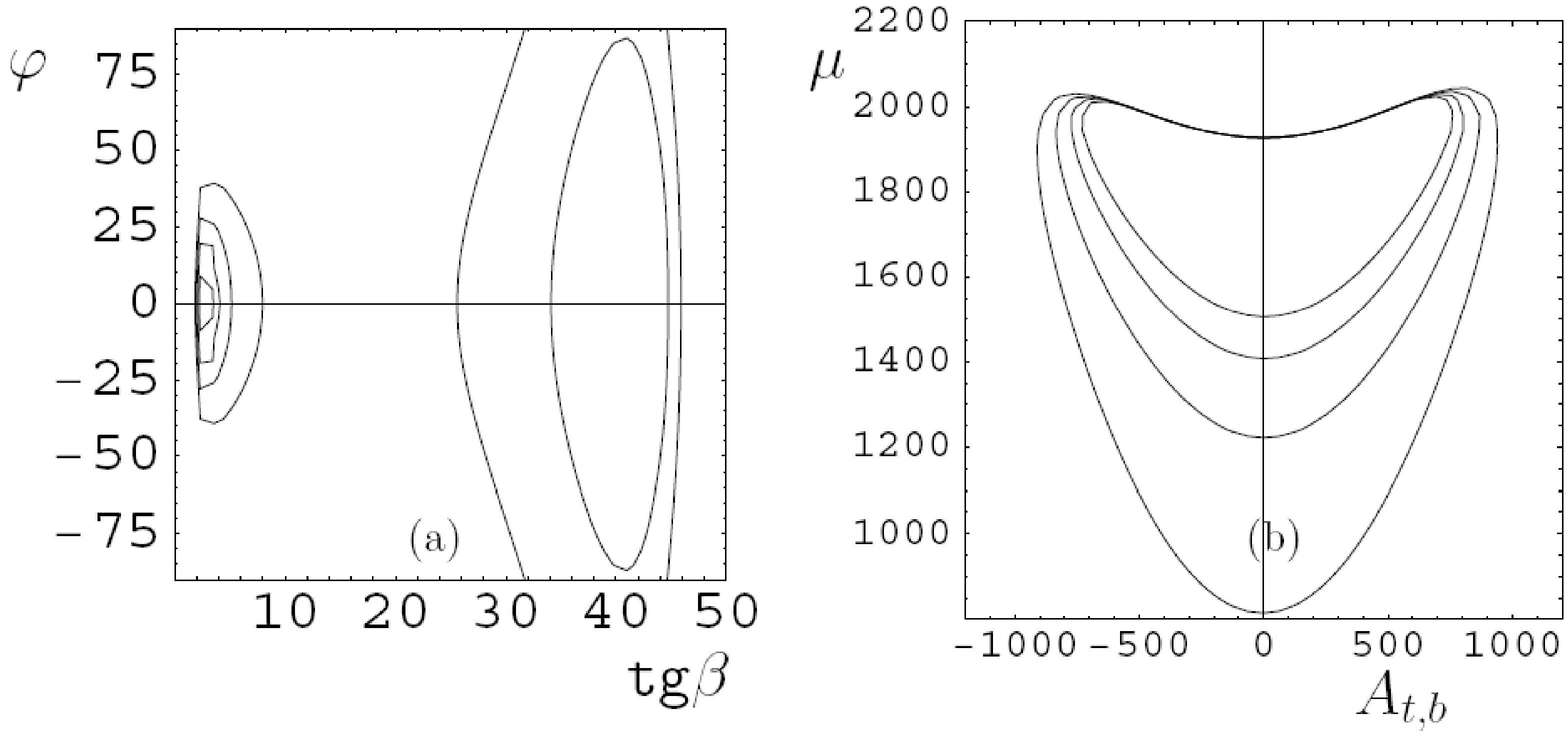
[6] – S.I. Bityukov and N.V. Krasnikov, Nucl. Instr. And Meth., A 534, P 152 (2004)

4. Universal error estimator

$$\tilde{\kappa} = \frac{A \bigcap B}{A \bigcup B} = \frac{\hat{\alpha} + \hat{\beta}}{2 - (\hat{\alpha} + \hat{\beta})}$$

$$\tilde{\kappa} = \frac{\hat{\kappa}}{1 - \hat{\kappa}}$$

Numerical Results. Limits for MSSM.



(a) Regions of lightest Higgs boson mass m_{h_1} positively defined, (b) Regions of m_{h_1} >50 GeV

Conclusions

- **In the MSSM with explicit CP violation (complex MSSM) and strong mixing of Higgs states (CPX-like scenarios) rather light charged scalar with the mass less than 50 GeV is admitted, not being in conflict with direct LEP2 exclusion** $m_h > 114\,GeV$

- **Additional** $H^{\pm}W$ **and** $H^{\pm}H^{\pm}$ **boxes could contribute substantially to the neutral meson mass splitting and non-direct CP-violation parameter** ε**. We have calculated nonstandard box contributions in the approximation of equaled-to-zero external momenta and found the analogies of Inami-Lim-Vysotsky functions in** $K^0 - \overline{K}^0$ **and** ${B_{s,d}}^0 - {\overline{B}_{s,d}}^0$ **systems.**

- **While for the** $K^0 - \overline{K}^0$ **system such HW and HH contributions are marginal, for the** ${B_{s,d}}^0 - {\overline{B}_{s,d}}^0$ **systems nonstandard contributions are on the level 0.5** σ **statistical significance at the existing experimental accuracy. If the experimental accuracy is improved by a factor of 5-6 the weak evidence level of** 2σ **could be achieved (especially at** B_s^0 **system).**

Conclusions

- **Uncertainties in QCD perturbative contributions and in the vacuum insertion can lead to a significant restriction of the desired improvement.**

- **Light charged Higgs scalar with the mass more than 50 GeV restricts strongly the MSSM parameter space, which was illustrated on the** $(\varphi\ tg\,\beta)$ **and** $(\mu\ \ A)$ **planes.**

- **MSSM boxes (squarks, chargino, neutralino, gluino) were not accounted for, being strongly depended on the region of MSSM parameter space.**

Thank You for Your Attention!