SUSY2K, CERN, 26 June - 1 July 2000

Athanasios Dedes

Rutherford Appleton Laboratory

SUSY CP-violating effects in Low Energy Phenomenology

Summary :

1. SUSY CP-violating Phases, EDMs and cancellations
2. Effect of the phases on Higgs boson production at hadron colliders

   A. Dedes and S. Moretti, Phys. Rev. Lett. 84(22)2000; Nucl.Phys.B576:29-55,2000

3. θ-angle versus CP-violation in the leptonic sector

   A. Dedes and M. Pospelov, Phys. Rev. D61:116010,2000

4. Electron, Neutrino and Neutron Electric Dipole Moments (EDMs) in the MSSM without R-Parity symmetry

   S. Abel, A. Dedes and H. Dreiner, JHEP0005:013,2000

5. Conclusions

SUSY CP-phases, EDMs and cancelations

- In what follows I will assume for simplicity:

$$\phi_{A_t}(M_Z) = \phi_{A_b}(M_Z) = \ldots \equiv \phi_A$$
$$\phi_\mu(M_Z) \equiv \phi_\mu$$

- Sparticle spectrum is different than in the phaseless case!

$$\begin{aligned} m^2_{\tilde{t}_1} &= M^2_{\tilde{q}_3} + m_t^2 + \frac{1}{4}M_Z^2 \cos 2\beta - \\ &\{(\frac{5}{6}M_Z^2 - \frac{4}{3}M_W^2)^2 \cos^2 2\beta + \\ &4m_t^2[|A|^2 + |\mu|^2 \cot^2\beta + 2|A||\mu| \cos(\phi_\mu - \phi_A) \cot\beta]\}^{1/2} \end{aligned}$$

- New couplings!

CP-Odd Higgs - squark -squark

$$\begin{aligned} \lambda_{A^0 \tilde{t}_1 \tilde{t}_1^*} &= -i[\frac{g m_t}{2M_W}] \sin 2\theta_{\tilde{t}} \times \\ &\{|\mu| \sin(\phi_{\tilde{t}} - \phi_\mu) - |A_t| \sin(\phi_{\tilde{t}} + \phi_{A_t}) \cot\beta\} \end{aligned}$$

Higgs Boson masses

- CP invariance in the Higgs sector is exact at tree level, but is broken by loop corrections.

A. Pilaftsis,Phys.Lett.B435:88-100,1998 ; Phys. Rev. **D58** (1998) 096010,

D. A. Demir, Phys. Rev. **D60** (1999) 055006; Phys.Rev.**D60** (1999) 095007

- The three neutral Higgs Bosons may mix each other resulting:

A. Pilaftsis and C. E. Wagner, Nucl. Phys. **B553** (1999) 3

M. Carena, J. Ellis, A. Pilaftsis and C. E. Wagner, hep-ph/0003180.

Significant corrections to the light Higgs boson mass for $M_{H^\pm} < 180$ GeV and for small $2 < \tan\beta < 10$ values. It also requires rather large values of $|A|$ and $|\mu| \gtrsim 1\ TeV$

Mass Splitting between the two heaviest Higgs bosons, $\sim 20\%$ for $M_{H^+} \simeq 300$ GeV and $|\mu| = 2$ TeV and $|A| \simeq 1$ TeV

EDMs in the MSSM and cancellations

•Experiment :

$|d_e| \leq 4.3 \times 10^{-27}$ e cm , $|d_n| \leq 6.3 \times 10^{-26}$ e cm

• The CP-Phases must be of order 10^{-2} in order to avoid the EDM constraints, unless....

Y. Kizukuri and N. Oshimo, Phys. Rev. **D46** (1992) 3025; S. Bertolini and F. Vissani, Phys. Lett. **B324** (1994) 164 `hep-ph/9311293`; A. Romanino and A. Strumia, Nucl. Phys. **B490** (1997) 3 `hep-ph/9610485`; S.A. Abel, Phys. Lett. **B410** (1997) 173 `hep-ph/9612272`; T. Ibrahim and P. Nath, Phys. Rev. **D57** (1998) 478; T. Falk and K.A. Olive, Phys. Lett. **B439** (1998) 71; T. Falk, A. Ferstl and K.A. Olive, Phys. Rev. **D59** (1999) 055009; T. Ibrahim and P. Nath, Phys. Rev. **D58** (1998) 111301; M. Brhlik, G.J. Good and G.L. Kane, Phys. Rev. **D59** (1999) 115004; A. Bartl, T. Gajdosik, W. Porod, P. Stockinger and H. Stremnitzer, `hep-ph/9903402`; T. Falk, K.A. Olive, M. Pospelov and R. Roiban, `hep-ph/9904393`. S. Pokorski, J. Rosiek and C.A. Savoy, Nucl. Phys. **B570** (2000) 81

$\surd$ Superpartner masses of order 1 TeV

$\surd$ Possible cancellations between the 2 diagrams for electron EDMs

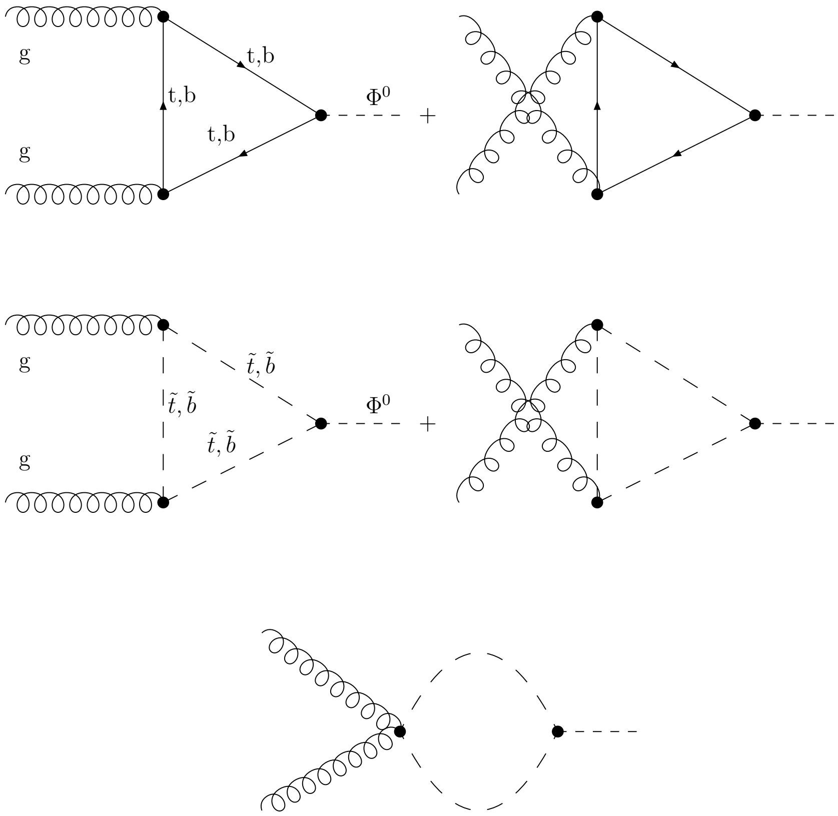
$\surd$ Possible cancellations between chargino and gluino contributions for the neutron EDMs

•2 loop EDMs : Direct constraints on the 3d generation trilinear couplings. In general $\tan\beta$ must be small (< 10), 1st and 2nd generation squark masses very large (> 1 TeV).

D. Chang, W. Keung and A. Pilaftsis, Phys. Rev. Lett. **82** (1999) 900

Higgs Boson Production

- Significant changes in the main Higgs boson production mechanism via gluon fusion



1

Effect of the phases at hadron colliders

A. Dedes and S. Moretti, Phys. Rev. Lett. 84(22)2000; Nucl.Phys.B576:29-55,2000,

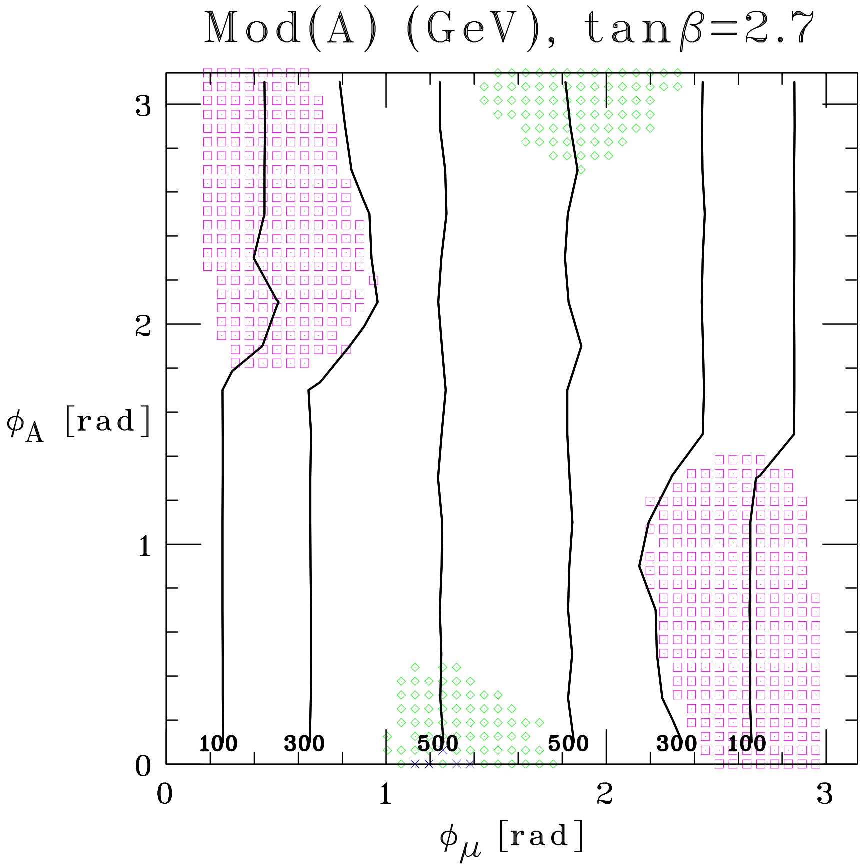
S. Y. Choi and J. S. Lee, Phys. Rev. **D61**, 115002 (2000)

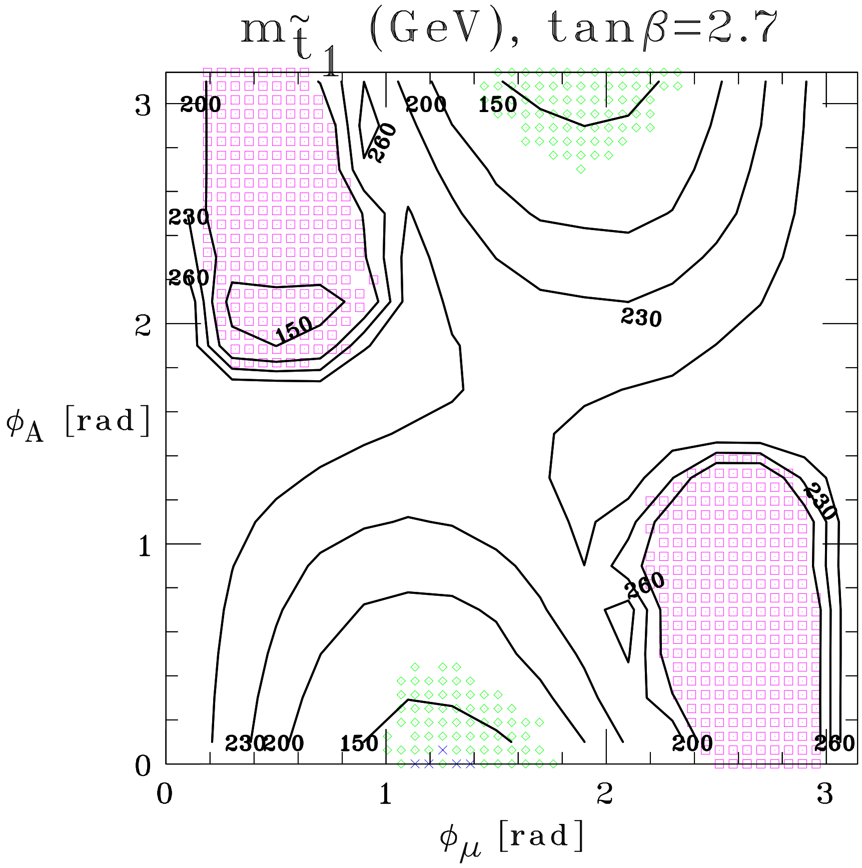
Example: Higgs Boson Production

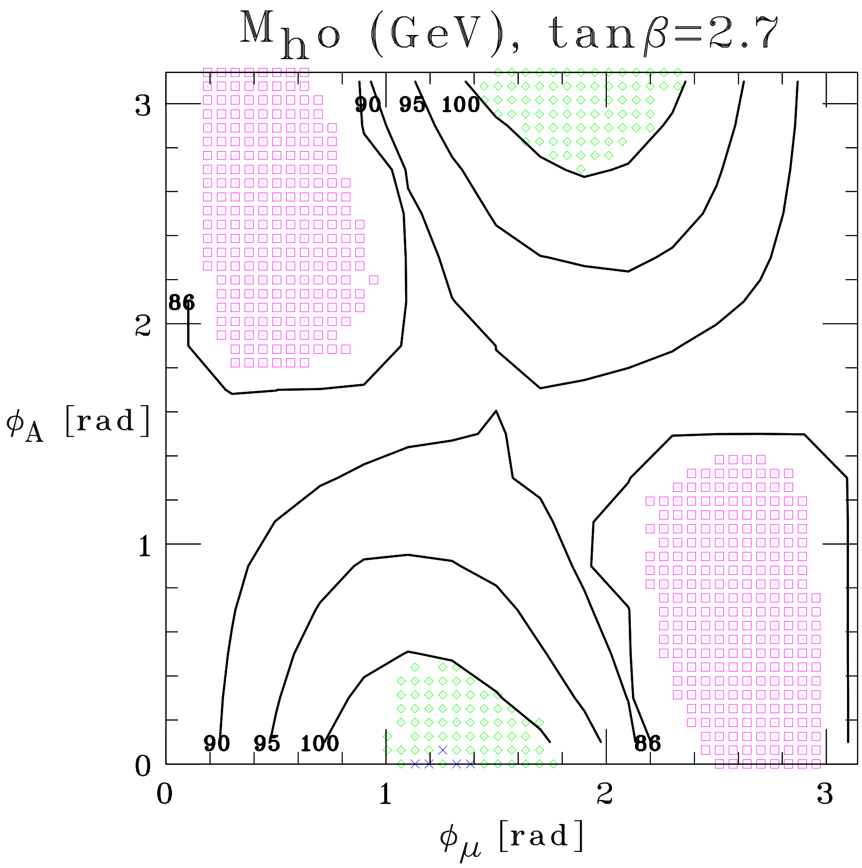
- We assume the following parameter space :

$\tan\beta$	$\lvert\mu\rvert$	$M_{\tilde{q}_{1,2}}$	$M_{\tilde{q}_3}$	$M_{\tilde{g}}$	M_{A^0}
2.7	600	2500	300	1000	200

- We find possible $|A|$'s such that the cancellation mechanism works..

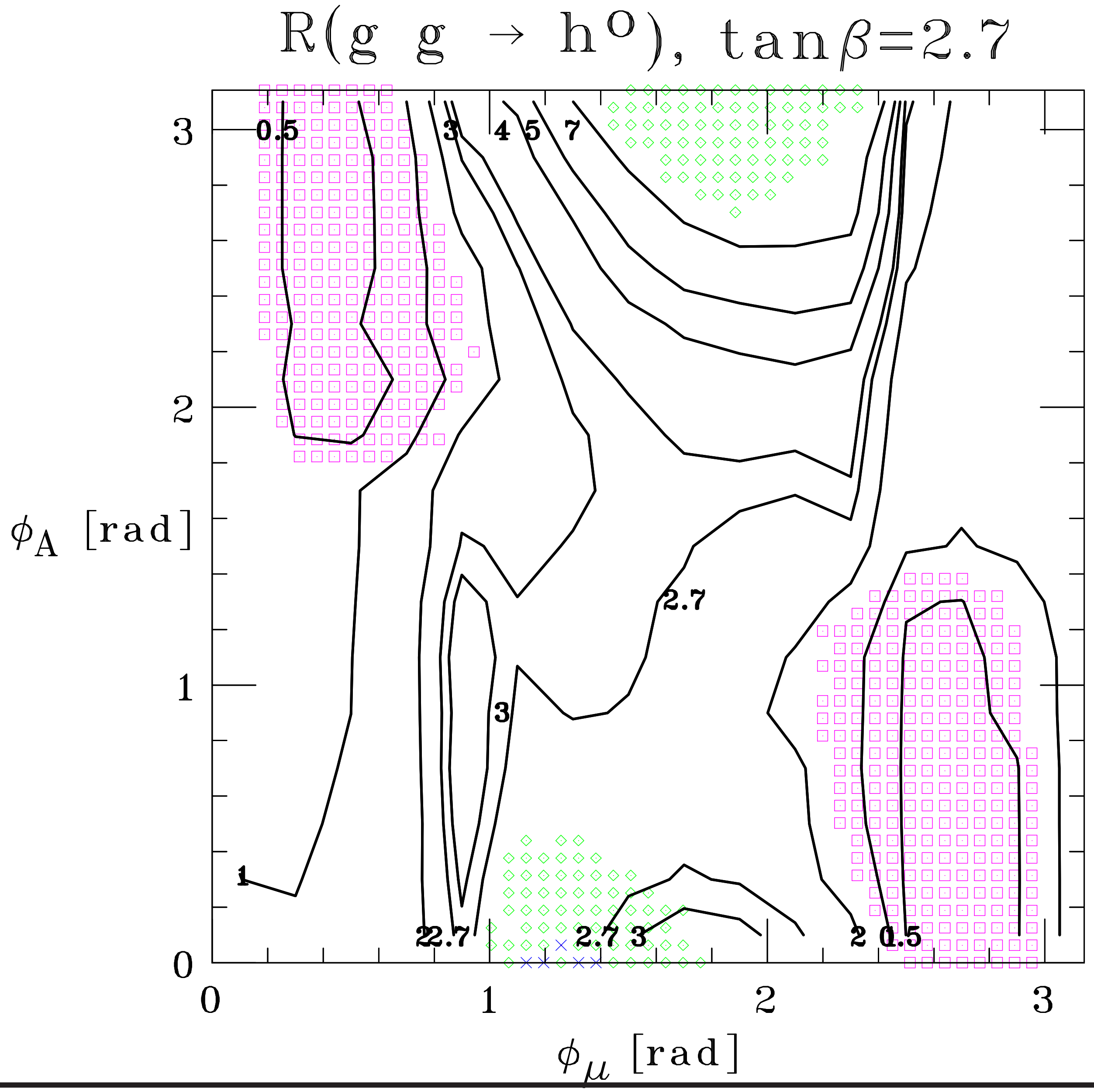


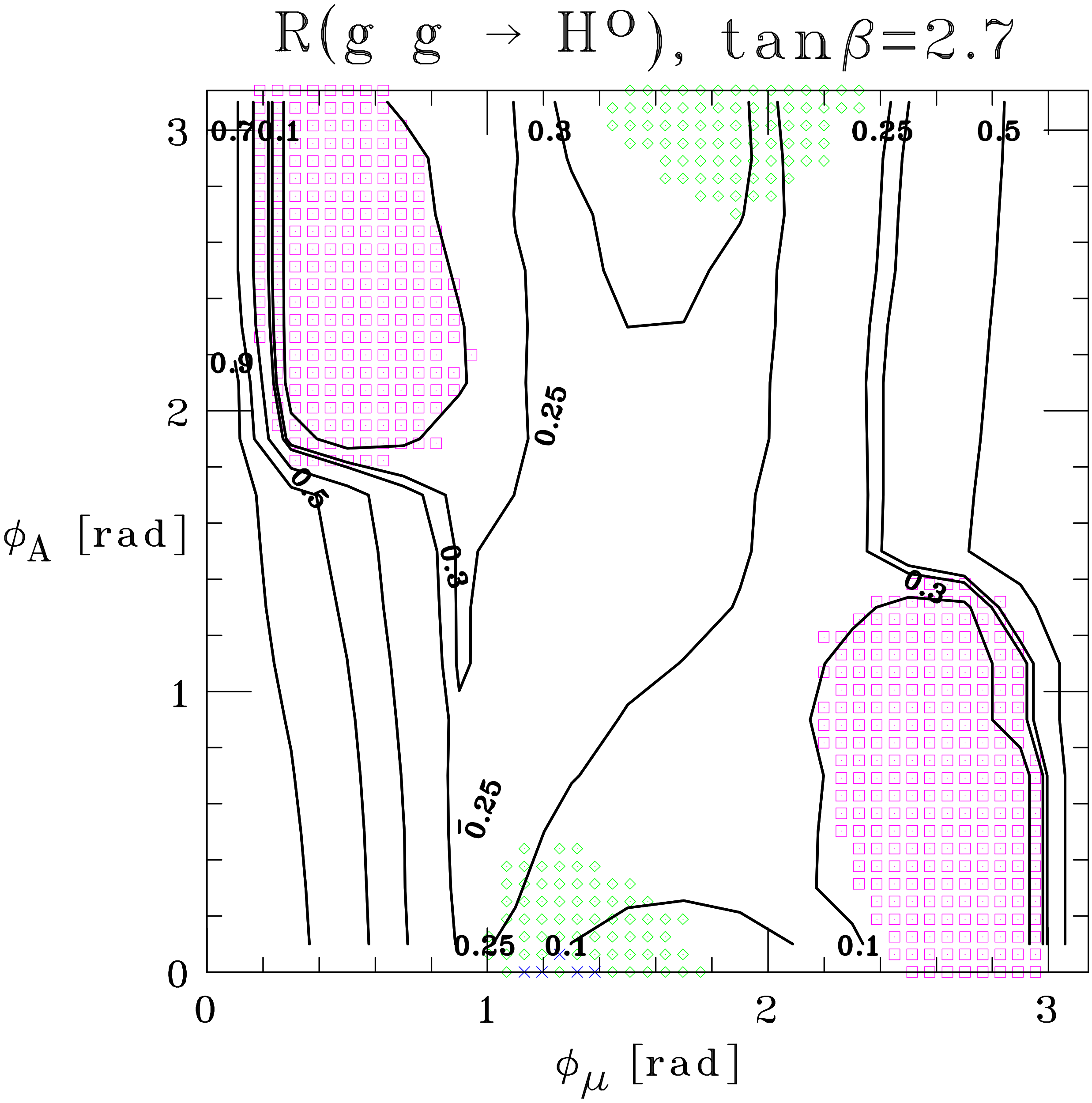

m$_{\tilde{t}_1}$ (GeV), tanβ=2.7
ϕ_A [rad]
ϕ_μ [rad]
200
230
260
150
200
150
260
230
230
260
230
200
150
200
260

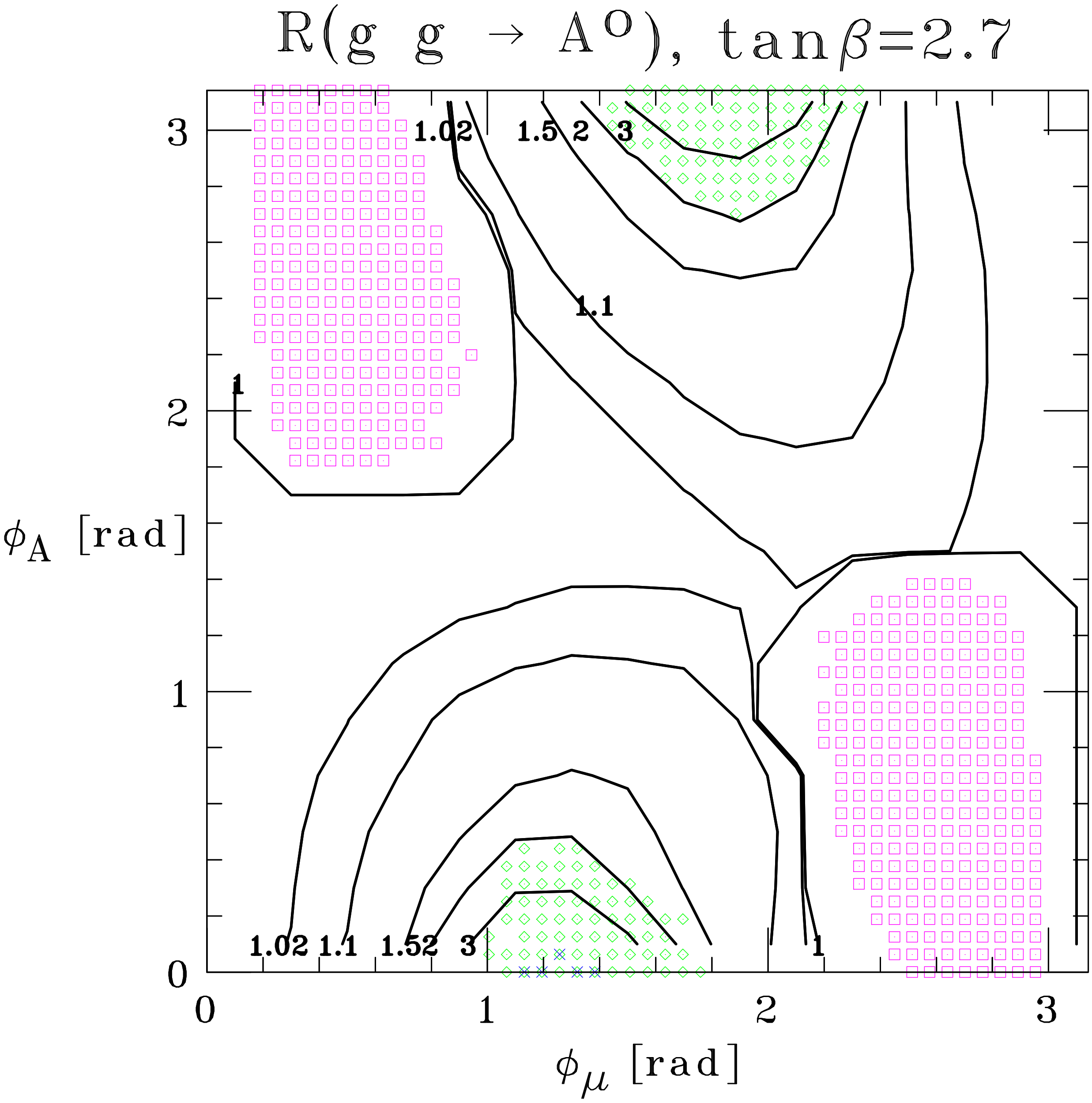

M$_{ho}$ (GeV), tanβ=2.7
ϕ_A [rad]
ϕ_μ [rad]
90
95
100
86
90
95
100
86

- We define the Ratio

$$R(gg \to \Phi^0) \;=\; \frac{\sigma_{\rm LO}^{\rm MSSM^*}(gg \to \Phi^0)}{\sigma_{\rm LO}^{\rm MSSM}(gg \to \Phi^0)}$$

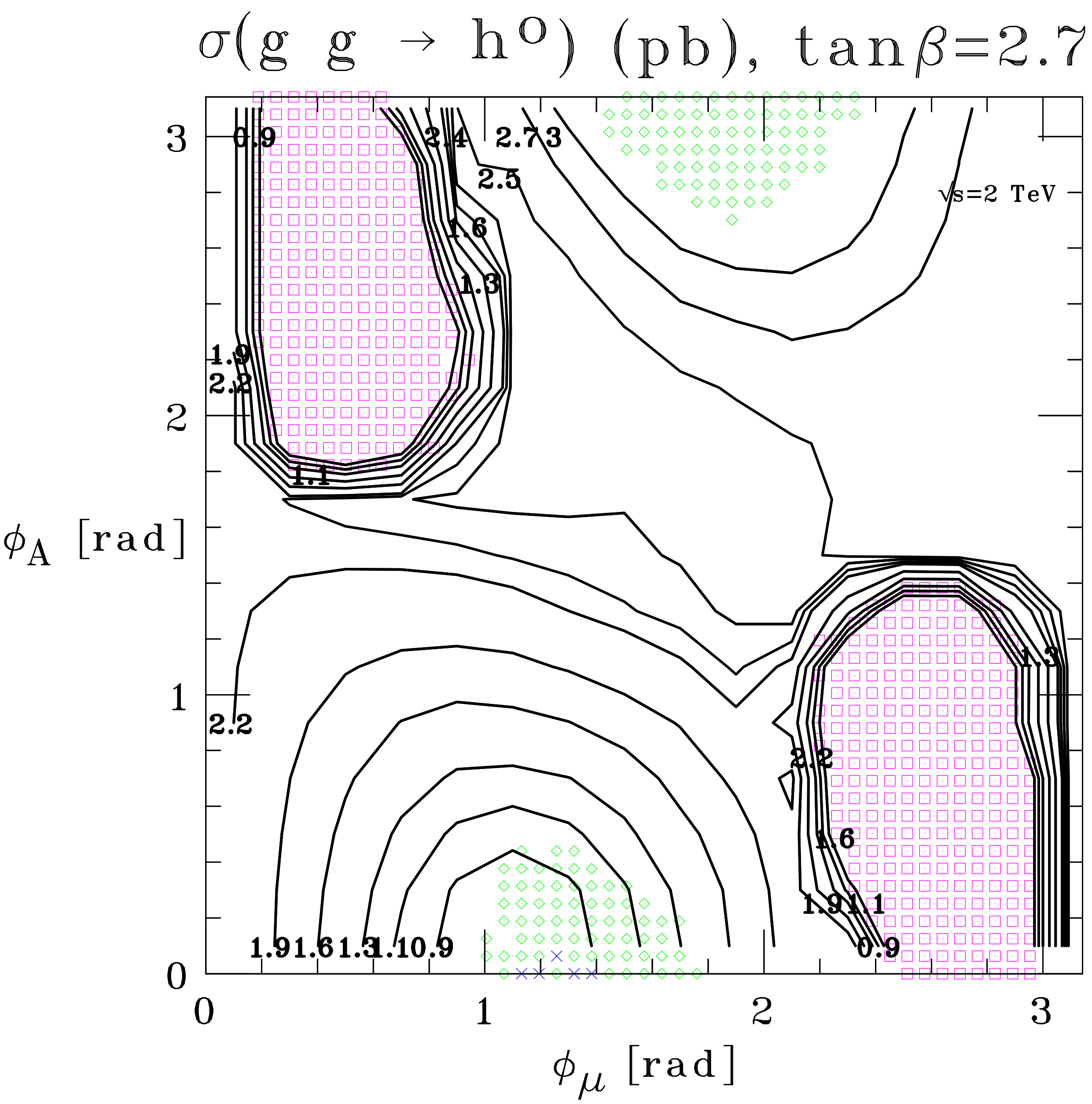



R(g g → H°), tanβ=2.7
ϕ_A [rad]
ϕ_μ [rad]
0.7
0.1
0.3
0.25
0.5
0.9
0.5
0.25
0.3
0.3
0.25
0.25
0.1
0.1
0
1
2
3

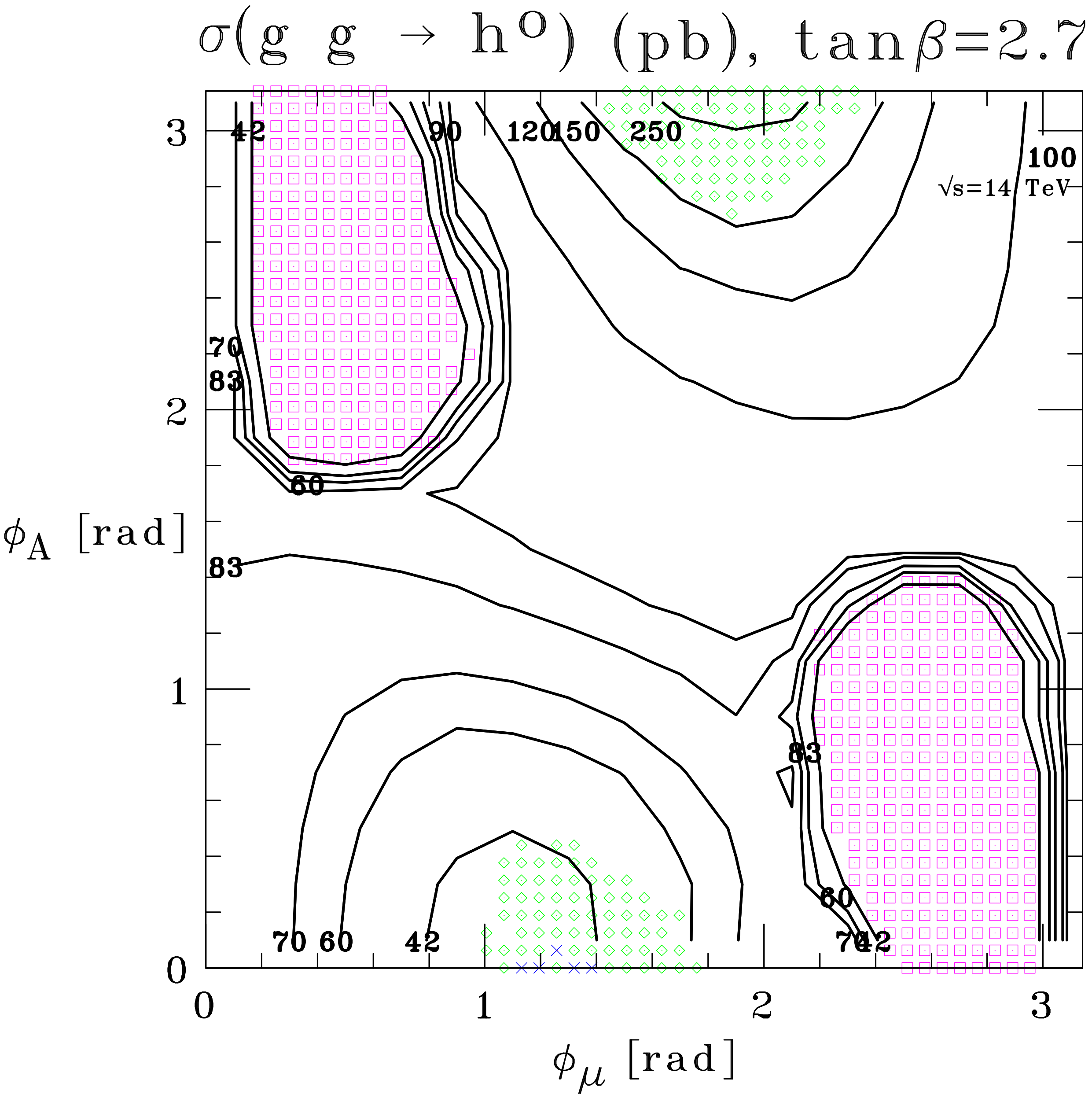

R(g g → A^O), tanβ=2.7
ϕ_A [rad]
ϕ_μ [rad]
0
1
2
3
1.02
1.5
2
3
1.1
1
1.02 1.1
1.52
3
1

• We include 2-loop QCD corrections and we find the cross sections for the Higgs boson production at the Tevatron

S. Dawson, A. Djouadi and M. Spira, Phys. Rev. Lett. **77** (1996) 16.



and for the LHC....



θ-angle versus CP-violation

A. Dedes and M. Pospelov, Phys. Rev. D61:116010,2000

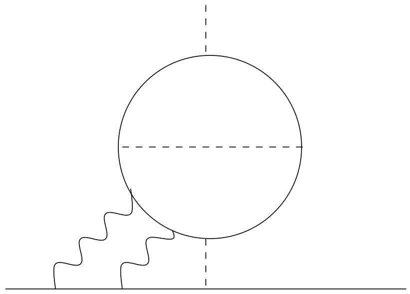
$$\bar{\theta} = \theta_{QCD} + arg\ det(M_u M_d) + \ldots$$

$$\mathcal{L}^{\theta} = \theta_{QCD} \frac{g_3^2}{32\pi^2} G^{\alpha}_{\mu\nu} \tilde{G}^{\alpha\mu\nu}$$

- θ-term breaks P and CP invariance
- From neutron EDMs : $\bar{\theta} < 6 \times 10^{-10}$!!
- Strong CP-problem : Why θ is so small??
- Assuming that the axion mechanism of solving the strong CP-problem does not exist and the vanishing of $\bar{\theta}$ at the tree level is achieved by some model building means, we study the naturalness of having large CP-violating sources in the leptonic sector.

$$arg\,\det(M_u M_d) = arg\,\det(Y_u) + arg\,\det Y_d + 3(arg\, v_u + arg\, v_d)$$

- In the SM : $v_u \equiv v_d^*$
- CP violation comes only from the complexity of Yukawa couplings



$$\bar{\theta} < \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{1}{16\pi^2}\right)^2 \frac{m_\tau^2}{M^2} J_{CP}^L$$

- SM: Induced theta term from the leptonic sector   Very small!

- MSSM

- Corrections already at 1-loop!

$$\begin{aligned} \mathcal{L}_{soft} \supset & - \epsilon_{ab}[(\mathbf{A}_e \mathbf{Y}_e)_{ij} \widetilde{l}_{Li}^{a} H_1^b \widetilde{e}_{Rj}^{*} + \mathrm{h.c}] \\ & - [\mu B \epsilon_{ab} H_1^a H_2^b + \mathrm{h.c}] \;, \end{aligned}$$

$$\Downarrow$$

$$\begin{aligned} \frac{d\bar{A}_\tau}{dt} &= \frac{8|Y_\tau|^2}{16\pi^2} \bar{A}_\tau \;, \\ \frac{d\bar{B}}{dt} &= \frac{2|Y_\tau|^2}{16\pi^2} \bar{A}_\tau \;. \end{aligned} \tag{1}$$

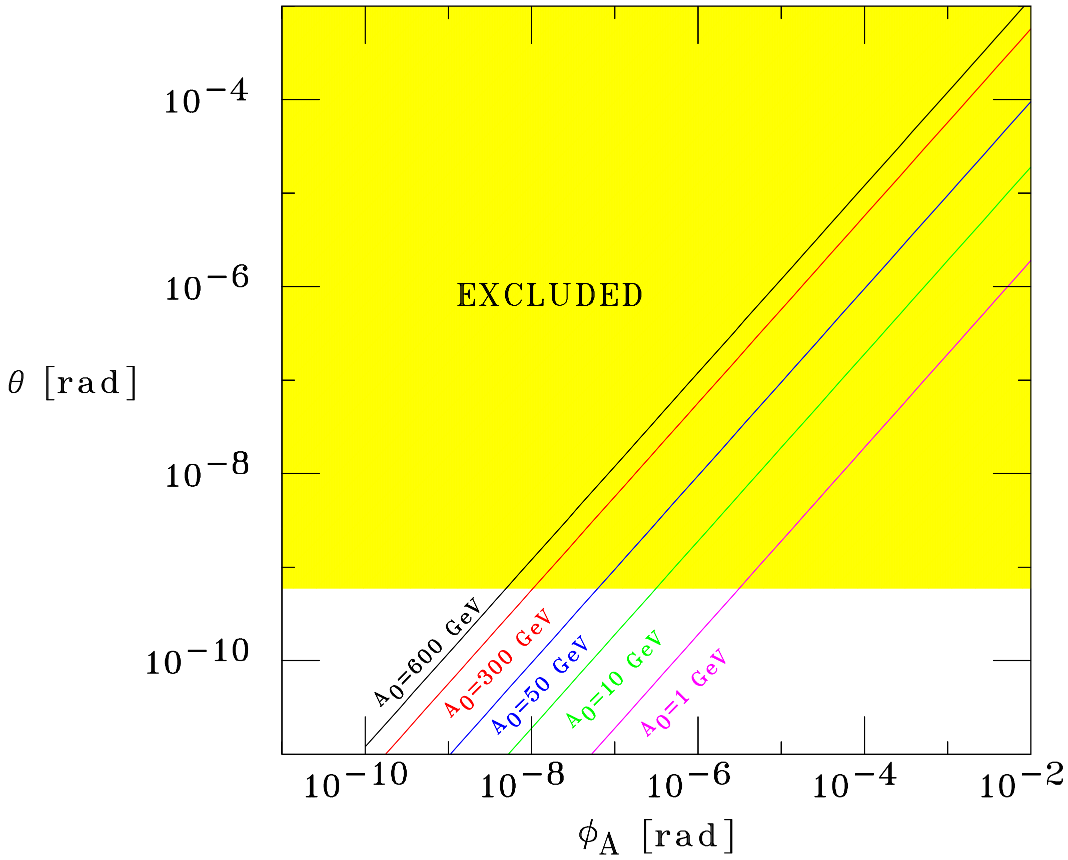
$$\Downarrow$$

$$\sin\phi_B(M_Z) \simeq -2 \times 10^{-4} \sin\phi_A$$

From the minimization conditions of the scalar Higgs potential

$$v_1 v_2 = \frac{\mu^* B^* |v|^2}{m_1^2 + m_2^2},$$

$$\Downarrow$$



$$\Downarrow$$

$$\phi_A(M_G) < 10^{-6},$$

$$\Downarrow$$

- In MSSM without an axion, a large phase of the leptonic A_l-parameter is excluded on the ground of naturalness

EDMs in the MSSM without R-Parity

S. Abel, A. Dedes and H. Dreiner, JHEP0005:013,2000

R. M. Godbole, S. Pakvasa, S. D. Rindani and X. Tata, Phys. Rev. **D61** (2000) 113003

P. Herczeg, Phys. Rev. **D61** (2000) 095010

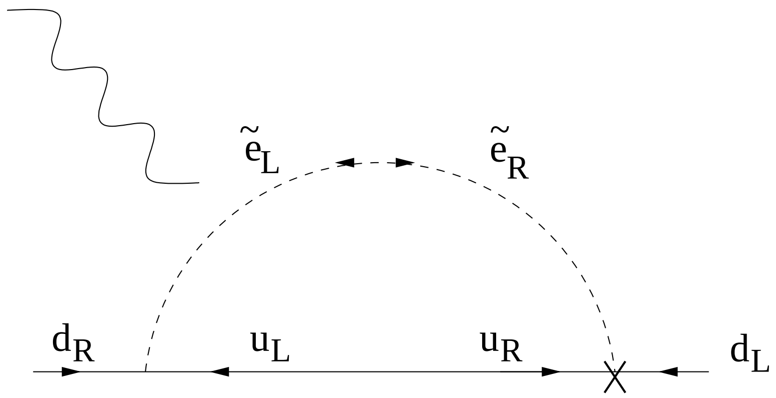
K. Choi, E. J. Chun and K. Hwang, hep-ph/0004101.

Y. Y. Keum and O. C. Kong, hep-ph/0004110.

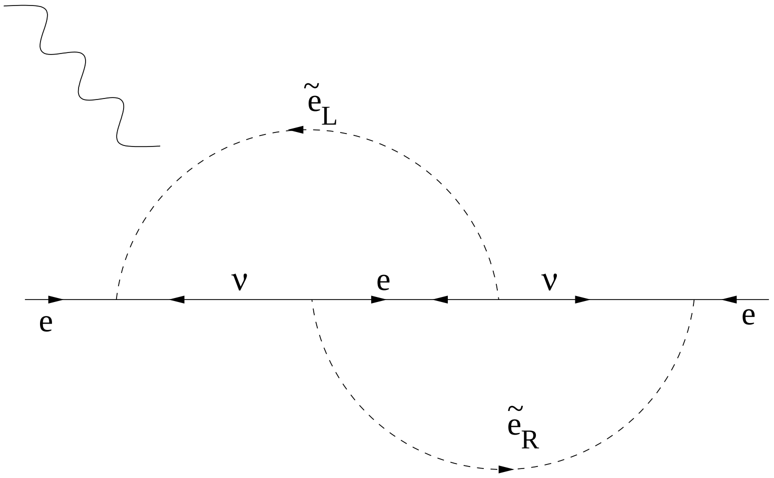
D. Chang, W. Chang, M. Frank and W. Keung, hep-ph/0004170.

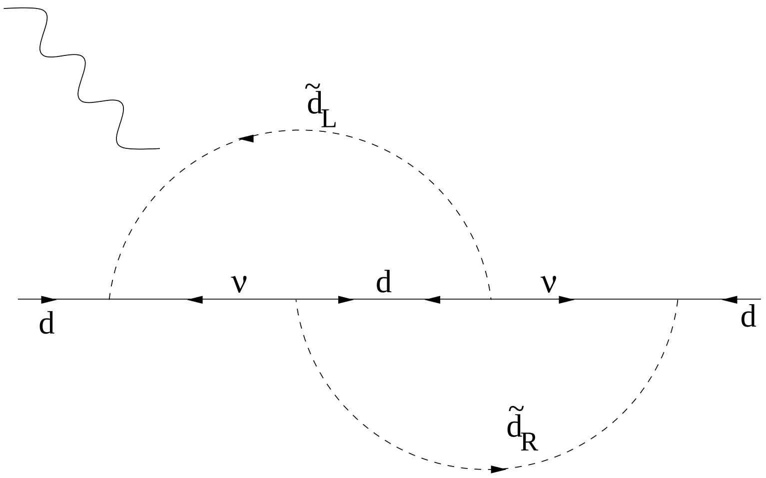
- We show that in the MSSM without R-parity symmetry there are *no* new contributions to electron and neutron electric dipole moments (EDMs) at one-loop induced by the R-parity violating Yukawa couplings.

$$\begin{aligned}\delta L_L \;=\; & \frac{1}{2}\lambda_{ijk}\{\tilde{e}_{L_j}\overline{e}_k P_L \nu_i + \tilde{\nu}_{L_i}\overline{e}_k P_L e_j + \tilde{e}^*_{R_k}\overline{\nu}^c_i P_L e_j - (i \leftrightarrow j)\} + \text{h.c.} \\ & + \lambda'_{ijk}\left\{\tilde{d}_{L_j}\overline{d}_k P_L \nu_i + \tilde{\nu}_{L_i}\overline{d}_k P_L d_j + \tilde{d}^*_{R_k}\overline{\nu}^c_i P_L d_j - \right. \\ & \qquad \left. - \tilde{u}_{L_j}\overline{d}_k P_L e_i - \tilde{e}_{L_i}\overline{d}_k P_L u_j - \tilde{d}^*_{R_k}\overline{e}_i P_L u_j\right\} + \text{ h.c.}\,,\end{aligned}$$



- There are contributions to the EDMs at 2-loop level : For example :





- Constraints on the R-parity violating couplings :

$$\mathrm{Im}\left(\sum_{ij\ell mn}\frac{m_\ell}{m_\tau}\lambda_{1mn}\lambda^*_{j\ell n}\lambda^*_{im\ell}\lambda_{ij1}\right)\leq 10^{-6}\,,$$

$$\mathrm{Im}\left(\sum_{ij\ell mn}\frac{m_\ell}{m_t}\lambda'_{1mn}\,\lambda'^*_{j\ell n}\,\lambda'^*_{im\ell}\,\lambda'_{ij1}\right)\leq 3\times 10^{-6}\,.$$

•Neutrino EDMs and MDMs

• If neutrinos are massive (as they indeed appear to be) then CP-symmetry can also be violated in the leptonic sector and one expects (transition) neutrino EDMs as well.

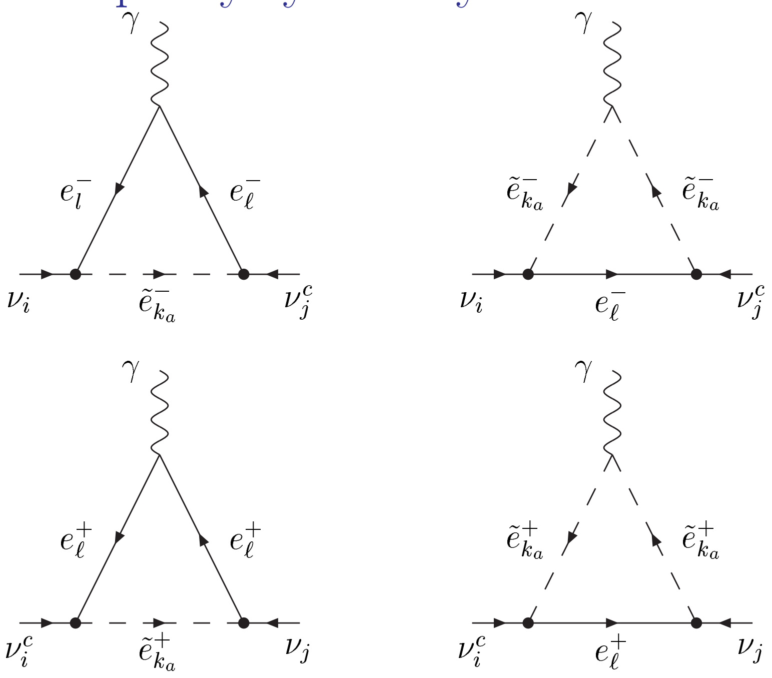
•"Earth bound" constraints

$$
\begin{aligned}
|\mu_\nu| &\leq 1.5 \times 10^{-10}\, \mu_B\,, \\
|d_{\nu_\tau}| &\leq 5.2 \times 10^{-17}\, e\,\mathrm{cm}\,,
\end{aligned}
$$

•Cosmological constraints

$$
\begin{aligned}
|\mu_\nu| &\leq 3 \times 10^{-12}\, \mu_B\,, \\
|d_\nu| &\leq 2.5 \times 10^{-22}\, e\ \mathrm{cm}
\end{aligned}
$$

• Neutrino EDMs or MDMs appear already at 1-loop in the MSSM without R-parity symmetry:



- By considering the SuperKamiokande constraint

$$\Re(\lambda_{121}\lambda_{212}) < 0.58\,,$$
$$\Re(\lambda_{131}\lambda_{213}) < 0.059\,,$$
$$\Re(\lambda_{123}\lambda_{232}) < 0.063\,,$$
$$\Re(\lambda'_{121}\lambda'_{212})\,,\ \Re(\lambda'_{221}\lambda'_{112}) < 0.60\,,$$
$$\Re(\lambda'_{131}\lambda'_{213})\,,\ \Re(\lambda'_{231}\lambda'_{113})\,,\ \Re(\lambda'_{132}\lambda'_{223})\,,\ \Re(\lambda'_{123}\lambda'_{232}) < 0.030\,.$$

- By considering the cosmological constraints we set limits on the R-parity violating couplings :

$$\mathrm{Im}(\lambda_{i21}\lambda_{j12}) < 0.05\,,$$
$$\mathrm{Im}(\lambda_{i31}\lambda_{j13}) < 0.004\,,$$
$$\mathrm{Im}(\lambda_{i23}\lambda_{j32}) < 0.005\,,$$
$$\mathrm{Im}(\lambda'_{i21}\lambda'_{j12}) < 0.06\,,$$
$$\mathrm{Im}(\lambda'_{i31}\lambda'_{j13})\,,\ \mathrm{Im}(\lambda'_{i32}\lambda'_{j23}) < 0.0024\,.$$

in addition to those presented in B.C. Allanach, A. Dedes and H.K. Dreiner, Phys. Rev. **D60** (1999) 075014

Conclusions

• We calculate the Higgs boson production cross sections in the MSSM with the CP-violating phases from the soft SUSY breaking sector.

$\surd$ If the Supersymmetric CP-violating phases can be large, then, the Higgs boson production at Hadron colliders can be drastically modified.

$\Rightarrow$ $\sigma(pp \to (H^0)h^0)$: up to 7 times larger or smaller.

$\Rightarrow$ New (always positive) contributions in the case of the CP-Odd Higgs boson production. The cross section of $pp \to A^0$ can be three times larger than it is in the phaseless case.

$\Rightarrow$ If there is no axion in the MSSM and a zero θ parameter at the tree level is obtained by model building means, then there is a huge contribution from the leptonic CP-phases to the θ-term already at 1-loop or in other words the (leptonic) phases must be unnaturally small and less than 10^{-6}.

$\Rightarrow$ There are no electron or neutron EDMs at 1-loop induced by the R-parity violating couplings. Bounds on their products are derived (possibly) first at 2-loop level.

$\Rightarrow$ Neutrino EDMs or MDMs obtained already at 1-loop. Weak constraints on the products of the various R-parity violating couplings.