# Flavour and CP Violation in the MSSM at Large $\tan\beta$

Apostolos Pilaftsis

*School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*

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- **Flavour and CP Problems in the Minimal Supersymmetric Standard Model**

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  - **Electric Dipole Moments (EDMs)**
  - **B-Meson Flavour Changing Neutral Current (FCNC) Observables**

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- **Conclusions and Future Directions**

## • Flavour and CP Problems in the MSSM

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- Gaugino masses: $3 \oplus 3 = 6$

$$-\mathcal{L}_{\rm soft} \supset \frac{1}{2}\left(M_3\,\widetilde{g}\widetilde{g} + M_2\,\widetilde{W}\widetilde{W} + M_1\,\widetilde{B}\widetilde{B} + {\rm h.c.}\right)$$

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- Trilinear couplings: $\mathbf{a}_{\mathbf{f}ij} \equiv \mathbf{h}_{\mathbf{f}ij} \cdot \mathbf{A}_{\mathbf{f}ij}$: $3 \times (3 \oplus 6 \oplus 9) = 54$

$$-\mathcal{L}_{\rm soft} \supset (\widetilde{u}^*_R\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{d}^*_R\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{e}^*_R\,\mathbf{a_e}\,\widetilde{L}H_d + \text{h.c.})$$

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- Higgs masses: $3 \oplus 1 = 4$, and the $\mu$-term: $1 \oplus 1 = 2$

$$-\mathcal{L}_{\rm soft} \supset M^2_{H_u} H^\dagger_u H_u + M^2_{H_d} H^\dagger_d H_d + (B\mu H_u H_d + \text{h.c.})$$

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$31 \oplus 33 \oplus 47 = \mathbf{111}$ **!**

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- The MFV:

$$m_0(M_{\rm MFV})\,,\quad m_{1/2}(M_{\rm MFV})\,,\quad A(M_{\rm MFV})\,;\quad \tan\beta(m_t)\,,\quad M_Z \quad \text{up to sign}(\mu)$$

with real and positive $m_0$, $m_{1/2}$, and $A$

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- Next to MFV:

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with complex $m_{1/2}$ and $A$

- Is there any maximal extension to MFV?

- Breaking of the $[SU(3)\otimes U(1)]^5$ flavour symmetries in the MSSM:

[R. S. Chivukula and H. Georgi, PLB188 (1987) 99;
Generalization of GIM mechanism: S.L. Glashow, J. Iliopoulos, L. Maiani, PRD2 (1970) 1285.]

$$\begin{aligned}
\mathbf{h}_{u,d} &\to \mathbf{U}^\dagger_{U,D}\,\mathbf{h}_{u,d}\,\mathbf{U}_Q\,, \qquad \mathbf{h}_e \to \mathbf{U}^\dagger_E\,\mathbf{h}_e\,\mathbf{U}_L\,,\\
\widetilde{\mathbf{M}}^2_{Q,L,U,D,E} &\to \mathbf{U}^\dagger_{Q,L,U,D,E}\,\widetilde{\mathbf{M}}^2_{Q,L,U,D,E}\,\mathbf{U}_{Q,L,U,D,E}\,,\\
\mathbf{a}_{u,d} &\to \mathbf{U}^\dagger_{U,D}\,\mathbf{a}_{u,d}\,\mathbf{U}_Q\,, \qquad \mathbf{a}_e \to \mathbf{U}^\dagger_E\,\mathbf{a}_e\,\mathbf{U}_L\,.
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\mathbf{a}_{u,d} &\to \mathbf{U}^\dagger_{U,D}\,\mathbf{a}_{u,d}\,\mathbf{U}_Q\,, \qquad \mathbf{a}_e \to \mathbf{U}^\dagger_E\,\mathbf{a}_e\,\mathbf{U}_L\,.
\end{aligned}
$$

- **Maximal CP and Minimal Flavour Violation (MCPMFV)**

[J. Ellis, J. S. Lee, A. P., PRD76 (2007) 115011.]

$$
M_{1,2,3}\,, \quad M^2_{H_{u,d}}\,, \quad \widetilde{\mathbf{M}}^2_{Q,L,U,D,E} = \widetilde{M}^2_{Q,L,U,D,E}\,\mathbf{1}_3\,, \quad \mathbf{A}_{u,d,e} = A_{u,d,e}\,\mathbf{1}_3
$$

$$
3 \oplus 3 \qquad 2 \qquad 5 \qquad 3 \oplus 3
$$

**$13 \oplus 6 = 19$ Parameters !**

- Beyond the MCPMFV:

$$\widetilde{\mathbf{M}}^2_Q(M_X) \;=\; \widetilde{M}^2_Q\,\mathbf{1}_3 \;+\; \widetilde{m}^2_1\,(\mathbf{h}^\dagger_d\mathbf{h}_d) \;+\; \widetilde{m}^2_2\,(\mathbf{h}^\dagger_u\mathbf{h}_u) \;+\; \widetilde{m}^2_3\,(\mathbf{h}^\dagger_d\mathbf{h}_d\,\mathbf{h}^\dagger_u\mathbf{h}_u) \;+\; \ldots$$

  - Flavour non-singlet mass scales $\widetilde{m}^2_n$ $(+\widetilde{M}^2_Q)$ can be as many as $9 = \dim(\widetilde{\mathbf{M}}^2_Q)$.
  - $\widetilde{m}^2_n \neq 0 \quad\Longrightarrow$ (i) flavon model and/or (ii) RG running.
  - With $\widetilde{m}^2_n \ll \widetilde{M}^2_Q$, FCNC effects are under control.

[G. D'Ambrosio, G. F. Giudice, G. Isidori, A. Strumia, NPB645 (2002) 155;
G. G. Ross, L. Velasco-Sevilla, O. Vives, NPB692 (2004) 50;
S. Antusch, S. F. King and M. Malinsky, arXiv:0708.1282 [hep-ph];
P. Paradisi, M. Ratz, R. Schieren and C. Simonetto, arXiv:0805.3989 [hep-ph].]

- **Higgs Mediation of Flavour and CP in the MSSM at Large $\tan\beta$**

## • Higgs Mediation of Flavour and CP in the MSSM at Large $\tan\beta$

**Flavour- and Gauge-Covariant Effective Lagrangian** $(H_u = \Phi_2,\ H_d = i\tau_2\Phi_1^*)$

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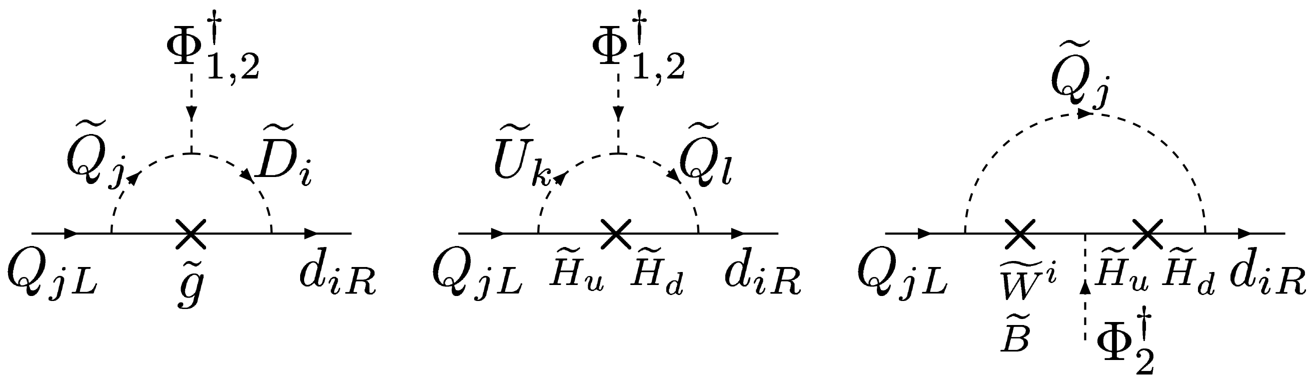


$$-\mathcal{L}_{\rm eff}^d[\Phi_1,\Phi_2] \;=\; \overline{d_{R\alpha}}\,\big(\,\mathbf{h}_d\,\Phi_1^\dagger \;+\; \Delta\mathbf{h}_d[\Phi_1,\Phi_2]\,\big)_{\alpha\beta}\,Q_{L\,\beta} \;+\; {\rm h.c.},$$

- $\Delta\mathbf{h}_d[\Phi_1,\Phi_2]$ is a Coleman-Weinberg functional depending on $\Phi_{1,2}$.

- $\Delta\mathbf{h}_d[\Phi_1,\Phi_2]$ flavour- and gauge-transforms as $\mathbf{h}_d\,\Phi_1^\dagger$.

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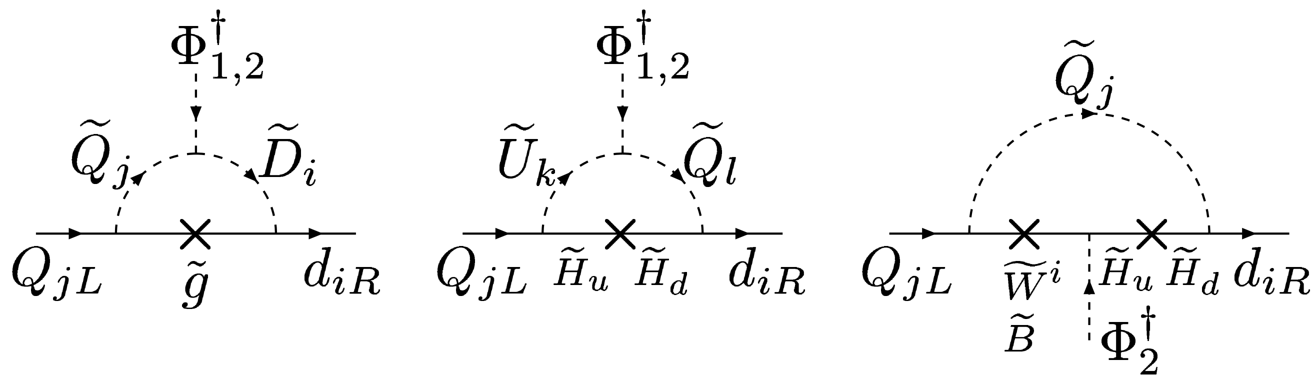

$$-\mathcal{L}_{\rm eff}^d[\Phi_1,\Phi_2] \;=\; \overline{d_{R\alpha}}\,(\,\mathbf{h}_d\,\Phi_1^\dagger \;+\; \Delta\mathbf{h}_d[\Phi_1,\Phi_2]\,)_{\alpha\beta}\,Q_{L\,\beta} \;+\; \text{h.c.},$$

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- $\Delta\mathbf{h}_d[\Phi_1,\Phi_2]$ flavour- and gauge-transforms as $\mathbf{h}_d\,\Phi_1^\dagger$.

[First studies: T. Banks, NPB303 (1988) 172; E. Ma, PRD39 (1989) 1922;
R. Hempfling, PRD49 (1994) 6168;
L. J. Hall, R. Rattazi, U. Sarid, PRD50 (1994) 7048.]

- Analytic form of $\Delta \mathbf{h}_d[\Phi_1, \Phi_2]$:

$$
\begin{aligned}
(\Delta \mathbf{h}_d)_{ij} \;&=\; \int \frac{d^n k}{(2\pi)^n\, i} \Big[ P_L \frac{2 g_s^2 C_F\, M_3^*}{k^2 - |M_3^2|} \left( \frac{1}{k^2 \mathbf{1}_{12} - \widetilde{\mathbf{M}}^2} \right)_{\widetilde{D}_i \widetilde{Q}_j^\dagger} \\
&+ P_L \left( \frac{1}{\not{k} \mathbf{1}_8 - \mathbf{M}_C P_L - \mathbf{M}_C^\dagger P_R} \right)_{\widetilde{H}_u \widetilde{H}_d} P_L\, (\mathbf{h}_d)_{il} \left( \frac{1}{k^2 \mathbf{1}_{12} - \widetilde{\mathbf{M}}^2} \right)_{\widetilde{Q}_l \widetilde{U}_k^\dagger} (\mathbf{h}_u)_{kj} \\
&+ (\sqrt{2} g', \frac{g_w \tau^i}{\sqrt{2}})\, P_L \left( \frac{1}{\not{k} \mathbf{1}_8 - \mathbf{M}_C P_L - \mathbf{M}_C^\dagger P_R} \right)_{\widetilde{H}_d \widetilde{B}\,, \widetilde{H}_d \widetilde{W}^i} P_L\, (\mathbf{h}_d)_{ij} \left( \frac{1}{k^2 \mathbf{1}_{12} - \widetilde{\mathbf{M}}^2} \right)_{\widetilde{Q}_j \widetilde{Q}_j^\dagger} \Big]
\end{aligned}
$$

$\widetilde{\mathbf{M}}^2[\Phi_1, \Phi_2]$ : $12 \times 12$ Higgs-field dependent squark mass matrix

$\mathbf{M}_C[\Phi_1, \Phi_2]$ : $8 \times 8$ Higgs-field dependent chargino-neutralino mass matrix

- Analytic form of $\Delta\mathbf{h}_d[\Phi_1,\Phi_2]$:

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& + P_L \Big( \frac{1}{\not{k}\mathbf{1}_8 - \mathbf{M}_C P_L - \mathbf{M}_C^\dagger P_R} \Big)_{\widetilde{H}_u \widetilde{H}_d} P_L\, (\mathbf{h}_d)_{il} \Big( \frac{1}{k^2\mathbf{1}_{12} - \widetilde{\mathbf{M}}^2} \Big)_{\widetilde{Q}_l \widetilde{U}_k^\dagger} (\mathbf{h}_u)_{kj} \\
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- Flavour covariance: $\Delta\mathbf{h}_d \;\to\; \mathbf{U}_D^\dagger\, \Delta\mathbf{h}_d\, \mathbf{U}_Q$

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- Flavour covariance: $\Delta\mathbf{h}_d \;\to\; \mathbf{U}_D^\dagger\, \Delta\mathbf{h}_d\, \mathbf{U}_Q$

- Normalization: $\mathbf{h}_d = \frac{\sqrt{2}}{v_1}\widehat{M}_d\, V_{\rm CKM}^\dagger\, R_d^{-1}$; $\quad R_d \equiv \mathbf{1} + \frac{\sqrt{2}}{v_1}\Delta_d\,$; $\quad \Delta_d \equiv h_d^{-1}\langle\Delta\mathbf{h}_d\rangle$

- The $12 \times 12$ Higgs-field dependent squark mass matrix $\widetilde{\mathbf{M}}^2[\Phi_1, \Phi_2]$:

$$\widetilde{\mathbf{M}}^2[\Phi_1, \Phi_2] = \begin{pmatrix} (\widetilde{\mathbf{M}}^2)_{\widetilde{Q}^\dagger \widetilde{Q}} & (\widetilde{\mathbf{M}}^2)_{\widetilde{Q}^\dagger \widetilde{U}} & (\widetilde{\mathbf{M}}^2)_{\widetilde{Q}^\dagger \widetilde{D}} \\ (\widetilde{\mathbf{M}}^2)_{\widetilde{U}^\dagger \widetilde{Q}} & (\widetilde{\mathbf{M}}^2)_{\widetilde{U}^\dagger \widetilde{U}} & (\widetilde{\mathbf{M}}^2)_{\widetilde{U}^\dagger \widetilde{D}} \\ (\widetilde{\mathbf{M}}^2)_{\widetilde{D}^\dagger \widetilde{Q}} & (\widetilde{\mathbf{M}}^2)_{\widetilde{D}^\dagger \widetilde{U}} & (\widetilde{\mathbf{M}}^2)_{\widetilde{D}^\dagger \widetilde{D}} \end{pmatrix}_{ij}$$

$$\begin{aligned}
(\widetilde{\mathbf{M}}^2)_{\widetilde{Q}_i^\dagger \widetilde{Q}_j} &= (\widetilde{\mathbf{M}}^2_Q)_{ij}\, \mathbf{1}_2 + (\mathbf{h}_d^\dagger \mathbf{h}_d)_{ij}\, \Phi_1 \Phi_1^\dagger + (\mathbf{h}_u^\dagger \mathbf{h}_u)_{ij}\, (\Phi_2^\dagger \Phi_2\, \mathbf{1}_2 - \Phi_2 \Phi_2^\dagger) \\
&\quad - \frac{1}{2} g^2\, \delta_{ij}\, (\Phi_1 \Phi_1^\dagger - \Phi_2 \Phi_2^\dagger) + \delta_{ij}\, (\frac{1}{4} g^2 - \frac{1}{12} g'^2)\, (\Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2)\, \mathbf{1}_2\,, \\
(\widetilde{\mathbf{M}}^2)_{\widetilde{U}_i^\dagger \widetilde{Q}_j} &= (\widetilde{\mathbf{M}}^2)^\dagger_{\widetilde{Q}_j^\dagger \widetilde{U}_i} = -(\mathbf{a}_u)_{ij}\, \Phi_2^T i\tau_2 + (\mathbf{h}_u)_{ij}\, \mu^*\, \Phi_1^T i\tau_2\,, \\
(\widetilde{\mathbf{M}}^2)_{\widetilde{D}_i^\dagger \widetilde{Q}_j} &= (\widetilde{\mathbf{M}}^2)^\dagger_{\widetilde{Q}_j^\dagger \widetilde{D}_i} = (\mathbf{a}_d)_{ij}\, \Phi_1^\dagger - (\mathbf{h}_d)_{ij}\, \mu^*\, \Phi_2^\dagger\,, \\
(\widetilde{\mathbf{M}}^2)_{\widetilde{U}_i^\dagger \widetilde{U}_j} &= (\widetilde{\mathbf{M}}^2_U)_{ij} + (\mathbf{h}_u \mathbf{h}_u^\dagger)_{ij}\, \Phi_2^\dagger \Phi_2 + \frac{1}{3} \delta_{ij}\, g'^2\, (\Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2)\,, \\
(\widetilde{\mathbf{M}}^2)_{\widetilde{D}_i^\dagger \widetilde{D}_j} &= (\widetilde{\mathbf{M}}^2_D)_{ij} + (\mathbf{h}_d \mathbf{h}_d^\dagger)_{ij}\, \Phi_1^\dagger \Phi_1 - \frac{1}{6} \delta_{ij}\, g'^2\, (\Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2)\,, \\
(\widetilde{\mathbf{M}}^2)_{\widetilde{U}_i^\dagger \widetilde{D}_j} &= (\widetilde{\mathbf{M}}^2)^\dagger_{\widetilde{D}_j^\dagger \widetilde{U}_i} = (\mathbf{h}_u \mathbf{h}_d^\dagger)_{ij}\, \Phi_1^T i\tau_2 \Phi_2
\end{aligned}$$

- The $8 \times 8$ Higgs-field dependent chargino-neutralino mass matrix $\mathbf{M}_C[\Phi_1, \Phi_2]$:

$$\mathbf{M}_C[\Phi_1, \Phi_2] \;=\; \begin{pmatrix} M_1 & 0 & -\frac{1}{\sqrt{2}}\, g' \Phi_2^\dagger & \frac{1}{\sqrt{2}}\, g' \Phi_1^T\,(i\tau_2) \\ 0 & M_2\, \mathbf{1}_3 & \frac{1}{\sqrt{2}}\, g \Phi_2^\dagger\, \tau_i & -\frac{1}{\sqrt{2}}\, g \Phi_1^T\,(i\tau_2)\,\tau_i \\ -\frac{1}{\sqrt{2}}\, g' \Phi_2^* & \frac{1}{\sqrt{2}}\, g\tau_i^T\, \Phi_2^* & \mathbf{0}_2 & \mu\,(i\tau_2) \\ -\frac{1}{\sqrt{2}}\,(i\tau_2)\, g' \Phi_1 & \frac{1}{\sqrt{2}}\, g\tau_i^T\,(i\tau_2)\Phi_1 & -\mu\,(i\tau_2) & \mathbf{0}_2 \end{pmatrix}$$

in the Weyl basis, $(\widetilde{B},\ \widetilde{W}^{1,2,3},\ \widetilde{H}_u,\ \widetilde{H}_d)$, with $\widetilde{H}_u = (\tilde{h}_u^+, \tilde{h}_u^0)$ and $\widetilde{H}_d = (\tilde{h}_d^0, \tilde{h}_d^-)$

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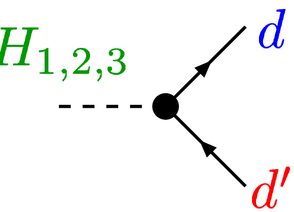
in the Weyl basis, $(\widetilde{B},\ \widetilde{W}^{1,2,3},\ \widetilde{H}_u,\ \widetilde{H}_d)$, with $\widetilde{H}_u = (\tilde{h}_u^+, \tilde{h}_u^0)$ and $\widetilde{H}_d = (\tilde{h}_d^0, \tilde{h}_d^-)$

- **Comment:** In the NMSSM or MNSSM, $\mathbf{M}_C[\Phi_1, \Phi_2]$ is a $9 \times 9$ matrix.

[See talk by R.N. Hodgkinson, at PS3.]

**Effective Yukawa couplings:**

[J. Ellis, J. S. Lee, A. P., PRD76 (2007) 115011.]




$$: \quad -\frac{i g_w}{2 M_W} \left( m_d \, g^L_{H_i \bar{d} d'} P_L + g^R_{H_i \bar{d} d'} m_{d'} \, P_R \right)$$

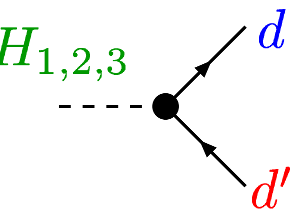
$$g^L_{H_i \bar{d} d'} \equiv \frac{O_{1i}}{c_\beta} V^\dagger_{\rm CKM} R_d^{-1} V_{\rm CKM} + \frac{O_{2i}}{c_\beta} V^\dagger_{\rm CKM} R_d^{-1} \Delta_d^{\phi_2} V_{\rm CKM}$$

$$+ \; i \, O_{3i} \, t_\beta \, V^\dagger_{\rm CKM} R_d^{-1} \left( \mathbf{1} - \frac{\Delta_d^{a_2}}{t_\beta} \right) V_{\rm CKM} \; \propto \; \boxed{t_\beta^2 \, V^\dagger_{\rm CKM} \Delta_d^{\phi_2} V_{\rm CKM}}$$

$$+ \; \mathcal{O}\left( \frac{m_b \, \mu \, t_\beta}{M^2_{\rm SUSY}} \right)^{n \geq 1}$$

## Effective Yukawa couplings:

[J. Ellis, J. S. Lee, A. P., PRD76 (2007) 115011.]




$$: \quad -\frac{i g_w}{2M_W}\left( m_d\, g^L_{H_i \bar{d} d'} P_L \;+\; g^R_{H_i \bar{d} d'} m_{d'}\, P_R \right)$$

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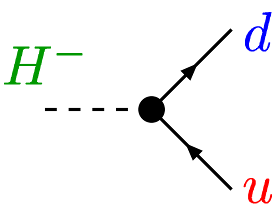


$$: \quad -\frac{i g_w}{2M_W}\left( \widehat{M}_d\, g^L_{H^- \bar{d} u} P_L \;+\; \widehat{M}_u\, g^R_{H^- \bar{d} u} P_R \right)$$

$$g^L_{H^- \bar{d} u} \;\equiv\; V^\dagger_{\rm CKM}\, R_d^{-1} \left( -t_\beta + \Delta_d^{\phi_2^-} \right)$$

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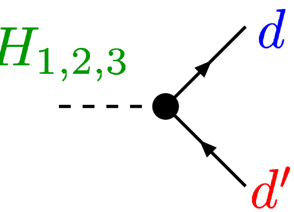


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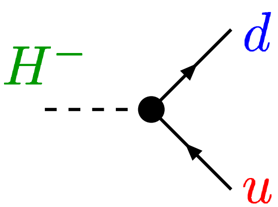
$$+\; \mathcal{O}\left( \frac{m_b\, \mu\, t_\beta}{M^2_{\rm SUSY}} \right)^{n \geq 1}$$




$$: \quad -\frac{i g_w}{2M_W}\left( \widehat{M}_d\, g^L_{H^- \bar{d} u} P_L \;+\; \widehat{M}_u\, g^R_{H^- \bar{d} u} P_R \right)$$

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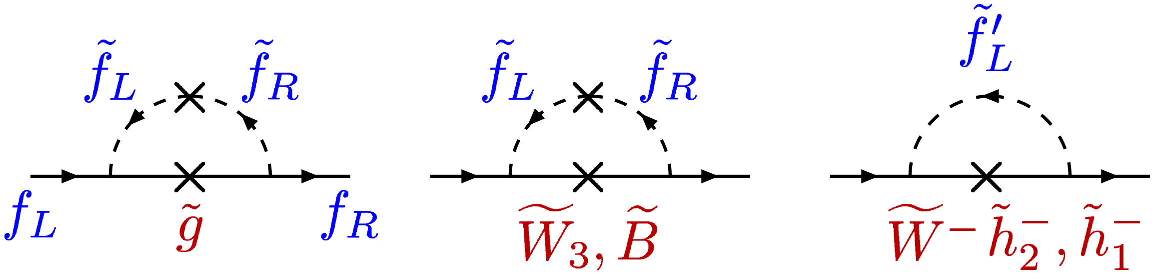
**Single Higgs Insertion approximation:** $\Delta_d^{\phi_2^-} = \Delta_d^{a_2} = \Delta_d^{\phi_2} = \frac{\sqrt{2}}{v_2}\, \Delta_d$

[A. Dedes, A. P., PRD67 (2003) 015012.]

– Electric Dipole Moments

## – **E**lectric **D**ipole **M**oments




with $f = e,\ u,\ d$

$$\left(\frac{d_f}{e}\right)^{1-\text{loop}} \sim\ (10^{-25}\ \text{cm}) \times \frac{\{\text{Im}\, m_\lambda,\ \text{Im}\, A_f\}}{\max(M_{\tilde{f}}, m_\lambda)} \left(\frac{1\ \text{TeV}}{\max(M_{\tilde{f}}, m_\lambda)}\right)^2 \left(\frac{m_f}{10\ \text{MeV}}\right)$$

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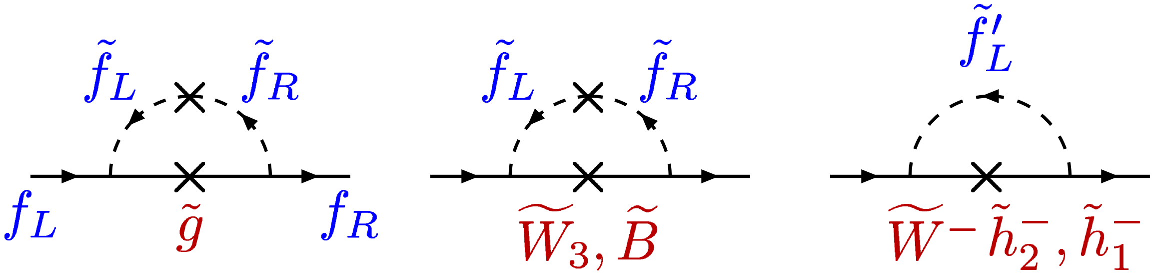


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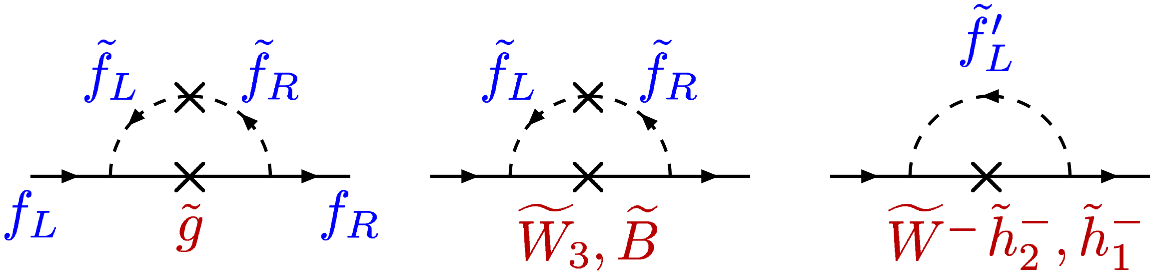
Schemes for resolving the 1-loop CP crisis:

– **Electric Dipole Moments**

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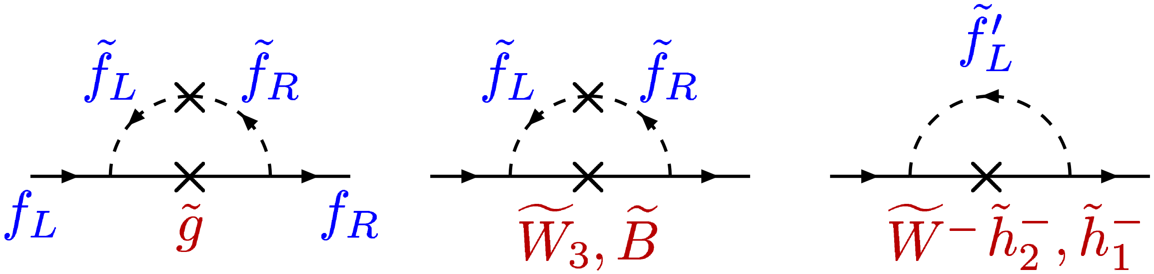
Schemes for resolving the 1-loop CP crisis:

- $\text{Im}\, m_\lambda/|m_\lambda|,\ \text{Im}\, A_f/|A_f| \lesssim 10^{-2}$; $M_{\tilde{f}}, m_\lambda \sim 200$ GeV

## – Electric Dipole Moments

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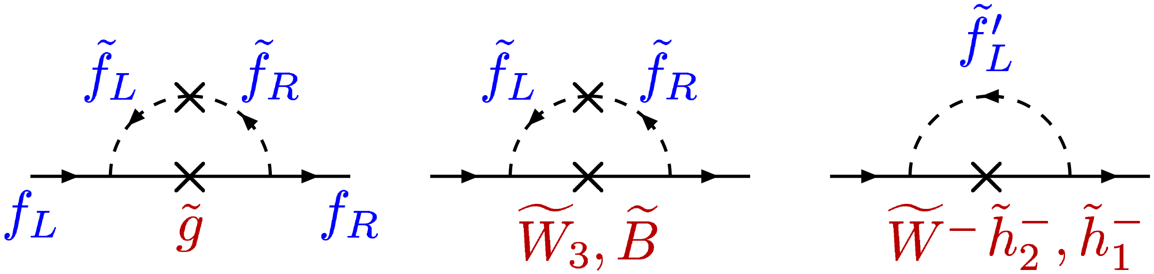
- CP phases $\sim 1$, but $M_{\tilde{f}} \gtrsim$ 1–3 TeV, for $\tilde{f} = \tilde{u}, \tilde{d}, \tilde{e}, \tilde{\nu}_L$

– **E**lectric **D**ipole **M**oments

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Schemes for resolving the 1-loop CP crisis:

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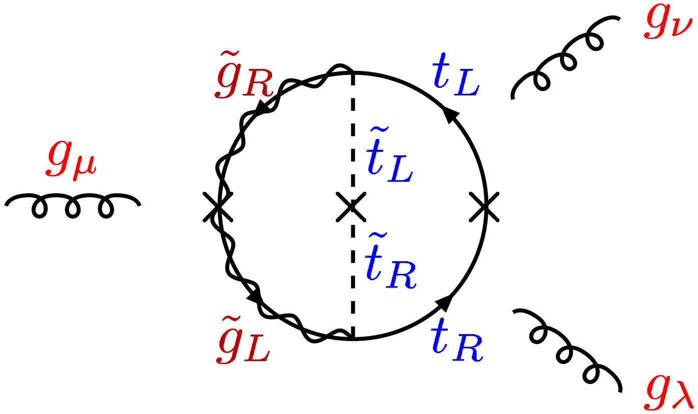
- CP phases $\sim 1$, but $M_{\tilde{f}} \gtrsim 1$–3 TeV, for $\tilde{f} = \tilde{u}, \tilde{d}, \tilde{e}, \tilde{\nu}_L$
- Cancellations between the different EDM terms

## An incomplete list of studies of EDMs:

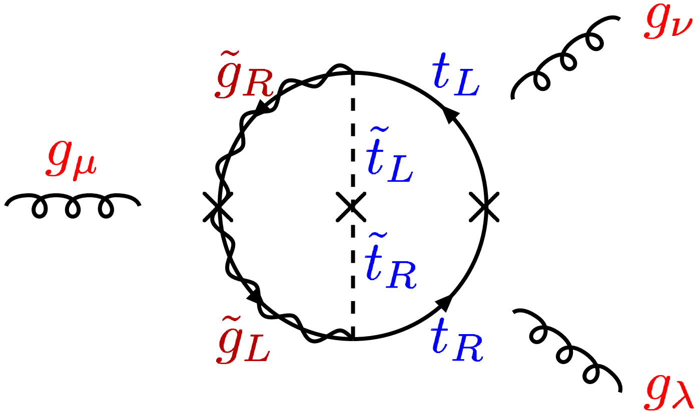
- 1-loop EDMs:
  J. Ellis, S. Ferrara and D.V. Nanopoulos, PLB114 (1982) 231;
  W. Buchmüller and D. Wyler, PLB121 (1983) 321;
  J. Polchinski and M. Wise, PLB125 (1983) 393; . . .
- Heavy squark/gaugino decoupling:
  P. Nath, PRL66 (1991) 2565;
  Y. Kizukuri and N. Oshimo, PRD46 (1992) 3025
- Cancellation mechanism:
  T. Ibrahim and P. Nath, PLB418 (1998) 98;
  M. Brhlik, L. Everett, G.L. Kane and J. Lykken, PRL83 (1999) 2124.
- Constraints from $d_{\rm Hg}$:
  T. Falk, K.A. Olive, M. Pospelov and R. Roiban, NPB600 (1999)3;
  S. Abel, S. Khalil and O. Lebedev, NPB606 (2001) 151.
- EDMs induced by the 3$g$-Weinberg operator:
  J. Dai, H. Dykstra, R.G. Leigh, S. Paban and D. Dicus, PLB237 (1990) 216.
- Higgs-Mediated 2-Loop EDMs:
  D. Chang, W.-Y. Keung and A.P., PRL82 (1999) 900;
  A.P., NPB644 (2002) 263.

## Weinberg's three-gluon operator




$$\mathcal{L}_{3g} \;=\; -\frac{1}{3!}\, d_{3g}\; f^{abc}\, \widetilde{G}^{a}_{\nu}{}^{\mu}\, G^{b}_{\lambda}{}^{\nu}\, G^{c}_{\mu}{}^{\lambda}$$

## Weinberg's three-gluon operator




$$\mathcal{L}_{3g} = -\frac{1}{3!}\, d_{3g}\, f^{abc}\, \widetilde{G}^{a\,\mu}_{\nu}\, G^{b\,\nu}_{\lambda}\, G^{c\,\lambda}_{\mu}$$

Estimate based on naive dimensional analysis:

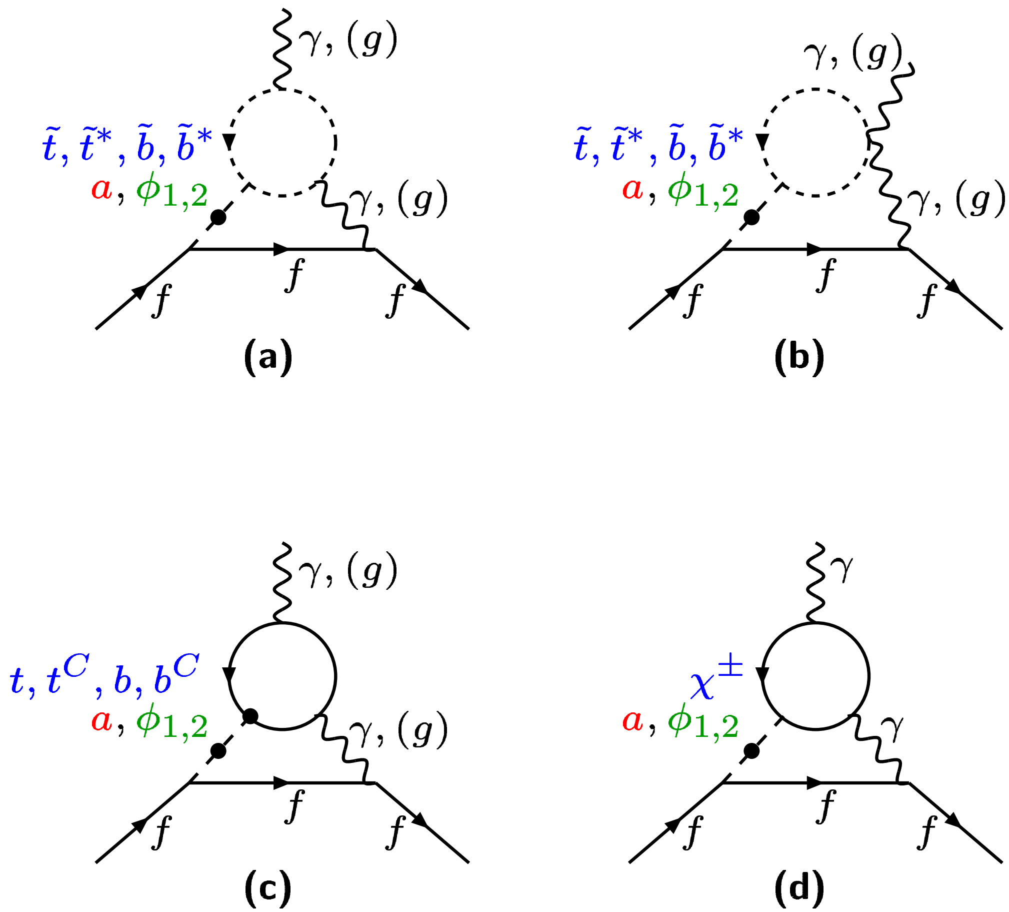
$$d_{3g} \sim \frac{g_s^3}{4\pi}\,\frac{3\alpha_s^2}{16\pi^2}\,\frac{m_{\tilde{g}}\, m_t^2\, \mathrm{Im}\,(A_t - \mu^* \cot\beta)}{m_{\tilde{g}}^4\, M_{\tilde{t}}^2}$$

$$\Longrightarrow \quad \left(\frac{d_n}{e}\right)^{3g} \sim (10^{-26}\ \mathrm{cm}) \times \left(\frac{0.5\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^2 \frac{m_t^2\, \mathrm{Im}\,(A_t - \mu^* \cot\beta)}{M_{\tilde{t}}^2\, m_{\tilde{g}}}$$

EDM constraint: $m_{\tilde{g}} \gtrsim 400$ GeV.

## Higgs-Mediated 2-Loop EDMs

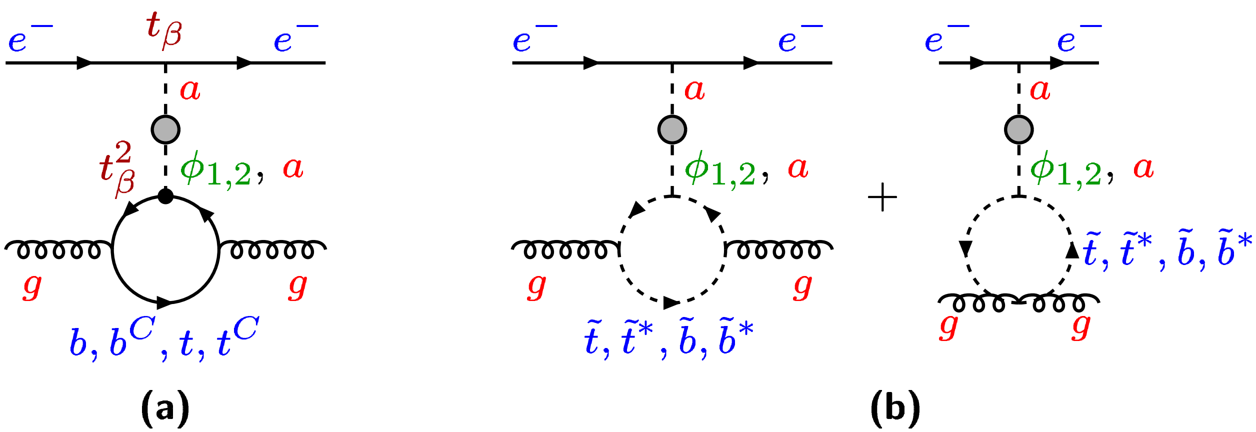
[ D. Chang, W.-Y. Keung, A.P., PRL82 (1999) 900; A.P., NPB644 (2002) 263;
SUSY extension of the mechanism by S.M. Barr, A. Zee, PRL65 (1990) 21.]




$$d_f \;\propto\; \arg(\mu A_t,\ \mu m_{\tilde{g}},\ \mu m_{\widetilde{W}})\,,\ \tan\beta\,,\ \frac{1}{M_a}$$

# Other Higgs-mediated contributions

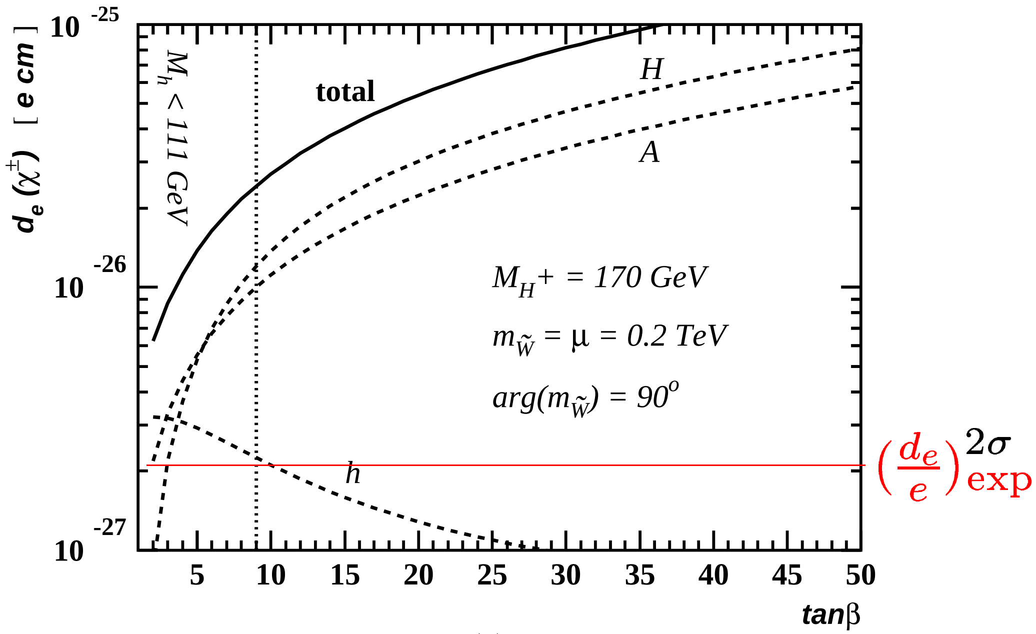
[ A.P., NPB644 (2002) 263;
D. A. Demir, O. Lebedev, K. A. Olive, M. Pospelov and A. Ritz, NPB680 (2004) 339;
First study in the 2HDM by S. Barr, PRL68 (1992) 1822.]



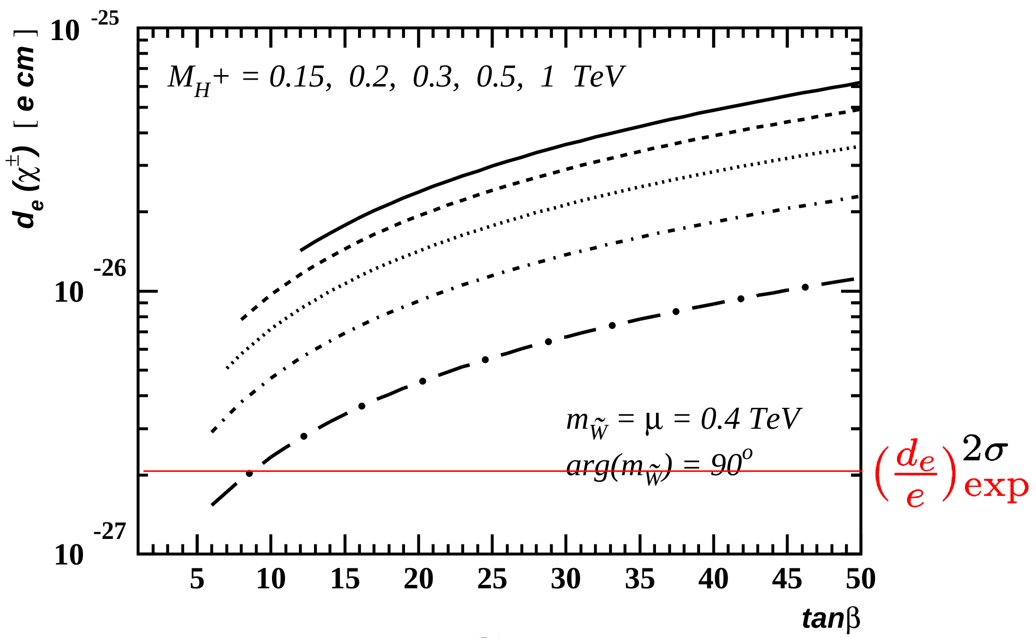

$$C_S^{(b,b^C)} \propto \arg(\mu A_t,\ \mu m_{\tilde{g}})\,,\ \tan^3\beta\,,\ \frac{1}{M_a^3}$$

# Constraints on Electroweak Baryogenesis

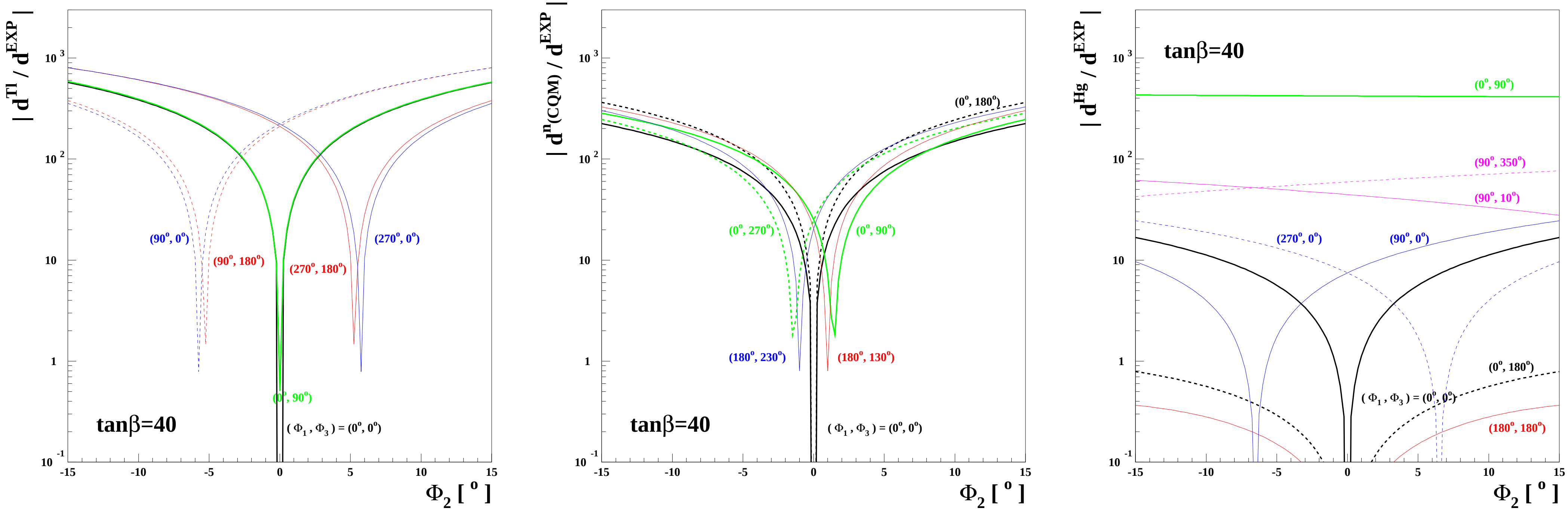
[A.P., NPB644 (2002) 263. ]




(a)



# PRELIMINARY: EDM Constraints on MCPMFV [J. Ellis, J. S. Lee, A.P., work in progress.]



## – B-Meson FCNC Observables

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- $\Delta M_{B_s}^{\rm SUSY} \;\leftrightarrow\; \tan\beta$
- $\Delta M_{B_d}^{\rm SUSY} \;\leftrightarrow\; \tan\beta$
- $B(\bar{B}_s^0 \to \mu^+\mu^-) \;\leftrightarrow\; \tan\beta$
- $R_{B\tau\nu} \equiv \frac{B(B^-\to\tau^-\nu)}{B^{\rm SM}(B^-\to\tau^-\nu)} \;\leftrightarrow\; \tan\beta$
- $B(B \to X_s\gamma),\; \mathcal{A}_{\rm CP}^{\rm dir}(B \to X_s\gamma) \;\leftrightarrow\; \tan\beta,\; \Phi_M$

$\vdots$

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- $B(B \to X_s\gamma),\; \mathcal{A}_{\rm CP}^{\rm dir}(B \to X_s\gamma) \;\leftrightarrow\; \tan\beta,\; \Phi_M$

$$\vdots$$

**Input parameters:**

$$|M_{1,2,3}| = 250 \;\; {\rm GeV}$$

$$M_{H_u}^2 = M_{H_d}^2 = \widetilde{M}_Q^2 = \widetilde{M}_U^2 = \widetilde{M}_D^2 = \widetilde{M}_L^2 = \widetilde{M}_E^2 = (100 \;\; {\rm GeV})^2$$

$$|A_u| = |A_d| = |A_e| = 100 \;\; {\rm GeV}$$

## Incomplete list of references:


- $B \to X_s\gamma$:
  S. Bertolini, F. Borzumati, A. Masiero, G. Ridolfi, NPB353 (1991) 591;
  M. Ciuchini, G. Degrassi, P. Gambino, G. F. Giudice, NPB534 (1998) 3;
  M. S. Carena, D. Garcia, U. Nierste, C. E. M. Wagner, PLB499 (2001) 141.

- Higgs-mediated $\Delta M_{B_{s,d}}^{\rm SUSY}$:
  A.J. Buras, P.H. Chankowski, J. Rosiek, L. Slawianowska, NPB619 (2001) 434; NPB659 (2003) 3;
  G. Isidori and A. Retico, JHEP0111 (2001) 001.

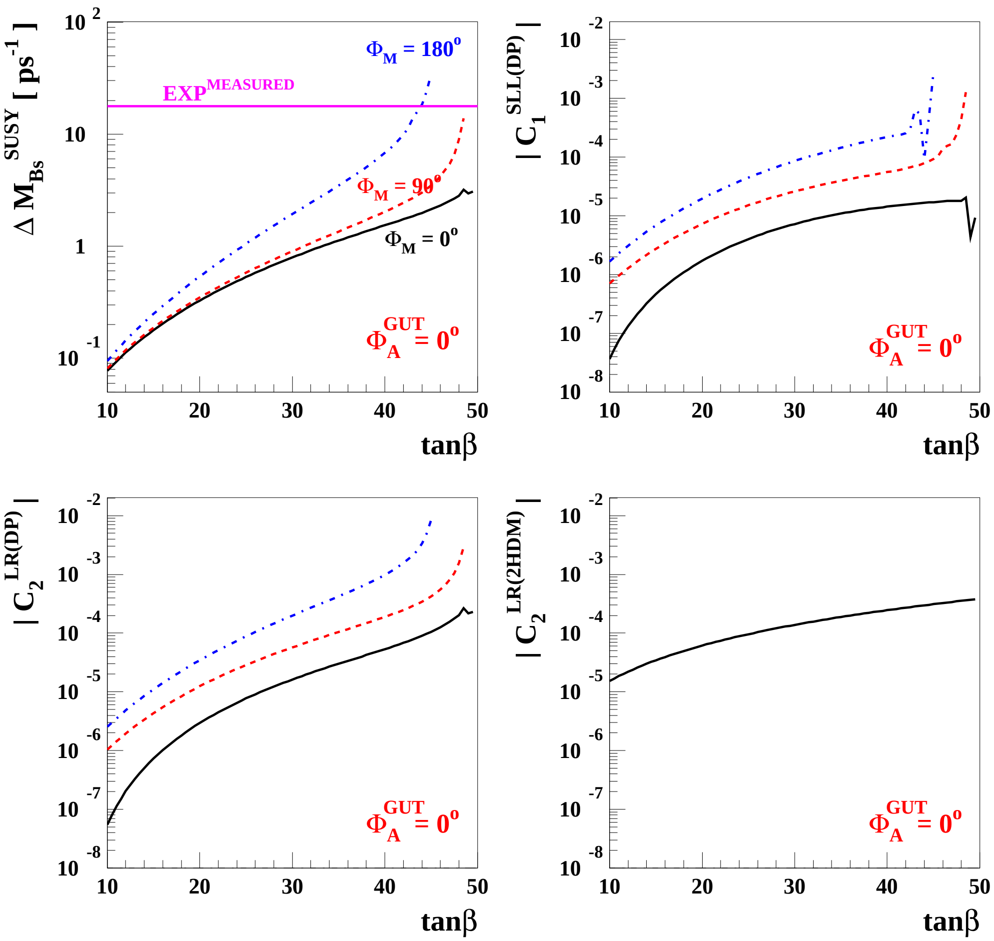
- Higgs-mediated $\Delta M_K{}^{\rm SUSY}$, $\varepsilon$, $\varepsilon'/\varepsilon$:
  A. Dedes, A. P., PRD67 (2003) 015012.

- $\bar{B}_s^0 \to \mu^+\mu^-$:
  C. S. Huang, Q.-S. Yan, PLB442 (1998) 209;
  S. R. Choudhury, N. Gaur, PLB451 (1999) 86;
  K. S. Babu, C. Kolda, PRL84 (2000) 228;
  S. Baek, P. Ko and W. Y. Song, PRL89 (2002) 271801.

- $B^- \to \tau^-\nu$:
  W. S. Hou, PRD48 (1993) 2342;
  A. G. Akeroyd, S. Recksiegel, JPG29 (2003) 2311;
  H. Itoh, S. Komine, Y. Okada, PTP114 (2005) 179.

- $\Delta M_{B_s}^{\rm SUSY} \leftrightarrow \tan\beta(M_{\rm SUSY})$

$\Phi_M \equiv \Phi_1 = \Phi_2 = \Phi_3,\ \Phi_A^{\rm GUT} = 0^\circ$




$$\Delta M_{B_s}^{\rm SUSY} = 2\,|\langle \bar{B}_s^0|\, H_{\rm eff}^{\Delta B=2}\,|B_s^0\rangle_{\rm SUSY}|$$

$$\Delta M_{B_s}^{\rm EXP} = 17.77 \pm 0.10(stat) \pm 0.07(syst)\,{\rm ps}^{-1}$$

H. G. Evans, arXiv:0705.4598v1 [hep-ex]

$$\langle \bar{B}_s^0|\, H_{\rm eff}^{\Delta B=2}\,|B_s^0\rangle_{\rm SUSY} = \frac{2310}{\rm ps}\left(\frac{\hat{B}_{B_s}^{1/2}\,F_{B_s}}{265\ {\rm MeV}}\right)^2\left(\frac{\eta_B}{0.55}\right)$$

$$\times\left[0.88\left(C_{2\,\rm LR}^{(\rm DP)} + C_{2\,\rm LR}^{\rm 2HDM}\right) - 0.52\left(C_{1\,\rm SLL}^{(\rm DP)} + C_{1\,\rm SRR}^{(\rm DP)}\right)\right]$$

$$C_{1\,\rm SLL}^{(\rm DP)} = -\frac{16\pi^2 m_b^2}{\sqrt{2}\,G_F M_W^2}\sum_{i=1}^{3}\frac{g_{H_i\bar{b}s}^L\, g_{H_i\bar{b}s}^L}{M_{H_i}^2}$$

$$C_{1\,\rm SRR}^{(\rm DP)} = -\frac{16\pi^2 m_s^2}{\sqrt{2}\,G_F M_W^2}\sum_{i=1}^{3}\frac{g_{H_i\bar{b}s}^R\, g_{H_i\bar{b}s}^R}{M_{H_i}^2}$$

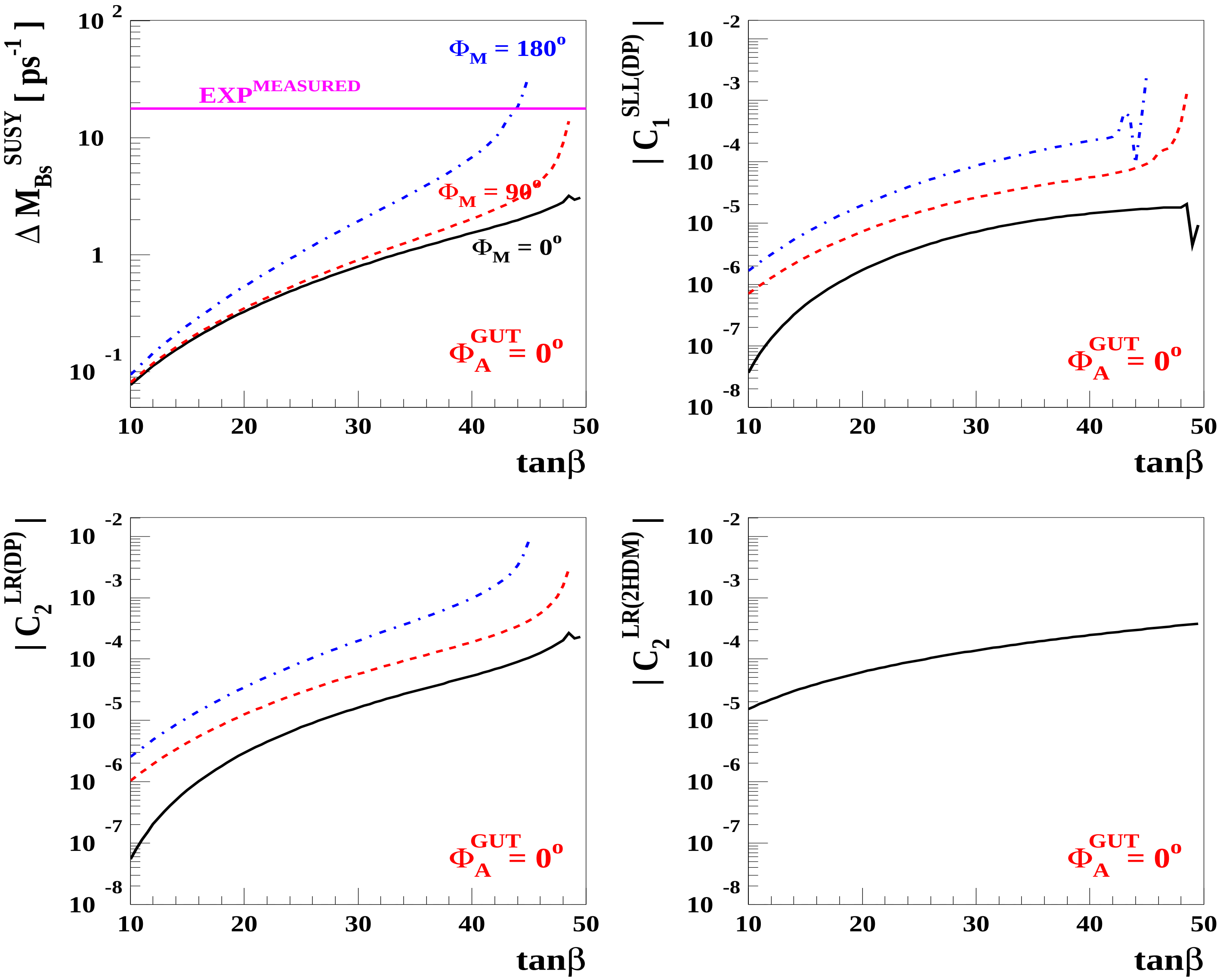
$$C_{2\,\rm LR}^{(\rm DP)} = -\frac{32\pi^2 m_b m_s}{\sqrt{2}\,G_F M_W^2}\sum_{i=1}^{3}\frac{g_{H_i\bar{b}s}^L\, g_{H_i\bar{b}s}^R}{M_{H_i}^2}$$

$$C_{2\,\rm LR}^{(\rm 2HDM)} \approx -\frac{2m_b m_s}{M_W^2}\,(V_{tb}^* V_{ts})^2\,\tan^2\beta$$

- $\Delta M_{B_s}^{\mathrm{SUSY}} \;\propto\; \tan^4\beta/M_{H^+}^2$

[J. Ellis, J. S. Lee, A. P., PRD76 (2007) 115011.]

$\Phi_M \equiv \Phi_1 = \Phi_2 = \Phi_3,\ \Phi_A^{\mathrm{GUT}} = 0^\circ$

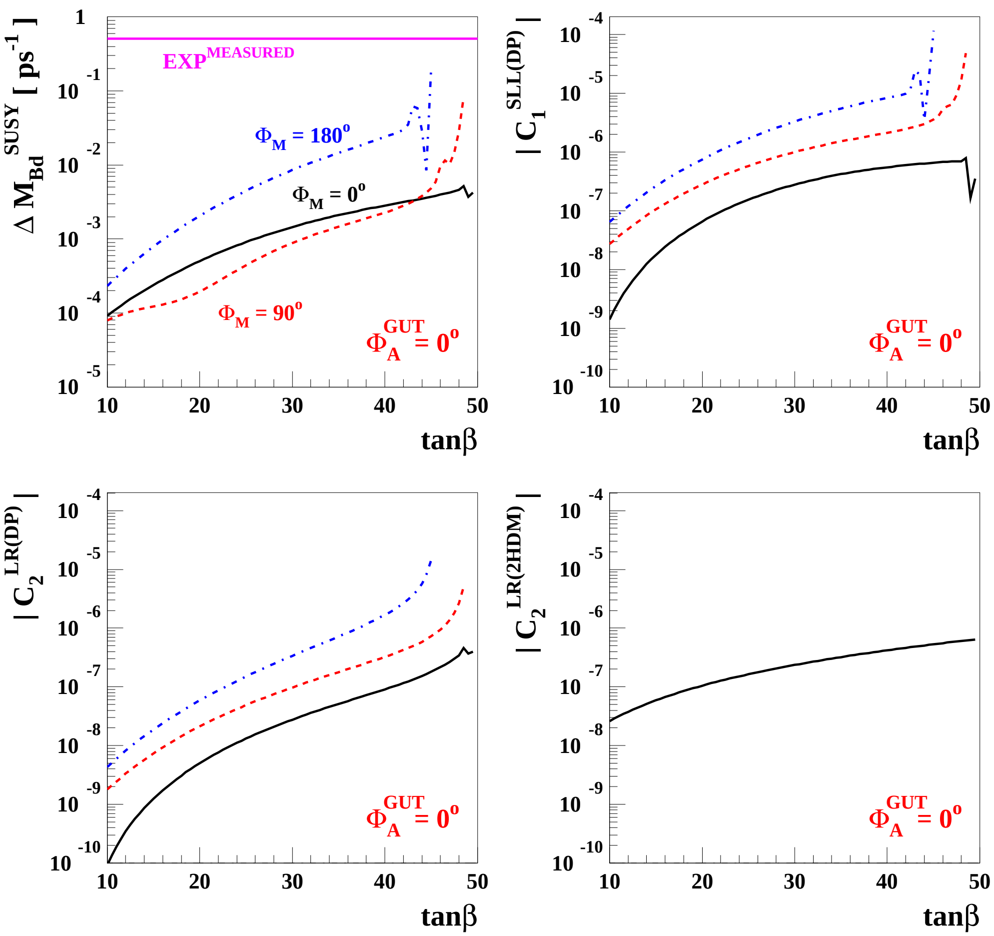


- $\Delta M_{B_d}^{\rm SUSY} \leftrightarrow \tan\beta(M_{\rm SUSY})$

$\Phi_M \equiv \Phi_1 = \Phi_2 = \Phi_3,\ \Phi_A^{\rm GUT} = 0^\circ$

$$\Delta M_{B_d}^{\rm SUSY} = 2\,|\langle \bar{B}_d^0|\, H_{\rm eff}^{\Delta B=2}\,|B_d^0\rangle_{\rm SUSY}|$$

$$\Delta M_{B_d}^{\rm EXP} = 0.507 \pm 0.005\ {\rm ps}^{-1}$$ PDG2006




$$\langle \bar{B}_d^0|\, H_{\rm eff}^{\Delta B=2}\,|B_d^0\rangle_{\rm SUSY} = \frac{1711}{\rm ps}\left(\frac{\hat{B}_{B_d}^{1/2}\,F_{B_d}}{230\ {\rm MeV}}\right)^2\left(\frac{\eta_B}{0.55}\right)$$

$$\times\left[0.88\left(C_{2\,{\rm LR}}^{\rm (DP)} + C_{2\,{\rm LR}}^{\rm 2HDM}\right) - 0.52\left(C_{1\,{\rm SLL}}^{\rm (DP)} + C_{1\,{\rm SRR}}^{\rm (DP)}\right)\right]$$

$$C_{1\,{\rm SLL}}^{\rm (DP)} = -\frac{16\pi^2 m_b^2}{\sqrt{2}\,G_F M_W^2}\sum_{i=1}^{3}\frac{g_{H_i\bar{b}d}^L\, g_{H_i\bar{b}d}^L}{M_{H_i}^2}$$

$$C_{1\,{\rm SRR}}^{\rm (DP)} = -\frac{16\pi^2 m_d^2}{\sqrt{2}\,G_F M_W^2}\sum_{i=1}^{3}\frac{g_{H_i\bar{b}d}^R\, g_{H_i\bar{b}d}^R}{M_{H_i}^2}$$

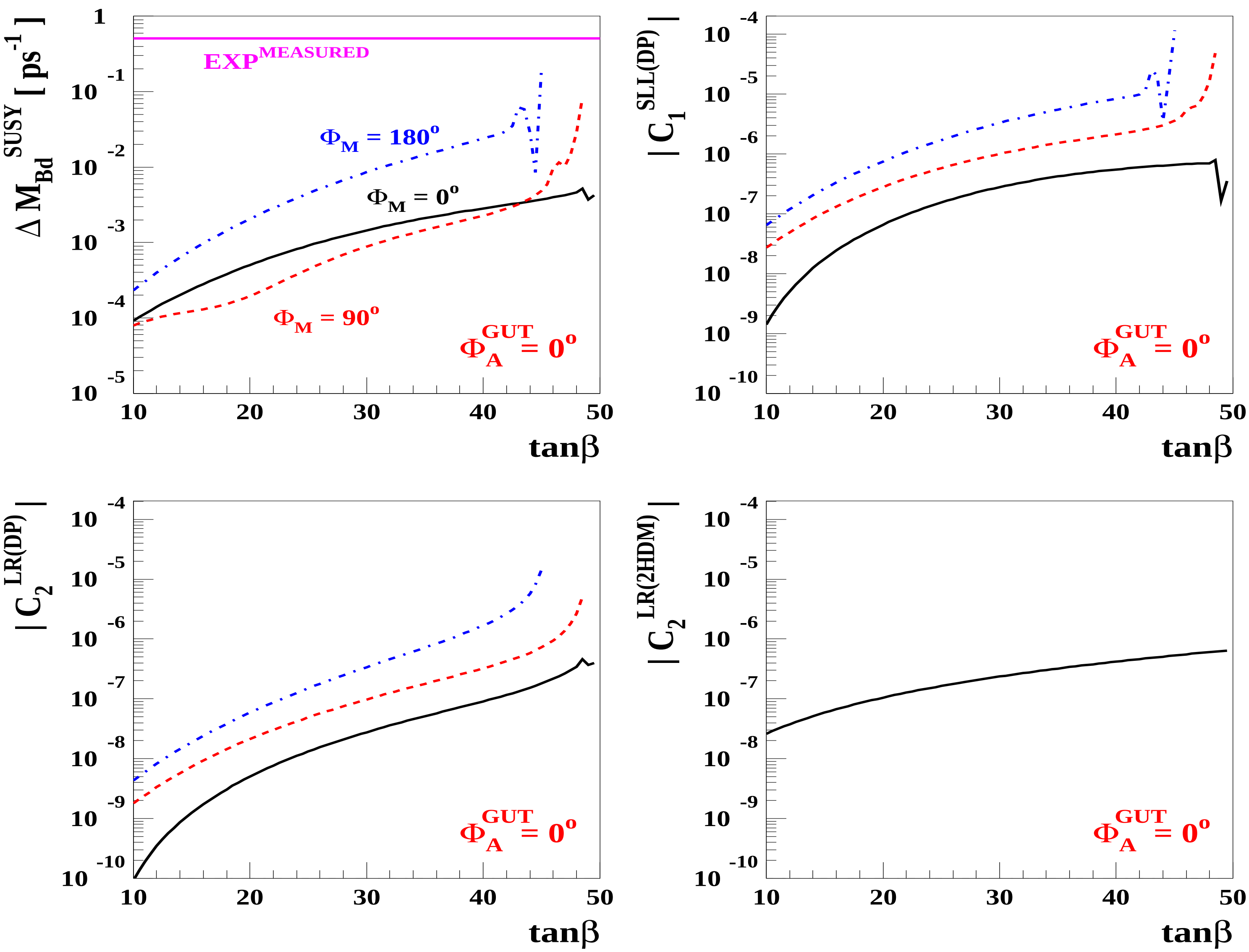
$$C_{2\,{\rm LR}}^{\rm (DP)} = -\frac{32\pi^2 m_b m_d}{\sqrt{2}\,G_F M_W^2}\sum_{i=1}^{3}\frac{g_{H_i\bar{b}d}^L\, g_{H_i\bar{b}d}^R}{M_{H_i}^2}$$

$$C_{2\,{\rm LR}}^{\rm (2HDM)} \approx -\frac{2m_b m_d}{M_W^2}\,(V_{tb}^* V_{td})^2\,\tan^2\beta$$

- $\Delta M_{B_d}^{\rm SUSY} \; \propto \; \tan^4\beta / M_{H^+}^2$

[J. Ellis, J. S. Lee, A. P., PRD76 (2007) 115011.]

$\Phi_M \equiv \Phi_1 = \Phi_2 = \Phi_3, \Phi_A^{\rm GUT} = 0^\circ$



- $B(\bar{B}_s^0 \to \mu^+\mu^-) \;\leftrightarrow\; \tan\beta(M_{\rm SUSY})$

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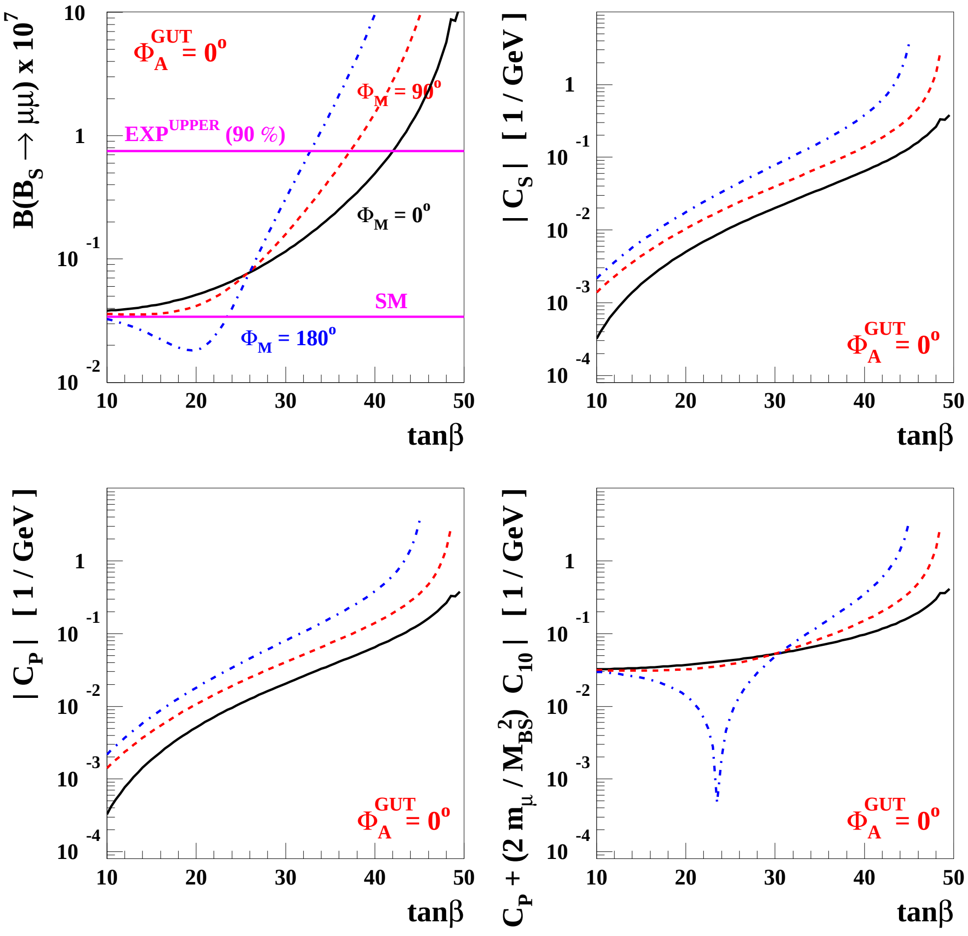


$$\boxed{B(\bar{B}_s^0 \to \mu^+\mu^-)} =$$

$$\frac{G_F^2\alpha_{\rm em}^2}{16\pi^3} M_{B_s}\tau_{B_s} |V_{tb}V_{ts}^*|^2 \sqrt{1-\frac{4m_\mu^2}{M_{B_s}^2}}$$

$$\times \left[ \left(1-\frac{4m_\mu^2}{M_{B_s}^2}\right) |F_S|^2 \;+\; |F_P \;+\; 2m_\mu F_A|^2 \right]$$

$$F_{S,P} \;=\; -\frac{i}{2} M_{B_s}^2 F_{B_s} \frac{m_b}{m_b+m_s} C_{S,P}$$

$$F_A \;=\; -\frac{i}{2} F_{B_s} C_{10}^{\rm SM}$$

where $C_{10}^{\rm SM} = -4.221$ and

$$C_{S(P)} = (i)\frac{2\pi m_\mu}{\alpha_{\rm em}} \frac{1}{V_{tb}V_{ts}^*} \sum_{i=1}^{3} \frac{g^R_{H_i\bar{s}b}\, g^{S(P)}_{H_i\bar{\mu}\mu}}{M_{H_i}^2},$$

$$g^S_{H_i\bar{\mu}\mu} \;=\; \frac{O_{1i}}{\cos\beta}, \qquad g^P_{H_i\bar{\mu}\mu} \;=\; -\tan\beta\, O_{3i}$$

Note $|C_P| \sim |C_S|$ since $H_1 \sim \phi_2$ and $M_{H_2} \sim M_{H_3}$

- $B(\bar{B}_s^0 \to \mu^+\mu^-) \ \propto \ \tan^6\beta / M_{H^+}^4$ [J. Ellis, J. S. Lee, A. P., PRD76 (2007) 115011.]

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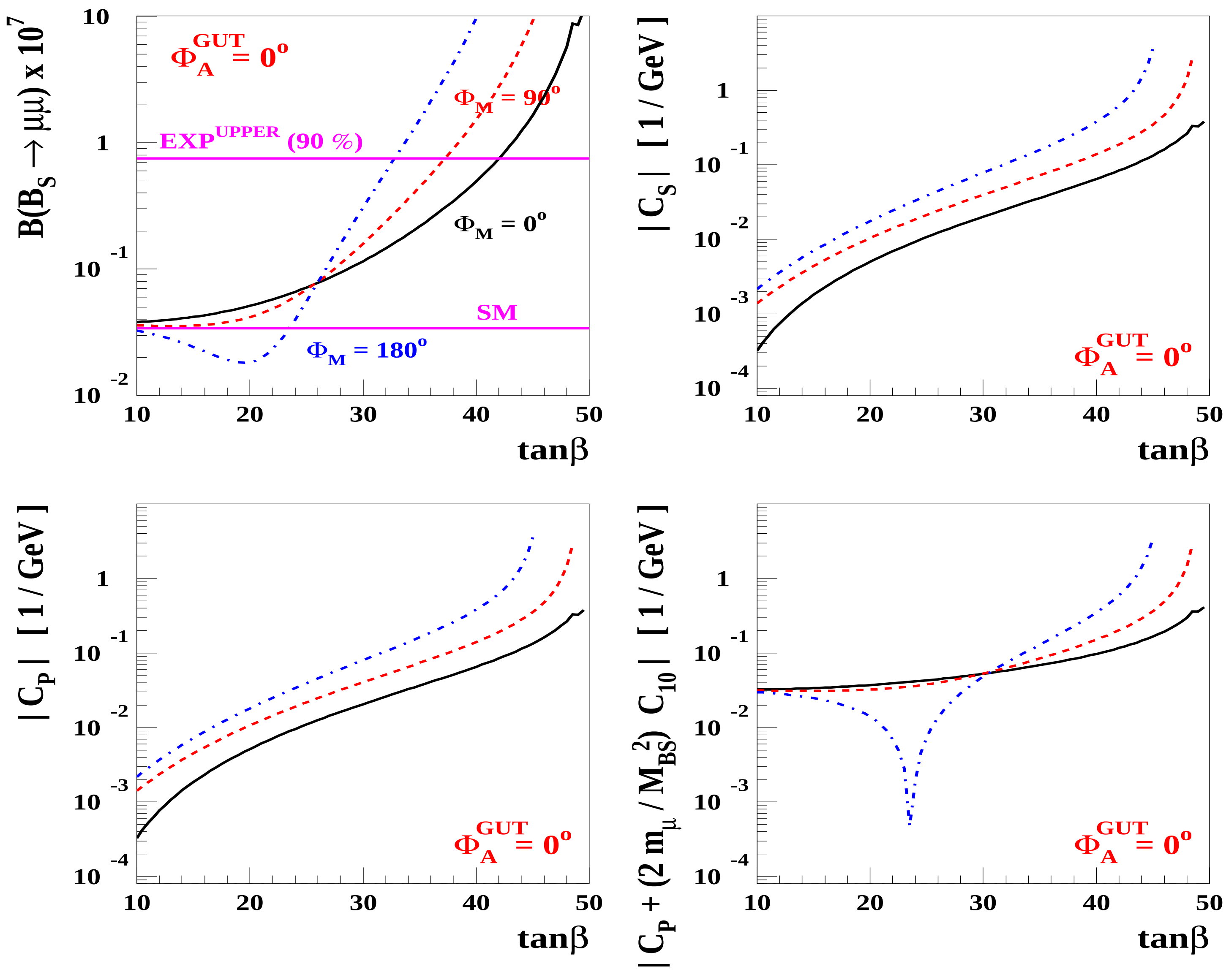

- $R_{B\tau\nu} \;\leftrightarrow\; \tan\beta(M_{\rm SUSY})$

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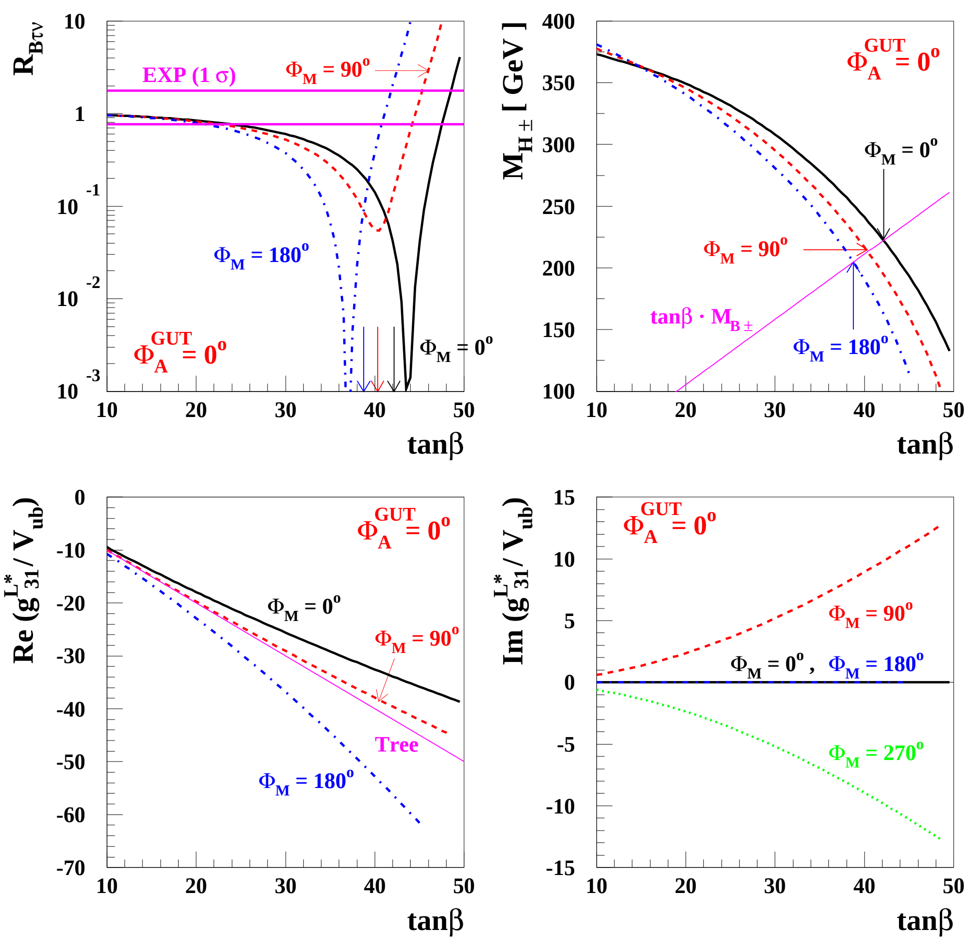


$$R_{B\tau\nu} \equiv \frac{B(B^-\to\tau^-\nu)}{B^{\rm SM}(B^-\to\tau^-\nu)}$$

$$= \left| 1 + \tan\beta \frac{\left(\mathbf{g}^{L\,\dagger}_{H^-\bar{d}u}\right)_{13}}{(\mathbf{V}_{\rm CKM})_{13}} \left(\frac{M_{B\pm}}{M_{H\pm}}\right)^2 \right|^2$$

At tree level, $\mathbf{g}^L_{H^-\bar{d}u} = -\tan\beta\, \mathbf{V}^\dagger_{\rm CKM}$

$$R^{\rm EXP}_{B\tau\nu} = 1.27 \pm 0.38$$

$$B(B^- \to \tau^-\bar{\nu}) \times 10^4 = 1.79^{+0.56}_{-0.49}\,({\rm stat})^{+0.46}_{-0.51}\,({\rm syst})$$

BELLE, PRL97(2006)251802

$$B(B^- \to \tau^-\bar{\nu}) \times 10^4 = 1.2 \pm 0.4\,({\rm stat}) \pm 0.3\,({\rm syst_{bkg}}) \pm 0.2\,({\rm syst'})$$

BABAR, arXiv : 0708.2260[hep − ex]

$$B(B^- \to \tau^-\bar{\nu})^{\rm SM} \times 10^4 = 1.41 \pm 0.33$$

UTfit, JHEP0610(2006)081

- $R_{B\tau\nu} \leftrightarrow \tan\beta(M_{\rm SUSY})$ [J. Ellis, J. S. Lee, A. P., PRD76 (2007) 115011.]

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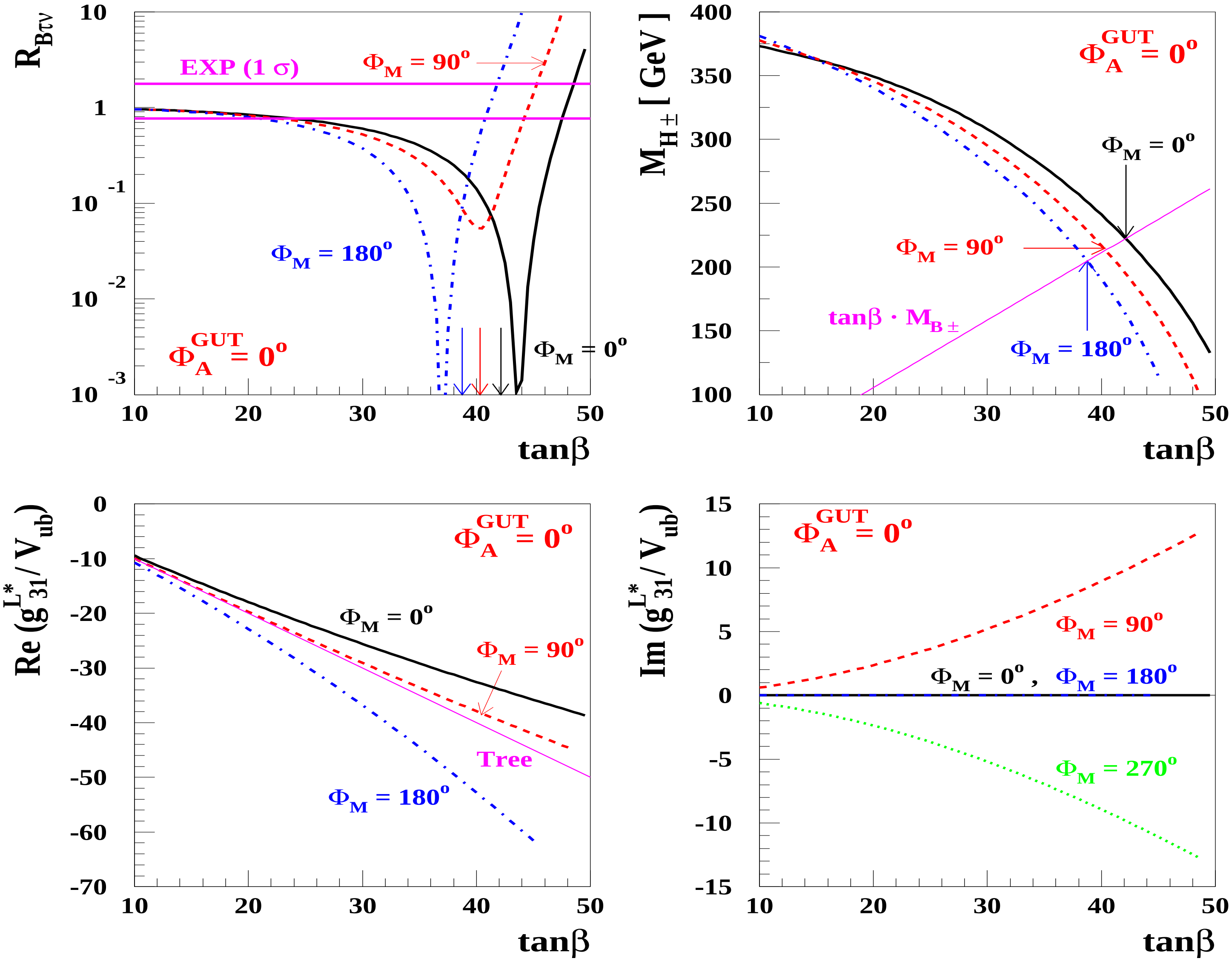

- $B(B \to X_s\gamma)$, $\mathcal{A}_{\rm CP}^{\rm dir}(B \to X_s\gamma)$ $\leftrightarrow$ $\tan\beta(M_{\rm SUSY})$

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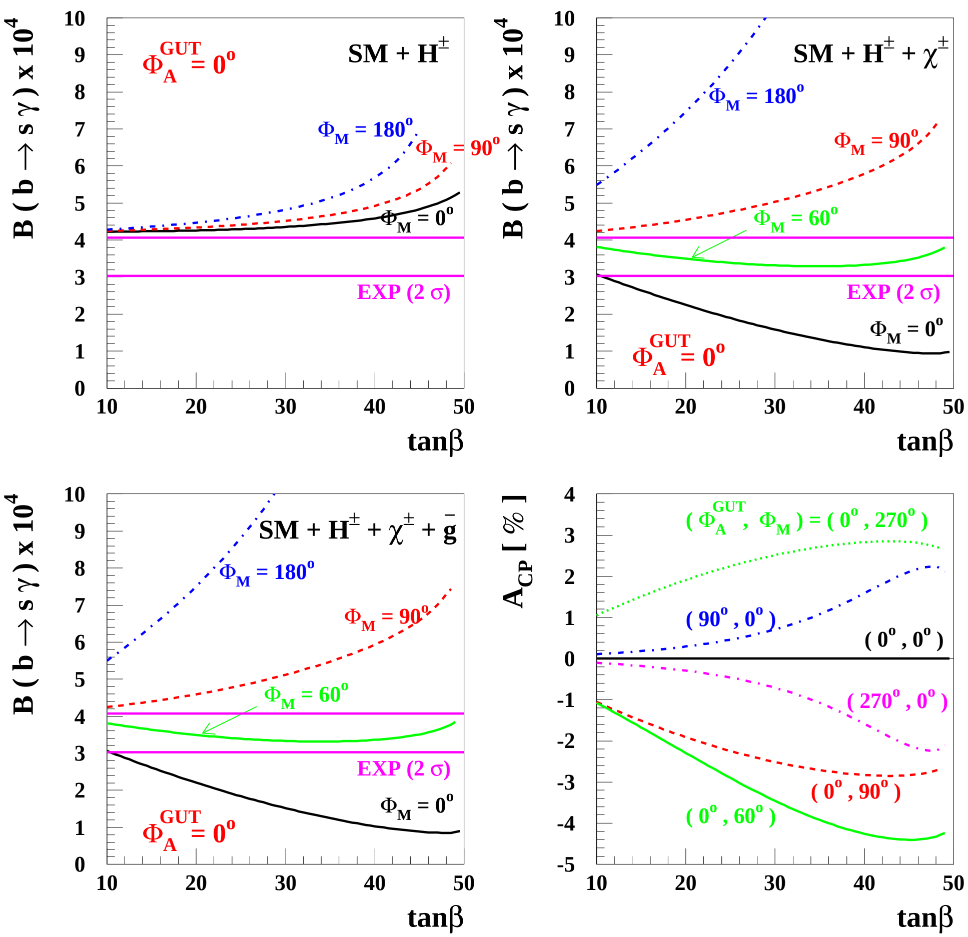



$$B^{\rm EXP} \times 10^4 = 3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03$$

HFAG, arXiv:0704.3575[hep-ex]

Comments:

- The charged-Higgs contribution is larger: $\tan\beta \Uparrow \;\to\; M_{H^\pm} \Downarrow$

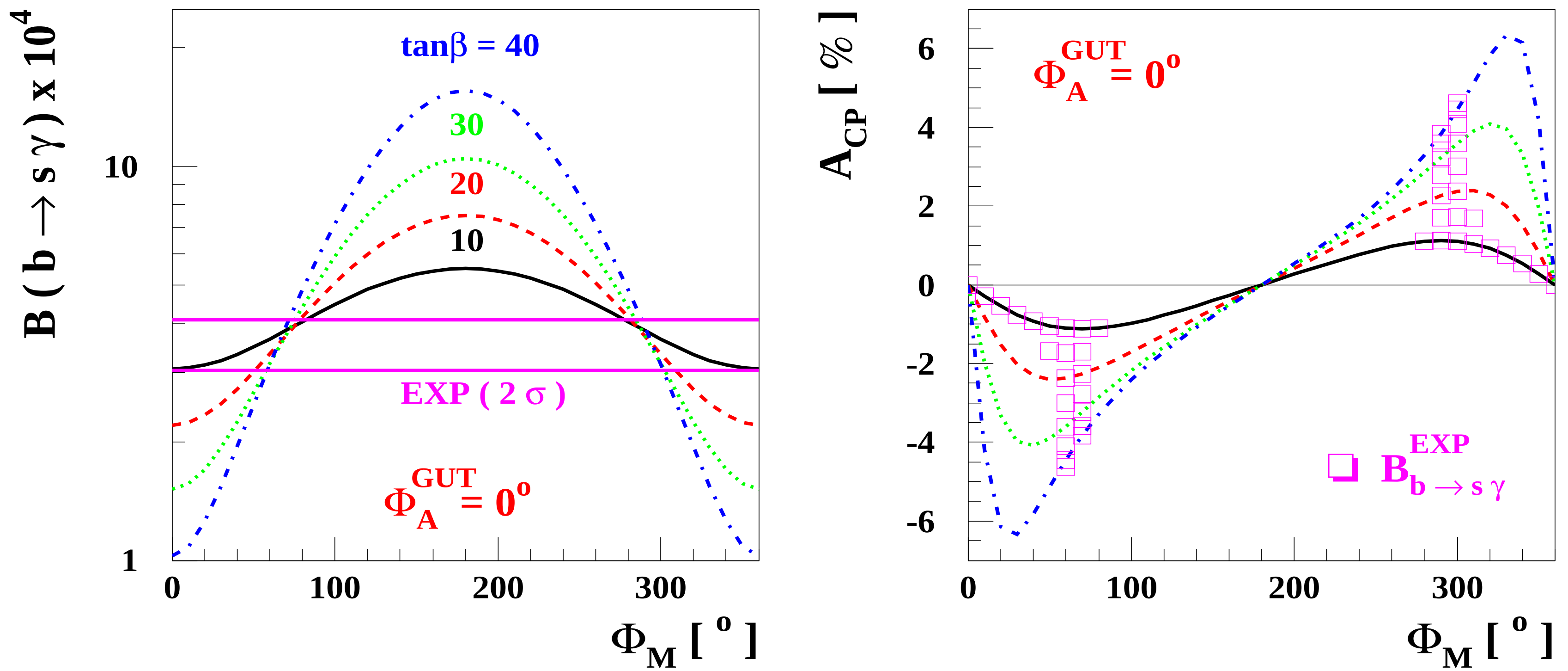
- The chargino contribution:
$$C_{7,8}^{\chi^\pm} \propto \; \sim -\Re{\rm e}\left(e^{i\,\Phi_{A_t}} / \cos_\beta\right)$$
$$\sim \cos\Phi_M / \cos_\beta$$
  ▽ N.B. $\cos(\Phi_{A_t}) \sim -\cos(\Phi_M)$

- The gluino contribution is negligible

- The case of $\Phi_M = 60^\circ \to$ small $\Phi_M$ dependence

[J. Ellis, J. S. Lee and A. P., PRD76 (2007) 115011.]

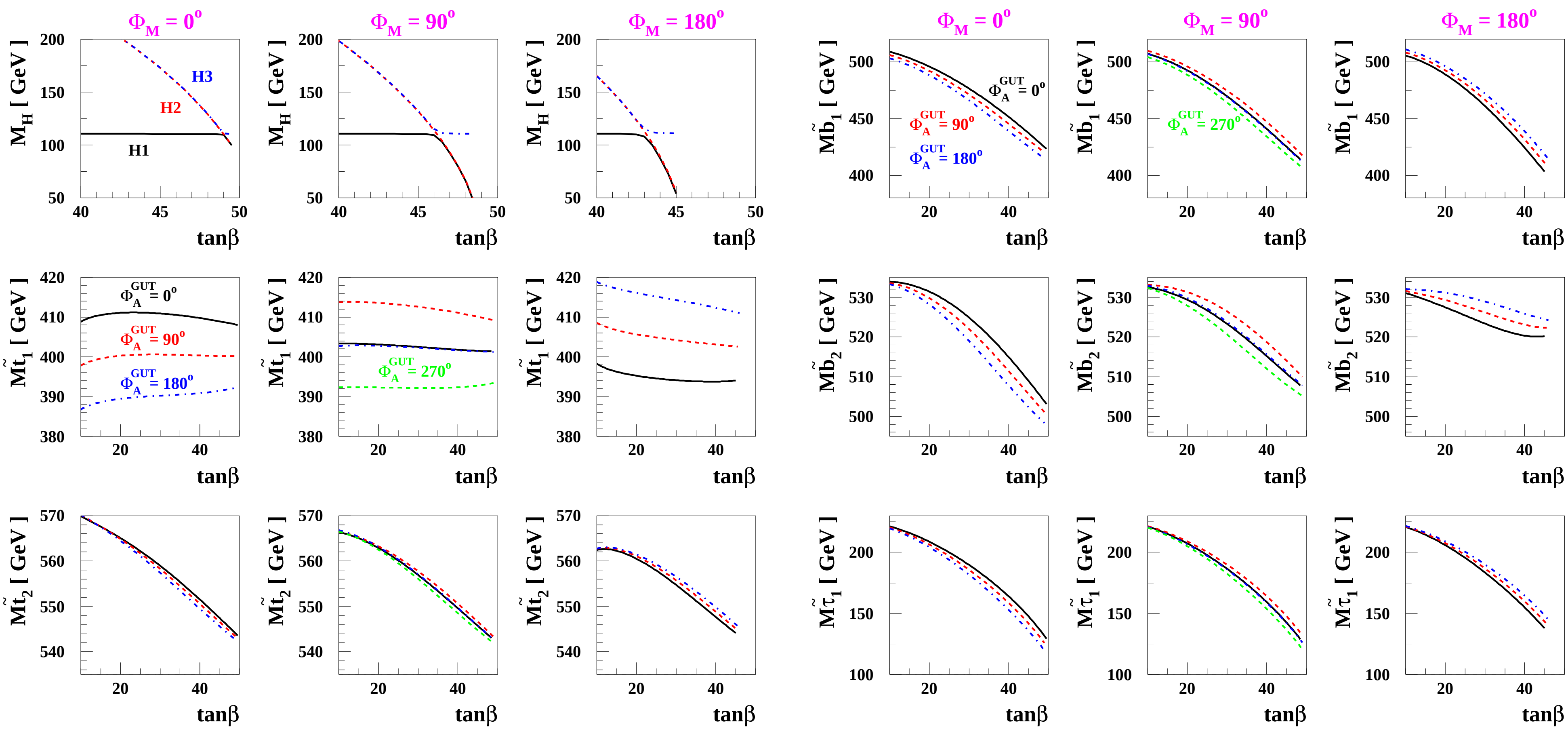
- $B(B \to X_s\gamma)$, $\mathcal{A}_{\rm CP}^{\rm dir}(B \to X_s\gamma)$ $\leftrightarrow$ $\Phi_M$




[J. Ellis, J. S. Lee and A. P., PRD76 (2007) 115011.]

- Masses $\leftrightarrow$ $\tan\beta(M_{\rm SUSY})$

$\Phi_M \equiv \Phi_1 = \Phi_2 = \Phi_3,\ \Phi_A^{\rm GUT} = 0^\circ,\ \widetilde{M}_{L,E} = 200$ GeV




[J. Ellis, J. S. Lee and A. P., PRD76 (2007) 115011.]

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[CPsuperH: J.S. Lee, A.P., M. Carena, S.Y. Choi, M. Drees, J. Ellis, C. Wagner, CPC156 (2004) 283;
CPsuperH2.0: J.S. Lee, M. Carena, J. Ellis, A.P., C.E.M. Wagner, arXiv:0712.2360]