Hunting SUSY through CP violation at the low energy

Paride Paradisi

Physik Department
Technische Universitat Munchen

Fifth Worshop on Particle Physics and Cosmology
Warsaw
February 4-7, 2009

General Considerations

Flavor Physics in the LHC era

- **High energy experiments** are the key tool to determine the **energy scale** Λ by direct production of NP particles.

- **Low energy experiments** are a fundamental ingredient to determine the **symmetry properties** of the new d.o.f. via their virtual effects in precision observables.

General Considerations

▸ *Flavour physics in the LHC era*

LHC [high p_T]

A *unique* effort toward the high-energy frontier

[to determine the energy scale of NP]

Flavour physics

Improved CKM fits

Rare B decays

CPV in the Bs system

LFV in μ & τ decays

Universality tests in B & K

EDMs

Rare K decays

g-2

A *collective* effort toward the high-intensity frontier

[to determine the flavour structure of NP]

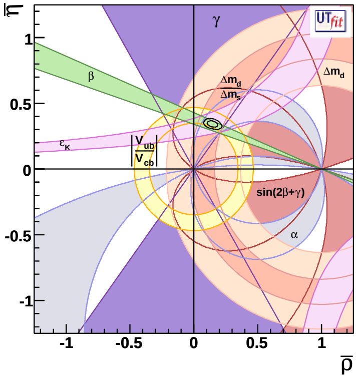
NP search strategies

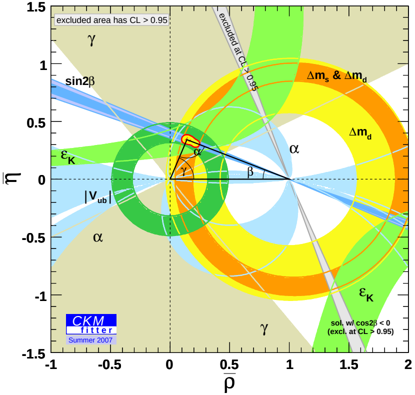
Where to look for New Physics?

- **Processes very suppressed or even forbidden in the SM**
  - FCNC processes ($\mu \to e\gamma$, $\tau \to \mu\gamma$, $B^0_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$)
  - CPV effects (electron/neutron EDMs, $d_{e,n}$....)
  - CPV in $B_{s,d}$ decay/mixing amplitudes

- **Processes predicted with high precision in the SM**
  - EWPO as $\Delta\rho$, $(g-2)_\mu$....
  - LU in $R_M^{e/\mu} = \Gamma(K(\pi) \to e\nu)/\Gamma(K(\pi) \to \mu\nu)$

SM success





Impressive confirmation
of the KM mechanism for CP violation

Minimal Flavor Violation

Model-independent fits

These general results are quite instructive if interpreted as bounds on the scale of new physics:

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{NP}\frac{1}{\Lambda^2}$$

contrbution of the new heavy degrees of freedom

c_{NP}:

- ~ 1 $\xrightarrow{\text{tree/strong + generic flavour}}$ $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ $\xrightarrow{\text{loop + generic flavour}}$ $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}{}^* V_{tj})^2$ $\xrightarrow{\text{tree/strong + MFV}}$ $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}{}^* V_{tj})^2/(16\,\pi^2)$ $\xrightarrow{\text{loop + MFV}}$ $\Lambda \gtrsim 0.5$ TeV [K & B]

recent analysis: Bona *et al.* '07

If you don't think this is an accident of $\Delta F=2$... $\Rightarrow$ MFV

Minimal Flavour Violation

- SM without Yukawa interactions: $SU(3)^5$ global **flavour symmetry**

$$\mathbf{SU(3)_u \otimes SU(3)_d \otimes SU(3)_Q \otimes SU(3)_e \otimes SU(3)_L}$$

- Yukawa interactions break this symmetry
- Proposal for any New Physics model:

Yukawa structures as the only sources of flavour violation

$$\Downarrow$$

Minimal Flavour Violation

CP violation & EDMs

CP-violation and EDMs

- Thus far (?), ~~CP~~ in K and B-meson mixing and decays is consistent with a single source

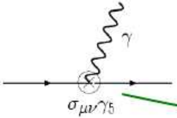
  - SM CKM phase $\delta_{KM} \sim O(1)$

- ~~CP~~ apparently hidden behind the flavour structure

$$\Rightarrow \; J_{CP} \sim 10^{-5} \sin(\delta_{KM})$$

Q: Are CP and flavour intrinsically linked ?

⇒ Look for ~~CP~~ in flavour diagonal channels



$$\boxed{H = -d\vec{S}\cdot\vec{E}}$$

— sensitivity through EDMs of neutrons, and para - and dia-magnetic atoms and molecules (violate T,P)

CP violation & EDMs

CP-violation and EDMs

<u>Motivation:</u>

- Baryogenesis requires extra $\cancel{CP}$
- SM also has an additional $\cancel{CP}$ source $\bar{\theta}$
- Most “UV completions” of SM (e.g. MSSM) provide additional sources of $\cancel{CP}$

Currently, all experimental data $\Rightarrow$ EDMs vanish to very <u>high precision</u> thus leading to very strong constraints on new physics.

NB: EDMs are observables accessible at the <u>amplitude level</u>, and so decouple more weakly than e.g. LFV observables

CP violation & EDMs

Constraints on TeV-Scale models

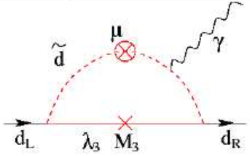
- E.G. MSSM: In general, the MSSM contains many new parameters, including multiple new CP-violating phases, e.g.

Complex ⇒ CP-odd phase

$$\begin{aligned}\Delta\mathcal{L} \sim\ & -\mu\,\bar{\tilde{H}}_1\tilde{H}_2 + B\mu\, H_1H_2 + h.c. \\ & -\frac{1}{2}\left(M_3\bar{\lambda}_3\lambda_3 + M_2\bar{\lambda}_2\lambda_2 + M_1\bar{\lambda}_1\lambda_1\right) + h.c. \\ & - A^d_{ij} H_1\tilde{q}_{Li}\tilde{q}_{Rj} + h.c + \cdots\end{aligned}$$

With a universality assumption, 2 new physical CP-odd phases $\{\theta_\mu, \theta_A\}$

- EG:1-loop EDM contribution:



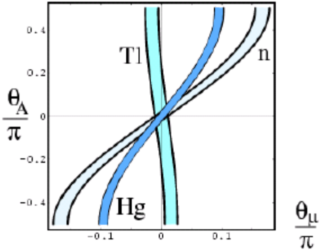
[Ellis, Ferrara & Nanopoulos '82]

$$\boxed{\frac{d_d}{m_d} \sim \frac{1}{16\pi^2}\frac{\mu m_{\tilde{g}}}{M^4}\sin\theta_\mu}$$

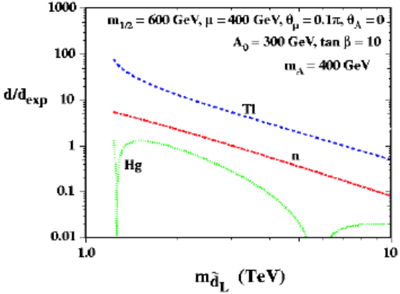
M ~ sfermion mass

CP violation & EDMs

SUSY CP Problem



$M_{soft} = 500\ GeV$



Generic Implications $\Rightarrow$ Soft CP-odd phases $O(10^{-2} - 10^{-3})$

[Olive, Pospelov, AR, Santoso '05]

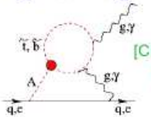
[Also: Barger et al. '01, Abel et al. '01, Pilaftsis '02]

C

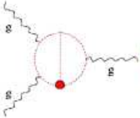
SUSY CP Constraints

MSSM parameter space: $phases < O(10^{-3} - 1)$

Decoupling 1st/2nd generation



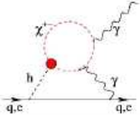
[Chang, Keung & Pilaftsis '98]



[Weinberg '89; Dai et al. 90]

Decoupling scalars (split SUSY, EW baryogenesis)

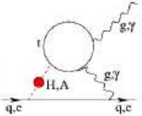
[Arkani-Hamed et al. '04]



Decoupling fermions

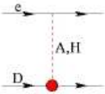
2 HDM

[Barr, Zee '92]



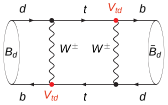
large tanβ

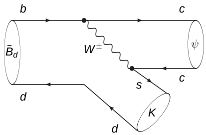
[Barr '92; Lebedev & Pospelov '02]

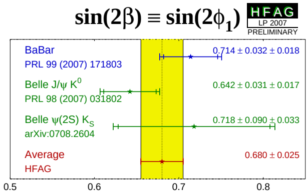


Hints for new sources of CP violation?

1. CP Asymmetry in $B \to \psi K_S$ and $\sin 2\beta$

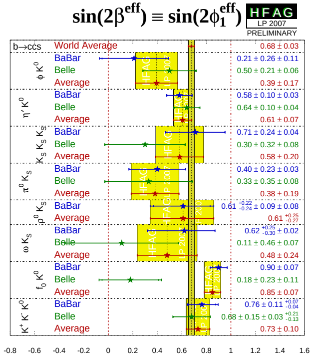






- Tree level decay $\to$ sensitivity to the phase of the mixing amplitude without NP in the decay amplitude
- in SM: $\mathrm{Arg}(M_{12}^d) = \mathrm{Arg}(V_{td}^2) = 2\beta$

$$\sin 2\beta \overset{SM}{=} S^{\text{exp.}}_{\psi K_S} = 0.680 \pm 0.025$$



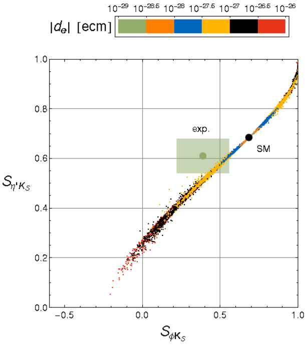
- In the SM also loop induced modes like $B \to \phi K_S$ and $B \to \eta' K_S$ give the same value

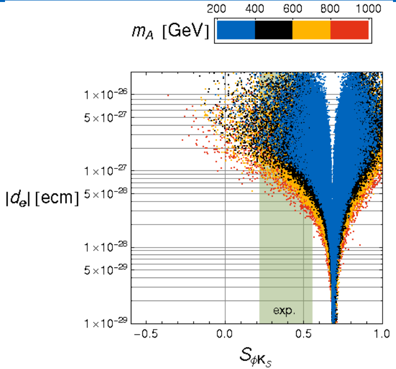
$$S^{SM}_{\phi K_S} = S^{SM}_{\eta' K_S} = S^{SM}_{\psi K_S} = \sin 2\beta$$

$$S^{\text{exp.}}_{\phi K_S} = 0.39 \pm 0.17 \qquad S^{\text{exp.}}_{\eta' K_S} = 0.61 \pm 0.07$$

$\Rightarrow$ New Phases in decays?

CP Asymmetries in $B \to \phi K_S$ and $B \to \eta' K_S$





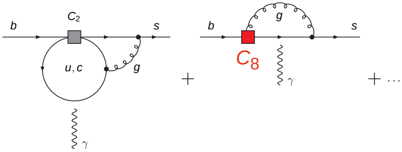
- sizeable, correlated effects in $S_{\phi K_S}$ and $S_{\eta' K_S}$
- larger effects in $S_{\phi K_S}$ as indicated by the data
- for $S_{\phi K_S} \simeq 0.4$, lower bounds on the electron and neutron EDMs:

$$d_e \gtrsim 5 \times 10^{-28} ecm \quad , \quad d_n \gtrsim 8 \times 10^{-28} ecm$$

Direct CP Asymmetry in $b \to s\gamma$

Soares '91; Kagan, Neubert '98

$$A_{CP}^{bs\gamma} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}$$

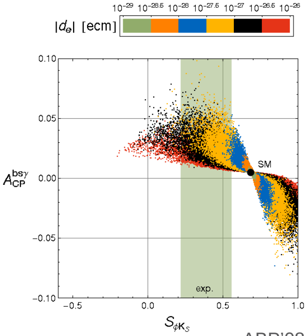


- arises first at order α_s
- doubly Cabibbo and GIM suppressed in the SM
- sizeable value would be clear signal for NP

$A_{CP}^{bs\gamma}(\mathrm{SM}) \simeq (0.44^{+0.24}_{-0.14})\%$ Hurth, Lunghi, Porod '03

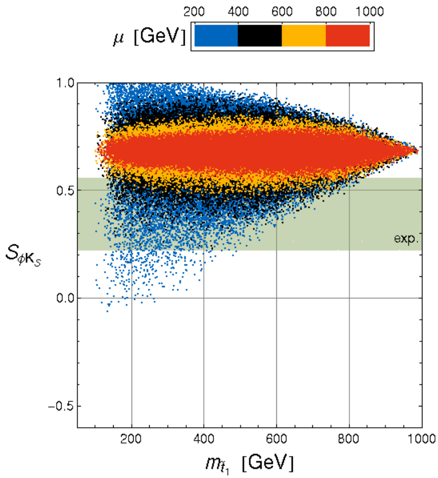
$A_{CP}^{bs\gamma}(\mathrm{exp.}) \simeq (0.4 \pm 3.6)\%$ HFAG

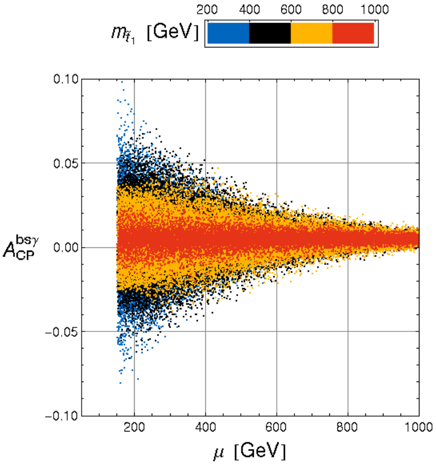
- Sign of $A_{CP}^{bs\gamma}$ is correlated with sign of $S_{\phi K_S}$
- For $S_{\phi K_S} < S_{\phi K_S}^{\mathrm{SM}} \Rightarrow 1\% \leq A_{CP}^{bs\gamma} \leq 6\%$



ABP'08

Implications for direct searches of SUSY particles





- $S_{\phi K_S} \simeq 0.4$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 700$GeV
- $A_{CP}^{bs\gamma} \gtrsim 2\%$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 800$GeV

Flavored EDMs

Electric Dipole Moment (EDM) : T-odd observable.

$$H_{eff} = -d_f \vec{S} \bullet \vec{E}$$

EDMs for electron, neutron and atoms are measured. CP phase in CKM matrix does not generate sizable EDMs, and EDMs are sensitive to beyond the standard model.

$$\begin{array}{lll} d_e < 10^{-40}\, e\,cm & & (\text{no contribution up to 3 loop}) \\ d_q \approx 10^{-(33-34)}\, e\,cm & & (O(\alpha_s G_F^2)) \\ d_n \approx 10^{-(31-32)}\, e\,cm & & (\text{long distance effects}) \end{array}$$

SUSY SM provides new $\cancel{CP}$ sources in ~~SUSY~~ terms.

Phases in F-term ~~SUSY~~ terms:

$$\phi_B = \text{ang}(M_{1/2} B^*), \quad \phi_A = \text{ang}(M_{1/2} A^*)$$

SUSY CP problem: from current EDM bounds,

$$|\sin\phi_B| <\sim \left(\frac{m_{\text{SUSY}}}{\text{TeV}}\right)^2 \tan^{-1}\beta, \quad |\sin\phi_A| <\sim \left(\frac{m_{\text{SUSY}}}{\text{TeV}}\right)^2$$

Some mechanism should suppress F-term phases.

Flavored EDMs

Sfermion mass terms are also sources of ~~flavor~~ and/or ~~CP~~.

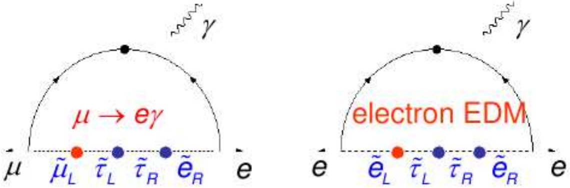
$$\delta_{ij}^{LL} \equiv \frac{\left(m^2_{\tilde{f}_L\tilde{f}_L}\right)_{ij}}{\bar{m}^2_{\tilde{f}}}, \quad \delta_{ij}^{RR} \equiv \frac{\left(m^2_{\tilde{f}_R\tilde{f}_R}\right)_{ij}}{\bar{m}^2_{\tilde{f}}}, \quad \delta_{ij}^{LR} \equiv \frac{\left(m^2_{\tilde{f}_L\tilde{f}_R}\right)_{ij}}{\bar{m}^2_{\tilde{f}}}$$

When left- and right-handed sfermions have mixing,

$$\delta_{ee}^{LR(\mathrm{eff})} \approx (m_\tau / m_e) \times \delta_{e\tau}^{LL}\delta_{e\tau}^{RR*}\delta_{ee}^{LR}, \qquad \delta_{dd}^{LR(\mathrm{eff})} \approx (m_b / m_d) \times \delta_{db}^{LL}\delta_{db}^{RR*}\delta_{dd}^{LR}.$$

And, if $\mathrm{Im}[\delta_{ij}^{LL}\delta_{ij}^{RR*}] \neq 0$, it contributes to EDMs even if $\phi_{B/A} = 0$.

FCNC processes and EDMs may be correlated to each others.



FCNC processes and EDMs probe flavor structure in ~~SUSY~~ terms.

Flavored EDMs

Supersymmetric SU(5) Ground Unification

Flavor-violating SUSY breaking mass terms for sfermion are induced by GUT interaction even if the flavor universality is imposed at the cutoff scale. (Hall, Kostelecky & Raby)

In MSSM with right-handed neutrinos,

CKM mixing ⇒ Left-handed sdown mixing
Neutrino mixing ⇒ Left-handed slepton mixing

In SUSY SU(5) GUT with right-handed neutrinos, quarks and leptons are unified, and then

CKM mixing ⇒ Right-handed slepton mixing
Neutrino mixing ⇒ Right-handed sdown mixing

We can check consistency among FCNCs and EDMs due to the GUT relation in flavor violation.

Flavored EDMs

RG induced Flavor Violating interactions in SUSY GUTs

- **SUSY SU(5)** [Barbieri & Hall, '95]

$$(\delta^{\tilde{q}}_{LL})_{ij} \sim {h^u h^u}^\dagger{}_{ij} \sim h_t^2 V^{ik}_{CKM} V^{kj*}_{CKM} \to (\delta^{\tilde{\ell}}_{RR})_{ij} \simeq (\delta^{\tilde{q}}_{LL})_{ij}$$

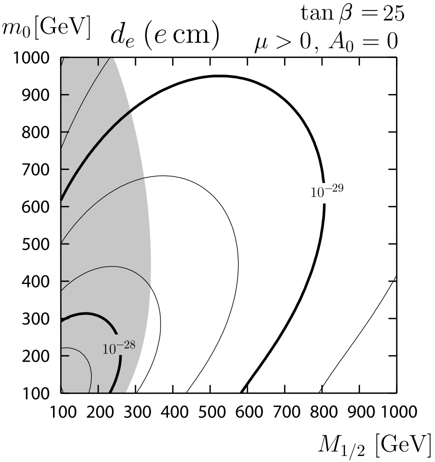
- **SUSY SU(5)+RN** [Yanagida et al., '95]

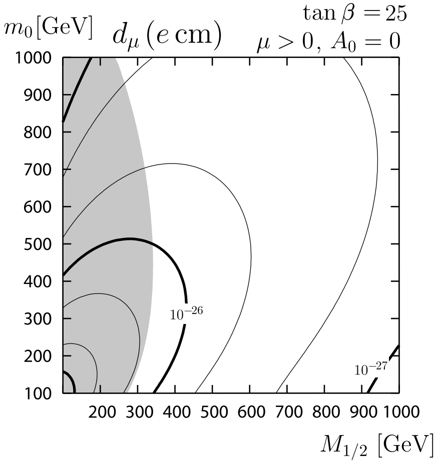
$$(\delta^{\tilde{\ell}}_{LL})_{ij} \sim (h^\nu h^{\nu\dagger})_{ij} \qquad \& \qquad (\delta^{\tilde{\ell}}_{RR})_{ij} \sim (h^u h^{u\dagger})_{ij}$$

- **SUSY SU(5)+RN** [Moroi, '00] **& SO(10)** [Chang et al., 02]

$$\sin\theta_{\mu\tau} \sim \frac{\sqrt{2}}{2} \Rightarrow (\delta^{\tilde{\nu}}_{LL})_{23} \sim 1 \Rightarrow (\delta^{\tilde{q}}_{RR})_{23} \sim 1$$

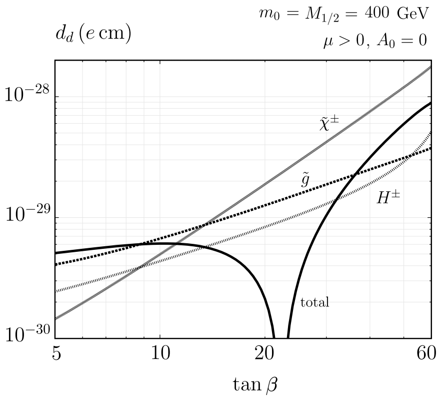
Leptonic EDMs in SUSY GUTs

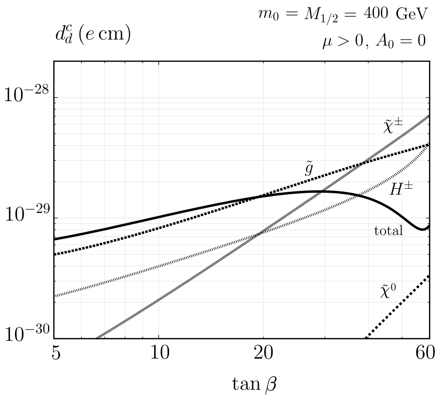




Hisano, Nagai, P.P., 06',07',08'

Hadronic EDMs in SUSY GUTs





Hisano, Nagai, P.P., 06’,07’,08’

Conclusions

Where to look for New Physics?

- Evidence of leptonic EDMs and $\ell_i \to \ell_j \gamma$ would be a clear evidence of NP
- Leptonic EDMs and $\ell_i \to \ell_j \gamma$ can probe $\Lambda_{NP} > \mathrm{TeV}$, even beyond the LHC reach
- CPV in $b \to s$ transitions like $B \to \phi K_S, \eta' K_S, X_s \gamma$ & B_s mixing
- A correlated analysis among EDMs and FCNC-CPV observables could shed light on the underlying mechanism for CPV in NP.

$$\Downarrow$$

Flavor and/or CP violating observables, represent a complementary tool to the LHC to discover or constrain NP.