FLAVOR-INDEPENDENT CP VIOLATION IN THE MSSM + ITS EXTENSIONS

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INTRODUCTION / MOTIVATION

LOW ENERGY SUPERSYMMETRY (SUSY) →
ARGUABLY STRONGEST CANDIDATE FOR BSM PHYSICS ⇨

- STABILIZATION OF GAUGE HIERARCHY
- GAUGE COUPLING UNIFICATION AT M_{GUT}
- RADIATIVE EWSB
- LSP CDM
- PRECISION EW
- ⋮

see e.g. Martin's review 97

SUCCESSES ABOVE ALL CONTINGENT ON
SOFT SUSY (SUPERPARTNER MASS SPLITTING)
OF ~ ELECTROWEAK TO TEV SCALE

⇨ ACCESSIBLE AT CURRENT + FORTHCOMING
COLLIDER EXPTS

MAIN POINT ➡ PARAMETER SPACE OF SUSY THEORIES
COMPLICATED + LARGE (FROM SUSY SECTOR)
UNCOVERING NATURE OF $\mathcal{L}_{soft}$ →
FORMIDABLE EXPERIMENTAL + THEORETICAL CHALLENGE!

(ASSUMING DISCOVERY)

OUTLINE OF PRESENTATION

- MOTIVATION
- LOW ENERGY SUPERSYMMETRY:
  WHERE WE ARE
  - THE MSSM PARAMETER SPACE
  - FOCUS → CP VIOLATION REVIEW
    (FLAVOR-INDEPENDENT)
    - EDM CONSTRAINTS
    - IMPLICATIONS FOR HIGGS/SPARTICLE SEARCHES, EW BARYOGENESIS
- LOW ENERGY SUPERSYMMETRY:
  WHERE WE ARE GOING
  - MAPPING THE PARAMETER SPACE AT LHC, LC
  - EXTENSIONS OF THE MSSM

LOW ENERGY SUPERSYMMETRY:
"WHERE WE ARE"

- PROTOTYPE MODEL → THE MSSM

  $\boxed{\text{MINIMAL}}$ SUSY EXTENSION OF THE SM

  WITH

  - 2 EW HIGGS DOUBLETS H_u, H_d
  - CONSERVED R-PARITY
  - GENERAL $\mathcal{L}_{soft}$

  → MINIMAL PARTICLE CONTENT, NOT PARAMETERS!

  (HERE MSSM ≠ "CMSSM" OR mSUGRA)

- EXTENSIONS (NOT AS FULLY EXPLORED)
  - SUSY SEESAW (ADD RH ν SECTOR)
  - MATTER + GAUGE EXTENSIONS:
    - EXTRA SM SINGLETS (NMSSM, ...)
    - EXTRA GAUGE STRUCTURE ($U(1)$'s, GUTs)

ALSO WITH GENERAL $\mathcal{L}_{soft}$ ...

MSSM BASICS

- MINIMAL $N=1$ SUSY EXTENSION OF SM →
  - 2 HIGGS DOUBLETS H_u, H_d
  - R_p CONSERVED

- PARTICLE CONTENT

GAUGE MULTIPLETS: (V_μ, λ) (BOSON, FERMION)

$$\hat{G} = (g, \tilde{g})$$
$$\hat{V}^a = (W^a, \tilde{W}^a)$$
$$\hat{V}_Y = (B, \tilde{B})$$

MATTER MULTIPLETS: (ϕ, ψ) (BOSON, FERMION)

$$\hat{Q}_i = (\tilde{Q}_i = (\tilde{u}_{Li}, \tilde{d}_{Li}), \quad Q_i = (u_{Li}, d_{Li}))$$
$$\hat{U}_i^c = (\tilde{U}_i^c = \tilde{U}^*_{Ri}, \quad U^c_{Li})$$
$$\hat{D}_i^c = (\tilde{D}_i^c = \tilde{d}^*_{Ri}, \quad d^c_{Li})$$
$$\hat{L}_i = (\tilde{L}_i = (\tilde{\nu}_{Li}, \tilde{e}_{Li}), \quad L_i = (\nu_i, e_i)_L)$$
$$\hat{E}_i^c = (\tilde{E}_i^c = \tilde{e}^+_{Ri}, \quad e^c_{Li})$$
$$\hat{N}_i^c = (\tilde{N}_i^c, \quad N_i)$$
$$(H_2)\quad \hat{H}_u = (H_u^i, \quad (\tilde{H}_u^+, \tilde{H}_u^0)_L)$$
$$(H_1)\quad \hat{H}_d = (H_d^i, \quad (\tilde{H}_d^0, \tilde{H}_d^-)_L)$$

THE MSSM PARAMETER SPACE

- RECALL MSSM (2 HIGGS DOUBLETS, R-PARITY)

EFF. THEORY SPECIFIED BY SUPERPOTENTIAL +

MOST GENERAL SET OF SOFT SUSY PARAMETERS:

(TAKE CANONICAL GAUGE FN. + KÄHLER POTENTIAL)

$$W = Y_{u\,ij}\,\hat{Q}_i\,\hat{U}^c_j\,\hat{H}_u + Y_{d\,ij}\,\hat{Q}_i\,\hat{D}^c_j\,\hat{H}_d + Y_e\,\hat{L}_i\,\hat{E}^c_j\,\hat{H}_d + \underline{\mu}\,\hat{H}_u\,\hat{H}_d$$

$$\mathcal{L}_{soft} = \mathcal{L}_M + \mathcal{L}_{SCALAR}$$

$$-\mathcal{L}_M = \tfrac{1}{2}\,\underline{M_a}\,\lambda_a\,\lambda_a + h.c.$$

$$-\mathcal{L}_{scalar} = \{\underline{\tilde{A}_{u\,ij}}\,\tilde{Q}_i\,\tilde{U}^c_j\,H_u + \underline{\tilde{A}_{d\,ij}}\,\tilde{Q}_i\,\tilde{D}^c_j\,H_d + \underline{\tilde{A}_{e\,ij}}\,\tilde{L}_i\,\tilde{E}^c_j\,H_d + \underline{b}\,H_u\,H_d + h.c.\}$$

$$+ \tilde{Q}_i\,\underline{m^2_{Q\,ij}}\,\tilde{Q}^*_j + \tilde{U}^{c*}_i\,\underline{m^2_{U\,ij}}\,\tilde{U}^c_j + \tilde{D}^{c*}_i\,\underline{m^2_{D\,ij}}\,\tilde{D}^c_j$$

$$+ \tilde{L}_i\,\underline{m^2_{L\,ij}}\,\tilde{L}^*_j + \tilde{E}^{c*}_i\,\underline{m^2_{E\,ij}}\,\tilde{E}^c_j$$

ALSO $\tan\beta = \dfrac{\langle H_u \rangle}{\langle H_d \rangle}$ IMPORTANT PARAMETER

MSSM PARAMETER SPACE

$\mathcal{L}_{soft}$ PARAMS :

- GAUGINO MASSES M_a
- [HIGGSINO MASS μ] $\Big\} \rightarrow \tilde{\chi}^{\pm}, \tilde{\chi}^{0}$
- TRILINEAR SCALAR COUPLINGS $(\tilde{A}_{u,d,e})_{ij} \longrightarrow m^2_{\tilde{u},\tilde{D},\tilde{E}}$
- BILINEAR SCALAR COUPLING b $[\equiv B\mu]$
- SOFT MASS-SQUARES $(m^2_{Q,L,U,D,E})_{ij}$
- $m^2_{H_u, H_d}$

ALSO $\tan\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}$

PARAMETER COUNT :

DINOPOULOS + SUTTER '96
HABER '97

33 MASSES

(*) 41 PHASES

31 MIXING ANGLES

105 NEW PARAMS + 19 SM PARAMS $\rightarrow$

" MSSM- 124 "

HABER '97

- OF COURSE, FOR PHENOM. STUDIES MODELS OF $\mathcal{L}_{SOFT}$ USED $\rightarrow$

mSUGRA, GMSB, ...
(m_0, A_0, $M_{H_{1,2}}$, $\tan\beta$, $\mathrm{sign}(\mu)$) BULK MEDIATION, ...

DRASTIC REDUCTION IN # OF BASIC PARAMS

- MANY CONSTRAINTS ON <u>MSSM-124</u> PARAMETER SPACE

$\longrightarrow$ FLAVOR-CHANGING COUPLINGS $\rightarrow$ $m^2_{\alpha\, ij}, (\tilde{A}_{u,d,e})_{ij}^{(i\neq j)}$

(SUSY FCNC "PROBLEM") SEVERELY CONSTRAINED FOR 1-2 MIXING
OPPORTUNITIES IN MIXING W/ 3RD FAMILY

$\longrightarrow$ $\not{CP}$ $\rightarrow$ MANY NEW COMPLEX COUPLINGS
$\rightarrow$ EDM BOUNDS

TWO CATEGORIES:

- "FLAVOR-DEPENDENT"

ROUGHLY, PHASES OF $m^2_{\alpha\, ij}, (\tilde{A}_{u,d,e})_{ij}$ $i \neq j$
$\rightarrow$ JARLSKOG-TYPE INVARIANTS $\longrightarrow$ O. LEBEDEV hep-ph/0209023

- (*) "FLAVOR-INDEPENDENT"
PHASES OF M_a, μ, b, $(\tilde{A}_{u,d,e})_{ii}$ ("OVERALL PHASE")
CONTRAST TO SM!

[FOCUS HERE ON $\not{CP}$ (*).]

REPARAM. INVARIANT PHASE COMBINATIONS $\longrightarrow$

GLOBAL SYMMS: $\longrightarrow$ INVARIANTS:

	$U(1)_{PQ}$	$U(1)_R$
$Q, \bar{u}, \bar{d}^c$	$-1/2$	1
$H_{u,d}$	1	0
μ	-2	2
b	-2	0
M_a	0	-2
$\tilde{A}_i$	0	-2

REPARAM. INVARIANT PHASES SPANNED BY

$$\boxed{\begin{aligned} \phi_{1i} &= \phi_\mu + \phi_{A_i} - \phi_b \\ \phi_{2a} &= \phi_\mu + \phi_{M_a} - \phi_b \end{aligned}}$$

$\not{CP}$ ⇨ SUMMARY OF FLAVOR-INDEPENDENT PHASES IN MSSM

NEGLECTING FAMILY MIXING —

- MSSM - 124 → BASIS OF REPHASING INVARIANT PHASES SPANNED BY

$$\phi_{1i} \equiv \phi_\mu + \phi_{A_i} - \cancel{\phi_b}^{\,=0}$$

[BY EXPLOITING $U(1)_{PQ}$ → TREE LEVEL VEVS REAL] i.e. $\tan\beta$

$$\phi_{2a} \equiv \phi_\mu + \phi_{M_a} - \cancel{\phi_b}^{\,=0}$$

[$\not{CP}$ "mSUGRA" → $\phi_{A_i} = \phi_A$, $\phi_{M_a} = \phi_M$ → ϕ_1, ϕ_2 → USUALLY $\phi_2 \equiv$ "ϕ_μ", $\phi_1 - \phi_2 \equiv$ "ϕ_A"]

THESE ENTER MASS MATRICES + COUPLINGS (FLAVOR CONSERVING)

∴ PHYSICAL MASSES, MIXINGS FUNCTIONS OF THESE PHASES:

$$\tilde{\chi}^\pm \longleftrightarrow \phi_{22} = \phi_\mu + \phi_{M2}$$

$$\tilde{\chi}^0 \longleftrightarrow \phi_{22},\ \phi_{21} = \phi_\mu + \phi_{M1}$$

$$m^2_{\tilde{f}_i} = \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^{2\dagger}_{LR} & m^2_{RR} \end{pmatrix}$$

$m^2_{LR} = m_f(A^* - \mu R_\beta)$

↳ $\phi_{1i} = \phi_\mu + \phi_{A_i}$

NOTE → WRITING $m^2_{LR} = |m^2_{LR}| e^{i\phi_{LR}}$,

$|m^2_{LR}| \sim f(\phi_{1i})$

ϕ_{LR} ~ NOT AN INVARIANT!

(+2 R-charge)

EDM CONSTRAINTS

- SM $\rightarrow \not{CP}$ INEXTRICABLY LINKED TO FLAVOR (CKM)
  (3-LOOP EDM CONTRIBUTION)
- MSSM $\rightarrow \not{CP}$ + FLAVOR CAN BE SEPARATED
  1-LOOP EDM CONTRIBUTIONS

$\downarrow$

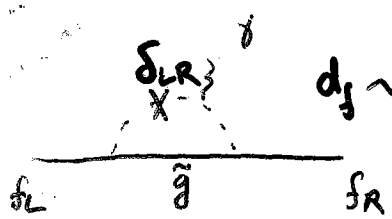
ELECTRIC DIPOLE MOMENT BOUNDS:

$$|d_{Tl}| < 9 \times 10^{-25}\ e\,cm \quad \left(\sim |d_e| \text{ FOR low } \tan\beta\right)$$

$$|d_{Hg}| < 2 \times 10^{-28}\ e\,cm$$

$$|d_n| < 6 \times 10^{-26}\ e\,cm$$

INDIVIDUALLY CONSTRAIN THE PHASES TO BE $< 10^{-2}$ 10^{-2}
FOR SPARTICLE MASSES IN EW to TEV RANGE



$d_f \sim \sin\phi\ 10^{-23}\ e\cdot cm$

for $\tilde{m} \sim 100$ GeV

$+ |\delta_{LR}| \sim \frac{m_f}{\tilde{m}} \sim 10^{-5}$

DUGAN, GRINSTEIN, HALL '85
ELLIS ET AL. '82, ...
BUCHMULLER, WYLER '82 ...
⋮

"SUSY CP PROBLEM"

SUSY CP PROBLEM: ALTERNATIVES

- TRADITIONAL SOLN → ALL PHASES ≈ 0

- HEAVY SUPERPARTNERS FOR 1st GENERATION → SUPPRESS EDMs + ALLOW LARGER PHASES

  COHEN, KAPLAN, NELSON

- CANCELLATIONS AMONG VARIOUS CONTRIBUTIONS

  FALK et al '96
  IBRAHIM, NATH ... '97
  BRHLIK, GOOD, KANE '98
  ⋮

  - NOTE → NO UNDERLYING SYMMETRY PRINCIPLE
    → FINE TUNING (OR EXPLAINED BY UNDERLYING ~~SUSY~~ HIGH SCALE THEORY)

  - CANCELLATION SCENARIO FIRST INVESTIGATED w/o MERCURY EDM BOUND

    ↓

    STRONGEST CONSTRAINTS ON SUSY PHASES

    BUT ALSO MOST CONTROVERSIAL →

    MANY THEORETICAL UNCERTAINTIES FOR BOTH d_n, d_{Hg}

→ CONSIDER EDM ANALYSIS BOTH FOR SMALL $\tan\beta$ + LARGE $\tan\beta$

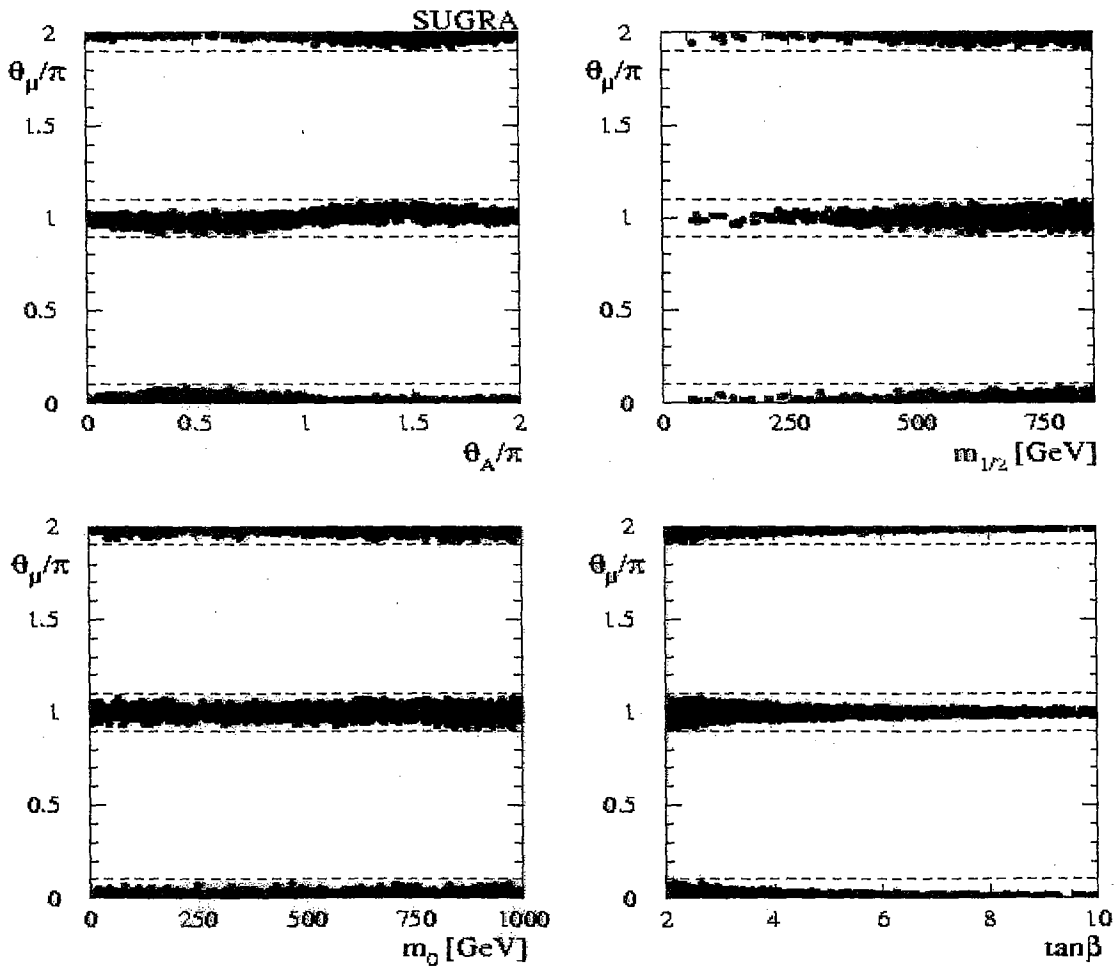
BARGER ET AL hep-ph/0101106

POSPELOV et al '0[illegible]
PILAFTSIS... '95; 0[illegible]

EDM constraints (I)

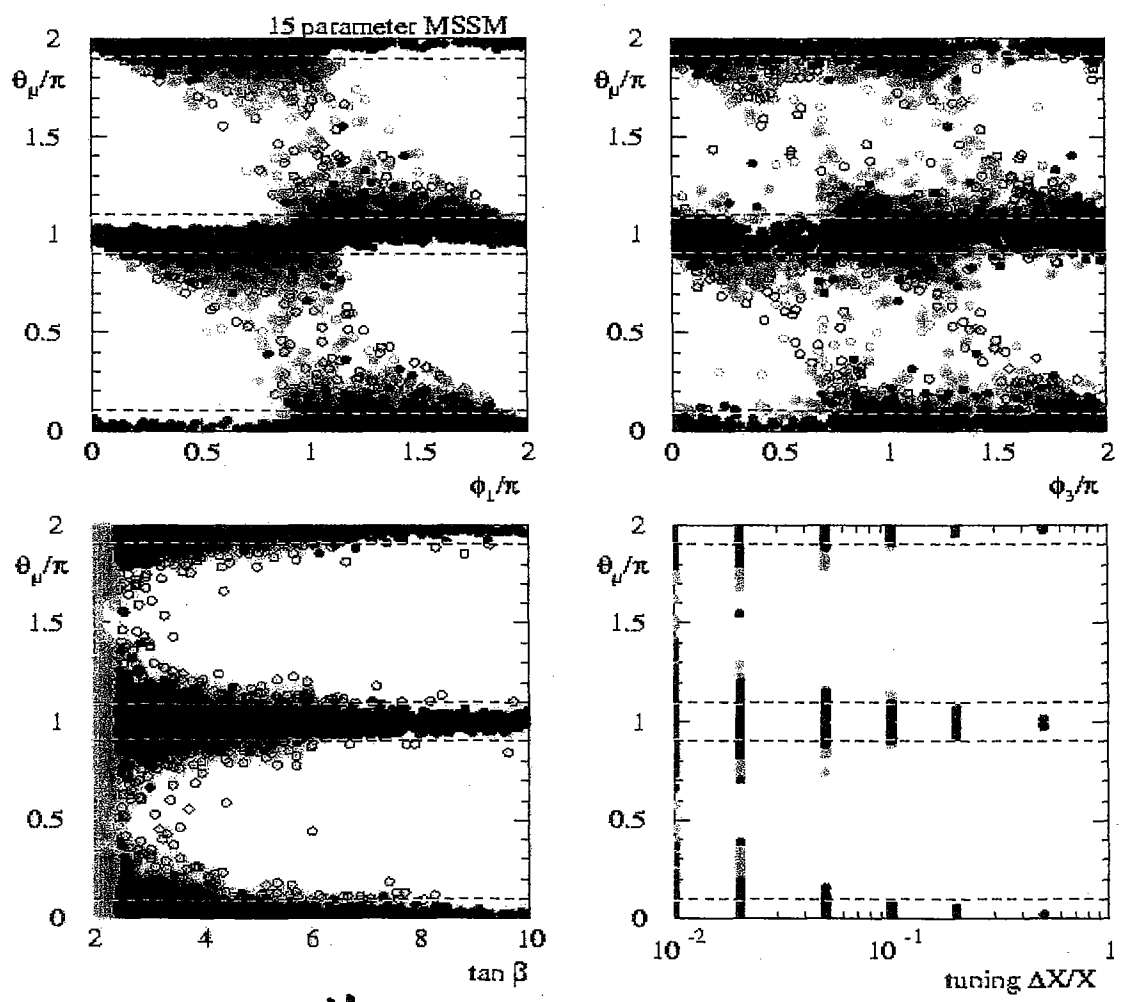
MSUGRA model (2 indep. phases),
constraints from d_e, d_n, d_{Hg}

Barger et al., hep-ph/0101106



EDM constraints (II)

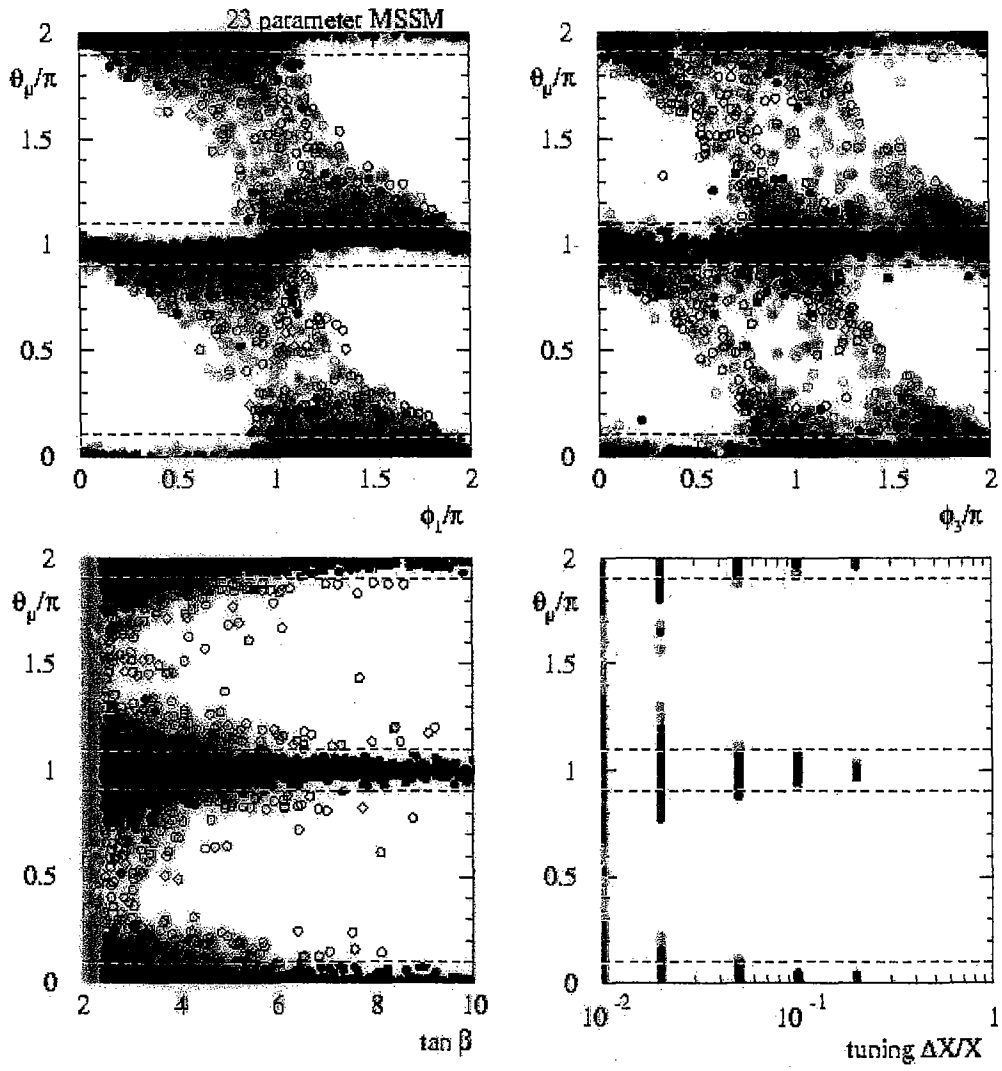
15 param MSSM: open circles = fine-tuned,
light circles = ruled out by Higgs mass bound



PARAMETERS: $M_{1,2,3}$, $\phi_{1,3}$ $\phi_{A_{e,u,d,t}}$, ϕ_μ,
$|A|$, $m^2_{\tilde{e}_R}$, $m^2_{\tilde{u}_R}$, $|\mu|$, $\tan\beta$
($\phi_{M_2} = 0$ CONVENTION)

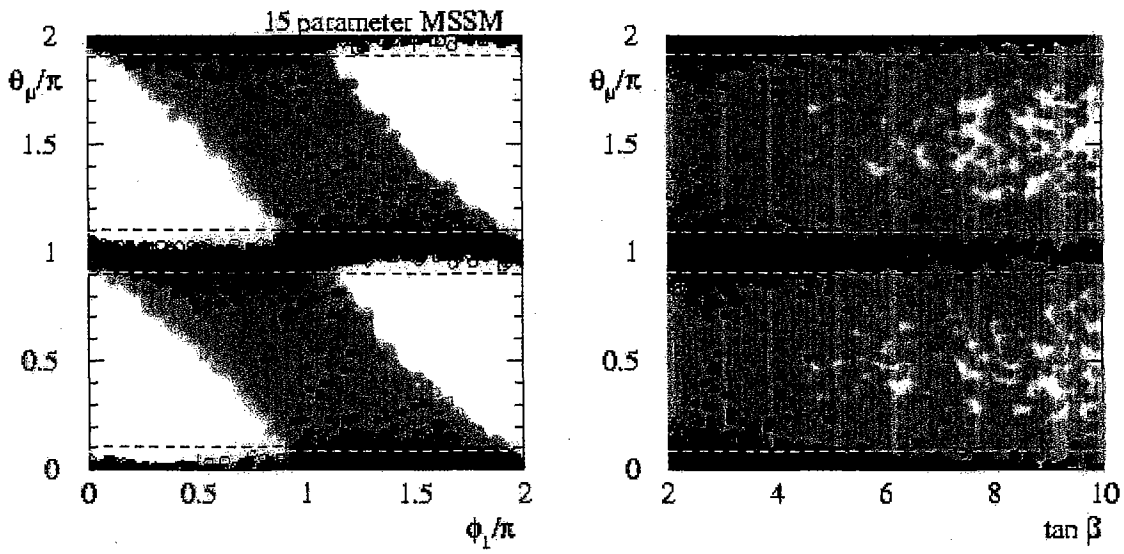
EDM constraints (III)

23 parameter MSSM:



Mercury EDM

d_{H_g} provides strongest bound:



15 param MSSM imposing d_e, d_n constraints.
green points forbidden, black points allowed by d_{H_g} constraint

→ SUMMARY:

BARGER ET AL '01

<u>LOW $\tan\beta$</u> : $\phi_\mu + \phi_{M_2} \lesssim \pi/5\tan\beta$

CHARGINO SECTOR PHASE CONSTRAINED!

OTHER PHASES UNCONSTRAINED

WHAT ABOUT <u>LARGE $\tan\beta$</u> ?

- 1-LOOP EDMs → LINEAR ENHANCEMENT IN $\tan\beta$ (LIKE $g_\mu - 2$, ...)

  ↓

  EDM CONSTRAINTS MORE DIFFICULT TO SATISFY

  (EITHER CANCELLATIONS OR HEAVY SPARTICLES)

- BUT ALSO →

  - 2-LOOP EFFECTS → BARR-ZEE CHANG, KEUNG, PILAFTSIS '98

    ↓ HIGGS-MEDIATED

ALSO → 4-FERMION OPERATORS LEBEDEV + POSPELOV '02

INDUCED WHICH CONTRIBUTE TO ATOMIC EDMs, SPOIL $d_{Tl} \propto d_e$

SYSTEMATIC STUDY OF ALL CONSTRAINTS STILL LACKING ...

POSPELOV ET AL. hep-ph/0311314

IMPLICATIONS OF NON-NEGLIGIBLE FI $\not{CP}$

- IF PHASES NONVANISHING + SIZEABLE, MANY IMPLICATIONS →
  - ELECTROWEAK BARYOGENESIS
  - HIGGS SECTOR $\not{CP}$ + PHENOMENOLOGY
  - COLLIDER SEARCHES FOR SPARTICLES

    ↓

    MASSES + COUPLINGS FUNCTIONS OF REPARAM. INV. PHASES

ELECTROWEAK BARYOGENESIS

- BARYON ASYMM. ORIGIN → FUNDAMENTAL QUESTION

  → EW BARYOGENESIS WELL-MOTIVATED, WELL-STUDIED SCENARIO

CURRENT STATUS:

CARENA, WAGNER, QUIROS ... '02
CLINE ET AL ...

VERY NARROW WINDOW OF MSSM-124 PARAM SPACE VIABLE →

REQUIRES LIGHT HIGGS, LIGHT STOP

→ DOMINANT $\not{CP}$: CHARGIND SECTOR PHASE

$$\boxed{\phi_\mu + \phi_{M_2}}$$

∴ SQUEEZED BY EDM CONSTRAINTS

- SCENARIO STILL VIABLE, MAY BE RULED OUT AT FORTHCOMING COLLIDERS...

- PHENOM. IMPLICATIONS FOR PARTICLE PHYSICS FROM EW BARYOGENESIS WINDOW

MURAYAMA + PIERCE, '02

- IN NMSSM →
  THINGS IMPROVE! (LANGACKER'S TALK)

HIGGS SECTOR $\not{CP}$

- MSSM HIGGS POTENTIAL CP CONSERVING AT TREE LEVEL, CP-VIOLATING IF $\mathcal{L}_{soft}$ IS $\not{CP}$

WAGNER, PILAFTSIS, DEMIR, CARENA ET AL, KANE + WANG ⋮

DOMINANT CONTRIBUTION →

STOP LOOPS

$\not{CP} \rightarrow \boxed{\phi_\mu + \phi_{A_t}}$ (STOP LR MIXING)

(RELATIVELY UNCONSTRAINED FROM EDMs, EXC. 2-LOOP AT LARGE $\tan\beta$)

- DRASTIC MODIFICATIONS TO HIGGS PHENOMENOLOGY, PARTICULARLY WHEN LIGHTEST h^0 HAS SIGNIFICANT MIXING WITH "A^0" (NONDECOUPLING REGIME)

"CPX" BENCHMARK MODEL DESIGNED TO OPTIMIZE SUCH EFFECTS

CARENA, ELLIS, PILAFTSIS, WAGNER hep-ph/0009212, ...

(MANY BOUNDS GO AWAY)

IMPLICATIONS FOR COLLIDER SEARCHES + MEASURING THE PHASES

- MANY STUDIES OF IMPACT OF PHASES ON COLLIDER SEARCHES

E.G.
- $\tilde{\chi}^0, \tilde{\chi}^\pm$ SECTORS — S. CHOI ET AL., ZERWAS ET AL., ...
- $\tilde{t}, \tilde{b}$ SEARCHES — BARTL ET AL., [illegible]

→ BRANCHING RATIOS OF THEIR DECAYS CAN CHANGE BY FACTOR OF 2 OR MORE...

MOST CASES →

SWITCH ON PHASES, COMPARE RESULTS WITH CP-CONSERVING CASE

BUT → $\not{CP}$ PHASES OF $\mathcal{L}_{SOFT}$ ARE MANIFEST IN BOTH CP CONSERVING + CP VIOLATING OBSERVABLES.

TO OBSERVE PHASES DIRECTLY AT LHC →

WANT $\not{CP}$ OBSERVABLES

(BUT MAYBE NOT ENOUGH EXPT. PRECISION)

EFFECTS OF PHASES IN CP CONSERVING OBSERVABLES CAN BE MASKED BY VARIATION OF REMAINING SUSY PARAMS!

- MEASURING "GLUINO PHASE" $(\phi_{M_3} - \phi_{M_2})$ AT FNAL
  KANE, MLENNA, WANG

- GROWING LITERATURE ON RECONSTRUCTION OF CHARGINOS + NEUTRALINOS WITH $\not{CP}$ PHASES: (NLC)

  S. CHOI et. al, hep-ph/9812236
  hep-ph/0001175
  hep-ph/0002033
  hep-ph/0108117
  hep-ph/0202039, [illegible]

  BARGER et al hep-ph/0101106

  KALINOWSKI et al, hep-ph/0202083

  ⋮

- SFERMION SECTORS →

  NEGLECTING INTERGENERATIONAL MIXING →
  LR MIXING → USUALLY ∝ FERMION MASS
  NEGIGIBLE FOR 1, 2 FAMILIES

  MIXING ANGLE ANALYSIS, TYPICALLY w/o $\not{CP}$
  e.g. $\tilde{\tau}$ → Nojiri et al '96

BOTTOM LINE: DIFFICULT TO MEASURE PHASES AT HADRON COLLIDERS,
~~still~~ MORE FEASIBLE AT LC

EXTENSIONS OF MSSM

(TALK BY MORRISSEY)

- BOTH THEORETICAL + PHENOMENOLOGICAL REASONS TO CONSIDER EXTENDED MODELS → nMSSM, NMSSM, ...
  - μ PROBLEM
  - HIGGS SECTOR → HIGGS MASS BOUNDS ALLEVIATED, ...
- EW B-GENESIS (Li)

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e.g. CONSIDER $\not{CP}$ IN e.g. NMSSM, MSSM × U(1)' LANGACKER'S TALK

→ SINCE EDM CONSTRAINTS ⟶ STRONGEST LIMIT ON ϕ_μ + ϕ_{M_2}

MODELS WHICH SOLVE/ADDRESS μ PROBLEM CAN YIELD INSIGHT INTO SUSY CP PROBLEM

$$\phi_\mu \sim f(\phi_A, \phi_M)$$

EXAMPLES → U(1)' MODELS

CVETIC, LANGACKER ET AL...
DEMIR, [illegible] '02 [illegible]

$W \sim h S H_u \cdot H_d$

$\mu \sim \langle S \rangle$

ϕ_μ dictated by ϕ_{A_S}

STRING-MOTIVATED SUGRA → ϕ_A + ϕ_M OFTEN RELATED

CONCLUSION

- $\boxed{\text{MSSM-124}}$ PARAMETER SPACE →

  COMPREHENSIVE MAP OF ALLOWED REGIONS NOT KNOWN,

  SIGNIFICANT CHALLENGE FOR FUTURE

- "FLAVOR-INDEPENDENT" PHASES →

  STRONGLY CONSTRAINED BY EDMs,

  BUT MAY BE TOO NAIVE TO DISMISS THEIR EFFECTS

  STRONGEST CONSTRAINT ON $\tilde{\chi}^{\pm}$ SECTOR OF "PHASE OF μ" $(\phi_\mu + \phi_{M_2})$

  CHALLENGE FOR SUSY MODEL BUILDING AS WELL

- NEED TO THINK OUTSIDE THE MSSM-MSUGRA BOX!