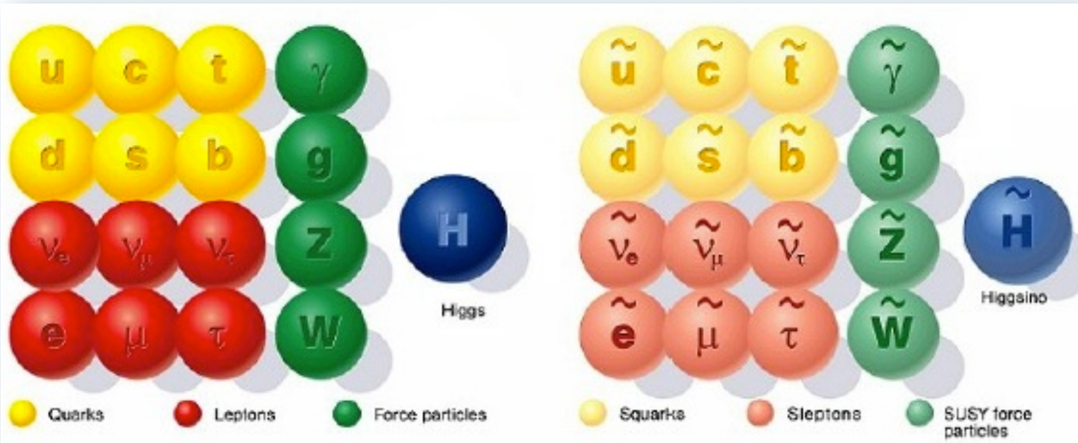
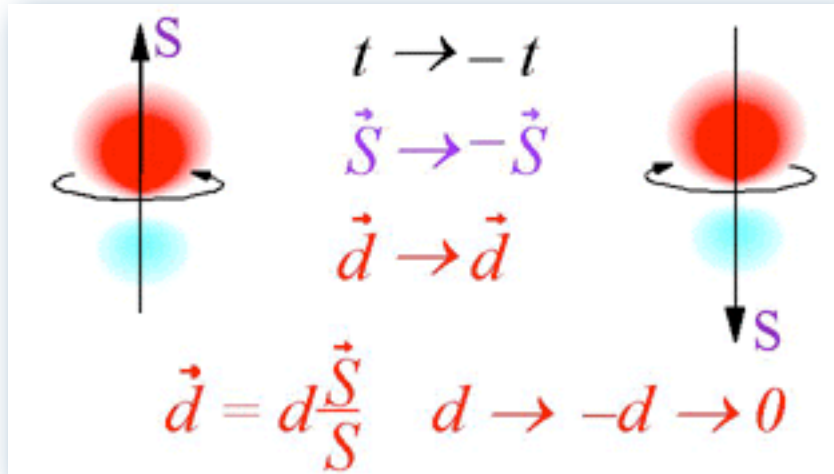
Supersymmetry and EDMS





Marcela Carena
Theoretical Physics Department, Fermilab
Enrico Fermi Institute and KICP, University of Chicago

Winter Workshop on EDMs
Fermilab, February 15, 2013

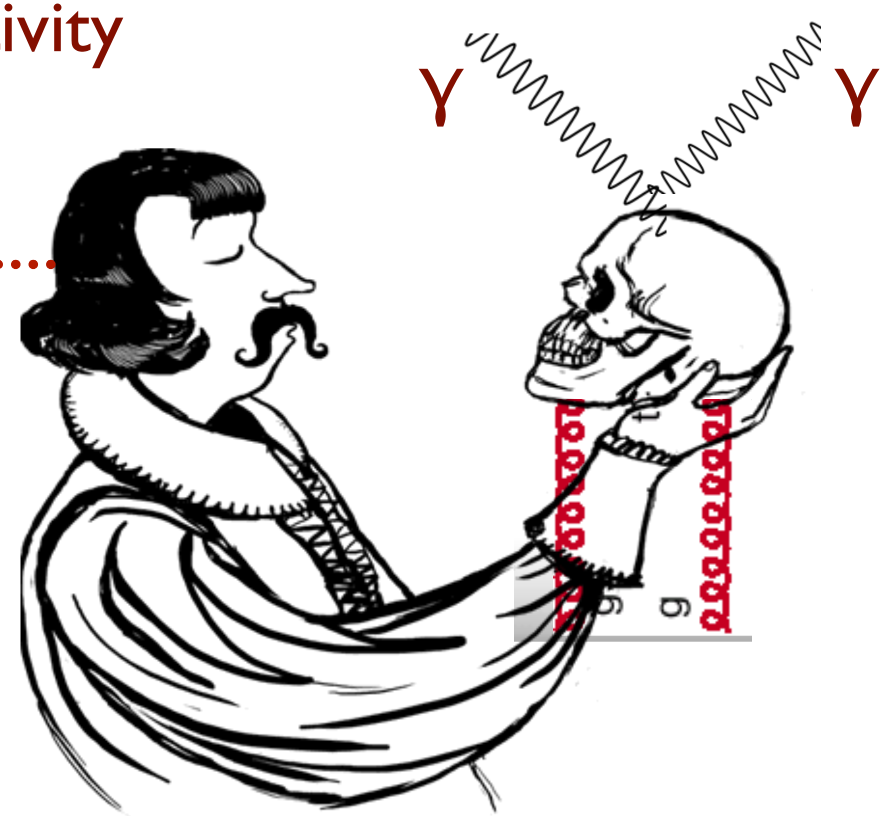
2012 has been an amazing year for HEP:

A Higgs -like particle has been discovered

CMS: $m_h \sim 126.2$ GeV (in ZZ); $m_h = 124.9.$ GeV (in $\gamma\gamma$)

ATLAS: $m_h = 123.5$ GeV (in ZZ); $m_h = 126.6$ GeV (in $\gamma\gamma$)

The mass results are consistent within present sensitivity



The SM-Higgs, or not the SM-Higgs....

and a possible enhanced $\gamma\gamma$ rate

$\mu = 1.8$ in ATLAS ($\sim 2.4\ \sigma$)

$\mu = 1.5$ (CMS/July 4th)

The SM might be complete

Origin of mass of fundamental particles = the quest of EWSB ===> HIGGS

but still many open questions

Generation of big hierarchy of scales

Generation of hierarchies of fermion masses.

Neutrinos: are they encoding a secret message?

Connection of electroweak and strong interactions with gravity

Explanation of matter-antimatter asymmetry of the universe

Dark Matter

Dark Energy

- The Hierarchy Problem of the SM Higgs Sector **Why v $\ll$ M_{Pl} ?**

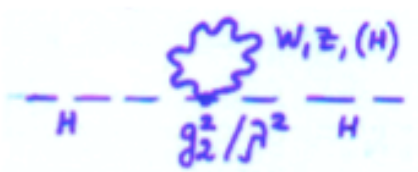
$$V(\phi) = m^2\phi^\dagger\phi + \frac{\lambda}{2}(\phi^\dagger\phi)^2 \qquad m^2 < 0$$

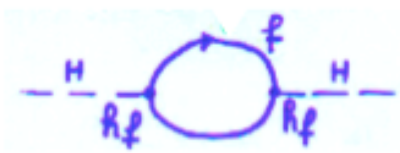
Quantum Corrections to the Higgs mass parameter diverge quadratically with the UV scale

$$m^2 = m^2(\Lambda_{UV}) + \Delta m^2 \longrightarrow \Delta m^2 \simeq \frac{n_W g^2_{hWW} + n_h\lambda^2 - n_f g^2_{hff}}{16\pi^2}\Lambda^2_{UV}$$

To explain $m^2 \propto v^2 \approx \mathcal{O}(M_W^2)$ either

$\Lambda_{UV} \leq$ few TeV or fine tunning

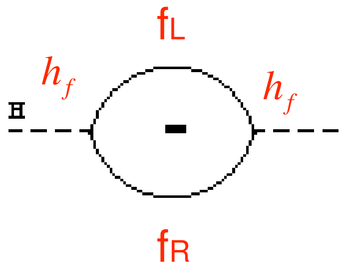


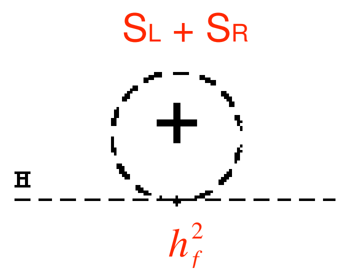


Quantum Corrections to the Higgs Mass Parameter

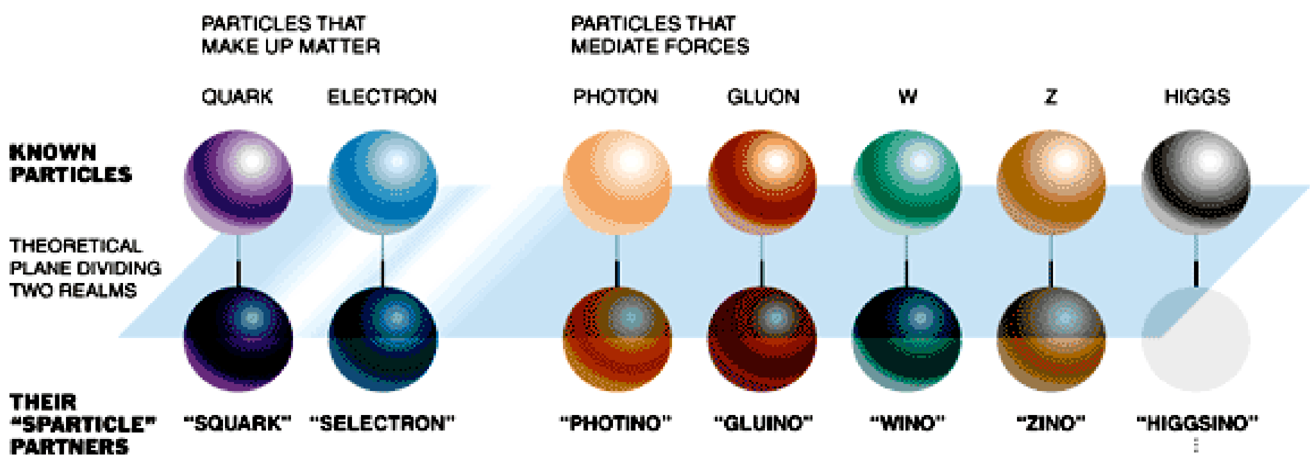
One loop quadratic divergent contributions cancel if the number of degrees of freedom and the couplings of bosons and fermions are equal to each other

$$\delta m_H^2 = \frac{N_C h_f^2}{16\pi^2}\left[-2\Lambda^2 + 3m_f^2 \log\left(\frac{\Lambda^2}{m_f^2}\right) + 2\Lambda^2 - 2m_s^2 \log\left(\frac{\Lambda^2}{m_f^2}\right)\right]$$





Supersymmetry: a symmetry between bosons and fermions



For every fermion there is a boson of equal mass and couplings

Automatic cancellation of Λ^2 loop corrections to the Higgs mass parameter

Why Supersymmetry?

- Helps stabilize the weak scale-Planck scale hierarchy
- SUSY algebra contains the generator of space translations
  → necessary ingredient of theory of quantum gravity
- Allows for Gauge Coupling Unification at a scale ~ 10^{16} GeV
- Starting from positive Higgs mass parameters at high energies, induces electroweak symmetry breaking radiatively.
- Provides a good Dark matter candidate:
  The Lightest SUSY Particle (LSP)

A good BSM

- Provides a solution to the baryon asymmetry of the universe.

if there are new sources of CP violation beyond those in the SM

The Minimal SUSY extension of the Standard Model (MSSM)

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
($\times 3$ families)	U	$\widetilde{u}_R^*$	$(u^C)_L$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	D	$\widetilde{d}_R^*$	$(d^C)_L$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \ \ \widetilde{e}_L)$	$(\nu \ \ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
($\times 3$ families)	E	$\widetilde{e}_R^*$	$(e^C)_L$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ \ H_u^0)$	$(\widetilde{H}_u^+ \ \ \widetilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \ \ H_d^-)$	$(\widetilde{H}_d^0 \ \ \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Matter Superfields

2 Higgs vev's

$\tan\beta = v_u/v_d$

Two Higgs doublets of opposite Hypercharges necessary to give mass to both up and down quarks and leptons in a gauge/SUSY invariant way

2 Higgsino doublets necessary for anomaly cancellation

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^{\pm} \ \ \widetilde{W}^0$	$W^{\pm} \ \ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Gauge Superfields

The winos and bino are not mass eigenstates, they mix with each other and with the Higgs superpartners, called higgsinos, of the same charge

Supersymmetry Breaking

If SUSY were an exact symmetry, the SM particles and their superpartners would have the exactly same masses

$m_{\tilde{e}_L} = m_{\tilde{e}_R} = m_e = 0.511$ MeV

$m_{\tilde{u}_L} = m_{\tilde{u}_R} = m_u$

$m_{\tilde{g}} = m_{\text{gluon}} = 0 +$ QCD-scale effects

etc.

- No supersymmetric particle have been seen: Supersymmetry is broken in nature
- Unless a specific mechanism of supersymmetry breaking is known, no information on the spectrum can be obtained.
- Cancellation of quadratic divergences:
  - Relies on equality of couplings and not on equality of the masses of particle and superpartners.
- Soft Supersymmetry Breaking: Give different masses to SM particles and their superpartners but preserves the structure of couplings of the theory.

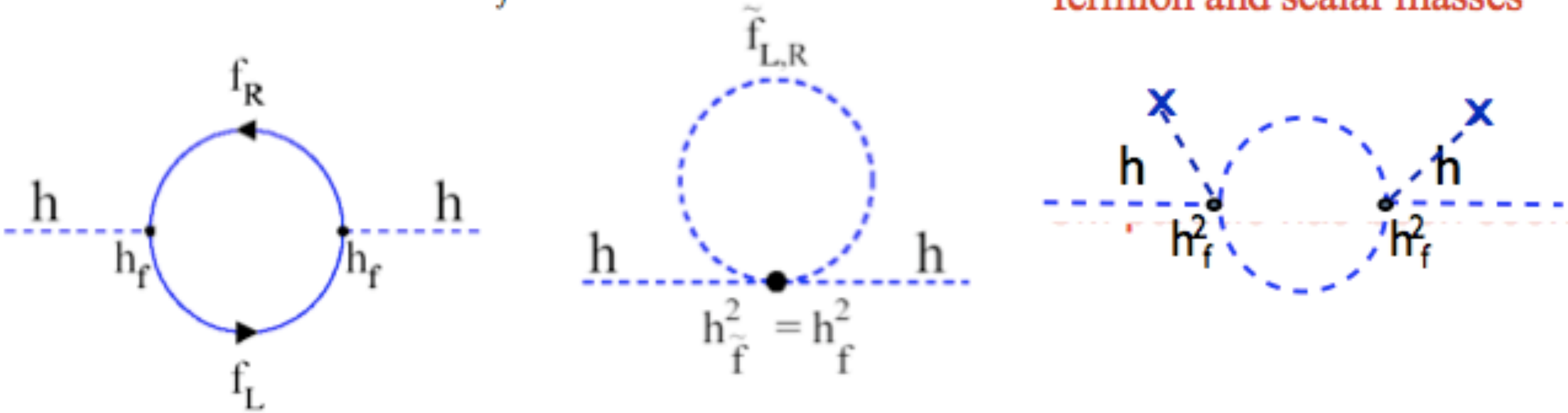
SUSY must be broken in nature

Back to SUSY corrections to the Higgs mass parameter:

Cancellation of quadratic divergences in Higgs mass quantum corrections has to do with SUSY relation between couplings and bosonic and fermionic degrees of freedom

$$\Delta m^2 \approx g^2_{hf\bar{f}}[m_f^2 - m_{\tilde{f}}^2]\ln(\Lambda^2_{eff} / m_h^2)$$

not with the exact equality of fermion and scalar masses



In low energy SUSY: quadratic sensitivity to Λ_{eff} replaced by quadratic sensitivity to SUSY breaking scale

The scale of SUSY breaking must be of order 1 TeV, if SUSY is associated with the scale of electroweak symmetry breaking

The Soft SUSY-breaking Lagrangian for the MSSM

Gaugino masses, squark/slepton squared mass terms and trilinear/biliniar terms prop. to scalar superpotential do not spoil cancellation of quadratic divergences

$$\mathcal{L}_{soft} = -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B})$$
$$-m_Q^2\tilde{Q}^\dagger\tilde{Q} - m_U^2\tilde{U}^\dagger\tilde{U} - m_D^2\tilde{D}^\dagger\tilde{D} - m_L^2\tilde{L}^\dagger\tilde{L} - m_E^2\tilde{E}^\dagger\tilde{E}$$
$$-m_{H_1}^2 H_1^* H_1 - m_{H_2}^2 H_2^* H_2 - (\mu B H_1 H_2 + cc.)$$
$$-(A_u h_u \tilde{U}\tilde{Q}H_2 + A_d h_d \tilde{D}\tilde{Q}H_1 + A_l h_l \tilde{E}\tilde{L}H_1) + c.c.$$

Trilinear terms - proportional to the Yukawa couplings -
induce L-R mixing in the sfermion sector once the Higgs acquire v.e.v.

B ⟶ SUSY breaking parameter determined from condition of proper EWSB

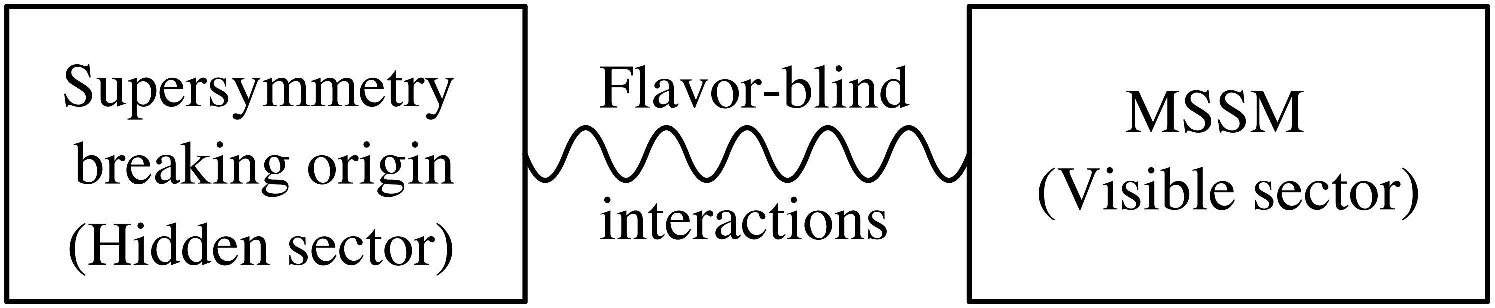
MSSM with R-parity: 105 new parameters not present in the SM
with many new CP phases possible

Most of what we do not really know about SUSY is expressed by the question: "How is SUSY broken?"

Understanding the origins of Spontaneous SUSY breaking:

Soft SUSY breaking terms arise indirectly,

not through treel level, renormalizable couplings to the SUSY breaking sector



Spontaneous SUSY breaking occurs in a Hidden sector of particles, with none or tiny direct couplings to the MSSM particles, when some components of the hidden sector acquire a vev $< F > \neq 0$

If the mediating interactions are flavor blind (gravity/ordinary gauge interactions), the MSSM soft SUSY breaking terms will also be flavor independent (favored experimentally)

Many alternatives: Gravity-type; Gauge; Extra Dimensional mediated, ...
$\Longrightarrow$ different boundary conditions at an specific SUSY breaking scale

The pattern of SUSY particle masses depend on the SUSY breaking scenario.

The SUSY Particles of the MSSM

Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	$+1$	$h^0\ H^0\ A^0\ H^\pm$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$
squarks	0	-1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	" "
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	" "
			$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$	$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$
sleptons	0	-1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	" "
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	" "
			$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$
neutralinos	$1/2$	-1	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$
charginos	$1/2$	-1	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$
gluino	$1/2$	-1	$\widetilde{g}$	" "

No SUSY particles discovered at the LHC yet, but....

Given the Discovery of a Higgs-like particle with mass ~ 125 GeV

- Do we still expect SUSY (some type of low energy SUSY) ?

- If yes, what are the implications of the new particle mass, production and decay rates for SUSY models?

- What do we expect in the extended SUSY Higgs sector?

- What are the implications for flavor?
  -- Flavor-Higgs connection within the MFV assumption at the SUSY breaking scale --

- What about new sources of CP violation?

The MSSM Higgs Sector

2 CP-even **h, H** with mixing angle α
1 CP-odd **A** and a charged pair H+- with mixing angle β

$$m_A^2 = m_1^2 + m_2^2 = m_{H_1}^2 + m_{H_2}^2 + 2\mu^2$$

$m_{H_1}^2 + m_{H_2}^2$ → Soft SUSY breaking Higgs mass parameters

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta \qquad m_{H^\pm}^2 = m_A^2 + M_W^2 \qquad m_H^2 \simeq m_A^2$$

Quantum Corrections: Higgs mass shifted due to incomplete cancellation of particles and sparticles in the loops (stops & for tanβ>10 also sbottoms/staus)

$$\mathbf{M}_{\tilde t}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

the off-diagonal term depends on the stop-Higgs trilinear couplings

$$X_t = A_t - \mu^* / \tan\beta$$

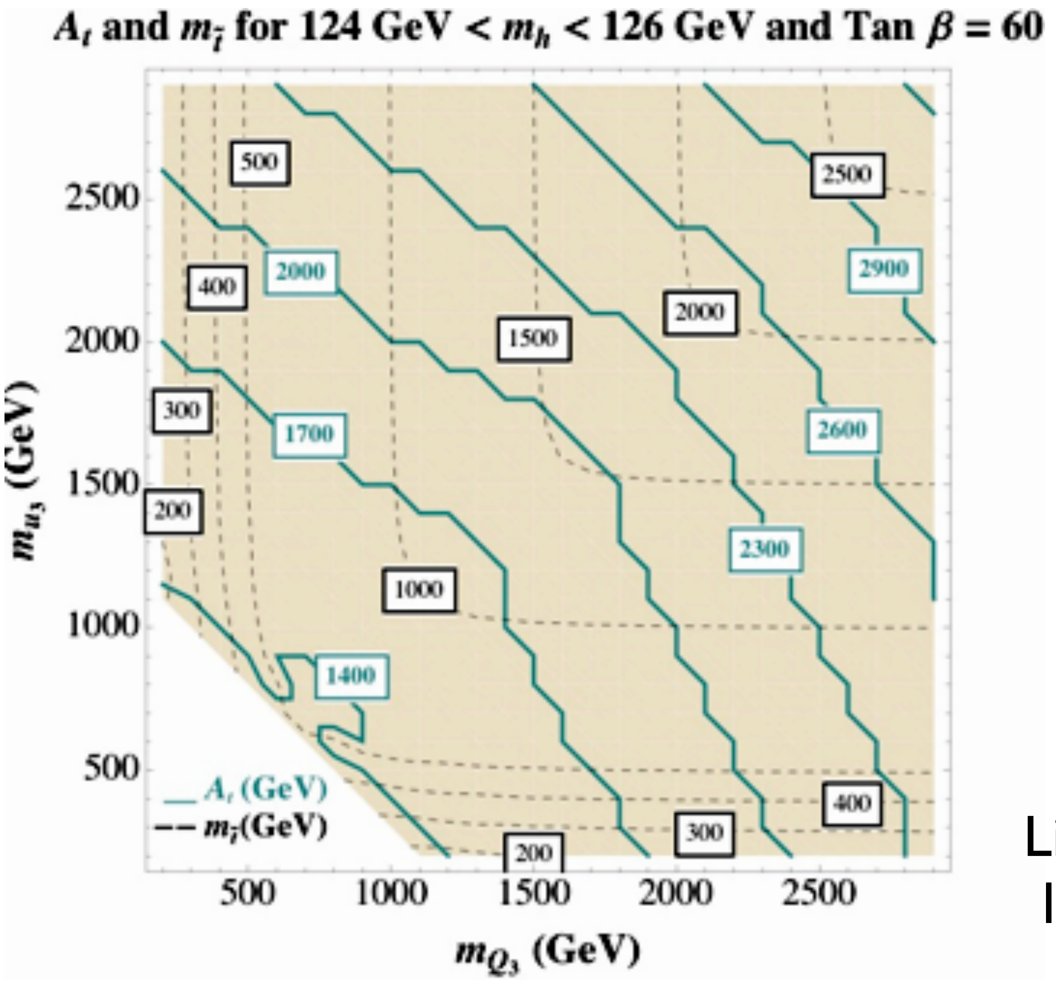
For large m_A, with $M_S = m_Q = m_U$ the dominant one-loop corrections are given by,

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right) \right)$$

2 loop result: $m_h < 135$ GeV

M.C. Espinosa, Quiros, Wagner '95; M.C. Quiros, Wagner '95
Haber, Hempfling, Hoang '96

MSSM Soft SUSY Breaking Parameters and M_h ~ 125 GeV



M. C., S. Gori, N. Shah, C. Wagner '11
+L.T.Wang '12

Similar results from
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon '11
Draper Meade, Reece, Shih'11

Large stop sector mixing
A_t > 1 TeV

No lower bound on the lightest stop
One stop can be light and the other heavy
or
in the case of similar stop soft masses.
both stops can be below 1TeV

Large mixing also constrains SUSY breaking model building

Light 3rd generation Sfermions can change loop induced production and decay rates

light staus with sizeable mixing
(large μ tan beta)
may enhanced γγ up to 50 %
with SM-like ZZ/WW ;

CP Violation in the MSSM

- In low energy SUSY, there are extra CP-violating phases beyond the CKM ones, associated with complex SUSY breaking parameters Af, Mi, Bμ and the complex SUSY Higgsino mass μ

Under the assumption of flavor universality in the scalar sector

$$M_S^2 = m_S^2 I \qquad \text{for S= Q,U,D,L,E}$$

and proportionality of trilinear soft mass terms to the Yukawa

$$A_f = a_f Y_f \qquad \text{for f= u,d,e}$$ at the SUSY breaking scale

One can redefine fields and absorb many phases,
but there are 4 rephasing invariant combinations

$$\mathrm{Arg}(\mu M_i m_{12}^{2*}) \qquad \mathrm{Arg}(A_f M_i^*) \qquad \mathrm{Arg}(M_j M_i^*) \qquad \mathrm{Arg}(A_f A_{f'}^*)$$

take m_{12}, and μ real and vary other phases

In many simplified analysis only two phases left:
all gaugino-higgsino phases set equal, all scalar sector phases equal

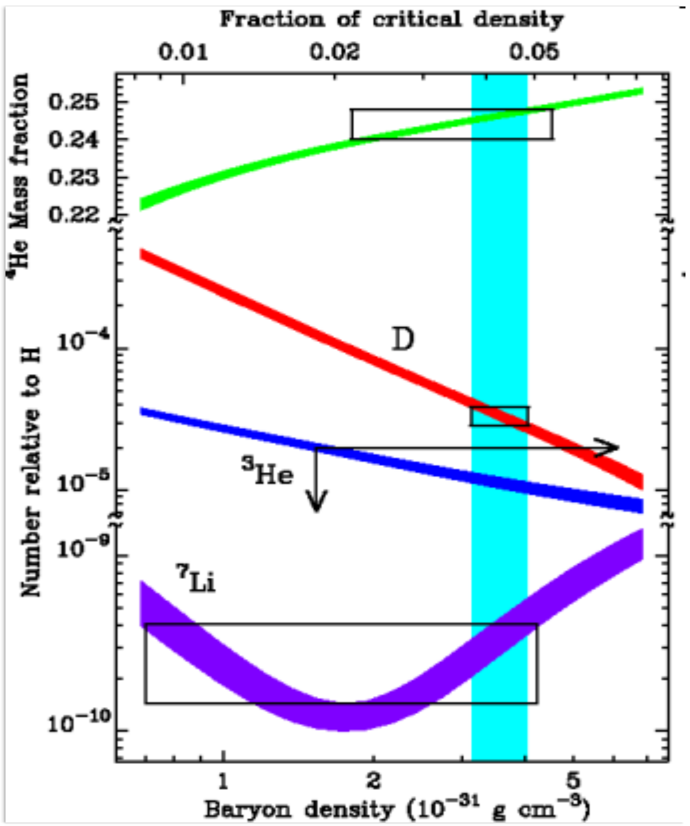
CPsuperH code by Lee, Pilaftsis, Carena, Choi, Drees, Ellis, Wagner

The Mystery of the Matter-Antimatter Asymmetry

One of the most important consequences of CP-violation is its possible impact on the explanation of the matter-antimatter asymmetry.

- Abundance of primordial elements
- Predictions from Big Bang Nucleosynthesis

$$\eta = n_B / n_\gamma \approx 6.10^{-10}$$



Antimatter governed by the same interactions as matter.

- Baryons, antibaryons and photons equally abundant in the early universe
- To remove preferentially antimatter, the CP symmetry relating B to $\bar{\mathrm{B}}$ must be violated
- No net Baryon number if B conserved at all times

What generated the small observed baryon--antibaryon asymmetry ?
Electroweak Baryogenesis ?

See also Cirigliano's talk

EWBG does not work in the SM ==> Higgs too heavy and not sufficient CP violation
may be realized in SUSY extensions of the SM, but demands
new sources of CP-violation

Baryogenesis in the Standard Model

Sakharov's Conditions

- **Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

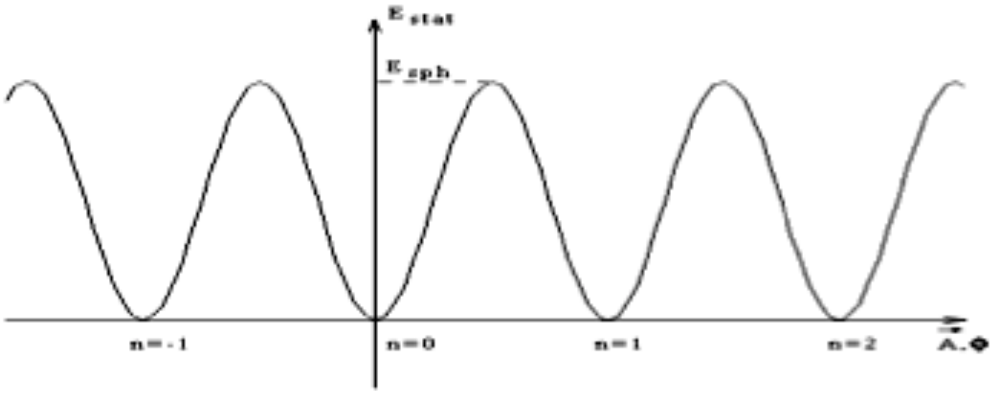
Baryon Number Violation at finite Temperature

Anomalous processes violate both B and L number, but preserve B-L (important for Leptogenesis idea).

- *At T = 0, Baryon number violating processes highly suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \exp(-2\pi / \alpha_W)$$

- *At very high temperatures they are highly unsuppressed*
- *At finite Temperature, only Boltzmann suppressed*



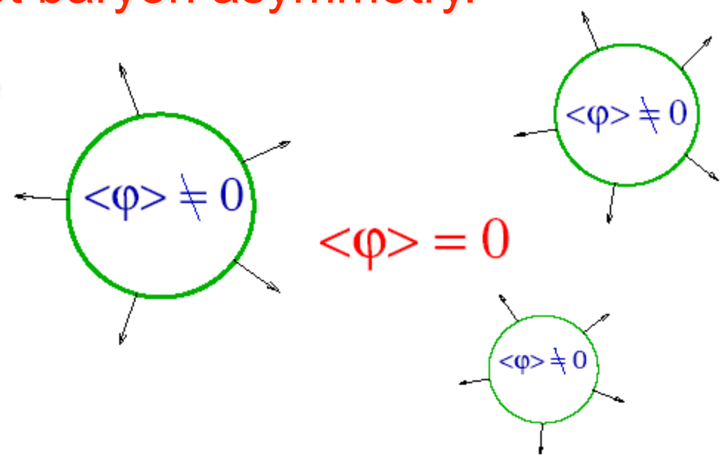
$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, T \exp(-E_{sph}(T)/T)$$

$$E_{sph} \cong 8\pi \, v(T)/g$$

Baryon Asymmetry at the Electroweak Phase Transition

Kuzmin, Rubakov, Shaposhnikov,; Cohen, Kaplan, Nelson, M.C. Quiros, Riotto, Vilja, Wagner, Moreno,Seco' Konstantin, Huber, Schmidt, Prokopec; ; Riotto, Trodden; Cirigliano, Profumo, Ramsey-Musolf

- Start with B=L=0 at $T>T_n$
- CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. Sphaleron processes create net baryon asymmetry.
- Net Baryon Number diffuse in the broken phase



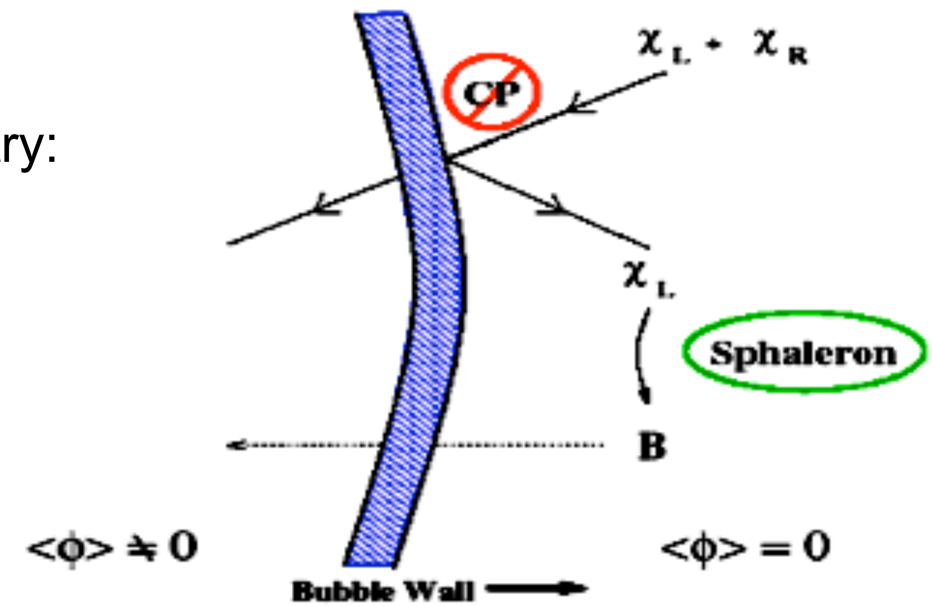
If $n_B \neq 0$ generated at T_n

$$\frac{n_B}{s} = \frac{n_B(T_n)}{s} \exp\left(-\frac{10^{16}}{T_n(\mathrm{GeV})}\exp\left(-\frac{E_{sph}(T_n)}{T_n}\right)\right)$$

To preserve the generated baryon asymmetry:
strong first order phase transition:

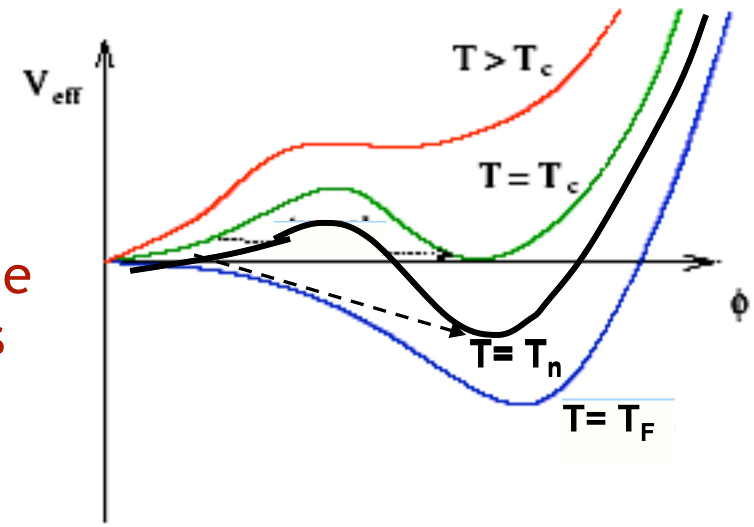
$$v(T_n)/T_n > 1$$

Baryon number violating processes out of equilibrium in the broken phase



Finite Temperature Higgs Potential

$$V = D(T^2 - T_0^2)H^2 + E_{SM} T\,H^3 + \lambda(T)\,H^4$$



- D term is responsible for the phenomenon of symmetry restoration
- E term receives contributions proportional to the sum of the cube of all light boson particle masses

and $\dfrac{v(T_n)}{T_n} \approx \dfrac{E}{\lambda}$, with $\lambda \propto \dfrac{m_H^2}{v^2}$

Since in the SM the only bosons are the gauge bosons and the quartic coupling is proportional to the square of the Higgs mass

$$\frac{v(T_n)}{T_n} > 1 \quad \text{implies} \quad m_H < 70\ \text{GeV} \Rightarrow \text{ruled out by LEP}$$

Electroweak Baryogenesis in the SM is ruled out

Independent Problem: not enough CP violation to create the asymmetry

Farrar and Shaposhnikov, Gavela et al., Huet and Satter

How to make Electroweak Baryogenesis work?

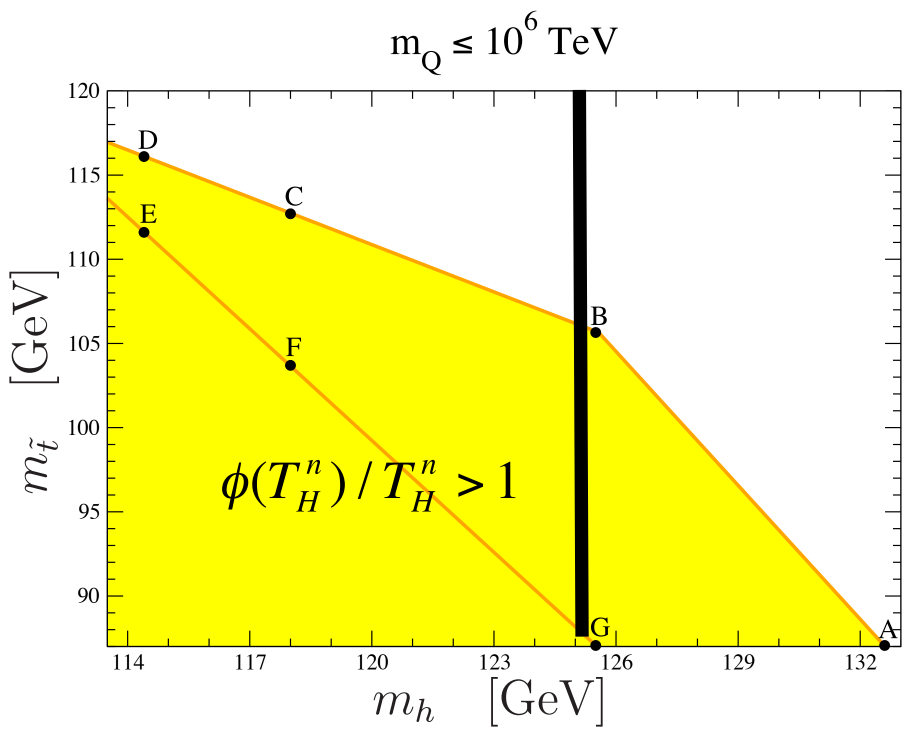
Baryogenesis Preservation

New bosonic degrees of freedom: superpartners of the top quark, with strong couplings to the Higgs allow for a sufficiently strong first order phase transition

In the MSSM

$$E_{MSSM} \approx E_{SM} + \frac{h_t^3 \sin^3\beta}{2\pi}\left(1 - \frac{X_t^2}{m_Q^2}\right)^{3/2}$$

Huet, Nelson '91; Giudice '91;
Espinosa Quiros, Zwirner '93
M.C. Quiros, Wagner, '96-' 98



Point	A	B	C	D	E	F	G
$\lvert A_t/m_Q \rvert$	0.5	0	0	0	0.3	0.4	0.7
$\tan\beta$	15	15	2.0	1.5	1.0	1.0	1.0

m_h ~ 125 GeV

lightest stop masses < 115 GeV

All other squarks heavy: 100-1000 TeV

Scenario challenged by
Higgs and Stops phenomenology

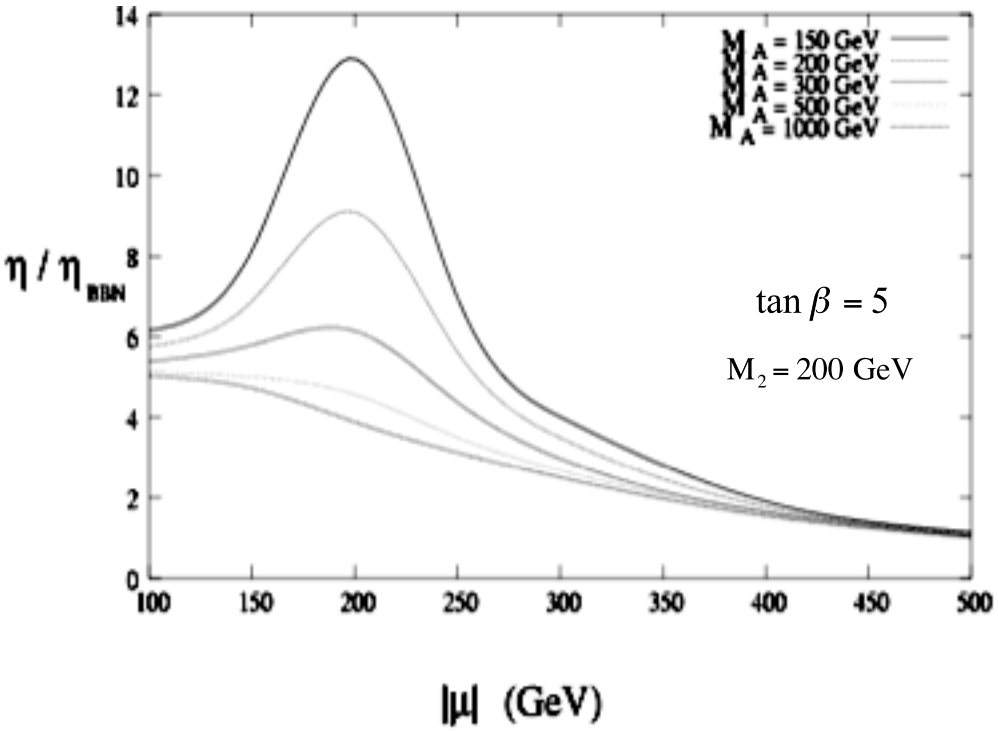
$Br(h \to \tilde{\chi}^0 \tilde{\chi}^0)$ $30 - 60\%$ to compensate enhanced gluon fusion production

Non-standard stop decays

$$\tilde{t} \to \chi^{\pm *} b \to \tilde{\nu}_\tau \tau b \to \tau b \not{E}_T$$

M.C. Nardini, Quiros, Wagner, 10-'12   Cohen, Morrisey , Pierce 12

Baryon Asymmetry



- New CP violating phases are crucial

Results for maximal CP violation
$\sin(\arg(\mu\, M_2)) = 1$

μ Higgsino mass; $M_{1,2} \to$ Bino,Wino masses

- Gaugino and Higgsino masses of order of the weak scale highly preferred

- Results scale with $\sin(\arg(\mu\, M_2))$ and linearly decrease with $\tan\beta$

Baryon Asymmetry Enhanced for:

similar Higgsino-Wino masses and smaller values of the CP -odd Higgs mass

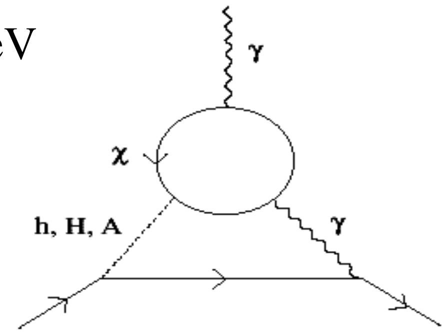
Acceptable values of the baryonic density for a sizeable range of SUSY particle masses and CP violating phases but

MSSM EWBG scenario very constrained by EDM limits

MSSM extensions (extra singlets) enlarge the SUSY space of EWBG

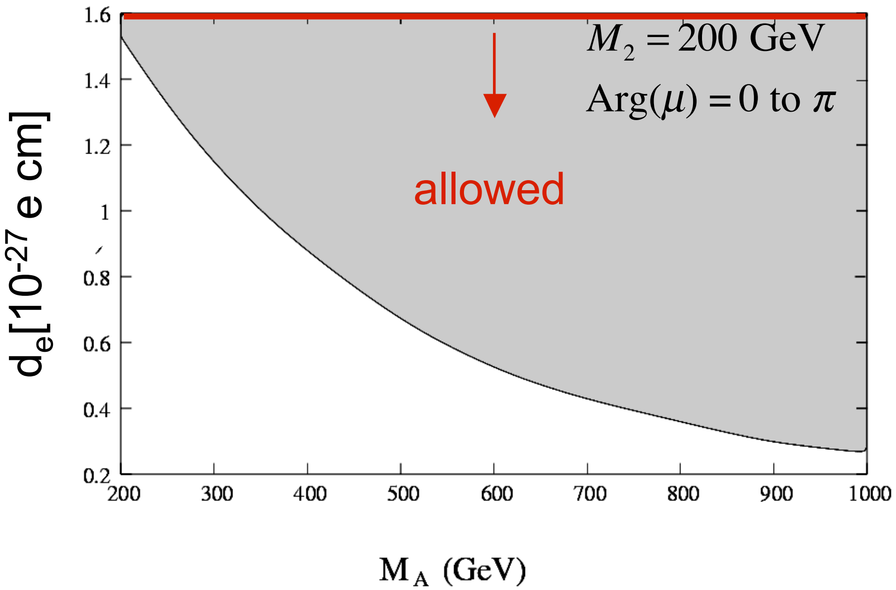
Phases in the MSSM EWBG scenario very constrained by EDM limits

- One loop contributions become negligible for $m_{\tilde{f}_{1,2}} \geq 10$ TeV
- At two loops, contributions from virtual charginos and Higgs bosons, proportional to $\sin(\arg(\mu\, M_2))$



Chang, Chang , Keung '02 Pilaftsis '02

Balazs, M.C, Menon, Morrissey, Wagner



experimental limit $\Rightarrow d_e < 1.6\ 10^{-27}$ e cm

$$\Rightarrow \quad 5 \leq \tan\beta \leq 10$$
$$M_A \geq 200 \text{ GeV}$$
$$110 \text{ GeV} \leq |\mu| \leq 550 \text{ GeV}$$

An order-of-magnitude improvement in the bound on the electron EDM
→ will leave little room for this scenario.

Note: There are O(1) theoretical uncertainties

Other possibility: phase in μM_1, Bino-induced EWBG (see later)

CP Violation in the MSSM cont'd

- These CP-violating phases may induce effects on observables such as
  -- new contributions to the e.d.m. of the electron and the neutron
  -- Higgs mediated FCNC in the K and B –meson systems

Effects on observables can be small/sizeable depending SUSY parameter space

- In the Higgs sector at tree-level, all CP-violating phases, if present, may be absorbed into a redefinition of the fields.

- CP-violation in the Higgs sector appears at the loop-level, associated with third generation scalars and/or the gaugino/Higgsino sectors,

take m_{12}, and μ real:

Arg (A_t) and Arg ($A_{b/\tau}$) for large $\tan\beta$

Arg(M_3) and less relevant Arg(M_1) Arg(M_2)

it can have important consequences for Higgs phenomenology and flavor physics

Electric Dipole Moments in the MSSM

- Consider effective CP-odd Lagrangians at the corresponding energy scales to relate experimental measurements of neutron and atom EDM's to fundamental CP-odd MSSM parameters at and above the EW scale

Many excellent talks: Ramsey-Musolf; Ritz, Izubuchi

1) CP-odd operators at the nuclear scale are related to:

EDM's of electron d_e, neutron d_n, proton d_p,

$$\mathcal{L}_{\rm edm} = -\frac{i}{2} \sum_{i=e,p,n} d_i \; \overline{\psi}_i (F\sigma)\gamma_5 \psi$$

electron-Nucleon and Nucleon-Nucleon interactions

$$\mathcal{L}_{eN} \supset C_S^{(0)} \bar{e} i \gamma_5 e \bar{N} N + C_S^{(1)} \bar{e} i \gamma_5 e \bar{N} \tau^3 N$$

$$\mathcal{L}_{\pi NN} \supset \bar{g}^{(1)}_{\pi NN} \bar{N} N \pi^0$$

dominated by pion exchange ==> by gluon-quark int.

Different calculations at the atomic/nuclear level allowed us to compute

d_{Tl} d_{Hg} d_D

in term of the above CP-odd operator coefficients

2) Considering different hadronic approaches one can compute the dependence of the nuclear scale coefficients on the CP-odd effective operators at the strong interaction scale (~1GeV)

[many uncertainties, taking into account in various ways]

$$d_n = d_n(\bar{\theta}, d_f^E, d_q^C, d^G, C_{ff'})$$

$$\bar{g}_{\pi NN}^{(i)} = \bar{g}_{\pi NN}^{(i)}(\bar{\theta}, d_q^C, d^G, C_{ff'})$$

C_S in terms of semileptonic 4-fermion coupling C_{eq}

3) One considers the contributions from the SUSY CP-odd effective higher dim. operators at the scale M_{SUSY} and evolve them down to 1GeV using anomalous dimensions,

Most relevant EDM effects in the MSSM:

Consider dimension 5 and dimension 6 (some effectively dim. 8) operators

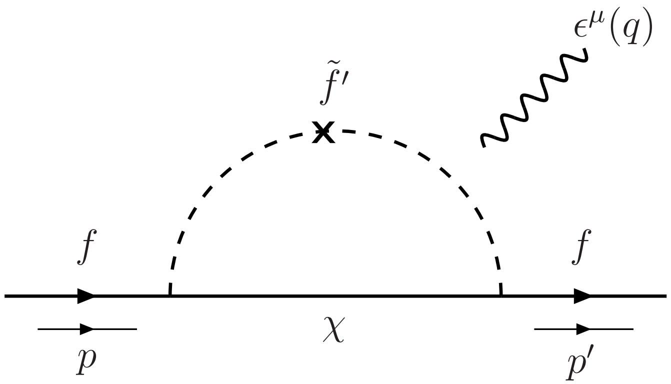
Assumed PQ axion takes care of dim. 4 potentially dominant terms

1-loop EDMs and for leptons

1-loop EDM's/CEDM's for quarks

Ellis, Lee, Pilaftsis
Pospelov,Ritz

$$\mathcal{L}_{\rm (C)EDM} \;=\; -\,\frac{i}{2}\,d_f^E\,F^{\mu\nu}\,\bar f\,\sigma_{\mu\nu}\gamma_5\,f\;-\;\frac{i}{2}\,d_q^C\,G^{a\,\mu\nu}\,\bar q\,\sigma_{\mu\nu}\gamma_5 T^a\,q$$



χ= chargino, neutralino or gluon; $\tilde f = \tilde u, \tilde d, \tilde l$

Analogously for CEDM's for up/down type quarks

to provide an estimate: simple expressions, with only 2 phases and all soft masses = MSUSY

$$e_u = 2e/3,\; e_d = -e/3. \qquad d_f \equiv d_f^E \qquad \tilde d_q \equiv d_q^C$$

$$\frac{d_e}{e\kappa_e} = \frac{g_1^2}{12}\sin\theta_A + \left(\frac{5g_2^2}{24}+\frac{g_1^2}{24}\right)\sin\theta_\mu\tan\beta,$$

$$\left.\begin{aligned}\frac{d_q}{e_q\kappa_q} &= \frac{2g_3^2}{9}\Big(\sin\theta_\mu[\tan\beta]^{\pm1}-\sin\theta_A\Big)+O(g_2^2,g_1^2),\\ \frac{\tilde d_q}{\kappa_q} &= \frac{5g_3^2}{18}\Big(\sin\theta_\mu[\tan\beta]^{\pm1}-\sin\theta_A\Big)+O(g_2^2,g_1^2).\end{aligned}\right\}\tilde g\tilde q$$

$$\kappa_i = \frac{m_i}{16\pi^2 M_{\rm SUSY}^2} = 1.3\times10^{-25}{\rm cm}\times\frac{m_i}{1{\rm MeV}}\left(\frac{1{\rm TeV}}{M_{\rm SUSY}}\right)^2$$

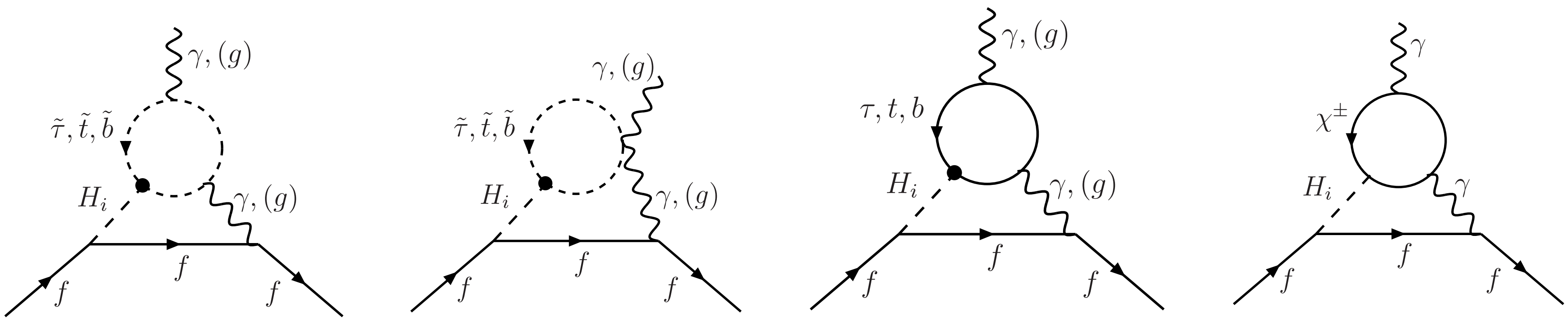
↓

present reach
M_{susy} ~ few TeV
for order 1 phases

Higher Order Contributions to EDM's

two loop Barr-Zee Graphs

Ellis, Lee, Pilaftsis
Pospelov ,Ritz



plus chargino-neutralino loops with WW and H^{+-}W

Li, Profumo, Ramsey-Musolf

These diagrams become the dominant ones from the 5D operators if the 1st and 2nd generation squarks are above a few/several TeV

a simple expression for the stop-loop, with only 2 phases and all soft masses = M_{SUSY}

$$d_e^{\text{two loop}} = -e\kappa_e \frac{\alpha Y_t^2}{9\pi} \ln\left[\frac{M_{\text{SUSY}}^2}{m_A^2}\right] \sin(\theta_A + \theta_\mu) \tan\beta, \qquad \kappa_e \simeq 0.6 \times 10^{-25} \text{cm}.$$

A-parameter which may also be tanβ–enhanced.

Sbottom/Stau loops enhanced by higher powers of tanβ.

Considering different phases for the Mi gaugino masses opens the possibility for bino induced EWBG

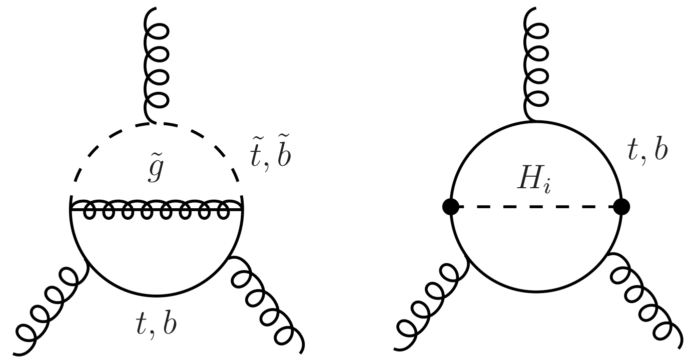
Higher Order Contributions to EDM's

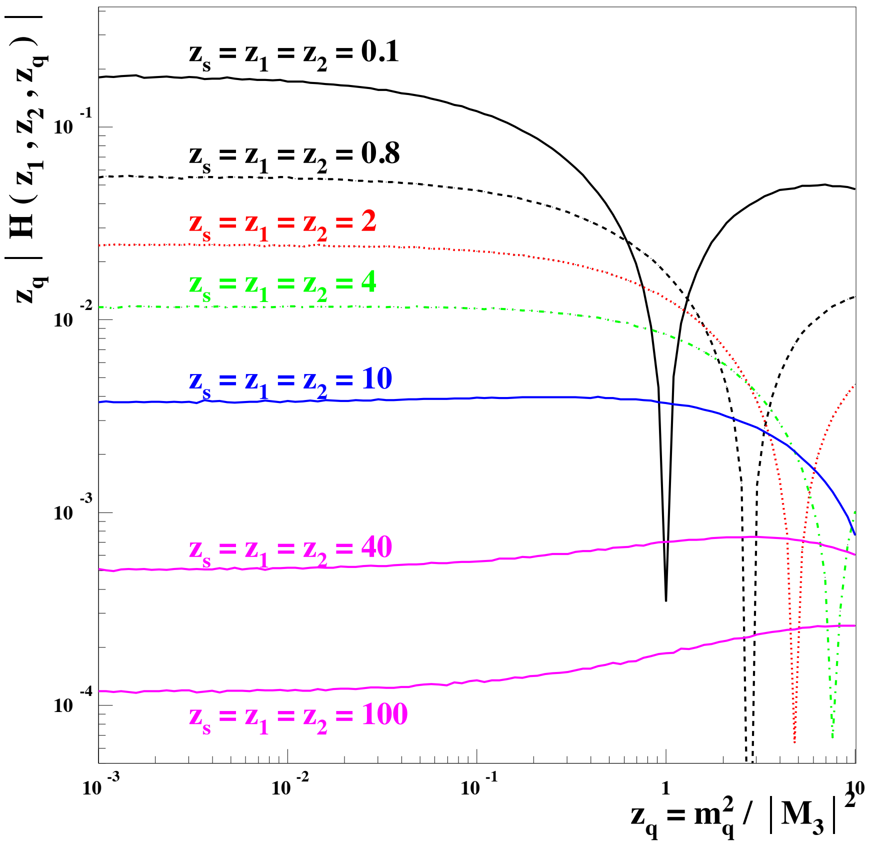
Ellis, Lee, Pilaftsis

gluino and Higgs mediated dimension 6 Weinberg operator

$$\mathcal{L}_{\mathrm{Weinberg}} = \frac{1}{3}\, d^G\, f_{abc}\, G^a_{\rho\mu}\, \tilde{G}^{b\,\mu\nu}\, G^c{}_\nu{}^\rho$$

$$d^G = (d^G)^{\tilde{g}} + (d^G)^H$$





Hi includes all neutral Higgs bosons with mixing
Dots indicate resummations of thresholds corrections to the Yukawa couplings

$$(d^G)^{\tilde{g}} \propto H(m^2_{\tilde{q}1}/|M_3|^2, m^2_{\tilde{q}2}/|M_3|^2, m^2_q/|M_3|^2)$$

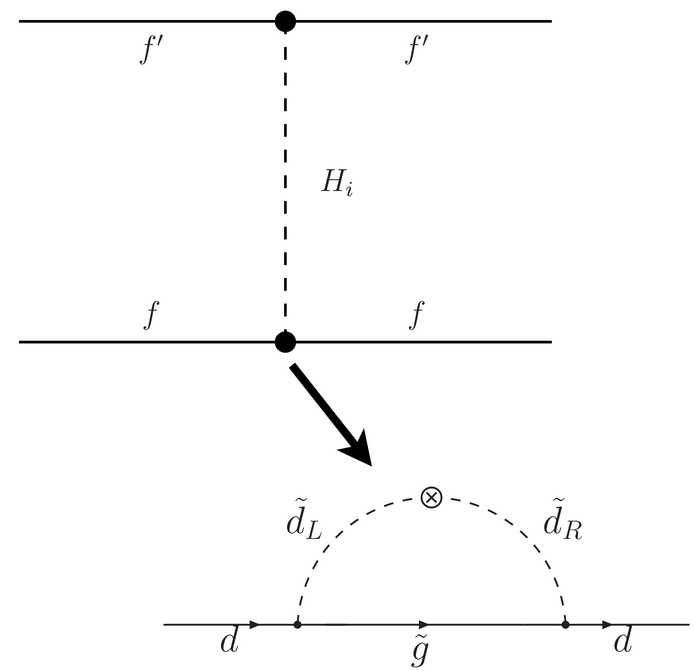
$$\propto H(z_1, z_2, z_q)$$

d_G relevant for d_n

Ellis, Lee, Pilaftsis
Pospelov, Ritz

Higher Order Contributions to EDM's

CP-odd four Fermion interactions



$$\mathcal{L}_{4\mathrm{f}} = \sum_{f,f'} C_{ff'} (\bar{f} f)(\bar{f}' i\gamma_5 f')$$

Significant effect generated by CP-violating neutral Higgs- boson mixing in the t-channel and by CP-violating Yukawa threshold corrections

for f'=e, f=d, tanβ^3 enhancement

to provide an estimate: simple expressions, with only 2 phases and all soft masses = M_{SUSY}

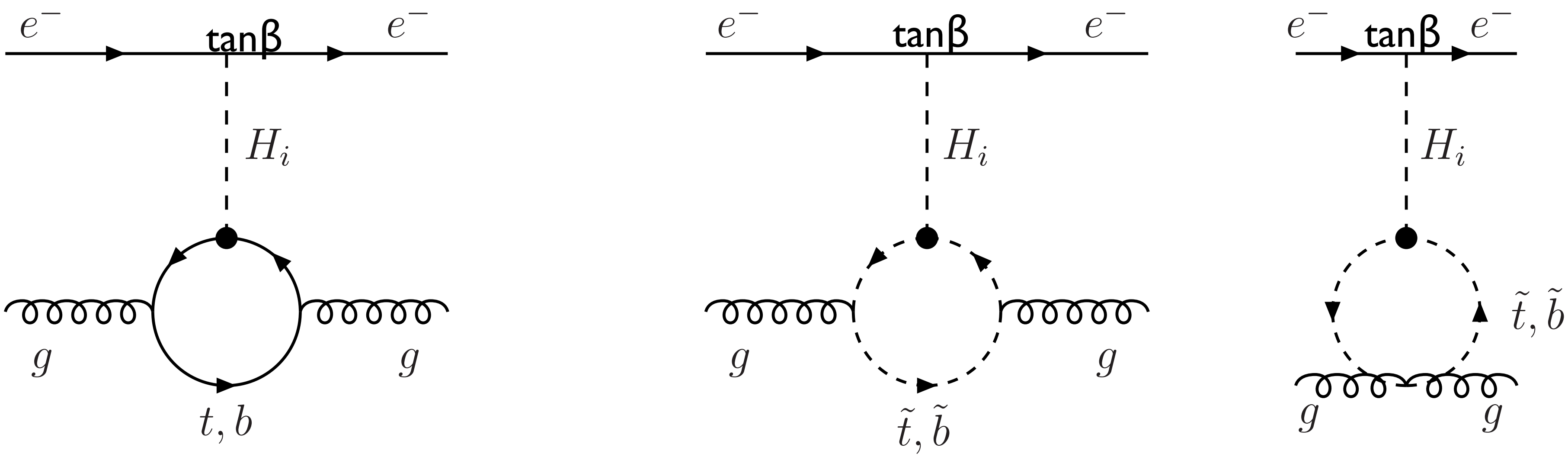
$$\frac{d_{\mathrm{Tl}}}{[d_{\mathrm{Tl}}]_{\mathrm{exp}}} \simeq \frac{\tan^3\beta}{330} \left(\frac{100\mathrm{GeV}}{m_A}\right)^2 \left[\sin\theta_\mu + 0.04\sin(\theta_\mu + \theta_A)\right].$$

It does not decouple for large M_{SUSY}

it becomes very relevant for large tanβ ~ 50

Higher Order Contributions to EDM's

two loop gluon-gluon Higgs interactions



This gives important contributions to dTl through the electron nucleon CP odd operators

$$\mathcal{L}_{eN} \supset C_S^{(0)} \bar{e} i\gamma_5 e \bar{N} N +$$

$$(C_S)^g = (0.1\,\mathrm{GeV}) \frac{m_e}{v^2} \sum_{i=1}^{3} \frac{g^S_{H_i gg} g^P_{H_i \bar{e}e}}{M^2_{H_i}},$$

With the scalar form factor in the heavy (s)quark limit:

$$g^S_{H_i gg} = \sum_{q=t,b} \left\{ \frac{2\,x_q}{3} g^S_{H_i \bar{q}q} - \frac{v^2}{12} \sum_{j=1,2} \frac{g_{H_i \tilde{q}^*_j \tilde{q}_j}}{m^2_{\tilde{q}_j}} \right\}$$

In Summary: SUSY CP framework

- 1-loop diagrams:

  either 1st and 2nd sfermion heavy (> TeV) or Arg (Af) < 0.01

- 2-loop diagrams involve 3rd generation sfermions and gauginos/ Higgsinos
  ==> if all scalars heavy, still gaugino loops relevant

MSSM CP phases and generation of EDM/CEDM operators

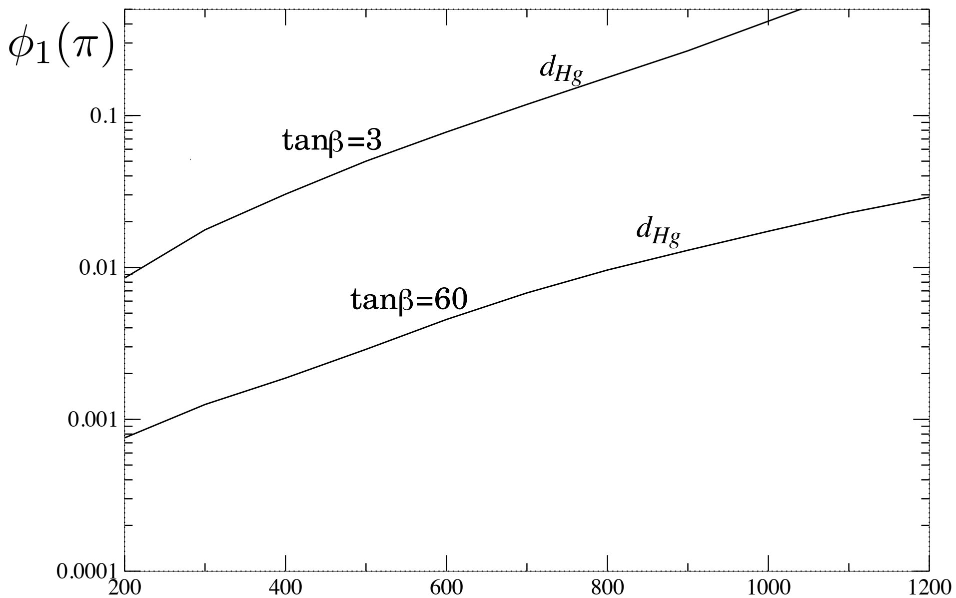
CP-violating phases	one-loop contribution	two-loop contribution
$\phi_{e,u,d}$	$d^{1-loop}_{u,d,e}, \tilde{d}^{1-loop}_{u,d}, C_{ff'}$	no
$\phi_{\mu,c,s}$	no	no
$\phi_{\tau,t,b}$	no	$d^{2-loop}_{u,d,e}(\tilde{t},\tilde{b},\tilde{\tau}),\ \tilde{d}^{2-loop}_{u,d}(\tilde{t},\tilde{b},\tilde{\tau}),\ d^{3G}$
$\phi_{1,2}$	$d^{1-loop}_{u,d,e}, \tilde{d}^{1-loop}_{u,d}, C_{ff'}$	$d^{2-loop}_{u,d,e}(\chi^{\pm,0})$
ϕ_3	$d^{1-loop}_{u,d}, \tilde{d}^{1-loop}_{u,d}, C_{ff'}$	d^{3G}

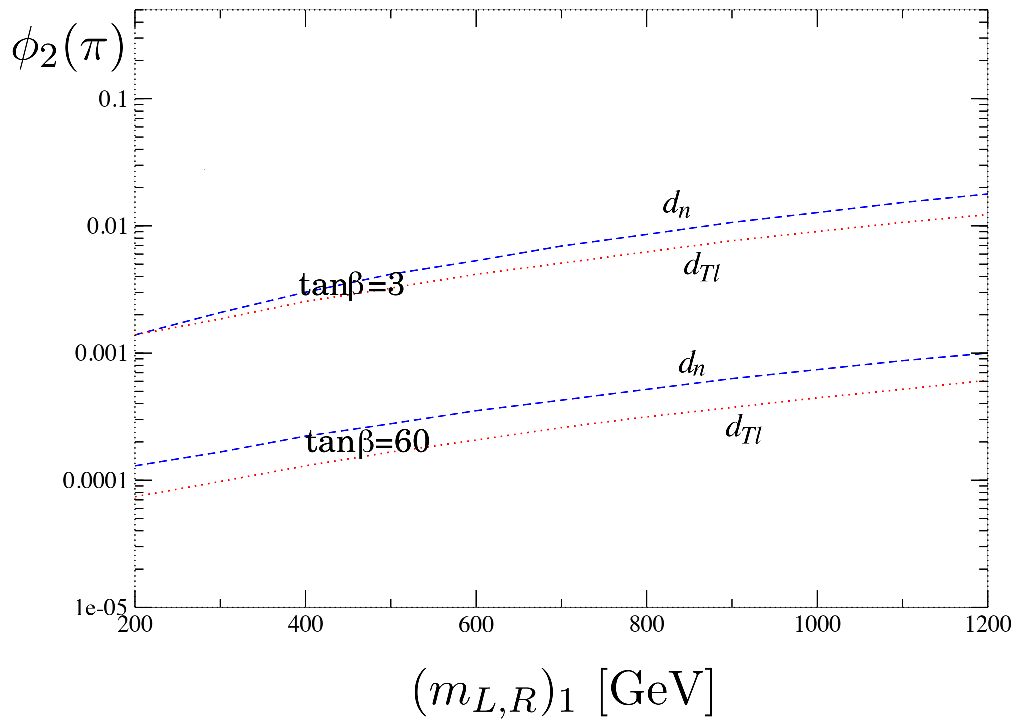
Relevant Operators

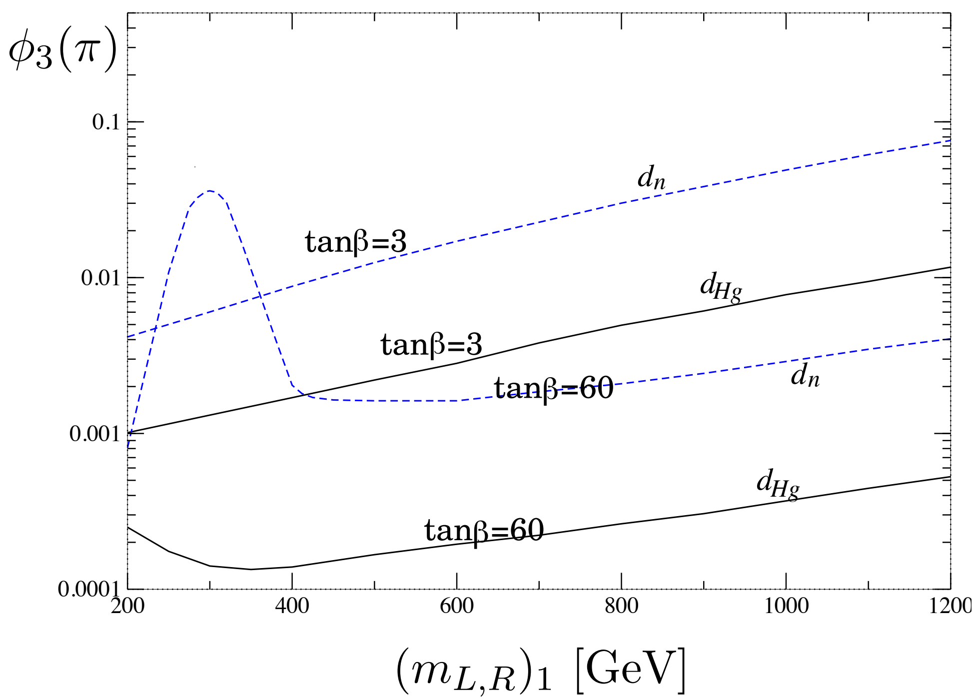
	d_n	d_{Tl}	d_{Hg}
Relevant Operators	$d_{u,d},\ \tilde{d}_{u,d},\ d^{3G},\ C_{ff'}$	$d_e,\ C_{ff'}$	$d_e,\ \tilde{d}_{u,d},\ C_{ff'}$

Li, Profumo, Ramsey-Musolf

1-loop EDM effects in SUSY: light 1st/2nd gen. sfermions





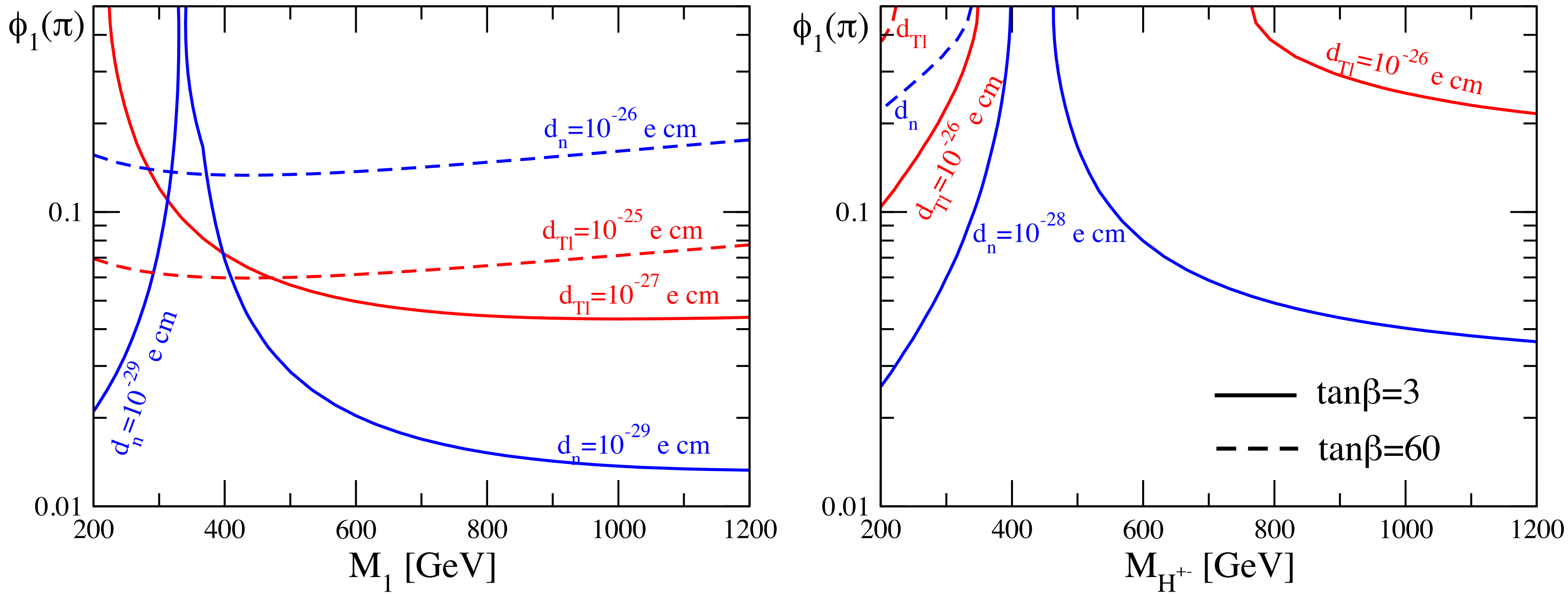


$$|M_1| = 150 \text{ GeV}, |M_2| = 250 \text{ GeV}, |M_3| = 550 \text{ GeV},$$
$$|\mu| = 225 \text{ GeV}, |A_f| = 175 \text{ GeV}, M_{H^\pm} = 500\text{GeV},$$
$$m_{L_3} = m_{R_3} = 200 \text{ GeV},$$

$$m_{L_{1,2}} = m_{R_{1,2}} = 200 \text{ GeV}$$

Li, Profumo, Ramsey-Musolf

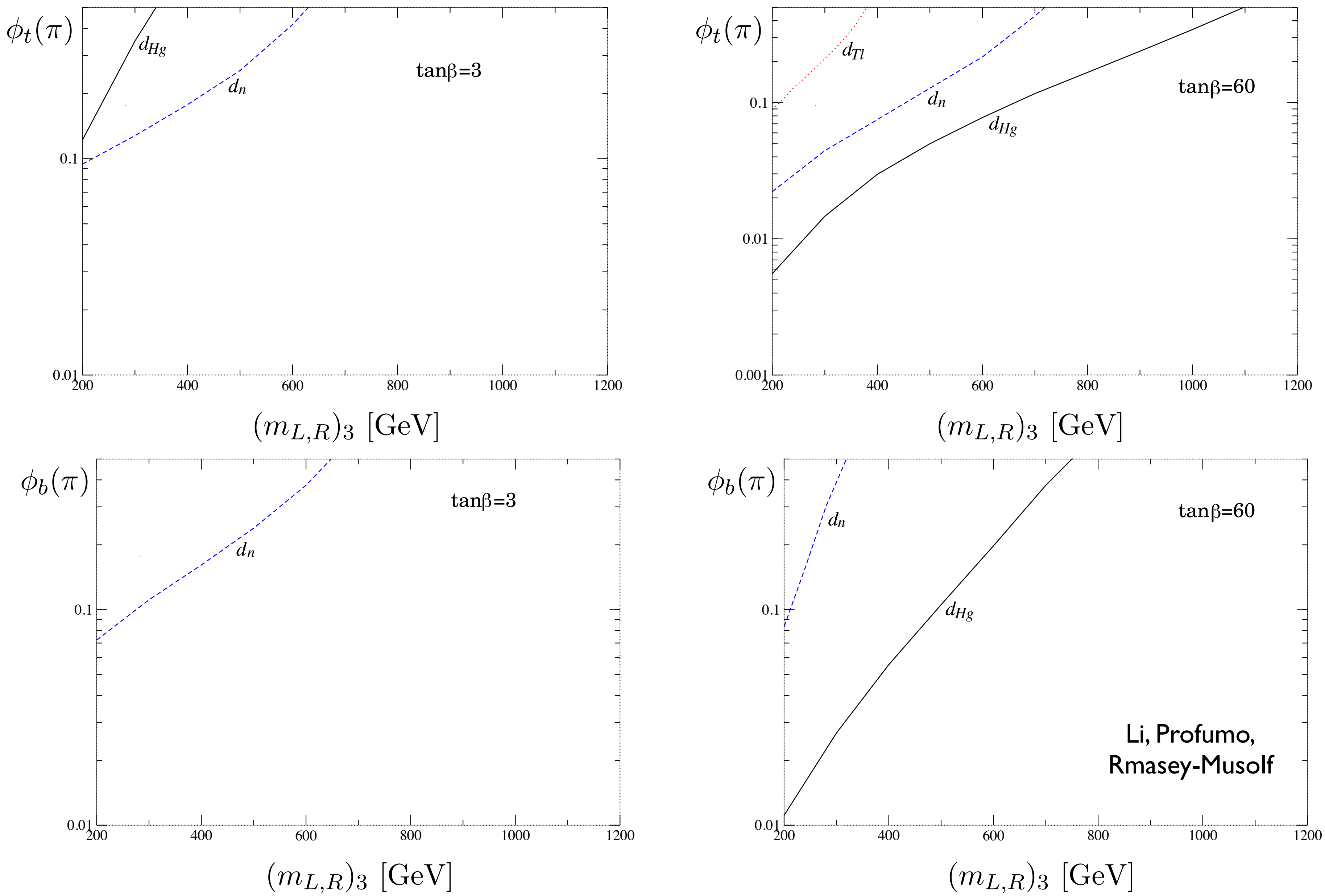
2-loop EDM effects in SUSY: 1st/2nd gen. sfermions ~ 10 TeV



Interesting scenario for bino-induced EWBS

The M_2, M_3 phases still restricted to be below a few $10^{-2}\pi$ for 1 TeV masses

2-loop EDM effects in SUSY:1st/2nd gen. sfermions ~ 10 TeV



The ϕ_t and ϕ_b are rather loosely bounded and can reach π/2 for (mL,R)3 of a few hundred GeV.

CP Violation in the Higgs Sector

Minimization should be performed with respect to real and imaginary parts of Higgs fluctuations $H_1^0 = \phi_1 + iA_1 \quad H_2^0 = \phi_2 + iA_2$

Performing a rotation: $A_1, A_2 \implies A, G^0$ (Goldstone)

$$\begin{pmatrix} A \\ \Phi_1 \\ \Phi_2 \end{pmatrix} = O \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

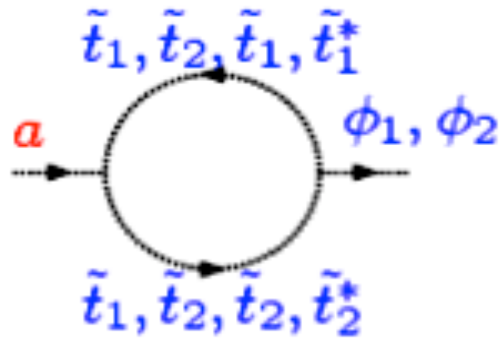
Main effect of CP-Violation is the mixing of the three neutral Higgs bosons

In the base (A, Φ_1, Φ_2)

$$M_N^2 = \begin{bmatrix} \mathbf{m}_A^2 & (\mathbf{M}_{SP}^2)^T \\ \mathbf{M}_{SP}^2 & \mathbf{M}_{SS}^2 \end{bmatrix}$$

M_{SS}^2 is similar to the mass matrix in the CP conserving case, and M_A^2 is the mass of the would-be CP-odd Higgs.

M_{SP} gives the mixing between would-be CP-odd and CP-even sates, predominantly governed by stop induced loop effects



$$\mathbf{M}_{SP}^2 \propto \frac{\mathbf{m}_t^4}{16\pi^2 \mathbf{v}^2} \, \mathrm{Im}\left(\frac{\mu A_t}{\mathbf{M}_S^2}\right)$$

Gluino phase relevant at two-loop level. Guagino effects may be enhanced for large tan beta

Comments on Higgs Boson Mixing

- m_A no longer a physical parameter, but the charged Higgs mass can be used as a physical parameter, together with

$$M_S, |\mu|, |A_t|, |m_{\tilde{g}}| \arg(A_t), \arg(m_{\tilde{g}})$$

- Elements of matrix O are similar to $\cos\alpha$ **and** $\sin\alpha$ in the CP-conserving case. But third row and column are zero in the non-diagonal elements in such a case.

- Three neutral Higgs bosons can now couple to the vector bosons in a way similar to the SM Higgs.

- Similar to the decoupling limit in the CP-conserving case: in the decoupling limit, $m_{H+} >> M_Z$,

The effective mixing between the lightest Higgs and the heavy ones is zero

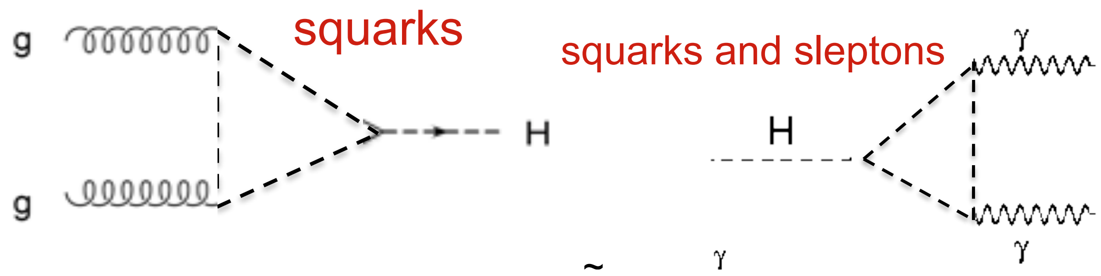
H_1 is SM-like

The mixing in the heavy sector H_2/H_3 still relevant

non decoupling of CP-violating vertex and self energy effects

Higgs Production in the diphoton channel in the MSSM

• Charged scalar particles with no color charge can change di-photon rate without modification of the gluon production process



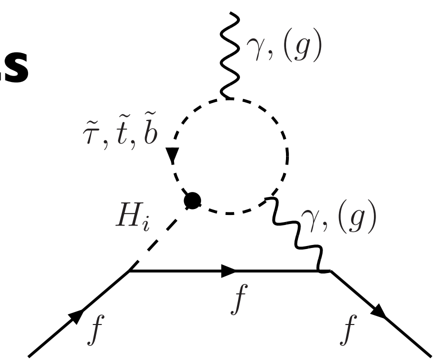
Light staus with large mixing
[sizeable μ and tan beta]:
enhancement of the
Higgs to di-photon decay rate
- up to 50 % with SM-like ZZ/WW

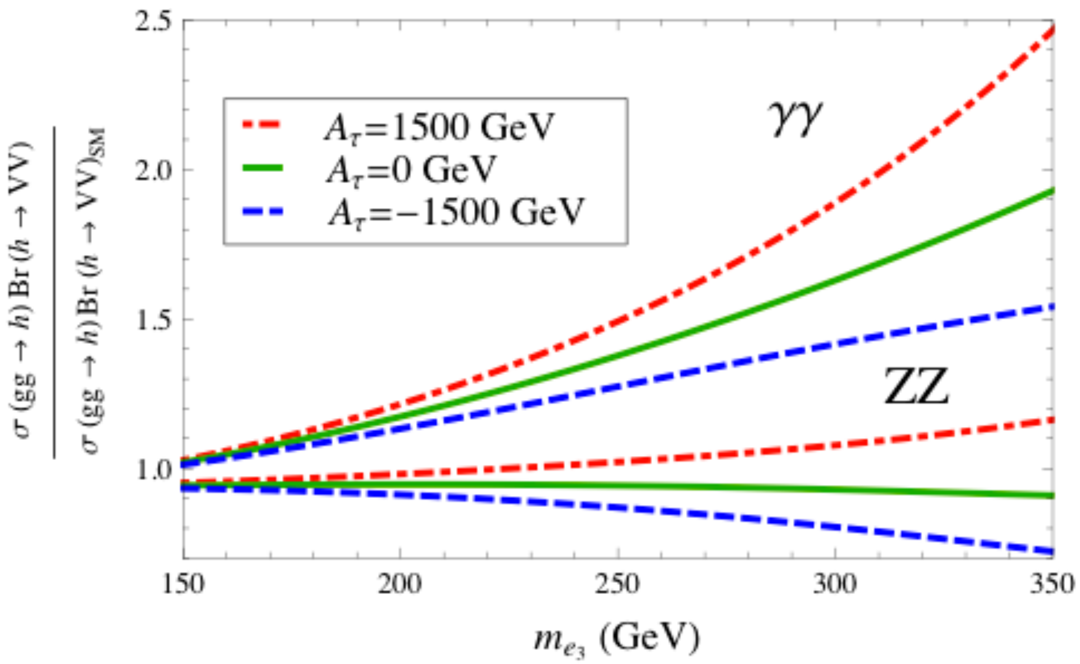
Additional modifications of the Higgs rates into gauge bosons via stau induced mixing effects in the Higgs Sector:

Aτ induced radiative corrections to the mixing angle α

$$g_{h\bar{b}b,h\tau^+\tau^-} \propto -\sin\alpha/\cos\beta$$

Strong constraints from Electron EDM via phase in Aτ





Final Comments

Supersymmetry, as a paradigm for New Physics,
provides an excellent ground to test effects of additional sources
of Flavor and CP violation

The MSSM can accommodate solutions to some of the puzzles in
particle physics, but is most probably too simplistic

Various MSSM extensions: models with extra singlets, additional gauge groups, etc,
extend further the particle content of the SM
and imply larger number of new parameters including many additional CP phases

New CP phases are a reasonable expectation in NP models and
EDM experiments open the opportunity to explore scales of new physics
well beyond the reach of the LHC