CP phases in SUSY

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CERN-TH institute
„From the LHC to a future collider“

WG3, 19/02/2009

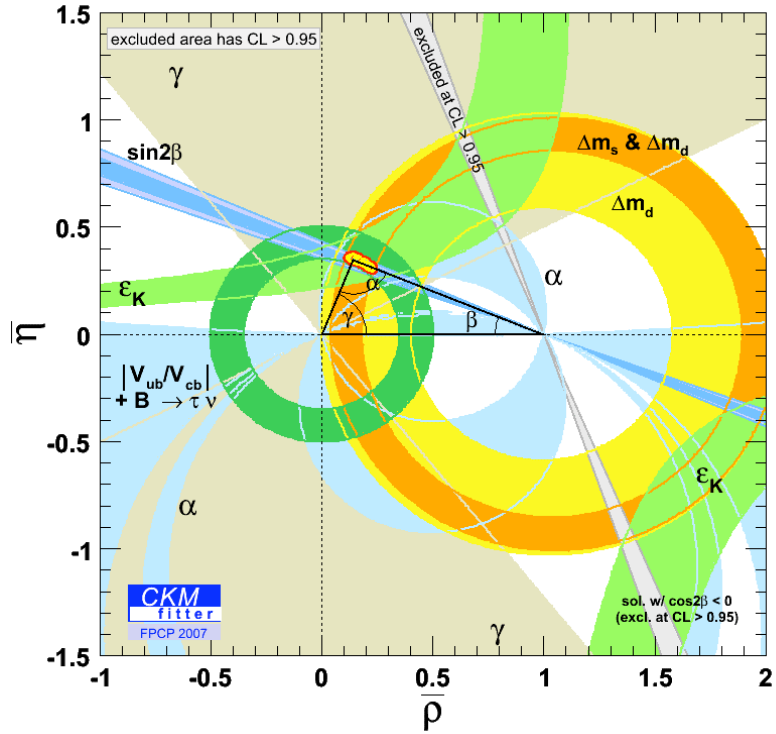
CP violation in the Standard Model

Described by the CKM matrix:
3 angles, 1 phase, unitarity Δs

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1-\frac{\lambda^2}{2} \end{pmatrix}$$

Observed in K and B systems,
both direct and indirect CPV.

$$\bar{\varrho} = \varrho(1-\frac{\lambda^2}{2}), \qquad \bar{\eta} = \eta(1-\frac{\lambda^2}{2})$$

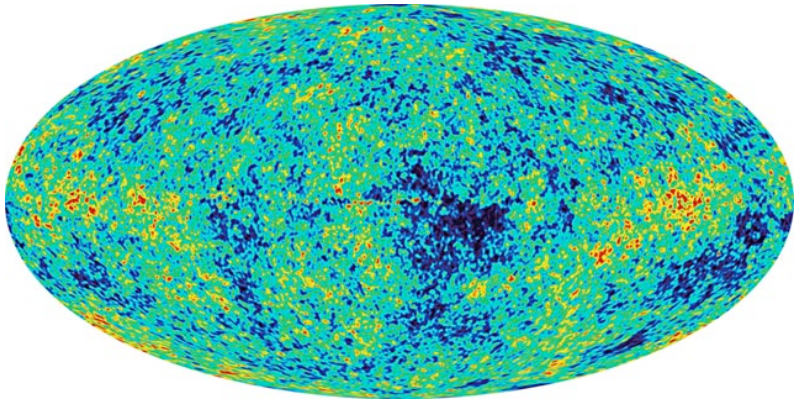


On the other hand, for the strong CP phase $|\bar{\theta}| < 10^{-9}$.

$$\bar{\theta} = \theta + \mathrm{Arg}\,\mathrm{Det} M_q$$

Baryon asymmetry of the Universe

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$
$$= (6.14 \pm 0.25) \times 10^{-10}$$



Sakharov conditions, 1967:

- baryon number violation
- C and CP violation
- departure from equilibrium

⇨ need BSM contributions

see e.g. Dine & Kusenko, 2003
Cline, 2006

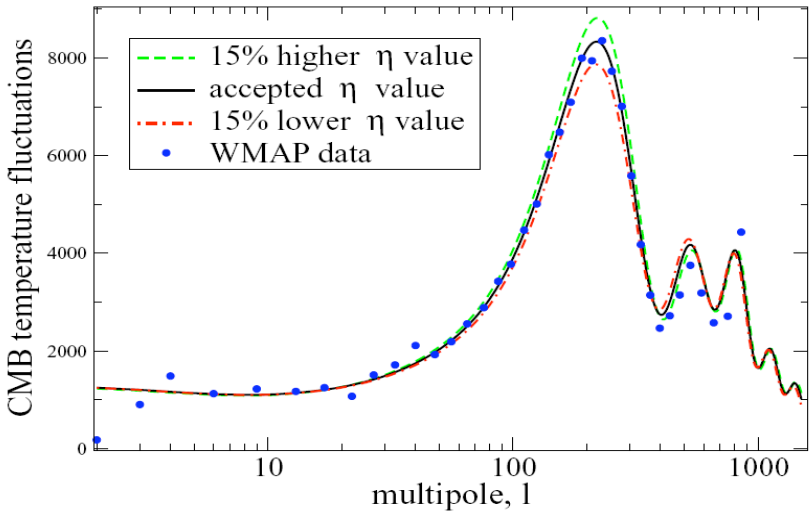


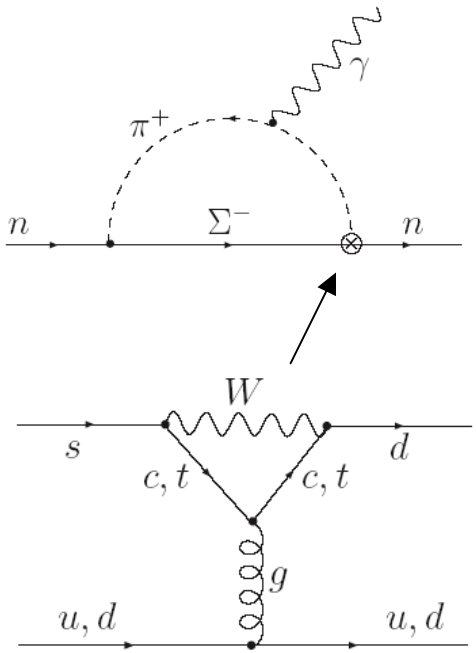
Fig. 2. Dependence of the CMB Doppler peaks on η.

e.g. Pospelov, Ritz, 2005

Electric dipole moments

$$|d_{\rm Tl}| < 9 \times 10^{-25} e\,{\rm cm}$$
$$|d_{\rm Hg}| < 2 \times 10^{-28} e\,{\rm cm}$$
$$|d_n| < 6 \times 10^{-26} e\,{\rm cm}$$

90% CL



$$d_{\rm Tl} = -585 d_e - e\ 43\ {\rm GeV} \times (C_S^{(0)} - 0.2 C_S^{(1)})$$

$$d_{\rm Hg} = -(1.8 \times 10^{-4}\,{\rm GeV}^{-1}) e\, \bar{g}^{(1)}_{\pi NN} + 10^{-2} d_e + (3.5 \times 10^{-3}\,{\rm GeV}) e\, C_S^{(0)},$$

$$d_n^{\rm KM} \simeq 10^{-32} e\ {\rm cm}$$
$$d_e^{\rm KM} \leq 10^{-38} e\ {\rm cm}$$

SM prediction orders of magnitudes below the experimental limits

Strong constraints but still ample room for new physics contributions

CP violation in SUSY

Early 1980's: Ellis, Ferrara, Nanopoulos; Buchmüller, Wyler; del Aguila; Polchinski, Wise; Dugan, Grinstein, Hall; Frere, Gavela; Gerard,…

- Explicit CPV (Lagrangian)
  - Scalar-pseudoscalar Higgs mixing
  - Changes in cross sections and branching ratios
  - CP-odd observables at colliders
  - Dipole moments, flavour observables
  - Neutralino relic density
  - Electroweak baryogenesis

- Spontaneous CPV (VEVs)
  - SUSY GUTs, SO(10) ?
  - Strong CP problem
  - Neutrino masses, leptogenesis, ..

MSSM with explicit CP violation

In the general MSSM, many parameters can be complex, thus inducing explicit CP violation in the model:

$$M_i = |M_i|\, e^{i\phi_i}, \quad \mu = |\mu|\, e^{i\phi_\mu}, \quad A_f = |A_f|\, e^{i\phi_f}$$

(assuming $B\mu$ to be real by convention).

The physical phases are $\mathrm{Arg}(M_i\,\mu)$ and $\mathrm{Arg}(A_f\,\mu)$. They

- affect sparticle masses and couplings through mixings
- induce CP mixing of (h, H, A) through radiative corrections
- influence CP-even observables like cross sections and BRs
- lead to interesting CP-odd observables at colliders
- etc...

Neutralino system

neutralino mass matrix in the $(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0)$ basis

$$\mathcal{M}_N = \begin{pmatrix} |M_1|e^{i\phi_1} & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & |\mu|e^{i\phi_\mu} \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & |\mu|e^{i\phi_\mu} & 0 \end{pmatrix}$$

Neutralino mass eigenstates

$$N^* \mathcal{M}_N N^\dagger = \mathrm{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}), \quad m_{\tilde{\chi}_1^0} < .... < m_{\tilde{\chi}_4^0}.$$

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2$$

CP phases induce shifts in masses and couplings

Chargino system

Mass matrix

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2}\, m_W \sin\beta \\ \sqrt{2}\, m_W \cos\beta & \mu \end{pmatrix}$$

diagonalized by the two unitary matrices U and V:

$$U^* \mathcal{M}_C V^\dagger = \mathrm{diag}(m_{\tilde{\chi}_1^\pm},\, m_{\tilde{\chi}_2^\pm})\,,$$

Interaction with neutralino and W

$$\mathcal{L}_{\tilde{\chi}\tilde{\chi}W} = g\, W_\mu^- \overline{\tilde{\chi}_j^0}\, \gamma^\mu \left(O_{ji}^L P_L + O_{ji}^R P_R \right) \tilde{\chi}_i^+$$

$$O_{ji}^L = \underbrace{N_{j2} V_{i1}^*}_{\textbf{wino}} - \underbrace{\tfrac{1}{\sqrt{2}} N_{j4} V_{i2}^*}_{\textbf{higgsino fractions}} \quad \text{and} \quad O_{ji}^R = N_{j2}^* U_{i1} + \underbrace{\tfrac{1}{\sqrt{2}} N_{j3}^* U_{i2}}_{\textbf{higgsino fractions}}$$

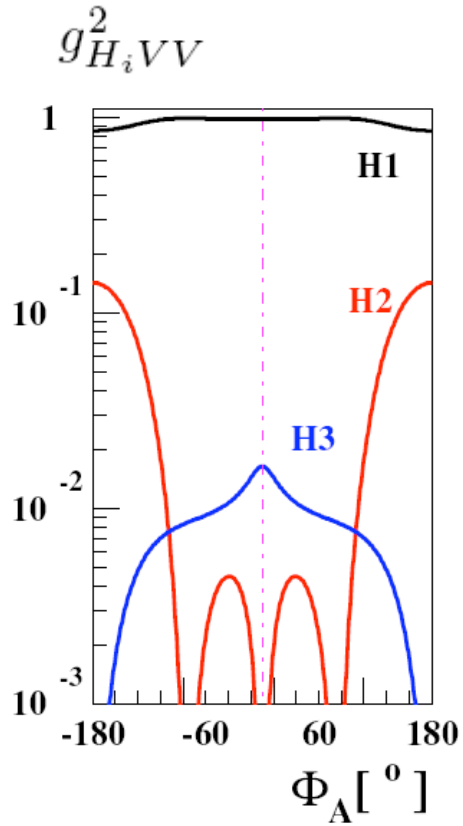
wino **higgsino fractions** (coupling vanishes in the pure bino case)

Demir; Pilaftsis; Choi, Drees, Lee;
Carena, Wagner; Heinemeyer et al.

Higgs CP mixing

Loop-induced mixing (h,H,A) → (H_1,H_2,H_3) with indefinite CP,
Size of mixing is proportional to

$$\frac{3}{16\pi^2}\frac{\mathrm{Im}\,(A_f\mu)}{m^2_{\tilde{f}_2}-m^2_{\tilde{f}_1}}$$



⇒ Drastic changes in Higgs phenomenology

Review:
- CPNSH report, hep-ph/0608079

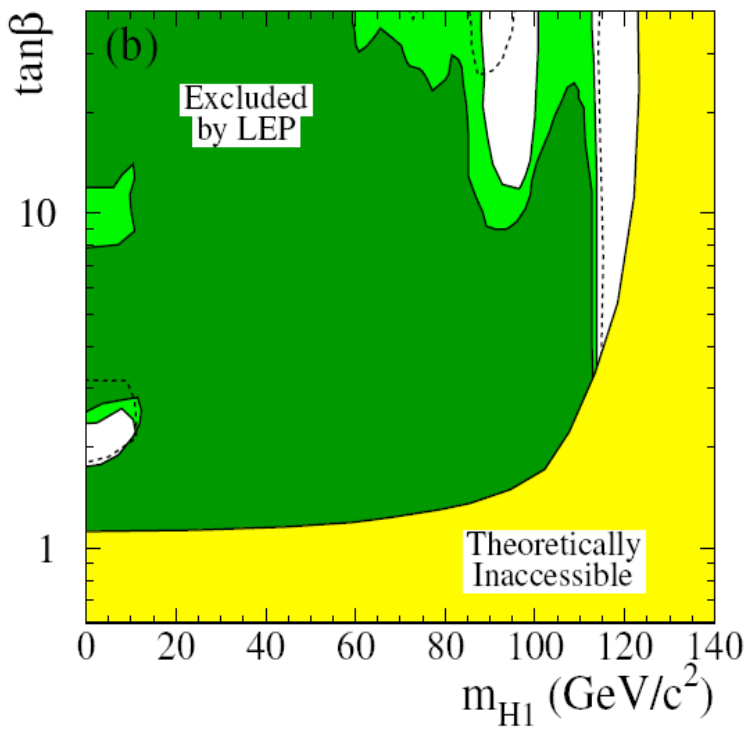
Public codes:
- CPsuperH by J.S. Lee et al.
- FeynHiggs by S. Heinemeyer et al.

LEP Higgs WG, P. Bechtle et al.
hep-ex/0602042

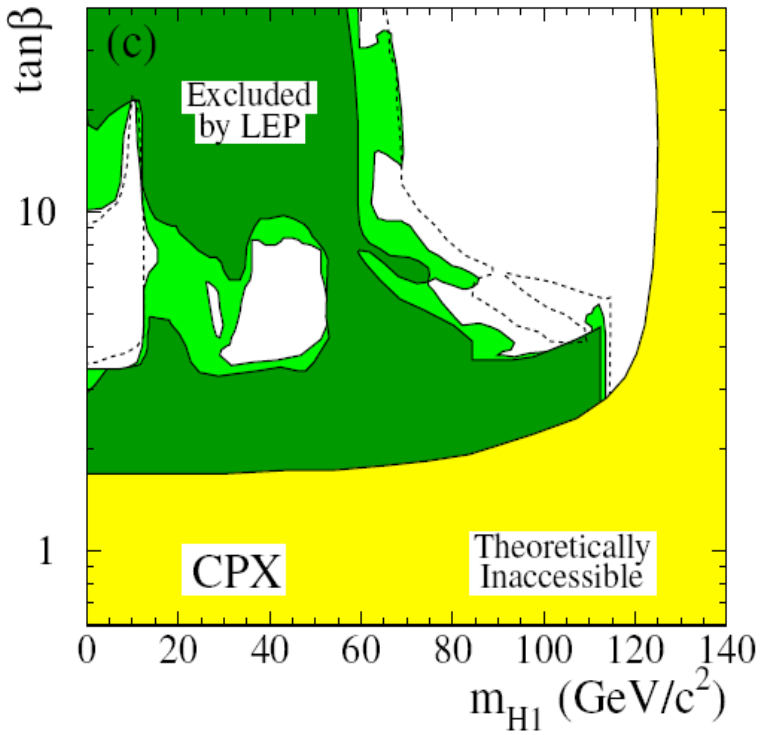
LEP limits in CPX scenario

$m_t = 174.3\,\mathrm{GeV}$

Arg(A)=60°



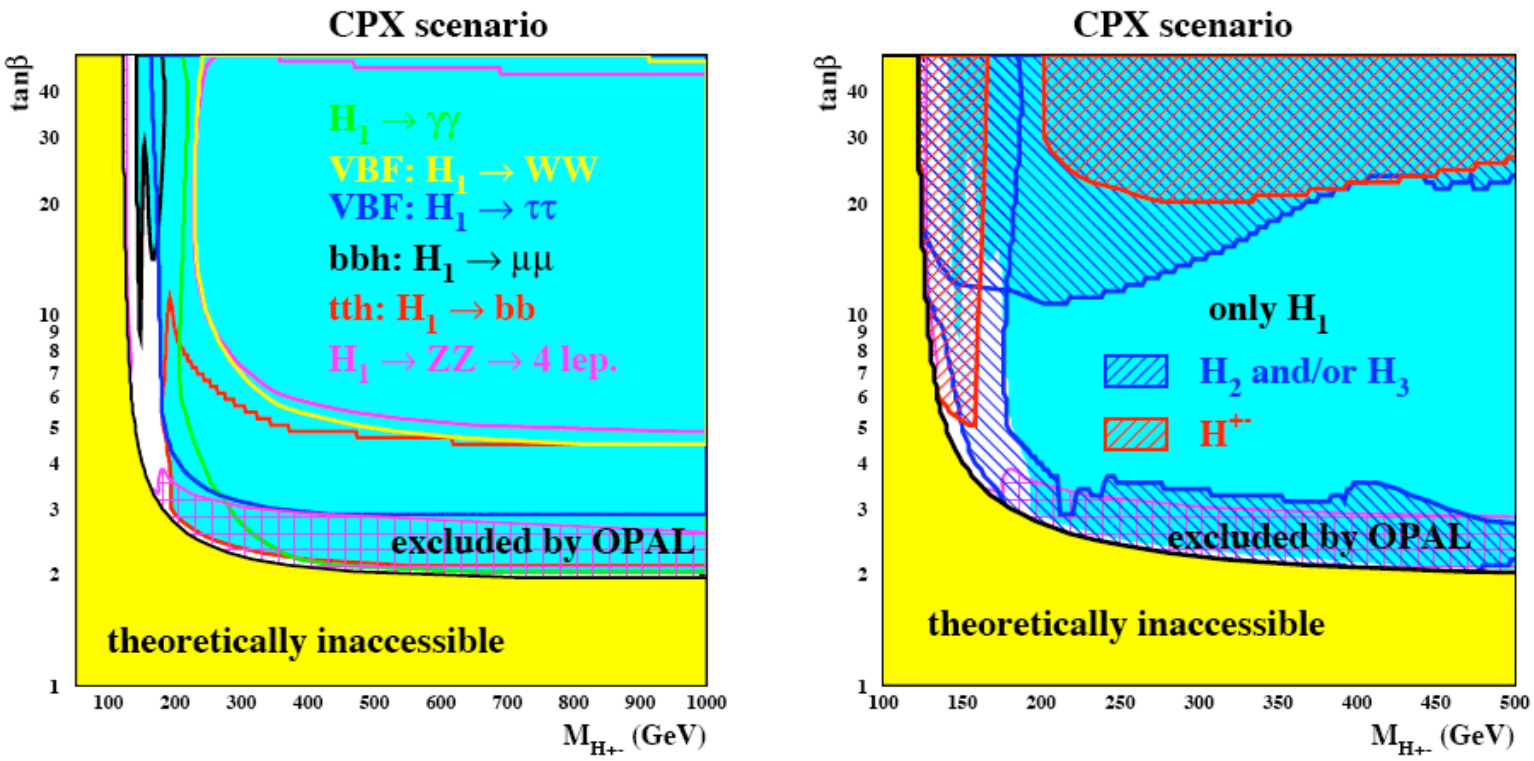
Arg(A)=90°



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\mathrm{SUSY}}\,,$$
$$|\mu| = 4\,M_{\mathrm{SUSY}}\,,\quad |A_{t,b,\tau}| = 2\,M_{\mathrm{SUSY}}\,,\quad |M_3| = 1\ \mathrm{TeV}\,.$$

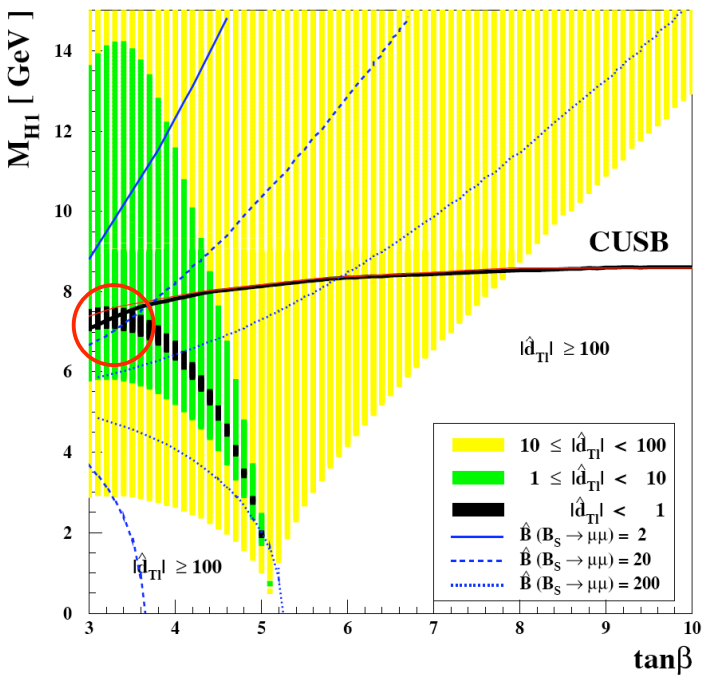
light green: 95% CL
dark green: 99.7% CL

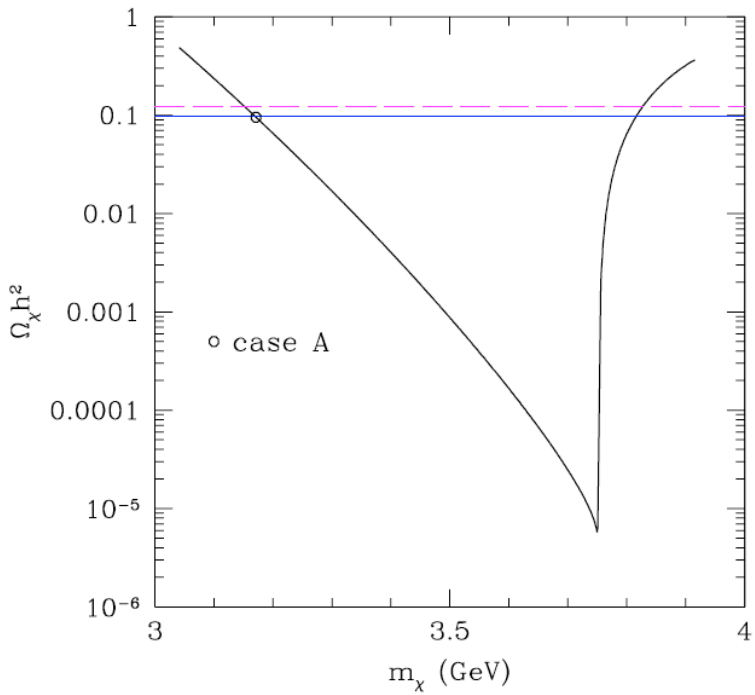
LHC potential in CPX scenario



ATLAS discovery potential with 300 fb^{-1}

Light relic neutralino in the CPX window?





$$7 \text{ GeV} \lesssim M_{H_1} \lesssim 10 \text{ GeV} \quad \text{and} \quad 3 \lesssim \tan\beta \lesssim 5\,,$$

$$\boxed{2.93 \text{ GeV} \lesssim m_\chi \lesssim 5 \text{ GeV}.}$$

Barger et al; Hagiwara, Stong;
TESLA TDR

Higgs CP at ILC

$$\frac{d\sigma}{d\cos\theta_Z} \propto \beta_{\Phi Z}\left[1+\frac{s\beta_{\Phi Z}^2}{8M_Z^2}\sin^2\theta_Z+\eta\frac{2s\beta_{\Phi Z}}{M_Z^2}\kappa\cos\theta_Z+\eta^2\frac{s^2\beta_{\Phi Z}^2}{8M_Z^4}(1+\cos^2\theta_Z)\right]$$

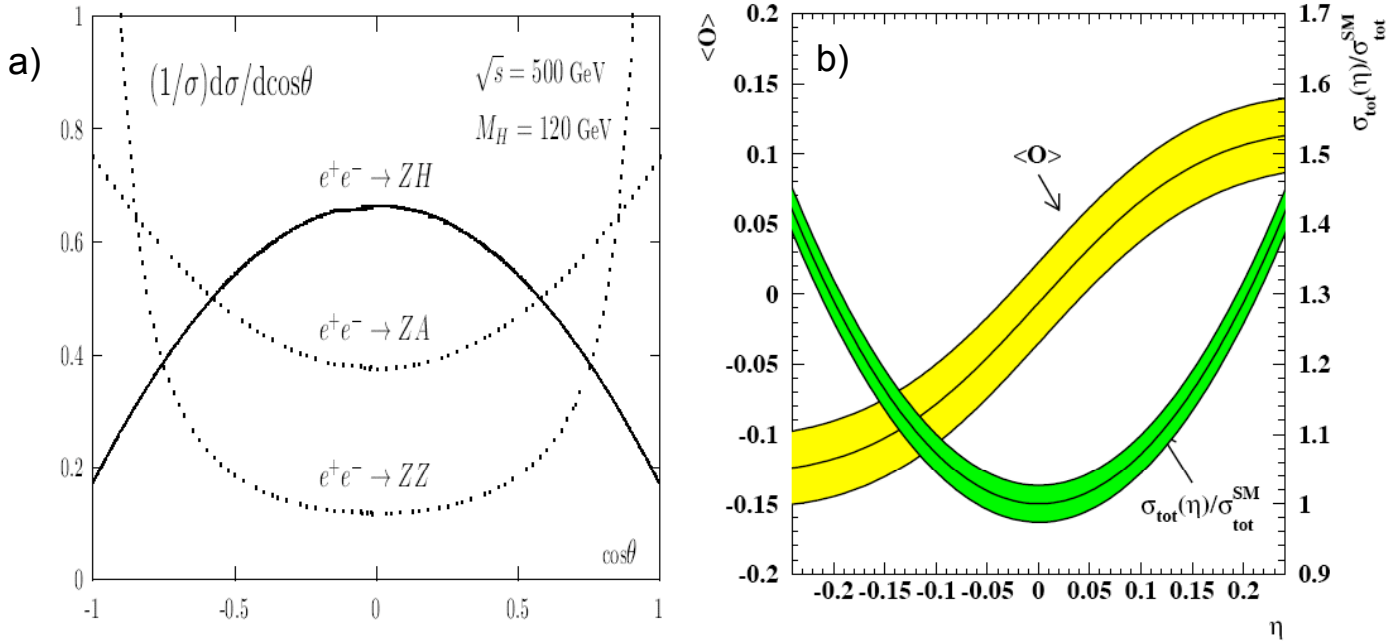


Figure 2.2.8: *a): The* $\cos\theta$ *dependence of* $e^+e^- \to ZH$, $e^+e^- \to ZA$, $e^+e^- \to ZZ$ *for* $\sqrt{s} = 500\,GeV$, *assuming* $M_H = M_A = 120\,GeV$ *[58] and b): the dependence of the expectation value of the optimal observable and the total cross–section on* η *for* $M_H = 120\,GeV$, $\sqrt{s} = 350\,GeV$ *and* $\mathcal{L} = 500\,fb^{-1}$ *after applying the selection cuts. The shaded bands show the* 1σ *uncertainty in the determination of* $\langle\mathcal{O}\rangle$ *and the total cross section.*

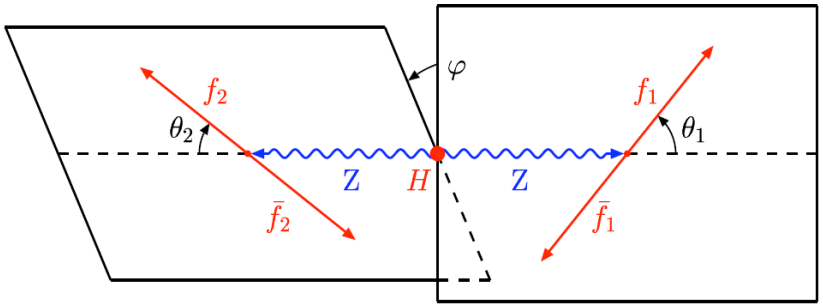
H → ZZ → 4leptons

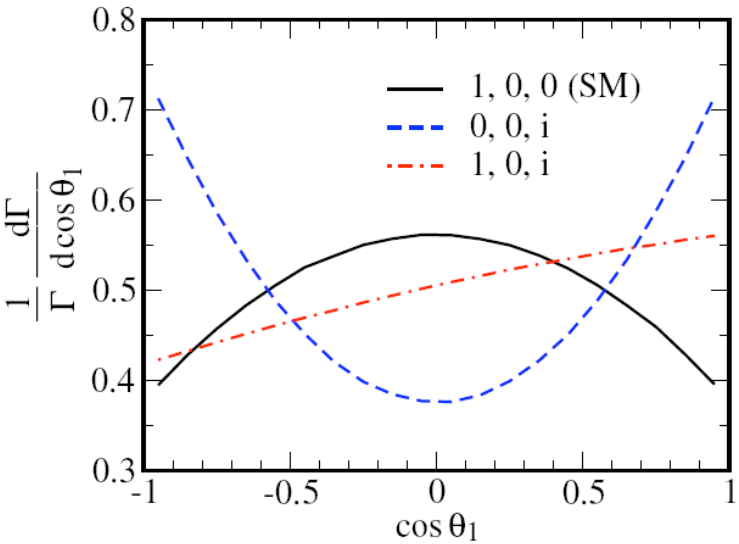
Godbole et al.,
Buszello et al.

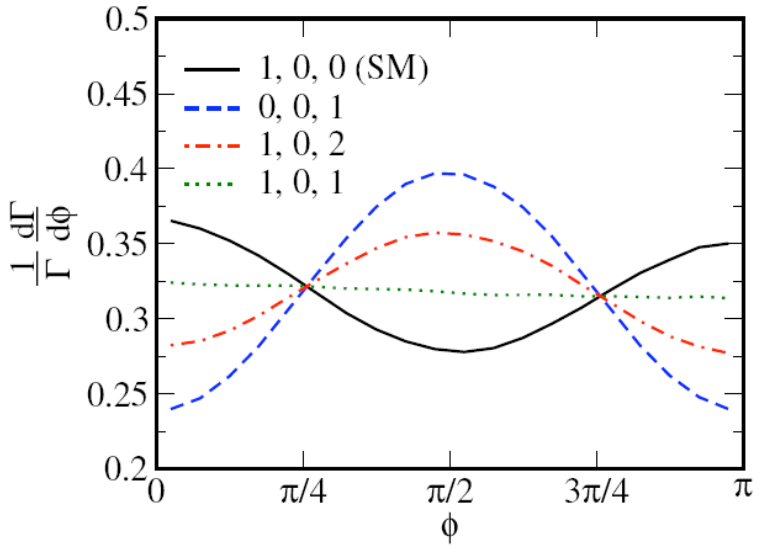
$$g_{HZZ} = \frac{ig}{m_Z \cos\theta_W}\left[a\, g_{\mu\nu} + b\,(k_{2\mu}k_{1\nu} - k_1\cdot k_2 g_{\mu\nu}) + c\,\epsilon_{\mu\nu\alpha\beta}k_1{}^{\alpha}k_2{}^{\beta}\right]$$

$$O_1 \equiv \cos\theta_1 = \frac{(\vec{p}_{\bar{f}_1} - \vec{p}_{f_1})\cdot(\vec{p}_{\bar{f}_2} + \vec{p}_{f_2})}{|\vec{p}_{\bar{f}_1} - \vec{p}_{f_1}||\vec{p}_{\bar{f}_2} + \vec{p}_{f_2}|}$$

$$\mathcal{A}_1 = \frac{\Gamma(\cos\theta_1 > 0) - \Gamma(\cos\theta_1 < 0)}{\Gamma(\cos\theta_1 > 0) + \Gamma(\cos\theta_1 < 0)}.$$



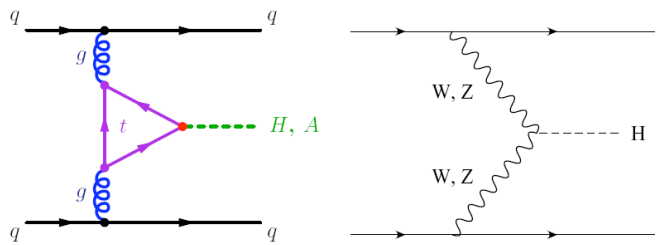


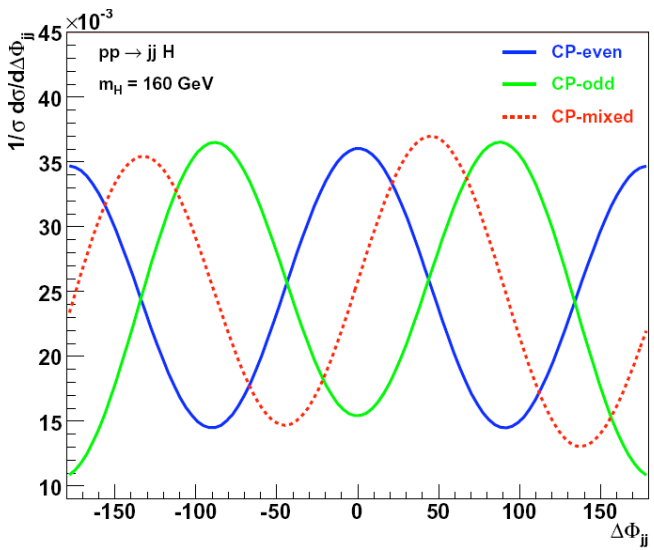


Zeppenfeld et al.

Hjj at LHC

Use distribution of azimuthal angle between the jets to determine the CP properties of the Higgs





CP odd

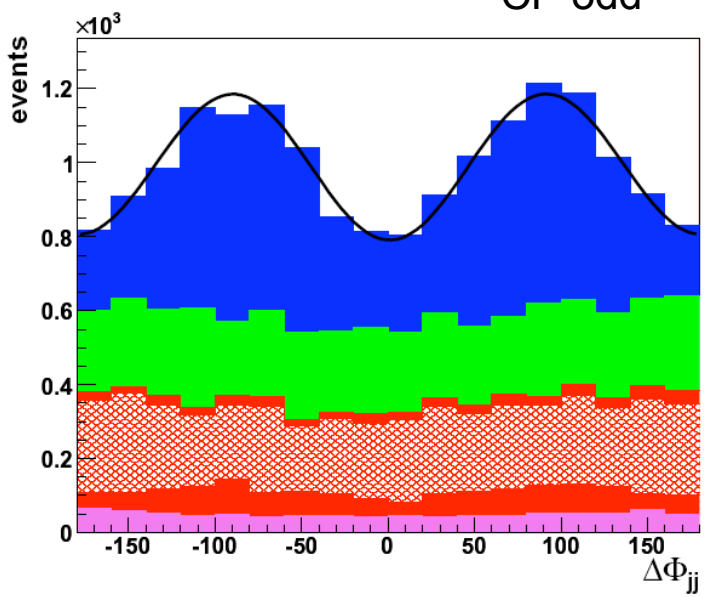


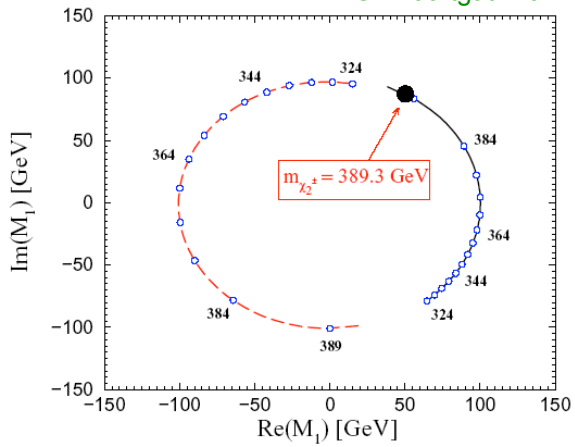
Figure 2: Normalized distributions of the jet-jet azimuthal angle difference as defined in the text. The curves are for the SM CP-even case ($a_3 = 0$), a pure CP-odd ($a_2 = 0$) and a CP-mixed case ($a_2 = a_3 \neq 0$).

Gauginos and sfermions at ILC

Choi, Djouadi, Guchait, Kalinowski, Moortgat-Pick, Song, Zerwas; Kneur, Moultaka; Barger et al; Drees, Gaissmaier; Rolbiecki; Bartl, Christova, Eberl, Gajdosik, Hesselbach, Kernreiter, Kittel, SK, Majerotto, Porod; etc etc

- CP-even observables: masses, cross sections, branching ratios
  - Parameter determination (M_i, μ, A_f,...) in principle possible
  - Beam polarization is essential
  - Ambiguities for phases remain

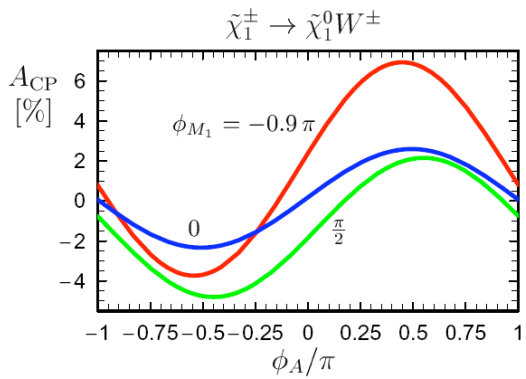
G. Moortgat-Pick



- CP-odd / T-odd observables
  - Triple product asymmetries
    (example p.18)
  - Charge asymmetries

$$A_{\mathrm{CP}} = \frac{\Gamma_{(+)}(\tilde{\chi}_i^+ \to \tilde{\chi}_j^0 W^+) - \Gamma_{(-)}(\tilde{\chi}_i^- \to \tilde{\chi}_j^0 W^-)}{\Gamma_{(+)}(\tilde{\chi}_i^+ \to \tilde{\chi}_j^0 W^+) + \Gamma_{(-)}(\tilde{\chi}_i^- \to \tilde{\chi}_j^0 W^-)}$$

through loops [Eberl et al]



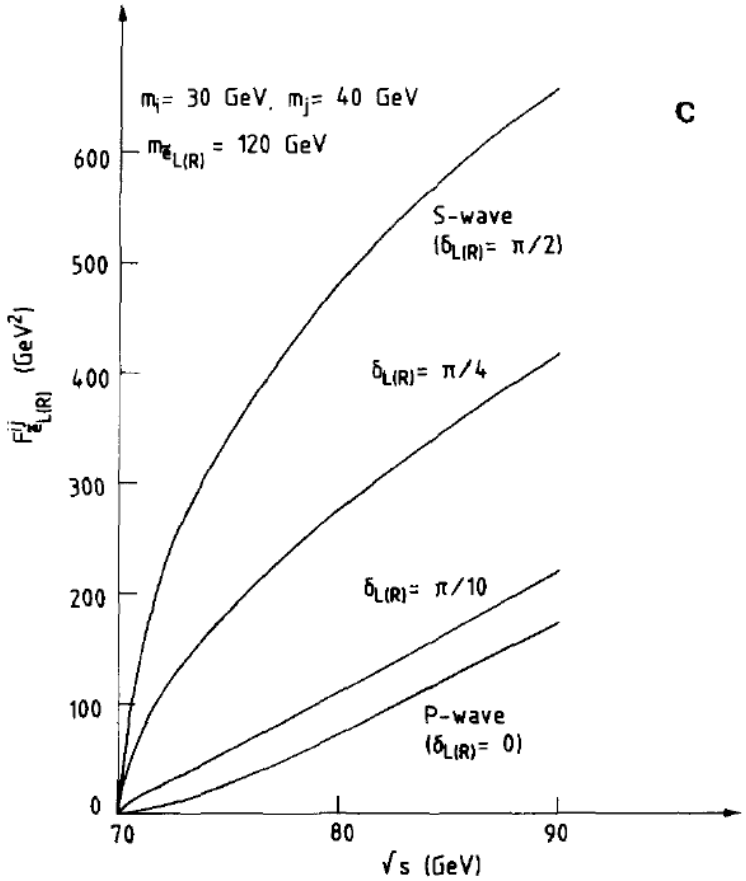
Petcov, PLB178 (1986)

Threshold behaviour: neutralino production

- Threshold curve of $e^+e^- \to \chi_i\chi_j$ ($i \neq j$) depends on the relative CP-parity of the 2 neutralinos.
- $CP(\chi_i\chi_j) = +1$: P-wave
  $CP(\chi_i\chi_j) = -1$: S-wave
- In case of CPV, we are somewhere in between

➡ Exploit threshold scans

$$\sigma(e^+e^- \to \chi_i\chi_j) = \sigma^{ij}_{Z} + \sigma^{ij}_{\tilde{e}Z} + \sigma^{ij}_{\tilde{e}}$$

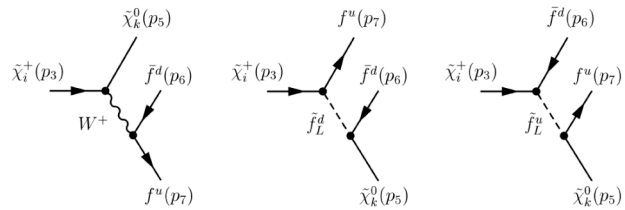


Triple products

Kizikuri, Oshimo;
Bartl et al;
Choi et al.

Spin correlations between production and decay → CP asymmetries.
Have been analyzed for neutralinos/charginos with 2 and 3body decays

Example $e^+e^- \to$ charginos

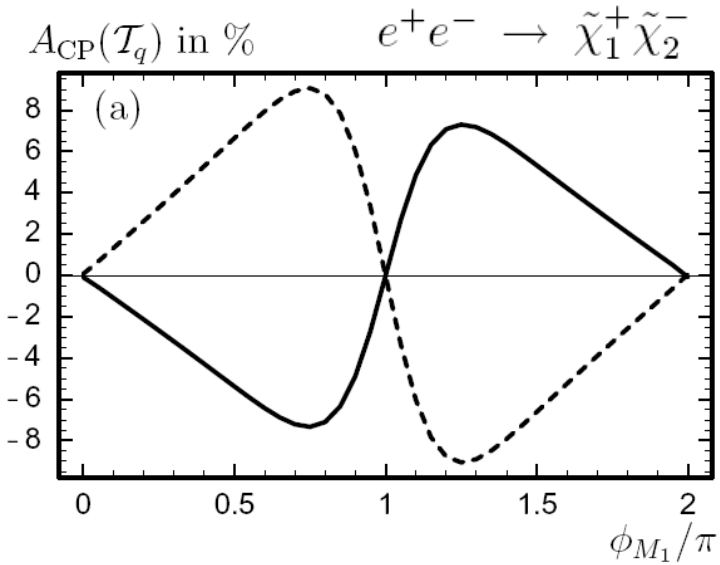


$$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0\ \nu\ \ell^+\ , \quad \mathcal{T}_\ell = \vec{p}_{\ell^+} \cdot (\vec{p}_{e^-} \times \vec{p}_{\tilde{\chi}_1^+})$$

$$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0\ \bar{s}\ c\ , \quad \mathcal{T}_q = \vec{p}_{\bar{s}} \cdot (\vec{p}_c \times \vec{p}_{e^-})$$

$$A_T(\mathcal{T}_{\ell,q}) = \frac{N[\mathcal{T}_{\ell,q} > 0] - N[\mathcal{T}_{\ell,q} < 0]}{N[\mathcal{T}_{\ell,q} > 0] + N[\mathcal{T}_{\ell,q} < 0]}$$

$$A_{\rm CP}(\mathcal{T}_{\ell,q}) = \frac{A_T(\mathcal{T}_{\ell,q}) - \bar{A}_T(\mathcal{T}_{\ell,q})}{2}$$



[Bartl et al]

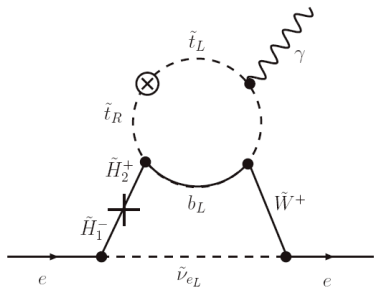
EDM constraints

Ibrahim, Nath; Abel, Khalil, Lebedev; Pospelov, Ritz; Ayazi, Farzan; Nihei et al; Olive et al.; Ellis, Lee, Pilaftsis.

At 1 loop:

tanβ enhancement

$$d_e = \frac{e m_e}{16\pi^2 M_{\rm SUSY}^2}\left[\left(\frac{5g_2^2}{24}+\frac{g_1^2}{24}\right)\tan\beta\sin\left[\mathrm{Arg}(\mu M_2 m_{12}^{2*})\right]+\frac{g_1^2}{12}\sin[\mathrm{Arg}(M_1^* A_e)]\right]$$



Arg($A_{tb\tau}$) enters at 2 loops, ca factor 10 suppressed

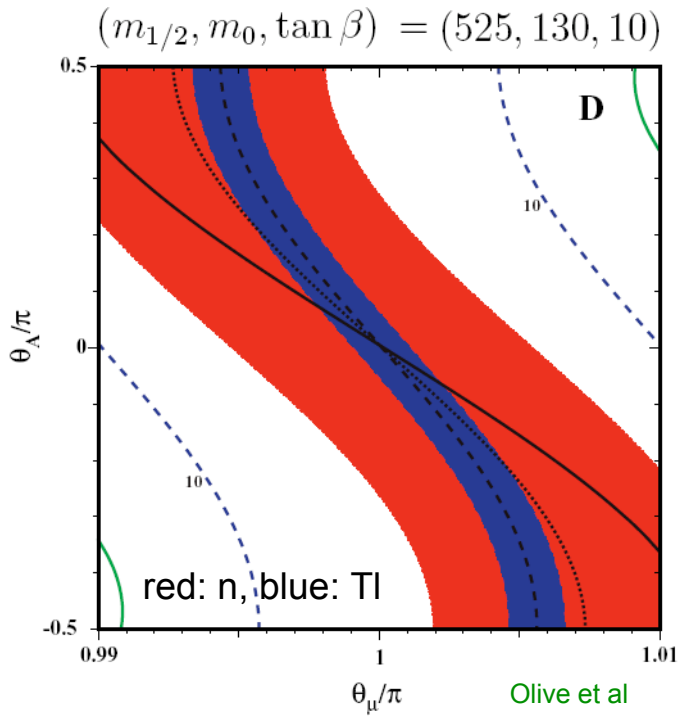
For O(100) GeV masses and O(1) phases, the EDMs are typically 3 orders o.M. too large.

⇨ Need suppression mechanism:

- small phases
- heavy sparticles

(in particular 1st and 2nd generation)

- cancellations

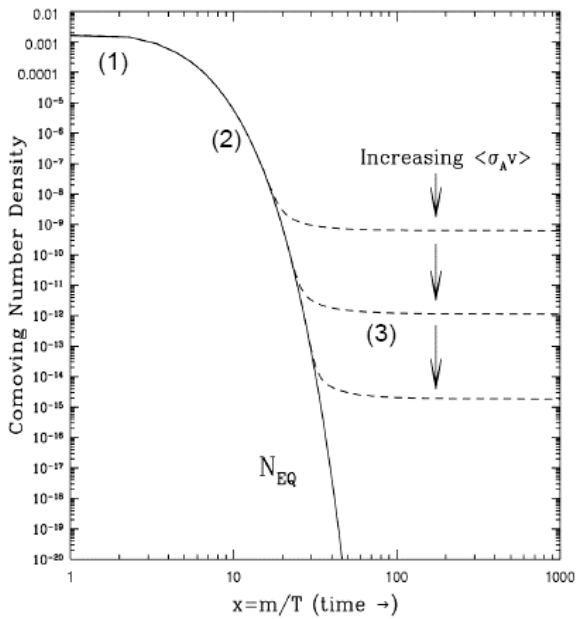


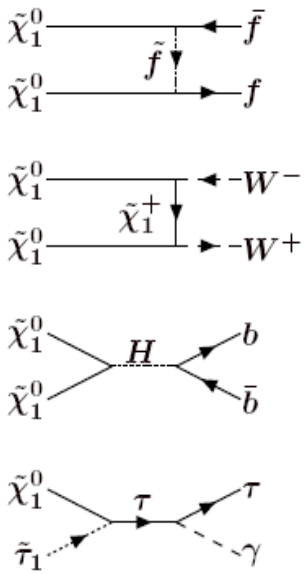
Olive et al

Falk et al; Argyrou et al; Gomez et al; Balazs et al; Gondolo, Frese; Nihei, Sasagawa; Choi, Kim; Boudjema et al.; Lee, Scopel.

Neutralino relic density

χ^0 LSP as thermal relic: relic density computed as thermally avaraged cross section of all annihilation channels → $\Omega h^2 \sim \langle \sigma v \rangle^{-1}$





bino LSP, bulk region
light $\tilde{\chi}_1^0$ and $\tilde{f}$

LSP with strong
higgsino component

Higgs funnel
$m_H \sim 2m_{\tilde{\chi}_1^0}$

Co-annihilation
LSP–NLSP mass difference

Neutralino couplings depend on phases → expect large influence on $\langle \sigma v \rangle$

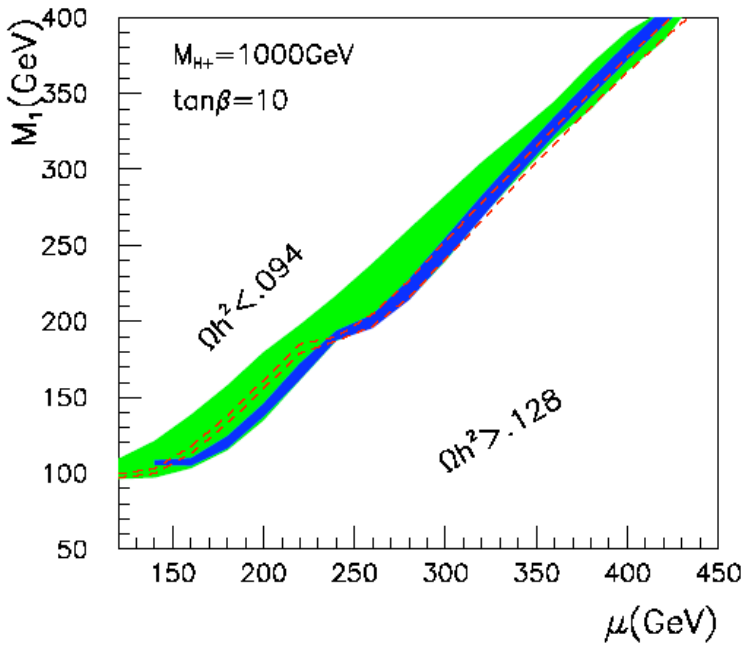
Caution: need to single out kinematic effects

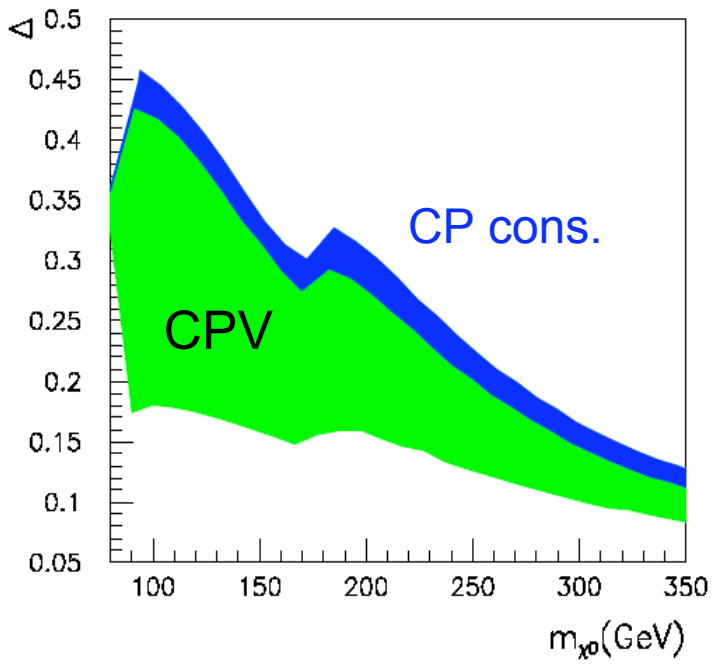
Boudjema et al.

Scan over phases in M_1-μ plane:

- $M_1 \sim \mu$ main channel is annihilation into WW
- in WMAP region, LSP has ~25% higgsino component

$\Delta = (m\chi_1^+ - mLSP) / mLSP$





Blue: WMAP-allowed range for phases=0
Green: same arbitrary phases of M_1, μ, ...

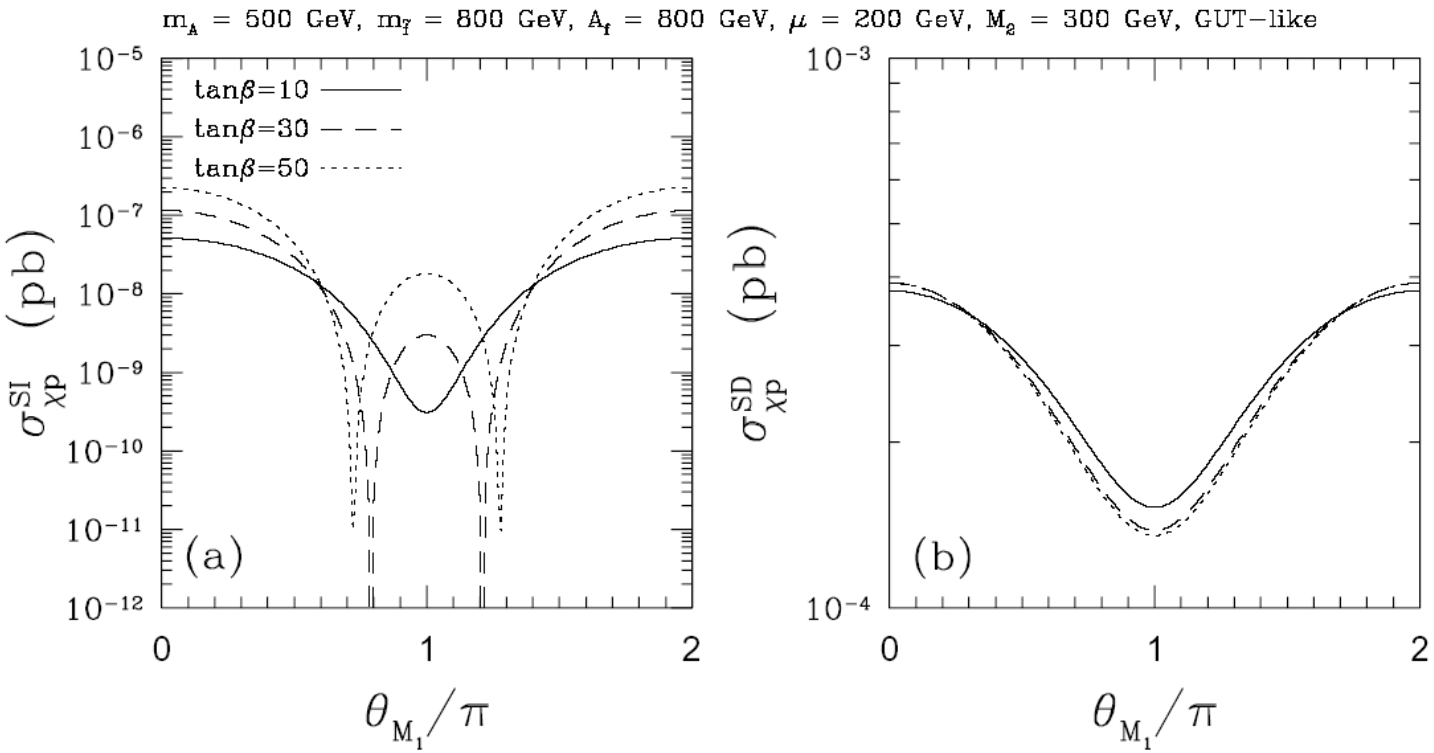
In CPV case, much smaller mass differences can give the right Ωh^2

Nihei, Sasagawa

Direct DM detection

$$\mathcal{L}_{\chi q} = d_q(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q) + f_q(\bar{\chi}\chi)(\bar{q}q).$$

Orders of magn. effects in SI cross sections



Spin independent (SI): t-channel neutral Higgs and s-channel squark exchange

Spin dependent (SD): t-channel Z and s-channel squark exchange

Well-tempered neutralino with CPV, relic density

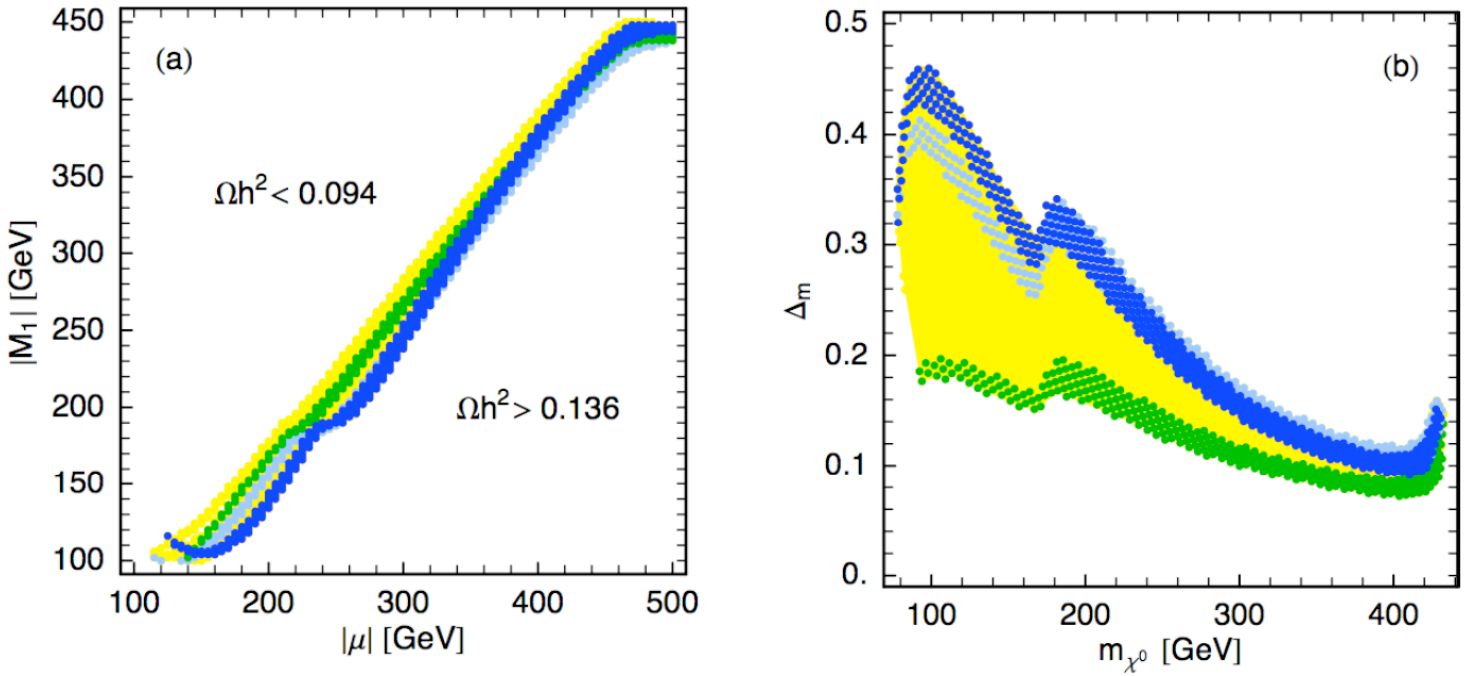


Figure 1: (a) Bands of $0.094 < \Omega h^2 < 0.136$ in the $|M_1|$ vs $|\mu|$ plane for $\tan\beta = 10$ and $m_{H^+} = m_{\tilde{f}} = |A_f| = 1$ TeV, in blue for all phases zero, in light blue for $\phi_\mu = 180°$ (or $\mu < 0$) and all other phases zero, in green for $\phi_1 = 180°$ and all other phases zero, and in yellow for all other cases, i.e. arbitrary phases. (b) The corresponding relative mass difference Δ_m of $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^+$ as function of $m_{\tilde{\chi}_1^0}$ in the WMAP-prefered region with the same colour code as in (a).

Well-tempered neutralino w/ CPV, direct detection

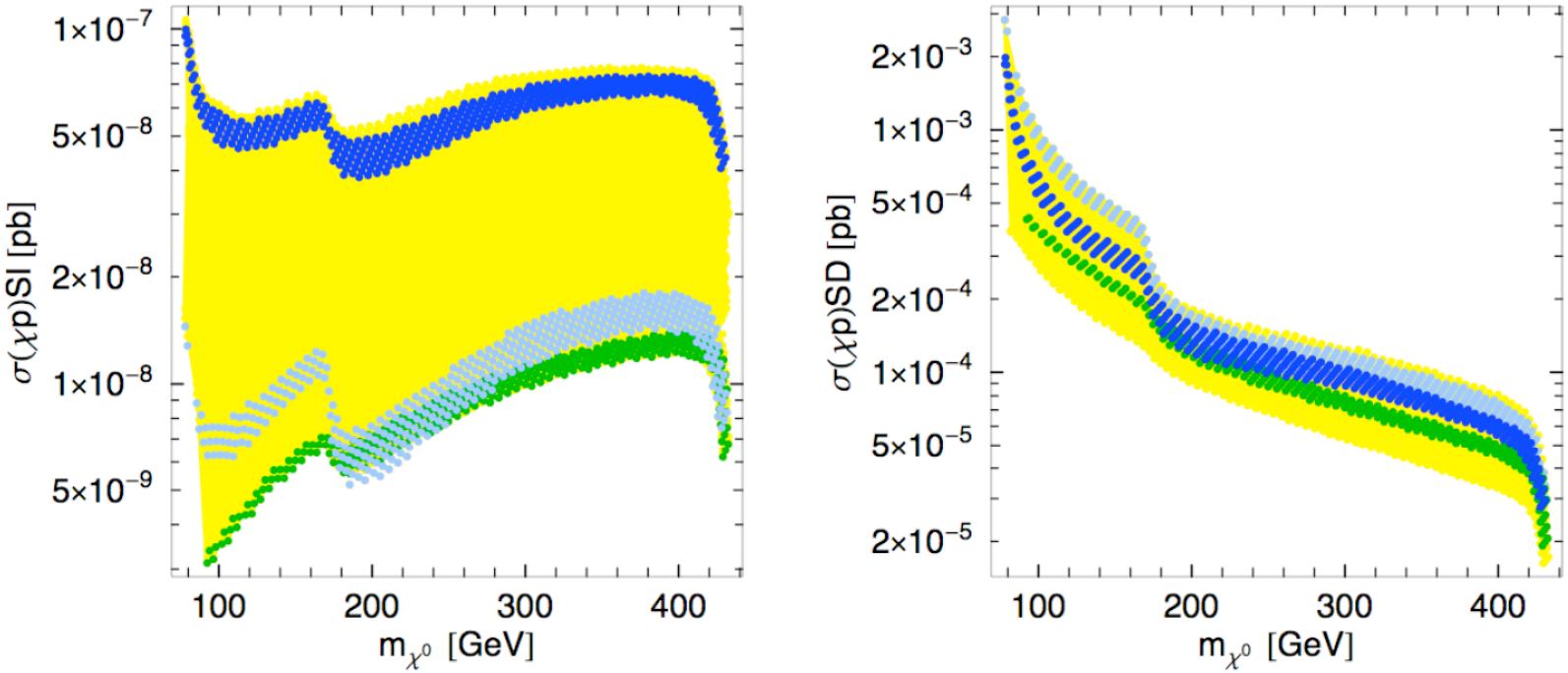


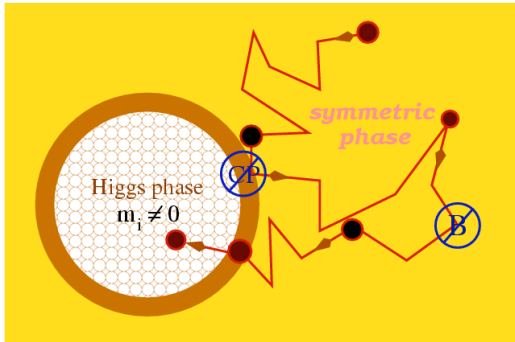
Figure 2: Cross sections for direct detection in the WMAP-prefered region of Fig. 1 as a function of the LSP mass. On the left the spin-independent case, $\sigma^{\rm SI}_{\chi p}$, and on the right the spin-dependent case, $\sigma^{\rm SD}_{\chi p}$. Same colour code as in Fig. 1.

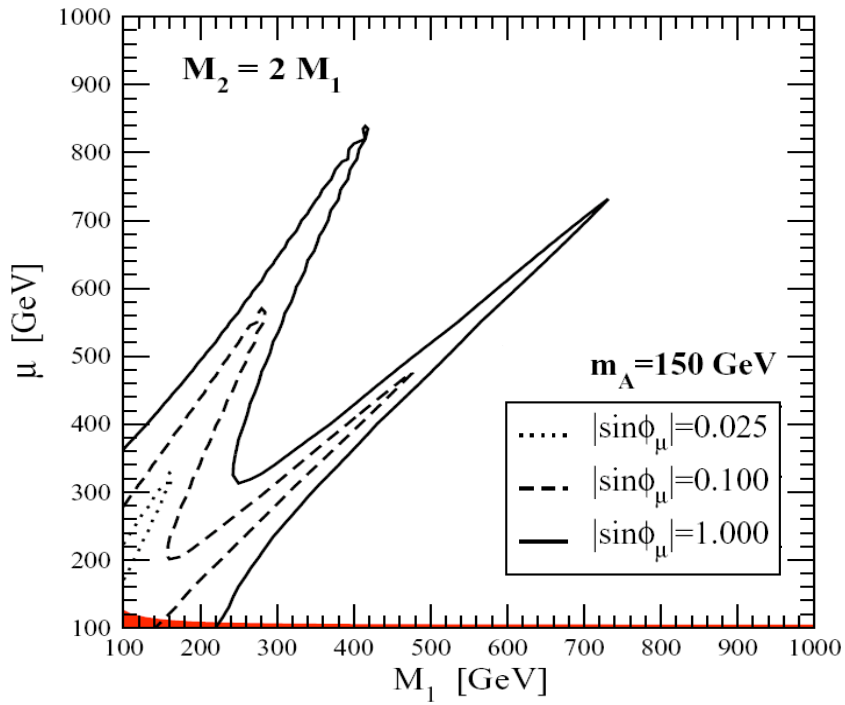
Electroweak baryogenesis

Balazs et al; Konstandin et al;
Cirigliano et al.
Carena et al.

Sakharov conditions:

- ✓ baryon number violation
  - ⇨ shaleron processes
- ✓ C and CP violation
  - ⇨ Resonant CPV in chargino sector, $M_2 \sim \mu$
- ✓ departure from equilibrium
  - ⇨ Light stop, $m<m_t$, for strong 1st-order phase transition





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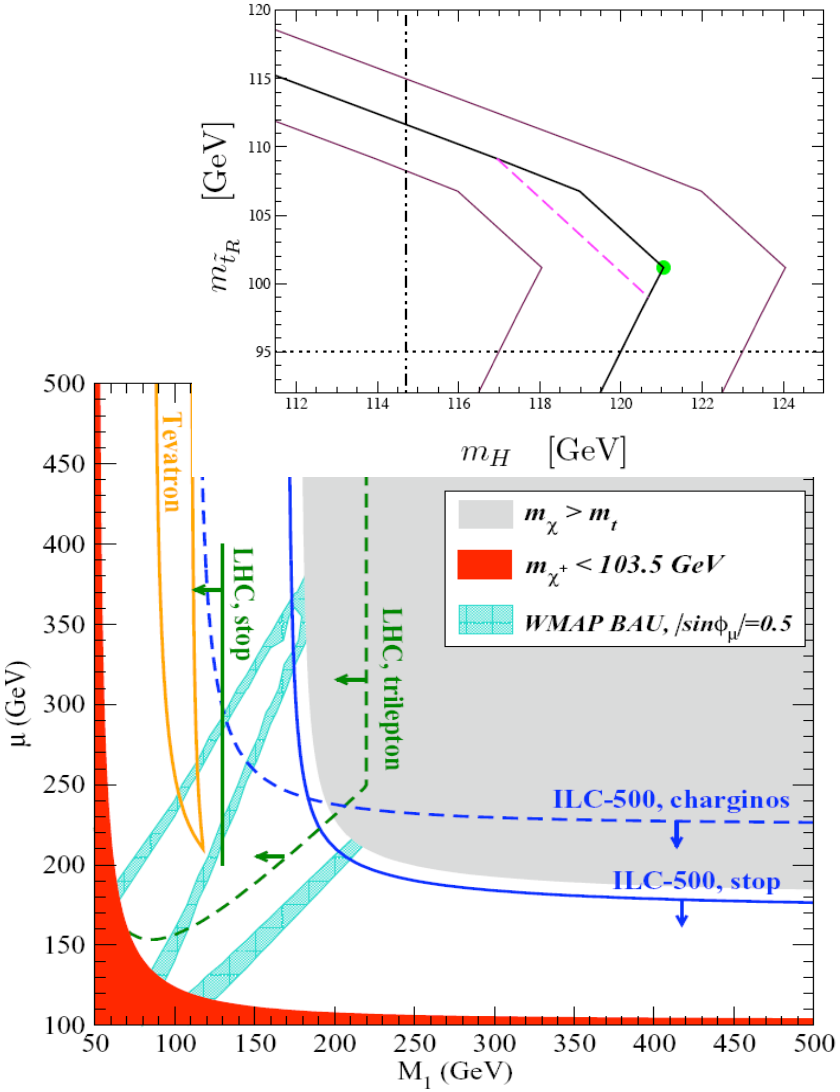

[Cirigliano et al.]

Spontaneous CP violation

T.D. Lee;
Branco, Mohapatra,
Achiman, Bora,
Hiller, Schmaltz.
...

- Arises through complex VEV of extra Higgs field
- Leads to vanishing θ_{QCD} at tree level
- Can lead to a complex CKM matrix

- SCPV is a very elegant idea but difficult to realize in SUSY; not possible in the MSSM
- Extra Higgses invoke FCNC → suppress by heavy mass scale (and/or extra SM singlet fermions)
- Consider L-R symmetric models, SUSY GUTs,...

- Interesting recent work on SUSY SO(10); link with neutrino seesaw and leptogenesis

⇨ exciting case for model building

Conclusions

- Explicit CPV (CP phases in Lagrangian)
  - Affects sparticle masses and couplings through mixing
  - Scalar-pseudoscalar Higgs mixing
  - Dipole moments, flavour observables
  - Changes in cross sections and branching rati
  - CP-odd observables at colliders
  - Neutralino relic density
  - Electroweak baryogenesis

Need precision measurements!

- Go e^+e^- (ILC, CLIC)
- Simulations still missing