CP violation in SUSY

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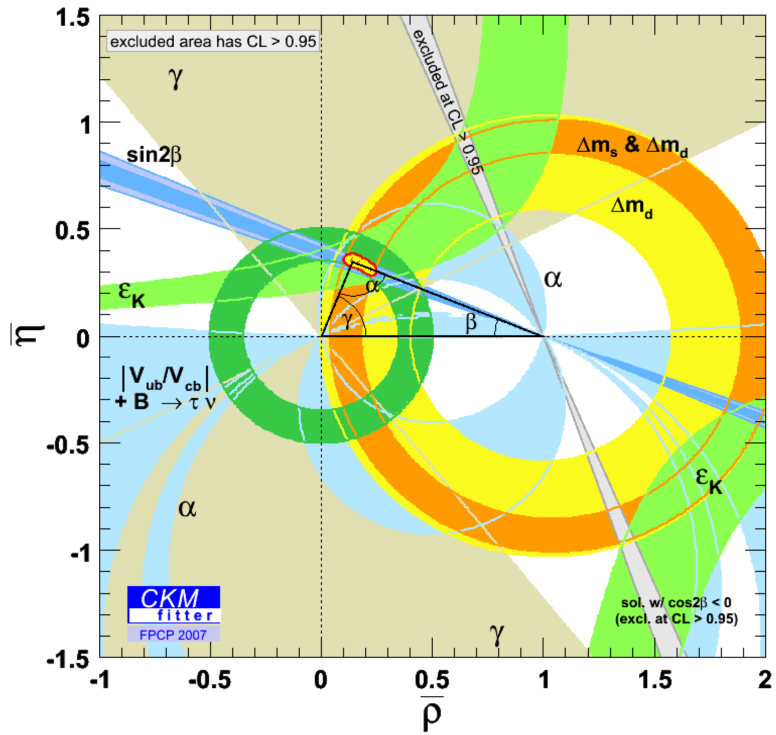
26 July – 1 Aug 2007

CP violation in the Standard Model

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



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.

c.f. talks by Isidori and in flavour session

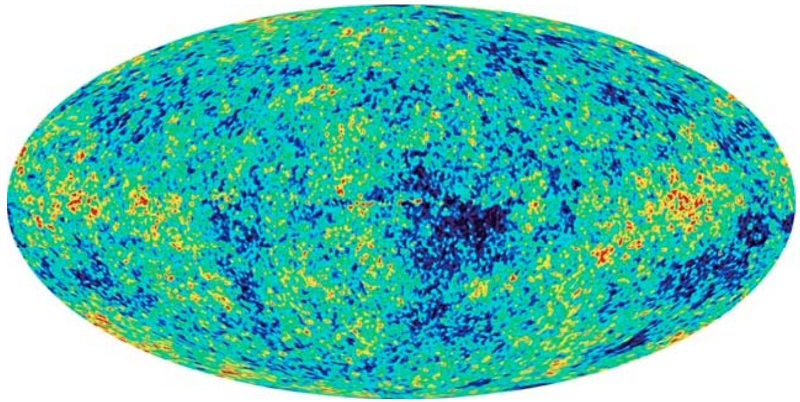
On the other hand, for the strong CP phase $|\bar{\theta}| < 10^{-9}$.

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

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

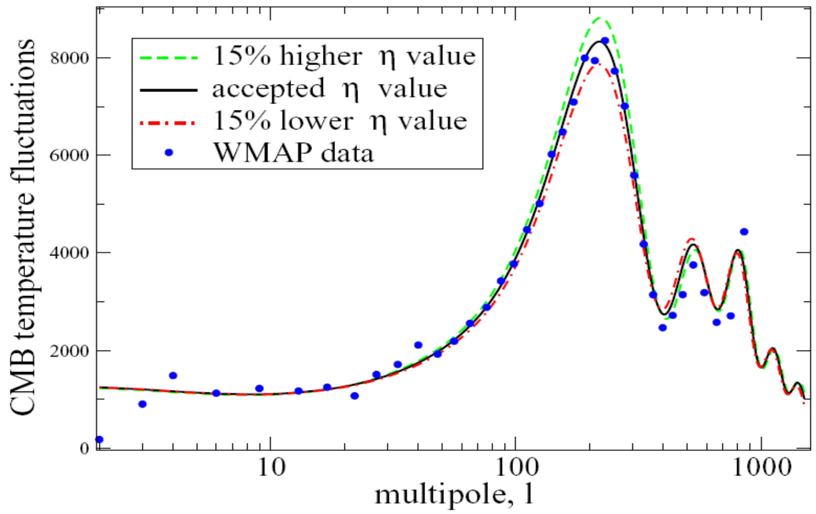


Fig. 2. Dependence of the CMB Doppler peaks on η.

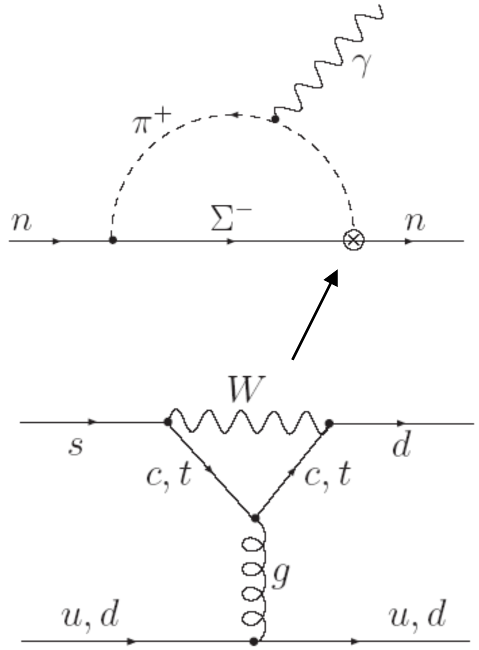
see e.g. Dine & Kusenko, 2003
Cline, 2006

e.g. Pospelov, Ritz, 2005

Electric dipole moments

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

90% CL



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

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

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

SM prediction orders of magnitudes below the experimental limits

Strong constraints but still ample room for new physics contributions

CP violation in SUSY

- 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

focus of this talk

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

Large field with vast amount of literature,
not possible to give a complete review in 25min.

I will not try a tour de force but rather
present selected examples for the above topics.

(appologies to those whose work is not mentioned here!)

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

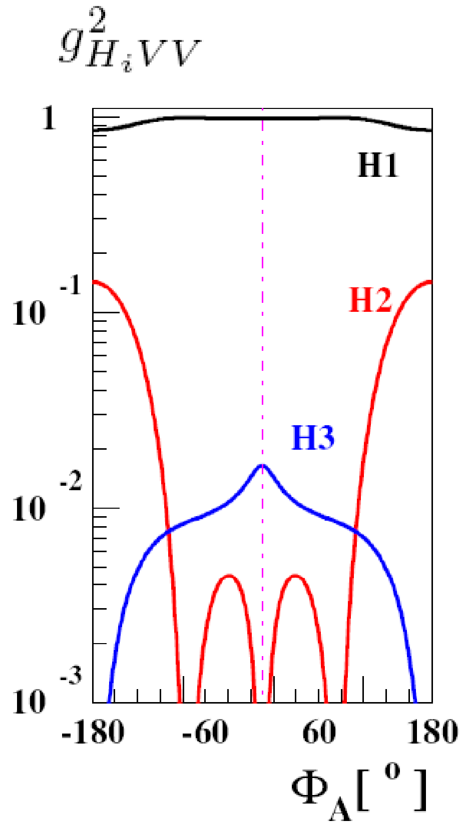
- affect sparticle masses and couplings through mixings
- induce CP mixing of (h, H, A) through radiative corrections
- influence CP-even observables like cross sections and BRs
- lead to interesting CP-odd observables at colliders
- etc...

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.

Talks at this conference

- Higgs boson decays in the complex MSSM, K. Williams
- Higgs production and decay in SUSY with CP violation, S. Hesselbach
- Higgs sector in the MSSM with CP-phases at higher orders, H. Rzehak
- Higgs masses in the complex MSSM with FeynHiggs, T. Hahn
- The lightest Higgs boson and relic neutralino in the MSSM with CP Violation, S. Scopel
- Determination of the CP quantum numbers of neutral Higgs bosons in the tau decay channels at the LHC, S. Berge

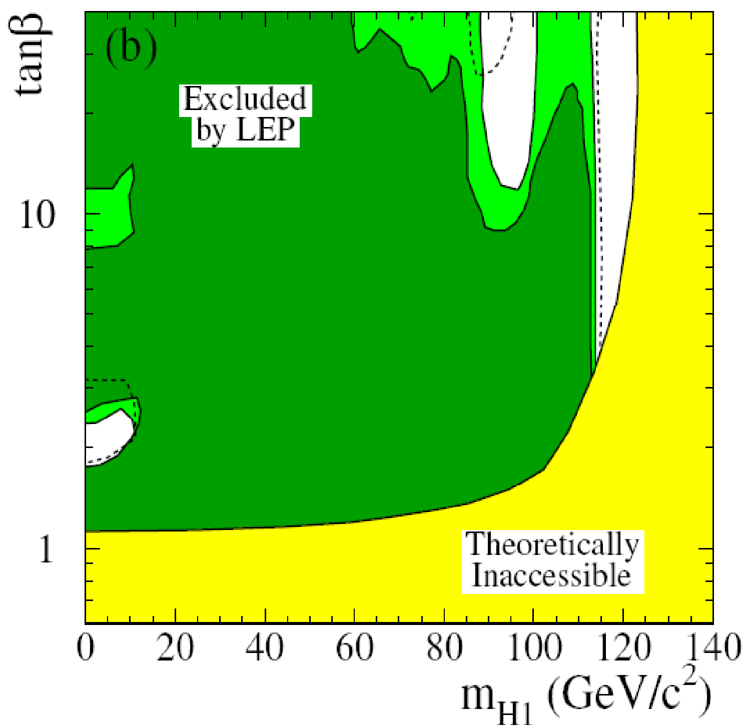
- One-loop corrections in chargino sector with CPV phases, K. Rolbiecki

LEP Higgs WG, P. Bechtle et al.

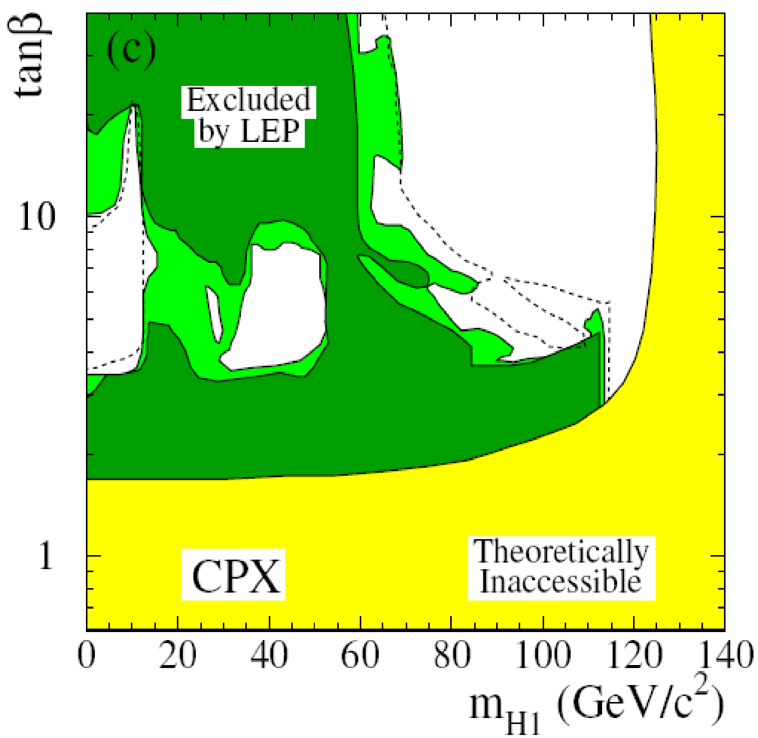
LEP limits in CPX scenario

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

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

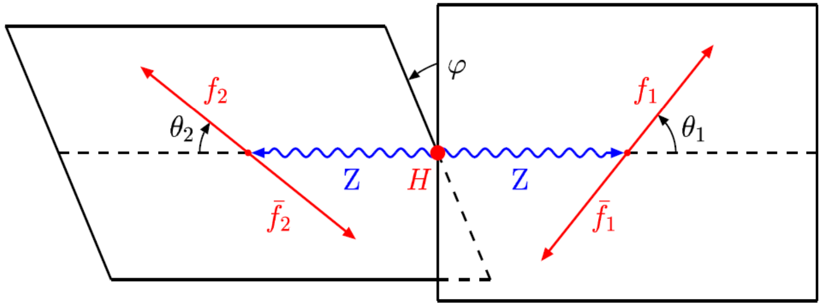
Godbole et al.,
Buszello et al.

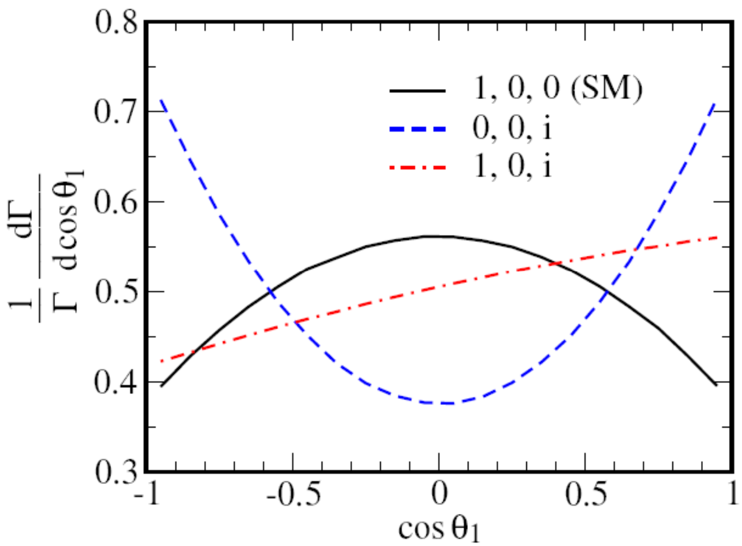
H → ZZ → 4leptons

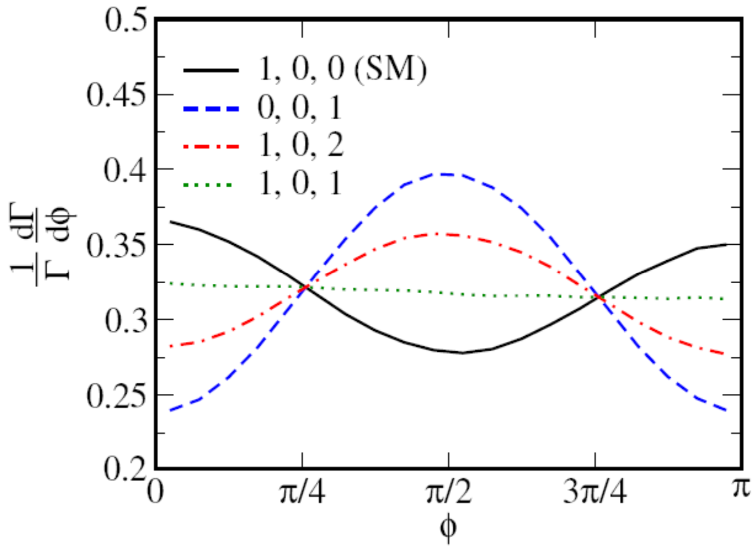
$$g_{HZZ} = \frac{ig}{m_Z \cos\theta_W}\left[a\, g_{\mu\nu} + b\,(k_{2\mu}k_{1\nu} - k_1\cdot k_2 g_{\mu\nu}) + c\,\epsilon_{\mu\nu\alpha\beta}{k_1}^{\alpha}{k_2}^{\beta}\right]$$

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

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



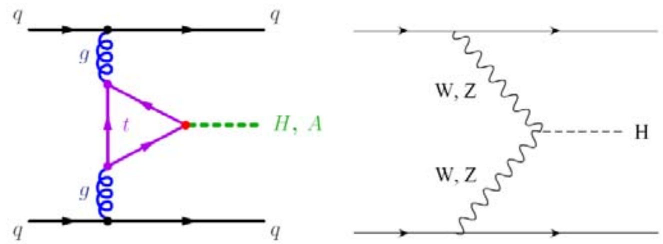




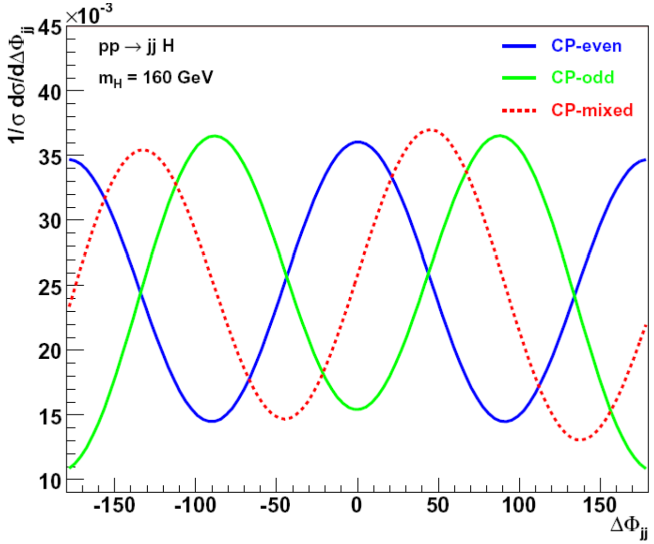
Zeppenfeld et al.

Hjj at LHC

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



CP odd



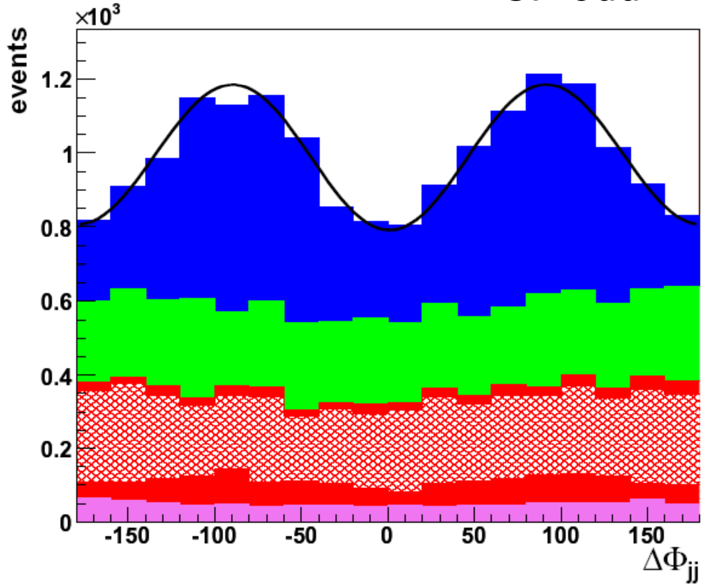


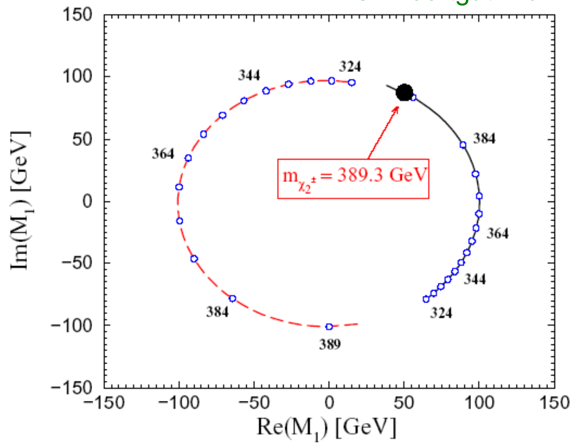
Figure 2: Normalized distributions of the jet-jet azimuthal angle difference as defined in the text. The curves are for the SM CP-even case ($a_3 = 0$), a pure CP-odd ($a_2 = 0$) and a CP-mixed case ($a_2 = a_3 \neq 0$).

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

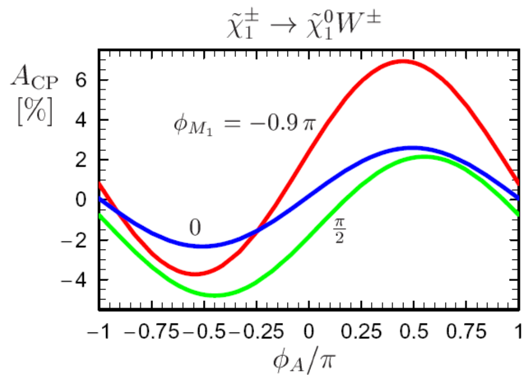
G. Moortgat-Pick



- CP-odd / T-odd observables
  - Triple product asymmetries
    (example next slide)
  - Charge asymmetries

$$A_{\rm CP} = \frac{\Gamma_{(+)}(\tilde\chi_i^+ \to \tilde\chi_j^0 W^+) - \Gamma_{(-)}(\tilde\chi_i^- \to \tilde\chi_j^0 W^-)}{\Gamma_{(+)}(\tilde\chi_i^+ \to \tilde\chi_j^0 W^+) + \Gamma_{(-)}(\tilde\chi_i^- \to \tilde\chi_j^0 W^-)}$$

through loops [Eberl et al]



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

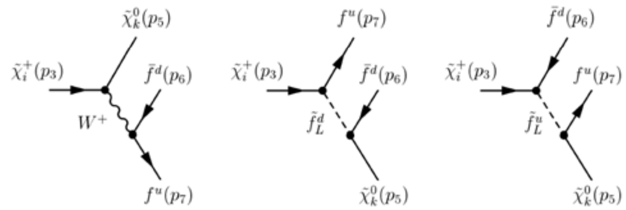
Triple products

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

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

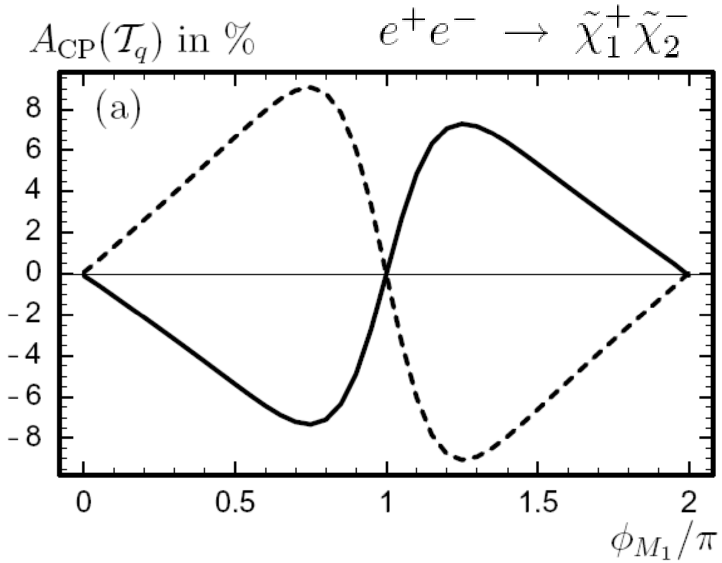
$$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \, \nu \, \ell^+ \, , \quad \mathcal{T}_\ell = \vec{p}_{\ell^+} \cdot (\vec{p}_{e^-} \times \vec{p}_{\tilde{\chi}_1^+})$$

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



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

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



[Bartl et al]

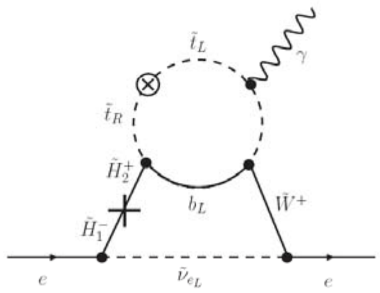
EDM constraints

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

At 1 loop:

tanβ enhancement

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



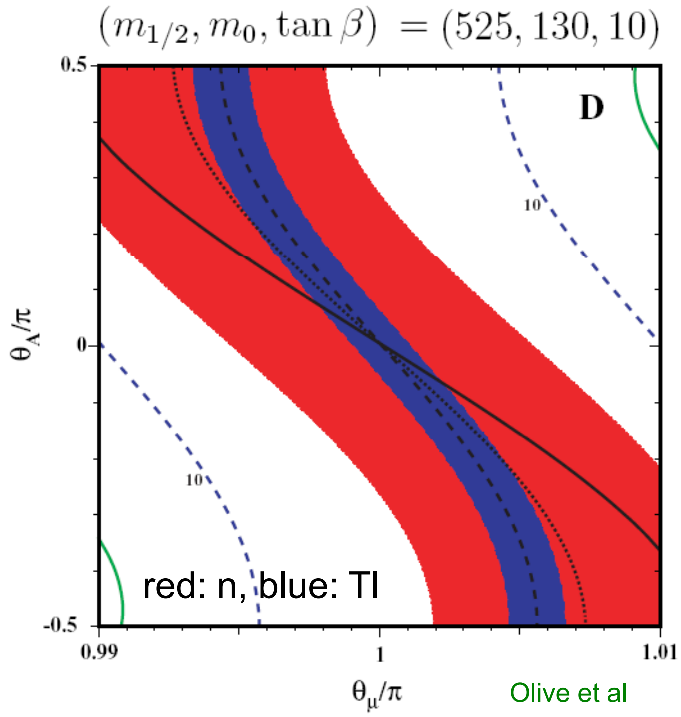
Arg($A_{tb\tau}$) enters at 2 loops, ca factor 10 suppressed

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

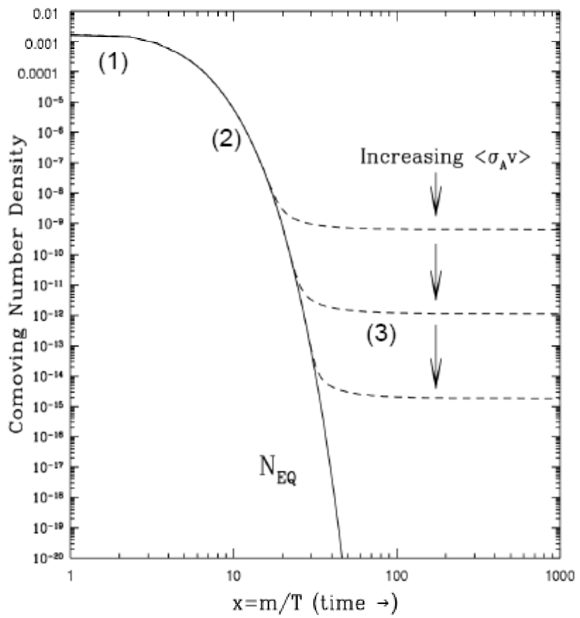


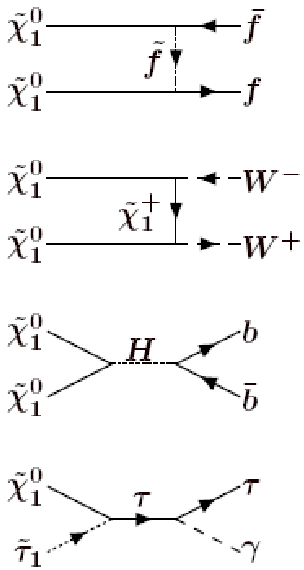
Olive et al

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 $\rightarrow$ $\Omega h^2 \sim \langle \sigma v \rangle^{-1}$





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

LSP with strong
higgsino component

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

Co-annihilation
LSP–NLSP mass difference

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

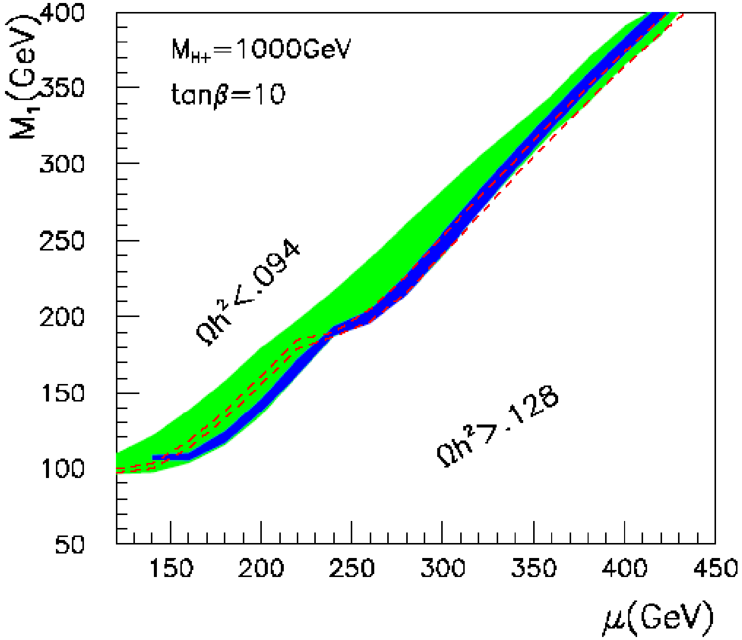
Caution: need to single out kinematic effects

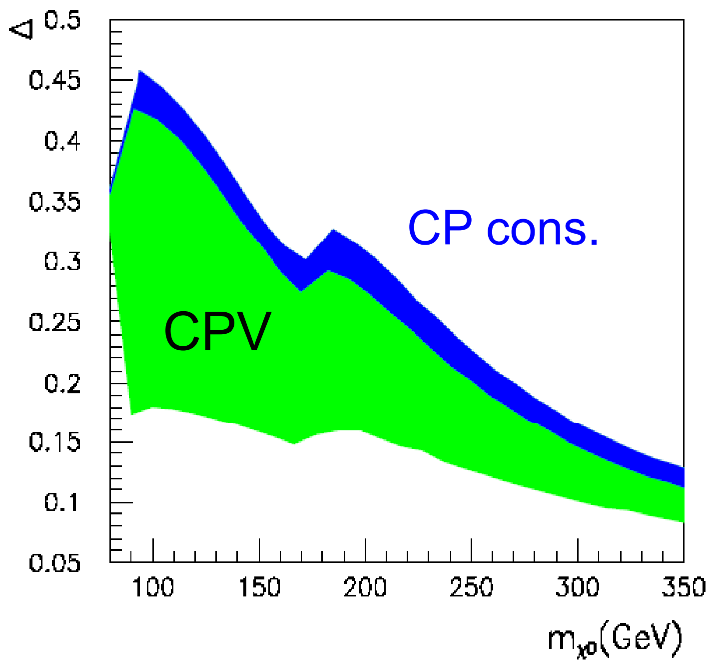
Boudjema et al.

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, ...

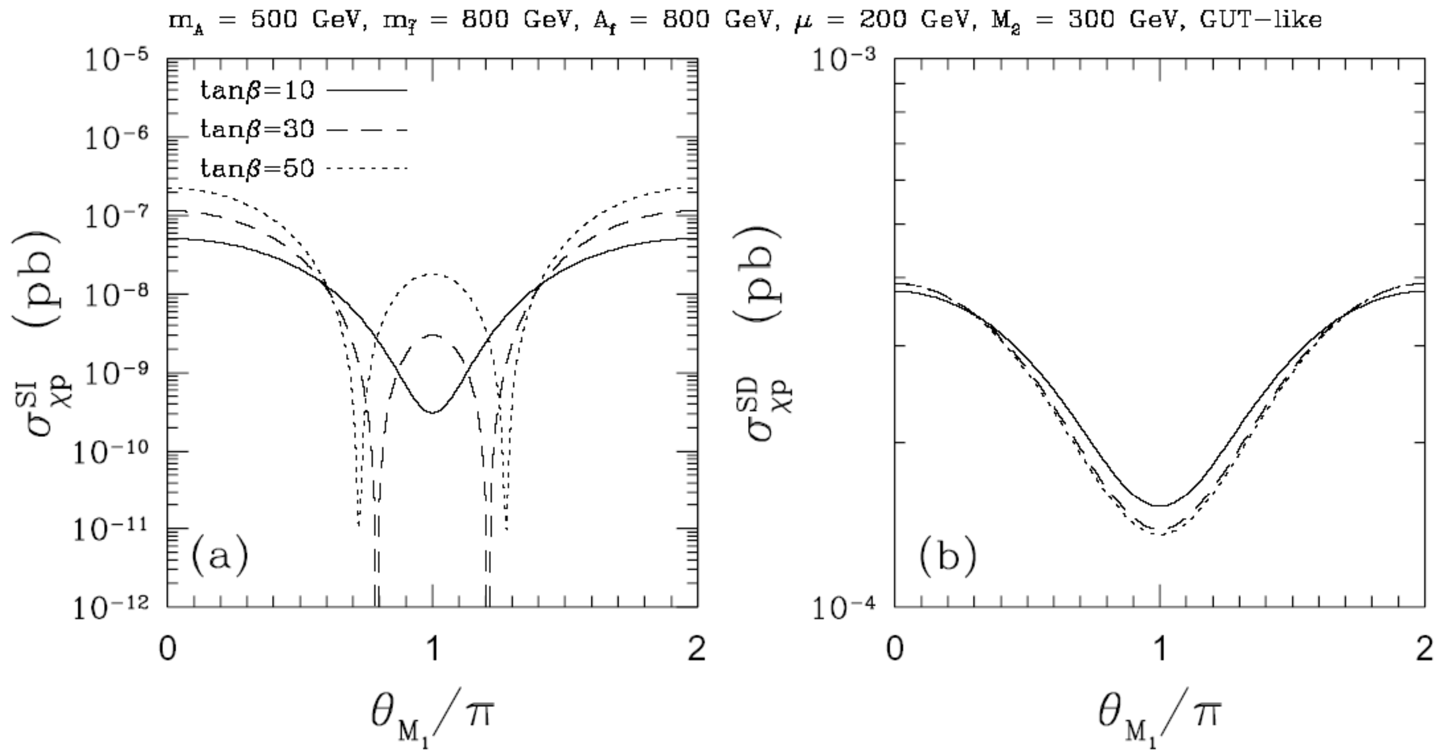
In CPV case, much smaller mass differences can give the right Ωh^2

Nihei, Sasagawa

Direct DM detection

Orders of magn. effects in SI cross sections

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

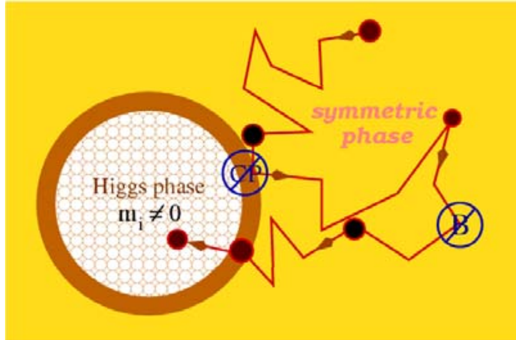


Spin independent (SI): t-channel neutral Higgs and s-channel squark exchange

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

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

Electroweak baryogenesis



Sakharov conditions:

✓ baryon number violation

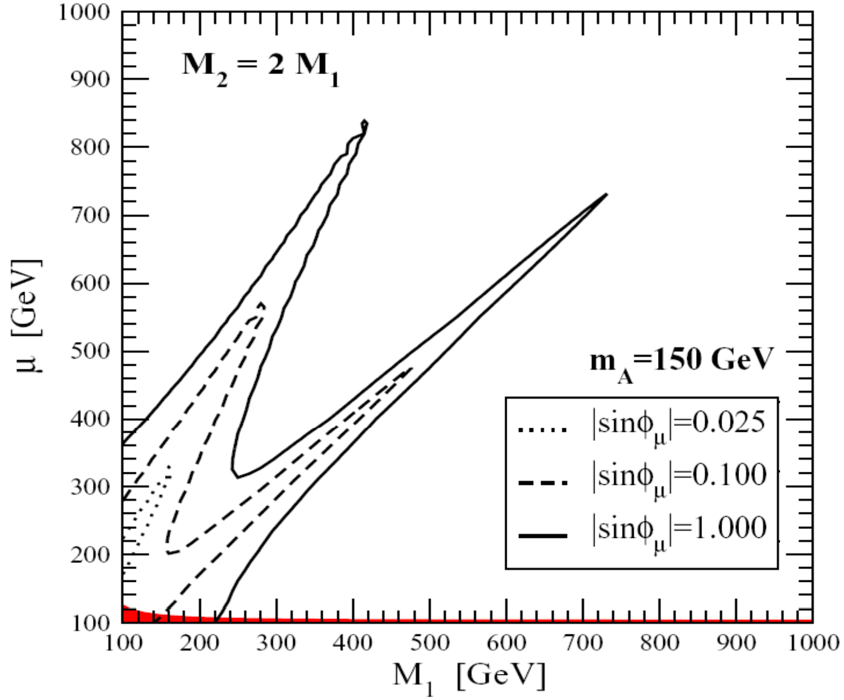
⇨ shaleron processes

✓ C and CP violation

⇨ Resonant CPV in chargino sector, M_2~μ

✓ departure from equilibrium

⇨ Light stop, $m<m_t$, for strong 1st-order phase transition



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Electroweak baryogenesis

Sakharov conditions:

✓ baryon number violation

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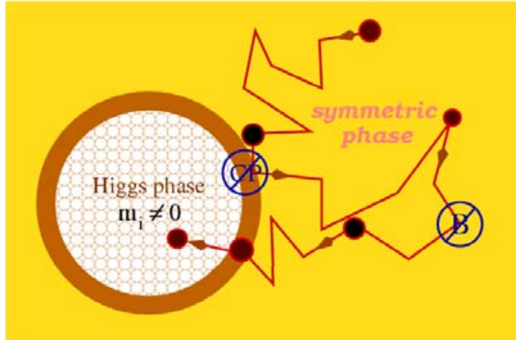
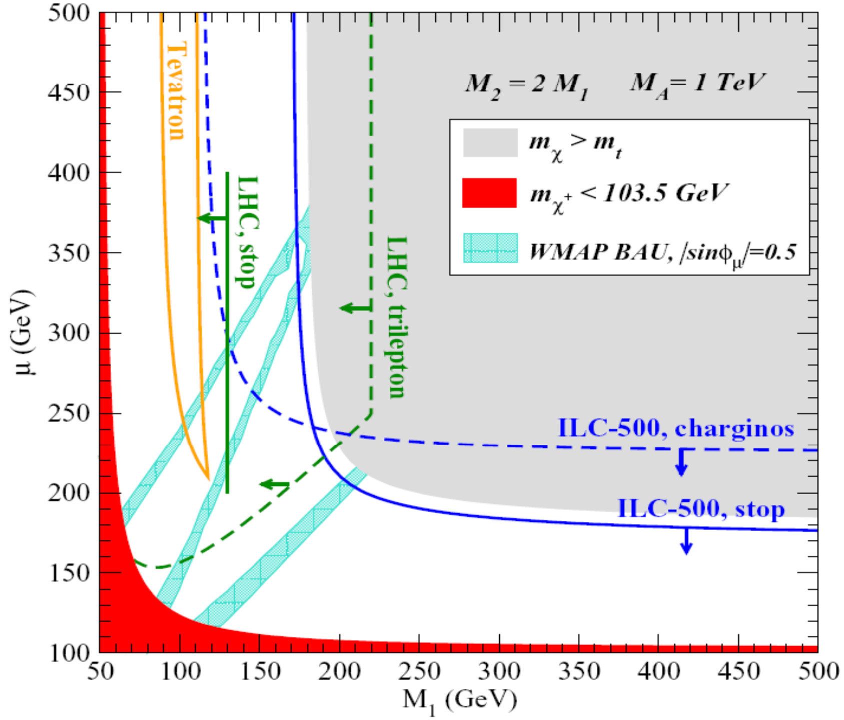
✓ departure from equilibrium

⇨ Light stop, $m < m_t$, for strong 1st-order phase transition





[Cirigliano et al.]

Balazs et al.

putting it together...

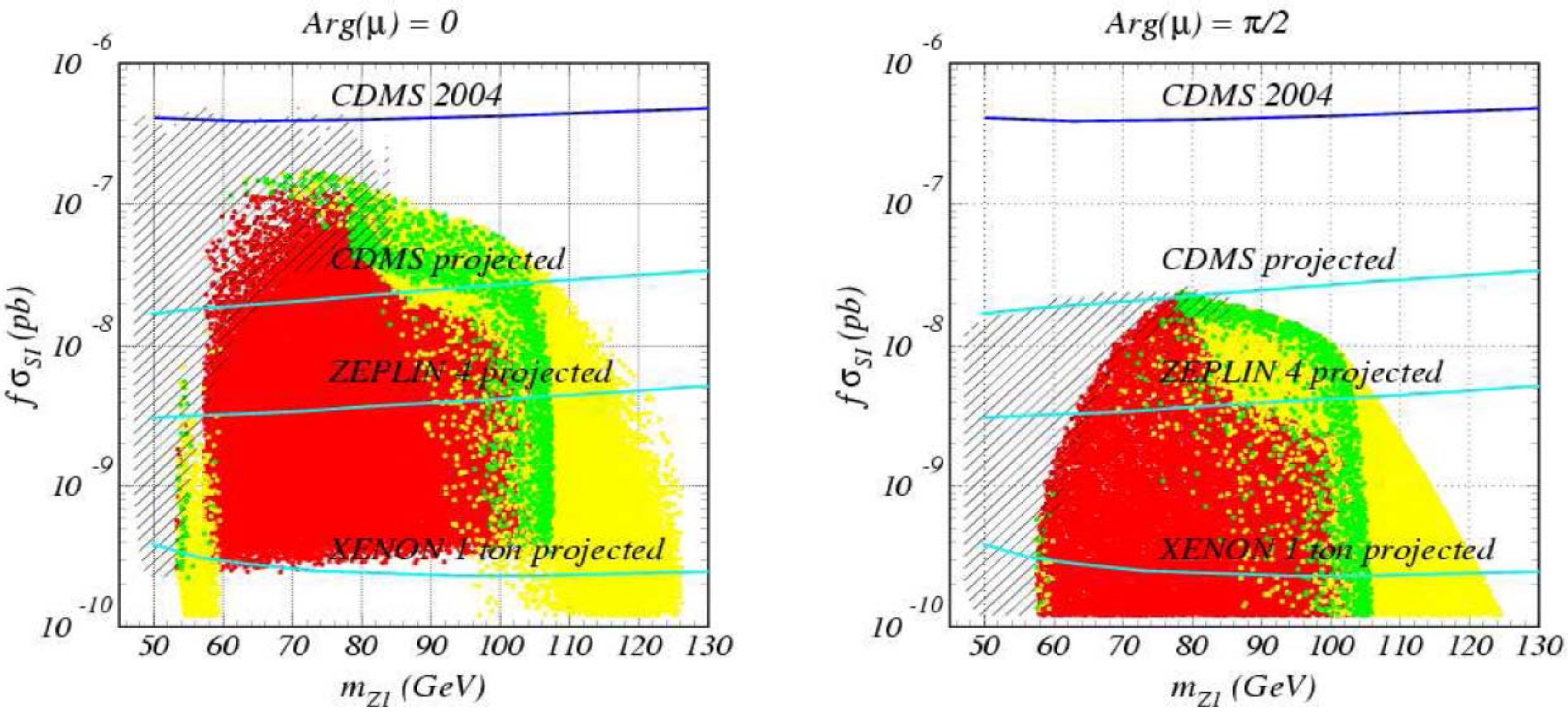


Figure 10: Spin independent neutralino-proton elastic scattering cross sections as a function of the neutralino mass for $Arg(\mu) = 0$ (left) and $Arg(\mu) = \pi/2$ (right). Red (dark gray), green (medium gray) and yellow (light gray) dots represent models in which the neutralino density is above, consistent or below the 2 σ WMAP bounds.

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: CPV in SUSY

- Explicit CPV (Lagrangian)
  - Scalar-pseudoscalar Higgs mixing
  - Changes in cross sections and BRs
  - CP-odd observables at colliders
  - Constraints from low-energy obs.
  - Neutralino relic density
  - Electroweak baryogenesis

Discussed this in the context of the MSSM.

Interesting possibility w. important consequences for phenomenology.

Much work done ....
could only cover small part

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

Thouched only briefly.
Not poss. in MSSM but interesting for model building, SUSY GUTs, ...