Neutralino relic density with CP violation

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Dark matter candidates: WIMPs

Neutralino, gravitino, axion, axino, lightest KK particle, T-odd little Higgs, branons, Q-balls, etc., etc...

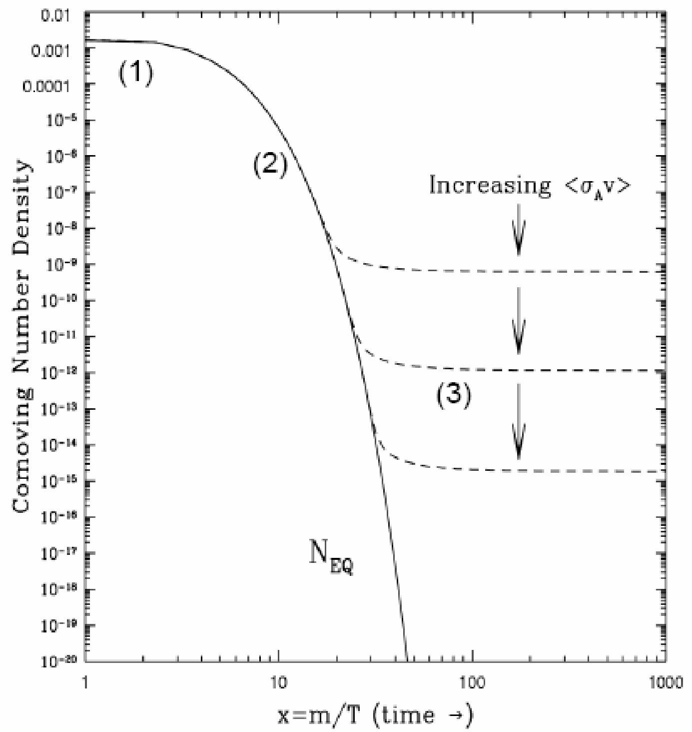
New Physics

Relic density of WIMPs

(1) Early Universe dense and hot; WIMPs in thermal equilibrium

(2) Universe expands and cools; WIMP density is reduced through pair annihilation; Boltzmann suppression: $n \sim e^{-m/T}$

(3) Temperature and density too low for WIMP annihilation to keep up with expansion rate → freeze out



Final dark matter density: $\Omega h^2 \sim 1/\langle\sigma v\rangle$

Thermally avaraged cross section of all annihilation channels

Neutralino-LSP in the MSSM

Neutralino system

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

Gauginos

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

Higgsinos

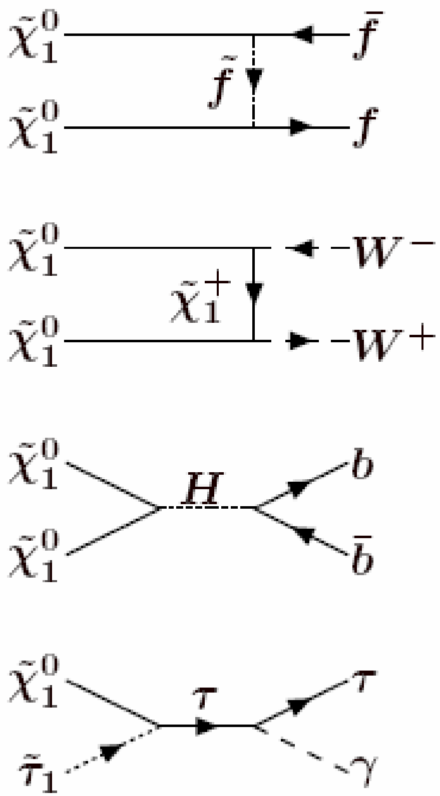
Neutralino mass eigenstates

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

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

Neutralino relic density

Specific mechanisms to get relic density in agreement with WMAP



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

$0.094 < \Omega h^2 < 0.129$ puts strong bounds on the parameter space

CP violation

- In the general MSSM, gaugino and higgsino mass parameters and trilinear couplings can be complex:

$$M_1 = |M_1| e^{i\phi_1},\ \mu = |\mu| e^{i\phi_\mu},\ A_f = |A_f| e^{i\phi_f}$$

- Important influence on sparticle production and decay rates → Expect similar influence on <**σv**>

NB1: M_2 can also be complex, but its phase can be rotated away.

NB2: CPV phases are strongly constrained by dipole moments;

we set ϕ_μ=0 and assume very heavy 1st+2nd generation sfermions

CP violation: Higgs sector

- Non-zero phases induce CP violation in the Higgs sector through loops → mixing of h,H,A:

$$(\phi_1, \phi_2, a)^T_\alpha = O_{\alpha i}(H_1, H_2, H_3)^T_i \ ,$$

$$O^T \mathcal{M}^2_H O \ = \ \mathrm{diag}\,(M^2_{H_1}, M^2_{H_2}, M^2_{H_3}) \ \text{ with } \ M_{H_1} \ \le \ M_{H_2} \ \le \ M_{H_3}.$$

- Couplings to neutralinos:

$$\mathcal{L}_{H^0\tilde{\chi}^0\tilde{\chi}^0} = -\frac{g}{2}\sum_{i,j,k} H_k \overline{\tilde{\chi}^0_i}\left(g^S_{H_k\tilde{\chi}^0_i\tilde{\chi}^0_j} + i\gamma_5 g^P_{H_k\tilde{\chi}^0_i\tilde{\chi}^0_j}\right)\tilde{\chi}^0_j \ :$$

$$g^S_{H_k\tilde{\chi}^0_i\tilde{\chi}^0_j} = \frac{1}{2}\Re\mathrm{e}[(N^*_{j2} - t_W N^*_{j1})(N^*_{i3}G^{\phi_1}_k - N^*_{i4}G^{\phi_2}_k) + (i \leftrightarrow j)]$$

$$g^P_{H_k\tilde{\chi}^0_i\tilde{\chi}^0_j} = -\frac{1}{2}\Im\mathrm{m}[(N^*_{j2} - t_W N^*_{j1})(N^*_{i3}G^{\phi_1}_k - N^*_{i4}G^{\phi_2}_k) + (i \leftrightarrow j)]$$

$$G^{\phi_1}_k = (O_{\phi_1 k} - i s_\beta O_{ak}),\ G^{\phi_2}_k = (O_{\phi_2 k} - i c_\beta O_{ak})$$

Previous studies

of neutralino relic density with CP violation

- T. Nihei, "Suppression of the neutralino relic density with supersymmetric CP violation", hep-ph/0508285.
- M. E. Gomez, et al., "WMAP dark matter constraints and Yukawa unification in SUGRA models with CP phases", hep-ph/0506243.
- C. Balazs, et al., "The supersymmetric origin of matter", hep-ph/0412264.
- M. Argyrou, et al., "Partial wave treatment of supersymmetric dark matter in the presence of CP-violation", hep-ph/0404286.
- T. Nihei and M. Sasagawa, "Relic density and elastic scattering cross sections of the neutralino in the MSSM with CP-violating phases", hep-ph/0404100.
- P. Gondolo and K. Freese, "CP-violating effects in neutralino scattering and annihilation", hep-ph/9908390.

CPV with `micrOMEGAs`

- We have implemented the general MSSM Lagrangian with CP-violating phases in CALCHEP / micrOMEGAs*
- Higgs and sparticle masses and mixing matrices are computed with CPsuperH†
- Fully automatical calculation of the relic density
- All possible channels included !
- No EDM constraints yet

* micrOMEGAs: G. Bélanger et al., Comput. Phys. Commun. 149 (2002) 103, hep-ph/0112278.

† CPsuperH: J. S. Lee et al., Comput. Phys. Commun. 156 (2004) 283, hep-ph/0307377. NB: Thanks to JSL for helpful discussions!

First results

$M_1 = 150$, $M_2 = 300$, $A_t = 1200$ GeV, $\tan\beta = 5$

masses of 3rd gen: 500 GeV, 1st+2nd gen: 10 TeV

- bino-like LSP, m ~ 150 GeV
- $\Omega h^2 < 0.129$ needs annihilation through Higgs

- Scenario 1: $\mu = 500$ GeV → small mixing in Higgs sector
- Scenario 2: $\mu = 1$ TeV → large mixing in Higgs sector

Higgs mixing ~ $\mathbf{Im}(A_t\mu)$

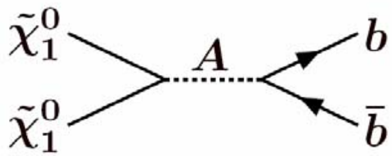
Scenario 1

$M_1 = 150$ GeV, $M_2 = 300$ GeV, $\mu = 500$ GeV, $\tan\beta = 5$

$m_{H^+} = 340$ GeV, $M_{Q_3,U_3,D_3} = 500$ GeV, $A_t = 1200$ GeV

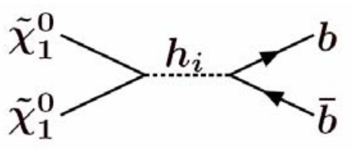
```
Masses of SuperParticles:
~o1 : MNE1   =   147.0
~1+ : MC1    =   282.2
~o2 : MNE2   =   282.7
~t1 : MSt1   =   317.8
~b1 : MSb1   =   497.9
~o3 : MNE3   =   503.4
....

Dark Matter candidate is ~o1
Omega=1.10E-01
```

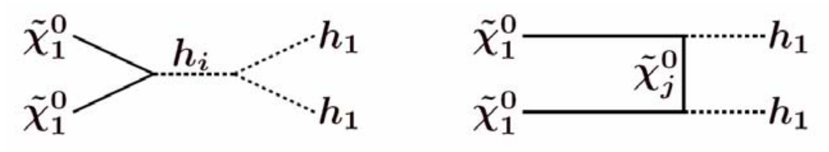
```
Masses of Higgs:
mh1 = 117.94 GeV
mh2 = 331.45 GeV
mh3 = 332.27 GeV
```

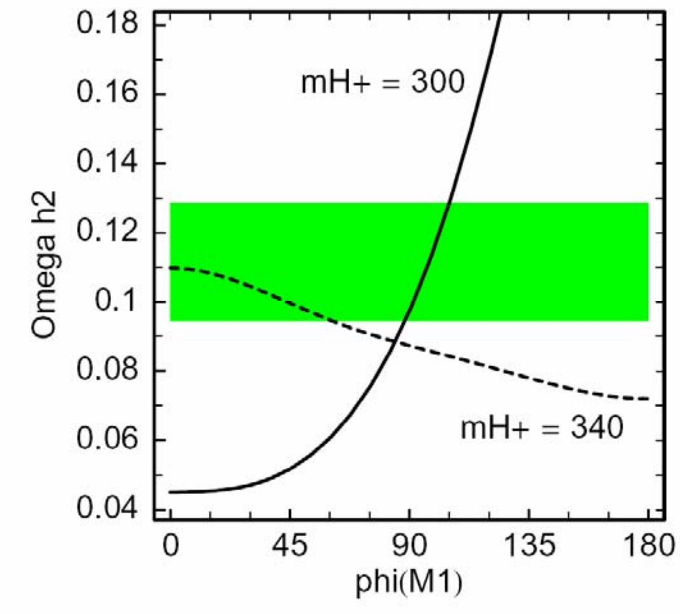


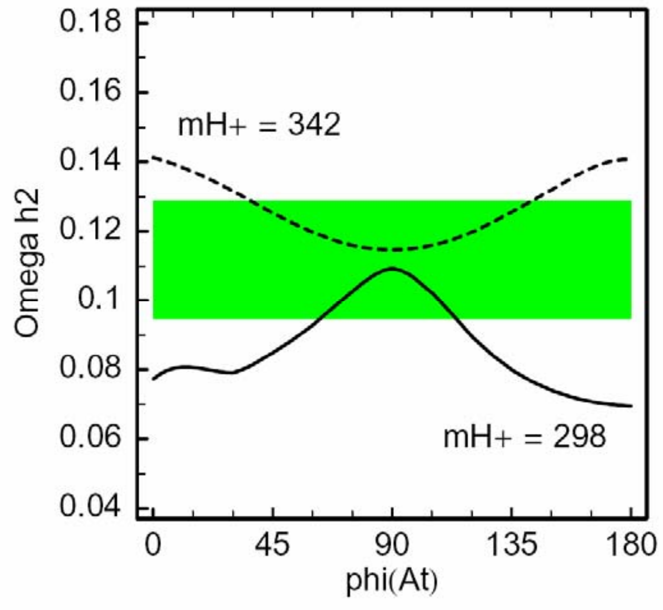
```
all phases zero
-----------------------
Omega=1.10E-01
   4% ~o1 ~o1 -> h1 h1
   6% ~o1 ~o1 -> Z h1
  78% ~o1 ~o1 -> b B
  10% ~o1 ~o1 -> l L
   1% ~o1 ~o1 -> W+ W-
```

```
phase(M1) = 90 deg
-----------------------
Omega=8.73E-02
 34% ~o1 ~o1 -> h1 h1
  1% ~o1 ~o1 -> Z h1
 46% ~o1 ~o1 -> b B
  6% ~o1 ~o1 -> l L
  9% ~o1 ~o1 -> W+ W-
  4% ~o1 ~o1 -> Z Z
```



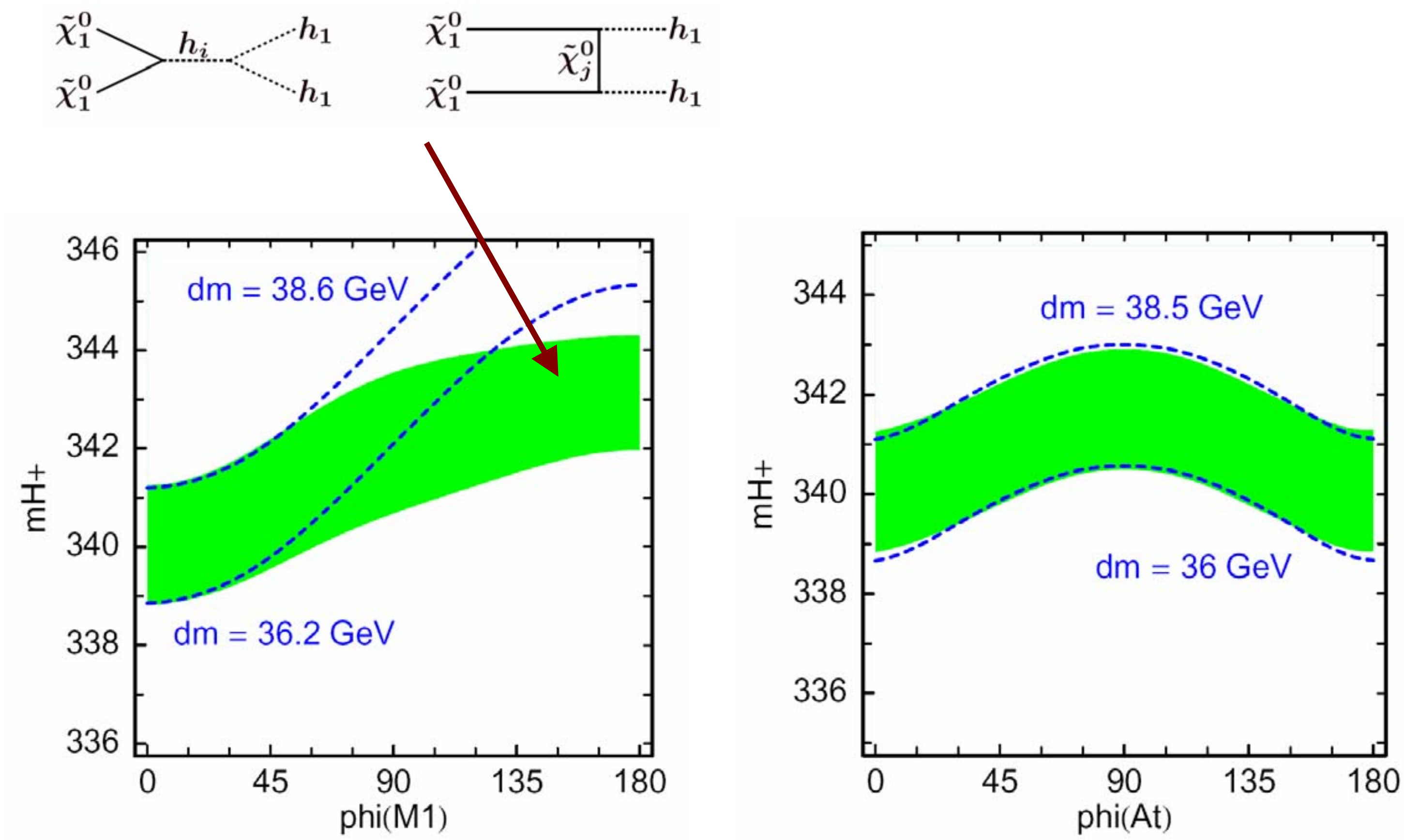






- Large changes with ϕ_1
- Orders of magn. dep. on m_{H+}
- Much of this due to change in m_{LSP}

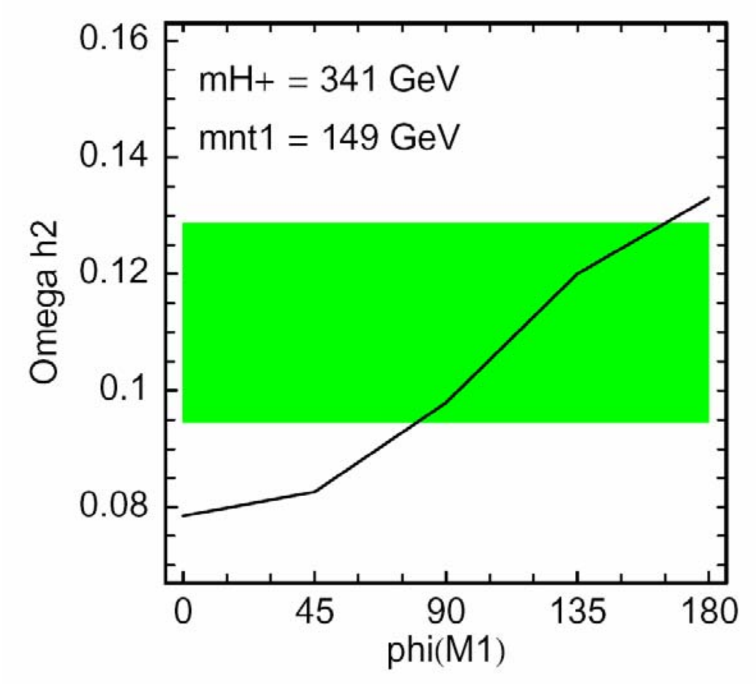
- h_2 is mostly pseudoscalar
- Max 8% HA mixing due to ϕ_t
- Mainly kinematic effect



Green bands: $0.94 < \Omega h^2 < 0.129$

$$\mathrm{dm} = m_{h_2} - 2m_{\tilde{\chi}_1^0}$$

Keeping LSP and Higgs masses fixed



$$\Delta(\Omega h^2) \sim 50\%$$

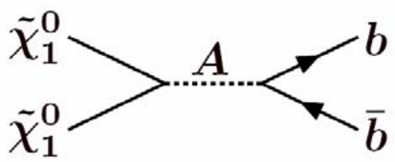
Scenario 2

$$M_1 = 150\ \text{GeV},\ M_2 = 300\ \text{GeV},\ \mu = 1\ \text{TeV},\ \tan\beta = 5$$

$$m_{H^+} = 334\ \text{GeV},\ M_{Q_3,U_3,D_3} = 500\ \text{GeV},\ A_t = 1200\ \text{GeV}$$

```
Masses of SuperParticles:
~o1 : MNE1  =   149.0
~1+ : MC1   =   295.2
~o2 : MNE2  =   295.2
~t1 : MSt1  =   342.0
~b1 : MSb1  =   491.7
~o3 : MNE3  =  1002.0
....

Masses of Higgs:
mh1 = 116.83 GeV
mh2 = 324.36 GeV
mh3 = 326.23 GeV
```

Smaller mass difference needed




```
Dark Matter candidate is ~o1
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```
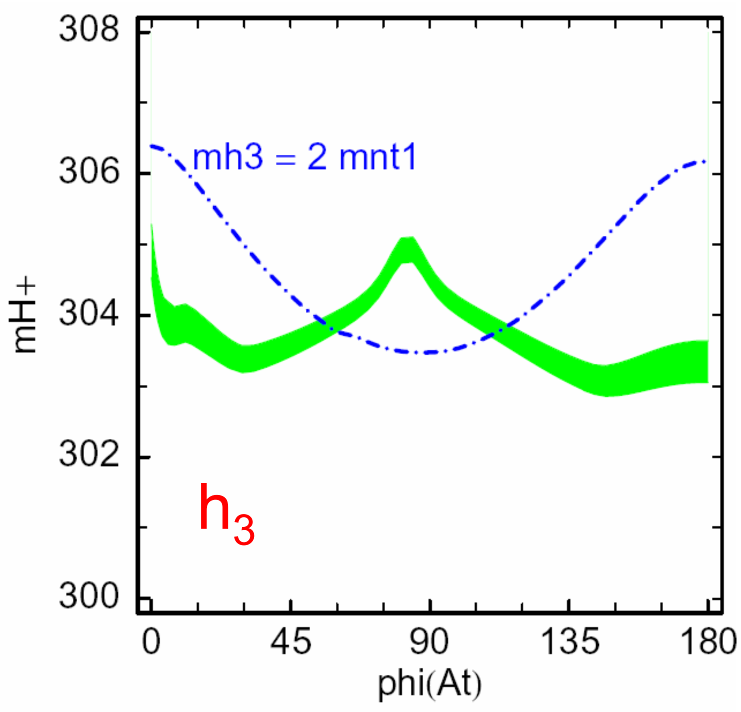
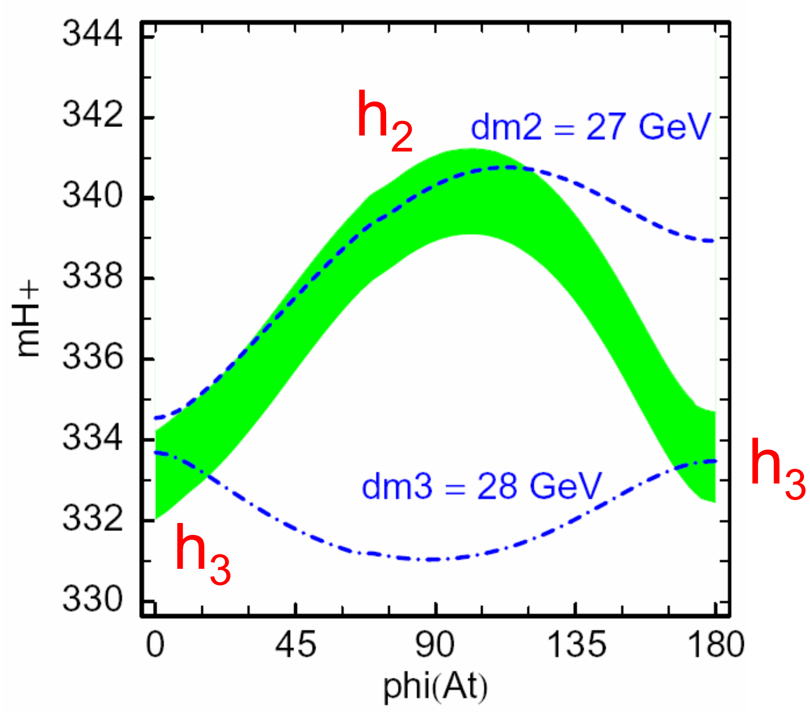

Large Higgs mixing due to ϕ_t

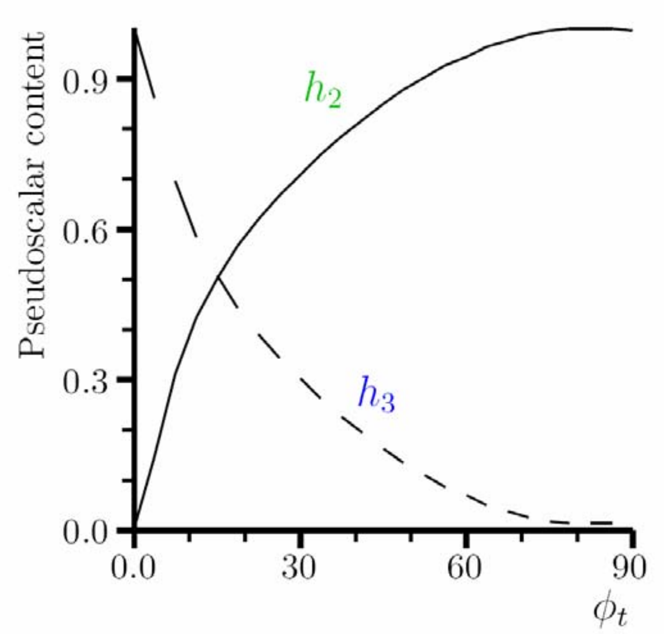


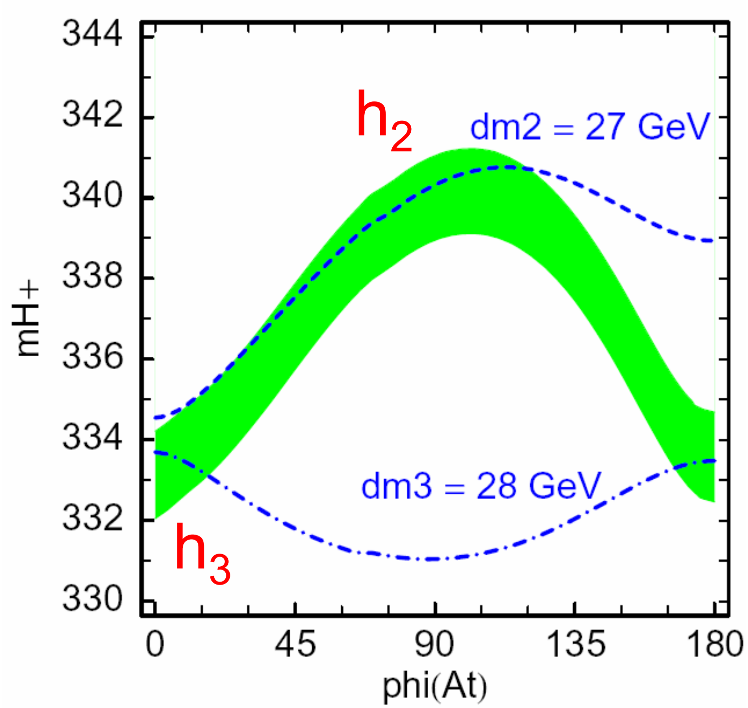


Green bands: $0.94 < \Omega h^2 < 0.129$

$dmi = m_{hi} - 2m_{LSP}$, $i=2,3$

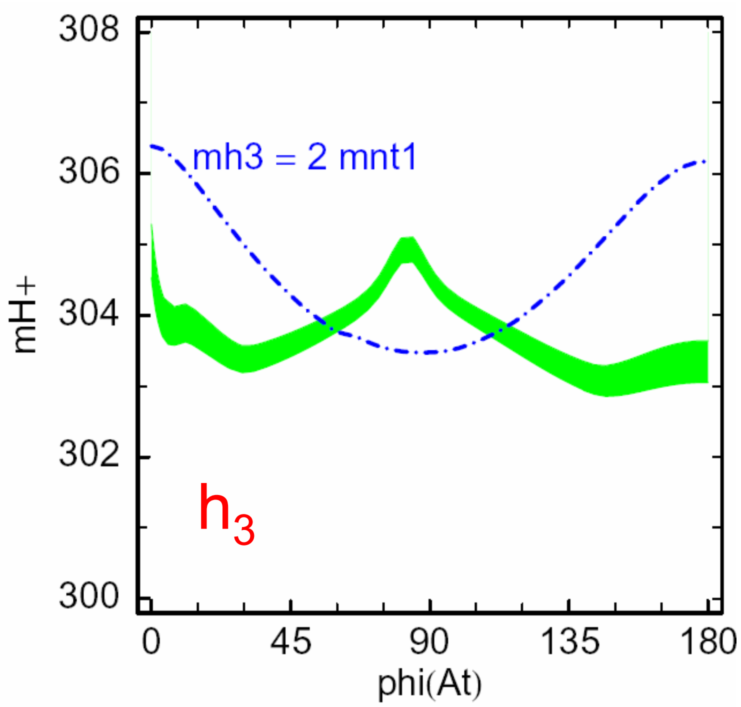
Large Higgs mixing with ϕ_t

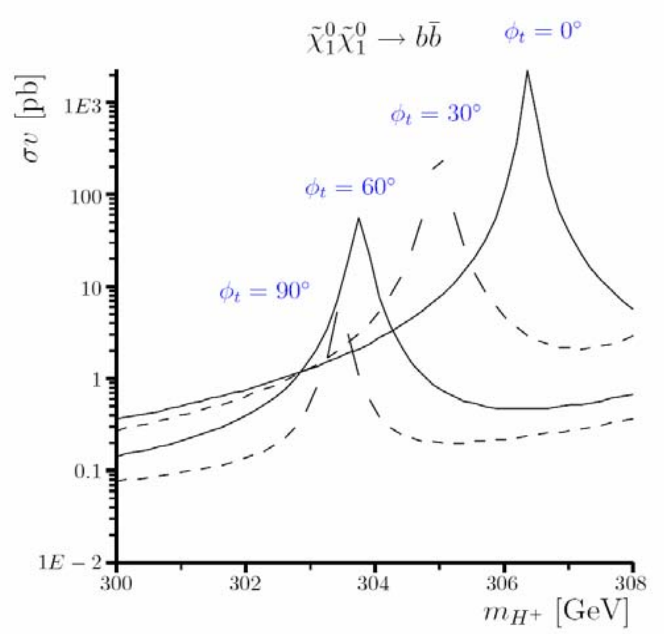




Green bands: $0.94 < \Omega h^2 < 0.129$

Large Higgs mixing due to ϕ_t





Order of magnitude effect on Ωh^2 for constant mass difference

Conclusions

- CPV in the MSSM is a very interesting option
- Important effects for collider phenomenology, in particular for Higgs physics
- Equally important influence for cosmology
- Discussed the neutralino relic density with CPV
  - Need to disentangle effects on kinematics and couplignss
  - Annihilation through Higgs → up to an order of magnitude change in Ωh^2 due to CP phases

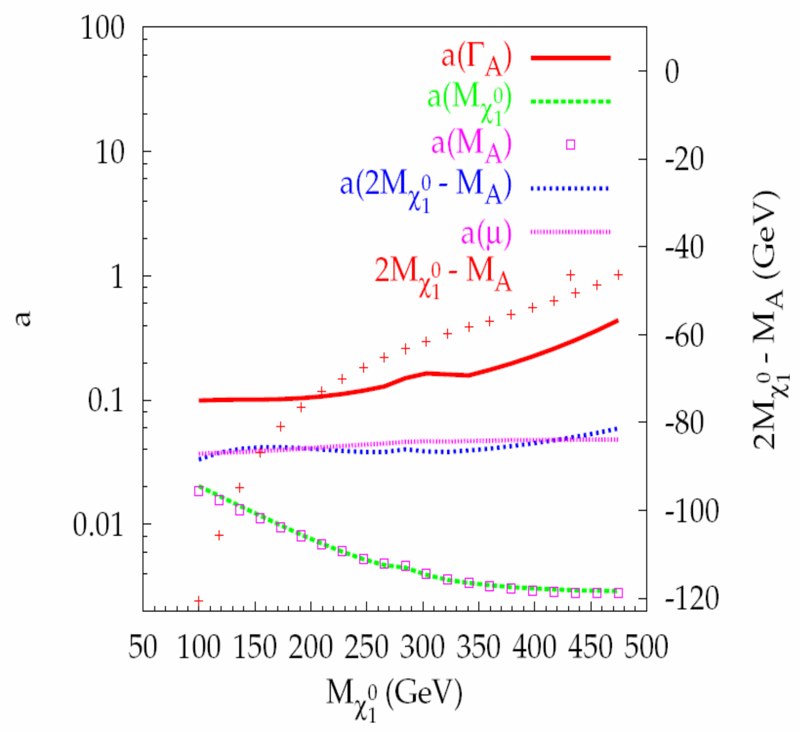
What do we need to measure with which precision: Annihilation through Higgs

- Mainly $\chi\chi \to A \to bb$
- CP even H exchange is P-wave suppressed
- m_χ and m_A to 2%-2‰
- (m_A-2m_χ) and μ to 5%
- A width to 10%

$g(A\chi\chi) \sim N_{13}^2 - N_{14}^2$, $g(Abb) \sim h_b$, ...

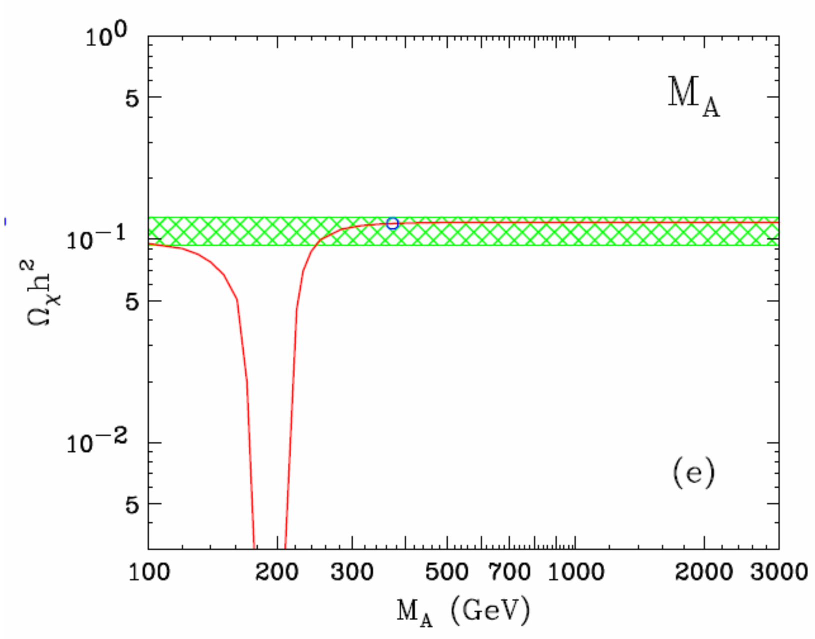
$$< \sigma v >^{-1}_{v=0} \propto \frac{4 m_{\tilde\chi_1^0} \Gamma_A}{g^2_{\tilde\chi_1^0 \tilde\chi_1^0 A}} \left(4 \left(\frac{M_A - 2m_{\tilde\chi_1^0}}{\Gamma_A} \right)^2 + 1 \right)$$

Fractional accuracies needed



[Allanach et al, hep-ph/0410091]

Influence of m_A on evaluation of Ωh^2



→ large uncertainty if lower limit on m_A is not >> 2 m_{LSP}

[Birkedal et al, hep-ph/0507214]

mSUGRA parameter space

- GUT-scale boundary conditions: m_0, $m_{1/2}$, A_0
- 4 regions with good Ωh^2
  - bulk (excl. by m_h from LEP)
  - co-annihilation
  - Higgs funnel ($\tan\beta \sim 50$)
  - focus point (higgsino scenario)