Neutralino relic density with CP violation

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in collaboration with

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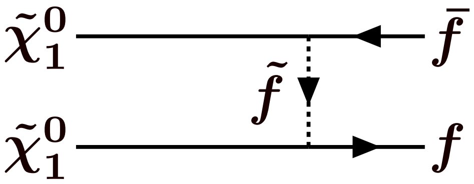
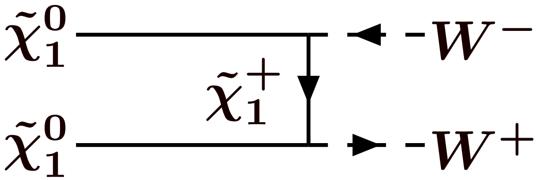
Neutralino relic density

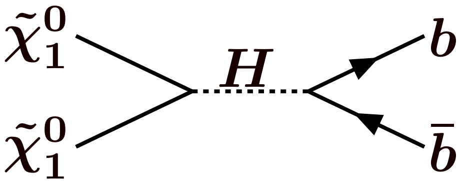
The typical O(100 GeV) WIMP has a too large relic density.
→ need specific mechanism for efficient annihilation!



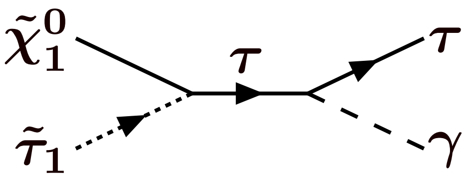
bino LSP, bulk region
light $\tilde{\chi}_1^0$ and $\tilde{f}$



LSP with strong
higgsino component



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



Co-annihilation
LSP–NLSP mass difference

CPV phases

- MSSM -ino masses and trilinear couplings can be complex:

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

CPV phases

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- Sparticle production and decay rates depend on phases.
$\longrightarrow$ Expect important influence also on $\langle \sigma v \rangle$

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- Caution: also the masses depend on the phases!
  $\longrightarrow$ Need to disentangle effects in kinematics and couplings

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- For example, $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \to H \to \ldots$ does not occur at $v = 0$ if H is a pure scalar.

  Non-zero phases can give the H some pseudoscalar component (loop-induced CPV in Higgs sector).

  However, they also change the Higgs masses, and Ωh^2 is very sensitive to $\Delta m_{\tilde{\chi}^0 H} = m_H - 2m_{\tilde{\chi}^0_1}$.

Previous studies

of neutralino relic density with CPV

- 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.

micrOMEGAs $\in$ CPV

- 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!

RESULTS

(FOR ANNIHILATION THROUGH HIGGS)

Scenario 1:

$$M_1 = 150\ \mathrm{GeV},\ M_2 = 300\ \mathrm{GeV},\ \mu = 500\ \mathrm{GeV}$$

(bino-like LSP, annihilation through Higgs, small Higgs mixing)

Scenario 1

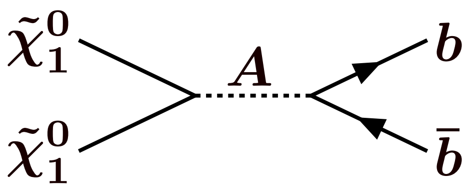
$$M_1 = 150 \text{ GeV}, \; M_2 = 300 \text{ GeV}, \; \mu = 500 \text{ GeV}, \; \tan\beta = 5$$

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

```
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
....
```

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

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



Scenario 1

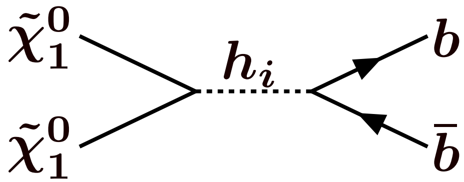
$$M_1 = 150 \text{ GeV},\ M_2 = 300 \text{ GeV},\ \mu = 500 \text{ GeV},\ \tan\beta = 5$$

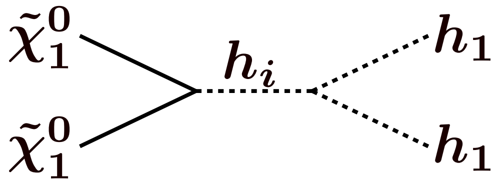
$$m_{H^+} = 340 \text{ GeV},\ M_{Q_3,U_3,D_3} = 500 \text{ GeV},\ A_t = 1200 \text{ GeV}$$

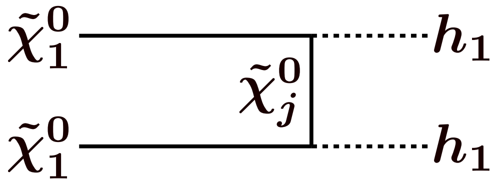
```
all phases zero
----------------------
Omega=1.10E-01
  4% ~o1 ~o1 -> h1 h1
  6% ~o1 ~o1 -> Z h1
 78% ~o1 ~o1 -> b B
 10% ~o1 ~o1 -> l L
  1% ~o1 ~o1 -> W+ W-
```

```
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
```

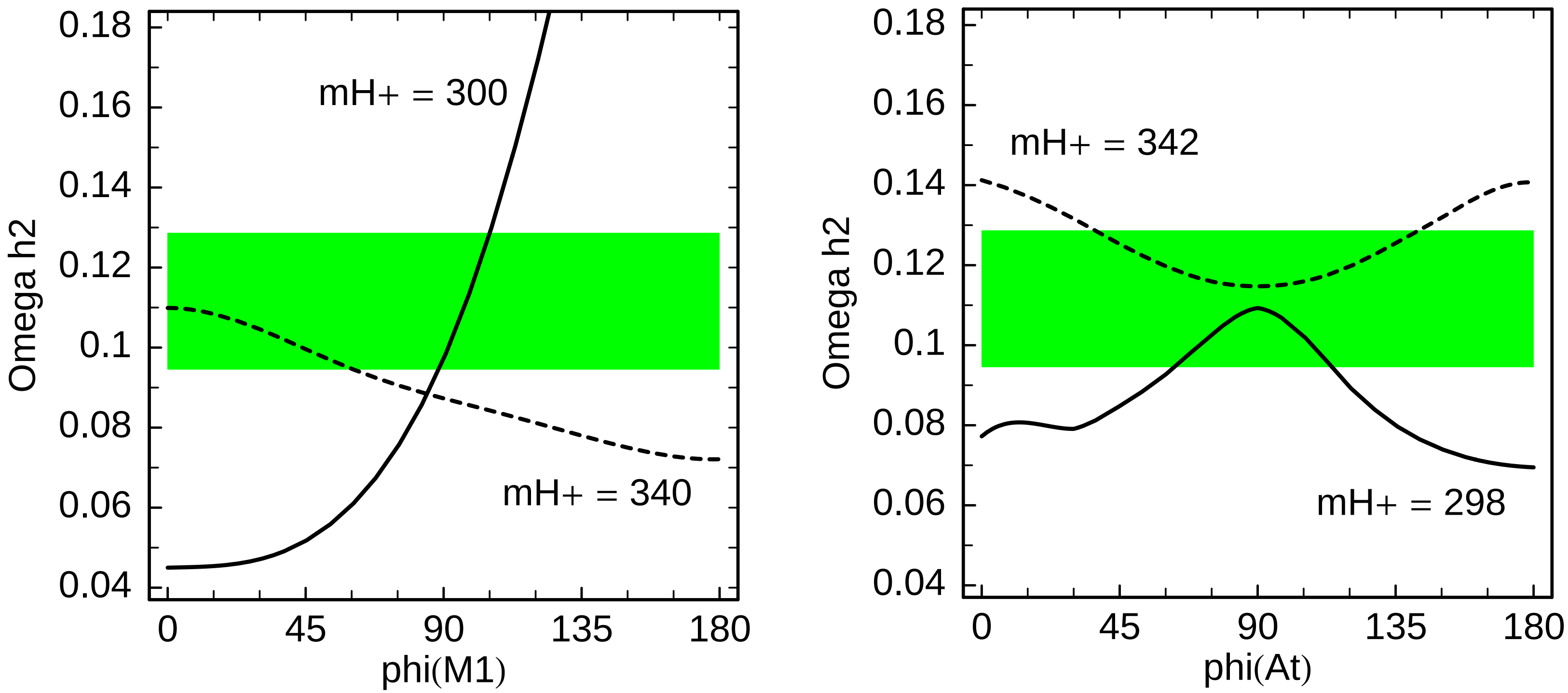
Scenario 1


$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
h_i
b
$\bar{b}$


$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
h_i
h_1
h_1


$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_j^0$
h_1
h_1

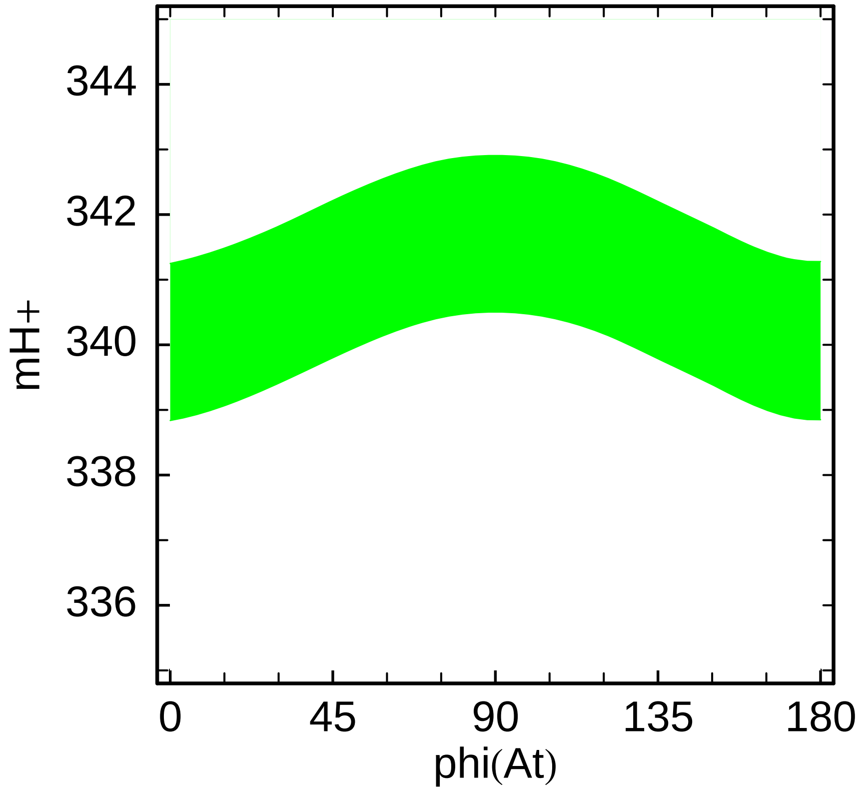
Scenario 1



However, also the masses change with the phases ....

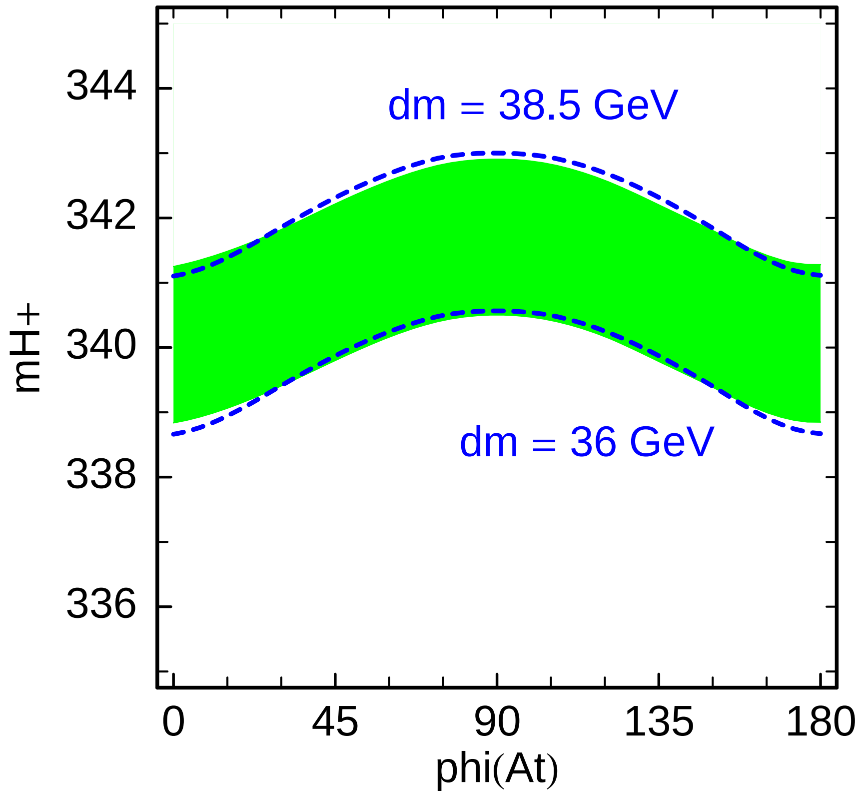
Scenario 1

WMAP-allowed band in the $(m_{H^+},\ \phi_t)$ plane



Scenario 1

WMAP-allowed band in the (m_{H^+}, ϕ_t) plane

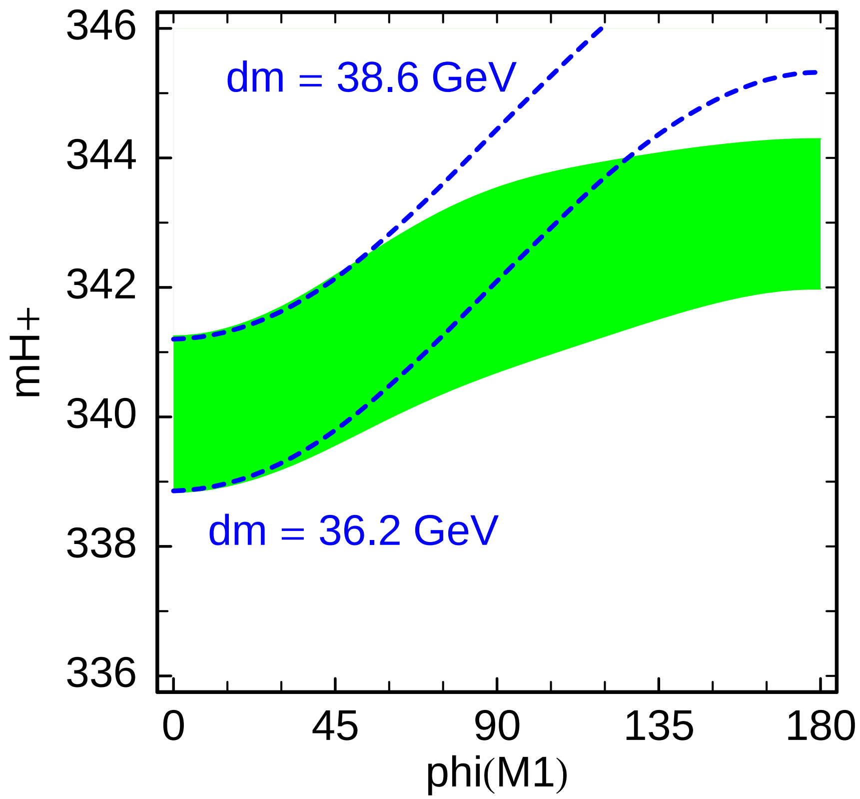


$$\mathbf{dm} = m_{h_2} - 2m_{\tilde{\chi}_1^0}$$

$\longrightarrow$ dependence on ϕ_t is mainly a kinematic effect

Scenario 1

WMAP-allowed band in the $(m_{H^+},\ \phi_1)$ plane

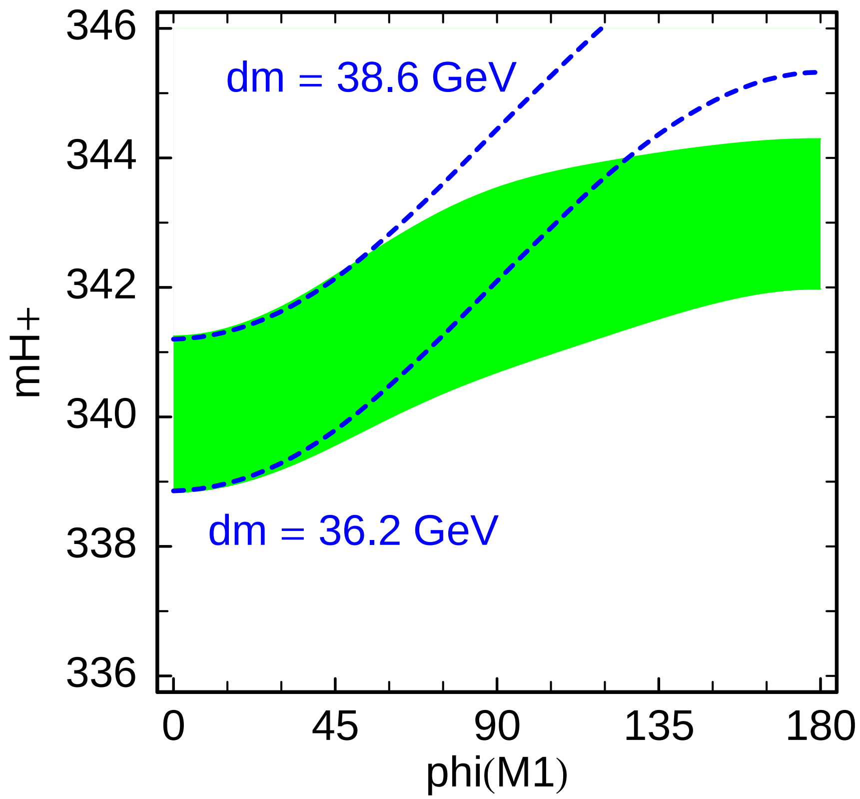


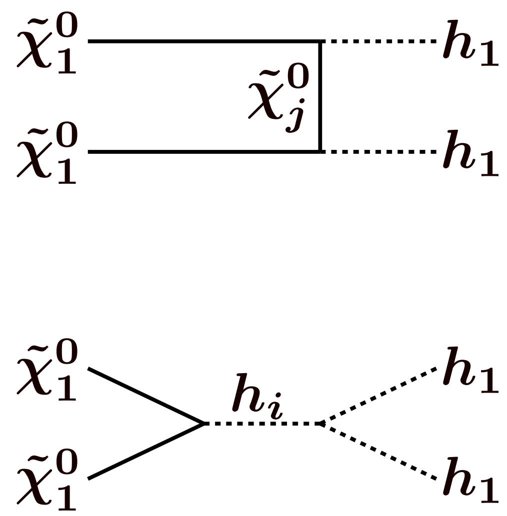
$$\mathbf{dm} = m_{h_2} - 2m_{\tilde{\chi}_1^0}$$

$\longrightarrow$ dependence on ϕ_1 is due to kinematics + couplings

Scenario 1

WMAP-allowed band in the $(m_{H^+},\ \phi_1)$ plane



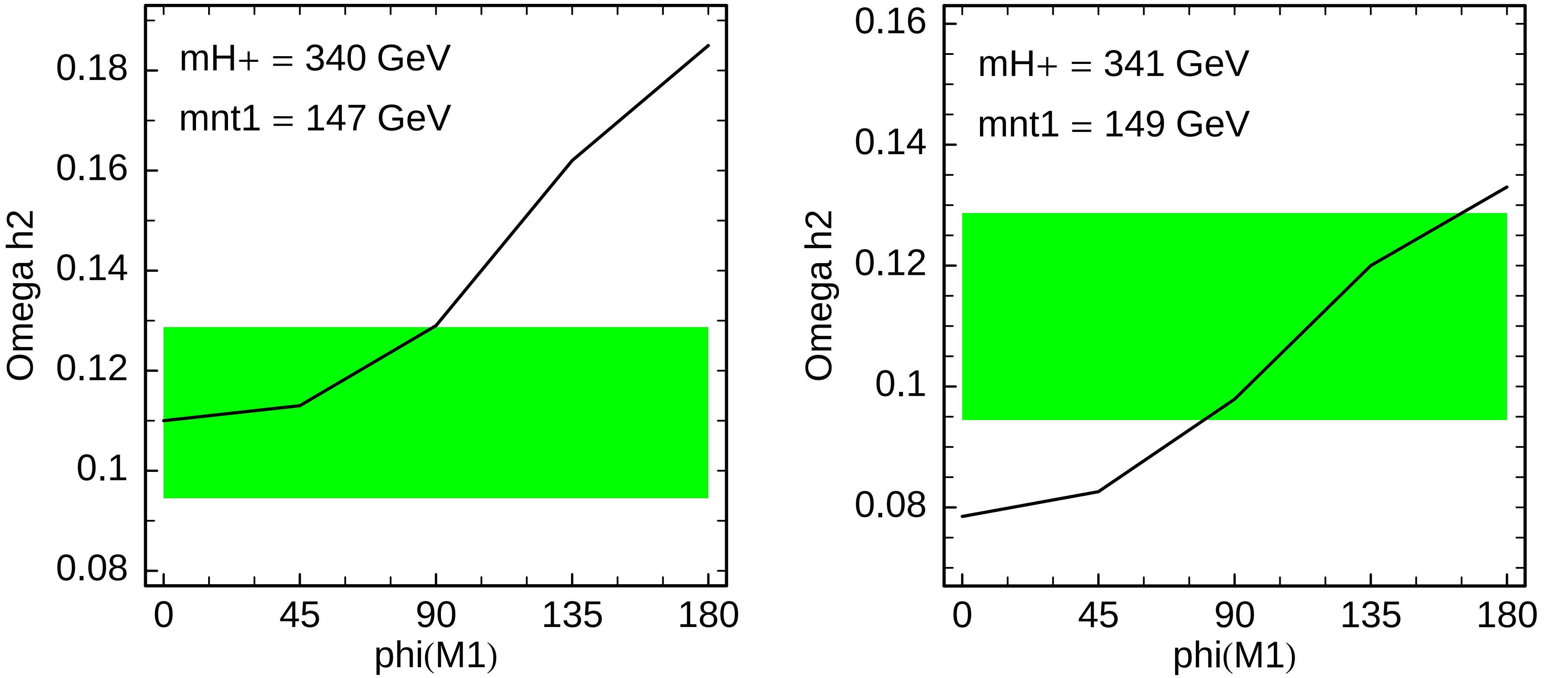


$$\mathbf{dm} = m_{h_2} - 2m_{\tilde{\chi}_1^0}$$

$\longrightarrow$ dependence on ϕ_1 is due to kinematics + couplings

Scenario 1

Keep LSP mass fixed by adjusting M_1



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

Scenario 2:

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

(bino-like LSP, annihilation through Higgs, LARGE Higgs mixing)

Scenario 2

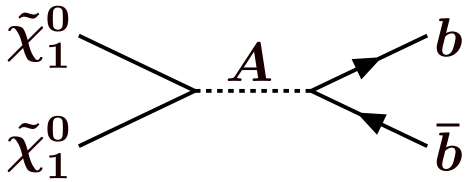
$$M_1 = 150 \text{ GeV}, \ M_2 = 300 \text{ GeV}, \ \mu = 1 \text{ TeV}, \ \tan\beta = 5$$

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

```
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
....
```

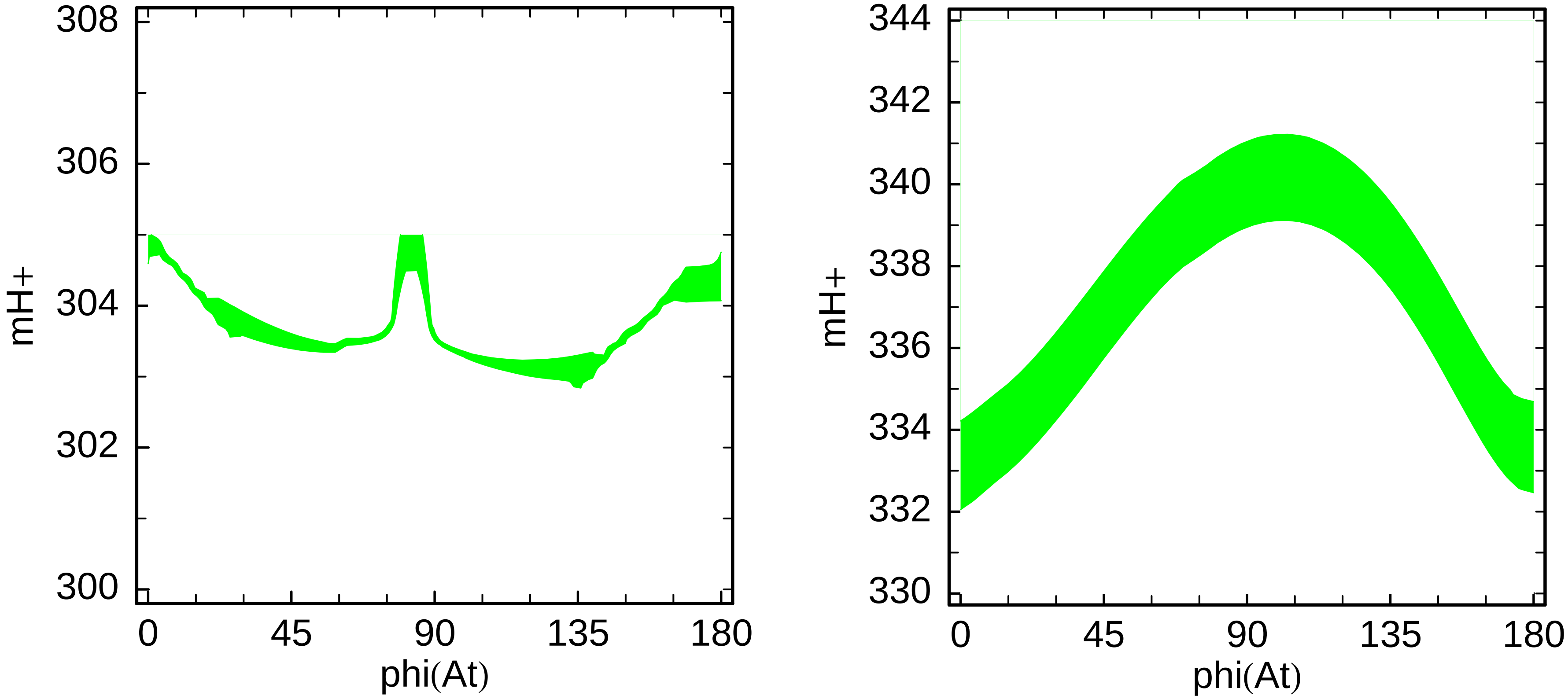
```
Masses of Higgs:
mh1 = 116.83 GeV
mh2 = 324.36 GeV
mh3 = 326.23 GeV
```

```
Dark Matter candidate is ~o1
Omega=1.25E-01
```



Scenario 2

2 WMAP-allowed bands in the $(m_{H^+},\ \phi_t)$ plane



Scenario 2

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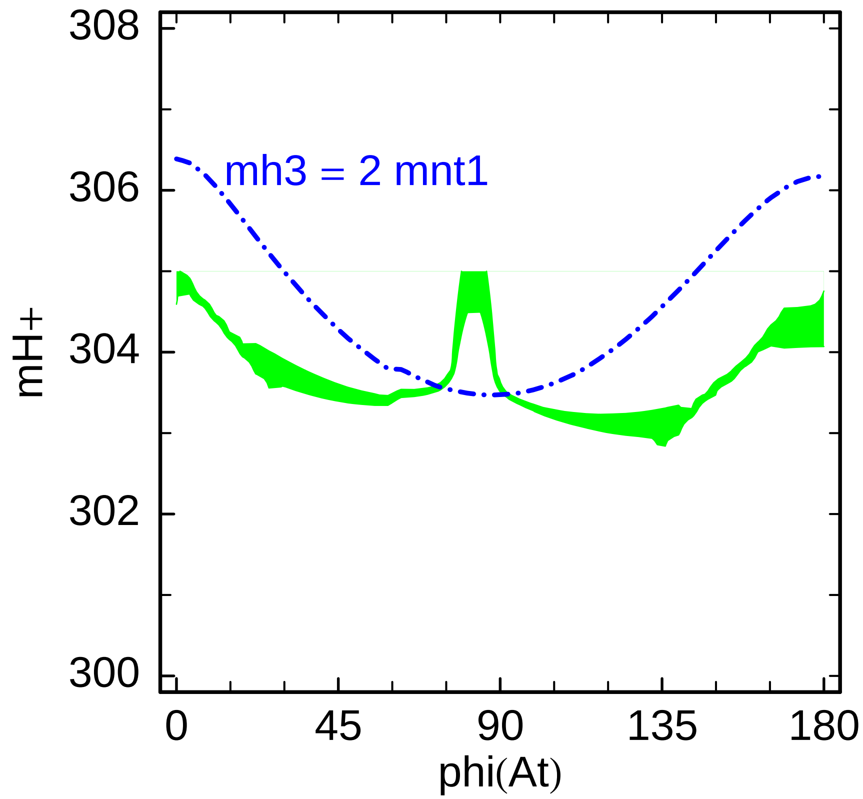
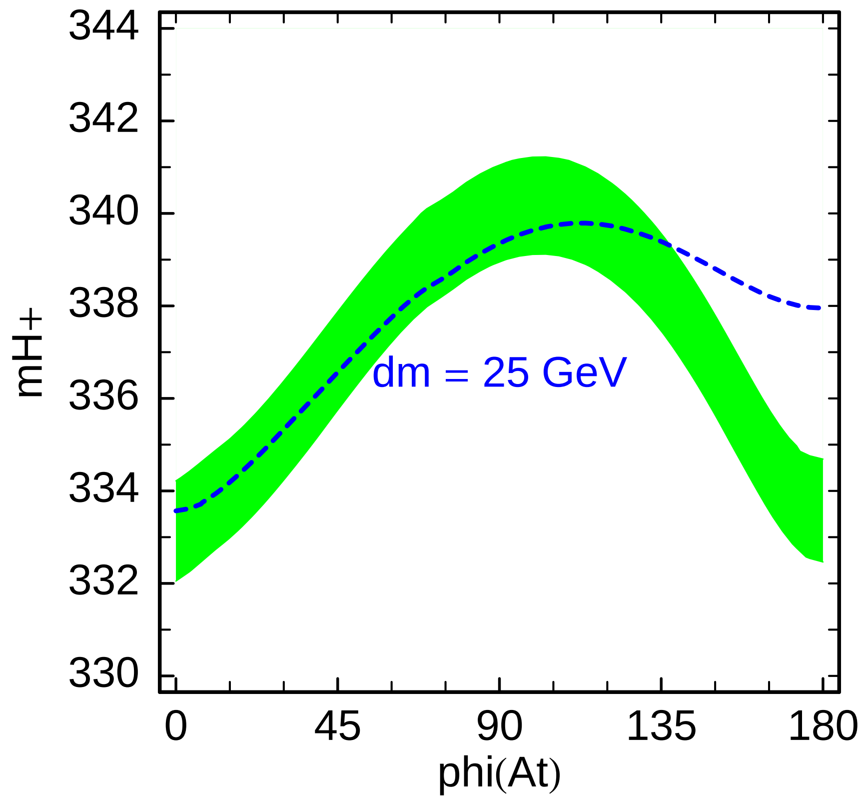
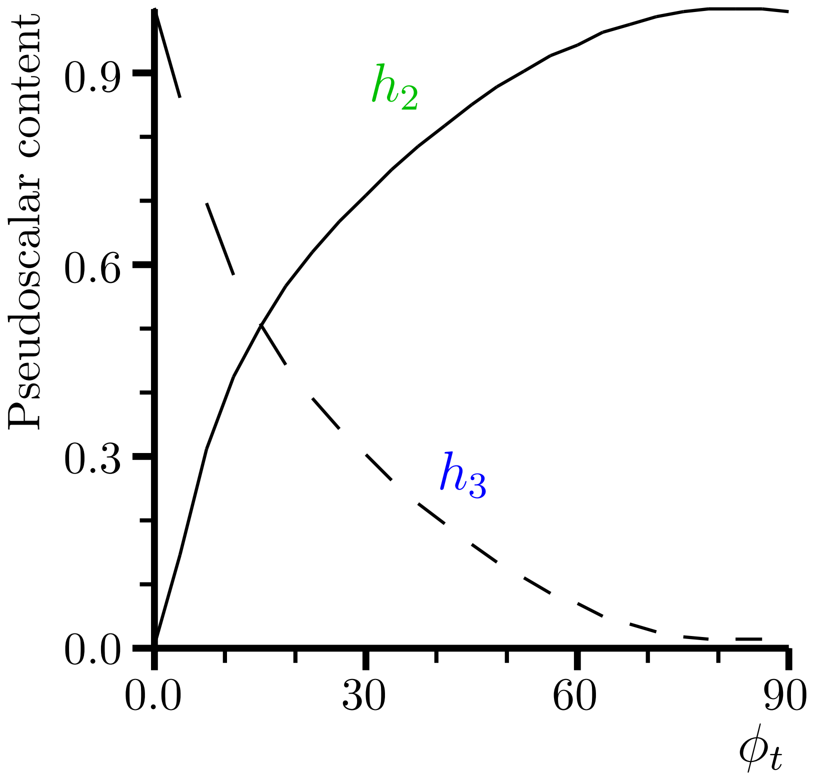




$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_{3,2} \to b\bar{b},\ h_1 h_1$

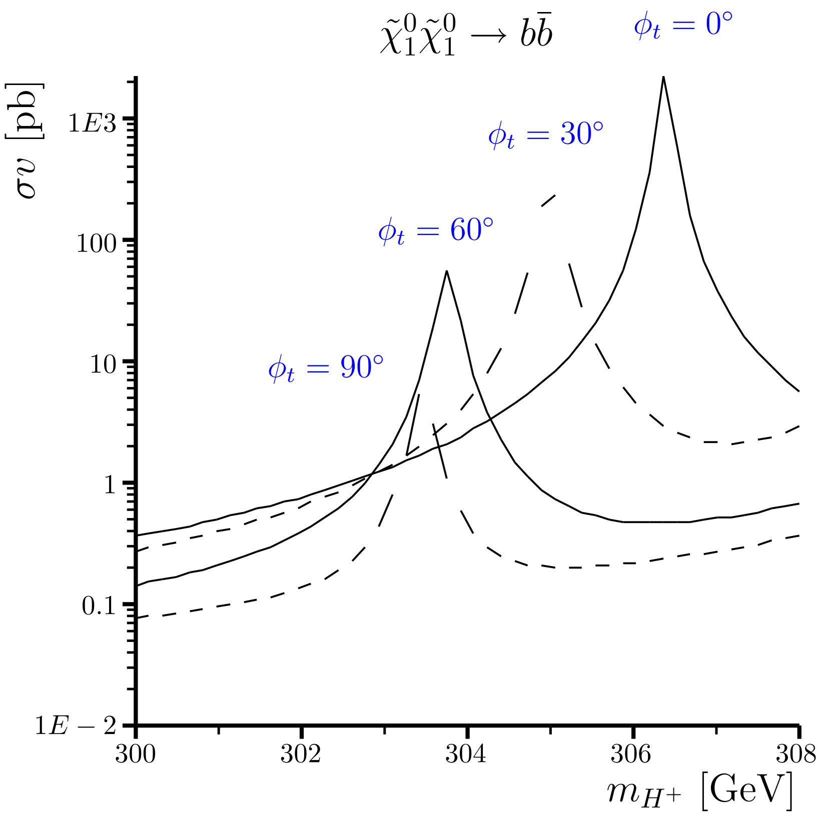
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_2 \to b\bar{b},\ (h_1 h_1)$

Scenario 2



Scenario 2

$m_{H^+} \sim 304$ GeV



Not only position but also height of the peak depends on ϕ_t.

Scenario 2

ϕ_t	$0°$	$15°$	$90°$
m_{H^+}	305.0	304.1	303.6
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_1h_1$		7%	31%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Zh_1$	10%	8%	1%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}$	80%	74%	52%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau\tau$	10%	9%	7%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to WW$		1%	6%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ZZ$			3%
pseudoscalar	h_3	50:50	h_2
Ωh^2	0.107	0.103	0.102

As ϕ_t increases, exchange of h_2 (s-channel) and $\tilde{\chi}^0$, $\tilde{\chi}^\pm$ (t-channel) becomes more important.

Other scenarios

- We are systematically investigating different scenarios:

  bino, wino, higgsino LSP; mixed gaugino-higgsino scenario; co-annihilation with stops or staus; large $\tan\beta$, etc.

- Interesting phase dependences, especially if interferences of several processes occur

Conclusions

- We have implemented the CPV-MSSM in `micrOMEGAs 2.0`
  - Masses and mixing matrices computed with `CPsuperH`
  - All channels contributing to Ωh^2 automatically included
- At this workshop, I have presented results for neutralino annhilation through s-channel Higgs exchange.
- CPV phases can have large effect; interesting dependences especially if interferences of several processes occur.
- Non-trivial to disentangle effects on masses and couplings.
- Systematic analysis of different annihilation and co-annihilation scenarios is in progress.
- Need to include contraints from EDMs, etc..
- Caution: loop corrections may be equally important....