

The relic density *of heavy neutralinos*

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last week on the arXiv:1601.04718

RPP16, LAPTh
25th January 2016

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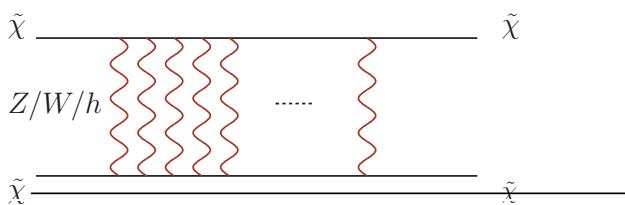
Relic density of heavy neutralinos

The Sommerfeld enhancement (Hisano et al. 2004,6, Arkani-Hamed et al. 2008)

- Heavier neutralinos difficult to detect both at LHC and at ID/DD experiments, however situation can change if annihilation enhanced by the Sommerfeld effect
- The Sommerfeld effect may have a large effect on the annihilation rate of SU(2) charged neutralinos, already studied to a great extent¹
- Enhancement factor $S(v)$ for charged particle annihilation due to Coulomb potential if $v \lesssim \pi\alpha$ well known (Sommerfeld '31),

$$S(v) = \frac{\pi\alpha}{v} \frac{1}{1 - e^{-\pi\alpha/v}}$$

- Large corrections also occur in general if also mass of mediator (M_W) such that $M_W < \alpha M_{\tilde{\chi}} \Rightarrow$ Yukawa potential $V(r) = -\frac{\alpha}{r} e^{-M_W r}$

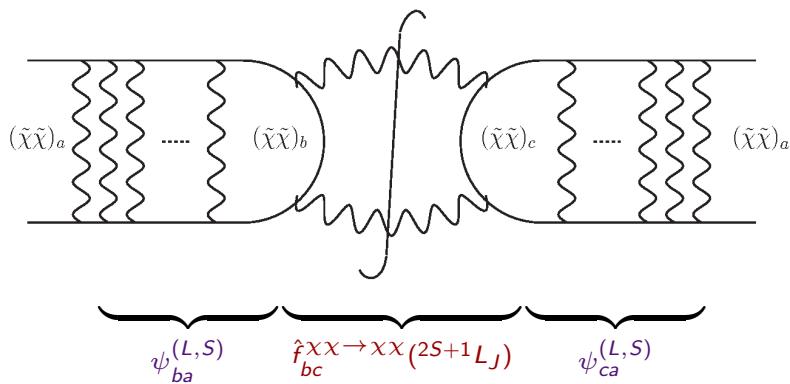


Aim: to calculate the relic density in general MSSM in wino-like region including the full effect of the Sommerfeld enhancement

¹ Cirelli et al. 2007,8,9, Hryczuk et al. 2010,14, Slatyer (et al) 2008,13,14, Fan et al 2013, Cabrera et al 2015

The Sommerfeld Enhancement

(Beneke, Hellmann, Ruiz-Femenia 2012,14, Hellmann, Ruiz-Femenia 2013)



$\hat{f}_{ab}(^{2S+1}L_J), \hat{g}_{ab}(^{2S+1}L_J)$:
absorptive part of Wilson
coefficients of local four-fermion
operators.
Sommerfeld factors computed by
solving Schrödinger eq. for
 $\psi_{ba}^{(L,S)}$ ² with leading-order
Yukawa/Coulomb potentials

$$\sigma^{(\chi\chi)_a \rightarrow \text{light}} v_{\text{rel}} = S_a[\hat{f}_h(^1S_0)] \hat{f}_{aa}(^1S_0) + S_a[\hat{f}_h(^3S_1)] 3 \hat{f}_{aa}(^3S_1) + \frac{\vec{p}_a^2}{M_a^2} \left(S_a[\hat{g}_\kappa(^1S_0)] \hat{g}_{aa}(^1S_0) \right. \\ \left. + S_a[\hat{g}_\kappa(^3S_1)] 3 \hat{g}_{aa}(^3S_1) + S_a \left[\frac{\hat{f}(^1P_1)}{M^2} \right] \hat{f}_{aa}(^1P_1) + S_a \left[\frac{\hat{f}(^3P_J)}{M^2} \right] \hat{f}_{aa}(^3P_J) \right) ,$$

Sommerfeld factors ($S_a[\hat{f}(^{2S+1}L_J)]$) given by:

$$S_a[\hat{f}(^{2S+1}L_J)] = \frac{\left[\psi_{ca}^{(L,S)} \right]^* \hat{f}_{bc}^{(\chi\chi \rightarrow \chi\chi)(2S+1L_J)} \psi_{ba}^{(L,S)}}{\hat{f}_{aa}^{(\chi\chi \rightarrow \chi\chi)(2S+1L_J)}} .$$

$\psi_{ba}^{(L,S)}$ is the $(\chi\chi)_b$ component of the scattering wavefunction for incoming state $(\chi\chi)_a$ with quantum nos. L, S evaluated for zero relative distance and normalized to the free scattering solution.

Details of the calculation

Based on Beneke, Hellmann, Ruiz-Femenia (2012,13,14):

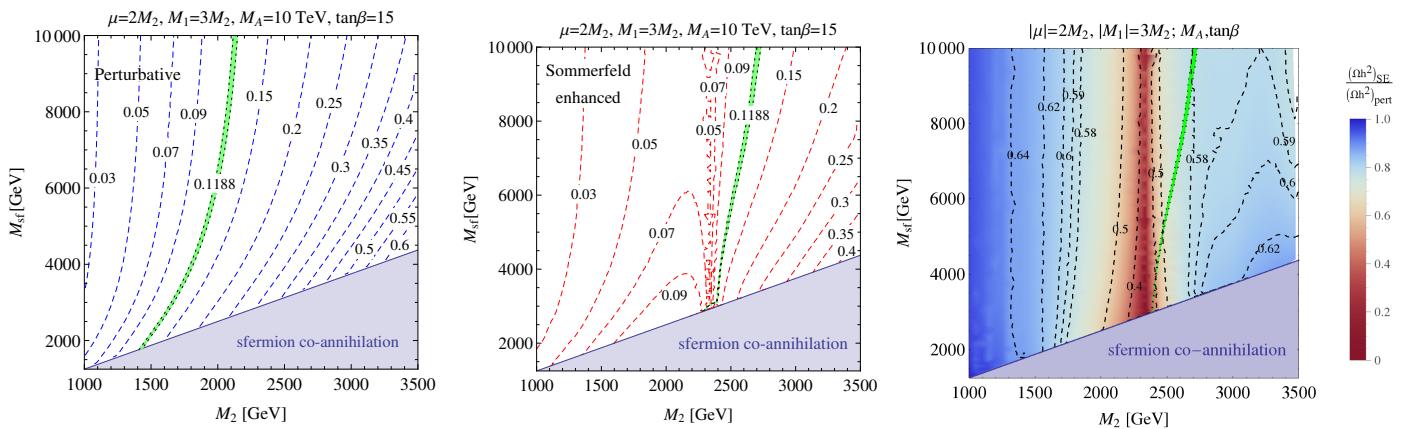
- **Mixed** neutralinos possible (beyond pure wino- or higgsino scenarios), including off-diagonals in potentials and annihilation matrices
- Partial wave separation for P- and $\mathcal{O}(v^2)$ S-wave (beyond leading order S-wave included)

In addition, the (to become public) code includes:

- Include **exp.constraints** on MSSM parameter space: $b \rightarrow s\gamma$, m_h , $(g - 2)_\mu$, ρ , DD and theoretical constraints on Higgs potential
- Include exact **1-loop on-shell mass splittings** and running couplings
- Allow extraction of separate exclusive final states to obtain **indirect detection** results
- Accuracy at $\mathcal{O}(\%)$, dominated by theoretical uncertainties due to EFT

Results

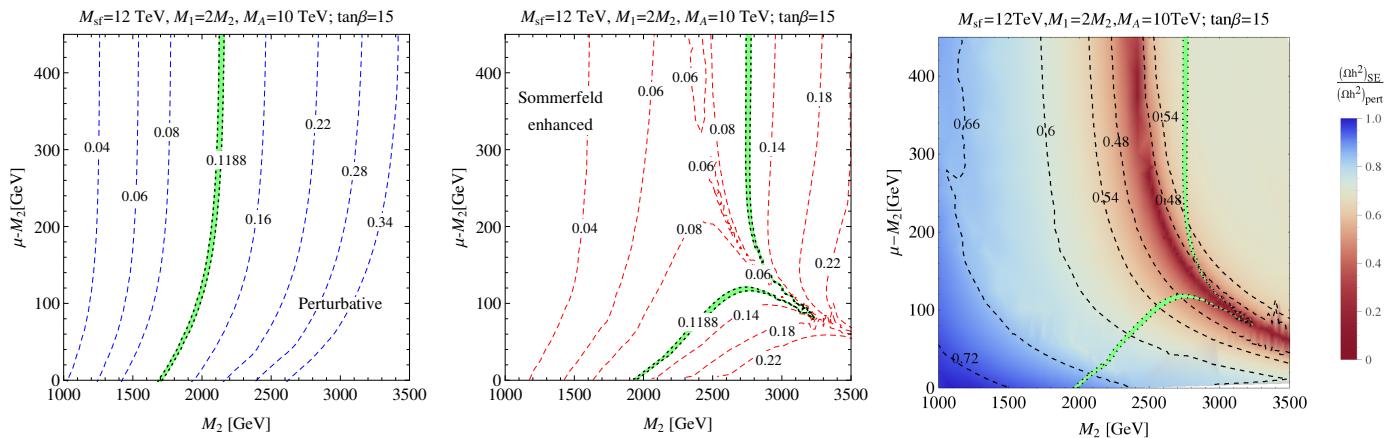
the pure wino with non-decoupled sfermions



- As the sfermion mass decreases the annihilation rate is suppressed due to t-channel interference and therefore the correct relic abundance is obtained for lighter neutralino masses of ~ 1400 GeV
- The correct relic density is moved from 1.5-2.1 TeV up to 2.4-2.7 TeV
- The resonance of the Sommerfeld effect is seen at around 2.4 TeV leading to the largest effects for the lightest sfermion masses

Results

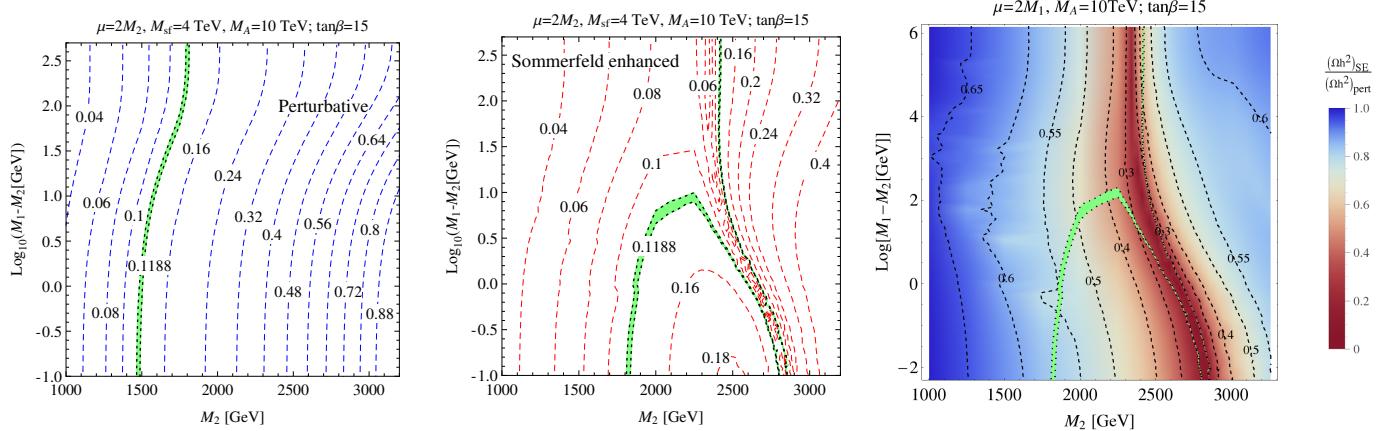
the wino-higgsino admixture



- As the Higgsinos annihilate less strongly, they dilute the wino annihilation
- The correct relic density is moved from 1.7-2.2 TeV up to 2-3.3 TeV
- The position of the resonance in the Sommerfeld effect is seen to be a function of μ , and largest effects are seen for $\mu - M_2 = 100$ GeV for the chosen parameters

Results

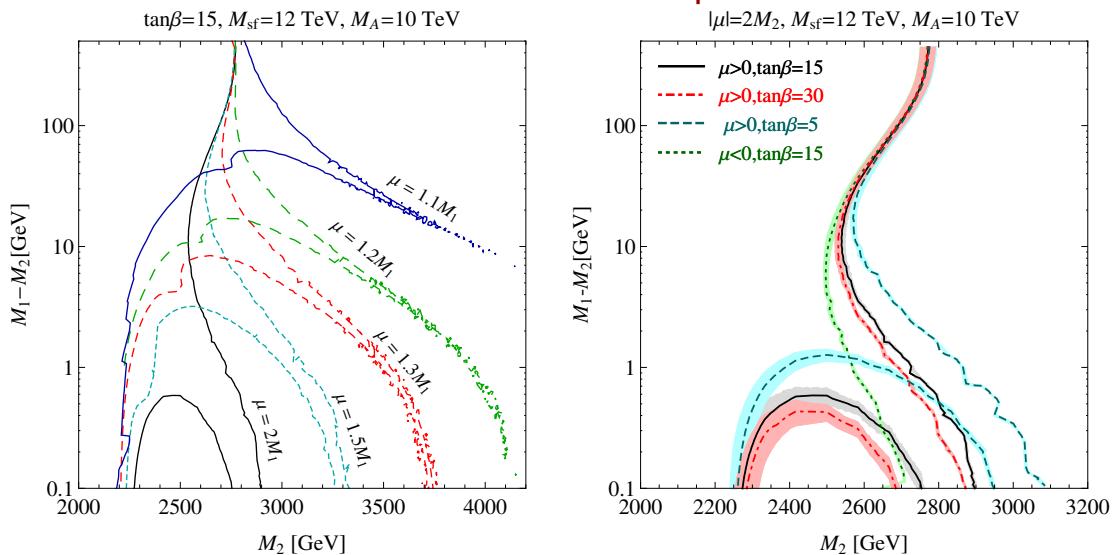
the wino-bino admixture



- The correct relic density is moved from 1.5-1.8 TeV up to 1.8-2.9 TeV
- The position of the resonance in the Sommerfeld effect is seen to be a function of M_1 , and largest effects are seen for smallest splittings between M_2 and M_1

Results

the wino-bino admixture-the affect of additional parameters



- The position of the resonance for bino-wino case is in fact strongly dependent on choice of parameters controlling mixing, i.e. μ , $\tan\beta$
- As the mixing is increased the effect is enhanced, i.e. when $|\mu|$ decreases, $\tan\beta$ decreases or when $\mu < 0$

Wino-like LSPs can give correct RD up to and beyond 4 TeV

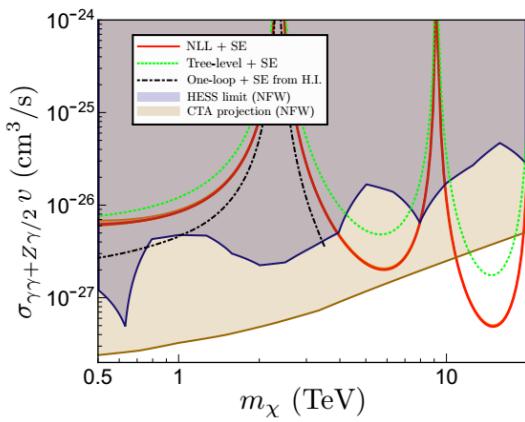
Summary

- Developed code and performed scan for relic density (RD) including the full Sommerfeld effect (SE) for wino-like region in general MSSM with accuracy $\mathcal{O}(\%)$ and running time $\mathcal{O}(\text{mins})$
- For the pure wino the effect is ~ 600 GeV but the sfermions alone can change value of M_2 giving the correct wino mass by several hundred GeV
- *For mixed wino-Higgsino scenarios:*
 - Correct relic density for M_2 from 1.75 TeV to 3.3 TeV, resonance depends on splitting and therefore mainly on $\mu - M_2$
- *For mixed wino-bino scenarios:*
 - M_2 1.8 TeV up to 2.9 TeV to satisfy RD constraint, resonance/splitting depend on $\tan \beta$ and μ .
 - Maximum possible LSP mass > 4 TeV for μ is small and positive and $\tan \beta$ is small.

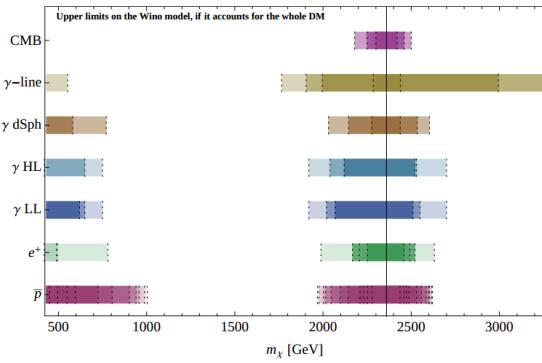
Outlook: Public code to become available with and indirect detection rates including full SE

Indirect detection

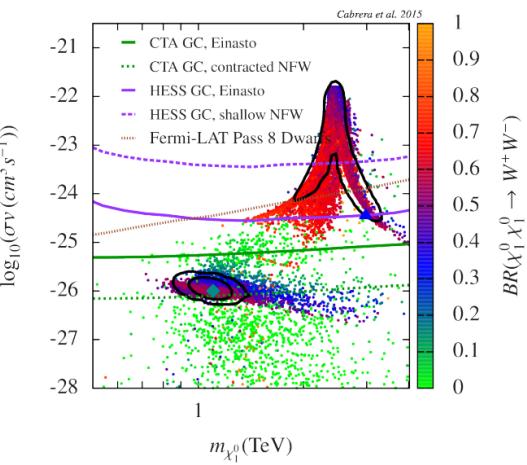
Limits on the wino and wino-like DM



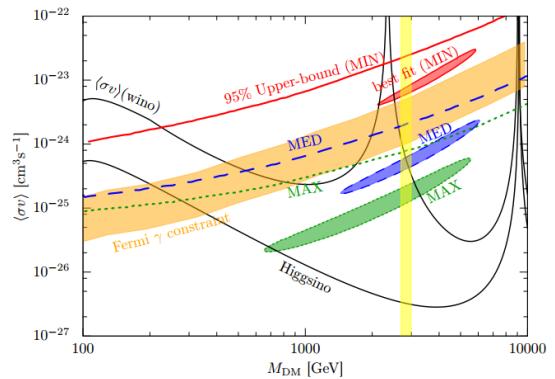
Ovanesyan, Slatyer, Stewart '14



Hryczuk, Cholis, Iengo, Tavakolie, Ullio '14

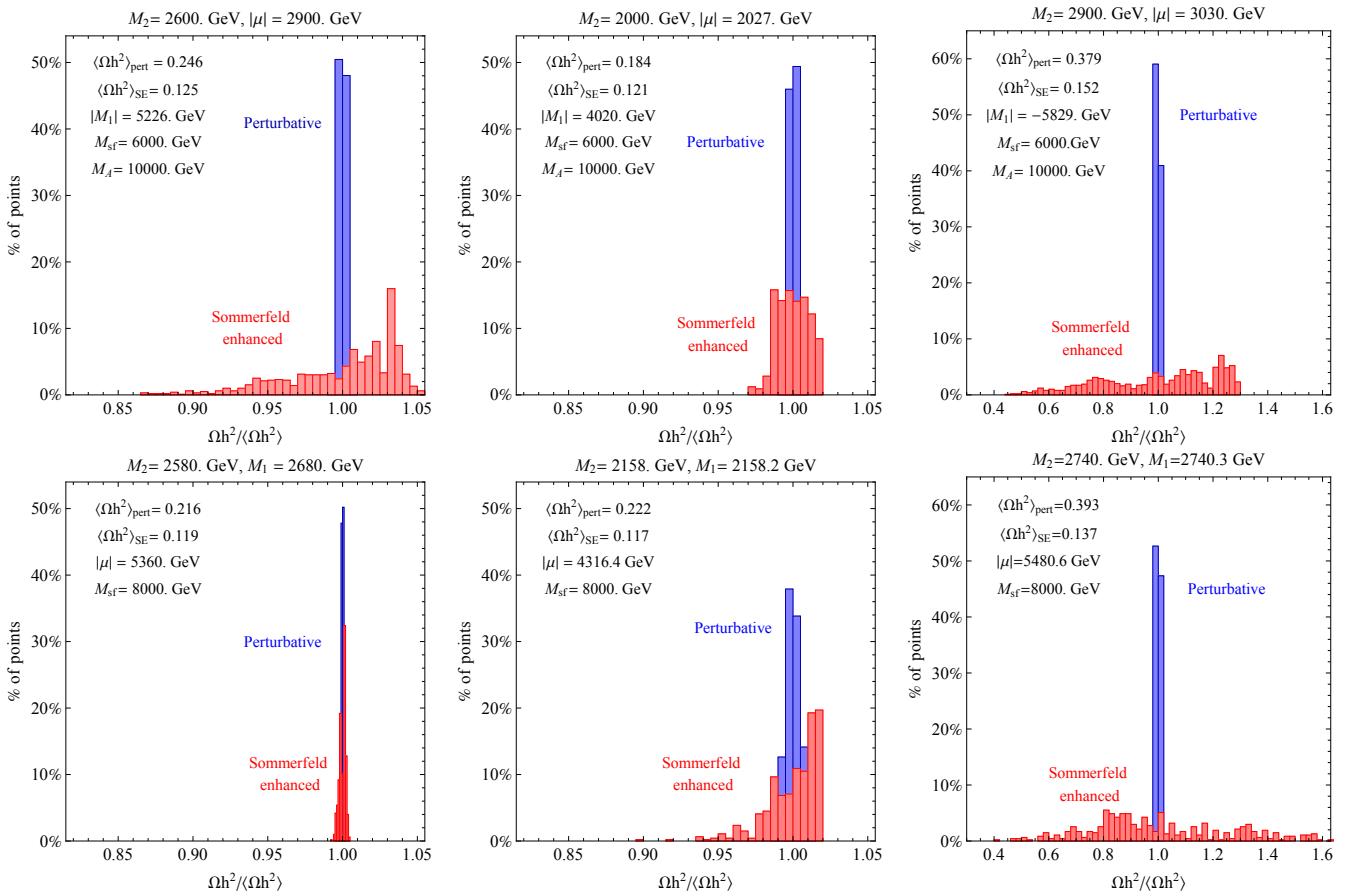


Cabrera, Ando, Weniger, Zandanel '15



Ibe, Matsumoto, Shirai, Yanagida '15

Effect of remaining parameters



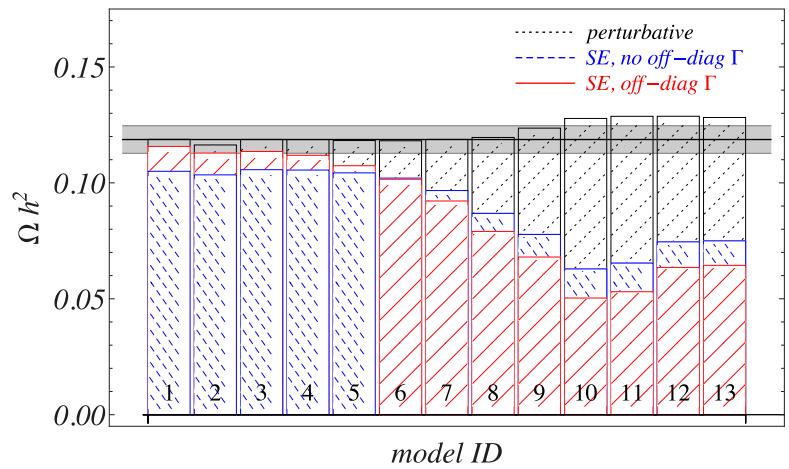
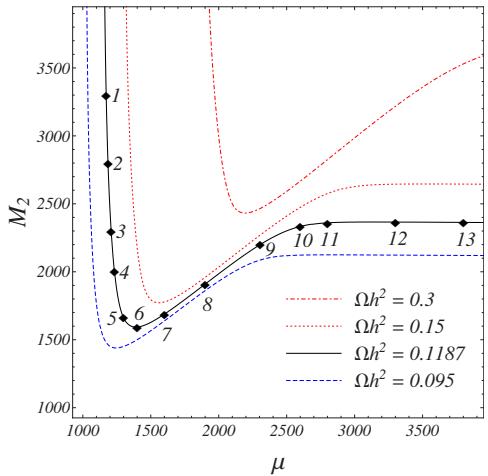
More details of calculation

Beneke, Hellmann, Ruiz-Femenia 2014

$$\text{Coupled Schrödinger equation: } \left(\left[-\frac{\vec{\nabla}^2}{2\mu_a} - E \right] \delta^{ab} + V^{ab}(r) \right) [\psi_E(\vec{r})]_{b,ij} = 0$$

$$\mathcal{L}_{\text{kin}} = \sum_{i=1}^{n_0} \xi_i^\dagger \left(i\partial_t - \delta m_i + \frac{\vec{\partial}^2}{2m_{\text{LSP}}} \right) \xi_i + \sum_{\psi=\eta,\zeta} \sum_{j=1}^{n_+} \psi_j^\dagger \left(i\partial_t - \delta m_j + \frac{\vec{\partial}^2}{2m_{\text{LSP}}} \right) \psi_j .$$

where $\delta m_i = m_i - m_{\text{LSP}}$, $\delta m_j = m_j - m_{\text{LSP}}$



Ranges of parameters

Parameter	Range
$ M_1 $	1 – 5 TeV M_2 – 3 M_2
$ \mu $	M_2 – 3 M_2
M_{sf}	1.25 – 12 TeV
	1 – 10 TeV 5 – 30
$ A_f $	0 – 8 TeV 3

Mixing

Wino-Higgsino mixing depends on if $\theta_h < 1$ where $\theta_h = \frac{(c_\beta + s_\beta)c_W M_Z}{\sqrt{2}(\mu - M_2)}$,

$\delta m_{\tilde{\chi}_1^+} \equiv m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}$ is given by

$$\begin{aligned}\delta m_{\tilde{\chi}_1^+} &\simeq \frac{1}{2} \frac{m_W^4 M_2 (c_\beta^2 - s_\beta^2)^2}{(\mu^2 - M_2^2)^2}, \\ \delta m_{\tilde{\chi}_1^+} &\simeq \frac{m_Z^2}{8M_2} \left(c_W^2 (1 \mp s_{2\beta}) \left(1 - \frac{\delta\mu}{\sqrt{2}(s_\beta \pm c_\beta) m_W} \right) + 2 s_W^2 (1 \pm s_{2\beta}) \frac{M_2}{M_1} \right),\end{aligned}$$

Wino-bino mixing depends on if $\theta_b < 1$ where $\theta_b = \frac{s_{2\beta} s_{2W} M_Z^2}{2\mu(M_1 - M_2)}$

$$\begin{aligned}\delta m_{\tilde{\chi}_1^+} &\simeq \theta_b^2 \delta M_1 \left(1 + \frac{2M_2}{s_{2\beta} \mu} \right) \quad \text{or} \\ \delta m_{\tilde{\chi}_1^+} &\simeq \begin{cases} s_W^2 \frac{m_Z^2}{\mu} \left(s_{2\beta} + \frac{M_2}{\mu} \right) - s_W^2 \delta M_1, & \text{if } \mu > 0 \text{ or } \frac{s_{2\beta} |\mu|}{M_2} < 1 \\ c_W^2 \frac{m_Z^2}{|\mu|} \left(s_{2\beta} + \frac{M_2}{\mu} \right) - c_W^2 \delta M_1, & \text{otherwise} \end{cases}\end{aligned}$$