

New results on Sommerfeld enhancement and $\Omega_\chi h^2$ of χ^0 dark matter in the general MSSM

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M.Beneke, CH, Pedro Ruiz Femenia: arXiv:1210.7928,
1303.0200, and work in preparation

Introduction

Sommerfeld enhancements ...

- Intrinsic in non-relativistic pair-annihilation or production



e.g. threshold production of heavy particles at colliders

- Coulomb enhancement: $\sigma_{l=0} v_{\text{rel}} = S(v) \sigma_{l=0}^{\text{tree}}$, $S(v) = \frac{\pi\alpha}{v} \frac{1}{1-e^{-\pi\alpha/v}}$
[Sommerfeld '31]

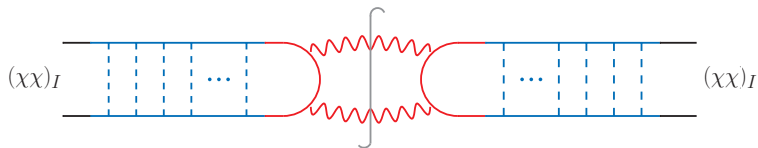
... in DM pair-annihilations

lengo '09; Cassel '09; Slatyer '10

1. Indirect detection: Explanation of cosmic ray anomalies?
Constraints on DM candidates: Cohen et al '13; Fan&Reece '13; Hryczuk et al '14
2. Relic density calculation ($\Omega_{\text{DM}} h^2 = 0.1187 \pm 0.0017$ (68%CL) [PLANCK '13])
 - DM candidates:
 χ_1^0 LSP in the MSSM: Hisano et al '04,'06; lengo et al '10,'11; ...
Minimal DM: Cirelli et al '07,'08,'09
DM in hidden sector: Arkani-Hamed et al '09; Feng et al '10; Hannestad et al '11; ...

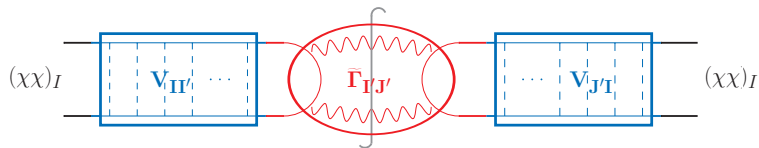
Effective field theory approach: the NRMSSM

Consider nearly mass-degenerate states $(\chi\chi)_I, I=1, \dots, N$



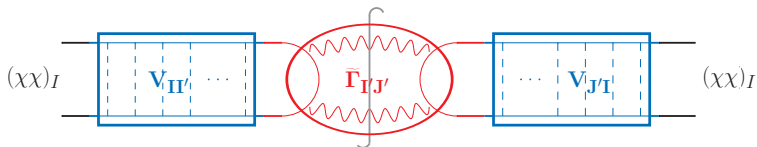
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Effective field theory approach: the NRMSSM

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Describe process within non-relativistic effective theory:

$$\sigma_{(\chi\chi)_{I \rightarrow \text{light}}} v_{\text{rel}} = \left(\frac{1}{4} \sum_{s_I} \right) 2 \Im \langle (\chi\chi)_I | \delta \mathcal{L}_{\text{ann}}(x) | (\chi\chi)_I \rangle$$

Analogous to Bodwin, Braaten, Lepage '95

- Short distance part: accounted for by local four-fermion operators \mathcal{O}

$$\delta \mathcal{L}_{\text{ann}}(x) = \sum_{I, J} \hat{f}^{(2s+1) L_{\mathcal{J}}}{}_{IJ} \mathcal{O}_{(\chi\chi)_I \rightarrow (\chi\chi)_J}^{(2s+1) L_{\mathcal{J}}; x}$$

- Long-range effects: encoded in $(\chi\chi)_I$'s scattering wave-function $\vec{\psi}^{(I)}$

$$\left(-\frac{\vec{\partial}^2}{m_\chi} \delta_{JJ'} + V_{JJ'}(r) \right) \psi_{J'}^{(I)}(\vec{r}) = m_\chi v^2 \psi_J^{(I)}(\vec{r})$$

Beyond leading order approximations in the MSSM

Sommerfeld enhancement of the $(\chi\chi)_I$, $I=1,\dots,N$ pair's annihilation rate

$$S^{(I)} = \frac{\vec{\psi}_{(\vec{r}=0)}^{(I)*} \cdot \vec{\Gamma} \cdot \vec{\psi}_{(\vec{r}=0)}^{(I)}}{\psi_{0(\vec{r}=0)}^{(I)*} \cdot \vec{\Gamma} \cdot \psi_{0(\vec{r}=0)}^{(I)}}$$

- Includes off-diagonal scattering and annihilation
- Individual $S^{(I)}$ for each $^{2s+1}L_J$ -wave

[For generic multi $(\chi\chi)_I$ state model: Slatyer '10]

Extension of previous work:

1. χ_1^0 in the generic MSSM (*beyond pure wino- or higgsino scenarios*)
2. Many nearly mass degenerate $(\chi\chi)_I$ states
(Including expansion in mass-differences) [At 1-loop level: Drees, Gu '12]
3. Including P - and $\mathcal{O}(v^2)$ S -wave (*beyond leading order S -wave*)
4. Analytic expressions for all (off-diagonal) partial-wave V_{IJ} and Γ_{IJ}
5. Deal with closed channels for larger mass-splittings

Enhanced cross sections and relic density

Sommerfeld enhanced χ^0/χ^\pm co-annihilation cross sections

- Active $(\chi\chi)_I$ channels: $\delta M_I \leq 0.2 m_{\chi_1^0}$

$$\sigma_{(\chi\chi)_I} v_{\text{rel}} = \sum_{^1S_0, ^3S_1} [S_I \Gamma_{II}] + \vec{p}_i^2 \left(\sum_{^1P_1, ^3P_J} [S_I \Gamma_{II}] + \sum_{^1S_0, ^3S_1} [S_I \Gamma_{II}^{(p^2)}] \right)$$

- $S_I = S_I(v)$ in non-trivial way!

Relic density from solving the Boltzmann equation

- Thermal weighting of all $\sigma_{(\chi\chi)_I} v_{\text{rel}}$: $\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle$

$$\frac{dY}{dx} = \frac{\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle}{H x} \left(1 - \frac{x}{3 g_{*s}} \frac{d g_{*s}}{dx} \right) s \left(Y^2 - (Y^{\text{eq}})^2 \right)$$

[Gondolo, Gelmini '91; Griest, Seckel '91]

Wino-like χ_1^0

- Active states: χ_1^0, χ_1^\pm (approx. $SU(2)_L$ triplet)
- mass-splitting: $\delta m_{\text{rad}} = m_{\chi_1^+} - m_{\chi_1^0} \approx 0.160 \text{ GeV}$
- (co-)annihilation sectors:

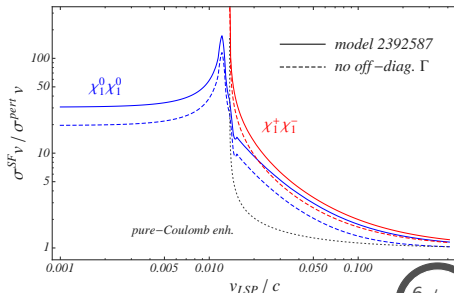
neutral	$\chi_1^0 \chi_1^0, \chi_1^+ \chi_1^-$
single charged	$\chi_1^0 \chi_1^+ (\chi_1^0 \chi_1^-)$
double charged	$\chi_1^+ \chi_1^+ (\chi_1^- \chi_1^-)$

→ coupled system: $V_{2 \times 2}, \Gamma_{2 \times 2}$

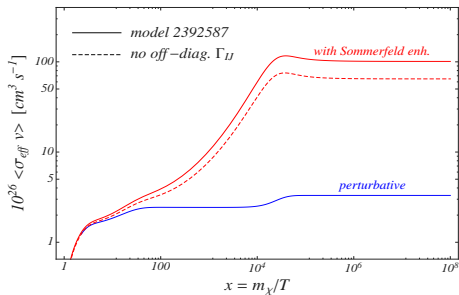
pMSSM benchmark model:

2392587 Cahill-Rowley et al. '13

- $m_{\chi_1^0} = 1650 \text{ GeV}$
- $|Z_{N21}|^2 = 0.999$
- $\delta m_{\chi_1^+} = 0.155 \text{ GeV}$

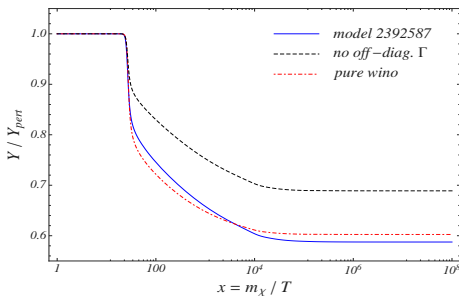


Wino-like χ_1^0 : Sommerfeld enhancements and $\Omega_\chi h^2$



$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle$:

- $x \simeq 20$:
Freeze-out if $\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle$ calculated pert.
→ delayed when considering $\sigma^{\text{SF}} v_{\text{rel}}$

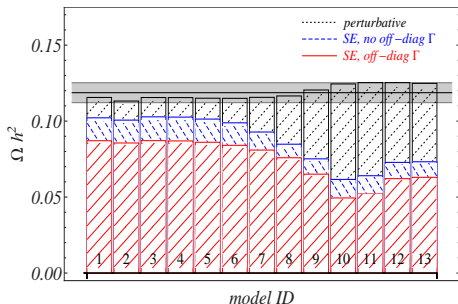
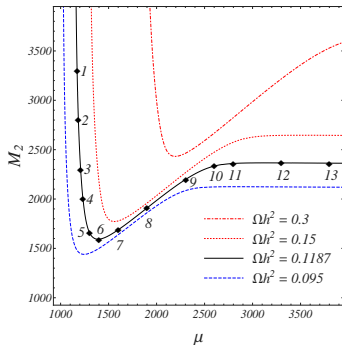


Yield $Y = \sum_i n_{\chi_i} / s$ and $\Omega_\chi h^2$:

- $\Omega_\chi^{\text{pert}} h^2 = 0.109$
- $\Omega_\chi^{\text{SF}} h^2 = 0.064 \rightarrow$ **40% reduction**
- $\sim 15\%$ error on $\Omega_\chi^{\text{SF}} h^2$ if no off-diag. Γ
- Pure wino: $\Omega_\chi^{\text{pert}} h^2 = 0.055$
 $\Omega_\chi^{\text{SF}} h^2 = 0.033$

Higgsino-to-wino trajectory

- 13 models, $\Omega^{\text{DarkSUSY}} h^2 = 0.1187$
[PLANCK+WMAP central value]
- Trajectory in $\mu - M_2$ plane:
 - Model 1 – 6: higgsino-like χ_1^0
 - Model 7 – 9: mixed higgsino-wino χ_1^0
 - Model 10 – 13: wino-like χ_1^0



• Models 1 – 6:

- $\Omega^{\text{SF}} / \Omega^{\text{pert}} \sim 0.75$
- $\sim 17\%$ error on $\Omega^{\text{SF}} h^2$ if no off-diag. Γ

• Models 7, 8, 9:

- $\Omega^{\text{SF}} / \Omega^{\text{pert}} \sim (0.70, 0.65, 0.54)$
- $\sim 15\%$ error if no off-diag. Γ

• Models 10 – 13:

- $\Omega^{\text{SF}} / \Omega^{\text{pert}} \sim 0.40 - 0.50$
- $\sim 25\%$ error if no off-diag. Γ

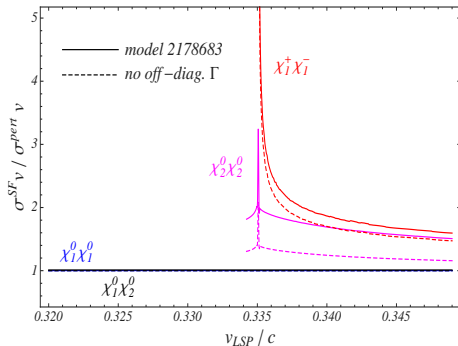
Bino χ_1^0 with enhancements in $\chi\chi$ co-annihilations

- Bino-like χ_1^0 is $SU(2)_L$ singlet state
→ no Sommerfeld enhancement in $\chi_1^0\chi_1^0$ annihilations
- BUT enhancements can potentially arise in co-annihilations

pMSSM benchmark model:

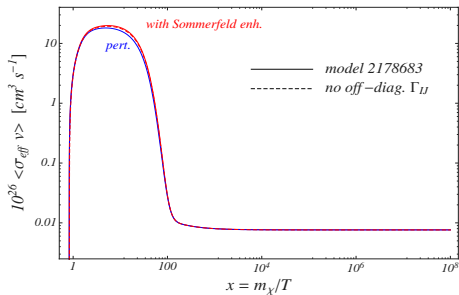
2178683 Cahill-Rowley et al. '13

- $m_{\chi_1^0} = 489$ GeV
- Wino-like χ_2^0, χ_1^\pm at 516 GeV



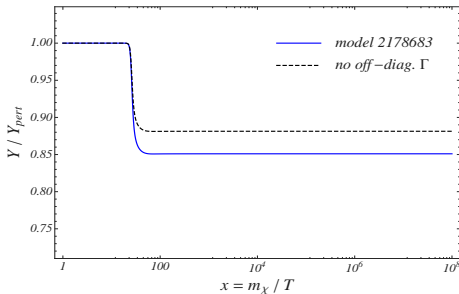
[Absolute χ_1^0 rates are $\mathcal{O}(10^{-3})$ smaller than those of the wino-like states]

Bino-like χ_1^0 : enhanced co-annihilations and $\Omega_\chi h^2$



$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle$:

- $x \simeq 50$: χ_2^0, χ_1^\pm decoupling
- Sommerfeld enhancement:
15 – 37% correction for $x \sim 20 - 100$



Yield $Y = \sum_i n_{\chi_i} / s$ and $\Omega_\chi h^2$:

- $\Omega_\chi^{\text{pert}} h^2 = 0.115$
- $\Omega_\chi^{\text{SF}} h^2 = 0.099 \rightarrow 14\%$ reduction
- 4% error on $\Omega_\chi^{\text{SF}} h^2$ if no off-diag. Γ

Conclusions

- Sommerfeld enhancement is essential in χ_1^0 DM $\Omega_\chi h^2$ calculation
- Provide method for $\Omega_\chi h^2$ calculation including $\sigma^{\text{SF}} v$:
 - Applicable in the general MSSM
 - Dealing with many nearly mass-degenerate $(\chi\chi)_I$ states
 - Including all off-diagonal potential and annihilation rates
- Largest effect for wino-like χ_1^0 : $\sim 40 - 60\%$ reduction of $\Omega_\chi h^2$
- Milder effect for higgsino-like χ_1^0 models: $\sim 20 - 25\%$ reduction
- First rigorous study of interpolating mixed wino-higgsino χ_1^0 models
- Effect on $\Omega_\chi h^2$ for bino-like χ_1^0 , if co-annihilations are enhanced