Neutralino Annihilation into Photons:

$$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma$$
$$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z\gamma$$

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Motivation

- Neutralino: a natural candidate to Dark Matter within the MSSM

- Astrophysical experiments performing direct and indirect searches

  Ground based: Cangaroo, HESS, MAGIC, VERITAS ...

  Space telescopes: EGRET, AMS, GLAST ...

- Indirect searches: looking for products of $\tilde{\chi}_1^0$ annihilation

  Photons point back the source

  Charged particles suffer propagation uncertainties

- “Direct” photon production gives a clear signal

  Energy spectrum peak at $M_{\tilde{\chi}_1^0}$

  No astrophysical background

- First application of a code computing one-loop processes in the MSSM

  Collider Physics

  Astrophysical/relic density calculations

Particle Physics Content

($\gamma\gamma$: Bergström, Ullio'97, Bern, Gondolo'97)
($Z\gamma$: Ullio, Bergström'97)

The gamma ray flux is

$$\Gamma_\gamma(\psi) \propto \frac{\sigma\, v}{M^2_{\tilde{\chi}^0_1}} \int_{l.o.s} \rho^2(l) dl(\psi)$$

where ρ is the neutralino density
ψ is the observation-galactic centre angle

- ## Particle physics:

  we compute the MSSM one-loop cross-sections:

$$\tilde{\chi}^0_1 \tilde{\chi}^0_1 \to \gamma\gamma$$
$$\tilde{\chi}^0_1 \tilde{\chi}^0_1 \to Z\gamma$$

  First results of a SUSY one-loop code

- ## Astrophysics content:

  to be implemented in micrOMEGAs

A very special computational strategy

Lagrangian of the model defined in LanHEP

- particle content
- interaction terms
- shifts in fields and parameters
- ghost terms constructed by BRST

↓ ↓

Generic Model
-kinematical structures

Classes Model
-Feynman rules, including CT

⇓

Evaluation via FeynArts-FormCalc

LoopTools modified!!

⇑

Renormalisation scheme

- definition of renorm. const. in the classes model

Very powerful tool

$\rightarrow$ Flexibility of the code allows

- Physics beyond the MSSM: Split SUSY, Majorana Neutrinos, NMSSM
- Different renormalisation schemes: $\tan\beta$ problem

$\rightarrow$ Tests on the results

- IR and UV finiteness: dependence on $C_{UV} = \frac{1}{\epsilon} - \gamma_E + log 4\pi$ and m_γ
- Gauge invariance: Non-linear gauge

$$\mathcal{L}_{GF} = -\frac{1}{\xi_W}|(\partial_\mu - ie\tilde{\alpha}\gamma_\mu - igc_W\tilde{\beta}Z_\mu)W^{\mu+} + \xi_W\frac{g}{2}(v + \tilde{\delta}h_o + \tilde{\omega}H_o + i\tilde{\kappa}\chi_3)\chi^+|^2$$
$$-\frac{1}{2\xi_Z}(\partial.Z + \xi_Z\frac{g}{2c_W}(v + \tilde{\epsilon}h_o + \tilde{\gamma}H_o)\chi_3)^2 - \frac{1}{2\xi_\gamma}(\partial.\gamma)^2$$

$\xi = 1 \rightarrow$ no high order tensor analysis
proper choice for gauge parameters simplifies computation

Tested for the SM

LoopTools Modified!

Routine computing loop integrals

If both χ are at rest $(v = 0)$ the kinematic is very special

General case: $p_\chi^{(1)} + p_\chi^{(2)} = p_\gamma + p_Z$

In this case: $p_\chi^{(1)} \simeq p_\chi^{(2)}$ so just two independent momentum

Tensor integrals reduction requires inverse Gram determinant computation

$$det \begin{bmatrix} p_1^2 & p_1 p_2 & p_1 p_3 \\ p_1 p_2 & p_2^2 & p_2 p_3 \\ p_1 p_3 & p_2 p_3 & p_3^2 \end{bmatrix} \propto v^2$$

in our case $v/c \simeq 10^{-3}$ giving numerical instabilities

To solve this problem we implement the

Segmentation of one-loop integrals at $v = 0$

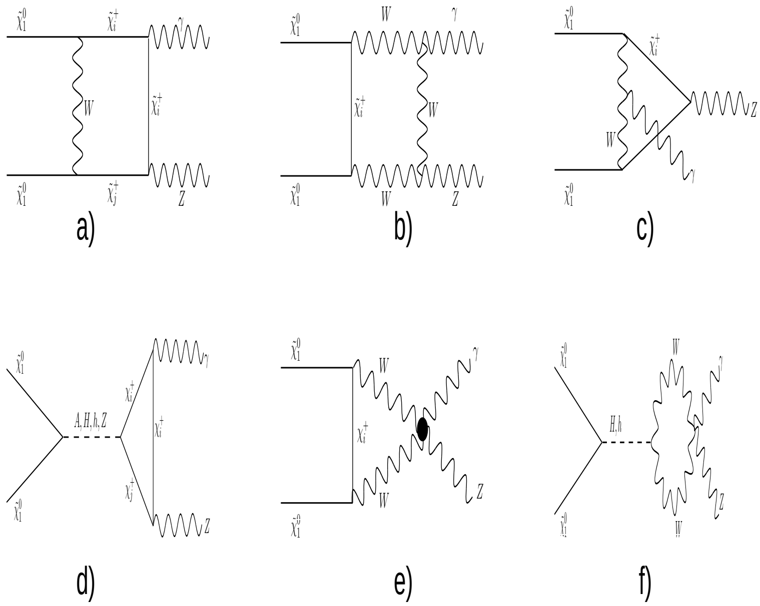
N-points integrals $\rightarrow$ (N-1) integrals

$$\frac{1}{D_0 D_1 D_2 D_3} \propto \frac{1}{D_0 D_1 D_2} + \frac{a}{D_0 D_1 D_3} + \frac{b}{D_0 D_2 D_3} - \frac{1+a+b}{D_1 D_2 D_3}$$

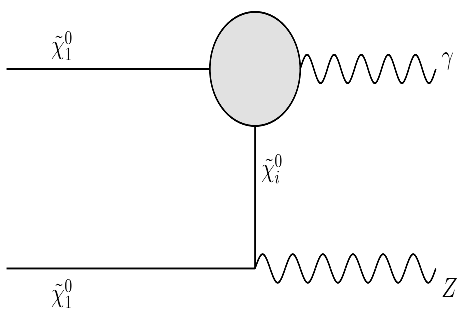
$D_0 = k^2 - m_0^2$, $D_i = (k + p_i)^2 - m_i^2$

Computing the cross-sections

More than a thousand diagrams including



New contribution found in $Z\gamma$!



Counterterm contribution:

- Obtained from tree-level $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ZZ$ and $\delta Z_{Z\gamma}$
- Since $\delta Z_{Z\gamma} \sim (1-\tilde{\alpha})$ CT can be put to zero if $\tilde{\alpha}=1$

Choosing a proper gauge simplifies the computation

Numerical results

DarkSUSY: Gondolo et al. `www.physto.se/edsjo/darksusy`
PLATON: Gounaris et al. `dtp.physics.auth.gr/platon`

	Sugra	nSugra	higgsino-1	higgsino-2	wino-1	wino-2
M_1	0.2	0.1	0.5	20.	0.5	20.0
M_2	0.4	0.4	1.0	40.	0.2	4.0
μ	1.0	1.0	0.2	4.0	1.0	40.0
M_A	1.0	1.0	1.0	10.	1.0	10.0
$m_{\tilde{f}}$	0.8	0.8	0.8	10.	0.8	10.0
Ωh^2	5.31	18.8	$6.41\ 10^{-3}$	1.59	$1.16\ 10^{-3}$	0.46
$\sigma v_{\gamma\gamma} \times 10^{27}$						
v=0	$5.82\ 10^{-5}$	$1.58\ 10^{-5}$	$7.01\ 10^{-2}$	$4.71\ 10^{-2}$	1.99	1.52
`PLATONdml`	$5.82\ 10^{-5}$	$1.58\ 10^{-5}$	$7.01\ 10^{-2}$	$4.72\ 10^{-2}$	1.99	1.53
`DarkSUSY`	$5.81\ 10^{-5}$	$1.58\ 10^{-5}$	$7.02\ 10^{-2}$	$4.71\ 10^{-2}$	1.99	1.52
v=0.5	$5.94\ 10^{-5}$	$1.60\ 10^{-5}$	$1.30\ 10^{-1}$	$5.42\ 10^{-3}$	2.36	$8.69\ 10^{-2}$
$\sigma v_{gg} \times 10^{30}$						
v=0	2.05	0.60	5.74	0.33	19.6	0.42
`PLATONdmg`	2.05	0.60	5.75	0.33	19.6	0.42
`DarkSUSY`	2.05	0.60	5.77	0.33	19.5	0.42
v=0.5	2.21	0.60	8.23	0.33	20.2	0.42
`PLATONgrel`	2.21	0.60	8.23	0.33	20.2	0.42
$\sigma v_{Z\gamma} \times 10^{27}$						
v=0,full	$2.03\ 10^{-5}$	$2.61\ 10^{-6}$	$2.19\ 10^{-1}$	$2.20\ 10^{-2}$	11.7	10.1
v=0,part	$1.94\ 10^{-5}$	$2.50\ 10^{-6}$	$2.61\ 10^{-1}$	$3.29\ 10^{-2}$	11.7	10.1
`DarkSUSY`	$1.42\ 10^{-5}$	$1.79\ 10^{-6}$	$2.61\ 10^{-1}$	$3.29\ 10^{-2}$	11.7	10.1
v=0.5,full	$2.45\ 10^{-5}$	$3.67\ 10^{-6}$	$2.99\ 10^{-1}$	$1.66\ 10^{-2}$	14.2	$5.76\ 10^{-1}$
v=0.5,part	$2.34\ 10^{-5}$	$3.53\ 10^{-6}$	$3.58\ 10^{-1}$	$2.47\ 10^{-1}$	14.2	$5.76\ 10^{-1}$

$\tan\beta = 10$, $A = 0$ but $A_t = -0.3$ when $m_{\tilde{f}} = 0.8$, all in TeV

Large cross-sections for $\tilde{\chi}_1^0$ mostly wino or higgsino

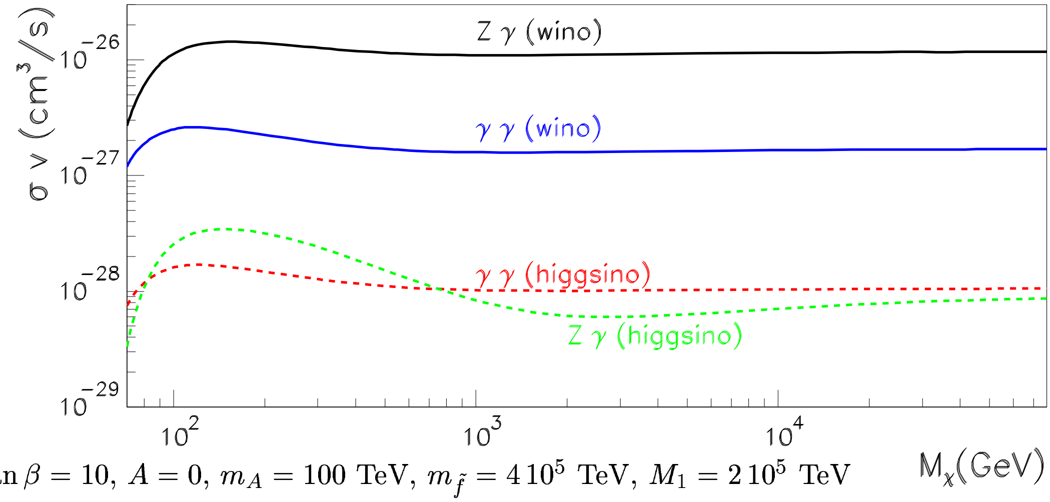
Good agreement for $\gamma\gamma$, gg and relevant $Z\gamma$

Large new contribution effects in the higgsino case

New $v = 0.5$ results for $\gamma\gamma$, $Z\gamma$

Higgsino and Wino limits

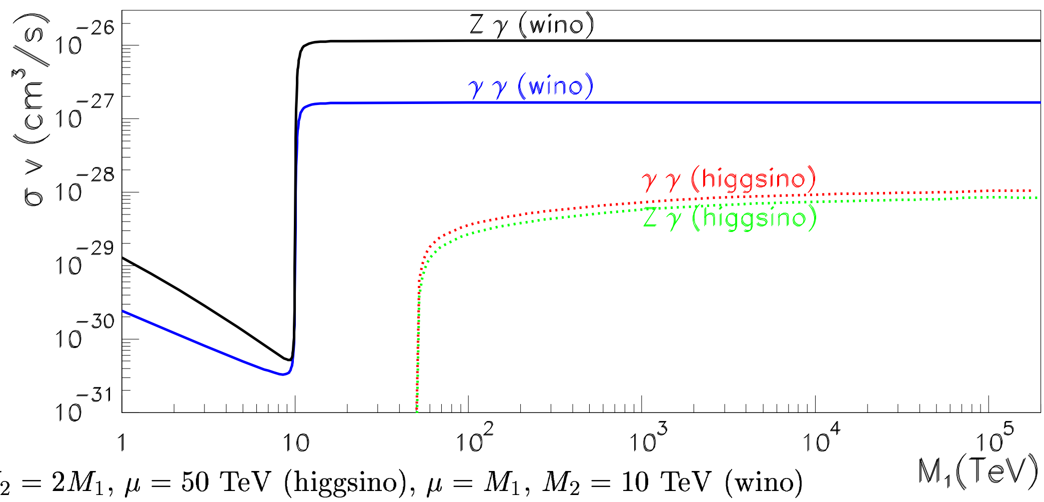
- σv vs. $M_{\tilde{\chi}_1^0}$ $(v = 0)$



$\tan\beta = 10,\ A = 0,\ m_A = 100$ TeV, $m_{\tilde{f}} = 4\,10^5$ TeV, $M_1 = 2\,10^5$ TeV

$M_2 = 2M_1$ (higgsino), $\mu = M_1$ (wino)

- σv vs. % higgsino/wino $(v = 0)$



$M_2 = 2M_1,\ \mu = 50$ TeV (higgsino), $\mu = M_1,\ M_2 = 10$ TeV (wino)

$\delta M = M_{\chi_1^+} - M_{\chi_1^0}$

Asymptotic value for large $M_{\tilde{\chi}_1^0}$, $\sigma v \sim 1/M_W^2$

Largest cross section for $Z\gamma$ in wino case

Smooth behaviour in higgsino case, $\delta M \sim m_z^2/M_1$

Constant value after transition in wino case, $\delta M \sim m_z^4/M_1^3$

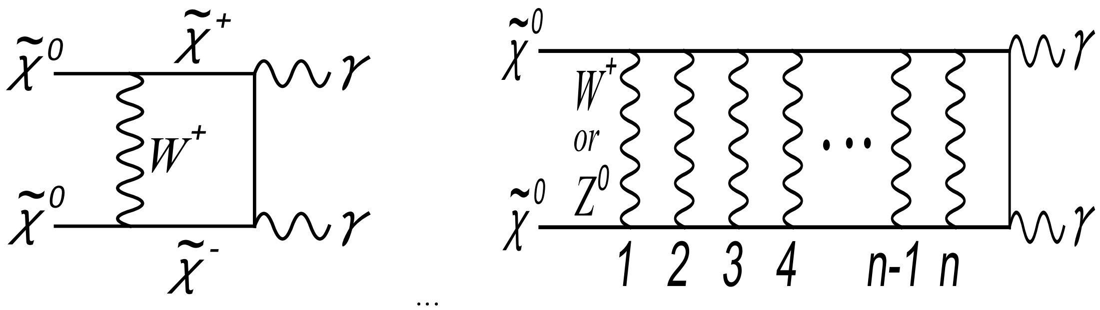
Numerical results reproduce analytical behaviour

Matching with non-perturbative computation

Hisano et al.'04

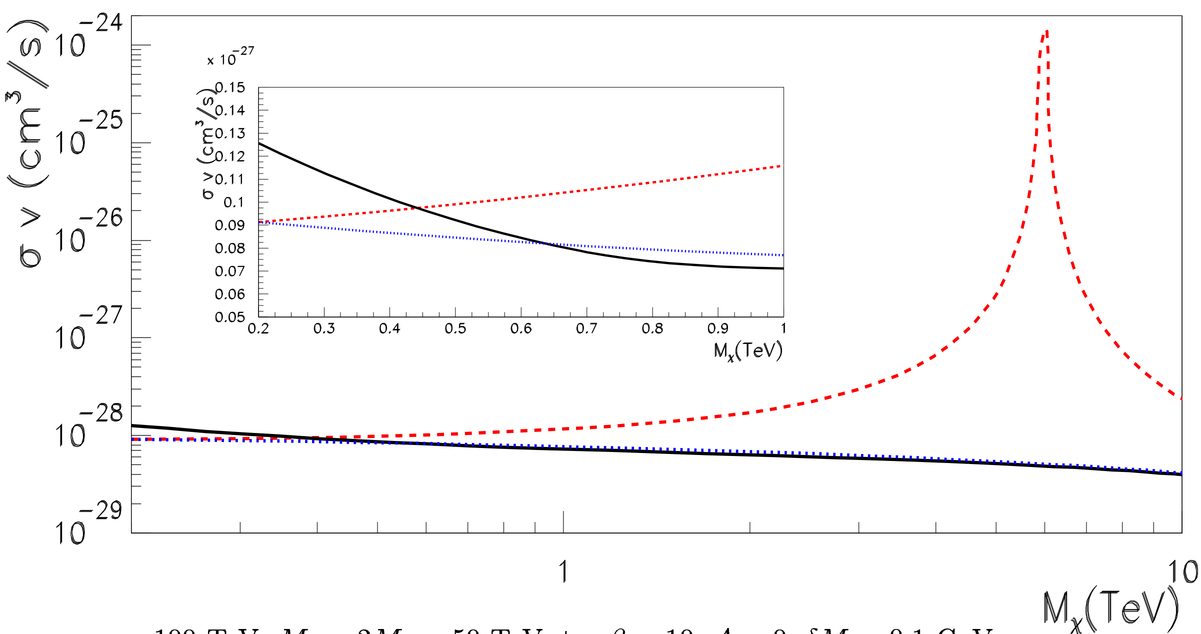
In the extreme higgsino and wino limits,

- one-loop treatment breaks unitarity
- non-perturbative non-relativistic approach



Non-perturbative computation and one-loop results

higgsino case $(v = 0)$



$m_{\tilde{f}} = m_A = 100$ TeV, $M_2 = 2M_1 = 50$ TeV, $\tan\beta = 10$, $A = 0$, $\delta M = 0.1$ GeV

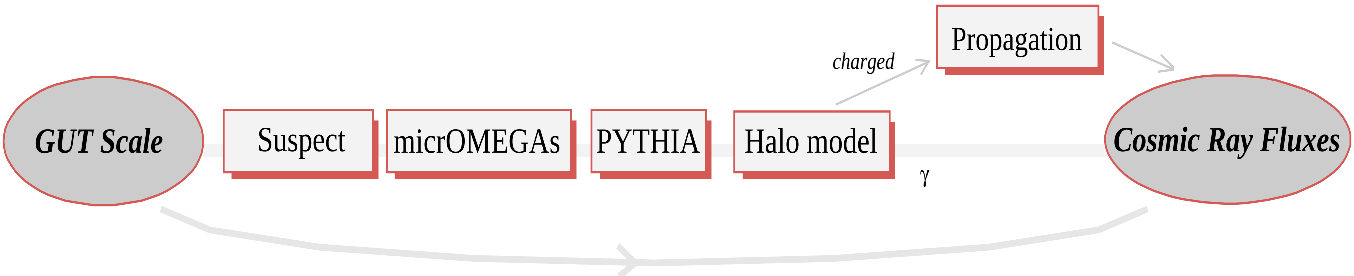
Resonances can enhance result several orders of magnitude

Matching will take place around $400 - 500$ GeV

Indirect Dark Matter searches

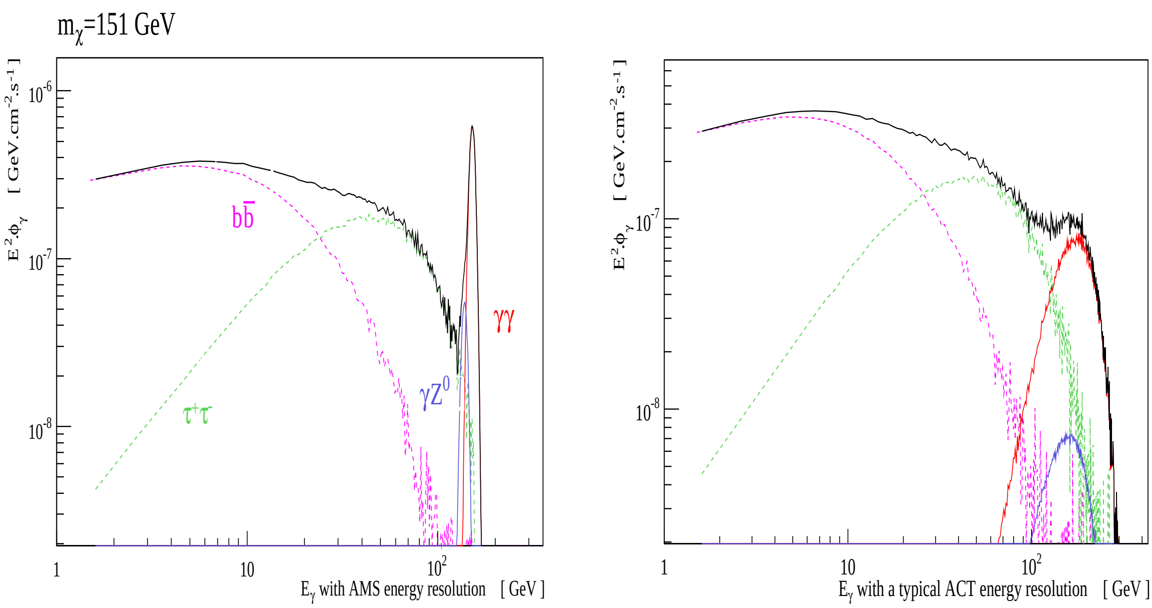
micrOMEGAs
Brun,Rosier-Lees'05 (AMS/HESS Coll.)

micrOMEGAs will perform indirect $\tilde{\chi}_1^0$ searches



First analysis, including our code for $\gamma\gamma$, $Z\gamma$

just Susy signals are shown
acceptance is not included



NFW halo param. $(\alpha, \beta, \gamma) = (1, 3, 1)$, $a = 25$ kpc. (core radius), $r_0 = 8kpc$ (galactic centre distance), $\rho_0 = 0.3\,GeV/cm^3$ (DM density), opening angle cone 1^o
$m_0 = 113$ GeV, $m_{1/2} = 375$ GeV, $A = 0$, $\tan\beta = 20$, $\mu > 0$

γ lines could be distinguished from diffuse background

Conclusions

- New powerful code computing one-loop MSSM processes
  Gauge invariance
  Different renormalisation schemes

- Astro/relic density and collider physics, allows combined LC-LHC-Cosmology analysis
  Integrals routine improved

- First results concerning indirect dark matter searches
  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma(Z\gamma)$

  - Finiteness and gauge invariance checked
  - Good agreement with previous calculations
  - Higgsino and wino limits studied in detail
  - First results given for $v \neq 0$
  - Matching with non-perturbative calculations analysed

- Code being implemented with micrOMEGAs to perform indirect neutralino searches

Very promising results up to now

$\Downarrow$

a lot of work to do!