micrOMEGAs_2.2 :
A tool for dark matter studies

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LAPTH

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hep-ph/0112278, hep-ph/0405253,
hep-ph/0607059, arXiv:08032360[hep-ph]

Plan

- General presentation – automation
- MSSM
- micrOMEGAs_2.0: generic model
- micrOMEGAs_2.2: direct detection
- Outlook
- Comparison with other tools

Motivation

- Strong evidence for dark matter
- CMB (WMAP+SDSS) gives precise information on the amount of dark matter
- Most attractive explanation for dark matter: new weakly interacting particle
- Cosmological measurements strongly constrains models of cold dark matter
- Need for a precise and accurate computation of the relic density of dark matter
- Codes that compute relic density in MSSM
  - Neutdriver, micrOMEGAs, DarkSUSY, Isatools
  - Many private codes: SSARD (Olive), Roszkowski, Drees …

- Many models for new physics whose main motivation is to solve the hierarchy problem also have a dark matter candidate – symmetry that ensures that lightest particle is stable

- R-parity like symmetry introduced to avoid rapid proton decay or guarantee agreement with electroweak precision

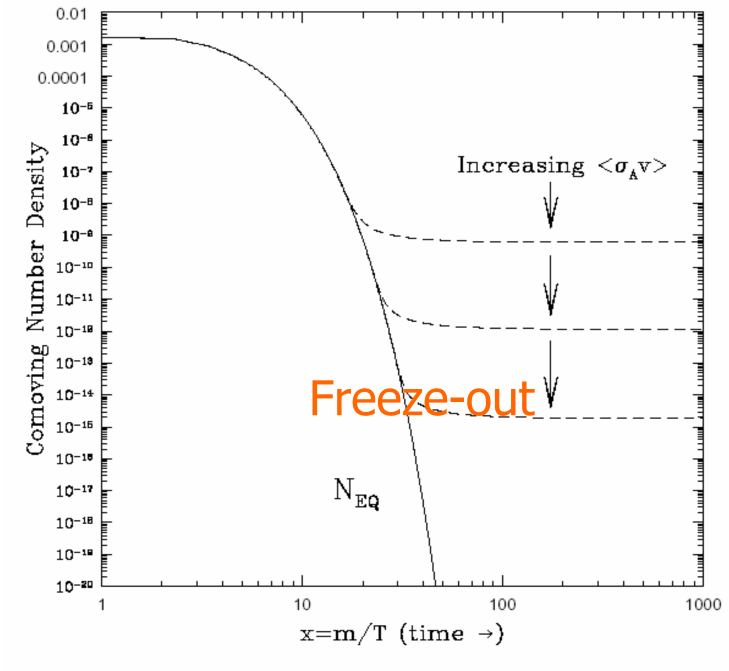
- Examples
  - MSSM and extensions
  - UED
  - Warped Xtra-Dim
  - Little Higgs
  - Technicolour
  - Other BSM..

- *Need for a tool that provide precise calculation of the relic density of dark matter in a wide variety of models - micrOMEGAs_2.0*

- *Complete tool for dark matter studies : relic density, direct detection, indirect detection, cross section at colliders and decays*

Relic density of wimps

- In early universe WIMPs are present in large number and they are in thermal equilibrium
- As the universe expanded and cooled their density is reduced through pair annihilation
- Eventually density is too low for annihilation process to keep up with expansion rate
  - Freeze-out temperature
- LSP decouples from standard model particles, density depends only on expansion rate of the universe



$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

$$\frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45}} M_p < \sigma v > (Y(T)^2 - Y_{eq}(T)^2)$$

Solving numerically, get present day abundance $Y(T_0)$ and

$$\Omega_{LOP} h^2 = \frac{8\pi}{3} \frac{s(T_0)}{M_p^2 (100(\mathrm{km/s/Mpc}))^2} M_{LOP} Y(T_0) = 2.742 \times 10^8 \frac{M_{LOP}}{GeV} Y(T_0)$$

Weakly interacting particle gives roughly the right annihilation cross section to have $\Omega h^2 \sim 0.1$

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} \quad .$$

Coannihilation

- If M(NLSP)~M(LSP) then $\chi + X \longrightarrow \chi' + Y$ maintains thermal equilibrium between NLSP-LSP even after non standard particles decouple from standard ones

- Relic density depends on rate for all processes involving LSP/NLSP → SM

- All particles eventually decay into LSP, calculation of relic density requires summing over all possible processes

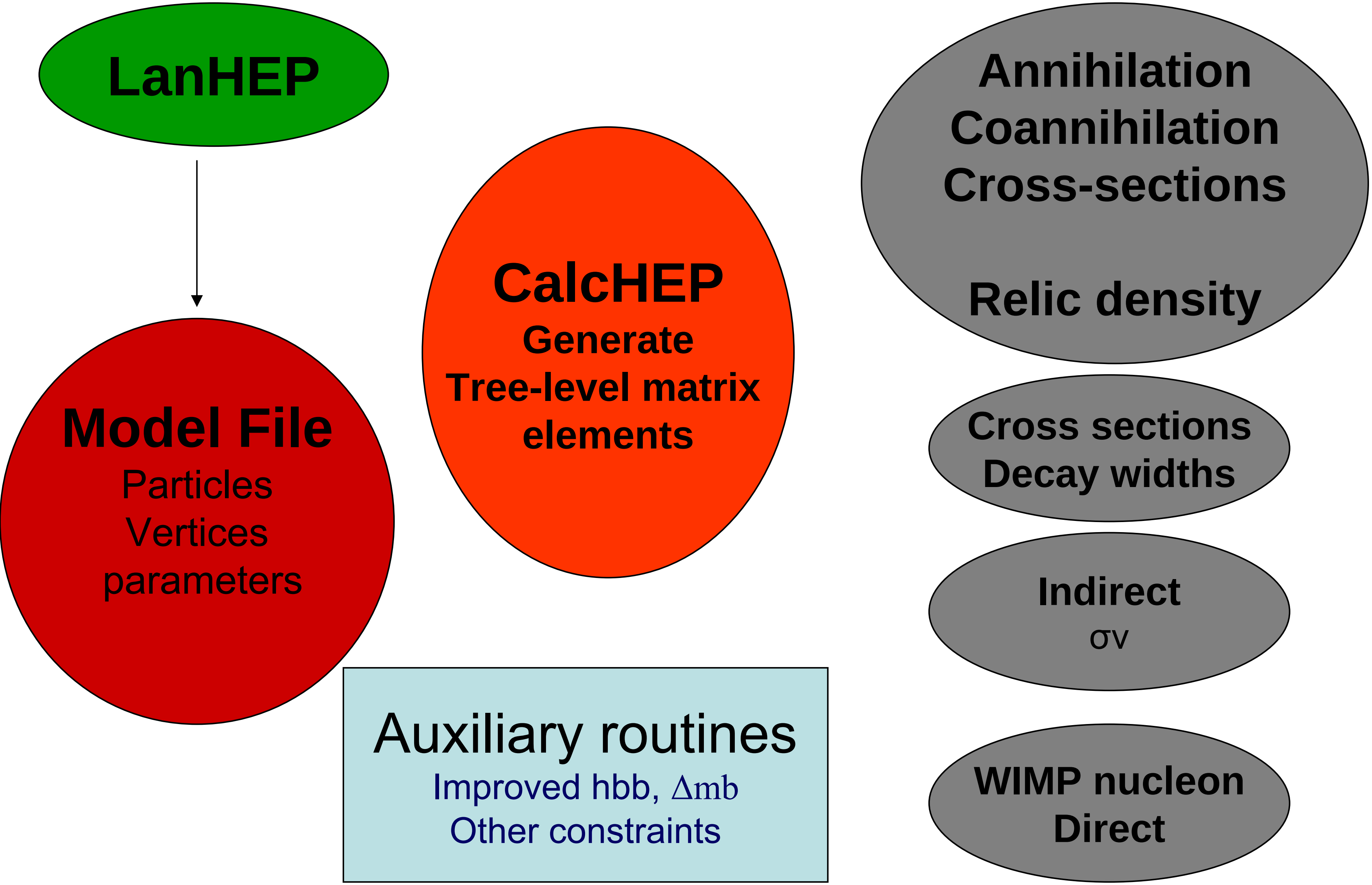
Exp(- ΔM)/T

$$< \sigma v >= \frac{\sum_{i,j} g_i g_j \int_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T\left(\sum_i g_i m_i^2 K_2(m_i/T)\right)^2}$$

- **Important processes are those involving particles close in mass to LSP, in total 3000 processes can contribute in MSSM**

- *Need for automation*

micrOMEGAs



LanHEP

Model File
Particles
Vertices
parameters

CalcHEP
Generate
Tree-level matrix elements

Annihilation
Coannihilation
Cross-sections

Relic density

Cross sections
Decay widths

Indirect
σv

WIMP nucleon
Direct

Auxiliary routines
Improved hbb, Δmb
Other constraints

micrOMEGAs

- C code
- Complete tree-level matrix elements for all subprocesses
- Include all possible annihilation and coannihilation channels
- Calculates the relic density for any LSP (even charged)

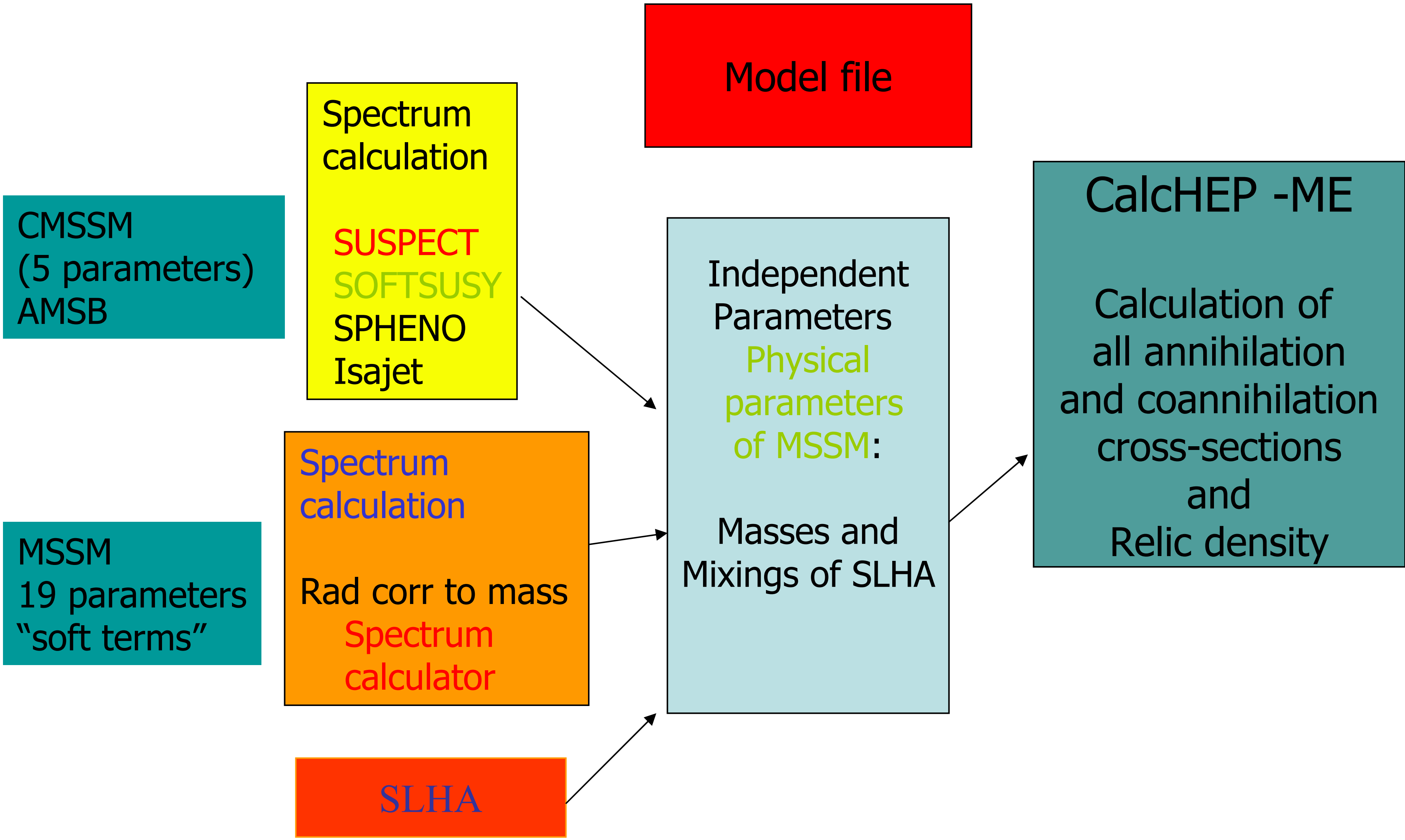
- Numerical solution of evolution equation and calculation of relic density with non-relativistic thermal averaging and proper treatment of poles and thresholds
  - Gondolo, Gelmini, NPB 360 (1991)145
- Generalisation to coannihilation : Edsjo, Gondolo PRD56(1997) 1879
- Automatically check for presence of resonances and improves the accuracy near pole
- Includes and compiles relevant channels only if needed (Beps)

$$B = \frac{K_1((m_i + m_j)/T)}{K_1(2m_{LOP}/T)} \approx e^{-X\frac{(m_i+m_j-2M_{LOP})}{M_{LOP}}} > B_\epsilon$$

- Computes σv, v->0 for LSP,LSP annihilation → indirect detection
- CalcHEP is included: computes all 2->2 processes and 1-> 2,3 decays at tree-level
- Interactive link to CalcHEP

MSSM

Parameters of MSSM model file



Model file

CMSSM
(5 parameters)
AMSB

Spectrum calculation

SUSPECT
SOFTSUSY
SPHENO
Isajet

MSSM
19 parameters
"soft terms"

Spectrum calculation

Rad corr to mass
Spectrum calculator

SLHA

Independent Parameters
Physical parameters of MSSM:

Masses and Mixings of SLHA

CalcHEP -ME

Calculation of
all annihilation
and coannihilation
cross-sections
and
Relic density

MSSM-Specific features

- Independent parameters of model are physical parameters of SHLA, flexibility: any model for which the MSSM spectrum can be calculated with an external code can be incorporated easily

- Input parameters to micromegas can be specified at the weak scale or at the GUT scale using some SpectrumCalc program, includes CMSSM, non-univ. SUGRA, AMSB

- ***Uses SUSY Les Houches Accord***

- Radiative corrections to masses can be important – SUSY masses and Higgs masses (via spectrum calculator)

- Package includes other constraints (developed for MSSM) – not automatic
  b->s γ (NLO) , $(g-2)_{\mu}$, B_s->$\mu\mu$, B->$\tau\nu$, $\Delta\rho$

Higgs sector

- General CP conserving effective potential

$$\begin{aligned}
V_{eff} \;=\;& (m_1^2+\mu^2)|H_1|^2+(m_2^2+\mu^2)|H_2|^2-[m_{12}^2(\epsilon H_1H_2)+h.c.]\\
&+\frac{1}{2}[\frac{1}{4}(g^2+g'^2)+\lambda_1](|H_1|^2)^2+\frac{1}{2}[\frac{1}{4}(g^2+g'^2)+\lambda_2](|H_2|^2)^2\\
&+[\frac{1}{4}(g^2-g'^2)+\lambda_3]|H_1|^2|H_2|^2+[-\frac{1}{2}g^2+\lambda_4](\epsilon H_1H_2)(\epsilon H_1^*H_2^*)\\
&+(\frac{\lambda_5}{2}(\epsilon H_1H_2)^2+[\lambda_6|H_1|^2+\lambda_7|H_2|^2](\epsilon H_1H_2)+h.c.)
\end{aligned}$$

- Higgs masses computed with high precision, available either in FeynHiggs or via spectrum calculator, with the effective potential have a consistent gauge invariant way of taking these corrections into account

- λ's include higher order corrections, extracted from Higgs masses and mixings (Boudjema, Semenov, hep-ph/0201219)

Higgs sector

- QCD corrections to Higgs couplings to fermion pairs ($m_{b\ eff}$ ($2M_{LSP}$))

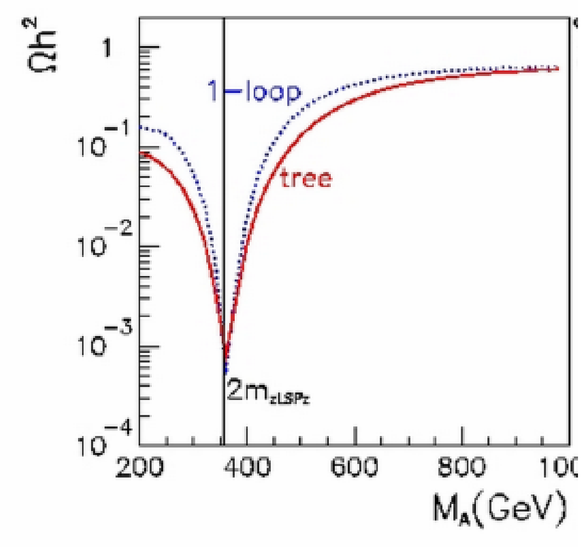
$a=\alpha/\pi$

$$\begin{aligned} M^2_{eff}(Q) &= M(Q)^2\left[1+5.67a+(35.94-1.36n_f)a^2\right. \\ &+ \left.(164.14-n_f(25.77-0.259n_f))a^3\right] \end{aligned}$$

- SUSY-QCD correction to Higgs->bb, effective Lagrangian, relevant at large tanβ
  - Guasch, Hapfliger, Spira, hep-ph/0305101

$$\begin{aligned} \mathcal{L}_{eff} = \sqrt{4\pi\alpha_{QED}}\frac{m_b}{1+\Delta m_b}\frac{1}{2M_W\sin\theta_W}&\left[-Hb\bar{b}\frac{\cos\alpha}{\cos\beta}\left(1+\frac{\Delta m_b\tan\alpha}{\tan\beta}\right)\right. \\ &\left.+iAb\bar{b}\tan\beta\left(1-\frac{\Delta m_b}{\tan\beta^2}\right)+hb\bar{b}\,\frac{1}{\cos\beta}\left(1-\frac{\Delta m_b}{\tan\alpha\tan\beta}\right)\right] \end{aligned}$$

Why improved couplings matter



Beyond MSSM

micromegas_2.0

- A generic program to calculate the relic density of DM in any model
- Assume some " R-parity " particles either odd/even under this parity (odd particles: ~)
- Need to specify model file in CalcHEP notation : particles, variables, vertices, functions in work/models (do by hand or with LanHEP)
- A simple example : RH neutrino + Z'

prtcls1.mdl

```
Full  name |A   |A+  | number|2S  | mass   |width |color|aux|LaTex|LaTeX
Z-boson    |Z   |Z   |23     |2   |MZ      |wZ    |1    |   |Z    |Z
LZP        |~n4|~N4|100000  |1   |MLZP    | wn4  |1    |   |     |
Zp-boson   |Zp  |Zp  |100023 |2   |MZp     |!wZp  |1    |   |Z'   |
```

vars1.mdl

```
Name  | Value    |> Comment
MLZP |100.       |n4 mass
wn4    |0            |n4 width
MZp    |3000       |Zp mass
gZ       |0.1          |Znn coupling
```

lgrng1.mdl

```
Vertices
A1   |A2   |A3   |A4| Factor  |>  Lorentz part
~N4 |~n4  |H    |      |gH        |1
~N4 |~n4  |Z     |     |gZ/2      |G(m3)*(1+G5)
~N4 |~n4  |Zp   |     |gZp/2    |G(m3)*(1+G5)
```

func1.mdl

```
Constraints
Name    |> Expression
QCDok |initQCD(alfSMZ,1.4,MbMb,Mtpole)
Mb       |MbEff(Q)*one(QCDok)
```

micromegas_2.0

- After the model is implemented and check with CalcHEP
  - Code then automatically looks for “LSP” and for resonances
  - Computes all annihilation and coannihilation cross-sections
  - Solves the evolution equation and obtains the relic density
  - Automatically also get any 2->2 cross section and 1->2,3 decay
  - Automatically computes σ v (for indirect detection) and direct detection rate
- *Other constraints must be provided by the user in fortran or C routine*

Beyond MSSM

- Models distributed
  - NMSSM (with C. Hugonie, hep-ph/0505142)
  - CPV-MSSM (with S. Kraml, hep-ph/0604150)
  - Right-handed neutrino (with G. Servant, arXiv:0706.0526)
  - Little Higgs (A. Belyaev)
- Other models available
  - Scalar DM (Lopez-Honorez et al., S. Su)
- Models under development
  - UED (with M. Kakizaki)
  - SUSY N=2 (with K. Benakli, C. Moura)

NMSSM

- MSSM with additional singlet superfield – provide naturally μ of weak scale

- Higgs sector: 3 scalars, 2 pseudoscalars

- Neutralino sector: 5 neutralinos

- Implementation in micrOMEGAs
  - LanHEP to write model file in CalcHEP notation
  - Input parameters : SLHA2
  - Masses/mixings of Higgses: from NMHDECAY (Ellwanger, Gunion, Hugonie)
  - Higgs sector: effective potential, extract parameters from Higgs masses and mixings, calculate Higgs self-couplings
  - Other SUSY masses: from NMSPEC (NMSSMTOOLS)
  - LEP, B physics, g-2 through NMSSMTOOLS
  - Input at weak scale or GUT scale with NMSSMTools

CPV-MSSM & micrOMEGAs2.0

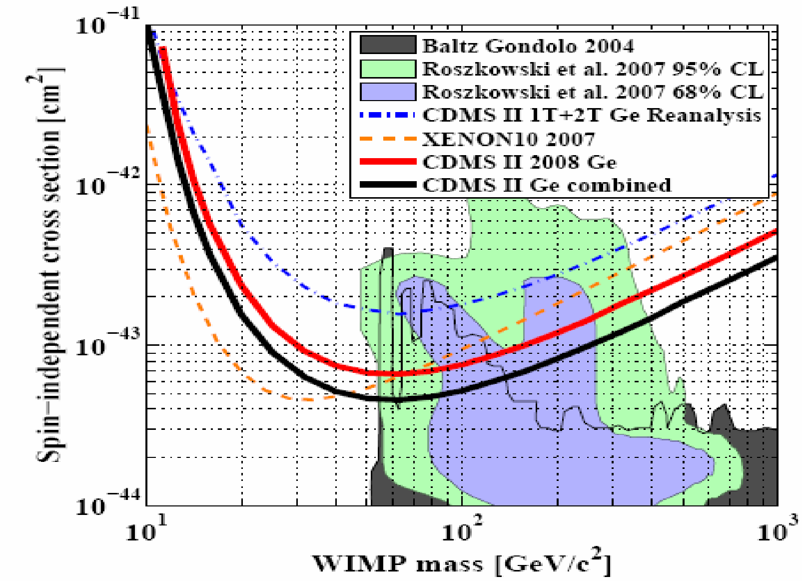
- Modify the model file in CalCHEP using LanHEP, real and imaginary parts for all complex parameters
- Input parameters : weak scale soft SUSY parameters
- Masses of 1st and 2nd generation sfermions: tree-level
- Interface to CPSuperH (J.S. Lee et al) : masses and mixings of Higgs, third generation sfermions, neutralino/chargino
- CPSuperH gives parameters of effective Higgs potential, as in MSSM 7 parameters, 3 of which can be complex ($\lambda_5\ \lambda_6\ \lambda_7$)
- Effective Lagrangian for Hbb, Htt including threshold corrections (from CPsuperH)
- Has all characteristics of micrOMEGAs
- edm constraints included, B-physics observables from CPSuperH

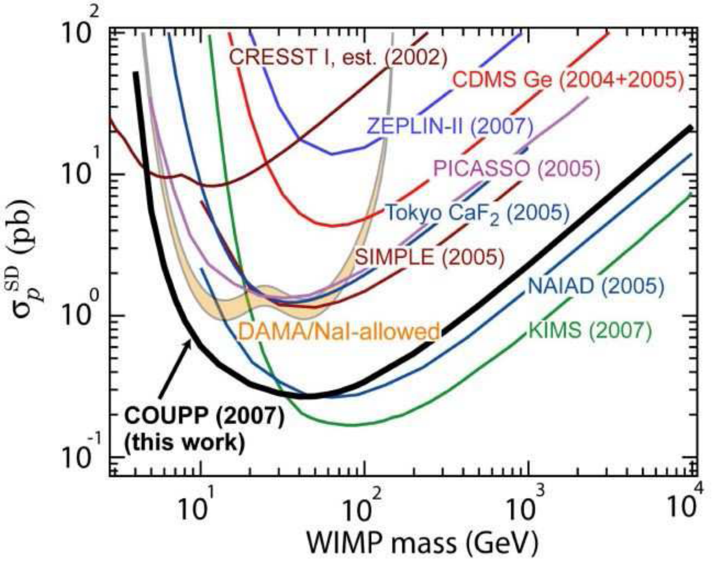
Direct detection

Direct detection

- Limits on LSP-nucleon cross section are improving every year, both for SI and SD
  - probe regions of parameter space of MSSM
  - constrain severely some other models (e.g. RHN)

- Recent results :
  - CDMS (0802.353 [astro-ph])
  - KIMS, COUPP (0804.2886[astro-ph])
  - DAMA confirm their annual modulation signal





Direct detection

- Scattering rate on nuclei

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n(A-Z)\right)^2 I(E)$$

$$\frac{dN^{SD}}{dE} = \frac{8M_{det}t}{2J+1}\frac{\rho_0}{M_\chi}(S_{00}(q)a_0^2 + S_{01}(q)a_0a_1 + S_{11}(q)a_1^2)I(E)$$

- WIMP-quark scattering
  - Particle physics model dependence
- WIMP – nucleon amplitude
- Nuclear form factors
- Velocity distribution of WIMPS
- Modularity and flexibility: can change velocity distribution, nuclear form factors, quark coefficients in nucleon

WIMP- Nucleon amplitude

- For any WIMP, need effective Lagrangian for WIMP-nucleon amplitude *at small momentum*,
- Generic form for a fermion

$$\begin{aligned}\mathcal{L}_F = &\boxed{\lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N} + i\kappa_1 \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \gamma_5 \psi_N + i\kappa_2 \overline{\psi}_\chi \gamma_5 \psi_\chi \overline{\psi}_N \psi_N + \kappa_3 \overline{\psi}_\chi \gamma_5 \psi_\chi \overline{\psi}_N \gamma_5 \psi_N \\ + &\kappa_4 \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \psi_N + \boxed{\xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N}\end{aligned}$$

- For Majorana fermion only 2 operators survive at small q^2

- First need to compute the WIMP quark amplitudes
  - normally computed symbolically from Feynman diagrams+ Fierz
  - Automatic approach (works for all models)

WIMP quark effective Lagrangian

	WIMP Spin	Even operators	Odd operators
SI	0 1/2 1	$2M_\chi \phi_\chi \phi^*_\chi \overline{\psi}_q \psi_q$ $\overline{\psi}_\chi \psi_\chi \overline{\psi}_q \psi_q$ $2M_\chi A_{\chi,\mu} A^\mu_\chi \overline{\psi}_q \psi_q$	$i(\partial_\mu \phi_\chi \phi^*_\chi - \phi_\chi \partial_\mu \phi^*_\chi) \overline{\psi}_q \gamma^\mu \psi_q$ $\overline{\psi}_\chi \gamma_\mu \psi_\chi \overline{\psi}_q \gamma^\mu \psi_q$ $+i\lambda_{q,o}(A^{*\alpha}_\chi \partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha \partial_\mu A^*_{\chi\alpha}) \overline{\psi}_q \gamma_\mu \psi_q$
SD	1/2 1	$\overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_q \gamma_\mu \gamma_5 \psi_q$ $\sqrt{6}(\partial_\alpha A^*_{\chi,\beta} A_{\chi\nu} - A^*_{\chi\beta} \partial_\alpha A_{\chi\nu})$ $\epsilon^{\alpha\beta\nu\mu} \overline{\psi}_q \gamma_5 \gamma_\mu \psi_q$	$-\frac{1}{2} \overline{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \overline{\psi}_q \sigma^{\mu\nu} \psi_q$ $i\frac{\sqrt{3}}{2}(A_{\chi\mu} A^*_{\chi\nu} - A^*_{\chi\mu} A_{\chi\nu}) \overline{\psi}_q \sigma^{\mu\nu} \psi_q$

- Operators for WIMP quark Lagrangian, extract automatically the coefficients for SI and SD –

$$\hat{\mathcal{L}}_{eff}(x) = \sum_{q,s} \lambda_{q,s} \hat{\mathcal{O}}_{q,s}(x) + \xi_{q,s} \hat{\mathcal{O}}'_{q,s}(x)$$

- In micrOMEGAs: evaluate coefficients numerically using projection operators
- Add all projection operators as new vertices in the model
- Compute χq-χq scattering element at zero momentum transfer
- Interference between one projection operator and effective vertex- single out SI or SD contribution

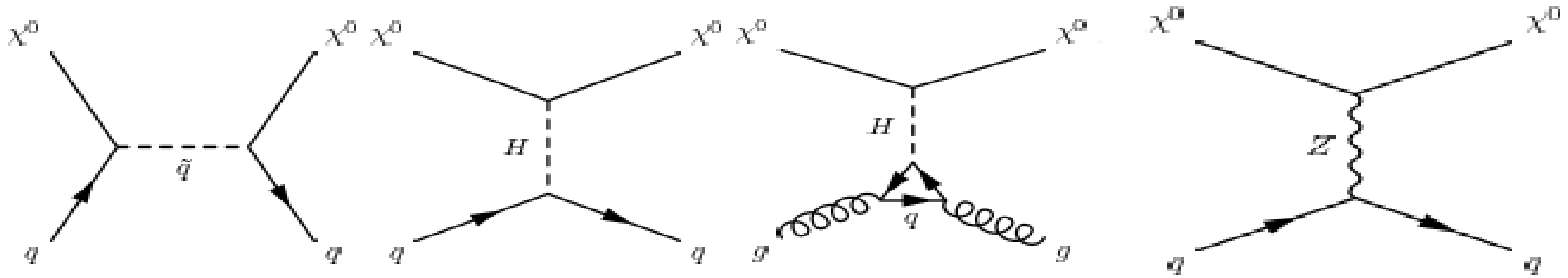
$$\lambda_{q,e} + \lambda_{q,o} = \frac{-i\langle q(p_1), \chi(p_2)|\hat{S}\hat{O}_{q,e}|q(p_1), \chi(p_2)\rangle}{\langle q(p_1), \chi(p_2)|\hat{O}_{q,e}\hat{O}_{q,e}|q(p_1), \chi(p_2)\rangle}$$

- Use quark and anti-quark scattering elements to split even/odd contributions
- The projection operators are added to the model file by micrOMEGAs
- Warning: in the model file must include couplings proportional to light quark masses (eg. Hqq coupling)

Direct detection

- Typical diagrams
- Higgs exchange often dominates

SD



For Dirac fermions Z exchange contributes to SI and SD

WIMP-quark to WIMP-nucleon

- Coefficients relate WIMP-quark operators to WIMP nucleon operators
  - Scalar, vector, pseudovector, tensor
  - Extracted from experiments
  - Source of theoretical uncertainties
- Example , scalar coefficients, contribution of q to nucleon mass

$$\langle N|m_q\overline{\psi}_q\psi_q|N\rangle = f_q^N M_N$$

$$\lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p}$$

$$f_Q^N = \frac{2}{27}\left(1 - \sum_{q\leq 3} f_q^N\right)$$

- Scalar coefficients extracted from ratios of light quark masses, pion-nucleon sigma term and σ_0 (size of SU(3) breaking effect)

$$\sigma_{\pi N} = 55 - 73\ \mathrm{MeV} \quad \text{and} \quad \sigma_0 = 35 \pm 5\ \mathrm{MeV}$$

- Large uncertainty in s-quark contribution

$$f_d^p = \frac{2\sigma_{\pi N}}{(1+\frac{m_u}{m_d})m_p(1+\alpha)}, \quad f_u^p = \frac{m_u}{m_d}\alpha f_d^p, \quad f_s^p = \frac{\sigma_{\pi N} y}{(1+\frac{m_u}{m_d})m_p}\frac{m_s}{m_d}$$

- Can lead to almost order of magnitude change in cross section
  - Bottino et al hep-ph/0010203
  - Ellis et al hep-ph/0502001

- Default values: (55,35) $f_s^p = 0.26$

- “standard values” : $\sigma_{\pi N}$=45MeV $f_S^p = 0.118 - 0.14.$

- Lattice calculations will help reduce uncertainties

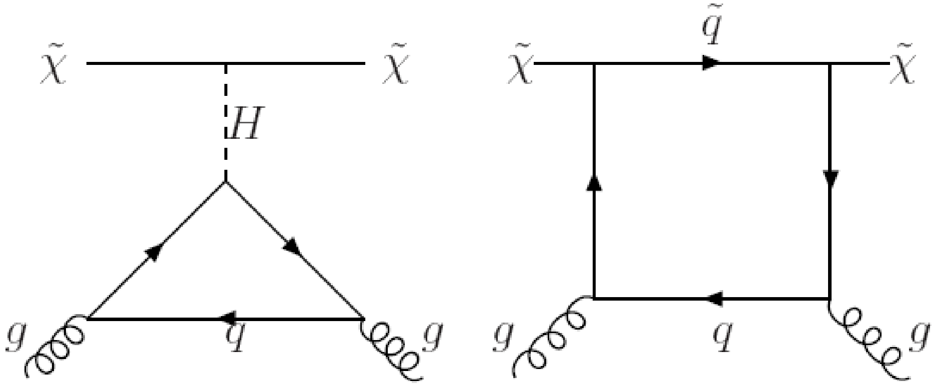
Tensor operators

- Tensor operator

$$\mathcal{O}_q^{\mu\nu} = \bar{q}(\gamma^\mu \overrightarrow{\partial}^\nu - \gamma^\mu \overleftarrow{\partial}^\nu + \gamma^\nu \overrightarrow{\partial}^\mu - \gamma^\nu \overleftarrow{\partial}^\mu + i m_q g^{\mu\nu})q$$

- To extract automatically coefficient of tensor operator- evaluate forward scattering at small momentum to take advantage of momentum dependence in matrix element of scalar-tensor operator
- In MSSM – tensor operators related to momentum dependence in squark diagram – large only for squarks not much heavier than LSP
- Contribution of twist-2 operator usually ~ %
- Nucleon form factors related to parton distribution functions (CTEQ)

Gluon and QCD



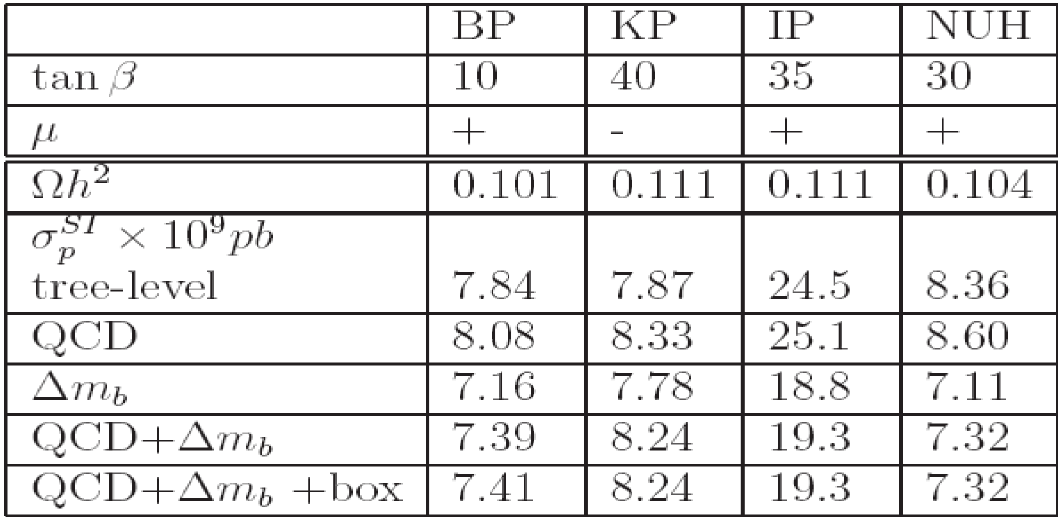
- Higgs-gluon contribution equivalent to Higgs heavy-quark contribution + factor for heavy quark content in nucleon
- Include QCD corrections

$$\langle N|m_Q\bar{\psi}_Q\psi_Q|N\rangle = -\frac{\Delta\beta}{2\alpha_s^2(1+2\gamma)}\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle$$

- Any coloured particle (squarks) treated similarly
- Box diagram usually subdominant, model-dependent, evaluated explicitly for SUSY models (Drees, Nojiri, 1993)

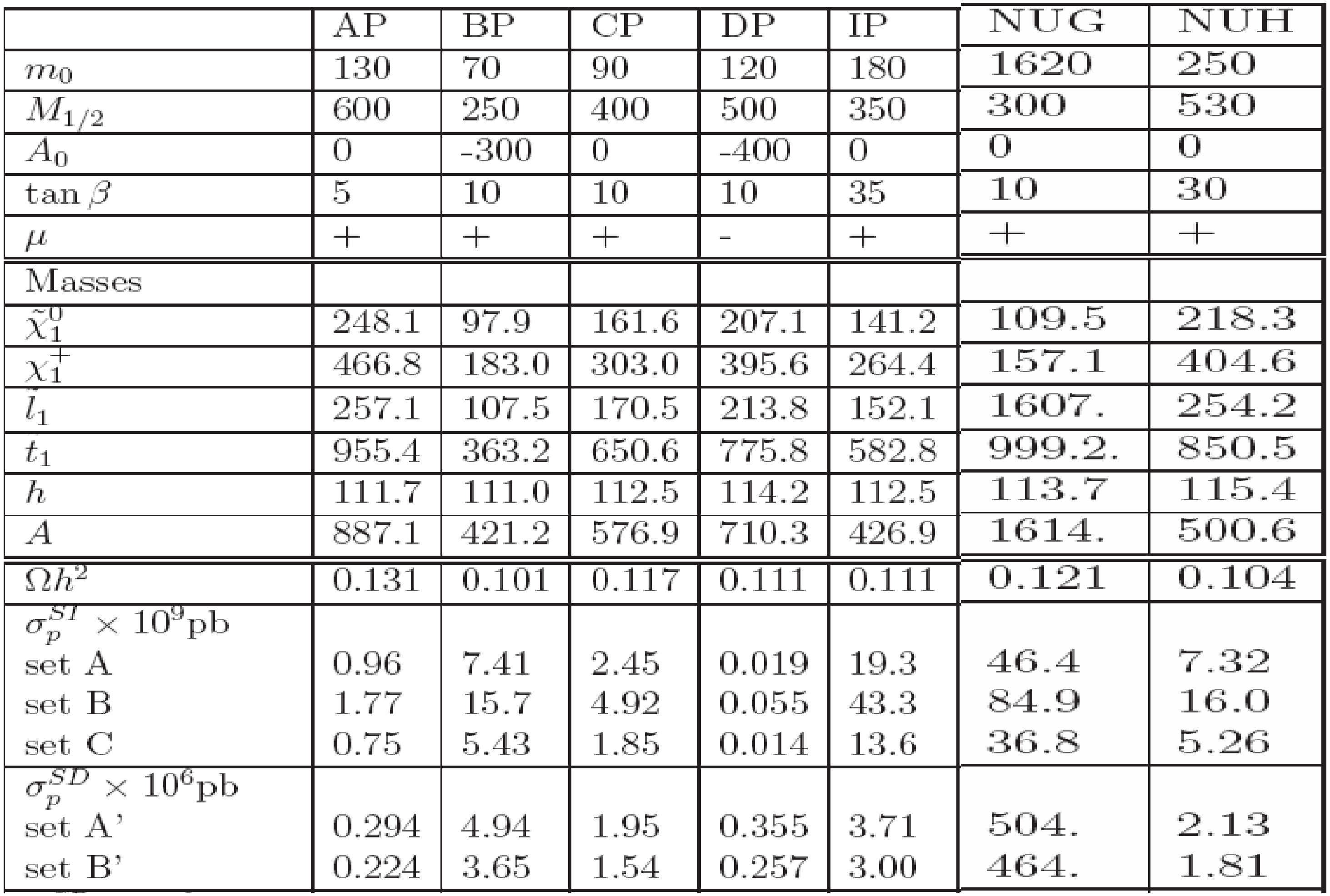
QCD and SUSY-QCD corrections

- In MSSM also include Δm_q corrections
- QCD and Δm_b corrections usually below 10% except at large tanβ
- QCD and Δm_b corrections reproduce well the one-loop result (includes also box diagram)



	BP	KP	IP	NUH
$\tan\beta$	10	40	35	30
μ	+	-	+	+
Ωh^2	0.101	0.111	0.111	0.104
$\sigma_p^{SI} \times 10^9 pb$ tree-level	7.84	7.87	24.5	8.36
QCD	8.08	8.33	25.1	8.60
Δm_b	7.16	7.78	18.8	7.11
QCD+Δm_b	7.39	8.24	19.3	7.32
QCD+Δm_b +box	7.41	8.24	19.3	7.32

Sample results -MSSM



	AP	BP	CP	DP	IP	NUG	NUH
m_0	130	70	90	120	180	1620	250
$M_{1/2}$	600	250	400	500	350	300	530
A_0	0	-300	0	-400	0	0	0
$\tan\beta$	5	10	10	10	35	10	30
μ	+	+	+	-	+	+	+
Masses							
$\tilde{\chi}_1^0$	248.1	97.9	161.6	207.1	141.2	109.5	218.3
χ_1^+	466.8	183.0	303.0	395.6	264.4	157.1	404.6
$\tilde{l}_1$	257.1	107.5	170.5	213.8	152.1	1607.	254.2
t_1	955.4	363.2	650.6	775.8	582.8	999.2.	850.5
h	111.7	111.0	112.5	114.2	112.5	113.7	115.4
A	887.1	421.2	576.9	710.3	426.9	1614.	500.6
Ωh^2	0.131	0.101	0.117	0.111	0.111	0.121	0.104
$\sigma_p^{SI} \times 10^9$pb							
set A	0.96	7.41	2.45	0.019	19.3	46.4	7.32
set B	1.77	15.7	4.92	0.055	43.3	84.9	16.0
set C	0.75	5.43	1.85	0.014	13.6	36.8	5.26
$\sigma_p^{SD} \times 10^6$pb							
set A'	0.294	4.94	1.95	0.355	3.71	504.	2.13
set B'	0.224	3.65	1.54	0.257	3.00	464.	1.81

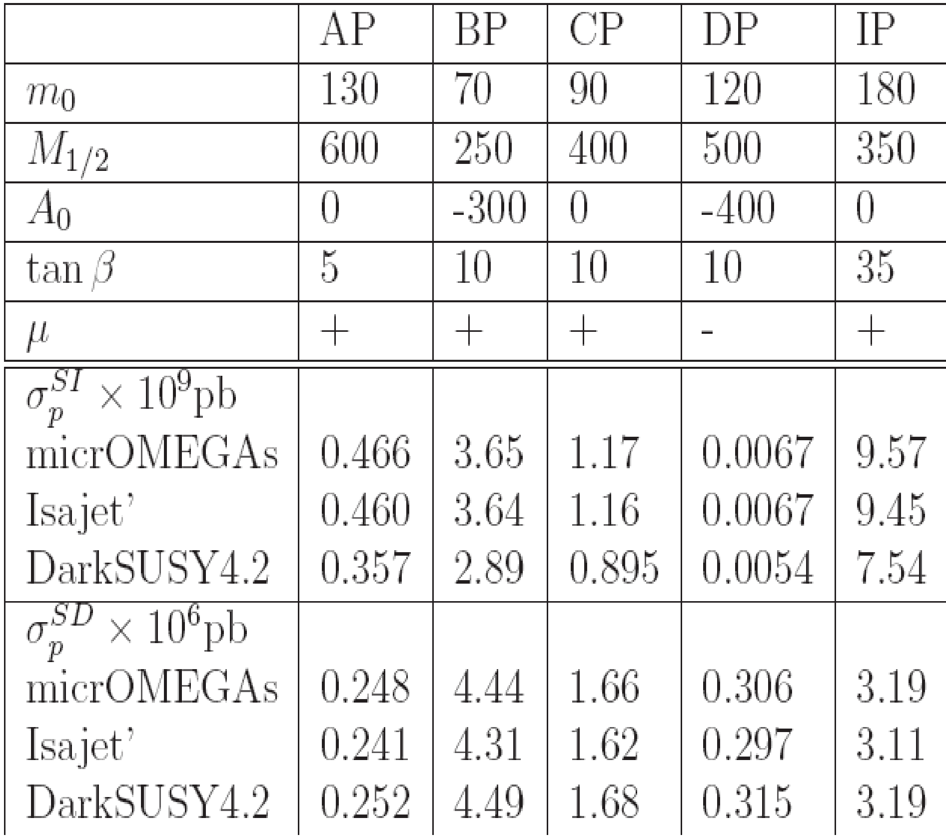
- ***Large uncertainty in σ^{SI} proton – coefficient for quark content in nucleon – in particular strange quark content***

Comparison with other codes- CMSSM

- Remove QCD and SUSY-QCD corrections in micrOMEGAs

- Micro - Isajet_7.77
  - Very good agreement

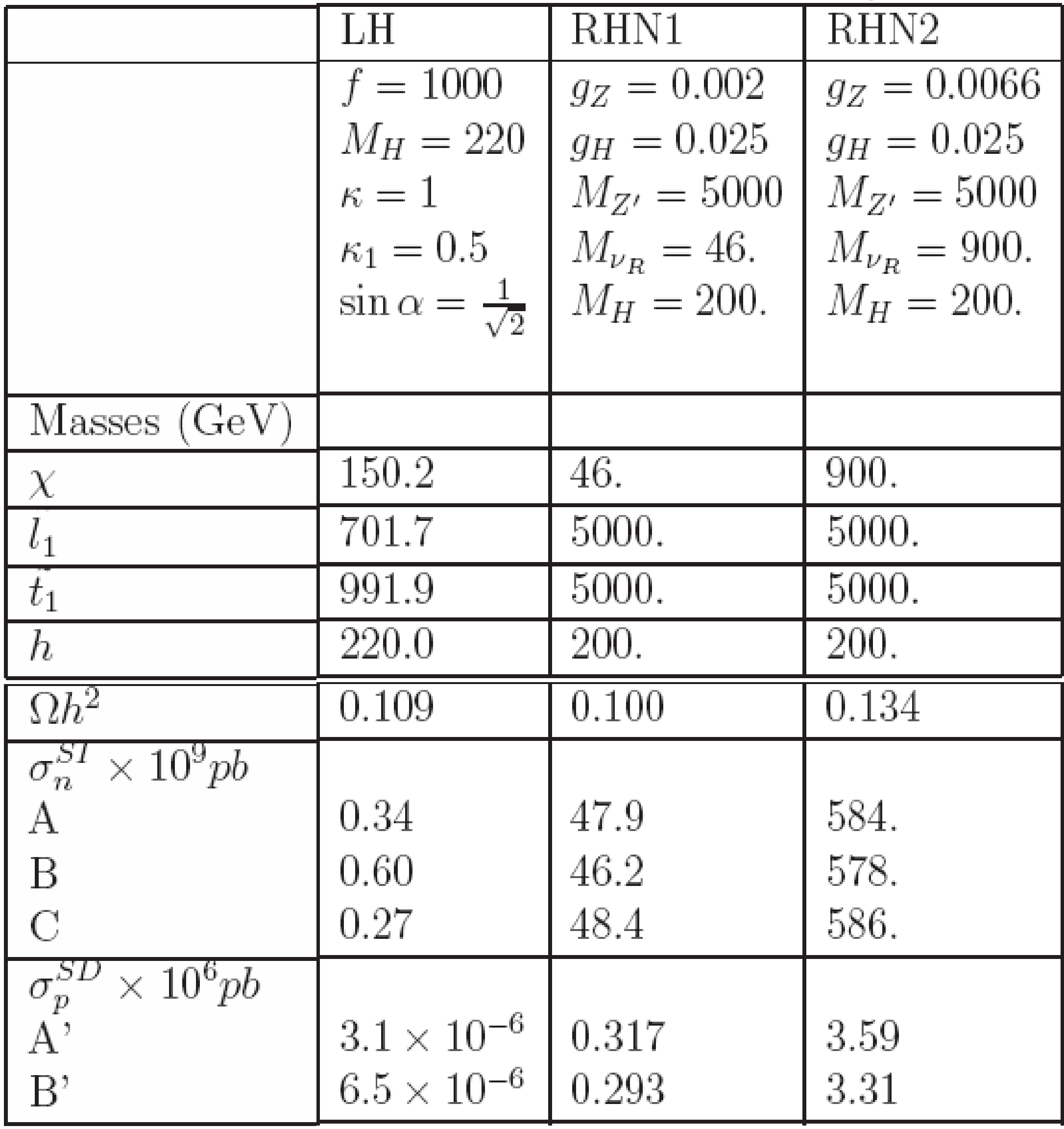
- Micro – DarkSUSY4.2
  - SI: difference in Higgs exchange (m_b mass)



	AP	BP	CP	DP	IP
m_0	130	70	90	120	180
$M_{1/2}$	600	250	400	500	350
A_0	0	-300	0	-400	0
$\tan\beta$	5	10	10	10	35
μ	+	+	+	-	+
$\sigma_p^{SI} \times 10^9$pb					
micrOMEGAs	0.466	3.65	1.17	0.0067	9.57
Isajet'	0.460	3.64	1.16	0.0067	9.45
DarkSUSY4.2	0.357	2.89	0.895	0.0054	7.54
$\sigma_p^{SD} \times 10^6$pb					
micrOMEGAs	0.248	4.44	1.66	0.306	3.19
Isajet'	0.241	4.31	1.62	0.297	3.11
DarkSUSY4.2	0.252	4.49	1.68	0.315	3.19

Results- other BSM

- RHN and LHM: analytical formula : good agreement
- LHM : suppressed SD contribution (no Z exchange)
- RHN : vector interaction no theoretical uncertainty from dominant contribution



	LH	RHN1	RHN2
	$f = 1000$ $M_H = 220$ $\kappa = 1$ $\kappa_1 = 0.5$ $\sin\alpha = \frac{1}{\sqrt{2}}$	$g_Z = 0.002$ $g_H = 0.025$ $M_{Z'} = 5000$ $M_{\nu_R} = 46.$ $M_H = 200.$	$g_Z = 0.0066$ $g_H = 0.025$ $M_{Z'} = 5000$ $M_{\nu_R} = 900.$ $M_H = 200.$
Masses (GeV)			
χ	150.2	46.	900.
l_1	701.7	5000.	5000.
t_1	991.9	5000.	5000.
h	220.0	200.	200.
Ωh^2	0.109	0.100	0.134
$\sigma_n^{SI} \times 10^9 pb$			
A	0.34	47.9	584.
B	0.60	46.2	578.
C	0.27	48.4	586.
$\sigma_p^{SD} \times 10^6 pb$			
A’	3.1×10^{-6}	0.317	3.59
B’	6.5×10^{-6}	0.293	3.31

Indirect detection

- Motivation: Pamela, GLAST, Hess, EGRET….
- Flux calculation

$$\Phi_{\gamma,\nu} = \frac{1}{8\pi}\boxed{\frac{< \sigma_{ann} v >}{m_\chi^2}}\overbrace{\boxed{\sum_{f.s.}\left(\frac{dN_{\gamma,\nu}}{dE}\right)_{f.s.}}}^{\text{From Pythia}}\overbrace{\boxed{\int_{l.o.s.}\rho_s^2}}^{\text{astrophysics}}$$

- For charged particles (positron, antiproton): propagation equations based on
  - Lavalle, Pochon, Salati, Taillet, astro-ph/0603796
  - Not yet in public version

- dN/dE : basic channels ff, VV, VH, HH
- For particles of unknown mass (H,Z'..) compute 1->2 decay recursively until only basic channels
- Loop level final states : γγ, γZ,gg
  - computed with Sloops (not in public version/not model independent)
  - lead to monoenergetic line
  - can be included with effective vertex in the model file
- Halo profile :

$$\rho_s(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/a)^\alpha}{1+(r/a)^\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}$$

$r_\odot = 8$ kpc

$\rho_\odot = 0.3$ GeV.cm^{-3}

Halo model	α	β	γ	a (kpc)
Isothermal with core	2	2	0	4
NFW	1	3	1	20
Moore	1.5	3	1.5	28

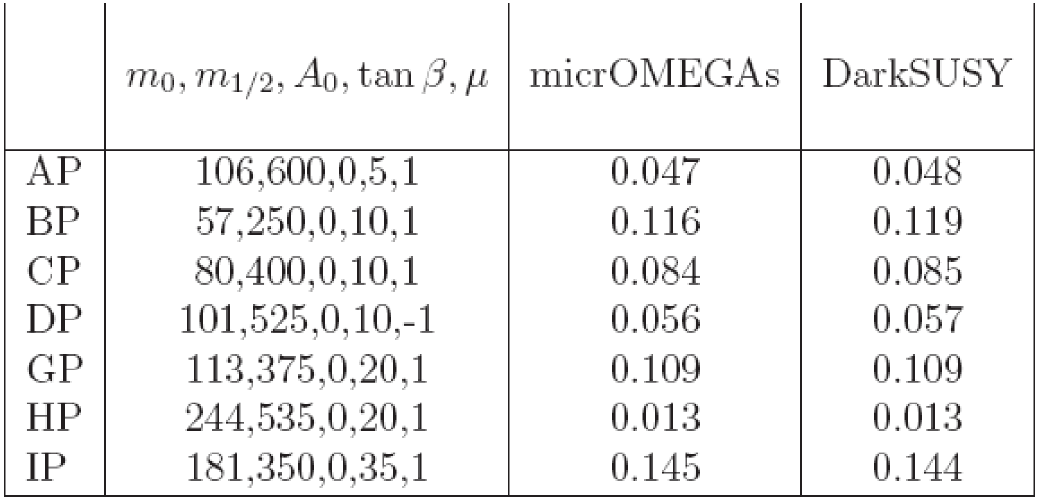
Comparison with other public dark matter tools

DM Tools

		micrOMEGAs	DarkSUSY	IsaTools
Observables	Relic density	$\star$	$\star$	$\star$
	resonances	$\star$	$\star$	$\star$
	$\sigma_{\chi p}$	$\star$	$\star$	$\star$
	$\sigma_{\chi N}$	$\star$	$\star$	$\star$
	$\sigma v\|_{v\approx 0}$	$\star$	$\star$	$\star$
	Detection rates	$\gamma, e^+, \bar{p}, \nu$	$\gamma, e^+, \bar{p}, \nu, \bar{D}$	
	Propagation	not public	GALPROP or semi-analytic	
	Neutrino rates		Sun, Earth	
Precision	Input GUT scale	SusPect, Isajet SoftSUSY, Spheno	Isajet, SuSpect	Isajet
	Input EW scale	Suspect, Isajet	SUSY(1loop)+FH	Isajet
	SLHA input	Yes	Yes	Yes
	Higgs masses	SpectCalc	FH or Isajet	Isajet
	hbb	(Susy-)QCD	QCD not in DD	(Susy-)QCD
	Higgs potential	Effective	Tree	Effective
Colliders	Collider applications	$2 \to 2, 1 \to 2, 3$ CalcHEP	No	Isajet
	$b \to s\gamma$, $B_s \to \mu^+\mu^-$	$+B \to \tau\nu$	yes	yes
	$(g-2)_\mu$, $\Delta\rho$	yes	yes	yes
		LEP	LEP	LEP
DM models	GUT scale models	SpectCalc	Isajet, Suspect	Isajet
	Other models	CPVMSSM, (C)NMSSM	complex(not tested)	MSSM+ν_R
		RHNM,LHM	No	No
	Speed	$\star\star$	$\star$	–

Comparison

- For relic density, extensive comparison of micrOMEGAs1.0 with DarkSUSY ~ 200x: very good agreement
  - Only differences : Higgs masses, treatment of Higgs vertices and SUSY QCD corrections
- Quick comparison of micrOMEGAs2.2 with DarkSUSY5.0.4 (yesterday) still very good agreement



	$m_0, m_{1/2}, A_0, \tan\beta, \mu$	micrOMEGAs	DarkSUSY
AP	106,600,0,5,1	0.047	0.048
BP	57,250,0,10,1	0.116	0.119
CP	80,400,0,10,1	0.084	0.085
DP	101,525,0,10,-1	0.056	0.057
GP	113,375,0,20,1	0.109	0.109
HP	244,535,0,20,1	0.013	0.013
IP	181,350,0,35,1	0.145	0.144

Download and Web interface

- New version micromegas_2.2
  - http:://wwwlapp.in2p3.fr/lapth/micromegas
  - For help, bug report : micro.omegas@lapp.in2p3.fr

- Interactive web page for direct/indirect detection rates--R.Lemrani

  http://pisno.pit.physik.uni-tuebingen.de/darkmatter/
  - **- Expected recoil spectra and exclusion plots**
  - **- Experimental strategy : quenching, resolution and efficiency**
  - **- Statistical treatment : Feldman Cousin, Yellin**
  - **- Indirect dark matter searches : fluxes for Neutralino only**

Outlook

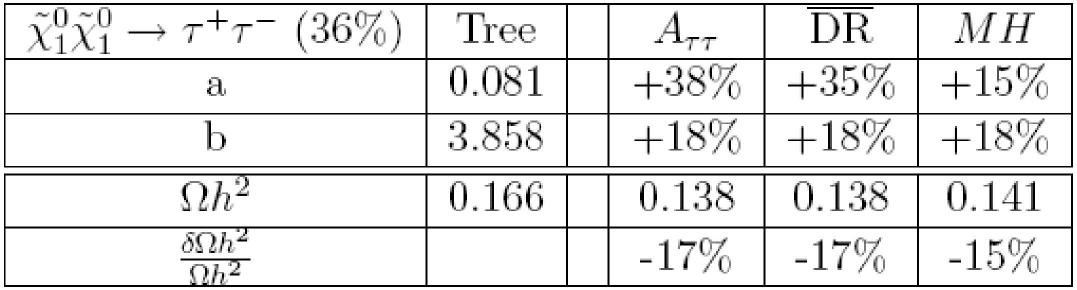
- *Public version with complete indirect detection module (with propagation)*
  - *P. Brun et al + A.Zhukov with GALPROP*
- *Incorporating one-loop for dominant processes in MSSM – beyond improved Higgs vertices*
  - *Sloops (Baro, Boudjema, Chalons, Semenov)*
- *Alternative cosmological scenarii*
- *Pursue implementation of new models*

An explicit example

- Computation of annihilation cross section of neutralinos in a few typical annihilation processes

- Bino LSP : annihilation into fermions
- One-loop corrections can be large

- Can most of these corrections be absorbed in effective couplings and masses ?



$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-$ (36%)	Tree		$A_{\tau\tau}$	$\overline{\mathrm{DR}}$	MH
a	0.081		+38%	+35%	+15%
b	3.858		+18%	+18%	+18%
Ωh^2	0.166		0.138	0.138	0.141
$\frac{\delta\Omega h^2}{\Omega h^2}$			-17%	-17%	-15%

Why one-loop

- Relic abundance extracted from cosmological measurements about 15% accuracy.
- Will improve with Planck (few percent)

- Tree-level computation of annihilation cross sections might not be precise enough

- (SUSY)-QCD corrections are expected to be large : already seen for Higgs
- EW corrections could be large

- SloopS: an automatic code for computation of one-loop diagrams in the MSSM
  - Based on LanHEP+ FormCalC
  - Baro, Boudjema, Semenov : arXiv:0710.1821

Conclusion

- *To understand the nature of* dark matter *clearly need information and cross checks from cosmology, direct and indirect detection as well as from collider physics*

- *Public tools to perform these analysis are available*
  - *micrOMEGAs_2.2 (generic model)*
  - *DarkSUSY, IsaRED (SUSY)*

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