Tools and Monte-Carlos for the New Physics

Tools for Dark Matter

(New Physics with emphasis on SUSY)

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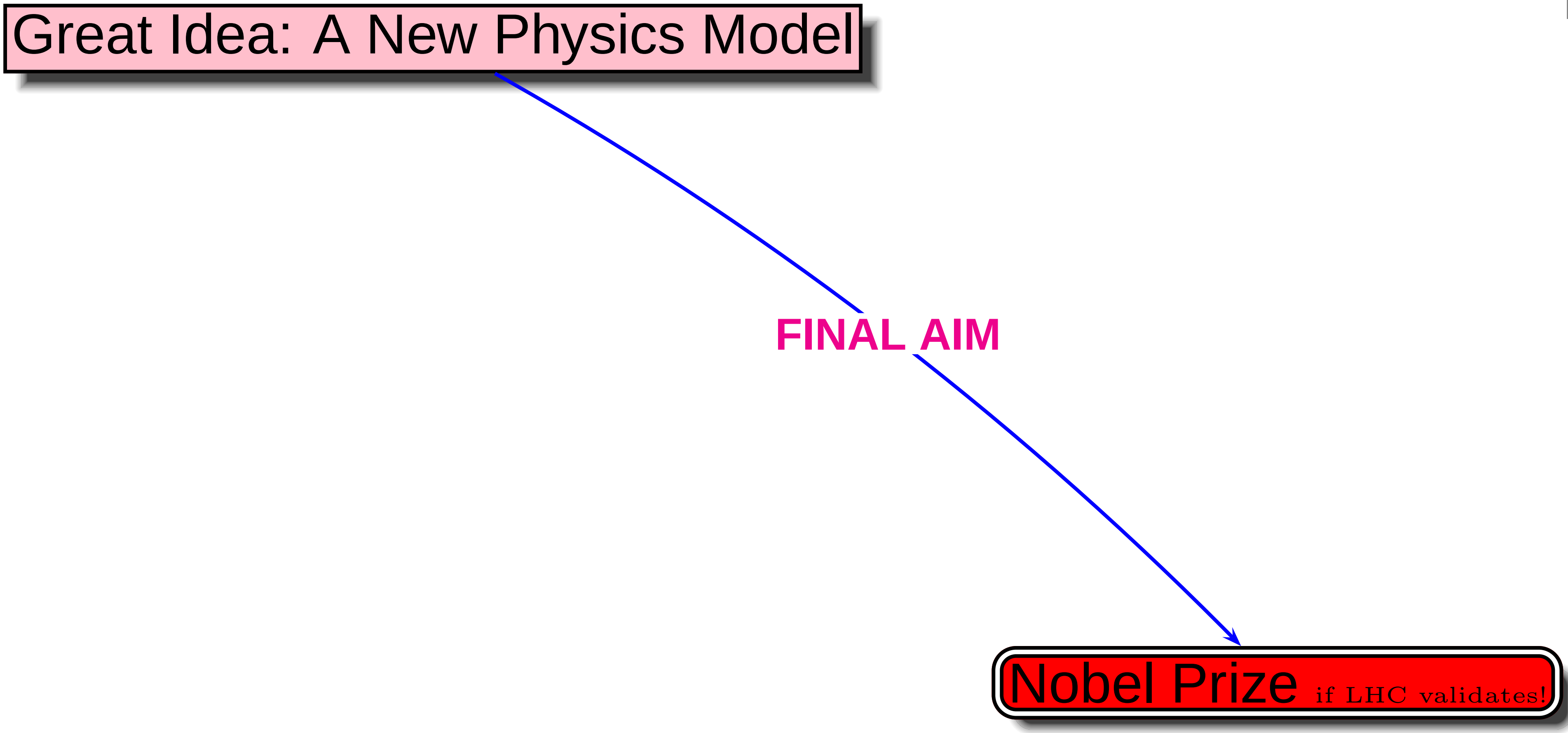
OUTLINE

- What's a tool? in particular for the New Physics
- Lessons from the Colliders and Particle Physics
  - Components and modular structures
  - shopping list with comments
  - Interface, Les Houches Accords
- DM codes, components
- Main DM codes, DarkSUSY vs micrOMEGAs vs...
- micrOMEGAs, automation and general New Physics
  - Relic density
  - Direct Detection and extraction of the effective $\mathcal{L}_{\chi q}$
  - Indirect detection and propagation, comparison of micrOMEGAs and DarkSUSY
  - DarkSUSY and ν from the Sun
- SloopS: a general code for SUSY at one-loop (collider and astrophyics/cosmology)
  - modular structure
  - loops and renormalisation
  - some results for annihilation cross section at one-loop
  - heavy winos: Sudakov logs and important $2 \to 3$ processes

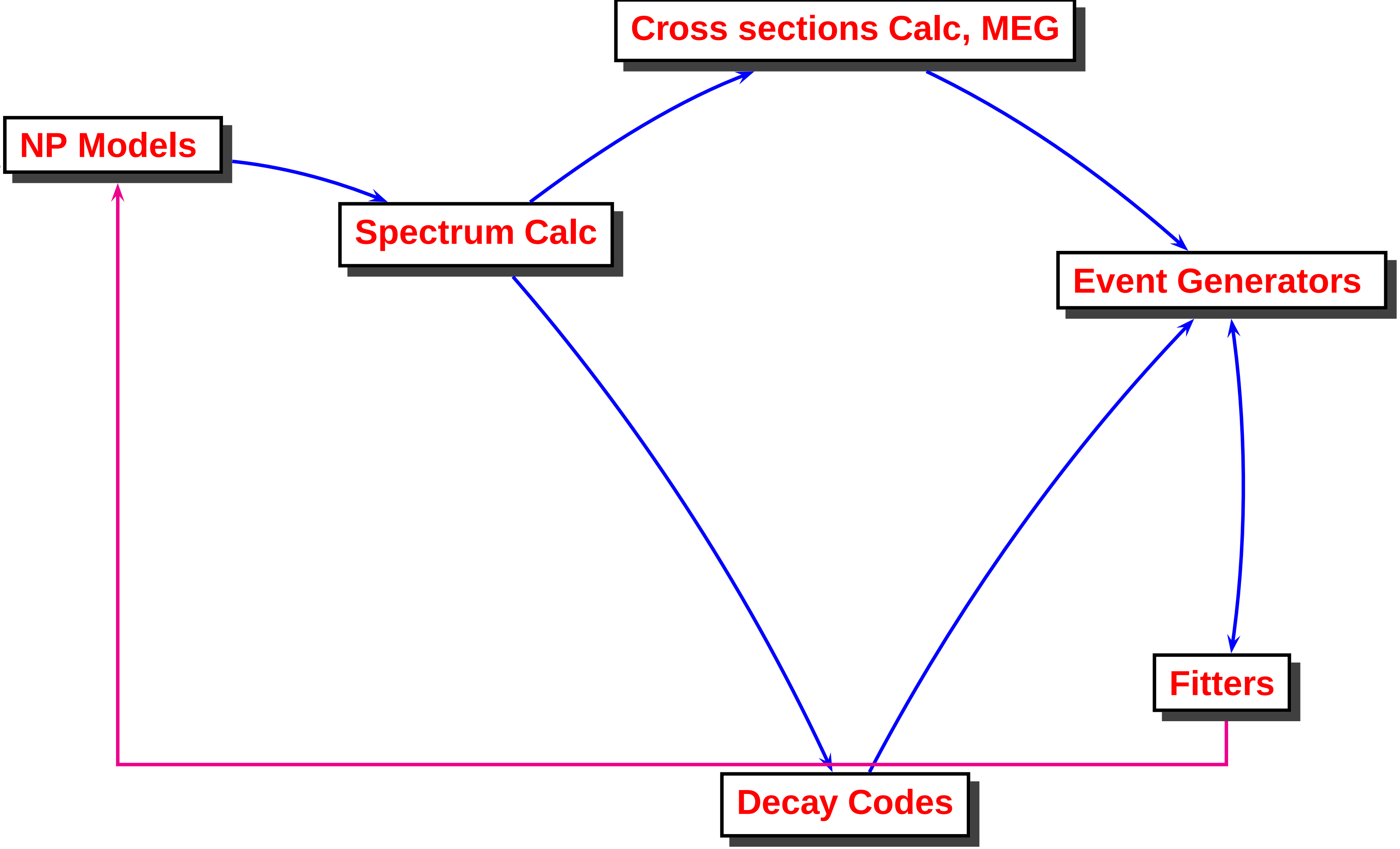
Nobel Dreams

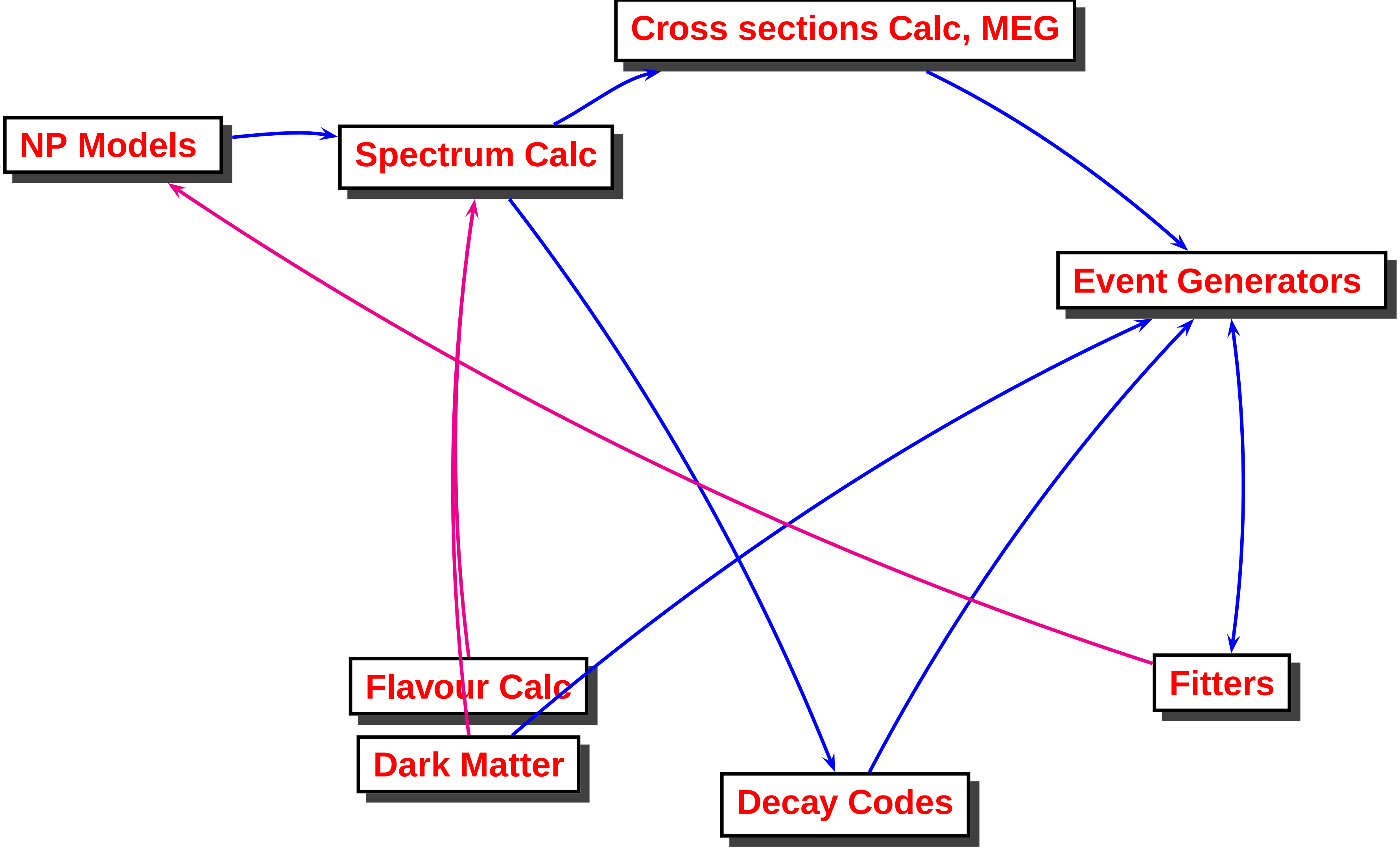


NP Models

FINAL AIM

Event Generators


Cross sections Calc, MEG
NP Models
Spectrum Calc
Event Generators
Fitters
Decay Codes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Cross sections Calc, MEG

NP Models

Spectrum Calc

- SUSY
  - MSSM
  - mSUGRA
  - GMSB, AMSB
  - NMSSM
  - RPV, CPV,...
- TeXColour
- Extra-dim
- Little Higgs
- $f^\star, V'$
- Black Holes (!)

Event Generators

Flavour Calc

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Spectrum Calc

- FeynHiggs
- NMHDECAY$\star$
- RGE Codes
  - Isasusy
  - SoftSusy
  - Spheno
  - Suspect

Event Generators

Flavour Calc

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Event Generators

Flavour Calc

- $(g-2)_\mu$
- $b \to s\gamma$
- $B_s \to \mu^+\mu^-$
- Asym, $\Delta M, \cdots$

Fitters

Decay Codes

Dark Matter

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Flavour Calc

Dedicated Codes

- SusyBSG
- SuperIso

Dark Matter

Cross sections Calc, MEG

- Tree-level,any
  - CalcHEP, CompHEP
  - GRACE, FORMCalc
  - Madgraph
  - SHERPA/Amegic++
  - Whizard/O'Mega
- 1-loop dedicated
  - AF's SLEPTONS
  - Prospino, hprod
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Flavour Calc

Dark Matter

- `SIsoRelic`
- `micrOMEGAs`
  `SloopS`$\star$
- `DARKSUSY`
- `IsaRED/RES`

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CatFish, Charybdis,
TrueNoir

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$\mathcal{L}$

Feynman rules

(Eff. Pot.)

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manual

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LanHEP/FeynRules

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automated

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Cross talks

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SLHA,BSM-LHEF

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yes. but we have a modular structure, let codes talk to each other and let's implement quickly and efficiently

from Konstantin Matchev

Experimentalist's complaint: This model is very nice,

but do you have an event generator for it? is it in Pythia?

not that many MC developers

On the other hand, too many model builders

$$N_{\rm model\ builders} \gg N_{MC dev.} \longrightarrow$$

$$N_{existing\ models} \gg N_{implemented\ model}$$

even worse

$$dN_{existing\ models}/dt \gg dN_{implemented\ model}/dt$$

SLHA 1 and 2

SLHA (1): MSSM, SLHA2 (CPV,RPV,NMSSM) Most of the authors have adopted it

- Signs (μ,..), factors of $\sqrt{2}$
- Mixing angles conventions
- Eigenstates decomposition
- Renormalisation schemes/scales !!!
- Effective field content (sparticles integrated out or not)
- SLHA2 more of a headache, but we got there eventually

BSM LHEF

This is a mix of

- SLHA2 and (model parameters)

  introduce new SLHA like blocks QNUMBERS for each BSM particle containing PDG code, spin, elec. charge, colour rep., particle/antiparticle

- and LHEF2 (xml format) for event files

Pass on the names in a standard manner: PDG code.

Code	Name	Code	Name	Code	Name	Code	Name
1	d	11	e^-	21	g		
2	u	12	ν_e	22	γ	35	H^0
3	s	13	μ^-	23	Z^0	36	A^0
4	c	14	ν_μ	24	W^+	37	H^+
5	b	15	τ^-	25	h^0		
6	t	16	ν_τ			39	G (graviton)

SM fundamental particle codes (+ extended Higgs sector)

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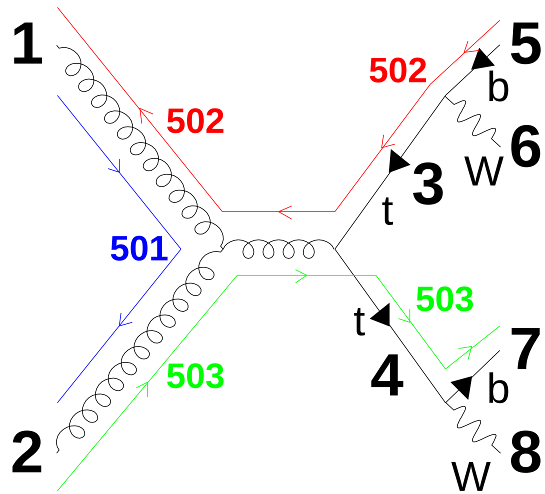
For New Physics particles, create new code names (1000000+), SLHA2

Scalar Quarks

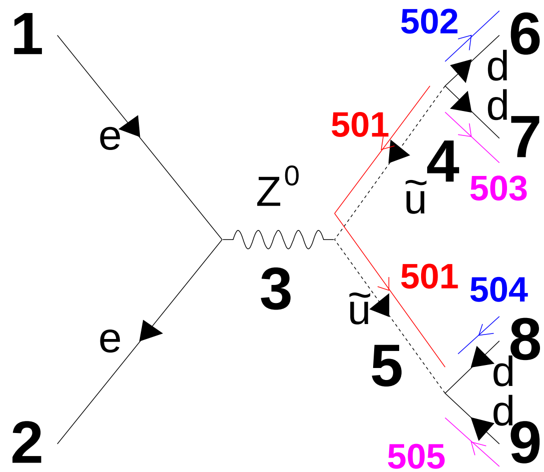
FLV / RPV / CPV	No / No / No	Yes / No / No	No / Yes / No	No / No / Yes	Yes / Yes / No	Yes / No / Yes	NMSSM
1000001	$\tilde{d}_L$	$\tilde{d}_1$	$\tilde{d}_1$	$\tilde{d}_L$	$\tilde{d}_1$	$\tilde{d}_1$	$\tilde{d}_L$
1000002	$\tilde{u}_L$	$\tilde{u}_1$	$\tilde{u}_1$	$\tilde{u}_L$	$\tilde{u}_1$	$\tilde{u}_1$	$\tilde{u}_L$
1000003	$\tilde{s}_L$	$\tilde{d}_2$	$\tilde{d}_2$	$\tilde{s}_L$	$\tilde{d}_2$	$\tilde{d}_2$	$\tilde{s}_L$
1000004	$\tilde{c}_L$	$\tilde{u}_2$	$\tilde{u}_2$	$\tilde{c}_L$	$\tilde{u}_2$	$\tilde{u}_2$	$\tilde{c}_L$
1000005	$\tilde{b}_1$	$\tilde{d}_3$	$\tilde{d}_3$	$\tilde{b}_1$	$\tilde{d}_3$	$\tilde{d}_3$	$\tilde{b}_1$
1000006	$\tilde{t}_1$	$\tilde{u}_3$	$\tilde{u}_3$	$\tilde{t}_1$	$\tilde{u}_3$	$\tilde{u}_3$	$\tilde{t}_1$
2000001	$\tilde{d}_R$	$\tilde{d}_4$	$\tilde{d}_4$	$\tilde{d}_R$	$\tilde{d}_4$	$\tilde{d}_4$	$\tilde{d}_R$
2000002	$\tilde{u}_R$	$\tilde{u}_4$	$\tilde{u}_4$	$\tilde{u}_R$	$\tilde{u}_4$	$\tilde{u}_4$	$\tilde{u}_R$
2000003	$\tilde{s}_R$	$\tilde{d}_5$	$\tilde{d}_5$	$\tilde{s}_R$	$\tilde{d}_5$	$\tilde{d}_5$	$\tilde{s}_R$
2000004	$\tilde{c}_R$	$\tilde{u}_5$	$\tilde{u}_5$	$\tilde{c}_R$	$\tilde{u}_5$	$\tilde{u}_5$	$\tilde{c}_R$
2000005	$\tilde{b}_2$	$\tilde{d}_6$	$\tilde{d}_6$	$\tilde{b}_2$	$\tilde{d}_6$	$\tilde{d}_6$	$\tilde{b}_2$
2000006	$\tilde{t}_2$	$\tilde{u}_6$	$\tilde{u}_6$	$\tilde{t}_2$	$\tilde{u}_6$	$\tilde{u}_6$	$\tilde{t}_2$

Particle codes and corresponding labels for squarks.
The labels in the first column correspond to the current PDG nomenclature.



I	ISTUP(I)	IDUP(I)	MOTHUP(1,I)	MOTHUP(2,I)	ICOLUP(1,I)	ICOLUP(2,I)
1	–1	21 (g)	0	0	501	502
2	–1	21 (g)	0	0	503	501
3	+2	–6 ($\bar{t}$)	1	2	0	502
4	+2	6 (t)	1	2	503	0
5	+1	–5 ($\bar{b}$)	3	3	0	502
6	+1	–24 (W^-)	3	3	0	0
7	+1	5 (b)	4	4	503	0
8	+1	24 (W^+)	4	4	0	0

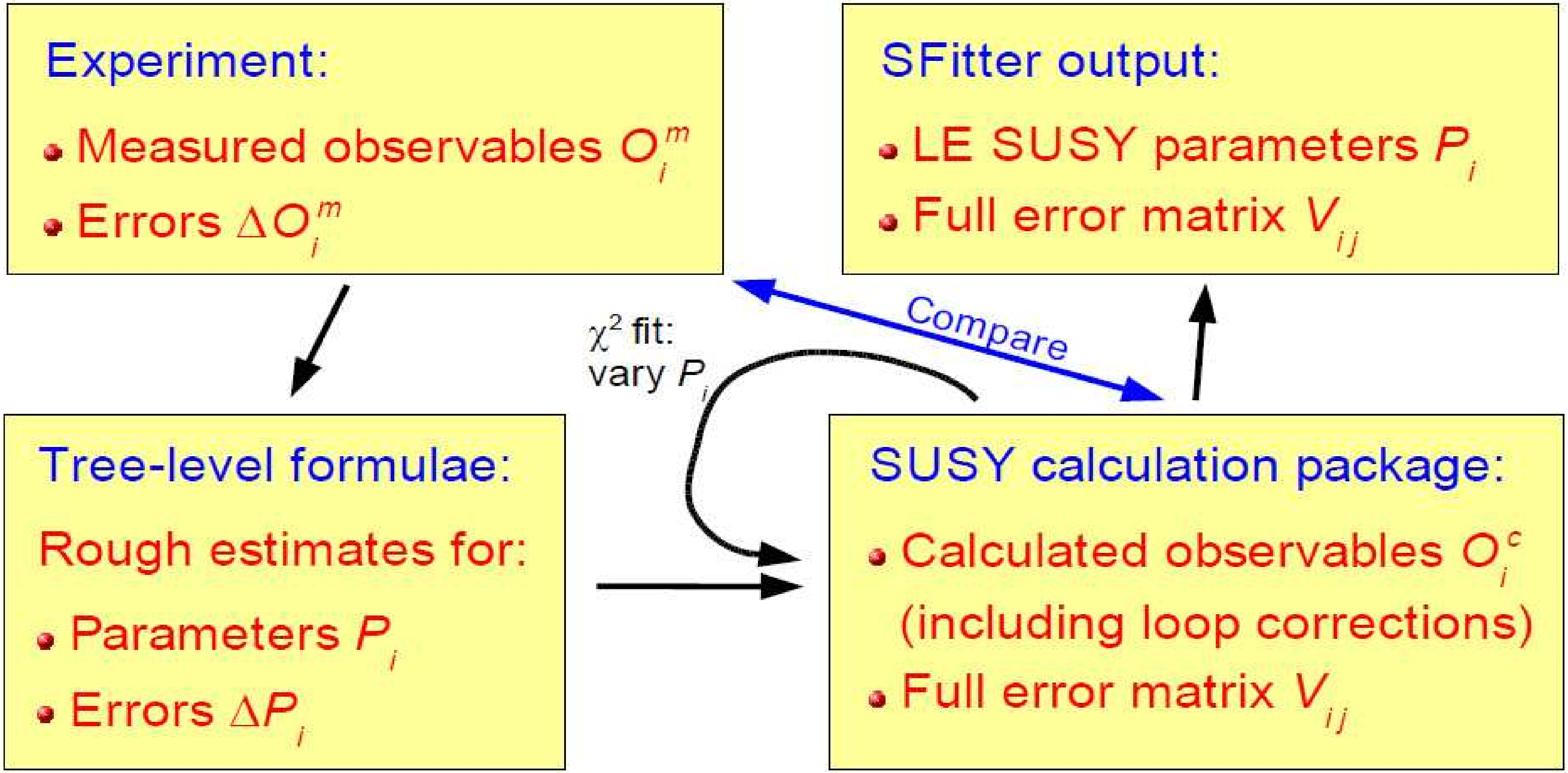
Pass the colour information, essential for parton shower and hadronisation, apart of course from the kinematics



I	ISTUP(I)	IDUP(I)	MOTHUP(1,I)	MOTHUP(2,I)	ICOLUP(1,I)	ICOLUP(2
1	–1	11 (e^-)	0	0	0	0
2	–1	–11 (e^+)	0	0	0	0
3	+2	23 (Z^0)	1	2	0	0
4	+2	–1000002 ($\tilde{\bar{u}}$)	3	3	0	501
5	+2	1000002 ($\tilde{u}$)	3	3	501	0
6	+1	1 (d)	4	4	502	0
7	+1	1 (d)	4	4	503	0
8	+1	–1 ($\bar{d}$)	5	5	0	504
9	+1	–1 ($\bar{d}$)	5	5	0	505

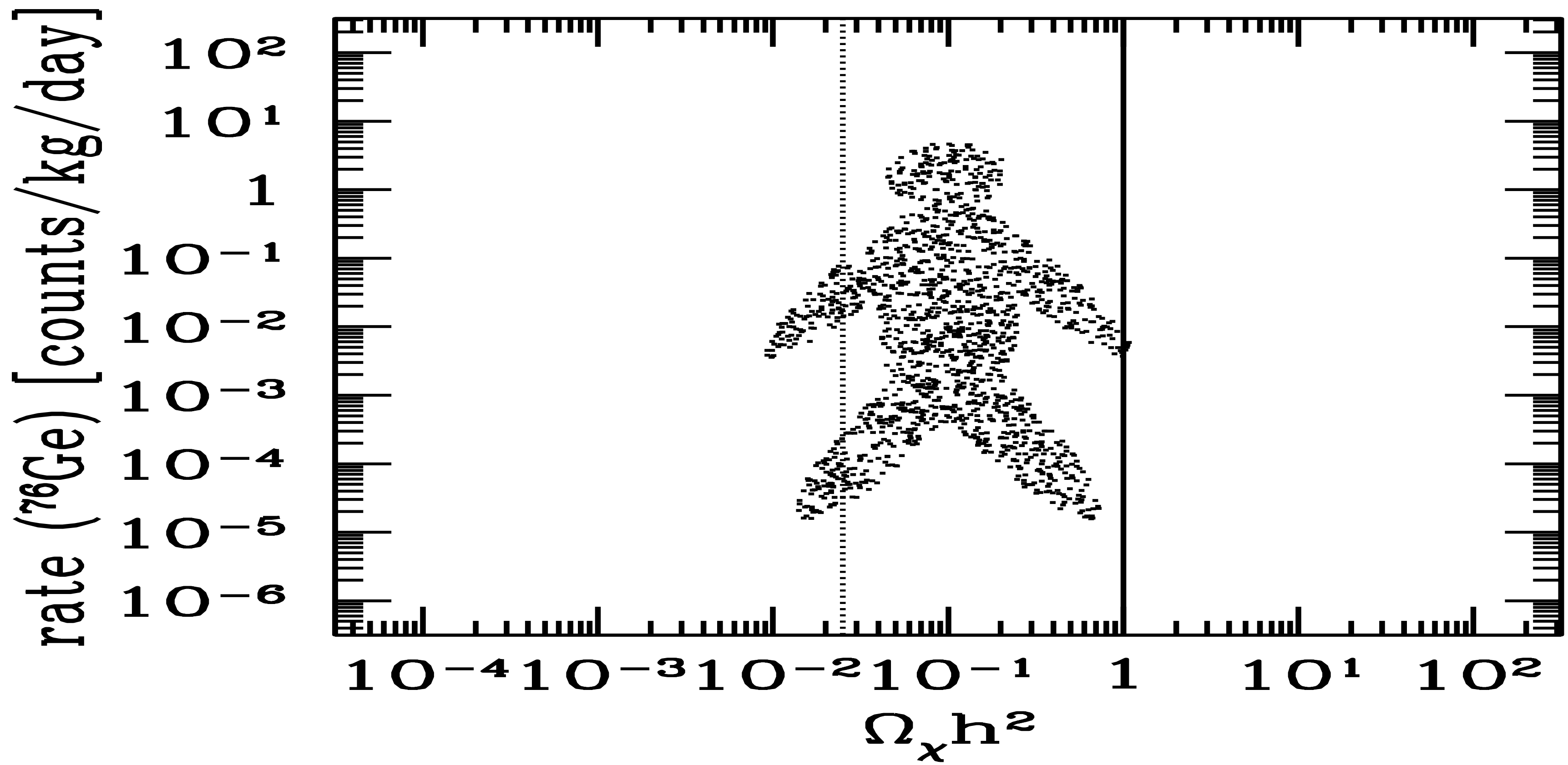
Baryon number violation, SUSY RPV

Codes for Fits: Fittino, SFITTER



tree-level vs "1-loop level", fits after background subtraction?

P. Gondolo, J. Edsjo



BSM Tools Repository

- http://www.ippp.dur.ac.uk/montecarlo/BSM

  Please submit your code or get a code from there

  If you contribute a code make it SLHA/LHEF compliant, if SLHA exists for the model please give a description of the code: what physics there is inside not just how to run it!!

  at the moment about 50 BSM tools listed so far...

- other repositories, e.g. http://mcelrath.org/Notes/Software (see also open directory project)

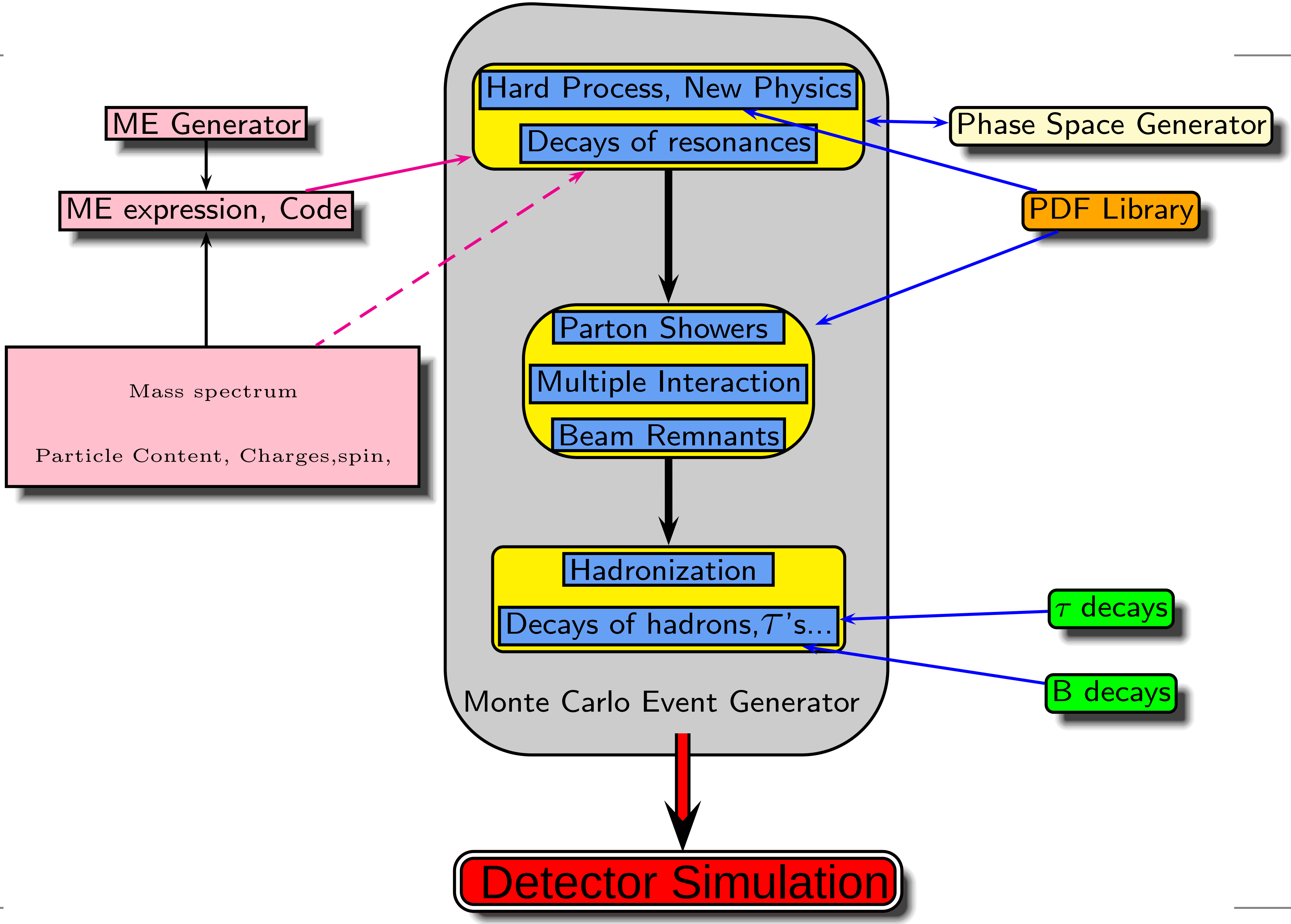
Organise round-tables involving model builders, calculation theorists, experimentalists, astrophysicists,...

- More work on New Physics which is not SUSY needed
- for some SUSY models, probably need “background tools”: contact with SM/QCD tools
- experimentalists need to speak up and ask what is needed most urgently : priority list (similar to what has been done for SM in Les Houches)
- for DM tools, theorists also need to speak up
- how should codes be interfaced and written: modules, C++, SLHA,LHEF

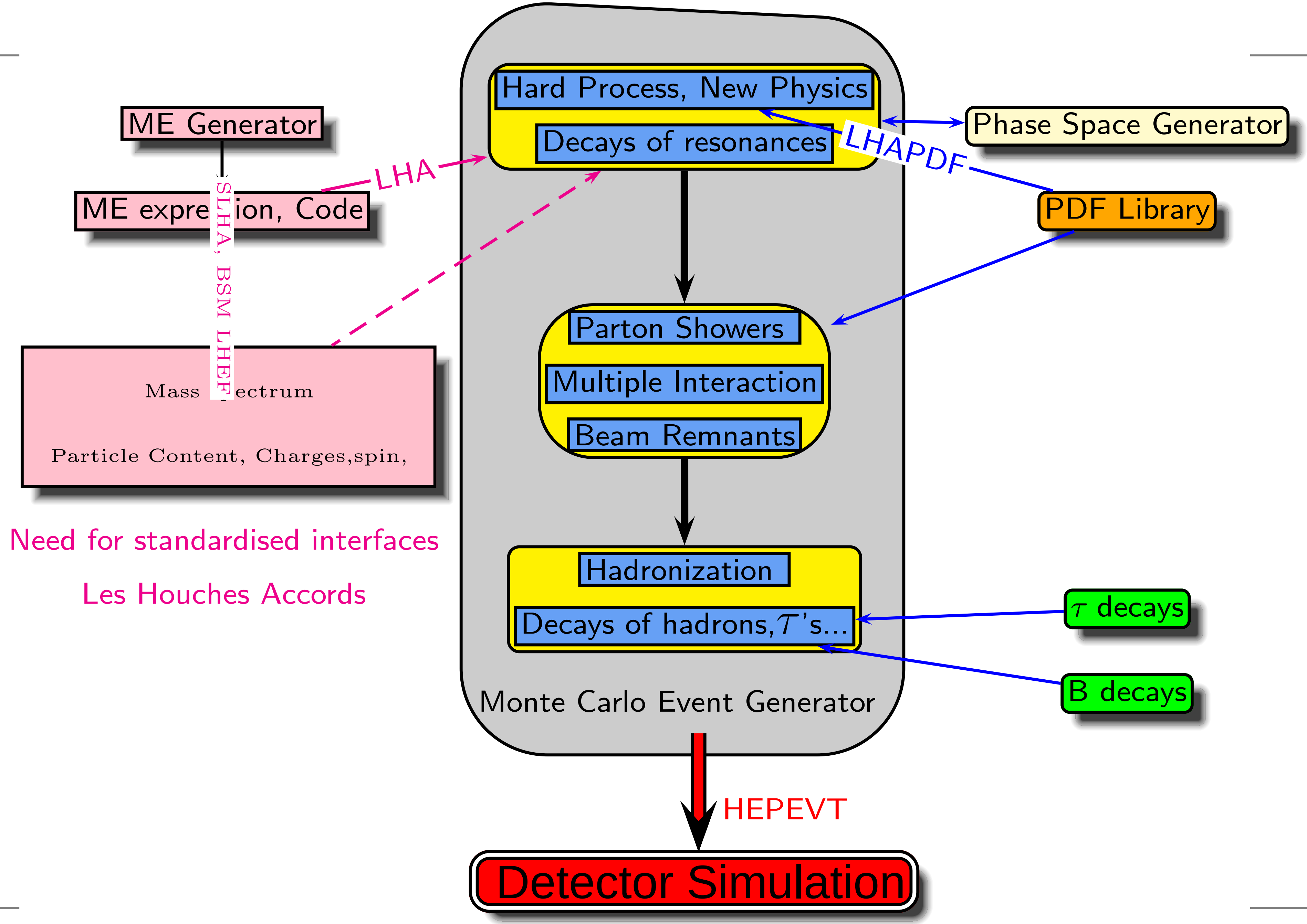
Progress Report on New Physics tools for the colliders

- A lot of progress and a lot of tools
- more and more on modularity and exchange of modules
- much easier now to contribute a new model
- Flexibility is the key
  [-] Need to be ready to implement a model quickly
  [-] Check output with different ME Calc./MC/MG
- This is now possible, while earlier even parameters of simple models hard wired, model implementation needed experts
- Now many tools automatize the different steps and as long as
  [-] particles has spin ≤ 2
  [-] Standard couplings through known Lorentz structures, this precludes higher order operators in some MEG but ALOHA is on the way and CalcHEP/CompHEP are ready...
  [-] decay chain does not end up in higher order or unusual colour representations

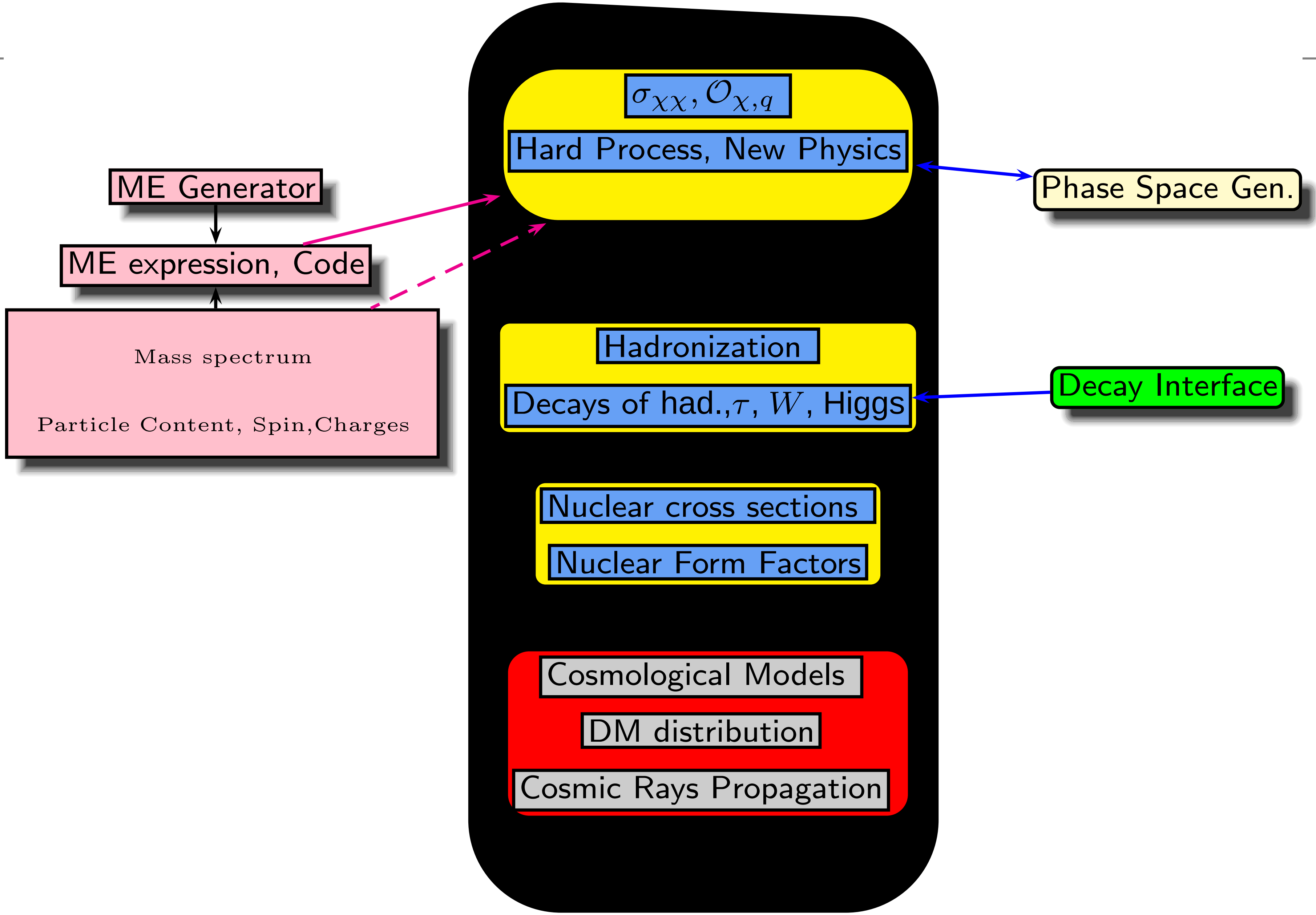
Putting all together, colliders



Putting all together, Les Houches Accords



Putting all together, Dark Matter Codes



Dark Matter Codes

- micrOMEGAs Any model of New Physics, relic density, direct and indirect detection
- DarkSUSY P. Gondolo, J. Edsjo, L. Bergstrom, P. Ullio, M. Schelke, T. Baltz, T. Bringmann and G. Duda; Supersymmetry, relic density, direct and indirect detection,...
- IsaTools H. Baer, Balazs, Belyaev Supersymmetry, relic density,(direct and indirect detection,...)
- superIsoRelic A. Arbey, N. Mahmoudi; Supersymmetry, relic density
- Galprop (Propagation), Moskalenko and Strong
- USINE (Propagation) Maurin, Taillet,...
- DRAGON: Maccione, Grasso, Di Bernardo,...
- Big Bang Nucleosynthesis (light elements abundance), Karsten Jedamzik, not public

micrOMEGAs

A Tool for Dark Matter and New Physics

in collaboration with Genevieve Blanger, Sacha Pukhov and Andrei Semenov

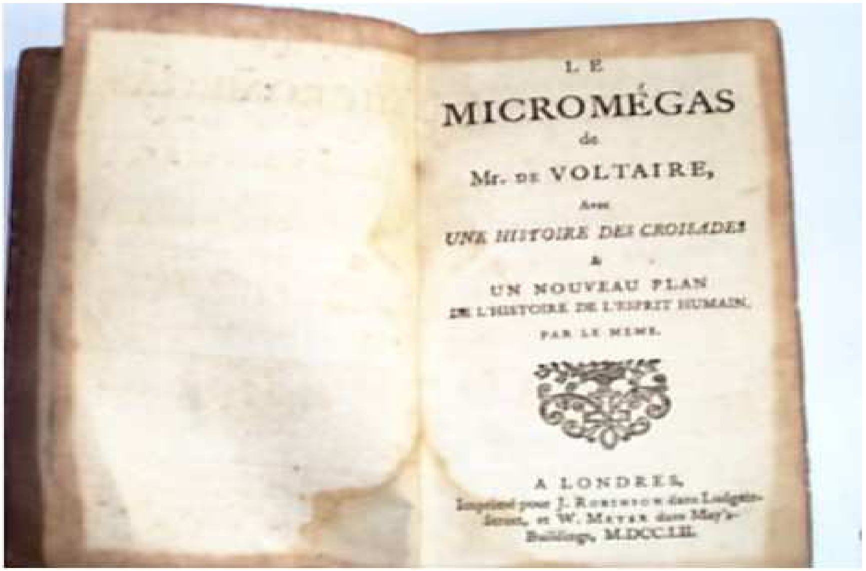
and Pierre Brun, Pierre Salati and Sylvie Rosier

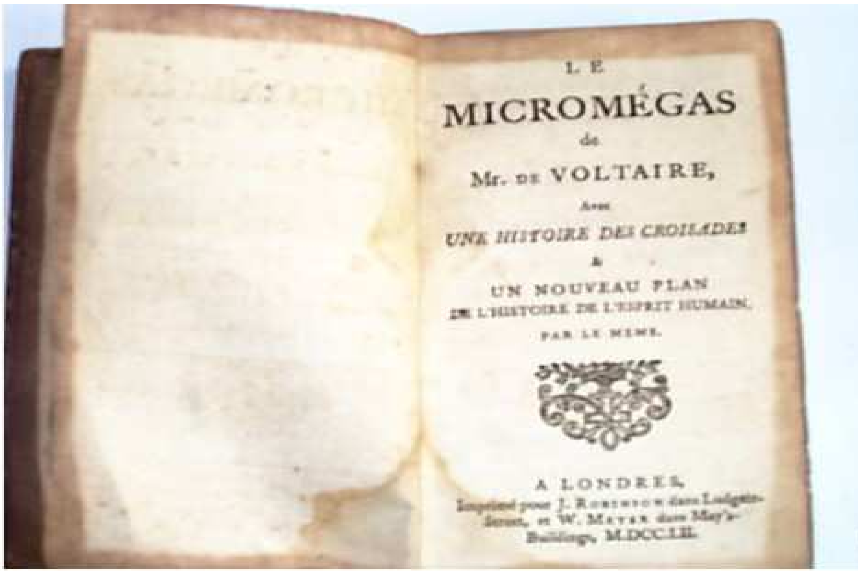
Ω

micrOMEGAs

$$\Omega$$

micrOMEGAs


LE
MICROMÉGAS
de
Mr. DE VOLTAIRE,
Avec
UNE HISTOIRE DES CROISADES
&
UN NOUVEAU PLAN
DE L'HISTOIRE DE L'ESPRIT HUMAIN,
PAR LE MEME.
A LONDRES,
M.DCC.LII.



" O atomes intelligents,

dans qui l'Etre éternel

s'est plu à manifester

son adresse et sa puissance,

vous devez sans doute

goûter des joies

bien pures sur

votre globe car,

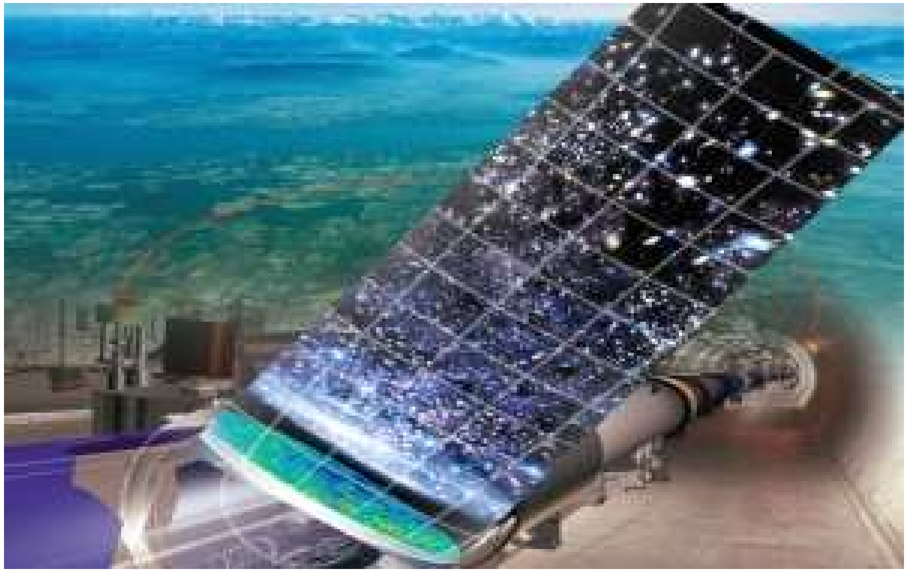
ayant si peu de matière...,"

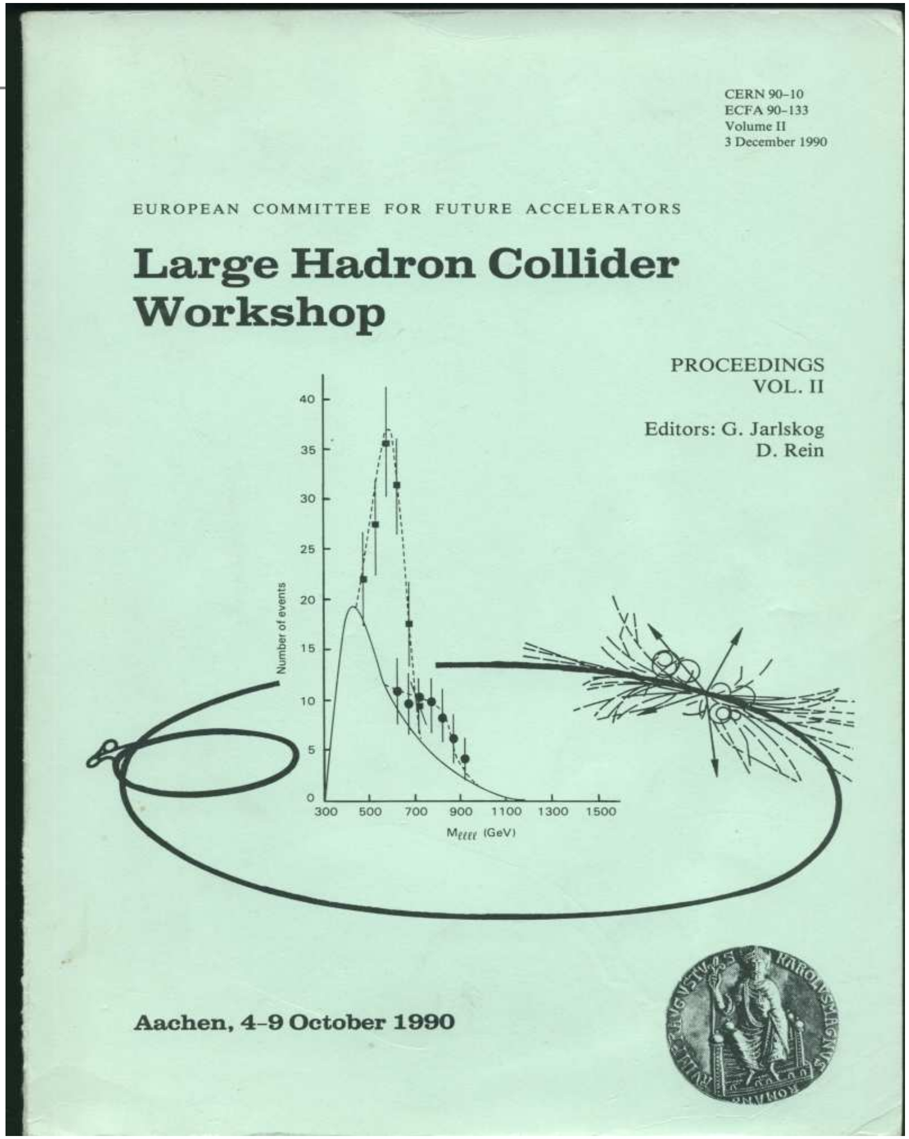
Voltaire, Micromegas,

chapitre septième,

conversation avec les hommes

LHC Dark Matter Connection





no mention of a connection, despite a SUSY WG

There is a mention of LSP to be stable/neutral because of cosmo reason, but no attempt at identifying it or weighing the universe at the LHC

LHC: Symmetry breaking and Higgs

New Paradigm, Dark Matter is New Physics. Dark Matter is being looked for everywhere

New Paradigm, Particle Physics to match the precision of recent cosmological measurements

Need powerful, modular and versatile tools

micrOMEGAs: Tools for DM/ Collider Physics/ Flavour for a general NP

Models of New Physics: Symmetry breaking and DM

- The SM Higgs naturalness problem has been behind the construction of many models of New Physics: at LHC not enough to see the Higgs need to address electroweak symmetry breaking
- DM is New Physics, most probable that the New Physics of EWSB provides DM candidate, especially that
- All models of NP can be made to have quite easily and naturally a conserved quantum number, Z_2 parity such that all the NP particles have $Z_2 = -1$ (odd) and the SM part. have Z_2 even (Z_3 can work also)
- Then the lightest New Physics particle is stable. If it is electrically neutral then can be a candidate for DM
- This conserved quantum number is not imposed just to have a DM candidate it has been imposed for the model to survive

Symmetry breaking and DM

- Survival

  evade proton decay

  indirect precision measurements (LEP legacy)

- Examples:

  R-parity and LSP in SUSY (majorana fermion)

  KK parity and the and LKP in UED (gauge boson)

  T-parity in Little Higgs with the LTP (gauge boson)

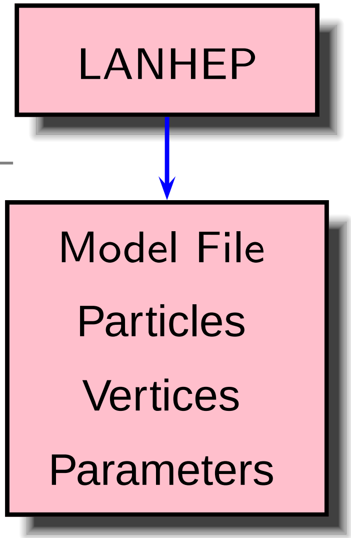
  LZP (warped GUTs) (actually it's a Z_3 here) (Dirac fermion)

  even modern technicolour has a DM candidate

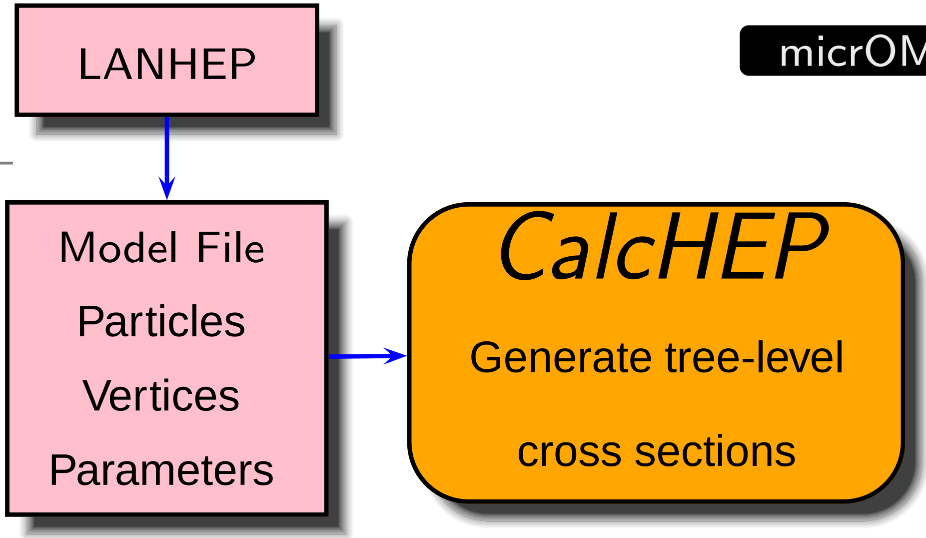
LANHEP

micrOMEGAs

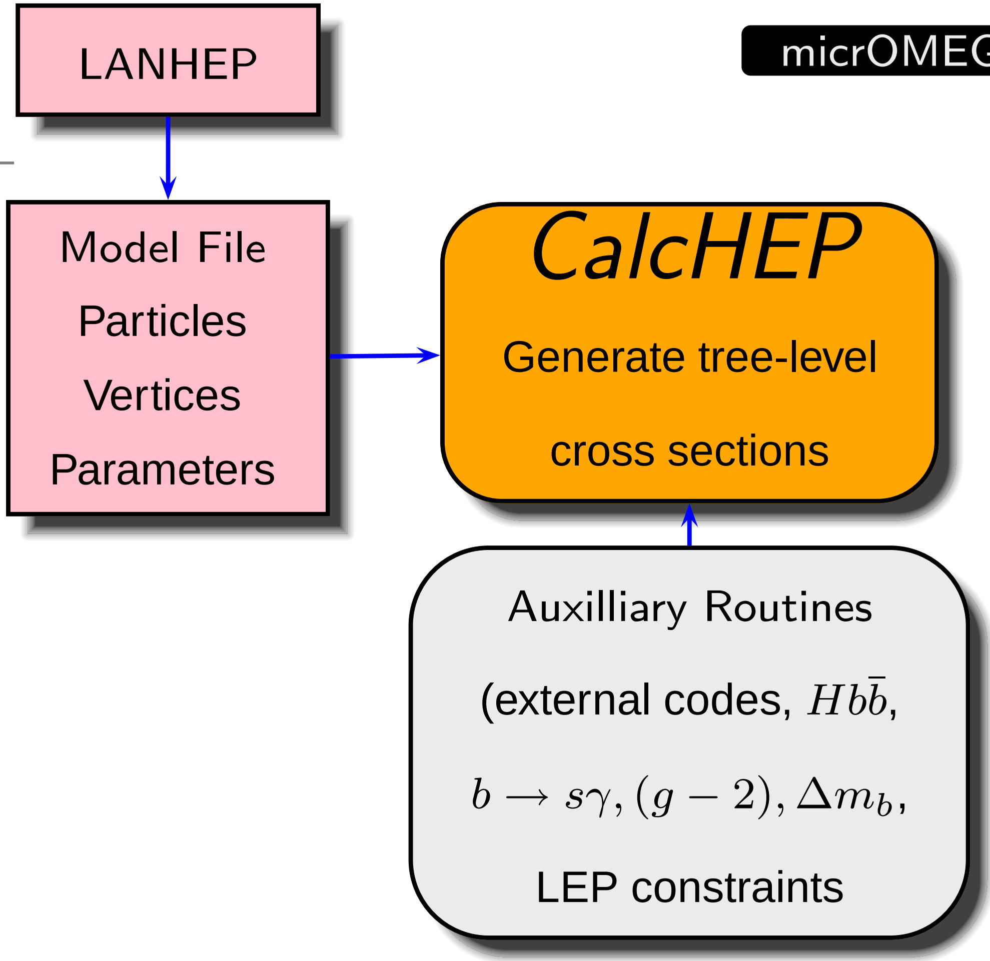
micrOMEGAs



micrOMEGAs


LANHEP
Model File
Particles
Vertices
Parameters
CalcHEP
Generate tree-level
cross sections

micrOMEGAs


LANHEP
Model File
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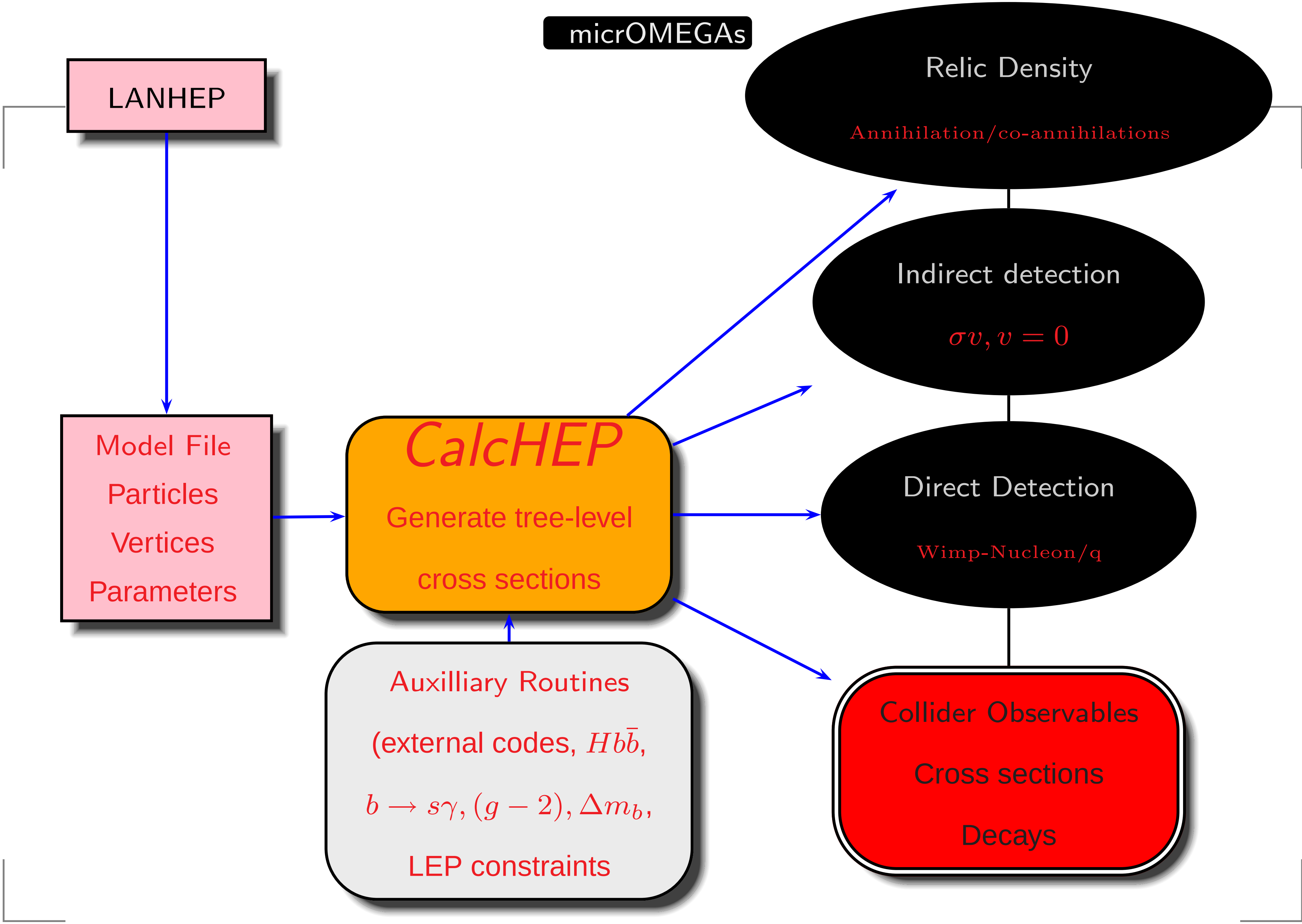
Vertices
Parameters
CalcHEP
Generate tree-level
cross sections
Auxilliary Routines
(external codes, $Hb\bar{b}$,
$b \rightarrow s\gamma, (g-2), \Delta m_b$,
LEP constraints



micrOMEGAs
LANHEP
Model File
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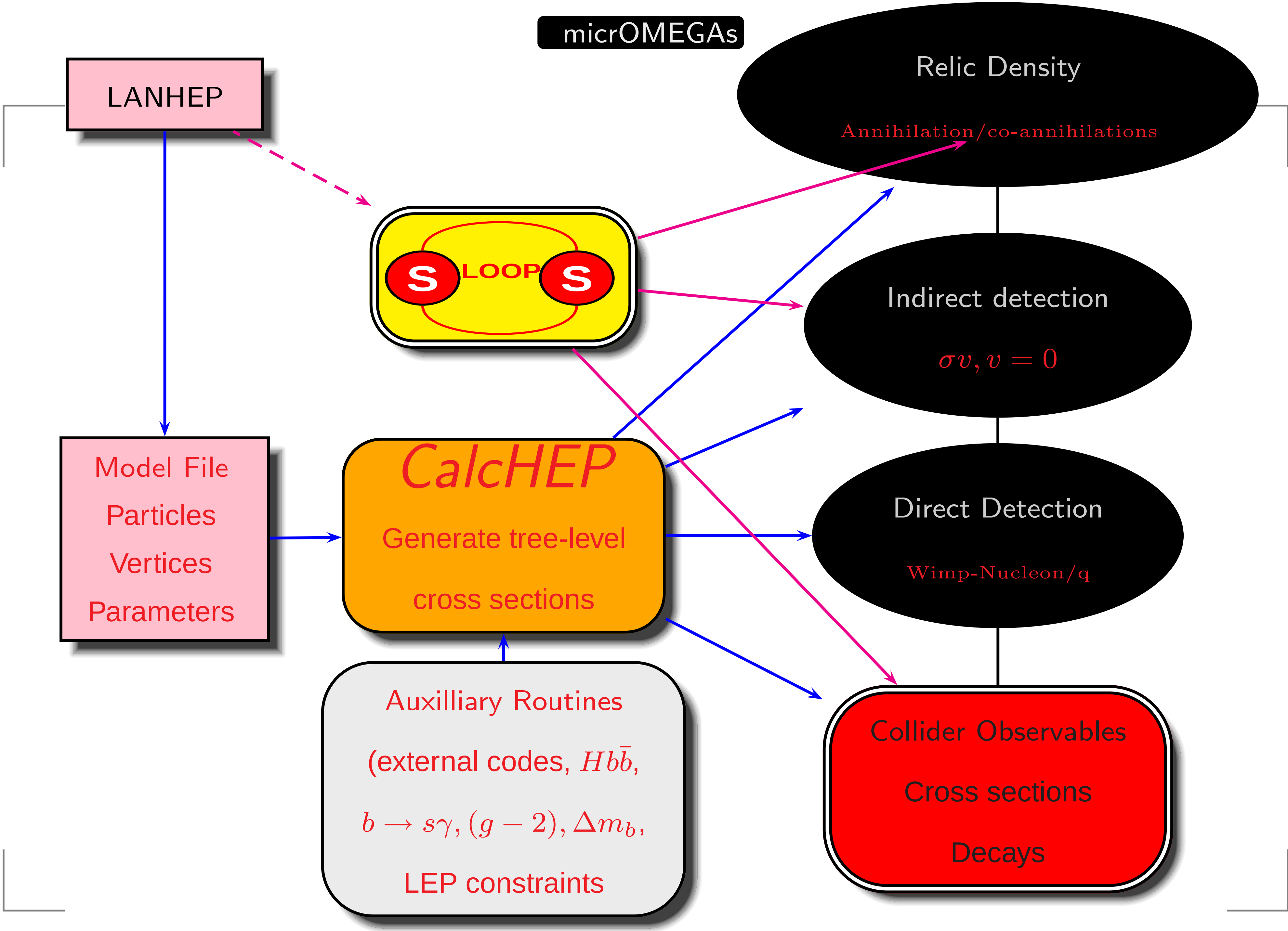
(external codes, $Hb\bar{b}$,
$b \to s\gamma, (g-2), \Delta m_b$,
LEP constraints
Relic Density
Annihilation/co-annihilations
Indirect detection
$\sigma v, v = 0$
Direct Detection
Wimp-Nucleon/q
Collider Observables
Cross sections
Decays


micrOMEGAs
LANHEP
Relic Density
Annihilation/co-annihilations
S
LOOP
S
Indirect detection
$\sigma v, v = 0$
Model File
Particles
Vertices
Parameters
CalcHEP
Generate tree-level
cross sections
Direct Detection
Wimp-Nucleon/q
Auxilliary Routines
(external codes, $Hb\bar{b}$,
$b \to s\gamma, (g-2), \Delta m_b$,
LEP constraints
Collider Observables
Cross sections
Decays

micrOMEGAs

- given any set of parameters it can identify LSP, NLSP, generate and calculate Ωh^2
- Model defined in Lanhep (more later)
- Fed into CalcHEP ....tree-level, some 3000 processes could be needed.
- Higgs sector (SUSY): improved Higgs masses/mixings (read from FeynHiggs, for example) but interpreted in terms of an effective scalar potential (GI), following FB and A. Semenov (PRD 02)
- Effective Lagrangian also includes important RC (Higgs couplings, Δm_b effects,..)
- Interfaced with Isajet, Suspect, SoftSUSY parameters at high scale run down to the ew scale
- $(g-2)_\mu$, $b \to s\gamma$, $B_s \to \mu^-\mu^+$,..
- NMSSM (with C. Hugonie), CP violation (with S. Kraml), UED, Dirac, host of others
- "open source": procedure to define your own model
- powerful generalised direct detection module
- indirect detection cross sections, interface with propagation, polarisation completed
- SLHA compliant, MCMC interface for parameter scans

- micrOMEGAs

  given any set of parameters it can identify LSP, NLSP, generate and calculate Ωh^2, direct and indirect

  cross sections are generated on the fly. Only those needed are generated. These are then stored, if needed in the future procedure is speedy

- DarkSusy

  comes with a (large) set of codes cross sections in SUSY.

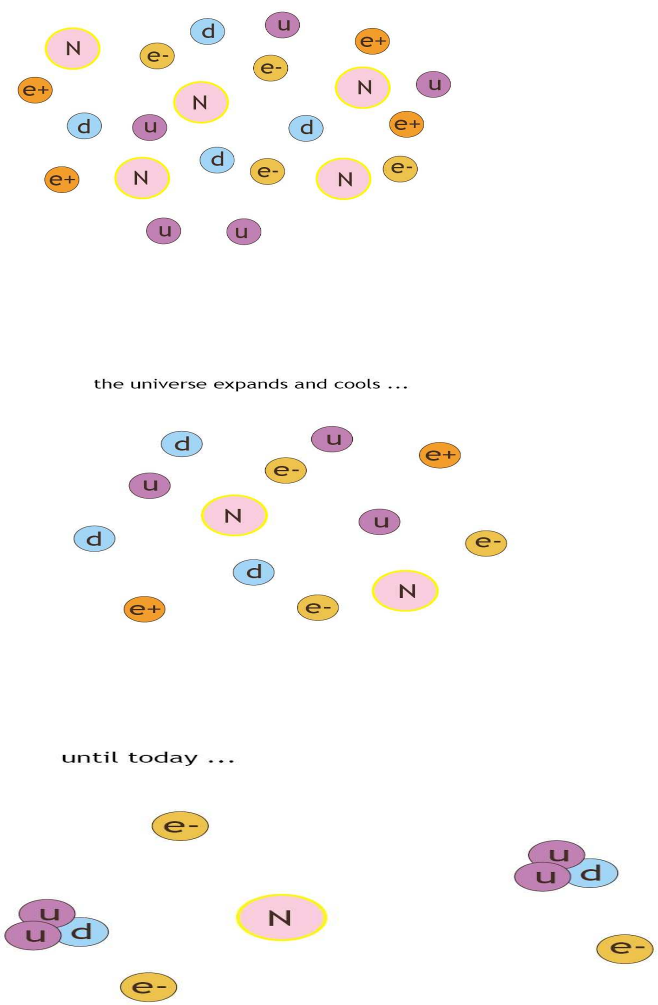
  you may have a weirdo model for which some (co-annihilation) cross sections are not provided, you will have to code them. In principle you could code a cross section from any model

- IsaRed: mostly based on mSUGRA scenarios, cross sections for annihilation extracted from CompHEP

- cross section from FeynCalc/FormCalc, interface to B-physics

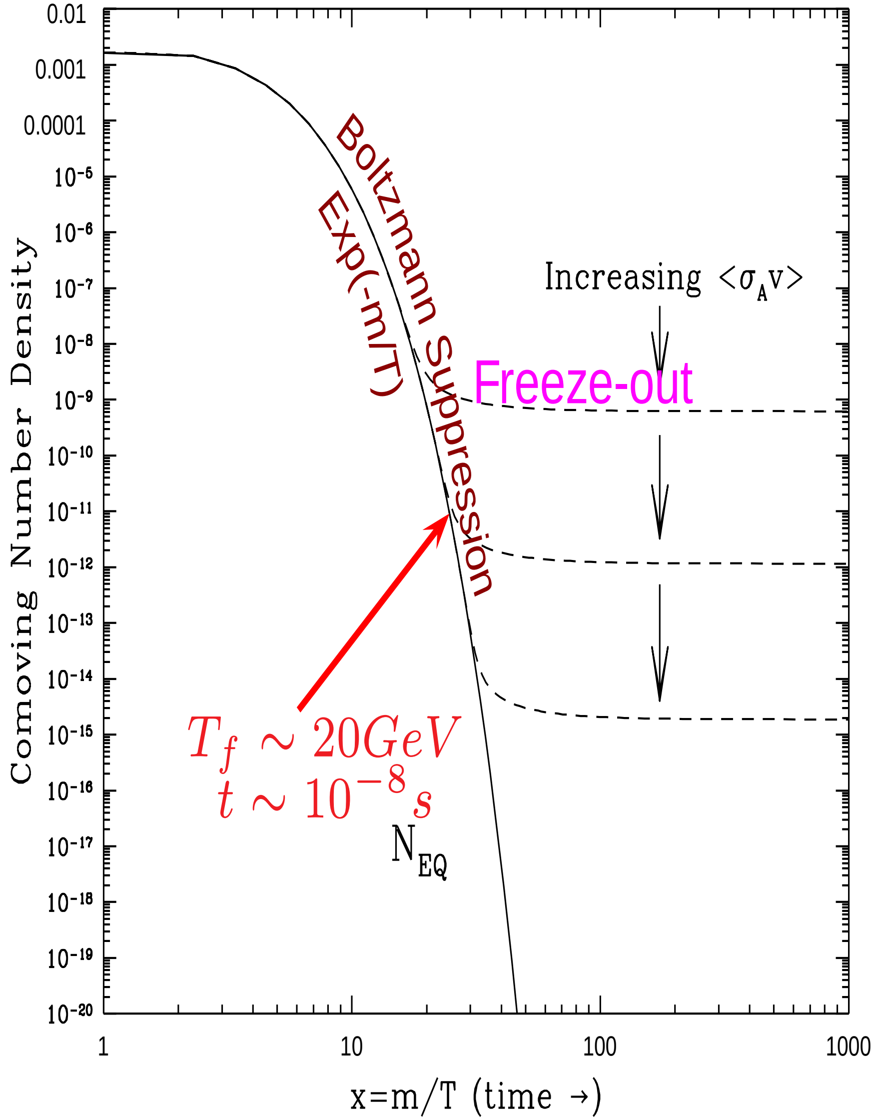
Relic Density

formation of DM: Very basics of decoupling



- At first all particles in thermal equilibrium, frequent collisions and particles are trapped in the cosmic soup
- universe cools and expands: interaction rate too small or not efficient to maintain Equil.
- (stable) particles can not find each other: freeze out and get free and leave the soup, their number density is locked giving the observed relic density
- from then on total number $(n \times a^3) = cste$
- Condition for equilibrium: mean free path smaller than distance traveled: $l_{\rm m.f.p} < vt \quad l_{\rm m.f.p} = 1/n\sigma$
  $t \sim 1/H$ or Equilbrium: $\Gamma = n\sigma v > H$

freeze ou/decoupling occurs at $T = T_D = T_F : \Gamma = H$ and $\Omega_{\tilde{\chi}_1^0} h^2 \propto 1/\sigma_{\tilde{\chi}_1^0}$



based on $\mathcal{L}[f] = \mathcal{C}[f]$

dilution due to expansion

$$dn/dt = -3Hn - <\sigma v> (n^2 - n_{eq}^2)$$

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to X$

$X \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$

- at early times $\Gamma \gg H \to n \sim n_{eq}$
- $T \sim m$ x not enough energy to give $X \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ n drops and so does Γ

$T_f \simeq m/25$

$$\Omega_{\tilde{\chi}_1^0} h^2 \propto 1/\sigma_{\tilde{\chi}_1^0}$$

Thermal average

must calculate all annihilation, co-annihilation processes. Each annihilation can consist of tens of cross sections...

$$\chi_i^0\chi_j^0 \rightarrow X_{SM}Y_{SM},\ \chi_1^0\tilde{f}_1 \rightarrow X_{SM}Y_{SM},\ldots \qquad v\times\sigma v$$

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

p_{ij} is the momentum of the incoming particles in their center-of-mass frame.

Origin of Boltzman factor $exp(-\delta M/T)$

Thermal average

must calculate all annihilation, co-annihilation processes. Each annihilation can consist of tens of cross sections...

$$\chi_i^0 \chi_j^0 \to X_{SM} Y_{SM}, \chi_1^0 \tilde{f}_1 \to X_{SM} Y_{SM}, \ldots \qquad v \times \sigma v$$

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

p_{ij} is the momentum of the incoming particles in their center-of-mass frame.

Origin of Boltzman factor $exp(-\delta M/T)$

$$B_f = \frac{K_1((m_i + m_j)/T_f)}{K_1(2m_{\tilde{\chi}_1^0}/T_f)} \approx e^{-X_f \frac{(m_i + m_j - 2m_{\tilde{\chi}_1^0})}{m_{\tilde{\chi}_1^0}}} \qquad if \; B_f < B_\epsilon \text{ do not compute}$$

In micrOMEGAs $B_\epsilon = 10^{-6}$ by default. Most often $B_\epsilon = 10^{-2}$ enough for 1% accuracy, only a few processes computed.

in DarkSUSY: cut off $f = m_i/m_{\tilde{\chi}_1^0} < 1.5$

Thermal average

must calculate all annihilation, co-annihilation processes. Each annihilation can consist of tens of cross sections...

$$\chi_i^0 \chi_j^0 \to X_{SM} Y_{SM}, \, \chi_1^0 \tilde{f}_1 \to X_{SM} Y_{SM}, \ldots \qquad v \times \sigma v$$

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

p_{ij} is the momentum of the incoming particles in their center-of-mass frame.

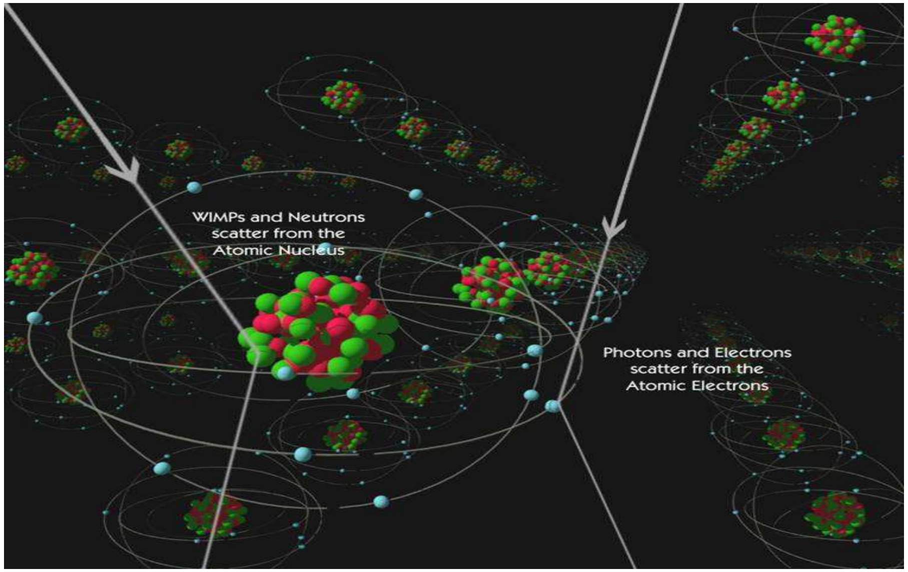
Origin of Boltzman factor $exp(-\delta M/T)$

In micrOMEGAs $< \sigma v > (T)$ is obtained from direct integration, through adaptive Simpson with two options (fast, default) and accurate (checks for accuracy). Adaptive: looks for poles and thresholds.

in DarkSUSY: tabulation

IsaRed does not solve the Boltzman equation numerically. Instead it finds an approx sol, based on the freeze-out temperature.

Direct detection



$\chi\mathcal{N} \to \chi\mathcal{N}$ **to** $\chi N \to \chi N \; (N = n, p)$

to $\chi q \to \chi q$

ingredients/Modules: dark matter density and modulation, velocity distribution quark content in nucleon, Nuclear form factors,.....

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

- N_T is the number of target nuclei per unit mass
- E_R= recoil energy
- $\vec{v}$ is the dark matter velocity in the frame of the Earth, $\vec{v_e}$ is the velocity of the Earth with respect to the galactic halo, and $f(\vec{v}, \vec{v_e})$ is the distribution function of dark matter particle velocities.
  In micrOMEGAs a truncated Maxwellian distribution is implemented by default, with free parameters to allow for study/deviations from the isothermal model.
- $\sigma_{W\mathcal{N}}$ Wimp-Nucleus cross section. Involves: BSM physics, nuclear physics, SM particle physics

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v \, v \, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

$$\frac{d\sigma_{W\mathcal{N}}}{dE_R} = \frac{m_\mathcal{N}}{2v^2\mu_\mathcal{N}^2} \left(\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right)$$

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\rm min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

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$F_{SI,SD}$ = Nuclear Form Factors

$\mu_\mathcal{N}^2$ reduced $\mathcal{N} - \chi$ mass

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

$$\frac{d\sigma_{W\mathcal{N}}}{dE_R} = \frac{m_\mathcal{N}}{2v^2\mu_\mathcal{N}^2} \left(\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2\right)$$

For SI further factorisation

$$\sigma_0^{SI} = \frac{4\mu_N^2}{\pi} \; [\lambda_p Z + \lambda_n (A - Z)]^2 \, ,$$

(For SD no factorisation but spin structure functions (more involved)).

Nuclear Physics: Fourier transform of the nucleus distribution function, use Fermi distribution (which leads to so called Woods-Saxon FF)

$$F_{SI} = F_\mathcal{N}(q) = \int e^{-iqx} \rho_\mathcal{N}(x) d^3x, \quad \rho_\mathcal{N}(r) = \frac{c_{norm}}{1 + exp((r - R_\mathcal{N})/a)}$$

Rates

$$\frac{dR}{dE_R} = N_T \frac{\rho_0^{DM}}{M_\chi} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma_{W\mathcal{N}}}{dE_R},$$

$$\frac{d\sigma_{W\mathcal{N}}}{dE_R} = \frac{m_\mathcal{N}}{2v^2\mu_\mathcal{N}^2} \left(\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2 \right)$$

For SI further factorisation

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$\lambda_{p,n}$ coupling of DM but also quark content in nucleon

The codes offer different choices for

- form factors
- velocity distributions
- routines for DD rates off composite targets beside nuclei

Wimp-Nucleon (N=n,p) at small momentum transfer (100MeV)

Take for exemple the case of a Majorana Wimp **Majorana:** $\chi = \overline{\chi}$

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

Majorana $q^2 \to 0$

$$\begin{aligned} \mathcal{L}_F &= \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N \quad \Rightarrow \text{scalar} \quad \text{spin} - \text{independent} \quad \text{SI} \\ &+ \xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N \quad \Rightarrow \text{spin} - \text{dependent} \quad \text{SD} \end{aligned}$$

Majorana $q^2 \to 0$

$$\begin{aligned} \mathcal{L}_F &= \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N \quad \Rightarrow \text{scalar} \quad \text{spin}-\text{independent} \quad \text{SI} \\ &+ \xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N \quad \Rightarrow \text{spin}-\text{dependent} \quad \text{SD} \end{aligned}$$

Generalisation to other DM particles, Spin-0, 1/2, 1 for $q^2 \to 0$

not necessarily of Majorana type : $\chi \neq \overline{\chi}$

Classify as two types of operators

1) $_e$=even under $\chi \leftrightarrow \overline{\chi}$ interchange

2) $_o$=odd under $\chi \leftrightarrow \overline{\chi}$ interchange, vanish for self-conjugate (Majorana) DM

Majorana $q^2 \to 0$

$$\begin{aligned} \mathcal{L}_F &= \lambda_N \overline{\psi}_\chi \psi_\chi \overline{\psi}_N \psi_N \quad \Rightarrow \text{scalar} \quad \text{spin} - \text{independent} \quad \text{SI} \\ &+ \xi_N \overline{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N \quad \Rightarrow \text{spin} - \text{dependent} \quad \text{SD} \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{s=1/2} &= \lambda_{N,e} \bar{\psi}_\chi \psi_\chi \bar{\psi}_N \psi_N + \lambda_{N,o} \bar{\psi}_\chi \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^\mu \psi_N \\ &+ \xi_{N,e} \bar{\psi}_\chi \gamma_5 \gamma_\mu \psi_\chi \bar{\psi}_N \gamma_5 \gamma^\mu \psi_N - \frac{1}{2} \xi_{N,o} \bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_N \sigma^{\mu\nu} \psi_N \end{aligned}$$

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\mathcal{L}_{s=0} &= 2\lambda_{N,e} M_\chi \phi_\chi \phi^*_\chi \bar{\psi}_N \psi_N + i\lambda_{N,o} (\partial_\mu \phi_\chi \phi^*_\chi - \phi_\chi \partial_\mu \phi^*_\chi) \bar{\psi}_N \gamma_\mu \psi_N
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\mathcal{L}_{s=1} &= 2\lambda_{N,e} M_\chi A_{\chi\mu} A_\chi^\mu \overline{\psi}_N \psi_N + \lambda_{N,o} i (A_\chi^{*\alpha} \partial_\mu A_{\chi,\alpha} - A_\chi{}^\alpha \partial_\mu A_{\chi\alpha}^*) \overline{\psi}_N \gamma_\mu \psi_N \\
&+ \sqrt{6} \xi_{N,e} (\partial_\alpha A_{\chi\beta}^* A_{\chi\gamma} - A_{\chi\beta}^* \partial_\alpha A_{\chi\gamma}) \epsilon^{\alpha\beta\gamma\mu} \overline{\psi}_N \gamma_5 \gamma_\mu \psi_N \\
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\end{aligned}$$

$$\begin{aligned}
\lambda_N &= \frac{\lambda_{N,e} \pm \lambda_{N,o}}{2} \quad \text{and} \quad \xi_N = \frac{\xi_{N,e} \pm \xi_{N,o}}{2} \\
+ &\mapsto \text{WIMP} \quad \text{and} \quad - \mapsto \text{anti}-\text{WIMP}
\end{aligned}$$

Wimp-quark effective Lagrangian, $\psi_N \to \psi_q$

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

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

In model files of `micrOMEGAs (CalcHEP)` these operators are added

- In the usual approach these low energy operators and their coefficients are extracted by computing WIMP-quark *amplitudes* from Feynman diagrams and using Fierz transformations,..

Wimp-quark effective Lagrangian: Automation

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- The trick is to use also $\chi q \to \chi q$ *vs* $\chi \bar{q} \to \chi \bar{q}$
- with the S-matrix, $\hat{S} = 1 - i\mathcal{L}$ obtained from the complete Lagrangian at the quark level

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

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

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

- warning: couplings proportional to light quark masses must be kept

χq to χN: Sandwich within nucleon, Nucleon form factors

$\langle N|\overline{\psi}_q\psi_q|N\rangle$, $\langle N|\overline{\psi}_q\gamma_\mu\psi_q|N\rangle$, $\langle N|\overline{\psi}_q\gamma_\mu\gamma_5\psi_q|N\rangle$, $\langle N|\overline{\psi}_q\sigma_{\mu\nu}\psi_q|N\rangle$

These are extracted from experiments (*e.g* $\sigma_{\pi N}$), lattice computations, plus a fair deal of theory (trace anomaly, chiral perturbation,...)

Large source of uncertainty, apart from vector (which counts number of quarks minus anti-quarks, valence quarks)

χq to χN: Sandwich within nucleon, Nucleon form factors

Scalar, light quarks

$$\langle N|m_q\overline{\psi}_q\psi_q|N\rangle = f_q^N M_N \Rightarrow \lambda_N = \sum_{q=1,6} f_q^N \lambda_q \quad M_N : \text{Nucleon mass}$$

$$f_q^{p,n} \quad = \quad \sigma_{\pi N} G_q^{n,p}(m_u/m_d, m_s/m_d, B_u/B_d, y), \quad B_q = \langle N|\bar{q}q|N\rangle, \quad y = 1 - \sigma_0/\sigma_{\pi N}$$

Large uncertainty in $\sigma_{\pi N}$ translates into very large range for $0.08 < f_s^{p,n} < 0.46$ and hence expect variations in detection range within an order of magnitude

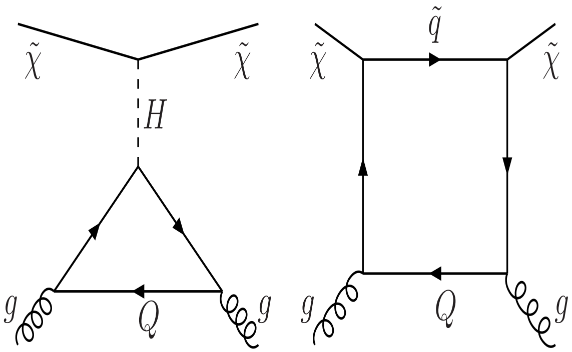
Lattice calculations are providing new estimates that will reduce uncertainty. Tensor coefficients are for example extracted from lattice calculations.

χq to χN: Sandwich within nucleon, Nucleon form factors

SI, heavy quarks, Gluons and QCD

$$\langle N|m_Q\bar{\psi}_Q\psi_Q|N\rangle = -\frac{\Delta\beta^{h.Q}}{2\alpha_s^2(1+\gamma)}\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle$$
$$= -\frac{1}{12\pi}(1+\frac{11\alpha_s(m_Q)}{4\pi})\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle$$

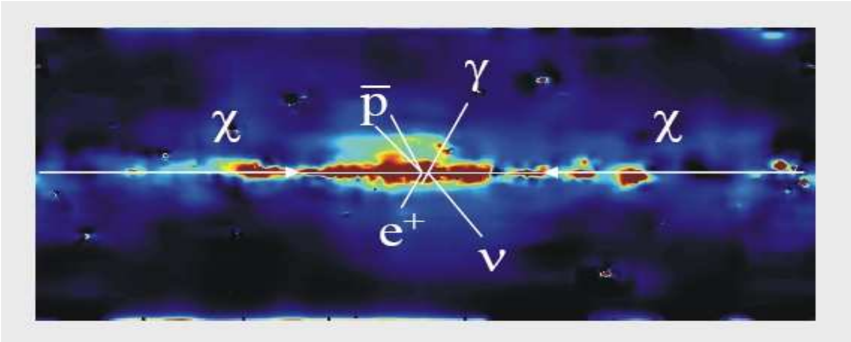
Good description of the dominant triangle, Box diagram model dependent, sub-dominant, evaluated for the MSSM only

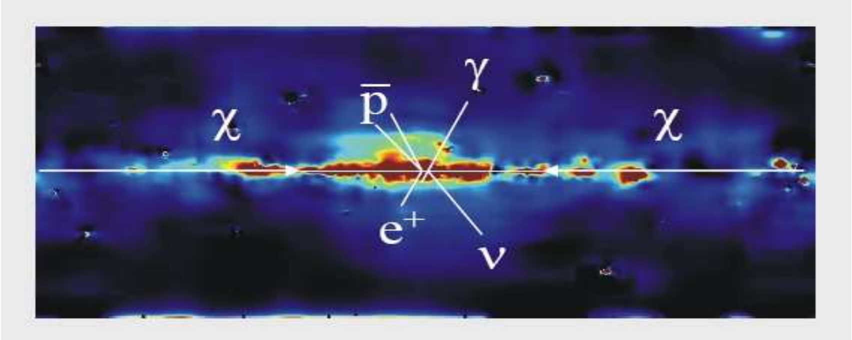


Diagrams that contribute to WIMP-gluon interaction via quark loops in the MSSM

Other QCD and SQCD corrections for MSSM

Indirect Detection





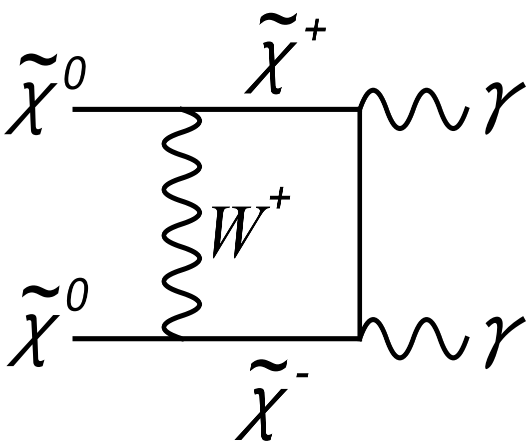
- ν from the Sun and the Earth
- γ, ν, charged cosmic rays $(e^+, \bar{p}, \bar{D})$ from annihilation in the galactic halo
- other signals: synchrotron emission,....?

Annihilation into photons

$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \underbrace{\sum_i \frac{dN^i_\gamma}{dE_\gamma}\sigma_i v \frac{1}{4\pi m^2_\chi}}_{\text{Particle physics}} \underbrace{\int (\rho + \delta\rho)^2 dl}_{\text{Astro}}$$

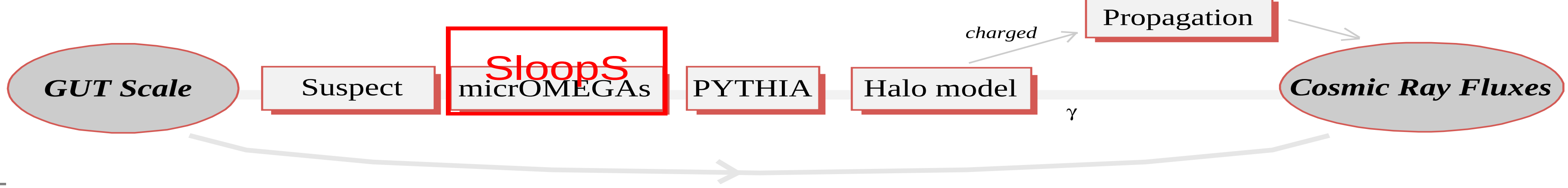
$\gamma' s$: Point to the source, independent of propagation model(s)

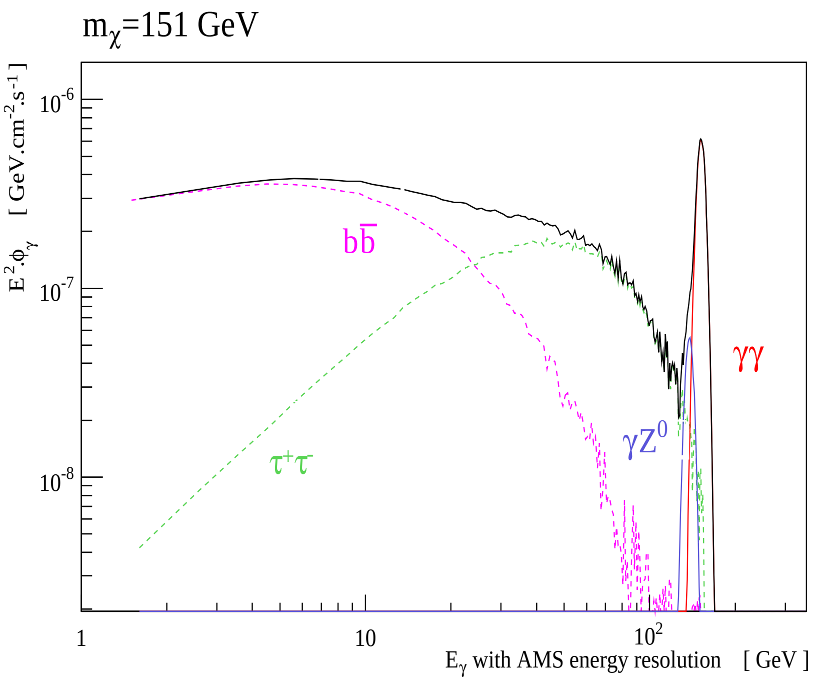
- continuum spectrum from $\tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow f\bar{f},\ldots,$ hadronisation/fragmentation ($\rightarrow \pi^0 \rightarrow \gamma$) done through isajet/herwig
- Loop induced mono energetic photons, $\gamma\gamma$, $Z\gamma$ final states

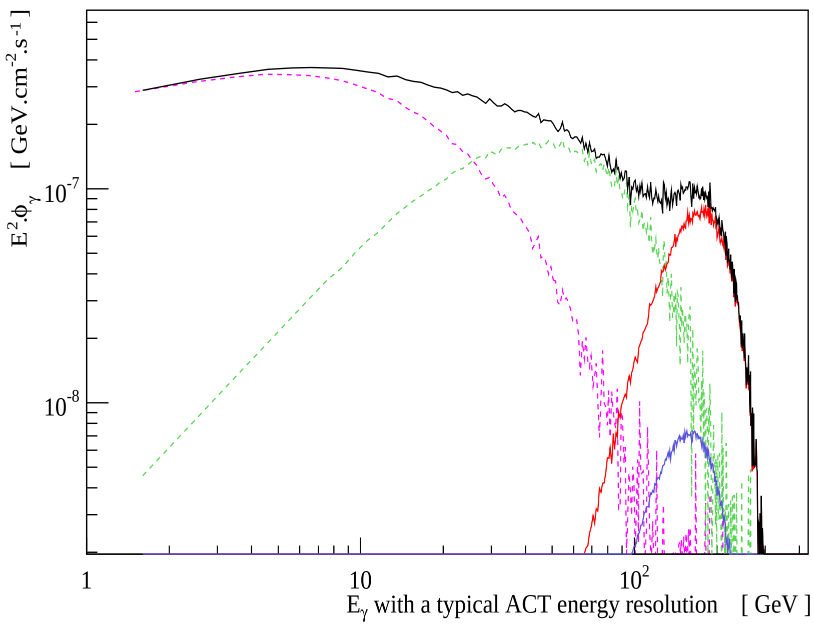


ACT: HESS, Magic, VERITAS, Cangoroo, ...

Space-based: AMS, Fermi-LAT, Egret,...







SIMULATION: (with/from P. Brun)

Parameterising the halo profile:

$(\alpha, \beta, \gamma) = (1, 3, 1)$, $a = 25$kpc. (core radius), $r_0 = 8kpc$ (distance to galactic centre), $\rho_0 = 0.3\, GeV/cm^3$ (DM density), opening angle cone 1^o

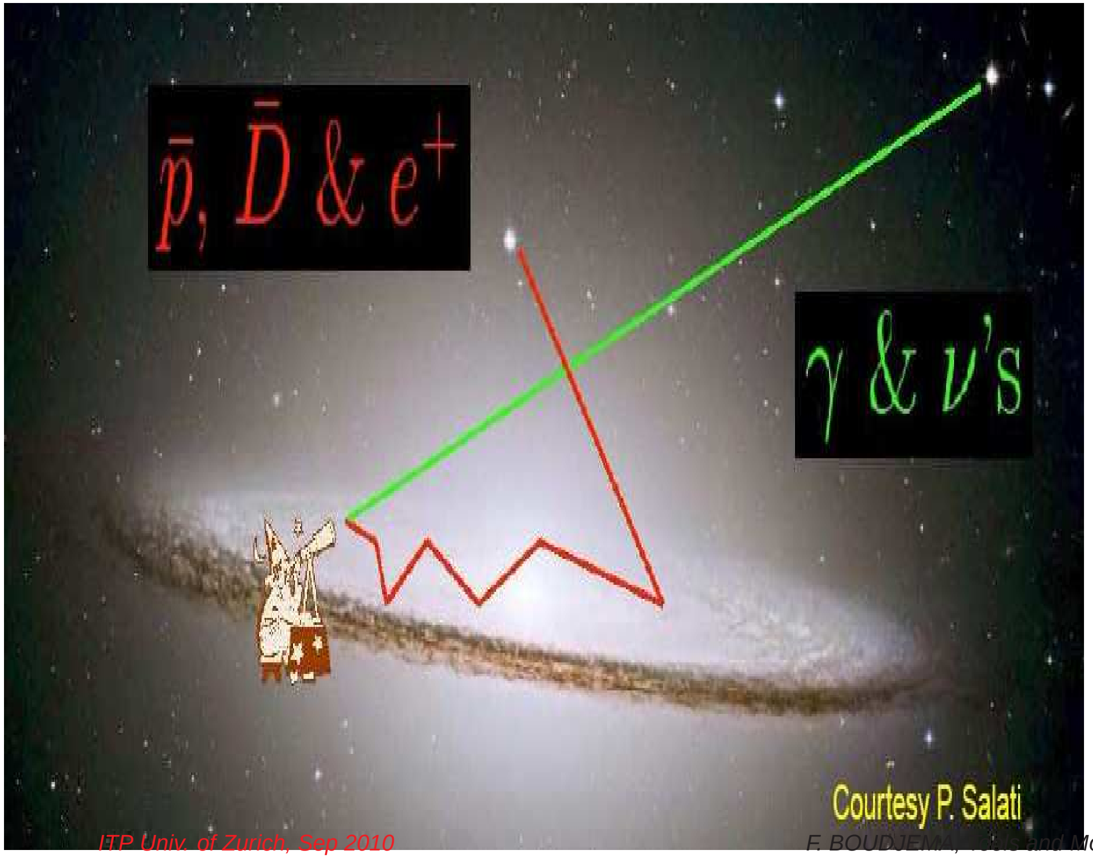
SUSY parameterisation

$m_0 = 113$GeV, $m_{1/2} = 375$ GeV, $A = 0$, $\tan\beta = 20$, $\mu > 0$

γ lines could be distinguished from diffuse background

Annihilation into $e^+, \bar{p}, \bar{D}$

$$\frac{d\Phi_{\bar{f}}}{d\Omega dE_{\bar{f}}} = \sum_i \underbrace{\frac{dN^i_{\bar{f}}}{dE_{\bar{f}}} \sigma_i v \frac{1}{4\pi m^2_\chi}}_{\text{Particle physics}} \underbrace{\int (\rho + \delta\rho)^2 P_{prop}}_{\text{Astro}}$$



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ACT: HESS, Magic, VERITAS, Cangoroo, ...

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charged particles: Model of propagation and background

- Halo Profile modeling, clumps, cusps,..boost factors,...

- Annihilation cross sections for all 2-body tree-level processes for all models.

Features in the Indirect Detection Module of micrOMEGas

- Annihilation cross sections for all 2-body tree-level processes for all models.
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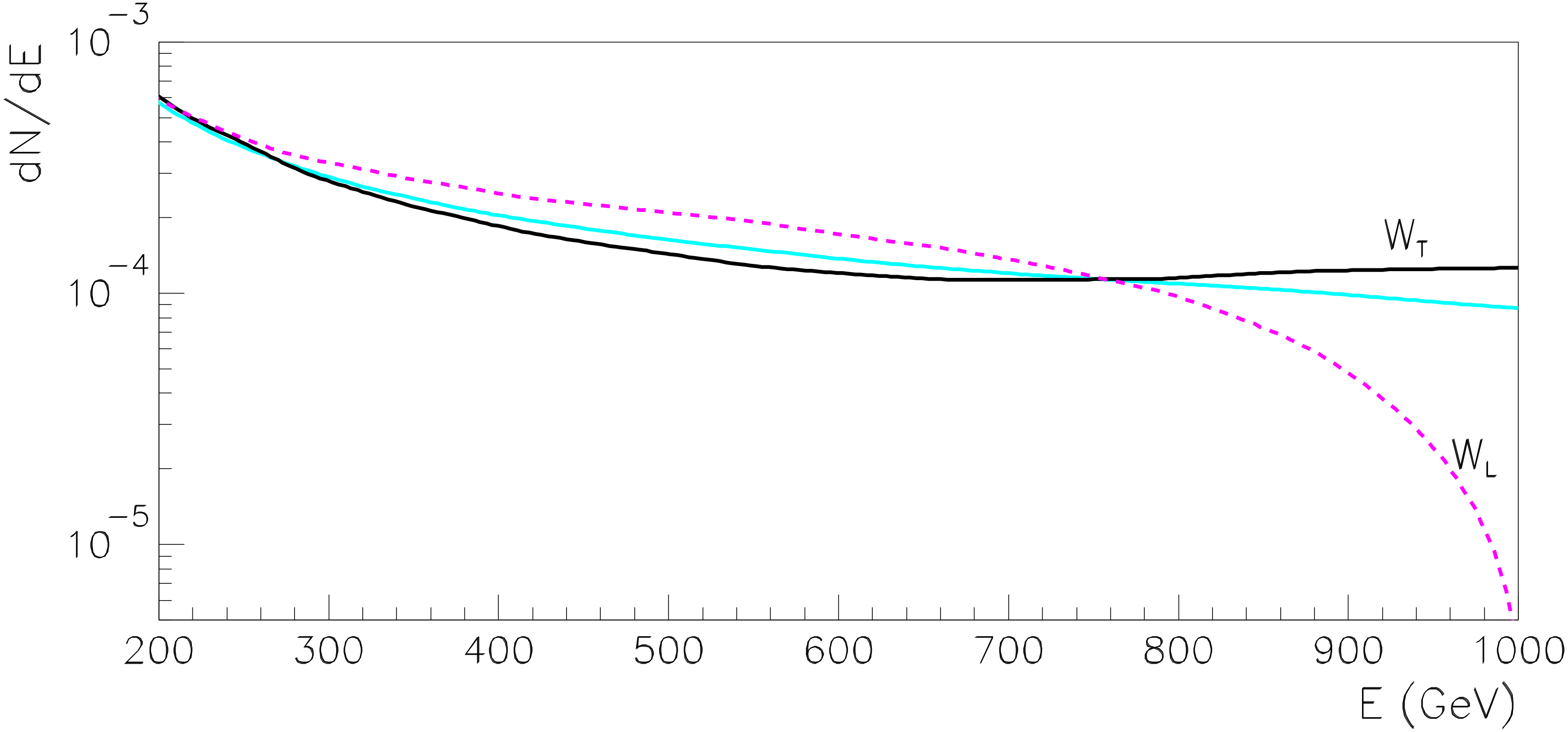
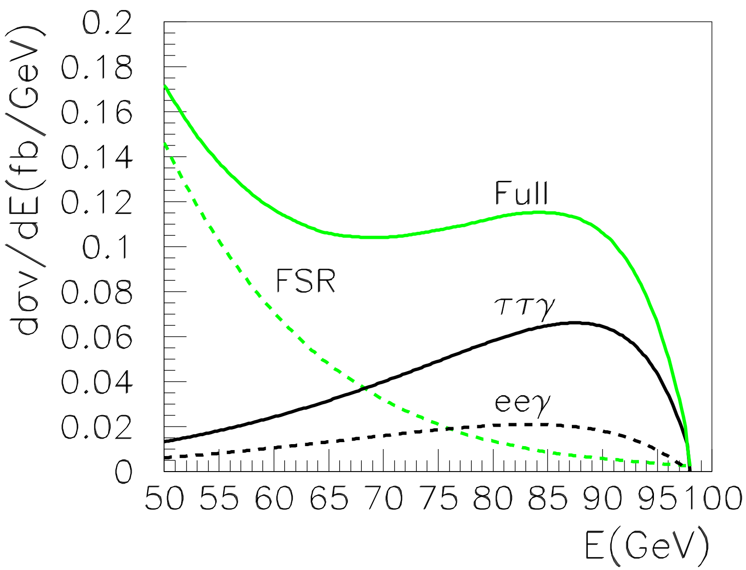
- The neutrino spectrum originating from dark matter annihilation is also computed, however the neutrino signal is usually dominated by neutrinos coming from DM capture in the Sun or the Earth. The inclusion of this signature is left for a further upgrade.

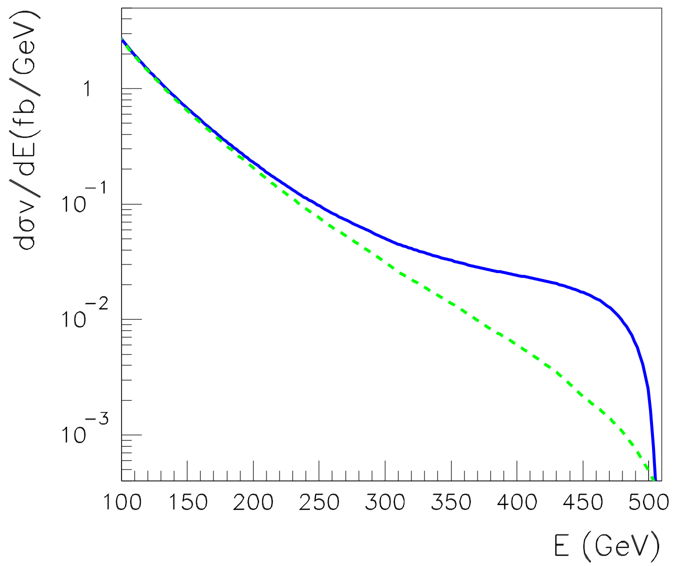
Effect of the polarisation



dN/dE_{e^+} for positrons from $\chi\chi \to W^+W^-$. $M_\chi = 1$ TeV.

Effects of non factorisable (non collinear, hard) photons

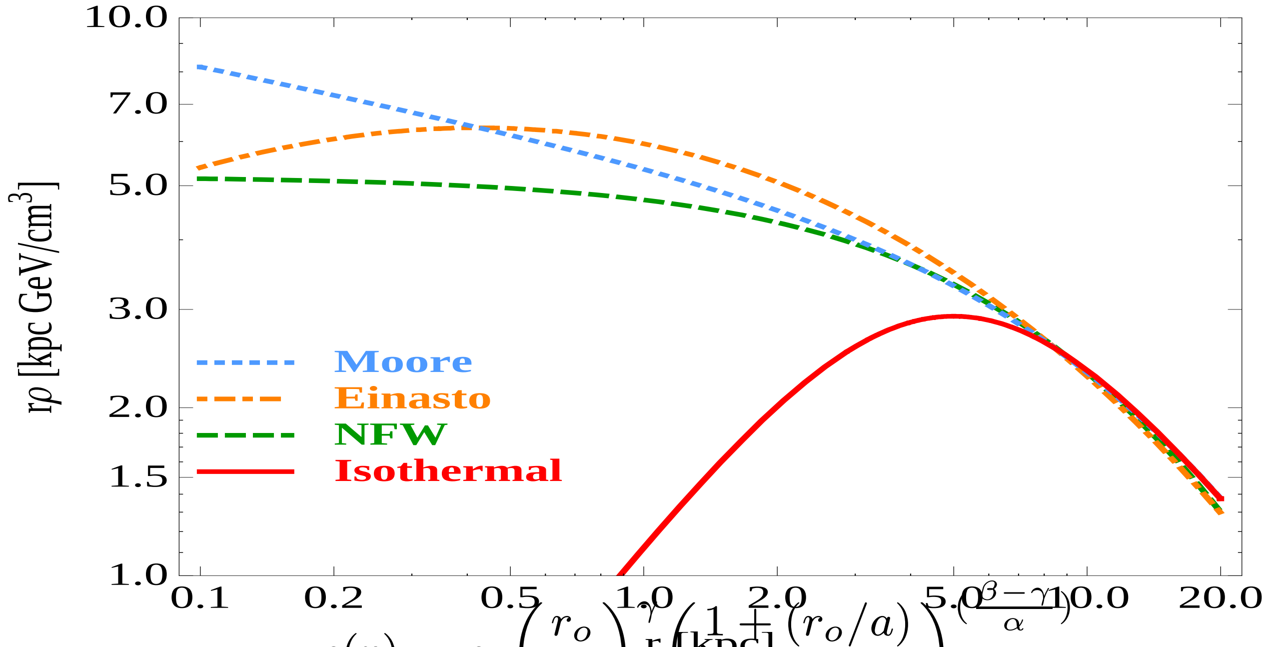




Photon spectrum within a CMSSM point including the aditional photon contribution from $2 \rightarrow 3$ $\tau\tau\gamma$, $e^+e^-\gamma$, and FSR photons from PYTHIA (FSR)

In a model for WW production, including full $WW\gamma$ as compared to PYTHIA FSR

Dark Matter Halo Profiles in micrOMEGAs



$$\rho(r) = \rho_o \left(\frac{r_o}{r}\right)^{\gamma} \left(\frac{1+(r_o/a)}{1+(r_o/a)}\right)^{\left(\frac{\beta-\gamma}{\alpha}\right)}$$

$$(\alpha, \beta, \gamma, a(kpc)) = (2, 2, 0, 4) \quad \text{Isothermal}$$

$$(\alpha, \beta, \gamma, a(kpc)) = (1, 3, 1, 20) \quad \text{NFW cusped}$$

$$(\alpha, \beta, \gamma, a(kpc)) = (1.5, 3, 1.5, 28) \quad \text{Moore, cusped}$$

$$\rho_o \sim 0.3 GeV/cm^3 \ \text{ at } r_o = 8.5 kpc \tag{1}$$

Other profiles (provided they are spherically symmetric are possible. For example Einasto

To avoid central divergence, we set $r > r_{min} = 10^{-3}$pc diffusion is assumed to take place in space only: steady state (DarkSUSY and micrOMEGAs)

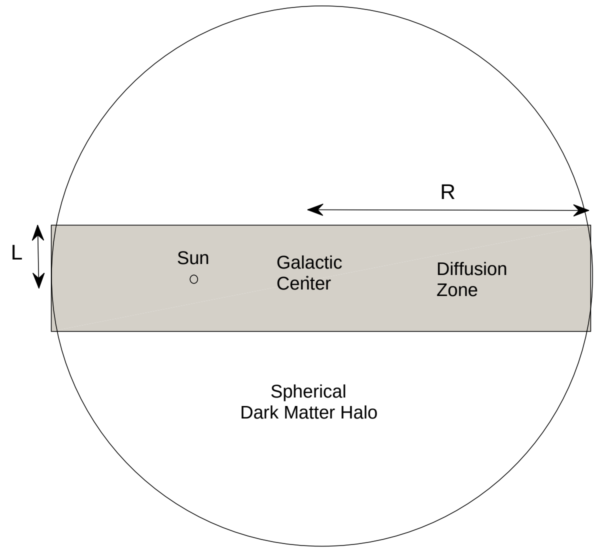
$$\frac{\partial \psi_a}{\partial t} - \nabla \cdot (K(E) \nabla \psi_a) - \frac{\partial}{\partial E}(b(E)\psi_a) + \frac{\partial}{\partial z}(V_C \psi_a) = Q_a(\mathbf{x}, E) + \tilde{\Gamma}_{ann}, \quad \psi_a = dn/dE$$

$$\frac{\partial \psi_a}{\partial t} - \nabla \cdot (K(E) \nabla \psi_a) - \frac{\partial}{\partial E}(b(E)\psi_a) + \frac{\partial}{\partial z}(V_C \psi_a) = Q_a(\mathbf{x}, E) + \tilde{\Gamma}_{ann}, \quad \psi_a = dn/dE$$

- $K(E) = K_0 \beta(E)(E/E_0)^\delta$ diffusion term, stochastic galactic magnetic fields
- b energy losses due to synchroton rad., CMB , ICS, negligible for $\bar{p}$
- V_C convection galactic wind wipes away charged particles from disk (not for e+)
- $\Gamma_{ann.}$ for $\bar{p}$ disappearance through nuclear reactions (H, H_e)
- from Sun to earth “rescaling", due to solar wind and energy loss. (use Fisk pot.)

$$\frac{\partial \psi_a}{\partial t} - \nabla \cdot (K(E)\nabla\psi_a) - \frac{\partial}{\partial E}(b(E)\psi_a) + \frac{\partial}{\partial z}(V_C\psi_a) = Q_a(\mathbf{x}, E) + \tilde{\Gamma}_{ann}, \quad \psi_a = dn/dE$$

Model	δ	K_0 $\mathrm{kpc}^2/\mathrm{Myr}$	L kpc	V_C km/s
MIN	0.85	0.0016	1	13.5
MED	0.7	0.0112	4	12
MAX	0.46	0.0765	15	5

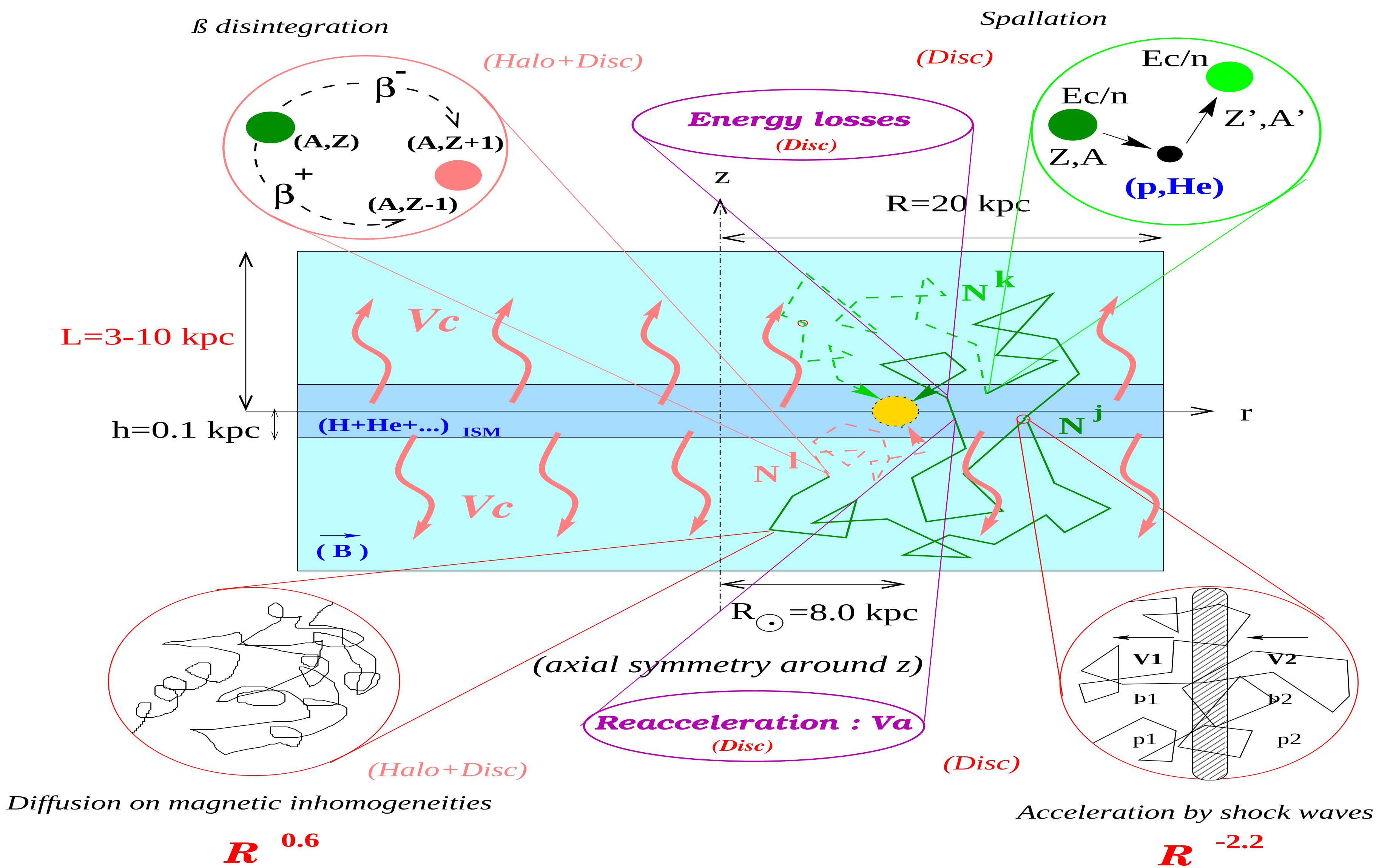


Two-zone diffusion model (Green's function and tabulation). Typical diffusion parameters that are compatible with the B/C analysis (Maurin et al. 2001) $E_0 = 1$GeV.

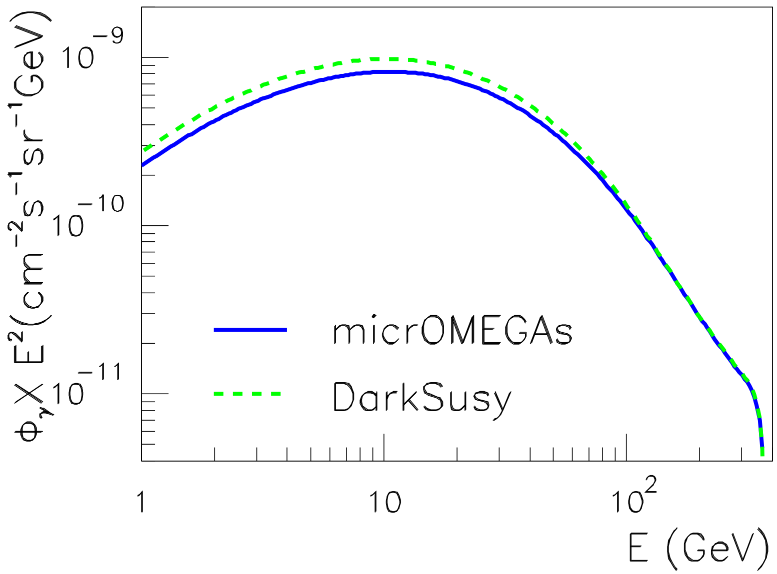
$\frac{\partial \psi_a}{\partial t} = 0$, steady state, takes e^+ 10^8y to reach the edge.

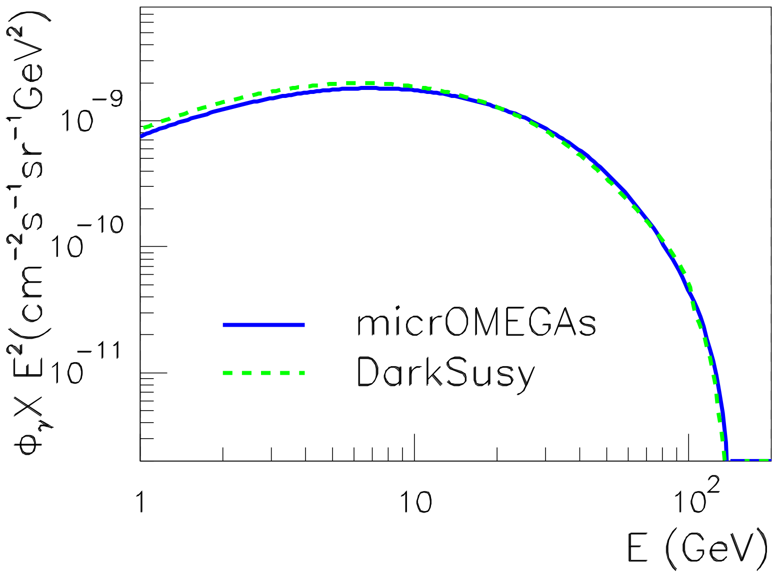
Equations solved semi-analytically

indirect detection: modelling propagation 1 (Maurin et al., 2002)



Results and Comparison, microMEGAs vs DARKSUSY, γ



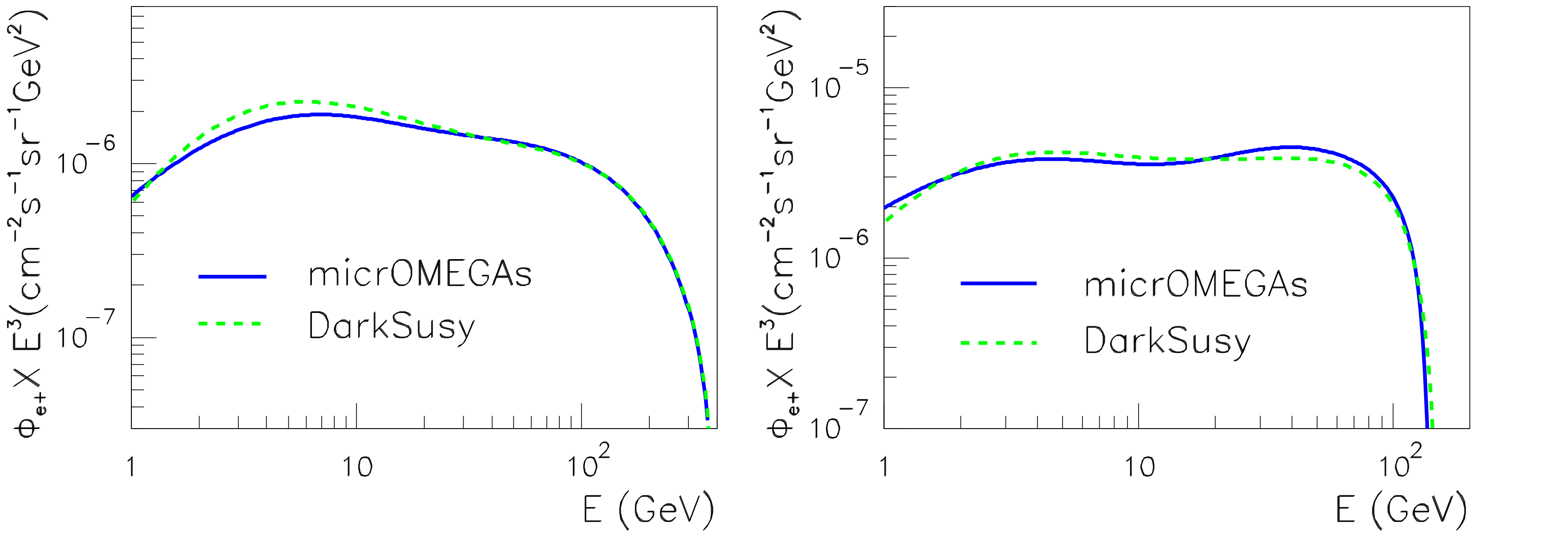


comparisons for γ signal from two CMSSM models, with NFW profile, signal from the GC in a cone of 1^o opening angle (corresponding to a solid angle of $\Delta\Omega = 10^{-3}$ sr)

slight difference due to σv

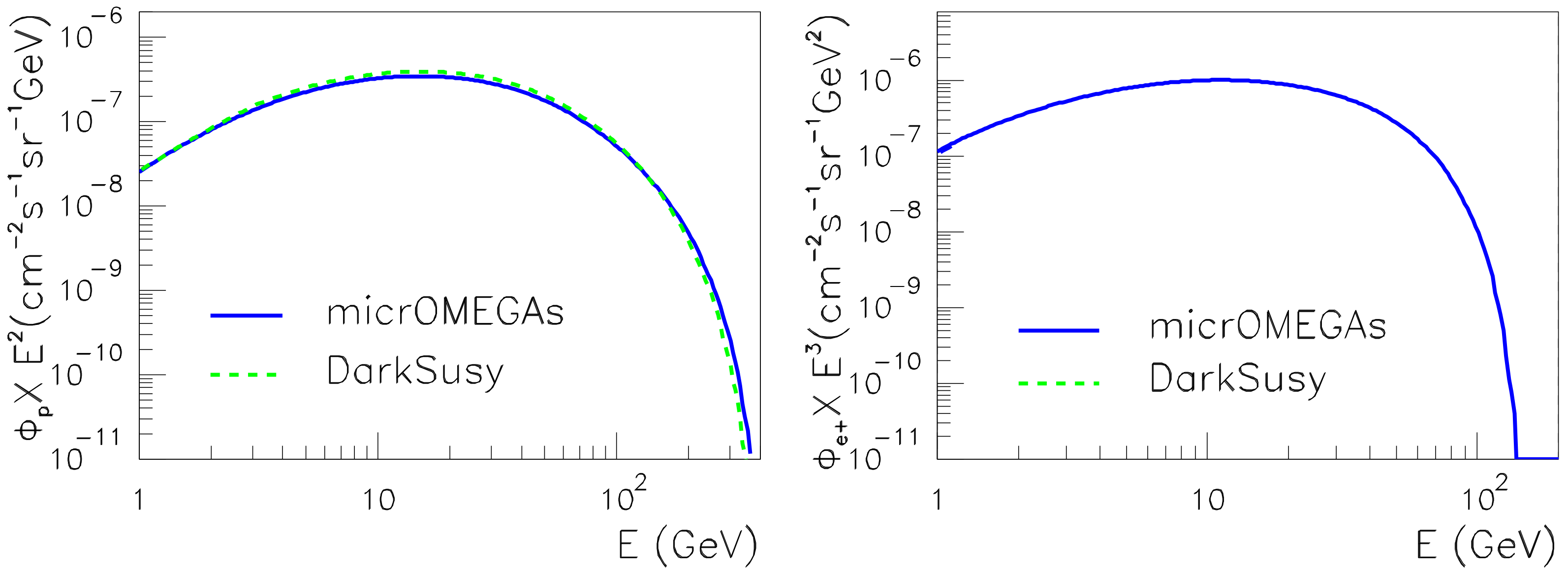
For γ line, good agreement from $\gamma\gamma$ but not $Z\gamma$, DS misses contributions

Results and Comparison, microMEGAs vs DARKSUSY, e^+



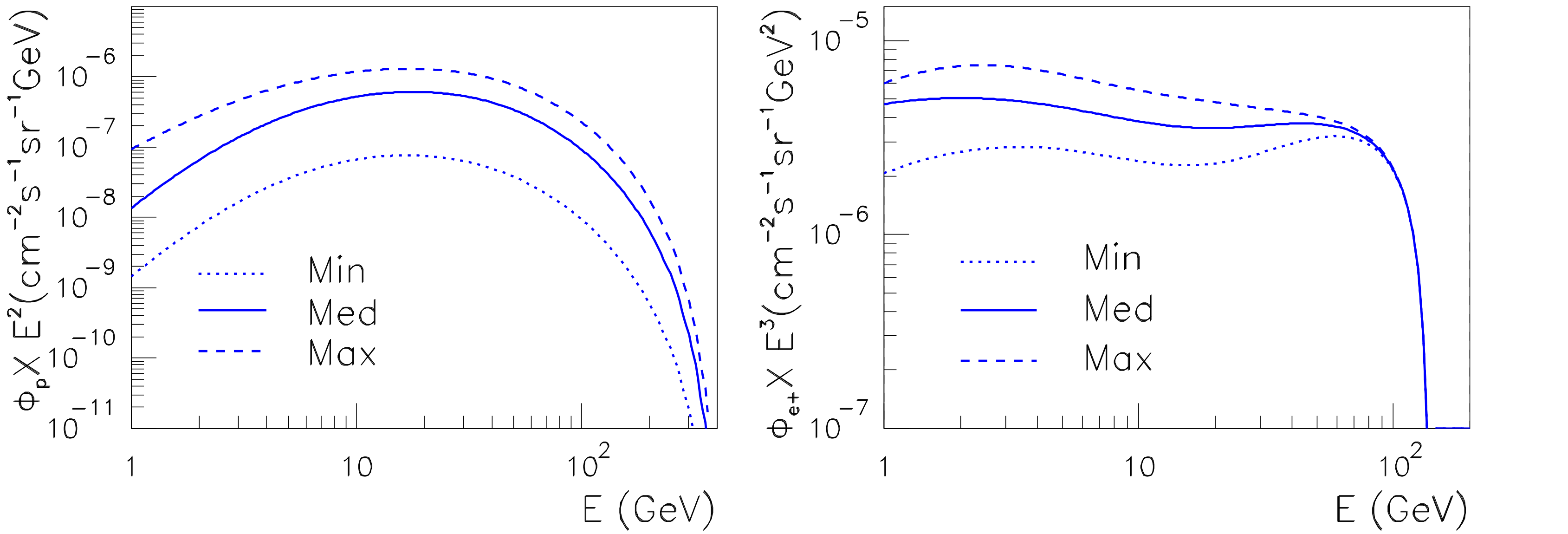
In the same SUSY models, default prop. parameters of microMEGAs tuned.

Results and Comparison, microMEGAs vs DARKSUSY, $\bar{p}$



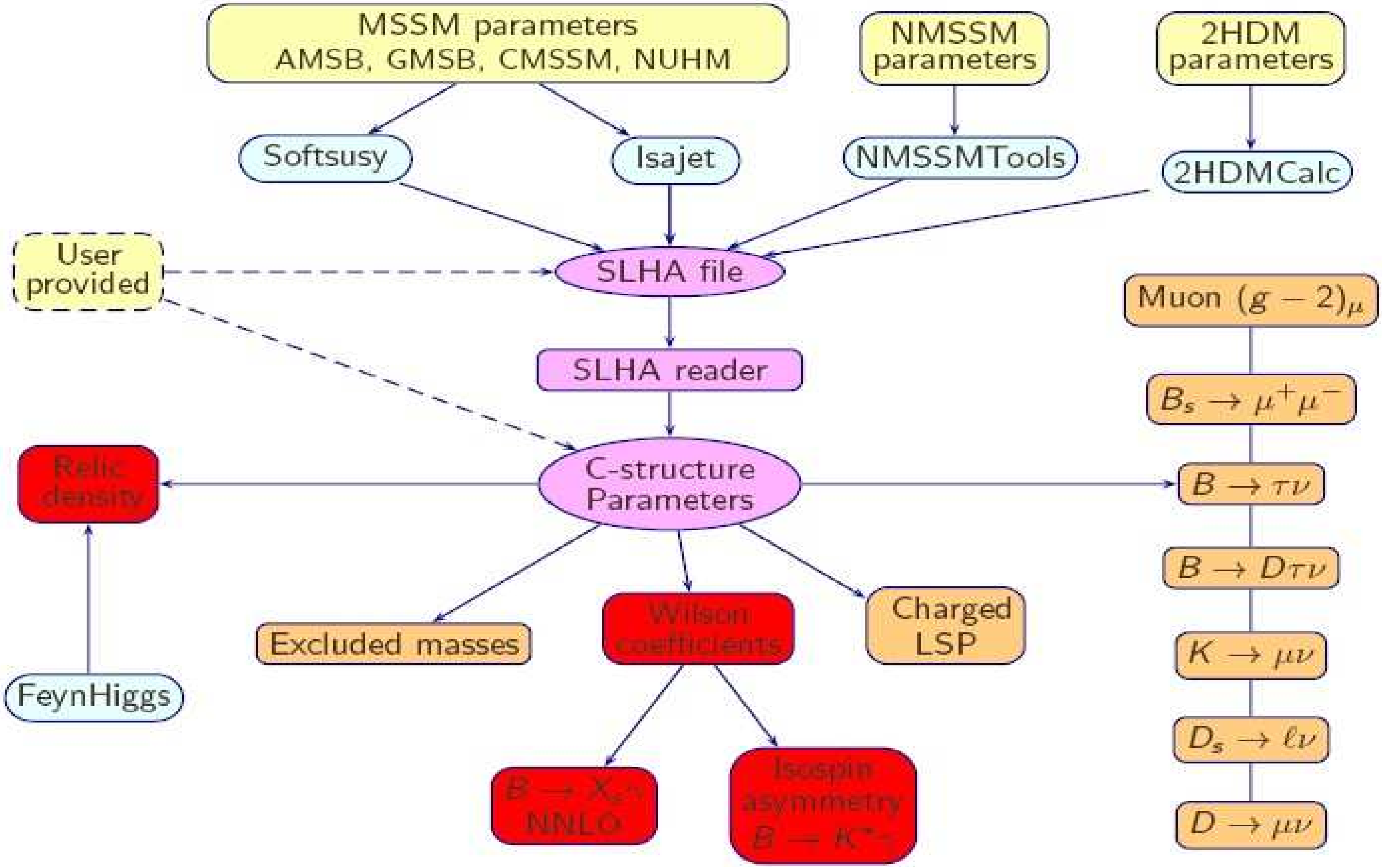
In the same SUSY models, default prop. parameters of microMEGAs tuned.

Uncertainties due to propagation microMEGAs



Neutrinos from from the Sun and the Earth, DarkSUSY

- calculates capture rate of neutralinos in Sun/Earth
- solve the evolution equation for capture
- Let neutralinos annihilate in the Centre into neutrinos (tabulation from `WimpSim` module)
- neutrinos propagate to the detector taking into account oscillations (tabulation `WimpSim` module)
- choice of velocity distributions


MSSM parameters
AMSB, GMSB, CMSSM, NUHM
NMSSM parameters
2HDM parameters
Softsusy
Isajet
NMSSMTools
2HDMCalc
User provided
SLHA file
SLHA reader
C-structure Parameters
Relic density
FeynHiggs
Excluded masses
Wilson coefficients
Charged LSP
$B \to X_s \gamma$ NNLO
Isospin asymmetry $B \to K^* \gamma$
Muon $(g-2)_\mu$
$B_s \to \mu^+\mu^-$
$B \to \tau\nu$
$B \to D\tau\nu$
$K \to \mu\nu$
$D_s \to \ell\nu$
$D \to \mu\nu$

Summary and outlook micrOMEGAs

- Indirect: Neutrino signals, full implementation to be released soon (work with Pasquale Serpico)
- Indirect: Improve the propagation code, clumps,...
- finish off $\bar{D}$
- Link to USINE (then **The DA NNECY CODE(s))**
- Sommerfeld Effects / Sudakov effect ($2 \to 3$ processes)
- Incorporating dominant loop effects (Interface to SloopS)
- Relic: Alternative cosmological scenarios
- Pursue implementation of new models

Table 1: Comparison micrOMEGAs2.4, DarkSUSY5.0 and Isajet7.78 and

comparison with other DM codes

	micrOMEGAs	DarkSUSY	IsaTools
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	**semi-analytic**	**GALPROP or semi-analytic**	
Neutrino rates		**Sun, Earth**	
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**
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**
GUT scale models	**SpectCalc**	**Isajet, Suspect**	**Isajet**
Other models	**CPVMSSM, (C)NMSSM**	**complex(not tested)**	**MSSM+ν_R**
	RHNM,LHM	**No**	**No**
Speed	$\star\star$	$\star$	$-$
Non SUSY Models	$\star\star$	$-$	$-$
	Open Source	$-$	$-$

MicrOMEGAs: a code for the calculation of Dark Matter Properties

including the relic density, direct *new* and indirect rates in a general supersymmetric model and other models of New Physics *new*

by
Geneviève Bélanger, Fawzi Boudjema, Alexander Pukhov and Andrei Semenov

«O atomes intelligents, dans qui

Micromegas v_2.2 for a generic model for the calculation of
Relic density
Direct detection rates
Indirect detection rates

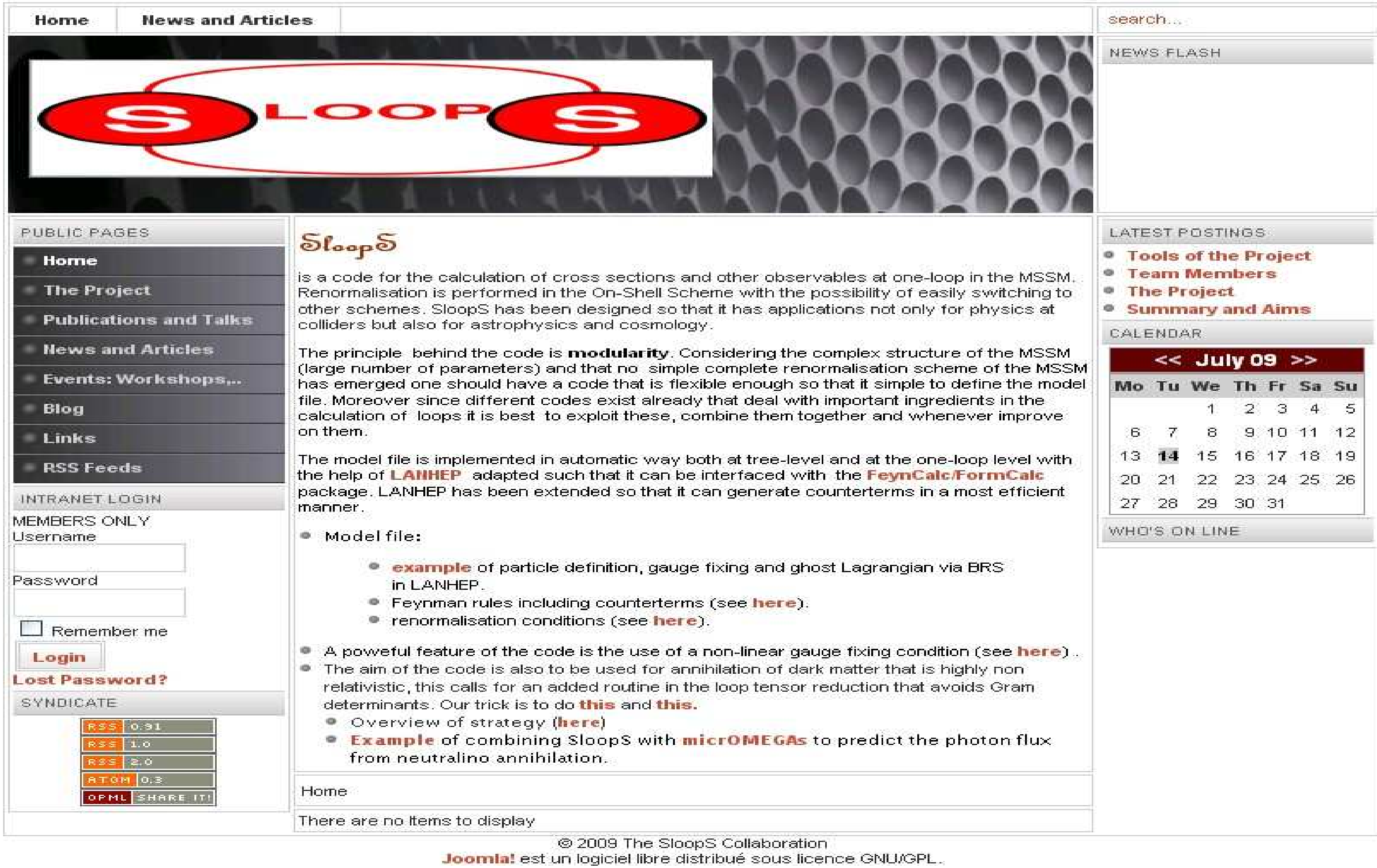
Code to calculate the properties of a stable massive particle in a generic model. First developed to compute the relic density of a stable massive particle, the code also computes the rates for direct and indirect detection rates of dark matter. It is assumed that a discrete symmetry like R-parity ensures the stability of the lightest odd particle. All annihilation and coannihilation channels are included in the computation of the relic density. Specific examples of this general approach include the MSSM and various extensions. Extensions to other models can be implemented by the user. The New Physics model first requires to write a new CalcHEP model file, a package for the automatic generation of squared matrix elements. This can be done through LanHEP. Once this is done, all annihilation and coannihilation channels are included automatically in any model.
The cross-sections for both spin dependent and spin independent interactions of WIMPS on protons are computed automatically as well as the rates for WIMP scattering on nuclei in a large detector.
Annihilation cross-sections of the drak matter candidate at zero velocity, relevant for indirect detection of dark matter, are also computed automatically.

The package includes the minimal supersymmetric standard model (MSSM), the NMSSM, the MSSM with complex phases (CPVMSSM), the little Higgs model (LHM) and a model with right-handed neutrino DM (RHNM).

Present version (December 2008) is micromegas 2.2.CPC

A web interface for the computation of the direct detection rates developed by Rachid Lemrani can be found here.

SloopS Webpage, Code not public...yet



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SYNDICATE

RSS 0.91
RSS 1.0
RSS 2.0
ATOM 0.3
OPML SHARE IT!

SloopS

is a code for the calculation of cross sections and other observables at one-loop in the MSSM. Renormalisation is performed in the On-Shell Scheme with the possibility of easily switching to other schemes. SloopS has been designed so that it has applications not only for physics at colliders but also for astrophysics and cosmology.

The principle behind the code is **modularity**. Considering the complex structure of the MSSM (large number of parameters) and that no simple complete renormalisation scheme of the MSSM has emerged one should have a code that is flexible enough so that it simple to define the model file. Moreover since different codes exist already that deal with important ingredients in the calculation of loops it is best to exploit these, combine them together and whenever improve on them.

The model file is implemented in automatic way both at tree-level and at the one-loop level with the help of **LANHEP** adapted such that it can be interfaced with the **FeynCalc/FormCalc** package. LANHEP has been extended so that it can generate counterterms in a most efficient manner.

- Model file:
  - **example** of particle definition, gauge fixing and ghost Lagrangian via BRS in LANHEP.
  - Feynman rules including counterterms (see **here**).
  - renormalisation conditions (see **here**).
- A poweful feature of the code is the use of a non-linear gauge fixing condition (see **here**).
- The aim of the code is also to be used for annihilation of dark matter that is highly non relativistic, this calls for an added routine in the loop tensor reduction that avoids Gram determinants. Our trick is to do **this** and **this.**
  - Overview of strategy (**here**)
  - **Example** of combining SloopS with **micrOMEGAs** to predict the photon flux from neutralino annihilation.

Home

There are no Items to display

LATEST POSTINGS

- **Tools of the Project**
- **Team Members**
- **The Project**
- **Summary and Aims**

CALENDAR

<< July 09 >>

Mo	Tu	We	Th	Fr	Sa	Su
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

WHO'S ON LINE

Present measurement at 2σ $\boxed{0.0975 < \omega = \Omega_{\rm DM} h^2 < 0.1223}$ **(6%)**

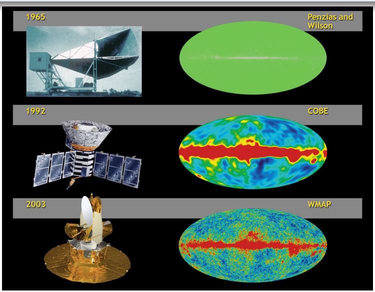
future (SNAP+Planck) $\rightarrow < 1\%$

Need more Precise Predictions

γ ray-line is a one-loop calc.

RELIC DENSITY OF DARK MATTER

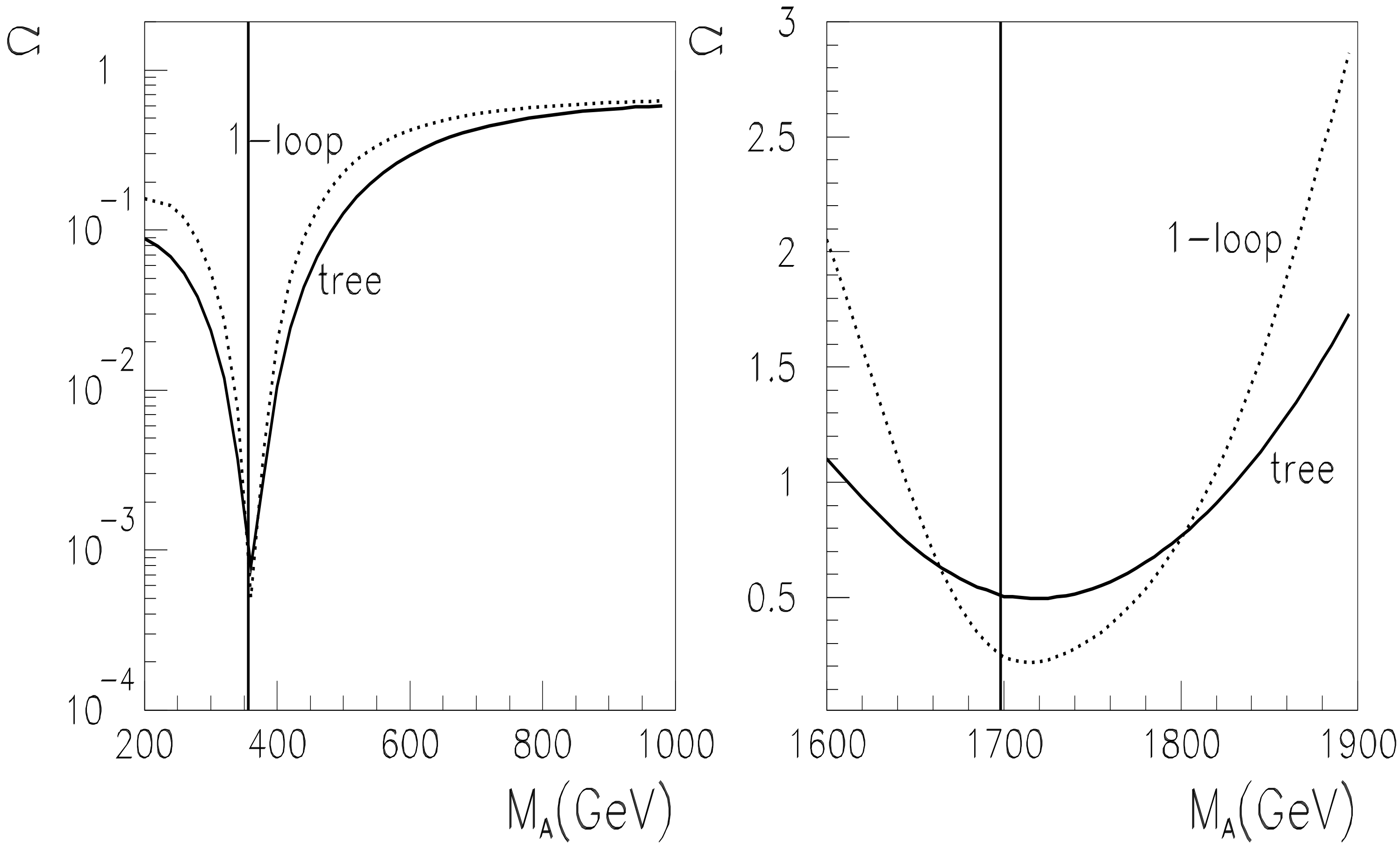
- WMAP : $0.0997 < \Omega_{DM} h^2 < 0.1221$ (10% precision)
- PLANCK : 2% precision



PRECISION MEASUREMENTS

Must be matched by th. calculations $\Rightarrow$ One-loop

2. Need to go beyond tree-level: Need percent level



N. Baro, FB, G. Chalons, G. Drieu La Rochelle, S. Hao, Ninh Le Duc, A. Semenov, (D. Temes)

- Need for an automatic tool for susy calculations
- handles large numbers of diagrams both for tree-level
- and loop level
- able to compute loop diagrams at $v = 0$: dark matter, LSP, move at galactic velocities, $v = 10^{-3}$
- ability to check results: UV and IR finiteness but also gauge parameter independence for example
- ability to include different models easily and switch between different renormalisation schemes
- Used for SM one-loop multi-leg: new powerful loop libraries (with Ninh Le Duc, Sun Hao)

Non-linear gauge implementation

$$\mathcal{L}_{GF} = -\frac{1}{\xi_W}|(\partial_\mu - ie\tilde{\alpha}A_\mu - igc_W\tilde{\beta}Z_\mu)W^{\mu\,+} + \xi_W\frac{g}{2}(v + \tilde{\delta}_h h + \tilde{\delta}_H H + i\tilde{\kappa}\chi_3)\chi^+|^2$$
$$-\frac{1}{2\xi_Z}(\partial.Z + \xi_Z\frac{g}{2c_W}(v + \tilde{\epsilon}_h h + \tilde{\epsilon}_H H)\chi_3)^2 - \frac{1}{2\xi_\gamma}(\partial.A)^2$$

- quite a handful of gauge parameters, but with $\xi_i = 1$, no "unphysical threshold"
- more important: no need for higher (than the minimal set)for higher rank tensors and tedious algebraic manipulations

SOME PREVIOUS WORK AT 1-L IN SUSY

One-loop calculation EW + QCD corrections

- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\gamma, Z\gamma, gg$: Boudjema, Semenov, Temes, *Phys. Rev.* **D72**, 055024 (2005)
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow ZZ, W^+W^-$: Baro, Boudjema, Semenov, *Phys. Lett.* **B660** (2008) 550
  Baro, Boudjema, Chalons, Sun Hao, *Phys. Rev* **D81** (2008) 015005
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tau^+\tau^-, b\bar{b}$: Baro, Boudjema, Semenov, *Phys. Lett* **B660** (2008) 550
- Co-annihilation with $\tilde{\tau}$: Baro, Boudjema, Semenov, *Phys. Lett* **B660** (2008) 550,

QCD corrections

- Co-annihilation with $\tilde{t}$ Freitas *Phys. Lett.* **B652** (2007) 280
- Annihilation into massive quarks Hermann, Klasen, Kovarik *Phys. Rev.* **D79** (2009)
  Herrmann, Klasen, *Phys. Rev.* **D76** (2007) 117704
  Herrmann, Klasen and Kovarik, *Phys. Rev.* **D80** (2009) 085025

FROM TREE TO LOOPS : NEED FOR AUTOMATION

- At tree-level we have for $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to WW$ 7 diagrams.
- Relic density predictions involve many annihilation (and coannihilation) channels.

Some efficient tree-level codes already exist for relic density calculations :

- DarkSUSY [Bergström *et al.* (2004)]
- micrOMEGAs [Bélanger, Boudjema, Pukhov, Semenov (2002)]
- Mainly $2 \to 2$ processes are taken into account in the computation.

At one-loop we have $\simeq$ 7000 diagrams

Then for an accurate and reliable relic density prediction at one-loop order we need :

$\longrightarrow$ A coherent renormalisation scheme and a choice of input parameters.

$\longrightarrow$ To generate counter-terms, for SUSY gigantic task.

$\longrightarrow$ To compute a huge amount of loop diagrams.

$\longrightarrow$ Loop Integrals library to handle Gram determinant when $v \to 0$.

$\longrightarrow$ To deal with IR and collinear divergencies $\longrightarrow$ include bremsstrahlung.

$\longrightarrow$ To evaluate many processes entering $\langle \sigma v \rangle$.

Strategy: Exploiting and interfacing modules from different codes

Lagrangian of the model defined in LanHEP

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

$\downarrow$ $\downarrow$

Generic Model
-kinematical structures

Classes Model
-Feynman rules, including CT

$\Downarrow$

Evaluation via FeynArts-FormCalc

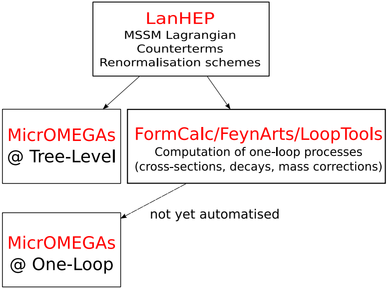
LoopTools modified!!
tensor reduction inappropriate for small relative velocities
(Zero Gram determinants)

$\Uparrow$

Renormalisation scheme

- definition of renorm. const. in the classes model

Non-Linear gauge-fixing constraints, gauge parameter dependence checks



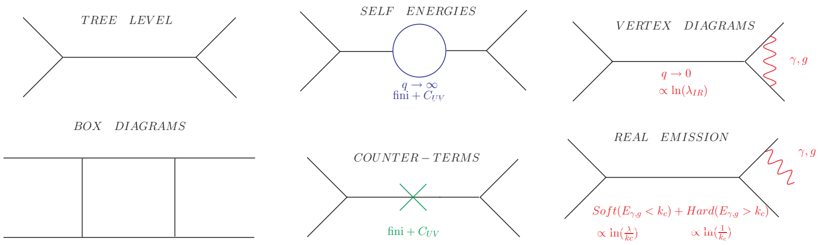
- Evaluation of one-loop diagrams including a complete and coherent renormalisation of each sector of the MSSM with an OS scheme.
- Modularity between different renormalisation schemes.
- Non-linear gauge fixing.
- Handles a large number of Feynman diagrams.
- Checks : results UV,IR finite and gauge independent.

http://code.sloops.free.fr/

RADIATIVE CORRECTIONS-RENORMALISATION

DIVERGENCES

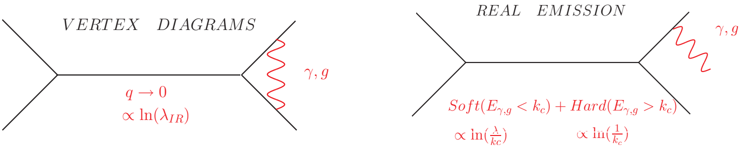
- Due to perturbative development in the coupling constant.



REGULARISATION

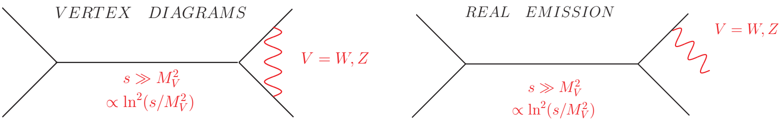
Isolate infinite parts in loops

- UV : $\ln \Lambda_{UV}$ with cut-off, $1/\epsilon_{UV}$ poles in DR.
- IR : $\ln \lambda_{IR}$ with cut-off, $1/\epsilon_{IR}$ poles in DR.



- Originate from
  - ↪ Massless gauge bosons (γ, g) coupling to on-shell external legs.
  - ↪ Soft and collinear regions of integration over boson momenta (appear as double log $\ln^2(\lambda_{IR})$ or $1/\epsilon^2_{IR}$).
- Adding real emission remove unphysical dependency in the cut-off λ_{IR} or $1/\epsilon^2_{IR}$.
- Integration over 3-particles phase space can be complicated.
- Usually for DM calculation $2 \to 2$ processes are enough, but if real corrections $\simeq$ vertex corrections, $2 \to 3$ processes should also be included.

A WORD ABOUT INFRARED DIVERGENCIES



- Originate from
  - ↪ Massless gauge bosons (γ, g) coupling to on-shell external legs.
  - ↪ Soft and collinear regions of integration over boson momenta (appear as double log $\ln^2(\lambda_{IR})$ or $1/\epsilon_{IR}^2$).
- Adding real emission remove unphysical dependency in the cut-off λ_{IR} or $1/\epsilon_{IR}^2$.
- Integration over 3-particles phase space can be complicated.
- Usually for DM calculation $2 \rightarrow 2$ processes are enough, but if real corrections $\simeq$ vertex corrections, $2 \rightarrow 3$ processes should also be included.
- If c.m energy $\sqrt{s} \gg M_V$, EW bosons behave like a photon $\Rightarrow$ Mass singularities in soft and collinear logs $\propto \ln^2(s/M_W^2)$

FERMION + GAUGE SECTOR

Input parameters as in the Standard Model $m_f, \alpha(0), M_W, M_Z$

HIGGS SECTOR

Input parameters : $M_{A^0}, t_\beta = v_2/v_1$. Several definitions for δt_β :

- $\overline{DR}$: δt_β is a pure divergence
- MH : δt_β is defined from the measurement of the mass m_H
- $A^0\tau\tau$: δt_β is defined from the decay $A^0 \to \tau^+\tau^-$ ($vertex \propto m_\tau t_\beta$)

SFERMIONS SECTOR

Input parameters : 3 sfermions masses $m_{\tilde{d}_1}, m_{\tilde{d}_2}, m_{\tilde{u}_1}$ and 2 conditions for $A_{u,d}$

NEUTRALINOS/CHARGINOS SECTOR

Input parameters : 2 charginos $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}$ and 1 neutralino $\tilde{\chi}_1^0$

```
vector
    A/A: (photon, gauge),
    Z/Z:('Z boson', mass MZ = 91.1875, gauge),
    'W+'/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar  H/H:(Higgs, mass MH = 115).
```

```
transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
    'W+'->'W+'*(1+dZW/2),'W-'->'W-'*(1+dZW/2).
transform H->H*(1+dZH/2), 'Z.f'->'Z.f'*(1+dZZf/2),
    'W+.f'->'W+.f'*(1+dZWf/2),'W-.f'->'W-.f'*(1+dZWf/2).

let pp = { -i*'W+.f',  (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).
```

```
lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
     where
    lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .

let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
     i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
    -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.

lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.

lterm -'Z.C'*brst(G_Z).
```

From the Lagrangian to the Feynman Rules

```
vector
    A/A: (photon, gauge),
    Z/Z:('Z boson', mass MZ = 91.1875, gauge),
    'W+'/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar  H/H:(Higgs, mass MH = 115).



transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
    'W+'->'W+'*(1+dZW/2),'W-'->'W-'*(1+dZW/2).
transform H->H*(1+dZH/2), 'Z.f'->'Z.f'*(1+dZZf/2),
    'W+.f'->'W+.f'*(1+dZWf/2),'W-.f'->'W-.f'*(1+dZWf/2).

let pp = { -i*'W+.f',  (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).



lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
     where
    lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .

let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
     i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
    -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.

lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.

lterm -'Z.C'*brst(G_Z).
```

with Counterterms !!

```
M$CouplingMatrices = {

  (*------    H   H   ------*)
   C[ S[3], S[3] ] == - I *
{
 { 0 , dZH },
 { 0 , MH^2 dZH + dMHsq }
},
  (*------    W+.f   W-.f   ------*)
   C[ S[2], -S[2] ] == - I *
{
 { 0 , dZWf },
 { 0, 0 }
},  (*------    A   Z   ------*)
   C[ V[1], V[2] ] == 1/2 I / CW^2 MW^2 *
{
 { 0, 0 },
 { 0 , dZZA },
 { 0, 0 }
},

(*------    H   H   H   ------*)
   C[ S[3], S[3], S[3] ] == -3/4 I EE / MW / SW *
{
 { 2 MH^2 , 3 MH^2 dZH -2 MH^2 / SW dSW - MH^2 / MW^2 dMWsq +
},
  (*------    H   W+.f   W-.f   ------*)
   C[ S[3], S[2], -S[2] ] == -1/4 I EE / MW / SW *
{
 { 2 MH^2 , MH^2 dZH + 2 MH^2 dZWf -2 MH^2 / SW dSW - MH^2 /
},

  (*------    W-.C   A.c   W+   ------*)
   C[ -U[3], U[1], V[3] ] == - I EE *
{
 { 1 },
 { - nla }
},
```

From the Lagrangian to the Feynman Rules

```
vector
    A/A: (photon, gauge),
    Z/Z:('Z boson', mass MZ = 91.1875, gauge),
    'W+'/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar  H/H:(Higgs, mass MH = 115).



transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
    'W+'->'W+'*(1+dZW/2),'W-'->'W-'*(1+dZW/2).
transform H->H*(1+dZH/2), 'Z.f'->'Z.f'*(1+dZZf/2),
    'W+.f'->'W+.f'*(1+dZWf/2),'W-.f'->'W-.f'*(1+dZWf/2).

let pp = { -i*'W+.f',  (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).



lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
     where
    lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .

let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
     i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
    -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.

lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.

lterm -'Z.C'*brst(G_Z).
```

```
RenConst[ dMHsq ] := ReTilde[SelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZH ] := -ReTilde[DSelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZZf ] := -ReTilde[DSelfEnergy[prt["Z.f"] -> prt["Z.f"],
MZ]] RenConst[ dZWf ] := -ReTilde[DSelfEnergy[prt["W+.f"] ->
prt["W+.f"], MW]]
```

Output of Feynman Rules with Counterterms !!

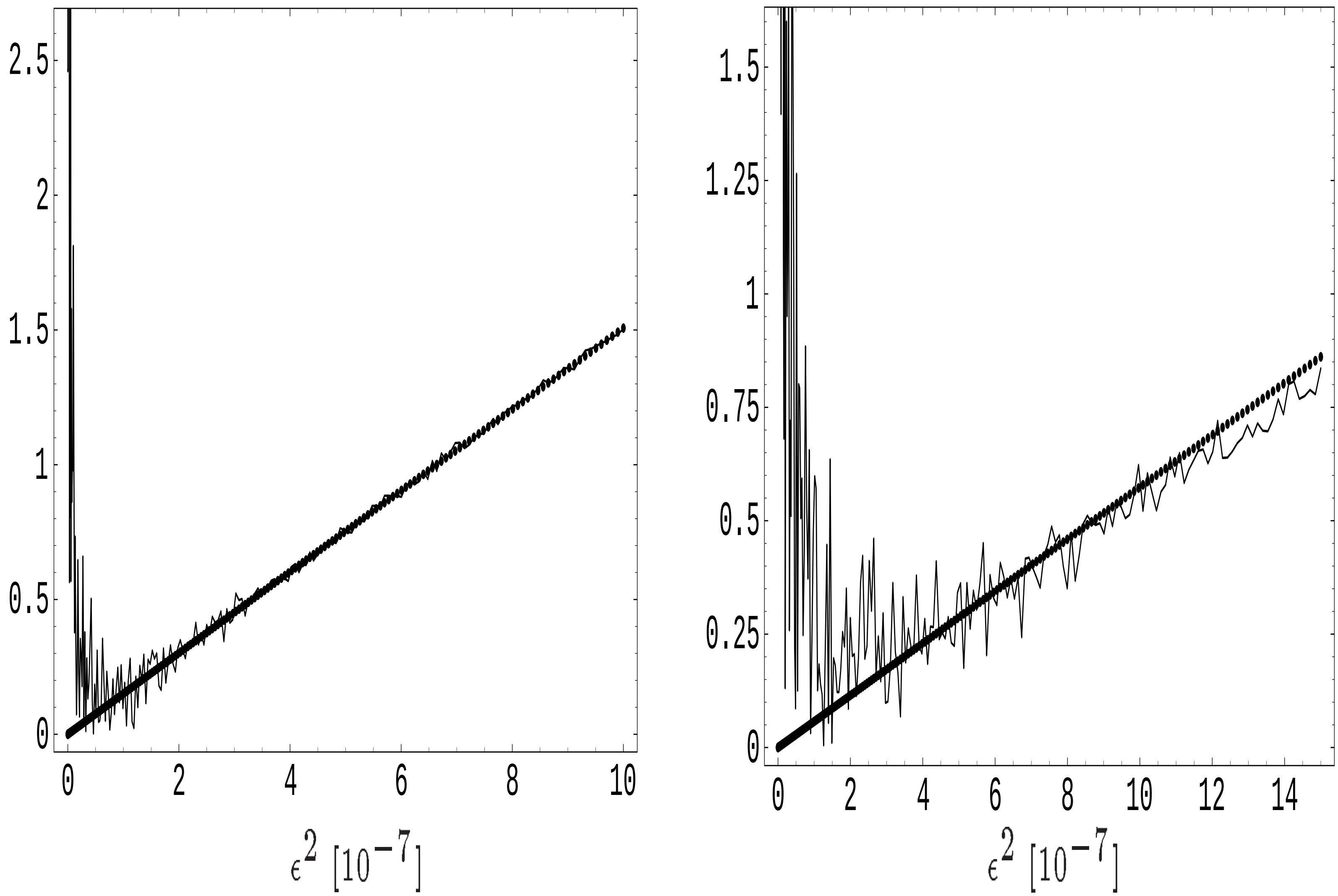
```
M$CouplingMatrices = {

  (*------     H   H   ------*)
   C[ S[3], S[3] ] == - I *
{
 { 0 , dZH },
 { 0 , MH^2 dZH + dMHsq }
},
  (*------     W+.f   W-.f   ------*)
   C[ S[2], -S[2] ] == - I *
{
 { 0 , dZWf },
 { 0, 0 }
}, (*------     A   Z   ------*)
   C[ V[1], V[2] ] == 1/2 I / CW^2 MW^2 *
{
 { 0, 0 },
 { 0 , dZZA },
 { 0, 0 }
},

(*------     H   H   H   ------*)
   C[ S[3], S[3], S[3] ] == -3/4 I EE / MW / SW *
{
 { 2 MH^2 , 3 MH^2 dZH -2 MH^2 / SW dSW - MH^2 / MW^2 dMWsq +
},
  (*------     H   W+.f   W-.f   ------*)
   C[ S[3], S[2], -S[2] ] == -1/4 I EE / MW / SW *
{
 { 2 MH^2 , MH^2 dZH + 2 MH^2 dZWf -2 MH^2 / SW dSW - MH^2 /
},

  (*------     W-.C   A.c   W+   ------*)
   C[ -U[3], U[1], V[3] ] == - I EE *
{
 { 1 },
 { - nla }
},
```

Gram determinant for small velocity



All annihilations and co-annihilations, Baro+FB (2008)

A FEW EXAMPLES

BINO-LIKE NEUTRALINO

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow l^+l^-$

M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
90	200	-600	1000	250/110 800/800	0	500	5

COANNIHILATION WITH A STAU

$\tilde{\chi}_1^0\tilde{\tau}_1^+ \rightarrow \tau^+\gamma$
$\tilde{\chi}_1^0\tilde{\tau}_1^+ \rightarrow \tau^+Z^0$
$\tilde{\tau}_1^+\tilde{\tau}_1^+ \rightarrow \tau^+\tau^+$

M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
166	300	400	1000	290-276/190-166 800/800	0	1000	10

MIXED-LIKE NEUTRALINO

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W^+W^-$
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow Z^0Z^0$

M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
110	150	-163	1000	1000	0	1000	5

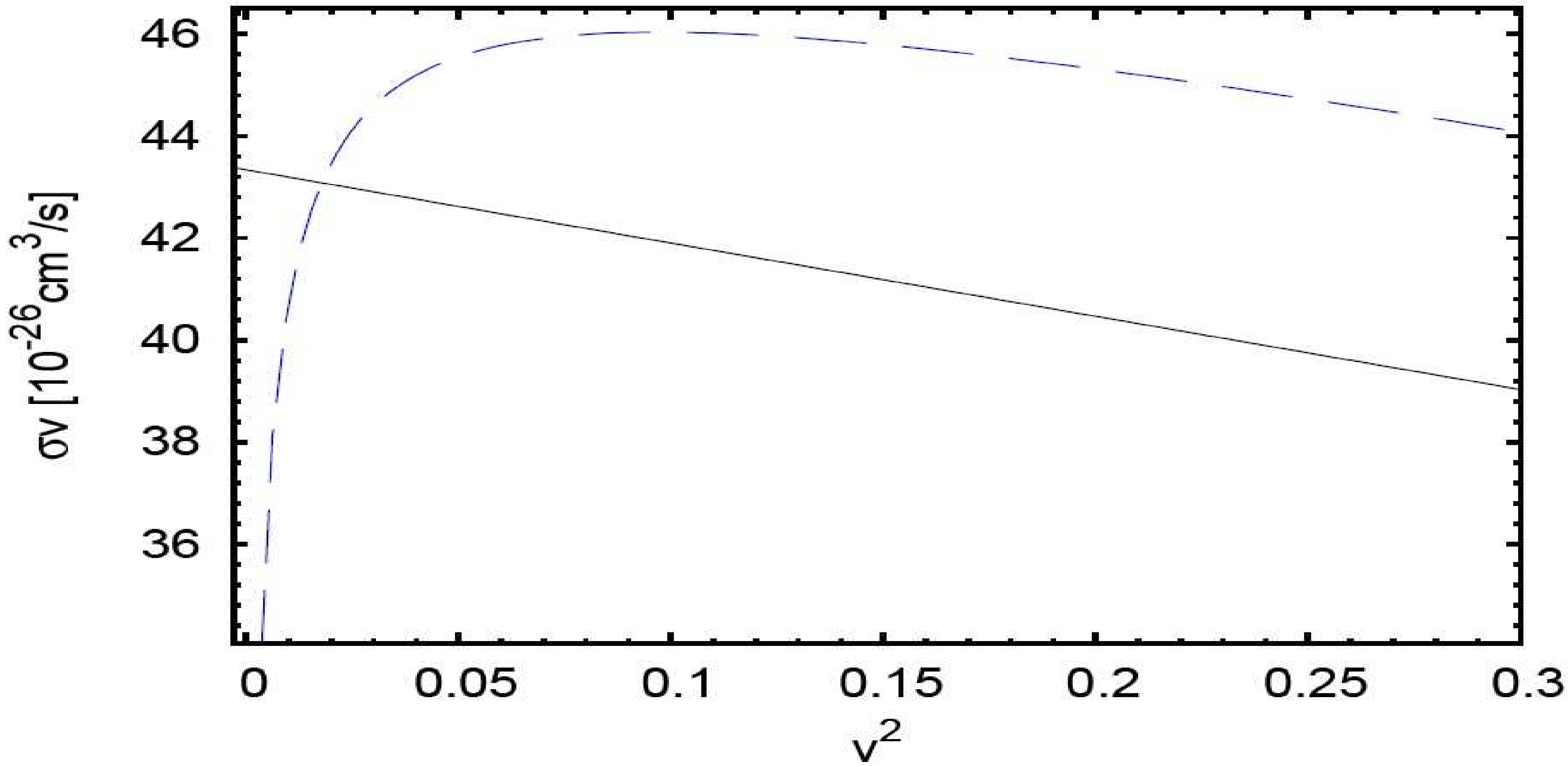
QCD CORRECTION

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

M_1	M_2	μ	M_3	$M_{\tilde{f}_{L,R}}$	A_f	M_{A^0}	t_β
250	150	-180	400	250/200	0	300	5

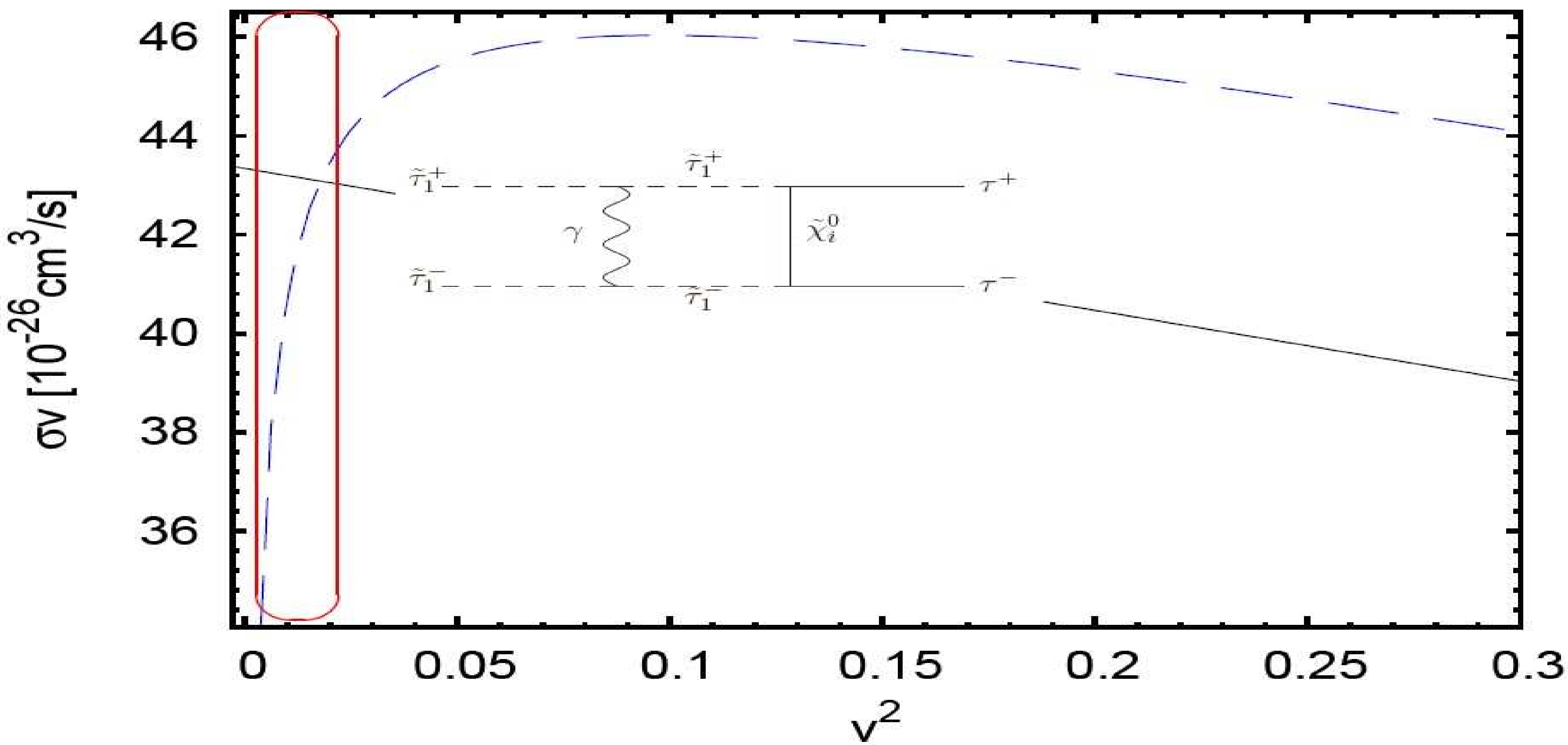
Coannihilation case

$\tilde{\tau}_1^+ \tilde{\tau}_1^+ \rightarrow \tau^+ \tau^+$ (23%)



COANNIHILATION CASE - COULOMB EFFECT

$\tilde{\tau}_1^+ \tilde{\tau}_1^+ \rightarrow \tau^+ \tau^+$ (23%)



Second example : annihilation into $b\bar{b}$

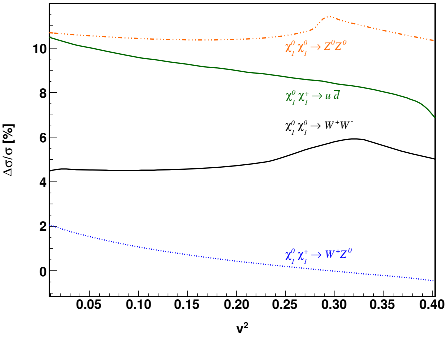
- Mixed case : bino-higgsino
- Important A^0-exchange in s-channel
  $m_{\tilde{\chi}_1^0} = 106$ GeV, $m_{A^0} = 300 GeV$
- $\sigma v = a + bv^2$
- δt_β scheme dependency
- Important corrections to $A^0 \to b\bar{b}$ vertex
  $\to$ anomalous dimension, Δm_b
- Modified Yukawa coupling implemented in `micrOMEGAs`

$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}$	$A_{\tau\tau}$	$\overline{\mathrm{DR}}$	MH
$\delta a/a$ EW	-1%	+3%	+31%
$\delta a/a$ QCD	-26%	-26%	-26%
$\delta b/b$ EW	-1%	+3%	+29%
$\delta b/b$ QCD	-30%	-30%	-30%

- Baro, Boudjema, Chalons, Sun Hao, *Phys. Rev* **D81** (2008) 015005
- Most difficult channels : Gauge invariance plays a prominent role.

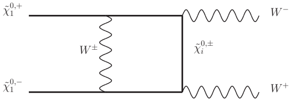
Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value	400	350	-250	4	1000	650	0	800

$$\tilde{\chi}_1^0 = 0.11\tilde{B} - 0.31\tilde{W} - 0.70\tilde{H}_1^0 - 0.63\tilde{H}_2^0$$



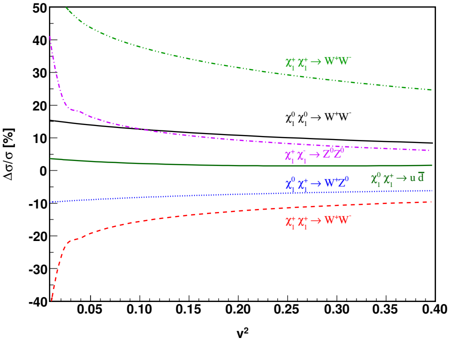
	$A_{\tau\tau}$	$\overline{\text{DR}}$	MH
$\delta\Omega h^2/\Omega h^2$	-2.4%	-2.5%	-3.3%

- Bulk of corrections to the s-wave coefficient
- Small δt_β scheme dependence
- QCD corrections to $u\bar{d} \simeq 3$ %
- Bump $= \tilde{\chi}_1^\pm$ threshold in boxes, not present at Tree-Level
- $a + bv^2$ expansion doesn't work anymore at 1-L

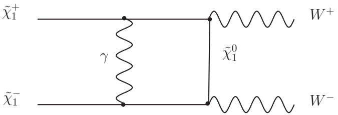


Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{u}_L}$	$M_{\tilde{e}_L}$	$M_{\tilde{u}_R,\tilde{e}_R}$	A_i	M_{A^0}
Value	550	210	-600	30	1200	387	360	800	0	700

$$\tilde{\chi}_1^0 = 0.005\tilde{B} - 0.99\tilde{W} - 0.15\tilde{H}_1^0 - 0.05\tilde{H}_2^0$$



- At 1-L new feature appear for $v \longrightarrow 0$: Coulomb effect
- Possible to capture its one-loop manifestation
- Degeneracy lifted between processes
- Large corrections
- Almost no δt_β scheme dependence
- Strong cancellations between QCD/EW corrections



	$A_{\tau\tau}$	$\overline{\text{DR}}$	MH
$\delta\Omega h^2/\Omega h^2$	-1.9%	-1.9%	-1.9%

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value(GeV)	3500	1800	4500	15	5000	5000	0	5000

$$\tilde{\chi}_1^0 = 0.000\tilde{B} - 0.999\tilde{W} + 0.004\tilde{H}_1^0 + 0.032\tilde{H}_2^0$$

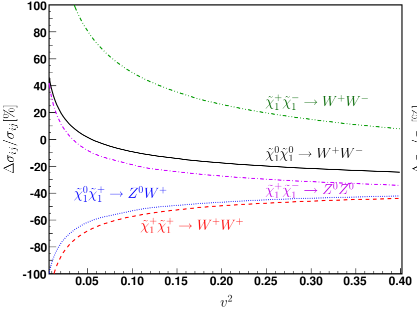
		Tree
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ [10%]	a	$+2.43$
	b	$+0.52$
$\tilde{\chi}_1^+\tilde{\chi}_1^+ \to W^+W^+$ [10%]	a	$+1.22$
	b	$+0.26$
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to Z^0W^+$ [9%]	a	$+0.51$
	b	$+0.12$
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to t\bar{b}$ [9%]	a	$+0.54$
	b	-0.23
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to u\bar{d}$ [9%]	a	$+0.54$
	b	-0.23
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to Z^0Z^0$ [6%]	a	$+0.73$
	b	$+0.16$
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-$ [6%]	a	$+0.65$
	b	$+0.17$
$\Omega_\chi h^2$		0.0997

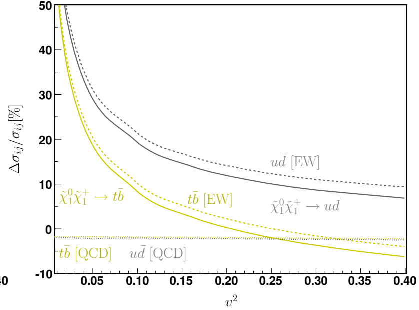
- $m_{\tilde{\chi}_1^0} = 1799.1$ GeV
- $\delta(m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}) = 0.0003$ GeV

- $\sigma_0 v = a + bv^2$
- $m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}$ almost degenerate
- Coannihilation very important
- Degeneracy between processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$ and $\tilde{\chi}_1^+\tilde{\chi}_1^+ \to W^+W^+$
- A lot of processes contribute

Virtual corrections + γ bremsstrahlung

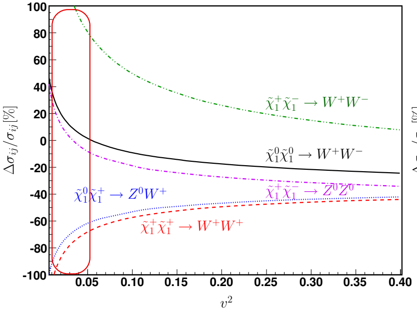
Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value(GeV)	3500	1800	4500	15	5000	5000	0	5000

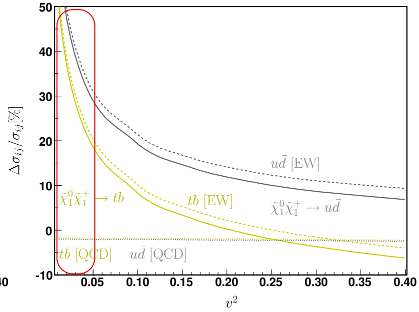




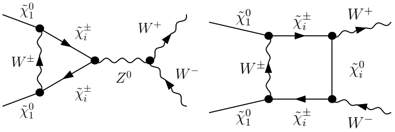
ANNIHILATION INTO GAUGE BOSONS : HEAVY-WINO

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value(GeV)	3500	1800	4500	15	5000	5000	0	5000



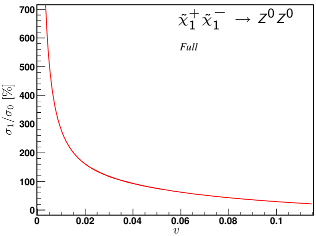


- $M_W/m_{\tilde{\chi}_1^0} = 0.045 \Rightarrow W^\pm, Z^0$ bosons almost considered as massless.
- $v \longrightarrow 0$: Large Sommerfeld (QED+EW) enhancement.



EXTRACTING THE ONE-LOOP SOMMERFELD EFFECT

- The EW Sommerfeld effect is expected to be cut-off, as opposed to the QED one.
- To extract it, remove the QED Coulomb effect first.



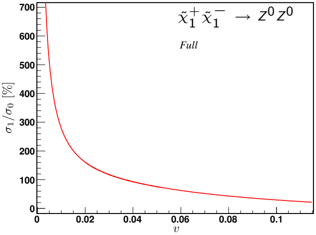
- $S_{nr} = X_{nr}/(1 - e^{-X_{nr}}) \quad X_{nr} = 2\pi\alpha Q_i Q_j / v$
- $S_{1L} = \frac{\pi\alpha}{v} \times \sigma_0 Q_i Q_j$

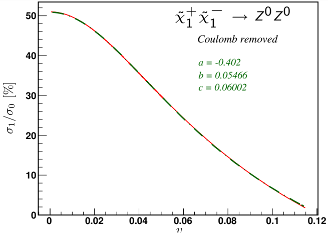
EXTRACTING THE ONE-LOOP SOMMERFELD EFFECT

- The EW Sommerfeld effect is expected to be cut-off, as opposed to the QED one.
- To extract it, remove the QED Coulomb effect first.
- Then, as behavior expected to be cut-off, fit with,

$$\sigma_1/\sigma_0 = a + \frac{b}{\sqrt{v^2 + c^2}}$$

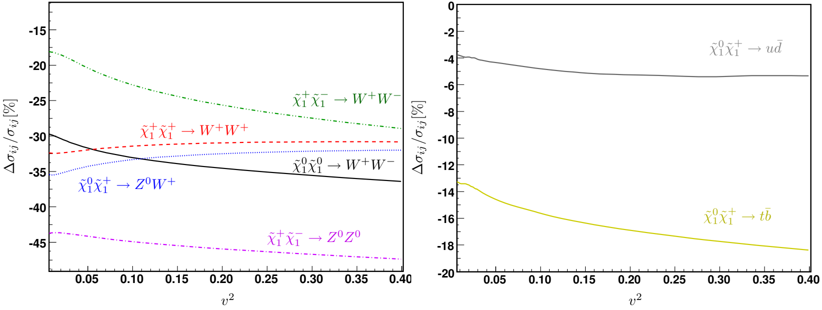
where c is supposed to be the cut-off, of order $M_W/m_{\tilde{\chi}_1^0}$.



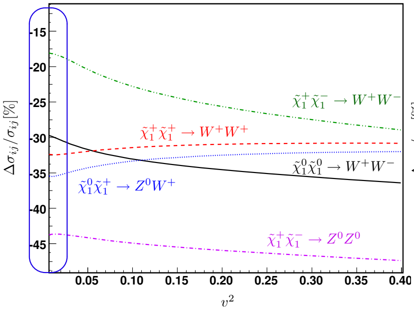


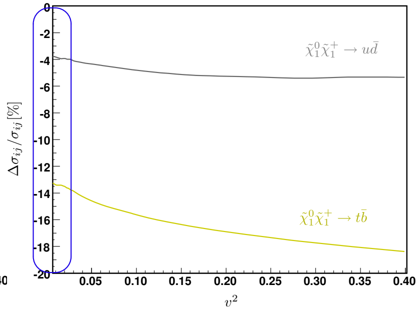
- Large corrections but < QED Sommerfeld for $v \to 0$.

Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value(GeV)	3500	1800	4500	15	5000	5000	0	5000

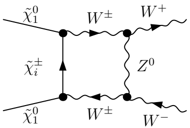


Parameter	M_1	M_2	μ	t_β	M_3	$M_{\tilde{L},\tilde{Q}}$	A_i	M_{A^0}
Value(GeV)	3500	1800	4500	15	5000	5000	0	5000



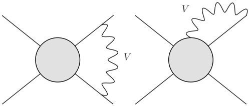


- Even after substraction of Sommerfeld effect, still large corrections of Sudakov type ($m_{\tilde{\chi}_1^0} \gg M_W, M_Z$) for individual processes.



- Originate from vertex and box diagrams involving virtual bosons.
- General form of one-loop Sudakov corrections

$$\alpha\left[C_2 \underbrace{\ln^2\left(\frac{s}{M_V^2}\right)}_{\mathrm{LL}} + C_1 \underbrace{\ln^1\left(\frac{s}{M_V^2}\right)}_{\mathrm{NLL}} + C_0\right] + \mathcal{O}\left(\frac{M_V^2}{s}\right) \quad V = \gamma, W^{\pm}, Z^0$$

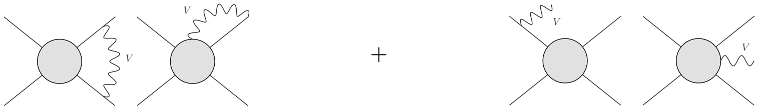


- The $\ln(s/M_V^2)$ represents mass singularities and originate from soft and collinear regions.
- For QED corrections always present ($M_\gamma \to 0$), for EW ones when $s \gg M_{W,Z}^2$.

SUDAKOV VIRTUAL CORRECTIONS

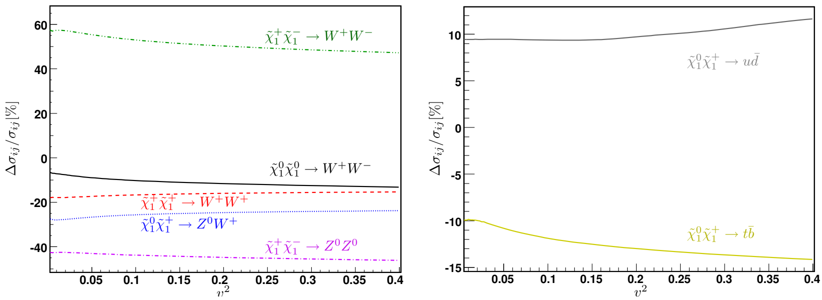
- Originate from vertex and box diagrams involving virtual bosons.
- General form of one-loop Sudakov corrections

$$\alpha\left[C_2 \underbrace{\ln^2\left(\frac{s}{M_V^2}\right)}_{\text{LL}} + C_1 \underbrace{\ln^1\left(\frac{s}{M_V^2}\right)}_{\text{NLL}} + C_0\right] + \mathcal{O}\left(\frac{M_V^2}{s}\right) \quad V = \gamma, W^\pm, Z^0$$



- The $\ln(s/M_V^2)$ represents mass singularities and originate from soft and collinear regions.
- For QED corrections always present ($M_\gamma \to 0$), for EW ones when $s \gg M_{W,Z}^2$.
- Dependency on M_γ unphysical $\Rightarrow$ removed by adding real emission as stated by the Bloch-Nordsieck theorem [Bloch,Nordsieck(1937)].
- For EW corrections, $M_{W,Z}$ physical and retained in the calculation.
- Adding real emission can counterbalance virtual corrections.

- For a specific channel adding the Z^0 reduces the overall corrections.
- But result still potentially large



- Not a complete cancellation due to Bloch-Norsieck violations [Ciafaloni, Comelli (2000)]
- $W^{\pm}$ emission changes isospin $\to$ one state of a mutliplet turned into another state of the same multiplet.
- By summing/averaging over all members of the same multiplet, the cancellation should take place $\Rightarrow$ Summing over all channels and processes.
- $W^{\pm}$ real emission must also be added to form an isospin singlet.

Virtual + real $2 \to 2 + \gamma, Z^0, W^\pm$.

Values of various cross section for $v = 0.3c$

Process	Tree-Level	1-Loop	W+Z emission	Total
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$	2.668051510	-0.232723594 (-9%)	0.608162875 ($+23\%$)	3.043490791 ($+12\%$)
$\tilde{\chi}_1^+\tilde{\chi}_1^+ \to W^+W^+ \times 2$	2.667542171	-1.542918600 (-58%)	0.196086090 ($+7.3\%$)	1.320709661 (-50.7%)
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-$	0.713966584	0.364979903 ($+51\%$)	0.541233676 ($+76\%$)	1.620180163 ($+127\%$)
$\tilde{\chi}_1^+\tilde{\chi}_1^- \to Z^0Z^0$	0.805841752	-0.147277293 (-18%)	0.008798936 ($+1\%$)	0.649765523 (-17%)
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to W^+Z^0 \times 2$	1.127875389	-0.605309188 (-54%)	0.250488943 ($+22\%$)	0.773055144 (-32%)
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to t\bar{b} \times 2$	1.111269832	0.099235806 ($+9\%$)	0.041938145 ($+3.8\%$)	1.252443783 ($+12.8\%$)
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to u\bar{d} \times 2$	1.116433207	0.222165895 ($+20\%$)	0.156287258 ($+14\%$)	1.494886360 ($+34\%$)
Total	10.210980445	-1.841847071 (-18%)	1.802995923 ($+17.6\%$)	10.172129297 (-0.4%)
Total only gauge	7.983277406	-2.163248772 (-27%)	1.604770520 ($+20\%$)	7.424799154 (-7%)

- Large corrections for individual processes $\Rightarrow$ important effect for Indirect Detection [Chalons PhD Thesis, Strumia et al]
- For relic density calculation, in the thermal bath sum over all members of the isospin multiplet automatically done [Chalons PhD Thesis] $\to$ small effect expected.

CONCLUSIONS AND PERSPECTIVES

- Importance of radiative corrections in the relic density calculations, can be very large.
- Need to control them to be able to extract informations from it and to constrain the underlying cosmological scenario.
- For some cases scheme dependence.
- For a heavy neutralino scenarios taking into account $2 \to 3$ processes is necessary.
- Large corrections due to soft/collinear logs and Sommerfeld enhancement.
- Corrections can be even larger for Indirect Detection, rate and spectra for specific signatures.
- In all cases for $\Omega_\chi h^2$ @ 1-2% $\Rightarrow$ one-loop corrections mandatory.
- Study of the dependency of the results on the chargino/neutralino renormalisation scheme.
- Improve the interface with `micrOMEGAs` .

Conclusions

- Tremendous progress over the last 1O years in the construction of tools for the New physics
- For DM, need much better interaction with nuclear physicists, lattice people, astrophysicists: better modular structure and exchange of modules
- Loop effects are not negligible (Sudakov, Sommerfeld) and for the relic full one-loop in all cases is necessary when precision is as good as that of LEP must go to one-loop..at least