MadDM

A computational tool of DM relic abundance and direct detection

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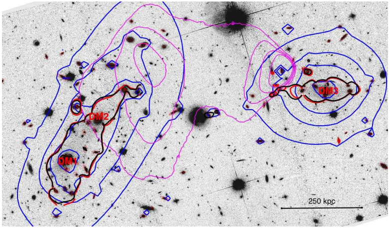
The mystery of dark matter

Observations

- galaxies rotational curves.
- Bullet cluster.
- Cosmic microwave background : $\Omega_{DM}h^2 = 0.1199 \pm 0.0027$.



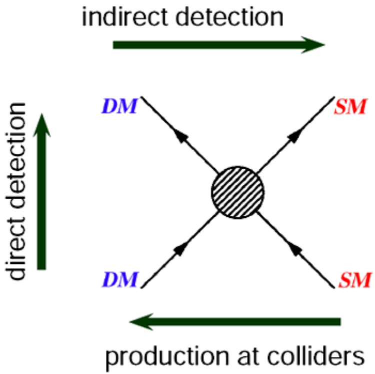
Candidates

- Heavy neutrinos
- Axions (Peccei-Quinn): CP violation in QCD.
- LSP (SUSY) : neutralino $\tilde{\chi}_1^0$, gravitino (supergravity)
- LKP (Kaluza-Klein) : extra-dimensions theories.
- ...

DM detection opportunities

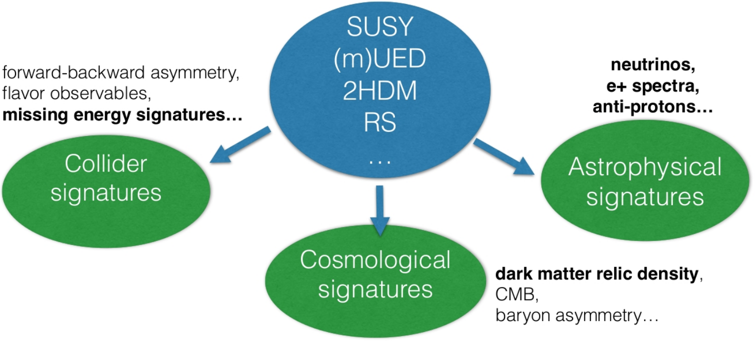
Three possibilities

- Indirect detection: FERMI-LAT, AMS-02.
- Direct detection: XENON100, LUX, CDMS.
- Production at collider: LHC.



BSM Physics in the LHC era

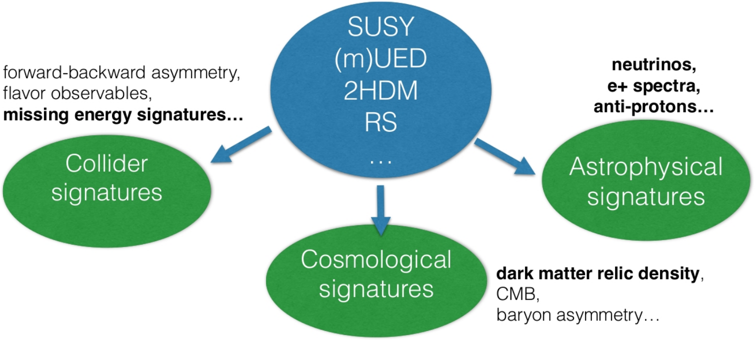
- If new physics exists, we don't have a good sense of the scale yet!
- The result is a vast number of possibilities and many approaches to measure them.



BSM Physics in the LHC era

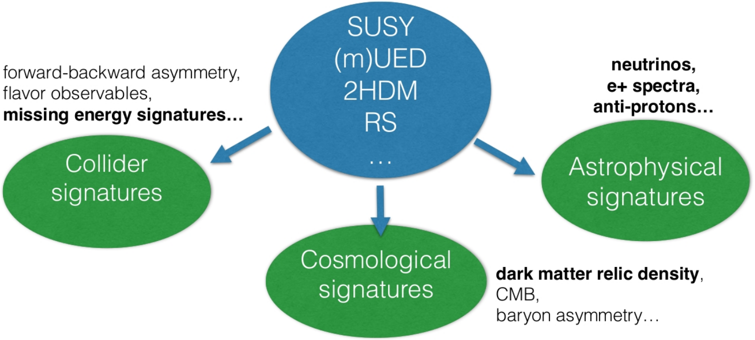
- We have good “hints” that there is BSM physics out there - **dark matter is a good example!**

- Important to look for DM both at colliders and in the galaxy!

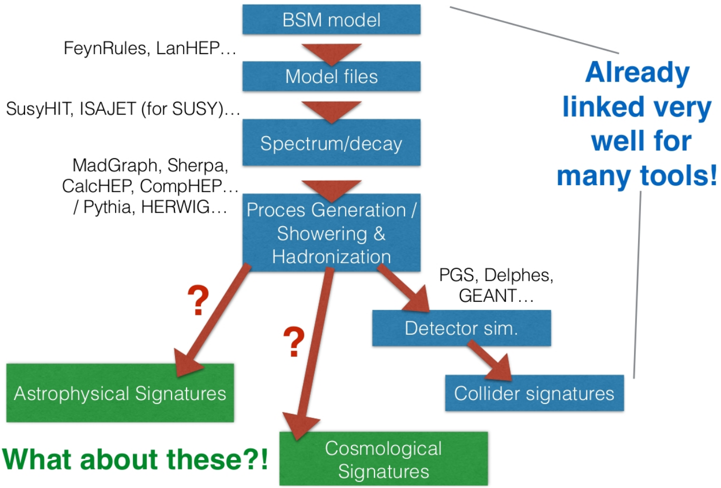


BSM Physics in the LHC era

- Models of new physics grew complex - Many fields, many parameters, many signatures.
- Much relies on the numerical tools nowadays.

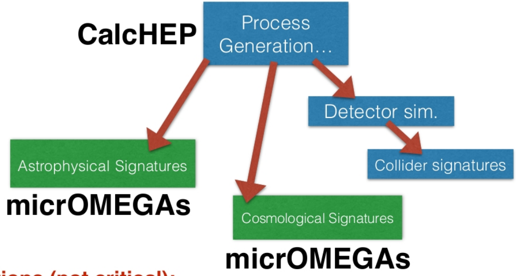


BSM Tools in the LHC era



DM Tools in the LHC era

Currently **CalcHEP/micrOMEGAs** (Comput.Phys.Commun. 149 (2002) 103-120) is the only tool available which can calculate Collider + Astrophyiscal + Cosmological signatures in a **generic model**.



Some limitations (not critical):

- 4 point interaction in SU(3) needs a special treatment. FeynRules does not generate correct model files for CalcHEP/micrOmegas.
- Practically limited by the fact that CalcHEP takes a long time to calculate collider processes beyond 4-6 final state particles.

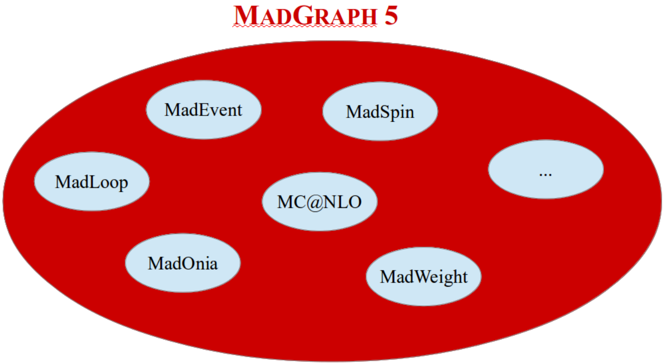
DM tools in the LHC era

Tools

- **darkSUSY** is a popular, although model specific DM tool (JCAP 0407 (2004) 008).
- SUSY contains a lot of generic DM features like **co-annihilations and resonant annihilations** => darkSUSY has a lot of useful technology for DM phenomenology in a generic model.
- darkSUSY can be 'hacked' to include other models, but this is not trivial !
- Many other (model specific) tools exist: Isatools, SSARD, Drees, Roszkowski...

MadGraph5

Since 1994, MadGraph has grown into a powerful collider phenomenology framework...



... but no capability to calculate astrophysical and cosmological signatures in models which contain dark matter candidates.

MadDM

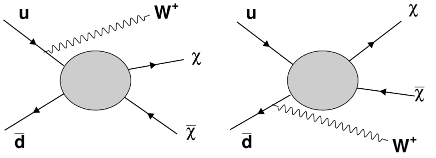
- First step to extend MadGraph5 capabilities to dark matter phenomenology
- Built on top of existing MadGraph5 architecture -
  inherits all of the existing MadGraph structure.

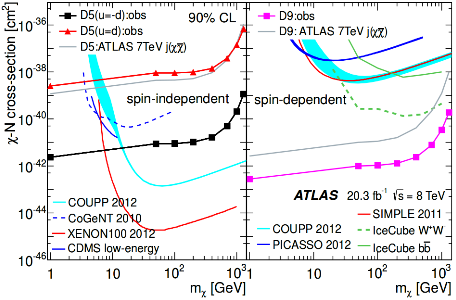
Why MadGraph5?

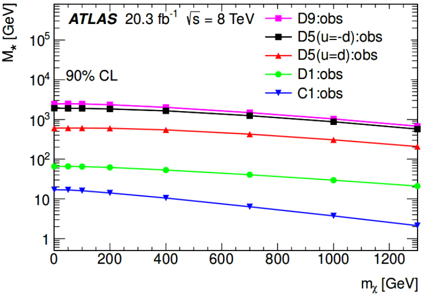
- Popular among experimentalists.
- Novel Python libraries make add-ons easy.
- MadGraph5_aMC@NLO is an NLO generator (future loop-induced processes).

ATLAS search for DM

ATLAS results from a DM search in fat jet + MET channel - constraints on a myriad of effective models.

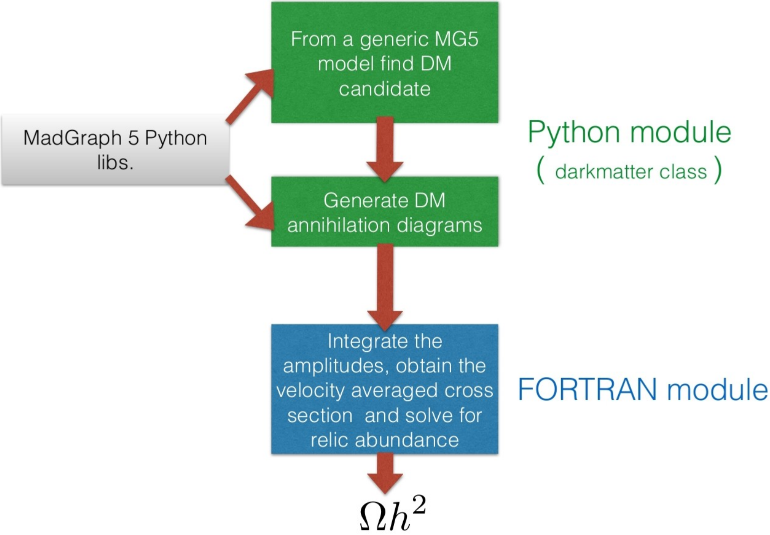






ATLAS used MG for collider analysis, why not add the MadDM output for relic density?

MadDM structure



MadDM structure

- MadGraph 5
  - **MadDM**
    - darkmatter.py — Contains MadDM Python classes
    - maddm.py — “User-friendly” executable
    - Templates
      - include
      - matrix_elements
      - src
      - output

      Template files/folders for each project
    - Projects

      Folder where all the projects are stored

MadDM works out of the box!
Just unpack the tarball in a MadGraph5 folder.

MadDM structure

- Projects
  - "project name"
    - Cards — contains param_card.dat
    - include — contains maddm_card.inc (precision parameters etc.)
    - output — output of "test routines"
    - src — All the fortran source code
    - maddm.x — MadDM standalone executable numerical module
    - matrix_elements — FORTRAN matrix elements for DM annihilation

A project folder is a result of executing the Python MadDM module. It is standalone and does not require any further Python MadDM code

example.py

```
#! /usr/bin/env python
from init import *
from darkmatter_eff import *


#Create the relic density object.
dm=darkmatter()
#Initialize it from the rsxSM model in the MadGraph model folder,
#and store all the results in the Projects/rsxSM subfolder.
dm.init_from_model('rsxSM', 'rsxSM_project', new_proj = True)
#dm.init_from_model('DM_eff_scalar', 'DM_eff_scalar', new_proj = True)


# Determine the dark matter candidate...
dm.FindDMCandidate(prompts=False, dm_candidate='')

#...and all the coannihilation partners with the mass splitting
# defined by |mX0 - mX1| / mX0 < coann_eps.
dm.FindCoannParticles(prompts = False, coann_eps = 0.1)

#Get the project name with the set of DM particles and see
#if it already exists.
dm.GetProjectName()
```

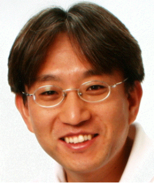
example.py

```
#Generate all 2-2 diagrams.
print "Generating annihilation diagrams..."
dm.GenerateDiagrams()

#Generate the diagrams for direct detection.
print "Generating direct detection diagrams..."
dm.GenerateDiagramsDirDetect()   (NEW feature !!!)
#Print some dark matter properties in the mean time.
print "------ Testing the darkmatter object properties ------"
print "Calc. Omega: "+str(dm._do_relic_density)
print "Calc. DD: "+str(dm._do_direct_detection)
print "DM name: "+dm._dm_particles[0].get('name')
print "DM spin: "+str(dm._dm_particles[0].get('spin'))
print "DM mass var: "+dm._dm_particles[0].get('mass')
print "Mass: "+ str(dm.GetMass(dm._dm_particles[0].get('pdg_code')))+"\n"
print "Project: "+dm._projectname

#Output the FORTRAN version of the matrix elements
#and compile the numerical code.
dm.CreateNumericalSession()

#Calculate relic density.
omega = dm.CalculateRelicAbundance()
print "-----------------------------------------------"
print "Relic Density: "+str(omega),
print "-----------------------------------------------"
```

MadDM v1.0 : relic abundance

M. Backovic

M. McCaskey



K.C. Kong

MadDM - Relic density calculation

In DM model with only one DM particle, the density evolution is described by the rate equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -2\left\langle \sigma_{eff} v \right\rangle \left(n_\chi^2 - \left(n_\chi^{EQ}\right)^2 \right),$$

with

$\left\langle \sigma_{eff} v \right\rangle \equiv \sum_{i,j=1}^{N} \left\langle \sigma\left(\chi_i \chi_j \to SM\right) v \right\rangle \frac{n_{\chi_i}^{EQ} n_{\chi_j}^{EQ}}{\left(n_\chi^{EQ}\right)^2}$, the thermally averaged cross section

n_χ^{EQ}, the equilibrium density

To obtain DM relic abundance in canonical models, integrate the rate equation from a freeze out time (determined by iteration over the rate equation integration)

$$\Omega h^2 \sim \left(\int_{x_f}^{\infty} dx \frac{\langle \sigma v \rangle}{x^2} \right)^{-1} \qquad x \equiv \frac{m_\chi}{T}$$

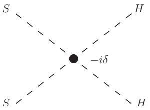
MadDM takes co-annihlation, treshold effects and resonances into account and is also able to deal with non-canonical models !

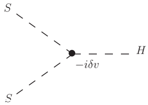
MadDM - Relic density validation

- Toy model : Real singlet extension of SM (rsxSM):

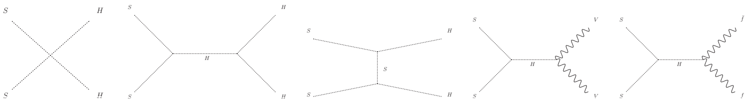
$$\mathcal{L}_{DM} = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}\left(H^\dagger H\right)^2 + \frac{\delta}{2} H^\dagger H S^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4$$

Only parameters are mass of DM and coupling to the H boson



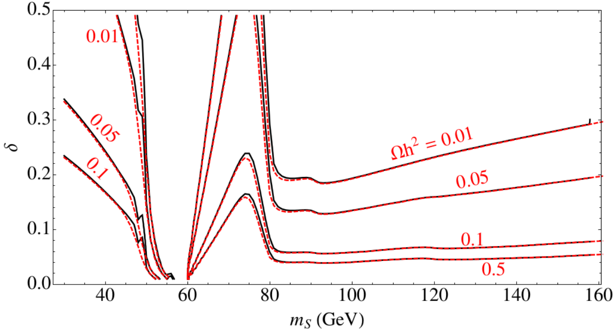


- Typical DM annihilation diagrams :



MadDM - Validations

Real singlet extension of SM



Black - MadDM
Red - micrOMEGAs

Excellent agreement over a wide range of DM parameters (Some precision issues in the resonance region where the Higgs sits right above threshold due to a saddle point in the integrand)

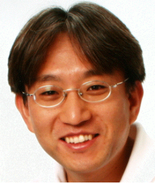
MadDM v2.0 : direct detection and DDM

M. Backovic

M. McCaskey

A. Martini

F. Maltoni



K.C. Kong

G. Mohlabeng

A. Para

J. Yoo

MadDM : Direct detection (NEW)

Typically $v_{DM} \sim 300\, km/s \ll c$

Transfer momentum to nuclei is very low $\rightarrow$ 0-momentum transfer approximation.

Calculation steps :

1. Lagrangian: extract spin-independent and spin-dependent operators.
2. DM-quarks amplitude computation with MadGraph.
3. DM-nucleon calculation (form factors).
4. DM-nucleus interaction.
5. Direct detection rates.

MadDM: operator expansion method

We implement an effective Lagrangian ($\mathcal{L}_{eff}$) including all the effective operators available for DM-quarks interactions for a specific DM spin and for SI (or SD) (similar as micrOMEGAs, arXiv:0803.2360) :

	DM spin	Even	Odd
SI	0	$2M_\chi \Phi_\chi \Phi_\chi^* \bar{\psi}_q \psi_q$	$i\left(\partial_\mu \Phi_\chi \Phi_\chi^* - \Phi_\chi \partial_\mu \Phi_\chi^*\right) \bar{\psi}_q \gamma^\mu \psi_q$
	$\frac{1}{2}$	$\bar{\psi}_\chi \psi_\chi \bar{\psi}_q \psi_q$	$\bar{\psi}_q \gamma_\mu \psi_\chi \bar{\psi}_q \gamma^\mu \psi_q$
	1	$2M_\chi A_{\chi\mu}^* A_\chi^\mu \bar{\psi}_q \psi_q$	$i\lambda_{q,o}\left(A_\chi^{*\alpha} \partial_\mu A_{\chi,\alpha} - A_\chi^\alpha \partial_\mu A_{\chi\alpha}^*\right) \bar{\psi}_q \gamma_\mu \psi_q$
SD	$\frac{1}{2}$	$\bar{\psi}_\chi \gamma_\mu \gamma_5 \psi_\chi \bar{\psi}_q \gamma^\mu \gamma^5 \psi_q$	$-\frac{1}{2} \bar{\psi}_\chi \sigma_{\mu\nu} \psi_\chi \bar{\psi}_q \sigma^{\mu\nu} \psi_q$
	1	$\sqrt{6}\left(\partial_\alpha A_{\chi\beta}^* A_{\chi\nu} - A_{\chi\beta}^* \partial_\alpha A_{\chi\nu}\right)$ $\varepsilon^{\alpha\beta\nu\mu} \bar{\psi}_q \gamma_5 \gamma_\mu \psi_q$	$i\frac{\sqrt{3}}{2}\left(A_{\chi\mu} A_{\chi\nu}^* - A_{\chi\mu}^* A_{\chi\nu}\right) \bar{\psi}_q \sigma^{\mu\nu} \psi_q$

Then the trick is to combine $\mathcal{L}_{eff}$ to the input model (related to $\mathcal{L}_{input}$) to get the interference term between the two models :

$$\left|\mathcal{M}_{eff+input}\right|^2 = \left|\mathcal{M}_{input}\right|^2 + \left|\mathcal{M}_{eff}\right|^2 + 2\left|\mathcal{M}_{eff} \cdot \mathcal{M}_{input}^*\right|$$

$\Rightarrow$ the interference term gives us the right contribution !

$\Rightarrow$ Already implemented in MadDM

DM-nucleus interaction

Matrix element $\langle \bar{q}q \rangle$ of quarks in a nucleon state :

$$\langle \bar{q}q \rangle = \frac{m_{p,n}}{m_q} f_q^{p,n} \text{ (light quarks); } \langle \bar{q}q \rangle = \frac{2}{27} \frac{m_{p,n}}{m_q} f_G^{p,n} \text{ (heavy quarks)}$$

DM-nucleon couplings:

$$f_{p,n}^{\chi} = m_{p,n} \sum_{q=u,d,s} \frac{\mathcal{C}_q}{m_q} f_q^{p,n} + \frac{2}{27} m_{p,n} f_G^{p,n} \sum_{q=c,b,t} \frac{\mathcal{C}_q}{m_q}$$

where $\mathcal{C}_q$ comes from the projection operator method (and $\langle \mathcal{M} \rangle = \mathcal{C}_q \langle \bar{q}q \rangle$).
Finally, you can compute the cross-section DM-nucleus (SI interactions),

$$\sigma = \frac{4 m_N^2 m_\chi^2}{\pi \left(M_\chi + m_N \right)^2} \cdot \left(A f_p^\chi + (A - Z) f_n^\chi \right)^2$$

$\Rightarrow$ Already implemented in MadDM !

DM-nucleus interaction

Spin dependent case :

$$\sigma = \frac{16 m_N^2 m_\chi^2}{\pi\left(M_\chi + m_N\right)^2} \frac{J_A + 1}{J_A} \left(\varepsilon_p S_p^a + \varepsilon_n S_n^A\right)^2$$

where J_A is the spin of the nucleus, $S_{p,n}^A$ are the expectation value of the spin content of the nucleon in a nucleus with A nucleons

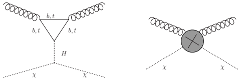
$\Rightarrow$ Already implemented in MadDM !

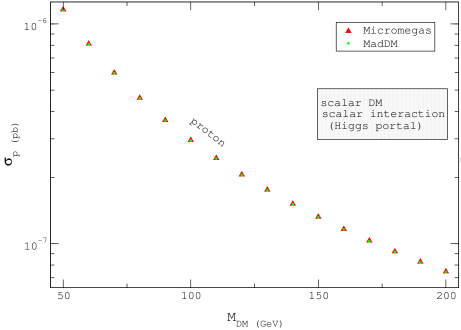
Differential rate :

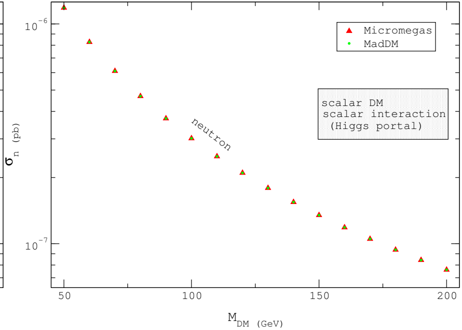
$$\frac{dR}{dE_r} = \frac{\rho_0 \sigma_0}{2 m_\chi m_r^2} F\left(E_r\right) \int_{v_{min}}^{\infty} \left[\frac{f(v)}{v}\right] dv$$

$\Rightarrow$ Available soon in MadDM !

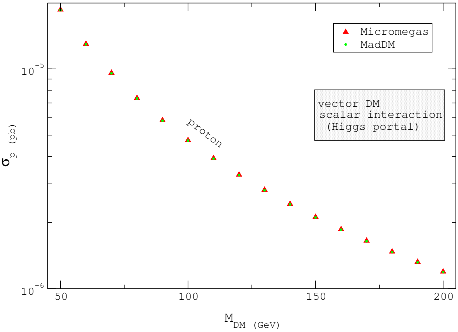
MadDM validations - rsxSM

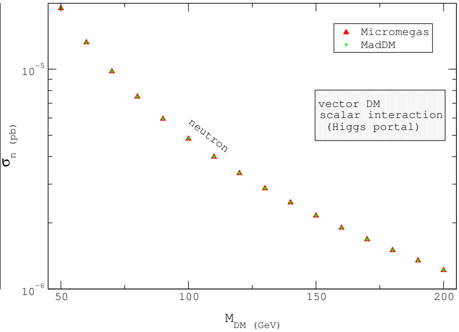




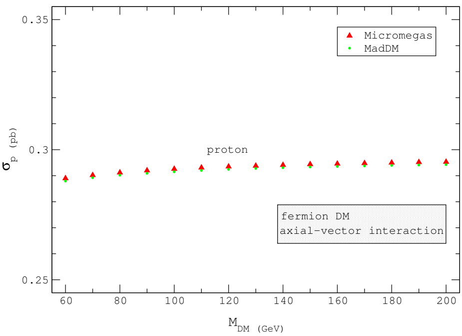


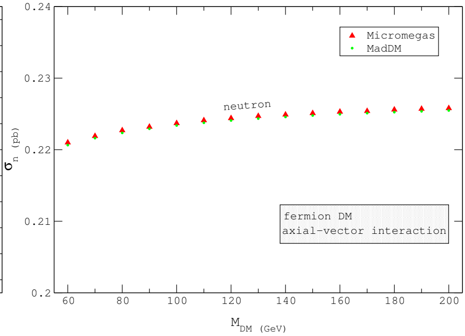
MadDM validations - Higgs portal (vector DM)





MadDM validations - Axial vector interaction (fermion DM)





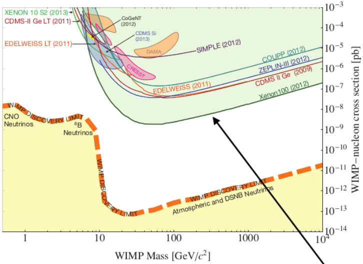
MadDM: directional detection

R
E
A
D
Y

MadDM - directional detection of DM

2 big reasons to care about directional information:

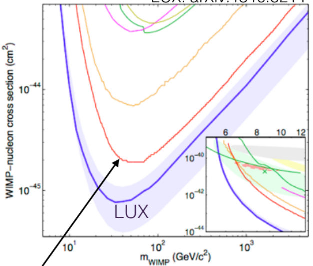
- **In case DM is discovered** - need to measure the halo properties. Directional information could be important in this case!
- **In case DM is not discovered** - future 1 ton scale detectors could result in strong limits on WIMP-nucleon cross section. Neutrinos could become a non-negligible background. <u>Directional information can be used to discriminate neutrino backgrounds!</u>



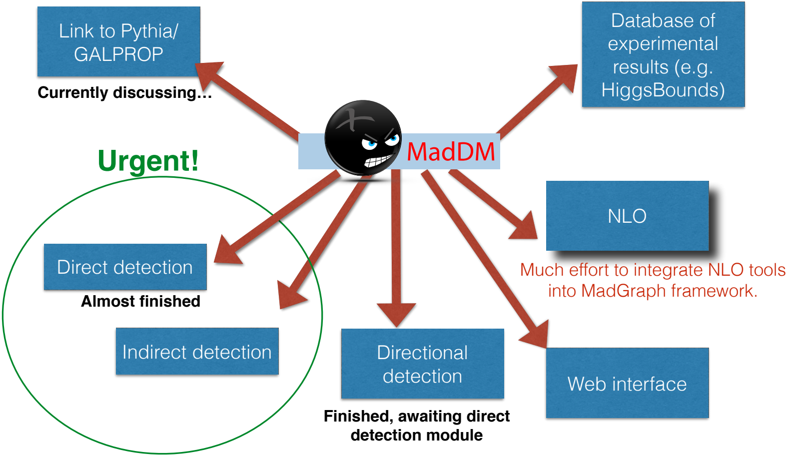
J. Billard, L. Strigari, E. Figueroa-Feliciano
(arXiv:1307.5458)

Xenon100

LUX: arXiv:1310.8214



MadDM - (near) future plans.



susy.phsx.ku.edu/~mihailo/

DEMO !

Tutorial : `http://susy.phsx.ku.edu/~mihailo/tutorial.html`