Dark Matter Tools
for collider and non-collider experiments

Alexander Belyaev

Southampton University & Rutherford Appleton LAB

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April 3 - 5, 2017

UCI Department of Physics & Astronomy
Outline

- **Theory ↔ Signature link**
  - MicrOMEGAs and MadDM
  - CalcHEP & MadGraph
  - models and repositories
  - Signatures, examples, remarks

- **Signature ↔ Data link**
  - Checkmate, MadAnalysis, Gambit

- **Data → Theory link**
  - The inverse problem of decoding of the underlying theory from signal
Why we are so keen to study DM?

![Graph showing the number of papers over the years for different topics: SUSY, Higgs, Top, EXD, and DM. The graph highlights the growth and trends in research related to dark matter.](image)
Because the existence of DM is the strongest evidence for BSM, even though we know almost nothing about it!

- Spin: ?
- Mass: ?
- Stable: Yes ? No ?
- Couplings gravity: V
- Weak: ?
- Higgs: ?
- Quarks/gluons: ?
- Leptons: ?
- New mediators: ?
- Thermal relic: Yes ? No ?
- symmetry behind stability: ?
To test DM theory we need to realise

\[ \text{theory} \leftrightarrow \text{data} \]

link

which is actually a non-trivial story
theory ↔ data requires observables to be compared with data
DM Observables: the power of WIMP

Correct Relic density: efficient (co) annihilation
WMAP, Planck; annihilation to photons can affect CMB

\[
\begin{array}{c}
\text{DM} \\
\downarrow \\
\text{SM}
\end{array} \quad \begin{array}{c}
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\downarrow \\
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\end{array}
\]
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Signatures from neutralino annihilation in halo, core of the Earth and Sun

- photons,
- Anti-protons
- positrons,
- Neutrinos

Neutrino telescopes:
- Amanda
- Icecube
- Antares

Efficient annihilation now: Indirect (ID) DM Detection
DM Observables: the power of WIMP

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Efficient scattering off nuclei:
DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,
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LHC signatures
- mono-jet
- mono-photon
- mono-Z
- mono Higgs
- VBF+MET
- soft leptons+MET
- …. 

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Efficient annihilation now: Indirect (ID) DM Detection
Efficient scattering off nuclei: Direct (DD) DM Detection

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

LHC signatures
- mono-jet
- mono-photon
- mono-Z
- mono Higgs
- VBF+MET
- soft leptons+MET
- ....

Note: there is no 100% correlation between signatures above. For example, the high rate of annihilation does not always guarantee high rate for DD!

Actually there is a great complementarity in this:
- In case of NO DM Signal – we can efficiently exclude DM models
- In case of DM signal – we can efficiently determine the nature of DM
Tools for theory → observables link
Tools for **theory → observables** link

- **DM Model**
  - LanHEP
  - FeynRules
  - SARAH

- **Feynman Rules**

- **Matrix Element**
  - CalcHEP, CompHEP
  - FormCalc, MadGraph
  - MCFM, MC@NLO
  - Sherpa, WHizard
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  - PYTHIA
  - HERWIG
  - ISAJET
  - Sherpa

- **Events**
Tools for **theory → observables** link

DM Model → Feynman Rules → Matrix Element → Events → Detector

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- FAST/FULL Detector Simulation
- PGS, Delphes
- CMSSW, ATHENA

Collider signatures
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- **Relic Density**
  - micrOMEGAs
  - CalcHEP
  - Madgraph

- **Collider signatures**

- **DM Direct Detection**

- **DM Indirect Detection**

- **MadDM**
Tools for theory → observables link

DM Model → Feynman Rules → Matrix Element → Events → Detector

<table>
<thead>
<tr>
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<th>Theory</th>
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Relic Density

DM Direct Detection

DM Indirect Detection

micrOMEGAs → MadDDM

? CMB constraint on $<\sigma v>$

"CMB constraints on Dark Matter models with large annihilation cross-section" '09 Gallia, Iocco, Bertone, Melchiorri
CMB constraint on $\langle \sigma v \rangle$

- secondary particles produced by DM annihilation with $z \sim 1000$ affect the process of recombination, leaving an imprint on CMB anisotropies and polarization
- WMAP place constraints on $\langle \sigma v \rangle$ especially for models that exhibit a large Sommerfeld enhancement
  Planck improves constraints by at least one order of magnitude

- $f(z)$ is the fraction of energy that is absorbed by the plasma at each $z$. Depends on DM mass and annihilation channel

It is important to incorporate this constraint to micrOMEGAs and MadDM!
MicrOMEGAs

http://lapth.in2p3.fr/micromegas
Belanger, Boudjema, Pukhov, Semenov

- Was born in 2001, the latest version 4.3
- Comprehensive tool for dark matter studies: precise calculation of relic density, direct detection, indirect detection, cross section at colliders and decays
- Comes with models: MSSM, NMSSM, CPV-MSSM, RH-neutrino, Littlest Higgs, Inert doublet+singlet Z3,Z4; many more models are available at hepmdb.soton.ac.uk

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- Recent features
  - **Neutrino signal** from DM capture (for SuperKamiokande, IceCube), both neutrino flux and muon flux are computed
  - **Higgs 3-body decays** and loop-induced decays are included – a good agreement with HDECAY (Djouadi et al) for SM-like Higgs
  - Links to external packages: HiggsSignals/HiggsBounds (Bechtle et al), Smodels (Kraml et al)
  - Includes **3/4-body processes** with one/two virtual W/Z
  - Z2, Z3, Z4, Z5 symmetries and **two DM candidates**
  - **Asymmetric DM**: option to define ΔY=Y⁺-Y
  - Collider limits for Z' on-shell mediator (Barducci et al)
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  - **Asymmetric DM**: option to define \( \Delta Y = Y^+ - Y \)
  - Collider limits for Z' on-shell mediator (Barducci et al)
- **Prospects**
  - Collider limits for any DM model (Belanger, Barducci, AB, Pukhov)
  - Improved propagation for ID DM signals, interface to USINE, GALPROP, CLUMPY

http://lapth.in2p3.fr/micromegas

Was born in 2013, version 2.1: DM relic density, DM direct and directional detection

MadDM Status, MC4BSM 2015

Urgent!
Link to Pythia/ GALPROP
Still discussing...

Urgent!
Direct detection

Urgent!
Indirect detection

Finished!
Directional detection

Finished!
Model testing

Finished!
Relic density

Finished!
Database of experimental results (e.g. HiggsBounds)

Urgent!
NLO

Urgent!
Integration with MG5_aMC@NLO

Finished!
Web interface
Was born in 2013, version 2.1: DM relic density, DM direct and directional detection

MadDM Status, NOW

- In development!
  - Link to Pythia/GALPROP
  - Full set of DD effective operators
  - Direct detection
  - Indirect detection
  - Loop induced ID

- Finished!
  - Relic density
  - Database of experimental results (e.g. HiggsBounds)
  - NLO (colliders, ID)
  - Integration with MG5_aMC@NLO
  - Web interface

Model testing (integration with MadAnalysis)

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Dark Matter Tools
MicroMEGAs – MadDM comparison: relic density

arXiv:1308.4955

- the agreement is at % level in general
- Real Singlet model: worse in the region very close to the resonance – can be improved by adjusting the precision parameters in MadDM
- MSSM: discrepancy of up to 30% in the parameter space where running b mass produce significant effects – related to micrOMEGAs – SUSPECT difference

<table>
<thead>
<tr>
<th>SPS Pt.</th>
<th>MadDM</th>
<th>micrOMEGAs</th>
<th>Difference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS1a</td>
<td>0.197</td>
<td>0.195</td>
<td>1%</td>
<td>neutralino DM</td>
</tr>
<tr>
<td>SPS1b</td>
<td>0.390</td>
<td>0.374</td>
<td>5%</td>
<td>coan. with stau</td>
</tr>
<tr>
<td>SPS2</td>
<td>7.914</td>
<td>7.860</td>
<td>1%</td>
<td>focus pt, higgsino DM</td>
</tr>
<tr>
<td>SPS3</td>
<td>0.118</td>
<td>0.116</td>
<td>2%</td>
<td>conn. with sleptons</td>
</tr>
<tr>
<td>SPS4</td>
<td>0.0596</td>
<td>0.0474</td>
<td>22%</td>
<td>resonance region</td>
</tr>
<tr>
<td>SPS5</td>
<td>0.332</td>
<td>0.338</td>
<td>-2%</td>
<td>neutralino DM</td>
</tr>
<tr>
<td>SPS9</td>
<td>0.00111</td>
<td>0.00117</td>
<td>-4%</td>
<td>AMSB, coan. w/ chargino</td>
</tr>
</tbody>
</table>
There is a good agreement between spin-Independent (SI) and spin-dependent (SD) rates.

<table>
<thead>
<tr>
<th>DM spin</th>
<th>Even</th>
<th>Odd</th>
</tr>
</thead>
</table>
| SI      | 0  
1/2  
1       | scalar current  
$2M_X S S^* \bar{\psi}_q \psi_q$  
$\bar{\psi}_X \gamma_\mu \bar{\psi}_q \psi_q$  
$2M_X A^*_\mu A_X^\mu \bar{\psi}_q \psi_q$ | vector current  
i$\left( \partial_\mu S - S \partial_\mu S^* \right) \bar{\psi}_q \gamma^\mu \psi_q$  
$\bar{\psi}_X \gamma_\mu \psi_q \psi_q \gamma^\mu \psi_q$  
i$\left( A^*_\alpha \partial_\mu A_\chi^\alpha - A_\alpha \partial_\mu A^*_\chi^\alpha \right) \bar{\psi}_q \gamma_\mu \psi_q$ |
| SD      | 1/2  
1       | axial-vector current  
$\sqrt{6} \left( \partial_\alpha A^*_\chi A_{\chi\nu} - A^*_\chi \partial_\alpha A_{\chi\nu} \right) \epsilon^{\alpha\beta\mu\nu} \bar{\psi}_q \gamma_5 \gamma_\mu \psi_q$ | tensor current  
$-\frac{1}{2} \bar{\psi}_X \sigma_{\mu\nu} \psi_q \bar{\psi}_q \sigma^{\mu\nu} \psi_q$  
i$\frac{\sqrt{3}}{2} \left( A_{\chi\mu} A^*_\chi - A^*_\chi A_{\chi\mu} \right) \bar{\psi}_q \sigma^{\mu\nu} \psi_q$ |
Importance of the MicroMEGAs – MadDM comparison

- Actually the main message here is the importance of the fact that **two independent tools exist** and are being cross checked!
Importance of the MicroMEGAs – MadDM comparison

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A recent example of this importance are the results for the S-mediated model used with MadDM 2.0.5 in arXiv:1603.08525 and brought at DM LHC forum (Caterina's talk):

- t-channel diagram was missed in MadDM 2.0.5, leading to the erroneous results
CalcHEP for DM studies at colliders

A. Pukhov, AB, N. Christensen
http://theory.sinp.msu.ru/~pukhov/calchep.html

Some highlights
- the “engine” of micOMEGAs
- has convenient graphical interface
- evaluates particle widths 'on the fly'
- allows to edit diagrams (inducing squared diagram level) – important for the dedicated interference studies
- allows easily modify an existing model (GUI) or to implement the new one (LanHEP, FeynRules)
- powerful batch interface – connects production and decay processes, allows to perform multidimensional scan and produce LHE files in one run
- adopted to HPC cluster, symbolic and numerical evaluations/simulations are parallelized
- exports plots to GNUPLOT, PAW and ROOT
- numerous models are implemented, see CalcHEP's site and HEPMDB database
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- DM Models:
  at CalcHEP, HEPMDB (hepmdb.soton.ac.uk) and FeynRules (feynrules.irmp.ucl.ac.be) sites

- Extra dimensions: 5D UED (MUED) with 2KK and 4KK layers, 6D UED with 2KK layers
- SUSY: CMSSM, MSSM, NMSSM, left-right symmetric MSSM, MSSM with CP violation, E6MSSM
- Technicolor & Composite Higgs models: TC with DM, VLQ with scalar DM
- Little Higgs: Littlest higgs model with T-parity
- DM EFT operators: The complete set of DIM5&6 operators with spin 0, 1/2, 1 DM

hep-ph/9908288
arXiv:1207.6082
MadGraph5_aMC@NLO for DM studies at colliders


arXiv:1106.0522
arXiv:1405.0301

http://madgraph.hep.uiuc.edu/
https://launchpad.net/mg5amcnlo

- the “engine” of MadDM
- has been most intensively used by ATLAS and CMS
- can perform NLO QCD corrections (not a generic for arbitrary model) but works for SM and NLO models located at FeynRules web site
- includes matching to parton showers
- DM models: at FeynRules and HEPMDB sites
  ➤ Extra dimensions: 5D UED (MUED)
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  ➤ DM EFT operators: The complete set of DIM5&6 operators with spin 0,1/2,1 DM
  ➤ NLO models at feynrules.irmp.ucl.ac.be/wiki/NLOModels
    - DM simplified models (s-channel spin 0,1,2)
    - SUSY-QCD
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**NOTE**
- **the models of LHC DM Forum** svnweb.cern.ch/cern/wsvn/LHCDMF/trunk/models are not public and MG specific!
- it is important to make models public and extend the models scope for both Magraph and CalcHEP for the cross-check and validation!
Example of DM characterization using CalcHEP&Madgraph within EFT

<table>
<thead>
<tr>
<th>Complex Scalar DM</th>
<th>Complex Vector DM</th>
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<tbody>
<tr>
<td>$\frac{m^2}{\Lambda^2} \phi^+ \phi \bar{q} q$</td>
<td>$\frac{m^2}{\Lambda^2} V_\mu^i V^{\mu}_i \bar{q} q$</td>
</tr>
<tr>
<td>$\frac{m^2}{\Lambda^2} \phi^+ \phi \bar{q} i \gamma^5 q$</td>
<td>$\frac{m^2}{\Lambda^2} V_\mu^i V^{\mu}_i \bar{q} i \gamma^5 q$</td>
</tr>
<tr>
<td>$\frac{1}{\Lambda^2} \phi \phi \gamma_\mu \phi \gamma_5 \gamma^5 q$</td>
<td>$\frac{1}{\Lambda^2} (V_\nu^i \gamma_\mu V^{\nu}_i - V^{\nu}<em>i \gamma</em>\mu V^{\nu}<em>i) i \gamma</em>\mu q$</td>
</tr>
<tr>
<td>$\frac{1}{\Lambda^2} \phi \phi \gamma^{\mu \nu} G_{\mu \nu}$</td>
<td>$\frac{1}{2\Lambda^2} (V_\nu^i \gamma_\mu V^{\nu}_i - V^{\nu}<em>i \gamma</em>\mu V^{\nu}<em>i) \bar{q} i \gamma</em>\mu \gamma^5 q$</td>
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Dark Matter Tools
Example of DM characterization using CalcHEP&Madgraph within EFT

One can distinguish some EFT operators with different DM spins are correlated with $M(DM,DM)$ distributions

$M_{DM} = 10$, $\sqrt{s} = 13$ TeV

arXiv:1610.07545
One can distinguish some EFT operators with different DM spins

Different MET shapes are correlated with $M(DM,DM)$ distributions

- energy dependence of the DM operator → $M_{DMDM}$ distributions → slopes of MET
- projection for 300 fb$^{-1}$: some operators C1-C2,C5-C6,D9-D10,V1-V2,V3-V4,V5-V6 and V11-12 can be distinguished from each other

Application beyond EFT: when the DM mediator is not produced on-the-mass-shell and $M_{DMDM}$ is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$
Importance of the operator running in the DM DD ↔ Collider interplay

- the connection between physics at high and low energy is crucial to properly explore complementarity collider and non-collider DM experiments
- RGEs for the EFT introduce the mixing between different operators

Kopp, Niro, Schwetz, Zupan (2009); Hill, Solon (2012); Frandsen, Haisch, Kahlhoefer, Mertsch, Schmidt-Hoberg (2012); Kopp, Michaels, Smirnov (2014); Crivellin, D'Eramo, Procura (2014); Crivellin, Haisch (2014); Berlin, Robertson, Solon, Zurek (2016); D'Eramo, de Vries, Panci (2016); D'Eramo, Kavanagh, Panci (2016)

\[ \mathcal{L} \supset -\frac{J^\mu_{DM} J_{SM, \mu}}{\Lambda^2}, \quad J^SM_\mu = \sum_q \left[ q^{(i)}(i) \gamma_\mu q^{(i)} + c_A^{(i)}(A) \bar{u}^{(i)} \gamma_\mu \gamma_5 u^{(i)} + \ldots \right] \]

let us take, for example,

\[ J^\mu_{DM} = c_V \bar{\chi} \gamma^\mu \chi + c_A \bar{\chi} \gamma^\mu \gamma_5 \chi \]

Once the wilson coefficient are evolved at the low scale, we need to match the low energy parton-level lagrangian with the low energy nucleon one

\[ \mathcal{L} \supset -\frac{J^\mu_{DM}}{\Lambda^2} \left( c_V^{(N)} \bar{N} \gamma_\mu N + c_A^{(N)} \bar{N} \gamma_\mu \gamma_5 N \right) \]

and

\[ \sigma_{SI}^N = \frac{\mu_N^2}{\pi} \frac{(c_V c_V^{(N)})^2}{\Lambda^4} \]

where

\[ \mu_N = m_\chi m_N / (m_\chi + m_N) \]
Importance of the operator running in the DM DD ↔ Collider interplay

In case of axial operators, e.g.

\[ c_A^{(q)} c_X \gamma_\mu \overline{X} \gamma_\mu q \gamma_5 q \quad (D7) \quad \text{or} \quad c_A^{(q)} c_\phi \phi^+ \overrightarrow{\partial_\mu \overline{q}} \gamma_\mu q \gamma_5 q \quad (C4) \]

...couplings \( c_V^{(q)} \) arise due to the running of the wilson coefficient \( c_A^{(q)} \) leading to sizable constraints on the DM DD constraints.

One can use runDM program (github.com/bradkav/runDM) by F. D’Eramo, B. J. Kavanagh & P. Panci

\[ c_A^{(u)}, c_A^{(d)}, c_V^{(u)}, c_V^{(d)} = (1,1,0,0) \rightarrow (1.1, 1.1, 0.04, -0.07) \]
Importance of the operator running in the DM DD ↔ Collider interplay

- In case of axial operators, e.g.
  \[
  c_A^{(q)} c_{\chi \chi} \gamma^\mu (q) \chi \bar{q} \gamma^\mu \gamma_5 q \quad (D7) \]

  or

  \[
  c_A^{(q)} c_{\phi \phi} \gamma^\mu (q) \phi \bar{q} \gamma^\mu \gamma_5 q \quad (C4)
  \]

  couplings \(c_{V}^{(q)}\) arise due to the running of the Wilson coefficient \(c_A^{(q)}\)
  leading to sizable constraints on the DM DD constraints.

- One can use runDM program (github.com/bradkav/runDM) by
  F. D’Eramo, B. J. Kavanagh & P. Panci

\[
\begin{align*}
  c_A^{(u)}, c_A^{(d)}, c_V^{(u)}, c_V^{(d)} = & \begin{pmatrix} 1,1,0,0 \end{pmatrix} \quad [5 \text{TeV}] \\
  \rightarrow & \begin{pmatrix} 1.1, 1.1, 0.04, -0.07 \end{pmatrix} \quad [1 \text{GeV}]
\end{align*}
\]

AB, Bertuzzo, Caniu, Eboli, di Cortona (preliminary)
The effect of ggH loop resolution with high PT jet: the effective ggH versus exact evaluation

At high Higgs PT one expects the EFT ggH approach to break down for Higgs PT ~ 400 GeV, EFT/EXACT = 1.4-1.5. What is about higher PT and different MH?

Alwall, Maltoni, Matched (2011)
Buschmann, Goncalves, Kuttimalai, Schonherr, Krauss Plehn (2014)
Frederix, Frixione, Vryonidou, Wiesemann (2016)
Greiner, Höche, Luisoni, Schönherr, Winter (2016)
The effect of ggH loop resolution with high PT jet: the effective ggH versus exact evaluation

- There factor 10 difference for MET~1 TeV and 100 for MET~2.5 TeV so EFT ggH approximation badly breaks down!

AB, Tomei, Gregores, Mercadante, Moon, Moretti, Novaes, Panizzi, Qazi, Rojas, Santos, Thomas: preliminary results
Tools for observables ↔ data link

- CheckMATE V2 ([checkmate.hepforge.org](http://checkmate.hepforge.org))
  - Drees, Schmeier, Dercks, Desai, Kim, Rolbiecki, Tattersall, Weber

- MadAnalysis ([madanalysis.irmp.ucl.ac.be](http://madanalysis.irmp.ucl.ac.be))
  - Conte, Dumont, Fuks, Schmitt, Kraml, Bein, Chalons

Both tools became leaders in verification of the BSM theories against the LHC data
- Monojet/mono-photon analysis from ATLAS (yet) are validated at the moment
- Quickly developing support from users (analysis validation)
- Relies on Delphes fast simulation
- Incorporates projection analysis (CheckMATE only)
- Great potential in creating public library of the analysis
- Needs validation of more DM searches and boosted objects analysis
Data → Theory link

- probably the most challenging problem to solve – the inverse problem of decoding of the underlying theory from signal
  - requires database of models, database of signatures
  - requires smart procedure based on machine learning of matching signal from data with the pattern of the signal from data
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**HEPMDB (High Energy Physics Model Database)** was created in 2011 to make the first step towards this: [hepmdb.soton.ac.uk/phenodata](http://hepmdb.soton.ac.uk/phenodata)
- recently has got a status of the permanent server at Southampton
- convenient centralized storage environment for HEP models
- it allows to evaluate the LHC predictions and perform event generation using CalcHEP, Madgraph for any model stored in the database
- users can upload their own model and perform simulation – became a very attractive feature for all range of researchers
- **no database of signatures yet** (is under development) – you input could play and important role
probably the most challenging problem to solve – the inverse problem of decoding of the underlying theory from signal

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HEPMDB
High Energy Physics Models DataBase

Search Models :: Results for [MSSM]

   
   *CalcHEP/MicrOEGAs groups*

   We present MSSM with SUGRA and AMSB scenario as well as MSSM with low energy input. Read file INSTALLATION for model installation and file CITE for references on scientific publications which pre...

2. **MSSM with bilinear R-Parity violation** [2011-11-17 20:00:51] hepmdb:1111.0036
   
   *Florian Staub*

   The MSSM with bilinear R-Parity violating terms in the superpotential and for the soft-breaking terms. Model files created by SARAH 3.1.0 Support of SLHA+ functionality to read spectrum files...

   
   *Florian Staub*

   Triplet extended MSSM (including possibility of flavor violation) Model files created by SARAH 3.1.0 Support of
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As a HEPMDB spin-off the PhenoData project was created hepmdb.soton.ac.uk/phenodata
  - stores data (digitized curves from figures, tables etc) from those HEP papers which did not provide data in arXiv or HEPData, and to avoid duplication of work of HEP researchers on digitizing plots.
  - has an easy search interface and paper identification via arXiv, DOI or preprint numbers. PhenoData is not intended to be a replication of any existing archive
What is NOT discussed in this talk

- Model-specific tools
  - Isajet: http://www.nhn.ou.edu/~isajet/
  - specialized for various SUSY models, has DM relic density (IsaRED) and DM DD modules (IsaRES) as parts of IsaTOOLS
  - DarkSUSY: http://www.darksusy.org/
    besides relic density and DM DD, predicts also DM ID, uses GLAPROP

- LanHEP and FeynRules:
  tools for Feynman rules (model) generation starting from the Lagrangian

- Some Recasting tools, especially those which are not public yet
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/RecastingTools
  - GAMBIT: the Global and Modular Beyond-Standard Model Inference Tool (GAMBIT) is a global fitting code for generic Beyond the Standard Model theories, designed to allow fast and easy definition of new models, observables, likelihoods, scanners and backend physics codes
  - ATOM: Atom is a general purpose framework for reinterpreting existing experimental analyses and designing new ones. Originally started as a fork of Rivet
Conclusions and Outlook

- DM Tools are powerful but should not blindly trusted or blamed!

- We should use independent public programs for the cross-check and the great point is that these are exist

- Not only tools but also models should be public – this will help us to validate and improve them – HEPMDB and FeynRules are good examples

- **Model → Signatures → Data** tools are in the good shape, it is time to start working on **Data → Model** link