Recent Developments in Tools for Beyond the Standard Model Phenomenology Studies

Federico Ambrogi
Seminar @ Univie, 16/10/2018
Introduction and Overview (1)

Need for Beyond the Standard Models (BSM) Theories: Dark Matter (DM)

Planck 2015 results. XIII. Cosmological parameters arXiv:1502.01589

A Universe filled with DM: DM constitute more than 1/4 of the total energy budget of the universe

Experimental Searches
- production of DM at colliders (e.g. proton proton collisions @ LHC)
- DM annihilation in regions of DM high density and Cosmic Rays production
- Scattering of DM particles onto heavy nuclei
Introduction and Overview (2)

- Many BSM theories can provide a DM candidate compatible with various astrophysical measurements
- Many experimental searches try to catch traces of such elusive particles
- The parameters space, often very large, of many BSM theories can be constrained by the same experimental data i.e. *many BSM theories offer the same experimental signature*

**Idea of Re-interpretation Tools**

Take the experimental results from the various experiments, and constrain alternative BSM scenarios in a systematic and automated way

**Key aspect: Computing time vs Accuracy**
I will discuss three different Tools:

- Simplified model approach
- ‘Full recast’ approach
Typically results for Beyond Standard Model (BSM) searches are presented in terms of Simplified Models Spectra (SMS)

**Simplified Models for a First Characterization of New Physics at the LHC**

Johan Alwall, Philip Schuster, Natalia Toro

(Submitted on 22 Oct 2008 (v1), last revised 4 Jun 2009 (this version, v2))

...If an excess of such events is seen in LHC data, a theoretical framework in which to describe it will be essential to constraining the structure of the new physics. We propose a basis of four deliberately simplified models, each specified by only 2-3 masses and 4-5 branching ratios, for use in a first characterization of data.

Completely described by:

- mass spectrum \((m\tilde{g}, m\tilde{\chi}_1^0)\)
- production cross section \(\sigma(pp \rightarrow \tilde{g}\tilde{g})\)
- decay branching ratio \(BR(\tilde{g} \rightarrow \chi_1^0 tt) \equiv 100\%\)
Typically results for Beyond Standard Model (BSM) searches are presented in terms of Simplified Models Spectra (SMS).
Typically results for Beyond Standard Model (BSM) searches are presented in terms of Simplified Models Spectra (SMS)

Definition of **Efficiency**

(precisely: **Acceptance x Efficiency**)

It is the ratio of the events passing all the selection cuts of an analysis, divided by the total number of Monte Carlo event generated

It measures the sensitivity of the analysis to a particular BSM signal
SUSY Simplified Model Results (8 TeV)

**Run 1 Total integrated luminosity ~ 20 fb⁻¹**

**Stops** excluded up to 800 GeV mass (under SMS assumptions)

**Gluinos** excluded up to 1.4 TeV mass (under SMS assumptions)

---

**Figure 8.3.4**

**CMS**

\[ \tilde{t}\tilde{t} \text{ production, } \tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0 \]

**Run 1 Total integrated luminosity ~ 20 fb⁻¹**

**Stops** excluded up to 800 GeV mass (under SMS assumptions)

**Gluinos** excluded up to 1.4 TeV mass (under SMS assumptions)
Recasting of the CMS-SUS-16-033 analysis with MadAnalysis 5
Principles of Analysis Recasting (1)

• Searches for new physics at the LHC (e.g. SUSY, DM, long-lived particles, heavy resonances etc.) are sensitive to numerous different BSM models

• Experimental Collaborations can provide results only for selected full/simplified models

Recasting tools are a powerful instrument able to constrain generic BSM models using the results from LHC searches

Basic ideas:
- reproduce the flow (selection of events) of an analysis outside the experiments
- calculate cross section UL for the model
- compare experimental results with theory prediction and determine if the model is excluded/allowed

CheckMATE, Rivet
MadAnalysis 5
Principles of Analysis Recasting (2)

The ‘slow’ way

Monte Carlo events generation (for BSM signals)

Detector simulation (ATLAS, CMS)

Analysis recast (extract the efficiency)

“Fast” ~10 min

!!! Up to several hours for a single BSM point !!!

Pro:
- most accurate method, since it is based on full event simulation
- based on standard Monte Carlo sample events: can be used with generic BSM model
Principles of Analysis Recasting (3)

The ‘slow’ way

MadAnalysis 5 Physics Analyses Database (PAD)
https://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase

<table>
<thead>
<tr>
<th>CMS analyses, 13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>CMS-SUS-16-033</td>
</tr>
<tr>
<td>CMS-SUS-16-039</td>
</tr>
<tr>
<td>CMS-SUS-16-052</td>
</tr>
<tr>
<td>CMS-SUS-17-001</td>
</tr>
<tr>
<td>CMS-EXO-16-010</td>
</tr>
<tr>
<td>CMS-EXO-16-012</td>
</tr>
<tr>
<td>CMS-EXO-16-022</td>
</tr>
<tr>
<td>CMS-TOP-17-009</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ATLAS analyses, 8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>ATLAS-SUSY-2013-05</td>
</tr>
<tr>
<td>ATLAS-SUSY-2013-11</td>
</tr>
<tr>
<td>ATLAS-HIGG-2013-03</td>
</tr>
<tr>
<td>ATLAS-EXOT-2014-06</td>
</tr>
<tr>
<td>ATLAS-SUSY-2014-10</td>
</tr>
<tr>
<td>ATLAS-SUSY-2013-02</td>
</tr>
<tr>
<td>ATLAS-SUSY-2013-04</td>
</tr>
</tbody>
</table>
Example: Validation of CMS-SUS-16-033

Search for supersymmetry in multijet events with missing transverse momentum in proton-proton collisions at 13 TeV

arXiv:1704.07781


From the analysis description to the implementation

4 Event selection and search regions

Events considered as signal candidates are required to satisfy:

- $N_{\text{jet}} \geq 2$, where jets must appear within $|\eta| < 2.4$;
- $H_T > 300 \text{ GeV}$, with $H_T$ the scalar $p_T$ sum of jets with $|\eta| < 2.4$;
- $H_T^{\text{miss}} > 300 \text{ GeV}$, where $H_T^{\text{miss}}$ is the magnitude of $\vec{H}_T^{\text{miss}}$, the negative of the vector $p_T$ sum of jets with $|\eta| < 5$; an extended $\eta$ range is used to calculate $H_T^{\text{miss}}$ so that it better represents the total missing transverse momentum in an event;
- no identified, isolated electron or muon candidate with $p_T > 10 \text{ GeV}$;
- no isolated track with $m_T < 100 \text{ GeV}$ and $p_T > 10 \text{ GeV}$ ($p_T > 5 \text{ GeV}$ if the track is identified as a PF electron or muon), where $m_T$ is the transverse mass [40] formed from the $p_T^{\text{miss}}$ and isolated-track $p_T$ vector, with $p_T^{\text{miss}}$ the negative of the vector $p_T$ sum of all PF objects;
Example: Validation of CMS-SUS-16-033

Search for supersymmetry in multijet events with missing transverse momentum in proton-proton collisions at 13 TeV

arXiv:1704.07781


From the analysis description to the implementation

```cpp
// Define the preselection cuts (not including Jet,Nb,HT,MHT binnings)
Manager()->AddCut("Njet>=2") ; // more or equal 2 jets with |eta|<2.4
Manager()->AddCut("HT>300") ; // HT = scalar sum of jets pt>30 GeV
Manager()->AddCut("MHT>300") ; // HTM = magnitude of the the vector HTmiss, i.e. negative of
Manager()->AddCut("NoIsoMuons") ; // No isolated muons with pt>10 GeV
Manager()->AddCut("NoMuonsTracks") ; // No isolated muons tracks
Manager()->AddCut("NoIsoElectrons") ; // No isolated electron with pt>10 GeV
Manager()->AddCut("NoElectronsTracks") ; // No isolated electron tracks
Manager()->AddCut("NoIsoTracks") ; // no isolated tracks with mT<100 GeV and pT>10 GeV
    // (pT > 5 GeV if track is a PF electron or muon)
    // mT = transverse mass formed with the pTmiss (all pT of the
Manager()->AddCut("DPhi(MHTj1)>0.5") ; // Azimutal angle between MHT and the pT of the 'i' jet
Manager()->AddCut("DPhi(MHTj2)>0.5") ;
Manager()->AddCut("DPhi(MHTj3)>0.3") ;
Manager()->AddCut("DPhi(MHTj4)>0.3") ;
```

Next Step: Validation of the code
### Pre-selection cuts

#### $T2tt = (700,50)$

<table>
<thead>
<tr>
<th>Cut</th>
<th>Absolute</th>
<th>Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MA5</td>
<td>CMS</td>
</tr>
<tr>
<td>$n_{jet} \geq 2$</td>
<td>98.90</td>
<td>99.80</td>
</tr>
<tr>
<td>$H_T &gt; 300$</td>
<td>92.30</td>
<td>96.40</td>
</tr>
<tr>
<td>$\hat{H}_T &gt; 300$</td>
<td>54.13</td>
<td>57.80</td>
</tr>
<tr>
<td>NoIsoMuons</td>
<td>48.16</td>
<td>46.60</td>
</tr>
<tr>
<td>NoMuonsTracks</td>
<td>47.74</td>
<td>46.10</td>
</tr>
<tr>
<td>NoElectrons</td>
<td>43.32</td>
<td>37.40</td>
</tr>
<tr>
<td>NoElectronsTracks</td>
<td>42.78</td>
<td>36.90</td>
</tr>
<tr>
<td>NoIsoTracks</td>
<td>42.16</td>
<td>35.80</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{H}_T, j1) &gt; 0.5$</td>
<td>42.03</td>
<td>35.70</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{H}_T, j2) &gt; 0.5$</td>
<td>40.03</td>
<td>34.00</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{H}_T, j3) &gt; 0.3$</td>
<td>38.77</td>
<td>33.10</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{H}_T, j4) &gt; 0.3$</td>
<td>35.45</td>
<td>31.80</td>
</tr>
</tbody>
</table>

#### $T2 = (1000,100)$

<table>
<thead>
<tr>
<th>Cut</th>
<th>Absolute</th>
<th>Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MA5</td>
<td>CMS</td>
</tr>
<tr>
<td>$n_{jet} \geq 2$</td>
<td>97.82</td>
<td>98.90</td>
</tr>
<tr>
<td>$H_T &gt; 300$</td>
<td>97.12</td>
<td>98.60</td>
</tr>
<tr>
<td>$\hat{H}_T &gt; 300$</td>
<td>79.16</td>
<td>80.00</td>
</tr>
<tr>
<td>NoIsoMuons</td>
<td>79.16</td>
<td>79.90</td>
</tr>
<tr>
<td>NoMuonsTracks</td>
<td>79.14</td>
<td>79.80</td>
</tr>
<tr>
<td>NoElectrons</td>
<td>79.14</td>
<td>79.60</td>
</tr>
<tr>
<td>NoElectronsTracks</td>
<td>79.12</td>
<td>79.30</td>
</tr>
<tr>
<td>NoIsoTracks</td>
<td>78.96</td>
<td>78.70</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{H}_T, j1) &gt; 0.5$</td>
<td>78.89</td>
<td>78.60</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{H}_T, j2) &gt; 0.5$</td>
<td>73.58</td>
<td>74.50</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{H}_T, j3) &gt; 0.3$</td>
<td>70.24</td>
<td>70.60</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{H}_T, j4) &gt; 0.3$</td>
<td>67.65</td>
<td>67.90</td>
</tr>
</tbody>
</table>

**Relative**

\[
\hat{H}_T = |\vec{\hat{H}}_T| = \left| \sum_{jets(p_T>30)} \vec{p}_T \right|
\]

\[
H_T = \sum_{jets(p_T>30)} |p_T|
\]

**Obtained with MA5**

**Provided by CMS**
3.1. Recasting Tools

T2 = (1000, 100), (700, 400)
T2bb = (650, 1), (500, 300)

Large mass gap Small mass gap

Validation needed for several mass points of the same simplified model
(to check mass dependent effects)
On the Validation

- An analysis is considered validated if MA5 results are compatible within ~20/30 % wrt official results.
- Implementing the code is easy if the selection cuts are properly described in the paper.
- Very important: description of the object selection efficiency (at the detector simulation or at the analysis level, e.g. b-tagging efficiency).
- Different Monte Carlo production settings might play a big role.

Example: b-jet misidentification

$$b\text{-jet Misidentification}$$

13 TeV, $\mathcal{L}=2.6$ fb$^{-1}$

$$0.0083 \times e^{0.00133 p_T}$$

$$0.009 - 4.0 \times 10^{-11} p_T^3 + 6.1 \times 10^8 p_T^2 - 4.9 \times 10^{-7} p_T$$
Making Systematic Use of Simplified Models Results from the LHC Searches with SModelS
Making Systematic Use of Simplified Model Results

Basic Idea: use the simplified models results from the ATLAS and CMS collaboration, to constrain generic BSM model

Tool designed to constrain any BSM model (with a Z₂ symmetry e.g. R-parity for SUSY models) with the Simplified Models Results from the LHC

http://smodels.hephy.at/wiki

From v1.2 onwards: exotic signatures e.g. long-lived charged particles
Future extension: resonances, …
SModelS: Basic Principles

1. Decomposition

Input model

• A generic input model is decomposed into its SMS
• If for a element/combination of elements

2. Element Combination

3. Comparison with LHC constraints

$w = \sigma_{(pp\rightarrow b\tilde{b}^*)} \times BR(b\rightarrow b\tilde{\chi}_1^0)$

Database results:
ATLAS-SUSY-2013-05
CMS-PAS-SUS-12-024
CMS-SUS-13-012-eff

...
The decomposition maps each BSM model into its SMS spectra

Each element is characterised by:
- the mass spectrum of particles
- \( \sigma \times \text{BR} \)
- the decay chain
A generic BSM model is decomposed into its SMS
(a $\mathbb{Z}_2$ symmetry is required, e.g. R-parity for SUSY models)
SModelS: Validation of the Implemented Results

CMS-SUS-13-004 T2tt UL result

Only ‘validated’ analyses enter the database

\[
\sigma_{\text{th.}} = \sigma(pp \rightarrow \tilde{t}\tilde{t})
\]

Validation Procedure

- Run SModelS over a grid of T2tt points
- Compare \(\sigma_{\text{th.}}\) with CMS \(\sigma_{\text{UL}}\)
- Extract SModelS exclusion

http://smodels.hephy.at/wiki/Validation
SModelS: Database of Experimental Results

**Complete set of Run 1 results**

- **ATLAS**
  - 8 TeV
  - CMS-SUS-13-012
    - globalInfo.txt
      - data
        - T1.txt
        - T1tttt.txt
        - T2.txt
        - (...)

- **CMS**
  - CMS-SUS-13-012-eff
    - globalInfo.txt
      - data
        - T1.txt
        - T1tttt.txt
        - T2.txt
        - (...)

**Large part of Run 2 results**

- **ATLAS**
  - 13 TeV
    - (...)

- **CMS**
  - (...)

---

**EM maps results**

- **Official ATLAS and CMS FastLim Collaboration**
- **SModelS Homegrown**

---

*Complete set of Run 1 results*
*FastLim Collaboration*
*SModelS Homegrown*
EMs produced by Phenomenologists: FastLim Collaboration and SModelS

Idea: using recasting tools to produce recast EMs for simplified models which are not covered by the existing experimental results

MC production only run once, and then the EMs in the database will be used for any BSM model tested
pMSSM constraints from ATLAS Run 1 Searches

- The phenomenological Minimal Supersymmetric Standard Model (pMSSM) is a widely studied “full” SUSY model
- It reduces the full MSSM to only ~20 free parameters
- Used as a benchmark by ATLAS and CMS to quantify the impact of Run 1 searches on a full SUSY model (leaving the SMS assumptions)

Realistic models are needed to capture "the complex effects that can result from large numbers of competing production and decay processes"

![Graphs showing pMSSM constraints from ATLAS Run 1 Searches](image)

(b) Lightest (1st/2nd gen) squark / LSP

(a) All LSP types
• The phenomenological Minimal Supersymmetric Standard Model (pMSSM) is a widely studied “full” SUSY model
• It reduces the full MSSM to only ~20 free parameters
• Used as a benchmark by ATLAS and CMS to quantify the impact of Run 1 searches on a full SUSY model (leaving the SMS assumptions)

Realistic models are needed to capture "the complex effects that can result from large numbers of competing production and decay processes"

Due to complex decay chains, the mass limits of SUSY particles in realistic model can be largely different wrt the interpretation with SMS
Constraining the pMSSM with SModelS

- We want to test how well a simplified model based interpretation performs wrt a full reinterpretation as done by ATLAS in the case of the pMSSM
- ATLAS provided all the model points tested
- We focused on the points excluded by ATLAS

<table>
<thead>
<tr>
<th>Number of Points</th>
<th>Bino-like LSP</th>
<th>Higgsino-like LSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>38575</td>
<td>45594</td>
</tr>
<tr>
<td>Excluded by UL</td>
<td>16957 (44 %)</td>
<td>25024 (55 %)</td>
</tr>
<tr>
<td>Excluded by UL+EM</td>
<td>21151 (55 %)</td>
<td>28669 (63 %)</td>
</tr>
</tbody>
</table>

arXiv:1707.09036
Constraining the pMSSM with SModelS: Missing Topologies

- Missing topologies: elements with the highest weight (cross section x BR) that are not included in the database
- Results for SMS that could potentially constrain the model tested if added to the database

### Missing topologies with the highest cross-sections (up to 10):

<table>
<thead>
<tr>
<th>Sqrts (TeV)</th>
<th>Weight (fb)</th>
<th>Element description</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0</td>
<td>1.554E+03</td>
<td>#</td>
</tr>
<tr>
<td>8.0</td>
<td>7.577E+02</td>
<td>#</td>
</tr>
<tr>
<td>8.0</td>
<td>5.975E+02</td>
<td>#</td>
</tr>
</tbody>
</table>

### SModelS Missing topologies for an example pMSSM point
Combined with the T3GQ model

- Special topology corresponding to two mass hierarchies
- pMSSM-19 has 3 light squark mass parameters
  \[
  m_{\tilde{u}_L} = m_{\tilde{d}_L} = m_{\tilde{c}_L} = m_{\tilde{s}_L} \\
  m_{\tilde{u}_R} = m_{\tilde{c}_R} \\
  m_{\tilde{d}_R} = m_{\tilde{s}_R}
  \]
Extending the database: EMs production for T3GQon, T2, and T5

- Use the EM Bakery machinery to produce results for T3GQon, T2, and T5
- Implement the new results in SModelS database
- Check the new constraints

<table>
<thead>
<tr>
<th>Txname</th>
<th>Mass Planes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>-</td>
<td>$\Delta M(\tilde{q}, \tilde{\chi}_1^0)$ as low as 5 GeV</td>
</tr>
<tr>
<td>T5</td>
<td>$x = (0.05, 0.50, 0.95)$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\Delta M(\tilde{g}, \tilde{g}) = 5$ GeV</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\Delta M(\tilde{q}, \tilde{\chi}_1^0) = 5$ GeV</td>
<td>-</td>
</tr>
<tr>
<td>T3GQon</td>
<td>Fixed $m_{\tilde{g}} = 200, 250, ..., 1200$</td>
<td>$m_{\tilde{g}}$ in 50 GeV bins</td>
</tr>
<tr>
<td></td>
<td>Fixed $m_{\tilde{g}} = 1300, 1400, ..., 2000$</td>
<td>$m_{\tilde{g}}$ in 100 GeV bins</td>
</tr>
<tr>
<td></td>
<td>$m_{\tilde{q}}$ in 50 GeV bins (up to 1 TeV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Delta M(\tilde{q}, \tilde{\chi}_1^0)$ as low as 5 GeV</td>
<td></td>
</tr>
</tbody>
</table>
Improving the pMSSM Coverage

New Results

<table>
<thead>
<tr>
<th>Number of Points</th>
<th>Bino-like LSP</th>
<th>Higgsino-like LSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>38527</td>
<td>45345</td>
</tr>
<tr>
<td>Excluded by UL+EM</td>
<td>28761 (74%)</td>
<td>32297 (71%)</td>
</tr>
</tbody>
</table>

+ 19%

+ 8%
Constraining DM models with signals from the space: MadDM (v.3.0)
MadDM v.3.0: a Comprehensive Tool for Dark Matter Studies

Federico Ambrogi, Chiara Arina, Mihailo Backovic, Jan Heisig, Fabio Maltoni, Luca Mantani, Olivier Mattelaer, Gopolang Mohlabeng

- **MadDM** is now a MadGraph5_aMC@NLo plugin
- to install: `./bin/mg5_aMC`
  install madd
  
  https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/MadDm

- MadDM v.1.0 : relic density
- MadDM v.2.0 : direct detection
- **MadDM v.3.0 : indirect detection**
  - dedicated module for DM indirect detection theory predictions
  - module for *experimental constraints*
  - inherits the capabilities of MG5 to automatically compute and generate ‘complicated’ processes
  - advanced functionalities for scanning from MG5 or PyMultiNest
DM annihilation in the halos (external galaxies or in the Milky way)

(Possible DM candidate)
DM annihilation in the halos (external galaxies or in the Milky way)

\[
\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle \sigma v \rangle}{2m_\chi^2} \sum_i B_i \frac{dN_i}{dE_\gamma} \frac{1}{4\pi} \int \frac{d\Omega}{\Delta\psi} \int_{\text{los}} \rho^2(\psi, l) \, dl
\]

Prediction for the differential flux of cosmic rays at the point of detection

Fermi-LAT, ICECUBE, AMS…
Main observable for indirect detection: differential flux of cosmic rays at detection (e.g. Gamma Rays)

\[
\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle \sigma v \rangle}{2m_\chi} \sum_i B_i \frac{dN^i_\gamma}{dE_\gamma} \int_\psi \frac{d\Omega}{\Delta \psi} \int_{\text{los}} \rho^2(\psi, l) \, dl
\]

\[\text{[particles/(GeV sr cm}^2 \text{ s}]}\]

**MadDM** calculates the velocity averaged annihilation cross section

**MadDM** produces the energy spectra of the cosmic rays

J-factor from astrophysical observation
Velocity Averaged Annihilation Cross Section

General expression for $\langle \sigma v \rangle$

$$\langle \sigma v \rangle = \int d^3v_1 d^3v_2 P_r(v_1) P_r(v_2) \sigma v_{\text{rel}}$$

**Inclusive**

- Very fast, but considers only $\text{DM DM} \rightarrow \text{2-body}$ (SM or BSM) at LO
- Takes $P(v) = \delta_D(v_{\text{rel}})$, integrates over angles
- 10-20% agreement wrt the other two more precise methods

**MadEvent**

- Amplitudes for all relevant subprocesses + full phase space integration
- Generic $\text{DM DM} \rightarrow \text{n-body}$
- Generates unweighted events to pass to Pythia8

**Reshuffling**

- MadEvent + events re-weighting with a Maxwell-Boltzmann distribution

$$\tilde{P}_{r,\text{rel}}(v_{\text{rel}}) = \sqrt{\frac{2}{\pi}} \frac{v_{\text{rel}}^2}{v_0^3} \exp\left(-\frac{v_{\text{rel}}^2}{2v_0^2}\right)$$
Energy Spectra from Cosmic Rays (1)

CR Energy spectra and indirect detection limits are typically presented in terms of DM annihilation into SM channels

\[ \chi \chi \to gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^- \]
\[ \nu_e \bar{\nu}_e, \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau, ZZ, W^+ W^-, hh \]

Two ways of extracting the spectra

- **PPPC4DMID Tables**
  - Requires the installation of the PPPC4DMID module
  - Fast but precise if annihilation is dominated by SM

- **Pythia8 Spectra**
  - Includes decays of BSM final states
Energy Spectra from Cosmic Rays (2)

PPPC4DMID = A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

http://www.marcocirelli.net/PPPC4DMID.html

\[ \chi \chi \rightarrow q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t} \]

- MadDM includes the PPPD4DMID tabulated energy spectra for **DM DM > SM SM**
- CR spectra added up according to their cross section (branching fraction)
\[ \chi \chi \rightarrow gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^- \\]
\[ \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh \]

Fermi-LAT sensitive to $\gamma$ in the energy range $\sim [0.5 - 500 \text{ GeV}]$
• The Fermi-LAT Collaboration gives limits on DM annihilation into two channels:

$$\text{DM DM} \rightarrow \bar{b} b, \tau^+ \tau^-$$

• They also made available the likelihood profiles for a set of dwarf spheroidal galaxies to derive the upper limits (UL) on $$\langle \sigma v \rangle$$
Fermi-LAT Limits (3)

- MadDM makes use of the likelihood profiles for the 6 dwarf spheroidal galaxies with the highest J-factors to extract the combined limits.
- It is possible to calculate the limits for arbitrary $DM DM > SM SM$.

![Fermi Limits - Combined](image)

- We calculated the limits of any $DM DM > SM SM$.
- Added the new limits in the Exp. constraints module.
Fermi-LAT Limits (3)

- MadDM makes use of the likelihood profiles for the 6 dwarf spheroidal galaxies with the highest J-factors to extract the combined limits.
- It is possible to calculate the limits for arbitrary $DM \, DM > SM \, SM$.

We calculated the limits of any $DM \, DM > SM \, SM$.
- Added the new limits in the Exp. constraints module.

**DM DM > SM SM**
## Two methods for calculation of indirect detection predictions

<table>
<thead>
<tr>
<th></th>
<th><strong>Fast</strong></th>
<th><strong>Precision</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>( &lt;\sigma v&gt; )</td>
<td><strong>Inclusive</strong></td>
<td><strong>Reshuffling (Madevent)</strong></td>
</tr>
<tr>
<td>Processes</td>
<td>DM DM &gt; SM SM</td>
<td>DM DM &gt; n-body</td>
</tr>
<tr>
<td>Spectra at Source</td>
<td><strong>PPPC4DMID_ew</strong> (PPPC4DMID) *only* from SM channels</td>
<td><strong>Pythia8</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>from any final state</td>
</tr>
<tr>
<td>Flux at Earth</td>
<td>Propagate and oscillate ( \gamma ) and ( v_i ) ( e^+ : ) <strong>PPPC4DMID_ep</strong> ( e^+ ) and ( p : DRAGON )</td>
<td>Propagate and oscillate ( \gamma ) and ( v_i ) ( e^+ ) and ( p : DRAGON )</td>
</tr>
<tr>
<td>Constraints</td>
<td>Fermi-LAT UL for each SM channels + SM combination</td>
<td>Fermi-LAT UL for each SM channels + limit for total gamma-ray spectrum including BSM states</td>
</tr>
</tbody>
</table>

\[\rightarrow See \ Table \ C.2 \ page \ 26 \ of \ the \ manual \ for \ the \ extended \ summary\]
Propagating of CR Rays

\[
\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle \sigma v \rangle}{2m^2_\chi} \sum_i B_i \frac{dN_i^\gamma}{dE_\gamma} \frac{1}{4\pi} \int_\psi \int_{\Delta\psi} \int_\text{los} \rho^2(\psi, l) \, dl
\]

[particles/(GeV sr cm^2 s)]

- Neutrinos oscillations (from far galaxies to Earth)
- PPPC4DMID Tables for e+
  - Halo profile: NFW, Moore, Einasto, Isothermal
  - Galactic magnetic field model: MF1, MF2, MF3
  - Propagation model: MIN, MED, MAX
- DRAGON
  - Interface with the fully numerical code DRAGON for the propagation of positrons/antiprotons within the galaxy
Conclusions

• Plethora of experimental results available from several types of experiments (not discussed: SM precision measurements e.g. flavour sector, Higgs etc.) able to constrain BSM theories

• Many existing tools can be efficiently used to constrain, in an automated way, the parameter space of many theories

• Tools are being constantly updated using the latest experimental input

Thank You!