SModelS - development beyond Missing Energy

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Discrete symmetries and new physics

1. Multiple examples of discrete symmetries in particle physics exist (within the Standard Model)
   - Charge
   - Parity

2. Many BSM scenarios employ discrete symmetries and are intimately tied to dark matter phenomenology
   - SUSY neutralino dark matter -> R-parity
   - Inert Doublet Model -> $Z_2$ symmetry
   - Self interacting dark matter -> e.g. $Z_3$ symmetry …

3. Collider signatures are a result of the symmetries, mass spectrum and couplings of the theory
   - Result in classic missing energy searches
   - Can also lead to more exotic final states
• Results for Sneutrino LSP
• Caveat: left plot inverted also shows many points non-excluded (not shown here)
• Caveat: right plot also has dependence on LSP mass (not shown here)
One model - many signatures

Heavy neutral leptons

SIMPs

SUSY

Extended scalar sectors

Dark matter

Hidden valley

Extra dimensions
Current efforts beyond MET

- Apply efficiency maps given by experiments ‘by hand’ to single topologies (a la simplified models approach)
  - Constrains specific parts of parameter space but difficult to get global picture for full models


- Improve fast detector simulators such as Delphes (see: Delphes 3.4.1)

  C.f. https://inspirehep.net/record/1667603/, LLP workshop talk

- Classify signatures dynamically and confront them with experimental searches (SModelS)

SModelS

• A tool to confront arbitrary (incl. non-SUSY) theoretical models with LHC results via decomposing theory models into simplified models dynamically


• Assumptions:
  - Model obeys $Z_2$ symmetry (R-parity)
    ✴ Implications: applicable only to pair production of BSM particles (i.e. can’t handle resonance searches at the moment)
  - All BSM particles decay to missing energy final states (SModelS v1.1.1)
  - Model can be approximated by sum over simplified models (i.e. long decay chains don’t contribute to signal cross section significantly)
  - No dependence on nature of BSM particles (i.e. quantum numbers)
  - Most relevant quantities for confronting theory with experimental results are:
    ✴ masses of BSM particles
    ✴ SM final state particles
    ✴ cross sections X branching ratios
• 95% CL UL is the maximum visible cross-section allowed for a specific decay chain and a mass combination

Is $\sigma \times \text{BR}$ (Mother mass, intermediate mass, LSP mass) of your model > the number on the plot? -- Yes, point excluded; No, point allowed
Given Spectra

\begin{align*}
\tilde{\chi}_1^+, \tilde{\chi}_2^0 \\
\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R \\
\tilde{\chi}_1^0
\end{align*}

Kraml et al, arXiv:1412.1745
Decomposition

Given Spectra

\[ \tilde{\chi}_1^+ , \tilde{\chi}_2^0 \]
\[ e_R, \tilde{\mu}_R, \tilde{\tau}_R \]
\[ \tilde{\chi}_1^0 \]

Kraml et al, arXiv:1412.1745
Look-up experimental limits

Is theory prediction > experimental limit?

Yes
Point excluded

No
Point allowed
• Signatures depend on quantum numbers of the underlying particles
• More things matter than just masses of BSM particles
• Must keep track of the quantum numbers of the particles

See: talk by A. Escalante del Valle for experimental results
It explodes!

- A single production channel gives rise to many many final states
- Exact weight of final state depends on the width of the particle
- Survival probability: \( F = \exp\left(-\Gamma \frac{l}{\beta \gamma \hbar c}\right) \)
• A single production channel gives rise to many many final states
• Exact weight of final state depends on the width of the particle
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So start at extremes

- In the first step either concentrate on prompt or stable fraction
- Discard everything else
- Reduces the number of diagrams
- Also need to think how to reinterpret all possible searches
- Even with this one can constrain large range of lifetimes if the cross sections are large -> not as limiting approach as it may look
Going beyond Missing Energy

\[ F_{\text{prompt}} = 1 - \exp \left( -\frac{1}{c\tau} \left\langle \frac{\ell_{\text{inner}}}{\gamma\beta} \right\rangle_{\text{eff}} \right) \]

\[ F_{\text{long}} = \exp \left( -\frac{1}{c\tau} \left\langle \frac{\ell_{\text{outer}}}{\gamma\beta} \right\rangle_{\text{eff}} \right). \]

- The cross section X branching ratio needs to be reweighted by the probabilities of BSM particles to decay promptly or outside the detector
- Reweight the theory cross section by this number
SModelS - recent news

- A version dealing with Heavy Stable Charged particles and R-hadron results is released
- Contains three analyses dealing with HSCP and R-Hadron searches
- Accounts for quantum numbers of particles in simple fashion: lists of quantum numbers
- Assumes constant boost for long lived particles
- Does not handle displaced vertices

\[ \mathcal{F}_{\text{prompt}} = 1 - \exp \left( -\frac{1}{c\tau} \frac{\ell_{\text{inner}}}{\gamma\beta} \right) \]

\[ \mathcal{F}_{\text{long}} = \exp \left( -\frac{1}{c\tau} \frac{\ell_{\text{outer}}}{\gamma\beta} \right) \]
SModelS - going beyond

- Fraction of particles decaying at a given point depend on boost and lifetime
- We discard everything in between prompt and stable particles
- We miss out on potentially powerful searches which constrain ‘in between decays’
**SModelS - going further**

- An elegant way to handle exotic final states is to **convert particles from strings to classes**
- Basic particle properties well defined however **mass, decay widths and decays are dynamically updated**
- One of the **crucial changes** in the upcoming SModelS version
- Also very important for going **beyond Z\text{2} symmetric models**
- Triggers higher level changes as particles are basic entities in the code; converting particle type leads to readapting major parts of the code

**SM example:**

```python
import Particle

e = Particle(
    Z2parity='even',
    label='e-',
    pdg=11,
    mass=0.5*MeV,
    eCharge=-1,
    colordim=0,
    spin=1./2,
    totalwidth = 0.*GeV,
    decays=[])```

**BSM example:**

```python
import Particle

gluino = Particle(
    Z2parity='odd',
    label='gluino',
    pdg=1000021,
    eCharge=0,
    colordim=8,
    spin=1./2)```
Topology dependent boost

$\beta\gamma$ for $\chi^\pm_1$ production at $\sqrt{s} = 13$ TeV

- red, green, blue:
  - $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$
- purple:
  - $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$
  - $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^\pm$ soft SM

Topology dependent beta gamma

Simulate several different topologies

Dependence on the analysis

Reweight on the experimental side rather than theory
Where are we now?

- Conversion of particle entities from simple string implementation to object oriented completed
- All higher level changes in the code taken care of
- Implementation of experimental searches and derivation of efficiency mops ongoing
- Validation (making sure that results are correct) ongoing
- Hope to start with some physics studies soon!
Conclusions

- Absence of any concrete positive signal for BSM physics necessitates exploring signatures beyond missing energy searches
- Exotic final states appear in many models besides supersymmetry
- Automatic classification of final states in arbitrary models will be useful
- Needs a comprehensive database of experimental results which can be easily used in order to confront theory with the experiments
- SModelS is making progress in this direction
- Recently released a version which can handle R-Hadrons and HSCP searches
- Current development aims at improving existing treatment and going well beyond extremely long lived particles