Physics Beyond the Standard Model (experimental) - Part 2

CATERINA DOGLIONI - LUND UNIVERSITY
Introduction

Problems with the SM

SUSY

Dark Matter (part 1)

Outline for these three BSM lectures

Lecture 1
The Standard Model has no apparent major problem!
Why should we look beyond, and how? Direct and indirect BSM searches

Lecture 2
The Standard Model has some problems!
Solving many problems at once: supersymmetry
Solving one problem at a time: generic dark matter searches (at the LHC, for today)

Lecture 3
Connecting DM@LHC with DM beyond the LHC (direct and indirect detection)
Darker matter: the rare and the unexpected (at the LHC and beyond)
Outline of other BSM theories & results
(Almost) back to the SM: neutrino physics
Recap of Lecture 1

The SM has no problems (...just wait until today’s lecture...)!
- Measurements and agreement with theory

✅ Energy frontier => exploration of the unknown
  "Generic" **direct search strategies**:
  look for (sizable) deviations signaling the presence of new particles
  A simple BSM search in more detail

❌ Energy frontier => but we’re not upgrading the LHC energy anytime soon!
**Indirect search strategies**:
  look for (small) deviations from the presence of new particles in loops
Introduction  Problems with the SM  SUSY  Dark Matter (part 1)

Wordcloud #1
Wordcloud #2
Future: poll results
Lecture 2
The SM has some problems!
- the Higgs and the hierarchy problem [some solutions: this afternoon]
- dark matter and dark energy [some solutions: this afternoon]
- neutrino masses [problem & solutions: tomorrow]

Solving many problems at once: **Supersymmetry (SUSY)**
  - How to search for SUSY & interpret results
  - SUSY @ LHC: where we are, where we are going

Solving at least one big problem: not-necessarily-SUSY **Dark Matter, part 1**
  - Dark matter
  - Invisible particles at colliders
  - Benchmark models and searches
Standard Model? Here are its problems!
A list of problems with the SM

**Preferred (by whom?) mass range for answers: TeV-scale**

- Fine-tuning needed for Higgs mass
- Large difference in scales of forces (hierarchy problem)
- Free SM parameters
- ...
Preference also due to a special time in history

C. Issever

Today .... Very Special Time

LHC above energy scale of Standard Model:

\[ \gg \text{TeV}^{-1} \sim 10^{-17} \text{ cm} \]

Probes New Physics

- LHCb
- ATLAS
- CMS
- ALICE

27 km circumference
Preference also due to a special time in history

Higgs Vacuum Expectation Value: 246 GeV \(\sim 10^{-16}\) cm
Can the Higgs indicate the scale of new physics? Not

http://rsta.royalsocietypublishing.org/content/370/1961/818 (2012)

"Only a narrow range of $m_h \in (130, 180)$ GeV is compatible with the survival of the Standard Model at all scales up to the Planck mass. This could be the ‘maximal conceivable disaster’ scenario for the LHC: a single Standard Model Higgs boson and nothing else!"

Problems with Higgs self-coupling inducing new non-perturbative physics

Problems with stability of the vacuum
Observed (Higgs mass)$^2$: $10^{32}$ times smaller than predicted

Think renormalisation: Large loop corrections needed to the Higgs mass
OR
cut-off the theory at scale $\Lambda$

$$m_H^2 = m_o^2 + \delta m^2$$
$$\delta m^2 \sim \Lambda^2$$

No indication of what this scale $\Lambda$ is (from previous slide)… could be limit of current physics knowledge (Planck scale)
Higgs mass and fine tuning

Is this natural?

\[ 36127890984789307394520932878928933023 - 36127890984789307394520932878928917398 = \]

\[ = m_H^2 = 125^2 \]

Unnatural cancellation or fine-tuning: \( O(10^{32}) - O(10^{32}) = O(1) \)

In analogy to: \( 0.7 - 0.4 \neq O(10^{-32}) \)
Higgs mass and fine tuning

Is this natural?

Fine-tuning in nature:
- Eclipse (moon and sun aligned to 1 %)
- A pen perfectly balanced on its tip

For further digressions: see [http://discovermagazine.com/2000/nov/cover/](http://discovermagazine.com/2000/nov/cover/)

But also: “Whatever combination of physical constants may exist, it would be one of a kind.” T. Drange
Why are the scales of the SM forces and the masses of its particles so far apart? 
[Why three families? Why masses not predicted?]
Take-home point #1:

The SM has problems that are both aesthetic (observations not matching a "beautiful" theory) and empirical (observations not explained).

These motivate the search for BSM physics at the scales reachable by the LHC.
A solution with many benefits: Supersymmetry
Introduction

Problems with the SM

SUSY

Dark Matter (part 1)

Supersymmetry: a new particle zoo

Particle zoo

Particles are divided into two families called bosons and fermions. Among them are groups known as leptons, quarks and force-carrying particles like the photon. Supersymmetry doubles the number of particles, giving each fermion a massive boson as a super-partner and vice versa. The LHC is expected to find the first supersymmetric particle.

The lightest supersymmetric particle is called the neutralino. It could be any one of the -inos, or a combination of them.
A solution with benefits

Every supersymmetric partner can compensate a loop that would increase the Higgs mass

\[ m_H^2 = m_o^2 + \delta m^2 + \delta \tilde{m}^2. \]

Cancellation ~exact only if equal masses

**Note:** need to apply R-parity conservation to avoid proton decays (not experimentally observed)

\[ R = (-1)^{(3B+L+2s)} \]

**SM particles:** \( R = +1 \)

**SUSY particles:** \( R = -1 \)

**Consequence:** decay chains, until pair-production of stable remnant (lightest supersymmetric particle, LSP)

\[ \rightarrow \text{benefit: this is a dark matter candidate (see later)} \]
Additional benefit: force unification

Coupling constants run with energy
if (TeV-scale) SUSY particles, they all run to the same value

Illustration: Typoform

https://xkcd.com/1956/
How to look for SUSY particles? Depends...

**SUSY has many realizations:** many new particles bring many parameter choices

Phenomenology depends on how the supersymmetry is broken

In a “naive experimental” picture the model depends on:

- Particle content and mass hierarchy (e.g. small/large mass splittings)
- Type of SUSY particle considered
- Coupling constants to SM particles, mixing angles (=decays)
- R-parity conservation/violation

Experiments “brand” searches for **strong/electroweak/compressed/3rd gen (..) SUSY**
How to look for SUSY particles? Depends...

Some "typical" SUSY decay chains

Event characteristics:
- High object multiplicity
- Missing transverse momentum

Backgrounds:
- QCD, with mis-measured jets
- W+jets
- top quarks
SUSY variables: include the MET in the ET

Example: \( M_{\text{eff}} \) variable (+ others)

\[
M_{\text{eff}} = \sum_{i=1}^{4} p_T^{\text{jet},i} + \sum_{i} p_T^{\text{lep},i} + E_T^{\text{miss}}
\]

D. Guadagnoli's slides

Number of events

Energy of the system (visible/invisible)

Signal

Background
Background estimation: use control regions

Control region

<table>
<thead>
<tr>
<th>Events / 200 GeV</th>
<th>ATLAS Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>v = 13 TeV, 139 fb⁻¹</td>
<td>CRT for MB-GGd</td>
</tr>
<tr>
<td>SM Total</td>
<td>Data</td>
</tr>
<tr>
<td>tt(EW) &amp; single top</td>
<td>W+jets</td>
</tr>
</tbody>
</table>

Define to be signal-depleted
Can serve as normalization for MC, reducing theory uncertainties

Signal region

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<td>MB-GGd</td>
</tr>
<tr>
<td>SM Total</td>
<td>Data</td>
</tr>
<tr>
<td>W+jets</td>
<td>tt(EW) &amp; single top</td>
</tr>
<tr>
<td>(3, Z⁻⁻) = (2400, 400)</td>
<td></td>
</tr>
</tbody>
</table>

Define to be signal-rich
This search: also use a second variable related to MET for multi-bin approach
Can make use of CR normalizations
Apply cut to increase signal/background

Recent search for squarks and gluinos: ATLAS-CONF-2019-040
Compare data and background estimation in SR

**Profile likelihood ratio**

**Bin bounds**

**Cumulative number of events in bin**

**ATLAS** Preliminary

$s=13$ TeV, $139$ fb$^{-1}$

SR for MB-GGd

$N_{el}=[4,\infty)$

**Significance (Data/SM)**

**Bin boundaries**

$m_{\text{eff}}$ [TeV], $E_T^{\text{miss}}$, $\sqrt{H_T}$ [GeV$^{1/2}$]

**Data**

- SM Total
- W+jets
- $t\bar{t}$ (+EW) & single top
- Z+jets
- Diboson
- Multi-jet

**Legend**

**ATLAS-CONF-2019-040**
An example SUSY limit plot

**ATLAS Preliminary**

\( \sqrt{s} = 13 \text{ TeV}, \) 139 fb\(^{-1}\)

0-leptons, 2-6 jets

All limits at 95% CL

**Mass limit for lightest stable neutralino (LSP)**

\[ \tilde{g} \text{ production, } B(\tilde{g} \to qq\tilde{\chi}_1^0) = 100\% \]
Strong SUSY limits (= the "problem" with natural SUSY)

CMS (preliminary) May 2019

Overview of SUSY results: gluino pair production

36/137 fb⁻¹ (13 TeV)

CMS SUSY public results

- **PP \( \rightarrow \tilde{g}\tilde{g} \)**
  - 0/f: SUS-19-005; SUS-19-006; arXiv:1710.11188; 1802.02110
  - 1/f: arXiv:1705.04673; 1709.09814
  - 2/f **same-sign**, \( \geq 3/f \): SUS-19-008

- **\( \tilde{g} \rightarrow \tilde{t}\tilde{t} \rightarrow t\tilde{t}\chi_1^0 \)**
  - 0/f: arXiv:1710.11188
  - 1/f: arXiv:1705.04673
  - 2/f **same-sign**, \( \geq 3/f \): SUS-19-008
  - \( \Delta M = M_t, M_{\tilde{\chi}_1^0} = 400 \text{ GeV} \)

- **\( \tilde{g} \rightarrow \tilde{t}\tilde{c}_1 \rightarrow t\tilde{c}_1\chi_1^0 \)**
  - 0/f: arXiv:1710.11188
  - \( \Delta M = 20 \text{ GeV} \)

- **\( \tilde{g} \rightarrow t\tilde{b}_1 \rightarrow t\tilde{b}_1\chi_1^0 \)**
  - 0/f: arXiv:1704.07781
  - \( \Delta M_{\tilde{b}_1} = 5 \text{ GeV}, M_{\tilde{\chi}_1^0} = 200 \text{ GeV} \)

- **\( \tilde{g} \rightarrow (t\tilde{t}_1/b\tilde{b}_1/\tilde{b}\tilde{b}_1) \rightarrow t\tilde{b}_1\chi_1^0 \)**
  - 0/f: arXiv:1704.07781; 1710.11188
  - \( \Delta M_{\tilde{b}_1} = 5 \text{ GeV} \)
  - \( \text{BF}(t\tilde{b}\tilde{b}tb\tilde{t}) = 1.2 \)

- **\( \tilde{g} \rightarrow bb\chi_1^0 \)**

- **\( \tilde{g} \rightarrow q\chi_1^0 \)**
  - 0/f: SUS-19-006
  - \( \text{BF}(\tilde{\chi}_1^0:\chi_2^0) = 2:1, x = 0.5 \)

- **\( \tilde{g} \rightarrow q\tilde{\chi}_1^\pm \rightarrow qW_1^0 \)**
  - 0/f: SUS-19-006
  - \( \text{BF}(\tilde{\chi}_1^\pm:\chi_2^0) = 2:1, x = 0.5 \)

- **\( \tilde{g} \rightarrow q\chi_1^0 \rightarrow qH_1^0 \)**
  - \( x = 0.5 \)

- **\( \tilde{g} \rightarrow q\chi_2^0 \rightarrow qH/Z\chi_1^0 \)**
  - 0/f: arXiv:1712.08501
  - \( \text{BF} = 50\% \)

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities \( \Delta M \) and \( x \) represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to \( \Delta M \), respectively, unless indicated otherwise.
Worth asking what will be the reach for gluinos at future hadron colliders (but the answer is intuitive)

Measure of "naturalness"

\[
\frac{m_Z^2}{2} = \frac{m_H^2 - \Sigma_d - (m_H^2 + \Sigma_u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2. 
\]

\[\Delta_{EW} \equiv \max|\text{each term on RHS of Eq. (1)}|/(m_Z^2/2)\]
Limits on masses of 3rd generation SUSY partners

ATLAS SUSY public results

<table>
<thead>
<tr>
<th>Observation</th>
<th>Expected limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>139.0 fb⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

- $t\bar{t}$ production at 95% CL

$\sqrt{s} = 13$ TeV, 36.1-139 fb⁻¹

July 2019

- Observed limits
- Expected limits

- 0L, $\tilde{t}\rightarrow t\tilde{\chi}_1^0$ / $\tilde{t}\rightarrow \ell_2\ell\tilde{\chi}_1^0$ [1709.04183]
- 1L, $\tilde{t}\rightarrow t\tilde{\chi}_1^0$ / $\tilde{t}\rightarrow Wb\tilde{\chi}_1^0$ [1711.11520]
- 2L, $\tilde{t}\rightarrow t\tilde{\chi}_1^0$ / $\tilde{t}\rightarrow Wb\tilde{\chi}_1^0$ [1708.03247]
- monojet, $\tilde{t}\rightarrow \ell\tilde{\chi}_1^0$ [1711.03001]
- $t\bar{t}$, $\tilde{t}\rightarrow \tilde{\chi}_1^0$ [1903.07570]
- cL, $\tilde{t}\rightarrow t\tilde{\chi}_1^0$ [1805.01649]
- monojet, $\tilde{t}\rightarrow t\tilde{\chi}_1^0$ [1711.03001]

Run 1, $\sqrt{s} = 8$ TeV, 20 fb⁻¹ [1506.08616]
### Limits on masses of 3rd generation SUSY partners

#### ATLAS SUSY Searches - 95% CL Lower Limits

**July 2019**

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$f_{	ext{L}}$ (fb$^{-1}$)</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{b}_1 \rightarrow b \tilde{b}_2$</td>
<td>0 e, $\mu$ mono-jet</td>
<td>0.361</td>
<td>0.943</td>
</tr>
<tr>
<td></td>
<td>0 e, $\mu$ 1-jet, 2-b</td>
<td>0.361</td>
<td>0.582</td>
</tr>
<tr>
<td>$\tilde{b}_2 \rightarrow b \tilde{b}_1$</td>
<td>0 e, $\mu$ mono-jet</td>
<td>0.361</td>
<td>0.23-0.8</td>
</tr>
<tr>
<td></td>
<td>0 e, $\mu$ 1-jet, 2-b</td>
<td>0.361</td>
<td>0.04-0.599</td>
</tr>
<tr>
<td>$\tilde{L}_{1R,2R} \rightarrow l \tilde{f}_1$</td>
<td>0 e, $\mu$ mono-jet</td>
<td>0.361</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>0 e, $\mu$ 1-jet, 2-b</td>
<td>0.361</td>
<td>0.032-0.898</td>
</tr>
<tr>
<td>$\tilde{L}_{1R,2R} \rightarrow l \tilde{f}_1$</td>
<td>0 e, $\mu$ mono-jet</td>
<td>0.361</td>
<td>0.32-0.898</td>
</tr>
<tr>
<td></td>
<td>0 e, $\mu$ 1-jet, 2-b</td>
<td>0.361</td>
<td>0.032-0.898</td>
</tr>
<tr>
<td>$\tilde{t}_{1R,2R} \rightarrow t \tilde{f}_1$</td>
<td>0 e, $\mu$ mono-jet</td>
<td>0.361</td>
<td>0.32-0.898</td>
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<td></td>
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<td>0.361</td>
<td>0.032-0.898</td>
</tr>
</tbody>
</table>

**References**

- 1712.00332
- 1711.03501
- 1712.00332
- 1712.00332
- 1706.03731
- 1805.11581
- 1708.02974
- ATLAS-CONF-2019-015
- ATLAS-CONF-2018-041
- ATLAS-CONF-2019-015

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**ATLAS Preliminary**

$v_{\text{t}} = 13$ TeV

**Direct SUSY searches**

- **Direct $\tilde{b}_1 \tilde{b}_2$ production, long-lived $\tilde{b}_2$**
  - Disapp. trk 1 jet, $E_{\text{T}}^{\text{miss}}$ 36.1
  - $m(\tilde{b}_2)$ < 100 GeV
  - $m(\tilde{b}_1)$ = 100 GeV

- **Stable $\neq R$-hadron**
  - Multi-jet 36.1
  - $m(\tilde{b}_2)$ = 100 GeV

- **Metastable $\neq R$-hadron, $R \rightarrow q_{\ell} q_{\ell}^\prime$**
  - $q_{\ell} q_{\ell}^\prime = W, Z, \text{ or Higgs}^\prime$ 36.1
  - $m(\tilde{b}_2)$ = 100 GeV

- **RPV**
  - $\tilde{b}_2 \rightarrow b \tilde{\chi}_1^+ \tilde{\chi}_1^-$ 36.1
  - $m(\tilde{b}_2)$ = 100 GeV

**Inclusive Searches**

- **$\tilde{b}_1 \rightarrow b \tilde{b}_2$**
  - Multi-jet 36.1
  - $m(\tilde{b}_2)$ = 100 GeV

- **$\tilde{b}_2 \rightarrow b \tilde{b}_1$**
  - Multi-jet 36.1
  - $m(\tilde{b}_1)$ = 100 GeV

---

**SUSY Limits**

- **$m(\tilde{t}_{1R,2R})$ = 300 GeV, BR($\tilde{t}_{1R,2R}$) = 0.5
  - $m(\tilde{t}_{1R,2R})$ = 200 GeV, BR($\tilde{t}_{1R,2R}$) = 0.5

---

**Dark Matter (part 1)**

- **$\tilde{b}_1 \rightarrow b \tilde{b}_2$**
  - Multi-jet 36.1
  - $m(\tilde{b}_2)$ = 100 GeV

---

**Conclusion**

- The limits on masses of 3rd generation SUSY partners are summarized in the table above.

---

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*
Are we done with SUSY? Not yet

Electroweak SUSY particles, especially those with challenging signatures, are not yet excluded in many viable SUSY models (e.g. those explaining dark matter).

**ATLAS SUSY public results**

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV

$pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \tilde{\chi}_2^0, \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^- (\text{Higgsino})$

All limits at 95% CL

- Observed limits
- Expected limits
Final word: the importance of reinterpretablity

Given the many SUSY incarnations, very important to allow theorists to reinterpret search results in terms of different models

(see also discussion on simplified models in next section of lecture)
Take-home point #2:

SUSY: elegant solution to many SM problems, including dark matter

No signs of SUSY @ LHC yet (but not all parameter space yet excluded): worth considering SUSY models that are harder to find, or models that solve only a few problems at a time

Dark Matter, what do we know about it?

- Dark matter (DM)
  - Dark energy
  - Matter vs antimatter
  - Weakness of gravity
  - Neutrino masses
it is dark
it is dark

it has mass
it is dark

it has mass

it constitutes most of the matter in the universe

- Ordinary Matter
- Dark Matter
- Dark Energy

68 %

5 %

27 %
many physicists are talking about it
This relic density can be explained with a new particle:
- that interacts only weakly with known matter
- with mass in the range of current experiments (WIMP)
Under these assumptions...

http://abstrusegoose.com/406

Assume a spherical cow of uniform density.

Moo.

...while ignoring the effects of gravity.

?

...in a vacuum.

CANT'T, BREATHE.

bastard theoretical physicists

How do you sleep at night?
...we could discover Dark Matter in the next decade!
Unless...

(this is here just to avoid constantly singling out theorists in jokes)

Rip 'Sparky'
29-4-16

Goodnight sweet prince
Take-home point #3:

we don’t know very much about DM beyond its gravitational interactions and astrophysics abundance

any LHC search will necessarily contain some hypotheses (e.g. about interactions/model) so that DM can be observed experimentally
How do we search for DM at colliders, depending on its properties?

- Generally assume some properties for the DM particle, our assumptions:
  - interacts with SM particles → we can **produce it at colliders**
  - [a matter of preference] is a thermal relic → **WIMP**
  - dark, stable → **invisible to detectors**

**Caveat:** very simplified diagram
An example of SUSY as DM @ future colliders

- Viable thermal relic WIMP candidate in SUSY terms: lightest neutralino - pure Wino/Higgsino
- Also standalone model of "minimal DM"

![Plots by M. McCullough (more theory in his lectures/discussion)
Another SUSY example in DM context: pMSSM scan

Start from parameter scan of a SUSY model, point corresponds to set of choices. Plot on a plane including the DM relic density, use searches to constrain. Points on very top of the plot (= observed relic): LSP makes up 100% of the DM. Points below: another kind of DM needed to complement this one.
Searches for DM invisible particles at colliders

- Switch to non-SUSY searches && switch terminology from DM to invisible particle
- if we discover a new particle, we don’t know how stable it is (also in SUSY) (it could decay outside the detector)

Signature of invisible particles
(like Dark Matter):
missing transverse momentum ( $E_T^{\text{miss}}$ )

Good performance of missing transverse momentum crucial for DM searches
e.g. reject fake $E_T^{\text{miss}}$
What visible to detect the invisible?

**Standard Model Particles**

insert known particle(s) here

interact with

**Dark Matter**

insert new particle(s) here

in signatures including

insert ISR/FSR boson, or additional particles

“monojet”

“mono-everything-mania”

also: a nomenclature problem for searches

(think of e.g. QCD corrections to simple picture, other more complex diagrams...)

better name: **Missing transverse momentum + X**
Broad categories of searches for DM@colliders

Generic searches

- Good for **simple models** with **sizable cross-sections**
- Fewer **assumptions** on specific model characteristics

More specific searches

- More sensitive to **specific models**
- More reliant on **model assumptions**

→ the way we think of benchmark models **influences** searches

\[ p, \pi, \ldots \to \text{jets} \]

\[ W, Z \to \text{leptons, jets...} \]
Dark Matter mediators at the LHC

If there’s a force there’s a mediator, and the LHC can see it: simplified models became Run-2 LHC search benchmarks

Consequences for colliders:
1. Can probe the dark interaction even if DM is inaccessible
2. Can look for both invisible and visible decays of the mediator
   (cf lecture about direct searches for new particles)
Some side thoughts on EFT

“EFTs are not evil, they just (model-)build them that way”

EFTs are very versatile (and necessary, when there’s no alternative)

EFTs are viable benchmarks that motivate new signatures

The "problematic parts" of EFTs can be removed

e.g. JHEP 1505 (2015) 009

Non-relativistic EFTs are a useful tool to break down signals and understanding their compatibility of future signals with models and compare LHC/DD

e.g. Phys. Rev. D 97 (2018) no.10, 103002

Talk by S. Wild
Now: LHC Dark Matter Working Group
http://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc
extending the menu of LHC benchmarks to less simplified models
Common benchmarks for collider WIMP searches

Simple models | More complex/complete models

- **Simple DM mediation**
- **Beyond-SM mediator**
- **Vector-like mediator**
- **Scalar-like mediator** and Two Higgs Doublet Models

**Supersymmetry**

(Simplified model diagram)

Also: DM models with long-lived particles [tomorrow’s lecture]
Choice of benchmarks

"Why should we believe such simple models?"
"Do we think DM is all made of a single WIMP model?"
(not necessarily)

Key particle discoveries

- Lesson from SM: most common particles discovered first

- Simplified models can encapsulate relevant experimental characteristics representing wider classes of theories

Why bother?
Because:

https://abstrusegoose.com/406

from DM ATLAS feature
Start simple: Higgs portal models

Introduction
Problems with the SM
SUSY
Dark Matter (part 1)

**Start simple: Higgs portal models**

\[
\Delta \mathcal{L}_X = -\frac{1}{2} M_X \bar{\chi}\chi - \frac{1}{4} \frac{\lambda_{HXX}}{\Lambda} \Phi^\dagger \Phi \bar{\chi}\chi .
\]

\[
\Delta \mathcal{L}_S = -\frac{1}{2} M_S^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{4} \lambda_{HSS} \Phi^\dagger \Phi S^2 ,
\]

Lambda for fermion EFT: assumed 1 TeV

- Only add the DM particle to SM
- Test different kinds of dark matter
  - Majorana fermion/scalar
  - Vector not there for historical reasons

**How to detect invisibly decaying Higgs:**
- **directly** (MET searches)

![Diagrams of Higgs portal models](image)

- **indirectly** (deviation of SM coupling through fits, using \(\kappa\)-framework)
  - including only \(\sigma \times\) Branching Ratio (BR) measurements/ratios, no high-pT Higgs keeping SM BR fixed, only allow invisible BR to float in the fit (subtracting SM)
Higgs portal DM results with partial Run-2 data

https://arxiv.org/abs/1809.05937

LHC sensitive to a Higgs to invisible BR of $\sim 0.2$

(SM value: invisible BR $\sim 10^{-3}$, reachable by future colliders)
Map possible types of s-channel mediator exchanges between DM and SM: vector, axial-vector, scalar, pseudo-scalar mediators

- How to detect them:
  - **invisible decays** (MET searches)
  - **visible decays of mediators**
LHC production of invisible particles

Production of invisible particles is common in the SM

\[ q \rightarrow g \rightarrow Z \rightarrow \bar{q} \nu \]

Production of invisible particles can be common in the SM. Use standard candles (Z boson) to search for non-SM production. Production of invisible particles can be common in the SM.
**Generic searches for DM: “X+MET”**

ISR (jet, photon, V boson...) + MET signature

Background normalized using data

Background shapes need precise theory predictions

Results can be interpreted in a variety of models

- ATLAS
  \[ \sqrt{s} = 13 \text{ TeV}, 36.1 fb^{-1} \]
  Mono-W/Z(qq): Vector, Dirac
  \[ g_{SM} = 0.25, \quad g_{DM} = 1.0 \]

- CMS
  - monojet
  - 35.9 fb\(^{-1}\) (13 TeV)

- arXiv:1807.11471
- EPJC 2017 77:829
Complementarity of visible/invisible searches

Illustrative example

Axial Vector mediator, Dirac DM
\( (g_q = 0.25, g_{DM} = 1) \)

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Complementarity of visible/invisible searches

Illustrative example

Axial Vector mediator, Dirac DM

\( (g_q = 0.25, g_{DM} = 1) \)

Searches for DM particles

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Complementarity of visible/invisible searches

Illustrative example

Axial Vector mediator, Dirac DM
\( (g_q = 0.25, g_{DM} = 1) \)

Searches for DM particles
Dijet searches for DM mediators

Collider strength for these models: searches for visible mediator decays
Complementarity of visible/invisible searches

Illustrative example

Axial Vector mediator, Dirac DM
($g_q = 0.25, g_{DM} = 1$)

about real-time selection and analysis for LHC searches and links to data taking challenges in astrophysics

Searches for DM particles
Dijet searches for DM mediators
Low-mass dijet searches for DM mediators

Collider strength for these models: searches for visible mediator decays

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Take-home point #4:

Generic searches for DM particles targeting simple (simplified) models show the unique LHC ability to look into the SM-DM interactions, but they are only a starting point.
Recap of Lecture 2 & wordclouds & another poll

Go to www.menti.com and use the code 21 90 19
Take-home point #1:

The SM has problems that are both aesthetic (observations not matching a "beautiful" theory) and empirical (observations not explained).

These motivate the search for BSM physics at the scales reachable by the LHC.
Take-home point #2:

SUSY: elegant solution to many SM problems, including dark matter

No signs of SUSY @ LHC yet (but not all parameter space yet excluded): worth considering SUSY models that are harder to find, or models that solve only a few problems at a time

Take-home point #3:

we don’t know very much about DM beyond its gravitational interactions and astrophysics abundance

any LHC search will necessarily contain some hypotheses (e.g. about interactions/model) so that DM can be observed experimentally
Take-home point #4:

Generic searches for DM particles targeting simple (simplified) models show the unique LHC ability to look into the SM-DM interactions, but they are only a starting point.