Interpretation of New Phenomena Results

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Rencontres de Moriond
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Missing energy signals are a big part of the new physics menu at colliders, largely because of the potential connection to dark matter.

We still don’t know what dark matter is, but we know it is at most weakly interacting.

We know it should look like “nothing” to a collider detector.

We have reason to think it should have reasonably large couplings to at least some of the Standard Model, in order to explain its abundance in the Universe.

“Cold Dark Matter: An Exploded View” by Cornelia Parker
A typical WIMP theory has a whole “layer” of new particles. E.g. SUSY, UED, Little Higgs, ...

The WIMP is the lightest of these new states, and must be neutral and ~stable to be viable dark matter.

Most of the heavier “WIMP siblings” usually are coloured and/or charged, and thus interact much more strongly with the Standard Model particles than the WIMP does.

They decay into the WIMP itself plus Standard Model particles.
LHC WIMP Production

LHC can produce WIMP siblings, which decay into WIMPs and other SM particles.

“KK Sgluquarkino Pair Production Followed by Decay into WIMPs”

LHC can directly produce WIMP pairs.

LHC can’t produce WIMPs.
Relic Density

If dark matter is a thermal relic, annihilation into the SM control its abundance in the Universe.

The observed relic abundance is suggestive of a cross section:

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$$

Without a detailed model, it isn’t clear how to translate it into an LHC or direct detection rate.

The dark matter could also be produced non-thermally, or the history of the Universe could be non-standard.

Feng, ARAA (2010)

53,40 Euro for 20 servings
Available in Blue Raspberry, Fruit Punch, and Grape flavors....
WIMP Sibling Production
Squarks and Gluinos

Searches for missing energy plus various numbers of jets put bounds on squark and/or gluino ("coloured sibling") production.

- Gluinos decay to two jets + WIMP
- Squarks into one jet + WIMP

For equal masses, searches require them to be larger than about 1 TeV.

Limits are still several hundred GeV when one or the other is very heavy.

These limits assume the WIMP mass is less than 200 GeV.
As Guido mentioned yesterday, naturalness requires SUSY to have light(ish) stops.

The left-handed stop comes along with a sbottom with a roughly similar mass.

The squark masses are also rather tightly coupled to the gluino mass through the renormalization group.

Searches for single flavors of squarks are becoming very interesting. The next year is likely to be very enlightening!
One can step away from specific MSSM assumptions by working with simplified models. These are phenomenological sketches of theories with some basic particles and decays built into them. The experimental collaborations have been willing to explore casting their SUSY searches into this framework, allowing for a much more flexible interpretation of limits.
Maybe SUSY dark matter is a red herring. We can get all of the naturalness properties we like from SUSY without asking it to explain dark matter as well.

Turning on R-parity violating interactions quickly runs into strong constraints. There should be some organizing principle such as minimal flavour violation.

The baryon-number-violating interaction can lead coloured superpartners to decay entirely into jets.

Csaki, Grossman, Heidenreich, 1111.1239

CMS Search for gluinos decaying into qqqq.
Producing WIMPs directly requires there to be some initial radiation from the incoming quarks or gluons: a “monojet” event.

We’re not very sensitive to the details of how the WIMP couples to quarks and gluons: we can use effective field theories to parameterize all leading contributions.

We can recycle existing ADD graviton searches (though they are not perfectly optimized).

This kind of process works best for very light WIMPs, because they can be produced easily with a lot of kinetic energy, leading to large missing energy.
As an example, we can write down operators of interest for a Majorana WIMP.

There are 10 leading operators consistent with Lorentz and SU(3) × U(1)_EM gauge invariance coupling the WIMP to quarks and gluons.

Each operator has a (separate) coefficient $M^*$ which parametrizes its strength.

$$\chi \quad q \quad \tilde{q}$$

$$\chi \quad q \quad \frac{g^2}{M^2_q} \leftrightarrow \frac{1}{M^2_*}$$

### Table I: The list of the example EFT operators

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>$G_\chi$</th>
<th>$\Gamma^\chi$</th>
<th>$\Gamma^q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>qq</td>
<td>$m_q/2M^*_q$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>M2</td>
<td>qq</td>
<td>$im_q/2M^*_q$</td>
<td>$\gamma_5$</td>
<td>1</td>
</tr>
<tr>
<td>M3</td>
<td>qq</td>
<td>$im_q/2M^*_q$</td>
<td>1</td>
<td>$\gamma_5$</td>
</tr>
<tr>
<td>M4</td>
<td>qq</td>
<td>$m_q/2M^*_q$</td>
<td>$\gamma_5$</td>
<td>$\gamma_5$</td>
</tr>
<tr>
<td>M5</td>
<td>qq</td>
<td>$1/2M^*_q$</td>
<td>$\gamma_5\gamma_\mu$</td>
<td>$\gamma^\mu$</td>
</tr>
<tr>
<td>M6</td>
<td>qq</td>
<td>$1/2M^*_q$</td>
<td>$\gamma_5\gamma_\mu$</td>
<td>$\gamma_5\gamma^\mu$</td>
</tr>
<tr>
<td>M7</td>
<td>GG</td>
<td>$\alpha_s/8M^*_q$</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>M8</td>
<td>GG</td>
<td>$i\alpha_s/8M^*_q$</td>
<td>$\gamma_5$</td>
<td>-</td>
</tr>
<tr>
<td>M9</td>
<td>G$\tilde{G}$</td>
<td>$\alpha_s/8M^*_q$</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>M10</td>
<td>G$\tilde{G}$</td>
<td>$i\alpha_s/8M^*_q$</td>
<td>$\gamma_5$</td>
<td>-</td>
</tr>
</tbody>
</table>
In terms of the WIMP mass and its interaction with quarks and/or gluons, we can predict the rate of monojet production.

There are SM backgrounds from producing a Z which decays into neutrinos plus a jet of hadrons as well as fakes.

The EFT also allows a more model-independent mapping from collider signals into direct and indirect searches.

The LHC collaborations are now working on doing these analyses themselves...
Colliders - Direct Detection

- Tevatron quarks
- CoGeNT limits
- CRESST limits
- Tevatron $\chi\chi G^2$ exclusion
- LHC $\chi\chi q 5\sigma$ reach
- CDMS limits
- Xenon 10 limits
- SCDMS reach
- Xenon 100 reach
- LHC $\chi\chi G^2 5\sigma$ reach

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286
Similar Results: Bai, Fox, Harnik 1005.3797
From WIMPs to SIMPs...


g_{N} (cm^{2})

10^{-23}

10^{-25}

10^{-27}

10^{-29}

10^{-31}

10^{-33}

10^{-35}

10^{-37}

10^{-39}

10^{-41}

10^{-43}

m_{\chi} (GeV)

1

10

100

Cosmic ray exclusion

Earth heating exclusion

\bar{\chi}\chi q exclusion

\bar{\chi}_{\mu}\gamma^{5}\bar{\chi}_{\mu}\gamma^{5}q exclusion

\bar{\chi}G^{2} exclusion

Tevatron

Direct detection exclusion

Earth screens conventional direct detection

Limit to Effective Theory

Mack, Beacom, Bertone, 0705.4298

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286


cartoon of

For up- and down-quark couplings adjusted such that \( f_n \sim -0.7 f_p \), constraints from Xenon are much weaker than the CoGeNT signal.

Naive MFV implementations are ruled out by colliders, but specific non-MFV constructions survive.

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Feng, Kumar, Marfatia, Sanford 1102.4331 (see also: Chang, Pierce, Weiner 1004.0697)
SD Bounds from ATLAS

Equal u- and d- couplings

FIG. 7: Spin dependent nucleon coupling cross section assuming equal down and up type couplings. The red and blue lines are the constraints from the Tevatron search and 7 TeV LHC search. The green line is the 8 TeV LHC discovery reach. The dashed black line is the XENON1y constraint, and the solid black line is the SIMPLE constraint on the proton cross section. For dark matter RSM interactions or have more complicated flavor structure in its couplings, in particular, theories which only couple the dark matter to up and down quarks and not members of the other generations are much more difficult to probe at colliders if they interact through mass-suppressed operators.

Acknowledgements

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Gamma-Ray Lines

The effective theory language can also be effectively mapped into indirect searches for dark matter.

For example, interactions with quarks can be closed into loops and turned into annihilation into gamma ray lines.

The Fermi limits are actually the best ones for some operators (such as for spin-dependent interactions).

One could also study continuum annihilation signals in the EFT framework.

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**Figure 1:** Representative Feynman diagram for the loop level annihilation of two DM particles to a photon and a second vector boson, either another photon or a $Z$ boson, through an operator coupling the DM to SM quarks (represented as the shaded circle).

III. GAMMA RAY LINE SEARCH CONSTRAINTS

We compute the rate for the processes $\chi\chi\rightarrow\gamma\gamma$ and $\chi\chi\rightarrow\gamma Z$ for each of the operators considered above. Generally, stronger bounds arise from the $\chi\chi\rightarrow\gamma\gamma$ process because it produces two photons per annihilation, compensating for the $Z$ coupling to quarks being typically a little stronger than the photon. Consequently, we consider the $Z$ final state only in the case where annihilation into $\gamma\gamma$ vanishes. For the cases with a Dirac fermion or complex scalar, we assume that the dark matter in our galactic halo is composed of equal numbers of particles and anti-particles. It should be borne in mind that one could evade the constraints from any annihilation process if the interactions preserve the $U$ isospin symmetry and the galactic halo is made entirely of WIMPs or antioWIMPs.

For the operators $D_{sw}$ and $Ds_{x}$ mediating a direct interaction between the WIMPs and the photon, this process occurs at tree level. Generally, the quark operators mediate annihilation into $\gamma\gamma$ or $\gamma Z$ at the one loop level as shown in Figure 1. For the operators of the form $\bar{\chi} \mu \chi$ in a final state containing two photons is forbidden by the Landau-Yang theorem. For these operators, we rely on $\chi\chi\rightarrow\gamma\gamma$ to determine the implications of searches for gamma ray lines. For operators coupling the WIMPs directly to gluons and for the tensor operators $D_{9}$ and $Ds_{r}$, the leading contribution to $\chi\chi\rightarrow\gamma\gamma$ and $\chi\chi\rightarrow\gamma Z$ final states occurs at two loops, and as a result the rate is expected to be small enough that these operators.

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Razoring Monojets

A recent study applies the CMS razor analysis to the dark matter production signal.

Though it requires more than one jet, these processes often contain extra radiation, so the loss of acceptance is modest.

They find modest improvements on the bounds extracted from the monojet analysis alone!

Fox, Harnik, Primulando, Yu 1203.1662
LHC Searches for new phenomena are going strong!

Already big statements are being made about missing energy, dark matter, and supersymmetric theories with R-parity conservation.

The next year will get into very interesting territory, with sensitivity to scalar stops and gluinos which should cover the most well-motivated regions of SUSY parameter space.

(And to say nothing about the Higgs mass and the MSSM...)

More direct maverick production of dark matter is less effective than traditional SUSY searches if we can produce coloured mediator particles directly. If they are too heavy, maverick production will be how we fall back to quantify limits on dark matter interactions, and make contact between accelerator data and (in)direct searches.
How Effective a Theory?

How good is the EFT approximation?

It depends on the momentum transfer of the process.

Direct Detection: $Q^2 \sim (50 \text{ MeV})^2$.

EFT should work well unless you have ultralight mediators.

Annihilation: $Q^2 \sim M^2$.

Fine in SUSY-like theories, problematic for quirky WIMPs or maybe coannihilators.

Colliders: $Q^2 \sim p_T^2$

Bounds are generically too conservative for colored mediators.

Too stringent for light neutral mediators.
To calibrate our simulations, we reproduce the CDF background using MadEvent with PYTHIA and PGS [CDF detector Model].

Including NLO k-factors, we succeeded at the % level.

The dominant physics backgrounds are:

- Z + jets (with $Z \rightarrow \nu\nu$).
- $W + \text{jets} (W \rightarrow e\nu$ with the e lost).
- The “QCD” background from jet mismeasurements creating fake missing energy is subdominant, as determined by CDF itself.

(And we don’t try to simulate it).
CMSSM Limits

A lot of searches are done in the framework of mSUGRA (closely related to cMSSM), which assumes a set of 4+1 parameters determine the super-particle spectrum:

- $M_0$: Universal scalar mass
- $M_{1/2}$: Universal gaugino mass
- $A_0$: Universal A-term
- $\tan \beta$: Ratio of Higgs VEVs
- $\text{Sgn}(\mu)$: Phase of the supersymmetric Higgs mass parameter.

CMS PAS SUS-11-004
Melzer-Pellmann, SUSY 2011

Impact of CMS EPS Results on SUSY
Including CMS @EPS

68% CL
95% CL
$P(\chi^2) > 5\%$

CMS searches significantly constrain allowed SUSY parameter space. The air is getting very thin for constrained SUSY models but it needs more data to be fully conclusive. More in the backup (incl. ATLAS)

We will know more after summer, but have to start preparing…

De Roeck, DMUH11
Gamma ray line bounds also have something interesting to say about the Magnetic inelastic DM models.

In this case, WIMPs can annihilate into a two photons at tree level through their magnetic moment interactions.

The Fermi line constraints are particularly relevant for lower mass WIMPs.
If dark matter is a thermal relic, annihilation into the SM control its abundance in the Universe.

In equilibrium with the SM plasma.

As the temperature falls, the number of WIMPs does too.

We track the equilibrium density until freeze-out:

\[ n_{eq} \langle \sigma v \rangle \sim H \]

\[ (mT)^{3/2} e^{-m/T} \sim \frac{g^4}{m^2} \sim \frac{T^2}{M_{Pl}} \]

\[ \frac{m}{T} \sim \log \left[ \frac{M_{Pl}}{m} \right] \]

\[ m \approx 100 \text{ GeV} : \frac{m}{T} \approx 40 \]

...leading to the final relic abundance.
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\]

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\frac{m}{T} \sim \log \left[ \frac{M_{Pl}}{m} \right] \quad m \sim 100 \text{ GeV} : \frac{m}{T} \sim 40
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