Lecture Note #8: Dark Matter at Colliders

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Dark matter (DM) can be created in high-energy particle colliders. While DM particles are not directly observable in collider detectors, they can still produce indirect signals of missing energy. Searches for WIMP-like DM at the LHC have placed limits that are comparable to those obtained from direct detection searches. In this note we describe some ways to search for DM at colliders.

1 High Energy Hadron Collisions

The most energetic collisions of elementary particles in the lab have been obtained at the Tevatron and the LHC. The Tevatron finished its high-energy running in 2011, and collected about 12 fb^{-1} of data from $p\bar{p}$ collisions at a centre of mass energy of $\sqrt{s} = 1.96$ TeV.[1] The LHC has performed two runs with pp collisions, the first generating about 5fb^{-1} of data at $\sqrt{s} = 7$ TeV, and the second generating about 25 fb^{-1} of data at $\sqrt{s}$. After some upgrades, the LHC is set to resume running at $\sqrt{s} = 14$ TeV and is expected to collect hundreds of fb^{-1} of data. Both machines collide particles in the hadronic (pp or $p\bar{p}$) centre of mass frame, and both have very sensitive detectors placed around the collision points to record the collision products. At the Tevatron the two main detectors ("experiments") were CDF and DZero, while at the LHC the two main detectors are ATLAS and CMS.

In a small fraction of high-energy pp or $p\bar{p}$ collisions, a hard collision among the constituent quarks or gluons will occur. The parents p or $\bar{p}$ are called *hadrons*, and the component quarks and gluons are collectively called *partons*. The partons within a hadron are all assumed to have momenta parallel to the hadronic momentum,

$$p_i^\mu = x_i P^\mu \ , \qquad 0 < x_i < 1 \ , \tag{1}$$

where x_i is called the *momentum fraction*. The specific values of the x_i for colliding partons are typically not known from the start, but it is possible to determine a probability distribution for them from data. These are called *parton distribution functions* (PDF), $f_i^{\tilde{n}}(x)$, corresponding to the probability for the i-th parton type in the hadron $\tilde{n}$ to have momentum fraction x.

The cross section for any high-energy process in a pp collision can be written as

$$\sigma_{pp}(P,-P) = \sum_{i,j}\int dx_1 dx_2\ f_i^p(x_1) f_j^p(x_2)\ \hat{\sigma}_{ij}(x_1 P, -x_2 P) \ , \tag{2}$$

where $\hat{\sigma}(p_1,p_2)$ is the cross section for any parton collision of i with j that contributes to the process. This *partonic cross section* can usually be calculated perturbatively.

[1] The amount of data obtained in colliders is quoted in units of inverse barns, where the barn = b = 10^{-24}cm^2 is a standard unit for cross sections. With 1 fb^{-1} of data, we would expect to have an average of one event from a process whose cross section is 1 fb.

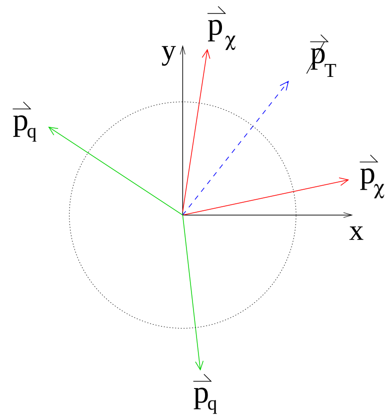

Figure 1: Missing transverse momentum.

Note that in general, the partonic collision does not occur in the CM frame of the colliding partons, even if though the lab frame corresponds to the CM frame of the hadronic parents. For this reason, it is usually not possible to apply momentum conservation along the beam axis (usually taken to be the z direction). Even so, we can still apply momentum conservation in the plane transverse to the beam axis.

A key signature of DM production at colliders is missing energy and momentum. In any given collision, we can apply momentum conservation in the transverse plane. If some DM particles are also created in the collision, they will carry off some of the energy and momentum with them, even though they will not be recorded by the detector. This implies that there will frequently be an imbalance in the momenta of the visible SM particles emitted in collisions that produce DM. To quantify this, a quantity called *missing transverse momentum* $\not{p}_T$ is defined,

$$\not{p}_T = -\sum_{i\in\{vis\}} \vec{p}_T^{\,i} \ , \tag{3}$$

where the sum runs over the transverse components of the momenta of all the visible particles emitted in the collision. By momentum conservation, $\not{p}_T$ is equal to the vector sum of the momenta of the two LSPs created in the event. This is illustrated in Fig. 1. The magnitude of the missing transverse momentum is usually called the missing transverse energy $\not{E}_T$,

$$\not{E}_T = |\not{p}_T| \ . \tag{4}$$

A related quantity is the *effective mass* of an event, defined by

$$m_{eff} = \not{E}_T + \sum_{j\in\{jets\}} |\vec{p}_T^{\,j}| \ , \tag{5}$$

where the sum runs over all the high-energy QCD jets in the event. In addition to DM, missing energy and momentum can be created by neutrinos and detector mismeasurements.

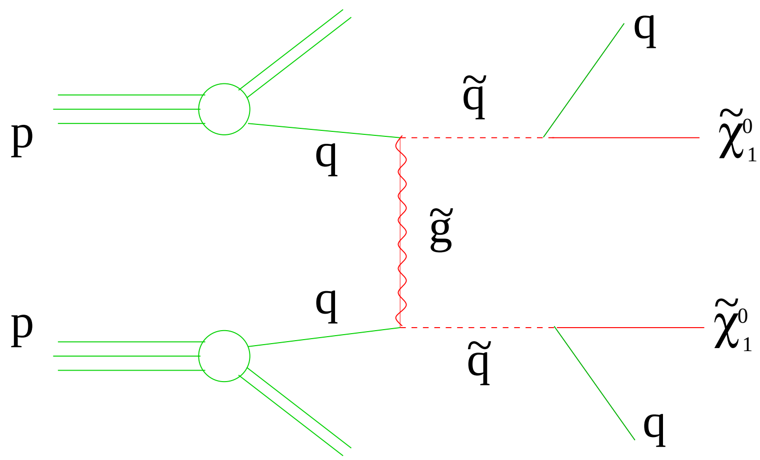

Figure 2: Production of a pair of squarks and their supersymmetric cascade.

2 DM in Supersymmetric Cascade Decays

An extremely popular candidate for WIMP DM is the lighest superpartner (LSP) in supersymmetry. In the minimal supersymmetric extension of the SM, the LSP should be the lightest neutralino χ_1^0 if it is to be the DM. Even though it is the lightest of the superpartners, the LSP is usually not produced as efficiently in hadron collisions as the heavier coloured squark ($\tilde{q}$) and gluino ($\tilde{g}$) superpartners. When they decay, they will both produce at least one LSP. As a result, squarks and gluinos are expected to be the most important source of DM creation at colliders in many supersymmetric theories.

Once created, each superpartner will decay in a *cascade* down to the lightest superpartner. At each step in the cascade, a superpartner decays to a SM particle and a lighter superpartner. The cascade terminates when it reaches the LSP, which can decay no further. Some examples of cascades are

$$\tilde{q} \to q\tilde{\chi}_1^0, \qquad \tilde{g} \to g\tilde{\chi}_1^0, \qquad \tilde{g} \to q\tilde{q}^* \to q\bar{q}\tilde{\chi}_1^0, \qquad .$$

In the left panel of Fig. 2, we show the production of a pair of squarks from a proton-proton collision and their subsequent cascades to a quark and a neutralino. The SM particles created by supersymmetric cascades are can be observed in the ATLAS and CMS detectors. In contrast, the $\tilde{\chi}_1^0$ LSP leaves the detector without leaving a direct trace.

Relative to SM processes, supersymmetric cascades initiated by squarks or gluinos tend to produce much more missing energy and larger values of m_{eff}. We illustrate this in Fig. 3, where we show the m_{eff} distributions predicted by the SM, two supersymmetric models, as well as the distribution measured experimentally by the ATLAS collaboration at the LHC [1]. By searching for events with energetic QCD jets (from the quarks and gluons emitted in the cascade decays) together with missing energy, the LHC has been able to test supersymmetric theories up to squark and gluino masses of about 1.5 TeV. So far no excesses have been seen (*e.g.* Fig. 3). Even so, a χ_1^0 LSP DM particle can still exist provided the squarks and the gluino are somewhat heavy.

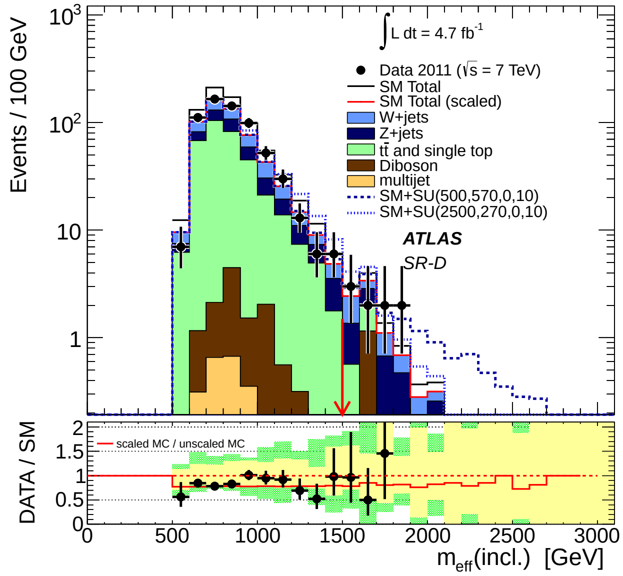

Figure 3: Distributions of m_{eff} in a jets plus $\not{E}_T$ search channel at the LHC predicted by the SM (filled histograms) and two supersymmetric models (dashed blue lines). The data obtained by the ATLAS collabaration is also shown. Figure from Ref. [1].

3 DM and Monojets

A more direct way to look for DM at colliders is through the immediate production of DM particles, $SM + SM \to \chi + \chi$. The problem with this is that the final state contains no visible particles. In hadronic collisions, however, an additional QCD jet will frequently be radiated off one of the quark legs, $SM + SM \to \chi + \chi + j$. Even though this process is higher-order in the strong coupling, the reasonably large value of this coupling $\alpha_s = g_s^2/4\pi \simeq 0.1$ means that the probability to have such an additional jet is reasonably large. The resulting collider signature is a single hard *monojet* recoiling against the invisible DM particles. This produces missing energy, and can be distinguished from SM backgrounds [2, 3].

Direct collider production of DM can be related in an interesting way to direct and indirect searches for DM, as illustrated in Fig. 4. As long as the DM mass is not too high, we can describe the effective interaction of (fermionic) DM with quarks by higher-dimensional operators of the form

$$-\mathscr{L} \supset \frac{1}{\Lambda^2}\,(\bar{q}\Gamma_1 q)\,(\bar{\chi}\Gamma_2\chi)\;, \tag{6}$$

where Γ_i refer to Dirac structures (such as SS, VV, or AA), and Λ has units of mass. We saw in `notes-5` that these interactions can mediate DM scattering with atomic nuclei. These interactions are also relevant for DM production at colliders, provided $\hat{s} \ll \Lambda$ in the underlying partonic collisions. Thus, constraints on DM production at colliders from monojets can be related to direct detection searches in many cases.

Given the interaction of Eq. (6), we can estimate the relative cross sections for direct

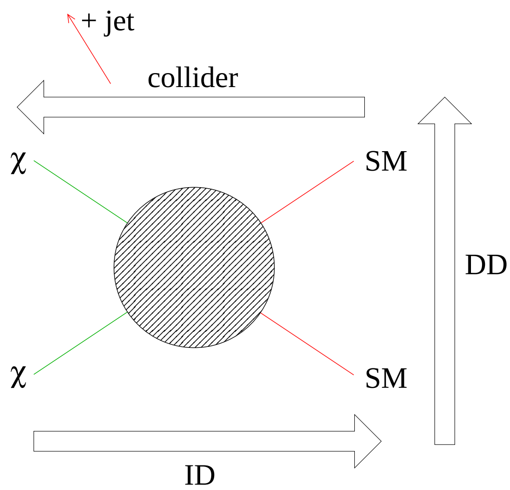

Figure 4: Many ways to detect DM.

detection and monojet searches. For DD, we have

$$\sigma_{DD} \sim \frac{\mu_p^2}{\Lambda^4} \,, \tag{7}$$

while for monojets we get

$$\hat{\sigma})1j \sim \begin{cases} \alpha_s p_T^2/\Lambda^4 & ; \quad p_T \lesssim \Lambda \\ \alpha_s/p_T^2 & ; \quad p_T \gtrsim \Lambda \end{cases} \,, \tag{8}$$

where p_T is the partonic collision energy and the factor of α_s accounts for the cost of radiating an extra hard jet. For $p_T \lesssim \Lambda$, we see that

$$\sigma_{1j} \sim \frac{\alpha_s p_T^2}{\mu_p^2} \,. \tag{9}$$

This can be a very significant enhancement for $p_T \gg \mu_p$.

A detailed analysis of monojet and related searches using LHC data has been made in Refs. [4, 5]. The limits obtained from collider searches (with a few built-in assumptions) tend to be stronger than from direct searches for spin-dependent (SD) scattering,and competitive with direct searches for spin-independent (SI) scattering. We show the limits obtained in Ref. [5] in Fig. 5.

References

[1] G. Aad *et al.* [ATLAS Collaboration], "Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum using $4.7 fb^{-1}$ of $\sqrt{s} =$ 7 TeV proton-proton collision data," Phys. Rev. D **87**, 012008 (2013) [arXiv:1208.0949 [hep-ex]].

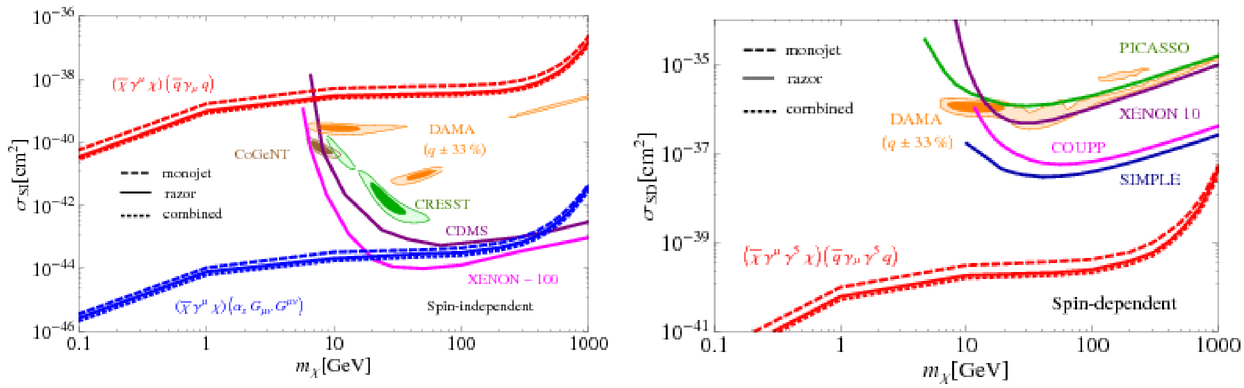

Figure 5: Limits on DM interactions with quarks and gluons from LHC data relative to direct detection in SI (left) and SD (right) channels. Plots from Ref. [5].

[2] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait, H. -B. Yu and , "Constraints on Light Majorana dark Matter from Colliders," Phys. Lett. B **695**, 185 (2011) [arXiv:1005.1286 [hep-ph]].

[3] Y. Bai, P. J. Fox, R. Harnik and , "The Tevatron at the Frontier of Dark Matter Direct Detection," JHEP **1012**, 048 (2010) [arXiv:1005.3797 [hep-ph]].

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[5] P. J. Fox, R. Harnik, R. Primulando, C. -T. Yu and , "Taking a Razor to Dark Matter Parameter Space at the LHC," Phys. Rev. D **86**, 015010 (2012) [arXiv:1203.1662 [hep-ph]].