Prospects for collider searches for dark matter with heavy quarks

Giacomo Artoni,[1,*] Tongyan Lin,[2,†] Björn Penning,[3,4,‡] Gabriella Sciolla,[1,§] and Alessio Venturini[1,¶]

[1] *Martin A. Fisher School of Physics, Brandeis University, Waltham, MA 02453*
[2] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637*
[3] *Fermilab, P.O. Box 500, Batavia, IL 60510, USA*
[4] *Enrico Fermi Institute, University of Chicago, Chicago, IL 60637*

(Dated: August 5, 2013)

We present projections for future collider searches for dark matter produced in association with bottom or top quarks. Such production channels give rise to final states with missing transverse energy and one or more b-jets. Limits are given assuming an effective scalar operator coupling dark matter to quarks, where the dedicated analysis discussed here improves significantly over a generic monojet analysis. We give updated results for an anticipated high-luminosity LHC run at 14 TeV and for a 33 TeV hadron collider.

I. INTRODUCTION

The properties of dark matter (DM), and its connection to known particles and physical laws, remain unknown. The WIMP hypothesis has guided the quest to understand this fundamental problem; however, rapid experimental progress continues to exclude historically popular models of dark matter. In light of this uncertainty, more model-independent searches for dark matter have gained significant traction. It is important to be able to combine collider searches, direct detection, and indirect detection in a complementary way, if we are to determine that any signal seen in an experiment is indeed from dark matter [1].

In particular, the effective operator approach takes a simplifying approach that allows one to relate the different experimental signatures in a model-independent way. Here it is assumed that new particles mediate interactions between dark matter and standard model particles, but that these particles are too heavy to be produced in experiments. Then the interaction can be described by a contact operator [2], and it possible to classify the operators in a systematic way. For each operator the relic abundance, direct detection signal, and collider predictions depend on a single parameter, M_*, and thus can be related simply.

The collider search for dark matter is a critical element of this approach, and can provide the strongest constraints in cases where the dark matter mass is below $\lesssim 10$ GeV or when the operator has suppressed direct detection signals. The generic signature of dark matter pair production in colliders is missing transverse energy from the dark matter and energetic visible particles that are used to tag the event. For contact operators with couplings between dark matter and quarks, the final state is a so-called "monojet" final state consisting of one or two hard jets plus large missing transverse energy from the dark matter. Experimental limits using monojet final states have been published using 7 and 8 TeV LHC data [3–6] for a variety of operators. In addition, similar final states with the form $\chi\bar{\chi} + X$, where χ is the dark matter particle and X can be a photon, jet, or other particle, have been studied in the context of effective operators (e.g. [7–10]).

In this note we focus on an effective scalar interaction between dark matter and quarks described by the operator

$$\mathcal{O} = \sum_q \frac{m_q}{M_*^3} \bar{q} q \bar{\chi} \chi, \tag{1}$$

where M_* parameterizes the strength of the interactions. The most generic effective scalar interaction could include more complicated couplings between different quark flavors, but this would lead to flavor violating effects. An ansatz which automatically suppresses these effects is minimal flavor violation (MFV) [11], which then fixes the m_q scaling of the operator above. Because of the form of the interaction, couplings to bottom and top quarks are significantly enhanced over those to light quarks. This means that traditional monojet searches provide relatively weak constraints on this scalar operator.

Despite the kinematic and PDF suppression for producing third generation quarks, it was shown in [12] that for the scalar operator, searches for $\chi\bar{\chi} + b$ and $\chi\bar{\chi} + t\bar{t}$ final states improve significantly over traditional monojet searches. The production mechanism of dark matter plus heavy quark modes at a hadron collider is shown in Fig. 1. In terms of limits on the direct detection cross section, the improvement is up to three orders of magnitude. Analyses of 8 TeV LHC data with these final states is already underway. In this report we present expected limits for a 14 TeV LHC run with 300 fb^{-1} and 3 ab^{-1} of data, and a 33 TeV pp collider with 3 ab^{-1} of data.

* Email: giacomo.artoni@cern.ch
† Email: tongyan@kicp.uchicago.edu
‡ Email: penning@cern.ch
§ Email: sciolla@cern.ch
¶ Email: alessio.venturini@cern.ch

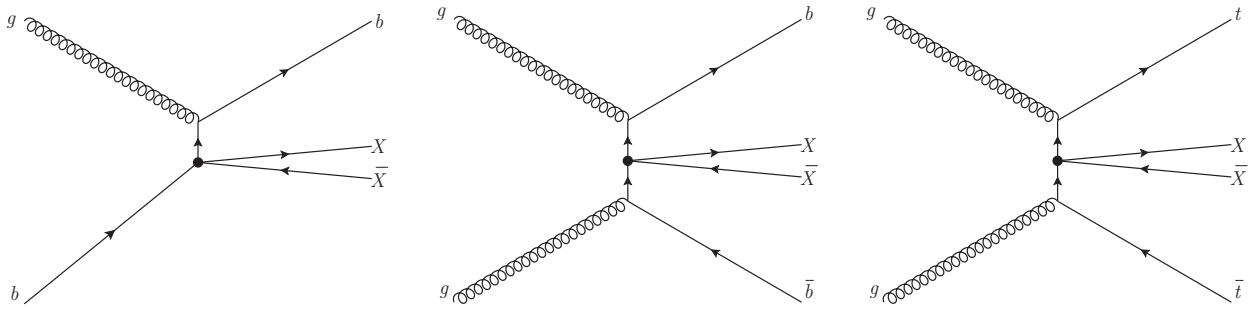

FIG. 1. The dominant diagrams for dark matter plus heavy quark production.

II. SIMULATION

We simulate signal events using MadGraph 5 [13] and PYTHIA [14] to model parton events and showering with MLM matching. The signal (background) events are produced using a MadGraph implementation provided from the work documented in Ref. [15] ([16]). Cross sections for dark matter in association with b-quarks are normalized using MCFM Dark [17], which calculates NLO corrections for dark matter production processes.

Detector effects are simulated using the fast multipurpose detector response simulation package DELPHES 3 [18] in the Snowmass Detector configuration [19]. The simulation includes a tracking system, embedded into a magnetic field, calorimeters and a muon system with performances similar to that of the Run 2 LHC detectors. In the DELPHES simulation used, the b-tagging efficiency is roughly 70% with a mistag rate of 1% for light quarks and 10% for charm.

In this work, we have considered three scenarios for future LHC datasets:

1. LHC Run 2 (R2-LHC): 300 fb^{-1} at 14 TeV with pileup of 50;
2. High-luminosity LHC (HL-LHC): 3000 fb^{-1} at 14 TeV with pileup of 140;
3. High-energy LHC (HE-LHC): 3000 fb^{-1} at 33 TeV with pileup of 140;

III. ANALYSIS STRATEGY

This analysis focuses on the so-called mono-b signature, analogous to the monojet signature but with the additional requirement of a b-tag. The search strategy is based on identifying the large $\not{E}_{\mathrm{T}}$ signature from the DM pair recoiling against an energetic b quark in the final state. Because in the model the dark matter pair production is mediated by heavy unobserved particles we expect a significant $\not{E}_{\mathrm{T}}$ signature even for light dark matter candidates.

For the mono-b analysis, both DM production in association with b-quarks and tops are important, although they differ qualitatively:

- $bg \to \bar{\chi}\chi + b$, $gg \to \bar{\chi}\chi + b\bar{b}$: for these production modes, the jet multiplicity is low and most of the events have only one reconstructed b-jet;
- $gg \to t\bar{t} + \bar{\chi}\chi$: these final states have a higher probability of having two reconstructed b-jets and a harder $\not{E}_{\mathrm{T}}$ spectrum. Although the jet multiplicity is high, the overall rate is large and thus this channel is important for a mono-b analysis.

Events with at least one tagged b-jet of $p_T > 50$ GeV and $\not{E}_{\mathrm{T}} \gtrsim 100$ GeV are considered in this study. To suppress backgrounds from Z+jets, W+jets and $t\bar{t}$ Standard Model production, we veto events with leptons in the final state.

Figure 2 (left) shows the $\not{E}_{\mathrm{T}}$ distribution obtained in the case of top production for several different dark matter masses and assuming M_*=150 GeV. Figure 2 (right) shows the same distribution for both direct b production and top production with a dark matter particle with a mass of 10 GeV. The same plot also shows the $\not{E}_{\mathrm{T}}$ distribution for the dominant background due to events with W/Z+jets in which a heavy flavor jet is produced or a light quark jet is mistagged. The distribution for $t\bar{t}$ plus jets background is also shown.

For each dark matter mass assumption and luminosity scenario, the cut on $\not{E}_{\mathrm{T}}$ cut is optimized by maximizing the sensitivity defined as $S/\sqrt{S+B}$.

IV. RESULTS

To obtain limit projections on M_* and the DM-nucleon cross section we produce signal samples for DM masses of m_χ = 1, 10, 50, 100, 200, 400, and 1000 GeV using both b and $\bar{t}t$ production modes. The analysis cuts were optimized for each DM mass value and for each scenario discussed in section II. The projected sensitivity for DM plus heavy quark production was calculated based on the total event rate. The expected 90% exclusion limits on the dark matter−SM coupling, parameterized by the suppression scale M_*, were computed for a given dark matter mass m_χ by requiring $S/\sqrt{S+B} < 1.28$ for a one-sided Gaussian.

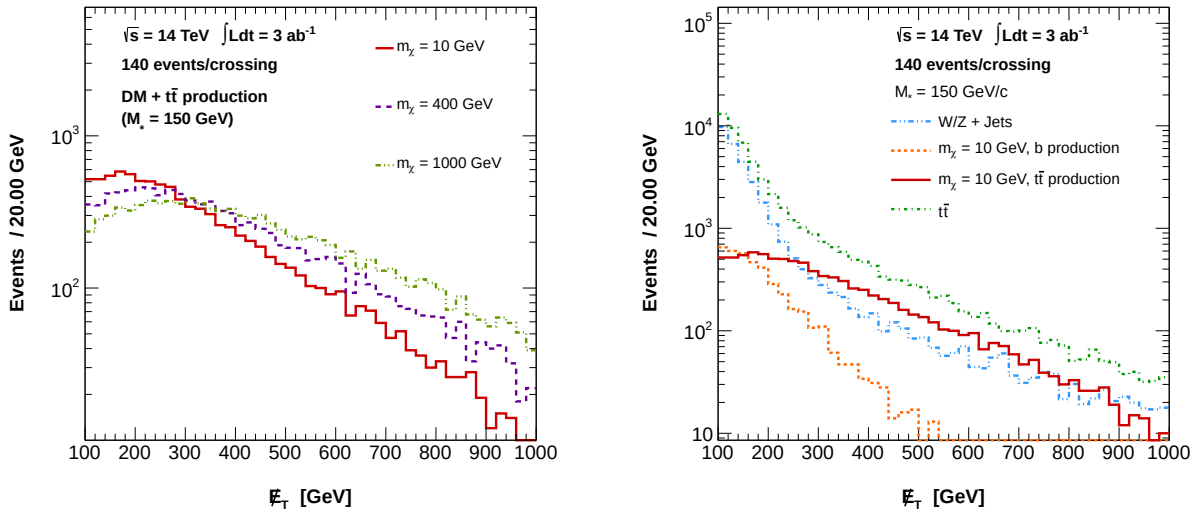

FIG. 2. Left: $\not{E}_T$ distribution of $t\bar{t} + \chi\bar{\chi}$ production for different DM masses m_χ assuming $\sqrt{s} = 14$ TeV, pile up of 140 events per bunch crossing and an integrated luminosity of 3 ab^{-1}. Right: $\not{E}_T$ distribution for direct b and $t\bar{t} + \chi\bar{\chi}$ production compared to backgrounds from $W/Z +$ jets and $t\bar{t}$ assuming $\sqrt{s} = 14$ TeV, pile up of 140 events per bunch crossing and an integrated luminosity of 3 ab^{-1}.

Process	Scenario 1	Scenario 2	Scenario 3
$\not{E}_T$ cut [GeV]	350	400	440
$Z/W +$ jets	46141.2	301602.0	1778520.0
Top	31759.8	203279.7	2193966.0
direct b	427.3	2825.943	89913.3
$t\bar{t} + \chi\bar{\chi}$	3927.7	29203.44	1699941

TABLE I. Numbers of events passing the selection requirements for the three considered scenarios. The $\not{E}_T$ selections used are optimized for a DM particle of $m_\chi = 10$ GeV.

Fig. 3 shows the expected limits on the M_* for the three LHC scenarios mentioned above. In mapping the collider constraints to the direct detection plane, we relate M_* to the spin-independent nucleon scattering cross section for a scalar operator:

$$\sigma_n = \frac{(0.38 m_n)^2 \mu_{\chi n}^2}{\pi M_*^6} \approx 2 \times 10^{-38} \mathrm{cm}^2 \left(\frac{30 \text{ GeV}}{M_*} \right)^6 . \quad (2)$$

V. DISCUSSION

We have shown that limits on scalar interactions of dark matter with quarks can be improved significantly by directly searching for final states with b-quarks. The expected limits for three different scenarios at the LHC were shown.

We show that limits on M_* can improve by a factor of ~ 7 and limits on σ_n can improve by 5 orders of magnitude with 300 fb^{-1} of data from a 14 TeV run, compared to current monojet limits using 7 TeV data from the LHC. We also expect that limits can be further improved by taking advantage of the shape differences between signal and background.

In addition to mono-b analysis discussed in this work, a dedicated analysis of the $t\bar{t} + \bar{\chi}\chi$ final state will also improve the limits. In [12] it was shown that σ_n bounds were stronger by a factor of a few with respect to the mono-b analysis. By probing both b production and top production, we could also gain insight into the flavor structure of dark matter couplings with quarks.

Progress is underway both from the experimental side, where DM plus heavy quark analyses are being applied to 8 TeV data, and from the theoretical side, where work is being done to build UV complete models and derive fully consistent constraints (for example [21, 22]). We anticipate this will lead to some of the strongest complementary constraints on the direct detection cross section, σ_n.

[1] Daniel Bauer, James Buckley, Matthew Cahill-Rowley, Randel Cotta, Alex Drlica-Wagner, et al. Dark Matter in the Coming Decade: Complementary Paths to Discovery

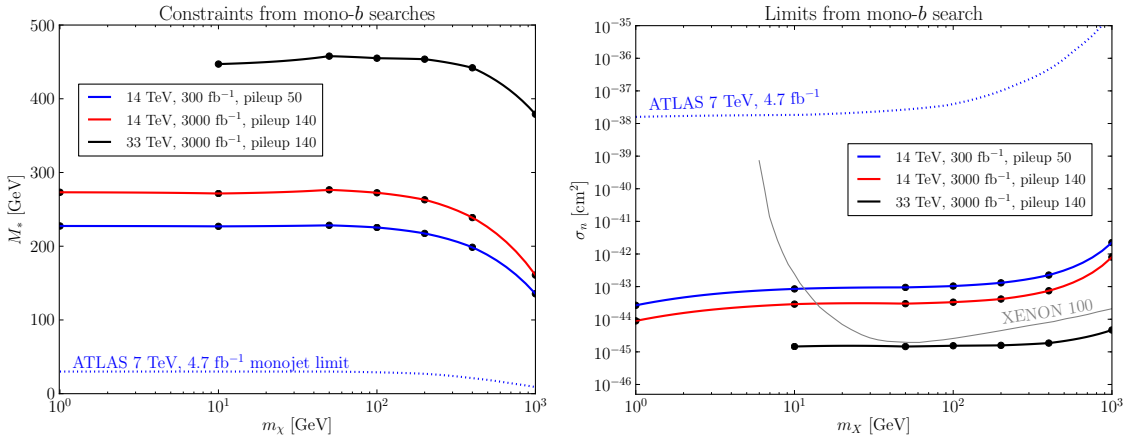

FIG. 3. Left: Expected 90% CL limits on the scalar operator from a DM plus heavy quark search, including couplings to tops and bottoms. The limits for $\sqrt{s} = 14$ and 33 TeV with correspondingly adjusted $\not{E}_T$ selections are shown. ATLAS 7 TeV limits come from [3]. Right: Corresponding constraints on the spin-independent nucleon scattering cross section, along with current XENON100 limits [20].

and Beyond. 2013.

[2] Maria Beltran, Dan Hooper, Edward W. Kolb, Zosia A.C. Krusberg, and Tim M.P. Tait. Maverick dark matter at colliders. *JHEP*, 1009:037, 2010.

[3] Georges Aad et al. Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the ATLAS detector. 2012.

[4] Search for new phenomena in monojet plus missing transverse momentum final states using 10fb-1 of pp collisions at sqrts=8 tev with the atlas detector at the lhc. Technical Report ATLAS-CONF-2012-147, CERN, Geneva, Nov 2012.

[5] Serguei Chatrchyan et al. Search for dark matter and large extra dimensions in monojet events in *pp* collisions at $\sqrt{s} = 7$ TeV. *JHEP*, 1209:094, 2012.

[6] Search for new physics in monojet events in pp collisions at sqrt(s)= 8 tev. Technical Report CMS-PAS-EXO-12-048, CERN, Geneva, 2013.

[7] Jessica Goodman, Masahiro Ibe, Arvind Rajaraman, William Shepherd, Tim M.P. Tait, et al. Constraints on Light Majorana dark Matter from Colliders. *Phys.Lett.*, B695:185–188, 2011.

[8] Patrick J. Fox, Roni Harnik, Joachim Kopp, and Yuhsin Tsai. Missing Energy Signatures of Dark Matter at the LHC. *Phys.Rev.*, D85:056011, 2012.

[9] Frank J. Petriello, Seth Quackenbush, and Kathryn M. Zurek. The Invisible Z' at the CERN LHC. *Phys.Rev.*, D77:115020, 2008.

[10] Patrick J. Fox, Roni Harnik, Joachim Kopp, and Yuhsin Tsai. LEP Shines Light on Dark Matter. 2011.

[11] G. D'Ambrosio, G.F. Giudice, G. Isidori, and A. Strumia. Minimal flavor violation: An Effective field theory approach. *Nucl.Phys.*, B645:155–187, 2002.

[12] Tongyan Lin, Edward W. Kolb, and Lian-Tao Wang. Probing dark matter couplings to top and bottom at the LHC. 2013.

[13] Johan Alwall, Michel Herquet, Fabio Maltoni, Olivier Mattelaer, and Tim Stelzer. MadGraph 5 : Going Beyond. *JHEP*, 1106:128, 2011.

[14] Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands. PYTHIA 6.4 Physics and Manual. *JHEP*, 0605:026, 2006.

[15] Jessica Goodman et al. Constraints on Dark Matter from Colliders. *Phys. Rev.*, D82:116010, 2010.

[16] A. Avetisyan et al. 2013. arXiv:1307.XXX.

[17] Patrick J. Fox and Ciaran Williams. Next-to-Leading Order Predictions for Dark Matter Production at Hadron Colliders. 2012.

[18] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lematre, et al. DELPHES 3, A modular framework for fast simulation of a generic collider experiment. 2013.

[19] A. Avetisyan et al. 2013. arXiv:1307.XXX.

[20] E. Aprile et al. Dark Matter Results from 225 Live Days of XENON100 Data. *Phys.Rev.Lett.*, 109:181301, 2012.

[21] H. Dreiner, D. Schmeier, and J. Tattersall. Contact Interactions Probe Effective Dark Matter Models at the LHC. *Europhys.Lett.*, 102:51001, 2013.

[22] Randel C. Cotta, Arvind Rajaraman, Tim M. P. Tait, and Alexander M. Wijangco. Particle Physics Implications and Constraints on Dark Matter Interpretations of the CDMS Signal. 2013.