Probing dark matter couplings to top and bottom at the LHC

Tongyan Lin
KICP/UChicago

with Liantao Wang and Rocky Kolb, arXiv:1303.6638

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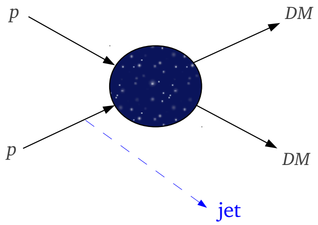
Dark matter at colliders

"Mono" searches

- **Monojets:** DM production (E_T^{miss}) plus one or two jets
- Can arise from initial state radiation of quarks, gluons



- Useful collider probe for light dark matter, and operators with SD scattering
- Related: monophoton, mono-Z, mono-leptons, **mono**-b

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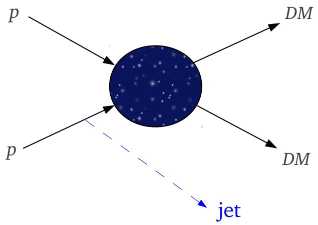

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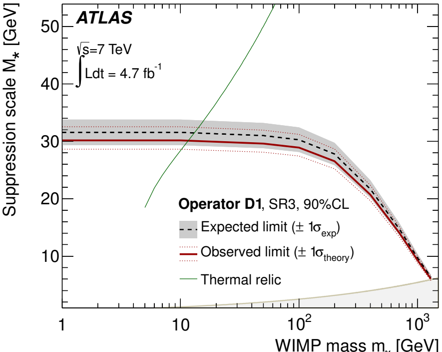
Constraints on operators

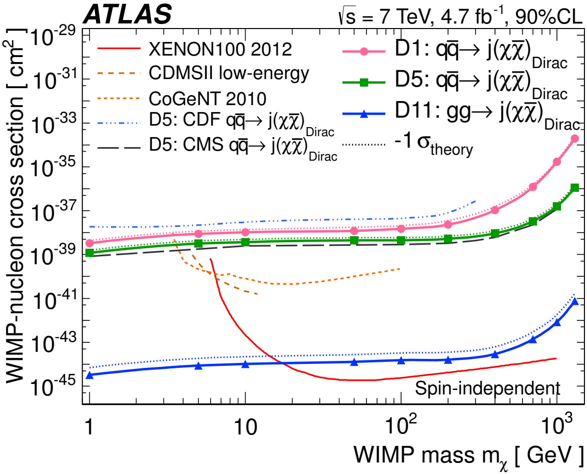
Model-independent effective field theory (EFT) approach: simple connection to direct detection and relic abundance (annihilation cross section)

Single scale M_* parameterizes size of interactions:

$$\text{D1/Scalar} : \mathcal{O} = \frac{m_q}{M_*^3} \bar{q} q \bar{X} X$$

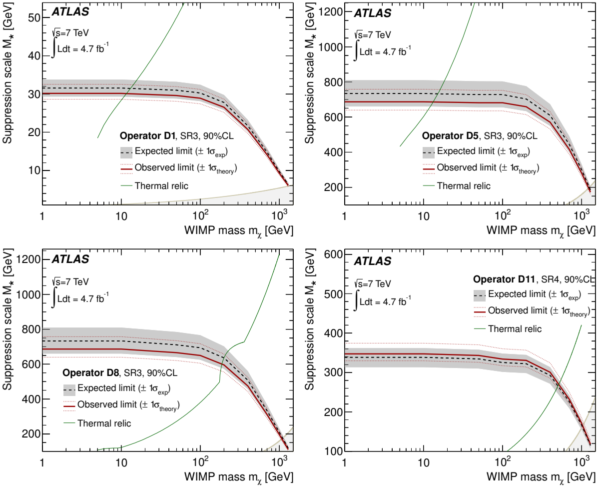


Map to direct detection



Constraints on operators

Constraints on M_* much worse for scalar operator:



Scalar operator

A closer look at scalar operators:

$$\mathcal{O}_S \equiv \frac{m_q}{M_*^3}\bar{q}q\bar{X}X \sim \frac{y_q g_X}{m_\phi^2}\bar{q}q\bar{X}X$$

- Why m_q? Flavor constraints $\rightarrow$ Minimal Flavor Violation
- Suppressed couplings to light quarks means suppressed monojet signal from gluons and light quarks
- ATLAS published result (2012) - only consider up to m_c

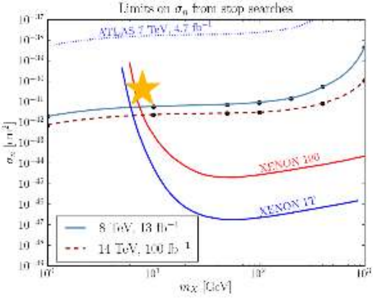
This operator gives rise to spin-independent scattering:

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

(Other operators like $\bar{q}\gamma^5 q\bar{X}\gamma^5 X$ give similar collider constraints but velocity-suppressed direct detection cross sections.)

Searches with bottoms and tops

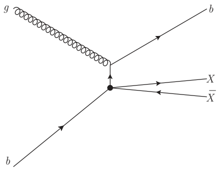
- Include heavy quarks in monojet signal
- Significant improvement in constraints on scalar interactions with b-tagging and $t\bar{t}$ final states
  - heavy flavor production: y_q^2 wins over pdf suppression
  - b-enriched final states from bottoms and tops
- Direct search for couplings to third generation

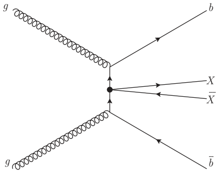


DM production

Direct b production:

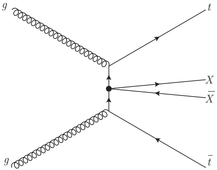
- $bg \to bX\bar{X}$, $gg \to b\bar{b}X\bar{X}$





DM production in association with tops:

- $bg \to bX\bar{X}$, $gg \to b\bar{b}X\bar{X}$



Factor of ~ 10 larger cross section than direct b production.

b-tagging on monojets

Monojet:

- $E_T^{miss} > 350\mathrm{GeV}$, $p_T^1 > 100$ GeV, No lepton
- No more than 2 jets with $p_T > 50$ GeV

Mono-b:

- **b-tag on leading jet**

b-tagging efficiency (calibrated on tops) $\sim 60\%$, mistag $\sim 0.2\%$ for light quarks at ATLAS

Dominant SM backgrounds for monojet searches: Z+jets (W + jets) cut from 500 fb to around 15 fb with b-tag.

Mono-b

	Process	Monojet	b-tag	b-tag on j_1
Signal	$\bar{X}X$+jets	11 fb	0.9 fb	0.7 fb
	$\bar{X}X + b$+jets	65 fb	40 fb	33 fb
	$\bar{X}X + t\bar{t}$	120 fb	63 fb	41 fb

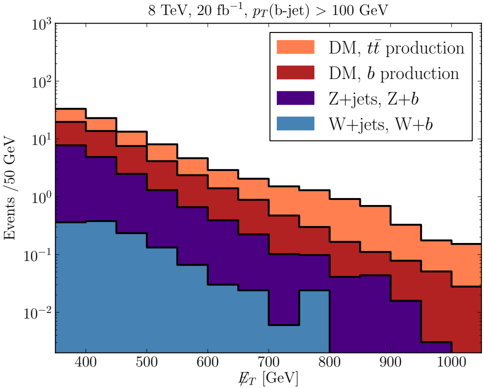
Table: **Inclusive mono-b search at 8 TeV:** Cross sections after cuts applied. For the signal we take $M^* = 50$ GeV.

Improvement in bounds from: (1) overall monojet production rate is bigger (2) monojets are b-enriched

Simulation of Events:

- MadGraph5 + PYTHIA6 + Delphes
- NLO cross sections from MCFM-Dark (Fox and Williams)

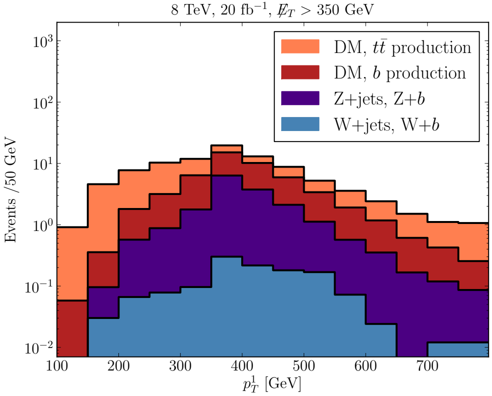
Mono-b MET distribution



$(M_* = 50\ \text{GeV})$

- Direct b-production isn't significantly harder
- Z+jets often initiated by at least one valence quark
- $t\bar{t}$ has different kinematics and a harder spectrum; it isn't coming from ISR

Mono-b p_T distribution

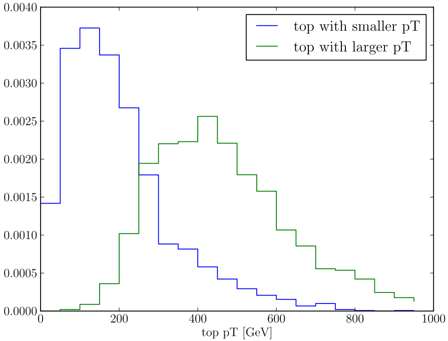


$(M_* = 50\ \text{GeV})$

- For b production, typically just one hard b-jet
- For top production, second jet may be harder, b-tagged 30% of the time

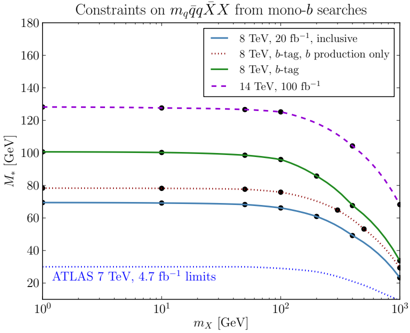
Top kinematics: events passing mono-b cuts

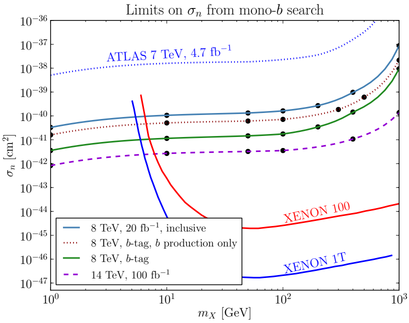
Associated production of $t\bar{t}$ can look like "mono-b" cuts if one top is boosted and the other is not too hard.



Efficiency WRT veto on 3rd jet: 0.17

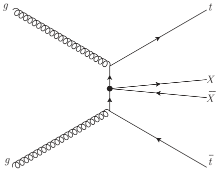
Mono-b limits





$t\bar{t}$ final state

A direct search for $t\bar{t}$ + MET would do better in this case:

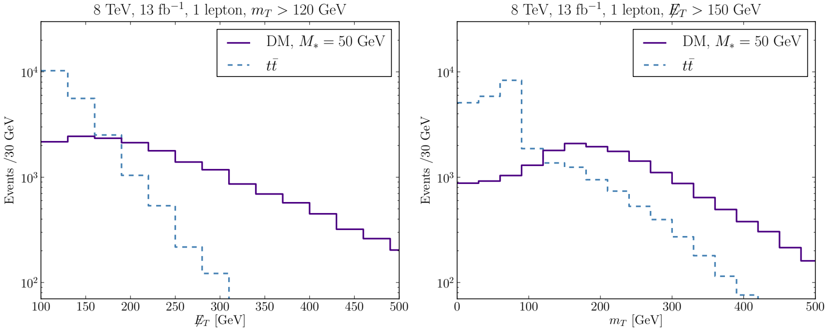


$\rightarrow$ SUSY top-partner searches

We apply the ATLAS 8 TeV, 13 fb^{-1} study with 1 lepton in the final state:

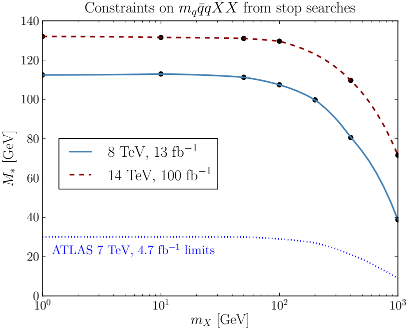
- 4 jets with $p_T > (80, 60, 40, 25)$ GeV with 1 b-tag
- We use signal region with $E_T^{miss} > 225$ GeV, $m_T > 130$ GeV

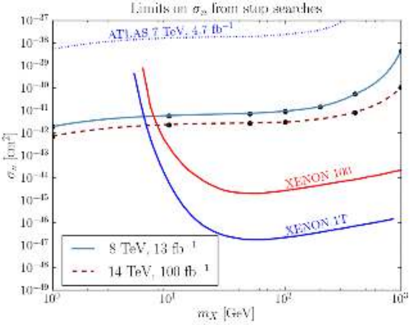
$t\bar{t}$ final state



Dominant SM background is $t\bar{t}$ dileptonic decay, where one lepton is either missed or a τ.

Limits from recasting stop search



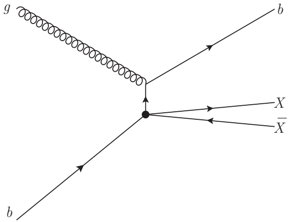


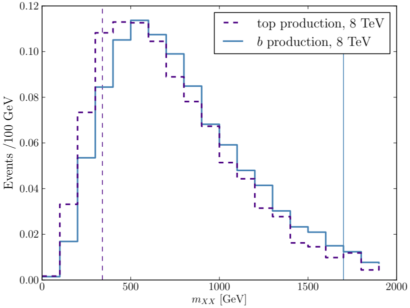
$\sim 20\%$ improvement in M_* constraint compared to mono$-b$.
Another 10% possible with all-hadronic final state.

Unitarity

Bounds on M_* still low - what do these constraints mean?
(Shoemaker and Vecchi; Fox, Harnik, Primulando, Yu):

$$\frac{\sqrt{3}}{8\pi}\frac{m_q}{M_*^3}m_{\chi\bar{\chi}}^2 \lesssim \frac{1}{2}$$

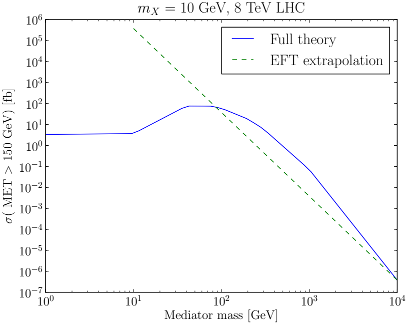




b-production seems safe, for top production it depends...

Example: neutral scalar mediator

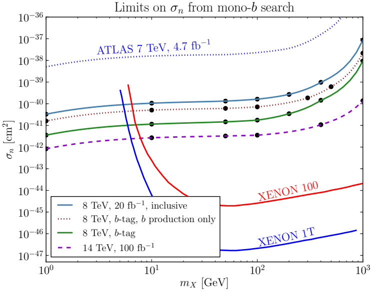
- Interactions through a mediator of mass M_ϕ can go through a resonance:

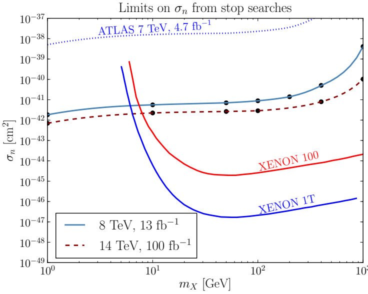


- Other constraints can also apply depending on the model.
- If the scalar is the Higgs, the constraints on Higgs invisible decay - $Br(H \to \chi\chi)$ - are already stronger.

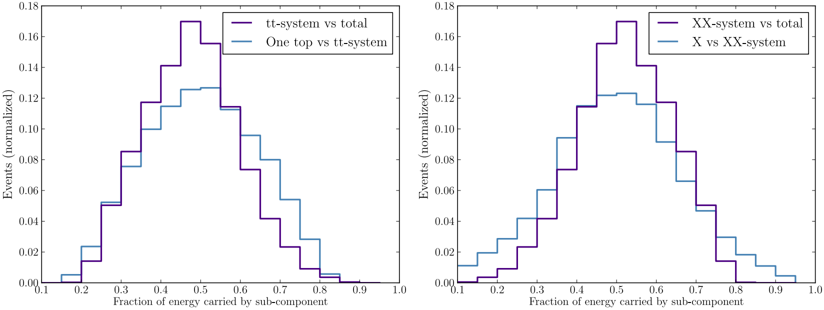
Conclusions

- Monojets searches useful to study DM-SM interactions
- For scalar operators, final states are b enriched. "Mono-b" gives significant improvement in bounds.
- Top production even more important: direct $t\bar{t} + E_T^{miss}$ search
- Direct probe of couplings to third generation



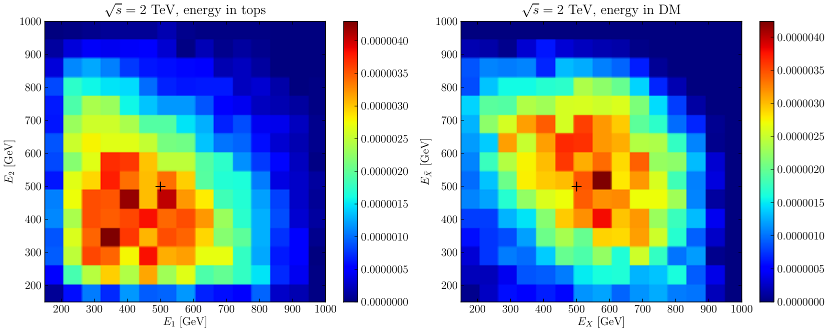


Top kinematics



Top kinematics

Compared to $t\bar{t}$ or stop pair production, in this case each particle carries off about $\sim 1/4$ of the energy in roughly uncorrelated directions $\rightarrow$ large E_T^{miss}.



2D parton level distributions for energies of tops (left) and DM (right)

Loops

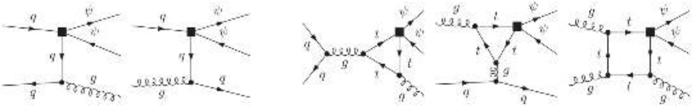
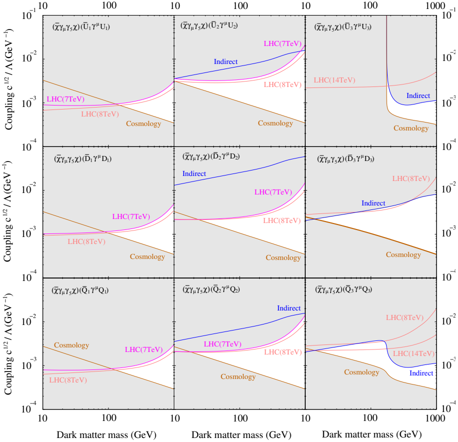


FIG. 1. Typical tree-level (left) and loop-level (right) diagrams leading to monojet events. The black squares denote insertions of four-fermion operators.

Haisch, Kahlhoefer, Unwin: M_* limit raised to 150 GeV.

Scalar operator constraints

- Recent paper by Bhattacherjee et al. [1212.5013], "Model Independent Analysis of Interactions between Dark Matter and Various Quarks":



- Kamenik and Zupan 2011 - "monotop" from MFV and dark matter