The impact of heavy-quark loops on LHC dark matter searches

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Mainly based on arXiv:1208.4605
with Felix Kahlhoefer & Uli Haisch

Effective operators

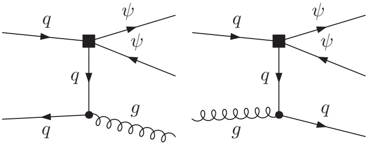
As a first step, effective operators provide a simple parametrisation for mono-j searches.

Can write down dimension 5 and 6 operators involving quarks and fermion ψ or scalar ϕ DM.

Contact operators arise from integrating out some 'heavy' mediator state, with mass around scale Λ.

Validity of the EFT depends on the scales involved.

For collider searches mediator mass should be in excess of event level energies $\gtrsim$ few $\times$ 100 GeV.



	$\Delta\mathscr{L}$
$\mathcal{O}^{\phi}_{s}$:	$\frac{1}{\Lambda}\phi^{\dagger}\phi\overline{f}f$
$\mathcal{O}^{\phi}_{v}$:	$\frac{1}{\Lambda^2}\phi^{\dagger}\partial^{\mu}\phi\overline{f}\gamma_{\mu}f$
$\mathcal{O}^{\phi}_{va}$:	$\frac{1}{\Lambda^2}\phi^{\dagger}\partial^{\mu}\phi\overline{f}\gamma_{\mu}\gamma^5 f$
$\mathcal{O}^{\phi}_{p}$:	$\frac{1}{\Lambda}\phi^{\dagger}\phi\overline{f}i\gamma^5 f$
$\mathcal{O}^{\psi}_{s}$:	$\frac{1}{\Lambda^2}\overline{\psi}\psi\overline{f}f$
$\mathcal{O}^{\psi}_{v}$:	$\frac{1}{\Lambda^2}\overline{\psi}\gamma^{\mu}\psi\overline{f}\gamma_{\mu}f$
$\mathcal{O}^{\psi}_{a}$:	$\frac{1}{\Lambda^2}\overline{\psi}\gamma^{\mu}\gamma^5\psi\overline{f}\gamma_{\mu}\gamma^5 f$
$\mathcal{O}^{\psi}_{t}$:	$\frac{1}{\Lambda^2}\overline{\psi}\sigma^{\mu\nu}\psi\overline{f}\sigma_{\mu\nu}f$
$\mathcal{O}^{\psi}_{p}$:	$\frac{1}{\Lambda^2}\overline{\psi}\gamma^5\psi\overline{f}\gamma^5 f$
$\mathcal{O}^{\psi}_{va}$:	$\frac{1}{\Lambda^2}\overline{\psi}\gamma^{\mu}\psi\overline{f}\gamma_{\mu}\gamma^5 f$
$\mathcal{O}^{\psi}_{pt}$:	$\frac{1}{\Lambda^2}\overline{\psi}i\sigma^{\mu\nu}\gamma^5\psi\overline{f}\sigma_{\mu\nu}f$
$\mathcal{O}^{\psi}_{ps}$:	$\frac{1}{\Lambda^2}\overline{\psi}i\gamma^5\psi\overline{f}f$
$\mathcal{O}^{\psi}_{sp}$:	$\frac{1}{\Lambda^2}\overline{\psi}\psi\overline{f}i\gamma^5 f$

Yukawa-like DM operators

Consider Lagrangian involving SM singlet scalar η & fermion DM ψ

$$\mathcal{L} = \lambda_X \eta \bar{\psi}\psi + \mu\eta|H|^2 + \frac{1}{2}m_\eta^2\eta^2 + V(H)\cdots$$

Expanding around the Higgs VEV

$$\mathcal{L} = \lambda_X \eta \bar{\psi}\psi + \sum_q y_q \bar{q} q h + \frac{1}{2}\mu\eta|h|^2 + \frac{1}{2}\left(\ \eta\ ,\ h\ \right)\left(\begin{array}{cc} m_\eta^2 & \mu v \\ \mu v & m_h^2 \end{array}\right)\left(\begin{array}{c} \eta \\ h \end{array}\right) + \cdots$$

Going to mass eigenbasis (η_1, h_1) given in terms of a mixing angle θ

$$\eta = \cos\theta\ \eta_1 + \sin\theta\ h_1\ , \quad h = -\sin\theta\ \eta_1 + \cos\theta\ h_1,$$

$$\mathcal{L} = \lambda_X \eta_1 \bar{\psi}\psi + \lambda_X \theta h_1 \bar{\psi}\psi + \frac{1}{2}\mu\eta_1 h_1^2 + \sum_q y_q \bar{q} q h_1 - \sum_q y_q \theta\ \eta_1 \bar{q} q + V(H)\ .$$

Integrating out η_1 gives the effective operator: $\frac{y_q \theta \lambda_X}{m_\eta^3}\overline{\psi}\psi\overline{q}q$.

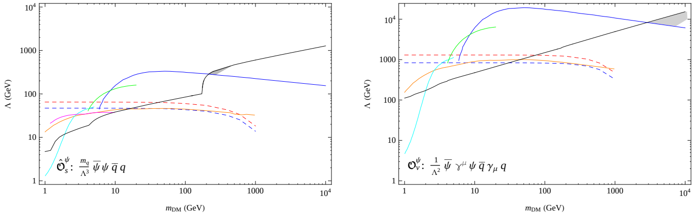
Operators of interest

We focus on the following motivated sub-class of operators with Yukawa structure:

$$\boxed{\begin{array}{ll} \hat{\mathcal{O}}_s^{\phi}: & \frac{m_q}{\Lambda^2}\phi^\dagger\phi\overline{f}f \\ \hat{\mathcal{O}}_s^{\psi}: & \frac{m_q}{\Lambda^3}\overline{\psi}\psi\overline{f}f \\ \hat{\mathcal{O}}_p^{\psi}: & \frac{m_q}{\Lambda^3}\overline{\psi}\gamma^5\psi\overline{f}\gamma^5 f \end{array}}$$

Monojet/relic density constraints

As cross sections for collider production, direct detection, and annihilation into SM fermions involve identical couplings, in simple models of WIMP and asymmetric DM they give complementary bounds on parameter space.



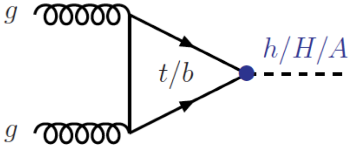
Solid lines: DD bounds, dashed: monojet limits, black line: relic density constraint.

From arXiv:1203.4854 (March-Russell, JU, West, /w Atlas 1fb^{-1} set), similar analyses see e.g.:
Irvine group 1005.1286, 1108.1196, Fermilab group 1005.3797,1203.1662, Chicago group 1305.0021, Buckley 1104.1429 $\cdots$

Mono-j limits are much weaker for Yukawa coupled operator, since for light quarks then m_q is small, whereas heavy quarks are PDF suppressed.

Higgs physics

That loops can be important for Yukawa-like operators can be seen from Higgs Physics, as gluon fusion is a leading Higgs production channel.

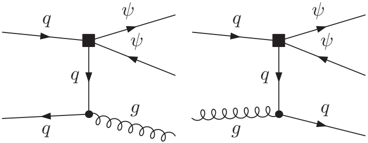


arXiv:hep-ph/0503173 Djouadi

Heavy top limit $m_t \to \infty$ works well for Higgs physics as $m_h \ll m_t$.

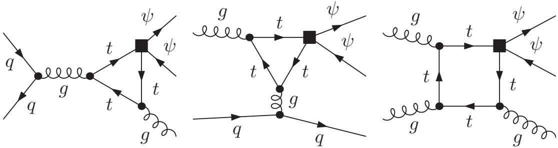
Analogous limit for DM scenario suggests operators like $G^a_{\mu\nu} G^{a\ \mu\nu} \overline{\psi}\psi$; but this does not accurately capture the physics as the mediator must be heavy for good EFT and typically this overestimates cross section by factor $\mathcal{O}(10)$.

Loop vs Tree with Yukawa-like DM operators



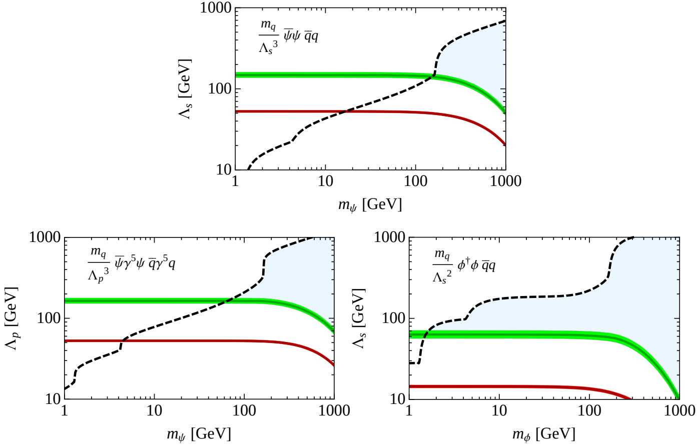
Main effects:

- Reduction compared to Tree level due to loop factor
- Gain by replacing $m_q \to m_t$ without PDF suppression
- **Net impact?**



Loop vs Tree with Yukawa-like DM operators

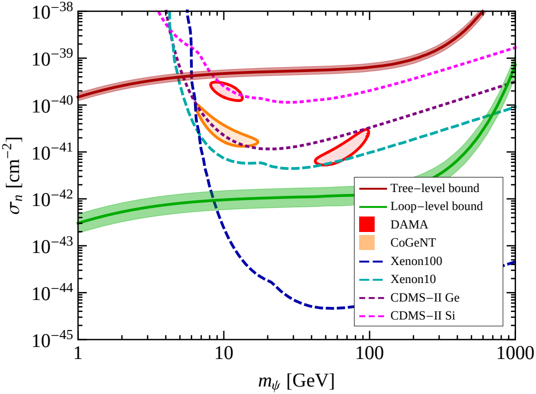
Using FeynArts/FormCalc/LoopTools we derive the following mono-j bounds from the 5 fb^{-1} search by CMS at $\sqrt{s} = 7$ TeV with $\not{E}_T > 350$ GeV.



We do not include additional jets, hadronisation or showering effects (expected to be small).

Comparison with direct detection (fermion DM)

For scalar Lorentz structure:



Note, new bound now in conflict with DAMA and Cogent signal regions.

For pseudoscalar there are essentially no direct detection limits as the scattering cross section is momentum suppressed.

Concluding remarks

Extended NLO study of wider range of operators presented by Fox and Williams, arXiv:1211.6390 and see talk of Kahlhoefer (next).

Edge of validity for EFT in many cases. With light mediators mass thresholds and resonances are important for monojet limits and also (relic density). Requiring careful study and typically more model dependent.

Recently, move towards simplified models:

Frandsen et al. 1204.3839, An et al. 1308.0592, Chang et al. 1307.8120, Bai & Berger 1308.0612, DiFranzo et al. 1308.2679, Buchmueller et al. 1308.6799 (see Friday AM session)

Summary: In the motivated class of DM models where DM couples to SM fermions through a Yukawa-like operator including loop effects increases the production cross section two orders of magnitude!