Momentum-dependent dark matter couplings and monojets

LPSC - Grenoble, 17/02/2017

Based on :

- arXiv:1605.02684 [hep-ph] (in Les Houches 2015 proceedings)

- JHEP 1701 (2017) 078, arXiv:1609.07490 [hep-ph]

In collaboration with D. Barducci, A. Bharucha, N. Desai, M. Frigerio, B. Fuks, S. Kulkarni, S. Lacroix, G. Polesello, D. Sengupta

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Dark matter : where we stand

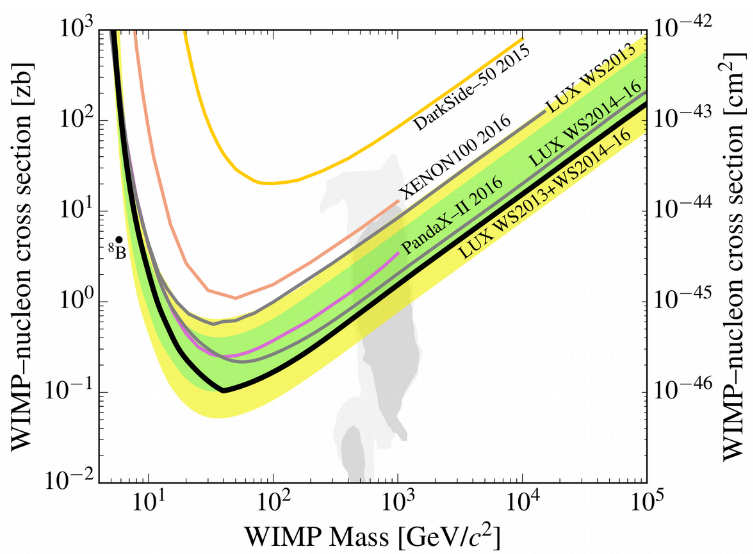
NB: Keeping in mind that our modified gravity colleagues are also on the hunt!

- Dark matter is basically something that gravitates and is not made up of standard baryons (CMB + BBN).

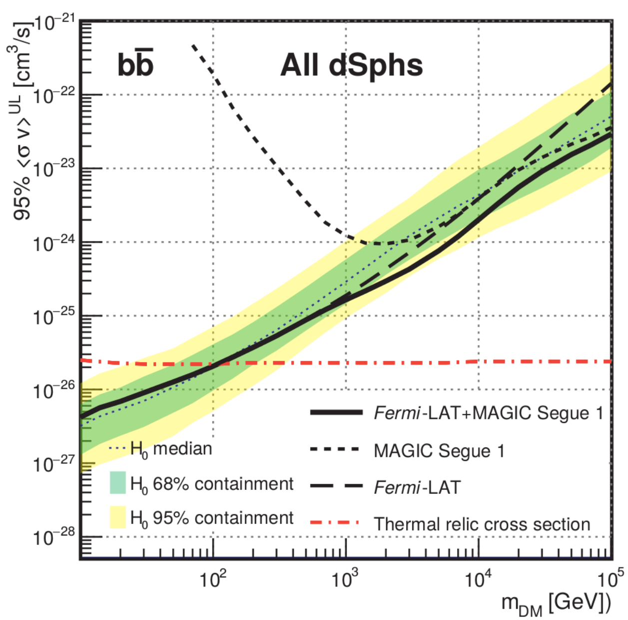
- It should have a relatively small free-streaming length at the time of structure formation.

- Origin: freeze-out, freeze-in, dark freeze-out, strongly interacting, gravitationally produced, from potential oscillations, from decays… In any case, it has to be *very* long lived ($\tau >> 10^{17}$ sec).

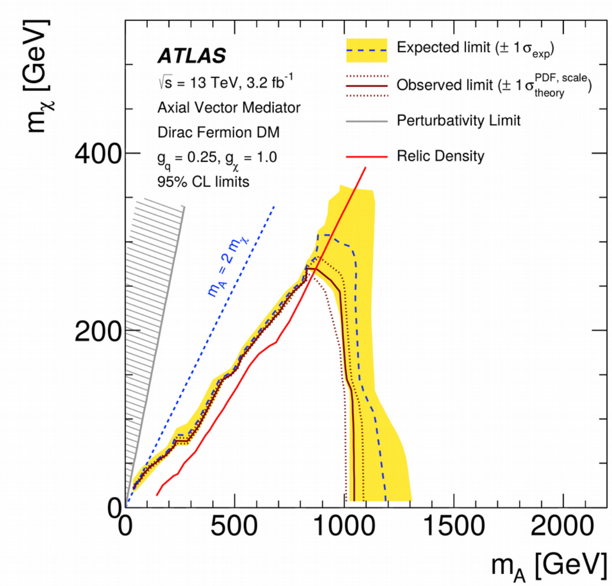
- Mass/couplings: essentially undetermined, but constrained (also related to origin).



LUX, arXiv:1608.07648



Fermi-LAT, arXiv:1611.03184



ATLAS, arXiv:1604.07773

(some) Signatures of dark matter @ the LHC

Useful guidelines to envisage dark matter signatures @ the LHC come from theory (esp. generation mechanism considerations) :

- Mono-j/γ/h/Z/W + MET (typically from ISR and potentially from the mediator). Mono-t/b (flavour-violating).

NB: In the 13 TeV Run monojets are no longer "genuine" monojets as more jet activity is allowed!

- Forward jets + MET (VBF – dark matter interacting with E/W gauge bosons).

Cf e.g. J. Brooke *et al*, arXiv:1603.07739

- Dijets + MET (as in squark searches, *e.g.* for coloured mediators), mono-/di-leptons + MET (if non-trivial SU(2) properties, more coming up).

Cf e.g. J. Abdallah *et al*, arXiv:1506.03116
G. Belanger *et al*, arXiv:1503.07367

- Increasing number of visible objects + MET (*e.g.* cascade decays in SUSY).

- Displaced vertices involving MET or charged tracks (e.g. super-WIMP mechanism).

Cf e.g. G. Arcadi *et al*, arXiv:1305.6587/1408.1005

- ...long story short, everything involving MET (even outside the detector)!

- An orthogonal (yet complementary!) approach : look for the mediator.

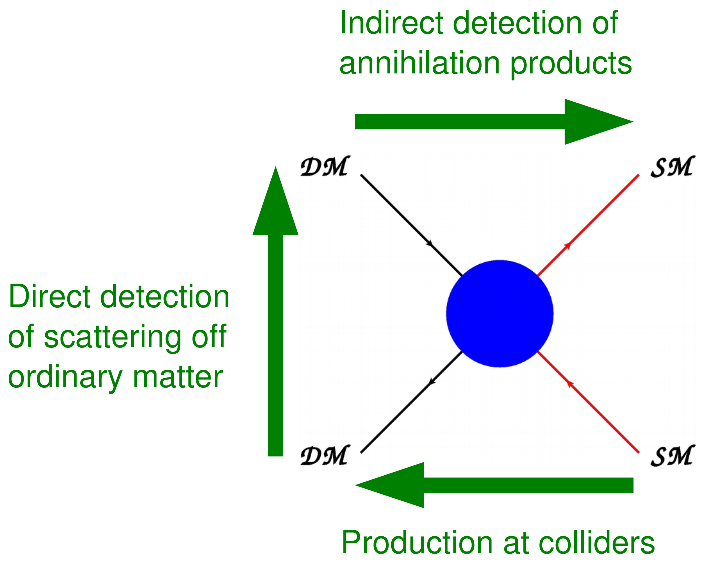
Cf e.g. M. Fairbairn *et al*, arXiv:1605.07940 + all resonance searches

(some) Signatures of dark matter @ the LHC

- Mono-j/γ/h/Z/W + MET (typically from ISR and potentially from the mediator). Mono-t/b (flavour-violating).

In this talk, I'll be focusing on the most "standard" dark matter search channel, comprised of one (or more) energetic jets + MET.

- Inspired by the freeze-out picture :



- Dark matter pair – annihilates into/is produced from SM particles in the early Universe.

It could be produced at the LHC

- But dark matter most likely manifests itself as missing energy, so a visible object is also needed.

- Further demand (at least) one visible object → mono-X searches

Simple models for LHC dark matter studies

LHC mono-X search results have so far been interpreted in terms of three main classes of models:

- Contact interactions of two DM and two SM particles : Very simple and handy approach, but needs quite a bit of attention (*e.g.* issues with perturbative unitarity).

- Simple "portal" models : Fewer consistency issues, but more free parameters (and still needs some attention!). Good for setting ballpark.

- Full – blown models (MSSM etc) : Fully consistent, but many free parameters.

Two remarks and two questions :

- When direct detection works, it works *really* well : *i.e.* for masses between ~10 GeV and ~300 GeV and if the scattering cross-section is not suppressed for low q^2 .

- But sometimes it doesn't! That's where the LHC shines : Less sensitivity to Lorentz structure. Massive difference if mediator on/off-shell, though.

What models can we think of that evade direct detection constraints?

Could the LHC distinguish between different underlying models?

e.g. "coy DM", J. Brooke *et al*, arXiv:1603.07739

T. Rizzo, arXiv:0805.0281

Momentum – dependent DM couplings ?

A simple model : The SM + a real gauge singlet scalar $\mathbf{Z_2}$ – odd field η ("dark matter") + a real gauge singlet scalar $\mathbf{Z_2}$ – even field s (mediator).

$$\mathcal{L}_{\eta,s} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}m_\eta^2\eta\eta + \frac{1}{2}\partial_\mu s\partial^\mu s - \frac{1}{2}m_s^2 ss$$
$$+ \frac{c_{s\eta}f}{2}s\eta\eta + \frac{\alpha_s}{16\pi}\frac{c_{sg}}{f}sG^a_{\mu\nu}G^{a\mu\nu}$$

Standard (MI) scalar coupling

Mediator coupling to gluons

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Standard (MI) scalar coupling

Mediator coupling to gluons

Derivative coupling

Free parameters : $m_s, \quad m_\eta, \quad f\,(\leftrightarrow c_{\partial s\eta})\,, \quad c_{s\eta}, \quad$ and $\quad c_{sg}$

The derivative term yields an interaction vertex that scales as $\sim \frac{p_s^2}{f}$ → MD coupling

UV motivation: Such terms arise in compositeness models if η is a pNGB involved in the breaking of a global symmetry at some scale f and is a result of the shift symmetry of pNGB's.

M. Frigerio, A. Pomarol, F. Riva, A. Urbano, arXiv:1204.2808
D. Marzocca, A. Urbano, arXiv:1404.7419
N. Fonseca, R. Z. Funchal, A. Lessa, L. Lopez-Honorez, arXiv:1501.05957

Why should MD couplings be interesting ?

Generically, the strongest constraints in monojet searches come from the high – energy tail of the jet p_T distribution.

But we saw that our interaction vertex scales as $\sim \frac{p_s^2}{f}$ → Enhanced at high energies.

i) Monojet constraints should be stronger than in conventional models. → This talk
ii) Could the spectral shape differences help distinguish such models? → In progress

However, note an important point :

When $m_\eta < m_s/2$, $\frac{p_s^2}{f} \rightarrow \frac{m_s^2}{f}$

Any differences between MI and MD couplings only arise in the *off-shell* regime.

From a DM standpoint, on/off-shell is pretty irrelevant. For the LHC, *it matters* : monojet searches shine when the mediator is produced and decays on-shell.

But now the signal is the most relevant signal regions is enhanced!

Can we hope to extract information on the underlying theory?

Constraints - 1

- Dijet searches for the mediator : SppS (140 – 300 GeV), Tevatron (200 – 1400 GeV), LHC Run I (up to 4.5 TeV). They are actually pretty (surprisingly!) weak.

For f ~ 1 TeV, they amount to c_{sg} < 100.

- DM relic abundance (micrOMEGAs + analytical cross-check) :

$$\Omega h^2|_\eta \leq \Omega h^2|_{\rm exp} = 0.1188 \pm 0.0010$$

Planck, arXiv:1502.01589

$$\langle \sigma v \rangle_{gg} \simeq \frac{\alpha_s^2 c_{sg}^2 m_\eta^2 \left(c_{s\eta} f^2 + 4 c_{\partial s\eta} m_\eta^2 \right)^2}{16\pi^3 f^4 \left(m_s^2 - 4 m_\eta^2 \right)^2} \,, \qquad \langle \sigma v \rangle_{ss} \simeq \frac{\sqrt{1 - \frac{m_s^2}{m_\eta^2}} \left(c_{\partial s\eta} m_s^2 + c_{s\eta} f^2 \right)^4}{16\pi f^4 m_\eta^2 \left(m_s^2 - 2 m_\eta^2 \right)^2}$$

- Direct detection (LUX – only relevant for MI couplings) : → Another reason why MD couplings are interesting!

$$\sigma_{\rm SI} = \frac{1}{\pi} \left(\frac{m_\eta m_p}{m_\eta + m_p} \right)^2 \left| \frac{8\pi}{9\alpha_s} \frac{m_p}{m_\eta} f_G f_{TG} \right|^2 \,, \qquad f_G = \frac{\alpha_s c_{sg} c_{s\eta}}{32\pi} \frac{1}{m_s^2}$$

Constraints - 2

Perturbative unitarity of the scattering matrix :

- Starting point: the optical theorem (from S-matrix unitarity)

$$\mathcal{M}_{i\to f} - \mathcal{M}^\dagger_{f\to i} = -i \sum_X \int \mathrm{d}\Pi^X_{\mathrm{LIPS}} \, (2\pi)^4 \delta^4(p_i - p_X) \, \mathcal{M}_{i\to X} \mathcal{M}^\dagger_{X\to f}$$

- This is an exact relation and holds if amplitudes are computed non-perturbatively.

- In practice, we demand that it be satisfied order-by-order in perturbation theory.

Otherwise using perturbation theory doesn't make sense in the first place!

In other words: perturbative unitarity is imposed to ensure that our calculations make (at least some) sense.

- We can then get restrictions for the various partial wave contributions to the gg → ηη scattering amplitude which, at the end of the day, boil down to two conditions :

$$(c_{s\eta} \times c_{sg}) < \frac{64\sqrt{2}\pi^2 (1 - \frac{m_s^2}{s})}{\alpha_s \left(1 - \frac{4m_\eta^2}{s}\right)^{1/4}}, \quad (c_{\partial s\eta} \times c_{sg}) < \frac{64\sqrt{2}\pi^2 f^2 (s - m_s^2)}{\alpha_s s^2 \left(1 - \frac{4m_\eta^2}{s}\right)^{1/4}}$$

→ ~ 2 TeV

Analysis setup

- Model implementation for MadGraph/CalcHEP/MicrOMEGAs performed with the FeynRules package.

So, model files are available for public use!

- Events generated with MadGraph5_aMC@NLO (with an 80 GeV jet p_T selection threshold) and matched to PYTHIA 6. Event processing performed with Delphes and jet reconstruction with FastJet.

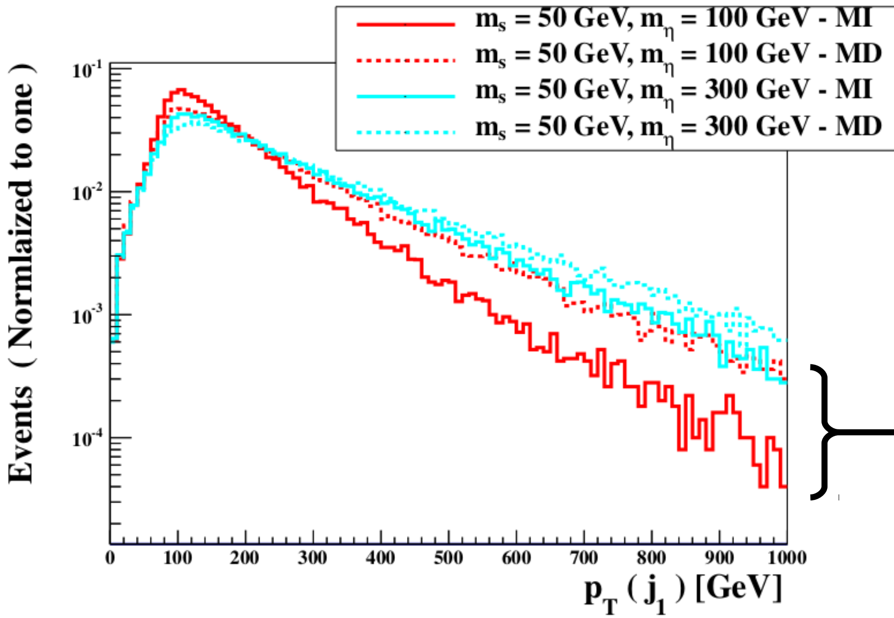
- Limits based on MADANALYSIS 5 implementation of ATLAS "monojet" search results with an integrated luminosity of 3.2 fb^{-1} @ 13 TeV. 13 signal regions in the original analysis, limits extracted from most sensitive one.

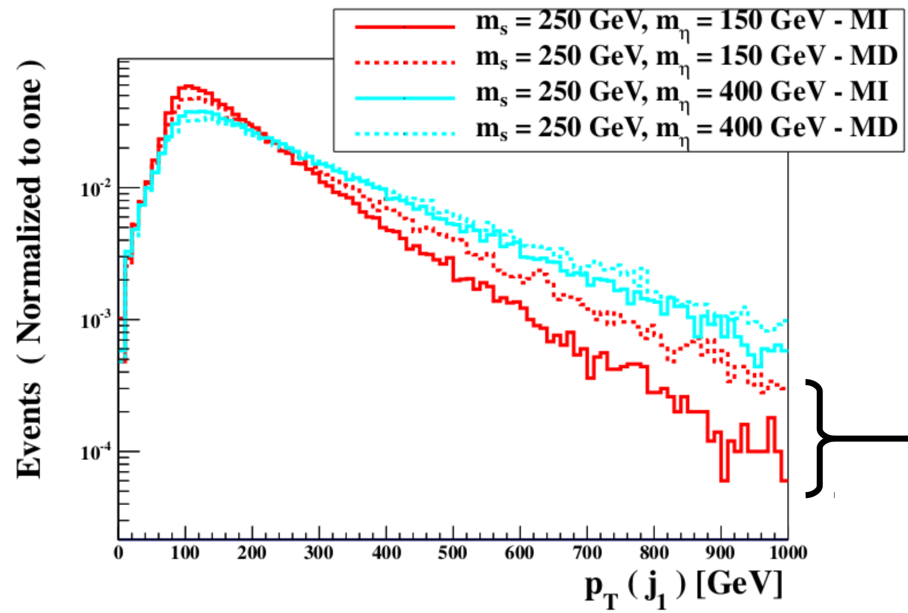
ATLAS, arXiv:1604.07773
D. Sengupta, https://inspirehep.net/record/1476800

- Projections for a 300 fb^{-1} integrated luminosity inspired from the same analysis, including tighter MET requirements with background extrapolation (incl. uncertainty estimation).

MD vs MI : A first look

Leading jet p_T distributions (normalised to 1) for a few representative examples of (m_η, m_s) combinations:



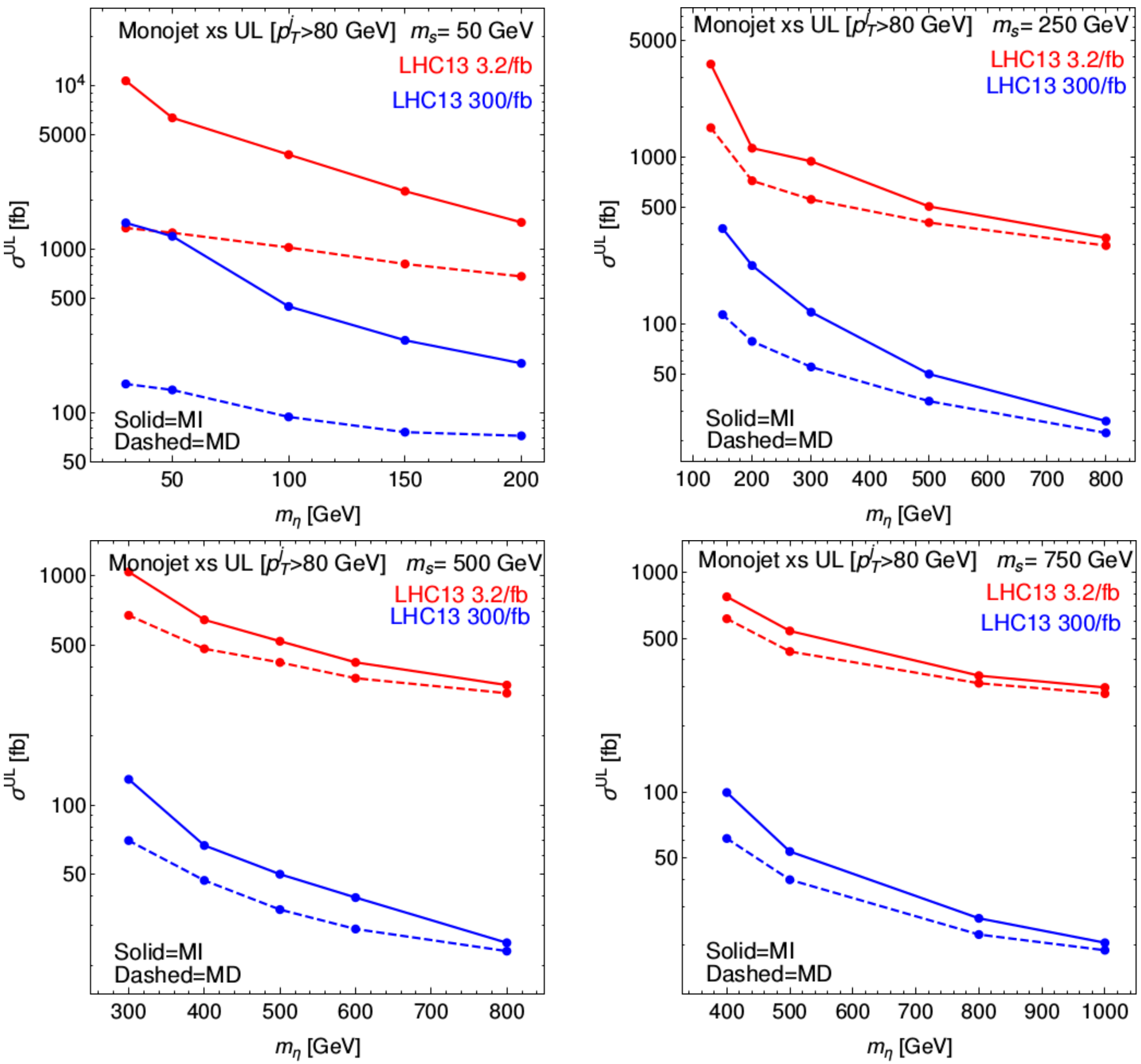


This is the effect we pointed out. Differences become maximal for small DM masses.

Efficiency associated with selection p_T > 300 GeV larger by ~50% for MD couplings.

Monojet constraints : cross section ULs

Fixing m_s, and assuming pure MI or MD interactions, the cross section ULs only depend on the kinematics (i.e. m_η) and not on the overall rate → Can be computed once and for all.



- MD operators are clearly more efficiently constrained, due to a larger number of events passing the selection criteria.

Smaller cross sections can be probed, by up to one order of magnitude, wrt the MI case.

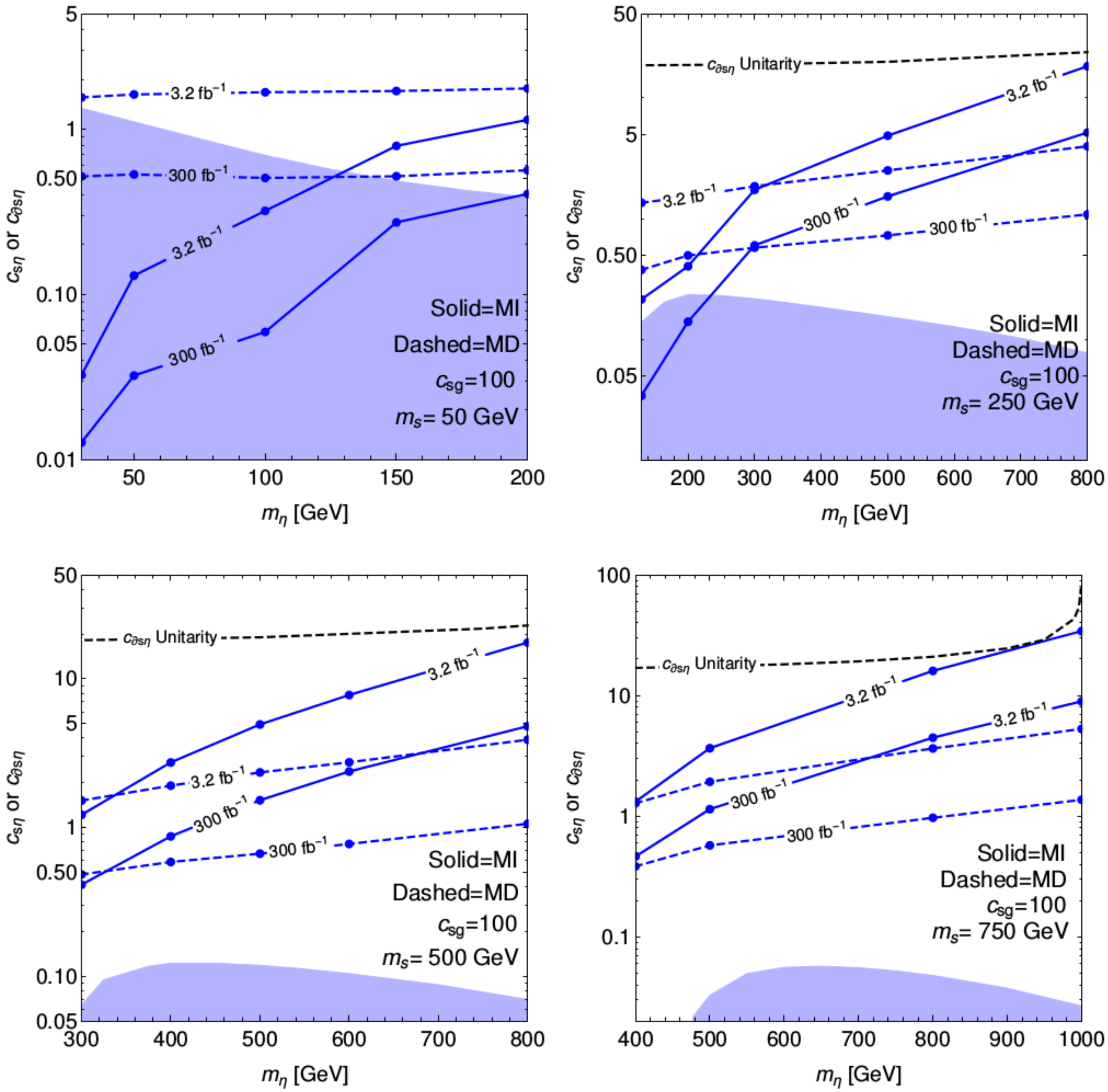
- The differences are most apparent for small dark matter masses.

- In both cases, the bounds become stronger as the dark matter mass increases.

NB: This is, nonetheless, somewhat fictitious: in reality, for large enough masses sensitivity is lost.

Connection to dark matter

Let's translate these ULs to our model and superimpose DM + TH constraints.



DD wipes out all relevant regions of the parameter space in the MI case → Ignore MI DM pheno.

But η might not be dark matter!

TH constraints OK throughout, more relevant for smaller c_{sg}.

Above threshold, existing limits probe subleading (but potentially existing!) DM components.

cf also D. Abercrombie *et al*, arXiv:1507.00966

Collider and cosmological constraints are complementary.

With 300 fb^{-1} the low-mass Planck-compatible region will, nonetheless, be tested.

Summary and outlook

· Momentum-dependent dark matter couplings to the visible sector can be motivated :

- From a UV perspective, as they appear in well-motivated extensions of the SM.

- From a DM perspective, as they provide a viable alternative to conventional dark matter scenarios. They can reproduce the observed DM abundance while evading direct detection constraints.

- From a collider perspective, as they can be constrained at the LHC.

· In the off-shell regime, monojet searches mostly probe underabundant dark matter candidates (multi-component dark matter? Some unconventional thermal history?). In MD scenarios the LHC can probe smaller cross sections than in conventional models.

· They appear to be among the most promising cases to distinguish even a subleading component of dark matter in the Universe from more conventional scenarios. Seen differently: assume the LHC observes an excess in monojet searches. To which extent can the DM properties be (mis-)identified?

Work in progress, stay tuned!

Additional material

An even simpler model

The simplest model : The SM + a real gauge singlet scalar $\mathbf{Z_2}$ – odd field η.

$$\mathcal{L}_\eta = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu \eta \partial^\mu \eta - \frac{1}{2}\mu_\eta^2 \eta^2 - \frac{1}{4}\lambda_\eta \eta^4 - \frac{1}{2}\lambda \eta^2 H^\dagger H + \frac{1}{2f^2}(\partial_\mu \eta^2)\partial^\mu (H^\dagger H)$$

Standard (dim-4) Higgs portal

Momentum-dependent coupling

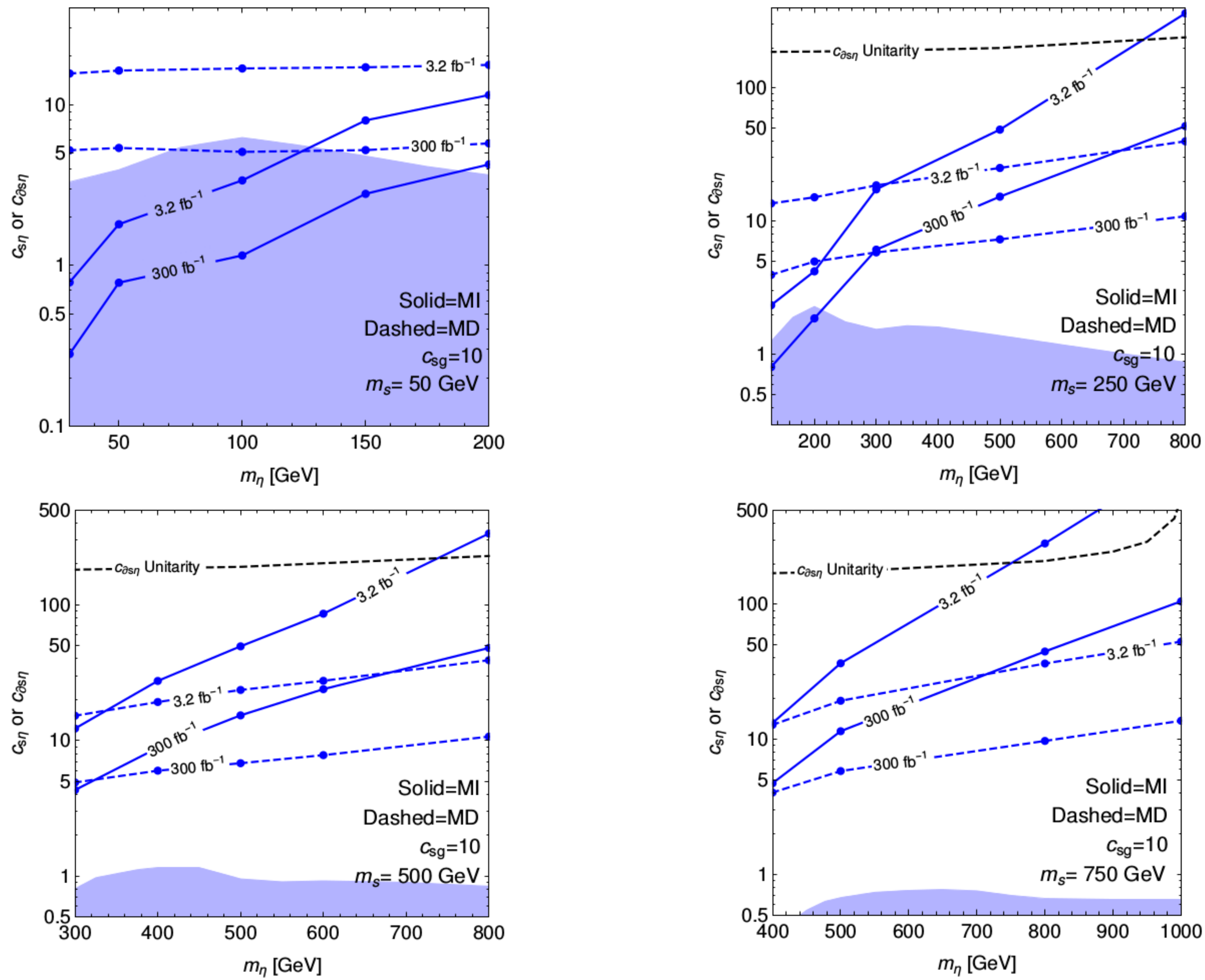
M. Frigerio, A. Pomarol, F. Riva, A. Urbano, arXiv:1204.2808

Upon EWSB, a Lagrangian term is generated $\mathcal{L}_\eta \supset -\frac{1}{4}(v+h)^2 \left(\lambda \eta^2 + \frac{1}{f^2}\partial_\mu \partial^\mu \eta^2\right)$

yielding an interaction vertex that scales as $\sim \dfrac{p_h^2}{f^2}$

But in this minimal model, both the Higgs production cross section and the “compositeness scale” f are severely bound → The signal is found to be too weak…

Varying c_{sg}


3.2 fb^{-1}
300 fb^{-1}
Solid=MI
Dashed=MD
c_{sg}=10
m_s= 50 GeV
$c_{s\eta}$ or $c_{\partial s\eta}$
m_η [GeV]
$c_{\partial s\eta}$ Unitarity
m_s= 250 GeV
m_s= 500 GeV
m_s= 750 GeV