Momentum-dependent dark matter couplings and monojets

TeV Particle Astrophysics 2016, CERN

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

- Contribution @ Les Houches 2015 proceedings, arXiv:1605.02684

- Paper to appear

Andreas Goudelis
LPTHE - Paris

Momentum – dependent DM couplings ?

A simple model : The SM + a real gauge singlet scalar **Z_2** – odd field η (“dark matter”) + a real gauge singlet scalar **Z_2** – even field s (mediator).

$$\mathcal{L}_{\eta,s} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu \eta \partial^\mu \eta - \frac{1}{2} m_\eta^2 \eta\eta + \frac{1}{2}\partial_\mu s \partial^\mu s - \frac{1}{2} m_s^2 ss$$

$$+ \underbrace{\frac{c_{s\eta} f}{2} s\eta\eta}_{\text{Standard (MI) scalar coupling}} + \underbrace{\frac{\alpha_s}{16\pi}\frac{c_{sg}}{f} s G^a_{\mu\nu} G^{a\mu\nu}}_{\text{Mediator coupling to gluons}}$$

Momentum – dependent DM couplings ?

A simple model : The SM + a real gauge singlet scalar **Z**$_2$ – odd field η (“dark matter”) + a real gauge singlet scalar **Z**$_2$ – even field s (mediator).

$$\mathcal{L}_{\eta,s} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}m_\eta^2\eta\eta + \frac{1}{2}\partial_\mu s\partial^\mu s - \frac{1}{2}m_s^2 ss$$

$$+ \underbrace{\frac{c_{s\eta}f}{2}s\eta\eta}_{\boxed{\text{Standard (MI) scalar coupling}}} + \underbrace{\frac{\alpha_s}{16\pi}\frac{c_{sg}}{f}sG^a_{\mu\nu}G^{a\mu\nu}}_{\boxed{\text{Mediator coupling to gluons}}} + \underbrace{\frac{c_{\partial s\eta}}{f}(\partial_\mu s)(\partial^\mu\eta)\eta}_{\boxed{\text{Derivative coupling}}}$$

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

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

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.

Still, we focus on the off-shell regime where differences might stand a chance of being observed.

Constraints

- Dijet searches for the mediator : SppS (140 – 300 GeV), Tevatron (200 – 1400 GeV), LHC Run I (up to 4.5 TeV).

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

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

$$\langle \sigma v \rangle_{gg} \simeq \frac{\alpha_s^2 c_{sg}^2 \left(c_{s\eta} f^2 + 4 c_{\partial s\eta} m_s^2\right)^2}{256 \pi^3 f^4 \left(m_s^2 - 4 m_\eta^2\right)^2} , \quad \langle \sigma v \rangle_{ss} \simeq \frac{\sqrt{1 - \frac{m_s^2}{m_\eta^2}} \left(c_{\partial s\eta} m_s^2 + c_{s\eta} f^2\right)^4}{16 \pi f^4 m_\eta^2 \left(m_s^2 - 2 m_\eta^2\right)^2}$$

- Direct detection (LUX – only relevant for MI couplings) :

Another reason why MD couplings are interesting!

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

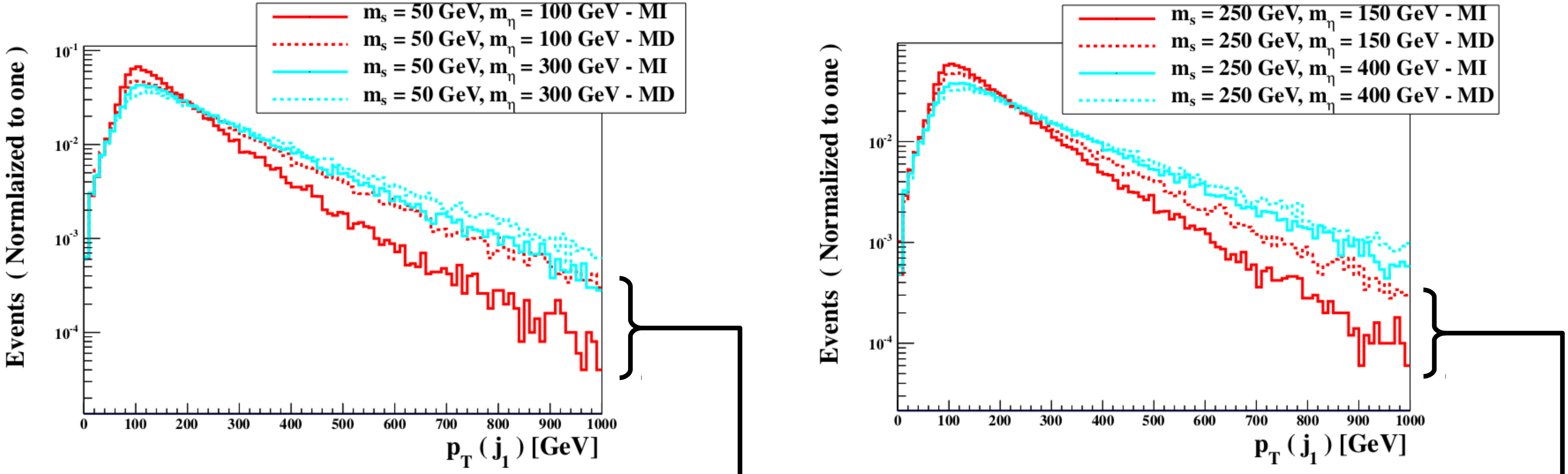
- Perturbative unitarity of the scattering matrix (for our calculations to make sense) :

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

~ 2 TeV

MD vs MI : A first look

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



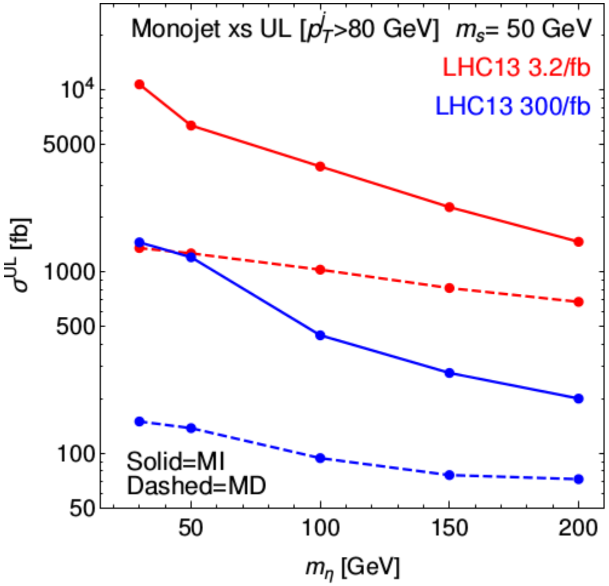
This is the effect we pointed out. Differences become maximal for small DM masses.

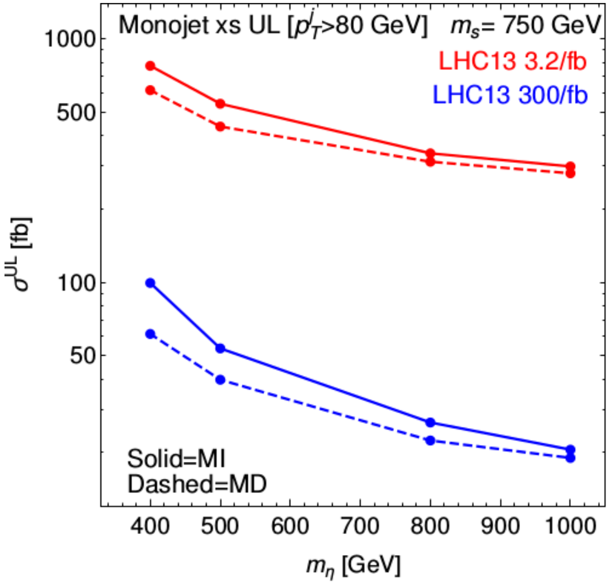
Distributions normalised to 1 with a generator-level cut $p_T > 80$ GeV.

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.





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

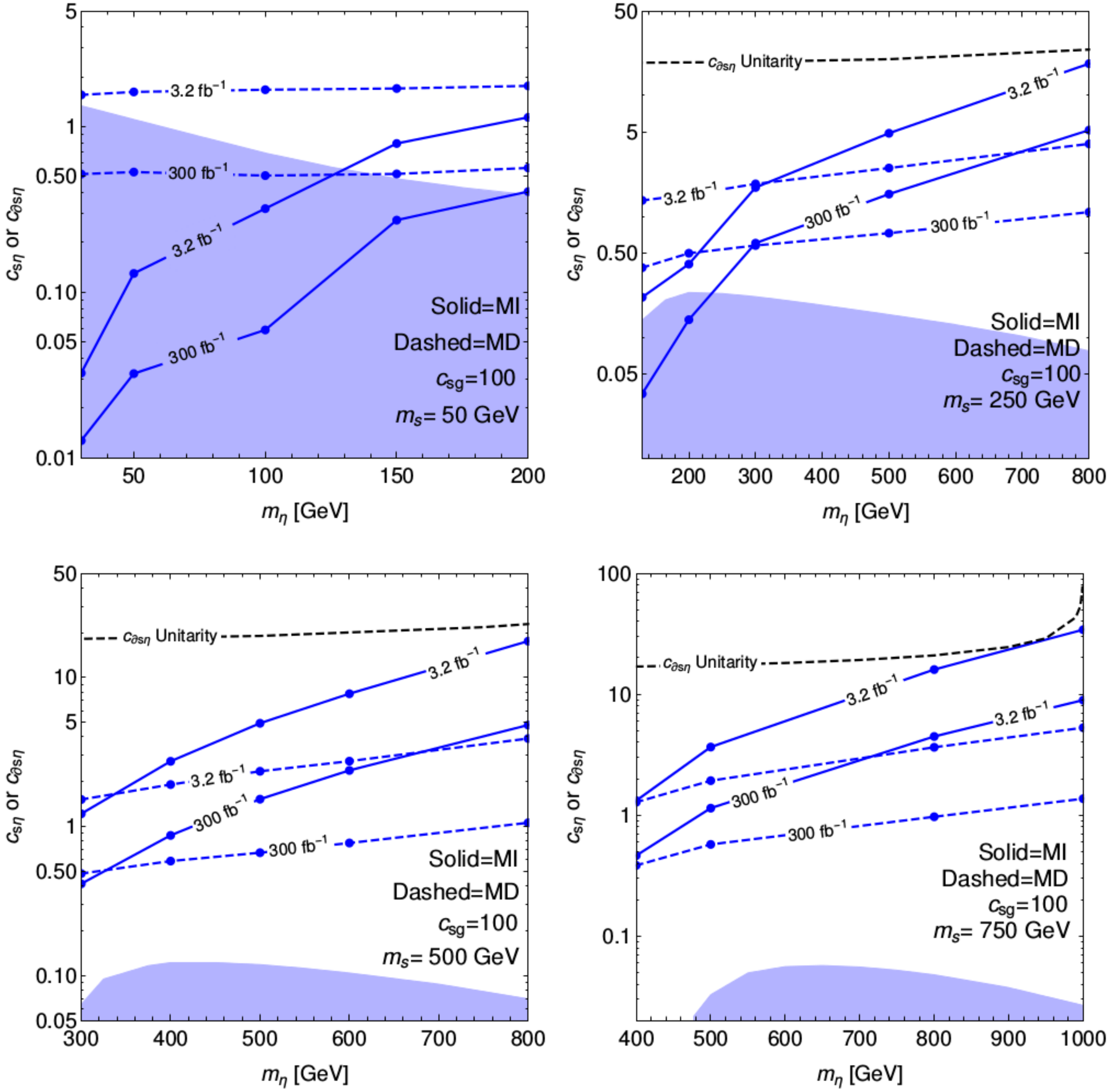
ATLAS Collaboration, arXiv:1604.07773
D. Sengupta, https://inspirehep.net/record/1476800

Projections inspired from the same analysis, including tighter MET requirements w/ background extrapolation (incl. uncertainty estimation).

MD operators are clearly more efficiently constrained, esp. for low dark matter masses. At higher masses the limits become essentially indistinguishable (although sensitivity gradually 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.

$$\mathcal{L}_\eta = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}\mu_\eta^2\eta^2 - \frac{1}{4}\lambda_\eta\eta^4 + \underbrace{\frac{1}{2}\lambda\eta^2 H^\dagger H}_{\text{Standard (dim-4) Higgs portal}} + \underbrace{\frac{1}{2f^2}(\partial_\mu\eta^2)\partial^\mu(H^\dagger H)}_{\text{Momentum-dependent coupling}}$$

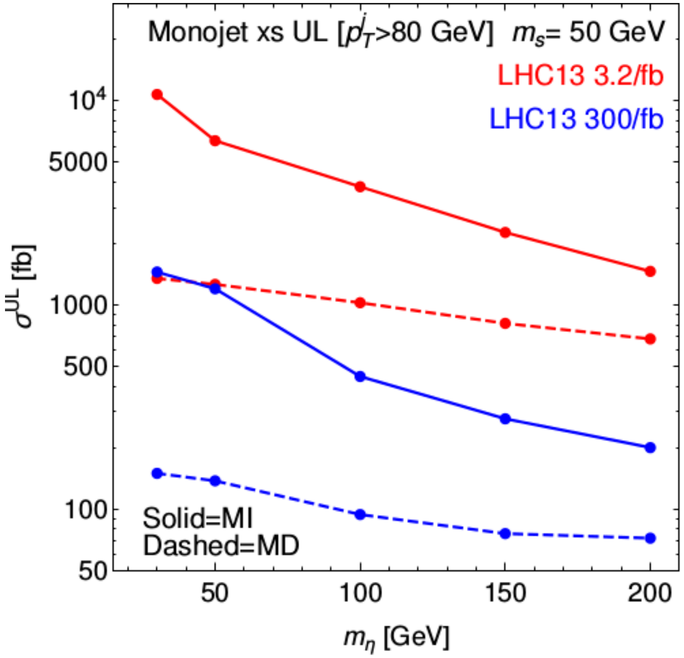
M. Frigerio, A. Pomarol, F. Riva, A. Urbano, arXiv:1204.2808

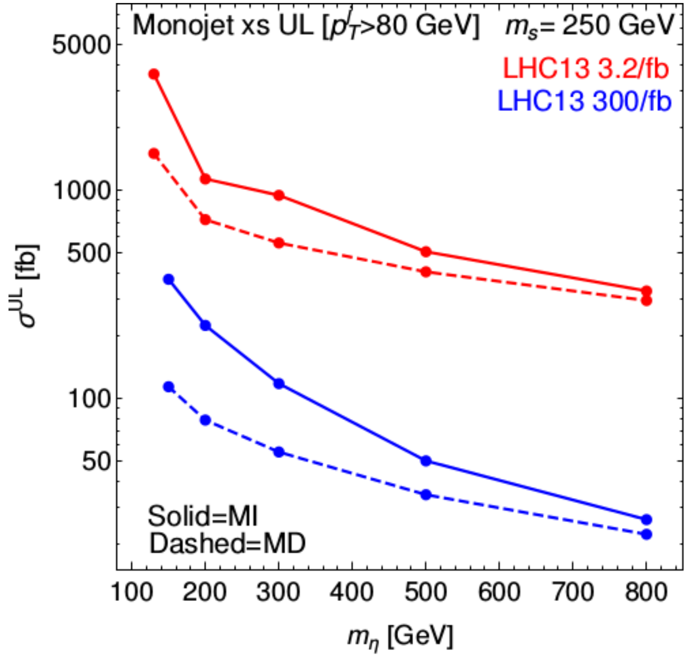
Upon EWSB, a Lagrangian term is generated $\mathcal{L}_\eta \supset -\frac{1}{4}(v+h)^2\left(\lambda\eta^2 + \frac{1}{f^2}\partial_\mu\partial^\mu\eta^2\right)$

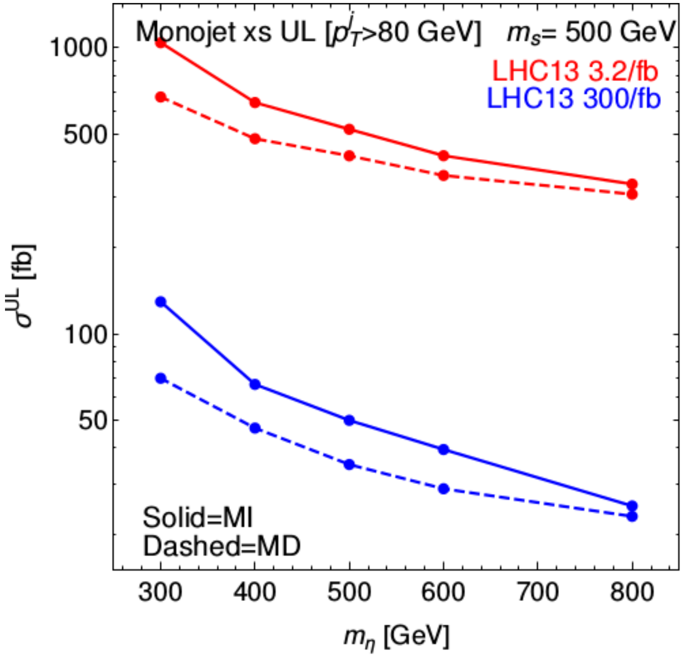
yielding an interaction vertex that scales as $\sim \frac{p_h^2}{f^2}$

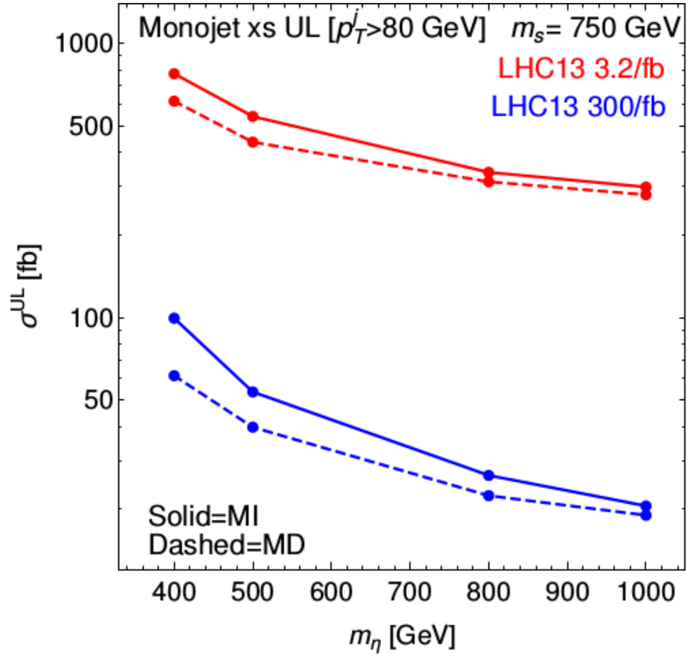
But in this minimal model, both the Higgs production cross section and the “compositeness scale” f are severely bound → The signal is found to be too weak...

Upper limits : more results

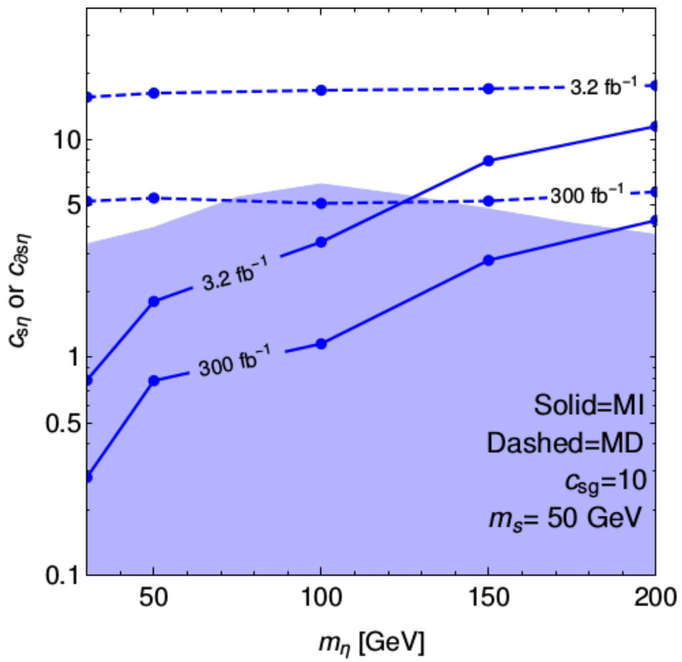




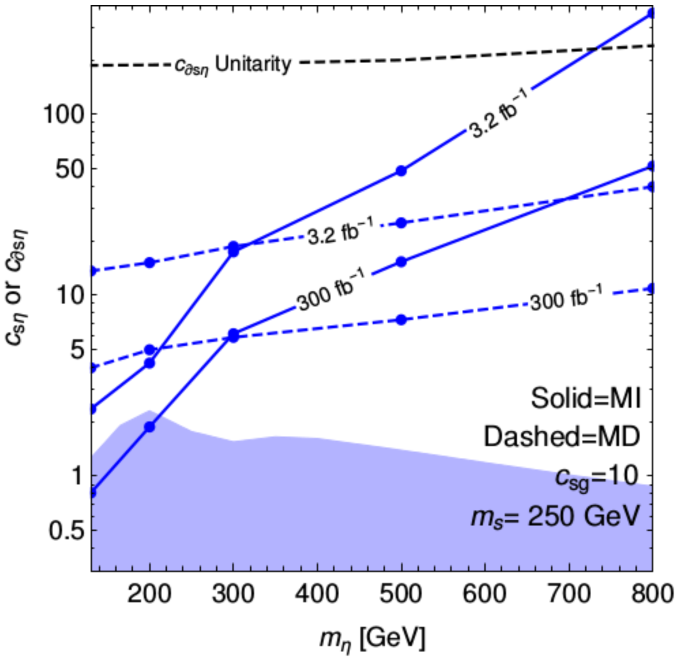




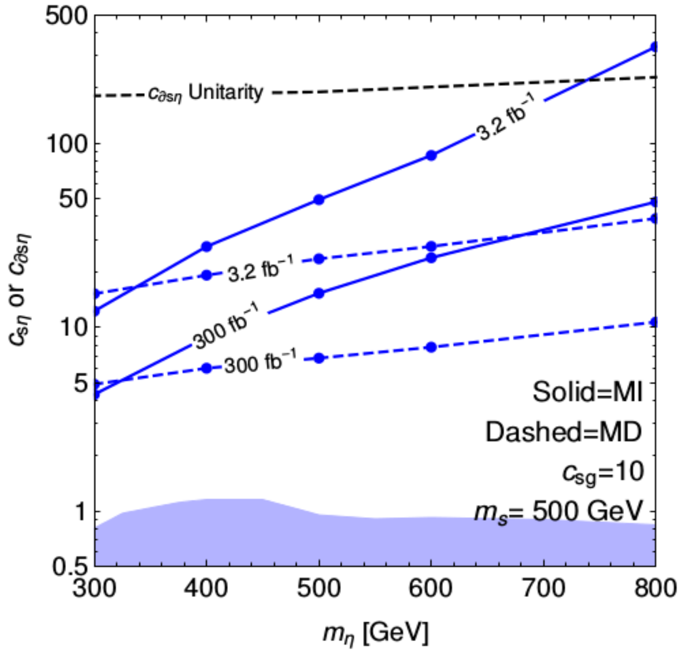
Varying c_{sg}



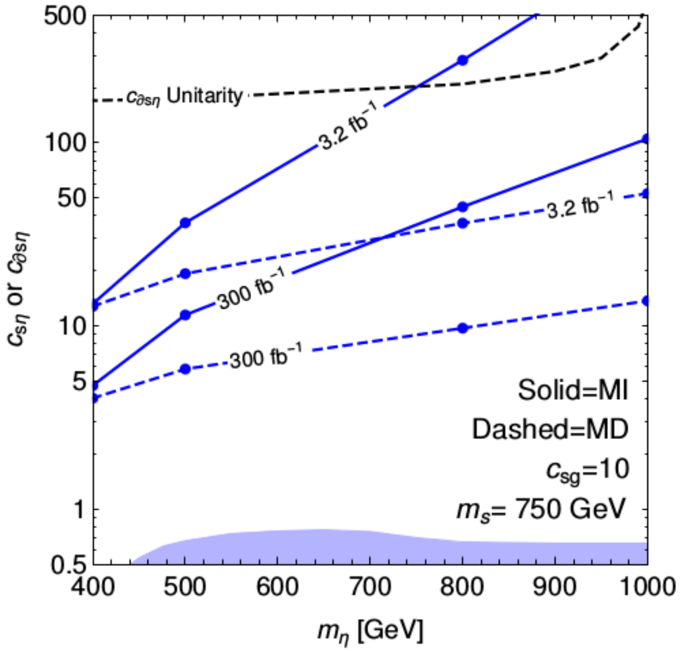
$c_{s\eta}$ or $c_{\partial s\eta}$
10
5
1
0.5
0.1
50
100
150
200
m_η [GeV]
3.2 fb^{-1}
300 fb^{-1}
3.2 fb^{-1}
300 fb^{-1}
Solid=MI
Dashed=MD
c_{sg}=10
m_s= 50 GeV



$c_{s\eta}$ or $c_{\partial s\eta}$
$c_{\partial s\eta}$ Unitarity
100
50
10
5
1
0.5
200
300
400
500
600
700
800
m_η [GeV]
3.2 fb^{-1}
3.2 fb^{-1}
300 fb^{-1}
300 fb^{-1}
Solid=MI
Dashed=MD
c_{sg}=10
m_s= 250 GeV



$c_{s\eta}$ or $c_{\partial s\eta}$
500
100
50
10
5
1
0.5
300
400
500
600
700
800
m_η [GeV]
$c_{\partial s\eta}$ Unitarity
3.2 fb^{-1}
3.2 fb^{-1}
300 fb^{-1}
300 fb^{-1}
Solid=MI
Dashed=MD
c_{sg}=10
m_s= 500 GeV



$c_{s\eta}$ or $c_{\partial s\eta}$
500
100
50
10
5
1
0.5
400
500
600
700
800
900
1000
m_η [GeV]
$c_{\partial s\eta}$ Unitarity
3.2 fb^{-1}
3.2 fb^{-1}
300 fb^{-1}
300 fb^{-1}
Solid=MI
Dashed=MD
c_{sg}=10
m_s= 750 GeV