Dark matter searches at the LHC

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Dark matter : Cosmology vs the LHC

(particle) Cosmology

- Dark matter is basically something that gravitates and is not made 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...

- Mass: essentially completely undetermined (depending on origin, though).

- Couplings to visible sector: idem.

- It has to be *very* long lived ($\tau >> 10^{17}$ sec).

LHC

- Dark matter is E_T^{miss} .

We have to be a bit lucky to find dark matter at the LHC!

(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 and, of course, G. Arcadi's talk :) !

- ...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

Vices and virtues of mono-X searches

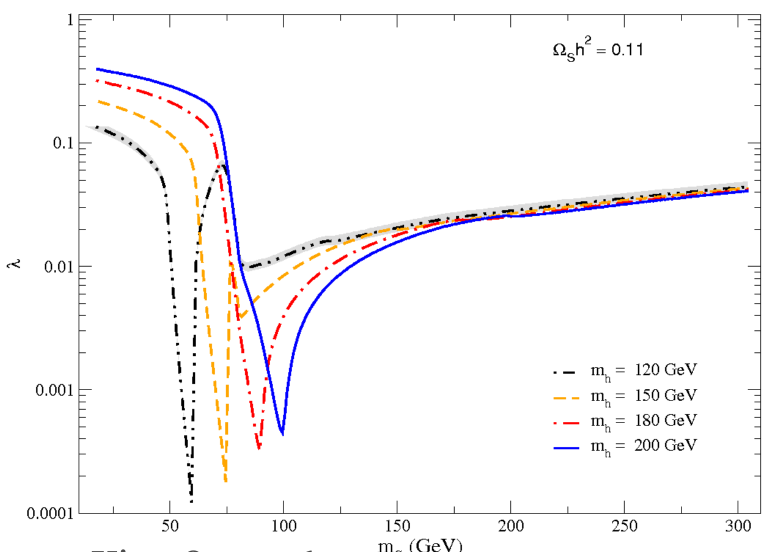
+ They are, perhaps, amongst the most generic dark matter searches (*e.g.* small dependence on Lorentz structure of underlying model).

- They say very little about the cosmological relevance of the “MET particles”.

+ For the moment, the only way to probe low mass (m_{DM} < (few) GeV) frozen-out relics.

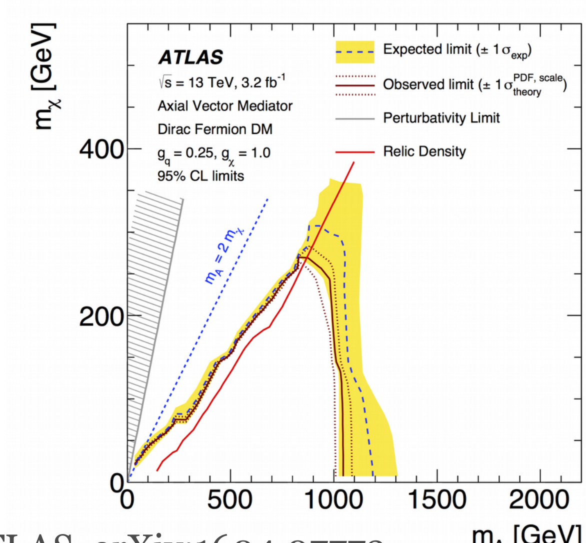
- For s-channel models (quite common), they can probe Planck – favoured regions for frozen-out relics only if $m_{DM} < m_{med}/2$.

The relic abundance prediction is insensitive to this condition (modulo thresholds).



C. Yaguna, arXiv:0810.4267

In the off-shell region, the LHC sensitivity drops dramatically.



ATLAS, arXiv:1604.07773

“Complementarity” is not just a buzzword, it’s essential!

Freeze-out and mono-X blind spots

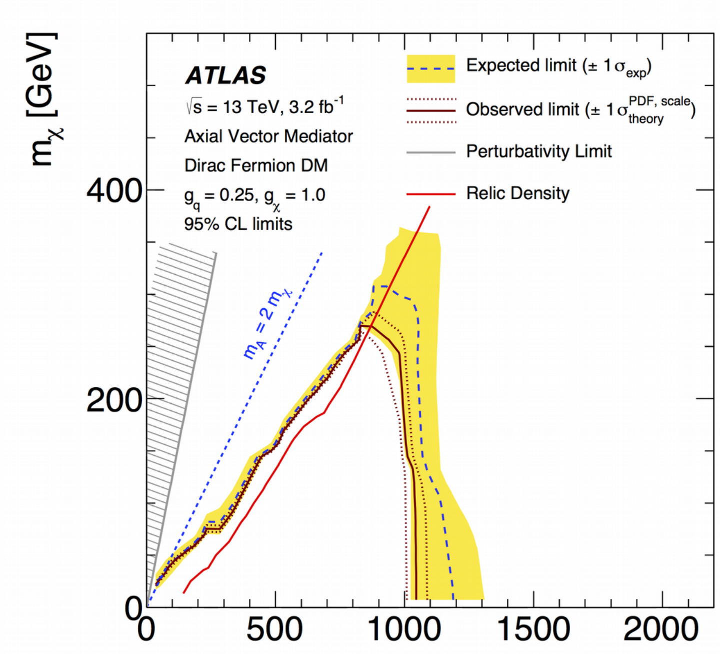
In thermal freeze-out models, typically 3 ways to obtain the correct relic abundance :

Adjust couplings — Probed by mono-X searches

Approach/take distance from resonances; Coannihilation — For general kinematics, imply very weak couplings

NB: Some would say fine-tuned

The most common (direct/indirect/mono-X) dark matter detection techniques fail in these configurations.



ATLAS, arXiv:1604.07773

And, in fact, in the simplest dark matter models (*e.g.* singlet scalar) it is essentially impossible to probe them.

But these are just "simplified models"! Typically, the dark sector consists of more than one states, which the LHC could produce

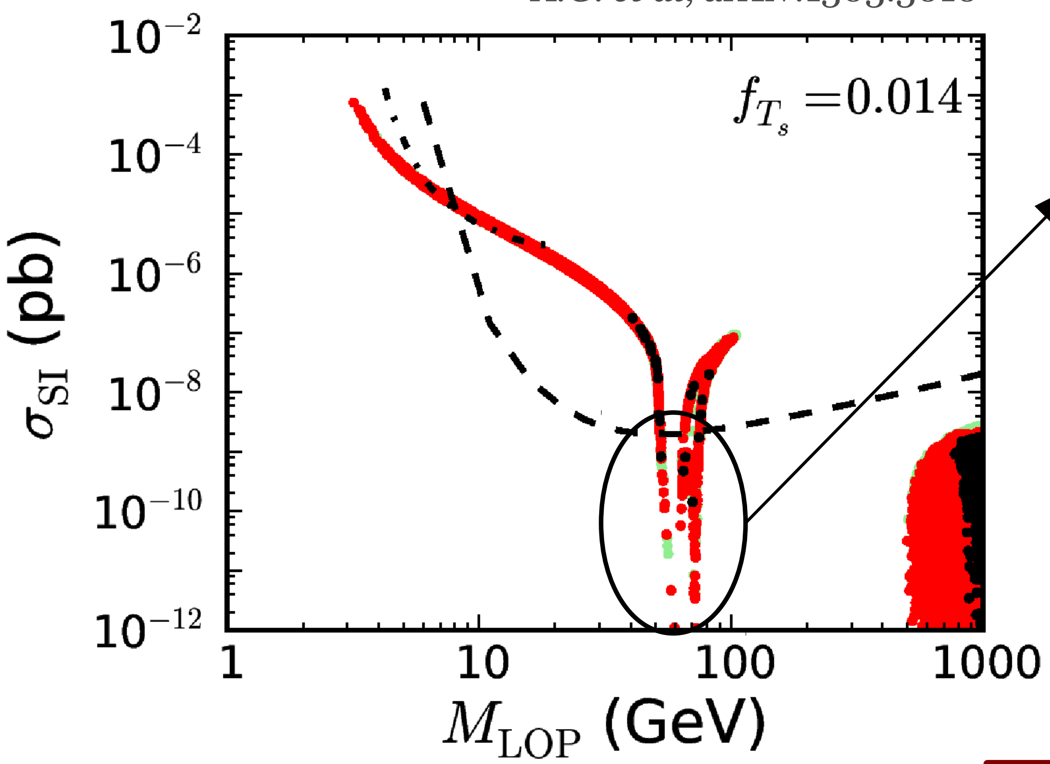
Probing funnels

Take the Inert Doublet Model as an example

- Gauge + spacetime symmetries : as in the SM.

- Particle content : $H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h^0 + iG^0\right) \end{pmatrix}, \quad \Phi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + iA^0\right) \end{pmatrix}$

A.G. *et al*, arXiv:1303.3010



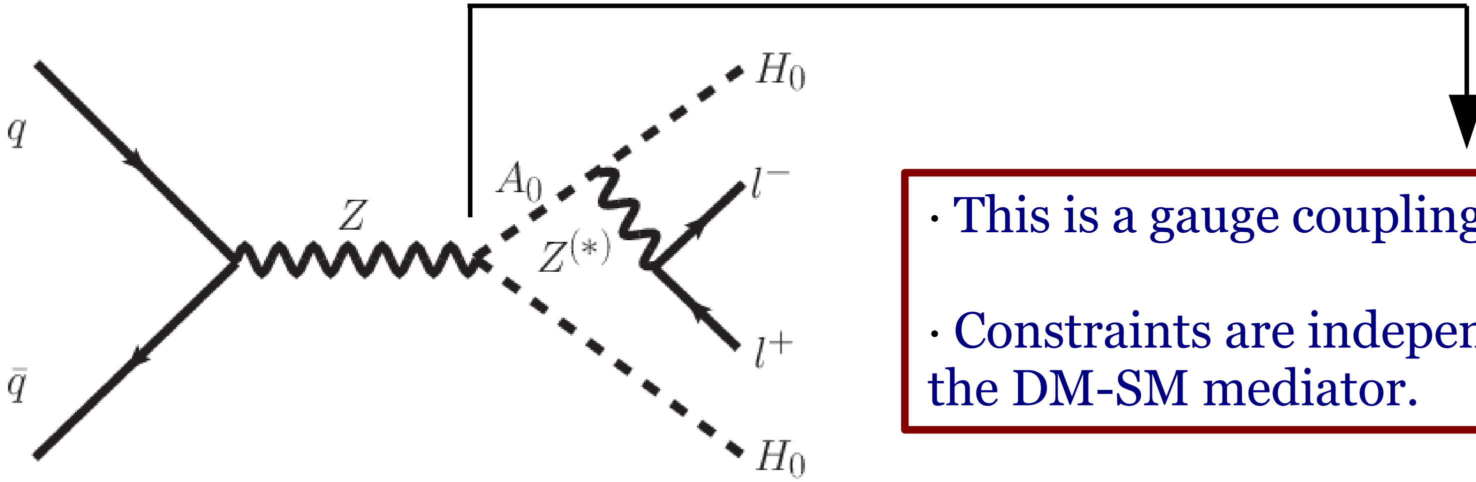
Contains the standard "Higgs funnel" region.

General idea: annihilation through s-channel resonance ($m_{DM} + E_{kin}$) in the early universe → small couplings. Resonance inefficient today (E_{kin} smaller), but couplings still small → hard to probe.

What about production of the heavier states?

Probing funnels

- The IDM contains a H° – A° – Z vertex. Consider the process



· This is a gauge coupling → it's fixed.

· Constraints are independent of the coupling to the DM-SM mediator.

Relevant LHC searches :

- SUSY searches for neutralinos/charginos/sleptons :

ATLAS-SUSY-2013-11
MA5 recasting: B. Dumont, http://inspirehep.net/record/1326686

$$\tilde{\chi}^{\pm} \to W^{\pm(*)} \tilde{\chi}_1^0$$
$$\tilde{\chi}^{\pm} \to \ell^{\pm} \tilde{\nu}$$
$$\tilde{\ell}^{\pm} \to \ell^{\pm} \tilde{\chi}_1^0$$

NB: Interestingly, $\tilde{\chi}_2^0 \tilde{\chi}_1^0 \to Z^{(*)}(\to \ell^+ \ell^-) \tilde{\chi}_1^0 \tilde{\chi}_1^0$ hasn't been considered.

- Searches for invisible Higgs decays.

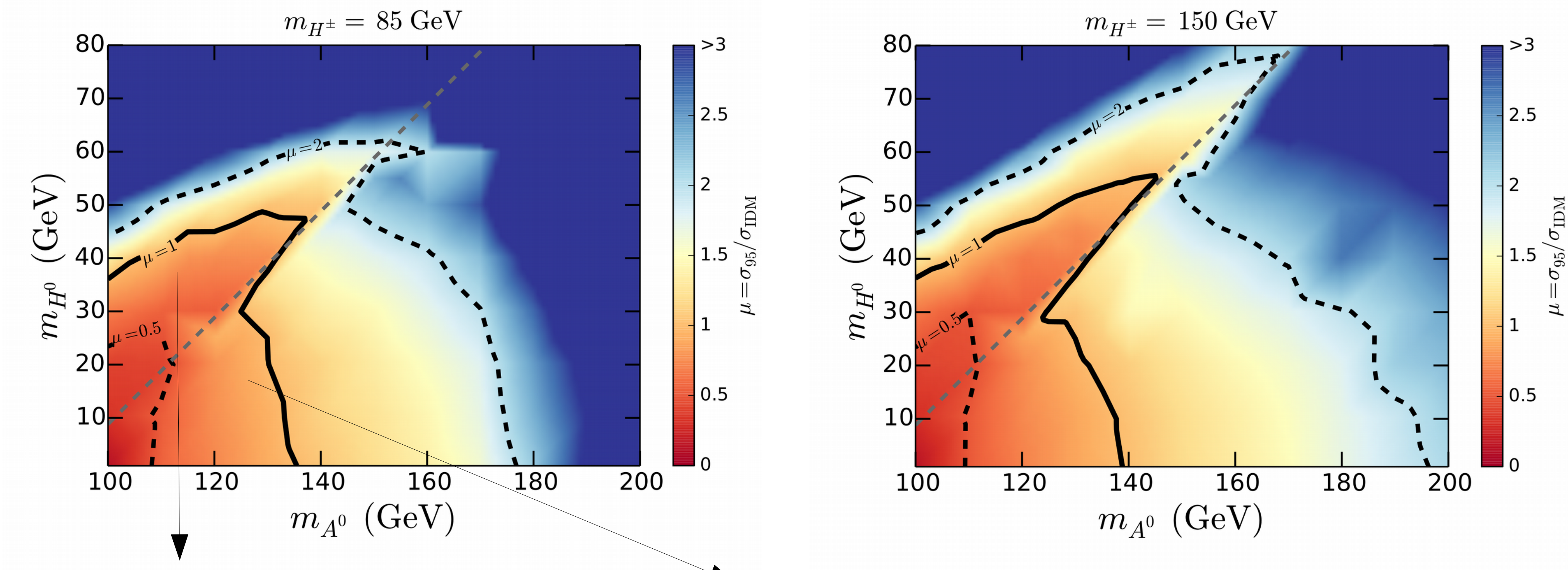
ATLAS-HIGG-2013-03
MA5 recasting: B. Dumont, https://inspirehep.net/record/1347081

- Mono-Z searches have too strong cuts → Inefficient.

Probing funnels

- The Run-1 results approached the funnel region.

G. Bélanger *et al*, arXiv:1503.07367



Mostly probed by SUSY searches.

Mostly probed by h → invisible searches.

- What about Run-2? Naive rescaling suggests that without any further optimisation, most of this parameter space will be probed with 300 fb^{-1} .

- A dedicated search could drastically increase the reach.

Perhaps a set of next-to-minimal simplified models?

Cf e.g. M. J. Baker *et al*, arXiv:1510.03434

The coannihilation region

- The coannihilation region suffers from similar problems as the funnel region: DM-SM couplings are too small.

- A systematic classification of coannihilation simplified models has been performed in arXiv:1510.03434. The problem: ***O***(140) models!

	$pp \to \ldots$	Prod. via	Signatures	Search
common	DM + DM + ISR	gauge int. or $SM_1 \in p$ for t-channel	mono-Y + $\slashed{E}_T$	[55,56,62,63,104]
	X ($\to SM_1^{soft}\ SM_2^{soft}$ DM) + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM) + ISR	gauge int. or $SM_2 \in p$ for t-channel	mono-Y + $\slashed{E}_T$ mono-Y + $\slashed{E}_T + \leq 4$ SM	[55,56,62,63,104] Partial coverage [105]
	DM + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM) + ISR	$(SM_1\ SM_2) \in p$	mono-Y + $\slashed{E}_T$ mono-Y + $\slashed{E}_T + \leq 2$ SM	[55,56,62,63,104] Partial coverage [105]
s-channel	M_s ($\to [SM_1\ SM_2]^{res}$) + M_s ($\to [SM_1\ SM_2]^{res}$)	gauge int.	2 resonances	[106–112]
	M_s ($\to [SM_1\ SM_2]^{res}$) + M_s ($\to$ DM + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM))		resonance + $\slashed{E}_T$ resonance + $\slashed{E}_T + \leq 2$ SM	No search No search
	M_s ($\to$ DM + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM)) + M_s ($\to$ DM + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM))		$\slashed{E}_T + \leq 4$ SM	[113,114,114–124]
	M_s ($\to [SM_1\ SM_2]^{res}$)	$(SM_1\ SM_2) \in p$	1 resonance	[125–146]
	M_s ($\to$ DM + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM))		$\slashed{E}_T + \leq 2$ SM	[120–122,124] [104,147–153]
	$SM_{1,2}$ + M_s ($\to [SM_1\ SM_2]^{res}$)	$SM_{2,1} \in p$	1 resonance + 1 SM	Partial coverage [154,155]
	$SM_{1,2}$ + M_s ($\to$ DM + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM))		$\slashed{E}_T + 1 \leq 3$ SM	[114,120–124] [147–153,156–158]
t-channel	M_t ($\to SM_1$ DM) + M_t ($\to SM_1$ DM)	gauge int.	$\slashed{E}_T + \leq 2$ SM	[120–122,124] [104,147–153]
	M_t ($\to SM_1$ DM) + M_t ($\to SM_2$ + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM))		$\slashed{E}_T + \leq 4$ SM	[106–112] [114,119–124]
	M_t ($\to SM_2$ + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM)) + M_t ($\to SM_2$ + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM))		$\slashed{E}_T + \leq 6$ SM	[113,114,120–124] [116–118,159–163]
	DM + M_t ($\to SM_1$ DM)	$SM_1 \in p$	$\slashed{E}_T + \leq 1$ SM	[55,56,62,63] [104,149]
	DM + M_t ($\to SM_2$ + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM))		$\slashed{E}_T + \leq 3$ SM	[114,120–124] [152,153,156–158]
	M_t ($\to SM_1$ DM) + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM)	$SM_2 \in p$	$\slashed{E}_T + \leq 3$ SM	[114,120–124] [152,153,156–158]
	M_t ($\to SM_2$ + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM)) + X ($\to SM_1^{soft}\ SM_2^{soft}$ DM)		$\slashed{E}_T + \leq 5$ SM	[113,114,116–124] [159–161,164]
hybrid	X ($\to$ DM + SM_3^{soft}) + X ($\to$ DM + SM_3^{soft})	gauge int. or $SM_3 \in p$	$\slashed{E}_T + \leq 2$ SM	[120–122,124] [104,147–153]
	DM + X ($\to$ DM + SM_3^{soft})	$SM_3 \in p$	$\slashed{E}_T + \leq 1$ SM	[128,129,149] [55,56,62,63,104]

- Signature-based classification is, nonetheless, more compact.

- Most cases involve soft objects (along with substantial MET, though).

- Many of these signatures are actually being considered by ATLAS/CMS, although not necessarily optimised for dark matter searches.

- Reinterpretations definitely missing.

The off-shell regime

- In s-channel mediated models, once $m_{DM} > m_{med}/2$, a $(m_{med}/Q)^2$ suppression appears which kills hard ISR.

- Consider at least models where such effects become milder, e.g. momentum-dependent dark matter couplings.

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

Standard (MI) scalar coupling

Mediator coupling to gluons

Derivative coupling

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

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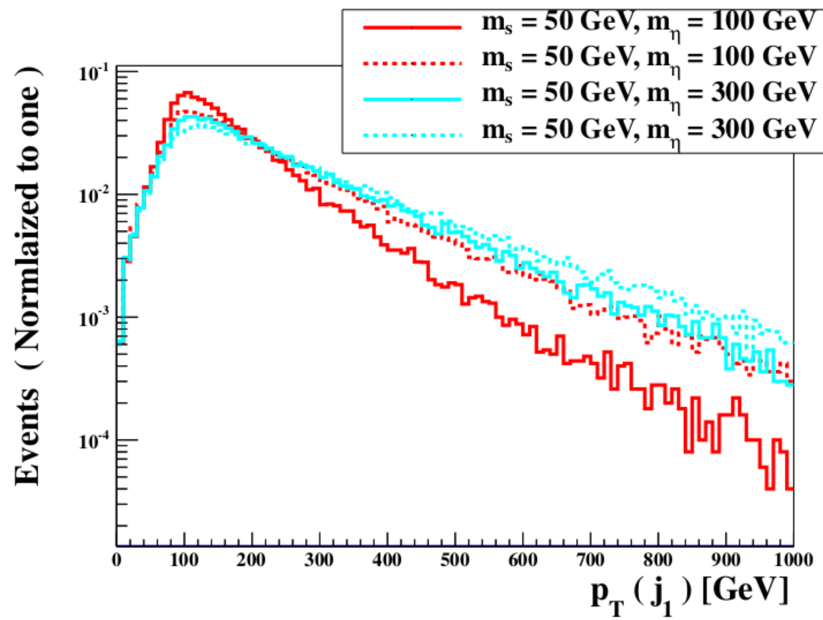
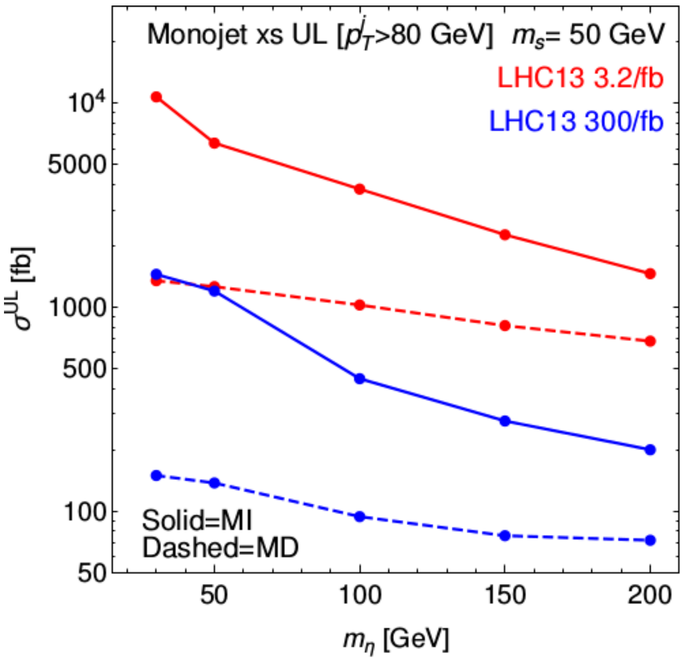
D. Barducci *et al*, arXiv:1609.07490





- High-energy tail of p_T distribution significantly enhanced, leading to stronger constraints wrt conventional scenarios.

NB: Effect only present in the off-shell regime.

- Part of Planck-favoured region can be probed.

- Could be used to pinpoint underlying theory? In progress, stay tuned :)

Summary and outlook

- The LHC can probe frozen-out dark matter candidates with masses from a few hundreds of GeV downwards.

- Conventional mono-X searches have blind spots: (early universe) resonances, coannihilation configurations. However, these blind spots affect all dark matter detection modes!

- Mono-X searches are, moreover, less sensitive to some subtleties that can be crucial for direct/indirect detection (*e.g.* velocity suppression).

- The LHC further offers numerous possibilities for dark matter searches beyond the mono-X ones, based on production of the heavier states in the dark sector → helpful for covering blind spots (and unique to the LHC), they could perhaps probe part of the super-WIMP mechanism.

Cf G. Arcadi's talk

- Can we figure out a tractable number of simple next-to-minimal dark matter models capturing extended signatures?

- What alternative dark matter generation mechanisms can the LHC explore?

- Assume we observe a dark matter signal at the LHC in some mono-X channel. Can we distinguish between different models? If yes, which?

Seen differently: what if we reconstruct the DM properties with the wrong model?

Thank you!