Dark matter at colliders.

A theory review

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Interplay between Particle and Astroparticle Physics
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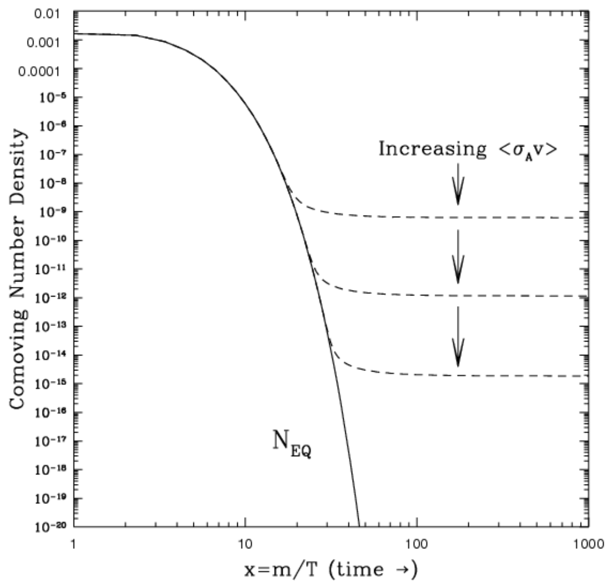
DESY

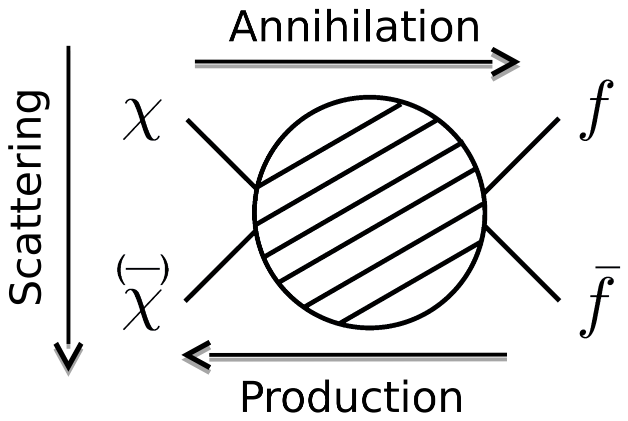
Outline

- Motivation for DM searches at colliders
- From effective field theories to simplified models
- Difficulties of the simplified-model approach
- Complementarity of different LHC searches
- Global analyses

Why do we search for dark matter at colliders?

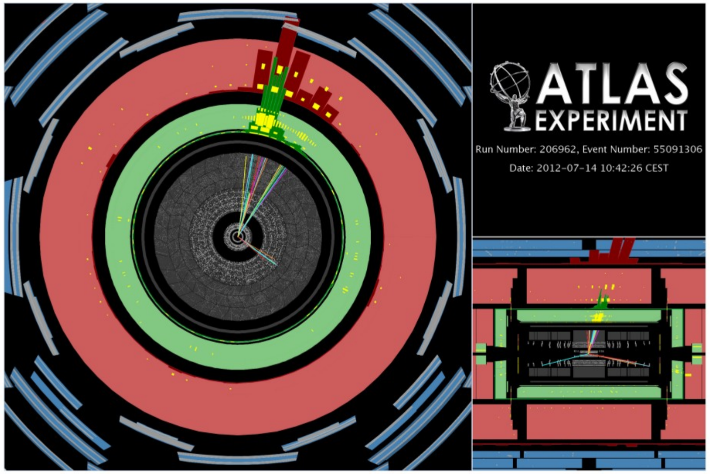
- Fundamental motivation: the paradigm of thermal freeze-out
  - DM was in thermal equilibrium with SM states at high temperatures
  - At lower temperatures the interactions freeze out
  - A particle with weak interactions and a weak-scale mass would obtain roughly the observed DM abundance



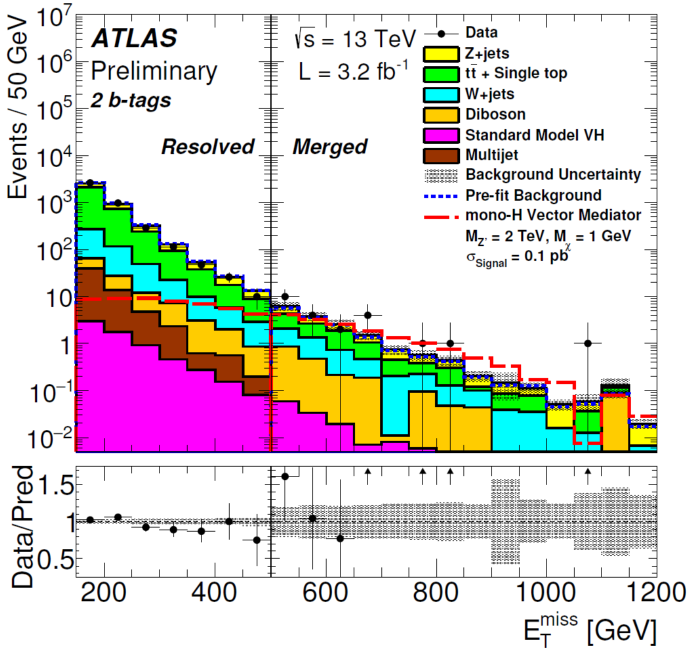


- In this framework, DM cannot be arbitrarily heavy (typically < 100 TeV) and must have sizeable interactions with SM particles
- Colliders may allow us to "invert" the annihilation processes that occurred in the early Universe

How do we search for dark matter at colliders?



- Since any DM particle produced at a collider will escape unnoticed, the central strategy to identify DM is to look for unbalanced transverse momentum.



- Unfortunately, DM is not the only invisible particle. There are large backgrounds from
  - $Z \to \nu\nu$
  - $W \to l\nu$ (with unobserved lepton)
  - misreconstructed jets

- For most backgrounds, however, the missing energy spectrum falls more steeply than the signal.

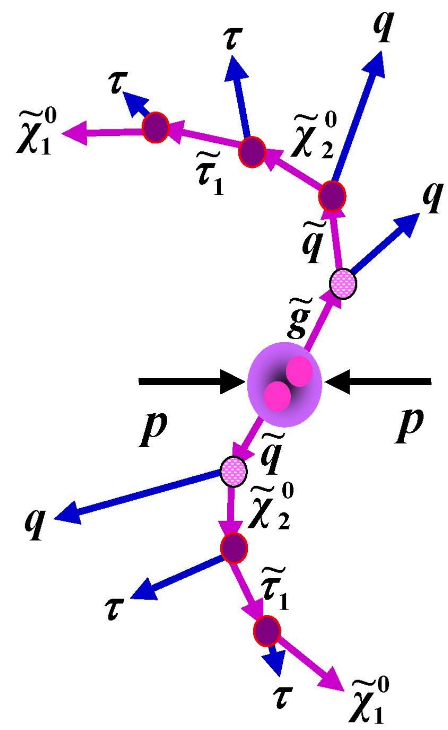
Searches for dark matter are everywhere

- Most models that attempt to solve the hierarchy problem need to introduce new states at the electroweak scale.

- The lightest of these states is typically stable and thus constitutes a typical WIMP.

- Many searches for these kinds of models rely on the fact that any new heavier state produced at the LHC needs to ultimately decay into the DM particle and SM states, leading to missing energy in the detector.

- However, in these models it is typically very difficult to produce the DM particle directly, so the LHC is often not sensitive to its properties.



- For the purpose of this talk, I will not consider these kinds of models and focus on the case where the LHC can hope to directly produce DM.

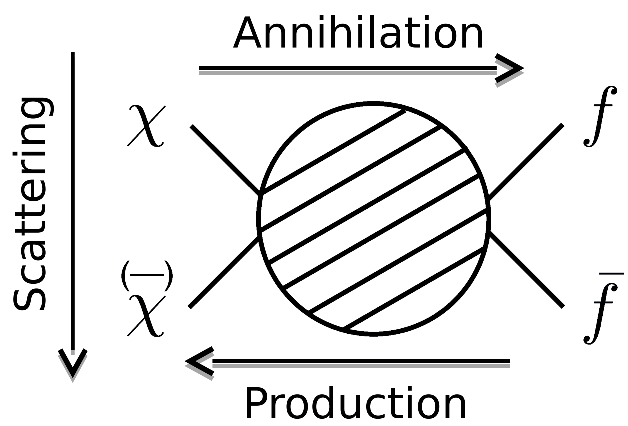
What makes LHC DM searches special?

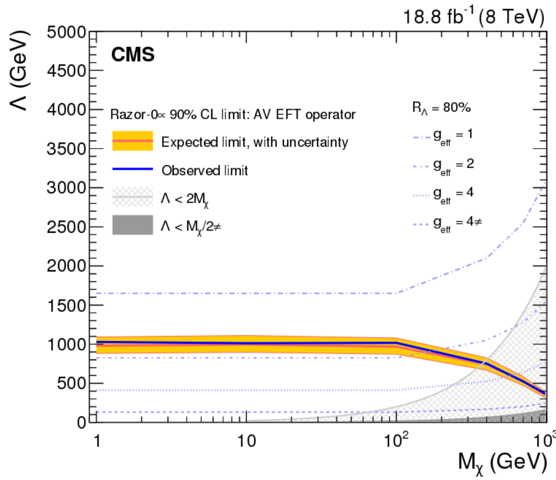
- Minimality:
  - We want to make as few assumptions as possible on the presence of new particles in the dark sector.
  - No complicated decay changes, small number of SM particles in the final state.
- Complementarity
  - The LHC alone cannot establish the stability of invisible particles.
  - To infer the DM nature of such a particle necessarily involves the connection to non-collider experiments, such as direct or indirect detection, and to cosmological observations, for example of the DM relic density.

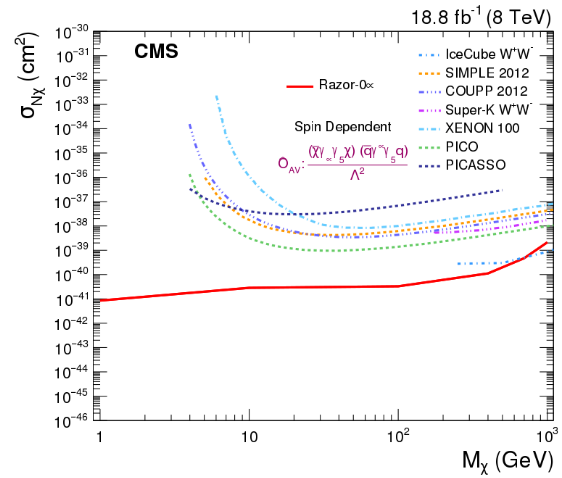
The EFT approach to DM searches

- In the interest of minimality, we can parametrise the interactions of DM and quarks in terms of effective operators.
- Resulting kinematic distributions are independent of the suppression scale *Λ*.
- All DM searches constrain the same scale Λ, so we can directly compare bounds from different search strategies.
- This approach promises a straight-forward and widely applicable interpretation of LHC searches.

$\Delta\mathscr{L}$		Int.	Suppression
$\mathcal{O}_s^\phi$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}f$	SI	1
$\mathcal{O}_v^\phi$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}_{va}^\phi$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2
$\mathcal{O}_p^\phi$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}_s^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}f$	SI	1
$\mathcal{O}_v^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}_a^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	1
$\mathcal{O}_t^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\sigma^{\mu\nu}\psi\bar{f}\sigma_{\mu\nu} f$	SD	1
$\mathcal{O}_p^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4
$\mathcal{O}_{va}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2, q^2
$\mathcal{O}_{pt}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}i\sigma^{\mu\nu}\gamma^5\psi\bar{f}\sigma_{\mu\nu} f$	SI	q^2
$\mathcal{O}_{ps}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}i\gamma^5\psi\bar{f}f$	SI	q^2
$\mathcal{O}_{sp}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}_{av}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu f$	SI SD	v^2 q^2
$\hat{\mathcal{O}}_s^\phi$:	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{f}f$	SI	1
$\hat{\mathcal{O}}_s^\psi$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\psi\bar{f}f$	SI	1
$\hat{\mathcal{O}}_p^\psi$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4



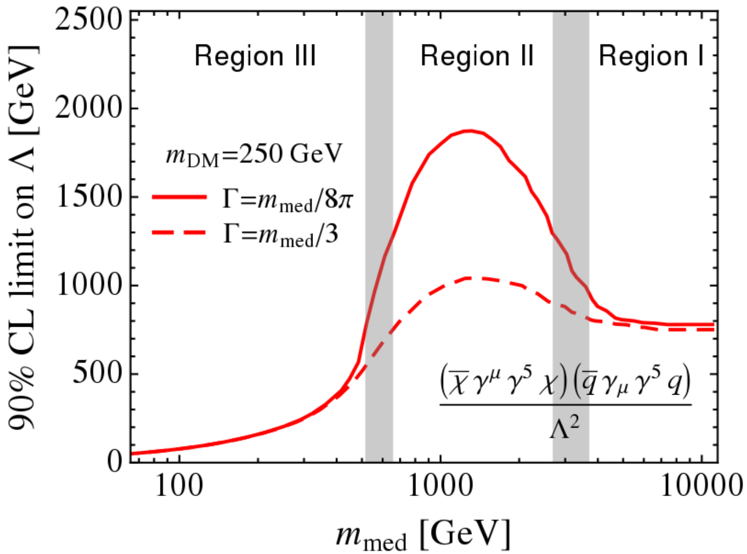




CMS, arXiv:1603.08914

Should we move beyond EFTs?

- Complaint 1:
  - EFTs predict very specific kinematics (hard MET spectra), so experimental searches may be biased.
  - To optimise the sensitivity for a wider range of models, one needs to consider a more flexible parametrization.



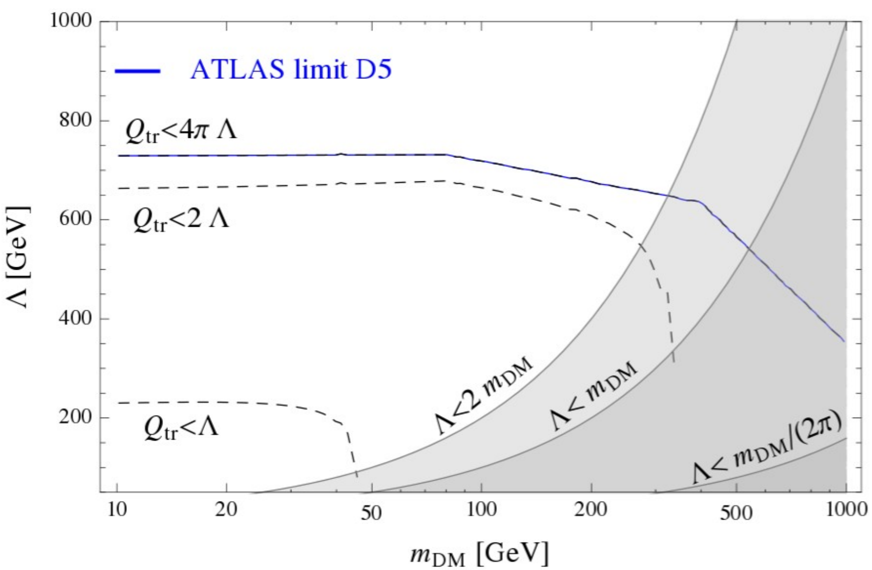
Buchmueller et al., arXiv:1308.6799

- Complaint 2:
  - Bounds on the EFT suppression scale may be unphysical (i.e. low compared to the region of EFT validity).
  - It is then not directly possible to compare LHC bounds to other kinds of DM searchers.

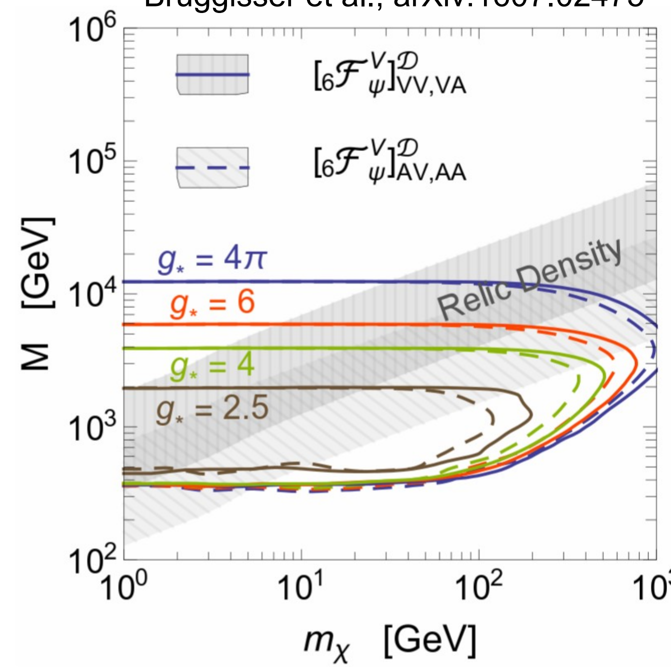
Consistent EFTs

- It is possible to address these issues within the EFT framework by introducing a self-consistent truncation procedure.

Busoni et al.,arXiv:1402.1275



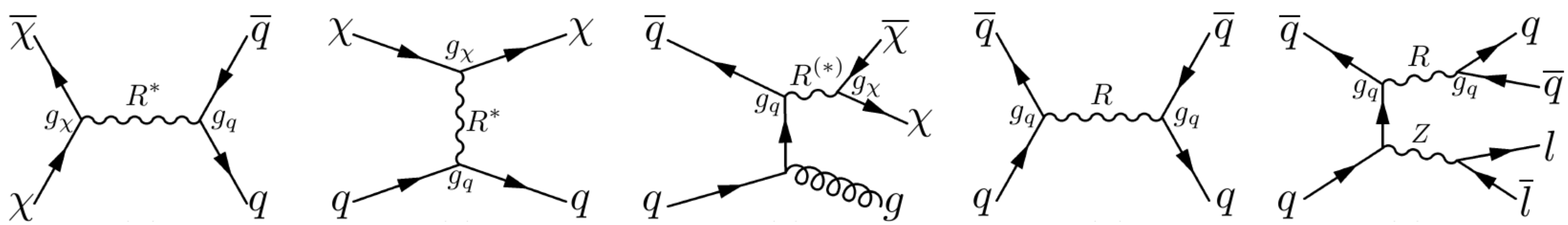
Bruggisser et al., arXiv:1607.02475



- This approach yields an appropriate (and in some cases even the only possible) description for DM models that are strongly coupled in the UV.

Simplified models

- Nevertheless, there are many models of DM which are simply not well described by an EFT at LHC energies.
- This makes it necessary to extend the parameter space in such a way that the kinematic distributions for a wider range of DM models can be captured.
- Basic idea: We should not limit ourselves to the assumption that the particles responsible for mediating DM interactions are very heavy.
- Indeed, if the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting.



New mediators

- The ATLAS/CMS DM Forum and the LHC DM Working Group have now compiled a list of “simplified models” containing an (s-channel or t-channel) mediator coupling to quarks and DM.

Abdallah, FK et al., arXiv:1506.03116
Abercrombie, FK et al., arXiv:1507.00966
Boveia, FK et al., arXiv:1603.04156

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

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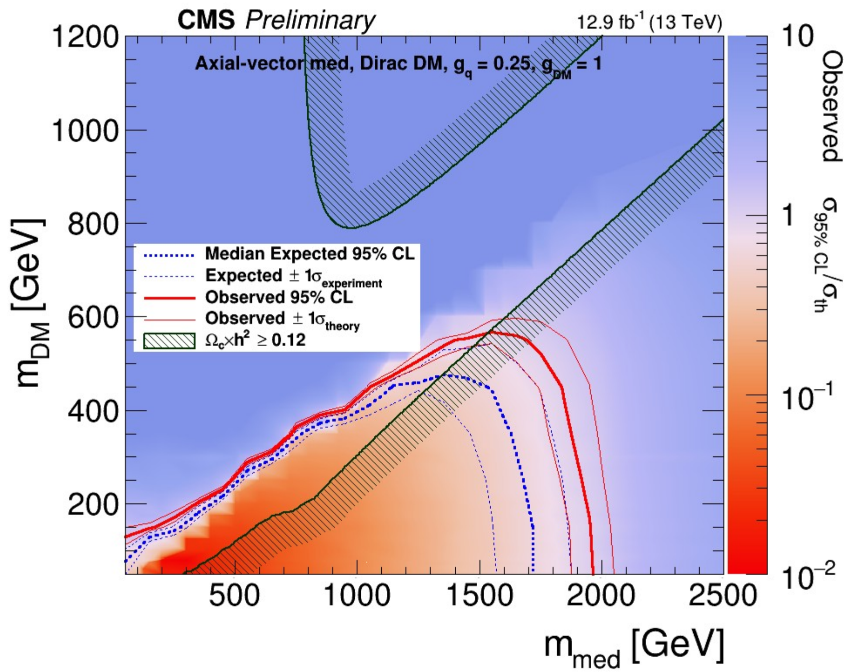
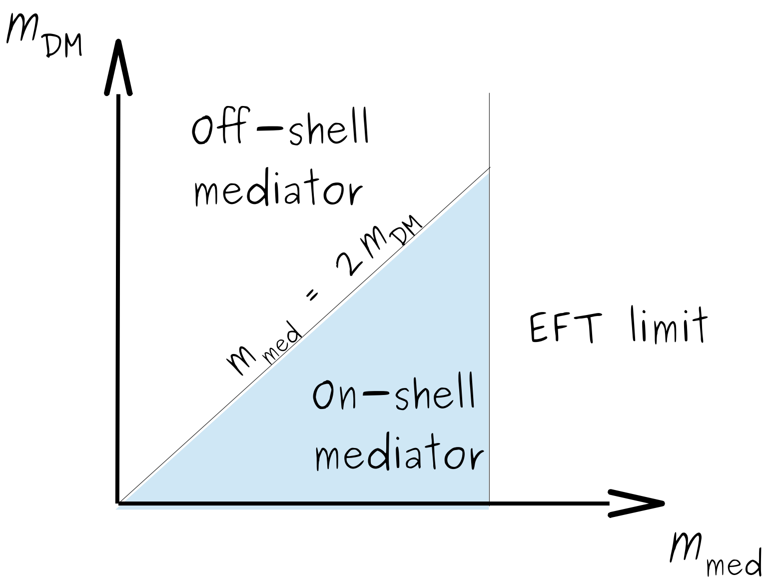
- There are two ways to think of these simplified models:
  - In a top-down approach, these models represent a simplification of a UV-complete theory of DM, boiled down to capture the most relevant experimental signatures.
  - In a bottom-up approach, these models contain the minimal number of ingredients necessary to calculate predictions for a range of different experiments in a self-consistent way.

Presentation of simplified model results

- Experimental bounds on DM simplified models are now conventionally presented in the parameter plane showing DM mass versus mediator mass.





- This presentation is useful for comparing the sensitivity of different LHC searches as well as for comparing the performance of the LHC with information inferred from the DM relic abundance.

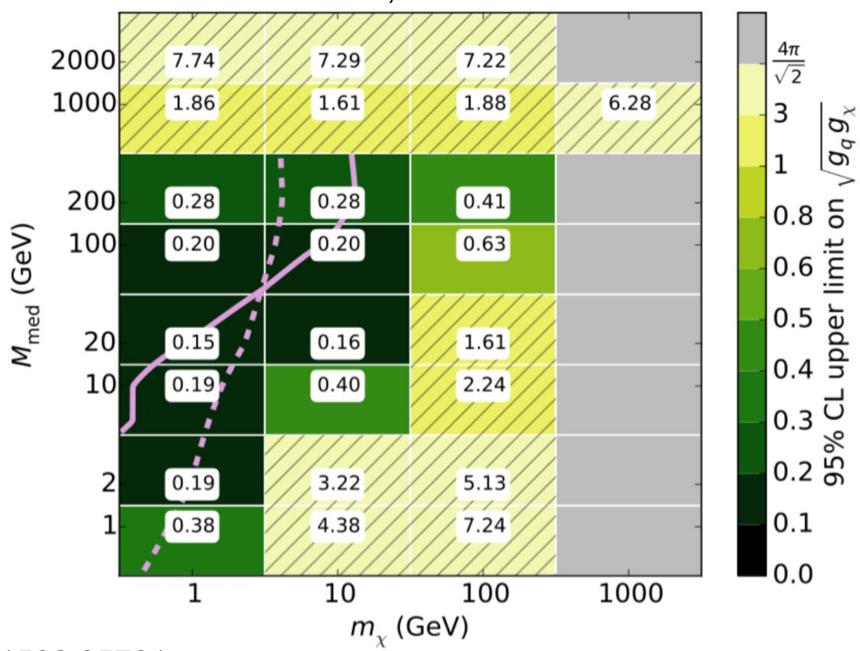
Reinterpretation of LHC DM searches

- It is not straight-forward to reinterpret these mass-mass plots for different model assumptions (or even just different coupling choices in the same model).
- There are some ideas for how to provide additional information to facilitate such a reinterpretation.
  - For example, one could make use of analytical approximations, such as the narrow-width approximation in the on-shell region:

$$\sigma(q\bar{q} \to Z' + Y \to xy + Y) = \sigma(q\bar{q} \to Z' + Y) \cdot \mathrm{BR}(Z' \to xy)$$

  - A bound on the signal strength can then be used to infer a limit on the invisible branching ratio of the mediator.
  - This approach fails, however, close to the boundary of the on-shell region and for broad widths.

Brennan et al., arXiv:1603.01366



Jacques & Nordstrom, arXiv:1502.05721

Are simplified models too simplified?

- For the LHC community, the main purpose of simplified DM models is to generate events with missing energy and to study the kinematic distributions.
- To be useful, a simplified model does not need to be theoretically consistent – it only needs to parametrize the properties of the invisible particles in an efficient way.
- As soon as one is interested in comparing results from the LHC with other experimental or observational probes of DM, however, a more ambitious approach is required.

FK et al., arXiv:1510.02110

- It then becomes essential that the models under consideration full certain basic requirements, such as gauge invariance and perturbative unitarity.

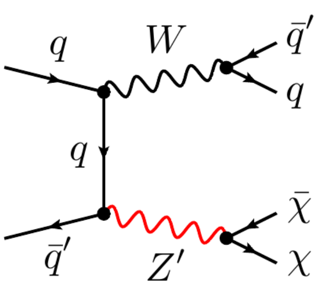
Simplified models: Problems with gauge invariance

- A number of simplified models have been proposed that only respect the symmetries of the broken gauge group SU(3) x U(1), but are not gauge invariant under SU(3) x SU(2) x U(1)

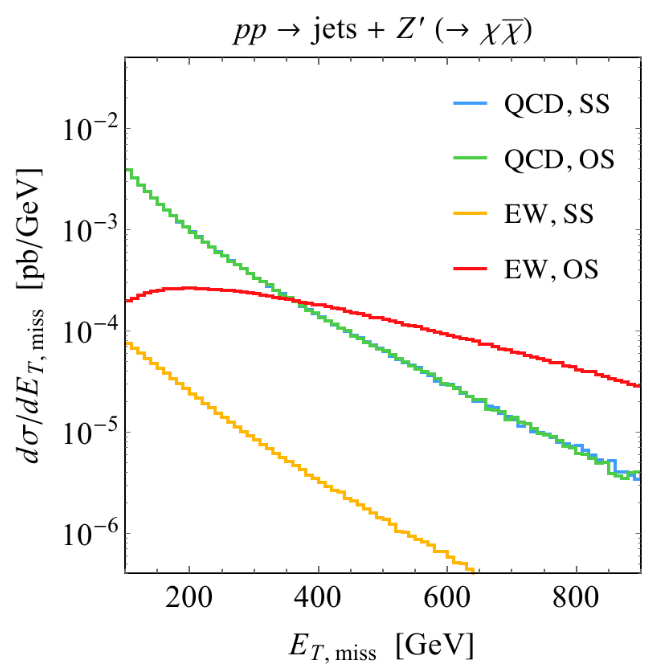
  Bell et al., arXiv:1512.00476

  - Spin-0 s-channel mediators
  - Spin-1 s-channel mediators with different couplings to up- and down-quarks.

- Such structures not only make it more difficult to find a viable UV-completion, but they may also lead to unphysical predictions, such as the violation of perturbative unitarity in LHC DM searches.



$$\mathcal{M}^1 = \frac{g\,s}{96\pi\, M_W\, M_{Z'}} \left(g_u^A - g_d^A - g_u^V + g_d^V\right)$$



Haisch, FK & Tait, arXiv:1603.01267

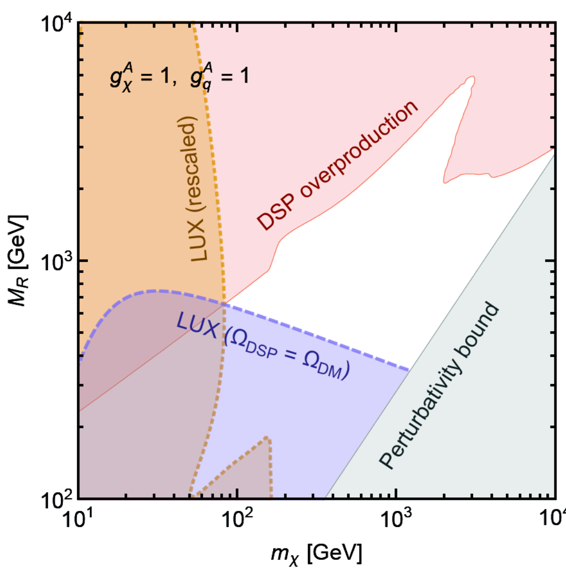
Simplified models: Problems with unitarity

- A more subtle issue arises for spin-1 s-channel mediators with axial couplings.
- In this case, the longitudinal component of the mediator couples to fermions with coupling strength $2\, g_f^A\, m_f / m_{Z'}$.
- The requirement that this coupling does not violate perturbative unitarity yields an upper bound on the fermion masses:

$$m_f \lesssim \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_f^A}$$

FK et al., arXiv:1510.02110

- This is not an issue for LHC searches, since only very light fermions contribute in the initial state. Englert et al., arXiv:1604.07975
- It does however become important for the calculation of the relic density, which depends on the annihilation cross section of DM into top-quarks.



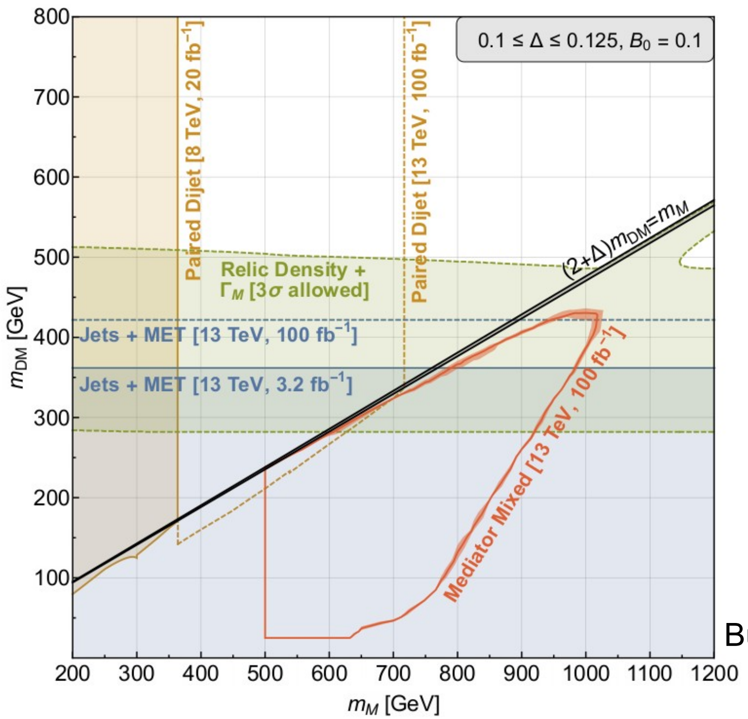
Chala, FK et al., arXiv:1503.05916

Extended simplified models

- For these and other reasons it is fairly clear that the current set of simplified models considered by the LHC collaborations will not be the end of the story.

- Many extensions have been proposed already:
  - Combinations of several simplified models (e.g. vector and Higgs portal mediator)

Choudhury et al., arXiv:1509.05771
Duerr, FK et al., arXiv:1606.07609



Buschmann et al., arXiv:1605.08056

  - Simplified models in which the DM particle can co-annihilate with a second dark sector state

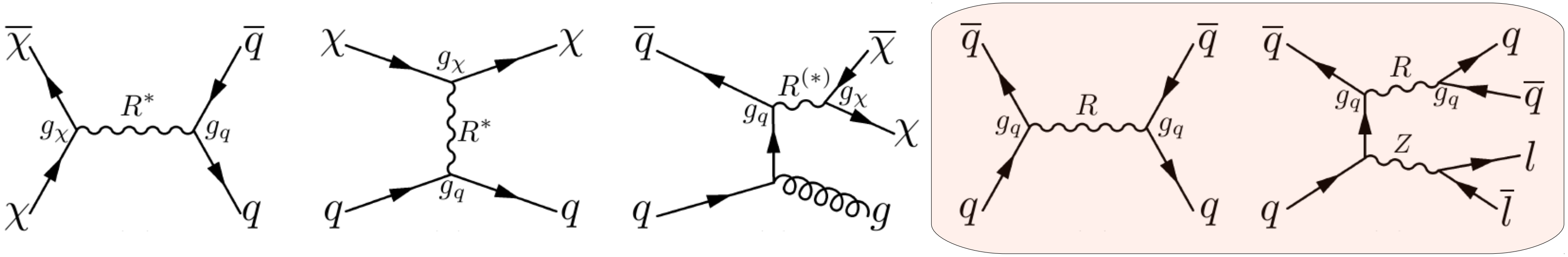
Baker et al., arXiv:1510.03434

In such models many new experimental signatures can be expected, like dijet resonances in association with missing energy.

Autran et al., arXiv:1504.01386
Bai et al., arXiv:1504.01395
Gupta et al., arXiv:1504.01385

Complementarity with other LHC searches

- A particularly interesting avenue is to consider the complementarity of LHC searches for missing energy with other LHC searches.
- The mediator of the DM interactions will also lead to new interactions between Standard Model states.

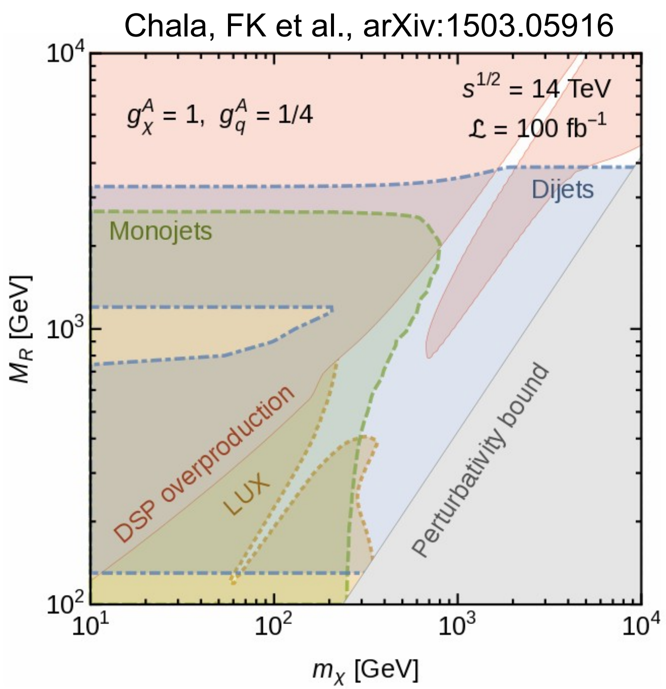


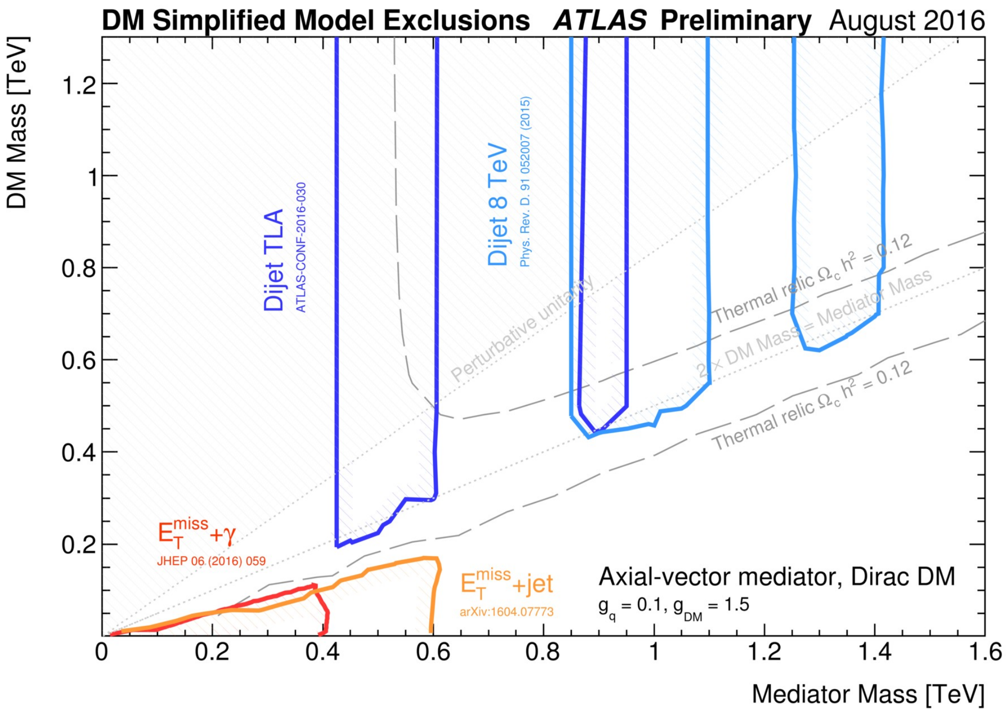
- There may be observable signals from processes involving no DM particles at all.
- For example, if the mediator can be produced at the LHC, it can also decay back into quarks.
- One should therefore consider dedicated searches for the mediator particles themselves, such as searches for dijet resonances.

An, Ji & Wang, arXiv:1202.2894
Chala, FK et al., arXiv:1503.05916

Complementarity of monojet and dijet searches

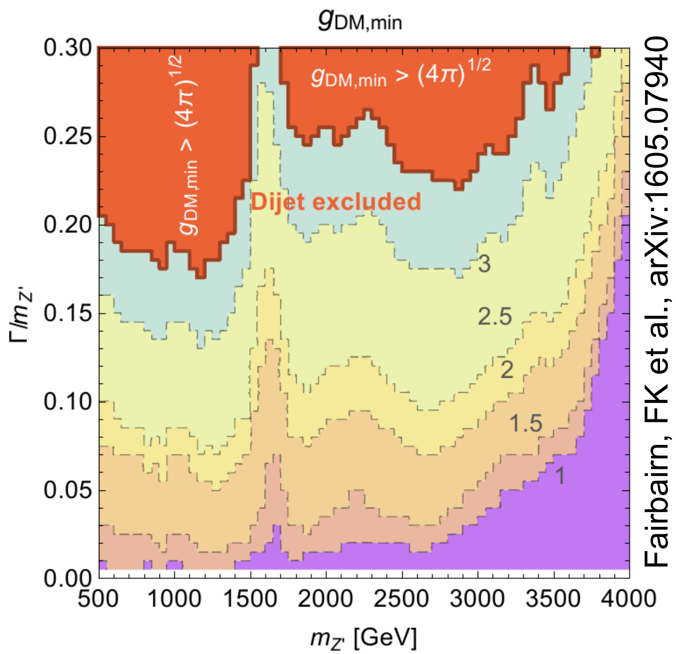
- By definition, searches for the visible decay modes of the mediator are highly complementary to searches for the invisible decay modes.



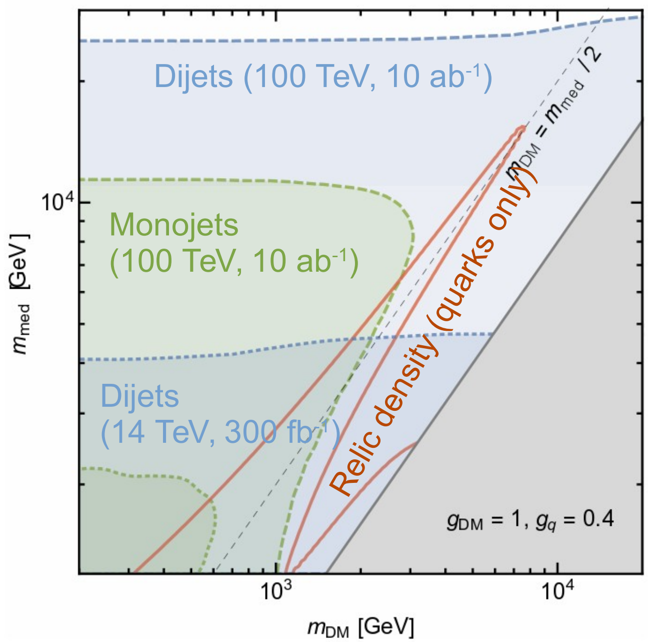


Dijets and relic density

- Searches for dijet resonances may be the most sensitive probe for models of Majorana DM in which the relic density is set via freeze-out into quarks.
- To be consistent with current bounds from the LHC, the Z'-DM coupling must be very large (to hide the resonance at the LHC via invisible decays).



Fairbairn, FK et al., arXiv:1605.07940



Physics at a 100 TeV pp collider: beyond the Standard Model phenomena, arXiv:1606.00947

- A 100 TeV collider may even be able to probe the resonance region $m_{DM} \sim m_{Z'}/2$

Mapping from the LHC onto direct detection experiments

- For Spin-0 and Spin-1/2 WIMPs, DM-nucleon interactions in the non-relativistic limit can be described by a set of 14 operators (requiring 28 parameters when allowing different couplings to protons and neutrons).

- Differential event rates and nuclear form factors have been calculated for all of these operators.

  Fitzpatrick et al., arXiv:1203.3542

- The mapping from simplified models onto these operators has recently been investigated in detail.

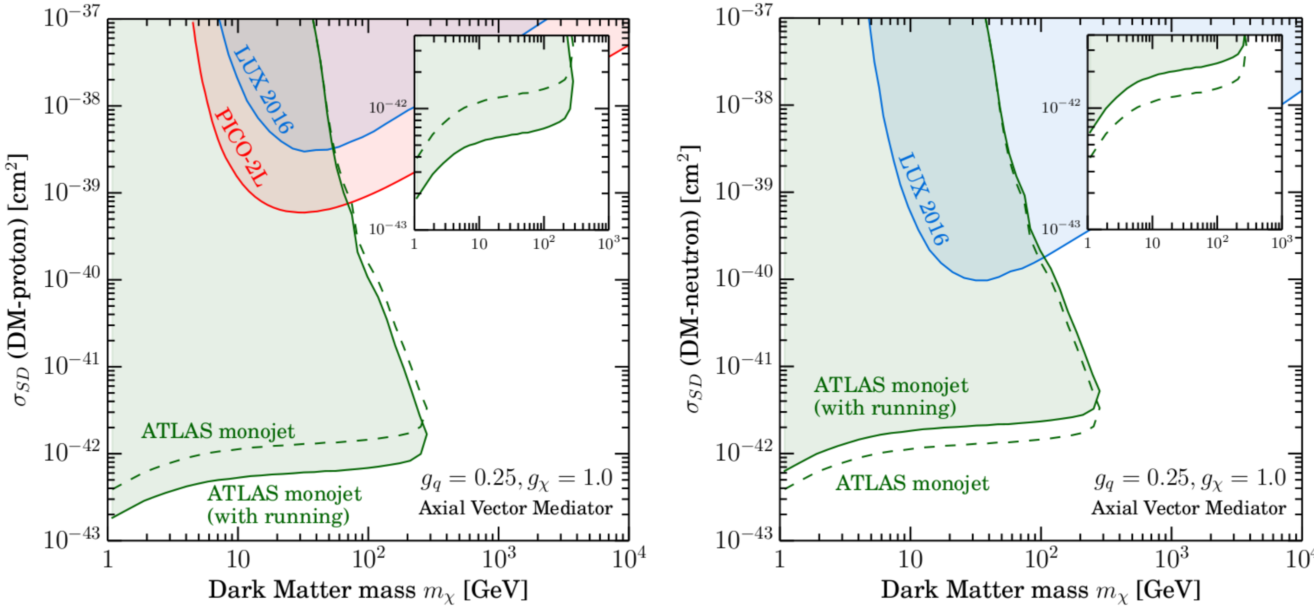
		$\mathcal{O}_1$	$\mathcal{O}_2$	$\mathcal{O}_3$	$\mathcal{O}_4$	$q^2\mathcal{O}_4$	$\mathcal{O}_5$	$\mathcal{O}_6$	$\mathcal{O}_7$	$\mathcal{O}_8$	$\mathcal{O}_9$	$\mathcal{O}_{10}$	$\mathcal{O}_{11}$	$\mathcal{O}_{12}$	$\mathcal{O}_{13}$	$\mathcal{O}_{14}$	$\mathcal{O}_{15}$	$\mathcal{O}_{17}$	$\mathcal{O}_{18}$
Spin-0 WIMP	(h_1, g_1)	✓																	
	(h_2, g_1)											✓							
	(h_4, g_4)											✓							
	(y_1)	✓										✓							
	(y_2)	✓										✓							
	(y_1, y_2)											✓							
Spin-$\frac{1}{2}$ WIMP	(h_1, λ_1)	✓																	
	(h_2, λ_1)											✓							
	(h_1, λ_2)												✓						
	(h_2, λ_2)							✓											
	(h_3, λ_3)	✓																	
	(h_4, λ_3)								✓		✓								
	(h_3, λ_4)									✓	✓								
	(h_4, λ_4)				✓														
	(l_1)	✓			✓			✓											
	(l_2)	✓			✓			✓											
	(d_1)	✓			✓			✓											
	(d_2)	✓			✓			✓											

Dent et al., arXiv:1505.03117

The importance of running

- An additional complication arises from the large separation of scales between the energies probed by the LHC and the nuclear scale relevant for direct detection.
- This means that RGE effects and threshold corrections must be taken into account and can affect the mapping visibly.

D'Eramo et al., arXiv:1605.04917



- Even larger effects are possible if direct detection event rates are suppressed for the tree-level operators, but unsuppressed at loop-level.

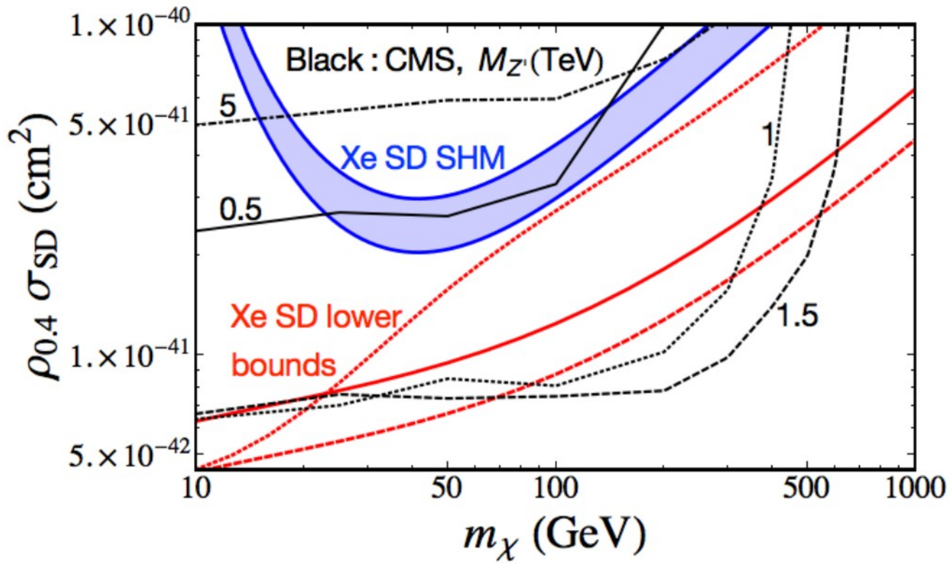
Haisch & FK, arXiv:1302.4454

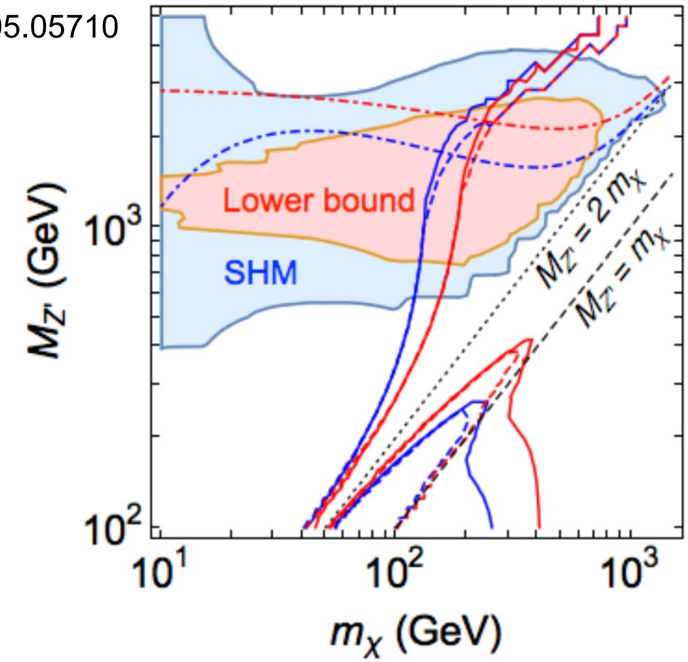
Astrophysical uncertainties

- Uncertainties in the local DM density and the DM velocity distribution further complicate the comparison between LHC searches and direct detection experiments.

- Nevertheless, once a signal is seen in a direct detection experiment, this can be used to construct a halo-independent lower bound on the DM-nucleon scattering cross section, which can be compared to upper bounds from the LHC.

Bellow et al., arXiv:1505.05710

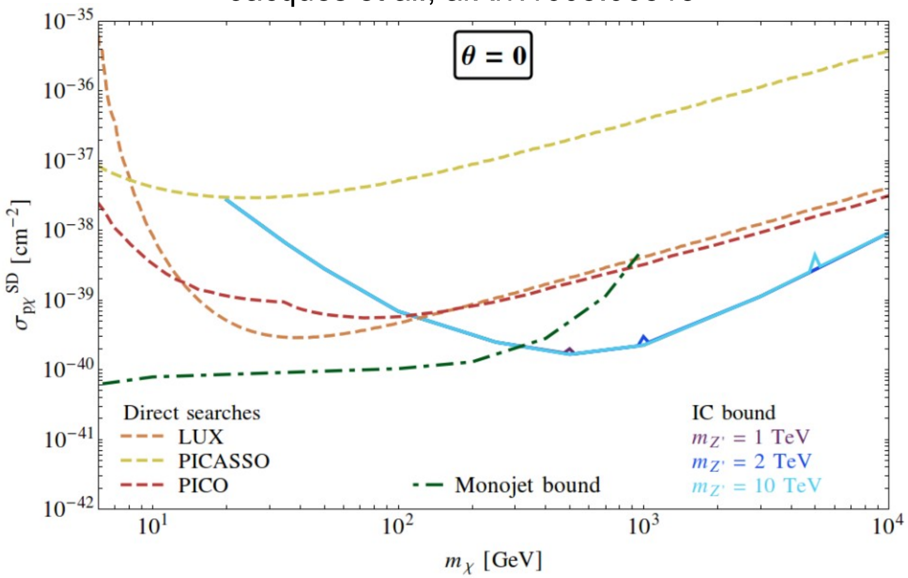


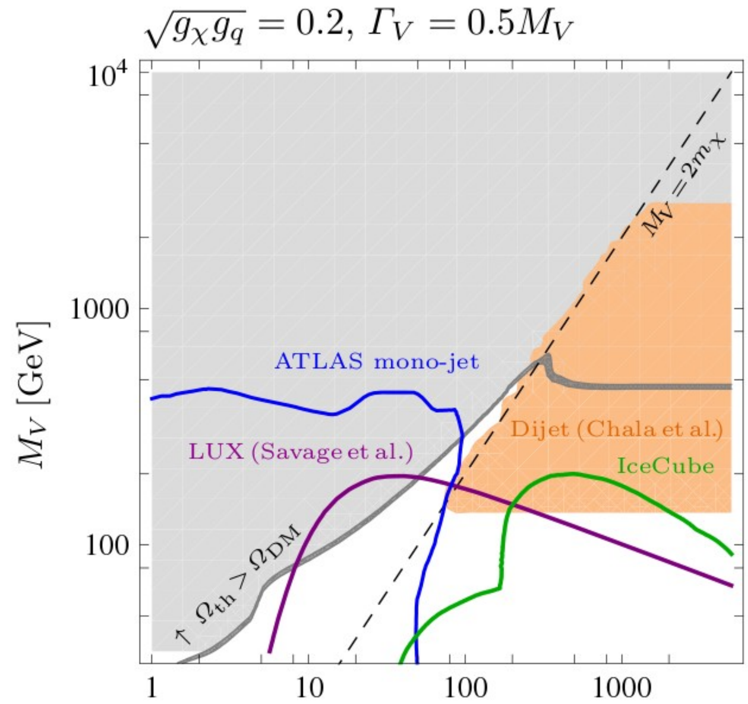


Complementarity of the LHC and other DM searches

- Various groups have in detail investigated the complementarity of LHC DM searches with direct detection experiments and constraints from IceCube.

Jacques et al., arXiv:1605.06513





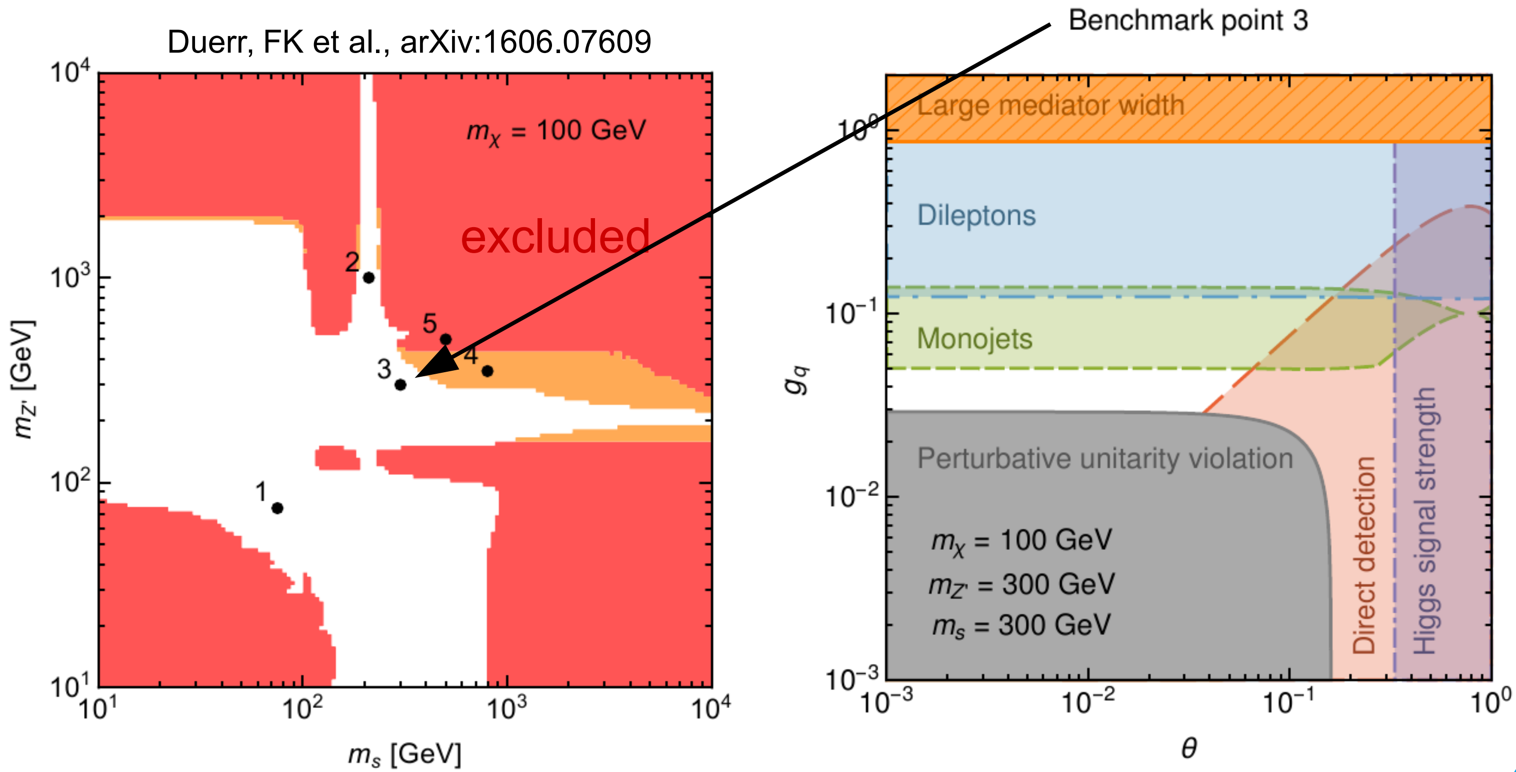
Heisig et al., arXiv:1509.07867

- The LHC is found to be particularly constraining for low-mass DM, while direct detection and IceCube give strong bounds on larger DM masses.

Global analyses

- Very recently there have been first studies of how to combine LHC searches for monojets, dijets and dileptons with EWPT, perturbative unitarity, as well as direct and indirect detection experiments.
- Scanning over couplings then allows to determine combinations of DM mass and mediator mass for which the relic density is compatible with all constraints.

Duerr, FK et al., arXiv:1606.07609



Going further with DarkBIT

- A statistically rigorous combination of all the different experimental probes of DM is a hugely challenging task.
- Nevertheless, this issue is essential in order to extract the maximal amount of information from data and narrow down the properties of the DM particle.
- These issues will be addressed by DarkBIT, a numerical framework for calculating DM observables and likelihoods, developed for the use in global scans (for example with GAMBIT).
  - High modularity, easy to implement new DM models
  - Rigorous treatment of nuisance parameters (e.g. related to the Galactic DM halo).
  - Interface with existing DM codes, such as DarkSUSY and micrOMEGAs.
  - Powerful tools for the analysis of direct detection (DDCal and indirect detection (nulike, gamlike) experiments.

DESY

Conclusions

- DM searches at colliders provide bounds on the interactions of DM that can be applied to a wide range of different DM models and provide information complementary to other kinds of DM searches.

- The EFT approach driven by minimality has largely be replaced by simplified models, which provide a more flexible framework to search for DM at the cost of a more complicated presentation and interpretation.

- It is essential to compare LHC searches for DM to other DM experiments and observations, but doing so often requires a theoretical framework beyond the simplified model approach.

- An interesting possibility is to constrain dark mediators using searches for di-jet resonances, which in many cases already probe the freeze-out paradigm.

- The big challenge will be to perform rigorous global analyses of DM models, taking into account many different constraints and the corresponding uncertainties. DarkBIT will be a big step forward in this direction.