Discrimination of the spin of dark matter candidates at the LHC

Luca Panizzi

Beyond the Higgs boson

open problems

The Standard Model is complete
but are we happy with it?

Observations

Dark Matter	Matter-antimatter asymmetry	Neutrino masses

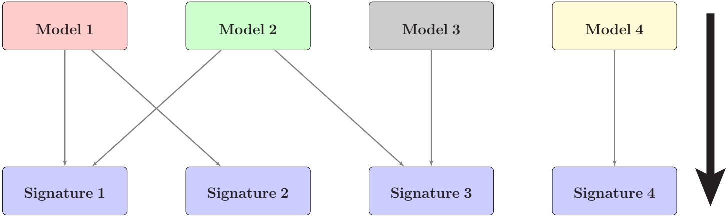
Theoretical issues

Fermion mass hyerarchies	Origin of flavour families	Gauge coupling unification	. . .

There must be new physics
and most probably it's already in our reach!

And if there's new physics we should be able to observe new particles (hopefully soon!)

Looking for new physics at the LHC



Designing searches or simulating signals to test specific models is a risky bet

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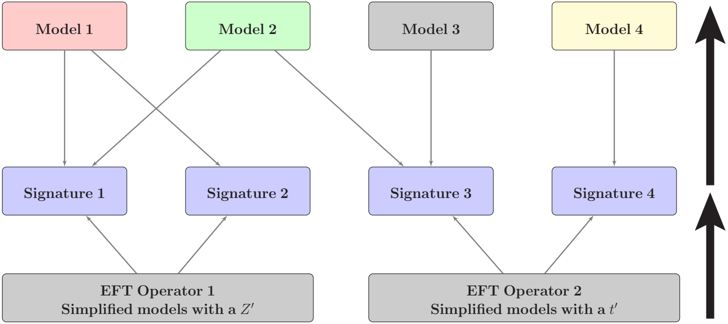

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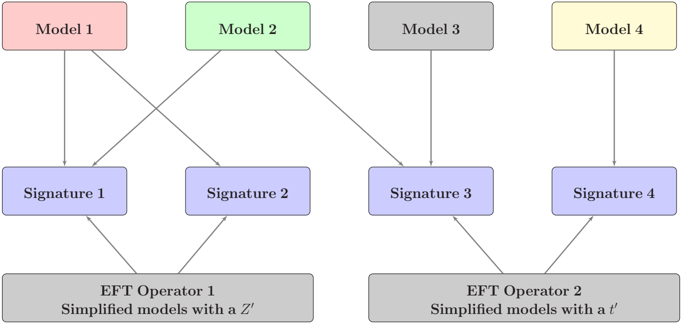
Model-independent approach

EFTs: higher dimension operators where heavy d.o.f. are integrated out
Simplified models: minimal extensions of the SM with new states
Approximate description of classes of theoretical models

Characterisation of new physics



Suppose Signature 1 is discovered

Is it possible to distinguish between Model 1 and Model 2?

Answer 1

Look for Signature 2 or Signature 3

Implies further experimental effort
and it takes an indefinite time

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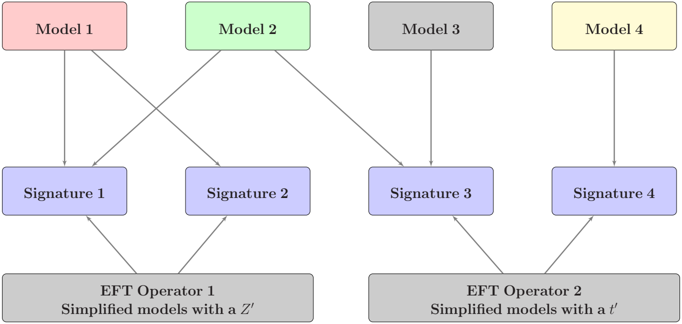

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Implies a detailed analysis of available data
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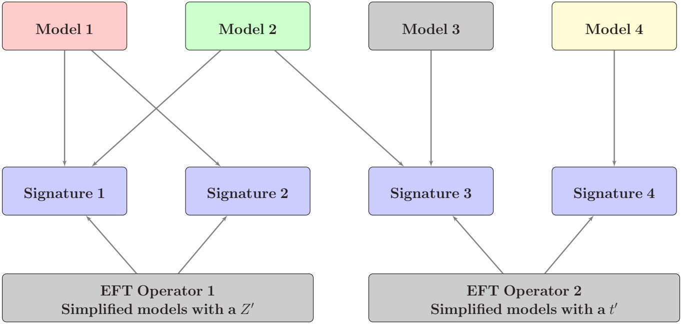

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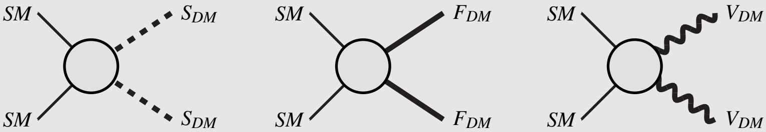
Let's focus on the Dark Matter!

The role of DM spin

Scalar, Fermion or Vector DM?



Examples:

- **Supersymmetry**: lightest R-odd particle, usually neutralino (fermion) or sneutrino (scalar)
- **Universal Extra Dimensions**: lightest KK-odd particle, usually photon partner (scalar or vector depending on the number of dimensions)

Determining the spin of a DM candidate would strongly constrain or rule out classes of BSM scenarios

The role of DM spin

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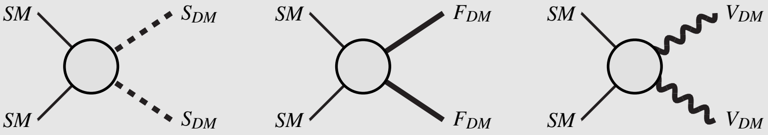

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Determining the spin of a DM candidate would strongly constrain or rule out classes of BSM scenarios

Report of the ATLAS/CMS Dark Matter Forum, arXiv:1507.00966 [hep-ex]:

"Different spins of Dark Matter particles will typically give similar results [. . .]. Thus the choice of Dirac fermion Dark Matter should be sufficient as benchmarks for the upcoming Run-2 searches"

Can the kinematical properties of DM candidates with different spin be **different enough to be detected** in certain channels?

The rationale

Interactions of the DM candidate

Vertices have different Lorentz structures

$$i\lambda \quad i\lambda\gamma^\mu \quad i\lambda g^{\mu\nu} \quad \dots$$

$\Downarrow$

Signal events

At fixed DM mass, distributions of final state objects are different for different DM spins
(and different EFT operators or different mediator spins)

$\Downarrow$

Analysis

Shape analysis of signatures with MET can help in the characterisation of the signal

A spin characterisation analysis requires enough signal events

Outline

1. Setup of the framework: EFTs and simplified models

2. Mono-objects
   - Mono-jet and EFT operators — A. Belyaev, **LP**, A. Pukhov, M. Thomas, JHEP **1704** (2017) 110
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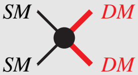
EFTs or simplified models

What to use?

Effective field theories (EFTs)



Heavy UV physics, not accessible at the LHC

Operators of dimension $d > 4$ suppressed by Λ_{UV}^{d-4}

Free parameters:

- DM mass
- UV scale (coefficient of the operator)

Easy to study
Limited applicability

EFTs or simplified models

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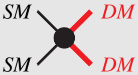

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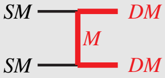
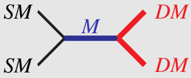
Simplified models





The **mediator** can be produced at the LHC either a BSM state or a particle of the SM itself (e.g. Z or Higgs portals)

Operators of dimension 4

Free parameters:

- DM mass
- Mediator mass (if BSM)
- Coupling between DM and mediator
- Coupling between SM and mediator (if BSM)

Applicable to more scenarios
EFTs as a limit for large mediator masses
More degrees of freedom, more complexity

d≤6 EFT operators for DM

Complex scalar DM†	
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	[C1]*
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}i\gamma^5 q$	[C2]*
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q$	[C3]
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu\gamma^5 q$	[C4]
$\frac{1}{\Lambda^2}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	[C5]*
$\frac{1}{\Lambda^2}\phi^\dagger\phi\tilde{G}^{\mu\nu}G_{\mu\nu}$	[C6]*

Dirac fermion DM†	
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$	[D1]*
$\frac{1}{\Lambda^2}\bar{\chi}i\gamma^5\chi\bar{q}q$	[D2]*
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}i\gamma^5 q$	[D3]*
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	[D4]*
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	[D5]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	[D6]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	[D7]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	[D8]
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	[D9]*
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}i\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	[D10]*

Complex vector DM‡	
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}q$	[V1]*
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}i\gamma^5 q$	[V2]*
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}\gamma^\mu q$	[V3]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$	[V4]
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}i\sigma^{\mu\nu}q$	[V5]
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}\sigma^{\mu\nu}\gamma^5 q$	[V6]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu q$	[V7P]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma^\mu q$	[V7M]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu\gamma^5 q$	[V8P]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$	[V8M]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar{q}\gamma_\mu q$	[V9P]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma_\mu q$	[V9M]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar{q}\gamma_\mu\gamma^5 q$	[V10P]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma_\mu\gamma^5 q$	[V10M]
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu G^{\rho\sigma}G_{\rho\sigma}$	[V11]*
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu\tilde{G}^{\rho\sigma}G_{\rho\sigma}$	[V12]*

* operators applicable to real DM fields, modulo a factor $1/2$

† Listed in J. Goodman *et al.*, *Constraints on Dark Matter from Colliders*, Phys.Rev. **D82** (2010) 116010, [arXiv:1008.1783]

‡ All but V11 and V12 listed in Kumar *et al.*, *Vector dark matter at the LHC*, Phys. Rev. **D92** (2015) 095027, [arXiv:1508.04466]

Simplified models

A common feature of DM candidates is that they are **odd** under a Z_2 symmetry under which SM particles are **even**. But what about mediators?

Odd mediators

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Even mediators

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Odd mediators

Even mediators

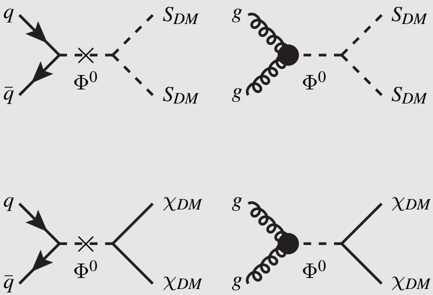
SM mediators

Mono-X from **t-channel** or **loop** topologies for **odd** mediators and from **s-channel** or **4-leg** topologies for **even** BSM or SM mediators

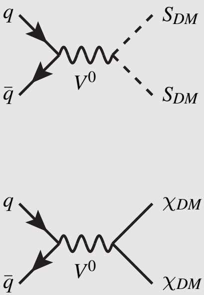
Are mediator and DM spins related?

s-channel

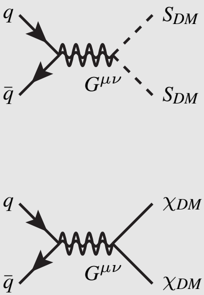
Scalar mediator



Vector mediator



Tensor mediator



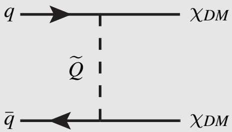
The relevance of gg initiated processes depends on couplings between scalar mediator and SM quarks

Same mediators for bosonic and fermionic DM

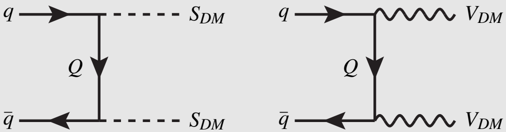
Are mediator and DM spins related?

t-channel

Scalar mediator



Fermion mediator

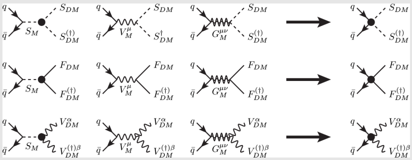


Plus diagrams at one-loop if the mediator does not couple to SM partons

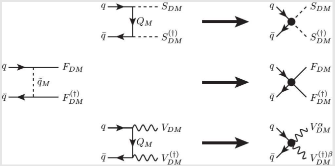
In t-channel the spin of the DM and the spin of the mediator are related

Simplified models to EFT

s-channel



t-channel



Different simplified scenarios can be described with the same EFT operators in the heavy mediator limit

- Scalar DM and scalar mediator in s-channel
- Scalar DM and fermion mediator in t-channel
- Scalar DM and (longitudinal component of) vector mediator in s-channel

$\Bigg\} \Longrightarrow \frac{\tilde{m}}{\Lambda^2}\phi^{(\dagger)}\phi\bar{q}q$ C1

Potentially different results with:

- EFT operators corresponding to **different DM spins**
- EFT operators corresponding to **same DM spin** but **different coupling structure**

How different they are, though? Are the differences observable?

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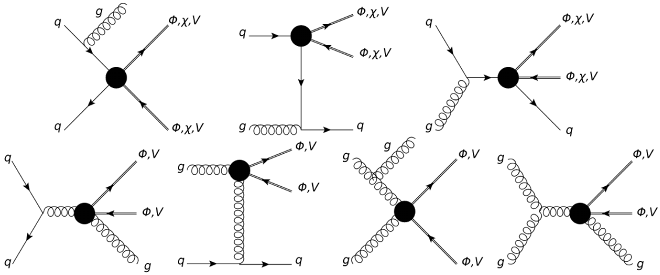
Topologies

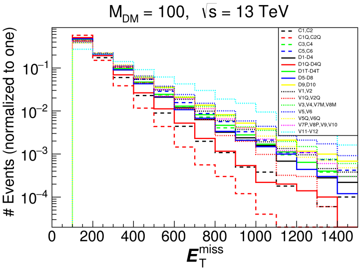


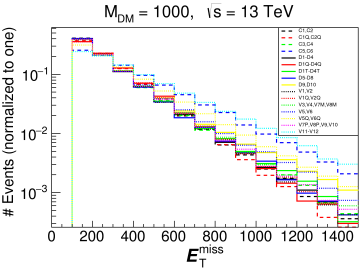
A spin-related difference to start with

Fermion DM cannot have the mono-jet topologies with gluon vertices through dim-6 operators
(at least dim-7)

Differential distributions

$\not\!\!E_T$, detector level at 13 TeV



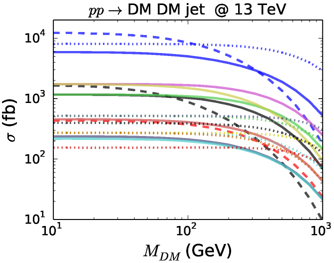


- **Relevant differences** in distributions as long as the DM mass is below the TeV
- Operators proportional to m_q (red lines) fall steeper than others from same-spin DM (due to PDFs) but σ too small
- Operators of dim-5 for scalar DM (**dashed black**) can be distinguished from others as they fall **kind-of steeper**
- Operators for vector DM interacting with gluons (dotted cyan) are always the least steep, even for large DM masses

To distinguish shapes, the cross-sections should be high enough, though

Cross-sections and recasting

Cross-sections for Λ=1 TeV

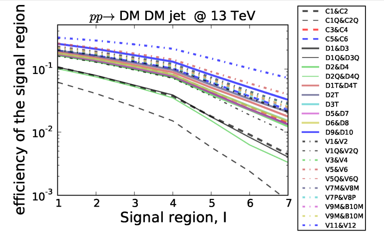


Mono-jet search
ATLAS
EXOT-2015-03
3.2 fb^{-1}

implemented in
CheckMATE

Inclusive SR	$\not{E}_T$ (GeV)
IM1	>250
IM2	>300
IM3	>350
IM4	>400
IM5	>500
IM6	>600
IM7	>700

Efficiencies for M_{DM}=100GeV

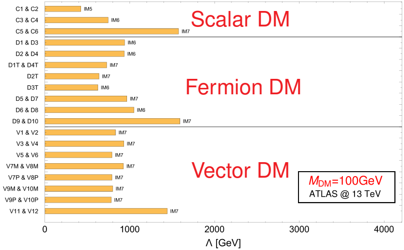


The different kinematics is reflected in sizably different efficiencies

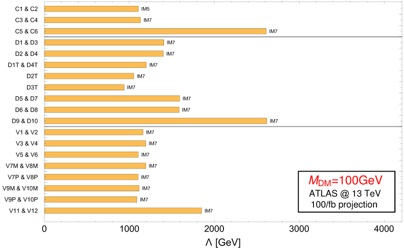
Bounds on Λ

and projections to higher luminosities

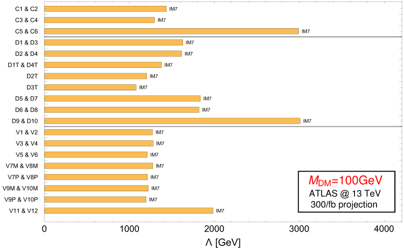
3.2 fb^{-1}



100 fb^{-1}



300 fb^{-1}



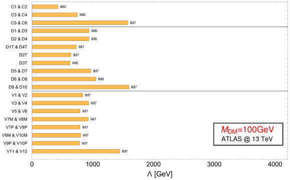
- M_{DM}=100 GeV
- Floor for background uncertainty at 1%
- Improvement of a factor 1.5-3 of the bounds, which then stabilise around 1-3 TeV depending on the operator

Not much room left for discovery of EFT scenarios with higher luminosities

SRs with higher MET cuts would help

Higher energies would help

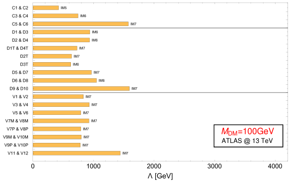
Limits on EFT Λ



The bounds on Λ may seem low
May new physics be produced directly instead of being too heavy?

Different answers:

Limits on EFT Λ



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May new physics be produced directly
instead of being too heavy?

Different answers:

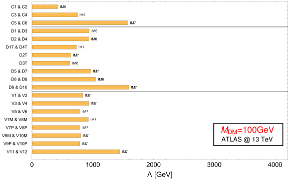
- **It can be, yes.**

  Interpretation for **single mediator**:
  - Small couplings: EFT validity limit (for fermion DM) around the TeV

    G. Busoni, A. De Simone, E. Morgante and A. Riotto, Phys. Lett. B **728** (2014) 412
  - Larger couplings: larger $\Lambda \longrightarrow \frac{1}{\Lambda^2} = \frac{g^2}{\Lambda'^2} \Longrightarrow$ **very large mediator width**

    O. Buchmueller, M. J. Dolan and C. McCabe, JHEP **1401** (2014) 025

Limits on EFT Λ



The bounds on Λ may seem low
May new physics be produced directly instead of being too heavy?

Different answers:

- **It can be, yes.**
- **The value of Λ may not necessarily correspond to the mass of the mediator**

Parametrisation in terms of **effective dimension** D

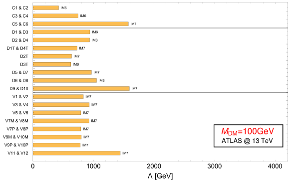
Asymptotic behaviour of the cross-section: $\sigma_{2\to 2} \propto \frac{1}{\Lambda^2} \times \left(\frac{E}{\Lambda}\right)^{\Delta_\sigma}$, $\Delta_\sigma = 2(D-5) \implies D = \Delta_\sigma/2 + 5$

Vector DM $\implies$ enhancement of E/M_{DM} for each allowed longitudinal polarisation

$\implies$ coefficient of the EFT operator: $\frac{1}{\Lambda_D^{d-4}} \left(\frac{M_{DM}}{\Lambda_D}\right)^{D-d} = \frac{M_{DM}^{D-d}}{\Lambda_D^{D-4}}$

V_{DM} Operator	Λ_d	d	Amplitude Enhancement	$\Delta_\sigma\,(\sigma_{2\to 2} \propto E^{\Delta_\sigma})$	Λ_D	D
V1,V2,V5,V6	$\frac{1}{\Lambda}$	5	$(E/M_{DM})^2$	4	$\frac{M_{DM}^2}{\Lambda^3}$	7
V3,V4,V7M,V8M,V11,V12	$\frac{1}{\Lambda^2}$	6	$(E/M_{DM})^2$	6	$\frac{M_{DM}^2}{\Lambda^4}$	8
V7P,V8P,V9,V10	$\frac{1}{\Lambda^2}$	6	E/M_{DM}	4	$\frac{M_{DM}}{\Lambda^3}$	7

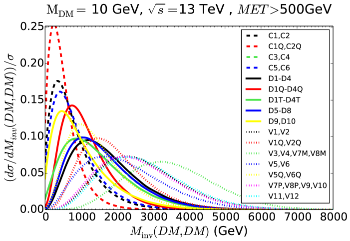
Limits on EFT Λ



The bounds on Λ may seem low
May new physics be produced directly
instead of being too heavy?

Different answers:

- **It can be, yes.**
- **The value of Λ may not necessarily correspond to the mass of the mediator**
- **Unitarity constraints are a robust criterion**



Applying a cut above E_{lim}
for which unitarity is violated
(numerical check)

$$M_{inv}(DM, DM) < 2E_{lim} \simeq 4\Lambda_{lim}$$

$\mathcal{O}(\%)$ decrease in the limit for Λ

Debate in literature, but this is a case study for characterising signals with MET

Discrimination between operators

- Assume that in the highest SR (IM7) there is signal at half of the number of excluded events at 95%
- Suppose that with an increase of luminosity the signal will be observed
- Use a χ^2 procedure on the last 4 bins (more sensitive to distribution tails) with 1% uncertainty on the background

$$\chi^2_{k,l} = \min_{\kappa} \sum_{i=3}^{7} [(\frac{1}{2} N_i^k - \kappa \cdot N_i^l)/(10^{-2} BG_i)]^2$$

- Compare with $\chi^2_{min} = 9.49$, the 95%CL limit with 4 d.o.f.

			Complex Scalar DM				Dirac Fermion DM				Complex Vector DM							
			100 GeV		1000 GeV		100 GeV		1000 GeV		100 GeV				1000 GeV			
			C1	C5	C1	C5	D1	D9	D1	D9	V1	V3	V5	V11	V1	V3	V5	V11
Complex Scalar DM	100 GeV	C1	0.0	**19.7**	**25.54**	**74.63**	**11.73**	**41.79**	**25.78**	**52.58**	**22.97**	**32.89**	**54.35**	**73.34**	**25.18**	**34.61**	**52.34**	**80.85**
		C5	**15.74**	0.0	0.37	**16.25**	1.11	3.93	0.74	7.35	0.18	1.53	8.2	**15.73**	0.44	1.9	7.24	**19.13**
	1000 GeV	C1	**19.89**	0.36	0.0	**11.82**	2.33	2.09	0.27	4.58	0.06	0.45	5.29	**11.41**	0.06	0.68	4.42	**14.36**
		C5	**50.86**	**13.86**	**10.34**	0.0	**21.03**	3.7	**11.18**	1.53	**11.57**	6.82	1.26	0.01	**10.84**	6.1	1.61	0.14
Dirac Fermion DM	100 GeV	D1	**9.88**	1.17	2.52	**25.99**	0.0	9.23	2.4	**14.17**	1.85	5.09	**15.34**	**25.37**	2.29	5.85	**13.85**	**29.81**
		D9	**30.49**	3.59	1.96	3.96	7.99	0.0	2.71	0.52	2.49	0.62	0.73	3.69	2.31	0.39	0.56	5.36
	1000 GeV	D1	**20.31**	0.73	0.27	**12.92**	2.25	2.93	0.0	5.42	0.32	0.82	6.33	**12.58**	0.08	1.18	5.08	**15.7**
		D9	**37.38**	6.54	4.18	1.6	**11.96**	0.5	4.89	0.0	4.98	2.02	0.06	1.44	4.56	1.61	0.04	2.55
Complex Vector DM	100 GeV	V1	**18.06**	0.17	0.06	**13.34**	1.72	2.68	0.32	5.5	0.0	0.77	6.25	**12.9**	0.1	1.06	5.34	**16.03**
		V3	**24.86**	1.45	0.44	7.57	4.57	0.65	0.79	2.14	0.74	0.0	2.68	7.25	0.57	0.03	2.04	**9.59**
		V5	**38.36**	7.24	4.79	1.3	**12.86**	0.7	5.67	0.06	5.61	2.5	0.0	1.14	5.24	2.04	0.13	2.13
		V11	**50.03**	**13.43**	**10.0**	0.01	**20.55**	3.45	**10.89**	1.39	**11.2**	6.54	1.11	0.0	**10.52**	5.83	1.49	0.16
	1000 GeV	V1	**19.73**	0.43	0.06	**12.46**	2.13	2.48	0.08	5.02	0.1	0.59	5.83	**12.09**	0.0	0.89	4.78	**15.14**
		V3	**25.96**	1.78	0.65	6.72	5.21	0.4	1.12	1.7	1.01	0.03	2.17	6.41	0.85	0.0	1.65	8.6
		V5	**37.33**	6.47	4.04	1.68	**11.72**	0.55	4.59	0.04	4.84	1.93	0.14	1.55	4.34	1.57	0.0	2.72
		V11	**54.48**	**16.14**	**12.42**	0.13	**23.85**	4.95	**13.43**	2.41	**13.74**	8.55	2.03	0.16	**13.01**	7.73	2.57	0.0

Discrimination is not always possible but in some cases different spins of DM can be distinguished

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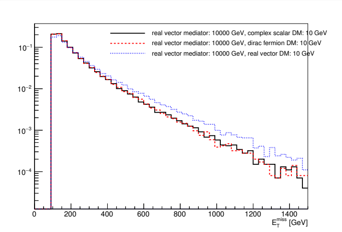
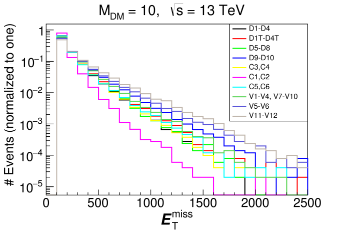
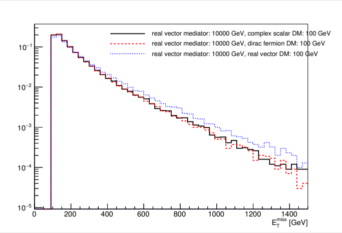
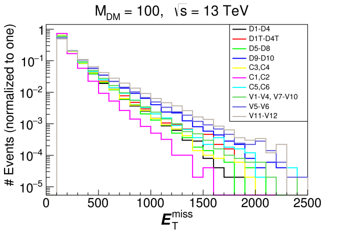
s-channel topologies

example with vector mediator

	Simplified model $M_V = 10$ TeV	EFT $\Lambda_{UV} = 10$ TeV
M_{DM} 10 GeV		
M_{DM} 100 GeV		

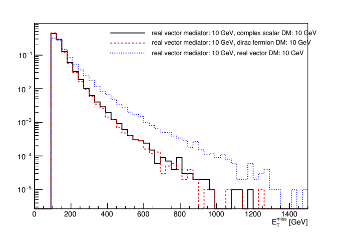
Same **qualitative** behaviour in the large mediator mass limit

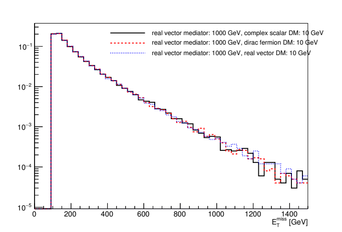
s-channel topologies

example with vector mediator

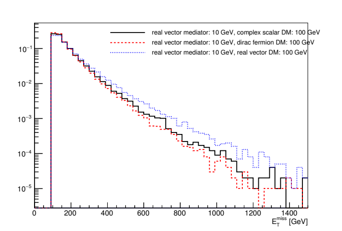
$M_V = 10$ GeV | $M_V = 1000$ GeV

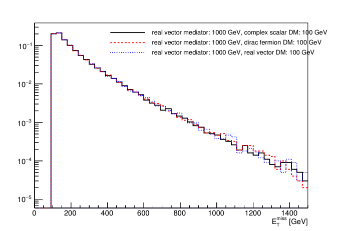
M_{DM} 10 GeV





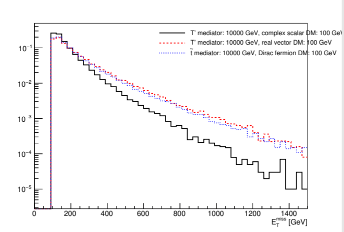
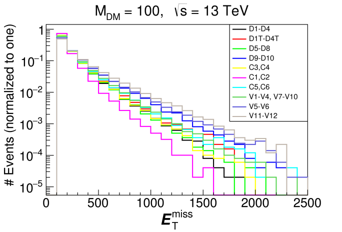
M_{DM} 100 GeV





More sensitivity to the spin of the DM when the mediator is not on-shell

t-channel topologies

	Simplified model $M_V = 10$ TeV	EFT $\Lambda_{UV} = 10$ TeV
M_{DM} 100 GeV		

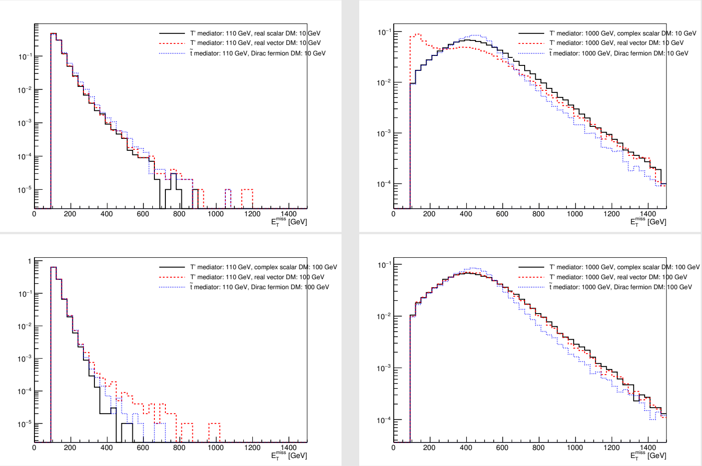
Same **qualitative** behaviour in the large mediator mass limit

t-channel topologies

$M_V = 110$ GeV | $M_V = 1000$ GeV

M_{DM} 10 GeV

M_{DM} 100 GeV



Potentially visible differences for all mediator and DM masses of different spins

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Signal topologies

mono-Z

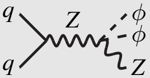
Assumptions

- The DM interacts **only** with the SM gauge bosons
- DM couplings of EW strength: $\begin{cases} g_{Z-Z-DM} = \lambda_Z \, e/s_W/c_W & \text{(Z 3-leg)} \\ g_{Z-Z-DM-DM} = (\lambda_Z \, e/s_W/c_W)^2 & \text{(Z 4-leg)} \\ g_{W-W-DM-DM} = (\lambda_W \, e/s_W)^2 & \text{(W 4-leg)} \end{cases}$

Scalar DM

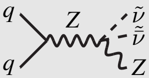
Real (ϕ)

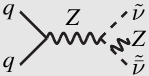
only 4-leg

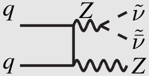


Complex ($\tilde{\nu}$, $\tilde{\bar{\nu}}$)

4-leg and 3-leg



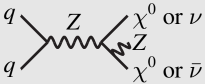


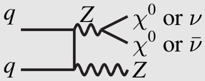


Fermion DM

Majorana (χ^0) Weyl (ν, $\bar{\nu}$)

only 3-leg



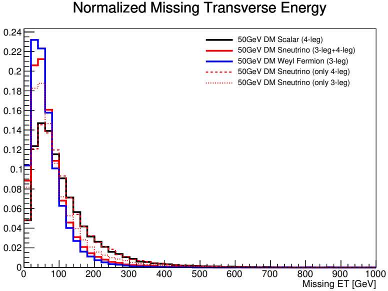


Can we distinguish effects given by spin from effects given by different topologies?

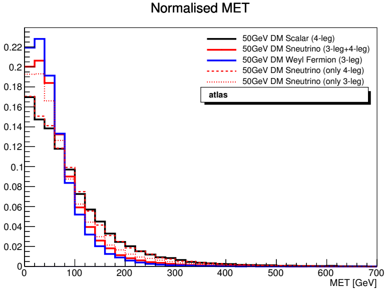
Mono-Z channel

$$M_{DM} = 50GeV, \lambda_Z = 1$$

Parton level after Z decay



Detector level (CheckMATE)

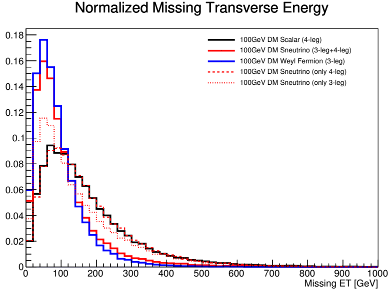


- Difficult to separate spin effects for topologies with **4-leg vertices**
- Spin effects much clearer for topologies with **3-leg vertices**
- Differences **increase** at large DM masses
- Differences are always **large enough** not to be smeared away at detector level

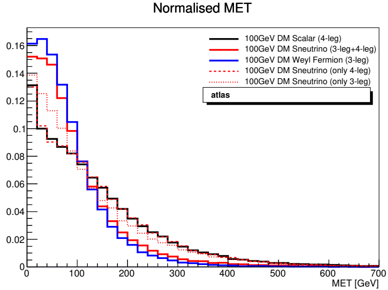
Mono-Z channel

$$M_{DM} = 100GeV, \lambda_Z = 1$$

Parton level after Z decay



Detector level (CheckMATE)



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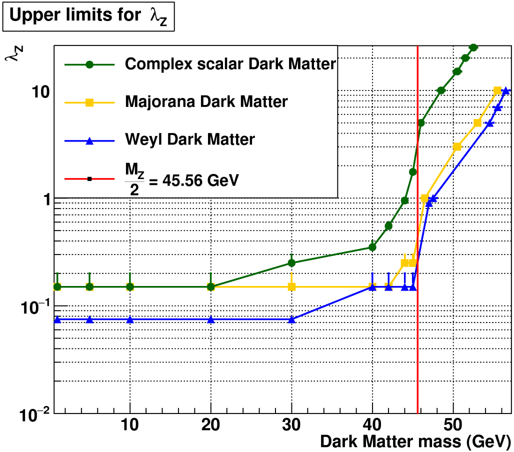
Bounds on the coupling



Bounds coming Z to invisible and $e^+e^- \to ZZ \to q\bar{q} + \not{E}_T$

For heavy DM there is basically no bound on the coupling

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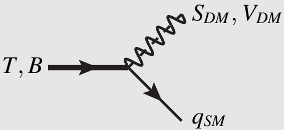
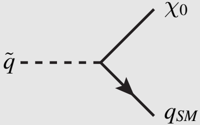
XQ vs SUSY

Decay into Dark Matter and SM quarks



Extra-quark

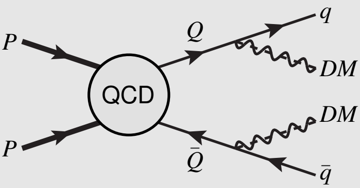


Supersymmetry

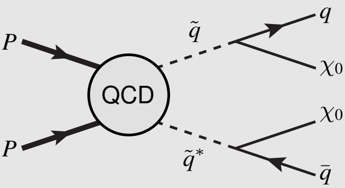
If heavy quarks decay into DM, it is possible to reinterpret any SUSY-inspired search
Due to the different nature of the DM particles, the kinematics may be different enough

XQ vs SUSY

Pair production

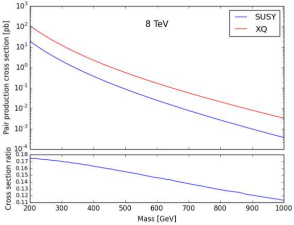


Heavy quark signal



SUSY signal

Decays into light SM quarks:
G. Cacciapaglia, A. Deandrea, J. Ellis, J. Marrouche and **LP**, Phys. Rev. D **87** (2013) 7, 075006, arXiv:1302.4750 [hep-ph]
L. Edelhäuser, M. Krämer and J. Sonneveld, JHEP **1504** (2015) 146, arXiv:1501.03942 [hep-ph]

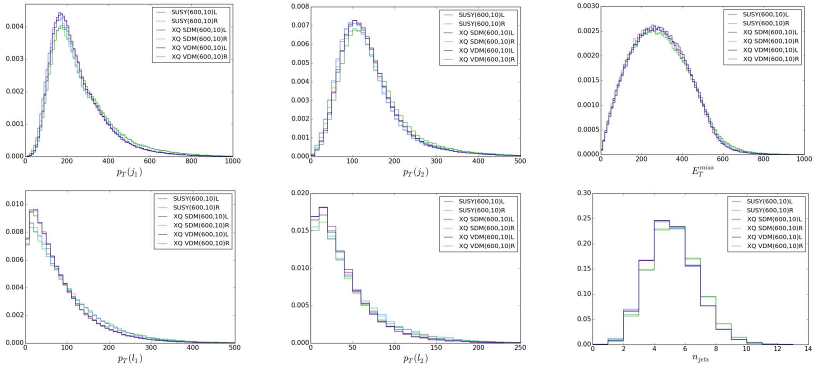


Bosonic DM has a much larger cross section than fermionic DM

Distributions

Showered and hadronised events

leading lepton   second lepton $\not\!\!E_T$



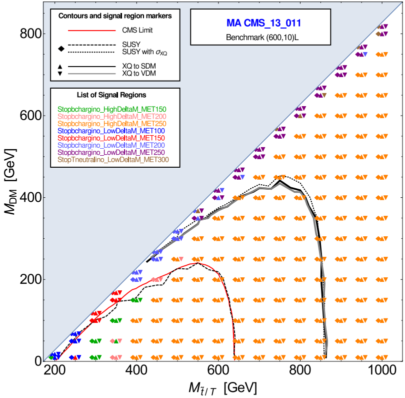
leading jet   second jet   number of jets

- **Small differences** overall between SUSY and VLQs
- Harder p_T for R chiralities (due to top polarisation)
- Somewhat more jets for SUSY (jets processed using anti-kt with p_T>5 GeV and cone radius 0.5)

$PP \to T\bar{T}/\tilde{t}\tilde{t}^* \to t\bar{t} + \not{E}_T$ @ 8 TeV

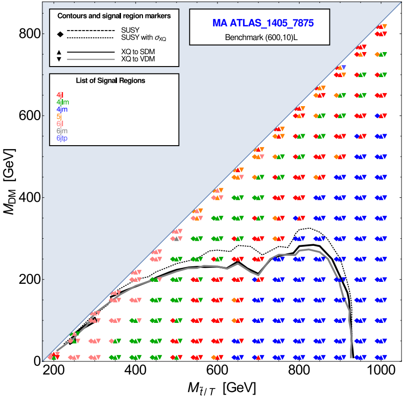
CMS SUS-13-011

single lepton and $\not{E}_T$



ATLAS SUSY-2013-02

2 to 6 high-p_T jets, 0 leptons and $\not{E}_T$



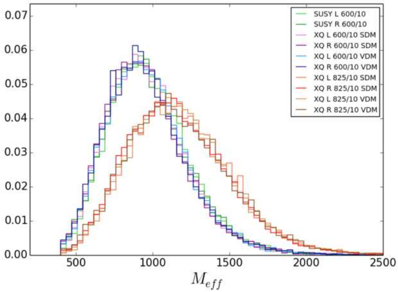
- **No differences** between scalar and vector DM for XQ scenario
- XQ results obtained by rescaling SUSY with XQ cross-sections $\Rightarrow$ **analogous kinematics**
- Higher x-sects for XQ with same mass configs $\Rightarrow$ **Allowed regions for SUSY are excluded for XQs**
- No SUSY bound in the fully hadronic search $\Rightarrow$ **useful probe for discrimination**

$PP \to T\bar{T}/\tilde{t}\tilde{t}^* \to t\bar{t} + \not{E}_T$ @ 8 TeV

Effective mass distributions

Points with **same mass configuration** vs Points which give the **same cross-section**

$$M_{eff} = \sum p_T(\text{jets}) + p_T(l) + \not{E}_T$$



"Cold" colours: SUSY and XQ with same mass configurations but different cross-sections

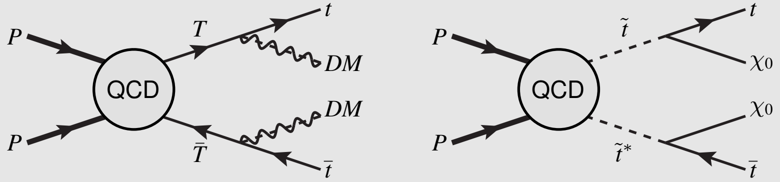
"Warm" colours: XQ with a mass configuration which gives the same cross-section as SUSY

trivially

Same mass configurations ⇒ different cross-sections ⇒ identical shapes
Different mass configurations ⇒ same cross-sections ⇒ different shapes

but this fact can be exploited in case a signal is observed

Discrimination in the $t\bar{t} + \not{E}_T$ channel



Heavy quark signal | **Supersymmetry signal**

Only fermionic vs bosonic DM, no vector vs scalar DM

- **Channel based**: the fully hadronic channel is more sensitive to scenarios with fermionic mediator and bosonic DM
- **Distribution based**: observation of a signal will exhibit different distributions due to same cross section with different mass configurations

N.B.: what we really discriminate here is the mediator spin!

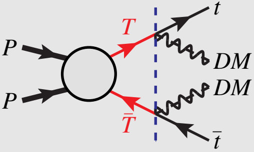
is it possible to go beyond and discriminate scalar and vector DM?

Scalar vs vector DM discrimination?

Going to large width regime

If the width of the T mediator is large the kinematics between scalar and vector DM may be different enough to be distinguished

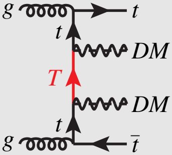
QCD pair production and decay of on-shell VLQs

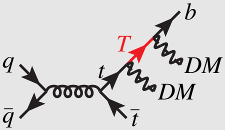


$$\sigma_X = \sigma_{2\to 2} \times BR(T)BR(\bar{T})$$

- Production and decays are factorized
- Basically no information on the spin of DM

Full signal



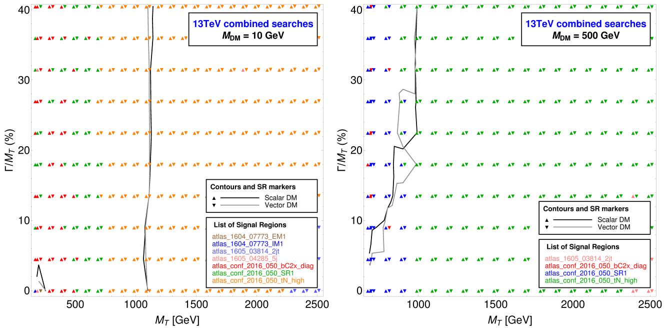


$\sigma_S = \sigma_{2\to 4}$ with any allowed topology

- Topologies with ≥ 1 VLQ propagator (generally subleading in the NWA)
- More sensitivity to the coupling structure between T and DM, and therefore to the DM spin

Width dependence of bounds

combination of ATLAS searches @ 13 TeV

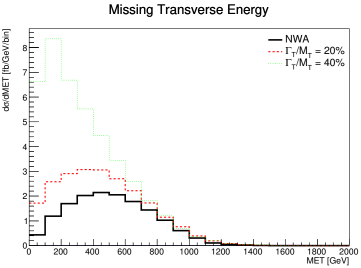


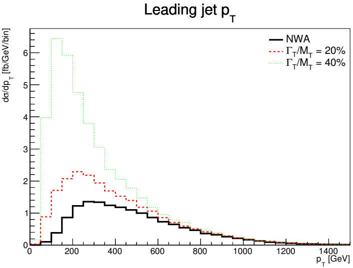
Almost **no distinction** between scalar and vector DM

The **bounds weakly depend on the width** for light DM, somewhat more if the DM mass increases

Kinematics of the signal

Scalar DM: M_T=1100 GeV and M_{DM}=10 GeV



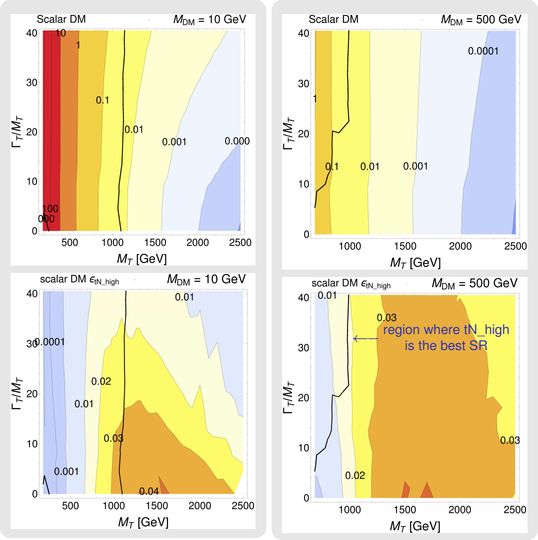


The distributions of $\not{E}_T$ and transverse momentum of the leading jet depend significantly on the width along the bound

Need to look at the performance of the searches

Cross-sections and efficiencies

SR tN_high of ATLAS CONF-2016-050 for scalar DM



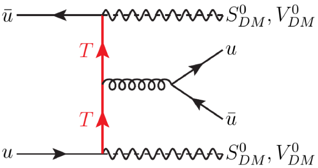
Cross-section weakly dependent on the width in the region of the bound

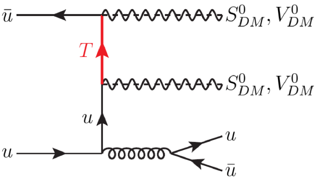
- Light DM: the efficiency of the best SR in the bound region depends in a complementary way, almost compensating the cross-section increase
- Heavier DM: the efficiency stays almost constant, as well as the cross-section

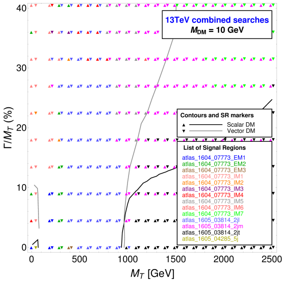
For vector DM results are qualitatively analogous

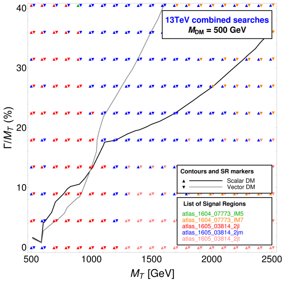
Interactions with light quarks

In this case the DM can interact directly with the initial state









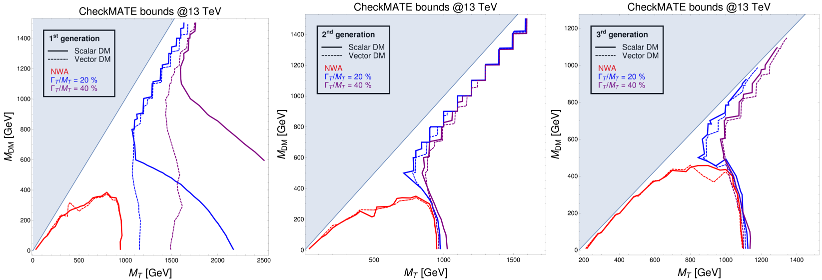
It is possible to distinguish scalar from vector DM

The bound strongly depends on the width

Different behaviour due to interplay between cross-sections and (shape-dependent) efficiencies

Exclusion limits

M_T vs M_{DM} plane



Only when the T interacts with the up quark a clear distinction between scalar and vector DM may be possible

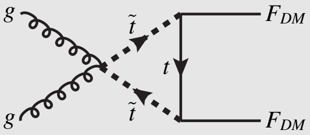
considering pair production final states and with the selections of current searches

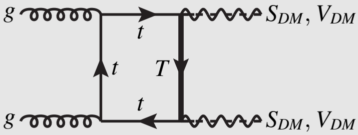
A shape analysis of the signal would provide information about different scenarios

Perspectives for DM interacting with top

work in progress

Mono-objects at one-loop

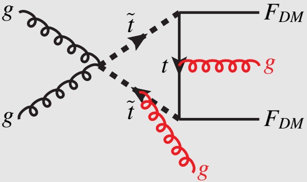


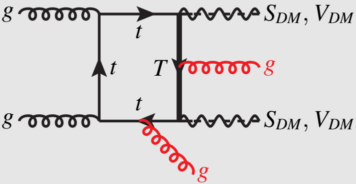


Perspectives for DM interacting with top

work in progress

Mono-objects at one-loop



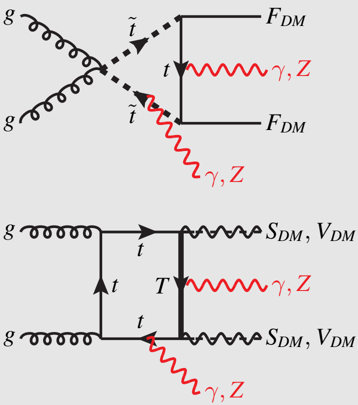


- Mono-jet

Perspectives for DM interacting with top

work in progress

Mono-objects at one-loop



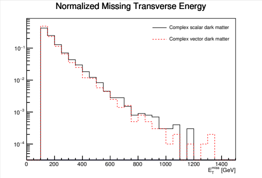
- Mono-jet
- Mono-photon
- Mono-Z

Perspectives for DM interacting with top

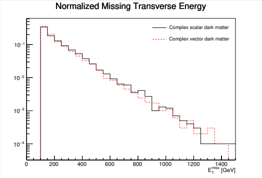
work in progress

Mono-jet and bosonic DM

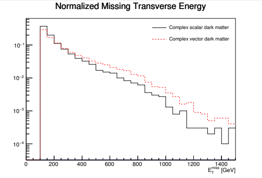
M_T=180 GeV, M_{DM}=5 GeV



M_T=500 GeV, M_{DM}=5 GeV



M_T=1000 GeV, M_{DM}=5 GeV



Potentially interesting configurations of masses for DM spin discrimination

but

Cross-section could be **too small** for this signal to be detected

Systematic study under way

Conclusions and Outlook

Summary

- Characterising the spin of a DM candidate at the LHC would be crucial for the interpretation in terms of theoretical scenarios
- Mono-X channels are a good probe in both the EFT and simplified model approaches
- Current searches with MET (often inspired by SUSY) can be a powerful tool for the reinterpretation of scenarios where the DM has a different spin

Work in progress

- Include interplay with other observables and constraints related to DM or mediators
- Determination of the relevance of mono-photon and mono-W channels with respect to mono-jet and mono-Z
- Exploration of the sensitivity of other channels for the characterization of the DM spin
- Exploration of different kinematical variables for the optimisation of analyses aimed at isolating scnearios with different spins