Dark matter spin characterization at the LHC

Luca Panizzi

University of Southampton & NExT, UK

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!)

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	...

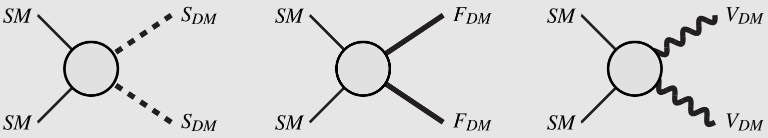
There must be new physics
and most probably it's already in our reach!

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

Let's focus on the Dark Matter!

The role of DM spin

Scalar, Fermion or Vector DM?



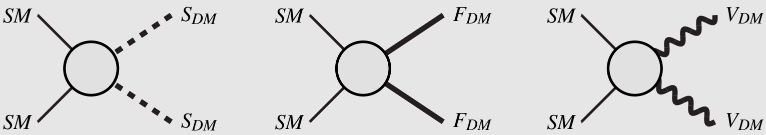
Examples:

- **Supersymmetry**: neutralino (fermion) or sneutrino (scalar)
- **Universal Extra Dimensions**: lightest KK-odd 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

Scalar, Fermion or Vector DM?



Examples:

- **Supersymmetry**: neutralino (fermion) or sneutrino (scalar)
- **Universal Extra Dimensions**: lightest KK-odd 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

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 atlas+cms dark matter forum the upcoming Run-2 searches"

Is it always true?

Can the kinematical properties of scalar/vector DM be **different enough to be detected** in certain channels?

The rationale

Vertices have different Lorentz structures

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

$\Downarrow$

Distributions of final states are in general different with different DM spins

$\Downarrow$

Shape analysis

$\Downarrow$

A spin characterisation analysis requires enough events

Outline

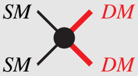
1. Setup of the framework: EFTs and simplified models
2. Mono-objects
   - Mono-jet (EFT)
   - Mono-jet (simplified models)
   - Mono-Z (simplified model with Z mediator)
3. Multi-particle + missing transverse energy (simplified model)

Outline

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:

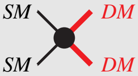
- DM mass
- UV scale (coefficient of the operator)

Easy to study
Limited applicability

EFTs or simplified models

What to use?

Effective field theories (EFTs)



Heavy UV physics, not accessible at the LHC

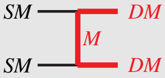
Operators of dimension $d > 4$ suppressed by Λ_{UV}^{d-4}

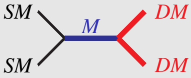
Free parameters:

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

Easy to study
Limited applicability

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

Effective field theories

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

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

* 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

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

Even mediators

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

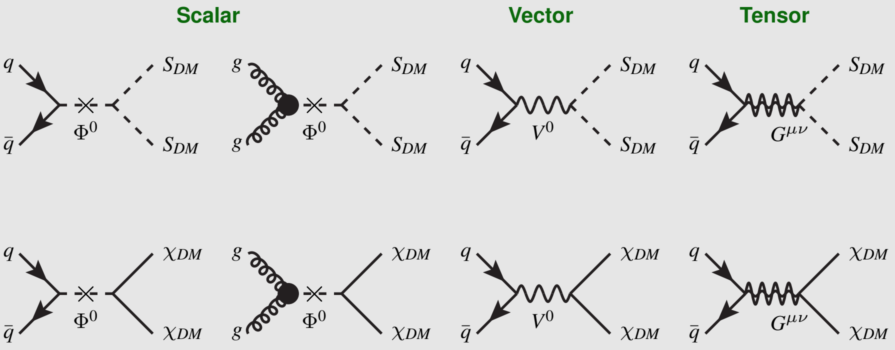
Even mediators

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

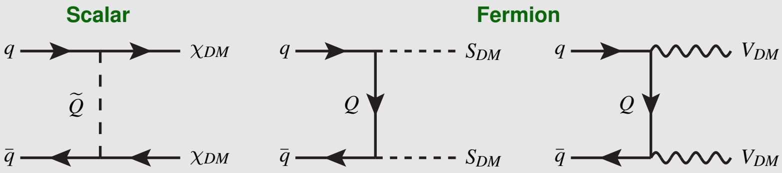


The relevance of gg initiated processes depends on couplings between scalar mediator and SM quarks

Same mediators for bosonic and fermionic DM

Are mediator and DM spins related?

t-channel

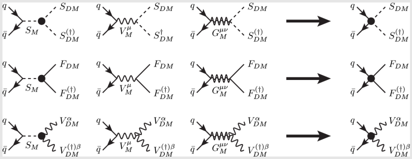


Plus diagrams at one-loop if the mediator does not couple to SM partons

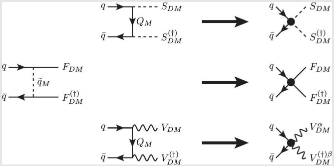
In t-channel the spin of the DM and the spin of the mediator are related

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

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

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?

Outline

1. Setup of the framework: EFTs and simplified models

2. Mono-objects
   - Mono-jet (EFT)
   - Mono-jet (simplified models)
   - Mono-Z (simplified model with Z mediator)

3. Multi-particle + missing transverse energy (simplified model)

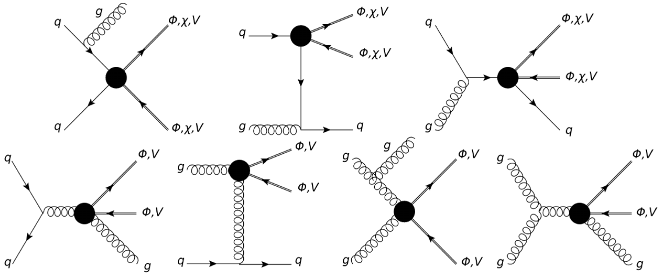
Outline

1. Setup of the framework: EFTs and simplified models

2. Mono-objects
   - Mono-jet (EFT)
   - Mono-jet (simplified models)
   - Mono-Z (simplified model with Z mediator)

3. Multi-particle + missing transverse energy (simplified model)

Topologies

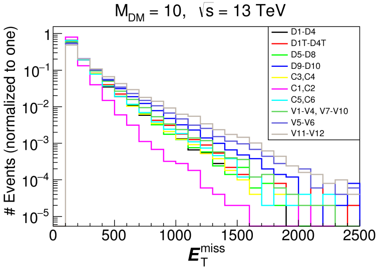


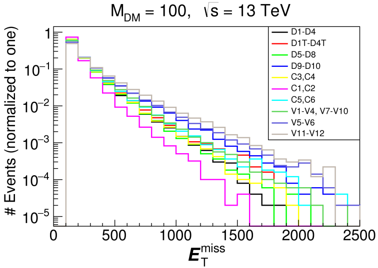
A spin-related difference to start with

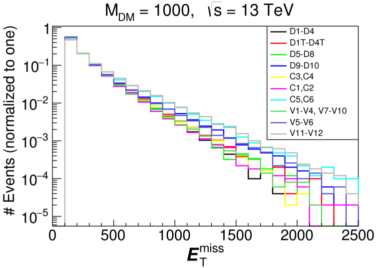
Fermion DM cannot have the topologies of the bottom row through dim-6 operators

Differential distributions

E_T^{miss}, parton level at 13 TeV





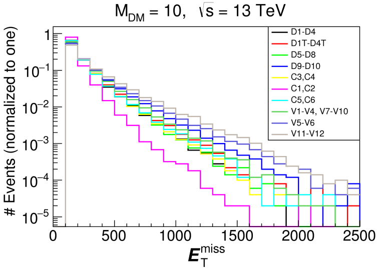


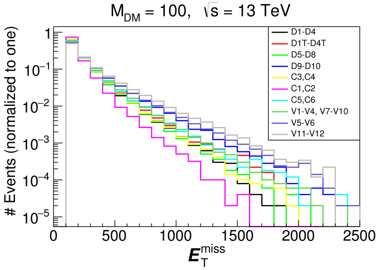
light DM ($\lesssim$ 100 GeV)

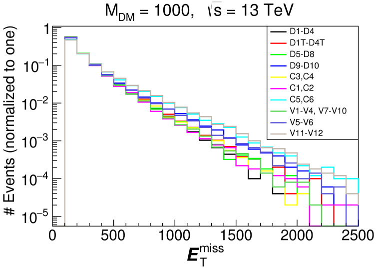
- C1-C2 (scalar DM with scalar coupling)
- D9-D10 (fermion DM with tensor coupling)
- V5-V6 (vector DM with tensor coupling) and V11-V12 (vector DM with gluon coupling)

Differential distributions

E_T^{miss}, parton level at 13 TeV





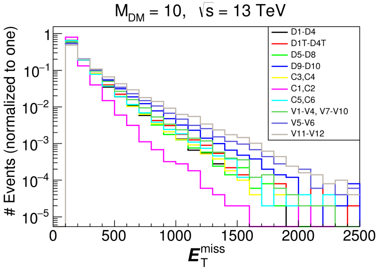


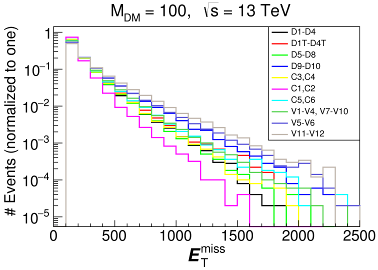
heavy DM (around 1 TeV)

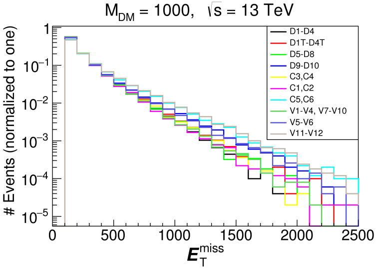
- C5-C6 (scalar DM with gluon coupling)
- D9-D10 (fermion DM with tensor coupling)
- V5-V6 (vector DM with tensor coupling) and V11-V12 (vector DM with gluon coupling)

Differential distributions

E_T^{miss}, parton level at 13 TeV



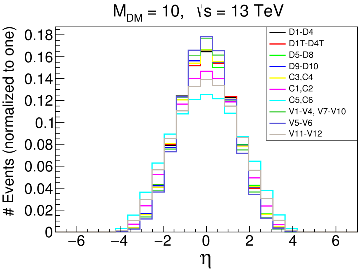


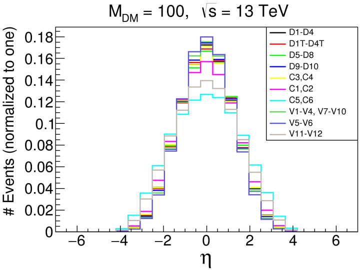


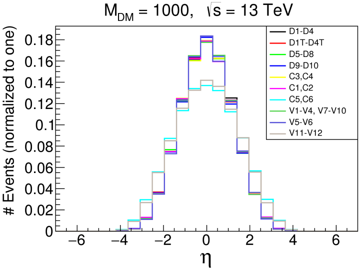
Some operators can be distinguished from others through the E_T^{miss} distribution

Differential distributions

Jet pseudorapidity, parton level at 13 TeV



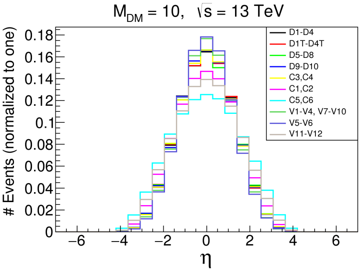


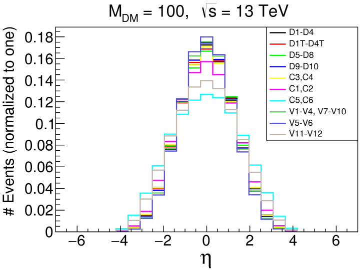


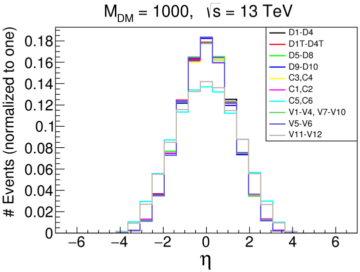
- C5-C6 (scalar DM with tensor coupling) and V11-V12 (vector DM with gluon coupling) always less central
- C1-C2 (scalar DM with scalar coupling) only less central for light DM
- Fermion operators all similar (D9-D10 tensor operator slightly more central for light DM)

Differential distributions

Jet pseudorapidity, parton level at 13 TeV



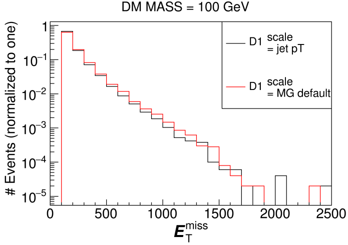


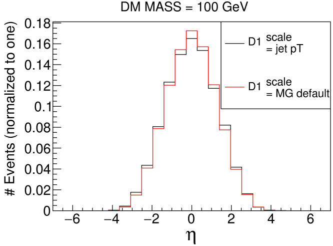


Some operators can be distinguished from others through the jet psudorapidity distribution, **but not necessarily the same for E_T^{miss}**

Scale dependence

MadGraph uses dynamical renormalisation and factorisation scales which are "set to the central m_T^2 scale after k_T-clustering of the event".





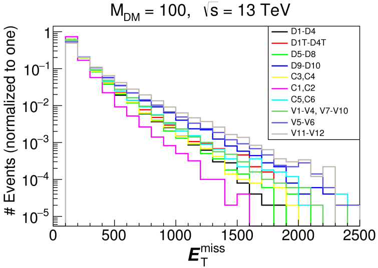
Cross-sections (in fb)

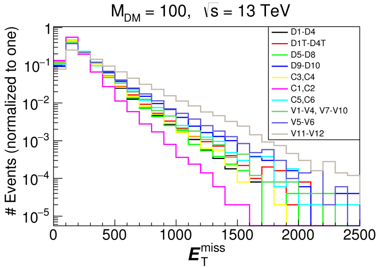
		M_{DM} (GeV) 10	100	1000
C1	k_T, m_T^2	16.0	8.20	0.0813
	p_T(jet)	18.8	10.6	0.181
	Relative difference	18%	29%	123%
C3	k_T, m_T^2	0.0389	0.0331	0.00197
	p_T(jet)	0.0619	0.0550	0.00490
	Relative difference	59%	66%	149%
C5	k_T, m_T^2	1.11	0.750	0.0145
	p_T(jet)	1.55	1.13	0.0385
	Relative difference	40%	51%	166%

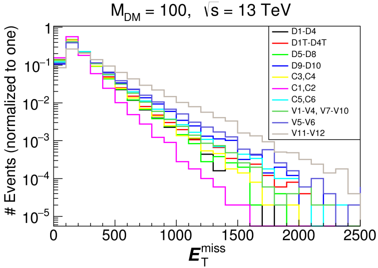
Changing the dynamical scale to the p_T of the jet has a small effect on the **shapes** of the distributions, but a much larger effect on the **cross-sections**

Differential distributions

From parton to dector level at 13 TeV



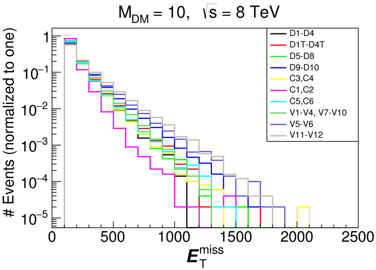




The differences are not smoothened too much by hadronisation or detector level effects

Comparison with 8 TeV

E_T^{miss}, parton level

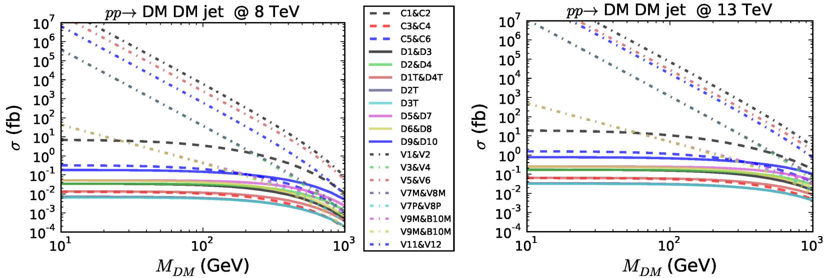


With same DM mass, the differences at 13 TeV are more pronounced!

Running with higher energies and luminosities increases the possibility of characterising the spin of the DM

Observability of the signal

Cross-sections



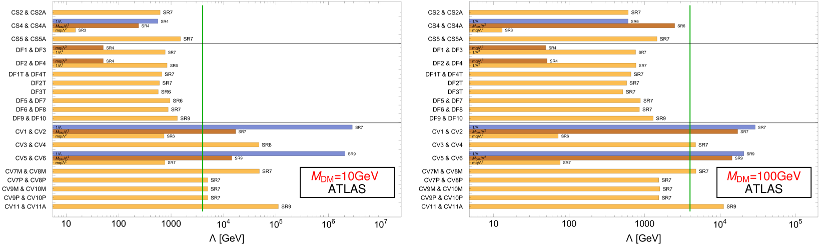
Similar scaling for scalar and fermion DM, much steeper scaling for vector DM

Expect stronger limits for light vector DM and similar limits for all spins for heavier DM

But will the number of events be enough for a shape analysis?

Observability of the signal

ATLAS mono-jet at 8 TeV and 20 fb^{-1}



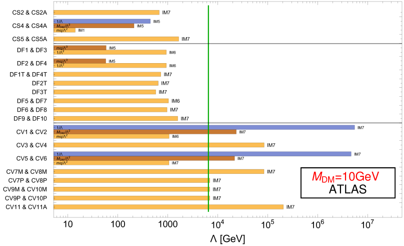
- **Scalar** and **fermion** DM: limits on Λ_{UV} much smaller than the minimum value for valid EFT with no direct production of new particles at the LHC
- **Vector** DM: exclusion limits stronger for light DM and similar to scalar and fermion DM for heavier DM

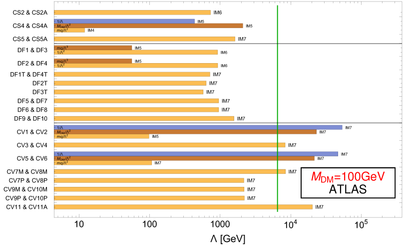
A shape analysis for the DM spin characterisation with 8 TeV data could only have identified a vector DM

Results obtained using the CheckMATE implementation of the ATLAS search, arXiv:1502.01518

Observability of the signal

ATLAS mono-jet at 13 TeV and 3.2 fb^{-1}





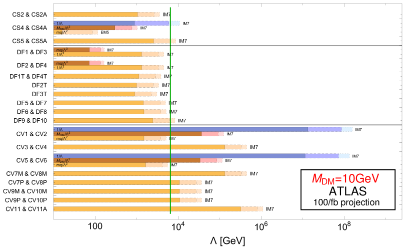
Very similar results to the 8 TeV data

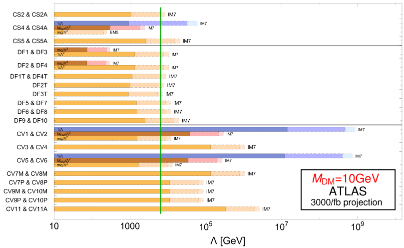
Which is expected due to the low luminosity

Results obtained using the CheckMATE implementation of the ATLAS search, arXiv:1604.07773

Projections at higher luminosities

ATLAS mono-jet at 13 TeV projected at 100 and 3000 fb^{-1}





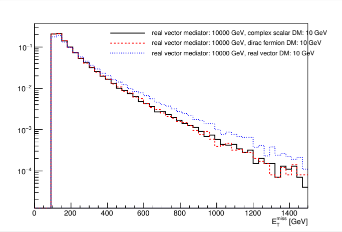
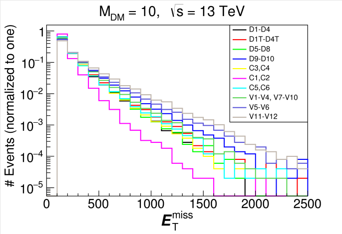
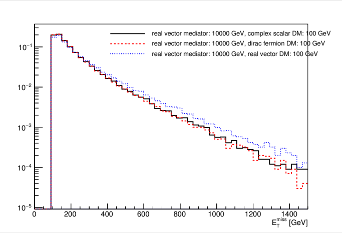
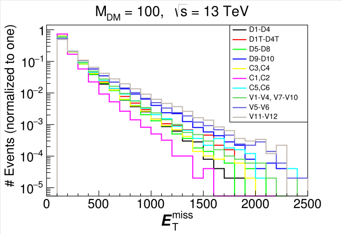
At very high luminosity, most operators produce enough signal events to allow a shape analysis

Results obtained using a custom CheckMATE implementation of the ATLAS search, arXiv:1604.07773 by rescaling the background linearly with the luminosity and uncertainties as the square root and imposing that they must be anyway larger than 4% of the background

Outline

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		

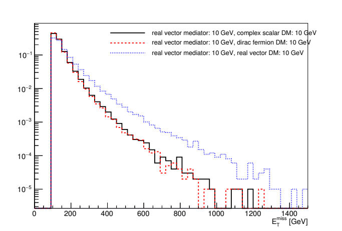
Same **qualitative** behaviour in the large mediator mass limit

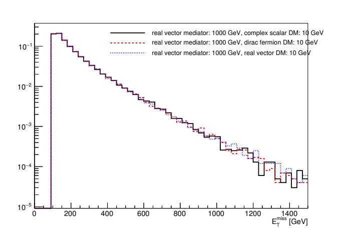
s-channel topologies

example with vector mediator

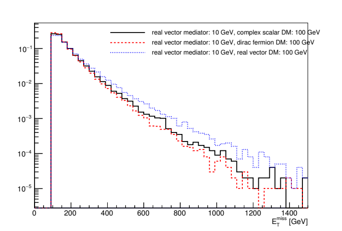
$M_V = 10$ GeV | $M_V = 1000$ GeV

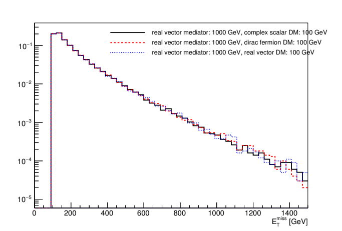
M_{DM} 10 GeV





M_{DM} 100 GeV



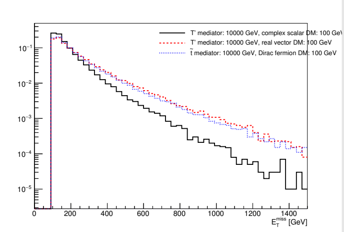


More sensitivity to the spin of the DM when the mediator is not on-shell

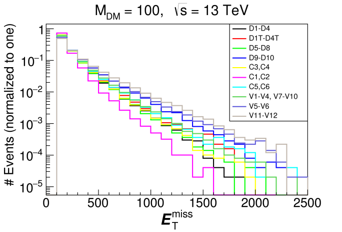
t-channel topologies

M_{DM} 100 GeV

Simplified model $M_V = 10$ TeV

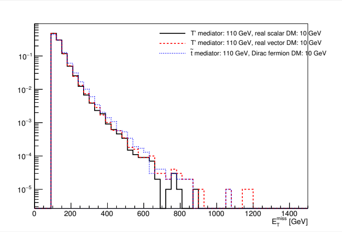
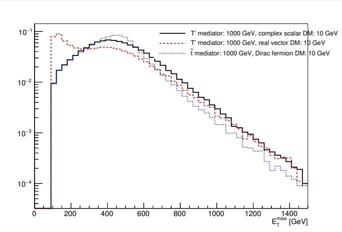
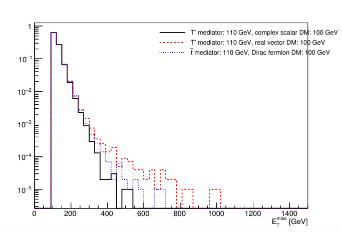
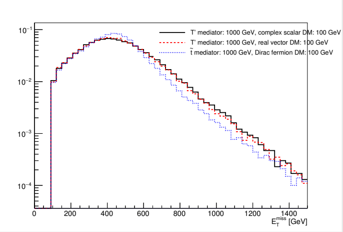


EFT $\Lambda_{UV} = 10$ TeV



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

Outline

Signal topologies

mono-Z

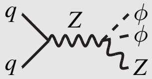
Assumptions

- 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

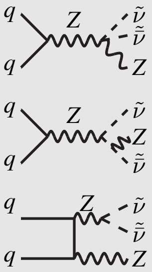
Real (ϕ)

only 4-leg



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

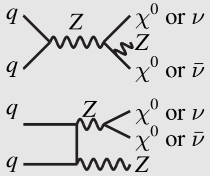
4-leg and 3-leg



Fermion DM

Majorana (χ^0) Weyl (ν, $\bar{\nu}$)

only 3-leg



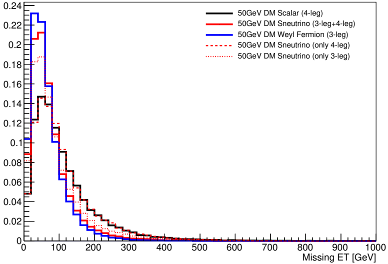
Can we distinguish effects given by spin from effects given by different topologies?

Mono-Z channel

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

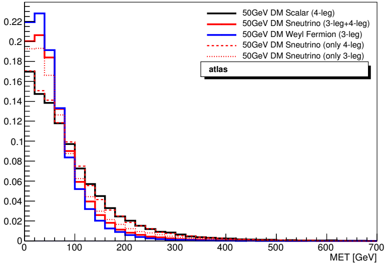
Parton level after Z decay

Normalized Missing Transverse Energy



Detector level (CheckMATE)

Normalised MET

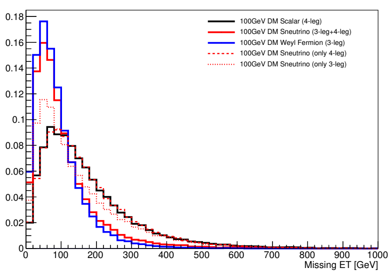


- Difficult to separate spin effects for topologies with **4-leg vertices**
- Spin effects much clearer for topologies with **3-leg vertices**
- Differences **increase** at large DM masses
- Differences are always **large enough** not to be smeared away at detector level

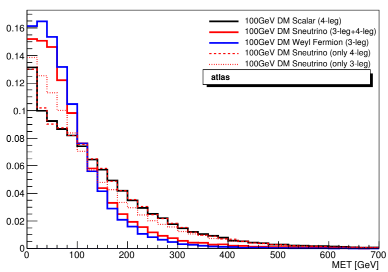
Mono-Z channel

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

Parton level after Z decay

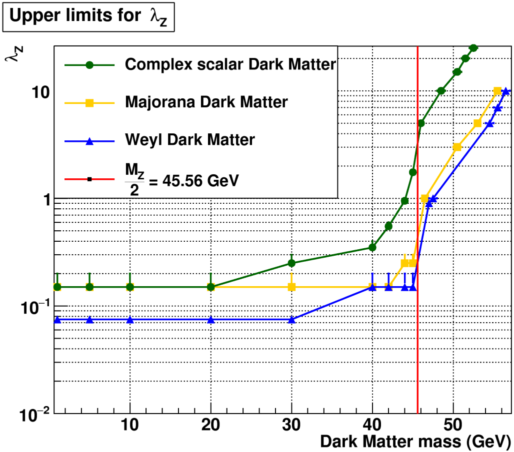


Detector level (CheckMATE)



- 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

Bounds on the coupling



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

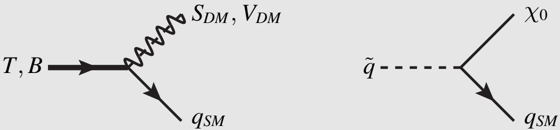
For heavy DM there is basically no bound on the coupling

Outline

1. Setup of the framework: EFTs and simplified models
2. Mono-objects
   - Mono-jet (EFT)
   - Mono-jet (simplified models)
   - Mono-Z (simplified model with Z mediator)
3. Multi-particle + missing transverse energy (simplified model)

XQ vs SUSY

Decay into Dark Matter and SM quarks



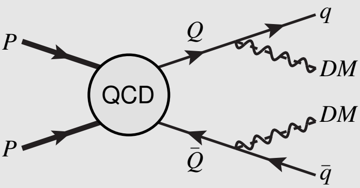
Extra-quark **Supersymmetry**

If heavy quarks decay into DM, it is possible to reinterpret any SUSY-inspired search

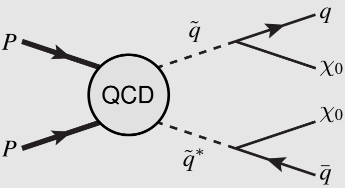
Due to the different nature of the DM particles, the kinematics may be different enough

XQ vs SUSY

Pair production

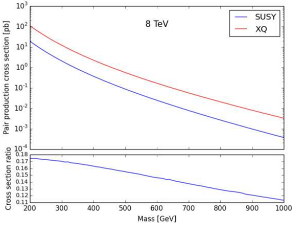


Heavy quark signal



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]

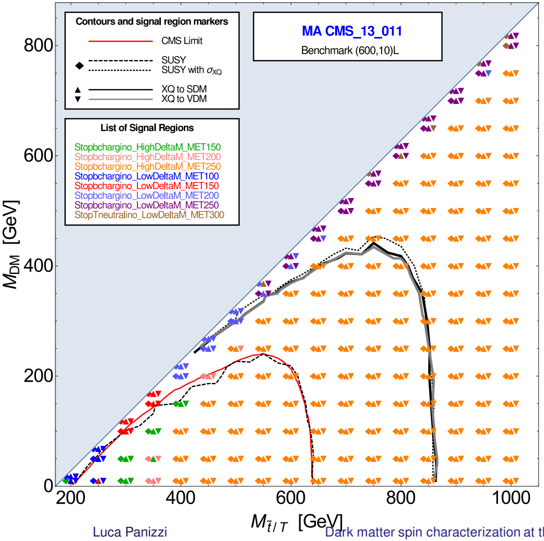


The cross-section for the bosonic DM is much larger than the fermionic one

$PP \to T\bar{T}/\tilde{t}\tilde{t}^* \to t\bar{t} + E_T^{miss}$

S.Kraml, U.Laa, **LP** and H.Prager, arXiv:1607.02050

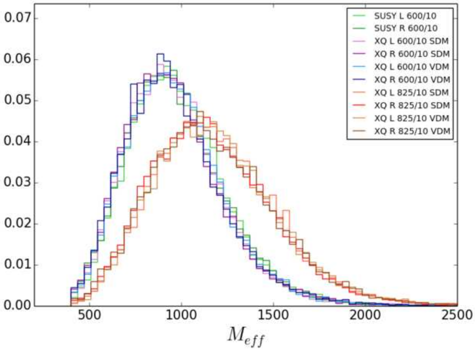
Both signals processed through MadAnalysis5 for the **CMS-SUS-13-011 search with single lepton + E_T^{miss}** in the final state and with XQ decaying to scalar or vector DM



Main results

- No differences between scalar and vector DM for XQ scenario
- The cross-section is higher for quarks with respect to squarks with analogous mass configurations
- Allowed regions for SUSY are excluded for XQs (only by LHC data)
- If we rescale the SUSY results with the XQs cross-section we obtain with good accuracy the same results as by performing a full simulation in the XQs framework
- Analogous results with different benchmarks and using CheckMATE

Correlation with cross-section



"Cold" colors: XQ points with **masses** similar to SUSY

"Warm" colors: XQ points with **cross-section** similar to SUSY

$$M_{eff} = \sum p_t(\text{jets}) + p_T(l) + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$$

Correlations between shape and cross-section may help in characterising the spin of the DM

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
- High luminosity needed to achieve enough events for a shape analysis

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