Dark matter at colliders

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LFC24 - Fundamental Interactions at Future Colliders
SISSA 16-20 September 2024

(Selected aspects of)
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and how?

We know dark matter exists but we only have astroparticle/cosmological evidences

It can be one or more particles
Can we produce it at the LHC or at future colliders?
Mabye, it depends on its properties!

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- it has to give observable effects within the range of energies of the collider
- it must be embedded in a consistent BSM theory (at least if a signal is observed)

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Stereotipical signal of DM at collider
Events with missing transverse energy

So far it looks trivial
but no signal has been observed so far!

So, let's investigate the implications of these aspects
and see how can we use them to design new searches at the LHC and future colliders

A caveat

often underrated

We cannot "discover dark matter" at colliders!

Signals with missing energy → **neutral particles stable within the detector size**

The only way to discovered dark matter is through **direct detection** experiments
rapidly reaching enough sensitivity to detect the neutrino floor/fog

However, a combination of evidences from **direct, indirect and collider experiments**
can lead us to pinpoint the **properties of dark matter**

DM at future colliders

what can we expect to achieve?

The obvious: increase sensitivity on already tested scenarios

signal discovery or stronger bounds on DM/mediator masses and new couplings

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Alternative processes which complement what can be tested at the LHC
e.g. if DM interacts mostly/exclusively with electrons or muons

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The good news

The range of possibilities for extending the SM to include DM is so wide that **any** future collider will improve current sensitivity on large classes of models

Parametrising dark matter

Many theories predicting dark matter candidates (SUSY, UED, Little Higgs. . .)
together with many other particles ⟶ **model-dependent constraints on parameter space**

Searches for specific models ⟶ difficult reinterpretation in other scenarios

so let's complicate our life in steps

Minimal requirements
A viable DM scenario must provide at least a fraction of the measured relic density

$$\Omega h^2 \leq 0.120 \pm 0.001$$

(so underabundant relic density is allowed ⟶ multiple DM components)

and not be excluded by indirect or direct detection

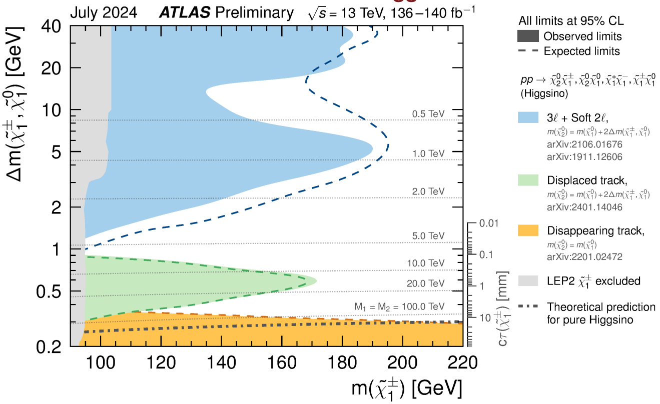
and let's **systematically study scenarios by gradually increasing complexity**
i.e. number of particles and/or degrees of freedom

Minimal dark matter

Lightest member of an EW multiplet :

- EW couplings (driven by representations)
- loop-induced splitting between neutral and charged χ
- **bounds depend only on masses**
- Representation-dependent upper limit on the mass (thermal relic)

Current mass bounds for higgsino-like DM



ATLAS, "SUSY July 2024 Summary Plot Update," ATL-PHYS-PUB-2024-014
(see also Dibyashree's talk)

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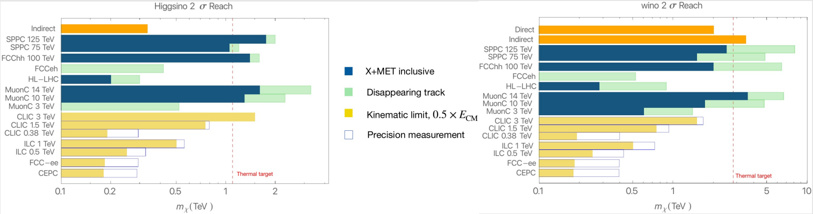
Future colliders projections for wino- or higgsino-like DM (compared to DD and ID):



T. Bose *et al.*, Snowmass2021 Energy Frontier BSM report arXiv:2209.13128

Potential to cover the entire relevant parameter space (when masses give $\Omega h^2 = 0.120$)

Higher multiplets (especially 5-plet) have also been studied

M. Cirelli *et al.*,"Minimal dark matter," Nucl. Phys. B **753** (2006), 178-194
E. Del Nobile *et al.*, "Millicharge or Decay: A Critical Take on Minimal Dark Matter," JCAP **04** (2016), 048
S. Bottaro *et al.*, "Minimal Dark Matter bound states at future colliders," JHEP **06** (2021), 143

This DM can only be fermion or scalar, what about vector? we need one more step

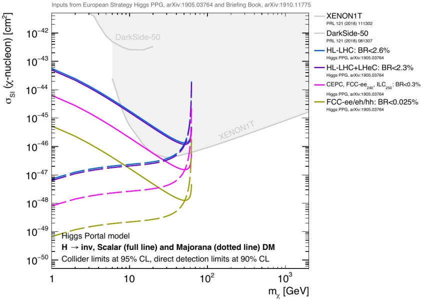
SM portals (H and Z)

- The Higgs boson can form a dim-2 singlet $H^\dagger H$ which can couple to bosonic DM or interact via Yukawa $\lambda H \bar{\chi}\chi$ to fermions
- The Z boson interacts with DM via $\bar{\chi}\gamma^\mu(g_L P_L + g_R P_R)\chi Z_\mu$ with $g_{L,R}$ free params.

Case 1 - DM lighter than $\mathbf{m_{H,Z}/2}$: $Z \rightsquigarrow$ constrained by LEP, $H \rightsquigarrow$ upper bounds on $\mathrm{BR}_{H\to\mathrm{inv}}$.

Collider	95% CL upper bound on BR_{inv} [%]			95% CL upper bound on BR_{unt} [%]	
	Direct searches	kappa-3 fit	Fit to BR_{inv} only	kappa-3 fit	Fit to BR_{unt} only
HL-LHC	2.6	1.9	1.9	4.0	3.6
HL-LHC + HE-LHC(S_2')		1.5	1.5	2.4	1.9
FCC-hh	0.025	0.024	0.024	1.0	0.36
HL-LHC + LHeC	2.3	1.1	1.1	1.3	1.3
HL-LHC + CEPC	0.3	0.27	0.26	1.1	0.49
HL-LHC + FCC-ee_{240}	0.3	0.22	0.22	1.2	0.62
HL-LHC + FCC-ee_{365}		0.19	0.19	1.0	0.54
HL-LHC + ILC_{250}	0.3	0.26	0.25	1.8	0.85
HL-LHC + ILC_{500}		0.23	0.22	1.4	0.55
HL-LHC + ILC_{1000}		0.22	0.20	1.4	0.43
HL-LHC + $CLIC_{380}$	0.69	0.63	0.56	2.7	1.0
HL-LHC + $CLIC_{1500}$		0.62	0.40	2.4	0.51
HL-LHC + $CLIC_{3000}$		0.62	0.30	2.4	0.33

J. de Blas *et al.*, "Higgs Boson Studies at Future Particle Colliders," JHEP **01** (2020), 139



T. Bose *et al.*, Snowmass2021 Energy Frontier BSM report arXiv:2209.13128

Results for vector DM in M. Zaazoua *et al.*, LHEP **2022** (2022), 270

Case 2 - off-shell H, Z: suppressed, low reach

There are also **neutrino portal** scenarios (effective operators, Yukawa interactions) but mostly testable through astrophysics experiments

M. Blennow *et.al.*, "Neutrino Portals to Dark Matter," Eur. Phys. J. C **79** (2019) no.7, 555

Minimal gauge vector DM

it also requires a new scalar to get mass

Abelian

- A $U(1)_D$ group: $\mathcal{L} = V_{D\mu\nu} V_D^{\mu\nu}$

A problem:

Abelian ➔ kinetic mixing ➔ not stable

Solution:

- Sequester $U(1)_D$ ➔ an exact $\mathbb{Z}_2$

$$V_D^\mu \to -V_D^\mu \quad \text{(Charge conjugation)}$$

V_D is stable, now make it massive:

- SSB ➔ complex singlet S ($S \xrightarrow{\mathbb{Z}_2} S^*$)

$$\mathcal{L} = |D_\mu S|^2 + \mu_S^2 |S|^2 - \lambda_S |S|^4$$
$$m_{V_D} = \sqrt{2} g_D v_D$$

V_D^μ is a DM candidate

Need to interact with the SM:

- **Higgs portal** ➔ $V(\Phi_H, S) = \lambda |\Phi_H|^2 |S|^2$

Widely studied

Lebedev, Lee & Mambrini 1111.4482,
Farzan & Akbarieh 1207.4272,
Baek, Ko, Park & Senaha 1212.2131, . . .

Non-abelian

- Various possible gauge groups

$$\mathcal{L} = V^a_{D\mu\nu} V_D^{\mu\nu a}$$

- No renormalizable kinetic mixing

Limiting to $SU(N)$:

- complete SSB with $N-1$ complex scalars ➔ preserved $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetries

Gross *et al* 1505.07480

$V_D^{\mu a}$ are all DM candidates

- Still can have **Higgs portal**

$$V(\Phi_H, S_{i,j,\ldots}) = \sum_{i,j} \lambda_{ij} |\Phi_H|^2 S_i^\dagger S_j + h.c.$$

Also widely studied

Hambye 0811.0172, Diaz-Cruz & Ma 1007.2631,
Fraser, Ma & Zakeri 1409.1162, Ko & Tang 1609.02307, . . .

Collider bounds mostly when V_{DM} lighter than H
but minimal extensions have richer phenomenology

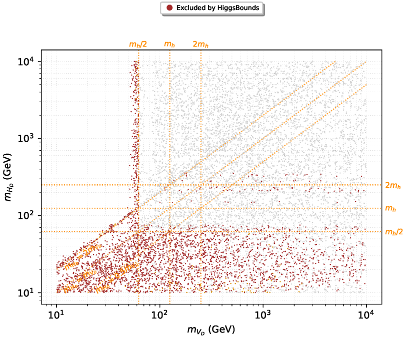
A. Belyaev, A. Deandrea, S. Moretti, **LP**, D. A. Ross and N. Thongyoi,
“Fermionic portal to vector dark matter from a new gauge sector,”
Phys. Rev. D **108** (2023) no.9, 095001

Minimal gauge vector DM

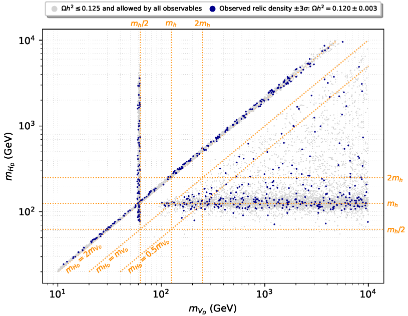
The $SU(2)$ case

All points in the $\{m_{DM}, m_{H_D}\}$ which give $\Omega h^2 \leq 0.120$

In red, excluded by Higgs measurements



In blue when $\Omega h^2 = 0.120$



N. Benincasa, L. Delle Rose, **LP** and M. Razzaq, (in preparation)

Future colliders can **improve Higgs measurements** significantly reducing even more the number of allowed points

Minimal extensions like FPVDM can be directly tested both at LHC and future collders

Simplified models

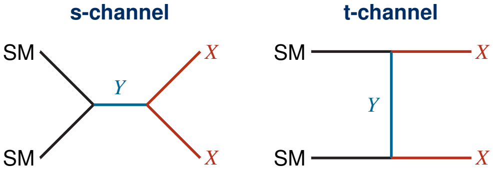
The DM interacts with SM particles via a BSM mediator

Stability of DM is ensured by a $\mathbb{Z}_2$ parity

The mediator can have different transformation properties

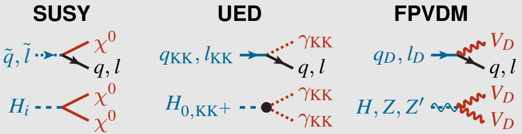
$\begin{cases} \mathbb{Z}_2\text{-even: } & \textbf{s-channel models} \\ \mathbb{Z}_2\text{-odd: } & \textbf{t-channel models} \end{cases}$

Schematic interactions (mediator Y and dark matter X)



Why are simplified models important?

Representative of classes of theoretical scenarios (with DM of different spins)



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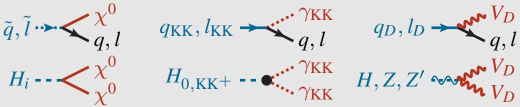
SUSY **UED** **FPVDM**

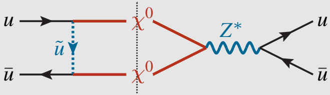


Complementarity between s-channel and t-channel

t-channel
mediator always heavier than DM
even number of mediator+DM in interactions

s-channel
mediator can also be lighter than DM
odd number of mediators allowed

But interferences can happen in non-minimal/full models. . .



Simplified models allow for a systematic description of more complex scenarios using "building blocks"

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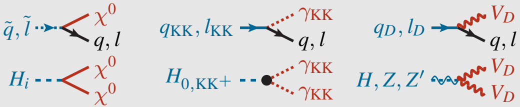

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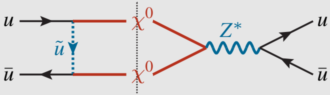


Simplified models allow for a systematic description of more complex scenarios using "building blocks"

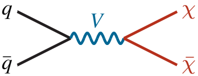
coloured mediators → high sensitivity at hadron colliders
non-coloured mediators → both hadron and lepton colliders

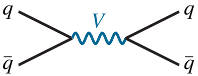
The s-channel scenario

Current status and projected bounds

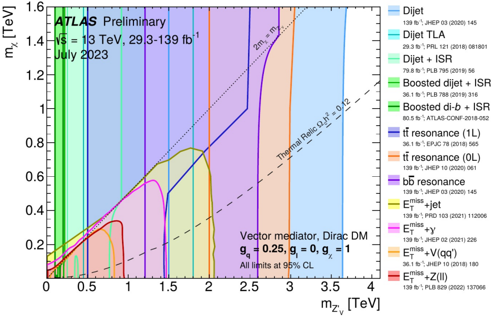
Example with vector mediator, Dirac fermion DM and fixed couplings (only to quarks)

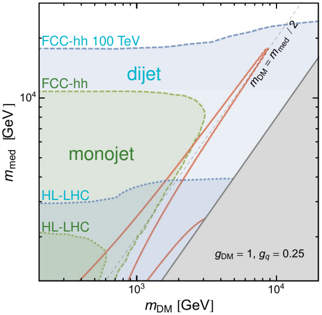
mono-object signatures





mediators can be tested by themselves





G. Aad *et al.* [ATLAS],
"Exploration at the high-energy frontier: ATLAS Run 2 searches investigating the exotic jungle beyond the Standard Model," arXiv:2403.09292
(see also L. Soffi's talk)

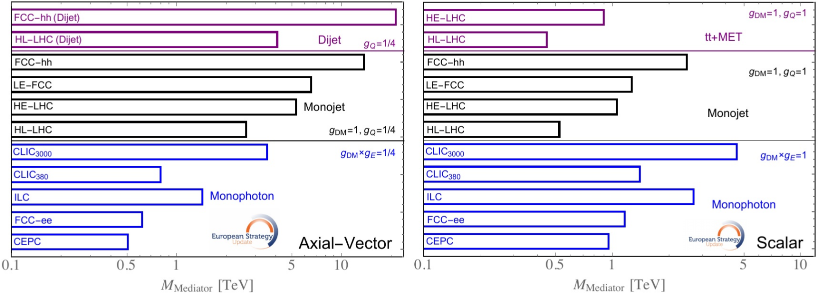
A. Abada *et al.*, FCC Physics Opportunities
Eur. Phys. J. C **79** (2019) no.6, 474

Huge increase covering the entire region which gives the measured relic density

The s-channel scenario

Current status and projected bounds

The case of axial vector and scalar mediators



R. K. Ellis *et al.*, "Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020," arXiv:1910.11775

Different colliders can be sensitive to different choice of couplings

There will be improvement regardless of which collider will be built

The t-channel scenario

A white paper is being written

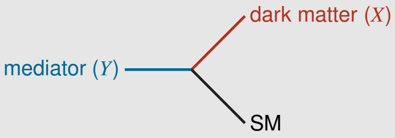
Dark Matter via t-channel Production
A Report of the LHC Dark Matter Working Group

Joint effort TH-EXP to provide guidelines and benchmarks for new analysis during Run 3 and future upgrades

More than 50 authors involved

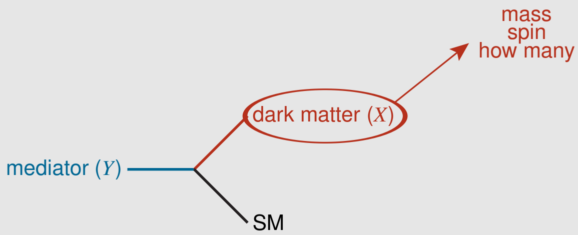
The t-channel scenario

guiding phenomenological questions



The t-channel scenario

guiding phenomenological questions



The t-channel scenario

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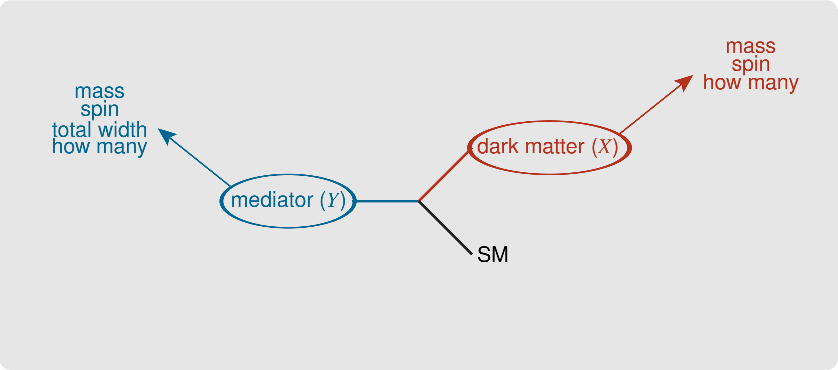

The t-channel scenario

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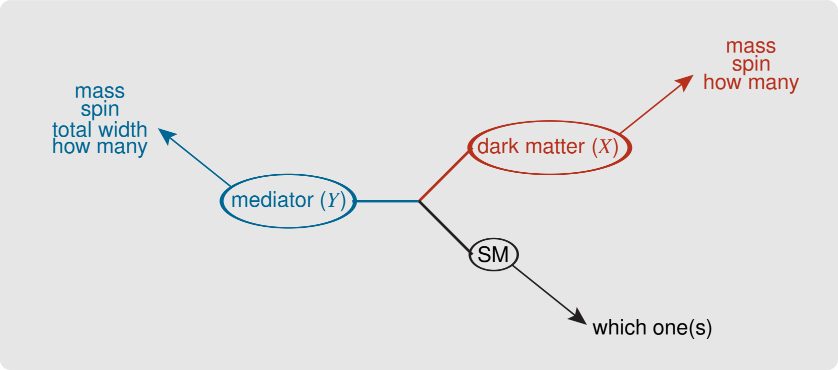

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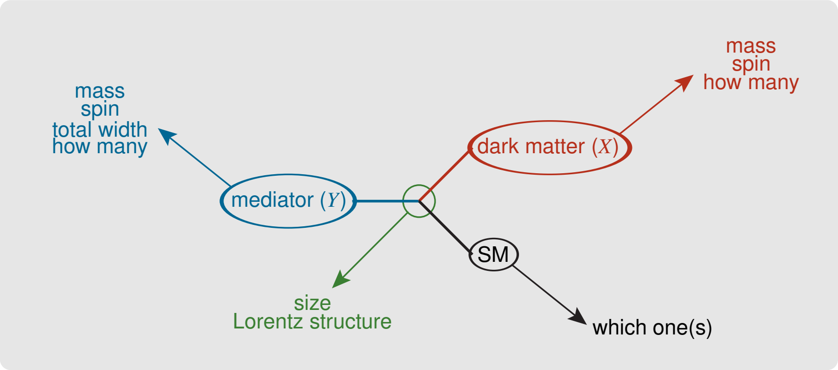

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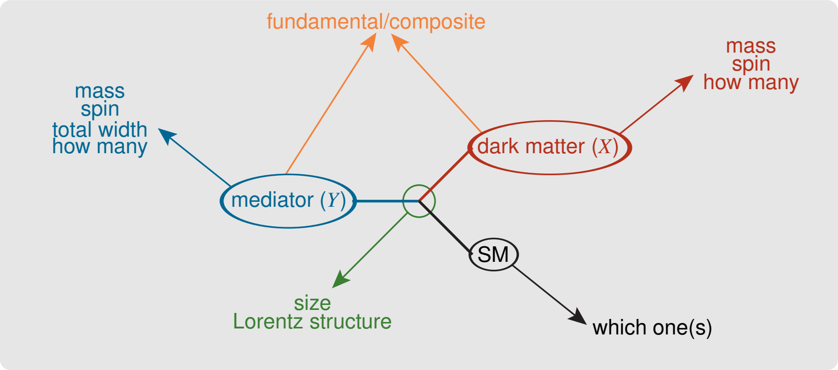
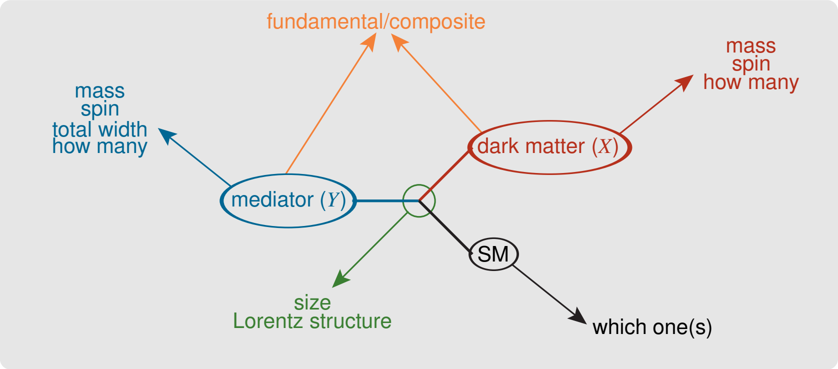


The t-channel scenario

guiding phenomenological questions

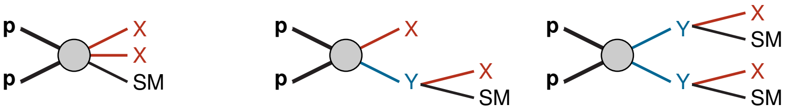


Depending on the possibilities:

- Can we observe a signal? And how?
- How do we reinterpret results?
- Can we define strategies to cover the widest range of possibilities at colliders?

The t-channel scenario

Which signatures

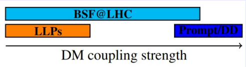


Not all processes might be possible at tree-level

depending on coupling or mass splitting

Long-lived mediators

Bound states
Displaced vertices
Delayed jets/photons



Mediators with prompt decay

MET+SM

depending on which SM particle

quark-philic { 1st generation, 2st generation, 3st generation, universal, . . . } **lepto-philic**

Interacting with SM gauge bosons (minimal DM is a subset) **or the Higgs boson**

The t-channel scenario

Classification

Real DM

		Mediator spin		
		0	$1/2$	1
DM spin	0	$\times$	**F3S**	$\times$
	1/2	**S3M**	$\times$	to be done
	1	$\times$	**F3V**	$\times$

Complex DM

		Mediator spin		
		0	$1/2$	1
DM spin	0	$\times$	**F3C**	$\times$
	1/2	**S3D**	$\times$	to be done
	1	$\times$	**F3W**	$\times$

Examples of theories which can be described by these simplified models

S3M	SUSY: squarks+neutralino (Majorana fermion)
S3D	Right-handed neutrino portals with extended scalar sectors
F3S	UED: KK quark partners + KK photon (real scalar)
F3C	SUSY: sleptons+sneutrinos
F3V	?
F3W	FPVDM: vector-like quark + vector DM (non-abelian dark gauge boson)

Complex DM scenarios excluded by cosmology for interactions with light quarks

C. Arina *et. al*, “Comprehensive exploration of t-channel simplified models of dark matter,”
Phys. Rev. D **108** (2023) no.11, 115007

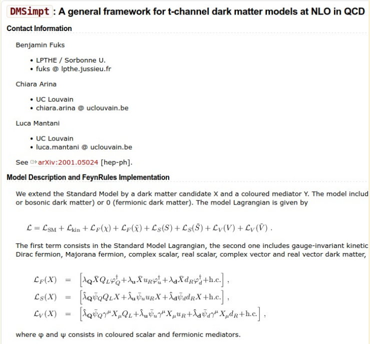
Is it true also for non-minimal models?
Is it true also for bottom and top?

The t-channel scenario

Numerical models

Simplified models suitable for performing MC simulations at NLO in QCD
and testing against cosmological observables

Coloured mediators



DMSimpt : A general framework for t-channel dark matter models at NLO in QCD

Contact Information

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- UC Louvain
- luca.mantani @ uclouvain.be

See arXiv:2001.05024 [hep-ph].

Model Description and FeynRules Implementation

We extend the Standard Model by a dark matter candidate X and a coloured mediator Y. The model includ
or bosonic dark matter) or 0 (fermionic dark matter). The model Lagrangian is given by

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \mathcal{L}_F(\chi) + \mathcal{L}_F(\tilde\chi) + \mathcal{L}_S(S) + \mathcal{L}_S(\tilde S) + \mathcal{L}_V(V) + \mathcal{L}_V(\tilde V)\ .$$

The first term consists in the Standard Model Lagrangian, the second one includes gauge-invariant kinetic
Dirac fermion, Majorana fermion, complex scalar, real scalar, complex vector and real vector dark matter,

$$\begin{aligned}
\mathcal{L}_F(X) &= \Big[\lambda_{\mathbf{Q}}\bar X Q_L \varphi_Q^\dagger + \lambda_{\mathbf{u}}\bar X u_R \varphi_u^\dagger + \lambda_{\mathbf{d}}\bar X d_R \varphi_d^\dagger + \text{h.c.}\Big]\ ,\\
\mathcal{L}_S(X) &= \Big[\hat\lambda_{\mathbf{Q}}\bar\psi_Q Q_L X + \hat\lambda_{\mathbf{u}}\bar\psi_u u_R X + \hat\lambda_{\mathbf{d}}\bar\psi_d d_R X + \text{h.c.}\Big]\ ,\\
\mathcal{L}_V(X) &= \Big[\hat\lambda_{\mathbf{Q}}\bar\psi_Q \gamma^\mu X_\mu Q_L + \hat\lambda_{\mathbf{u}}\bar\psi_u \gamma^\mu X_\mu u_R + \hat\lambda_{\mathbf{d}}\bar\psi_d \gamma^\mu X_\mu d_R + \text{h.c.}\Big]\ ,
\end{aligned}$$

where φ and ψ consists in coloured scalar and fermionic mediators.

http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt

	Spin	
Mediator	0	1/2
Dark matter	1/2	0 or 1

- DM real or complex
- Couplings with any SM quark
- Restrictions to select representations or coupling hierarchies (only one generation, universal couplings. . .)

C. Arina, B. Fuks and L. Mantani, Eur. Phys. J. C **80** (2020) no.5, 409, [arXiv:2001.05024 [hep-ph]].

Other models available for specific problems (leptophilic DM, multi-component DM. . .)
A unified model will also be released

t-channel with quark interactions

How the analysis is performed

We need to provide useful information for both TH and EXP community

t-channel with quark interactions

How the analysis is performed

We need to provide useful information for both TH and EXP community

- **Accurate kinematical description of the signal**
  → LO vs NLO

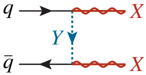
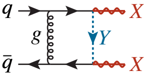
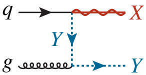
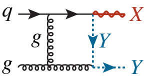
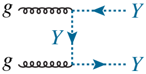
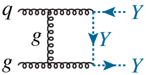
t-channel with quark interactions

How the analysis is performed

We need to provide useful information for both TH and EXP community

- **Accurate kinematical description of the signal**

  → LO vs NLO

Process	LO	NLO
XX		
XY		
YY		

t-channel with quark interactions

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  → LO vs NLO

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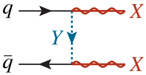
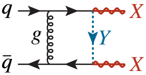
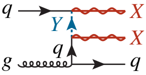
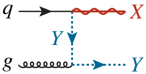
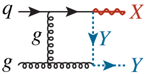
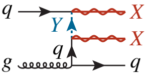
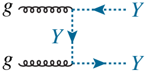
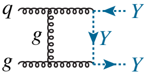
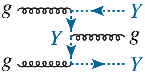
XX			
XY			
YY			

t-channel with quark interactions

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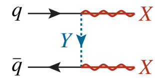
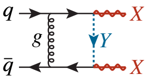
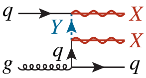
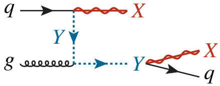
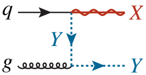
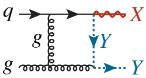
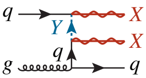
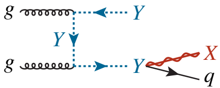
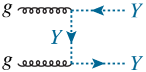
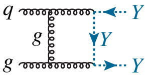
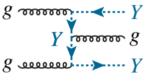
XX				
XY				
YY				

t-channel with quark interactions

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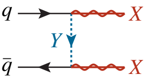
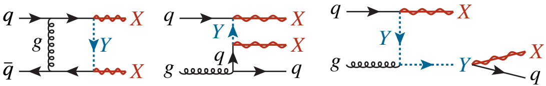
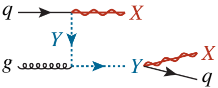
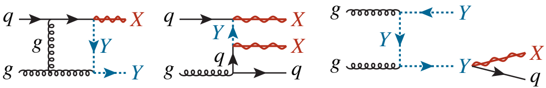
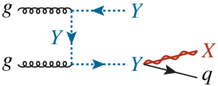
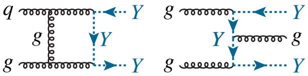
XX		
XY		
YY		

Double-counting between real emission and tree-level processes
Removed through suitable algorythm in MadGraph (MadSTR)

t-channel with quark interactions

How the analysis is performed

We need to provide useful information for both TH and EXP community

- **Accurate kinematical description of the signal**
  → LO vs NLO
  → beware of limitations: **narrow width approximation** $\Gamma_Y \ll m_Y$

t-channel with quark interactions

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  - → recasts using publicly available codes in MadAnalysis 5
  - → is there any model-independent conclusion we can make?

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  ⟶ How do we reinterpret the simplified model results in fully fledged models with more mediators or more DM candidates?

t-channel with quark interactions

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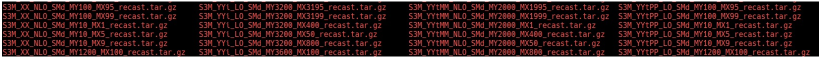
- **Widest possible reinterpretation potential**
  → How do we reinterpret the simplified model results in fully fledged models with more mediators or more DM candidates?
- **Provide public models and simulated data for (at least) Run 3 studies**
  → Writing easy-to-use tools to map simplified model parameters to any theory



Database of simulated samples and recast data under construction (not public yet)

t-channel with quark interactions

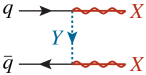
Deconstruct and reconstruct

Master equation to reconstruct signal for any flavour hypothesis

$$\begin{aligned}
\sigma^{eff}_{\rm Tot}(M_Y, M_X, \lambda) = & \lambda^0 \, \hat{\sigma}_{Y\bar{Y}_{QCD}}(M_Y) \quad \epsilon_{Y\bar{Y}_{QCD}}(M_Y, M_X) \\
& + \lambda^4 \, \hat{\sigma}_{YY_t}(M_Y, M_X) \, \epsilon_{YY_t}(M_Y, M_X) \\
& + \lambda^4 \, \hat{\sigma}_{Y\bar{Y}_t}(M_Y, M_X) \, \epsilon_{Y\bar{Y}_t}(M_Y, M_X) \\
& + \lambda^4 \, \hat{\sigma}_{\bar{Y}\bar{Y}_t}(M_Y, M_X) \, \epsilon_{\bar{Y}\bar{Y}_t}(M_Y, M_X) \\
& + \lambda^2 \, \hat{\sigma}_{Y\bar{Y}_i}(M_Y, M_X) \, \epsilon_{Y\bar{Y}_i}(M_Y, M_X) \\
& + \lambda^4 \, \hat{\sigma}_{XX}(M_Y, M_X) \, \epsilon_{XX}(M_Y, M_X) \\
& + \lambda^2 \, \hat{\sigma}_{XY}(M_Y, M_X) \, \epsilon_{XY}(M_Y, M_X)
\end{aligned}$$

$\hat{\sigma}$ are the cross-sections after factorizing the new coupling
ϵ are the efficiencies associated with a given experimental signal region

Example with XX



$$\mathcal{M} \propto \lambda^2 \rightarrow \sigma \propto \lambda^4$$

For each subprocess

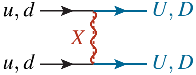
The kinematic properties are driven **only** by the masses
λ just **rescales** the cross-sections without affecting the shape of distributions

We can combine the **same simulated samples** in multiple ways by changing the coupling
Trivial in case of interaction with one quark, more interesing for multicomponent DM or multiple interactions

t-channel with quark interactions

Do we need to study all interactions?

- **up and down** ⟶ large PDF enhancement for YY_t, unique to these two quarks



Only for real DM

t-channel with quark interactions

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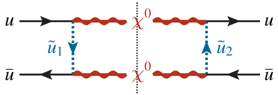
Possibility to combine individual result to describe
universal scenarios
$\mathcal{L} \sim \lambda\, Y_f X q_f$ with same λ for each q_f

Actually, results can be recombined in **almost any** way
Simulated samples can also be **recycled** using appropriate weights

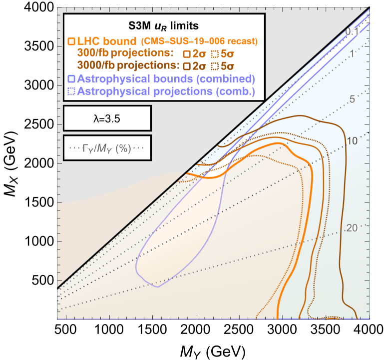
Potential to reconstruct complex models
with multiple mediators or DM candidates

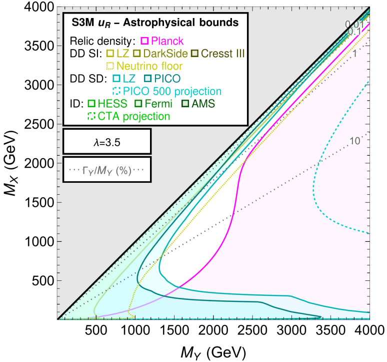
Missing some interference contributions at the moment



t-channel with quark interactions

interaction with up quark





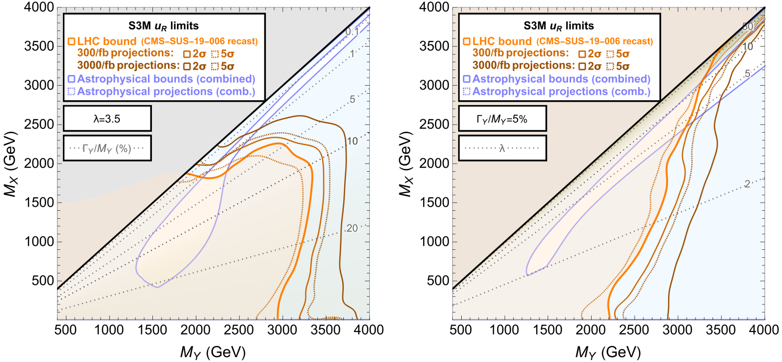
C. Arina *et.al*, “Comprehensive exploration of t-channel simplified models of dark matter,” Phys.Rev.D 108 (2023),

Only HL-LHC results at the moment

- Combination of all channels, relevance of NLO corrections and interference effects
- **Gradually covering the region with correct relic density**

t-channel with quark interactions

interaction with up quark



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t-channel with quark interactions

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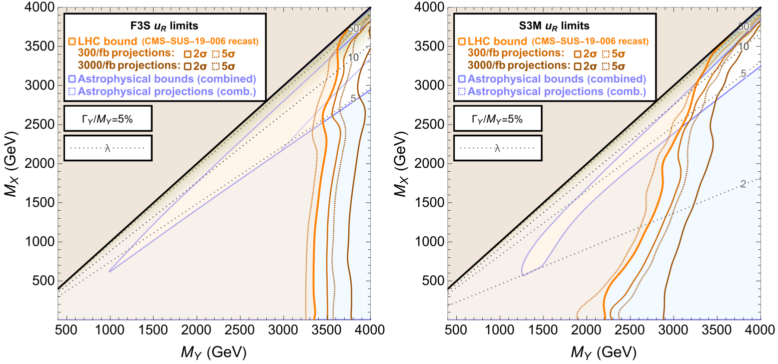

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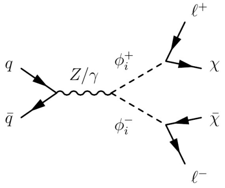
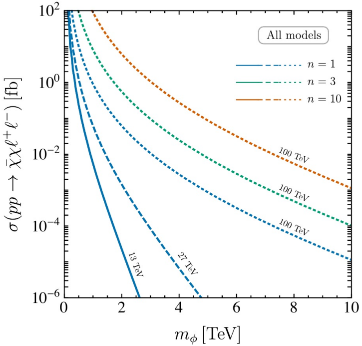
- **Discrimination between spin configurations**

t-channel with lepton interactions

Only DY production of mediators at hadron colliders

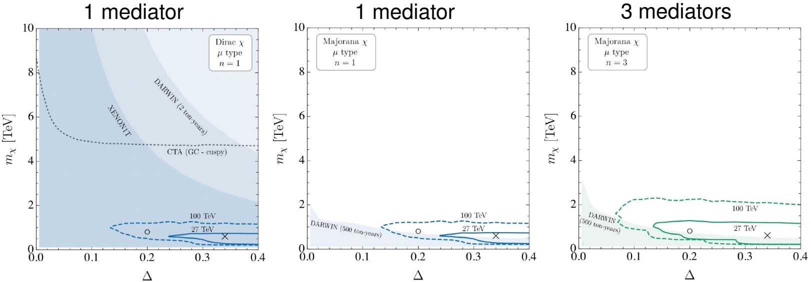




The cross-section drops fast significantly reducing the collider reach

M. J. Baker and A. Thamm, "Leptonic WIMP Coannihilation and the Current Dark Matter Search Strategy," JHEP **10** (2018), 187

t-channel with lepton interactions



$$\Delta = \frac{m_\phi - m_\chi}{m_\chi}$$

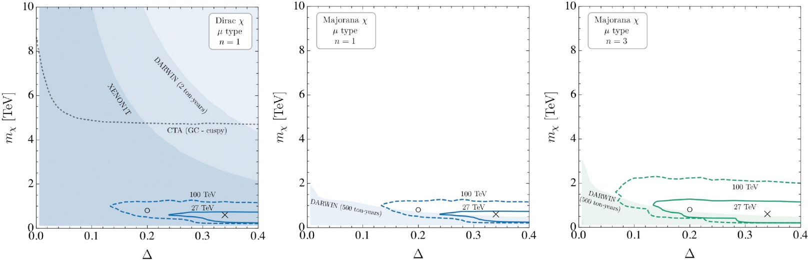
Dominating constraints from DD for Dirac DM

complementary reach between DD and HL-LHC/FCC-hh for Majorana DM

M. J. Baker and A. Thamm, "Leptonic WIMP Coannihilation and the Current Dark Matter Search Strategy," JHEP **10** (2018), 187

t-channel with lepton interactions

1 mediator 1 mediator 3 mediators



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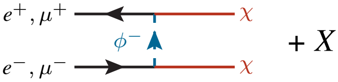
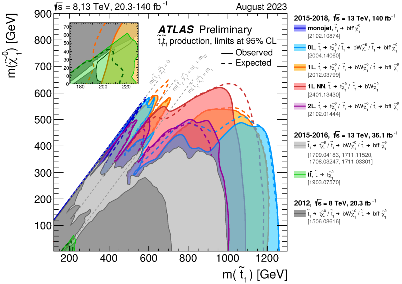
Potential for probing larger mass splitting at future lepton colliders



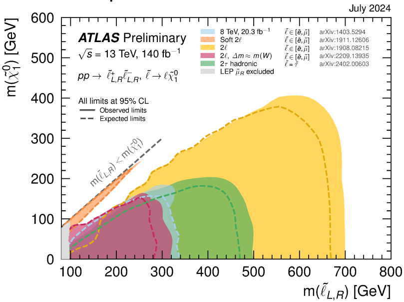
Full models

Example with SUSY

stop-neutralino bounds



Slepton-neutralino bounds

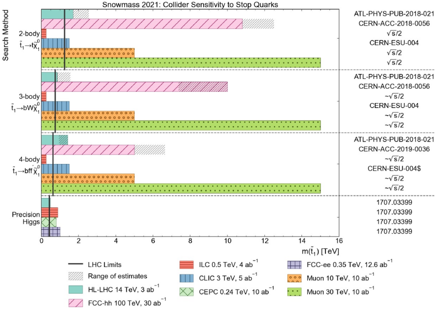


ATLAS, “SUSY July 2024 Summary Plot Update,”
ATL-PHYS-PUB-2024-014

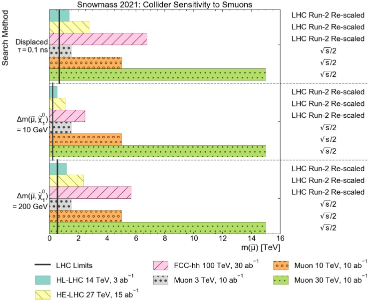
Full models

Example with SUSY

stop projections



Slepton projections



T. Bose *et al.*, Snowmass2021 Energy Frontier BSM report
arXiv:2209.13128

Huge improvement in any scenario, translating to stronger neutralino DM bounds

To conclude

- DM is tested in a **huge number of directions** at colliders
  including others I did not cover here (EFT, non-minimal SM extensions. . .)
- Synergy between **collider and non-collider** experiments
  → complementary approaches to probe parameter spaces of theories
- Efforts for **systematic and comprehensive analyses**
  → maximum gain with minimum effort (and minimum resource consumption)

Large increase on sensitivity for entire classes of models under each hypothesis about future colliders