Update on DM t-channel signatures

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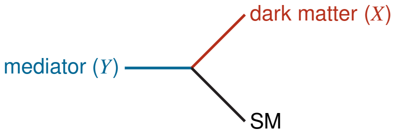
with embedded contributions by
C. Arina, M. Baker, A. Cornell, R. Costa Batalha Pedro and J. Heisig

Motivation

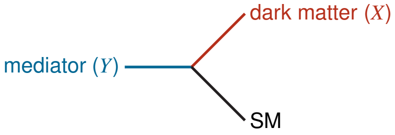
Joint effort TH-EXP to provide guidelines and benchmarks for new analysis during Run 3 and future upgrades

Coordinators
Benjamin Fuks, LP (theory)
Benedikt Maier, David Yu (CMS)
Rute Pedro, Dominique Trischuk (ATLAS)
and $50+$ authors

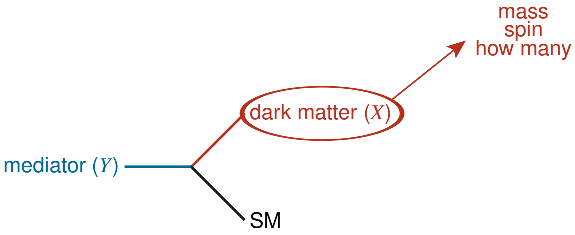
Study of scenarios based on the schematic interaction



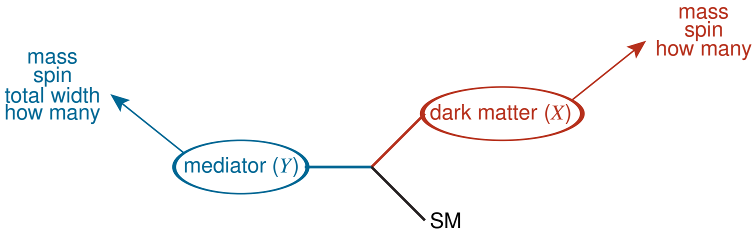
Guiding questions



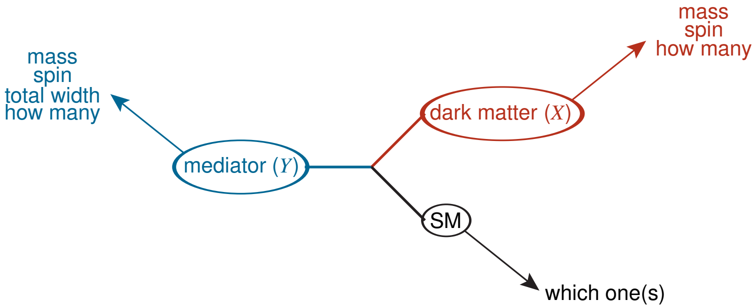
Guiding questions



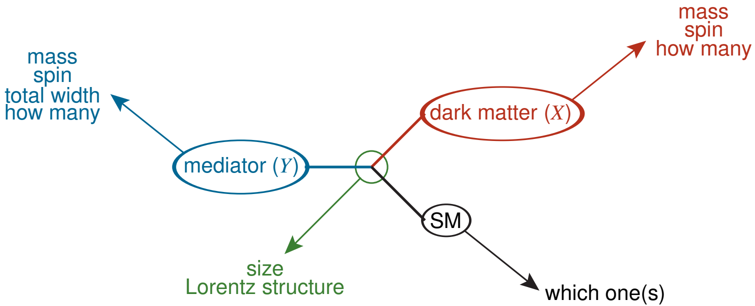
Guiding questions



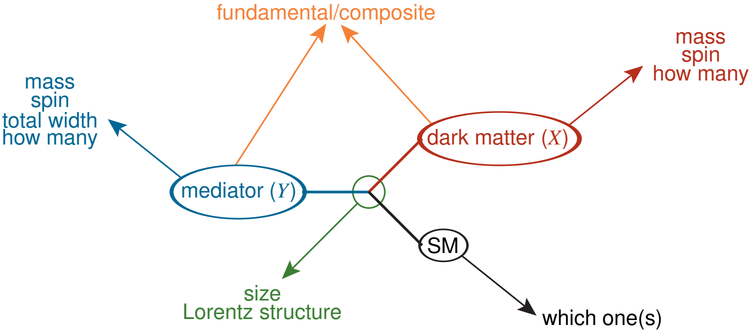
Guiding questions



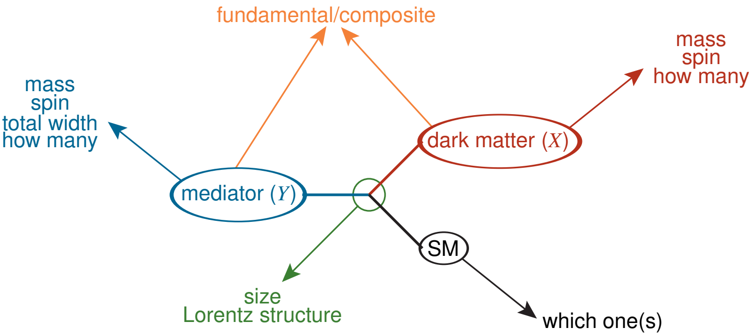
Guiding questions



Guiding questions



Guiding questions



Depending on the possibilities:

- Can we observe a signal? And how?
- How does cosmology constrain the parameters?
- How do we reinterpret results?
- Can we define benchmarks for LHC to cover the widest range of possibilities?

Temporary structure

To be reorganized
once all contributions
are in advanced state

The 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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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 will be used for specific problems
(leptophilic DM, multi-component DM. . .)

Mapping results from simplified models to theoretical scenarios

Cosmology

contribution by C. Arina

Cosmology of t-channel DM models

Goals of the section

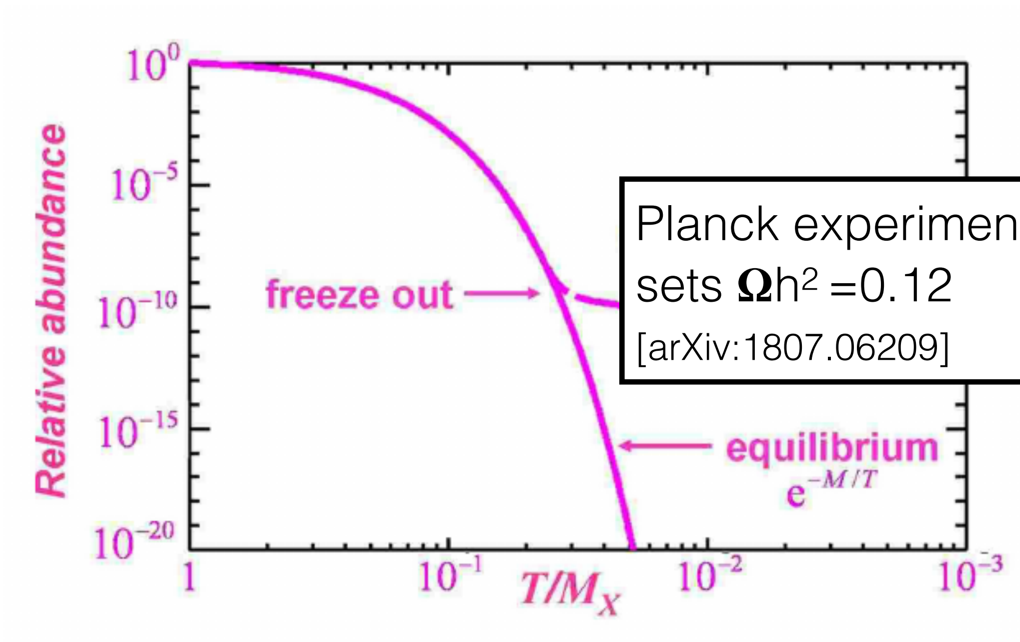
- Provide a general overview of the cosmology of t-channel models and point to the relevant literature
- Give overview of production mechanisms
- Give overview of main searches for:
- Direct detection
- Indirect detection
- Illustrate cosmological bounds for the models selected in the t-channel paper (minimal model, universal couplings, flavored, leptophilic, …)
- From parameter space available define viable benchmarks for collider searches

Contributors: C. Arina (section coordinator), M. Becker, E. Coppello, J. Harz, J. Heisig, A. Ibarra, S. Khalil, M. Kirtiman, M. Kraemer, L. Lopez-Honorez, L. Panizzi, D. Sengupta, Y. Sheng, S. Tentori

If you are interested in joining please contact Chiara Arina (Chiara.arina@uclouvain.be)

Dark Matter production in the early universe

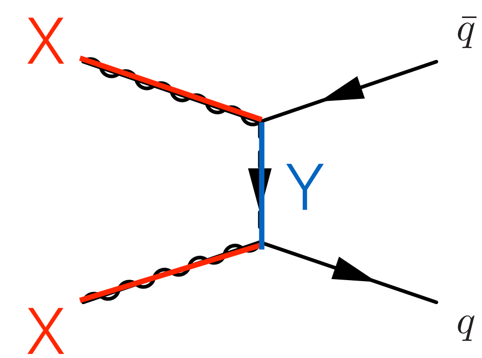
Relic abundance via freeze-out
Standard mechanism



Planck experiment sets $\Omega h^2 = 0.12$ [arXiv:1807.06209]

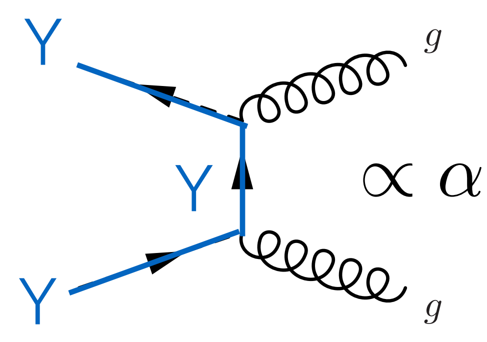
LO processes

DM annihilation

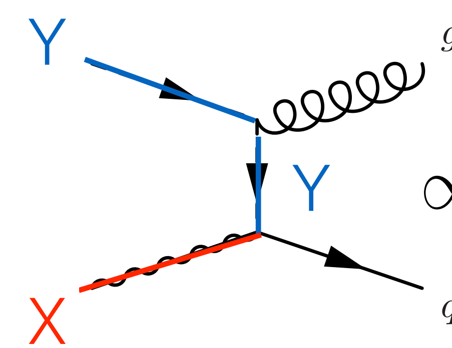


$\propto \lambda_\varphi^4$

coannihilation (compressed spectrum)



$\propto \alpha_s^2$



$\propto \lambda_\varphi^2 \alpha_s$

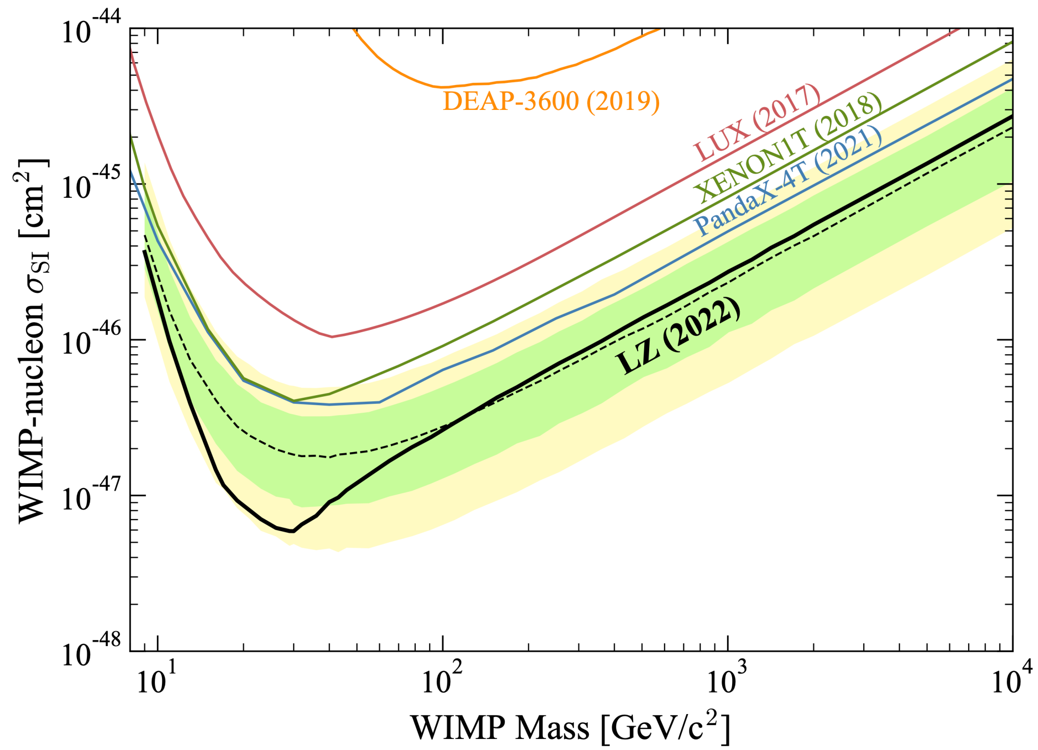
LO processes + non perturbative corrections (Sommerfeld enhancement + bound states)

Freeze-in, SuperWIMPs achieve relic density via decay of heavy species and provide LLPs signatures also detailed

T-channel white paper - Cosmology section

Dark Matter direct and indirect searches

Direct detection

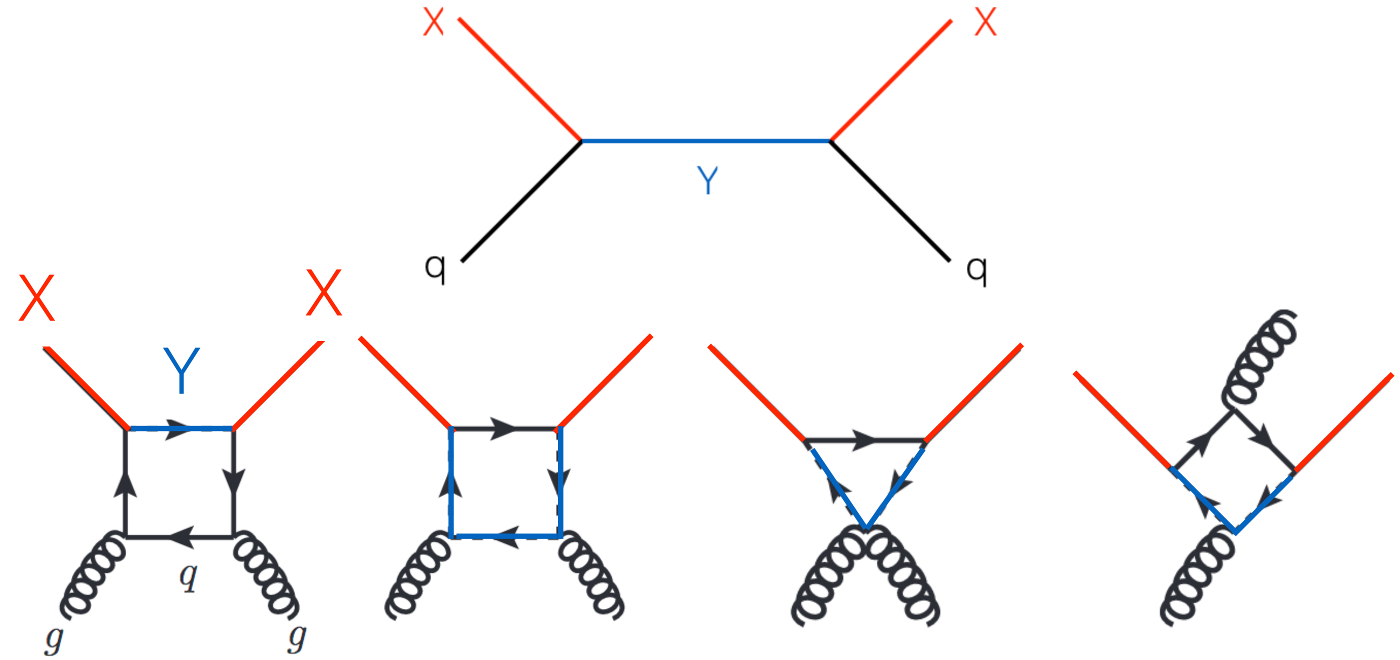


Indirect detection

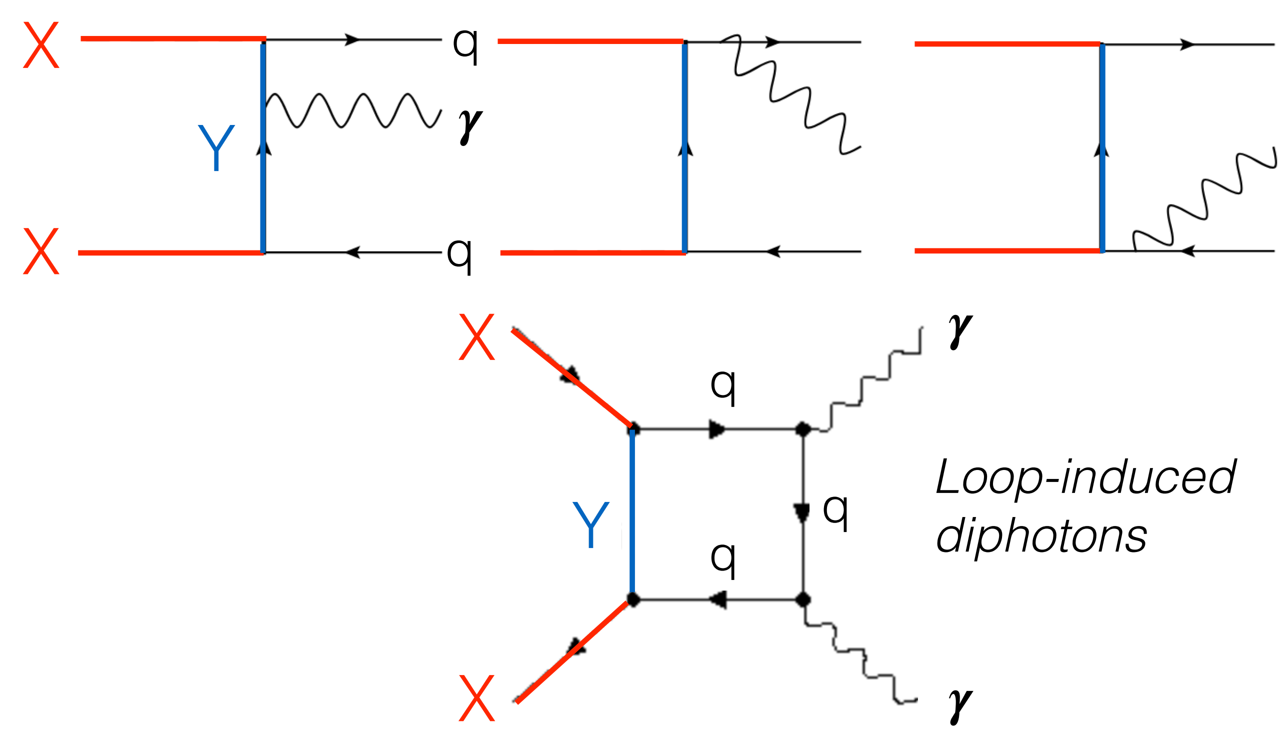
- In many models LO annihilation is p-wave suppressed
- NLO processes uplift the suppression and produce a sharp feature in the gamma-ray energy spectrum

T-channel white paper - Cosmology section

LO and/or NLO/loop processes



Virtual internal bremsstrahlung (VIB)



Cosmology: current status

The section is divided mainly into two parts

1. **general overview of t-channel models concerning**

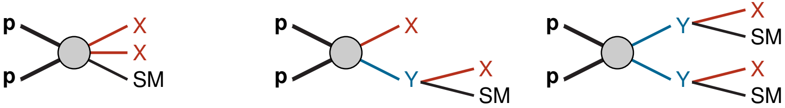
 - ✓ production mechanisms in the early universe (freeze-out, freeze-in, conversion driven freeze-out, super wimp) $\longrightarrow$ **basically all done**
 - ✓ addition of non-perturbative corrections such as bound states to the relic density computation (freeze-out, conversion driven cases) $\longrightarrow$ **done**
 - ✓ direct, indirect searches (gamma-rays lines especially) $\longrightarrow$ **yet to be written but literature widely available**

2. **benchmark models**

 - ✓ coupling to third generation (b_R, t_R) for Majorana dark matter for all production mechanisms $\longrightarrow$ **basically all done**
 - ✓ u_R case for all DM spin and mediators $\longrightarrow$ **to be written but data already available**
 - ✓ non perturbative corrections for universal case (freeze-out and conversion driven) $\longrightarrow$ **writing almost complete**
 - ✓ frustrated DM (see A. Cornell's contribution later) $\longrightarrow$ **will be written by the authors, first contact made some time ago**

Collider signatures

Which signatures

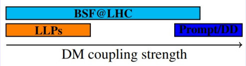


Not all processes might be possible at tree-level

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

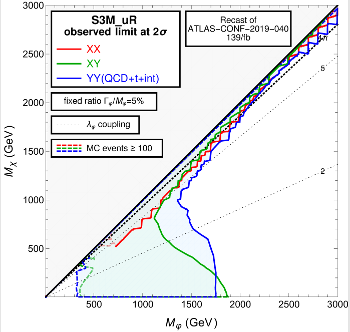
Interacting with SM gauge bosons (Z/W) or the Higgs boson

Prompt mediator decays

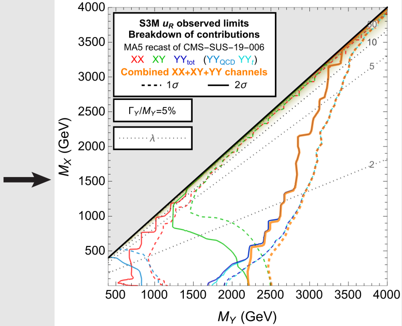
interaction with the up quark

Goals

- Go beyond existing results



C. Arina, B. Fuks, L. Mantani, H. Mies, LP and J. Salko, Phys. Lett. B **813** (2021), 136038



C. Arina, B. Fuks, Jan Heisig, Michael Krämer, L. Mantani and LP, arXiv:2307.10367, to appear on PRD

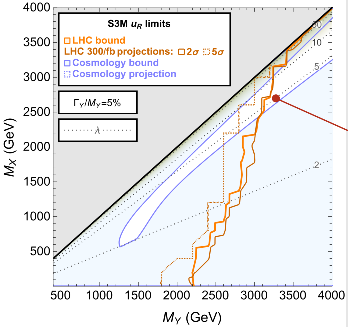
Combination of all channels, relevance of NLO corrections and interference effects

Prompt mediator decays

interaction with the up quark

Goals

- Go beyond existing results
- Identify benchmarks allowed by LHC and cosmology observables



C. Arina, B. Fuks, Jan Heisig, Michael Krämer, L. Mantani and LP, arXiv:2307.10367, to appear on PRD

	M_Y	M_X	λ
S3M_uR	3300	2700	4.79563
F3S_uR	3400	2500	4.88088
F3V_uR	3500	1500	1.0066

Prompt mediator decays

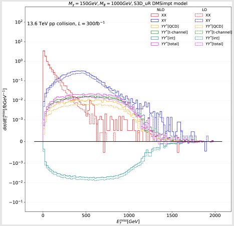
interaction with the up quark

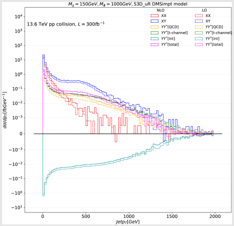
Goals

- Go beyond existing results
- Identify benchmarks allowed by LHC and cosmology observables

	M_Y	M_X	λ
S3M_uR	3300	2700	4.79563
F3S_uR	3400	2500	4.88088
F3V_uR	3500	1500	1.0066

- Store event samples and kinematical distributions for subsequent analyses





Collider: current status

This section requires long simulations but writing will be fast at the end

1. Simulation status (only authors with access to clusters)

- ✓ u_R, d_R, c_R, t_R recast done for all simplified scenarios
- ✓ s_R, b_R in progress
- ✓ MC samples not ready

2. Development of a common simulation framework on condor

dmmc.sh	first commit of the instructions	last week
sub_mass_condor.py	removing unused variables, updated template cfg	1 hour ago
submit_condor.py	removing unused variables, updated template cfg	1 hour ago

README.md

DMt

DMt simplified models

General description:

This package implements the running of parallel MG5 + madanalysis

The workflow is the following:

1. Download and install MG5_aMC locally

1.1 Includes installing the 6.5.4 LHAPDF

2. Prepare the conditions for running madanalysis

2.1 prepare a py3 environment

2.2 edit the installation scripts

3. Write templates for the 4 configuration cards for madgraph and madanalysis:

3.1 topology

3.2 run

3.3 MA5

3.4 sfs

4. Run a script (done by "sub_mass_condor.py") that prepares and launches jobs on condor, performing the following actions for a selected model/mass range:

4.1 editing the files in 3.1 - 3.4 to change the mass points and the input/output folders

4.2 check the existence of the events / madanalysis folder or whether the model/mass combination was already successful

4.3 for each of the unsuccesful files: write the condor runner and configuration files (done by "submit_condor.py")

4.4 launch them.

5. Clear the directories of the heavy files (.lhe, .gz, the pythia split run folder). This is done with the "sub_mass_condor.py" as well.

1. Downloading and installing MG5

2. Prepare the conditions for installing madanalysis

3. Write template configuration cards

4. Run the scripts

5. Clear the directory

O. Iorio and A. Cagnotta (CMS)

3. Analysis code for interpretation in general scenarios

Example_Output	restructure folder	last month
Example_Programs	restructure folder	last month
.gitignore	update	last week
LICENSE	Initial commit	last month
NLOCombine.py	add quark loop	last week
README.md	restructure folder	last month

README.md

MA5_combine

Madanalysis5 scripts to combine samples for DMSimpt Model in the context of t-channel WG

GeneralSimulation/OutputStructure/Results_scan_F3C/MA5_Recast

A. Desai

Flavoured dark matter

contribution by R. Costa Batalha Pedro

M. Blanke, G. Polesello, H. Acaroglu, M. Krämer

Top-philic Dark Matter

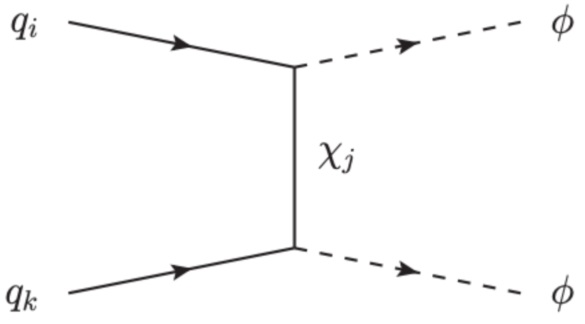
- **Models of flavoured DM beyond Minimal Flavour Violation**
  - 1702.08457 1702.08457
  - Flavour carried by the DM candidate and not by the mediator
  - DM is either a Dirac or Majorana fermion
  - Quark-flavoured DM coupling to the SM quarks
    - Lepton-flavoured models may link to the $(g-2)_\mu$ anomaly 2212.08142

- **Constrains from LHC for top-philic scenario**
  - Mainly on mediator pair production
  - $tj + \not{E}_T$ and $t\bar{t} + \not{E}_T$ final states (common to searches for SUSY squarks)

- **Majorana-specific phenomenology**
  - t-channel ϕ-pair-production leading to same-sign $tt + \not{E}_T$
  - Enhanced cross-section at the LHC due to the *up*-quark PDF in the protons

$$\lambda^{ij}\bar{q}_i\chi_j\phi$$

q_i	SM quarks
χ_j	DM fermion, flavoured
ϕ	coloured scalar mediator
λ	flavour-violating coupling matrix



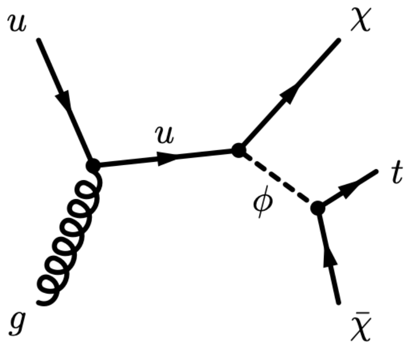
(b) $\phi\phi$ **production**

Majorana-specific

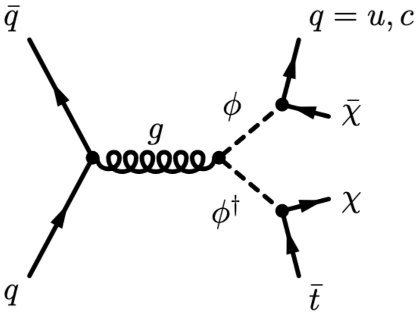
Single top signatures

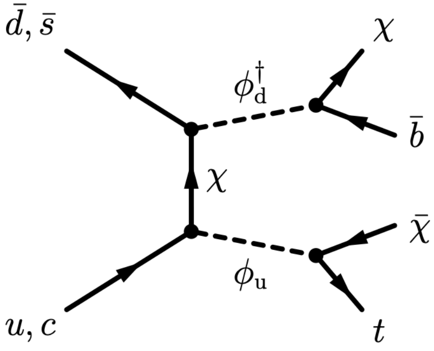
M. Blanke, G. Polesello, H. Acaroglu, M. Krämer

- **Simplified models of top-flavoured Dark Matter**
  - 2010.10530
  - Within the framework of Minimal Flavour Violation
  - ϕ coloured mediator
    - Right-handed model: couplings to up-type quarks only
    - Left-handed model: couplings to up/down-type quarks (more constrained by flavour physics)



- **Single top signatures**
  - $t + \not{E}_T$
  - $tq + \not{E}_T$, where $q = \{u, d, s, c\}$
  - $tb + \not{E}_T$





Charm/strange-philic DM

F. Benoit, A. Diyar, B. Fuks, M. Godsell, F. Parraud, D. Tuckler

- **Review/draw constrains on charm-flavoured DM**
  - Limits for the charm-philic model using four jets+MET searches
  - Phenomenology investigations of charm tagging

- **Similar content for a strange-philic model?**

Leptophilic models

contribution by M. Baker

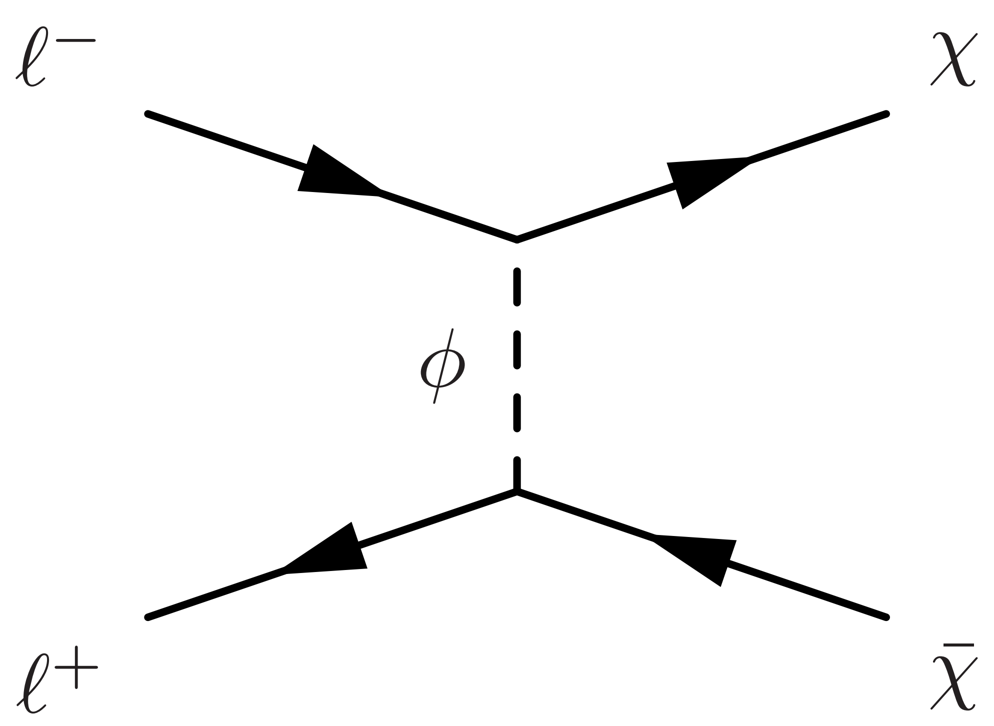
Leptophilic Models: Classification

Leptophilic t-channel models:

DM **only** couples to SM leptons via a t-channel diagram

- DM can couple to RH and/or LH e, μ and/or τ
- DM is gauge singlet $\implies$ charged mediator
- Fermionic DM $\implies$ bosonic mediator and vice versa
- DM could be a real or complex scalar, a Majorana or Dirac fermion or a real or complex vector
- The mediator must be complex/Dirac

E.g.,



RH Model Parameters:

- m_χ
- $\Delta = (m_\phi - m_\chi)/m_\chi$
- y_R^i

$$\mathcal{L} \supset y_R^{ij} \phi^j \overline{\chi} \ell_R^i + y_L^{ik} \varphi^k \overline{\chi} L_L^i + h.c.$$

Field	$(su(3)_C, su(2)_L, u(1)_Y)$	Spin
ℓ_R	$(1, 1, -1)$	$1/2$
L_L	$(1, 2, -1/2)$	$1/2$
χ	$(1, 1, 0)$	$0, 1/2, 1$
ϕ	$(1, 1, 1)$	$1/2, \{0, 1\}, 1/2$
φ	$(1, 2, 1/2)$	$1/2, \{0, 1\}, 1/2$

Leptophilic Models: Phenomenology

Phenomenology depends on

Mass Regime

- Decoupled: $0.3 \lesssim \Delta$
- Coannihilation: $0.02 \lesssim \Delta \lesssim 0.3$
- Quasi-degenerate: $\Delta \lesssim 0.02$

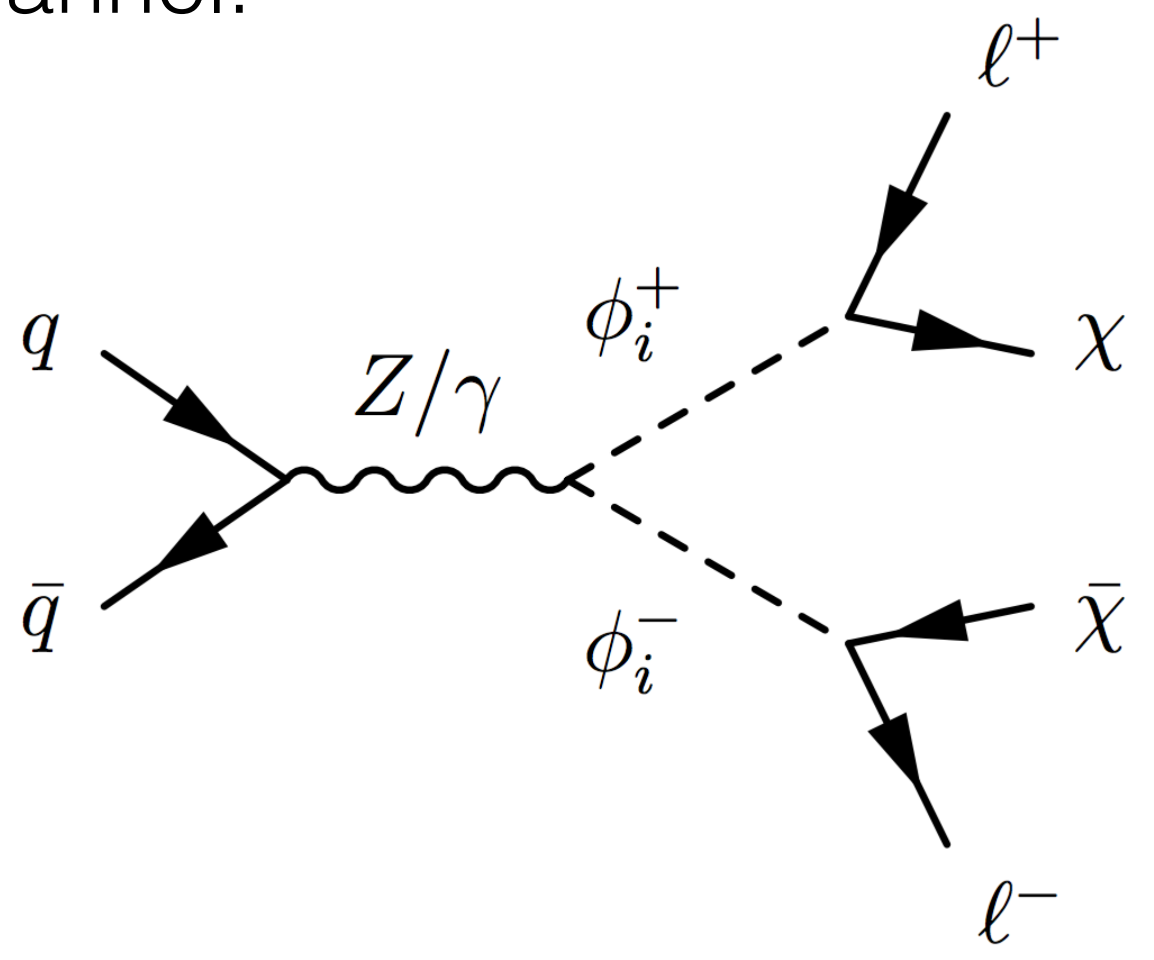
DM Production Mechanism (3 → 2 parameters)

- Freeze-out
- Freeze-in
- Other
- Undefined (3 parameters)

DM Particle Identity

- Real scalar and Majorana fermion has velocity suppressed freeze-out, direct detection and indirect detection processes
- Not directly relevant at LHC, but important when comparing with other searches or using production as constraint

Main LHC channel:



Two (SF) OS leptons + MET

(Also one lepton + MET in LH models from $W^{\pm} \to \phi^0 \phi^{\pm}$)

Mass Regimes:

- Decoupled: $\Longrightarrow$ hard leptons
- Coannihilation: $\Longrightarrow$ soft leptons (ISR boost?)
- Quasi-degenerate and small couplings: $\Longrightarrow$ long-lived mediator

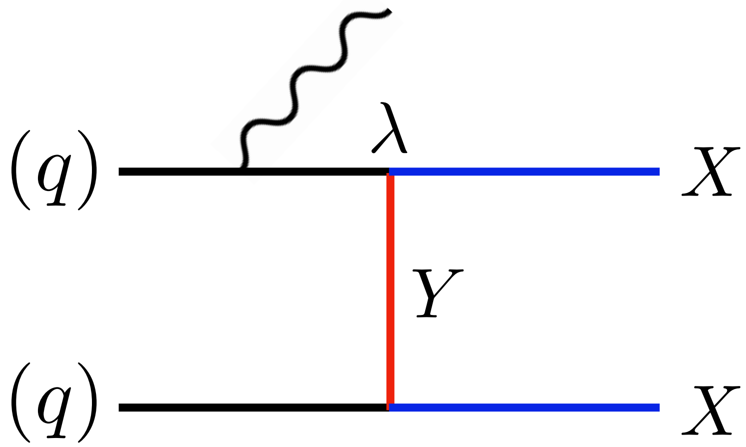
Status

- Classification complete
- Benchmark models defined
- Completing work on combining existing limits and relic surfaces

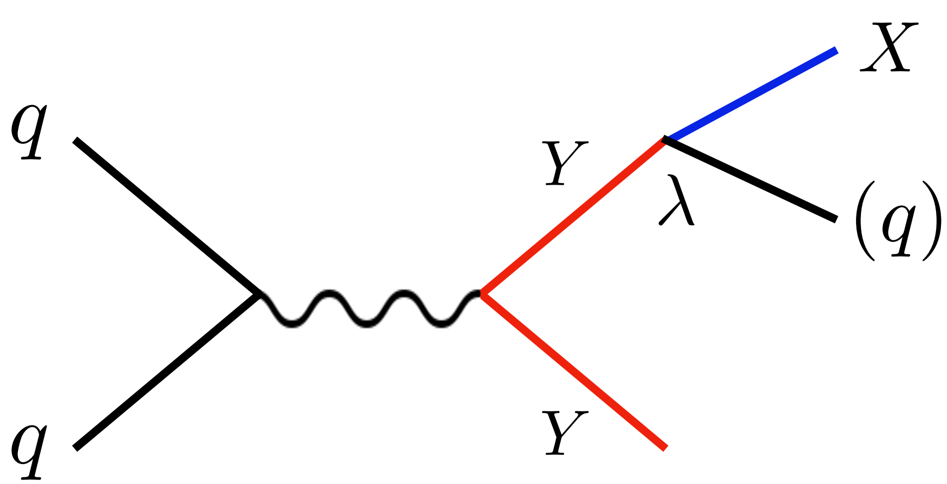
Long-lived mediators

contribution by J. Heisig

Why long-lived particles (LLPs)?



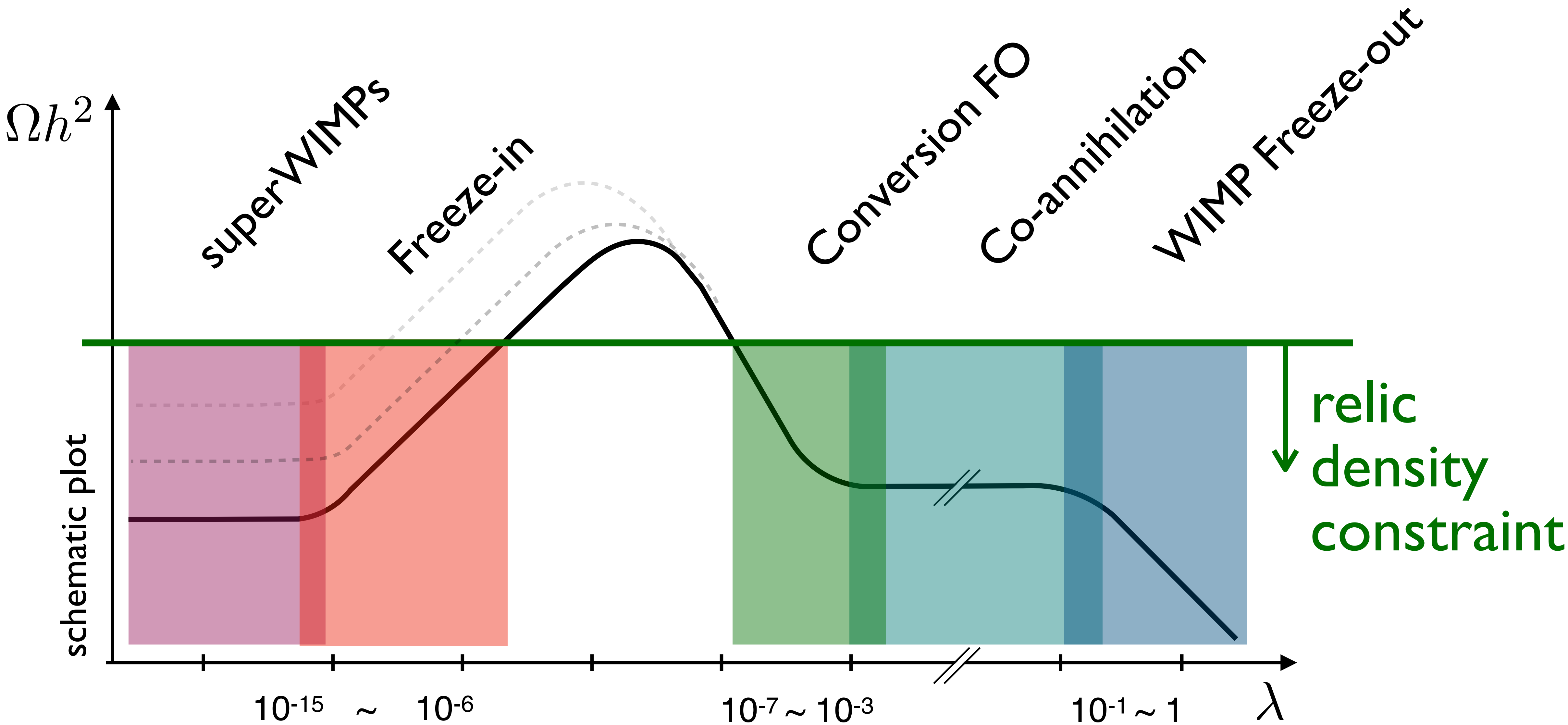
$\Rightarrow$ MET signature



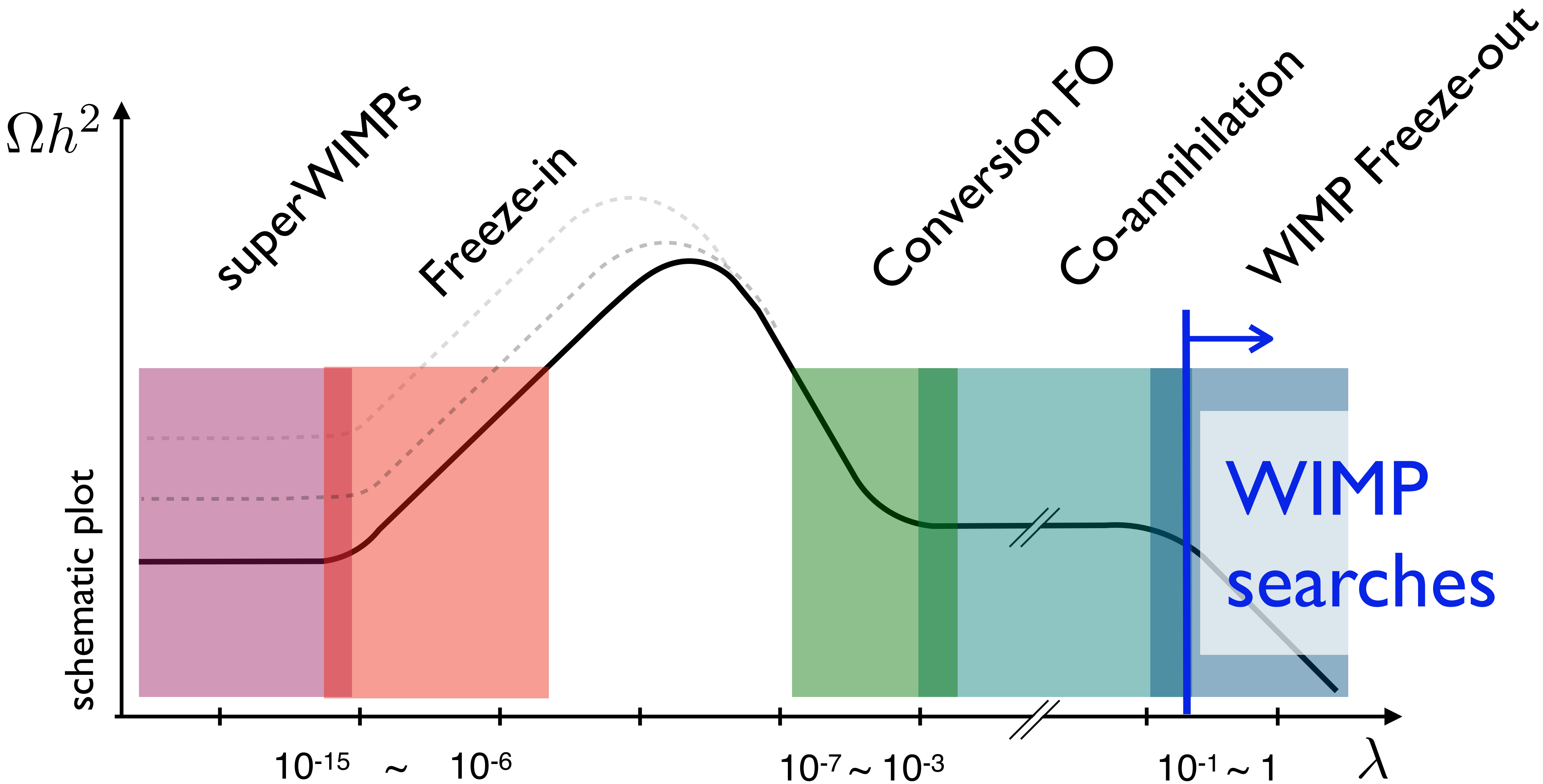
$\Rightarrow$ LLPs if:

- λ small or/and
- Small mass splitting, in particular: $\Delta m = m_Y - m_X < m_{(q)}$

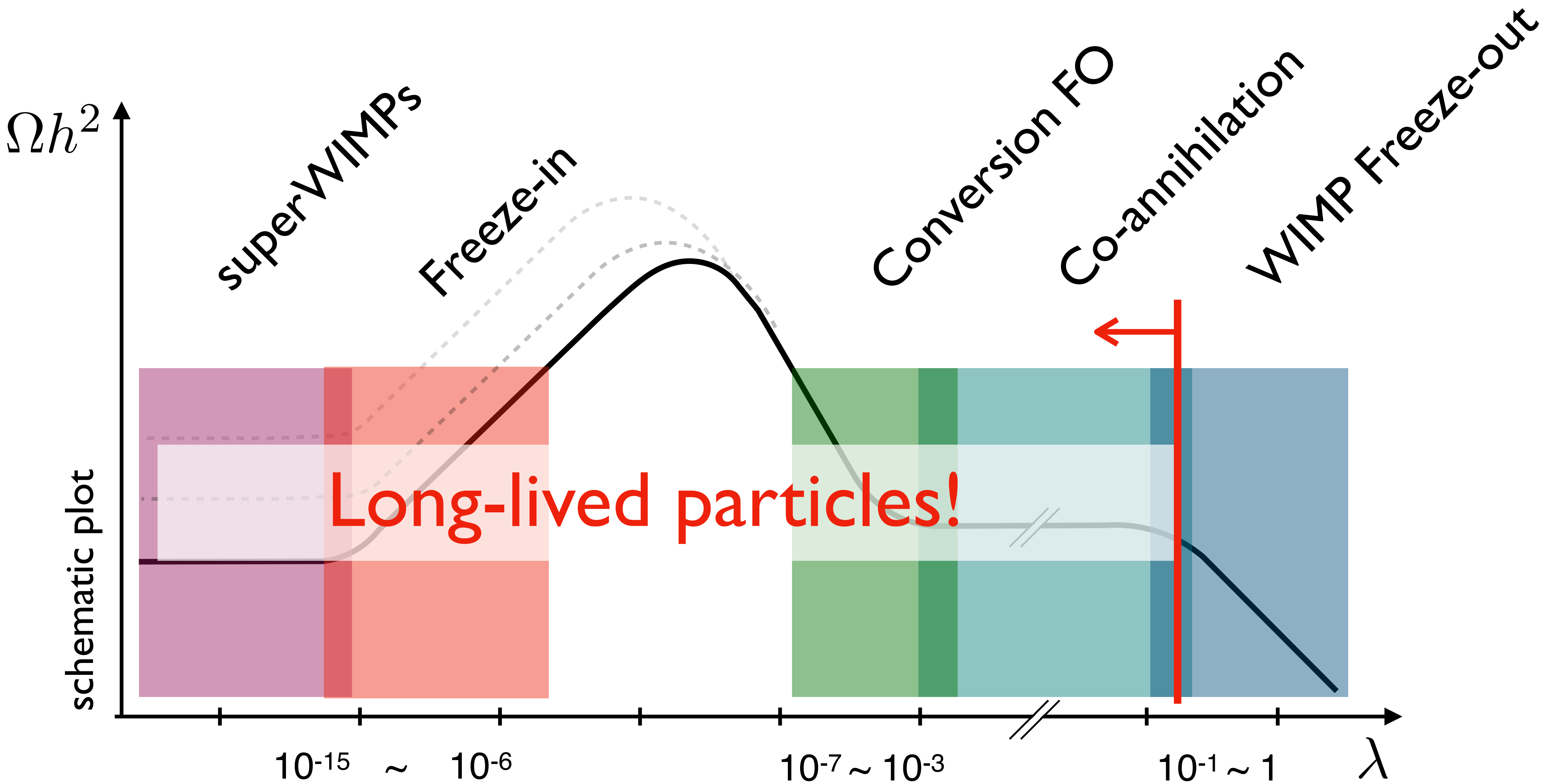
Range of dark matter couplings



Range of dark matter couplings

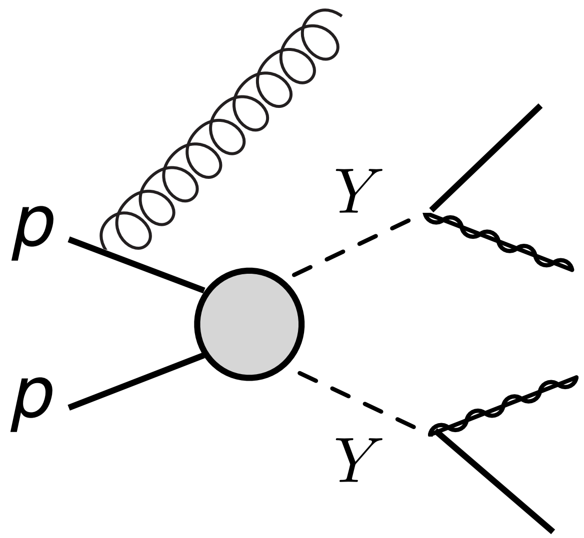


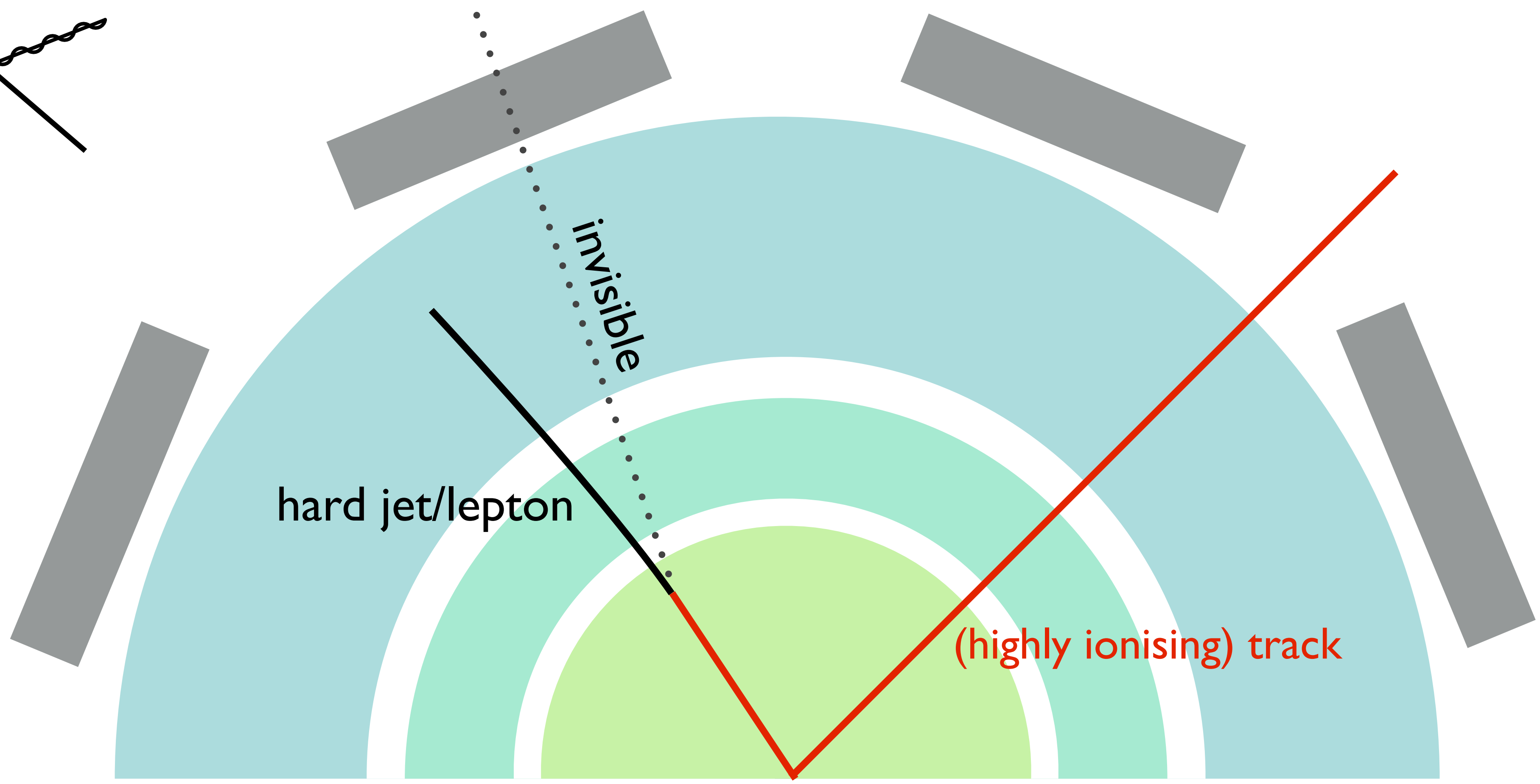
Range of dark matter couplings



LLP Signatures: light dark matter

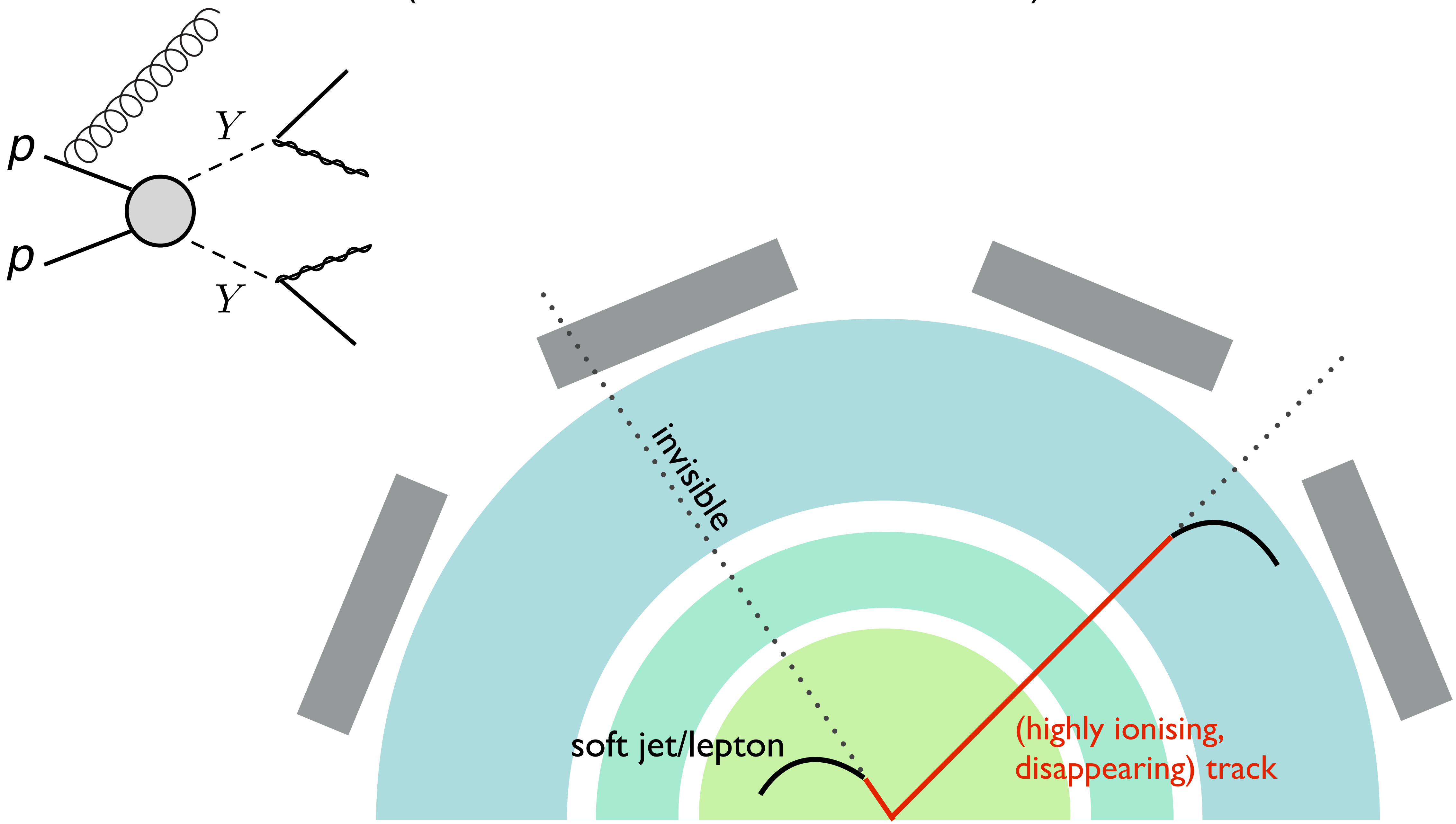
(superWIMPs, Freeze-in)





LLP Signatures: small mass splitting

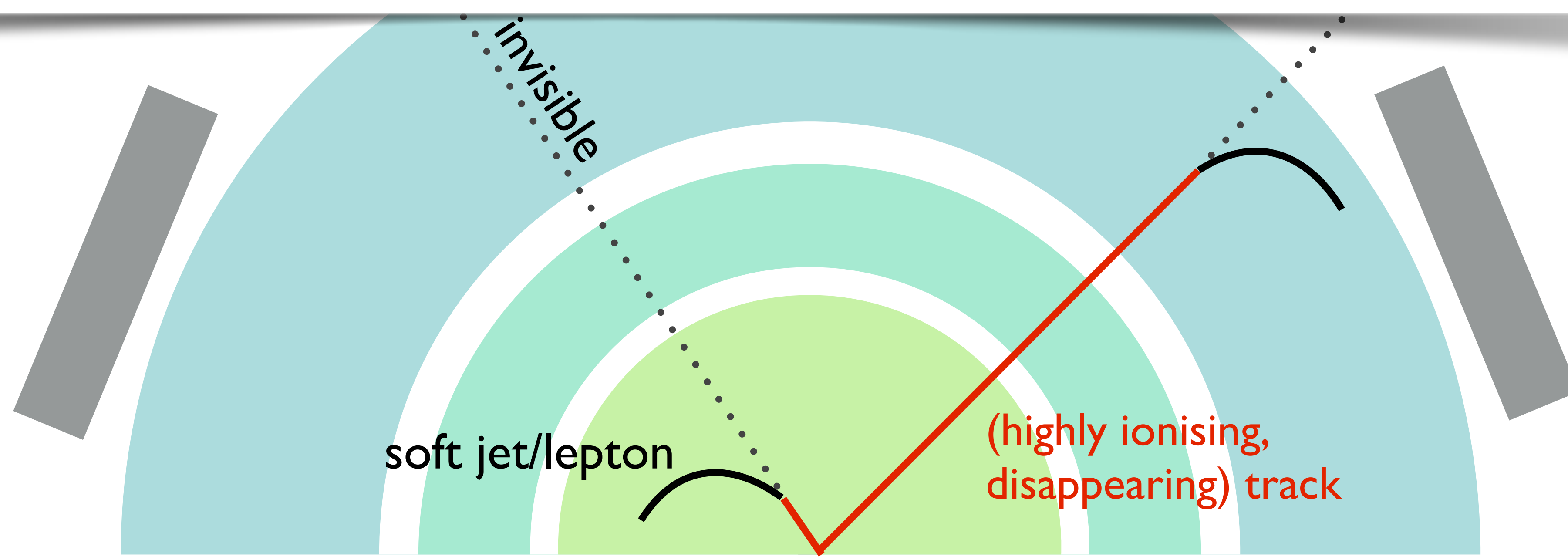
(Conversion FO, Co-annihilation)



LLP Signatures: small mass splitting

Closing experimental gaps:

- How far do MET searches cover LLP regime? (transition prompt-LLP)
- How to tackle small mass splittings, i.e. softish displaced objects?



Going beyond the minimal setup

contribution by A. Cornell

Subsection 8.1

Top-philic composite dark matter

- Top-philic scalar DM models represent very simple, testable and viable models of WIMP DM:
  [S.W. Baek, P. Ko, P. Wu (2016)],[Colucci, Fuks, Giacchino etal. (2018)]
  - very few new particles and parameters
    (one DM scalar *S* and a vector-like fermion mediator *T*),
  - renormalizable,
  - simple cosmology (thermal relic, standard evolution),
  - testable in DM direct detection, indirect detection (photons), and at colliders.

- VLQs which primarily couple to the SM top quark are common in many SM extensions (extra dimensions, little Higgs, twin Higgs, VLQ extensions of SUSY, Composite Higgs Models ….)

- If *S* and *T* are part of a UV completion with additional states/dynamics at typical scale Λ (of a few TeV), integrating out the additional states induces higher-dimensional operators in the top-philic scalar DM Lagrangian.

Sub-section 8.2

Frustrated dark matter models

- All mediator fields couple both to χ and to SM fields

  carry SM gauge charges that preclude renormalizable gauge-invariant interactions between the DM and any SM fermion.

- Interactions of the DM are ***frustrated*** in the sense that the specific mediator assignments preclude its tree level interaction with the SM

$$\text{SM} \longleftrightarrow \text{mediators} \begin{Bmatrix} \varphi \text{ (scalar)} \\ \psi \text{ (Dirac)} \end{Bmatrix} \longleftrightarrow \text{DM } \chi.$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{med}} + \mathcal{L}_{\chi},$$

$$\mathcal{L}_{\text{med}} = (D_\mu \varphi)^{\dagger s}(D^\mu \varphi)_s - m_\varphi^2 \varphi^{\dagger s}\varphi_s + \bar{\psi}^s(\mathrm{i}\not{D} - m_\psi)\psi_s + \mathcal{L}_{\text{decay}}$$

$$\mathcal{L}_\chi = \bar{\chi}(\mathrm{i}\not{\partial} - m_\chi)\chi + y_\chi(\varphi^{\dagger s}\bar{\chi}\psi_s + \text{H.c.})$$

Sub-section 8.3

B-mesogenesis models

- Mesogenesis is a recent experimentally testable mechanism of baryogenesis and dark matter production which utilizes CP violation in Standard Model mesons

- In the Mesogenesis mechanism, a scalar field Φ with a mass of 10 to O(100 GeV) decays at a low temperature $T_R \sim$O(MeV) to equal numbers quarks and anti-quarks pairs.

- Critical to the setup of these mechanisms is a t-channel coloured scalar mediator which mediates the decays of mesons in to dark sector baryons

- In neutral B mesogenesis, the CP violation of $B^0_{s,d}$–$\bar{B}^0_{s,d}$ is leveraged

$$\mathcal{L}_Y = \sum_{i,j} Y^* \bar{u}_{i,R} d^c_{j,R} - \sum_k y_{\psi_{\mathcal{B}} k} Y d^c_{kR} \psi_{\mathcal{B}} + \text{h.c.}$$

Conclusion

Work is proceeding on multiple fronts

Tentative timescales of the white paper

- End of the year $\rightarrow$ complete production of numerical data (mostly collider side)
- End of the year / Early January $\rightarrow$ Advanced draft
- Early 2024 $\rightarrow$ General meeting to finalise writeup
- Spring 2024 $\rightarrow$ Full white paper 🤞