Flavored Dark Matter:
Direct Detection and Collider Signals

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Introduction

It is now well established from astrophysical and cosmological observations that about 80% of the matter in the universe is made up of non-luminous, non-baryonic dark matter.

Optical Dark Matter X-ray Gas

However, the nature of the particles of which dark matter is composed remains a mystery.

The SM quarks and leptons (Q, U^C, D^C, L, E^C) each come in 3 different copies or `flavors'. Could the dark matter particle χ also come in 3 copies carrying flavor quantum numbers?

Examples of flavored dark matter are sneutrino dark matter in supersymmetry and Kaluza- Klein neutrino dark matter in theories of universal extra dimensions.

The SM has an approximate $[U(3)]^5$ flavor symmetry acting on the matter fields. This symmetry is broken by the SM Yukawa couplings that generate the quark and lepton masses.

To incorporate 3 flavors of dark matter we extend the $[U(3)]^5$ symmetry of the SM to $[U(3)]^5 \times U(3)_\chi$, if χ is a complex field. If χ is real we extend the symmetry to $[U(3)]^5 \times O(3)_\chi$.

Renormalizable contact interactions between the SM matter fields and the dark matter fields χ , if present, must take the form

SM$_i$

ϕ

$\chi\alpha$
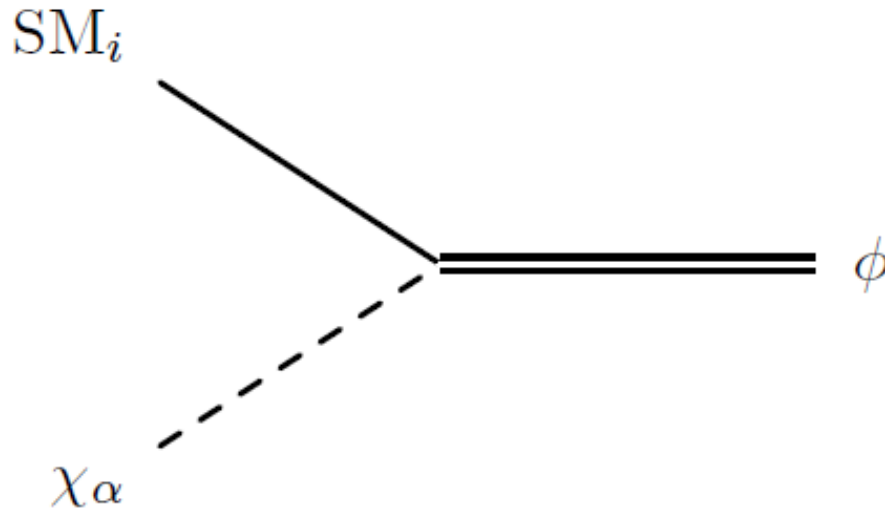
This interaction could either preserve the $[U(3)]^5 \times U(3)\chi$ flavor symmetry, or break it, in analogy with the SM Yukawa couplings.

If the flavor symmetry is to be preserved, the mediator ϕ must transform under both the SM and dark matter flavor symmetries.

We will focus on the case when this interaction breaks the flavor symmetry, and the mediator ϕ is a flavor singlet.

SM$_i$

ϕ

χ_α
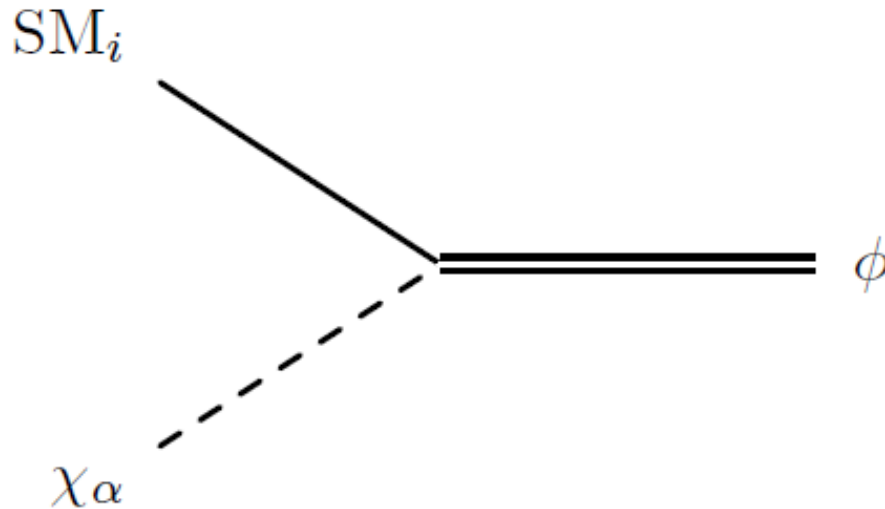
If the SM field that χ couples to above is a lepton, the different dark matter flavors are associated with the lepton flavors. We refer to this scenario as `lepton flavored dark matter'.

Alternatively, the SM field that χ couples to may be a quark. We refer to this possibility as `quark flavored dark matter'.

Another class of theories are those where direct couplings of dark matter to the SM matter fields are completely absent.
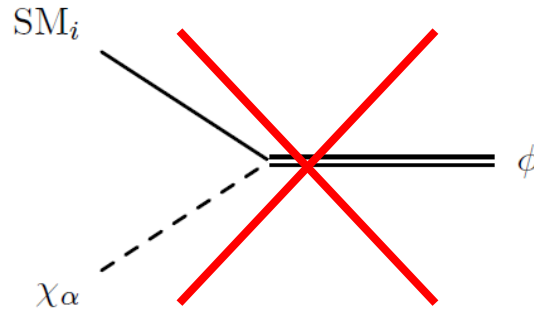
Instead the only contact interactions between χ and the SM fields are to the *W, Z* or Higgs.
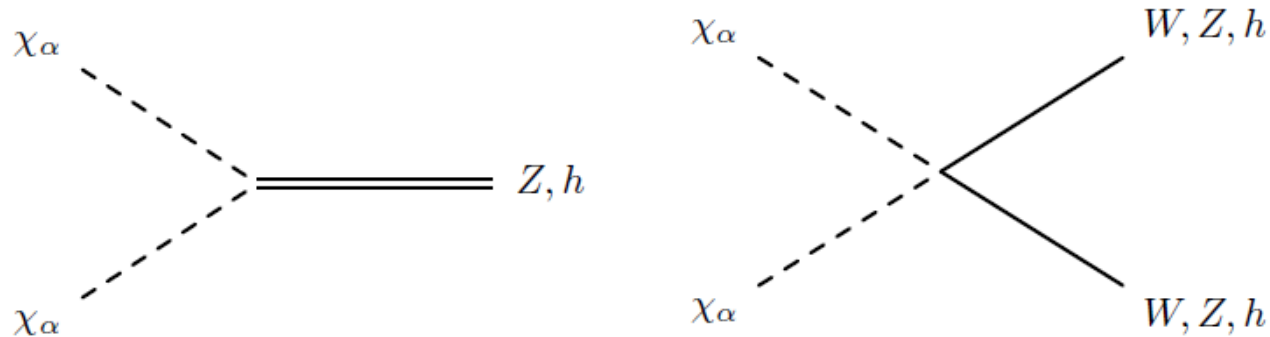
These interactions can naturally preserve the $[U(3)]^5 \times U(3)_\chi$ flavor symmetry.

In this framework dark matter is not associated with either quark or lepton flavor. We refer to this as `internal flavored dark matter'.

Lepton Flavored Dark Matter

Lepton flavored dark matter is associated with vertices of the form
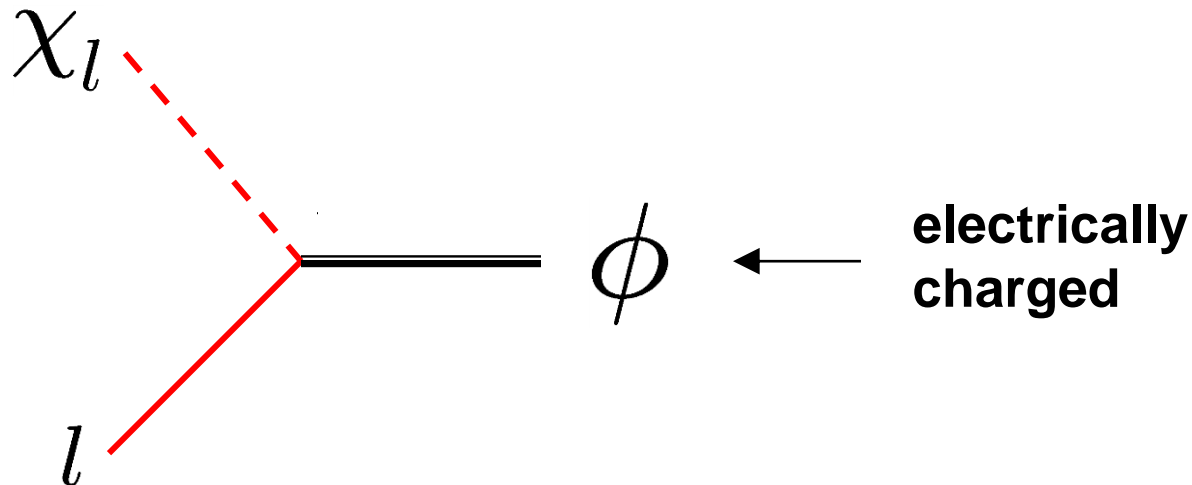
χ_l

ϕ ← electrically charged

l

The fact that the SM flavor symmetries are not exact naturally leads to a splitting of the states in the dark matter multiplet, with the lightest state constituting the observed dark matter.

Any quantum number that keeps the dark matter stable will carry over to ϕ. Therefore ϕ cannot decay entirely into SM states.

Any symmetry that keeps dark matter stable will also ensure that lepton flavor violating processes only arise at loop level.

At one loop level, these interactions can give rise to lepton flavor violating processes, such as μ → e γ.
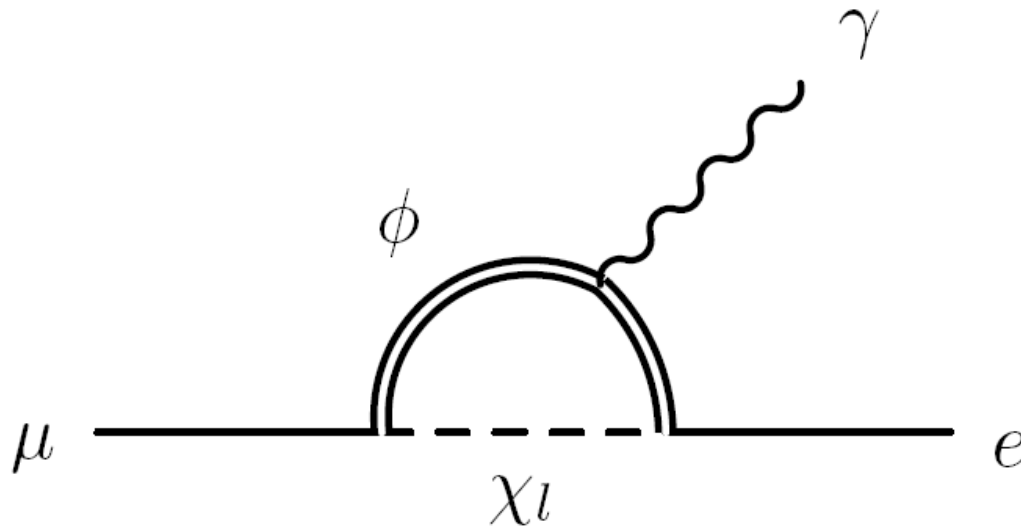

The bounds are avoided if the mixing between the different flavors is small, or alternatively if the couplings of dark matter are weak.

If χ is to be a thermal relic, its interactions cannot be weak.

Mixing will be small if the lepton sector respects `minimal flavor violation' (MFV), up to effects of the small neutrino masses.

A direct detection signal is generated by dark matter scattering off nucleons via a lepton loop.

Focus on the scenario where χ is a Dirac fermion and ϕ is a scalar.
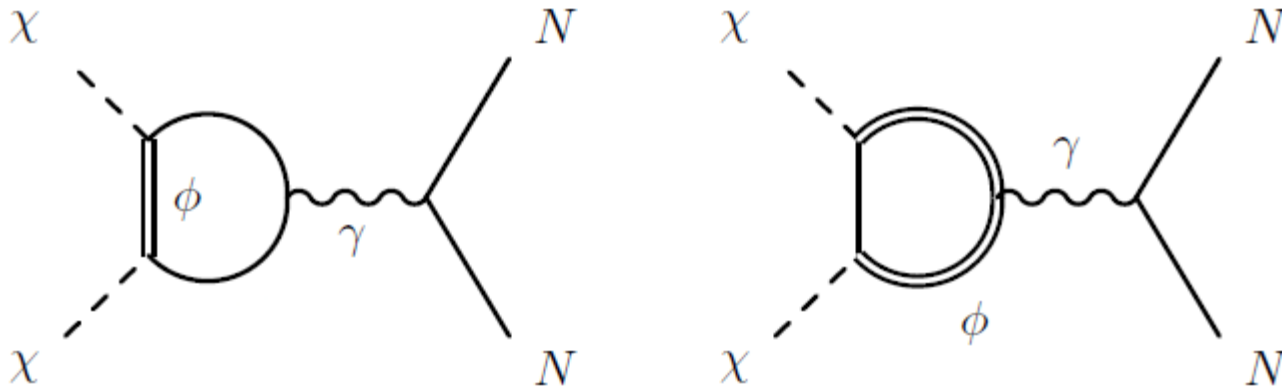
These diagrams give rise to charge-charge, dipole-charge and dipole-dipole type interactions. In general the charge-charge contribution dominates.
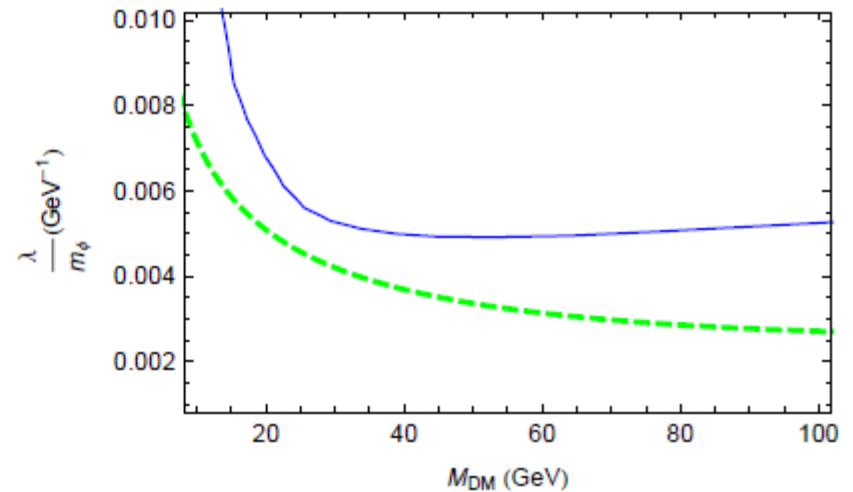
$$\sigma_{ZZ}^0 = \frac{\mu^2 Z^2}{\pi} \left[\frac{\lambda^2 e^2}{64\pi^2 m_\phi^2} \left[\frac{1}{3} + \frac{2}{3} \log \left(\frac{m_\ell^2}{m_\phi^2} \right) \right] \right]^2 .$$

For thermal relic dark matter, the predicted rate is close to current limits set by the Xenon 100 collaboration.
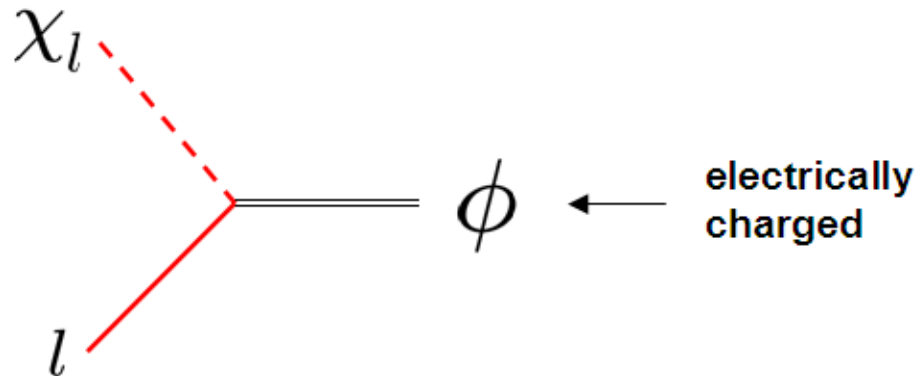
Electron flavored dark matter
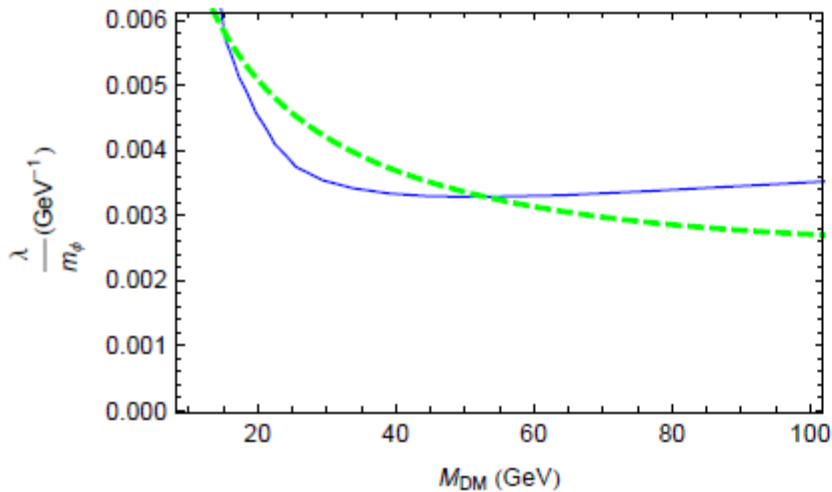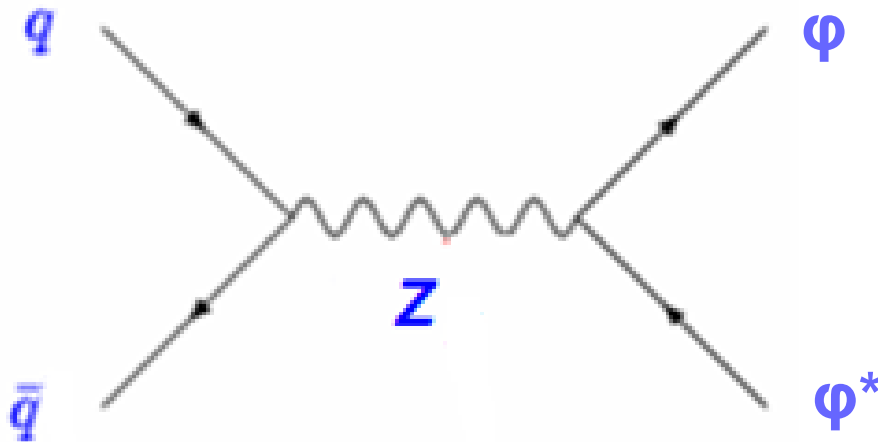
Tau flavored dark matter

– – – – – thermal relic prediction

———— current limit

**How can we search for lepton FDM at colliders?**

The fundamental vertex is

χ_l

ϕ ← electrically charged

l

The particle φ can then be pair produced through the photon or Z.
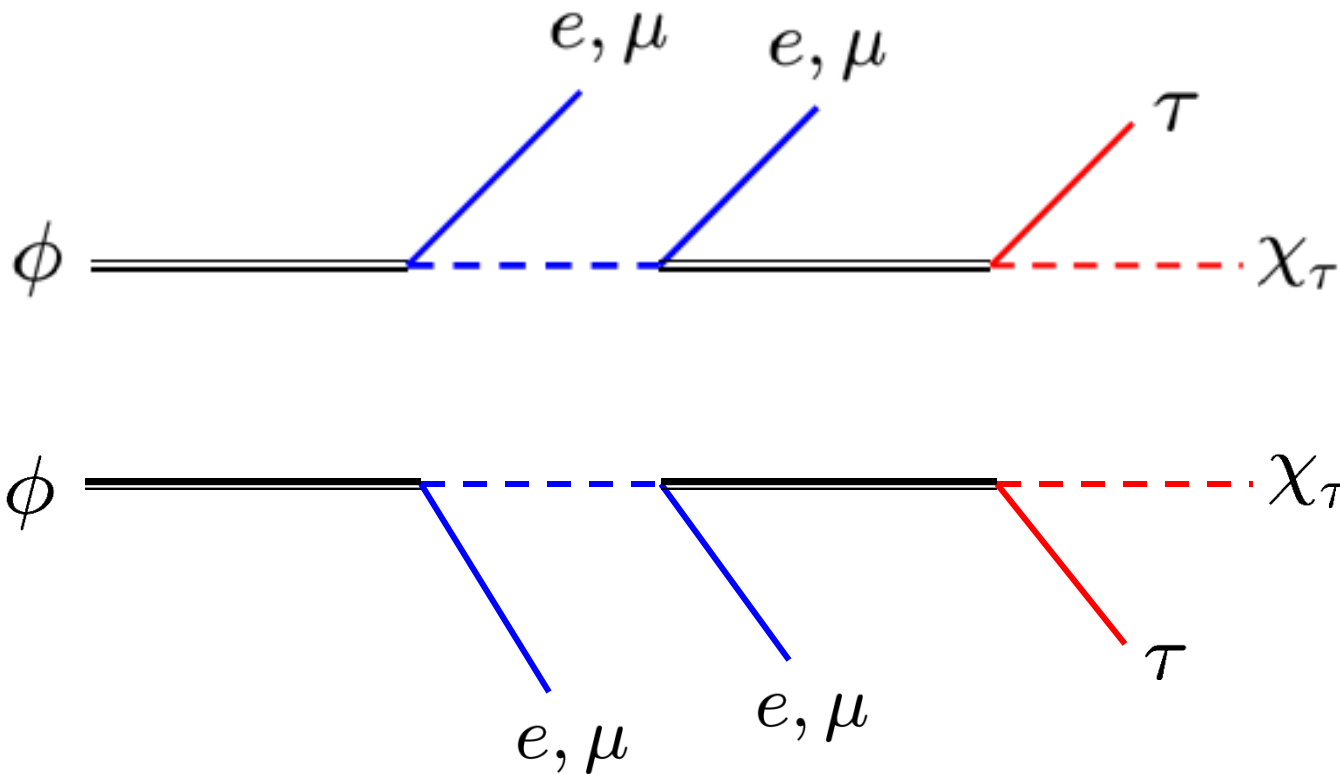

q φ

Z

$\bar{q}$ φ*

The nature of the signals is determined by how the two φ's decay. For concreteness, consider MFV motivated framework where masses of χ_e , χ_μ are equal, and greater than mass of χ_τ , which is dark matter.

Then each φ can decay either through a long chain, or through a short chain.
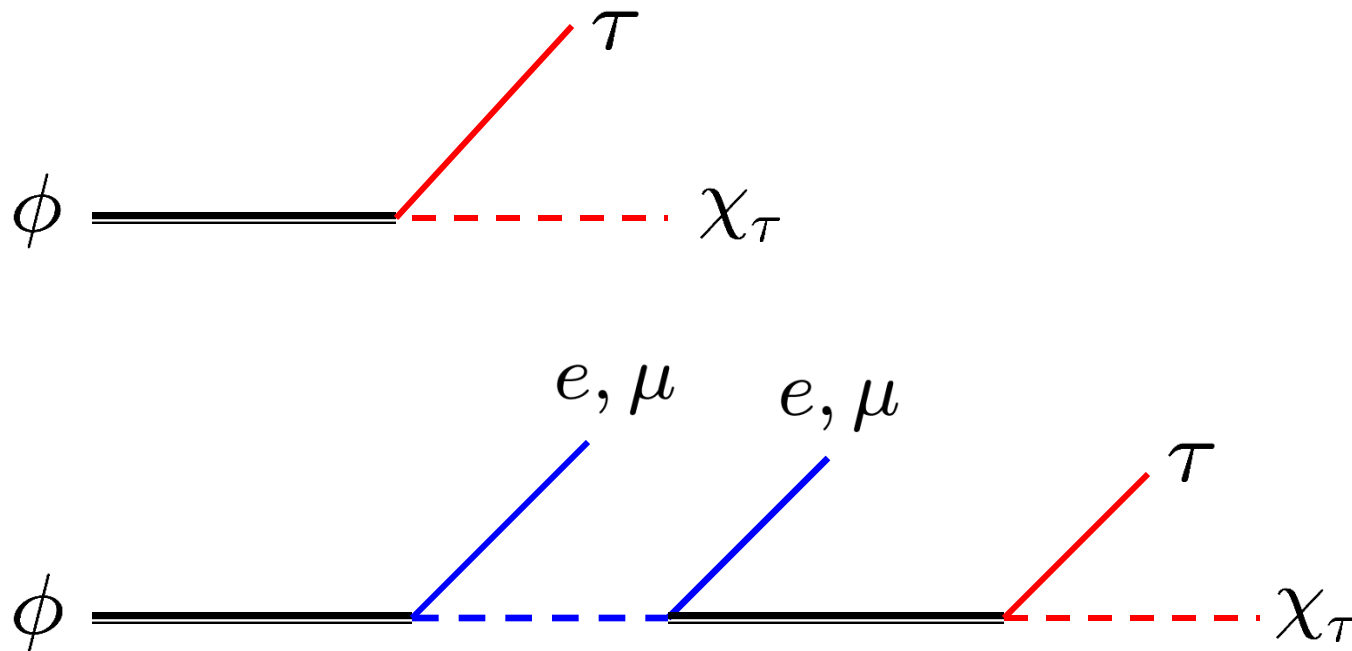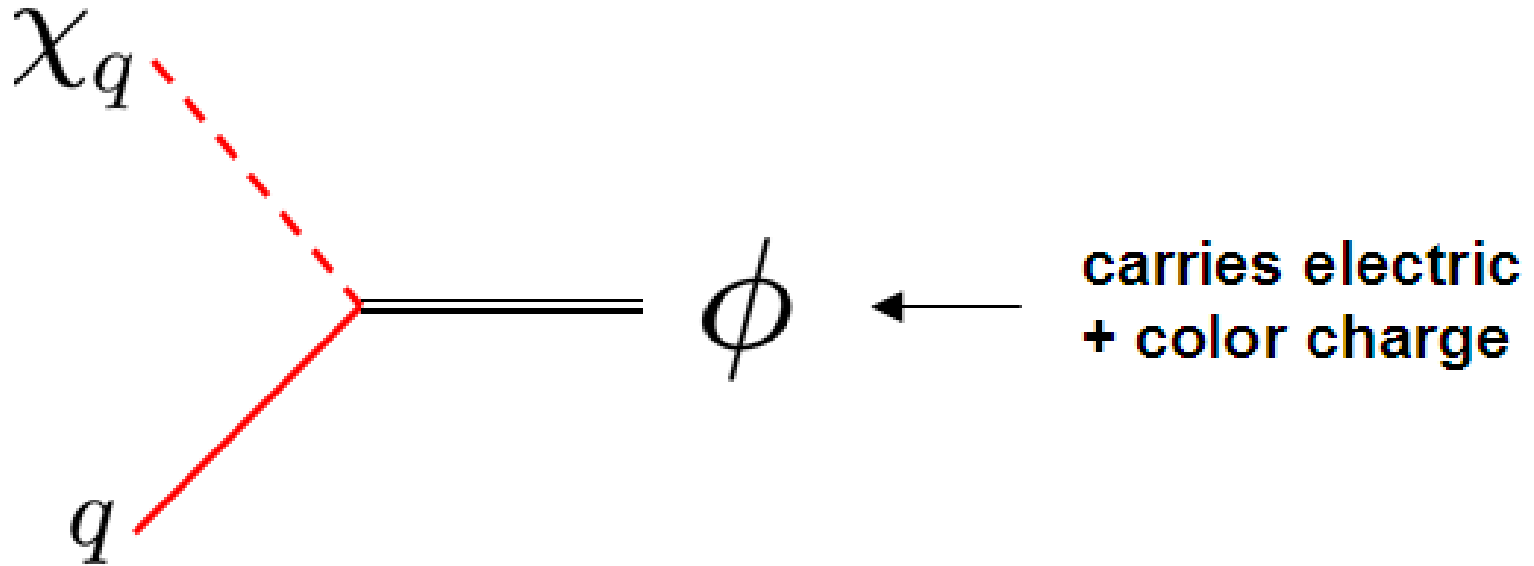
Events with two long chains are the most promising.

A signal event will therefore involve at least four isolated leptons and missing energy.
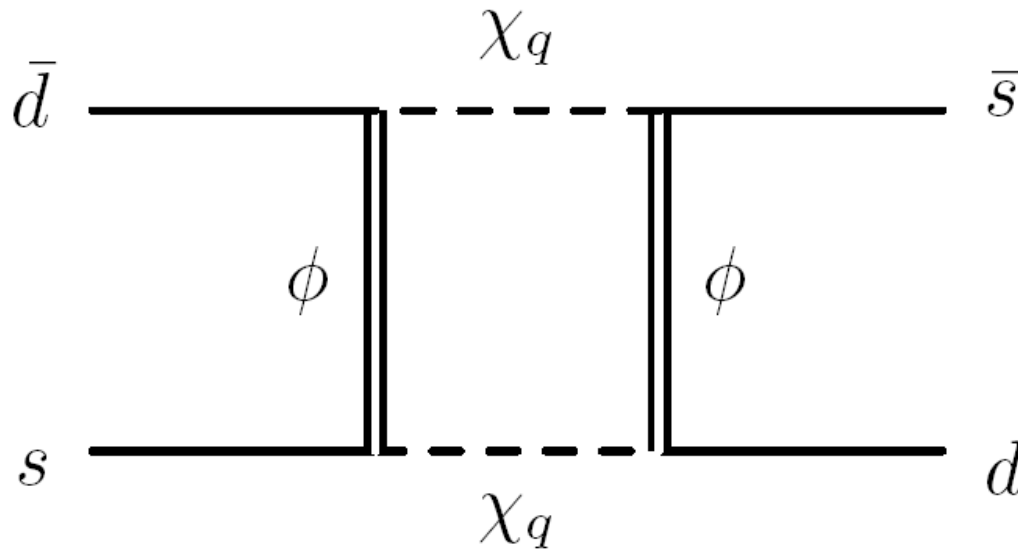
Quark Flavored Dark Matter

χ_q

ϕ ← carries electric + color charge

q

Once again, the fact that the SM flavor symmetries are not exact naturally leads to a splitting of the states in the dark matter multiplet χ. The lightest state constitutes the observed dark matter.

As before, any symmetry that keeps dark matter stable will serve to postpone flavor violating effects to loop level.

These interactions will give rise to mixing between the neutral kaons at the one loop level.


These and similar bounds can be avoided provided the couplings of the quarks to dark matter respect MFV.

Then a GIM mechanism analogous to the one in supersymmetric theories comes into play, and protects against flavor violation.

Alternatively, flavor bounds are satisfied if dark matter couplings to SM are small. Not consistent if χ is a thermal relic.

The leading contribution to direct detection depends on the flavor that constitutes dark matter.
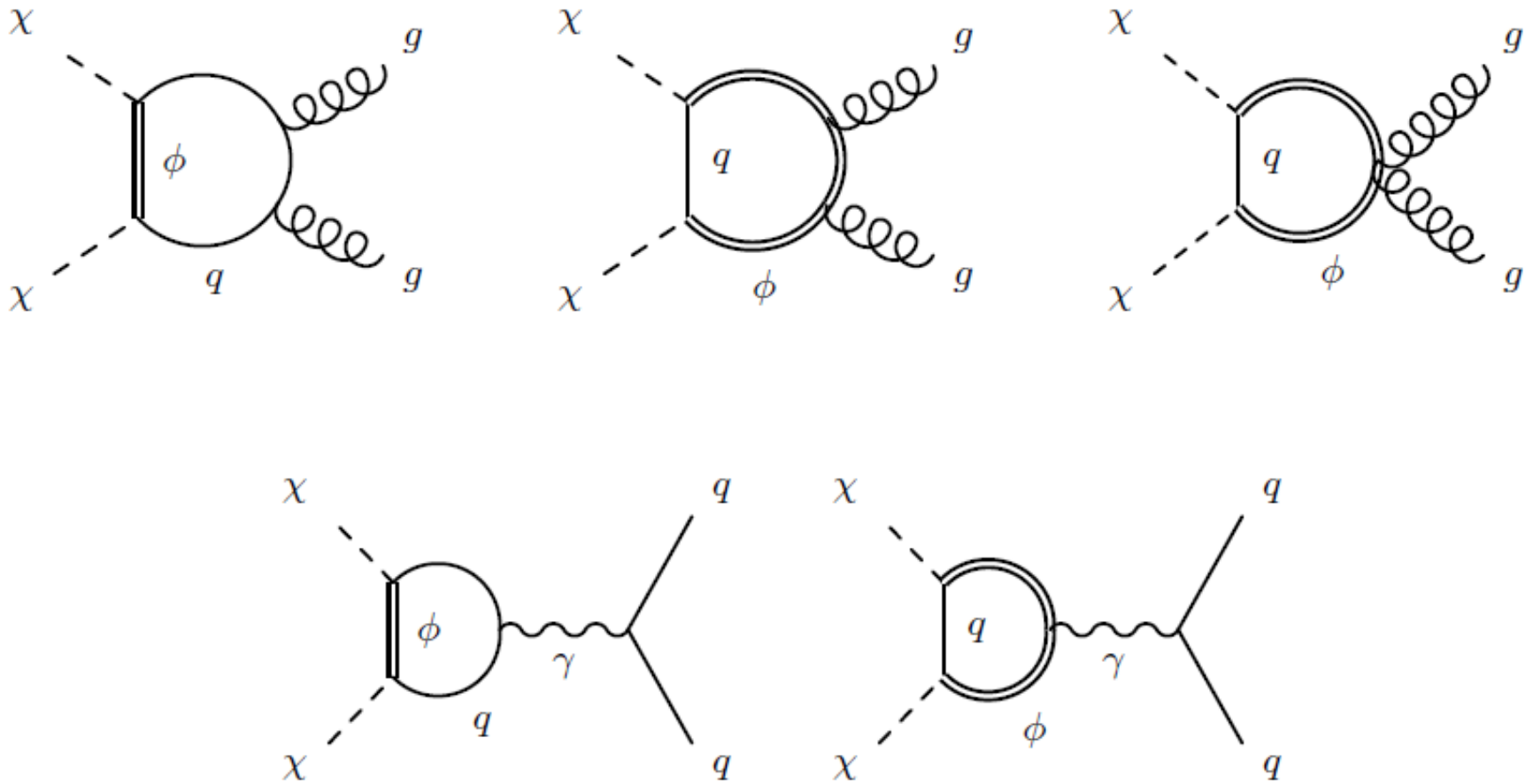
If dark matter carries up or down flavor, there is a tree level diagram that contributes to scattering.
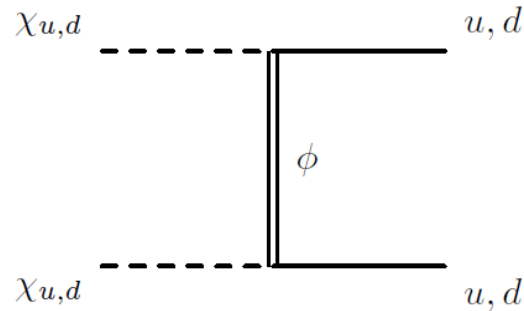
**This is severely constrained. Thermal dark matter is excluded.**
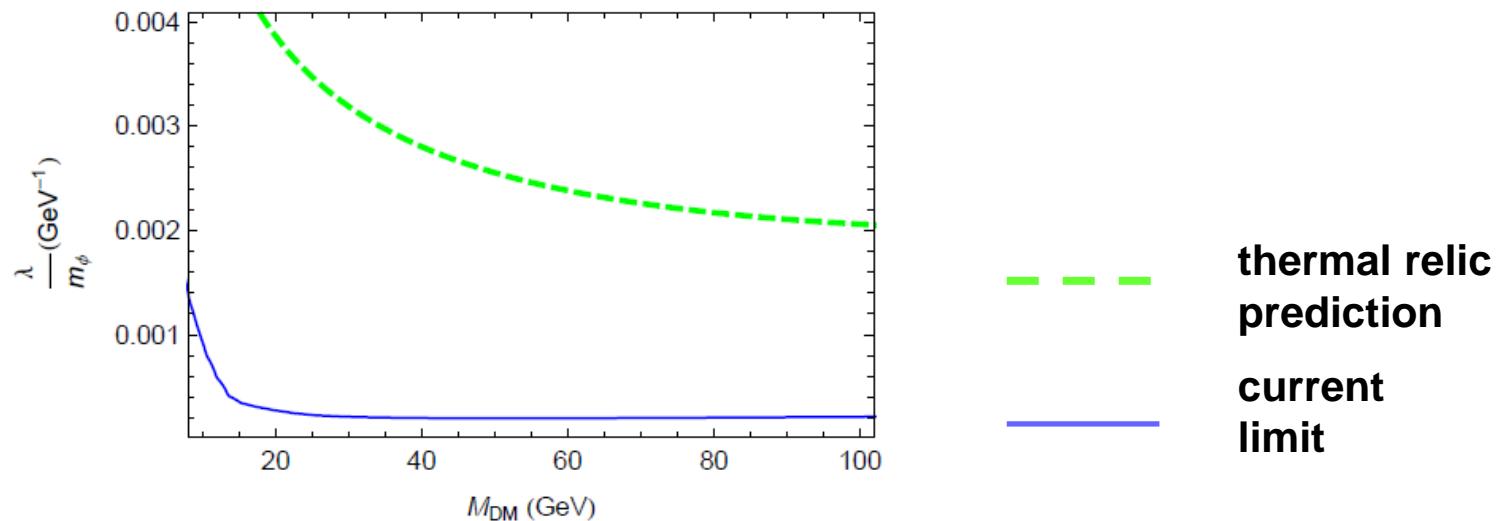
If dark matter carries top or bottom flavor, the leading contributions arise at one loop. The photon exchange contribution dominates over effects arising from scattering off gluons.
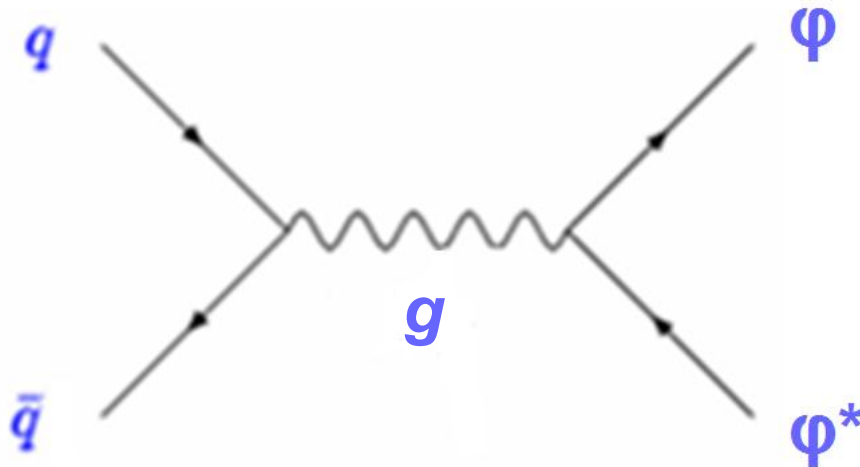

The predicted cross section is within reach of current experiments.

How do we search for quark FDM at colliders?

The fundamental vertex is

χ_q

$\phi \leftarrow$ carries electric + color charge

q
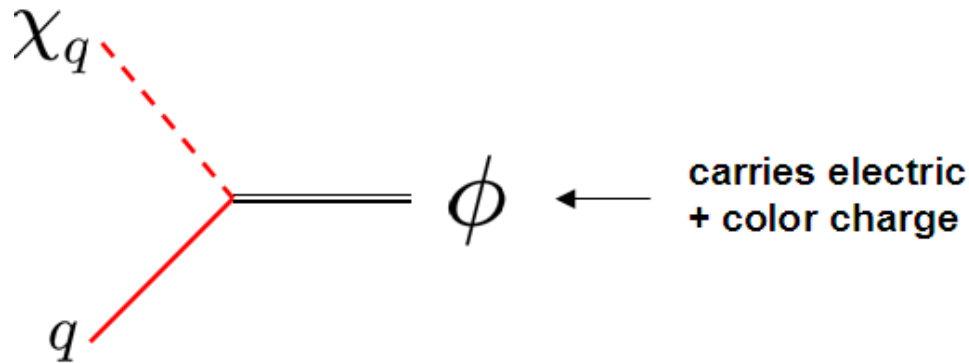
Since φ is colored, it can be pair produced through off-shell gluons.

q ϕ

g

$\bar{q}$ ϕ^*

The nature of the signals is again determined by how the two φ's decay. We work in MFV framework where the masses of χ_d and χ_s are nearly equal, and more than mass of χ_b, which is dark matter.

Then each φ can decay either through a long chain, or through a short chain.
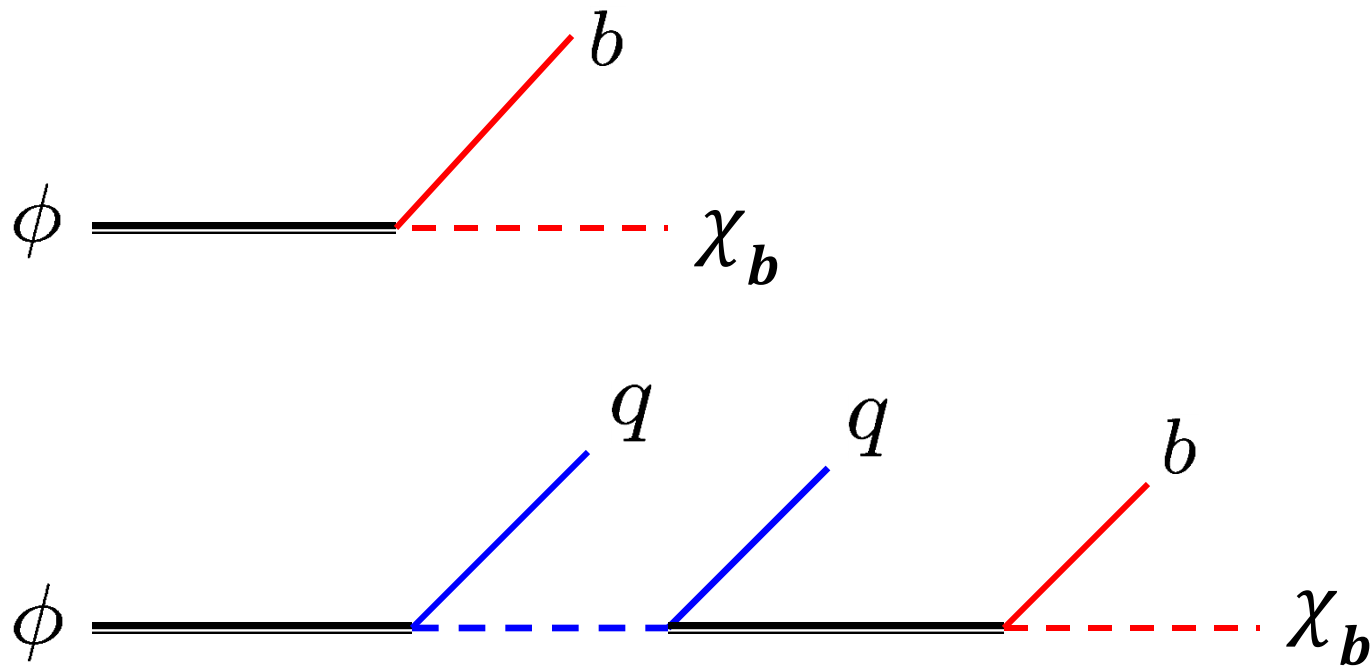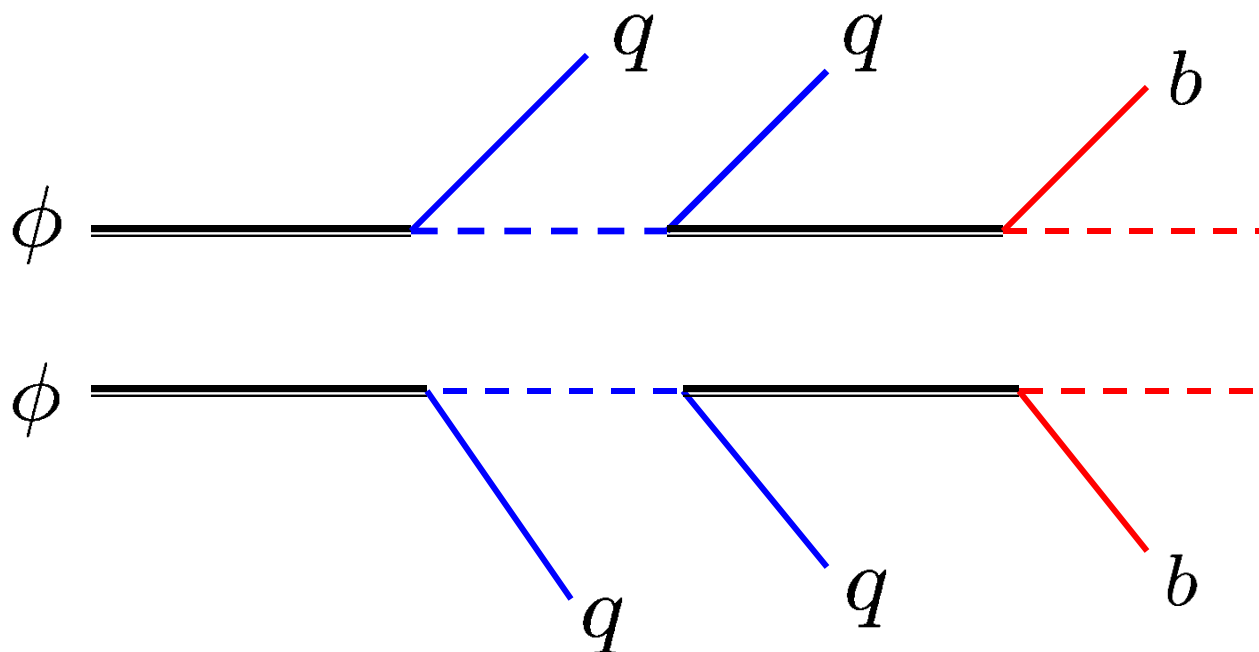
The signal is 6 jets, including 2 b-jets, and missing energy.

Relies heavily on the b-tagging efficiency. Significant backgrounds from t t-bar + jets and b b-bar + jets.

Internal Flavored Dark Matter

Internal flavored dark matter is associated with vertices of the type

χ_i

χ_i

Z, h ← electric and color neutral

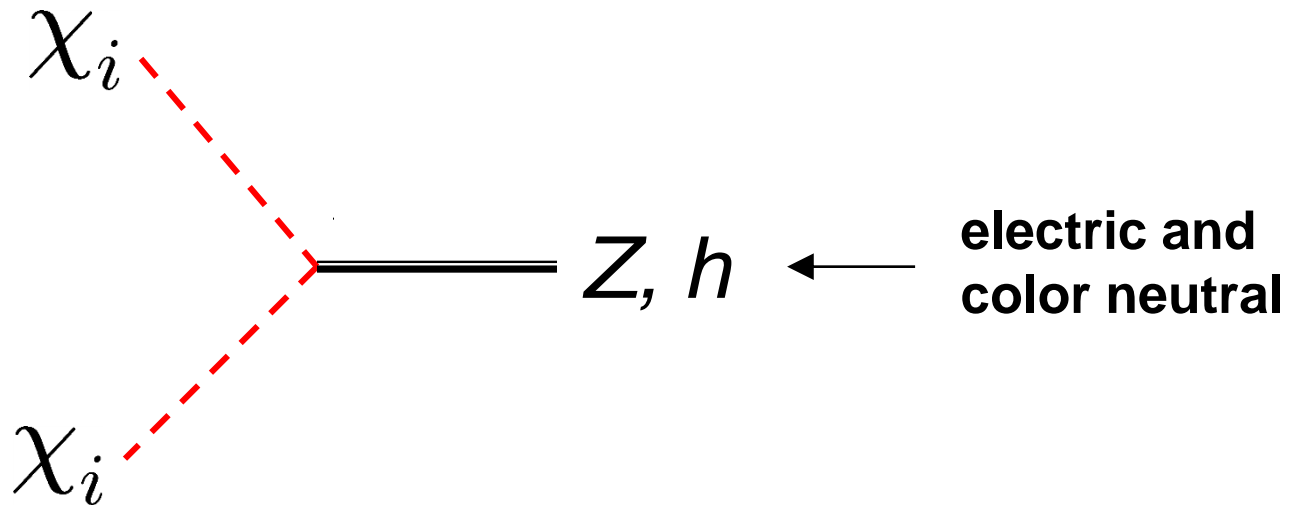**Unless these or other interactions violate the (internal) dark matter flavor symmetry, all the dark matter flavors will be stable.**

This scenario is not constrained by SM flavor bounds, since the couplings of the Z and Higgs to SM matter fields preserve flavor.

The direct detection signal depends on the strengths of couplings to Z and Higgs. Very similar to analogous non-flavored theories.

The collider phenomenology is very sensitive to if and how the heavier dark matter flavors decay, and is model dependent.

Tau FDM at Colliders

We now study in detail the prospects for detecting a specific model of tau flavored dark matter at the LHC.

We take ϕ to be a scalar and χ to be a Dirac fermion. We also choose χ to couple to right-handed, rather than left-handed, SM leptons.

χ_l

ϕ ← charged scalar

l_R
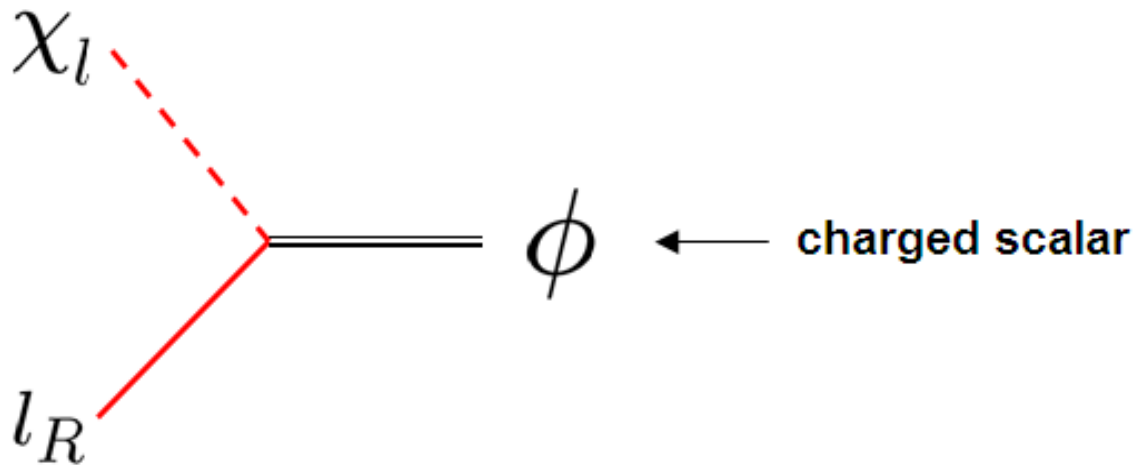
We also choose χ not to carry weak charge. Its SM quantum numbers are then completely fixed. It is completely SM neutral.

The SM quantum numbers of ϕ are then also completely fixed. It is charged under both the photon and the Z.

Then, for a given ϕ mass, its production cross section at the LHC is completely fixed. It is p-wave suppressed since ϕ is a scalar.
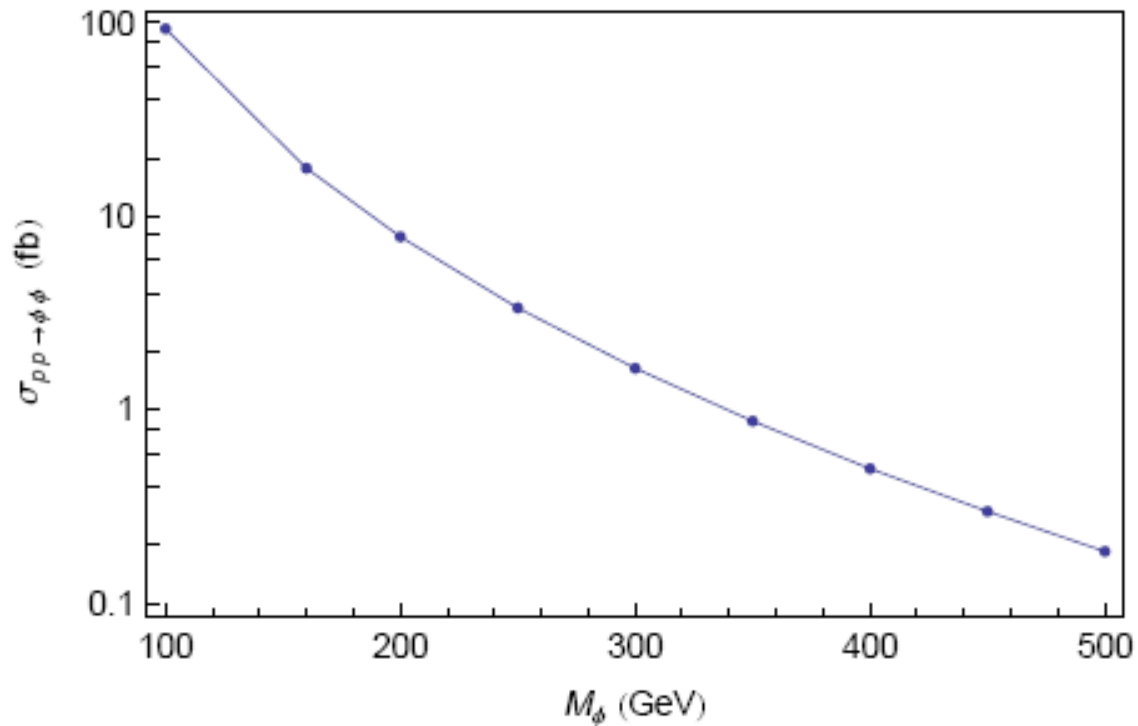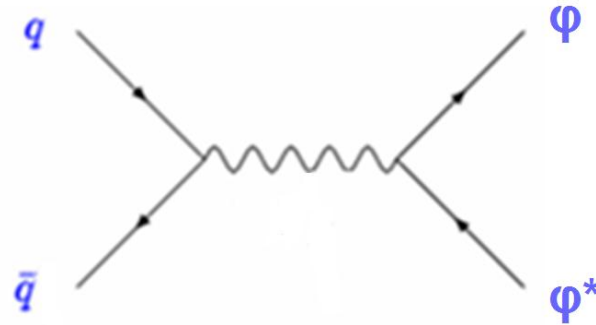
For concreteness, we work in an MFV motivated framework where the masses of χ_e and χ_μ are very nearly equal.

Focus on events with two long chains.
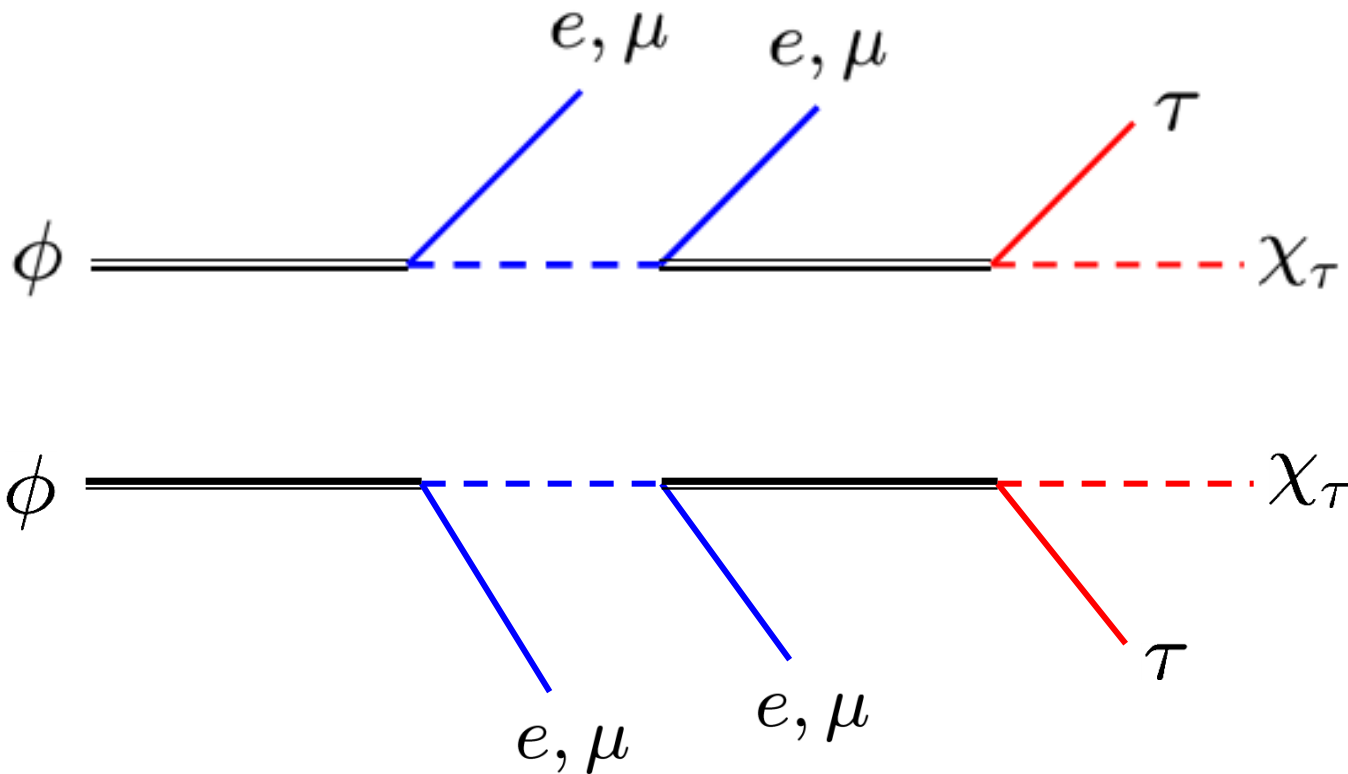
Signal events involve at least four leptons and missing energy.

We choose two benchmark spectra.

$$m_{\chi,e} = 110 \text{ GeV}$$
$$m_{\chi,\mu} = 110 \text{ GeV}$$
$$m_{\chi,\tau} = 90 \text{ GeV}$$
$$m_{\phi} = 160 \text{ GeV}$$

$$m_{\chi,e} = 90 \text{ GeV}$$
$$m_{\chi,\mu} = 90 \text{ GeV}$$
$$m_{\chi,\tau} = 70 \text{ GeV}$$
$$m_{\phi} = 150 \text{ GeV}$$

We perform a full collider study, incorporating detector effects.

There are several SM backgrounds, and removing these will require cuts. We go through these one by one.

$(l^+ l^-)(l^+ l^-)$

Each pair of leptons could arise from decay of an on-shell Z, either directly, or indirectly through the leptonic decays of a pair of taus. They could also arise from the decays of an off-shell Z or photon.

This background can be reduced by imposing a Z-veto. Also, since the electrons and muons arising from tau decays are generally soft, require high energy leptons, and large missing energy.

$W W (l^+ l^-)$

The production cross section for this process is relatively low, and almost all such events can be removed by a Z-veto.

$t\,t\text{-bar}\,(l^+ l^-)$

The Z-veto significantly reduces this background. In addition, we discard events with two or more hard p_T jets.

Dataset	Production cross-section (pb)	Event rate after cuts at 100^{-1} fb			
		Lepton cuts	Jet cuts	Z veto	MET
τFDM1	0.0177	46.73	42.83	38.41	35.01
τFDM2	0.0224	75.39	69.30	63.26	57.04
$\ell^+\ell^-\ell^+\ell^-$	0.148	1617.94	1582.42	140.3	13.32
$t\bar{t}\ell^+\ell^-$	0.087	89.57	19.45	4.92	4.7
$WW\ell^+\ell^-$	0.009	14.7	13.98	2.51	2.51

$\left.\right\}$ 21

The table shows that it should be possible to distinguish these models of tau flavored dark matter from the SM.

The first spectrum can be distinguished with about 40 fb^{-1}. The second spectrum will require 20 fb^{-1}.

Conclusions

Dark matter could carry flavor quantum numbers, just as the quarks and leptons do. We have studied theories where dark matter carries flavor and has renormalizable contact interactions with the SM.

The simplest theories of this type involve lepton flavored, quark flavored or internal flavored dark matter. Each of these possibilites is associated with a characteristic type of vertex, and leads to different predictions for direct detection and distinct collider signals.

We have studied the collider signals of theories where dark matter carries tau flavor. Signal events are associated with multiple leptons and missing energy. After cuts, these theories can be distinguished from SM.

Tau FDM can also be distinguished from simple theories where dark matter does not carry flavor, making use of charge and flavor correlations among the leptons in signal events.