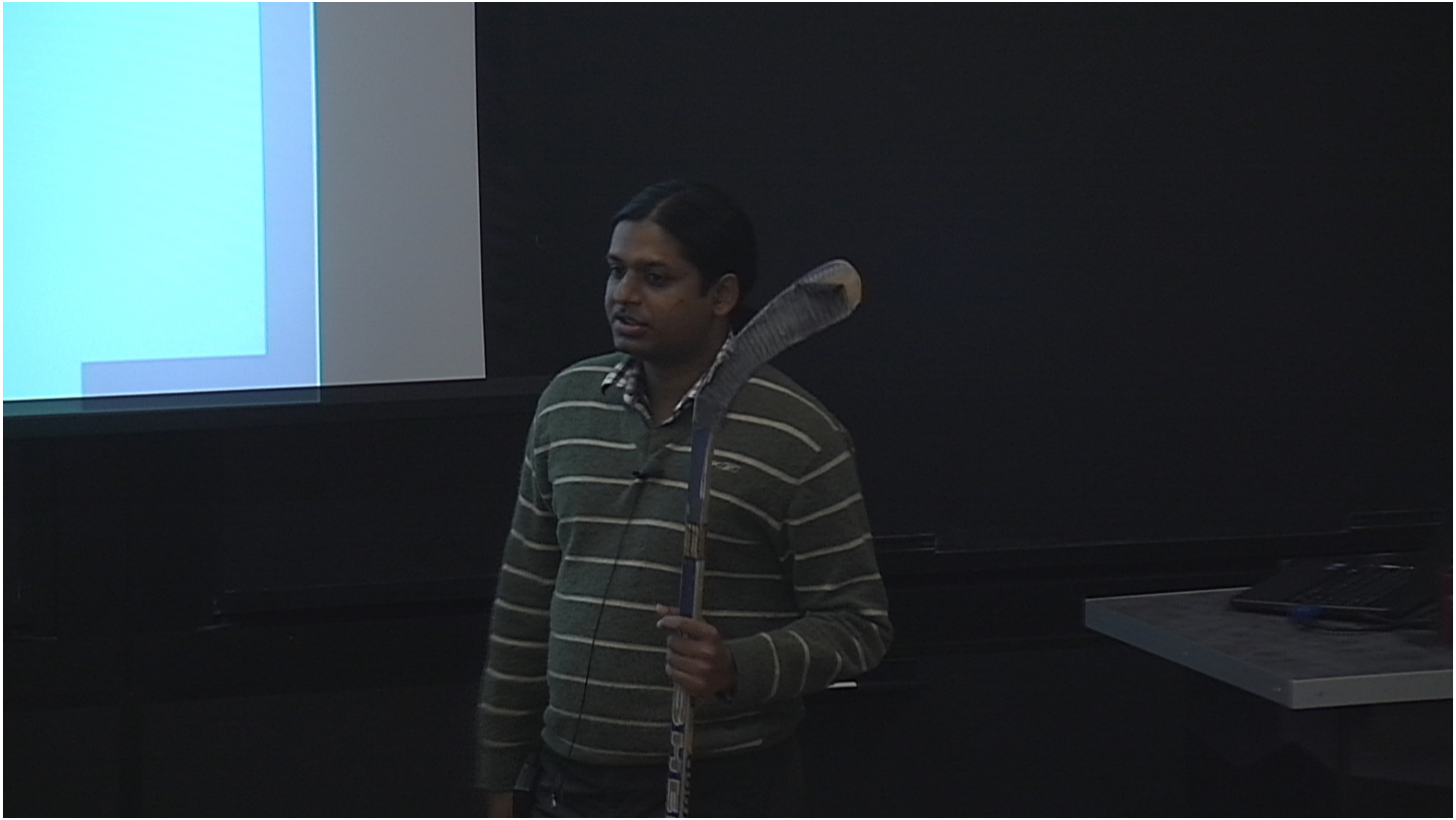
Title: Flavored Dark Matter: Direct Detection and Collider Signals

Date: Dec 07, 2011 11:00 AM

URL: http://pirsa.org/11120065

Abstract: I will present a class of models in which the dark matter particle carries flavor quantum numbers, and has renormalizable contact interactions with Standard Model fields. In particular, I will focus on models where the dark matter flavor is identified with lepton flavor in the Standard Model. The region of parameter space where the dark matter has the right abundance to be a thermal relic is accessible at current direct detection experiments. A full simulation of the signal and backgrounds, including detector effects, shows that in a significant part of parameter space these theories can be discovered above Standard Model backgrounds at the LHC. Further, flavor and charge correlations among the final state leptons might allow models of this type to be distinguished from theories where dark matter couples to leptons but does not carry flavor.

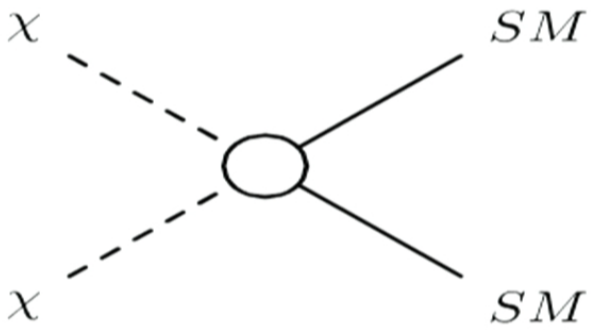


Evidence for dark matter

- Galactic rotation curves
- Cosmic Microwave Background
- Big Bang Nucleosynthesis
- Gravitational lensing observations

The WIMP Miracle

Miracle up to orders of magnitude



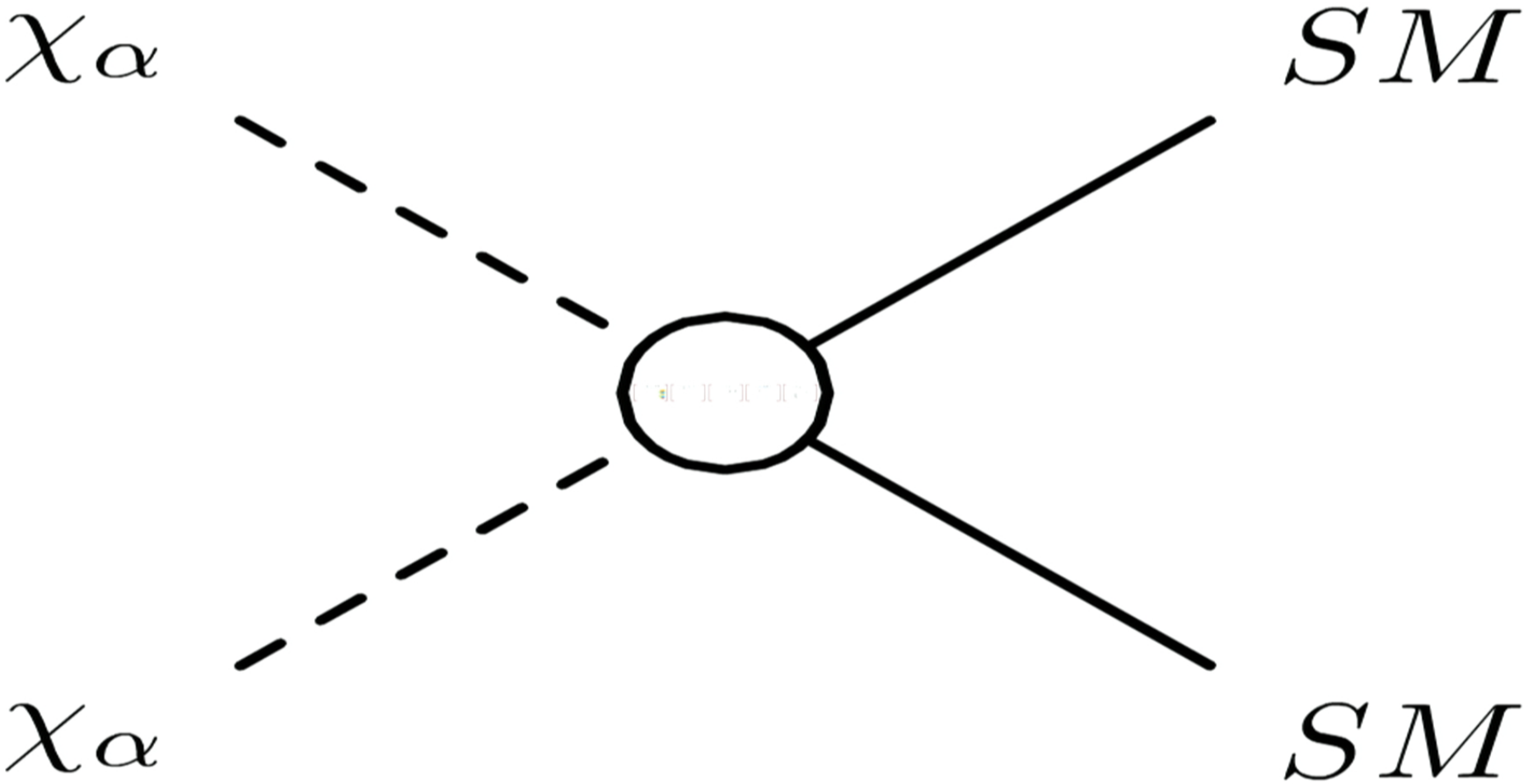
$$\sim \frac{\lambda^2}{m_\phi^2}$$

$$\langle \sigma_A v \rangle \sim \frac{\lambda^4 m_\chi^2}{32\pi m_\phi^4} \sim \frac{(0.45)^4 (100\ \mathrm{GeV})^2}{32\pi (200\ \mathrm{GeV})^4} \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

$$\sigma^{(n)} \sim \frac{\lambda^4 m_n^2}{64\pi m_\phi^4} \sim \frac{(0.45)^4 (1\ \mathrm{GeV})^2}{64\pi (200\ \mathrm{GeV})^4} \sim 5 \times 10^{-41}\ \mathrm{cm}^2$$

Current limits from Xenon100 experiment: $10^{-44}\ \mathrm{cm}^2$

(for $m_\chi \sim 100$ GeV)


$\chi\alpha$
SM
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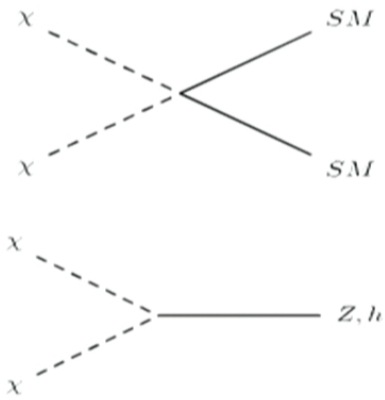
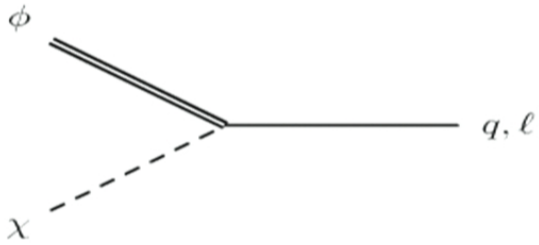
SM

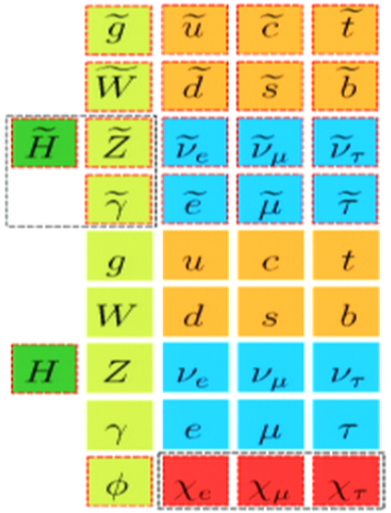
Flavored Dark Matter

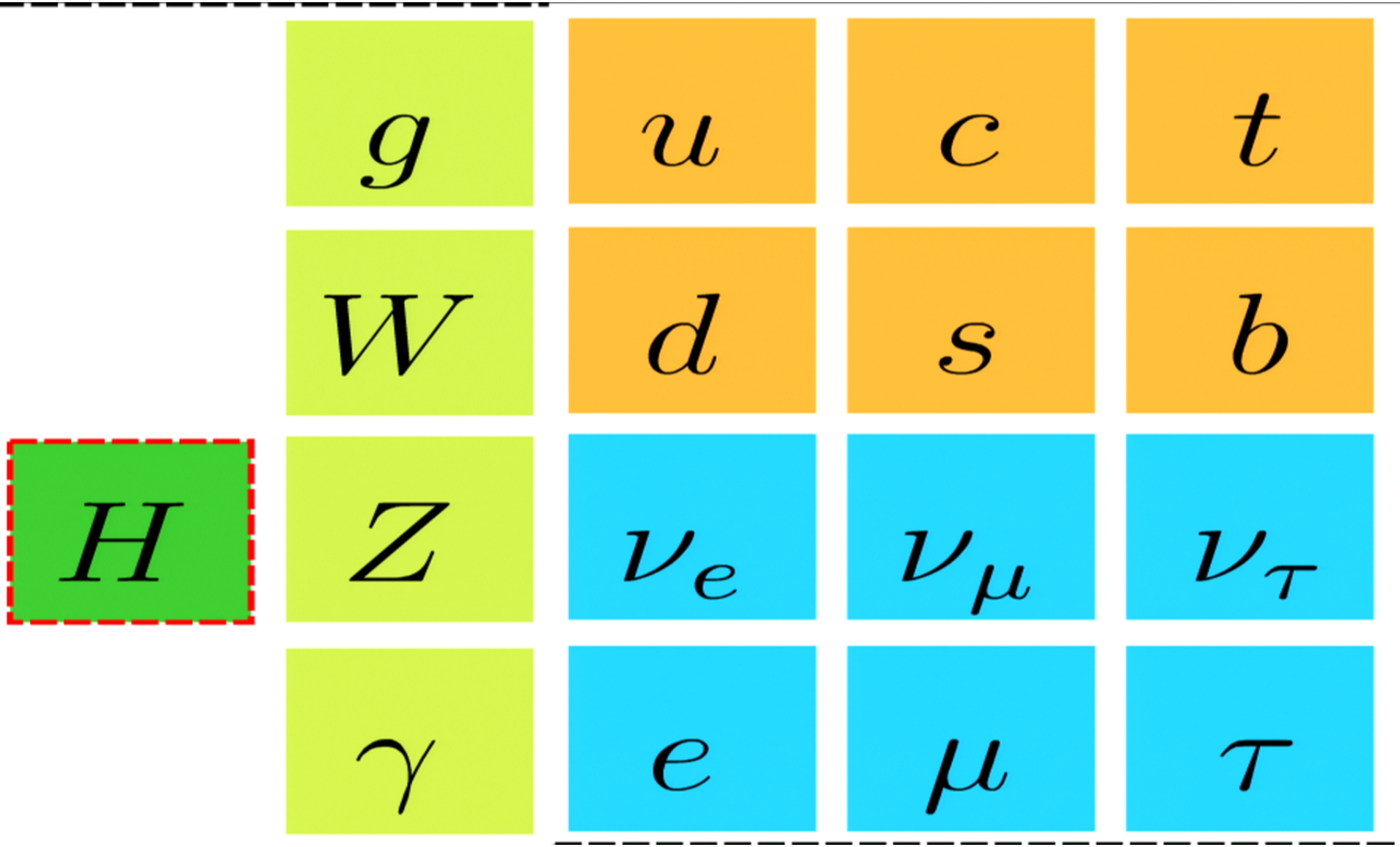
Who ordered that?

- Renormalizable contact interactions with standard model



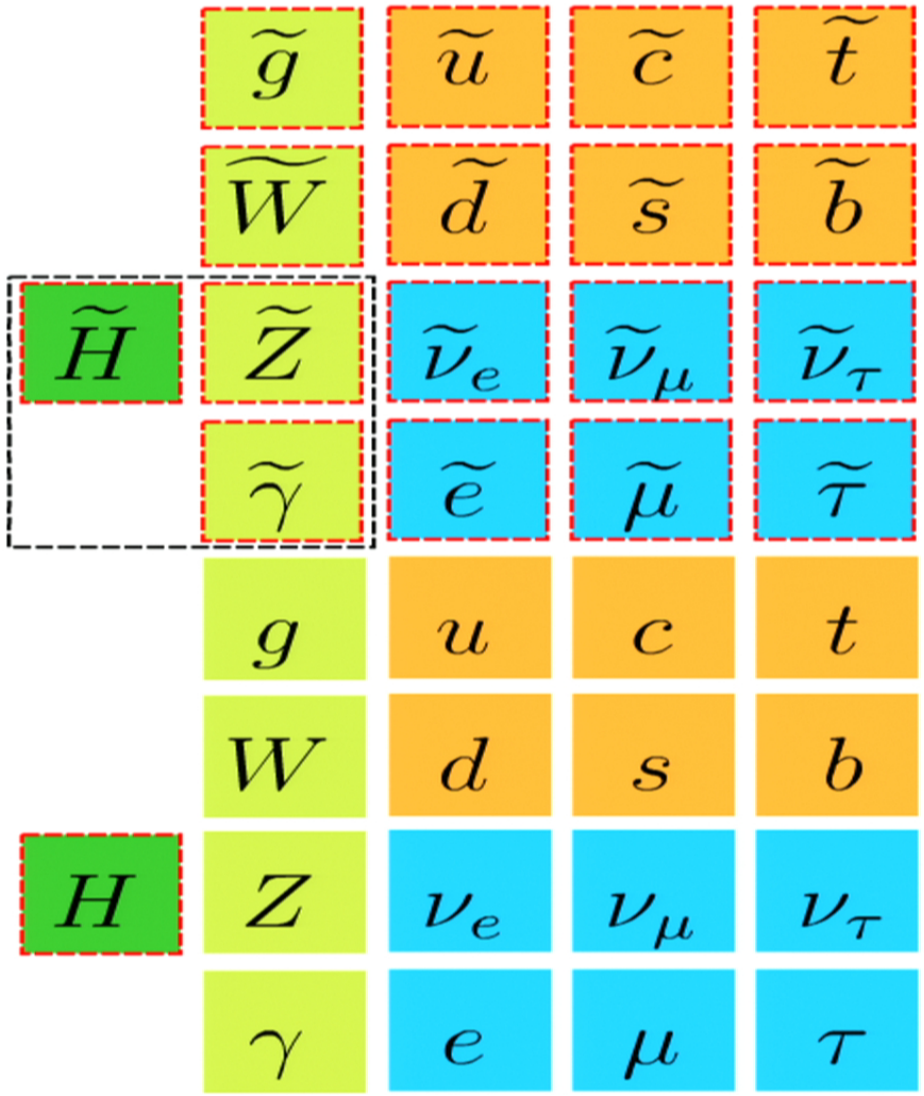





g u c t
W d s b
H Z ν_e ν_μ ν_τ
γ e μ τ

th

q, ℓ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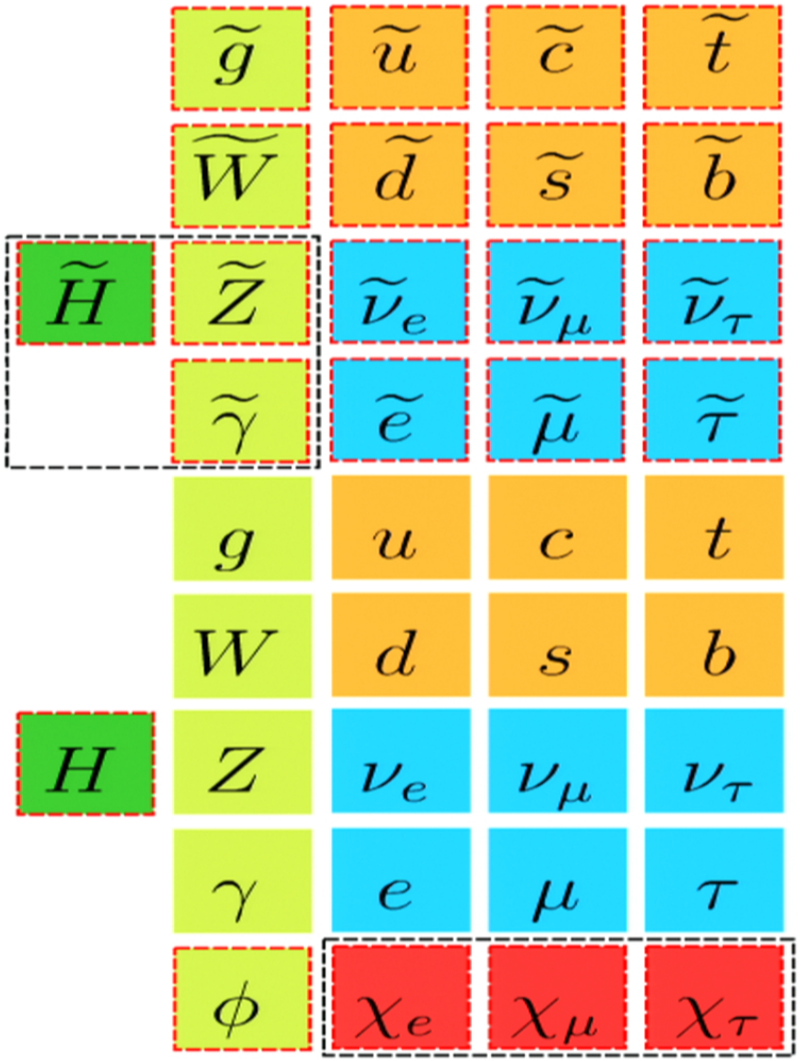
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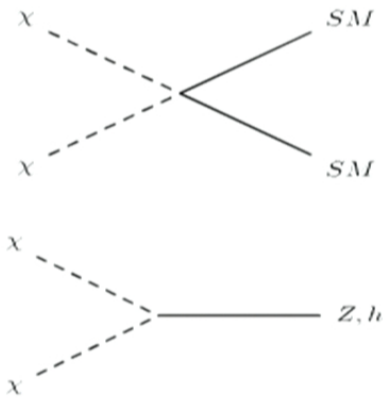
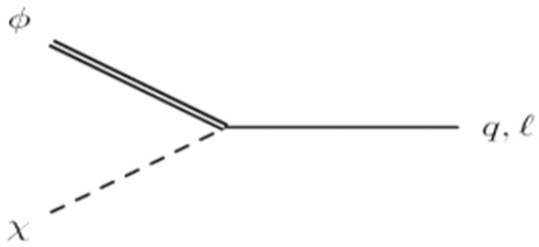
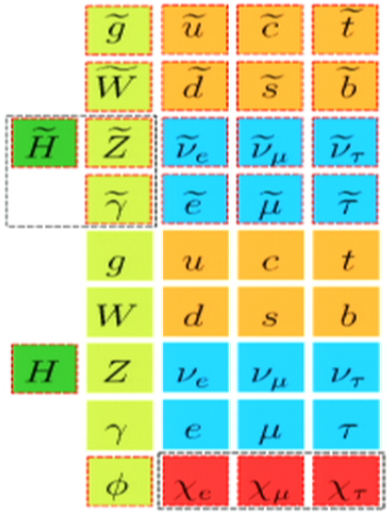


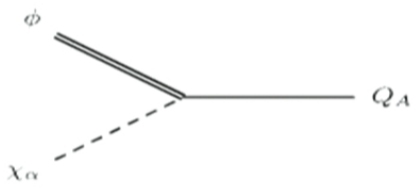


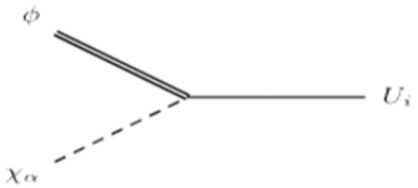


Phenomenology

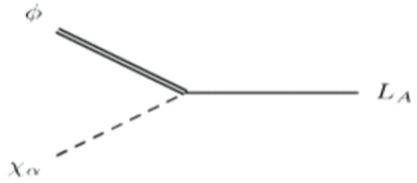
Phenomenology of FDM depends sensitively on the standard model matter fields to which the dark matter couples

- Quark FDM



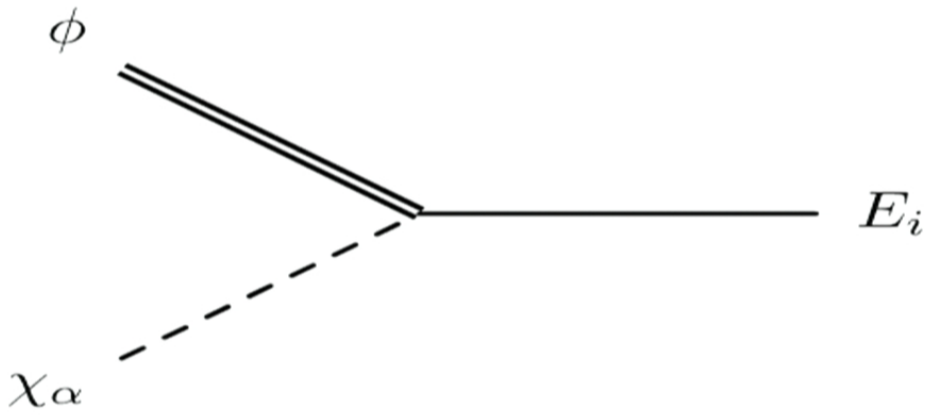


- Lepton FDM



- couples with right-handed leptons
- is a Dirac fermion
- is a Standard Model singlet

$$\lambda_\alpha{}^i \chi^\alpha E_i^c \phi + h.c.$$



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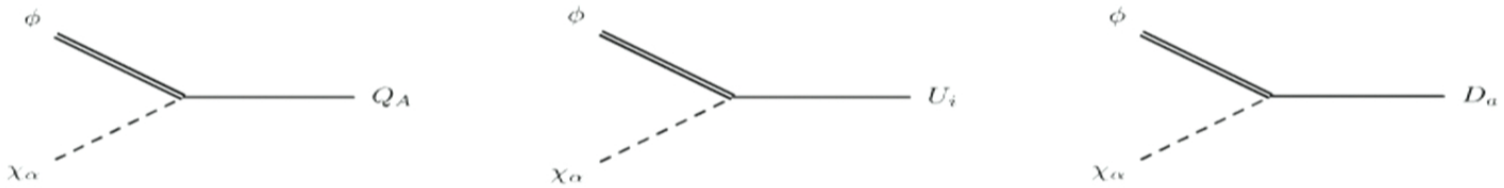

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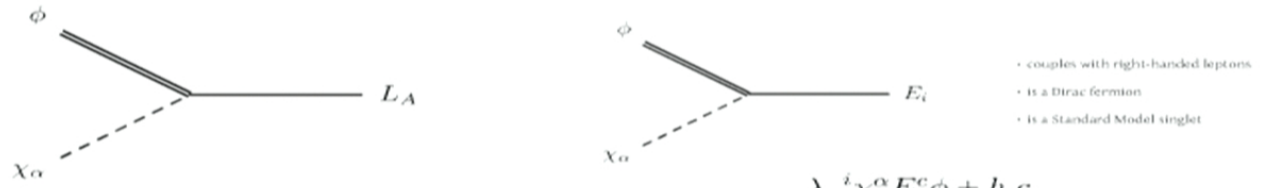

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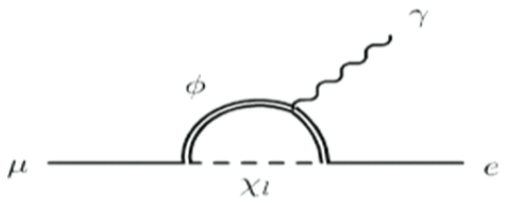
Flavor structure

- Generic flavor structure mediates flavor changing processes



$$m_\mu^5 \left[\frac{e\lambda^2}{16\pi^2 m_\phi^2}\right]^2 \sim \frac{10^{-11}}{2\ \mu\text{s}}$$

$$\Rightarrow \frac{\lambda}{m_\phi} \sim \frac{10^{-3}}{200\ \text{GeV}}$$

- Coupling too small to produce relic abundance
- Mediator decays promptly on collider timescales

Flavor structure

Minimal Flavor Violation

- Lepton sector of SM has a $U(3)_L \times U(3)_E$ global symmetry, broken by the Yukawa couplings

$$y_A{}^i L^A E_i^c H + h.c.$$

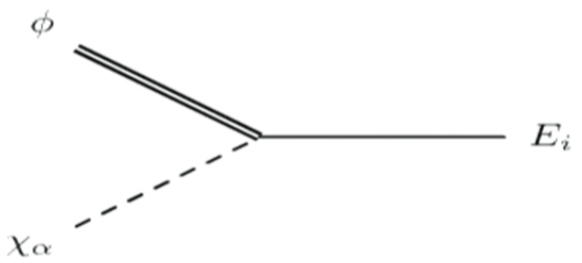
$$y_A{}^i : (3, \bar{3}) \text{ under } SU(3)_L \times SU(3)_E$$

- Minimal flavor violating interactions

$$\lambda_j{}^i = \left(\alpha I + \beta\, y^\dagger y\right)_j^{\ i}$$

$$[m_\chi]_i{}^j = \left(m_0 I + \Delta m\, y^\dagger y\right)_i^{\ j}$$

  - Equal coupling
  - Small splittings



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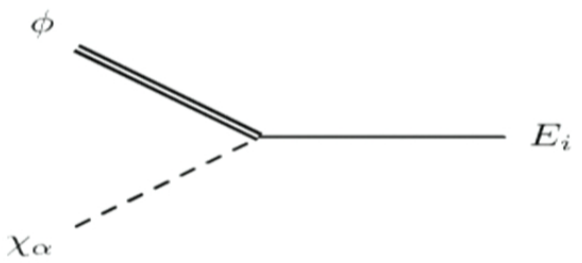

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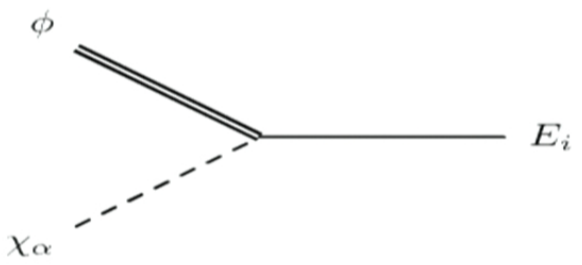


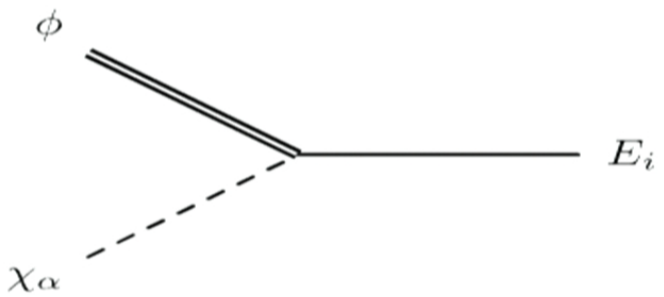
The Model

- Choose universal coupling

$$\lambda_i^j = \lambda \, \mathbb{I}_i^j$$

- Choose χ_τ to be the dark matter

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



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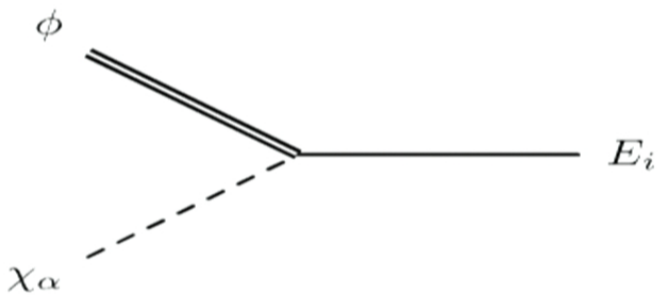
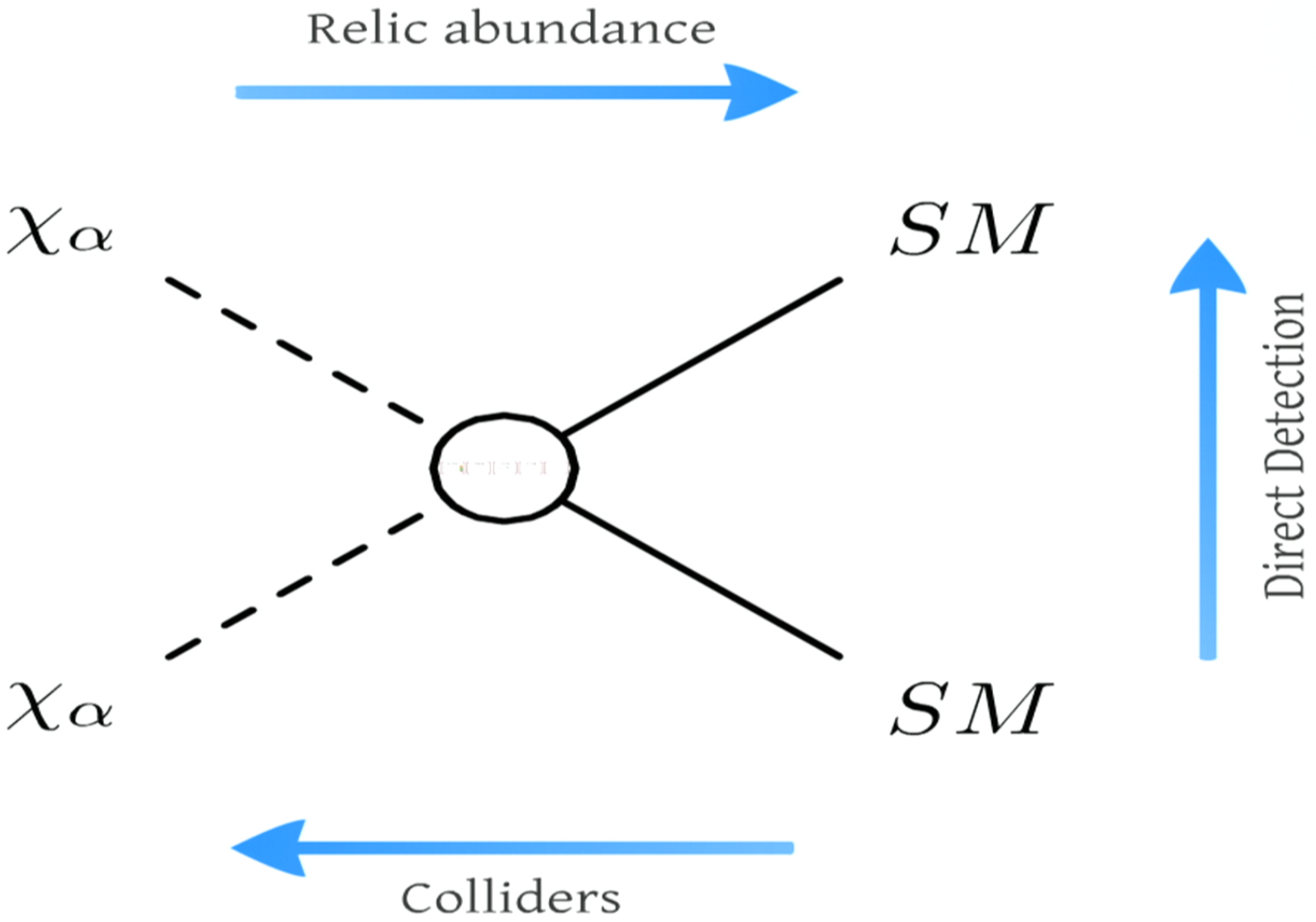
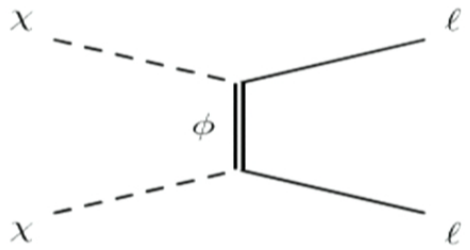



Relic abundance
$\chi\alpha$
SM
$\chi\alpha$
SM
Direct Detection
Colliders

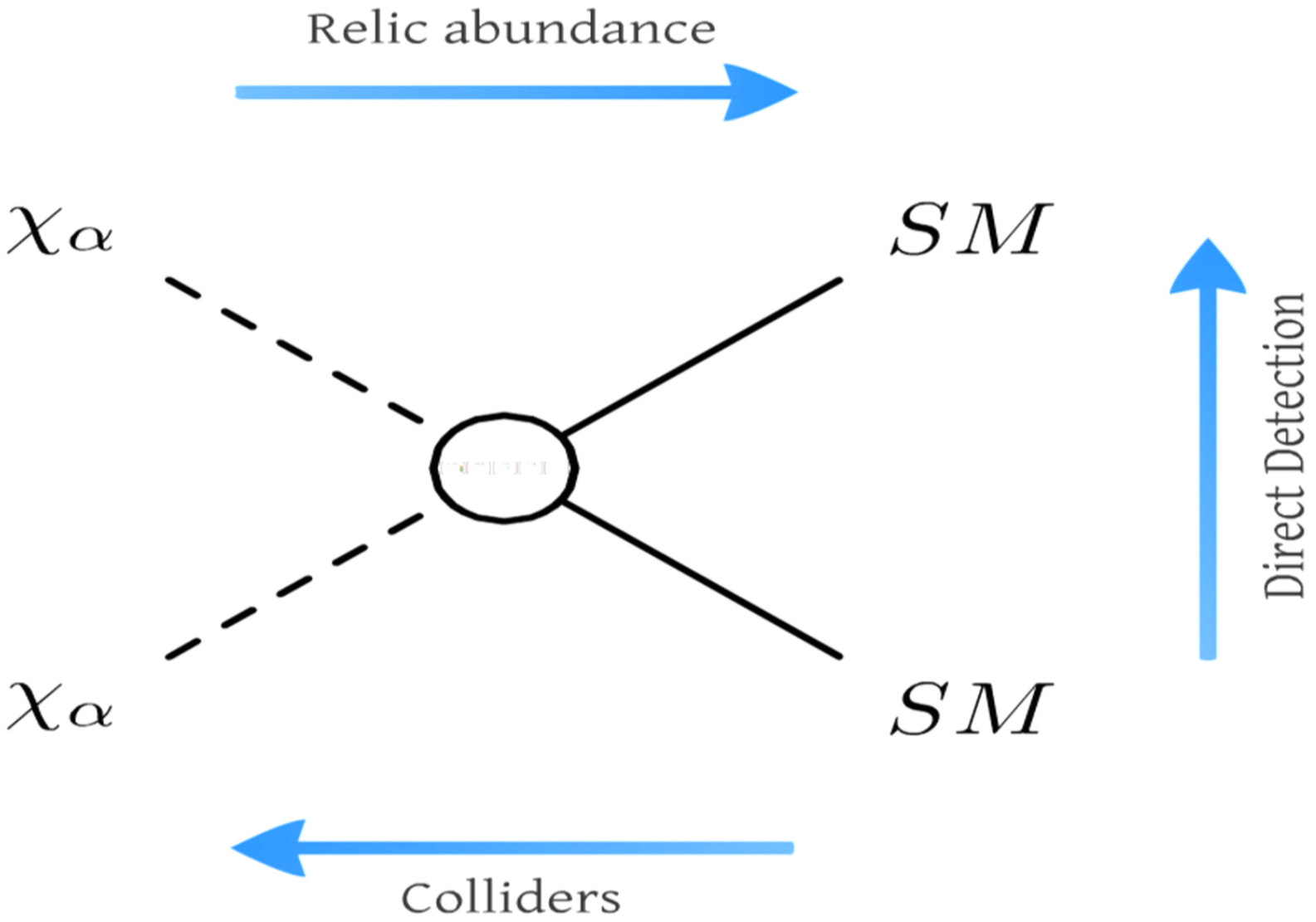
- Annihilation via t-channel



$$\langle \sigma v \rangle \approx \frac{\lambda^4 m_\chi^2}{32\pi (m_\chi^2 + m_\phi^2)^2}$$

- With additional couplings more channels open up, allowing smaller coupling values

Relic abundance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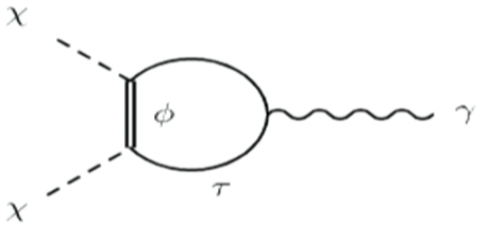
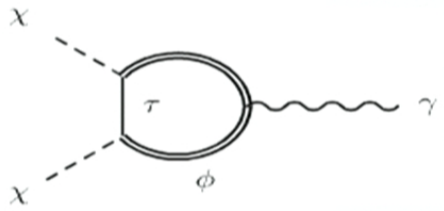
Direct Detection

Leptophilic dark matter





$$\frac{d\sigma_{DD}}{dE_r} = \frac{1}{v^2} m_N \mu_{nuc}^2 \mu_\chi^2 \left(\frac{S_{nuc}+1}{3S_{nuc}}\right) F_D^2(E_r)$$

$$\frac{d\sigma_{DZ}}{dE_r} = \frac{1}{E_r} Z^2 \frac{e^2 \mu_\chi^2}{4\pi} \left[1 - \frac{E_r m_\chi + 2m_N}{v^2 \; 2m_N m_\chi}\right] F^2(E_r)$$

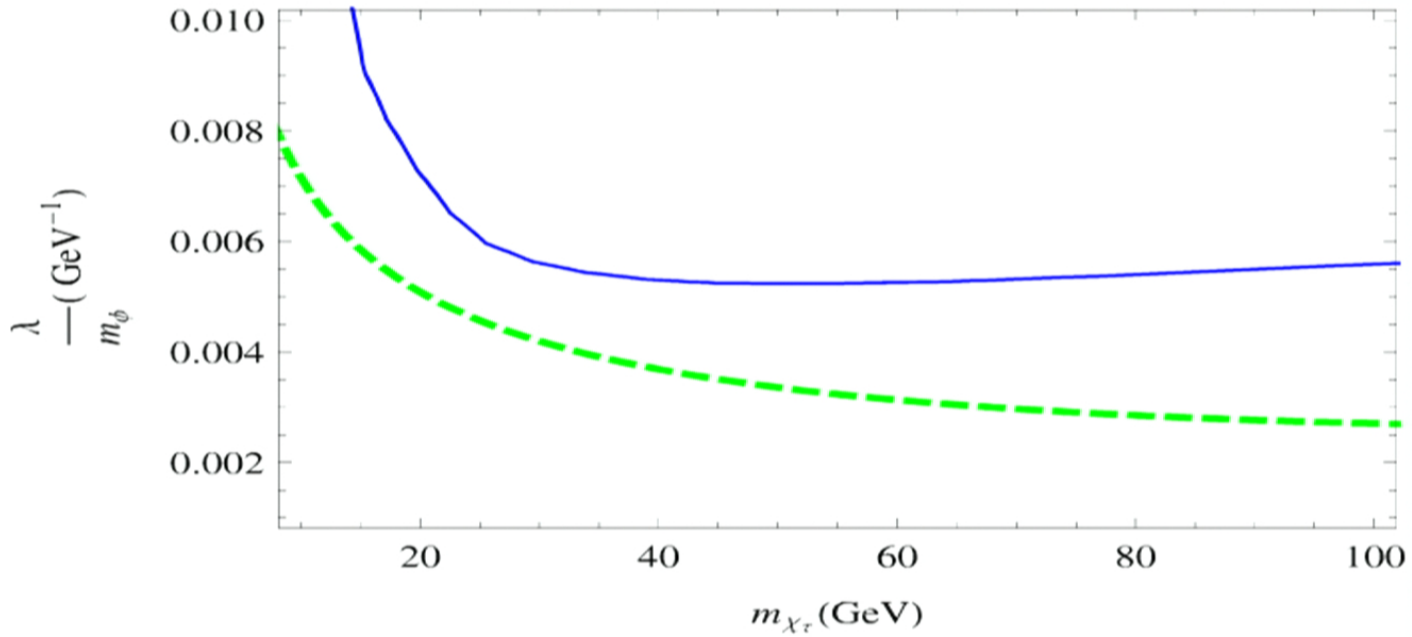
$$\frac{d\sigma_{ZZ}}{dE_r} = \frac{1}{v^2} Z^2 \frac{2m_N}{4\pi} b_p^2 F^2(E_r)$$

[arXiv:1007.4200]
Chang, Weiner, Yavin

[arXiv:1007.4345]
Barger, Keung, Marfatia

Direct Detection bounds

Leptophilic dark matter



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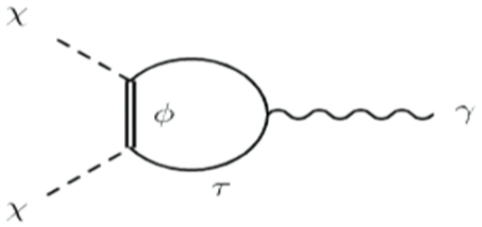

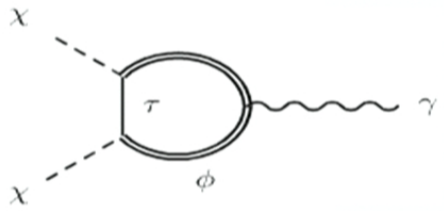

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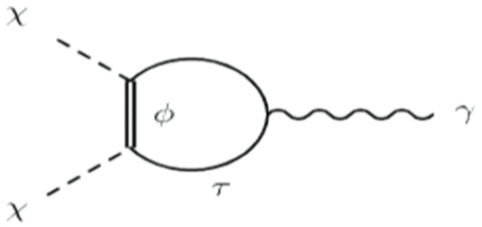

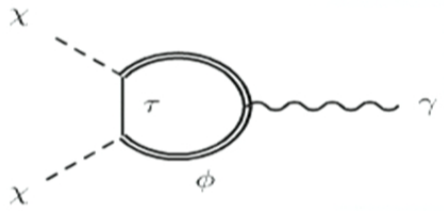

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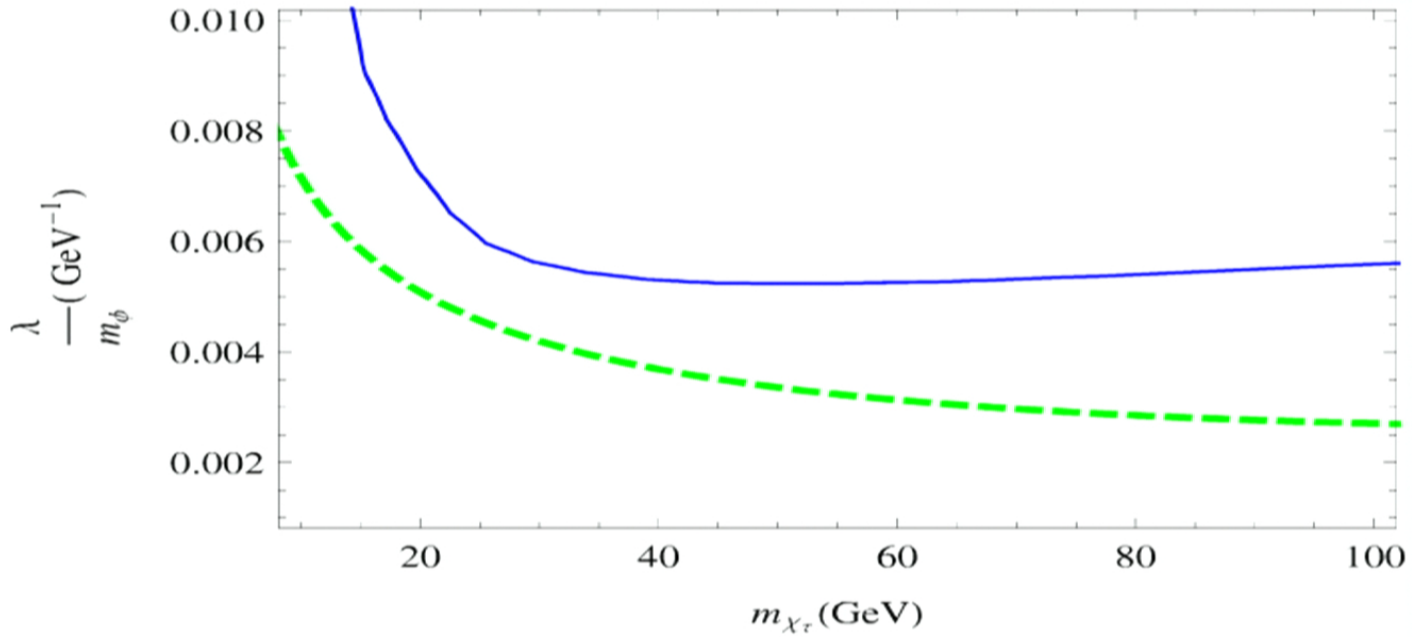

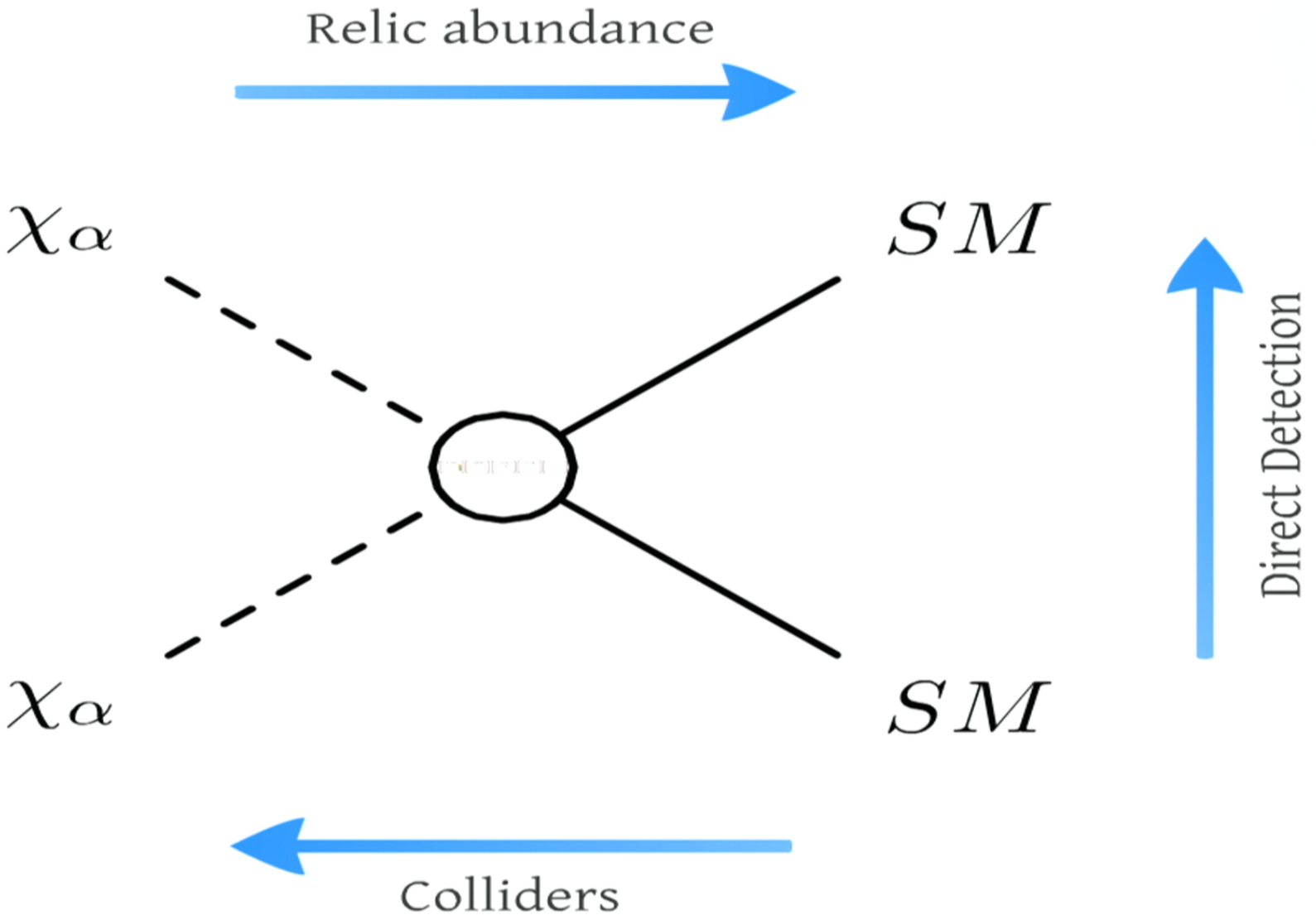
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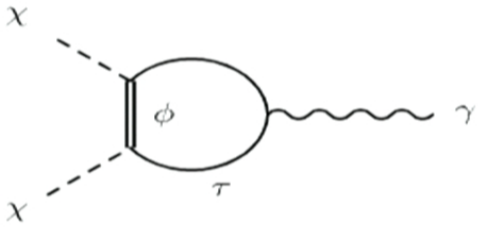
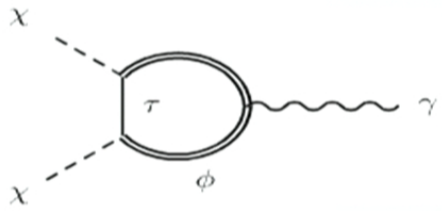
Direct Detection

Leptophilic dark matter





$$\frac{d\sigma_{DD}}{dE_r} = \frac{1}{v^2} m_N \mu_{nuc}^2 \mu_\chi^2 \left(\frac{S_{nuc}+1}{3S_{nuc}}\right) F_D^2(E_r)$$

$$\frac{d\sigma_{DZ}}{dE_r} = \frac{1}{E_r} Z^2 \frac{e^2 \mu_\chi^2}{4\pi} \left[1 - \frac{E_r m_\chi + 2m_N}{v^2 \; 2m_N m_\chi}\right] F^2(E_r)$$

$$\frac{d\sigma_{ZZ}}{dE_r} = \frac{1}{v^2} Z^2 \frac{2m_N}{4\pi} b_p^2 F^2(E_r)$$

[arXiv:1007.4200]
Chang, Weiner, Yavin

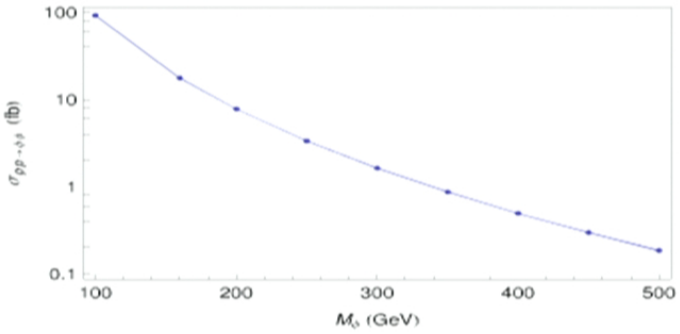
[arXiv:1007.4345]
Barger, Keung, Marfatia

Colliders

Production

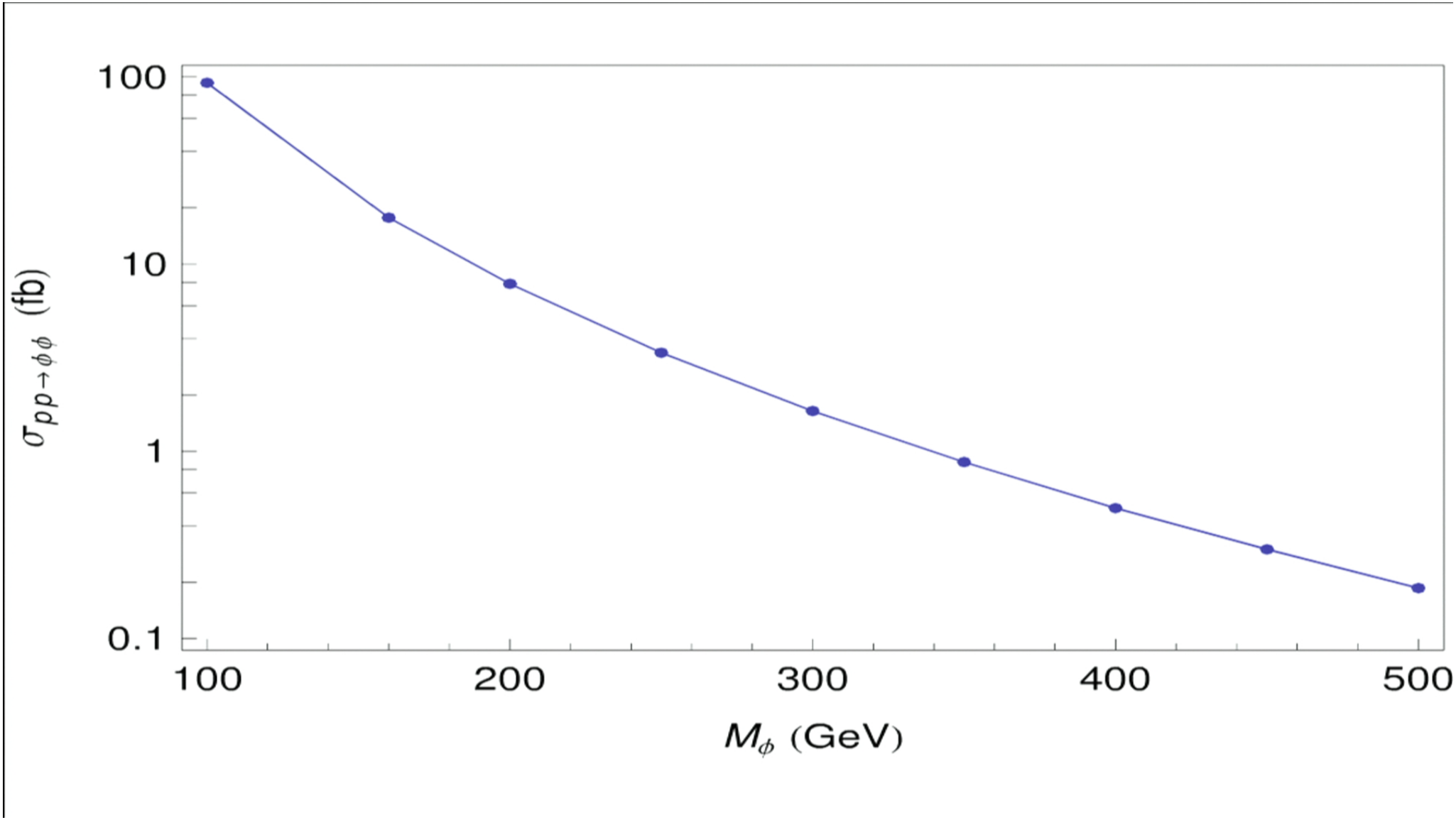
- Spectrum

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



- Weak Production
- Clean signal - lots of leptons

Not an early discovery at the LHC


100
10
1
0.1
$\sigma_{pp\to\phi\phi}$ (fb)
100
200
300
400
500
M_ϕ (GeV)

Production

- Spectrum

$$m_{\chi,e} = 90 \text{ GeV}$$
$$m_{\chi,\mu} = 90 \text{ GeV}$$
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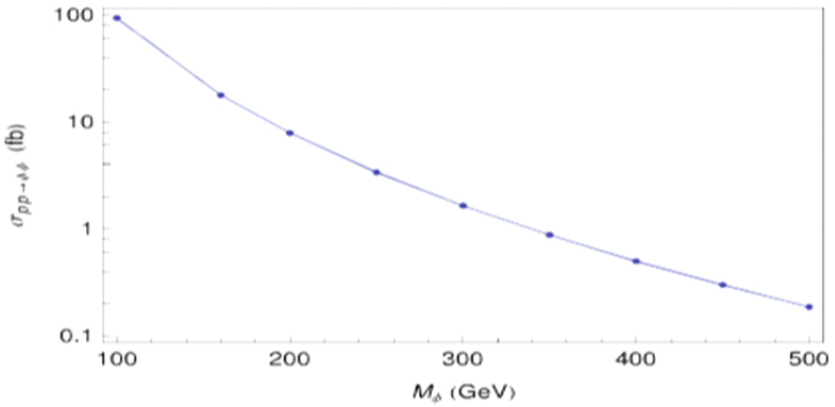

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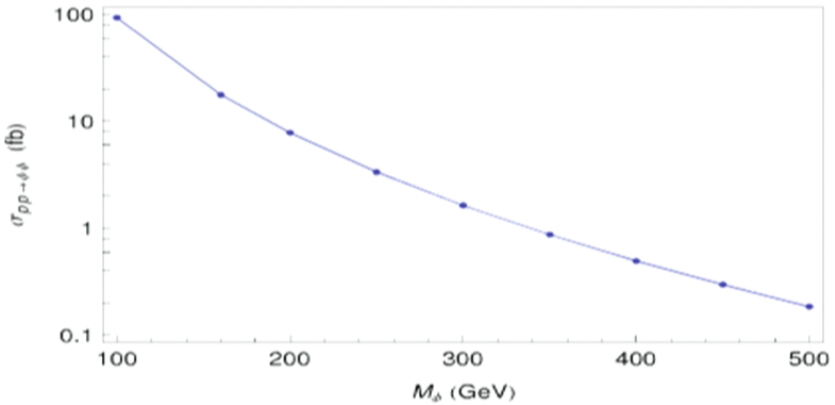
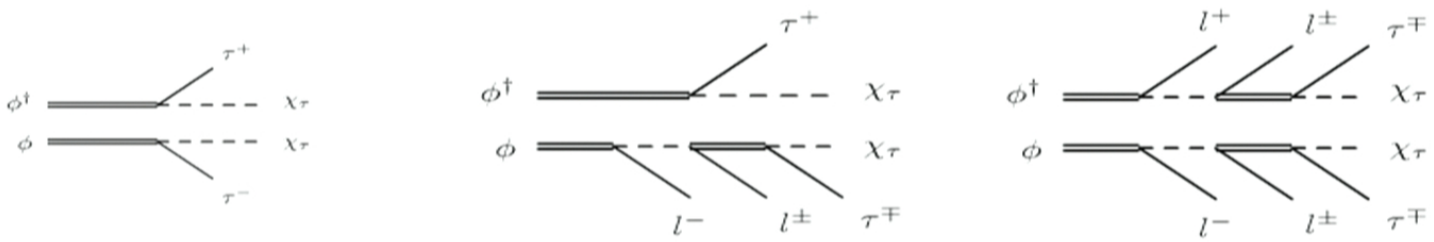


- Weak Production
- Clean signal - lots of leptons

Not an early discovery at the LHC

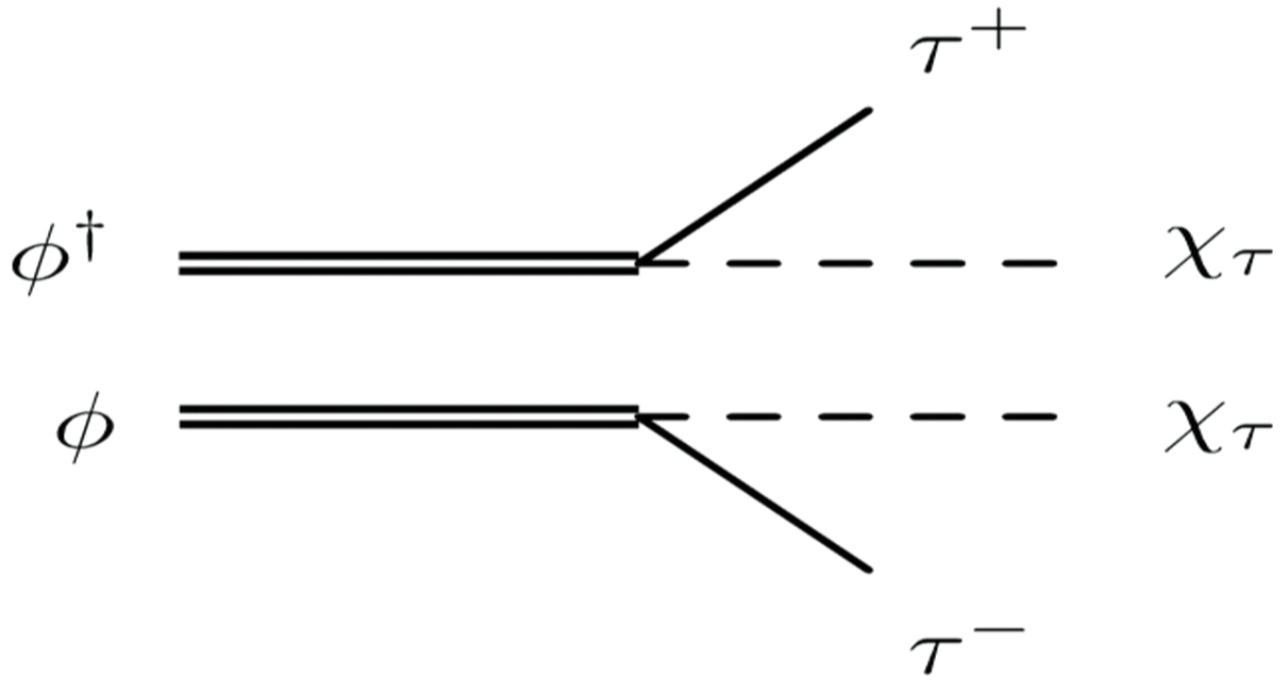
Signal Topologies

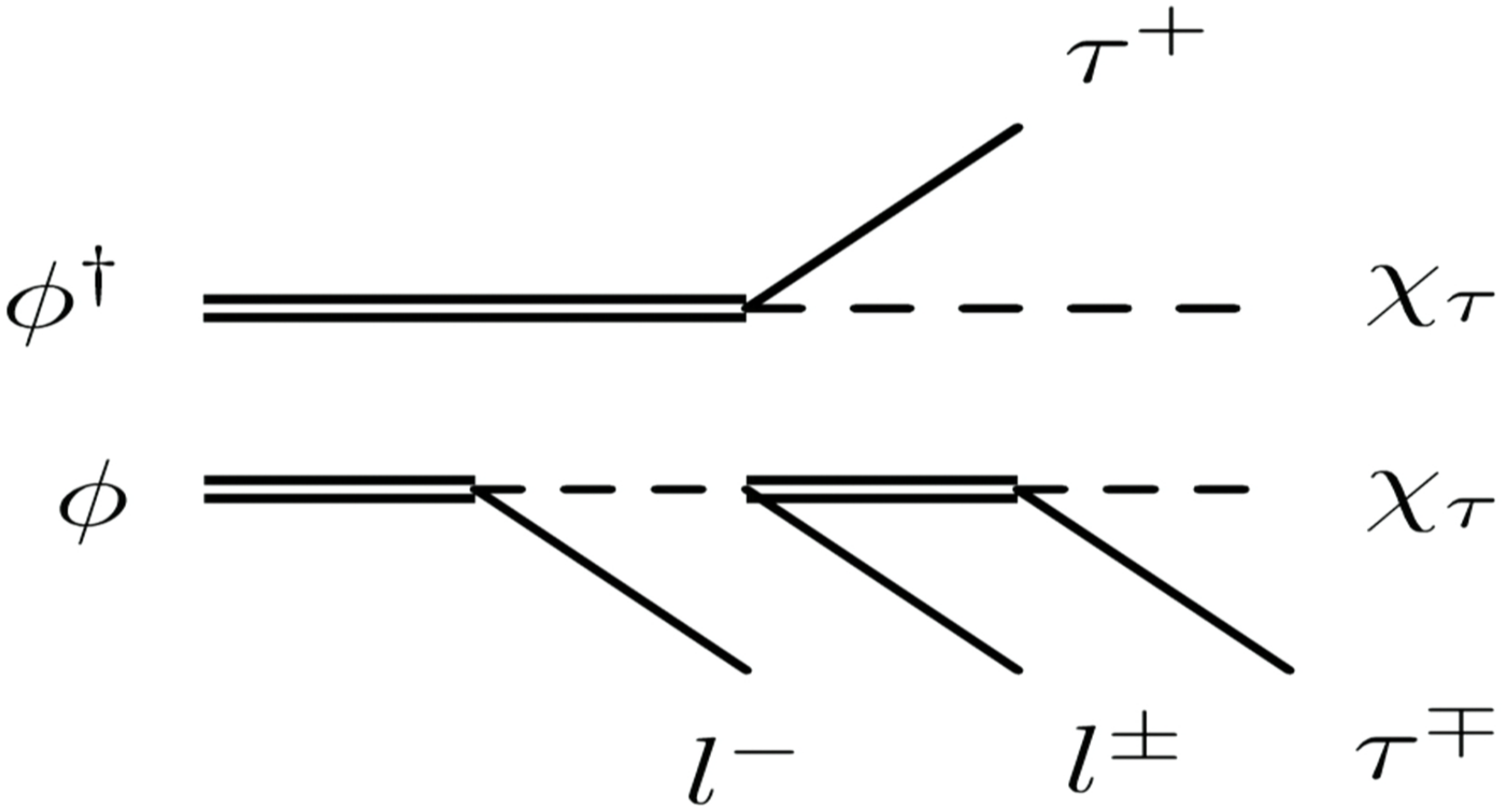
- Since coupling is universal, ϕ decays to all three flavors
- Three event topologies

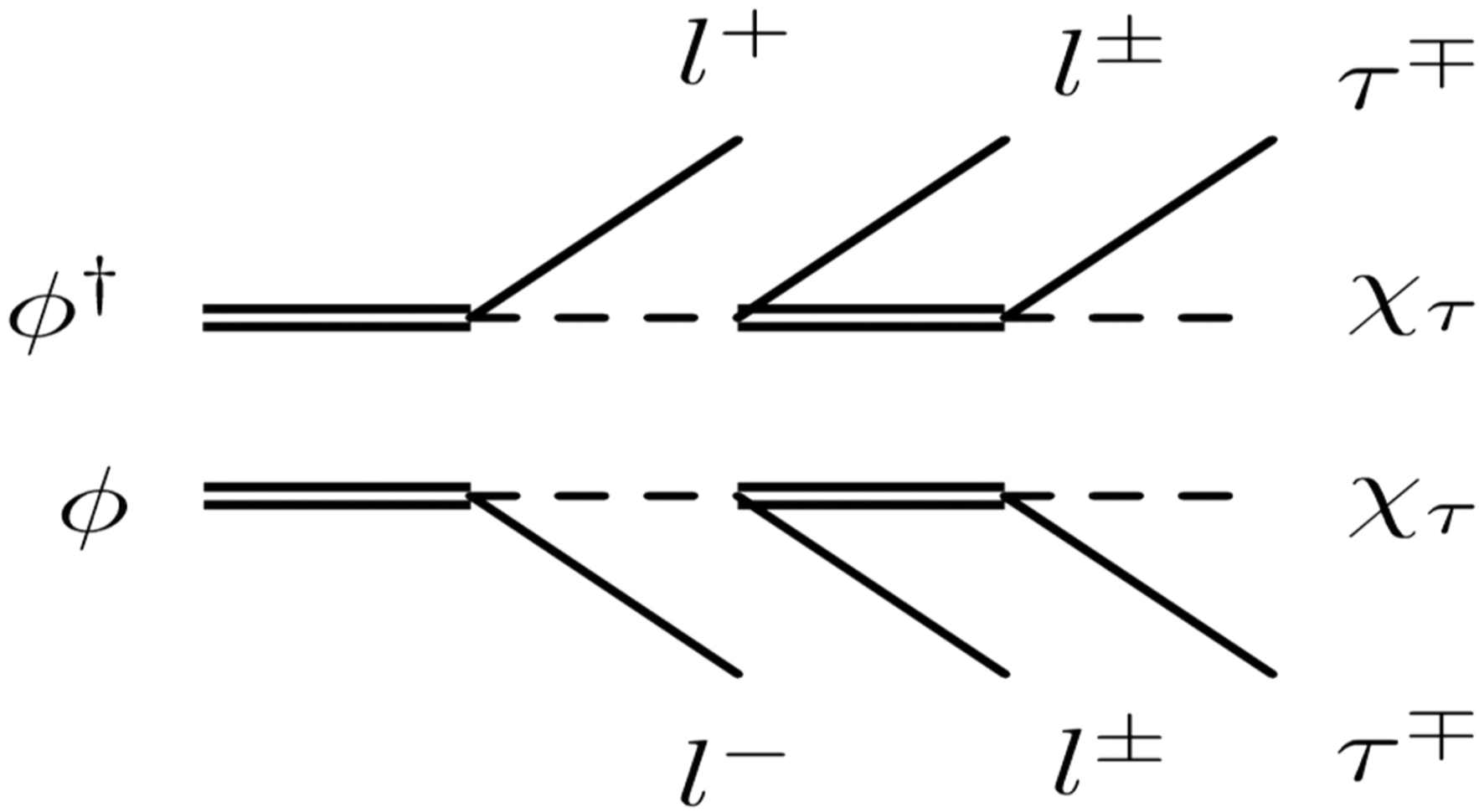


- Focus on the long decay chains

Signal : Four leptons + missing transverse energy


τ^+
$\phi^\dagger$
χ_τ
ϕ
χ_τ
τ^-


τ^+
$\phi^\dagger$
χ_τ
ϕ
χ_τ
l^-
$l^\pm$
$\tau^\mp$


l^+
$l^\pm$
$\tau^\mp$
$\phi^\dagger$
χ_τ
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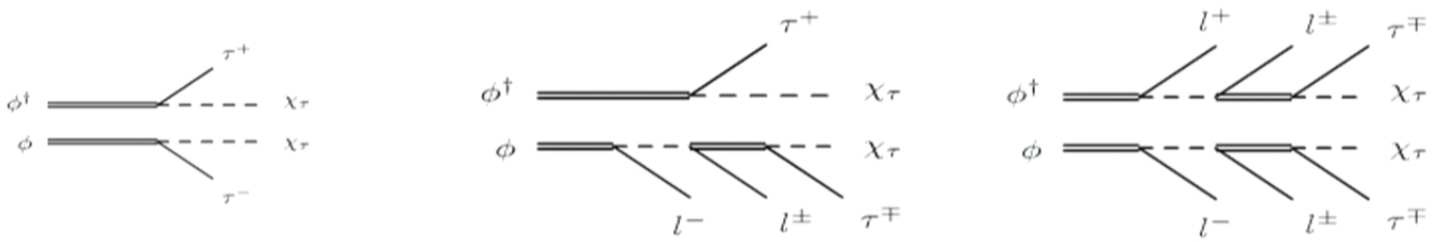

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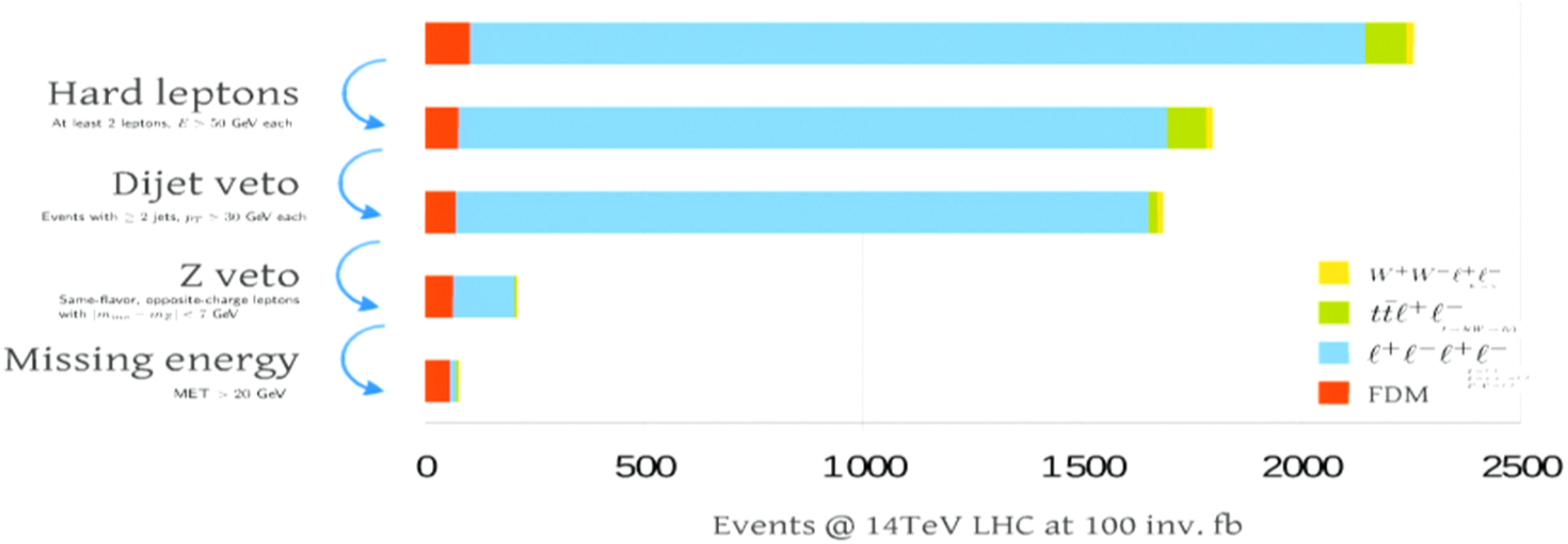
Backgrounds and cuts

Pre-selection: At least 4 leptons, pT>7 GeV each



56.87 signal + 14.34 SM background @ 14TeV LHC at 100 inv. fb

$\ell^+\ell^-\ell^+\ell^-$

$Z \longrightarrow \ell^+\ell^-$
$Z \longrightarrow \tau^+\tau^- \longrightarrow \ell^+\ell^-$
$Z^*, A^* \longrightarrow \ell^+\ell^-$

FDM

90

250

$t\bar{t}\ell^+\ell^-$

$t \longrightarrow b(W \longrightarrow l\nu)$

$\ell^+\ell^-\ell^+\ell^-$

$Z \longrightarrow \ell^+\ell^-$

$Z \longrightarrow \tau^+\tau^- \longrightarrow \ell^+\ell^-$

$Z^*, A^* \longrightarrow \ell^+\ell^-$

FDM

$$W^+W^-\ell^+\ell^-$$

$W \to l\nu$

$$t\bar{t}\ell^+\ell^-$$

$t \to b(W \to l\nu)$

$$\ell^+\ell^-\ell^+\ell^-$$

$Z \to \ell^+\ell^-$

$Z \to \tau^+\tau^- \to \ell^+\ell^-$

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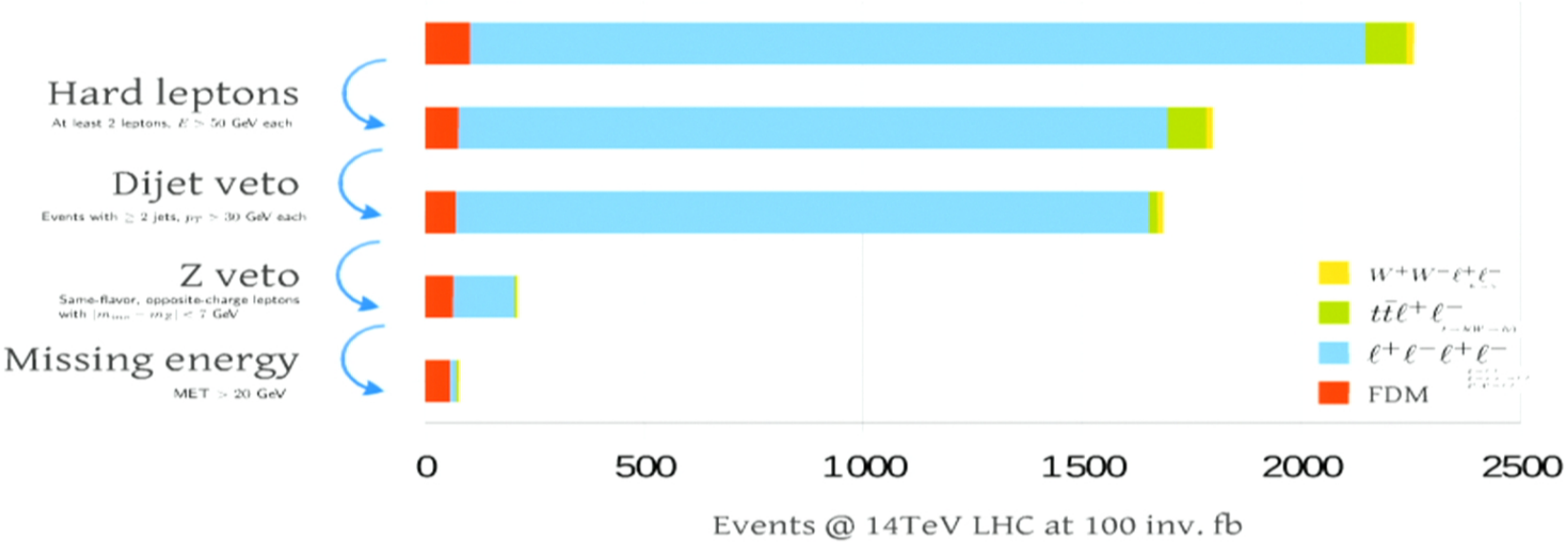


56.87 signal + 14.34 SM background @ 14TeV LHC at 100 inv. fb

Hard leptons

At least 2 leptons, $E > 50$ GeV each

Dijet veto

Events with ≥ 2 jets, $p_T > 30$ GeV each

Dijet veto

Events with ≥ 2 jets, $p_T > 30$ GeV each

Z veto

Same-flavor, opposite-charge leptons with $|m_{inv} - m_Z| < 7$ GeV

Events with ≥ 2 jets, $p_T > 30$ GeV each

Z veto

Same-flavor, opposite-charge leptons with $|m_{inv} - m_Z| < 7$ GeV

Missing energy

MET > 20 GeV

Distinguishing FDM at the LHC

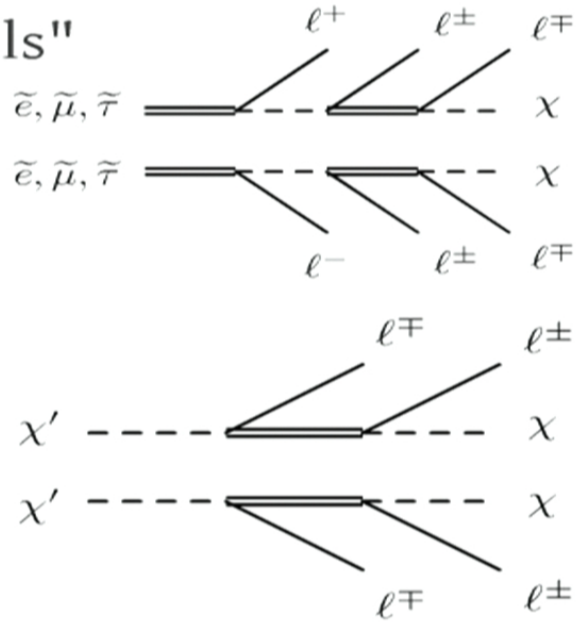
Can we establish that this signal above is from FDM?

Compare with "SuSy strawman models"

- Only light states are

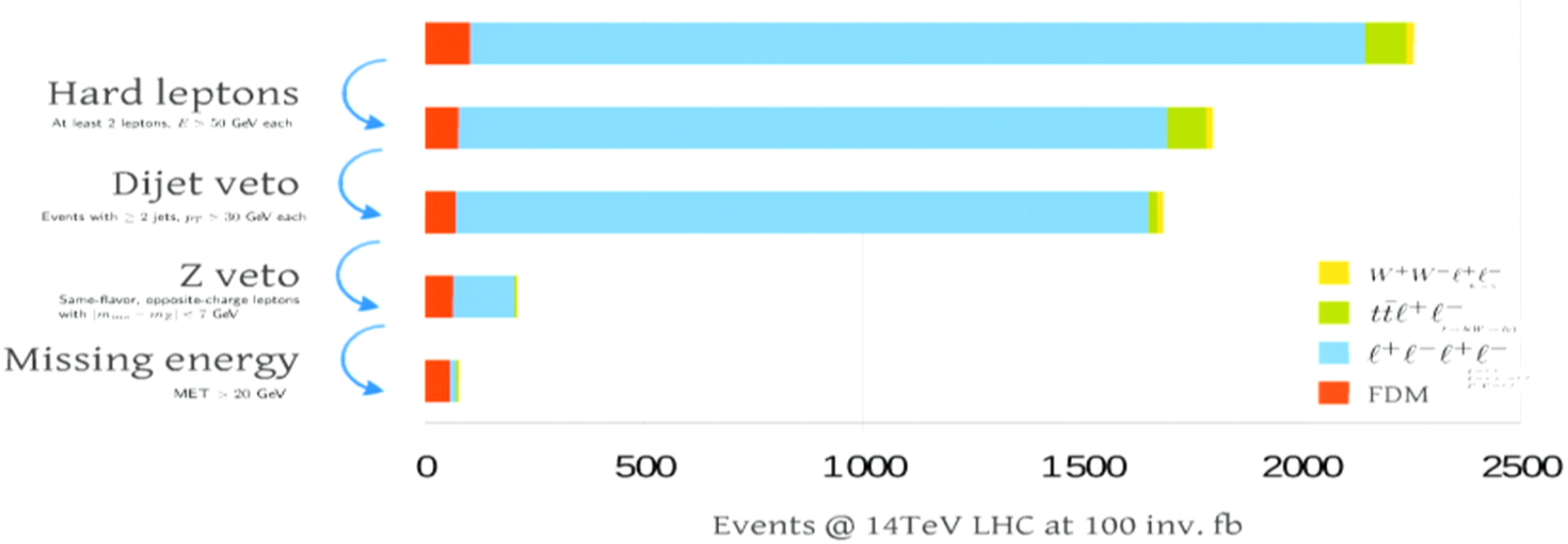
  sleptons: $\widetilde{e}, \widetilde{\mu}, \widetilde{\tau}$
  neutralinos: χ', χ

- Same mass splittings as FDM



Backgrounds and cuts

Pre-selection: At least 4 leptons, pT>7 GeV each



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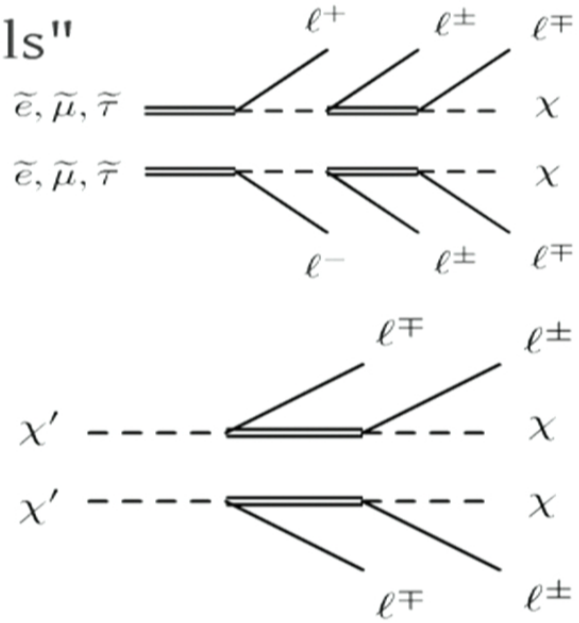

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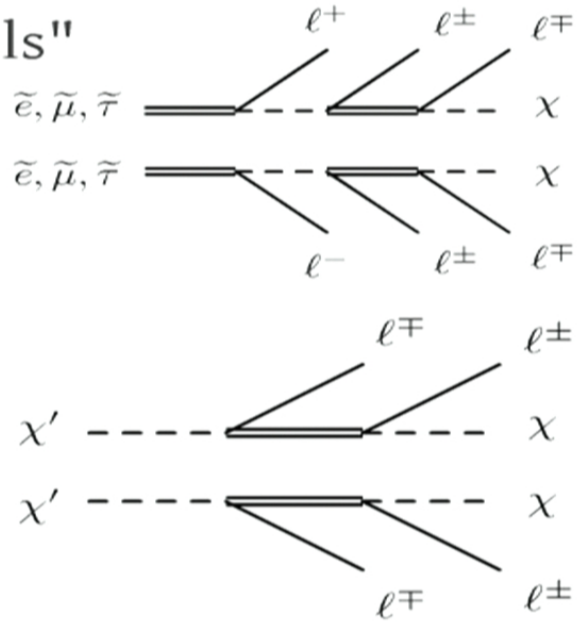
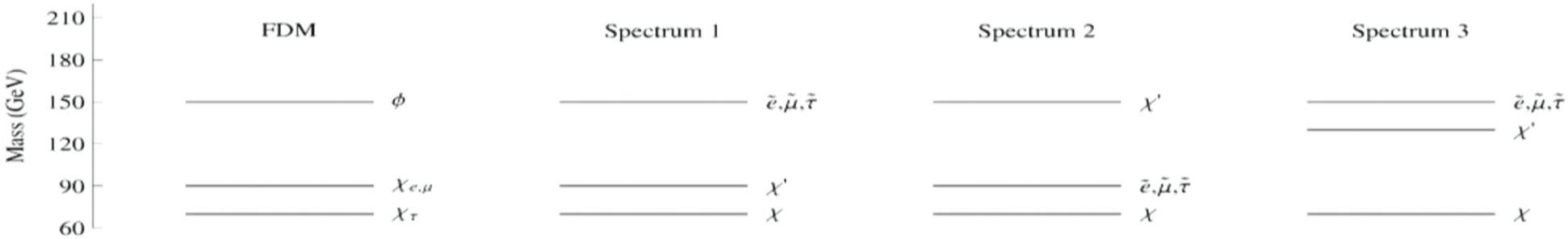


Same mass splittings as FDM



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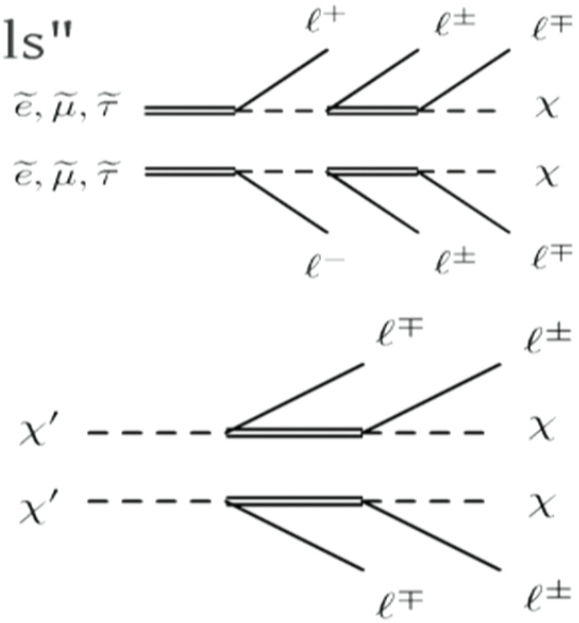
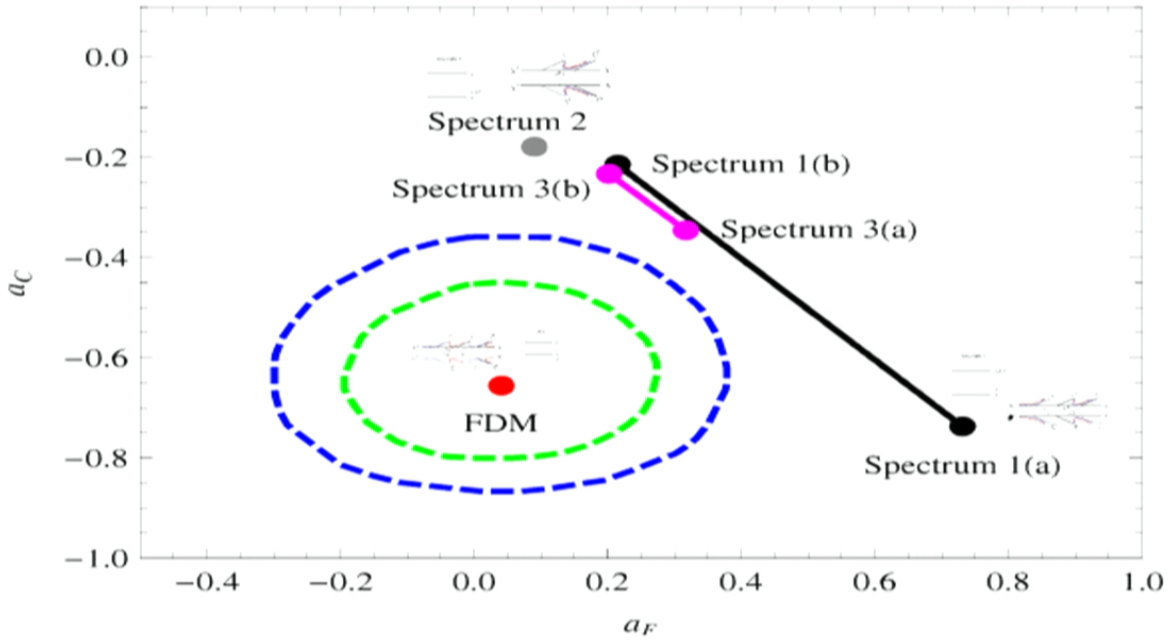
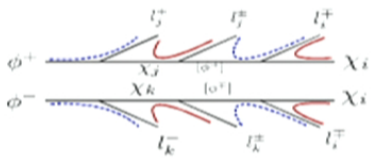
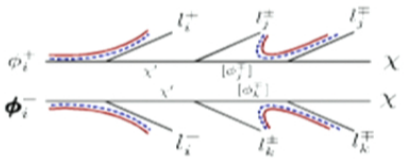


Flavor and charge correlations

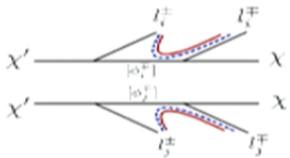




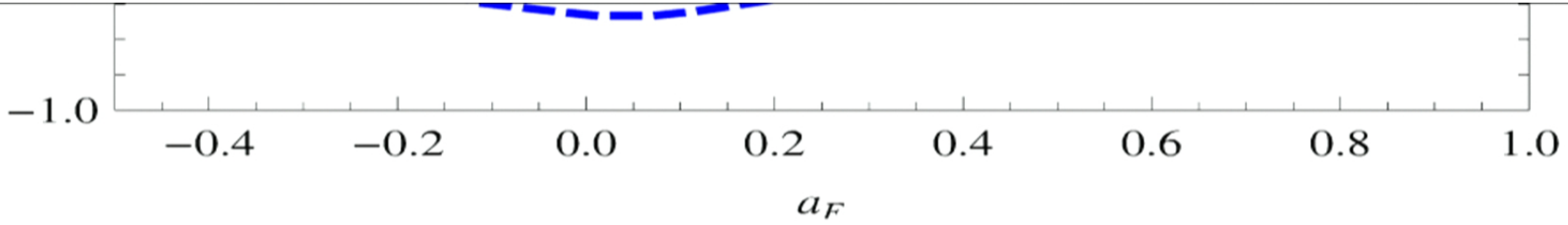
FDM

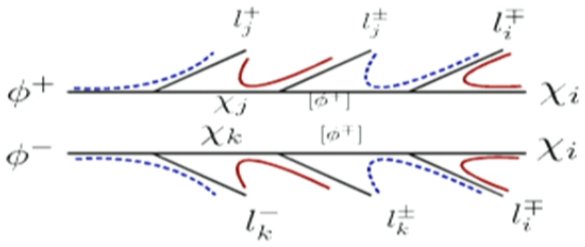


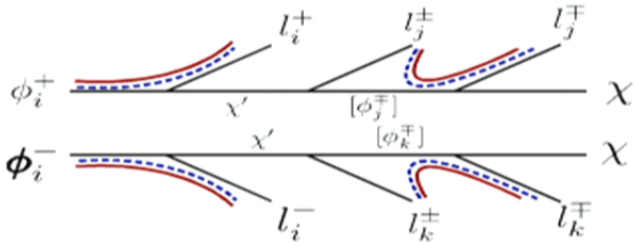
(a)

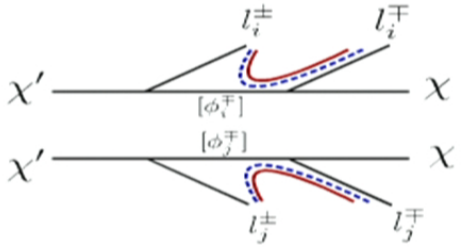


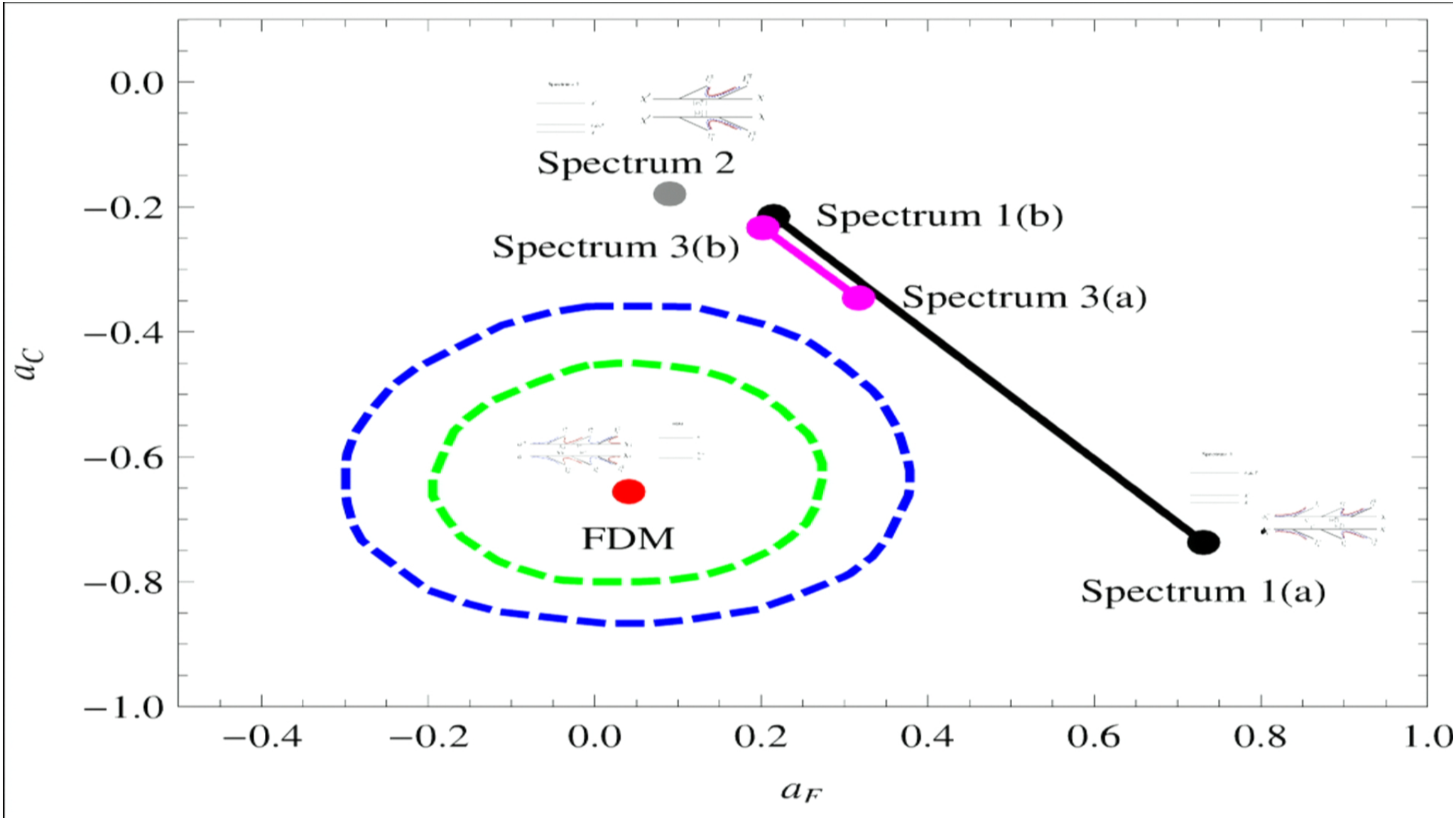
(b)

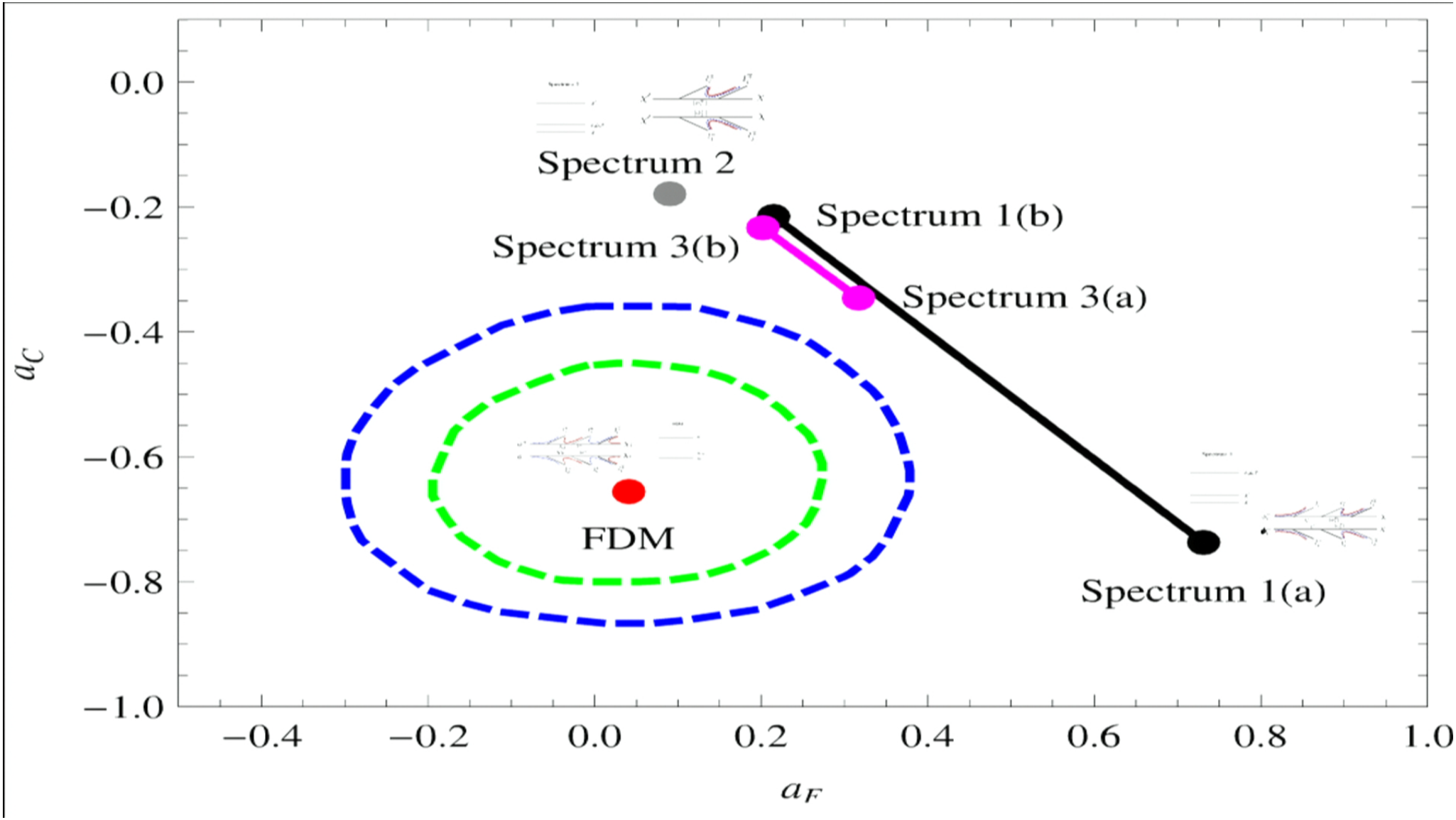

−1.0
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
a_F

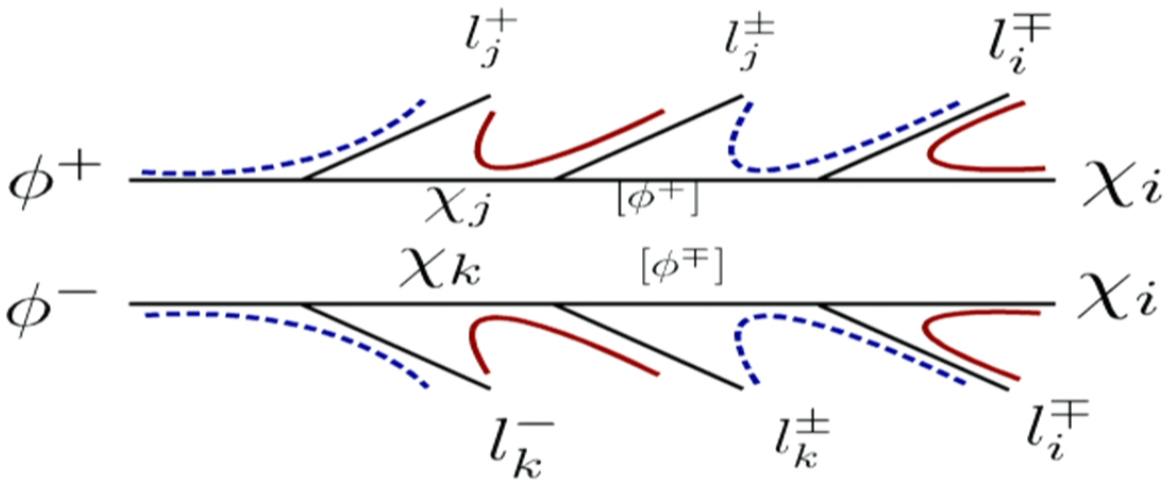

ϕ^+
ϕ^-
χ_i
χ_i
FDM


ϕ_i^+
$\boldsymbol{\phi}_i^-$
χ
χ
(a)


χ'
χ'
χ
χ
(b)


Spectrum 2
Spectrum 1(b)
Spectrum 3(b)
Spectrum 3(a)
FDM
Spectrum 1(a)
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
a_C
a_F


Spectrum 2
Spectrum 1(b)
Spectrum 3(b)
Spectrum 3(a)
FDM
Spectrum 1(a)
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
a_C
a_F

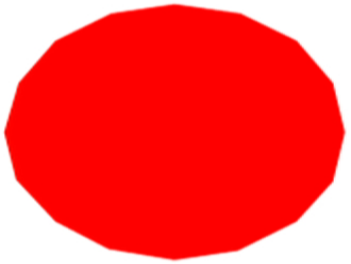


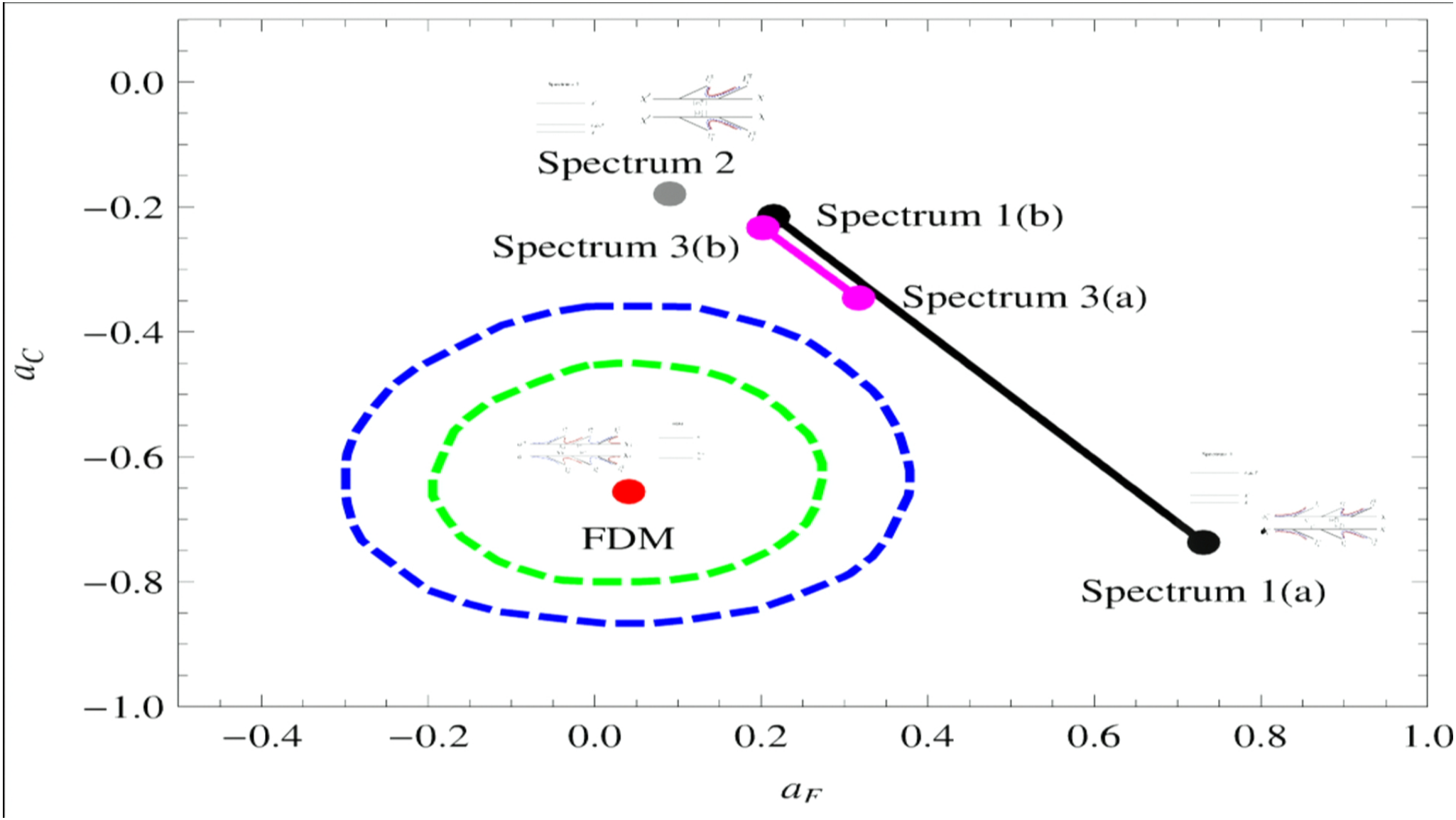
FDM

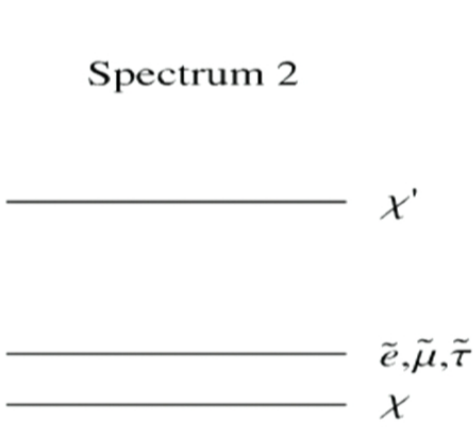
ϕ

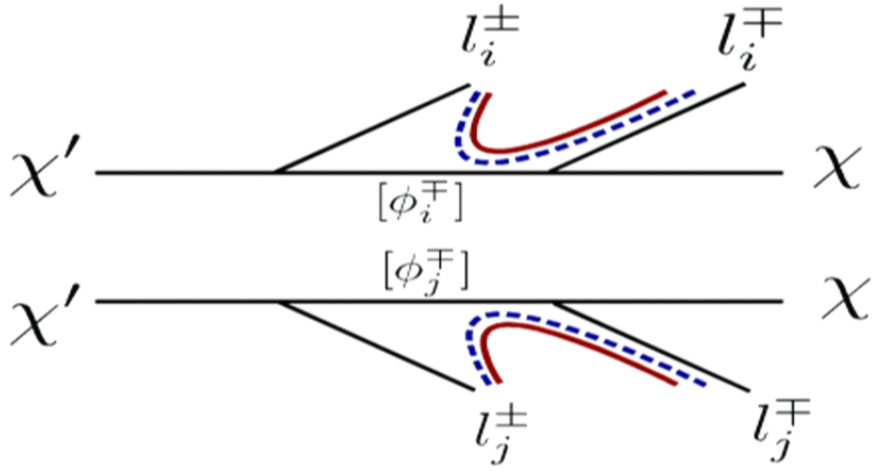
$\chi_{e,\mu}$

χ_τ



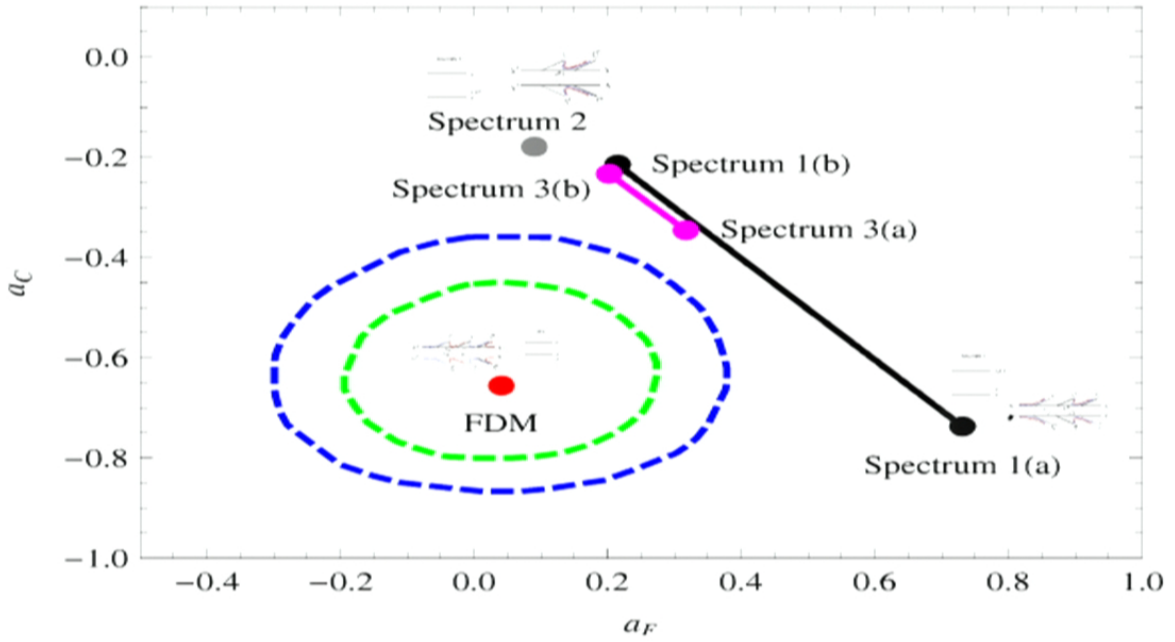

Spectrum 2
Spectrum 1(b)
Spectrum 3(b)
Spectrum 3(a)
FDM
Spectrum 1(a)
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
a_C
a_F

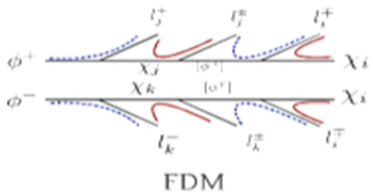

Spectrum 2
χ'
$\tilde{e},\tilde{\mu},\tilde{\tau}$
χ


$l_i^{\pm}$
$l_i^{\mp}$
χ'
χ
$[\phi_i^{\mp}]$
$[\phi_j^{\mp}]$
χ'
χ
$l_j^{\pm}$
$l_j^{\mp}$

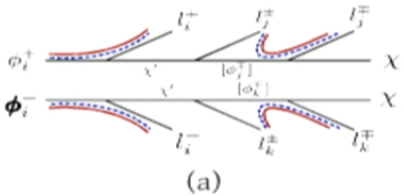
Spectrum 2

Flavor and charge correlations

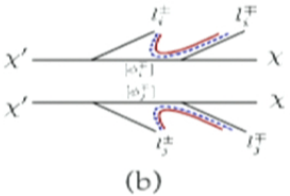




FDM



(a)



(b)

Conclusion

- Flavored dark matter is a simple possibility which has not been explored in a model-independent way.
- It is possible to discover and distinguish a τFDM model at the LHC.
- Our analysis can be extended in many ways
  - Kinematic variables to identify particles in decay chains
  - Kinematic distributions: edges, end-points, mT2
  - Identification of hadronically decaying taus
- Similar conclusions are expected to hold for quark-flavored dark matter. Stay tuned...

thank you