Phenomenological analysis of multi-pseudoscalar mediated dark matter models

Disha Bhatia
The Institute of the Mathematical Sciences, India

Based on JHEP 07 (2022) 111

July 28, 2022

Introduction

- LHC searches focuses on WIMP DM candidates i.e. with mass ranges $\mathcal{O}(10$ GeV) - few TeVs.
- These candidates are theoretically well motivated because the annihilation cross-sections required to establish abundances are of the order of weak scale, hence attractive both from theoretical and experimental searches $\Rightarrow$ WIMP miracle.
- Many well motivated scenarios UV scenarios like super-symmetry, extradimensions already contain a dark matter candidate.

  UV complete frameworks have increasingly become disfavoured as they tend to be very specific.
- Need a generic theoretical framework which can be used to cover large classes of models.

Introduction

- LHC searches focuses on WIMP DM candidates i.e. with mass ranges $\mathcal{O}$(10 GeV) - few TeVs.
- These candidates are theoretically well motivated because the annihilation cross-sections required to establish abundances are of the order of weak scale, hence attractive both from theoretical and experimental searches $\Rightarrow$ WIMP miracle.
- Many well motivated scenarios UV scenarios like super-symmetry, extradimensions already contain a dark matter candidate.

  UV complete frameworks have increasingly become disfavoured as they tend to be very specific.
- Need a generic theoretical framework which can be used to cover large classes of models.

Introduction

- LHC searches focuses on WIMP DM candidates i.e. with mass ranges $\mathcal{O}$(10 GeV) - few TeVs.
- These candidates are theoretically well motivated because the annihilation cross-sections required to establish abundances are of the order of weak scale, hence attractive both from theoretical and experimental searches $\Rightarrow$ WIMP miracle.
- Many well motivated scenarios UV scenarios like super-symmetry, extradimensions already contain a dark matter candidate.

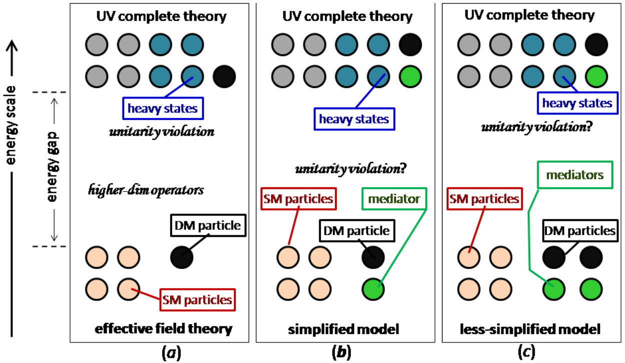
  UV complete frameworks have increasingly become disfavoured as they tend to be very specific.
- Need a generic theoretical framework which can be used to cover large classes of models.

Introduction

- LHC searches focuses on WIMP DM candidates i.e. with mass ranges $\mathcal{O}$(10 GeV) - few TeVs.
- These candidates are theoretically well motivated because the annihilation cross-sections required to establish abundances are of the order of weak scale, hence attractive both from theoretical and experimental searches $\Rightarrow$ WIMP miracle.
- Many well motivated scenarios UV scenarios like super-symmetry, extradimensions already contain a dark matter candidate.

  UV complete frameworks have increasingly become disfavoured as they tend to be very specific.
- Need a generic theoretical framework which can be used to cover large classes of models.

Three theoretical approaches of DM searches at the LHC



Disadvantages of the three frameworks

- EFT: fails to capture the correct momentum dependence, since the assumption $q^2 << m^2$ breaks.
- Simplified model: Broadly 4 s-channel simplified models are considered:

$$\mathcal{L}_{\rm V} = g_{\rm SM}\overline{q}\gamma^\mu q Z'_\mu + g_\chi \overline{\chi}\gamma^\mu \chi Z'_\mu \quad \mathcal{L}_{\rm AV} = g_{\rm SM}\overline{q}\gamma^\mu \gamma_5 q Z'_\mu + g_\chi \overline{\chi}\gamma^\mu \gamma_5 \chi Z'_\mu$$
$$\mathcal{L}_{\rm S} = \frac{m_q}{v} g_{\rm SM}\overline{q} q S + g_\chi \overline{\chi}\chi S \quad \mathcal{L}_{\rm P} = {\rm i}\frac{m_q}{v} g_{\rm SM}\overline{q}\gamma_5 q P + {\rm i} g_\chi \overline{\chi}\gamma_5 \chi P$$

- Captures broad features of several models.
- Tells about favorable lorentz structures from combined cosmological+direct detection+collider constraints.
- However in doing so left with fewer channels to probe (by large monojets).
- may be new physics lying in some other channels.
- Simps like EFT's do not respect full gauge symmetry, construction based on gauge invariance $\Rightarrow$ more phenomenological particles hence channels)

Disadvantages of the three frameworks

- EFT: fails to capture the correct momentum dependence, since the assumption $q^2 << m^2$ breaks.
- Simplified model: Broadly 4 s-channel simplified models are considered:

$$\mathcal{L}_{\rm V} = g_{\rm SM}\overline{q}\gamma^\mu q Z'_\mu + g_\chi \overline{\chi}\gamma^\mu \chi Z'_\mu \quad \mathcal{L}_{\rm AV} = g_{\rm SM}\overline{q}\gamma^\mu\gamma_5 q Z'_\mu + g_\chi\overline{\chi}\gamma^\mu\gamma_5\chi Z'_\mu$$
$$\mathcal{L}_{\rm S} = \frac{m_q}{v} g_{\rm SM}\overline{q}qS + g_\chi\overline{\chi}\chi S \quad \mathcal{L}_{\rm P} = {\rm i}\frac{m_q}{v} g_{\rm SM}\overline{q}\gamma_5 qP + {\rm i}g_\chi\overline{\chi}\gamma_5\chi P$$

- Captures broad features of several models.
- Tells about favorable lorentz structures from combined cosmological+direct detection+collider constraints.
- However in doing so left with fewer channels to probe (by large monojets).
- may be new physics lying in some other channels.
- Simps like EFT's do not respect full gauge symmetry, construction based on gauge invariance $\Rightarrow$ more phenomenological particles hence channels)

Disadvantages of the three frameworks

- EFT: fails to capture the correct momentum dependence, since the assumption $q^2 << m^2$ breaks.
- Simplified model: Broadly 4 s-channel simplified models are considered:

$$\mathcal{L}_{\rm V} = g_{\rm SM}\overline{q}\gamma^{\mu}qZ'_{\mu} + g_{\chi}\overline{\chi}\gamma^{\mu}\chi Z'_{\mu} \quad \mathcal{L}_{\rm AV} = g_{\rm SM}\overline{q}\gamma^{\mu}\gamma_5 qZ'_{\mu} + g_{\chi}\overline{\chi}\gamma^{\mu}\gamma_5\chi Z'_{\mu}$$
$$\mathcal{L}_{\rm S} = \frac{m_q}{v}g_{\rm SM}\overline{q}qS + g_{\chi}\overline{\chi}\chi S \quad \mathcal{L}_{\rm P} = {\rm i}\frac{m_q}{v}g_{\rm SM}\overline{q}\gamma_5 qP + {\rm i}g_{\chi}\overline{\chi}\gamma_5\chi P$$

- Captures broad features of several models.
- Tells about favorable lorentz structures from combined cosmological+direct detection+collider constraints.
- However in doing so left with fewer channels to probe (by large monojets).
- may be new physics lying in some other channels.
- Simps like EFT's do not respect full gauge symmetry, construction based on gauge invariance $\Rightarrow$ more phenomenological particles hence channels)

Disadvantages of the three frameworks

- EFT: fails to capture the correct momentum dependence, since the assumption $q^2 << m^2$ breaks.
- Simplified model: Broadly 4 s-channel simplified models are considered:

$$\mathcal{L}_{\mathrm{V}} = g_{\mathrm{SM}}\overline{q}\gamma^{\mu}qZ'_{\mu} + g_{\chi}\overline{\chi}\gamma^{\mu}\chi Z'_{\mu} \quad \mathcal{L}_{\mathrm{AV}} = g_{\mathrm{SM}}\overline{q}\gamma^{\mu}\gamma_5 qZ'_{\mu} + g_{\chi}\overline{\chi}\gamma^{\mu}\gamma_5\chi Z'_{\mu}$$
$$\mathcal{L}_{\mathrm{S}} = \frac{m_q}{v}g_{\mathrm{SM}}\overline{q}qS + g_{\chi}\overline{\chi}\chi S \quad \mathcal{L}_{\mathrm{P}} = \mathrm{i}\frac{m_q}{v}g_{\mathrm{SM}}\overline{q}\gamma_5 qP + \mathrm{i}g_{\chi}\overline{\chi}\gamma_5\chi P$$

- Captures broad features of several models.
- Tells about favorable lorentz structures from combined cosmological+direct detection+collider constraints.
- However in doing so left with fewer channels to probe (by large monojets).
- may be new physics lying in some other channels.
- Simps like EFT's do not respect full gauge symmetry, construction based on gauge invariance $\Rightarrow$ more phenomenological particles hence channels)

Disadvantages of the three frameworks

- EFT: fails to capture the correct momentum dependence, since the assumption $q^2 << m^2$ breaks.
- Simplified model: Broadly 4 s-channel simplified models are considered:

$$\mathcal{L}_{\rm V} = g_{\rm SM}\overline{q}\gamma^\mu q Z'_\mu + g_\chi\overline{\chi}\gamma^\mu\chi Z'_\mu \quad \mathcal{L}_{\rm AV} = g_{\rm SM}\overline{q}\gamma^\mu\gamma_5 q Z'_\mu + g_\chi\overline{\chi}\gamma^\mu\gamma_5\chi Z'_\mu$$
$$\mathcal{L}_{\rm S} = \frac{m_q}{v} g_{\rm SM}\overline{q}qS + g_\chi\overline{\chi}\chi S \quad \mathcal{L}_{\rm P} = {\rm i}\frac{m_q}{v} g_{\rm SM}\overline{q}\gamma_5 qP + {\rm i}g_\chi\overline{\chi}\gamma_5\chi P$$

- Captures broad features of several models.
- Tells about favorable lorentz structures from combined cosmological+direct detection+collider constraints.
- However in doing so left with fewer channels to probe (by large monojets).
- may be new physics lying in some other channels.
- Simps like EFT's do not respect full gauge symmetry, construction based on gauge invariance $\Rightarrow$ more phenomenological particles hence channels)

Disadvantages of the three frameworks

- EFT: fails to capture the correct momentum dependence, since the assumption $q^2 << m^2$ breaks.
- Simplified model: Broadly 4 s-channel simplified models are considered:

$$\mathcal{L}_{\rm V} = g_{\rm SM}\overline{q}\gamma^{\mu}qZ'_{\mu} + g_{\chi}\overline{\chi}\gamma^{\mu}\chi Z'_{\mu} \quad \mathcal{L}_{\rm AV} = g_{\rm SM}\overline{q}\gamma^{\mu}\gamma_5 qZ'_{\mu} + g_{\chi}\overline{\chi}\gamma^{\mu}\gamma_5\chi Z'_{\mu}$$
$$\mathcal{L}_{\rm S} = \frac{m_q}{v}g_{\rm SM}\overline{q}qS + g_{\chi}\overline{\chi}\chi S \quad \mathcal{L}_{\rm P} = {\rm i}\frac{m_q}{v}g_{\rm SM}\overline{q}\gamma_5 qP + {\rm i}g_{\chi}\overline{\chi}\gamma_5\chi P$$

- Captures broad features of several models.
- Tells about favorable lorentz structures from combined cosmological+direct detection+collider constraints.
- However in doing so left with fewer channels to probe (by large monojets).
- may be new physics lying in some other channels.
- Simps like EFT's do not respect full gauge symmetry, construction based on gauge invariance $\Rightarrow$ more phenomenological particles hence channels)

Disadvantages of the three frameworks

- EFT: fails to capture the correct momentum dependence, since the assumption $q^2 << m^2$ breaks.
- Simplified model: Broadly 4 s-channel simplified models are considered:

$$\mathcal{L}_{\mathrm{V}} = g_{\mathrm{SM}} \overline{q} \gamma^{\mu} q Z'_{\mu} + g_{\chi} \overline{\chi} \gamma^{\mu} \chi Z'_{\mu} \quad \mathcal{L}_{\mathrm{AV}} = g_{\mathrm{SM}} \overline{q} \gamma^{\mu} \gamma_5 q Z'_{\mu} + g_{\chi} \overline{\chi} \gamma^{\mu} \gamma_5 \chi Z'_{\mu}$$

$$\mathcal{L}_{\mathrm{S}} = \frac{m_q}{v} g_{\mathrm{SM}} \overline{q} q S + g_{\chi} \overline{\chi} \chi S \quad \mathcal{L}_{\mathrm{P}} = \mathrm{i} \frac{m_q}{v} g_{\mathrm{SM}} \overline{q} \gamma_5 q P + \mathrm{i} g_{\chi} \overline{\chi} \gamma_5 \chi P$$

- Captures broad features of several models.
- Tells about favorable lorentz structures from combined cosmological+direct detection+collider constraints.
- However in doing so left with fewer channels to probe (by large monojets).
- may be new physics lying in some other channels.
- Simps like EFT's do not respect full gauge symmetry, construction based on gauge invariance $\Rightarrow$ more phenomenological particles hence channels)

Disadvatanges of three frameworks continued...

- Less simplified models: They are closer to UV complete models, hence phenomenological viable channgels but also more combersome.
- The simplest gauge extensions of pseudoscalar models require – two generations of Higgs doublet along with an additional scalar $\Rightarrow$ 15 free parameters.
- Not all particles lead to significant DM phenomenology. Several assumptions required.

Disadvatanges of three frameworks continued...

- Less simplified models: They are closer to UV complete models, hence phenomenological viable channgels but also more combersome.
- The simplest gauge extensions of pseudoscalar models require – two generations of Higgs doublet along with an additional scalar $\Rightarrow$ 15 free parameters.
- Not all particles lead to significant DM phenomenology. Several assumptions required.

Disadvatanges of three frameworks continued...

- Less simplified models: They are closer to UV complete models, hence phenomenological viable channgels but also more combersome.
- The simplest gauge extensions of pseudoscalar models require – two generations of Higgs doublet along with an additional scalar $\Rightarrow$ 15 free parameters.
- Not all particles lead to significant DM phenomenology. Several assumptions required.

Revisiting the reasons for going to less-simplified models from simplified models

1. Gauge invariance: The requirement of gauge invariance is going to introduce more states and would possibly prevent violation of unitarity i.e. $S^{\dagger}S = I$ in some processes.
   - But the question really is does this lead to violation of unitarity in the processes relevant for our purposes?
   - The ans. is it happens at really large couplings and has very little to do with addition of new states for typical mono-X searches (arXiv: 1604.07579 [hep-ph])
2. More phenomenologically relevant channels:
   - They can be described in a model independent manner if we classify the models on the basis of additional number of relevant mediators + DM particles (S. Banerjee, G. Bélanger, D. Bhatia, B. Fuks and S. Raychaudhuri, JHEP 07, 111 (2022)).

Revisiting the reasons for going to less-simplified models from simplified models

1. Gauge invariance: The requirement of gauge invariance is going to introduce more states and would possibly prevent violation of unitarity i.e. $S^\dagger S = I$ in some processes.
   - But the question really is does this lead to violation of unitarity in the processes relevant for our purposes?
   - The ans. is it happens at really large couplings and has very little to do with addition of new states for typical mono-X searches (arXiv: 1604.07579 [hep-ph])
2. More phenomenologically relevant channels:
   - They can be described in a model independent manner if we classify the models on the basis of additional number of relevant mediators + DM particles (S. Banerjee, G. Bélanger, D. Bhatia, B. Fuks and S. Raychaudhuri, JHEP 07, 111 (2022)).

Revisiting the reasons for going to less-simplified models from simplified models

1. Gauge invariance: The requirement of gauge invariance is going to introduce more states and would possibly prevent violation of unitarity i.e. $S^\dagger S = I$ in some processes.
   - But the question really is does this lead to violation of unitarity in the processes relevant for our purposes?
   - The ans. is it happens at really large couplings and has very little to do with addition of new states for typical mono-X searches (arXiv: 1604.07579 [hep-ph])
2. More phenomenologically relevant channels:
   - They can be described in a model independent manner if we classify the models on the basis of additional number of relevant mediators + DM particles (S. Banerjee, G. Bélanger, D. Bhatia, B. Fuks and S. Raychaudhuri, JHEP 07, 111 (2022)).

Revisiting the reasons for going to less-simplified models from simplified models

1. Gauge invariance: The requirement of gauge invariance is going to introduce more states and would possibly prevent violation of unitarity i.e. $S^\dagger S = I$ in some processes.
   - But the question really is does this lead to violation of unitarity in the processes relevant for our purposes?
   - The ans. is it happens at really large couplings and has very little to do with addition of new states for typical mono-X searches (arXiv: 1604.07579 [hep-ph])
2. More phenomenologically relevant channels:
   - They can be described in a model independent manner if we classify the models on the basis of additional number of relevant mediators + DM particles (S. Banerjee, G. Bélanger, D. Bhatia, B. Fuks and S. Raychaudhuri, JHEP **07**, 111 (2022)).

Revisiting the reasons for going to less-simplified models from simplified models

1. Gauge invariance: The requirement of gauge invariance is going to introduce more states and would possibly prevent violation of unitarity i.e. $S^\dagger S = I$ in some processes.
   - But the question really is does this lead to violation of unitarity in the processes relevant for our purposes?
   - The ans. is it happens at really large couplings and has very little to do with addition of new states for typical mono-X searches (arXiv: 1604.07579 [hep-ph])
2. More phenomenologically relevant channels:
   - They can be described in a model independent manner if we classify the models on the basis of additional number of relevant mediators + DM particles (S. Banerjee, G. Bélanger, D. Bhatia, B. Fuks and S. Raychaudhuri, JHEP **07**, 111 (2022)).

Advatanges of Phenomenological approach:

- Just like Simplified models, we can examine the constraints at LHC based on the well-defined mediators.
- For example, the scalar mediators are heavily constrained using combined constraints for relic + direct-detection.
- Less simplified models necessarily introduce large number of mediators, among which only some mediators can be relevantly compared across different experiments for example. pseudoscalar mediators.

Advatanges of Phenomenological approach:

- Just like Simplified models, we can examine the constraints at LHC based on the well-defined mediators.
- For example, the scalar mediators are heavily constrained using combined constraints for relic + direct-detection.
- Less simplified models necessarily introduce large number of mediators, among which only some mediators can be relevantly compared across different experiments for example. pseudoscalar mediators.

Advatanges of Phenomenological approach:

- Just like Simplified models, we can examine the constraints at LHC based on the well-defined mediators.
- For example, the scalar mediators are heavily constrained using combined constraints for relic + direct-detection.
- Less simplified models necessarily introduce large number of mediators, among which only some mediators can be relevantly compared across different experiments for example. pseudoscalar mediators.

Two mediated pseudoscalar models

- We extend our theoretical framework by considering two pseudoscalar mediators as we saw that the apperance of the atleast a second pseudoscalar is inevitable in the UV completion.
- For simplicity we assume that P_1^0 couples only to SM and P_2^0 couples only to DM.

$$\mathcal{L}^{(0)} \supset -\sum_q \left(\frac{i y_q g_q}{\sqrt{2}} \bar{q}\gamma_5 q \; P_1^0 \right) - i y_\chi \; \bar{\chi}\gamma_5\chi \; P_2^0 \; .$$

Two mediated pseudoscalar models

- We extend our theoretical framework by considering two pseudoscalar mediators as we saw that the apperance of the atleast a second pseudoscalar is inevitable in the UV completion.
- For simplicity we assume that P_1^0 couples only to SM and P_2^0 couples only to DM.

$$\mathcal{L}^{(0)} \supset -\sum_q \left(\frac{i y_q g_q}{\sqrt{2}} \bar{q} \gamma_5 q \; P_1^0 \right) - i y_\chi \; \bar{\chi} \gamma_5 \chi \; P_2^0 \; .$$

Two-mediator dark matter models

- The mass mixings between them leads to effective interactions between the SM and DM sector.

$$\mathcal{L}_{\rm mass} \supset -\sum_q \left(\frac{i y_q g_q}{\sqrt{2}} \cos\theta \; \bar{q}\gamma_5 q \; P_1 \right) - i y_\chi \sin\theta \; \bar{\chi}\gamma_5\chi \; P_1$$
$$+ \sum_q \left(\frac{i y_q g_q}{\sqrt{2}} \sin\theta \; \bar{q}\gamma_5 q \; P_2 \right) - i y_\chi \cos\theta \; \bar{\chi}\gamma_5\chi \; P_2 \; .$$

- The scalar self interactions :

$$\mathcal{L}_{\rm int,2} \supset m_{11} P_2 P_1 H + m_{22} H P_1 P_1 + m_{33} H P_2 P_2 .$$

- Set of free parameters:

$$\left\{ g_q,\; y_\chi,\; \theta,\; m_{P_1},\; m_{P_2},\; m_\chi,\; m_{11},\; m_{22},\; m_{33} \right\}.$$

Two-mediator dark matter models

- The mass mixings between them leads to effective interactions between the SM and DM sector.

$$\mathcal{L}_{\rm mass} \supset -\sum_q \left(\frac{iy_q g_q}{\sqrt{2}} \cos\theta \; \bar{q}\gamma_5 q \; P_1 \right) - iy_\chi \sin\theta \; \bar{\chi}\gamma_5\chi \; P_1$$
$$+ \sum_q \left(\frac{iy_q g_q}{\sqrt{2}} \sin\theta \; \bar{q}\gamma_5 q \; P_2 \right) - iy_\chi \cos\theta \; \bar{\chi}\gamma_5\chi \; P_2 \; .$$

- The scalar self interactions :

$$\mathcal{L}_{\rm int,2} \supset m_{11} P_2 P_1 H + m_{22} H P_1 P_1 + m_{33} H P_2 P_2 .$$

- Set of free parameters:

$$\left\{ g_q, \; y_\chi, \; \theta, \; m_{P_1}, \; m_{P_2}, \; m_\chi, \; m_{11}, \; m_{22}, \; m_{33} \right\}.$$

Two-mediator dark matter models

- The mass mixings between them leads to effective interactions between the SM and DM sector.

$$\mathcal{L}_{\rm mass} \supset \; -\sum_q \left(\frac{i y_q g_q}{\sqrt{2}} \cos\theta \; \bar{q}\gamma_5 q \; P_1 \right) - i y_\chi \sin\theta \; \bar{\chi}\gamma_5 \chi \; P_1$$
$$+\sum_q \left(\frac{i y_q g_q}{\sqrt{2}} \sin\theta \; \bar{q}\gamma_5 q \; P_2 \right) - i y_\chi \cos\theta \; \bar{\chi}\gamma_5 \chi \; P_2 \; .$$

- The scalar self interactions :

$$\mathcal{L}_{\rm int,2} \supset m_{11} P_2 P_1 H + m_{22} H P_1 P_1 + m_{33} H P_2 P_2 .$$

- Set of free parameters:

$$\left\{ g_q, \; y_\chi, \; \theta, \; m_{P_1}, \; m_{P_2}, \; m_\chi, \; m_{11}, \; m_{22}, \; m_{33} \right\}.$$

Two-mediator dark matter models

To make results more accessible, we make following simplifying choices:

- The coupling constant modifiers g_q are assumed to be the same across all generations and for up-type and down-type quarks
- The mixing of the two pseudoscalars is taken maximal, $\theta = \pi/4$.
- $y_\chi = 1$.
- Fix $m_{11} P_2 P_1 H$ by requiring $\Gamma(P_2)/m_{P_2} < 10\%$.
- Similarly, the other trilinears can be fixed using higgs decay to invisibles.
- Essentially we are left with following free parameters:

$$\left\{ g_q,\ m_{P_1},\ m_{P_2},\ m_\chi \right\}.$$

Two-mediator dark matter models

To make results more accessible, we make following simplifying choices:

- The coupling constant modifiers g_q are assumed to be the same across all generations and for up-type and down-type quarks
- The mixing of the two pseudoscalars is taken maximal, $\theta = \pi/4$.
- $y_\chi = 1$.
- Fix $m_{11} P_2 P_1 H$ by requiring $\Gamma(P_2)/m_{P_2} < 10\%$.
- Similarly, the other trilinears can be fixed using higgs decay to invisibles.
- Essentially we are left with following free parameters:

$$\left\{ g_q,\ m_{P_1},\ m_{P_2},\ m_\chi \right\}.$$

Two-mediator dark matter models

To make results more accessible, we make following simplifying choices:

- The coupling constant modifiers g_q are assumed to be the same across all generations and for up-type and down-type quarks
- The mixing of the two pseudoscalars is taken maximal, $\theta = \pi/4$.
- $y_\chi = 1$.
- Fix $m_{11} P_2 P_1 H$ by requiring $\Gamma(P_2)/m_{P_2} < 10\%$.
- Similarly, the other trilinears can be fixed using higgs decay to invisibles.
- Essentially we are left with following free parameters:

$$\left\{ g_q,\ m_{P_1},\ m_{P_2},\ m_\chi \right\}.$$

Two-mediator dark matter models

To make results more accessible, we make following simplifying choices:

- The coupling constant modifiers g_q are assumed to be the same across all generations and for up-type and down-type quarks
- The mixing of the two pseudoscalars is taken maximal, $\theta = \pi/4$.
- $y_\chi = 1$.
- Fix $m_{11} P_2 P_1 H$ by requiring $\Gamma(P_2)/m_{P_2} < 10\%$.
- Similarly, the other trilinears can be fixed using higgs decay to invisibles.
- Essentially we are left with following free parameters:

$$\left\{ g_q,\ m_{P_1},\ m_{P_2},\ m_\chi \right\}.$$

Two-mediator dark matter models

To make results more accessible, we make following simplifying choices:

- The coupling constant modifiers g_q are assumed to be the same across all generations and for up-type and down-type quarks
- The mixing of the two pseudoscalars is taken maximal, $\theta = \pi/4$.
- $y_\chi = 1$.
- Fix $m_{11} P_2 P_1 H$ by requiring $\Gamma(P_2)/m_{P_2} < 10\%$.
- Similarly, the other trilinears can be fixed using higgs decay to invisibles.
- Essentially we are left with following free parameters:

$$\left\{ g_q,\ m_{P_1},\ m_{P_2},\ m_\chi \right\}.$$

Two-mediator dark matter models

To make results more accessible, we make following simplifying choices:

- The coupling constant modifiers g_q are assumed to be the same across all generations and for up-type and down-type quarks
- The mixing of the two pseudoscalars is taken maximal, $\theta = \pi/4$.
- $y_\chi = 1$.
- Fix $m_{11} P_2 P_1 H$ by requiring $\Gamma(P_2)/m_{P_2} < 10\%$.
- Similarly, the other trilinears can be fixed using higgs decay to invisibles.
- Essentially we are left with following free parameters:

$$\left\{ g_q,\ m_{P_1},\ m_{P_2},\ m_\chi \right\}.$$

Phenomenology of the 2-mediator pseudoscalar models

- The most immediate question which we may ask is when is the effect of second pseudoscalar mediator starts to important
- Alternatively what are the cases where we can still describe the analysis using single-mediator models.

Scenarios	Relic density	LHC phenomenology
$m_{P_2} \gg m_{P_1}$	single-mediator case	single-mediator case
$m_{P_2} > m_{P_1}$	single-mediator case	two-mediator case (enhanced mono-Higgs rates)
$m_{P_2} \sim m_{P_1}$	single-mediator case (as effective coupling)	single-mediator case (as effective coupling)

Phenomenology of the 2-mediator pseudoscalar models

- The most immediate question which we may ask is when is the effect of second pseudoscalar mediator starts to important
- Alternatively what are the cases where we can still describe the analysis using single-mediator models.

Scenarios	Relic density	LHC phenomenology
$m_{P_2} \gg m_{P_1}$	single-mediator case	single-mediator case
$m_{P_2} > m_{P_1}$	single-mediator case	two-mediator case (enhanced mono-Higgs rates)
$m_{P_2} \sim m_{P_1}$	single-mediator case (as effective coupling)	single-mediator case (as effective coupling)

Monohiggs

Approach:

- Assumpe BSM contributions to mono-jet production are dominated by the effect of the first mediator (when it can decay into dark matter).
- Find the limit in which other mono-X signatures may become dominant.
- Criteria is set by:

$$\frac{g_q^2 y_\chi^2}{m_{P_2}^2} \leq 0.1 \ \frac{g_q^2 y_\chi^2}{m_{P_1}^2} \quad \text{or} \quad m_{P_2} \geq 3.16 \ m_{P_1} \ ,$$

  This demands the the cs contribution is less than equal to 10%, which easily lies in the theory error regime.
  This also assumes that we are focusing on the case where $m_{P_1,P_2} > 2m_\chi$.
- Both monojet and relic density constraints are then identical to the single mediator case.

Monohiggs

Approach:

- Assumpe BSM contributions to mono-jet production are dominated by the effect of the first mediator (when it can decay into dark matter).
- Find the limit in which other mono-X signatures may become dominant.
- Criteria is set by:

$$\frac{g_q^2 y_\chi^2}{m_{P_2}^2} \leq 0.1 \; \frac{g_q^2 y_\chi^2}{m_{P_1}^2} \quad \text{or} \quad m_{P_2} \geq 3.16 \; m_{P_1} \; ,$$

  This demands the the cs contribution is less than equal to 10%, which easily lies in the theory error regime.
  This also assumes that we are focusing on the case where $m_{P_1, P_2} > 2m_\chi$.
- Both monojet and relic density constraints are then identical to the single mediator case.

Monohiggs

Approach:

- Assumpe BSM contributions to mono-jet production are dominated by the effect of the first mediator (when it can decay into dark matter).
- Find the limit in which other mono-X signatures may become dominant.
- Criteria is set by:

$$\frac{g_q^2 y_\chi^2}{m_{P_2}^2} \leq 0.1 \; \frac{g_q^2 y_\chi^2}{m_{P_1}^2} \quad \text{or} \quad m_{P_2} \geq 3.16 \; m_{P_1} \;,$$

  This demands the the cs contribution is less than equal to 10%, which easily lies in the theory error regime.
  This also assumes that we are focusing on the case where $m_{P_1,P_2} > 2m_\chi$.
- Both monojet and relic density constraints are then identical to the single mediator case.

Monohiggs

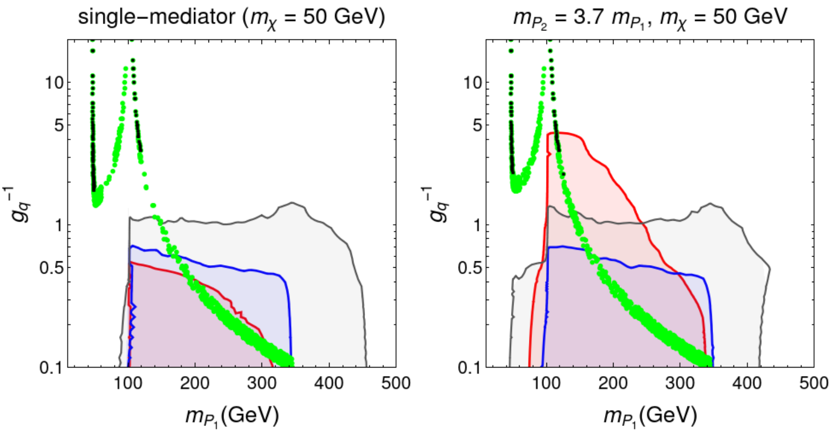
Approach:

- Assumpe BSM contributions to mono-jet production are dominated by the effect of the first mediator (when it can decay into dark matter).
- Find the limit in which other mono-X signatures may become dominant.
- Criteria is set by:

$$\frac{g_q^2 y_\chi^2}{m_{P_2}^2} \leq 0.1 \; \frac{g_q^2 y_\chi^2}{m_{P_1}^2} \quad \text{or} \quad m_{P_2} \geq 3.16 \; m_{P_1} \; ,$$

  This demands the the cs contribution is less than equal to 10%, which easily lies in the theory error regime.
  This also assumes that we are focusing on the case where $m_{P_1,P_2} > 2m_\chi$.
- Both monojet and relic density constraints are then identical to the single mediator case.

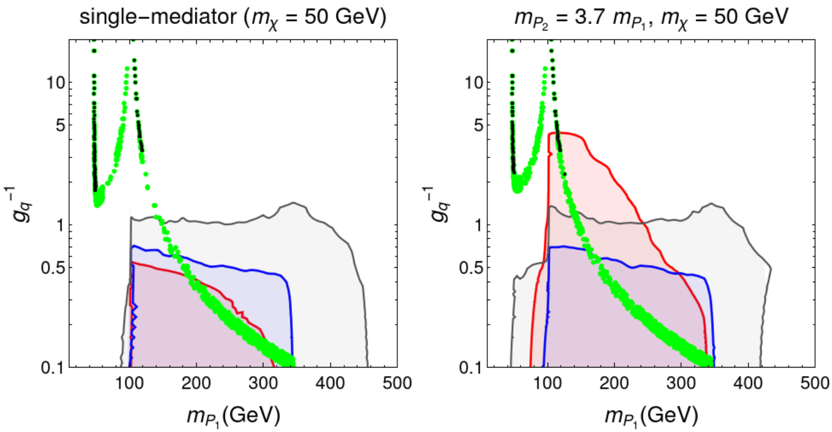
Effect of second mediator



Constraints incorporated:

- relic + indirect
- monohiggs, monojet, tt+met

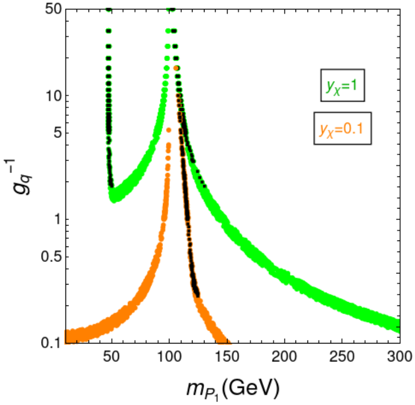
Effect of second mediator



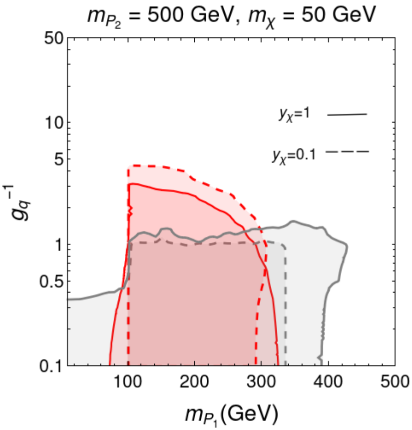
Constraints incorporated:

- relic + indirect
- monohiggs, monojet, tt+met

Effect of yx

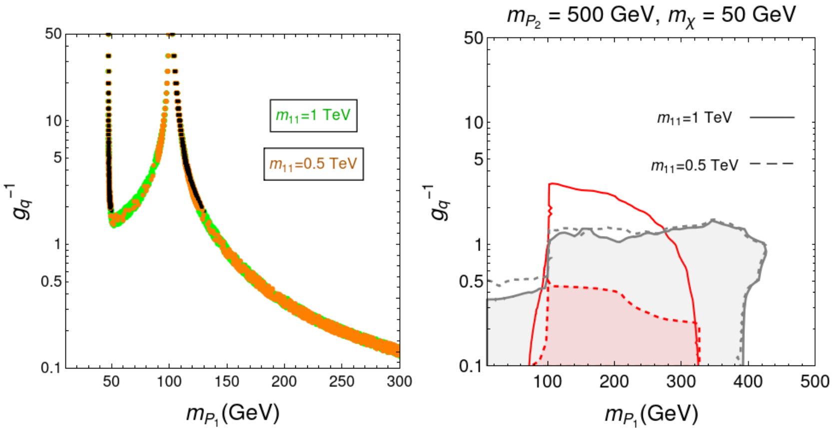


50
10
5
1
0.5
0.1
50
100
150
200
250
300
g_q^{-1}
m_{P_1}(GeV)
y_χ=1
y_χ=0.1

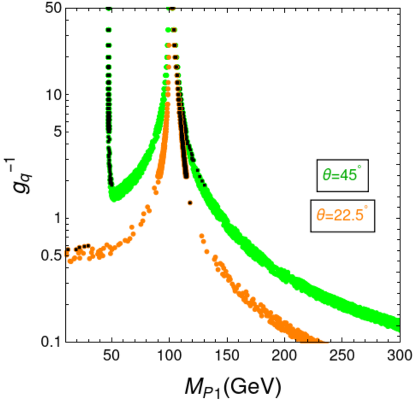


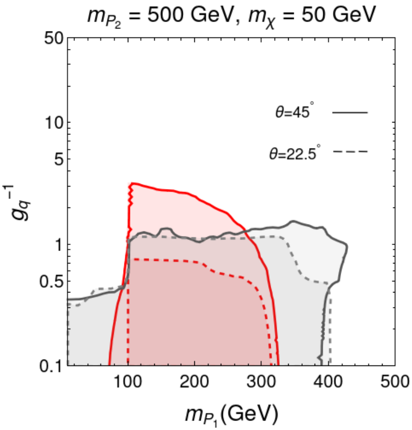
m_{P_2} = 500 GeV, m_χ = 50 GeV
50
10
5
1
0.5
0.1
100
200
300
400
500
g_q^{-1}
m_{P_1}(GeV)
y_χ=1
y_χ=0.1

Effect of m_{11}



Effect of θ





Understanding the results

- The monohiggs constraint does become important even when the monojet and the tt+met are decoupled.
- The total missing momentum can be determined using the Kallen function, and hence missing ET peaks at that.
- In general the constraints weakens after the top threshold is reached.

Understanding the results

- The monohiggs constraint does become important even when the monojet and the tt+met are decoupled.
- The total missing momentum can be determined using the Kallen function, and hence missing ET peaks at that.
- In general the constraints weakens after the top threshold is reached.

Understanding the results

- The monohiggs constraint does become important even when the monojet and the tt+met are decoupled.
- The total missing momentum can be determined using the Kallen function, and hence missing ET peaks at that.
- In general the constraints weakens after the top threshold is reached.

Understanding the results

- Smaller the cs, larger is the relic abundance as delpetion is small. (points above green predict over-abundant DM $\Rightarrow$ ruled out).
- The cs is largely s-wave at leading order away from resonance

$$< \sigma v >_{\mathrm{relic}} \approx < \sigma v >_{\mathrm{indirect}}$$

- Most parameter space below 100 GeV ruled out, since the dominant decay is $b\bar{b}$, excepting near Breit-Wigner where T plays a role.

Understanding the results

- Smaller the cs, larger is the relic abundance as delpetion is small. (points above green predict over-abundant DM $\Rightarrow$ ruled out).
- The cs is largely s-wave at leading order away from resonance

$$< \sigma v >_{\rm relic} \approx < \sigma v >_{\rm indirect}$$

- Most parameter space below 100 GeV ruled out, since the dominant decay is $b\bar{b}$, excepting near Breit-Wigner where T plays a role.

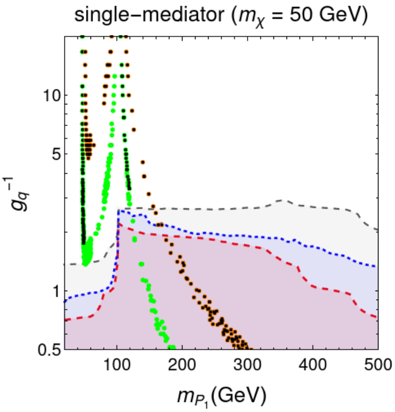
Understanding the results

- Smaller the cs, larger is the relic abundance as delpetion is small. (points above green predict over-abundant DM $\Rightarrow$ ruled out).
- The cs is largely s-wave at leading order away from resonance

$$< \sigma v >_{\rm relic} \approx < \sigma v >_{\rm indirect}$$

- Most parameter space below 100 GeV ruled out, since the dominant decay is $b\bar{b}$, excepting near Breit-Wigner where T plays a role.

Projection of results to higher dark matter mass and luminosities



For dilution scenarios, one is allowed to over-produce DM in the early universe.

Summary:

- We presented the less-simplified models using a more phenomenological description.
- As an example considered a two mediator pseudoscalar model
- This is by large less constrained from the combined constraints of relic+direct detection
- LHC could serve as a potential in by large constraining these models specially for standard cosmologies.

Summary:

- We presented the less-simplified models using a more phenomenological description.
- As an example considered a two mediator pseudoscalar model
- This is by large less constrained from the combined constraints of relic+direct detection
- LHC could serve as a potential in by large constraining these models specially for standard cosmologies.

Summary:

- We presented the less-simplified models using a more phenomenological description.
- As an example considered a two mediator pseudoscalar model
- This is by large less constrained from the combined constraints of relic+direct detection
- LHC could serve as a potential in by large constraining these models specially for standard cosmologies.

Summary:

- We presented the less-simplified models using a more phenomenological description.
- As an example considered a two mediator pseudoscalar model
- This is by large less constrained from the combined constraints of relic+direct detection
- LHC could serve as a potential in by large constraining these models specially for standard cosmologies.