Hunting the dark Higgs.

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based on:
arXiv:1606.07609 and arXiv:1701.08780

in collaboration with:
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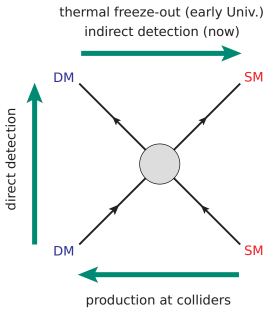
Connecting different DM experiments.



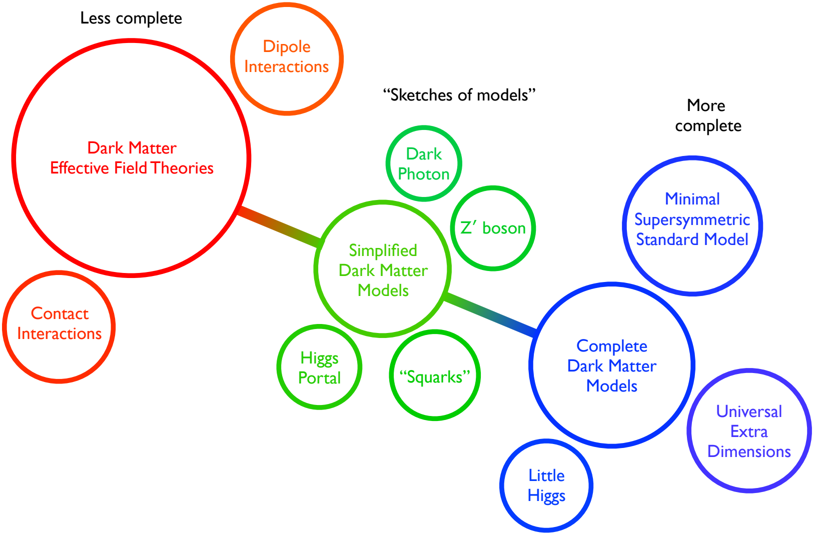
> Top-down approach:

Study well-motivated candidates for DM, obtained in complete models that solve theoretical issues of the SM (e.g., the hierarchy problem).
Most signatures/constraints not related to DM.

> Bottom-up approach:

Add the minimal amount of structure to the SM that is necessary to explain DM.
How simple can these setups be?

Dark matter theory space.



[Worm *et al.*, arXiv:1506.03116]

Spin-1 simplified DM model.

- Fermionic DM χ interacts with SM fermions f via a Z' gauge boson

$$\mathcal{L} \supset -Z'_\mu \bar{\chi}\left(g^V_{\mathrm{DM}}\gamma^\mu + g^A_{\mathrm{DM}}\gamma^\mu\gamma_5\right)\chi - \sum_f Z'_\mu \bar{f}\left(g^V_f\gamma^\mu + g^A_f\gamma^\mu\gamma_5\right)f$$

Questions

- Where does this model come from?
- What's the origin of the masses?
- Are there relations between the couplings?
- Are the results obtained reliable?
- Is SM gauge invariance guaranteed?
- How to find interesting regions of parameter space?
- ...

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Perturbative unitarity in $\chi\chi \to Z'_L Z'_L$ for axial coupling

> Matrix element grows with energy: $\mathcal{M} \propto \frac{\left(g^A_{\text{DM}}\right)^2 \sqrt{s} m_\chi}{m^2_{Z'}}$

> theory only valid up to $\sqrt{s} < \frac{\pi m^2_{Z'}}{\left(g^A_{\text{DM}}\right)^2 m_\chi}$

> New physics below that scale to restore perturbative unitarity

> Use the Higgs mechanism to generate mass of the mediator, break a new $U(1)'$ with the vev of a SM singlet scalar.

Dark matter model with two mediators.

- Majorana DM particle χ and two mediators:
  - massive vector boson Z' and real scalar s
- Natural framework: SM gauge group extended by spontaneously broken $U(1)'$ → generation of mass for χ and Z'
- Interactions of DM and the SM quarks with the mediators:

$$\mathcal{L}_\chi \supset -\frac{g_\chi}{2}\bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu - \frac{y_\chi}{2\sqrt{2}}\bar{\chi}\chi s$$

$$\mathcal{L}_q \supset -\sum_q \left(g_q \bar{q}\gamma^\mu q Z'_\mu + \sin\theta \frac{m_q}{v}\bar{q}q s \right)$$

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- couplings are connected:

$$\frac{y_\chi}{m_\chi} = 2\sqrt{2}\,\frac{g_\chi}{m_{Z'}}$$

- 6 independent parameters:

particle masses		coupling constants	
DM mass	m_χ	dark-sector coupling	g_χ or y_χ
Z' mass	$m_{Z'}$	quark–Z' coupling	g_q
dark Higgs mass	m_s	Higgs mixing angle	θ

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$$\mathcal{L}_q \supset -\sum_q \Big(g_q \bar{q}\gamma^\mu q Z'_\mu + \mathrm{si}\ldots$$

flavor-universal vector couplings to quarks

= baryon number

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The connection to simplified models.

> A combination of different simplified models:

	$g_q \gg \sin\theta$	$g_q \sim \sin\theta$	$\sin\theta \gg g_q$
$m_s \gg m_{Z'}$	Spin-1 mediator simplified model		Spin-0 mediator with spin-1 terminator
$m_{Z'} \sim m_s$		Two-mediator model	
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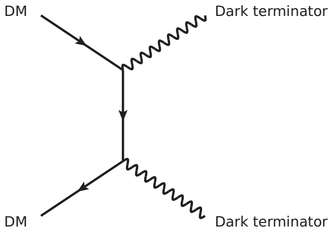

Dark terminator

new final state for DM annihilation

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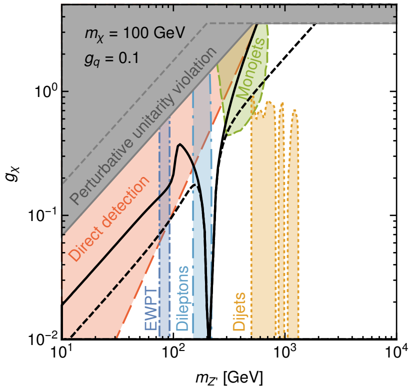
$m_{Z'} \gg m_s$	Spin-1 mediator with spin-0 terminator		Spin-0 mediator simplified model

- Additional effects not present in usual simplified models:
  - The two mediators can interact with each other: leading to processes like $\chi\chi \to Z'^* \to Z's$ or $\chi\chi \to s^* \to Z'Z'$
  - Mixing between the dark Higgs and the SM Higgs: gauge-invariant realisation of simplified model with spin-0 *s*-channel mediator
  - DM stability is a consequence of the gauge symmetry

Spin-1 mediation ($\theta \approx 0$).



- Relic density curve
  - solid: $m_s = 3m_\chi$
  - dashed: $m_s = 0.1m_\chi$

Partial wave perturbative unitarity:

- conditions on couplings and masses
  - from $\chi\chi \to \chi\chi$:

$$g_\chi < \sqrt{4\pi}\,, \qquad y_\chi < \sqrt{8\pi}$$

  - equations can be rewritten in terms of the couplings, e.g.,

$$g_\chi\, m_\chi/m_{Z'} < \sqrt{\pi}$$

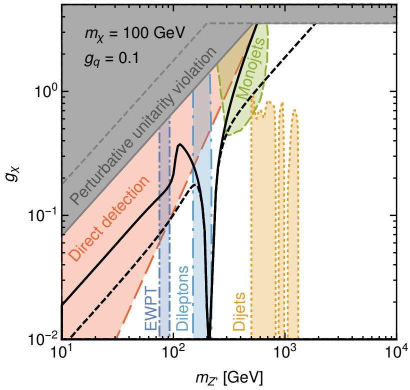
  - from $ss \to ss$ and $hh \to hh$:

$$3(\lambda_h + \lambda_s) \pm \sqrt{9(\lambda_h - \lambda_s)^2 + \lambda_{hs}^2} < 16\pi$$

  - for $\lambda_{hs} = 0$ (no Higgs mixing):

$$m_s < \sqrt{4\pi/3}\, m_{Z'}/g_\chi$$

Spin-1 mediation ($\theta \approx 0$).



> Relic density curve
  > solid: $m_s = 3m_\chi$
  > dashed: $m_s = 0.1m_\chi$

EWPT and Dileptons

> Assumption: tree-level kinetic mixing absent.

> SM quarks are charged under both $U(1)_Y$ and $U(1)'$ and will induce kinetic mixing at loop level:

$$\mathcal{L} = -1/2 \sin\epsilon \, F'^{\mu\nu} B_{\mu\nu}$$

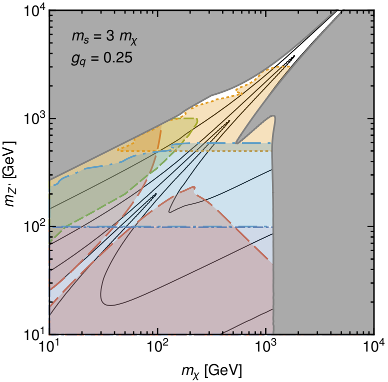
$$\epsilon(\mu) = \frac{e\, g_q}{2\pi^2 \cos\theta_W} \log\frac{\Lambda}{\mu} \simeq 0.02\, g_q \log\frac{\Lambda}{\mu}$$

> kinetic mixing leads to couplings of the Z' to leptons, constrained by dilepton searches at the LHC and the Tevatron

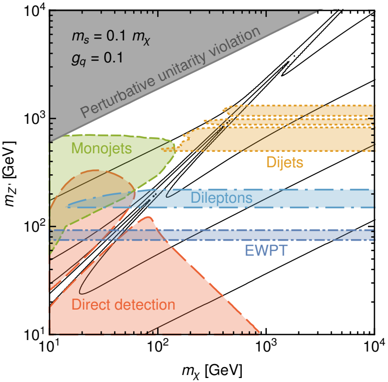
> kinetic mixing also modifies the S and T parameters, which are constrained by EWPT

Spin-1 mediation: results.

- Dark Higgs decoupled (heavy)

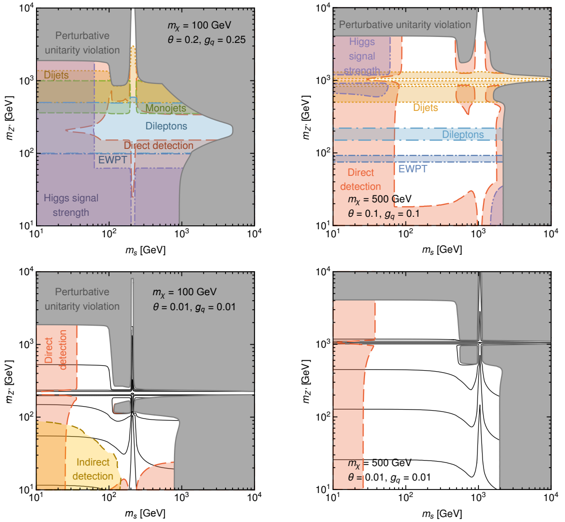


- Dark Higgs terminator (light)



- Dark sector coupling fixed to reproduce observed relic density

Two mediators: results.



> sizeable g_q and $\sin\theta$:

- for $m_\chi = 100\,\mathrm{GeV}$, only small regions close to the resonances remain viable
- for $m_\chi = 500\,\mathrm{GeV}$, larger regions are allowed because s or Z' can be terminators without being strongly constrained

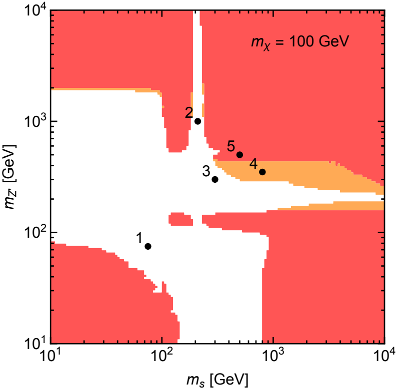
> secluded from the SM:

- region with $m_{Z'}, m_s > m_\chi$ is tightly constrained because annihilations into SM final states cannot reproduce the relic abundance with perturbative couplings
- for $m_{Z'}, m_s < m_\chi$, annihilation into dark terminators typically dominates
- experimental constraints can be suppressed since g_q and θ can be small → difficult to probe
- for small masses, set-up can still be probed by indirect detection

Global scan of couplings: set-up.

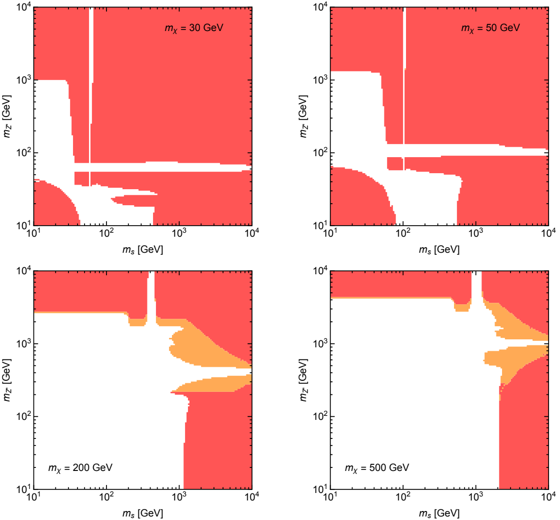
- Scan over g_q and θ for fixed masses, dark sector coupling determined by the relic abundance

- Three categories of mass combinations:
  - Red: all combinations of g_q and θ are excluded by at least one constraint
  - White: at least one combination of g_q and θ is consistent with all constraints
  - Orange: for at least one combination of g_q and θ current constraints do not apply (broad mediator width, $\Gamma_{Z'}/m_{Z'} > 0.3$)



Global scan of couplings: results.

> Scan for different values of m_χ:



> Small DM masses are tightly constrained: only allowed on a resonance or with at least one dark terminator.

> For large DM masses, the inconclusive regions become more important, but heavy mediators still tightly constrained. No constraints from indirect detection.

A light dark Higgs.

- If the dark Higgs s is lighter than the DM χ, the relic abundance can be dominantly set by $\chi\chi \to ss$ (and subsequent decay of s to SM states)
- Relic density dominantly depends on dark sector couplings and couplings to SM particles can be small

How to test such a scenario?

A light dark Higgs.

- If the dark Higgs s is lighter than the DM χ, the relic abundance can be dominantly set by $\chi\chi \to ss$ (and subsequent decay of s to SM states)
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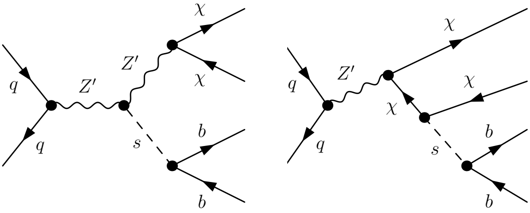
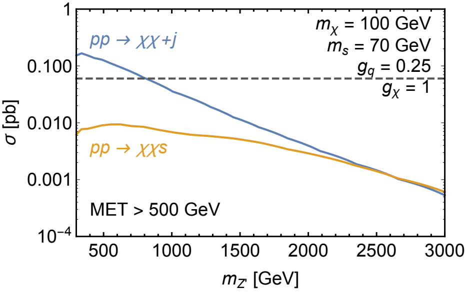
How to test such a scenario?

- A larger dark sector (present in realistic models) will provide a mechanism to produce dark sector states (e.g., via a Z')
- Any dark sector state can radiate off dark Higgs bosons (large couplings in the dark sector!)
- If the dark Higgs is the lightest state in the dark sector, it will decay visibly



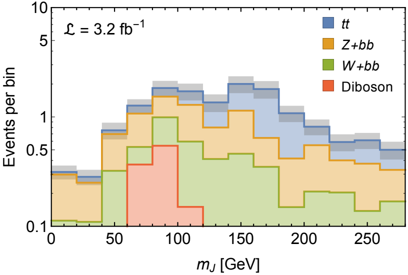
Mono-jet vs. mono-dark-Higgs searches.

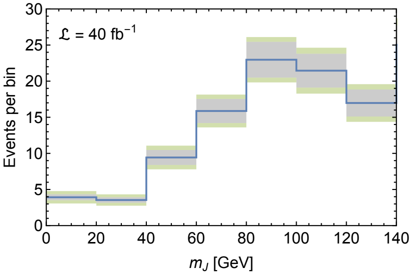


- Heavy Z': cross section for mono-dark-Higgs becomes comparable to the mono-jet signal for $m_{Z'} \geq 2\,\text{TeV}$
- Very characteristic mono-dark-Higgs signal: single fat jet (with invariant mass of the dark Higgs) containing two b jets accompanied by large amounts of missing transverse momentum
  $\Rightarrow$ Better sensitivities can be achieved for mono-dark-Higgs searches through efficient background suppression

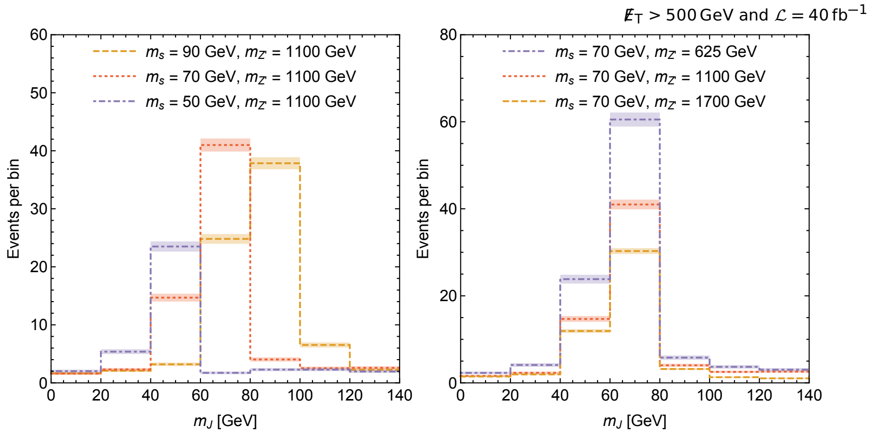
SM backgrounds.

- Event selection (compare mono-Higgs in ATLAS-CONF-2016-019):
  - Fat jet ($R = 1.0$, $p_T > 250\,\text{GeV}$, $\eta < 2.0$) with two associated b-tagged track jets ($R = 0.2$, $p_T > 10\,\text{GeV}$, $\eta < 2.5$)
  - MET $> 500\,\text{GeV}$, no isolated leptons ($p_T > 7\,\text{GeV}$, $\eta < 2.5$)
- Dominant backgrounds:
  - $V + b\bar{b}$ for $m_s < m_h$
  - $t\bar{t}$ for $m_s > m_h$
  - good agreement with ATLAS estimates (moderate rescaling factors)



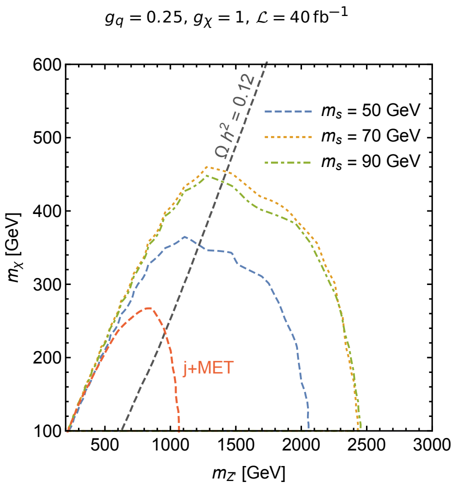


Signal prediction.



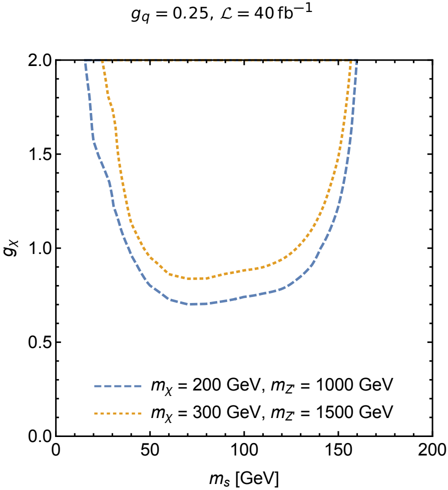
- > Clear peak in the invariant mass of the leading jet close to the mass of the dark Higgs: dark Higgs produced with large transverse momentum and decay products are boosted into a single fat jet
- > striking difference between the shapes of signal and background

Sensitivity results.



- mono-dark-Higgs search can probe regions in parameter space inaccessible to conventional mono-jet searches
- sensitivity almost identical for $m_s = 70\,\text{GeV}$ and $m_s = 90\,\text{GeV}$, extending up to $m_{Z'} = 2.5\,\text{TeV}$ and $m_\chi = 450\,\text{GeV}$
- sensitivity lower for $m_s = 50\,\text{GeV}$: the two b jets merge into a single track jet and dark Higgs tagging efficiency drops rapidly below 50 GeV

Sensitivity results.



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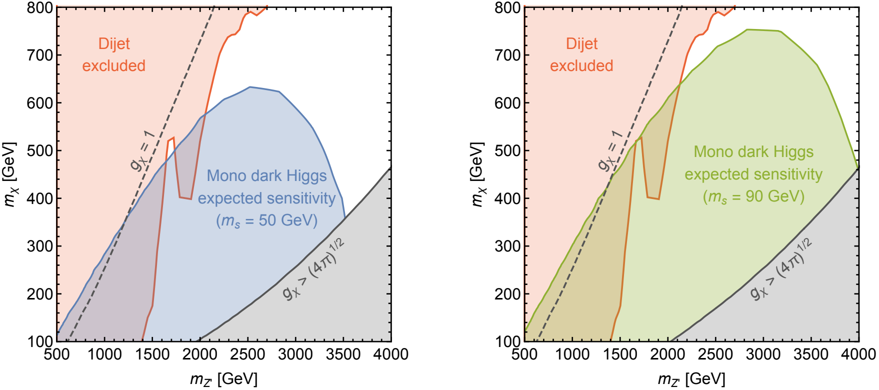
> sensitivity lower for $m_s = 50\,\text{GeV}$: the two b jets merge into a single track jet and dark Higgs tagging efficiency drops rapidly below 50 GeV

Sensitivity for correct DM relic density.

- Before: specific choice of couplings $g_q = 0.25$ and $g_\chi = 1$
- Now: fix dark sector coupling by relic density ($g_q = 0.25$)



- Complementarity between mono-dark-Higgs and di-jet searches

Summary.

- DM models with two mediators as a framework to realize simplified DM models in a theoretically consistent way
- WIMP hypothesis under severe pressure, heavy mediators strongly constrained. Two viable options:
  - DM and mediator masses are tuned close to an *s*-channel resonance
  - One or both mediators are lighter than the DM and open additional parameter space as a dark terminator
- Novel collider signature of DM from the emission of a dark Higgs boson that decays to SM particles through mixing:
  - Characteristic large-radius jet containing two *b*-tagged subjets plus large MET allow for efficient discrimination of signal from background
  - Searches with collected data can probe large regions of parameter space inaccessible to conventional mono-jet or di-jet searches

Backup slides.

Spin-0 simplified DM model.

> Interaction of the scalar S with SM quarks q and DM χ:

$$\mathcal{L} \supset y_\chi \bar{\chi}\chi S + \sum_q \frac{g_q y_q}{\sqrt{2}} \bar{q} q S = y_\chi \bar{\chi}\chi S + \sum_q \frac{g_q y_q}{\sqrt{2}} \left(\bar{q}_L q_R + \bar{q}_R q_L \right) S$$

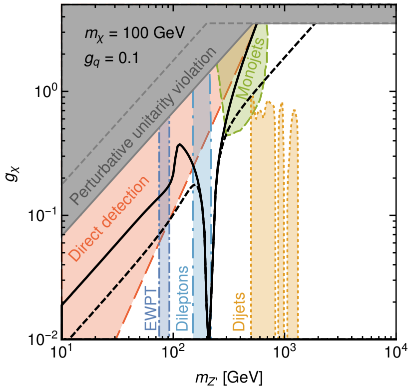
Problems

- gauge invariance: left- and right-handed SM fermions have different $SU(2)_L \otimes U(1)_Y$ charges
- S is a SM singlet: why are terms like $S|H|^2$, $S^2|H|^2$, S^3, S^4 not included although allowed by EW symmetry.

Solution

- Add terms $\mathcal{L} \supset y_\chi \bar{\chi}\chi S + \mu S|H|^2$ to SM Lagrangian
- There is mixing between the SM Higgs and the singlet, resulting in two mass eigenstates h_1 and h_2
- Interaction with the SM quarks through mixing.

Spin-1 mediation ($\theta \approx 0$).



- Relic density curve
  - solid: $m_s = 3m_\chi$
  - dashed: $m_s = 0.1m_\chi$

Direct detection:

- DM–nucleus scattering is suppressed by the DM velocity $\vec{v}$ and the momentum transfer $\vec{q}$:

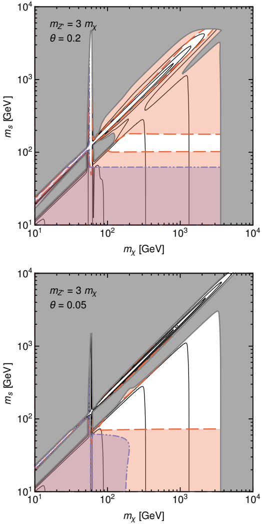
$$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q$$

$$\rightarrow 2\vec{v}^\perp\cdot\vec{S}_\chi + 2i\vec{S}_\chi\cdot\left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$

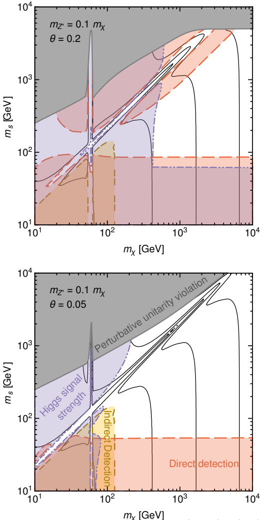
- coherent enhancement of the scattering cross section leads nevertheless to relevant constraints
- recoil spectrum substantially different from standard spin-(in)dependent interactions
- we translate the LUX 2015 results into bound on this interaction

Spin-0 mediation ($g_q \ll 1$).

> Z' decoupled



> Z' terminator



Higgs signal strength

- > Reduction of SM Higgs signal strength:
  - > Mixing reduces SM Higgs production cross section
  - > for $m_\chi < m_h/2$: invisible decays
  - > for $m_s < m_h/2$ or $m_{Z'} < m_h/2$: decays into dark Higgs or Z'
- > $$\mu = \frac{\cos^2\theta\,\Gamma_{\rm SM}}{\Gamma_{\rm SM} + \Gamma_{ss} + \Gamma_{Z'Z'} + \Gamma_{\rm inv}}$$
- > Current bound:

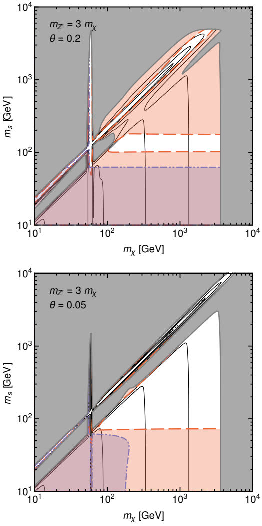
$$\mu > 0.89$$

- > for $\Gamma_{ss} = \Gamma_{Z'Z'} = \Gamma_{\rm inv} = 0$:

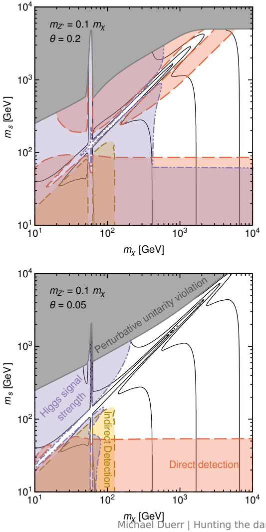
$$\theta < 0.34$$

Spin-0 mediation ($g_q \ll 1$).

> Z' decoupled



> Z' terminator



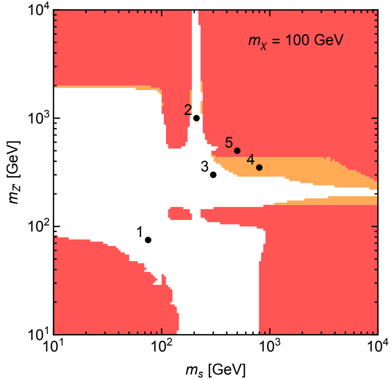
Direct detection

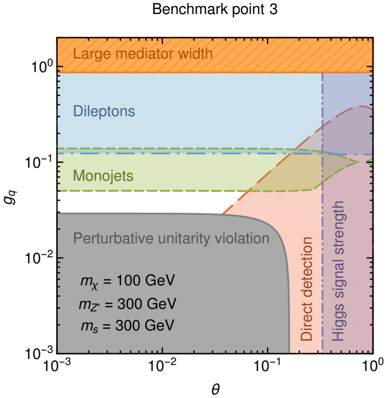
- the scalar mediators induce unsuppressed spin-indep. DM–nucleus interactions

Indirect detection

- $\chi\chi \to sZ'$ is dominantly s-wave, and dominates thermal freeze-out when kinematically allowed
- Then, observable indirect detection signals may be obtained from cascade annihilations
- Relevant constraints can be set using FermiLAT observations of MW dwarf spheroidals for $m_{Z'}, m_s < m_\chi \lesssim 100\,\text{GeV}$

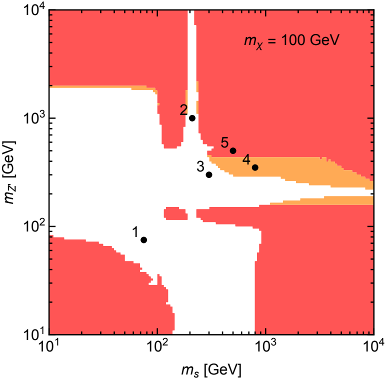
Global scan of couplings: benchmark 3.

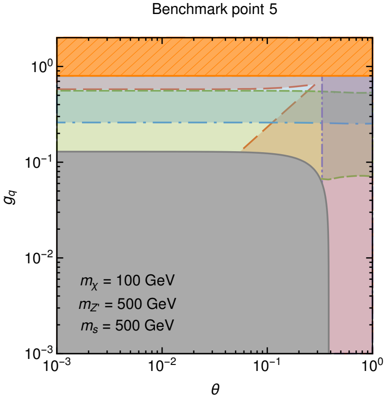




> Parameter point allowed for $g_q \approx 0.04$ and small θ

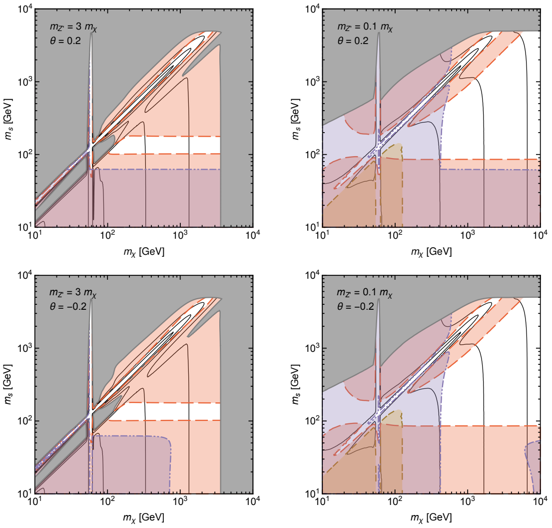
Global scan of couplings: benchmark 5.





> A combination of all constraints rules out this parameter point

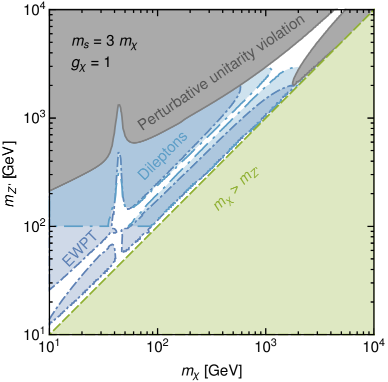
Spin-0 mediation: negative mixing angle.



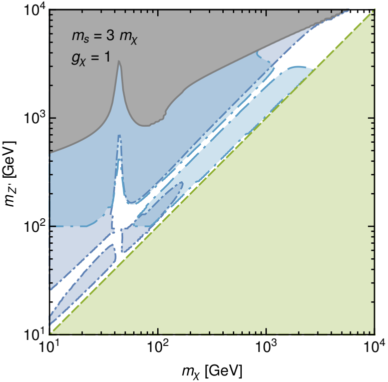
- Sign of θ relevant for trilinear vertices between the SM Higgs and the dark Higgs.
- Considering $\theta < 0$ modifies the prediction for $h \rightarrow ss$, hence the bound from the Higgs signal strength is significantly relaxed for $m_s < m_h/2$
- However, this parameter region is independently excluded by direct detection experiments (not sensitive to the sign of θ).
- Relic density calculation not significantly affected by the sign of θ
- Effect is smaller for smaller values of $|\theta|$

Tree-level kinetic and mass mixing.

> Kinetic mixing ϵ



> Axial couplings

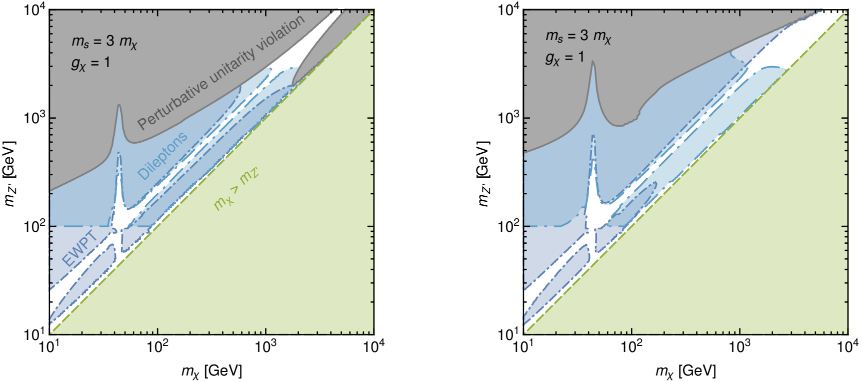


- Mass mixing can be realized if the SM Higgs is charged under the $U(1)'$. This leads to axial couplings of the Z' to SM fermions.
- ϵ (left) and g_q^A (right) are varied for the correct relic abundance.

Tree-level kinetic and mass mixing.

> Kinetic mixing ϵ

> Axial couplings



> Only possible for resonant enhancement from the Z or the Z'.

Cut flow for signal and background.

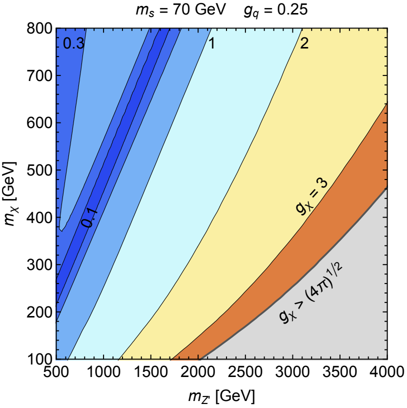
$m_\chi = 100\,\text{GeV}$, $m_s = 70\,\text{GeV}$, $g_q = 0.25$, $g_\chi = 1$, $\not{E}_T > 500\,\text{GeV}$ and $\mathcal{L} = 40\,\text{fb}^{-1}$

	$p_T(j_1) > 250\,\text{GeV}$	Dark Higgs tagged	$40\,\text{GeV} \leq m_J \leq 80\,\text{GeV}$
Background	14063 ± 790	193 ± 21	25.3 ± 3.4
$m_{Z'} = 0.5\,\text{TeV}$	5015 + 363	124	88.6
$m_{Z'} = 1\,\text{TeV}$	1448 + 274	88.4	60.5
$m_{Z'} = 2\,\text{TeV}$	158 + 116	39.1	27.6

- Dark Higgs tagging and exploitation of the shape of the m_J distribution are crucial to reduce background
- Background reduction by 99.8 %, signal efficiency up to 20 %
- signal to background ratio of 3.5 ($m_{Z'} = 0.5\,\text{TeV}$), 2.4 ($m_{Z'} = 1\,\text{TeV}$), 1.1 ($m_{Z'} = 2\,\text{TeV}$)

Reproducing the DM relic abundance.

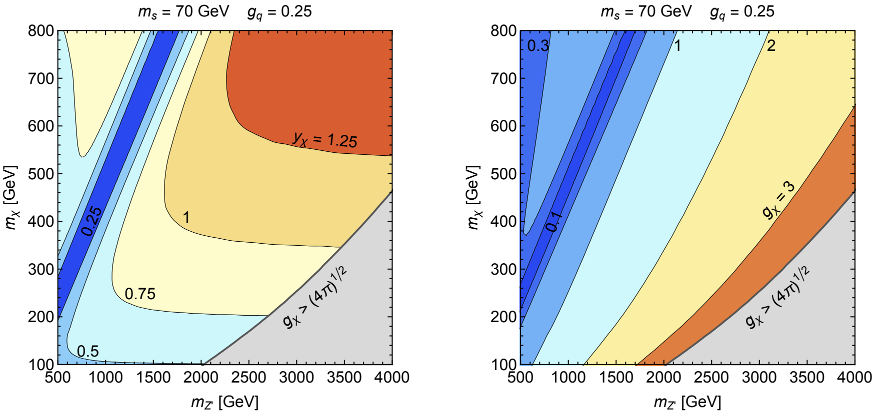
> Fix dark sector coupling by DM relic abundance



- Larger Z' masses require larger g_χ
- This changes sensitivities of the various searches in a non-trivial way:
  - parameter space bounded by the requirement of perturbativity of the couplings
  - signal rates larger than for fixed couplings
  - suppression of dijet sensitivity due to larger invisible branching ratio

Reproducing the DM relic abundance.

> Fix dark sector coupling by DM relic abundance



> Relation between couplings: $g_\chi = \dfrac{m_{Z'}}{m_\chi} \dfrac{y_\chi}{2\sqrt{2}}$

Background rescaling.

- Validation of our background prediction with ATLAS mono-Higgs analysis (ATLAS-CONF-2016-019)
- Signal region: MET > 500 GeV and 80 GeV $\leq m_J \leq$ 280 GeV
- Good shape agreement but underestimation of number of predicted events
- Scale factors between 1.6 to 2.1 depending on background

	$t\bar{t}$	$W + b\bar{b}$	$Z + b\bar{b}$	Diboson
Simulation	2.83 ± 0.12	1.16 ± 0.06	2.42 ± 0.07	0.56 ± 0.02
ATLAS prediction	4.83 ± 0.88	2.48 ± 0.71	3.80 ± 0.44	1.20 ± 0.12
Rescaling factor	1.7 ± 0.3	2.1 ± 0.6	1.6 ± 0.2	2.1 ± 0.2