Dark Matter and the LHC

Why we need realistic simplified models for collider searches

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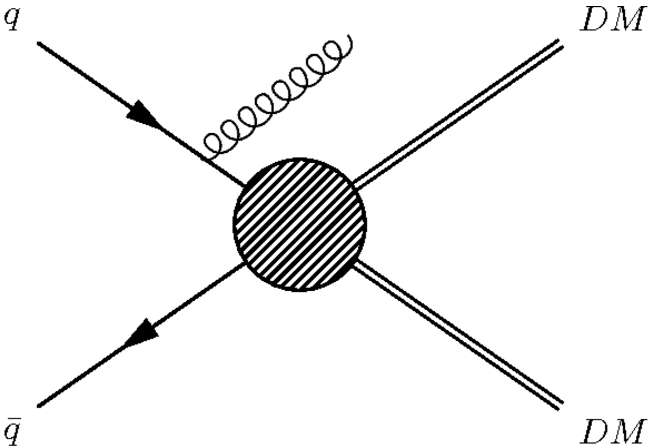
Outline

How can we search for dark matter at the LHC?

LHC and Dark Matter

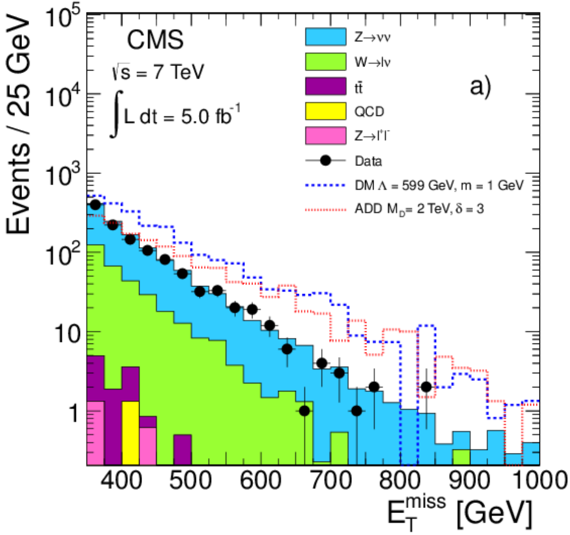
- experimentally very challenging environment with huge backgrounds
- dark matter does not interact with detector
- only one observable directly connected to dark matter: missing transverse energy E_{miss}^{T}
- only SM source of E_{miss}^{T}: neutrinos
- two options:
  - dark matter part of new sector, look for signs of mediators
  - more model independent look for E_{miss}^{T} and something (jet, photon, Z, ...)
    $\hookrightarrow$ let's try to follow this line of thought for now

Monojets



plot stolen from CMS

High energy tail of monojet events



What does an excess (the absence of an excess) of events tell us?

average physicist: not much

We need:

- framework for interpretation of LHC searches
- framework for interpretation of different experiments
- provide guide to relevant regions of the parameter space
- ...

$\hookrightarrow$ models for dark matter at the LHC

General BSM models

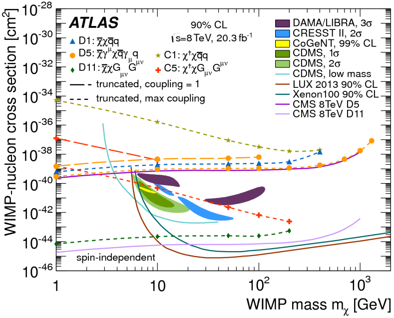
- many models for BSM physics at the weak scale can easily accommodate dark matter
  - Supersymmetry: many different potential dark matter candidates (neutralino, gravitino, ...)
  - extra dimensions: Kaluza-Klein dark matter ...
- these models offer well motivated candidates, everything is calculable, many experimental signatures
- **BUT**: most of the experimental signatures and/or theoretical constraints are not related to DM properties

Model independent interpretation: EFT

new physics is heavy $\rightarrow$ Fermi-like theory for DM?

$$\mathcal{L} = \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$$

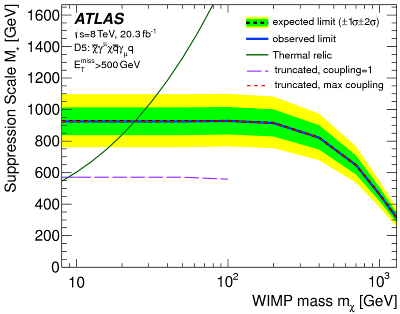
- $\mathcal{O}(10)$ possible operators
- some operators only generated by loops
- very few parameters (m_{DM} , Λ)
- easy comparison with other observables



Model independent interpretation:EFT

$$\frac{g_{DM} g_q}{q^2 - M^2} \rightarrow \frac{g_{DM} g_q}{M^2} + \mathcal{O}(q^2/M^2) + \ldots$$

- expansion relies on $q < M$
- typical momentum transfer: $q = \mathcal{O}(100 \text{ GeV})$
- typical excluded scale: $M = \mathcal{O}(100 \text{ GeV})$



$\Rightarrow$ **unreliable**

Not quite as model independent interpretation: Simplified models

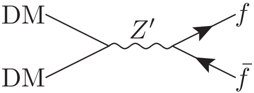
- if new physics is not very heavy we have to keep those particles to capture the phenomenology
  $\Rightarrow$ keep dark matter particle and the mediator(s) between dark matter and the Standard Model
- possible ways to think about this:
  - simplification of more complex UV model
  - could be a viable model in itself (dark matter connected to SM by $U(1)_{\text{B-L}}$ etc)
- substantial number of possibilities:
  scalar dark matter, fermionic dark matter, vector dark matter, scalar mediators, fermionic mediators ...

see "Report of the ATLAS/CMS Dark Matter Forum", 1507.00966 [160 pp.]

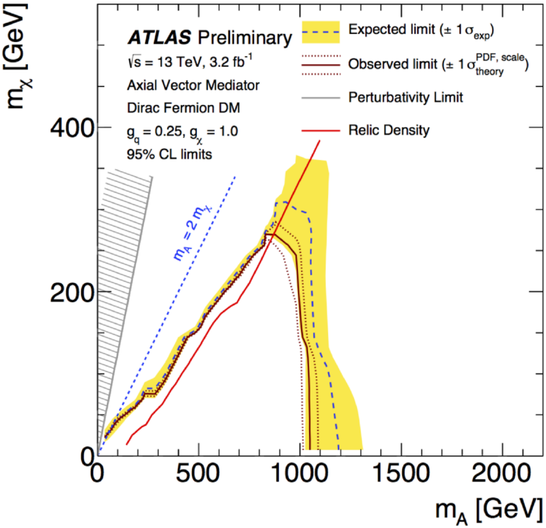
S-channel vector mediator

- fermionic dark matter interacts with SM fermions via a Z' boson

$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\,\bar{f}\left[g_f^V\gamma_\mu + g_f^A\gamma_\mu\gamma^5\right] f - Z'^{\mu}\,\bar{\psi}\left[g_{\rm DM}^V\gamma_\mu + g_{\rm DM}^A\gamma_\mu\gamma^5\right]\psi\,.$$



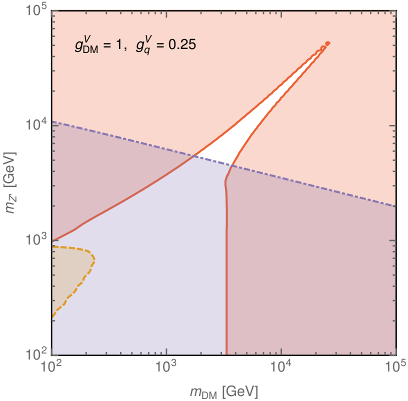
LHC benchmark models



- ATLAS and CMS report limits on this benchmark model

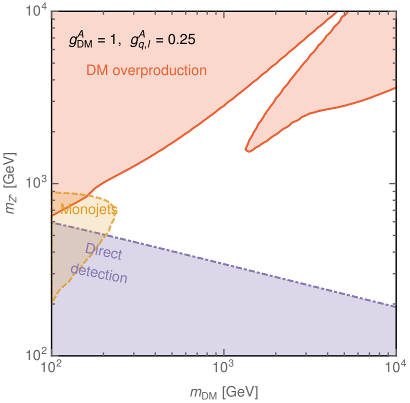
Simplified phenomenology: vector interactions

- spin-independent direct detection cross section
- LHC monojet search not competitive
- thermal dark matter under pressure



Simplified phenomenology: axial interactions

- spin-dependent direct detection
- LHC monojet search complementary
- substantial parameter space for thermal dark matter



Z' mediators: more questions

fermionic dark matter interactions with SM fermions are mediated by a Z' boson

$$\mathcal{L} = - \sum_{f=q,l,\nu} Z'^{\mu} \, \bar{f} \left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5 \right] f - Z'^{\mu} \, \bar{\psi} \left[g_{\mathrm{DM}}^V \gamma_\mu + g_{\mathrm{DM}}^A \gamma_\mu \gamma^5 \right] \psi \, .$$

- Are results obtained in simplified model reliable?
- Where does this model come from?
- Are there relations between different couplings/parameters?
- which parts of parameter space are favored for thermal dark matter
- ...

Let's get out the toolbox

Perturbative Unitarity

- we know from SM that massive vector boson lead to issues with unitarity
- partial wave analysis of the amplitude

$$\mathcal{M}_{if}^{J}(s) = \frac{1}{32\pi}\beta_{if}\int_{-1}^{1} \mathrm{d}\cos\theta \, d_{\mu\mu'}^{J}(\theta)\,\mathcal{M}_{if}(s,\cos\theta)$$

with β_{if} : kinematical factor and $d_{\mu\mu'}^{J}(\theta)$: Wigner d-function

- perturbative unitarity requires

$$0 \leq \mathrm{Im}(\mathcal{M}_{ii}^{J}) \leq 1\,, \quad \left|\mathrm{Re}(\mathcal{M}_{ii}^{J})\right| \leq \frac{1}{2}\,.$$

- check validity of model

DM side: self scattering

- longitudinal component of vector couples proportional to $g_A^f m_f / m_{Z'}$
- leads to a constant matrix element independent of s
- perturbative unitarity is violated unless

$$m_f \lesssim \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_f^A}$$

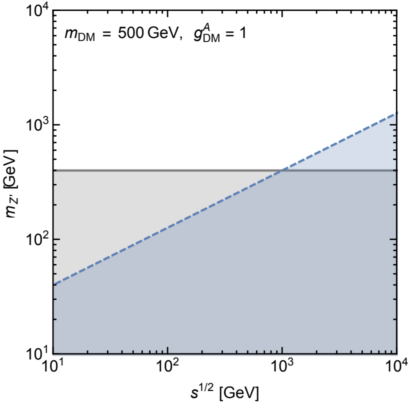
- DM can not be arbitrary heavy compared to mediator (or is arbitrarily weakly coupled)

DM side: DM DM $\to Z'Z'$

- even worse: matrix element diverges in high energy limit

$$\mathcal{M} \propto \frac{(g^A_{\rm DM})^2 \sqrt{s}\, m_{\rm DM}}{m^2_{Z'}}$$

- theory only valid up to scale $\sqrt{s} < \frac{\pi\, m^2_{Z'}}{(g^A_{\rm DM})^2\, m_{\rm DM}}$
- thermal dark matter typically requires $g^A_{\rm DM}$ of $\mathcal{O}(1) \Rightarrow$ dangerous $\sqrt{s}$ typically low
- need new physics to unitarize vector boson



A dark Higgs

- need to restore perturbative unitarity ⇒ Higgs mechanism
- break $U(1)'$ with scalar singlet S
- Lagrangian is given by (Majorana dark matter)

$$\mathcal{L}_{\rm DM} = \frac{i}{2}\bar{\psi}\partial\!\!\!/\psi - \frac{1}{2}g^A_{\rm DM}Z'^\mu\bar{\psi}\gamma^5\gamma_\mu\psi - \frac{1}{2}y_{\rm DM}\bar{\psi}(P_L S + P_R S^*)\psi\,,$$

$$\mathcal{L}_S = \left[(\partial^\mu + i\,g_S\,Z'^\mu)S\right]^\dagger\left[(\partial_\mu + i\,g_S\,Z'_\mu)S\right] + \mu_s^2\,S^\dagger S - \lambda_s\left(S^\dagger S\right)^2$$

side remark: vector interaction don't generate these problems ($m_{Z'}$ from Stueckelberg mechanism) but phenomenology boring (excluded)

A look at the SM side: gauge invariance

- fermionic dark matter interactions with SM fermions mediated by Z' boson

$$\mathcal{L} = - \sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f} \left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5 \right] f - Z'^{\mu}\, \bar{\psi} \left[g_{\rm DM}^V \gamma_\mu + g_{\rm DM}^A \gamma_\mu \gamma^5 \right] \psi \,.$$

- looks fine but:

$$g_f^V = \frac{1}{2} g' (q_{f_R} + q_{f_L}) \,, \quad g_f^A = \frac{1}{2} g' (q_{f_R} - q_{f_L})$$

- general Z' couplings break SM gauge invariance (SM Yukawa terms)

SM side: gauge invariance

- need a consistent picture for $SU(2) \times U(1) \times U(1)'$ breaking

$$g_f^A = \frac{1}{2} g'(q_{f_R} - q_{f_L}) \text{ breaks gauge invariance}$$
$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L} \text{ restores it}$$

- leads to following Lagrangian:

$$\mathcal{L}'_{\rm SM} = - \sum_{f=q,\ell,\nu} g' \, Z'^{\mu} \, \left[q_{f_L} \, \bar{f}_L \gamma_\mu f_L + q_{f_R} \, \bar{f}_R \gamma_\mu f_R \right]$$
$$+ \left[(D^\mu H)^\dagger (-i \, g' \, q_H \, Z'_\mu \, H) + \text{h.c.} \right] + g'^2 \, q_H^2 \, Z'^\mu Z'_\mu \, H^\dagger H$$

This is a simple solution, not a unique solution!

Anomalies

- we do not specify additional particles which cancel anomalies
- there is no color anomaly

$$A_{ggZ'} = 3(2q_{q_L} - q_{u_R} - q_{d_R}) = 0 \;\text{ for }\; q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L}$$

- no new colored states
- expect that new states do not modify phenomenology

Implications for Phenomenology

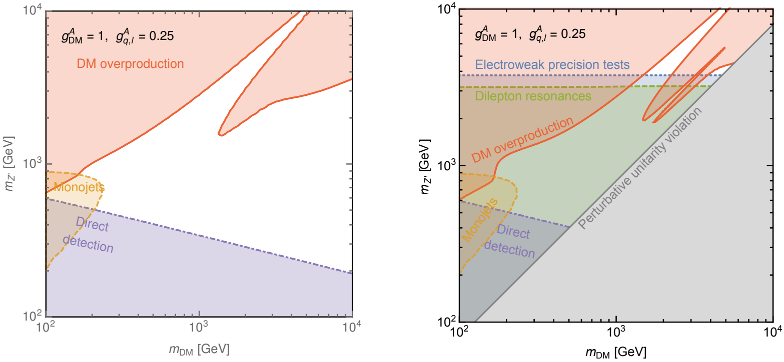
$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

- Z' interacts with all generations of quarks and with **leptons**
  $\Rightarrow$ stringent constraints from searches for dilepton resonances
- off-diagonal mass term $\delta m^2 Z^\mu Z'_\mu$ with

$$\delta m^2 = \frac{1}{2} \frac{e\, g'\, q_H}{s_\mathrm{W}\, c_\mathrm{W}} v^2$$

  $\Rightarrow$ constraints from electroweak precision tests
- not all $g_q^V = 0$ at the same time
  in the following we assume couplings just to right handed fields

Spot the difference: axial(DM)-axial(SM)

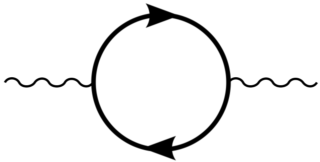


- stringent constraints from EWPTs and dilepton resonance
- substantial part of parameter space inconsistent
- modified thermal expectation

What about vector couplings to the SM?

Kinetic mixing

- kinetic mixing $-\frac{1}{2}\sin\epsilon F'^{\mu\nu}B_{\mu\nu}$ allowed at tree level
- quarks charged under $U(1)_Y$ and $U(1)'$ generate kinetic mixing at 1-loop

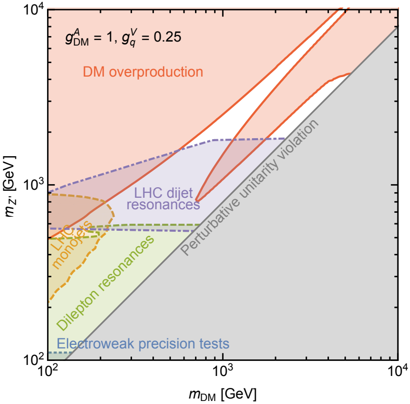


- expect:

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

Limit on loop induced kinetic mixing

- relevant limits from loop induced coupling to leptons
- di-jet resonance
- different searches complementary



Coupling structure

- Vector(DM)–Vector(SM)
  - UV-complete, no new degrees of freedom necessary
  - stringent constraints from spin-independent direct detection

Axial(SM/DM) couplings require new physics

- Vector(DM)–Axial(SM)
  - simple gauge invariant models: Axial(SM) $\Rightarrow$ Axial(SM)+Vector(SM)
  - new stringent constraints from spin-independent direct detection
- Axial(DM)–Axial(SM)+Vector(SM)
  - mass mixing between Z and Z' (EWPT)
  - universal axial coupling $\Rightarrow$ stringent constraints from dilepton searches
- Axial(DM)–Vector(SM)
  - least constrained scenario
  - kinetic mixing at loop level expected

Coupling structure wrap up

- Vector(DM)–Vector(SM)
  - UV-complete, no new degrees of freedom necessary
  - stringent constraints from spin-independent direct detection

Axial(SM/DM) couplings require new physics

- Vector(DM)–Axial(SM)
  - simple gauge invariant models: Axial(SM) $\Rightarrow$ Axial(SM)+Vector(SM)
  - new stringent constraints from spin-independent direct detection
- Axial(DM)–Axial(SM)+Vector(SM)
  - mass mixing between Z and Z' (EWPT)
  - universal axial coupling $\Rightarrow$ stringent constraints from dilepton searches
- Axial(DM)–Vector(SM)
  - least constrained scenario
  - kinetic mixing at loop level expected

Let's take a look under this rock

Where is thermal dark matter?

The two mediator model

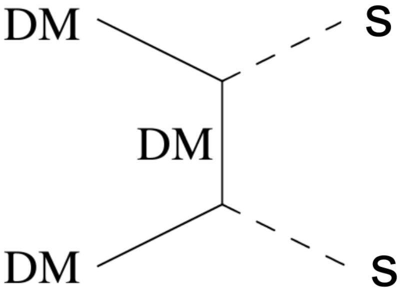
- 3 particles ⇒ 3 masses: m_χ, $m_{Z'}$ and m_S
- one dark sector coupling g_χ or y_χ (one fixed $U(1)'$ breaking)
- vector coupling of quarks to Z' g_q
- mixing between SM and dark Higgs: θ

$$\Rightarrow 6 \text{ parameters}$$

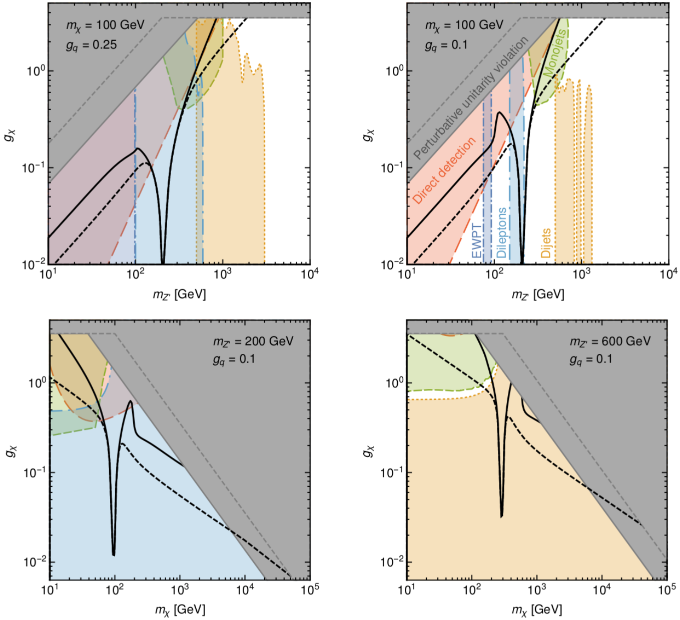
- just two new parameters

Possible cases

- one mediator heavy and weakly coupled: reduces to standard simplified model
- mass and interaction strength comparable: true two mediator model
- one mediator light: relic density potentially set by new final states



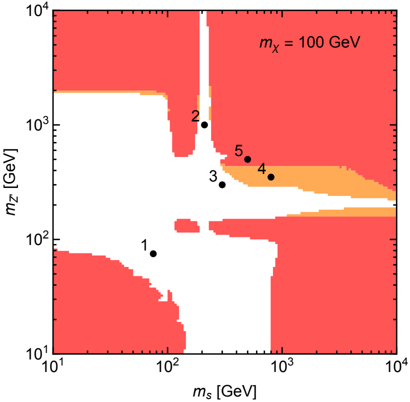
Slicing the parameter space



Global scan

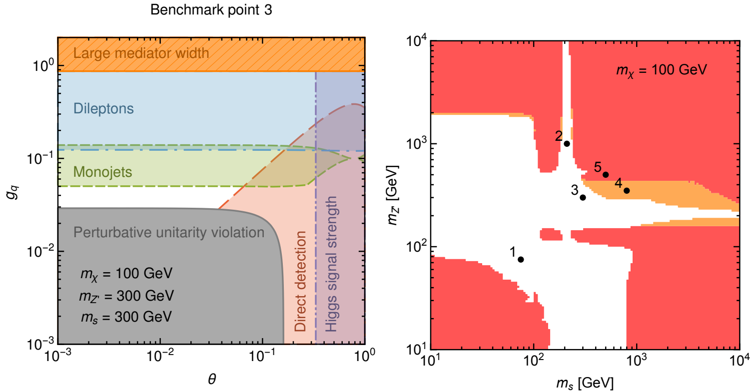
scan g_q and θ $\rightarrow$ determine thermal value for g_{DM}

- all values of g_q and θ $\rightarrow$ are excluded by at least one experiment or perturbative unitarity
- there is at least one unstrained combination
- there is at least one unexcluded combination for which the applicability of LHC constraints can not be guaranteed (broad resonance)



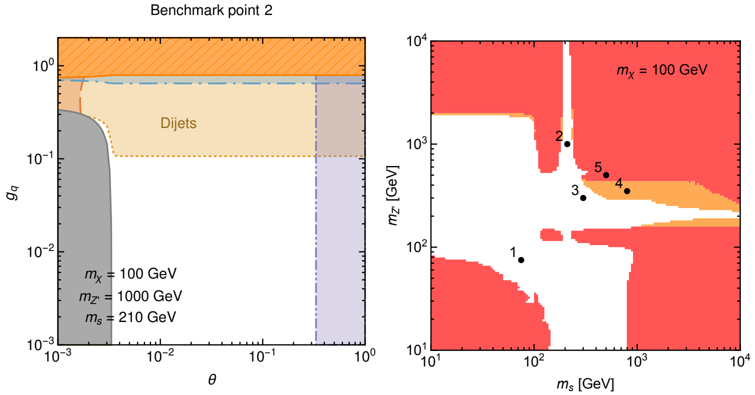
Benchmark 3: "classic" WIMP

Warning: g_χ is allowed to change



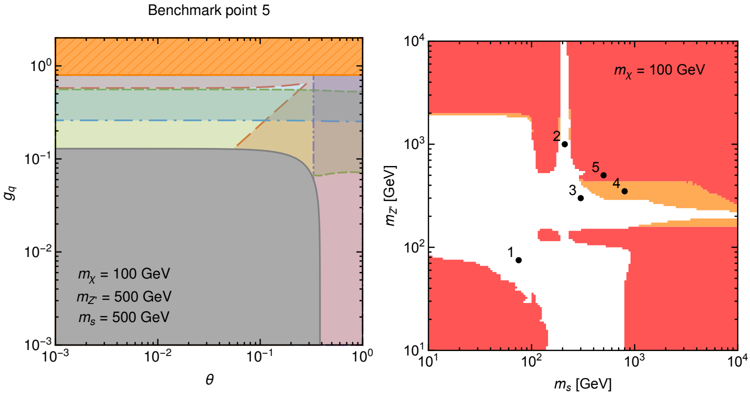
allowed parameter space for small g_q and θ

Benchmark 2: resonant annihilations



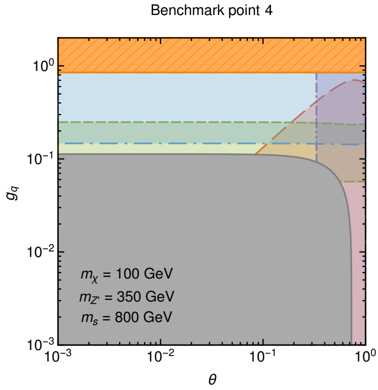
resonant annihilations

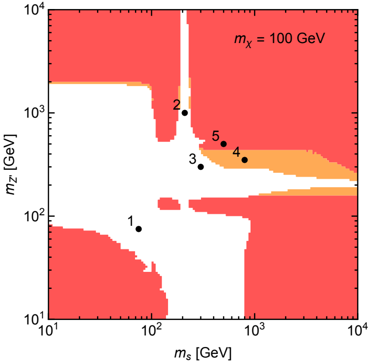
Benchmark 5: heavy mediators



combination of all searches exclude this point

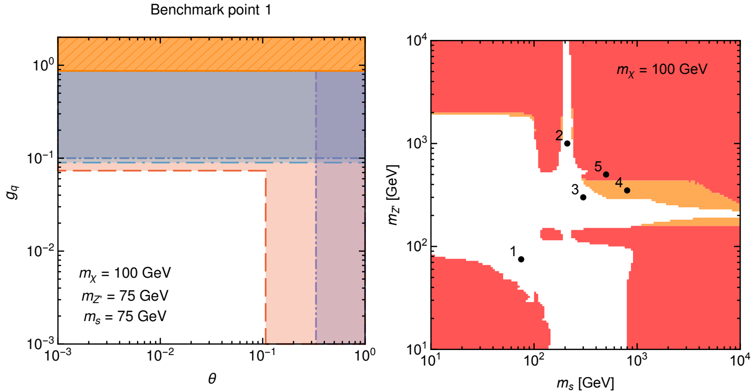
Benchmark 4: broad resonances





potentially allowed if dijet search not applicable

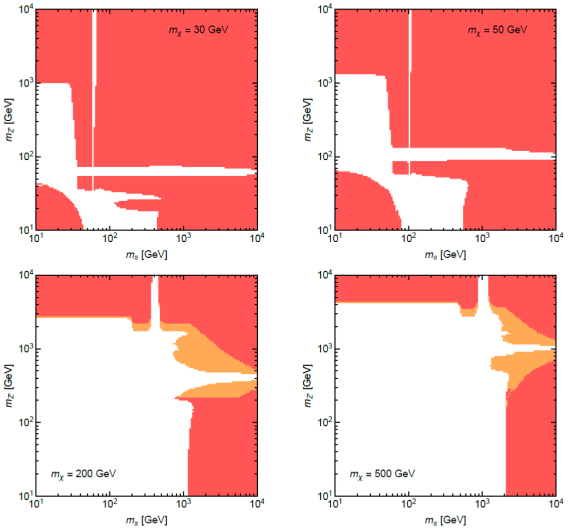
Benchmark 1: light mediators



"secluded" dark matter from annihilations into $Z's$ final states
small couplings allowed

Global picture

- light DM very constrained: resonant annihilation or at least one light mediator
- heavy DM: slightly more space and regions with broad resonances



Outlook

- heavy mediators already very constrained
- annihilation to light mediators/ resonant annihilations are hard to probe
- potential ways forward
  - non standard Higgs decays $H \to ss$ or $H \to Z'Z'$
  - mono-dark-Higgs production from dark Higgs Strahlung

$$q\bar{q} \to Z'^{*} \to Z's$$

  or final state radiation

$$q\bar{q} \to Z' \to \chi\chi \to \chi\chi s$$

  - indirect detection with next generation instruments (CTA)
    side remark: Galactic center excess can be accommodated

Conclusion

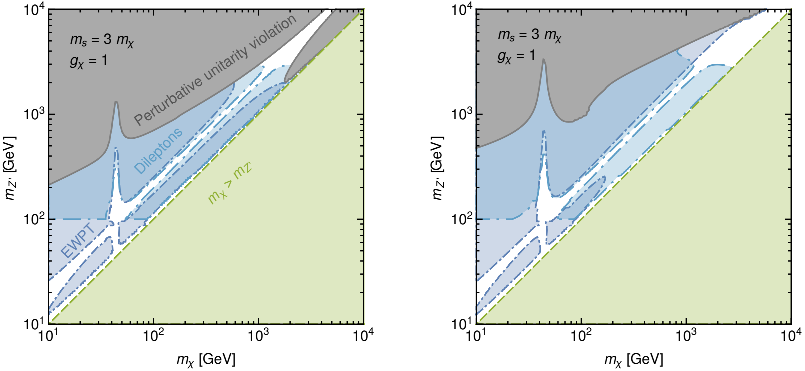
- simplified models are a useful tool for DM/collider phenomenology
- "naive" simplified models can violate gauge invariance and perturbative unitarity
- interpretation needs care
- realistic models lead to powerful new signatures
- LHC, direct and indirect detection constrain thermal dark matter severely
- two mediator model opens new parameter space for thermal dark matter

Backup material

Kinetic mixing and axial couplings

Couplings which can not account for thermal dark matter

- axial coupling for SM fermions (EWPT and dilepton resonance!)
- tree level kinetic mixing



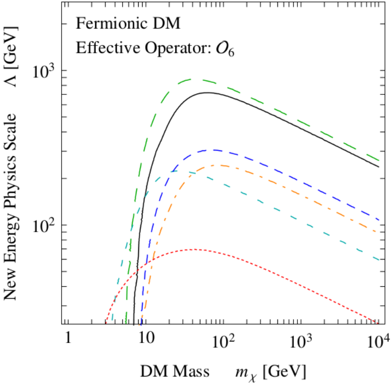
Will not consider these in the following

Velocity suppressed direct detection

- $\mathcal{L} = \chi\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$ leads to velocity dependent interactions in non-relativistic limit

$$\mathcal{L}_{AV} \approx \mathcal{L}_{VV} \times \vec{v} \cdot \vec{s}_\chi$$

- current direct detection limits are strong enough to constrain operator despite suppression



Cirelli, Del Nobile, Panci, 2013