On the way to the Dark Matter Simplified Models for Run-2

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GRAPPA
GRavitation AstroParticle Physics Amsterdam

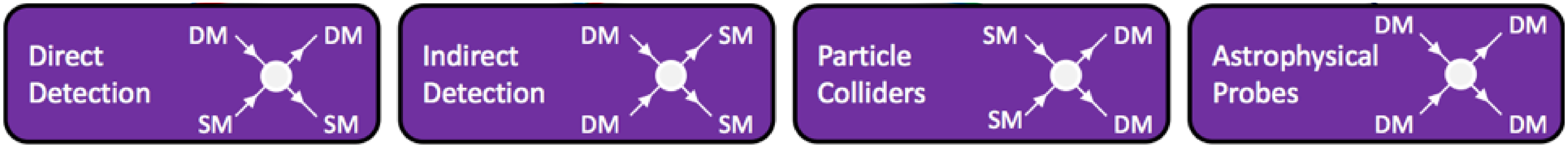
From Higgs to Dark Matter 2014
Geilo, Norway
14 - 17 December 2014

Two recent white papers

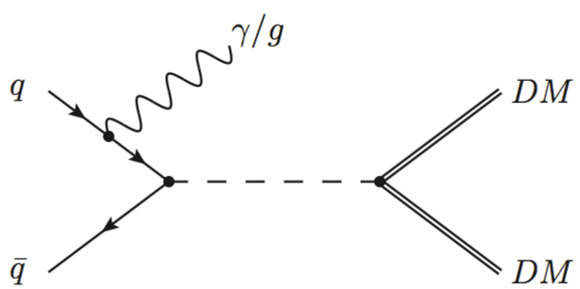
Simplified Models for Dark Matter and Missing Energy Searches at the LHC
Jalal Abdallah, Adi Ashkenazi, Antonio Boveia, Giorgio Busoni, Andrea De Simone, Caterina Doglioni, Aielet Efrati, Erez Etzion, Johanna Gramling, Thomas Jacques, Tongyan Lin, Enrico Morgante, Michele Papucci, Bjoern Penning, Antonio Walter Riotto, Thomas Rizzo, David Salek, Steven Schramm, Oren Slone, Yotam Soreq, Alessandro Vichi, Tomer Volansky, Itay Yavin, Ning Zhou, Kathryn Zurek
http://arxiv.org/abs/1409.2893

Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection Experiments
Sarah A. Malik, Christopher McCabe, Henrique Araujo, Alexander Belyaev, Celine Boehm, Jim Brooke, Oliver Buchmueller, Gavin Davies, Albert De Roeck, Kees de Vries, Matthew J. Dolan, John Ellis, Malcolm Fairbairn, Henning Flaecher, Loukas Gouskos, Valentin V. Khoze, Greg Landsberg, Dave Newbold, Michele Papucci, Timothy Sumner, Marc Thomas, Steven Worm
http://arxiv.org/abs/1409.4075

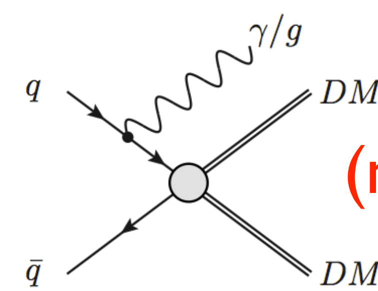
Contact interactions



- Contact interactions (dimension-6 operator) form a simple framework for the description of the collider and astro-particle experimental results and were widely used in Run-1 by both ATLAS and CMS.



$Q^2_{\rm tr} \ll M^2 \sim \Lambda^2$

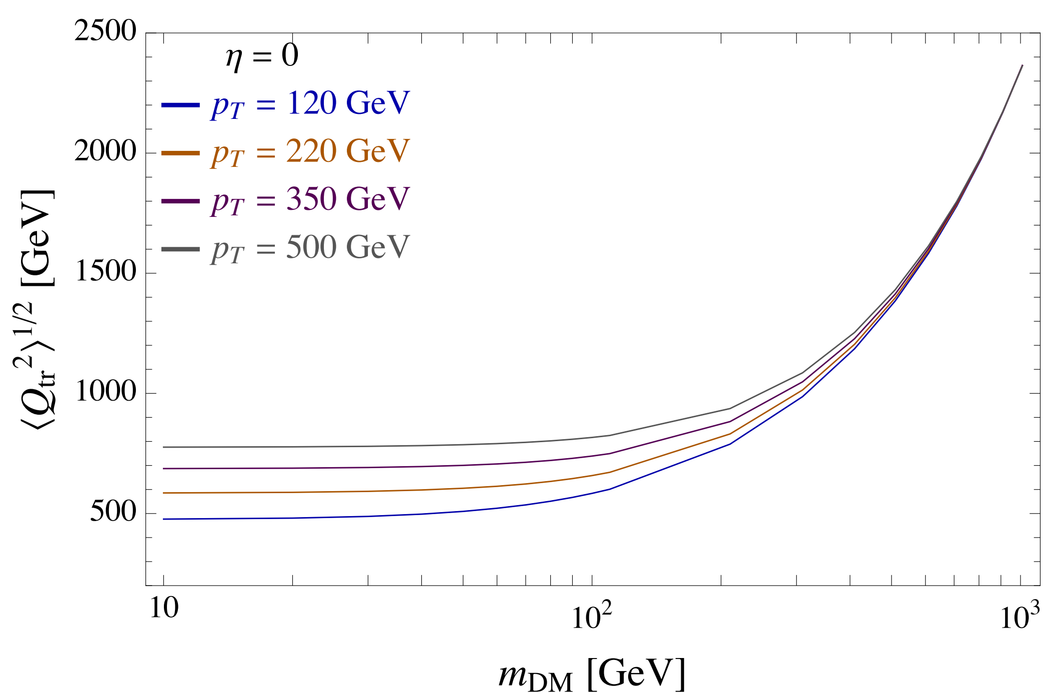


EFT has two parameters (m_{DM} and suppression scale Λ)

$$\frac{1}{Q^2_{\rm tr} - M^2} = -\frac{1}{M^2}\left(1 + \frac{Q^2_{\rm tr}}{M^2} + \mathcal{O}\left(\frac{Q^4_{\rm tr}}{M^4}\right)\right)$$

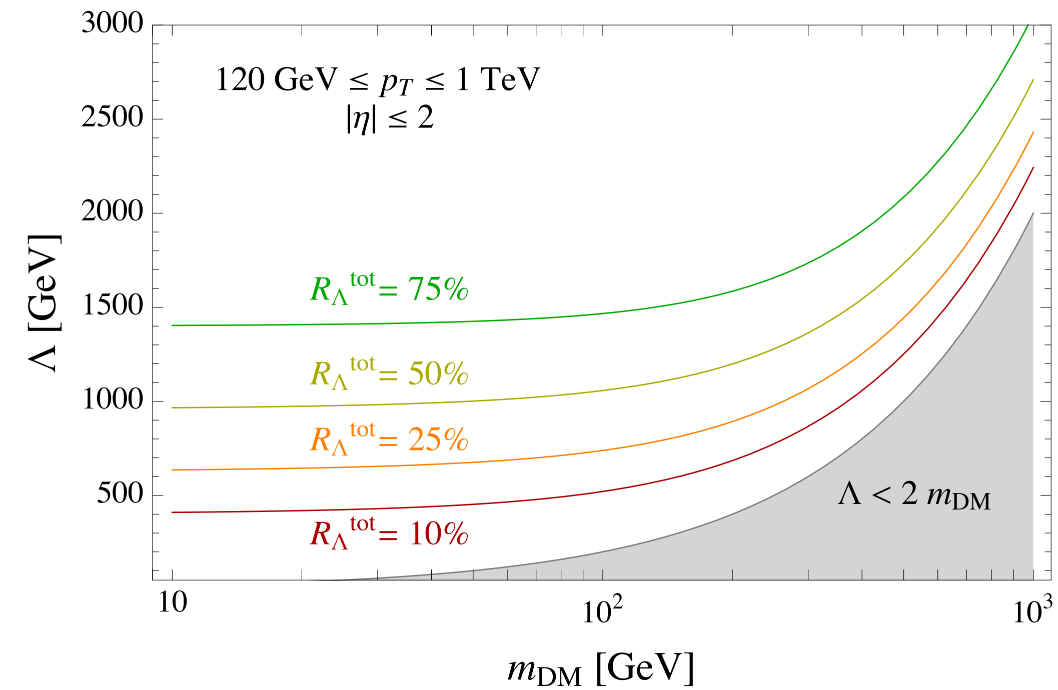
$$\mathcal{O}_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q) \qquad \frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$$

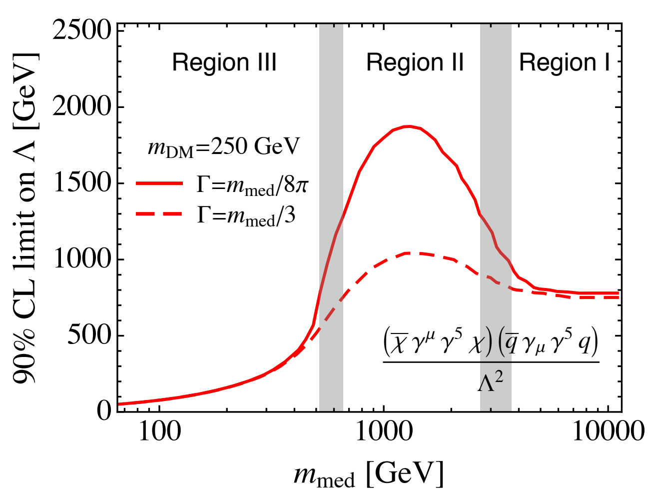
- It is safe to use EFT when the mediator can be integrated out.
- However, at the LHC energies, the limits on the suppression scale are comparable to the momentum transfer!

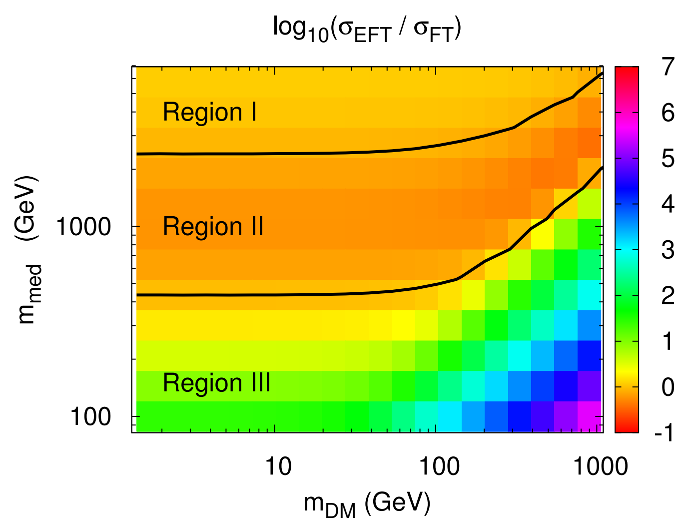


EFT validity

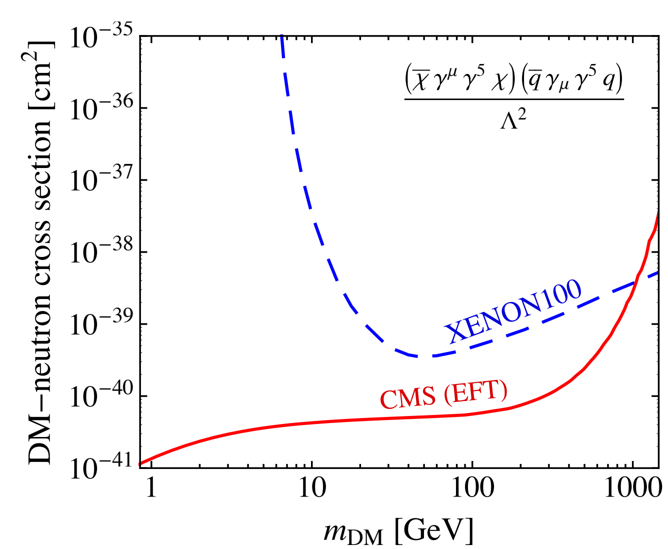
- ratio of valid events $R_\Lambda^{\rm tot} \equiv \frac{\sigma_{\rm eff}|_{Q_{\rm tr}<\Lambda}}{\sigma_{\rm eff}}$
- The collider limits do not satisfy the EFT validity condition.
- How do the EFT limits compare to the limits from s-channel models with light mediators?

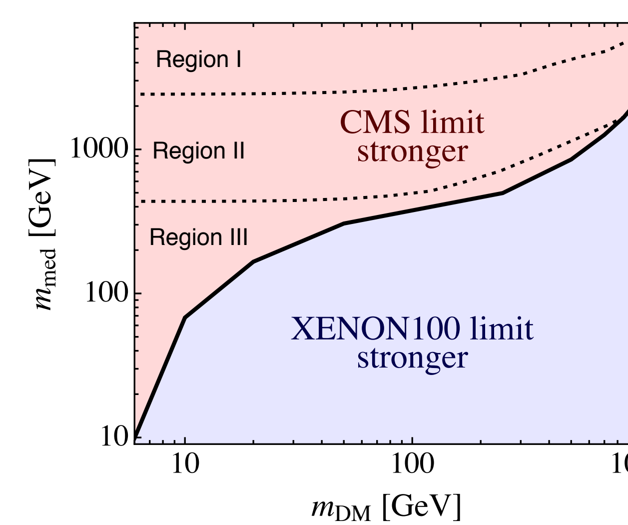






- EFT limits are aggressive in region III, DD limits are stronger at low DM and mediator masses!





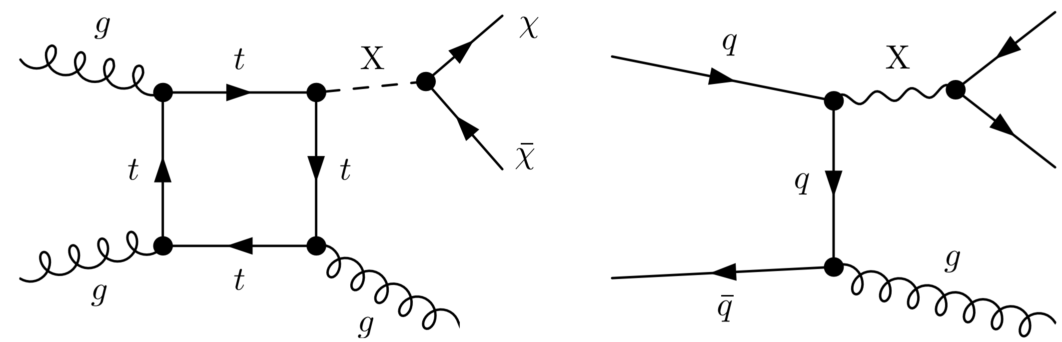
s-channel simplified models

$$\mathcal{L}_{\rm scalar} \supset -\frac{1}{2}m^2_{\rm MED}S^2 - g_{\rm DM}S\,\bar\chi\chi - g^t_{SM}S\,\bar t t - g^b_{SM}S\,\bar b b\,,$$

$$\mathcal{L}_{\rm pseudo-scalar} \supset -\frac{1}{2}m^2_{\rm MED}P^2 - g_{\rm DM}P\,\bar\chi\gamma^5\chi - g^t_{SM}P\,\bar t\gamma^5 t - g^b_{SM}P\,\bar b\gamma^5 b\,,$$

$$\mathcal{L}_{\rm vector} \supset \frac{1}{2}m^2_{\rm MED}Z'_\mu Z'^\mu - g_{\rm DM}Z'_\mu\bar\chi\gamma^\mu\chi - \sum_q g^q_{SM}Z'_\mu\bar q\gamma^\mu q\,,$$

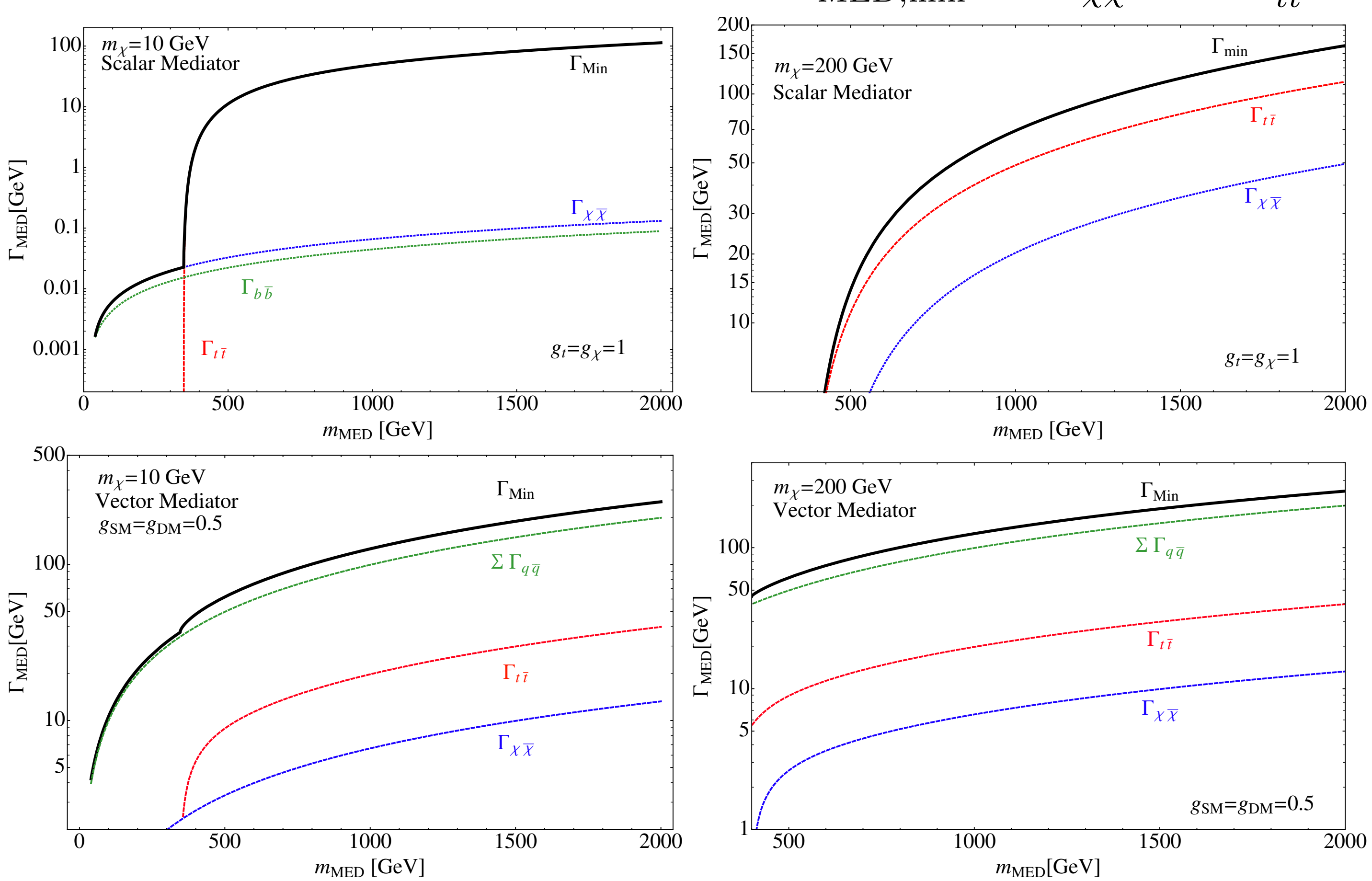
$$\mathcal{L}_{\rm axial} \supset \frac{1}{2}m^2_{\rm MED}Z''_\mu Z''^\mu - g_{\rm DM}Z''_\mu\bar\chi\gamma^\mu\gamma^5\chi - \sum_q g^q_{SM}Z''_\mu\bar q\gamma^\mu\gamma^5 q\,.$$

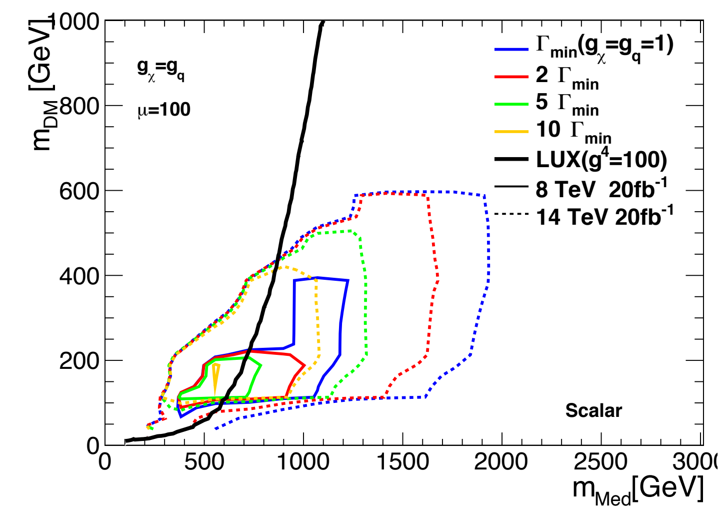


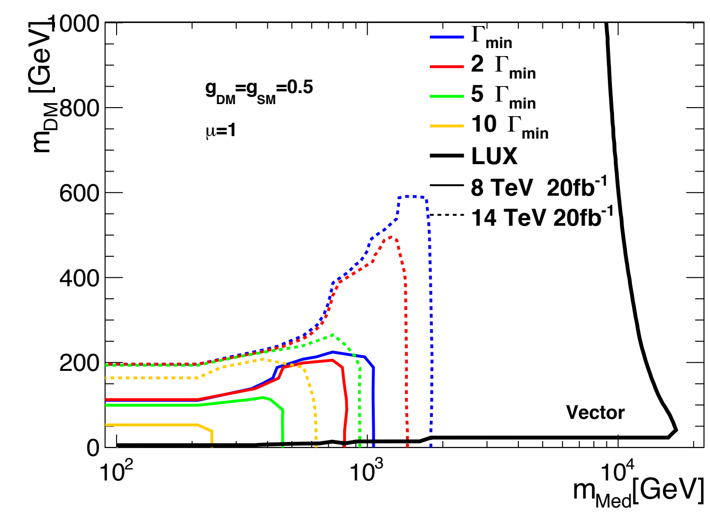
- Yukawa couplings are taken proportional to the Higgs Yukawa couplings.
- minimal mediator width

$$\Gamma^{V,A}_{\rm MED,min} = \Gamma^{V,A}_{\chi\bar\chi} + \sum_{i=1}^{N_f} N_c\Gamma^{V,A}_{q_i\bar q_i} + N_c\Gamma^{V,A}_{t\bar t}$$

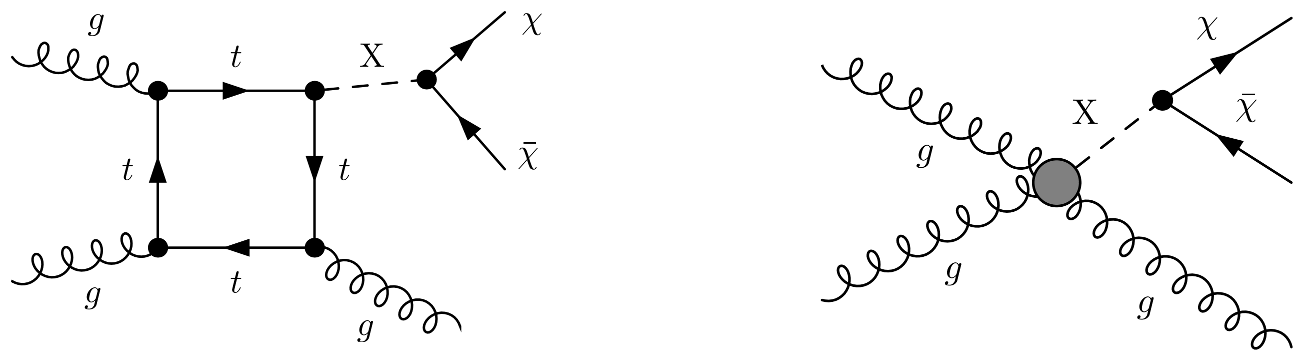
$$\Gamma^{S,P}_{\rm MED,min} = \Gamma^{S,P}_{\chi\bar\chi} + N_c\Gamma^{S,P}_{t\bar t}$$





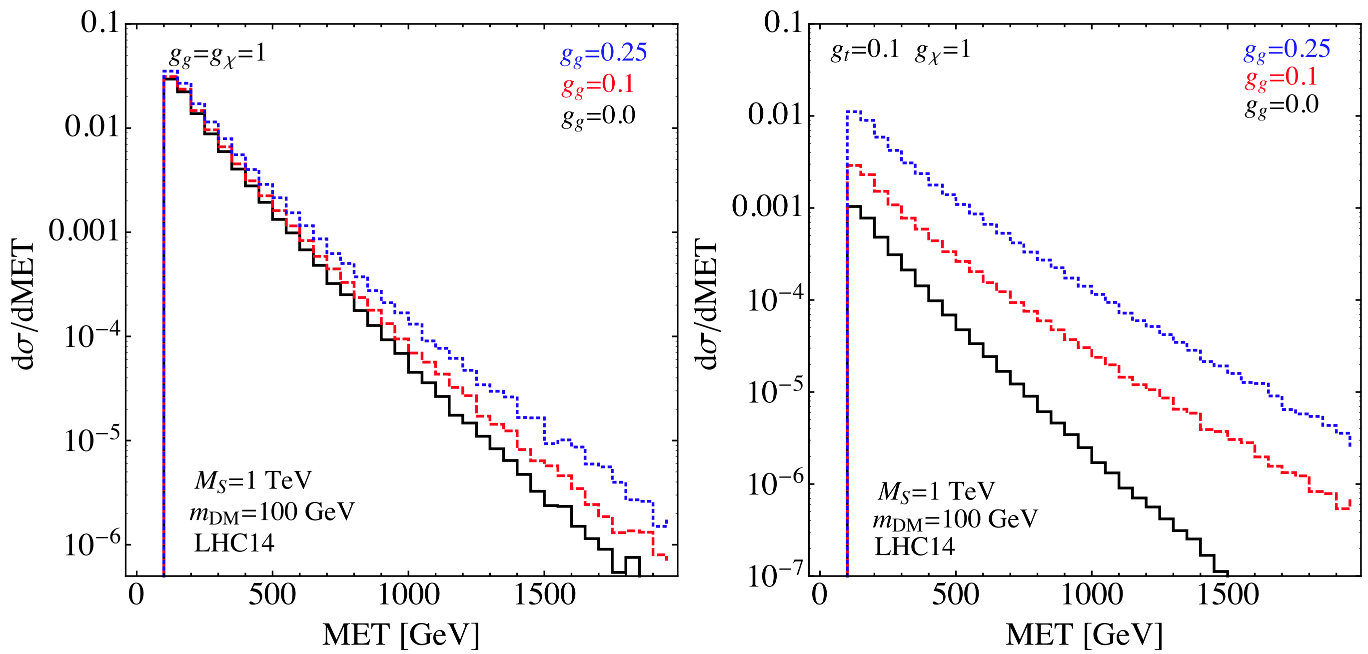


Additional heavy sector particles



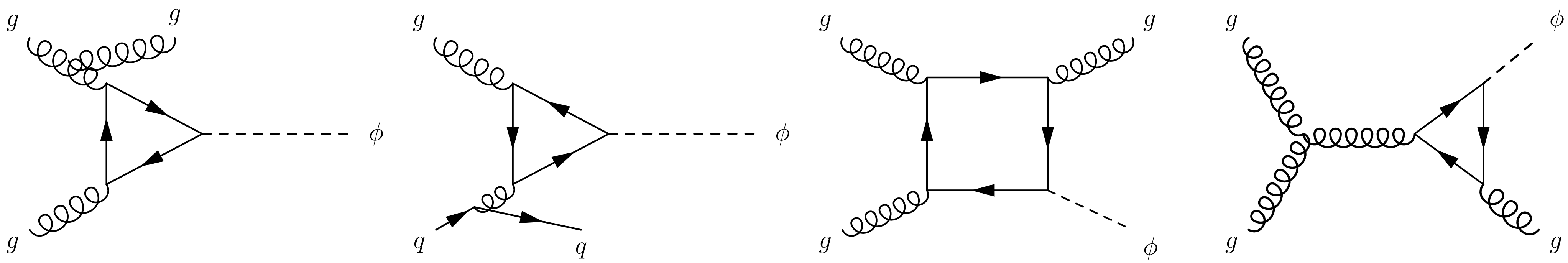
- Let us consider additional heavy degrees of freedom charged under SU(N_c) → EFT Lagrangian

$$\mathcal{L}_{\rm EFT} = g_g \frac{\alpha_s}{12\pi v} S \; {\rm Tr}\left(G^{\mu\nu} G_{\mu\nu}\right)$$



- Higher dimensional operators are relatively less suppressed at high energies compared to their 4-dimensional counterparts.
- Setting NP = 2 TeV and assuming g_{NP} is O(1), EFT can be used for values g_g < ~0.1
- Should a propagating resonance be found in the mono-jet channel, coupling constraints on loop-induced heavy particles can be investigated.

Scalar simplified models



$$\mathcal{L}_S = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + i\bar{\chi}\partial\!\!\!/\chi - m_\chi\bar{\chi}\chi - g_\chi\phi\bar{\chi}\chi - \sum_{\rm fermions} g_v\frac{y_f}{\sqrt{2}}\phi\bar{f}f\ ,$$

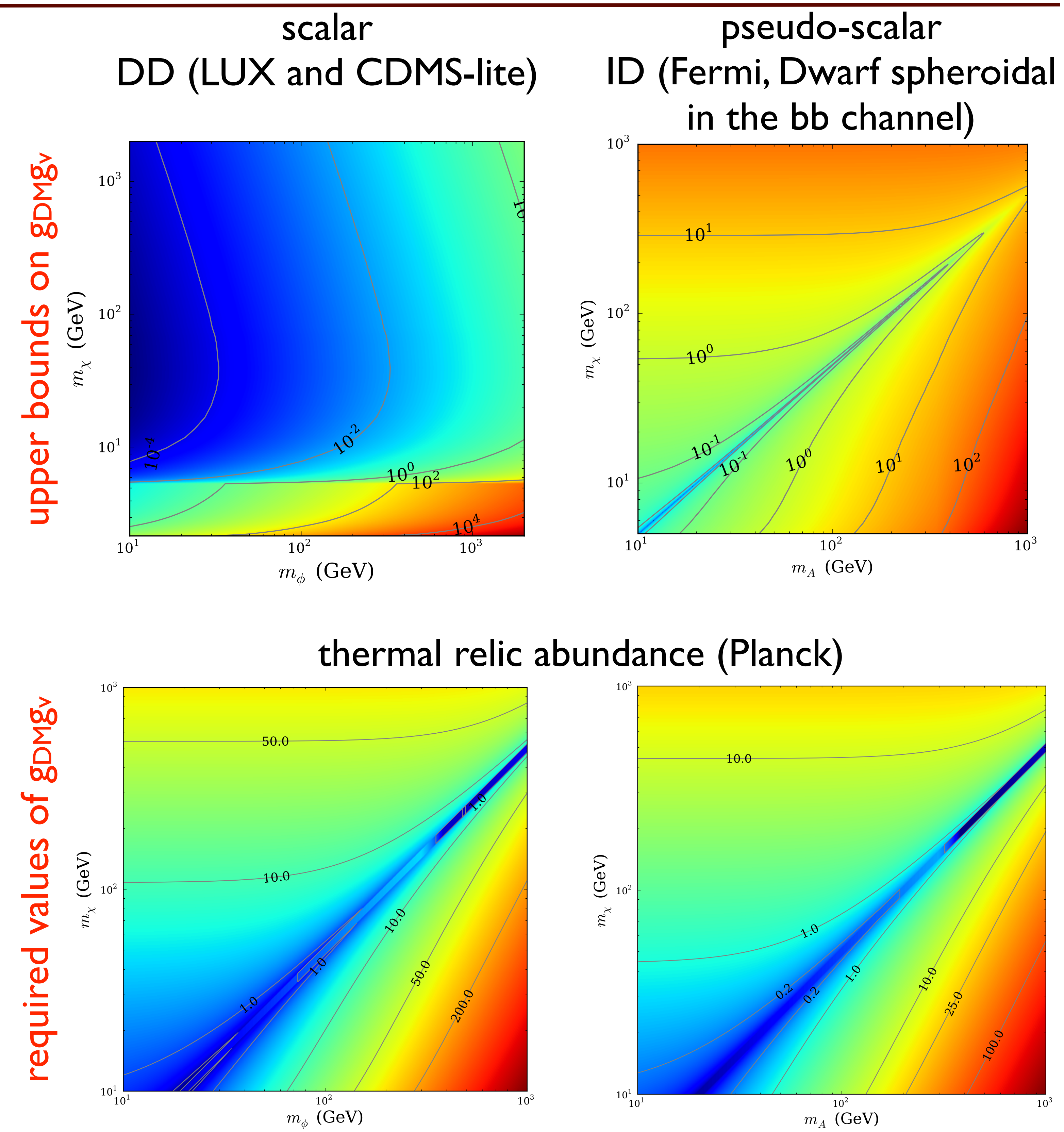
$$\mathcal{L}_A = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu A)^2 - \frac{1}{2}m_A^2A^2 + i\bar{\chi}\partial\!\!\!/\chi - m_\chi\bar{\chi}\chi - ig_\chi A\bar{\chi}\gamma^5\chi - \sum_{\rm fermions} ig_v\frac{y_f}{\sqrt{2}}A\bar{f}\gamma^5 f.$$

- 5 parameters: DM mass, mediator mass, DM-mediator coupling, flavor-universal SM-mediator coupling, mediator width
- Keeping the width as a free parameter allows for couplings to additional particles, perhaps in an expanded dark sector.
- Fermion couplings follow Minimal Flavor Violation
- Mediator couplings to SM fermions are proportional to the Higgs Yukawa couplings.
- Dominant production at the LHC would be through ggF as the tree-level couplings to light quarks are Yukawa-suppressed.

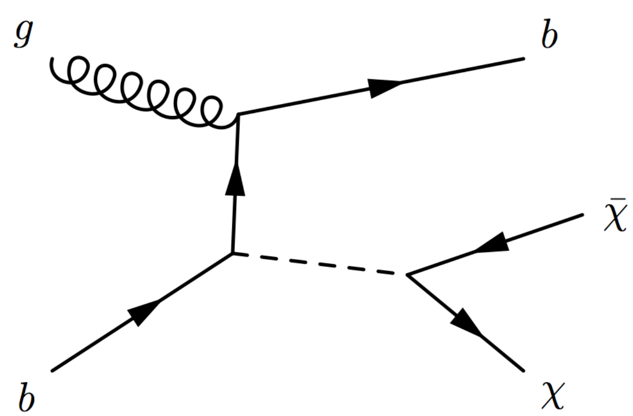
1410.6497

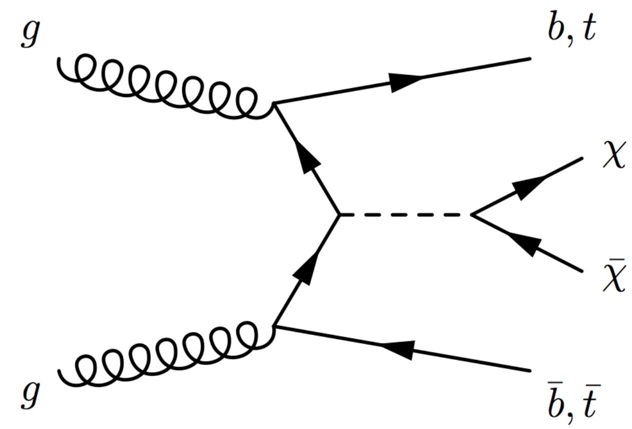
Bounds from DD, ID, thermal relic

- The pseudo-scalar model has no velocity or momentum independent scattering cross section with protons and neutrons → no significant limits from DD.
- <σv> is proportional to v^2 for scalar models → no significant signals in ID ($v \lesssim 10^{-2}c$).
- Thermal abundance is shown assuming the only open channel is $\bar{\chi}\chi \to \phi(A) \to ff$



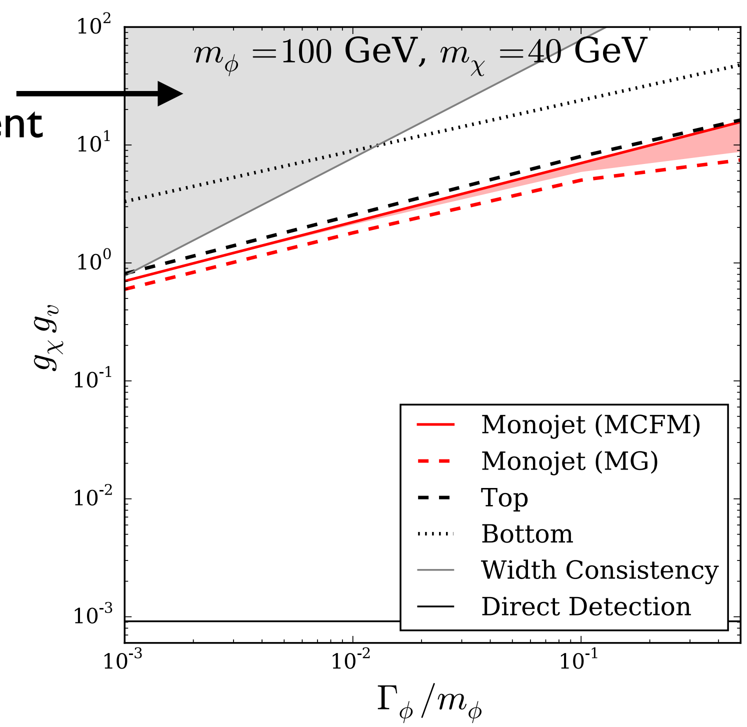
Heavy flavour searches

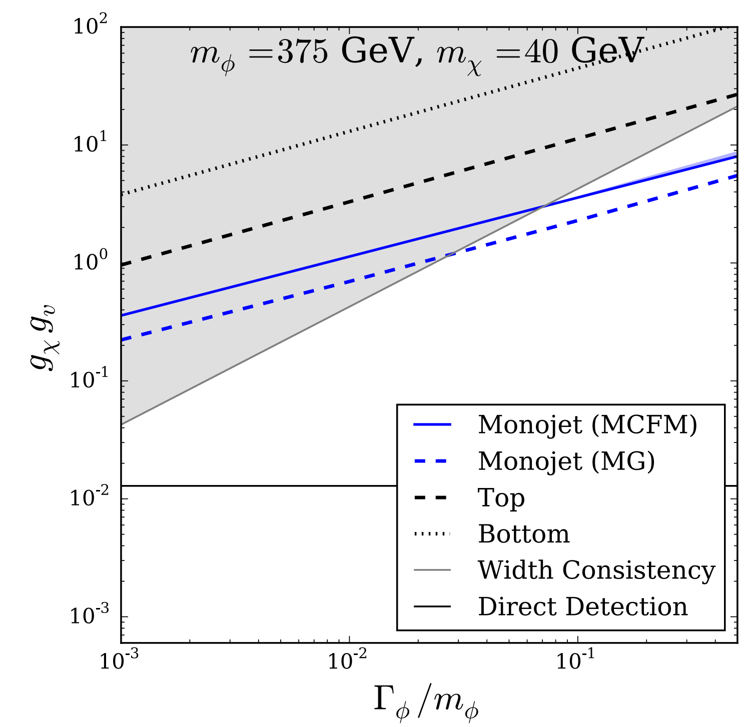




- With MVF, the mediator is most strongly coupled to the heaviest fermions.

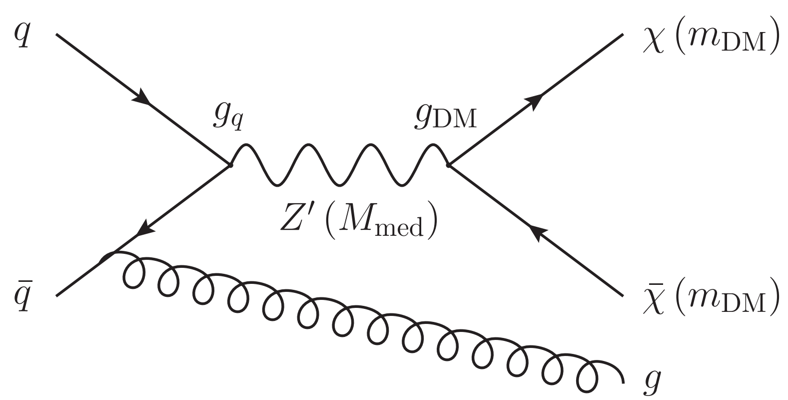
$g_{DM}g_v$ and width are theoretically inconsistent

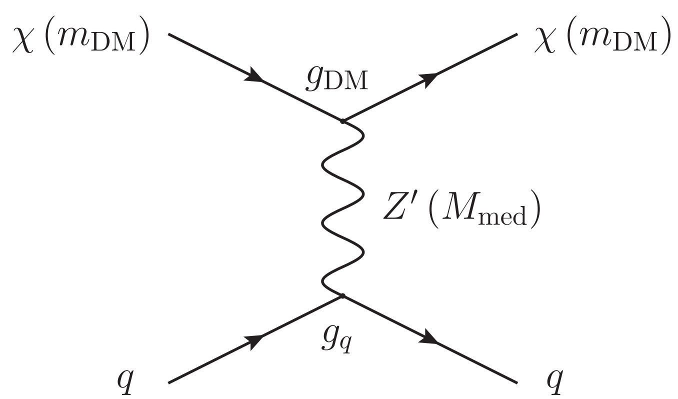




- The b-tagged channel places significantly weaker constraints than the mono-jet or top channels.

Minimal Simplified Dark Matter models





$$\mathcal{L}_{\rm vector} \supset -\sum_q g_q Z'_\mu \bar{q}\gamma^\mu q - g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu \chi$$

$$\mathcal{L}_{\rm axial} \supset -\sum_q g_q Z'_\mu \bar{q}\gamma^\mu\gamma^5 q - g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu\gamma^5 \chi$$

- s-channel vector and axial-vector simplified models
- It is possible to have mixed vector and axial-vector couplings. However, such interactions are suppressed by v_{DM}^2 for the direct detection ($v_{DM} \sim 10^{-3}$).
- No additional visible or invisible decays contribute to the width.

$$\Gamma_{\rm med} \equiv \Gamma(Z' \to \bar{\chi}\chi)\Theta\left(M_{\rm med} - 2m_{\rm DM}\right) + \sum_q \Gamma(Z' \to \bar{q}q)\Theta\left(M_{\rm med} - 2m_q\right)$$

- 4 parameters: M_{med}, m_{DM}, g_q, g_{DM}
- The results can be interpreted in the following way:
  - m_{DM} vs. M_{med}, for fixed g_q and g_{DM}
  - M_{med} vs g_q=g_{DM}, for fixed m_{DM}
  - m_{DM} vs g_q=g_{DM}, for fixed M_{med}

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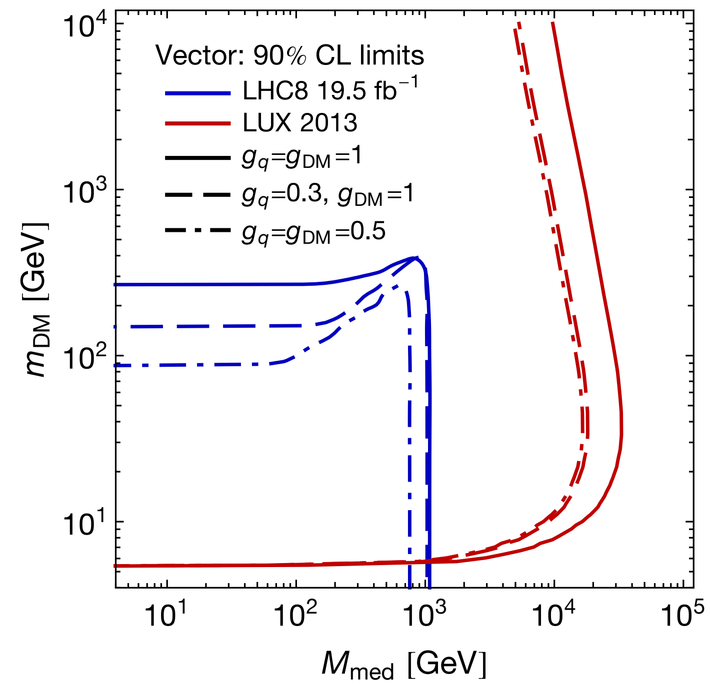
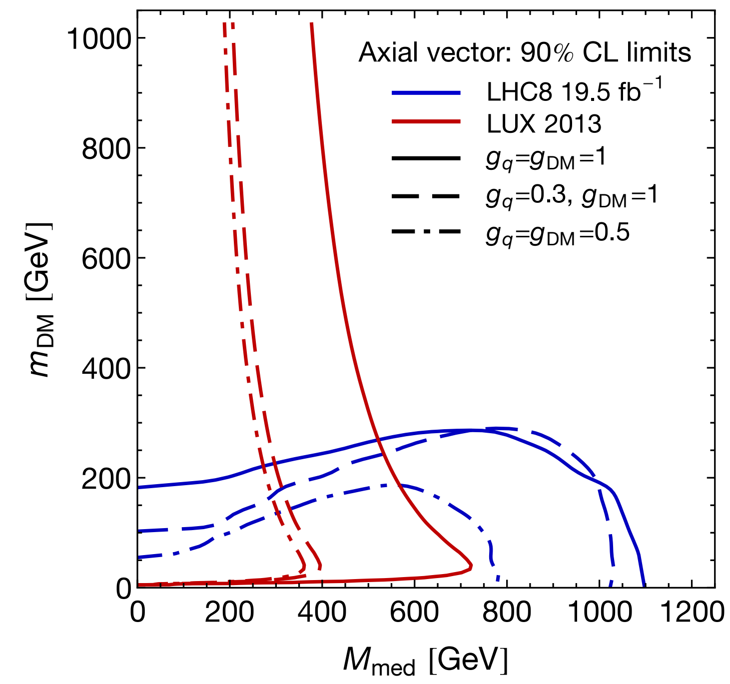
Minimal Simplified Dark Matter models

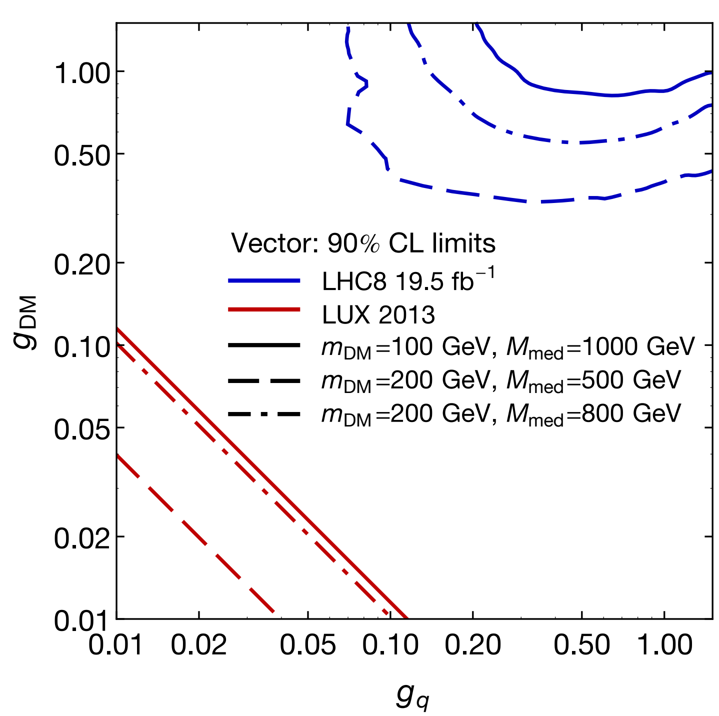
- SI cross-section is enhanced by A^2 for a vector mediator.
- Cross section for DD scales by $g_q^2 g_{DM}^2/M_{med}^4$

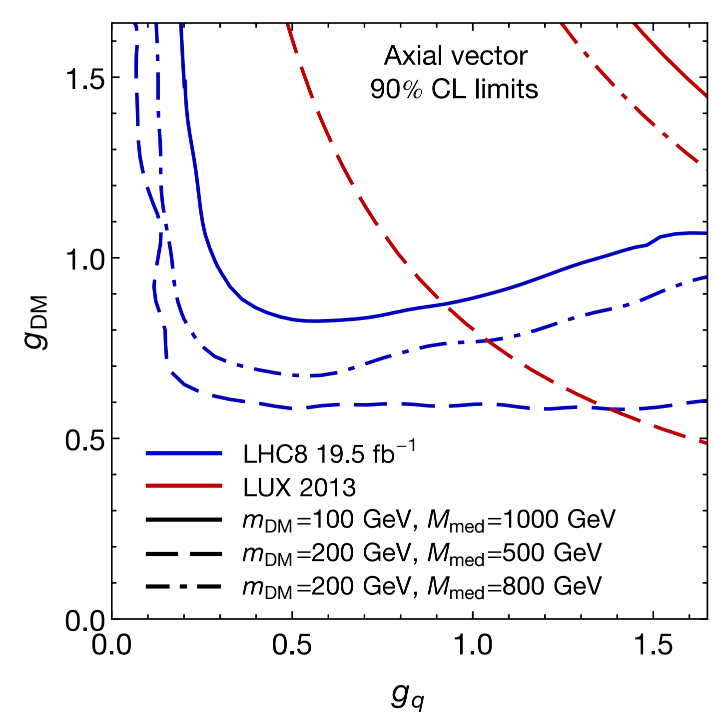




- DD limits are fully symmetric in this plane.
- Mono-jet search is able to break this degeneracy, since the mediator width is not symmetric in g_q and g_{DM}

$$\Gamma_{\rm med} \propto 18 g_q^2 + g_{\rm DM}^2$$





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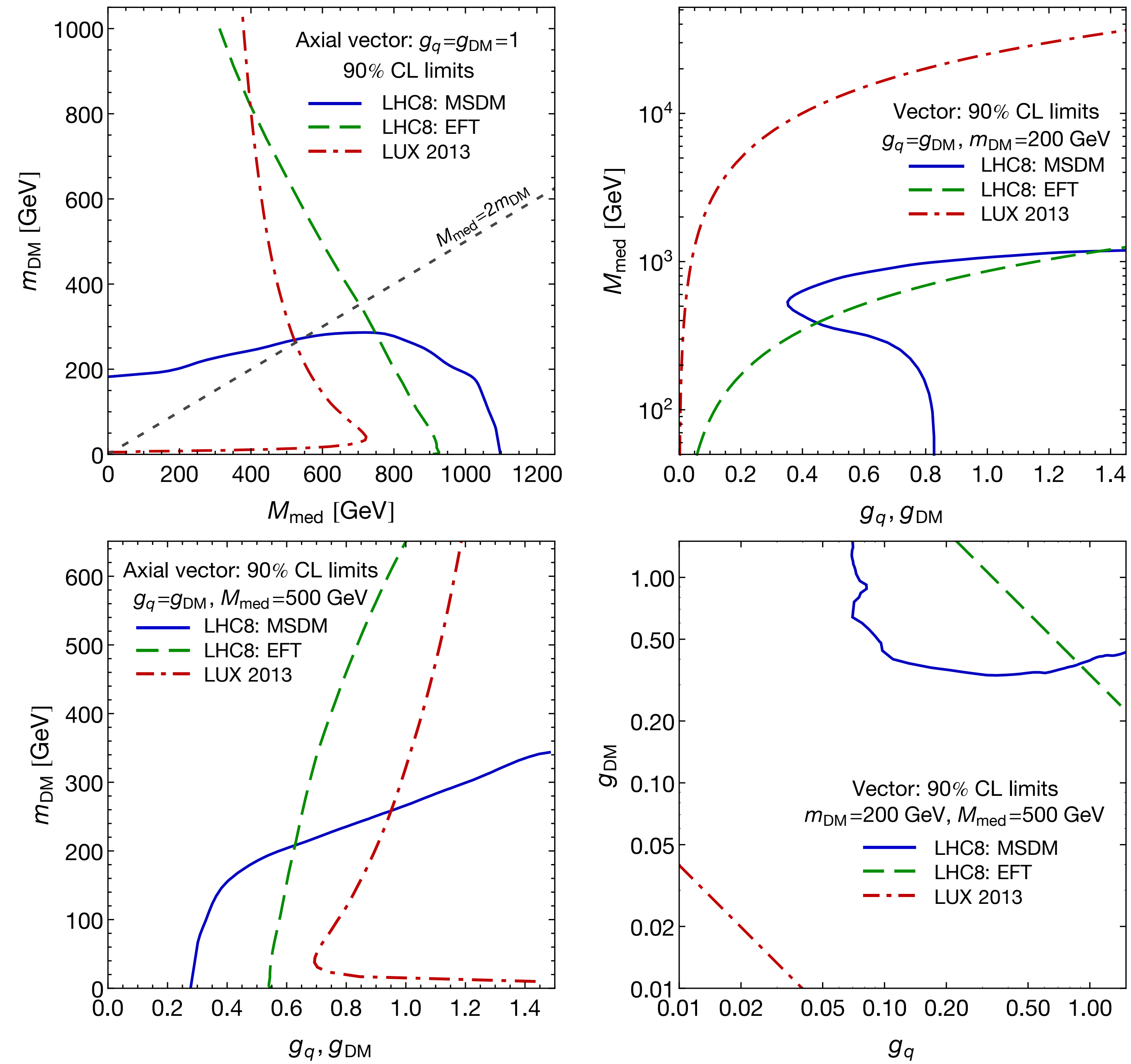
EFT limitations

- EFT overstates the limit at low M_{med} or large m_{DM} as the suppressed off-shell mediator production is not taken into account.
- The underlying coupling structure is not resolved by EFT.



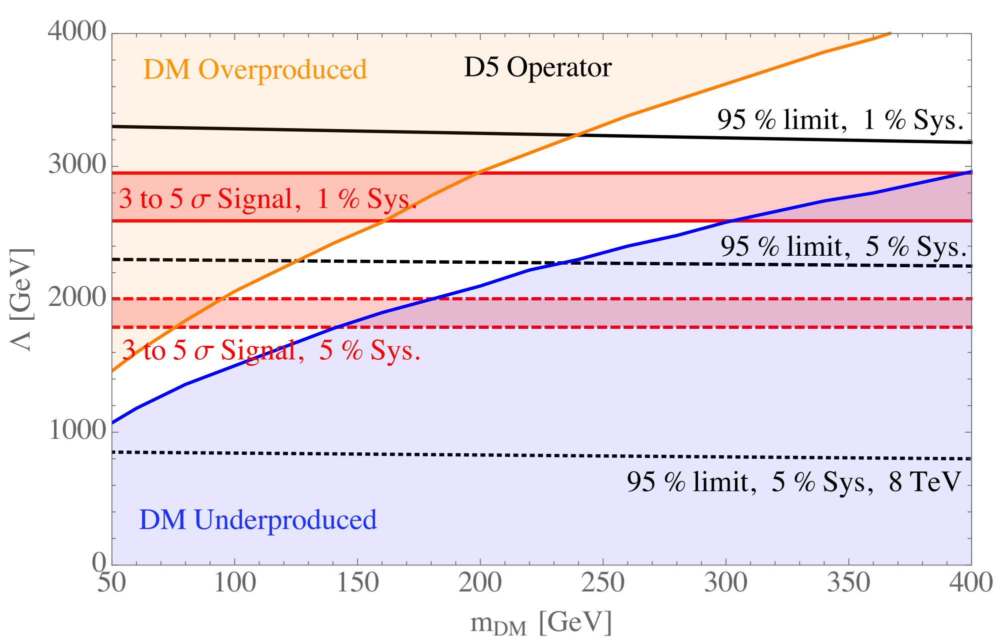
Implications from relic density

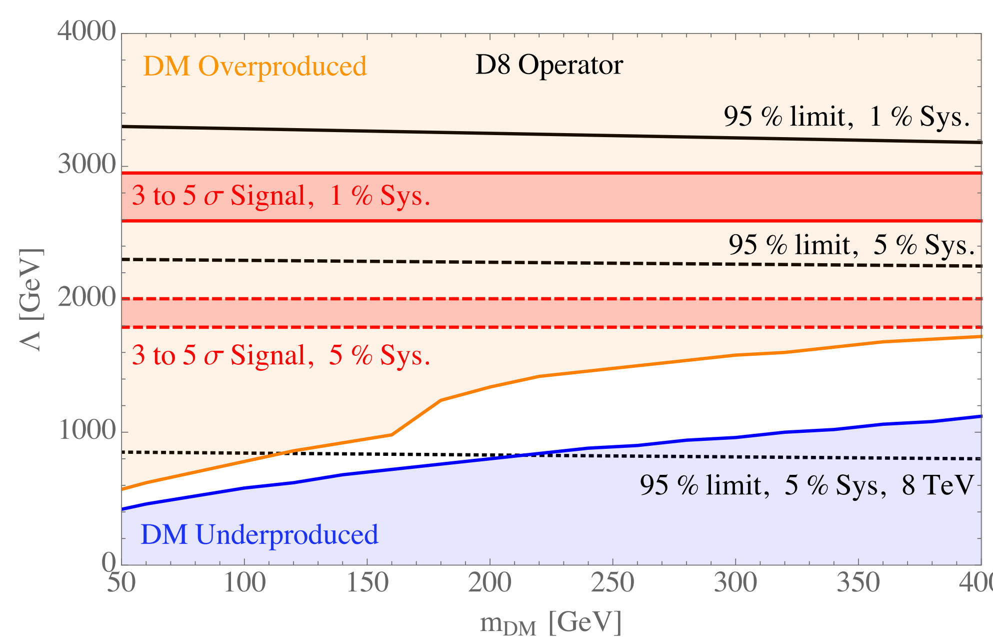
- Planck measurement $\Omega_{\rm DM}^{\rm obs} h^2 = 0.1199 \pm 0.0027$ $\qquad \Omega_{\rm DM} h^2 \simeq \frac{2 \times 2.4 \times 10^{-10}\,{\rm GeV}^{-2}}{\langle \sigma v \rangle_{\rm ann}}$
- DM interacts with the first-generation quarks. $\qquad \langle \sigma v \rangle_* \equiv \langle \sigma v \rangle_{\chi\bar\chi \to u\bar u} + \langle \sigma v \rangle_{\chi\bar\chi \to d\bar d},$
- Besides that, there can be additional channels.
- Let us assume the coupling to the first-generation quarks is no less than the coupling to other SM fermions.

$$\langle \sigma v \rangle_{\rm ann} \leq \sum_{\text{quark gen.}} \langle \sigma v \rangle_* + \sum_{\text{lepton gen.}} \frac{1}{3} \langle \sigma v \rangle_* = 4 \langle \sigma v \rangle_*$$

$$\Rightarrow \quad 1.0 \times 10^{-9}\,{\rm GeV}^{-2} \simeq \frac{1}{4} \langle \sigma v \rangle_{\rm ann} \leq \langle \sigma v \rangle_* \leq \langle \sigma v \rangle_{\rm ann} \simeq 4.0 \times 10^{-9}\,{\rm GeV}^{-2}$$

Overproduction line	$\langle \sigma v \rangle_{\rm ann} \simeq 4 \langle \sigma v \rangle_*$	**EFT:** Max Λ, min $m_{\rm DM}$. **Simp. model:** Max M, min $g_{({\rm DM},f)}$ and $m_{\rm DM}$.
Underproduction line	$\langle \sigma v \rangle_{\rm ann} = \langle \sigma v \rangle_*$	**EFT:** Min Λ, max $m_{\rm DM}$ **Simp. model:** Min M, max $g_{({\rm DM},f)}$ and $m_{\rm DM}$.



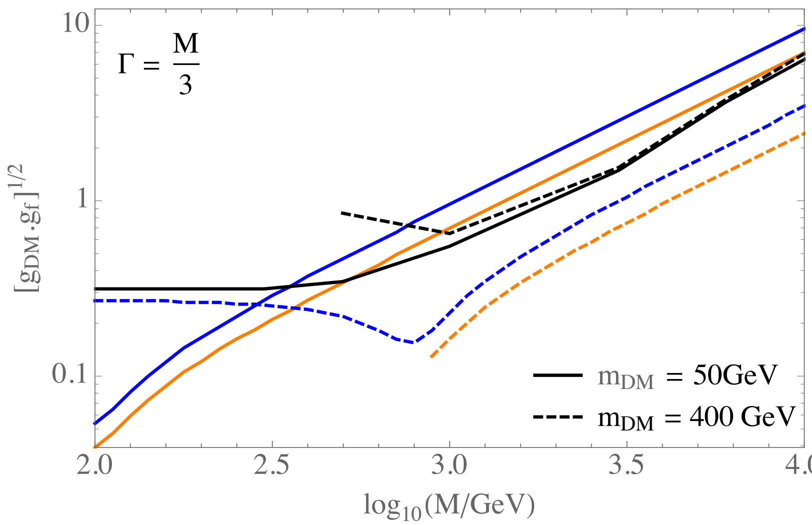


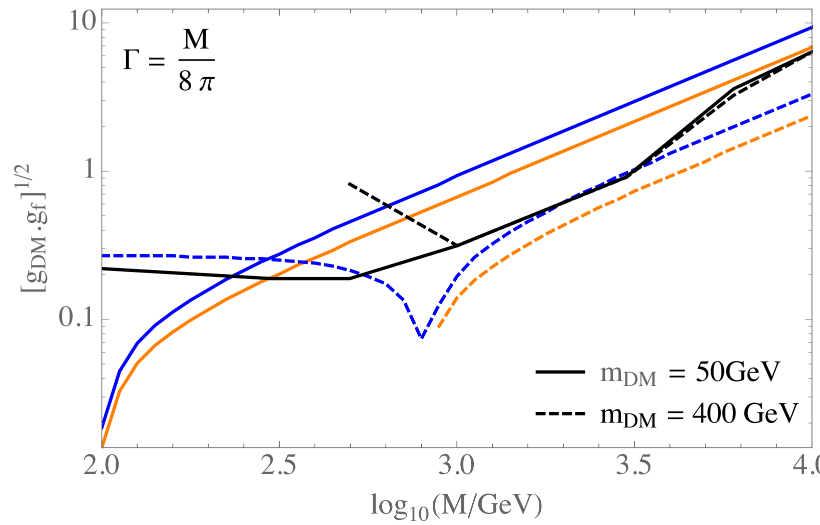
14 TeV, 3000 fb^{-1}

14 TeV, 300 fb^{-1}

1410.7409

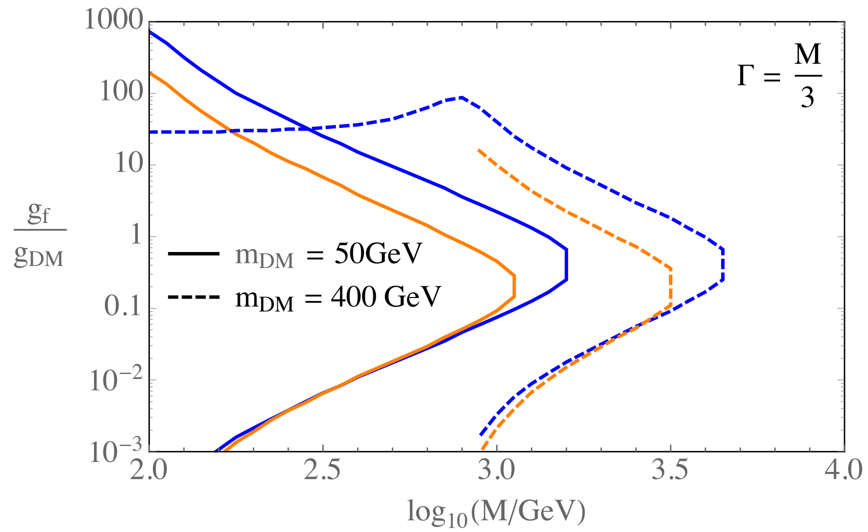
Mediator width in the s-channel Z'

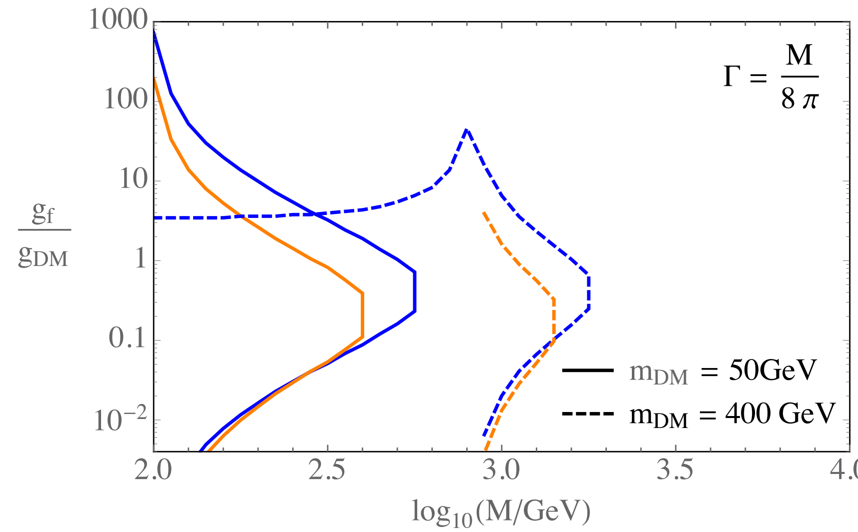




14 TeV, 25 fb^{-1}

- The annihilation rate only depends on the product $g_{DM}g_f$, the mediator width depends on each coupling individually.
- For fixed values of the mediator width, one can recast the limit on $\sqrt{g_{DM}g_f}$ into a bound on the ratio fix g_f/g_{DM}.





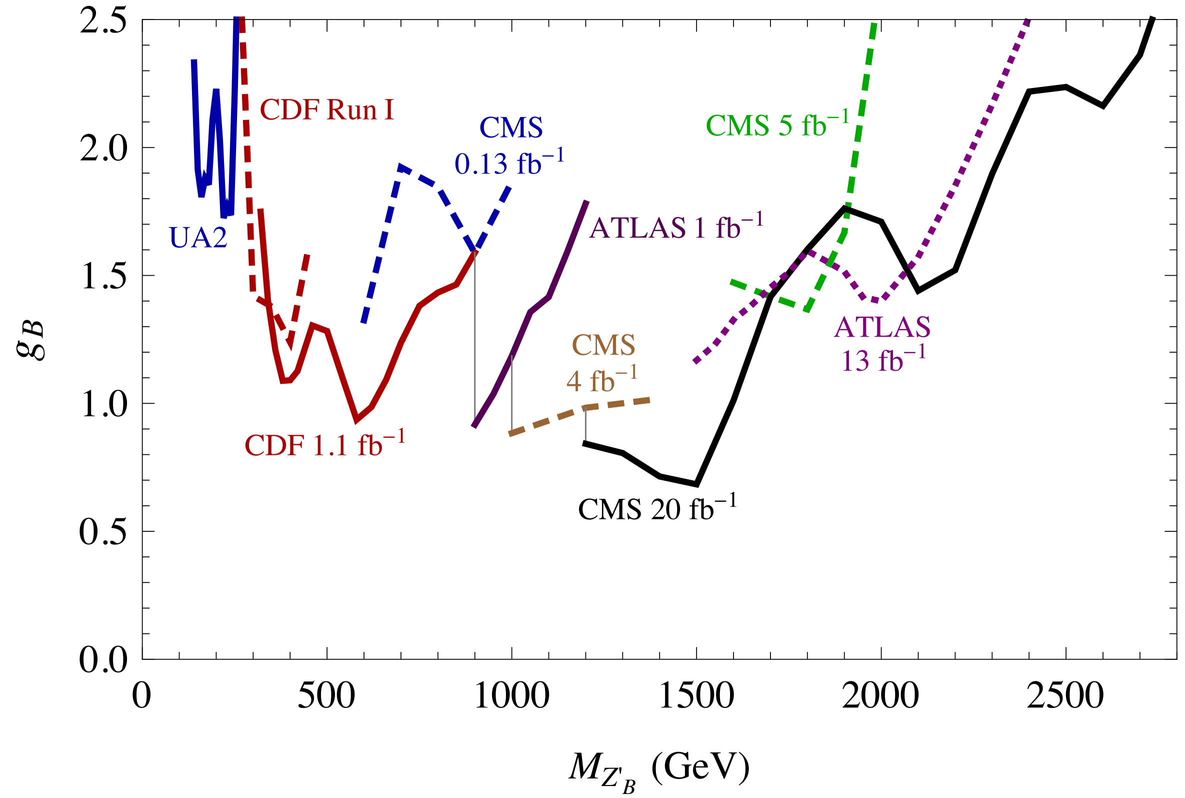
- The widths are unphysical at large mediator masses (no solution exists).

➡ avoid using arbitrary mediator widths!

1306.2629

Searches for narrow dijet resonances

- A naive hope is that limits set at higher $\sqrt{s}$ and with larger integrated luminosity would supersede previous limits.
- However, backgrounds also increase so that the jet trigger thresholds need to be increased.
- Consequently, the sensitivity to lighter resonances may decrease.



- The coupling reach is rather poor at 700-900 GeV and below 300 GeV.
- Non-conventional methods, such as data scouting, are important for extending the LHC sensitivity in the sub-TeV mass range.

DM forum

- Following the discussions at the DM@LHC Workshop in Oxford, a common forum among ATLAS, CMS and theorists has been established with the following goals:
  - Agree on a list of simplified models that both collaborations will use in Run-2.
    - useful, minimal set of building blocks for reinterpretation
    - practical for experiments, endorsed by theory community
    - s-channel, t-channel, heavy flavor, mono-W/Z/γ/H
  - Harmonize technical details (generator, parton matching, theory uncertainties).
  - Common treatment of EFT
  - Presentation of the results (complementarity of the searches)
  - Write a comprehensive document as a reference/explanation for ATLAS and CMS collaborations, theory and non-collider communities.

next DM @ LHC Workshop

NIKHEF

GRAPPA

GRavitation AstroParticle Physics Amsterdam

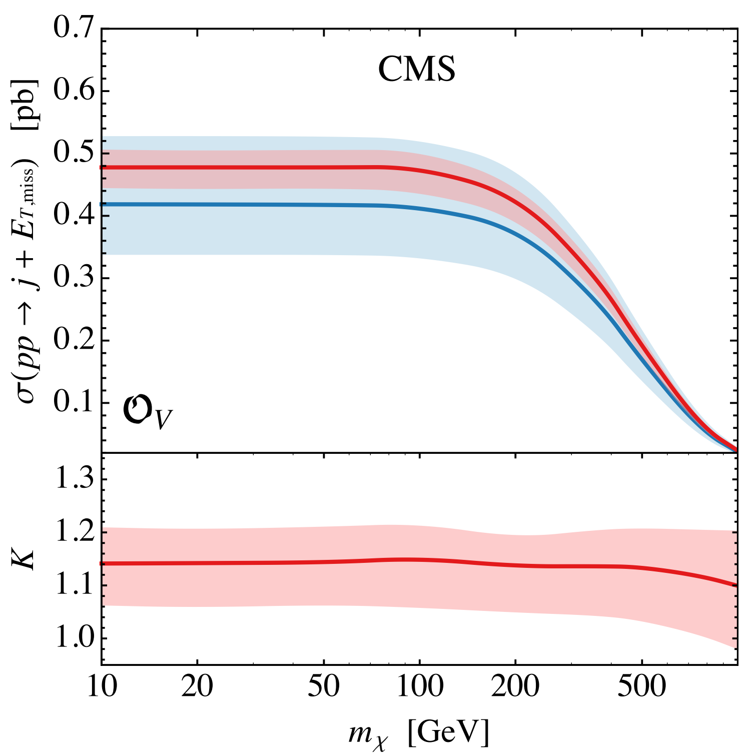
exact dates to be announced

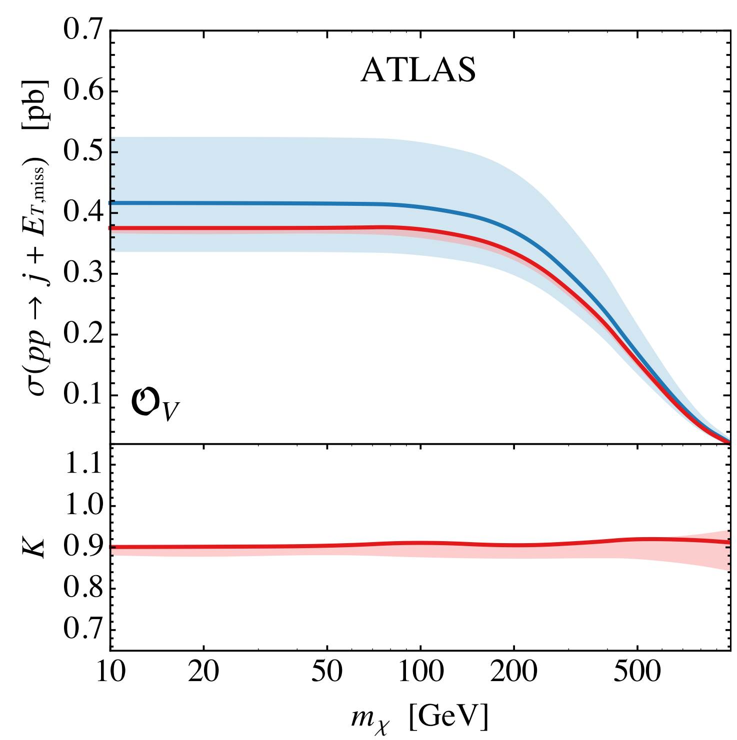
Looking forward to seeing you in Amsterdam!

extra material

LO and NLO

- POWHEG BOX allows for generation of the signal to NLO accuracy.
- Including NLO corrections results in a small enhancement of the cross-section compared to LO.
- dynamic scale $H_T = \sqrt{m_{\chi\chi}^2 + p_{T,j_1}^2} + p_{T,j_1}$ $\mu = \xi H_T/2 = \mu_R = \mu_F$
- It also leads to substantial reduction in the dependence on the choice of the renormalisation and factorisation scales.
- It leads to more robust bounds.





$$K = \frac{\sigma(pp \to j + E_{T,\mathrm{miss}})_{\mathrm{NLO}}^{\xi=[1/2,2]}}{\sigma(pp \to j + E_{T,\mathrm{miss}})_{\mathrm{LO}}^{\xi=1}}$$

- Pathological cancellation of scale uncertainties with ATLAS cuts due to the symmetric jet pT and MET cuts.

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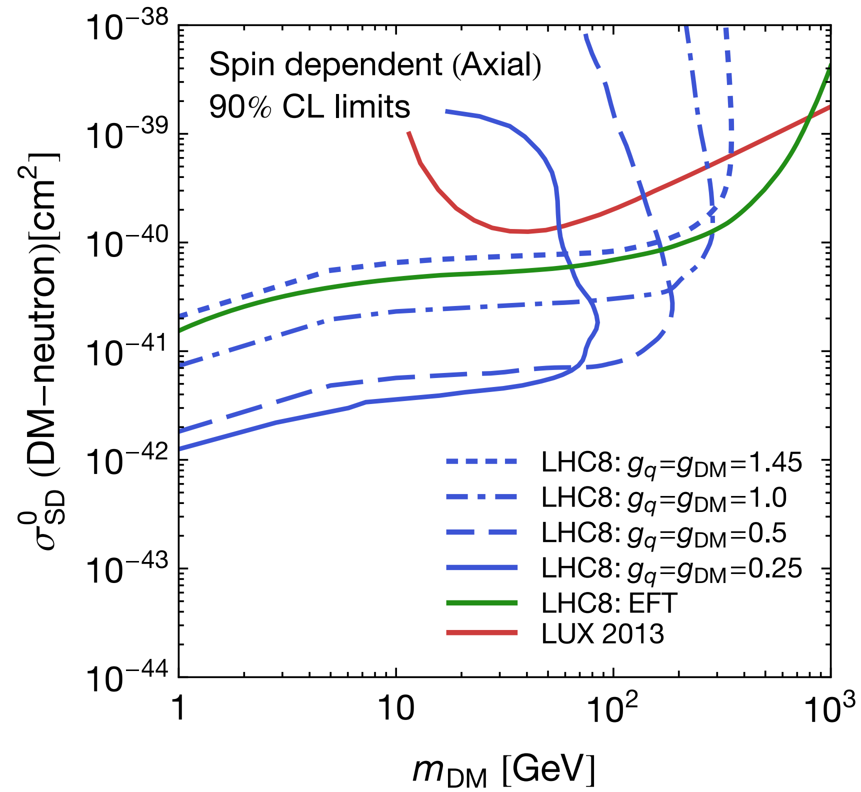
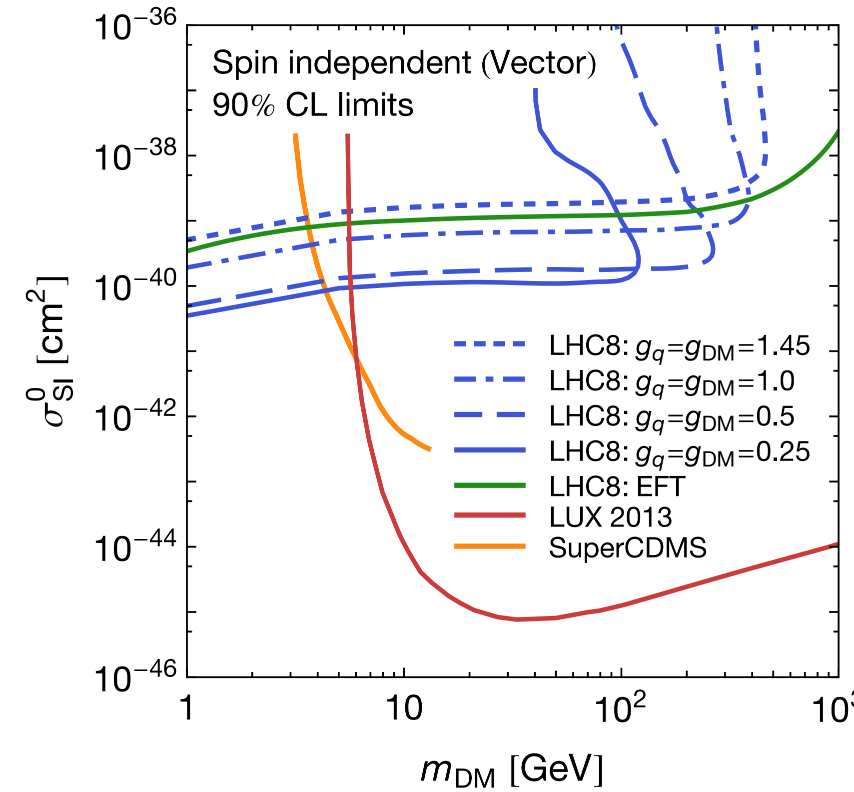
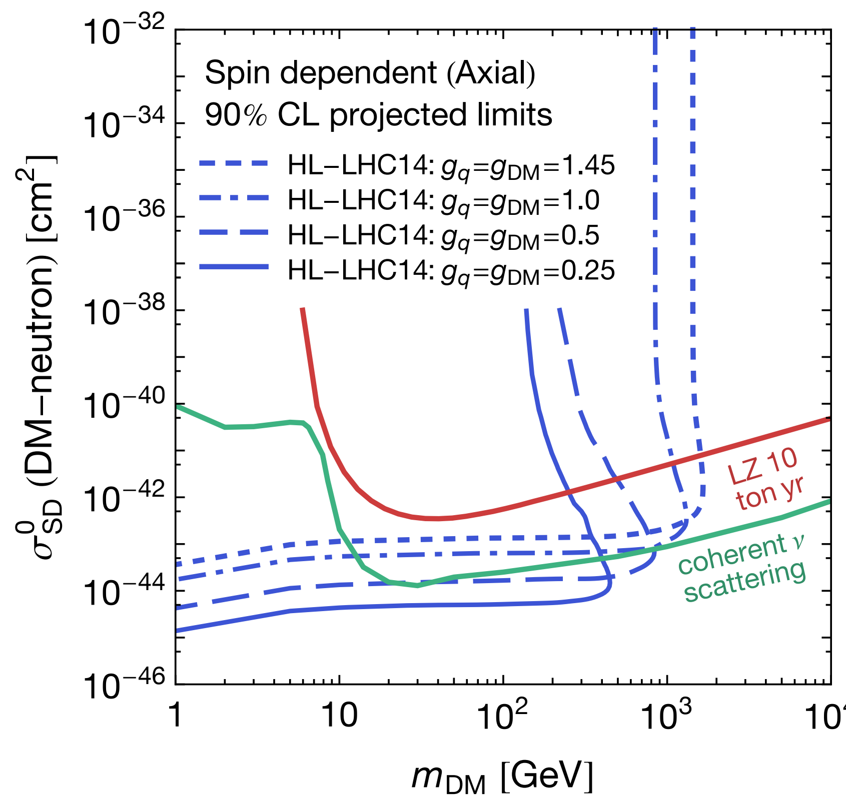
Future projections

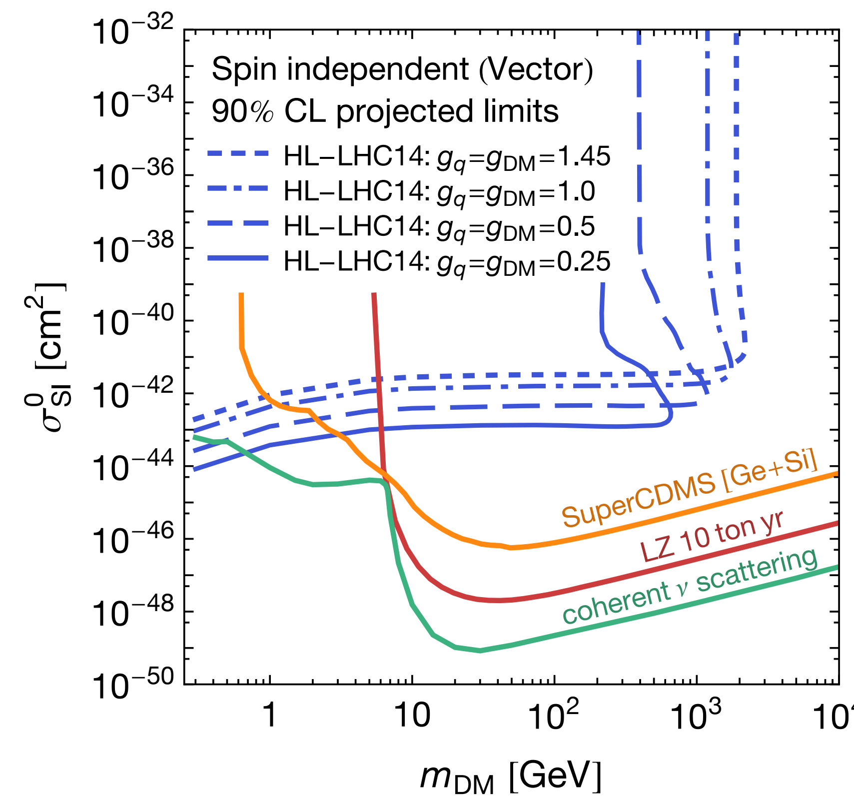
8 TeV, 20 fb^{-1}





14 TeV, 3000 fb^{-1}





Higgs portal DM

$$\mathcal{L} = -H^\dagger H \left[\bar{\psi}_{\rm DM} \frac{(y_{\rm DM} + i y^P_{\rm DM} \gamma_5)}{2v} \psi_{\rm DM} + \frac{\lambda_{\rm DM}}{4} s^2_{\rm DM} \right]$$