Theory interpretations and challenges of DM searches

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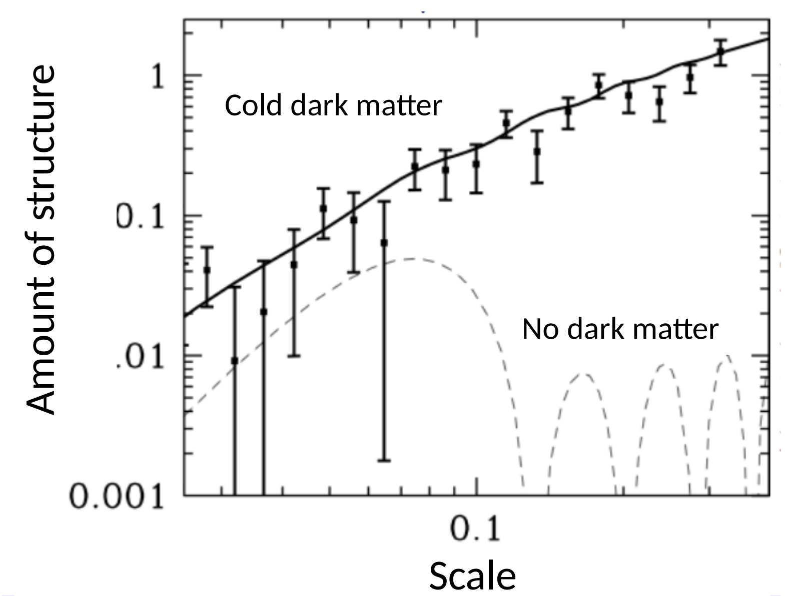
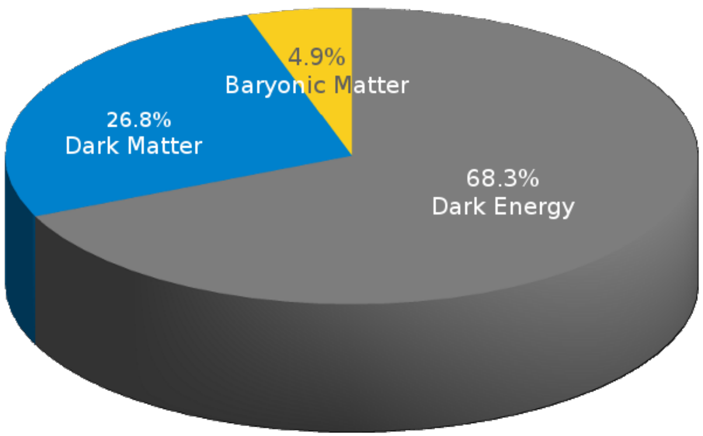
Why dark matter?

- Dark matter (DM) is an **essential ingredient** to describe Early Universe cosmology
  - Acts as the seed for **structure formation**
  - Creates the **potential wells** for stars and galaxies
- DM **explains** the amount and distribution of structure that we observe today

  Note: Substantial evidence for DM also in the present Universe (galactic rotation curves, gravitational lensing…)





- A wealth of **successful predictions** from a very simple model
- Only draw-back: We understand only **5%** of the Universe!

Dark matter models

- **Particle physics** is the language of the early Universe
  - Example: Cosmology depends on the number, mass and interaction strength of neutrinos

- Likewise, we would like to understand DM in terms of particle physics
  - Require a **new stable particle** beyond the Standard Model

- At first sight, no obvious connection to LHC physics
  - There are viable DM models that are fundamentally unobservable at the LHC (too heavy, too weakly coupled)

FK, arXiv:1801.07621

- Still, the LHC can probe many of the most attractive and most predictive DM models
  - **Attractive:** DM models connected to the hierarchy problem (e.g. SUSY)
  - **Predictive:** DM models where the observed relic abundance is obtained naturally

Dark matter production

- The one thing we know about dark matter is how much there is in the Universe:

$$\Omega h^2 = 0.1199 \pm 0.0027$$

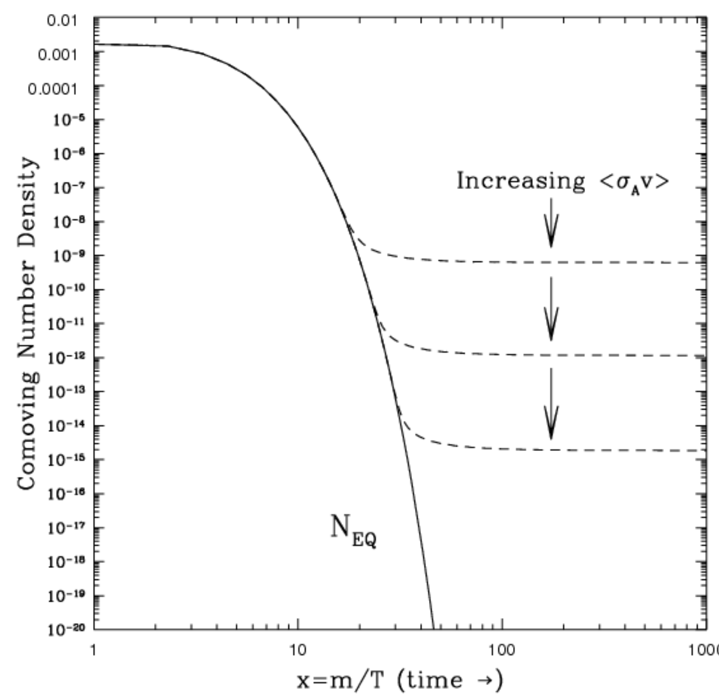
- Any model of dark matter must provide a mechanism to explain this number

- Most widely studied paradigm: **Thermal freeze-out**

  - **Fundamental assumption:** Thermal equilibrium between DM and other particles in the early Universe

  - New particles with weak interactions and weak-scale mass (so-called WIMPs) freeze out with the correct relic density

  - WIMPs can neither be too heavy nor too weakly coupled, so we can **search for them at the LHC**



How does dark matter interact?

- **Simplest assumption:** DM particles couple directly to SM particles (e.g. gauge bosons or Higgs bosons)
  - Many **interesting models** (Higgs portal, minimal DM, …)
  - Strong **experimental constraints** (e.g. from direct detection)

- What if there are **no direct interactions** between DM and SM particles?
  - Assume dark matter (DM) is uncharged under the Standard Model (SM) gauge group
  - Focus on models where the DM particle is exactly stable (e.g. due to a Z_2 symmetry)

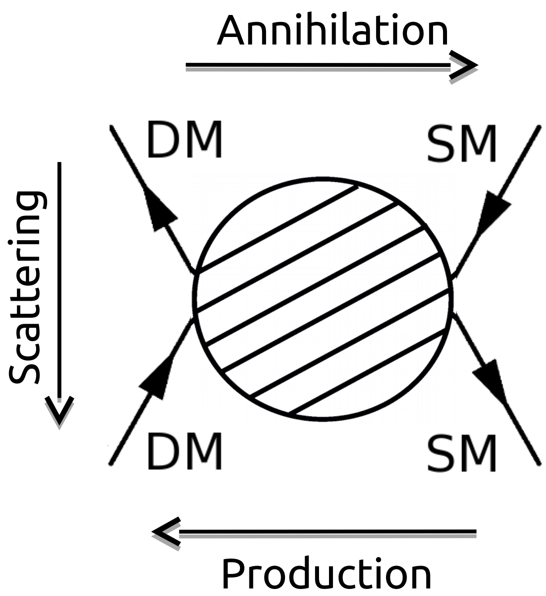
Two possible directions:

Consider **non-renormalisable** interactions, i.e. higher-dimension effective operators

Insist on **renormalisable interactions** but allow additional particles interacting with SM particles and DM (so-called **mediators**)

Effective interactions

- Very attractive idea: Parametrise interactions of DM in terms of **unknown scale of new physics Λ**
  - Finite number of possible operators
  - Simple parameter space and kinematics
  - Direct connection between different experiments

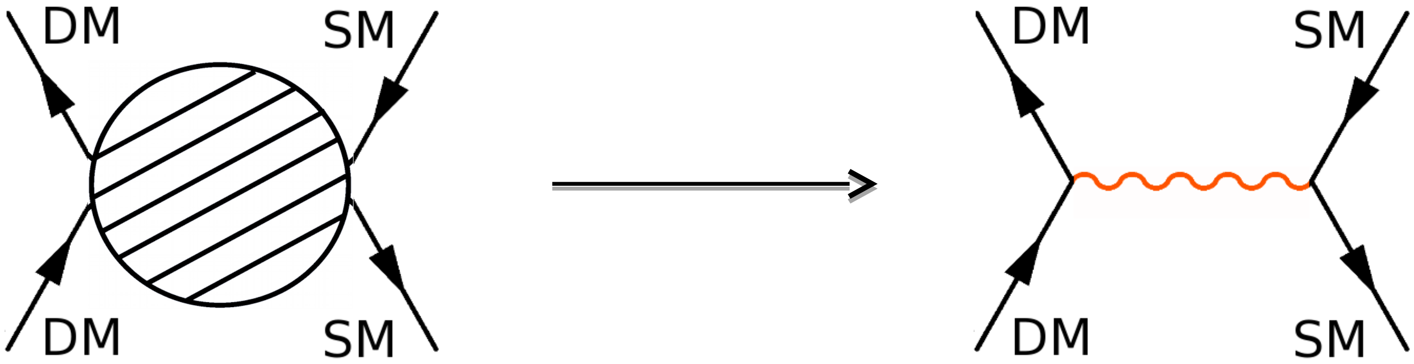


- In practice: Approach breaks down if Λ is too small
  - Need truncation procedure to restrict search to kinematic regions where effective field theory (EFT) is valid
  - Many interesting features are not captured by effective operators

Busoni et al., arXiv:1307.2253
Bruggisser et al., arXiv:1607.02475

From EFTs to renormalisable models

- We can address the shortcomings of effective interactions by introducing a **new mediating particle** connecting DM to the SM



- The move to renormalisable models comes at a high price
  - Large number of possible models → **loss of generality**
  - Large number of parameters for each model → **increase of complexity**

Why study renormalisable models?

- **Pragmatist's answer:** Renormalisable models remains valid in all kinematic regions
  - Straight-forward signal generation and calculation of NLO corrections
- **Theorist's answer:** We can study DM interactions at a more fundamental level
  - Comparison of different models in terms of their plausibility or complexity
- **Phenomenologist's answer:** Renormalisable models predict many new signatures, which can be correlated by exploiting the underlying structure of the theory
  - Understanding of relative importance of different search channels
  - Prediction of unexpected signals or kinematic distributions

Renormalisable models provide an excellent compromise between predictivity and flexibility

New mediators (lightning review)

- The most common extension involves new *s*-channel mediators, which can have
  - Spin 1:

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q \,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q$$

  - Spin 0:

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q \,,$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -i g_{\text{DM}} \phi \bar{\chi}\gamma_5 \chi - i g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q$$

- All these simplified models appear renormalisable (all couplings are dimensionless), but there are a lot of hidden complications

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Renormalisable models of spin-1 mediators

- Adding a massive spin-1 mediator to the SM yields a **non-renormalisable theory**
- Mediators with longitudinal polarisation **violate unitarity** at high energies

$$\langle Z'^{\mu}(k) Z'^{\nu}(-k) \rangle = \frac{1}{k^2 - m_{Z'}^2} \left(g^{\mu\nu} - \frac{k^\mu k^\nu}{m_{Z'}^2} \right)$$

- If the mediator has axial couplings, the longitudinal polarisations do not decouple

FK et al., arXiv:1510.02110

- Solution: Generate mediator mass via the vev of an **additional Higgs boson**
  - Consistent theory requires two mediators, each of which can give rise to new signatures

    Duerr, FK et al., arXiv:1606.07609
  - To fully remove unitarity violation, coupling structure must respect gauge structure of unbroken electroweak symmetry

    Bell et al., arXiv:1512.00476
    Haisch, FK et al., arXiv:1603.01267

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Renormalisable models of spin-0 mediators

- Scalar mediators can only couple to SM quarks via **mixing** with the SM Higgs
  - Modification of **branching ratios** of the SM-like Higgs
  - Scalar mediator picks up couplings to gauge bosons

Albert et al., arXiv:1607.06680
Bell et al., arXiv:1612.03475

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Bell et al., arXiv:1612.03475

- Pseudoscalar mediators cannot mix with the SM Higgs (without CP violation)
  - Simplest extension requires a **second Higgs doublet**
  - The pseudoscalar mediator then mixes with the pseudoscalar component of the second Higgs doublet
  - New diagrams restore unitarity (e.g. in single-top production)

No, arXiv:1509.01110
Ipek et al., arXiv:1404.3716
Goncalves et al., arXiv:1611.04593
Bauer, Haisch & FK, arXiv:1701.07427

Pani & Polesello, arXiv:1712.03874

Central predictions of renormalisable models (I)

- In effective (or simplified) DM models, the properties (branching ratios, masses) of SM particles are not modified

- In consistent renormalisable models, **modifications occur copiously**:

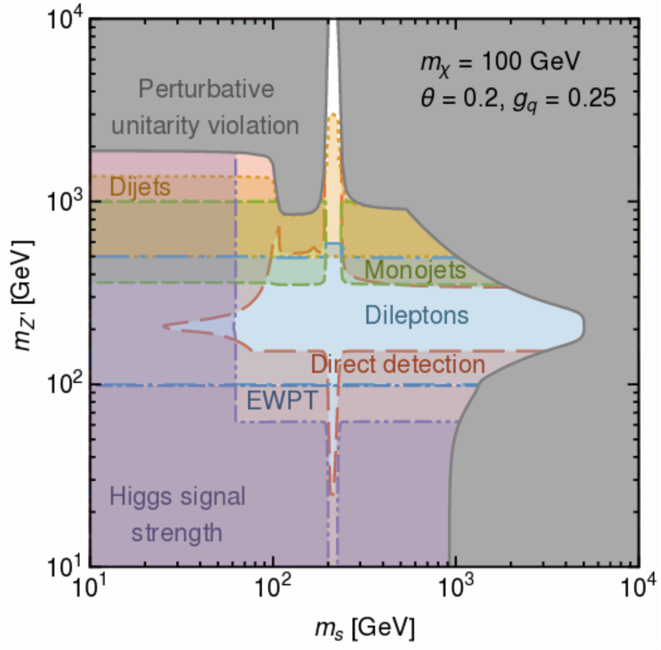
  - Kinetic mixing and radiative corrections modify gauge boson masses (constrained by EWTP)

  - Higgs mixing reduces the overall **Higgs signal strength**

  - New decay modes lead to non-standard Higgs decays

- Moreover, we can observe **new signatures in SM final states** (dijet resonances, dilepton resonances, ...)

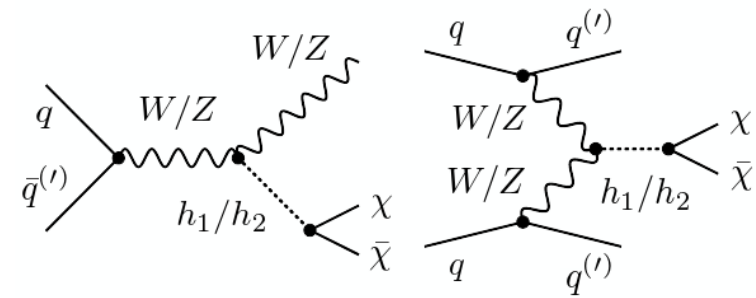
Duerr, FK et al., arXiv:1606.07609

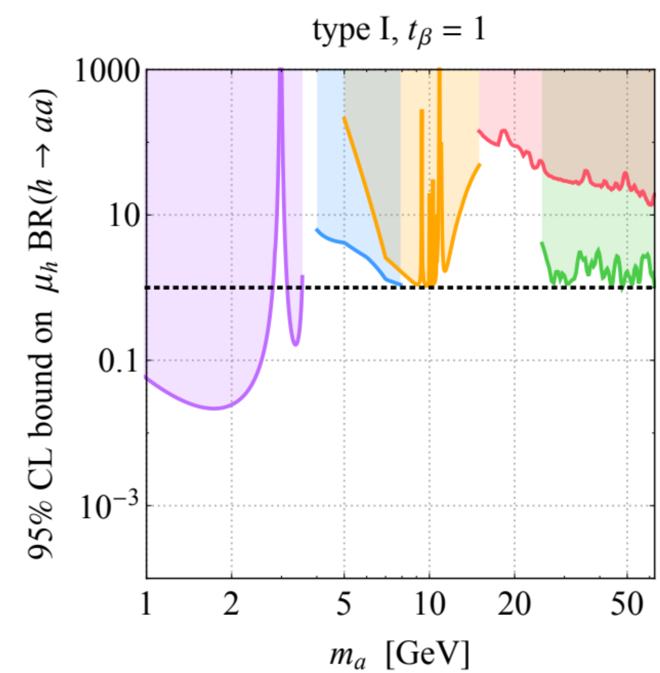


A closer look: Higgs decay modes

- Simplest example: Mixing between SM Higgs (*h*) and new "dark" Higgs boson (*s*)
  - **Invisible decay modes** open up if $m_{DM} < m_h/2$ or $m_s < m_h/2$ (and *s* long-lived)
    - Direct searches for invisible decays in VBF, *h*+*V* and *h*+*j* channels
  - **Higgs signal strength reduced** by factor $\cos^2\theta$
    - Constraints from global Higgs fits
  - **Exotic decay modes** if *s* decays back into SM particles
    - Relevant constraints from searches for h → 4l

See e.g. Haisch et al., arXiv:1802.02156





Central predictions of renormalisable models (II)

- In effective (or simplified) DM models, the signatures of DM production at the LHC stem from the initial state radiation of SM particles (mono-X signatures)

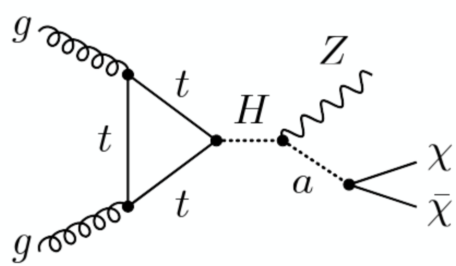
Bauer et al., arXiv:1712.06597

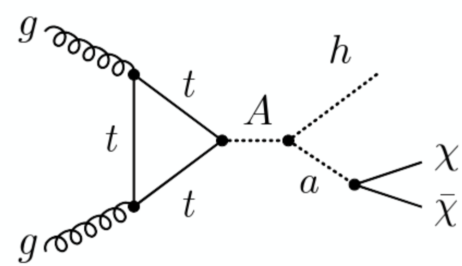
- One therefore expects a **very simple pattern**:

mono-jet > mono-photon > mono-*Z*/*W* > mono-Higgs

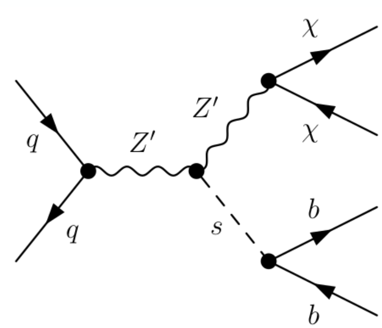
- In renormalisable models, SM particles can also be produced together with invisible particles…

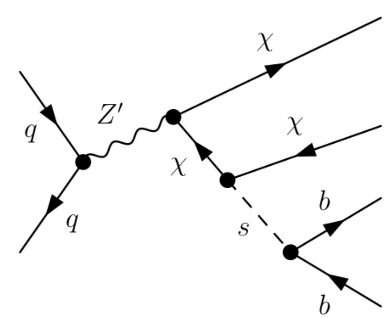
…in the **decays of heavier states**:





…via **final-state radiation**:





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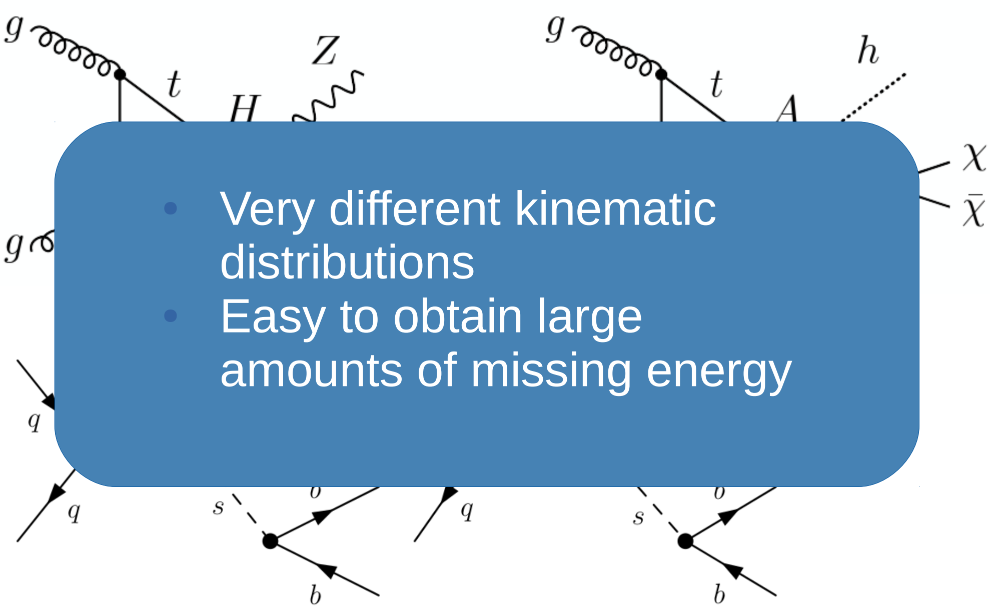


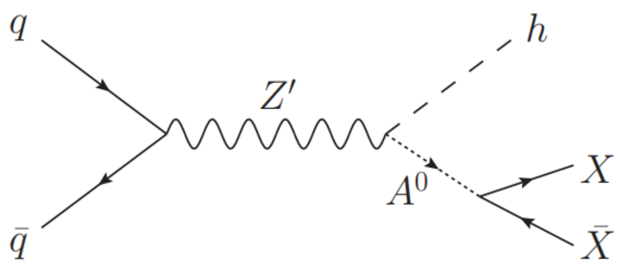
- Very different kinematic distributions
- Easy to obtain large amounts of missing energy

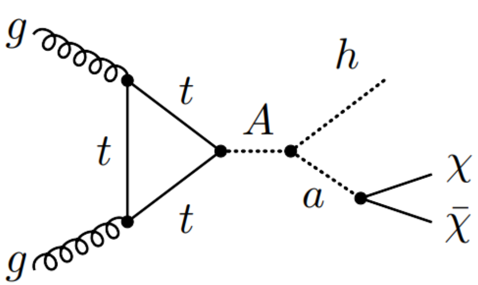
A closer look: mono-Higgs

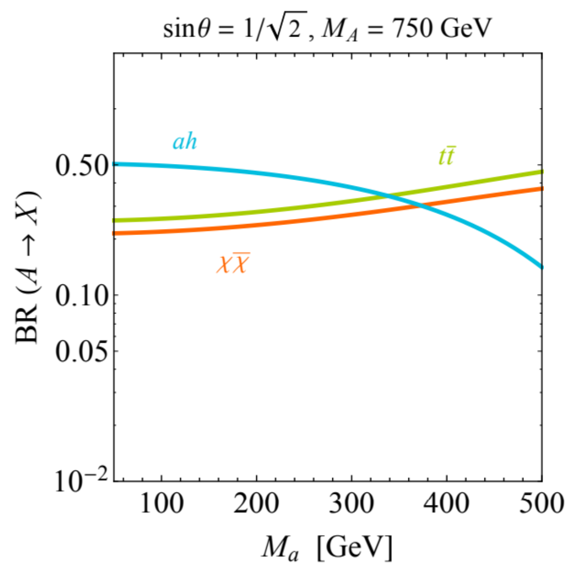
- Even if DM couples dominantly to heavy quarks, the cross section for mono-Higgs events from initial state radiation or from top-quark loops are completely negligible

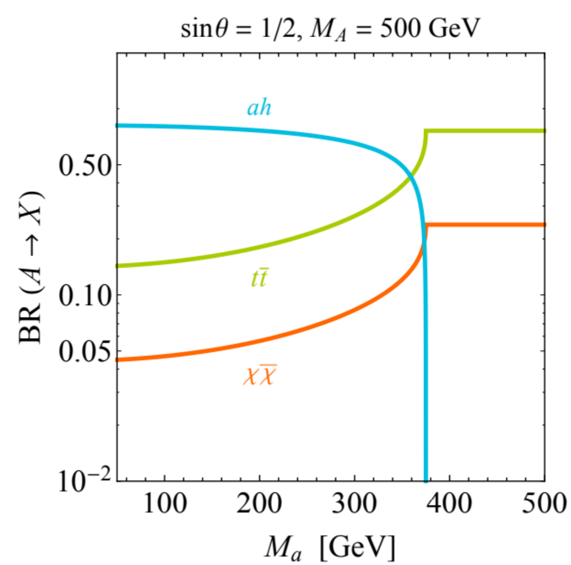
- Much stronger signals if Higgs can be produced in **decays of a new heavy particle**

Berlin et al., arXiv:1402.7074
No, arXiv:1509.01110
Bauer, FK et al., arXiv:1701.07427





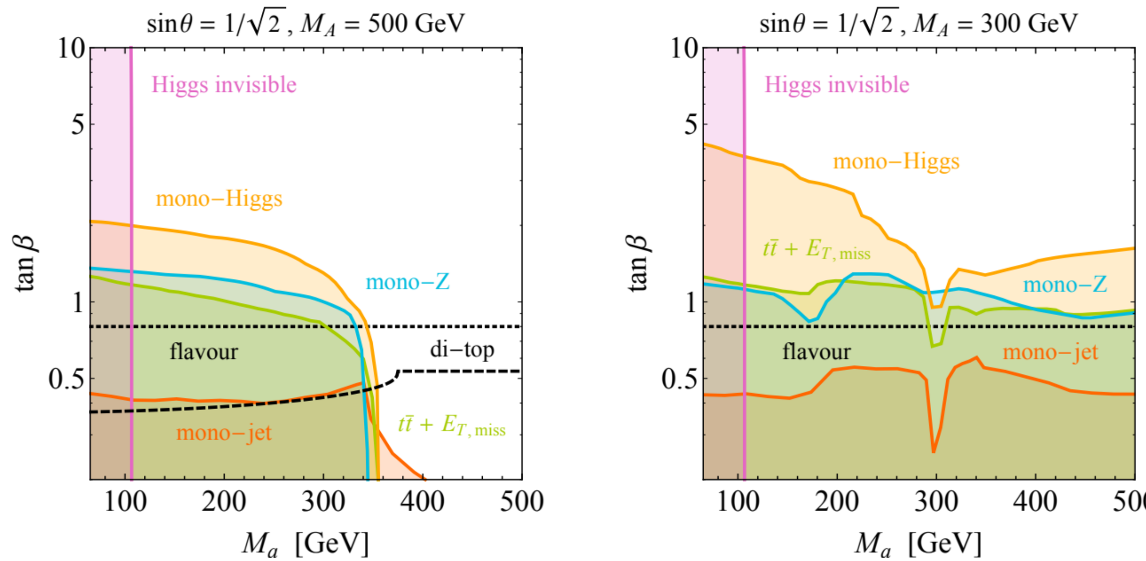




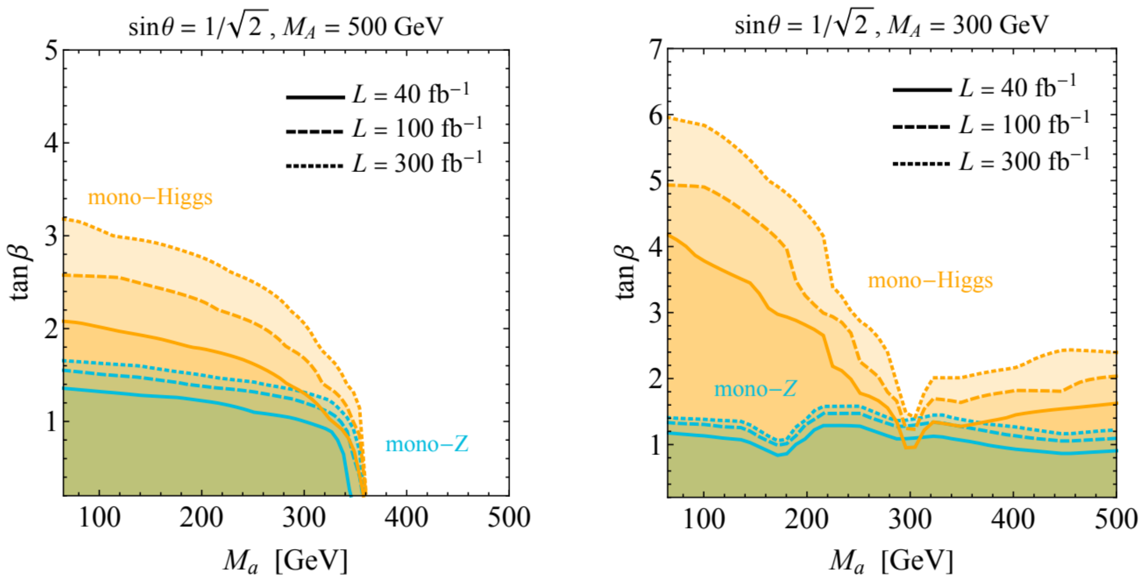
A closer look: mono-Higgs

- Example: 2HDM extensions with pseudoscalar mediator

- Mono-Higgs searches give some of the **dominant constraints** on the parameter space



Bauer, FK et al., arXiv:1701.07427



- Sensitivity (at least for $h \to \gamma\gamma$) is still **statistics limited**

- Substantial room for improvement in future searches

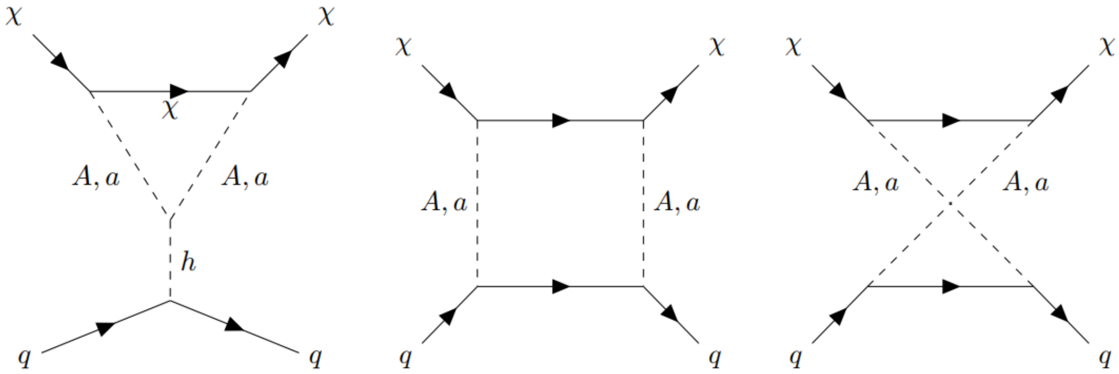
Outlook

- Current focus of the attention: **2HDM + pseudoscalar mediator**
  - Very rich model with many different signatures
  - Non-trivial constraints on the parameter space from EWPT and flavour physics

- More work needed to **understand the allowed regions** of parameter space
  - LHC DM working group: Detailed study of search channels and kinematic distributions
  - To appear soon: Whitepaper with recommended benchmark models and parameter grids

- Ongoing effort: Study direct detection and relic density constraints, including loop effects

Bell et al., arXiv:1710.10764
Arcadi et al., arXiv:1711.02110
Bell et al., arXiv:1803.01574



Instead of conclusions

From DM models to *dark sector* models

- Renormalisable DM models typically require **several new particles** in addition to the DM particle, which cannot be arbitrarily heavy

- These new particles can give rise to a **wide range of exotic signatures**:

  - Missing energy + exotic resonances (mono-Z', mono-dark-Higgs, …)

    Duerr, FK et al., arXiv:1701.08780

  - Missing energy + long-lived particles

    Buchmueller et al., arXiv:1704.06515

  - Emerging (or semi-visible) jets

    Schwaller et al., arXiv:1502.05409
    Cohen et al., arXiv:1503.00009

Many unexplored signatures – much work remains to be done!