Colored Dark Sectors at (HL-)LHC and FCC

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with
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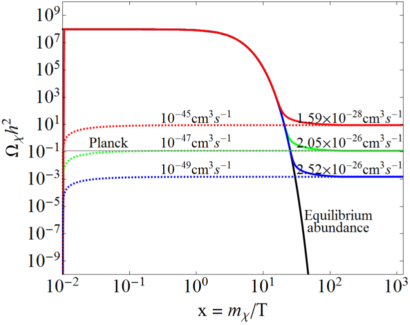
Introduction: Thermal Dark Matter

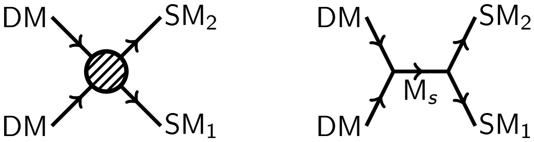
- How to explain the Dark Matter relic density?
- Assume thermal equilibrium
  DM DM ↔ SM SM
- m_{DM} and the DM-SM coupling determine the relic density
- Heavier DM mass ⇒ Larger annihilation rate



How heavy can the Dark Matter be in generic models?

Constraining thermal Dark Matter

- First step: DM ↔ SM exchange through self-annihilation
  $\Rightarrow$ EFT/Simplified Models: SM + DM (+ Mediator)
  Cirelli, Fornengo, Strumia [2005], Abdallah et al. [2015], ...



- Very tight constraints, $m_{DM} \lesssim$ a few TeV!
- Major loophole: new particle X, ***close in mass to and in thermal equilibrium with*** the DM
  $\Rightarrow$ Additional processes to deplete the Dark Matter!
- How far up can co-annihilation push the Dark Matter mass?

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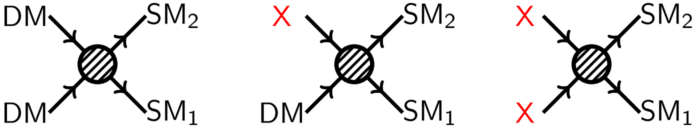

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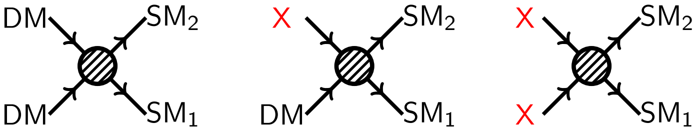
How far can we go with coannihilation?

X can be colored or charged ⇒ huge number of simplified models



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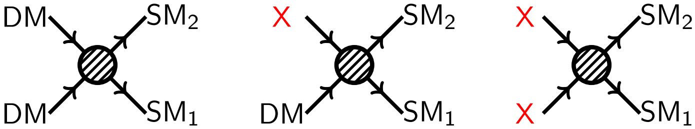

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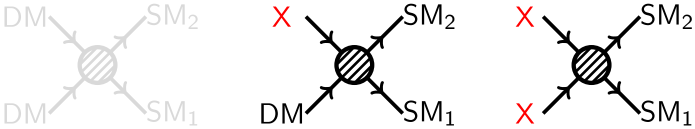

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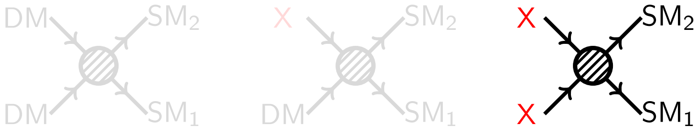

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- X X → SM SM is dominated by the strong interaction
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- If no new strong gauge group or SUSY, DM X → SM_1 SM_2 is subdominant
- The relic density and collider bounds on strongly coupled coannihilation are model-independent!

The models

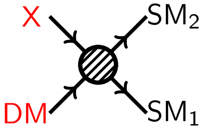
- Dark Sector: X and DM, protected by a $\mathbb{Z}_2$ symmetry
- $SU(2) \times U(1)$ effects neglected ⇒ DM is a SM singlet
- X is a triplet, sextet or octet of $SU(3)$
- X and DM are scalars, vectors or fermions
- For this talk...keep the spin fixed, vary the color:

$$\mathrm{DM_F} + \mathrm{X_{F3}} \qquad \mathrm{DM_F} + \mathrm{X_{F6}} \qquad \mathrm{DM_F} + \mathrm{X_{F8}}$$

- Only interaction(s): $\mathrm{X\,X}\,g$ $(\mathrm{X\,X}\,g\,g)$
- Not a viable theory of Dark Matter yet...

The DM-X interaction

- Necessary for X decay and chemical/thermal equilibrium
- Negligible for (co)annihilation and collider studies
  $\Rightarrow$ *Use effective operator!*



$$\mathcal{L} \propto \frac{C_{ijk}}{\Lambda^n} \mathrm{DM}\,\mathrm{X_i}\,\mathrm{SM}_{1j}\,\mathrm{SM}_{2k}$$

- Introduced for models with scalar and fermion X
- Mediator out of the reach of the LHC/FCC $\Rightarrow \Lambda = 10/50$ TeV
- SM_1 and SM_2 chosen to be quarks or gluons
  $\Rightarrow$ *Weakest possible collider bounds (soft jets)*

$$\boxed{\mathcal{L} = \mathcal{L}_{\mathrm{DM}} + \mathcal{L}_{\mathrm{X}} + \mathcal{L}_{\mathrm{DM+SM}}}$$

Constraints

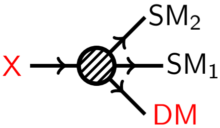
"Model-independent" constraints

- Relic density requirement
  Annihilation through $XX \to q\bar{q}, gg$
- LHC/FCC searches
  Pair-production of X

Constraints on the DM X SM$_1$ SM$_2$ interaction

- X decay rate
  Avoid long-lived particle searches at colliders
- Chemical/Thermal equilibrium
  Ensure conversion of DM into X before freeze-out

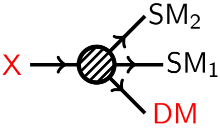
Lifetime – LHC



$$\propto \frac{m_{\mathrm{DM}}^{2n+1}\Delta^{k}}{(10\ \mathrm{TeV})^{2n}}\left[\times\frac{1}{(16\pi^{2})^{2}}\right]$$

- X decay rate only depends on m_{DM} and $\Delta = \frac{m_{\mathrm{X}}-m_{\mathrm{DM}}}{m_{\mathrm{DM}}}$
- Long-lived X strongly constrained by LHC R-hadron searches
- Exclude $(m_{\mathrm{DM}}, \Delta)$ for which *at least one* particle travels through the beam pipe $d_{\mathrm{beam}} \sim 2.5$ cm at a given luminosity
- Constant upper bound on the mass splitting, $m_{\mathrm{X}} - m_{\mathrm{DM}} \gtrsim 20$ GeV for $\mathrm{DM_F} - \mathrm{X_{F6}}, \mathrm{X_{F8}}$ at 3 ab^{-1}

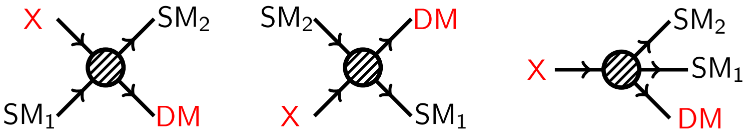
Lifetime – FCC-hh



$$\propto \frac{m_{\rm DM}^{2n+1}\Delta^{k}}{(50\ \text{TeV})^{2n}}\left[\times\frac{1}{(16\pi^{2})^{2}}\right]$$

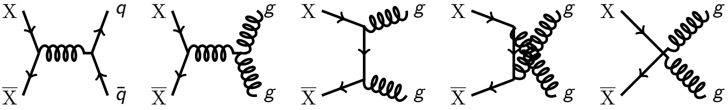
- X decay rate only depends on $m_{\rm DM}$ and $\Delta = \frac{m_{\rm X}-m_{\rm DM}}{m_{\rm DM}}$
- Large boosts at FCC-hh $\Rightarrow$ significant improvement of the reach of the R-hadron searches
- Exclude $(m_{\rm DM}, \Delta)$ for which *at least one* particle travels through the beam pipe $d_{\rm beam} \sim 2.5$ cm at a given luminosity
- Upper bound on the mass splitting, $m_{\rm X} - m_{\rm DM}$ from 50 to 150 GeV for X_{F8} at 3 ab^{-1}

Thermal equilibrium



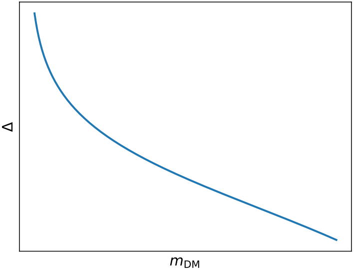
- Γ(DM $\leftrightarrow$ X) must be larger than the Hubble rate at freeze-out
- Weaker than the X lifetime constraints for most of our models
- Non-trivial constraints at large Δ for loop-suppressed operators, such as in $\mathrm{DM_S} - \mathrm{X_{F3}}$

Relic density



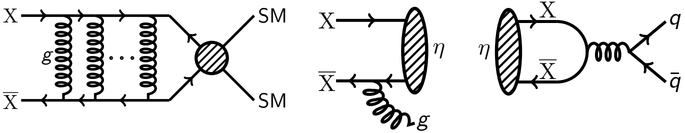
- Dominated by $X\overline{X} \to q\bar{q}, gg$ annihilation cross sections
- Depends only on $m_{\rm DM}$ and $\Delta = \frac{m_X - m_{\rm DM}}{m_{\rm DM}}$

$$\sigma_{\rm ann} \propto \frac{m_{\rm DM}^{-2}}{\left[1 + \frac{g_{\rm DM}}{g_X} e^{x_{FO}\Delta}\right]^2}$$



- What about non-perturbative effects?

Sommerfeld effect and bound state formation



- Long-range interactions caused by gluon exchange
- Strongest effects at low velocity – Coulomb interaction between initial states

Sommerfeld effect

- Analytical solutions for LO partial-waves ($L, S,$ Color)
  De Simone et al. [arXiv:1402.6287], Cassel [arXiv:0903.5307], Iengo [arXiv:0902.0688]
- Extension: include subleading order partial waves

Bound state formation and decay

- Considered only s-wave color singlet bound states. Follow the procedure described in Liew, Luo [arXiv:1611.08133]
- Alternate strategy in Mitridate et al. [arXiv:1702.01141]

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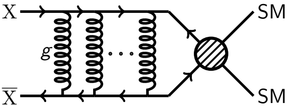

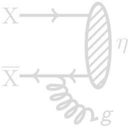

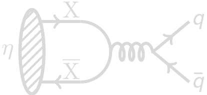

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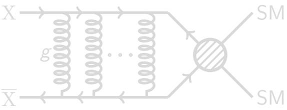

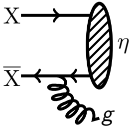

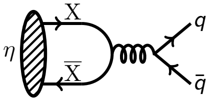

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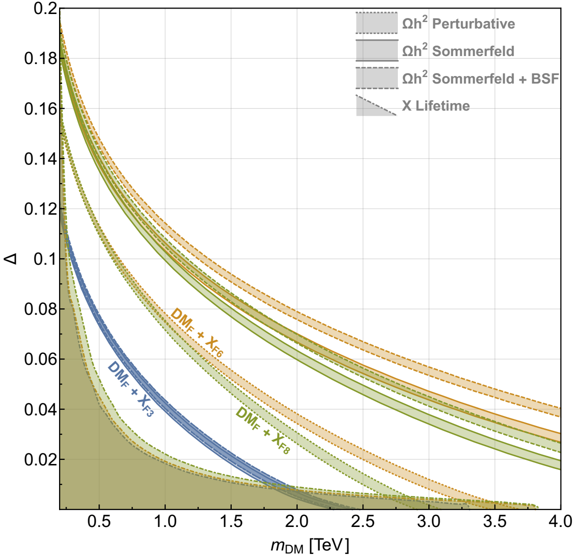
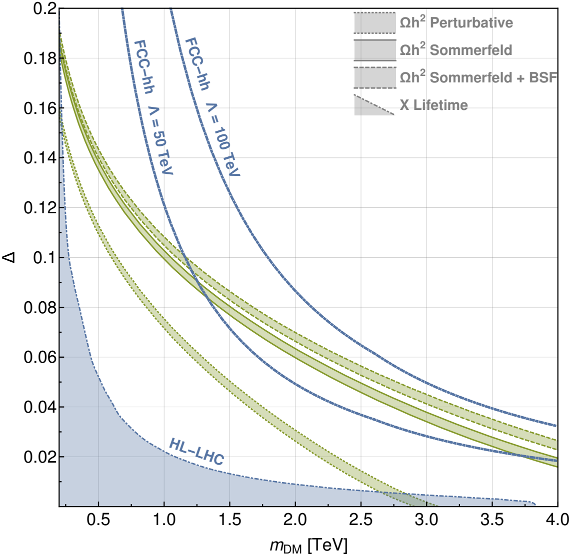
Results: $\mathrm{X_F} - \mathrm{DM_F}$

- Strong Sommerfeld corrections for most models
- Negligible non-perturbative effects for $\mathrm{DM_F} - \mathrm{X_{F3}}$
- Upper bound on the DM mass of up to 10 TeV!
- Lifetime of X $\Delta \gtrsim 0.5\%$

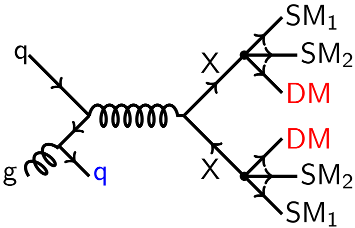


Lifetimes: $\mathrm{X_{F8}} - \mathrm{DM_F}$

- Strong boosts + large X_{F8} production rates $\Rightarrow$ huge improvement compared to HL-LHC!
- Searches for LLPs will be crucial to understand coannihilating DM models at FCC
- Complementary work: reintroduce the mediator...



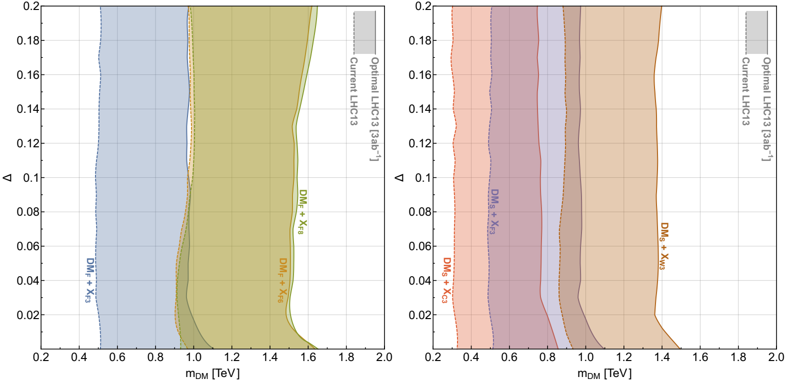
Collider Searches



- 1,2 hard jets + $\not{E}_T$ + soft jets
- m_X dependence through the production rate
- *Weak* Δ dependence for multijet searches

- At low Δ: traditional monojet signature
  ATLAS 3.2 fb^{-1} [arXiv:1604.07773], CMS 12.9 fb^{-1} CMS-PAS-SUS16-06
  - Hard cuts on $\not{E}_T$ and first jet p_T
  - Extra jets tolerated under certain conditions
- $\Delta > 2\%$: multijet searches…"monojet-like" channel
  ATLAS 13.3 fb^{-1} ATLAS-CONF-2016-078, CMS 12.9 fb^{-1} CMS-PAS-SUS16-014
  - Hard cuts on $\not{E}_T$ and first jet p_T
  - Mild cuts up to the 4th extra jet

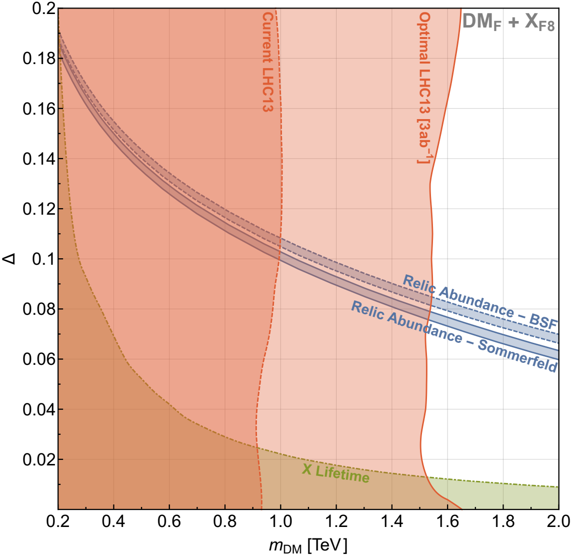
Results – (HL-)LHC



- From current to 3000 fb^{-1} with *no systematics*
- With current systematics, no dependence in the luminosity
- Optimal limits around 1 TeV — Very weak dependence in Δ

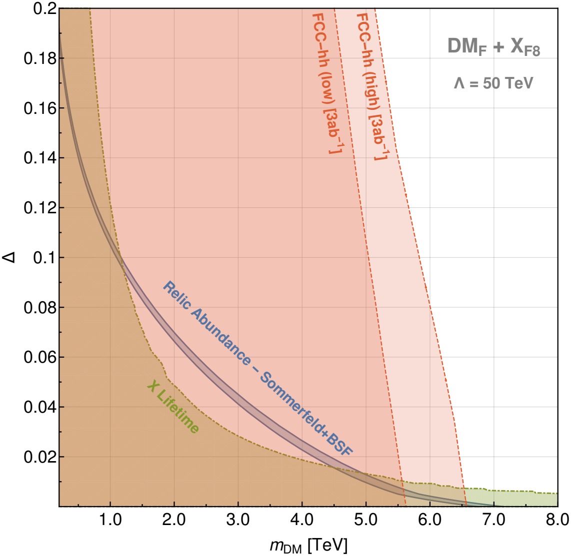
Combined constraints (LHC) – $\mathrm{X}_{\mathrm{F8}} - \mathrm{DM}_{\mathrm{F}}$

- Current constraints
  $\Delta \lesssim 10\%$
- Optimal constraints
  $\Delta \lesssim 8\%$
- Upper bound around 7 TeV from relic
- The LHC mass reach is far too low...what happens at higher CM energy?



Combined constraints at FCC-hh – X_{F8} – DM_{F}

- Use Snowmass search for compressed gluinos
  Cohen et al, [arXiv:1311.6480]
- FCC-hh could probe the full parameter space of colored dark sector models!
- "Very compressed region" $\Delta \lesssim 0.5\%$: excellent motivation for LLP searches even if the mediator is resolved...



Conclusion

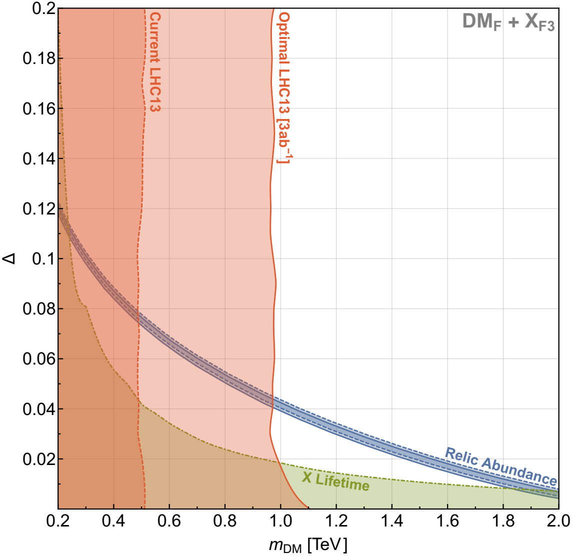
- Coannihilation with a strongly interacting particle is the simplest mechanism to loosen the bounds on thermal Dark Matter models
- *Generically*, self-annihilation of X with strong couplings will drive the Dark Matter depletion $\Rightarrow$ model-independent bounds can be derived!
- Upper bounds on the DM mass pushed from a few TeV up to more than 10TeV
- The LHC can probe all the way down to $\Delta \sim 10\%$ for all models
- FCC-hh can cover *all* the remaining region
- Searches for long-lived particles are complementary to the jets $+ \not{E}_T$ searches and will be crucial in covering the high mass/low Δ region

Combined constraints – $\mathrm{X}_{\mathrm{F3}} - \mathrm{DM}_{\mathrm{F}}$

- Current constraints

  $\Delta \lesssim 8\%$
- Optimistic constraints

  $\Delta \lesssim 4\%$
- *Upper* bound at 2 TeV from X lifetime
- The LHC selects a “wedge” in the parameter space



The DM X SM_1 SM_2 interaction

- Choose the lowest possible dimensionality

$$\mathcal{L}_{\mathrm{DM_F+X_{F3}}} = \frac{1}{\Lambda^2}\epsilon_{kij}\left(\bar{\psi}_k\psi_{\mathrm{DM}}\right)\left(\bar{d}_{R,i}u^C_{R,j}\right)$$
$$\mathcal{L}_{\mathrm{DM_S+X_{C3}}} = \frac{1}{\Lambda}\epsilon_{kij}\left(S_{\mathrm{DM}}S_k\right)\left(\bar{d}_{R,i}u^C_{R,j}\right)$$
$$\mathcal{L}_{\mathrm{DM_S+X_{F3}}} = \frac{1}{16\pi^2\Lambda^2}T^a_{ij}S_{\mathrm{DM}}\left(\bar{d}_{R,i}\sigma^{\mu\nu}\psi_j\right)G^a_{\mu\nu}$$

- Operators involving gluons are loop-suppressed
  $\Rightarrow$ *Choose quarks over gluons whenever possible*
- Most suppressed operator: $\mathrm{DM_S+X_{F3}}$ (loop factor + dimension 6)

$$\boxed{\mathcal{L} = \mathcal{L}_{\mathsf{DM}} + \mathcal{L}_{\mathsf{X}} + \mathcal{L}_{\mathsf{DM+SM}}}$$

Results: $X_3 - DM_S$

- $m_{DM} \lesssim$ a few TeV for triplet models
- Color stronger than spin due to non-perturbative effects
- Non-trivial lifetime and equilibrium constraints for loop-suppressed effective operators