LHC Phenomenology of DM Coannihilations

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[arXiv:1612.02825]
[arXiv:1703.00452]

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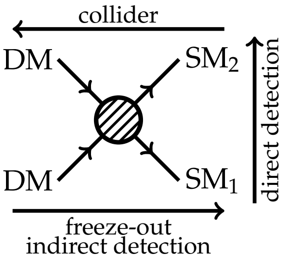
INTRODUCTION

- Dark matter (DM) is observed using gravitational probes, but we are ignorant about its particle identity
- The thermal hypothesis: elegant explanation of current DM relic density that implies DM interactions with the SM
- DM annihilation implies direct detection, indirect detection and collider (LHC) signatures through crossing symmetry

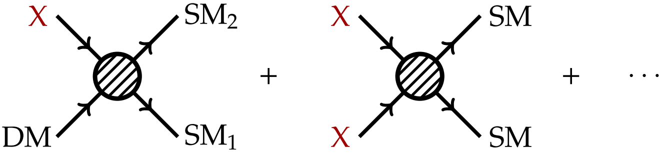


- Simple WIMP picture leads to tight relations between different probes, however many ways out. Examples: Non-thermal DM, Multicomponent DM, Coannihilation, ...

COANNIHILATION

[Griest & Seckel 1991]
[Coannihilation Codex arXiv:1510.03434]

- Focus on the mechanism of coannihilation, ingredients:
  - Additional particle in dark sector, called X
  - Low mass splitting: $\Delta = \frac{m_X - m_{DM}}{m_{DM}} \lesssim \mathcal{O}(20\%)$ (X is colored)
  - Set of interactions mediating DM X $\to$ SM_1 SM_2
- Relic density set by the processes:



- Sizable contributions from coannihilation to the relic abundance alleviate the tight connection between the different DM detection probes (especially if X is colored)
- Direct and indirect detection rates are suppressed and novel strong LHC signatures may appear depending on the nature of X and the coannihilation mechanism

COLORED DARK SECTORS

[arXiv:1402.6287 De Simone et al.]
[arXiv:1611.08133 Liew & Luo]
[arXiv:1703.00452 El Hedri et al.]

Ingredients of a colored dark sector:

- Dark sector particles protected by a symmetry (e.g. $\mathbb{Z}_2$)
- One DM candidate (scalar, fermion, vector and real, complex)
- One colored coannihilation partner X (scalar, fermion, vector and **3**, **6**, **8** of $SU(3)_c$)
- Some interaction connecting DM and X

We have 6 possible DM candidates and 12 possible X candidates giving 72 different models, we consider

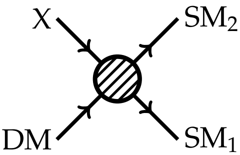
$$\mathrm{DM_F} + \mathrm{X_{F3}} \qquad \mathrm{DM_F} + \mathrm{X_{F6}} \qquad \mathrm{DM_F} + \mathrm{X_{F8}}$$
$$\mathrm{DM_S} + \mathrm{X_{C3}} \qquad \mathrm{DM_S} + \mathrm{X_{F3}} \qquad \mathrm{DM_S} + \mathrm{X_{W3}}$$

Further assumptions:

- DM is a SM-singlet (self-annihilations are negligible)
- Relic density set by self-annihilations of X

CONNECTING DM AND X

- Thermal and chemical equilibrium between DM and X:
  $\mathrm{DM}\,\mathrm{SM}_1 \leftrightarrow \mathrm{X}\,\mathrm{SM}_2, \quad \mathrm{DM}\,\mathrm{SM}_2 \leftrightarrow \mathrm{X}\,\mathrm{SM}_1, \quad \mathrm{X} \leftrightarrow \mathrm{DM}\,\mathrm{SM}_1\,\mathrm{SM}_2$
- Lifetime of X, long-lived colored particles are tightly constrained (LHC and early universe)

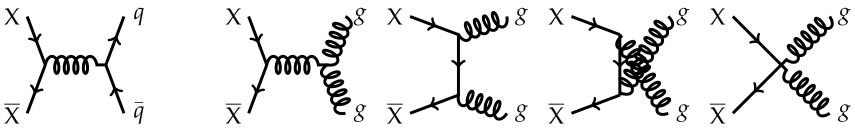


- SM_1 and SM_2 depend on nature of DM and X
- Mediator of EFT operator beyond LHC reach
- Suppression scale fixed $\Lambda = 10$ TeV
- Connection between DM and X is weak

- X can decay through EFT operator: $\mathrm{X} \rightarrow \mathrm{DM}\,\mathrm{SM}_1\,\mathrm{SM}_2$
- Most stringent arise limits from LHC searches
- Set limits by requiring at most one event for which X leaves the beam pipe using LHC13 with 3 ab^{-1}

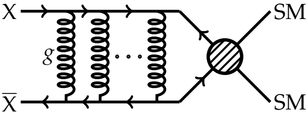
RELIC DENSITY

- Each model has two free parameters m_{DM} and $\Delta = \frac{m_X - m_{\mathrm{DM}}}{m_{\mathrm{DM}}}$
- $X\,X \to \mathrm{SM}\,\mathrm{SM}$ annihilation dominant over $\mathrm{DM}\,X \to \mathrm{SM}_1\,\mathrm{SM}_2$



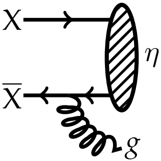
- Determine regions giving the measured relic abundance in the Δ vs. m_{DM} plane
- DM effective annihilation more efficient if:
  - Low mass and low Δ
  - DM has less degrees of freedom
  - X has a high annihilation rate and less degrees of freedom
- Corrections to annihilation cross section by Sommerfeld effects and bound state formation processes

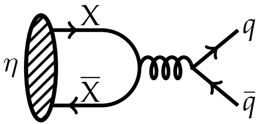
Sommerfeld Corrections & Bound States



[arXiv:1612.02825 El Hedri, Kaminska, MdV]

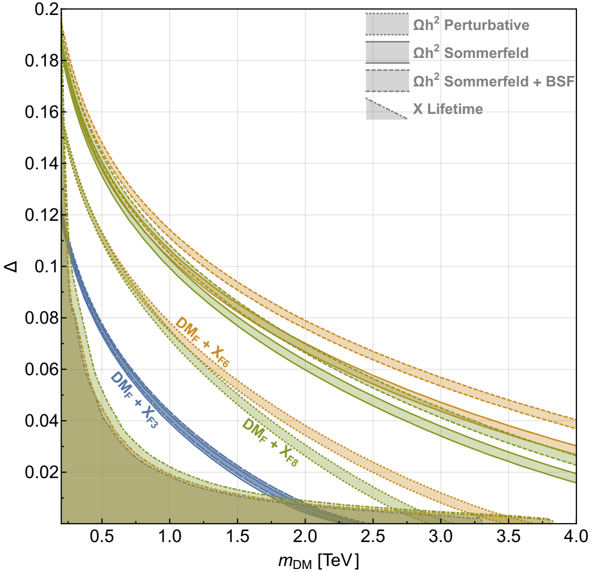
- Non-perturbative Sommerfeld corrections due to soft gluon exchanges in $X\,\overline{X} \to gg/q\bar{q}$
- Corrections for s-wave QCD described in [arXiv:1402.6287 De Simone et al.]
- Higher partial waves for Coulomb potential known [arXiv:0903.5307 Cassel] [arXiv:0902.0688 Iengo]
- We combine treatments expanding amplitudes in $l+s$ to get analytical correction factors for higher partial waves for QCD potentials (convergence now in wave number l)





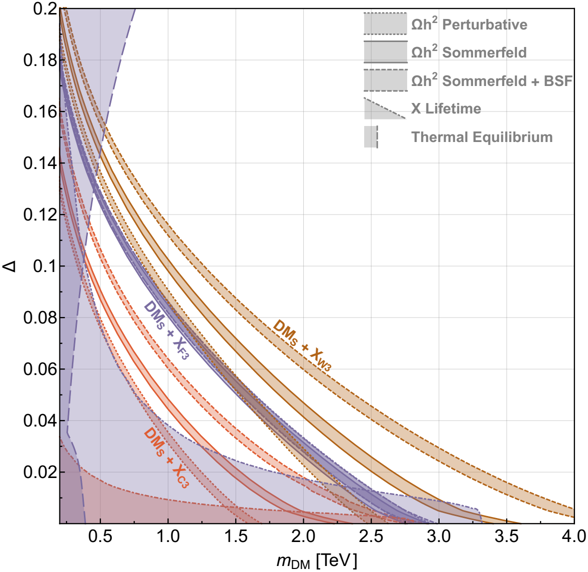
- BSF treatment for colored particles in [arXiv:1611.08133 Liew & Luo]
- Alternative treatment including non-Abelian effects, etc. in [arXiv:1702.01141 Mitridate et al.]

RELIC DENSITY (MODELS I)



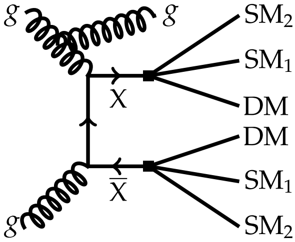
- Lifetime constraints are relevant
- Region of correct relic abundance in LHC range
- Sommmerfeld corrections and bound state formation sizable, especially at high masses
- $\mathrm{DM_F} + \mathrm{X_{F3}}$ no corrections: QCD potential repulsive for annihilations into $q\bar{q}$ and attractive for gg

RELIC DENSITY (MODELS II)



- Lifetime constraints are relevant
- Region of correct relic abundance in LHC range
- Sommmerfeld corrections and bound state formation sizable, especially at high masses
- Thermal equilibrium constraints relevant for $\mathrm{DM_S} + \mathrm{X_{F3}}$, because EFT is loop-suppressed and dimension 6

LHC PROBES

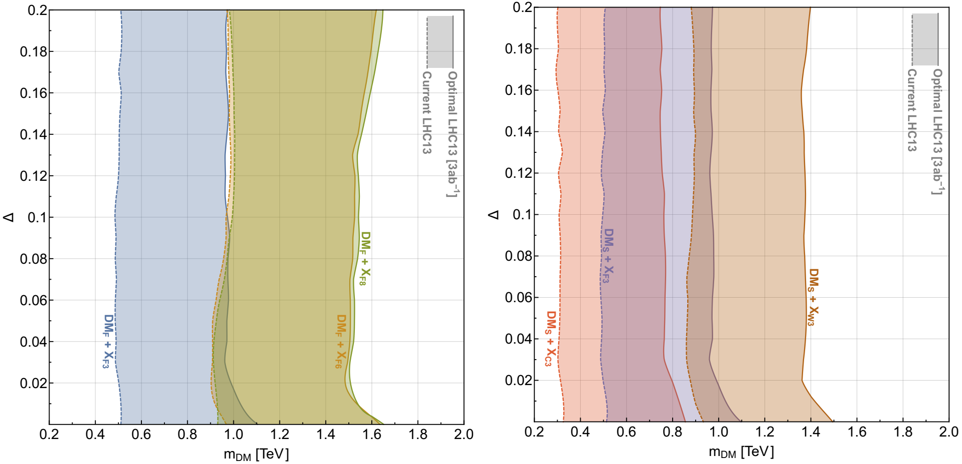


- $SM_{1/2}$ manifest themselves as jets
- Jets from X decay are soft for low Δ
- Soft jets become visible around $\Delta = 0.2$
- Hard jets from ISR

Topology gives hard jets + soft jets + MET, captured by:

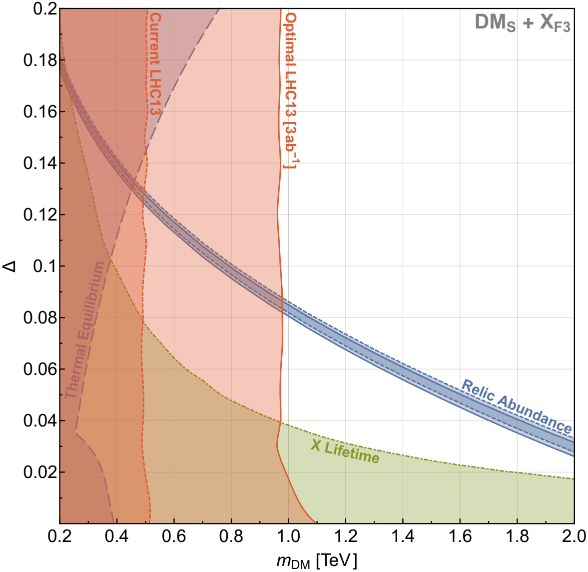
- Monojet + MET:
  [ATLAS 3.2 fb^{-1} arXiv:1604.07773] [CMS 12.9 fb^{-1} CMS-PAS-SUS-16-016]
- Jets + MET:
  [ATLAS 13.3 fb^{-1} ATLAS-CONF-2016-078] [CMS 12.9 fb^{-1} CMS-PAS-SUS-16-014]
- Now new results available (not included):
  [ATLAS-CONF-2017-022 (Jets + MET)] [CMS-PAS-SUS-16-036 (Jets + MET)]

LHC EXCLUSIONS



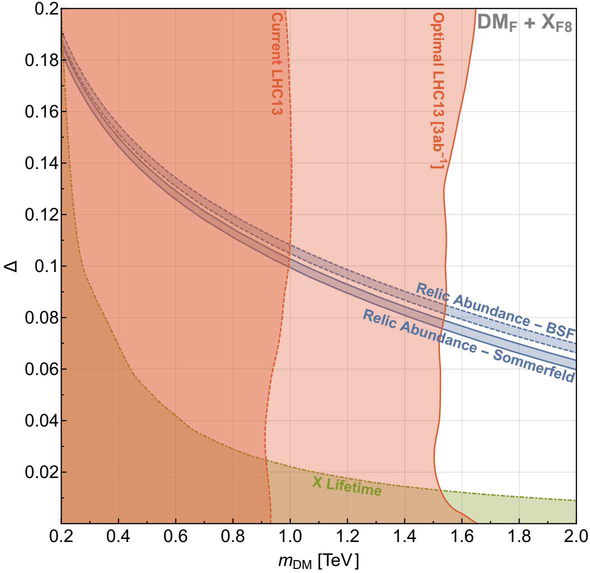
- Current: LHC13 run I with Monojet + MET and Jets + MET
- Optimal: LHC13 with $3ab^{-1}$ and no systematic error

Combinations: $DM_S + X_{F3}$



- Current limits:
  Monojet 3.2 fb^{-1}
  Jets + MET 13.3 fb^{-1}
- Optimal limits assume no systematic errors
- LHC can still discover/exclude a large region of the dark sector thermal relic parameter space
- Parameter space is closed by direct searches and constraints on the lifetime of X

COMBINATIONS: $\mathrm{DM_F} + \mathrm{X_{F8}}$



- Current limits:
  Monojet 3.2 fb^{-1}
  Jets + MET 13.3 fb^{-1}
- Optimal limits assume no systematic errors
- LHC can still discover/exclude a large region of the dark sector thermal relic parameter space
- Higher color representations lead to high masses beyond the reach of LHC, even $m_{\mathrm{DM}} \sim 10$ TeV for $\Delta = 0$

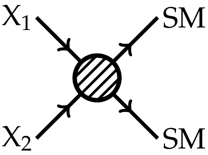
Multiple Coannihilation Partners

What happens if we add more coannihilation partners (X_2)?

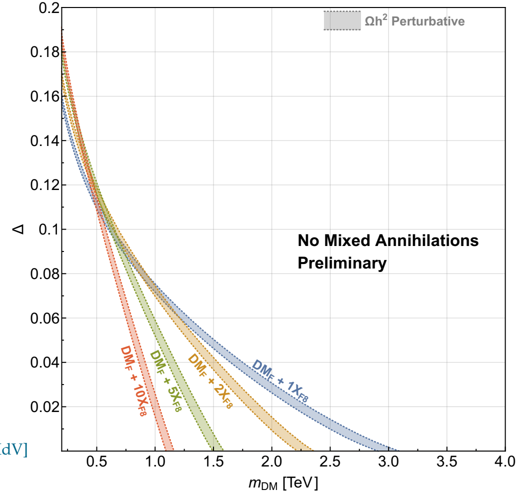
MULTIPLE COANNIHILATION PARTNERS

What happens if we add more coannihilation partners (X_2)?

- New mixed annihilation channel:



- Generically much weaker than $X_1\, X_1 \rightarrow$ SM SM
- LHC limits improve due to higher production rates
- Multiple X are more constrained [Work in Progress El Hedri, MdV]



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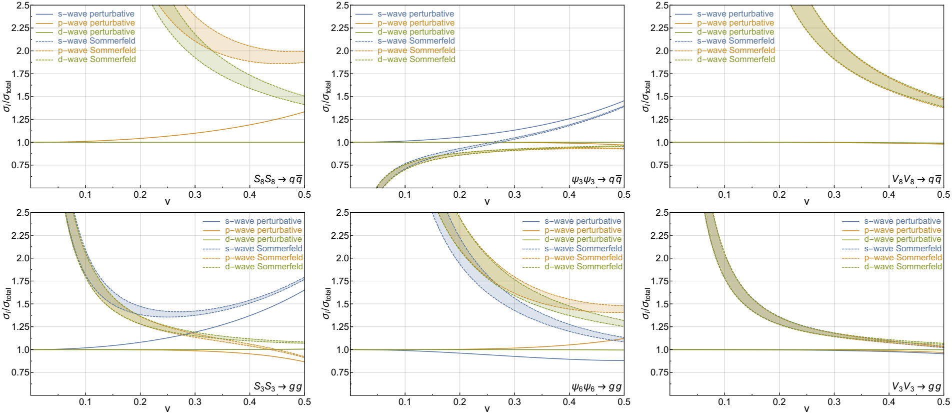
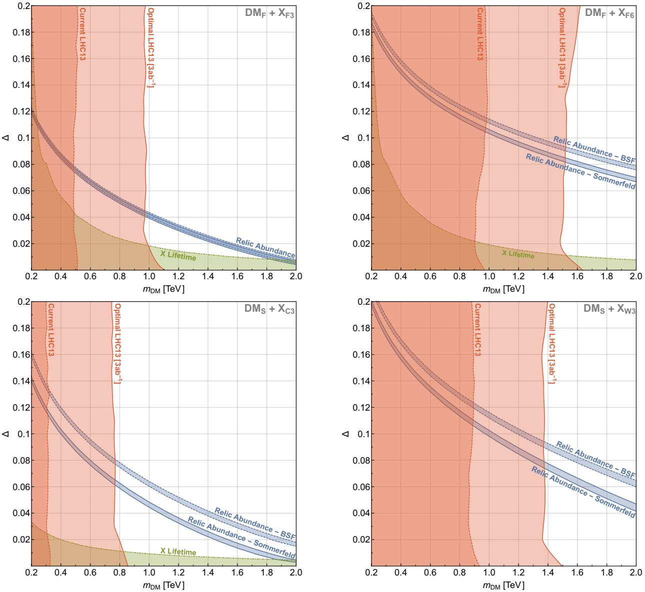
Thank you for your attention!

SOMMERFELD CORRECTIONS

- Correction factors for X X → SM SM cross sections
- In general enhancement factors
- Suppression for fermion triplets to $q\,\bar{q}$
- Bands show mass range $500 \leq m_X \leq 2500$ GeV



COMBINATIONS: OTHER MODELS

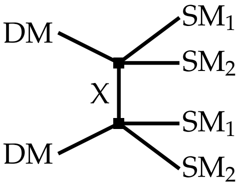


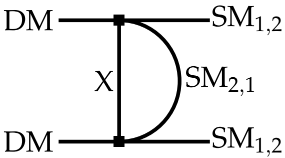
DIRECT AND INDIRECT DETECTION

Direct detection takes place through effective operators:

- DM DM $H^\dagger H$: loop-suppressed and proportional to Higgs portal coupling which can be set to zero
- DM DM $G^a_{\mu\nu} G^{a\mu\nu}$: suppressed by a loop factor and two/three powers of heavy mass, leading to negligible σ_{direct}
- DM DM $\psi_{\text{SM}} \bar{\psi}_{\text{SM}}$: suppressed by one/two powers of heavy mass

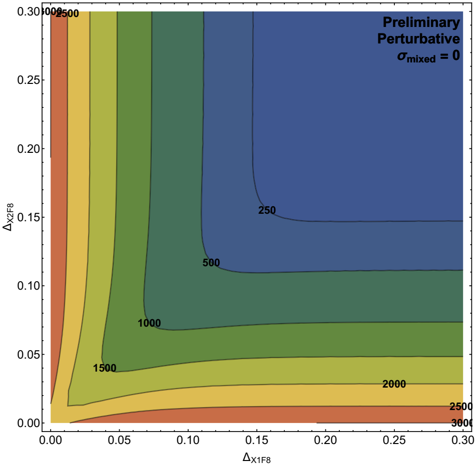
Indirect detection suppressed by the absence of direct DM self-annihilations, alternatives are:

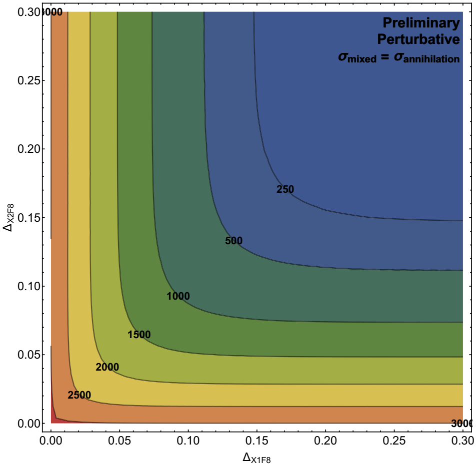




DM DM $\to$ 4 SM is phase-space suppressed and DM DM $\to$ 2 SM is loop suppressed, hence indirect detection is challenging

MULTIPLE COANNIHILATION PARTNERS





- Contours of m_{DM} required to explain measured relic density
- Allowing for different Δ_i does not change conclusions
- Only substantial mixing ($\sigma_{\text{mixed}} \gtrsim \sigma_{\text{annihilation}}$) changes results