Technische Universität München

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Phenomenological Implications of Non-Perturbative Effects for Colored Dark Sectors

in collaboration with

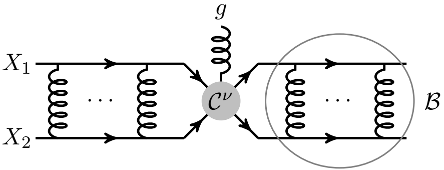
Emanuele Copello, Julia Harz, Kirtimaan Mohan and Dipan Sengupta

supported by DFG Emmy Noether Grant No. HA 8555/1-1.

Mathias Becker

SUSY 2021

Sommerfeld Effect and Bound State Formation



n-gluon exchanges contribute with $\left(\frac{\alpha}{v}\right)^n$ for $\alpha \sim v$

Sommerfeld effect

$$\sigma(X_1 X_2 \to SM\,SM) = S\left(\frac{\alpha}{v}\right)\sigma_{\text{pert.}}$$

Bound State Formation (BSF)

$$\sigma(X_1 X_2 \to \mathcal{B}(X_1 X_2)\; g) = \sigma_{\text{BSF}}$$

Bound state as an additional particle in the thermal bath.

Figure from [Harz,Petraki (2018)]

Simplified t-Channel Dark Matter

Universal framework for t-channel DM models [Arina,Fuks,Mantani (2020)]

S3M-uR t-channel Dark Matter

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{kin,BSM}} + g_{\mathrm{DM}}\overline{\chi}(u_R)_i(X^\dagger)_i + h.c.$$

$$\chi = (\mathbf{1},\mathbf{1})_0 \qquad X_i = (\mathbf{3},\mathbf{1})_{2/3}$$

- Discrete $\mathcal{Z}_2$: SM fields even, dark sector fields odd
- Majorana fermion DM to avoid direct detection constraints from Z vector current
- 3 generation of mediator fields that couple democratically diagonally to the SM quarks
- Parameters: $(M_\chi, \Delta = M_X - M_\chi, g_{\mathrm{DM}})$

Annihilation Channels

Process: $(X_1)_{\mathbf{R_1}} + (X_2)_{\mathbf{R_2}} \to \mathcal{B}(X_1 X_2)_{\mathbf{R}} + g$

Color Potential

$$V(r) = -\frac{\alpha_s}{2r}\left[C_2(\mathbf{R_1}) + C_2(\mathbf{R_2}) - C_2(\mathbf{R})\right]$$

Color Configurations

$$\mathbf{3} \times \overline{\mathbf{3}} = \mathbf{1} + \mathbf{8}$$

$$\mathbf{3} \times \mathbf{3} = \overline{\mathbf{3}} + \mathbf{6}$$

- Only **1** and $\overline{\mathbf{3}}$ provide attractive potential.
- $\overline{\mathbf{3}}$ BSF suppressed compared to **1**.

Annihilation Channels

Process	Contribution to $\langle \sigma_{\text{eff}} v \rangle$	Color Structure	BSF
$\chi\chi \to q_i \bar{q}_i$	g_{DM}^4	none	✗
$X_i X_j^* \to gg$	$g_{\text{DM}}^2 g_s^2 \exp\left(-2x \frac{\Delta}{M_\chi}\right)$	$\|\mathcal{M}\|^2 \sim \frac{2}{7}[\mathbf{1}] + \frac{5}{7}[\mathbf{8}]$	✓
$X_i X_j \to q_i q_j$	$g_{\text{DM}}^4 \exp\left(-2x \frac{\Delta}{M_\chi}\right)$	$\|\mathcal{M}\|^2 \sim \frac{1}{3}[\bar{\mathbf{3}}] + \frac{2}{3}[\mathbf{6}]$	(✓)
$X_i X_i \to q_i q_i$	$g_{\text{DM}}^4 \exp\left(-2x \frac{\Delta}{M_\chi}\right)$	$\|\mathcal{M}\|^2 \sim [\mathbf{6}]$	(✓)
$X_i X_j^* \to q_i \bar{q}_j$	$(\alpha g_{\text{DM}}^2 + \beta g_s^2)^2 \exp\left(-2x \frac{\Delta}{M_\chi}\right)$	$\|\mathcal{M}\|^2 \sim f_1(g_{\text{DM}}, g_s)[\mathbf{1}] + f_8(g_{\text{DM}}, g_s)[\mathbf{8}]$	✓
$X_i \chi \to q_i g/Z/\gamma$	$g_{\text{DM}}^2 g_s^2 \exp\left(-x \frac{\Delta}{M_\chi}\right)$	none	✗

Assumptions during DM freeze-out:

- Dark sector in *kinetic* eq. with the SM.
- Dark sector particles in *chemical* eq. with themselves.

Coannihilation

$$\langle \sigma_{\text{eff}} v \rangle = \sum_{i,j} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{\text{eq}}}{n^{\text{eq}}} \frac{n_j^{\text{eq}}}{n^{\text{eq}}}$$

- Dark sector in *kinetic* eq. with the SM.
- Dark sector particles in *chemical* eq. with themselves.

Coannihilation

$$\langle \sigma_{\mathrm{eff}} v \rangle = \sum_{i,j \in \{\chi, X\}} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{\mathrm{eq}}}{n^{\mathrm{eq}}} \frac{n_j^{\mathrm{eq}}}{n^{\mathrm{eq}}} + \langle \sigma_{\mathrm{BSF}} v \rangle_{\mathrm{eff}} \frac{n_X^{\mathrm{eq}}}{n^{\mathrm{eq}}} \frac{n_X^{\mathrm{eq}}}{n^{\mathrm{eq}}}$$

Bound states effectively provide an additional annihilation channel.

Bound State contribution to $\langle \sigma_{\mathrm{eff}} v \rangle$

$$\langle \sigma_{\mathrm{BSF}} v \rangle_{\mathrm{eff}} = \langle \sigma_{\mathrm{BSF}} v \rangle \frac{\Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{ion}} + \Gamma_{\mathrm{decay}}}$$

$\rightarrow$ BSF only contributes to the annihilation cross section of DM if the bound states decay into SM particles!

Calculation of the Relic Density

We adjusted micrOMEGAs 5.2.7 such that

- the Sommerfeld effect is included for colored scalars up to the adjoint representation
- Bound state effects are included for colored scalars up to the adjoint representation

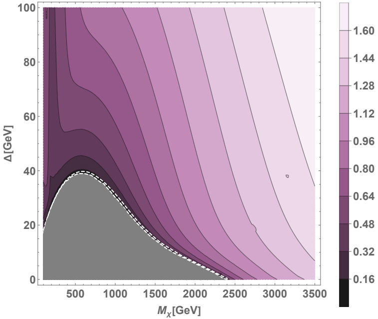
Determine $g_{DM,0}$ for each data point (M_χ, Δ) such that DM is *not* overproduced.

For instance, we find $g_{DM,0}\left(M^{\text{u.b.}}, 0\right) = \sqrt{4\pi}$ for

Upper Bound on the DM mass

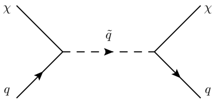
$$\left\{M^{\text{u.b.}}_{\text{pert.}}, M^{\text{u.b.}}_{\text{Som.}}, M^{\text{u.b.}}_{\text{BSF}}\right\} = \{7.2, 6.7, 21.1\}\ \text{TeV}$$

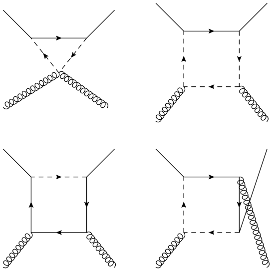
Lower bound on g_{DM}



- Gray region: No lower bound on g_{DM} can be found in the context of conventional freeze-out production.
- Within the white dashed lines: g_{DM} small enough to allow for long lived particles at colliders.

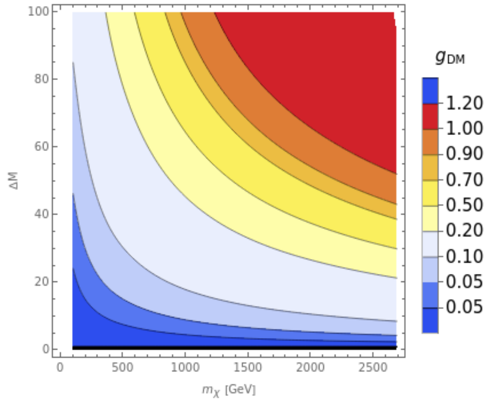
Direct Detection [Mohan et. al (2019)]





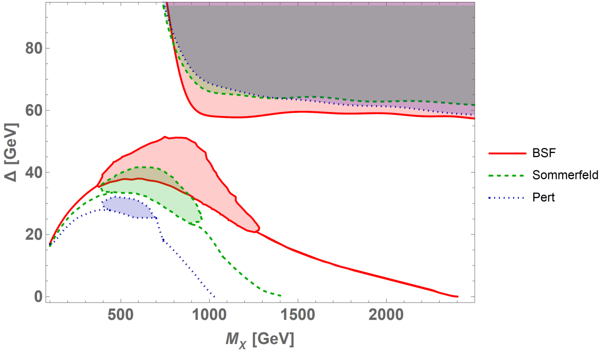
- Wilson coefficients of the effective *DM-q*/*DM-g* interaction are RGE evolved from $\mu \sim M_X$ to $\mu \sim \mathrm{GeV} \to$ factor ~ 2 on amplitude level. [Mohan et. al (2019)]
- 1-loop or velocity suppressed SI contribution typically more constraining than spin-dependent limits (for coannihilating regions).

Direct Detection



Strong constraints for small mass splittings.

Exclusion Limits from Direct Detection



- BSF has a sizable impact for small mass splittings.
- Shift in largest allowed mass from $M_\chi \sim 1\,\mathrm{TeV}$ to $M_\chi \sim 2.5\,\mathrm{TeV}$ for $\Delta \to 0$.
- Viable region for $\Delta \sim 100\,\mathrm{GeV}$ slightly enlarged.

Upcoming Collider Constraints

Three types of processes:

- Mediator pair production: $g\,g \to X\,X^*$
- Associated production: $q\,g \to \chi + X$
- DM pair production with an initial state jet: $g\,q \to \chi\,\chi\,q$

Using data from:

- mono-jet + $\not{E}_T$ [Atlas (2021)]
- multi-jet + $\not{E}_T$ [Atlas (2020)]

Small coupling (freeze-out) regions potentially constrained by

- Heavy Stable Charged Particle (HSCP) searches
- Displaced Vertices

Conclusion

- The Sommerfeld effect and bound state formation (BSF) arise for long range interactions in a dark sector
- BSF and subsequent bound state decay into SM particles efficiently provides an additional DM annihilation channel
- We have analyzed a model of colored coannihilation (Simplified t-channel: S3M-uR) using a modified micrOMEGAs version.
- The coannihilating region strongly impacted by non-perturbative effects. Viable paramter space involving tiny couplings of DM to the SM is shifted from 1 TeV to 2.5 TeV
- Potentially interesting for long-lived particle searches
- Effect can be enhanced by a non-vanishing Higgs-portal coupling