Colored window on dark sectors

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Motivation

- dark matter coannihilation with colored partners dramatically changes relic density predictions

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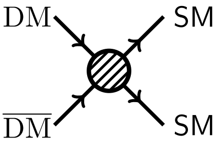
- it can be tested at colliders
- proper description requires considering several effects
  - Sommerfeld enhancement
  - bound states formation
  - thermal equilibrium constraints
  - lifetime of new colored particles

1510.03434 M. J. Baker, J. Brod, S. El Hedri, AK, J. Kopp, J. Liu, A. Thamm, M. de Vries, X.-P. Wang, F. Yu J. Zurita
1605.08056 M. Buschmann, S. El Hedri, AK, J. Liu, M. de Vries, X.-P. Wang, F. Yu, J. Zurita
1612.02825 S. El Hedri, AK, M. de Vries
1703.00452 S. El Hedri, AK, M. de Vries, J. Zurita

Coannihilation



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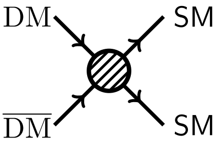

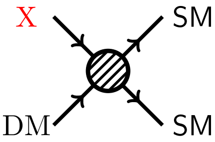

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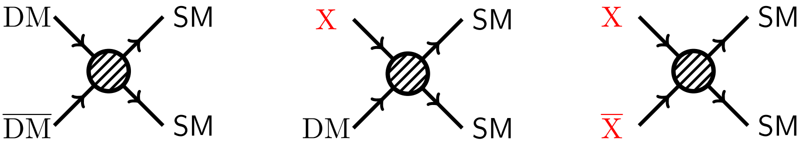
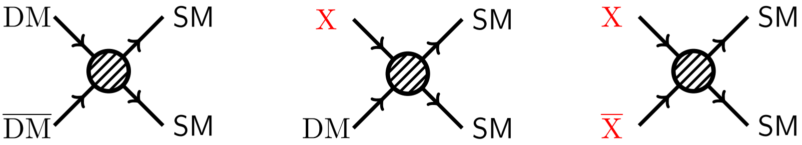


$$\Delta \equiv \frac{m_X - m_{DM}}{m_{DM}}, \qquad \Delta \ll 1$$

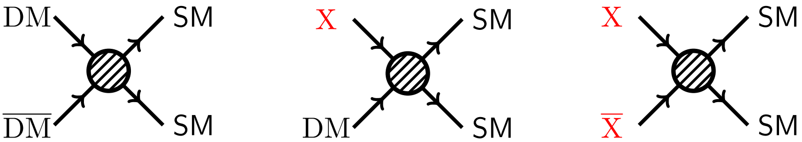
Coannihilation



$$\Delta \equiv \frac{m_X - m_{DM}}{m_{DM}}, \qquad \Delta \ll 1$$

$$\sigma_{\text{eff}} = \frac{g_{\mathrm{DM}}^2}{g_{\text{eff}}^2}\Big\{\sigma_{\mathrm{DM\,DM}} + 2\sigma_{\mathrm{DM\,X}}\frac{g_{\mathrm{X}}}{g_{\mathrm{DM}}}(1+\Delta)^{3/2}\exp(-x\Delta)$$
$$+\,\sigma_{\mathrm{X\,\overline{X}}}\frac{g_{\mathrm{X}}^2}{g_{\mathrm{DM}}^2}(1+\Delta)^3\exp(-2x\Delta)\Big\}$$

Coannihilation



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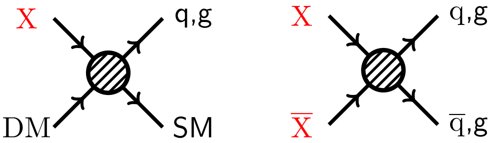
$$\left. + \sigma_{\mathrm{X\,\overline{X}}}\frac{g_{\mathrm{X}}^2}{g_{\mathrm{DM}}^2}(1+\Delta)^3\exp(-2x\Delta)\right\}$$

X can have $U(1)_{EM}$ and/or QCD charges

Colored X



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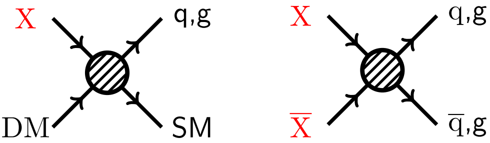
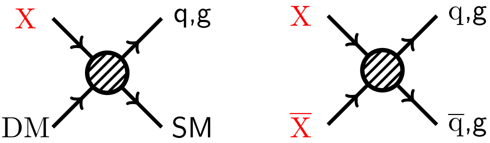


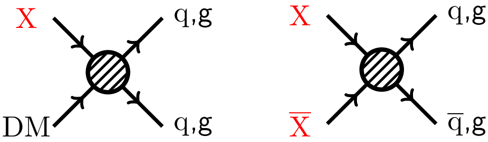
- strong $\mathrm{X}\,\overline{\mathrm{X}} \to \mathrm{g}\,\mathrm{g},\;\; \mathrm{q}\,\overline{\mathrm{q}}$
- at least one quark or gluon as decay product of X
  $\to$ jet(s) + MET as a generic search strategy for colored dark sector models

Colored X

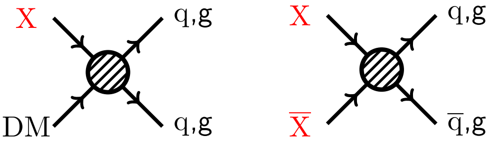


- strong $\mathrm{X}\,\overline{\mathrm{X}} \to \mathrm{g}\,\mathrm{g},\ \mathrm{q}\,\overline{\mathrm{q}}$
- at least one quark or gluon as decay product of X
  $\to$ jet(s) + MET as a generic search strategy for colored dark sector models
- if other kinds of SM particles couple to X, can be used in LHC search strategies, e.g. monojet + MET + soft leptons (1510.03434, 1312.7350)
- if the mediator is light, its production can contribute to coannihilation; strong pair production at the LHC, interesting signatures for M_s e.g. (ℓj) resonance + MET (1510.03434), dijet resonance + MET (1605.08056)

"Minimal" Colored X



"Minimal" Colored X



- relic density driven by $\mathrm{X}\,\overline{\mathrm{X}} \to \mathrm{g}\,\mathrm{g},\ \ \mathrm{q}\,\overline{\mathrm{q}}$
- jet(s) + MET as the LHC handle

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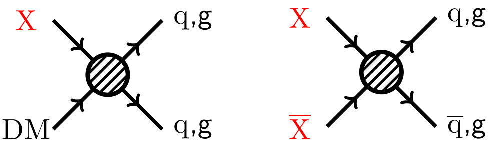
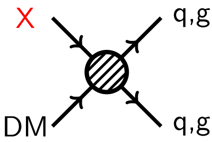


- relic density driven by $\mathrm{X}\,\overline{\mathrm{X}} \to \mathrm{g}\,\mathrm{g},\ \ \mathrm{q}\,\overline{\mathrm{q}}$
- jet(s) + MET as the LHC handle
- we choose a representative set of models with DM being a SM singlet, X charged under $SU(3)$ and a single effective operator connecting X and DM to SM particles manifesting as jets (1703.00452)

DM X SM_1 SM_2 effective interaction



$$
\begin{aligned}
\mathbf{3} \otimes \overline{\mathbf{3}} &= \mathbf{1} \oplus \mathbf{8} \\
\mathbf{3} \otimes \mathbf{3} &= \overline{\mathbf{3}} \oplus \mathbf{6} \\
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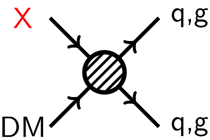
\mathbf{8} \otimes \mathbf{8} &= \mathbf{1}_{\mathrm{S}} \oplus \mathbf{8}_{\mathrm{A}} \oplus \mathbf{8}_{\mathrm{S}} \oplus \mathbf{10}_{\mathrm{A}} \oplus \overline{\mathbf{10}}_{\mathrm{A}} \oplus \mathbf{27}_{\mathrm{S}}
\end{aligned}
$$

DM X SM_1 SM_2 effective interaction



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\end{aligned}$$

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

where S (real scalar), C (complex scalar), F (Dirac fermion), W (complex vector)

DM X SM_1 SM_2 effective interaction

Example effective interaction vertices we choose for our models

$$\mathcal{L}_{\mathrm{DM_F+X_{F3}}} = \frac{1}{\Lambda^2}\epsilon_{kij}\left(\bar{\psi}_k\psi_{\mathrm{DM}}\right)\left(\bar{d}_{R,i}u^C_{R,j}\right) + \mathrm{h.c.}$$

$$\mathcal{L}_{\mathrm{DM_F+X_{F6}}} = \frac{1}{\Lambda^2}K^u_{6,ij}\left(\bar{\psi}_{\mathrm{DM}}\psi^u\right)\left(\bar{u}_{R,i}u^C_{R,j}\right) + \mathrm{h.c.}$$

$$\mathcal{L}_{\mathrm{DM_F+X_{F8}}} = \frac{1}{\Lambda^2}T^a_{ij}\left(\bar{\psi}_{\mathrm{DM}}\gamma_\mu\psi^a\right)\left(\bar{u}_{R,i}\gamma^\mu u_{R,j}\right) + \mathrm{h.c.}$$

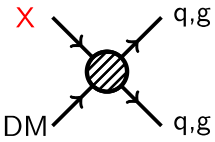
$$\mathcal{L}_{\mathrm{DM_S+X_{C3}}} = \frac{1}{\Lambda}\epsilon_{kij}\left(S_{\mathrm{DM}}S_k\right)\left(\bar{d}_{R,i}u^C_{R,j}\right) + \mathrm{h.c.}$$

$$\mathcal{L}_{\mathrm{DM_S+X_{F3}}} = \frac{1}{16\pi^2\Lambda^2}T^a_{ij}S_{\mathrm{DM}}\left(\bar{d}_{R,i}\sigma^{\mu\nu}\psi_j\right)G^a_{\mu\nu} + \mathrm{h.c.}$$

The DM X SM_1 SM_2 interaction is relevant for

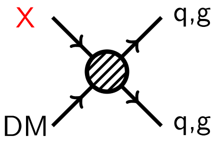
- thermal equilibrium between X and DM
- X lifetime

Thermal equilibrium



$$\mathrm{DM\,SM_1} \leftrightarrow \mathrm{X\,SM_2} \qquad \mathrm{DM\,SM_2} \leftrightarrow \mathrm{X\,SM_1} \qquad \mathrm{X} \leftrightarrow \mathrm{DM\,SM_1\,SM_2}$$

Thermal equilibrium

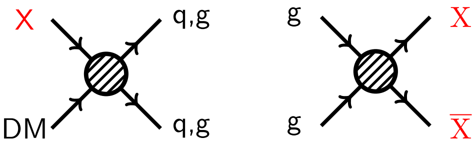


$$\mathrm{DM\,SM_1} \leftrightarrow \mathrm{X\,SM_2} \quad \mathrm{DM\,SM_2} \leftrightarrow \mathrm{X\,SM_1} \quad \mathrm{X} \leftrightarrow \mathrm{DM\,SM_1\,SM_2}$$

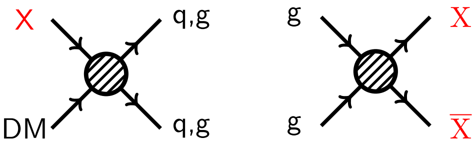
$$\Gamma_{\mathrm{DM}\leftrightarrow\mathrm{X}} = \int_{E_{\mathrm{min}}}^{\infty} \sigma_{\mathrm{DM}\leftrightarrow\mathrm{X}}(s)\, \frac{g_{\mathrm{SM}}}{2\pi^2} \frac{p^2}{e^{\frac{p}{T}} \pm 1}\, \mathrm{d}p$$

$$\Gamma_{\mathrm{DM}\leftrightarrow\mathrm{X}} > \mathrm{H} \approx \left(\frac{4\pi^3}{45}\right)^{1/2} g_\rho^{1/2} \frac{m_{\mathrm{DM}}^2}{x^2 M_{Pl}}$$

Lifetime of X



Lifetime of X



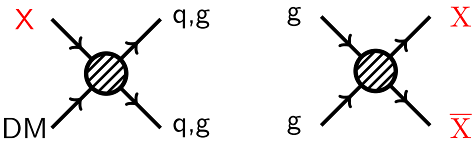
X is long-lived $\leftrightarrow$ transverse distance d_T traveled by X before it decays is larger than the beam pipe radius

$$d_T = d \sin\theta \geq d_{\rm beam} \sim 2.5 \text{ cm}$$

$$P(d_T > d_{\rm beam}) = \int_0^\infty \exp\left(-\frac{d_{\rm beam}}{d_0^T(p_T)}\right) \mathcal{P}_{p_T}(p_T) p_T \mathrm{d}p_T$$

$$d_0^T(p_T) = \frac{\hbar c}{\Gamma}\frac{p_T}{m_{\rm X}}$$

Lifetime of X



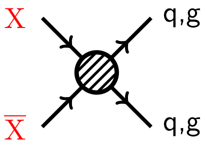
generate a large number N of $p\,p \to \mathrm{X}\,\overline{\mathrm{X}}$ events

$$P(d_T > d_{\mathrm{beam}}) = \frac{1}{N}\sum_i \exp\left(-\frac{d_{\mathrm{beam}}}{d_0^T(p_{Ti})}\right) \tag{1}$$

a $(m_{\mathrm{DM}}, \Delta)$ parameter point is ruled out if at least one long-lived particle is expected to be produced at the working luminosity $\mathcal{L}$

$$2 \times \sigma_{\mathrm{X}\overline{\mathrm{X}}} \times \mathcal{L} \times P(d_T > d_{\mathrm{beam}}) < 1$$

The Sommerfeld effect

$\mathcal{M}^0 =$ 

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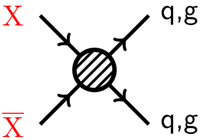
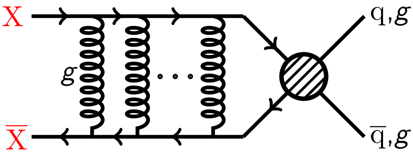


$\mathcal{M}^{(S)} =$



$$\mathcal{M}^{(S)}_{\beta\alpha} = \mathcal{M}^0_{\beta\alpha} + \int d\gamma \frac{\mathcal{M}^{(S)}_{\beta\gamma} V_{\gamma\alpha}}{E_\alpha - E_\gamma + i\epsilon}$$

α and β - initial and final states respectively

$V_{\gamma\alpha}$ - distorting potential

Sommerfeld correction (1612.02825)

$$\mathcal{M}(p; ll_z; ss_z; m_3 m_4) = \sum_{n\geq 0} \alpha^{(m_3,m_4)}_{ll_z ss_z,n}\, p^{l+2n}$$

$$\left|\mathcal{M}^{(S)}_{ll_z;ss_z;\mathbf{m}_f}(p)\right|^2 = S_l(x) \sum_{n,n'} \alpha^{\mathbf{m}_f}_{ll_z;ss_z;n} \left(\alpha^{\mathbf{m}_f}_{ll_z;ss_z;n'}\right)^* \mathcal{D}_{ln}(x)\mathcal{D}^*_{ln'}(x)\, p^{2(l+n+n')}$$

$$S_l(x) = |\mathcal{C}_l(x)|^2 = \frac{\pi x}{1-e^{-\pi x}} \prod_{b=1}^{l} \left(1 + \frac{x^2}{4b^2}\right)$$

$$\mathcal{D}_{ln}(x) = \frac{n!(2l+2n+1)!}{(l+n)!} \sum_{j=0}^{2n} \frac{(-2)^j (l+j)!}{j!(2n-j)!(2l+j+1)!} \left[\prod_{b=l+1}^{l+j} \left(1 + \frac{ix}{2b}\right)\right]$$

where $x = Am/p, \quad V = -A/r$

QCD potentials

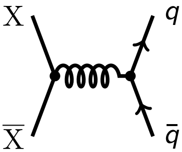
$$V_{\mathbf{R}\otimes\mathbf{R}'} = -\frac{\alpha_s(\hat{\mu})}{2r}\sum_{\mathbf{Q}}\left[C_2(\mathbf{Q})\mathbb{1}_{\mathbf{Q}} - C_2(\mathbf{R})\mathbb{1} - C_2(\mathbf{R}')\mathbb{1}\right]$$

where $\mathbf{R}\otimes\mathbf{R}' = \bigoplus_{\mathbf{Q}}\mathbf{Q}$

$\mathbf{R}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{6}$	$\mathbf{8}$	$\mathbf{10}$	$\mathbf{15}$	$\mathbf{27}$	$\mathbf{64}$
$C(\mathbf{R})$	0	$\frac{1}{2}$	$\frac{5}{2}$	3	$\frac{15}{2}$	10	27	120
$C_2(\mathbf{R})$	0	$\frac{4}{3}$	$\frac{10}{3}$	3	6	$\frac{16}{3}$	8	15

$$V_{\mathbf{3}\otimes\overline{\mathbf{3}}} = \frac{\alpha_s}{r}\begin{cases} +\frac{4}{3} & (\mathbf{1}) \\ -\frac{1}{6} & (\mathbf{8}) \end{cases}, \quad V_{\mathbf{6}\otimes\overline{\mathbf{6}}} = \frac{\alpha_s}{r}\begin{cases} +\frac{10}{3} & (\mathbf{1}) \\ +\frac{11}{6} & (\mathbf{8}) \\ -\frac{2}{3} & (\mathbf{27}) \end{cases}, \quad V_{\mathbf{8}\otimes\mathbf{8}} = \frac{\alpha_s}{r}\begin{cases} +3 & (\mathbf{1}_S) \\ +\frac{3}{2} & (\mathbf{8}_A, \mathbf{8}_S) \\ 0 & (\mathbf{10}_A, \overline{\mathbf{10}}_A) \\ -1 & (\mathbf{27}_S) \end{cases}$$

Sommerfeld correcting coannihilation



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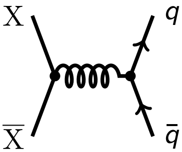
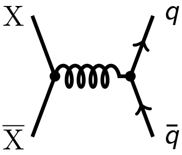


$$\mathcal{A}^a\big|_j^i \propto (T^a_{\mathbf{R}})^i_j$$

$$\sum_{\text{color}} \left|A_{\mathbf{R}\otimes\overline{\mathbf{R}}}\right|^2 = \sum_{\text{color}} \left|[\mathbf{8}]\right|^2$$

Sommerfeld correcting coannihilation



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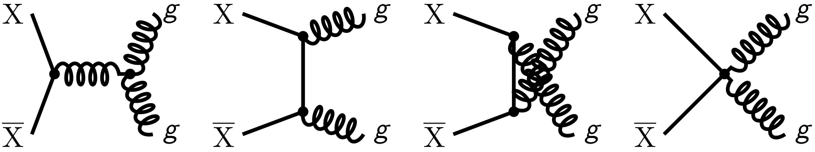
$$\sigma^{(S)}_{\mathbf{3}\otimes\overline{\mathbf{3}}\to q\,\overline{q}} = \sigma^{(S)}_C \left[-\frac{\alpha_s}{6}\right]$$

$$\sigma^{(S)}_{\mathbf{6}\otimes\overline{\mathbf{6}}\to q\,\overline{q}} = \sigma^{(S)}_C \left[\frac{11\alpha_s}{6}\right]$$

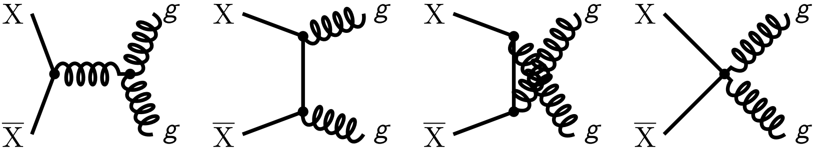
$$\sigma^{(S)}_{\mathbf{8}\otimes\mathbf{8}\to q\,\overline{q}} = \sigma^{(S)}_C \left[\frac{3\alpha_s}{2}\right]$$

Sommerfeld correcting coannihilation



$$\mathcal{A}^{ab}\Big|^i_j = \alpha \left\{ T^a_{\mathbf{R}}, T^b_{\mathbf{R}} \right\}^i_j + \beta \left[T^a_{\mathbf{R}}, T^b_{\mathbf{R}} \right]^i_j$$

Sommerfeld correcting coannihilation

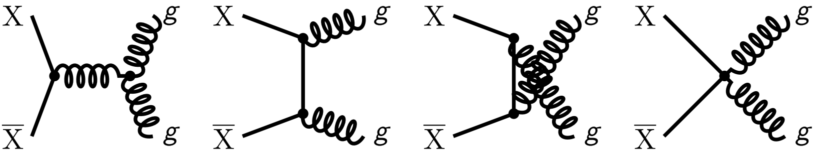


$$\mathcal{A}^{ab}\big|^{i}_{j} = \alpha \left\{ T^a_{\mathbf{R}}, T^b_{\mathbf{R}} \right\}^{i}_{j} + \beta \left[T^a_{\mathbf{R}}, T^b_{\mathbf{R}} \right]^{i}_{j}$$

$$\mathcal{A}^{ab}\big|^{i}_{j} = (-1)^{l+s} \mathcal{A}^{ba}\big|^{i}_{j}$$

$$\mathcal{A}^{ab}\big|^{i}_{j} \sim \begin{cases} \left\{ T^a_{\mathbf{R}}, T^b_{\mathbf{R}} \right\}^{i}_{j} & \text{even } l+s \\ [T^a_{\mathbf{R}}, T^b_{\mathbf{R}}]^i_j = i f^{abc} T^c_{\mathbf{R}}{}^i_j & \text{odd } l+s \end{cases}$$

Sommerfeld correcting coannihilation



$$\sigma^{(S)}_{\mathbf{3}\otimes\bar{\mathbf{3}}\to g\,g} = \begin{cases} \frac{2}{7}\sigma_C^{(S)}\left[\frac{4\alpha_s}{3}\right] + \frac{5}{7}\sigma_C^{(S)}\left[-\frac{\alpha_s}{6}\right] & \text{even } l+s \\ \sigma_C^{(S)}\left[-\frac{\alpha_s}{6}\right] & \text{odd } l+s \end{cases}$$

$$\sigma^{(S)}_{\mathbf{6}\otimes\bar{\mathbf{6}}\to g\,g} = \begin{cases} \frac{5}{31}\sigma_C^{(S)}\left[\frac{10\alpha_s}{3}\right] + \frac{49}{155}\sigma_C^{(S)}\left[\frac{11\alpha_s}{6}\right] + \frac{81}{155}\sigma_C^{(S)}\left[-\frac{2\alpha_s}{3}\right] & \text{even } l+s \\ \sigma_C^{(S)}\left[\frac{11\alpha_s}{6}\right] & \text{odd } l+s \end{cases}$$

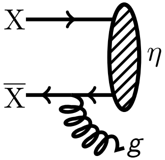
$$\sigma^{(S)}_{\mathbf{8}\otimes\mathbf{8}\to g\,g} = \begin{cases} \frac{1}{6}\sigma_C^{(S)}\left[3\alpha_s\right] + \frac{1}{3}\sigma_C^{(S)}\left[\frac{3\alpha_s}{2}\right] + \frac{1}{2}\sigma_C^{(S)}\left[-\alpha_s\right] & \text{even } l+s \\ \sigma_C^{(S)}\left[\frac{3\alpha_s}{2}\right] & \text{odd } l+s \end{cases}$$

Mathematica package with (1612.02825)

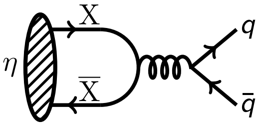
Bound states

based on 1611.08133 by S. P. Liew and F. Luo

bound state formation



bound state decay



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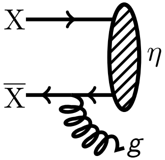
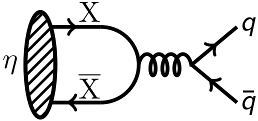
based on 1611.08133 by S. P. Liew and F. Luo

bound state formation

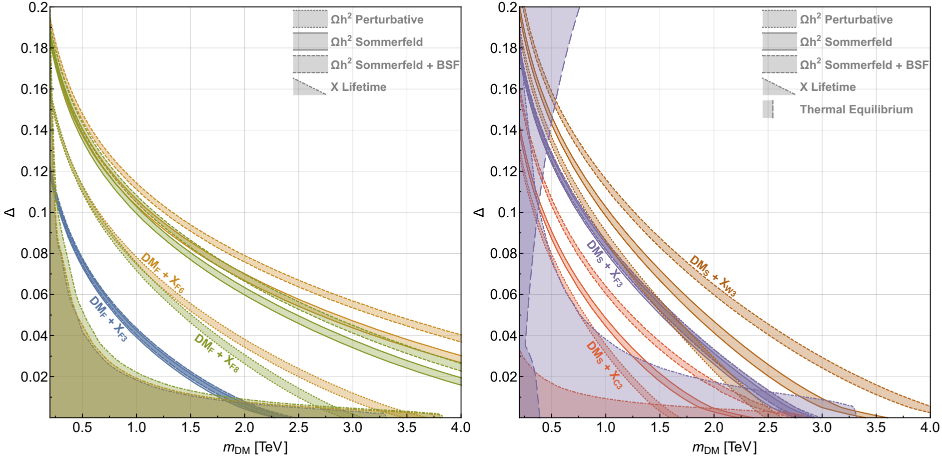


bound state decay



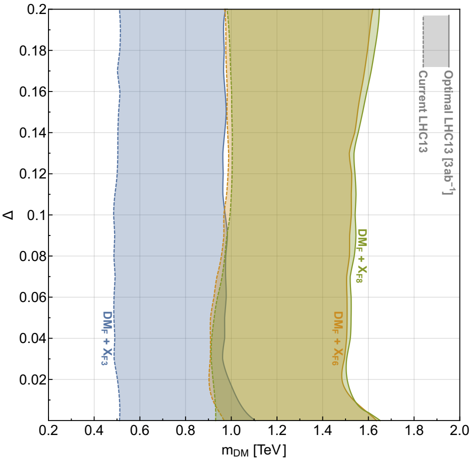
$$\langle \sigma v \rangle_{\mathrm{X}\,\overline{\mathrm{X}}} = \langle \sigma v \rangle_{\mathrm{X}\,\overline{\mathrm{X}} \to gg, q\bar{q}} + \langle \sigma v \rangle_{\mathrm{X}\,\overline{\mathrm{X}} \to \eta \mathrm{g}} \frac{\langle \Gamma \rangle_{\mathrm{decay}}}{\langle \Gamma \rangle_{\mathrm{decay}} + \langle \Gamma \rangle_{\mathrm{dissociation}}}$$

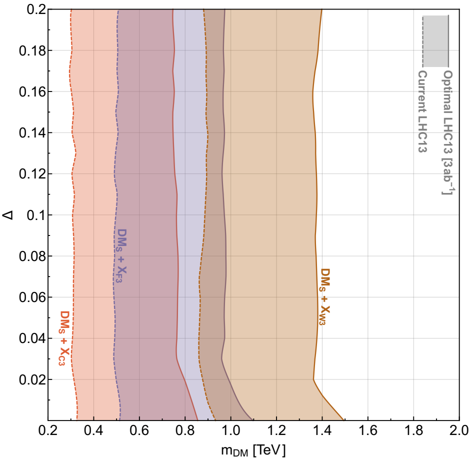
Relic density + thermal eq. + X lifetime



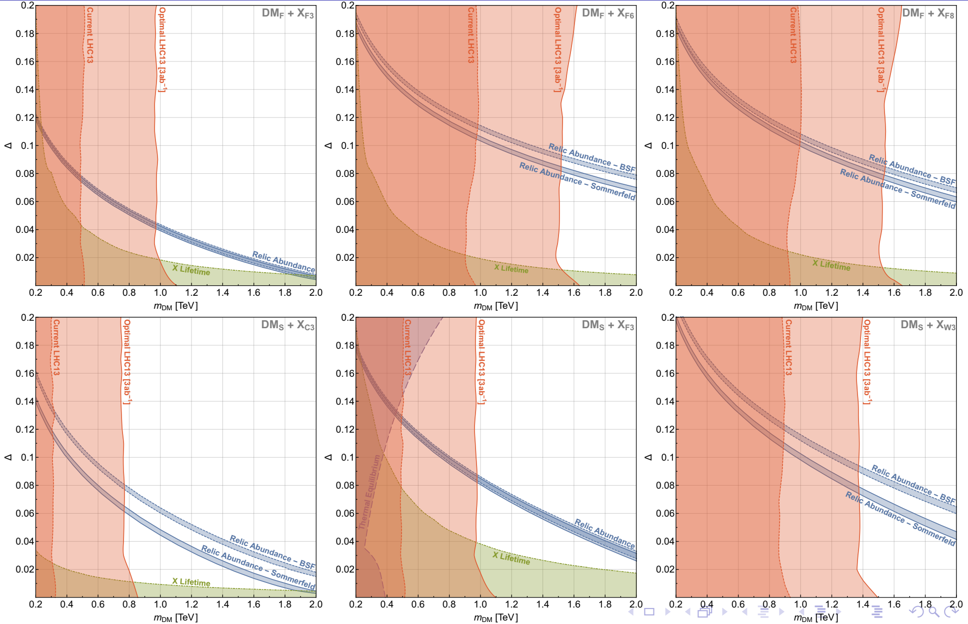
mono-jet(s)+MET reach

ATLAS mono-jet + MET with 3.2fb^{-1} 1604.07773
ATLAS multi-jet + MET with 13.3fb^{-1} ATLAS-CONF-2016-078





Combined results



Conclusions

- coannihilation with color partners can drastically extend the allowed DM mass range by driving the relic density prediction by $\mathrm{X}\,\overline{\mathrm{X}} \to q\,\bar{q},\ g\,g$; thermal DM masses $\gtrsim$ 10TeV can be consistent with Planck
- collider phenomenology of these scenarios is dominated by strong pair production of X, followed by its decay into DM and additional jets $\to$ multi-jet(s) $+$ MET collider searches
- demanding X prompt decays at colliders constrains the small Δ region of parameter space
- thermal equilibrium condition between X and DM in the early Universe can place additional relevant bounds if the coupling between X and DM is small
- Sommerfeld corrections and bound state effects can significantly affect the derivation of the relic density motivated parameter space of models with a strongly interacting X