Strongly Coannihilating Dark Matter at the LHC

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[arXiv:1510.03434] [JHEP 1512 (2015) 120]
[arXiv:1605.08056] [JHEP 1609 (2016) 033]

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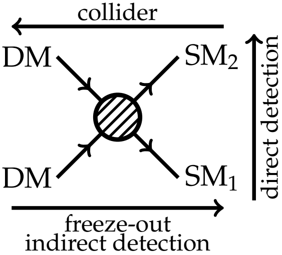
INTRODUCTION

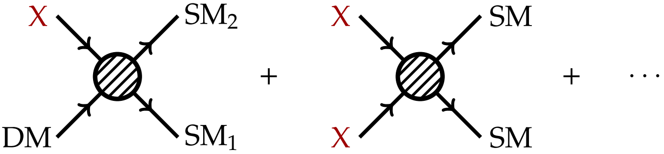
- Dark matter (DM) is observed using gravitational probes, but we are ignorant about its particle identity
- The thermal hypothesis: elegant explanation of current DM relic density that implies DM interactions with the SM
- DM annihilation implies direct detection, indirect detection and collider signatures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

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



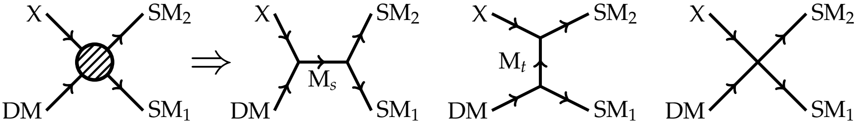
- Sizable contributions from coannihilation to the relic abundance alleviate the tight connection between the different DM detection probes
- Especially direct and indirect detection are suppressed and novel strong LHC signatures may appear depending on the nature of X and the coannihilation mechanism

THE COANNIHILATION CODEX

[arXiv:1510.03434]

Codex: a minimal basis of simplified models for coannihilation

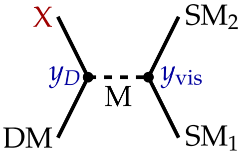
- Resolve the effective coannihilation diagram into channels



- Use known DM properties:
  - DM particle is cold, non-baryonic, colorless and EM neutral
  - Relic density constraint motivates the belief that DM (co)annihilates to SM particles (DM is a thermal relic)
- Result: A bottom-up framework for discovering dark matter at the LHC
  - LHC probes motivated by how DM obtains its relic density
  - Nature's choice for DM guaranteed to be in the Codex given our assumptions (two-to-two diagrams; spin 0, ½ or 1; tree-level and renormalizable interactions; $\mathbb{Z}_2$ stabilizes dark sector)

COLORED COANNIHILATION PARTNER

- Focus on colored X and *s*-channel mediators
- Provide a set of models with novel & strong LHC signatures
- All model content given by coannihilation diagram:



- 5 parameters: $m_{\mathrm{DM}}, m_{\mathrm{X}} = m_{\mathrm{DM}}(1+\Delta), m_{\mathrm{M}}, y_{\mathrm{vis}}, y_D$
- Choose flavor structure of y_{vis} to be first generation only
- Interchange couplings for $B_0 = \mathrm{Br}(M \to \mathrm{vis})|_{m_{\mathrm{DM}}=0}$ and Γ_{M}

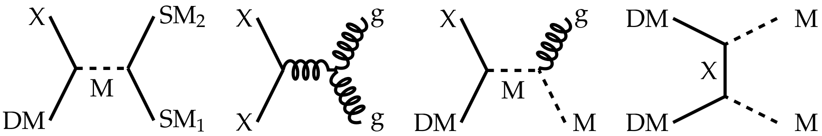
Leptoquark model (LQ)

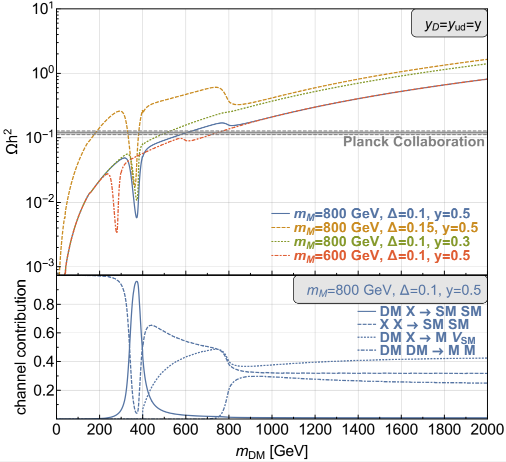
Field	Rep.	Spin assignment
DM	$(1, 1, 0)$	Majorana fermion
X	$(3, 2, \frac{7}{3})$	Dirac fermion
$\mathrm{M} \equiv \mathrm{LQ}$	$(3, 2, \frac{7}{3})$	Scalar
$\mathrm{SM}_1, \mathrm{SM}_2$	$(Q_L\,\overline{\ell_R}), (u_R\,\overline{L_L})$	

Diquark model (DQ)

Field	Rep.	Spin assignment
DM	$(1, 1, 0)$	Majorana fermion
X	$(3, 1, -\frac{2}{3})$	Dirac fermion
$\mathrm{M} \equiv \mathrm{DQ}$	$(3, 1, -\frac{2}{3})$	Scalar
$\mathrm{SM}_1, \mathrm{SM}_2$	$(\overline{u_R}\,\overline{d_R})$	

RELIC DENSITY - ANNIHILATION CHANNELS

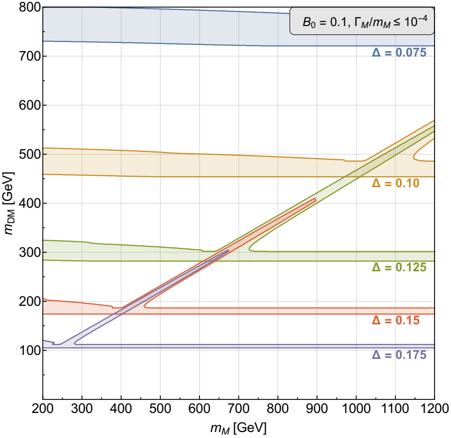


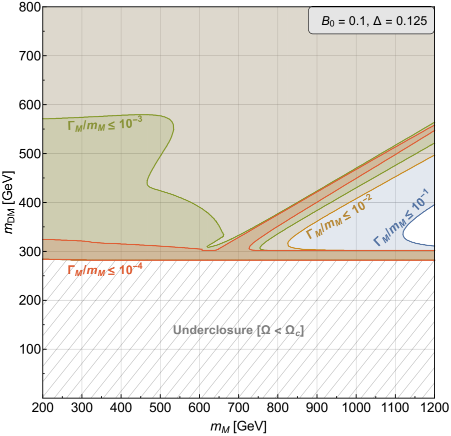


- Diquark model as example
- No DM self-annihilation (Standard Model singlet)
- Chemical equilibrium by:
  - DM DM $\leftrightarrow$ X $\bar{\text{X}}$
  - DM SM $\leftrightarrow$ X SM
  - X $\leftrightarrow$ DM SM SM
- X $\bar{\text{X}}$ $\to gg/q\bar{q}$ is independent of couplings and mediator mass, depends on m_{DM} and Δ
- Other channels turn on as m_{DM} increases compared to m_{M}
- Goal: fit $\Omega h^2 = 0.1198 \pm 0.0026$

RELIC DENSITY - PARAMETER SPACE

- Move to the collider mass plane (m_{M} versus m_{DM})
- Choose a relatively small branching to visible states to enhance dark signatures ($B_0 = 0.1$)
- Show dependence on parameters Δ and Γ_{M} (DQ model)



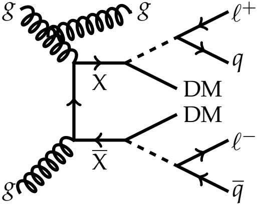


LHC: COANNIHILATION PARTNER PRODUCTION

- Due to $\mathbb{Z}_2$-parity X must be pair produced, need ISR to produce MET and a trigger-able signal
- Diquark: X decays to soft jets: model is constrained by existing monojet and jets + MET searches
- Leptoquark: X decays to a soft lepton and jet: monojet + MET (leptons are soft) or new search (leptons can be detected)

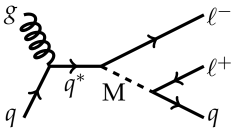
- New search: hard jet + MET + soft leptons
- Similar to monojet + MET search
- Additional requirement of 2 soft leptons
- Table shows 2σ exclusion limit on m_X
- Limits exceed monojet + MET (overview)

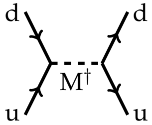
	$p_T > 10$ GeV	$p_T > 15$ GeV	$p_T > 25$ GeV
$\Delta = 0.05$	1030	930	700
$\Delta = 0.1$	1030	1000	870
$\Delta = 0.2$	1030	1020	1000



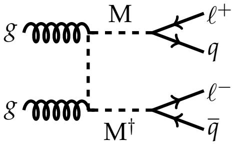
LHC: MEDIATOR PRODUCTION

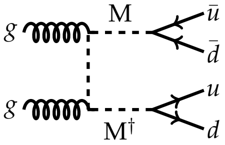
- Single production of LQ: in association with a lepton, constrained by single leptoquark searches
- Single production of DQ: through y_{vis} coupling, constrained by dijet resonance searches



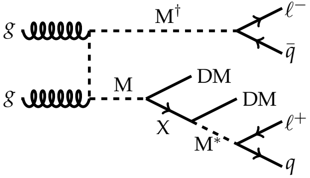


- Pair production of the mediator (3 options)
- Visible decays: production of paired resonances
  - Leptoquark: standard LHC search for pair-production of LQ's
  - Diquark: standard search for paired dijet resonances (colorons)
- Invisible decays: needs ISR, weaker than pair production of X
- Mixed decay: leads to resonance + MET (new!)

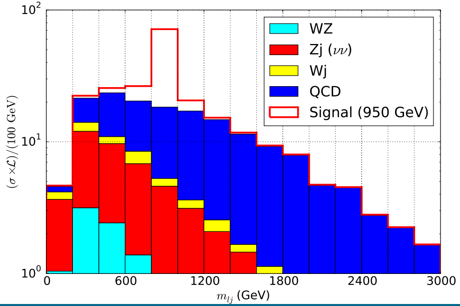




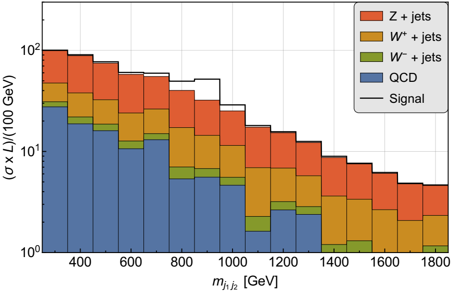
LHC: MEDIATOR MIXED DECAY



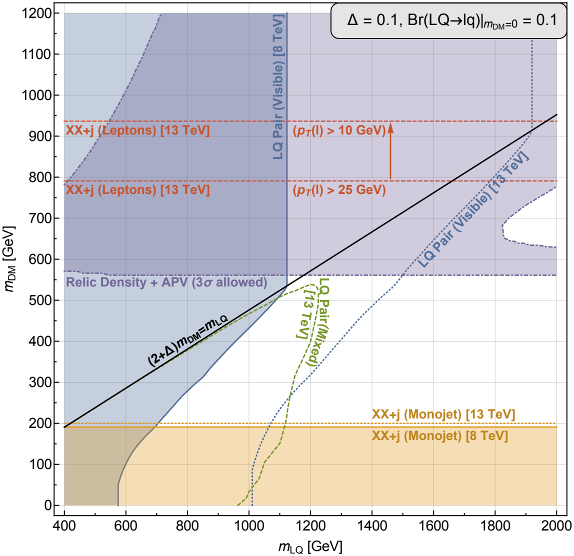
- Leptoquark: $\ell\, q$ resonance + MET
- soft ℓ, q from invisible decay
- Main cuts: MET, m_T, $m_{\ell q}$



- Diquark: dijet resonance + MET
- two jets from invisible decay chain are soft, typically beyond detection
- Basic cuts: 2 jets ($p_T > 100$ GeV) and $|\Delta\eta(j_1, j_2)| < 1.3$
- Selection cuts: MET, m_{dijet}
- Both searches are new at the LHC!

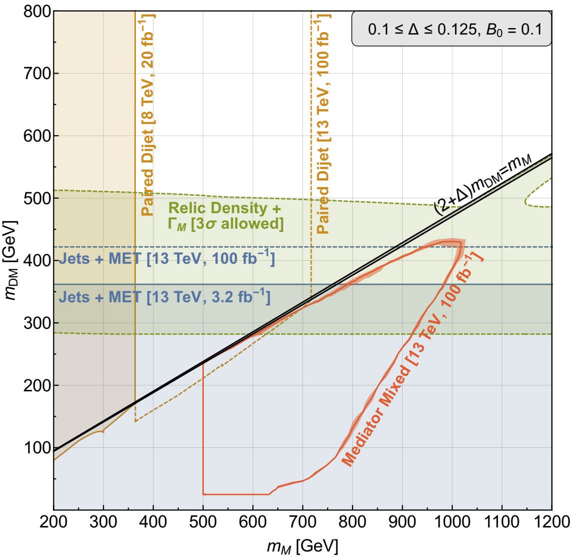


LHC POTENTIAL (LEPTOQUARK)



- Combined exclusion and projections
- Relic density + APV allowed contour
  APV: $|y_{\text{vis}}| < 0.40\,\left(\frac{m_{\text{LQ}}}{1\,\text{TeV}}\right)$
- Fix couplings y_D, y_{vis} such that branching ratios are ($m_{\text{DM}} = 0$):
  LQ → visible = 10%
  LQ → dark = 90%
- Mixed topology is maximized relative to fully visible topology

LHC POTENTIAL (DIQUARK)

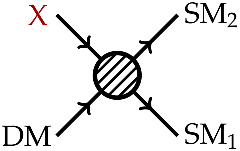


- Combined exclusion and projections
- Relic density + maximum width (dijet searches)
- Fix couplings y_D, y_{vis} such that branching ratios are ($m_{\text{DM}} = 0$):
  DQ → visible = 10%
  DQ → dark = 90%
- Mixed topology is maximized relative to fully visible topology

REMOVING THE MEDIATOR

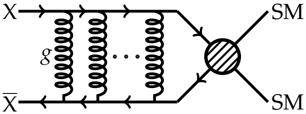
[arXiv:1612.????? El-Hedri, Kaminska, Zurita, MdV]

- There is no fundamental reason for the mediator to be light, i.e. within the reach of the LHC
- Construct an EFT for SM plus DM & X with the operator:



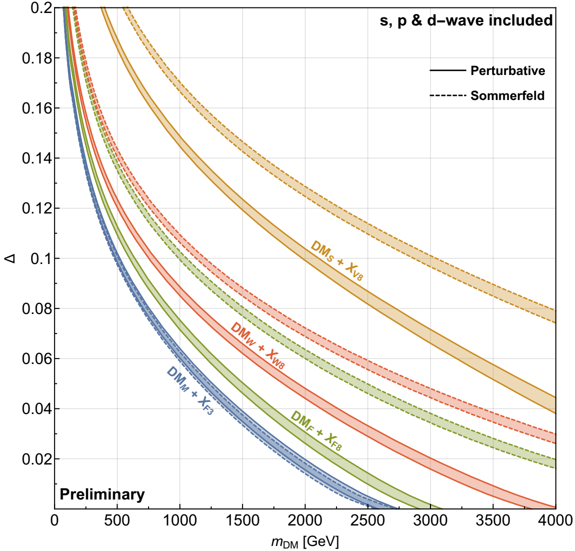
- Model content: DM, X, EFT operator with a small coefficient
- EFT operator is required for X decay (not long-lived) and chemical equilibrium (DM SM $\leftrightarrow$ X SM)
- DM can be any SM singlet: scalar, fermion or vector
- X can be scalar, fermion or vector and have color charges **3**, **6** or **8** (more exotic **10**, **15** & **27** require loop induced operators)
- Relic density is solely determined by X $\overline{\text{X}} \rightarrow gg/q\bar{q}$
- Collider signature is pair-production of X + ISR jets, where X decays to soft jets + MET (monojet + MET & jets + MET)

SOMMERFELD CORRECTIONS [arXiv:1612.????? El-Hedri, Kaminska, MdV]



- Non-perturbative Sommerfeld corrections due to soft gluon exchanges in X $\overline{\text{X}} \to gg/q\bar{q}$
- Sommerfeld enhancement for QCD and s-wave (lowest order in v) described in De Simone et al. [arXiv:1402.6287]
- Higher order partial waves for Coulomb potential described in Cassel [arXiv:0903.5307] & Iengo [arXiv:0902.0688]
- Sommerfeld enhancement for higher order waves partially cancels the velocity suppression, i.e. makes higher order waves more important (convergence now in wave number l)
- Goal: include higher order waves to X $\overline{\text{X}} \to gg/q\bar{q}$ for an analytic and reliable calculation of the relic abundance
- Important for Codex models, gluino/stop coannihilation, ...

DM & X PHENOMOLOGY



- Example ($\mathrm{DM_M}$-$\mathrm{X_{F3}}$)
  - DM is a Majorana fermion
  - X is Dirac fermion and color triplet
- Relic density determines a strip in the m_{DM} vs. Δ plane
- $m_{\mathrm{DM}} \gtrsim \mathcal{O}(400)$ GeV for $\mathrm{X_{F3}}$ from monojet & jets + MET searches
- Natural values for Δ (i.e. splitting not fine-tuned)
- Sommerfeld corrections can be sizable
- For fermion triplet: gg enhanced, $q\bar{q}$ suppressed

CONCLUSIONS

- The mechanism of coannihilation loosens the connections between the several different probes of DM and gives rise to interesting and novel LHC signatures

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- In the case of heavy mediators the situation simplifies to an EFT for DM + colored coannihilation partners and natural regions in m_{DM} and Δ give the correct relic abundance together with collider phenomenology testable at the LHC

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- The mechanism of coannihilation loosens the connections between the several different probes of DM and gives rise to interesting and novel LHC signatures
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- In the case of heavy mediators the situation simplifies to an EFT for DM + colored coannihilation partners and natural regions in m_{DM} and Δ give the correct relic abundance together with collider phenomenology testable at the LHC

Thank you for your attention!

CONSTRUCTING THE CODEX

How to construct a minimal basis of simplified models

ASSUMPTIONS:

- DM is colorless, EM neutral
- DM is a thermal relic
- The (co)annihilation diagram is two-to-two
- Tree-level and renormalizable interactions only
- New particles have spin 0, ½ or 1
- Dark sector stabilized by discrete symmetry
- All gauge bosons obey renormalizability and gauge invariance

CONSTRUCTING THE CODEX

How to construct a minimal basis of simplified models

- Work in the unbroken $SU(2)_L \times U(1)_Y$ phase
- DM transforms as $(1, N, \beta)$ under $(SU(3)_c, SU(2)_L, U(1)_Y)$, with hypercharge β such that one component is EM neutral
- Iterate over SM_1 SM_2 pairings to define the possible set of coannihilation partners X (gauge charges and spin)
- Resolve each DM, X, SM_1 and SM_2 set with an *s*-channel mediator M_s or *t*-channel mediator M_t
- Group models by channel:
  S (*s*-channel), **T** (*t*-channel), **H** (hybrid, next slide)
  and by $SU(3)_c$ representation of X:
  U(ncolored), **T**(riplet), **O**(ctet), **E**(xotic)

THE COANNIHILATION CODEX

Contains 161 models in hybrid, *s*-channel and *t*-channel categories

Category (# of models)	New fields	New couplings	
hybrid (7)	DM, X	DM–X–SM_3	
s-channel (49)	DM, X, M_s	DM–X–M_s	M_s–SM_1–SM_2
t-channel (105)	DM, X, M_t	DM–M_t–SM_1	X–M_t–SM_2

HYBRID MODELS:

Here SM_3 acts as the *s*-channel mediator and DM/X as the *t*-channel mediator

ID	X	$\alpha+\beta$	SM_3	Extensions
H1	$(1, N, \alpha)$	0	$B, W_i^{N\geq 2}$	SU1, SU3, TU1, TU4–TU8
H2		-2	ℓ_R	SU6, SU8, TU10, TU11
H3	$(1, N\pm 1, \alpha)$	-1	$H^\dagger$	SU10, TU18–TU23
H4			L_L	SU11, TU16, TU17
H5	$(3, N, \alpha)$	$\frac{4}{3}$	u_R	ST3, ST5, TT3, TT4
H6		$-\frac{2}{3}$	d_R	ST7, ST9, TT10, TT11
H7	$(3, N\pm 1, \alpha)$	$\frac{1}{3}$	Q_L	ST14, TT28–TT31

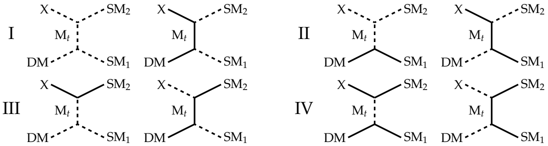
THE COANNIHILATION CODEX

S-CHANNEL MODELS:

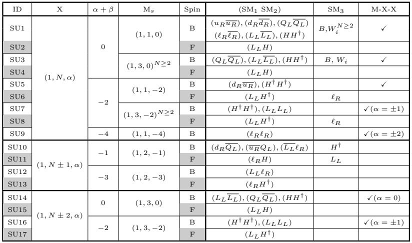
ID	X	$\alpha+\beta$	M_s	Spin	(SM_1 SM_2)	X–DM–SM_3	M_s–X–X
ST1	$(3, N, \alpha)$	$\frac{10}{3}$	$(3, 1, \frac{10}{3})$	B	$(u_R\, \overline{l_R})$		✓ $(\alpha = -\frac{5}{3})$
ST2		$\frac{4}{3}$	$(3, 1, \frac{4}{3})$	B	$(d_R\, \overline{\ell_R}), (Q_L\, \overline{L_L}), (\overline{d_R}\, \overline{d_R})$		✓ $(\alpha = -\frac{2}{3})$
ST3				F	$(Q_L\, H)$	H5	
ST4			$(3, 3, \frac{4}{3})^{N\geq 2}$	B	$(Q_L\, \overline{L_L})$		✓ $(\alpha = -\frac{2}{3})$
ST5				F	$(Q_L\, H)$	H5	
ST10		$-\frac{8}{3}$	$(3, 1, -\frac{8}{3})$	B	$(\overline{u_R}\, \overline{u_R}), (d_R\, \ell_R)$		✓ $(\alpha = \frac{4}{3})$
ST11	$(3, N \pm 1, \alpha)$	$\frac{7}{3}$	$(3, 2, \frac{7}{3})$	B	$(Q_L\, \overline{\ell_R}), (u_R\, \overline{L_L})$		
ST12				F	$(u_R\, H)$		

T-CHANNEL MODELS:

ID	X	$\alpha+\beta$	M_t	Spin	(SM_1 SM_2)	X–DM–SM_3
TE1	$(6, N, \alpha)$	$\frac{8}{3}$	$(\bar{3}, N, \beta - \frac{4}{3})$	IV	$(u_R\, u_R)$	
TE2		$\frac{2}{3}$	$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L\, Q_L)$	
TE3			$(\bar{3}, N, \beta - \frac{4}{3})$	IV	$(u_R\, d_R)$	
TE4			$(\bar{3}, N, \beta + \frac{2}{3})$	IV	$(d_R\, u_R)$	
TE5		$-\frac{4}{3}$	$(\bar{3}, N, \beta + \frac{2}{3})$	IV	$(d_R\, d_R)$	

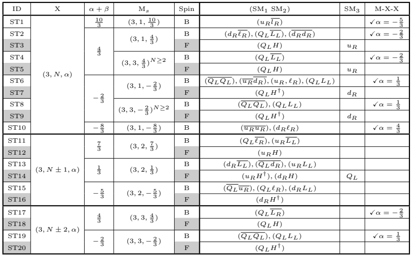


CODEX SIMPLIFIED MODELS: *s*-CHANNEL



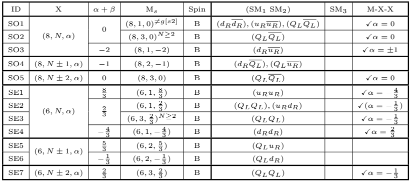
ID	X	$\alpha+\beta$	M$_s$	Spin	(SM$_1$ SM$_2$)	SM$_3$	M-X-X
SU1	$(1, N, \alpha)$	0	$(1,1,0)$	B	$(u_R\overline{u_R}), (d_R\overline{d_R}), (Q_L\overline{Q_L})$ $(\ell_R\overline{\ell_R}), (L_L\overline{L_L}), (HH^\dagger)$	$B, W_i^{N\geq 2}$	✓
SU2				F	$(L_L H)$		
SU3			$(1,3,0)^{N\geq 2}$	B	$(Q_L\overline{Q_L}), (L_L\overline{L_L}), (HH^\dagger)$	$B,\ W_i$	✓
SU4				F	$(L_L H)$		
SU5		-2	$(1,1,-2)$	B	$(d_R\overline{u_R}), (H^\dagger H^\dagger)$		✓
SU6				F	$(L_L H^\dagger)$	ℓ_R	
SU7			$(1,3,-2)^{N\geq 2}$	B	$(H^\dagger H^\dagger), (L_L L_L)$		$\checkmark(\alpha=\pm 1)$
SU8				F	$(L_L H^\dagger)$	ℓ_R	
SU9		-4	$(1,1,-4)$	B	$(\ell_R\ell_R)$		$\checkmark(\alpha=\pm 2)$
SU10	$(1, N\pm 1, \alpha)$	-1	$(1,2,-1)$	B	$(d_R\overline{Q_L}), (\overline{u_R}Q_L), (\overline{L_L}\ell_R)$	$H^\dagger$	
SU11				F	$(\ell_R H)$	L_L	
SU12		-3	$(1,2,-3)$	B	$(L_L\ell_R)$		
SU13				F	$(\ell_R H^\dagger)$		
SU14	$(1, N\pm 2, \alpha)$	0	$(1,3,0)$	B	$(L_L\overline{L_L}), (Q_L\overline{Q_L}), (HH^\dagger)$		$\checkmark(\alpha=0)$
SU15				F	$(L_L H)$		
SU16		-2	$(1,3,-2)$	B	$(H^\dagger H^\dagger), (L_L L_L)$		$\checkmark(\alpha=\pm 1)$
SU17				F	$(L_L H^\dagger)$		

SU type - 17 models



ID	X	$\alpha+\beta$	M$_s$	Spin	(SM$_1$ SM$_2$)	SM$_3$	M-X-X
ST1	$(3, N, \alpha)$	$\frac{10}{3}$	$(3,1,\frac{10}{3})$	B	$(u_R\overline{l_R})$		$\checkmark\alpha=-\frac{5}{3}$
ST2		$\frac{4}{3}$	$(3,1,\frac{4}{3})$	B	$(d_R\overline{\ell_R}), (Q_L\overline{L_L}), (\overline{d_R d_R})$		$\checkmark\alpha=-\frac{2}{3}$
ST3				F	$(Q_L H)$	u_R	
ST4			$(3,3,\frac{4}{3})^{N\geq 2}$	B	$(Q_L\overline{L_L})$		$\checkmark\alpha=-\frac{2}{3}$
ST5				F	$(Q_L H)$	u_R	
ST6		$-\frac{2}{3}$	$(3,1,-\frac{2}{3})$	B	$(\overline{Q_L Q_L}), (\overline{u_R d_R}), (u_R, \ell_R), (Q_L L_L)$		$\checkmark\alpha=\frac{1}{3}$
ST7				F	$(Q_L H^\dagger)$	d_R	
ST8			$(3,3,-\frac{2}{3})^{N\geq 2}$	B	$(\overline{Q_L Q_L}), (Q_L L_L)$		$\checkmark\alpha=\frac{1}{3}$
ST9				F	$(Q_L H^\dagger)$	d_R	
ST10		$-\frac{8}{3}$	$(3,1,-\frac{8}{3})$	B	$(\overline{u_R u_R}), (d_R\ell_R)$		$\checkmark\alpha=\frac{4}{3}$
ST11	$(3, N\pm 1, \alpha)$	$\frac{7}{3}$	$(3,2,\frac{7}{3})$	B	$(Q_L\overline{\ell_R}), (u_R\overline{L_L})$		
ST12				F	$(u_R H)$		
ST13		$\frac{1}{3}$	$(3,2,\frac{1}{3})$	B	$(d_R\overline{L_L}), (\overline{Q_L d_R}), (u_R L_L)$		
ST14				F	$(u_R H^\dagger), (d_R H)$	Q_L	
ST15		$-\frac{5}{3}$	$(3,2,-\frac{5}{3})$	B	$(\overline{Q_L}\,\overline{u_R}), (Q_L\ell_R), (d_R L_L)$		
ST16				F	$(d_R H^\dagger)$		
ST17	$(3, N\pm 2, \alpha)$	$\frac{4}{3}$	$(3,3,\frac{4}{3})$	B	$(Q_L\overline{L_R})$		$\checkmark\alpha=-\frac{2}{3}$
ST18				F	$(Q_L H)$		
ST19		$-\frac{2}{3}$	$(3,3,-\frac{2}{3})$	B	$(\overline{Q_L Q_L}), (Q_L L_L)$		$\checkmark\alpha=\frac{1}{3}$
ST20				F	$(Q_L H^\dagger)$		

ST type - 20 models



ID	X	$\alpha+\beta$	M$_s$	Spin	(SM$_1$ SM$_2$)	SM$_3$	M-X-X
SO1	$(8, N, \alpha)$	0	$(8,1,0)^{\neq g[s2]}$	B	$(d_R\overline{d_R}), (u_R\overline{u_R}), (Q_L\overline{Q_L})$		$\checkmark\alpha=0$
SO2			$(8,3,0)^{N\geq 2}$	B	$(Q_L\overline{Q_L})$		$\checkmark\alpha=0$
SO3		-2	$(8,1,-2)$	B	$(d_R\overline{u_R})$		$\checkmark\alpha=\pm 1$
SO4	$(8, N\pm 1, \alpha)$	-1	$(8,2,-1)$	B	$(d_R\overline{Q_L}), (Q_L\overline{u_R})$		
SO5	$(8, N\pm 2, \alpha)$	0	$(8,3,0)$	B	$(Q_L\overline{Q_L})$		$\checkmark\alpha=0$
SE1	$(6, N, \alpha)$	$\frac{8}{3}$	$(6,1,\frac{8}{3})$	B	$(u_R u_R)$		$\checkmark\alpha=-\frac{4}{3}$
SE2		$\frac{2}{3}$	$(6,1,\frac{2}{3})$	B	$(Q_L Q_L), (u_R d_R)$		$\checkmark(\alpha=-\frac{1}{3})$
SE3			$(6,3,\frac{2}{3})^{N\geq 2}$	B	$(Q_L Q_L)$		$\checkmark\alpha=-\frac{1}{3}$
SE4		$-\frac{4}{3}$	$(6,1,-\frac{4}{3})$	B	$(d_R d_R)$		$\checkmark\alpha=\frac{2}{3}$
SE5	$(6, N\pm 1, \alpha)$	$\frac{5}{3}$	$(6,2,\frac{5}{3})$	B	$(Q_L u_R)$		
SE6		$-\frac{1}{3}$	$(6,2,-\frac{1}{3})$	B	$(Q_L d_R)$		
SE7	$(6, N\pm 2, \alpha)$	$\frac{2}{3}$	$(6,3,\frac{2}{3})$	B	$(Q_L Q_L)$		$\checkmark\alpha=-\frac{1}{3}$

SO and SE type - 5 and 7 models

CODEX SIMPLIFIED MODELS: *t*-CHANNEL

ID	X	$\alpha+\beta$	M$_t$	Spin	(SM$_1$ SM$_2$)	SM$_3$
TU1	$(1,N,\alpha)$	0	$(1,N\pm1,\beta-1)$	I	$(HH^\dagger)$	$B,\ W_i^{N\geq2}$
TU2			$(1,N\pm1,\beta+1)$	II	(L_LH)	
TU3			$(1,N\pm1,\beta-1)$	III	(HL_L)	
TU4			$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\overline{Q_L})$	$B,\ W_i^{N\geq2}$
TU5			$(\bar3,N,\beta-\frac43)$	IV	$(u_R\overline{u_R})$	$B,\ W_i^{N\geq2}$
TU6			$(\bar3,N,\beta+\frac23)$	IV	$(d_R\overline{d_R})$	$B,\ W_i^{N\geq2}$
TU7			$(1,N\pm1,\beta+1)$	IV	$(L_L\overline{L_L})$	$B,\ W_i^{N\geq2}$
TU8			$(1,N,\beta+2)$	IV	$(\ell_R\overline{\ell_R})$	$B,\ W_i^{N\geq2}$
TU9		-2	$(1,N\pm1,\beta+1)$	I	$(H^\dagger H^\dagger)$	
TU10			$(1,N\pm1,\beta+1)$	II	$(L_LH^\dagger)$	ℓ_R
TU11			$(1,N\pm1,\beta+1)$	III	$(H^\dagger L_L)$	ℓ_R
TU12			$(1,N\pm1,\beta+1)$	IV	(L_LL_L)	
TU13			$(3,N,\beta+\frac43)$	IV	$(\overline{u_R}d_R)$	
TU14			$(\bar3,N,\beta+\frac23)$	IV	$(d_R\overline{u_R})$	
TU15		-4	$(1,N,\beta+2)$	IV	$(\ell_R\ell_R)$	
TU16	$(1,N\pm1,\alpha)$	-1	$(1,N,\beta+2)$	II	(ℓ_RH)	L_L
TU17			$(1,N\pm1,\beta-1)$	III	$(H\ell_R)$	L_L
TU18			$(1,N,\beta+2)$	IV	$(\ell_R\overline{L_L})$	$H^\dagger$
TU19			$(1,N\pm1,\beta-1)$	IV	$(\overline{L_L}\ell_R)$	$H^\dagger$
TU20			$(\bar3,N,\beta+\frac23)$	IV	$(d_R\overline{Q_L})$	$H^\dagger$
TU21			$(3,N\pm1,\beta+\frac13)$	IV	$(\overline{Q_L}d_R)$	$H^\dagger$
TU22			$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\overline{u_R})$	$H^\dagger$
TU23			$(3,N,\beta+\frac43)$	IV	$(\overline{u_R}Q_L)$	$H^\dagger$
TU24		-3	$(1,N\pm1,\beta+1)$	IV	$(L_L\ell_R)$	
TU25			$(1,N,\beta+2)$	IV	(ℓ_RL_L)	
TU26	$(1,N\pm2,\alpha)$	0	$(1,N\pm1,\beta-1)$	I	$(HH^\dagger)$	
TU27			$(1,N\pm1,\beta+1)$	II	(L_LH)	
TU28			$(1,N\pm1,\beta-1)$	III	(HL_L)	
TU29			$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\overline{Q_L})$	
TU30			$(1,N\pm1,\beta+1)$	IV	$(L_L\overline{L_L})$	
TU31		-2	$(1,N\pm1,\beta+1)$	I	$(H^\dagger H^\dagger)$	
TU32			$(1,N\pm1,\beta+1)$	II	$(L_LH^\dagger)$	
TU33			$(1,N\pm1,\beta+1)$	III	$(H^\dagger L_L)$	

TU type - 33 models

ID	X	$\alpha+\beta$	M$_t$	Spin	(SM$_1$ SM$_2$)	SM$_3$
TO1	$(8,N,\alpha)$	0	$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\overline{Q_L})$	
TO2			$(\bar3,N,\beta-\frac43)$	IV	$(u_R\overline{u_R})$	
TO3			$(\bar3,N,\beta+\frac23)$	IV	$(d_R\overline{d_R})$	
TO4		-2	$(\bar3,N,\beta+\frac23)$	IV	$(d_R\overline{u_R})$	
TO5			$(3,N,\beta+\frac43)$	IV	$(\overline{u_R}d_R)$	
TO6	$(8,N\pm1,\alpha)$	-1	$(\bar3,N,\beta+\frac23)$	IV	$(d_R\overline{Q_L})$	
TO7			$(3,N\pm1,\beta+\frac13)$	IV	$(\overline{Q_L}d_R)$	
TO8			$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\overline{u_R})$	
TO9			$(3,N,\beta+\frac43)$	IV	$(\overline{u_R}Q_L)$	
TO10	$(8,N\pm2,\alpha)$	0	$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\overline{Q_L})$	
TE1	$(6,N,\alpha)$	$\frac83$	$(\bar3,N,\beta-\frac43)$	IV	(u_Ru_R)	
TE2		$\frac23$	$(\bar3,N\pm1,\beta-\frac13)$	IV	(Q_LQ_L)	
TE3			$(\bar3,N,\beta-\frac43)$	IV	(u_Rd_R)	
TE4			$(\bar3,N,\beta+\frac23)$	IV	(d_Ru_R)	
TE5		$-\frac43$	$(\bar3,N,\beta+\frac23)$	IV	(d_Rd_R)	
TE6	$(6,N\pm1,\alpha)$	$\frac53$	$(\bar3,N,\beta-\frac43)$	IV	(u_RQ_L)	
TE7			$(\bar3,N\pm1,\beta-\frac13)$	IV	(Q_Lu_R)	
TE8		$-\frac13$	$(\bar3,N,\beta+\frac23)$	IV	(d_RQ_L)	
TE9			$(\bar3,N\pm1,\beta-\frac13)$	IV	(Q_Ld_R)	
TE10	$(6,N\pm2,\alpha)$	$\frac23$	$(\bar3,N\pm1,\beta-\frac13)$	IV	(Q_LQ_L)	

TO and TE type - 10 and 10 models

ID	X	$\alpha+\beta$	M$_t$	Spin	(SM$_1$ SM$_2$)	SM$_3$
TT1	$(3,N,\alpha)$	$\frac{10}{3}$	$(\bar3,N,\beta-\frac43)$	IV	$(u_R\overline{\ell_R})$	
TT2			$(1,N,\beta-2)$	IV	$(\overline{\ell_R}u_R)$	
TT3		$\frac43$	$(\bar3,N\pm1,\beta-\frac13)$	II	(Q_LH)	u_R
TT4			$(1,N\pm1,\beta-1)$	III	(HQ_L)	u_R
TT5			$(1,N,\beta-2)$	IV	$(\overline{\ell_R}d_R)$	
TT6			$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\overline{L_L})$	
TT7			$(1,N\pm1,\beta-1)$	IV	$(\overline{L_L}Q_L)$	
TT8			$(\bar3,N,\beta+\frac23)$	IV	$(d_R\overline{\ell_R})$	
TT9			$(3,N,\beta-\frac23)$	IV	$(\overline{d_Rd_R})$	
TT10		$-\frac23$	$(\bar3,N\pm1,\beta-\frac13)$	II	$(Q_LH^\dagger)$	d_R
TT11			$(1,N\pm1,\beta+1)$	III	$(H^\dagger Q_L)$	d_R
TT12			$(3,N,\beta+\frac43)$	IV	$(\overline{u_R}\overline{d_R})$	
TT13			$(3,N\pm1,\beta+\frac13)$	IV	$(\overline{Q_LQ_L})$	
TT14			$(\bar3,N,\beta-\frac43)$	IV	$(u_R\ell_R)$	
TT15			$(1,N,\beta+2)$	IV	(ℓ_Ru_R)	
TT16			$(\bar3,N\pm1,\beta-\frac13)$	IV	(Q_LL_L)	
TT17			$(1,N\pm1,\beta+1)$	IV	(L_LQ_L)	
TT18			$(3,N,\beta-\frac23)$	IV	$(\overline{d_R}\overline{u_R})$	
TT19		$-\frac83$	$(3,N,\beta+\frac43)$	IV	$(\overline{u_Ru_R})$	
TT20			$(\bar3,N,\beta+\frac23)$	IV	$(d_R\ell_R)$	
TT21			$(1,N,\beta+2)$	IV	(ℓ_Rd_R)	
TT22	$(3,N\pm1,\alpha)$	$\frac73$	$(\bar3,N,\beta-\frac43)$	II	(u_RH)	
TT23			$(1,N\pm1,\beta-1)$	III	(Hu_R)	
TT24			$(\bar3,N,\beta-\frac43)$	IV	$(u_R\overline{L_L})$	
TT25			$(1,N\pm1,\beta-1)$	IV	$(\overline{L_L}u_R)$	
TT26			$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\overline{\ell_R})$	
TT27			$(1,N,\beta-2)$	IV	$(\overline{\ell_R}Q_L)$	
TT28		$\frac13$	$(\bar3,N,\beta-\frac43)$	II	$(u_RH^\dagger)$	Q_L
TT29			$(\bar3,N,\beta+\frac23)$	II	(d_RH)	Q_L
TT30			$(1,N\pm1,\beta+1)$	III	$(H^\dagger u_R)$	Q_L
TT31			$(1,N\pm1,\beta-1)$	III	(Hd_R)	Q_L
TT32			$(\bar3,N,\beta-\frac43)$	IV	(u_RL_L)	
TT33			$(1,N\pm1,\beta+1)$	IV	(L_Lu_R)	
TT34			$3,N,\beta-\frac23)$	IV	$(\overline{d_RQ_L})$	
TT35			$(3,N\pm1,\beta+\frac13)$	IV	$(\overline{Q_Ld_R})$	
TT36		$-\frac53$	$(\bar3,N,\beta+\frac23)$	II	$(d_RH^\dagger)$	
TT37			$(1,N\pm1,\beta+1)$	III	$(H^\dagger d_R)$	
TT38			$(\bar3,N,\beta+\frac23)$	IV	(d_RL_L)	
TT39			$(1,N\pm1,\beta+1)$	IV	(L_Ld_R)	
TT40			$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\ell_R)$	
TT41			$(1,N,\beta+2)$	IV	(ℓ_RQ_L)	
TT42			$(3,N,\beta+\frac43)$	IV	$(\overline{u_R}\overline{Q_L})$	
TT43			$(3,N\pm1,\beta+\frac13)$	IV	$(\overline{Q_L}\overline{u_R})$	
TT44	$(3,N\pm2,\alpha)$	$\frac43$	$(\bar3,N\pm1,\beta-\frac13)$	II	(Q_LH)	
TT45			$(1,N\pm1,\beta-1)$	III	(HQ_L)	
TT46			$(\bar3,N\pm1,\beta-\frac13)$	IV	$(Q_L\overline{L_L})$	
TT47			$(1,N\pm1,\beta-1)$	IV	$(\overline{L_L}Q_L)$	
TT48		$-\frac23$	$(\bar3,N\pm1,\beta-\frac13)$	II	$(Q_LH^\dagger)$	
TT49			$(1,N\pm1,\beta+1)$	III	$(H^\dagger Q_L)$	
TT50			$(\bar3,N\pm1,\beta-\frac13)$	IV	(Q_LL_L)	
TT51			$(1,N\pm1,\beta+1)$	IV	(L_LQ_L)	
TT52			$(3,N\pm1,\beta+\frac13)$	IV	$(\overline{Q_LQ_L})$	

TT type - 52 models

FLAVOR FOR LEPTOQUARKS AND DIQUARKS

Flavor constraints motivate the chosen flavor structure of y_{vis}

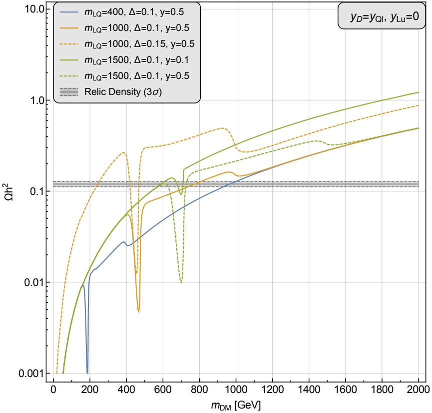
LEPTOQUARK MEDIATOR:

- Neutral meson mixing constrains: $y^{ij}_{\text{vis}}, i \neq j$ must be small
- Branching ration of $K_L \to \mu e$: $y^{11}_{\text{vis}} \times y^{22}_{\text{vis}}$ must be small
- Electron anomalous magnetic moment: $y^{11}_{Ql} \times y^{11}_{Lu}$ small
- Choice: only y^{11}_{vis} or y^{22}_{vis} nonzero
- Strongest limit from APV: $|y^{11}_{\text{vis}}| < 0.40 \left(\frac{m_{\text{LQ}}}{TeV}\right)$

DIQUARK MEDIATOR:

- Proton stability bounds forbid additional couplings of the mediator to leptons and quarks
- Possible to have both LH and RH couplings (set them equal)
- $K^0 - \bar{K}^0$ mixing: $y^{11}_{\text{vis}} \times y^{12}_{\text{vis}}$ small and $y^{11}_{\text{vis}} \times y^{22}_{\text{vis}}$ small
- Choice: only y^{11}_{vis} nonzero
- Strongest limit on y^{11}_{vis} from dijet resonances at LHC

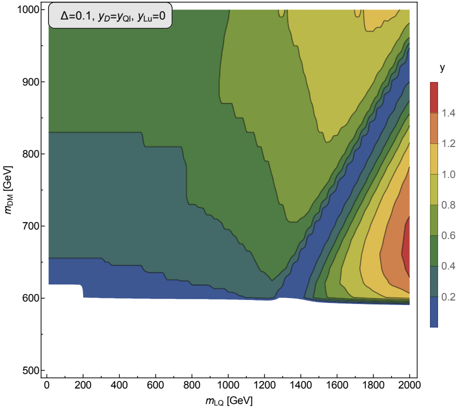
RELIC DENSITY (LEPTOQUARK)



Goal: fit $\Omega h^2 = 0.1198 \pm 0.0026$

Chemical equilibrium:

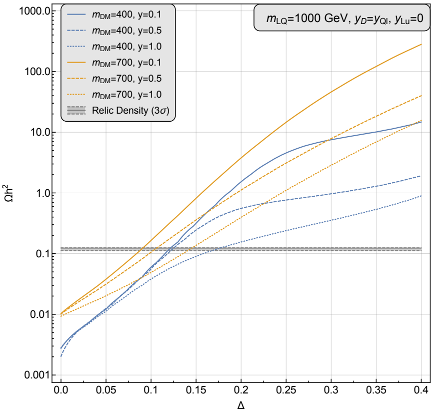
- DM DM ⇔ X $\overline{\text{X}}$
- DM SM ⇔ X SM
- X ⇔ DM SM SM



(Co)annihilation channels:

- X $\overline{\text{X}}$ → g g
- X DM → SM SM
- DM DM → M M → 4 SM
- X $\overline{\text{X}}$ → M M → 4 SM

RELIC DENSITY (ADDITIONAL PLOTS)



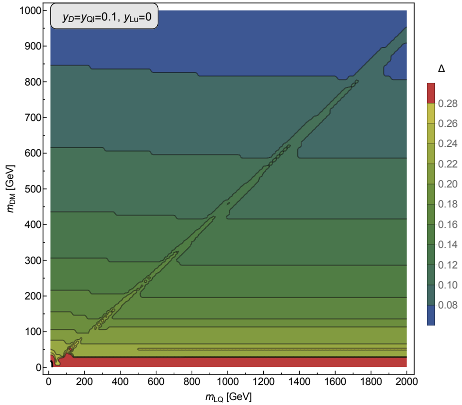
Annihilation channels:

- $X\,\overline{X} \to g\,g$
- $X\,DM \to SM\,SM$
- $DM\,DM \to M\,M \to 4\,SM$
- $X\,\overline{X} \to M\,M \to 4\,SM$

Goal: fit $\Omega h^2 = 0.1198 \pm 0.0026$

Chemical equilibrium:

- $DM\,DM \Leftrightarrow X\,\overline{X}$
- $DM\,SM \Leftrightarrow X\,SM$
- $X \Leftrightarrow DM\,SM\,SM$



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 three powers of heavy mass, leading to negligible σ_{direct}
- DM DM $\psi_{\text{SM}}\, \bar{\psi}_{\text{SM}}$: Majorana DM implies scalar nature for the fermion-bilinears and m_ψ / m_{M} suppression

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

DM DM → 4 SM is p-wave suppressed and DM DM → 2 SM is loop suppressed, hence indirect detection is challenging

LHC: NEW SEARCHES (CUT-FLOW)

LQ MIXED DECAY:

$m_{\rm DM} = 405$ GeV, $m_{\rm DM} = 445$ GeV and $m_{\rm DM} = 950$ GeV

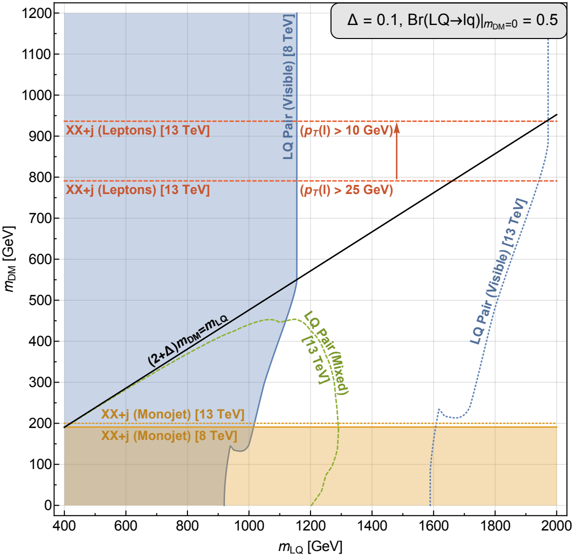
	QCD	$W+1,2j$	$t\bar{t}$	$Z_{\nu\nu}+j$	$Z_{\tau\tau}+j$	W^+W^-	$WZ_{\nu\nu}+j$	WZ_{jj}	signal
$p_T(j_1) > 50$ GeV	2.1×10^{12}	4.4×10^{8}	1.3×10^{8}	7.0×10^{7}	1.3×10^{7}	1.2×10^{6}	1.3×10^{5}	3.1×10^{5}	600
$N_e^{\rm h} = 1, N_e \le 2$	4.8×10^{9}	8.8×10^{7}	1.2×10^{7}	8.6×10^{4}	4.8×10^{5}	2.4×10^{5}	1.9×10^{4}	6.1×10^{4}	415
b-jet veto	4.0×10^{9}	8.2×10^{7}	5.0×10^{6}	8.2×10^{4}	4.6×10^{5}	2.2×10^{5}	1.9×10^{4}	5.4×10^{4}	395
$N_{\rm hard\ jets} \le 3$	3.9×10^{9}	8.2×10^{7}	4.3×10^{6}	8.2×10^{4}	4.6×10^{5}	2.2×10^{5}	1.9×10^{4}	5.4×10^{4}	335
Z veto	3.9×10^{9}	8.2×10^{7}	1.7×10^{6}	8.2×10^{4}	4.6×10^{5}	2.2×10^{5}	1.9×10^{4}	5.4×10^{4}	326
$\not{E}_T > 700$ GeV	133	1738	15	19	9	10	27	2	75
$m_T > 150$ GeV	132	16	10^{-3}	18	0.005	0.01	10	0.001	67
mass window	3	0.2	$< 10^{-5}$	0.3	10^{-5}	10^{-5}	0.1	10^{-5}	24

LQ XX + JET:

$m_{\rm DM} = 600$ GeV, $m_{\rm DM} = 660$ GeV and $m_{\rm DM} = 1700$ GeV

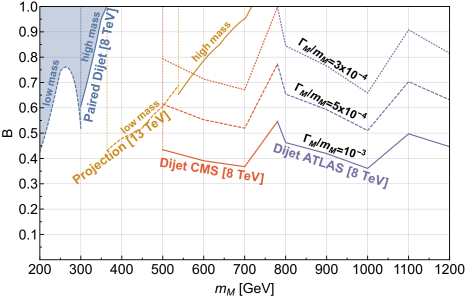
	$t\bar{t}$	$Z_{\ell\ell}+j$	Diboson	$W_{\ell\nu}+j$	$t+j$	Signal
$\not{E}_T > 50$ GeV	1.9×10^{7}	7.9×10^{6}	1.1×10^{6}	1.9×10^{8}	5.6×10^{5}	8.5×10^{4}
$p_T^{\rm lead} > 50$ GeV	1.8×10^{7}	6.1×10^{6}	5.9×10^{5}	1.5×10^{8}	4.6×10^{5}	7.1×10^{4}
$\Delta\phi_{j_1 j_2} < 2.5$	1.2×10^{7}	4.2×10^{6}	5.0×10^{5}	1.1×10^{8}	2.9×10^{5}	5.4×10^{4}
Z and μ veto	8.5×10^{6}	2.7×10^{6}	4.0×10^{5}	8.6×10^{7}	1.9×10^{5}	5.2×10^{4}
b veto	3.6×10^{6}	2.6×10^{6}	3.7×10^{5}	8.2×10^{7}	1.1×10^{5}	2.0×10^{4}
$N_l \ge 2$	2.5×10^{4}	4371	1076	9.8×10^{4}	382	1748
$\not{E}_T > 400$ GeV	12	11	0.07	780	2	118
$\left\lvert\frac{p_{T\,j_1}}{\not{E}_T} - 1\right\rvert < 0.2$	1	11	0.07	148	0.2	85

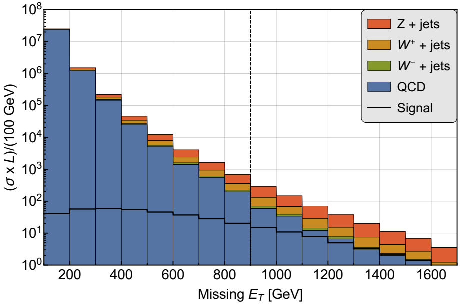
LHC: COMBINED RESULTS (MUONS)



- Combined exclusion and projections
- Relic density allowed region (muons do not have APV contour): $m_{\mathrm{DM}} > 570$ GeV
- Fix couplings $y_D, y_{Q\ell}^{11}$ such that branching ratios are ($m_{\mathrm{DM}} = 0$):
  LQ → visible = 50%
  LQ → dark = 50%
- Mixed topology is maximized

LHC: ADDITIONAL DIQUARK MATERIAL





- Limits on DQ mediator from dijet and paired dijet searches
- Dijet resonance limits satisfied if $\Gamma_M/m_M \lesssim 10^{-4}$

- Jets + MET limits only have a slight dependence on Δ

Search	$\Delta = 0.1$	$\Delta = 0.125$	$\Delta = 0.15$
8 TeV	384 GeV	396 GeV	392 GeV
13 TeV, current	398 GeV	399 GeV	396 GeV
13 TeV, 100 fb^{-1}	464 GeV	468 GeV	477 GeV

- Mixed dijet resonance + MET search main discriminators are MET and $m_{j_1 j_2}$
- S/B obtained by in $m_{j_1 j_2}$ while signal is fitted using a Crystal Ball function