The Coannihilation Codex

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with
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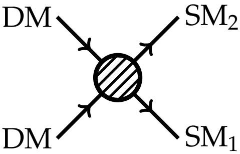
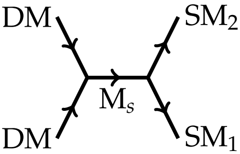
INTRODUCTION

- 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

  ⇒ EFT/Simplified Models: SM + DM (+ Mediator)





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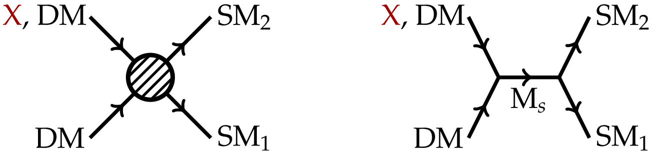
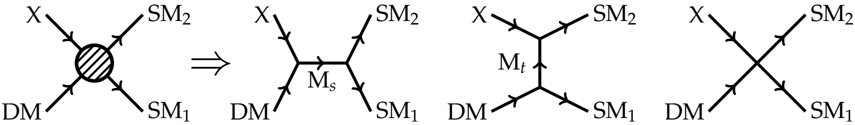


- Often coannihilation is needed to obtain correct relic density
  ⇒ coannihilation partner X
- Study all possible (DM, X, M) extensions of the SM characterizing simplified models for coannihilation

COANNIHILATION

Characterize all possible two-to-two DM (co)annihilation processes as simplified models



- 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
- Result: A bottom-up framework for discovering dark matter at the LHC
  - LHC probes motivated by how DM obtains its relic density
  - Natures choice for DM guaranteed to be realized in our framework given our assumptions

COANNIHILATION

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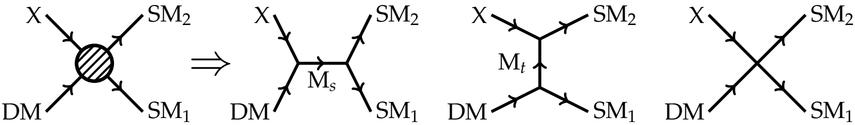


ASSUMPTIONS:

- 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 minimal coupling (renormalizability and gauge invariance)

CONSTRUCTING THE CODEX

Construction a minimal basis of simplified models

- Work in the unbroken $SU(2)_L \times U(1)_Y$ phase
- DM transforms as $(1, N, \beta)$, 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 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)

REFINING THE CODEX

- Notice that X = DM reproduces pair annihilation simplified models
- Accidental $\mathbb{Z}_2$ parity protects against DM decay and also prohibits role reversal between *s*- and *t*-channel models ($X_s = M_t$ and $X_t = M_s$) because M_s is $\mathbb{Z}_2$-even and M_t is $\mathbb{Z}_2$-odd
- In some models four-point interactions provide additional coannihilation channels
- Minimal coupling provision reduces number of possible simplified models
  - Coannihilation product SM_1 or SM_2 is a SM gauge boson ⇒ hybrid simplified model
  - In hybrid models $M_s = SM_3$ and M_t = DM or X (reduced field content and couplings)
  - Hybrid models have both *s*-channel and *t*-channel coannihilation (if DM and X not gauge singlets)
- EWSB effects can be included into models (phenomenology of such models already captured by current classification)

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:

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

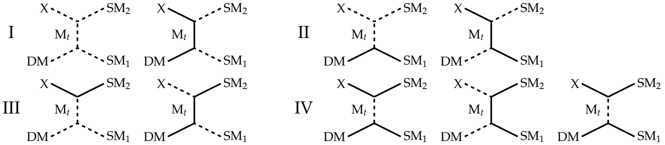
THE COANNIHILATION CODEX

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:

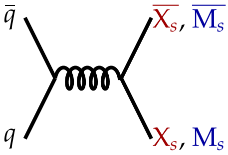
ID	X	$\alpha+\beta$	M_t	Spin	(SM_1 SM_2)	X–DM–SM_3
TE1	$(6, N, \alpha)$	$\frac{8}{3}$	$(\bar{3}, N, \beta - \frac{4}{3})$	IV	$(u_R\, u_R)$	
TE2		$\frac{2}{3}$	$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L\, Q_L)$	
TE3			$(\bar{3}, N, \beta - \frac{4}{3})$	IV	$(u_R\, d_R)$	
TE4			$(\bar{3}, N, \beta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



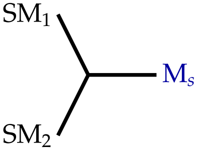
PHENOMENOLOGY: s-CHANNEL

PRODUCTION:

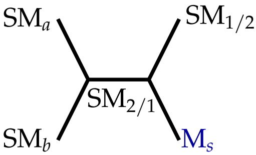
Pair X_s/M_s:



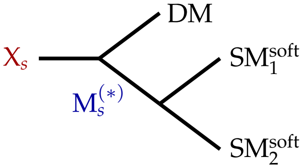
Single M_s:

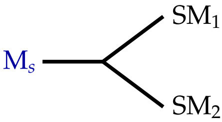


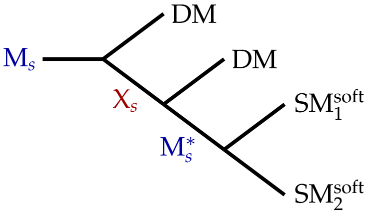
M_s + SM:



DECAY:



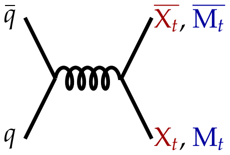




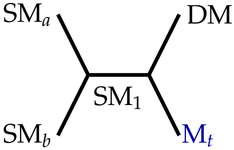
PHENOMENOLOGY: t-CHANNEL

PRODUCTION:

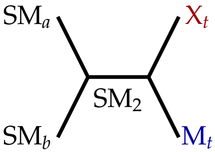
Pair X_t/M_t:



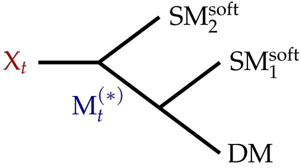
M_t + DM:

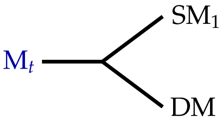


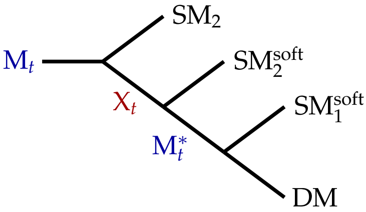
M_t + X_t:



DECAY:







INESCAPABLE LHC SIGNATURES

- Assume coannihilation sizable: $\Delta = \frac{m_X - m_{DM}}{m_{DM}} = \mathcal{O}(5 - 20\%)$
- Pair production and decays of M and X guaranteed

1) MONO-Y + MET:

- DM DM, DM X, X X + ISR (X decays may be resolved depending on Δ and detector performance New!)
- Pair production of M ($2 \times \mathrm{M} \to \mathrm{DM\ X}$)

2) S-CHANNEL RESONANCES:

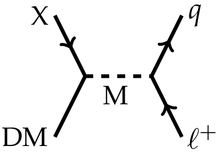
- Paired resonances ($2 \times \mathrm{M} \to \mathrm{SM}_1\ \mathrm{SM}_2$)
- Resonance + MET ($\mathrm{M} \to \mathrm{SM}_1\ \mathrm{SM}_2$ and $\mathrm{M} \to \mathrm{DM\ X}$) New!

3) T-CHANNEL CASCADES:

- Cascade decays always with final state MET (no resonances)
- SM legs from mediator hard, from X soft, new kinematics

LEPTOQUARK-MEDIATED COANNIHILATION

Field	Rep.	Spin and mass 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

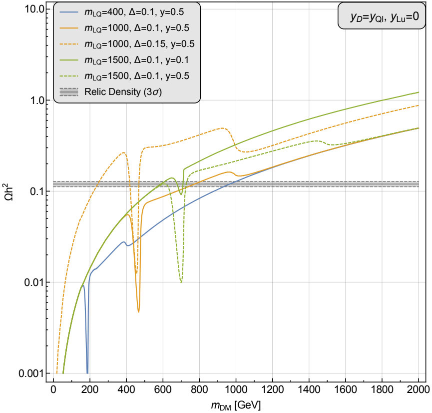


$$\mathcal{L} \supset \mathcal{L}_{\text{kin}} + y_D \overline{\mathrm{X}}\,\mathrm{M}\,\mathrm{DM} + y_{Q\ell}\overline{Q_L}\mathrm{M}\ell_R + y_{Lu}\overline{L_L}\mathrm{M}^c u_R + h.c.$$

$$\Delta = \frac{m_{\mathrm{X}} - m_{\mathrm{DM}}}{m_{\mathrm{DM}}} \qquad y_{Q\ell}^{ij} = y_{Lu} = 0 \qquad y_D \neq 0 \neq y_{Q\ell}^{11}$$

- Satisfies flavor constraints, APV gives $|y_{Q\ell}^{11}| < 0.40\,\left(\frac{m_{\mathrm{LQ}}}{1\,\mathrm{TeV}}\right)$
- Branching ratios of M depend on y_{LQ}, y_D, m_{DM} and Δ

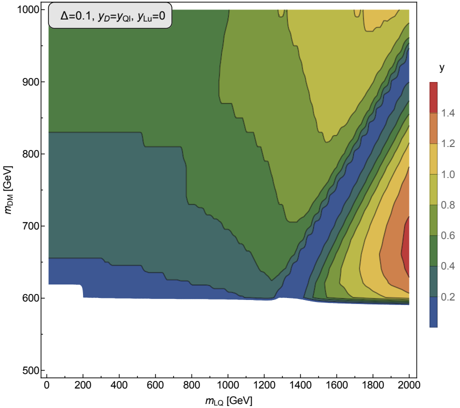
RELIC DENSITY



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

Chemical equilibrium:

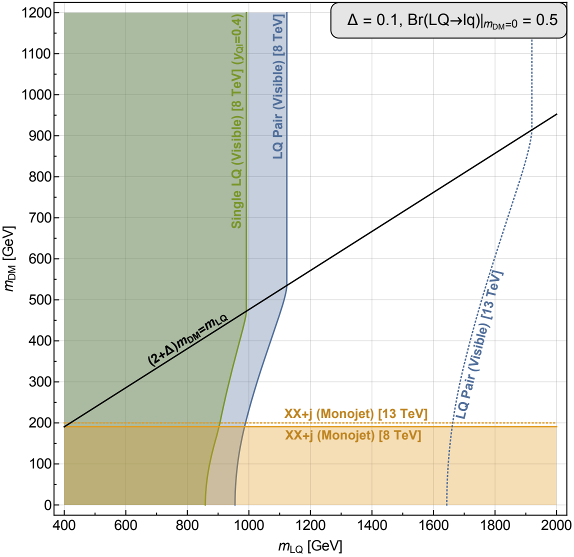
- DM DM ⇔ X X
- DM SM ⇔ X SM
- X ⇔ DM SM SM

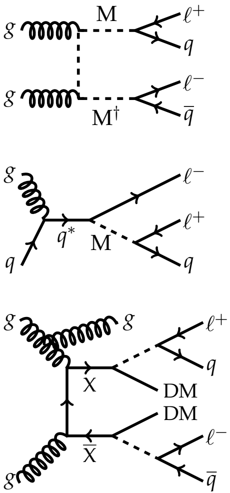


(Co)annihilation channels:

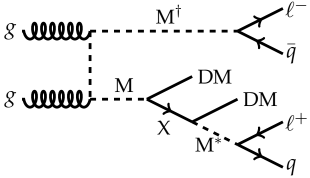
- X X → g g
- X DM → SM SM
- DM DM → M M → 4 SM
- X X → M M → 4 SM

LHC: CURRENT EXCLUSIONS

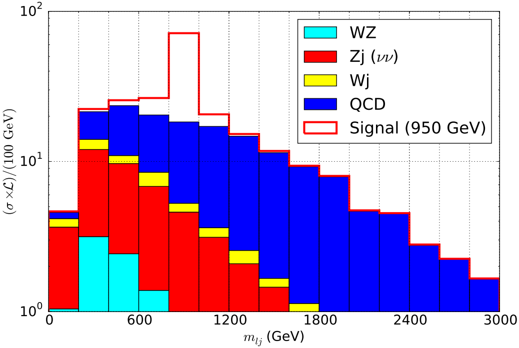




LHC: NEW SEARCHES

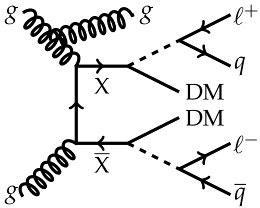


- ℓ and q from invisible decay chain are soft
- Main cuts: MET, m_T, $m_{\ell q}$

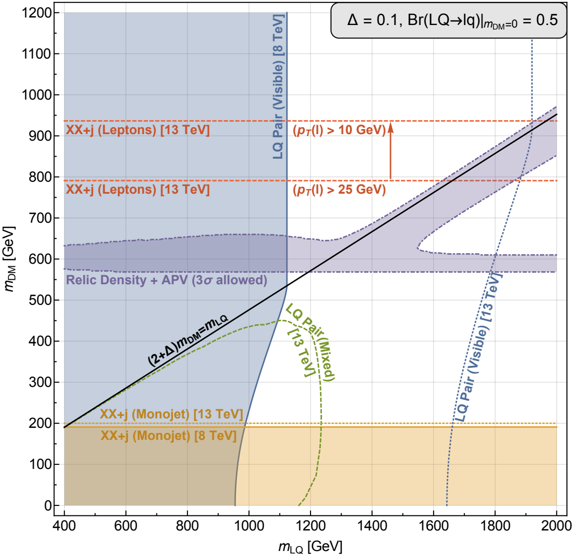


- Similar to monojet + MET search
- Additional requirement of 2 soft leptons
- Table shows 2σ exclusion limit on m_X

	$p_T > 10$ 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

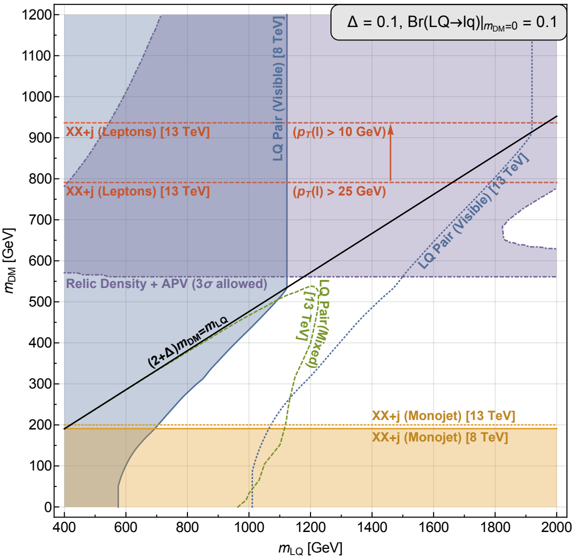


LHC: COMBINED RESULTS (EQUAL BRANCHING)



- Combined exclusion and projections
- Relic density + APV allowed contour
  APV: $|y^{11}_{Q\ell}| < 0.40 \left(\frac{m_{\mathrm{LQ}}}{1\,\mathrm{TeV}}\right)$
- Fix couplings $y_D, y^{11}_{Q\ell}$ such that branching ratios are ($m_{\mathrm{DM}} = 0$):
  LQ → visible = 50%
  LQ → dark = 50%
- Mixed topology is maximized

LHC: COMBINED RESULTS (DARK $\gg$ VISIBLE)



- Combined exclusion and projections
- Relic density + APV allowed contour
  APV: $|y^{11}_{Q\ell}| < 0.40 \left(\frac{m_{\text{LQ}}}{1\,\text{TeV}}\right)$
- Fix couplings $y_D, y^{11}_{Q\ell}$ such that branching ratios are ($m_{\text{DM}} = 0$):
  LQ → visible = 10%
  LQ → dark = 90%
- Mixed topology is maximized relative to fully visible topology

CONCLUSIONS

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- Guaranteed kinetic & coannihilation vertices
  $\Rightarrow$ inescapable signatures
  - We identified these new LHC signatures
  - We identified interesting models, e.g., leptoquarks and DM
  - Other low-hanging fruit: dijet/dilepton resonances + MET

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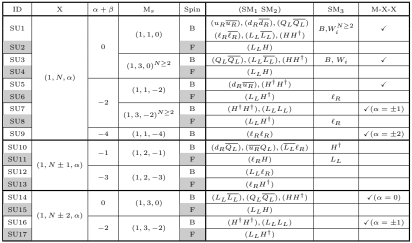
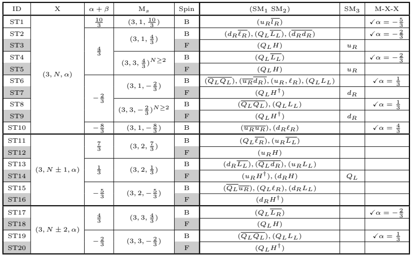
Thank you for your attention!

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	$(H^\dagger H^\dagger), (L_L L_L)$		$✓(\alpha=\pm 1)$
SU8				F	$(L_L H^\dagger)$	ℓ_R	
SU9		-4	$(1,1,-4)$	B	$(\ell_R\ell_R)$		$✓(\alpha=\pm 2)$
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	$(L_L\overline{L_L}), (Q_L\overline{Q_L}), (HH^\dagger)$		$✓(\alpha=0)$
SU15				F	$(L_L H)$		
SU16		-2	$(1,3,-2)$	B	$(H^\dagger H^\dagger), (L_L L_L)$		$✓(\alpha=\pm 1)$
SU17				F	$(L_L H^\dagger)$		

SU type - 17 models



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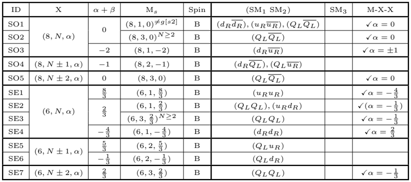
ST2		$\frac{4}{3}$	$(3,1,\frac{4}{3})$	B	$(d_R\overline{\ell_R}), (Q_L\overline{L_L}), (\overline{d_R d_R})$		$✓\alpha=-\frac{2}{3}$
ST3				F	$(Q_L H)$	u_R	
ST4			$(3,3,\frac{4}{3})^{N\geq 2}$	B	$(Q_L\overline{L_L})$		$✓\alpha=-\frac{2}{3}$
ST5				F	$(Q_L H)$	u_R	
ST6		$-\frac{2}{3}$	$(3,1,-\frac{2}{3})$	B	$(\overline{Q_L Q_L}), (\overline{u_R}\,\overline{d_R}), (u_R, \ell_R), (Q_L L_L)$		$✓\alpha=\frac{1}{3}$
ST7				F	$(Q_L H^\dagger)$	d_R	
ST8			$(3,3,-\frac{2}{3})^{N\geq 2}$	B	$(\overline{Q_L Q_L}), (Q_L L_L)$		$✓\alpha=\frac{1}{3}$
ST9				F	$(Q_L H^\dagger)$	d_R	
ST10		$-\frac{8}{3}$	$(3,1,-\frac{8}{3})$	B	$(\overline{u_R u_R}), (d_R\ell_R)$		$✓\alpha=\frac{4}{3}$
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	$(Q_L\overline{L_R})$		$✓\alpha=-\frac{2}{3}$
ST18				F	$(Q_L H)$		
ST19		$-\frac{2}{3}$	$(3,3,-\frac{2}{3})$	B	$(\overline{Q_L Q_L}), (Q_L L_L)$		$✓\alpha=\frac{1}{3}$
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	$(d_R\overline{d_R}), (u_R\overline{u_R}), (Q_L\overline{Q_L})$		$✓\alpha=0$
SO2			$(8,3,0)^{N\geq 2}$	B	$(Q_L\overline{Q_L})$		$✓\alpha=0$
SO3		-2	$(8,1,-2)$	B	$(d_R\overline{u_R})$		$✓\alpha=\pm 1$
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	$(Q_L\overline{Q_L})$		$✓\alpha=0$
SE1	$(6, N, \alpha)$	$\frac{8}{3}$	$(6,1,\frac{8}{3})$	B	$(u_R u_R)$		$✓\alpha=-\frac{4}{3}$
SE2		$\frac{2}{3}$	$(6,1,\frac{2}{3})$	B	$(Q_L Q_L), (u_R d_R)$		$✓(\alpha=-\frac{1}{3})$
SE3			$(6,3,\frac{2}{3})^{N\geq 2}$	B	$(Q_L Q_L)$		$✓\alpha=-\frac{1}{3}$
SE4		$-\frac{4}{3}$	$(6,1,-\frac{4}{3})$	B	$(d_R d_R)$		$✓\alpha=\frac{2}{3}$
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	$(Q_L Q_L)$		$✓\alpha=-\frac{1}{3}$

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			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\overline{Q_L})$	$B,\ W_i^{N\geq2}$
TU5			$(\bar{3}, N, \beta-\frac{4}{3})$	IV	$(u_R\overline{u_R})$	$B,\ W_i^{N\geq2}$
TU6			$(\bar{3}, N, \beta+\frac{2}{3})$	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			$(3, N, \beta+\frac{4}{3})$	IV	$(\overline{u_R}d_R)$	
TU14			$(\bar{3}, N, \beta+\frac{2}{3})$	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			$(\bar{3}, N, \beta+\frac{2}{3})$	IV	$(d_R\overline{Q_L})$	$H^\dagger$
TU21			$(3, N\pm1, \beta+\frac{1}{3})$	IV	$(\overline{Q_L}d_R)$	$H^\dagger$
TU22			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\overline{u_R})$	$H^\dagger$
TU23			$(3, N, \beta+\frac{4}{3})$	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			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	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

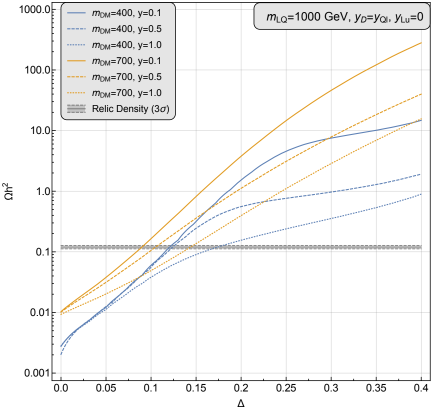
ID	X	$\alpha+\beta$	M$_t$	Spin	(SM$_1$ SM$_2$)	SM$_3$
TO1	$(8, N, \alpha)$	0	$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\overline{Q_L})$	
TO2			$(\bar{3}, N, \beta-\frac{4}{3})$	IV	$(u_R\overline{u_R})$	
TO3			$(\bar{3}, N, \beta+\frac{2}{3})$	IV	$(d_R\overline{d_R})$	
TO4		-2	$(\bar{3}, N, \beta+\frac{2}{3})$	IV	$(d_R\overline{u_R})$	
TO5			$(3, N, \beta+\frac{4}{3})$	IV	$(\overline{u_R}d_R)$	
TO6	$(8, N\pm1, \alpha)$	-1	$(\bar{3}, N, \beta+\frac{2}{3})$	IV	$(d_R\overline{Q_L})$	
TO7			$(3, N\pm1, \beta+\frac{1}{3})$	IV	$(\overline{Q_L}d_R)$	
TO8			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\overline{u_R})$	
TO9			$(3, N, \beta+\frac{4}{3})$	IV	$(\overline{u_R}Q_L)$	
TO10	$(8, N\pm2, \alpha)$	0	$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\overline{Q_L})$	
TE1	$(6, N, \alpha)$	$\frac{8}{3}$	$(\bar{3}, N, \beta-\frac{4}{3})$	IV	(u_Ru_R)	
TE2		$\frac{2}{3}$	$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	(Q_LQ_L)	
TE3			$(\bar{3}, N, \beta-\frac{4}{3})$	IV	(u_Rd_R)	
TE4			$(\bar{3}, N, \beta+\frac{2}{3})$	IV	(d_Ru_R)	
TE5		$-\frac{4}{3}$	$(\bar{3}, N, \beta+\frac{2}{3})$	IV	(d_Rd_R)	
TE6	$(6, N\pm1, \alpha)$	$\frac{5}{3}$	$(\bar{3}, N, \beta-\frac{4}{3})$	IV	(u_RQ_L)	
TE7			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	(Q_Lu_R)	
TE8		$-\frac{1}{3}$	$(\bar{3}, N, \beta+\frac{2}{3})$	IV	(d_RQ_L)	
TE9			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	(Q_Ld_R)	
TE10	$(6, N\pm2, \alpha)$	$\frac{2}{3}$	$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	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	$(3, N, \alpha)$	$\frac{10}{3}$	$(\bar{3}, N, \beta-\frac{4}{3})$	IV	$(u_R\overline{\ell_R})$	
TT2			$(1, N, \beta-2)$	IV	$(\overline{\ell_R}u_R)$	
TT3		$\frac{4}{3}$	$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	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			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\overline{L_L})$	
TT7			$(1, N\pm1, \beta-1)$	IV	$(\overline{L_L}Q_L)$	
TT8			$(\bar{3}, N, \beta+\frac{2}{3})$	IV	$(d_R\overline{\ell_R})$	
TT9			$(3, N, \beta-\frac{2}{3})$	IV	$(\overline{d_R}d_R)$	
TT10		$-\frac{2}{3}$	$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	II	$(Q_LH^\dagger)$	d_R
TT11			$(1, N\pm1, \beta+1)$	III	$(H^\dagger Q_L)$	d_R
TT12			$(3, N, \beta+\frac{4}{3})$	IV	$(\overline{u_R}\overline{d_R})$	
TT13			$(3, N\pm1, \beta+\frac{1}{3})$	IV	$(\overline{Q_L}\overline{Q_L})$	
TT14			$(\bar{3}, N, \beta-\frac{4}{3})$	IV	$(u_R\ell_R)$	
TT15			$(1, N, \beta+2)$	IV	(ℓ_Ru_R)	
TT16			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	(Q_LL_L)	
TT17			$(1, N\pm1, \beta+1)$	IV	(L_LQ_L)	
TT18			$(3, N, \beta-\frac{2}{3})$	IV	$(\overline{d_R}\overline{u_R})$	
TT19		$-\frac{8}{3}$	$(3, N, \beta+\frac{4}{3})$	IV	$(\overline{u_R}\overline{u_R})$	
TT20			$(\bar{3}, N, \beta+\frac{2}{3})$	IV	$(d_R\ell_R)$	
TT21			$(1, N, \beta+2)$	IV	(ℓ_Rd_R)	
TT22	$(3, N\pm1, \alpha)$	$\frac{7}{3}$	$(\bar{3}, N, \beta-\frac{4}{3})$	II	(u_RH)	
TT23			$(1, N\pm1, \beta-1)$	III	(Hu_R)	
TT24			$(\bar{3}, N, \beta-\frac{4}{3})$	IV	$(u_R\overline{L_L})$	
TT25			$(1, N\pm1, \beta-1)$	IV	$(\overline{L_L}u_R)$	
TT26			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\overline{\ell_R})$	
TT27			$(1, N, \beta-2)$	IV	$(\overline{\ell_R}Q_L)$	
TT28		$\frac{1}{3}$	$(\bar{3}, N, \beta-\frac{4}{3})$	II	$(u_RH^\dagger)$	Q_L
TT29			$(\bar{3}, N, \beta+\frac{2}{3})$	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			$(\bar{3}, N, \beta-\frac{4}{3})$	IV	(u_RL_L)	
TT33			$(1, N\pm1, \beta+1)$	IV	(L_Lu_R)	
TT34			$3, N, \beta-\frac{2}{3})$	IV	$(\overline{d_R}\overline{Q_L})$	
TT35			$(3, N\pm1, \beta+\frac{1}{3})$	IV	$(\overline{Q_L}\overline{d_R})$	
TT36		$-\frac{5}{3}$	$(\bar{3}, N, \beta+\frac{2}{3})$	II	$(d_RH^\dagger)$	
TT37			$(1, N\pm1, \beta+1)$	III	$(H^\dagger d_R)$	
TT38			$(\bar{3}, N, \beta+\frac{2}{3})$	IV	(d_RL_L)	
TT39			$(1, N\pm1, \beta+1)$	IV	(L_Ld_R)	
TT40			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\ell_R)$	
TT41			$(1, N, \beta+2)$	IV	(ℓ_RQ_L)	
TT42			$(3, N, \beta+\frac{4}{3})$	IV	$(\overline{u_R}\overline{Q_L})$	
TT43			$(3, N\pm1, \beta+\frac{1}{3})$	IV	$(\overline{Q_L}\overline{u_R})$	
TT44	$(3, N\pm2, \alpha)$	$\frac{4}{3}$	$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	II	(Q_LH)	
TT45			$(1, N\pm1, \beta-1)$	III	(HQ_L)	
TT46			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\overline{L_L})$	
TT47			$(1, N\pm1, \beta-1)$	IV	$(\overline{L_L}Q_L)$	
TT48		$-\frac{2}{3}$	$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	II	$(Q_LH^\dagger)$	
TT49			$(1, N\pm1, \beta+1)$	III	$(H^\dagger Q_L)$	
TT50			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	(Q_LL_L)	
TT51			$(1, N\pm1, \beta+1)$	IV	(L_LQ_L)	
TT52			$(3, N\pm1, \beta+\frac{1}{3})$	IV	$(\overline{Q_L}\overline{Q_L})$	

TT type - 52 models

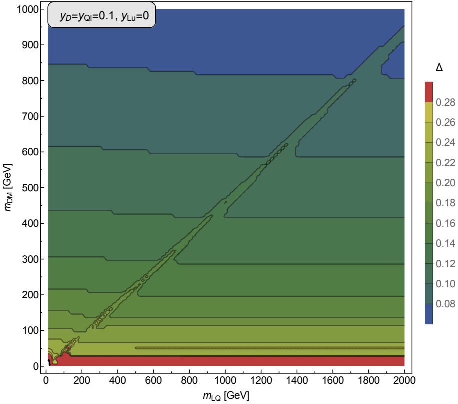
RELIC DENSITY (ADDITIONAL PLOTS)



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

Chemical equilibrium:

- DM DM ⇔ X X
- DM SM ⇔ X SM
- X ⇔ DM SM SM



Annihilation channels:

- X X → g g
- X DM → SM SM
- DM DM → M M → 4 SM
- X X → M M → 4 SM

LHC: NEW SEARCHES (CUT-FLOW)

LQ MIXED DECAY:

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

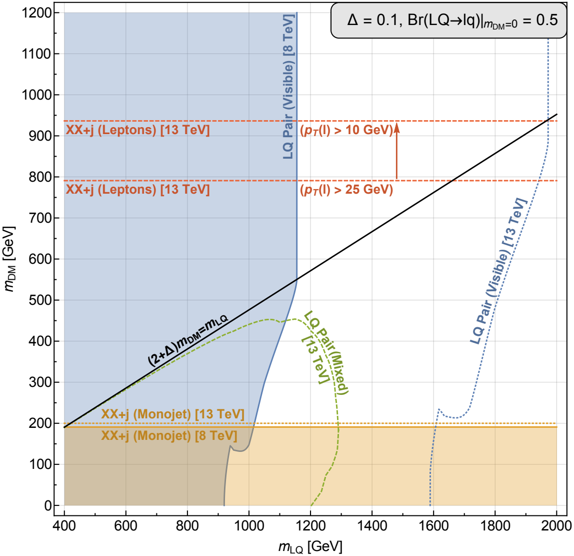
	QCD	$W+1,2j$	$t\bar{t}$	$Z_{\nu\nu}+j$	$Z_{\tau\tau}+j$	W^+W^-	$WZ_{\nu\nu}+j$	WZ_{jj}	signal
$p_T(j_1) > 50$ GeV	2.1×10^{12}	4.4×10^{8}	1.3×10^{8}	7.0×10^{7}	1.3×10^{7}	1.2×10^{6}	1.3×10^{5}	3.1×10^{5}	600
$N_e^{\mathrm{h}} = 1, N_e \leq 2$	4.8×10^{9}	8.8×10^{7}	1.2×10^{7}	8.6×10^{4}	4.8×10^{5}	2.4×10^{5}	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
$N_{\text{hard jets}} \leq 3$	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:

$m_{\mathrm{DM}} = 600$ GeV, $m_{\mathrm{DM}} = 660$ GeV and $m_{\mathrm{DM}} = 1700$ 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}
$p_T^{\mathrm{lead}} > 50$ 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}
$\Delta\phi_{j_1j_2} < 2.5$	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}
$N_l \geq 2$	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): $m_{\rm DM} > 570$ GeV
- Fix couplings $y_D, y_{Q\ell}^{11}$ such that branching ratios are ($m_{\rm DM} = 0$):
  LQ → visible = 50%
  LQ → dark = 50%
- Mixed topology is maximized