

Strongly Coannihilating Dark Matter at the LHC

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[arXiv:1510.03434] [JHEP 1512 (2015) 120]

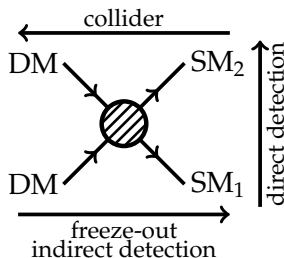
[arXiv:1605.08056] [JHEP 1609 (2016) 033]

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September 28, 2016

INTRODUCTION

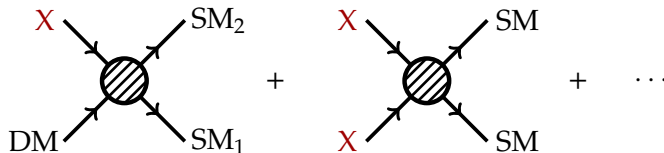
- Dark matter (DM) is observed using gravitational probes, but we are ignorant about its particle identity
- The thermal hypothesis: elegant explanation of current DM relic density that implies DM interactions with the SM
- DM annihilation implies direct detection, indirect detection and collider signatures 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: $\Delta = \frac{m_X - m_{\text{DM}}}{m_{\text{DM}}} \lesssim \mathcal{O}(20\%)$
 - Set of interactions mediating $\text{DM } X \rightarrow \text{SM}_1 \text{ SM}_2$
- Relic density set by the processes:



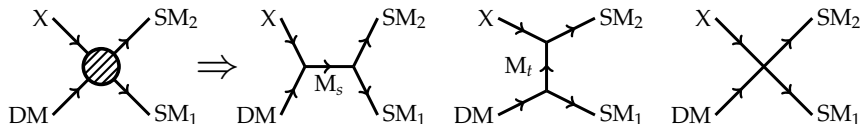
- Sizable contributions from coannihilation to the relic abundance alleviate the tight connection between the different DM detection probes
- Especially direct and indirect detection are suppressed and novel strong LHC signatures may appear depending on the nature of X and the coannihilation mechanism

THE COANNIHILATION CODEX

[arXiv:1510.03434]

Codex: a **minimal basis** of simplified models for coannihilation

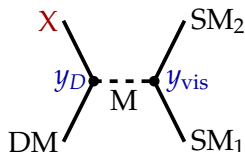
- Resolve the effective coannihilation diagram into channels



- 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, $\frac{1}{2}$ 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: $m_{\text{DM}}, m_X = m_{\text{DM}}(1 + \Delta), m_M, y_{\text{vis}}, y_D$
- Choose flavor structure of y_{vis} to be first generation only
- Interchange couplings for $B_0 = \text{Br}(M \rightarrow \text{vis})|_{m_{\text{DM}}=0}$ and Γ_M

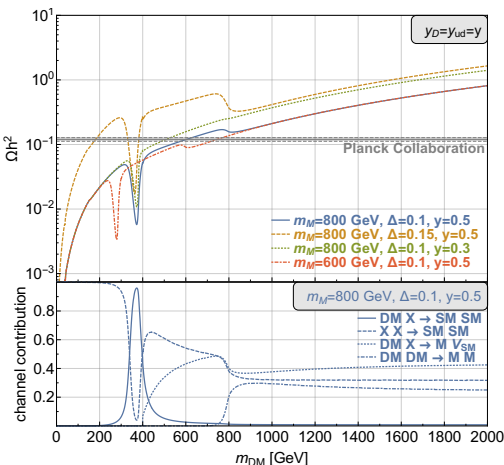
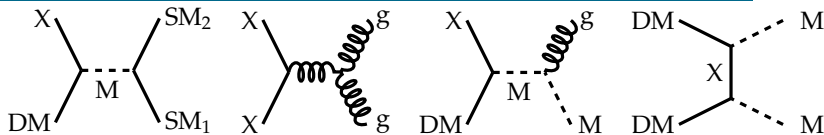
Leptoquark model (LQ)

Field	Rep.	Spin assignment
DM	$(1, 1, 0)$	Majorana fermion
X	$(3, 2, \frac{7}{6})$	Dirac fermion
$M \equiv \text{LQ}$	$(3, 2, \frac{2}{3})$	Scalar
SM_1, SM_2	$(Q_L \bar{\ell}_R), (u_R \bar{L}_L)$	

Diquark model (DQ)

Field	Rep.	Spin assignment
DM	$(1, 1, 0)$	Majorana fermion
X	$(3, 1, -\frac{2}{3})$	Dirac fermion
$M \equiv \text{DQ}$	$(3, 1, -\frac{4}{3})$	Scalar
SM_1, SM_2	$(\bar{u}_R \bar{d}_R)$	

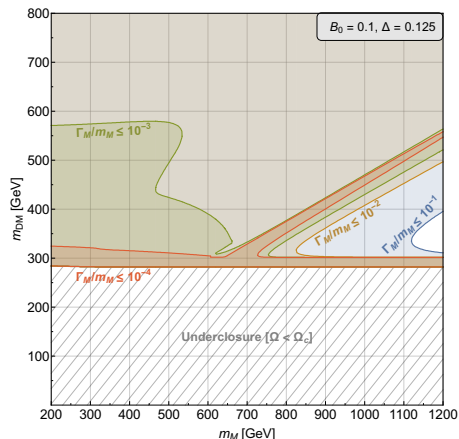
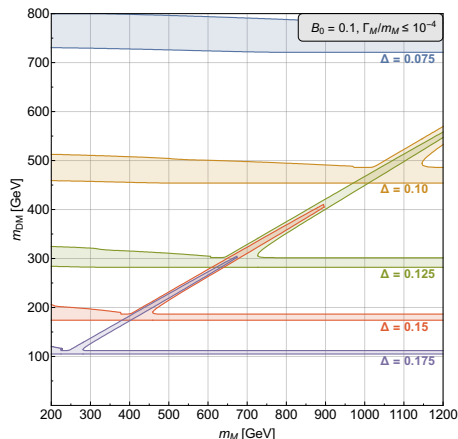
RELIC DENSITY - ANNIHILATION CHANNELS



- Diquark model as example
- No DM self-annihilation (Standard Model singlet)
- Chemical equilibrium by:
 - DM DM $\leftrightarrow$ X X
 - DM SM $\leftrightarrow$ X SM
 - X $\leftrightarrow$ DM SM SM
- X X $\rightarrow$ 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

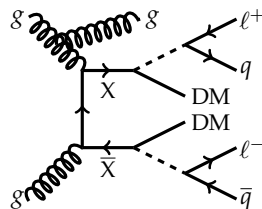
- Move to the collider mass plane (m_M versus m_{DM})
- Choose a relatively small branching to visible states to enhance dark signatures ($B_0 = 0.1$)
- Show dependence on parameters Δ and Γ_M (DQ model)



LHC: COANNIHILATION PARTNER PRODUCTION

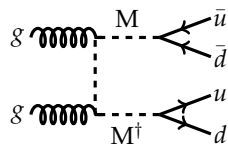
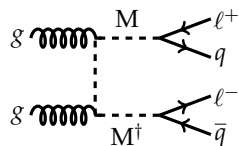
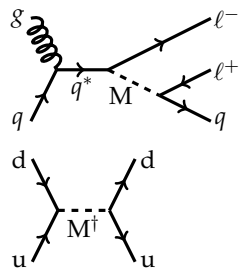
- Due to $\mathbb{Z}_2$ parity X must be pair produced, need ISR to produce MET and a trigger-able signal
 - Diquark: X decays to soft jets: model is constrained by existing monojet and jets + MET searches
 - Leptoquark: X decays to a soft lepton and jet: monojet + MET (leptons are soft) or **new search**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

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

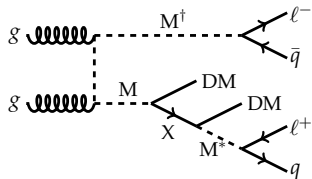


LHC: MEDIATOR PRODUCTION

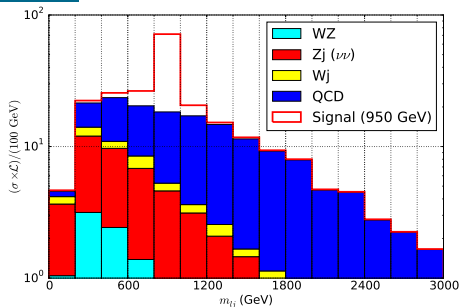
- Single production of LQ: in association with a lepton, constrained by single leptoquark searches
- Single production of DQ: through y_{vis} coupling, constrained by dijet resonance searches
- Pair production of the mediator (3 options)
- **Visible decays:** production of paired resonances
 - Leptoquark: 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!**)



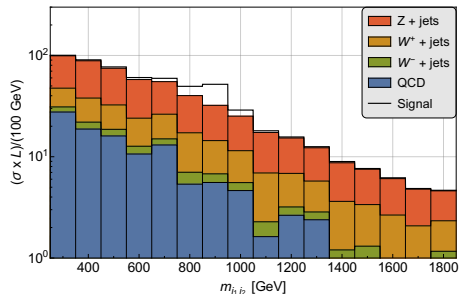
LHC: MEDIATOR MIXED DECAY



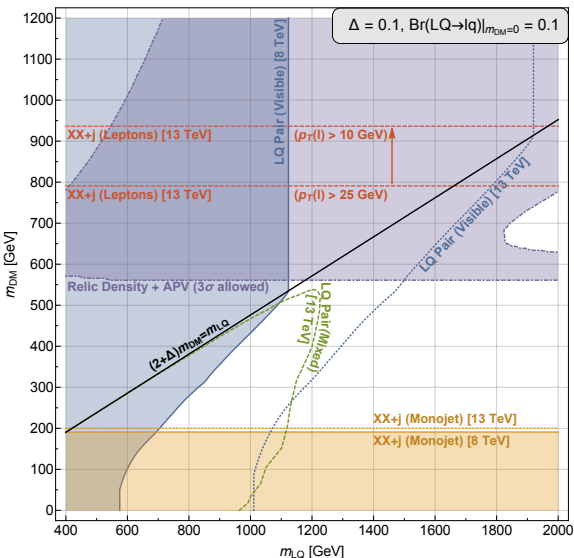
- Leptoquark: ℓq resonance + MET
- soft ℓ, q from invisible decay
- Main cuts: MET, m_T , $m_{\ell q}$



- 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!

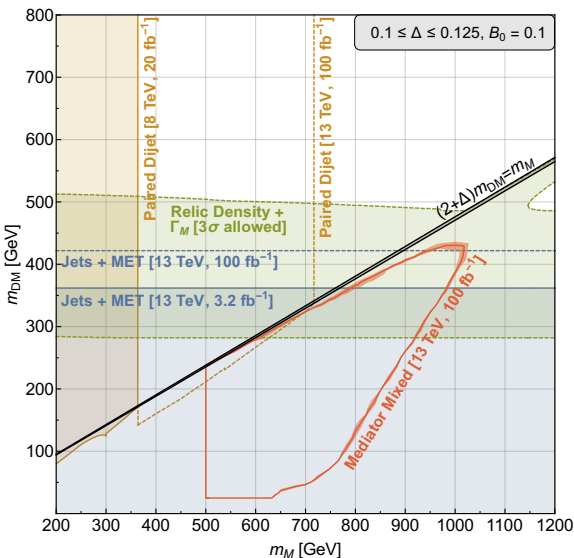


LHC POTENTIAL (LEPTOQUARK)



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

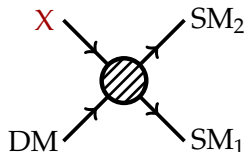
LHC POTENTIAL (DIQUARK)



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

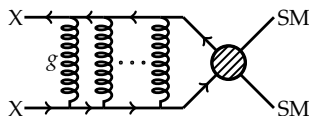
REMOVING THE MEDIATOR [arXiv:16???.????? El-Hedri, Kaminska, Zurita, MdV]

- There is no 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:



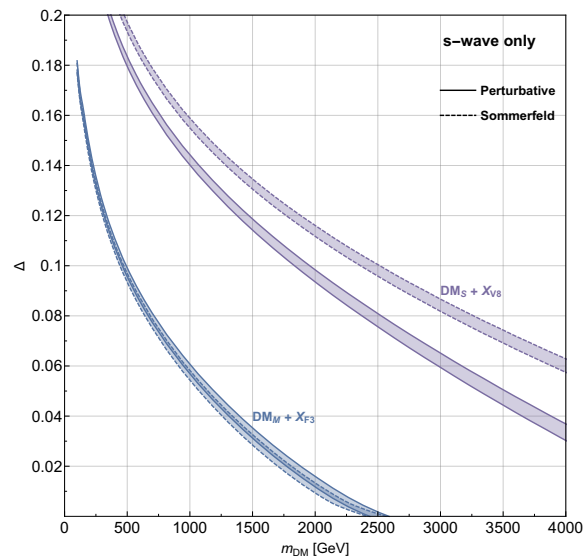
- Model content: DM, X, EFT operator with a small coefficient
- EFT operator is required for X decay (not long-lived) and chemical equilibrium ($\text{DM SM} \leftrightarrow \text{X SM}$)
- DM can be any SM singlet: scalar, fermion or vector
- X can be scalar, fermion or vector and have color charges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

SOMMERFELD CORRECTIONS [arXiv:16???.????? El-Hedri, Kaminska, MdV]



- Non-perturbative Sommerfeld corrections due to soft gluon exchanges in $X X \rightarrow gg/q\bar{q}$
- 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
- Goal: include higher order waves to $X X \rightarrow gg/q\bar{q}$ for a reliable calculation of the relic abundance
- Important for Codex models, gluino/stop coannihilation, ...

DM & X PHENOMOLOGY



- Example model:
 - DM is a Majorana fermion
 - X is Dirac fermion and color triplet
- Relic density determines a strip in the m_{DM} vs. Δ plane
- Monojet and Jets + MET searches constrain $m_{\text{DM}} \gtrsim \mathcal{O}(400)$ GeV for fermion triplet
- Natural values for Δ (i.e. no fine-tuned splitting)
- 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, giving 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, giving interesting and novel LHC signatures
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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, $\frac{1}{2}$ or 1
- Dark sector stabilized by discrete symmetry
- All gauge bosons obey minimal coupling (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:
 $\mathbf{S}$ (s -channel), $\mathbf{T}$ (t -channel), $\mathbf{H}$ (hybrid, next slide)
 and by $SU(3)_c$ representation of X :
 $\mathbf{U}$ (ncolored), $\mathbf{T}$ (riplet), $\mathbf{O}$ (ctet), $\mathbf{E}$ (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 SM₃ 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

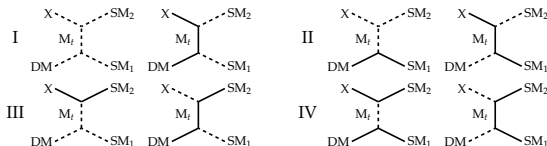
THE COANNIHILATION CODEX

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	$(u_R \ell_R)$		$\checkmark (\alpha = -\frac{5}{3})$
ST2		$\frac{4}{3}$	$(3, 1, \frac{4}{3})$	B	$(d_R \ell_R), (Q_L L_L), (d_R d_R)$		$\checkmark (\alpha = -\frac{2}{3})$
ST3				F	$(Q_L H)$	H5	
ST4			$(3, 3, \frac{4}{3})^{N \geq 2}$	B	$(Q_L L_L)$		$\checkmark (\alpha = -\frac{2}{3})$
ST5				F	$(Q_L H)$	H5	
ST10		$-\frac{8}{3}$	$(3, 1, -\frac{8}{3})$	B	$(\bar{u}_R \bar{u}_R), (d_R \ell_R)$		$\checkmark (\alpha = \frac{4}{3})$
ST11	$(3, N \pm 1, \alpha)$	$\frac{7}{3}$	$(3, 2, \frac{7}{3})$	B	$(Q_L \bar{\ell}_R), (u_R \bar{L}_L)$		
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, α)	0	(1, 1, 0)	B	$(u_R \overline{u}_R), (d_R \overline{d}_R), (Q_L \overline{Q}_L)$ $(\ell_R \overline{\ell}_R), (L_L \overline{L}_L), (H H^\dagger)$	$B, W_i^{N \geq 2}$	$\checkmark$
SU2				F	$(L_L H)$		
SU3			$(1, 3, 0)^{N \geq 2}$	B	$(Q_L \overline{Q}_L), (L_L \overline{L}_L), (H H^\dagger)$	B, W_i	$\checkmark$
SU4				F	$(L_L H)$		
SU5		-2	(1, 1, -2)	B	$(d_R \overline{u}_R), (H^\dagger H^\dagger)$		$\checkmark$
SU6				F	$(L_L H^\dagger)$	ℓ_R	
SU7			$(1, 3, -2)^{N \geq 2}$	B	$(H^\dagger H^\dagger), (L_L \overline{L}_L)$		$\checkmark (\alpha = \pm 1)$
SU8				F	$(L_L H^\dagger)$	ℓ_R	
SU9	(1, N ± 1 , α)	-4	(1, 1, -4)	B	$(\ell_R \ell_R)$		$\checkmark (\alpha = \pm 2)$
SU10		-1	(1, 2, -1)	B	$(d_R \overline{Q}_L), (\overline{u}_R \overline{Q}_L), (\overline{L}_R \overline{\ell}_R)$	$H^\dagger$	
SU11				F	$(\ell_R H)$	L_L	
SU12		-3	(1, 2, -3)	B	$(L_L \overline{\ell}_R)$		
SU13				F	$(\ell_R H^\dagger)$		
SU14		0	(1, 3, 0)	B	$(L_L \overline{L}_L), (Q_L \overline{Q}_L), (H H^\dagger)$		$\checkmark (\alpha = 0)$
SU15				F	$(L_L H)$		
SU16		-2	(1, 3, -2)	B	$(H^\dagger H^\dagger), (L_L \overline{L}_L)$		$\checkmark (\alpha = \pm 1)$
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, α)	$\frac{1}{2}$	(3, 1, $\frac{1}{2}$)	B	$(u_R \overline{u}_R)$		$\checkmark \alpha = -\frac{1}{2}$
ST2				B	$(d_R \overline{\ell}_R), (Q_L \overline{L}_L), (d_R \overline{d}_R)$		$\checkmark \alpha = -\frac{1}{2}$
ST3			(3, 1, $\frac{3}{2}$)	F	$(Q_L H)$	u_R	
ST4				B	$(Q_L \overline{L}_L)$		$\checkmark \alpha = -\frac{1}{2}$
ST5		- $\frac{3}{2}$	$(3, 3, \frac{1}{2})^{N \geq 2}$	F	$(Q_L H)$	u_R	
ST6				B	$(Q_L \overline{Q}_L), (\overline{u}_R \overline{d}_R), (u_R \overline{\ell}_R), (Q_L \overline{L}_L)$		$\checkmark \alpha = \frac{1}{2}$
ST7			(3, 1, $-\frac{3}{2}$)	F	$(Q_L H^\dagger)$	d_R	
ST8				B	$(Q_L \overline{Q}_L), (Q_L \overline{L}_L)$		$\checkmark \alpha = \frac{1}{2}$
ST9		- $\frac{5}{2}$	$(3, 1, -\frac{5}{2})$	F	$(Q_L H^\dagger)$	d_R	
ST10				B	$(\overline{u}_R \overline{u}_R), (d_R \overline{\ell}_R)$		$\checkmark \alpha = \frac{1}{2}$
ST11	(3, N ± 1 , α)	$\frac{3}{2}$	(3, 2, $\frac{3}{2}$)	B	$(Q_L \overline{\ell}_R), (u_R \overline{L}_L)$		
ST12				F	$(u_R H)$		
ST13			(3, 2, $\frac{1}{2}$)	B	$(d_R \overline{L}_L), (Q_L \overline{d}_R), (u_R \overline{L}_L)$		
ST14				F	$(u_R H^\dagger), (d_R H)$	Q_L	
ST15		- $\frac{1}{2}$	(3, 2, $-\frac{1}{2}$)	B	$(Q_L \overline{u}_R), (Q_L \overline{\ell}_R), (d_R \overline{L}_L)$		
ST16				F	$(d_R H^\dagger)$		
ST17			(3, 3, $\frac{1}{2}$)	B	$(Q_L \overline{u}_R)$		$\checkmark \alpha = -\frac{1}{2}$
ST18				F	$(Q_L H)$		
ST19		- $\frac{3}{2}$	(3, 3, $-\frac{3}{2}$)	B	$(Q_L \overline{Q}_L), (Q_L \overline{L}_L)$		$\checkmark \alpha = \frac{1}{2}$
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, α)	0	$(8, 1, 0)^{N \geq 2}$	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		-1	$(8, 2, -1)$	B	$(d_R \overline{Q}_L), (Q_L \overline{u}_R)$		
SO5	(6, N, α)	0	$(8, 3, 0)$	B	$(Q_L \overline{Q}_L)$		$\checkmark \alpha = 0$
SE1		$\frac{5}{6}$	$(6, 1, \frac{5}{6})$	B	$(u_R \overline{u}_R)$		$\checkmark \alpha = -\frac{4}{6}$
SE2				B	$(Q_L \overline{Q}_L), (u_R \overline{d}_R)$		$\checkmark (\alpha = -\frac{4}{6})$
SE3			$(6, 3, \frac{5}{6})^{N \geq 2}$	B	$(Q_L \overline{Q}_L)$		$\checkmark \alpha = -\frac{4}{6}$
SE4				B	$(d_R \overline{d}_R)$		$\checkmark \alpha = \frac{2}{6}$
SE5		- $\frac{1}{6}$	$(6, 2, \frac{1}{6})$	B	$(Q_L \overline{u}_R)$		
SE6				B	$(Q_L \overline{d}_R)$		
SE7			$(6, 2, -\frac{1}{6})$	B			
SE8				B			
SE9		$\frac{2}{3}$	$(6, 3, \frac{2}{3})$	B	$(Q_L \overline{Q}_L)$		$\checkmark \alpha = -\frac{1}{3}$
SE10				B			
SE11			$(6, 3, -\frac{2}{3})$	B			
SE12				B			

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, α)	0	$(1, N \pm 1, \beta - 1)$	I	(HH^1)	$B, W^{N \geq 2}$
TU2			$(1, N \pm 1, \beta + 1)$	II	$(L_L H)$	
TU3			$(1, N \pm 1, \beta - 1)$	III	(HL_L)	
TU4			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L Q_L)$	$B, W^{N \geq 2}$
TU5			$(3, N, \beta - \frac{1}{2})$	IV	$(u_R \overline{u}_R)$	$B, W^{N \geq 2}$
TU6			$(3, N, \beta + \frac{1}{2})$	IV	$(d_R \overline{d}_R)$	$B, W^{N \geq 2}$
TU7			$(1, N \pm 1, \beta + 1)$	IV	$(L_L \overline{L}_L)$	$B, W^{N \geq 2}$
TU8			$(1, N, \beta + 2)$	IV	$(\overline{L}_R \overline{L}_R)$	$B, W^{N \geq 2}$
TU9			$(1, N \pm 1, \beta + 1)$	I	$(H^1 H^1)$	
TU10			$(1, N \pm 1, \beta + 1)$	II	$(L_L H^1)$	ℓ_R
TU11		-2	$(1, N \pm 1, \beta + 1)$	III	$(H^1 L_L)$	ℓ_R
TU12			$(1, N \pm 1, \beta + 1)$	IV	$(L_L L_L)$	
TU13			$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{u}_R d_R)$	
TU14			$(3, N, \beta + \frac{1}{2})$	IV	$(d_R \overline{u}_R)$	
TU15		-4	$(1, N, \beta + 2)$	IV	$(\ell_R \ell_R)$	
TU16		-1	$(1, N, \beta + 2)$	II	$(\ell_R H)$	L_L
TU17			$(1, N \pm 1, \beta - 1)$	III	$(H \ell_R)$	L_L
TU18			$(1, N, \beta + 2)$	IV	$(\ell_R L_L)$	H^1
TU19			$(1, N \pm 1, \beta - 1)$	IV	$(L_L \ell_R)$	H^1
TU20			$(3, N, \beta + \frac{1}{2})$	IV	$(d_R Q_L)$	H^1
TU21			$(3, N \pm 1, \beta + \frac{1}{2})$	IV	$(Q_L d_R)$	H^1
TU22			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L \overline{u}_R)$	H^1
TU23			$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{u}_R Q_L)$	H^1
TU24			$(1, N \pm 1, \beta + 1)$	IV	$(L_L \ell_R)$	
TU25		-3	$(1, N, \beta + 2)$	IV	$(\ell_R L_L)$	
TU26	(1, N ± 2 , α)	0	$(1, N \pm 1, \beta - 1)$	I	(HH^1)	
TU27			$(1, N \pm 1, \beta + 1)$	II	$(L_L H)$	
TU28			$(1, N \pm 1, \beta - 1)$	III	(HL_L)	
TU29			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L Q_L)$	
TU30			$(1, N \pm 1, \beta + 1)$	IV	$(L_L L_L)$	
TU31			$(1, N \pm 1, \beta + 1)$	I	$(H^1 H^1)$	
TU32			$(1, N \pm 1, \beta + 1)$	II	$(L_L H^1)$	
TU33		-2	$(1, N \pm 1, \beta + 1)$	III	$(H^1 L_L)$	

TU type - 33 models

TT type - 52 models

ID	X	$\alpha + \beta$	M_t	Spin	(SM ₁ SM ₂)	SM ₃
TO1	(8, N, α)	0	$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L Q_L)$	
TO2			$(3, N, \beta - \frac{1}{2})$	IV	$(u_R \overline{u}_R)$	
TO3			$(3, N, \beta + \frac{1}{2})$	IV	$(d_R \overline{d}_R)$	
TO4			$(3, N, \beta + \frac{1}{2})$	IV	$(d_R \overline{u}_R)$	
TO5			$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{u}_R d_R)$	
TO6	(8, N ± 1 , α)	-1	$(3, N, \beta + \frac{1}{2})$	IV	$(d_R Q_L)$	
TO7			$(3, N \pm 1, \beta + \frac{1}{2})$	IV	$(Q_L d_R)$	
TO8			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L \overline{u}_R)$	
TO9			$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{u}_R Q_L)$	
TO10		0	$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L Q_L)$	
TE1	(6, N, α)	$\frac{1}{2}$	$(3, N, \beta - \frac{1}{2})$	IV	$(u_R u_R)$	
TE2			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L Q_L)$	
TE3			$(3, N, \beta - \frac{1}{2})$	IV	$(u_R \overline{u}_R)$	
TE4		$\frac{3}{2}$	$(3, N, \beta + \frac{1}{2})$	IV	$(d_R u_R)$	
TE5			$(3, N, \beta + \frac{1}{2})$	IV	$(d_R d_R)$	
TE6			$(3, N, \beta - \frac{1}{2})$	IV	$(u_R Q_L)$	
TE7		$-\frac{1}{2}$	$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L u_R)$	
TE8			$(3, N, \beta + \frac{1}{2})$	IV	$(d_R Q_L)$	
TE9			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L d_R)$	
TE10		$-\frac{3}{2}$	$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L Q_L)$	

TO and TE type - 10 and 10 models

ID	X	$\alpha + \beta$	M_t	Spin	(SM ₁ SM ₂)	SM ₃
TT1	(1, N, α)	$\frac{1}{2}$	$(3, N, \beta - \frac{1}{2})$	IV	$(u_R \overline{u}_R)$	SM ₃
TT2			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R s_R)$	
TT3			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	SM ₃
TT4			$(3, N, \beta - \frac{1}{2})$	III	$(\overline{d}_R t_R)$	SM ₃
TT5			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT6			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(\overline{d}_R Q_L)$	
TT7			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(\overline{d}_R Q_L)$	
TT8			$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{u}_R \overline{u}_R)$	
TT9			$(3, N, \beta + \frac{1}{2})$	III	$(Q_L H^1)$	d_R
TT10			$(3, N, \beta + \frac{1}{2})$	III	$(Q_L H^1)$	d_R
TT11	(1, N, α)	$-\frac{1}{2}$	$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{u}_R Q_L)$	
TT12			$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{d}_R Q_L)$	
TT13			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R s_R)$	
TT14			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	
TT15			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT16			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L L_L)$	
TT17			$(3, N \pm 1, \beta - \frac{1}{2})$	IV	$(Q_L L_L)$	
TT18			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R \overline{u}_R)$	
TT19			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R \overline{d}_R)$	
TT20			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R \overline{d}_R)$	
TT21	(1, N, α)	$-\frac{3}{2}$	$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{d}_R s_R)$	
TT22			$(3, N, \beta + \frac{1}{2})$	III	$(\overline{d}_R s_R)$	
TT23			$(3, N, \beta - \frac{1}{2})$	III	$(\overline{d}_R t_R)$	
TT24			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT25			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	
TT26			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT27			$(3, N, \beta - \frac{1}{2})$	III	$(\overline{d}_R t_R)$	
TT28			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT29			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	
TT30			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT31	(1, N ± 2 , α)	$\frac{1}{2}$	$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{u}_R \overline{u}_R)$	
TT32			$(3, N, \beta + \frac{1}{2})$	III	$(Q_L H^1)$	
TT33			$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{d}_R Q_L)$	
TT34			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R s_R)$	
TT35			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	
TT36			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT37			$(3, N, \beta - \frac{1}{2})$	III	$(\overline{d}_R t_R)$	
TT38			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT39			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	
TT40			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT41	(1, N ± 2 , α)	$-\frac{1}{2}$	$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{u}_R \overline{u}_R)$	
TT42			$(3, N, \beta + \frac{1}{2})$	III	$(Q_L H^1)$	
TT43			$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{d}_R Q_L)$	
TT44			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R s_R)$	
TT45			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	
TT46			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT47			$(3, N, \beta - \frac{1}{2})$	III	$(\overline{d}_R t_R)$	
TT48			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT49			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	
TT50			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT51	(1, N ± 2 , α)	$-\frac{3}{2}$	$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{u}_R \overline{u}_R)$	
TT52			$(3, N, \beta + \frac{1}{2})$	III	$(Q_L H^1)$	
TT53			$(3, N, \beta + \frac{1}{2})$	IV	$(\overline{d}_R Q_L)$	
TT54			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R s_R)$	
TT55			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	
TT56			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT57			$(3, N, \beta - \frac{1}{2})$	III	$(\overline{d}_R t_R)$	
TT58			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	
TT59			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R t_R)$	
TT60			$(3, N, \beta - \frac{1}{2})$	IV	$(\overline{d}_R b_R)$	

FLAVOR FOR LEPTOQUARKS AND DIQUARKS

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

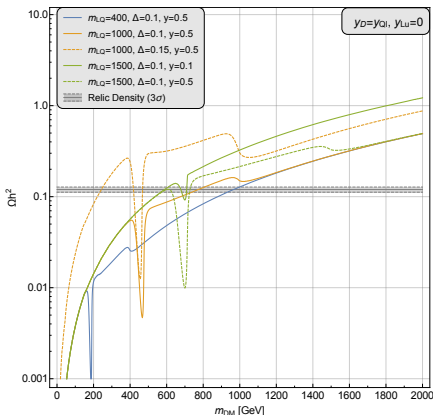
LEPTOQUARK MEDIATOR:

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

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: $y_{\text{vis}}^{11} \times y_{\text{vis}}^{12}$ small and $y_{\text{vis}}^{11} \times y_{\text{vis}}^{22}$ small
- Choice: only y_{vis}^{11} nonzero
- Strongest limit on y_{vis}^{11} from dijet resonances at LHC

RELIC DENSITY (LEPTOQUARK)



(Co)annihilation channels:

$$X X \rightarrow g g$$

$$X DM \rightarrow SM SM$$

$$DM DM \rightarrow M M \rightarrow 4 SM$$

$$X X \rightarrow M M \rightarrow 4 SM$$

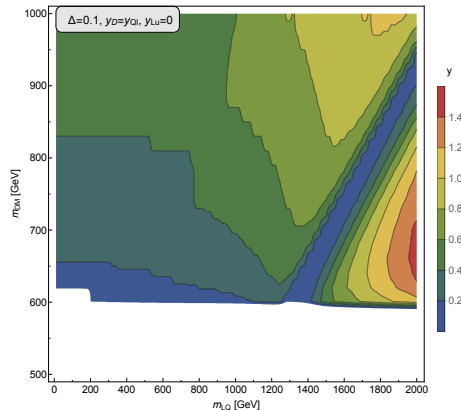
Goal: fit $\Omega h^2 = 0.1198 \pm 0.0026$

Chemical equilibrium:

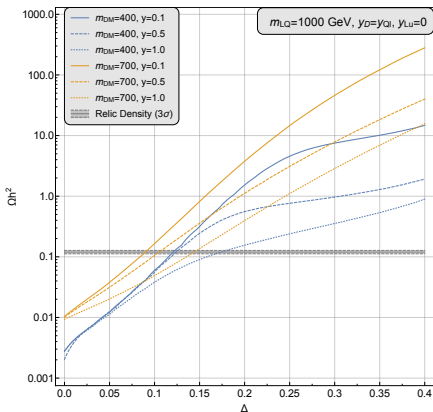
$$DM DM \Leftrightarrow X X$$

$$DM SM \Leftrightarrow X SM$$

$$X \Leftrightarrow DM SM SM$$



RELIC DENSITY (ADDITIONAL PLOTS)



Annihilation channels:

$$X X \rightarrow g g$$

$$X DM \rightarrow SM SM$$

$$DM DM \rightarrow M M \rightarrow 4 SM$$

$$X X \rightarrow M M \rightarrow 4 SM$$

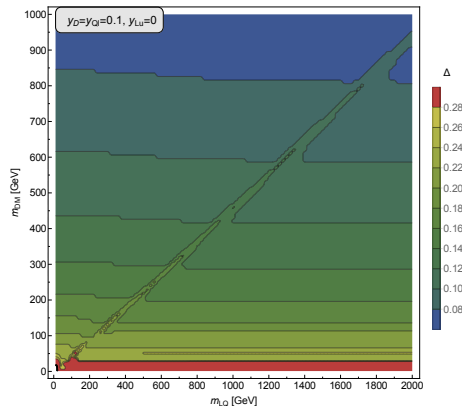
Goal: fit $\Omega h^2 = 0.1198 \pm 0.0026$

Chemical equilibrium:

$$DM DM \Leftrightarrow X X$$

$$DM SM \Leftrightarrow X SM$$

$$X \Leftrightarrow DM SM SM$$



DIRECT AND INDIRECT DETECTION

Direct detection takes place through effective operators:

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



$\text{DM DM} \rightarrow 4 \text{ SM}$ is p -wave suppressed and $\text{DM DM} \rightarrow 2 \text{ SM}$ is loop suppressed, hence indirect detection is challenging

LHC: NEW SEARCHES (CUT-FLOW)

LQ MIXED DECAY:

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

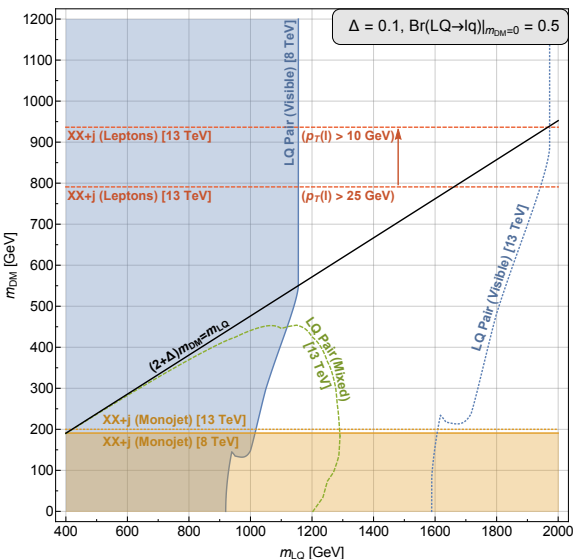
	QCD	$W + 1, 2j$	$t\bar{t}$	$Z\nu\nu + j$	$Z\tau\tau + j$	W^+W^-	$WZ\nu\nu + j$	$WZjj$	signal
$p_T(j_1) > 50 \text{ GeV}$	2.1×10^{12}	4.4×10^8	1.3×10^8	7.0×10^7	1.3×10^7	1.2×10^6	1.3×10^5	3.1×10^5	600
$N_e^h = 1, N_e \leq 2$	4.8×10^9	8.8×10^7	1.2×10^7	8.6×10^4	4.8×10^5	2.4×10^5	1.9×10^4	6.1×10^4	415
b -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
$\cancel{E}_T > 700 \text{ GeV}$	133	1738	15	19	9	10	27	2	75
$m_T > 150 \text{ GeV}$	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:

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

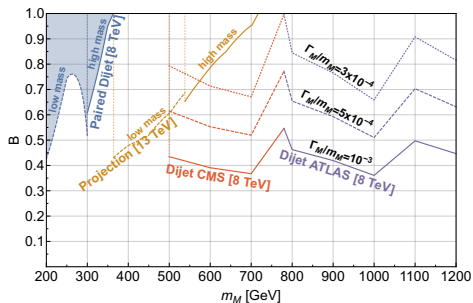
	$t\bar{t}$	$Z\ell\ell + j$	Diboson	$W\ell\nu + j$	$t + j$	Signal
$\cancel{E}_T > 50 \text{ GeV}$	1.9×10^7	7.9×10^6	1.1×10^6	1.9×10^8	5.6×10^5	8.5×10^4
$p_T^{\text{lead}} > 50 \text{ GeV}$	1.8×10^7	6.1×10^6	5.9×10^5	1.5×10^8	4.6×10^5	7.1×10^4
$\Delta\phi_{j_1j_2} < 2.5$	1.2×10^7	4.2×10^6	5.0×10^5	1.1×10^8	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
$\cancel{E}_T > 400 \text{ GeV}$	12	11	0.07	780	2	118
$\left \frac{p_T(j_1)}{\cancel{E}_T} - 1 \right < 0.2$	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):
 $m_{\text{DM}} > 570 \text{ GeV}$
- Fix couplings $y_D, y_{Q\ell}^{11}$ such that branching ratios are ($m_{\text{DM}} = 0$):
 $\text{LQ} \rightarrow \text{visible} = 50\%$
 $\text{LQ} \rightarrow \text{dark} = 50\%$
- Mixed topology is maximized

LHC: ADDITIONAL DIQUARK MATERIAL



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

