Simplified Models for Co-annihilating Dark Matter

Michael J. Baker

with

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arXiv:1510.03434

JGU Mainz

ABHM Research Unit: New Physics at the LHC - Bonn - 28 October 2015

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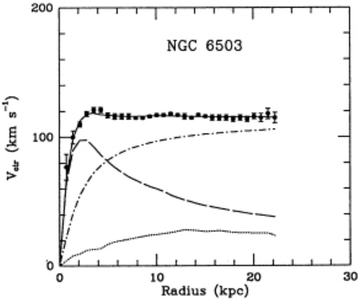
Outline

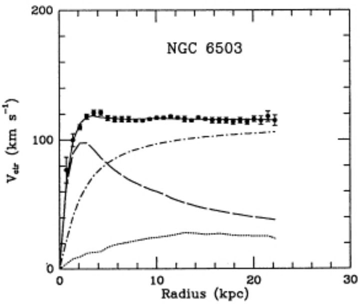
Outline

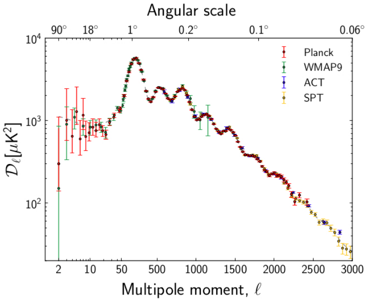
Dark Matter



Begeman, Broeils & Sanders, 1991

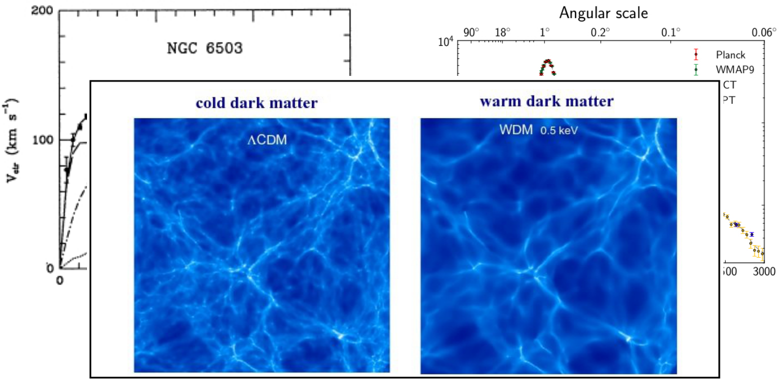
Dark Matter





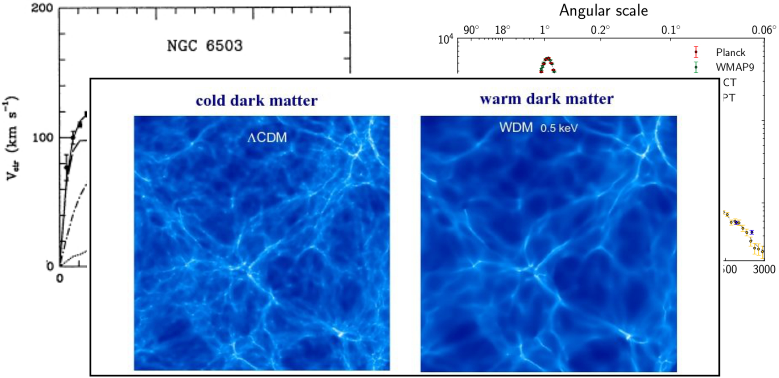
Planck, 2013

Dark Matter



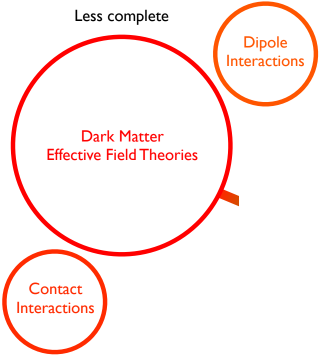
Viel, Becker, Bolton & Haehnelt, 2013

Dark Matter



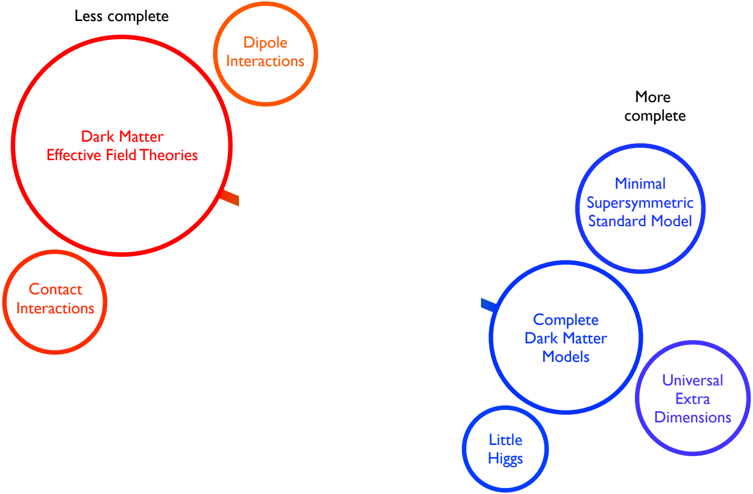
$$\Omega_{\text{nbm}} h^2 = 0.1198 \pm 0.0026$$

Theoretical Framework



Abdallah *et al.*, 1506.03116

Theoretical Framework



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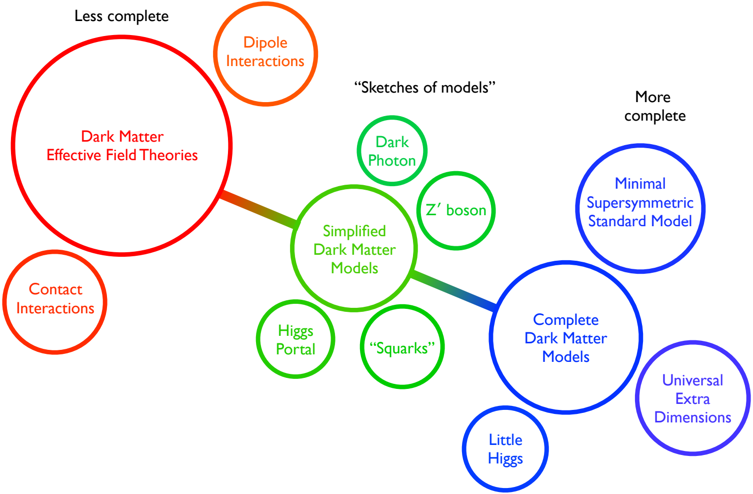

Abdallah *et al.*, 1506.03116

Simplified Models

- Much recent work on simplified models of DM, e.g.,
  - Profumo *et al.* 1307.6277,
  - De Simone *et al.* 1402.6287,
  - Abdallah *et al.* 1506.03116, ...
- Various tensions, e.g., between relic density and direct/indirect constraints
- Coannihilating models can relieve these tensions

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Our Goal

A complete classification of simplified coannihilation models

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The Coannihilation Codex

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A complete classification of simplified coannihilation models

The Coannihilation Codex

This allows us to

- Study connections between experimental probes
- Discuss general phenomenology of models
- Identify lesser studied scenarios
- In the event of a signal, gives a framework for the inverse problem

Outline

Assumptions

To complete a classification we need to make some assumptions

- DM is a thermal relic
- DM is a colourless, electrically neutral particle in $(1, N, \beta)$
- Coannihilation diagram is 2-to-2 via dimension four, tree-level couplings
- New particles have spin 0, 1/2 or 1

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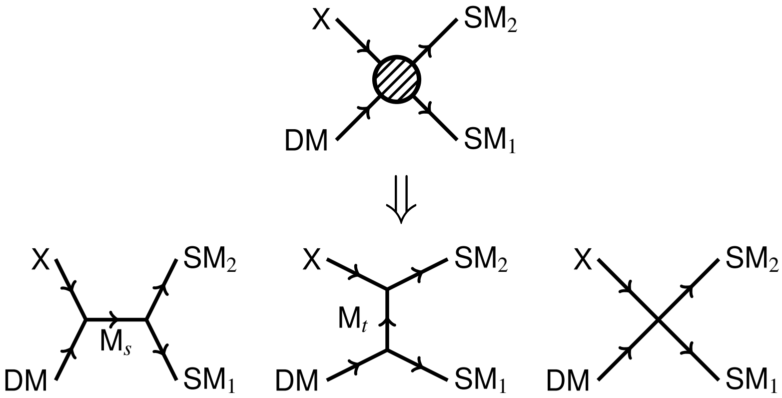
Coannihilation Diagrams



Classification Procedure

- Work in unbroken $SU(2)_L \times U(1)_Y$
- Given SM field content, iterate over SM_1 and SM_2 to find all possible X using
  - Gauge invariance
  - Lorentz invariance
  - $\mathbb{Z}_2$ parity (to prevent DM decay)
- Then find all s-channel and t-channel mediators, using same restrictions and
  - Dimension four, tree-level couplings
  - Gauge bosons only couple through kinetic terms

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s-channel classification - sample

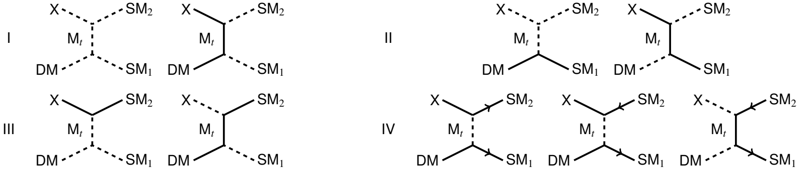
DM in $(1, N, \beta)$

ID	X	$\alpha+\beta$	M$_s$	Spin	(SM$_1$ SM$_2$)	SM$_3$	M-X-X
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	$(Q_L H^\dagger)$		

t-channel classification - sample

DM in $(1, N, \beta)$

ID	X	$\alpha + \beta$	M_t	Spin	$(\mathrm{SM}_1\ \mathrm{SM}_2)$	SM_3
TU26			$(1, N \pm 1, \beta - 1)$	I	$(H H^\dagger)$	
TU27			$(1, N \pm 1, \beta + 1)$	II	$(L_L H)$	
TU28		0	$(1, N \pm 1, \beta - 1)$	III	$(H L_L)$	
TU29	$(1, N \pm 2, \alpha)$		$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L \overline{Q_L})$	
TU30			$(1, N \pm 1, \beta + 1)$	IV	$(L_L \overline{L_L})$	
TU31			$(1, N \pm 1, \beta + 1)$	I	$(H^\dagger H^\dagger)$	
TU32		-2	$(1, N \pm 1, \beta + 1)$	II	$(L_L H^\dagger)$	
TU33			$(1, N \pm 1, \beta + 1)$	III	$(H^\dagger L_L)$	



Classification: hybrid models

ID	X	$\alpha+\beta$	SM partner	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

7 models

Classification: 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_LH)		
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_LH)		
SU5		-2	$(1,1,-2)$	B	$(d_R\overline{u_R}),(H^\dagger H^\dagger)$		✓
SU6				F	$(L_LH^\dagger)$	ℓ_R	
SU7			$(1,3,-2)^{N\geq 2}$	B	$(H^\dagger H^\dagger),(L_LL_L)$		✓$(\alpha=\pm 1)$
SU8				F	$(L_LH^\dagger)$	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	(ℓ_RH)	L_L	
SU12		-3	$(1,2,-3)$	B	$(L_L\ell_R)$		
SU13				F	$(\ell_RH^\dagger)$		
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_LH)		
SU16		-2	$(1,3,-2)$	B	$(H^\dagger H^\dagger),(L_LL_L)$		✓$(\alpha=\pm 1)$
SU17				F	$(L_LH^\dagger)$		

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	$(u_R\overline{l_R})$		✓$\alpha=-\frac{5}{3}$
ST2		$\frac{4}{3}$	$(3,1,\frac{4}{3})$	B	$(d_R\overline{\ell_R}),(Q_L\overline{L_L}),(\overline{d_Rd_R})$		✓$\alpha=-\frac{2}{3}$
ST3				F	(Q_LH)	u_R	
ST4			$(3,3,\frac{4}{3})^{N\geq 2}$	B	$(Q_L\overline{L_L})$		✓$\alpha=-\frac{2}{3}$
ST5				F	(Q_LH)	u_R	
ST6		$-\frac{2}{3}$	$(3,1,-\frac{2}{3})$	B	$(\overline{Q_LQ_L}),(\overline{u_Rd_R}),(u_R,\ell_R),(Q_LL_L)$		✓$\alpha=\frac{1}{3}$
ST7				F	$(Q_LH^\dagger)$	d_R	
ST8			$(3,3,-\frac{2}{3})^{N\geq 2}$	B	$(\overline{Q_LQ_L}),(Q_LL_L)$		✓$\alpha=\frac{1}{3}$
ST9				F	$(Q_LH^\dagger)$	d_R	
ST10		$-\frac{8}{3}$	$(3,1,-\frac{8}{3})$	B	$(\overline{u_Ru_R}),(d_R\ell_R)$		✓$\alpha=\frac{4}{3}$
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_RH)		
ST13		$\frac{1}{3}$	$(3,2,\frac{1}{3})$	B	$(d_R\overline{L_L}),(\overline{Q_Ld_R}),(u_RL_L)$		
ST14				F	$(u_RH^\dagger),(d_RH)$	Q_L	
ST15		$-\frac{5}{3}$	$(3,2,-\frac{5}{3})$	B	$(\overline{Q_L}\overline{u_R}),(Q_L\ell_R),(d_RL_L)$		
ST16				F	$(d_RH^\dagger)$		
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_LH)		
ST19		$-\frac{2}{3}$	$(3,3,-\frac{2}{3})$	B	$(\overline{Q_LQ_L}),(Q_LL_L)$		✓$\alpha=\frac{1}{3}$
ST20				F	$(Q_LH^\dagger)$		

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_Ru_R)		✓$\alpha=-\frac{4}{3}$
SE2		$\frac{2}{3}$	$(6,1,\frac{2}{3})$	B	$(Q_LQ_L),(u_Rd_R)$		✓$(\alpha=-\frac{1}{3})$
SE3			$(6,3,\frac{2}{3})^{N\geq 2}$	B	(Q_LQ_L)		✓$\alpha=-\frac{1}{3}$
SE4		$-\frac{4}{3}$	$(6,1,-\frac{4}{3})$	B	(d_Rd_R)		✓$\alpha=\frac{2}{3}$
SE5	$(6,N\pm 1,\alpha)$	$\frac{5}{3}$	$(6,2,\frac{5}{3})$	B	(Q_Lu_R)		
SE6		$-\frac{1}{3}$	$(6,2,-\frac{1}{3})$	B	(Q_Ld_R)		
SE7	$(6,N\pm 2,\alpha)$	$\frac{2}{3}$	$(6,3,\frac{2}{3})$	B	(Q_LQ_L)		✓$\alpha=-\frac{1}{3}$

SO and SE type - 5 and 7 models

U: X uncoloured

T: X $SU(3)$ triplet

O: X $SU(3)$ octet

E: X $SU(3)$ exotic

Classification: 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	$(\overline{d_Rd_R})$	
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	$(\overline{Q_LQ_L})$	
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	$(\overline{u_Ru_R})$	
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	$(\overline{d_RQ_L})$	
TT35			$(3,N\pm1,\beta+\frac{1}{3})$	IV	$(\overline{Q_Ld_R})$	
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	$(Q_L\overline{L_L})$	
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TT48		$-\frac{2}{3}$	$(\bar{3},N\pm1,\beta-\frac{1}{3})$	II	$(Q_LH^\dagger)$	
TT49			$(1,N\pm1,\beta+1)$	III	$(H^\dagger Q_L)$	
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TT51			$(1,N\pm1,\beta+1)$	IV	(L_LQ_L)	
TT52			$(3,N\pm1,\beta+\frac{1}{3})$	IV	$(\overline{Q_LQ_L})$	

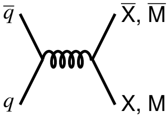
TT type - 52 models

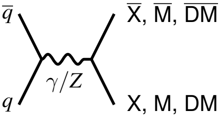
Complete Classification

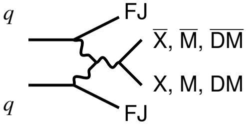
Given our assumptions, one of these simplified models of coannihilating dark matter is the one chosen by Nature!

Outline

Production: s-channel







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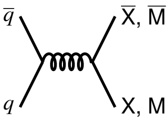
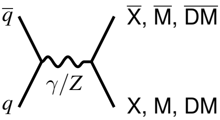
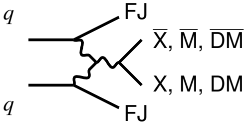
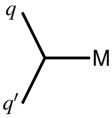
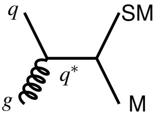
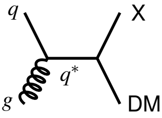




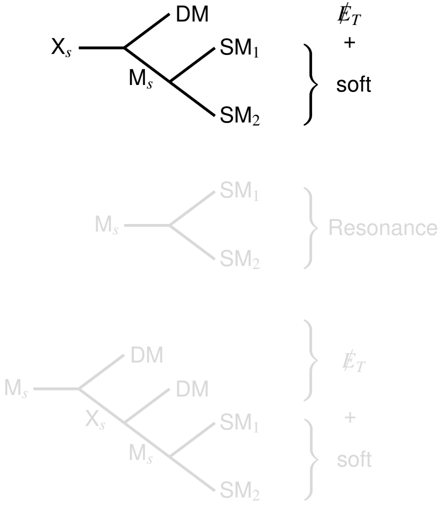








Decay: s-channel



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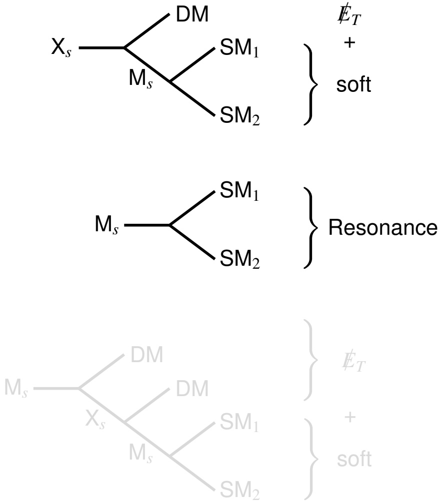

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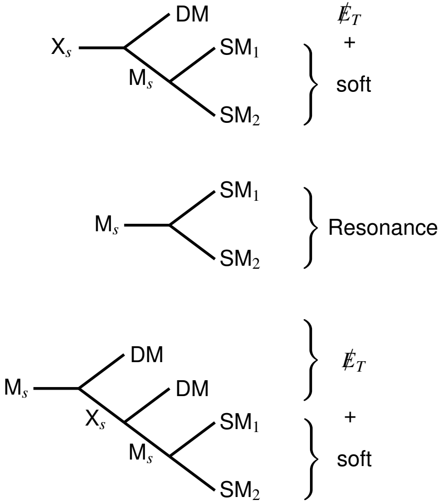

Inescapable Signatures: s-channel

- **Mono-Y (Y=jet, photon, Z,...) + $\not{E}_T$** from DM DM, XX,...
  - classic signature
- **Single and Double Resonances** from M and MM
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- **Mono-Y + $\not{E}_T$ + soft** from XX, MM,...
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Example - ST11

ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	SM_3	M-X-X
ST11	$(3, N \pm 1, \alpha)$	$\frac{7}{3}$	$(3, 2, \frac{7}{3})$	B	$(Q_L \overline{\ell_R}), (u_R \overline{L_L})$		

DM in $(1, N, \beta)$

Field	Rep.	Spin and mass assignment
DM	(1,1,0)	Majorana fermion
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$$\Delta = \frac{m_{\text{X}} - m_{\text{DM}}}{m_{\text{DM}}} \qquad y^{ij}_{Q\ell} = y_{Lu} = 0 \qquad y_D = y^{11}_{Q\ell}$$

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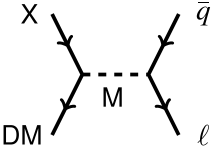

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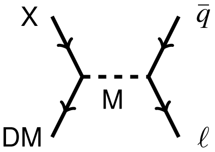

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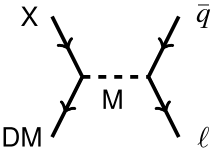

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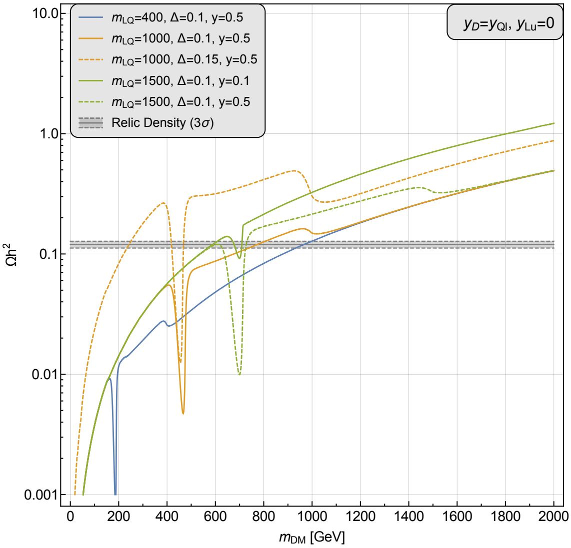
Example - ST11 - Relic Density



DM DM ⇔ X X
DM SM ⇔ X SM
X ⇔ DM SM SM

e.g.,

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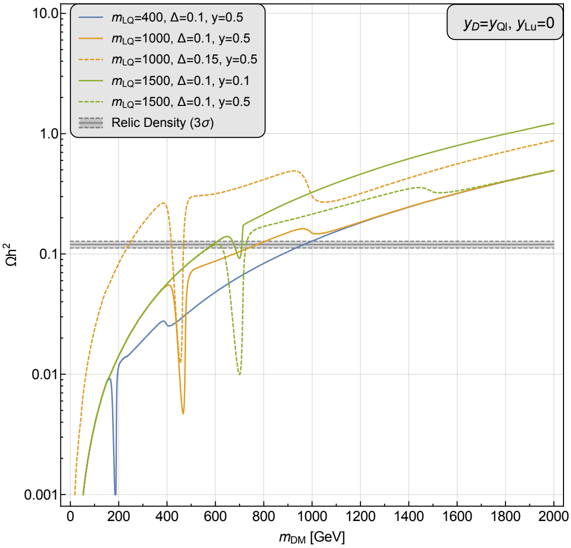

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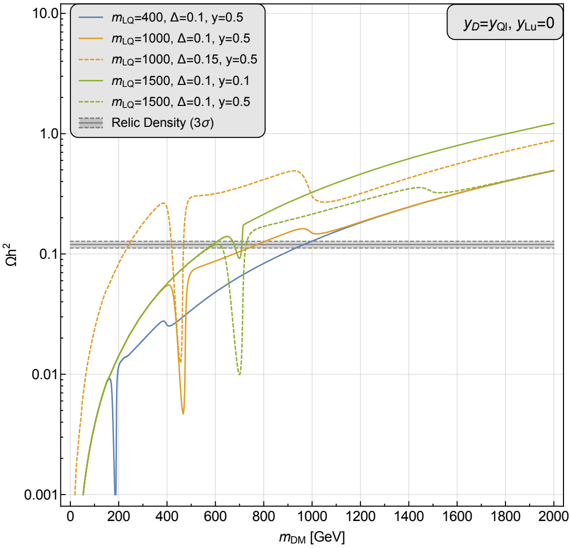

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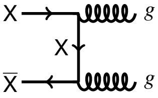

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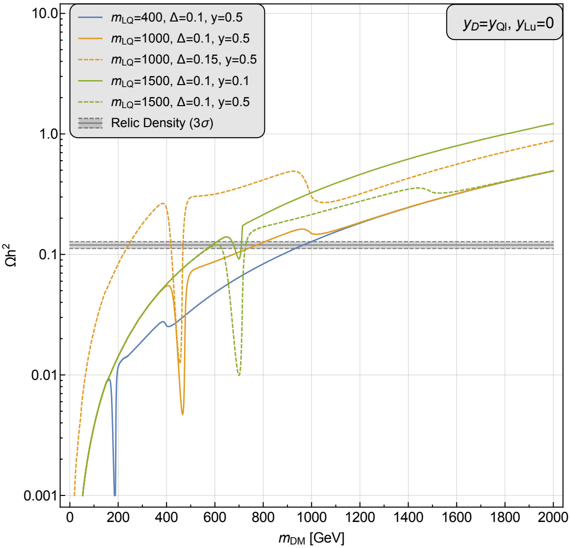

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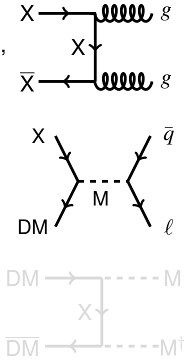

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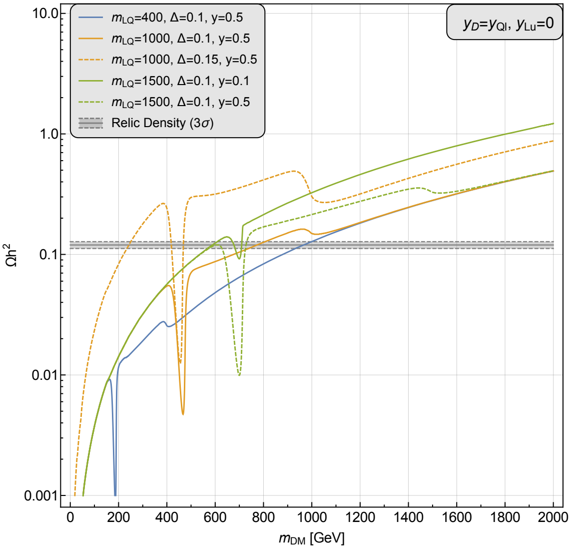

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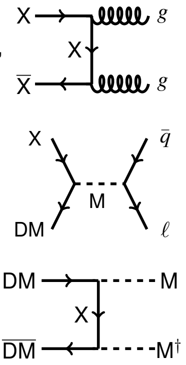
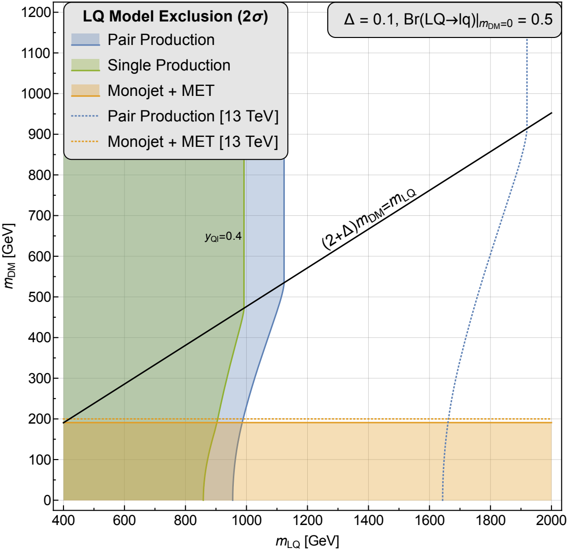


Example - ST11 - Existing Collider Constraints



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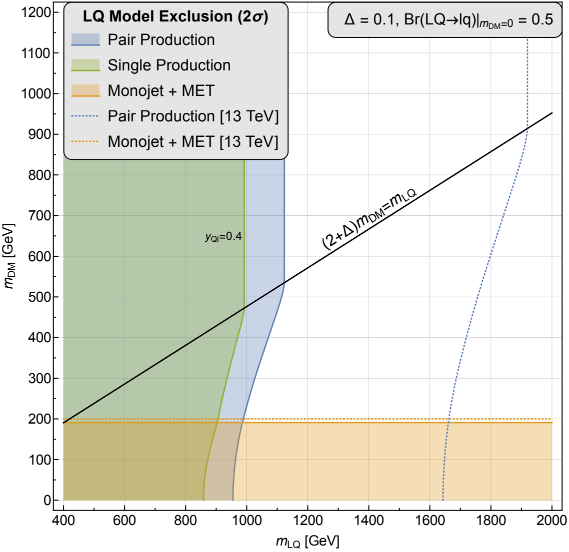

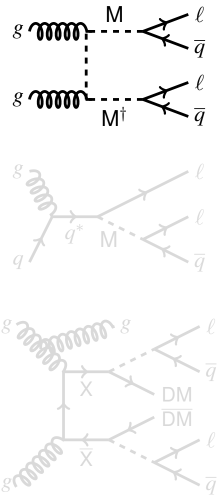

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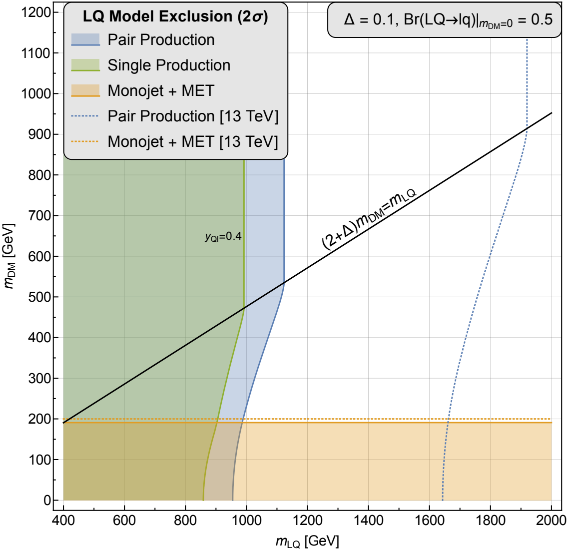

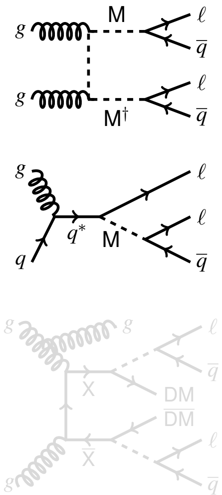

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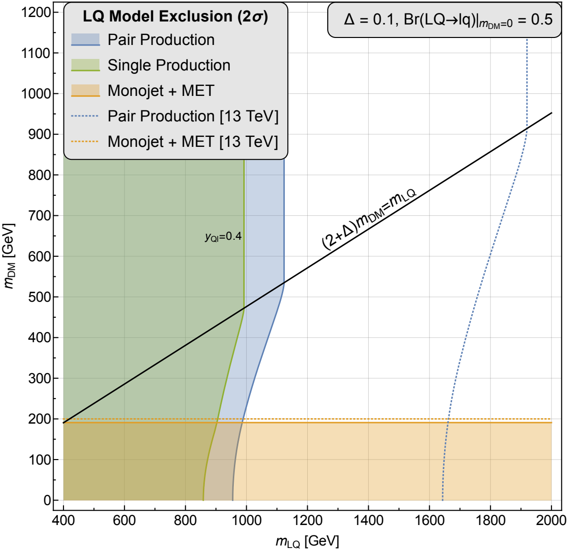
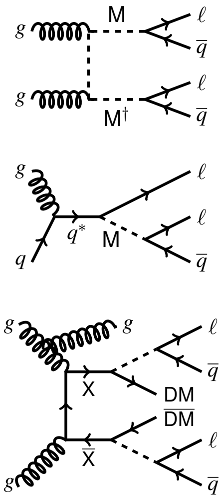
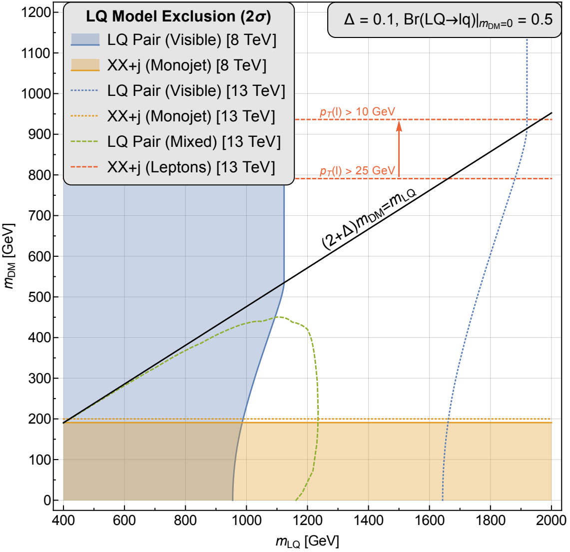
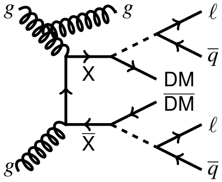




Example - ST11 - Constraints from New Searches





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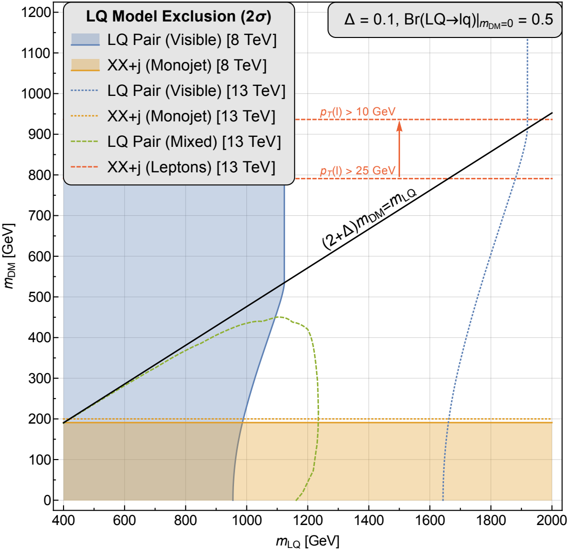

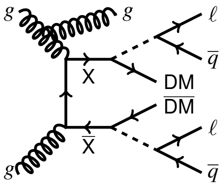

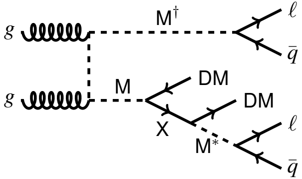

Summary

- Coannihilation Codex contains the real model of Nature!*
- Guaranteed kinetic & coannihilation vertices $\rightarrow$ signatures
- Classify general signatures
  - Identify new signatures
  - Identify interesting models, e.g., leptoquarks and DM
- Huge number of DM models
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  - direct and indirect detection
  - precision tests
  - flavour bounds
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