THE COANNIHILATION CODEX

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Introduction and Motivation

- Dark matter is a fundamental puzzle
- Many traditional particle probes, but no discovery
  - Direct detection (LUX, CDMS, Xenon1T)
  - Indirect detection (FERMI, AMS-02)
  - Colliders (ATLAS, CMS)
- Direct knowledge of particle nature of dark matter is very limited
  - Cold, non-baryonic, colorless, EM neutral
  - Relic density $\Omega h^2 = 0.1198 \pm 0.0026$ Planck [1502.01589]

Introduction and Motivation

- Goal: Use known DM properties as a basis for constructing minimal dark sectors
  - DM particle is colorless and EM neutral
  - Relic density constraint motivates the belief that DM annihilates to SM particles
- Characterize all possible two-to-two DM (co)annihilation processes as simplified models
- Establish a complete framework for LHC signatures that test how DM obtains its relic density
  - Nature's choice for DM guaranteed to be realized in our framework given our assumptions

Outline

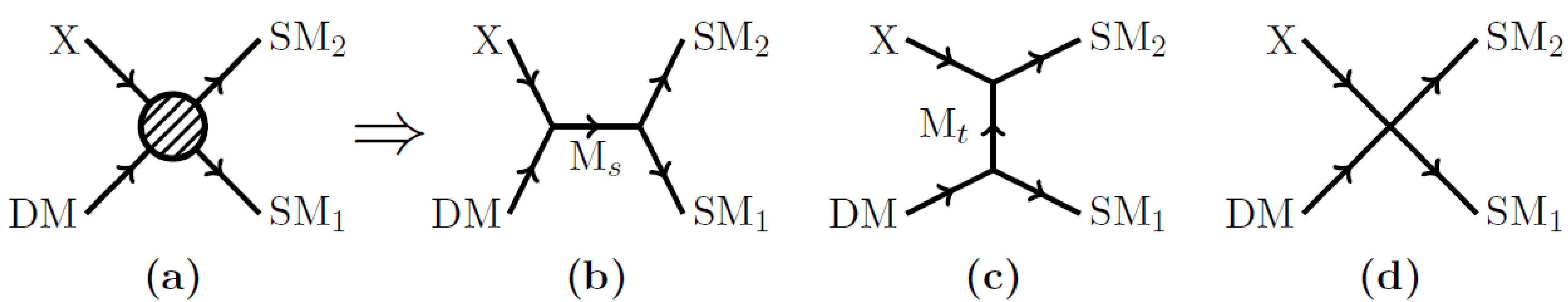
- Establishing the framework
  - Assumptions, methodology
- Simplified models
  - Hybrid, s-channel mediator, t-channel mediator tables
- Cosmological probes
- LHC signature classes
- Case study: **Model ST11**
  - s-channel leptoquark mediator
  - Relic density, LHC strategies for mediator and coannihilation partner
- Conclusions and future outlook

The Framework: Assumptions

- Our assumptions forming the basis of our simplified model framework are
  1. DM is colorless, EM neutral
  2. DM is a thermal relic
  3. The (co)annihilation diagram is two-to-two
  4. Interaction vertices are realized via tree-level Lagrangian terms
  5. New particles have spin 0, ½, or 1, and spin-1 particles are massive gauge bosons of a new gauge group
  6. All gauge bosons obey minimal coupling

Building the Codex

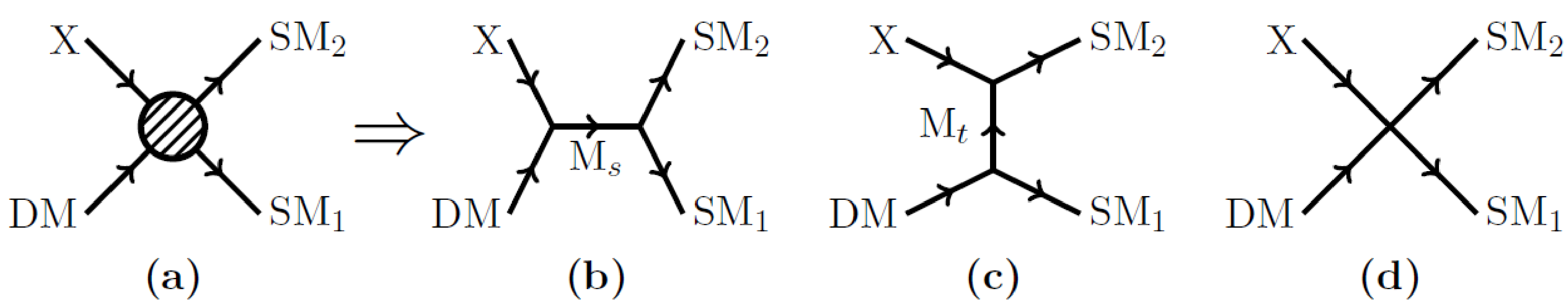
- DM transforms as (1, N, β), with hypercharge β s.t. one component is EM neutral
- Iterate over SM_1 SM_2 pairings to define possible set of coannihilation partners X
- Resolve each DM, X, SM_1 and SM_2 set with an s-channel M_s or t-channel mediator M_t



Arrows denote gauge representation convention

Refining the Codex

- X = DM reproduces pair annihilation simplified models
- Accidental Z_2 parity (X, DM, M_t odd, M_s and SM fields even) protects against DM decay and role reversal between simplified models
  - Can study s-channel and t-channel models separately



Arrows denote gauge representation convention

Refining the Codex

- (Up to) three new fields DM, X, and M are defined by SM gauge quantum numbers
  - Additional global or gauge symmetries will further restrict models and allowed interactions
  - Horizontal symmetries can also be included
  - Flavor structure of couplings and global SM numbers treated on case-by-case basis
- Minimal coupling provision reduces number of possible simplified models
  - If SM gauge bosons are coannihilation products SM_1 or SM_2, then becomes a **hybrid** simplified model

The Coannihilation Codex

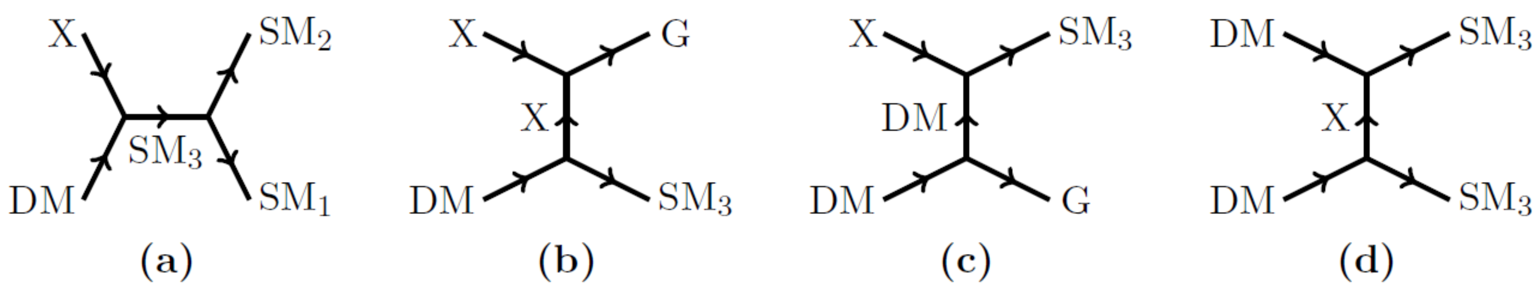
- Define simplified models by new model content and interaction vertices that realize the two-to-two DM (co)annihilation diagram

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 M_t-X-SM_2

The Coannihilation Codex: Hybrid

– Hybrid models have both s-channel and t-channel two-to-two coannihilation diagrams, given X and DM are not pure SM gauge singlets

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



Note
DM = (1, N, β)

The Coannihilation Codex: s-channel

- X and M_s have same color charge
- Organize models into tables according to color charges of X and M_s
  - "SU" (s-channel, uncolored): 17
  - "ST" (s-channel, color triplet): 20
  - "SO" (s-channel, color octet): 5
  - "SE" (s-channel, 'exotic' [i.e. color rep. not realized in SM]): 7
- Some are "Extensions" of hybrid models

The Coannihilation Codex: s-channel

– "SU" models

ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	X-DM-SM$_3$	M-X-X
SU1	$(1,N,\alpha)$	0	$(1,1,0)$	B	$(u_R\overline{u_R}),(d_R\overline{d_R}),(Q_L\overline{Q_L})$ $(\ell_R\overline{\ell_R}),(L_L\overline{L_L}),(HH^\dagger)$	H1	✓
SU2				F	(L_LH)		
SU3			$(1,3,0)^{N\geq2}$	B	$(Q_L\overline{Q_L}),(L_L\overline{L_L}),(HH^\dagger)$	H1	✓
SU4				F	(L_LH)		
SU5		-2	$(1,1,-2)$	B	$(d_R\overline{u_R}),(H^\dagger H^\dagger)$		✓
SU6				F	$(L_LH^\dagger)$	H2	
SU7			$(1,3,-2)^{N\geq2}$	B	$(H^\dagger H^\dagger),(L_LL_L)$		✓$(\alpha=\pm1)$
SU8				F	$(L_LH^\dagger)$	H2	
SU9		-4	$(1,1,-4)$	B	$(\ell_R\ell_R)$		✓$(\alpha=\pm2)$
SU10	$(1,N\pm1,\alpha)$	-1	$(1,2,-1)$	B	$(d_R\overline{Q_L}),(\overline{u_R}Q_L),(\overline{L_L}\ell_R)$	H3	
SU11				F	(ℓ_RH)	H4	
SU12		-3	$(1,2,-3)$	B	$(L_L\ell_R)$		
SU13				F	$(\ell_RH^\dagger)$		
SU14	$(1,N\pm2,\alpha)$	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	$(H^\dagger H^\dagger),(L_LL_L)$		✓$(\alpha=\pm1)$
SU17				F	$(L_LH^\dagger)$		

The Coannihilation Codex: s-channel

– "ST" models

ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	X-DM-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	$(Q_L H)$	H5	
ST4			$(3, 3, \frac{4}{3})^{N \geq 2}$	B	$(Q_L \overline{L_L})$		$\checkmark \alpha = -\frac{2}{3}$
ST5				F	$(Q_L H)$	H5	
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	$(Q_L H^\dagger)$	H6	
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	$(Q_L H^\dagger)$	H6	
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	$(u_R H^\dagger), (d_R H)$	H7	
ST15		$-\frac{5}{3}$	$(3, 2, -\frac{5}{3})$	B	$(\overline{Q_L u_R}), (Q_L \ell_R), (d_R L_L)$		
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	$(Q_L H^\dagger)$		

The Coannihilation Codex: s-channel

– “SO” and “SE” models

ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	X-DM-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	$(Q_L Q_L)$		$\checkmark\ \alpha=-\frac{1}{3}$

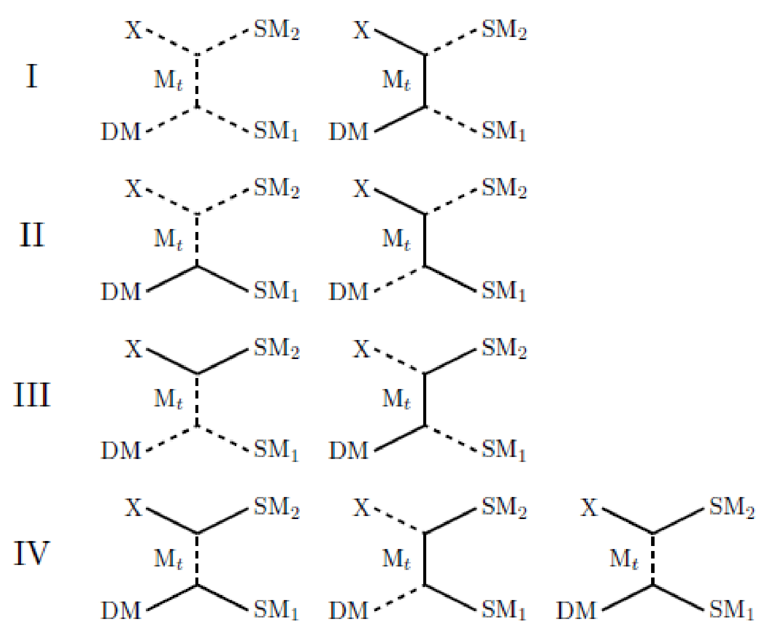
The Coannihilation Codex: t-channel

- Organize models into tables according to color charges of X
  - “TU” (t-channel, uncolored): 33
  - “TT” (t-channel, color triplet): 52
  - “TO” (t-channel, color octet): 10
  - “TE” (t-channel, ‘exotic’ [i.e. color rep. not realized in SM]): 10
- Again, some are “Extensions” of hybrid models

t-channel

- "TU" models

Spin categories



Note

DM = (1, N, β)

ID	X	$\alpha+\beta$	M_t	Spin	$(SM_1\ SM_2)$	X-DM-SM$_3$
TU1	$(1,N,\alpha)$	0	$(1,N\pm1,\beta-1)$	I	$(HH^\dagger)$	H1
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	$(Q_L\overline{Q_L})$	H1
TU5			$(\bar{3},N,\beta-\frac{4}{3})$	IV	$(u_R\overline{u_R})$	H1
TU6			$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\overline{d_R})$	H1
TU7			$(1,N\pm1,\beta+1)$	IV	$(L_L\overline{L_L})$	H1
TU8			$(1,N,\beta+2)$	IV	$(\ell_R\overline{\ell_R})$	H1
TU9		-2	$(1,N\pm1,\beta+1)$	I	$(H^\dagger H^\dagger)$	
TU10			$(1,N\pm1,\beta+1)$	II	$(L_LH^\dagger)$	H2
TU11			$(1,N\pm1,\beta+1)$	III	$(H^\dagger L_L)$	H2
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)	H4
TU17			$(1,N\pm1,\beta-1)$	III	$(H\ell_R)$	H4
TU18			$(1,N,\beta+2)$	IV	$(\ell_R\overline{L_L})$	H3
TU19			$(1,N\pm1,\beta-1)$	IV	$(\overline{L_L}\ell_R)$	H3
TU20			$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\overline{Q_L})$	H3
TU21			$(3,N\pm1,\beta+\frac{1}{3})$	IV	$(\overline{Q_L}d_R)$	H3
TU22			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\overline{u_R})$	H3
TU23			$(3,N,\beta+\frac{4}{3})$	IV	$(\overline{u_R}Q_L)$	H3
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	$(H^\dagger L_L)$	

t-channel

- "TT" models

1-21

ID	X	$\alpha+\beta$	M_t	Spin	(SM_1 SM_2)	X-DM-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		$\frac{4}{3}$	$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	II	$(Q_L H)$	H4
TT4			$(1, N \pm 1, \beta - 1)$	III	$(H Q_L)$	H4
TT5			$(1, N, \beta - 2)$	IV	$(\overline{\ell_R}d_R)$	
TT6			$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L\overline{L_L})$	
TT7			$(1, N \pm 1, \beta - 1)$	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		$-\frac{2}{3}$	$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	II	$(Q_L H^\dagger)$	H5
TT11			$(1, N \pm 1, \beta + 1)$	III	$(H^\dagger Q_L)$	H5
TT12			$(3, N, \beta + \frac{4}{3})$	IV	$(\overline{u_R}\overline{d_R})$	
TT13			$(3, N \pm 1, \beta + \frac{1}{3})$	IV	$(\overline{Q_L Q_L})$	
TT14			$(\bar{3}, N, \beta - \frac{4}{3})$	IV	$(u_R\ell_R)$	
TT15			$(1, N, \beta + 2)$	IV	$(\ell_R u_R)$	
TT16			$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L L_L)$	
TT17			$(1, N \pm 1, \beta + 1)$	IV	$(L_L Q_L)$	
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	$(\overline{u_R u_R})$	
TT20			$(\bar{3}, N, \beta + \frac{2}{3})$	IV	$(d_R\ell_R)$	
TT21			$(1, N, \beta + 2)$	IV	$(\ell_R d_R)$	

t-channel

- “TT” models

22-52

TT22	$(3, N \pm 1, \alpha)$	$\frac{7}{3}$	$(3, N, \beta - \frac{4}{3})$	II	$(u_R H)$	
TT23			$(1, N \pm 1, \beta - 1)$	III	$(H u_R)$	
TT24			$(\bar{3}, N, \beta - \frac{4}{3})$	IV	$(u_R \overline{L_L})$	
TT25			$(1, N \pm 1, \beta - 1)$	IV	$(\overline{L_L} u_R)$	
TT26			$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	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	$(u_R H^\dagger)$	H6
TT29			$(\bar{3}, N, \beta + \frac{2}{3})$	II	$(d_R H)$	H6
TT30			$(1, N \pm 1, \beta + 1)$	III	$(H^\dagger u_R)$	H6
TT31			$(1, N \pm 1, \beta - 1)$	III	$(H d_R)$	H6
TT32			$(\bar{3}, N, \beta - \frac{4}{3})$	IV	$(u_R L_L)$	
TT33			$(1, N \pm 1, \beta + 1)$	IV	$(L_L u_R)$	
TT34			$3, N, \beta - \frac{2}{3})$	IV	$(\overline{d_R}\overline{Q_L})$	
TT35			$(3, N \pm 1, \beta + \frac{1}{3})$	IV	$(\overline{Q_L d_R})$	
TT36		$-\frac{5}{3}$	$(\bar{3}, N, \beta + \frac{2}{3})$	II	$(d_R H^\dagger)$	
TT37			$(1, N \pm 1, \beta + 1)$	III	$(H^\dagger d_R)$	
TT38			$(\bar{3}, N, \beta + \frac{2}{3})$	IV	$(d_R L_L)$	
TT39			$(1, N \pm 1, \beta + 1)$	IV	$(L_L d_R)$	
TT40			$(3, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L \ell_R)$	
TT41			$(1, N, \beta + 2)$	IV	$(\ell_R Q_L)$	
TT42			$(3, N, \beta + \frac{4}{3})$	IV	$(\overline{u_R}\overline{Q_L})$	
TT43			$(3, N \pm 1, \beta + \frac{1}{3})$	IV	$(\overline{Q_L}\overline{u_R})$	
TT44	$(3, N \pm 2, \alpha)$	$\frac{4}{3}$	$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	II	$(Q_L H)$	
TT45			$(1, N \pm 1, \beta - 1)$	III	$(H Q_L)$	
TT46			$(3, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L \overline{L_L})$	
TT47			$(1, N \pm 1, \beta - 1)$	IV	$(\overline{L_L} Q_L)$	
TT48		$-\frac{2}{3}$	$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	II	$(Q_L H^\dagger)$	
TT49			$(1, N \pm 1, \beta + 1)$	III	$(H^\dagger Q_L)$	
TT50			$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L L_L)$	
TT51			$(1, N \pm 1, \beta + 1)$	IV	$(L_L Q_L)$	
TT52			$(3, N \pm 1, \beta + \frac{1}{3})$	IV	$(\overline{Q_L Q_L})$	

The Coannihilation Codex: t-channel

- "TO" and "TE" models

ID	X	$\alpha+\beta$	M_t	Spin	$(SM_1\ SM_2)$	X-DM-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			$(3, N\pm1, \beta-\frac{1}{3})$	IV	(Q_Ld_R)	
TE10	$(6, N\pm2, \alpha)$	$\frac{2}{3}$	$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	(Q_LQ_L)	

EWSB effects

- Thus far, simplified models are constructed in EW symmetric phase
  - Field content admits coannihilation diagram with tree-level vertices without violating EW symmetry
- Straightforward to include EWSB effects in simplified models thus far
- Can also formulate procedure for identifying simplified models that require EWSB
  - Model content is orthogonal to those already written
  - Can capture phenomenology of such models already with current classification

Phenomenology

- Goal: Explore the cosmological, astrophysical, and collider phenomenology for each (co)annihilation diagram
  - Each simplified model can be realized independently
  - And each simplified model can be a distilled version of many distinct UV completions
- By construction, marginal new physics couplings are introduced in a controlled manner
  - Enables tighter connection between relic density constraint and experimental searches

Coannihilation condition

Griest, Seckel PRD **43** (1991)

- Fractional mass splitting Δ between X and DM of around 10%-20% or less ensures X number density is close to DM number density during freezeout
  - Larger Δ can also be important if DM pair annihilation is small
  - Important handle for collider searches

$$\Delta \equiv \frac{m_{\rm X} - m_{\rm DM}}{m_{\rm DM}}$$

$$x = m_{\rm DM}/T$$

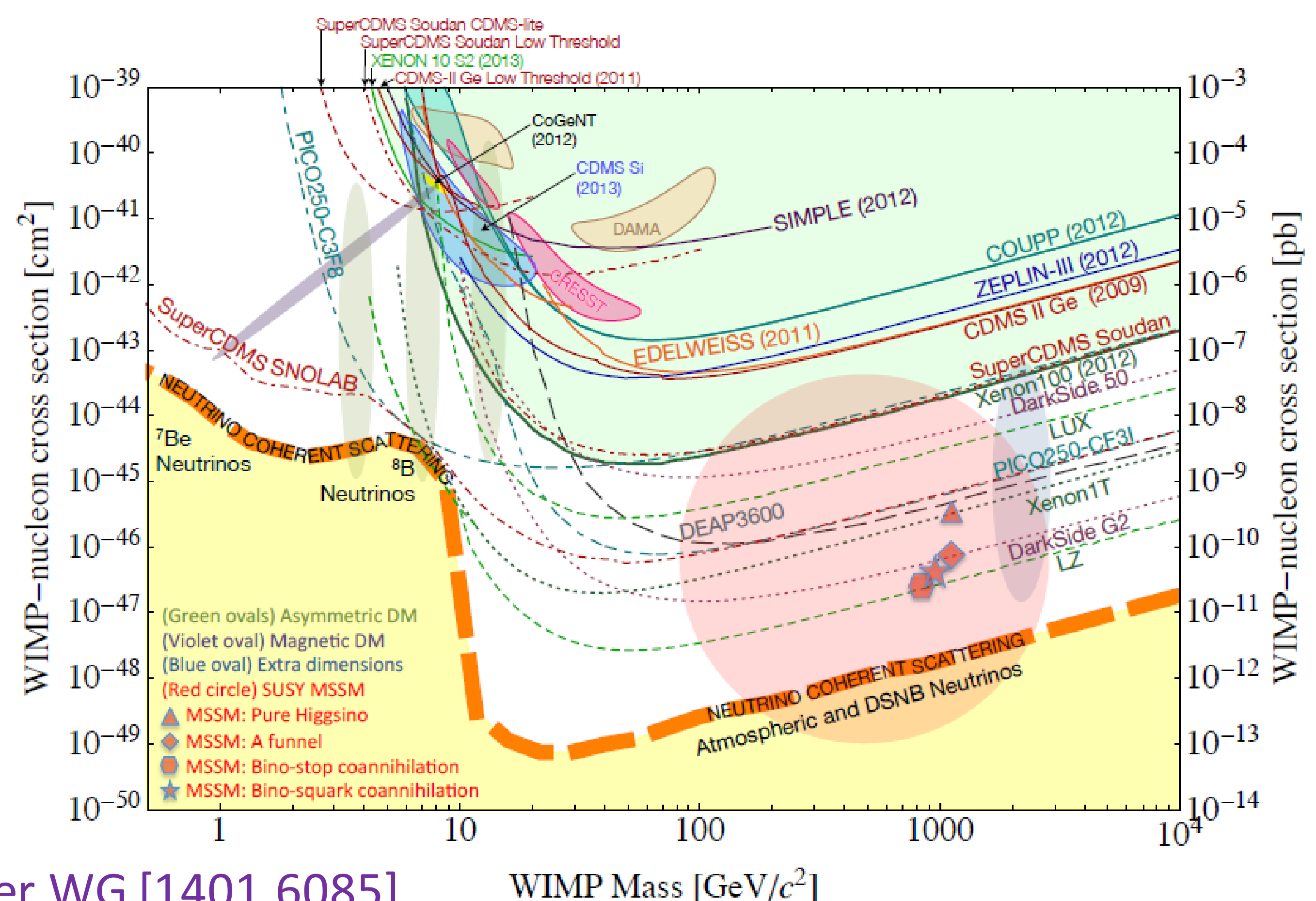
$$\sigma_{\rm eff} = \frac{g_{\rm DM}^2}{g_{\rm eff}^2}\left\{\sigma_{\rm DM\,DM} + 2\sigma_{\rm DM\,X}\frac{g_{\rm X}}{g_{\rm DM}}(1+\Delta)^{\frac{3}{2}}\exp(-x\Delta) + \sigma_{\rm X\,X}\frac{g_{\rm X}^2}{g_{\rm DM}^2}(1+\Delta)^3\exp(-2x\Delta)\right\}.$$

Direct and indirect detection

- Direct detection and indirect detection signals are generally model dependent

Can generally eliminate DM-DM-Z coupling by mixing with a (1, N, -β) field

Assume X and M have decayed



Snowmass Cosmic Frontier WG [1401.6085]

Collider signatures

- Production processes
  - Strong and weak pair production
  - Single production of M_s
  - Associated production of M_s+SM, M_t+DM, and M_t+X
- Decays
  - Simply recycle coannihilation vertices, assume prompt
  - X has three-body decay to $(SM_1+SM_2)_{soft}$+DM via M_s
  - M_s decays to X+DM or $(SM_1+SM_2)_{resonant}$
  - M_t decays to DM+SM_1 or X+SM_2

Collider signatures

- Stitching together production and decay gives

	prod. conditions	s-channel	t-channel
unique	pair production via gauge int.	$2\mathrm{M}_s \to 2\,(\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{res}}$ $2\mathrm{M}_s \to (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{res}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$	$2\mathrm{M}_t \to 2\,(\mathrm{SM}_1)_{\mathrm{hard}} + \not{E}_T$ $2\mathrm{M}_t \to 2\,(\mathrm{SM}_2)_{\mathrm{hard}} + 2\,(\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$ $2\mathrm{M}_t \to (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{hard}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$
	$(\mathrm{SM}_1\mathrm{SM}_2) \in p$	$\mathrm{M}_s \to (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{res}}$	
	$\mathrm{SM}_1 \in p$	$\mathrm{M}_s\ \mathrm{SM}_2 \to (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{res}} + (\mathrm{SM}_2)_{\mathrm{hard}}$	$\mathrm{M}_t\ \mathrm{DM} \to (\mathrm{SM}_1)_{\mathrm{hard}} + \not{E}_T$
	$\mathrm{SM}_2 \in p$	$\mathrm{M}_s\ \mathrm{SM}_1 \to (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{res}} + (\mathrm{SM}_1)_{\mathrm{hard}}$	$\mathrm{X}\ \mathrm{M}_t \to (\mathrm{SM}_2)_{\mathrm{hard}} + 2\,(\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$
common	p.p. via g. int.	$2\mathrm{M}_s$ or $2\mathrm{X} \to 2\,(\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$	$2\mathrm{X} \to 2\,(\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$
	$(\mathrm{SM}_1\mathrm{SM}_2) \in p$	$\mathrm{M}_s \to (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$	$\mathrm{X}\ \mathrm{DM} \to (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$
	$\mathrm{SM}_1 \in p$	$\mathrm{M}_s\ \mathrm{SM}_2 \to (\mathrm{SM}_2)_{\mathrm{hard}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$	$\mathrm{M}_t\ \mathrm{DM} \to (\mathrm{SM}_2)_{\mathrm{hard}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$
	$\mathrm{SM}_2 \in p$	$\mathrm{M}_s\ \mathrm{SM}_1 \to (\mathrm{SM}_1)_{\mathrm{hard}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$	$\mathrm{X}\ \mathrm{M}_t \to (\mathrm{SM}_1)_{\mathrm{hard}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$

- Many s-channel resonances, t-channel cascade decays, signatures with and without MET

Signature class I: the new mono-Y

- For small Δ, the SM decay products from X can be too soft to reconstruct
  - X and DM pair production and X DM associated production give same MET signature, but X can be colored
  - Mono-Y (Y = jet, photon, Z, etc.) searches become very powerful and less model dependent
- For moderate Δ or large DM mass, soft SM decay products start to pass detector thresholds
  - SM products come in many pairs, can define many new variants with different object classes

Signature class II: s-channel resonances

- Mediator M_s generally pair-produced via strong or EW interactions
- Generates a suite of two-body resonances, competes against "invisible" X+DM decay channel
  - Three signatures: paired resonances, resonance + MET, mono-Y – needed for coupling measurements
- Single production and associated production also possible
  - Rate scales with NP coupling, more model dependent
  - Many striking signatures (e.g. LQ + lepton)

Signature class III: t-channel cascades

- Mediator M_t also generally pair-produced via strong or EW interactions
- Always have MET in the final state
- SM legs from cascade chain are typically hard, complicated by possible soft decays from X
  - Many kinematic handles and edges

Case study **ST11**

- Perform a case study of s-channel model ST11
- Prescribe the spin assignments and Lagrangian as

Field	$(SU(3), SU(2), U(1))$	Spin assignment
DM	(1, 1, 0)	Majorana fermion
X	(3, 2, 7/3)	Dirac fermion
M	(3, 2, 7/3)	Scalar

$$\mathcal{L} = \frac{i}{2}\overline{\mathrm{DM}}\partial\!\!\!/\mathrm{DM} \; + i\overline{\mathrm{X}}D\!\!\!\!/\mathrm{X} \; + |D_\mu \mathrm{M}|^2 + \frac{m_{\mathrm{DM}}}{2}\overline{\mathrm{DM}}\,\mathrm{DM} \; + m_{\mathrm{X}}\overline{\mathrm{X}}\,\mathrm{X} \; - V(\mathrm{M}, H)$$
$$+ \left(y_D \overline{\mathrm{X}}\,\mathrm{M}\,\mathrm{DM} \; + \mathrm{h.c.}\right) + \left(y_{Q\ell}\overline{Q_L}\mathrm{M}\,\ell_R + \mathrm{h.c.}\right) + \left(y_{Lu}\overline{L_L}\mathrm{M}^c u_R + \mathrm{h.c.}\right),$$
$$V(\mathrm{M}, H) = V(H) + m_{\mathrm{M}}^2 \mathrm{M}^\dagger \mathrm{M} + \frac{1}{4}\lambda_{\mathrm{M}}\left(\mathrm{M}^\dagger \mathrm{M}\right)^2 + \epsilon_{\mathrm{M}}\mathrm{M}^\dagger \mathrm{M}\left(H^2 - \frac{v^2}{2}\right),$$

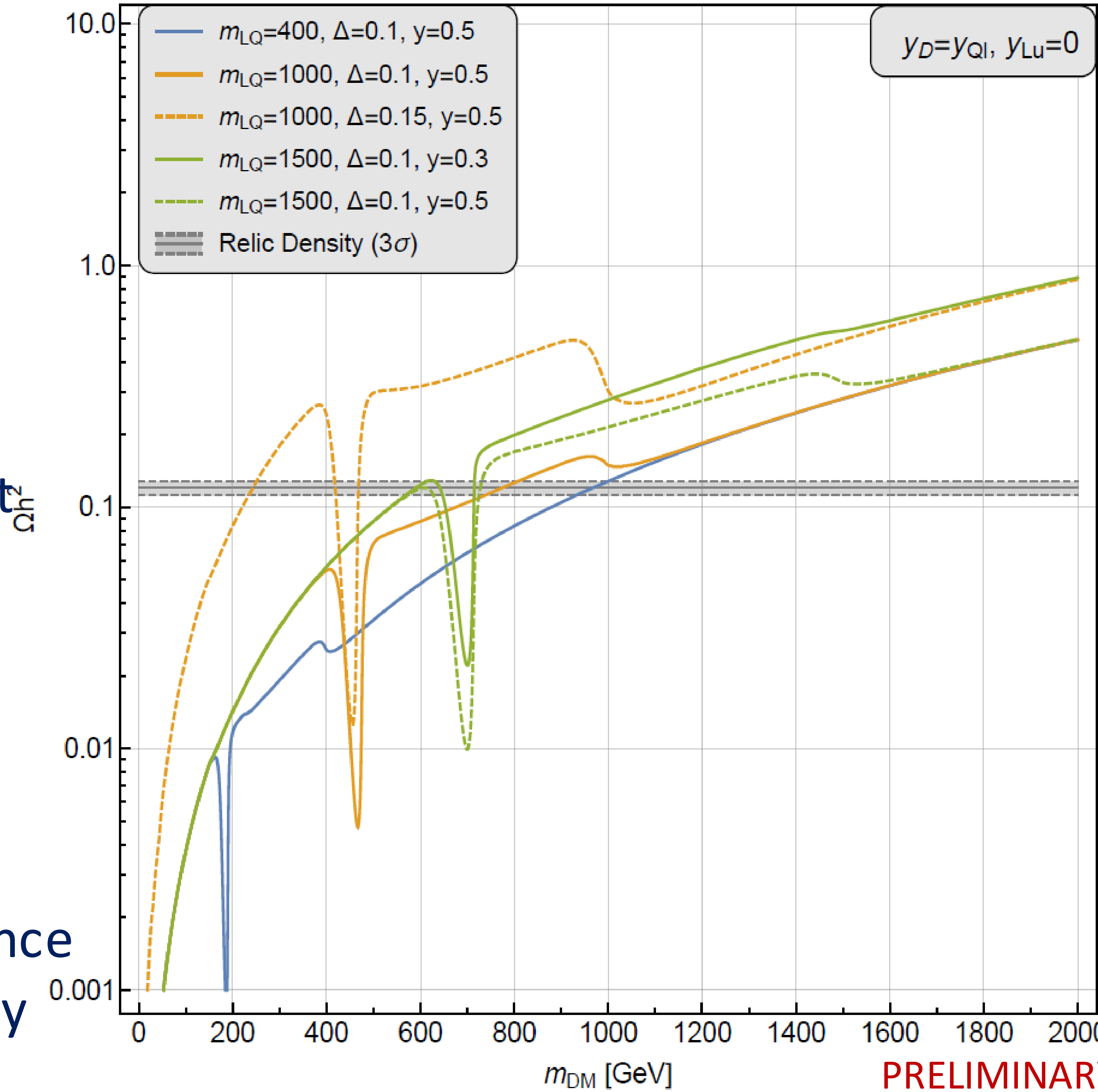
Ωh^2

First study relic density vs. DM mass

Fix $y \equiv y_D = y_{Ql}$, set $y_{Lu}=0$

Coannihilation spikes clearly visible

Show dependence on LQ mass, Δ, y



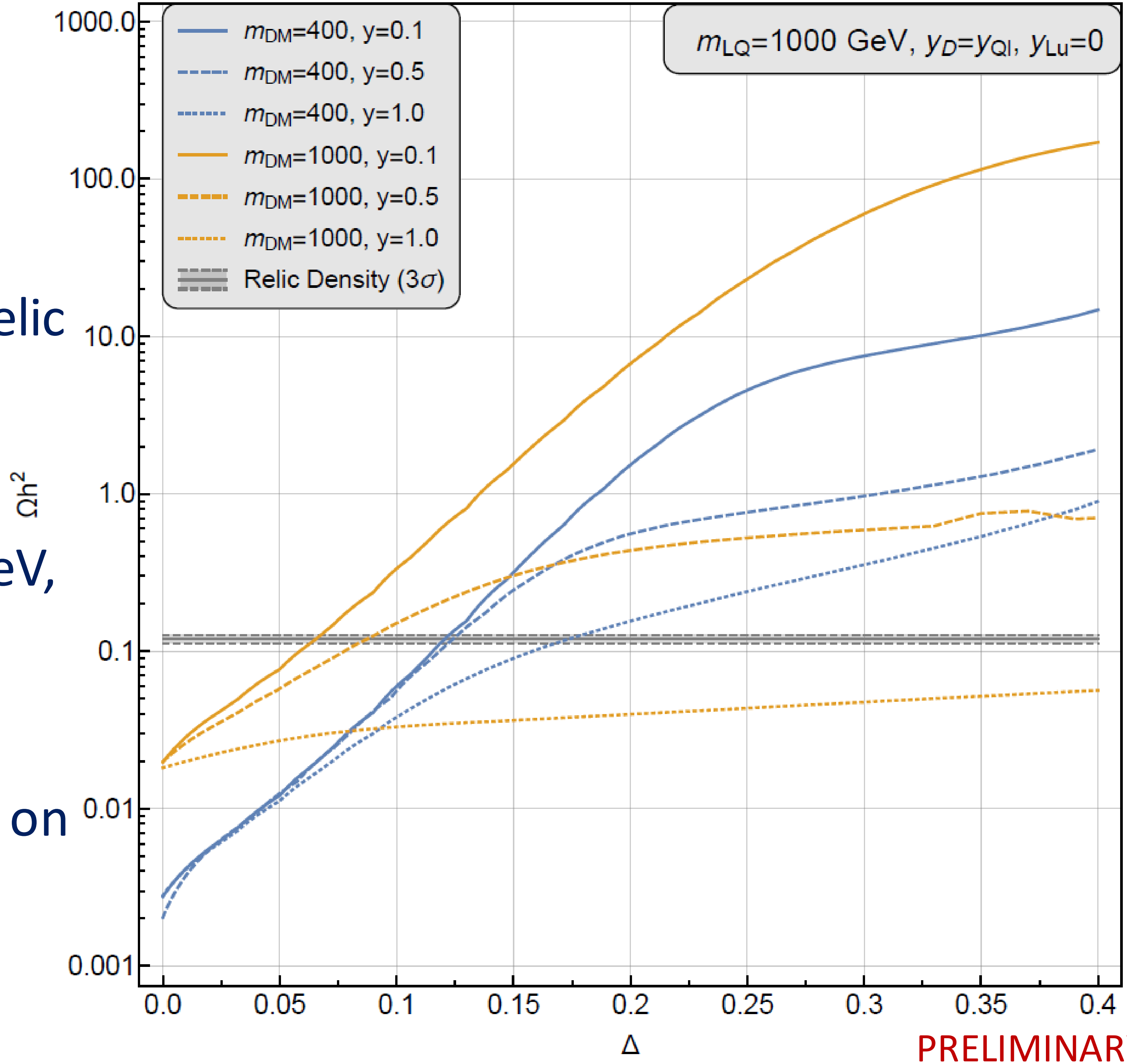
PRELIMINARY

Ωh^2

Next study relic density vs. Δ

Fix $y \equiv y_D = y_{Ql}$, m_{LQ}=1000 GeV, set y_{Lu}=0

Show dependence on DM mass, y

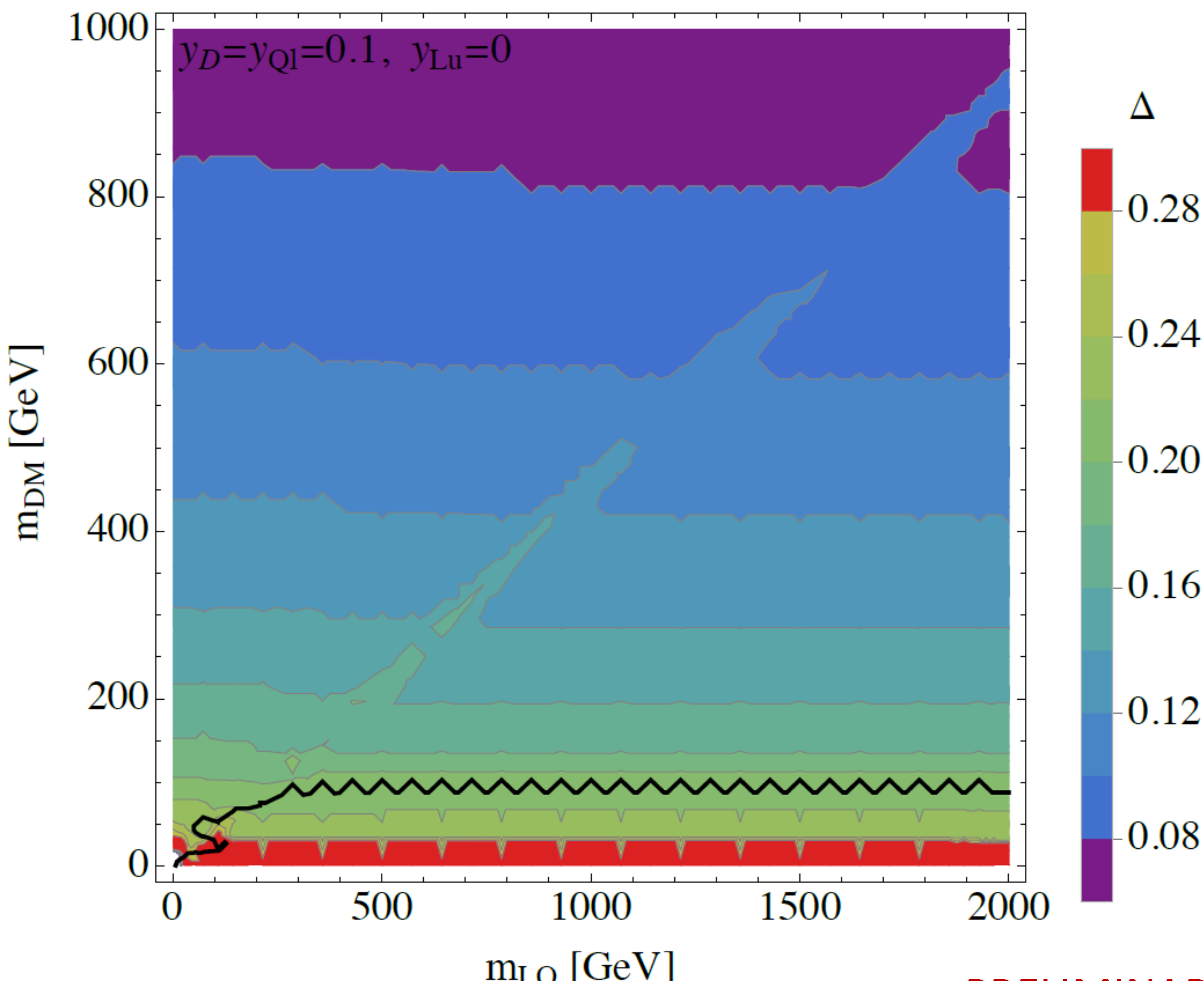


PRELIMINARY

ST11: Ωh^2

Can also solve for Δ given y=0.1 and DM and LQ masses

Below black line indicates multiple solutions for Δ are possible

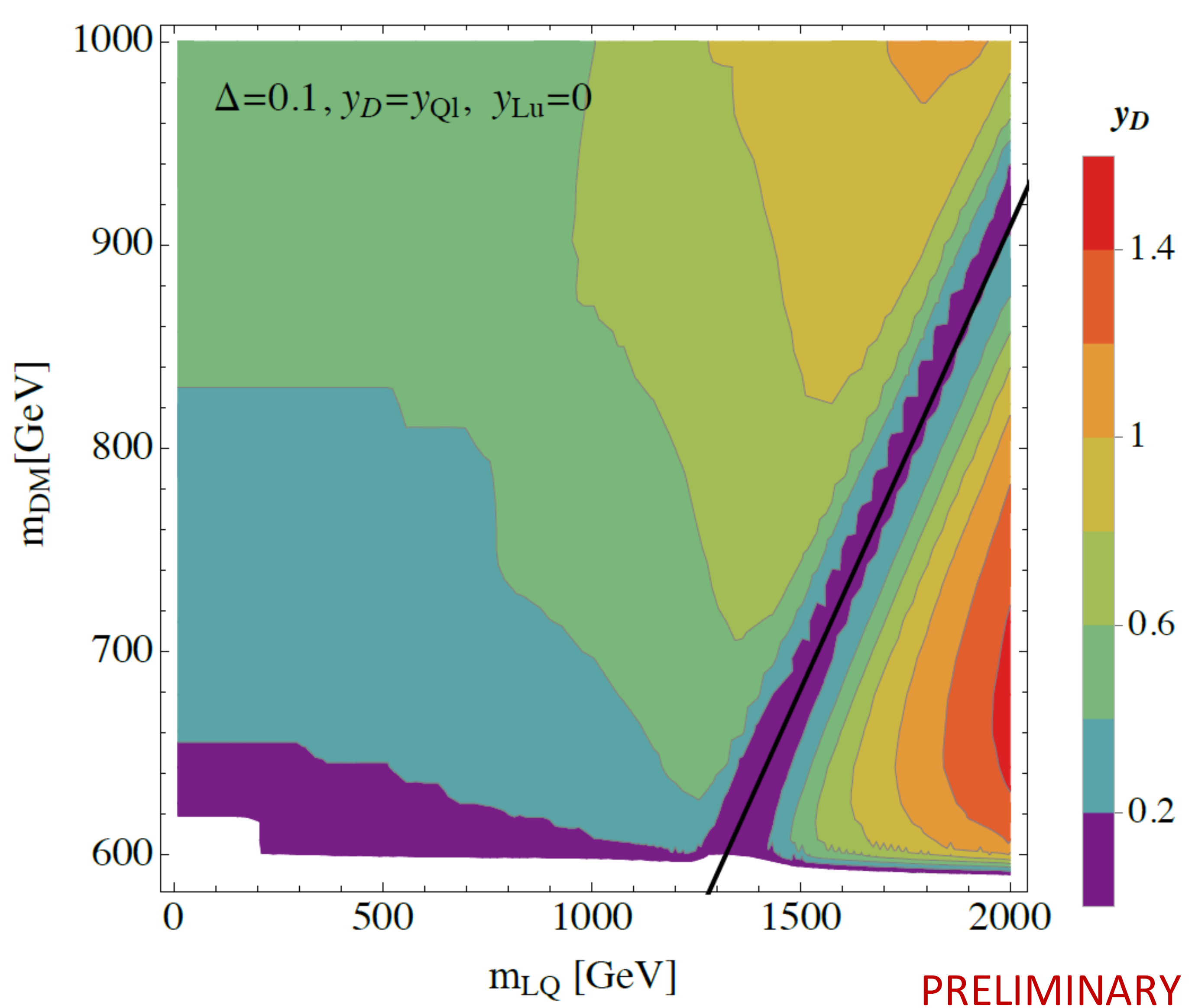


PRELIMINARY

ST11: Ωh^2

Can also solve for y given Δ=0.1 and DM and LQ masses

Black line here indicates the resonant coannihilation region



PRELIMINARY

ST11: direct detection

- DM (Z_2 odd, SM gauge singlet Majorana fermion) has no tree-level pair annihilation diagram to SM particles
- Resulting higher dimensional operators for DM-nucleon scattering are loop-suppressed and experimentally insensitive

ST11: LHC signatures

- Mono-Y
  - XX + ISR j: Gives 2 soft (lj) pairs + MET + tagging jet new+ NEW!
- s-channel mediator pair production $\propto g_s^2$
  - $M_s M_s \rightarrow (lj)_{res} (lj)_{res}$: Usual paired leptoquark resonances
  - $M_s M_s \rightarrow (lj)_{res}$ X DM : Novel targeted analysis NEW!
  - $M_s M_s \rightarrow$ X DM X DM : Similar to mono-Y
- s-channel mediator associated production $\propto g_s\, y_{Ql}$
  - M_s l $\rightarrow (lj)_{res}$ l: Known single leptoquark search
  - M_s l $\rightarrow$ X DM l: Gives monolepton signature
- Focus on first generation LQ = electron+jet (second generation results in backup)

ST11: LHC signatures

- Recasting existing paired leptoquark searches depends on branching fractions of mediator
  - $\beta \equiv \mathrm{Br}(M_s \to ej)$
  - Benchmark has β_0 = 50%, maximizes mixed decay rate
- Relic density constrains y_D, complementary parameter space

$$\tau = m_{\rm DM}^2/m_{\rm LQ}^2 \text{ and } \beta_0 = y_{Q\ell}^2/(y_{Q\ell}^2 + 2y_D^2).$$

$$\Gamma\left(\mathrm{LQ} \to \ell\, q\right) = \frac{y_{Q\ell}^2}{16\pi} m_{\rm LQ}\,,$$

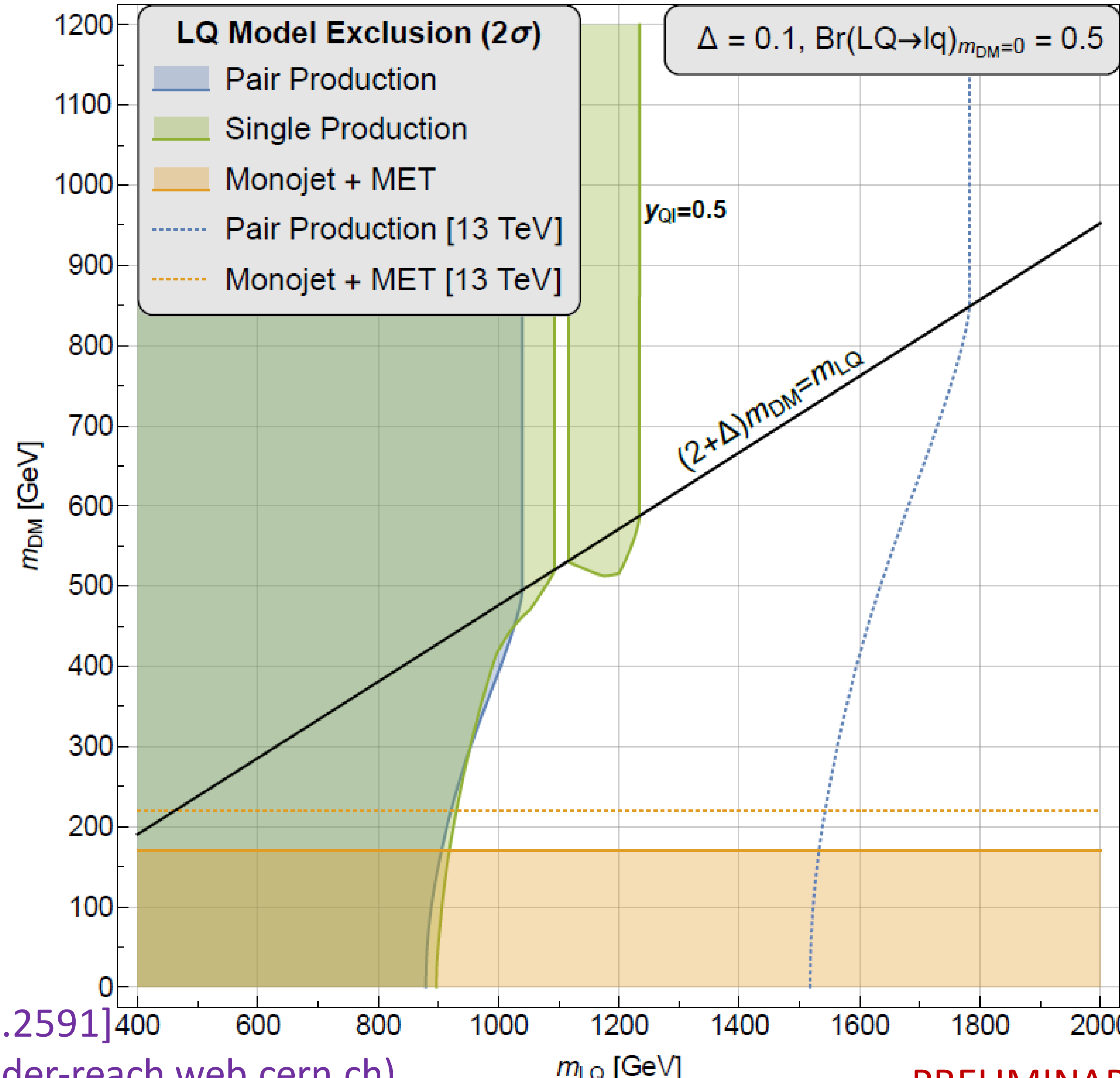
$$\Gamma\left(\mathrm{LQ} \to \mathrm{DM\ X}\right) = \frac{y_D^2}{8\pi} m_{\rm LQ}\left(1-\Delta^2\tau\right)^{1/2}\left[1-(2+\Delta)^2\tau\right]^{3/2} \equiv \frac{y_D^2}{8\pi} m_{\rm LQ} K(\Delta,\tau)\,,$$

$$\mathrm{Br}\left(LQ \to \ell\, q\right) = \frac{y_{Q\ell}^2}{y_{Q\ell}^2 + 2y_D^2 K(\Delta,\tau)} = \frac{\beta_0}{\beta_0 + (1-\beta_0)K(\Delta,\tau)}\,.$$

ST11

CheckMATE[1] used for 8 TeV recasting

Collider Reach[2] used for 100 fb^{-1} 13 TeV LHC projection



[1]Drees, et. al. [1312.2591]

[2]Salam, Weiler (collider-reach.web.cern.ch)

PRELIMINARY

ST11: Targetting the mixed decay (ej)

- One mediator decays to ej, second mediator decays to $(ej)_{soft}$ + MET
- Use MET and transverse mass cuts to reduce lepton + jet backgrounds
  - Look for bump in smooth m_{ej} distribution

ST11: Backgrounds for 13 TeV LHC

– MadGraph 5 + Pythia 6 (+ MLM matching if multiple jets) + Delphes 3.2

PRELIMINARY

Validate QCD with 13 TeV ATLAS dijets
ATLAS-CONF-2015-042

Validate W+jets, Z+jets with 8 TeV CMS monojets
CMS [1408.3583]

K-factors calculated with MCFM 6.8

Background	LO Cross section (pb)	k-factor (× "adjusting" factor)
QCD	2.1×10^7	1.3 [119, 120]
Leptonic $W^\pm + 1, 2$ jets	2222	1.15 (×2)
$(Z \to \nu\nu) + j$	736	1.15
$t\bar{t}$ (all modes)	465	1.67
$(Z \to \ell^+\ell^-) + j$	370	1.15
$(Z \to \tau^+\tau^-) + j$	163	1.15
Semileptonic $t\bar{t}$	124	1.67
WW, WZ, ZZ	37	1.7
$t + 1, 2j$	16.9	1.07
Semileptonic W^+W^-	9.8	1.5
$W(Z \to \nu\nu) + j$	2.2	1.7
$W(Z \to jj)$	2.2	1.7

ST11: Mixed decay cut flow

ATLAS-CONF-2014-032

- Jet faking electron rate = 0.0023
- Signal benchmark is M_s = 950 GeV, DM = 405 GeV, X = 445 GeV
- Mass window is 40 GeV wide

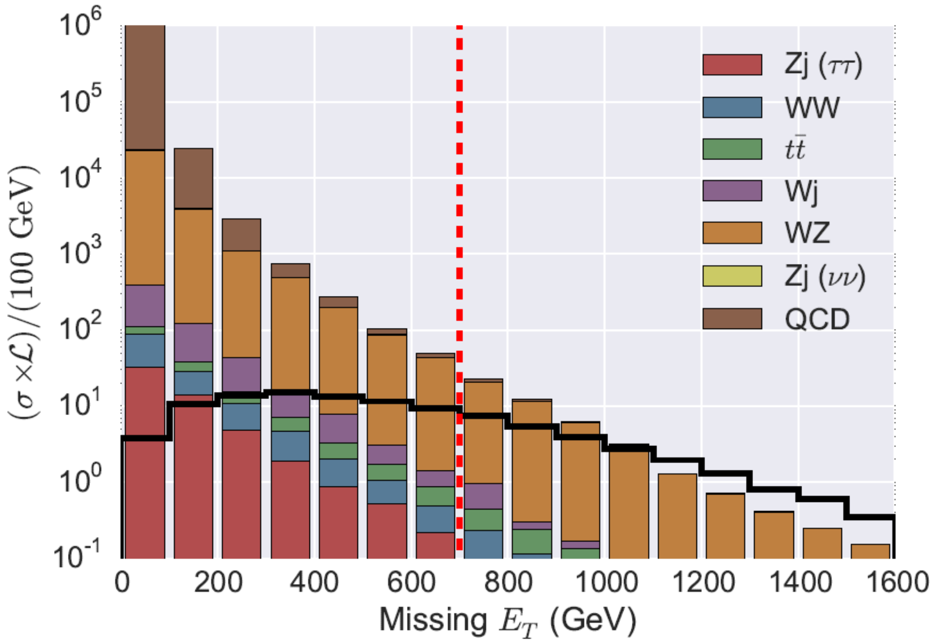
N_{ev} for 13 TeV, 100 fb^{-1}

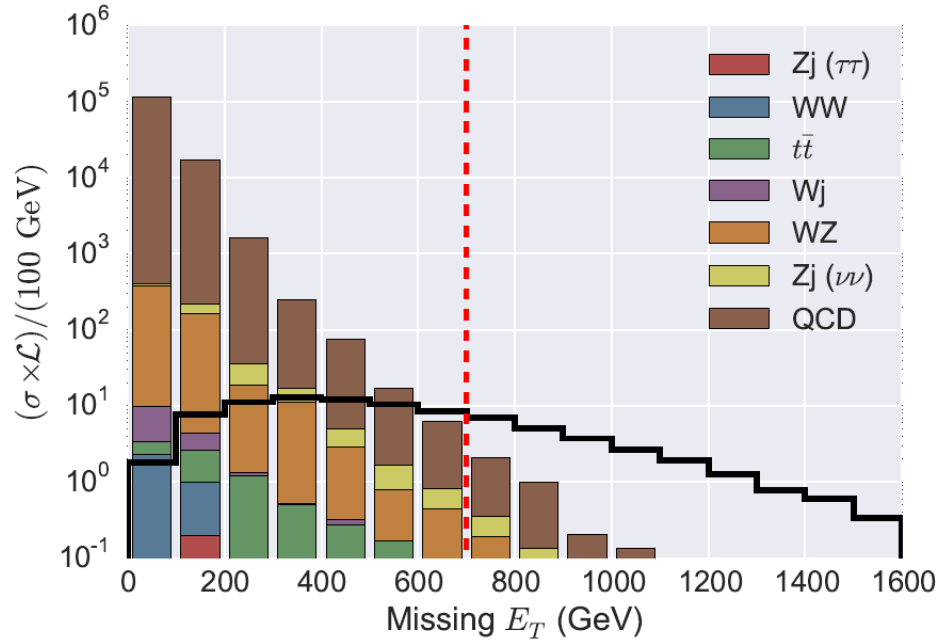
PRELIMINARY

	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	0	0.3	10^{-5}	10^{-5}	0.1	10^{-5}	24

ST11: Mixed decay MET distribution

- Left: no transverse mass cut
- Right: m_T > 150 GeV

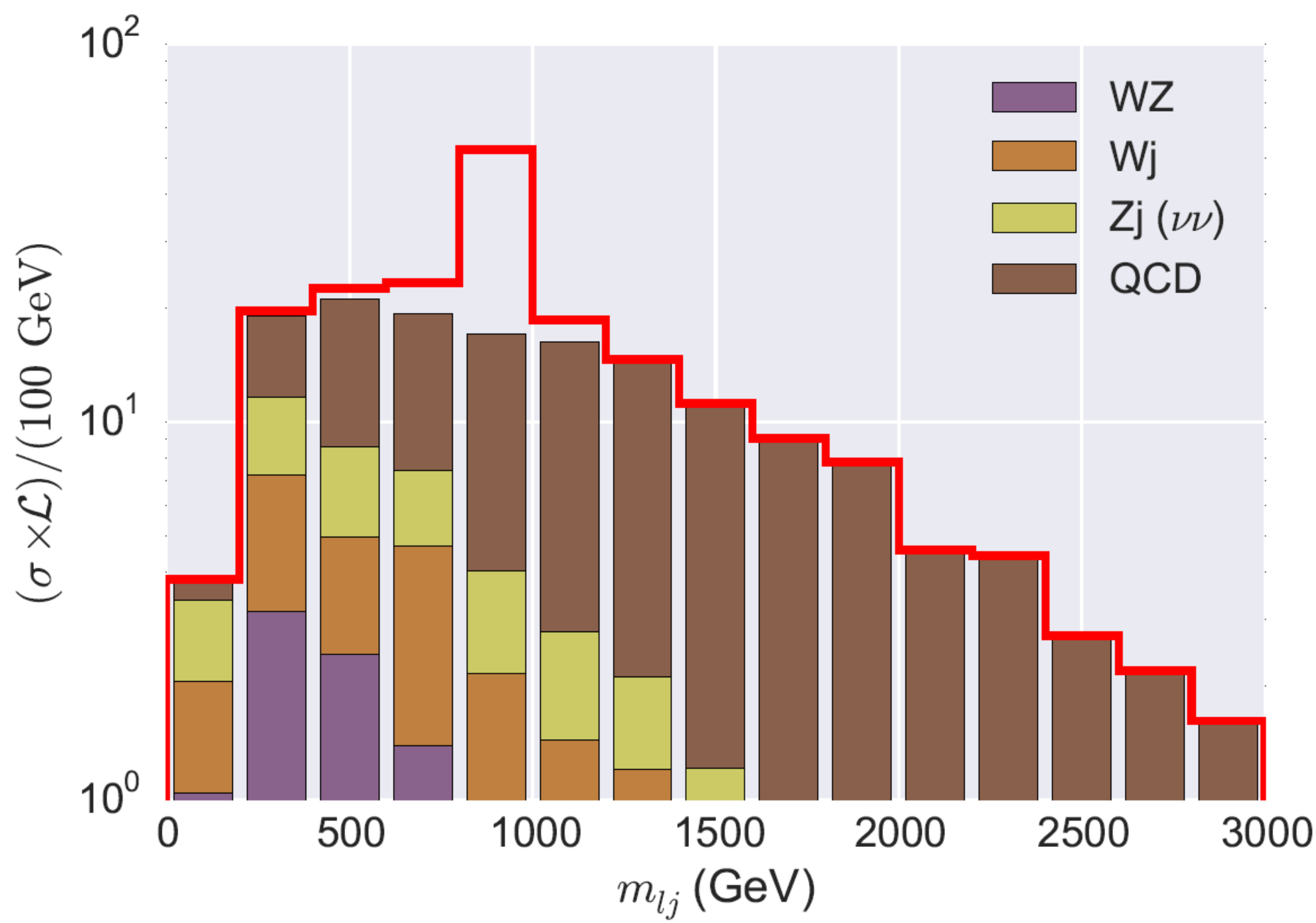




PRELIMINARY

ST11: Mixed decay m_{ej} distribution

- Prominent leptoquark resonance



PRELIMINARY

ST11: Soft lepton analysis

- Second new analysis targets the soft decays of X
- Important interplay between pure monojet and monojet + soft lepton analyses
  - Fractional mass splitting Δ controls visibility of X decays
  - 13 TeV lepton p_T thresholds have large impact on signal sensitivity
- Can generalize to all XX production in our simplified model catalog

ST11: Soft lepton cut flow

PRELIMINARY

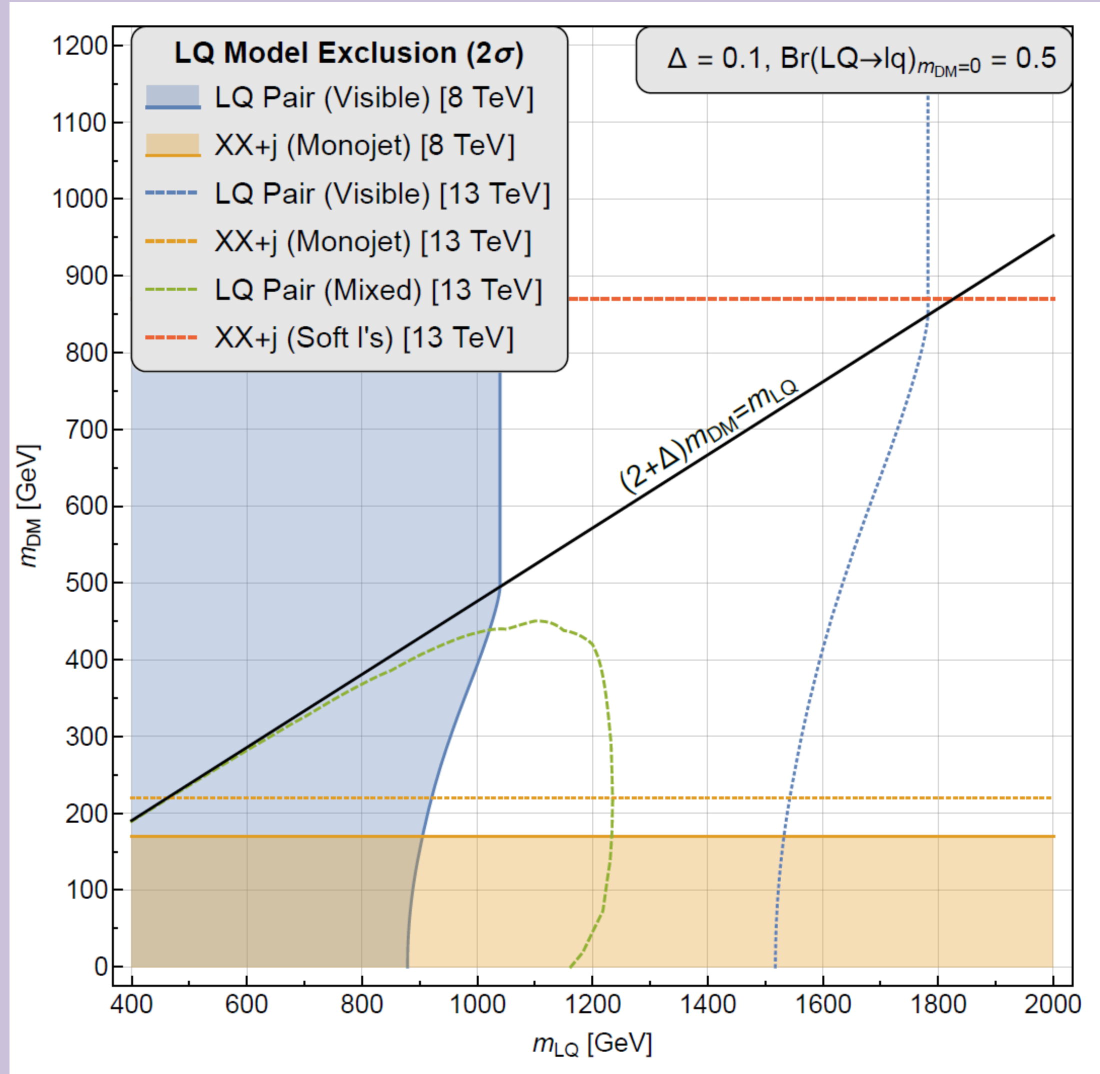
- Use monojet analysis as baseline
- Allow additional soft leptons, $p_T > 25$ GeV
- Signal has M_s = 1.7 TeV, DM = 600 GeV, X = 660 GeV

N_{ev} for 13 TeV, 100 fb^{-1}

	$t\bar{t}$	$Z_{ll}+j$	Diboson	$W_{l\nu}+j$	$t+j$	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
$N_l \geq 2$	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

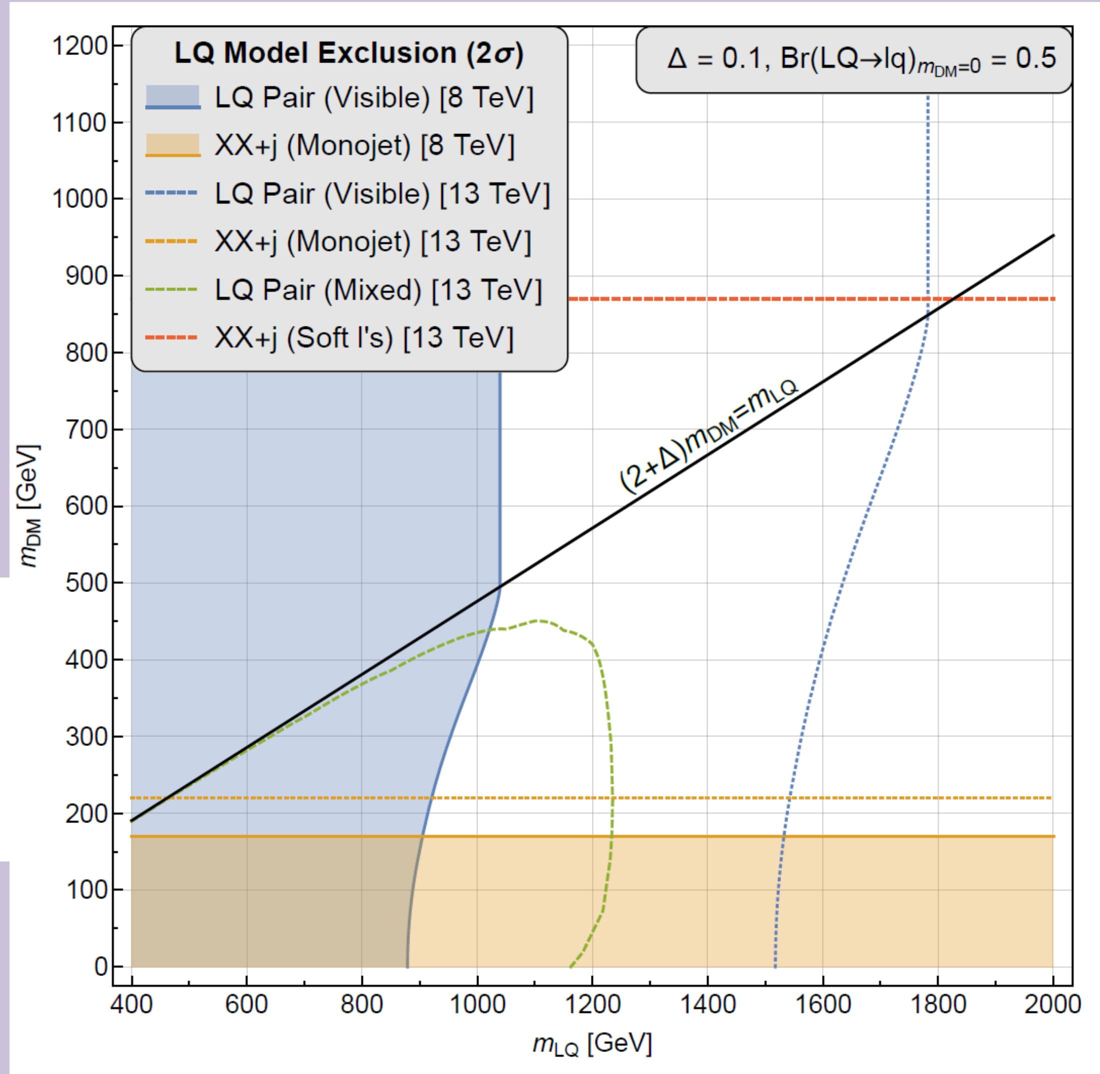
ST11: Mixed + soft lepton projections

- Different coverage from mixed decay vs. paired LQ
- Great reach for soft l analysis



ST11: Mixed + soft lepton projections

- Different coverage from mixed decay vs. paired LQ
- Great reach for soft l analysis



DM reach for lepton p_T thresholds and Δ

	$p_T > 10$ GeV	$p_T > 15$ GeV	$p_T > 25$ GeV
$\Delta = 5\%$	1030 (860)	930 (790)	700 (500)
$\Delta = 10\%$	1030 (860)	1000 (830)	870 (730)
$\Delta = 20\%$	1030 (860)	1020 (870)	1000 (850)

Future outlook

- Comprehensive framework for testing how DM annihilates to SM
  - Huge array of LHC signatures
  - Kinematics of coannihilation motivate new variants of mono-Y searches
  - Multiple decay channels guaranteed by coannihilation topology
    - Provides critical post-discovery cross-channels for measuring dark sector couplings
- If assumptions about tree-level, two-to-two scattering, thermal relic DM are correct, Nature is realized as one of our simplified models

Conclusions

- We have established a simplified model codex for testing DM annihilation mechanism
  - Grounded in general assumptions
- Framework directly leads guaranteed production and decay modes for X and M
  - Recycling the coannihilation diagram and classification under SM gauge quantum numbers
  - Many searches avoid strong model dependence on marginal couplings – especially attractive for experiment

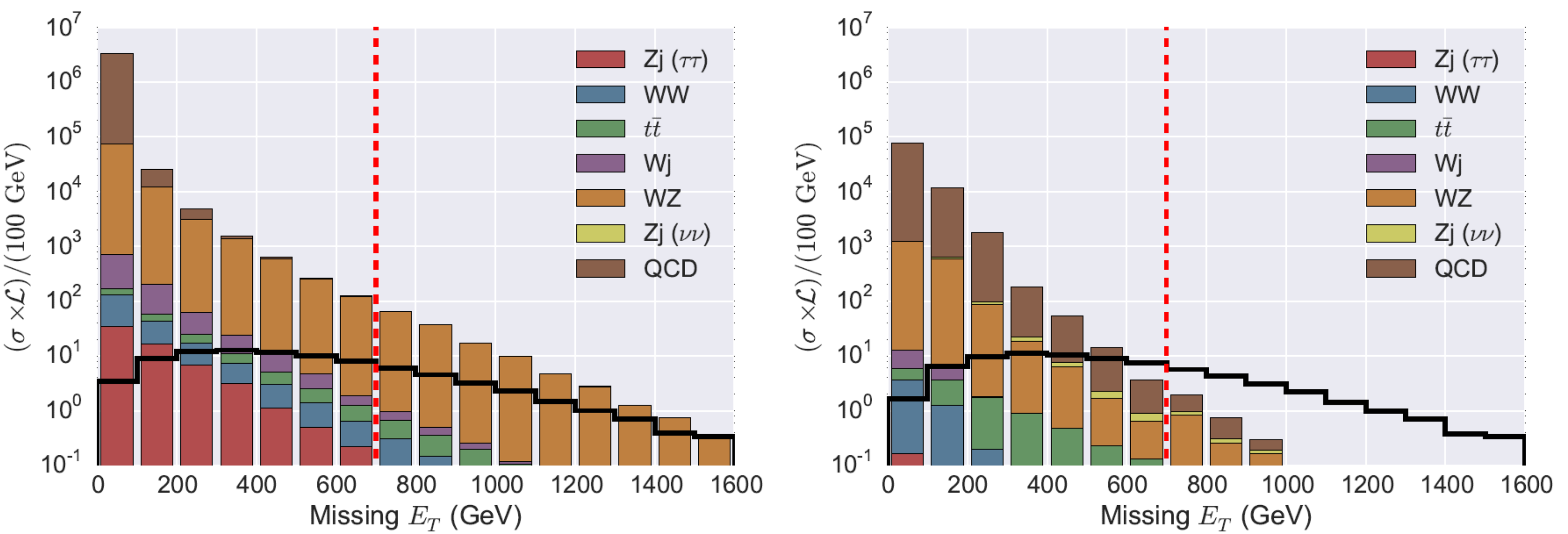
ST11: Mixed decay analysis (μj)

- Cut flow table

	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}	502
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}	360
$N_{\mathrm{hard\ jets}}\leq 3$	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}	306
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}	297
$\not{E}_T > 700$ GeV	133	1738	15	19	9	10	27	2	62
$m_T > 150$ GeV	132	16	10^{-3}	18	0.005	0.01	10	0.001	58
mass window	3	0.2	0	0.3	10^{-5}	10^{-5}	0.1	10^{-5}	13

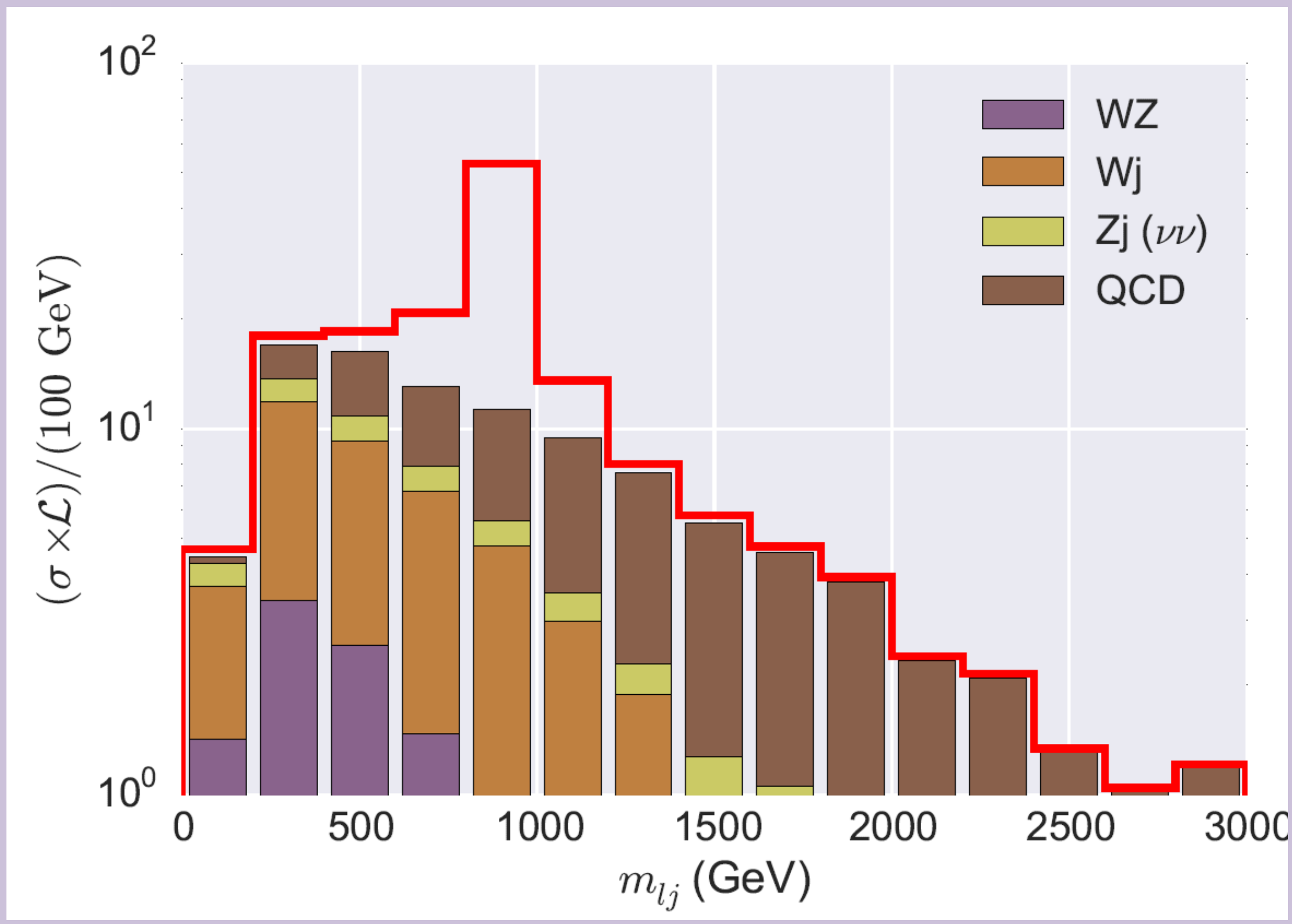
PRELIMINARY

ST11: Mixed decay analysis (μj)



PRELIMINARY

ST11: Mixed decay analysis (μj)



PRELIMINARY