THE COANNIHILATION CODEX

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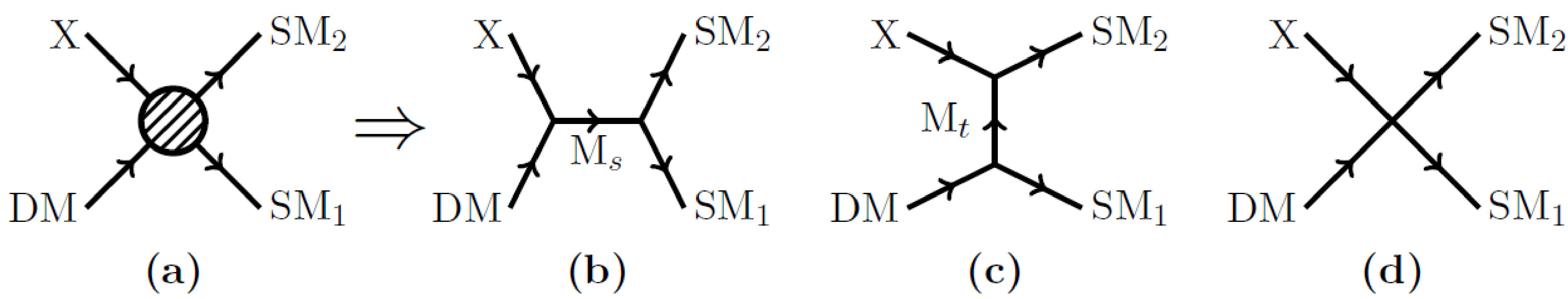
Introduction

- Dark matter is a fundamental puzzle
- Many traditional particle probes, but no discovery
    - Null results offer little guidance about where to look next
- 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]

Physics of the Coannihilation Codex

- Goal: Characterize all possible two-to-two DM (co)annihilation processes as simplified models
  - Simplified models not based on "UV-completing" effective operators or MET + Y signatures
  - Instead, simplified models are driven by known DM properties (relic density + colorless, EM neutral particle)
- Result: A bottom-up framework for discovering dark matter at the LHC
  - LHC as a test how DM obtains its relic density
    - Nature's choice for DM guaranteed to be realized in our framework given our assumptions

Building the Codex



Arrows denote gauge representation convention

- 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
  - X = DM reproduces pair annihilation simplified models

The Coannihilation Codex

- Simplified models defined by new model content and interaction vertices that realize the two-to-two DM (co)annihilation diagram
  - (Up to) three new fields DM, X, and M, two new couplings

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 big picture

- DM, as a thermal relic, annihilates to SM via two-to-two diagram
- (Co)annihilation diagram involves up to three new fields and two new couplings
  - By construction, marginal new physics couplings are introduced in a controlled manner
    - Enables tighter connection between relic density constraint and experimental searches
  - Coannihilation condition further reduces model complexity relevant for LHC phenomenology
    - Reduce to mediator mass scale and DM mass scale

Power of the codex: inescapable conclusions

- Production modes
  - Pair production processes for X, DM, M **guaranteed**
    - Depend only on masses and representations charges
  - Single production rates more model-dependent
    - Scale with NP coupling
    - Single production of M_s
    - Associated production of M_s+SM, M_t+DM, and M_t+X
- Decay modes **guaranteed**
  - Simply recycle coannihilation vertices, assume prompt
  - X has three-body decay to $(SM_1+SM_2)_{soft}$+DM via M
  - M_s decays to X+DM or $(SM_1+SM_2)_{resonant}$
  - M_t decays to DM+SM_1 or X+SM_2

Power of the codex: inescapable conclusions

- Production modes
  - Pair production processes for X, DM, M **guaranteed**
    - Depend only on masses and representations charges
  - Single production rates more model-dependent

By construction, have inescapable collider signatures – complete bottom-up control of marginal parameters

- Decay modes **guaranteed**
  - Simply recycle coannihilation vertices, assume prompt
  - X has three-body decay to $(SM_1+SM_2)_{soft}$+DM via M
  - M_s decays to X+DM or $(SM_1+SM_2)_{resonant}$
  - M_t decays to DM+SM_1 or X+SM_2

Three classes of collider signatures

- Signature class I: Stitching together production and decay gives ***common mono-Y*** signatures
  - For small Δ, the SM decay products from X can be too soft to reconstruct
    - 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

Three classes of collider signatures

- Signature class I: Stitching together production and decay gives ***common mono-Y*** signatures
- Signature class II: M_s pair production gives ***paired resonances, resonance + MET, mono-Y*** signatures
  - Single production and associated production also possible
    - Rate scales with NP coupling, more model dependent
    - Many striking signatures (e.g. LQ + lepton)

Three classes of collider signatures

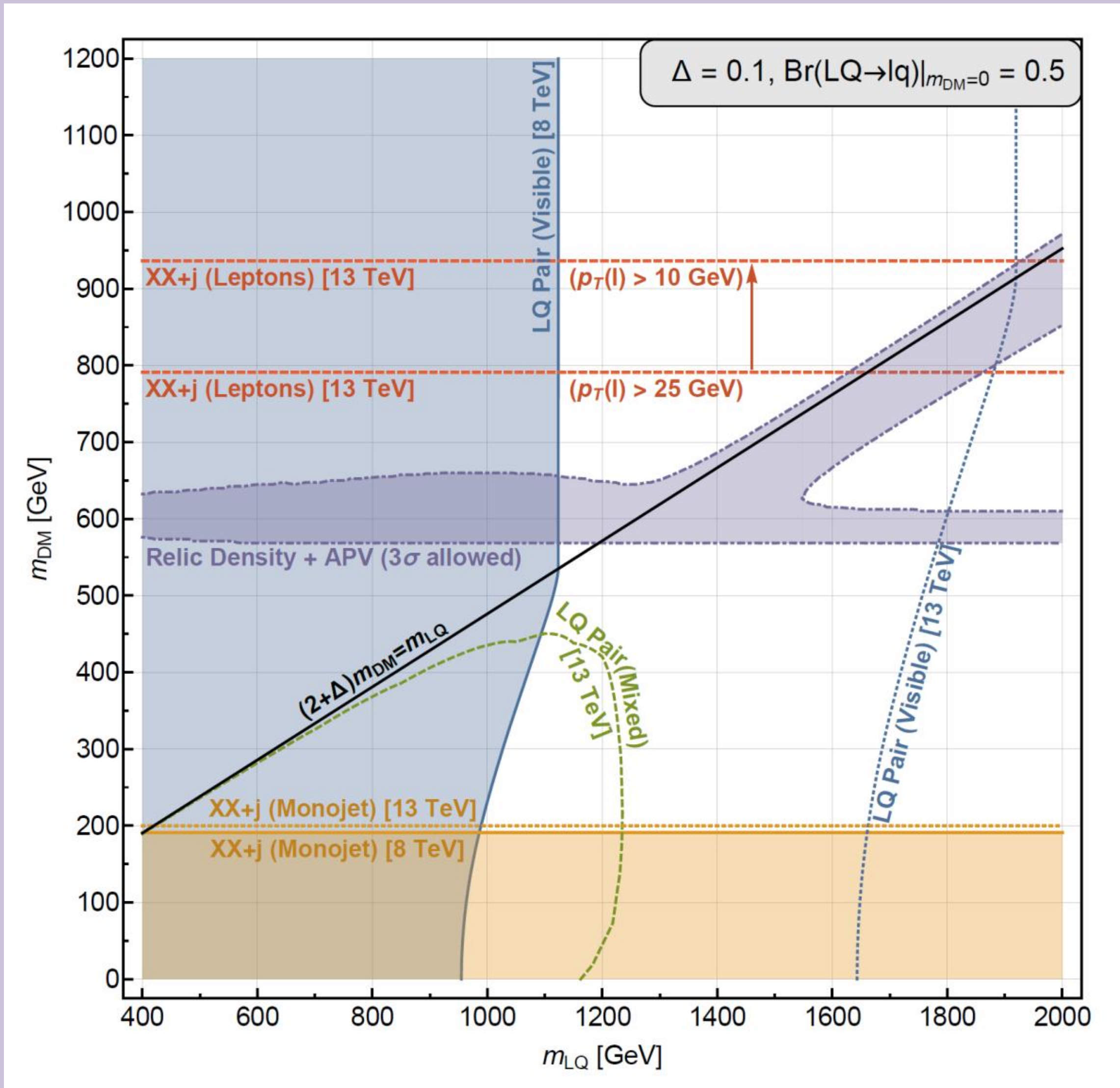
- Signature class I: Stitching together production and decay gives ***common mono-Y*** signatures
- Signature class II: M_s pair production gives ***paired resonances, resonance + MET, mono-Y*** signatures
- Signature class III: M_t pair production gives ***hierarchical cascade decays***
  - SM legs from cascade chain are typically hard, complicated by possible soft decays from X
    - Many kinematic handles and edges

Differences from previous simplified models

- Turn relic density constraint into feature
  - LHC tests the annihilation mechanism of DM, unifies treatment of searches for all related mediator and DM signatures
- New physics couplings subsumed into branching fraction of mediator
  - Still have to fix NP coupling for single production modes
- Much stronger constructions of LHC simplified models of dark matter

One example: the new mass-mass plane

- Leptoquark mediator, dark leptoquark X, gauge singlet DM
- Bounds: paired (lj)(lj) resonances, (lj) resonance + MET, mono-jet, mono-jet + leptons, flavor bounds
- Relic density favored region (not a line)



Conclusions

- We have established a simplified model codex for testing the DM annihilation mechanism at LHC
  - Grounded in general assumptions
- Framework directly leads guaranteed production and decay modes for X and M
  - Classification under SM gauge quantum numbers dictates production rates
  - Recycling the coannihilation diagram dictates decay topologies
  - Many searches avoid strong model dependence on marginal couplings – especially attractive for LHC
- Relic density is a feature, not afterthought

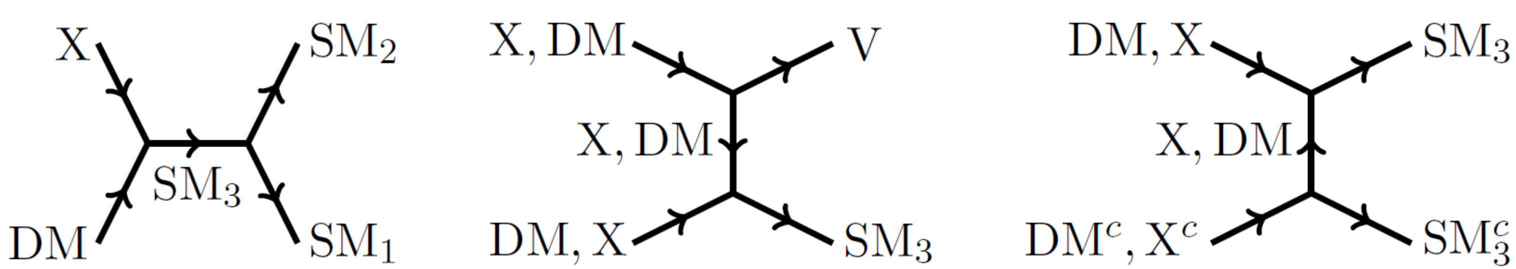
The Framework: Assumptions

- The 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
  6. All gauge bosons obey renormalizability and gauge invariance

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 (uncolored *s*-channel mediator)

ID	X	$\alpha+\beta$	M_s	Spin	$(\mathrm{SM}_1\ \mathrm{SM}_2)$	X–DM–SM_3	M_s–X–X
SU1	$(1, N, \alpha)$	0	$(1,1,0)$	B	$(u_R\,\overline{u_R}), (d_R\,\overline{d_R}), (\ell_R\,\overline{\ell_R})$ $(Q_L\,\overline{Q_L}), (L_L\,\overline{L_L}), (H\,H^\dagger)$	H1	✓
SU2				F	$(L_L\,H)$		
SU3			$(1,3,0)^{N\geq 2}$	B	$(Q_L\,\overline{Q_L}), (L_L\,\overline{L_L}), (H\,H^\dagger)$	H1	✓
SU4				F	$(L_L\,H)$		
SU5		-2	$(1,1,-2)$	B	$(d_R\,\overline{u_R}), (H^\dagger\,H^\dagger), (L_L\,L_L)$		✓
SU6				F	$(L_L\,H^\dagger)$	H2	
SU7			$(1,3,-2)^{N\geq 2}$	B	$(H^\dagger\,H^\dagger), (L_L\,L_L)$		✓$(\alpha=\pm 1)$
SU8				F	$(L_L\,H^\dagger)$	H2	
SU9		-4	$(1,1,-4)$	B	$(\ell_R\,\ell_R)$		✓$(\alpha=\pm 2)$
SU10	$(1, N\pm 1, \alpha)$	-1	$(1,2,-1)$	B	$(d_R\,\overline{Q_L}), (\overline{u_R}\,Q_L), (\overline{L_L}\,\ell_R)$	H3	
SU11				F	$(\ell_R\,H)$	H4	
SU12		-3	$(1,2,-3)$	B	$(L_L\,\ell_R)$		
SU13				F	$(\ell_R\,H^\dagger)$		
SU14	$(1, N\pm 2, \alpha)$	0	$(1,3,0)$	B	$(Q_L\,\overline{Q_L}), (L_L\,\overline{L_L}), (H\,H^\dagger)$		✓$(\alpha=0)$
SU15				F	$(L_L\,H)$		
SU16		-2	$(1,3,-2)$	B	$(H^\dagger\,H^\dagger), (L_L\,L_L)$		✓$(\alpha=\pm 1)$
SU17				F	$(L_L\,H^\dagger)$		

The Coannihilation Codex: *s*-channel

– "ST" models (color triplet *s*-channel mediator)

ID	X	$\alpha+\beta$	M_s	Spin	$(\mathrm{SM}_1\ \mathrm{SM}_2)$	X–DM–SM_3	M_s–X–X
ST1	$(3, N, \alpha)$	$\frac{10}{3}$	$(3, 1, \frac{10}{3})$	B	$(u_R\ \overline{l_R})$		$\checkmark(\alpha=-\frac{5}{3})$
ST2		$\frac{4}{3}$	$(3, 1, \frac{4}{3})$	B	$(d_R\ \overline{\ell_R}), (Q_L\ \overline{L_L}), (\overline{d_R}\ \overline{d_R})$		$\checkmark(\alpha=-\frac{2}{3})$
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	$(\overline{Q_L}\ \overline{Q_L}), (\overline{u_R}\ \overline{d_R}), (u_R\ \ell_R), (Q_L\ L_L)$		$\checkmark(\alpha=\frac{1}{3})$
ST7				F	$(Q_L\ H^\dagger)$	H6	
ST8			$(3, 3, -\frac{2}{3})^{N\geq 2}$	B	$(\overline{Q_L}\ \overline{Q_L}), (Q_L\ L_L)$		$\checkmark(\alpha=\frac{1}{3})$
ST9				F	$(Q_L\ H^\dagger)$	H6	
ST10		$-\frac{8}{3}$	$(3, 1, -\frac{8}{3})$	B	$(\overline{u_R}\ \overline{u_R}), (d_R\ \ell_R)$		$\checkmark(\alpha=\frac{4}{3})$
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	$(d_R\ \overline{L_L}), (\overline{Q_L}\ \overline{d_R}), (u_R\ L_L)$		
ST14				F	$(u_R\ H^\dagger), (d_R\ H)$	H7	
ST15		$-\frac{5}{3}$	$(3, 2, -\frac{5}{3})$	B	$(\overline{Q_L}\ \overline{u_R}), (Q_L\ \ell_R), (d_R\ L_L)$		
ST16				F	$(d_R\ H^\dagger)$		
ST17	$(3, N\pm 2, \alpha)$	$\frac{4}{3}$	$(3, 3, \frac{4}{3})$	B	$(Q_L\ \overline{L_L})$		$\checkmark(\alpha=-\frac{2}{3})$
ST18				F	$(Q_L\ H)$		
ST19		$-\frac{2}{3}$	$(3, 3, -\frac{2}{3})$	B	$(\overline{Q_L}\ \overline{Q_L}), (Q_L\ L_L)$		$\checkmark(\alpha=\frac{1}{3})$
ST20				F	$(Q_L\ H^\dagger)$		

The Coannihilation Codex: *s*-channel

- “SO” and “SE” models (color octet and color sextet *s*-channel mediator)

ID	X	$\alpha+\beta$	M_s	Spin	$(\mathrm{SM}_1\ \mathrm{SM}_2)$	X–DM–SM_3	M_s–X–X
SO1	$(8, N, \alpha)$	0	$(8, 1, 0)$	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	$(Q_L\,Q_L)$		$\checkmark(\alpha=-\frac{1}{3})$

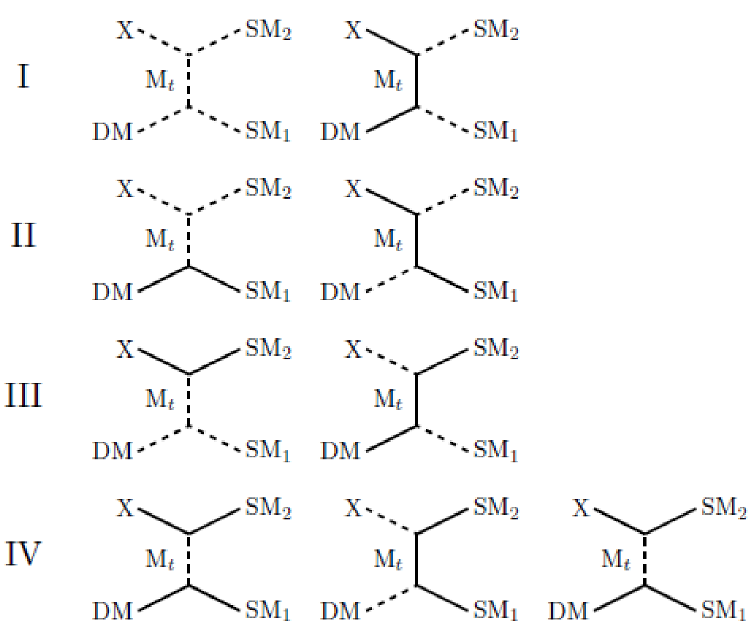
The Coannihilation Codex: *t*-channel

- 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 (uncolored t-channel mediator)

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	$(L_L H)$	
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	$(L_L H^\dagger)$	H2
TU11			$(1, N\pm1, \beta+1)$	III	$(H^\dagger L_L)$	H2
TU12			$(1, N\pm1, \beta+1)$	IV	$(L_L L_L)$	
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	$(\ell_R H)$	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	$(\ell_R L_L)$	
TU26	$(1, N\pm2, \alpha)$	0	$(1, N\pm1, \beta-1)$	I	$(HH^\dagger)$	
TU27			$(1, N\pm1, \beta+1)$	II	$(L_L H)$	
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	$(L_L H^\dagger)$	
TU33			$(1, N\pm1, \beta+1)$	III	$(H^\dagger L_L)$	

t-channel

- "TT" models

1-21 (color triplet

t-channel mediator)

ID	X	$\alpha+\beta$	M_t	Spin	$(\mathrm{SM}_1\ \mathrm{SM}_2)$	X-DM-SM_3
TT1		$\frac{10}{3}$	$(\bar{3}, N, \beta-\frac{4}{3})$	IV	$(u_R\overline{\ell_R})$	
TT2			$(1, N, \beta-2)$	IV	$(\overline{\ell_R}u_R)$	
TT3			$(\bar{3}, N\pm 1, \beta-\frac{1}{3})$	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		$\frac{4}{3}$	$(\bar{3}, N\pm 1, \beta-\frac{1}{3})$	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			$(\bar{3}, N\pm 1, \beta-\frac{1}{3})$	II	$(Q_L H^\dagger)$	H5
TT11			$(1, N\pm 1, \beta+1)$	III	$(H^\dagger Q_L)$	H5
TT12	$(3, N, \alpha)$		$(3, N, \beta+\frac{4}{3})$	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		$-\frac{2}{3}$	$(1, N, \beta+2)$	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			$(3, N, \beta+\frac{4}{3})$	IV	$(\overline{u_R u_R})$	
TT20		$-\frac{8}{3}$	$(\bar{3}, N, \beta+\frac{2}{3})$	IV	$(d_R\ell_R)$	
TT21			$(1, N, \beta+2)$	IV	$(\ell_R d_R)$	

t-channel

- "TT" models

22-52 (color triplet

t-channel mediator)

TT22			$(3, N, \beta - \frac{4}{3})$	II	$(u_R H)$	
TT23			$(1, N \pm 1, \beta - 1)$	III	$(H u_R)$	
TT24		$\frac{7}{3}$	$(\bar{3}, N, \beta - \frac{4}{3})$	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			$(\bar{3}, N, \beta - \frac{4}{3})$	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		$\frac{1}{3}$	$(1, N \pm 1, \beta - 1)$	III	$(H d_R)$	H6
TT32	$(3, N \pm 1, \alpha)$		$(\bar{3}, N, \beta - \frac{4}{3})$	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	$(\overline{d_R Q_L})$	
TT35			$(3, N \pm 1, \beta + \frac{1}{3})$	IV	$(\overline{Q_L d_R})$	
TT36			$(\bar{3}, N, \beta + \frac{2}{3})$	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		$-\frac{5}{3}$	$(3, N \pm 1, \beta - \frac{1}{3})$	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			$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	II	$(Q_L H)$	
TT45		$\frac{4}{3}$	$(1, N \pm 1, \beta - 1)$	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	$(3, N \pm 2, \alpha)$		$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	II	$(Q_L H^\dagger)$	
TT49		$-\frac{2}{3}$	$(1, N \pm 1, \beta + 1)$	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 (color octet and color sextet *t*-channel mediator)

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)	

Moving from EW symmetric to broken phase

- 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

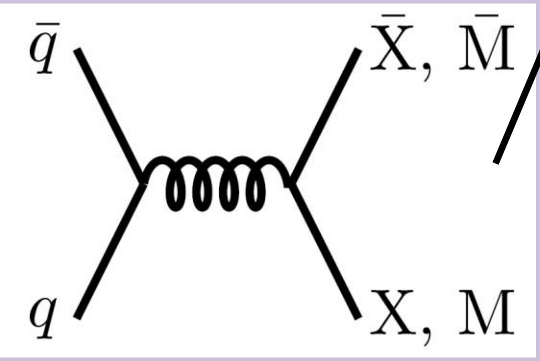
The codex in action

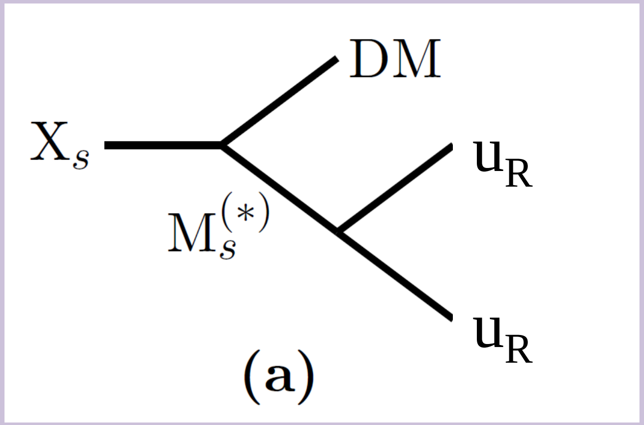
ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	X–DM–SM_3	M_s–X–X
SO1	$(8, N, \alpha)$	0	$(8,1,0)$	B	$(d_R\,\overline{d_R}), (u_R\,\overline{u_R}), (Q_L\,\overline{Q_L})$		$\checkmark(\alpha=0)$
SO2			$(8,3,0)^{N\geq 2}$	B	$(Q_L\,\overline{Q_L})$		$\checkmark(\alpha=0)$
SO3		-2	$(8,1,-2)$	B	$(d_R\,\overline{u_R})$		$\checkmark(\alpha=\pm 1)$
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	$(d_R\,d_R)$		$\checkmark(\alpha=\frac{2}{3})$

- Take SE1 as an example
  - Di-quark *s*-channel mediator, di-quark coannihilation partner X, SM_1 and SM_2 are RH up-type quarks

The codex in action

- M M*, X X* production from color charge





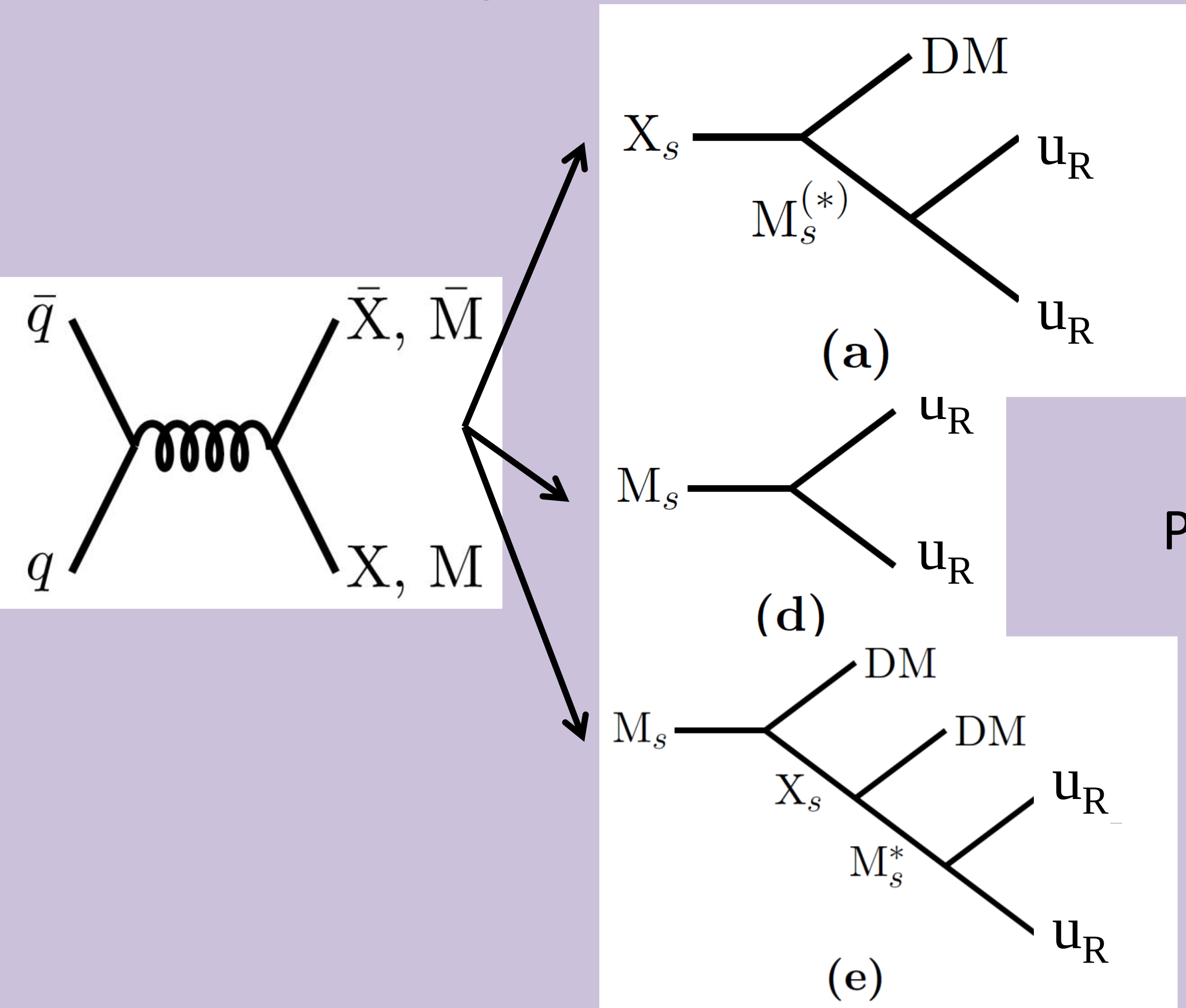
X X*

4 soft jets + MET (difficult)

or 4 medium jets + MET (depends on Δ)

The codex in action

- M M*, X X* production from color charge



X X*

4 soft jets + MET (difficult)
or 4 medium jets + MET (depends on Δ)

M M*

Paired di-jet resonances (same-sign!)
and di-jet resonance (same-sign!) + MET
and 4 soft jets + 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

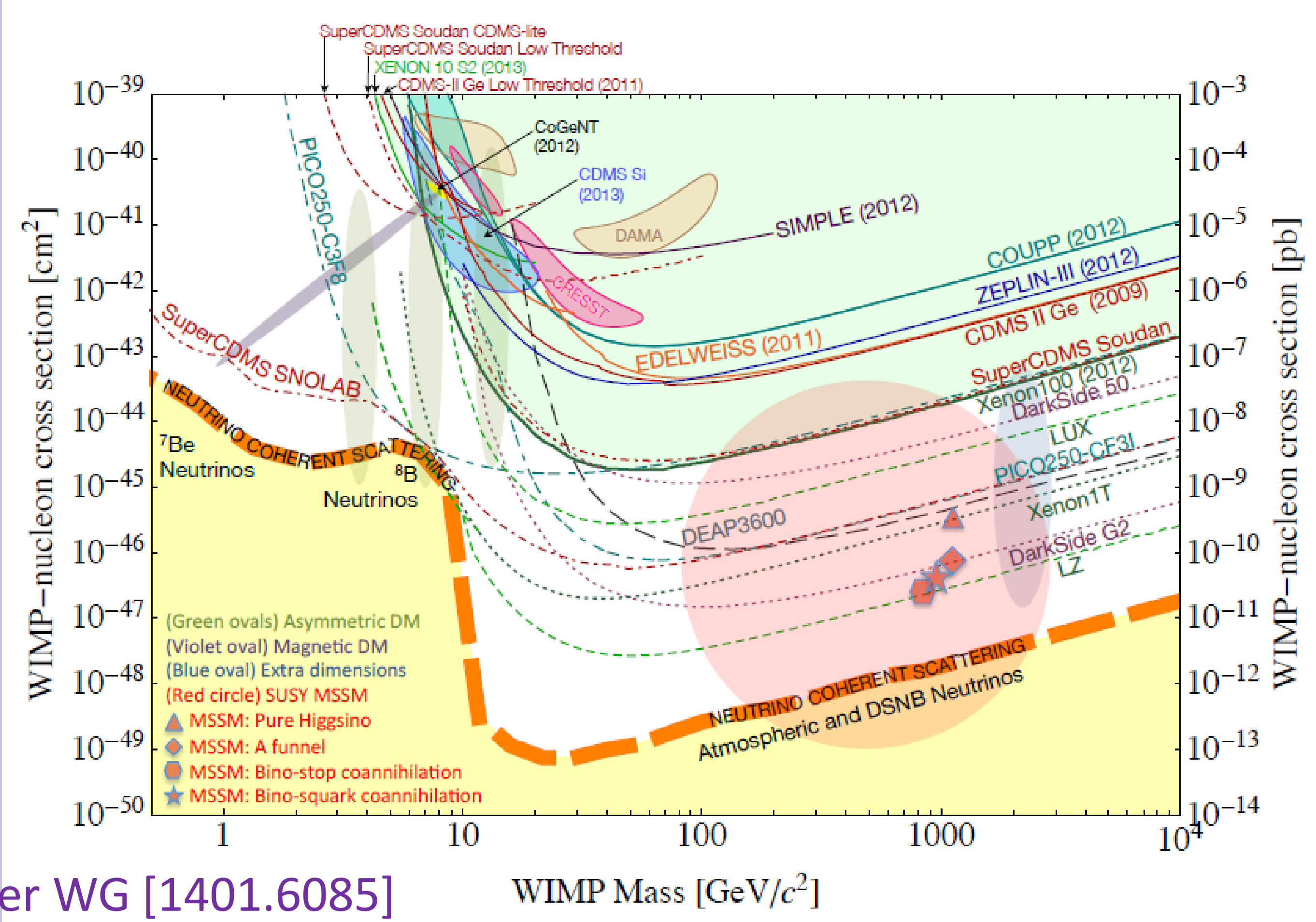
- Mediator M_t also generally pair-produced via strong or EW interactions
- Always have MET in the final state
- SM legs from cascade chain are typically hard, complicated by possible soft decays from X
  - Many kinematic handles and edges

Direct and indirect detection

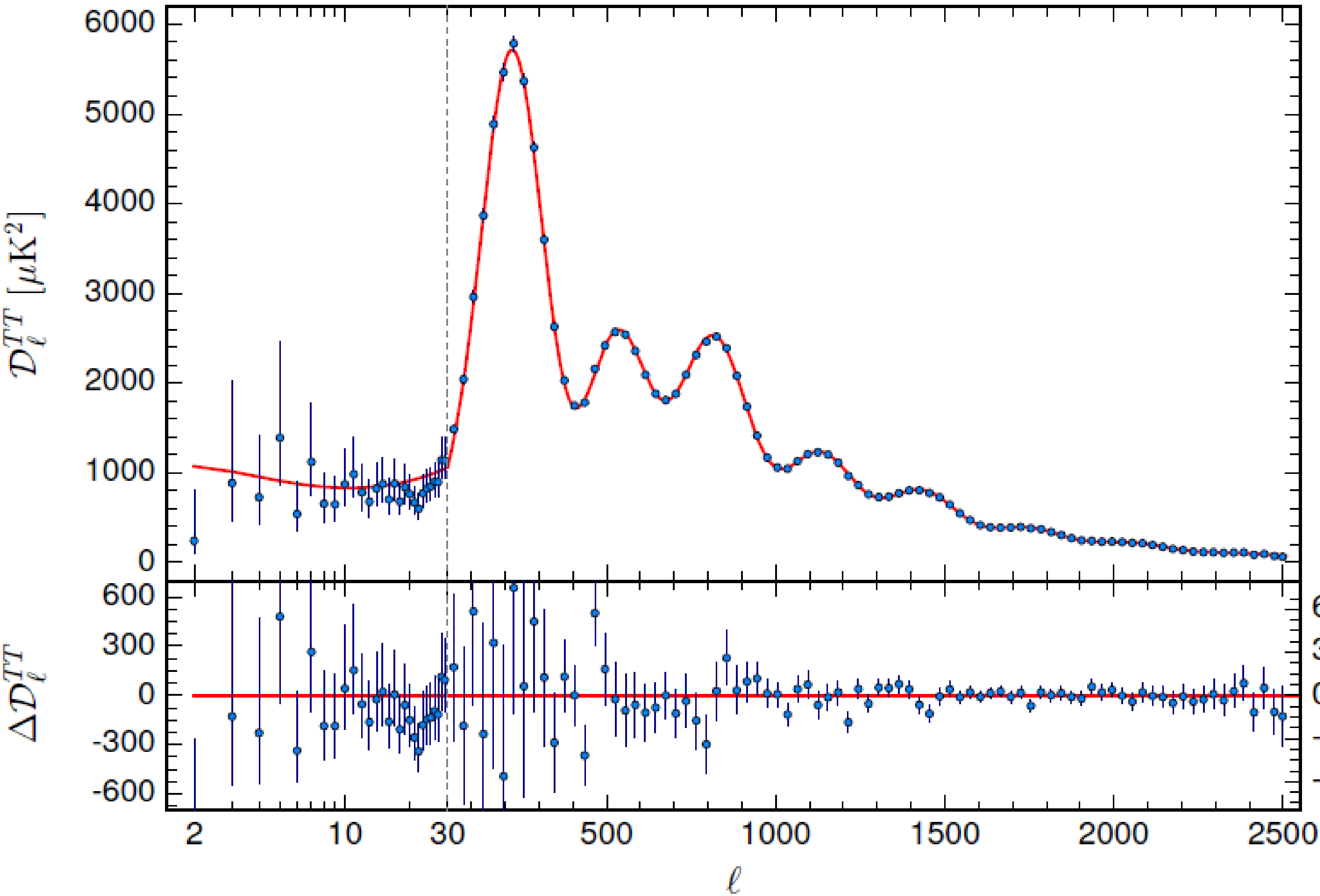
- Direct detection and indirect detection signals are generally model dependent

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]



$\Omega h^2 = 0.1198 \pm 0.0026$

Planck [1502.01589]

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

$$\mathcal{L} = \frac{i}{2}\overline{\mathrm{DM}}\partial\!\!\!/\mathrm{DM} + i\overline{\mathrm{X}}D\!\!\!\!/\mathrm{X} + |D_\mu \mathrm{M}_s|^2 - \frac{m_{\mathrm{DM}}}{2}\overline{\mathrm{DM}}\,\mathrm{DM} - m_{\mathrm{X}}\overline{\mathrm{X}}\,\mathrm{X} - V(\mathrm{M}_s, H)$$

$$- \left(y_D \overline{\mathrm{X}}\,\mathrm{M}_s\,\mathrm{DM} + y_{Q\ell}\overline{Q_L}\mathrm{M}_s\,\ell_R + y_{Lu}\overline{L_L}\mathrm{M}_s^c u_R + \mathrm{h.c.}\right),$$

$$V(\mathrm{M}_s, H) = V(H) + m_{\mathrm{M}_s}^2 \mathrm{M}_s^\dagger \mathrm{M} + \frac{1}{4}\lambda_{\mathrm{M}_s}\left(\mathrm{M}_s^\dagger \mathrm{M}_s\right)^2 + \epsilon_{\mathrm{M}_s}\mathrm{M}_s^\dagger \mathrm{M}_s\left(H^\dagger H - \frac{v^2}{2}\right)$$

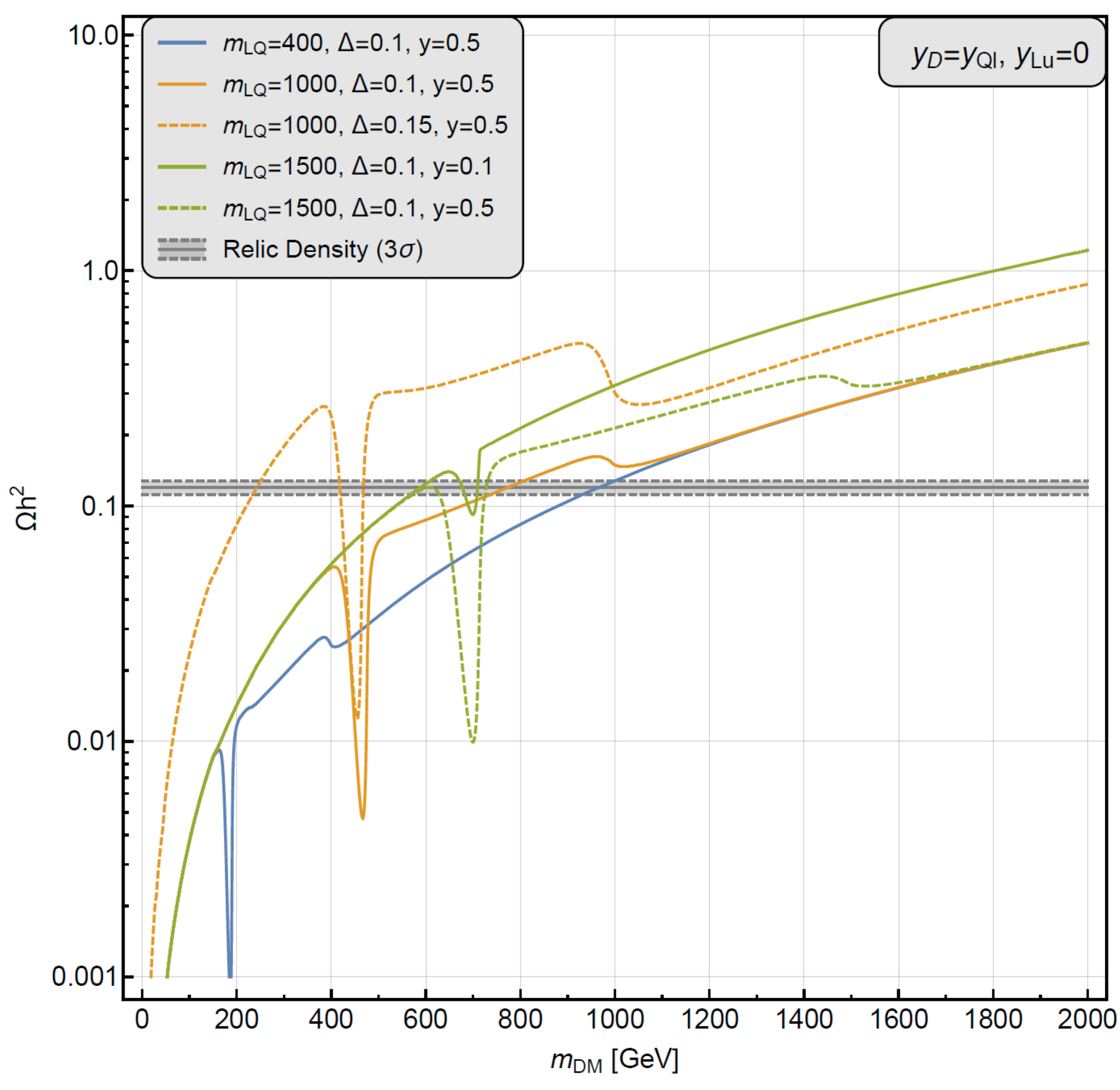
Ωh^2

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

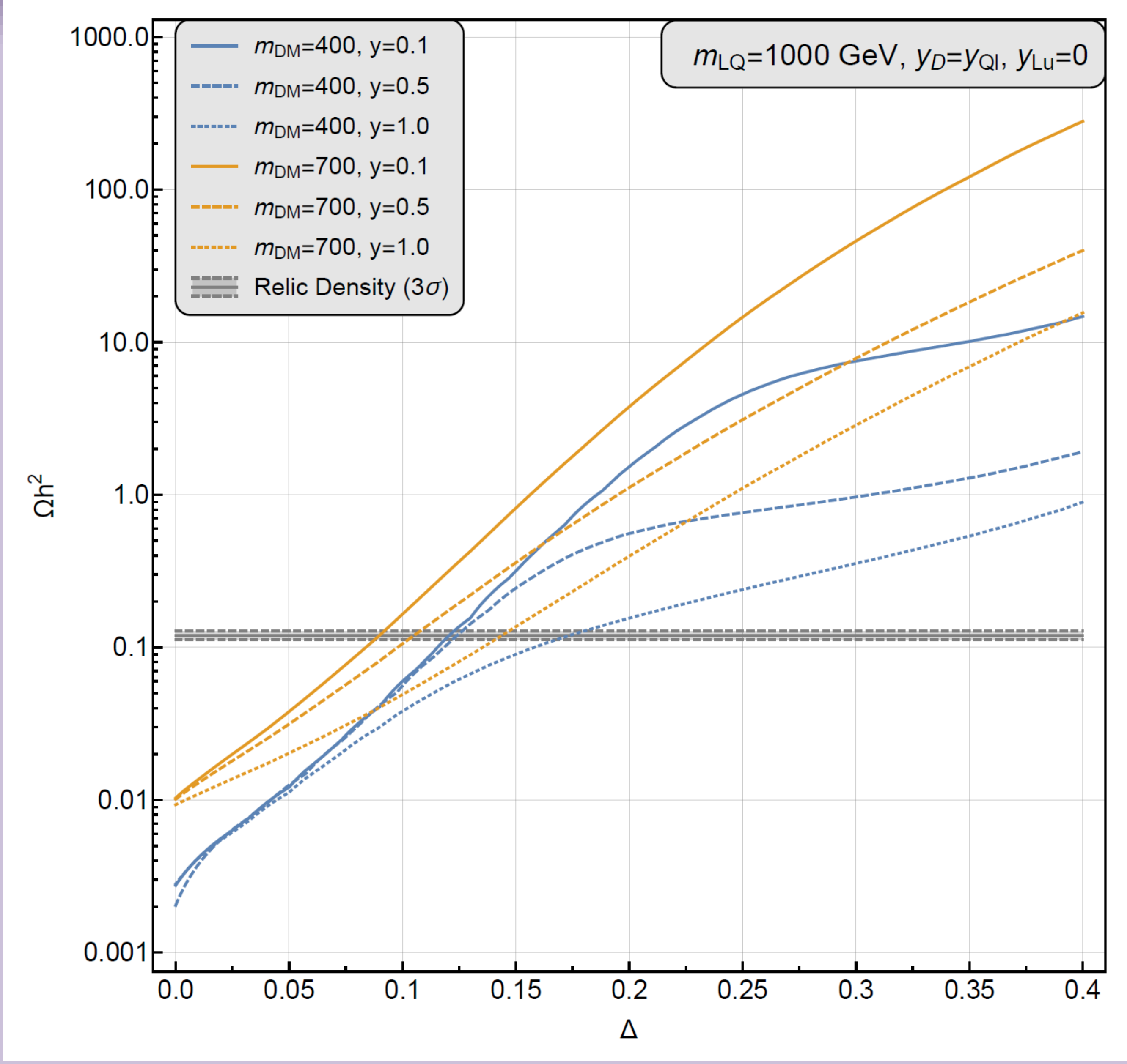


Ωh^2

Next study relic density vs. Δ

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

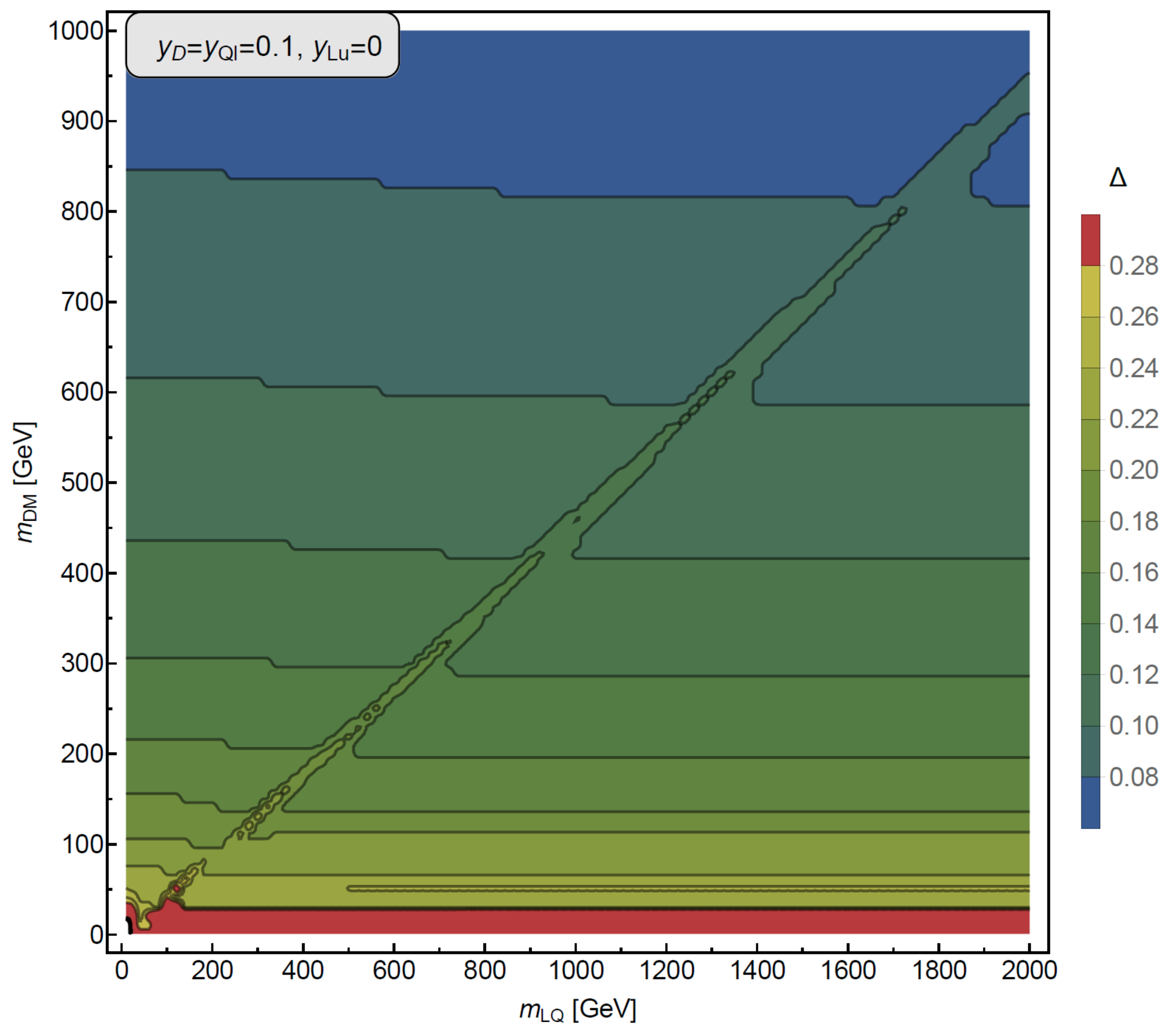
Show dependence on DM mass, y



ST11: Ωh^2

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

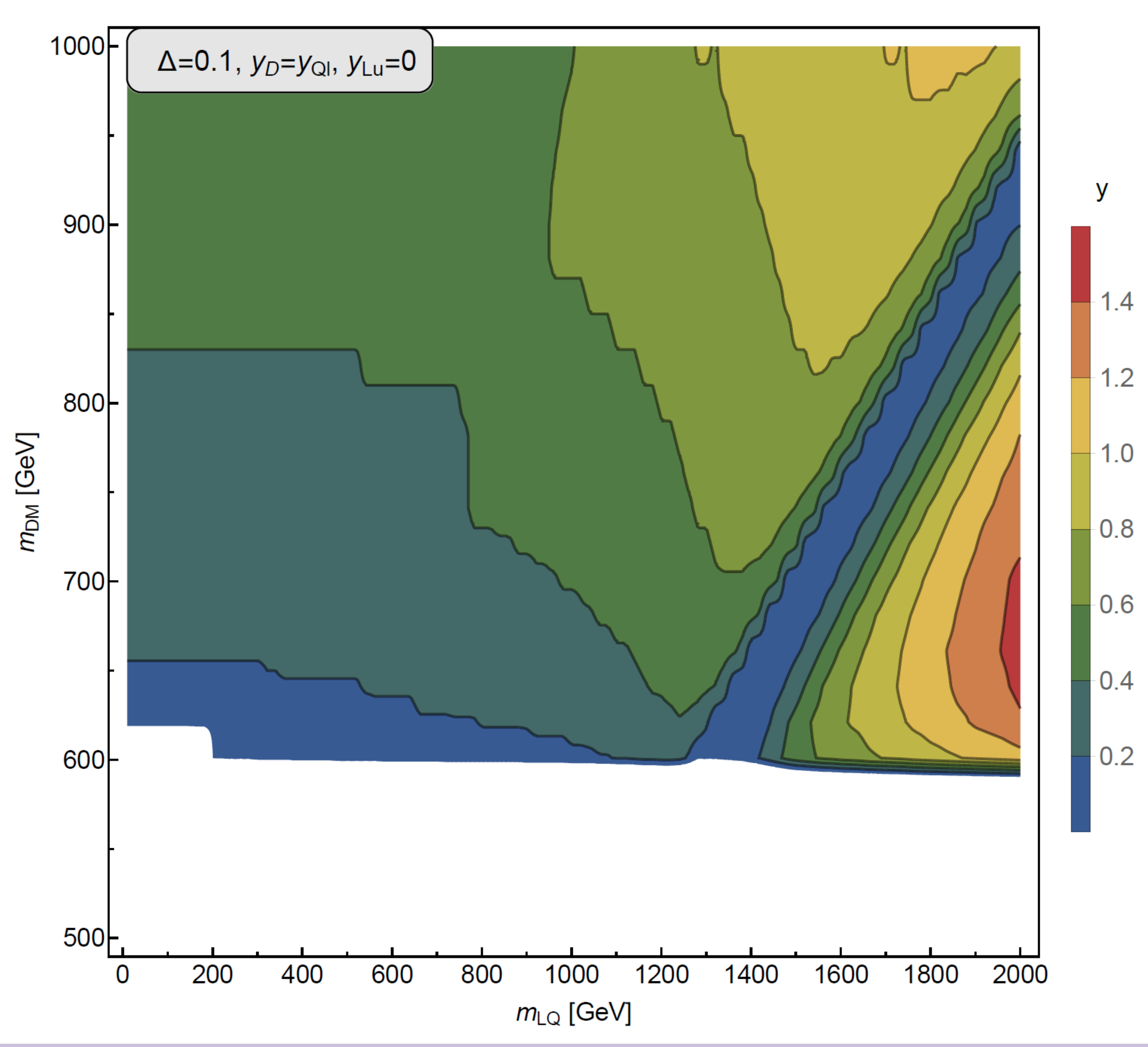
Δ controls visibility of X decay products



ST11: Ωh^2

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

y_D and y_{Ql} control relative branching fractions of M_s



ST11: LHC signatures

- Mono-Y
  - XX + ISR j: Gives 2 (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
  - $\beta \equiv \mathrm{Br}(M_s \rightarrow ej)$
  - Benchmark has $\beta_0 = 50\%$, maximizes mixed decay rate
- Relic density constrains y_D, complementary parameter space

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

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

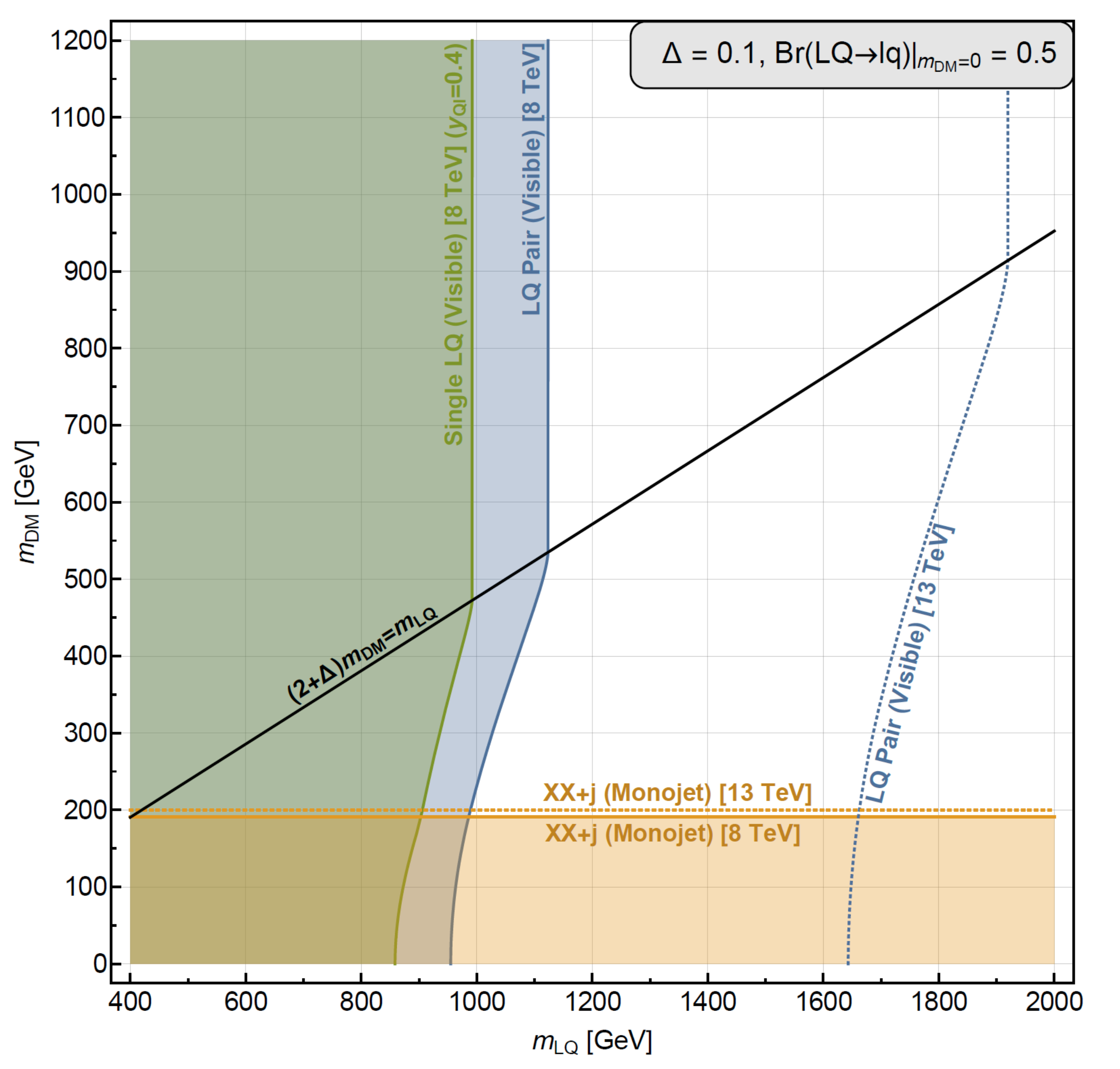
$$\Gamma\left(\mathrm{LQ} \to \mathrm{DM}\ \mathrm{X}\right) = \frac{y_D^2}{8\pi} m_{\mathrm{LQ}}\left(1-\Delta^2\tau\right)^{1/2}\left[1-(2+\Delta)^2\tau\right]^{3/2} \equiv \frac{y_D^2}{8\pi} m_{\mathrm{LQ}} K(\Delta,\tau)\,,$$

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

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)

ST11: mono-Y + lepton analysis

- New analysis targets the decays of X
- Important interplay between pure monojet and monojet + 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
  - In coannihilation, mono-Y + XX production introduces new multiplicities for associated particles

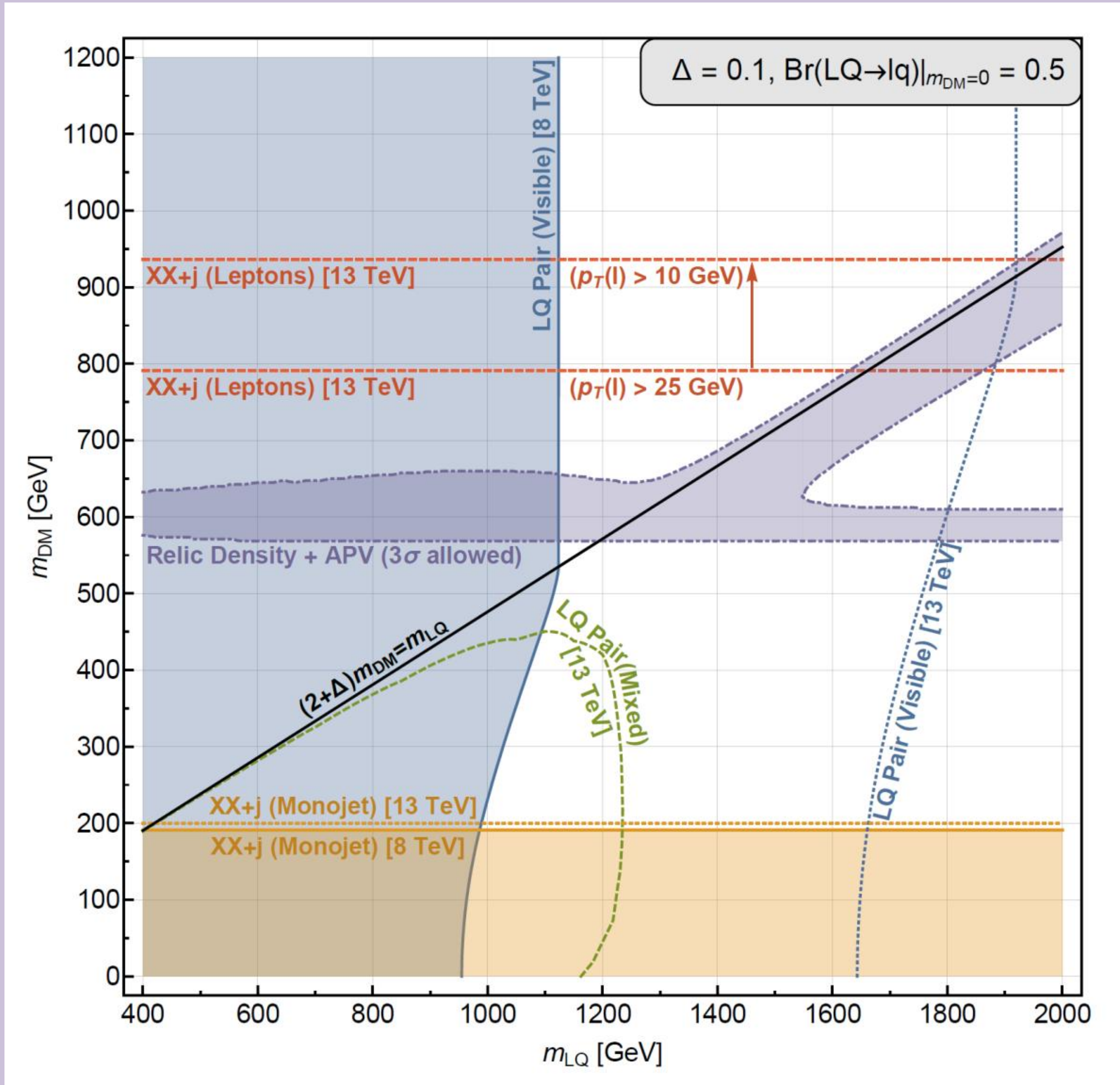
ST11: mono-jet + lepton cut flow

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

	$t\bar{t}$	$Z_{\ell\ell}+j$	Diboson	$W_{\ell\nu}+j$	$t+j$	Signal
$\not{E}_T > 50$ GeV	1.9×10^7	7.9×10^6	1.1×10^6	1.9×10^8	5.6×10^5	8.5×10^4
$p_T^{\text{lead}} > 50$ 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: Mono-jet + lepton projections

- Great improvement in reach compared to pure mono-jet analysis

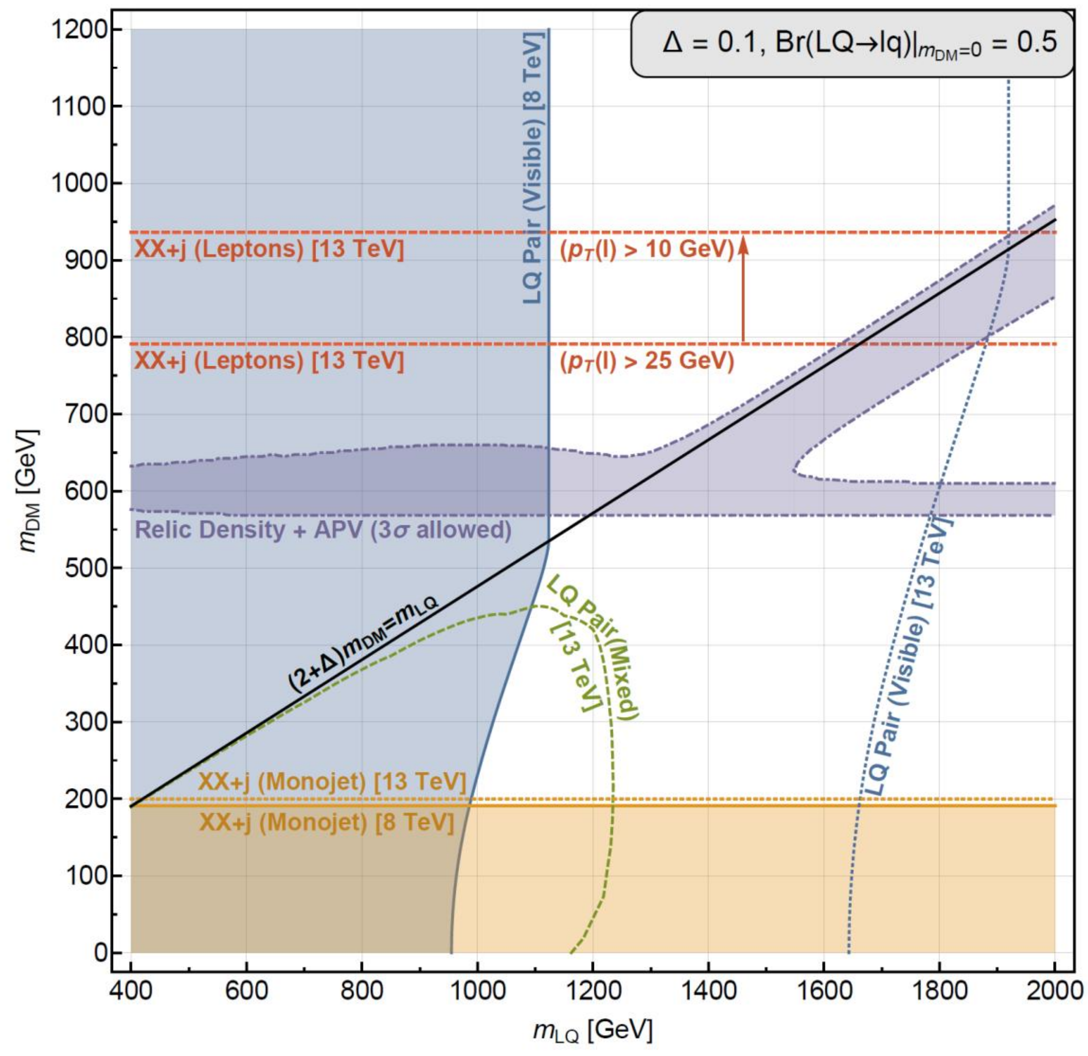


ST11: Mono-jet + lepton projections

- Great improvement in reach compared to pure mono-jet analysis
- Limits depend on p_T

DM reach for lepton p_T thresholds and Δ

	$p_T > 10$ GeV	$p_T > 15$ GeV	$p_T > 25$ GeV
$\Delta = 0.05$	1030 (860)	930 (790)	700 (500)
$\Delta = 0.1$	1030 (860)	1000 (830)	870 (730)
$\Delta = 0.2$	1030 (860)	1020 (870)	1000 (850)



ST11: Targeting 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

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	Cross section (pb)	NLO K-factor ($\times$ "extra" factor)
QCD, 2-3 jets	2.1×10^7	1.3 [203, 204]
Leptonic $W^\pm + 1$, 2 jets	2222	1.15 ($\times$2)
$Z(\to \nu\nu) + 1, 2j$	736	1.15
$t\bar{t}$ (all modes)	465	1.67
$Z(\to \ell^+\ell^-) + 1, 2j$	370	1.15
$Z(\to \tau^+\tau^-) + 1j$	163	1.15
Semileptonic $t\bar{t}$	124	1.67
$W^+W^-, W^\pm Z, ZZ$	37	1.7
$t + 1, 2j$	16.9	1.07
Semileptonic W^+W^-	9.8	1.5
$W^\pm(\to \ell^\pm\nu) + Z(\to jj) + 0, 1j$	2.2	1.7
$W^\pm(\to \ell^\pm\nu) + Z(\to \nu\nu) + j$	2.2	1.7

ST11: Mixed decay cut flow

ATLAS-CONF-2014-032

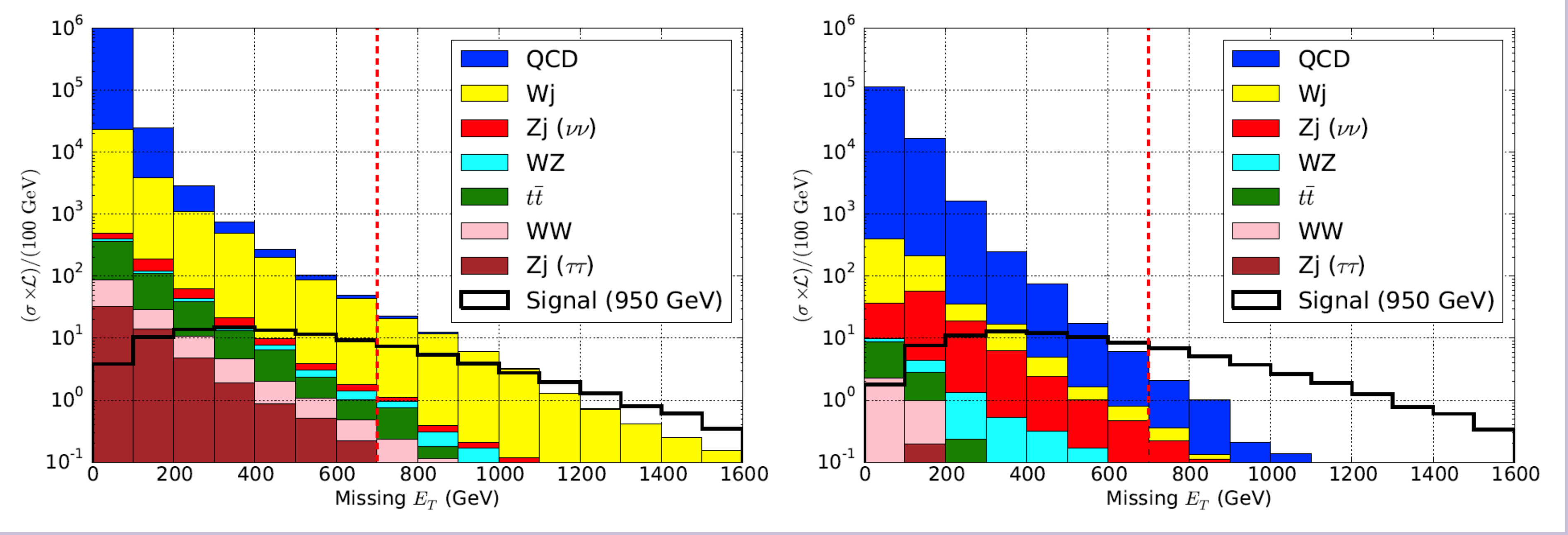
- Jet faking electron rate = 0.0023
- Signal benchmark is M_s = 950 GeV, DM = 405 GeV, X = 445 GeV
- Mass window is 40 GeV wide

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

	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
$N_e^{\rm h}=1,\ N_e\leq 2$	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
$N_{\rm hard\ jets}\leq 3$	3.9×10^9	8.2×10^7	4.3×10^6	8.2×10^4	4.6×10^5	2.2×10^5	1.9×10^4	5.4×10^4	335
Z veto	3.9×10^9	8.2×10^7	1.7×10^6	8.2×10^4	4.6×10^5	2.2×10^5	1.9×10^4	5.4×10^4	326
$\not{E}_T > 700$ GeV	133	1738	15	19	9	10	27	2	75
$m_T > 150$ GeV	132	16	10^{-3}	18	0.005	0.01	10	0.001	67
mass window	3	0.2	$< 10^{-5}$	0.3	10^{-5}	10^{-5}	0.1	10^{-5}	24

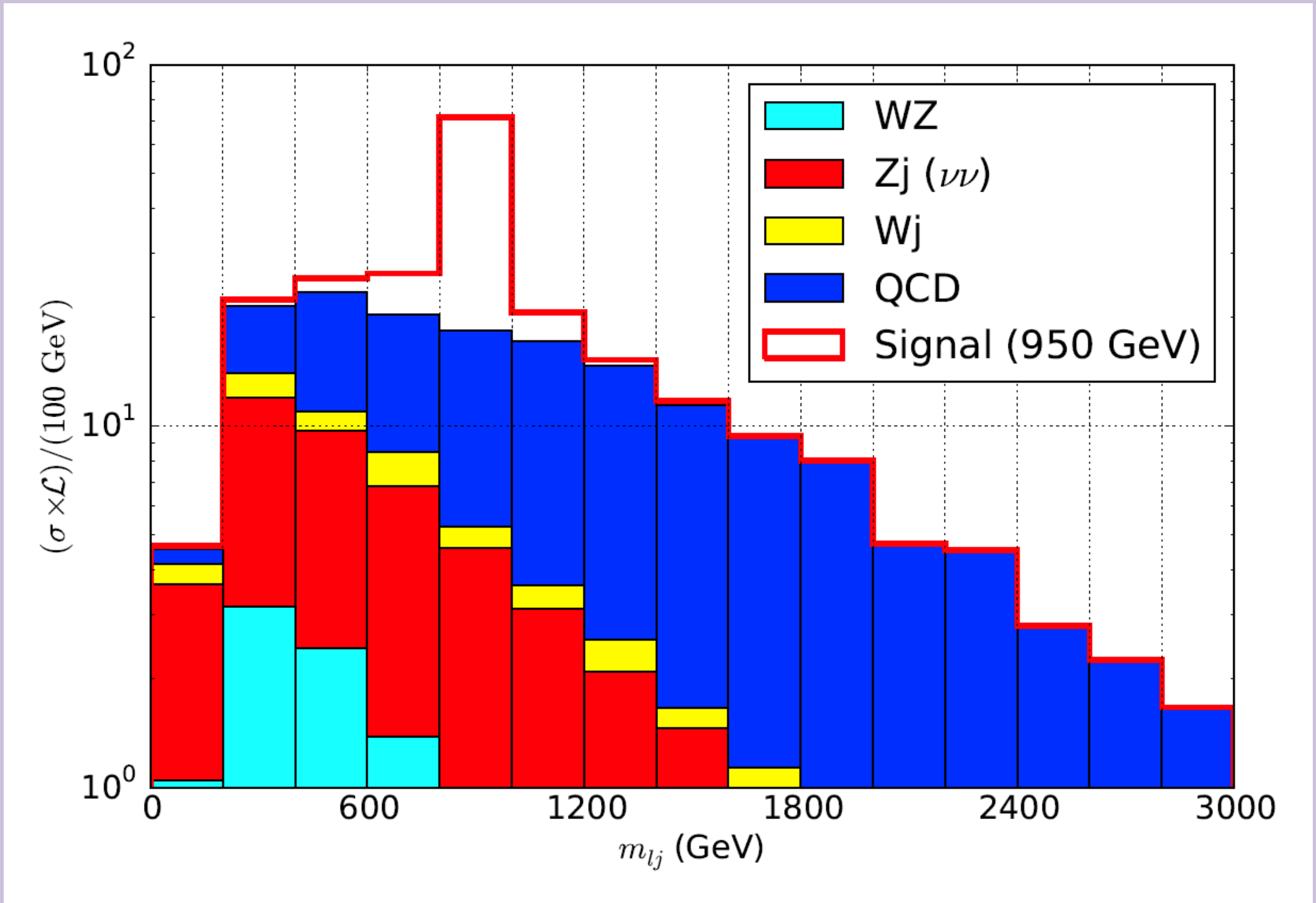
ST11: Mixed decay MET distribution

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



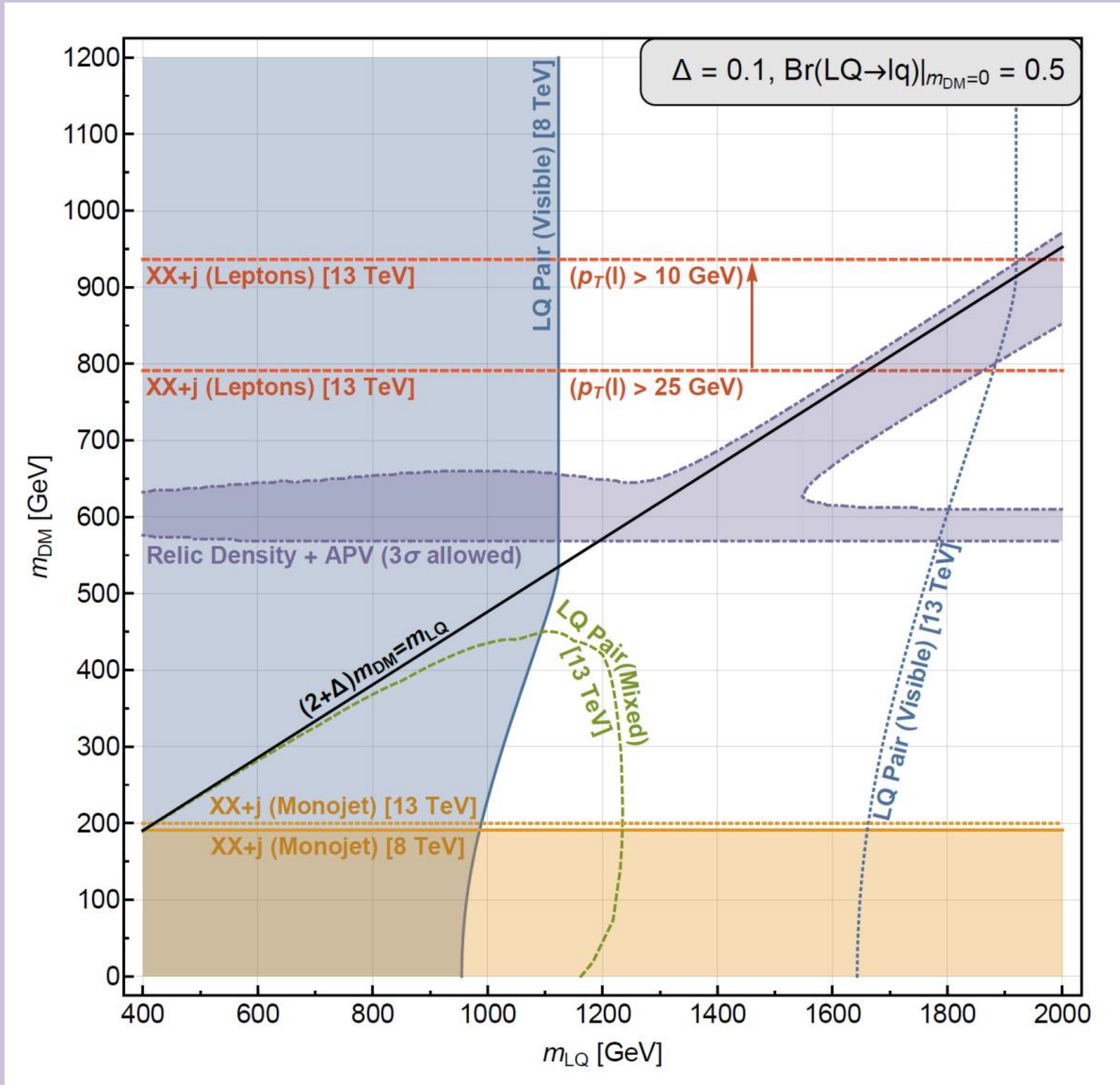
ST11: Mixed decay m_{ej} distribution

- Prominent leptoquark resonance
  - Just one example of many resonance + MET signatures



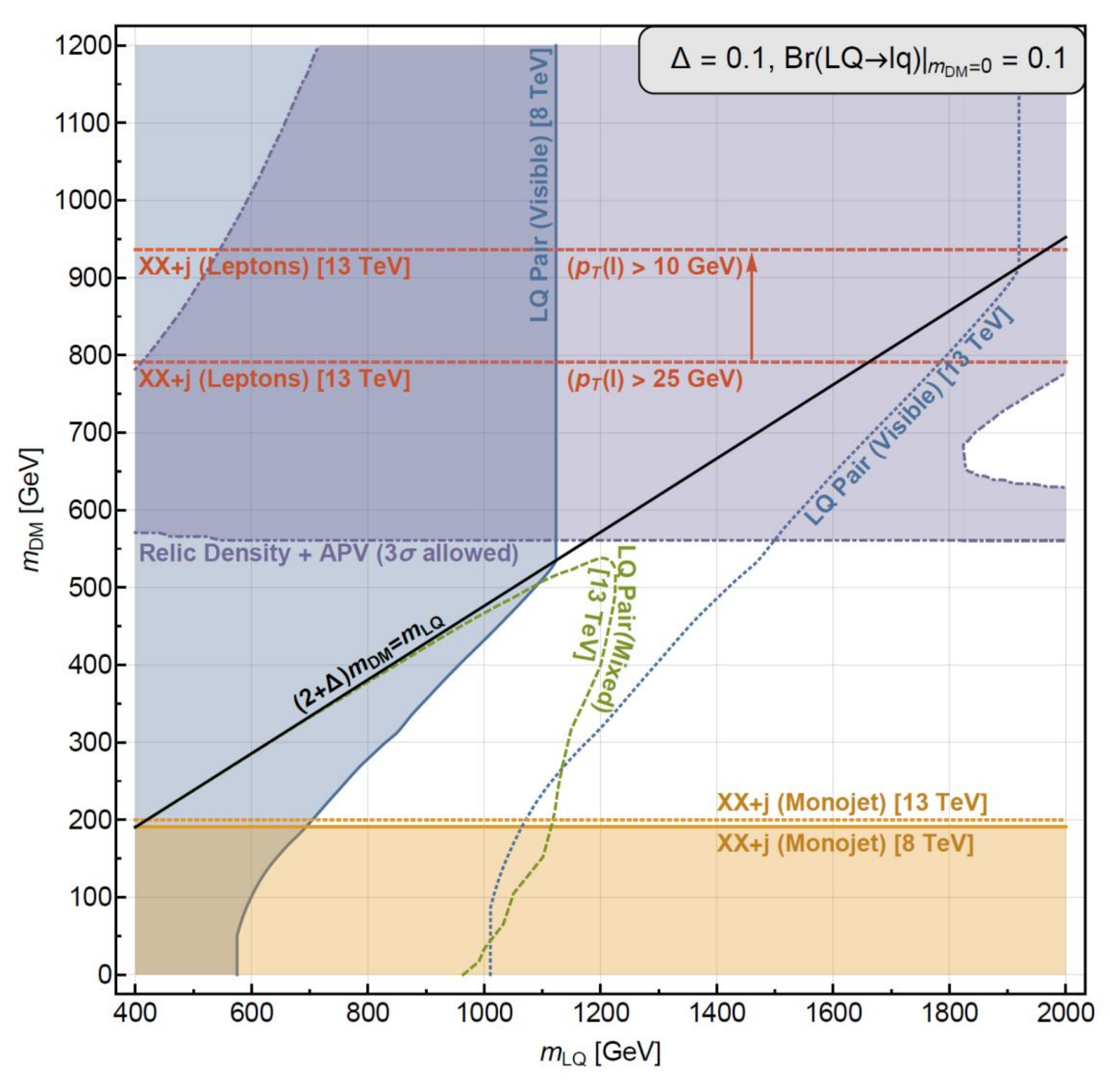
ST11: Mixed and mono-Y + lepton projections

- Different coverage from mixed decay vs. paired LQ
- Impressive reach covers large part of relic density region



ST11: Mixed and mono-Y + lepton projections

- Different coverage from mixed decay vs. paired LQ
- Impressive reach covers large part of relic density region
- Different y_D and y_{Ql} choices impact visible and mixed decay rates



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: Atomic parity violation

- Effective Lagrangian

$$\mathcal{L}^{\mathrm{APV}} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left[C_{1q}(\overline{q}\gamma_\mu q)(\overline{e}\gamma^\mu\gamma_5 e) + C_{2q}(\overline{q}\gamma_\mu\gamma_5 q)(\overline{e}\gamma^\mu e)\right]$$

- Induced Wilson coefficients

$$\Delta Q_W(Z,N) = -2\big[(2Z+N)C_{1u} + (2N+Z)C_{1d}\big]$$

- Experiment $Q_W(\mathrm{Cs}) = -72.62(43)$
- SM $Q_W^{\mathrm{SM}}(\mathrm{Cs}) \simeq -73.26$
- Our result $|y_{Q\ell}^{11}| < 0.40 \left(\frac{m_{\mathrm{LQ}}}{1\,\mathrm{TeV}}\right)$

ST11: flavor constraints

- Gyromagnetic ratio of electron $|\Delta a_e| \simeq 1.6 \times 10^{-10}\, y_{Q\ell}^{11}\, y_{Lu}^{11}$
- Constraint $|\Delta a_e| < 8.1 \times 10^{-13}$
- Our result $|y_{Q\ell}^{11}\, y_{Lu}^{11}| < 5.0 \times 10^{-3}$

- Rare Kaon decays $$\mathrm{Br}(K_L \to \mu^+ e^-) = \tau_{K_L} \frac{\left(y_{Q\ell}^{11}\, y_{Q\ell}^{22}\right)^2}{512\pi} \frac{m_\mu^2 M_K f_K^2}{m_{\mathrm{LQ}}^4} \left(1 - \frac{m_\mu^2}{M_K^2}\right)^2$$
- Our result $$y_{Q\ell}^{11} y_{Q\ell}^{22} \left(\frac{1\,\mathrm{TeV}}{m_{\mathrm{LQ}}}\right)^2 \lesssim 2.74 \times 10^{-5}$$

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
$N_\mu^{\rm h}=1,\ N_\mu \leq 2$	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
$N_{\rm hard\ jets} \leq 3$	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	$< 10^{-5}$	0.3	10^{-5}	10^{-5}	0.1	10^{-5}	13

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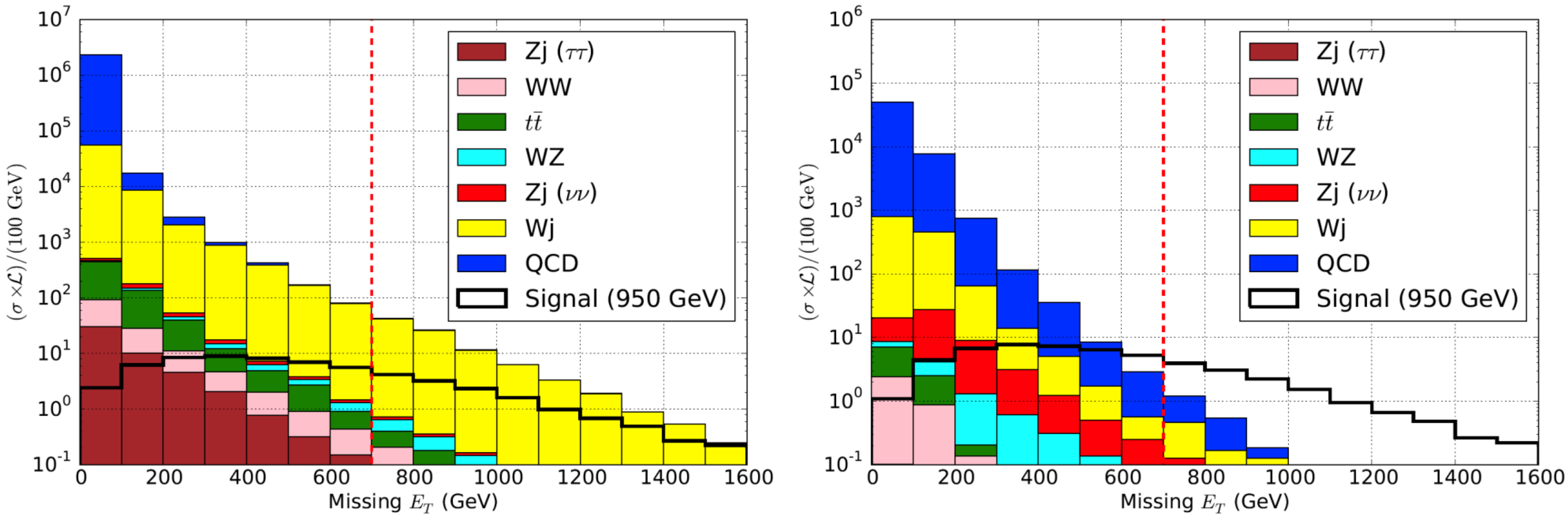

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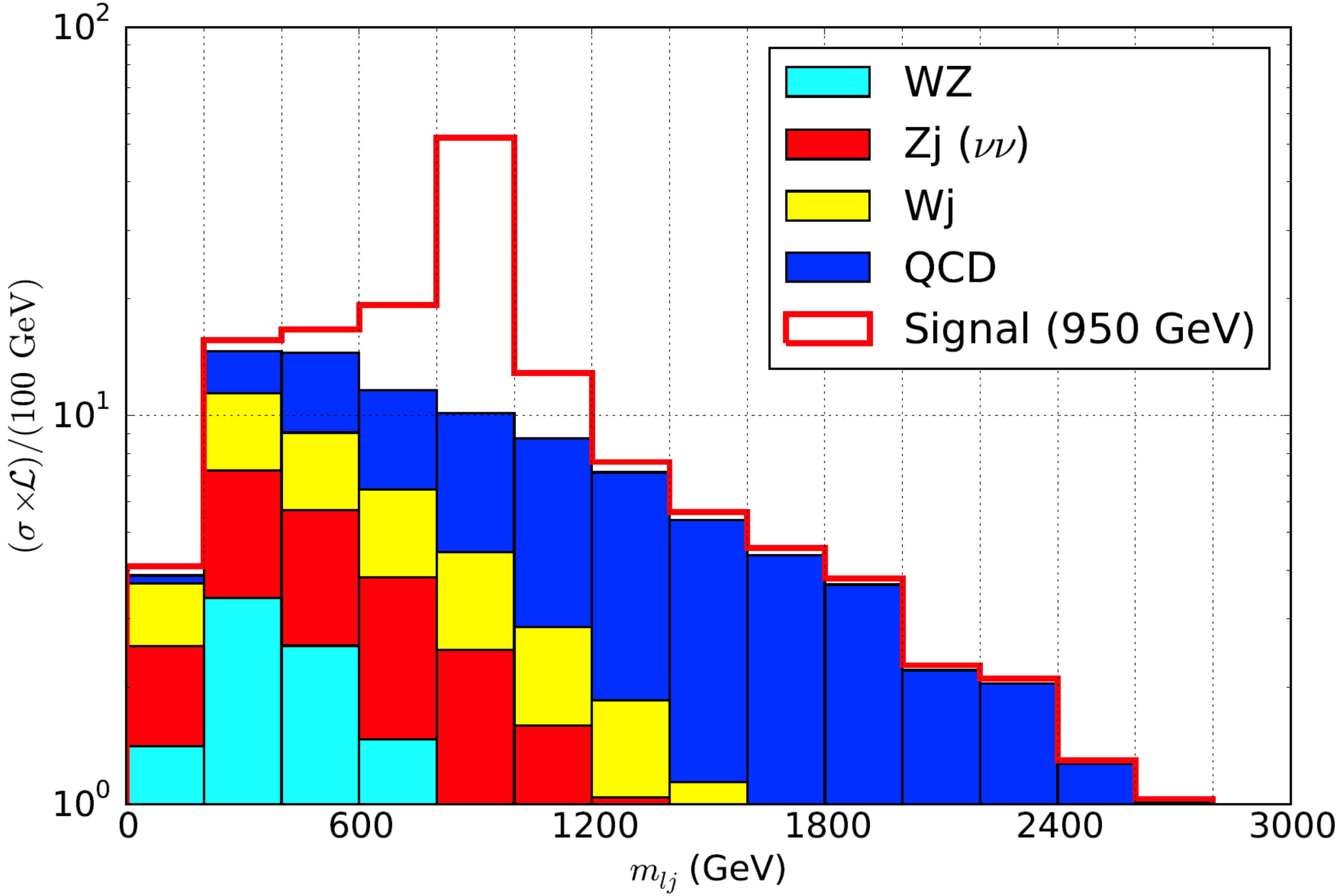

Coannihilation condition

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
  - Interesting handle for collider searches

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

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

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