Simplified Models of Coannihilating Dark Matter and its LHC phenomenology

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Outline

- Motivation
- Classification of Coannihilating Dark Matter
- Cosmology and Astroparticle Physics
- Collider phenomenological overview
- Example: Leptoquark mediated Dark Matter
- Conclusions

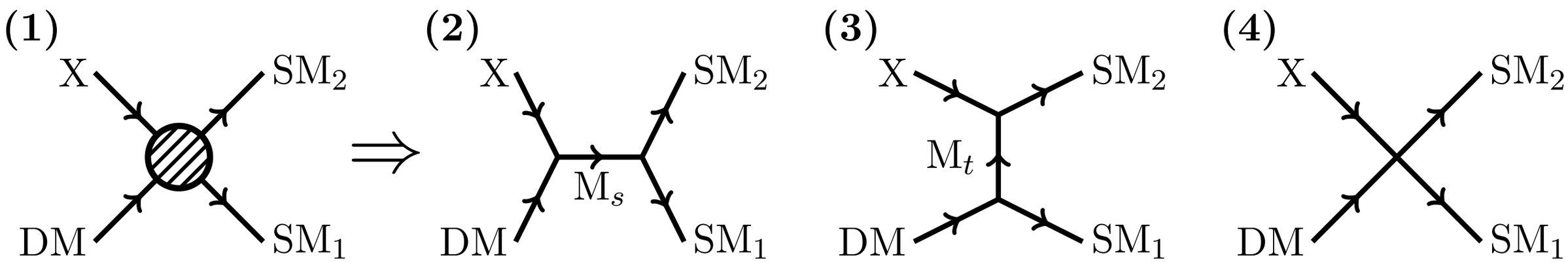
Motivation

- We have not (yet) found any evidence of New Physics, but dark matter relic density hints towards EW/TeVish scale.
- We know that dark matter (DM) is out there due to gravitational probes, but are utterly ignorant about its particle identity.
- If DM is a thermal relic, typically a nearby (co)annihilating partner (X) is required to obtain the correct relic density (ignore asymmetric DM). Reversing the coannihilation diagram gives "stealth" LHC signatures due to compressed spectra.
- Working at the dimension 4 operator level we might also need mediators, since DM and X are charged under a discrete symmetry.
- Idea: Completely classify all sets of quantum numbers for (DM, X, M) arising from the coannihilation diagram and study the implications of these simplified models on LHC searches, direct and indirect detection.

Classification of Dark Matter Coannihilation

Framework

a) Coannihilation diagrams



b) Assumptions:

- DM is a thermal relic, colorless, electrically neutral, $\mathrm{DM} = (1, N, \beta)$.
- DM and X co-annihilate in a 2 to 2 process via renormalizable, tree-level interactions.
- All particles have spin 0, 1/2 or 1.
- Massive vectors are gauge bosons from broken gauge groups.
- Lorentz and gauge invariance.
- Agnostic on flavor symmetries, dark charges, additional particle content, etc…

Along the road ...

1. Gauge boson selection rules:

In QCD, the g-A-B vertex obliges A and B to have the same color charge.
If a SM gauge group arises from the breaking of a larger one (i.e: GUT, 3-3-1-1) the gauge boson coupling vanishes for two broken and one unbroken boson.
(No coupling of two gluons to a "heavy-gluon")

2. Breaking of SU(2)xU(1):

EWSB leads to SU(2) violating vertexes and also mixing among fields with different EW quantum numbers. Unbroken SU(2)xU(1) greatly simplifies the classification. We have devised an algorithm to obtain the broken phase results from the unbroken ones.

3. Parity to prevent DM decay:

Role reversal is dangerous, i.e: $M_s=X_t$, $M_t=X_s$ gives DM $\longrightarrow$ 4 SM particles.
Requiring lifetime larger than age of the Universe too contrived.
Solution: impose a Z_2 parity, under which DM,X,M_t are odd and M_s, SM are even.

Overview

- **Topology:** s-channel and t-channel (M being Z_2 even/odd).
- $SU(3)_{\mathrm{X}}$: 1 (Uncolored), 3 (Fundamental), 8 (Octet), 6,10,15,27 (Exotic).
- **LHC:** q,g (proton) vs VB (V) vs H vs L

SM	SU	SF	TU	TF
p-p	5	10	10	13
p-V	-	3	-	6
p-H	-	9	-	16
p-L	-	11	-	26
V-V	2	-	1	-
V-H	1	-	1	-
V-L	1	-	5	-
H-H	6	-	4	-
H-L	8	-	10	-
L-L	8	-	9	-
Total	17	20	40	58

→ All SO [5], SE[7], TO [10], TE[10]

→ Non-standard DM pheno!

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SM	SU	SF	TU	TF
p-p	5	10	10	13
p-V	-	3	-	6
p-H	-	9	-	16
p-L	-	11	-	26
V-V	2	-	1	-
V-H	1	-	1	-
V-L	1	-	5	-
H-H	6	-	4	-
H-L	8	-	10	-
L-L	8	-	9	-
Total	17	20	40	58

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Tables (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	$(u_R\bar{u}_L),(d_R\bar{d}_L),(Q_L\bar{Q}_R),(\ell_R\bar{\ell}_L),(L_L\bar{L}_R)$ $(H\bar{H})$	B,$W_i^{N\geq 2}$	✓
SU2				F	$(L_L H)$		
SU3			$(1,3,0)^{N\geq 2}$	B	$(Q_L\bar{Q}_R),(L_L\bar{L}_R),(H\bar{H}),(W_iW_i)$	B, W_i	✓
SU4				F	$(L_L H)$		
SU5		-2	$(1,1,-2)$	B	$(d_R\bar{u}_L),(\bar{H}\bar{H})$		✓
SU6				F	$(L_L\bar{H}),(\ell_R B)$	ℓ_R	
SU7			$(1,3,-2)^{N\geq 2}$	B	$(\bar{H}\bar{H}),(L_L L_L)$		✓$(\alpha=\pm 1)$
SU8				F	$(L_L\bar{H})$	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	$(d_R\bar{Q}_R),(\bar{u}_L Q_L),(\bar{L}_R\ell_R),(\bar{H}B),(\bar{H}W_i)$	$\bar{H}$	
SU11				F	$(\ell_R H),(L_L B),(L_L W_i)$	L_L	
SU12		-3	$(1,2,-3)$	B	$(L_L\ell_R)$		
SU13				F	$(\ell_R\bar{H})$		
SU14	$(1,N\pm 2,\alpha)$	0	$(1,3,0)$	B	$(L_L\bar{L}_R),(Q_L\bar{Q}_R),(H\bar{H}),(W_iW_i)$		✓$(\alpha=0)$
SU15				F	$(L_L H)$		
SU16		-2	$(1,3,-2)$	B	$(\bar{H}\bar{H}),(L_L L_L)$		✓$(\alpha=\pm 1)$
SU17				F	$(L_L\bar{H})$		

SU [17]

ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	SM_3	M-X-X
SF1	$(3,N,\alpha)$	$\frac{10}{3}$	$(3,1,\frac{10}{3})$	B	$(u_R\bar{l}_L)$		✓$\alpha=-\frac{5}{3}$
SF2		$\frac{4}{3}$	$(3,1,\frac{4}{3})$	B	$(d_R\bar{\ell}_L)$, $(Q_L\bar{L}_R)$, $(\bar{d}_L\bar{d}_L)$		✓$\alpha=-\frac{2}{3}$
SF3				F	$(Q_L H)$, $(u_R B)$, $(u_R g)$	u_R	
SF4			$(3,3,\frac{4}{3})^{N\geq 2}$	B	$(Q_L\bar{L}_R)$		✓$\alpha=-\frac{2}{3}$
SF5				F	$(Q_L H)$	u_R	
SF6		$-\frac{2}{3}$	$(3,1,-\frac{2}{3})$	B	$(\bar{Q}_R\bar{Q}_R),(\bar{u}_L\bar{d}_L),(u_R,\ell_R),(Q_L L_L)$	✓$\alpha=\frac{1}{3}$	
SF7				F	$(Q_L\bar{H})$, $(d_R B)$, $(d_R g)$	d_R	
SF8			$(3,3,-\frac{2}{3})^{N\geq 2}$	B	$(\bar{Q}_R\bar{Q}_R),(Q_L L_L)$		✓$\alpha=\frac{1}{3}$
SF9				F	$(Q_L\bar{H})$	d_R	
SF10		$-\frac{8}{3}$	$(3,1,-\frac{8}{3})$	B	$(\bar{u}_L\bar{u}_L),(d_R\ell_R)$		✓$\alpha=\frac{4}{3}$
SF11	$(3,N\pm 1,\alpha)$	$\frac{7}{3}$	$(3,2,\frac{7}{3})$	B	$(Q_L\bar{\ell}_L),(u_R\bar{L}_R)$		
SF12				F	$(u_R H)$		
SF13		$\frac{1}{3}$	$(3,2,\frac{1}{3})$	B	$(d_R\bar{L}_R),(\bar{Q}_R\bar{d}_L),(u_R L_L)$		
SF14				F	$(u_R\bar{H}),(d_R H),(Q_L B),(Q_L W_i),(Q_L g)$	Q_L	
SF15		$-\frac{5}{3}$	$(3,2,-\frac{5}{3})$	B	$(\bar{Q}_R\bar{u}_L),(Q_L\ell_R),(d_R L_L)$		
SF16				F	$(d_R\bar{H})$		
SF17	$(3,N\pm 2,\alpha)$	$\frac{4}{3}$	$(3,3,\frac{4}{3})$	B	$(Q_L\bar{L}_R)$		✓$\alpha=-\frac{2}{3}$
SF18				F	$(Q_L H)$		
SF19		$-\frac{2}{3}$	$(3,3,-\frac{2}{3})$	B	$(\bar{Q}_R\bar{Q}_R),(Q_L L_L)$		✓$\alpha=\frac{1}{3}$
SF20				F	$(Q_L\bar{H})$		

SF [20]

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	$(d_R\bar{d}_L),(u_R\bar{u}_L),(Q_L\bar{Q}_R)$		✓$\alpha=0$
SO2			$(8,3,0)^{N\geq 2}$	B	$(Q_L\bar{Q}_R)$		✓$\alpha=0$
SO3		-2	$(8,1,-2)$	B	$(d_R\bar{u}_L)$		✓$\alpha=\pm 1$
SO4	$(8,N\pm 1,\alpha)$	-1	$(8,2,-1)$	B	$(d_R\bar{Q}_R),(Q_L\bar{u}_L)$		
SO5	$(8,N\pm 2,\alpha)$	0	$(8,3,0)$	B	$(Q_L\bar{Q}_R)$		✓$\alpha=0$
SE1	$(6,N,\alpha)$	$\frac{8}{3}$	$(6,1,\frac{8}{3})$	B	$(u_R u_R)$		✓$\alpha=-\frac{4}{3}$
SE2		$\frac{2}{3}$	$(6,1,\frac{2}{3})$	B	$(Q_L Q_L),(u_R d_R)$		✓$(\alpha=-\frac{1}{3})$
SE3			$(6,3,\frac{2}{3})^{N\geq 2}$	B	$(Q_L Q_L)$		✓$\alpha=-\frac{1}{3}$
SE4		$-\frac{4}{3}$	$(6,1,-\frac{4}{3})$	B	$(d_R d_R)$		✓$\alpha=\frac{2}{3}$
SE5	$(6,N\pm 1,\alpha)$	$\frac{5}{3}$	$(6,2,\frac{5}{3})$	B	$(Q_L u_R)$		
SE6		$-\frac{1}{3}$	$(6,2,-\frac{1}{3})$	B	$(Q_L d_R)$		
SE7	$(6,N\pm 2,\alpha)$	$\frac{2}{3}$	$(6,3,\frac{2}{3})$	B	$(Q_L Q_L)$		✓$\alpha=-\frac{1}{3}$

SO[5], SE [7]

t-channel

ID	X	$\alpha+\beta$	M_t	Spin	$(SM_1\ SM_2)$	SM_3
TU1	$(1,N,\alpha)$	0	$(1,N,\beta)$	I	$(BB),(BW_i),(W_iB),(W_iW_i)$	$B,\ W_i^{N\geq 2}$
TU2			$(1,N\pm1,\beta-1)$	I	$(H\bar{H})$	$B,\ W_i^{N\geq 2}$
TU3			$(1,N\pm1,\beta+1)$	II	(L_LH)	
TU4			$(1,N\pm1,\beta-1)$	III	(HL_L)	
TU5			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\bar{Q}_R)$	$B,\ W_i^{N\geq 2}$
TU6			$(\bar{3},N,\beta-\frac{4}{3})$	IV	$(u_R\bar{u}_L)$	$B,\ W_i^{N\geq 2}$
TU7			$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\bar{d}_L)$	$B,\ W_i^{N\geq 2}$
TU8			$(1,N\pm1,\beta+1)$	IV	$(L_L\bar{L}_R)$	$B,\ W_i^{N\geq 2}$
TU9			$(1,N,\beta+2)$	IV	$(\ell_R\bar{\ell}_L)$	$B,\ W_i^{N\geq 2}$
TU10		-2	$(1,N\pm1,\beta+1)$	I	$(\bar{H}\bar{H})$	
TU11			$(1,N,\beta+2)$	II	$(\ell_RB),(\ell_RW_i)^{N\geq 2}$	ℓ_R
TU12			$(1,N\pm1,\beta+1)$	II	$(L_L\bar{H})$	ℓ_R
TU13			$(1,N,\beta)$	III	$(B\ell_R),(W_i\ell_R)^{N\geq 2}$	ℓ_R
TU14			$(1,N\pm1,\beta+1)$	III	$(\bar{H}L_L)$	ℓ_R
TU15			$(1,N\pm1,\beta+1)$	IV	(L_LL_L)	
TU16			$(3,N,\beta+\frac{4}{3})$	IV	$(\bar{u}_Ld_R)$	
TU17			$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\bar{u}_L)$	
TU18		-4	$(1,N,\beta+2)$	IV	$(\ell_R\ell_R)$	
TU19	$(1,N\pm1,\alpha)$	-1	$(1,N,\beta)$	I	$(B\bar{H}),(W_i\bar{H})^{N\geq 2}$	$\bar{H}$
TU20			$(1,N\pm1,\beta+1)$	I	$(\bar{H}B),(\bar{H}W_i)$	$\bar{H}$
TU21			$(1,N,\beta+2)$	II	(ℓ_RH)	L_L
TU22			$(1,N\pm1,\beta+1)$	II	$(L_LB),(L_LW_i)$	L_L
TU23			$(1,N\pm1,\beta-1)$	III	$(H\ell_R)$	L_L
TU24			$(1,N,\beta)$	III	$(BL_L),(W_iL_L)$	L_L
TU25			$(1,N,\beta+2)$	IV	$(\ell_R\bar{L}_R)$	$\bar{H}$
TU26			$(1,N\pm1,\beta-1)$	IV	$(\bar{L}_R\ell_R)$	$\bar{H}$
TU27			$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\bar{Q}_R)$	$\bar{H}$
TU28			$(3,N\pm1,\beta+\frac{1}{3})$	IV	$(\bar{Q}_Rd_R)$	$\bar{H}$
TU29			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\bar{u}_L)$	$\bar{H}$
TU30			$(3,N,\beta+\frac{4}{3})$	IV	$(\bar{u}_LQ_L)$	$\bar{H}$
TU31		-3	$(1,N\pm1,\beta+1)$	IV	$(L_L\ell_R)$	
TU32			$(1,N,\beta+2)$	IV	(ℓ_RL_L)	
TU33	$(1,N\pm2,\alpha)$	0	$(1,N\pm1,\beta-1)$	I	$(H\bar{H})$	
TU34			$(1,N\pm1,\beta+1)$	II	(L_LH)	
TU35			$(1,N\pm1,\beta-1)$	III	(HL_L)	
TU36			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\bar{Q}_R)$	
TU37			$(1,N\pm1,\beta+1)$	IV	$(L_L\bar{L}_R)$	
TU38		-2	$(1,N\pm1,\beta+1)$	I	$(\bar{H}\bar{H})$	
TU39			$(1,N\pm1,\beta+1)$	II	$(L_L\bar{H})$	
TU40			$(1,N\pm1,\beta+1)$	III	$(\bar{H}L_L)$	

TU [40]

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	$(Q_L\bar{Q}_R)$	
TO2			$(\bar{3},N,\beta-\frac{4}{3})$	IV	$(u_R\bar{u}_L)$	
TO3			$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\bar{d}_L)$	
TO4		-2	$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\bar{u}_L)$	
TO5			$(3,N,\beta+\frac{4}{3})$	IV	$(\bar{u}_Ld_R)$	
TO6	$(8,N\pm1,\alpha)$	-1	$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\bar{Q}_R)$	
TO7			$(3,N\pm1,\beta+\frac{1}{3})$	IV	$(\bar{Q}_Rd_R)$	
TO8			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\bar{u}_L)$	
TO9			$(3,N,\beta+\frac{4}{3})$	IV	$(\bar{u}_LQ_L)$	
TO10	$(8,N\pm2,\alpha)$	0	$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\bar{Q}_R)$	
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 [10], TE [10]

ID	X	$\alpha+\beta$	M_t	Spin	$(SM_1\ SM_2)$	SM_3
TF1	$(3,N,\alpha)$	$\frac{10}{3}$	$(\bar{3},N,\beta-\frac{4}{3})$	IV	$(u_R\bar{\ell}_L)$	
TF2			$(1,N,\beta-2)$	IV	$(\bar{\ell}_Lu_R)$	
TF3		$\frac{4}{3}$	$(\bar{3},N,\beta-\frac{4}{3})$	II	$(u_RB),(u_RW_i),(u_Rg)$	u_R
TF4			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	II	(Q_LH)	u_R
TF5			$(1,N\pm1,\beta-1)$	III	(HQ_L)	u_R
TF6			$(1,N,\beta)$	III	$(Bu_R),(W_iu_R)$	u_R
TF7			$(1,N,\beta-2)$	IV	$(\bar{\ell}_Ld_R)$	
TF8			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\bar{L}_R)$	
TF9			$(1,N\pm1,\beta-1)$	IV	$(\bar{L}_RQ_L)$	
TF10			$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\bar{\ell}_L)$	
TF11			$(3,N,\beta-\frac{2}{3})$	IV	$(\bar{d}_L\bar{d}_L)$	
TF12		$-\frac{2}{3}$	$(\bar{3},N,\beta+\frac{2}{3})$	II	$(d_RB),(d_RW_i),(d_Rg)$	d_R
TF13			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	II	$(Q_L\bar{H})$	d_R
TF14			$(1,N,\beta)$	III	$(Bd_R),(W_id_R)$	d_R
TF15			$(1,N\pm1,\beta+1)$	III	$(\bar{H}Q_L)$	d_R
TF16			$(3,N,\beta+\frac{4}{3})$	IV	$(\bar{u}_L\bar{d}_L)$	
TF17			$(3,N\pm1,\beta+\frac{1}{3})$	IV	$(\bar{Q}_R\bar{Q}_R)$	
TF18			$(\bar{3},N,\beta-\frac{4}{3})$	IV	$(u_R\ell_R)$	
TF19			$(1,N,\beta+2)$	IV	(ℓ_Ru_R)	
TF20			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	(Q_LL_L)	
TF21			$(1,N\pm1,\beta+1)$	IV	(L_LQ_L)	
TF22			$(3,N,\beta-\frac{2}{3})$	IV	$(\bar{d}_L\bar{u}_L)$	
TF23		$-\frac{8}{3}$	$(3,N,\beta+\frac{4}{3})$	IV	$(\bar{u}_L\bar{u}_L)$	
TF24			$(\bar{3},N,\beta+\frac{2}{3})$	IV	$(d_R\ell_R)$	
TF25			$(1,N,\beta+2)$	IV	(ℓ_Rd_R)	
TF26	$(3,N\pm1,\alpha)$	$\frac{7}{3}$	$(\bar{3},N,\beta-\frac{4}{3})$	II	(u_RH)	
TF27			$(1,N\pm1,\beta-1)$	III	(Hu_R)	
TF28			$(\bar{3},N,\beta-\frac{4}{3})$	IV	$(u_R\bar{L}_R)$	
TF29			$(1,N\pm1,\beta-1)$	IV	$(\bar{L}_Ru_R)$	
TF30			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\bar{\ell}_L)$	
TF31			$(1,N,\beta-2)$	IV	$(\bar{\ell}_LQ_L)$	
TF32		$\frac{1}{3}$	$(\bar{3},N,\beta-\frac{4}{3})$	II	$(u_R\bar{H})$	Q_L
TF33			$(\bar{3},N,\beta+\frac{2}{3})$	II	(d_RH)	Q_L
TF34			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	II	$(Q_LB),(Q_LW_i),(Q_Lg)$	Q_L
TF35			$(1,N\pm1,\beta+1)$	III	$(\bar{H}u_R)$	Q_L
TF36			$(1,N\pm1,\beta-1)$	III	(Hd_R)	Q_L
TF37			$(1,N,\beta)$	III	$(BQ_L),(W_iQ_L)$	Q_L
TF38			$(\bar{3},N,\beta-\frac{4}{3})$	IV	(u_RL_L)	
TF39			$(1,N\pm1,\beta+1)$	IV	(L_Lu_R)	
TF40			$3,N,\beta-\frac{2}{3})$	IV	$(\bar{d}_L\bar{Q}_R)$	
TF41			$(3,N\pm1,\beta+\frac{1}{3})$	IV	$(\bar{Q}_R\bar{d}_L)$	
TF42		$-\frac{5}{3}$	$(\bar{3},N,\beta+\frac{2}{3})$	II	$(d_R\bar{H})$	
TF43			$(1,N\pm1,\beta+1)$	III	$(\bar{H}d_R)$	
TF44			$(\bar{3},N,\beta+\frac{2}{3})$	IV	(d_RL_L)	
TF45			$(1,N\pm1,\beta+1)$	IV	(L_Ld_R)	
TF46			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\ell_R)$	
TF47			$(1,N,\beta+2)$	IV	(ℓ_RQ_L)	
TF48			$(3,N,\beta+\frac{4}{3})$	IV	$(\bar{u}_L\bar{Q}_R)$	
TF49			$(3,N\pm1,\beta+\frac{1}{3})$	IV	$(\bar{Q}_R\bar{u}_L)$	
TF52	$(3,N\pm2,\alpha)$	$\frac{4}{3}$	$(\bar{3},N\pm1,\beta-\frac{1}{3})$	II	(Q_LH)	
TF54			$(1,N\pm1,\beta-1)$	III	(HQ_L)	
TF55			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	$(Q_L\bar{L}_R)$	
TF56			$(1,N\pm1,\beta-1)$	IV	$(\bar{L}_RQ_L)$	
TF58		$-\frac{2}{3}$	$(\bar{3},N\pm1,\beta-\frac{1}{3})$	II	$(Q_L\bar{H})$	
TF60			$(1,N\pm1,\beta+1)$	III	$(\bar{H}Q_L)$	
TF61			$(\bar{3},N\pm1,\beta-\frac{1}{3})$	IV	(Q_LL_L)	
TF62			$(1,N\pm1,\beta+1)$	IV	(L_LQ_L)	
TF63			$(3,N\pm1,\beta+\frac{1}{3})$	IV	$(\bar{Q}_R\bar{Q}_R)$	

TF [58]

s-channel

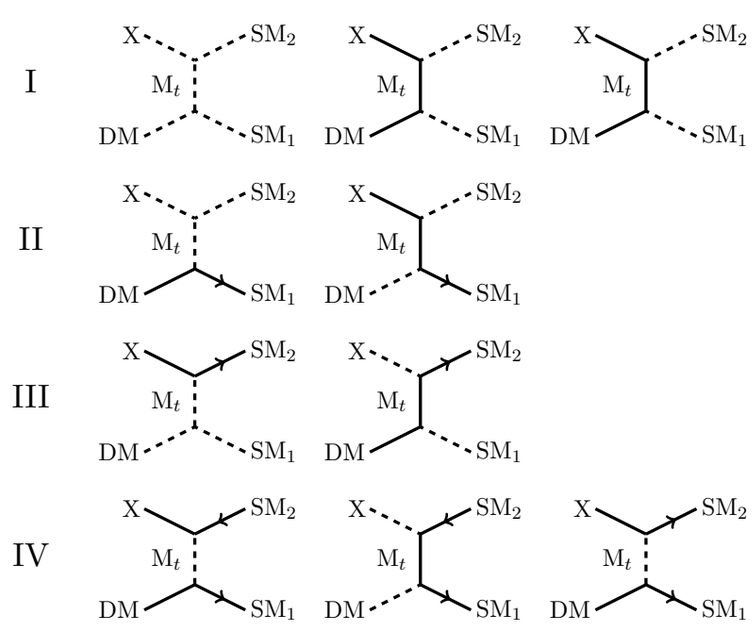
Mediator spin

Additional vertices

ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	SM_3	M-X-X
SF11	$(3, N\pm 1, \alpha)$	$\frac{7}{3}$	$(3, 2, \frac{7}{3})$	B	$(Q_L\bar{\ell}_L), (u_R\bar{L}_R)$		
SF12				F	$(u_R H)$		
SF13		$\frac{1}{3}$	$(3, 2, \frac{1}{3})$	B	$(d_R\bar{L}_R), (\bar{Q}_R\bar{d}_L), (u_R L_L)$		
SF14				F	$(u_R\bar{H}), (d_R H), (Q_L B), (Q_L W_i), (Q_L g)$	Q_L	
SF15		$-\frac{5}{3}$	$(3, 2, -\frac{5}{3})$	B	$(\bar{Q}_R\bar{u}_L), (Q_L\ell_R), (d_R L_L)$		
SF16				F	$(d_R\bar{H})$		

t-channel

4 spin assignments



DM-X-SM3

ID	X	$\alpha+\beta$	M_t	Spin	$(SM_1\ SM_2)$	SM_3
TU33	$(1, N\pm 2, \alpha)$	0	$(1, N\pm 1, \beta-1)$	I	$(H\bar{H})$	
TU34			$(1, N\pm 1, \beta+1)$	II	$(L_L H)$	
TU35			$(1, N\pm 1, \beta-1)$	III	$(H L_L)$	
TU36			$(\bar{3}, N\pm 1, \beta-\frac{1}{3})$	IV	$(Q_L\bar{Q}_R)$	
TU37			$(1, N\pm 1, \beta+1)$	IV	$(L_L\bar{L}_R)$	
TU38		-2	$(1, N\pm 1, \beta+1)$	I	$(\bar{H}\bar{H})$	
TU39			$(1, N\pm 1, \beta+1)$	II	$(L_L\bar{H})$	
TU40			$(1, N\pm 1, \beta+1)$	III	$(\bar{H} L_L)$	

s-channel

Mediator spin

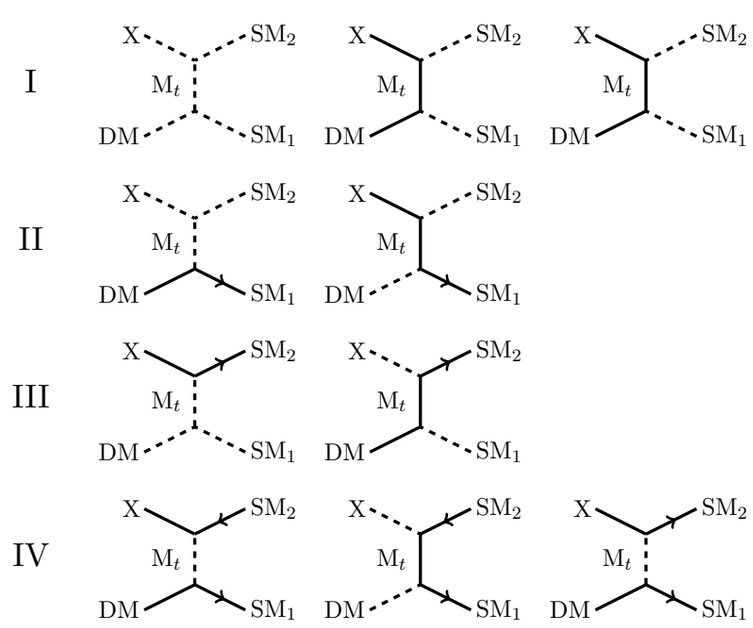
Additional vertices

ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	SM_3	M-X-X
SF11	$(3, N\pm1, \alpha)$	$\frac{7}{3}$	$(3, 2, \frac{7}{3})$	B	$(Q_L\bar{\ell}_L), (u_R\bar{L}_R)$		
SF12				F	$(u_R H)$		
SF13		$\frac{1}{3}$	$(3, 2, \frac{1}{3})$	B	$(d_R\bar{L}_R), (\bar{Q}_R\bar{d}_L), (u_R L_L)$		
SF14				F	$(u_R\bar{H}), (d_R H), (Q_L B), (Q_L W_i), (Q_L g)$	Q_L	
SF15		$-\frac{5}{3}$	$(3, 2, -\frac{5}{3})$	B	$(\bar{Q}_R\bar{u}_L), (Q_L\ell_R), (d_R L_L)$		
SF16				F	$(d_R\bar{H})$		

SF11: chosen one! (for LHC pheno study later)

t-channel

4 spin assignments



DM-X-SM3

ID	X	$\alpha+\beta$	M_t	Spin	$(SM_1\ SM_2)$	SM_3
TU33	$(1, N\pm2, \alpha)$	0	$(1, N\pm1, \beta-1)$	I	$(H\bar{H})$	
TU34			$(1, N\pm1, \beta+1)$	II	$(L_L H)$	
TU35			$(1, N\pm1, \beta-1)$	III	$(H L_L)$	
TU36			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\bar{Q}_R)$	
TU37			$(1, N\pm1, \beta+1)$	IV	$(L_L\bar{L}_R)$	
TU38		-2	$(1, N\pm1, \beta+1)$	I	$(\bar{H}\bar{H})$	
TU39			$(1, N\pm1, \beta+1)$	II	$(L_L\bar{H})$	
TU40			$(1, N\pm1, \beta+1)$	III	$(\bar{H}L_L)$	

s-channel

Mediator spin

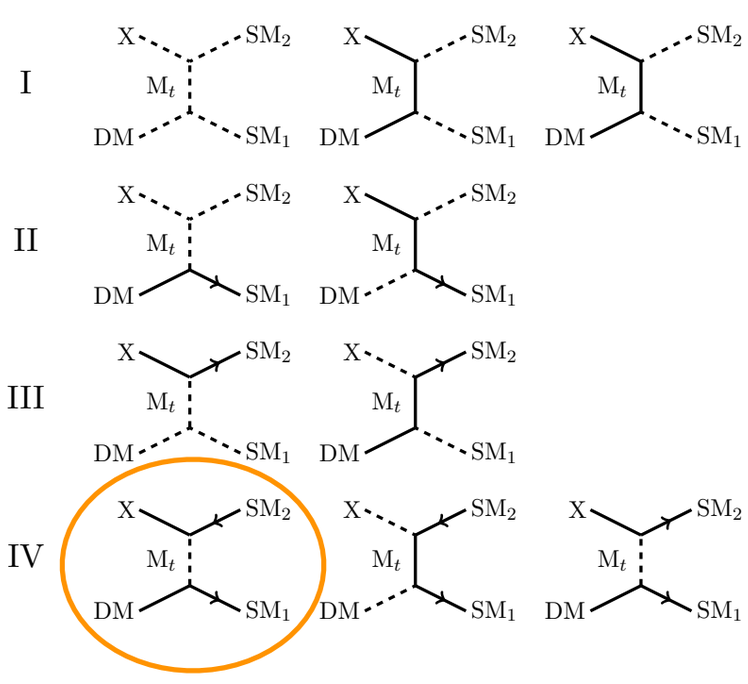
Additional vertices

ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	SM_3	M-X-X
SF11	$(3, N\pm1, \alpha)$	$\frac{7}{3}$	$(3, 2, \frac{7}{3})$	B	$(Q_L\bar{\ell}_L), (u_R\bar{L}_R)$		
SF12				F	$(u_R H)$		
SF13		$\frac{1}{3}$	$(3, 2, \frac{1}{3})$	B	$(d_R\bar{L}_R), (\bar{Q}_R\bar{d}_L), (u_R L_L)$		
SF14				F	$(u_R\bar{H}), (d_R H), (Q_L B), (Q_L W_i), (Q_L g)$	Q_L	
SF15		$-\frac{5}{3}$	$(3, 2, -\frac{5}{3})$	B	$(\bar{Q}_R\bar{u}_L), (Q_L\ell_R), (d_R L_L)$		
SF16				F	$(d_R\bar{H})$		

SF11: chosen one! (for LHC pheno study later)

t-channel

4 spin assignments



DM-X-SM3

ID	X	$\alpha+\beta$	M_t	Spin	$(SM_1\ SM_2)$	SM_3
TU33	$(1, N\pm2, \alpha)$	0	$(1, N\pm1, \beta-1)$	I	$(H\bar{H})$	
TU34			$(1, N\pm1, \beta+1)$	II	$(L_L H)$	
TU35			$(1, N\pm1, \beta-1)$	III	$(H L_L)$	
TU36			$(\bar{3}, N\pm1, \beta-\frac{1}{3})$	IV	$(Q_L\bar{Q}_R)$	
TU37			$(1, N\pm1, \beta+1)$	IV	$(L_L\bar{L}_R)$	
TU38		-2	$(1, N\pm1, \beta+1)$	I	$(\bar{H}\bar{H})$	
TU39			$(1, N\pm1, \beta+1)$	II	$(L_L\bar{H})$	
TU40			$(1, N\pm1, \beta+1)$	III	$(\bar{H}L_L)$	

TU36, N=1, spin IV (left): bino, wino, squark.

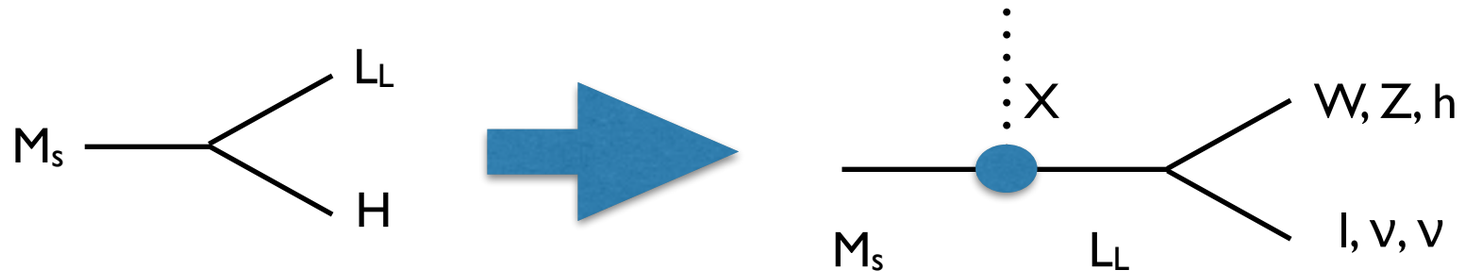
EW Symmetry Breaking

1- O(100 MeV) splitting among components due to EW bosons loops.

Thomas, Wells, hep-ph/9804359, Cirelli, Formengo, Strumia, hep-ph/0512090

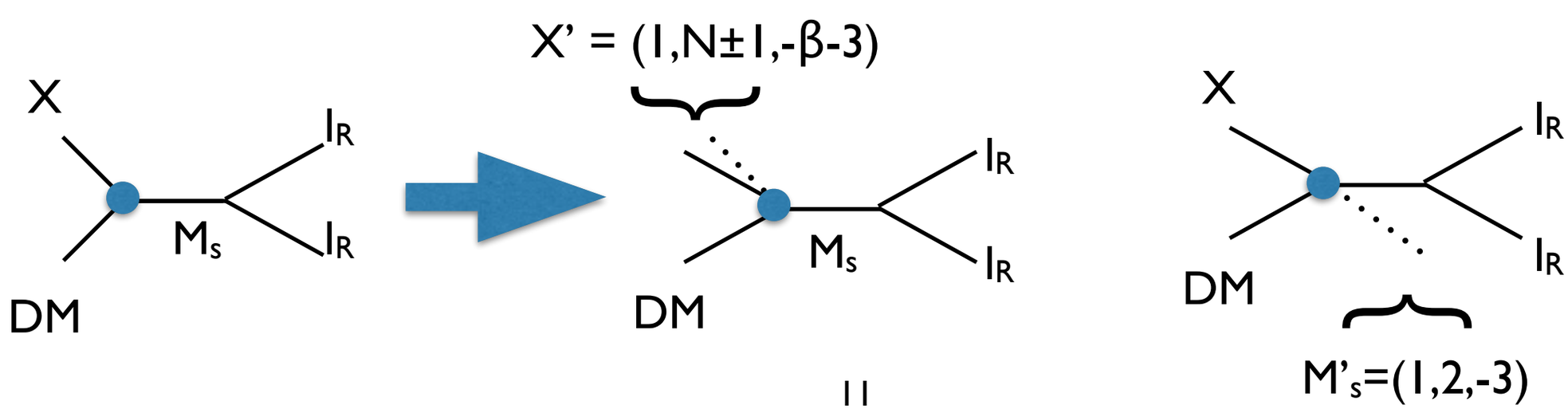
2 - Higgs vevs insertions give:

a) mass mixing SU2: DM=(1,N,β), X=(1,N,-β), M_s=(1,1,0), $SM_1=L_L$,SM_2=H.



b) New X', M' options differing from X,M by Higgs quantum numbers

SU9: DM=(1,N,β), X=(1,N,-β-4), M_s=(1,1,-4), $SM_1=SM_2=l_R$.



Cosmology and Astroparticle Physics

Direct detection

1. Z-exchange: force DM with $T_3=Y=0$?
   - Certainly not! Many ways out:
     - Add DM and choose parameters to kill Z-current (i.e: $\sin(\beta-\alpha)$ in MSSM).
     - DM can be below the detection threshold (light DM).
     - If DM is a fermion choose it Majorana.
     - …
2. DD rate is highly model dependent
   - Very hard to make robust statements. Check case-by case!
3. iDM included in our classification.
   - Complete list of upscatterers!

Indirect detection

1. If additional M-DM-DM vertex is present:

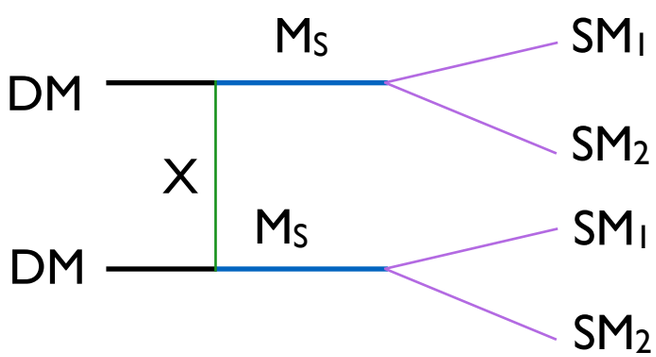
   A. N=1: model dependence (i.e Higgs couplings).

   B. N > 1: well studied in WIMP literature.

2. Without new interactions (behind CA diagram)

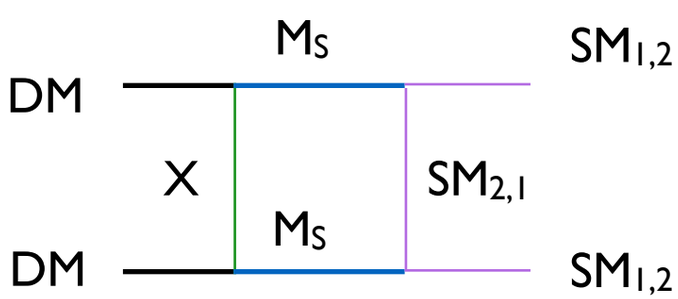
- s-channel:

<u>Annihilation into 4 SM particles</u>

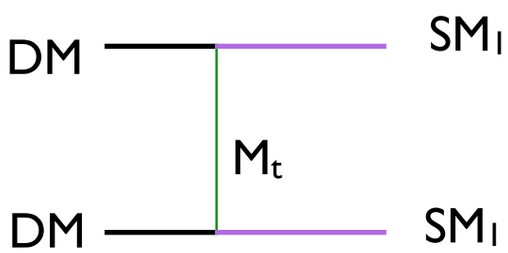


+

<u>Loop suppressed annihilation into SM pairs.</u>



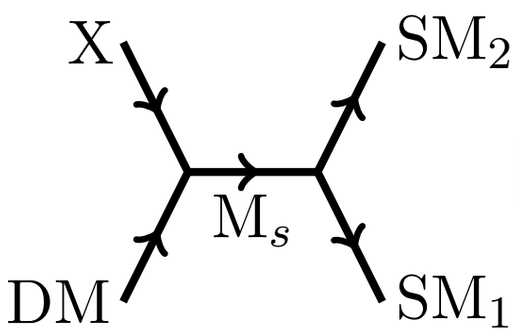
- t-channel:



<u>Tree level decay only into SM_1 pairs.</u>

Collider Phenomenology

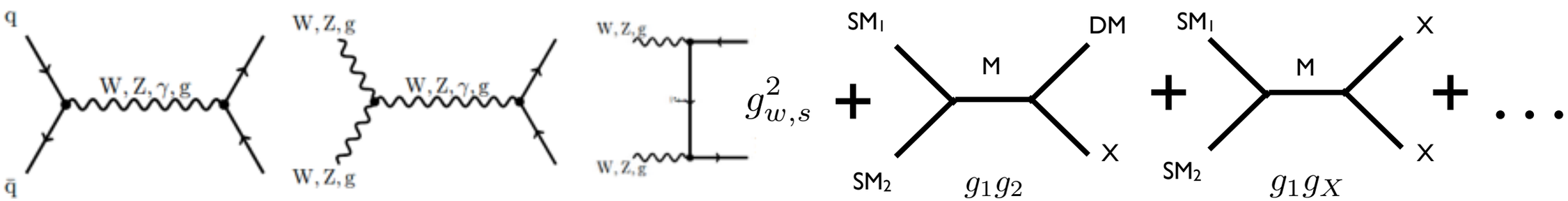
Production (s-channel)



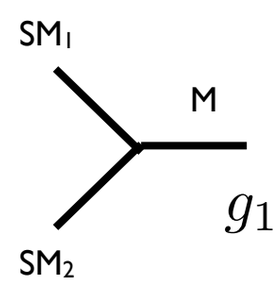
$$\mathcal{L} \supset g_1 \mathrm{SM}_1\ \mathrm{SM}_2\ \mathrm{M_s} + g_2 \mathrm{DM\ X\ M_s} + g_3 \mathrm{SM}_3\ \mathrm{DM\ X} + g_X \mathrm{M\ X\ X} + g_{DM} \mathrm{M\ DM\ DM} + \mathcal{L}_{kin}$$

$\phi_i = (\mathrm{DM}, \mathrm{X})$ are Z_2-odd, M_s is Z_2-even.

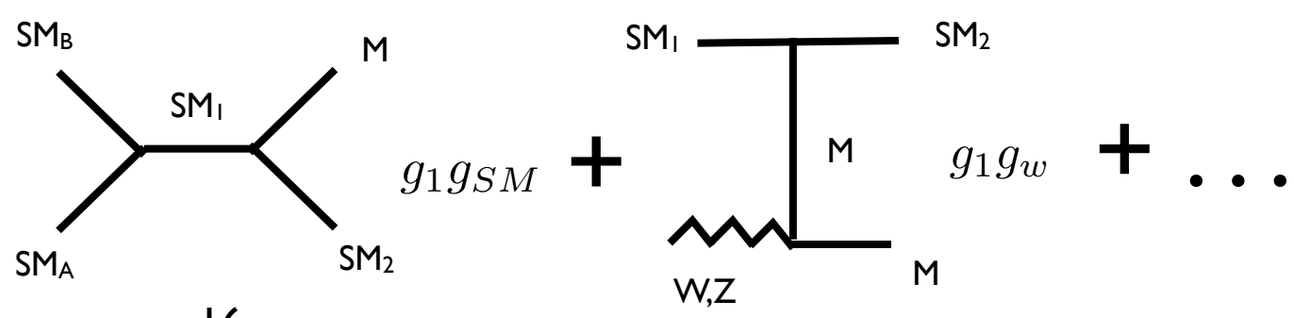
1) Pair production via kinetic terms + coannihilation diagram (and related)



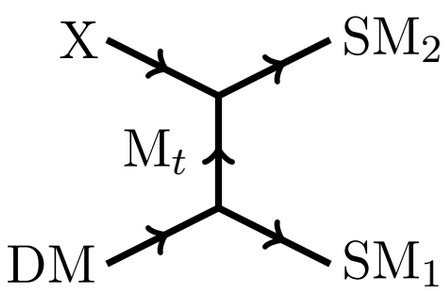
2) Single mediator production



3) M_s + SM particle in association



Production (t-channel)

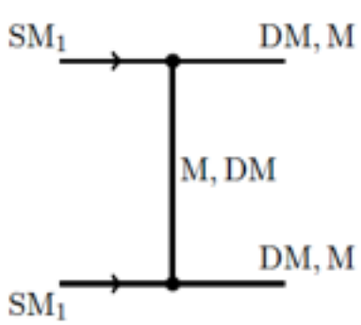


$$\mathcal{L} \supset g_1 \mathrm{SM}_1 \ \mathrm{DM} \ \mathrm{M_t} + g_2 \mathrm{SM}_2 \ \mathrm{X} \ \mathrm{M_t} + g_3 \mathrm{SM}_3 \ \mathrm{DM} \ \mathrm{X} + \mathcal{L}_{kin}$$

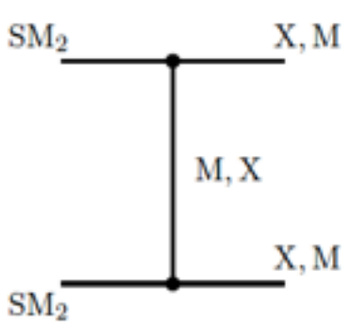
$\phi_i = (\mathrm{DM}, \mathrm{X}, \mathrm{M_t})$ are Z_2-odd.

Pair production $\phi_i \, \phi_j$

- $i = j$ production via kinetic terms + coannihilation diagram (recycled!)
- $i \neq j$ production via SM_j in the s-channel [g_j]

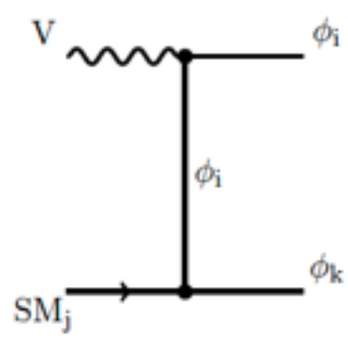


g_1^2



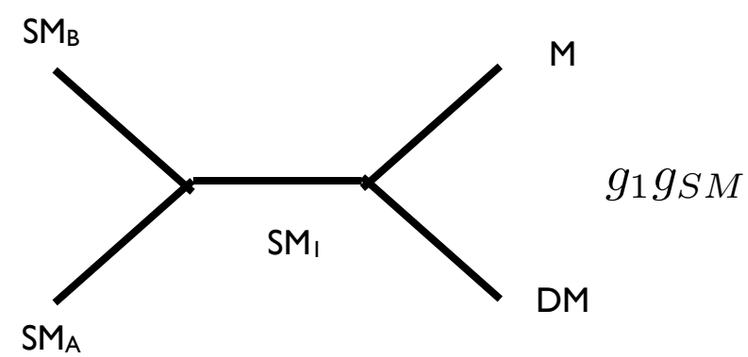
g_2^2

+



$g_j g_w$

+



$g_1 g_{SM}$

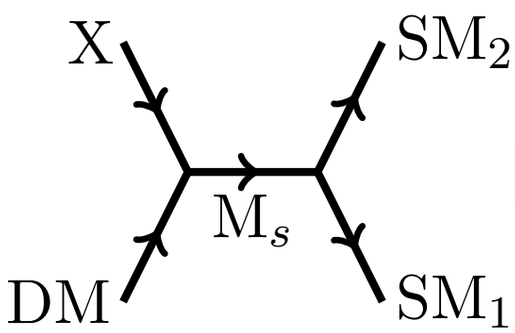
(loop over SM_i)

For LHC phenomenology is important to determine if $SM_{1,2}$ "belong" to the proton.

Naively: quarks, gluons and, to some extent, W,Z and photons do.

Higgs has a smallish XS (versus W,Z) and leptons come from O(10%) decays of W,Z.

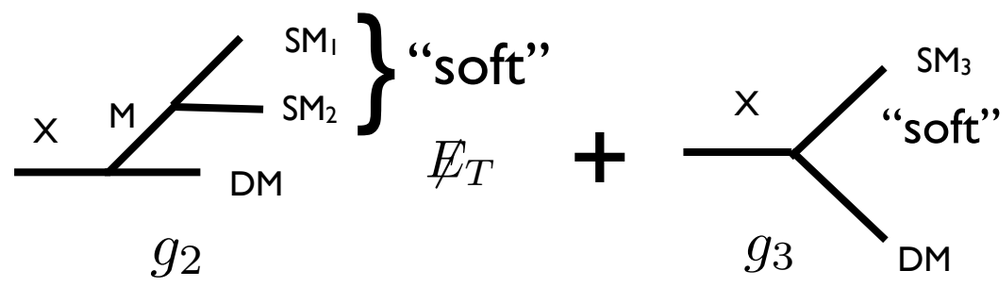
Decays (s-channel)



$$\mathcal{L} \supset g_1 \mathrm{SM}_1\ \mathrm{SM}_2\ \mathrm{M_s} + g_2 \mathrm{DM\ X\ M_s} + g_3 \mathrm{SM}_3\ \mathrm{DM\ X}$$
$$+ g_X \mathrm{M\ X\ X} + g_{DM} \mathrm{M\ DM\ DM} + \mathcal{L}_{kin}$$

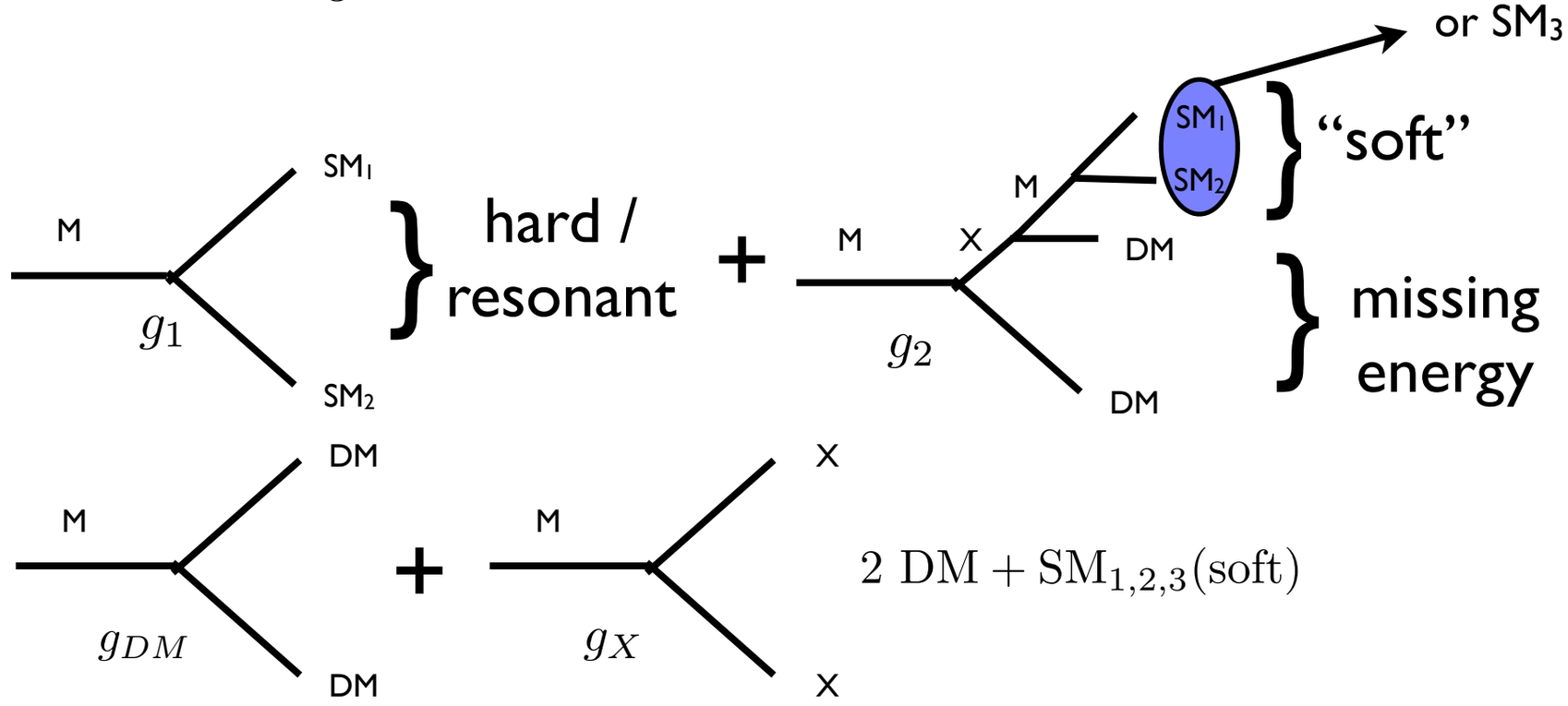
$\phi_i = (\mathrm{DM}, \mathrm{X})$ are Z_2-odd, M is Z_2-even

X:



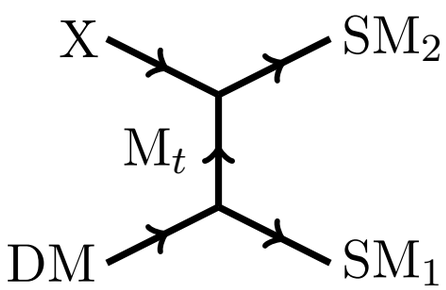
X always decays to $\not{E}_T + \mathrm{SM_{soft}}$.
Compressed spectra (ongoing efforts)

Mediator:



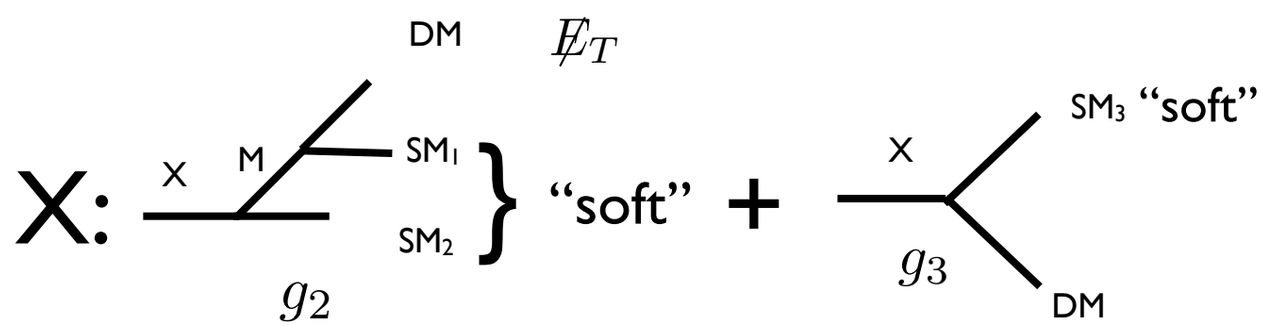
$2\ \mathrm{DM} + \mathrm{SM}_{1,2,3}(\mathrm{soft})$

Decays (t-channel)

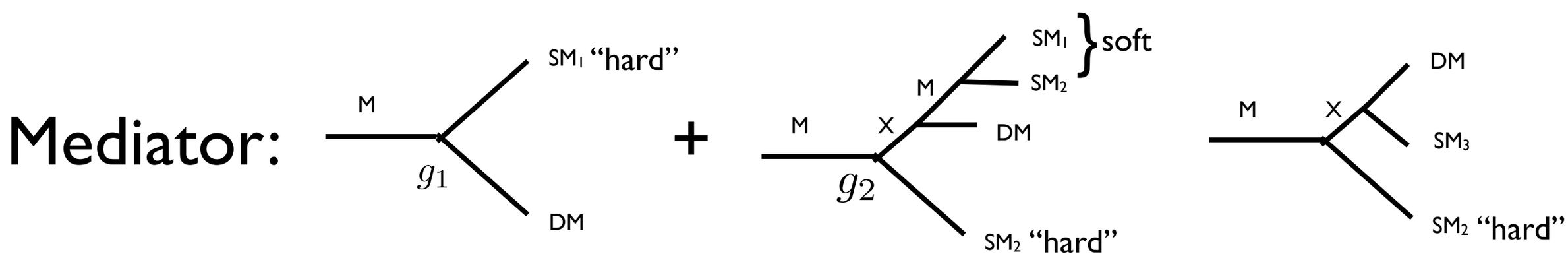


$$\mathcal{L} \supset g_1 \mathrm{SM}_1\ \mathrm{DM}\ \mathrm{M_t} + g_2 \mathrm{SM}_2\ \mathrm{X}\ \mathrm{M_t} + g_3 \mathrm{SM}_3\ \mathrm{DM}\ \mathrm{X} + \mathcal{L}_{kin}$$

$\phi_i = (\mathrm{DM}, \mathrm{X}, \mathrm{M_t})$ are Z_2-odd.



If M is also degenerate with X, DM: copycat X.

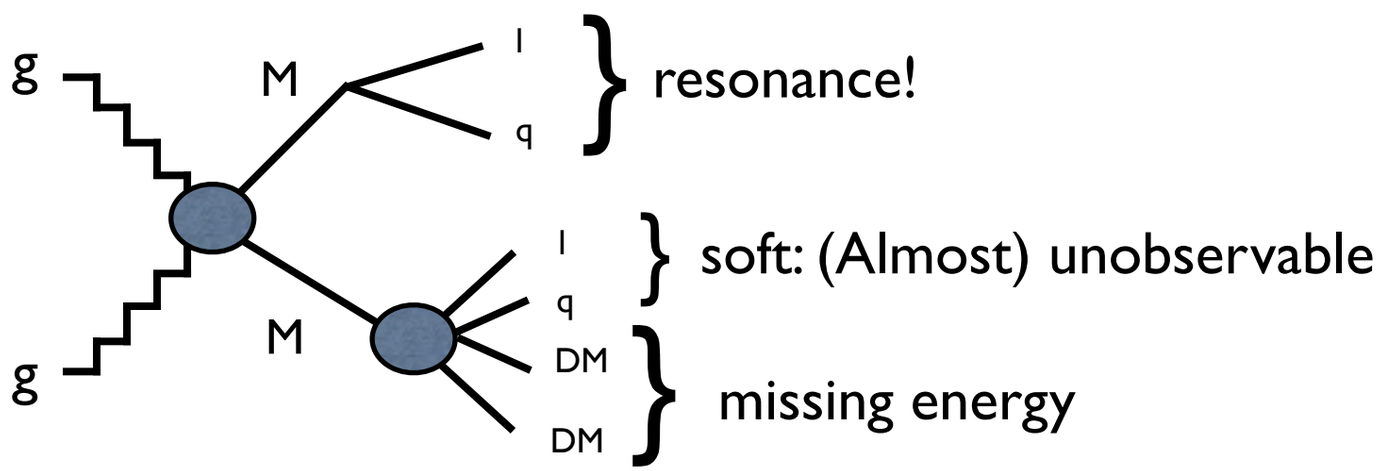


- Every M_t gives one (and only one) hard SM particle in the final state.
- All decays here involve missing transverse energy, unlike the s-channel case.

Signatures (s-channel)

- 1: Resonant M or MM production (covered by exotic searches at the LHC)
- 2: Monojet + MET + soft SM particles (under exploration...)
- 3: Mixed signature from M pair production: $\mathrm{MM} \to (\mathrm{SM}_1\ \mathrm{SM}_2)_{\mathrm{res}} + \not{E}_T + \mathrm{soft}$

<u>Example: leptoquark!</u>



- Production goes via gauge interactions, could be strong: large XS!
- Not covered by any existing LHC search.
- Resonant feature: good handle to kill the background and identify the signal.
- Predicts correlated excesses in di-resonance (LQ pairs) and monojet (plus soft).

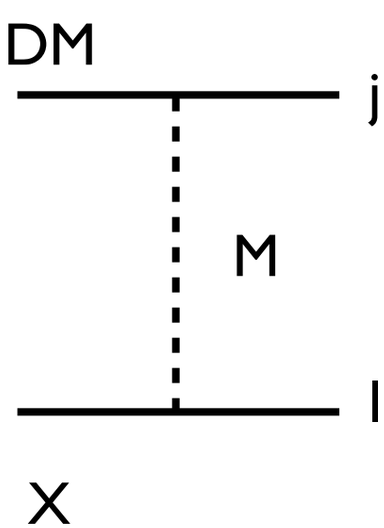
Signatures (t-channel)

- MSSM-like signatures covered by SUSY searches.
- Strongly produced X partner with soft leptons.
- Dilepton final states with strong production: *dark leptoquark*

The "dark" leptoquark

X, M colored.
M gives hard q or l.

ID	X	$\alpha+\beta$	M_t	SA	(SM1 SM2)	Vertices
TF1	$(3, N, \alpha)$	$\frac{10}{3}$	$(\bar{3}, N, \beta - \frac{4}{3})$	IV	$(u_R \bar{\ell}_L)$	
TF2			$(1, N, \beta - 2)$	IV	$(\bar{\ell}_L u_R)$	



ignore soft jets

$$\mathrm{M}\ \bar{\mathrm{M}} \to \mathrm{X}\ \bar{\mathrm{X}}\ l_{\mathrm{h}}^{+}\ l_{\mathrm{h}}^{-} \to\ l_{\mathrm{h}}^{+}\ l_{\mathrm{h}}^{-} l_{\mathrm{s}}^{+} l_{\mathrm{s}}^{-} \mathrm{DM}\ \mathrm{DM} = 2\ \mathrm{OSL} + \not{E}_T + 2 l_{\mathrm{s}}$$

"Slepton" pairs with strong production!!!

$$\mathrm{M}\ \mathrm{M} \to \mathrm{X}\ l_{\mathrm{hard}}\ \mathrm{DM}\ j_{\mathrm{hard}} \to l_{\mathrm{hard}} + j_{\mathrm{hard}} + \not{E}_T + l, j_{soft}$$

100% unconventional signature!!!

Signatures

	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 $2\mathrm{X} \to 2\,(\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$	$2\mathrm{X} \to 2\,(\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$
	$(\mathrm{SM}_1\mathrm{SM}_2) \in p$	$\mathrm{M}_s \to (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$	$\mathrm{X}\ \mathrm{DM} \to (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$
	$\mathrm{SM}_1 \in p$	$\mathrm{M}_s\ \mathrm{SM}_2 \to (\mathrm{SM}_2)_{\mathrm{hard}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$	$\mathrm{M}_t\ \mathrm{DM} \to (\mathrm{SM}_2)_{\mathrm{hard}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$
	$\mathrm{SM}_2 \in p$	$\mathrm{M}_s\ \mathrm{SM}_1 \to (\mathrm{SM}_1)_{\mathrm{hard}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$	$\mathrm{X}\ \mathrm{M}_t \to (\mathrm{SM}_1)_{\mathrm{hard}} + (\mathrm{SM}_1\mathrm{SM}_2)_{\mathrm{soft}} + \not{E}_T$

s-channel features unique resonant signature and hard radiation. Not considered at the LHC in the context of DM searches.

t-channel signatures are MSSM-like. Interesting to consider all $\mathrm{SM}_{1,2}$ possibilities for hard particles coming from M_t decays.

Dark Matter mediated by Leptoquarks

Example: SF 11

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SF12				F	$(u_R H)$	

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2- Assign spins, quantum numbers:

Field	$(SU(3), SU(2), U(1))$	Spin assignment
DM	(1, 1, 0)	Majorana fermion
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DM, X could have been scalars or vectors.

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3- Write down the Lagrangian

$$\mathcal{L} = i\mathrm{DM}^c \not{D}\mathrm{DM} \ + i\overline{\mathrm{X}}\not{D}\mathrm{X} \ + |D_\mu \mathrm{M}|^2 + \frac{m_{\mathrm{DM}}}{2}\mathrm{DM}\ \mathrm{DM} \ + m_{\mathrm{X}}\overline{\mathrm{X}}\ \mathrm{X}$$
$$- \left[V(H) + \frac{1}{2}m_{\mathrm{M}}^2\mathrm{M}^2 + \frac{1}{4}\lambda_{\mathrm{M}}\mathrm{M}^4 + \epsilon_{\mathrm{M}}\mathrm{M}^2\left(H^2 - \frac{v^2}{2}\right)\right]$$
$$+ \left(y_D\overline{\mathrm{X}}\ \mathrm{M}\ \mathrm{DM} \ + \mathrm{h.c.}\right) + \left(y_{Q\ell}\overline{Q}_R\mathrm{M}\ \ell_R + \mathrm{h.c.}\right) + \left(y_{Lu}\overline{L}_R\mathrm{M}^c u_R + \mathrm{h.c.}\right)\ .$$

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4- Free params: $m_{\mathrm{DM}}, m_{\mathrm{X}}, m_{\mathrm{M}}, y_D, y_{Q\ell}, y_{Lu}, \lambda_{\mathrm{M}}, \epsilon_{\mathrm{M}}$

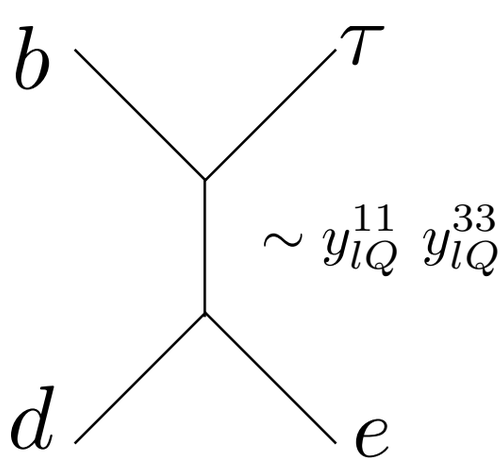
The flavor story

- y_{Ql}, y_{Lu} are matrices in flavor space. Neglect CP-violation.

$$\mathcal{L} \supset \left\{ y_{Q\ell}^{ij} \left[\overline{u_L}^i \phi^{5/3} \ell_R^j + \overline{d_L}^i \phi^{2/3} \ell_R^j \right] + y_{Lu}^{ij} \left[\overline{\nu_L}^i \left(\phi^{2/3}\right)^* u_R^j - \overline{\ell_L}^i \left(\phi^{5/3}\right)^* u_R^j \right] + \text{h.c.} \right\}$$

- Strong constraints from meson mixing (i.e $K - \bar{K}, B - \bar{B}, B_s - \bar{B}_s, D - \bar{D}$) gives strong constraints, take off-diagonal elements to zero.

- Lepton-flavor violating probes



$\text{Br}(B_d \to \tau^+ e^-) < 2.8 \times 10^{-5}$ → $y_{lQ}^{11}\ y_{lQ}^{33} < 1.1,\ m_\phi = 1\ \text{TeV}$

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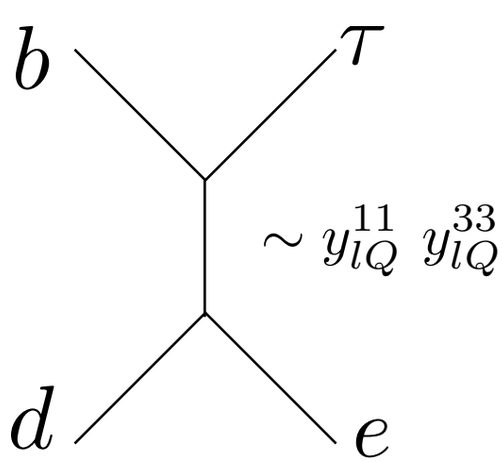

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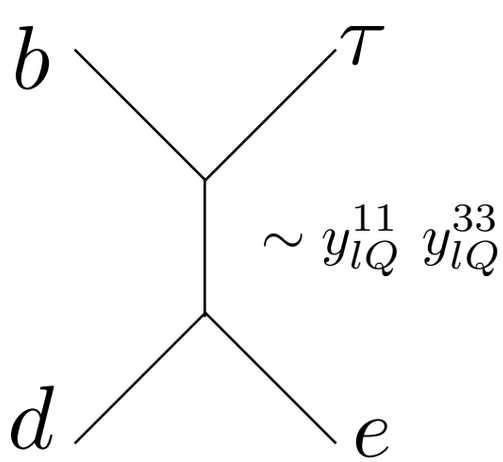

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↓

Belle II? LHCb?

Simplifications and analysis

- Avoid neutrinos and obvious issues with flavor:

$$y_{Lu} = 0, y_{Ql}^{11} \neq 0 \text{ (electrons) OR } y_{Ql}^{22} \neq 0 \text{(muons)}\,.$$

- λ_M, ϵ_M are irrelevant for the pheno. No H-M mixing.

- Equal BRs into SM and dark-sector.

- DM, X close in mass, $\Delta = (m_{\rm X} - m_{{\rm D}M})/m_{\rm X}$ is not arbitrary.

Pheno analysis

Mixed: $\mathrm{M\ M} \to (lq)_{\rm res}\ (\mathrm{X\,DM}) \to (lq)_{\rm res} + \not{E}_T$

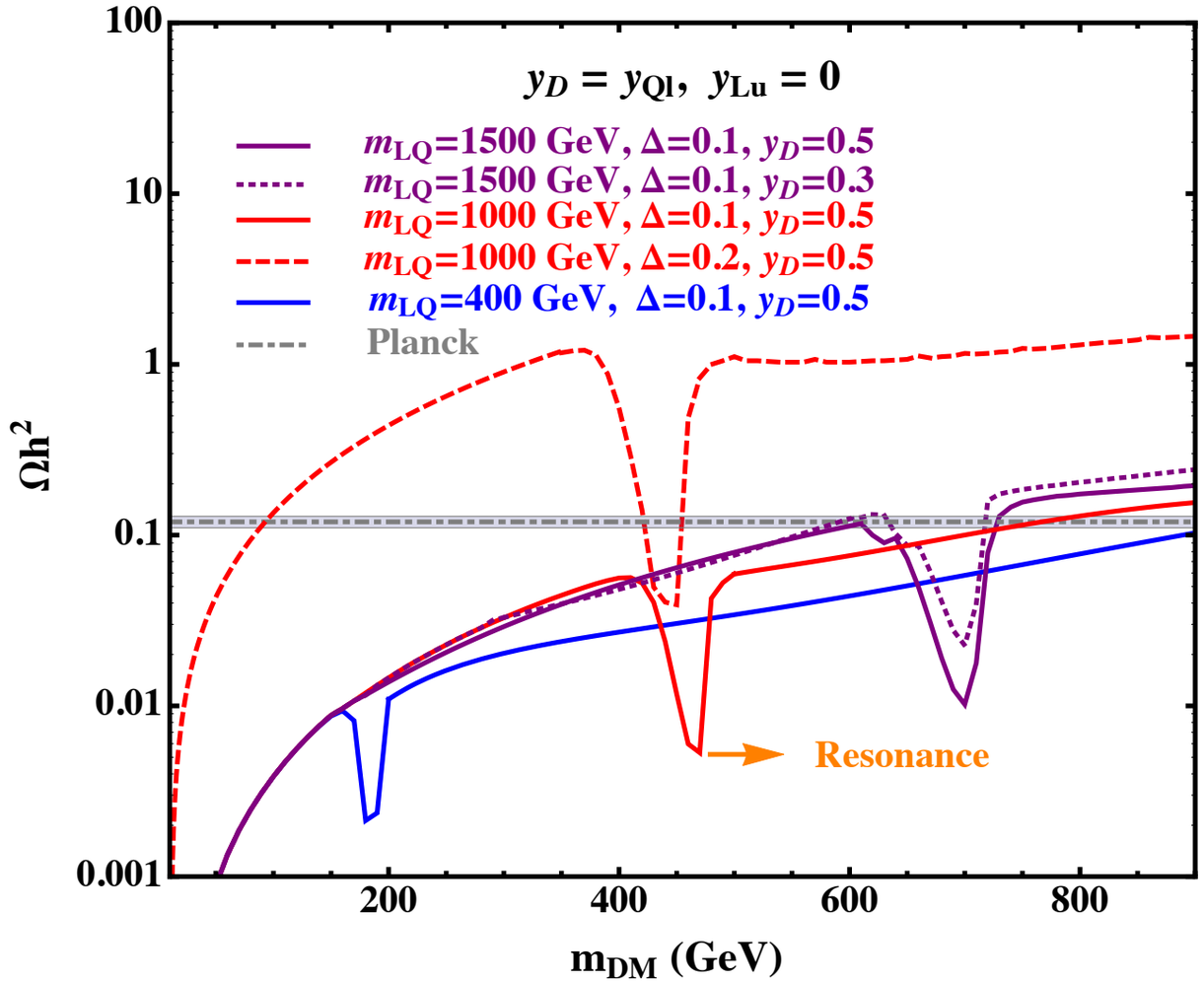
Monojet: $\mathrm{X\ X} + j \to j + \not{E}_T + l_{\rm s}^+ l_{\rm s}^-$

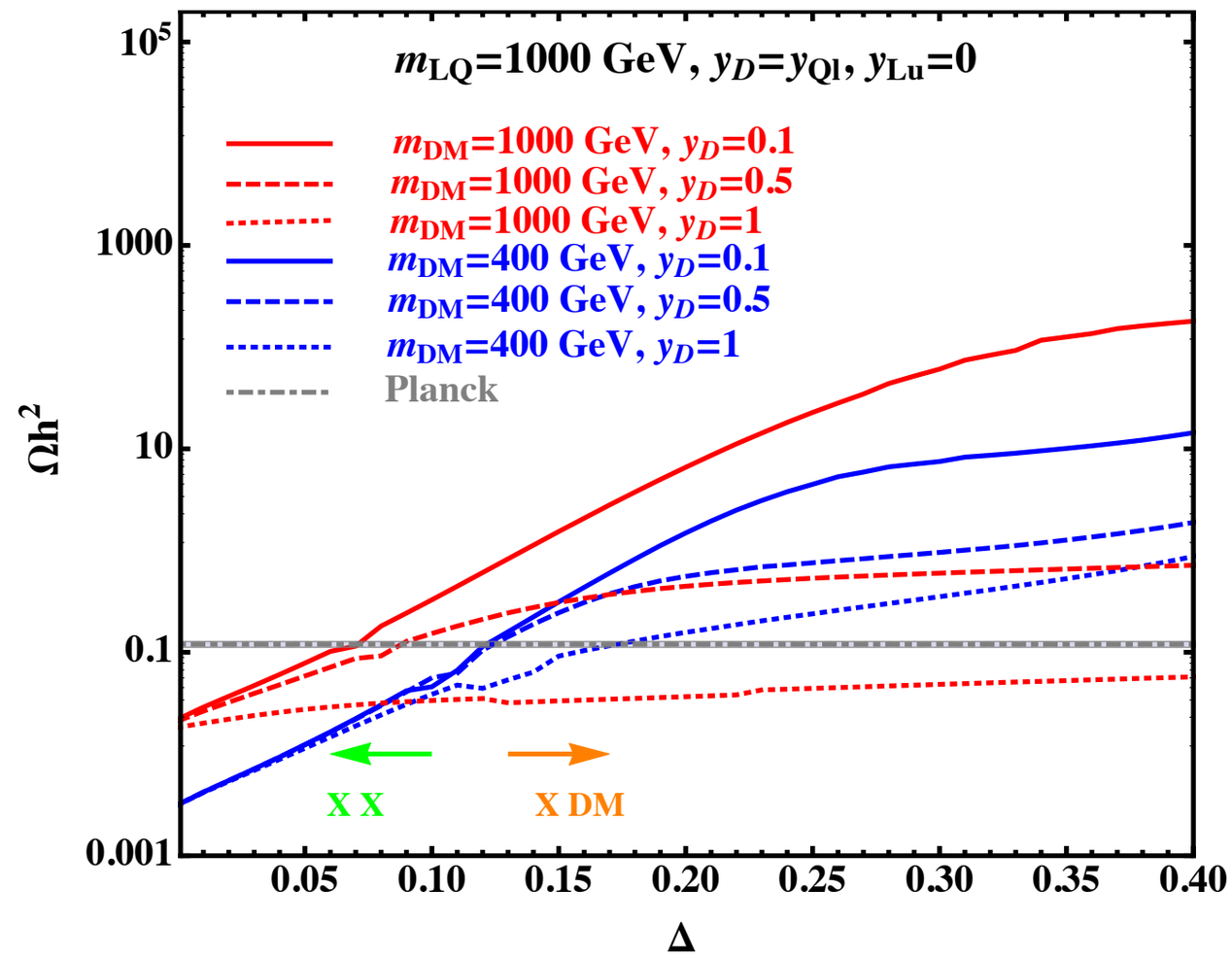
Current bounds

$\mathrm{M\ M} \to (lq)\ (lq)$ ATLAS (arXiv 1508.04735), CMS-PAS-EXO-12-041

$\mathrm{M}\ l \to (lq)\ l$ CMS-PAS-EXO-12-043

Relic density





- Thresholds can be seen (resonances).

- Strong dependence on Δ, y_D .

LHC phenomenology

$pp \to \mathrm{M}\ \mathrm{M} \to (lq)_{\mathrm{res}} + (lq)_{\mathrm{soft}} + \not{E}_T$ in MG5_aMC@NLO / Pythia 6.4 / Delphes 3.2

Background	Cross section (pb)
QCD	2.1×10^7
Leptonic $W^\pm + 1$, 2 jets	2235
Semileptonic $t\bar{t}$	791
$(Z \to \nu\nu) + j$	738
$(Z \to \tau^+\tau^-) + j$	163
Semileptonic W^+W^-	9.8
$W(Z \to \nu\nu) + j$	2.2
$W(Z \to jj)$	2.2

Basic cuts:

$p_T(j_1) > 50\ \mathrm{GeV},\ p_T(e_1) > 30\ \mathrm{GeV}$

$N_e < 2\,, N_{hard\ jets} \leq 3\,.$

vetoes: b jets, Z

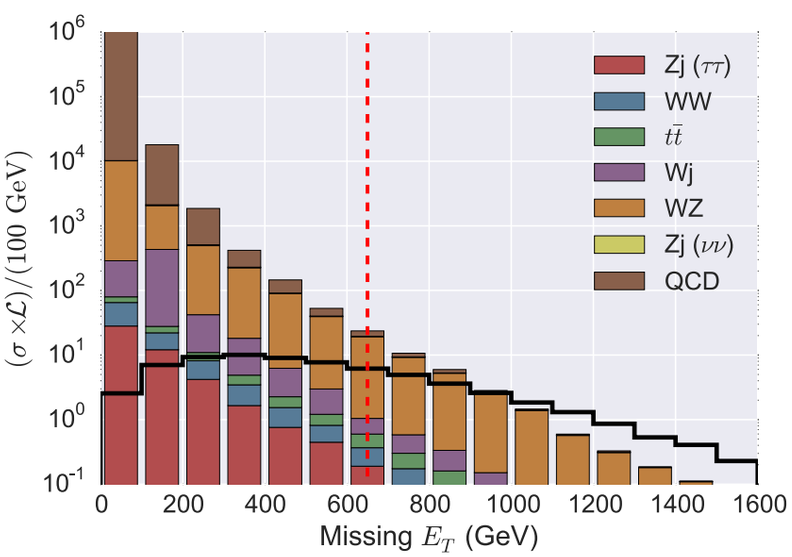
Signal benchmark

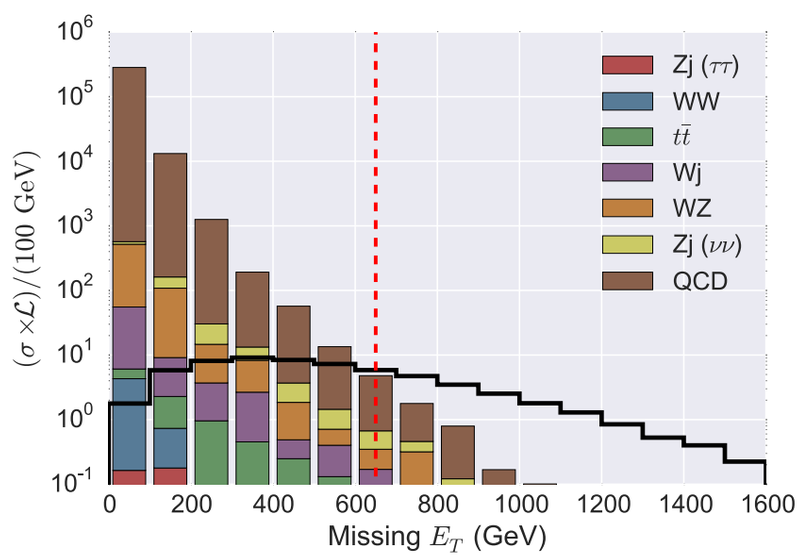
DM=405 GeV

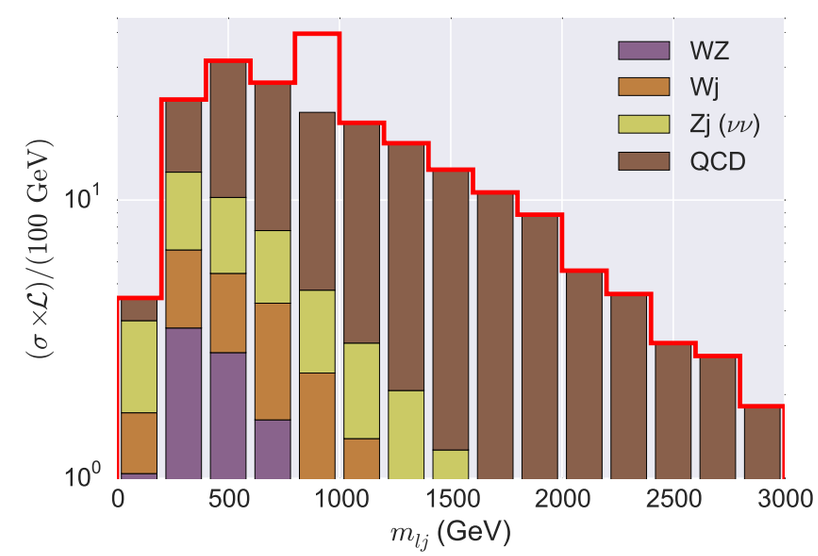
X=445 GeV

M=950 GeV

σ(MM) = 8 fb







Basic cuts → $m_T > 100\ \mathrm{GeV}$ → $\not{E}_T > 650\ \mathrm{GeV}$

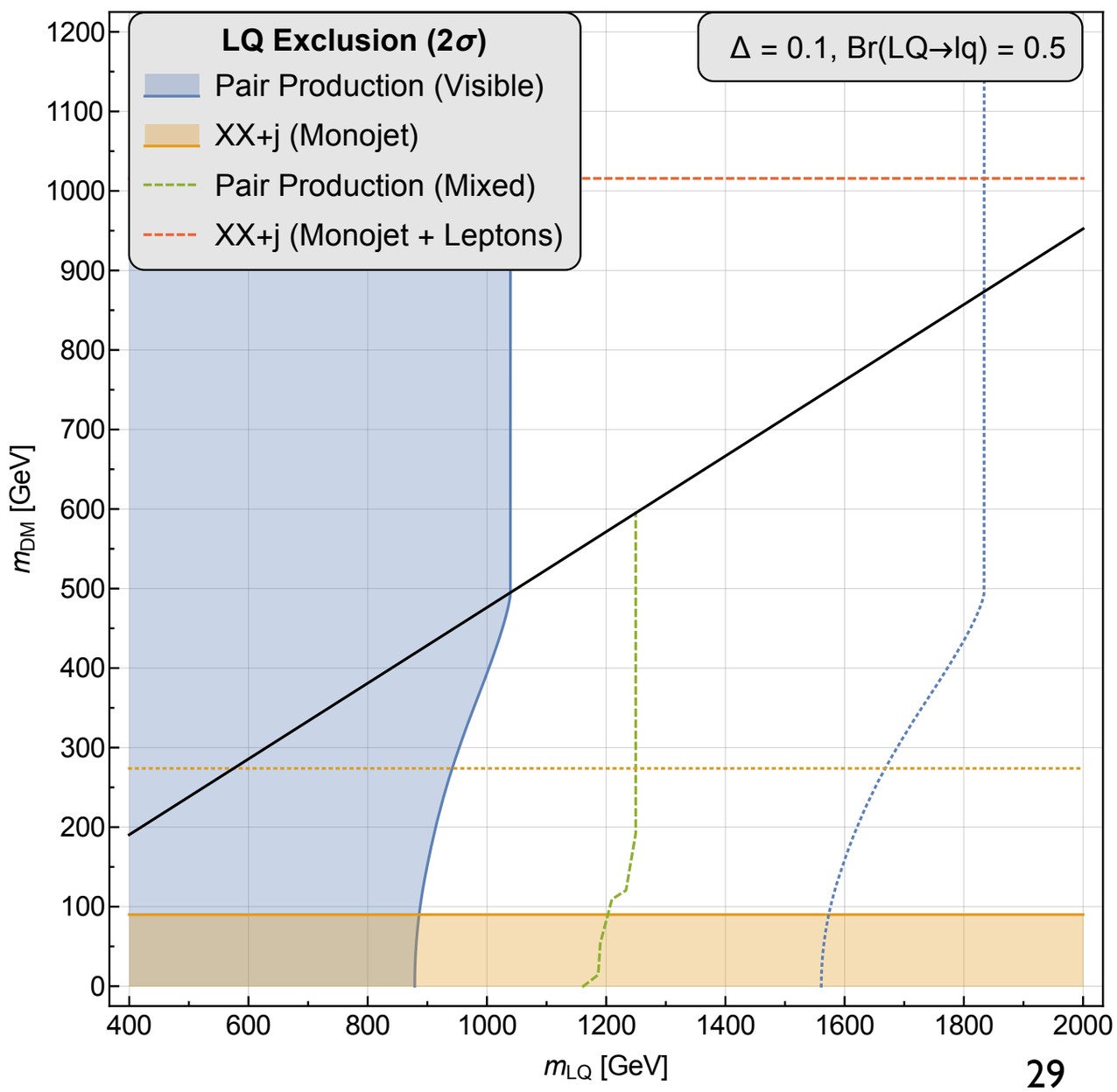
↓

Apply 40 GeV mass window

Pheno status

Existing searches (8, 13 TeV)
- LQ single
- LQ pairs
- monojet (XX+j)

Future probes (13 TeV)
- LQ pairs "mixed"
- monojet + soft leptons



LQ pairs insensitive to y_D, y_{Lq}, strong production, limited by mass.

LQ single prod. very sensitive to y_D, y_{Lq}, no meaningful constraints for $y_D = 0.1$.

Mixed: Exclusion up to 1.2 TeV with $\mathrm{BR}(\mathrm{M} \to lq) = 0.5$ and $\mathcal{L} = 100\ \mathrm{fb}^{-1}$.

XX+j, excludes m_X <0.3 (1.1) TeV for traditional monojet (+soft leptons).

Mixed signature is key to establish co-annihilation at the LHC.

Conclusions

- We have performed a general classification of coannihilating dark matter, assuming only that dark-matter is a thermal relic described by dimension 4 operators.

- We build a compact minimal basis of simplified models under our assumptions.

- Our basis provide the building blocks for *any renormalizable thermal DM theory*, which can be reached by combining several entries and adding mixing and Higgs insertions.

- We have studied the potential signatures of all of our models, which leads to a very rich phenomenology at colliders.

- Our basis is also useful for GeV/MeVish DM (most likely Uncolored models).

- We have presented a non-standard DM search in the context of leptoquark mediators, which are not being searched for at the LHC.

- Plenty left for future studies: direct/indirect detection, cosmology, flavor bounds, additional "non-standard" models, etc...