

The Coannihilation Codex

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Planck 2016

- first general and complete classification of simplified (co)annihilating dark matter models
- complete characterization of dark matter collider signatures
- strong production of "dark sector" particles
- testing the dark matter (co)annihilation hypothesis at the LHC

The Coannihilation Codex

M.Baker, J.Brod, S.El Hedri, A.Kaminska, J.Kopp, J.Liu, A.Thamm,
M.de Vries, X.Wang, F.Yu, J.Zurita
JHEP 1512 (2015) 120

Assumption 1. DM is colorless and electrically neutral

Assumption 2. DM interacts with the SM

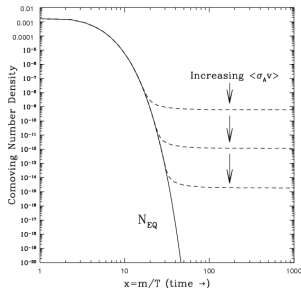
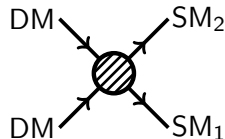
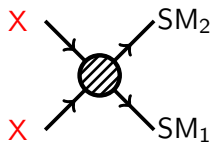
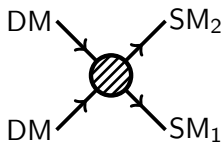
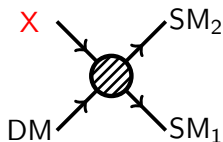


figure by Dan Hooper



- ⇒ relic density
- ⇒ indirect detection
- ⇒ direct detection
- ⇒ LHC searches

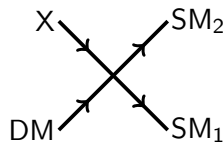
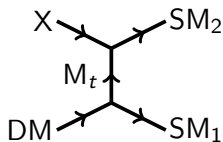
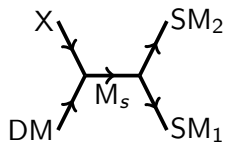
Coannihilation



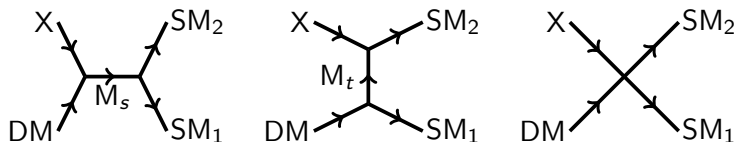
$$m_X = m_{\text{DM}} (1 + \Delta), \quad \Delta \ll 1$$

X can have $U(1)_{EM}$ and/or QCD charges

Coannihilation - simplified models



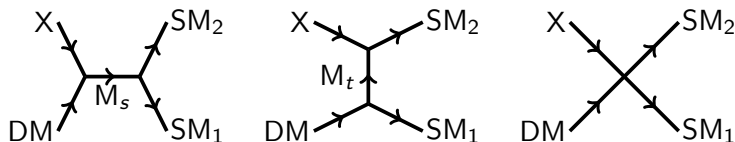
Coannihilation - simplified models



Assumptions 3.

- (co)annihilation via a two-to-two process
- tree-level interaction vertices
- at most 3 new fields with spin 0, 1/2 or 1
- new spin 1 particles are massive vectors with minimal coupling

Coannihilation - simplified models



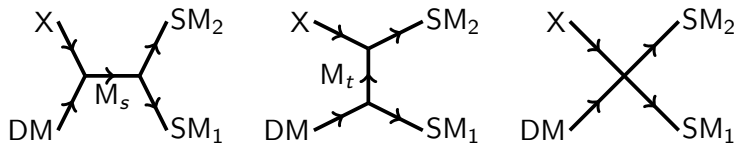
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Exciting new LHC pheno

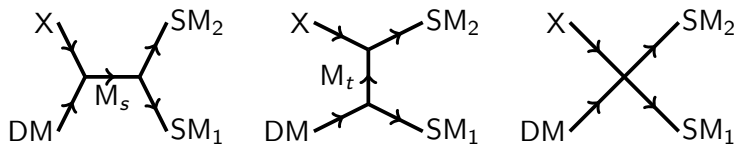
- going beyond mono-jet+MET \rightarrow new resonances, compressed spectra, new signatures
- possible strong production of X and M (model independent!)

Building the classification



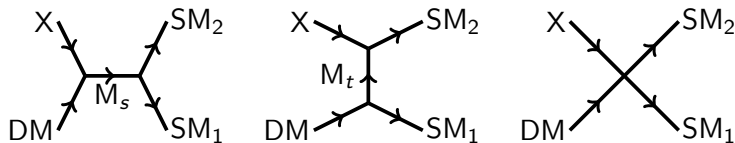
- order according to $SU(3)_C \times SU(2)_L \times U(1)_Y$ charges
→ EW group unbroken

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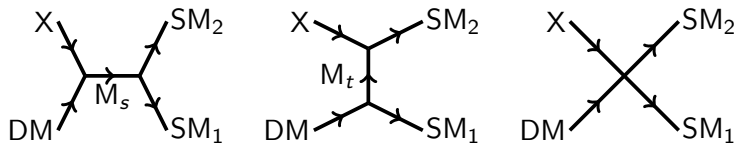
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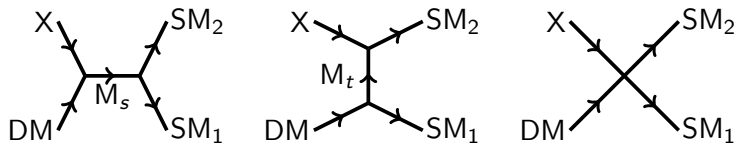
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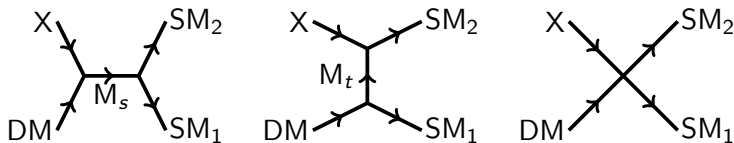
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Building the classification

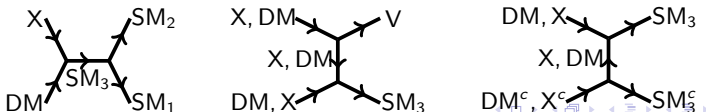


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- dark sector parity introduces a division into s-channel and t-channel mediated models

Building the classification



- order according to $SU(3)_C \times SU(2)_L \times U(1)_Y$ charges
 - EW group unbroken
 - $DM = (1, N, \beta)$
 - go over all $(SM_1 SM_2)$ combinations determining X
 - introduce a mediator, spin assignment, check self-consistency
- dark sector parity introduces a division into s-channel and t-channel mediated models
- the special case of "hybrid" models



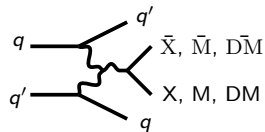
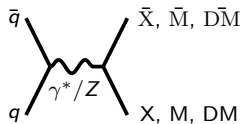
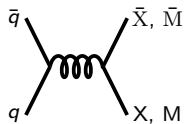
A small sample of models - M_S , X color singlets

ID	X	$\alpha + \beta$	M_S	Spin	(SM ₁ SM ₂)	X-DM-SM ₃	M_S -X-X
SU1	(1, N, α)	0	(1, 1, 0)	B	$(u_R \bar{u}_R), (d_R \bar{d}_R), (\ell_R \bar{\ell}_R)$ $(Q_L \bar{Q}_L), (L_L \bar{L}_L), (H H^\dagger)$	H1	✓
SU2				F	$(L_L H)$		
SU3				B	$(Q_L \bar{Q}_L), (L_L \bar{L}_L), (H H^\dagger)$	H1	✓
SU4		F	$(L_L H)$				
SU5		-2	(1, 1, -2)	B	$(d_R \bar{u}_R), (H^\dagger H^\dagger), (L_L \bar{L}_L)$		✓
SU6				F	$(L_L H^\dagger)$	H2	
SU7			B	$(H^\dagger H^\dagger), (L_L \bar{L}_L)$		✓ ($\alpha = \pm 1$)	
SU8			F	$(L_L H^\dagger)$	H2		
SU9		-4	(1, 1, -4)	B	$(\ell_R \bar{\ell}_R)$		✓ ($\alpha = \pm 2$)
SU10	(1, N \pm 1, α)	-1	(1, 2, -1)	B	$(d_R \bar{Q}_L), (\bar{u}_R Q_L), (\bar{L}_L \bar{\ell}_R)$	H3	
SU11				F	$(\ell_R H)$	H4	
SU12		-3	(1, 2, -3)	B	$(L_L \bar{\ell}_R)$		
SU13				F	$(\ell_R H^\dagger)$		
SU14	(1, N \pm 2, α)	0	(1, 3, 0)	B	$(Q_L \bar{Q}_L), (L_L \bar{L}_L), (H H^\dagger)$		✓ ($\alpha = 0$)
SU15				F	$(L_L H)$		
SU16		-2	(1, 3, -2)	B	$(H^\dagger H^\dagger), (L_L \bar{L}_L)$		✓ ($\alpha = \pm 1$)
SU17				F	$(L_L H^\dagger)$		

List of possible models which give rise to coannihilation diagrams in the s-channel, for DM representation $(1, N, \beta)$ and X a color singlet. Gray shaded entries denote models with fermionic mediators, while unshaded entries represent models with bosonic mediators.

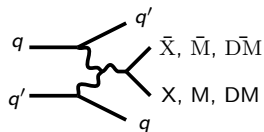
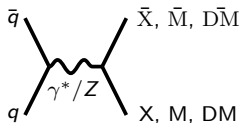
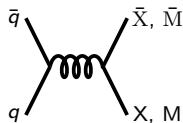
Phenomenology: LHC production

pair production via gauge interactions

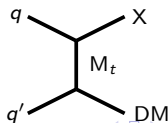
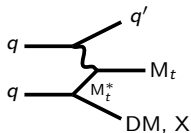
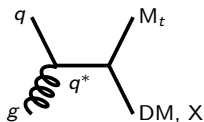
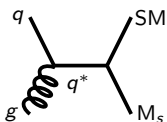
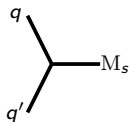


Phenomenology: LHC production

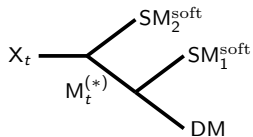
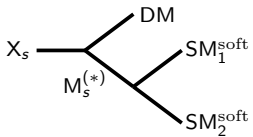
pair production via gauge interactions



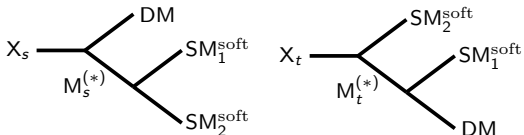
production via coannihilation diagram vertices



Common signature classes

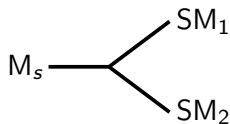


Common signature classes



- $X X + \text{ISR} \rightarrow \text{mono-}Y + \text{MET} + \text{soft}$
 - extending the traditional mono-jet+MET to include additional soft but resolvable particles
 - potential for a strongly produced MET signature at the LHC

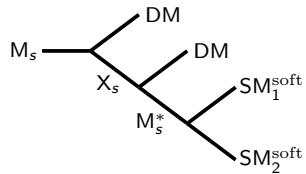
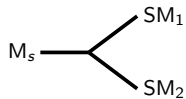
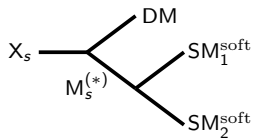
s-channel models: resonances



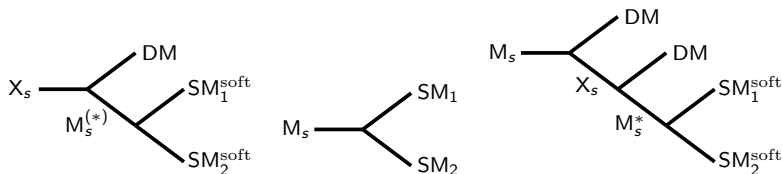
M_s class	$(SM_1 SM_2)$	M_s type
uncolored B	QQ,LL,BB	$SU(2)_L$ singlet
		H'
		Higgs triplet
		Z'
	LL	W'
uncolored F	BL	dilepton
		L'
colored B	QL	lepton partner
	QQ,QL	leptoquark
	QQ	leptoquark-diquark
colored F	QB,Qg	diquark
	QB	quark partner
		Q'

Overview of s-channel mediator properties

s-channel models: decay modes



s-channel models: decay modes

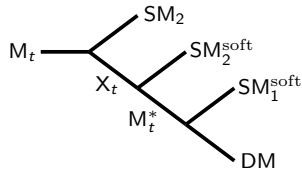
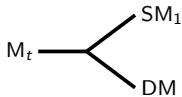
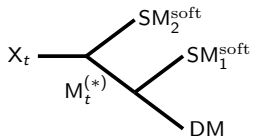


complementary to the (SM_1 SM_2) resonance

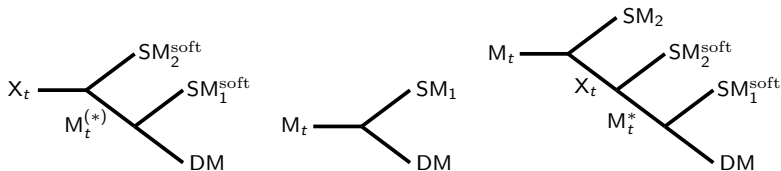
- $M_s M_s \rightarrow$ resonance + MET (+ soft)
 - allows to directly probe the dark sector connection in case of a new resonance discovery
 - "mixed signature" not targeted at the LHC
- $M_s M_s \rightarrow$ MET + soft

parallel use of direct new resonance searches, extended mono-jet+MET and "mixed" mediator decay searches allows for a complete test of dark matter coannihilation hypothesis at the LHC

t -channel models: decay modes



t -channel models: decay modes



- no new resonances
- always + MET
- many SUSY-like signatures
- compressed spectra
- cascade decays of M_t

Lookout - *strong* coannihilation models

Don't miss the talk by José Zurita, Thursday 16:20!!!

M.Buschmann, S.El Hedri, A.Kaminska, J.Liu, M.de Vries, X.Wang, F.Yu, J.Zurita,
1605.XXXXX

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→ leptoquark, diquark

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- novel LHC signatures
- $XX + \text{ISR} \rightarrow \text{hard ISR jet} + 2\ell + 2j + \cancel{E}_T$
- $M_s M_s \rightarrow \text{a single } (\ell j) \text{ resonance} + \ell + j + \cancel{E}_T$
- $M_s M_s \rightarrow \text{a single } (jj) \text{ resonance} + \text{jets} + \cancel{E}_T$
- "mixed" mediator decay signature as a direct test of coannihilation at the LHC

Conclusions

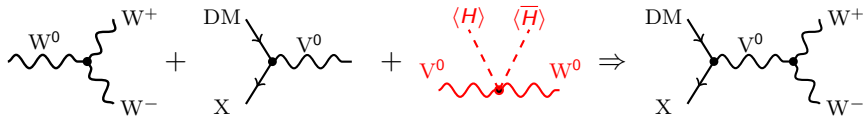
- first complete general classification of two-to-two simplified coannihilation models
- coannihilation allows for the possibility of strong (model independent) production of the coannihilation partner X and mediator M at the LHC
- topology of the coannihilation diagram, gauge charges and coannihilation condition $\Delta \ll 1$
→ general classes of collider signatures
- signatures not targeted at the LHC
 - modified mono-jet
mono- $Y + \cancel{E}_T + \leq 4 \text{ SM}$
 - mixed mediator decays
 $M_s M_s \rightarrow \text{resonance} + \text{MET} (+ \text{soft})$
- in case of discovery of a new resonance → set of complementary searches testing the dark sector connection and coannihilation hypothesis at the LHC

Backup - Impact of electroweak symmetry breaking

$SU(2)_L \times U(1)_Y$ -violating vertices can be generated through Higgs insertions:

- new SM_1, SM_2 : $H \leftrightarrow \{W_i, B\}, f_L \leftrightarrow f_R$
- mixing between different $SU(2)$ -conserving models
- new possible X and M
- mass splitting inside multiplets

Example: from $W_i (1, 3, 0)$ to $V_i (1, 5, 0)$ in the 3 – 3 – 1 model

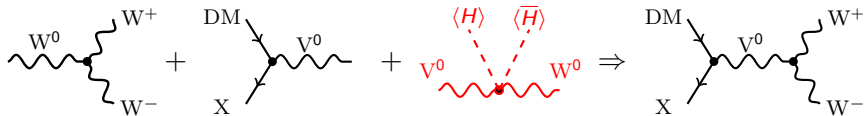


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From each $SU(2)$ -conserving model, one can readily build an **equivalence class** of $SU(2)$ -breaking models.

The $SU(2)$ -conserving models remain the most fundamental building blocks for our classification.