

The Coannihilation Codex

Michael J. Baker

with

Joachim **Brod**, Sonia **El Hedri**, Anna **Kaminska**, Joachim **Kopp**, Jia **Liu**,
Andrea **Thamm**, Maikel **de Vries**, Xiao-Ping **Wang**, Felix **Yu**, José **Zurita**

arXiv:1510.03434

JGU Mainz

TeVPA 2016 - CERN - 13 September 2016



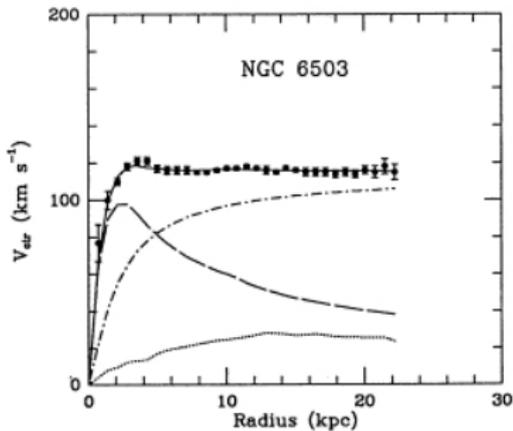
Outline

- 1 Motivation
- 2 Coannihilation Codex
- 3 Using the Codex

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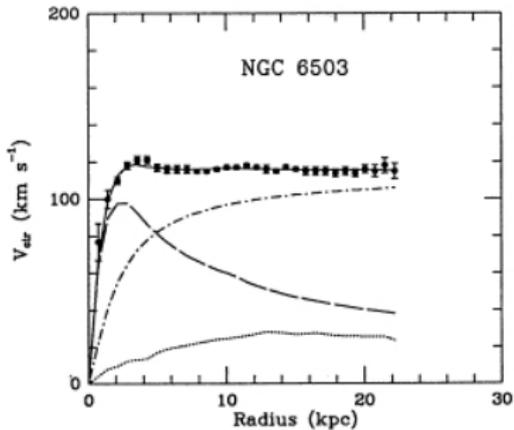
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Dark Matter

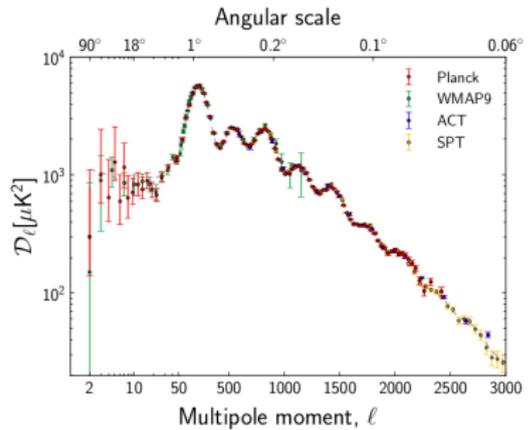


Begeman, Broeils & Sanders, 1991

Dark Matter

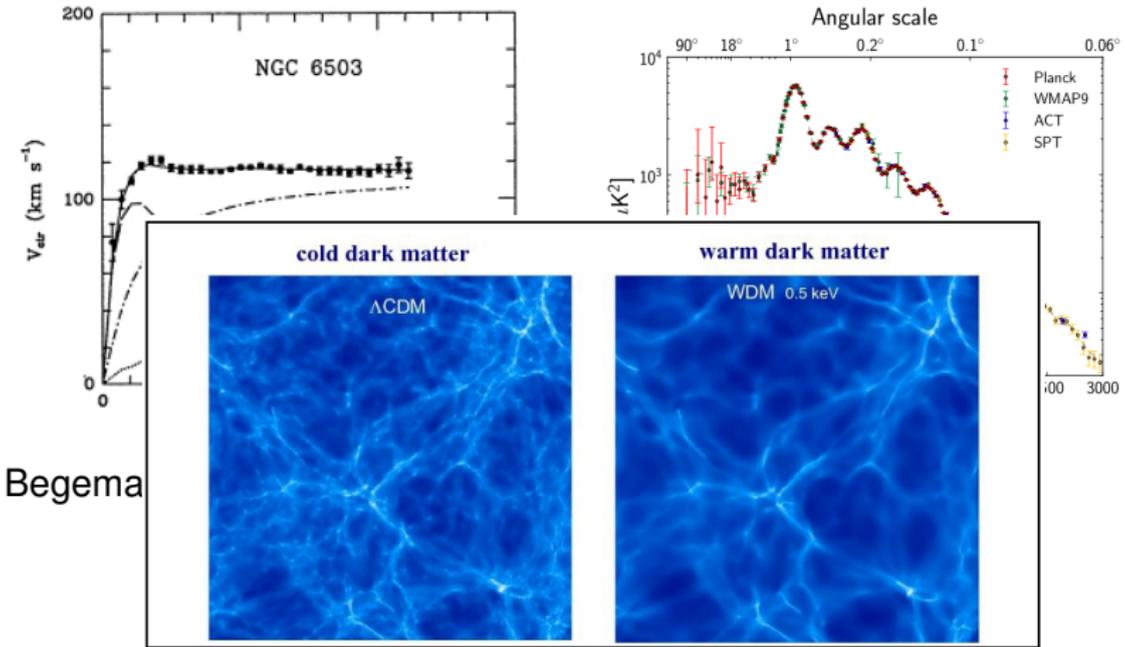


Begeman, Broeils & Sanders, 1991



Planck, 2013

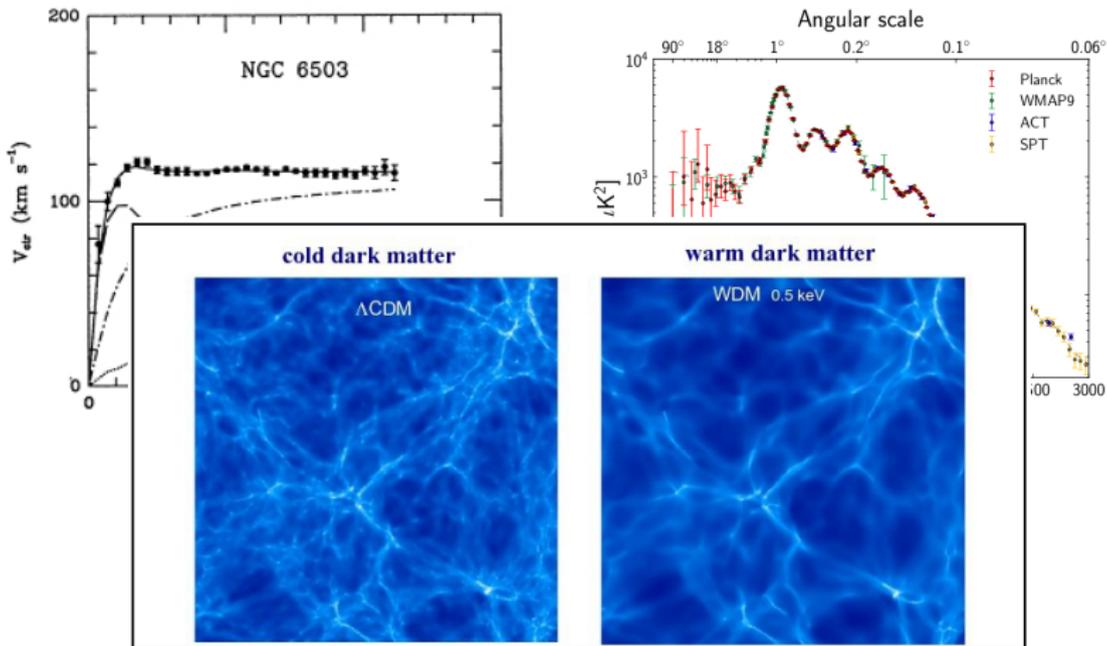
Dark Matter



Begema

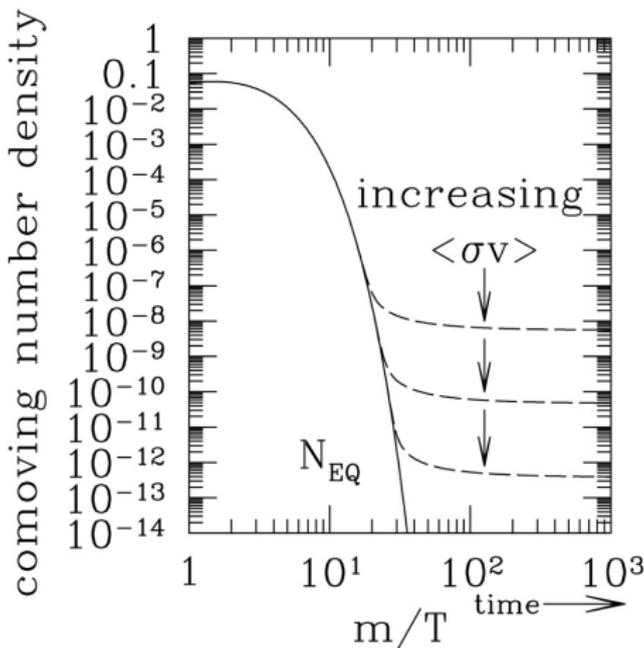
Viel, Becker, Bolton & Haehnelt, 2013

Dark Matter



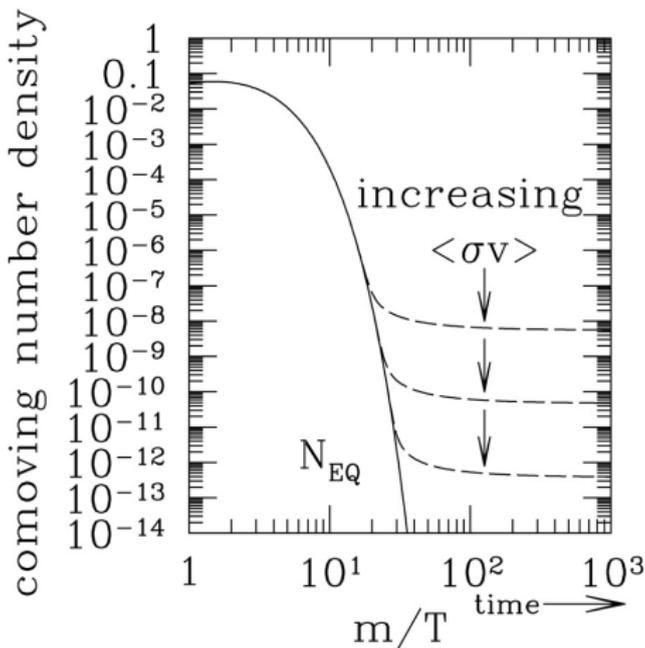
$$\Omega_{\text{nbm}} h^2 = 0.1198 \pm 0.0026$$

Relic Density from Thermal Freeze-out



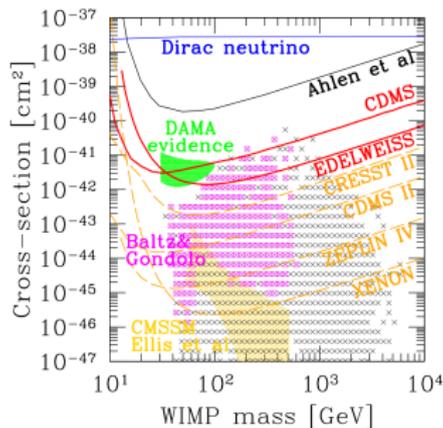
$$\frac{dn}{dt} = -\langle \sigma v \rangle (n(t)^2 - n_{eq}(t)^2) - 3H(t)n(t)$$

Relic Density from Thermal Freeze-out



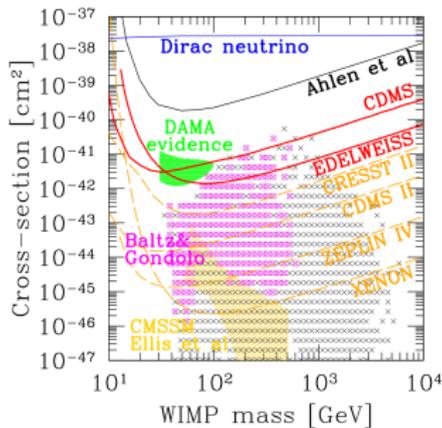
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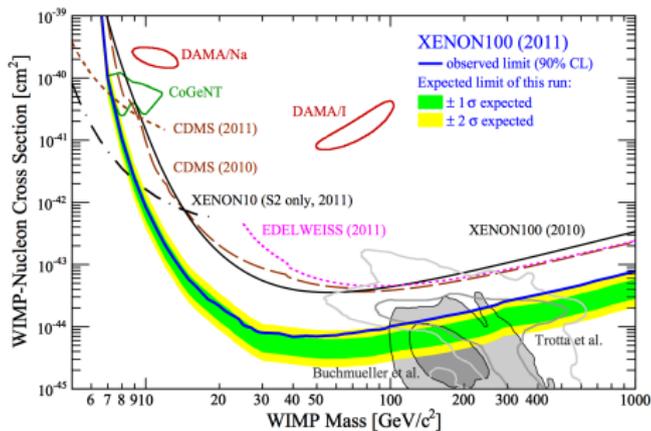


P. Gondolo, astro-ph/0403064

Relic Density from Thermal Freeze-out

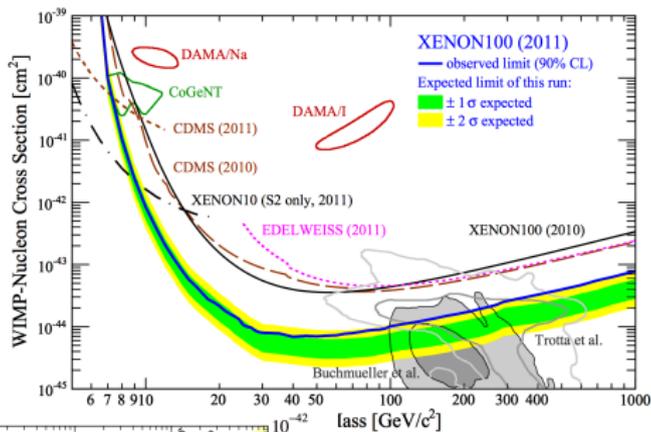
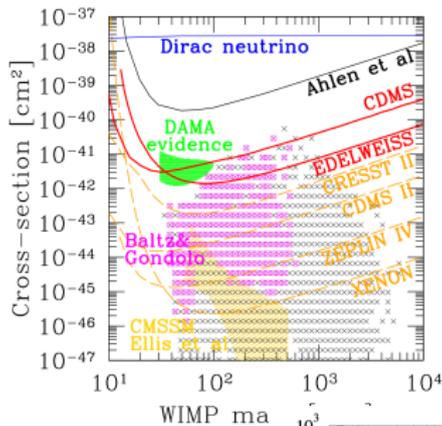


P. Gondolo, astro-ph/0403064

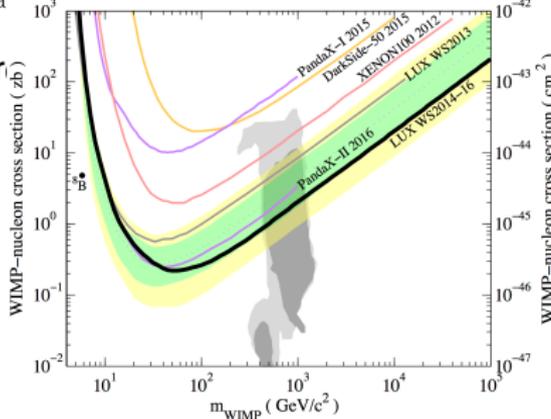


Xenon100, 1104.2549

Relic Density from Thermal Freeze-out



P. Gondolo, astr



1104.2549

LUX, 1608.07648

Coannihilation

PHYSICAL REVIEW D

VOLUME 43, NUMBER 10

15 MAY 1991

Three exceptions in the calculation of relic abundances

Kim Griest

Center for Particle Astrophysics and Astronomy Department, University of California, Berkeley, California 94720

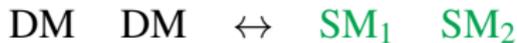
David Seckel

Bartol Research Institute, University of Delaware, Newark, Delaware 19716

(Received 15 November 1990)

Forbidden annihilation
Resonant annihilation
Coannihilation

Coannihilation

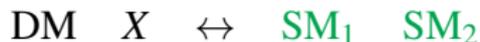


$$\frac{dn}{dt} = - \langle \sigma_{\text{eff}} v \rangle (n(t)^2 - n_{\text{eq}}(t)^2) - 3Hn$$

$$\sigma_{\text{eff}} \sim \sigma_{\text{DMDM}} + 2\sigma_{\text{DMX}}(1 + \Delta)^{3/2} e^{-x_f \Delta} + \sigma_{\text{XX}}(1 + \Delta) e^{-2x_f \Delta}$$

$$\Delta = \frac{m_{\text{DM}} - m_X}{m_{\text{DM}}}, \quad x_f = \frac{m_{\text{DM}}}{T_f}$$

Coannihilation



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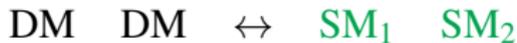


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Coannihilation in the literature

Bino-Higgsino: 1601.01569, 1510.06151, 1510.02760, 1509.08838

Bino-gluino: 1509.03613, 1508.04811

Bino-wino: 1509.03613, 1506.08206

Bino-stau: 1509.08838, 1509.07152

Bino-sleptons: 1506.08202

Bino-stop: 1509.08838

Neutralino-chargino: 1509.08485, 1507.02288, 1506.08202

Neutralino-sbottom: 1507.01001

Neutralino-gluino: 1510.03498

Radiative Neutrino Mass Models: 1512.07961, 1509.04068, 1507.067

Scalar DM & vector-like quark mediator: 1511.04452

Triplet-Quadruplet DM: 1601.01354

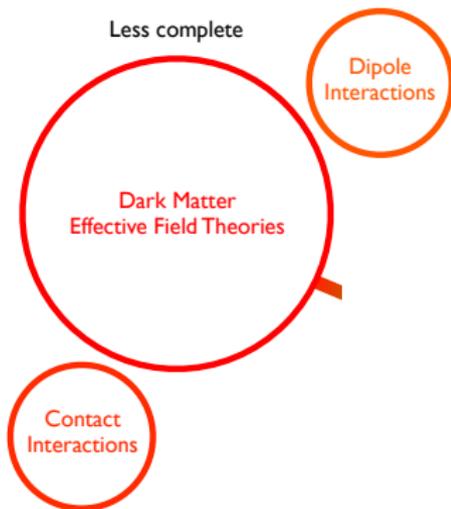
Lepton-flavored DM: 1510.00100

Kaluza-Klein DM: 1601.00081

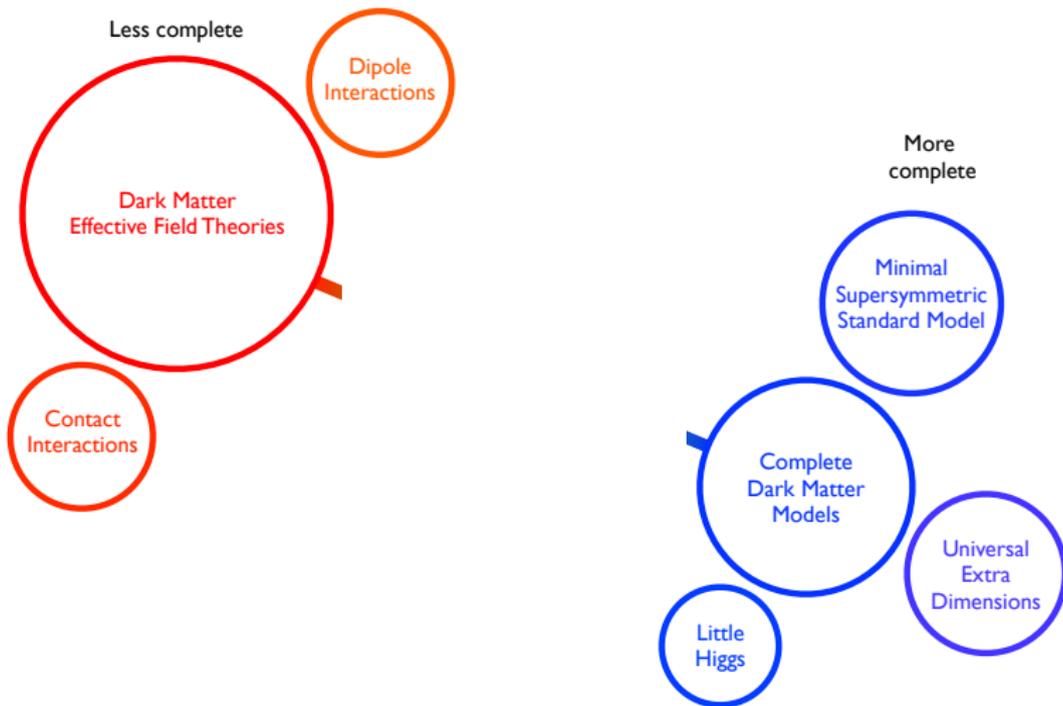
Inert Zee model: 1511.01873

Flavoured DM: 1510.04694

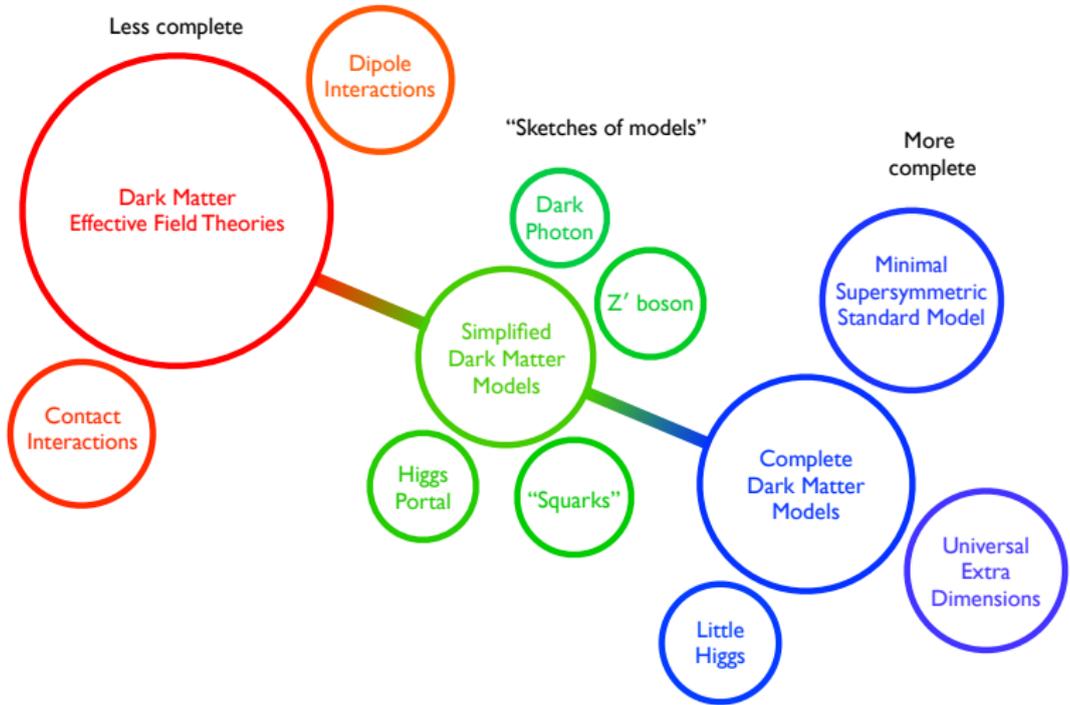
Theoretical Framework



Theoretical Framework



Theoretical Framework



Simplified Models of DM at the LHC

Simplified Models for Dark Matter Searches at the LHC

Abdallah *et al.* 1506.03116

... outlines a set of simplified models of DM for searches at the LHC

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Abercrombie *et al.* 1507.00966

... a minimal basis of dark matter models that should influence the design of the early Run-2 searches. At the same time, a thorough survey of realistic collider signals of Dark Matter

Our Goal

A complete classification of simplified coannihilation models

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A complete classification of simplified coannihilation models

The Coannihilation Codex

- A bottom-up framework for discovering dark matter at the LHC
- LHC phenomenology testing DM freeze-out
- Identify lesser studied models & searches
- In the event of a signal, gives a framework for the inverse problem

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Assumptions

To complete a classification we need to make some assumptions

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

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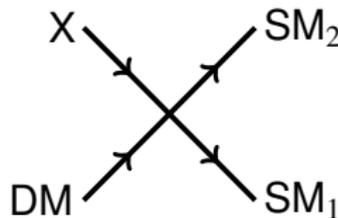
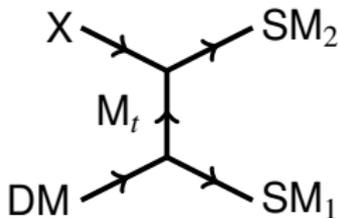
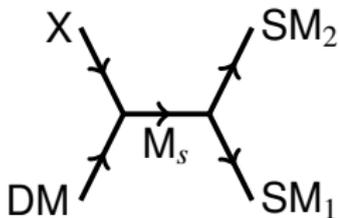
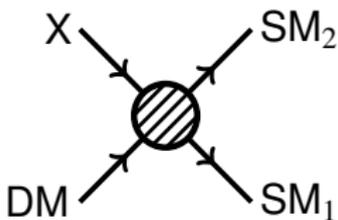
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Coannihilation Diagrams



Classification Procedure

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

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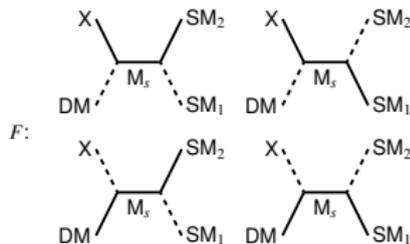
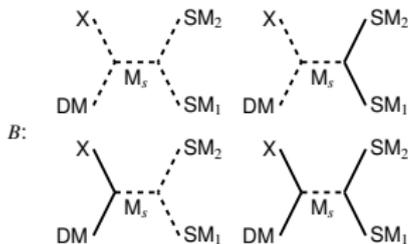
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s-channel classification - sample

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

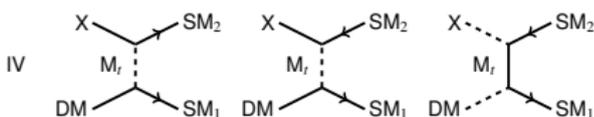
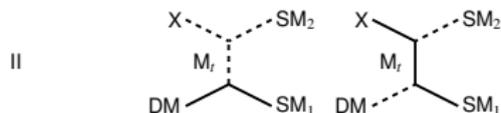
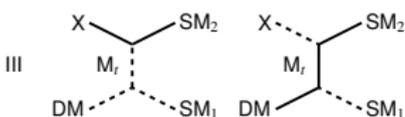
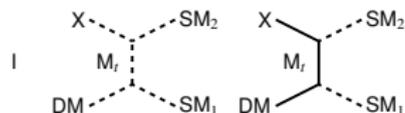
ID	X	$\alpha + \beta$	M_s	Spin	$(SM_1 \ SM_2)$	SM_3	M-X-X
ST11	$(3, N \pm 1, \alpha)$	$\frac{7}{3}$	$(3, 2, \frac{7}{3})$	B	$(Q_L \bar{\ell}_R), (u_R \bar{L}_L)$		
ST12				F	$(u_R H)$		
ST13		$\frac{1}{3}$	$(3, 2, \frac{1}{3})$	B	$(d_R \bar{L}_L), (\bar{Q}_L \bar{d}_R), (u_R L_L)$		
ST14				F	$(u_R H^\dagger), (d_R H)$	Q_L	
ST15		$-\frac{5}{3}$	$(3, 2, -\frac{5}{3})$	B	$(\bar{Q}_L \bar{u}_R), (Q_L \ell_R), (d_R L_L)$		
ST16				F	$(d_R H^\dagger)$		
ST17	$(3, N \pm 2, \alpha)$	$\frac{4}{3}$	$(3, 3, \frac{4}{3})$	B	$(Q_L \bar{L}_R)$		$\checkmark \alpha = -\frac{2}{3}$
ST18				F	$(Q_L H)$		
ST19		$-\frac{2}{3}$	$(3, 3, -\frac{2}{3})$	B	$(\bar{Q}_L \bar{Q}_L), (Q_L L_L)$		$\checkmark \alpha = \frac{1}{3}$
ST20				F	$(Q_L H^\dagger)$		



t-channel classification - sample

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

ID	X	$\alpha + \beta$	M_t	Spin	$(SM_1 SM_2)$	SM_3
TU26	$(1, N \pm 2, \alpha)$	0	$(1, N \pm 1, \beta - 1)$	I	(HH^\dagger)	
TU27			$(1, N \pm 1, \beta + 1)$	II	(LLH)	
TU28			$(1, N \pm 1, \beta - 1)$	III	(HLL)	
TU29			$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(QL\bar{Q}L)$	
TU30		$(1, N \pm 1, \beta + 1)$	IV	$(LL\bar{L}L)$		
TU31		-2	$(1, N \pm 1, \beta + 1)$	I	$(H^\dagger H^\dagger)$	
TU32			$(1, N \pm 1, \beta + 1)$	II	(LLH^\dagger)	
TU33			$(1, N \pm 1, \beta + 1)$	III	$(H^\dagger LL)$	



Classification: hybrid models

ID	X	$\alpha + \beta$	SM partner	Extensions
H1	$(1, N, \alpha)$	0	$B, W_i^{N \geq 2}$	SU1, SU3, TU1, TU4–TU8
H2		-2	ℓ_R	SU6, SU8, TU10, TU11
H3	$(1, N \pm 1, \alpha)$	-1	H^\dagger	SU10, TU18–TU23
H4			L_L	SU11, TU16, TU17
H5	$(3, N, \alpha)$	$\frac{4}{3}$	u_R	ST3, ST5, TT3, TT4
H6		$-\frac{2}{3}$	d_R	ST7, ST9, TT10, TT11
H7	$(3, N \pm 1, \alpha)$	$\frac{1}{3}$	Q_L	ST14, TT28–TT31

7 models

Classification: s-channel

ID	X	$\alpha + \beta$	M_s	Spin	(SM_1, SM_2)	SM_3	M-X-X
SU1	(1, N, α)	0	(1, 1, 0)	B	$(u_R \overline{u}_R), (d_R \overline{d}_R), (Q_L \overline{Q}_L)$ $(\ell_R \overline{\ell}_R), (L_L \overline{L}_L), (H H^\dagger)$	$B, W_1^{N \geq 2}$	✓
SU2				F	$(L_L H)$		
SU3		$(1, 3, 0)^{N \geq 2}$	B	$(Q_L \overline{Q}_L), (L_L \overline{L}_L), (H H^\dagger)$	B, W_1	✓	
SU4			F	$(L_L H)$			
SU5		-2	(1, 1, -2)	B	$(d_R \overline{u}_R), (H^\dagger H^\dagger)$		✓
SU6				F	$(L_L H^\dagger)$	ℓ_R	
SU7			$(1, 3, -2)^{N \geq 2}$	B	$(H^\dagger H^\dagger), (L_L L_L)$		✓ ($\alpha = \pm 1$)
SU8				F	$(L_L H^\dagger)$	ℓ_R	
SU9	-4	(1, 1, -4)	B	$(\ell_R \ell_R)$		✓ ($\alpha = \pm 2$)	
SU10	(1, N $\pm 1, \alpha$)	-1	(1, 2, -1)	B	$(d_R \overline{Q}_L), (\overline{u}_R \overline{Q}_L), (\overline{L}_L \overline{\ell}_R)$	H^\dagger	
SU11				F	$(\ell_R H)$	L_L	
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	$(L_L \overline{L}_L), (Q_L \overline{Q}_L), (H H^\dagger)$		✓ ($\alpha = 0$)
SU15				F	$(L_L H)$		
SU16		-2	(1, 3, -2)	B	$(H^\dagger H^\dagger), (L_L L_L)$		✓ ($\alpha = \pm 1$)
SU17				F	$(L_L H^\dagger)$		

SU type - 17 models

ID	X	$\alpha + \beta$	M_s	Spin	(SM_1, SM_2)	SM_3	M-X-X
ST1	(3, N, α)	$\frac{1}{2}$	(3, 1, $\frac{1}{2}$)	B	$(u_R \overline{u}_R)$		✓ $\alpha = -\frac{1}{2}$
ST2				B	$(d_R \overline{u}_R), (Q_L \overline{L}_L), (d_R \overline{d}_R)$		✓ $\alpha = -\frac{1}{2}$
ST3		$\frac{1}{2}$	(3, 1, $\frac{1}{2}$)	F	$(Q_L H)$	u_R	
ST4				B	$(Q_L \overline{L}_L)$		✓ $\alpha = -\frac{1}{2}$
ST5		$\frac{3}{2}$	$(3, 3, \frac{3}{2})^{N \geq 2}$	F	$(Q_L H)$	u_R	
ST6				B	$(Q_L \overline{Q}_L), (\overline{u}_R \overline{d}_R), (\overline{u}_R \overline{\ell}_R), (Q_L L_L)$		✓ $\alpha = \frac{1}{2}$
ST7		- $\frac{1}{2}$	(3, 1, - $\frac{1}{2}$)	F	$(Q_L H^\dagger)$	d_R	
ST8				B	$(\overline{Q}_L \overline{Q}_L), (\overline{Q}_L L_L)$		✓ $\alpha = \frac{1}{2}$
ST9				F	$(Q_L H^\dagger)$	d_R	
ST10		- $\frac{3}{2}$	(3, 1, - $\frac{3}{2}$)	B	$(\overline{u}_R \overline{u}_R), (d_R \overline{\ell}_R)$		✓ $\alpha = \frac{1}{2}$
ST11				B	$(Q_L \overline{\ell}_R), (\overline{u}_R \overline{L}_L)$		
ST12		(3, N $\pm 1, \alpha$)	$\frac{1}{2}$	(3, 2, $\frac{1}{2}$)	F	$(u_R H)$	
ST13	B				$(d_R \overline{L}_L), (\overline{Q}_L \overline{d}_R), (\overline{u}_R L_L)$		
ST14	$\frac{1}{2}$		(3, 2, $\frac{1}{2}$)	F	$(u_R H^\dagger), (d_R H)$	Q_L	
ST15				B	$(\overline{Q}_L \overline{u}_R), (Q_L \overline{\ell}_R), (d_R L_L)$		
ST16	- $\frac{1}{2}$		(3, 2, - $\frac{1}{2}$)	F	$(d_R H^\dagger)$		
ST17				B	$(Q_L \overline{L}_R)$		✓ $\alpha = -\frac{1}{2}$
ST18	(3, N $\pm 2, \alpha$)	$\frac{1}{2}$	(3, 3, $\frac{1}{2}$)	F	$(Q_L H)$		
ST19				B	$(\overline{Q}_L \overline{Q}_L), (\overline{Q}_L L_L)$		✓ $\alpha = \frac{1}{2}$
ST20	- $\frac{3}{2}$	(3, 3, - $\frac{3}{2}$)	F	$(Q_L H^\dagger)$			

ST type - 20 models

- U: X uncoloured
 T: X $SU(3)$ triplet
 O: X $SU(3)$ octet
 E: X $SU(3)$ exotic

ID	X	$\alpha + \beta$	M_s	Spin	(SM_1, SM_2)	SM_3	M-X-X
SO1	(8, N, α)	0	$(8, 1, 0)^{\neq \beta(\neq 2)}$	B	$(d_R \overline{u}_R), (u_R \overline{u}_R), (Q_L \overline{Q}_L)$		✓ $\alpha = 0$
SO2		$(8, 3, 0)^{N \geq 2}$	B	$(Q_L \overline{Q}_L)$		✓ $\alpha = 0$	
SO3		-2	(8, 1, -2)	B	$(d_R \overline{u}_R)$		✓ $\alpha = \pm 1$
SO4	(8, N $\pm 1, \alpha$)	-1	(8, 2, -1)	B	$(d_R \overline{Q}_L), (Q_L \overline{u}_R)$		
SE1	(6, N, α)	0	(8, 3, 0)	B	$(Q_L \overline{Q}_L)$		✓ $\alpha = 0$
SE2		$\frac{1}{2}$	(6, 1, $\frac{1}{2}$)	B	$(u_R u_R)$		✓ $\alpha = -\frac{1}{2}$
SE3		$\frac{3}{2}$	(6, 3, $\frac{3}{2})^{N \geq 2}$	B	$(Q_L Q_L), (u_R d_R)$		✓ ($\alpha = -\frac{1}{2}$)
SE4				B	$(d_R d_R)$		✓ $\alpha = \frac{1}{2}$
SE5		$\frac{5}{2}$	(6, 2, $\frac{5}{2}$)	B	$(Q_L u_R)$		
SE6		- $\frac{1}{2}$	(6, 2, - $\frac{1}{2}$)	B	$(Q_L d_R)$		
SE7		$\frac{3}{2}$	(6, 3, $\frac{3}{2}$)	B	$(Q_L Q_L)$		✓ $\alpha = -\frac{1}{2}$

SO and SE type - 5 and 7 models

Complete Classification

We have written down all possible simplified models of 2-to-2 coannihilating dark matter!

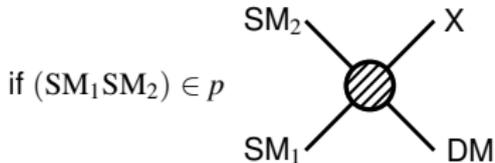
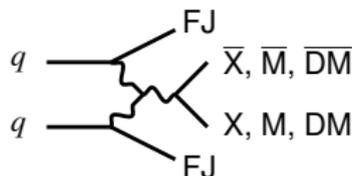
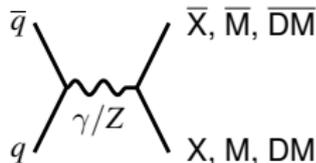
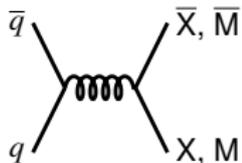
LHC Phenomenology

Complete Classification

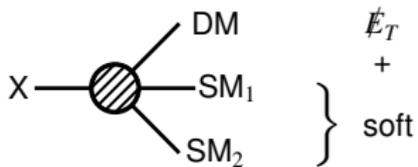
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LHC Phenomenology

LHC Production: Common

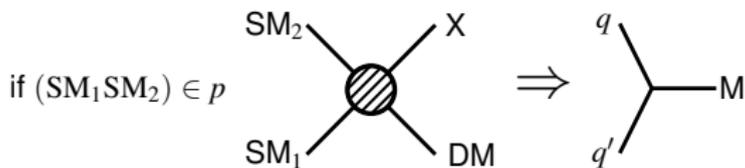


Decays: Common



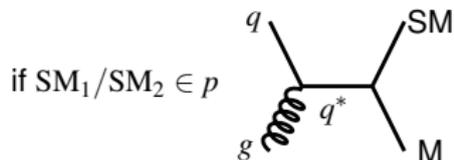
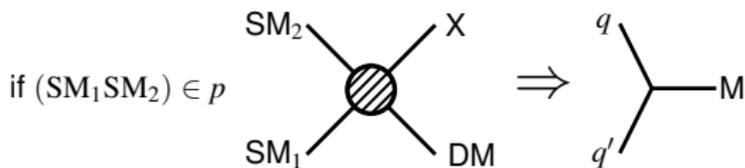
LHC Production: s-channel

Gauge boson production +

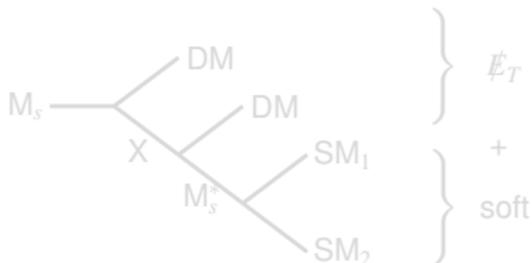
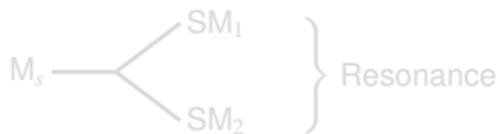
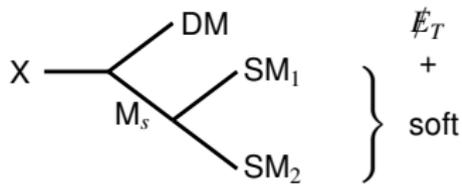


LHC Production: s-channel

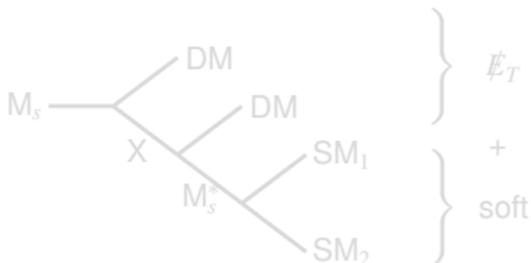
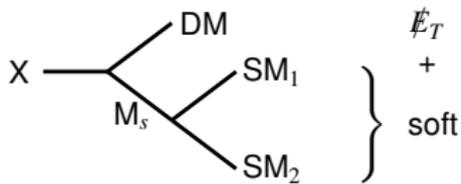
Gauge boson production +



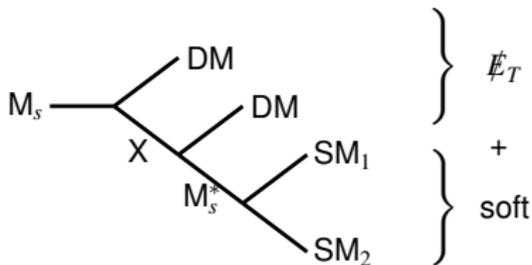
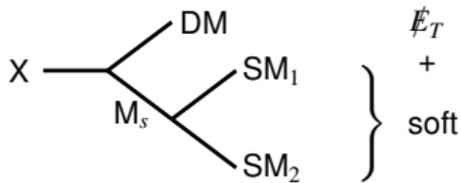
Decays: s-channel



Decays: s-channel



Decays: s-channel



Signature Table: s-channel

	$pp \rightarrow \dots$	Prod. via	Signatures	Search
s-channel	$\begin{cases} M_s \rightarrow [SM_1 SM_2]^{res} \\ M_s \rightarrow [SM_1 SM_2]^{res} \end{cases}$	gauge int.	2 resonances	[106-112]
	$\begin{cases} M_s \rightarrow [SM_1 SM_2]^{res} \\ M_s \rightarrow DM + X (\rightarrow SM_1^{soft} SM_2^{soft} DM) \end{cases}$		resonance + \cancel{E}_T resonance + $\cancel{E}_T + \leq 2$ SM	No search No search
	$\begin{cases} M_s \rightarrow DM + X (\rightarrow SM_1^{soft} SM_2^{soft} DM) \\ M_s \rightarrow DM + X (\rightarrow SM_1^{soft} SM_2^{soft} DM) \end{cases}$		$\cancel{E}_T + \leq 4$ SM	[113-124]
	$M_s \rightarrow [SM_1 SM_2]^{res}$	$(SM_1 SM_2) \in p$	1 resonance	[125-146]
	$M_s \rightarrow DM + X (\rightarrow SM_1^{soft} SM_2^{soft} DM)$		$\cancel{E}_T + \leq 2$ SM	[120-122,124] [104,147-153]
	$SM_{1,2} + M_s \rightarrow [SM_1 SM_2]^{res}$	$SM_{2,1} \in p$	1 resonance + 1 SM	Partial coverage [154,155]
	$\begin{cases} SM_{1,2} \\ M_s \rightarrow DM + X (\rightarrow SM_1^{soft} SM_2^{soft} DM) \end{cases}$		$\cancel{E}_T + 1 \leq 3$ SM	[114,120-124] [147-153,156-158]

Signature Table

	$pp \rightarrow \dots$	Prod. via	Signatures	Search
common	DM + DM + ISR	gauge int. or $SM_1 \in p$ for t -channel	mono- $Y + \cancel{E}_T$	[55,56,62,63,104]
	$\begin{cases} X (\rightarrow SM_1^{orth} SM_2^{orth} DM) \\ X (\rightarrow SM_1^{orth} SM_2^{orth} DM) \\ \text{ISR} \end{cases}$	gauge int. or $SM_2 \in p$ for t -channel	mono- $Y + \cancel{E}_T$ mono- $Y + \cancel{E}_T + \leq 4$ SM	[55,56,62,63,104] Partial coverage [105]
	DM + $X (\rightarrow SM_1^{orth} SM_2^{orth} DM)$ + ISR	$(SM_1, SM_2) \in p$	mono- $Y + \cancel{E}_T$ mono- $Y + \cancel{E}_T + \leq 2$ SM	[55,56,62,63,104] Partial coverage [105]
s-channel	$\begin{cases} M_i (\rightarrow [SM_1, SM_2]^{orth}) \\ M_i (\rightarrow [SM_1, SM_2]^{orth}) \end{cases}$	gauge int.	2 resonances	[106-112]
	$\begin{cases} M_i (\rightarrow [SM_1, SM_2]^{orth}) \\ M_i (\rightarrow DM + X (\rightarrow SM_1^{orth} SM_2^{orth} DM)) \end{cases}$		resonance + \cancel{E}_T resonance + $\cancel{E}_T + \leq 2$ SM	No search No search
	$\begin{cases} M_i (\rightarrow DM + X (\rightarrow SM_1^{orth} SM_2^{orth} DM)) \\ M_i (\rightarrow DM + X (\rightarrow SM_1^{orth} SM_2^{orth} DM)) \end{cases}$		$\cancel{E}_T + \leq 4$ SM	[113-124]
	$M_i (\rightarrow [SM_1, SM_2]^{orth})$	$(SM_1, SM_2) \in p$	1 resonance	[125-146]
	$M_i (\rightarrow DM + X (\rightarrow SM_1^{orth} SM_2^{orth} DM))$	$(SM_1, SM_2) \in p$	$\cancel{E}_T + \leq 2$ SM	[120-122,124] [104,147-153]
	$\begin{cases} SM_{1,2} + M_i (\rightarrow [SM_1, SM_2]^{orth}) \\ SM_{1,2} \\ M_i (\rightarrow DM + X (\rightarrow SM_1^{orth} SM_2^{orth} DM)) \end{cases}$	$SM_{1,2} \in p$	1 resonance + 1 SM $\cancel{E}_T + 1 \leq 3$ SM	Partial coverage [154,155] [114,120-124] [147-153,156-158]
t-channel	$\begin{cases} M_i (\rightarrow SM_i, DM) \\ M_i (\rightarrow SM_i, DM) \end{cases}$	gauge int.	$\cancel{E}_T + \leq 2$ SM	[120-122,124] [104,147-153]
	$\begin{cases} M_i (\rightarrow SM_i, DM) \\ M_i (\rightarrow SM_{i_2} + X (\rightarrow SM_1^{orth} SM_2^{orth} DM)) \end{cases}$		$\cancel{E}_T + \leq 4$ SM	[106-112] [114,119-124]
	$\begin{cases} M_i (\rightarrow SM_{i_2} + X (\rightarrow SM_1^{orth} SM_2^{orth} DM)) \\ M_i (\rightarrow SM_{i_2} + X (\rightarrow SM_1^{orth} SM_2^{orth} DM)) \end{cases}$		$\cancel{E}_T + \leq 6$ SM	[113,114,120-124] [116-118,159-163]
	DM + $M_i (\rightarrow SM_i, DM)$	$SM_i \in p$	$\cancel{E}_T + \leq 1$ SM	[55,56,62,63] [104,149]
	$\begin{cases} DM \\ M_i (\rightarrow SM_{i_2} + X (\rightarrow SM_1^{orth} SM_2^{orth} DM)) \end{cases}$	$SM_i \in p$	$\cancel{E}_T + \leq 3$ SM	114,120-124] [152,153,156-158]
	$\begin{cases} M_i (\rightarrow SM_i, DM) \\ X (\rightarrow SM_1^{orth} SM_2^{orth} DM) \\ M_i (\rightarrow SM_{i_2} + X (\rightarrow SM_1^{orth} SM_2^{orth} DM)) \\ X (\rightarrow SM_1^{orth} SM_2^{orth} DM) \end{cases}$	$SM_{i_2} \in p$	$\cancel{E}_T + \leq 3$ SM $\cancel{E}_T + \leq 5$ SM	[114,120-124] [152,153,156-158] [113,114,116-124] [159-161,164]
hybrid	$\begin{cases} X (\rightarrow DM + SM_1^{orth}) \\ X (\rightarrow DM + SM_1^{orth}) \end{cases}$	gauge int. or $SM_3 \in p$	$\cancel{E}_T + \leq 2$ SM	[120-122,124] [104,147-153]
	DM + $X (\rightarrow DM + SM_2^{orth})$	$SM_3 \in p$	$\cancel{E}_T + \leq 1$ SM	[128,129,149] [55,56,62,63,104]

Outline

- 1 Motivation
- 2 Coannihilation Codex
- 3 Using the Codex**

Bino-gluino Coannihilation

Label	Field	Rep.	Spin assignment
DM	Bino	$(1, 1, 0)$	Fermion
X	Gluino	$(8, 1, 0)$	Fermion
M	Squark	$(\bar{3}, 1, -4/3)$	Scalar

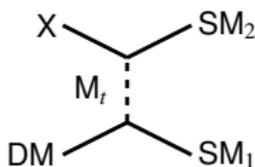
$$DM \sim (1, N, \beta)$$

$$X \sim (8, N, \alpha)$$

$$\alpha + \beta = 0$$

$$M \sim (\bar{3}, N, \beta - 4/3)$$

t-channel: IV



Bino-gluino Coannihilation

$$X \sim (8, N, \alpha) \quad \alpha + \beta = 0$$

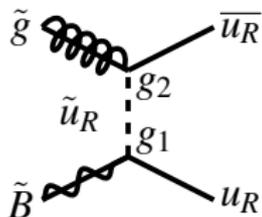
$$M \sim (\bar{3}, N, \beta - 4/3) \quad \text{Spin: IV}$$

ID	X	$\alpha + \beta$	M_t	Spin	(SM ₁ SM ₂)	SM ₃
TO1	(8, N, α)	0	$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L \bar{Q}_L)$	
TO2			$(\bar{3}, N, \beta - \frac{4}{3})$	IV	$(u_R \bar{u}_R)$	
TO3			$(\bar{3}, N, \beta + \frac{2}{3})$	IV	$(d_R \bar{d}_R)$	
TO4		-2	$(\bar{3}, N, \beta + \frac{2}{3})$	IV	$(d_R \bar{u}_R)$	
TO5			$(3, N, \beta + \frac{4}{3})$	IV	$(\bar{u}_R d_R)$	
TO6	(8, N ± 1 , α)	-1	$(\bar{3}, N, \beta + \frac{2}{3})$	IV	$(d_R \bar{Q}_L)$	
TO7			$(3, N \pm 1, \beta + \frac{1}{3})$	IV	$(\bar{Q}_L d_R)$	
TO8			$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L \bar{u}_R)$	
TO9			$(3, N, \beta + \frac{4}{3})$	IV	$(\bar{u}_R Q_L)$	
TO10	(8, N ± 2 , α)	0	$(\bar{3}, N \pm 1, \beta - \frac{1}{3})$	IV	$(Q_L \bar{Q}_L)$	

Bino-gluino Coannihilation

$$DM \sim (1, 1, 0)_F \quad X \sim (8, 1, 0)_F$$

$$M \sim (\bar{3}, 1, -4/3)_B \quad (SM_1 SM_2) = (u_R \bar{u}_R)$$



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$$DM \sim (1, 1, 0)_F \quad X \sim (8, 1, 0)_F$$

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	$pp \rightarrow \dots$	Prod. via	Signatures	Search	Strength
common	DM + DM + ISR	gauge int. or $SM_1 \in p$ for t -channel	mono-Y + \cancel{E}_T	[55,56,62,63,104]	$g_1^4 \alpha_i$
	$\left\{ \begin{array}{l} X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM) \\ X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM) \\ \text{ISR} \end{array} \right.$	gauge int. or $SM_2 \in p$ for t -channel	mono-Y + \cancel{E}_T mono-Y + $\cancel{E}_T + \leq 4$ SM	[55,56,62,63,104] Partial coverage [105]	$\alpha_s^2 \alpha_i, g_2^4 \alpha_i$
	DM + X ($\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM$) + ISR	$(SM_1 SM_2) \in p$	mono-Y + \cancel{E}_T mono-Y + $\cancel{E}_T + \leq 2$ SM	[55,56,62,63,104] Partial coverage [105]	$g_1^2 g_2^2 \alpha_i$

Bino-gluino Coannihilation

$$DM \sim (1, 1, 0)_F \quad X \sim (8, 1, 0)_F$$

$$M \sim (\bar{3}, 1, -4/3)_B \quad (SM_1 SM_2) = (u_R \bar{u}_R)$$

	$pp \rightarrow \dots$	Prod. via	Signatures	Search	Strength
r-channel	$\begin{cases} M_i (\rightarrow SM_1 DM) \\ M_i (\rightarrow SM_1 DM) \end{cases}$	gauge int.	$\cancel{E}_{T^+} \leq 2 \text{ SM}$	[120-122,124] [104,147-153]	α_s^2
	$\begin{cases} M_i (\rightarrow SM_1 DM) \\ M_i (\rightarrow SM_2 + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM)) \end{cases}$		$\cancel{E}_{T^+} \leq 4 \text{ SM}$	[106-112] [114,119-124]	α_s^2
	$\begin{cases} M_i (\rightarrow SM_2 + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM)) \\ M_i (\rightarrow SM_2 + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM)) \end{cases}$		$\cancel{E}_{T^+} \leq 6 \text{ SM}$	[113,114,120-124] [116-118,159-163]	α_s^2
	$DM + M_i (\rightarrow SM_1 DM)$	$SM_1 \in p$	$\cancel{E}_{T^+} \leq 1 \text{ SM}$	[55,56,62,63] [104,149]	$\alpha_s g_1^2$
	$\begin{cases} DM \\ M_i (\rightarrow SM_2 + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM)) \end{cases}$		$\cancel{E}_{T^+} \leq 3 \text{ SM}$	[114,120-124] [152,153,156-158]	$\alpha_s g_1^2$
	$\begin{cases} M_i (\rightarrow SM_1 DM) \\ X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM) \end{cases}$	$SM_2 \in p$	$\cancel{E}_{T^+} \leq 3 \text{ SM}$	[114,120-124] [152,153,156-158]	$\alpha_s g_2^2$
	$\begin{cases} M_i (\rightarrow SM_2 + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM)) \\ X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM) \end{cases}$		$\cancel{E}_{T^+} \leq 5 \text{ SM}$	[113,114,116-124] [159-161,164]	$\alpha_s g_2^2$

Summary

- Coannihilation Codex gives a complete list of simplified models of coannihilation
- Guaranteed kinetic & coannihilation vertices → signatures
- Classify signatures of a wide range of models
 - Identify new signatures
 - Identify interesting models, e.g., leptoquarks and DM
- Huge number of coannihilating models of DM
 - with interesting collider signatures to study
 - at the LHC and future colliders

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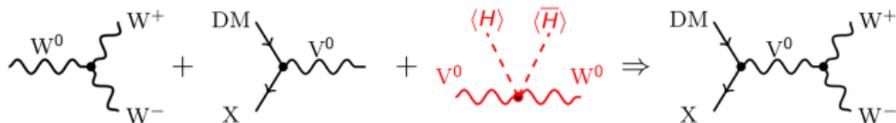
The main effect of EWSB on our models is from mixing:

- Due to \mathbb{Z}_2 symmetry, in t-channel models the effects of the mixing will be entirely in the dark sector
- Mediators in s-channel models may mix with SM particles, giving hybrid model like signatures

EWSB II

It is also possible to construct new 2-to-2 diagrams exist thanks to EWSB

E.g.: mixing between $W_i(1, 3, 0)$ and $V_i(1, 5, 0)$ in the 3-3-1 model



However, all diagrams are built from vertices present in our tables and LHC signatures (almost always) differ only by mixing angles and group theory factors

Cut-flow table - Mixed decay

	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
$N_e^h = 1, N_e \leq 2$	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
$N_{\text{hard jets}} \leq 3$	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
$E_T > 700$ GeV	133	1738	15	19	9	10	27	2	75
$m_T > 150$ GeV	132	16	10^{-3}	18	0.005	0.01	10	0.001	67
mass window	3	0.2	0	0.3	10^{-5}	10^{-5}	0.1	10^{-5}	24

Cut-flow table - XXj

	$t\bar{t}$	$Z_{\ell\ell} + j$	Diboson	$W_{\ell\nu} + j$	$t + j$	Signal
$\cancel{E}_T > 50 \text{ GeV}$	1.9×10^7	7.9×10^6	1.1×10^6	1.9×10^8	5.6×10^5	8.5×10^4
$p_T^{\text{lead}} > 50 \text{ GeV}$	1.8×10^7	6.1×10^6	5.9×10^5	1.5×10^8	4.6×10^5	7.1×10^4
$\Delta\phi_{j_1j_2} < 2.5$	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
$\cancel{E}_T > 400 \text{ GeV}$	12	11	0.07	780	2	118
$\left \frac{p_{Tj_1}}{\cancel{E}_T} - 1 \right < 0.2$	1	11	0.07	148	0.2	85