General approach to dark matter coannihilation

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Motivation

- general approach to coannihilating dark matter
  $\rightarrow$ simplified models
- main classes of collider signatures
- the role of strong interactions
- leptoquark and diquark examples

The Coannihilation Codex

M.Baker, J.Brod, S.El Hedri, AK, J.Kopp, J.Liu, A.Thamm, M.de Vries, X.Wang, F.Yu, J.Zurita

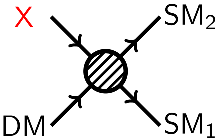
JHEP 1512 (2015) 120

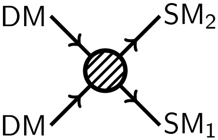
Hunting for Dark Matter Coannihilation by Mixing Dijet Resonances and Missing Transverse Energy

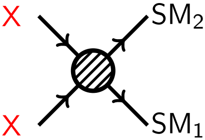
M.Buschmann, S.El Hedri, AK, J.Liu, M.de Vries, X.Wang, F.Yu, J.Zurita

1605.08056

Coannihilation



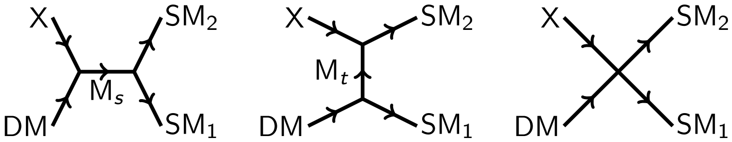




$$m_{\mathrm{X}} = m_{\mathrm{DM}}\,(1+\Delta)\,, \qquad \Delta \ll 1$$

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

Coannihilation - simplified models



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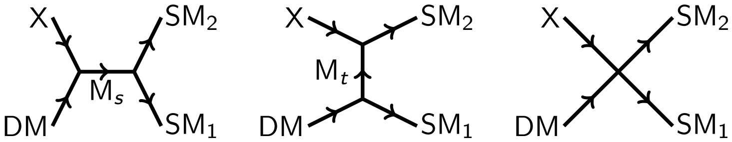
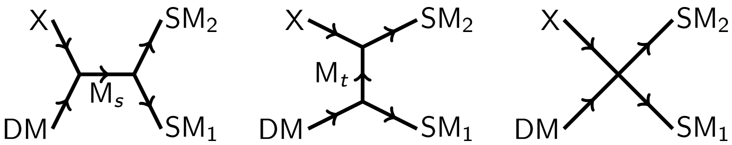


Assumptions

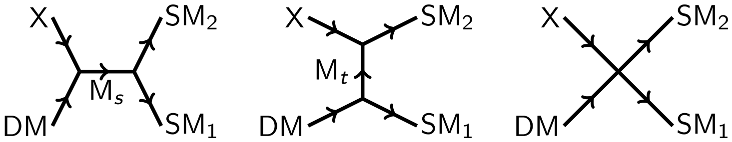
- DM is colorless and electrically neutral, DM is thermal
- (co)annihilation via a two-to-two process
- tree-level interaction vertices
- at most 3 new fields with spin 0, $1/2$ or 1
- new spin 1 particles are massive vectors with minimal coupling

Building the classification



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

Building the classification



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  - $\rightarrow$ DM $= (1,\ N,\ \beta)$

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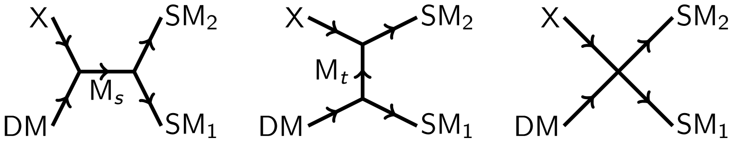

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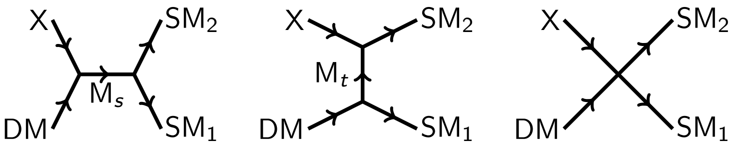

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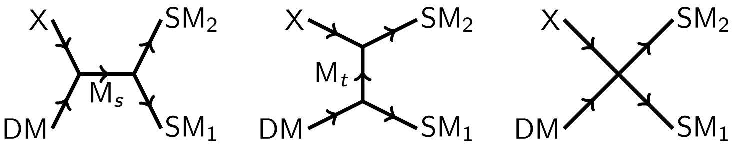

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  - $\rightarrow$ introduce a mediator and spin, check constraints
- dark sector parity introduces a division into *s*-channel and *t*-channel mediated models

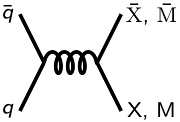
A small sample of models - M_s, X color singlets

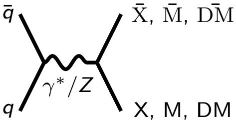
ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	X–DM–SM_3	M_s–X–X
SU1	$(1, N, \alpha)$	0	$(1,1,0)$	B	$(u_R\,\overline{u_R}), (d_R\,\overline{d_R}), (\ell_R\,\overline{\ell_R})$ $(Q_L\,\overline{Q_L}), (L_L\,\overline{L_L}), (H\,H^\dagger)$	H1	✓
SU2				F	$(L_L\,H)$		
SU3			$(1,3,0)^{N\geq 2}$	B	$(Q_L\,\overline{Q_L}), (L_L\,\overline{L_L}), (H\,H^\dagger)$	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	$(L_L\,H^\dagger)$		

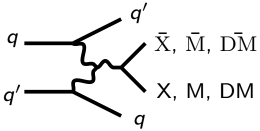
List of possible models which give rise to coannihilation diagrams in the s-channel, for DM representation $(1, N, \beta)$ and X a color singlet. Gray shaded entries denote models with fermionic mediators, while unshaded entries represent models with bosonic mediators.

Phenomenology: LHC production

pair production via gauge interactions







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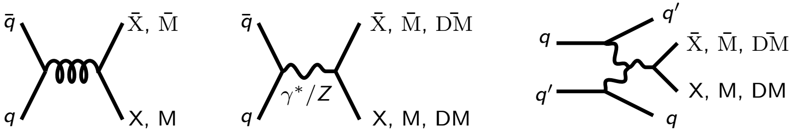
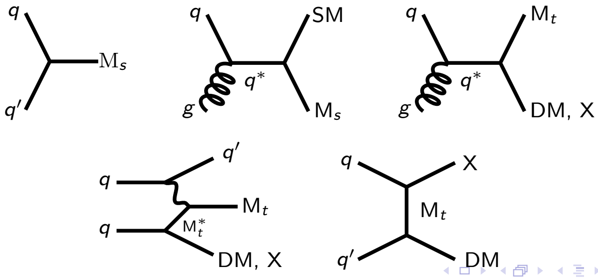
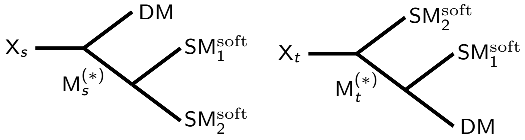


production via coannihilation diagram vertices



Common signature classes



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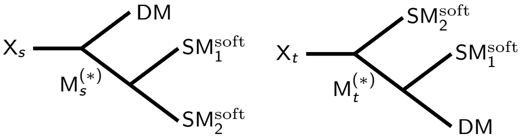
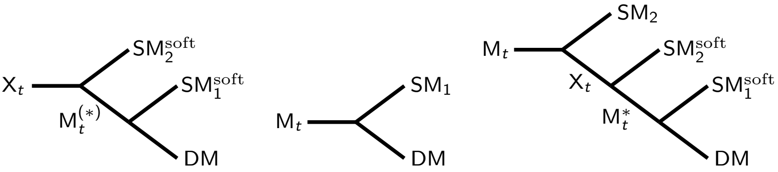
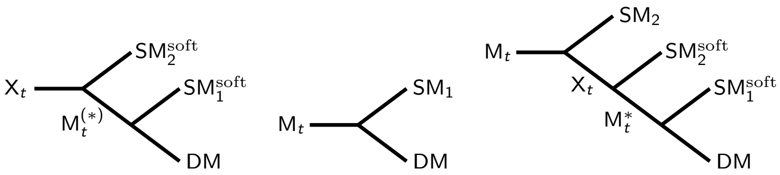


- X X + ISR $\rightarrow$ mono-Y + MET + soft
  - extending the traditional mono-jet+MET to include additional soft particles
  - potential for a strongly produced MET signature

t-channel models: decay modes

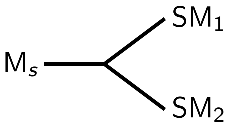


t-channel models: decay modes



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

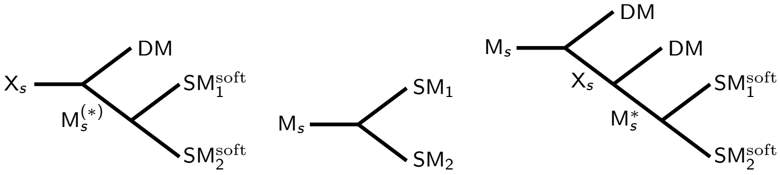
s-channel models: resonances



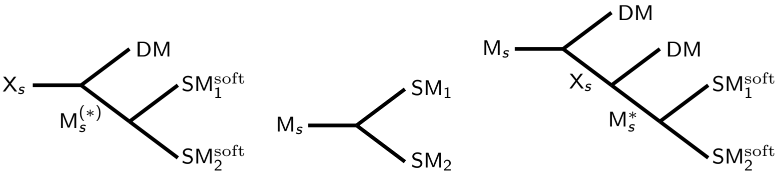
M_s class	(SM_1SM_2)	M_s type
uncolored B	QQ,LL,BB	$SU(2)_L$ singlet
		H'
		Higgs triplet
		Z'
		W'
	LL	dilepton
uncolored F	BL	L'
		lepton partner
colored B	QL	leptoquark
	QQ,QL	leptoquark-diquark
	QQ	diquark
colored F	QB,Qg	Q'
	QB	quark partner

Overview of *s*-channel mediator properties

s-channel models: decay modes



s-channel models: decay modes



complementary to the $(\mathrm{SM}_1\ \mathrm{SM}_2)$ resonance searches

- $M_s\ M_s\ \rightarrow$ resonance + MET (+ soft)
  - allows to directly probe the dark sector connection of a new resonance
  - "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

Example 1: leptoquark mediated coannihilation

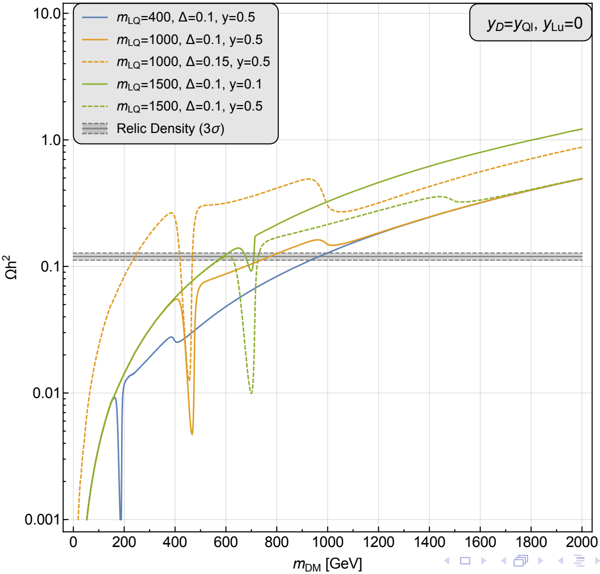
Field	$(SU(3), SU(2), U(1))$	Spin assignment
DM	(1, 1, 0)	Majorana fermion
X	(3, 2, 7/3)	Dirac fermion
M_s	(3, 2, 7/3)	Scalar

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

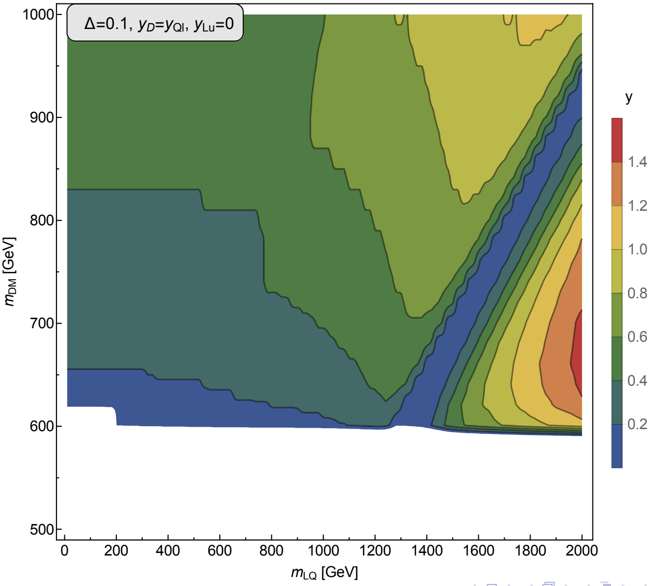
- both M_s and X are colored, strong production at the LHC
- direct and indirect detection bounds very weak
- flavor $\rightarrow$ consider $y_{Q\ell}^{11} \neq 0$ with all other $y_{Q\ell,\,Lu}^{ij} = 0$
- APV $\rightarrow$ $|y_{Q\ell}^{11}| < 0.40\ \left(\frac{m_{\mathrm{LQ}}}{1\ \mathrm{TeV}}\right)$

Relic density

$X\ \bar{X} \to g\ g \qquad X\ \bar{X} \to Q\ \bar{Q} \qquad X\ DM \to \ell\ Q$



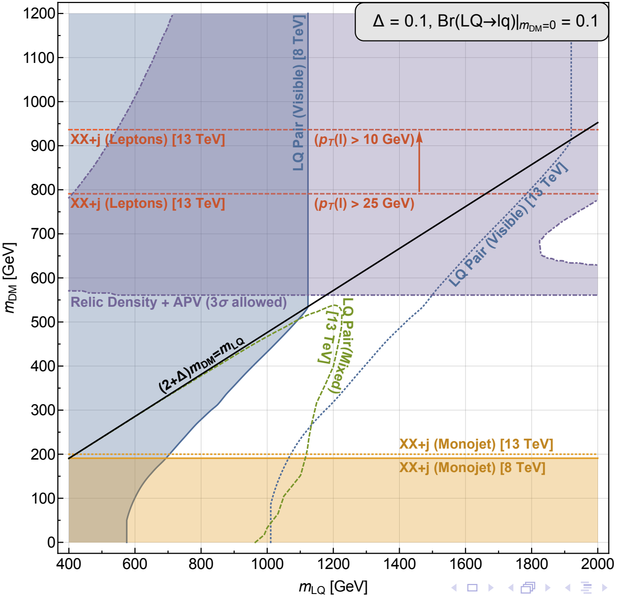
Relic density



LHC pheno

- strong pair production of both X and M_s
- $XX + \text{ISR} \to \text{hard ISR jet} + 2\,\ell + 2\,j + \not{E}_T$
  tagging the typically relatively soft leptons leads to a significant improvement over usual mono-jet searches
- $M_s M_s \to \text{two } (\ell j) \text{ resonances}$
  covered by the traditional LHC leptoquark searches
- $M_s M_s \to \text{a single } (\ell j) \text{ resonance} + \ell + j + \not{E}_T$
  mixed decay signature not yet studied by the LHC experiments
- $M_s M_s \to 2\,\ell + 2\,j + \not{E}_T$
  covered by SUSY searches
- $M_s\,\ell \to \text{a single } (\ell j) \text{ resonance} + \ell$
- $M_s\,\ell \to \ell + \ell + j + \not{E}_T$
  SUSY or mono-lepton searches

Probing leptoquark mediated coannihilation at the LHC



Example 2: diquark mediated coannihilation

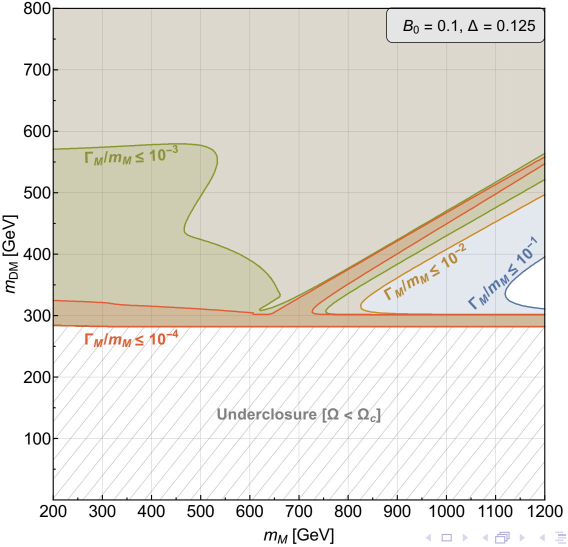
Field	$(SU(3)_C, SU(2)_L, U(1)_Y)$	Spin assignment
DM	(1, 1, 0)	Majorana fermion
X	(3, 1, -2/3)	Dirac fermion
M	(3, 1, -2/3)	Scalar

$$\mathcal{L} \ni -\left(y_D \overline{\mathrm{X}}\,\mathrm{DM}\,\mathrm{M} + \varepsilon_{abc}\mathrm{M}_a \overline{u_b^C}\left(Y_{ud}^L P_L + Y_{ud}^R P_R\right) d_c\right)$$

- both M_s and X are colored, strong production at the LHC
- direct and indirect detection bounds very weak
- flavor $\rightarrow$ consider $(Y_{ud}^L)_{11} = (Y_{ud}^R)_{11} = y_{ud} \neq 0$ with all other $Y_{ud}^{L,\, ij} = 0$
- dijet searches will constrain mediator couplings if $\Gamma_M/m_M \lesssim 0.0001 \rightarrow$ no constraints

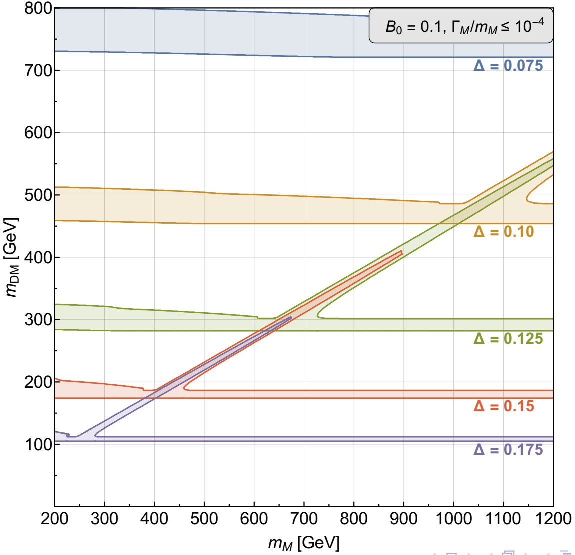
Relic density

$$B_0 \equiv \mathrm{Br}\left(\mathrm{M} \to \bar{u}\bar{d}\right)\Big|_{m_{\mathrm{DM,X}}=0} = \frac{y_{ud}^2}{y_{ud}^2 + \frac{1}{2}y_D^2}$$



Relic density

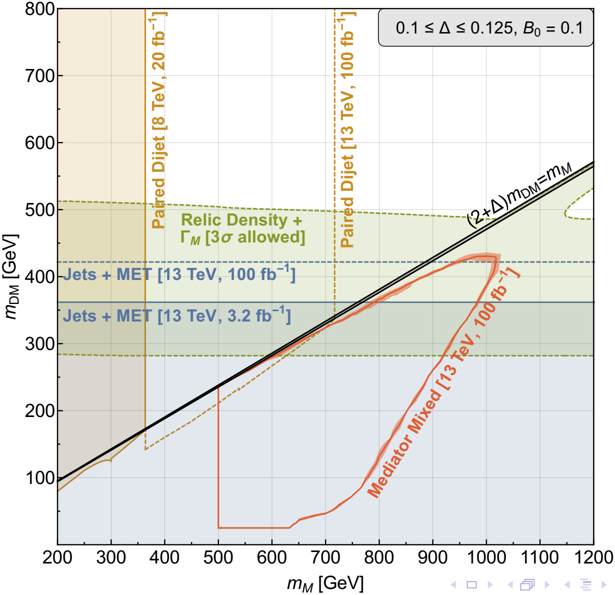
$$\mathrm{X}\ \bar{\mathrm{X}} \to \mathrm{g}\ \mathrm{g} \qquad \mathrm{X}\ \bar{\mathrm{X}} \to \mathrm{Q}\ \bar{\mathrm{Q}} \qquad \mathrm{X}\ \mathrm{DM} \to \mathrm{Q}\ \mathrm{Q}$$



LHC pheno

- strong pair production of both X and M_s
- XX + ISR $\rightarrow$ hard ISR jet $+ 4j + \not{E}_T$
  constrained by mono-jet + MET or gluino searches
- $M_s \rightarrow$ a single (jj) resonance
  no constraints for $\Gamma_M / m_M \lesssim 0.0001$
- $M_s M_s \rightarrow$ two (jj) resonances
  covered by standard LHC diquark searches
- $M_s M_s \rightarrow$ a single (jj) resonance $+ 2j + \not{E}_T$
  mixed decay signature not yet studied by the LHC experiments
- $M_s M_s \rightarrow 4j + \not{E}_T$
  covered by SUSY searches

Probing diquark mediated coannihilation at the LHC



Conclusions

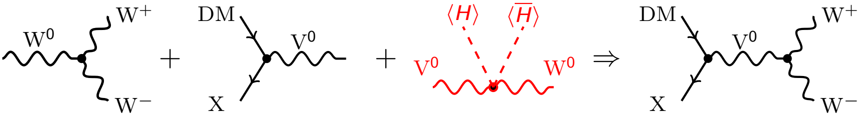
- first complete general classification of two-to-two simplified coannihilation models
- topology of the coannihilation diagram, gauge charges and coannihilation condition $\Delta \ll 1$
  $\rightarrow$ general classes of collider signatures
- coannihilation allows for the possibility of strong (model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

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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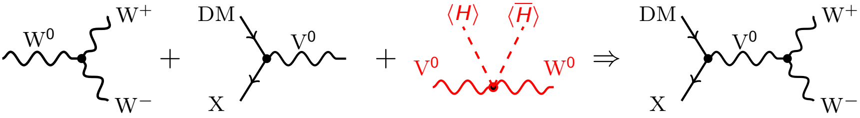


From each $SU(2)$-conserving model, one can readily build an ***equivalence class*** of $SU(2)$-breaking models.
The $SU(2)$-conserving models remain the most fundamental building blocks for our classification.

Modified mono-jet search

$$\mathrm{XX} + \mathrm{ISR} \to \text{hard ISR jet} + 2\,\ell + 2\,j + \not{E}_T$$

	$t\bar{t}$	$Z_{\ell\ell}+j$	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
$p_T^{\mathrm{lead}} > 50$ 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

Cut flow for the backgrounds and for a signal with $m_{\mathrm{X}} = 660$ GeV, $m_{\mathrm{LQ}} = 1.7$ TeV and $m_{DM} = 600$ GeV ($\Delta \sim 0.1$). These cuts correspond to a mono-jet plus $\not{E}_T$ search where we require two leptons. The numbers of events quoted correspond to a center of mass energy of 13 TeV and a luminosity of 100 fb^{-1}.

Mixed mediator decay search - leptoquark

$M_s M_s \to$ a single (ℓj) resonance $+\ell + j + \not{E}_T$

	QCD	$W+1,2j$	$t\bar{t}$	$Z_{\nu\nu}+j$	$Z_{\tau\tau}+j$
$p_T(j_1) > 50$ GeV	2.1×10^{12}	4.4×10^{8}	1.3×10^{8}	7.0×10^{7}	1.3×10^{7}
$N_e^{\rm h}=1,\ N_e\leq 2$	4.8×10^{9}	8.8×10^{7}	1.2×10^{7}	8.6×10^{4}	4.8×10^{5}
b-jet veto	4.0×10^{9}	8.2×10^{7}	5.0×10^{6}	8.2×10^{4}	4.6×10^{5}
$N_{\rm hard\ jets}\leq 3$	3.9×10^{9}	8.2×10^{7}	4.3×10^{6}	8.2×10^{4}	4.6×10^{5}
Z veto	3.9×10^{9}	8.2×10^{7}	1.7×10^{6}	8.2×10^{4}	4.6×10^{5}
$\not{E}_T > 700$ GeV	133	1738	15	19	9
$m_T > 150$ GeV	132	16	10^{-3}	18	0.005
mass window	3	0.2	$<10^{-5}$	0.3	10^{-5}

	W^+W^-	$WZ_{\nu\nu}+j$	WZ_{jj}	signal
$p_T(j_1) > 50$ GeV	1.2×10^{6}	1.3×10^{5}	3.1×10^{5}	600
$N_e^{\rm h}=1,\ N_e\leq 2$	2.4×10^{5}	1.9×10^{4}	6.1×10^{4}	415
b-jet veto	2.2×10^{5}	1.9×10^{4}	5.4×10^{4}	395
$N_{\rm hard\ jets}\leq 3$	2.2×10^{5}	1.9×10^{4}	5.4×10^{4}	335
Z veto	2.2×10^{5}	1.9×10^{4}	5.4×10^{4}	326
$\not{E}_T > 700$ GeV	10	27	2	75
$m_T > 150$ GeV	0.01	10	0.001	67
mass window	10^{-5}	0.1	10^{-5}	24

Benchmark 950 GeV LQ, 405 GeV DM, 445 GeV X. $N_e^{\rm h}$ is the number of hard electrons, $p_T(e) > 30$ GeV. The mass window cut corresponds to $\left|m_{\ell j} - 950\ {\rm GeV}\right| < 20$ GeV. Center of mass energy of 13 TeV, luminosity 100 fb^{-1}.

Mixed mediator decay search - diquark

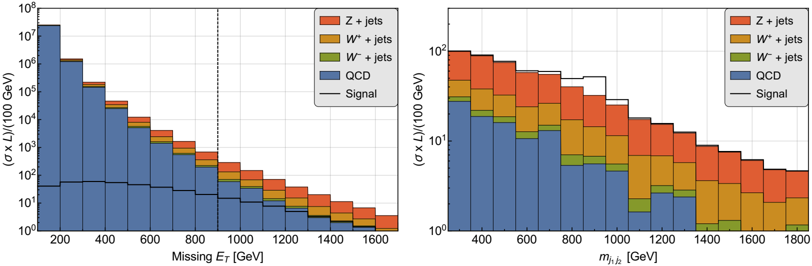
$$\mathrm{M}_s\mathrm{M}_s \to \text{a single } (jj) \text{ resonance} + 2j + \not{E}_T$$

σ_{NLO} (pb)	signal 7.60×10^{-3}	$Z_{\nu\nu}$ + jets 93.21	$W^{+}_{\ell\nu}$ + jets 157.33	$W^{-}_{\ell\nu}$ + jets 75.48	QCD 6948.76
ℓ veto	100	100	71.4	69.0	100
b-jet veto	86.9	89.3	66.8	64.5	87.3
$p_T(j_1),\ p_T(j_2) > 100$ GeV	83.0	11.8	9.76	9.68	27.6
$\Delta\phi(j_i, \not{E}_T) > 0.2$	75.0	10.9	8.50	7.99	6.20
$\lvert\Delta\eta(j_1, j_2)\rvert < 1.3$	51.5	6.36	5.01	4.82	3.61
$\not{E}_T > 900\ \mathrm{GeV}$	6.29	3.51×10^{-3}	7.74×10^{-4}	2.83×10^{-4}	1.71×10^{-5}
	(48)	(327)	(122)	(21)	(119)
Mass window	3.56	3.35×10^{-4}	8.70×10^{-5}	1.93×10^{-5}	1.28×10^{-6}
	(27)	(31)	(14)	(2)	(9)

Detailed cut flow for a signal benchmark with $(m_{\mathrm{DM}}, m_{\mathrm{X}}, m_{\mathrm{M}}) = (379,\ 417,\ 900)$ GeV and the Z + jets, $W^{\pm}$ + jets, and QCD multijet backgrounds. The cross sections quoted include the preliminary cuts K-factors for 13 TeV LHC. The $\not{E}_T$ and $m_{j_1 j_2}$ cuts are optimized for each signal point individually, and we quote both the efficiency (in %) and the number of events at 100 fb^{-1} luminosity for each process. The dijet mass window considered for this benchmark point is $[812, 987]$ GeV.

Mixed mediator decay search - diquark

$\mathrm{M}_s \mathrm{M}_s \to$ a single (jj) resonance $+ 2j + \not{E}_T$



Signal and background $\not{E}_T$ (left) and $m_{j_1 j_2}$ (right) distributions for a signal benchmark model with $(m_{\mathrm{DM}}, m_{\mathrm{X}}, m_{\mathrm{M}}) = (379, 417, 900)$ GeV. The signal distribution is shown in black outline. The stacked background distributions are from top to bottom: $Z+$ jets (red), $W^+ +$ jets (orange), $W^- +$ jets (green) and QCD (blue). The vertical dashed line at 900 GeV on the left panel represents the optimal $\not{E}_T$ cut for this benchmark point. The $m_{j_1 j_2}$ distribution is shown for events that passed this $\not{E}_T$ cut.