

# Coannihilating Dark Matter at the LHC

Sonia El Hedri

with

M. Baker, J. Brod, A. Kaminska, J. Kopp, J. Liu, A. Thamm,  
M. de Vries, X. Wang, F. Yu, J. Zurita

JGU Mainz

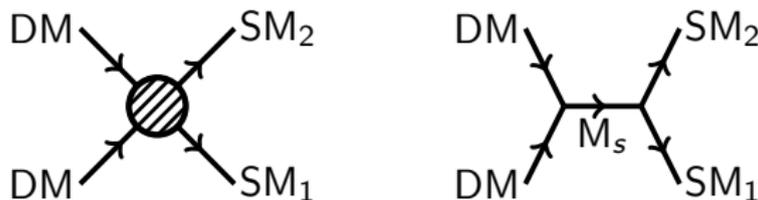
August 28, 2015

# Introduction

- ▶ The thermal hypothesis: elegant explanation of current DM relic density that implies DM interactions with the SM
- ▶ DM annihilation implies direct detection, indirect detection and collider signatures through crossing symmetry

⇒ EFT/Simplified Models: SM + DM ( + Mediator )

Cirelli, Fornengo, Strumia [2005], Abdallah et al. [2015], ...



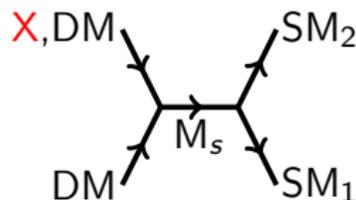
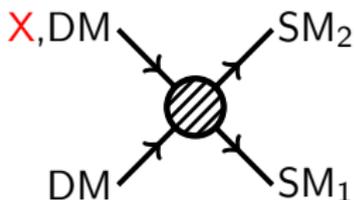
- ▶ Often, coannihilation is needed ⇒ new particle X.
- ▶ Study all possible (X,M,DM) extensions of the SM  
⇒ characterizing minimal models for coannihilation!

# Introduction

- ▶ The thermal hypothesis: elegant explanation of current DM relic density that implies DM interactions with the SM
- ▶ DM annihilation implies direct detection, indirect detection and collider signatures through crossing symmetry

⇒ EFT/Simplified Models: SM + DM ( + Mediator )

[Cirelli, Fornengo, Strumia \[2005\]](#), [Abdallah et al. \[2015\]](#), ...



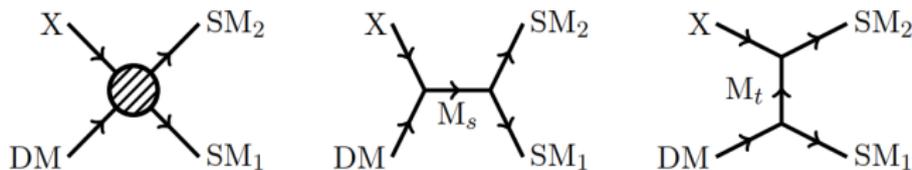
- ▶ Often, coannihilation is needed ⇒ new particle X.
- ▶ Study all possible (X,M,DM) extensions of the SM  
⇒ characterizing minimal models for coannihilation!

## Classification overview

Phenomenology

# Basic assumptions: Simplified Models

- ▶ Fully resolve the coannihilation process



Consider only simplified models:

- ▶ Tree-level and 4D interactions only
- ▶ Richer collider phenomenology
  - ▶  $s$  and  $t$ -channel interactions with distinct signatures
  - ▶ introduce a mediator
    - $\Rightarrow$  new signatures beyond monojets and compressed spectra
  - ▶ If a new particle is discovered, it can be mapped to a coannihilation mechanism

# Additional assumptions

## Core assumptions

- ▶ Dark Matter is stable  $\Rightarrow$  Introduce a  $\mathbb{Z}_2$  symmetry
- ▶ Dark Matter is a color singlet, electrically neutral
- ▶ All particles have spin 0, 1/2 and 1
- ▶ All spin 1 particles are gauge bosons  
 $\Rightarrow$  new broken gauge groups

## Model-dependent elements

- ▶ Agnostic about dark charge assignments
- ▶ Agnostic about flavor (model dependent)
- ▶ Ignore additional particle content for collider phenomenology

# Building Simplified Models: Guiding Principles

Building a **minimal basis** of simplified models

⇒ Work in the unbroken  $SU(2) \times U(1)$  phase

- ▶ Dark Matter quantum numbers  $(1, N, \beta)$
- ▶ Find all possible X and M using  $SU(3) \times SU(2) \times U(1)$  gauge conservation
- ▶ Find all possible spin configurations using the spins of  $SM_1$ ,  $SM_2$ .
- ▶ Different classifications for  $s$  and  $t$ -channel models



# s-channel classification

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

ID	X	$\alpha + \beta$	$M_s$	Spin	(SM <sub>1</sub> SM <sub>2</sub> )	SM <sub>3</sub>	M-X-X
SF11	(3, N ± 1, α)	$\frac{7}{3}$	(3, 2, $\frac{7}{3}$ )	B	(Q <sub>L</sub> $\bar{\ell}_L$ ), (u <sub>R</sub> $\bar{L}_R$ )		M-X-X
SF12				F	(u <sub>R</sub> H)		
SF13		$\frac{1}{3}$	(3, 2, $\frac{1}{3}$ )	B	(d <sub>R</sub> $\bar{L}_R$ ), (Q <sub>R</sub> $\bar{d}_L$ ), (u <sub>R</sub> L <sub>L</sub> )		
SF14				F	(u <sub>R</sub> $\bar{H}$ ), (d <sub>R</sub> H), (Q <sub>L</sub> B), (Q <sub>L</sub> W <sub>i</sub> ), (Q <sub>L</sub> g)	Q <sub>L</sub>	
SF15		$-\frac{5}{3}$	(3, 2, $-\frac{5}{3}$ )	B	(Q <sub>R</sub> $\bar{u}_L$ ), (Q <sub>L</sub> $\ell_R$ ), (d <sub>R</sub> L <sub>L</sub> )		
SF16				F	(d <sub>R</sub> $\bar{H}$ )		

Leptoquark model  
(case study)

Additional vertices

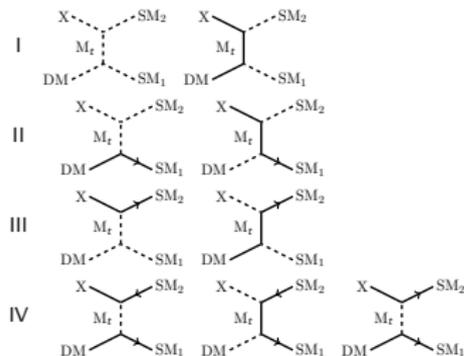
- ▶ Color for X: **U**(ncolored), **F**(undamental), **O**(ctet), **E**(xotic)
- ▶ Mediator and  $\alpha + \beta$  entirely determined by SM<sub>1</sub> and SM<sub>2</sub>
- ▶ Possible X-DM-SM<sub>3</sub> vertex  $\Leftrightarrow$  SM mediator also allowed
- ▶ Possible additional M-X-X, M-DM-DM vertices
- ▶ **Other vertices forbidden by the parity!**

# t-channel classification

ID	X	$\alpha + \beta$	$M_t$	Spin	$(SM_1 SM_2)$	SM <sub>3</sub>
TU33	$(1, N \pm 2, \alpha)$	0	$(1, N \pm 1, \beta - 1)$	I	$(H\bar{H})$	SM <sub>3</sub>
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	$(\bar{H} L_L)$	

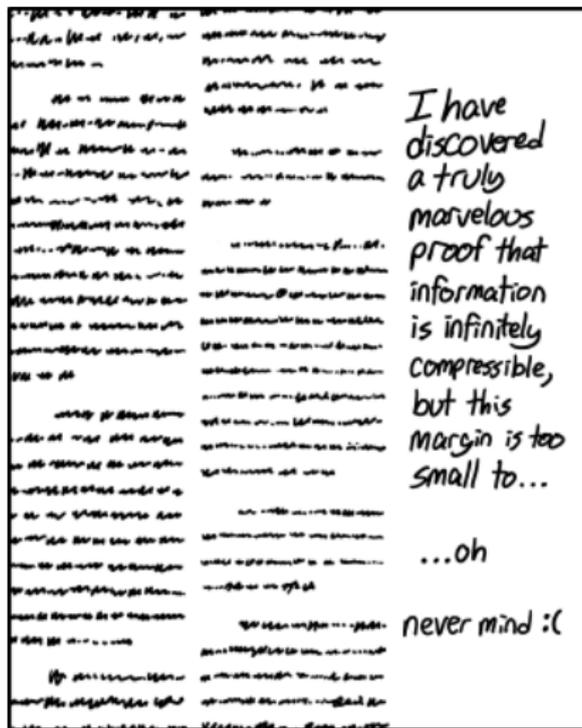
Four possible spin assignments

Only extra vertex X-DM-SM



If Dark Matter is thermal and (co)-annihilates with 4D tree-level interactions then one of the models in our classification is the real model of nature!

# Show me all the models!



xkcd.com/1381

# The Tables: s-channel

ID	X	$\alpha + \beta$	$M_L$	Spin	$(SM_1, SM_2)$	$SM_3$	M-X-X
SU1	(1, N, $\alpha$ )	0	(1, 1, 0)	B	$(\nu_R \nu_L), (d_R d_L), (Q_L \bar{Q}_R), (l_R \bar{l}_L), (L_L \bar{L}_R)$ ( $\bar{H} \bar{H}$ )	$B, W, \nu \geq 2$	$\checkmark$
SU2			F	$(L_L \bar{H})$			
SU3		(1, 3, 0) $N \geq 2$	B	$(Q_L \bar{Q}_R), (L_L \bar{L}_R), (H \bar{H}), (W, W_2)$	$B, W_1$	$\checkmark$	
SU4		F	$(L_L \bar{H})$				
SU5	(1, N, $\alpha$ )	-2	(1, 1, -2)	B	$(d_R \bar{u}_L), (\bar{H} \bar{H})$		$\checkmark$
SU6			F	$(L_L \bar{H}), (l_R \bar{H})$	$d_R$		
SU7		(1, 3, -2) $N \geq 2$	B	$(\bar{H} \bar{H}), (L_L \bar{L}_L)$	$\bar{e}_R$	$\checkmark (\nu = \pm 1)$	
SU8		F	$(L_L \bar{H})$	$\bar{e}_R$			
SU9	-4	(1, 1, -4)	B	$(f_R \bar{f}_R)$		$\checkmark (\nu = \pm 2)$	
SU10	(1, N $\pm 1, \alpha$ )	-1	(1, 2, -1)	B	$(d_R \bar{Q}_R), (u_L \bar{Q}_L), (L_R \bar{H}), (H \bar{H}), (W, W_1)$	$\bar{H}$	
SU11			F	$(f_R \bar{H}), (L_L \bar{L}_R), (L_L \bar{W}_1)$	$L_L$		
SU12		-3	(1, 2, -3)	B	$(L_L \bar{L}_R)$		
SU13		F	$(f_R \bar{H})$				
SU14	(1, N $\pm 2, \alpha$ )	0	(1, 3, 0)	B	$(L_L \bar{L}_R), (Q_L \bar{Q}_R), (H \bar{H}), (W, W_2)$		$\checkmark (\alpha = 0)$
SU15			F	$(L_L \bar{H})$			
SU16		-2	(1, 3, -2)	B	$(\bar{H} \bar{H}), (L_L \bar{L}_L)$		$\checkmark (\nu = \pm 1)$
SU17		F	$(L_L \bar{H})$				

SU[17]

ID	X	$\alpha + \beta$	$M_L$	Spin	$(SM_1, SM_2)$	$SM_3$	M-X-X	
SF1	(3, N, $\alpha$ )	$\frac{1}{2}$	(3, 1, $\frac{1}{2}$ )	B	$(\nu_R \bar{\nu}_L)$		$\checkmark \alpha = -\frac{1}{2}$	
SF2			F	$(d_R \bar{L}_L), (Q_L \bar{L}_R), (d_R \bar{L}_L)$		$\checkmark \alpha = -\frac{1}{2}$		
SF3		$\frac{3}{2}$	(3, 1, $\frac{3}{2}$ )	B	$(Q_L \bar{H}), (\nu_R \bar{H}), (\nu_R \bar{H})$	$u_R$	$\checkmark \alpha = -\frac{3}{2}$	
SF4			F	$(Q_L \bar{L}_L)$				
SF5		(3, 3, $\frac{3}{2}$ ) $N \geq 2$	B	$(Q_L \bar{H})$				
SF6		- $\frac{3}{2}$	(3, 1, - $\frac{3}{2}$ )	B	$(\bar{Q}_R \bar{Q}_R), (\nu_L \bar{L}_L), (\nu_R \bar{L}_R), (Q_L \bar{L}_L)$	$\bar{e} \alpha = \frac{1}{2}$		
SF7				F	$(Q_L \bar{H}), (d_R \bar{H}), (d_R \bar{H})$	$d_R$		
SF8			(3, 3, - $\frac{3}{2}$ ) $N \geq 2$	B	$(\bar{Q}_R \bar{Q}_R), (Q_L \bar{L}_L)$		$\checkmark \alpha = \frac{1}{2}$	
SF9			F	$(Q_L \bar{H})$	$d_R$			
SF10		- $\frac{5}{2}$	(3, 1, - $\frac{5}{2}$ )	B	$(u_L \bar{L}_L), (d_R \bar{H})$		$\checkmark \alpha = \frac{3}{2}$	
SF11	(3, N $\pm 1, \alpha$ )	$\frac{1}{2}$	(3, 2, $\frac{1}{2}$ )	B	$(Q_L \bar{L}_L), (\nu_R \bar{L}_R)$			
SF12			F	$(\nu_R \bar{H})$				
SF13		$\frac{3}{2}$	(3, 2, $\frac{3}{2}$ )	B	$(d_R \bar{L}_R), (\bar{Q}_R \bar{H}), (\nu_R \bar{L}_L)$			
SF14				F	$(\nu_R \bar{H}), (d_R \bar{H}), (Q_L \bar{H}), (Q_L \bar{W}_1), (Q_L \bar{H})$	$Q_L$		
SF15		- $\frac{1}{2}$	(3, 2, - $\frac{1}{2}$ )	B	$(Q_R \bar{u}_L), (Q_L \bar{f}_R), (d_R \bar{L}_L)$			
SF16		F	$(d_R \bar{H})$					
SF17		(3, N $\pm 2, \alpha$ )	$\frac{1}{2}$	(3, 3, $\frac{1}{2}$ )	B	$(Q_L \bar{L}_R)$		$\checkmark \alpha = -\frac{3}{2}$
SF18				F	$(Q_L \bar{H})$			
SF19			- $\frac{3}{2}$	(3, 3, - $\frac{3}{2}$ )	B	$(\bar{Q}_R \bar{Q}_R), (Q_L \bar{L}_L)$		$\checkmark \alpha = \frac{1}{2}$
SF20			F	$(Q_L \bar{H})$				

SF[20]

ID	X	$\alpha + \beta$	$M_L$	Spin	$(SM_1, SM_2)$	$SM_3$	M-X-X
SO1	(8, N, $\alpha$ )	0	(8, 1, 0) $N \geq 2$	B	$(d_R \bar{d}_L), (\nu_R \bar{\nu}_L), (Q_L \bar{Q}_R)$		$\checkmark \alpha = 0$
SO2		-2	(8, 3, 0) $N \geq 2$	B	$(Q_L \bar{Q}_R)$		$\checkmark \alpha = 0$
SO3		(8, 1, -2)	B	$(d_R \bar{u}_L)$		$\checkmark \alpha = \pm 1$	
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	$(Q_L \bar{Q}_R)$		$\checkmark \alpha = 0$
SE1	(6, N, $\alpha$ )	$\frac{1}{2}$	(6, 1, $\frac{1}{2}$ )	B	$(\nu_R \bar{\nu}_R)$		$\checkmark \alpha = -\frac{1}{2}$
SE2			F	$(Q_L \bar{Q}_L), (\nu_R \bar{d}_R)$		$\checkmark \alpha = -\frac{1}{2}$	
SE3		$\frac{3}{2}$	(6, 3, $\frac{3}{2}$ ) $N \geq 2$	B	$(Q_L \bar{Q}_L)$		$\checkmark \alpha = -\frac{1}{2}$
SE4			F	$(d_R \bar{d}_R)$		$\checkmark \alpha = \frac{1}{2}$	
SE5	(6, N $\pm 1, \alpha$ )	$\frac{1}{2}$	(6, 2, $\frac{1}{2}$ )	B	$(Q_L \bar{u}_R)$		
SE6	- $\frac{1}{2}$	(6, 2, - $\frac{1}{2}$ )	B	$(Q_L \bar{d}_R)$			
SE7	(6, N $\pm 2, \alpha$ )	$\frac{3}{2}$	(6, 3, $\frac{3}{2}$ )	B	$(Q_L \bar{Q}_L)$		$\checkmark \alpha = -\frac{1}{2}$

SO[5], SE[7]



Classification overview

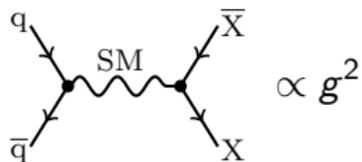
Phenomenology

# Phenomenology, s-channel

Production

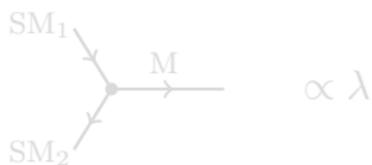
Decay

Pair



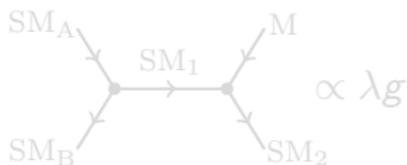
soft +  $\cancel{E}_T$

Single M



Resonance

M + SM



soft +  $\cancel{E}_T$

# Phenomenology, s-channel

Production

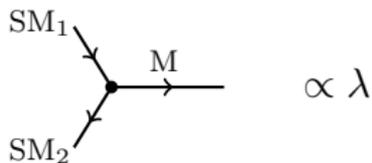
Decay

Pair



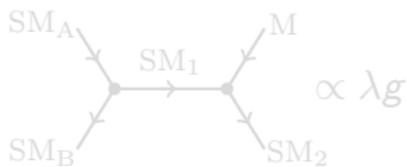
soft +  $\cancel{E}_T$

Single M



Resonance

M + SM



soft +  $\cancel{E}_T$

# Phenomenology, s-channel

Production

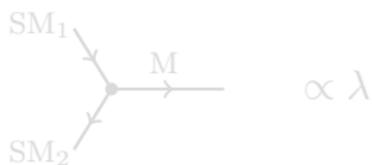
Decay

Pair



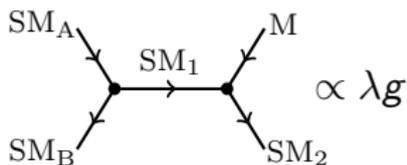
soft +  $\cancel{E}_T$

Single M



Resonance

M + SM



soft +  $\cancel{E}_T$

# Phenomenology, s-channel

Production

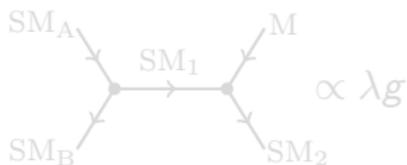
Pair



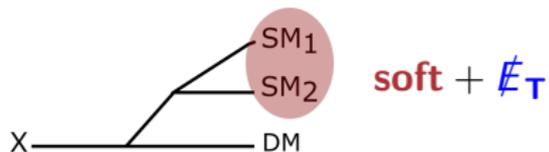
Single M



M + SM



Decay



**soft** +  $\cancel{E}_T$

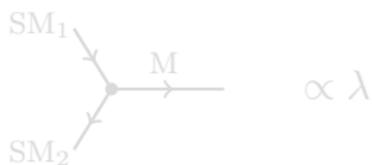
# Phenomenology, s-channel

Production

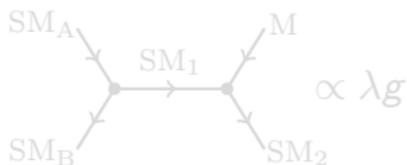
Pair



Single M

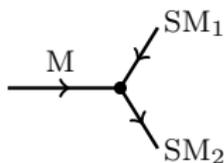


M + SM



Decay

soft +  $\cancel{E}_T$



**Resonance**

soft +  $\cancel{E}_T$

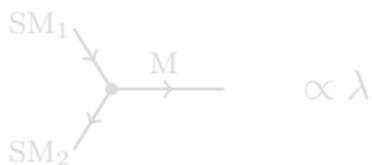
# Phenomenology, s-channel

Production

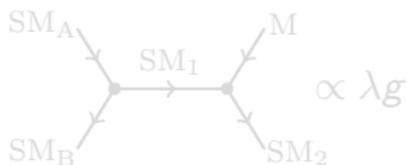
Pair



Single M

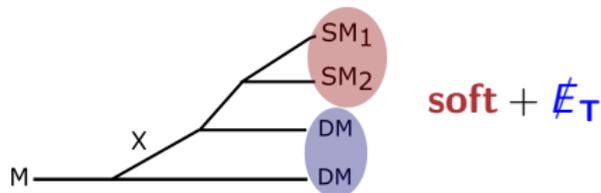
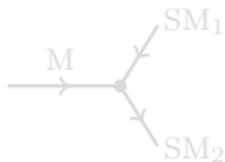


M + SM



Decay

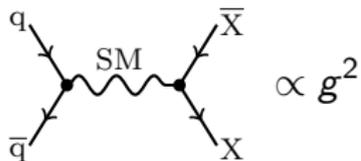
soft +  $\cancel{E}_T$



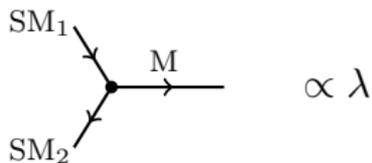
# Phenomenology, s-channel

Production

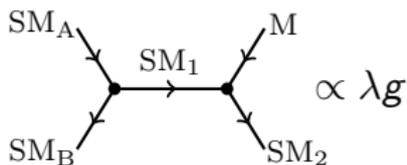
Pair



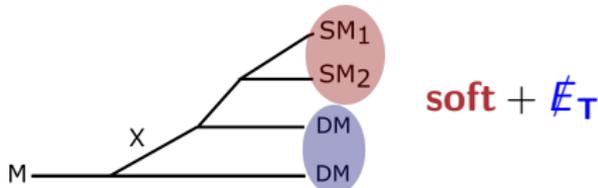
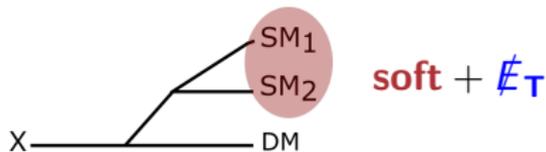
Single M



M + SM

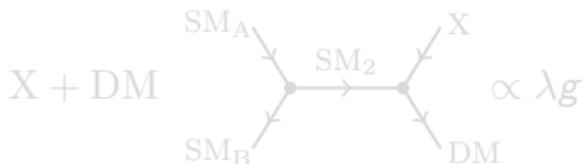
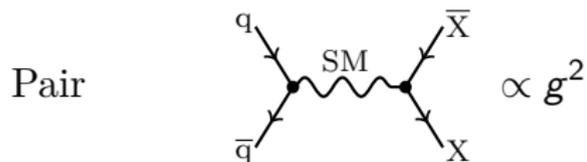


Decay



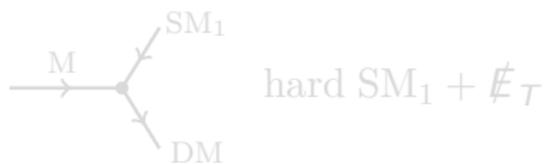
# Phenomenology: $t$ -channel

Production



Decay

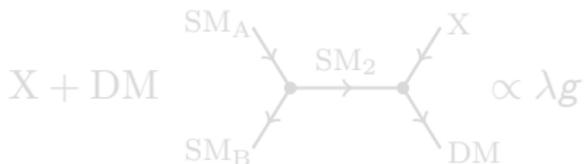
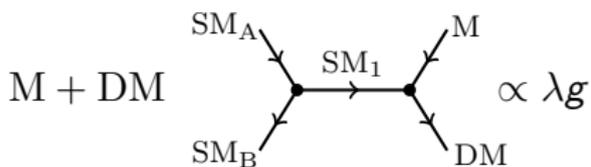
soft +  $\cancel{E}_T$



hard  $SM_2$   
+ **soft** +  $\cancel{E}_T$

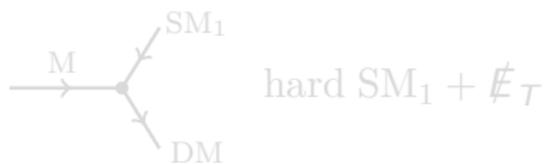
# Phenomenology: $t$ -channel

Production



Decay

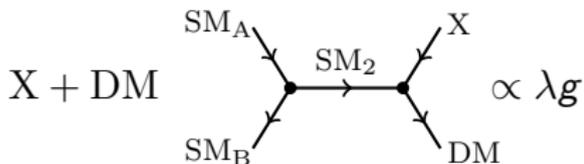
soft +  $\cancel{E}_T$



hard  $SM_2$   
+ **soft** +  $\cancel{E}_T$

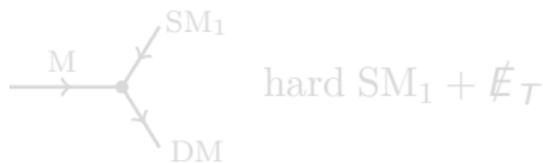
# Phenomenology: $t$ -channel

Production



Decay

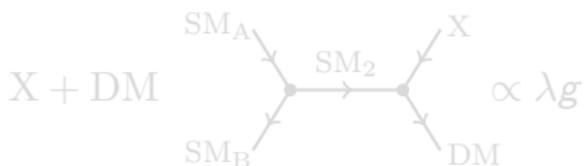
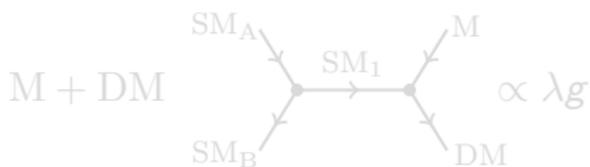
soft +  $\cancel{E}_T$



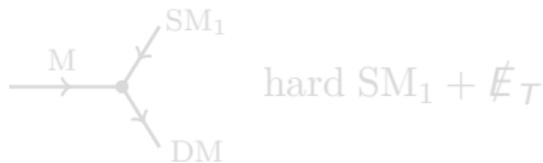
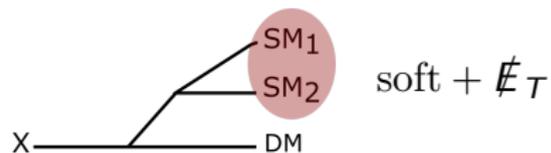
hard  $SM_2$   
+ **soft** +  $\cancel{E}_T$

# Phenomenology: $t$ -channel

## Production



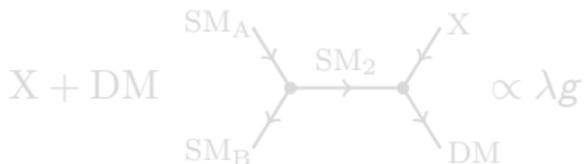
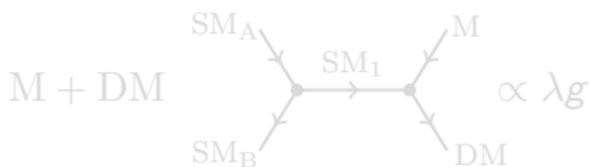
## Decay



hard SM<sub>2</sub>  
+ soft +  $\cancel{E}_T$

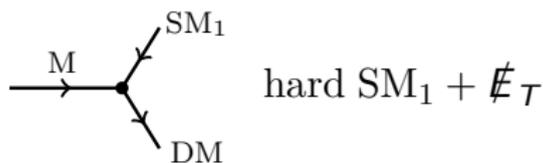
# Phenomenology: $t$ -channel

Production



Decay

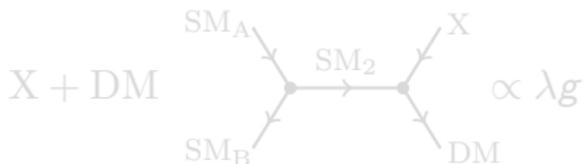
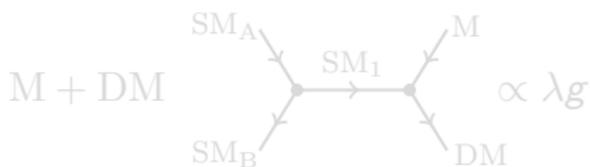
soft +  $\cancel{E}_T$



hard  $SM_2$   
+ soft +  $\cancel{E}_T$

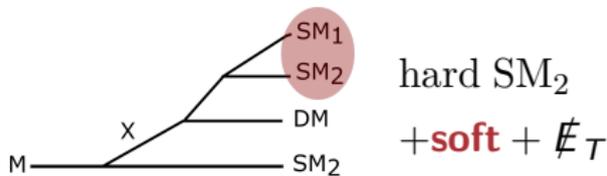
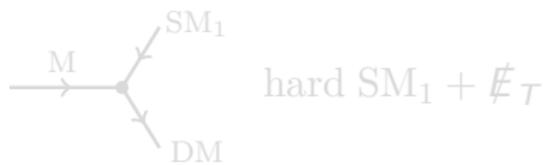
# Phenomenology: $t$ -channel

Production



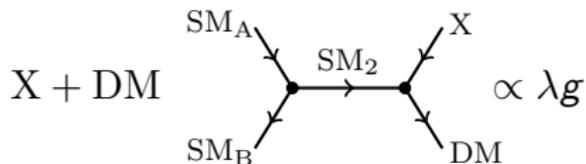
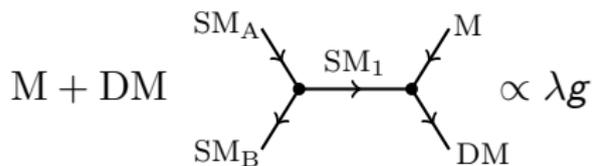
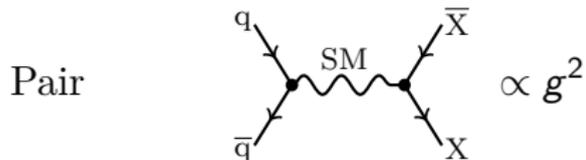
Decay

soft +  $\cancel{E}_T$

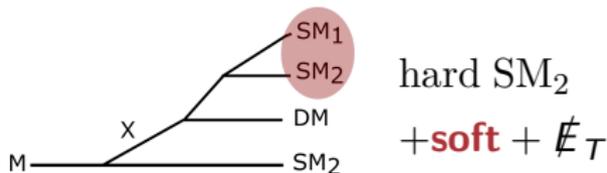
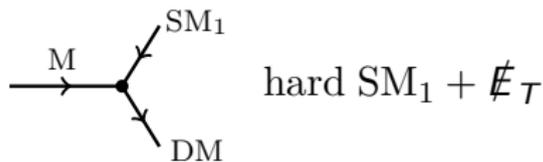
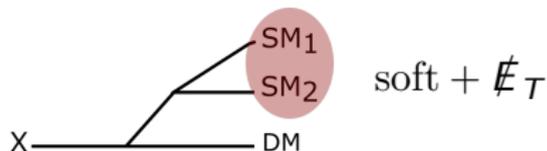


# Phenomenology: $t$ -channel

Production

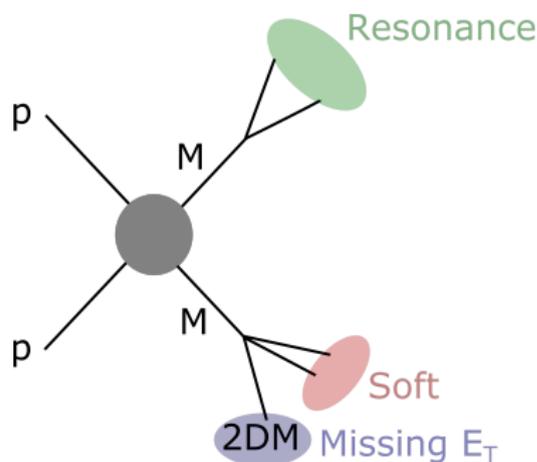


Decay



## Signatures: s-channel

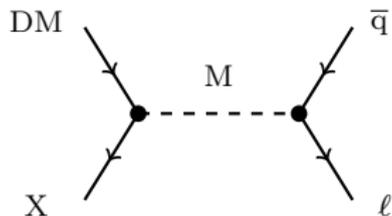
- ▶ **Double resonances** from pair-produced mediator (exotica)
- ▶ **Single resonances** (Higgs and  $Z'$  searches)
- ▶ **Monojet** +  $\cancel{E}_T$  + soft particles  
(compressed spectra searches, under study)
- ▶ **Mixed resonance** +  $\cancel{E}_T$  from M pair production  
 $\Rightarrow$  new signature to explore!



- ▶ Direct evidence for DM
- ▶ Two smoking-gun signatures of new physics
- ▶ Hint of coannihilation through soft radiation
- ▶ May be favored by branching ratio

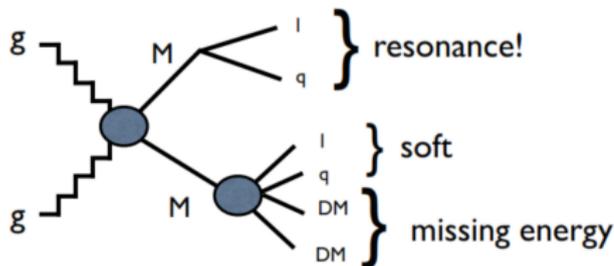
## Example: s-channel leptoquark

Linking leptoquarks to Dark Matter!



$$\Rightarrow \mathcal{L} \supset \mathcal{L}_{\text{kin}} + \lambda_{Qe} \bar{Q}_R M e_R + \lambda_{Lu} \bar{L}_R M u_R + \lambda_{\text{dark}} \bar{X} M DM$$

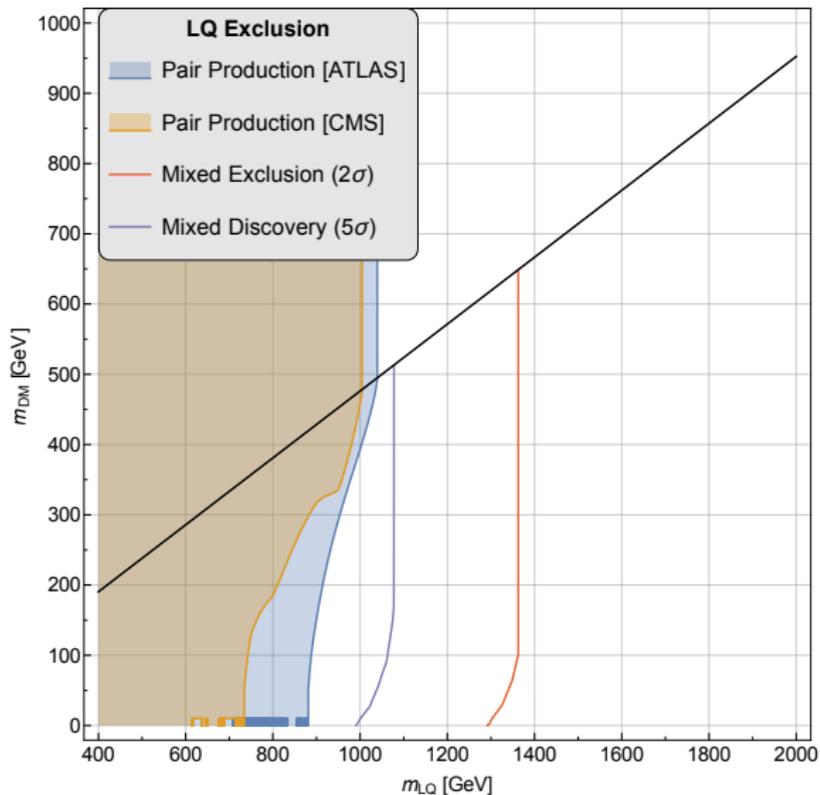
Smoking-gun evidence of a "dark" leptoquark sector



- ▶ Strong production
- ▶ Lepton +  $\cancel{E}_T$   
⇒ Clean signature
- ▶ No dedicated LHC search!

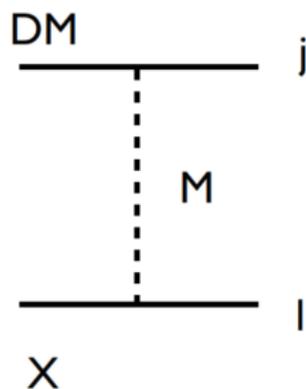
Expect TeV-scale *discovery* reach at 13 TeV LHC!

# s-channel leptoquark: sensitivity



## Signatures: $t$ -channel

- ▶  $2SM_i + \cancel{E}_T$ : MSSM-like signatures
- ▶ Strong production of soft leptons (colored X, uncolored "slepton-like" mediator)
- ▶ **Strong production of hard leptons**: "dark leptoquark"



- ▶ "Slepton" signature with strong production

$$MM \rightarrow 2l + \cancel{E}_T (+\text{soft leptons})$$

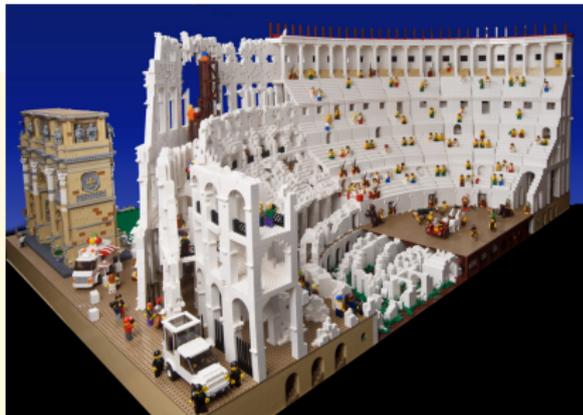
- ▶ "Mixed" lepton-jet signature  $\Rightarrow$  NEW!

$$MM \rightarrow l + j + \cancel{E}_T (+\text{soft lepton})$$

# Conclusion

- ▶ As in the pure annihilation case, minimal (DM, X, M) models can be build for DM coannihilation
- ▶ We build a *minimal basis* of simplified models with minimal assumptions.
- ▶ The huge variety of models can be mapped to a few broad classes of LHC signatures.
- ▶ New possible topology to investigate: mixed resonance/MET signature
- ▶ Plenty left for future studies: direct/indirect detection, cosmology, unexplored models...

If our (mild) assumptions are verified, our classification contains the real model of nature...



Time to start exploring!