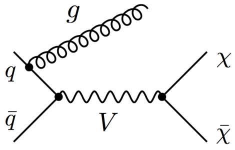
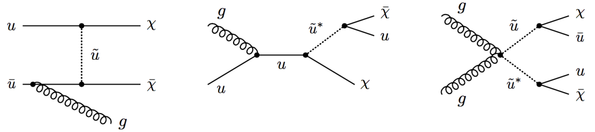
The Future of Simplified Models

Joachim Kopp

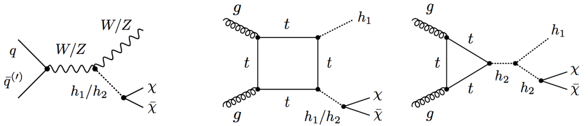
The current simplified model portfolio



s-channel



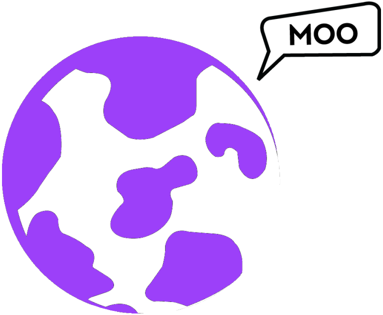
t-channel



Scalar portal

see talks by Sarah A. Malik and Oliver Buchmueller

Outline



Simplified Models off the Beaten Paths

What may we be missing?

A bottom-up exercise
in classifying simplified models

What may we be missing?

A bottom-up exercise
in classifying simplified models

Allow for coannihilation
$\rightarrow$ thermal relics even at weak coupling/heavy mass

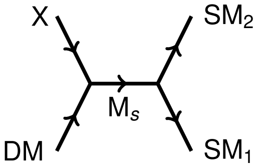
One step beyond minimal simplified models

Assumptions:

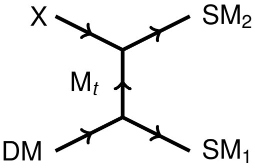
- ≤ 3 new multiplets:
  - Dark matter
  - Coannihilation partner
  - Mediator
- DM is colorless and electrically neutral
- DM is a thermal relic
- DM annihilation/coannihilation is a 2–2 process
- Tree-level, renormalizable interactions
- New particles are spin 0, $1/2$, or 1

Baker et al., *The Coannihilation Codex*, arXiv:1510.03434

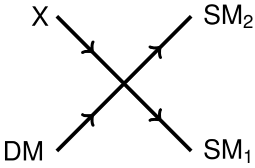
Four classes of simplified models



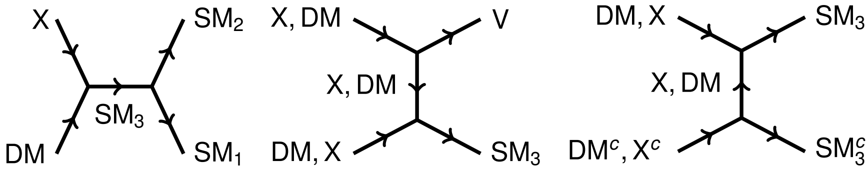
s-channel



t-channel



4-scalar



Hybrid

Classification procedure

- Choose DM in $(1, N, \beta)$ of $SU(3) \times SU(2) \times U(1)$.

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  - Determines the spins of DM and X

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- Choose representation of coannihilation partner X.
- Allowed representations for mediator M are now fixed
- Choose spin of mediator M
  - Determines the spins of DM and X
- Allowed couplings to SM particles now determined

Tables, tables, tables

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	$(L_L\,H^\dagger)$		

DM — in $(1, N, \beta)$ representation of $SU(3)\times SU(2)\times U(1)$

X — coannihilation partner

M_s — s-channel mediator

SM_1, SM_2 — SM particles in coannihilation DM + X $\to$ $SM_1 SM_2$

SM_3 — Possible additional vertex DM–X–SM_3

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ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	X–DM–SM_3	M_s–X–X
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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			[illegible]	B	$(d_R\,\overline{u_R}), (H^\dagger\,H^\dagger), (L_L\,L_L)$		✓
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	$(Q_L\,\overline{Q_L}), (L_L\,\overline{L_L}), (H\,H^\dagger)$		✓$(\alpha=0)$
SU15				F	$(L_L\,H)$		
SU16		-2	$(1,3,-2)$	B	$(H^\dagger\,H^\dagger), (L_L\,L_L)$		✓$(\alpha=\pm 1)$
SU17				F	$(L_L\,H^\dagger)$		

Tally

In total 161 simplified models (defined by representations of DM, X and M)

49 s-channel, 105 t-channel, 7 hybrid

DM	in $(1, N, \beta)$ representation of $SU(3)\times SU(2)\times U(1)$
X	coannihilation partner
M_s	s-channel mediator
SM_1, SM_2	SM particles in coannihilation DM + X $\to SM_1SM_2$
SM_3	Possible additional vertex DM–X–SM_3

LHC pheno classification

Another table . . .

	$pp \to \ldots$	Prod. via	Signatures	Search
common	DM + DM + ISR	gauge int. or $SM_1 \in p$ for t-channel	mono-Y + $\not{E}_T$	[55,56,62,63,104]
	X (→ SM_1^{soft} SM_2^{soft} DM) + X (→ SM_1^{soft} SM_2^{soft} DM) + ISR	gauge int. or $SM_2 \in p$ for t-channel	mono-Y + $\not{E}_T$ mono-Y + $\not{E}_T + \leq 4$ SM	[55,56,62,63,104] Partial coverage [105]
	DM + X (→ SM_1^{soft} SM_2^{soft} DM) + ISR	$(SM_1\ SM_2) \in p$	mono-Y + $\not{E}_T$ mono-Y + $\not{E}_T + \leq 2$ SM	[55,56,62,63,104] Partial coverage [105]
s-channel	M_s (→ $[SM_1\ SM_2]^{res}$) + M_s (→ $[SM_1\ SM_2]^{res}$)	gauge int.	2 resonances	[106–112]
	M_s (→ $[SM_1\ SM_2]^{res}$) + M_s (→ DM + X (→ SM_1^{soft} SM_2^{soft} DM))		resonance + $\not{E}_T$ resonance + $\not{E}_T + \leq 2$ SM	No search No search
	M_s (→ DM + X (→ SM_1^{soft} SM_2^{soft} DM)) + M_s (→ DM + X (→ SM_1^{soft} SM_2^{soft} DM))		$\not{E}_T + \leq 4$ SM	[113,114,114–124]
	M_s (→ $[SM_1\ SM_2]^{res}$)	$(SM_1\ SM_2) \in p$	1 resonance	[125–146]
	M_s (→ DM + X (→ SM_1^{soft} SM_2^{soft} DM))		$\not{E}_T + \leq 2$ SM	[120–122,124] [104,147–153]
	$SM_{1,2}$ + M_s (→ $[SM_1\ SM_2]^{res}$)	$SM_{2,1} \in p$	1 resonance + 1 SM	Partial coverage [154,155]
	$SM_{1,2}$ + M_s (→ DM + X (→ SM_1^{soft} SM_2^{soft} DM))		$\not{E}_T$ + $1 \leq 3$ SM	[114,120–124] [147–153,156–158]
	M_t (→ SM_1 DM) + M_t (→ SM_1 DM)		$\not{E}_T + \leq 2$ SM	[120–122,124] [104,147–153]
	M_t (→ SM_1 DM)			[106–112]

LHC pheno classification

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	$pp \to \ldots$	Prod. via	Signatures	Search
…on	DM + DM + ISR	gauge int. or $SM_1 \in p$ for t-channel	mono-Y + $\not{E}_T$	[55,56,62,63,104]
	X (→ SM_1^{soft} SM_2^{soft} DM)	gauge int.	mono-Y + $\not{E}_T$	[55,56,62,63,104]

Frequent features

- **Cascade decays**
  (1- or 2-step, involves MET)
- **Soft SM particles**
  (in coannihilation scenarios)
- **Resonances**
  mediator $M_s \to SM_1\, SM_2$

	$pp \to \ldots$	Prod. via	Signatures	Search
s-c…	M_s (→ DM + X (→ SM_1^{soft} SM_2^{soft} DM))	$(SM_1\ SM_2) \in p$	$\not{E}_T + \leq 2$ SM	[120–122,124] [104,147–153]
	$SM_{1,2}$ + M_s (→ $[SM_1\ SM_2]^{res}$)	$SM_{2,1} \in p$	1 resonance + 1 SM	Partial coverage [154,155]
	$SM_{1,2}$ + M_s (→ DM + X (→ SM_1^{soft} SM_2^{soft} DM))		$\not{E}_T + 1 \leq 3$ SM	[114,120–124] [147–153,156–158]
	M_t (→ SM_1 DM) + M_t (→ SM_1 DM)		$\not{E}_T + \leq 2$ SM	[120–122,124] [104,147–153]

Take-home messages (part 1)

- Look for the mediators!
- Many searches sensitive
  (though not yet interpreted in terms of DM)
  - Important role for recasting tools
    (ATOM, CheckMate, GAMBIT, MadAnalysis 5, SModelS, . . .)

Looking for the Mediators

Specific example: a leptoquark model

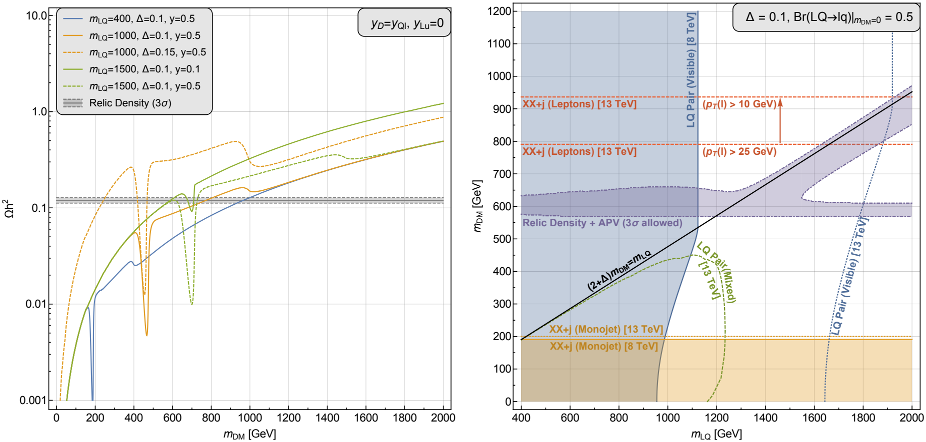
ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	X–DM–SM_3	M_s–X–X
ST1	$(3, N, \alpha)$	$\frac{10}{3}$	$(3, 1, \frac{10}{3})$	B	$(u_R\,\overline{l_R})$		$\checkmark(\alpha=-\frac{5}{3})$
ST2		$\frac{4}{3}$	$(3, 1, \frac{4}{3})$	B	$(d_R\,\overline{\ell_R}), (Q_L\,\overline{L_L}), (\overline{d_R}\,\overline{d_R})$		$\checkmark(\alpha=-\frac{2}{3})$
ST3				F	$(Q_L\,H)$	H5	
ST4			$(3, 3, \frac{4}{3})^{N\geq 2}$	B	$(Q_L\,\overline{L_L})$		$\checkmark(\alpha=-\frac{2}{3})$
ST5				F	$(Q_L\,H)$	H5	
ST6		$-\frac{2}{3}$	$(3, 1, -\frac{2}{3})$	B	$(\overline{Q_L}\,\overline{Q_L}), (\overline{u_R}\,\overline{d_R}), (u_R\,\ell_R), (Q_L\,L_L)$		$\checkmark(\alpha=\frac{1}{3})$
ST7				F	$(Q_L\,H^\dagger)$	H6	
ST8			$(3, 3, -\frac{2}{3})^{N\geq 2}$	B	$(\overline{Q_L}\,\overline{Q_L}), (Q_L\,L_L)$		$\checkmark(\alpha=\frac{1}{3})$
ST9				F	$(Q_L\,H^\dagger)$	H6	
ST10		$-\frac{8}{3}$	$(3, 1, -\frac{8}{3})$	B	$(\overline{u_R}\,\overline{u_R}), (d_R\,\ell_R)$		$\checkmark(\alpha=\frac{4}{3})$
ST11	$(3, N\pm 1, \alpha)$	$\frac{7}{3}$	$(3, 2, \frac{7}{3})$	B	$(Q_L\,\overline{\ell_R}), (u_R\,\overline{L_L})$		
ST12				F	$(u_R\,H)$		
ST13		$\frac{1}{3}$	$(3, 2, \frac{1}{3})$	B	$(d_R\,\overline{L_L}), (\overline{Q_L}\,\overline{d_R}), (u_R\,L_L)$		
ST14				F	$(u_R\,H^\dagger), (d_R\,H)$	H7	
ST15		$-\frac{5}{3}$	$(3, 2, -\frac{5}{3})$	B	$(\overline{Q_L}\,\overline{u_R}), (Q_L\,\ell_R), (d_R\,L_L)$		
ST16				F	$(d_R\,H^\dagger)$		
ST17	$(3, N\pm 2, \alpha)$	$\frac{4}{3}$	$(3, 3, \frac{4}{3})$	B	$(Q_L\,\overline{L_L})$		$\checkmark(\alpha=-\frac{2}{3})$
ST18				F	$(Q_L\,H)$		
ST19		$-\frac{2}{3}$	$(3, 3, -\frac{2}{3})$	B	$(\overline{Q_L}\,\overline{Q_L}), (Q_L\,L_L)$		$\checkmark(\alpha=\frac{1}{3})$
ST20				F	$(Q_L\,H^\dagger)$		

Specific example: a leptoquark model

Lagrangian

$$\mathcal{L} = \frac{i}{2}\overline{\mathrm{DM}}\,\partial\!\!\!/\,\mathrm{DM} + i\overline{\mathrm{X}}\,D\!\!\!\!/\,\mathrm{X} + |D_\mu \mathrm{M}_s|^2 - \frac{m_{\mathrm{DM}}}{2}\overline{\mathrm{DM}}\,\mathrm{DM} - m_{\mathrm{X}}\overline{\mathrm{X}}\,\mathrm{X} - V(\mathrm{M}_s, H) - \Big(y_D \overline{\mathrm{X}}\,\mathrm{M}_s\,\mathrm{DM} + y_{Q\ell}\,\overline{Q_L}\mathrm{M}_s\,\ell_R + y_{Lu}\overline{L_L}\mathrm{M}_s^c u_R + \mathrm{h.c.} \Big),$$

Specific example: a leptoquark model

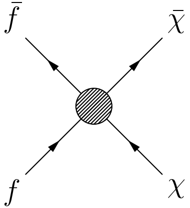


Baker et al., *The Coannihilation Codex*, arXiv:1510.03434

Non-Minimal Dark Sectors

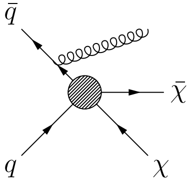
Dark Matter Production at the LHC

Traditional DM searches: initial state radiation

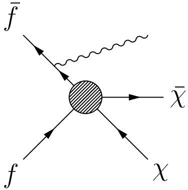


DM pair production
(invisible @ LHC)

→

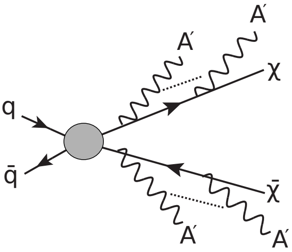


Monojet



Monophoton

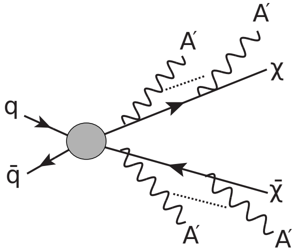
How about final state radiation?



Model Framework: Self-Interacting DM

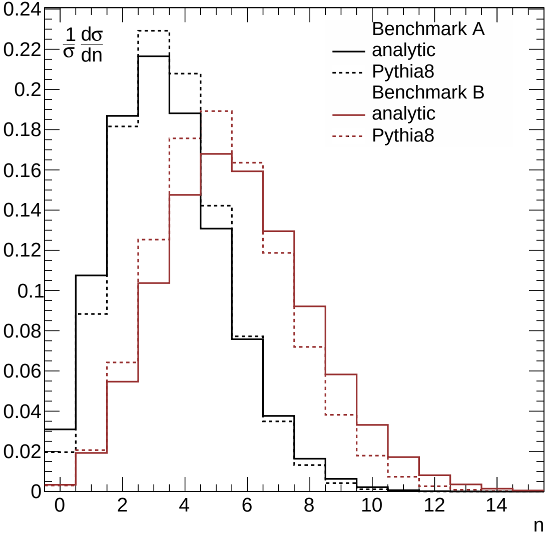
Dark Sector Lagrangian

$$\mathcal{L}_{\text{dark}} \equiv \bar{\chi}(i\not{\partial} - m_\chi + i g_{A'} \not{A}')\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\nu - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} ,$$

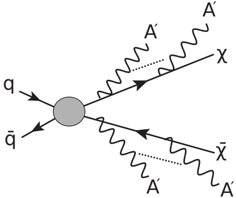


Buschmann JK Liu Wang, arXiv:1505.07459

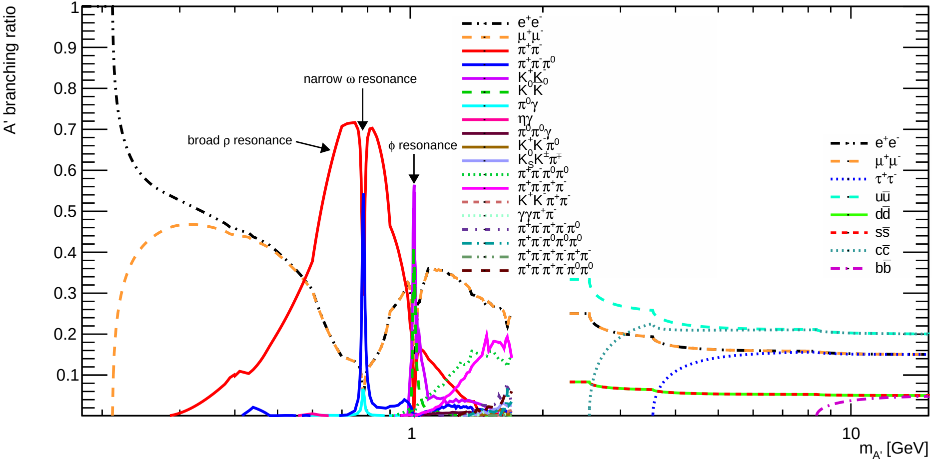
Dark Radiation — Analytics vs. Numerics



A' Decay



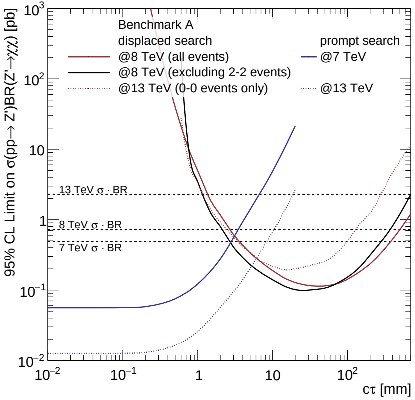
q
q̄
A′
A′
χ
χ̄
A′
A′

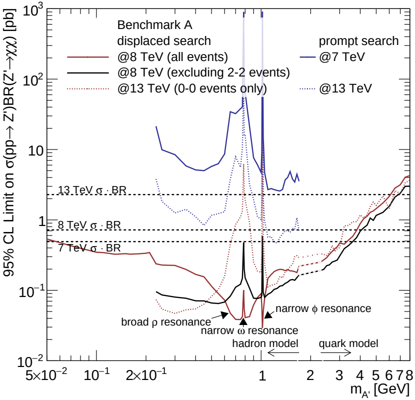


A' branching ratio
narrow ω resonance
broad ρ resonance
ϕ resonance
e^+e^-
$\mu^+\mu^-$
$\pi^+\pi^-$
$\pi^+\pi^-\pi^0$
K^+K^-
$K^0\bar{K}^0$
$\pi^0\gamma$
$\eta\gamma$
$\pi^0\pi^0\gamma$
$K^+K^-\pi^0$
$K_S^0K^\pm\pi^\mp$
$\pi^+\pi^-\pi^0\pi^0$
$\pi^+\pi^-\pi^+\pi^-$
$K^+K^-\pi^+\pi^-$
$\gamma\gamma\pi^+\pi^-$
$\pi^+\pi^-\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0\pi^0\pi^0$
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
$u\bar{u}$
$d\bar{d}$
$s\bar{s}$
$c\bar{c}$
$b\bar{b}$
$m_{A'}$ [GeV]

Phenomenological Results

- Recast ATLAS prompt lepton jet search (arXiv:1212.5409)
- Recast ATLAS displaced lepton jet search (arXiv:1409.0746)
- Conservative projections for 13 TeV
  - Type-0 (muonic lepton jets only) — cannot estimate multijet background





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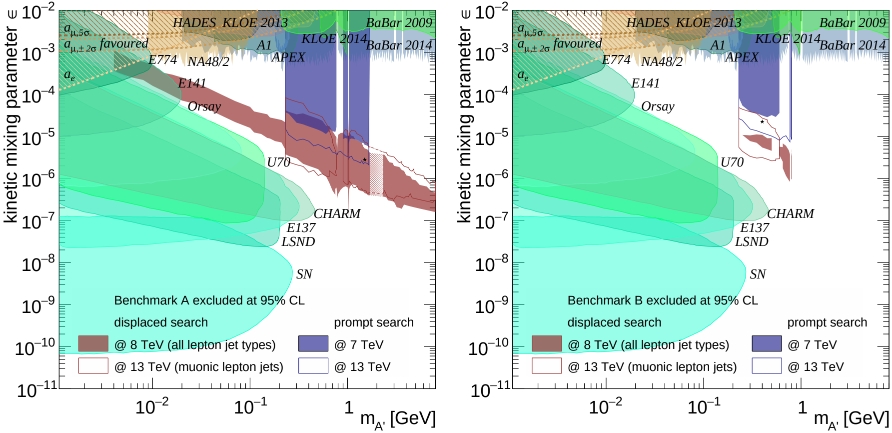

Take-home messages (part 2)

- Very conventional dark sectors may lead to very unconventional signatures
  - Lepton jets

    e.g. Buschmann et al., arXiv:1505.07459
  - Emerging jets

    e.g. talk by Will Shepherd
    Strassler Zurek, hep-ph/0604261
    Bai Rajaraman, arXiv:1109.6009
    Schwaller Stolarski Weiner, arXiv:1502.05409
  - Missing energy within jets

    e.g. Cohen Lisanti Lou, arXiv:1503.00009
  - ...
- In extended dark sectors, the particle that is easiest to discover is typically the one with the lowest cosmological abundance
  (large coupling to SM $\rightarrow$ low relic density)
- Don't take simplified models too serious!

Data-Driven Phenomenology

Why Ambulance Chasing is Awesome

From Data to Theory

Traditional Motivation for Simplified Models

Present experimental results in a way that allows theorists to apply them to large classes of models

Problem

Theorists invent too many exotic models
(which cannot be reduced to the established simplified models)

My Dream

Exchange data on event-by-event basis
(like many direct/indirect searches)

A Pheno-Level Event Record

```
class HEPEventRecord {
  int np;                          // Number of particles
  HEPParticle *p;                  // List of particles
  ...
};

class HEPParticle {
  double pT, eta, phi;             // 3-momentum
  double E;                        // Energy
  int type;                        // Type - jet, photon, e+, e-, etc.
  double em_fraction;              // Fraction of E in E-cal
  int n_tracks;                    // Number of tracks
  bool b_tag;
  int n_spec;
  double *spec;                    // Analysis-specific info
  ...
};
```

(Heavily inspired by the good old LHC Olympics Format)

- Easy to implement in existing analysis frameworks
- Easy to use
- Customizable

Criticism

- Less credit for experimental collaborations
  - Share data after collaboration has exploited it (ATLAS/CMS have demonstrated that they can act very fast!)
  - Experimentalists' analyses will always be more trusted

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- Some will misinterpret/overinterpret data
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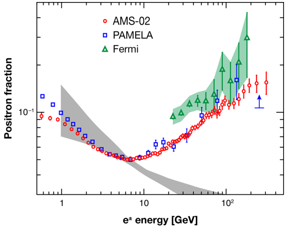
  - Not aware of any experiment whose reputation has suffered from this
- Even more ambulance chasing
  - IMHO not a bad thing

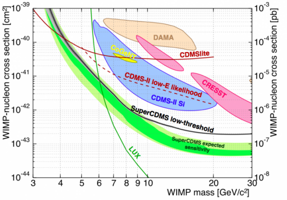
Recent Ambulances



We've learned about

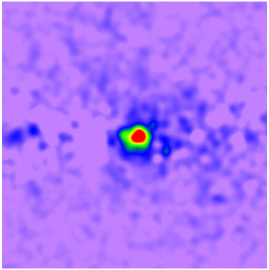
- Pulsars
- Cosmic ray propagation
- Innumerable new DM models
- Sommerfeld enhancement

PAMELA



- Spurred Interest in low-mass DM
- Now main target for many experiments (→ talk by J. Billard)

DAMA/CoGeNT



We've learned about

- High-E astrophysics
- Better CR models
- Analyzing Fermi data (→ talk by M. Lisanti)

Galactic Center Excess

Take-home messages (part 3)

- Sharing event-level data
  - is easy
  - benefits experimentalists and theorists
  - works great in astrophysics
- Ambulance chasing
  - moves the field forward
  - is educational
  - is great fun!

Summary

- Look for the mediators!
- Many searches sensitive
  (though not yet interpreted in terms of DM)
- Very conventional dark sectors may lead to very unconventional signatures
- Don't take simplified models too serious!
- Sharing event-level data would be great.
- Ambulance chasing is a great


Thank You!

Bonus Slides

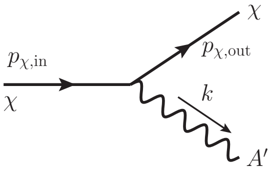
Dark Radiation Showers — Semi-Analytical Results

Notation, notation, notation, ...

- Incoming (off-shell) DM particle: $p_{\chi,\text{in}} = (E, 0, 0, p)$
- Outgoing DM particle: $p_{\chi,\text{out}} = \left(xE,\ -k_t,\ 0,\ \sqrt{x^2E^2 - k_t^2 - m_\chi^2}\right)$
- Outgoing dark photon: $k = \left((1-x)E,\ k_t,\ 0,\ \sqrt{(1-x)^2E^2 - k_t^2 - m_{A'}^2}\right)$
- Virtuality: $t \equiv (p_{\chi,\text{out}} + k)^2 - m_\chi^2$

Probability for a collinear splitting:

$$\frac{\alpha_{A'}}{2\pi} dx \, \frac{dt}{t} P_{\chi\to\chi}(x, t)$$



with the splitting kernel

$$P_{\chi\to\chi}(x, t) = \frac{1+x^2}{1-x} - \frac{2(m_\chi^2 + m_{A'}^2)}{t}$$

Dark Radiation Showers — Semi-Analytical Results

Average number radiated dark photons

$$\langle n_{A'} \rangle \simeq \frac{\alpha_{A'}}{2\pi} \int_{x_{\rm min}}^{x_{\rm max}} dx \int_{t_{\rm min}}^{t_{\rm max}} \frac{dt}{t} P_{\chi \to \chi}(x) \,.$$

Splitting is a Poisson process.

- Probability for m splittings

$$p_m = \frac{e^{-\langle n_{A'} \rangle} \langle n_{A'} \rangle^m}{m!}$$

- Probability for no splitting (Sudakov factor)

$$\Delta \equiv p_0 = e^{-\langle n_{A'} \rangle}$$

Dark Radiation — Energy Spectrum of DM Particles

Compute first the moments of the E spectrum $f_\chi(X \equiv E_\chi/E_0)$:

- Events with one emission

$$p_1 \langle X^s \rangle_{1A'} = e^{-\langle n_{A'} \rangle} \frac{\alpha_{A'}}{2\pi} \int_{x_{\rm min}}^{x_{\rm max}} dx\, x^s \int_{t_{\rm min}}^{t_{\rm max}} \frac{dt}{t} P_{\chi\to\chi}(x)$$

$$\equiv e^{-\langle n_{A'} \rangle} \langle n_{A'} \rangle \overline{X^s}$$

- Events with two emissions

$$p_2 \langle X^s \rangle_{2A'} = e^{-\langle n_{A'} \rangle} \left(\frac{\alpha_{A'}}{2\pi}\right)^2 \int_{x_{\rm min}}^{x_{\rm max}} dx\, x^s \int_{t_{\rm min}}^{t_{\rm max}} \frac{dt}{t} \int_{x_{\rm min}}^{x_{\rm max}} dx'\, x'^s \int_{t_{\rm min}}^{t} \frac{dt'}{t'} P_{\chi\to\chi}(x) P_{\chi\to\chi}(x')$$

$$\simeq e^{-\langle n_{A'} \rangle} \frac{1}{2!} \left(\frac{\alpha_{A'}}{2\pi}\right)^2 \int_{x_{\rm min}}^{x_{\rm max}} dx\, x^s \int_{t_{\rm min}}^{t_{\rm max}} \frac{dt}{t} \int_{x_{\rm min}}^{x_{\rm max}} dx'\, x'^s \int_{t_{\rm min}}^{t_{\rm max}} \frac{dt'}{t'} P_{\chi\to\chi}(x) P_{\chi\to\chi}(x')$$

$$= e^{-\langle n_{A'} \rangle} \frac{\langle n_{A'} \rangle^2}{2!} \overline{X^s}^2$$

- Events with m emissions

$$p_m \langle X^s \rangle_{mA'} = e^{-\langle n_{A'} \rangle} \frac{\langle n_{A'} \rangle^m}{m!} \overline{X^s}^m .$$

Dark Radiation — Energy Spectrum of DM Particles

- Summing over all m

$$\varphi(s+1) \equiv \langle X^s \rangle = \sum_{m=0}^{\infty} p_m \langle X^s \rangle_{mA'} = e^{-\langle n_{A'} \rangle (1-\overline{X^s})} \,.$$

Mellin Transform

$$\mathcal{M}[f](s+1) \equiv \varphi(s+1) \equiv \int_0^\infty dX\, X^s f(X)$$

Inverse Mellin Transform

$$f(X) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} ds\, X^{-s}\, \varphi(s)$$

Efficient numerical evaluation using Fast Fourier Transform (FFT)

Dark Radiation — Energy Spectrum of Dark Photons

With $Z \equiv E_{A'}/E_0$:

$$p_m \langle Z^s \rangle_{mA'} = \frac{1}{\langle n_{A'} \rangle} e^{-\langle n_{A'} \rangle} \frac{\langle n_{A'} \rangle^m}{m!} \overline{Z^s} \sum_{k=1}^{m} \overline{X^s}^{k-1}$$

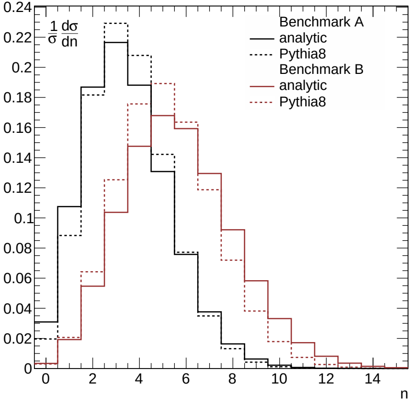
with

$$\overline{Z^s} \equiv \frac{1}{\langle n_{A'} \rangle} \frac{\alpha_{A'}}{2\pi} \int_{x_{\min}}^{x_{\max}} dx\, (1-x)^s \int_{t_{\min}}^{t_{\max}} \frac{dt}{t} P_{\chi \to \chi}(x)\,.$$

Therefore,

$$\varphi(s+1) \equiv \langle Z^s \rangle = \frac{\overline{Z^s}}{\langle n_{A'} \rangle} \frac{1 - e^{-\langle n_{A'} \rangle (1 - \overline{X^s})}}{1 - \overline{X^s}}\,.$$

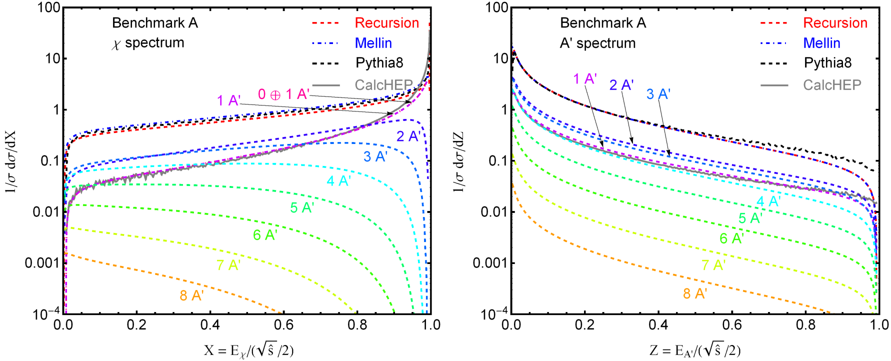
Dark Radiation — Analytics vs. Numerics



Reasons for minor discrepancies:

- Assumption that integration limits are independent of x, t.
  - Energy loss in each splitting small
- Neglect of t-dependence in $P_{\chi\to\chi}(x)$

Dark Radiation — Analytics vs. Numerics



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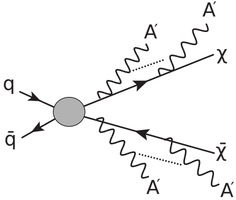
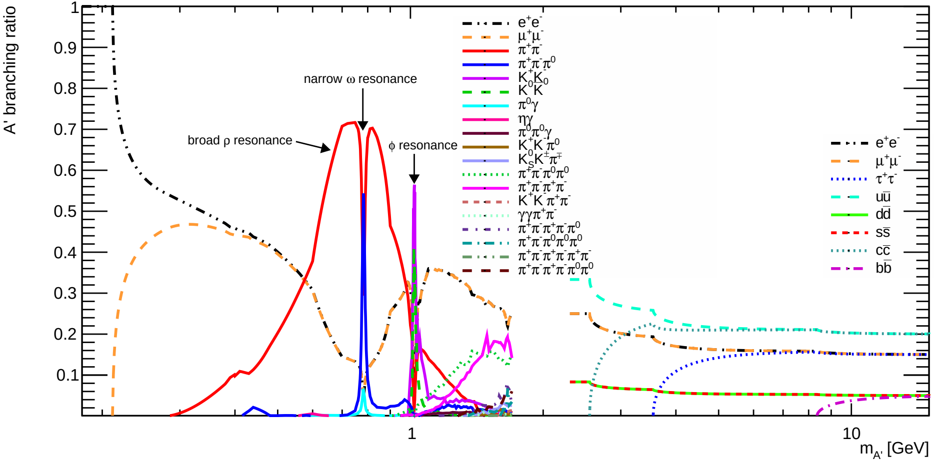
A' Decay



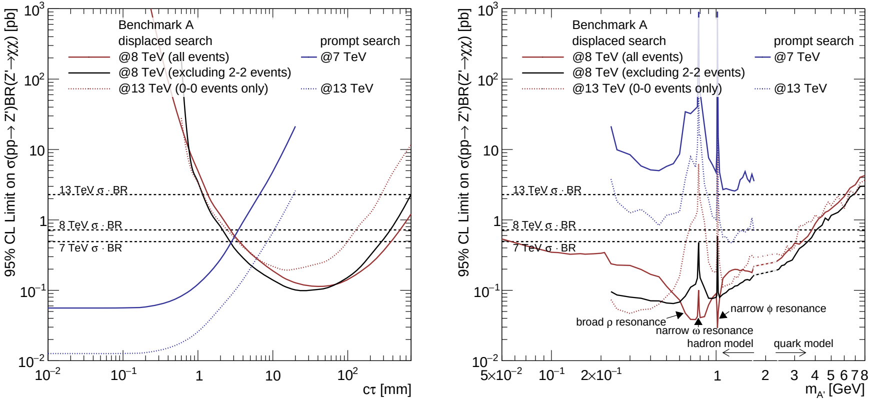
q
q̄
A′
A′
χ
χ̄
A′
A′



A' branching ratio
m_A' [GeV]
narrow ω resonance
broad ρ resonance
φ resonance
e+e-
μ+μ-
π+π-
π+π-π0
K+K-
K0K̄0
π0γ
ηγ
π0π0γ
K+K-π0
K0S K± π∓
π+π-π0π0
π+π-π+π-
K+K-π+π-
γγπ+π-
π+π-π+π-π0
π+π-π0π0π0
π+π-π+π-π+π-
π+π-π+π-π0π0
e+e-
μ+μ-
τ+τ-
uū
dd̄
ss̄
cc̄
bb̄

Phenomenological Results

- Recast ATLAS prompt lepton jet search (arXiv:1212.5409)
- Recast ATLAS displaced lepton jet search (arXiv:1409.0746)
- Conservative projections for 13 TeV
  - Type-0 (muonic lepton jets only) — cannot estimate multijet background



Phenomenological Results

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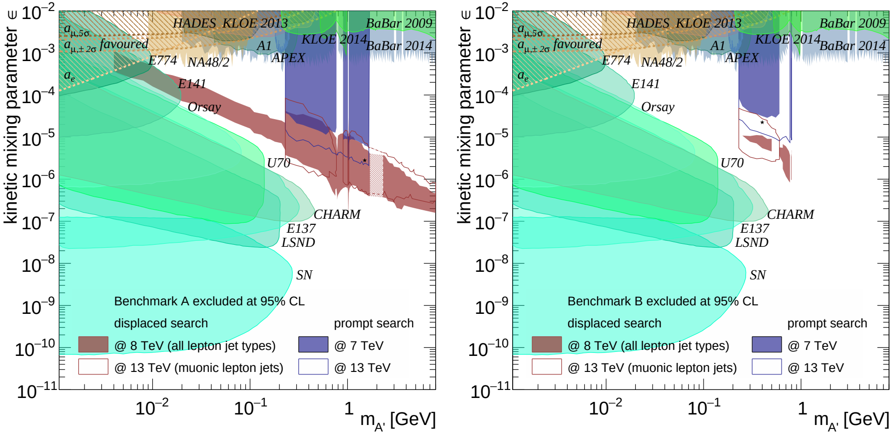

Prompt Lepton Jets

For short A' lifetime:

- Consider only muonic lepton jets
  - other categories difficult to implement without full detector simulation
- Selection criteria
  - 1 muon with $p_T > 18$ GeV
  - or 3 muons with $p_T > 6$ GeV
  - $|\eta| < 2.5$
  - Track in the inner detector
  - Small impact parameter $|d_0| < 1$ mm

Displaced Lepton Jets

For long A' lifetime:

- Type 0 ("muonic") LJ
  - ≥ 2 muons (and no calorimeter jets) within $\Delta R = 0.5$.
- Type 1 ("mixed") LJ
  - ≥ 1 muon + exactly 1 calorimeter jet
- Type 2 ("calorimeter") LJ
  - All other calorimeter jets with small EM fraction
  - Includes $A' \to ee$ with large displacement
  - Includes hadronic A' decay modes

Detector	$A' \to e^+e^-$	$A' \to \mu^+\mu^-$	$A' \to \pi^+\pi^-/K^+K^-$
LJ type	2 (calorimeter)	0 (muonic)	2 (calorimeter)
ID	track	track	track
ECAL	EM fraction	✓	✓
HCAL	✓	✓	✓

Detector	$A' \to \pi^+\pi^-\pi^0$	$A' \to K^0_L K^0_S$
LJ type	2 (calorimeter)	2 (calorimeter)
ID	track	(✓)
ECAL	EM fraction	(✓)
HCAL	✓	✓