



New Signatures of Dark Matter at the LHC

Joachim Kopp

University of Mainz / PRISMA Cluster of Excellence

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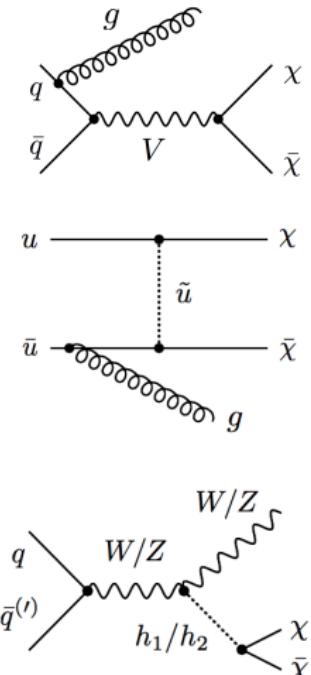
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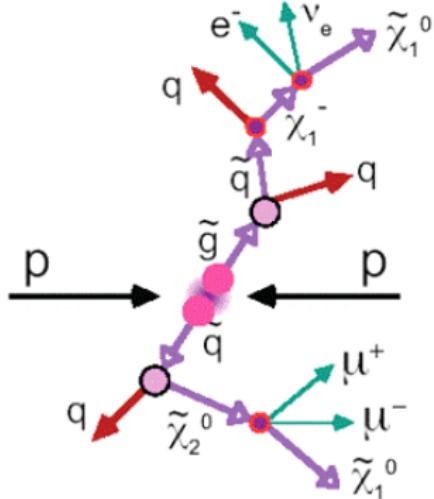
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PRISMA

Current LHC Searches: Simplified Models



Generic Scenarios



SUSY

LHC DM Forum, arXiv:1506.03116
LHC DM Working Group, arXiv:1603.04156
see talks by David Šálek, Felix Kahlhoefer



This Talk: Exotic DM Signatures

Outline

- 1 Simplified Models off the Beaten Paths: The Coannihilation Codex
- 2 Lepton Jets from Radiating Dark Matter
- 3 Emerging and Semi-Visible Jets from Dark QCD
- 4 750 GeV Diphotons and Dark Matter
- 5 Summary



Simplified Models off the Beaten Paths: The Coannihilation Codex

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
→ thermal relics even at weak coupling/heavy mass

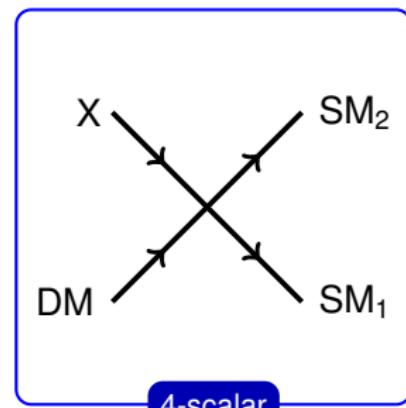
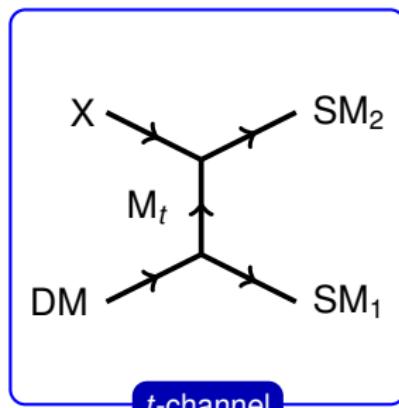
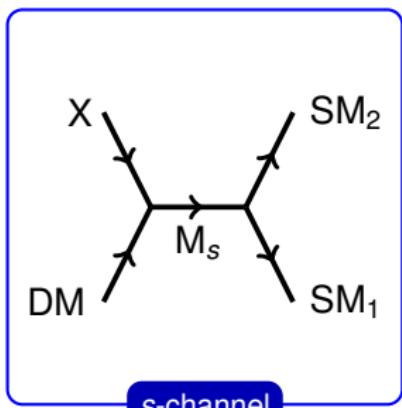
One step beyond minimal simplified models

Assumptions:

- ≤ 3 new multiplets:
 - ▶ Dark matter
 - ▶ Coannihilation partner
 - ▶ Mediator
- DM is colorless and electrically neutral
 - ▶ Not millicharged
- DM is a thermal relic
 - ▶ No axions or sterile neutrinos
 - ▶ Not produced in late-time decays
- DM annihilation/coannihilation is a 2–2 process
- Tree-level, renormalizable interactions
 - ▶ DM annihilation not dominated by loops
(these would suppress interactions)
- New particles are spin 0, 1/2, or 1
 - ▶ No gravitons/gravitinos

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

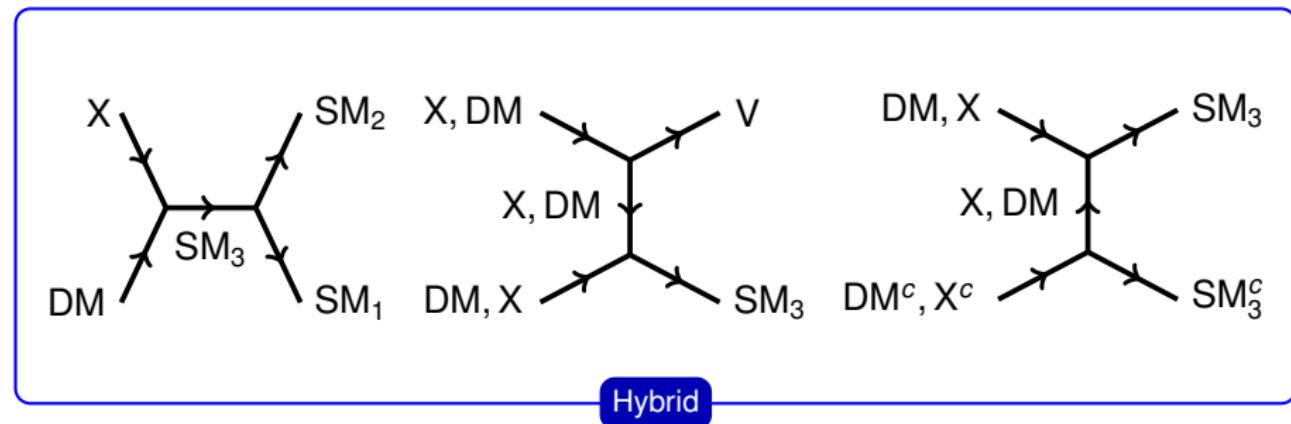
Four classes of simplified models



s-channel

t-channel

4-scalar



Hybrid

Classification procedure

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

Classification procedure

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- Choose representation of coannihilation partner X .

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- Allowed representations for mediator M are now fixed

Classification procedure

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

Classification procedure

- Choose DM in $(1, N, \beta)$ of $SU(3) \times SU(2) \times U(1)$.
- 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	$(u_R \bar{u}_R), (d_R \bar{d}_R), (\ell_R \bar{\ell}_R)$ $(Q_L \bar{Q}_L), (L_L \bar{L}_L), (H H^\dagger)$	H1	✓
SU2				F	$(L_L H)$		
SU3		$(1, 3, 0)^{N \geq 2}$	B		$(Q_L \bar{Q}_L), (L_L \bar{L}_L), (H H^\dagger)$	H1	✓
SU4				F	$(L_L H)$		
SU5		-2	$(1, 1, -2)$	B	$(d_R \bar{u}_R), (H^\dagger H^\dagger), (L_L L_L)$		✓
SU6				F	$(L_L H^\dagger)$	H2	
SU7			$(1, 3, -2)^{N \geq 2}$	B	$(H^\dagger H^\dagger), (L_L L_L)$		$\checkmark(\alpha = \pm 1)$
SU8				F	$(L_L H^\dagger)$	H2	
SU9		-4	$(1, 1, -4)$	B	$(\ell_R \ell_R)$		$\checkmark(\alpha = \pm 2)$
SU10	$(1, N \pm 1, \alpha)$	-1	$(1, 2, -1)$	B	$(d_R \bar{Q}_L), (\bar{u}_R Q_L), (\bar{L}_L \ell_R)$	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	$(Q_L \bar{Q}_L), (L_L \bar{L}_L), (H H^\dagger)$		$\checkmark(\alpha = 0)$
SU15				F	$(L_L H)$		
SU16		-2	$(1, 3, -2)$	B	$(H^\dagger H^\dagger), (L_L L_L)$		$\checkmark(\alpha = \pm 1)$
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 → SM₁SM₂

SM_3

Possible additional vertex DM-X-SM₃

Tables, tables, tables

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		$(1, 3, 0)^{N \geq 2}$	$(1, 3, 0)^{N \geq 2}$	B	$(Q_L \bar{Q}_L), (L_L \bar{L}_L), (H H^\dagger)$	H1	✓
SU4				F	$(L_L H)$		
SU5				B	$(d_R \bar{u}_R), (H^\dagger H^\dagger), (L_L L_L)$		✓

Tally

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

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

$SU(2)$		-3	$(1, 2, -3)$	B	$(u_L \bar{u}_R)$		
SU13	$(1, N \pm 2, \alpha)$	0	$(1, 3, 0)$	B	$(Q_L \bar{Q}_L), (L_L \bar{L}_L), (H H^\dagger)$		
SU14				F	$(L_L H)$		$\checkmark(\alpha = 0)$
SU15		$(1, N \pm 2, \alpha)$	$(1, 3, -2)$	B	$(H^\dagger H^\dagger), (L_L L_L)$		$\checkmark(\alpha = \pm 1)$
SU16				F	$(L_L H^\dagger)$		
SU17							

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 $DM + X \rightarrow SM_1 SM_2$

SM_3 Possible additional vertex $DM - X - SM_3$

LHC pheno classification

Another 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]
	X ($\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM$) + X ($\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM$) + ISR	gauge int. or $SM_2 \in p$ for t -channel	mono-Y + \cancel{E}_T mono-Y + $\cancel{E}_T + \leq 4 \text{ SM}$	[55,56,62,63,104] Partial coverage [105]
	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 + $\cancel{E}_T + \leq 2 \text{ SM}$	[55,56,62,63,104] Partial coverage [105]
s -channel	$M_s (\rightarrow [SM_1 SM_2]^{\text{res}})$ + $M_s (\rightarrow [SM_1 SM_2]^{\text{res}})$	gauge int.	2 resonances	[106–112]
	$M_s (\rightarrow [SM_1 SM_2]^{\text{res}})$ + $M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM))$		resonance + \cancel{E}_T resonance + $\cancel{E}_T + \leq 2 \text{ SM}$	No search No search
	$M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM))$ + $M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM))$		$\cancel{E}_T + \leq 4 \text{ SM}$	[113,114,114–124]
	$M_s (\rightarrow [SM_1 SM_2]^{\text{res}})$		1 resonance	[125–146]
	$M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM))$	$(SM_1 SM_2) \in p$	$\cancel{E}_T + \leq 2 \text{ SM}$	[120–122,124] [104,147–153]
	$SM_{1,2} + M_s (\rightarrow [SM_1 SM_2]^{\text{res}})$	$SM_{2,1} \in p$	1 resonance + 1 SM	Partial coverage [154,155]
	$SM_{1,2}$ + $M_s (\rightarrow DM + X (\rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM))$		$\cancel{E}_T + 1 \leq 3 \text{ SM}$	[114,120–124] [147–153,156–158]
t -channel	$M_t (\rightarrow SM_1 DM)$ + $M_t (\rightarrow SM_1 DM)$		$\cancel{E}_T + \leq 2 \text{ SM}$	[120–122,124] [104,147–153]
	$M_t (\rightarrow SM_1 DM)$			[106–112]

LHC pheno classification

Another table ...

	$pp \rightarrow \dots$	Prod. via	Signatures	Search
mon	DM + DM + ISR	gauge int. or $SM_1 \in p$ for t -channel	mono-Y + \cancel{E}_T	[55,56,62,63,104]
	$X \rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM$	gauge int.	mono-Y + $\cancel{E}_{T\gamma}$	[55,56,62,63,104]

Frequent features

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

$M_s \rightarrow DM + X \rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM$	$(SM_1 SM_2) \in p$	$\cancel{E}_T + \leq 2 \text{ SM}$	[120–122,124] [104,147–153]
$SM_{1,2} + M_s \rightarrow [SM_1 SM_2]^{\text{res}}$	$SM_{2,1} \in p$	1 resonance + 1 SM	Partial coverage [154,155]
$SM_{1,2} + M_s \rightarrow DM + X \rightarrow SM_1^{\text{soft}} SM_2^{\text{soft}} DM$		$\cancel{E}_T + 1 \leq 3 \text{ SM}$	[114,120–124] [147–153,156–158]
$M_t \rightarrow SM_1 DM$ $+ M_t \rightarrow SM_1 DM$		$\cancel{E}_T + \leq 2 \text{ SM}$	[120–122,124] [104,147–153]
$M_c \rightarrow SM_1 DM$			[106,110]

Specific example: a leptoquark model

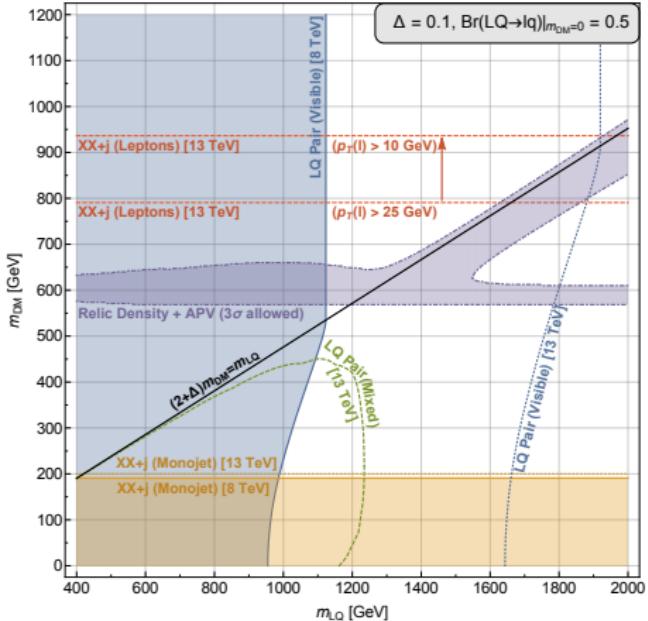
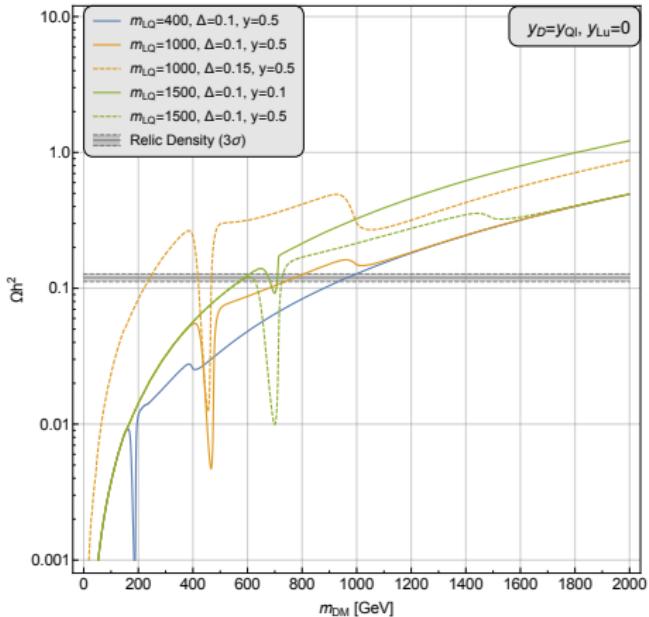
ID	X	$\alpha + \beta$	M_s	Spin	(SM ₁ SM ₂)	X-DM-SM ₃	$M_s - X - X$
ST1	$(3, N, \alpha)$	$\frac{10}{3}$	$(3, 1, \frac{10}{3})$	B	$(u_R \bar{l}_R)$		$\checkmark (\alpha = -\frac{5}{3})$
ST2		$\frac{4}{3}$	$(3, 1, \frac{4}{3})$	B	$(d_R \bar{\ell}_R), (Q_L \bar{L}_L), (\bar{d}_R \bar{d}_R)$		$\checkmark (\alpha = -\frac{2}{3})$
ST3		$\frac{4}{3}$		F	$(Q_L H)$	H5	
ST4		$(3, 3, \frac{4}{3})^{N \geq 2}$		B	$(Q_L \bar{L}_L)$		$\checkmark (\alpha = -\frac{2}{3})$
ST5		$(3, 3, \frac{4}{3})^{N \geq 2}$		F	$(Q_L H)$	H5	
ST6		$-\frac{2}{3}$	$(3, 1, -\frac{2}{3})$	B	$(\bar{Q}_L \bar{Q}_L), (\bar{u}_R \bar{d}_R), (u_R \ell_R), (Q_L L_L)$		$\checkmark (\alpha = \frac{1}{3})$
ST7		$-\frac{2}{3}$		F	$(Q_L H^\dagger)$	H6	
ST8		$(3, 3, -\frac{2}{3})^{N \geq 2}$		B	$(\bar{Q}_L \bar{Q}_L), (Q_L L_L)$		$\checkmark (\alpha = \frac{1}{3})$
ST9		$(3, 3, -\frac{2}{3})^{N \geq 2}$		F	$(Q_L H^\dagger)$	H6	
ST10		$-\frac{8}{3}$	$(3, 1, -\frac{8}{3})$	B	$(\bar{u}_R \bar{u}_R), (d_R \ell_R)$		$\checkmark (\alpha = \frac{4}{3})$
ST12	$(3, N \pm 1, \alpha)$	$\frac{3}{2}$	$(3, 1, \frac{3}{2})$	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		$\frac{1}{3}$		F	$(u_R H^\dagger), (d_R H)$	H7	
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		$-\frac{5}{3}$		F	$(d_R H^\dagger)$		
ST17	$(3, N \pm 2, \alpha)$	$\frac{4}{3}$	$(3, 3, \frac{4}{3})$	B	$(Q_L \bar{L}_L)$		$\checkmark (\alpha = -\frac{2}{3})$
ST18		$\frac{4}{3}$		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		$-\frac{2}{3}$		F	$(Q_L H^\dagger)$		

Specific example: a leptoquark model

Lagrangian

$$\begin{aligned}\mathcal{L} = & \frac{i}{2} \overline{\text{DM}} \not{\partial} \text{DM} + i \overline{X} \not{\partial} X + |D_\mu M_s|^2 \\ & - \frac{m_{\text{DM}}}{2} \overline{\text{DM}} \text{DM} - m_X \overline{X} X - V(M_s, H) \\ & - \left(y_D \overline{X} M_s \text{DM} + y_{Q\ell} \overline{Q_L} M_s \ell_R + y_{Lu} \overline{L_L} M_s^c u_R + \text{h.c.} \right),\end{aligned}$$

Specific example: a leptoquark model



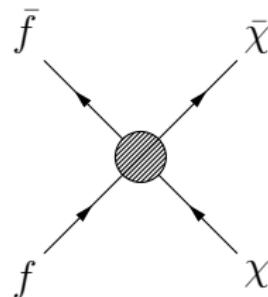
Baker et al., *The Coannihilation Codex*, arXiv:1510.03434



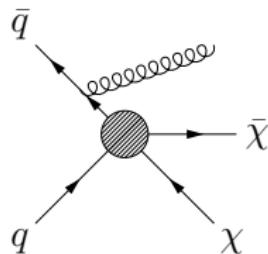
Radiating Dark Matter

Dark Matter Production at the LHC

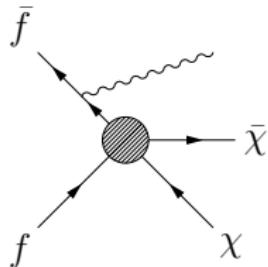
Traditional DM searches: initial state radiation



DM pair production
(invisible @ LHC)

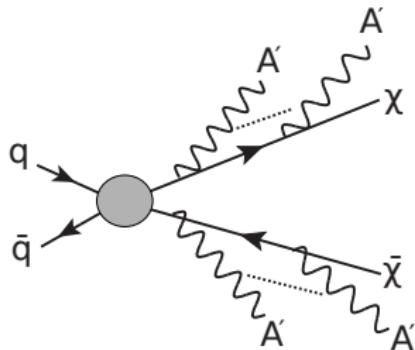


Monojet



Monophoton

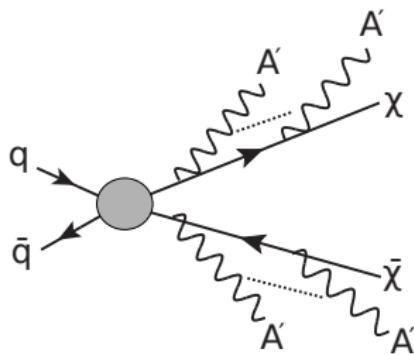
How about final state radiation?



Model Framework: Self-Interacting DM

Dark Sector Lagrangian

$$\mathcal{L}_{\text{dark}} \equiv \bar{\chi}(i\partial - m_\chi + ig_{A'} A')\chi - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\nu - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu},$$

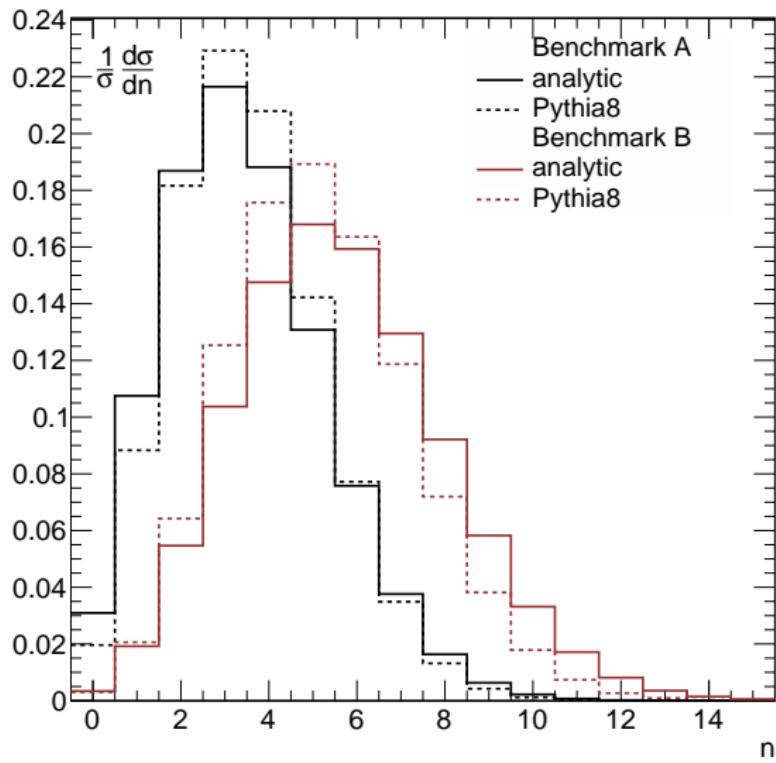


Buschmann JK Liu Wang, arXiv:1505.07459

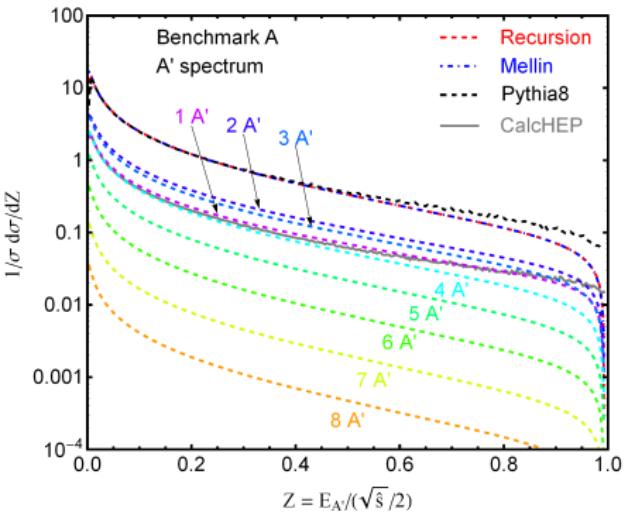
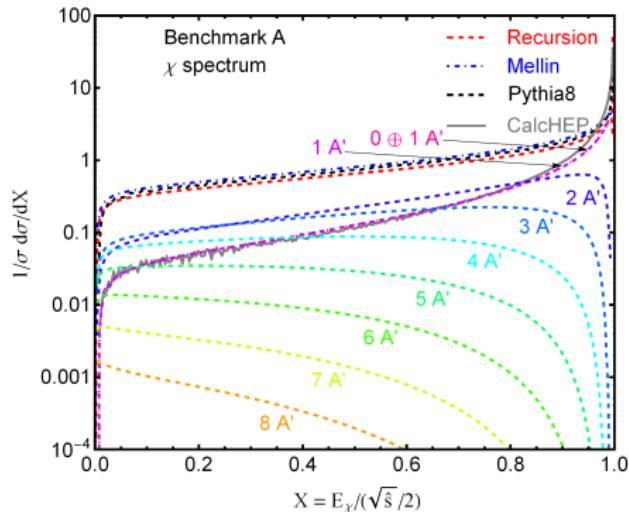
Dark Radiation — Analytics vs. Numerics (1)

- Number of radiated A' follows Poisson distribution
- Energy fraction Z carried away by each A' :
 - ▶ Compute analytically the **moments** of Z distribution, \bar{Z}^s
 - ▶ Inverse Mellin transform yield A' spectrum
 - ★ Fast numerical evaluation via FFT

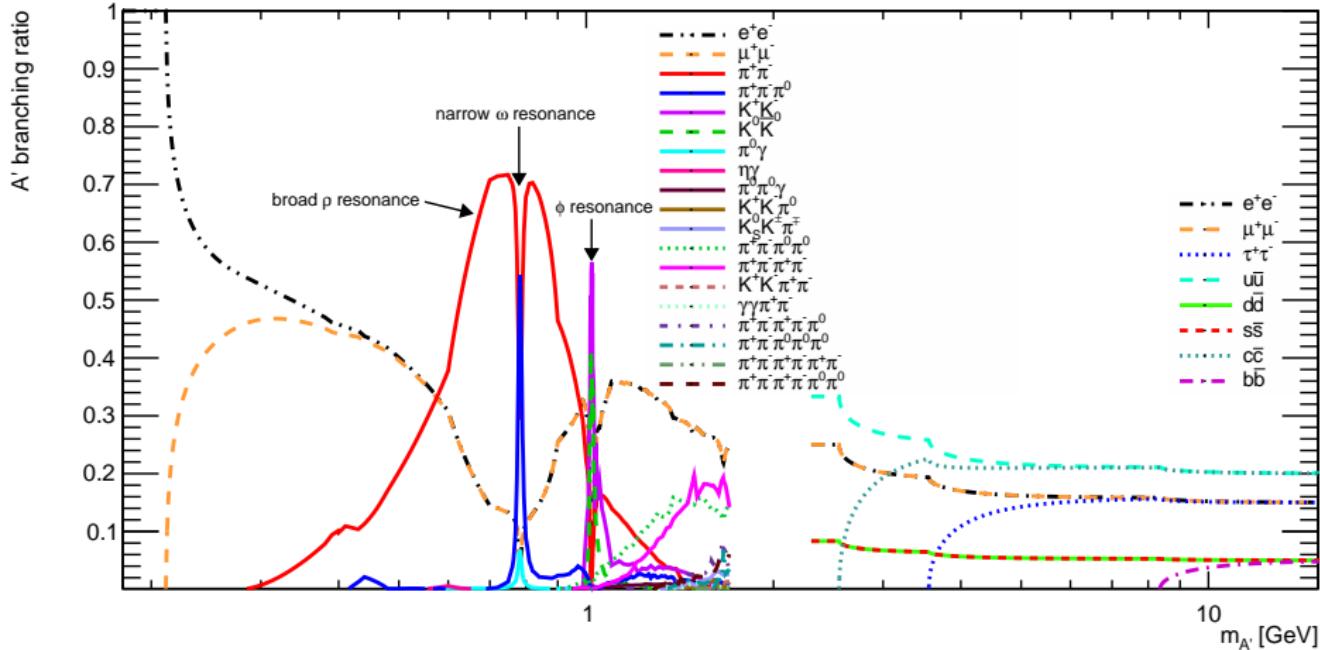
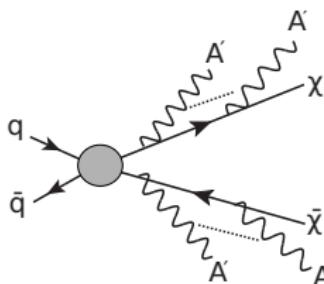
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Dark Radiation — Analytics vs. Numerics

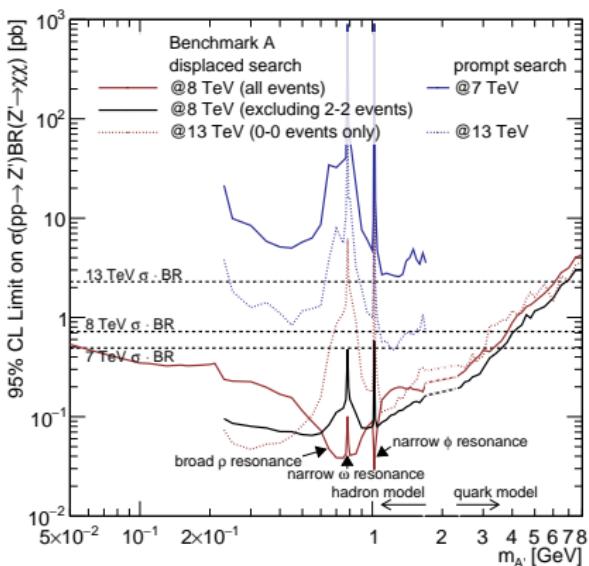
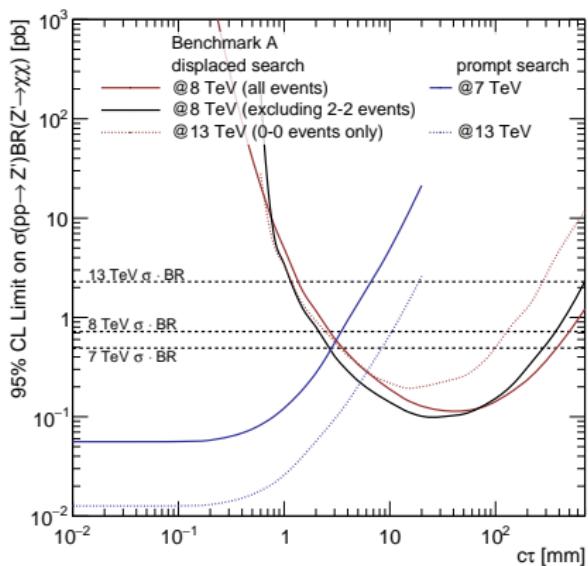


A' Decay



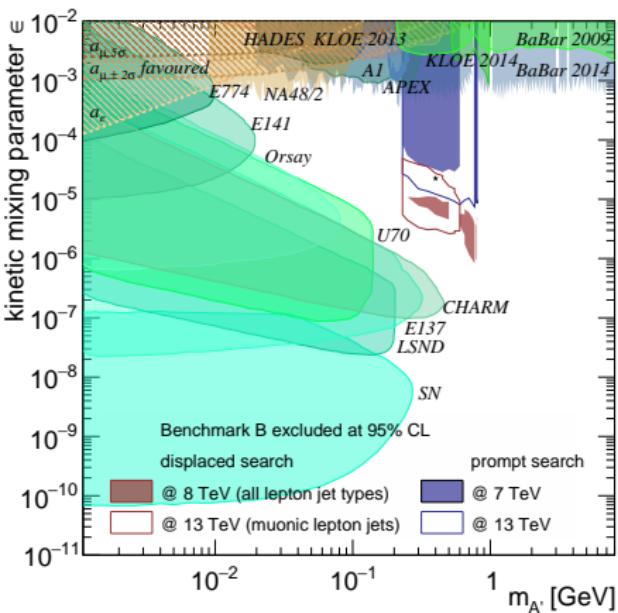
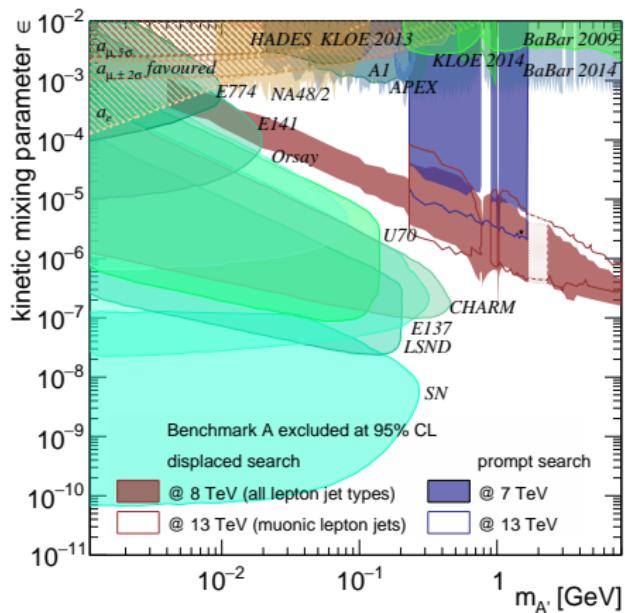
Phenomenological Results

- 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

- Recast ATLAS prompt lepton jet search (arXiv:1212.5409)
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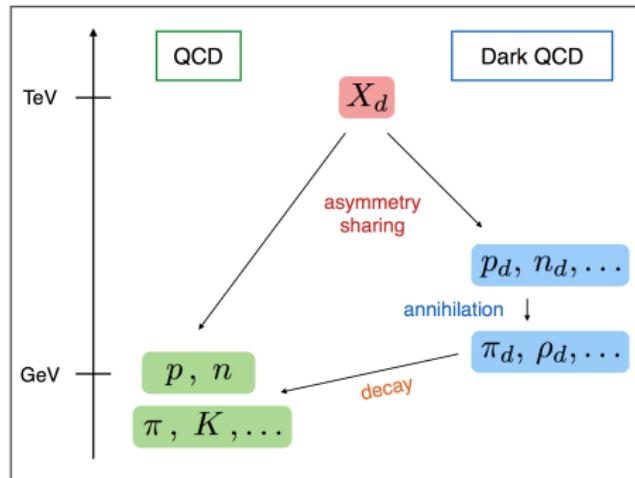


Emerging and Semi-Visible Jets from Dark QCD

Dark QCD

General Idea: Analogy with SM

DM as the “proton” or “neutron” of QCD-like dark sector



Schwaller Stolarski Weiner, arXiv:1502.05409

Dark Sector Lagrangian

Dark QCD

$$\mathcal{L} \supset \bar{Q}_{d_i} (\not{D} - m_{d_i}) Q_{d_i} - \frac{1}{4} G_d^{\mu\nu} G_{\mu\nu,d}$$

Mediator Sector

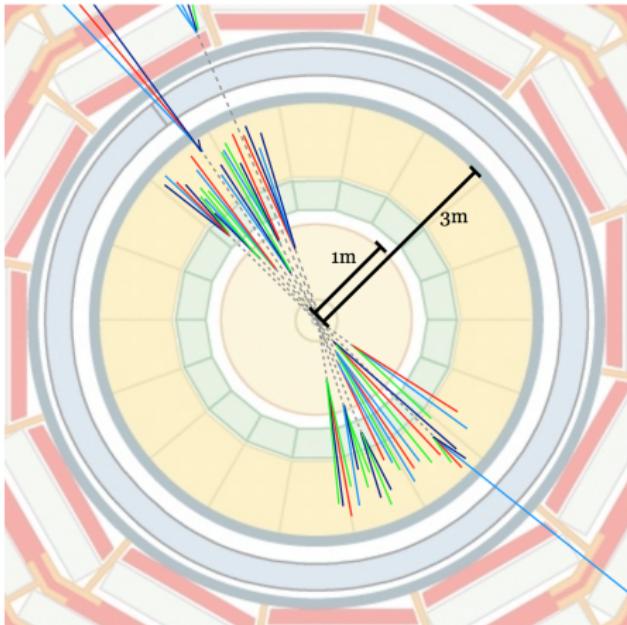
$$\mathcal{L}_\kappa = (D_\mu X_d)(D^\mu X_d)^\dagger - M_{X_d}^2 X_d X_d^\dagger + \kappa_{ij} \bar{Q}_{d_i} q_j X_d + \text{h.c.}$$

The mediator X_d

- is a bifundamental of $SU(3)_{QCD} \times SU(3)_{\text{dark}}$
- transfers **baryon asymmetry** to the dark sector
- mediates **dark meson** decays
- can be **pair-produced** at the LHC

Schwaller Stolarski Weiner, arXiv:1502.05409

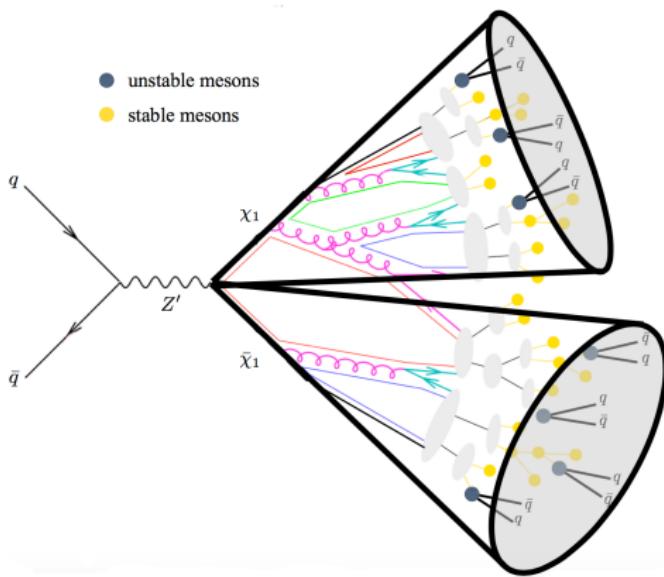
Emerging Jets at the LHC



- $pp \rightarrow X_d X_d \rightarrow QQqq$
- Q creates dark parton shower and hadronizes
- Dark baryons: \not{E}_T
- Dark mesons: Emerging Jet

Schwaller Stolarski Weiner, arXiv:1502.05409

Semi-Visible Jets at the LHC



Alternatively: for prompt decay:

- $pp \rightarrow$ dark hadrons
- Dark mesons: Decay to QCD jet
- Dark baryons: \cancel{E}_T within the jet
- For DM particles from resonance decay:
use transverse mass to suppress QCD background

Cohen Lisanti Lou, arXiv:1503.00009



750 GeV Diphotons and Dark Matter

Decay of 750 GeV Diphotons to DM

$$\mathcal{L}_{0+} = \frac{c_1}{\Lambda} S B_{\mu\nu} B^{\mu\nu} + \frac{c_2}{\Lambda} S W^{\mu\nu} W_{\mu\nu} + \frac{c_3}{\Lambda} S G_{\mu\nu}^a G_a^{\mu\nu} + g_\phi S \bar{\chi}\chi + m_\psi S \chi\chi$$

- S mediates DM–SM interactions
 - ▶ Sets relic density
- $S \rightarrow \bar{\chi}\chi$ could explain large S width
 - ▶ But requires huge S production x-sec

Mambrini Arcadi Djouadi, arXiv:1512.04913

Dark Matter-Mediated $S(750)$ Decays

Idea: DM χ as part of electroweak multiplet that mediates $S \rightarrow \gamma\gamma$.

Dark Matter-Mediated $S(750)$ Decays

Idea: DM χ as part of **electroweak multiplet** that mediates $S \rightarrow \gamma\gamma$.

Relic density: two windows of opportunity

- $m_\chi \sim 100 \text{ GeV}$
 - ▶ Annihilation, in particular $\chi\chi \rightarrow WW$
 - ▶ Fast $S \rightarrow \chi\chi$ decay
 - ▶ Difficult to achieve large **prodution rate** to compensate small $\text{BR}(S \rightarrow \gamma\gamma)$.
 - ▶ May require many new colored particles
- $m_\chi > \text{TeV}$
 - ▶ Coannihilation
 - ▶ Difficult to generate large enough $\text{BR}(S \rightarrow \gamma\gamma)$.
 - ▶ May require many such multiplets

Baker Bauer Neubert JK Thamm, work in progress

Dark Matter-Mediated $S(750)$ Decays

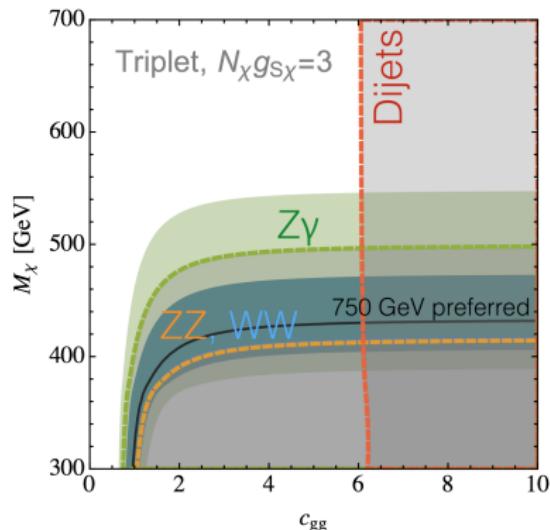
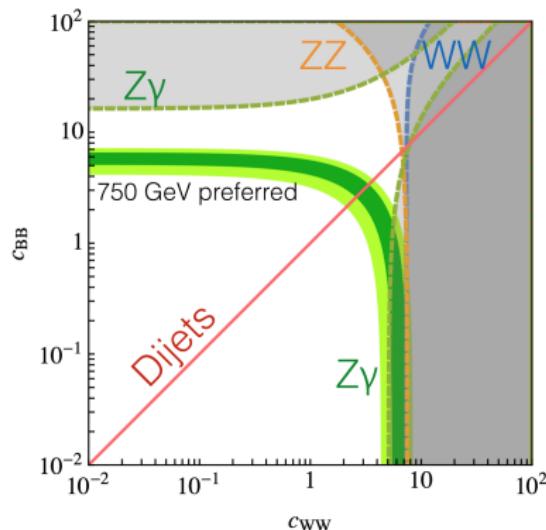
Idea: DM χ as part of **electroweak multiplet** that mediates $S \rightarrow \gamma\gamma$.

Relic density: two windows of opportunity

- $m_\chi \sim 100$ GeV
- $m_\chi >$ TeV

Constraints:

- $S \rightarrow \gamma\gamma$ via $Y = 0$ multiplet: in **tension with Run I** (mainly $Z\gamma$)



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Constraints:

- $S \rightarrow \gamma\gamma$ via $Y = 0$ multiplet: in **tension with Run I** (mainly $Z\gamma$)
- $Y \neq 0$ multiplet:
 - ▶ Relic density still difficult
 - ▶ Difficult to avoid Z -mediated DM–nucleon scattering
- For $m_\chi >$ TeV: Gamma ray line constraints

Scenario that may work:

- Several multiplets \rightarrow multi-component DM
- Mixed doublet–triplet DM
- ...

Baker Bauer Neubert JK Thamm, work in progress

Summary

Dark Matter can leave very strange footprints at the LHC

- Look for the mediators!
- Many searches sensitive
(though not yet interpreted in terms of DM)
- Huge simplified model space
 - ▶ But don't take simplified models too serious!
- Very conventional dark sectors may lead to very unconventional signatures
 - ▶ Lepton Jets
 - ▶ Emerging Jets
 - ▶ Semi-VISIBLE Jets
 - ▶ 750 GeV diphotons

→ talk by Felix Kahlhoefer

Thank you!

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: $p_{\chi,\text{out}} = (\textcolor{brown}{x}E, -k_t, 0, \sqrt{\textcolor{brown}{x}^2 E^2 - k_t^2 - m_\chi^2})$
- Outgoing dark photon: $k = ((1-x)E, \textcolor{blue}{k}_t, 0, \sqrt{(1-x)^2 E^2 - k_t^2 - m_{A'}^2})$
- Virtuality: $t \equiv (p_{\chi,\text{out}} + k)^2 - m_\chi^2$

Probability for a collinear splitting:

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

with the splitting kernel

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

Dark Radiation Showers — Semi-Analytical Results

Average number radiated dark photons

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

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

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

- Events with two emissions

$$p_2 \langle X^s \rangle_{2A'} = e^{-\langle n_{A'} \rangle} \left(\frac{\alpha_{A'}}{2\pi} \right)^2 \int_{x_{\min}}^{x_{\max}} dx x^s \int_{t_{\min}}^{t_{\max}} \frac{dt}{t} \int_{x_{\min}}^{x_{\max}} dx' x'^s \int_{t_{\min}}^t \frac{dt'}{t'} P_{\chi \rightarrow \chi}(x) P_{\chi \rightarrow \chi}(x')$$
$$\simeq e^{-\langle n_{A'} \rangle} \frac{1}{2!} \left(\frac{\alpha_{A'}}{2\pi} \right)^2 \int_{x_{\min}}^{x_{\max}} dx x^s \int_{t_{\min}}^{t_{\max}} \frac{dt}{t} \int_{x_{\min}}^{x_{\max}} dx' x'^s \int_{t_{\min}}^{t_{\max}} \frac{dt'}{t'} P_{\chi \rightarrow \chi}(x) P_{\chi \rightarrow \chi}(x')$$
$$= e^{-\langle n_{A'} \rangle} \frac{\langle n_{A'} \rangle^2}{2!} \overline{X^s}^2$$

- 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

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

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

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

with

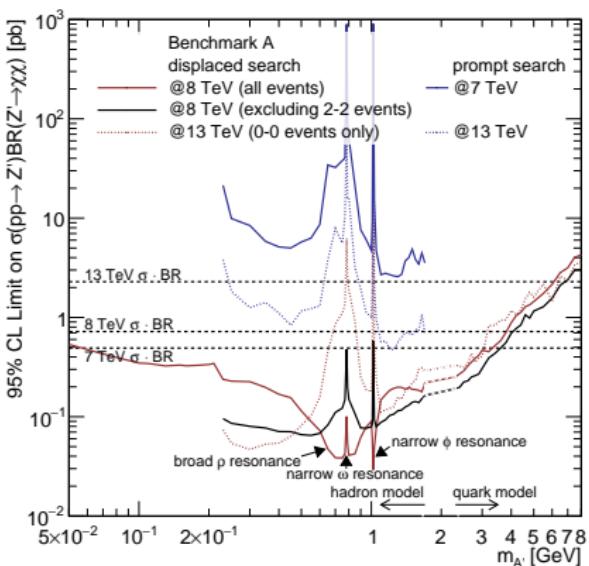
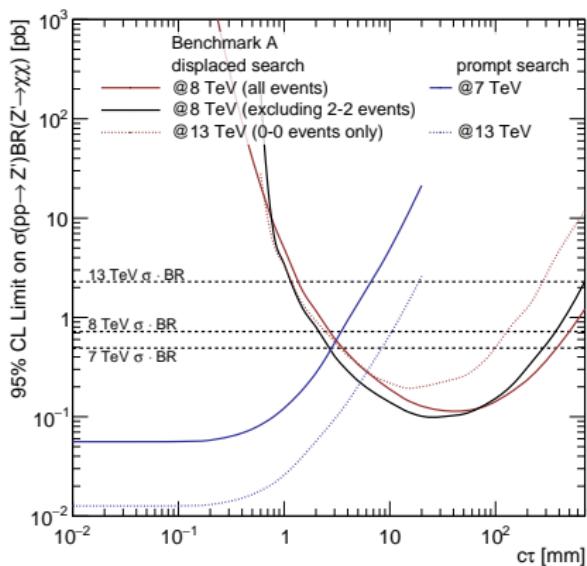
$$\bar{Z}^s \equiv \frac{1}{\langle n_{A'} \rangle} \frac{\alpha_{A'}}{2\pi} \int_{x_{\min}}^{x_{\max}} dx (1-x)^s \int_{t_{\min}}^{t_{\max}} \frac{dt}{t} P_{x \rightarrow \chi}(x).$$

Therefore,

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

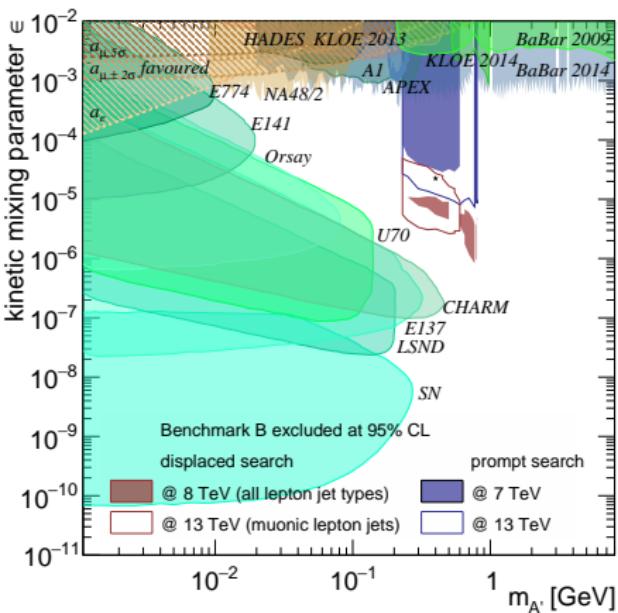
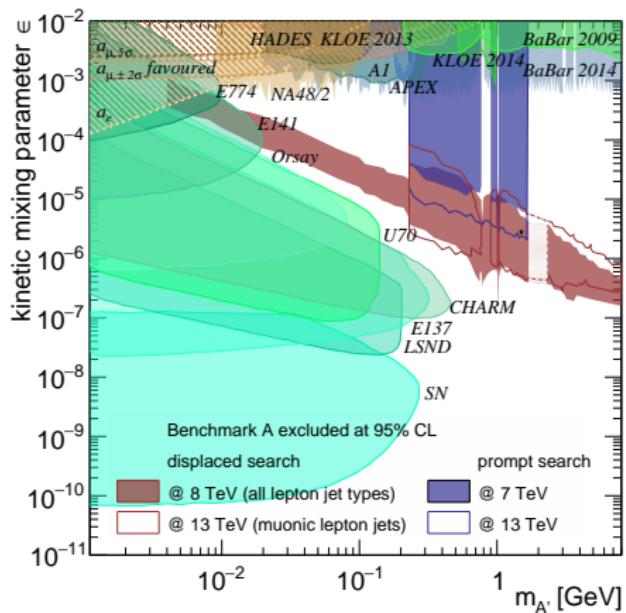
Phenomenological Results

- 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 $p_T > 18 \text{ GeV}$
 - ▶ or 3 muons with $p_T > 6 \text{ GeV}$
 - ▶ $|\eta| < 2.5$
 - ▶ Track in the inner detector
 - ▶ Small impact parameter $|d_0| < 1 \text{ mm}$

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 $A' \rightarrow ee$ with large displacement
 - ▶ Includes hadronic A' decay modes

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

Detector	$A' \rightarrow \pi^+ \pi^- \pi^0$	$A' \rightarrow K_L^0 K_S^0$
LJ type	2 (calorimeter)	2 (calorimeter)
ID	track	(✓)
ECAL	EM fraction	(✓)
HCAL	✓	✓