Radiating Dark Matter at the LHC

based on work with J. Kopp, J. Liu, and P.A.N. Machado

Malte Buschmann

University of Michigan

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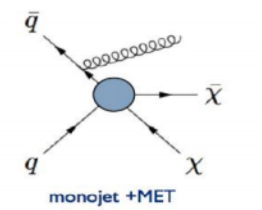
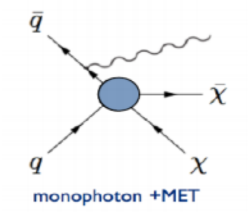
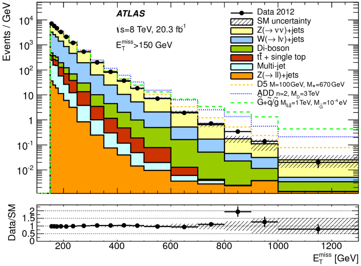
Dark Matter at the LHC





- DM pair production alone **not** detectable.
- Traditionally: Need **ISR** for tagging and boosting $\Rightarrow$ Missing Energy signature



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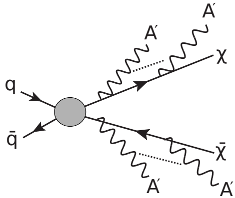
Radiating Dark Matter Model

This talk: **FSR instead of ISR!**



Relevant Lagrangian:

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

DM pair production for toy model:

$$\mathcal{L}_{Z'} \equiv g_q \sum_f \bar{q}_f Z\!\!\!/' q_f + g_\chi \bar{\chi} Z\!\!\!/' \chi$$

A' Branching Ratios

$m_{A'} > 2$ GeV:

For **leptons**: $\Gamma_{\ell^+\ell^-} = \frac{1}{3}\alpha\epsilon^2 m_{A'}\sqrt{1-4\frac{m_\ell^2}{m_{A'}^2}}\left(1+2\frac{m_\ell^2}{m_{A'}^2}\right)$

For **hadrons**: QCD language applicable, $\Gamma_{q_f\bar{q}_f} = N_c Q_{q_f}^2 \Gamma_{\ell^+\ell^-}\Big|_{m_\ell = m_{q_f}}$

$m_{A'} < 2$ GeV:

For **leptons**: $\Gamma_{\ell^+\ell^-} = \ldots$

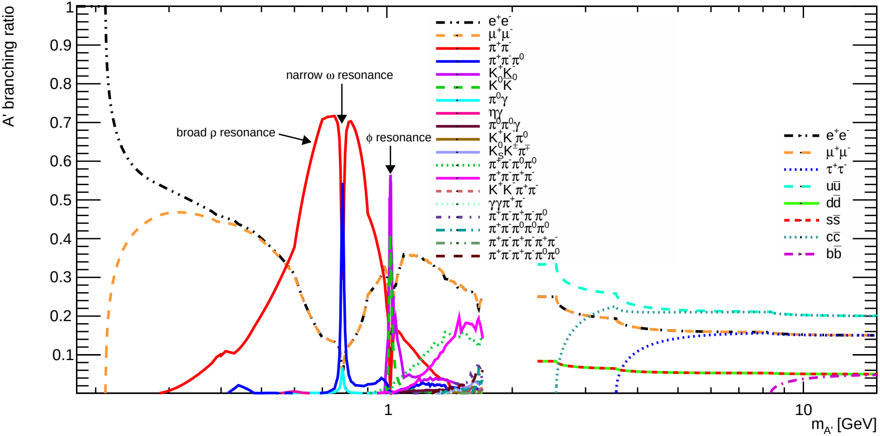
For **hadrons**: Use e^+e^- collider measurements of

$$R(s) = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$$

to determine partial decay width

$$\Gamma_{\text{hadrons}} = \Gamma_{\mu^+\mu^-} R(s = m_{A'}^2)$$

A' Branching Ratios



Questions to ask:

- **Shouldn't we have seen this somewhere else?**
  $\Rightarrow$ Not necessarily.
- **How many A' are produced? How energetic are they?**
  $\Rightarrow$ We can understand this even (semi-)analytically.
- **How can we see these showers at the LHC?**
  $\Rightarrow$ Lepton jets: more powerful than a monojet search.
  $\Rightarrow$ Can test unexplored parameter regime.

Benchmarks

	$m_{Z'}$ [TeV]	g_q	g_χ	m_χ [MeV]	$m_{A'}$ [MeV]	$\alpha_{A'}$	$c\tau$ [mm]
A	1	0.1	1	400	400	0.2	10

Table: Fixed model parameters

	ϵ [10^{-6}]	$\sigma_8(Z')$ [pb]	$\sigma_{13}(Z')$ [pb]	$\mathrm{BR}(Z' \to \chi\bar{\chi})$	$2\langle n_{A'}\rangle_8$	$2\langle n_{A'}\rangle_{13}$
A	2.8	0.85	2.7	84.8%	3.50	3.51

Table: Derived quantities

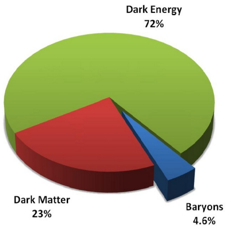
Code package available at:
https://github.com/MSABuschman/DarkRadiation

Benchmarks

How about existing constraints?

Symmetric Dark Matter

- Large $\langle \sigma v \rangle_{\chi\bar{\chi}\to A'A'}$ and small $\langle \sigma v \rangle_{\chi\bar{\chi}\to q\bar{q}}$
  $\Rightarrow \chi$ subdominant DM component
- Subdominant component
  $\Rightarrow$ direct/indirect detection and DM self interaction constraints irrelevant.
- χ might still account for all DM if different portal (not Z') is used!

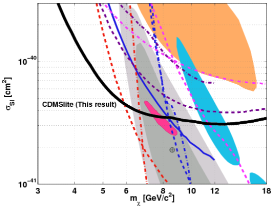


Benchmarks

How about existing constraints?

Asymmetric Dark Matter

- χ can provide correct thermal relic density
- Indirect detection: Trivially fulfilled (no $\chi\bar{\chi}$ annihilation)
- Direct detection limits around threshold and thus weak
- DM self interactions:
  $\sigma_{\chi\chi}/m_\chi = 10^{-29}\ \mathrm{cm}^2/\mathrm{GeV} < 1.78 \times 10^{-24}\ \mathrm{cm}^2/\mathrm{GeV}$



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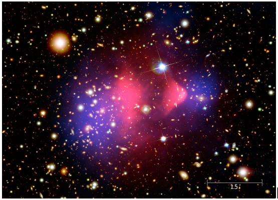
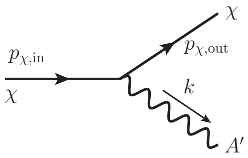


Magellan/Hubble/Chandra

Analytic Description
of
Dark Parton Showers

Dark Parton Shower



Differential collinear splitting probability

$$\frac{\alpha_{A'}}{2\pi} dx \, \frac{dt}{t} P_{\chi\to\chi}(x,t) \quad \text{with} \quad P_{\chi\to\chi}(x,t) = \frac{1+x^2}{1-x} - \frac{2(m_\chi^2 + m_{A'}^2)}{t} \quad (1)$$

Physical limits:

$$x_{\min} \equiv m_\chi / E_0 \,, \qquad x_{\max} \equiv 1 - m_{A'}/E_0 \,, \quad (2)$$

$$t_{\min}(x) = m_{A'}^2 + 2(E_0^2 x(1-x) - \sqrt{x^2 E_0^2 - m_\chi^2}\sqrt{(1-x)^2 E_0^2 - m_{A'}^2}) \quad (3)$$

$$t_{\max}(x) = m_{A'}^2 + 2 p_{\chi,\mathrm{out}} \cdot k \Big|_{k_{t,\max}} \quad (4)$$

Via Recursive Formalism

Single splitting (with $X = E_\chi/E_0$):

$$f_{\chi,1}(X) \equiv \frac{1}{\langle n_{A'}\rangle}\frac{\alpha_{A'}}{2\pi}\int_{t_{\rm min}}^{t_{\rm max}}\frac{dt}{t}P_{\chi\to\chi}(X)\,\Theta(x_{\rm min}\leq X\leq x_{\rm max})$$

Next splittings:

$$f_{\chi,m+1}(X) = \int_{x_{\rm min}}^{x_{\rm max}} dx_m\, f_{\chi,1}(x_m)\,\frac{f_{\chi,m}(X/x_m)}{x_m}\,\Theta(x_{\rm min}\leq X\leq x_{\rm max})$$

Full DM energy spectrum:

$$f_\chi(X) = \sum_{m=0}^{\infty} p_m\, f_{\chi,m}(X)\,,$$

where $f_{\chi,m}$ are energy distribution with exactly m emitted A'.

Via Mellin Transform

Mellin transform:

$$\{\mathcal{M}f\}(s) = \varphi(s) = \int_0^\infty x^{s-1} f(x) dx$$

Alternatively: Calculate moments of energy spectrum first

First moment:

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

Second moment:

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

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

mth moment:

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

Via Mellin Transform

Then: Sum moments . . .

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

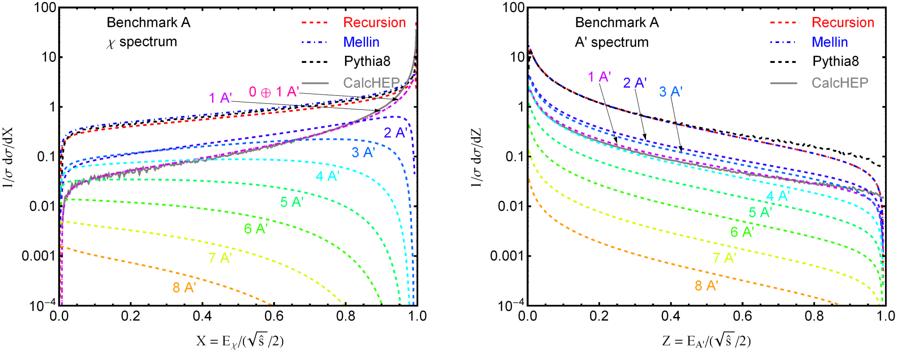
. . . and use inverse Mellin transformation to obtain $f_\chi(X)$:

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

Advantage: (Inverse) Mellin transform are fast and numerically stable when rewritten as a Fourier transform:

$$\{\mathcal{M} f\}(s) = \{\mathcal{F} f(e^{-x})\}(-is)$$

Comparison to Monte Carlo



Minor discrepancies due to:

- Integrations limits are not independent of x and t (Assumption that energy loss in each splitting is small)
- Neglect of t-dependence in splitting kernel $P_{\chi\to\chi}(x)$

Phenomenology

of

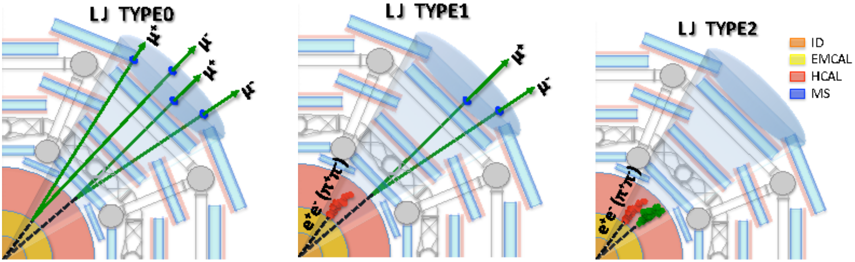
Dark Radiation Showers

Long A' lifetime: Displaced Search

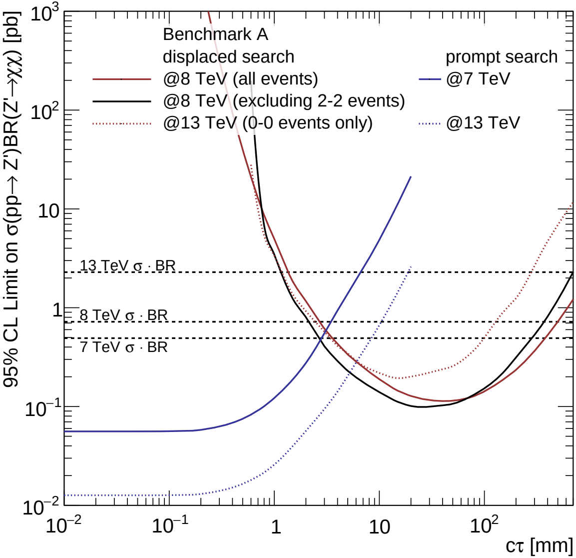
Based on ATLAS, 8 TeV, 20.3 fb^{-1}, arXiv:1409.0746

3 LJ types:

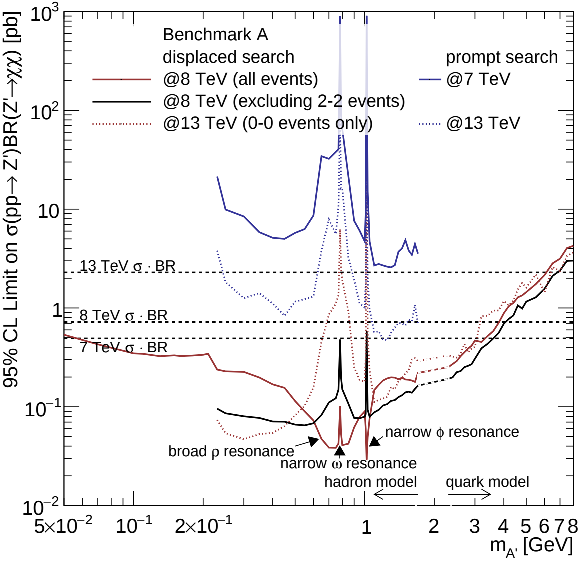
- Muonic (type-0): $\geq 2\mu$'s inside cone $\Delta R = 0.5$
- Mixed (type-1): $\geq 2\mu$'s + 1 jet inside cone $\Delta R = 0.5$
- Calorimeter (type-2): jet with small EM fraction



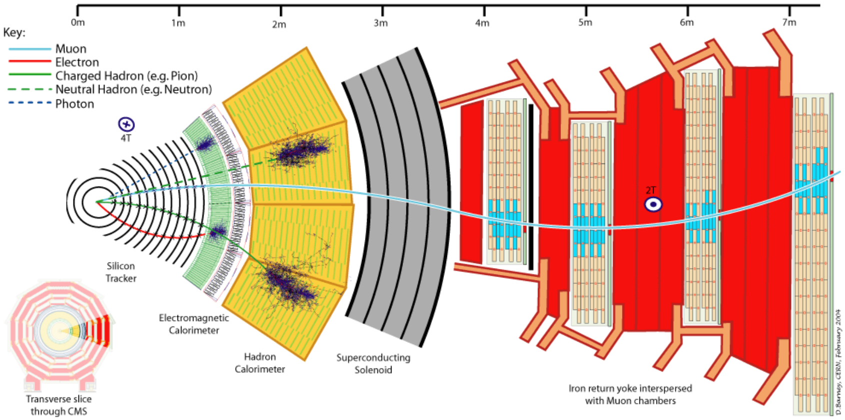
Parameter Scans



Parameter Scans

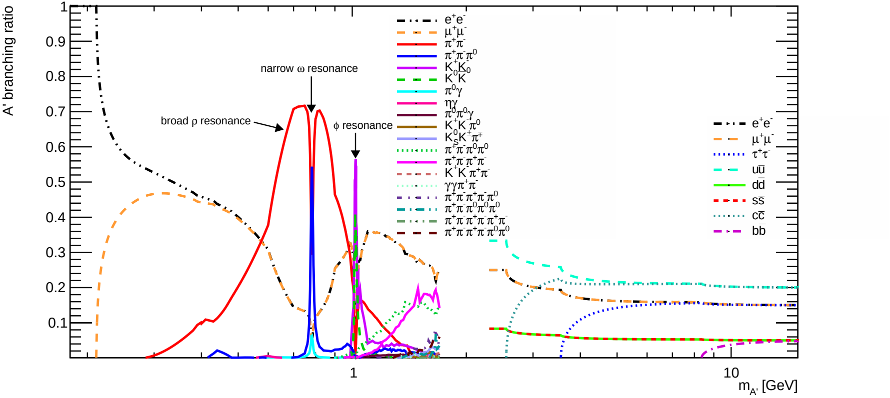


Parameter Scans



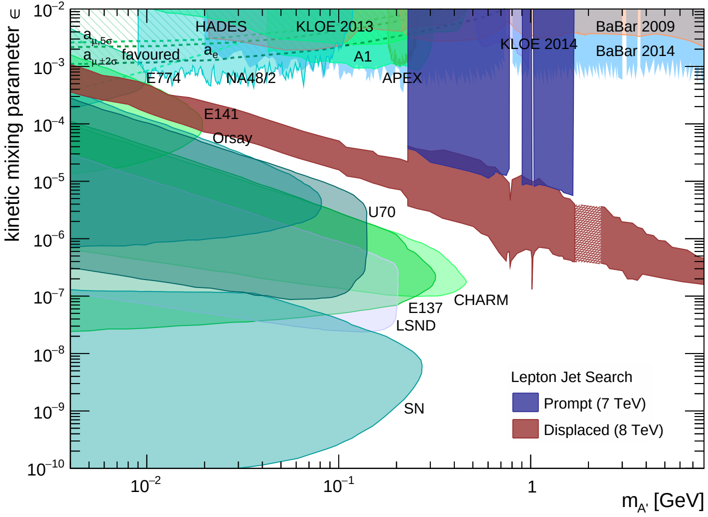
Detector	$A' \to e^+e^-$	$A' \to \mu^+\mu^-$	$A' \to \pi^+\pi^- / K^+K^-$	$A' \to \pi^+\pi^-\pi^0$	$A' \to K_L^0 K_S^0$
LJ type	2 (calorimeter)	0 (muonic)	2 (calorimeter)	2 (calorimeter)	2 (calorimeter)
ID	track	track	track	track	(✓)
ECAL	EM fraction	✓	✓	EM fraction	(✓)
HCAL	✓	✓	✓	✓	✓

Parameter Scans



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

Exclusion Limits



Summary

- Semi-analytic description of dark photon radiation via Mellin transform
  $\rightarrow$ Good agreement with Monte Carlo
- Dark radiation leading to lepton jets at the LHC
  $\rightarrow$ Powerful limits on not yet tested parameter space
- Large improvement at 13 TeV expected