Lepton Jets from Radiating Dark Matter

based on JHEP 07 (2015) 045 (arXiv:1505.07459)

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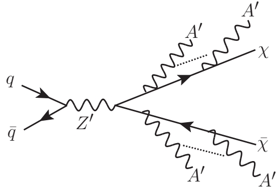
Pheno16 05/09/2016

Model

Use FSR instead of ISR!

Motivated by self-interacting DM



Relevant Lagrangian:

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

DM pair production for toy model:

$$\mathcal{L}_{Z'} \equiv g_q \sum_f \bar{q}_f \not{Z}' q_f + g_\chi \bar{\chi} \not{Z}' \chi \quad (2)$$

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

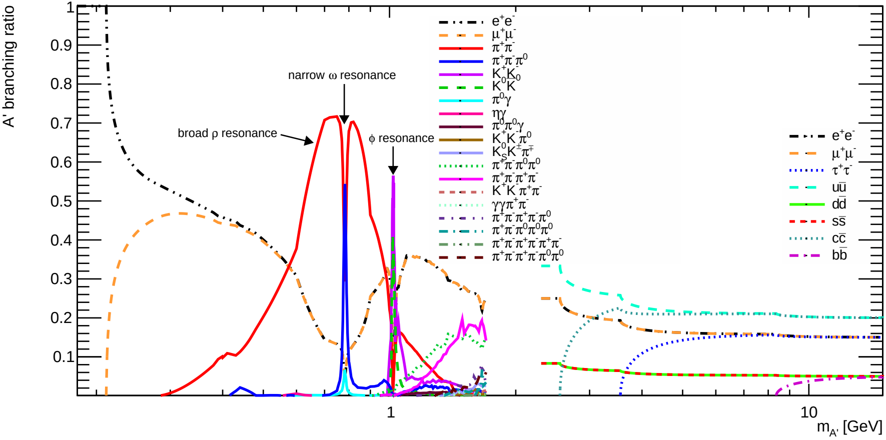
For **hadrons**: Use e^+e^- collider measurements of

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

to determine partial decay width

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

A' Branching Ratios



Benchmarks

	$m_{Z'}$ [TeV]	g_q	g_χ	m_χ [GeV]	$m_{A'}$ [GeV]	$\alpha_{A'}$	$c\tau$ [mm]
A	1	0.1	1	4	1.5	0.2	10
B	1	0.03	0.3	0.4	0.4	0.2	1

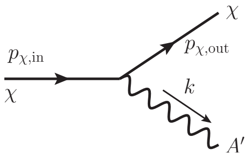
Table 1: Fixed model parameters

	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
B	24	0.076	0.244	84.8%	5.15	5.17

Table 2: Derived quantities

Benchmarks not excluded by: mono- and dijet searches, limits on thermal relic density, direct and indirect DM searches, DM self-interactions, limits on ϵ and $m_{A'}$.

Dark Parton Shower



Differential collinear splitting probability

$$\frac{\alpha_{A'}}{2\pi} dx \, \frac{dt}{t} P_{\chi\to\chi}(x,t) \quad \text{with} \quad P_{\chi\to\chi}(x,t) = \frac{1+x^2}{1-x} - \frac{2(m_\chi^2 + m_{A'}^2)}{t} \tag{3}$$

Physical limits:

$$x_{\text{min}} \equiv m_\chi / E_0 \,, \qquad x_{\text{max}} \equiv 1 - m_{A'}/E_0 \,, \tag{4}$$

$$t_{\text{min}}(x) = m_{A'}^2 + 2(E_0^2 x(1-x) - \sqrt{x^2 E_0^2 - m_\chi^2}\sqrt{(1-x)^2 E_0^2 - m_{A'}^2}) \tag{5}$$

$$t_{\text{max}}(x) = m_{A'}^2 + 2 p_{\chi,\text{out}} \cdot k \Big|_{k_{t,\text{max}}} \tag{6}$$

Via Recursive Formalism

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

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

Next splittings:

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

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'.

A' spectrum analogue!

Via Mellin Transform

Mellin transform:

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

Idea: Calculate moments of energy spectrum first
First moment:

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

Second moment:

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

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

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 . . .

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

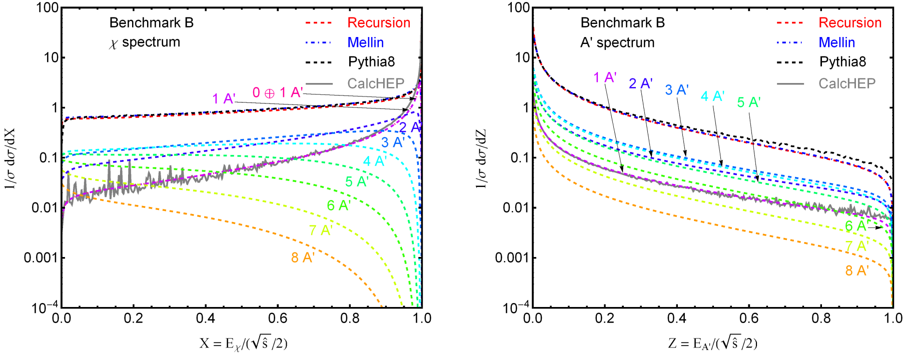
. . . and use inverse Mellin transformation to obtain $f_\chi(X)$:

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

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



Minor discrepancies due to:

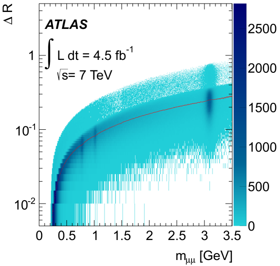
- Integrations limits are not independent of x and t
  (Assumption that energy loss in each splitting is small)
- Neglect of t-dependence in splitting kernel $P_{\chi\to\chi}(x)$

Short A' lifetime: Prompt Search

Based on ATLAS, 7 TeV, 5 fb^{-1}, arXiv:1212.5409

Muonic lepton jet (LJ)

$\geq 2\mu$'s inside cone $\Delta R = 0.1$



- μ's have track in inner detector (transverse distance from beam < 122.5mm)
- $m_{\mu\mu} < 2$ GeV
- Very soft muons: 6 GeV at trigger level (for 3 or more μ)
- LJ isolated in the calorimeter
- 2 LJs required

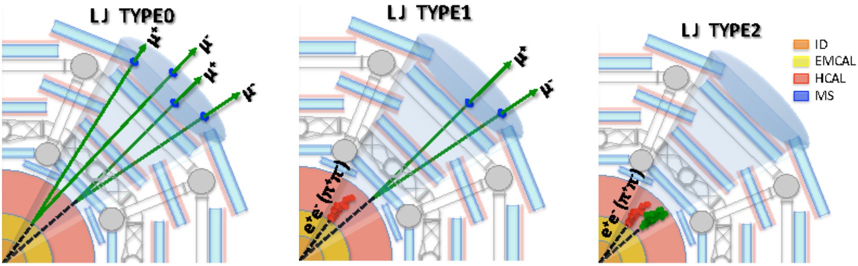
$\rightarrow$ high signal efficiency if $c\tau$ small
$\rightarrow$ rely on branching to muons

Long A' lifetime: Displaced Search

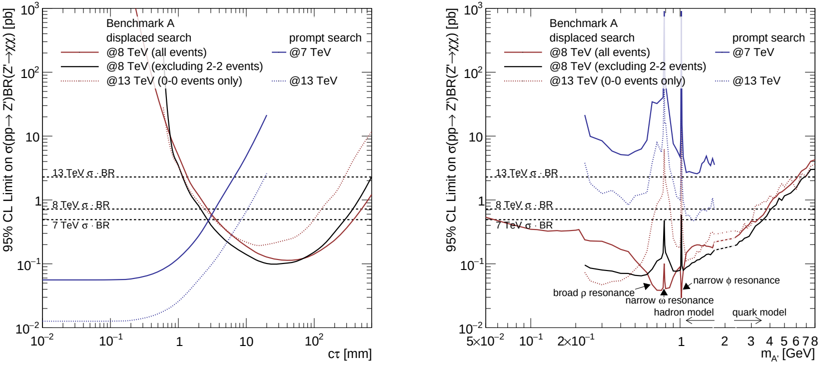
Based on ATLAS, 8 TeV, 20.3 fb^{-1}, arXiv:1409.0746

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



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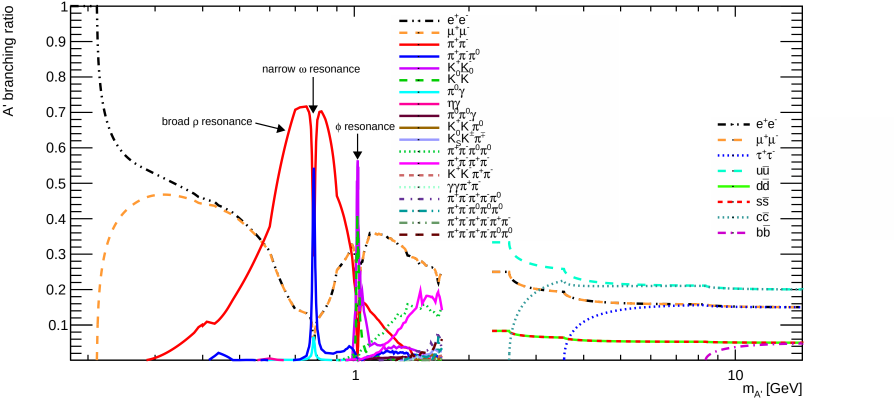
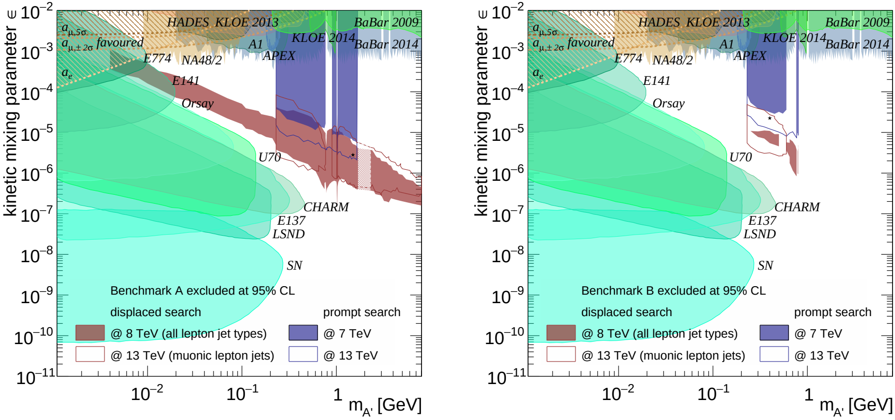


Detector	$A' \to e^+e^-$	$A' \to \mu^+\mu^-$	$A' \to \pi^+\pi^- / K^+K^-$	$A' \to \pi^+\pi^-\pi^0$	$A' \to K_L^0 K_S^0$
LJ type	2 (calorimeter)	0 (muonic)	2 (calorimeter)	2 (calorimeter)	2 (calorimeter)
ID	track	track	track	track	(✓)
ECAL	EM fraction	✓	✓	EM fraction	(✓)
HCAL	✓	✓	✓	✓	✓

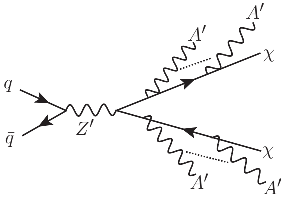
Exclusion Limits



(a) (b)

Summary

- Semi-analytic description of dark photon radiation via recursive integration and Mellin transform
  $\rightarrow$ Good agreement with Monte Carlo
- Recast of prompt and displaced ATLAS searches
  $\rightarrow$ Powerful limits on not yet tested parameter space
- Large improvement at 13 TeV expected

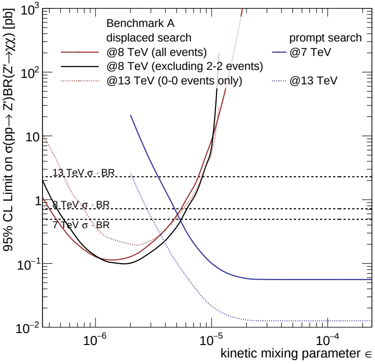


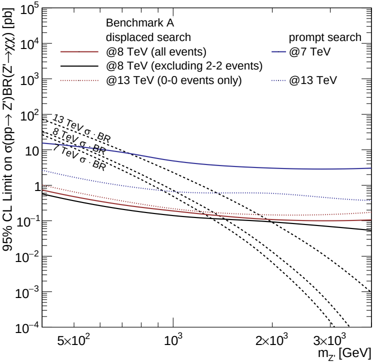
Backup

	7 TeV	13 TeV
Benchmark A	0.8	109
Benchmark B	3.9	334
All background	0.5 ± 0.3	30 ± 18
data	3	

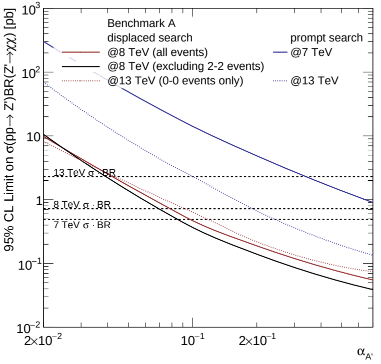
	0-0	0-1	0-2	1-1	1-2	2-2
Cosmic ray bkg.	15	0	14	0	0	11
8 TeV						
Muli-jet bkg.						
Benchmark A	14	3	104	0	14	200
Benchmark B	2.1	0.4	3.0	0	0.3	1.2
data	11	0	11	4	3	90
13 TeV						
Benchmark A	169					
Benchmark B	28					

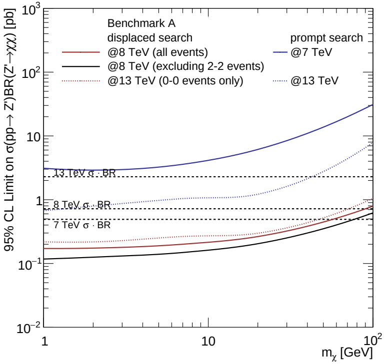
Backup


95% CL Limit on σ(pp→ Z')BR(Z'→χχ) [pb]
Benchmark A
displaced search
@8 TeV (all events)
@8 TeV (excluding 2-2 events)
@13 TeV (0-0 events only)
prompt search
@7 TeV
@13 TeV
13 TeV σ · BR
8 TeV σ · BR
7 TeV σ · BR
kinetic mixing parameter ∈


95% CL Limit on σ(pp→ Z')BR(Z'→χχ) [pb]
Benchmark A
displaced search
@8 TeV (all events)
@8 TeV (excluding 2-2 events)
@13 TeV (0-0 events only)
prompt search
@7 TeV
@13 TeV
13 TeV σ · BR
8 TeV σ · BR
7 TeV σ · BR
m_Z' [GeV]

Backup


Benchmark A
displaced search
@8 TeV (all events)
@8 TeV (excluding 2-2 events)
@13 TeV (0-0 events only)
prompt search
@7 TeV
@13 TeV
13 TeV σ · BR
8 TeV σ · BR
7 TeV σ · BR
95% CL Limit on σ(pp→ Z')BR(Z'→χχ) [pb]
$\alpha_{A'}$
2×10⁻²
10⁻¹
2×10⁻¹


Benchmark A
displaced search
@8 TeV (all events)
@8 TeV (excluding 2-2 events)
@13 TeV (0-0 events only)
prompt search
@7 TeV
@13 TeV
13 TeV σ · BR
8 TeV σ · BR
7 TeV σ · BR
95% CL Limit on σ(pp→ Z')BR(Z'→χχ) [pb]
m_χ [GeV]