Lepton Jets from Radiating Dark Matter

(based on arXiv:1505.07459, accepted by JHEP)
collaborated with Malte Buschmann, Joachim Kopp, Pedro Machado

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Educational background

- **Postdoc**
  - Johannes Gutenberg University Mainz — Oct 2014 - present
  - PRISMA Cluster of Excellence & Mainz Institute for Theoretical Physics
- **Ph.D.**
  - New York University, New York — Sept 2009 - July 2014
  - Center for Cosmology and Particle Physics
  - Adviser: Neal Weiner
- **Master**
  - Peking University, Beijing, China — Sept 2006 - Sept 2009
  - Institute of Theoretical Physics
  - Adviser: Shou-hua Zhu
- **Bachelor**
  - Tsinghua University, Beijing, China — Sept 2002 - Sept 2006
  - Department of Physics

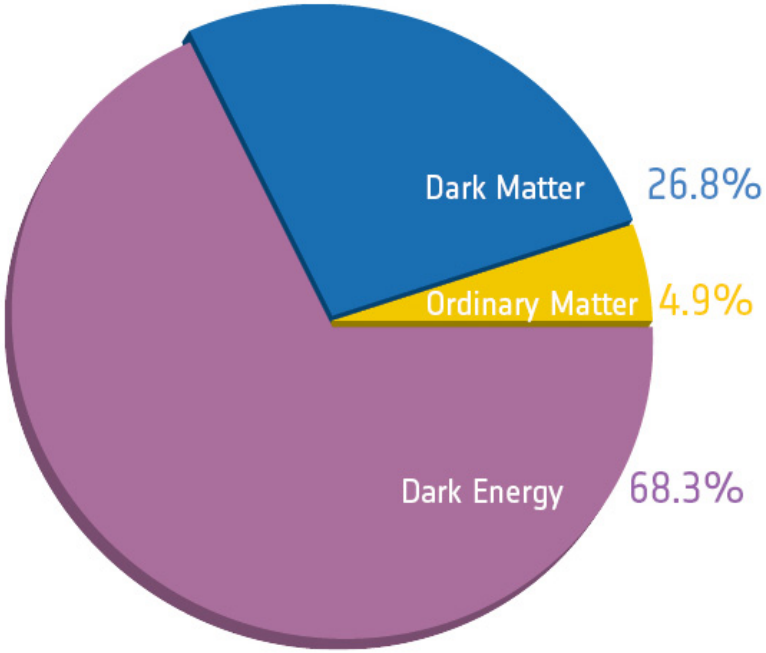
Publication

1. J. Liu, P. -f. Yin and S. -h. Zhu, "Neutrino Signals from Solar Neutralino Annihilations in Anomaly Mediated Supersymmetry Breaking Model," Phys. Rev. D **77**, 115014 (2008) [arXiv:0803.2164 [hep-ph]]. *8 citations.*
2. P. -f. Yin, J. Liu, Q. Yuan, X. -j. Bi and S. -h. Zhu, "Constraints on the Dark Matter Annihilations by Neutrinos with Substructure Effects Included," Phys. Rev. D **78**, 065027 (2008) [arXiv:0806.3689 [astro-ph]]. *3 citations.*
3. P. -f. Yin, Q. Yuan, J. Liu, J. Zhang, X. -j. Bi and S. -h. Zhu, "PAMELA data and leptonically decaying dark matter," Phys. Rev. D **79**, 023512 (2009) [arXiv:0811.0176 [hep-ph]]. *172 citations.*
4. J. Zhang, X. -J. Bi, J. Liu, S. -M. Liu, P. -F. Yin, Q. Yuan and S. -H. Zhu, "Discriminating different scenarios to account for the cosmic e + /- excess by synchrotron and inverse Compton radiation," Phys. Rev. D **80**, 023007 (2009) [arXiv:0812.0522 [astro-ph]]. *83 citations.*
5. J. Liu, P. -f. Yin and S. -h. Zhu, "Prospects for Detecting Neutrino Signals from Annihilating/Decaying Dark Matter to Account for the PAMELA and ATIC results," Phys. Rev. D **79**, 063522 (2009) [arXiv:0812.0964 [astro-ph]]. *65 citations.*
6. P. -f. Yin, J. Liu and S. -h. Zhu, "Detecting light leptophilic gauge boson at BESIII detector," Phys. Lett. B **679**, 362 (2009) [arXiv:0904.4644 [hep-ph]]. *34 citations.*
7. Q. Yuan, X. -J. Bi, J. Liu, P. -F. Yin, J. Zhang and S. -H. Zhu, "Clumpiness enhancement of charged cosmic rays from dark matter annihilation with Sommerfeld effect," JCAP **0912**, 011 (2009) [arXiv:0905.2736 [astro-ph.HE]]. *21 citations.*
8. J. Liu, "Dark Matter as a Possible New Energy Source for Future Rocket Technology," arXiv:0908.1429 [astro-ph.CO].

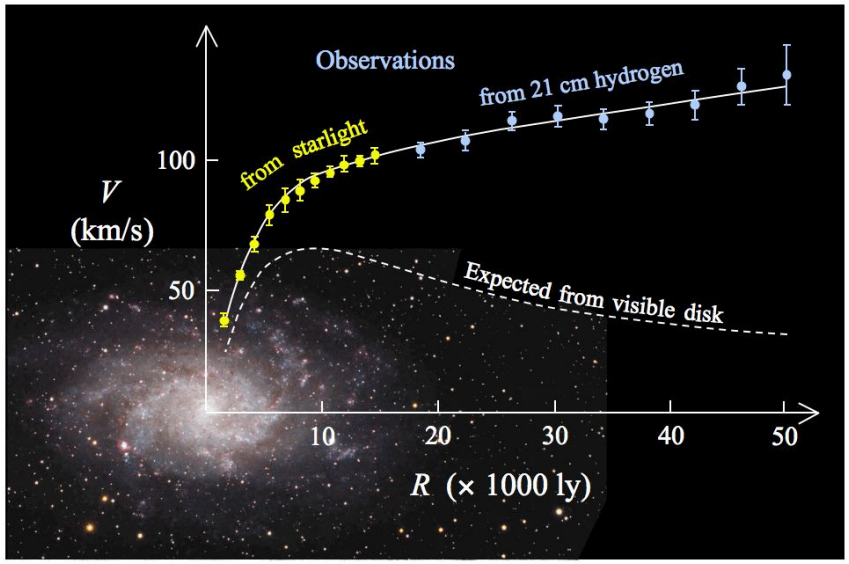
Publication

9. S. Chang, J. Liu, A. Pierce, N. Weiner and I. Yavin, "CoGeNT Interpretations," JCAP **1008**, 018 (2010) [arXiv:1004.0697 [hep-ph]]. *177 citations.*
10. P. J. Fox, J. Liu and N. Weiner, "Integrating Out Astrophysical Uncertainties," Phys. Rev. D **83**, 103514 (2011) [arXiv:1011.1915 [hep-ph]]. *103 citations.*
11. P. J. Fox, J. Liu, D. Tucker-Smith and N. Weiner, "An Effective Z', " Phys. Rev. D **84**, 115006 (2011) [arXiv:1104.4127 [hep-ph]]. *67 citations.*
12. J. Liu, B. Shuve, N. Weiner and I. Yavin, "Looking for new charged states at the LHC: Signatures of Magnetic and Rayleigh Dark Matter," JHEP **1307**, 144 (2013) [arXiv:1303.4404 [hep-ph]]. *15 citations.*
13. J. Liu, X. -P. Wang and S. -h. Zhu, "Discovering extra Higgs boson via pair production of the SM-like Higgs bosons," arXiv:1310.3634 [hep-ph]. *21 citations.*
14. D. S.M. Alves, J. Liu, N. Weiner, "Hiding Missing Energy in Missing Energy," JHEP **1504**, 088 (2015) [arXiv:1312.4965 [hep-ph]]. *8 citations.*
15. J. Liu, N. Weiner and W. Xue, "Signals of a Light Dark Force in the Galactic Center," arXiv:1412.1485 [hep-ph]. *10 citations.*
16. J. Kopp, J. Liu and X. P. Wang, "Boosted Dark Matter in IceCube and at the Galactic Center," JHEP **1504**, 105 (2015) [arXiv:1503.02669 [hep-ph]]. *3 citations.*
17. M. Buschmann, J. Kopp, J. Liu and P. A. N. Machado, "Lepton Jets from Radiating Dark Matter," arXiv:1505.07459 [hep-ph]. *1 citations.*

Dark matter evidence



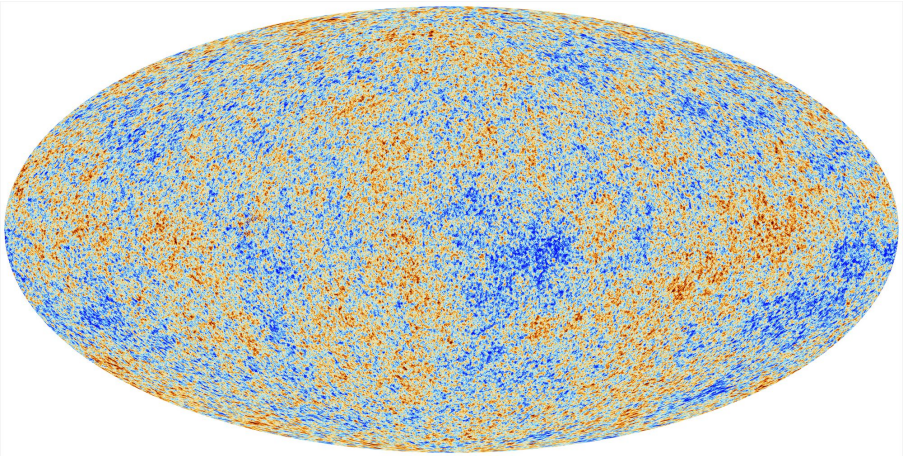
(Credit: ESA/Planck)

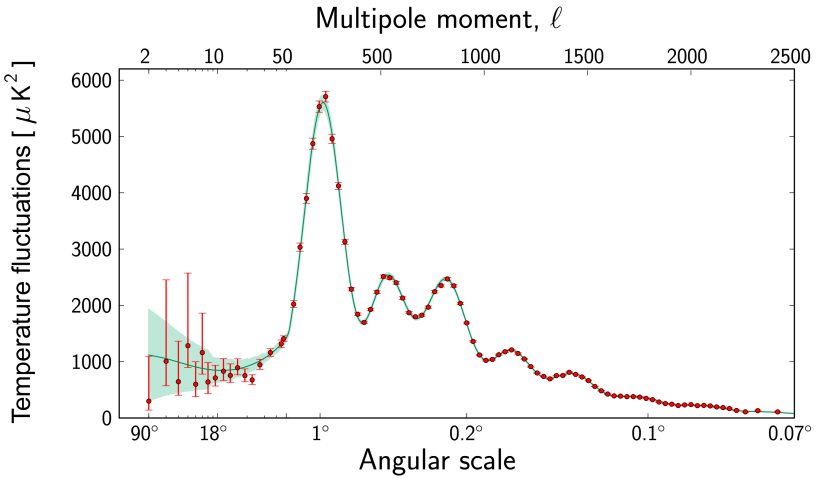


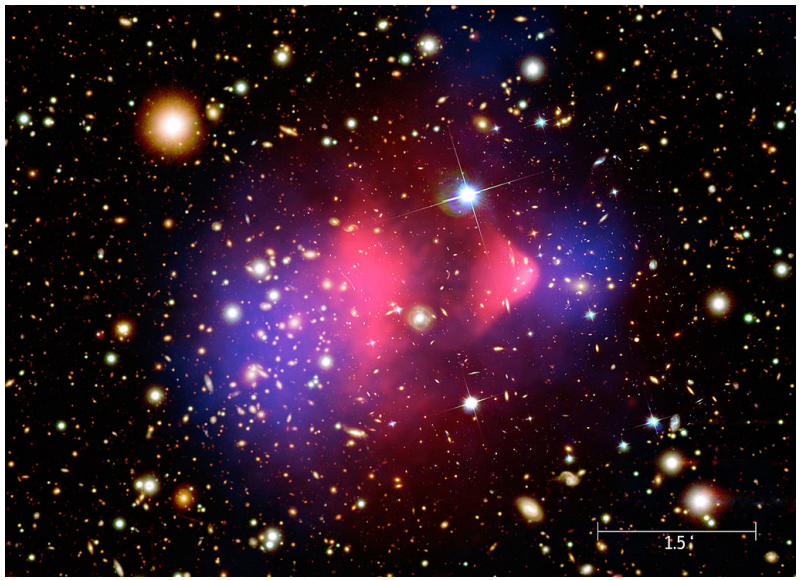
(Credit: Stefania)

- Property
  - No electric and color charge
  - weakly interacting with normal matter
  - stable or long lived
  - not in SM particle list

Dark matter evidence

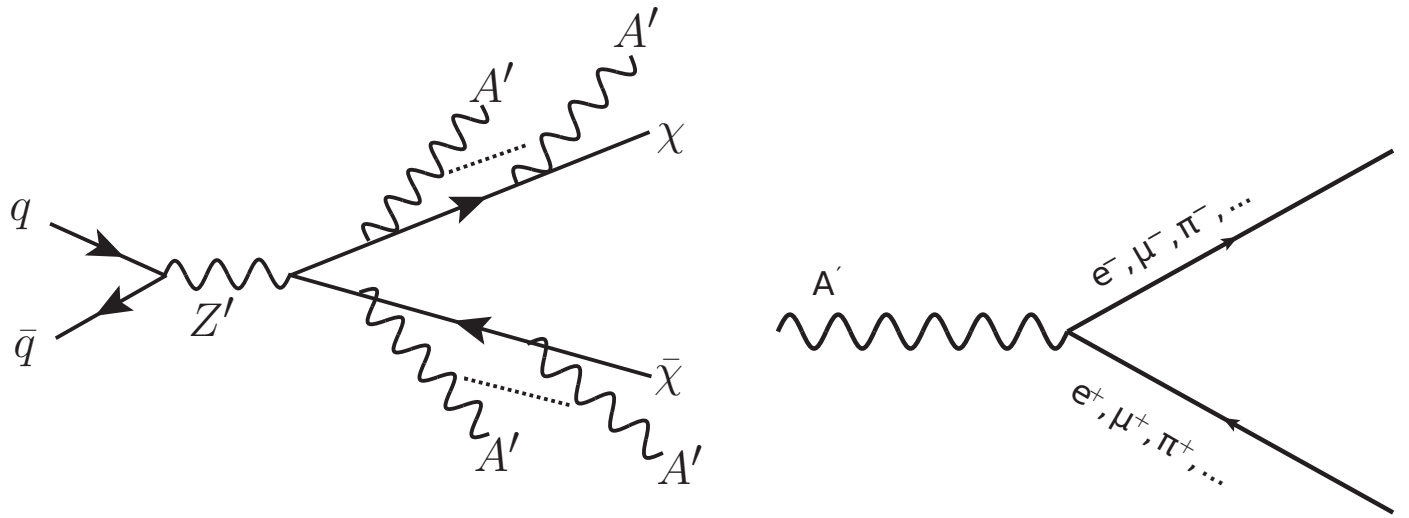






(Credit: NASA, Planck, ESA)

Motivation for radiating dark matter



- Dark sector might be complicated
  - multiple particles
  - strong interaction inside dark sector (e.g. self-interacting DM)
  - weak connection to Standard Model
- Dark matter could have strong radiation
  - multiple radiation of A'
  - light A' highly boosted
  - A' decay products highly collimated, forming Lepton Jets

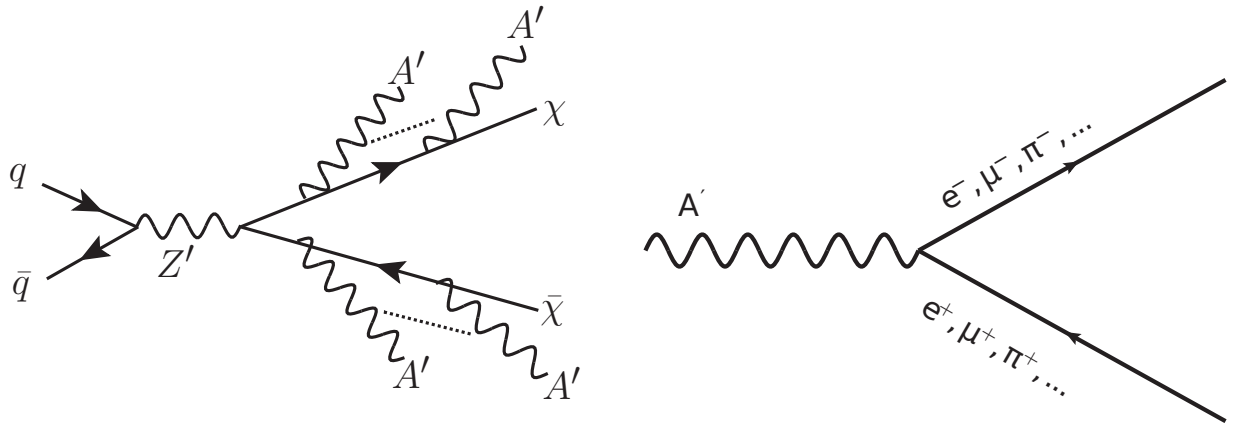
Previous Lepton Jet works

- Cascade decay of heavy new particles in SUSY
  - light particles produces lepton pair
  - Nima, Neal 08; L.T. Wang *et al.* 09; Y. Bai, Z. Han 09; C.C. Han 15 (light mass gap);
- non-standard Higgs decays to Dark Sector
  - e.g. decay to two A'
  - J. Ruderman *et al.* 10; D. Curtin *et al.* 13; A. Gupta *et al.* 15;
- single A' associated with DM pair production
  - A. Gupta *et al.* 15; M. Autran *et al.*; Y. Bai *et al.*;
- hadronic jets with non-standard properties
  - hidden valley (Tao Han, Zongguo Si *et al.* 07)
  - high multiplicities in the jet cone (P. Schwaller *et al.*
  - missing energy aligned with a jet (T. Cohen *et al.* 15)
  - DM strongly interaction with SM, DM produce hadronic trackless jets (Y. Bai *et al.* 11)

Our work

- Parton Shower analytic calculation compared with Monte Carlo
- high multiplicity of A' from DM pair production
- prompt and displaced searches (recast from ATLAS)

Model



Relevant Lagrangian:

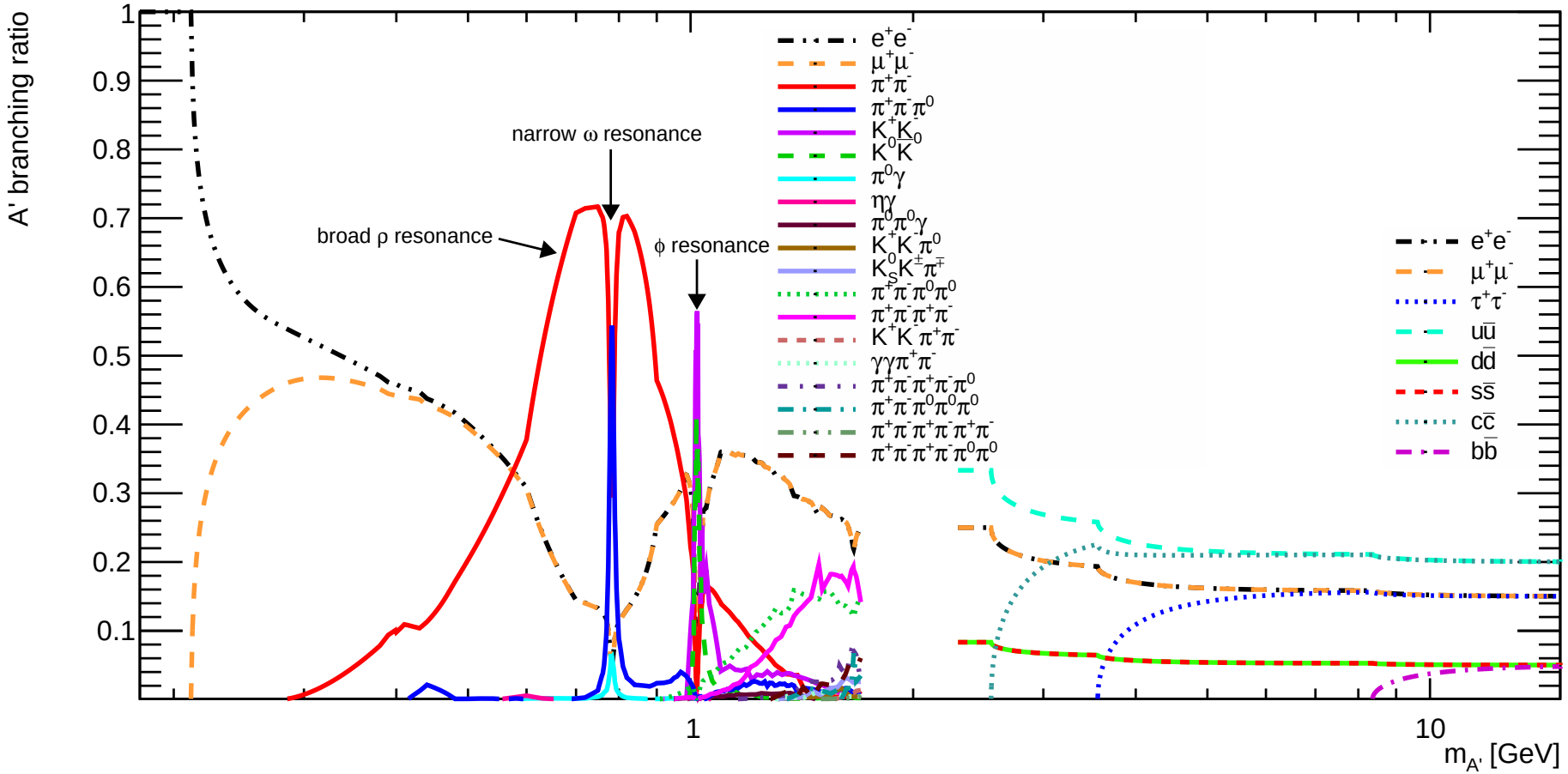
$$\mathcal{L}_{\text{dark}} \equiv \bar{\chi}(i\partial\!\!\!/ - m_\chi + i g_{A'} A\!\!\!/')\chi - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m^2_{A'} A'_\mu A'^\nu - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} \tag{1}$$

DM pair production for toy model:

$$\mathcal{L}_{Z'} \equiv g_q \sum_f \bar{q}_f Z\!\!\!/' q_f + g_\chi \bar{\chi} Z\!\!\!/' \chi \tag{2}$$

A' Branching Ratios

BR calculated by datas from low energy e^+e^- collider



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

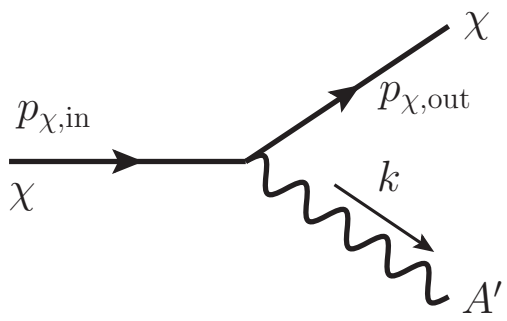
Table 1: Fixed model parameters

	ϵ [10^{-6}]	$\sigma_8(Z')$ [pb]	$\sigma_{13}(Z')$ [pb]	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-jet and dijet searches; thermal relic density limits, direct and indirect DM searches, DM self-interactions limits; ϵ limit.

Dark Parton Shower



Differential collinear splitting probability

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

$$x \equiv E_\chi / E_0 \qquad t \equiv (p_{\chi,\text{out}} + k)^2 - m_\chi^2 \tag{4}$$

Physical limits:

$$x_{\text{min}} \equiv m_\chi / E_0\,, \qquad x_{\text{max}} \equiv 1 - m_{A'}/E_0\,, \tag{5}$$

$$t_{\text{min}}(x) = m_{A'}^2 + 2(E_0^2 x(1-x) - \sqrt{x^2 E_0^2 - m_\chi^2}\sqrt{(1-x)^2 E_0^2 - m_{A'}^2}) \tag{6}$$

$$t_{\text{max}}(x) = m_{A'}^2 + 2 p_{\chi,\text{out}} \cdot k\big|_{k_{t,\text{max}}} \tag{7}$$

Recursive Formalism

- DM energy spectrum:

$$f_\chi(X) = \sum_{m=0}^{\infty} p_m \, f_{\chi,m}(X) \quad \text{with} \quad p_m = \frac{e^{-\langle n_{A'} \rangle} \, \langle n_{A'} \rangle^m}{m!} \tag{8}$$

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

$$f_{\chi,m+1}(X) = \int_{x_{\min}}^{x_{\max}} dx_m \, f_{\chi,1}(x_m) \, \frac{f_{\chi,m}(X/x_m)}{x_m} \, \Theta(x_{\min} \leq X \leq x_{\max}) \,, \tag{9}$$

with

$$f_{\chi,1}(X) \equiv \frac{1}{\langle n_{A'} \rangle} \frac{\alpha_{A'}}{2\pi} \int_{t_{\min}}^{t_{\max}} \frac{dt}{t} P_{\chi\to\chi}(X) \, \Theta(x_{\min} \leq X \leq x_{\max}) \tag{10}$$

- A' spectrum analogue

Mellin Transform

DM spectrum given by inverse Mellin transform (*Fourier analogue*)

$$f(X) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} ds\, X^{-s}\, \varphi(s)\,. \tag{11}$$

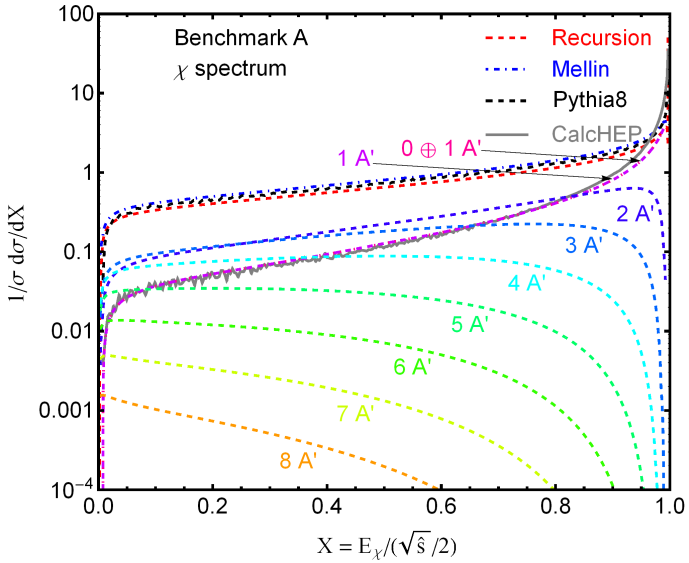
where the different moments are

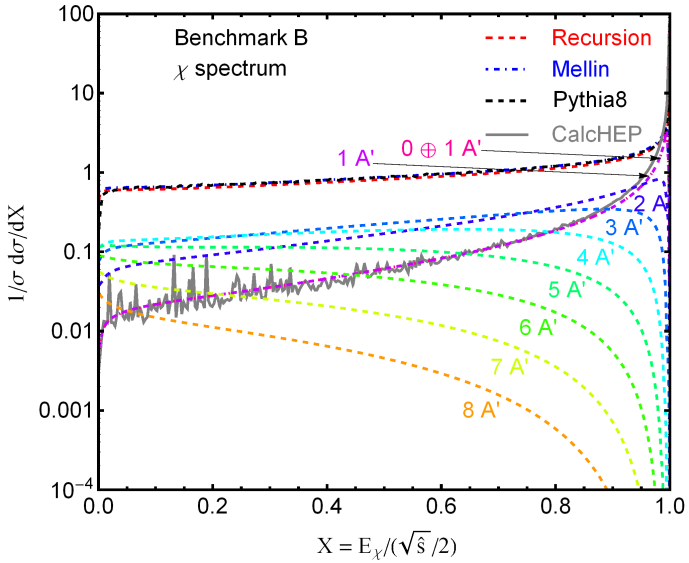
$$\mathcal{M}[f](s+1) \equiv \varphi(s+1) \equiv \int_0^\infty dX\, X^{s-1} f(X) = e^{-\langle n_{A'}\rangle (1-\overline{X^s})} \tag{12}$$

with

$$\overline{X^s} \equiv \frac{1}{\langle n_{A'}\rangle} \frac{\alpha_{A'}}{2\pi} \int_{x_{\min}}^{x_{\max}} dx\, x^s \int_{t_{\min}}^{t_{\max}} \frac{dt}{t} P_{\chi\to\chi}(x)\,. \tag{13}$$

Comparison


Benchmark A
χ spectrum
Recursion
Mellin
Pythia8
CalcHEP
1 A'
0 ⊕ 1 A'
2 A'
3 A'
4 A'
5 A'
6 A'
7 A'
8 A'
1/σ dσ/dX
X = E_χ/(√ŝ/2)


Benchmark B
χ spectrum
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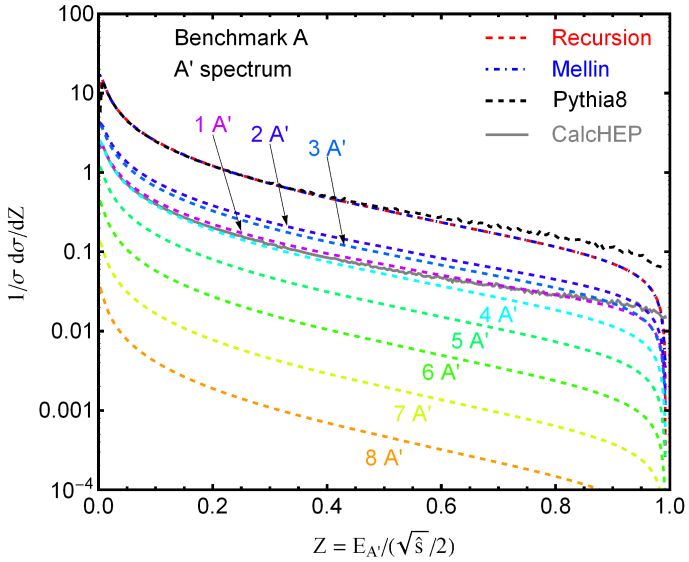
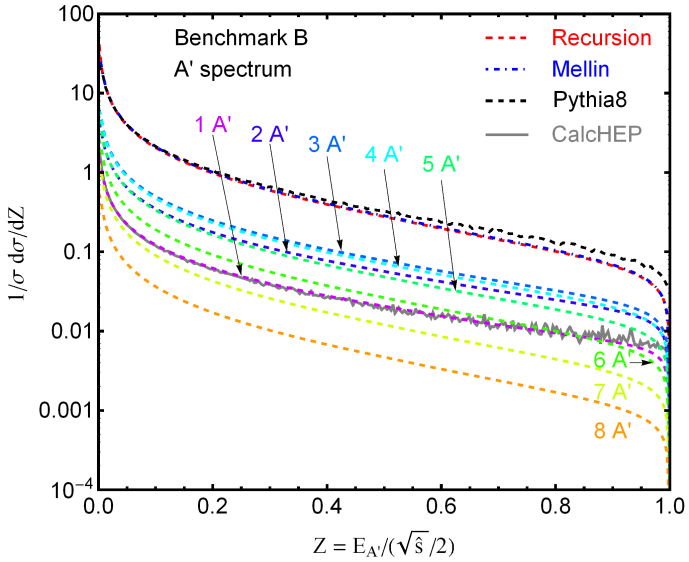

Benchmark A
A' spectrum
Recursion
Mellin
Pythia8
CalcHEP
1 A'
2 A'
3 A'
4 A'
5 A'
6 A'
7 A'
8 A'
1/σ dσ/dZ
Z = E_A'/(√ŝ/2)


Benchmark B
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1 A'
2 A'
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8 A'
1/σ dσ/dZ
Z = E_A'/(√ŝ/2)

Prompt Search

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

Muonic lepton jet (LJ)

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

- proper primary vertex ($d_0 < 1mm$)
- μ's have track in inner detector ($L_{xy} < 122.5mm$)
- $m_{\mu\mu} < 2$ GeV
- LJ isolated in the calorimeter
- 2 LJs required

$\rightarrow$ high signal efficiency ($\sim 10\%$) if $c\tau$ small
$\rightarrow$ rely on branching to muons

Prompt Search

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

two LJ event

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

- Dominant background: hadronic multi-jet and $\gamma +$ jets events by photon conversion
- Benchmarks not ruled out by 7TeV, but will by 13TeV
- 8TeV might exclude BKG only model already

Displaced Search

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

three different LJ types

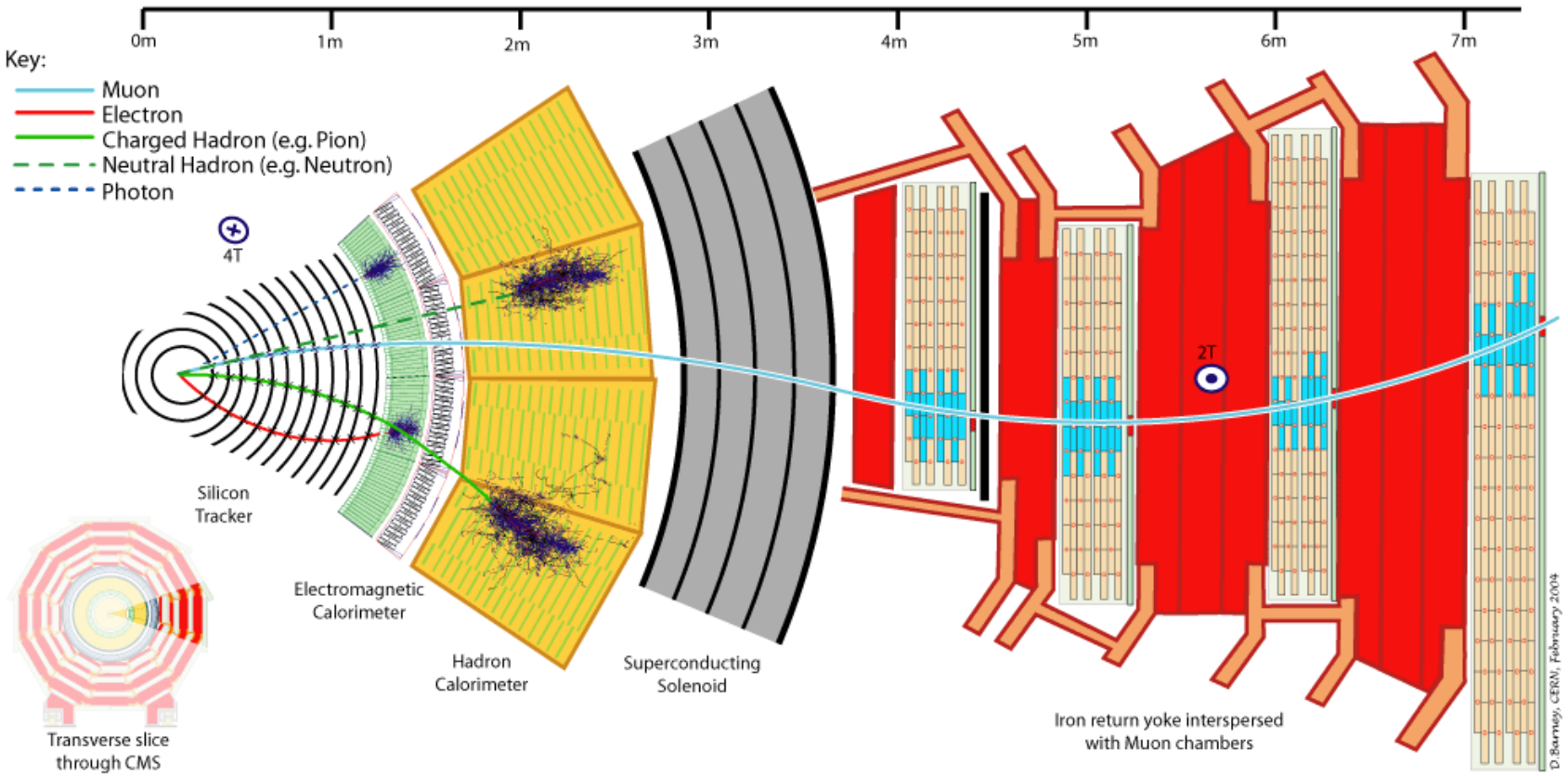
- Muonic: $\geq 2\mu$'s inside cone $\Delta R = 0.5$
- Mixed: $\geq 2\mu$'s + 1 jet inside cone $\Delta R = 0.5$
- Calorimeter: jet with small EM fraction

- μ's don't have a track in ID ($L_{xy} > 122.5mm$)
- LJ isolated in ID
- 2 LJs required

$\rightarrow$ low signal efficiency if $c\tau$ too small or too large
$\rightarrow$ hadronic channels contribute

Displaced Search

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	✓	✓	✓	✓	✓

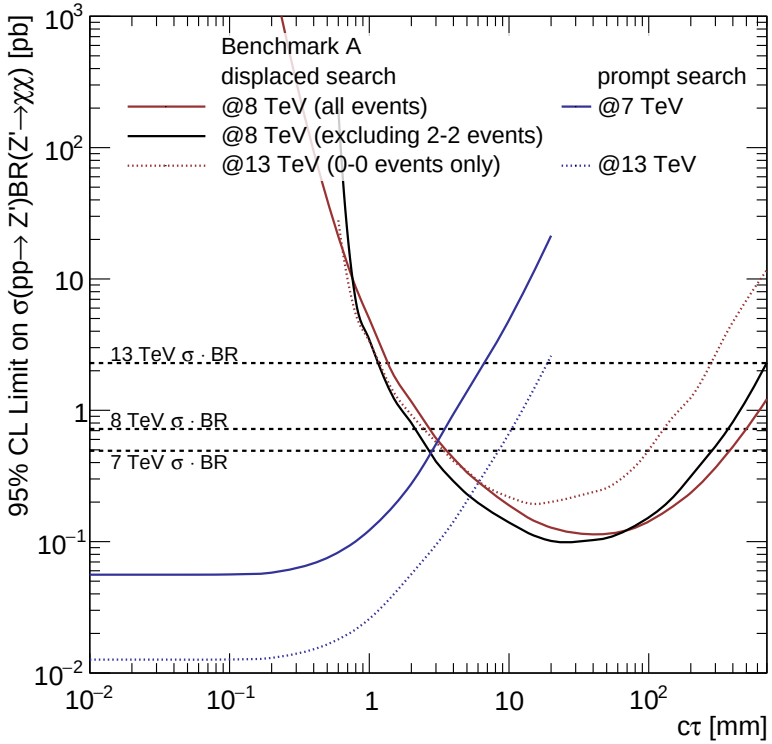


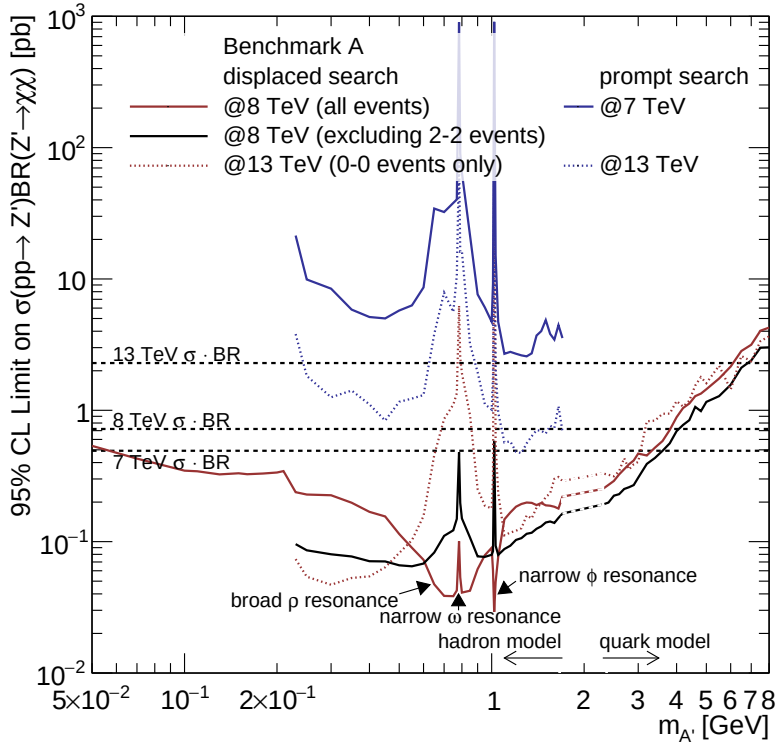
Displaced Search

	Lepton jet type							
	0-0	0-1	0-2	1-1	1-2	2-2	All	All excl. 2-2
Cosmic ray bkg.	15	0	14	0	0	11	$40 \pm 11 \pm 9$	$29 \pm 9 \pm 29$
8 TeV								
Multi-jet bkg.							$70 \pm 58 \pm 11$	$12 \pm 9 \pm 2$
Benchmark A	14	3	104	0	14	200	$335 \pm 18 \pm 100$	$135 \pm 12 \pm 41$
Benchmark B	2.1	0.4	3.0	0	0.3	1.2	$7 \pm 2.1 \pm 2.6$	$5.8 \pm 1.7 \pm 2.4$
data	11	0	11	4	3	90	119	29
13 TeV								
Benchmark A	169							
Benchmark B	28							

- Dominant background: multi-jet and cosmic ray
- type 1 (mixed) LJ is hard to produce
- type 2 (calorimeter) LJ usually dominates
- 13TeV conservatively calculated by 0-0 type LJ

Parameter Scans

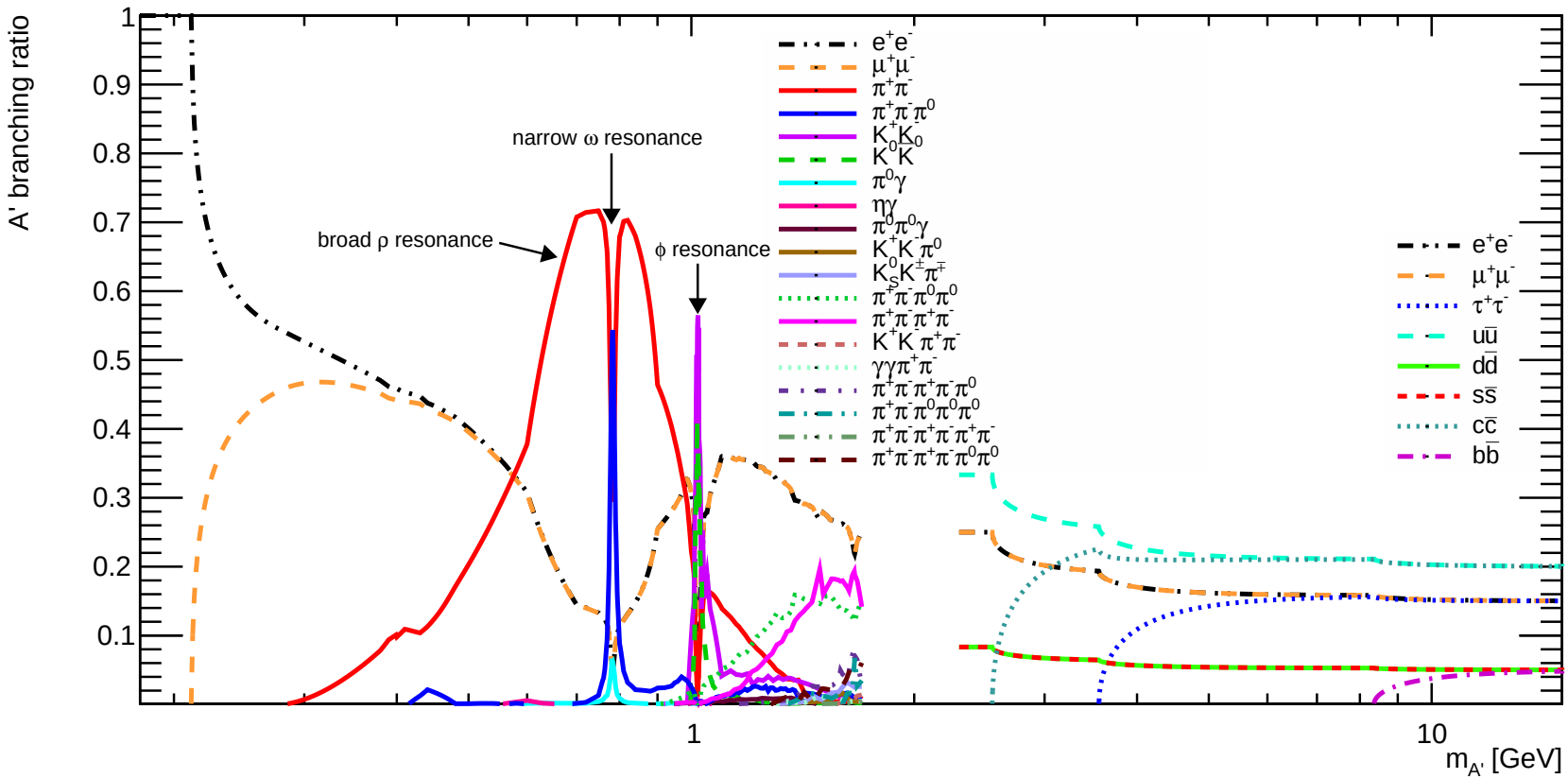




- Features from $\rho^0 \to \pi^+\pi^-$, $\omega \to \pi^+\pi^-\pi^0$ and $\phi \to K^+K^-/K_L^0K_S^0$

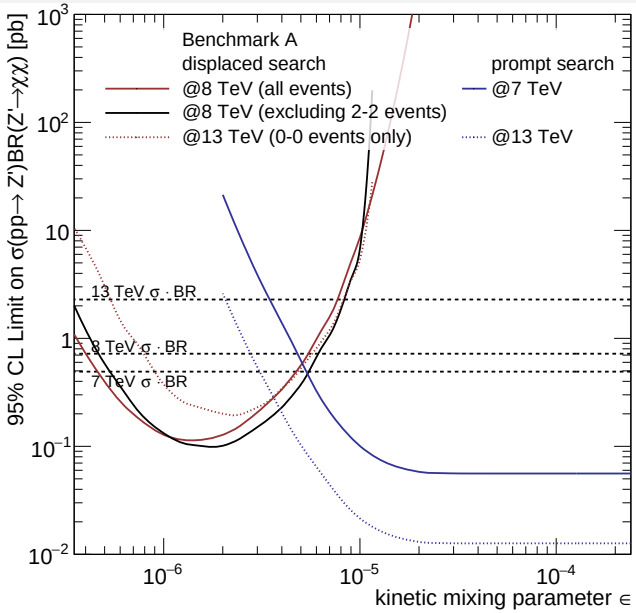
Detector	$A' \to e^+e^-$	$A' \to \mu^+\mu^-$	$A' \to \pi^+\pi^-/K^+K^-$	$A' \to \pi^+\pi^-\pi^0$	$A' \to K_L^0K_S^0$
LJ type	2 (calorimeter)	0 (muonic)	2 (calorimeter)	2 (calorimeter)	2 (calorimeter)
ID	track	track	track	track	(✓)
ECAL	EM fraction	✓	✓	EM fraction	(✓)
HCAL	✓	✓	✓	✓	✓

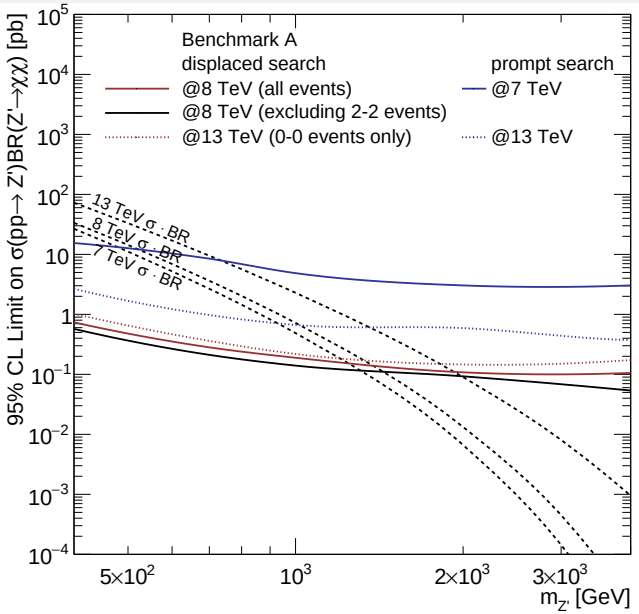
Parameter Scans

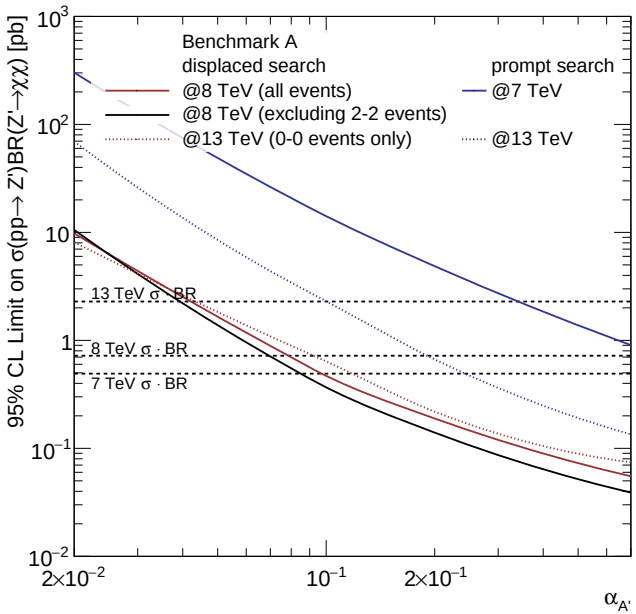


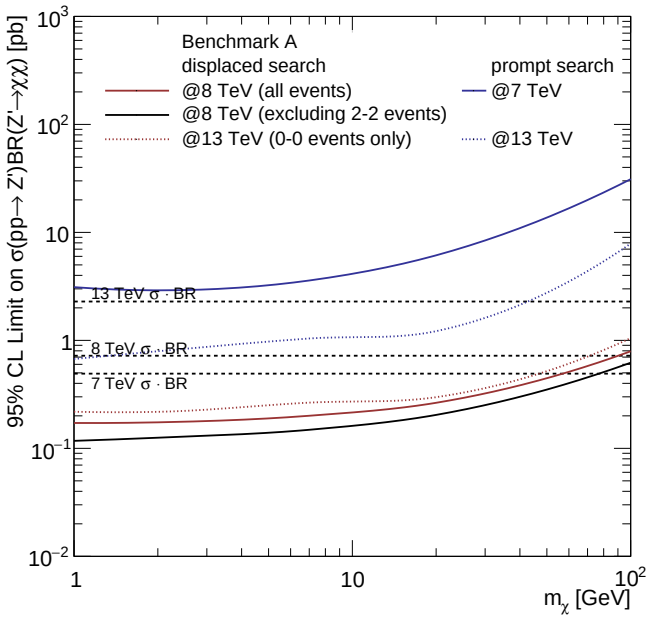
Detector	$A' \to e^+e^-$	$A' \to \mu^+\mu^-$	$A' \to \pi^+\pi^-/K^+K^-$	$A' \to \pi^+\pi^-\pi^0$	$A' \to K_L^0 K_S^0$
LJ type	2 (calorimeter)	0 (muonic)	2 (calorimeter)	2 (calorimeter)	2 (calorimeter)
ID	track	track	track	track	(✓)
ECAL	EM fraction	✓	✓	EM fraction	(✓)
HCAL	✓	✓	✓	✓	✓

Parameter Scans

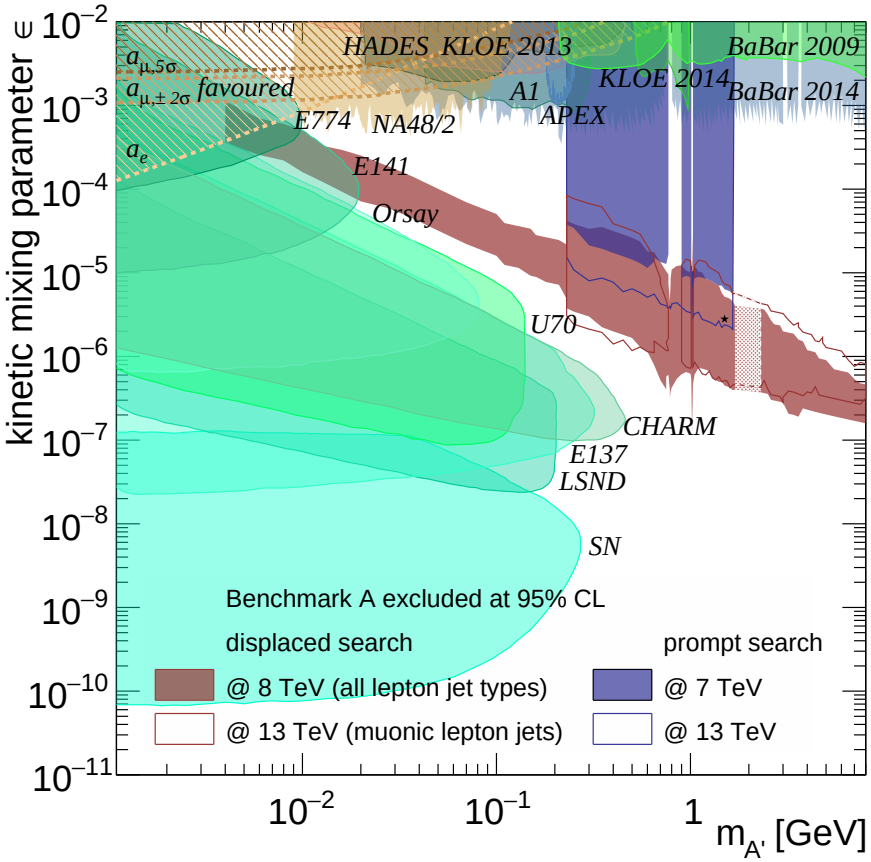




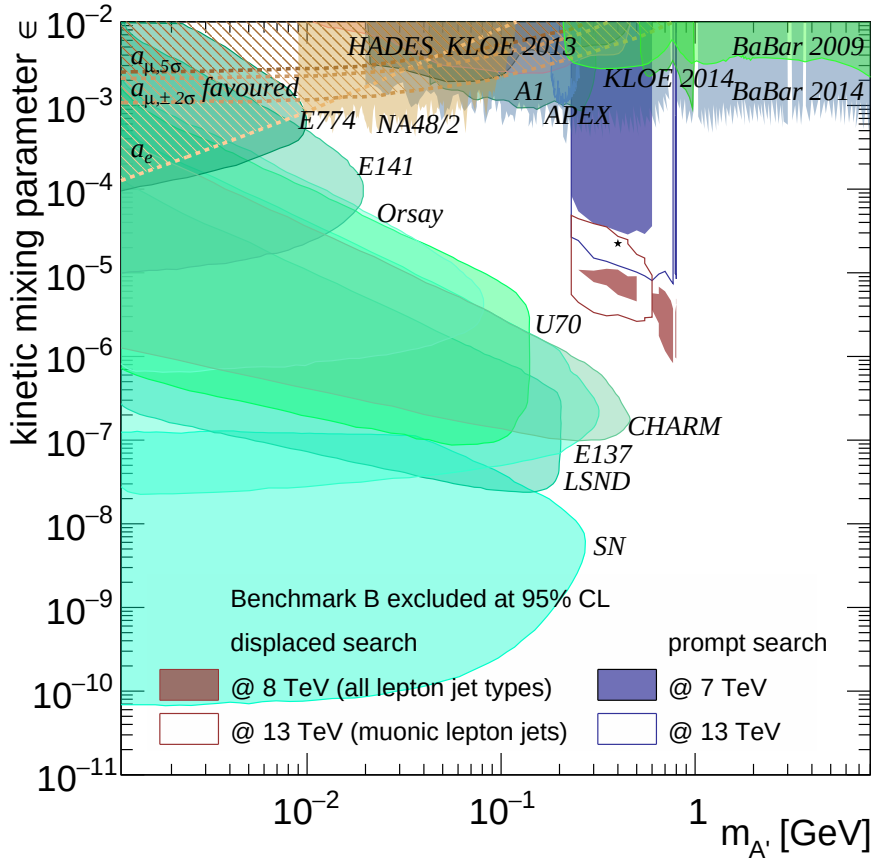




Exclusion Limits



(Benchmark A)



(Benchmark 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

Thank you!