# Lepton Jets from Radiating Dark Matter

(based on arXiv:1505.07459, JHEP 07 (2015) 045)
collaborated with Malte Buschmann, Joachim Kopp, Pedro Machado

Jia Liu

Johannes Gutenberg University Mainz

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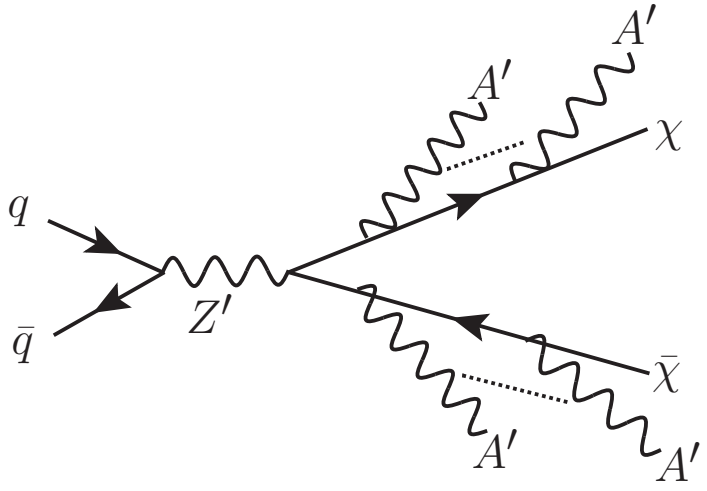
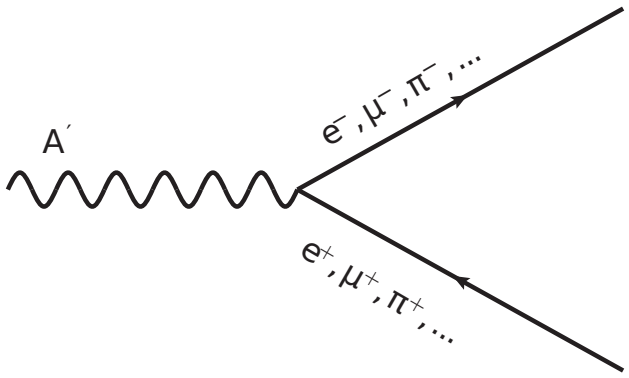
# Motivation for radiating dark matter




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

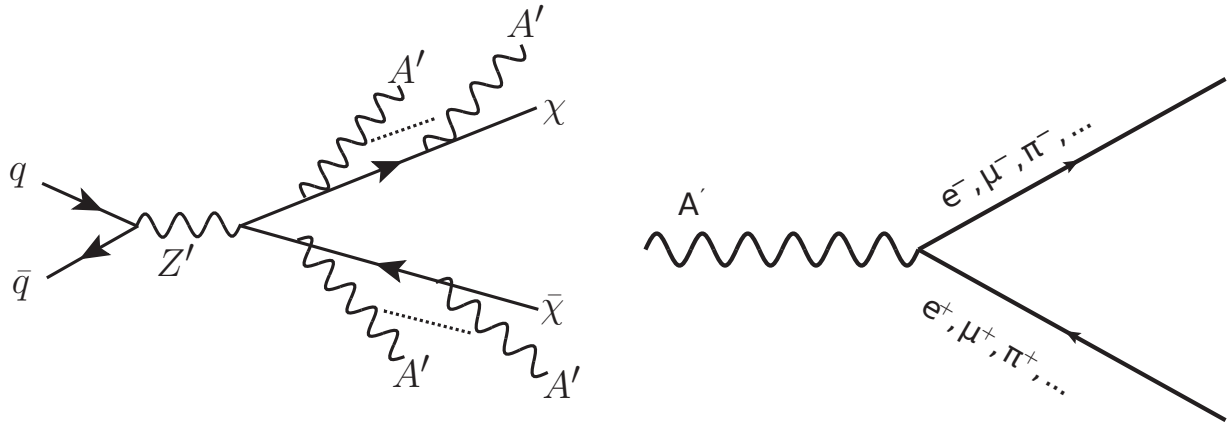
# Previous Lepton Jet works

- 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.* 15)
  - 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 (see also Arbuzov 99)
- high multiplicity of $A'$ from DM pair production
- prompt and displaced searches (recast from ATLAS)

# Model




## Relevant Lagrangian:

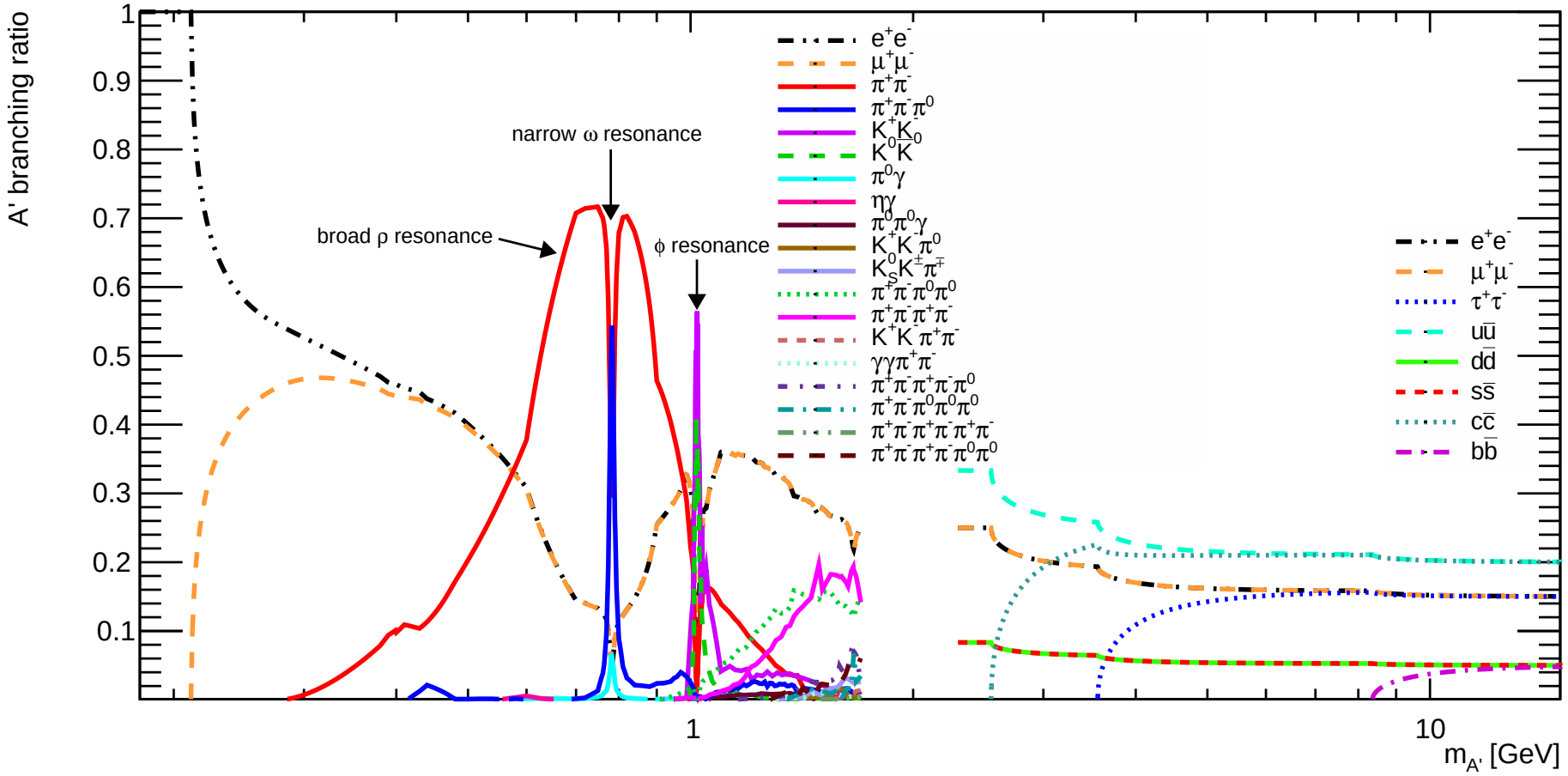
$$\mathcal{L}_{\text{dark}} \equiv \bar{\chi}(i\partial\!\!\!/ - m_\chi + ig_{A'} A\!\!\!/' )\chi - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\nu - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} \tag{1}$$

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] | $g_q$ | $g_\chi$ | $m_\chi$ [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 |

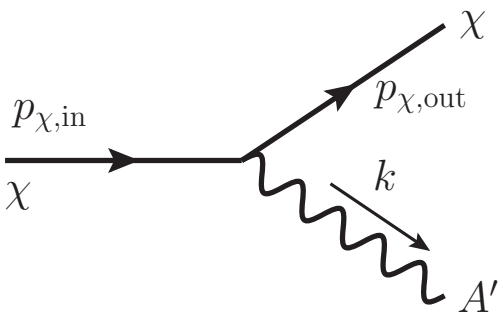
Table 1: Fixed model parameters

| | $\epsilon$ [$10^{-6}$] | $\sigma_8(Z')$ [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; $\epsilon$ limit.

# Dark Parton Shower




Differential collinear splitting probability

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

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

Physical limits:

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

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

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

# 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*)

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

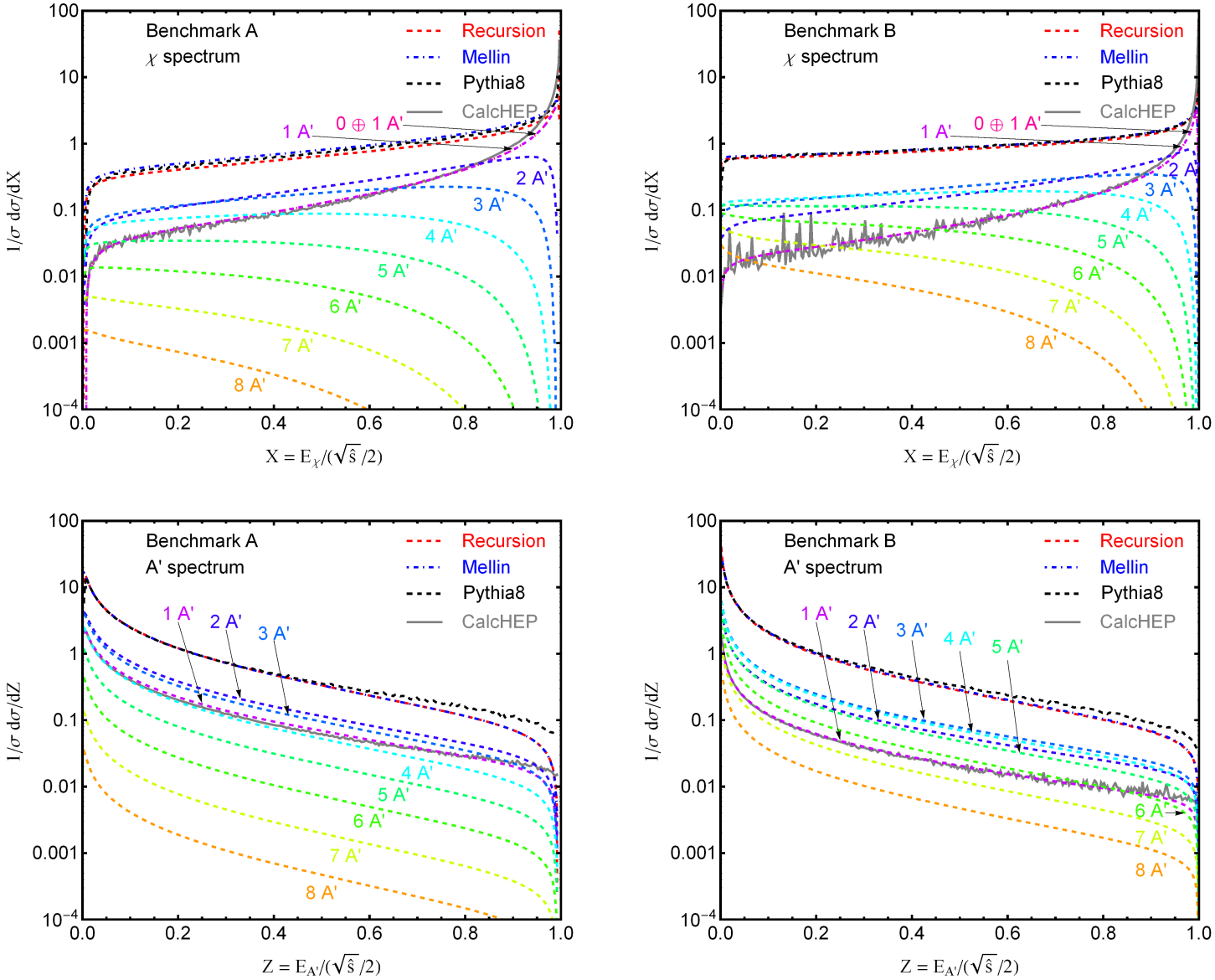
where the different moments are

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

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: $e^+e^- \to \bar{\chi}\chi + \text{any}A'$ at 1TeV



# Prompt Search

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

**Muonic lepton jet (LJ)**

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

- proper primary vertex ($d_0 < 1mm$)
- $\mu$'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 | $0.5 \pm 0.3$ | $30 \pm 18$ |
| 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

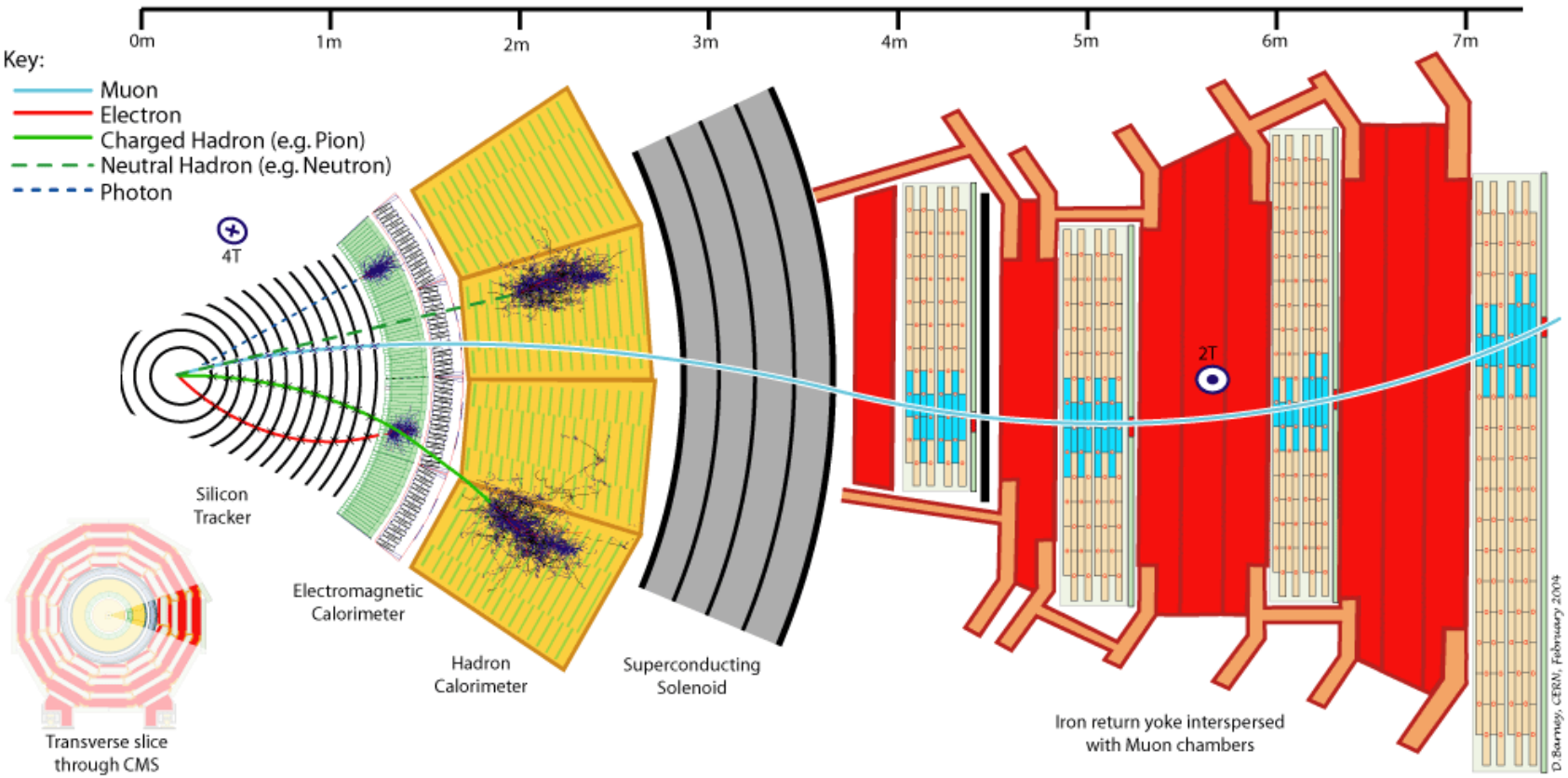
- Muonic: $\geq 2\mu$'s inside cone $\Delta R = 0.5$
- Mixed: $\geq 2\mu$'s + 1 jet inside cone $\Delta R = 0.5$
- Calorimeter: jet with small EM fraction

- $\mu$'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 | ✓ | ✓ | ✓ | ✓ | ✓ |

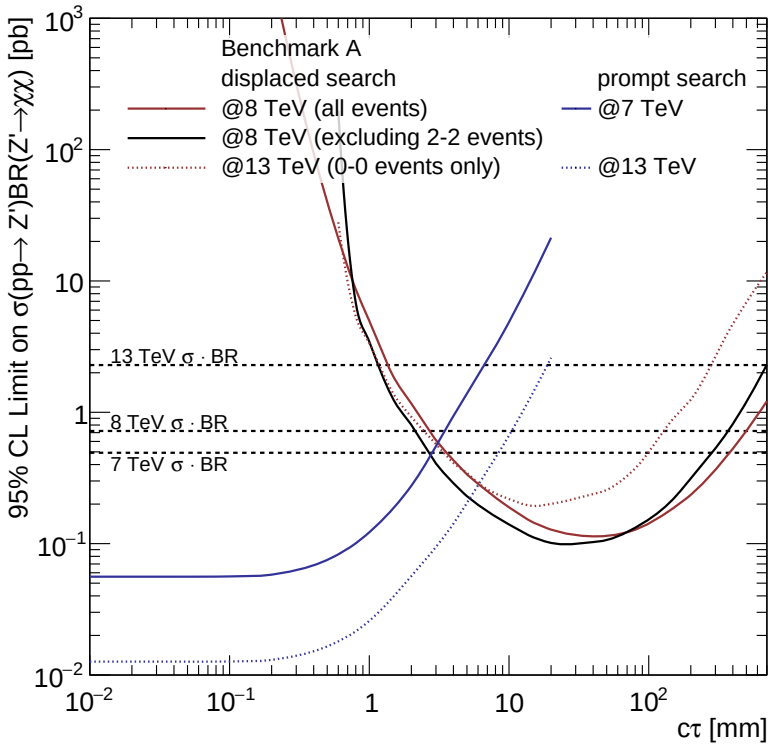


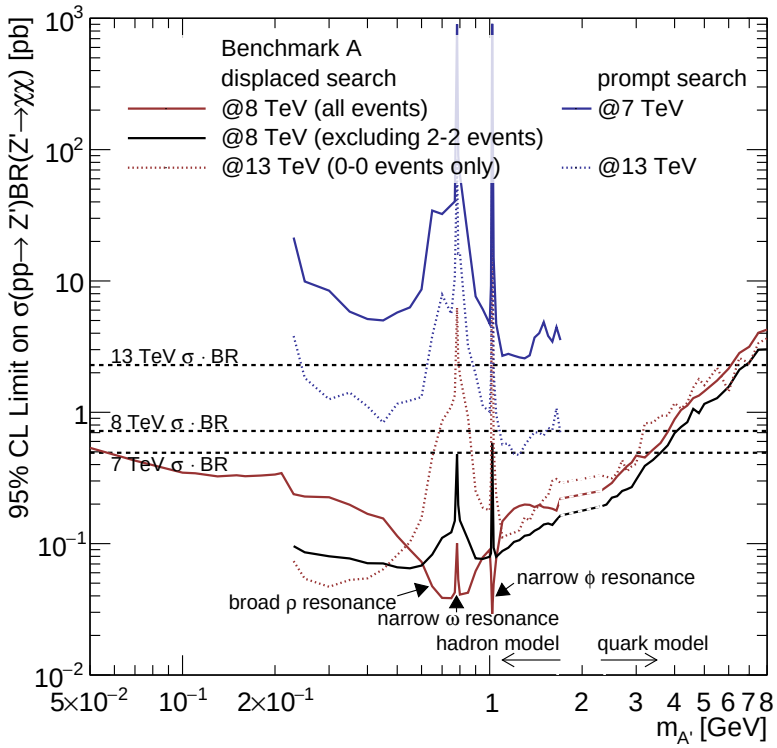
# Displaced Search

| | 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

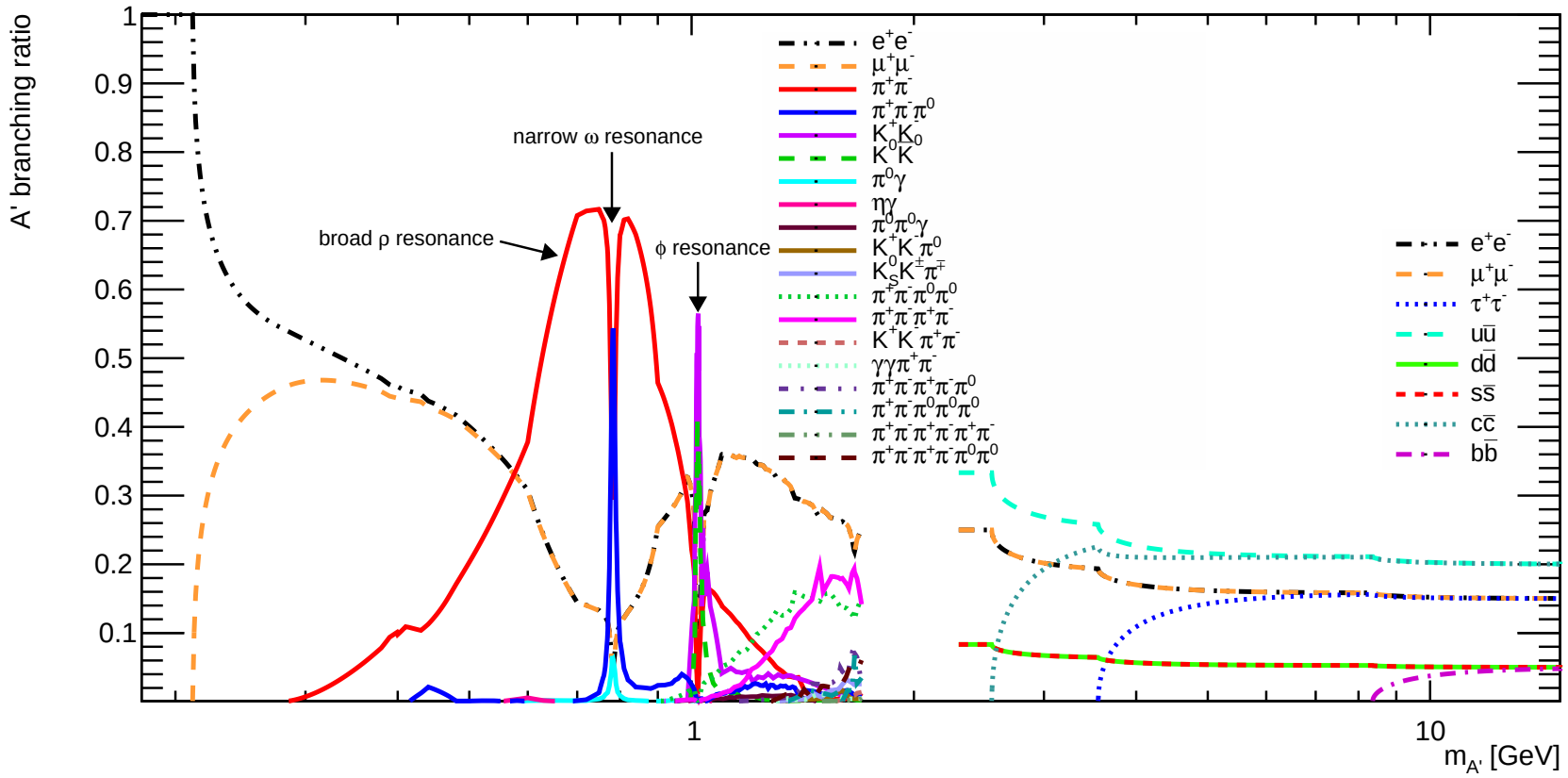



- Features from $\rho^0 \to \pi^+\pi^-$, $\omega \to \pi^+\pi^-\pi^0$ and $\phi \to K^+K^-/K_L^0K_S^0$

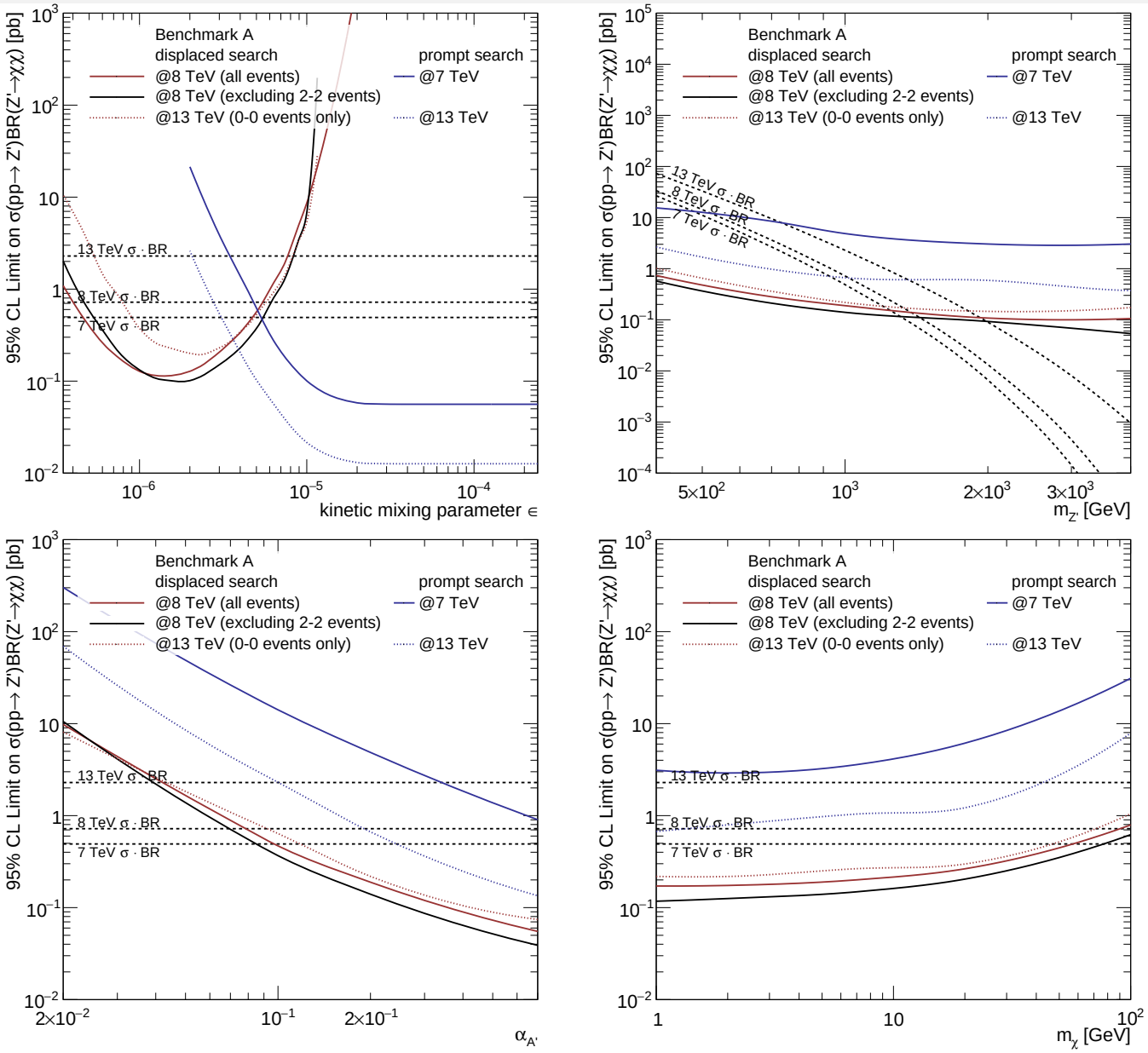
| Detector | $A' \to e^+e^-$ | $A' \to \mu^+\mu^-$ | $A' \to \pi^+\pi^-/K^+K^-$ | $A' \to \pi^+\pi^-\pi^0$ | $A' \to K_L^0K_S^0$ |
|---|---|---|---|---|---|
| LJ type | 2 (calorimeter) | 0 (muonic) | 2 (calorimeter) | 2 (calorimeter) | 2 (calorimeter) |
| ID | track | track | track | track | (✓) |
|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

# Parameter Scans

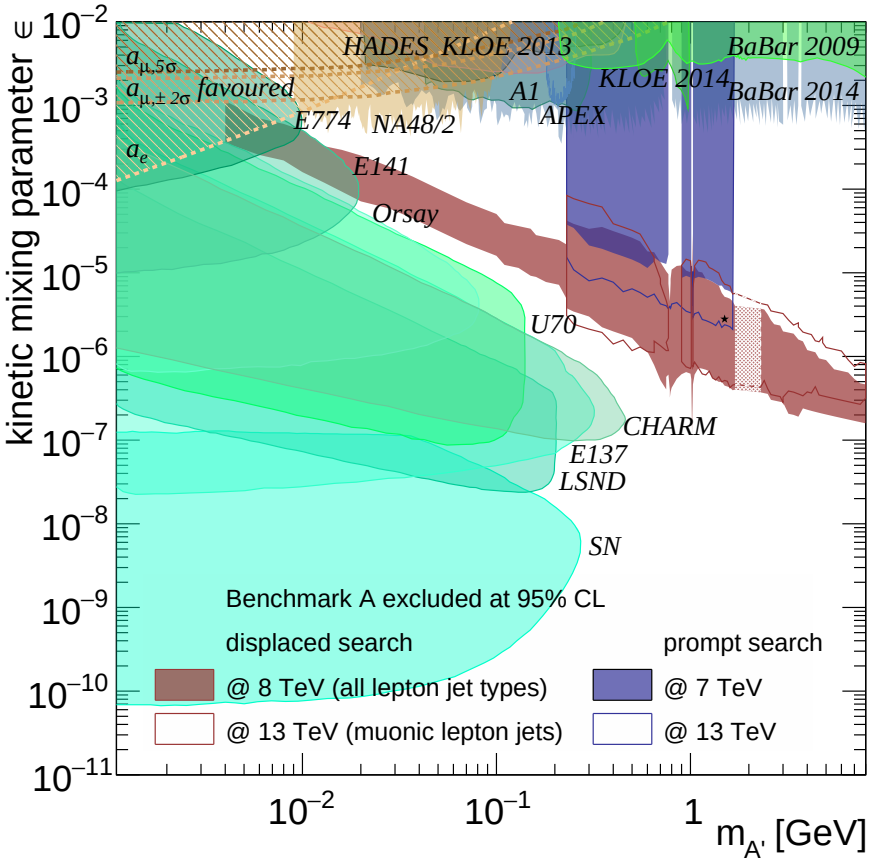



| Detector | $A' \to e^+e^-$ | $A' \to \mu^+\mu^-$ | $A' \to \pi^+\pi^-/K^+K^-$ | $A' \to \pi^+\pi^-\pi^0$ | $A' \to K_L^0 K_S^0$ |
|---|---|---|---|---|---|
| LJ type | 2 (calorimeter) | 0 (muonic) | 2 (calorimeter) | 2 (calorimeter) | 2 (calorimeter) |
| ID | track | track | track | track | (✓) |
|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

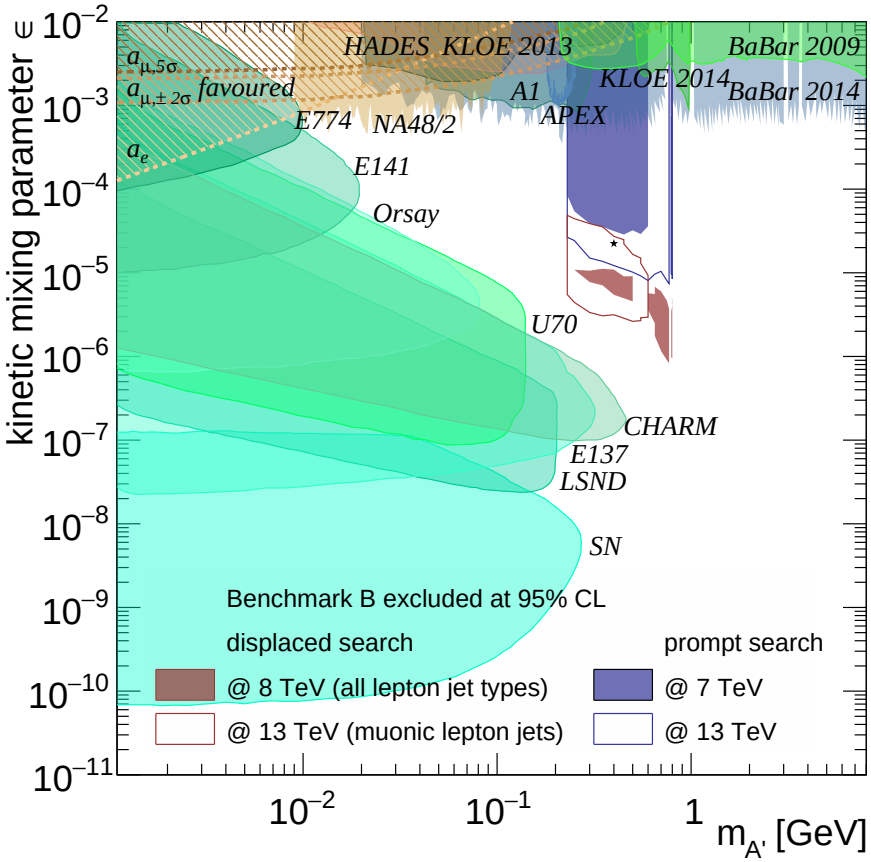
# Parameter Scans



# 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!**