# Lepton Jets from Radiating Dark Matter

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

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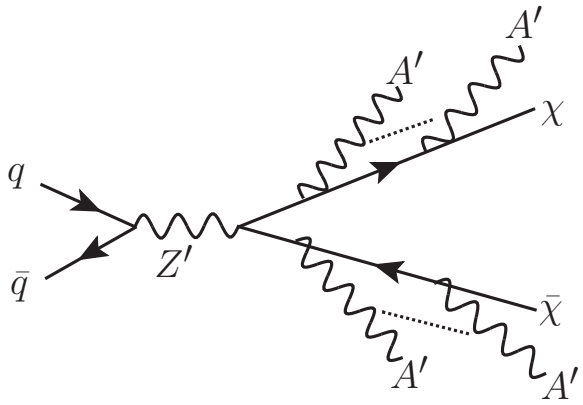
PRISMA Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

# Model



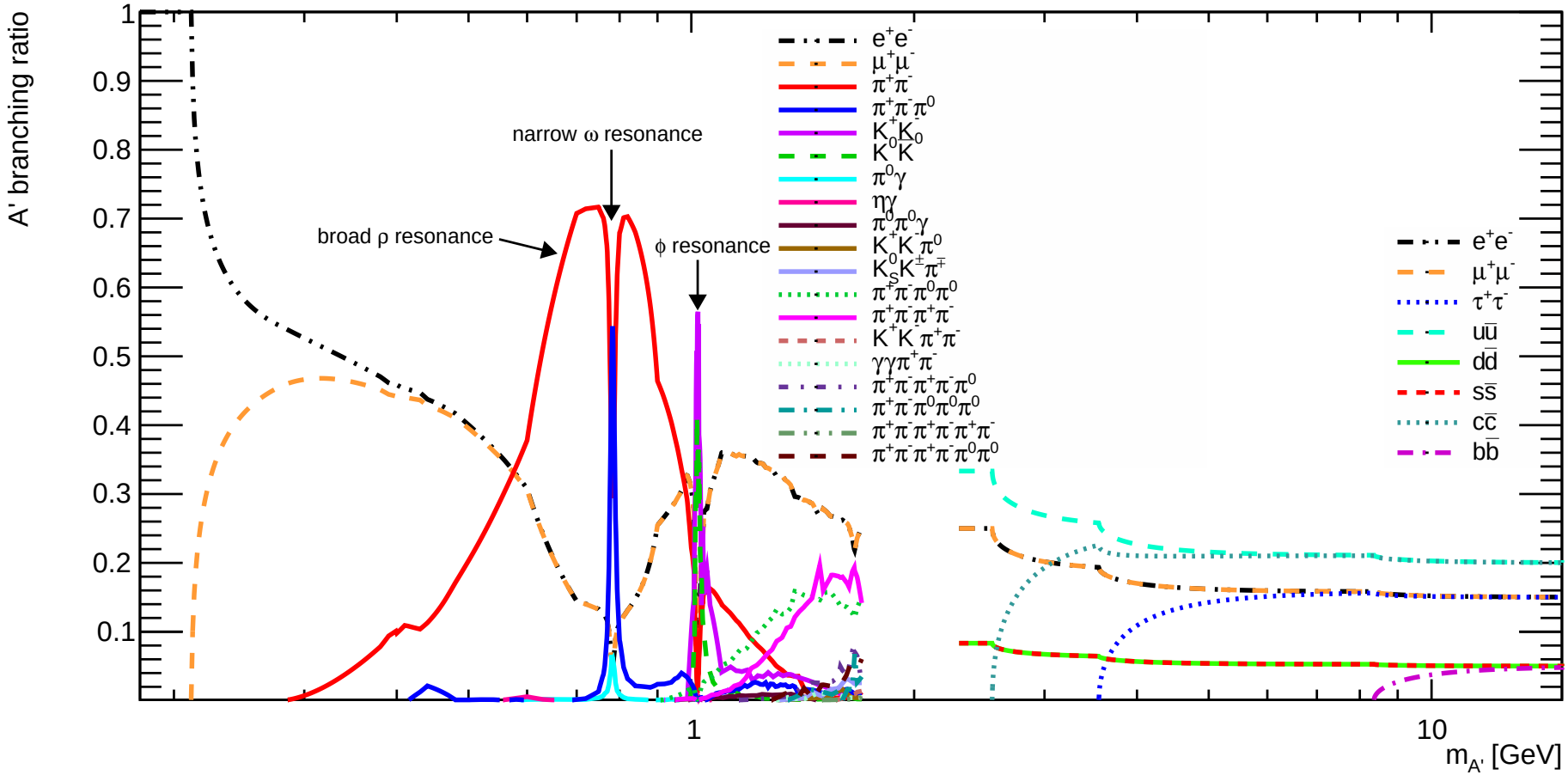

## Relevant Lagrangian:

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

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



# 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 |

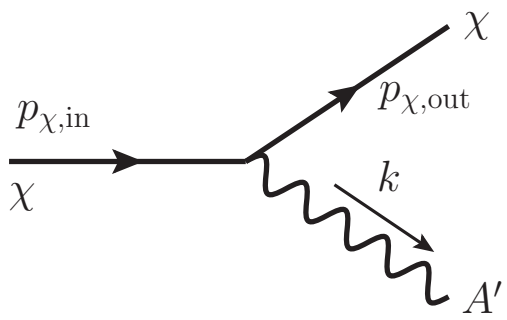
Table 1: Fixed model parameters

| | $\epsilon$ [$10^{-6}$] | $\sigma_8(Z')$ [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- and dijet searches, limits on thermal relic density, direct and indirect DM searches, DM self-interactions, limits on $\epsilon$ 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:

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

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

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

# Recursive Formalism

- DM energy spectrum:

$$f_\chi(X) = \sum_{m=0}^{\infty} p_m \, f_{\chi,m}(X)\,, \tag{7}$$

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

$$f_{\chi,m+1}(X) = \int_{x_{\text{min}}}^{x_{\text{max}}} dx_m \, f_{\chi,1}(x_m) \, \frac{f_{\chi,m}(X/x_m)}{x_m} \, \Theta(x_{\text{min}} \leq X \leq x_{\text{max}})\,, \tag{8}$$

with

$$f_{\chi,1}(X) \equiv \frac{1}{\langle n_{A'} \rangle} \frac{\alpha_{A'}}{2\pi} \int_{t_{\text{min}}}^{t_{\text{max}}} \frac{dt}{t} P_{\chi\to\chi}(X) \, \Theta(x_{\text{min}} \leq X \leq x_{\text{max}}) \tag{9}$$

- $A'$ spectrum analogue

# Melin Transform

DM spectrum given by inverse Melin transform

$$f(X) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} ds\, X^{-s}\, \varphi(s)\,. \tag{10}$$

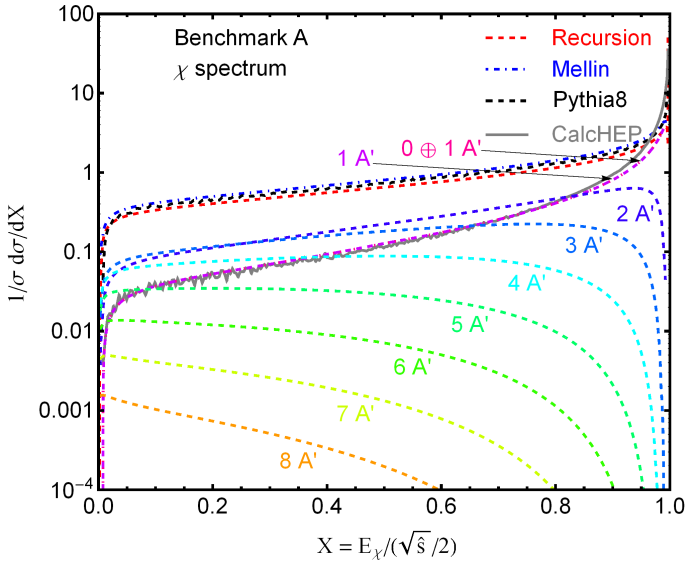
where the different moments are

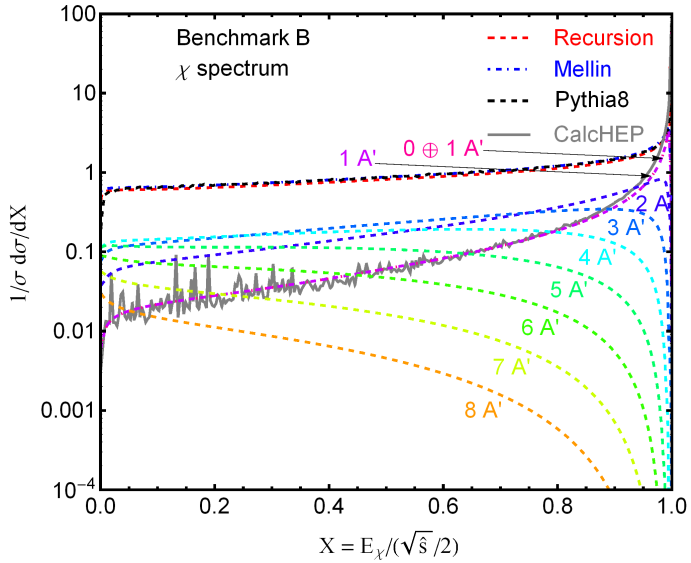
$$\varphi(s+1) = e^{-\langle n_{A'} \rangle (1-\overline{X^s})}\,. \tag{11}$$

with

$$\overline{X^s} \equiv \frac{1}{\langle n_{A'} \rangle} \frac{\alpha_{A'}}{2\pi} \int_{x_{\min}}^{x_{\max}} dx\, x^s \int_{t_{\min}}^{t_{\max}} \frac{dt}{t} P_{\chi\to\chi}(x)\,. \tag{12}$$

# 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)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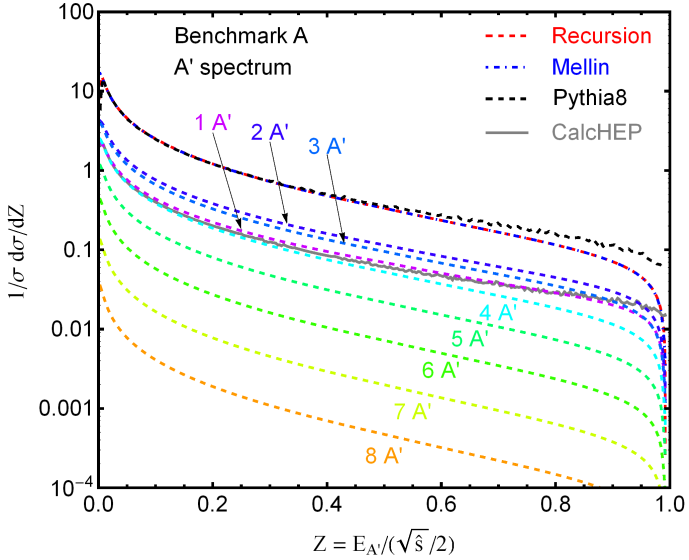
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1 A'
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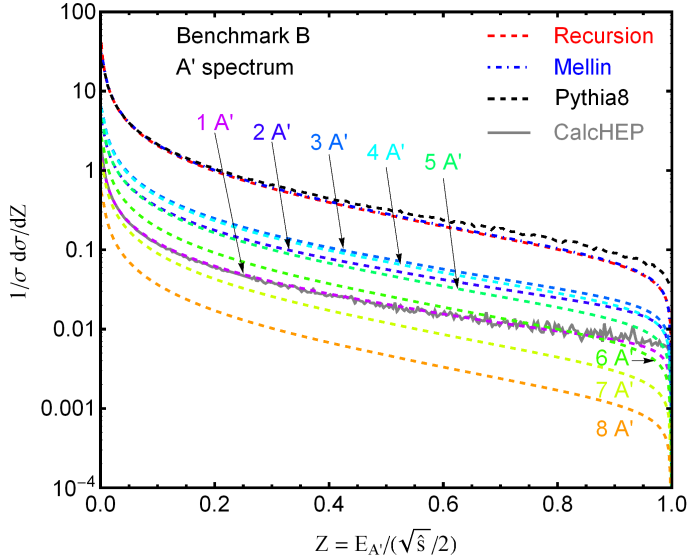
8 A'
1/σ dσ/dZ
Z = E_A'/(√ŝ/2)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# Prompt Search

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

**Muonic lepton jet (LJ)**

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

- $\mu$'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 if $c\tau$ small
$\rightarrow$ rely on branching to muons

# Displaced Search

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

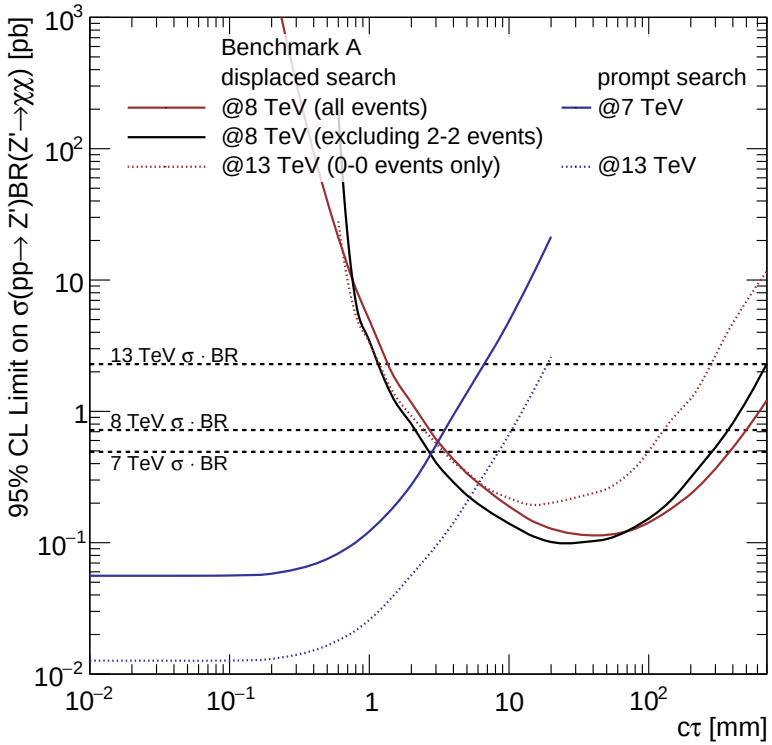
## 3 LJ types

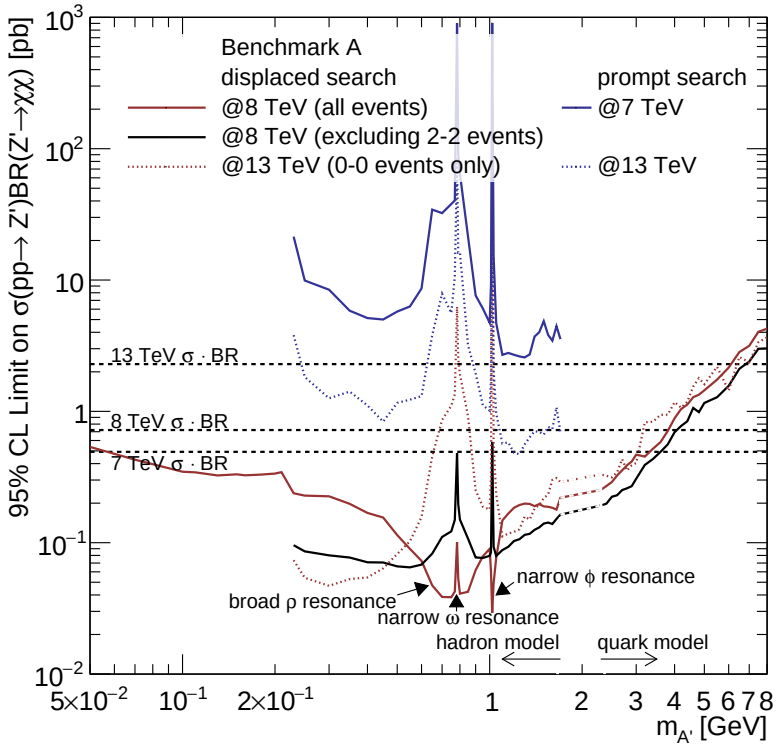
- Muonic: $\geq 2\mu$'s inside cone $\Delta R = 0.5$
- Mixed: $\geq 2\mu$'s + 1 jet inside cone $\Delta R = 0.5$
- Calorimeter: jet with small EM fraction

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

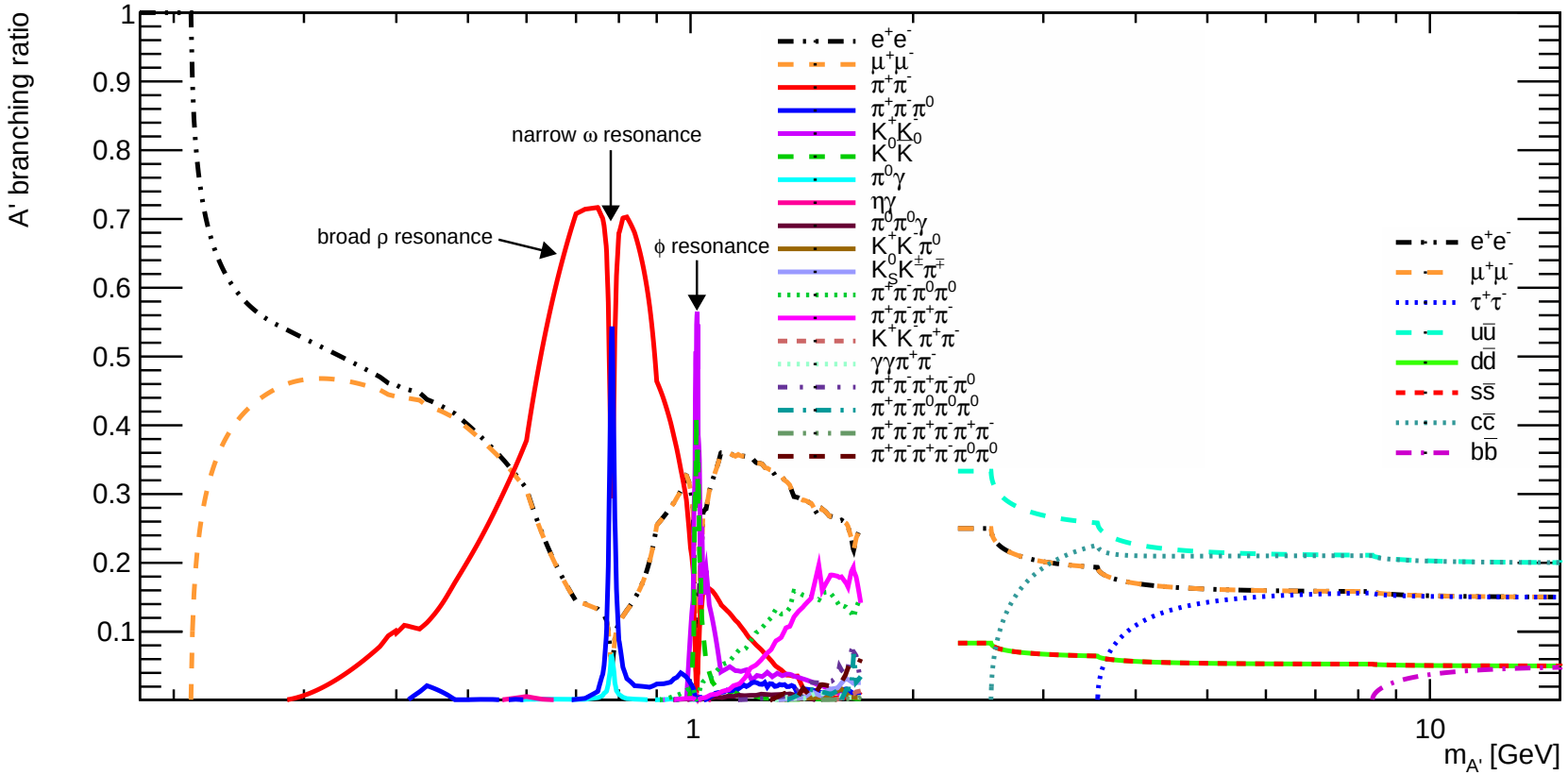
$\rightarrow$ low signal efficiency if $c\tau$ too small or too large
$\rightarrow$ hadronic channels contribute

# Parameter Scans



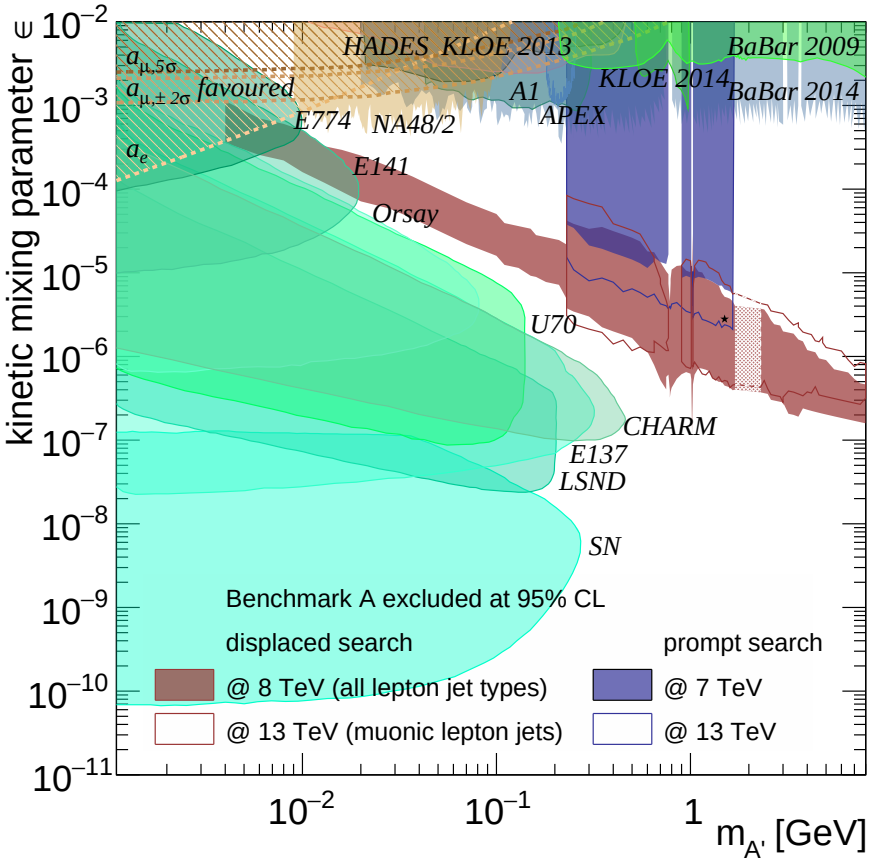



# Parameter Scans

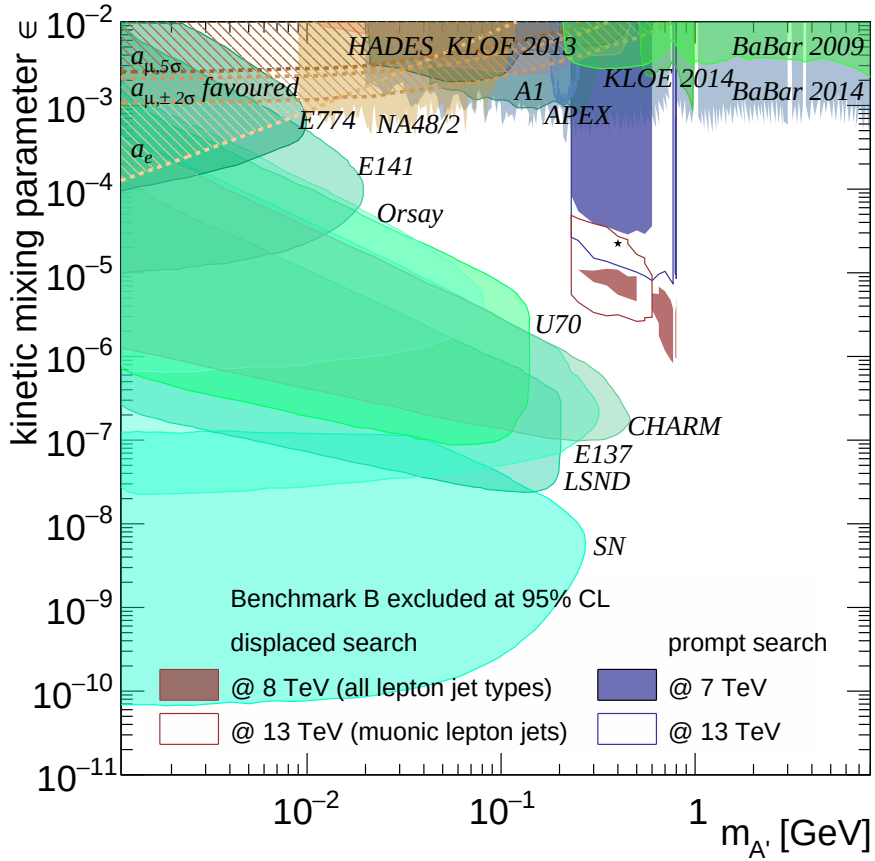



| Detector | $A' \to e^+e^-$ | $A' \to \mu^+\mu^-$ | $A' \to \pi^+\pi^-/K^+K^-$ | $A' \to \pi^+\pi^-\pi^0$ | $A' \to K_L^0 K_S^0$ |
|---|---|---|---|---|---|
| LJ type | 2 (calorimeter) | 0 (muonic) | 2 (calorimeter) | 2 (calorimeter) | 2 (calorimeter) |
| ID | track | track | track | track | (✓) |
|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

# Exclusion Limits




(a)




(b)

# Summary

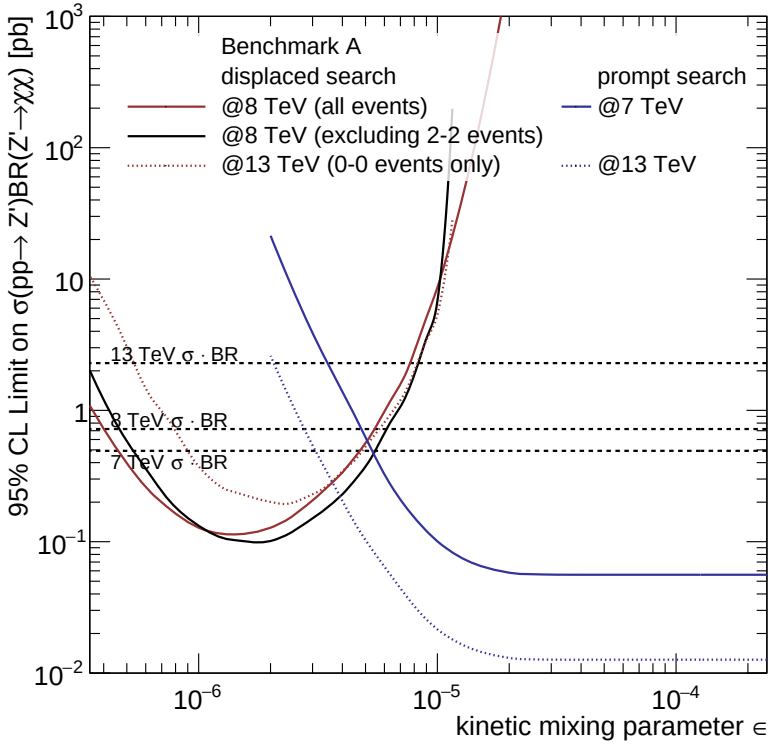
- Semi-analytic description of dark photon radiation via recursive integration and Mellin transform
  $\rightarrow$ Good agreement with Monte Carlo
- Recast of prompt and displaced ATLAS searches
  $\rightarrow$ Powerful limits on not yet tested parameter space
- Large improvement at 13 TeV expected

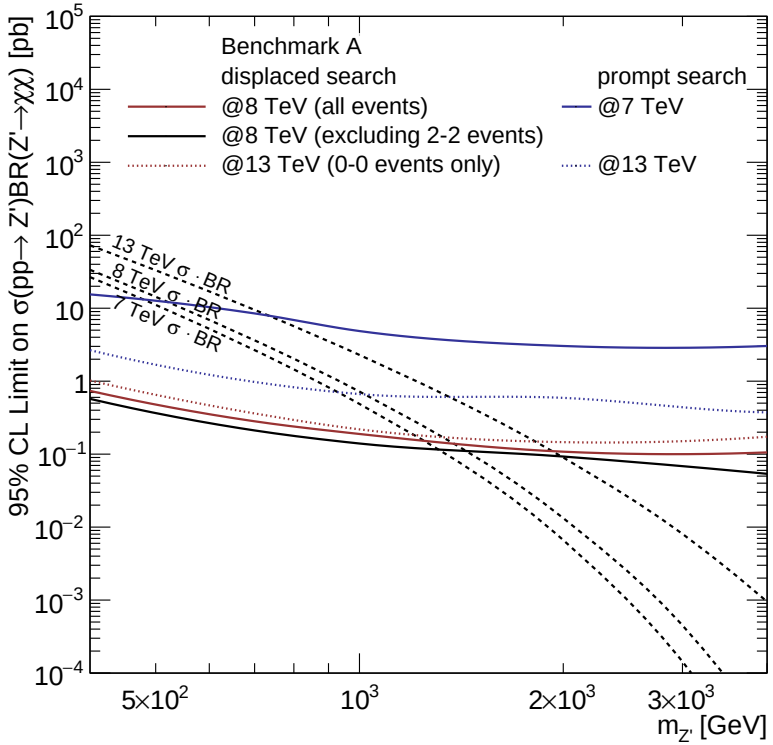
# Backup

| | 7 TeV | 13 TeV |
|---|---|---|
| Benchmark A | 0.8 | 109 |
| Benchmark B | 3.9 | 334 |
| All background | $0.5 \pm 0.3$ | $30 \pm 18$ |
| 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


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]
kinetic mixing parameter ∈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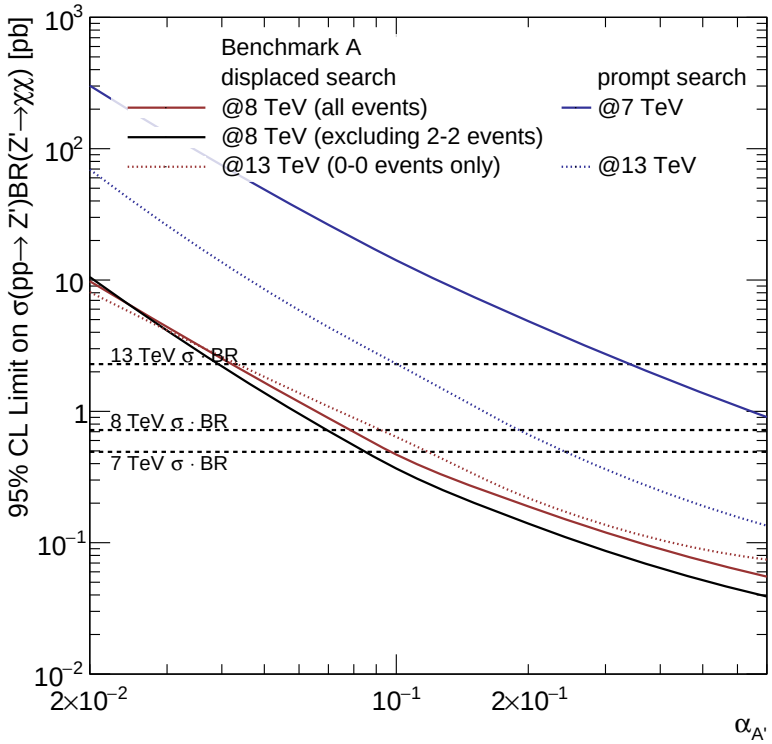
prompt search
@7 TeV
@13 TeV
13 TeV σ · BR
8 TeV σ · BR
7 TeV σ · BR
95% CL Limit on σ(pp→ Z')BR(Z'→χχ) [pb]
m_Z' [GeV]

# Backup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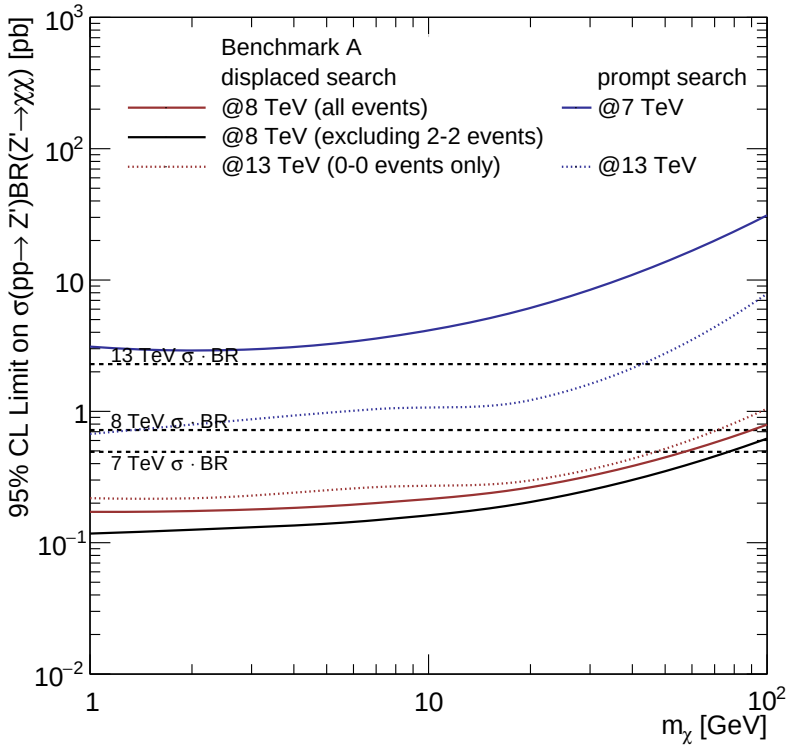
prompt search
@7 TeV
@13 TeV
13 TeV σ · BR
8 TeV σ · BR
7 TeV σ · BR
95% CL Limit on σ(pp→ Z')BR(Z'→χχ) [pb]
$\alpha_{A'}$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7 TeV σ · BR
95% CL Limit on σ(pp→ Z')BR(Z'→χχ) [pb]
$m_\chi$ [GeV]