A Boost for Dark Matter Searches

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(University of Mainz / PRISMA Cluster of Excellence)

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Based on work done in collaboration with
Malte Buschmann, Jia Liu, Pedro Machado, Xiaoping Wang
arXiv:1503.02669, arXiv:1505.07459

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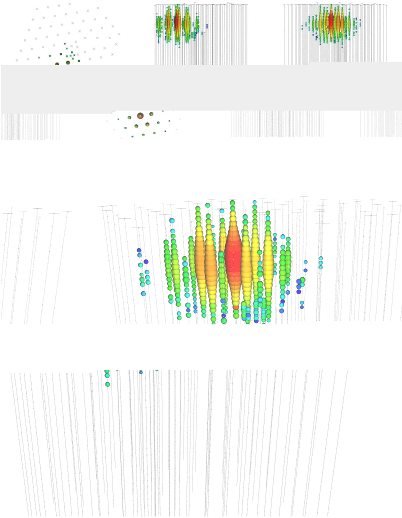
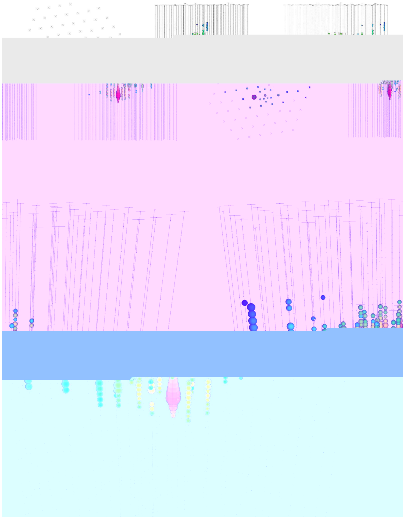
Outline

Boosted Dark Matter Scattering in IceCube

IceCube results

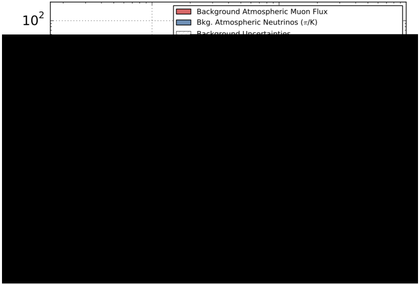


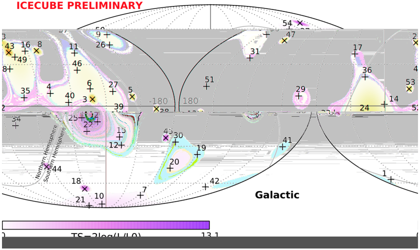
Shower event (ν_e, ν_τ)



Track event (mostly ν_μ)

IceCube results (2)





Significant excess of events & 30 TeV

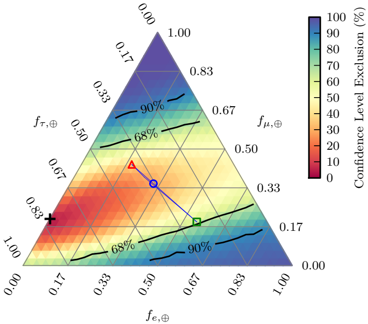
Spatially uniform within uncertainties

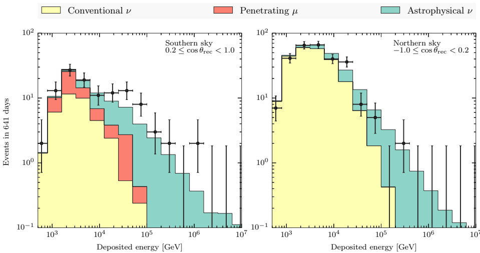
IceCube Collaboration, arXiv:1405.5303 and ICRC 2015 talk by Claudia Kopper

Conventional interpretation:

Astrophysical neutrinos from unknown sources.

IceCube results (3)





Flavor ratios: more shower events (not significant yet)

Bump in the southern sky

IceCube Collaboration, arXiv:1502.03376, arXiv:1410.1749

This talk:

Alternative explanation in terms of

boosted dark matter

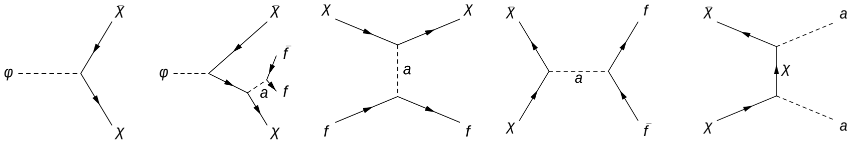
Boosted dark matter Lagrangian

New particles:

- ϕ . . . Main component of DM [$\mathcal{O}$(PeV)]
- χ . . . DM decay product [$\mathcal{O}$(10 GeV)]
- a . . . Pseudoscalar mediator [$\mathcal{O}$(10 GeV)] of DM–SM interactions

$$\mathcal{L} \supset -y_{\phi\chi}\phi\bar{\chi}\chi + ig_\chi a\bar{\chi}\gamma^5\chi + i\sum_f g_{Y_f}\frac{\sqrt{2}m_f}{v}\, a\bar{f}\gamma^5 f$$

Phenomenology:

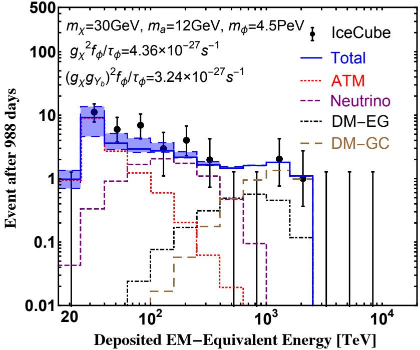


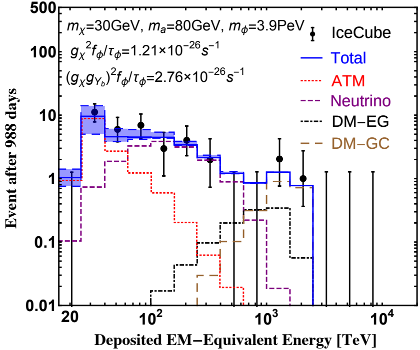
ϕ decay to boosted χ (possibly + a radiation)

χ scattering

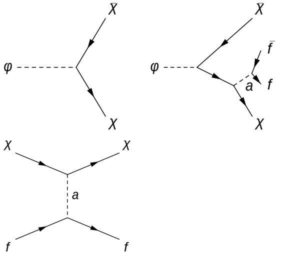
χ annihilation

IceCube signals

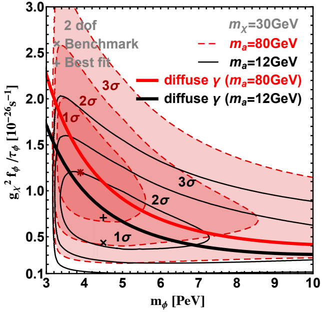




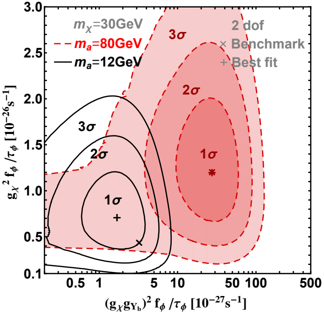
- Two signal components:
  - Scattering of boosted χ
    - Only shower-like events
  - Neutrinos from decay of radiated a
    - SM-like flavor ratios
    - Bumpy spectrum
  - Small dip between the two components
  - Prediction: Larger flux from South (where Galactic Center is located)



IceCube fit



2 dof
× Benchmark
+ Best fit
m_χ=30GeV
m_a=80GeV
m_a=12GeV
diffuse γ (m_a=80GeV)
diffuse γ (m_a=12GeV)
1σ
2σ
3σ
$g_\chi{}^2 f_\phi/\tau_\phi$ [10^{-26}s^{-1}]
m_ϕ [PeV]



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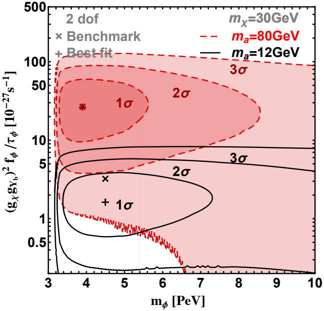
3σ
$g_\chi{}^2 f_\phi/\tau_\phi$ [10^{-26}s^{-1}]
$(g_\chi g_{Y_b})^2 f_\phi/\tau_\phi$ [10^{-27}s^{-1}]



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m_ϕ [PeV]

Relic density

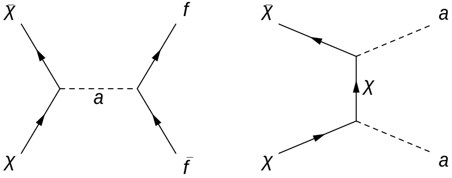
Several mechanisms to generate correct relic density for PeV-scale DM:

Harigaya Kawasaki Mukaida Yamada, arXiv:1402.2846

- Cascade decays of the inflaton
- Inelastic scattering of high-E particles from inflaton decay on low-T plasma.
- Thermal production and freeze-out during reheating, dilution as inflatons continue to decay after DM freeze-out.

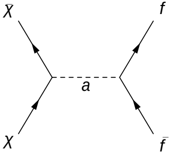
What about the light DM species χ?

- Thermalization and freeze-out in the early Universe



- Abundance naturally comparable to abundance of heavy DM ϕ

A Hooperon



Light DM particles χ can annihilate in the galactice center.

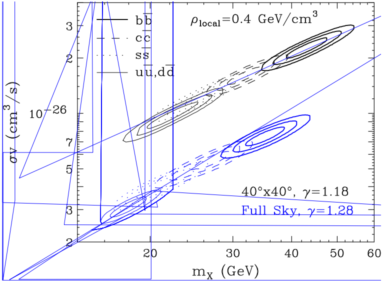
For $m_\chi \sim 30$ GeV, and couplings

$$\mathcal{L} \supset i \sum_f g_{Y_f} \frac{\sqrt{2} m_f}{v} \, a \bar{f} \gamma^5 f$$

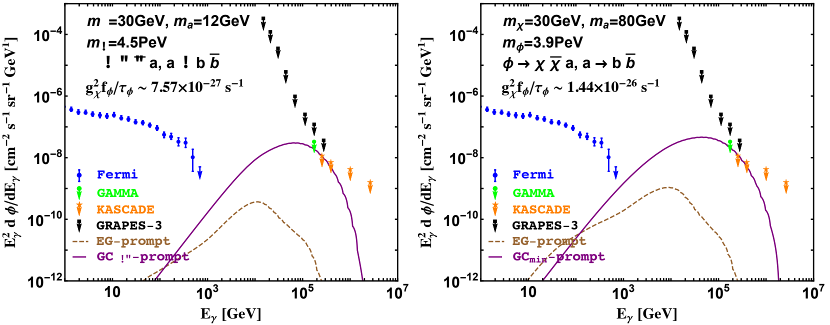
dominant annihilation mode is $\bar{\chi}\chi \to b\bar{b}$.

χ could thus explain the galactic center gamma ray excess.

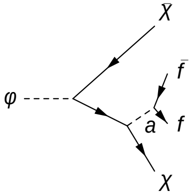
Goodenough Hooper arXiv:0910.2998; Hooper Goodenough arXiv:1010.2752
Daylan Finkbeiner Hooper Linden Portillo Rodd Slatyer arXiv:1402.6703



Diffuse gamma ray flux



Diffuse γ ray flux from 3-body decays $\phi \to \bar{\chi}\chi a$ . . . OK.



Direct detection

Constraints very weak due to pseudoscalar mediator a
$\rightarrow$ velocity-suppression

Collider limits

3 UV completions of boosted DM model:

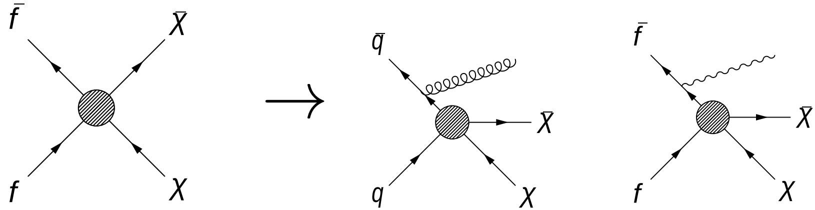
MSSM-like	*Flipped*	*Vector quark*
a mixes with A^0 in type-II 2HDM	a mixes with A^0 in flipped 2HDM	a couples to new vector-like quarks, mixed with SM quarks

- K and B meson decays to pseudoscalar a
  - kinematically forbidden for m_a & 10 GeV
- $B_s \to \mu^+\mu^-$
  - avoided for sufficiently heavy m_a
  - Weakened in *Flipped* model
  - Absent in *Vector quark* model
- $h \to aa$
  - avoided for sufficiently heavy m_a
  - Absent in *Vector quark* model

Lepton Jets
from Radiating Dark Matter

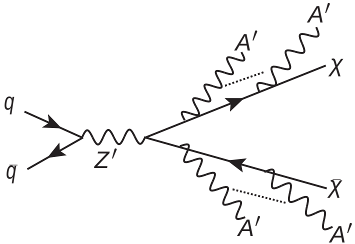
Dark Matter Production at the LHC

Traditional DM searches: initial state radiation



DM pair production (invisible @ LHC) | Monojet | Monophoton

This talk: final state radiation



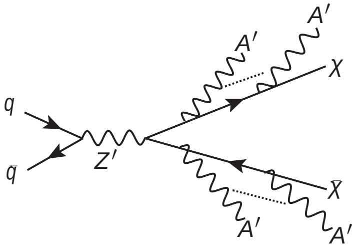
Model Framework: Self-Interacting DM

Dark Sector Lagrangian

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

Mediator Sector

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



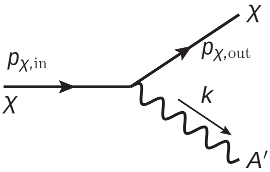
Dark Radiation Showers — Semi-Analytical Results

Notation, notation, notation, . . .

- Incoming (off-shell) DM particle: $p_{\chi,\text{in}} = (E, 0, 0, p)$
- Outgoing DM particle: $p_{\chi,\text{out}} = \left(xE,\ -k_t,\ 0,\ \sqrt{x^2E^2 - k_t^2 - m_\chi^2}\right)$
- Outgoing dark photon: $k = \left((1-x)E,\ k_t,\ 0,\ \sqrt{(1-x)^2E^2 - k_t^2 - m_{A'}^2}\right)$
- Virtuality: $t \equiv (p_{\chi,\text{out}} + k)^2 - m_\chi^2$

Probability for a collinear splitting:

$$\frac{\alpha_{A'}}{2\pi} dx \, \frac{dt}{t} P_{\chi\to\chi}(x, t)$$



with the splitting kernel

$$P_{\chi\to\chi}(x, t) = \frac{1 + x^2}{1 - x} - \frac{2(m_\chi^2 + m_{A'}^2)}{t}$$

Dark Radiation Showers — Semi-Analytical Results

Average number radiated dark photons

$$\langle n_{A'} \rangle \simeq \frac{\alpha_{A'}}{2\pi} \int_{x_{\min}}^{x_{\max}} dx \int_{t_{\min}}^{t_{\max}} \frac{dt}{t} P_{\chi\to\chi}(x) \,.$$

Splitting is a Poisson process.

- Probability for m splittings

$$p_m = \frac{e^{-\langle n_{A'} \rangle} \langle n_{A'} \rangle^m}{m!}$$

- Probability for no splitting (Sudakov factor)

$$\Delta \equiv p_0 = e^{-\langle n_{A'} \rangle}$$

Dark Radiation — Energy Spectrum of DM Particles

Compute first the moments of the E spectrum $f_\chi(X \equiv E_\chi/E_0)$:

- Events with one emission

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

$$\equiv e^{-\langle n_{A'} \rangle} \langle n_{A'} \rangle \overline{X^s}$$

- Events with two emissions

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

$$\simeq e^{-\langle n_{A'} \rangle} \frac{1}{2!} \left(\frac{\alpha_{A'}}{2\pi}\right)^2 \int_{x_{\min}}^{x_{\max}} dx\, x^s \int_{t_{\min}}^{t_{\max}} \frac{dt}{t} \int_{x_{\min}}^{x_{\max}} dx'\, x'^s \int_{t_{\min}}^{t_{\max}} \frac{dt'}{t'} P_{\chi\to\chi}(x) P_{\chi\to\chi}(x')$$

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

- Events with m emissions

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

Dark Radiation — Energy Spectrum of DM Particles

- Summing over all m

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

Mellin Transform

$$\mathcal{M}[f](s+1) \equiv \varphi(s+1) \equiv \int_0^\infty dX \, X^s f(X)$$

Inverse Mellin Transform

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

Efficient numerical evaluation using Fast Fourier Transform (FFT)

Dark Radiation — Energy Spectrum of Dark Photons

With $Z \equiv E_{A'}/E_0$:

$$p_m \langle Z^s \rangle_{mA'} = \frac{1}{\langle n_{A'} \rangle} e^{-\langle n_{A'} \rangle} \frac{\langle n_{A'} \rangle^m}{m!} \overline{Z^s} \sum_{k=1}^{m} \overline{X^s}^{k-1}$$

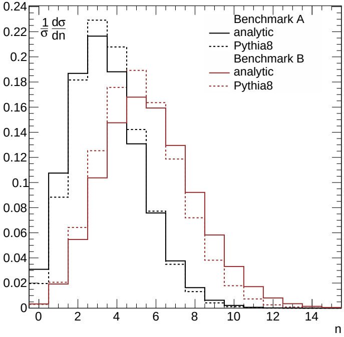
with

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

Therefore,

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

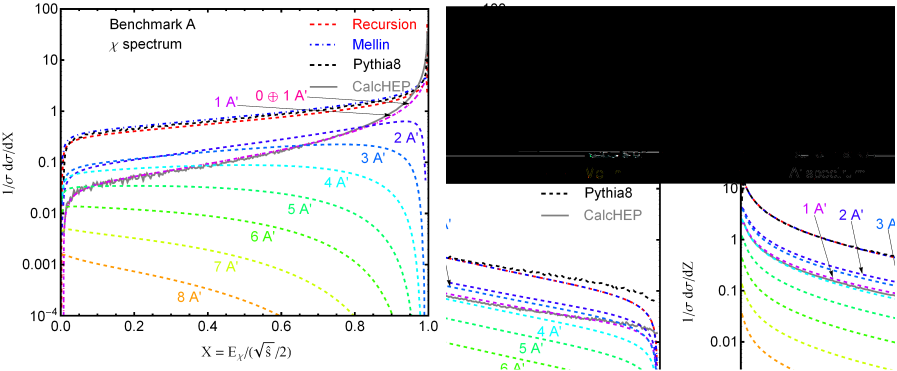
Dark Radiation — Analytics vs. Numerics



Reasons for minor discrepancies:

- Assumption that integration limits are independent of x, t.
  - Energy loss in each splitting small
- Neglect of t-dependence in $P_{\chi\to\chi}(x)$

Dark Radiation — Analytics vs. Numerics



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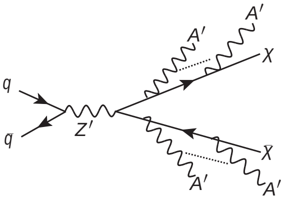
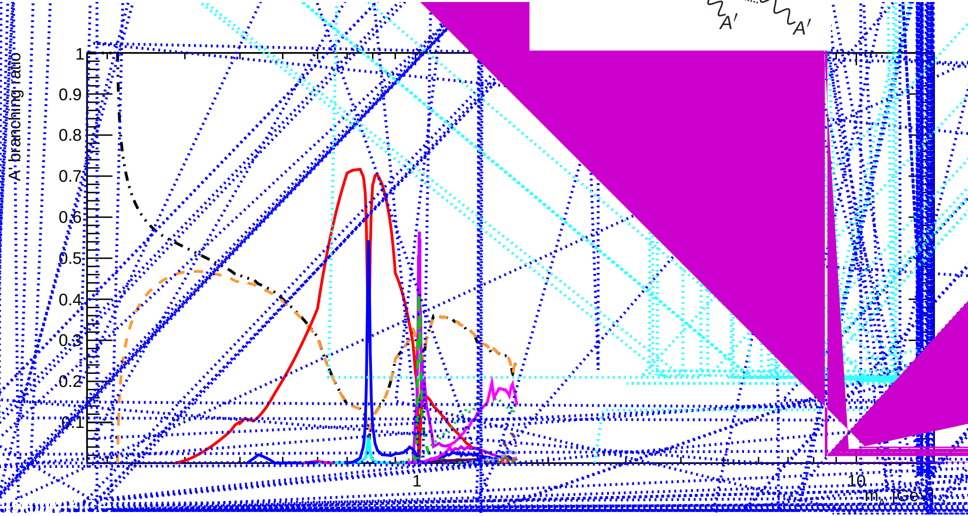
A' Decay





Prompt Lepton Jets

For short A' lifetime:

- Consider only muonic lepton jets
  - other categories difficult to implement without full detector simulation
- Selection criteria
  - 1 muon with $p_T > 18$ GeV
  - or 3 muons with $p_T > 6$ GeV
  - $|\eta| < 2.5$
  - Track in the inner detector
  - Small impact parameter $|d_0| < 1$ mm

Displaced Lepton Jets

For long A' lifetime:

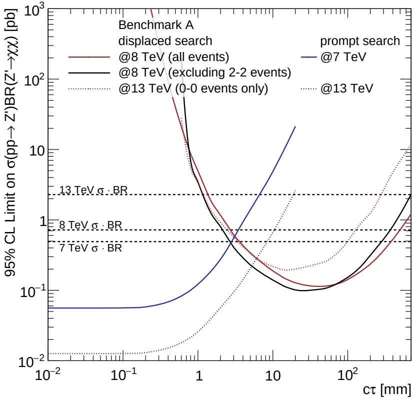
- Type 0 ("muonic") LJ
  - ≥ 2 muons (and no calorimeter jets) within $\Delta R = 0.5$.
- Type 1 ("mixed") LJ
  - ≥ 1 muon + exactly 1 calorimeter jet
- Type 2 ("calorimeter") LJ
  - All other calorimeter jets with small EM fraction
  - Includes $A' \to ee$ with large displacement
  - Includes hadronic A' decay modes

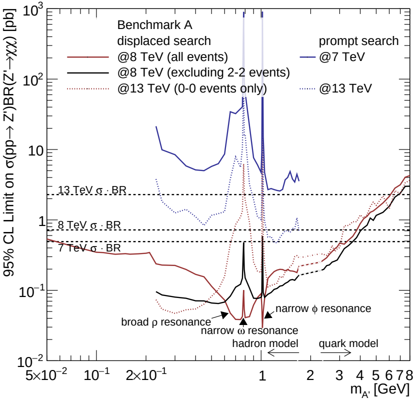
Detector	$A' \to e^+e^-$	$A' \to \mu^+\mu^-$	$A' \to \pi^+\pi^-/K^+K^-$
LJ type	2 (calorimeter)	0 (muonic)	2 (calorimeter)
ID	track	track	track
ECAL	EM fraction	X	X
HCAL	X	X	X

Detector	$A' \to \pi^+\pi^-\pi^0$	$A' \to K_L^0 K_S^0$
LJ type	2 (calorimeter)	2 (calorimeter)
ID	track	(X)
ECAL	EM fraction	(X)
HCAL	X	X

Phenomenological Results

- Recast ATLAS prompt lepton jet search (arXiv:1212.5409)
- Recast ATLAS displaced lepton jet search (arXiv:1409.0746)
- Conservative projections for 13 TeV
  - Type-0 (muonic lepton jets only) — cannot estimate multijet background





Phenomenological Results

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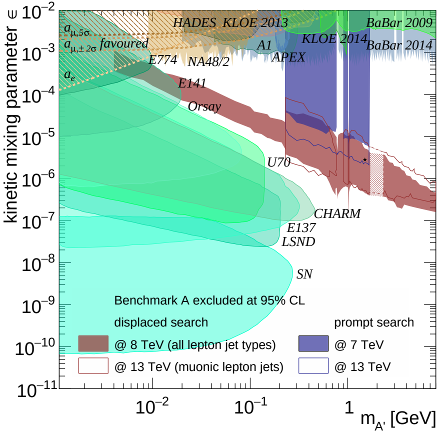

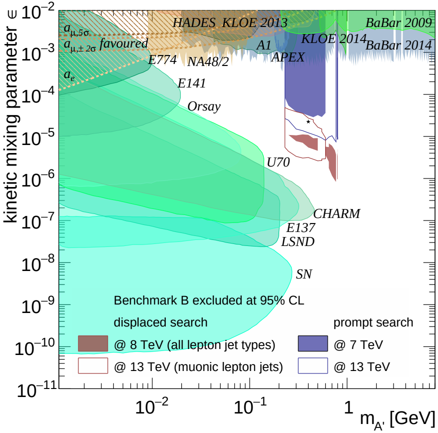

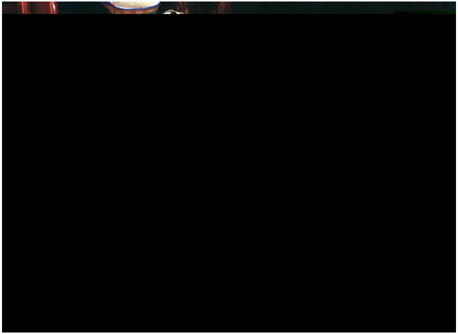

Summary

Summary

Boosted DM in IceCube explains:

- Energy spectrum of high-E events (Possible dip at several 100 GeV)
- Morphology (Prediction: larger signal from the GC)
- Flavor ratio (Prediction: more shower-like at PeV, SM-like at lower E)
- Galactic Center gamma ray excess (Hooperon)

Boosted DM at the LHC:

- Dark radiation showers leading to lepton jets
- Beautiful analytical formalism
- Significant discovery reach

Malte Buschmann

Jia Liu

Pedro Machado

Xiaoping Wang

Thank you!

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