Hunting for Dark Matter with a Jet

Patrick Fox

with Yang Bai and Roni Harnik
(arXiv:1005.3797)
Dark Matter

Lots of evidence for non-baryonic matter:

Cosmological abundance

\[ \Omega_{DM} \sim 0.2 \]

Local abundance

\[ \rho_{DM} \sim 0.3 \text{ GeV cm}^{-3} \]
Dark Matter

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Dark Matter

Near us: $\rho_{DM} \sim 0.3$ GeV cm$^{-3}$

Escape velocity in galactic frame

$$498 \text{ km/s} \leq v_{esc} \leq 608$$

Maxwell-Boltzmann velocity distribution

$$f(v) \propto d^3v \ e^{-(v/v_0)^2}$$

$$v_0 = 220 \text{ km s}^{-1}$$

You are here

$\rho$ vs $r$ [kpc]

$\rho$ vs $v$

$\rho_{DM}$ vs $r$ [kpc]

$\rho_{DM}$ vs $v$

$\rho_{DM}$ vs $v_0$

$\rho_{DM}$ vs $v_{esc}$

$\rho_{DM}$ vs $v_{esc}$ [kpc]
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$$v_0 = 220 \text{ km s}^{-1}$$

$$498 \text{ km/s} \leq v_{esc} \leq 608$$

$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-v^2/v_0^2}$$
Searching for dark matter
(here, there and everywhere)
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(here, there and everywhere)

Type I

Type IIA

Type IIB
Searching for dark matter
(here, there and everywhere)

Type I

Type IIA

Type IIB
Searching for dark matter
(here, there and everywhere)

Indirect detection

Look up
Anti-matter excesses in cosmic rays, photons from centre of galaxy

Direct detection

Look down
Low rate, low energy recoil events in underground labs

Collider searches

Look small
Missing energy events at colliders
Searching for dark matter
(here, there and everywhere)

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Direct detection

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Look small
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Thermal relic? Predicts x-sec $\sim 1$ pb
How to distinguish this small number of low energy events from backgrounds?

\[ E_R \sim \frac{q^2}{2 M_T} \sim 100 \text{ keV} \]

\[ R \sim N_T \frac{\rho \chi}{m \chi} \langle \sigma v \rangle \approx 1 \text{ event/day/kg} \]
Direct Detection

One Way:
• Remove cosmic backgrounds by going underground
• Shield experiment from radioactive elements
• Cool equipment
• Take multiple measurements to distinguish background from nuclear recoils e.g. ionization, scintillation, phonons

[CDMS collaboration]

[XENON10 collaboration]
Existing DD bounds

CDMS, XENON, DAMA, CoGeNT, COUPP, CRESST, ...
Direct detection vs Collider production

Direct detection \( q \sim 100 \text{ MeV} \)

Collider searches \( q \sim 10 - 100 \text{ GeV} \)

How does one search impact the other?

[Birkedal, Matchev and Perelstein]
Mediator Mass dependence

Only consider mediators with mass \( \gtrsim 100 \, \text{MeV} \)

\[
\sigma_{\text{DD}} \sim g_X^2 g_q^2 \frac{\mu^2}{M^4}
\]

\[
\mu = \frac{m_X m_N}{m_N + m_X}
\]

Mono-jet + \( \not{E}_T \)

\[
\sigma_{1j} \sim \begin{cases} 
\alpha_s g_X^2 g_q^2 \frac{1}{p_T^2} & M \lesssim 100 \, \text{GeV} \\
\alpha_s g_X^2 g_q^2 \frac{p_T^2}{M^4} & M \gtrsim 100 \, \text{GeV}
\end{cases}
\]

CDF analysed 1 fb\(^{-1}\) and saw no significant deviation

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\alpha_s g_X^2 g_q^2 \frac{p_T^2}{M^4} & M \gtrsim 100 \text{ GeV}
\end{cases}
\]

CDF analysed 1 \( \text{fb}^{-1} \) and saw no significant deviation

Consider massive mediator:

\[ \sigma_{1j} \sim \alpha_s g_X^2 g_q^2 \frac{p_T^2}{M^4} \]

\[ \sigma_{DD} \sim g_X^2 g_q^2 \frac{\mu^2}{M^4} \]

\[ \frac{\sigma_{1j}}{\sigma_{DD}} \sim \mathcal{O}(1000) \]

In 1 invfb CDF saw 8449 mono-jet events, expected 8663 ± 332

⇒ \( \sigma_{1j} \lesssim 500 \text{ fb} \)

\[ \sigma_{DD} \lesssim 0.5 \text{ fb} = 5 \times 10^{-40} \text{ cm}^2 \]
Existing DD bounds

ROI’s

- Light mass DM
- Non-standard DM introduced to explain DAMA
- Velocity, momentum or spin suppression
Existing DD bounds

ROI’s

- Light mass DM
- Non-standard DM introduced to explain DAMA
- Velocity, momentum or spin suppression
Outline

• Motivation and estimation
• Operator analysis
• Heavy mediators
• Collider bounds
• Light mediators
• Conclusions
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  • Operator analysis
  • Heavy mediators
  • Collider bounds
  • Light mediators
  • Conclusions
Operators

\[ O_1 = \frac{i g_\chi g_q}{q^2 - M^2} (\bar{q}q) (\bar{\chi}\chi) , \quad \text{SI, scalar exchange} \]

\[ O_2 = \frac{i g_\chi g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q) (\bar{\chi}\gamma^\mu \chi) , \quad \text{SI, vector exchange} \]

\[ O_3 = \frac{i g_\chi g_q}{q^2 - M^2} (\bar{q}\gamma_\mu \gamma_5 q) (\bar{\chi}\gamma^\mu \gamma_5 \chi) , \quad \text{SD, axial-vector exchange} \]

\[ O_4 = \frac{i g_\chi g_q}{q^2 - M^2} (\bar{q}\gamma_5 q) (\bar{\chi}\gamma_5 \chi) , \quad \text{SD and mom. dep., pseudo-scalar exchange} \]

• DM a Dirac fermion
• Consider each operator, and each flavour separately
CDF mono-jet search

- 1/fb analysed
  \[ \not{E}_T > 80 \text{ GeV} \]
  \[ p_T(j1) > 80 \text{ GeV} \]
  \[ p_T(j2) < 30 \text{ GeV} \]
  \[ p_T(j3) < 20 \text{ GeV} \]

Observed: 8449 events
Bounds on operators

Assume a heavy mediator: \[ \Lambda = \frac{M}{\sqrt{g_{\chi} g_1}} \]

Simulate events in calcHEP, one operator at a time

**Figure 1**: The constraints on the cutoffs of different operators from the CDF mono-jet search data at 90% C.L.

2.1 Tevatron limits

The CDF collaboration has performed a search for one jet events with large missing transverse energy using 1.1 fb\(^{-1}\) of data [2]. CDF considered events with a leading jet \( p_T \) and missing transverse energy both greater than 80 GeV. Events with a second jet with \( p_T < 30 \) GeV were included but events with additional jets with transverse energy above 20 GeV were not. The number of observed events was 8449, a slight deficit compared to an expected background of 8663 ± 332. The standard model backgrounds are dominated by \( Z + \text{jet} \), \( W + \text{jet} \) with a missed lepton. QCD and "non-collision" background events contribute subdominantly to the background, but due to their high uncertainty they add a significant portion to the uncertainty of the background. The \( p_T \) spectrum observed by CDF compares well with the expected background, however since the background uncertainty was only presented for the total number of events we will only use a simple counting experiment to place the bounds.
Collider bounds on direct detection

• Up quark bounds typically strongest
• Collider bounds relatively strongest when DD suppressed e.g. SD, MDDM, light, ....
• iDM splitting not important at colliders
• Tevatron not constrained by velocity distribution - low mass DM
• DM with vector couplings to 2 or 3 gen. quarks
• .....

Tuesday, November 2, 2010
Spin independent

\[ O_1 = \frac{i g_X g_q}{q^2 - M^2} (\bar{q}q) (\bar{\chi}\chi) , \]
\[ O_2 = \frac{i g_X g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q) (\bar{\chi}\gamma^\mu \chi) \]

\[ \sigma_{1}^{Nq} = \frac{\mu^2}{\pi \Lambda^4} B_{Nq}^2 , \]
\[ \sigma_{2}^{Nq} = \frac{\mu^2}{\pi \Lambda^4} f_{Nq}^2 , \]

\[ B_u^p = B_d^n = 8.22 \pm 2.26 , \quad f_u = f_d = 2 \]
\[ B_d^p = B_u^n = 6.62 \pm 1.92 , \quad f_d = f_u = 1 \]

otherwise \( f = 0 \)
Spin independent

\[ O_1 = \frac{i g_X g_q}{q^2 - M^2} (\bar{q}q)(\bar{\chi}\chi), \]

\[ O_2 = \frac{i g_X g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu \chi) \]

World’s best limits at low mass

\[ \sigma_{Nq}^N = \frac{\mu^2}{\pi \Lambda^4} B_{Nq}^2, \]

\[ \sigma_1 = \frac{\mu^2}{\pi \Lambda^4} B_{Nq}^2, \]

\[ \sigma_2 = \frac{\mu^2}{\pi \Lambda^4} f_{Nq}^2, \]

**World’s best limits at low mass**

- \( B_u = B_d = 8.22 \pm 2.26 \)
- \( B_d^p = B_u^p = 6.62 \pm 1.92 \)
- \( B_s^p = B_s^n = 3.36 \pm 1.45 \)

otherwise \( f = 0 \)
**Spin dependent**

\[ \mathcal{O}_3 = \frac{ig_{\chi g_q}}{q^2 - M^2} (\bar{q} \gamma_\mu \gamma_5 q) (\bar{\chi} \gamma^\mu \gamma_5 \chi) \]

\[ \mathcal{O}_3^{Nq} = \Delta_q^N \frac{\bar{N} \gamma^\mu \gamma_5 N (\bar{\chi} \gamma_\mu \gamma_5 \chi)}{\Lambda^2} \]

\[ \sigma_3^{Nq} = \frac{3 \mu^2}{\pi \Lambda^4} (\Delta_q^N)^2 \]

\[ \Delta_u = \Delta_d = 0.842 \pm 0.012, \]
\[ \Delta_u = \Delta_d = -0.427 \pm 0.013, \]
\[ \Delta_s = \Delta_s = -0.085 \pm 0.018. \]
Spin dependent

\[ \mathcal{O}_3 = \frac{i g_X g_q}{q^2 - M^2} (\bar{q} \gamma_{\mu} \gamma_5 q) (\bar{X} \gamma_{\mu} \gamma_5 X) \]

\[ \mathcal{O}_3^{Nq} = \Delta_q^N \frac{(\bar{N} \gamma_{\mu} \gamma_5 N) (\bar{X} \gamma_{\mu} \gamma_5 X)}{\Lambda^2} \]

\[ \sigma_3^{Nq} = \frac{3 \mu^2}{\pi \Lambda^4} (\Delta_q^N)^2 \]

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\[ \Delta_s = \Delta_s = -0.085 \pm 0.018 . \]

World’s best limits, up to \( \sim 200 \) GeV
iDM, exothermic

\[ \frac{dR}{dE_R} \propto n_{\chi} \sigma_N \int_{v_{\text{min}}}^{v_{\text{esc}}} \frac{f(v)}{v} dv , \]

\[ v_{\text{min}} = \sqrt{\frac{1}{2m_T E_R}} \left( \frac{m_T E_R}{\mu_T} + \delta \right) \]
iDM, exothermic

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\frac{dR}{dE_R} \propto n_\chi \sigma_N \int_{v_{\text{min}}}^{v_{\text{esc}}} \frac{f(v)}{v} dv,
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\[
\delta \sim 100 \text{ keV}, \ 5 \text{ keV}
\]
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\[ \delta \sim 100 \text{ keV, } 5 \text{ keV} \]

[Diagram showing direct detection cross sections for different channels.]
iDM, exothermic

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\[ \delta \sim 100 \text{ keV}, \ 5 \text{ keV} \]
Light mediators

\[ \sigma_{\text{DD}} \sim g_\chi^2 g_q^2 \frac{\mu^2}{M^4} \]

\[ \sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2} \]

Direct detection wins

Two body vs three body production: \(2m_\chi < M < s^{1/2}\)
Light mediators

\[ \sigma_{\text{DD}} \sim g_\chi^2 g_q^2 \frac{\mu^2}{M^4} \quad \quad \quad \sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2} \]

Direct detection wins

Two body vs three body production: \( 2m_\chi < M < s^{1/2} \)

![Graph showing the comparison of two-body and three-body production in dark matter search experiments.](image)

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Momentum dependent

\[ \mathcal{O}_4^{Nq} = -i C_q^N \frac{\langle \bar{N} \gamma_5 N \rangle (\bar{\chi} \gamma_5 \chi)}{\Lambda^2} \]

\[ \frac{d\sigma_4^{Nq}}{d \cos \theta} = \frac{1}{32\pi \Lambda^4} \frac{q^4}{(m_\chi + m_N)^2} (C_q^N)^2 \]

\[ C_u^p = 168.5, \quad C_u^m = -165.2, \]
\[ C_d^p = -164.2, \quad C_d^m = 165.8, \]
\[ C_s^p = -4.3, \quad C_s^m = -0.67. \]
Momentum dependent

\[ \mathcal{O}^{Nq}_4 = -i C_q^N \left( \bar{N} \gamma_5 N \right) \frac{\left( \bar{\chi} \gamma_5 \chi \right)}{\Lambda^2} \]

\[ \frac{d\sigma^{Nq}_4}{d\cos \theta} = \frac{1}{32\pi \Lambda^4} \frac{q^4}{(m_\chi + m_N)^2} (C_q^N)^2 \]

\[
\begin{align*}
C_{u}^p &= 168.5, & C_{u}^m &= -165.2, \\
C_{d}^p &= -164.2, & C_{d}^m &= 165.8, \\
C_{s}^p &= -4.3, & C_{s}^m &= -0.67.
\end{align*}
\]

\[ M=1 \text{ GeV} \]

\[ M=10 \text{ GeV} \]

\[ \sigma_{SD-P} \text{ (cm}^2) \]

\[ m_\chi \text{ (GeV)} \]

\[ 10^{-39} \quad 10^{-37} \quad 10^{-35} \quad 10^{-33} \quad 10^{-31} \]

\[ 0.5 \quad 1.0 \quad 5.0 \quad 10.0 \quad 50.0 \quad 100.0 \]

The DAMA allowed region is shown in the green contours and is taken from Ref. [15]. The results are shown in Figure 6; we consider the constraints to the region of parameter space that best fits the data. This option may well be ruled out by other limits. The diagram shows the constraints on the momentum and spin dependent dark matter with a possible explanation for the DAMA modulation signal, but it is worthwhile to consider possible improvements to the data. The results are shown in Figure 6; we consider the case of SI DM, where the production of DM in mono-jet events can take place. In going from quark to nucleonic operators or scalar and consider the effects as its mass is lowered. In particular, we consider the case of a light mediator for the case of SI DM, with both a light mediator and light DM, the constraint on direct detection will not be competitive with those from direct detection experiments. The most stringent. This is due to a small branching fraction to jets, leading to a di-jet invariant mass peak, though this is model dependent and will vary with mediator mass. In this case the mediator could also have a substantial branching fraction to jets, leading to a di-jet invariant mass peak, though this is model dependent and will vary with mediator mass.
Improvements?

So far only CDF analysis on 1/fb Mono-photon could also be done

![Graph showing event distribution](image)

Use shape information, limited by theory

Tevatron reach limited to \( \sim 300 \) GeV
Improvements?

So far only CDF analysis on 1/fb Mono-photon could also be done

\[ m_\chi = 10 \text{ GeV} \]

Use shape information, limited by theory

Recently CDF + Bai, Harnik, PJF have started a “real” analysis on full data set!

Tevatron reach limited to \( \sim 300 \) GeV
Improvements

[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu]

LHC

\[ \sqrt{s} = 14 \text{ TeV} \]

\[ \mathcal{L} = 100 \text{ fb}^{-1} \]

\[ \not{E}_T > 500 \text{ GeV} \]

No longer monojet search

BSM backgrounds?
Conclusions

• Mono-jet searches at the Tevatron already place strong constraints on dark matter
• Competitive with direct detection searches
  • Light DM
  • Spin dependent
  • Non-standard DM e.g. iDM, exoDM, MDDM
• Independent of all astrophysics uncertainties
• Shape information, reduce theory errors,...
• Light mediators weaken collider bounds
• If we see a DD signal in a region ruled out by colliders we have discovered 2 particles

Mono-jet + mono-photon analyses important
Backup Slides
$\Lambda = 1 \text{ TeV}$

$\bar{u}\gamma^\mu u \bar{\chi}\gamma_\mu \chi / \Lambda^4$

- **Calchep**
- **Mad–parton**
- **Mad–PGS**

In this work we show that the Tevatron mono-jet search places competitive bounds on dark matter–nucleus cross sections relevant for direct detection experiments. In particular, the Tevatron limits are the current world-best for light dark matter, below a mass of 5 GeV. The Tevatron also sets the best limit spin dependent dark matter scattering. Various models built to explain the DAMA modulation signal such as inelastic and exothermic dark matter are also constrained by current Tevatron searches.

In addition to considering dark matter that couples to quarks via contact interactions we have taken the possibility of light mediators, as motivated by cosmic ray excesses [30] into account. We find that...
ADD analysis

Data Selection:
- Central Photon $E_T > 50$ GeV
- Missing $E_T > 50$ GeV
- No jets with $E_T > 15$ GeV
- No tracks with $P_T > 10$ GeV
- At least 3 low $P_T$ COT tracks

Background Predictions:

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\gamma E_T &gt; 50$ GeV</th>
<th>$\gamma E_T &gt; 90$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e \gamma$</td>
<td>$47.3 \pm 5.1$</td>
<td>$2.6 \pm 0.4$</td>
</tr>
<tr>
<td>$W \rightarrow \mu/\tau \gamma$</td>
<td>$19.1 \pm 4.2$</td>
<td>$1.0 \pm 0.2$</td>
</tr>
<tr>
<td>$W\gamma \rightarrow \mu\gamma \rightarrow \gamma$</td>
<td>$33.1 \pm 10.2$</td>
<td>$1.7 \pm 1.2$</td>
</tr>
<tr>
<td>$W\gamma \rightarrow e\gamma \rightarrow \gamma$</td>
<td>$8.0 \pm 3.0$</td>
<td>$0.8 \pm 0.7$</td>
</tr>
<tr>
<td>$W\gamma \rightarrow \tau\gamma \rightarrow \gamma$</td>
<td>$17.6 \pm 1.6$</td>
<td>$2.5 \pm 0.2$</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow \gamma$</td>
<td>$18.9 \pm 2.3$</td>
<td>$2.3 \pm 0.6$</td>
</tr>
<tr>
<td>cosmics</td>
<td>$36.4 \pm 2.5$</td>
<td>$9.8 \pm 1.3$</td>
</tr>
<tr>
<td>$Z\gamma \rightarrow \nu\nu\gamma$</td>
<td>$99.7 \pm 9.5$</td>
<td>$25.2 \pm 2.8$</td>
</tr>
<tr>
<td>Total</td>
<td>$280.1 \pm 15.7$</td>
<td>$46.7 \pm 3.0$</td>
</tr>
<tr>
<td>Data</td>
<td>$280$</td>
<td>$40$</td>
</tr>
</tbody>
</table>

Optimized Search for LED:
- Leading Jet $E_T > 150$ GeV
- Event Missing $E_T > 120$ GeV
- Allow 2nd Jet with $E_T < 60$ GeV
- No 3rd Jet with $E_T > 20$ GeV

Results:

Background Predictions:

<table>
<thead>
<tr>
<th>Background</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \nu\nu$</td>
<td>$390 \pm 30$</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>$187 \pm 14$</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>$117 \pm 9$</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>$58 \pm 4$</td>
</tr>
<tr>
<td>$Z \rightarrow 1\ell$</td>
<td>$6 \pm 4$</td>
</tr>
<tr>
<td>QCD</td>
<td>$23 \pm 20$</td>
</tr>
<tr>
<td>Gamma plus Jet</td>
<td>$17 \pm 5$</td>
</tr>
<tr>
<td>Non-Collision</td>
<td>$10 \pm 10$</td>
</tr>
<tr>
<td>Total Predicted</td>
<td>$808 \pm 62$</td>
</tr>
<tr>
<td>Data Observed</td>
<td>$809$</td>
</tr>
</tbody>
</table>