# $\overline{16}$   $\overline{16}$  Hunting for Dark Matter with a Jet Patrick Fox 幸Fermilab



 $\overline{a}$ with Yang Bai and Roni Harnik (arXiv:1005.3797)

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# **Dark Matter**

### Lots of evidence for non-baryonic matter:



 $\Omega_{DM} \sim 0.2$ 



 $\rho_{DM} \sim 0.3$  GeV cm<sup>-3</sup>

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Cosmological abundance Local abundance

 $\rho_{DM} \sim 0.3$  GeV cm<sup>-3</sup>

### **Dark Matter** galaxy is Maxwell-Boltzmann with velocity distribution is made with velocity of th  $\overline{\phantom{a}}$



 $\mathcal{L}_{\mathcal{L}}$  and the sum of the Sun  $\mathcal{L}_{\mathcal{L}}$  and the Sun  $\mathcal{L}_{\mathcal{L}}$  and the Sun  $\mathcal{L}_{\mathcal{L}}$  and the Sun  $\mathcal{L}_{\mathcal{L}}$ 

### volocity distribution Maxwell-Boltzmann velocity distribution



**Escape velocity in galactic frame** 498 km/s  $\leq v_{esc} \leq 608$  $k=1$  for concrete  $\frac{1}{\sqrt{2}}$  km/s. Increases our slightly  $J(v) = \frac{1}{(\pi v^2)^{3/2}} e^{-\gamma v^2}$  $\frac{1}{2}$ Tuesdav November 2, 2010 Escape velocity in galactic frame  $f(v) = \frac{1}{(v^2)^2}$  $\frac{1}{(\pi v_0^2)^{3/2}} e^{-v^2/v_0^2}$ 0

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Near us:  $\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$  $\boldsymbol{\mathsf{u}}$ s:  $\rho_{DM}$   $\boldsymbol{\mathsf{\cdot}}$ 0)3/2 e−("")3<br>3/2 e−(")3/2 e−(")3<br>3/2 e−(")3/2 e−(")3  $\vee$   $\vee$   $\vee$ 

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### volocity distribution Maxwell-Boltzmann velocity distribution



**(here, there and everywhere)**



**(here, there and everywhere)**





 $q_{\parallel}$ 

 $q$ 





Type I Type IIA Type IIB

**(here, there and everywhere)**



**(here, there and everywhere)**



 $\chi$  $\chi$  $\overline{q}$   $\overline{$ 

 $\overline{q}$ 

 $\overline{q}$ 



Collider searches

Indirect detection

Direct detection

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

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

Look small Missing energy events at colliders

**(here, there and everywhere)**



Indirect detection





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Collider searches

q  $\lambda$ 

Thermal relic? Predicts x-sec ~1 pb

# **Direct Detection**





$$
R \sim N_T \frac{\rho_\chi}{m_\chi} \langle \sigma v \rangle \approx 1 \ \text{event/day/kg}
$$

### How to distinguish this small number of low energy events from backgrounds?

# **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





# **Existing DD bounds** CDMS, XENON, DAMA, CoGeNT, COUPP, CRESST, ......





# **Direct detection vs Collider production**



### How does one search impact the other?

[Birkedal, Matchev and Perelstein]

### **Mediator Mass dependence** and light mediators M " 100 GeV. The momentum exchange at direction experiments is sufficiently low that for all but the sufficient of all but the suff

 $\vert$  Only consider mediators with mass  $\gtrsim 100~\mathrm{MeV}$ 

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\sum_{\substack{q \text{odd } q}} \mu = \frac{m_{\chi} m_N}{m_N + m_{\chi}}
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SM, thus limiting the DM + mono-jet production cross section to be smaller than ∼ 500 fb. Due

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The momentum exchange at direct detection experiments is sufficiently low that for all  $\alpha$  all  $\beta$ 

1

In 1 invfb CDF saw 8449 monoiet events, expected  $8663 \pm 332$   $+ 01j \approx 00010$  $\Rightarrow \quad \sigma_{1j} \lesssim 500 \,\text{fb}$ ⇒

 $1\leq d\leq K$  and  $\leq d$  $\sigma_{DD}\lesssim 0.5{\rm\,fb}=5\times 10^{-40}{\rm cm}^2$ 

this.

# **Existing DD bounds**



#### $\blacksquare$  $\mathcal{F}_{\mathbf{1}}$  is defined and 3  $\mathcal{F}_{\mathbf{2}}$  and 3  $\mathcal{F}_{\mathbf{3}}$  and constraints from other experiments from  $\mathcal{F}_{\mathbf{3}}$ ROI's

- (90% CL) for SI scattering  $\mathcal{L}$  sattering of protons (right). Shaded DAMA regions (right). Shaded DAM  $\bullet$  Light mass  $\Box$  in  $\Box$  while the channeling to  $\Box$  while the black contour con •Light mass DM<br>•  $\mathbf{h}$ ing the channeling effect according to  $\mathbf{u}$ , while the black contour curves  $\mathbf{$
- . Non-standard DM introduced to explain DAMA

 $90\%$  C.L

 $10^3$ 

 $10^{2}$ 

• Velocity, momentum or spin suppression in fig. 2 the old and show also the impact of different assumptions on  $\mathbf{I}$  and  $\mathbf{I}$ •Velocity, momentum or spin suppression To study the impact of the study control in the incrementation in the new 2009 and CDMS in the control of the c in fig. 2 the old and new data sets, and new data sets, and show also the impact of different assumptions on d<br>The impact of different assumptions on different assumptions on different assumptions on the impact of differe

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#### $\blacksquare$ FIG. 1: DAMA allowed regions (90% and 30% and 3 ROI's

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# **Outline**

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

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# •Motivation and estimation

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# **Operators**

$$
\begin{array}{rcl}\n\mathcal{O}_1 &=& \frac{i\,g_\chi\,g_q}{q^2 - M^2} \left( \bar{q} q \right) \left( \bar{\chi} \chi \right) \,, & \text{SI, scalar exchange} \\
\mathcal{O}_2 &=& \frac{i\,g_\chi\,g_q}{q^2 - M^2} \left( \bar{q} \gamma_\mu q \right) \left( \bar{\chi} \gamma^\mu \chi \right) \,, & \text{SI, vector exchange} \\
\mathcal{O}_3 &=& \frac{i\,g_\chi\,g_q}{q^2 - M^2} \left( \bar{q} \gamma_\mu \gamma_5 q \right) \left( \bar{\chi} \gamma^\mu \gamma_5 \chi \right) \,, & \text{SD, axial-vector exchange} \\
\mathcal{O}_4 &=& \frac{i\,g_\chi\,g_q}{q^2 - M^2} \left( \bar{q} \gamma_5 q \right) \left( \bar{\chi} \gamma_5 \chi \right) \,, & \text{SD and mom.} \\
& & \text{dep., pseudo--} \\
\text{scalar exchange}\n\end{array}
$$

### $\overline{\phantom{a}}$  op $\overline{\phantom{a}}$  be easy to deduce momentum and the suppression suppression scale  $\overline{\phantom{a}}$ • Consider each operator, and each flavour separately •DM a Dirac fermion

This is a representative set of operators that will generate a variety of  $\alpha$  variety of data matter scattering scattering scattering  $\alpha$ 

# **CDF mono-jet search**

[[http://www-cdf.fnal.gov/physics/exotic/r2a/20070322.monojet/public/ykk.html](http://www-cdf.fnal.gov/physics/exotic/r2a/20070322.monojet/public/ykk.html%5D)]

### •1/fb analysed

 $p_T(j1) > 80 \,\text{GeV}$  $\not\hspace{-1.2mm}E_{T} > 80\,\rm{GeV}$  $p_T(j2) < 30 \,\text{GeV}$  $p_T(j3) < 20 \,\text{GeV}$ 





Observed: 8449 events

## **Bounds on operators**

Assume a heavy mediator: Λ  $M \,$  $\sqrt{g_{\chi}g_1}$ 

Simulate events in calcHEP, one operator at a time



# **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 • .....

#### **Spin independent**  $T_{\rm{max}}$ At low discusses in each contribution in each case are the scattering cross section in each case are the scattering content of the scattering content of the scattering content of the scattering content of the scattering co The o1 and O2 induce a spin independent scattering of dark mattering of dark matter of nuclei. To compute of n<br>To compute a spin independent scattering of nuclei. To compute a spin independent of nuclei. To compute a spin



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 $T_{\text{recoary}}$ , november  $E$ ,  $E_{\text{c}}$  rotation by the up-type operators, where  $\sigma$ Tuesday, November 2, 2010

#### **Spin dependent** Spin depender in ground can be designed to compute the DM scattering cross section of a nucleon, N  $\alpha$ caused by the axial vector operator operator operator operator O3. For a complete list of all operators, see [ ndent

i g<sup>χ</sup> g<sup>q</sup>



because the scattering is not coherent over the whole nucleus, while there is no relative suppresion

between the two at high energies. Of the operators under consideration, spin dependent scattering is

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context of the DAMA modulation signal.The event rate in a direct detection experiment at a given

$$
v_{min} = \sqrt{\frac{1}{2m_T E_R}} \left(\frac{m_T E_R}{\mu_T} + \delta\right)
$$



Tuesday, November 2, 2010

species in question.

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### **Light mediators** lightest mediators below O(100 MeV), which we do not consider here, the mediator can effectively be

$$
\sigma_{\rm DD} \sim g_\chi^2 \, g_q^2 \, \frac{\mu^2}{M^4}
$$

In contrast the two regimes behave very differently at colliders. Concentrating on direct production

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### $\nabla$ in the cross section. Here, g<sup>χ</sup> and g<sup>q</sup> are couplings of the mediator to DM and quarks. µ is the reduced Direct detection wins

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



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# **Improvements?**

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



### limited by theory Use shape information, *u*ΓΜu ΧΓΜ Χ # &<sup>4</sup>

 $1000$   $1000$   $1000$   $1000$   $1000$   $1000$   $1000$   $1000$ 

### Tevatron reach limited to ~300 GeV Figure 7: (a) Comparisons of the shapes of the signal, the SM background and CDF measured events.

The SM predictions are shown in the green and the CDF observed data are shown in red. (b) Tuesday, November 2, 2010

# **Improvements?**

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alysis on iuli data l analysis on full data Recently CDF + Bai, Harnik, PJF have started a "real" set!

### Tevatron reach limited to ~300 GeV Figure 7: (a) Comparisons of the shapes of the signal, the SM background and CDF measured events.

# **Improvements** [Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu]

for the LHC, (S)CDMs  $\mathcal{L}_{\mathcal{A}}$  and  $\mathcal{L}_{\mathcal{A}}$ 



#### $\Box$  Fig.  $\Box$  Regions of parameter space excludes by Teva- $\Box$ tron searches, CDMS/Xenon 10 [7, 8], CoGeNT [26], and LHC

is the parameter space favored by a WIMP interpretation of  $t/c = 14$   $\text{TeV}$   $\blacksquare$  $\sqrt{s} = 14 \text{ TeV}$  N  $\mathcal{L} = 100$  fb<sup>-1</sup>  $\n *E*<sub>T</sub> > 500 \text{ GeV}$ 

### No longer monojet search ckgi u BSM backgrounds?

<u>4</u> χ #

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"2

, (5)

σ<br>Π

SI;M7 = 1

# **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



(a) (b)

# **Phys.Rev.Lett.101:181602,2008**<br>arXiv:0807.3132

### **Data Selection:**

- Central Photon  $Et > 50$  GeV
- $\bullet$  Missing Et > 50 GeV
- No jets with  $Et > 15 GeV$
- No tracks with  $Pt > 10$  GeV
- At least 3 low Pt COT tracks

#### **Background Predictions:**



### • Optimized Search for LED:

- Leading Jet  $Et > 150$  GeV
- Event Missing  $Et > 120 GeV$
- Allow 2nd Jet with  $Et < 60$  GeV
- No 3rd Jet with  $Et > 20$  GeV

### • Results:



