Dark Matter @ Colliders

David-fest 2011

Roni Harnik, Fermilab

Bai, Fox, RH - 1005.3797 Fox, RH, Kopp, Tsai -1103.0240 Fox, RH, Kopp, Tsai - 1109.4389

Very related work by the "Irvine Clan":

Goodman, Ibe, Rajaraman, Shepherd, Tait and Haibo Yu -1005.1286 Goodman, Ibe, Rajaraman, Shepherd, Tait and Haibo Yu - 1008.1783 Fortin and Tait - 1103.3289 Rajaraman, Shepherd,Tait and Wijangco - 1108.1196 Shepherd and Goodman - 1111.2359

Dark Matter needs no introduction.

But it has a lot to answer for:

- * What sets its abundance?
- Does it interact with matter *apart* from gravity?
- ***** How strong/weak are these interactions?

- * Does it fit into a larger framework?
- * What is the particle mediating this interaction?

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Answers (and limits) come from **direct & indirect searches**.

Directly complemented by past and present colliders.

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LHC (e.g. Higgs mediated interactions)

Outline

- ***** Motivation: Colliders as direct detection experiments.
- ***** Tevatron & LHC mono-jets:
	- Rough estimates. \bullet
	- **Operators** \bullet
	- Results \mathbf{O}
- ***** LEP mono-photons.
- ***** Scattering via the Higgs & LHC Higgs searches.
- * Coffee.

The WIMP Hint

- Does DM have interactions with matter? \ast
- ***** If we throw a weakly interacting particle with weak

scale mass into the primordial hot soup,

the DM abundance comes out roughly right.

Hint: There is an interaction.

Leads to pb-ish cross sections

Probes of DM Interactions

***** We hope to probe dark matter in several ways: DM-nucleus scattering DM annihilation

Focus on direct detection in this talk. (a similar game can be played for indirect)

Direct detection

q

DM DM

q

- ***** Direct detection places limits on
- * Heroic effort with remarkable results.
- ***** DD has some weaknesses.

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* DM experiments and colliders are often said to be related *in a specific framework* (SUSY).

 $X = \begin{bmatrix} 1 & \mathbf{N} & \mathbf{N}$ "XENON100 is starting to probe the MSSM's pseudopod, α octorrhoom is still sofo[?] LHC killed the Membrane, but the ectoplasm is still safe." [submitted to nature]

In order to get a particular DM-nucleon cross \ast

and a density of ρ^χ = 0*.*3 GeV*/*cm³. The S1 energy res-

incorporated into the limit. The resulting $\mathbf{0}$ e interactio The impact of *L*eff data below 3 keVnr is negligible at absence of a signal above background and is also shown in \mathbb{R}^n i morning a hadron machine. weaker than expected. This limit is consistent with the The same interaction can lead to DM production at

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Mono-jet searches can place limits on the direct detection plane. ⁵

 $\frac{1}{2}$ spin-independent elastic WIMP-nucleon cross-section cross **These are conservative** at 90% CL, as derived with the Profile Likelihood methods with the Profile Likelihood methods with the Profile In a coopifie model thorous <u>in a specinc inouel there in</u> sensitivity of this run (shaded blue band). The limits from D_{LO} duce I JM e σ through P , acuse P , $\mathsf{$ *v*esc = 544 km/s, *v*⁰ = 220 km*/*s) are also shown. Expectatuiti ed states. These are **conservative** limits. (1985); G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rept. 267, 195 (1996). \prime he other ways to \sim In a specific model there may be other ways to 0.4001 produce DM, e.g. through cascades from heavy \overline{A} definition and \overline{A} p , p , p m Ono j , j , j , m ds colored states.
Enter mono-jet are certainly good to set bounds.

 DUC $A = 500$

 \mathcal{I} E. April 105, Phys. Rev. Lett. 105, Phys. Rev. Lett. 105, Phys. Rev. Lett. 105, Phys. Rev. Lett. 105, Phys. Rev. 205, Phys. Rev. 205

 200

131302 (2010).

Mono-jet searches can place limits on the plane.

7e Collider does The collider does

taking into account all relevant systematic uncertainties, into account systematic uncertainties, is \mathbf{r} sot have a (n) not have a low

 $\cos\theta$, dhashed, $\sin\theta$ *v*esc = 544 km/s, *v*⁰ = 220 km*/*s) are also shown. Expecta- $\mathcal{L}_{\mathcal{F}}$ energy threshold

[1] G. Steigman and M. S. Turner, Nucl. Phys. B253, 375 The collider does

 \mathcal{A} as the al., Astrophys. J. Suppl. 192, 14 (2011); noc pay a price not pay a price

 $\overline{3}$ M. W. W. W. Goodman and E. Witten, Phys. Rev. $\overline{1}$ τ Ol [4] J. D. Lewin and P. F. Smith, Astropart. Phys. 6, 87 for spin dependence

Cross Sections

The direct detection cross section $(q \sim 100\;\mathrm{MeV})$: \mathbf{F} The direct detection cross section $(x + 100 \text{ MeV})$ integrated out and the scattering rate in both regimes $\setminus I$ $q \sim 100 \text{ MeV}$

* Mono-jet + $\not\hspace{-1.2mm}E_{T}^{\prime}$ ($q \sim 10-100 \,\, \mathrm{GeV}$):

Back of an Envelope:

-
-
-
-
-
-
- -

Back of an Envelope:

Consider a heavy mediator:

assume $p_T < M$ (just a contact operator)

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 $\sigma_{1j}\sim \alpha_s g_\chi^2 g_q^2$ $p_{\mathcal{T}}^2$ \overline{T} $\overline{M^4}$

 $(p_T \sim 100 \,\text{GeV})$

Back of an Envelope: consider when comparing bounds from the two types of experiments: heavy mediators M ! 100 GeV mediators M ! 10
The two types of experiments: heavy mediators M ! 100 GeV mediators M ! 100 GeV mediators M ! 100 GeV mediator and Dack Of d

lightest mediators below O(100 MeV), which we do not consider here, the mediator can effectively be Consider a heavy mediator:

assume $p_T \times m$ yasc a concact operator, assume $p_T < M$ (just a contact operator)

 $\sigma_{\rm DD} \sim g_\chi^2 \, g_q^2$ μ^2 $\frac{\mu}{M^4}$ $(p_T \sim 100 \,\text{GeV})$ ($\mu \sim 1 \,\text{GeV}$) $(\mu \sim 1 \,\text{GeV})$ $\sigma_{1j}\sim \alpha_s g_\chi^2 g_q^2$ $p_{\mathcal{T}}^2$ \overline{T} $\overline{M^4}$

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

$$
(p_T \sim 100 \,\text{GeV}) \qquad (\mu \sim 1 \,\text{GeV})
$$

$$
\sigma_{1j} \qquad \mathcal{O}(1000)
$$

 $\frac{\partial f}{\partial x}$ $I\subset L$ σ DD $\sim \mathcal{O}(1000)$

Front of an Envelope:

Front of an Envelope:

In 1 fb-1 CDF saw 8449 mono-jet events, expected 8663 ± 332 $\Rightarrow \sigma_{1j} \lesssim 500 \,\text{fb}$

The Limit

* Estimated limits from a back of the envelope recasting an old CDF study:

Sets best limit below $~\sim$ 5GeV. **SECS NESC INING MEIOW** taking into account all relevant systematic uncertainties, is

ast limit danandant **Best limit dependent DM detector.** [2] N. Jarosik et al., Astrophys. J. Suppl. 192, 14 (2011);

CDF Run II Preliminary 6.7/fb

CDF Limits:

CDF did a dedicated shape analysis of monojet spectra.

*

u Signature in 6.7 fb^{-1} $\overline{}$ **2** A Search For Dark Matter in the Monojet + Missing Transverse Energy **U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%**

FIG. 2: *Shalhout⁺*, *T. Schwarz²*, *R. Erbacher⁺, J. Conway⁺, P. Fox², R. Harnik², Y. Bai²
EPPERTIDE* OC Davis containing red histograms contains contain a combin S.Z. Shalhout¹, T. Schwarz², R. Erbacher¹, J. Conway¹, P. Fox², R. Harnik², Y. Bai² UC Davis¹ Fermilab²

A neural net with our name on it ?! :-0 energy signature. We analyze a sample of Tevatron *pp* collisions at √*s*=1.96 TeV, recorded by

In the rest of the talk:

How is the translation from Colliders done?

What can LHC say? What did LEP say?

What assumptions are made?

Operators can describe the field the field theory. from the effective field theory framework changes our results in sections 4 as well as 6.) Since our

Describe DM interactions as higher DM operators (possibly mediated by light mediators) goal is not to do not to do a function of a function of a wide to include the model of the model of the model o variety of phenomenological distinct cases. (possibly included by ight included)

$$
\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2},
$$
\nSl, vector exchange
\n
$$
\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2},
$$
\nSD, axial-vector exchange
\n
$$
\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R),
$$
\nSl (or SD), t-channel
\n
$$
\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi) (G^a_{\mu\nu} G^{a\mu\nu})}{\Lambda^3}
$$
\nSl gluon operator

Which Cuts? Our analysis will, for the most part, be based on the ATLAS search [25] which looked for mono j of j in the earlier compare to the earlier \sim

* ATLAS's Ifb analysis employs 3 sets of cuts

LowPT Selection requires $\not{E}_T > 120 \text{ GeV}$, one jet with $p_T(j_1) > 120 \text{ GeV}$, $|\eta(j_1)| < 2$, and events are vetoed if they contain a second jet with $p_T(j_2) > 30$ GeV and $|\eta(j_2)| < 4.5$.

- HighPT Selection requires $\not{E}_T > 220 \text{ GeV}$, one jet with $p_T(j_1) > 250 \text{ GeV}$, $|\eta(j_1)| < 2$, and events are vetoed if there is a second jet with $|\eta(j_2)| < 4.5$ and with either $p_T(j_2) > 60$ GeV or $\Delta\phi(j_2, \mathcal{L}_T) < 0.5$. Any further jets with $|\eta(j_2)| < 4.5$ must have $p_T(j_3) < 30$ GeV.
- veryHighPT Selection requires $\not{E}_T > 300$ GeV, one jet with $p_T(j_1) > 350$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if there is a second jet with $|\eta(j_2)| < 4.5$ and with either $p_T(j_2) > 60$ GeV or $\Delta\phi(j_2, \mathcal{E}_T) < 0.5$. Any further jets with $|\eta(j_2)| < 4.5$ must have $p_T(j_3) < 30$ GeV.

³ Both ATLAS and CMS impose additional isolation cuts, which we do not mimic in our analysis for simplicity and

Uncertainties.

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I: The 2: Alexander mission of *its* and hatter and the three ATLAS and the three ATLAS and the CMS an α is an the text (black data points with error background pre-ATLAS 7 TEV 1919 Hard cuts are better.

Limits on $\Lambda \equiv \frac{M}{\sqrt{2\pi}}$: Limits on $\Lambda \equiv \frac{1}{\sqrt{a_0 a_1}}$: *M* √*g*χ*g*¹ analyses with different *p^T* cuts allows a crude version of a shape analysis to be carried out. Since the contribute the ratio of signal to background, as is reflected in figure 2. To α $\sqrt{9\chi91}$ \sqrt{a} \sqrt{a} γ or γ and γ and γ bars) compared to the collaborations' background predictions (yellow shaded histograms) and to our Monte Carlo prediction with \mathbf{v}

Set 90% CL limits:
$$
\chi^2 = \frac{[\Delta_N - N_{\rm DM}(m_\chi, \Lambda)]^2}{N_{\rm DM}(m_\chi, \Lambda) + N_{\rm SM} + \sigma_{\rm SM}^2} = 2.71.
$$

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Other Operators:

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 \overline{J} same limit for SI and SD

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GOES UIT CI Tho $link$ \overline{C} $\sqrt{2}$ $A = \frac{1}{2}$ The limit is flat up to ~200 GeV. Goes all the way to zero.

The limit is flat up to ~200 GeV. Goes all the way to zero. The limit is flat up to ~200 GeV. G oes all the usal to zero bounds are shown as solid (dashed) lines.

Figure 2: Left panels: the spin-independent $\sqrt{q_{\gamma}q_1}$ $\mathbf{v} \in \mathcal{N}$ and vector constraints for the up-type and vector coupling operator are shown in the dot-type and vector coupling operator are shown in the dot-type and vector coupling $\mathbf{v} \in \mathcal{N}$. The dot-type are \overline{M} \blacksquare ind that the slightly $\Lambda \equiv \frac{1}{\Lambda}$ $\sqrt{9\chi_{31}}$ Limits on $\Lambda \equiv \frac{M}{\sqrt{2\pi}}$: $\Lambda \equiv$ *M* √*g*χ*g*¹

- **delight in experimental bounds are fairly flat in mass (upto ~200 GeV).** The limits are fairly flat in mass (upto \sim 200 GeV).
- ***** The limits are fairly independent of the operator 2 Operators and mono-jets
2 Operators and mono-jets
2 Operators and mono-jets The limits are fairly independent of the operator structure. Strong SD constraints.
- At little apply to IDM It realibilitions to the section in each case are seen in each case are are are assembly contributed to the section in the section in the section in the section in each case are are as a section in * These limits apply to iDM - Tevatron doesn't care about 100 keV splittings.
	- \bullet TO **D** lin ν ν matrices: For DD limits:

$$
\mathcal{O}_2 \;\; = \;\; \frac{i\,g_\chi\,g_q}{q^2-M^2}\,(\bar{q}\gamma_\mu q)\,(\bar{\chi}\gamma^\mu\chi) \quad \Longrightarrow \quad \sigma_2^{Nq} \;\; = \;\; \frac{\mu^2}{\pi\Lambda^4}\,f_{Nq}^2\,,
$$

 $f_u^p = f_d^n = 2$ $f_d^p = f_u^n = 1$ $f_u^p = f_d^n = 2$ $\frac{p}{f}$ gives $\frac{p}{f}$ $f_d^{\nu} = f_u^{\nu} = 1$ $f_u^p = f_d^n = 2$ $f_d^p = f_u^n = 1$ with $\sum_{n=0}^{\infty}$. Same can be done for all operators.

SI Limit

ATLAS 7TeV, 1fb

ATLAS 7TeV, 1fb⁻¹ VeryHighPt ATLAS 7TeV, 1fb

SI Limit

ATLAS 7TeV, 1fb

ATLAS 7TeV, 1fb⁻¹ VeryHighPt ATLAS 7TeV, 1fb

SD Limit

Annihilation

* A minimal light thermal relic is ruled out:

Annihilation into *q q*

CDF Analysis

Light Mediators integrated out and the scattering rate in both regimes scales as a set of the scales as L_1

Lets fix $\sigma_{\text{DD}} \sim g_\chi^2 g_q^2 \frac{\mu^2}{M^4}$ and lower M. Then $\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{g^2}$ drops as M^4 . μ^2 $\frac{m}{M^4}$ and lower M. $n \nabla$ simplicity, $n \nabla$ inch cross χ sq are couplings on η 1 $\overline{p_T^2}$

> the limits is **enhanced** b/c of on-shell production, (depends on the width).

M⁴ Collider losses

LEP mono-photon

w/ Fox, Kopp and Tsai arXiv:1103.0240

LEP

- ***** Directly constrain DM coupling to electrons.
- **But**, in many models quark and lepton coupling are related (consider 2 benchmarks).
- ***** LEP is a clean environment. Ability to measure missing mass.

* Places non-trivial limits also on indirect searches in lepton channels (e.g. the Hooperon).

Operators of a series. In the case of the phenomenology in an effective field theory with \mathcal{L}

* Same story w/ leptons (assume universality) E Sanne story for replacing (assum-

$$
\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^{\mu}\ell)}{\Lambda^2},
$$

\n
$$
\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2},
$$

\n
$$
\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma_5\ell)}{\Lambda^2},
$$

\n
$$
\mathcal{O}_t = \frac{(\bar{\chi}\ell)(\bar{\ell}\chi)}{\Lambda^2},
$$

(vector, *s*-channel)

(scalar, *s*-channel)

(axial vector, *s*-channel)

(scalar, *t*-channel)

Mono-photon

* Use spectrum shape to reject background peak.

Model Dependence

- ***** We limit lepton couplings.
- * But how does DM couple to quarks?
- * Consider 2 extreme cases:
	- Couplings to **quarks are same as leptons**. \bullet
	- Couplings to quarks are **zero**. \bullet
- ***** Any other case can be derived from these two.

DD Limits

DD Limits

Leptophilic DM

***** Consider zero couplings to quarks.

 $\Xi_{12} = 42 \frac{XY}{Y}$ Γ are sense at the loop-level induced at the local Γ 10^{-43} pays a big price. $\overline{}$ *i* mits are stro Collider limits are strong. Direct detection

90% C.L. 10^{-45} $\frac{1}{10^0}$ 10^1 10^2 10^3 10^{-44} 10^{-43} 10^{-42} 10^{-41} 10^{-40} 10^{-39} 10^{-38} 10^{-37} WIMP mass m_X [GeV] WIMP -proton cross section φ *p* $\mathrm{[cm^2]}$ " Couplings to leptons only Spin-independent $\overline{\chi} \gamma^\mu$ $\sqrt[\mu]{\ell}\gamma_\mu\ell$ ^Χ!!^Χ CDMS XENON-100 DAMA $(q \pm 33\%)$ **CoGeNT** 10^{-45}

 $\overline{\chi}\gamma^{\mu}\chi\overline{f}\gamma_{\mu}f$

Many more..

Light mediators: \ast

* Indirect detection:

Indirect Detection

Tension with the "Hooperon". Light thermal relic ruled out.

Mono-something!

- ***** For specific models, we can probe the identity of the mediator with other mono-somthings.
- **Mono-top** signals can probe DM that is coupling via MFV operators (kamenik and Zupan).
- ***** In many models DM couples via the **Higgs**. **Mono-Z** (and **VBF**) may be sensitive to this.

 χ

 χ

A Characteristic Higgs Channel

can confirm Higgs mediation!

Higgs Mediator S I

parametrically smaller!

Fox, RH, Kopp and Tsai

Games: Higgs searches & DM

- ***** Assume the Higgs hint is real w/ SM production.
- ***** The fact that is was seen in diphoton with the rate that is has, places limits on competing modes, e.g. Higgs to invisible.
- Places **upper** limit on higgs mediated direct detection.
- ***** Assume a Higgs mass that is already excluded for SM.
- ***** Assume the reason it was excluded is an invisible branching fraction.
- ***** This places a lower limit on the invisible BR. Places a **lower** limit on higgs mediated direct detection.

To Conclude:

Colliders are placing competitive and complementary bounds to direct and to indirect detection:

The **Tevatron** is the world record holder for light dark matter and for spin dependent. **LHC**
 evatro

matter ar LHc

- Dedicated CDF **mono-jet** is out. CMS, and ATLAS studies are underway.
- ***** LEP mono-photons provide strong constraints.
- ***** There is a nice interplay b/w visible and invisible Higgs searches and DM searches for **Higgs-coupled DM**.

Happy Birthday Graham!

Current Higgs limits vs DM

- * Assume a Higgs mass that was already excluded for SM.
- ***** Assume the reason it was excluded is an invisible branching fraction.
- ***** This places a lower limit on the invisible BR.
- **Places a lower limit on higgs mediated direct detection**.

Current Higgs limits vs DM

Also, if a light SM Higgs is discovered, boson from future ATLAS searches for invisible Higgs decays. Limits are shown for the *Z* + *H* and vector an upper limit on DD can be extracted.

CDF: jet + MET (1fb-1)

counting experiment:

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

Observed: 8449 events

[[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)]

Collider Connections?

* DM experiments and colliders are often said to be related *in a specific framework* (SUSY).

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