Fermion Portal Dark Matter

Yang Bai

University of Wisconsin-Madison

NHETC Seminar @ Rutgers

Nov. 5, 2013

with Joshua Berger at SLAC

"quark portal dark matter" "lepton portal dark matter" [308.06]2 [3]].xxxx

NHETC Seminar @ Rutgers

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"quark portal dark matter" "lepton portal dark matter" 1308.0612 1311.xxxx

see also Chang, Edezhath, Hutchinson, Luty, 1307:8120; An, Wang, Zhang, 1308.0592; DiFranzo, Nagao, Rajaraman, Tait, 1308.2679.

Matter Pie of Our Universe

Ordinary Matter

5.5%

2

An, Wang, Zhang, 1308.0592; DiFranzo, Nagao, Rajaraman, Tait, 1308.2679.



Dark Matter 84.5%

From Planck

3

Candidates of Dark Matter





Dark Matter 84.5%

From Planck

3

Candidates of Dark Matter



4

The WIMP "Miracle"





The WIMP "Miracle"



Lots of beyond-standard models predict WIMP candidates

5

The Hunt of Dark Matter

Colliders

Indirect Detection















7

IceCube High Energy Neutrino Excess







7

IceCube High Energy Neutrino Excess



8

IceCube High Energy Neutrino Excess

28 events

Einasto profile (decay)

istics (TS⁵) less the *p*-value for a homogenous distribution is 72.14% for consider a set all 28 events, which agrees with the result obtained by $\sim 0^{\circ} \left(\frac{-150^{\circ} - 120^{\circ} - 90^{\circ}}{-150^{\circ} - 120^{\circ} - 90^{\circ}} the free Cube collaboration [5, 6]. <math>\circ \left(\frac{-150^{\circ} - 120^{\circ} - 90^{\circ}}{-150^{\circ} - 120^{\circ}} \frac{-90^{\circ}}{-90^{\circ}} \frac{-30^{\circ}}{-90^{\circ}} \frac{\pi}{2} \frac{30^{\circ}}{-90^{\circ}} \frac{\pi}{2} \frac{30^{\circ}}{-90^{\circ}} \frac{\pi}{2} \frac{\pi}{$



	$\bar{\alpha} = 0.25$	$\bar{\alpha} = 0.17$	Homogeneous
all 28 events	20.34%	21.98%	72.14%
8 events with $E \gtrsim 50 \text{ TeV}$	18.16%	20.16%	70.14%
21 cascade events	38.84%	41.86%	95.38%

38.84%

41.86%

-13.5

-12.0

1

-10.5

-9.0

 $\log(p_{data})$

-7.5

-6.0

-4.5

YB, Lu, Salvado, to be published

-12.4 - 12.0 - 11.6 - 11.2 - 10.8 - 10.4 - 10.0

 $Log(p_{DM})$

-96

10

equatorial coord.

IceCube High Energy Neutrino Excess

9

YB, Lu, Salvado, to be published



	$\bar{\alpha} = 0.25$	$\bar{\alpha} = 0.17$	Homogeneous
all 28 events	20.34%	21.98%	72.14%
18 events with $E \gtrsim 50 \text{ TeV}$	18.16%	20.16%	70.14%
21 cascade events	38.84%	41.86%	95.38%

YB, Lu, Salvado, to be published

IceCube High Energy Neutrino Excess

YB, Lu, Salvado, to be published



Possible explanation from dark matter decays

10

Direct Detection





Possible explanation from dark matter decays

10











12

Effective Approach to Dark Matter







Effective Approach to Dark Matter



Model-independent approach to dark matter

$$\frac{1}{\Lambda^2} \bar{q} q \bar{\chi} \chi \qquad \qquad \frac{1}{\Lambda^2} \bar{q} \gamma_\mu q \, \bar{\chi} \gamma^\mu \chi \qquad \frac{1}{\Lambda^2} \bar{q} \gamma_\mu \gamma_5 q \, \bar{\chi} \gamma^\mu \gamma_5 \chi$$

The same operator describes collider and direct detection searches



The same operator describes collider and direct detection searches

13

Dark Matter at Colliders







YB, Fox, Harnik, JHEP, 1012, 048 (2010)

see also: Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu: Phys. Lett. B695 (2011)



14

400

350

Using CDF monojet data



World's best spin-dependent limit up to 100 GeV



World's best spin-dependent limit up to 100 GeV

15

PRL 108, 211804 (2012)

PHYSICAL REVIEW LETTERS

Search for Dark Matter in Events with One Jet and Missing Transverse Energy in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV



Spin-independent

YB, Fox, Harnik, JHEP 1012(2010)





Spin-independent

YB, Fox, Harnik, JHEP 1012(2010)



			, , jeu	— - , j	=(vv)		$\chi c D$	onigie top	1000	
		Cross section (pb)	229.0	34.1	588.3	225.2	1904.8	113.5		-
		Generated	1.27e7	2.6e6	1.05e7	6.92e6	2.29e7	7.05e6	6.3e7	
		Preselection	255647	1 7 20348	106463	50520	46076	7334	486389	
		$N_{Jets} \le 2$	183861	15056	80792	8585	15238	2723	306254	_
		$\Delta \phi(j_1, j_2) < 2$	166743	13798	75397	7150	585	2217	265890	
		Muon veto	73439	800	75395	2639	C 562	868	153703	
		Slectron veto	54236	5 31	75 374	1603	543	610	132898	
		Tau veto	52098	491	74870	1506	526	573	130064	
		$E_{\rm T}^{\rm miss} > 250 { m GeV}$	16528	120	28818	470	177	156	46269	
\sum		$E_{\rm T}^{\rm miss}$ > 300 GeV	6031	~ <u>4</u> 0°	°∎11999⊺	175	' '76	52	18373	
<u>6</u> 1000		$E_{\rm T}^{\rm miss} > 350 {\rm GeV}$	$248\overline{6}$	517.3	7 5469	, 72	23	CMS Pretimi	nary ₈₀₈₇	
V		$E_{\rm T}^{\rm miss} > 400 {\rm GeV}$	1109		Ē 2679	32	3	7	3837	
	_	$E_{\rm T}^{\rm miss} > 450 {\rm GeV}$	537	Б 110 ⁻³	^B 1406	13	$CMS \sqrt{s} = \frac{2}{7}$	$1 \text{ eV} 5.1 \text{ fb}^{-1}$ 2	196 4	
	-	$E_{\rm T}^{\rm miss} > 500 {\rm GeV}$	277	i i i i	F 766		1	1	1053	
	_	$E_{\rm T}^{\rm miss} > 550 {\rm GeV}$	136		429	3	CMS, √s = 8 T	eV, 19.5 fb ⁻¹ 0	569	_
				ທ ^{10⁻⁴}	0 <u>[</u>	K	Ge	NT 2011		
	CMS Prelimi	hary	\\-	S S S S S S	, F		Cocic	- 0010	Ę	
	$\sqrt{s} = 8 \text{ TeV} \text{Ta}$	ble 2: Event yields	for the Z	(µµ dat	acontrol	sample	and the	Background	s from M	1C
	-10^{-1} L dt = 19.5 fb ⁻¹	Z+i	ets W+	iets 170 ⁴	f/∎⁄) tŦ	Sing	et OC	D All MC	Data	-

World's best spin-independent limit for light dark matter

17

Current Limits from CMS



data driven $N(Z(\nu\nu)) = \frac{N^{\text{obs}} - N^{\text{bgd}}}{A \times \epsilon} \cdot R\left(\frac{Z(\nu\nu)}{Z(\mu\mu)}\right)$

18

Improvement

CMS monojet search

$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV) $ ightarrow$	> 400
$Z(\nu\nu)$ +jets	2569 ± 188
W+jets	1044 ± 51
tī	32 ± 16
$\nabla (00)$	

inderstanding how dark matter interacts with guarks, where eptons can actually furnish the strongest current bound on dark is photophysical strong to the strong spin violating with guarks where the photophysical strong strong spin violating strong strong to the week photophysical strongest current bound on dark ons can actually furnish the strongest current bound on dark sh-dependent) interactions and iso-spin violating couplings.





434

dominants

a cleaner channel may do better

19

Monolepton



YB and Tait 1208.4361

$$\frac{1}{\Lambda^2} \,\overline{\chi}\gamma_\mu \chi \,\left(\overline{u}\gamma^\mu u + \xi \,\overline{d}\gamma^\mu d\right)$$

$$\frac{1}{\Lambda^2} \,\overline{\chi}\gamma_\mu\gamma_5\chi \,\left(\overline{u}\gamma^\mu\gamma_5u + \xi \,\overline{d}\gamma^\mu\gamma_5d\right)$$

interesting interference effects



or spin-0 GeV) e where vith the sults in to down quarks relative to up-quarks, and for simplicity we restrict our discussion to quarks of the first generation. This tates ditignine added on the scattering with nuclei. We also consider a spin-dependent case with an axial vector structure,

CMS Data



CMS: EXO-13-004-pas

Limits on cutoff





Limits on cutoff



22

Caveat #I

 $q < \mathcal{O}(\text{GeV})$

★ The colliders become less effective as the mediator mass decreases

$$\sigma^{\text{DD}} \sim g_{\chi}^2 g_q^2 \, \frac{\mu_{\chi n}^2}{[q^2 - M^2]^2} \sim g_{\chi}^2 g_q^2 \, \frac{\mu_{\chi n}^2}{M^4}$$

	$\xi = -1$	$\xi = 0$	$\xi = +1$	$\xi = -1$	$\xi = 0$	$\xi = +1$
M_{χ}		V Λ[TeV]		A	AV Λ[TeV]
1	1.06	0.75	0.33	0.99	0.69	0.33
10	1.05	0.74	0.34	1.01	0.71	0.32
100	1.06	0.75	0.31	1.01	0.70	0.33
500	0 72	0.51	0.23	0 89	0.62	በ 28

Caveat #1

The colliders become less effective as the mediator mass decreases

$$\sigma^{\text{DD}} \sim g_{\chi}^2 g_q^2 \, \frac{\mu_{\chi n}^2}{[q^2 - M^2]^2} \sim g_{\chi}^2 g_q^2 \, \frac{\mu_{\chi n}^2}{M^4} \qquad \qquad q < \mathcal{O}(\text{GeV})$$

$$\sigma_{1j} \sim \alpha_s g_{\chi}^2 g_q^2 \frac{p_T^2(1j)}{[q^2 - M^2]^2} \sim \alpha_s g_{\chi}^2 g_q^2 \frac{1}{p_T^2(1j)} \qquad q \sim p_T(1j)$$

 σ_{1j}/σ^{DD} drops like M^4

23

Effects of Light Mediator



01j/0 drops like 1/1



Effects of Light Mediator



If a direct dark matter signal is in conflict with collider bounds, a new light state should be introduced to reconcile

24

Caveat #2

 The effective field theory could break down, especially at the I3 TeV LHC



If a direct dark matter signal is in conflict with collider bounds, a new light state should be introduced to reconcile

24

Caveat #2

 The effective field theory could break down, especially at the 13 TeV LHC



* A UV (simple) model is required to interpret data

25

Possibilities



Figure 9: Observed limits on Λ as a function of the mass of the mediator (M), assuming vector interactions and a dark matter mass of 50 GeV/ c^2 (blue) and 500 GeV/ c^2 (red). The width (Γ) of the mediator is varied beev enviolated M/S π .required to interpret data

Table 14: Expected and observed 95% CL upper fimits on Λ_U (in TeV) for S = 0 Unparticles



Simplified Dark Matter Models





★ Z', dilaton, radion ...



Simplified Dark Matter Models



It exists in MSSM

The SUSY searches are still relevant for many DM models



It exists in MSSM

27

The SUSY searches are still relevant for many DM models



Figure 3: Bino-squark coannihilation benchmark sparticle spectrum. I 305.6921, Cahill-Rowley, Cotta, Drlica-Wagner, Funk, Hewett, Ismail, Rizzo, Wood

28

Fermion Portal Dark Matter

Conserving the Lorentz symmetry, at least two particles in the dark matter sector are required

 $m \bullet$

one boson and one fermion

Figure 3: Bino-squark coannihilation benchmark sparticle spectrum. I 305.6921, Cahill-Rowley, Cotta, Drlica-Wagner, Funk, Hewett, Ismail, Rizzo, Wood

28

Fermion Portal Dark Matter

Conserving the Lorentz symmetry, at least two particles in the dark matter sector are required



a Majorana or Dirac Fermion or a scalar dark matter

Fermion Portal DM at the LHC has "signatures" beyond the simplified SUSY DM

29

Quark Portal Dark Matter

 $\mathcal{L}_{\text{fermion}} \supset \lambda_{u_i} \phi_{u_i} \overline{\chi}_L u_R^i + \lambda_{d_i} \phi_{d_i} \overline{\chi}_L d_R^i + \text{h.c.}$



Quark Portal Dark Matter

 $\mathcal{L}_{\text{fermion}} \supset \lambda_{u_i} \phi_{u_i} \overline{\chi}_L u_R^i + \lambda_{d_i} \phi_{d_i} \overline{\chi}_L d_R^i + \text{h.c.}$



Thermal Relic Abundance Majorana fermion dark matter Majorana fermion dark matter Dirac fermion dark matter 2000 Dirac fermion dark matter (CeV) m_{χ} (GeV) $m_{\chi^{-1}}(\text{GeV})$ E

 m_{χ} (GeV)

Dirac and Majozande Gases on diagrams for scattering of a fermion dark matte arly, for ado**coptex**bated at a latter fext in and cits epartuler, bøth (æ) lantrifted to the inter assessors 30



p-wave suppressed

31

Signatures at LHC





^r ¹gurfigure fit Left Fander. The shasses of a Dirac formion data in the data wave support of the share of coupling lafter after instable of physical data and the superstanding of the supersta

Signatures at LHC

at the LHC



Quark Portal Dark Matter





Fig. 3. Feynman Diagrams contributing to jets plus missing energy signals at a hadron collider. For scalar quark partners Q, there is an additional diagram involving the gluon-Q quartic interaction that is not shown.

that they should be taken seriously as phenomenologically-motivated models of d matter under the assumption that a small number of states is relevant. Another po

 $\tau(pp \rightarrow \phi \phi^+)$ (fb)

60

33

QCD and Yukawa Interference



interesting deconstructive interference region

34

Current Allowed Parameter Space







and, while the right panel is in the $\sigma - m_{\chi}$ plane.

We also study the same model, but for the down quark case with only $\lambda_d \neq 0$. For $\lambda_d = 1$, the



Dirac Fermion Dark Matter

the the quark. up-quark



Complex Scalar Dark Matter



up-quark

38

MET Distribution in mono-jet



The 9: 95% exclusion limits from the most sensitive searches for complex scalar dark matter with coupling to the up quark. pling to the up quark. 38

MET Distribution in mono-jet



Majorana third generation





Mr g TTexpolarenmoredermion poetal dark matter parameter space, we emphasize the importance of a

**** χ

Majorana third generation



Chang, Edezhath, Hutchinson, Luty, 1307:8120

40

Lepton Portal Dark Matter

Sin Eplitic Ucork Weaker of Constra hts Ifrom

fermonic (Dirac or Majorana) dark matter particle, χ , we have its partner to be a scala ctric charge +1. The renormalizable operators for the dark matter coupling to the rights are

$$\mathcal{L}_{\text{fermion}} \supset \lambda_i \phi_i \overline{\chi}_L e_R^i + \text{h.c.},$$

 $e^i = e, \mu, \tau$ are different charged leptons. The dark matter mass m_{χ} is smaller than if m_{ϕ} such that ϕ_i has a decay branching ratio of 100% into χ and \overline{e}^i . For a complex some particle, X, we have promer Roberta Dirad terms of M and the interactions as

$$\mathcal{L}_{\text{scalar}} \supset \lambda_i X \overline{\psi}_L^i e_R^i + \text{h.c.}.$$

, we have $\operatorname{Br}(\psi^i \to X + e^i) = 100\%$.

o simplify our discussion, we define the Yukawa couplings in Eqs. (1) and (2) to be in the mass eigenstates, so there is no new contributions to the flavor violation processes matter sector.

41

Lepton g-2

epton-portal models considered here can also generate additional contributions to t alous magnetic moment that any partial part, the bactuar provides the most raint is the $a_{\mu} = (g - 2)_{\mu}/2$. On the other hand, there is a disagreement above 3σ be etical prediction and $\partial \dot{\mu} \phi \dot{\chi}_{\mu} \rho \dot{e}_{R}^{i}$ nental measurement \mathcal{L}_{scalar} quantity. $\overline{\psi}_{\mu}^{i} \rho \dot{e}_{R}^{i}$ pdated and adronic contributions has the SM prediction to be [1]

Lepton anomalous magnetic moment: $a_{\mu}^{\text{SM}} = (11659182.8 \pm 4.9) \times 10^{-10}$,

the experimental measured value is [2,3] $a_{\mu} \equiv (g-2)_{\mu}/2$

$$a_{\mu}^{\text{EXP}} = (11659208.9 \pm 6.3) \times 10^{-10}$$
 hep-ex/0602035, Muon G-2 Collab.
 $a_{\mu}^{\text{EXP}} = (11659208.9 \pm 6.3) \times 10^{-10}$.

Lepton Portal Dark Matter

 $\mathcal{L}_{\text{fermion}} \supset \lambda_i \phi_i \overline{\chi}_L e_R^i \qquad \qquad \mathcal{L}_{\text{scalar}} \supset \lambda_i X \overline{\psi}_L^i e_R^i$

Lepton anomalous magnetic moment:

 $a_{\mu} \equiv (g-2)_{\mu}/2$

 $a_{\mu}^{\text{EXP}} = (11659208.9 \pm 6.3) \times 10^{-10}$ hep-ex/0602035, Muon G-2 Collab.

 $a_{\mu}^{\rm SM} = (11659182.8 \pm 4.9) \times 10^{-10}$

1105.3149, Hagiwara et. al.

 $a_{\mu}^{\text{EXP}} - a_{\mu}^{\text{SM}} = (26.1 \pm 8.0) \times 10^{-10}$

may need a positive contribution from new physics

42

Muon g-2 $\int_{200}^{400} \delta a_{\mu} \times 10^{10} \qquad \lambda = 1$ $\int_{200}^{300} \delta a_{\mu} \times 10^{10} \qquad \lambda = 2.5$



for one

43



ATLAS kept both selectron and smuon and used MT2





Indirect Detection Constraints



44



[see also model-independent constraints: 1306.3983 by Bergstrom, Bringmann, Cholis, Hooper, Weniger; 1309.2570 by Ibarra, Lamperstorfer, Silk]

46

Complex Scalar DM

The annihilation is p-wave suppressed; the indirect detection limits are irrelevant



Complex Scalar DM

The annihilation is p-wave suppressed; the indirect detection limits are irrelevant



47

Direct detection





Agrawal, Chacko, Blanchet, Kilic, 1109.3516

for Dirac fermion DM:

 $\overline{\chi}\gamma^{\mu}(1-\gamma^5)\partial^{\nu}\chi F_{\mu\nu}$



calculated as (see Ref. [6] for more detailed discussion)

$$\sigma_{\chi-\text{nucleon}} = \frac{\mu_{\chi-n}^2 Z^2}{Comp} \left\{ \frac{\lambda^2 e^2}{64\pi^2 m_s^2} \left[1 + \frac{2}{3} \ln\left(\frac{m_{e^i}^2}{r_s^2}\right) \right] \right\}^2.$$
(11)

Here, only the leading order in transferred momentum and lepton mass has been kept. For the electron operator, one could replace the electron mass in the above formula by the typical exchange momentum of $\mathcal{O}(10-100 \text{ MeV})$.

For the complex scalar case, the dominant contribution can be related to the charge radius operator:

$$\partial^{\mu} X \partial^{\nu} \mathcal{K}^{\dagger}(\mathbf{F}_{\mu\nu}, \mathbf{m}_{2}) = t \frac{2\lambda^{2} e}{16\pi^{2}} \left[\frac{m_{1}^{4} - 6m_{1}^{2}m_{2}^{2} + m_{2}^{4}}{(m_{1}^{2} - m_{2}^{2})^{3}} C \frac{4(m_{1}^{2} + m_{2}^{2})(m_{1}^{4} - 5m_{1}^{2}m_{2}^{2} + m_{2}^{4})}{3(m_{1}^{2} - m_{2}^{2})^{4}} \ln \left(\frac{m_{1}}{m_{2}}\right) \right]$$

$$C(m_{1}, m_{2}) = \frac{2\lambda^{2} e}{\mathbf{troe}} \left[\frac{m_{1}^{4} - 6m_{1}^{2}m_{2}^{2} + m_{2}^{4}}{(m_{1}^{2} - m_{2}^{2})^{3}} - \frac{4(m_{1}^{2} + m_{2}^{2})(m_{1}^{4} - 5m_{1}^{2}m_{2}^{2} + m_{2}^{4})}{3(m_{1}^{2} - m_{2}^{2})^{4}} \ln \left(\frac{m_{1}}{m_{2}}\right) \right], \quad (12)$$

where $C(m_1, m_2) \propto (m_1 - m_2)$ in the limit of $m_1 - m_2 \ll 0$. In the limit of $m_1 \ll m_2$, we have $C(m_1, m_2) \simeq (m_1 - m_2)^2 \ll 0$. In the limit of $m_1 \ll m_2$, we have $C(m_1, m_2) = -\frac{2\lambda^2 e}{\frac{16\pi^2 m_2^2}{16\pi^2 m_2^2}} \left[\left[1 + \frac{2}{3} \ln \left(\frac{m_1^2}{m_2^2} \right)^2 \right] \right] \cdot m_1 \ll m_2$ (13)

The SI elastic scattering cross section is calculated to be

Complex scalar DM

$$\partial_{\mu} X \partial_{\nu} X^{\dagger} F^{\mu\nu}$$

$$C(m_1, m_2) = \frac{2\lambda^2 e}{16\pi^2} \left[\frac{m_1^4 - 6m_1^2 m_2^2 + m_2^4}{(m_1^2 - m_2^2)^3} - \frac{4(m_1^2 + m_2^2)(m_1^4 - 5m_1^2 m_2^2 + m_2^4)}{3(m_1^2 - m_2^2)^4} \ln\left(\frac{m_1}{m_2}\right) \right]$$

two interesting limits:

$$C(m_1, m_2) \propto (m_1 - m_2) \qquad m_1 - m_2 \ll 0$$

$$C(m_1, m_2) = -\frac{2\lambda^2 e}{16\pi^2 m_2^2} \left[1 + \frac{2}{3} \ln\left(\frac{m_1^2}{m_2^2}\right) \right] \qquad m_1 \ll m_2$$

$$\sigma_{X-\text{nucleon}} = \frac{Z^2 e^2 C^2(m_{e^i}, m_{\psi})}{8\pi A^2} \left[\frac{m_p^2 m_X^2}{(m_p + m_X)^2} + \frac{m_p m_X^2 (2m_p^2 + m_X^2)}{2(m_p + m_X)^3} v^2 \right]$$

 $\begin{array}{ll} \mbox{for muon and Xenon} & \\ \sigma_{X-\rm nucleon} \approx 6 \times 10^{-45} \ {\rm cm}^2 & \lambda = 1.0 \\ & \\ m_{\psi} = 500 \ {\rm GeV} \end{array}$

49

Stringent constraints from LUX



Stringent constraints from LUX





Can we define MET just based on leptons?

51

Another comment: lepton pt



Another comment: lepton pt



could have a large correlation with MT2

52

Can we repeat the W discovery?

Volume 122B, number 1

PHYSICS LETTERS

24 February 1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT \sqrt{s} = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland



Can we repeat the W discovery?

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Conclusions

- More searches for simplified SUSY or non-SUSY dark matter models should be performed at the LHC
- Dedicated searches in the two jets + MET and two leptons + MET channels have chances to

Conclusions

- More searches for simplified SUSY or non-SUSY dark matter models should be performed at the LHC
- Dedicated searches in the two jets + MET and two leptons + MET channels have chances to discover the Fermion Portal Dark Matter



Thanks

55