# **More Dark Matter Signatures at the LHC**

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Nuclear Aspects of Dark Matter Searches@UWashington

December 11, 2014

## **Hunt of Dark Matter**

### Indirect Detection





### Direct Detection



## **Collider vs. Direct Detection**



- more complicated detector
- know when to produce DM
- don't know whether it is *the* dark matter
- limited for very heavy mass



- less complicated detector
- wait for DM collision
- search for *the* dark matter
- limited for very light mass

# **Different Backgrounds**



- Standard Model processes
- background-rich environment



- backgrounds for detectors
- cosmic rays
- small background

# **Different Interpretation Uncertainties**

- Parton distribution function
- Validity of the model description

### Collider **Direct Detection**

- Nuclear form factor
- Astrophysical: density and velocity distributions

$$
m_c \bar{c} i \gamma_5 c \rightarrow -\frac{\alpha_s}{8\pi} G \widetilde{G}
$$

 $\alpha_s$  $8\pi$  $GG \rightarrow (389 \text{ MeV}) \bar{p} i \gamma_5 p$   $(-2 \text{ MeV}) \bar{n} i \gamma_5 n$ 

Large uncertainties Cheng, Chiang, arxiv:1202.1292

## **Model Independent Signature**



# **Standard Signature: monojet+MET**



### **Fermi-theory for Dark Matter**



### **5 Standard Signature: monojet+MET** certainties include both statistical and systematic components. The last two rows gives  $\mathbf{r}$ expected and observed upper limits, at 95% CL, for the contribution of events from non-SM Ctandard Cignatures manaiat LMET expected and observed upper limits, at 95% CL, for the contribution of events from non-SM





 $\sim$  0.11111.2000 97 systematic errors

Exp. upper limit+1*s* 5940 2470 1200 639 410 221 187

from the modeling of the ISR, which contributes at the level of  $5\%$ 

from the modeling of the ISR, which contributes at the level of 5% for the dark matter models

### Historical "Discovery" of SUSY in Monojet production in the set of the set o



physical phenomenon. The spectacular values of the UA1, PLB, 139, 115 (1984)

### **Historical "Discovery" of SUSY in Monojet** Filstorical Discovery o two-jet final states with particle final states with particle  $\mathcal{S}$  and fulfiller conditions as  $\mathcal{S}$  ,  $\overline{\mathcal{S}}$  ,

SUSY SM





J. Ellis and H. Kowalski, NPB, 246, 189 (1984)

S. Ellis, R. Kleiss and W. Stirling, PLB, 158, 341 (1985)



other radiated particles from proton can be better measured

UV-complete the EFT operators may lead to cleaner signatures

### **EFT Framework**

### leptons are better measured: mono-lepton



YB and Tait, 1208.4361

### mono-Z (dilepton): Bell et. al., 1209.0231

Carpenter: 1212.3352

### **2.4 Danish matter inter-lepton Limits from Mono-lepton** acts with up (u) and  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$ dependent interactions and for low mass ( $\mu$ WIMPS IN THIS ARTICLE, WE EXPLORE THE SIGNATURE WHEN we restrict our discussion to the first general term of the first tion. This interaction leads to spin-independent scatter  $\mathbf{r}_i$  $\blacksquare$ ing with nuclei. We also consider a spin-dependent case and consider a spin-dependent case and case and

1  $\frac{1}{\Lambda^2} \overline{\chi} \gamma_\mu \chi \left( \overline{u} \gamma^\mu u + \xi \overline{d} \gamma^\mu d \right)$  $\left($ a charged lepton and and a neutrino, leading to events charged lepton and a neutrino,  $\frac{1}{\sqrt{2}}$  $\frac{1}{\Lambda^2} \chi \gamma_\mu \chi \left( u \gamma^\mu u + \xi \ d \gamma^\mu d \right)$ 

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





so far, we have considered only initial state radiation of visible particle

Dark sector could be more interesting:

• It may has its own dark  $U(1)'$ 

• It may also have some nearby states

### **Probing Dark U(1)' at the LHC.** will decay back to SM particles and behavior as visible particles at the dark matter of the dark matter matter matter are dark be described by effective higher dimensional operators. For simplicity, we choose dark matter to be  $\kappa$  U(1)′ at the LMU



 $\Box$   $\Box$   $\Box$  The mottor final state radiated a  $\Box$ <sup>*the signal*</sup> Dark matter final state radiated a Z', the signature depends on how Z' decay  $\epsilon$  is distant of  $\mathbf{Z}$ , the signature depends on how Z' decay Dark matter final state radiated a  $\angle$  , the signature

operator dependence models. In different models. In general, the first models. The first models. The first section of the first section of the monometer  $\mathbf{Y}$ YB, James Bourbeau, Tongyan Lin; in progress

cross section !fb"

### **Dark Z' Decay** For the vector-like coupling operator-like coupling operator Overator Overator Overator Can between Z° and up  $\Gamma$  $\blacksquare$ **Source Dark Z Decay** w is zero. This is zero. This is a manifestation of well-known fact in the literature that particles in the li not have a millicharge under the unbroken massless gauge boson [9]. On the other hand, for a nonzero

$$
\frac{\tilde{c}}{\Lambda^2} \left( \phi'^\dagger D_\mu \phi' - \phi' D_\mu {\phi'}^\dagger \right) \left( \overline{u} \gamma^\mu u \right) \qquad \longrightarrow \qquad c \frac{M_{Z'}^2}{\Lambda^2} Z'_\mu \overline{u} \gamma^\mu u
$$

For a heavy Z', the signature is just like mono-QCD-jet + MET, except the production cross section is increased. + MET, except the production cross section is increased. eavy Z', the signature is just like mono-OCD-je with c as an order-one number.  $\alpha$  is a near  $\alpha$  is equal to  $\alpha$  $\cdot$  a heavy Z', the signature is just like mono-QCD-jet  $\hspace{0.1cm}$  $\pm$  MFT except the production cross section is increased of and the operators in terms pions: up and the operators to the operators pions: up and the operators in terms<br>The operators in terms pions: up and the operators in the operators in the operators in the state operators i

For a light  $Z'$  at  $O(1 \text{ GeV})$ , the signature is more interesting  $\overline{u}\gamma_\mu u \to \pi^+ \partial_\mu \pi^- - \pi^- \partial_\mu \pi^+ + K^+ \partial_\mu K^- - K^- \partial_\mu K^+$  $\Gamma(Z' \to \pi^-\pi^+) = \frac{M_{Z'}}{2} \left(\frac{c M_{Z'}^2}{2}\right)^2 \left(1 - \frac{4m_\pi^2}{2}\right)^{3/2}$  $U(\mathcal{U})$  and  $U(\mathcal{U})$  is independent which if  $\mathcal{U}(\mathcal{U})$ For a light Z' at O(I GeV), the signature is more  $\frac{d_{Z^{\prime}}}{8\,\pi}\,\left(\frac{c\,M_{Z^{\prime}}^2}{\Lambda^2}\right)^{-}\,\left(1-\frac{4\,m_{\pi}^2}{M_{Z^{\prime}}^2}\right)^{5/2}$  $\mathbb{Z}^r$  $\Gamma$ (z<sup>/</sup>  $48 \pi \sqrt{T}$  $\Gamma(Z'\to\pi^-\pi^+) = \frac{M_{Z'}}{48\,\pi}$  $\int c M_{Z'}^2$  $\overline{\Lambda^2}$  $\bigg)^2 \left( 1 - \frac{4 \, m_\pi^2}{M_\pi^2} \right)$  $\pi$  $M_{Z^\prime}^2$  $M_{Z'}^2$ <sup>2</sup>  $\left(1 - 4 m_{\pi}^2\right)^{3/2}$  $\rightarrow \pi^+ \partial_\mu \pi^- - \pi^- \partial_\mu \pi^+ + K^+ \partial_\mu K^- - K^- \partial_\mu K^ _{\iota}K^{+}$ A similar formula can be obtained for <sup>Z</sup>′ <sup>→</sup> <sup>K</sup>−K<sup>+</sup> from replacing <sup>m</sup><sup>π</sup> by <sup>m</sup><sup>K</sup> and with a more

 $c_1_0 \approx 3$  cm  $c = 1$ ,  $M_{Z'} = 1$  GeV and  $\Lambda = 1$  TeV  $C_I$  so  $C_{II}$   $C = 1$ ,  $M_Z' = 1$  dev and  $K = 1$  keV  $\tau_0 \approx 3 \text{ cm}$   $\alpha$ M<sup>2</sup> Z′  $c\tau_0 \approx 3$  cm  $c = 1, M_{Z'} = 1$  GeV and  $\Lambda = 1$  TeV

is different from an ordinary quantum and the chiral Lagrangian and Lagrangian to convert the operators in terms i

5

Mono-Z' jet: fewer particles and could be long-lived suppressed pressed phase space factor. For c 1, MZ^ = 1, MZ^

 $\mathcal{F}_{\mathcal{F}}$  axi-vector axi-vector operator, a similar UV completion model can lead to the following operator, a similar operator, a similar  $\mathcal{F}_{\mathcal{F}}$ 

### **Production Cross Sections** a light MZ° with Andrew and approximately valid effective<br>Approximately valid effective and approximately valid effective and approximately valid effective valid effect operator description. As a comparison, we also show the mono-jet production cross sections





# **Jet Substruct**

mZp=2, CDF QCD jet, CDF



vents  $/2$  GeV<br> $\frac{1}{\omega}$ 

vents  $/2$  GeV

0*.*4



## **Jet Substructure Analysis**



One can dramatically reduce the QCD backgrounds regering of  $100$ 

 $\Omega$ 



 $1.0 \rightarrow$  $MET > 350 GeV$ , leading  $R=0.1$  subjet pT fraction

### **Discovery Potential**

YB, James Bourbeau, Tongyan Lin; in progress



 $\mathbf{F}_{\mathbf{G}}$  . The energy constraints on the vector-vector Tag-efficiency: 50% for signal, 2% for QCD



other radiated particles from proton can be better measured

UV-complete the EFT operators may lead to cleaner signatures



### **Higgs Portal Dark Matter**



### **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





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si (Dirac) = | kuning | kunin<br>Si (

<sup>L</sup> d<sup>i</sup>

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### **Lepton-portal Dark Matter**



see also: Chang, Edezhath, Hutchinson, Luty, 1402.7358

Majorana fermion DM has suppressed direct detection case costions due to the epenele moment 20 fb−<sup>1</sup> [42]. Right panel: the dark matter-nucleon scattering cross section as a function of dark essed direct detection-six one- $\sim$   $\sim$   $\sim$   $\sim$   $\sim$   $\sim$ cross sections due to the anapole moment Majorana fermion DM has suppressed direct detection

 $f_{\text{min}}$   $f_{\text{and}}$   $f_{\text{min}}$   $f_{\text{min}}$   $f_{\text{min}}$   $f_{\text{max}}$ Del Nobile, Gelmini, Gondolo, Huh, 1401.4508

matter see Ref. [26, 27] and especially Ref. [28] and especially Ref. [27].

### **Dilepton Signature from Dark Matter**



In addition to the turn-on of Im*M*,

Altmannshofer, Fox, Harnik, Kribs, Raj, 1411.6743 *A*ltmannshofer, Fox, Harnik, Kribs, Raj, 1411.6743 FIG. 2. The discussion of the Magnus Altmannshoter, rox, Harnik, Nribs, Naj, 1411.6743<br>20  $411/742$ 

write the double division in the double division in the double division in the double division in the double distribution of the double division in the double division in the double division in the double division in the d

(pure Dirac limit), = 1*.*8 and *M* = *M* = 500 GeV. Here,

### **Chromo-Rayleigh Interaction of DM** er Cuon or , (1)



 $2.1$  Thermal Relic Abundance  $1$ UV-completed by adding a new QCD-charged scalar

 $\gamma$ B, James Osborne, in progress can only provide a guidance for the potential parameter space in M<sup>X</sup> and Λ<sup>i</sup> for a thermal dark matter. YB, James Osborne, in progress

1

Therefore, the data matter the dark matter the dark matter the dark matter of the operators in  $\bf S$  as a  $\bf S$  of the operators in Eq. (2) and  $\bf S$  and  $\bf S$  on the operators in Eq. (2) and  $\bf S$  on the operators in Eq. can only provide a guidance for the potential parameter space in MX and  $\sim$  a For the first operator, we have the dark matter self-annihilation rate from the process X+10  $\epsilon$  $\frac{10}{\sqrt{2}}$  $\Box$ e<br>Salah<br>Salah glet UV-cor for QCD-singlet UV-completion ≡ s , (3) See also: Buckley, Feld, Goncalves: 1410.6497

 $F_{\rm eff}$  the dark matter self-annihilation rate from the process  $\mathcal{F}_{\rm eff}$ 

### **Chromo-Rayleigh Interaction of DM** and dimension-six operator for two dark matter particles interacting with the gluon field αs

 $\alpha_s$  $4\,\pi\,\Lambda_1^2$  $X^\dagger X G^a_{\mu\nu} G^{a\,\mu\nu}$ 

 $\frac{1}{4} \frac{\partial}{\partial X} (XX - X^{\dagger} X^{\dagger}) G^{a}_{\mu\nu} G^{a \mu\nu}$  $i$   $\alpha_s$  $4\,\pi\,\Lambda_2^2$  $(XX - X^{\dagger} X^{\dagger}) G^{a}_{\mu\nu} \widetilde{G}^{a \, \mu\nu}$ 

**2.1 Thermal Relic Abundance** from mono-jet: current collider bound

2



matter-nucleon scattering cross section from the LHC monojet searches in Fig. 1. In the left panel, we

π3

Λ4

≡ s , (3)

=

2

Table 1: The collider constraints on the cutoff of the effective operators for different dark matter traints are pretty weak. The analysis with  $\sim$ descript Depending on the UV process.<br>The data matter sector contracted than  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and state than  $\frac{1}{2}$ The dark matter the dark matter the dark matter thermal relic abundance calculation based just on the operators in Eq. (2) The constraints are pretty weak.<br>The constraints are pretty weak. The EFT description breaks down for a mass above 100 GeV.

### UV Completion of the cRayleigh Interaction approximation with  $\mathbf{c}_1$

$$
\mu_G d_{abc} G^a_H G^b_H G^c_H \qquad \qquad \Gamma(G_H \to gg) = \frac{15 \alpha_s^2 \mu_G^2}{128 \pi^3 M_{G_H}} \left(\frac{\pi^2}{9} - 1\right)^2
$$

The pair-produced dijet resonances can be used to  $\overline{\phantom{a}}$ constrain this UV model as in Ref. [24], we have re



..

MG<sup>H</sup> ! 420 GeV , for Z2-even G<sup>H</sup> , (15)

# **Conclusions**

- ★ There are more collider signatures for discovering dark matter particles
- $\star$  Dark matter can radiate its own charged Z' and have a mono-z' jet
- ★ One class of simplified fermion-portal dark matter models can lead to dijet+MET, dilepton+MET and even just a dilepton bump
- ★ A UV completed dark matter model can usually have a higher chance to be discovered at the LHC

