Dark matter (and relaxions) beams at proton fixed target experiments

28 July 2016 CERN ‘Charting the unknown’
Probing
dark matter/nucleon
coupling at neutrino facilities

in collaboration with B.Dobrescu, P.Coloma and R.Harnik
Dark matter direct detection

dark matter scattering off nuclei

100 eV rms ionization
50 eV rms phonons

$8^B$ solar neutrinos

Surface rejection demonstrated $<0.6 \text{evt/0.3 ton yr}$

Cylindrical Surface rejection still needs to be satisfactorily demonstrated
Dark matter direct detection

dark matter scattering off nuclei

Insensitive to DM lighter than few GeV
What about LDM?

Recently a lot of effort has been put on filling this gap by the theory community.

**Direct detection:**
- electron-DM interaction more promising direction

Essig, Mardon, Volansky 2011  
Essig et al 2015  
Zurek et al. 2015

Can we measure nucleon dark matter coupling?

**Yes at neutrino facilities**

*we can produce relativistic DM beams*

Batell, Pospelov and Ritz 2009
Looking for light dark matter
@ neutrino short baseline experiments
Batell, Pospelov and Ritz 2009
Quarks/dark sector portal

\[ \frac{g_z}{2} Z' \mu \frac{1}{3} \sum_q \bar{q} \gamma_{\mu} q \] \[ \frac{g_z}{2} Z' \mu \chi \bar{\chi} \chi \]

it could be the DM particle or a particle of a more complex dark sector

- indirect production, i.e. mesons decay
- direct production, i.e. resonant $Z'$ production

\[ pp \rightarrow Z' \rightarrow \chi \bar{\chi} \]

We produce a dark matter beam!
Basic idea: we produce a DM beam

and we look for DM-nuclei scattering inside the near detector

Weak point: neutrino background irreducible bkg

Very large number of events required
DM search @ Miniboone

Batell et al, 2013

8 GeV proton on target - reach up to 1 GeV in mV

DM is produced via meson decay

Signal process:
elastic DM nucleon scattering

How many signal events do we get?
DM search @ Miniboone

Batell et al, 2013
DM search @ Miniboone

What about the neutrino bkg? Order $10^4$ NC events
DM search @ Miniboone

Neutrino bkg reduction
proton beam dump + time flight decay
DM search @ Miniboone

Batell et al, 2013

What about heavier masses?
Dark matter beams at the Fermilab main injector

• 120 GeV (14 GeV CME) protons from Main Injector at Fermilab hitting a carbon target
  
  it can extend the reach of MiniBoone towards heavier DM and Z’!

\[ pp \rightarrow Z' \rightarrow \chi\chi \]

• Resonant Z’ production

Several near detectors to consider Minos, NOVA and Minerva
What is the DM signal inside these detectors?

DM particles are fairly energetic $M_Z = 3 \text{ GeV}$

$\frac{1}{\sigma} \frac{d\sigma}{dE} (\text{GeV}^{-1})$

$E (\text{GeV})$

NOVA

MINOS

DM particles are fairly energetic
What is the DM signal inside these detectors?

DM particles are fairly energetic.

\[ M_{Z^0} = 3 \text{ GeV} \]

\[ E_{\chi} = \frac{m^2_{Z'}}{2E_{Z'}(1-\beta \cos \theta)} \]

Dobrescu & CF, JHEP 1502 (2015) 019

DM particles are fairly energetic.
DM energy profile inside the detector

DM energetic - deeply inelastic events

for lighter DM
Soper et al. 2014

DM particles are fairly energetic
Number of DM DIS scattering events in NOVA

$N_{POT} = 10^{21}$
Number of DM DIS scattering events in NOVA

what about neutrinos?

Dobrescu & CF 2014
Neutrinos energy profile

\[ E_\nu = \frac{m_\pi^2 / K}{2E_\pi / K (1 - \beta \cos \theta)} \]

\[ E_\chi = \frac{m_{Z'}^2}{2E_{Z'} (1 - \beta \cos \theta)} \]

Dark matter more energetic (peak around 20-30 GeV)
Neutrino energy profile peaked at a few GeV

Naive idea: in order to reduce neutrino bkg we focus on the more energetic events

Deep inelastic scattering

Cut on hadronic energy $E_j > 2$ GeV
Deep inelastic scattering

Naive idea: in order to reduce neutrino bkg we focus on the more energetic events

Cut on hadronic energy $E_j > 2$ GeV

still a big neutrino tail!
$10^6$ bkg NC DIS events-not enough to have sensitivity!
Neutrino energy profile peaked at a few GeV

**Naive idea:** in order to reduce neutrino bkg we focus on the more energetic events

**Deep inelastic scattering**

Can we kill the neutrino bkg more efficiently or shall we forget about these experiments?
Neutrinos energy profile

\[ E_\nu = \frac{m_\pi^2/\xi}{2E_\pi/\xi(1-\beta \cos \theta)} \]

large tail of neutrinos coming from kaon decays
Neutrinos energy profile

\[ E_\nu = \frac{m_\pi^2 / K}{2E_\pi / K (1 - \beta \cos \theta)} \]

off axis detectors to kill bkg!

large tail of neutrinos coming from kaon decays
We have already an off axis detector!

$\theta_{MB} \sim 6.5^\circ$

off axis

700 m

120 GeV p beam

graphite target

absorber

Mini-Microboone

NOVA

minos

$pp \rightarrow Z' \rightarrow \chi\chi$

DM particle enter the near detector and scatter with nuclei
Dm energy inside Miniboone

$d\Phi_\chi/dE_\chi$ vs $E_\chi$ (GeV)
$E_\nu = \frac{m_\pi^2/K}{2E_\pi/K(1-\beta \cos \theta)}$
Going off axis we kill efficiently neutrino bkg- what would be an optimal location for a LBNF detector?
Ideal position for a future LBNF detector

\[ g_z = 0.1 \]

contours of \( \frac{S}{\sqrt{B}} \)

miniboone

optimal

Off-axis angle [°]

L [m]
\( \chi^2 \text{ contour} \)

![Graph showing the \( \chi^2 \) contour with different regions for optimal and SBL location.](image)
Miniboone location close to optimal!

Ideal detector for SHIP? New study of neutrino bkg needed (work in progress with P.Coloma)
Lighter masses work in progress with P. Coloma
How do we probe the lighter mass region

- Production via meson decay (Batell&co)
  good but need a special run in proton beam dump

- What about direct production?

\[
pp \rightarrow Z' \quad \text{below threshold}
\]

\[
\text{NLO process} \quad pp \rightarrow Z' j \quad p_t > 1 \text{ GeV}
\]

pQCD requires partonic scale must be $>1$ GeV
Limits

Strongest bounds on the market above kaon threshold

$\alpha_B \sim 10^{-4}$
Strongest bounds on the market above kaon threshold

A significant improvement over the whole parameter space can be achieved only trying to find new observables for invisible decays at proton fixed target experiments.
Outlook

• Neutrino facilities could offer the possibility to probe light DM/quarks couplings.

• Off axis near LBNF detector could set the strongest bounds available on few GeV leptophobic, but Miniboone/Microboone collaboration must look at their data!

• BSM physics program can be parasitic to LBNF neutrino program!

• Dark matter detector for SHIP

• Strong motivation to think about new observable at proton fixed target experiments to measure invisible decays
Other physics opportunities?

Relaxion beams at proton fixed target experiments

work in progress
with T.Flacke, E.Fuchs, R. Gupta and G.Perez
A dynamical solution to the hierarchy problem

Non QCD relaxion

\[ V(H) = \mu^2(\phi) H^\dagger H + \lambda (H^\dagger H)^2 \]

\[ \mu^2(\phi) = -\Lambda^2 + g\Lambda \phi + \ldots \quad \Lambda \gg \nu \]

The initial value of the Higgs mass is positive and large

\[ \phi > \Lambda/g \]

During inflation the relaxion slow roll and scan the mass of the Higgs

\[ V(\phi, H) = g\Lambda^3 \phi + \ldots \]

slow roll term
the quadratic term cross the zero so the Higgs gets a vev

$$\phi > \frac{\Lambda}{g}$$

$$V(\phi, H) = r g \Lambda^3 \phi + \tilde{M}^{4-j} \hat{h}^j \cos \left( \frac{\phi}{f} \right)$$

height of the barrier starts to grow and at some point stops the rolling of the relaxion
the quadratic term cross the zero so the Higgs gets a vev

\[ \phi > \Lambda/g \]

The rolling stops when

\[ \Lambda^3 \sim \frac{\tilde{M}^{4-j} v^j}{\sqrt{2^j} g f} \]

so for small very small value of g we could get the EW scale from a high scale

cosmological upper bound on the cutoff

\[ \Lambda \lesssim \left( \frac{\tilde{M}^{4-j} v^j}{f} \right)^{1/6} \sqrt{M_{Pl}} \]

not a solution to the full hierarchy problem
How do we probe this scenario?

We might have some LHC signals, but very model dependent

Can we look for the relaxion?

We generically expect the relaxion is a (very) weakly coupled light particle

Hierarchy problem at the low energy frontier!

What is its mass? How does it couple to the SM?

Which experiments can probe it?
consider the following back reaction \( \Delta V_{br} = \tilde{M}^2 H^2 \cos\left(\frac{\phi}{f}\right) \)

\[
m^2 \phi \sim \frac{\tilde{M}^2 v^2}{2f^2} \left(1 - \frac{2\tilde{M}^2}{m_h^2}\right)
\]

the relaxion mixes with the Higgs

\[
\sin \theta \sim \frac{v}{f} \frac{\tilde{M}^2}{m_h^2}
\]

Higgs portal model constraints apply!
Higgs/relaxion mixing

consider the following back reaction \( \Delta V_{br} = \tilde{M}^2 H^2 \cos \left( \frac{\phi}{f} \right) \)

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m^2_\phi \sim \frac{\tilde{M}^2 v^2}{2 f^2} \left( 1 - \frac{2 \tilde{M}^2}{m^2_h} \right)
\]

the relaxion mixes with the Higgs

\[
\sin \theta \sim \frac{v}{f} \frac{\tilde{M}^2}{m^2_h}
\]

Higgs portal model constraints apply!
\[ f \sim \Lambda \sim 50 \text{ TeV} \]
\[ \sin \theta \sim 10^{-4} - 10^{-8} \]

\[ f \sim \Lambda \sim 1000 \text{ TeV} \]
lighter relaxion
& more weakly coupled
MeV region probes

proton fixed target experiments could probe the region of low cutoff for relaxion models
Low energy probes of the relaxion

- fifth force experiments
- powerful bound also for models with higher cutoff
- supernovae
- beam dump and rare meson decays

$p^5$ expansion:

$\phi(k) = g(k^3 f) + \cdots$
Low energy probes of the relaxion

Relaxion models provide a new strong motivation to keep improving the reach and the precision of the low energy frontier.
Low energy probes of the relaxion

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Thank you!