Searching for Dipolar Dark Matter in Beam Dump Experiments

Soumya Rao

National Centre for Nuclear Research (NCBJ),
Warsaw.

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Beam Dump Experiments

- Direct and indirect searches for Dark Matter(DM) have been analysed in various models of DM
- Complimenting these searches are the so called **beam dump experiments** or **fixed target experiments**
- Beam dump experiments involve high energy beam incident on fixed target
- DM particles are produced in the high energy collision, subsequently detected in suitable detector
- We focus here on **E613** experiment conducted at Fermilab originally to study prompt muon neutrino production
- Advantage of such experiment over direct detection is higher luminosity
- On the other hand only light DM masses can be probed (1-10 GeV)

Dipolar DM model

- Previously *Soper etal, Phys. Rev. D* **90**, *no. 11, 115005 (2014)*, discussed E613 constraints on DM in context of dark vector boson
- We follow the same approach to study constraints on "Dipolar DM" model
- Dipolar DM model assumes DM couples to photons via loops to give rise to electric and magnetic dipole moments
- Effective lagrangian for dipolar interactions :

$$\mathcal{L}_{ddm} = -\frac{i}{2}\bar{\chi}\sigma_{\mu\nu}(\mu + \gamma^5\mathcal{D})\mathcal{F}^{\mu\nu}$$

E613 Beam Dump Experiment

- E613 experiment comprises of a 400 GeV proton beam that strikes a Tungsten target producing a beam of DM particles which pass through appropriate shielding
- A lead detector placed after the shielding then detects these DM particles as they scatter off lead nuclei

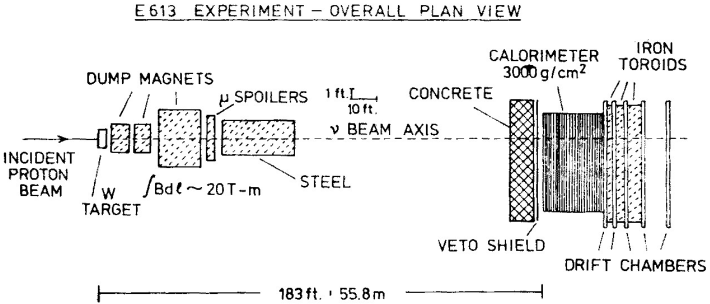
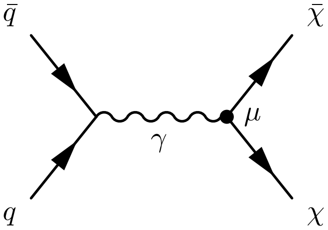


Fig. 2. E613 overall plan view

DM production from proton beam

- DM particles are produced when proton beam strikes the Tungsten target



- Calculate cross section for the process $p\,p \to \chi\chi$ (using MadGraph)
- Distribution of DM thus produced is

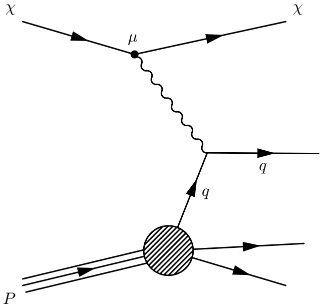
$$\frac{dN}{dEd\theta} = A\frac{d\sigma(pp \to \chi\chi)}{dEd\theta} L_T n_T n_p$$

- No. of DM particles produced is restricted by detector geometry,

$$\frac{dN}{dE} = \int_0^{\theta_{max}} d\theta \frac{dN}{dEd\theta}, \;\; \theta_{max} = 0.0134$$

Deep Inelastic Scattering of DM

- Scattering of light DM particles produced from a 400 GeV proton beam can be treated as deep inelastic scattering (DIS)
- DIS of DM involves dipolar interaction DM with quarks via photon



Deep Inelastic Scattering of DM

- Following DIS formalism we can write

$$\frac{d\sigma}{d\nu dQ^2} = \frac{e^2 g^2_{dipole}}{16\pi m_N (E_\chi^2 - m_\chi^2)} \frac{L^{\mu\nu} W_{\mu\nu}}{Q^4}$$

- We calculate the leptonic piece as
  μDM :

$$L^{\mu\nu} = Q^2 \left[4 p_\chi^\mu p_\chi^\nu - 2\left(k^\mu q^\nu + q^\mu k^\nu\right) + q^\mu q^\nu\right] - 4 m_\chi^2 \left(Q^2 g^{\mu\nu} + q^\mu q^\nu\right)$$

EDM :

$$L^{\mu\nu} = Q^2 \left[4 k^\mu k^\nu - 2\left(k^\mu q^\nu + q^\mu k^\nu\right) + q^\mu q^\nu\right]$$

Deep Inelastic Scattering of DM

- Finally we end up with the differential scattering cross section μDM :

$$d\sigma = \frac{e^2\mu^2}{16\pi}\frac{d\nu dQ^2}{E^2-m_\chi^2}\frac{\nu}{Q^4}\left[\frac{Q^2\left(2E-\nu\right)^2}{\nu^2+Q^2} - Q^2 + 4m_\chi^2\right]\sum_q x f_{q/A}(x,Q^2)$$

  EDM :

$$d\sigma = \frac{e^2\mathcal{D}^2}{16\pi}\frac{d\nu dQ^2}{E^2-m_\chi^2}\frac{\nu}{Q^4}\left[\frac{Q^2\left(2E-\nu\right)^2}{\nu^2+Q^2} - Q^2 - 4m_\chi^2\right]\sum_q x f_{q/A}(x,Q^2)$$

- We use pdfs for lead nucleus provided at leading order by Hirai-Kumano-Nagai

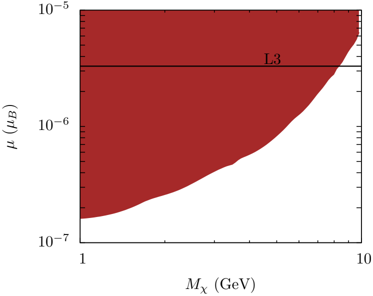
E613 constraint

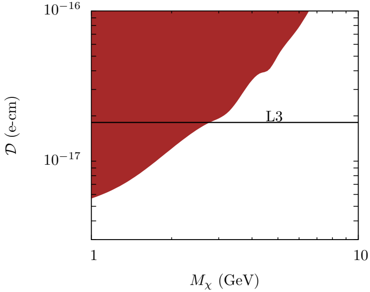
- The differential scattering cross section is then integrated over the following limits

$$E_{\rm cut} < \nu < E - m_\chi \tag{1}$$
$$Q_l^2 < Q^2 < 4(k^2 - E\nu) - Q_l^2 \tag{2}$$

where $Q_l^2 = \dfrac{2m_\chi^2\nu^2}{k^2 - E\nu + \sqrt{(k^2 - E\nu)^2 - m_\chi^2\nu^2}}$ with $k^2 = E^2 - m_\chi^2$
and $E_{\rm cut} = 20$ GeV

- Cross section so obtained gives the MFP $\lambda = \rho\sigma$ and the probability of DM scattering inside detector, $P = 1 - e^{-L/\lambda}$
- Total no. of events : $N_{\rm ev} = \int dE\,[P_{\rm Pb}(1 - P_{\rm Fe})]\,\dfrac{dN}{dE}$
- Only those values of *mchi*, μ and $\mathcal{D}$ allowed for which no. of events less than 180





- L3 - limit on dipole moment from search for new physics in single photon production in e^+e^- annihilation at Z resonance
- Bound on magnetic dipole moment of DM from helioseismological data is estimated to be 1.6×10^{-17} e-cm, for DM mass < 4.3 GeV (Lopes etal, Astrophys. J. Lett. **780**, L15 (2014))

Summary

- We study constraint from Beam Dump experiment E613 consisting of a 400 GeV proton beam striking Tungsten target in context of Dipolar DM model
- We see a low mass region (1-10 GeV) of DM which is additionally constrained by E613
- Bounds from solar physics data are also broadly compatible with this mass range and dipole moment
- Dipolar DM model offers an alternative that is compatible with constraints from wide ranging experimental data from beam dump experiments to helioseismology
- Future experiments like the new fixed target facility proposed at the CERN SPS called SHiP (Search for Hidden Particles) can explore this possibility

Outlook

- Work in progress to analyse searches for vector portal dark matter or dark photon model in beam dump experiments involving electron and proton beams in collaboration with Leszek Roszkowski, Luc Darme(NCBJ) and Arghya Choudhury(Sheffield University)