

# Detecting Dipolar Dark Matter in Beam Dump Experiments

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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)

- Previously *Soper et al, 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
- The effective lagrangian for such interactions can be written as

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

# 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

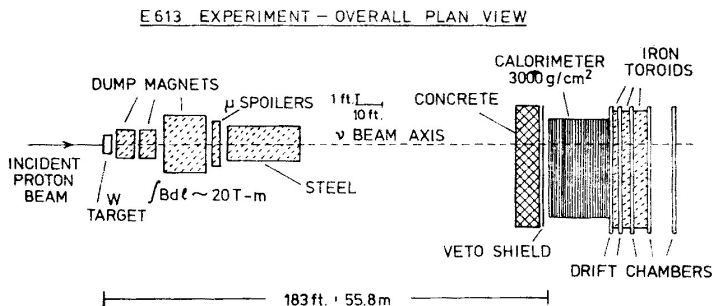
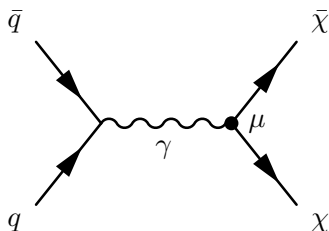


Fig. 2. E613 overall plan view

# DM production from proton beam

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



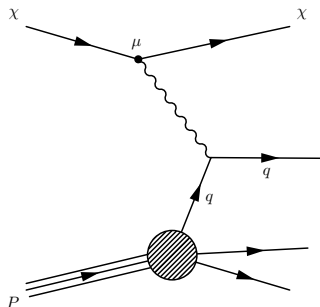
- Calculate cross section for the process  $pp \rightarrow \chi\chi$  (using MadGraph)
- Distribution of DM thus produced is

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

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

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

- 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



- Following DIS formalism we can write

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

- We calculate the leptonic piece as  
 $\mu$ DM :

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

EDM :

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

- Finally we end up with the differential scattering cross section  $\mu$ DM :

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

EDM :

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

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



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

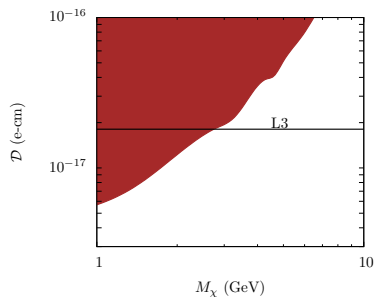
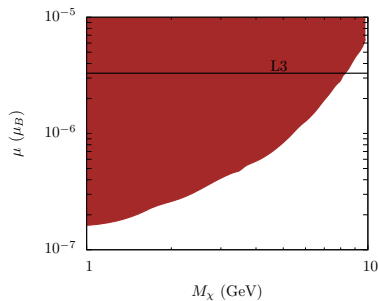
$$E_{\text{cut}} < \nu < E - m_\chi \quad (1)$$

$$Q_I^2 < Q^2 < 4(k^2 - E\nu) - Q_I^2 \quad (2)$$

where  $Q_I^2 = \frac{2m_\chi^2\nu^2}{k^2 - E\nu + \sqrt{(k^2 - E\nu)^2 - m_\chi^2\nu^2}}$  with  $k^2 = E^2 - m_\chi^2$

and  $E_{\text{cut}} = 20 \text{ GeV}$

- 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 :  $N_{\text{ev}} = \int dE [P_{\text{Pb}}(1 - P_{\text{Fe}})] \frac{dN}{dE}$
- Only those values of  $m_{\text{chi}}$ ,  $\mu$  and  $\mathcal{D}$  allowed for which no. of events less than 180



- Bound on magnetic dipole moment of DM from helioseismological data is estimated to be  $1.6 \times 10^{-17}$  e-cm, for DM mass  $< 4.3$  GeV (Lopes et al, *Astrophys. J. Lett.* **780**, L15 (2014))
- Momentum and/or velocity dependent scattering of DM find most favorable DM mass to be  $\sim 3$  GeV (Vincent et al, *JCAP* **1508**, no. 08, 040 (2015))

- 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 strongly constrained by Beam Dump experiment
- 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