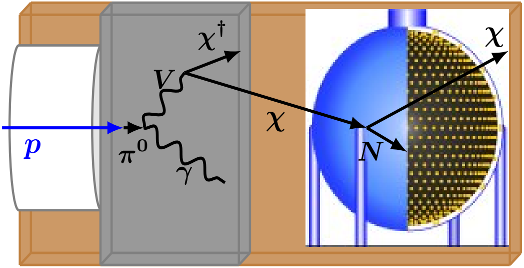


sub-GeV DM Searches at FNAL

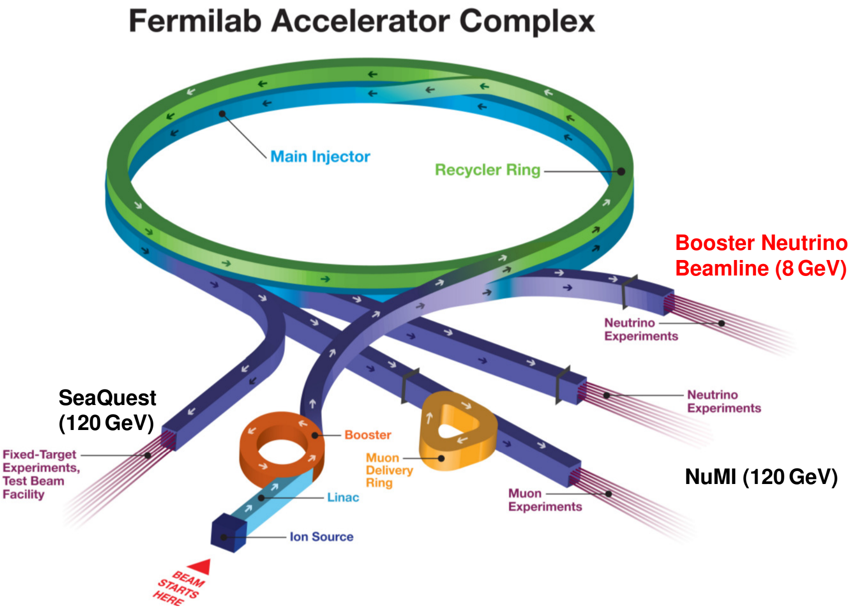
R. T. Thornton

MiniBooNE-DM Collaboration

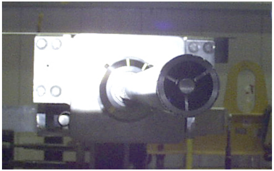
LDMA17 - Isola d'Elba

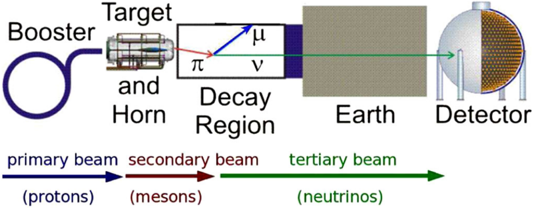
INDIANA UNIVERSITY

Fermi National Accelerator Laboratory

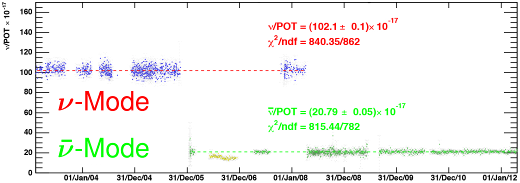


Booster Neutrino Beamline



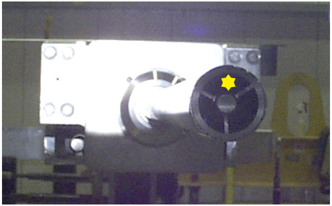


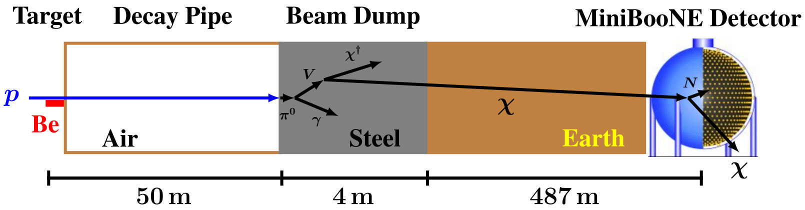
- Beam: 8 GeV protons
- Target: Be
- Distance to MiniBooNE: 541 m
- Stable and "well-understood" beam



Beam Dump (Off-Target) Mode

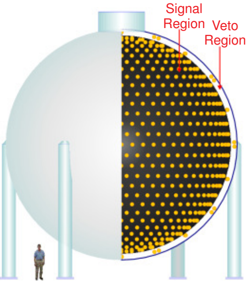
- Can reduce νs by steering beam past target
- Target is air cooled $\Rightarrow$ can run beam so target is not hit



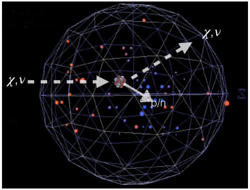


- Charged mesons are absorbed in the steel beam dump before decaying $\Rightarrow$ reduces the measured ν flux

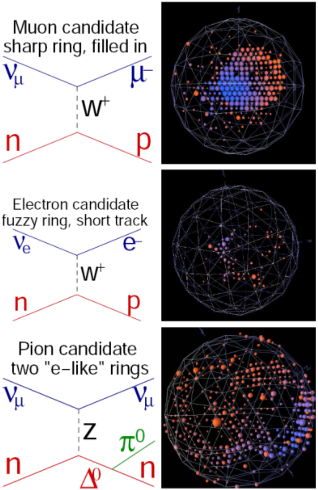
MiniBooNE Detector



Neutral-Current Nucleon (NCE)

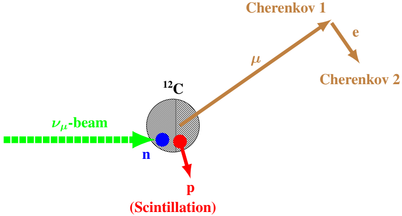


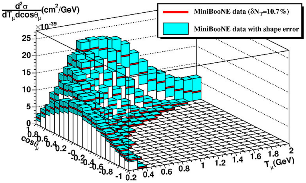
- 800 tons of mineral oil (CH_2)
- Cherenkov tracking detector with scintillator component
- 1280 inner and 240 veto PMTs.
- Ran for a decade in $\nu/\bar{\nu}$ Modes and has obtained/published 27 papers
- ***The detector is well understood***
- This analysis focuses on NCE interactions



Neutrino Interaction Channels

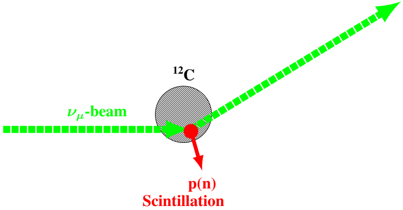
Charge-Current Quasi-Elastic (CCQE)[1]

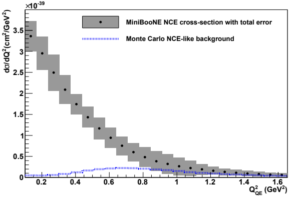




First ν double-differential CCQE cross section measurement

Neutral-Current Elastic (NCE)[2]



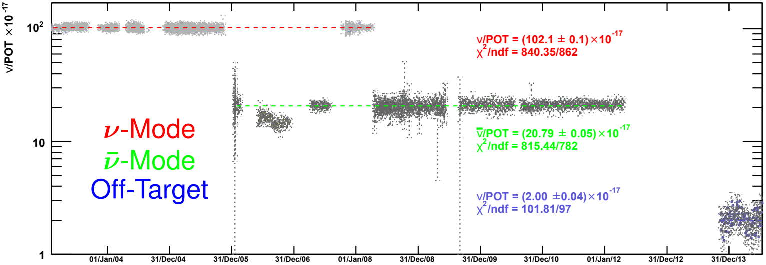


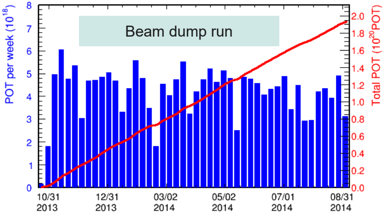
Produced absolute and relative cross sections

[1] A. A. Aguilar-Arevalo et al., Phys. Rev. **D81**, 092005 (2010), arXiv:`1002.2680 [hep-ex]`

[2] A. A. Aguilar-Arevalo et al., Phys. Rev. **D82**, 092005 (2010), arXiv:`1007.4730 [hep-ex]`

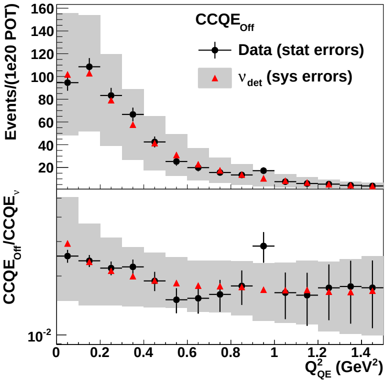
Off-Target Run Stability

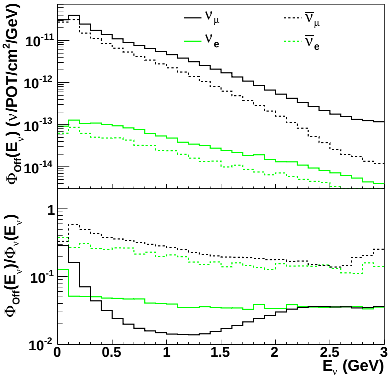




- Ran 9 months, Nov 2013 to begining of Sept. 2014, collected 1.86×10^{20} POT
- CCQE ν “event”/POT decreased by $\sim$50 compared to ν-Mode

Off-Target Neutrino Flux



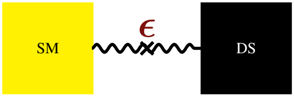


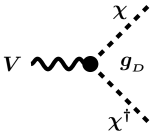
- Event rate reduced by $\simeq 50$
- Flux rate reduced by $\simeq 30$

Vector Portal Kinetic Mixing Theory

Four Free Parameters

- $m_\chi \rightarrow$ mass of dark matter (χ)
- $m_V \rightarrow$ mass of dark vector mediator ("dark photon") (V)
- $\epsilon \rightarrow$ kinetic mixing angle between V and SM photon
- $\alpha_D = g_D^2/4\pi \rightarrow$ coupling constant between V and χ





Annihilation Cross Section

$$\sigma v \sim \alpha_D \epsilon^2 \alpha \times \frac{m_\chi^2}{m_V^4} \rightarrow Y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_V}\right)^4 \Rightarrow \sigma v \sim \frac{Y\alpha}{m_\chi^2}$$

$Y \equiv$ Dimensionless parameter controlling cross section

---

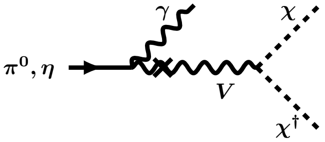
[2] C. Boehm and P. Fayet, Nucl.Phys. **B683**, 219 (2004), arXiv:hep-ph/0305261 [hep-ph], C. Boehm et al., Phys.Rev.Lett. **92**, 101301 (2004), arXiv:astro-ph/0309686 [astro-ph]

[2] B. Batell et al., Phys.Rev.Lett. **113**, 171802 (2014), arXiv:1406.2698 [hep-ph]

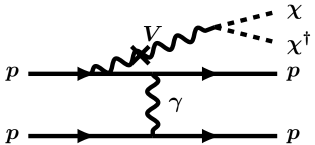
Light Dark Matter: Production and Detection

Production $\left(O\left(\epsilon^2 g_D\right)\right)$

Neutral-Meson Decay

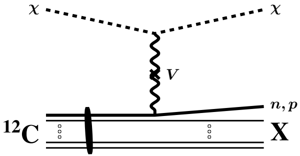


Proton Bremsstrahlung

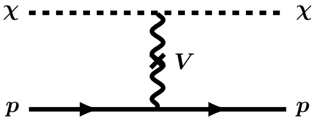


Detection $\left(O\left(\epsilon^2 g_D\right)\right)$

Elastic Bound Nucleon



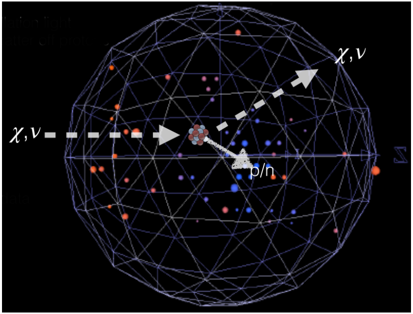
Elastic Free Nucleon



N-DM event selection

Single p/n Track

- 1 track (single recoil) in beam timing window
- Event is centralized contained
  - No activity in the veto
  - Within tank fiducial volume
- Signal above visible energy and number of hits threshold
- PID: nucleon or electron



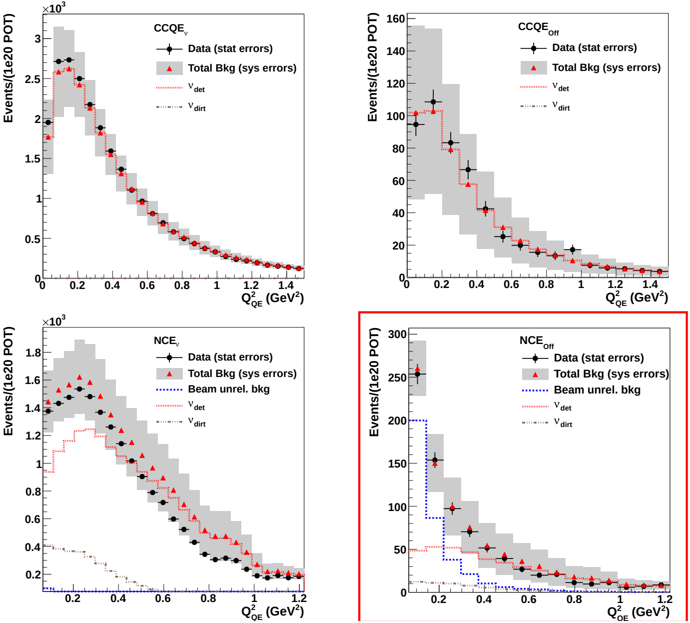
Based on the $\bar{\nu}$-NCE cross section analysis [1]

[1] A. A. Aguilar-Arevalo et al., Phys. Rev. **D91**, 012004 (2015), arXiv:1309.7257 [hep-ex]

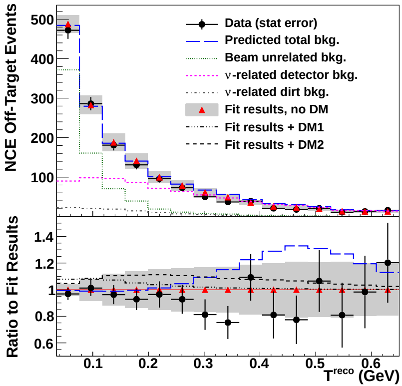
Fit Strategy

Do a combined fit as a function of Q^2_{QE} (reconstructed four momentum squared) to reduce systematic effects on $\mathrm{NCE_{Off}}$

Include nuisance parameters to better fit NCE ν – Mode data



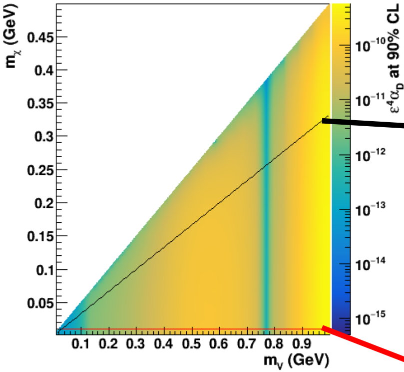
Null Fit Results

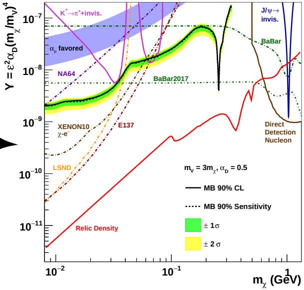


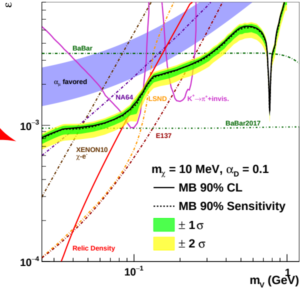
	#events	uncertainty
Beam unrel. bkg	697	
Beam rel: ν_{det} bkg	775	
Beam rel: ν_{dirt} bkg	107	
Total Bkg	1579	34% (pred. sys.)
Data	1465	3% (stat.)
Fit Results	1548	13% (fit effective error)

- Data consistent with background only
- Systematics dominated
- Constraint samples reduce systematics to 13%
- Detailed simulation to predict DM interactions in detector (arXiv:1609.01770)
- DM1
  - m_V = 10 MeV
  - m_χ = 1 MeV
  - $\epsilon^4 \alpha_D = 8.1 \times 10^{-14}$
- DM2
  - m_V = 769 MeV
  - m_χ = 381 MeV
  - $\epsilon^4 \alpha_D = 1.3 \times 10^{-14}$

90% Confidence Limits Results (arXiv:1702.02688)

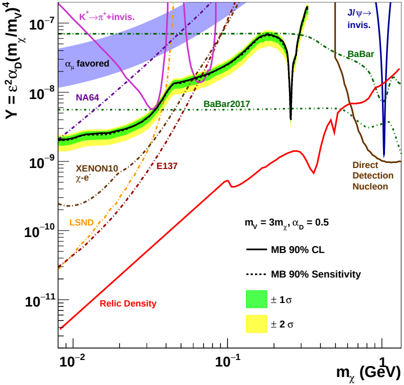


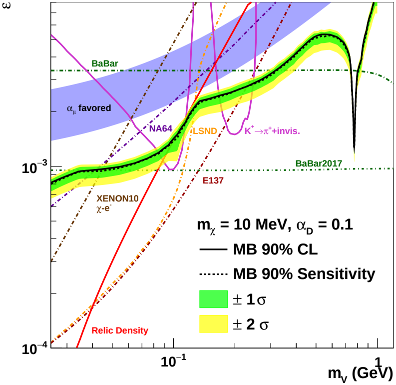




- Only considered on-shell decay ($m_V > 2m_\chi$)
- CL in $\epsilon^4\alpha_D$ for a given m_V, m_χ
- Slice space to compare to other experiments

Confidence Limit Results (arXiv:1702.02688)



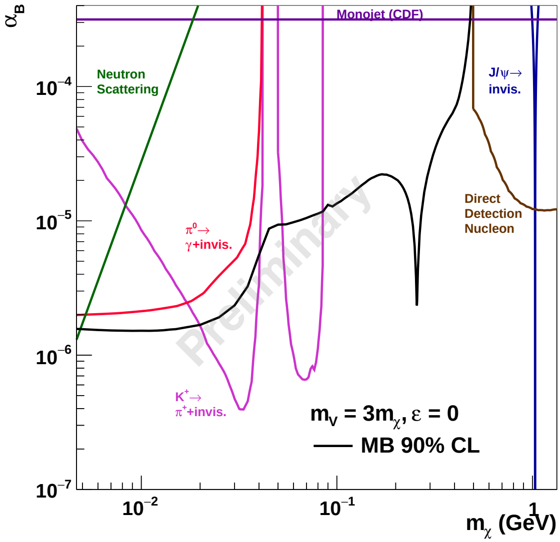


- **Relic density** line is where this model satisfies the thermal relic
- Dip in confidence limit is from increase production around m_ρ
- Exclude where this model solves muon g-2 discrepancy in most parameter space
- Exclude where this model matches relic density in some parameter space
- Exclude new parameter space regions
- Cover most of the gap between 1 MeV $< m_\chi <$ direct detection

Future: MiniBooNE N-DM Analysis: Model Independent Fit

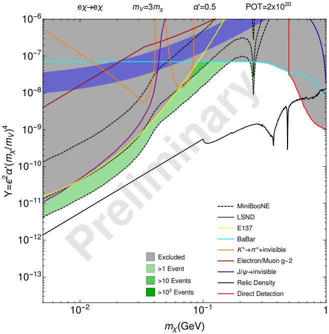
- Results in efficiency corrected excess nuclear recoil events as a function of true nuclear recoil energy
- This will be in a data release with covariance matrix
- Integrated = 130 ± 270 events/1e20 POT (last bin goes out to 2 GeV)
- Used by theorist to test other DM models

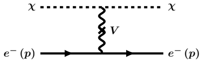
Leptophopic Model



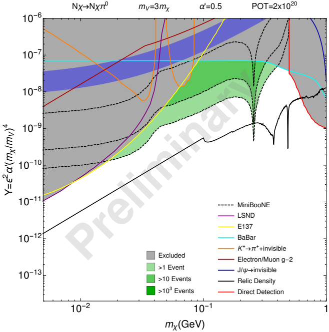
Future: MiniBooNE

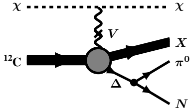
Electron Scattering





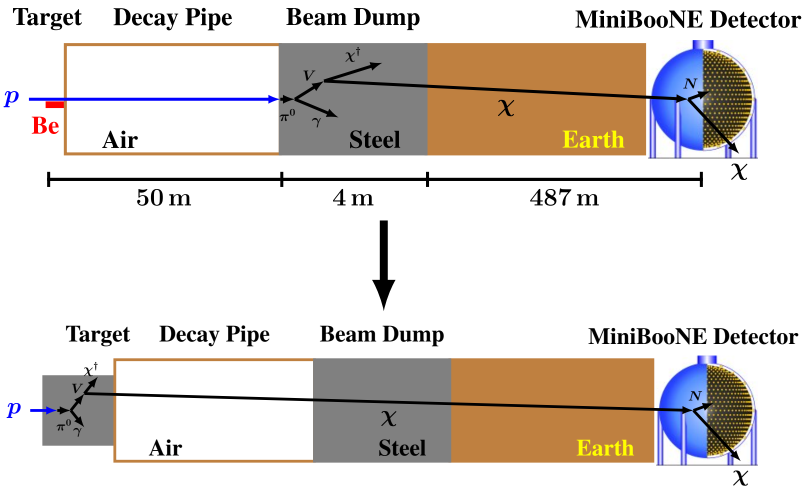
π^0 Production



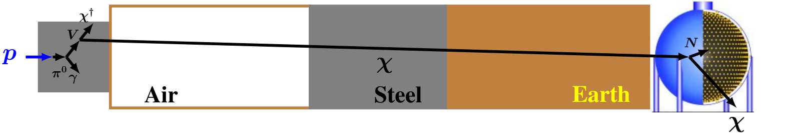


- Future MiniBooNE analysis is promising
- Electron and π^0 sensitivity plots provided by Patrick deNiverville

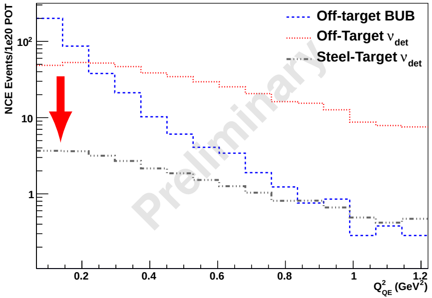
Future: Possible New Beam Configuration



Future: Possible New Beam Configuration

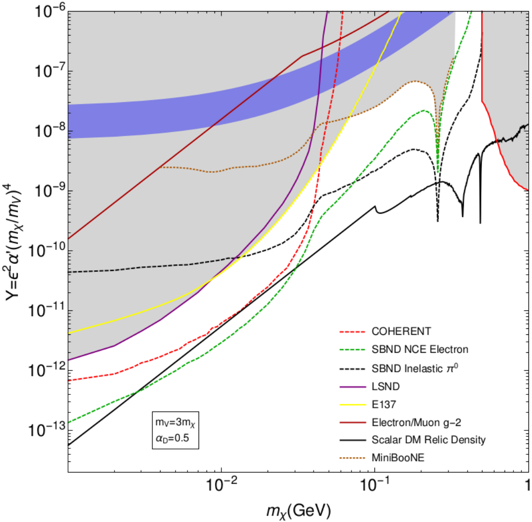


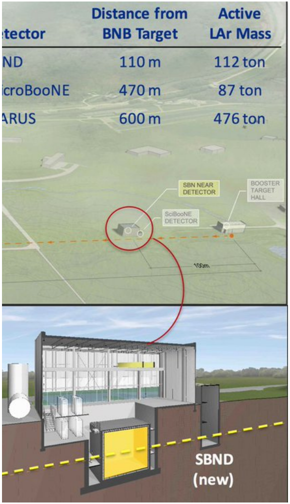
- Initial look shows neutrino event rate suppressed by $\sim$20 compared to Off-Target running



Prediction at MiniBooNE for illustration

Future: Short Baseline Near Detector





- Predicted sensitivities for SBND electron and π^0 channels with 6×10^{20} POT and steel target
- Plot from Patrick deNiverville

MiniBooNE-DM Collaboration

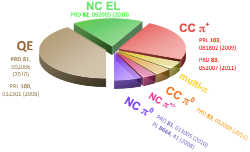
A.A. Aguilar-Arevalo [1] M. Backfish [3] A. Bashyal [15] B. Batell [2] B.C. Brown [3] R. Carr [4] A. Chatterjee [15] R. Cooper [5,12] P. deNiverville [6] R. Dharmapalan [7] Z. Djurcic [10] R. Ford [3] F.G. Garcia [3] G. T. Garvey [8] J. Grange [9,10] J.A. Green [8] W. Huelsnitz [8] I. L. de Icaza Astiz [1] G. Karagiorgi [4] T. Katori [11] T. Kobilarcik [3] W. Ketchum [8] Q. Liu [8] W.C. Louis [8] W. Marsh [3] C.D. Moore [3] G.B. Mills [8] J. Mirabal [8] P. Nienaber [13] Z. Pavlovic [8] D. Perevalov [3] H. Ray [9] B.P. Roe [14] M.H. Shaevitz [4] S. Shahsavarani [15] I. Stancu [7] R. Tayloe [5] C. Taylor [8] R.T. Thornton [5] R. Van de Water [8] W. Wester [3] D.H. White [8] J. Yu [15]

[1] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, D.F. México
[2] University of Pittsburgh, Pittsburgh, PA 15260, USA
[3] Fermi National Accelerator Laboratory, Batavia, IL 60510
[4] Columbia University; New York, NY 10027
[5] Indiana University, Bloomington, IN 47405
[6] University of Victoria, Victoria, BC, V8P 5C2
[7] University of Alabama, Tuscaloosa, AL 35487
[8] Los Alamos National Laboratory, Los Alamos, NM 87545
[9] University of Florida, Gainesville, FL 32611
[10] Argonne National Laboratory, Argonne, IL 60439
[11] Queen Mary University of London, London, E1 4NS, UK
[12] New Mexico State University, Las Cruces, NM 88003
[13] Saint Mary's University of Minnesota, Winona, MN 55987
[14] University of Michigan, Ann Arbor, MI 48109
[15] University of Texas (Arlington), Arlington, TX 76019

Extra Slides

Lessons Learned

Understand Backgrounds



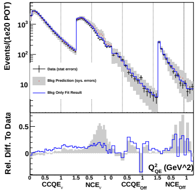
- Beam related backgrounds: decade of data used to reduce systematics
- Dirt events small because MiniBooNE is huge with veto region
- Beam unrelated backgrounds: Measured with 12 (2)Hz trigger for off-target (ν — Mode)

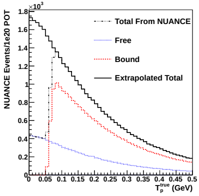
Include Nuclear Physics in DM Prediction

- Stripping a nucleus of a proton involves complex nuclear physics: e.g. binding energy, Pauli blocking, etc
- **Honest sensitivity estimate must include a decent nuclear model $\Rightarrow$ threshold effects**

Include sideband/other channels

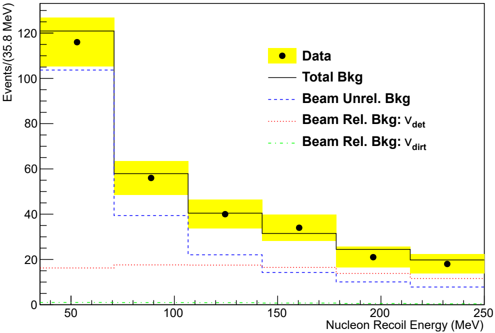
- Introduces correlations between the samples
- Results: Smaller systematic correlations on signal sample
- Results: Increases sensitivity





Reducing Beam Unrelated Background

Limited Sample Off-Target-NCE (NCE_{Off})



- Initial look showed Beam unrelated bkg. = 69% of data
- Using previous trigger info. to reject events that had hit info. before the beam trigger

- Reduced Beam unrelated bkg. to 58% of data with BRB efficiency of 95%
- Off-target Beam unrelated bkg. measured with random trigger at $\sim$10 Hz

Extension to sub-GeV Dark Matter

- Add baryonic current[1]

$$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4} F_{\mu\nu_D} F^{\mu\nu}_{D} + \frac{1}{2} m_V^2 V_\mu V^\mu - \frac{\epsilon}{2} F_{\mu\nu} F^{\mu\nu}_{D} + q_B g_{D} V_\mu J^\mu_B + \cdots$$

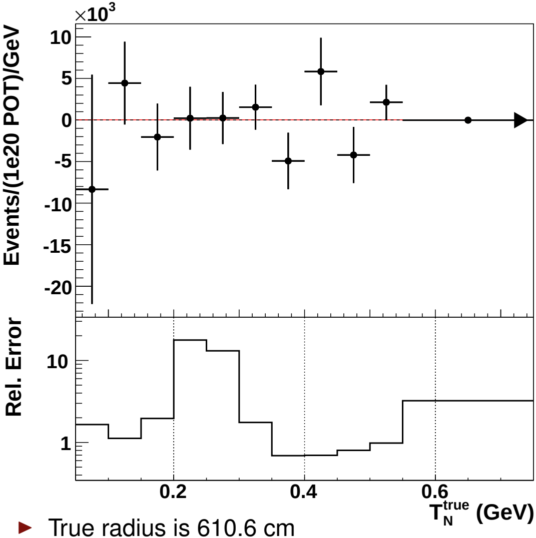
$$J^B_\mu = \frac{1}{3} \sum_i \bar{q}_i \gamma_\mu q_i \quad \text{sum over all quark species}$$

- When $\epsilon = 0$ $g_{D} \to g_B$ ($\alpha_B = g_B^2/4\pi$) $\mathcal{L}$ is solely dependent on baryonic current
- This scenario is called leptophobic
- MiniBooNE NCE analysis is sensitive to this model (proton production and proton/neutron detection)

[1] B. Batell et al., Phys. Rev. **D90**, 115014 (2014), arXiv:1405.7049 [hep-ph], P. deNiverville et al., (2016), arXiv:1609.01770 [hep-ph]

Model Independent Fit

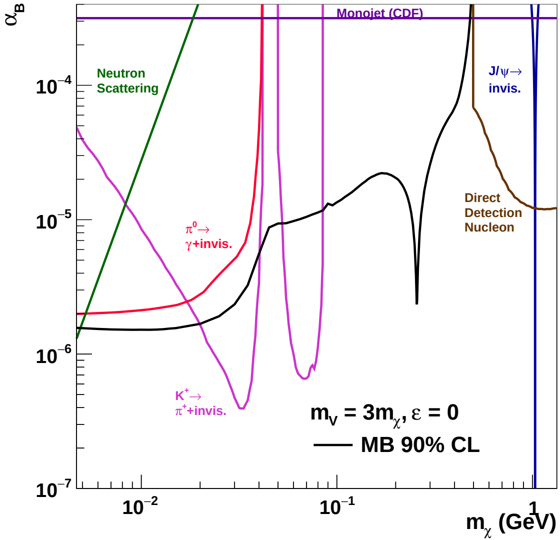
- Added fit parameters, one for each T_N^{true} bin
- Efficiency corrected predicted # events in true nuclear recoil energy
- Integrated = 130 ± 270 events/1e20 POT
- This will be in a data release with covariance matrix



- True radius is 610.6 cm
- Last bin is $[0.55, 2)$ GeV

Leptophobic Model

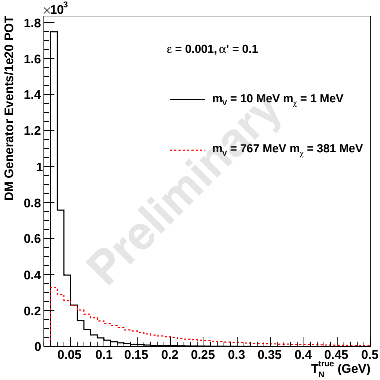
- Used Model Independent Fit to produce 90% CL[1]
- LSND, E137, etc. do not constrain due to lepton final state interaction
- MiniBooNE covers a lot of new parameter space



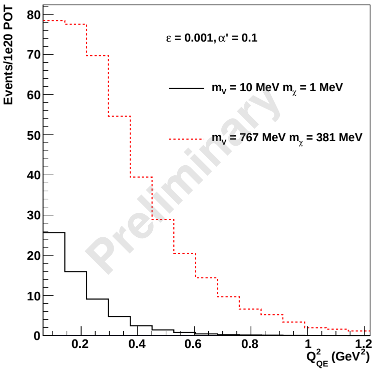
[1] Thanks to P. deNiverville for doing the analysis

Detector and Cut Effects on DM Pred.

True



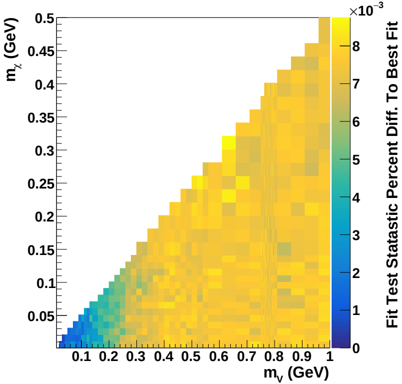
Reco



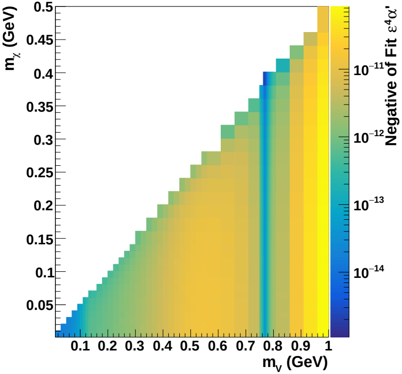
- Detector and Cut efficiencies reduces the number of low energy DM scatters
- MiniBooNE sensitive to $\langle T_N^{\text{true}} \rangle = \mathcal{O}\,(100\ MeV)$ after efficiencies applied
- Expect to see higher sensitivity around m_ρ than below m_{π^0}

Signal Best Fit

Fit Statistic



$\epsilon^4 \alpha_D$



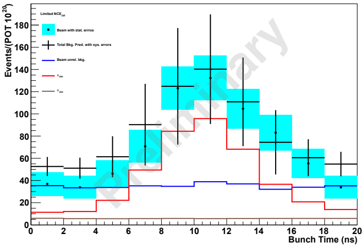
- Little change in test statistic when changing V, χ
- Huge change in $\epsilon^4 \alpha_D$

Next Analyses in this Data Set

RF spill-event timing

- Massive DM will be delayed relative to ν backgrounds
- Predictable timing spectrum vs. dirt which is flat in time
- Timing is even applicable to ν-oscillation data to separate e-γ

Limited $\mathrm{NCE_{Off}}$ RF Timing Spectrum



DM-Electron Scattering

- ν-e scattering as background
- Expect better sensitivity than NDM

$$\chi N \to \Delta + X,\ \Delta \to \pi^0$$

- $\mathrm{NC}\pi^0$ background
- π^0 is a clean detection signal
- BUB small and expect better sensitivity than NDM

Future sub-GeV DM Searches

What would more data do?

- NDM is systematics limited more data will further optimization of analysis
- π^0 *DM* and *eDM* are currently statistics limited and more data is crucial

Recent BNB Upgrade: Dual beam on-/off-target running

- Fast trim magnet to switch proton trajectory is installed
- BNB horn operates at 5 Hz but 7 Hz can be delivered to BNB when NuMI is down for maintenance or repair
- Gates around MI are installed; more opportunities for BNB beam

Short Baseline Neutrino Program

- Entire program can search for low-mass DM
- Short Baseline Near Detector DM signal is $\sim 20\times$ the MiniBooNE rate

References I

[1] A. A. Aguilar-Arevalo et al., Phys. Rev. **D81**, 092005 (2010), arXiv:1002.2680 [hep-ex].

[2] A. A. Aguilar-Arevalo et al., Phys. Rev. **D82**, 092005 (2010), arXiv:1007.4730 [hep-ex].

[3] C. Boehm and P. Fayet, Nucl.Phys. **B683**, 219 (2004), arXiv:hep-ph/0305261 [hep-ph].

[4] C. Boehm, D. Hooper, J. Silk, M. Casse, and J. Paul, Phys.Rev.Lett. **92**, 101301 (2004), arXiv:astro-ph/0309686 [astro-ph].

[5] B. Batell, R. Essig, and Z. Surujon, Phys.Rev.Lett. **113**, 171802 (2014), arXiv:1406.2698 [hep-ph].

[6] A. A. Aguilar-Arevalo et al., Phys. Rev. **D91**, 012004 (2015), arXiv:1309.7257 [hep-ex].

[7] B. Batell, P. deNiverville, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. **D90**, 115014 (2014), arXiv:1405.7049 [hep-ph].

[8] P. deNiverville, C.-Y. Chen, M. Pospelov, and A. Ritz, (2016), arXiv:1609.01770 [hep-ph].