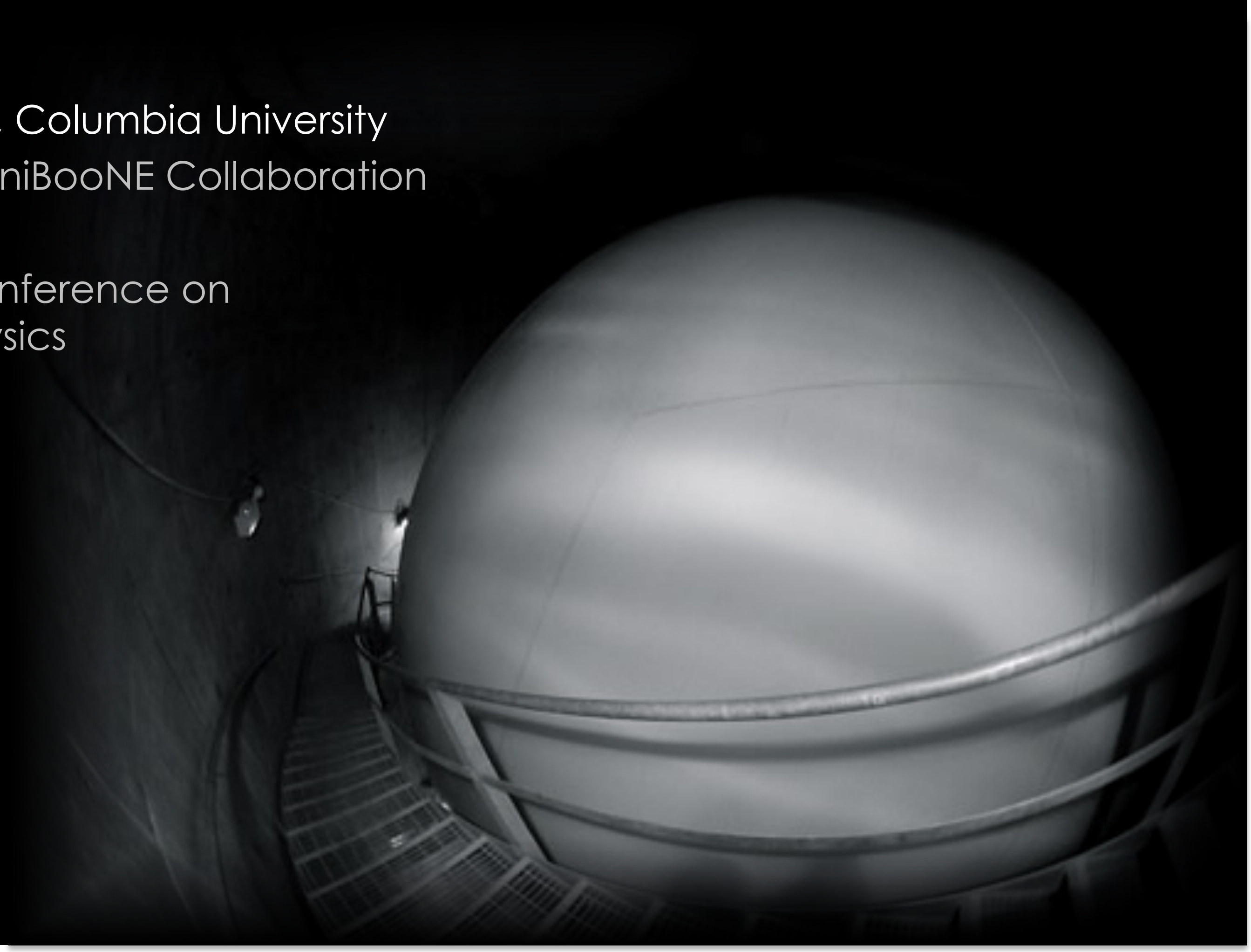
Searching for Dark Sector Physics with MiniBooNE

Georgia Karagiorgi, Columbia University
On behalf of the MiniBooNE Collaboration

3rd International Conference on
New Frontiers in Physics
August 6, 2014



MiniBooNE: Past & current highlights

MiniBooNE, an **accelerator-based neutrino experiment** at Fermilab, **has run for 10 years** with **neutrino and antineutrino beams**, collecting data for ~2×10^{21} POT, amounting to 100k's of neutrino interactions.

It has been able to **address the two-neutrino oscillation interpretation** of an anomalous excess previously observed by the **LSND experiment**. It has also observed evidence of an **unexplained EM shower excess** at low reconstructed neutrino energies. The nature of the excess will be investigated by MicroBooNE (currently being commissioned in the same beamline).

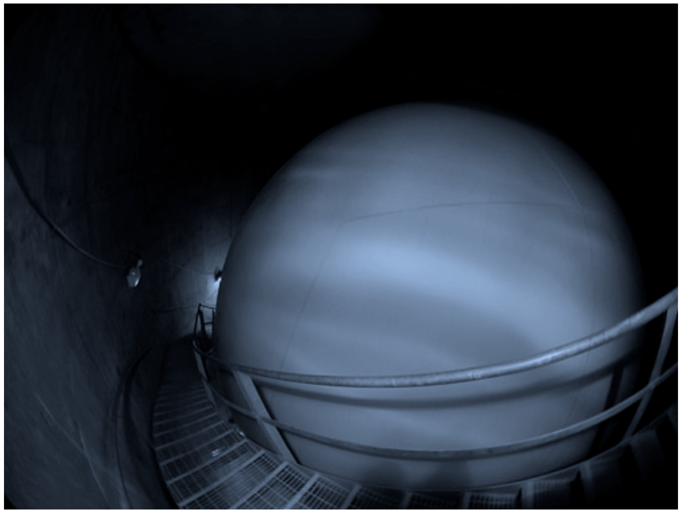
In addition to searching for New Physics in the neutrino sector, MiniBooNE has performed many **neutrino cross-section measurements**, relevant for future neutrino oscillation experiments.

Currently, MiniBooNE is running in a special beam-dump configuration which allows for sensitive searches for **Dark Sector Physics**, in particular light (<1 GeV) dark matter.

- 11 oscillation papers
- 14 cross-section and flux papers
- 1 detector and 1 supernova neutrino search paper
- 18 Ph.D. theses

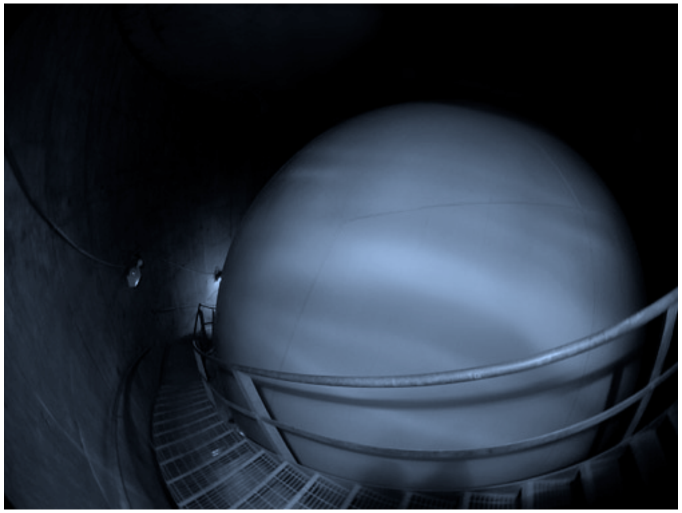
→ **The experiment is well understood!**

The Dark Sector Physics Search leverages this decade of work and experience!



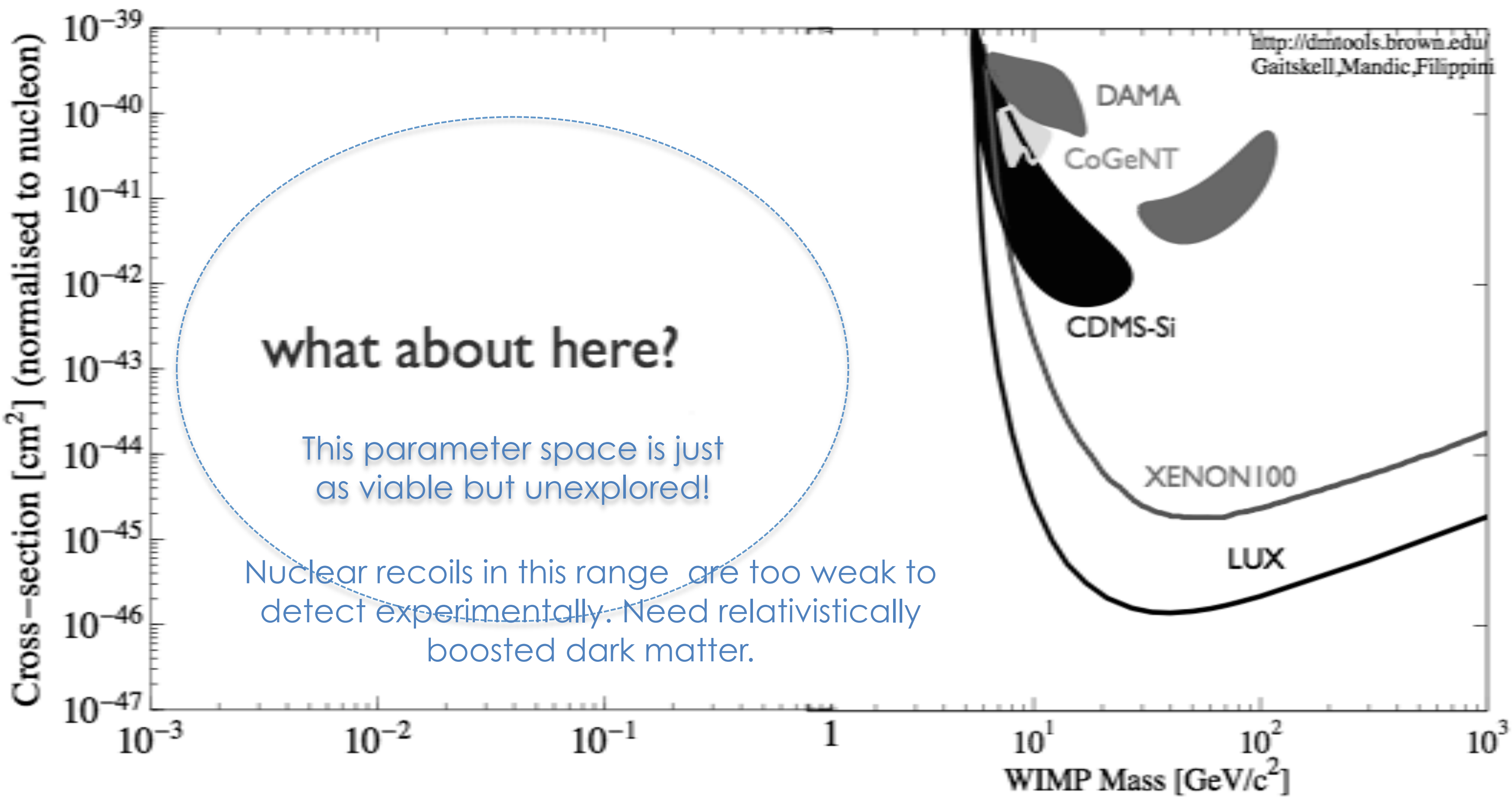
Outline

1. The case for light dark matter
2. The Booster Neutrino Beam and MiniBooNE detector at Fermilab
3. The MiniBooNE search for light dark matter
4. Preliminary results
    1. Past antineutrino running
    2. Current beam-dump running
5. Summary and outlook



The case for light dark matter (I)

Traditional underground direct detection experiments run out of sensitivity below ~1 GeV due to the low velocity of galactic halo WIMPs.



This parameter space is just as viable but unexplored!

Nuclear recoils in this range are too weak to detect experimentally. Need relativistically boosted dark matter.

A simple theoretical framework

Low-mass WIMPs require light vector mediator(s):

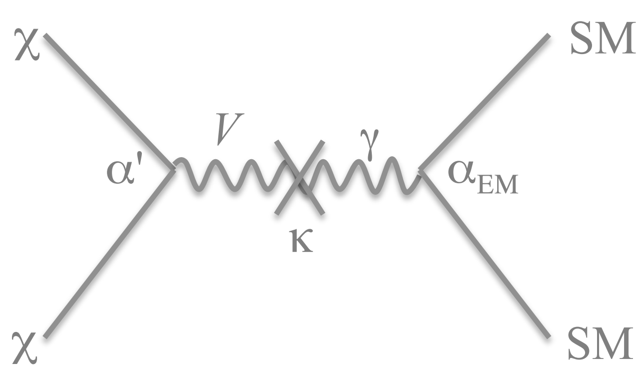
- The new mediators mediate interactions with SM particles
- They also increase the annihilation cross section of the dark matter to give the correct relic density

A minimal extension to the Standard Model:

$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 - \frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu} + \ldots$$

$$D_\mu = \partial_\mu - i\alpha' V_\mu$$

leads to:



4 new parameters:

m_χ, m_V, κ, α'

model assumptions:

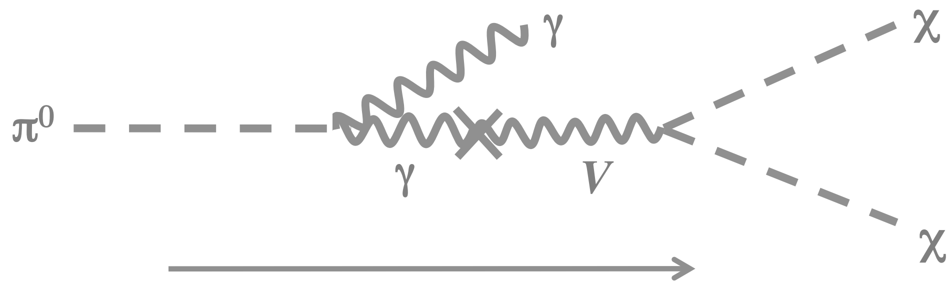
$\alpha' \sim \alpha_{EM}$

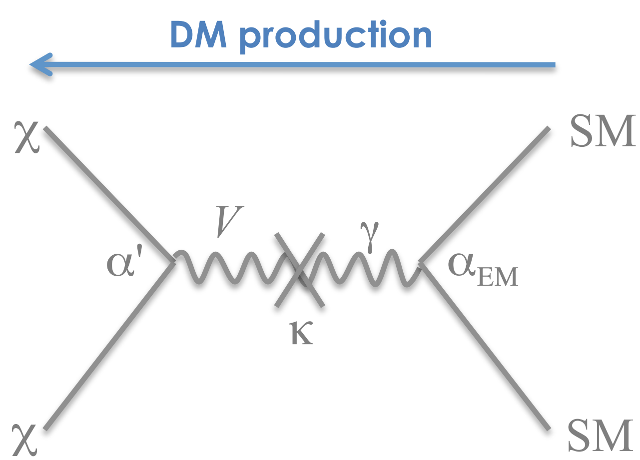
κ is small

$m_V > 2m_\chi$

Experimental principle

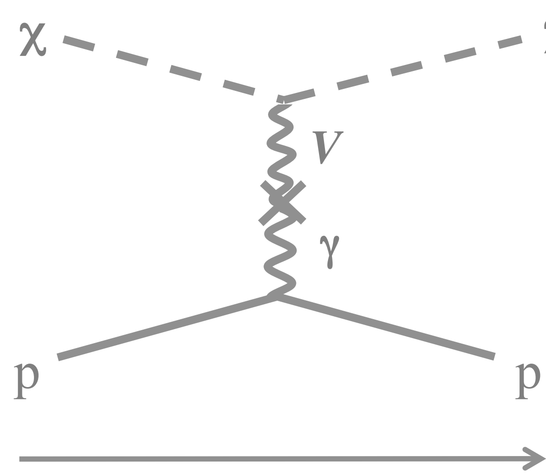
Dark matter production: via photon production, e.g. π^0 decays

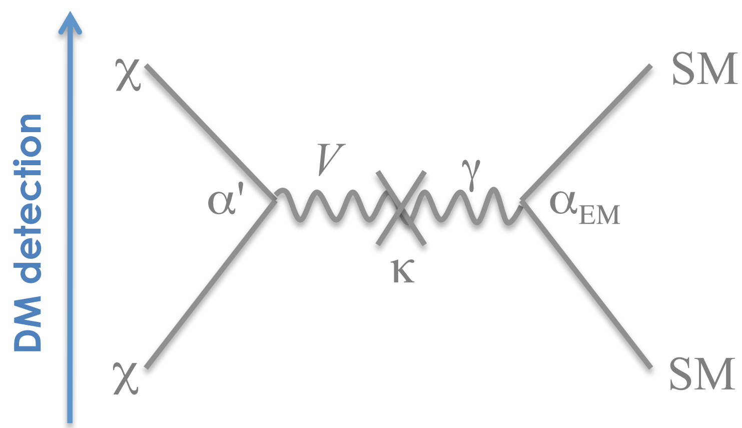




Experimental principle

Dark matter detection: via elastic scattering on any EM-charged particle, e.g. p

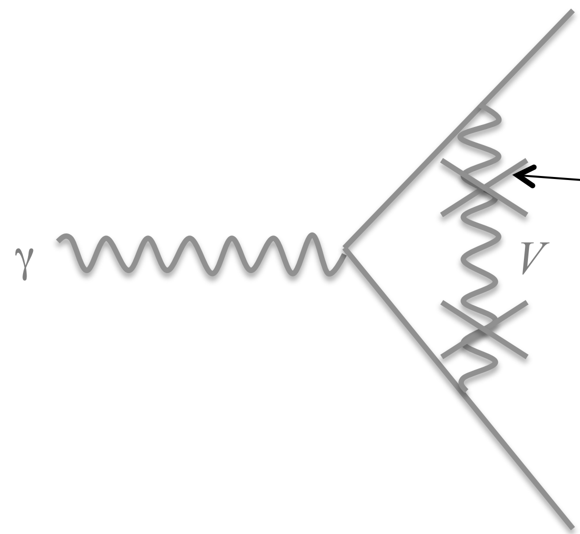




The case for light dark matter (II)

Model consequences for muon g-2:

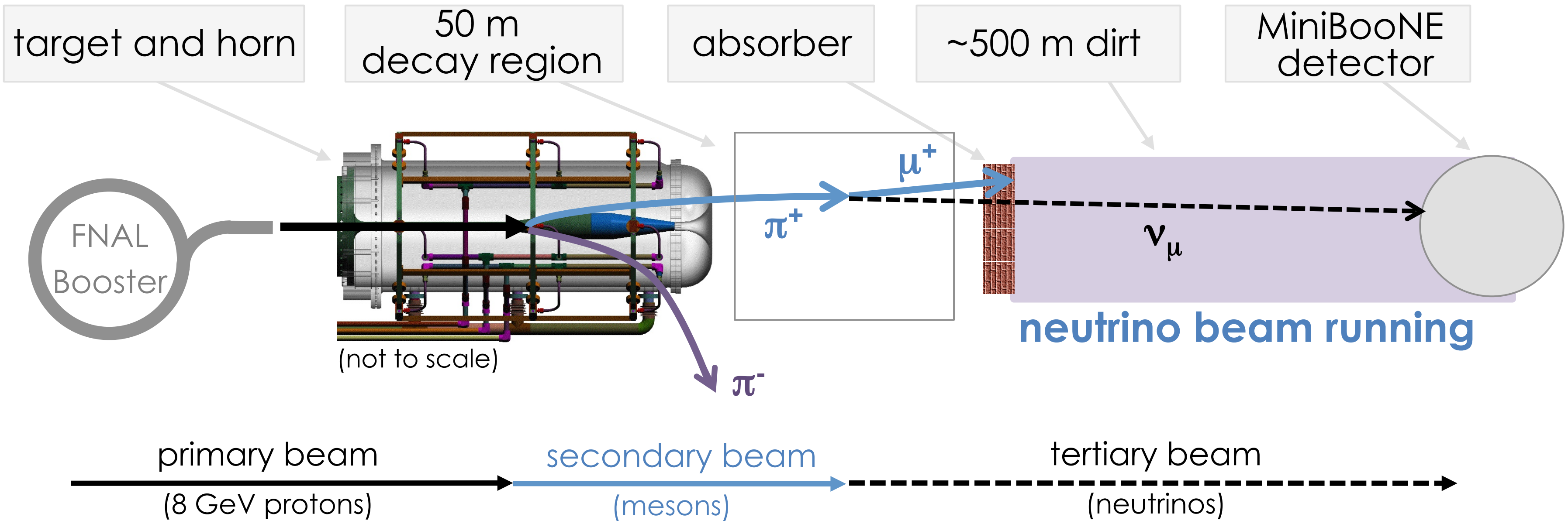
- Light kinetically mixed vector V that serves as a mediator in this model also contributes to the anomalous magnetic moment of SM fermions
- This can explain the muon g-2 discrepancy [Fayet, Pospelov]



The crosses represent the kinetic mixing κ of the vector V with the SM photon

These models are gaining attention as a possible explanation of the muon g-2 anomaly.

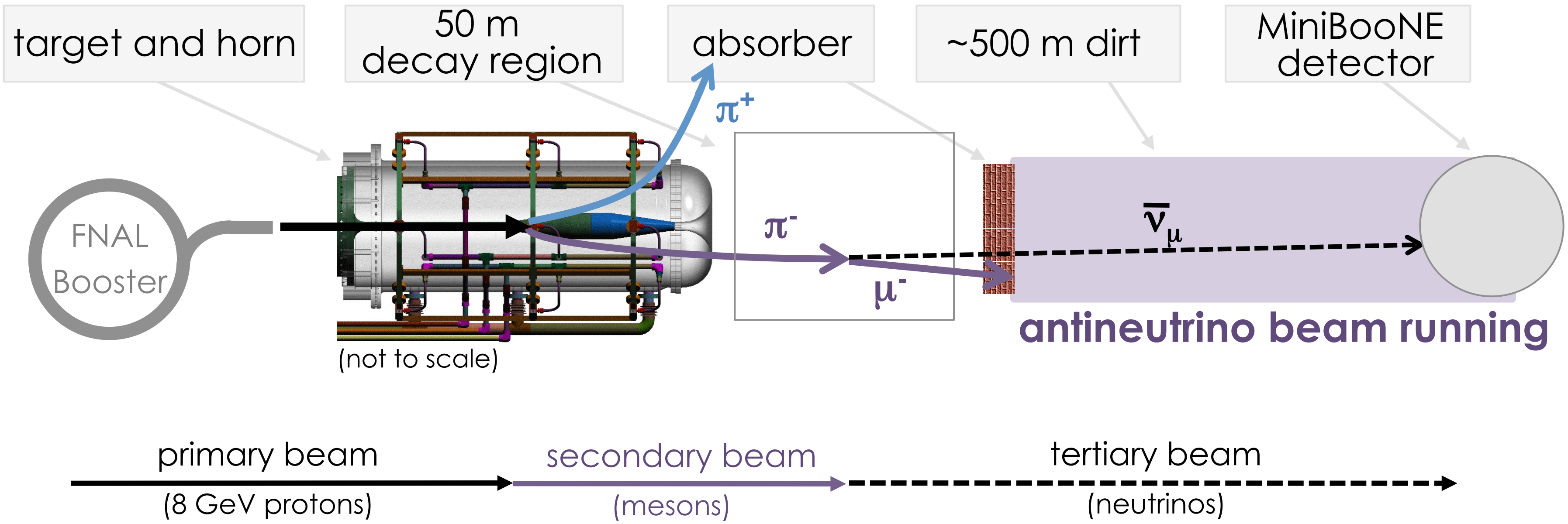
The Booster Neutrino Beam at Fermilab



Neutrinos are produced by protons from the FNAL Booster accelerator:

- 8 GeV protons hit Be target, producing hadrons
- hadrons are sign-selected and directed to a 50 m decay pipe filled with air
- neutrinos are produced in hadron decays; other by-products are absorbed in Fe absorber at the end of the decay pipe

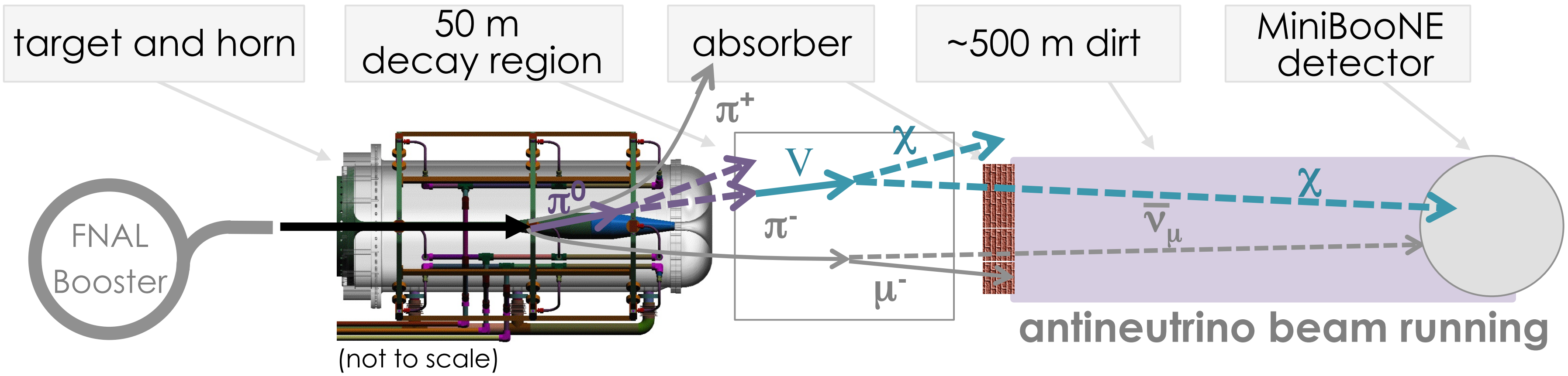
The Booster Neutrino Beam at Fermilab

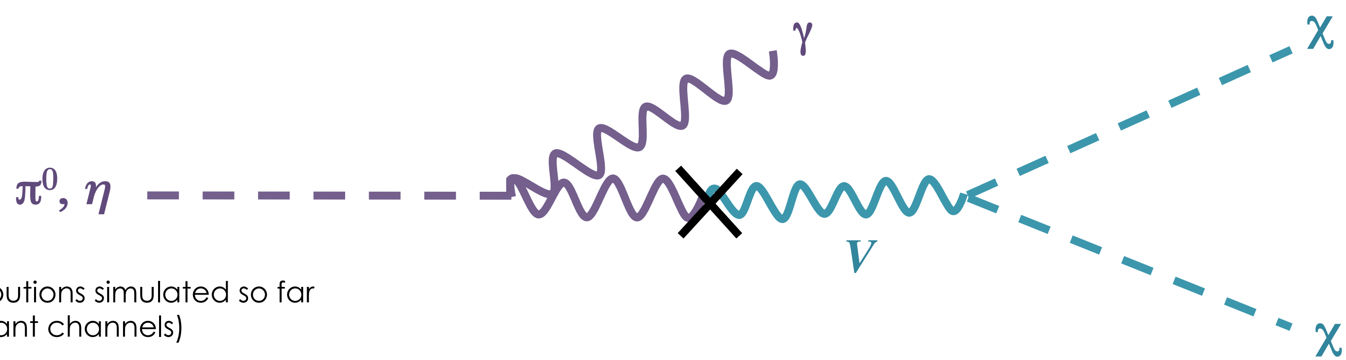


Neutrinos are produced by protons from the FNAL Booster accelerator:

- 8 GeV protons hit Be target, producing hadrons
- hadrons are sign-selected and directed to a 50 m decay pipe filled with air
- neutrinos are produced in hadron decays; other by-products are absorbed in Fe absorber at the end of the decay pipe

Relativistic DM production in the beam



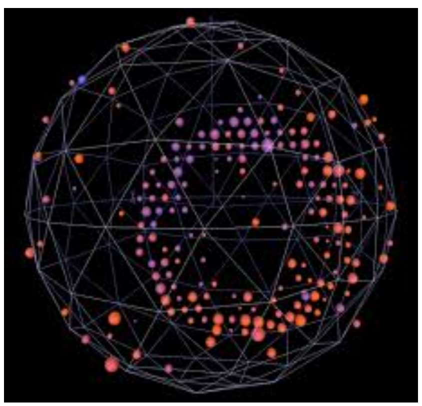


Only π^0, η contributions simulated so far
(dominant channels)

The MiniBooNE detector

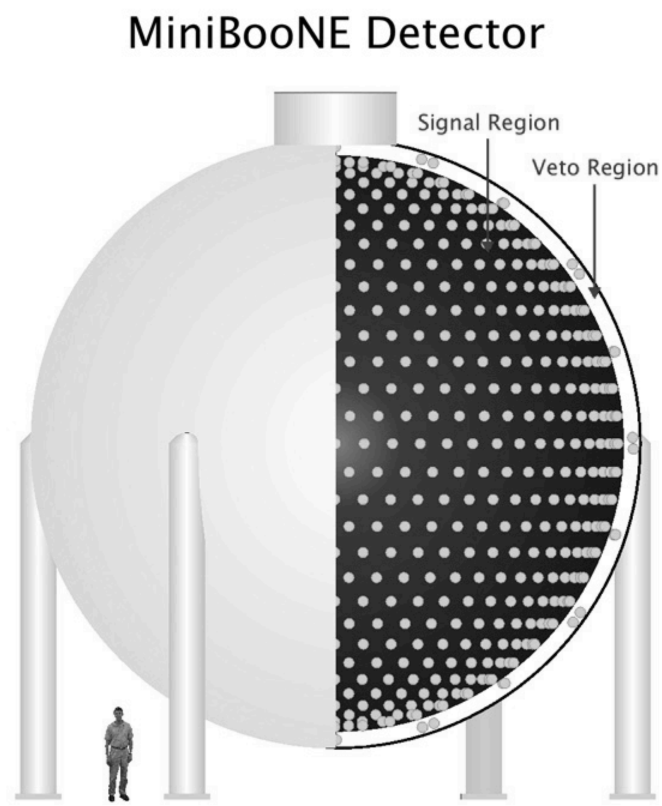
12 m diameter spherical detector
filled with 800 tons of C_NH_{2N} (pure mineral oil)
located at 540 m from BNB proton target

Cherenkov detector, also some sensitivity to
scintillation light (trace fluors)
lined with 1280 PMT's (10% photocathode)
and optically isolated veto (240 PMT's)



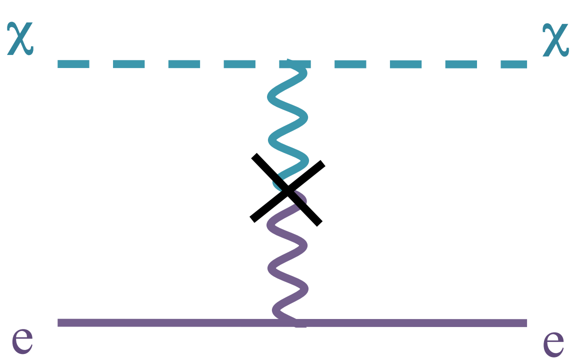
Cherenkov light signature from a charged-current neutrino interaction.

In contrast, scintillation light from neutral-current or DM nuclear recoils is isotropic, lower in energy.

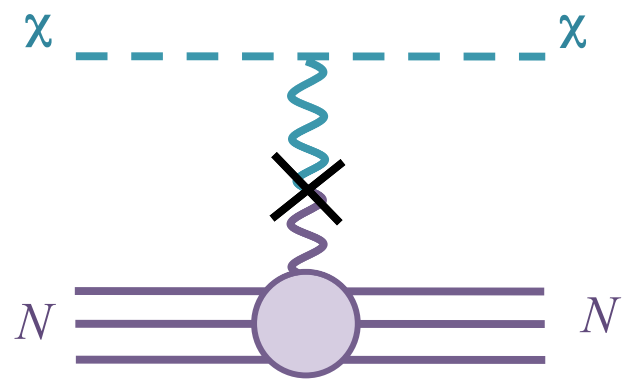


Light dark matter detection in MiniBooNE

Dark Matter can interact in the oil by elastically scattering off **nucleons** or **electrons**:



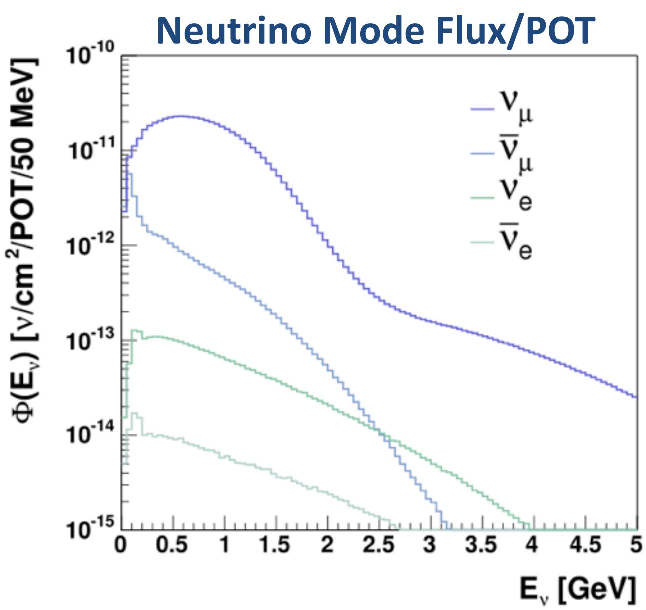
Electron Elastic Scattering

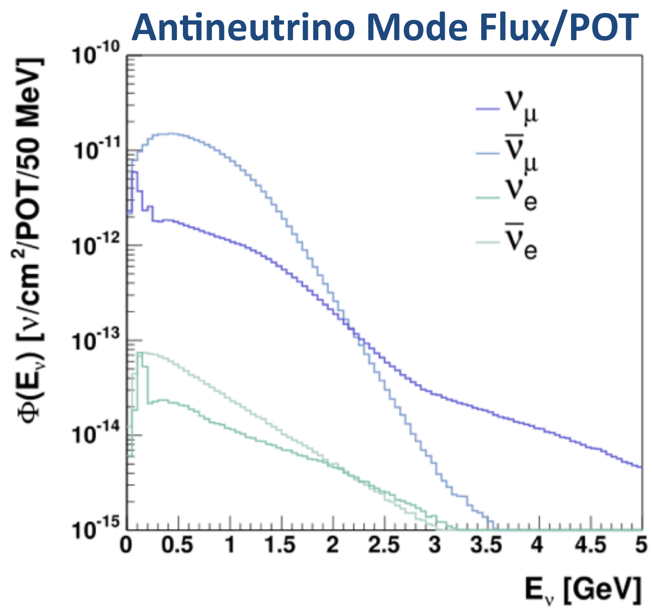


Nucleon Elastic Scattering

- Events look like neutrino neutral-current scattering off nucleons or electrons but possibly with different kinematics (momentum, angle, timing, etc)
- Neutrino and anti-neutrino neutral-current interactions are a background!

Reducing neutrino backgrounds:
A neutrino experiment that doesn't like neutrinos?!



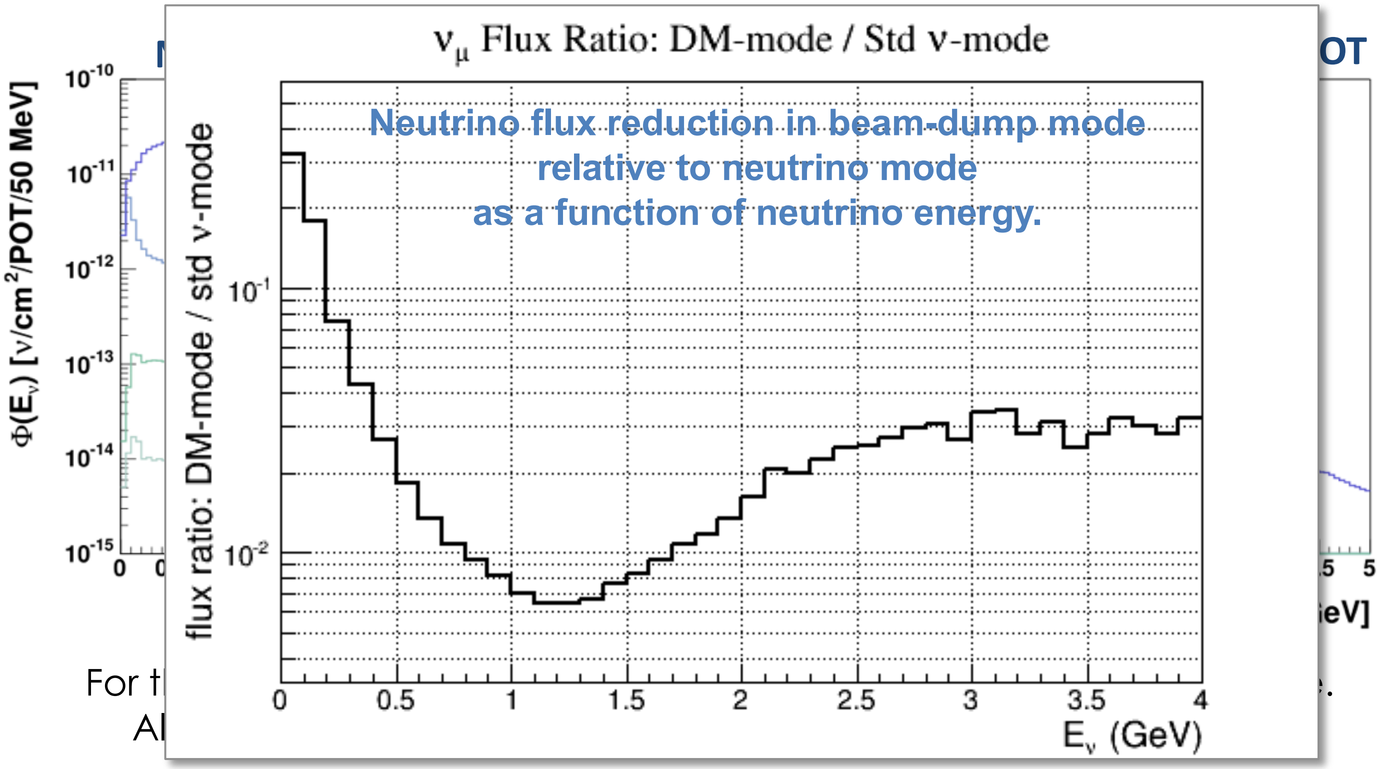


For the same POT, total neutrino flux is ~ x2 lower in antineutrino mode.
Also, additional ~ x2 reduction in event rate due to cross-section.

Option 1: Perform search in antineutrino mode, where backgrounds from neutrinos in the beam are lower.
Option 2: Beam-dump running mode…

MiniBooNE is pursuing both options!

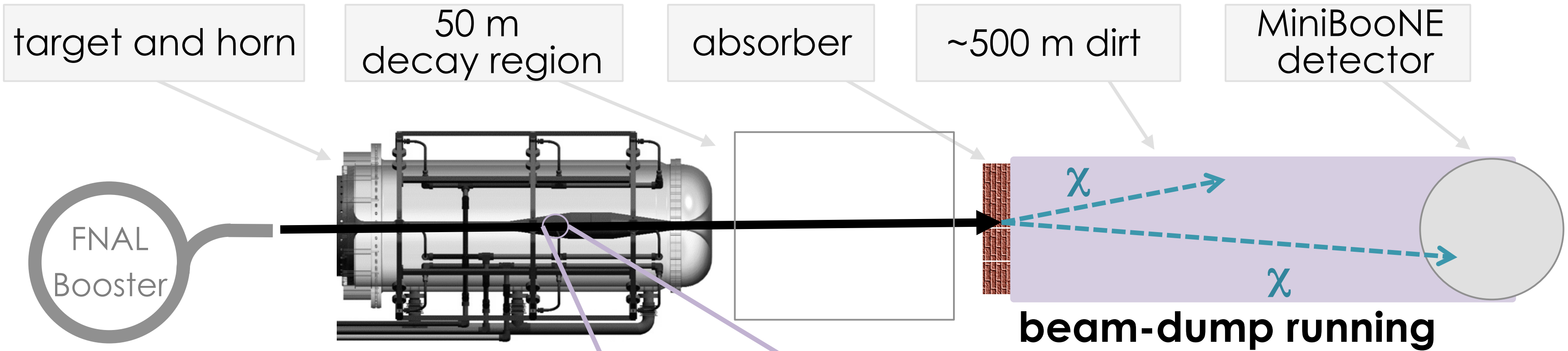
Reducing neutrino backgrounds: A neutrino experiment that doesn't like neutrinos?!



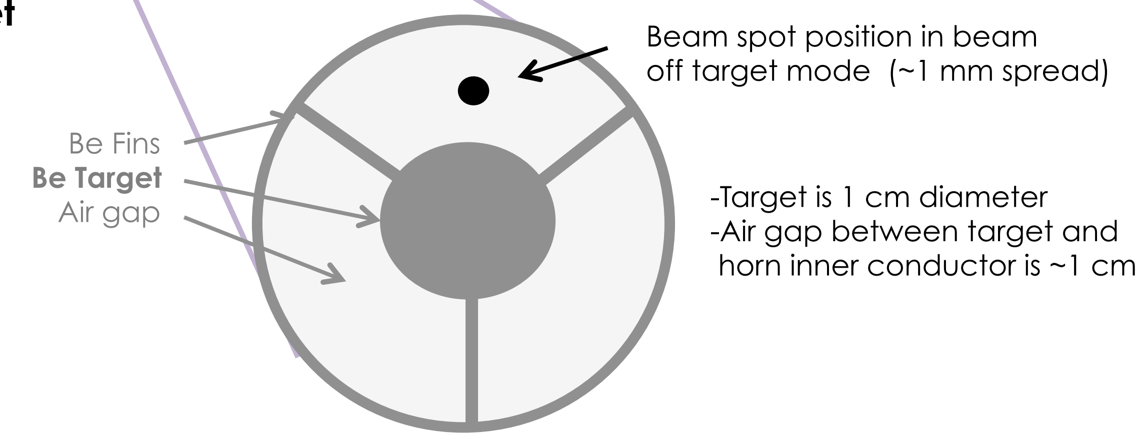
Option 1: Perform search in antineutrino mode, where backgrounds from neutrinos in the beam are lower.
Option 2: Beam-dump running mode…

MiniBooNE is pursuing both options!

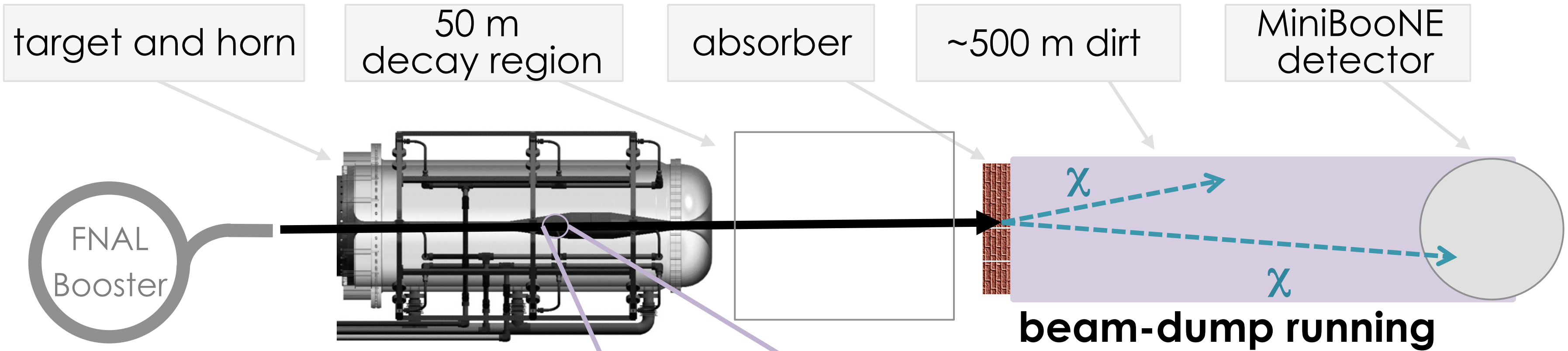
Beam off-target (beam-dump) running



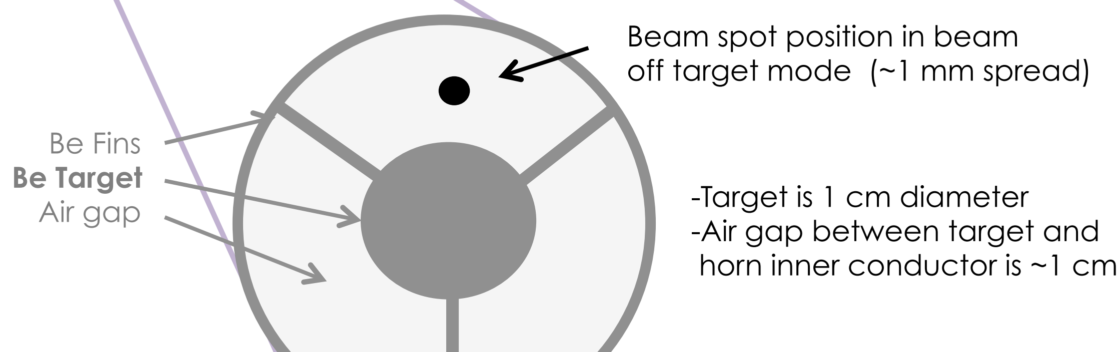
MiniBooNE has the capability to steer the protons past the target and onto the 50 m iron dump (absorber)



Beam off-target (beam-dump) running



MiniBooNE has the capability to steer the protons past the target and onto the 50 m iron dump (absorber)



π^0 and η produced by protons in the Fe quickly decay producing dark matter.

Charged mesons are absorbed in the Fe before decaying, which **significantly reduces the neutrino flux** (still some production from proton-Air interactions), **while leaving the signal unaffected**.

Why MiniBooNE is well-suited for a light dark matter search

The MiniBooNE experiment employs:

High-intensity and reasonably high-energy (8 GeV) **proton beam** with high protons-on-target rate (~2E20 POT/year)

→ Allows for and enhances relativistic DM production
in proton-target interactions

Detector at close proximity (500 m) **to proton target** which maximizes signal rate but far enough to minimize beam-related backgrounds

→ Enhances sensitivity to possible DM event signatures

Large (1 kton), **sensitive, well-understood detector** with good particle ID and event reconstruction (~20 MeV energy threshold, ~nsec timing resolution, and p, n, μ, π, γ/e reconstruction)

→ Enhances interaction rate and reconstruction/PID efficiency
for a wide range of model parameters

Analysis method: nucleon scattering

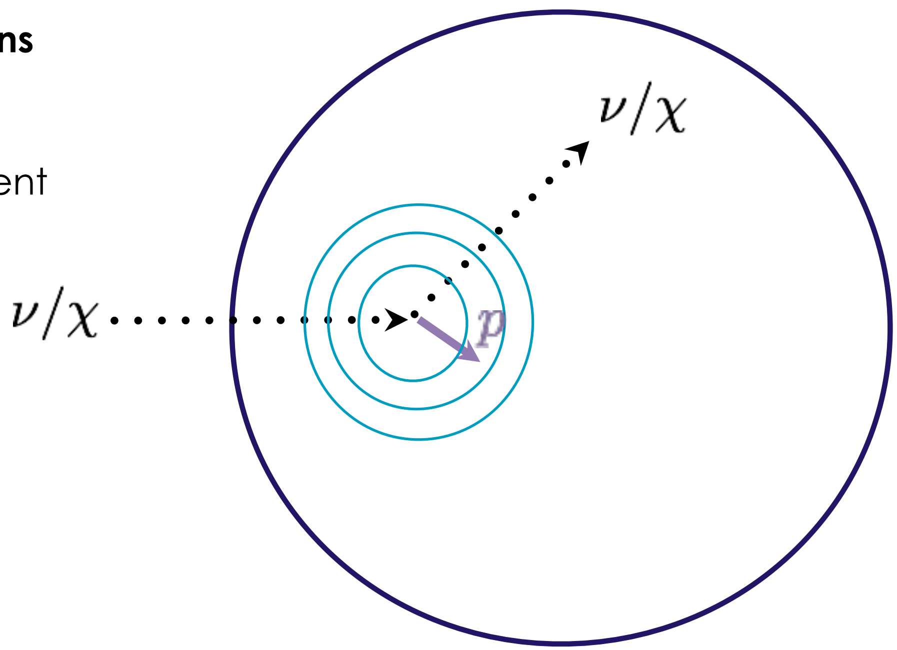
Testing the "invisible decay" of V, for $m_V > 2m_\chi$

Reconstruct **NC elastic events on nucleons** by requiring no muon or pion produced in the interaction.

Reco. E = sum of charge from PMT's / event

Event selection requirements:
Low veto activity
Sufficient active volume activity
Coincidence with beam window
Contained (FV) event
PID likelihood-based cut
  minimizing backgrounds from e

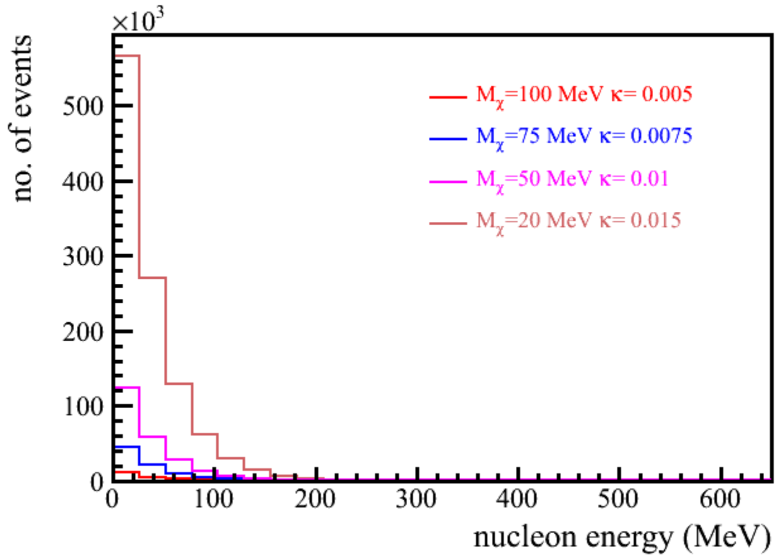
→ Look at reconstructed E…



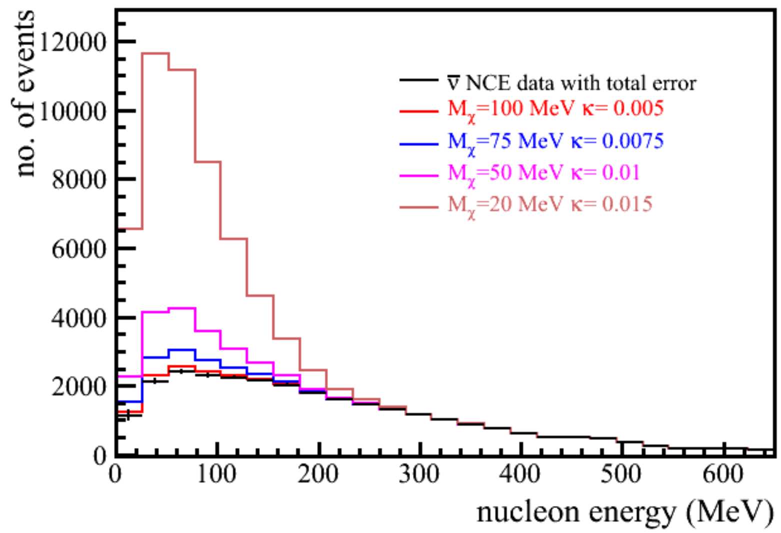
Analysis method: nucleon scattering

Fit the dark matter template plus the neutrino background prediction to the data as a function of reconstructed E. Use full NC cross section error matrix (20% systematic error).

assuming a new vector m_V=300 MeV



Nucleon energy from Dark Matter scattering

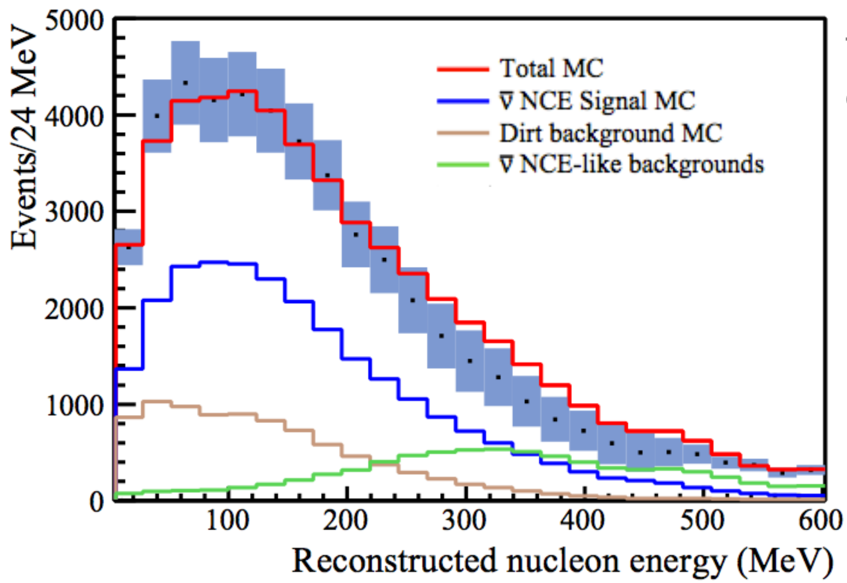


Efficiency corrected DM signal+antinu NCE data

- Average nucleon reconstruction efficiency is 35%, above 40 MeV
- Energy resolution is ~10%

Analysis method: nucleon scattering

In-situ background constraints:



The antineutrino NCE scattering energy spectrum.
Background such as the NC pion, dirt events and cosmics have been studied and measured.

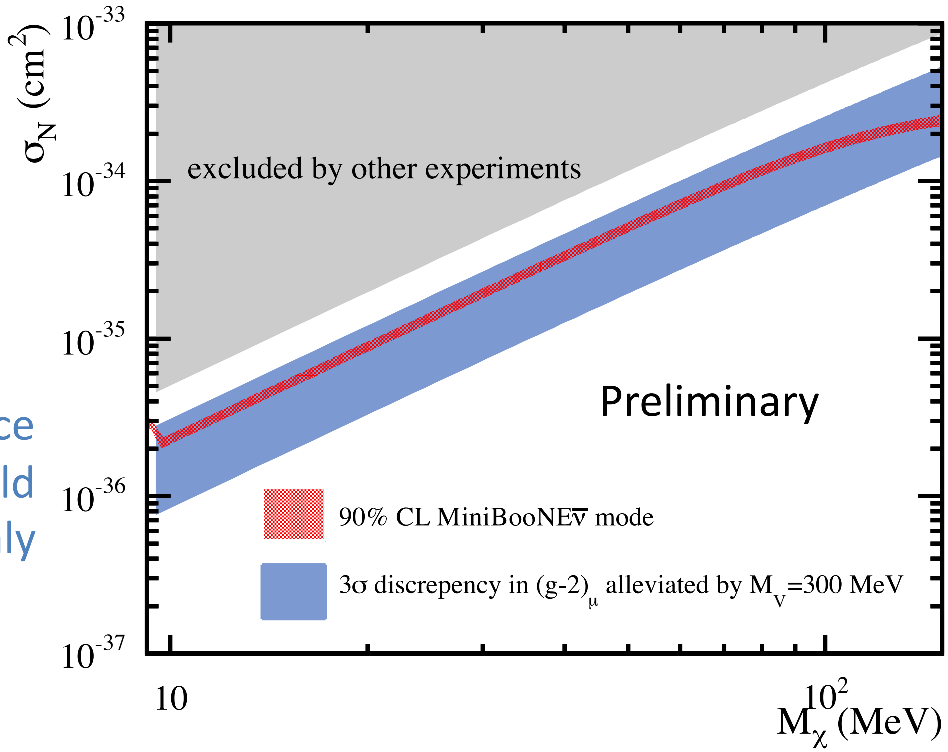
- MiniBooNE has published neutrino NC elastic and CC elastic cross sections as well as ratios for neutrinos and antineutrinos
  - PRD D81, 092005 (2010), PRD 82, 092005 (2010)
    PRD D88, 032001 (2013), arXiv:1309.7257 (2013)
- Measurements can be used to directly constrain background predictions to the DM nucleon scattering search:
  CC elastic analysis constrains flux; NC elastic analysis constrains background

Preliminary results: 1. Antineutrino mode

Nucleon scattering search:

- Preliminary exclusion limit from antineutrino run, corresponding to 10.1E20 POT

Blue band: parameter space for this model that could explain g-2 anomaly



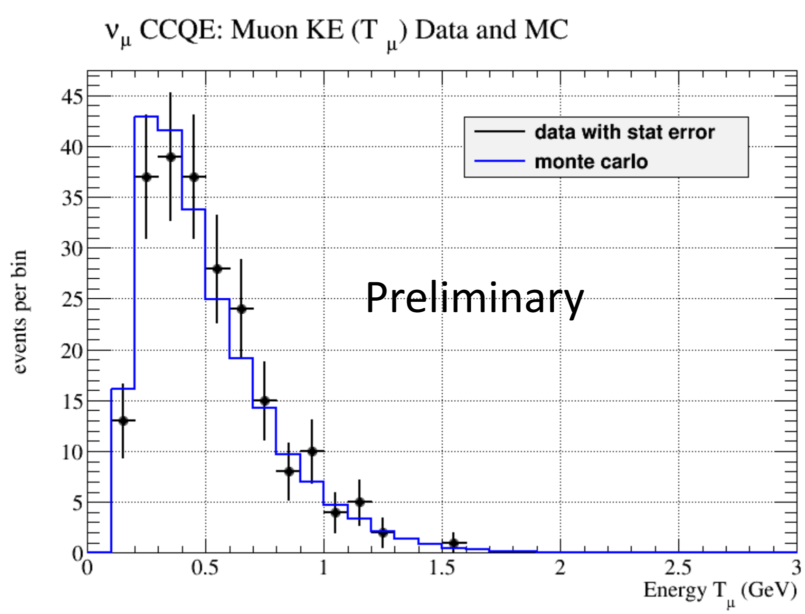
- MiniBooNE is starting to probe the "g-2 region"
- **To do better, need to reduce neutrino background → beam-dump mode**

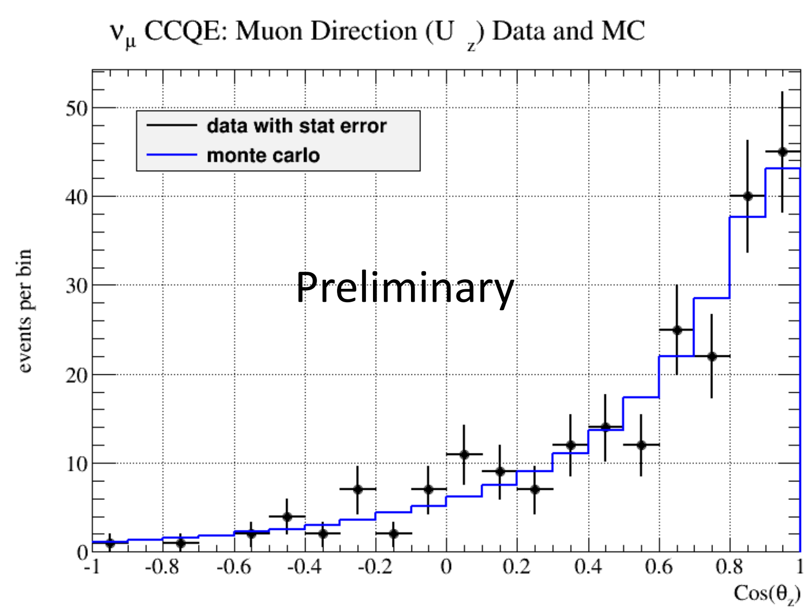
Preliminary results: 2. Beam-dump mode

Estimated neutrino background rate reduction:

(events/POT)$^{\nu \text{ mode}}$ / (events/POT)$^{\text{beam off-target}}$ = **44 ± 3 (stat error)**

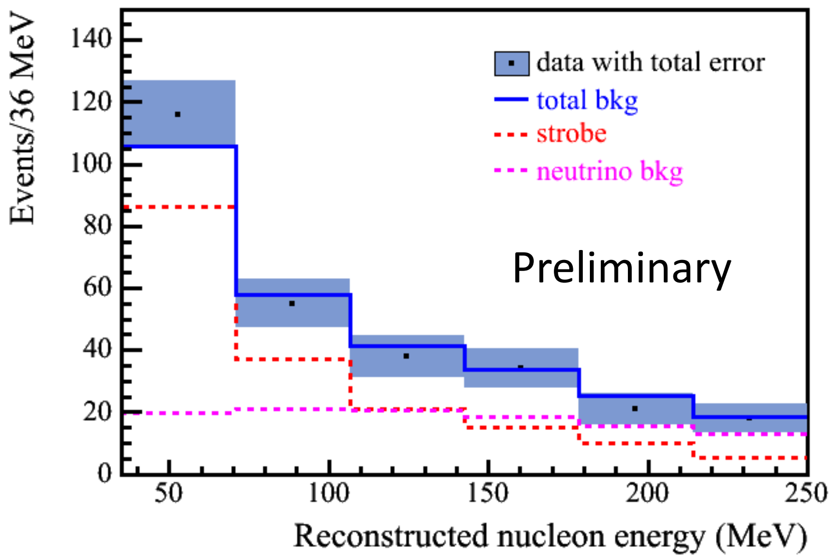
Meson production in p-air interactions not well-predicted →
Use neutrino CCQE data rate from 50m absorber beam-dump test run
(~30% of total expected POT) **to constrain the NCE neutrino background rate**





Preliminary results: 2. Beam-dump mode

Nucleon scattering search: A first look at 30% of beam-dump data:



	#events
Cosmics	177
nu bkg	107.8
Total Bkg	284.8 +/-18 (sys.)
Data	282 +/-17(stat)

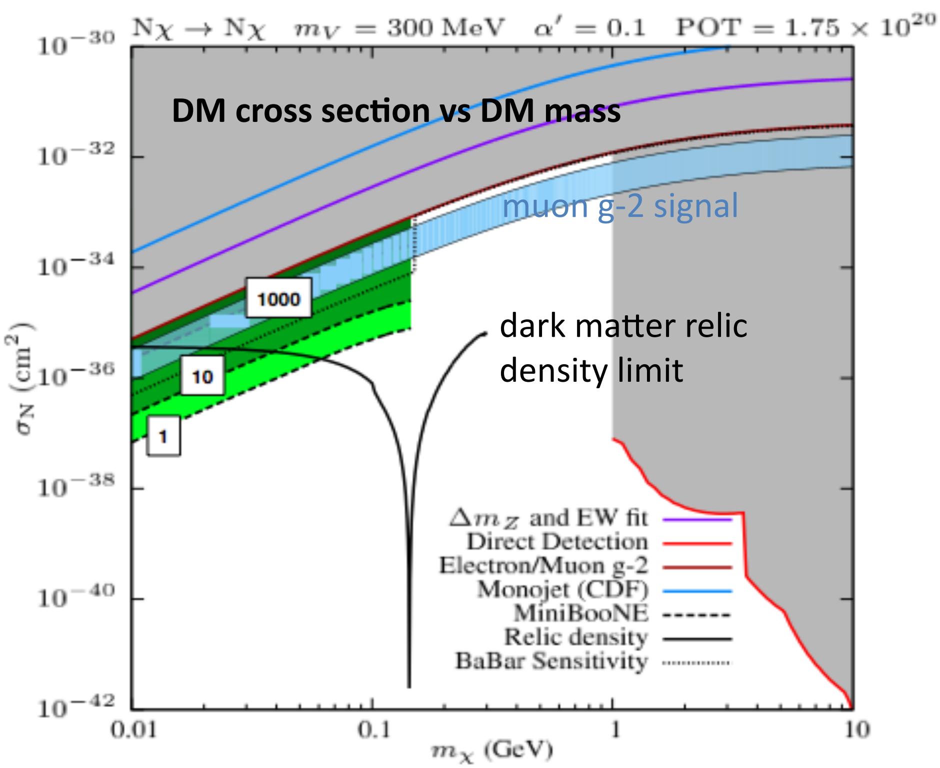
Total error= 24.6 events, or 23% of nu bkg

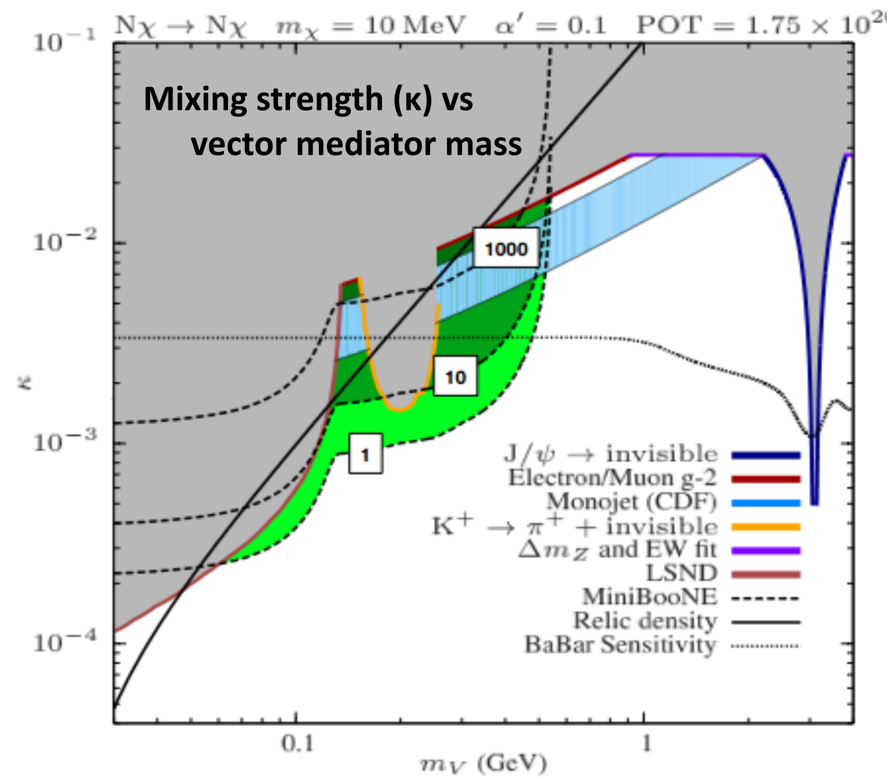
- Similar event reconstruction as in beam-on-target antineutrino analysis.
- Monte Carlo neutrino background prediction tied to measured muon CCQE rate.
- Background stat error dominated by beam-unrelated (cosmics) events.
- Working on further decreasing the ~16% systematic error on NC neutrino background.
- **Data in agreement with background predictions.**
- **We will use this dataset to study PID and background reduction techniques. The rest of the data will be used for the analysis.**

Sensitivity estimates: Beam-dump mode

MiniBooNE's expected reach using beam-dump data:

Nucleon scattering search





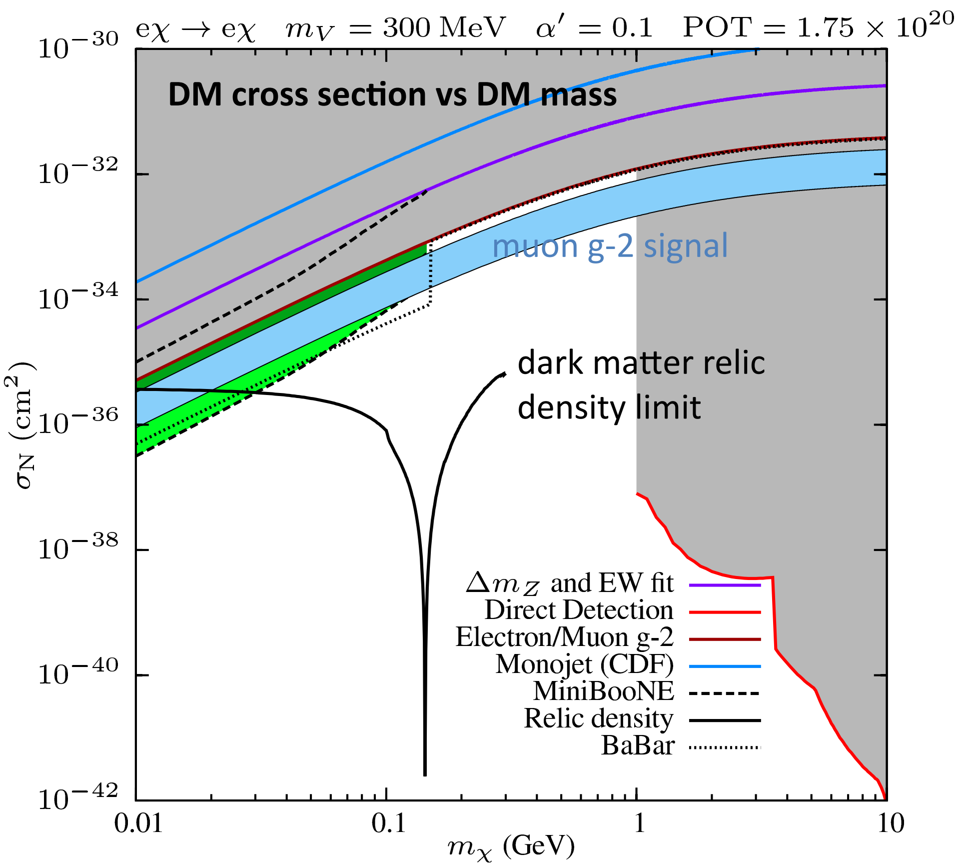
Number of DM signal events expected in MiniBooNE:

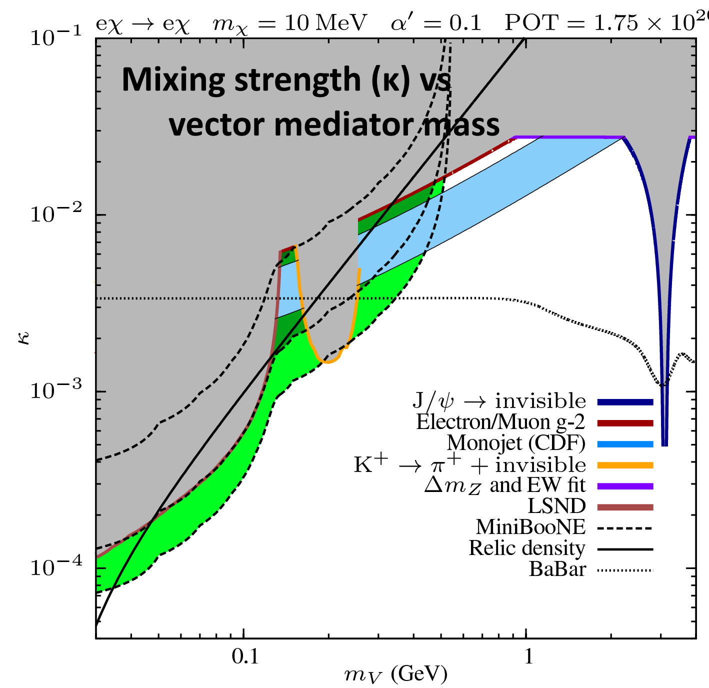
Dark Green: >1000 Green: 10-1000 Light Green: 1-10

Sensitivity estimates: Beam-dump mode

MiniBooNE's expected reach using beam-dump data:

Electron scattering search





Electron scattering cross-section is lower than nucleon scattering one, but better handle on backgrounds…

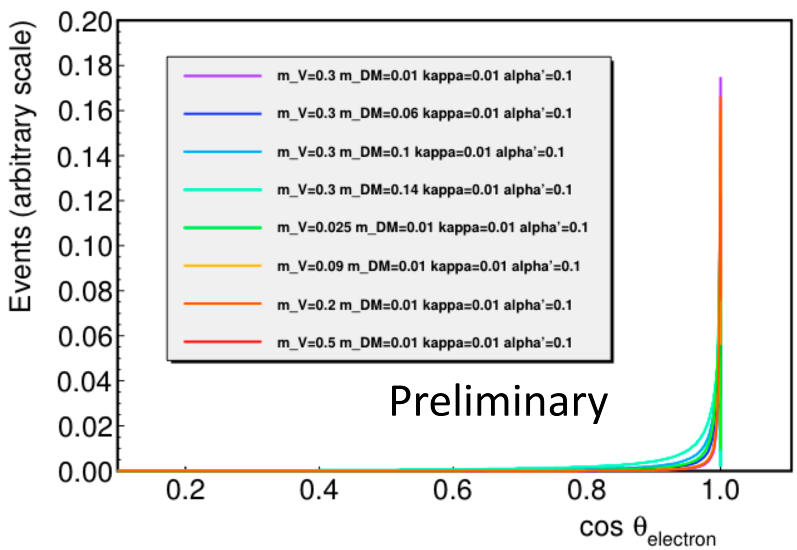
Sensitivity estimates: Beam-dump mode

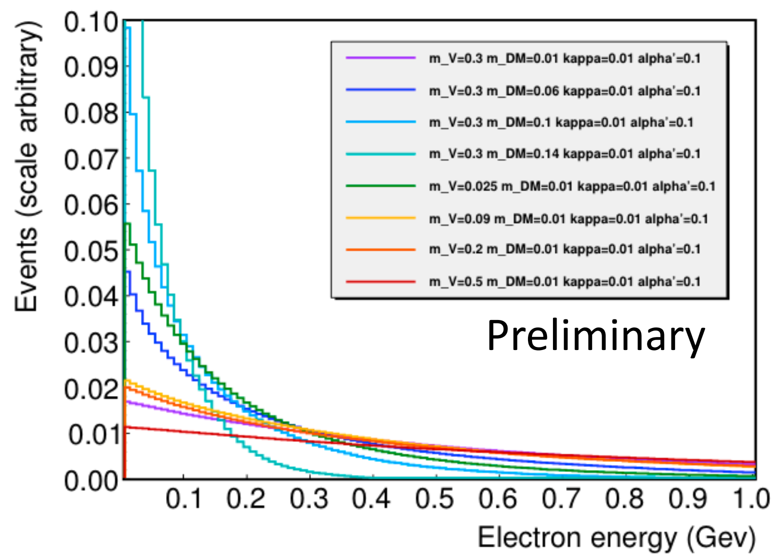
MiniBooNE's expected reach using beam-dump data:

Electron scattering search

Electron channel could be most sensitive channel despite lower signal rate, due to lower backgrounds and systematic errors. Analysis effort is on-going.

This analysis is complementary to the nucleon scattering search (e.g. leptophobic models…).





- DM-electron scattering is forward peaked.
- A forward angle ($\cos\theta_{electron}$) cut can reduce neutrino-induced backgrounds by 98%. Systematic errors are ~12%.
- Also requires pushing the energy threshold to < 140 MeV, which is challenging.

Summary & Outlook

Light dark matter models are interesting and well-motivated.

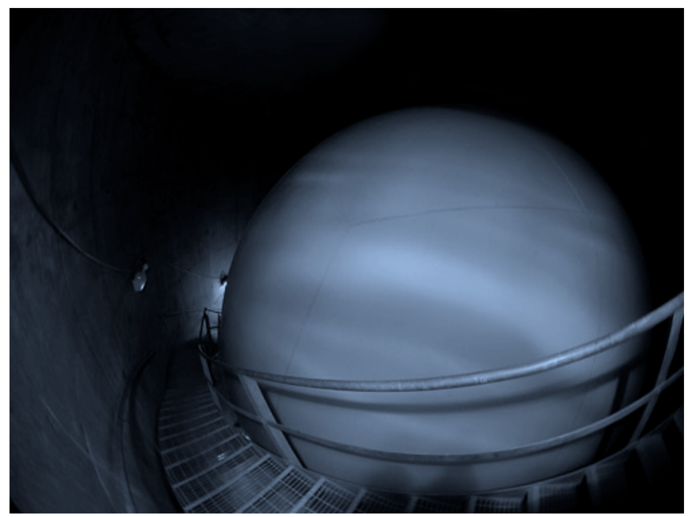
Searches with the BNB and MiniBooNE are complementary to underground direct-search experiments, as they can test the low-mass WIMP region.

A preliminary analysis using past MiniBooNE antineutrino run data is starting to probe the "muon g-2 region".

More recently, MiniBooNE has successfully proposed and is nearing completion of a beam-dump run to search for Dark Sector Physics with enhanced sensitivity. The projected analyzable data by the end of the run in Sept. 2014 corresponds to ~1.8E20 POT (only 1.5E20 POT requested)!

Both analyses are in progress, and are expected to lead to publications this coming year.

If MiniBooNE observes a signal, this will motivate future running with new detectors in the BNB, such as the currently proposed LAr1-ND, which could provide an independent check of the result.

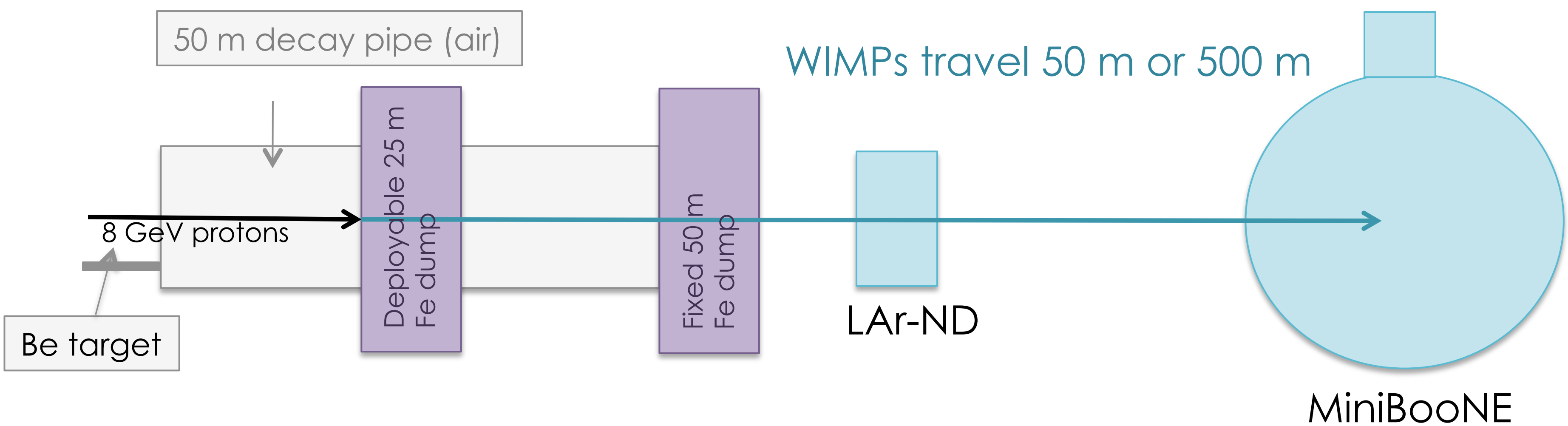


Backup Slides

Future prospects with LAr1-ND

LAr TPC detector: advantages include better energy reconstruction, background rejection, lower systematic errors → enhanced sensitivity to DM

In particular, LAr1-ND, due to its proximity to the dump, will have significantly better signal sensitivity than MiniBooNE.



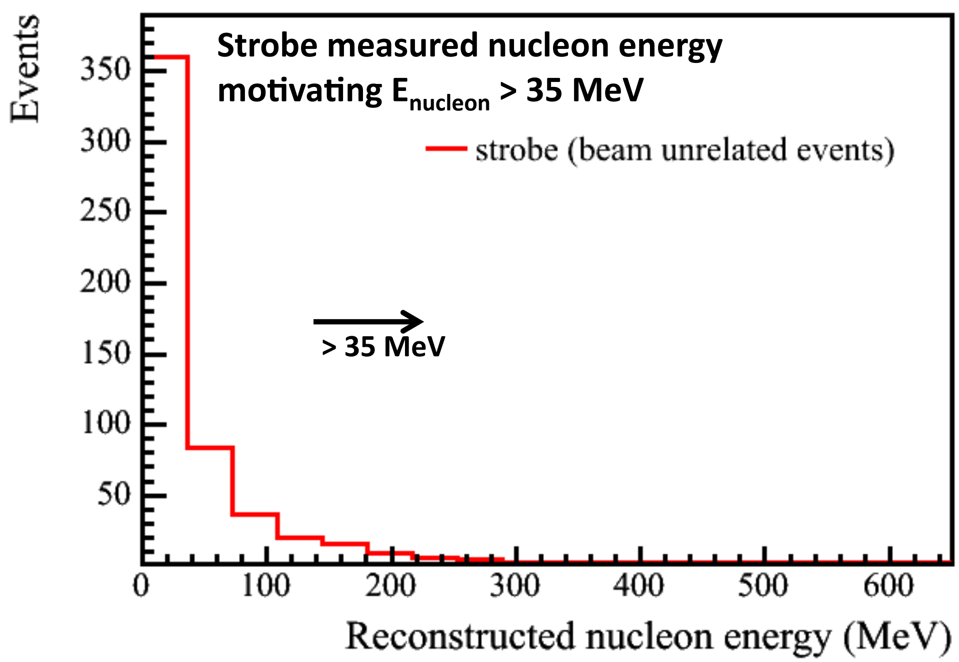
Beam-dump search: reducing backgrounds

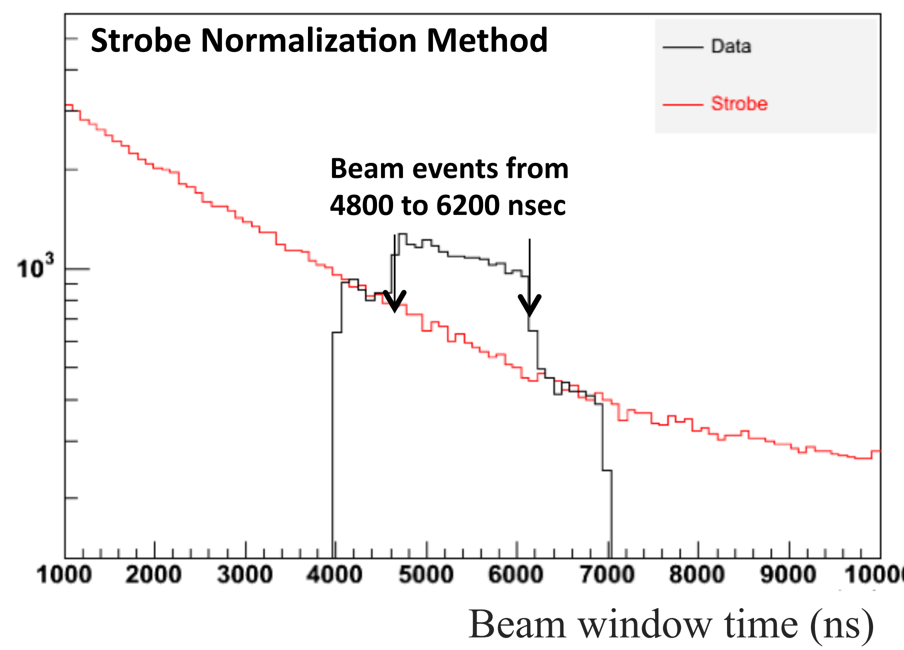
Beam-unrelated background dominated by cosmic rays, especially at low energy. Motivates 35 MeV cut.

Measure beam-unrelated events with a 15 Hz continuous strobe trigger that uses the same DAQ window as for beam.

Ratio of beam triggers to strobe trigger gives scaling. Systematic errors on beam-unrelated background 2% (→ beam duty factor important in proton beam-dump).

Working on method to reduce beam-unrelated rates by a factor of two.



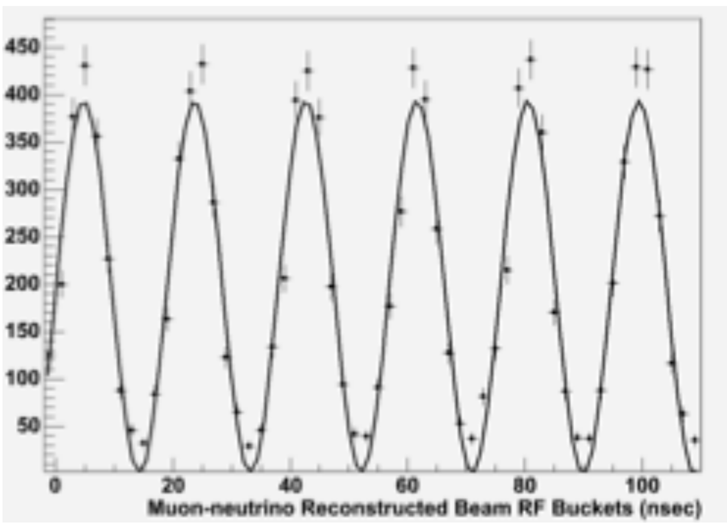


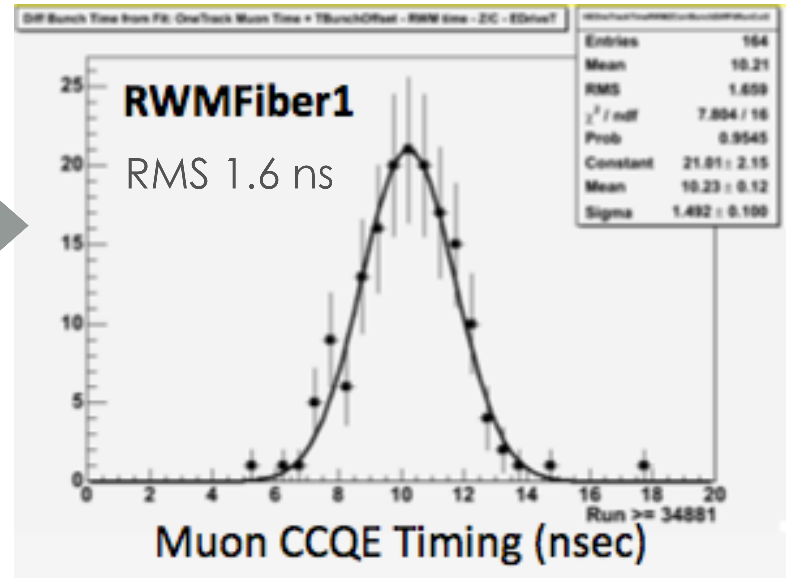
Beam-dump search: reducing backgrounds

Exploiting timing

- Dark Matter heavier than neutrinos - arrives later at the detector
- MiniBooNE timing resolution ~ns

Can reconstruct RF bucket structure with muon neutrino events





- Components to the spread: beam RF bucket, electronics (discriminator, QT channel) and detector reconstruction.
- Resolution is worse (RMS ~4.5 ns) for NC events due to scintillation light

Beam-dump search: reducing backgrounds

- Beam-unrelated and neutrino dirt interactions are flat in time.
- In-time (4-16 nsec) region rejects flat backgrounds, enhances m_{DM} < 120 MeV
- Out-time (0-4; 16-20 nsec) region rejects NCE bkgs, enhances m_{DM} > 120 MeV
- More sophisticated dark matter time distribution fits being developed.