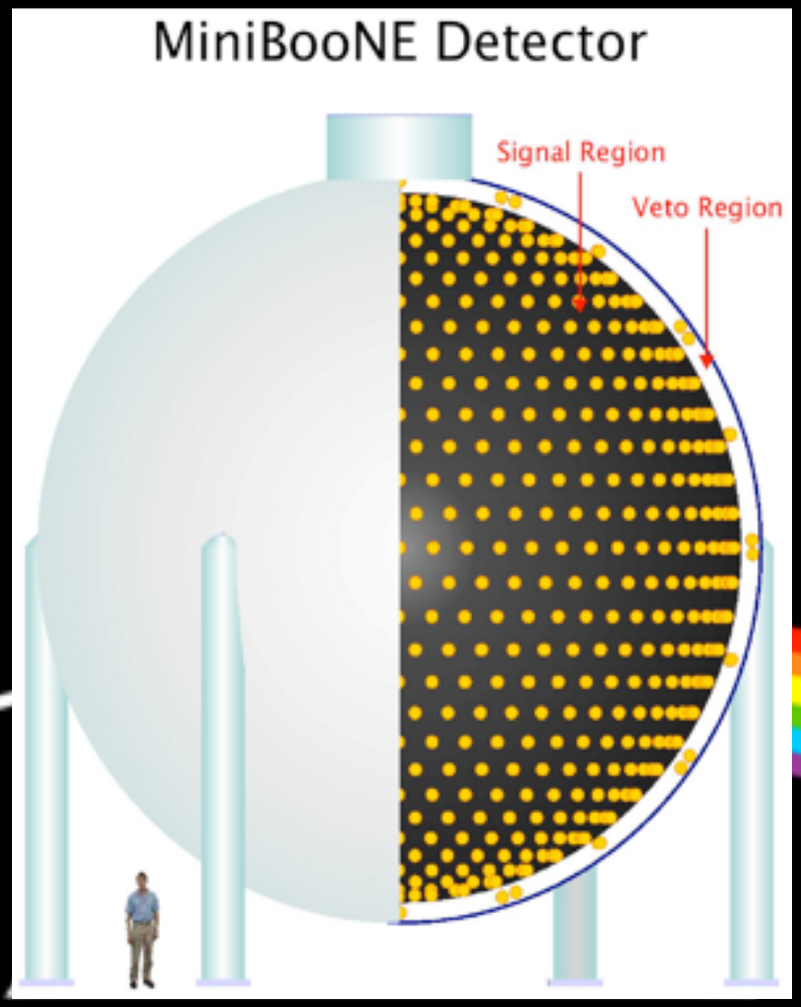
Dark Matter Searches at MiniBooNE



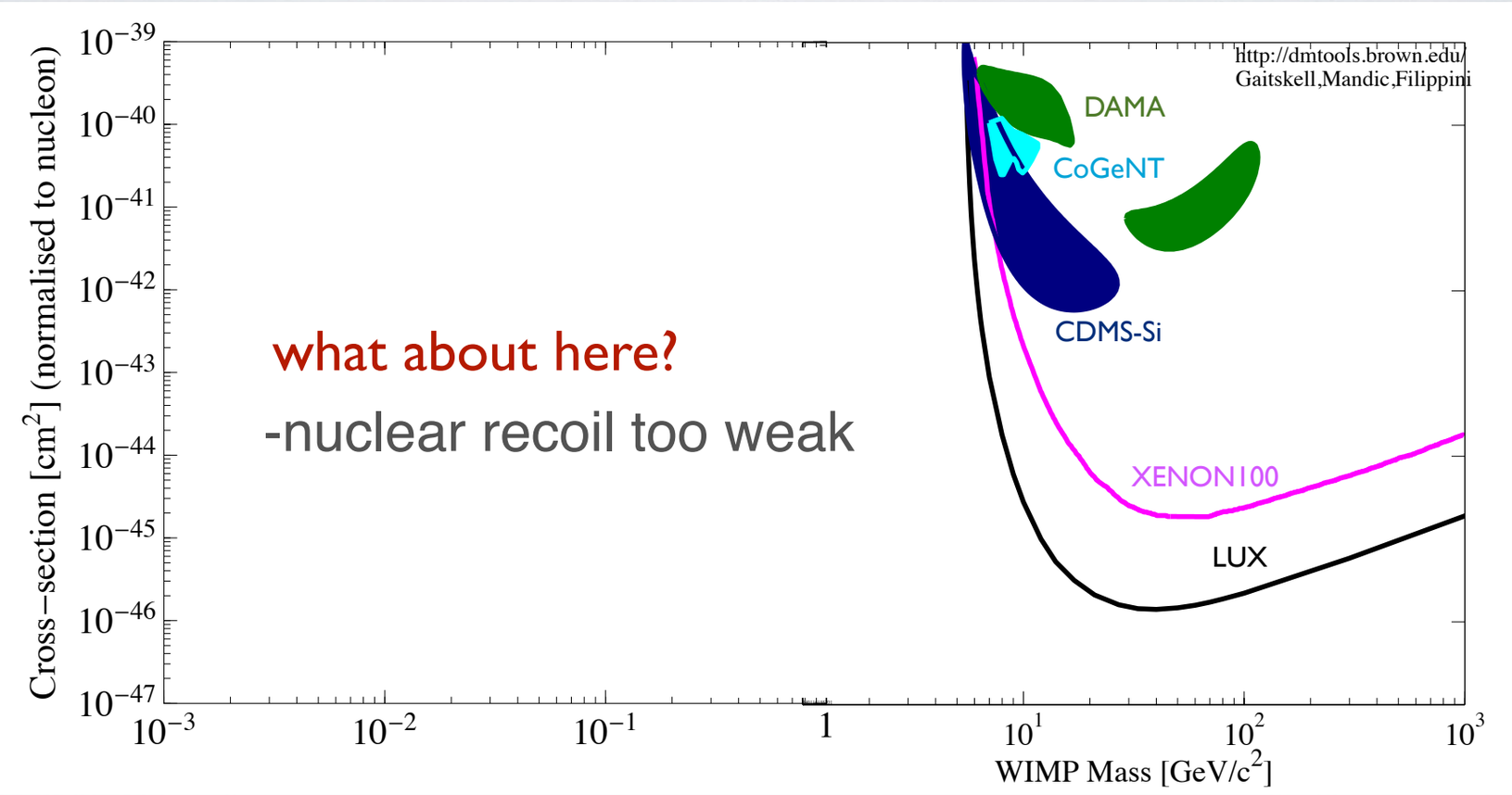
New Perspectives on Dark Matter
Fermilab
28th April 2014

Ranjan Dharmapalan
Argonne National Laboratory

Outline

- Motivation
- The experimental principle
- MiniBooNE neutrino mode Dark Matter search
- Beam-dump mode and enhanced sensitivity
- MiniBooNE Dark Matter search strategies

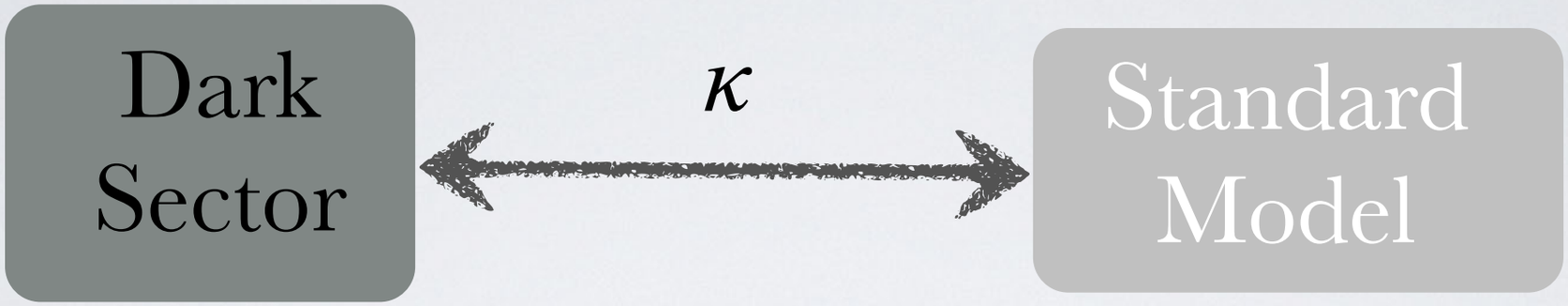
Motivation: Light Dark Matter



If Dark Matter is relativistically boosted, we can observe possible signature.

Motivation: The benchmark model

A Minimal extension to the Standard Model:



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

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

4 new parameters:

$$m_\chi, m_V, \kappa, \alpha'$$

B. Batell, M. Pospelov, A. Ritz Phys.Rev., vol. D80, p. 095024, (2009)

P. deNiveville, M. Pospelov, A. Ritz Phys.Rev.D84:075020 (2011)

P. deNiveville, D. McKeen, A. Ritz Phys.Rev.D86:035022 (2012)

- The new mediators increase the annihilation cross section of the dark matter to give the correct relic density.

- Also mediate interactions with the Standard Model.

Motivation: Why MiniBooNE is ideal

Production:

- From proton-target interactions'. So require intense beam with high protons on target (POT).

Location:

- Detector needs to be close to source (for rate) but far enough to minimize beam related backgrounds.

Detection:

- Require large, sensitive, well-understood detector. Good particle id and event reconstruction.

Motivation: Why MiniBooNE is ideal

Production:

- From proton-target interactions'. So require intense beam with high protons on target (POT).

✓ MiniBooNE has ~2E21 POT at 8 GeV proton energy

Location:

- Detector needs to be close to source (for rate) but far enough to minimize beam related backgrounds.

✓ 500 m away from the target

Detection:

- Require large, sensitive, well-understood detector. Good particle id and event reconstruction.

✓ Size: 1Kton
Reconstructs p, n, μ, π, and γ
Energy threshold ~20 MeV and timing resolution ~nsec.

Motivation: Why MiniBooNE is ideal

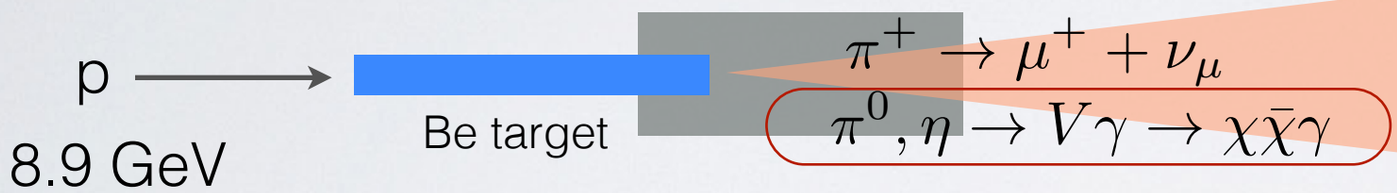
- Neutrino mode: 6.5E20 POT
- Antineutrino mode: 11.3E20 POT
- 11 oscillation papers
- 14 cross section and flux papers
- 1 detector and 1 supernova search paper
- 18 PhD theses
- The experiment is well understood!

The dark matter search heavily leverages this decade of work.

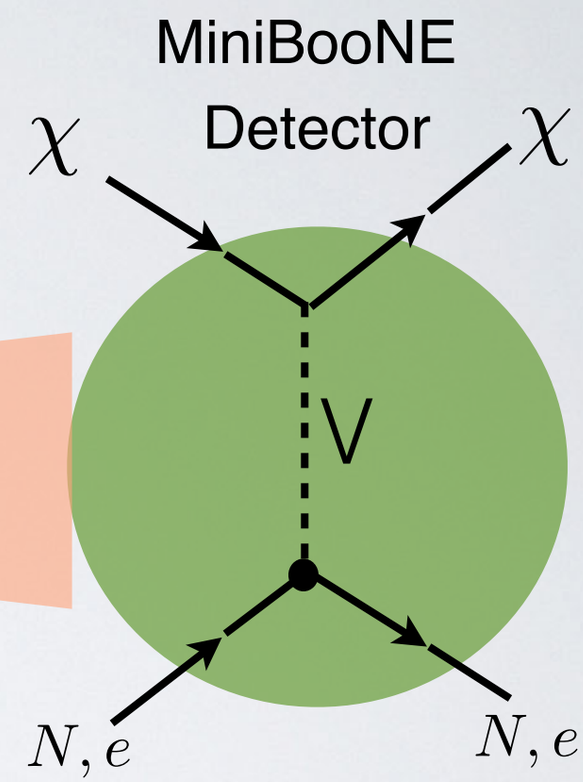
The experimental principle: Setup

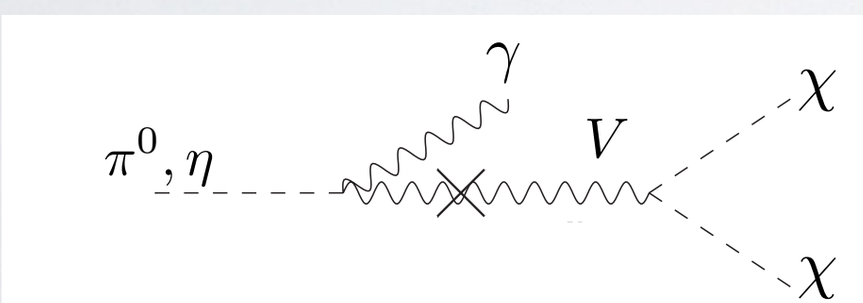
Production

The HARP-MiniBooNE Be target Sanford-Wang meson production model is used.
The errors on π^0 and η range ~ 25%.



DM beam accompanying the neutrino beam





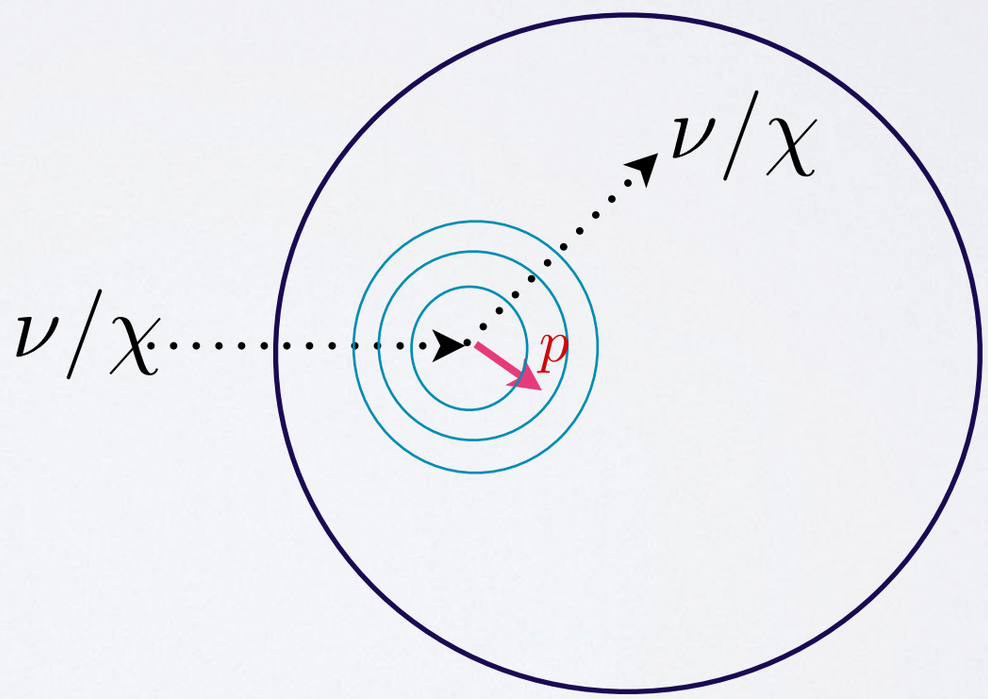
MiniBooNE will test the "invisible decay" of V
$M_V > 2M_\chi$

Detection

The DM particles scatter off of nucleons or electrons in the detector medium, mimicking NCE scattering, but possibly with different kinematics (momentum, angle, timing etc.)

The experimental principle: MiniBooNE reconstruction

- MiniBooNE oil Cherenkov detector
- Scintillation light due to trace fluors
- NC Elastic signature: Activity in detector with no muon or pion
- Reco. E= sum of Q from all PMTs /event



The experimental principle: Selection cuts

1. Only one subevent
2. Veto hits < 6
3. Tank hits > 12
4. Event in beam window
5. $\ln(L_e/L_p) < 0.42$
6. Reconstructed energy cut
7. Fiducial volume cut

- A subevent is a cluster of at least 10 tank hits with less than 10 ns difference between them.

$$\nu/\chi + N \rightarrow \nu/\chi + N \qquad \nu + n \rightarrow \mu^- + p$$

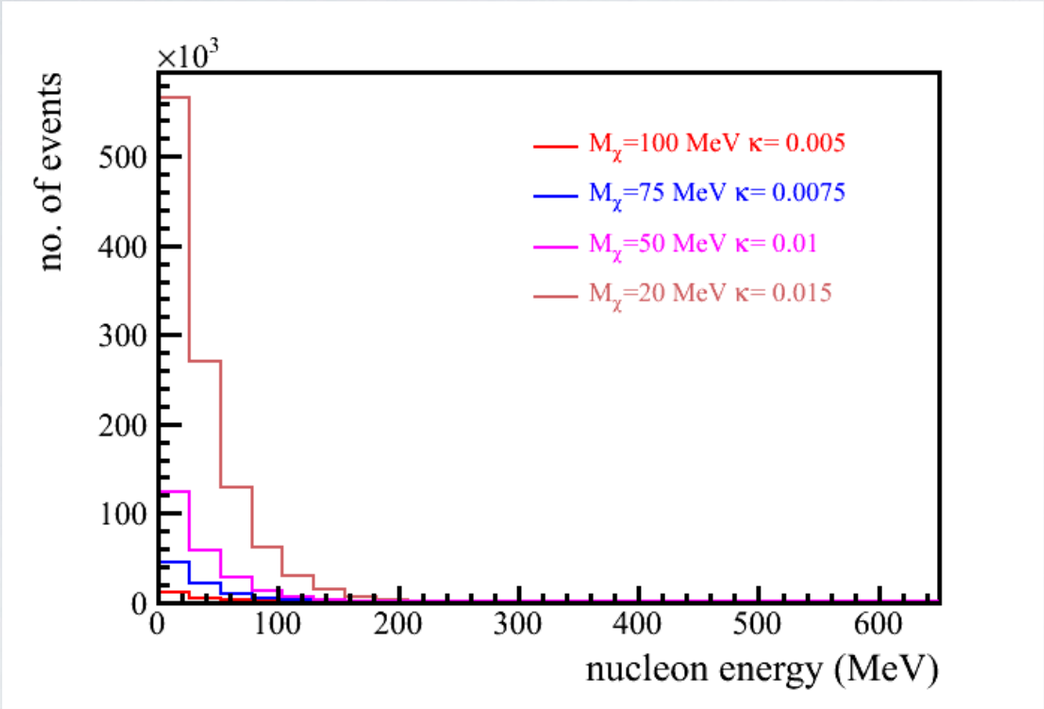
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

- 4400 ns < event time < 6500 ns, ensures events happened in the beam window
- Removes beam unrelated background

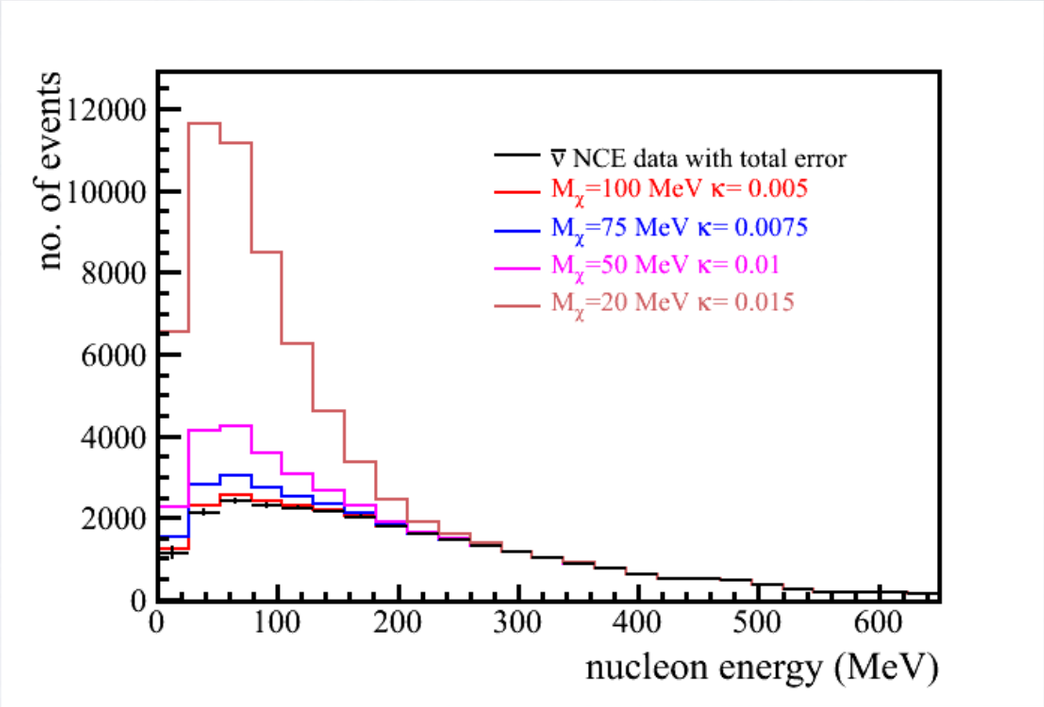
Apply cuts and look at reconstructed nucleon energy

Reco. E= sum of Q from all PMTs /event

The experimental principle: DM search in Neutrino mode



Nucleon energy from Dark Matter scattering

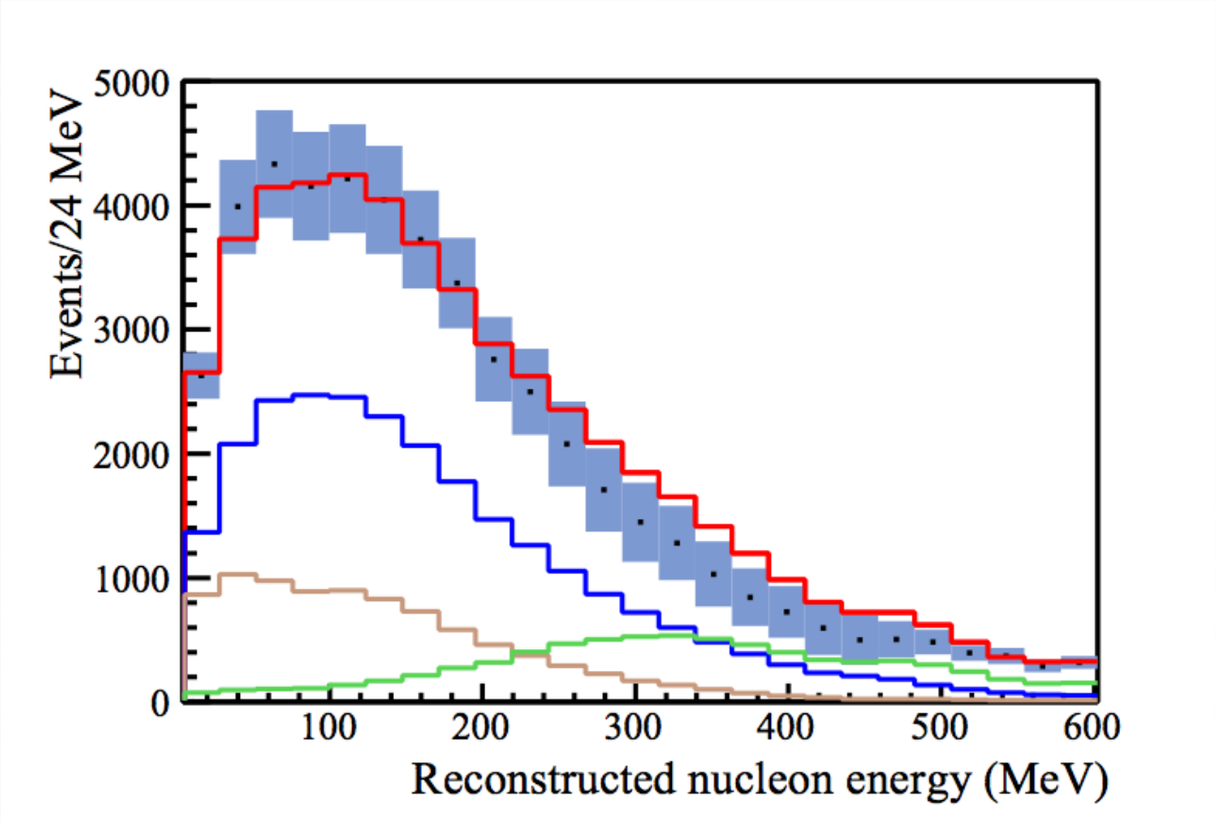


Efficiency corrected DM signal+antinu NCE data

- Signal falls off rapidly below 40 MeV due to detector reconstruction efficiency
- Fit the dark matter template plus the neutrino background prediction to the data. Use full NC cross section error matrix (20% systematic error).
- MiniBooNE nucleon reconstruction 35% efficiency, 10% energy resolution
- Exploits the shape difference
  -Parameter space of κ (mixing parameter) and Dark Matter mass M_χ assuming a new vector M_V=300 MeV

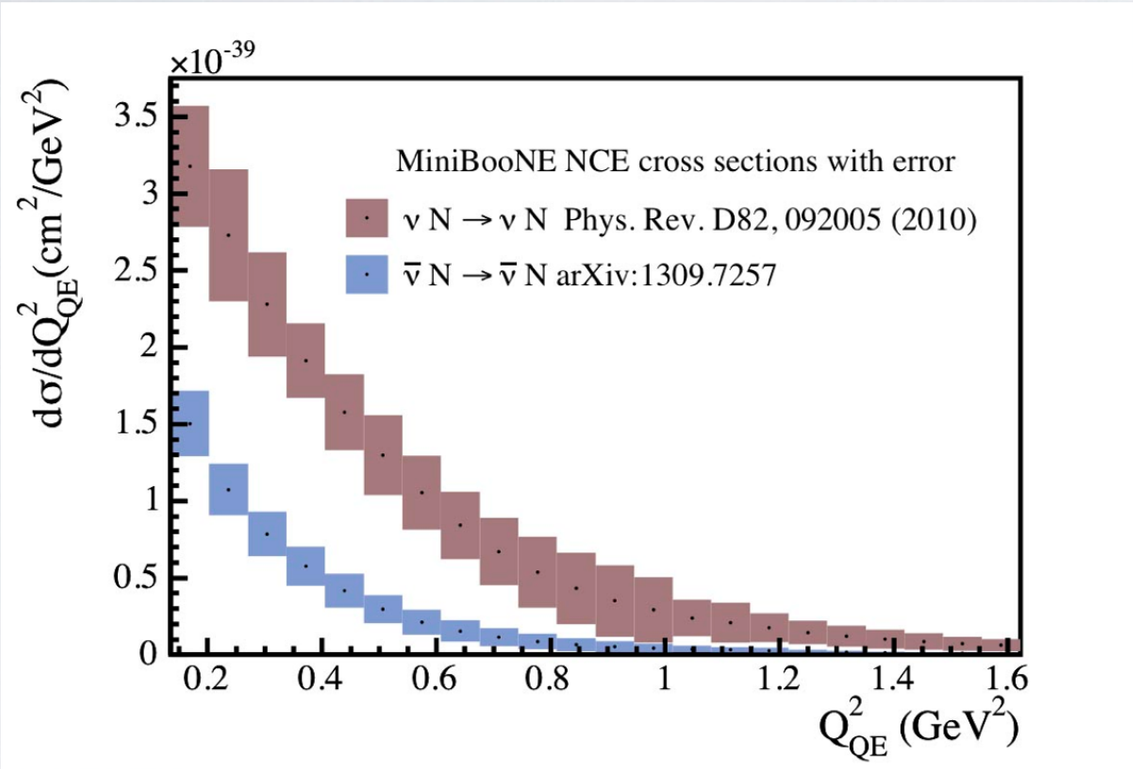
The experimental principle: Constraining backgrounds

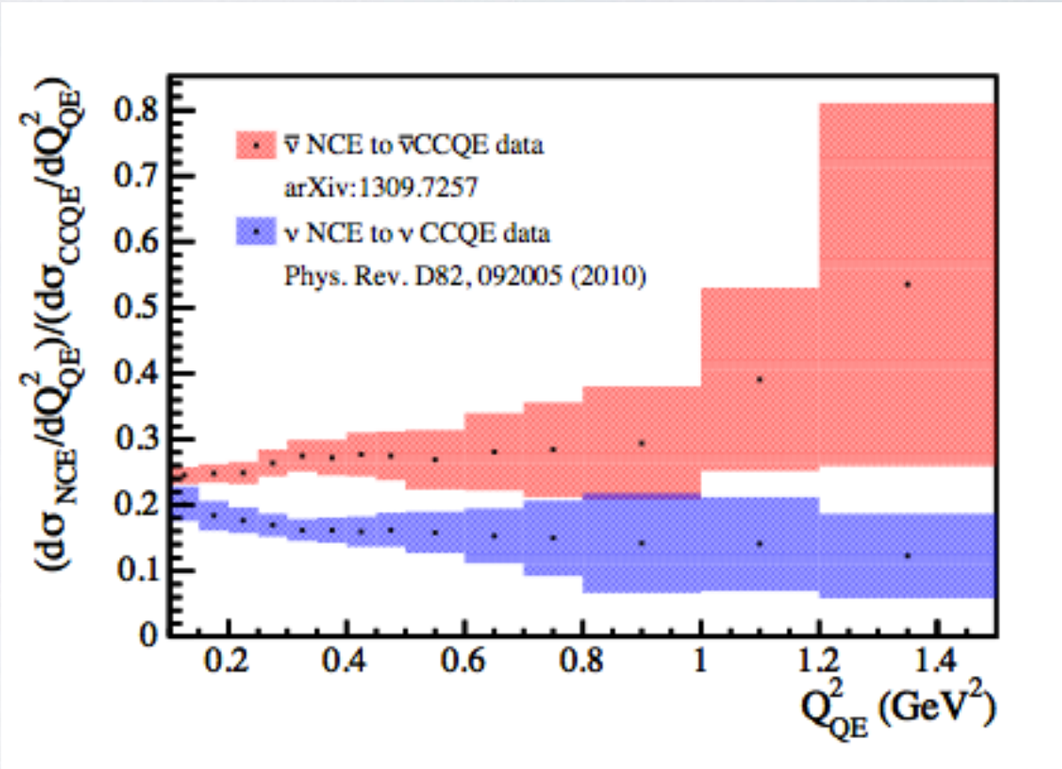
MiniBooNE antinu NCE cross section
(arXiv:1309.7257) submitted to PRD



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

The experimental principle: Constraining backgrounds

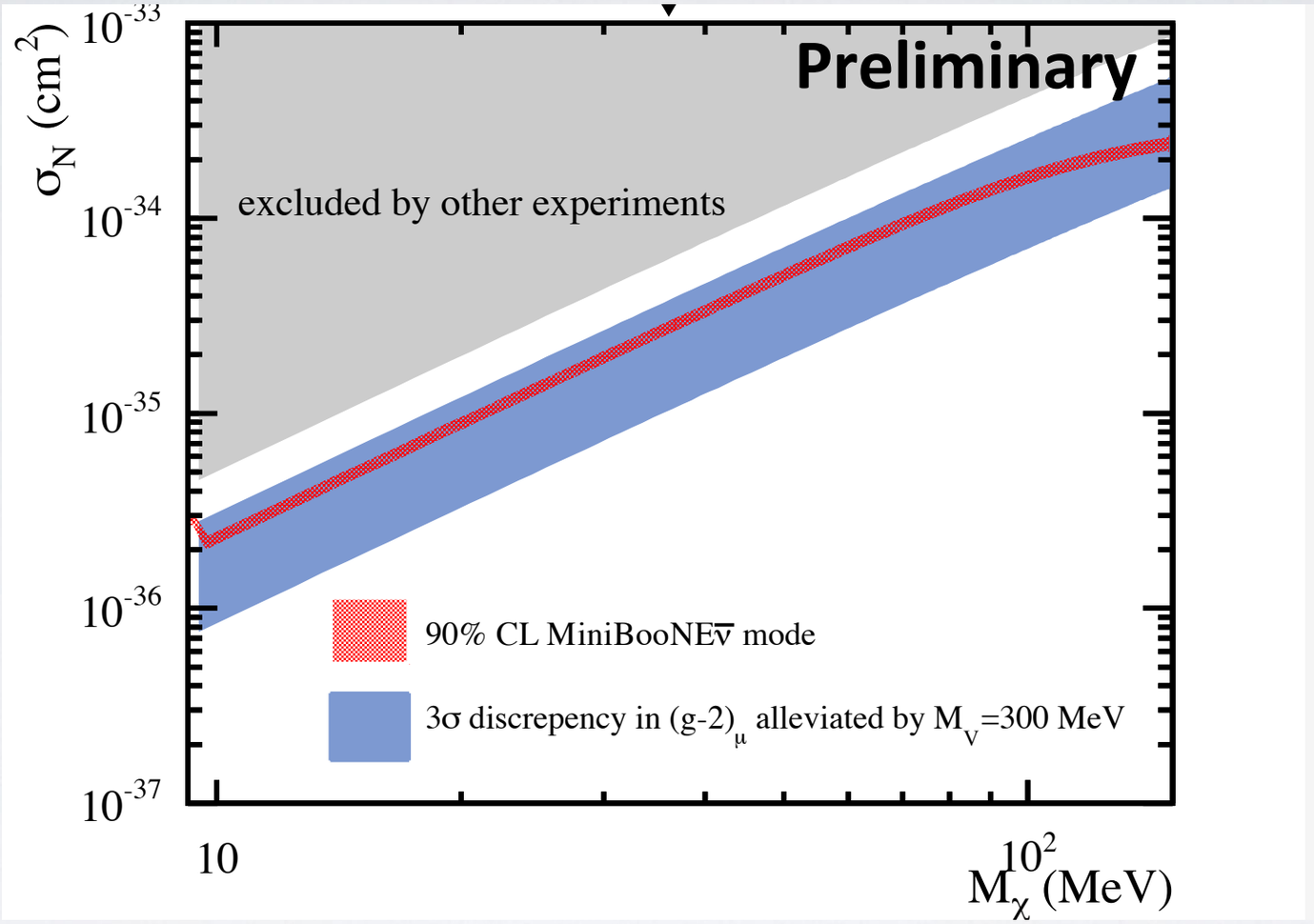




MiniBooNE has published the neutrino and antineutrino NC elastic and CC elastic scattering cross sections as well as the ratios.

PRD D81, 092005 (2010)
PRD 82, 092005 (2010)
PRD D88, 032001 (2013)
arXiv:1309.7257 (2013)

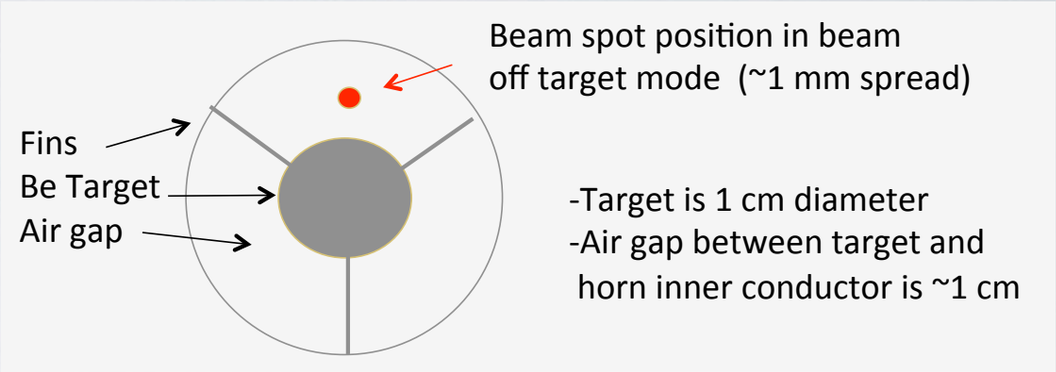
The experimental principle:Neutrino mode results and conclusions



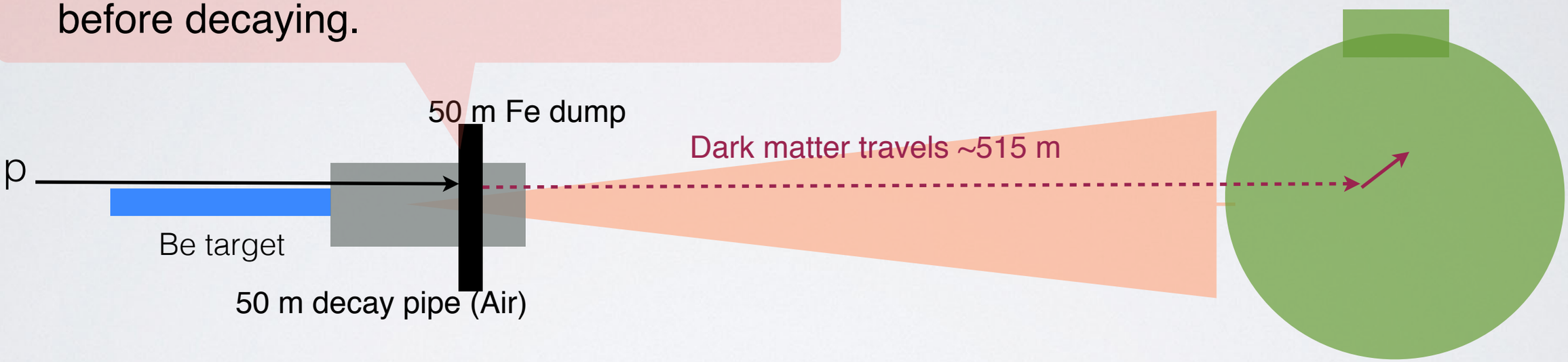
- Corresponding to 10.1E20 POT
- Dark Matter-Nucleon scattering limits from the antineutrino data suffer from large neutrino induced backgrounds.
- Neutrino mode 4 times worse.

Conclusion: Neutrinos a background! We need beam-dump mode.

MiniBooNE Beam-dump mode: Setup



- π^0 and η decay quickly (to new vector bosons and subsequently dark matter)
- The charged mesons are absorbed before decaying.

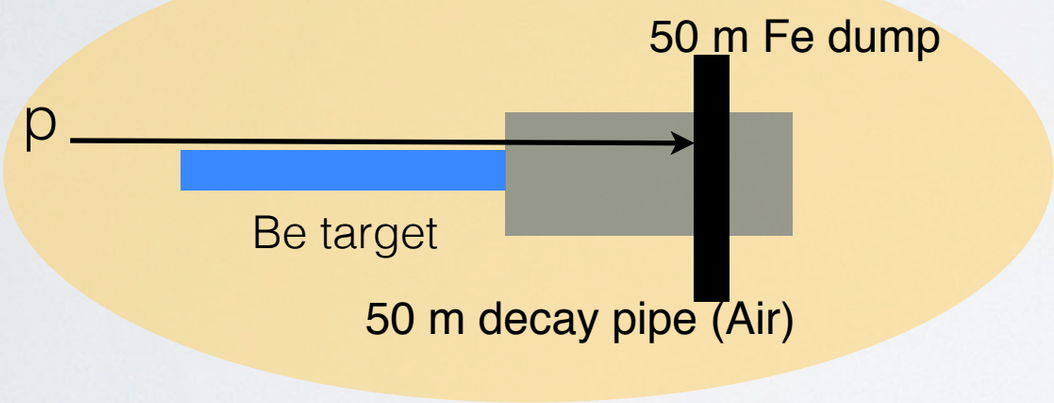


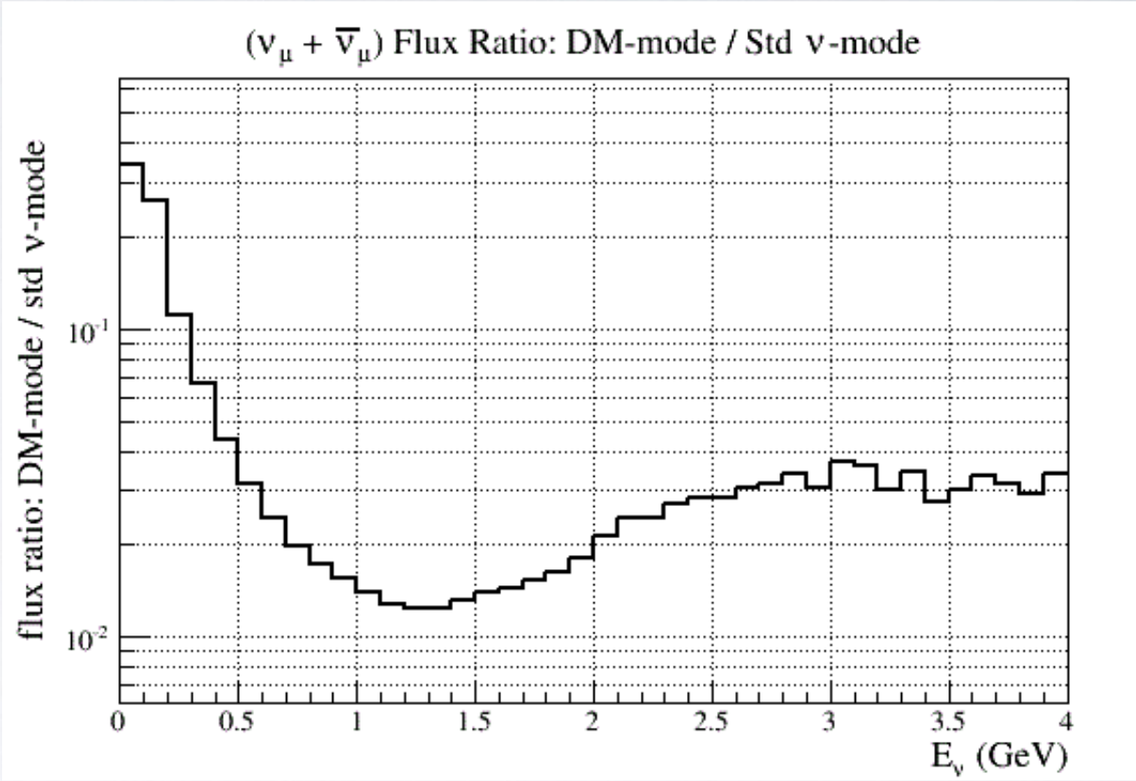
Beam off-target mode reduces the neutrino background by a factor of ~40.

MiniBooNE Beam-dump mode

Flux prediction in Beam-dump mode

- Neutrinos from p-Air interaction before the dump.
- Not constrained by external measurements, large systematic errors
- Look at data!



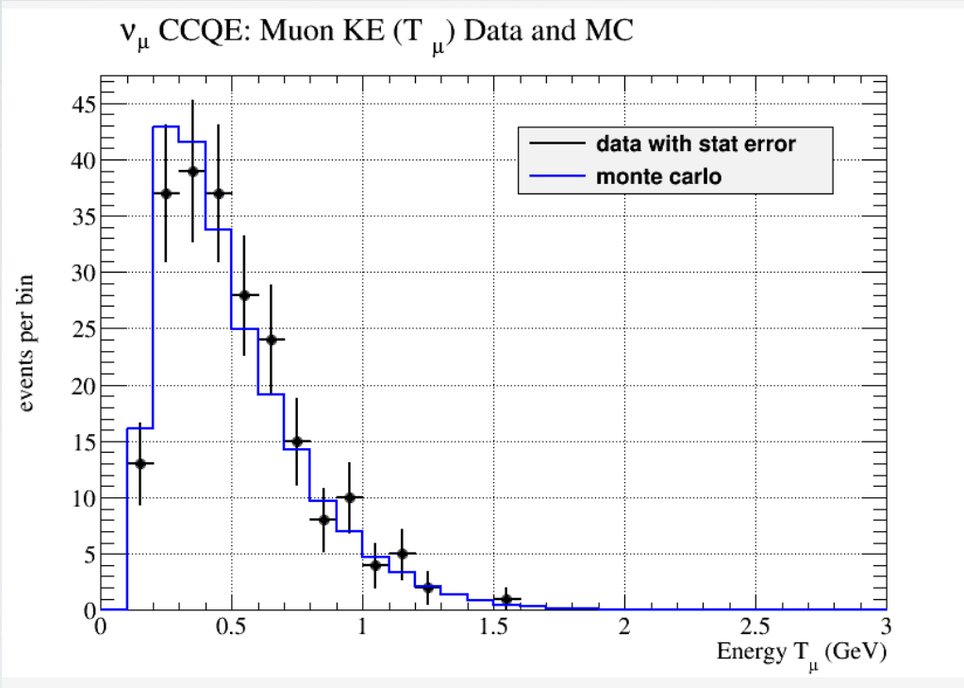


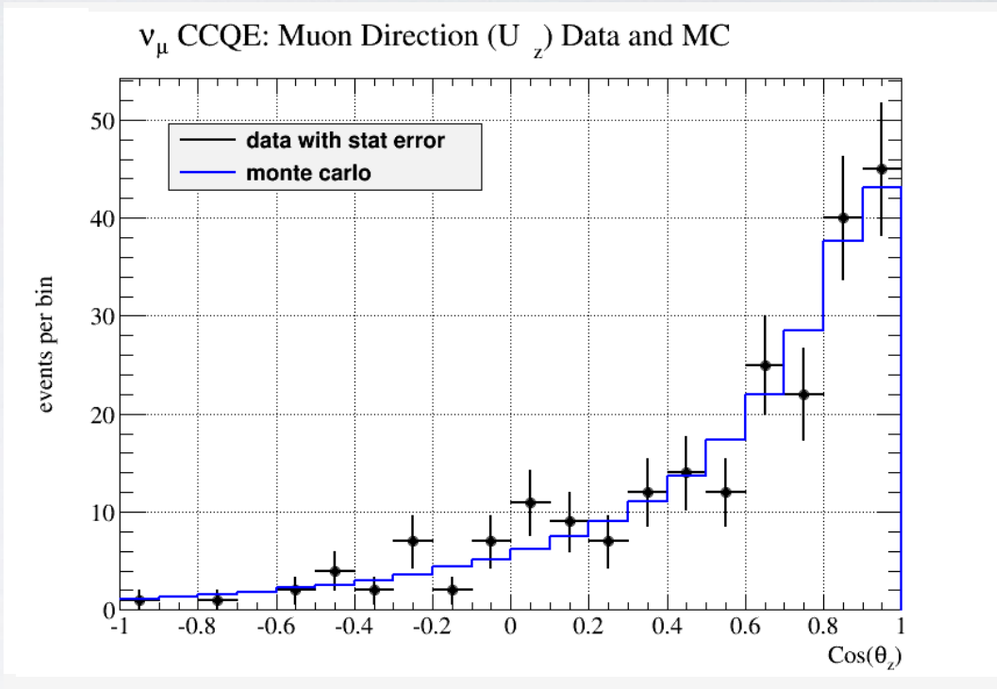
Neutrino flux reduction in beam-dump mode relative to neutrino mode as a function of neutrino energy.

Beam off-target mode reduces the neutrino background by a factor of ~40.

MiniBooNE Beam-dump mode

Rate prediction in Beam-dump mode





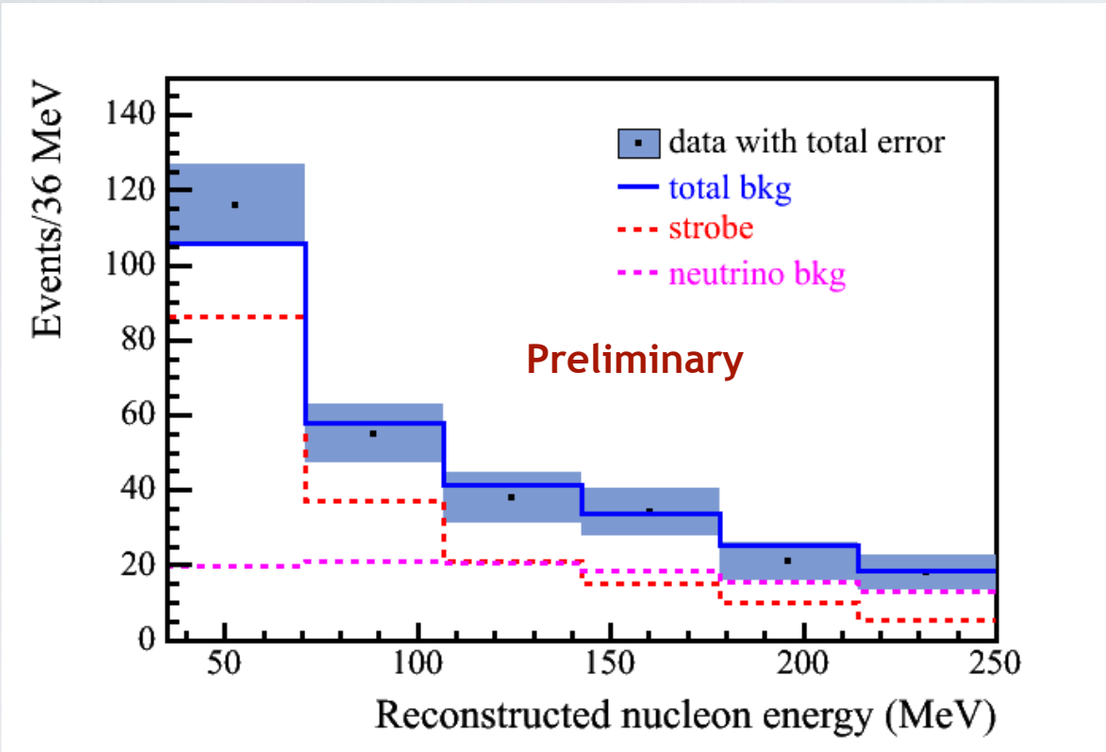
- Use data (nu CCQE muon)
- CCQE muon (neutrino mode/beam dump) = 44 +/- 3
- Kinematic distribution: shape agrees.
- Also looked at NCπ^0

Use the CCQE muon rate to predict the NCE scattering rate

Beam off-target mode reduces the neutrino background by a factor of ~40.

MiniBooNE Beam-dump mode

Dark Matter-Nucleon Scattering (3.19×10^{19} POT)



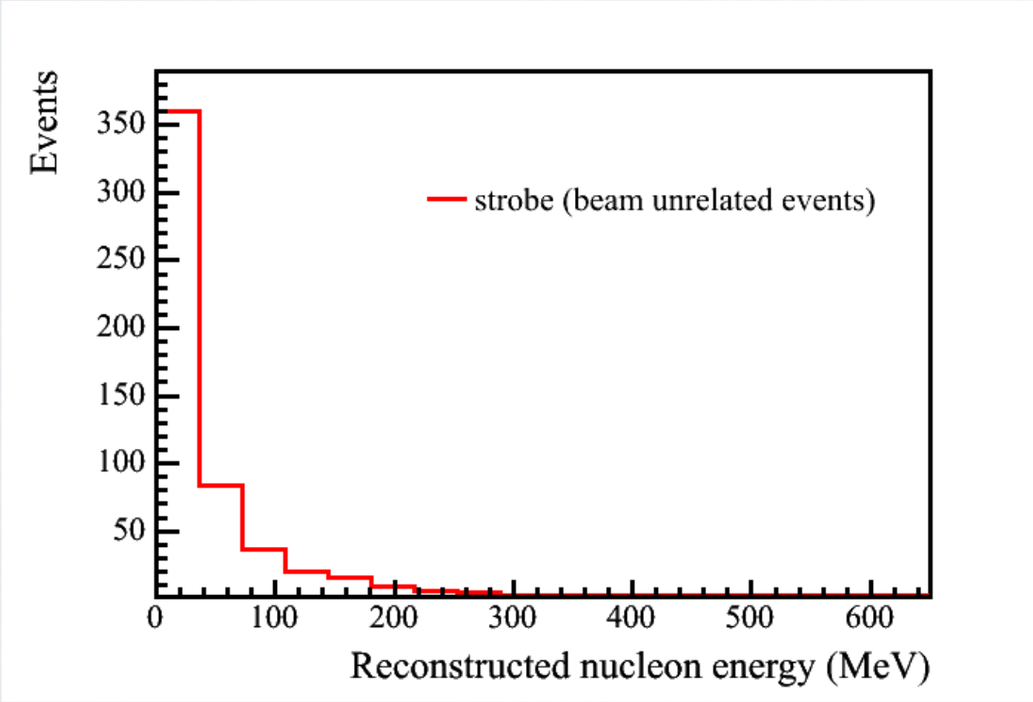
	#events
Cosmics	177
nu bkg	107.8
Total Bkg	284.8 +/-18 (sys.)
Data	282 +/-17(stat)

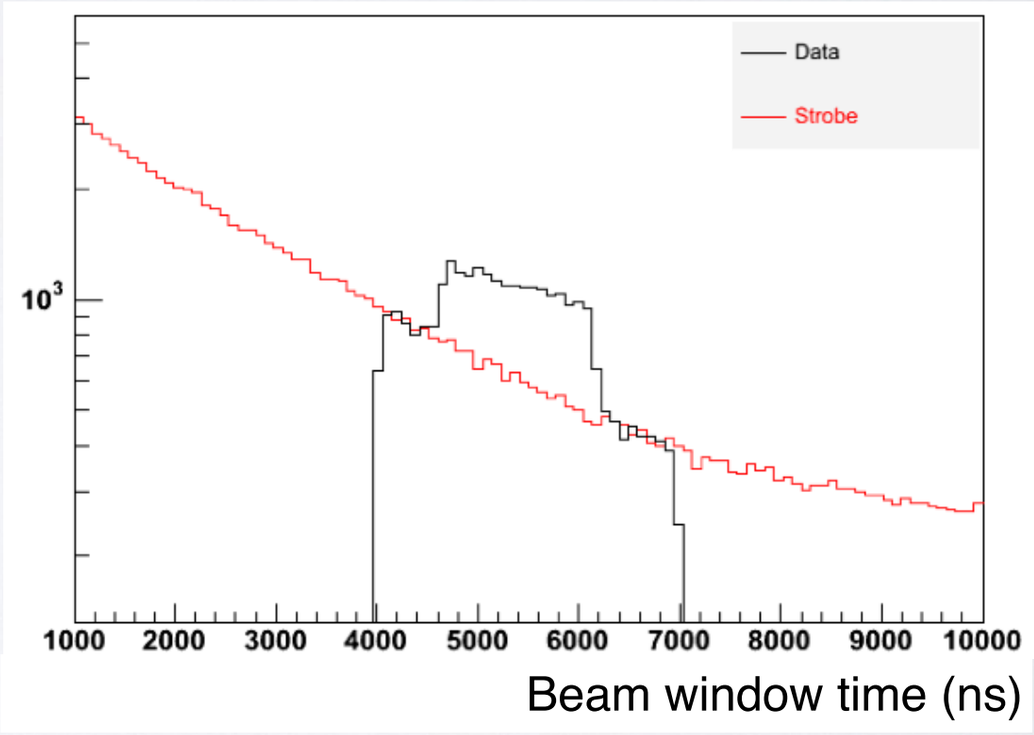
Total error= 24.6 events, or 23% of nu bkg

- Similar event reconstruction as in antineutrino analysis. Monte Carlo neutrino background prediction tied to measured muon CCQE rate.
- Background stat error dominated by Beam-unrelated (strobe) events.
- Data in agreement with background predictions. Currently ~16% systematic error on NC neutrino background.

MiniBooNE Beam-dump mode: background

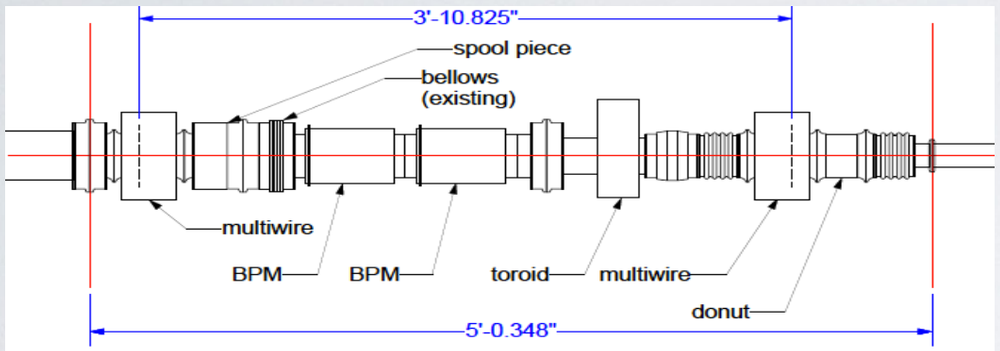
- Beam-unrelated background dominated by cosmic rays, especially at low energy. Motivates 35 MeV cut.
- Measure beam-unrelated events with a 15 Hz continuous strobe trigger that uses the same DAQ window as for beam.
- Ratio of beam triggers to strobe trigger gives scaling. Systematic errors on beam-unrelated background 2% (->beam duty factor important in proton beam-dump)
- Working on method to reduce beam-unrelated rates by a factor of two.



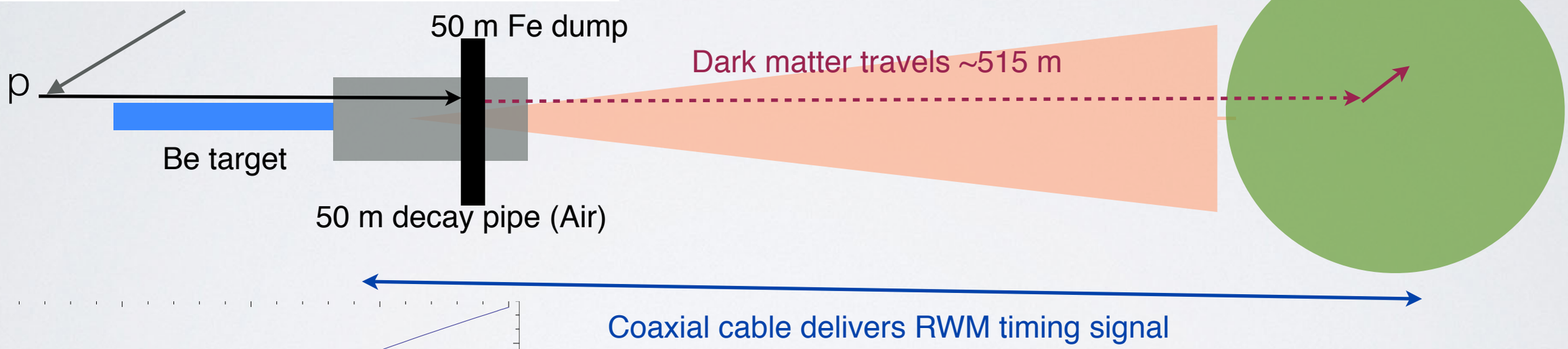


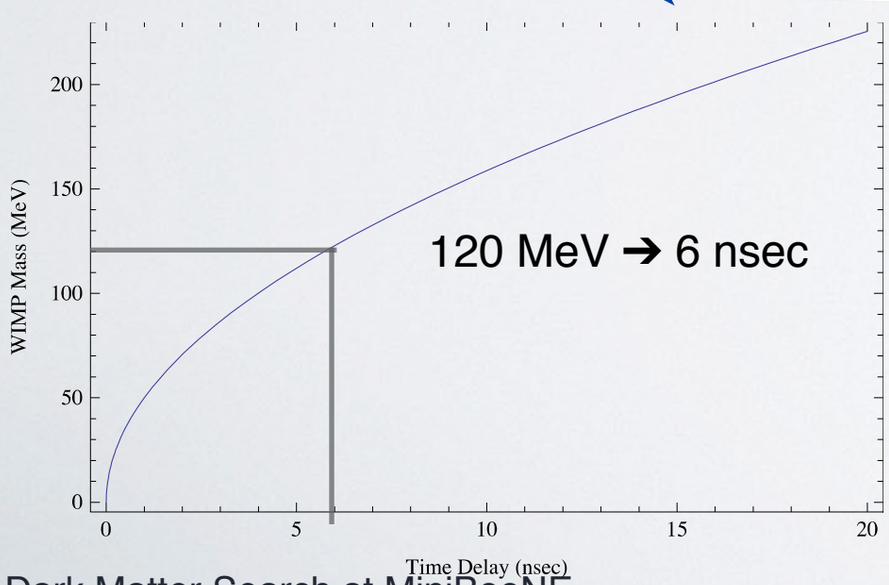
MiniBooNE Dark Matter search strategies

Hardware upgrades



New dual low-mass multi wires. Will be able to reliably point the proton beam at the detector within 0.5 mrad or 25cm spatial resolution





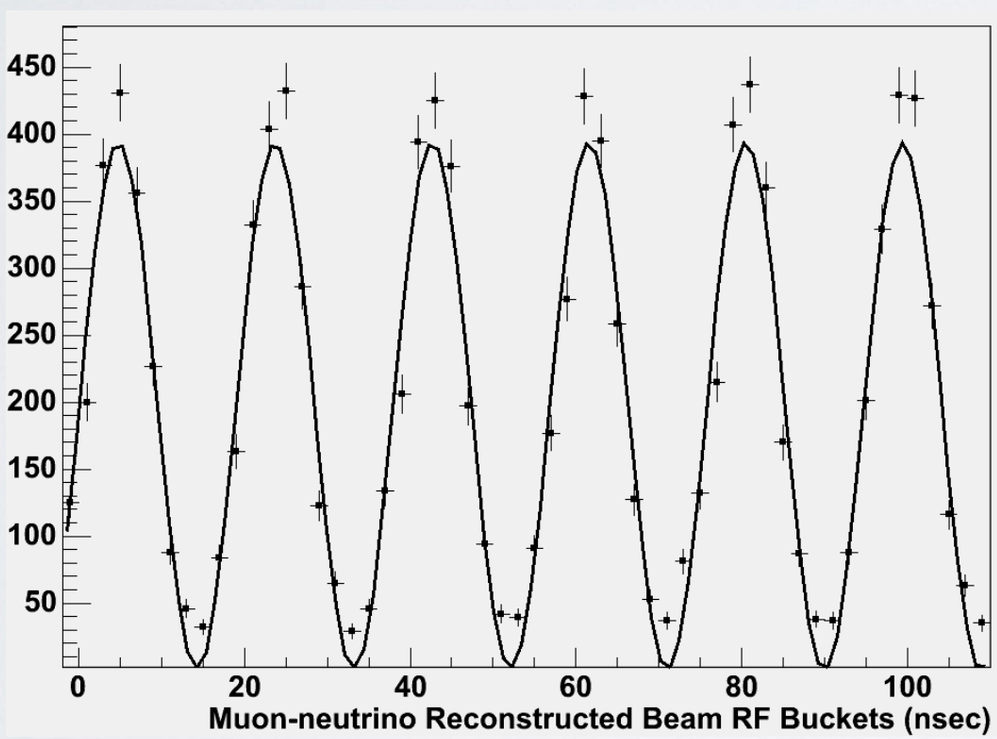
New fast timing discriminator and optical fiber system. Delivers beam crossing signal to the detector.

- Dark Matter heavier than neutrinos - arrives later at the detector

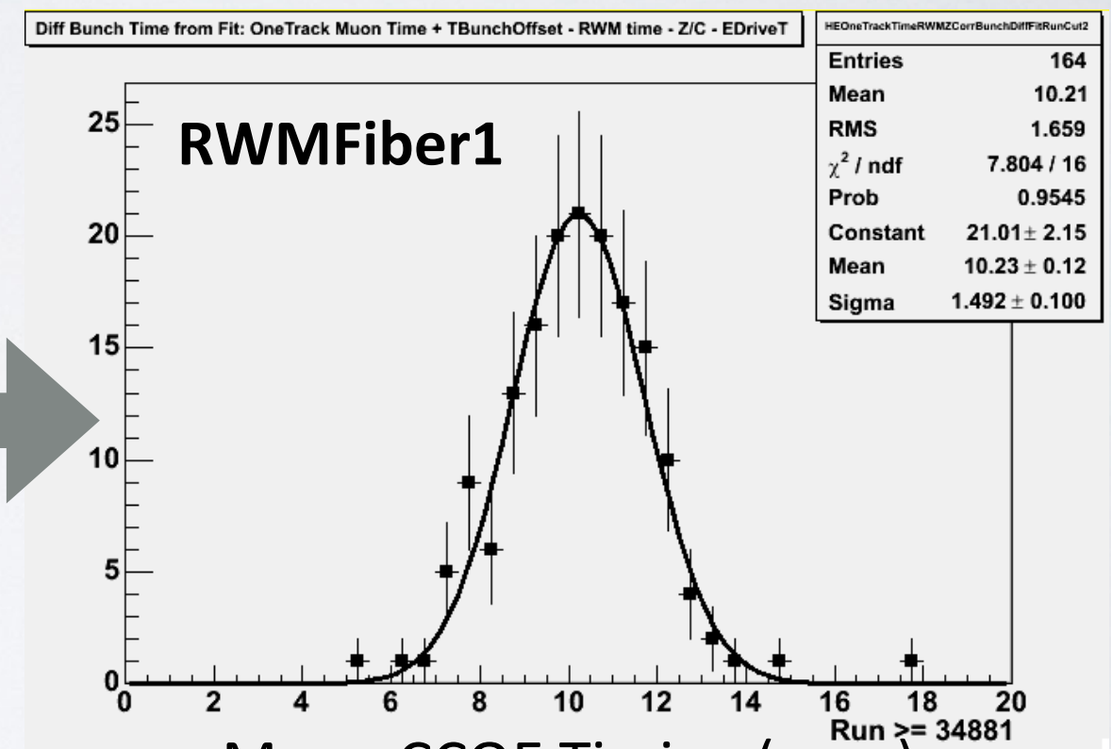
MiniBooNE Dark Matter search strategies: Timing

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

Can reconstruct RF bucket structure with muon neutrino events



RMS 1.6 ns



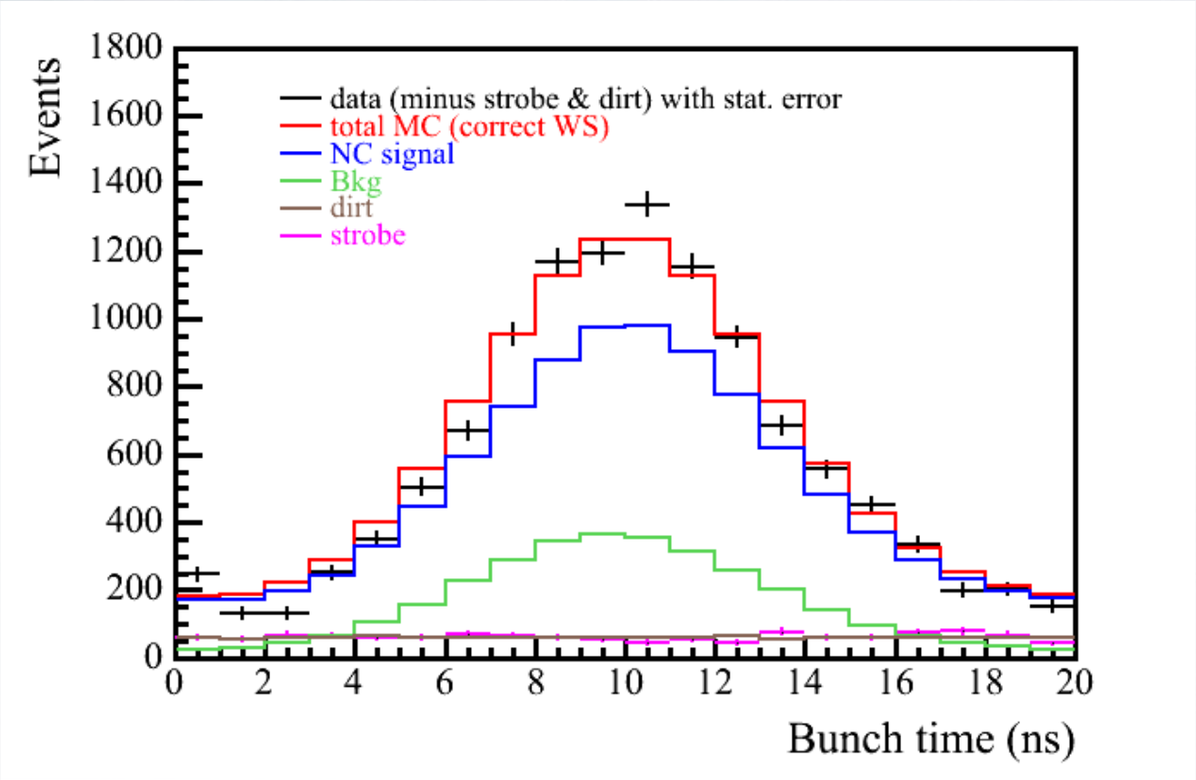
Muon CCQE Timing (nsec)

- components to the spread: beam RF bucket, electronics (discriminator, QT channel) and detector reconstruction.

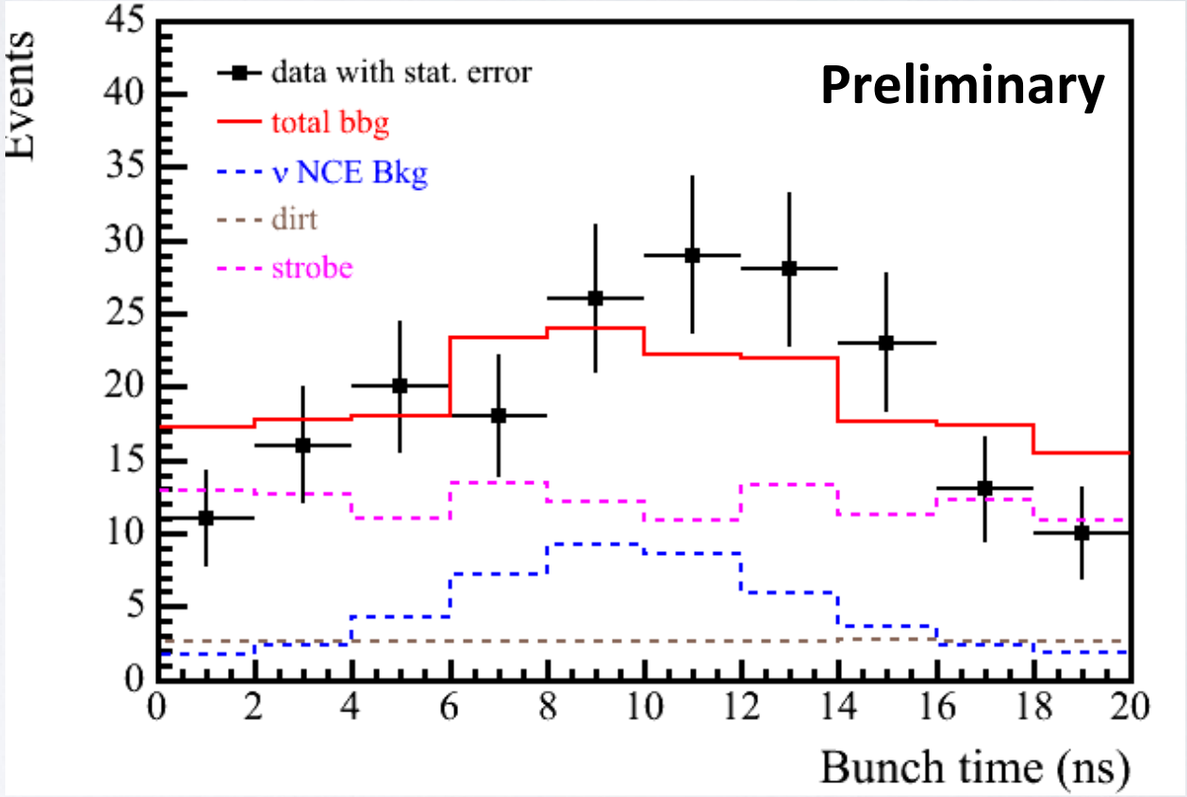
MiniBooNE Dark Matter search strategies: Timing

- Resolution worse for NC as reconstruction via scintillation light
- Beam-unrelated and neutrino dirt interactions are flat in time

RMS 4.5 ns



10.1E20 POT Antineutrino mode

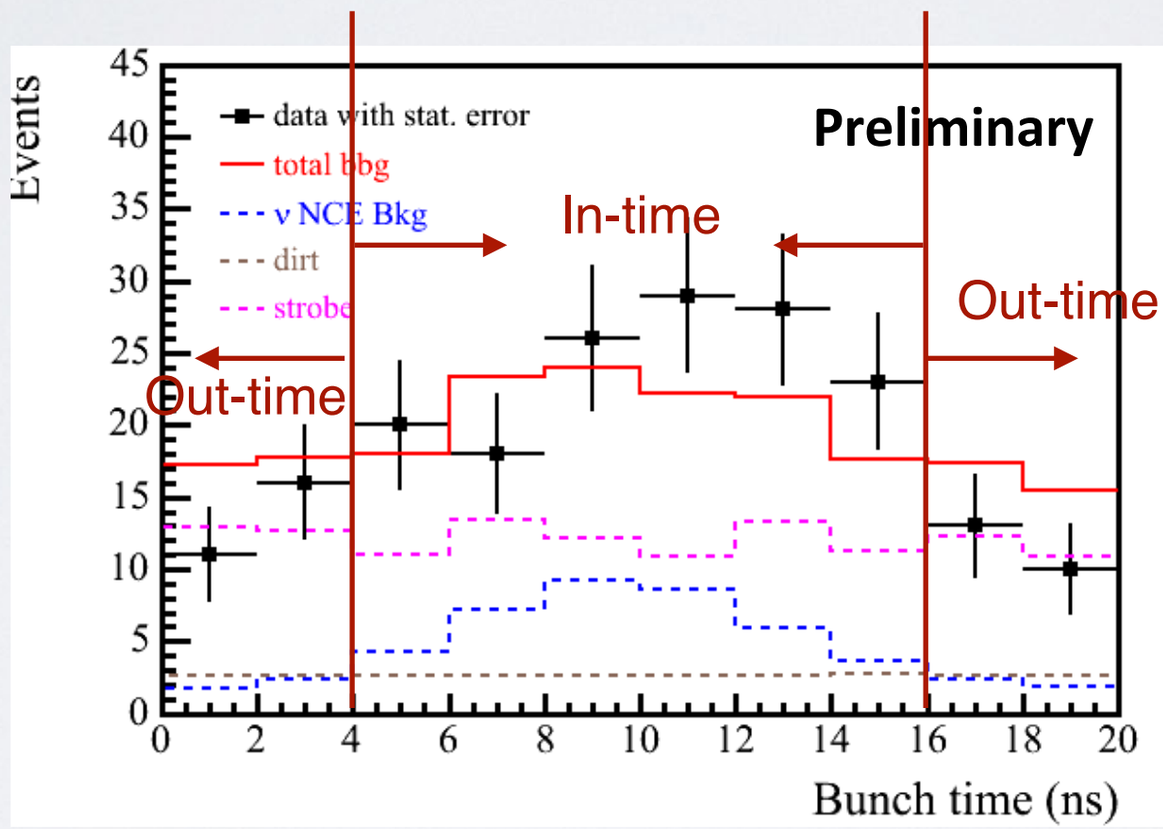


0.35E20 POT Beam dump mode

- Lesson learnt: Timing can be used to constrain beam unrelated background!

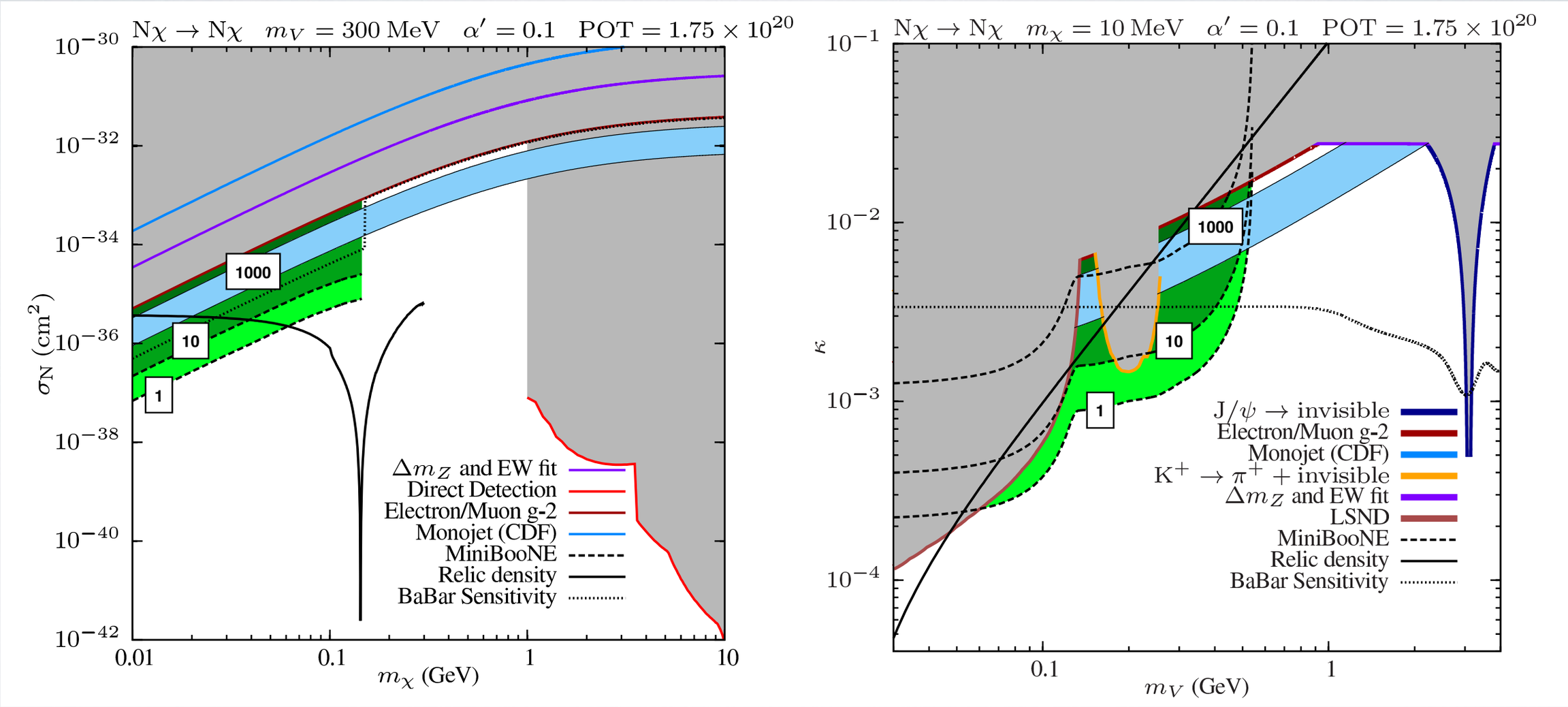
MiniBooNE Dark Matter search strategies: Timing

- 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.



- Lesson learnt: Timing can be used to constrain beam unrelated events!

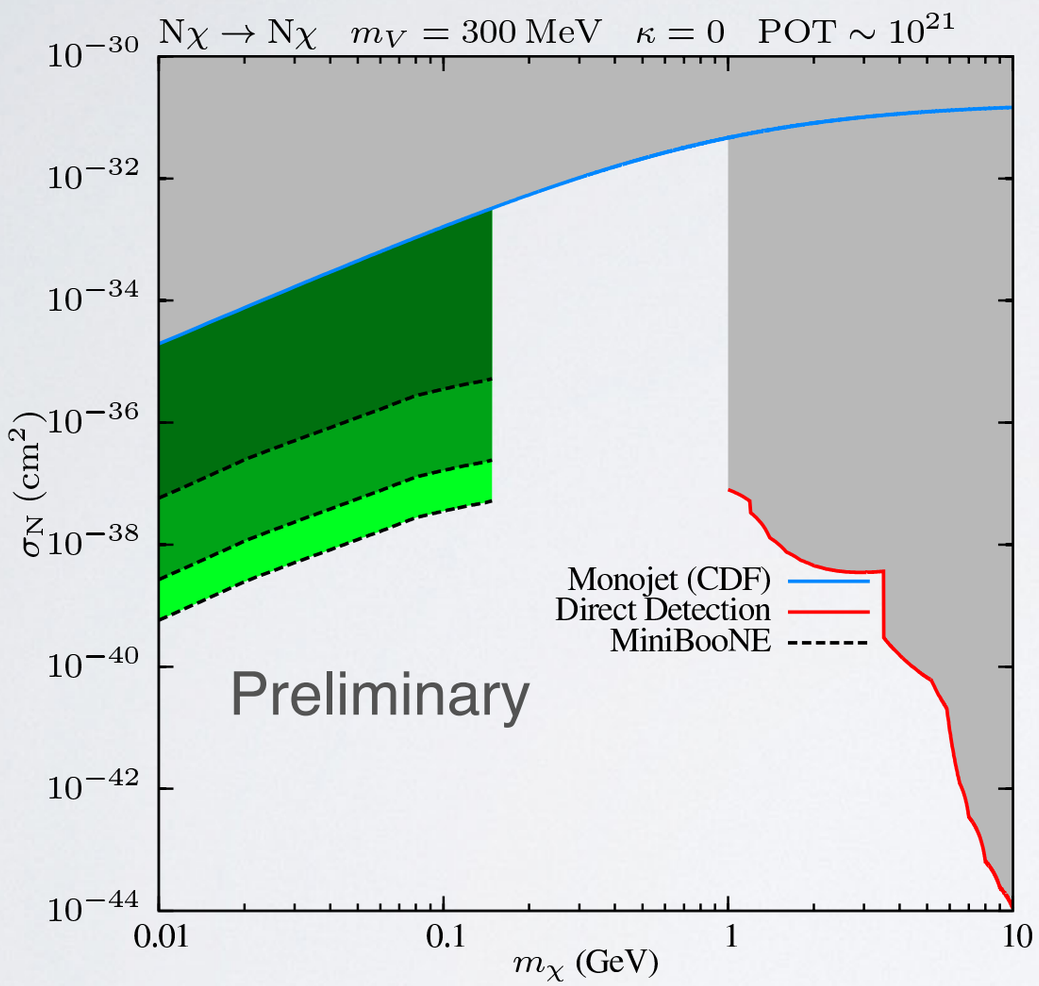
MiniBooNE Beam-dump mode: Projections

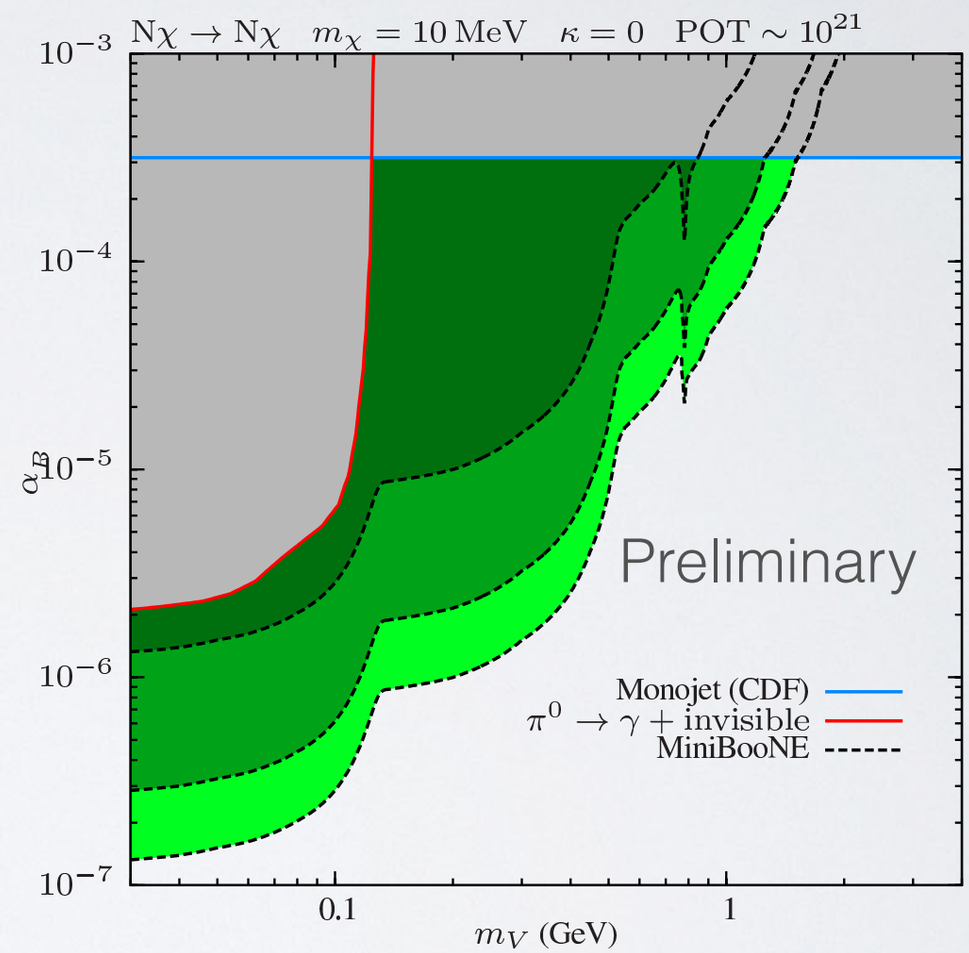


Plots by P. deNiverville, Univ. of Victoria

MiniBooNE Beam-dump mode: Projection

If the new vector only couples to quarks-MiniBooNE has the best sensitivity.

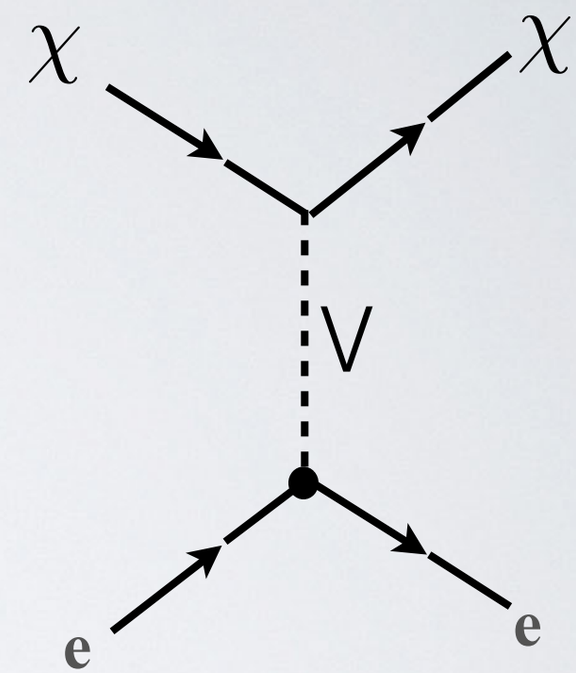




Plots by P. deNiverville, Univ. of Victoria

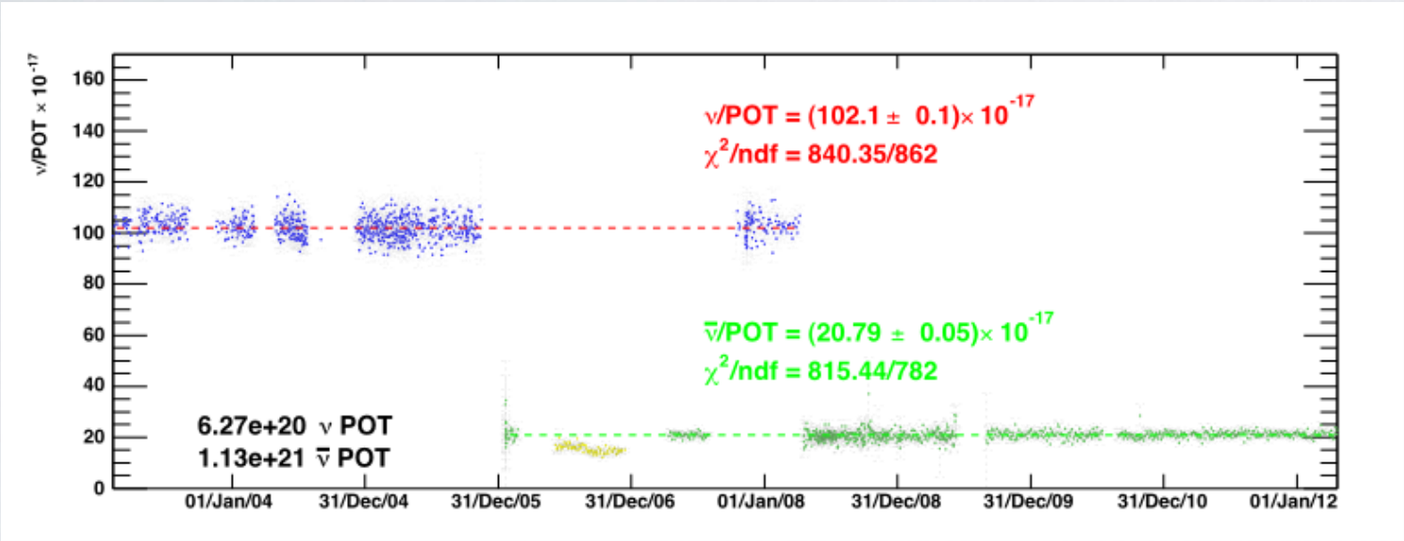
MiniBooNE Beam-dump mode: Dark Matter-Electron Scattering

- Dark matter-electron scattering is forward peak. With a forward angle cut, can reject 98% of neutrino induced backgrounds.
- Systematic errors around 12%.
- Requires dropping the current energy threshold of 140 MeV. Much of the dark matter-electron scattering signal resides below this.
- A team is currently pursuing this analysis.

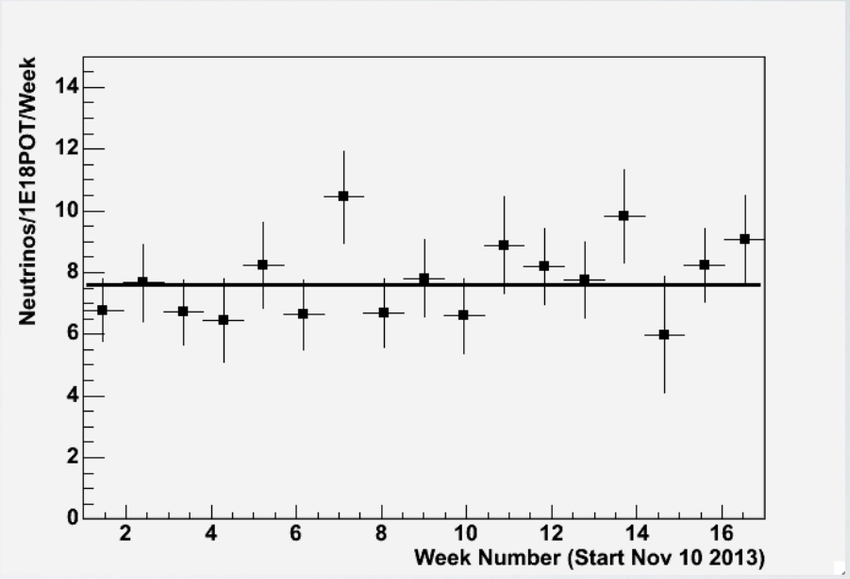


MiniBooNE: Detector and Beamline stability

Over 10 years

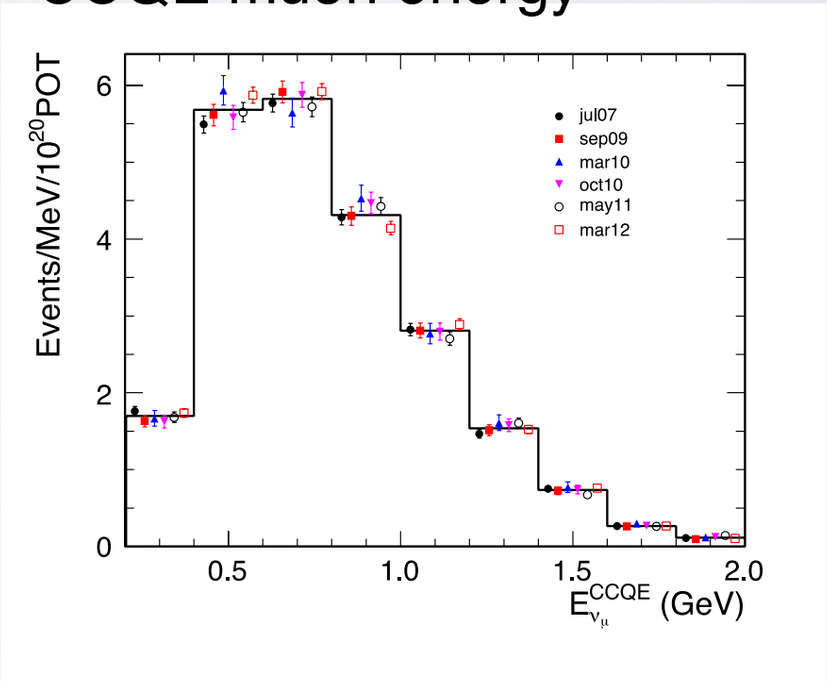


Current beam-dump mode

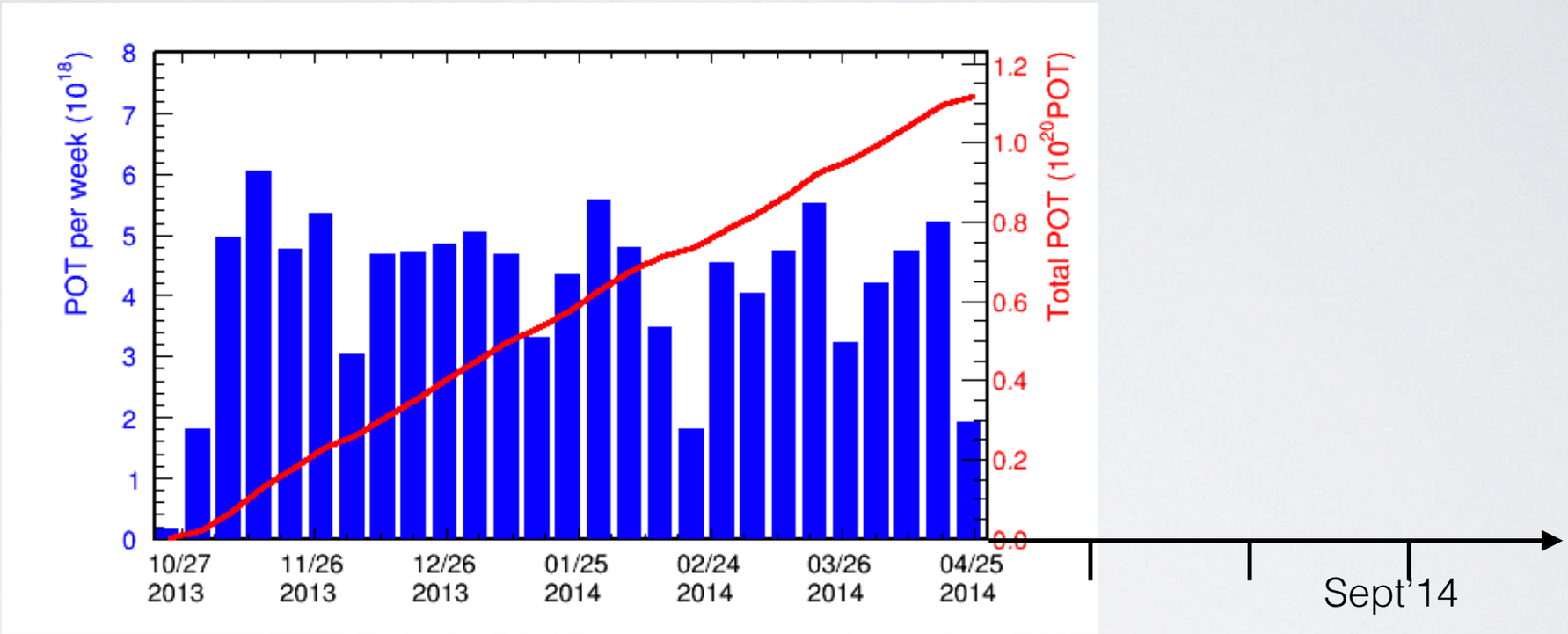


Stable running in beam-dump mode

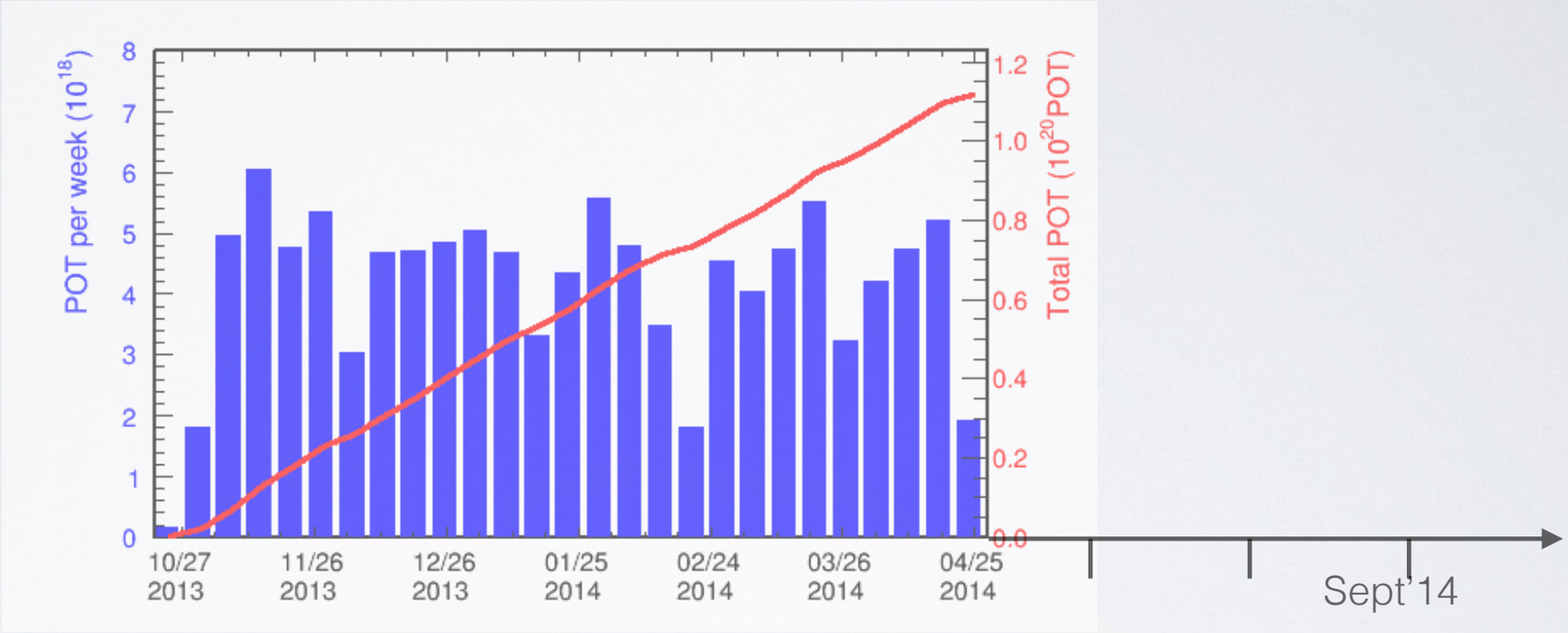
CCQE muon energy



MiniBooNE Beam-dump mode: Analysis strategy

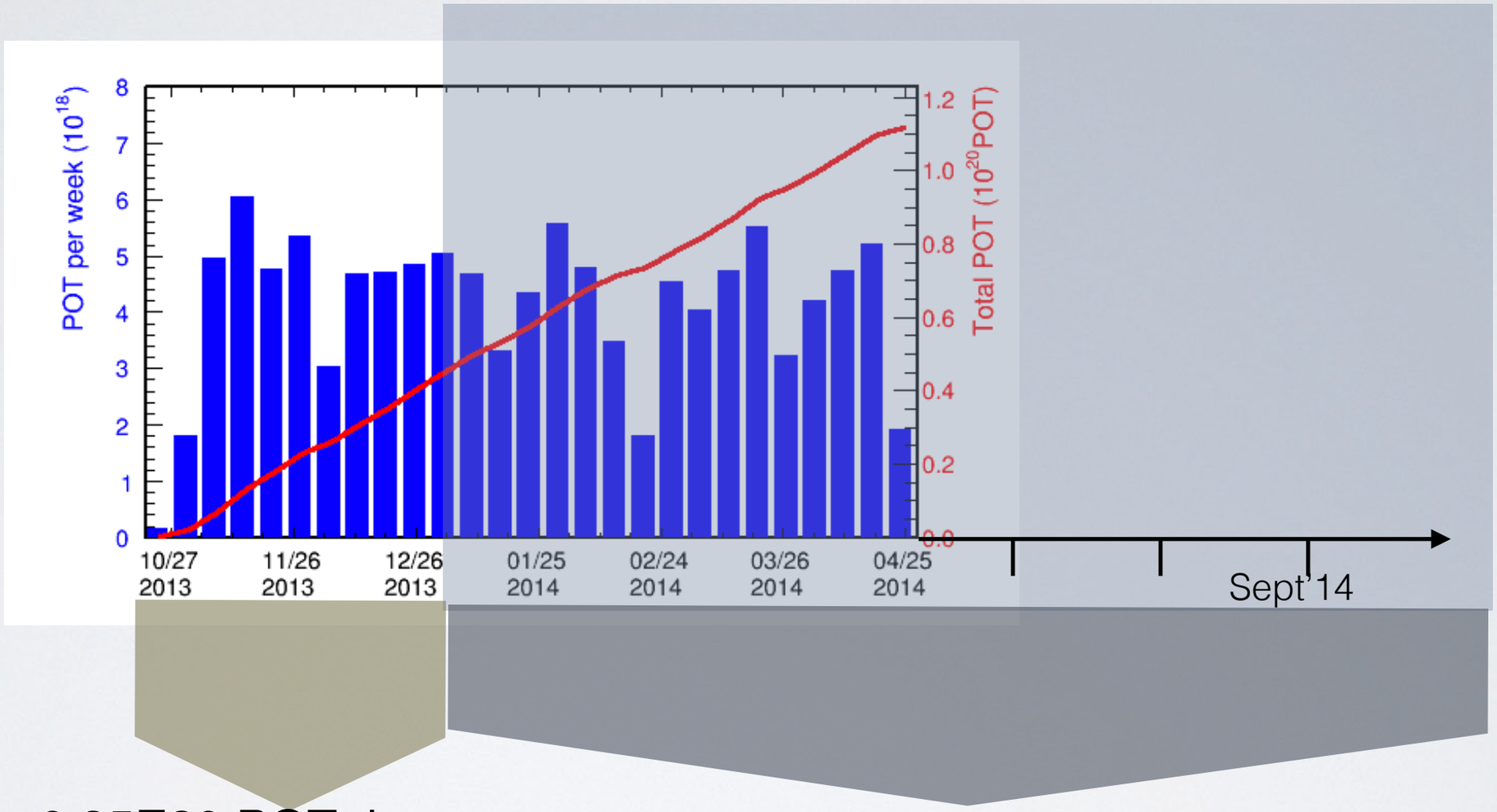


MiniBooNE Beam-dump mode: Analysis strategy



Many thanks to:
Fermilab…AD, BNB, Alignment…

MiniBooNE Beam-dump mode: Analysis strategy



Use 0.35E20 POT data to develop analysis, background estimates etc.

Rest of data “blind” until end of run

Outlook for low mass Dark Matter searches

STAGE 1: Operate in tandem with existing Intensity Frontier experiments

STAGE 2: Dedicated searches using existing (future) neutrino experiments.
--for example: Beam off target

STAGE 3: Dedicated experiments to produce and observe hidden sector particles

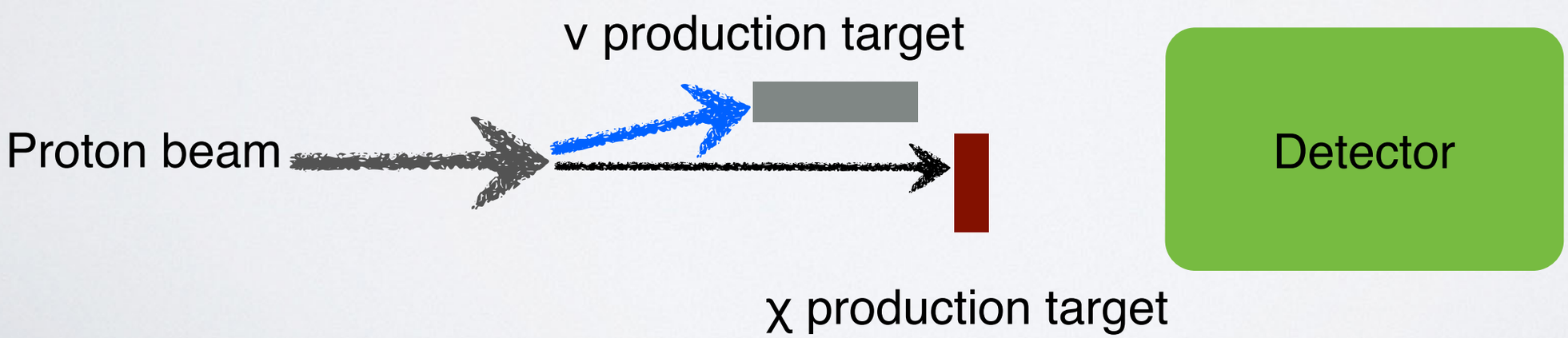
Looking to the future

Production

- Design dedicated beam dump that can handle high wattage beams
  -Reduce neutrino flux >1000x!
- Beam structure and timing important
- Multipurpose:Spur-line so as to co-exist with neutrino(on-target) experiments

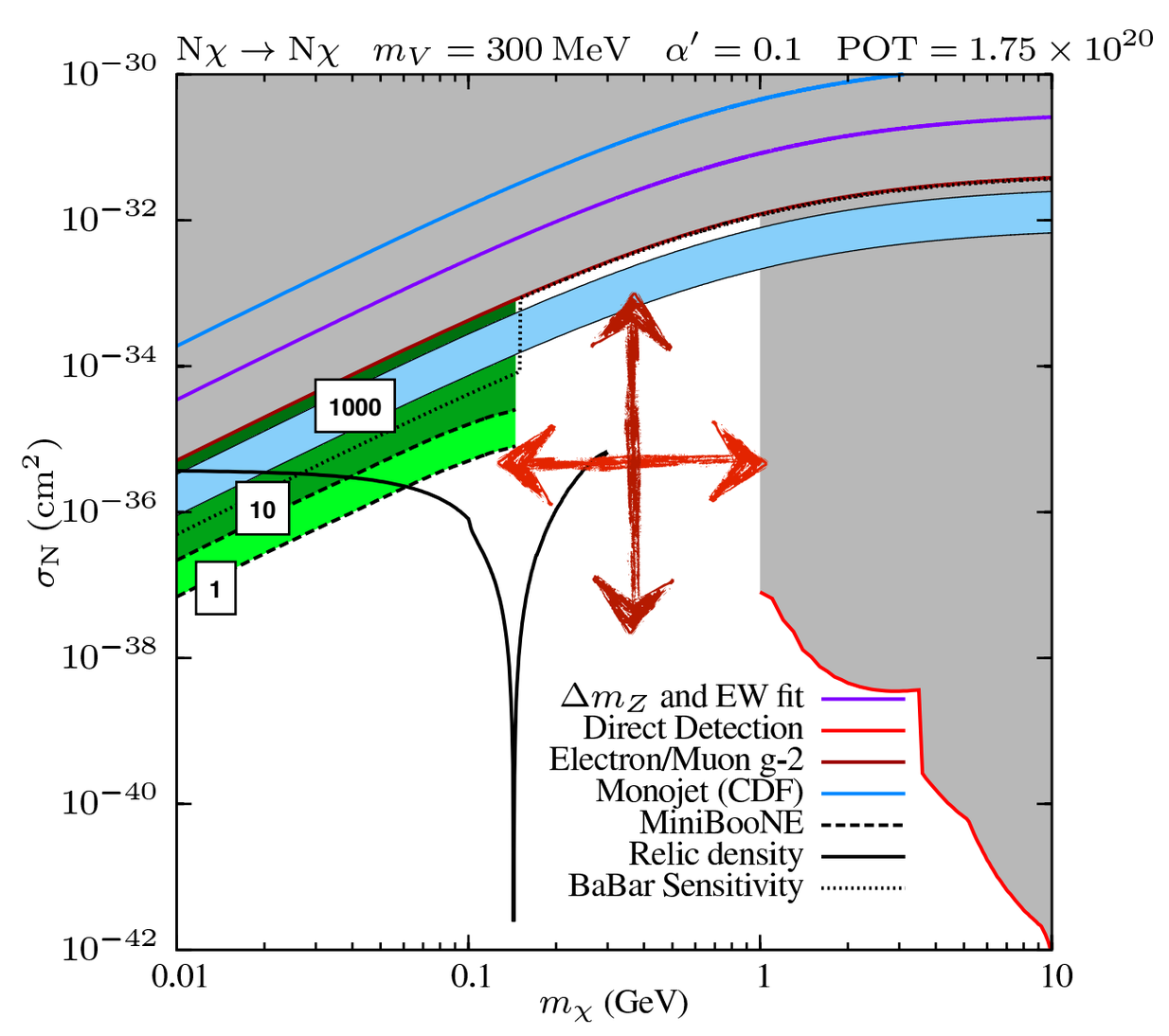
Detection

- Excellent spatial and timing resolution
- Low (~1 MeV) energy threshold
- Defocussing charged mesons.
- Go to pico second timing resolution (Ex: LAPPDs)
- explore fast scintillators



Looking to the future

- Future IF experiments can bridge the gap up to direct detection experiments and go lower in threshold

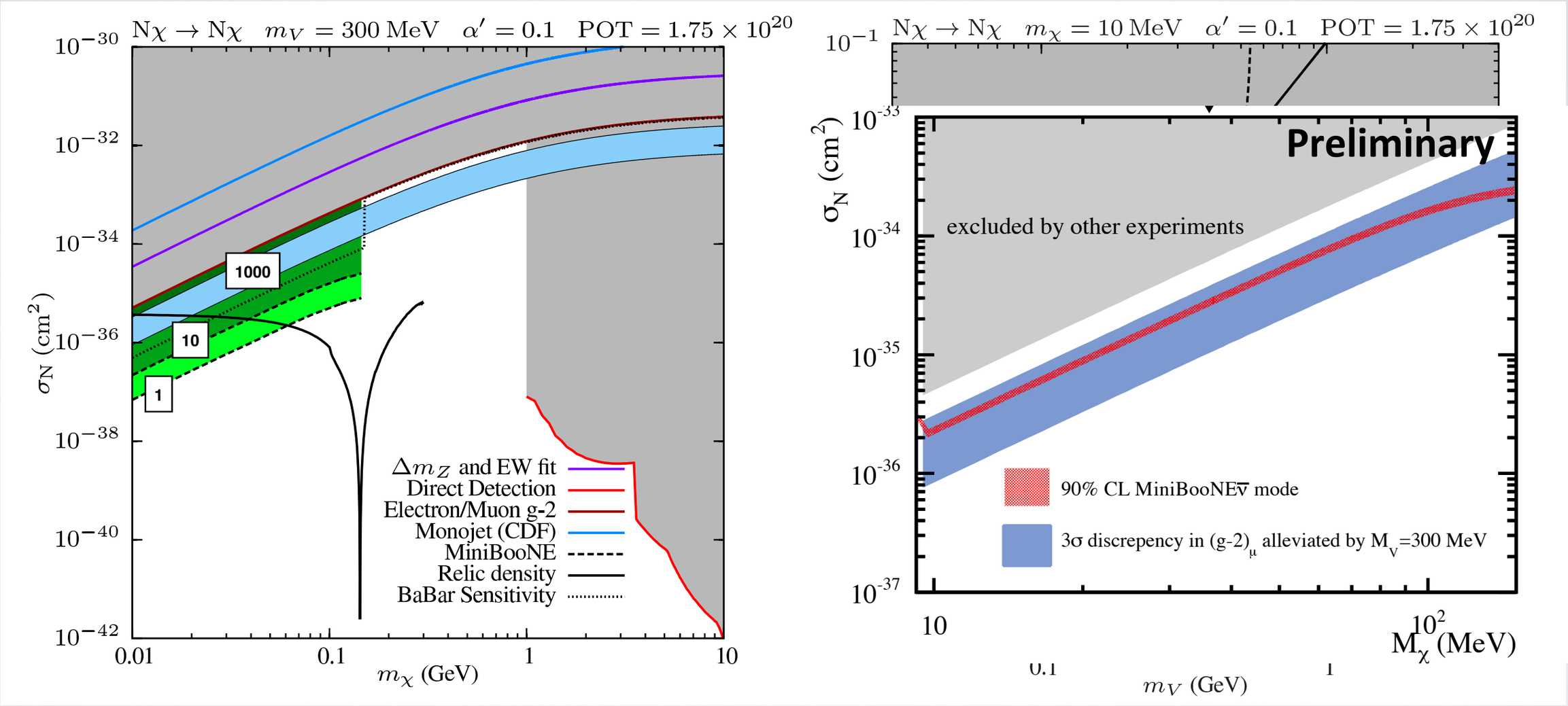


Summary: Stay tuned…

- For the first time, an accelerator based neutrino detector is being employed to search for light MeV-scale dark matter leading the way for other Intensity Frontier experiments.

- MiniBooNE is currently collecting data and we aim to publish our results soon.

MiniBooNE Beam-dump mode: Projections



Plots by P. deNiverville, Univ. of Victoria