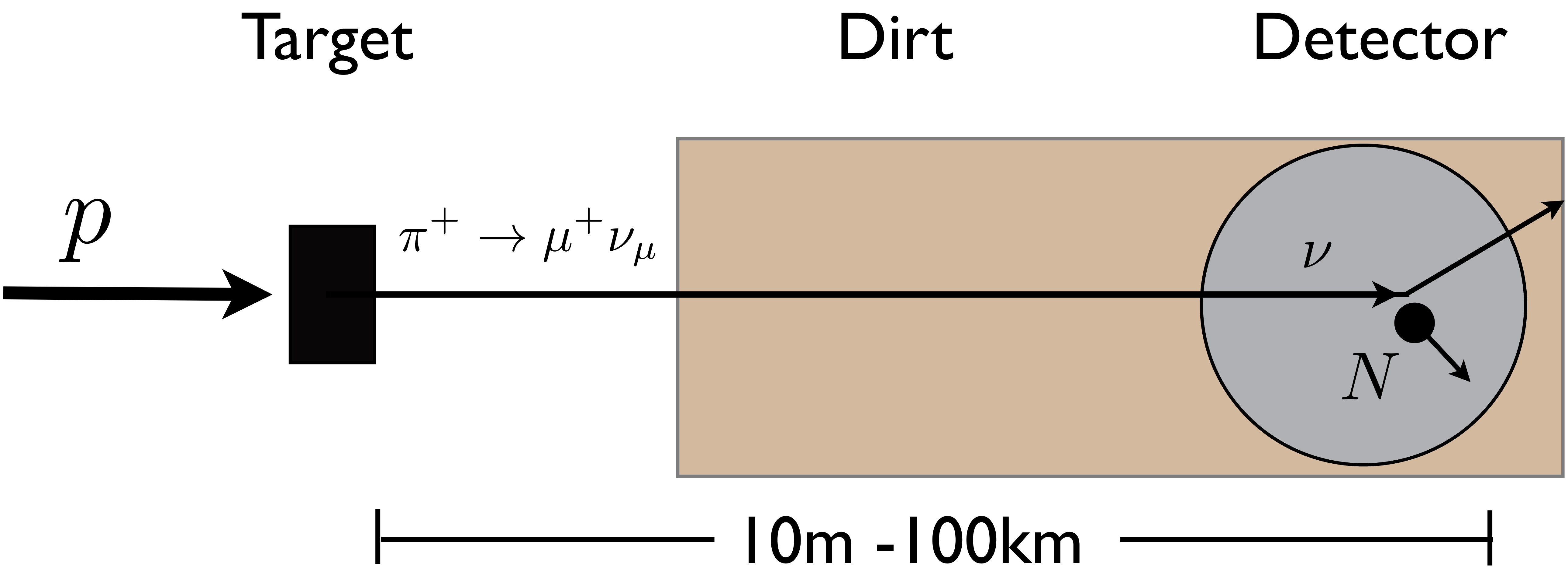
Next Generation Proton Beam Dump Searches for Dark Matter

Brian Batell
The Enrico Fermi Institute
The University of Chicago

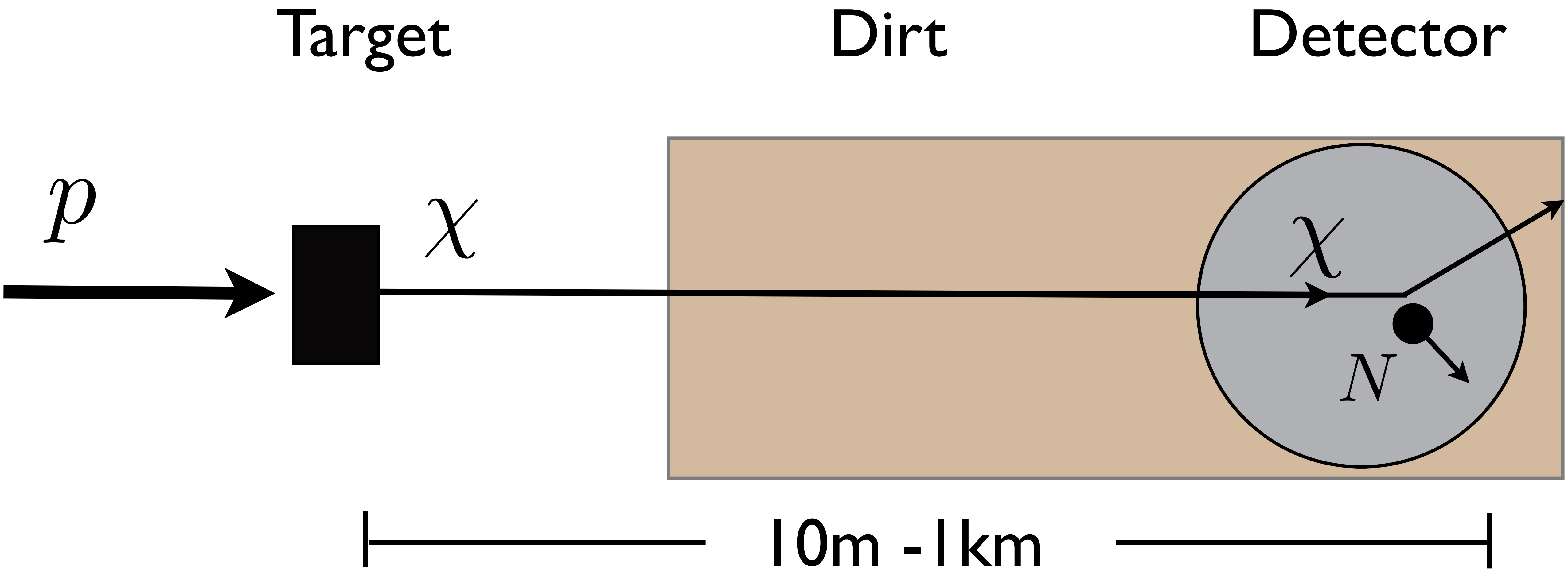
Community Summer Study 2013
University of Minnesota

Basic proton beam - target -detector setup

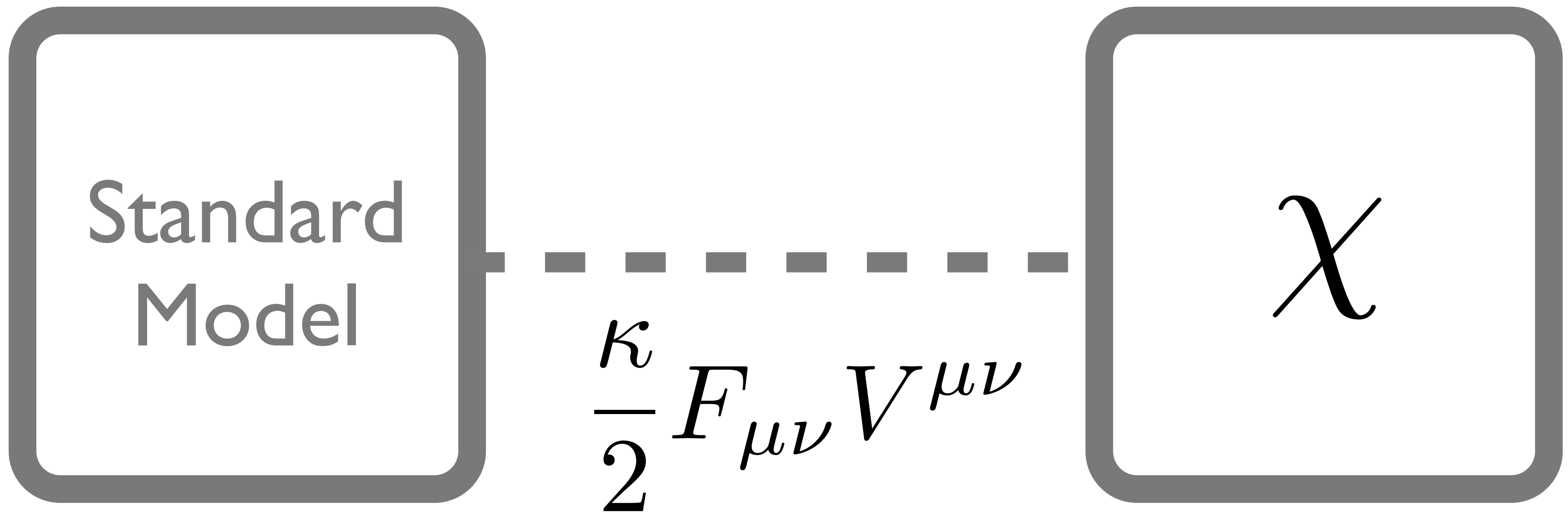
→ Neutrino beam



A dark matter beam!



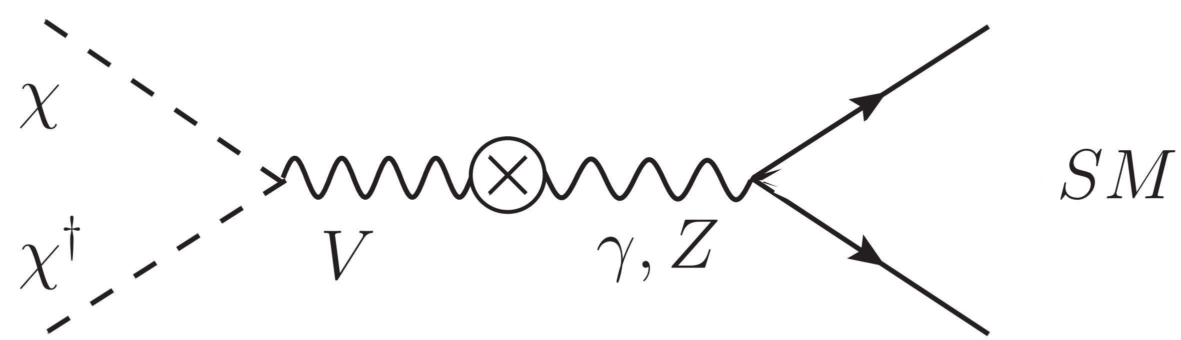
[BB, Pospelov, Ritz ‘09]
[deNiverville, Pospelov, Ritz ’11]
[deNiverville, McKeen, Ritz ’12]



[Pospelov, Ritz, Voloshin, Arkani-Hamed, Finkbeiner, Slatyer, Weiner]

New forces → viable light thermal relic dark matter

[Boehm, Fayet]

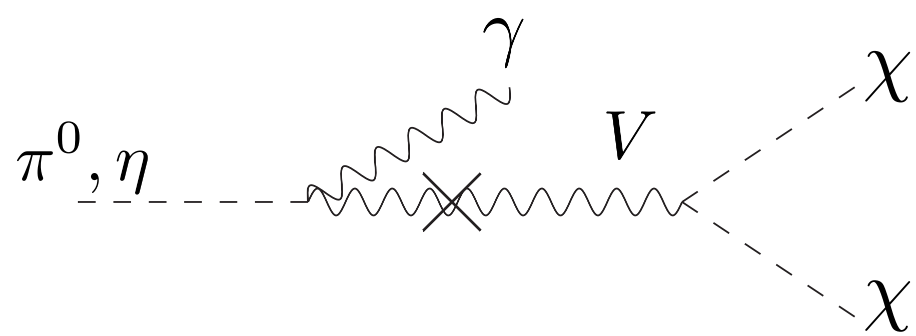


Scalar DM: p-wave annihilation, CMB ok [deNiverville, Pospelov, Ritz]

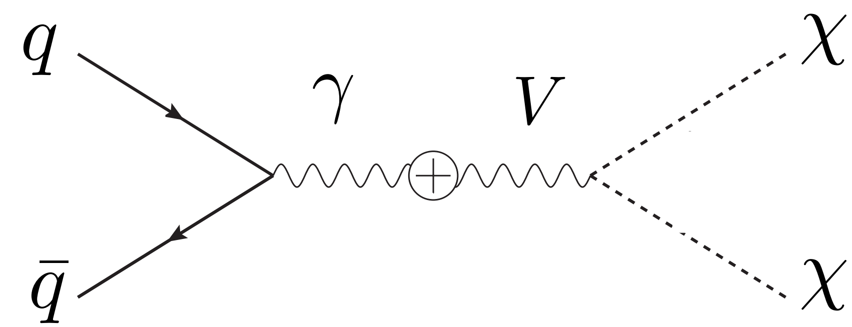
Dark photon can address g-2 anomaly [Pospelov]

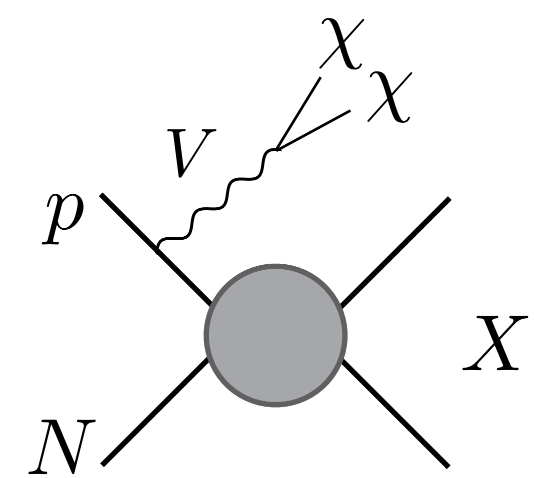
Production of the Dark Matter beam

Decays of mesons:



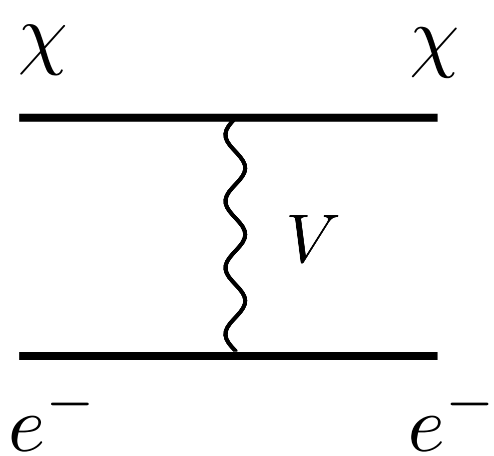
Direct production



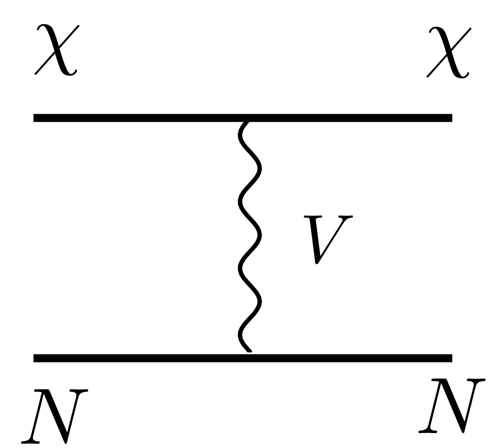


(not studied yet)

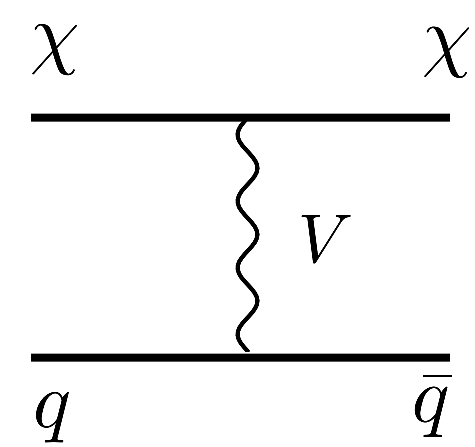
Detection via scattering



$\chi - e^-$ elastic



$\chi -$nucleon elastic



deep inelastic

(not studied yet)

Low Mass WIMP Searches with a Neutrino Experiment: A Proposal for Further MiniBooNE Running

Presented to the FNAL PAC Oct 15, 2012

The MiniBooNE Collaboration

R. Dharmapalan, S. Habib, C. Jiang, & I. Stancu
University of Alabama, Tuscaloosa, AL 35487

R. A. Johnson & D.A. Wickremasinghe
University of Cincinnati, Cincinnati, OH 45221

F.G. Garcia , R. Ford, T. Kobilarcik, W. Marsh,
C. D. Moore, D. Perevalov, & C. C. Polly
Fermi National Accelerator Laboratory, Batavia, IL 60510

J. Grange & H. Ray
University of Florida, Gainesville, FL 32611

R. Cooper & R. Tayloe
Indiana University, Bloomington, IN 47405

G. T. Garvey, W. Huelsnitz, W. Ketchum, W. C. Louis, G. B. Mills,
J. Mirabal, Z. Pavlovic, & R. Van de Water,
Los Alamos National Laboratory, Los Alamos, NM 87545

B. P. Roe
University of Michigan, Ann Arbor, MI 48109

A. A. Aguilar-Arevalo
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, D.F. México

P. Nienaber
Saint Mary's University of Minnesota, Winona, MN 55987

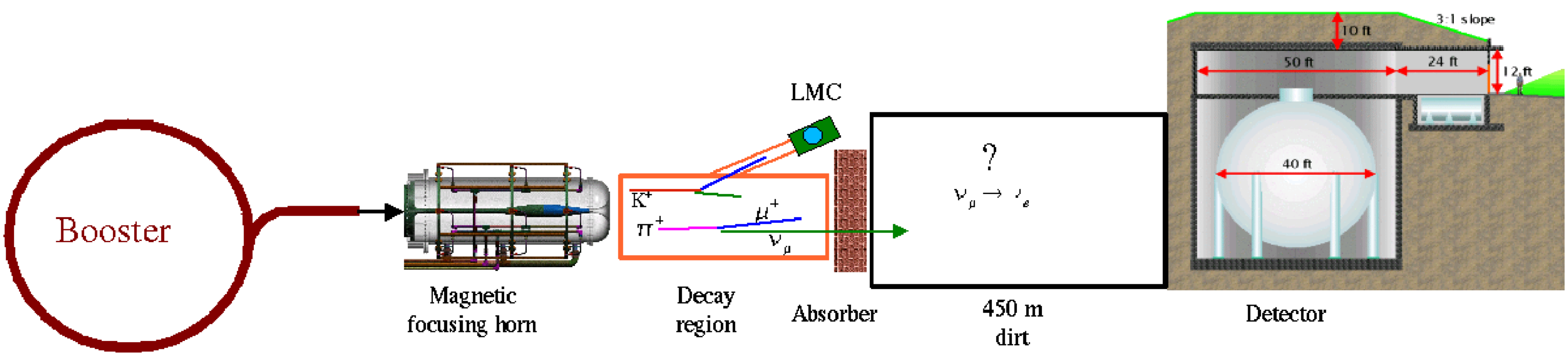
The Theory Collaboration

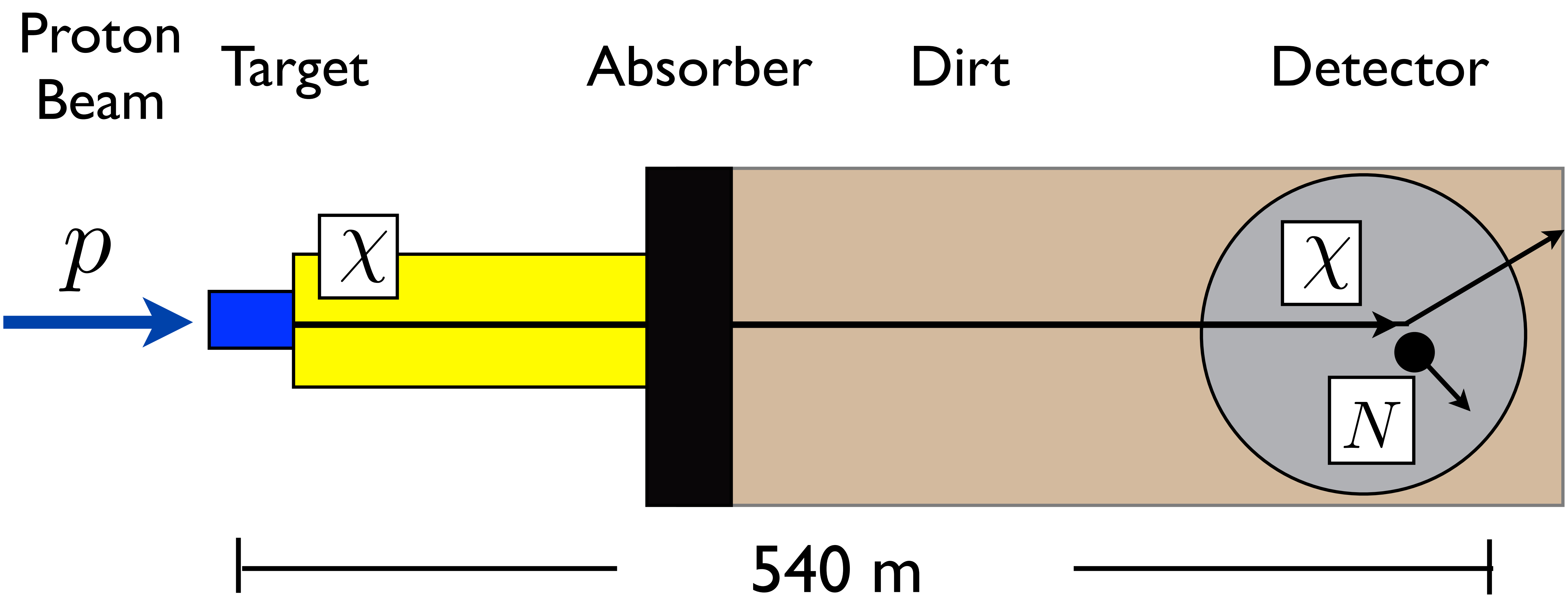
B. Batell
University of Chicago, Chicago, IL, 60637

P. deNiverville , D. McKeen, M. Pospelov, & A. Ritz
University of Victoria, Victoria, BC, V8P 5C2

MiniBooNE

- 8.9 GeV proton beam
- 1.8 x 10^{21} Protons on Target (POT) delivered
- Beryllium target, 71 cm length, 1 cm diameter; 1.7 interactions lengths
- 50 m long decay volume (filled with air)
- Detector: 12 m diameter sphere, 800 tons of mineral oil, 1520 PMTs
- Magnetic Horn focuses charged hadrons





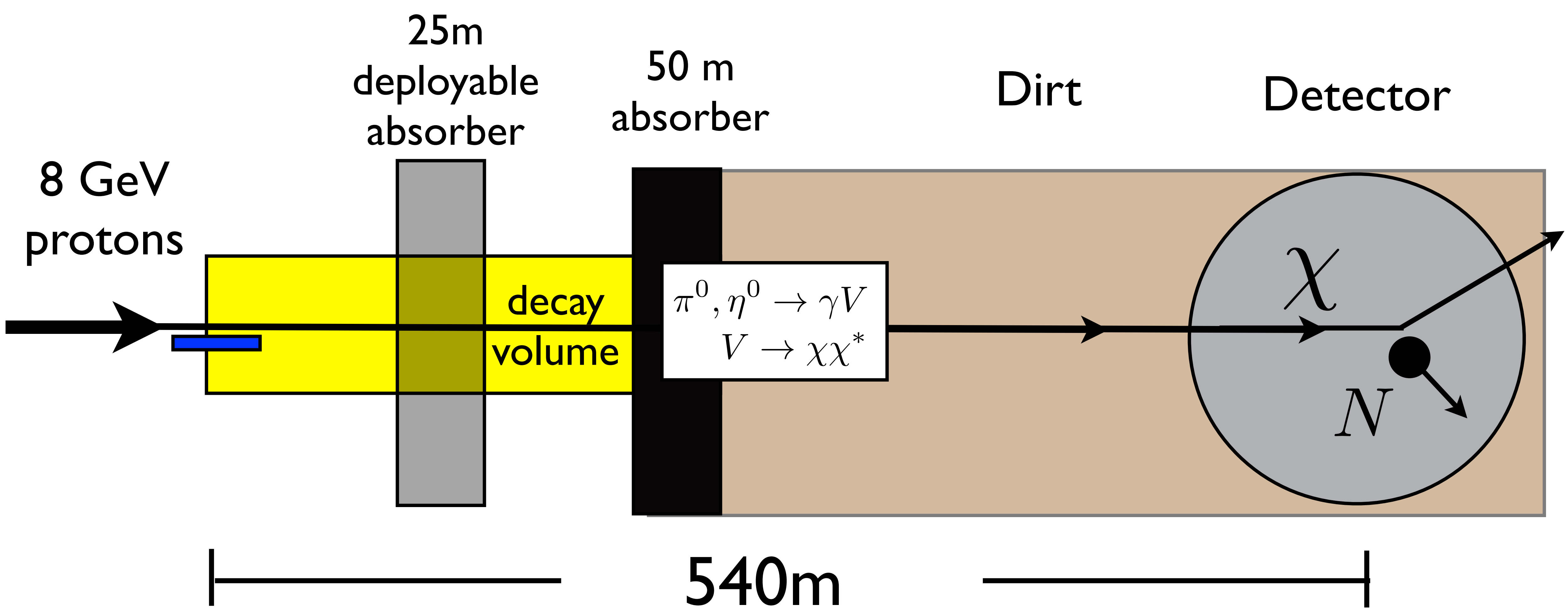
Proton Beam
p
Target
χ
Absorber
Dirt
Detector
χ
N
540 m

Beating down the neutrino background

The signature of dark matter is a neutral current scattering event

Very similar to neutrino induced neutral current event!

Focus beam onto an absorber!

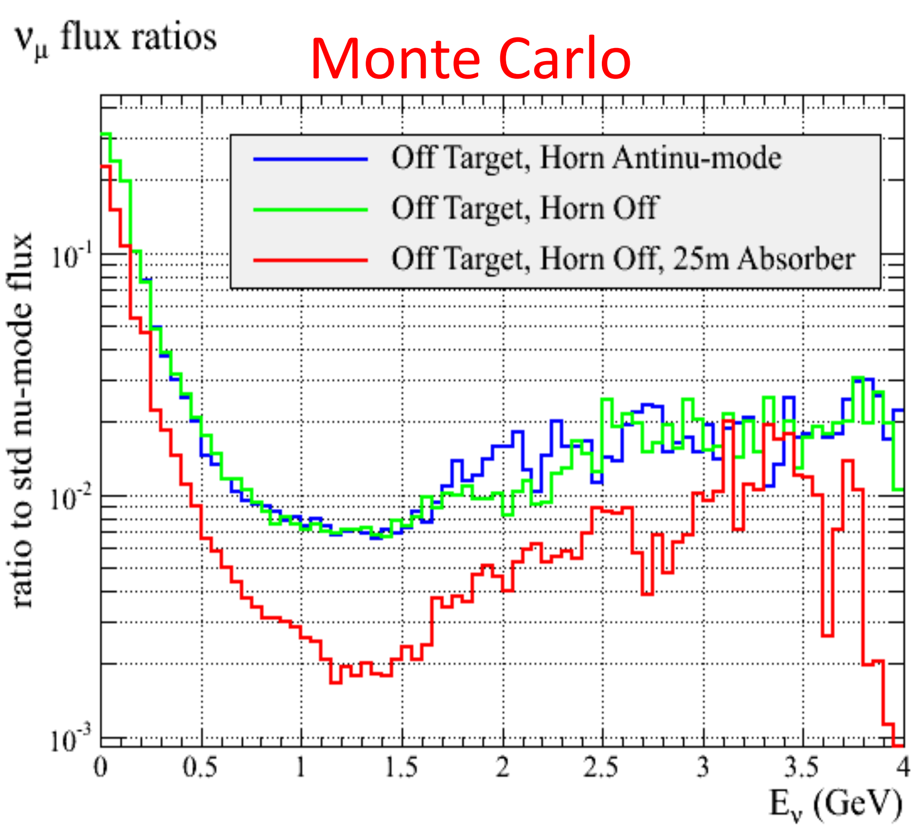


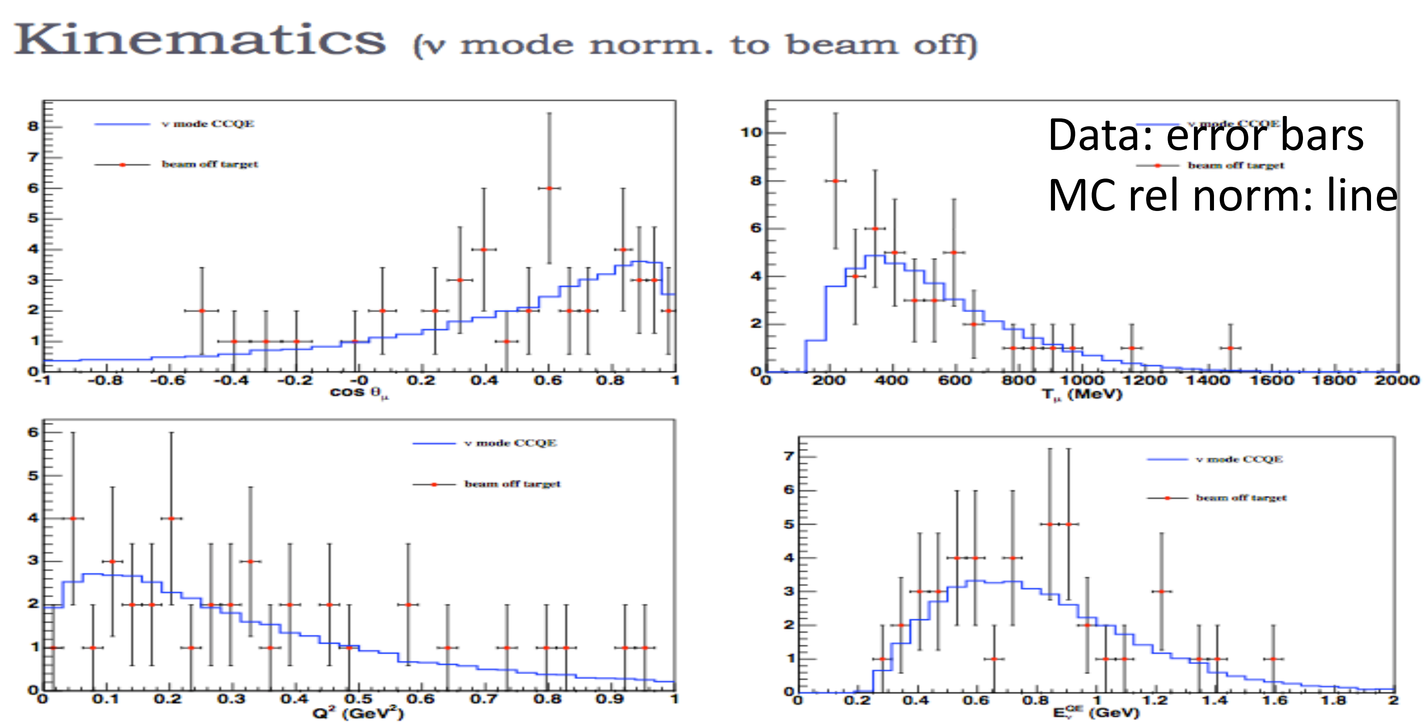
Neutrino background reduced by up to 2 orders of magnitude!

Neutrino Rate Reduction with Beam Off Target Running (1 week test run)

- Estimated neutrino rate reduction:
  - 50m absorber one week beam off target run (~5.54e18 POT):
    $(\text{events/POT})^{\nu\ \text{mode}}/(\text{events/POT})^{\text{beam off target}} = 42 \pm 7$ ← Data rate reduction
  - 50m MC: $(\text{events/POT})^{\nu\ \text{mode}}/(\text{events/POT})^{\text{beam off target}} = 36$
  - 25m MC: $(\text{events/POT})^{\nu\ \text{mode}}/(\text{events/POT})^{\text{beam off target}} = 72$

MC flux reduction

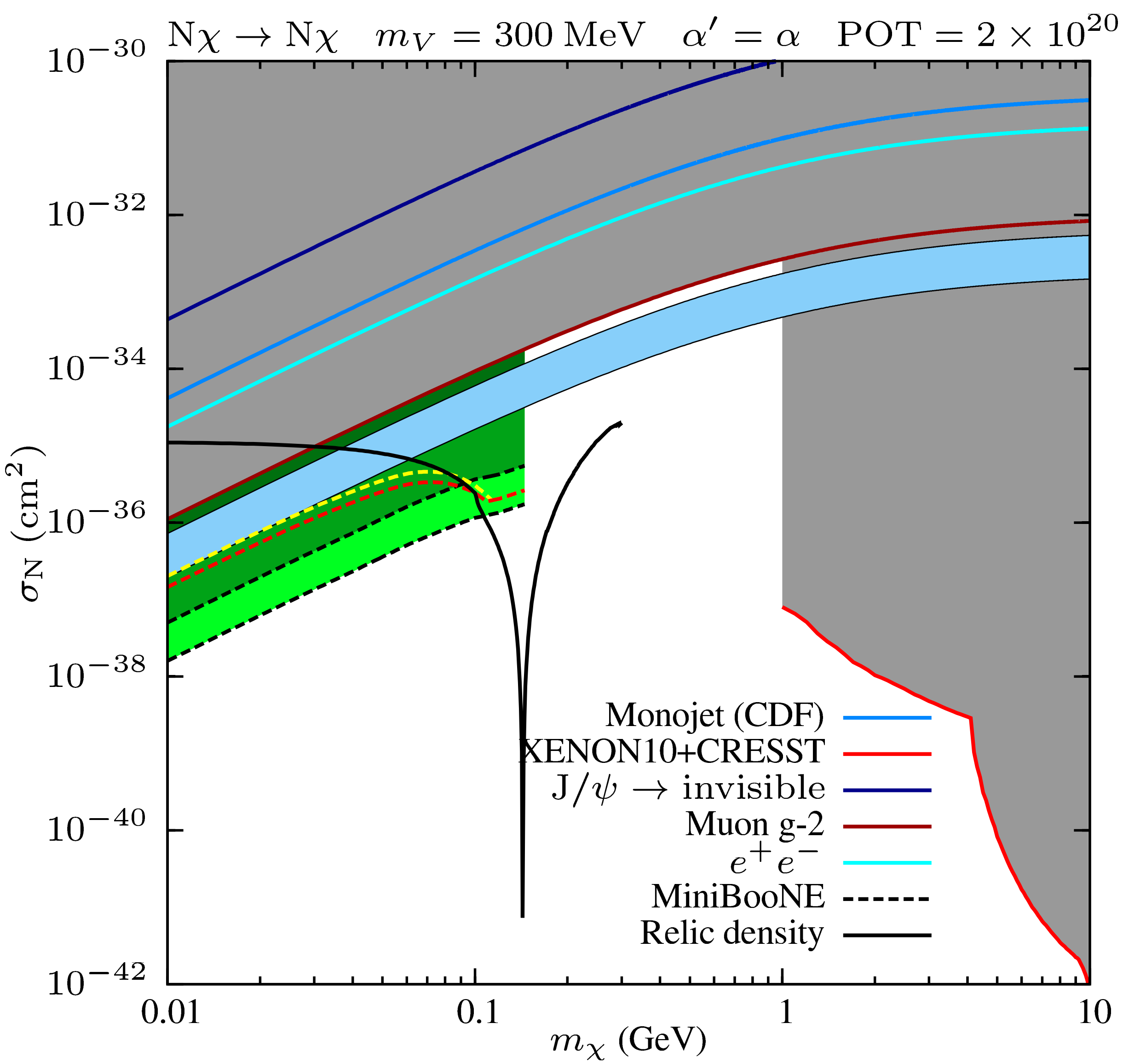


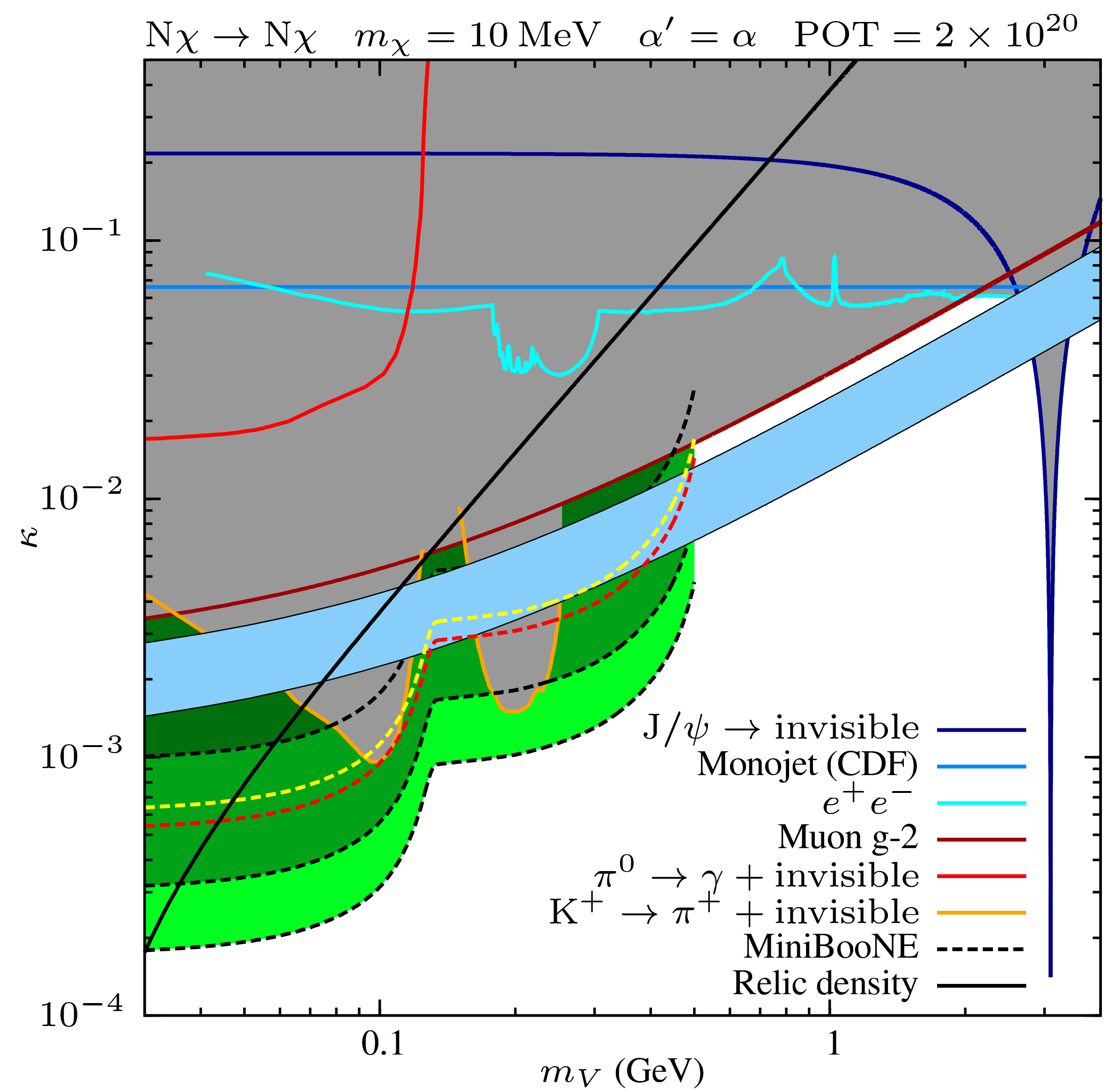


slide from R.Van De Water

MiniBooNE Sensitivity

[Aguilar-Arevalo et al., arXiv:1211.2258]



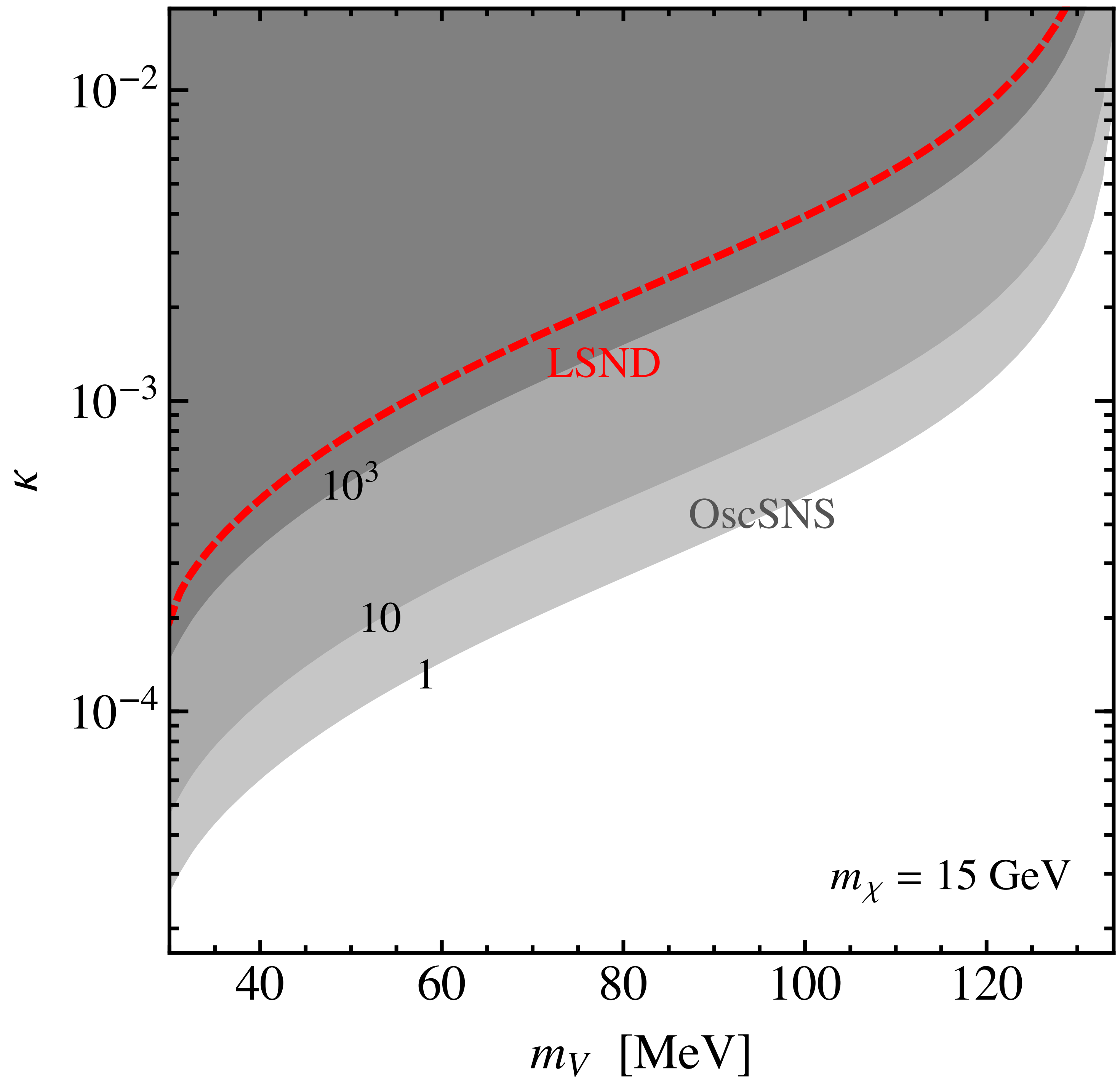


See also talk by R. Van de Water at Snowmass IF5 Meeting

https://indico.fnal.gov/contributionDisplay.py?contribId=38&sessionId=4&confId=6248

OscSNS

- 1 GeV protons at Spallation Neutron Source,
- 2.2 x 10^{23} POT/yr
- liquid mercury target
- detector: 60m back of the target, cylindrical, 800 tons mineral oil



Sensitivity to $\chi e \to \chi e$

Factor of 2-3 improvement in κ

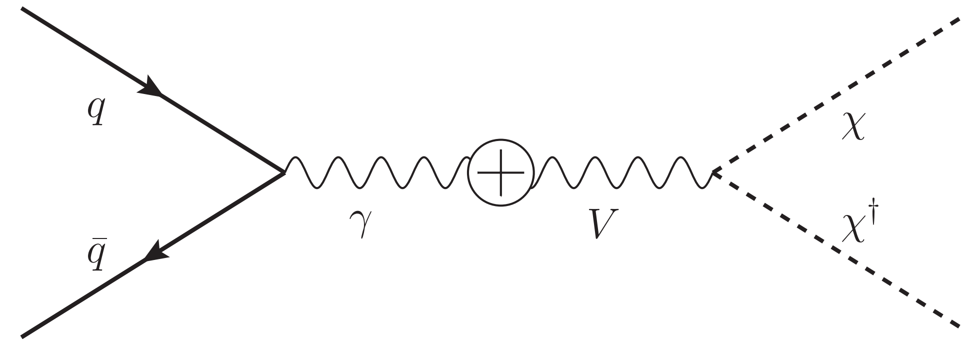
[BB, Essig, Surujon, to appear]

NuMi/MINOS

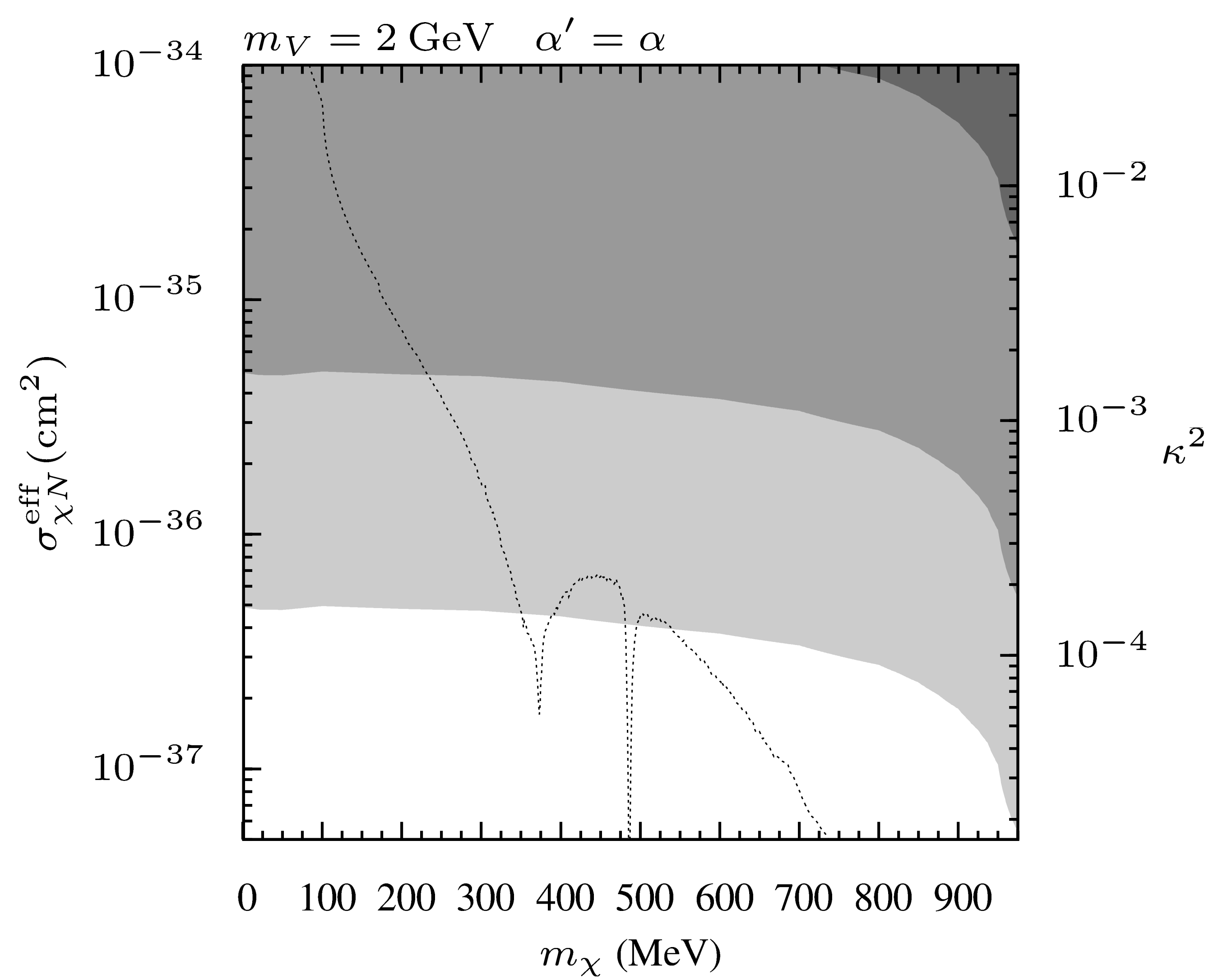
- Fermilab Main Injector, 120 GeV protons
- ~10^{21} POT
- Near Detector: Layered steel & plastic

scintillator, 4.8m x 3.8m 16.6m,

965 m from target $\theta_{\rm det} \sim 0.2^{o}$



Yield for $\chi N \to \chi N$ elastic scattering



In principle there is sensitivity, however...

- New ideas needed to overcome large neutrino background
- Studies of deep inelastic scattering do not yet exist

[deNiverville, McKeen Ritz, '11]

NOvA

- Fermilab Main Injector, 120 GeV protons
- ~ (6-10) x 10^{20} POT/yr
- Near Detector: Off-Axis 14.6 mrad, liquid scintillator cells

2.8m x 4.1 m x 14.3 m, ~1km from target, $\theta_{\rm det} \sim 0.2^{\rm o}$

LBNE

- Fermilab Main Injector, 120 GeV protons
- ~ 5 x 10^{20} POT/yr
- Near Detector: Straw Tube tracker + ECAL

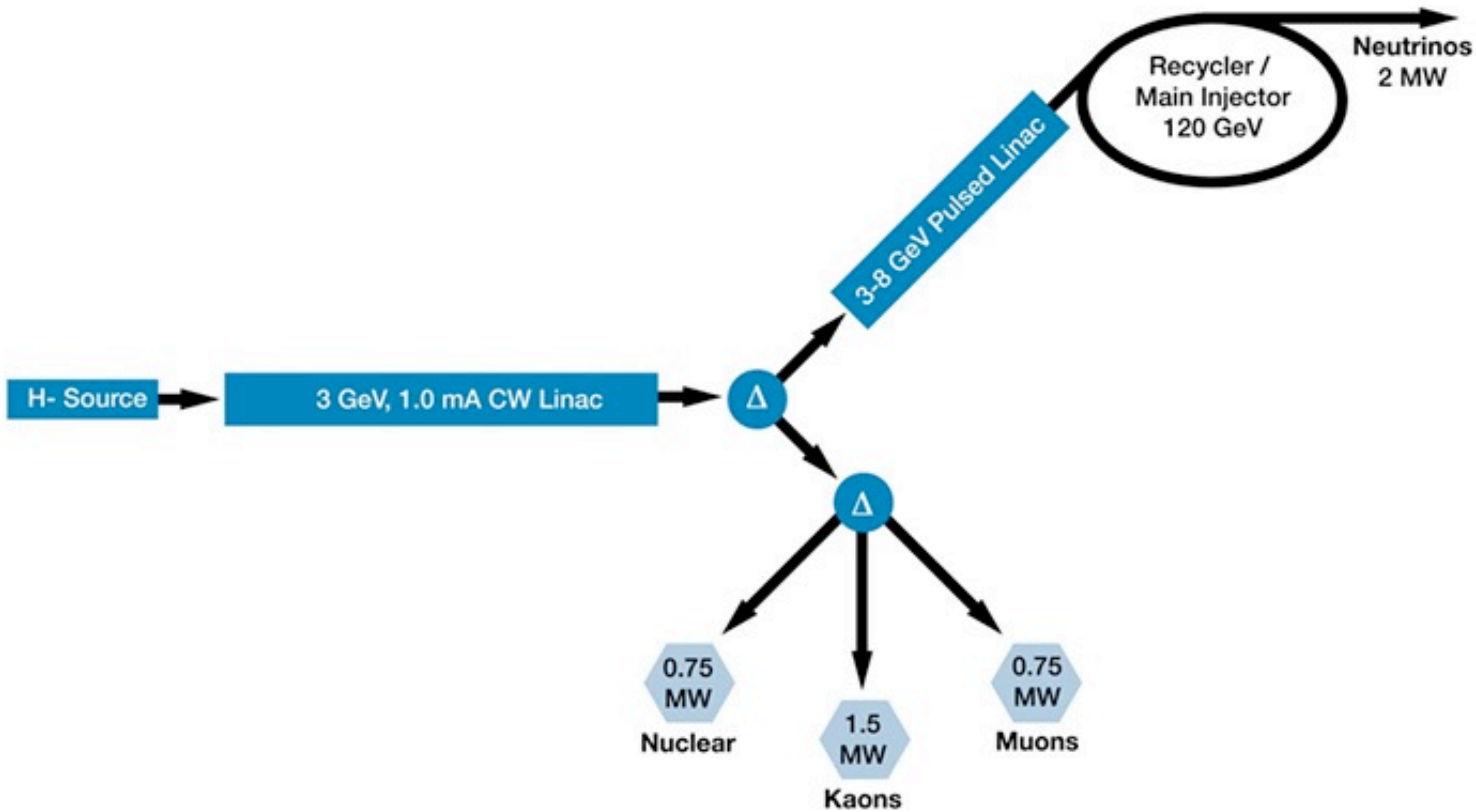
3.5m x 3.5 m x 7.5 m, 500m from target, $\theta_{\rm det} \sim 0.4^{\rm o}$

Dedicated studies needed!

Again, main obstacle is the neutrino neutral current background

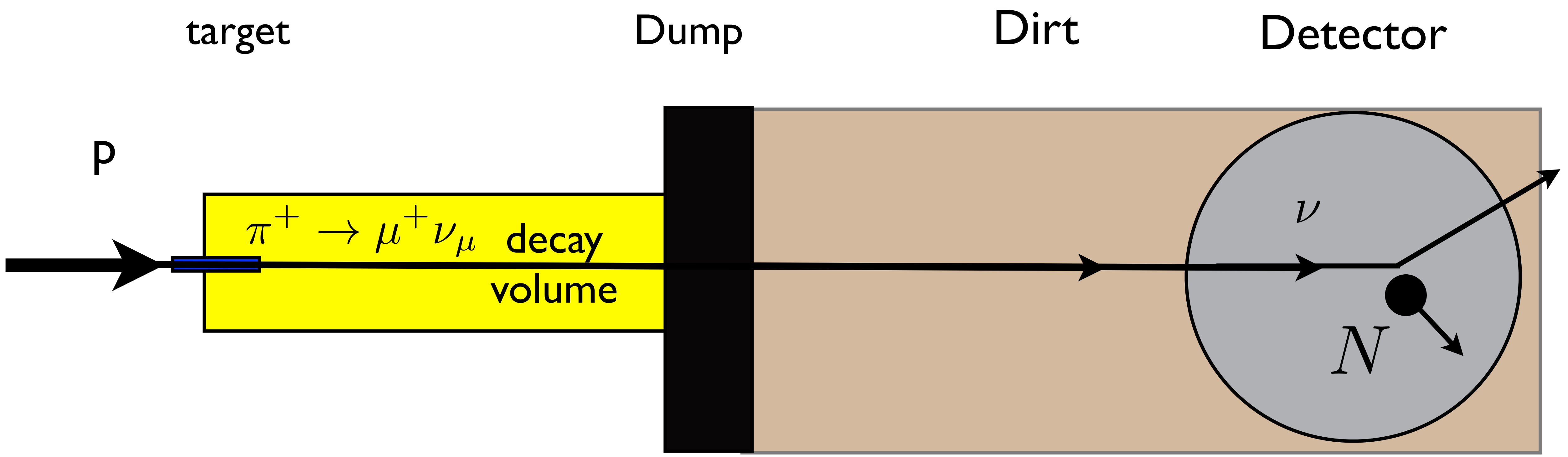
Project X: New high-intensity proton source

3 MW at 3 GeV ➡ potential for $\sim 10^{23} \frac{\mathrm{POT}}{\mathrm{yr}}$

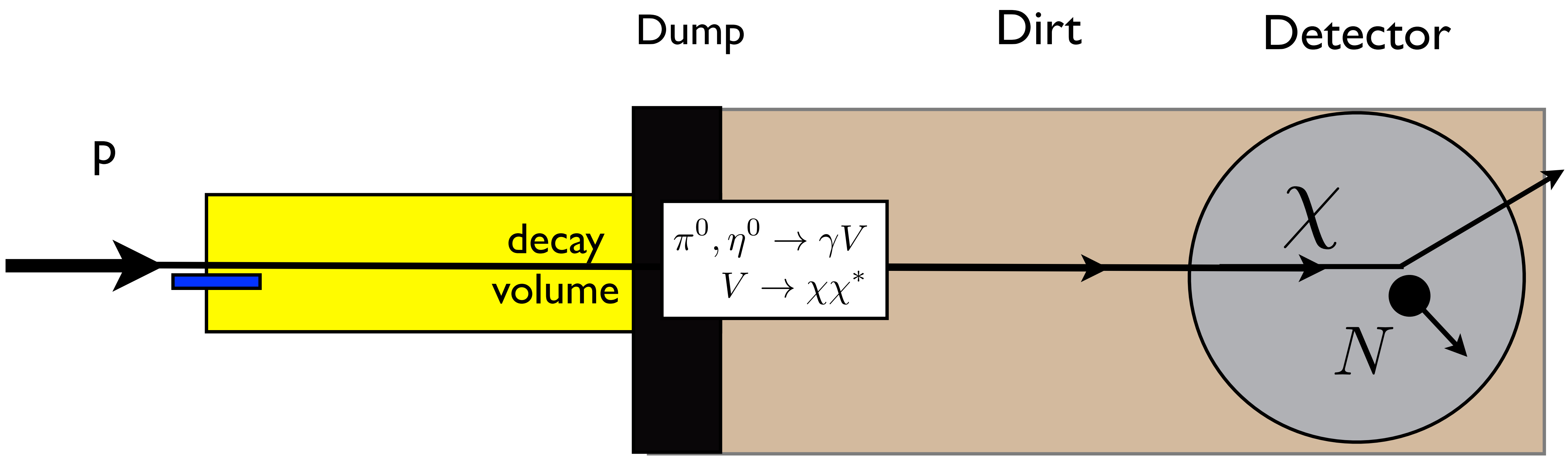


Overcoming the neutrino background

- Neutrinos produced from meson decays in the decay pipe

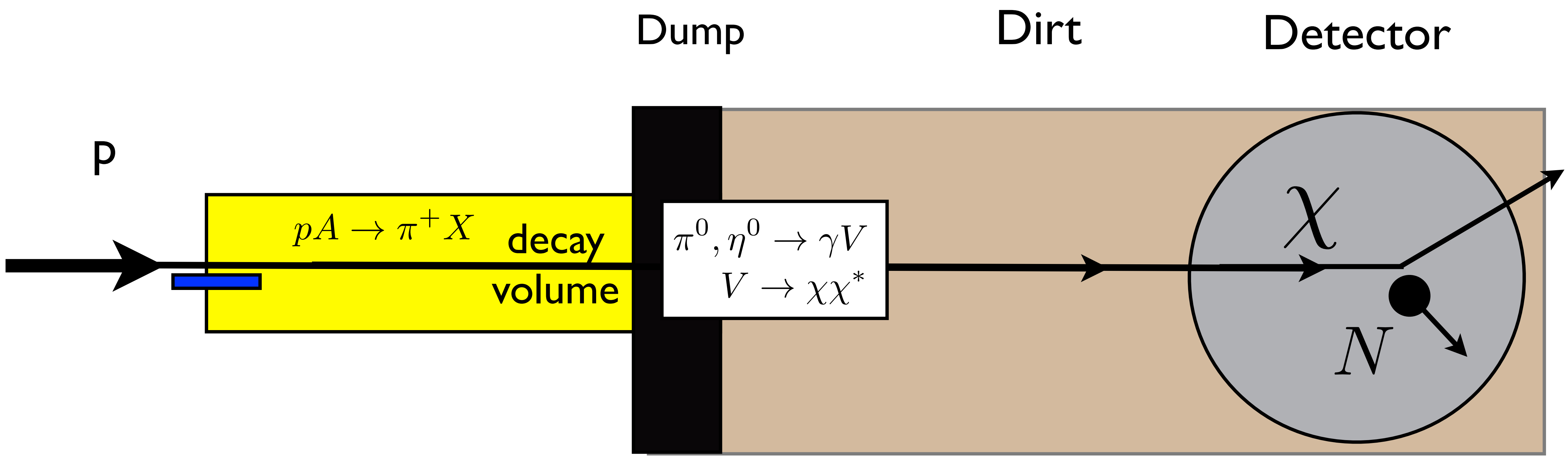


MiniBooNE proposal: run protons into the dump

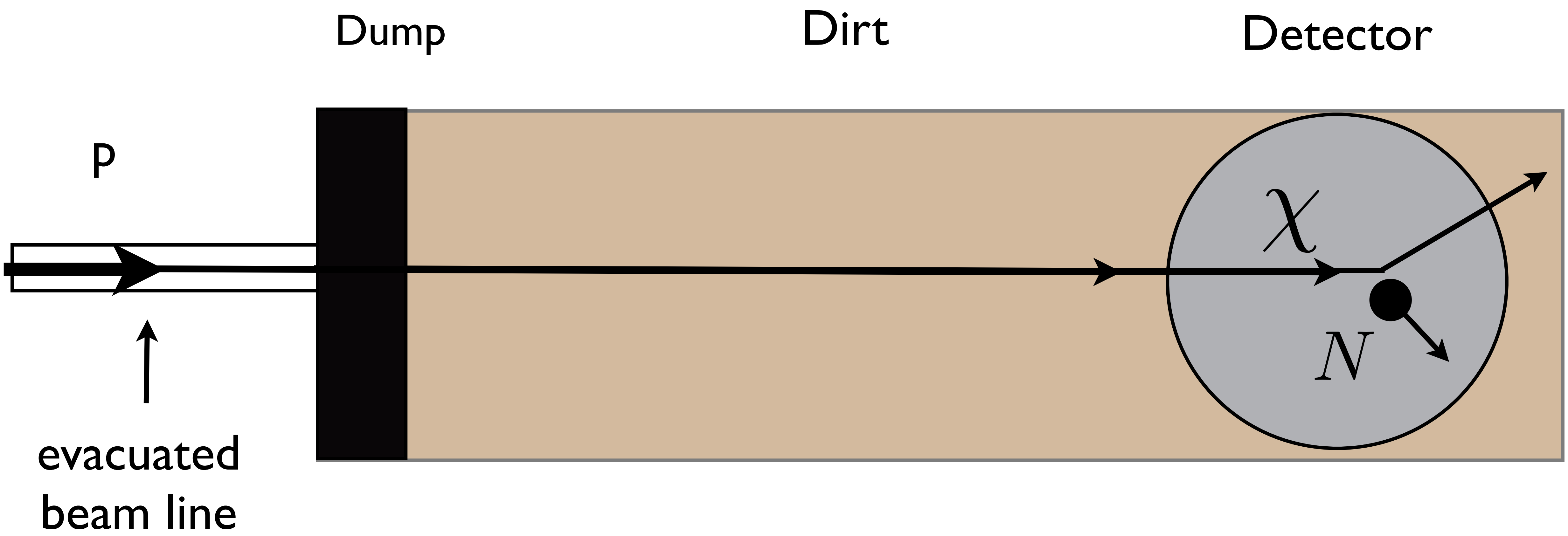


Neutrino background reduced by factor of ~ 50

Still, neutrinos produced through proton - air reactions in decay pipe



Optimally, dump should be positioned immediately following beam line

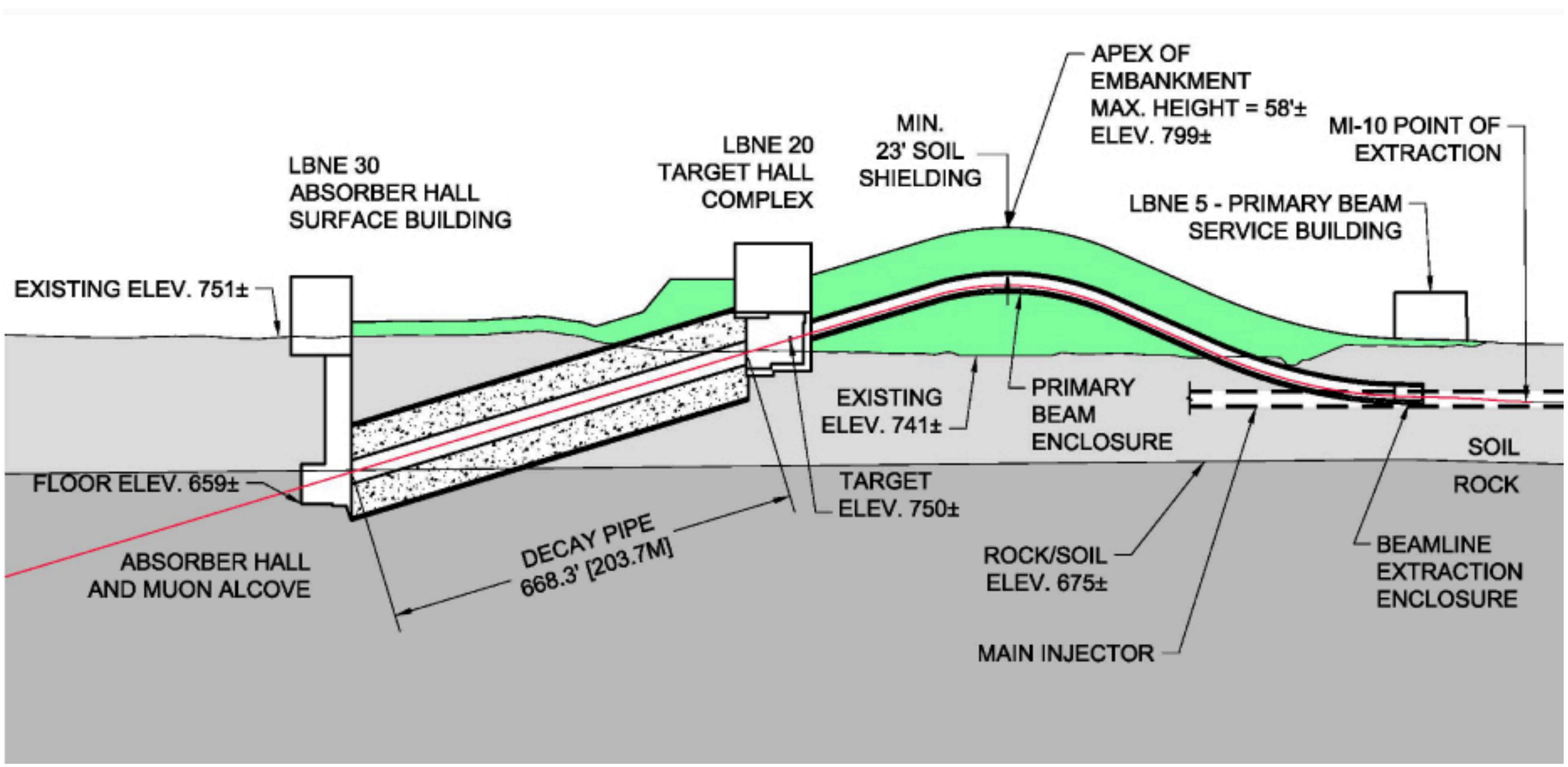


Neutrino background potentially reduced by factor of ~ 2-3 orders of magnitude!

Currently, none of the existing or proposed experiments can run in such a mode

Either

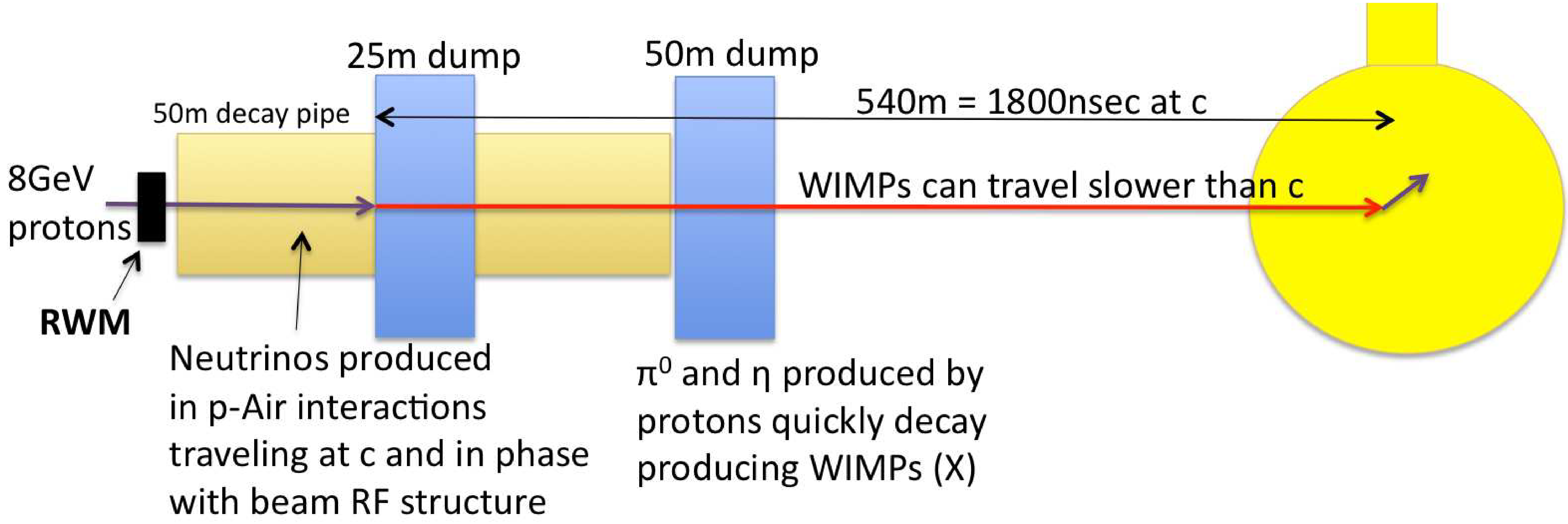
- Design a dedicated beam line/dump experiment (requires new detector)
- Adapt existing proposals, e.g. add spur line to LBNE:



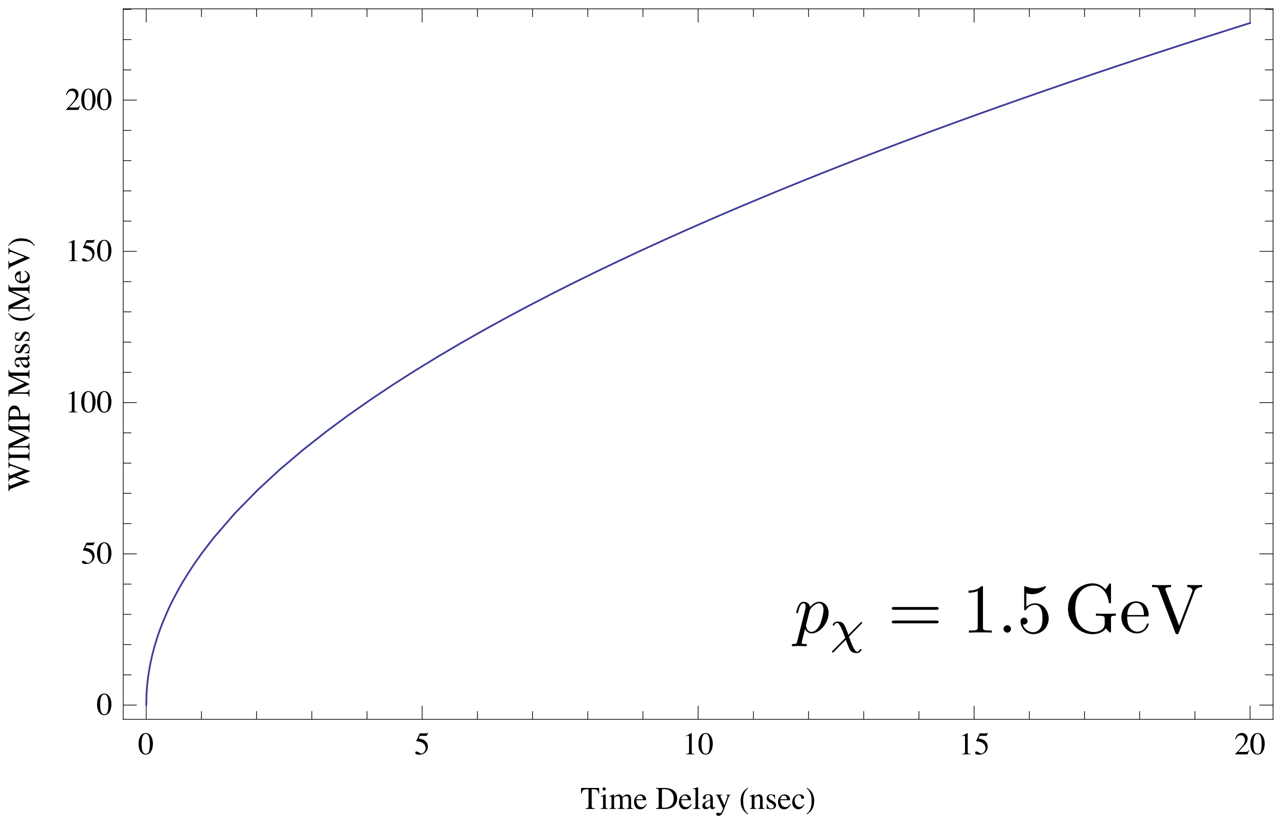
Timing

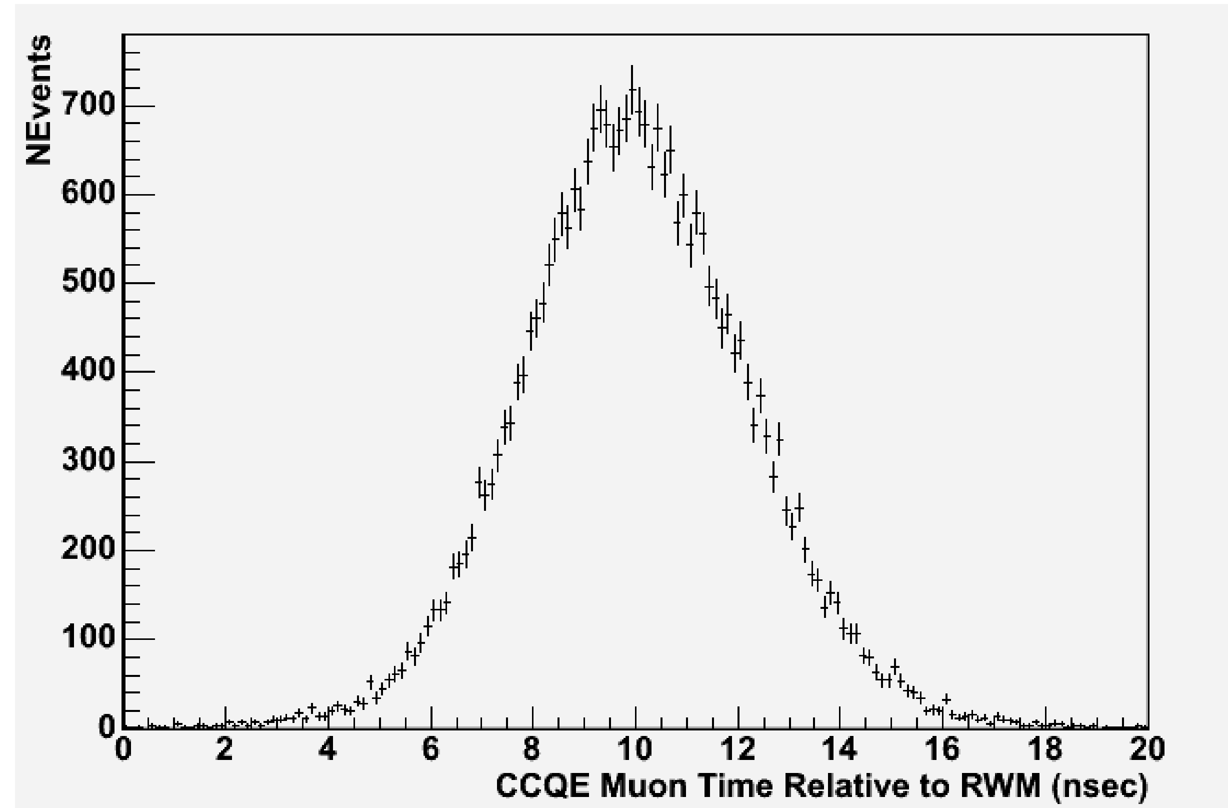
Dark matter is heavier than neutrinos - arrives at the detector later!

e.g. at MiniBooNE



Timing

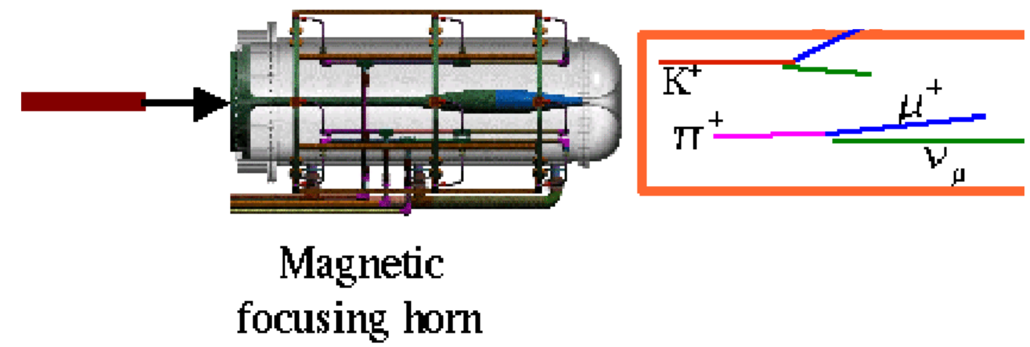




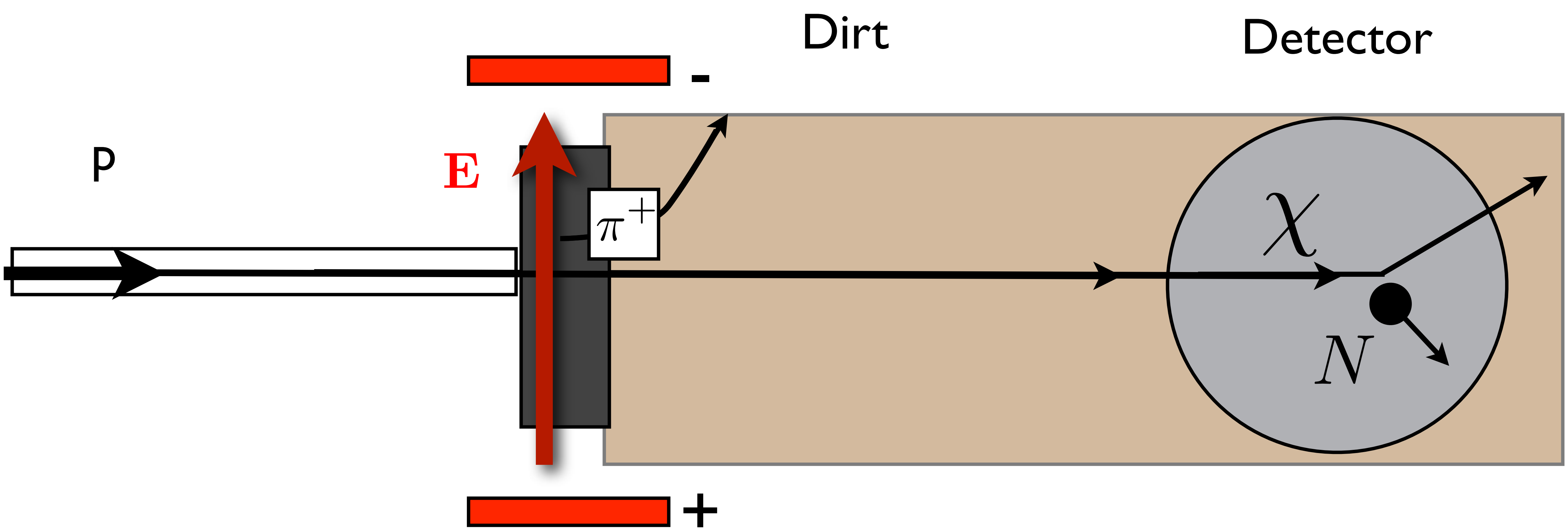
Timing cut (nsec)	Background Reduction (%)	WIMP Velocity β	WIMP Mass (MeV)
3.0	90	0.9984	85
4.6	99	0.9974	108
5.9	99.9	0.9967	122

Defocusing

Typically, neutrinos are focused toward the target by a magnetic horn



Instead, defocus charged particles, using E or B field



Beyond portals

Portals are the simplest way to couple dark matter to SM, but we should keep an open mind to other possible mediators

Experiments will put a limit (or see an excess!) on number of neutral current events. Can be interpreted in a variety of ways.

If dark matter couples dominantly to quarks, proton beams will have unique sensitivity. If instead it couples dominantly to electrons, then electron beams will have unique sensitivity.

Given that we know absolutely nothing about how/if DM interacts with the SM, it is important to pursue both approaches!

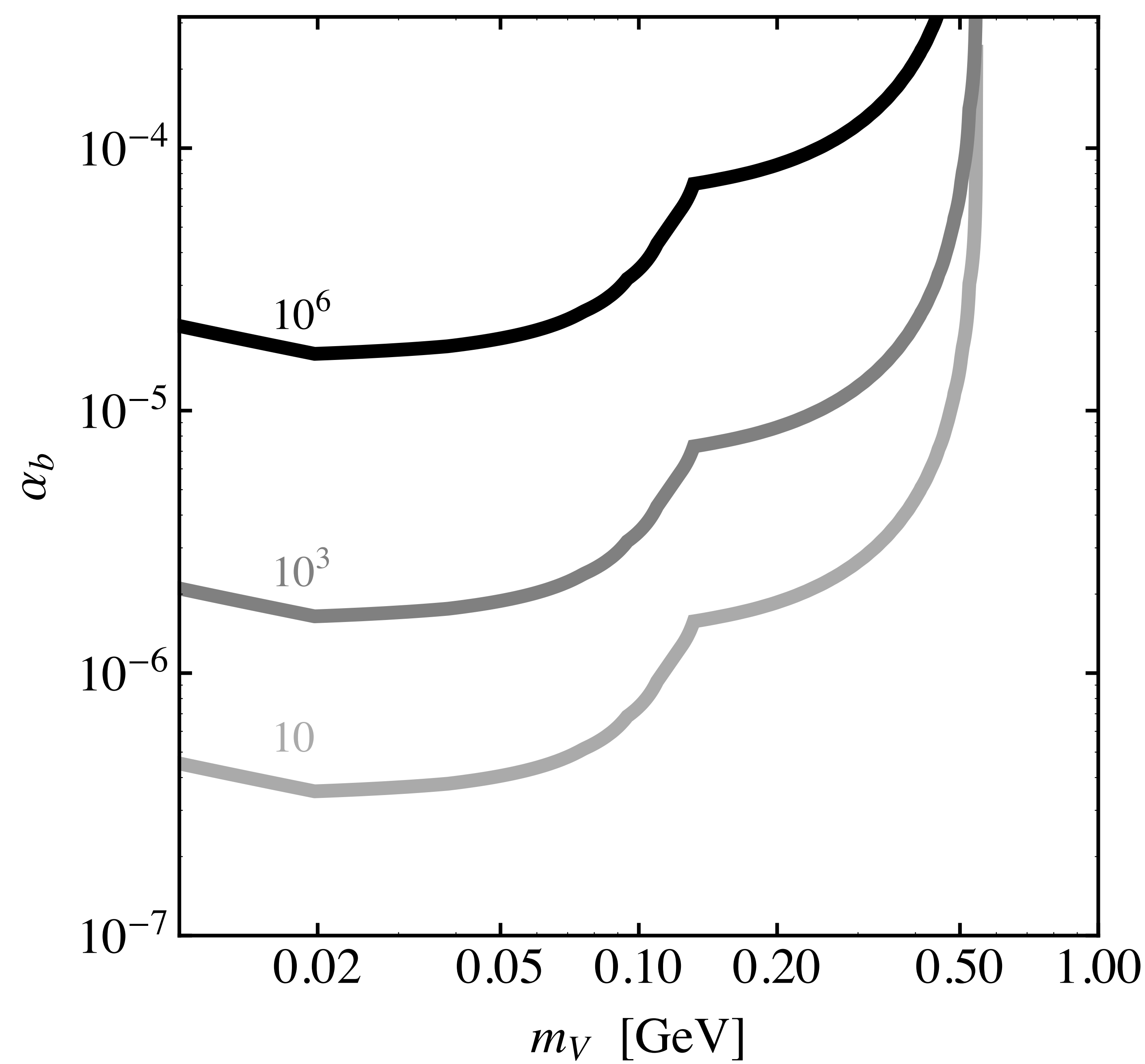
As an aside: there is interesting work to be done here also on the theory/pheno side, in terms of model building (are there other interesting, viable ways to couple light DM to SM?), and ``model independent" characterization of results

Simplified model: Vector coupled to baryon current

$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}^2 + |(\partial_\mu - i g_b Q_b V_\mu)\chi|^2 + \bar{q} i \gamma^\mu (\partial_\mu - i g_b \tfrac{1}{3} V_\mu) q$$

Constraints from precision QED, B-factories & electron fixed targets do not apply

Proton beams have unique sensitivity, e.g. MinBooNE:



Outlook

- Proton and electron beam dumps offer a new way to search for dark matter in a difficult region of parameter space
- Complementary to traditional probes, such as direct detection experiments
- First analysis is underway at MiniBooNE ... limits soon!
- Main obstacle is neutrino neutral current background
  - Dump, Timing, Defocusing... new ideas needed
- Future neutrino experiments could run in a ``Dark matter mode'', or can design dedicated experiments
- Early days! Studies needed for both theory and experiment