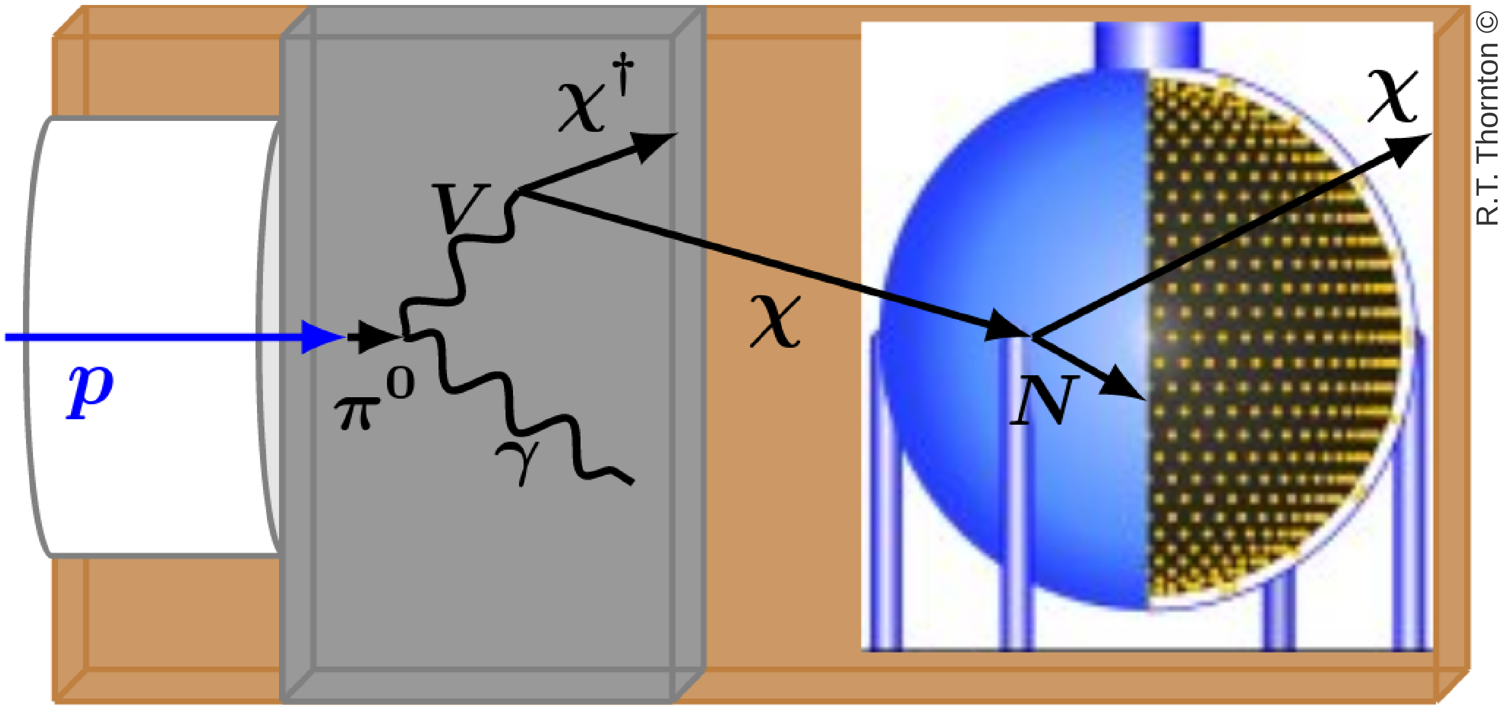


MiniBooNE-DM: a dark matter search in a proton beam dump

Alexis A. Aguilar-Arévalo (ICN-UNAM)
for the MiniBooNE-DM collaboration

XV International Conference on Topics on Astroparticle and Underground Physics (TAUP 2017)
Sudbury, ON, Canada, 24-28 July, 2017

Outline

Motivation: Sub-GeV dark matter

The BNB and the MiniBooNE detector

Dark Matter search in beam-dump mode

Results

Future perspectives

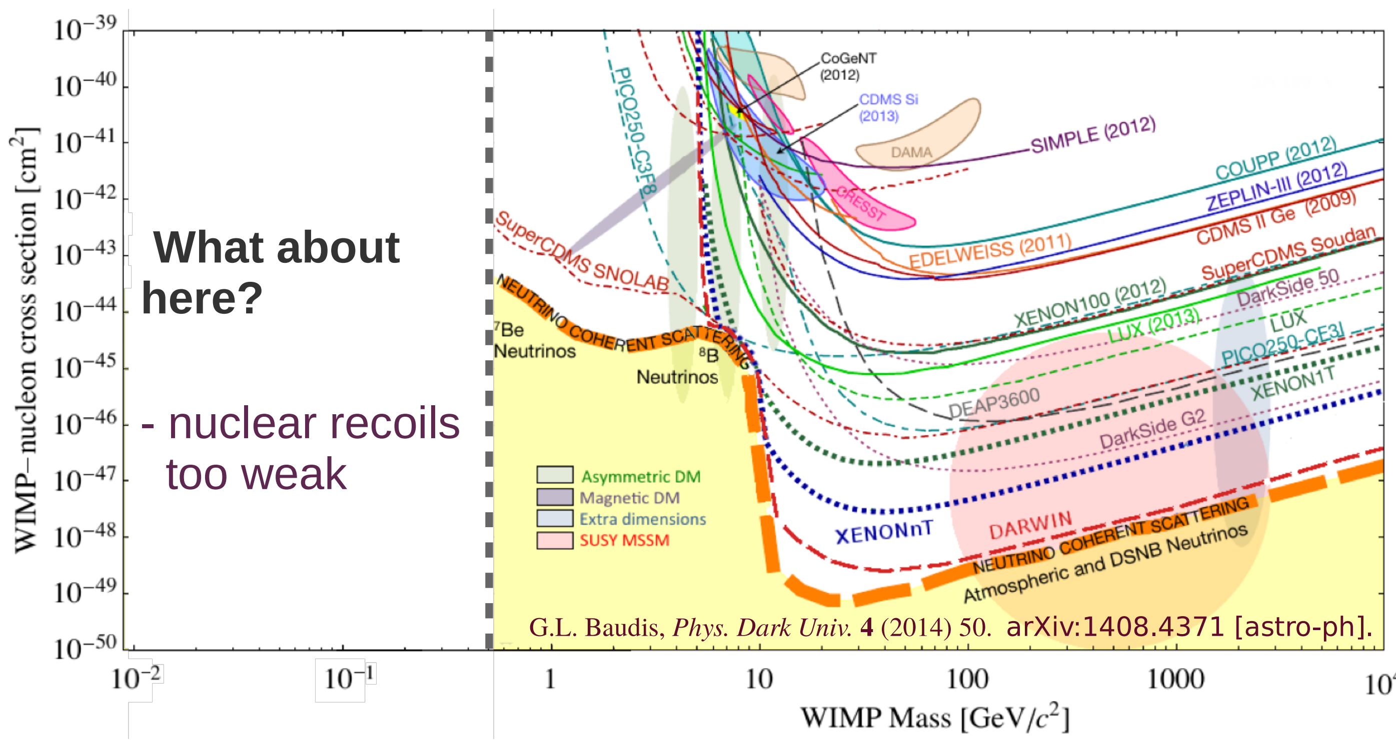
Conclusions

Motivation

- Light (sub-GeV) particles from a **Dark Sector** interacting with ordinary matter through a **light mediator** are viable dark matter candidates.

B. Batell,M. Pospelov,A. Ritz, Phys.Rev. D 80, 095024 (2009),
P. deNiveville,D. McKeen,A. Ritz, Phys.Rev. D 86, 035022 (2012)

- **Vector portal** models → most viable for thermal, sub-GeV DM.

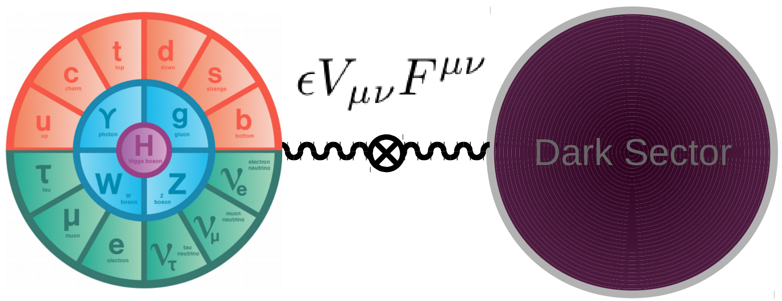


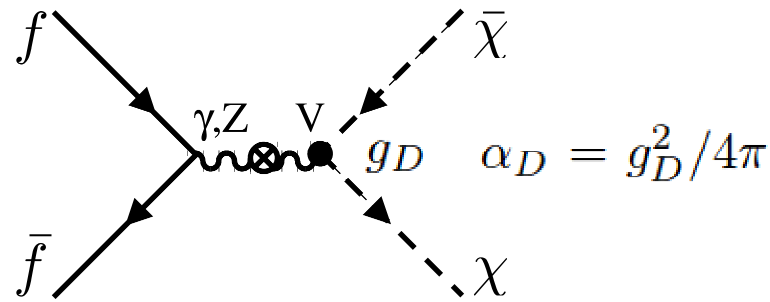
G.L. Baudis, *Phys. Dark Univ.* **4** (2014) 50. arXiv:1408.4371 [astro-ph].

- Sub-GeV masses significantly less explored, but theoretically well motivated. Accessible to accelerator beam dump experiments.

Minimal kinetically mixed dark photon

- A minimal extension to the Standard Model:





$$\mathcal{L}_{V,\chi} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 + \epsilon V_{\mu\nu} F^{\mu\nu} + \ldots$$

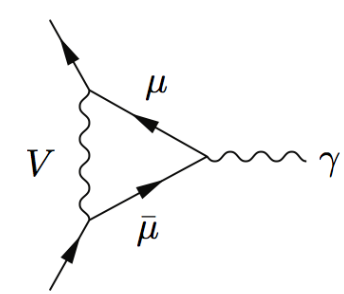
$$D_\mu = \partial_\mu - i g_D V_\mu \;, \quad g_D = \sqrt{4\pi\alpha_D}$$

4 parameters: $m_\chi,\ m_V,\ \epsilon,\ \alpha_D$

B. Batell, M. Pospelov, A. Ritz, Phys.Rev. D 80, 095024 (2009)
P. deNiveville, D. McKeen, A. Ritz, Phys.Rev. D 86, 035022 (2012)

- $U(1)_D$ gauge boson (**"dark photon"**) increases the DM annihilation cross section to give the correct relic density.

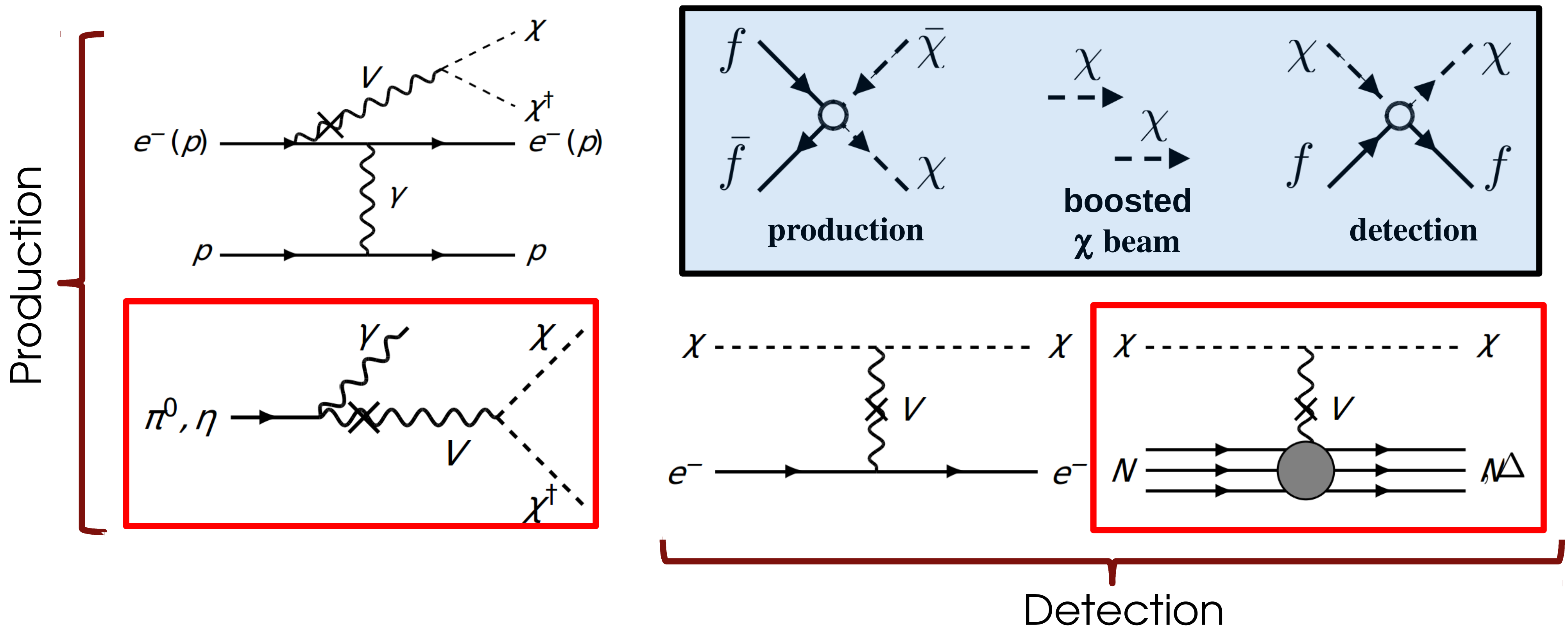
- Mediator with mass *O*(10-10^3 MeV) could resolve the $(g\text{-}2)_\mu$ anomaly.



P. Fayet, Phys. Rev. D 75, 115017 (2007)
M. Pospelov, Phys. Rev. D 80, 095002 (2009)

Dark Matter Beam and Detection

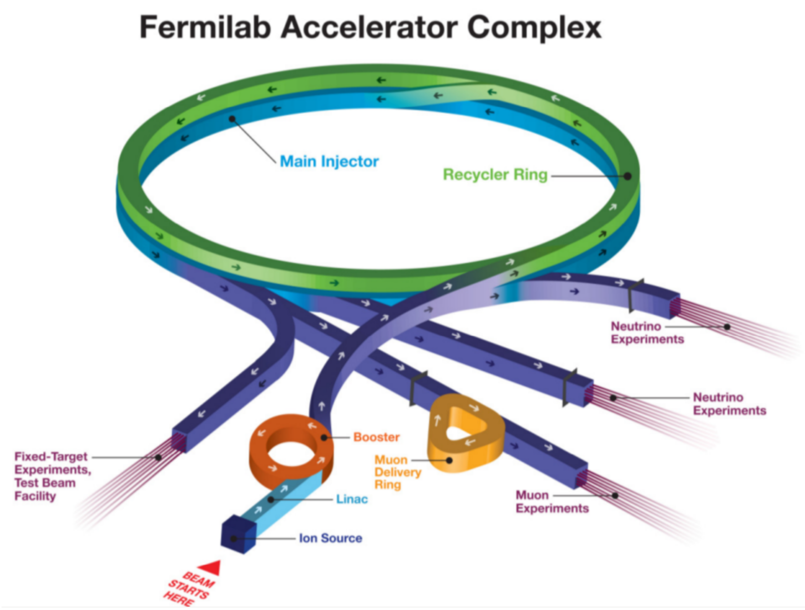
- Production in high-energy collisions and detection by scattering.

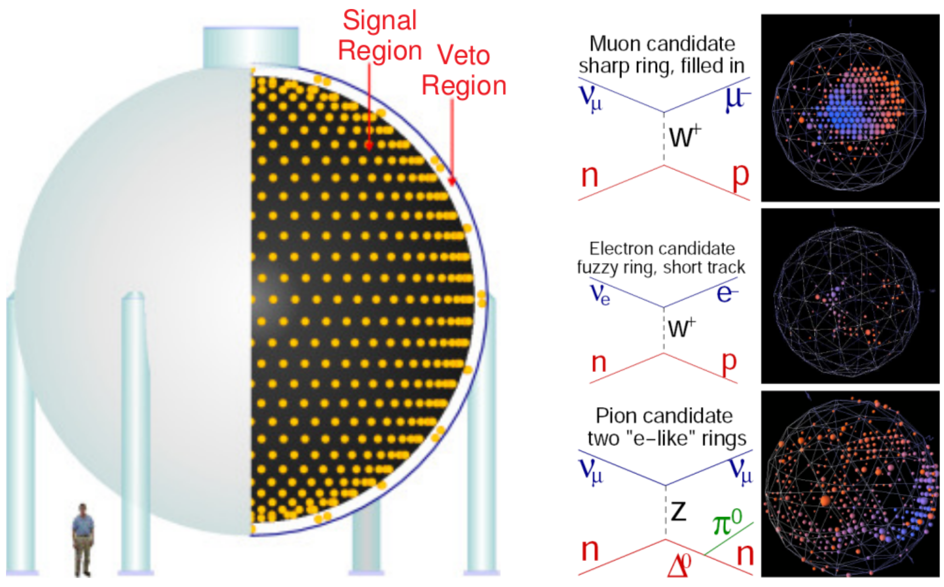


Event rate: $\sim \epsilon^4 \alpha_D$, for $m_V > 2m_\chi$ (*invisible* decay of *V*).

B. Batell et al., *Phys. Rev. Lett.* **113** (2014) 171802. arXiv:1406.2698 [hep-ph].
P. deNiverville et al., *Phys. Rev.* **D84** (2011) 075020. arXiv:1107.4580 [hep-ph].

The BNB and the MiniBooNE detector





The Booster Neutrino Beam

- 8 GeV protons from the FNAL Booster
- Target: Be , 1.7 interaction lengths, 541 m to the detector
- Magnetic horn focuses mesons
- Mesons decay along 50 m pipe (air), with Fe beam dump at the end.

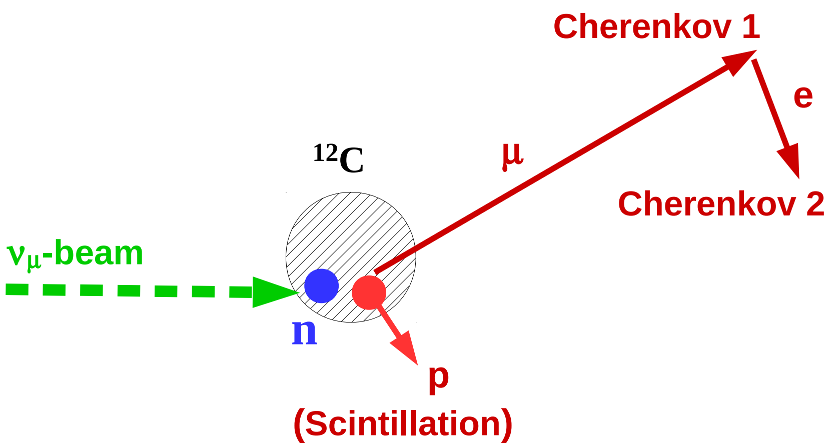
The MiniBooNE detector

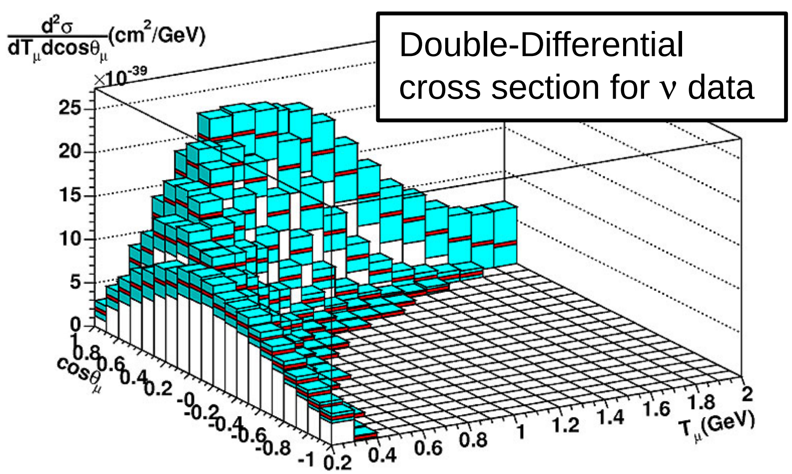
- 800 tons of mineral oil (CH_2)
- Cherenkov detector with some scintillation from trace fluors in oil
- 1280 main and 240 veto PMTs
- Ran for >10 yr in ν and $\bar{\nu}$ modes, published 27 papers.

The beam and the detector are stable and well understood

CCQE and NCE events

CCQE: Charged-Current Quasi-Elastic
Single μ events + decay e

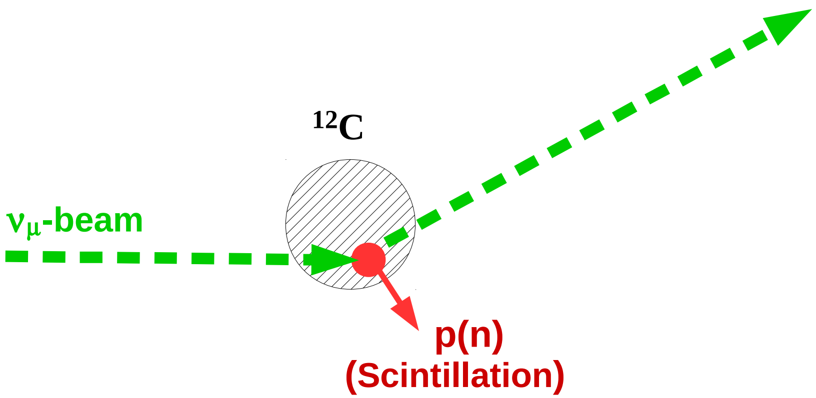


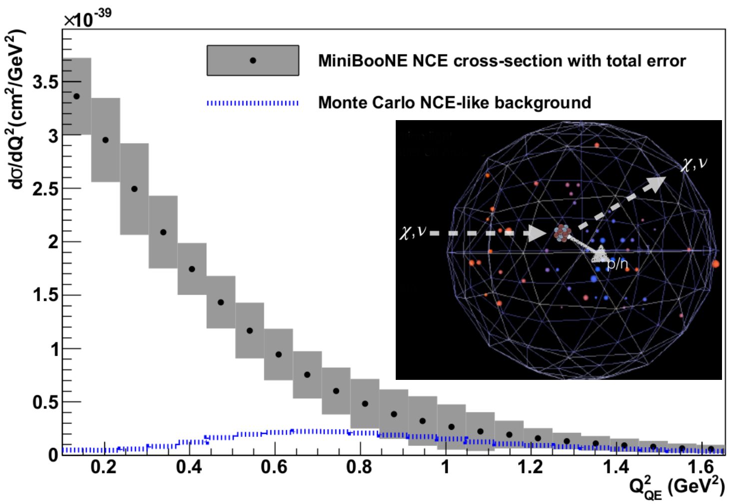


- First double differential cross-section measurement.

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

NCE: Neutral-Current Elastic
Low hits activity with no μ or π



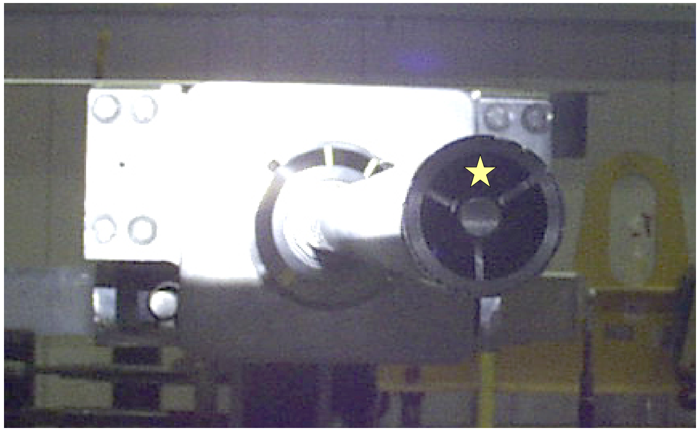


- Absolute and relative (to CCQE) cross-sections.

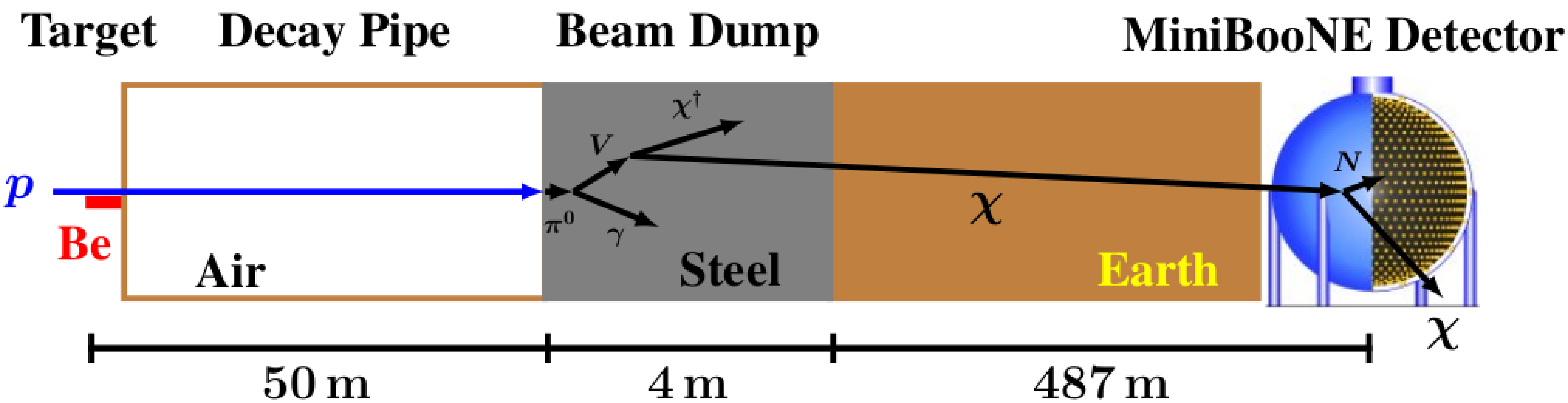
A. A. Aguilar-Arevalo et al., Phys. Rev. D82, 092005 (2010), arXiv:1007.4730 [hep-ex]

Beam Dump (Off Target) mode

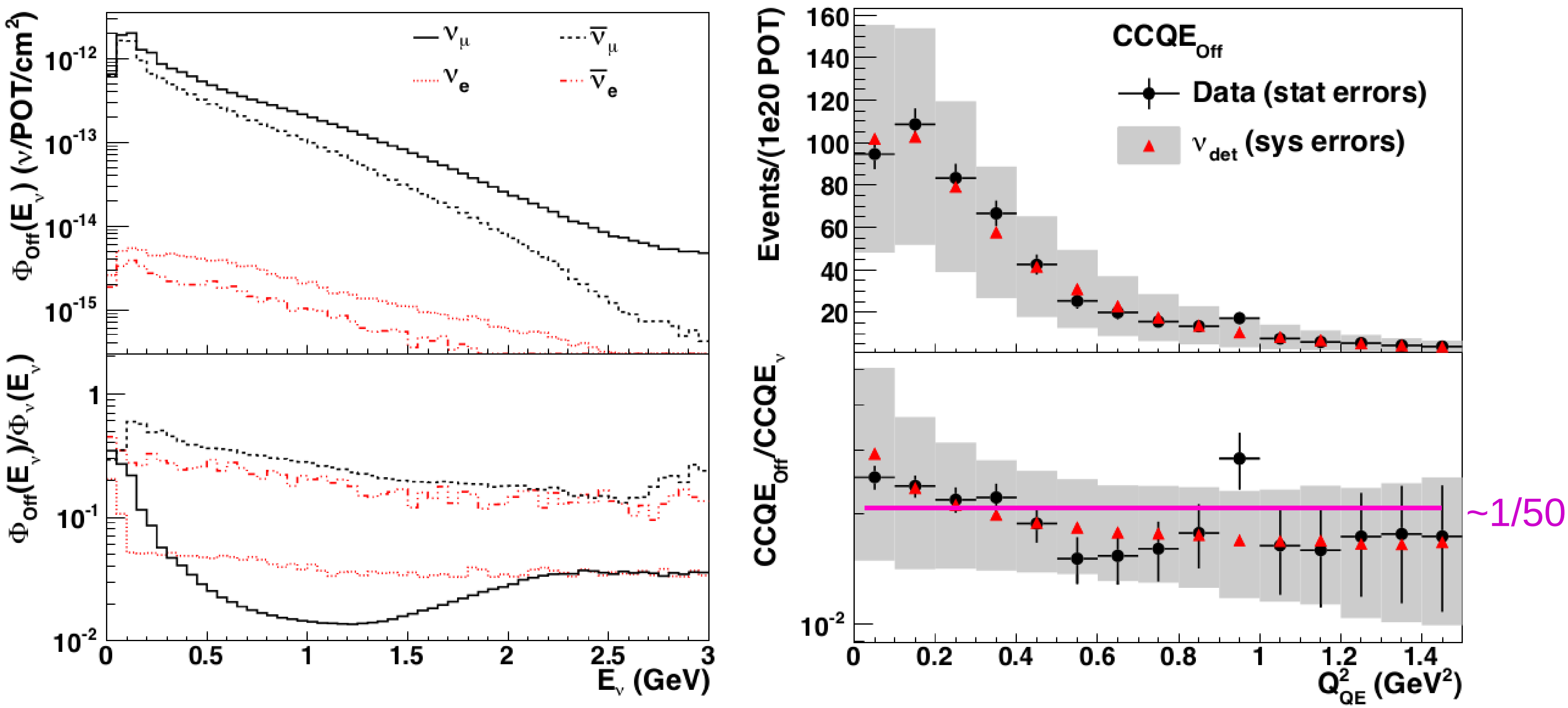
- Reduce ν production by steering beam to miss the target (horn powered off).
- Beam impacts on the beam dump
- Charged mesons absorbed in the steel beam dump before decay → reduces the neutrino flux.



MiniBooNE target assembly



Neutrino flux reduction

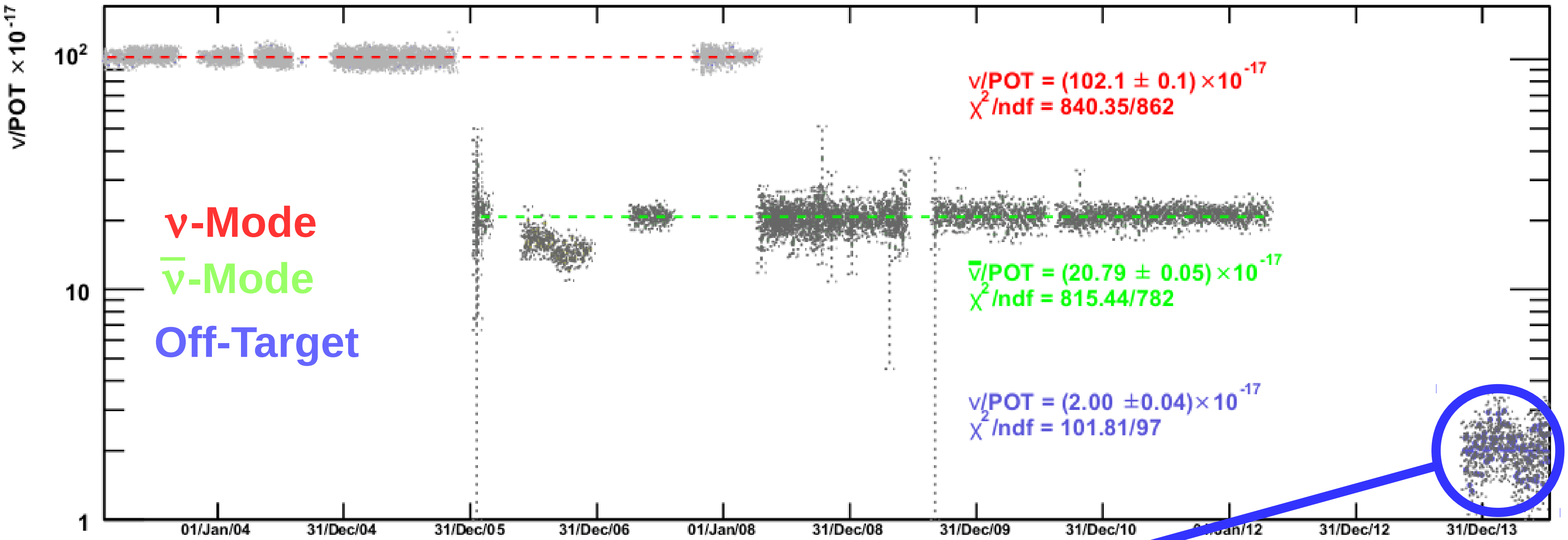


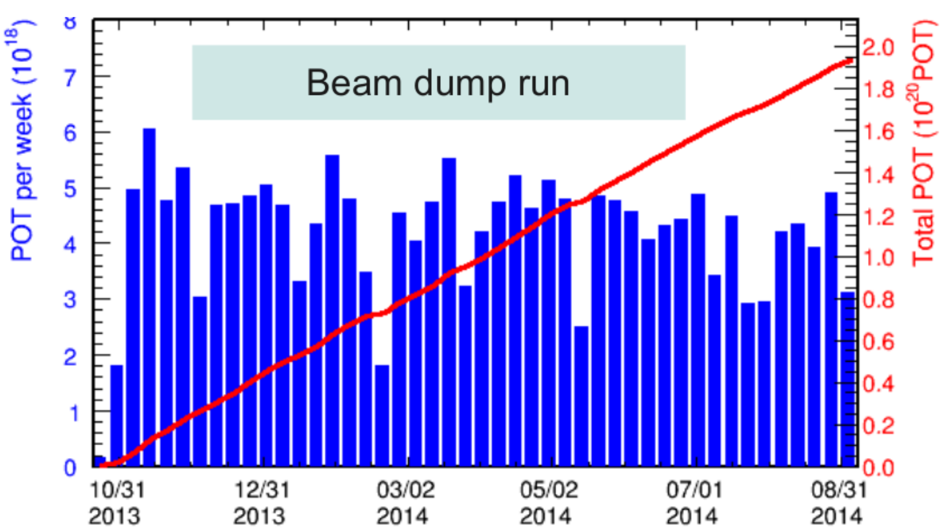
Off-Target flux: Φ_{off} = (1.19 ± 1.1)×10^{-11} ν/(POT · cm^2), $0.2 < E_\nu < 3$ GeV

Comp. to ν-Mode: - Flux reduced by factor of ~30

- Event rate reduced by factor of ~50.

Off Target beam stability



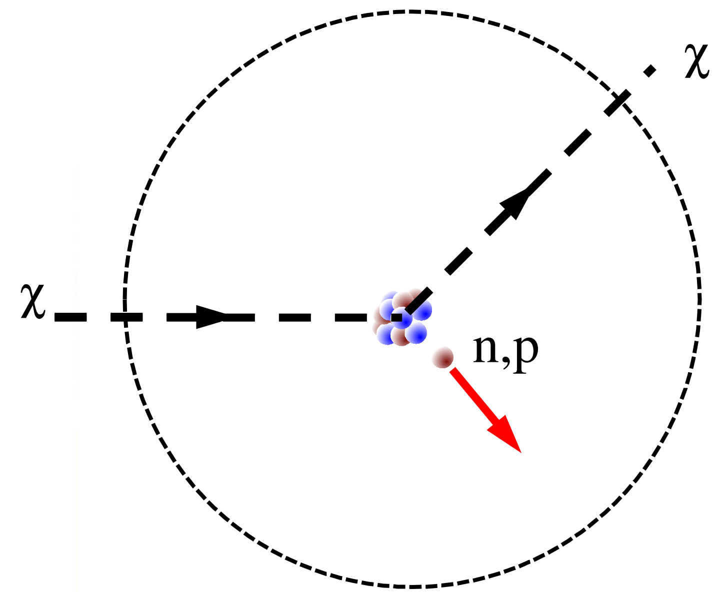


- Ran 9 months, Nov 2013 to Sep 2014, collected 1.86×10^{20} POT.
- ν/POT decreased by ~50 compared to ν Mode.

N-DM event selection

Single *p*/*n* track with a few hundred MeV kinetic energy.

- 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

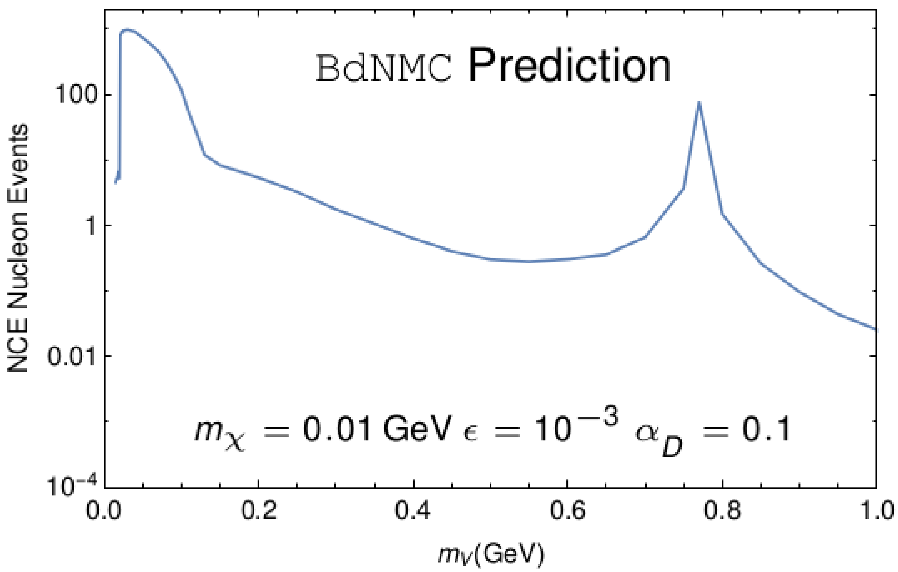


Based on the $\bar{\nu}$ NCE cross section analysis.

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

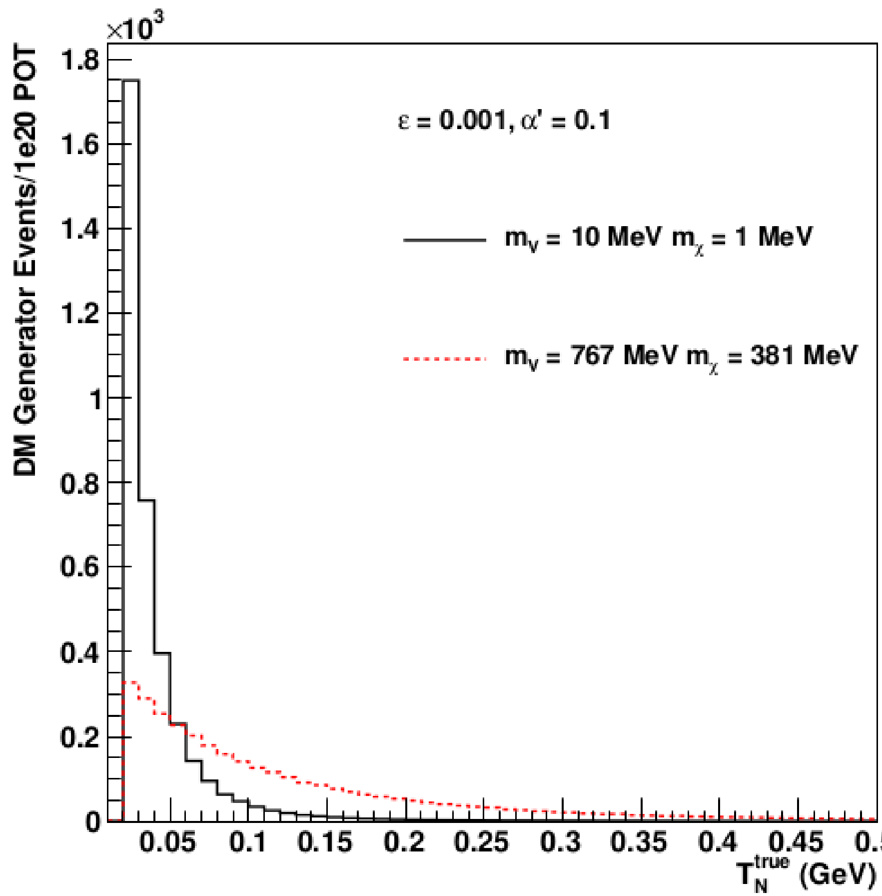
Dark Matter generator

- Used BdNMC to generate T_N^{true} event lists.
- Produced event lists $m_V \in$ [0.01,0.1] GeV/c^2 and $m_\chi \in$ [0.001,m_V/2) GeV/c^2
- Included π^0/η -decay and Bremsstrahlung channels.



P. deNiverville et al., (2008), arXiv:1609.01770 [hep-ph]

- π^0/η event lists from beam MC used to generate π^0 and η distributions.



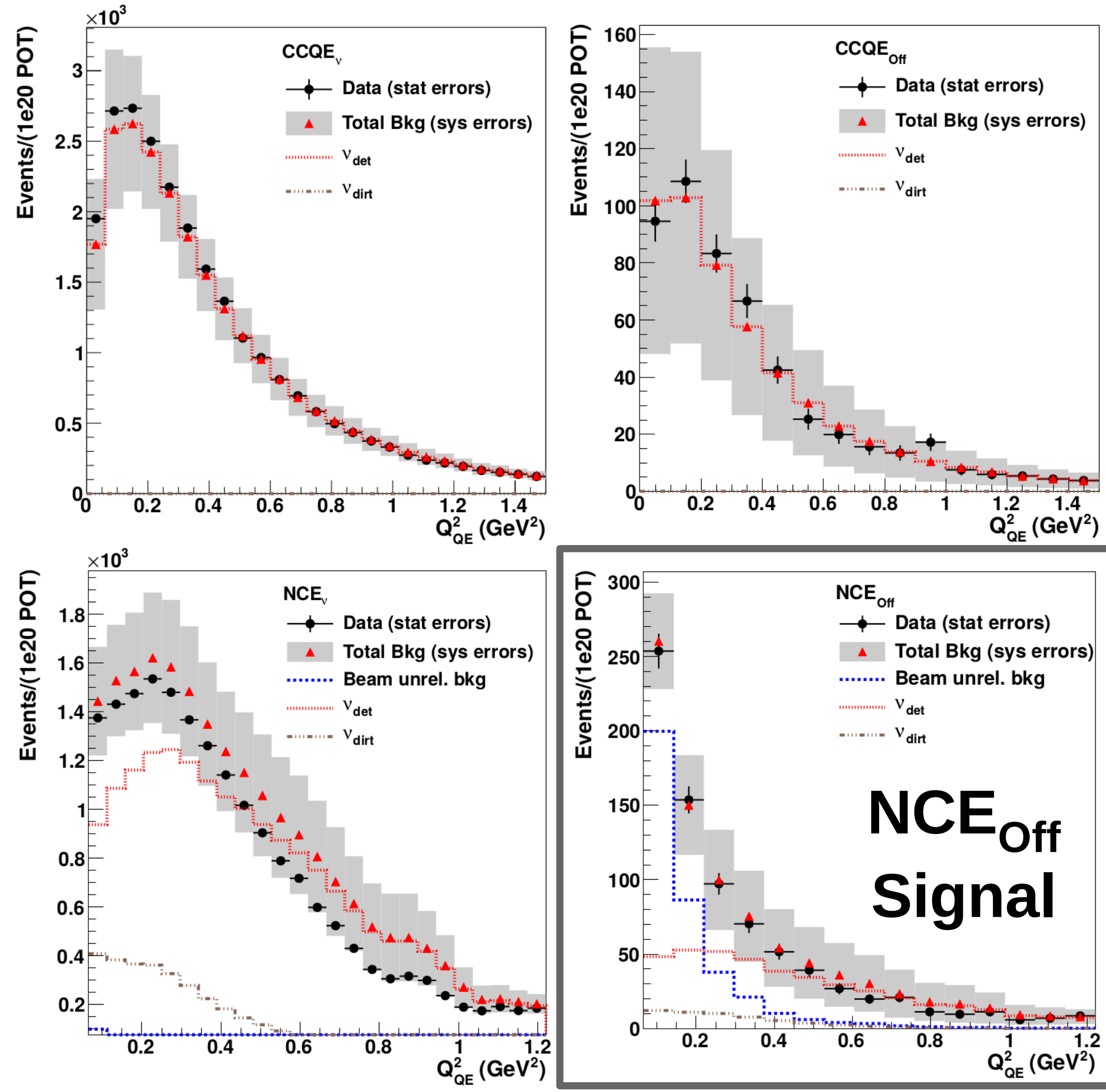
Fit strategy

- Use 4 distributions:

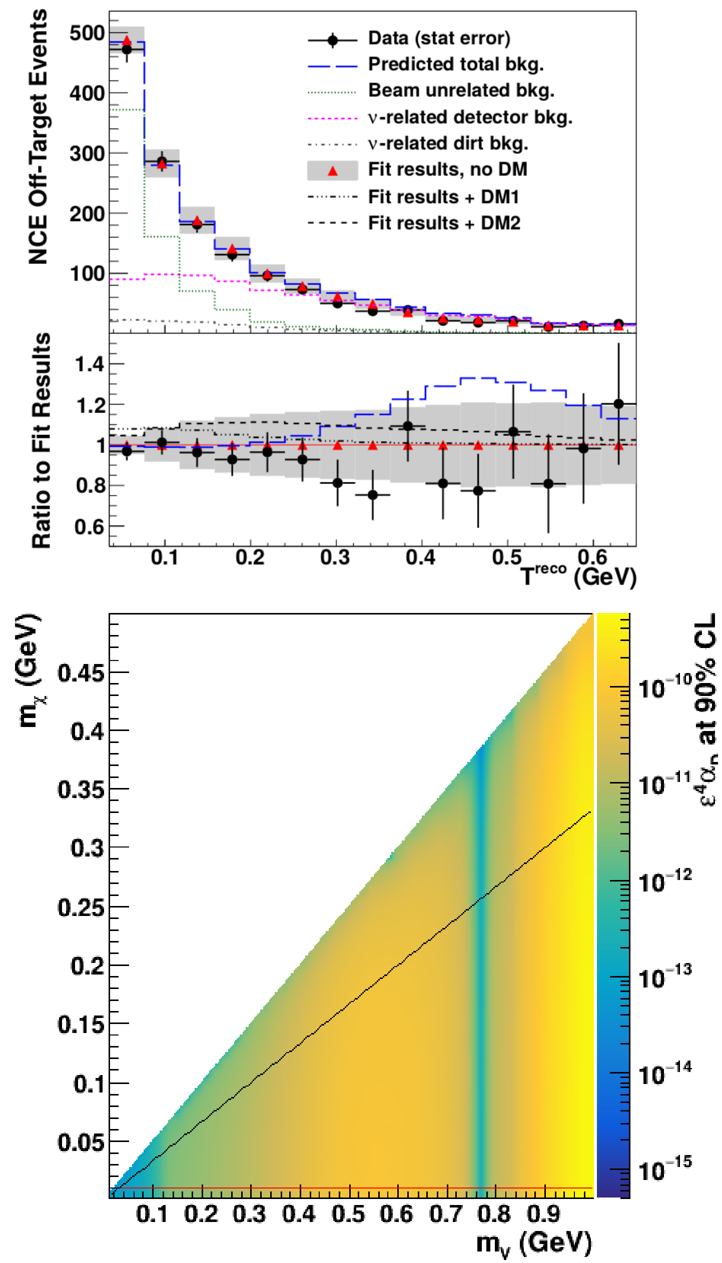
  - $CCQE_\nu$ neutrino-Mode
  - $CCQE_{Off}$ BDump-Mode
  - NCE_ν neutrino-Mode
  - **NCE_{Off} BDump-Mode (signal)**

- Use correlations among bins across all samples.

  - CC data help constrain flux uncertainties.
  - NC data help constrain ν cross-section uncertainties.



Results



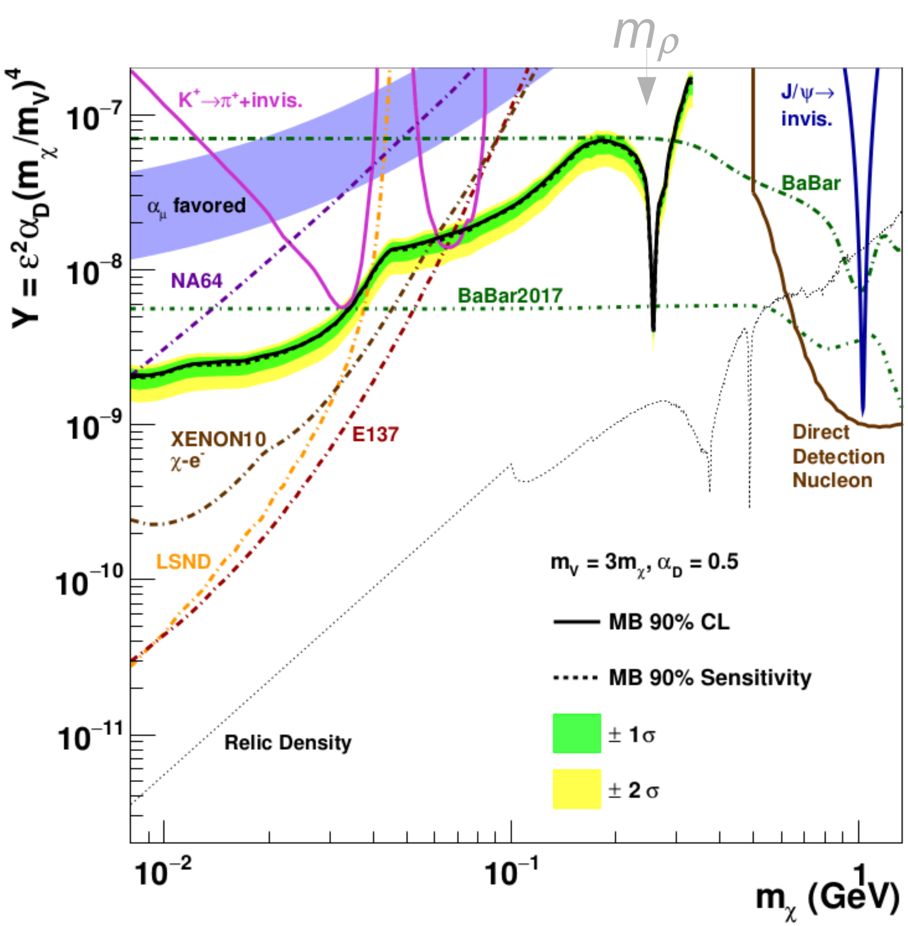
	#events	uncertainty
Beam unrel. bkg	697	
Beam rel: ν_{det} bkg	775	
Beam rel: ν_{dirt} bkg	107	
Total Bkg	1579	34% (pred. sys.)
Data	1465	3% (stat.)
Fit Results	1548	13% (fit effective error)

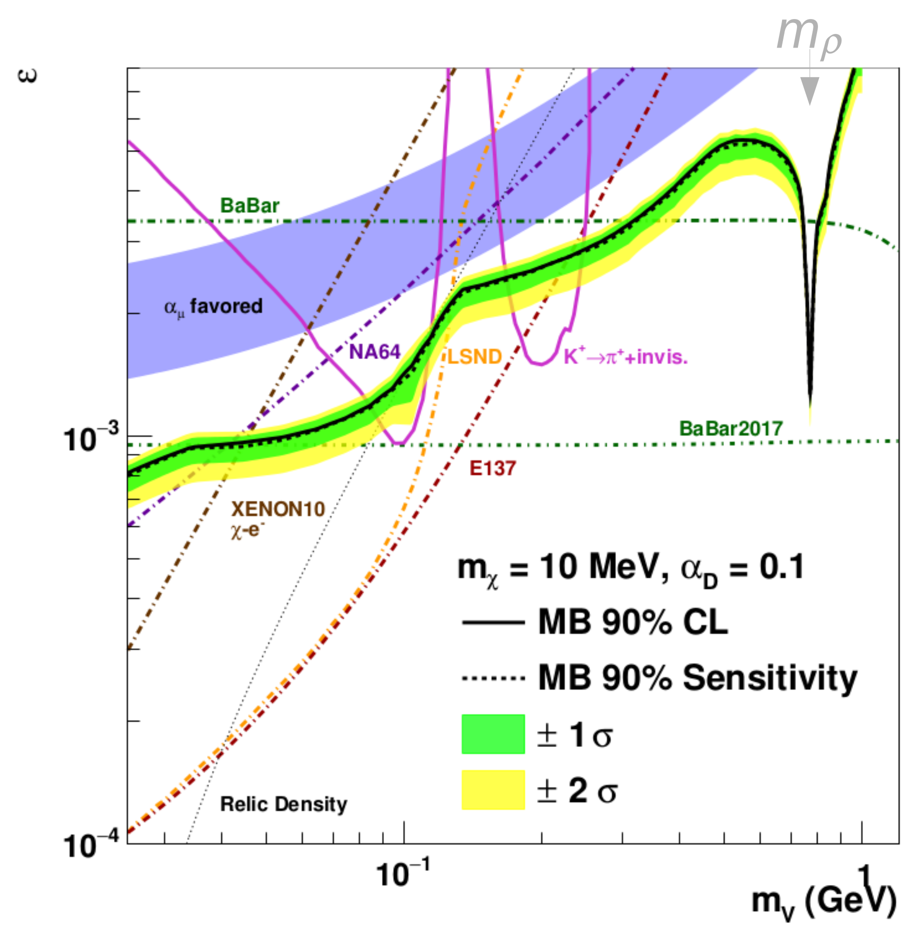
- Data consistent with background-only.
- Systematics dominated.
- Constraint samples reduce syst → 13%.

90% C.L. limits

- CL limit on $\varepsilon^4\alpha_D$ for a given m_V and m_χ .
- Only considered on-shell decays (m_V>2m_χ).
- Slice to compare to other experiments.

Results





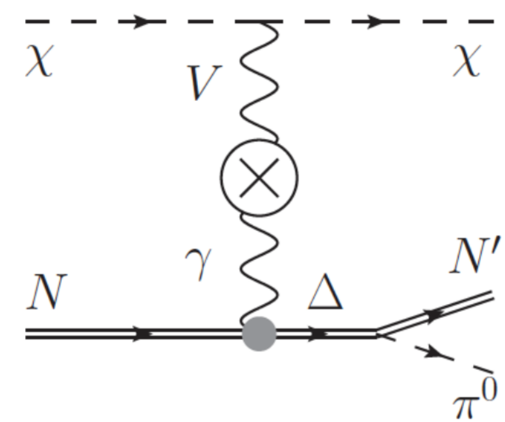
- **In most of par. space:** exclude model solutions to the $(g\text{-}2)_\mu$anomaly
- **in some of par. space:** exclude model solutions matching the relic density.
- Overall: new regions of parameter space excluded.
- Cover most of the gap between 1 MeV/c^2 < m_χ < direct detection.

Next analyses of the MB data set

Increase sensitivity wrt. nucleon-DM elastic scattering:

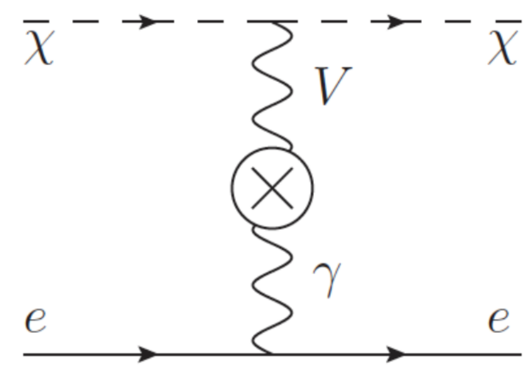
DM resonance scattering $\Delta \rightarrow \pi^0$, where $NC\pi^0$ ν-scattering is the main background.

- π^0 is a clean signal
- expect small beam unrelated backgrounds



Elastic DM-electron scattering where SM ν-e scattering is the main background.

- like ν-e is very forward peaked



RF spill event timing

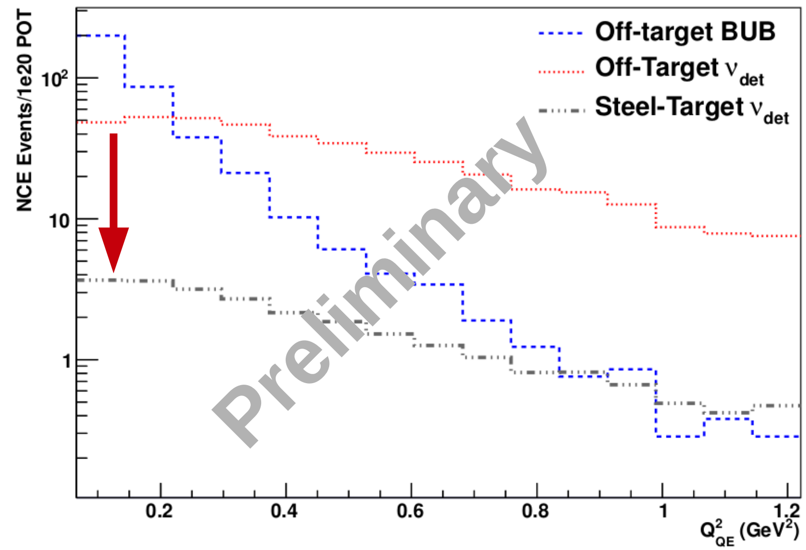
- Use time structure of the BNB
- Massive DM delayed relative to ν backgrounds
- Will increase sensitivity to DM masses > 70 MeV/c^2

Future: a dedicated beam dump

Replace ***BNB target and horn*** with a ***dedicated steel beam dump*** → x10 fewer ν's than in off-target

A non-trivial upgrade to the BNB
→ include a sub-GeV DM search to the Short Baseline Neutrino (SBN) program?

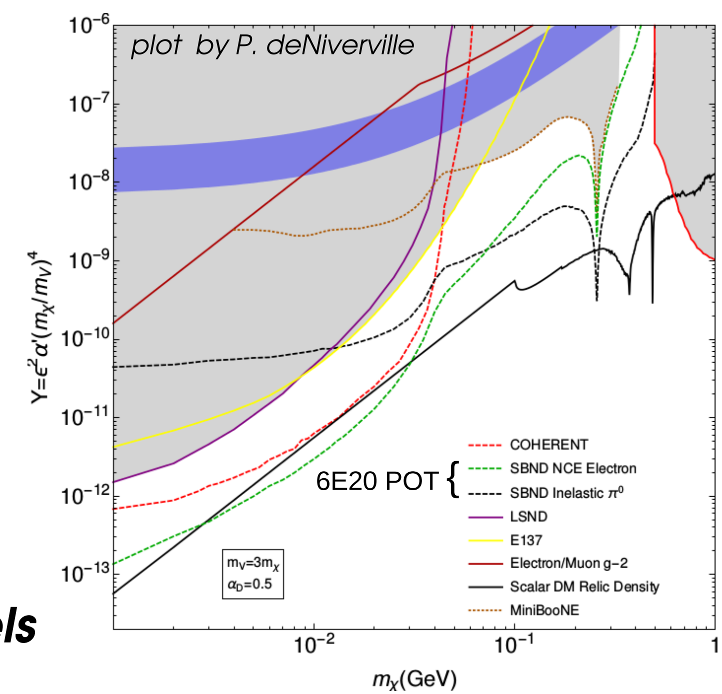
(see talk by R. Van de Water @ U.S. Cosmic Visions 2017)



A sub-GeV DM search with the SBND:

- Will achieve x10 improvement in signal sensitivity relative to MiniBoooNE
- Requires deployment of improved absorber (replacing TGT assembly+horn)
- Sensitivity estimates are robust, based on lessons learned from MB search.
- LOI submitted to FNAL PAC

π^0 & e channels



Conclusions

- MiniBooNE collected data (1.86×10^{20} POT) in beam-off-target mode to search for sub-GeV dark matter.
- Beam-off-target suppresses neutrino backgrounds. Beam unrelated backgrounds significant.
- First of its kind proton beam dump search with a large well characterized neutrino detector (dedicated collab).
- Nucleon-DM elastic scatter analysis is complete e-DM and inelastic π^0 channels are underway.
- Future opportunities (e.g. DM search with SBN) are being explored.

Thank you for your attention!

A.A. Aguilar-Arevalo et al.,Phys. Rev. Lett. **118**, 221803 (2017), arXiv:1702.2688 [hep-ex].

Backups

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
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[5] Indiana University, Bloomington, IN 47405
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[9] University of Florida, Gainesville, FL 32611
[10] Argonne National Laboratory, Argonne, IL 60439
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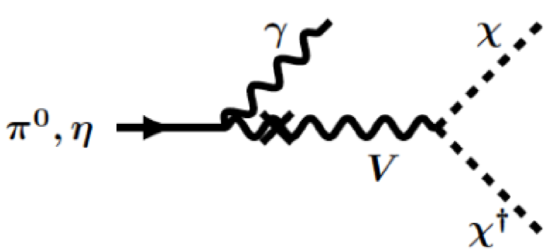
[12] New Mexico State University, Las Cruces, NM 88003
[13] Saint Mary's University of Minnesota, Winona, MN 55987
[14] University of Michigan, Ann Arbor, MI 48109
[15] University of Texas (Arlington), Arlington, TX 76019

BdNMC

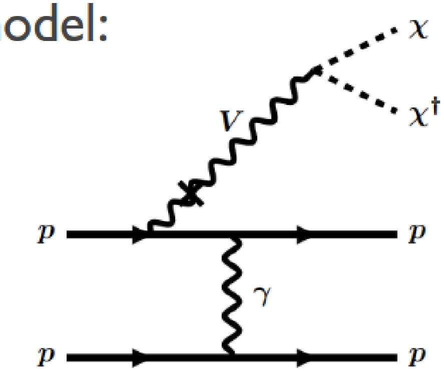
[deNivervile, Chen, Pospelov, Ritz]
https://github.com/pgdeniverville/BdNMC/releases

- Publicly available proton beam fixed target DM simulation tool developed by Patrick deNiverville (U. Victoria) and collaborators.

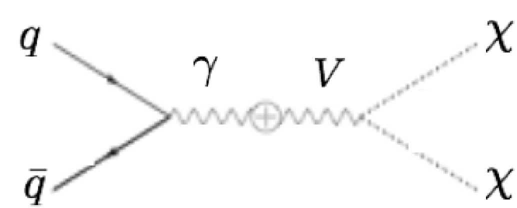
Detailed DM production model:



Neutral mesons decays

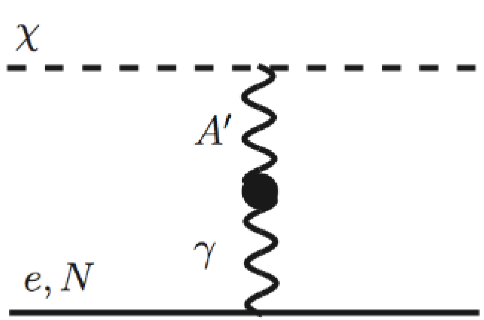


Bremsstrahlung + vector meson mixing

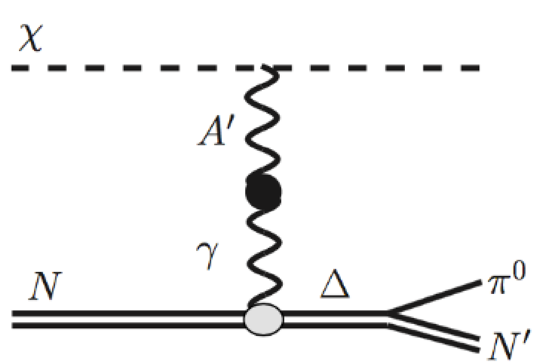


Direct production

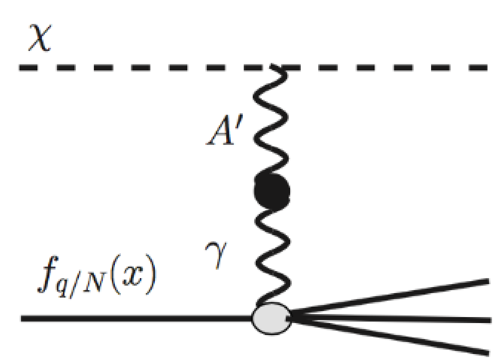
Several DM scattering processes included



Elastic NC nucleon or electron scattering

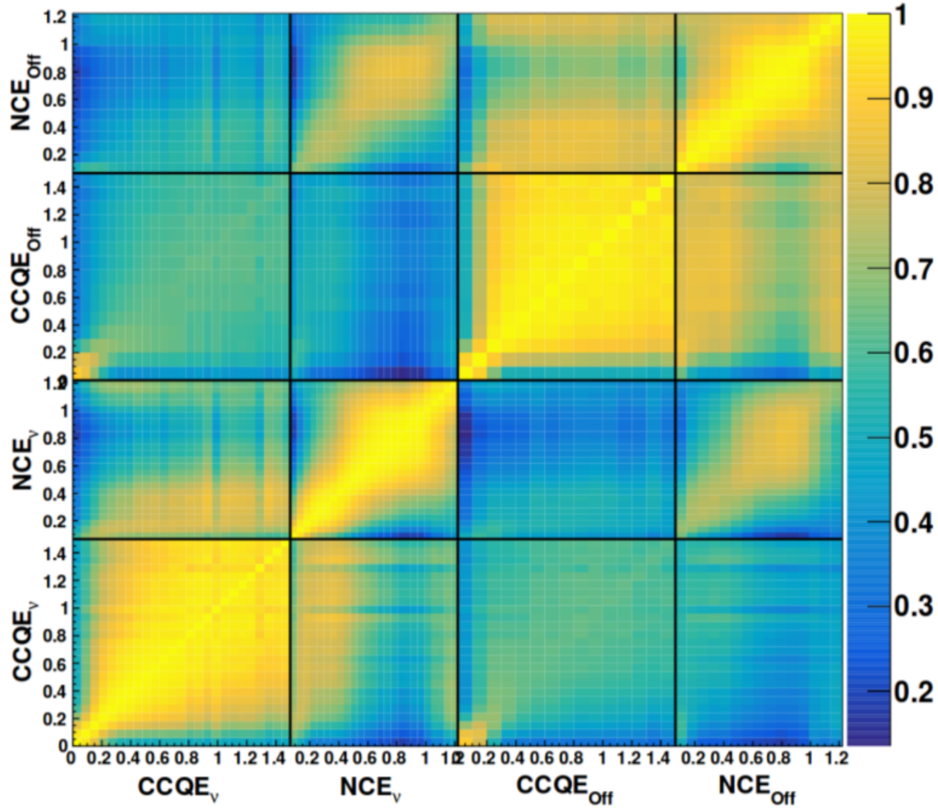


Inelastic NC neutral pion - like scattering

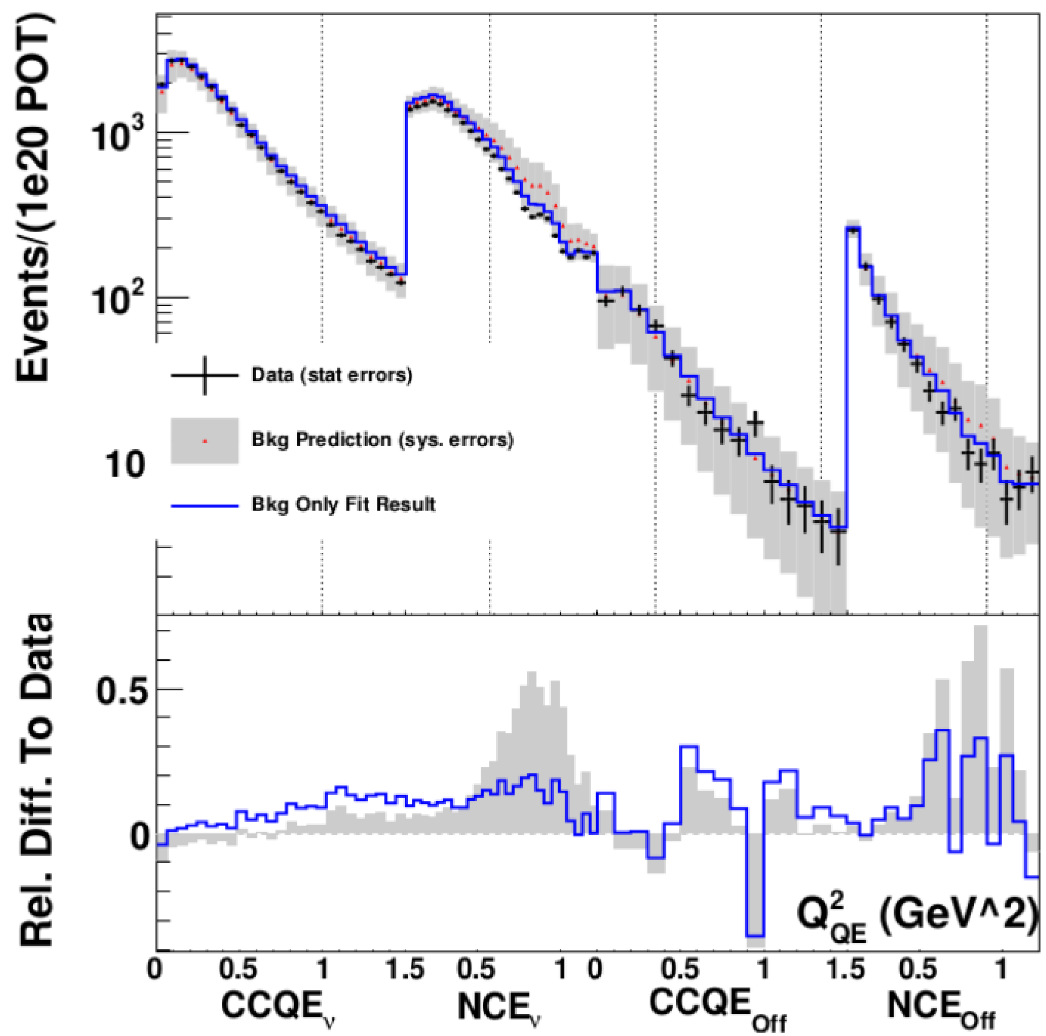


Deep Inelastic scattering

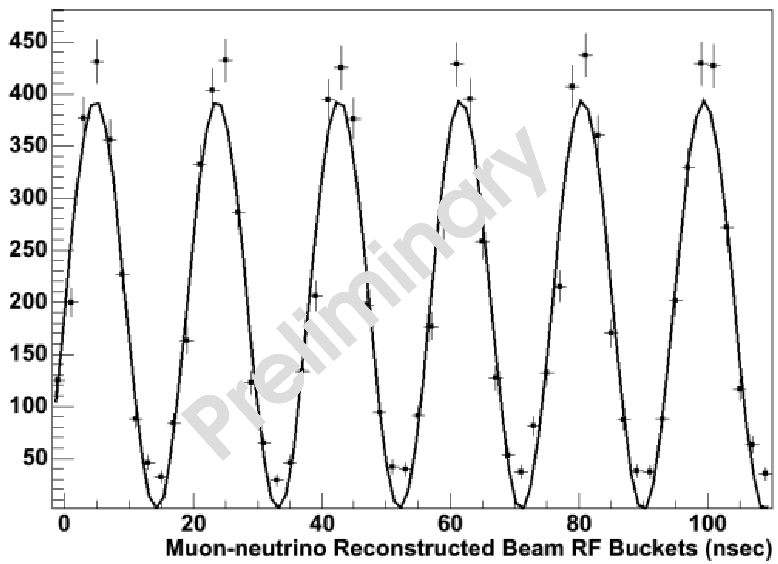
Simultaneous Fit

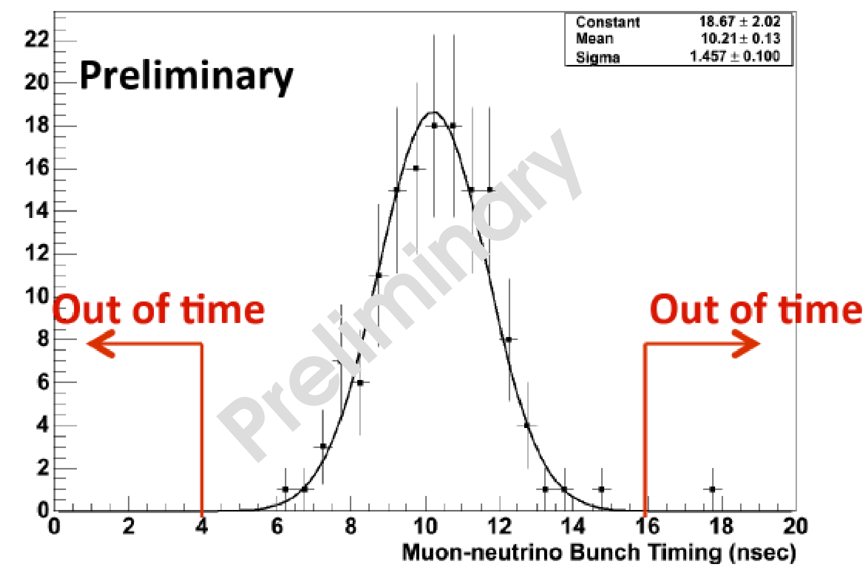


Covariance matrix

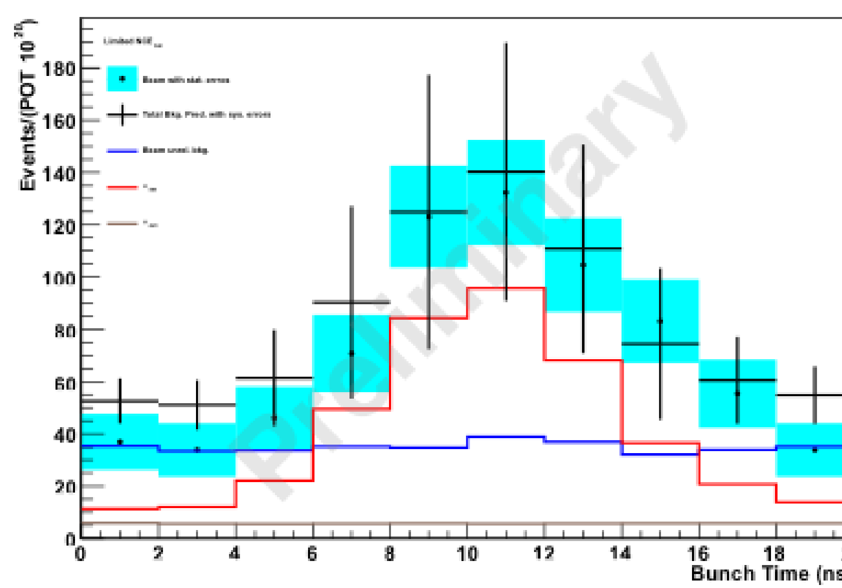


Future MB analyses



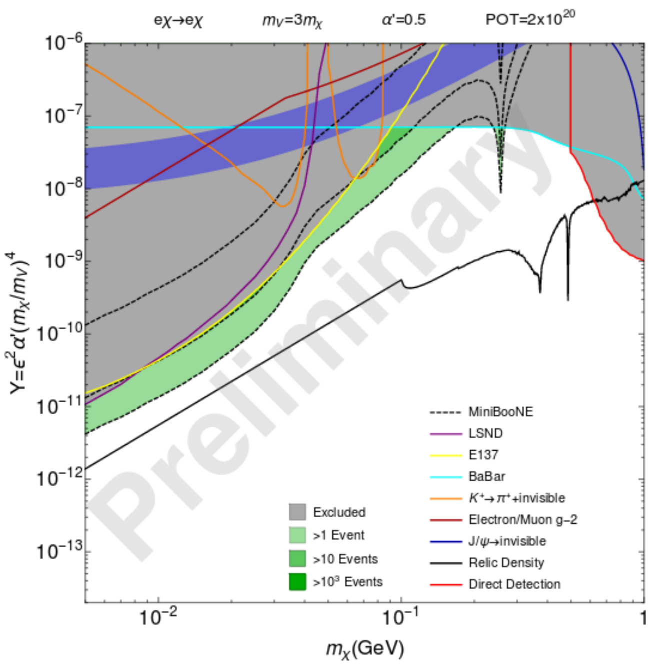


- Proton beam is comprised of 81 ns RF pulses (buckets)
- Massive dark matter will propagate sub-luminal
- Characteristic intra-bunch timing improve "high" mass dark matter sensitivity

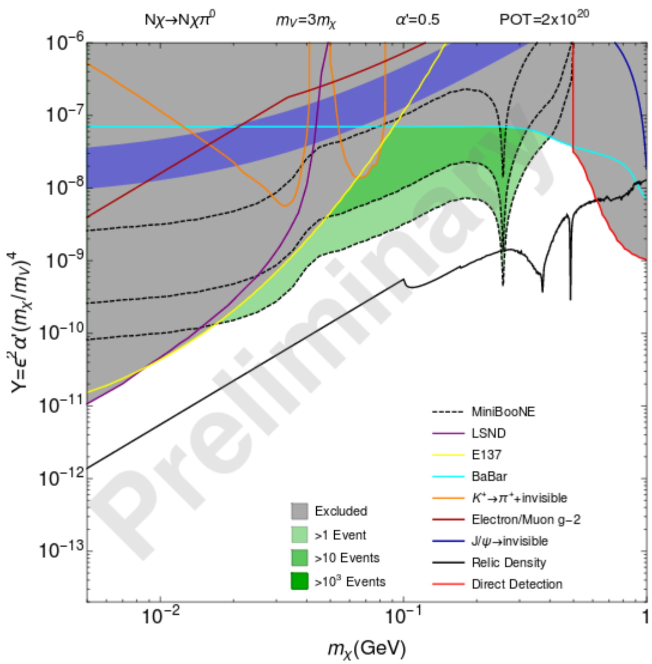


Future MB analyses

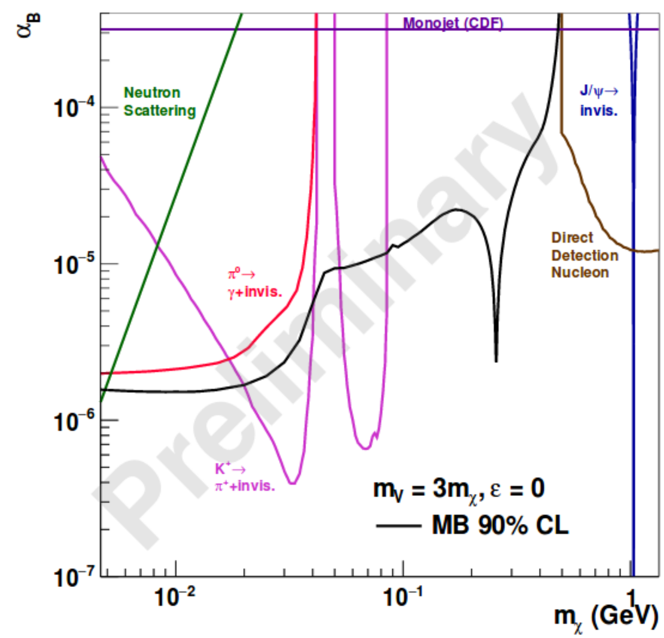
Electron Scattering



π^0 production



Leptophobic Model



- Will exclude new parameter space in vector portal kinetic mixing theory.
- Produced Model Independent Fit (MIF) for use with other theories.
- MIF used to set CL in leptophobic theory (very significant exclusion).
- Timing analysis underway to improve sensitivity to heavier masses.
- Future MiniBooNE analysis is promising.

Leptophobic Dark Matter

- It is possible that dark matter couples dominantly to quarks.
- **Many constraints are evaded - proton beams have a significant advantage!**
- Simplified model (based on local $U(1)_B$ baryon number)

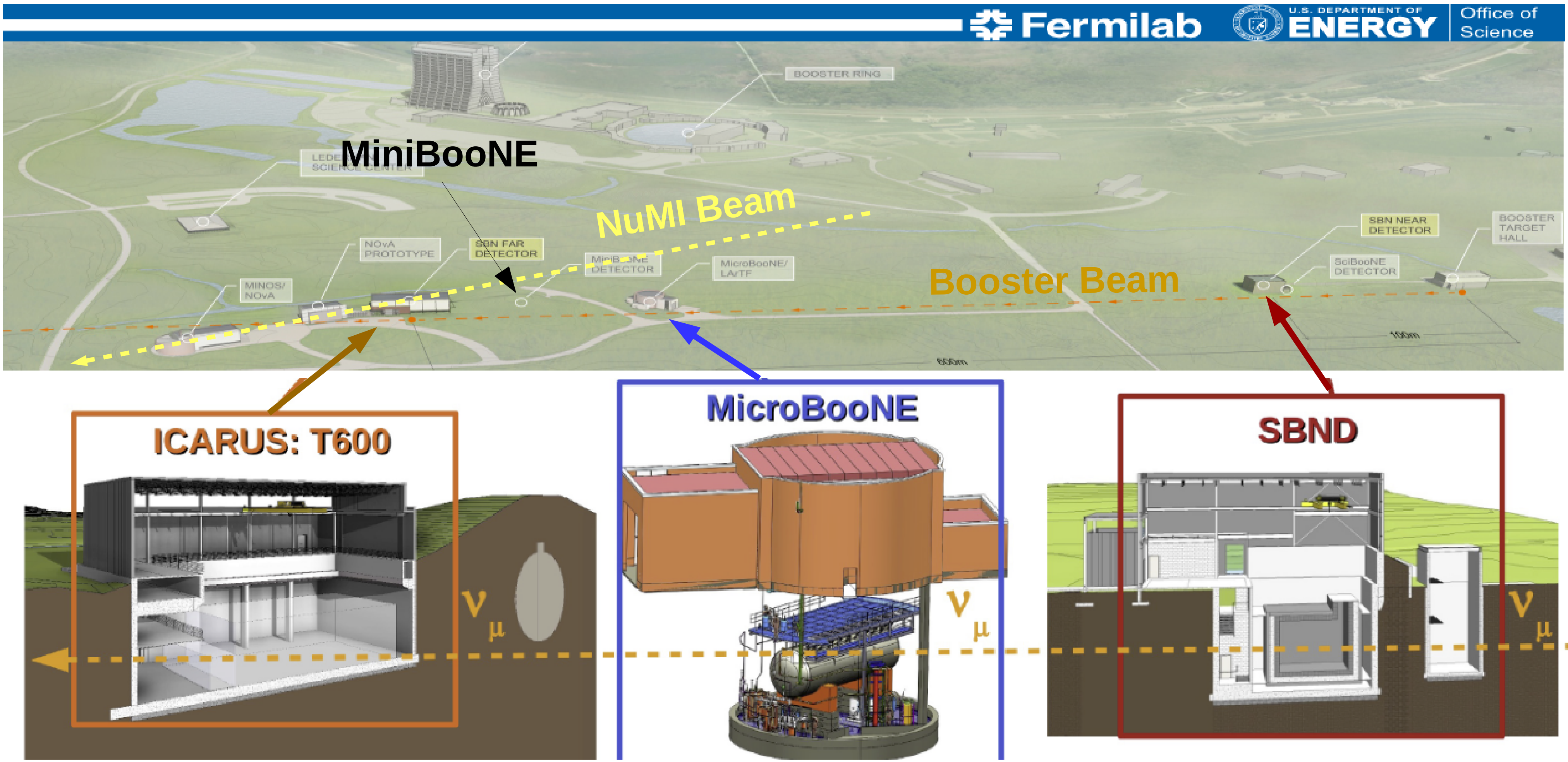
$$\mathcal{L} = i\bar{\chi}\gamma^\mu D_\mu \chi - m_\chi \bar{\chi}\chi - \frac{1}{4}(V_B^{\mu\nu})^2 + \frac{1}{2}m_V^2 (V_B^\mu)^2 + \frac{g_B}{3} V_B^\mu \sum_i \bar{q}_i \gamma_\mu q_i + \ldots$$

$$D^\mu = \partial^\mu - i g_B q_B V_B^\mu$$

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

- 4 new parameters: $m_\chi, m_V, \alpha_B, q_B$
- $U(1)_B$ is "safe" - preserves approximate symmetries of SM (CP, P, flavor)
- Gauge anomalies can be canceled by new states at the weak scale

Short Baseline Neutrino (SBN) program



- Motivated by LSND/MiniBooNE to study ν oscillations. To begin operations in 2018.
- Short Baseline Near Detector (**SBND**) → Ideal for beam dump sub-GeV DM search.

SBN and MiniBooNE signal estimates

- For all configurations, assume 50 m beam dump, 2×10^{20} POT

	MiniBooNE	MicroBooNE	SBND
Distance from 50m Dump (m)	500	420	50
Analysis Fiducial Mass (tons)	450	60	40
Efficiency (N or e^-)	30%	60%	60%
Approximate scaling[1]	1.0	0.38	17.7
DM-N signal[2]	**1,326**	**503**	**23,500**
ν-N elastic background[3]	406+/-80	40	2,500
DM-e^- signal[2]	**4.8**	**1.8**	**85.0**
ν-e^- elastic background[3]	~0.6	< 0.1	~10

[1]Sensitivity plots contain other scaling factors, e.g., $1/r^2$ distance scaling, energy, etc.
[2]Assume M_χ = 50 MeV, and $\sigma = 8\times10^{-36}$ cm^2.
[3]Contains beamdump neutrino flux suppression 1/44, POT, efficiency, and $\cos\theta_{e\text{-beam}} > 0.98$ cut

Previous beam dump / Fixed Target experiments – Proton Beams

Experiment	Location	approx. Date	Amount of Beam (10^{20} POT)	Beam Energy (GeV)	Target Mat.	Ref.
CHARM	CERN	1983	0.024	400	Cu	[16]
PS191	CERN	1984	0.086	19.2	Be	[17, 18]
E605	Fermilab	1986	4×10^{-7}	800	Cu	[19]
SINDRUM	SIN,PSI					
ν-Cal I	IHEP Serpukhov	1989	0.0171	70	Fe	[20–22]
LSND	LANSCE	1994-1995 1996-1998	813 882	0.798	H20, Cu W,Cu	[23]
NOMAD	CERN	1996-1998	0.41	450	Be	[18, 24]
WASA	COSY	2010		0.550	LH2	[25]
HADES	GSI	2011	0.32 pA*t	3.5	LH2,No,Ar+KCl	[26]
MiniBooNE	**Fermilab**	**2003-2008** **2005-2012** **2013-2014**	**6.27** **11.3** **1.86**	**8.9**	**Be** **Be** **Steel**	**[27]** **[28]** **[29]**

Table by R.T. Thornton, Indiana University Nuclear Physics Seminar, Nov. 21, 2014