An Accelerator-Produced, Sub-GeV Dark Matter Search with the MiniBooNE Neutrino Detector

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Outline

- The Evidence for Dark Matter
- A Model for Sub-GeV Dark Matter
- The MiniBooNE Detector and Its Sensitivity
- Dark Matter Beams and Neutrino Contamination
- Current Analysis and Preliminary Results
- Upcoming work and conclusions

dark matter
http://www.particlezoo.net/

THE EVIDENCE FOR DARK MATTER

Historical Postulation of Dark Matter

- Fritz Zwicky applied virial theorem to Coma cluster[1]
- Visible matter can not explain rotational velocities of the cluster
- Order 100 times more matter unseen
  → Dark Matter

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[1]F. Zwicky, *Helv. Phys. Acta* **6** (1933) 110.

Modern Validations: Galaxy Rotation

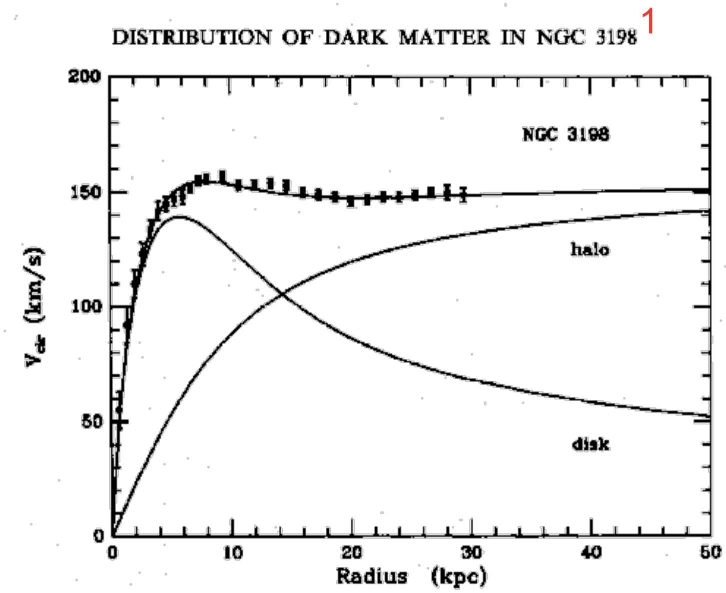
- Rotational velocity a distance *r* from center is

$$v = \sqrt{\frac{GM(r)}{r}}$$

  where *M(r)* is contained mass

- Visible mass implies a falling rotational velocity, *but*…

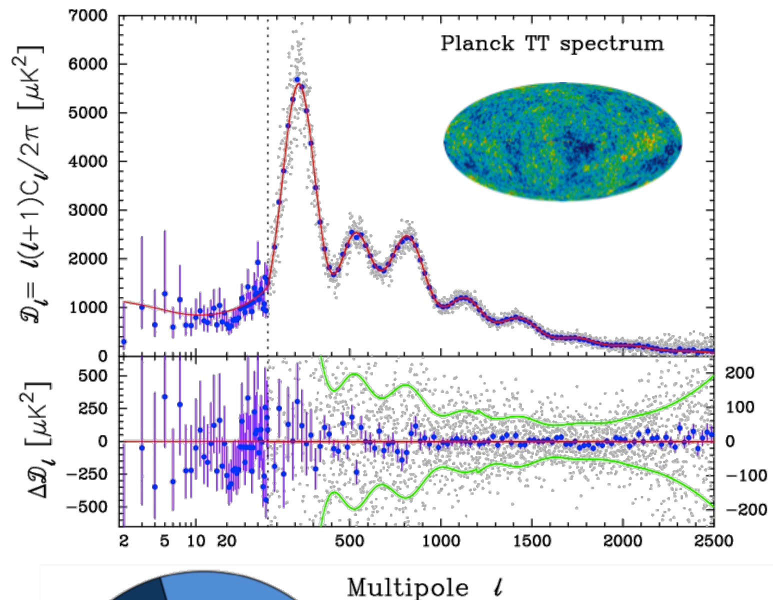
- Rotational velocity appears flat

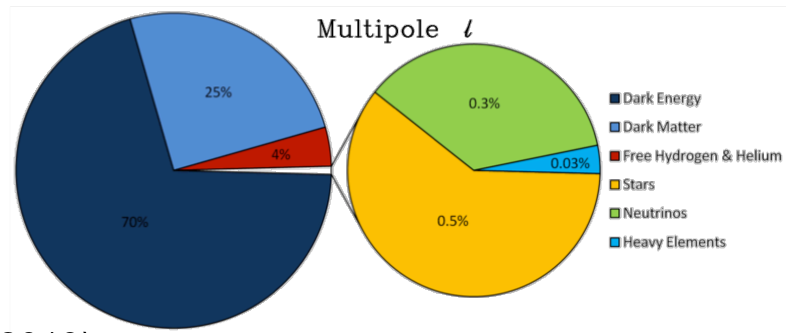


[1]T. S. van Albada et al., *Astrophysical Journal* **295** (1985) 305.

Modern Validations: CMB

- Precision cosmic microwave background temperature anisotropy measurements
- COBE, WMAP, Planck satellites
- Planck collaboration uses multi-parameter fit to extract dark energy, dark matter, etc. of universe[1]

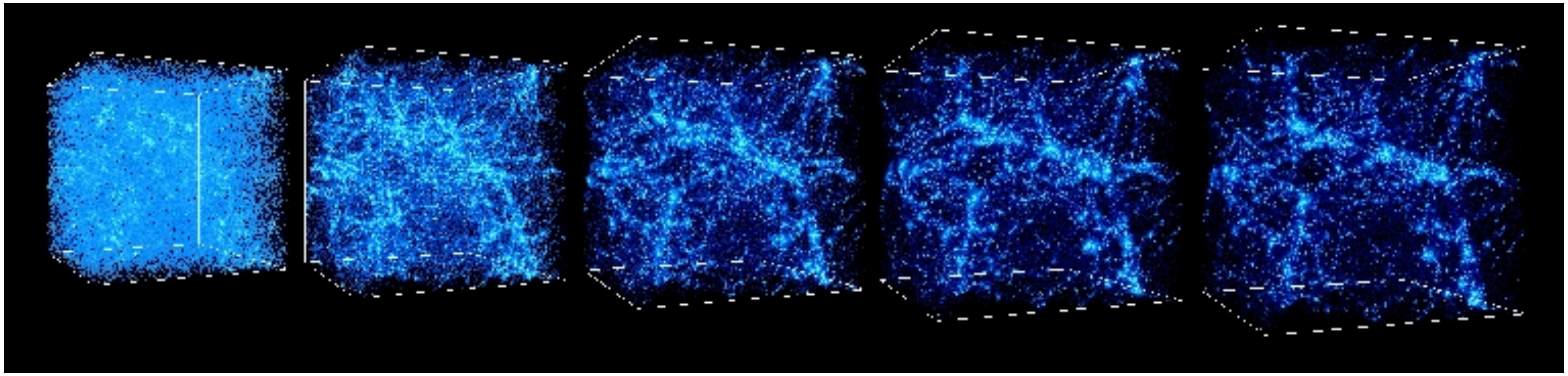




[1]Planck Collaboration: P. A. R. Ade et al., *A&A Preprint* (2013)

Modern Validations: Large Structure

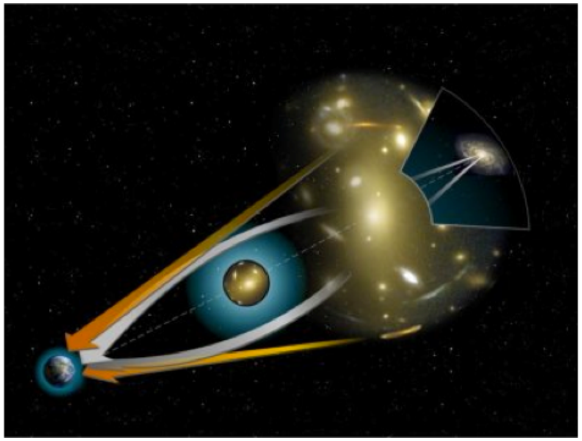
- Numerical *N*-body simulations require dark matter model[1]
- Bottom-up scenarios favored from vanilla cold dark matter models (in favor of top-down from hot dark matter)

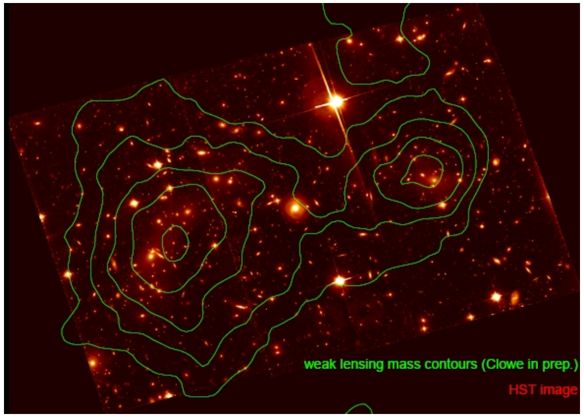


[1]http://cosmicweb.uchicago.edu/filaments.html

Modern Validations: Gravity Lensing

- Weak gravitational lensing can map mass distribution
- Chandra X-Ray observatory mapped Bullet Cluster
- Strong evidence for dark matter rather than modified gravitation

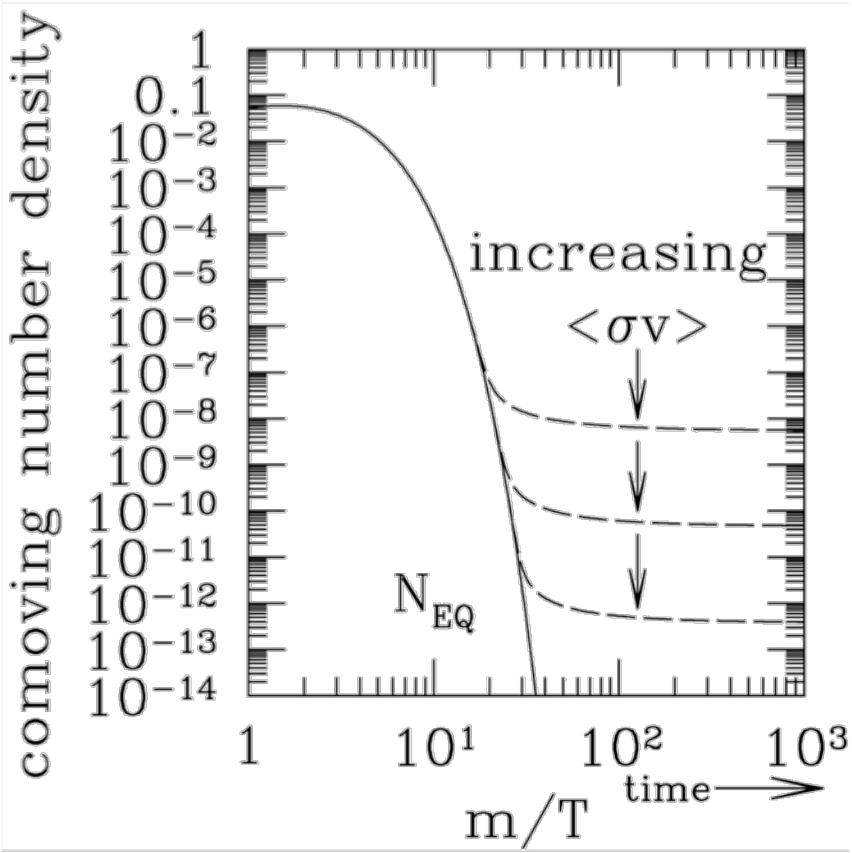




[1] Images from Wikipedia

What We Know About Dark Matter

- Annihilate with cross section <σ*v*> against Hubble expansion
- Freezes-out relic abundance
- Energy density today
  $\rho_{DM} = n_{DM} M_{DM} \approx 0.3$ GeV/cm^3
- Local galactic velocity
  $v \approx 220$ km/s ($\sim 10^{-3}c$)

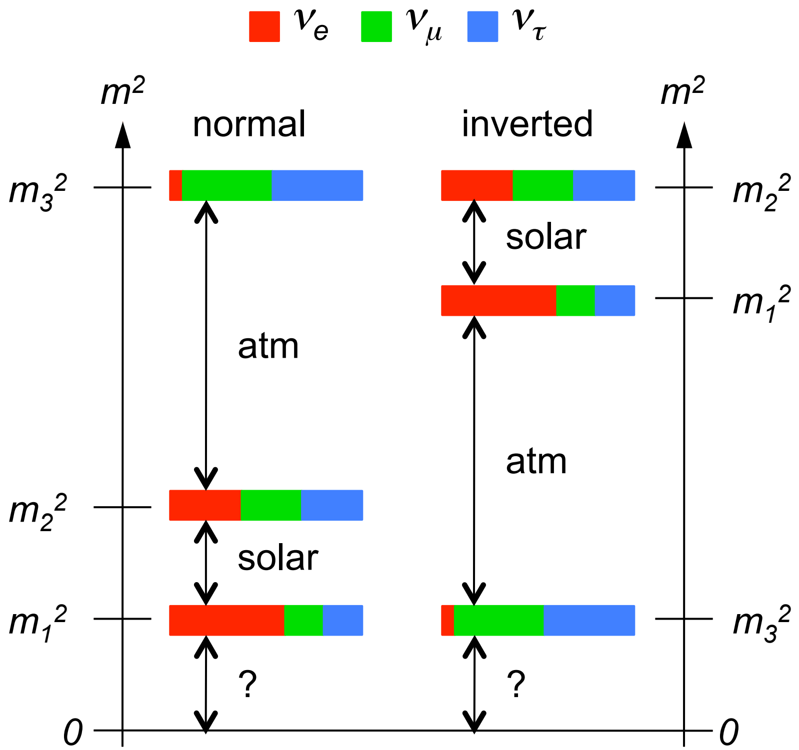


[1]Image from P. Gondolo, arXiv:astro-ph/0403064 [astro-ph]

Possible Models For Dark Matter?

Neutrinos

- They exist
- Not enough mass and relativistic → hot dark matter
- Prefers top-down structure
- Sterile neutrinos have other cosmological constraints → possible cold dark matter



[1]G. Bertone et al., *Phys. Rept.* **405** (2005) 279. arXiv:hep-ph/0404175 [hep-ph]

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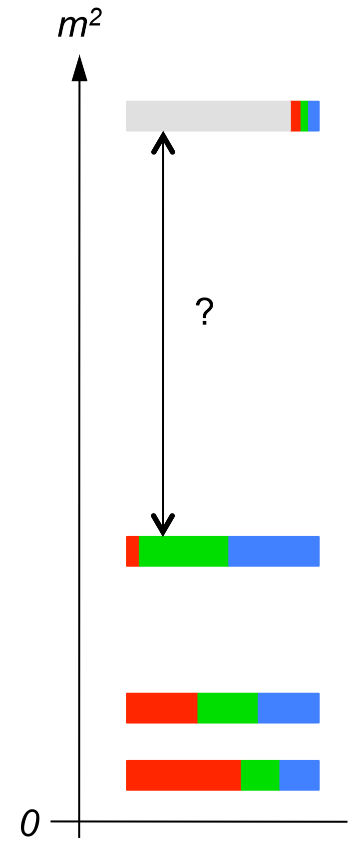
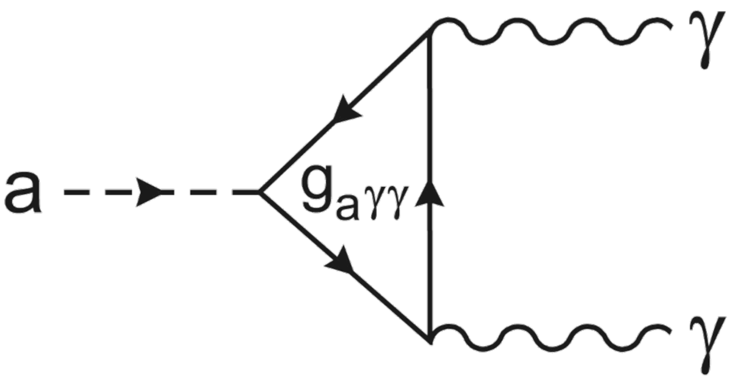


[1]G. Bertone et al., *Phys. Rept.* **405** (2005) 279. arXiv:hep-ph/0404175 [hep-ph]

Possible Models For Dark Matter?

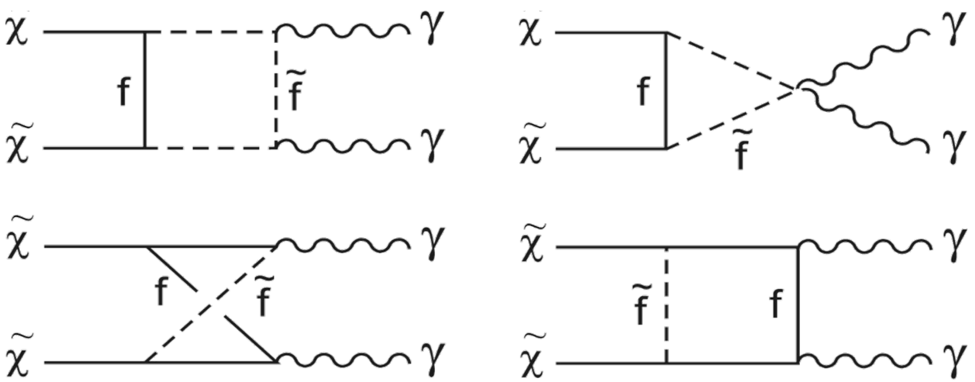
Axions

- Introduced to solve strong-CP problem, but have low mass < 0.01 eV



Supersymmetry Candidates

- Neutralino
- Sneutrino
- Axino…



Etc…

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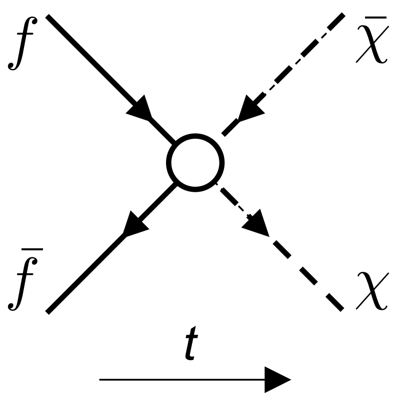
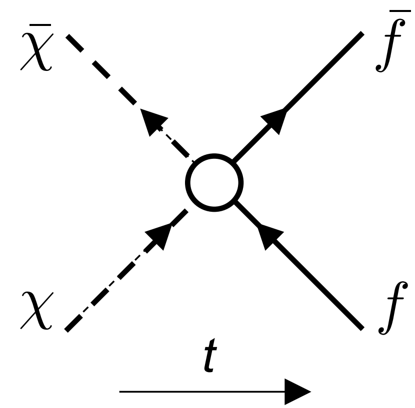
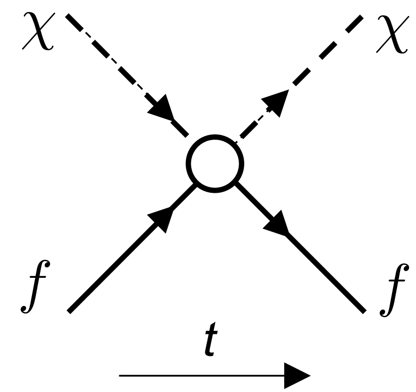
[1]G. Bertone et al., *Phys. Rept.* **405** (2005) 279. arXiv:hep-ph/0404175 [hep-ph]

How To Look For Dark Matter







Collider Production

- Can cover most of mass range
- Signal is lack of a signal (Missing E_T)

Annihilation

- Energetic particle / antiparticle signals
- Also gamma rays (e.g., 511 keV)

Scattering

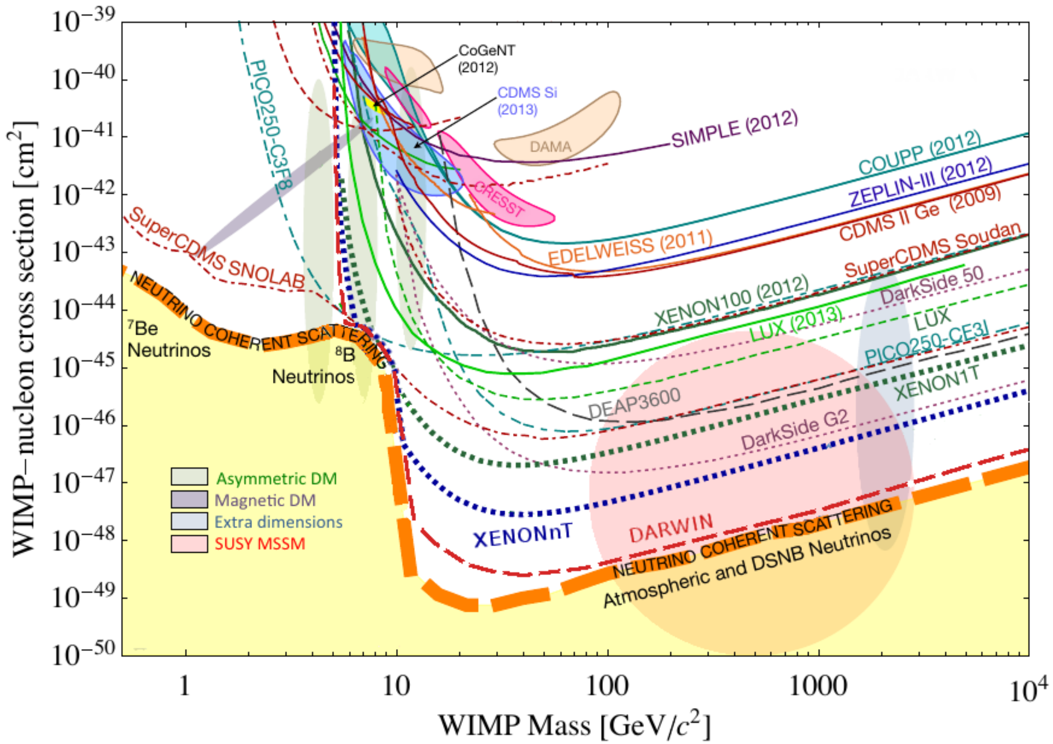
- Galactic halo DM scatters in detector
- Very low energy deposits

Where Are We With Direct Searches?

"WIMP Miracle"

- Electroweak scale masses (~100 GeV) and cross sections (10^{-38} cm^2) give correct relic abundances
- Conflicting claims, mostly ruled out phase space
- A rich dark sector easily bypasses "miracle"

Dark Matter Sensitivity

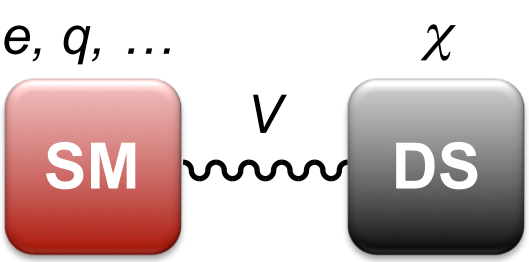


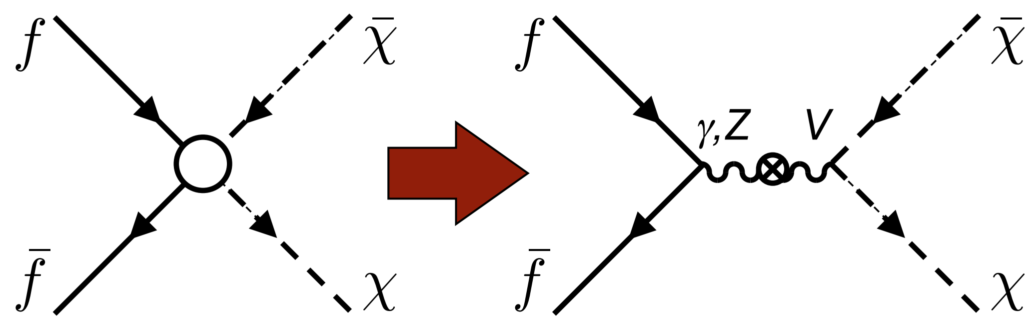
[1] G. L. Baudis, *Phys. Dark Univ.* **4** (2014) 50. arXiv:1408.4371 [astro-ph]

Why Not Sub-GeV Dark Matter?

- Lee-Weinberg bound: $M_\chi > O(1\ \text{GeV})$ presumes weak annihilation rate $\sim M_\chi^2 / M_Z^4$ which is too low

- New forces and force carriers → viable light thermal relic
  1. Mediate SM interactions to a dark sector
  2. Open up annihilation channels – circumventing L-W bound



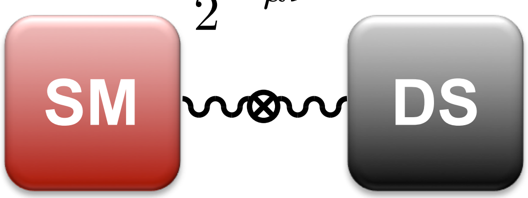


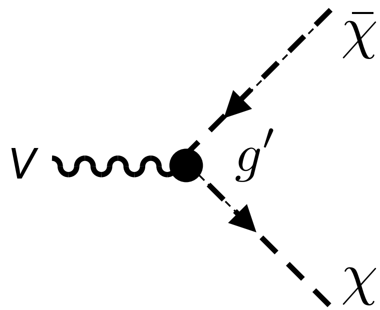
[1]C. Boehm & P. Fayet, *Nucl. Phys.* **B683** (2004) 219. arXiv:hep-ph/0305261 [hep-ph]

Minimal Vector Portal Model

- Postulated to solve excess 511 keV γs from central galaxy bulge → extends more familiar dark photon concept
- U(1) vector mediator kinematically mixed
- Requires 4 parameters: $m_\chi,\ m_V,\ \kappa,\ g'$

$$\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$$



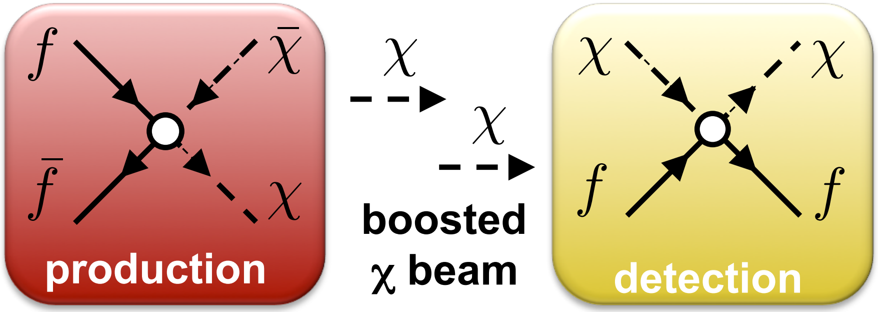


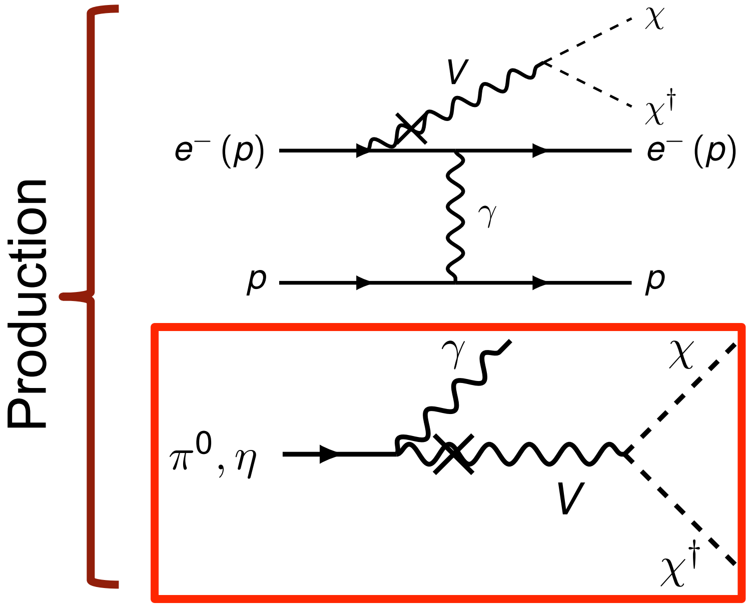
$$\alpha' = g'^2/4\pi$$

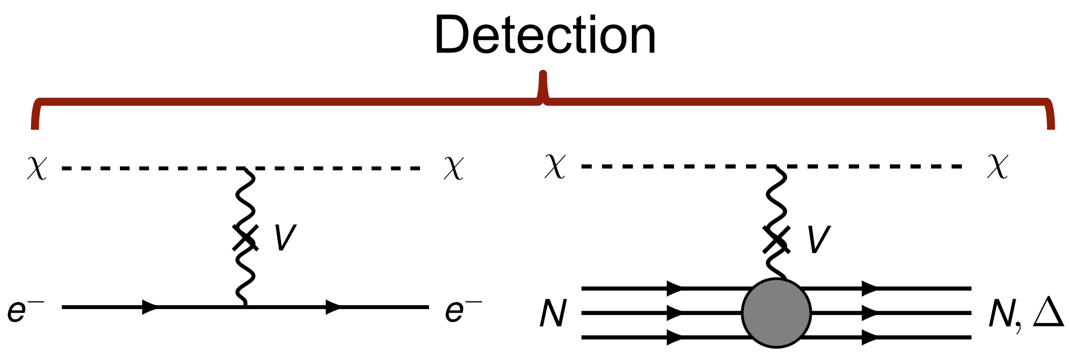
[1] C. Boehm & P. Fayet, *Nucl. Phys.* **B683** (2004) 219. arXiv:hep-ph/0305261 [hep-ph]
C. Boehm et al., *Phys. Rev. Lett.* **92** (2004) 101301. arXiv:astro-ph/0309686 [astro-ph]

Dark Matter Beam and Detector

- High-energy production and scattering detection





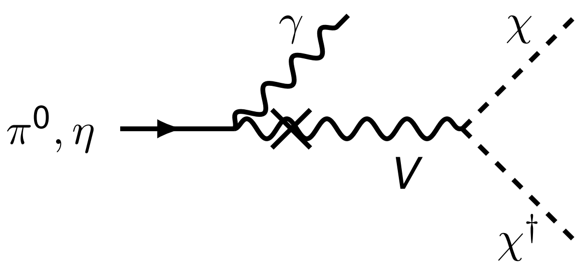


[1] B. Batell et al., *Phys. Rev. Lett.* **113** (2014) 171802. arXiv:1406.2698 [hep-ph].
P. deNiverville et al., *Phys. Rev.* **D84** (2011) 075020. arXiv:1107.4580 [hep-ph].

Our Primary Sensitivity

- To create a "beam" of dark matter traveling 500 m in dirt, require invisible decays

$$m_V > 2m_\chi$$



- Want final state of *V* decays to prefer pairs of χs

$$V \rightarrow \chi\chi^\dagger$$

- SM final state suppression

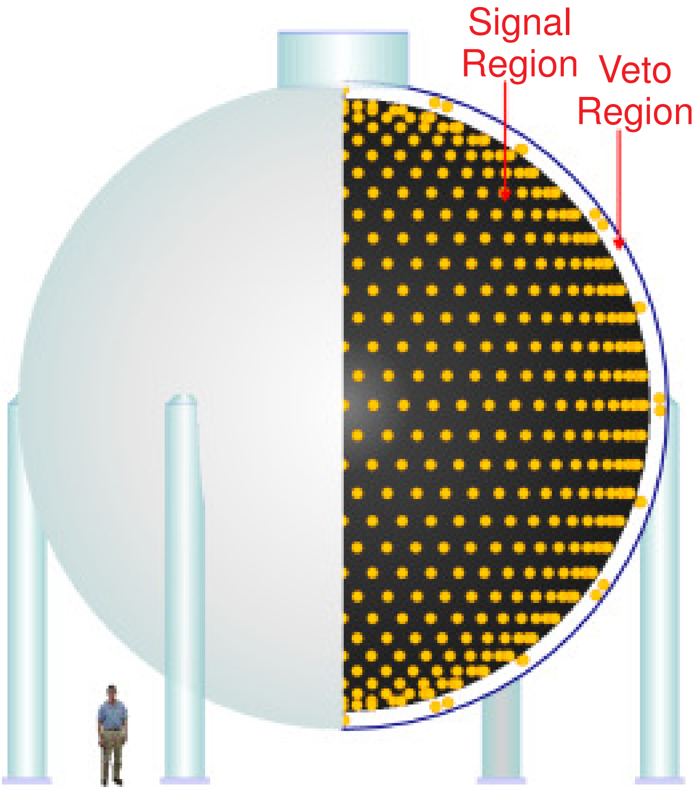
- Minimal vector portal model initially motivated run
- Not the only viable model (e.g. leptophobic dark matter)

[1]B. Battell et al., *Phys. Rev.* **D90** (2014) 115014. arXiv:1405.7049 [hep-ph].

MINIBOONE DETECTOR

The MiniBooNE Detector

- 12 m spherical detector with 800 tons pure mineral oil (CH_2)
- Cherenkov response with some scintillation from trace fluors
- Inner signal region 1280× 8” PMTs
  Outer veto region 240× 8” PMTs
  (10% photocathode coverage)
- **Detector is very well characterized**



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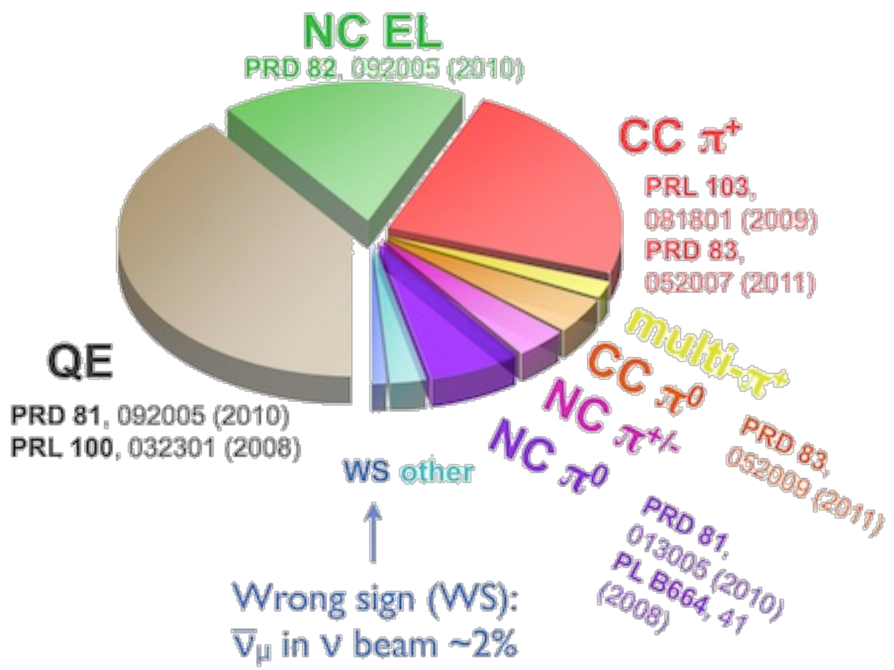
[1]A.A. Aguilar-Arevalo et al., *Nucl. Instrum. Meth.* **A599** (2009) 28. arXiv:0806.4201 [hep-ex].

The MiniBooNE Detector

- Run for over 10 years
- 11 oscillation papers
- 14 cross section and flux papers
- Relevant to this work

  NC elastic ν-mode (6.7×10^{20} POT)

  NC elastic $\bar{\nu}$-mode (11.5×10^{20} POT)
- 19 Ph.D. Theses



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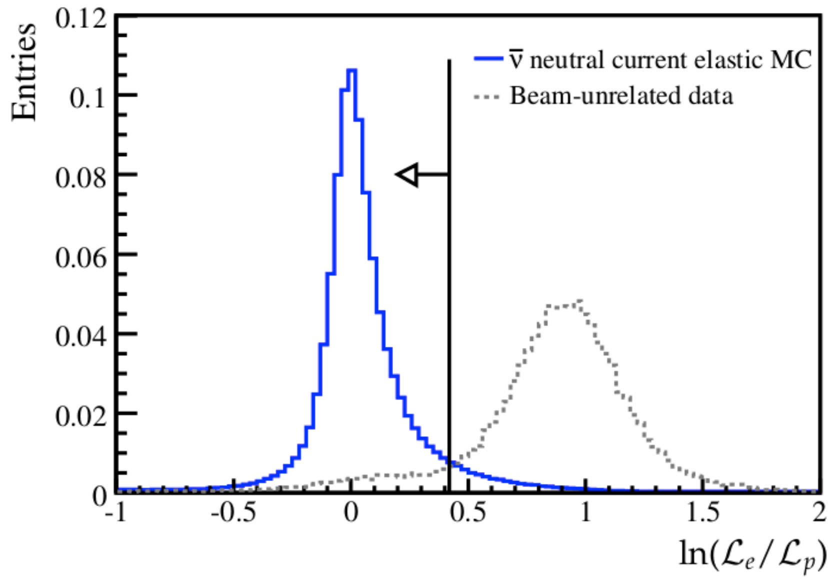
[1]See our website for a list of all publications. http://www-boone.fnal.gov/

Particle IDentification

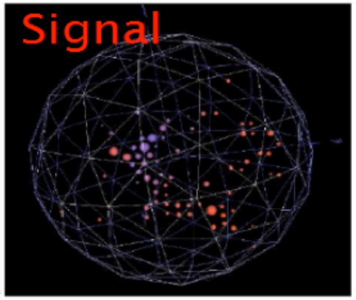
Nucleon PID

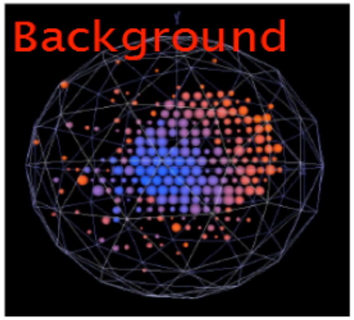
- Slow scintillation, very little Cherenkov
- Poorer energy resolution p - 20%, n – 30%

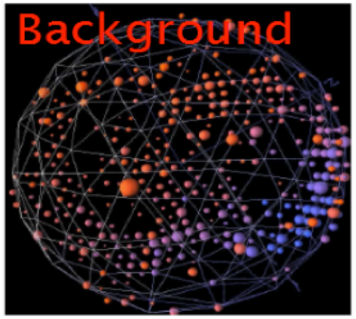


Electron PID

- Mostly Cherenkov but shape is important
- e/μ – fuzzy/sharp ring
- π^0 – 2 rings → degeneracy
- $e\chi$ collision forward peaked → another cut







Previous Beam Dump / Fixed Target Experiments – Proton Beams

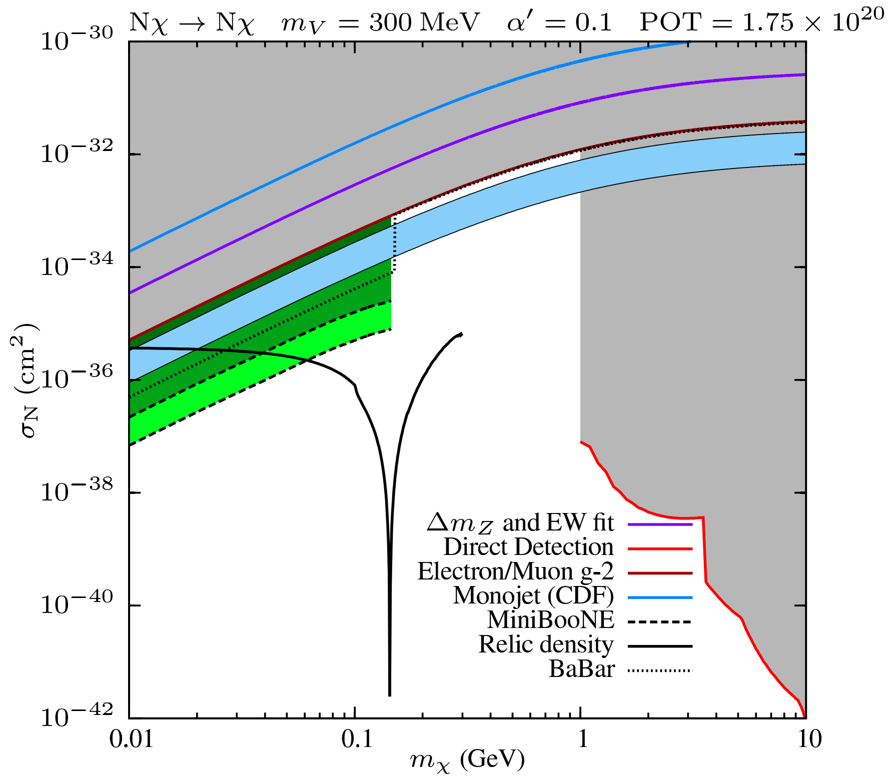
Experiment	Location	approx. Date	Amount of Beam (10^{20} POT)	Beam Energy (GeV)	Target Mat.	Ref.
CHARM	CERN	1983	0.024	400	Cu	[16]
PS191	CERN	1984	0.086	19.2	Be	[17, 18]
E605	Fermilab	1986	4×10^{-7}	800	Cu	[19]
SINDRUM	SIN,PSI					
ν-Cal I	IHEP Serpukhov	1989	0.0171	70	Fe	[20–22]
LSND	LANSCE	1994-1995 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]**

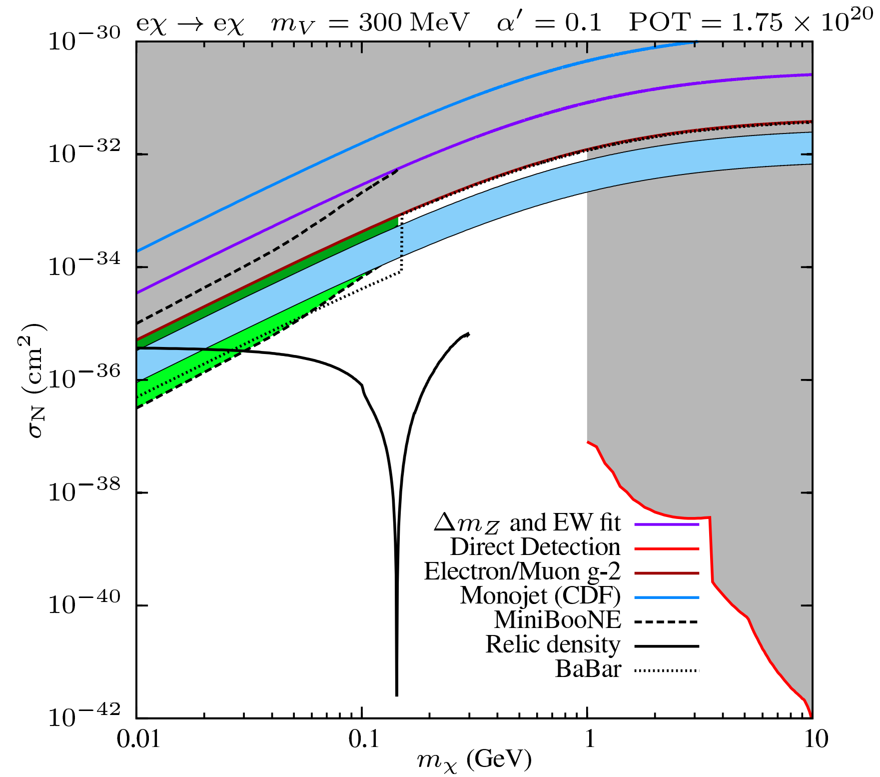
[1]Table by R.T. Thornton, Indiana University Nuclear Physics Seminar, Nov. 21, 2014

Dark Matter Exclusion Plots

Nucleon – DM | **Electron – DM**

1-10 events | 10-100 events | 100-1000 events

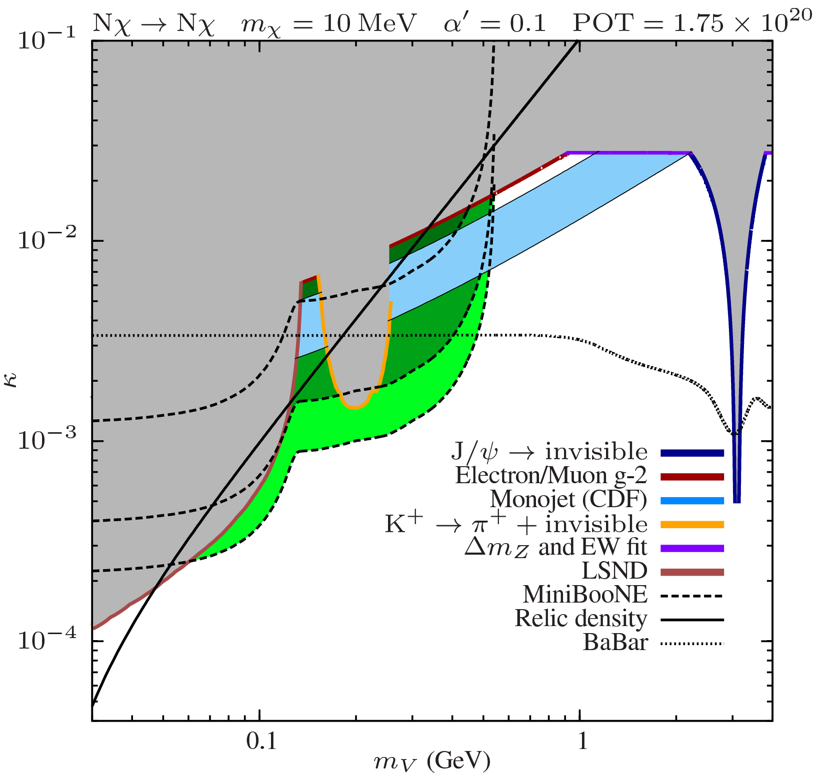


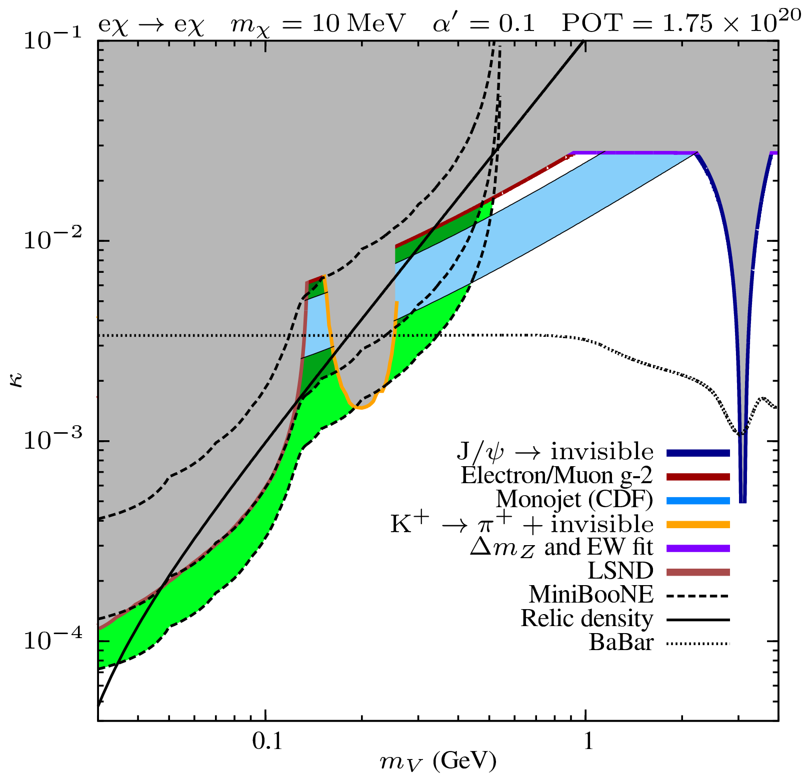


Vector Portal Exclusion Plots

Nucleon – DM | **Electron – DM**

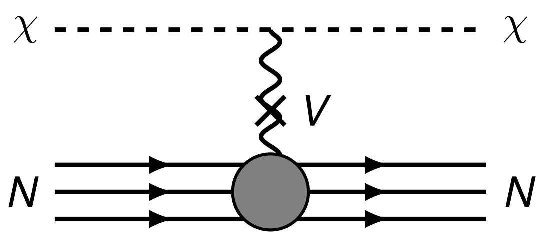
1-10 events | 10-100 events | 100-1000 events





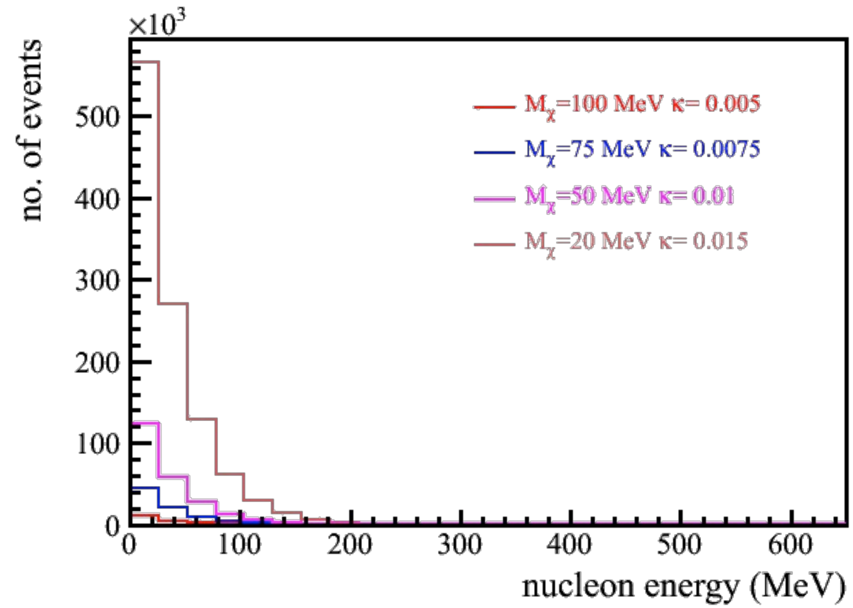
What Is Expected In MiniBooNE?

- Consider nucleon elastic scattering



- Same as ν NC elastic → **MUST SUPPRESS ν**

True Nucleon Recoil



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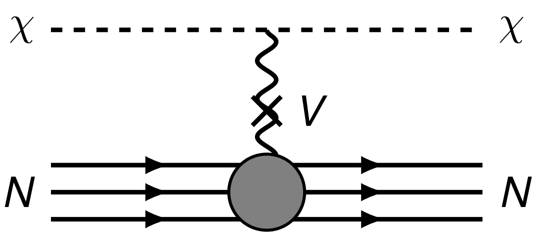

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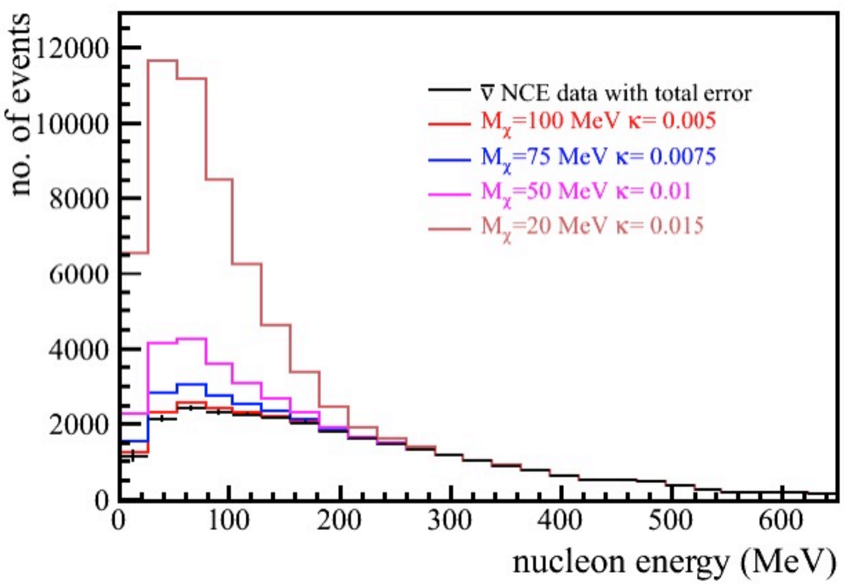
With Detector Efficiency



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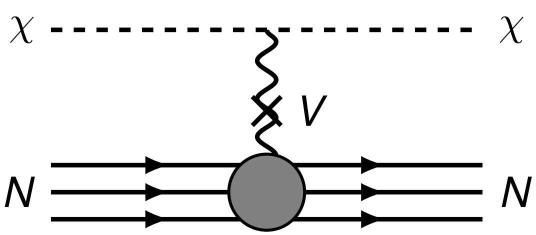

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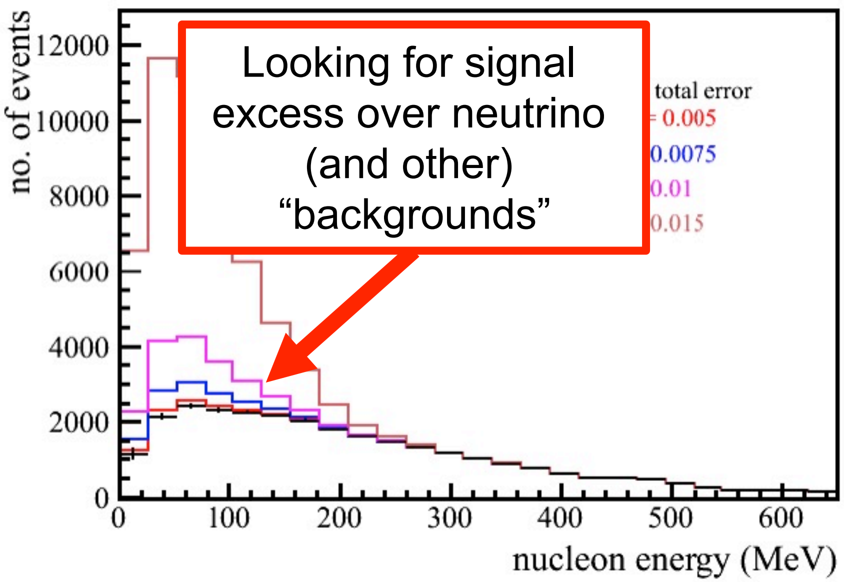

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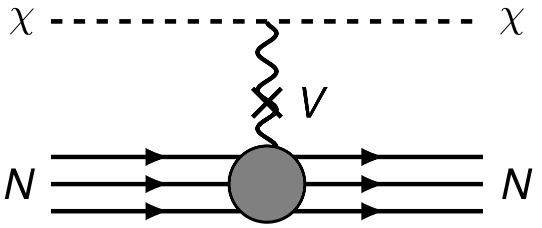

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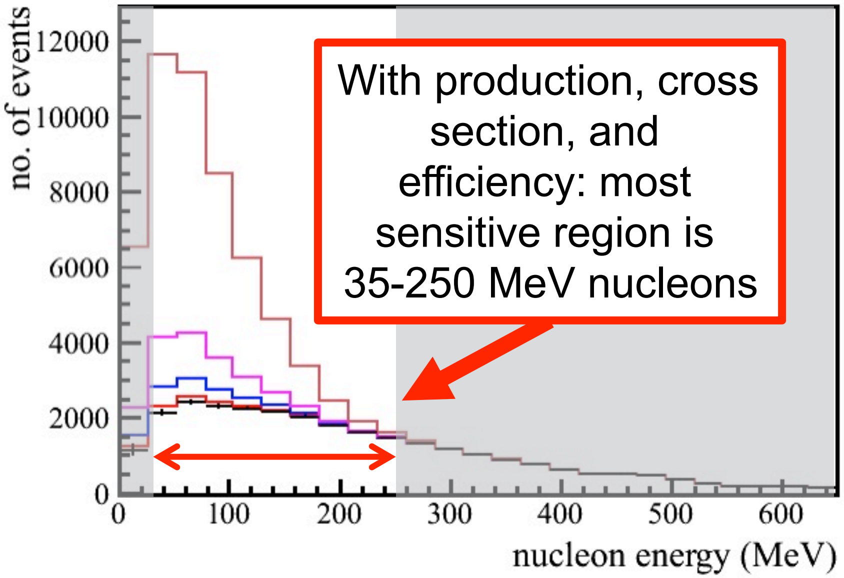

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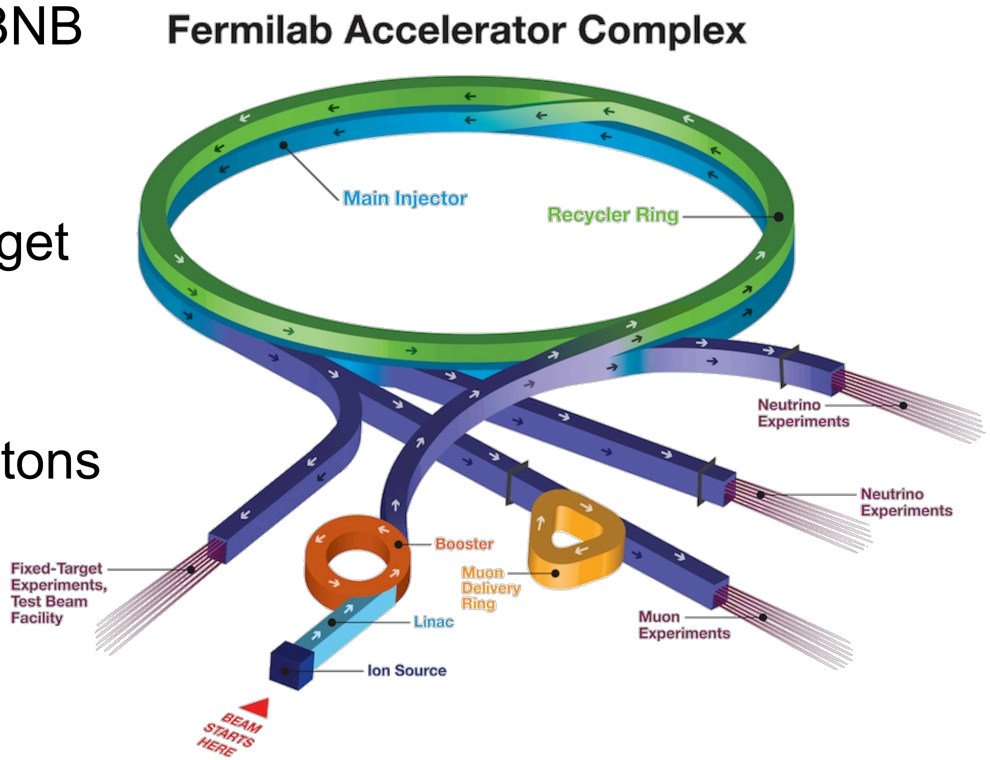
DARK MATTER FROM BNB

The Booster Neutrino Beamline (BNB)

- 8.9 GeV Booster protons to BNB endstation (or Main Injector)
- At BNB, protons strike Be target (1.8 radiation lengths)
- Typical operation: $2{\times}10^{20}$ protons on target (POT) per year



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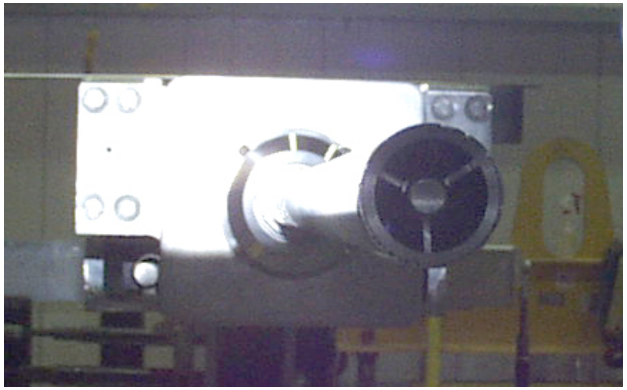
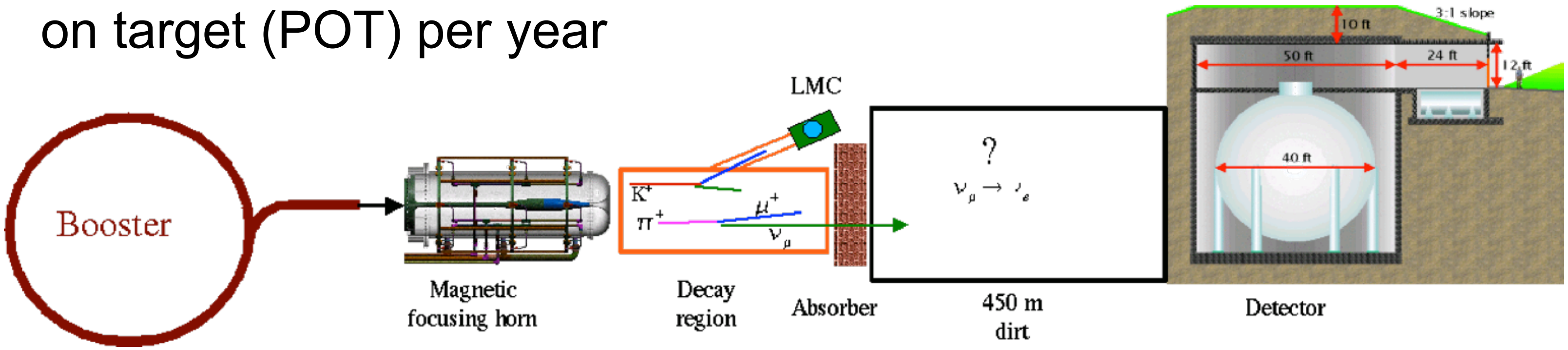
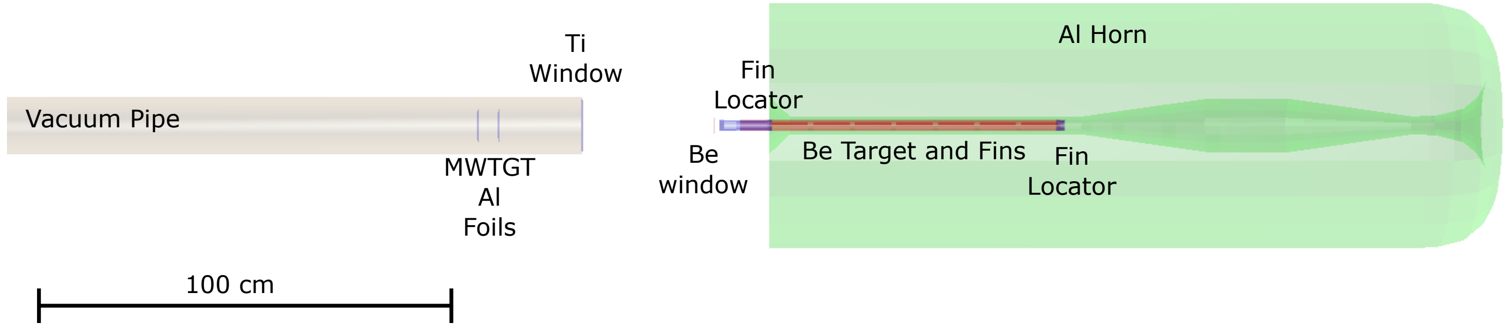




Accelerator Neutrino Production

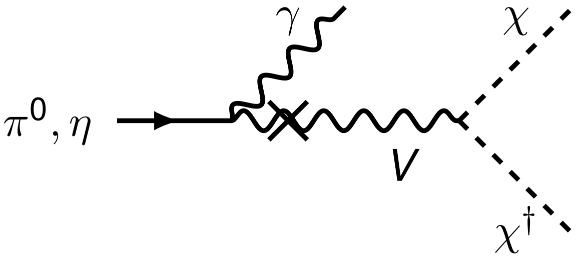


In MiniBooNE this works because pion production target is small

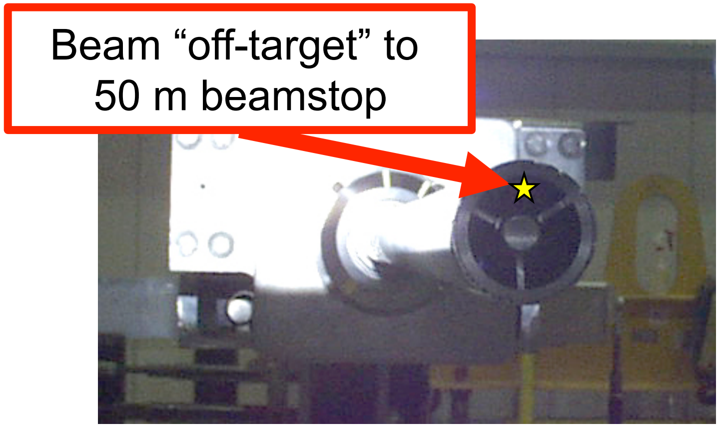
Pions escape and can decay in flight

How To Suppress ν and Produce χ

- ν_μ from π^+ → don't let "escape" into air, absorb them in material
- χ from π^0, η: short lifetimes ($\tau \sim 10^{-16}$ s) → decays before absorption in material

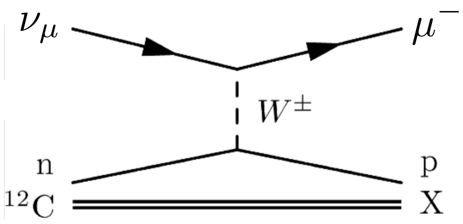


- Bypass Be target, hit steel beam stop
- π^0 production in Fe and Be similar



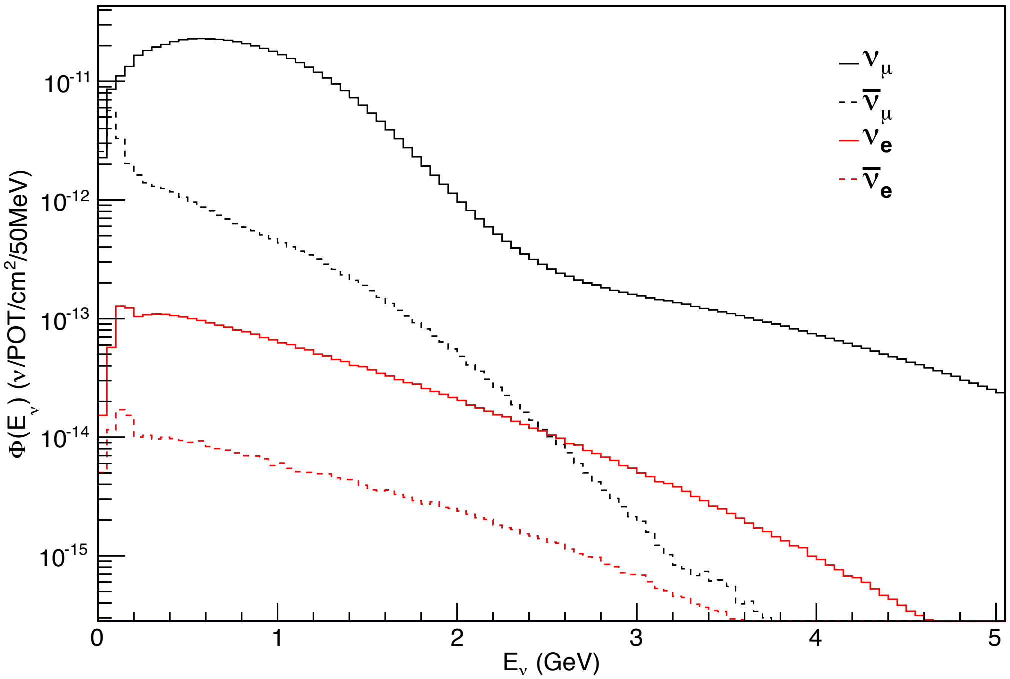
Off-Target vs. On-Target Monte Carlo

- Neutrino-mode horn-on for on-target MC
- flux-weighted MC suppression ~40 → CCQE data ~50



- Better beamline MC

On-Target Flux



[1]A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D79** (2009) 072002. arXiv:0806.1449 [hep-ex]

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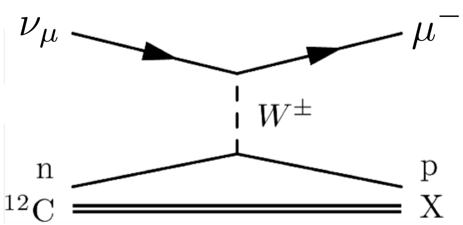

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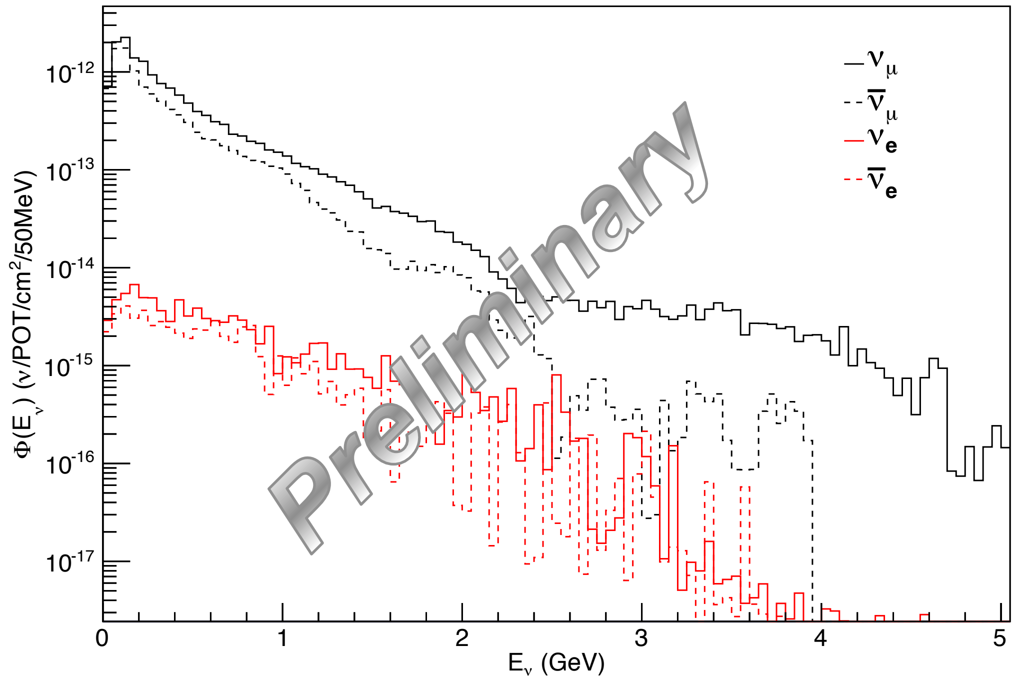

[1]A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D79** (2009) 072002. arXiv:0806.1449 [hep-ex]

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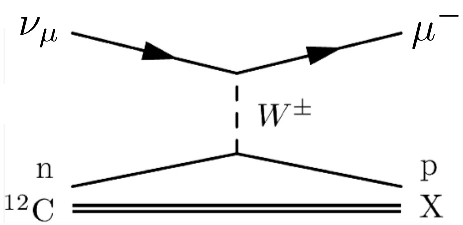
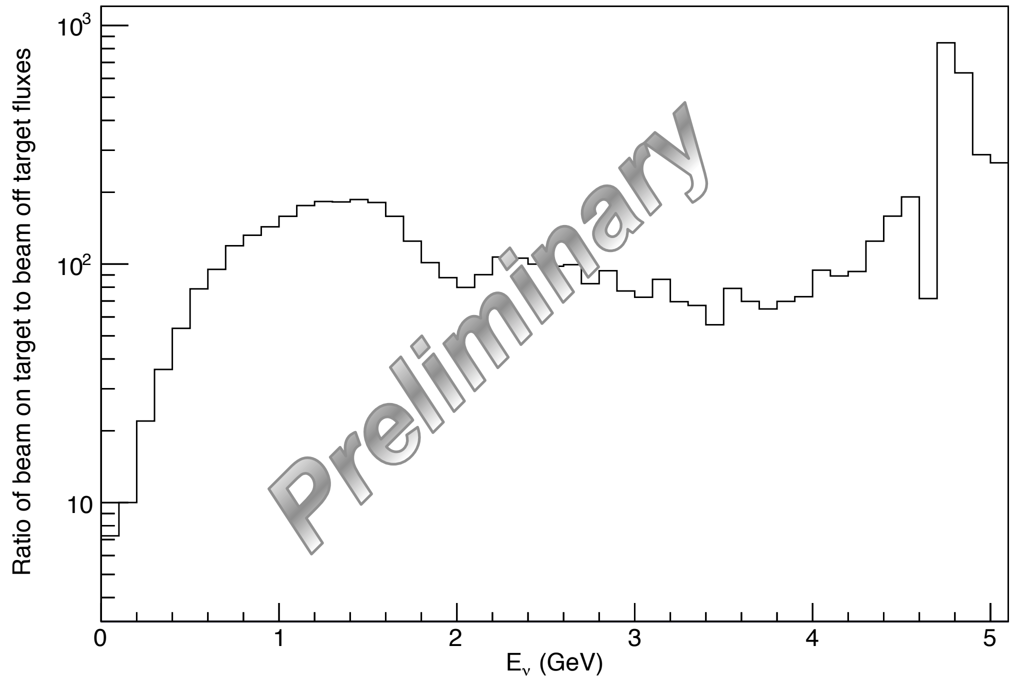


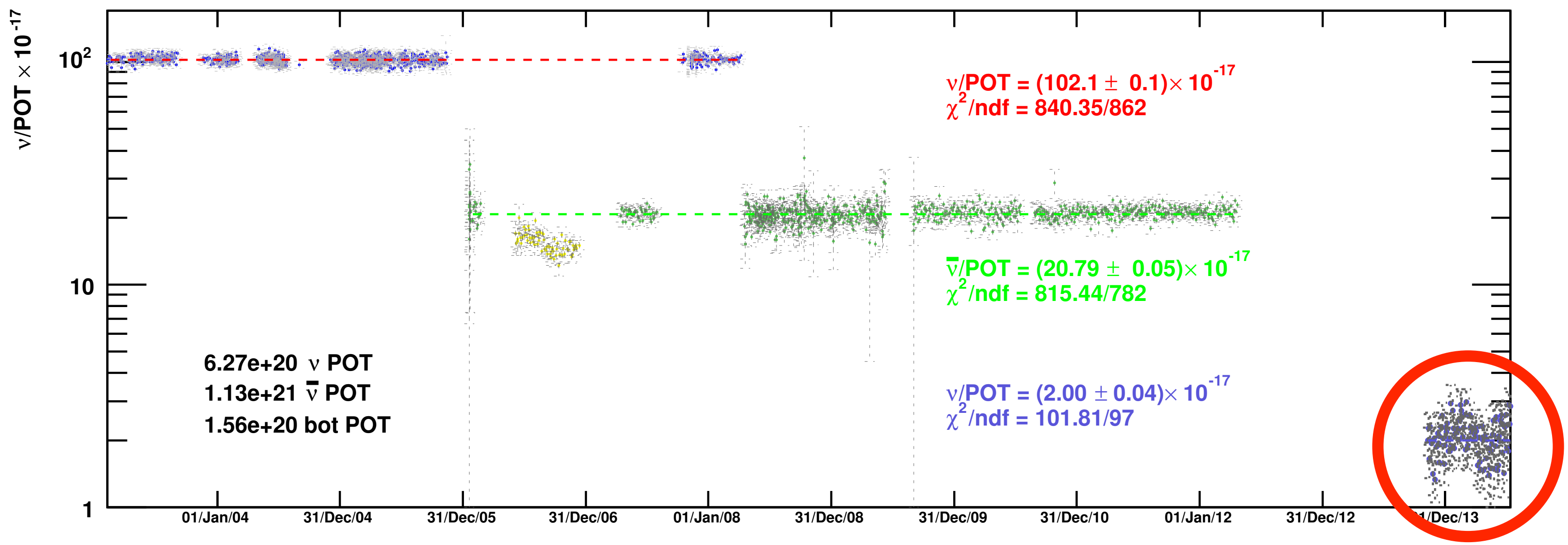
- Better beamline MC

On- to Off- Ratio



[1] A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D79** (2009) 072002. arXiv:0806.1449 [hep-ex]

MiniBooNE Neutrino Suppression



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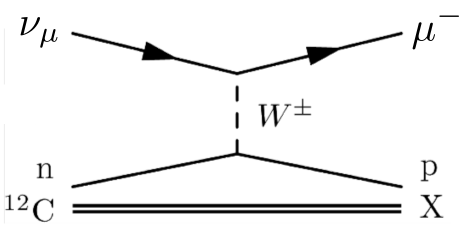
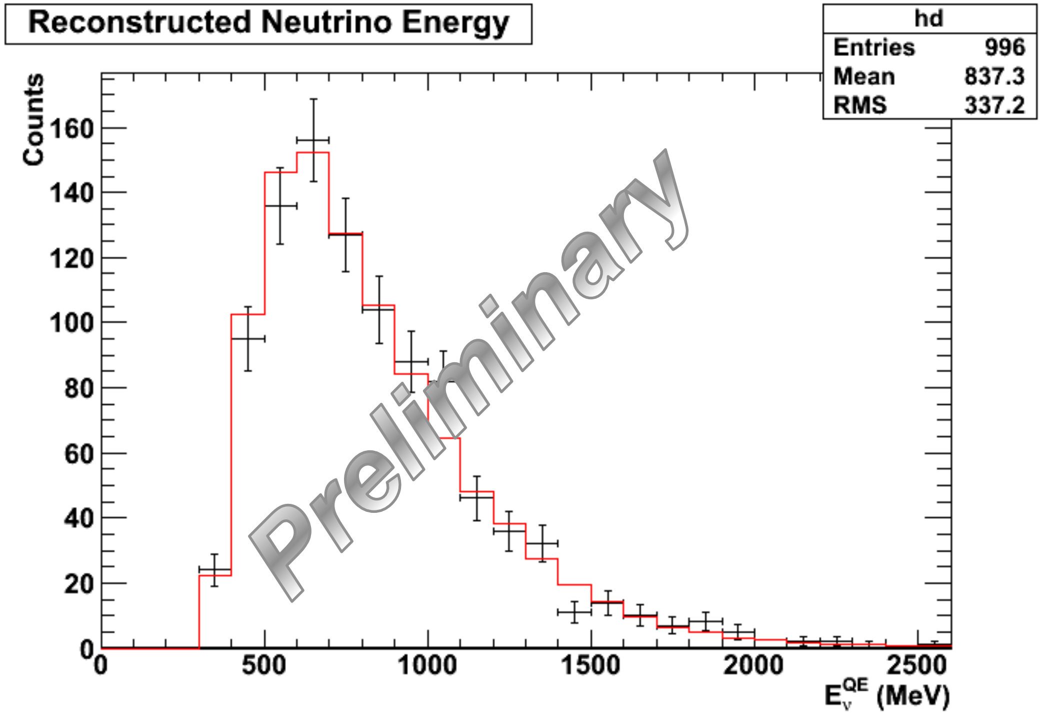


- Better beamline MC

CCQE E_ν reconstructed



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[1]A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D79** (2009) 072002. arXiv:0806.1449 [hep-ex]

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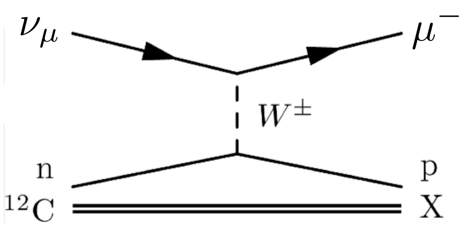
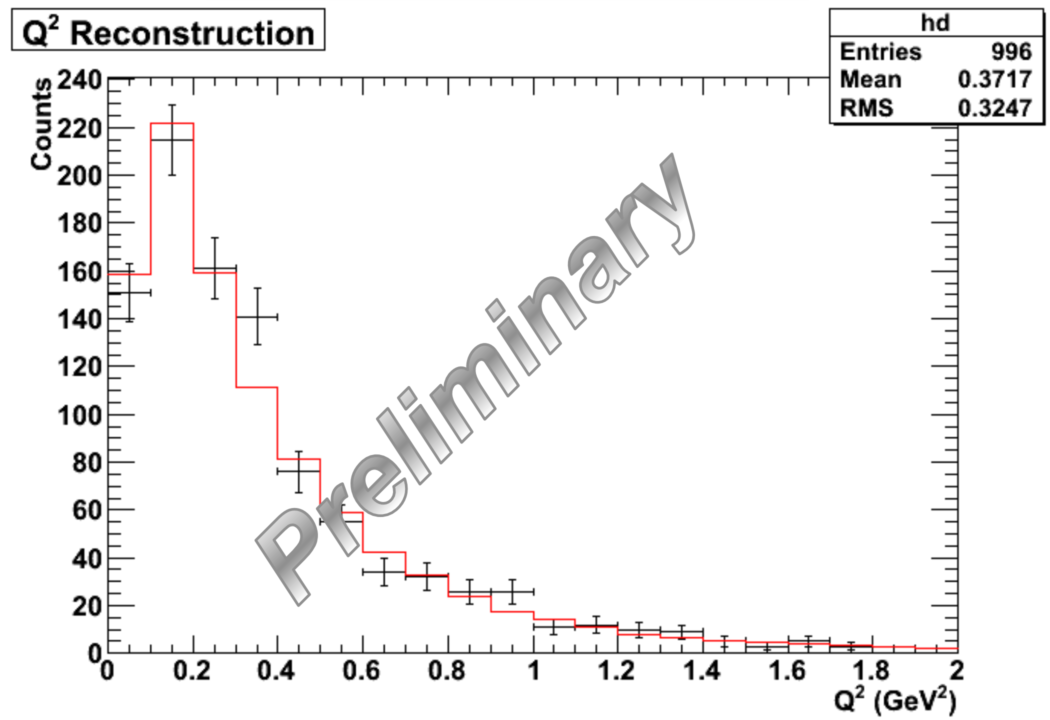


- Better beamline MC

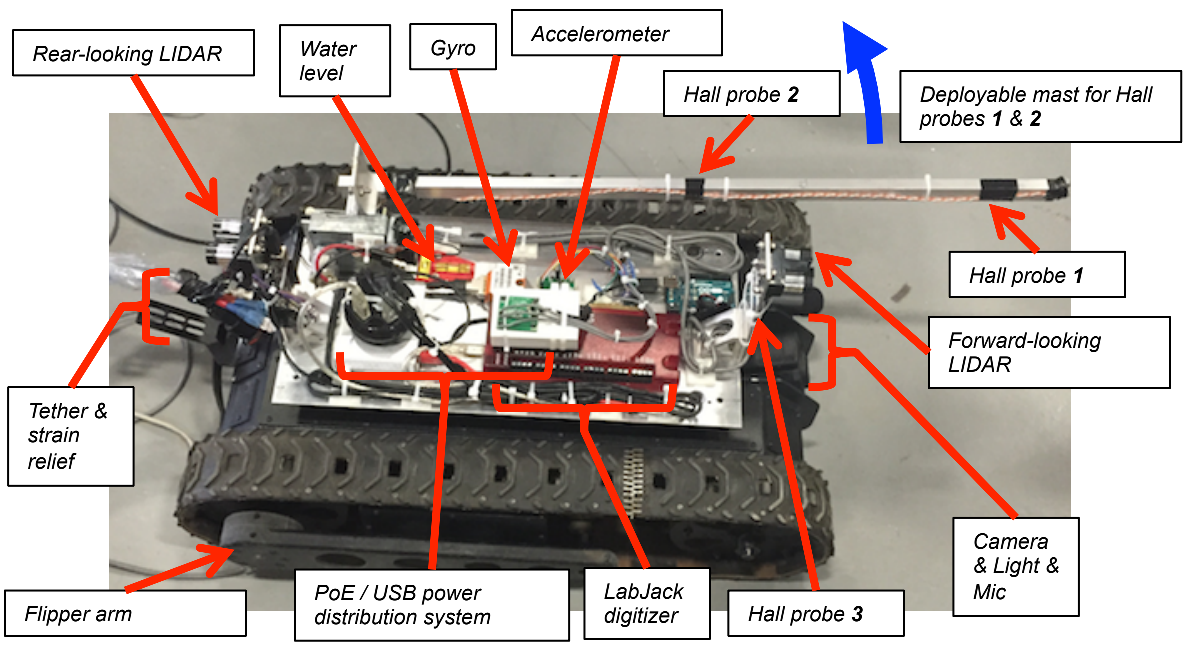
CCQE Q² reconstructed

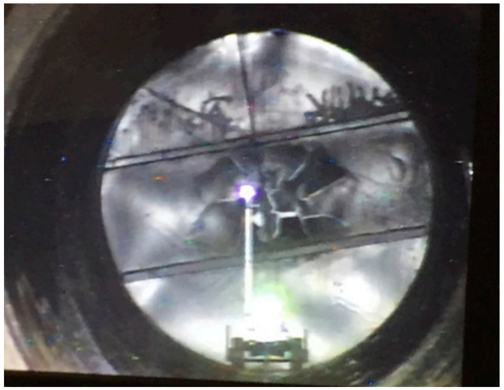


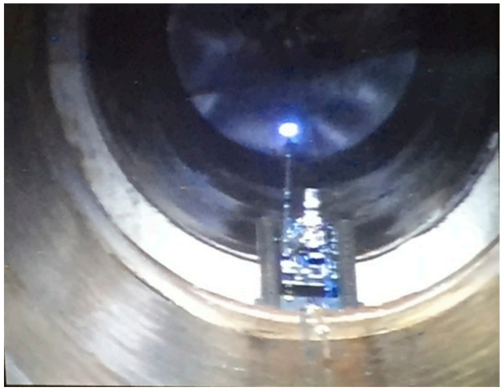
[1]A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D79** (2009) 072002. arXiv:0806.1449 [hep-ex]

Beampipe Survey with FRED

- **FRED**: **F**inding **R**adiation **E**vidence in the **D**ecay pipe
- Visual and magnetic field survey
  → no anomalies



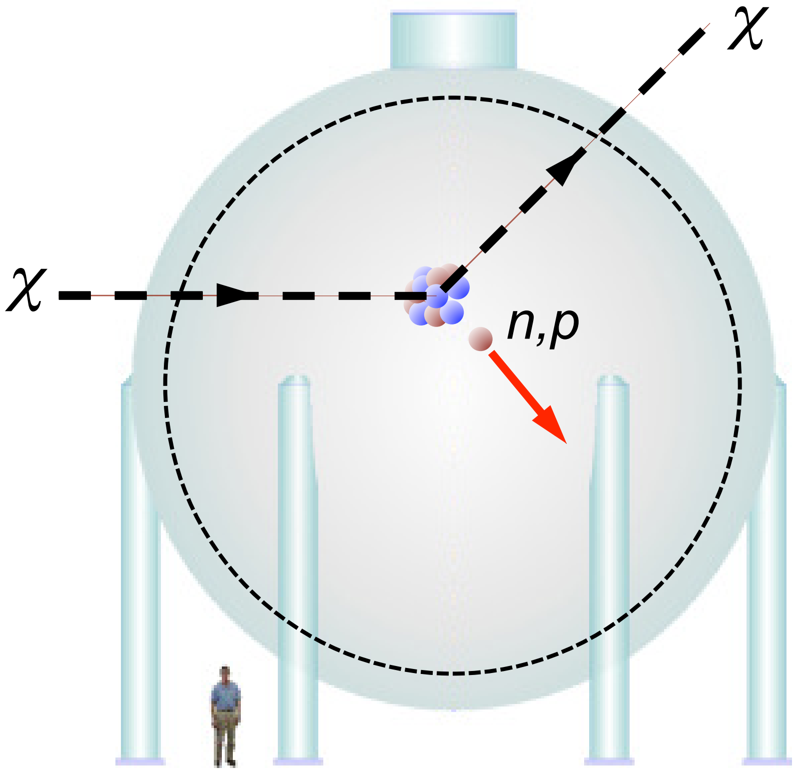




DATA ANALYSIS

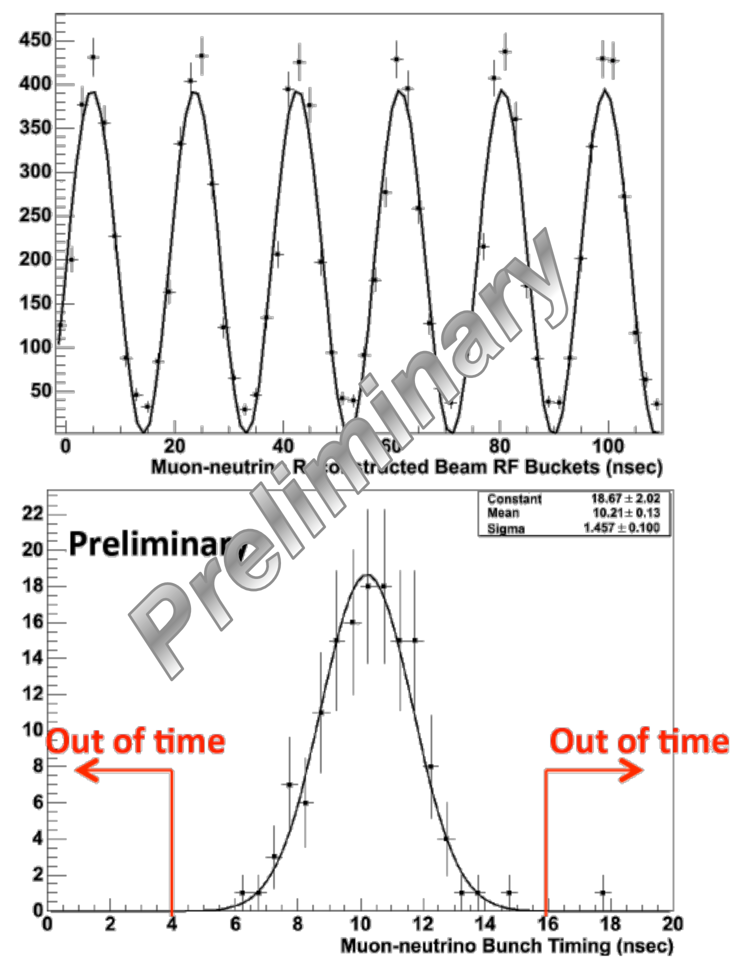
Event Selection Cuts

- 1 Track (single recoil) in beam timing window
- Event is centralized contained
  - No activity in veto
  - Fiducialized inner tank
- Signal above hits and visible energy threshold
- PID: Nucleon or electron



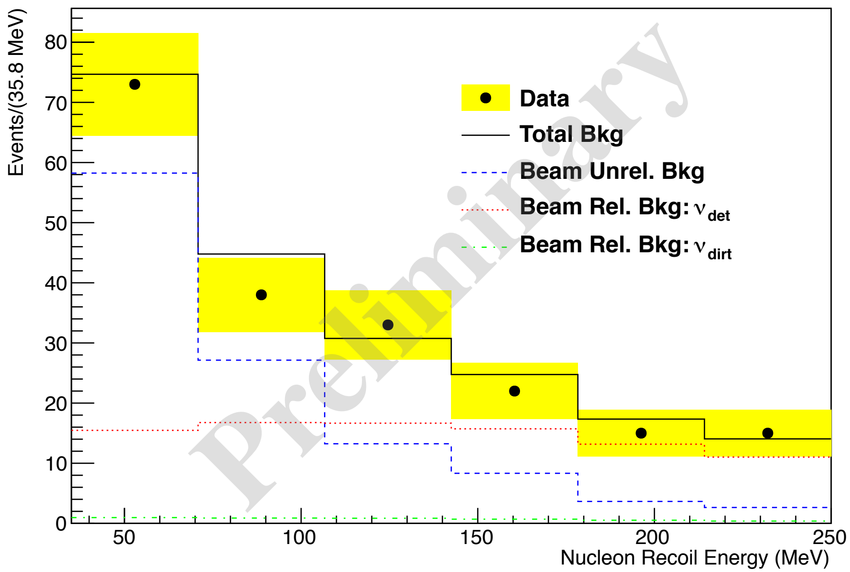
Dark Matter Propagation Time

- χ is massive so travels the 500 m slower than *c* ($m\chi$ = 120 MeV, *E* = 1.5 GeV → 6 ns delay)
- Beam – 81 RF bunches
- Can correlate events to a particular bunch
  - δt ~ 1.5 ns Cherenkov (eχ)
  - δt ~ 4.2 ns Scintillation (Nχ)
- Provides more sensitivity to dark matter parameter space



Preliminary Results (3.19×10^{19} POT)

- Total 1.86×10^{20} POT in 10 month run
- Semi-blind: open analysis of 17% of data
- Beam unrelated biggest contribution (measured in strobe)
- Anticipate ~10% systematic uncertainty



	# events	error	projected error
ν_{dirt}	4.31		
ν_{det}	88.8		
N_{BUB}	113.24		
Total Bkg	206.35	15%(sys.)	10%(sys.)
Data	196	7.1%(stat.)	3.0%(stat.)

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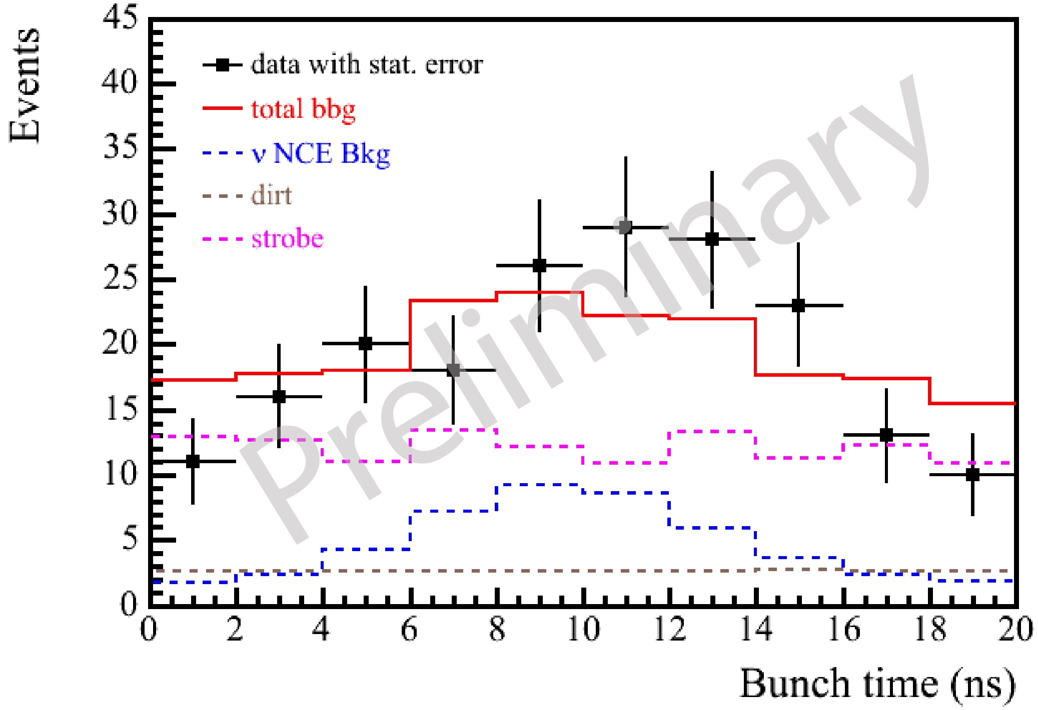

UPCOMING WORK AND CONCLUSIONS

Conclusions

- MiniBooNE has collected 1.86×10^{20} POT in beam-off-target configuration to search for sub-GeV dark matter
- Beam-off-target suppresses neutrino backgrounds
→ beam uncorrelated backgrounds dominant
- First of its kind, proton beam dump to a large neutrino detector → an extremely well characterized detector!
- N-DM analysis will be completed soon → e-DM and inelastic π^0 channels are underway

Thank You!

A Proposal to Search for Dark Matter with MiniBooNE

Submitted to the FNAL PAC Dec 16, 2013

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[1]A.A. Aguilar-Arevalo et al. arXiv:1211.2258 [hep-ex]

BACKUPS

Previous Beam Dump / Fixed Target Experiments – Electron Beams

Experiment	Location	approx. Date	Amount of Beam (10^{20} EOT)	Beam Energy (GeV)	Target Mat.	Ref.
E137	SLAC	1980-1982	1.87	20	Al	[6, 8, 9]
E141	SLAC	1986	2×10^{-5}	9	W	[8, 10]
KEK-PF	KEK	1986	1.67×10^{-3}	2.5	Fe,PB,Plastic	[11]
LAL 86/25	Orsay	1986	$\sim 9.6 \times 10^{-5}$	1.5	W	[12]
E774	Fermilab	1991	0.52×10^{-10}	275	W	[8, 13]
A1	MAMI	2011	90 µA*t	0.855	Ta	[14]
APEX	JLAB	2011	150 µA*t	2.260	Ta	[15]

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

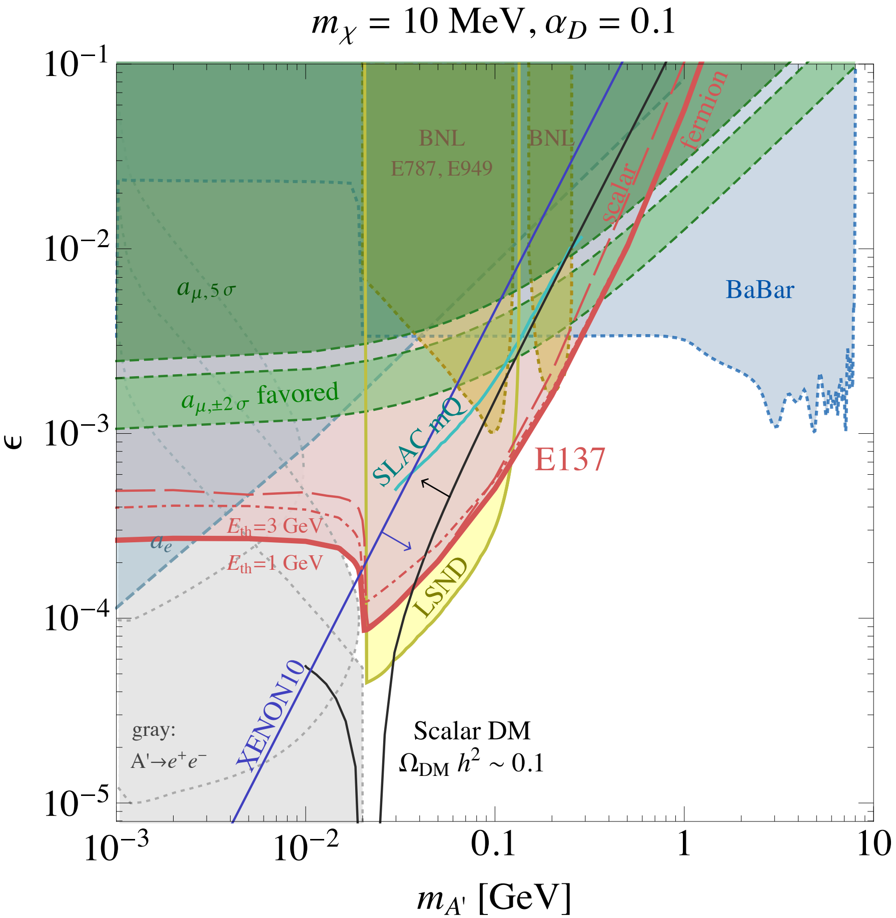
Current Limits

Invisible

- $m_V > 2m_\chi$
- Final state V decays prefer to go to pairs of χs

$$V \rightarrow \chi\chi^\dagger$$

- SM final states suppressed
- We need these for χ beams



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

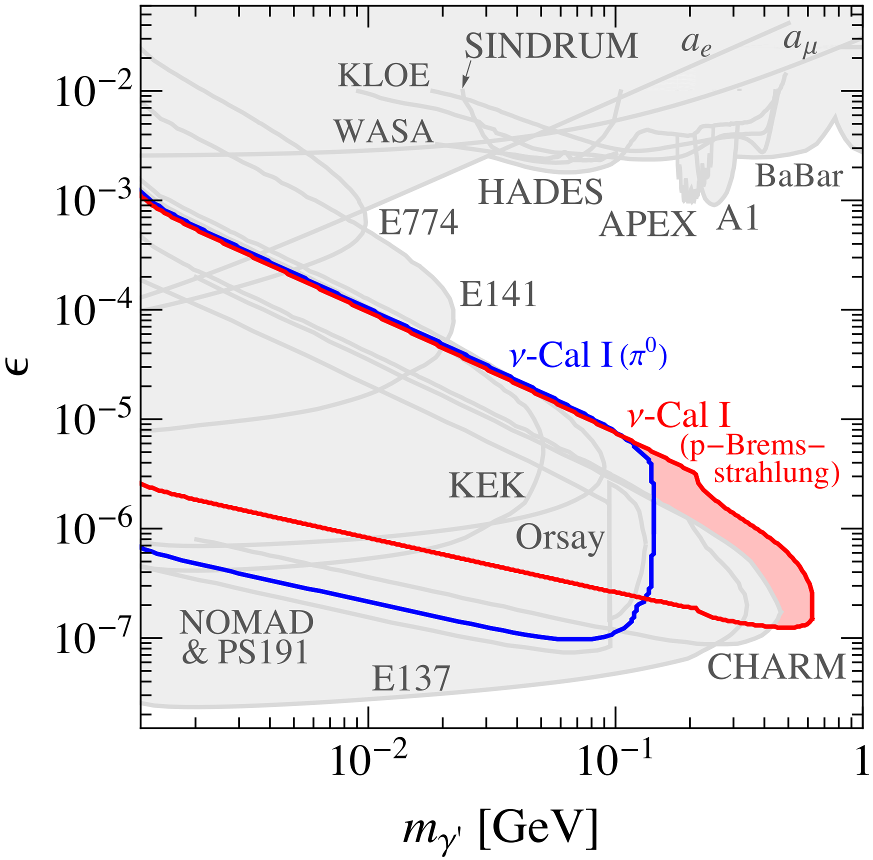
Current Limits

Visible

- $m_V < 2m_\chi$
- Final state *V* decays are visible SM model particles, e.g.,

$$V \rightarrow \ell^- \ell^+ \rightarrow \gamma\gamma$$

- Can't produce a pair of χs



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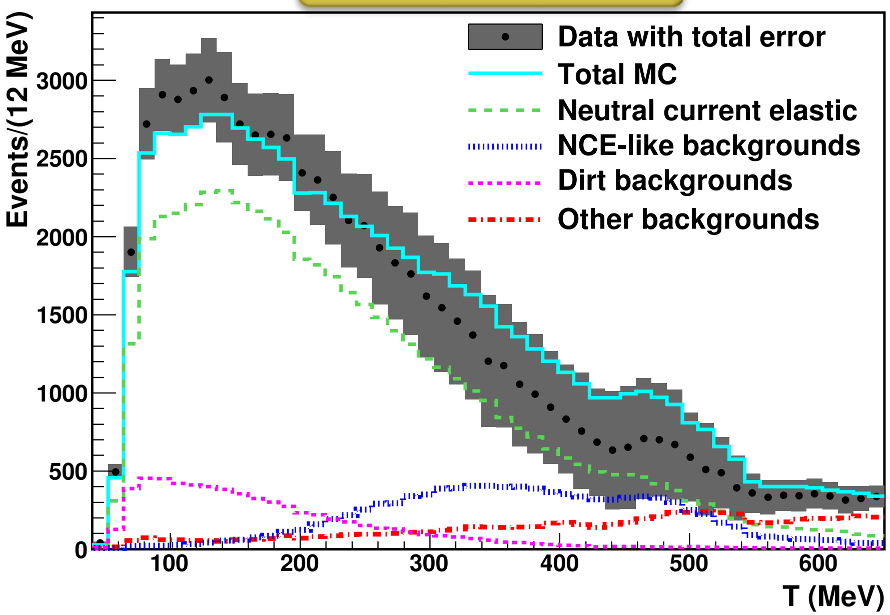
[1] J. Blümlein & J. Brunner, *Phys. Lett.* **B4** (2014) 320. arXiv:1311.3870 [hep-ph].

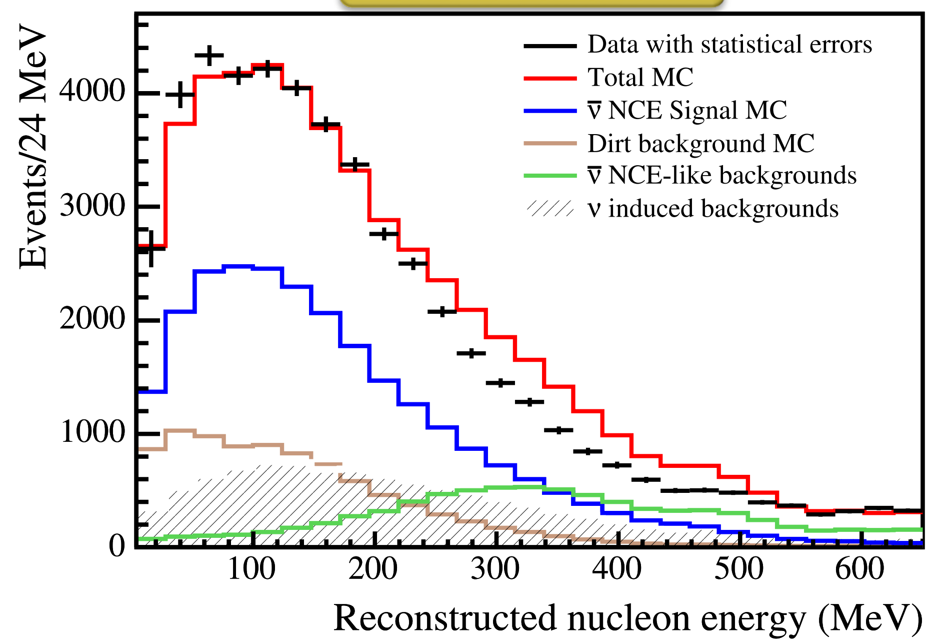
Energy Spectrum Reconstruction

- Previous neutrino running important for spectrum reconstruction

ν NC elastic



ν̅ NC elastic

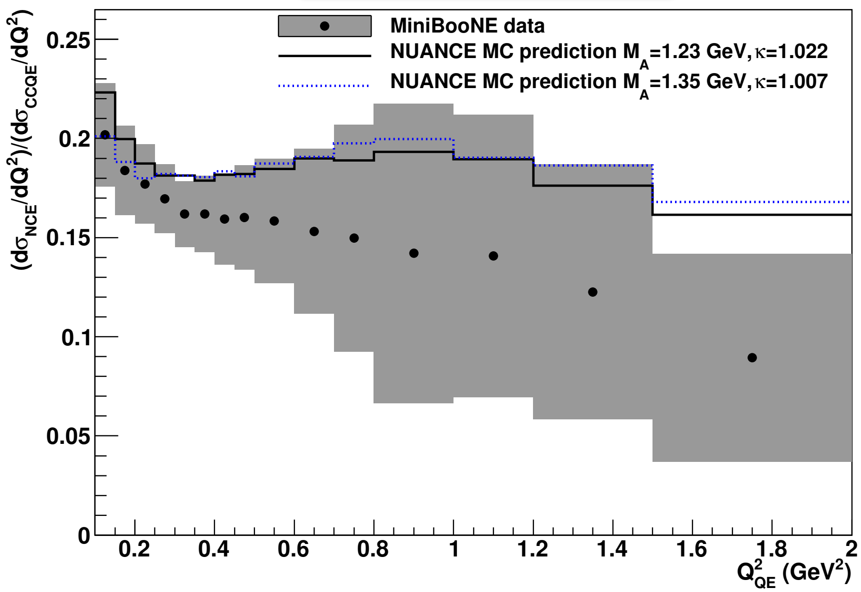


[1] A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D82** (2010) 092005. arXiv:1007.4730 [hep-ex].
A.A. Aguilar-Arevalo et al., *Phys. Rev.* **DXX** (2015) XXXXX. arXiv:1309.7257[hep-ex].

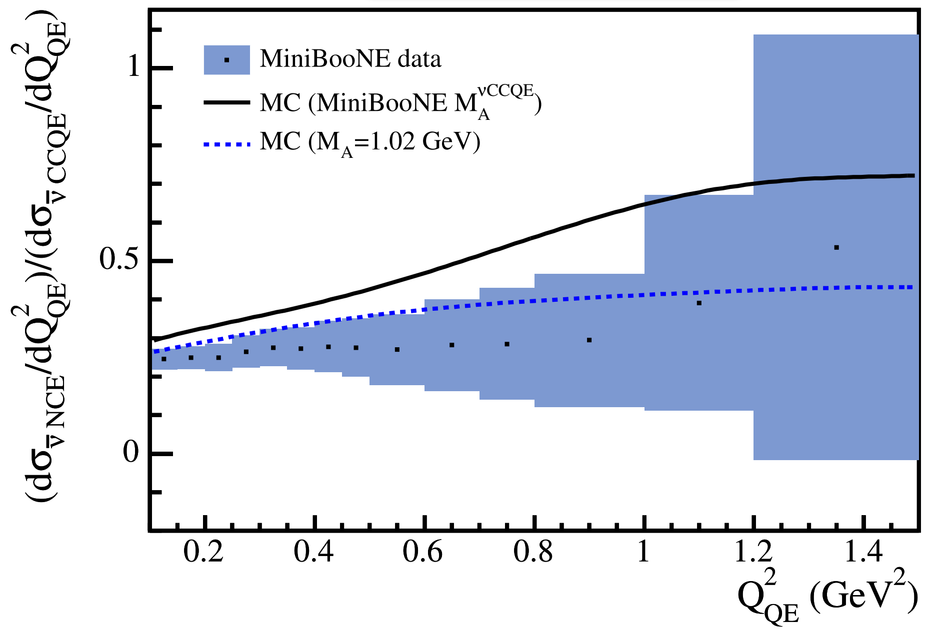
Energy Spectrum Reconstruction

- CCQE is a "standard candle" to fix new cross sections against

ν NC elastic



ν̄ NC elastic



[1]A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D82** (2010) 092005. arXiv:1007.4730 [hep-ex].
A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D91** (2015) 012004. arXiv:1309.7257[hep-ex].