New Mexico State University
All About Discovery!
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Current and Future Results from MiniBooNE-DM (arXiv:1702.02688 [hep-ex])

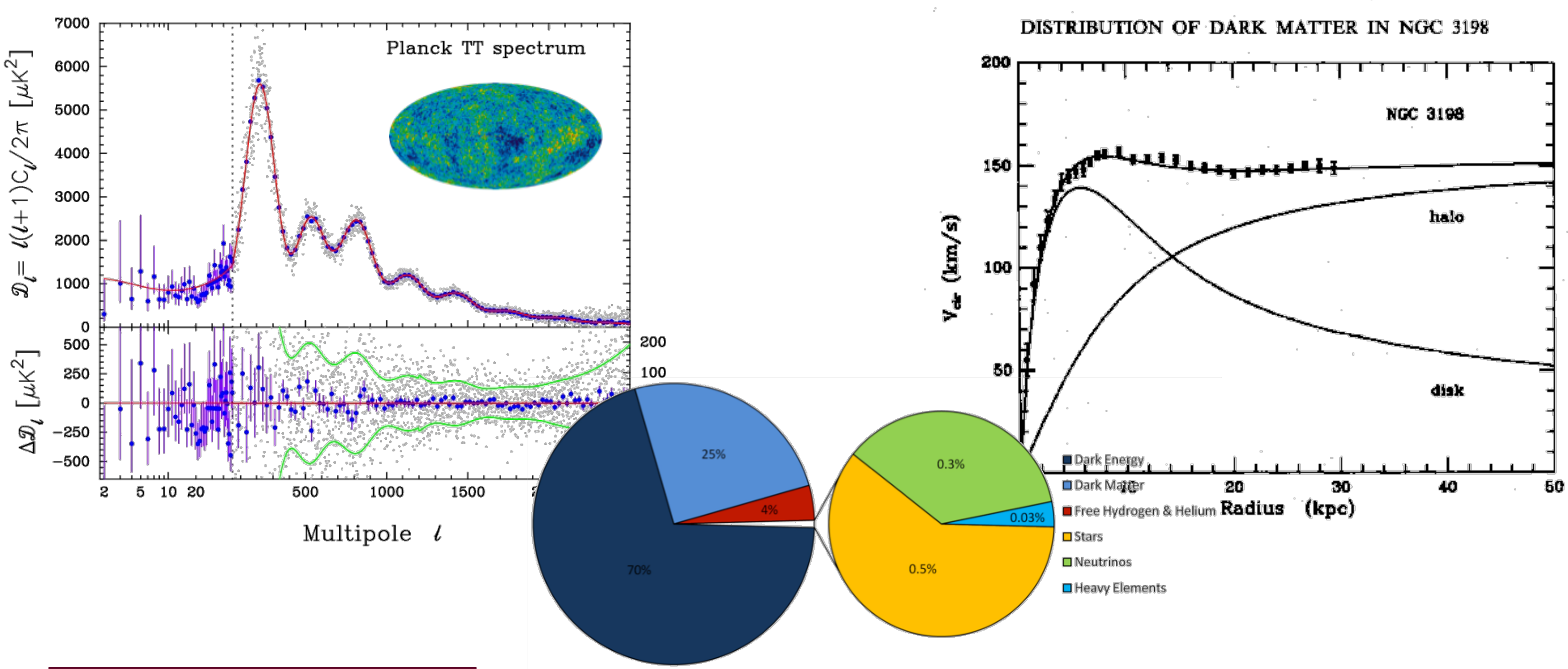
R.L. Cooper
New Mexico State University / LANL

On behalf of the MiniBooNE-DM Collaboration

MiniBooNE DM Search Road Map

- 2002-2012 MiniBooNE neutrino program.
- 2013 Socialized MiniBooNE DM search idea at SNOMASS, received well by community.
- 2014 Propose and received FNAL PAC approval to run in beam off target mode (DM search enhanced)
- 2014 Ran beam off target, collected 1.86E20 POT.
- 2017 First results on DM search with NCE sample.
- 2017+ working on beam timing and other channels. Expect significant improvement in sensitivity/limits.

Ample Evidence for Gravitationally Interacting Dark Matter; But What Is It?

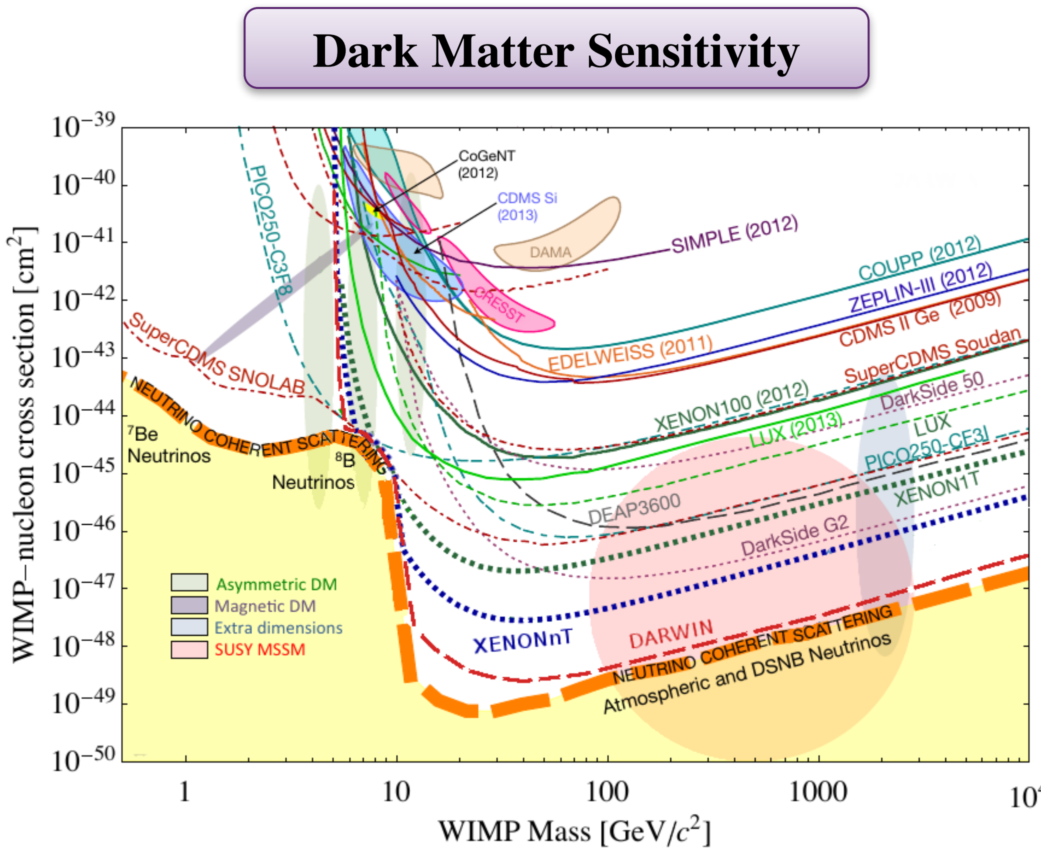


T. S. van Albada et al., *Astrophysical Journal* **295** (1985) 305.
Plank Collaboration: P. A. R. Ade et al., *A&A Preprint* (2013).

Where Are We With Direct Searches?

<u>"WIMP Miracle"</u>

- Electroweak scale masses (~100 GeV) and cross sections (10^{-36} cm^2) give correct relic abundances
- Conflicting claims, mostly ruled out phase space
- A rich dark sector easily bypasses "miracle"



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

Where Are We With Direct Searches?

"WIMP Miracle"

What about here

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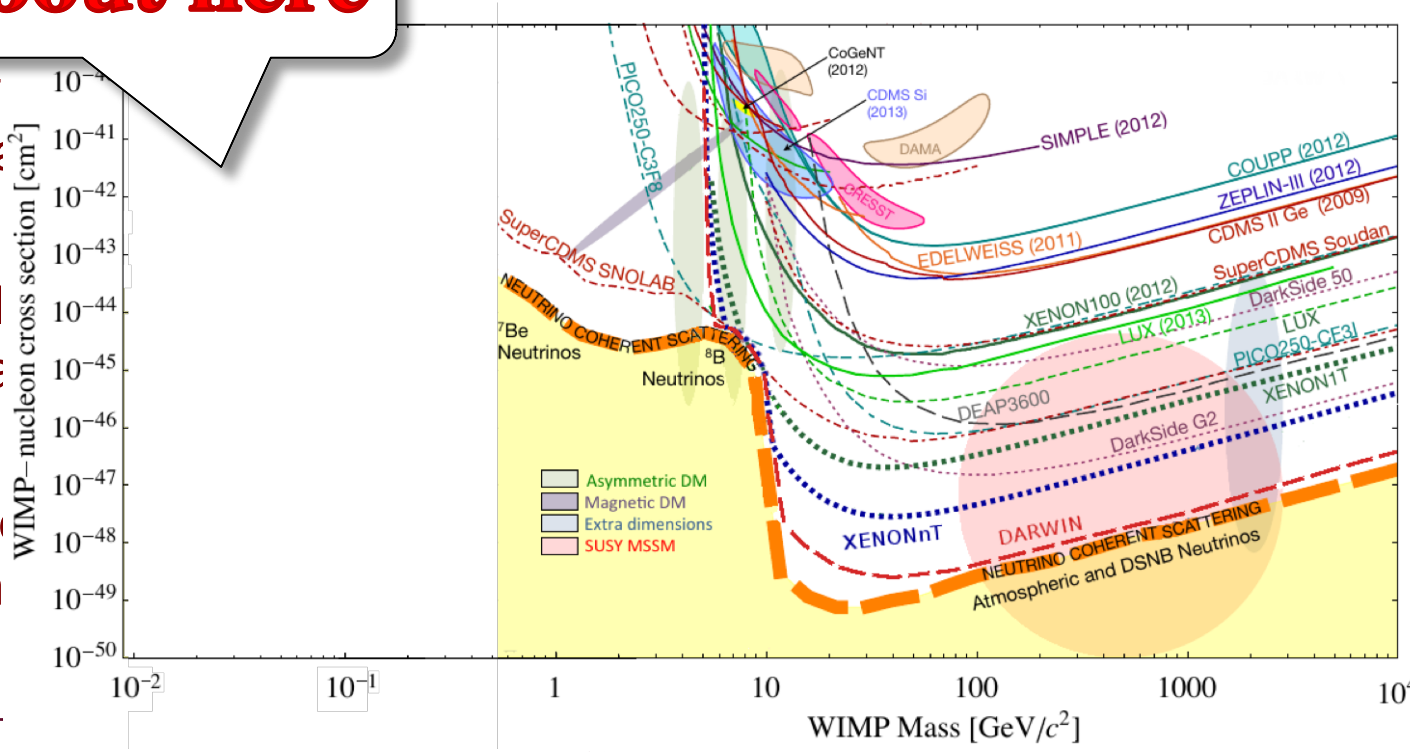
Dark Matter Sensitivity



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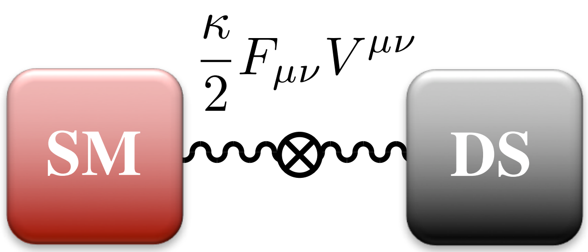
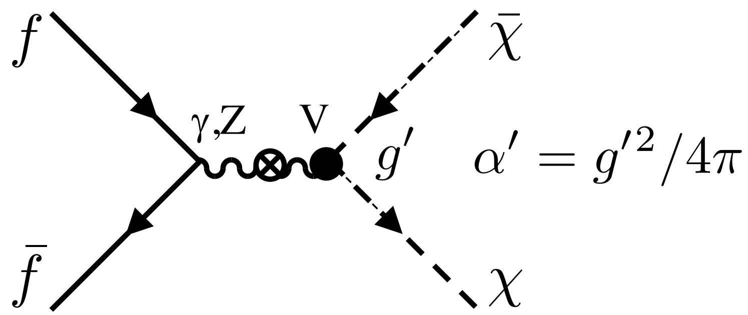
Sub-GeV Dark Matter: Vector Portal

- 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

- U(1) kinematic mixing with 4 parameters: m_χ, m_V, k, g'

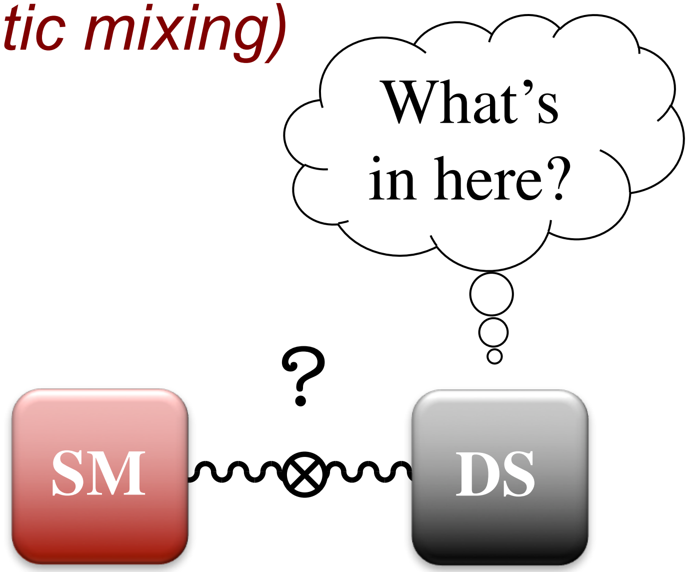




C. Boehm & P. Fayet, *Nucl. Phys.* **B683** (2004) 219. arXiv:hep-ph/0305261 [hep-ph].
C. Boehm et al., *Phys. Rev. Lett.* **92** (2004) 101301. arXiv:astro-ph/0309686 [astro-ph].

Sub-GeV Theories in General

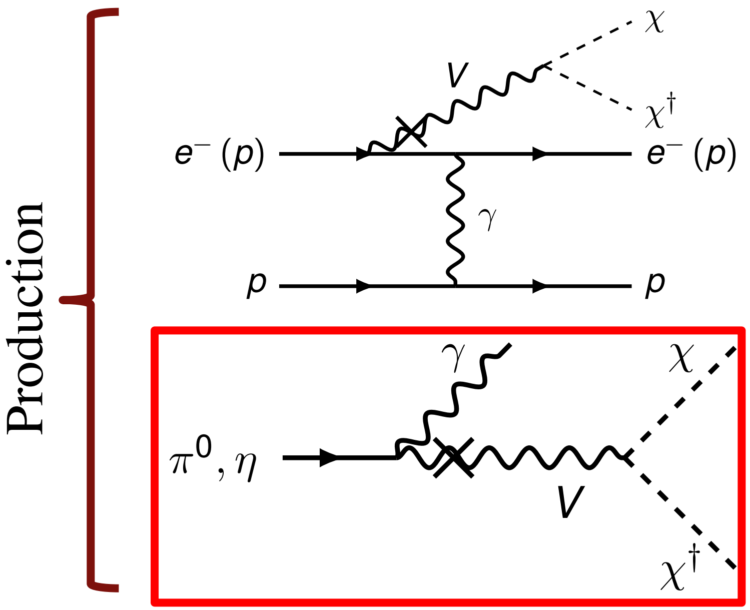
- Vector portal is just one particular model
- Other linkages between Standard Model and potential rich Dark Sector possible
  - *Hypercharge portal (U(1) kinematic mixing)*
  - Higgs portal
  - Neutrino portal
- Field is richly summarized in SLAC Dark Sectors 2016 proceedings (required reading!)

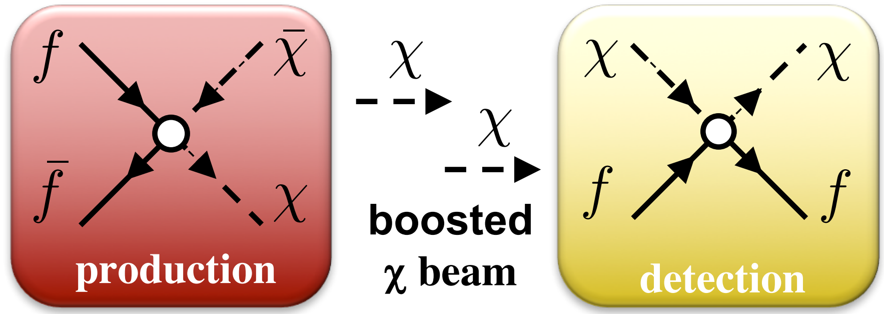


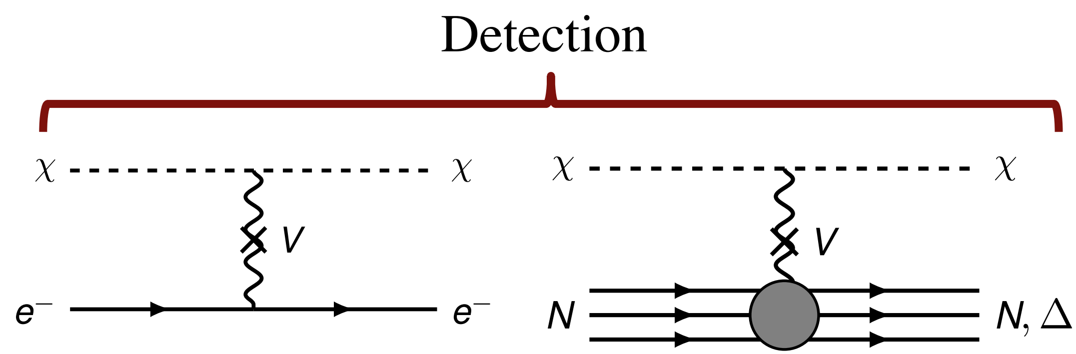
Dark Sectors 2016 Workshop: arXiv:1608.08632 [hep-ph].

Dark Matter Beams and Detection

- High-energy production and scattering detection







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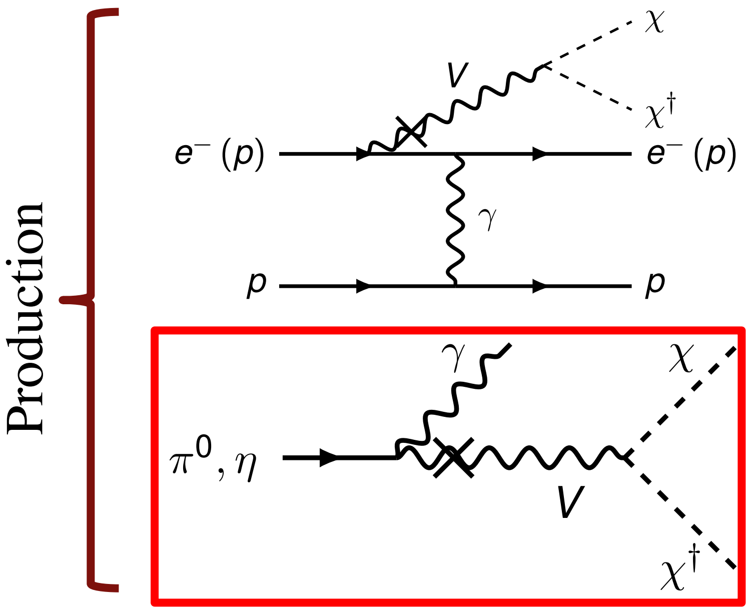

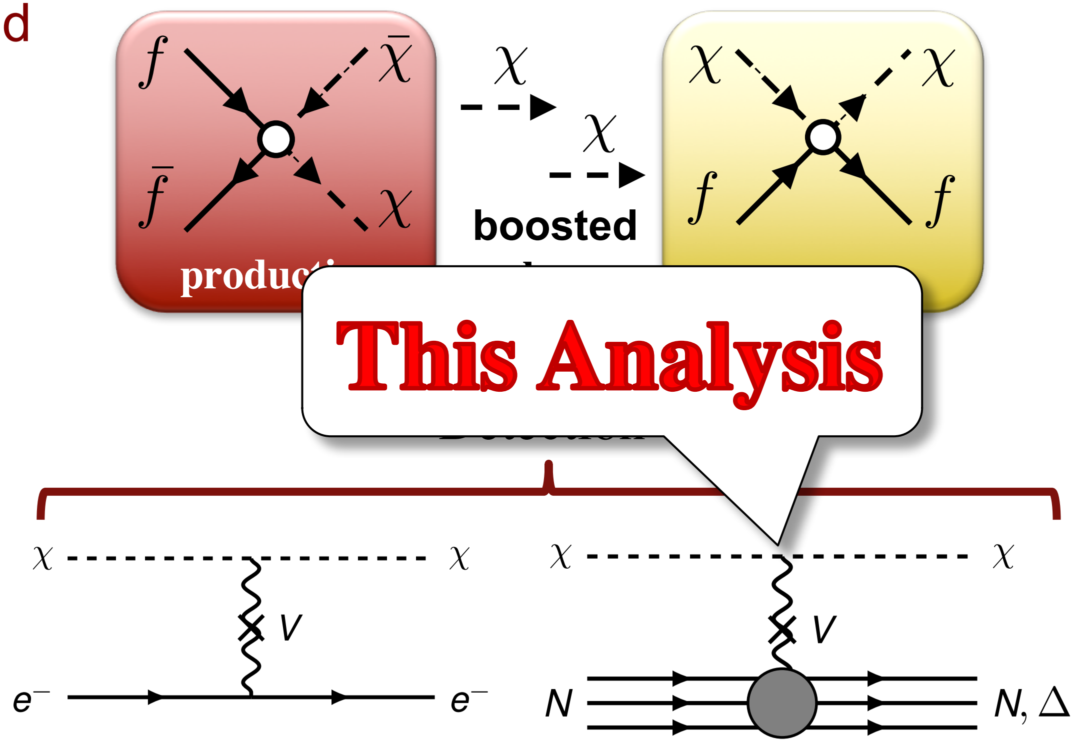

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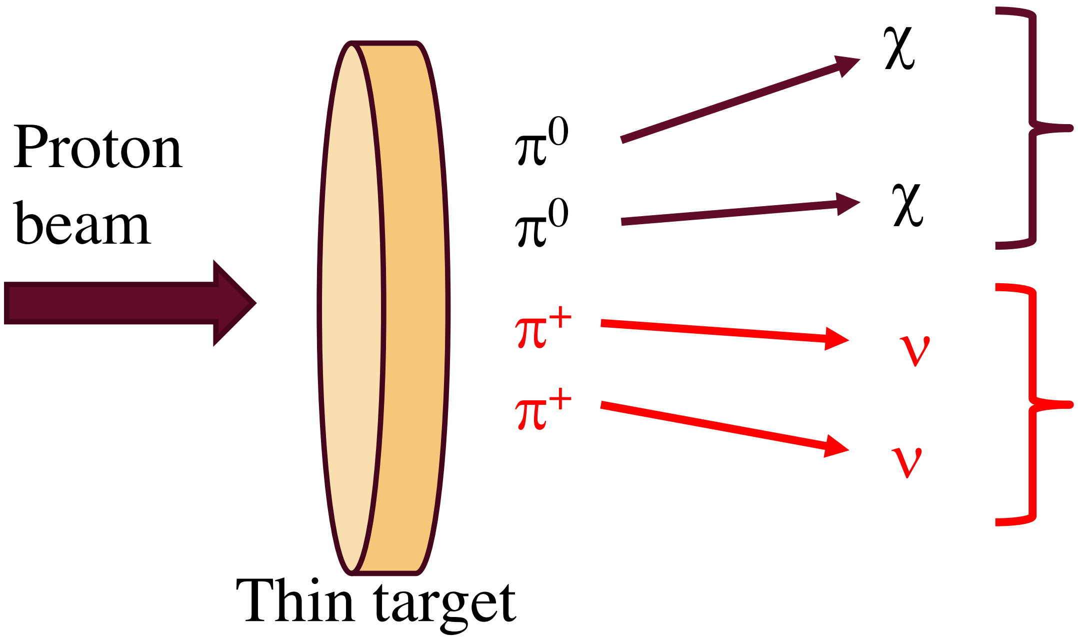
Why a Beam Dump Experiment?

- Neutrinos scatters are a background to the DM search
- Beam dump reduces neutrino backgrounds (~50)



Decays very quickly (before too much matter interactions) into dark sector ✔

Decays with longer lifetime to high-energy neutrinos ✘

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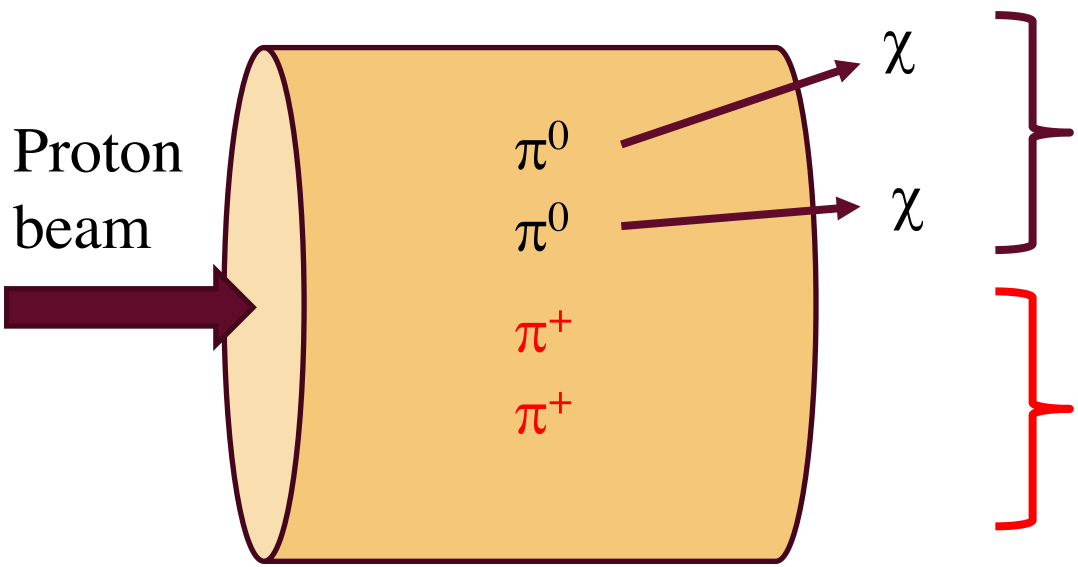


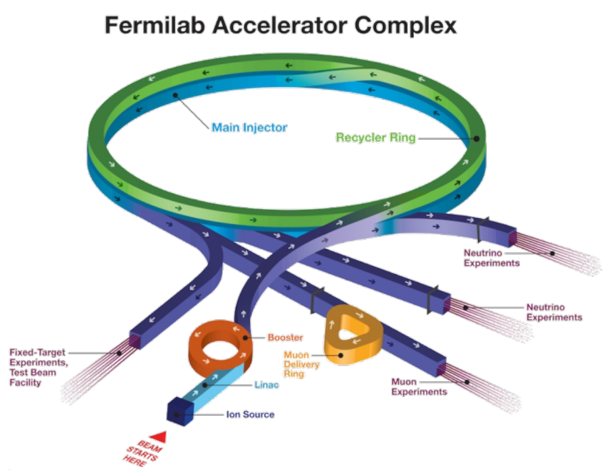
Thick target (e.g., beam dump)

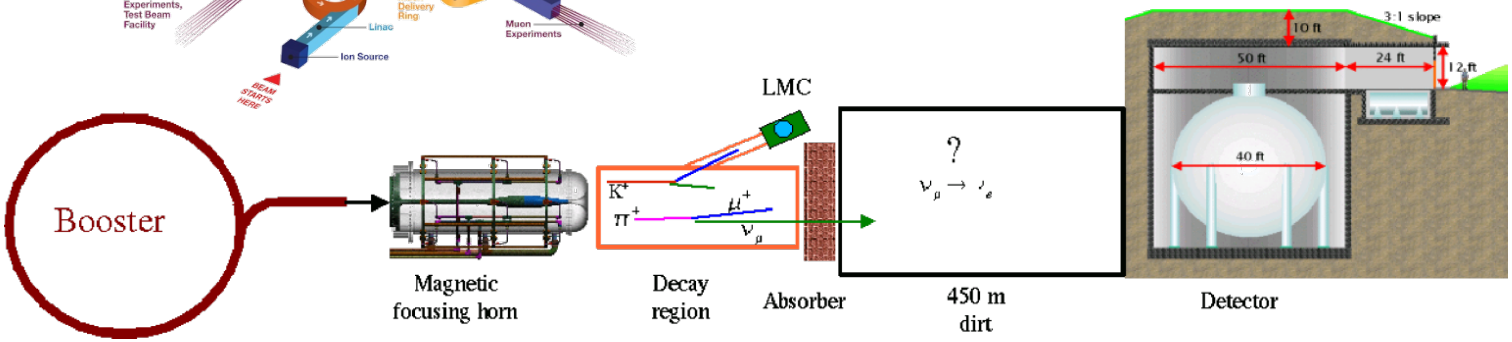
Decays very quickly (before too much matter interactions) into dark sector ✔

Absorbed before decay to neutrinos (or decay at rest for low-energy neutrinos) ✔

Beam Off-Target Mode

- Steer beam around target to 50 m beam dump
- Residual neutrino backgrounds from “scraping” and air





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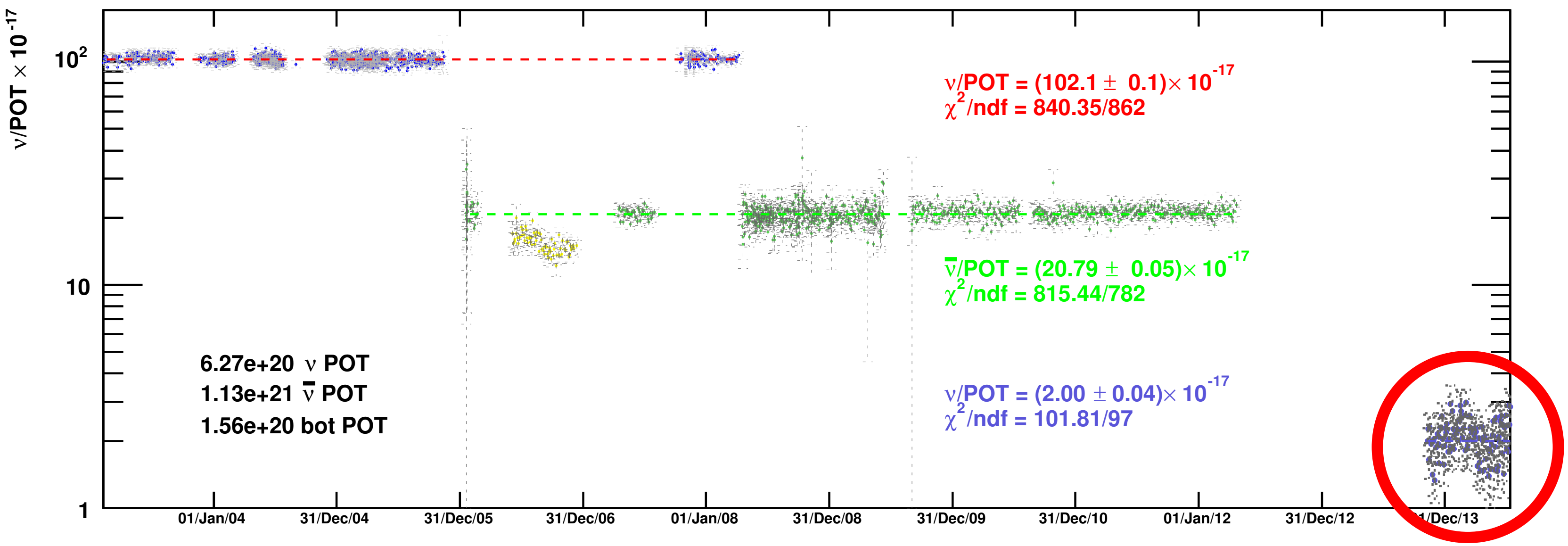

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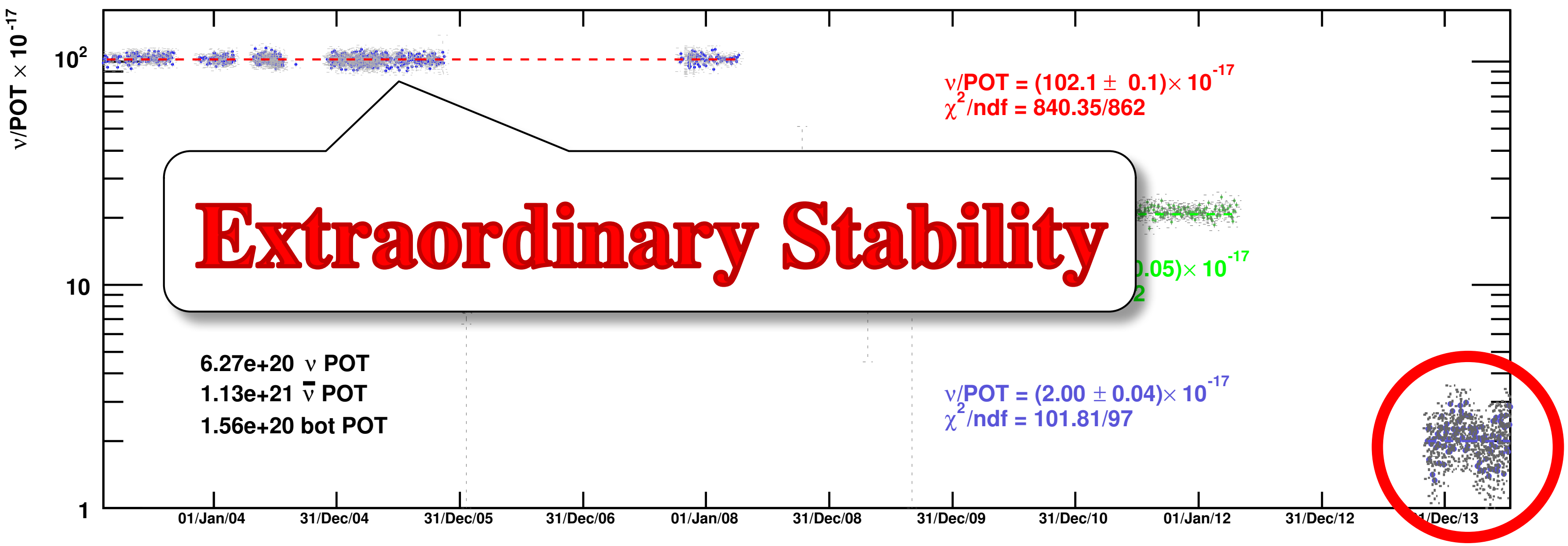
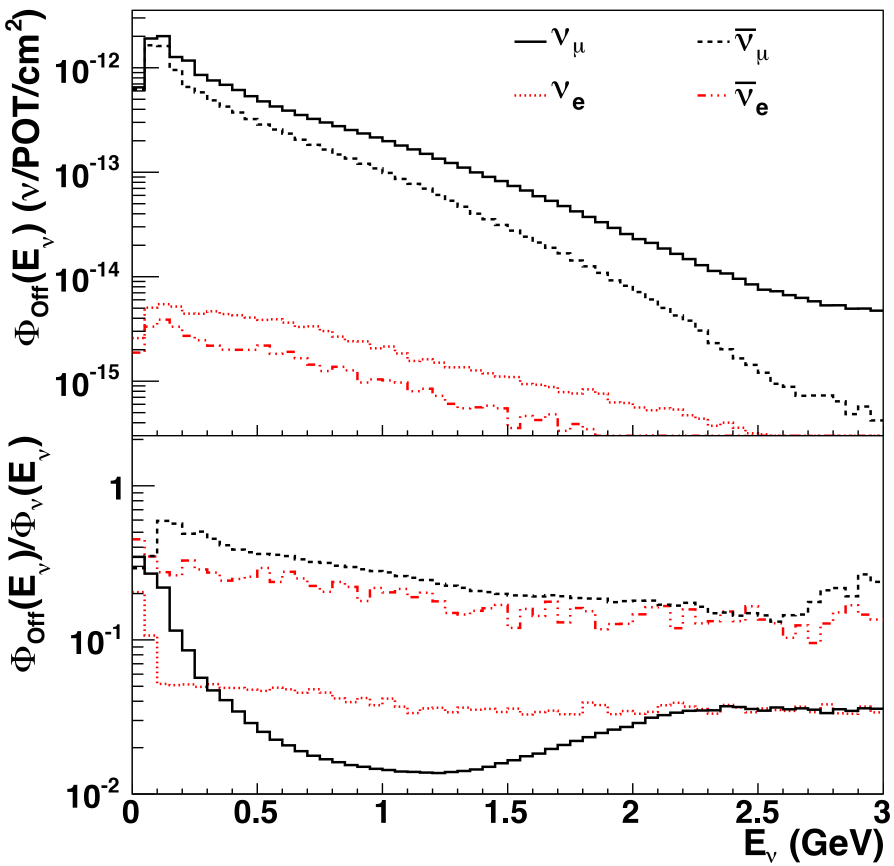
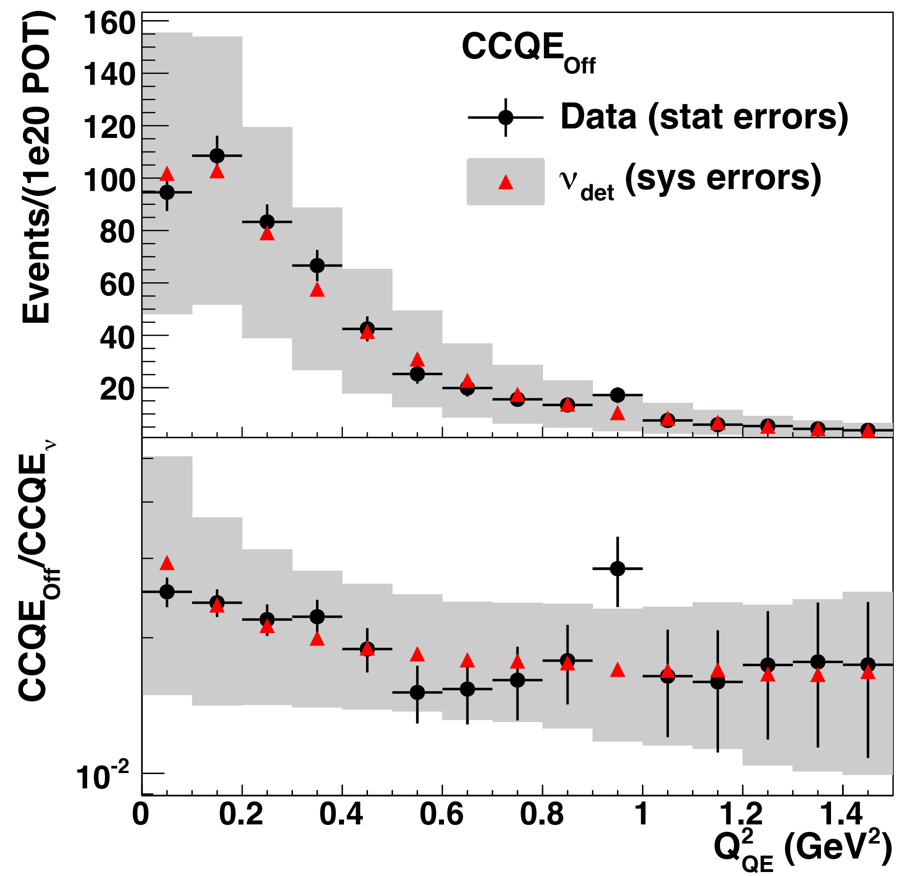


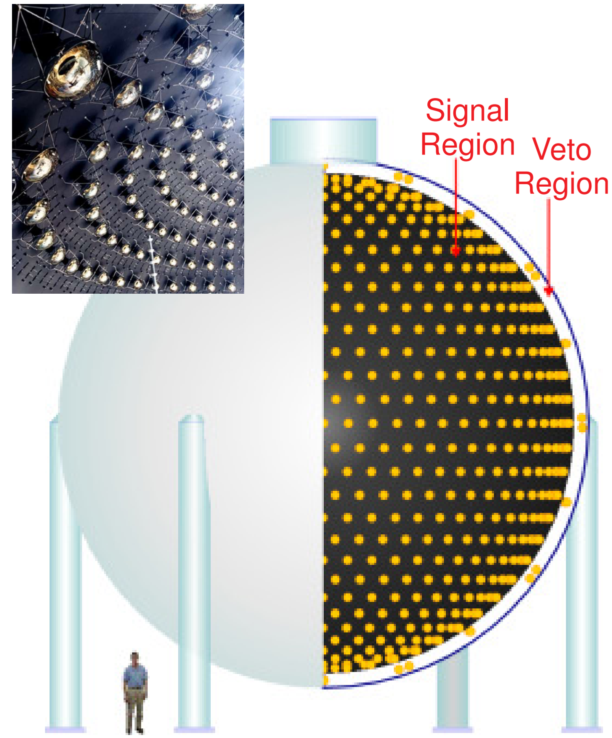
Flux Reduction and CCQE Data

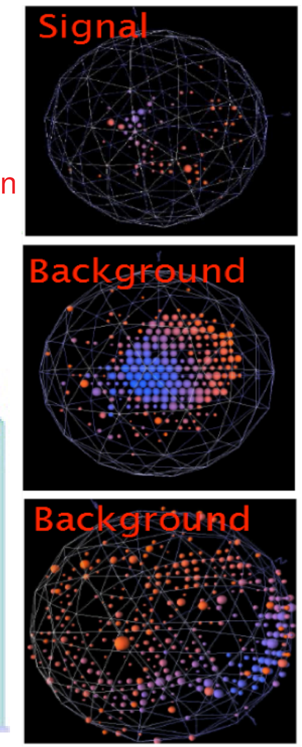




The MiniBooNE Detector

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

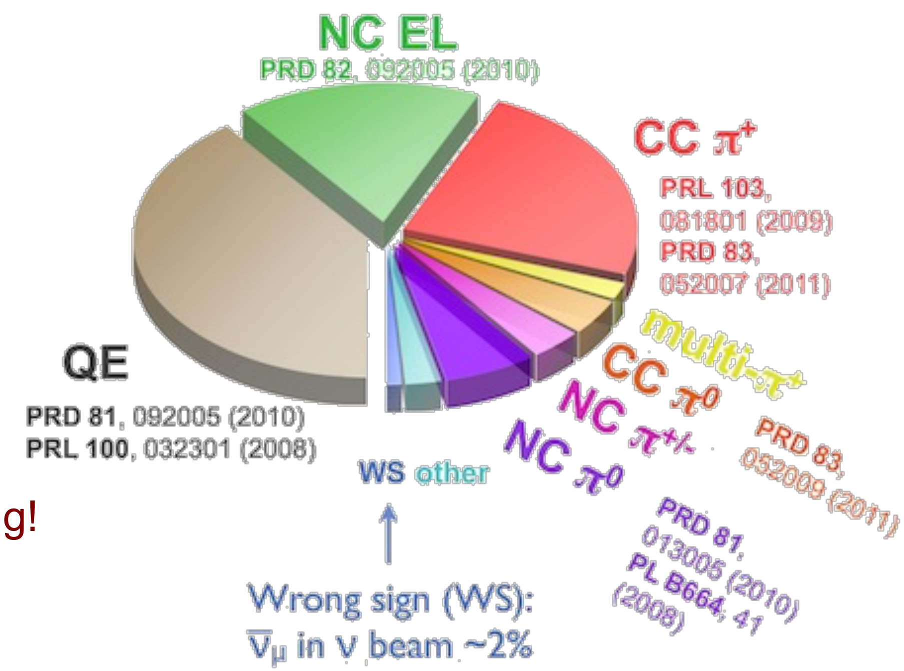




A.A. Aguilar-Arevalo et al., *Nucl. Instrum. Meth.* **A599** (2009) 28. arXiv:0806.4201 [hep-ex].

The MiniBooNE Detector

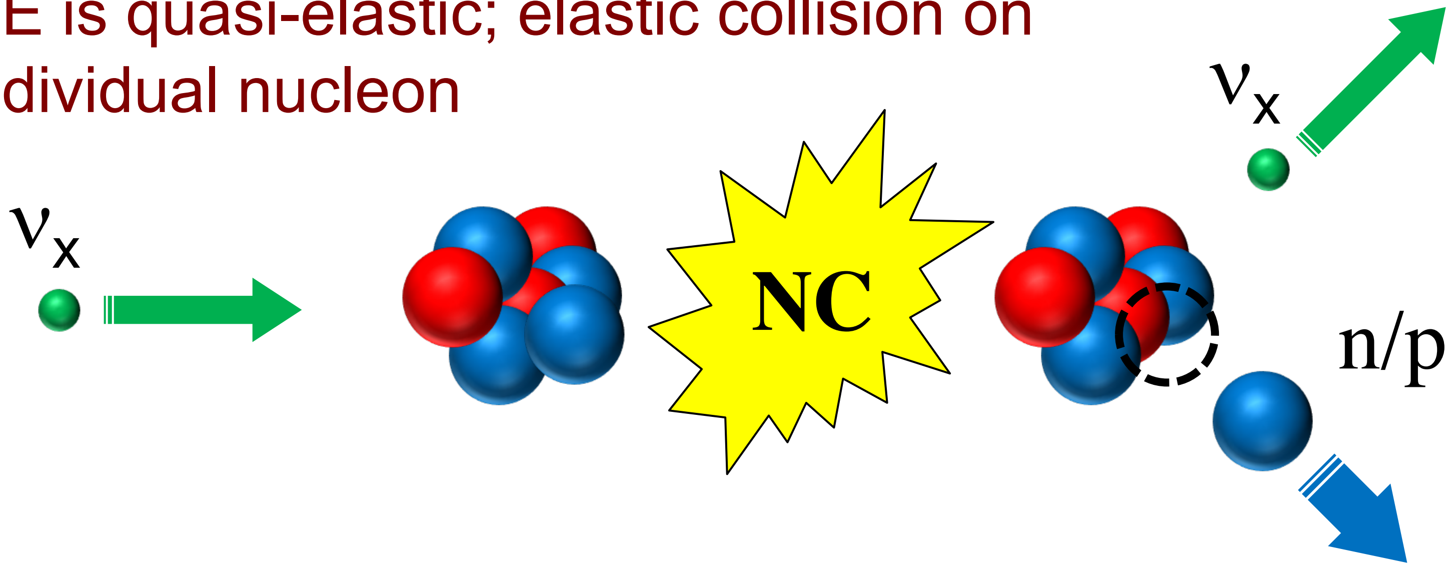
- Run for over 10 years
- 11 oscillation papers
- 14 cross section and flux papers
- Relevant to this work
  - ν-mode (6.7×10^{20} POT) and counting!
  - $\bar{\nu}$-mode (11.5×10^{20} POT)
- 19 Ph.D. Theses



See our website for a full list of publications. http://www-boone.fnal.gov/

NC, CC, QE and All That

- Neutrinos interact via the weak current:
  - $W^{\pm}$ → charged current (CC)
  - Z^0 → neutral current (NC)
- CC "flips" isospin, e.g., beta decay n → p + e + $\bar{\nu}_e$
- QE is quasi-elastic; elastic collision on individual nucleon



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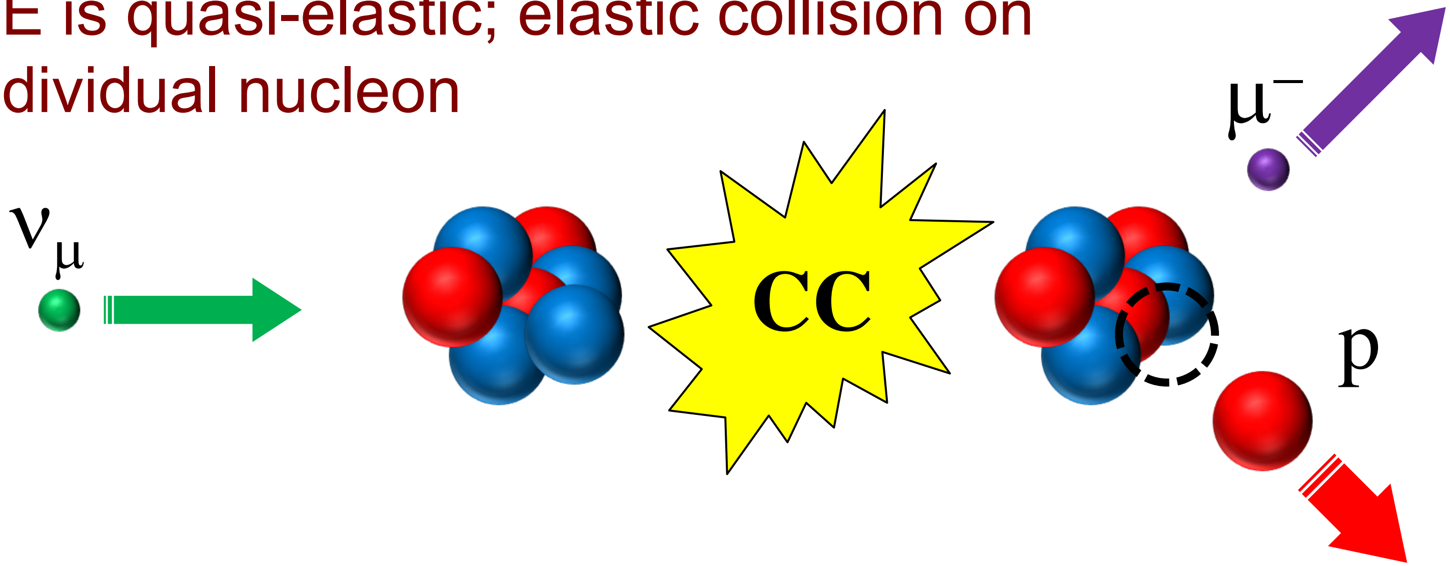
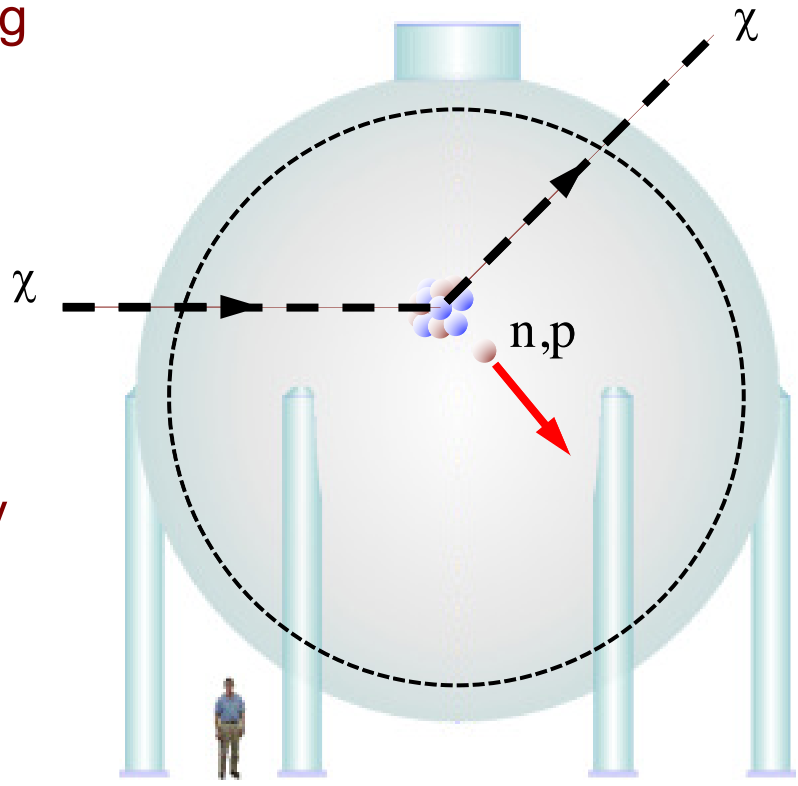


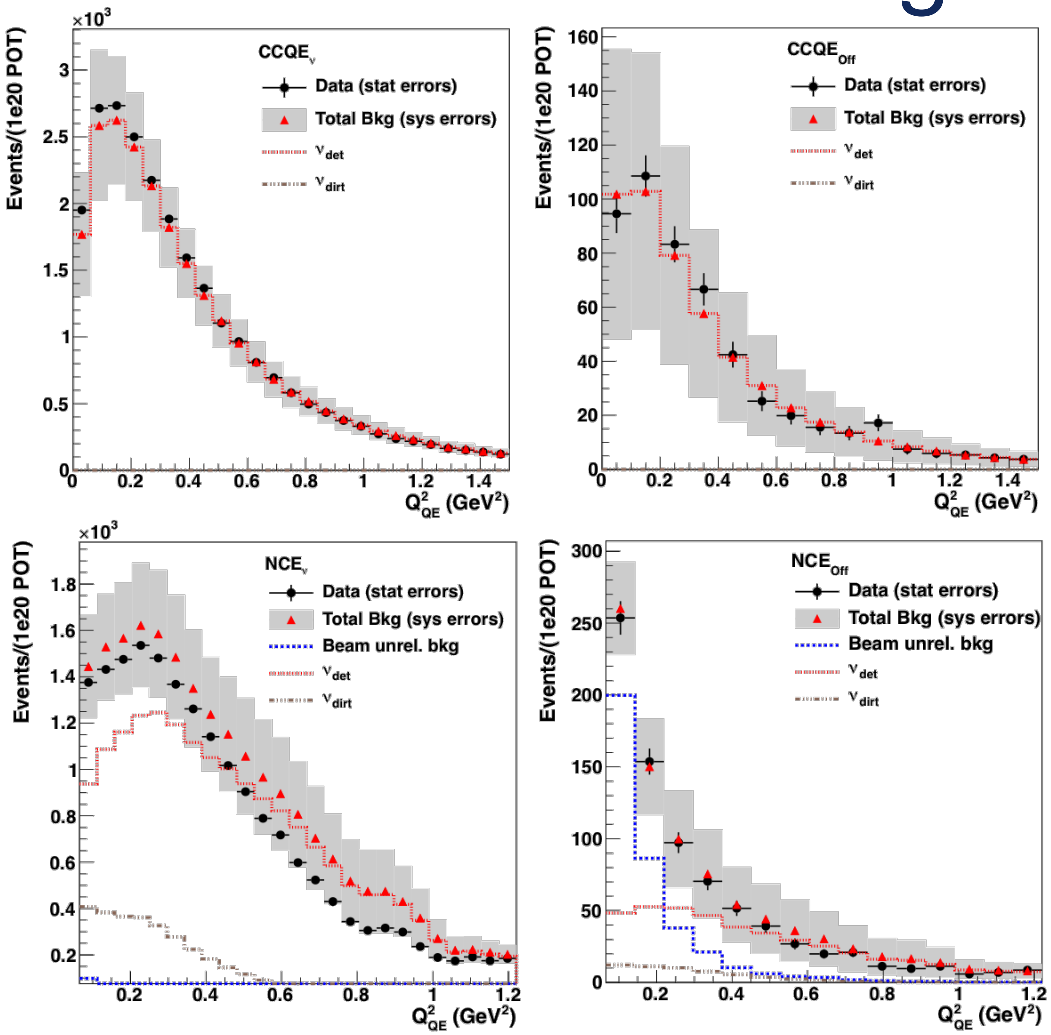
N-DM Event Selection Cuts

- 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



Improving Errors – Simultaneous Fitting

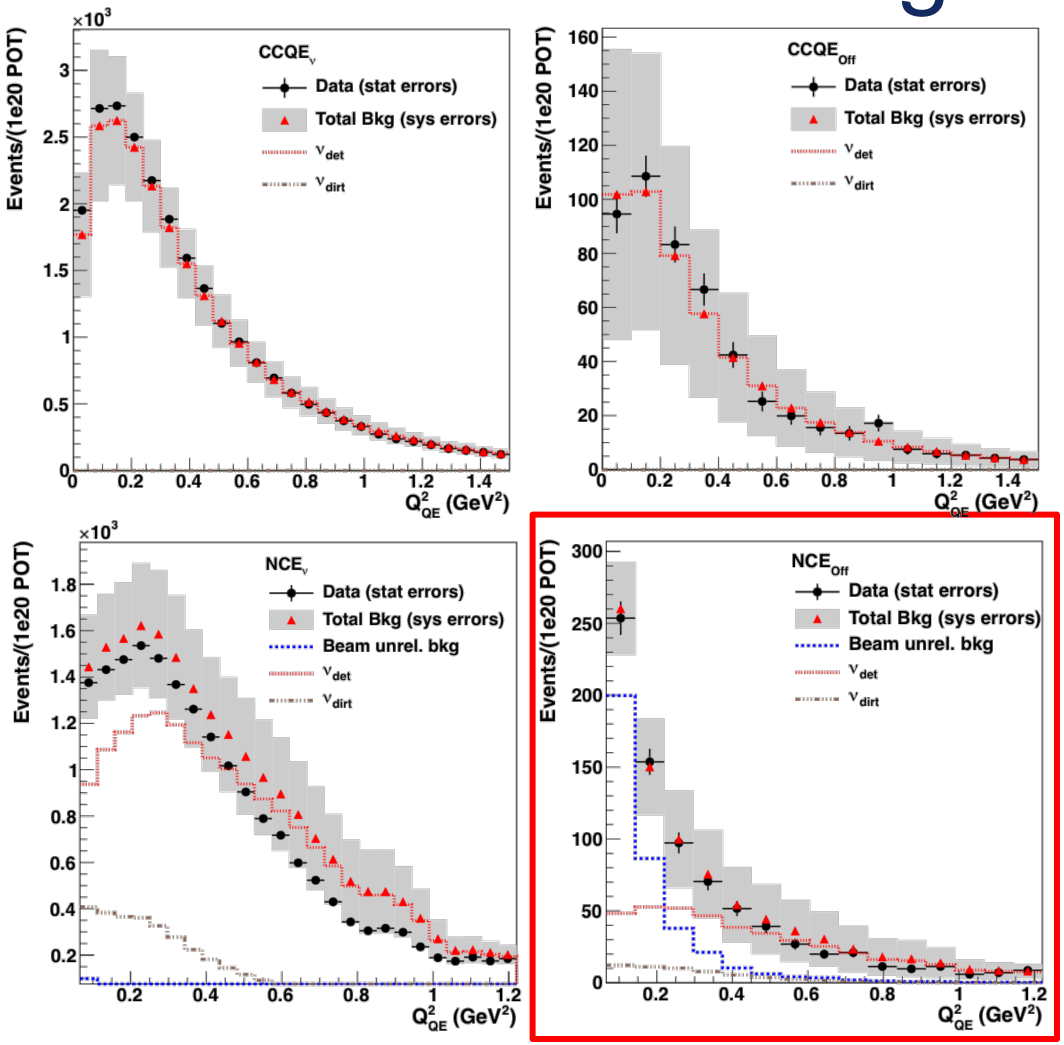
- 4 distributions
  - NC beam off
  - CC beam off
  - NC beam on
  - CC beam on



- CC ratios help reduce flux uncertainties
- NC ratios help reduce neutrino cross section uncertainties

Improving Errors – Simultaneous Fitting

- 4 distributions
  - **NC beam off (signal)**
  - CC beam off
  - NC beam on
  - CC beam on

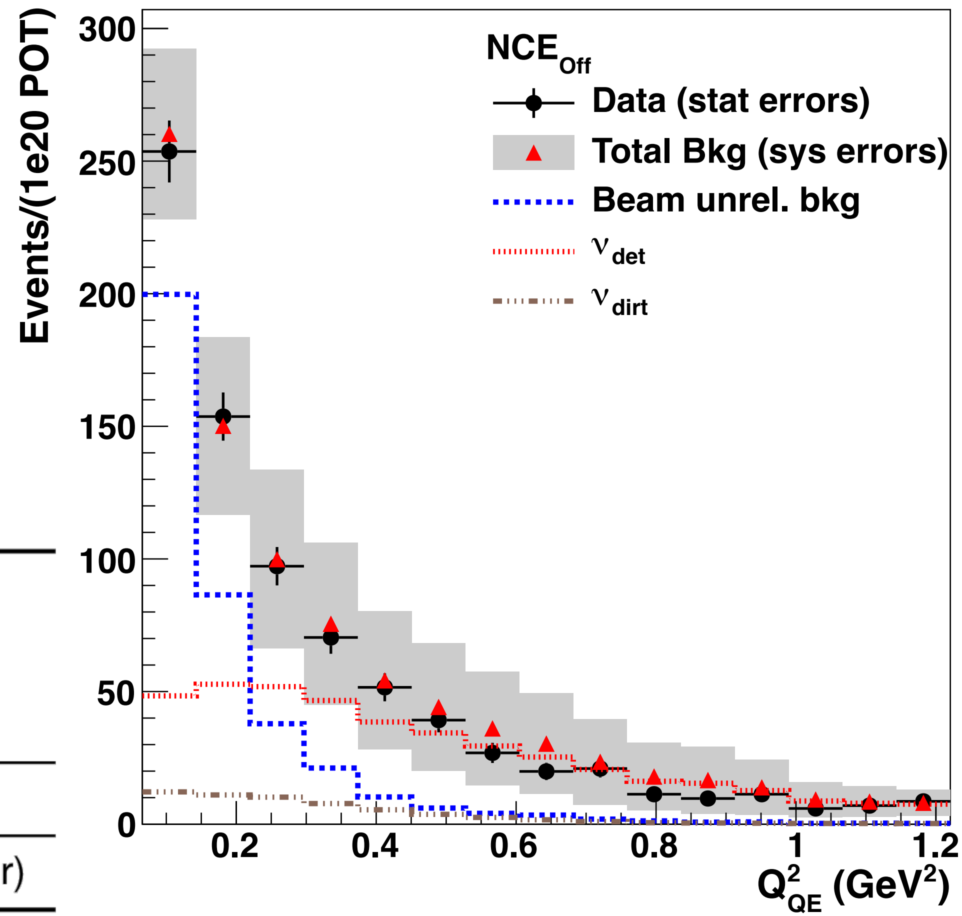


- CC ratios help reduce flux uncertainties
- NC ratios help reduce neutrino cross section uncertainties

Nucleon NC-Like Events – No Excess

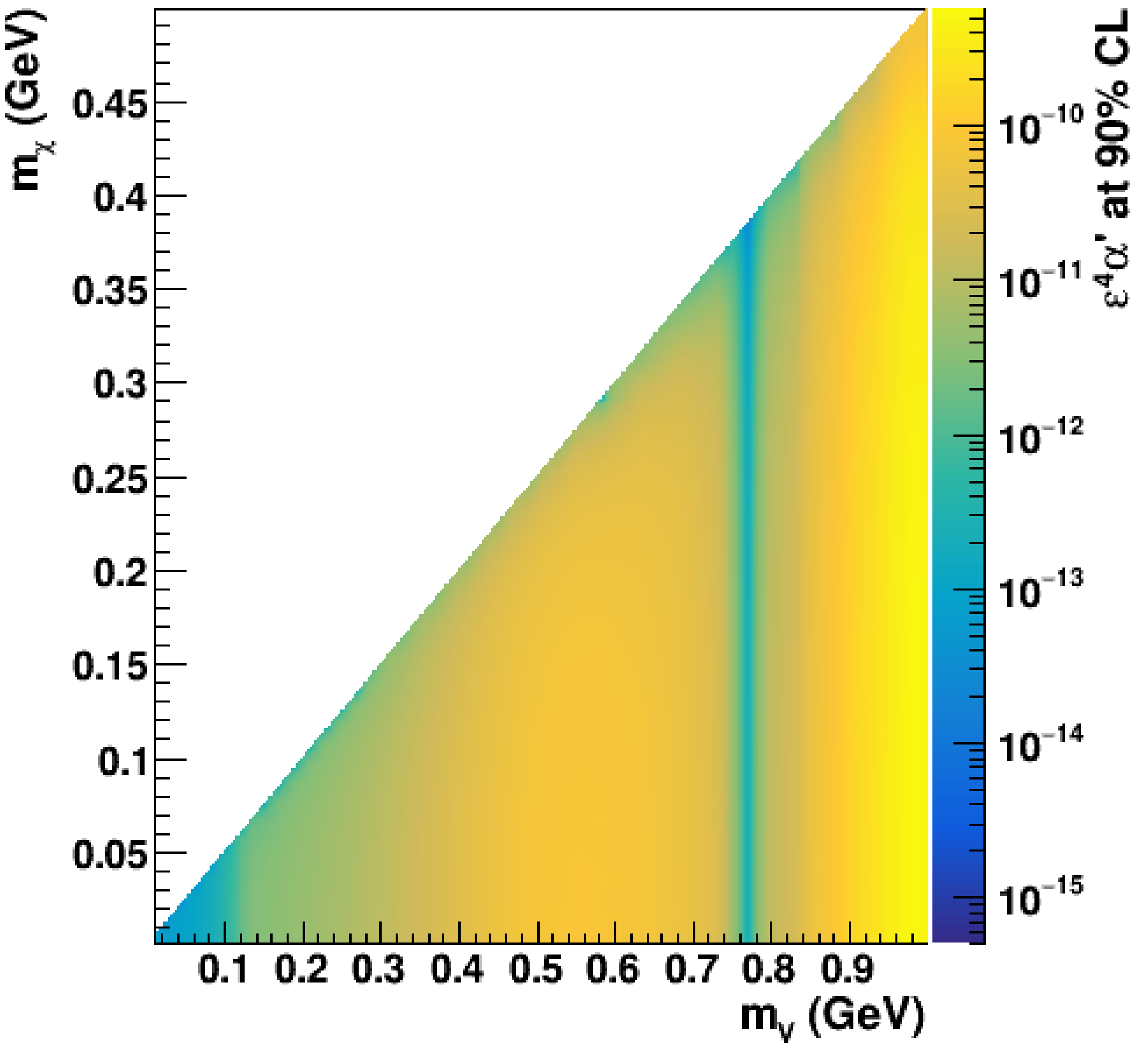
- A significant excess found with simple search
- Large uncertainties → must improve!
- Use auxiliary channels with correlated errors

	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	33.5% (pred. sys.)
Data	1465	2.6% (stat.)
Fit Results	1548	12.8% (fit effective error)



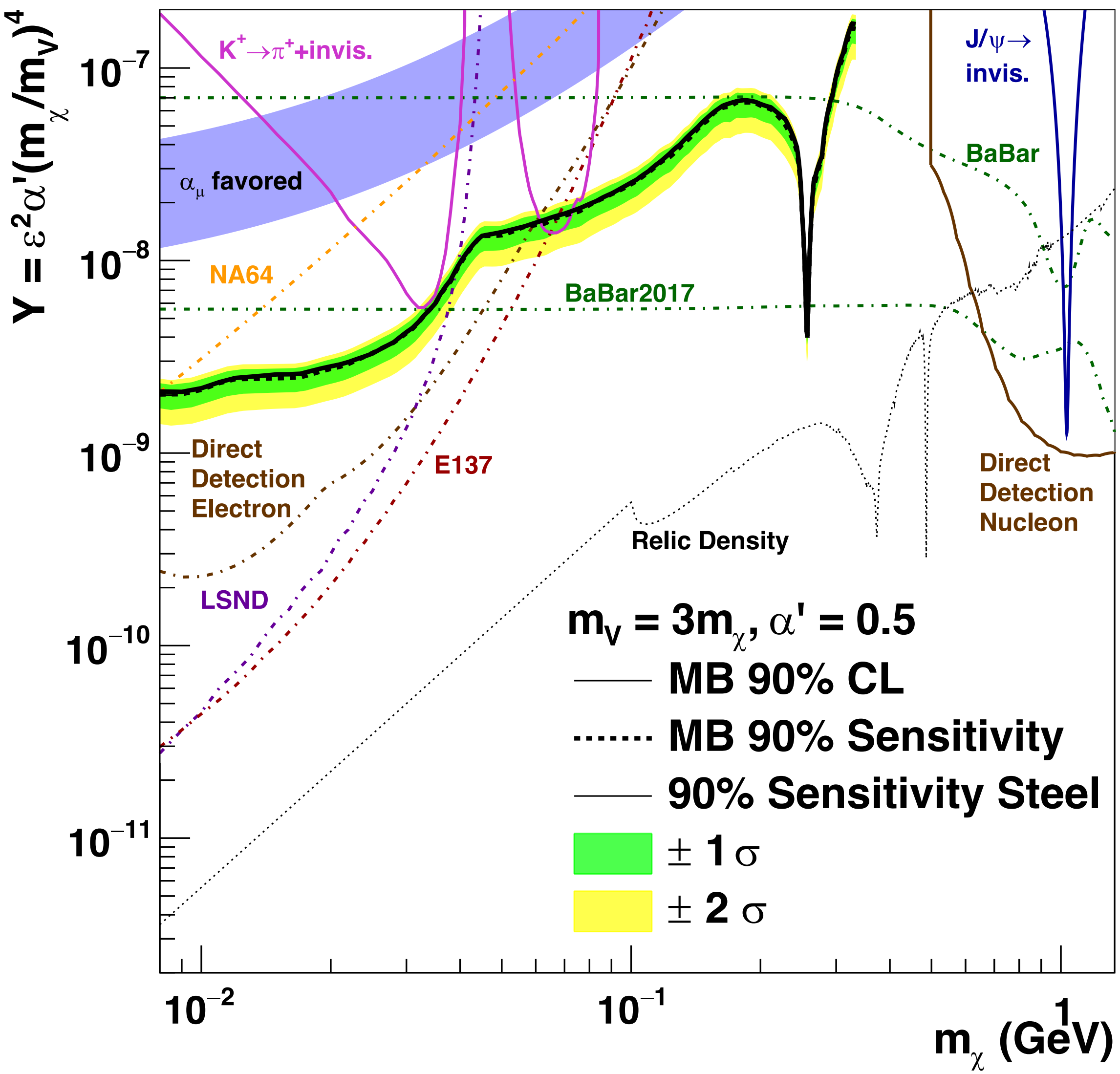
Confidence Limit Results

- Treating invisible mode
  $m_V > 2\, m_\chi$
- Best sensitivity at m_V = 769 MeV, m_χ = 381 MeV due to ρ meson production



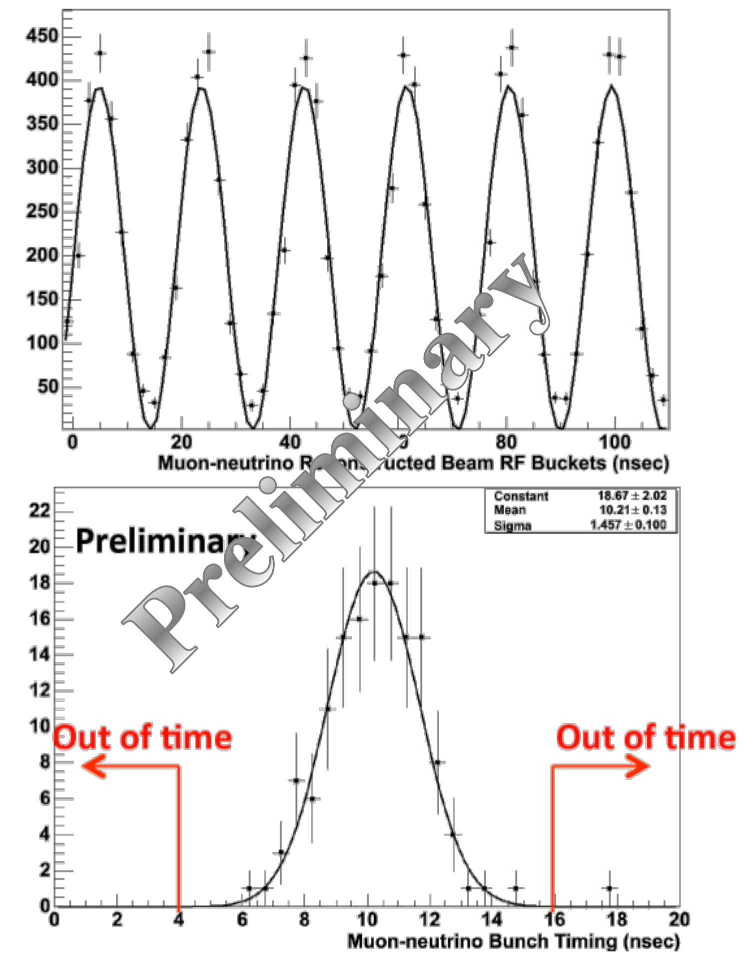
Confidence Limit Results

- Many ways to "slice" parameter space
- This parameter choice is rejected as solution for *g*-2 anomaly (Vector Portal)



Future Analyses for MiniBooNE

- Beam is comprised of 81 ns-scale RF pulses
- Massive dark matter will propagate sub-luminally
- Characteristic intra-bunch timing improve “high” mass dark matter sensitivity
- Improves higher mass sensitivity



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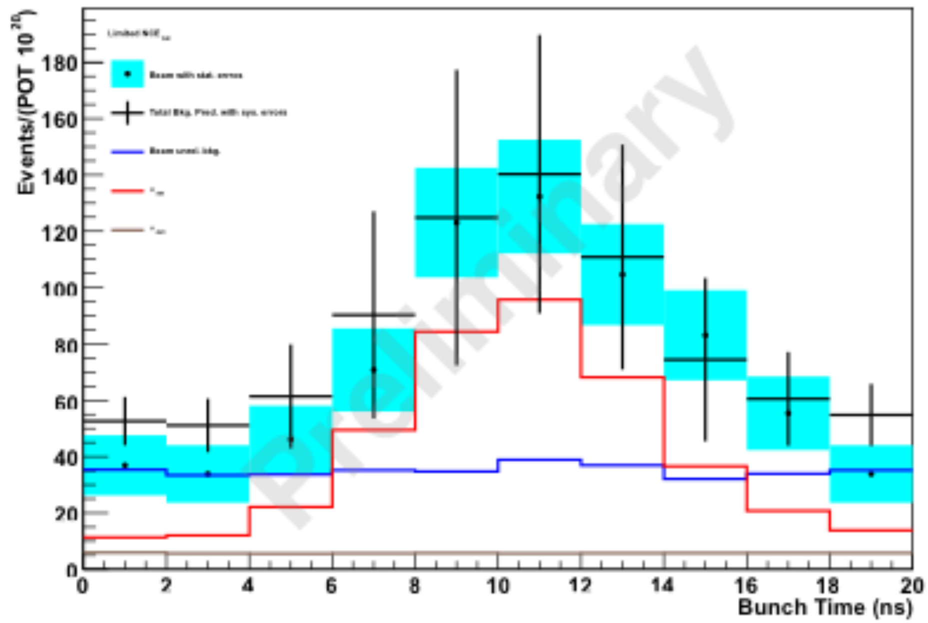

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Future Analyses for MiniBooNE

Electron-DM Elastic

- MiniBooNE searched for ν_e oscillations
- Excellent electron tracker
- $\nu_e + e \rightarrow \nu_e + e$ is dominant background → clean SM prediction
- Connected to low-energy excess from oscillation search

Δ Resonance (π^0)

- Neutral pion π^0 decays to 2 energetic photons
- Main background to ν_e oscillation → well studied
- Hard to fake with beam-unrelated backgrounds
- Estimate 1-10 total beam unrelated background events

Future Analyses for MiniBooNE

Both samples are stats limited

Electron-DM Elastic

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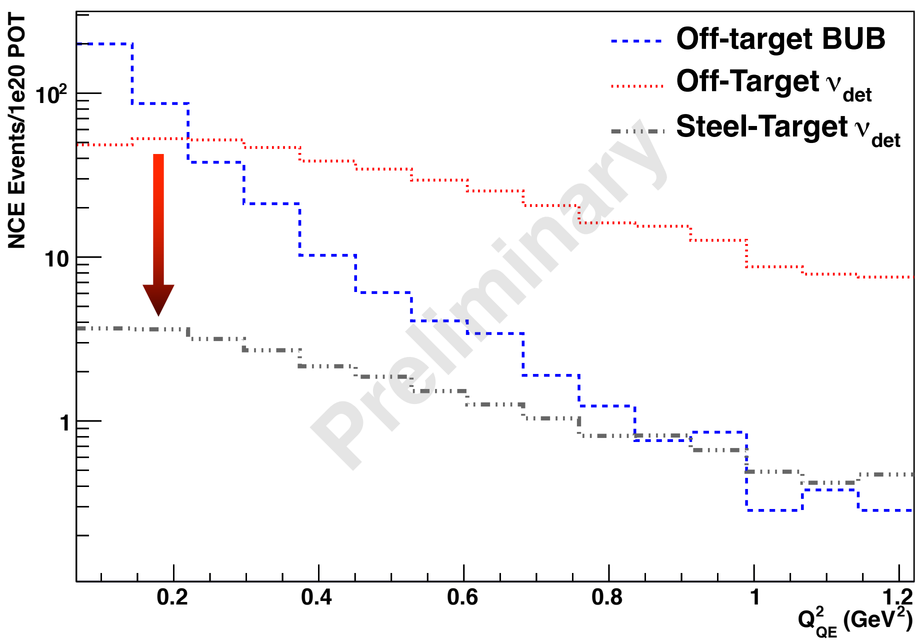
A Dedicated Beam Dump

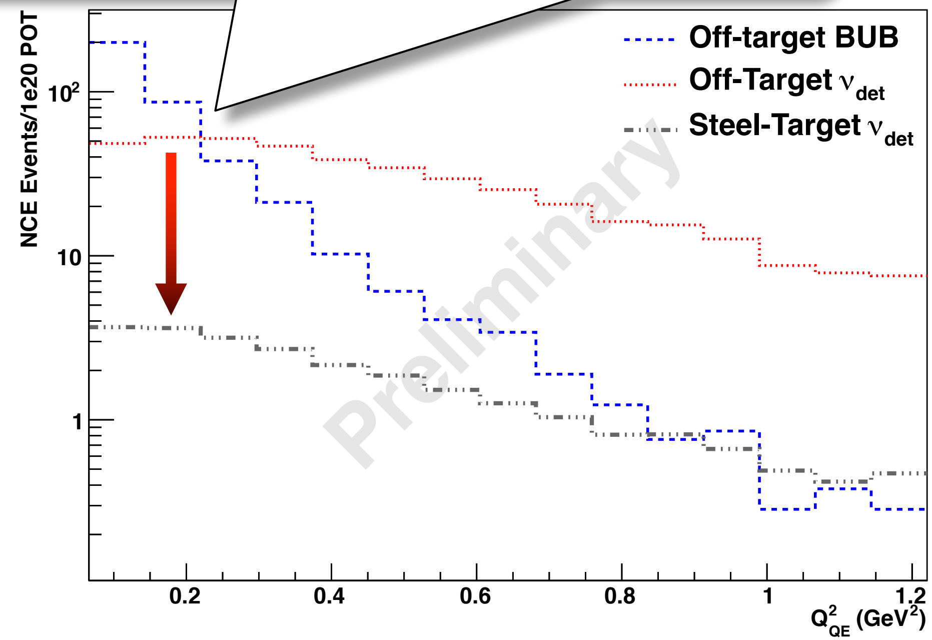
- The proton beam halo can “scrape” against material and produce neutrinos
- One idea: remove target and focusing horn
- Replace with dedicated steel dump



A Dedicated Beam Dump

See Richard Van de Water's Talk

- The p "scrape" against material and produce neutrinos



- One idea: remove target and focusing horn

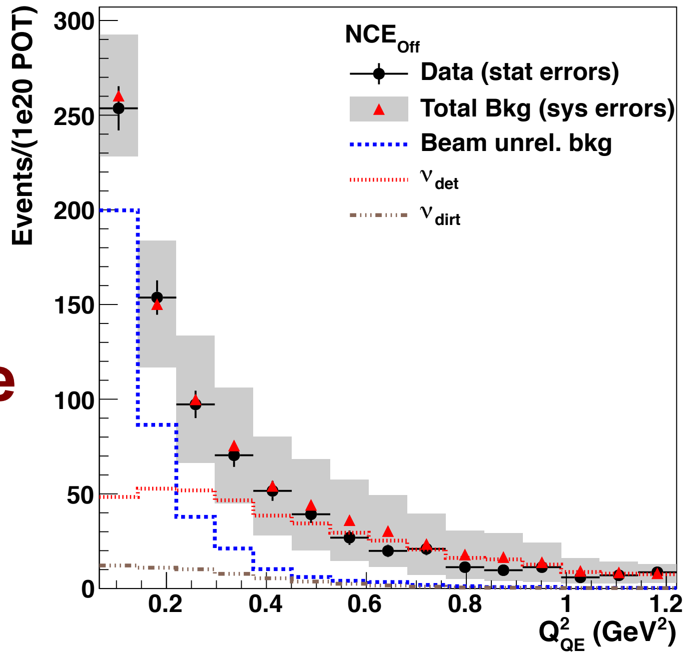
- Replace with dedicated steel dump

LESSONS LEARNED

(OR “SO YOU WANT TO SEARCH FOR SUB-GEV DARK MATTER”)

Backgrounds!

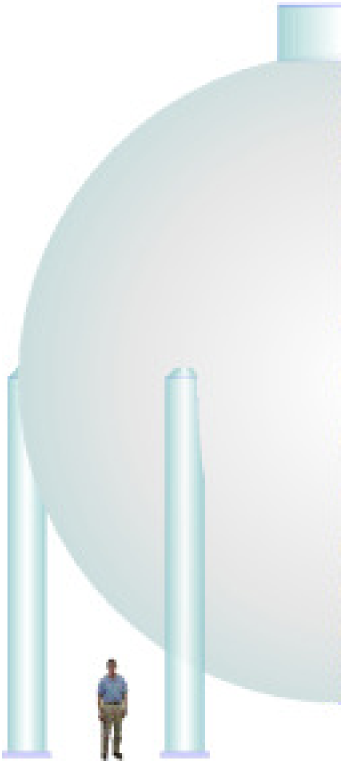
- We sample cosmics with a random trigger → normal operation is 2 Hz but significantly increased to 15 Hz
- We needed **better part of a decade of data** to decrease beam-related background uncertainty



- Beam interactions in surrounding dirt small (more later)
- Lesson learned: Work very hard on your backgrounds

Why Is Dirt Event Rate So Small?

- Short answer: MiniBooNE is huge!
- Dirt events are most likely neutrons that can penetrate very deep into detector (otherwise they interact in veto and get rejected)
- In this analysis, they will elastically scatter and be indistinguishable from our signal
- Lesson learned: Be big, or handle your neutrons with auxiliary measurements



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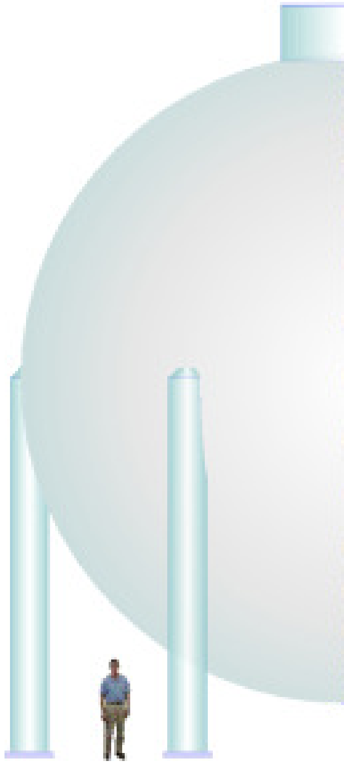
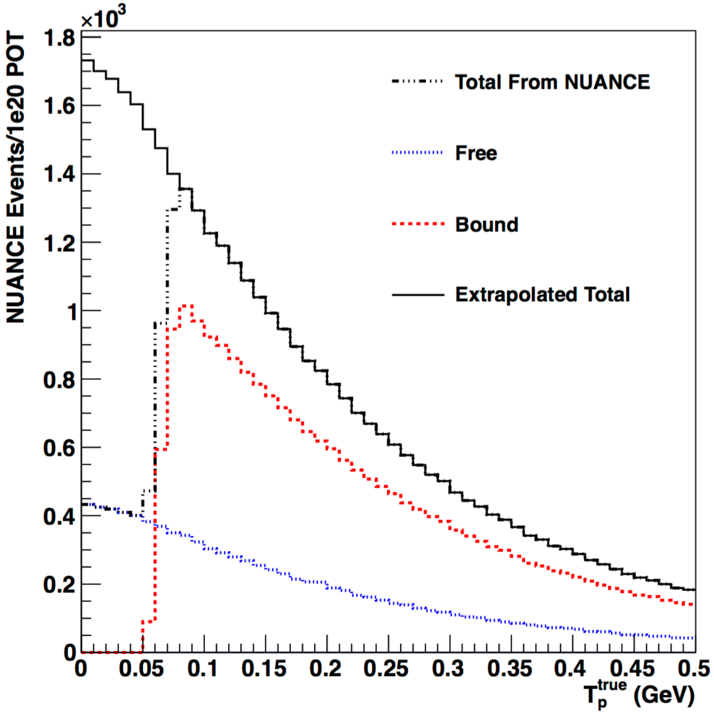


Nuclear Physics

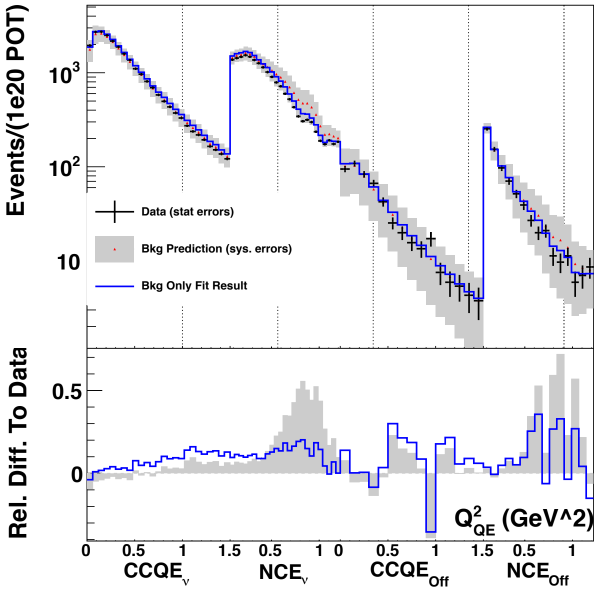
- Final sensitivity does not reach as far as initial predictions
- Not an experimental issue
- Stripping a nucleus of a proton involves complex nuclear physics: e.g., binding, Pauli blocking, etc.



- Lesson learned: An honest sensitivity estimate must include a decent nuclear model → threshold effects

Correlated Errors and Sidebands

- Because MiniBooNE has been running for over a decade, there are numerous "sideband" analyses with similar systematic uncertainties



- Don't be afraid to get your hands dirty and deal with correlated errors → yes, they can be difficult

- Lesson Learned: Consider every possible sideband measurement to reduce the final correlated uncertainties

Conclusions

- MiniBooNE combines a high-intensity proton beam in an off-target configuration (DM beam) with a large volume, sensitive neutrino detector to search for sub-GeV dark matter
- Beam dump mode suppresses beam-correlated neutrino backgrounds
- Nucleon-DM elastic scatter analysis is complete (arXiv:1702.02688 submitted to PRL) → e-DM and inelastic π^0 channels are underway
- A litany of lessons learned
- Future opportunities at BNB can help MiniBooNE too

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See Richard Van de Water's Talk

Thank You!

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

BACKUPS

Previous Beam Dump / Fixed Target Experiments – Proton Beams

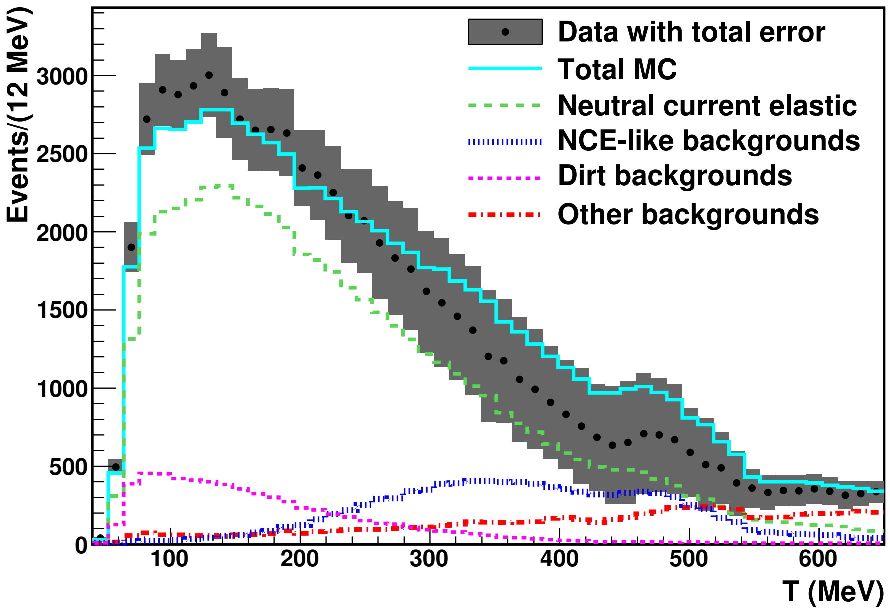
Experiment	Location	approx. Date	Amount of Beam (10^{20} POT)	Beam Energy (GeV)	Target Mat.	Ref.
CHARM	CERN	1983	0.024	400	Cu	[16]
PS191	CERN	1984	0.086	19.2	Be	[17, 18]
E605	Fermilab	1986	4×10^{-7}	800	Cu	[19]
SINDRUM	SIN,PSI					
ν-Cal I	IHEP Serpukhov	1989	0.0171	70	Fe	[20–22]
LSND	LANSCE	1994-1995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

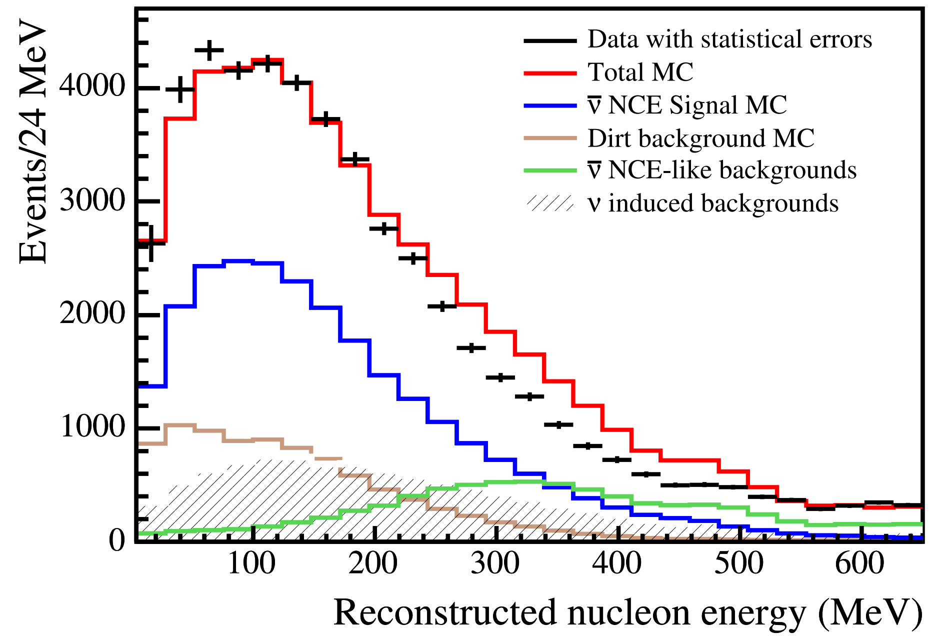
Previous NC Elastic Results

- Previous neutrino running important for spectrum reconstruction

ν NC elastic



$\bar{\nu}$ NC elastic

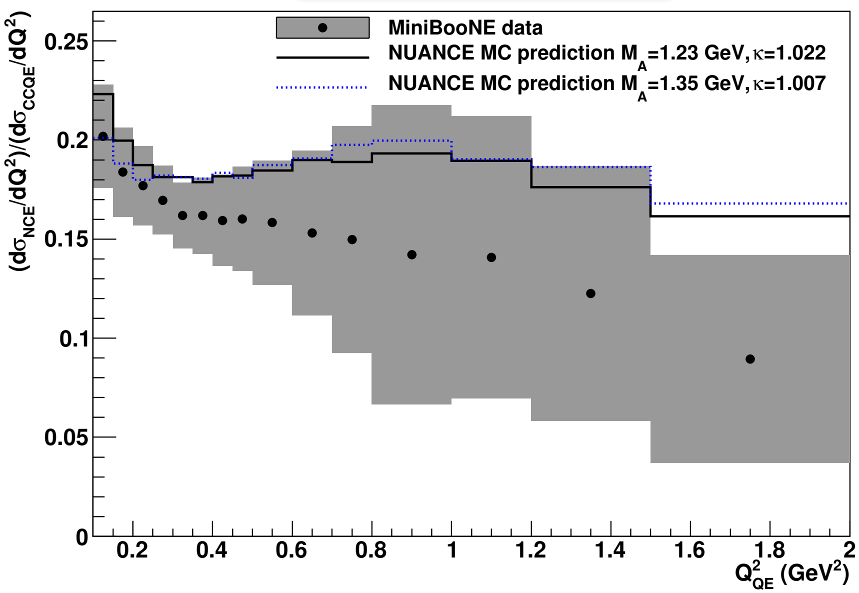


A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D82** (2010) 092005. arXiv:1007.4730 [hep-ex].
A.A. Aguilar-Arevalo et al., *Phys. Rev.* **D91** (2014) 012004. arXiv:1309.7257 [hep-ex].

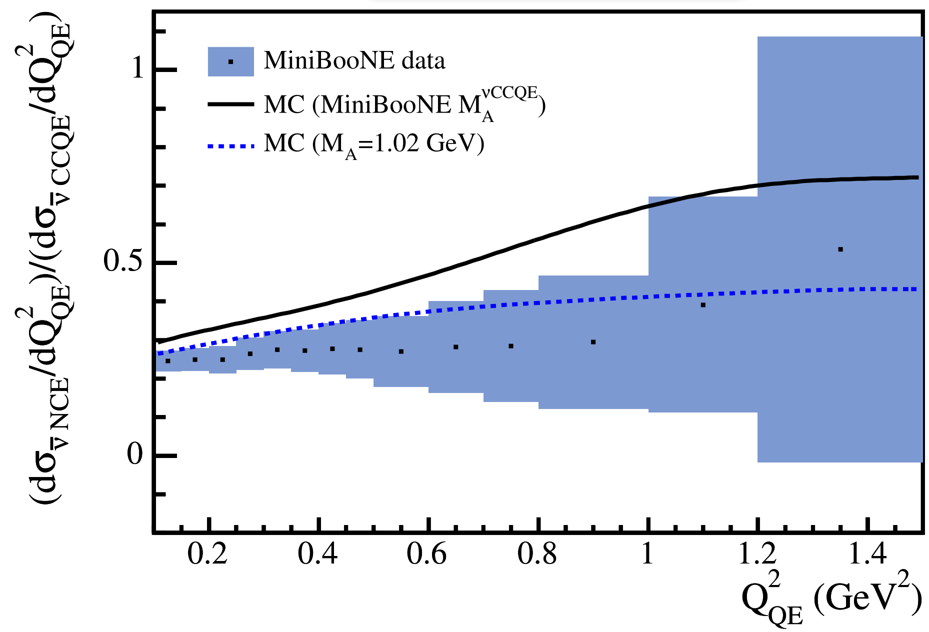
NC Elastic Scaled to CCQE

- CCQE is a ``standard candle'' to help fix new cross section results

ν NC elastic



ν̄ NC elastic



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** (2014) 012004. arXiv:1309.7257 [hep-ex].

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 $M_\chi = 50$ MeV, and $\sigma = 8 \times 10^{-36}$ cm^2.
[3]Contains beamdump neutrino flux suppression 1/44, POT, efficiency, and $\cos\theta_{e\text{-beam}} > 0.98$ cut