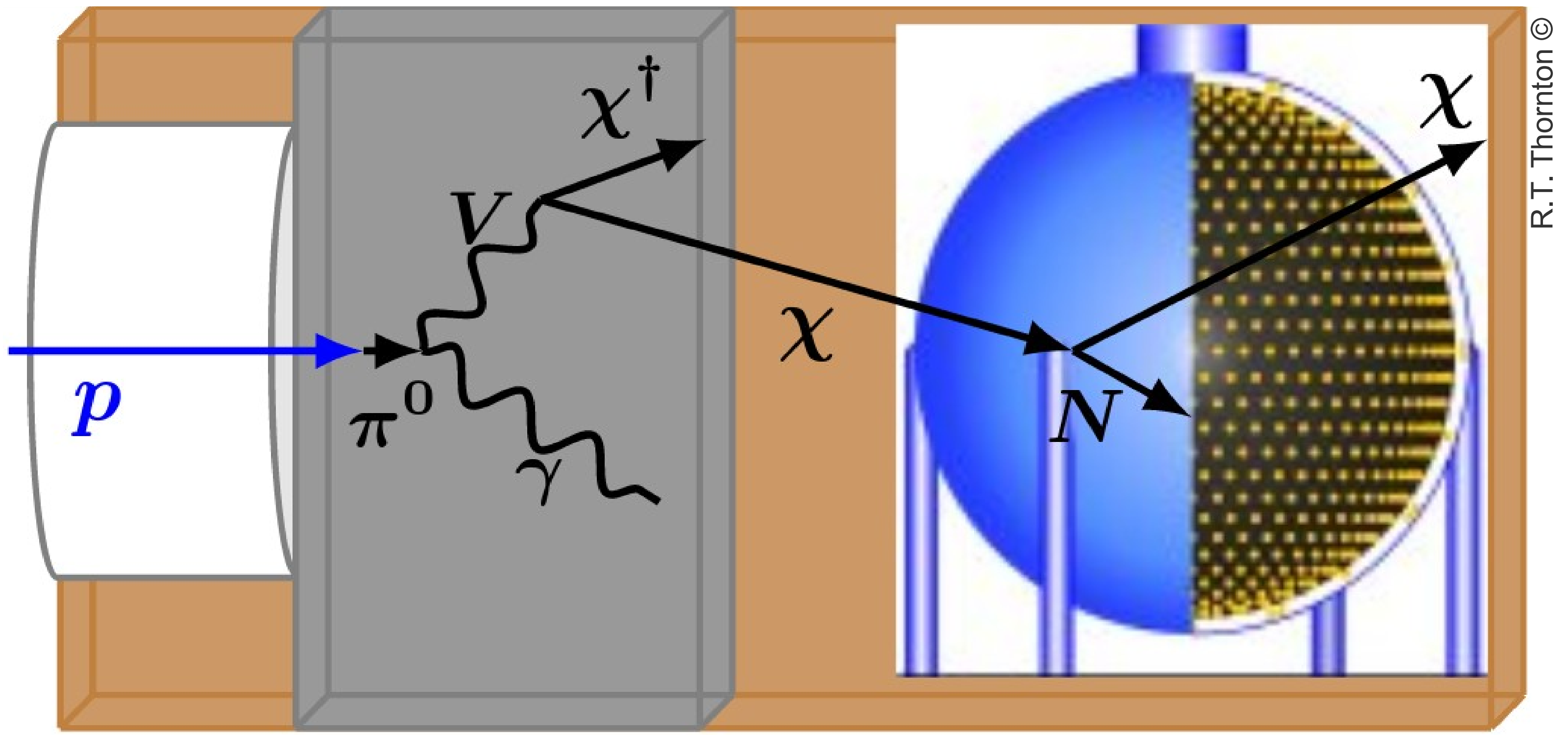

Search for Dark Matter in the beam-dump of a proton beam with MiniBooNE

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

XXXI Reunión Anual, División de Partículas y Campos, SMF
Departamento de Física, CINVESTAV, Zacatenco,
Ciudad de México, 24-26 de mayo, 2017

Outline

Motivation: Sub-GeV dark matter

MiniBooNE detector

Dark Matter search in beam-dump mode

Results

Lessons learned and future perspectives

Conclusions

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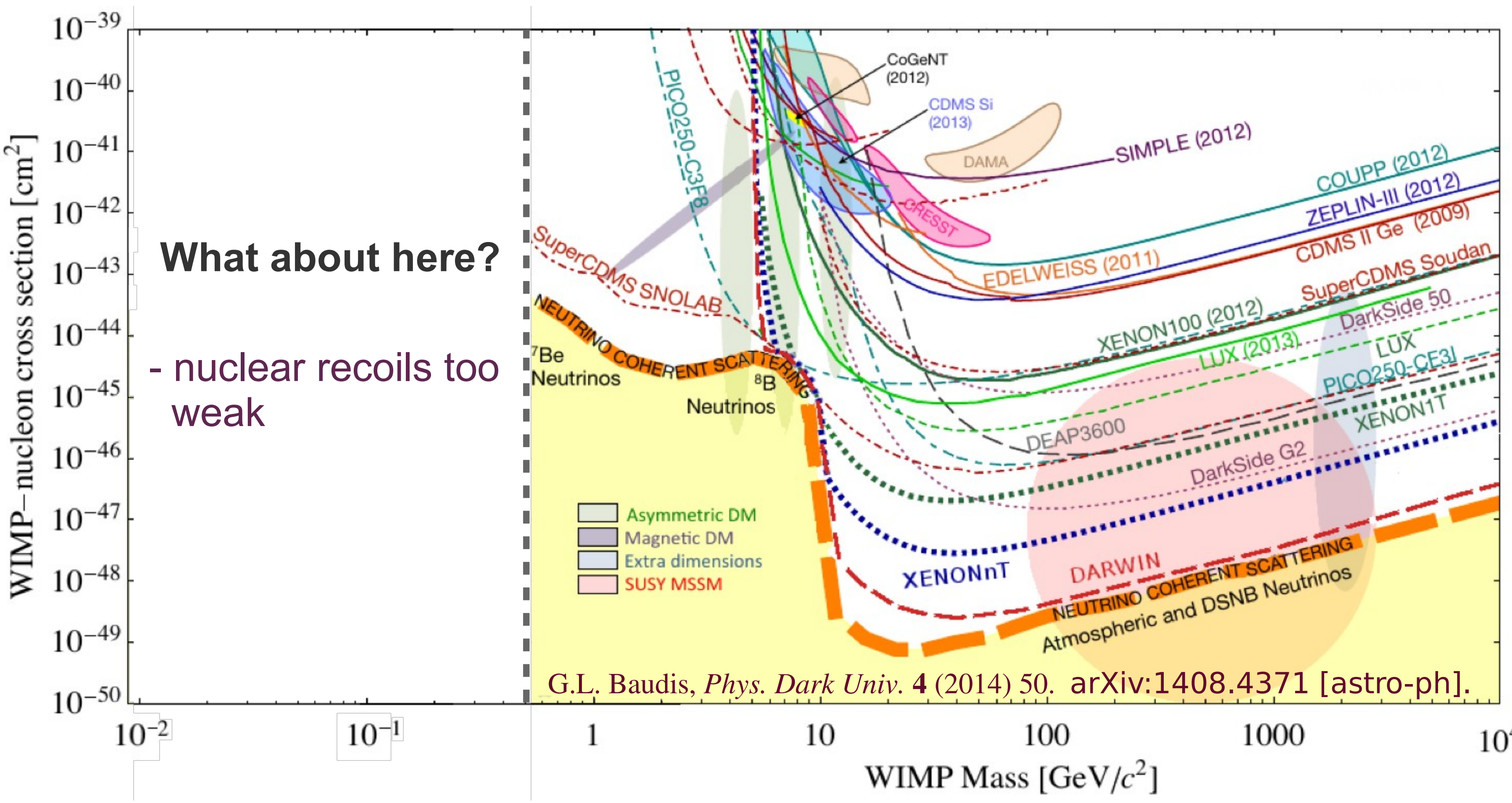
Motivation



- Sub-GeV mass range significantly less explored, but theoretically well motivated.
- Accessible, among others, with accelerator beam dump experiments.

Sub-GeV Dark Matter

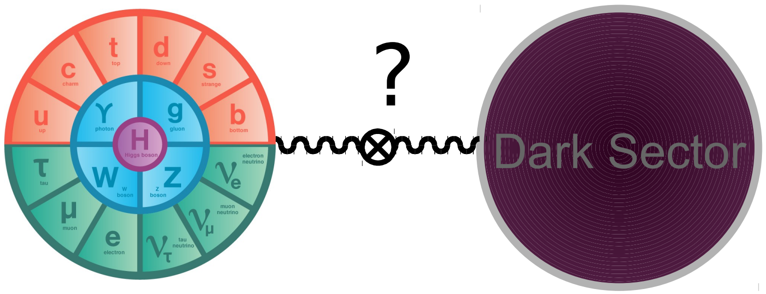
- Evidence of Dark Matter motivates extending the Standard Model to include a **“Dark Sector”** → new fields with no SM gauge charges.
- DM particles in the Dark Sector couple to the SM via a ***“mediator”***.
- Many possible ways to connect the Standard Model and the Dark Sector, constrained by SM symmetries (called ***portals***):

Vector portal → *vector mediator* V^{μ}

Higgs portal → *scalar mediator* ϕ

Neutrino portal → *fermion mediator N*

3 *renormalizable* portals to the SM

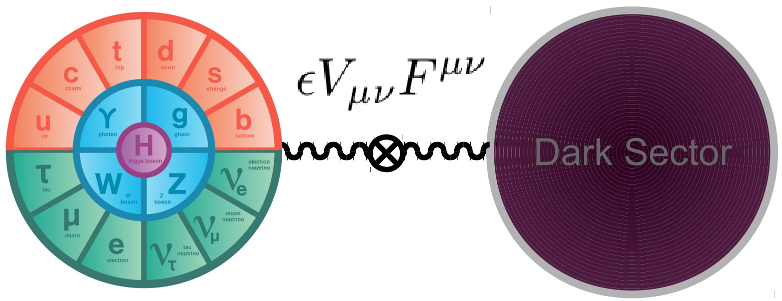


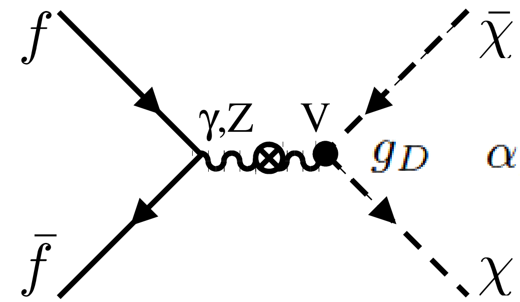
- **Vector portal** models → most viable for thermal, sub-GeV DM.

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

Minimal kinetically mixed dark photon

- A minimal extension to the Standard Model:





$\alpha_D = g_D^2/4\pi$

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

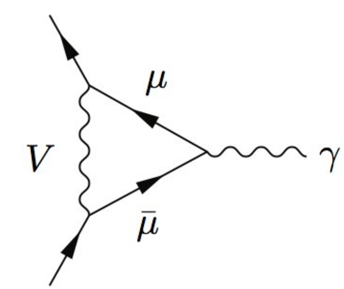
$$D_\mu = \partial_\mu - ig_D V_\mu \ , \quad g_D = \sqrt{4\pi\alpha_D}$$

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

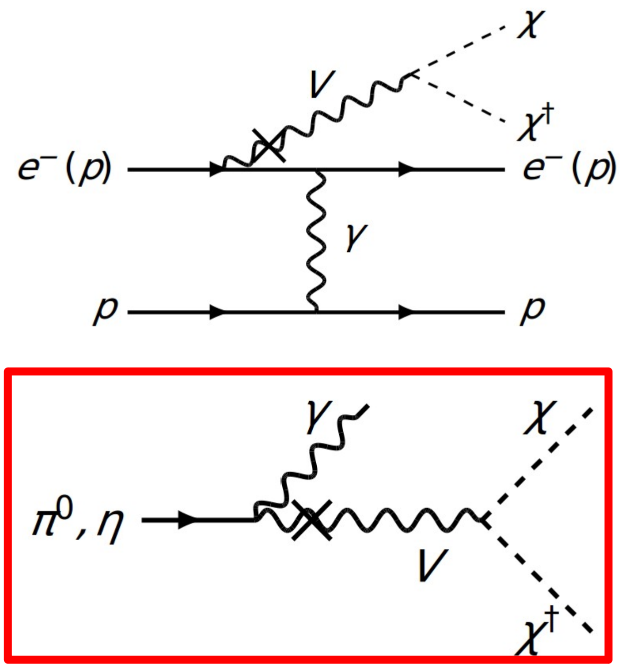


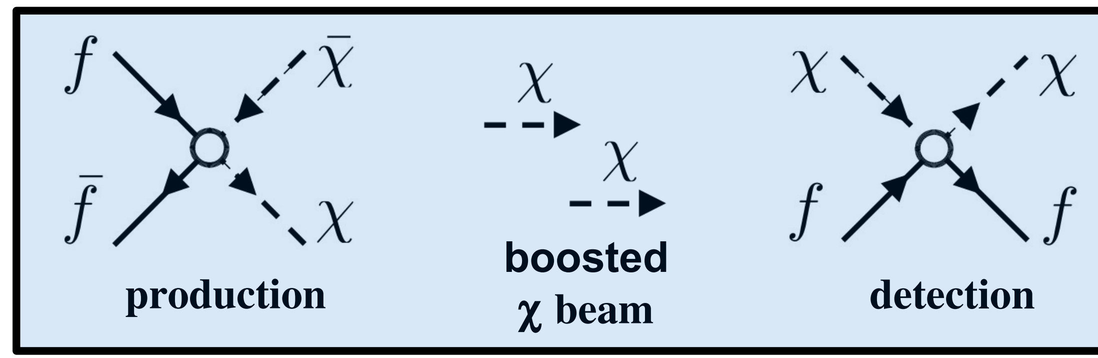
P. Fayet, Phys. Rev. D 75, 115017 (2007)
M. Pospelov, Phys. Rev. D 80, 095002 (2009)

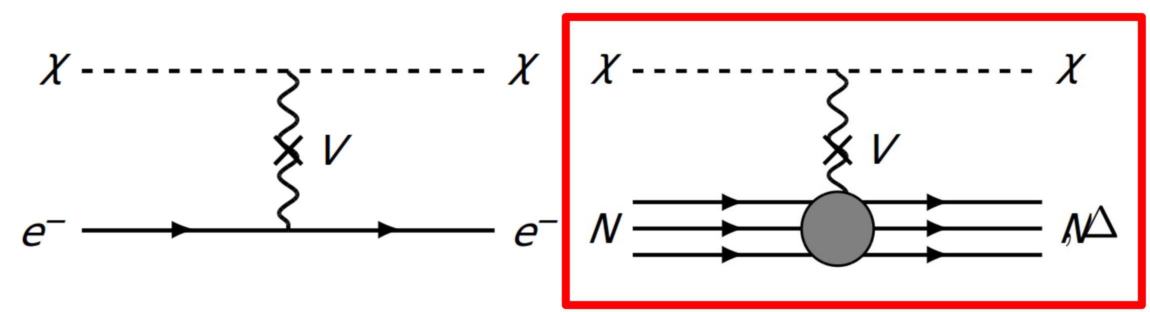
Dark Matter Beam and Detection

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

Production







Detection

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

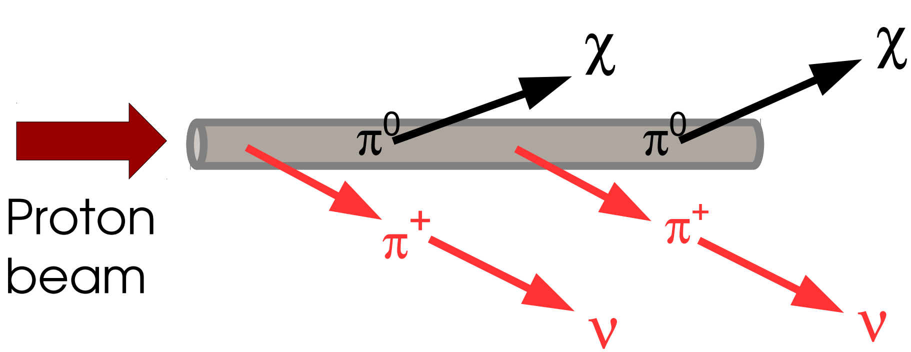
B. Batell et al., *Phys. Rev. Lett.* **113** (2014) 171802. arXiv:1406.2698 [hep-ph].
P. deNiverville et al., *Phys. Rev.* **D84** (2011) 075020. arXiv:1107.4580 [hep-ph].

Why a beam dump experiment?

- Neutrino interactions are a background to such DM search.
- A beam dump produces significantly fewer neutrinos.

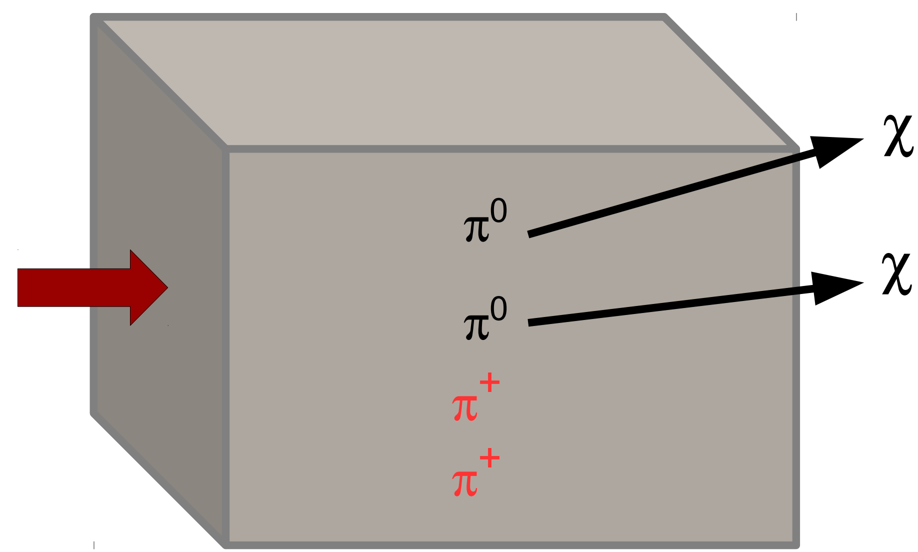
Neutrino production target (thin)

Charged mesons escape and produce ν's



- π^0 decay quickly into dark sector
- π^+ decay with longer lifetime into high-energy neutrinos

Beam dump (thick target)



- π^0 decay quickly into dark sector
- π^+ absorbed before decay to ν's (or DAR to low-energy ν's)

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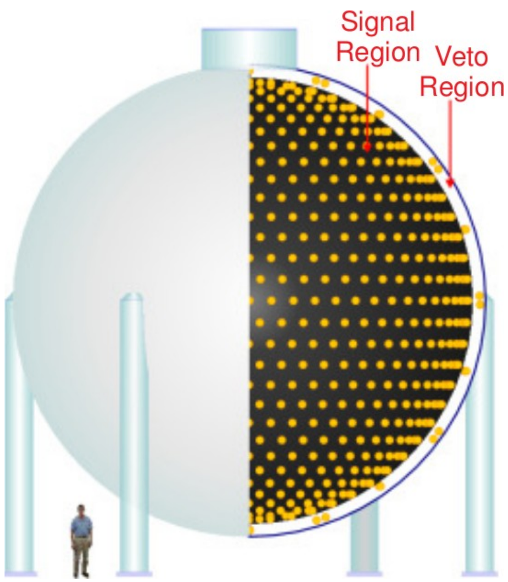
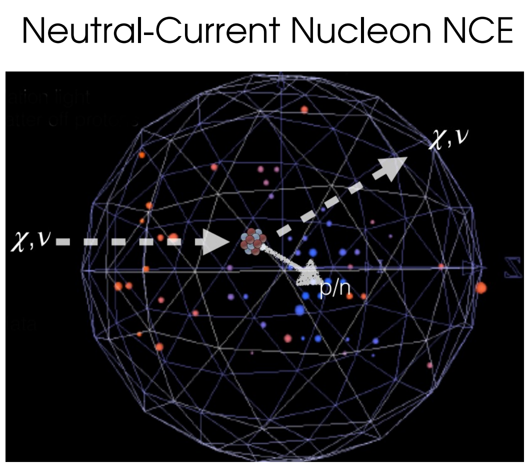
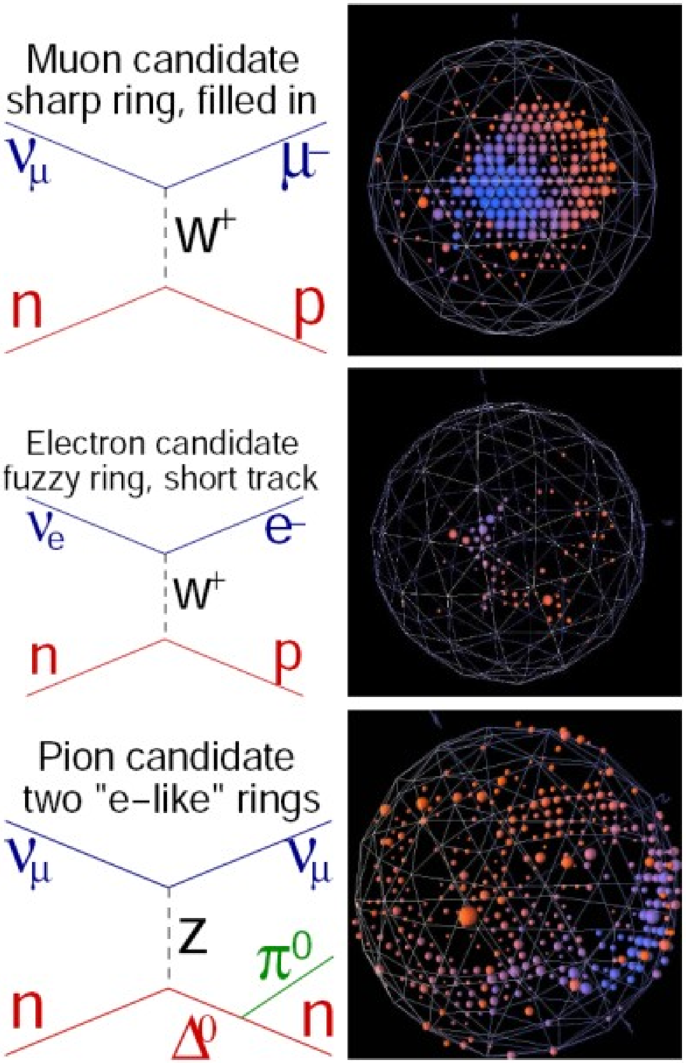
The MiniBooNE detector

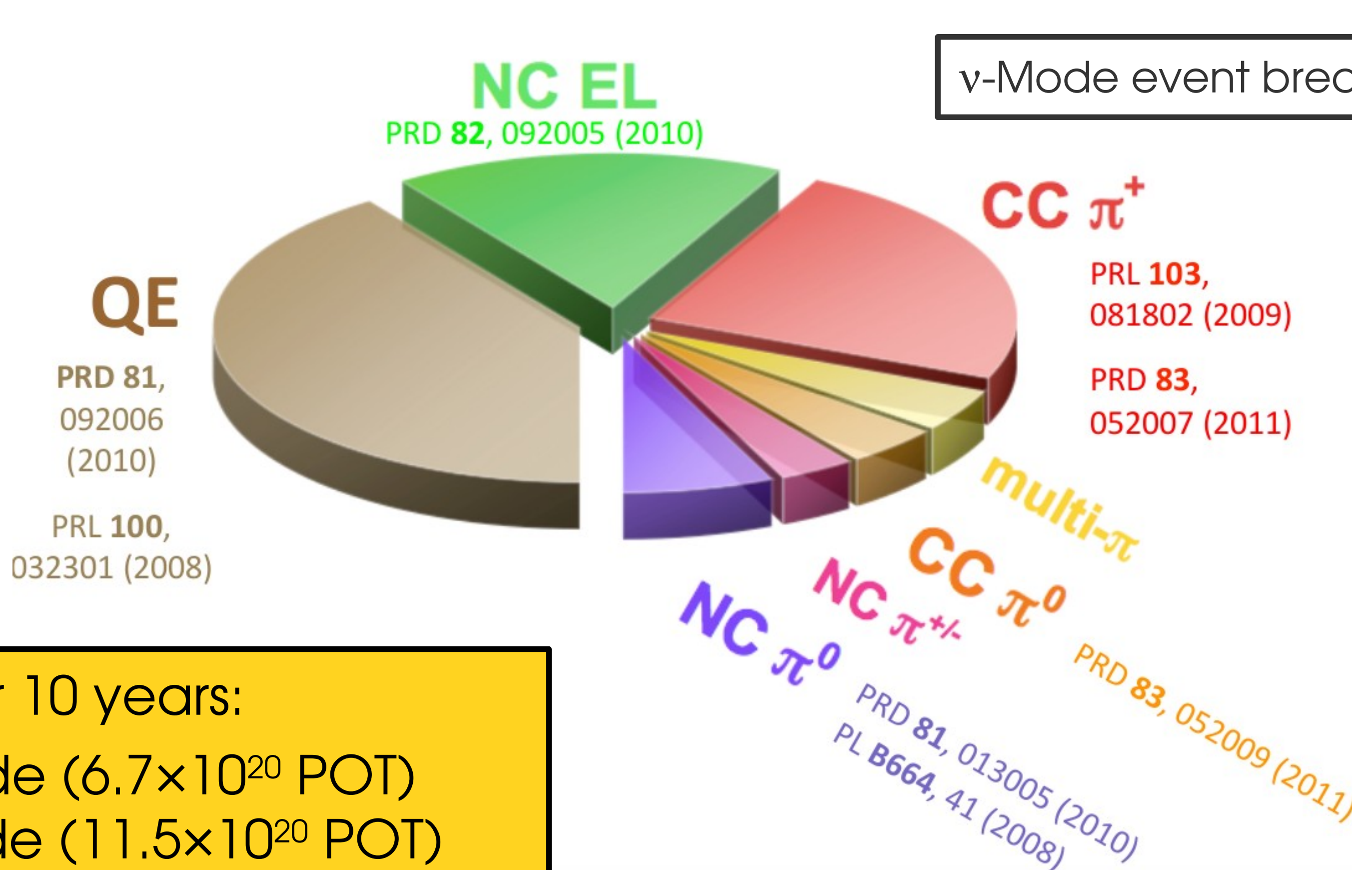






- 800 tons of mineral oil (CH_2)
- Cherenkov detector with some scintillation from trace fluors
- 1280 inner and 240 veto PMTs
- Ran for >10 yr in ν and $\bar{\nu}$ modes and has published 27 papers.
- **The detector is well understood**

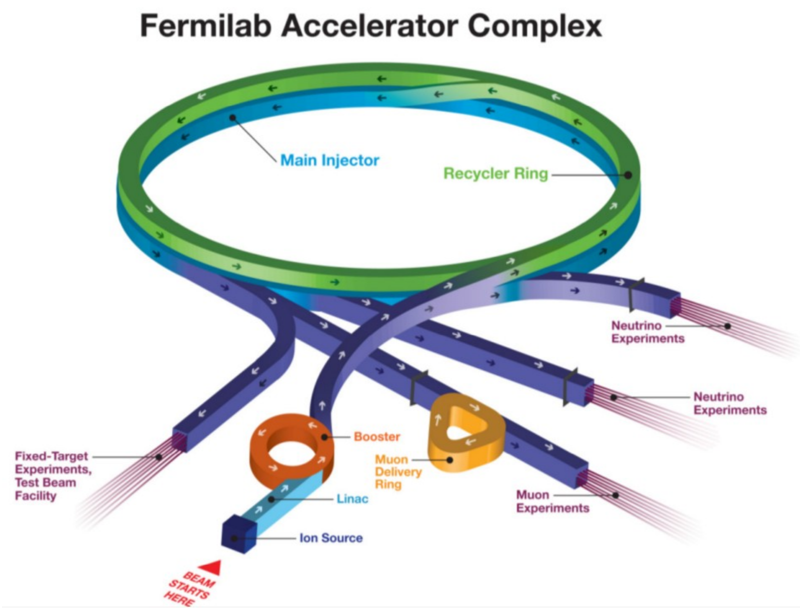
MiniBooNE before "-DM"

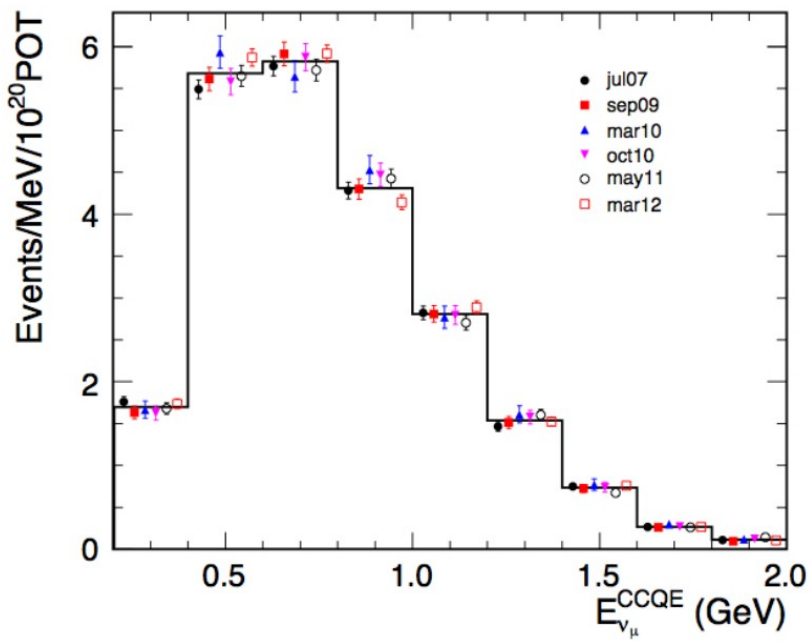


- Ran for over 10 years:
  - ν-mode (6.7×10^{20} POT)
  - $\bar{\nu}$-mode (11.5×10^{20} POT)
- 11 oscillation papers
- 14 cross section and flux papers
- 19 Ph.D. Theses

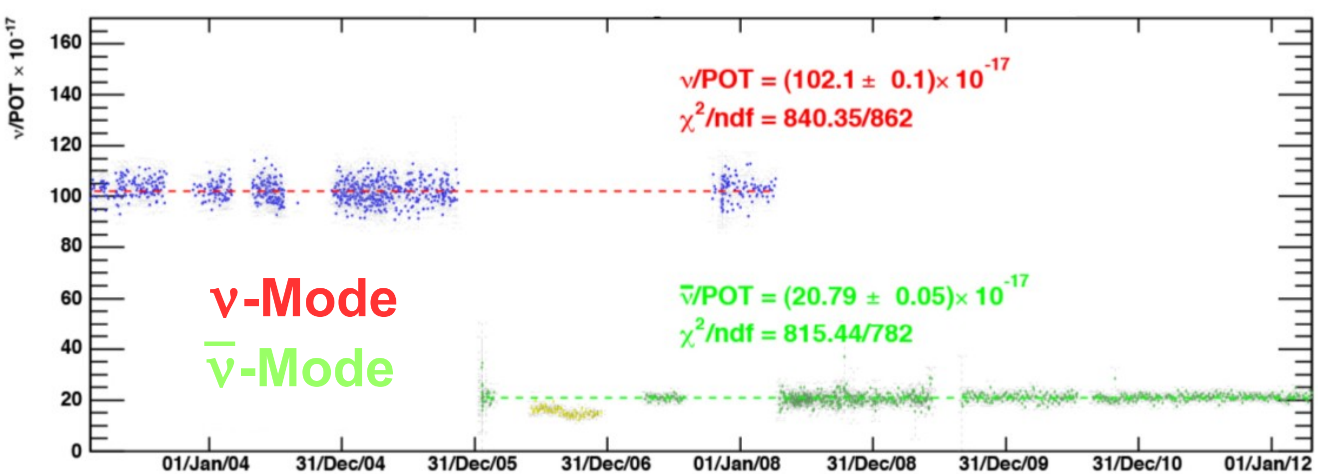
See our website for a full list of publications. http://www-boone.fnal.gov/

Booster Neutrino Beam (BNB)



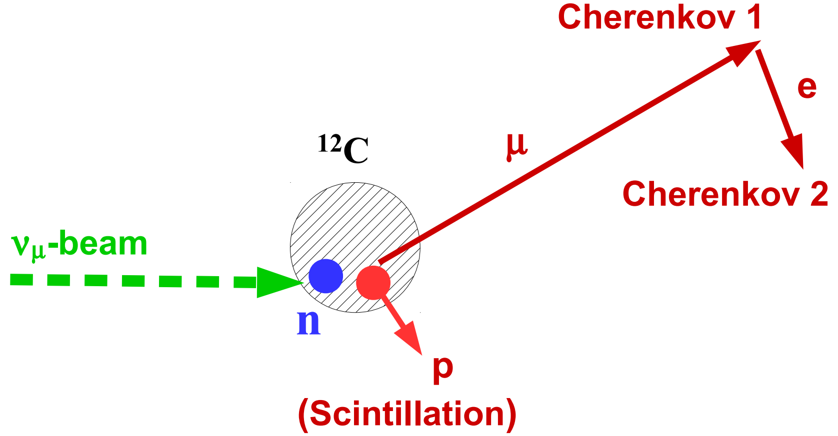


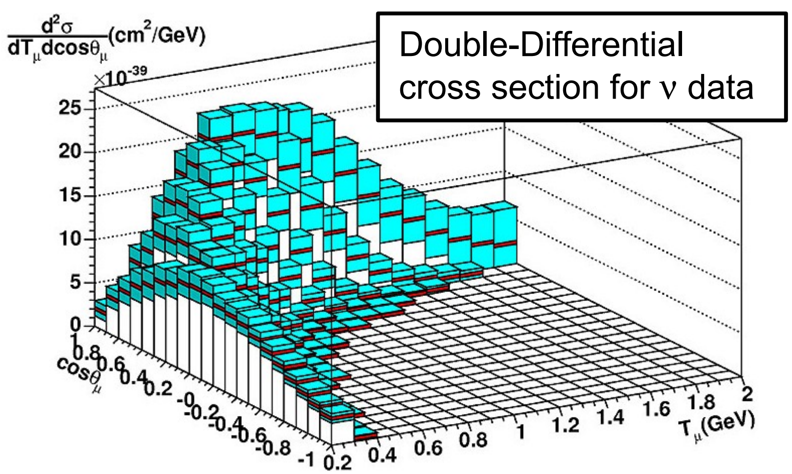
- Beam: 8 GeV protons
- Target: Be
- Distance to MiniBooNE: 541 m
- Stable and well understood



CCQE and NCE events

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

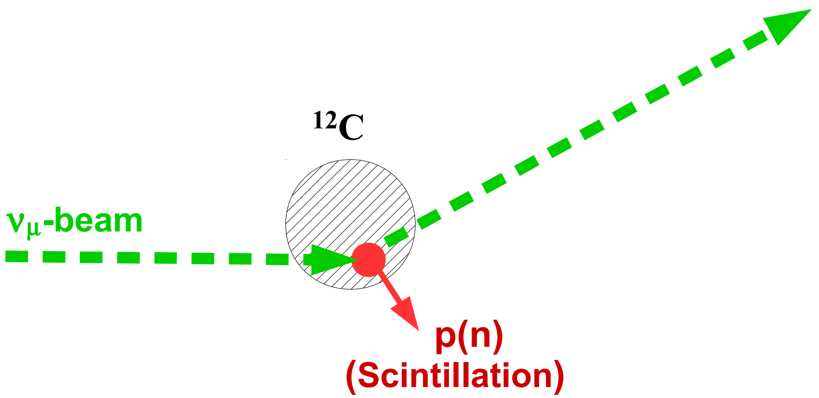


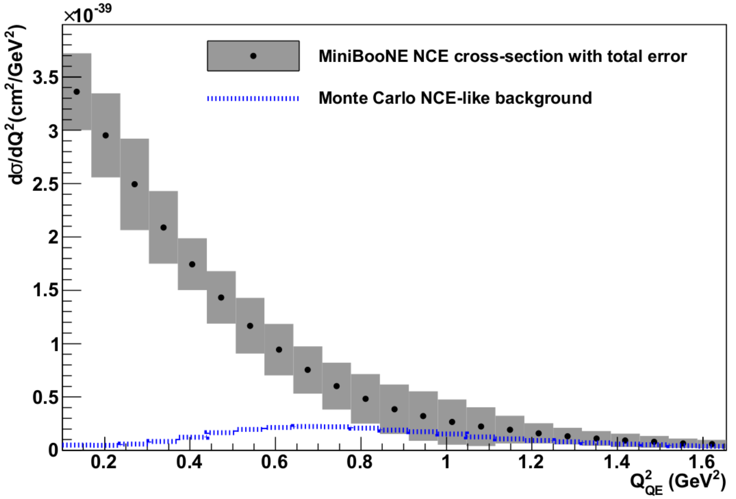


- First double differential cross-section measurement.

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]

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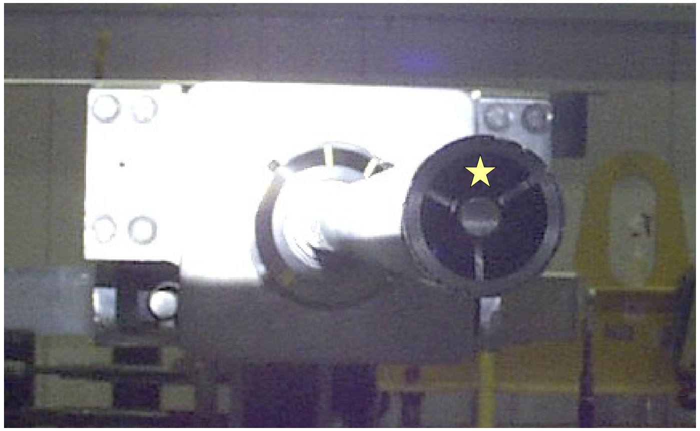
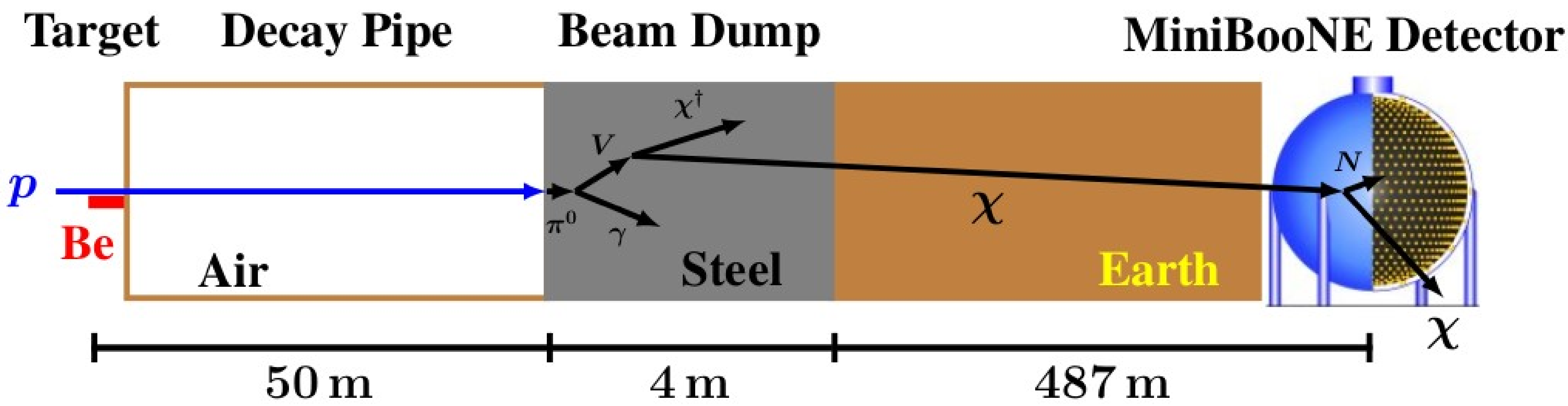
Beam Dump (Off Target) mode

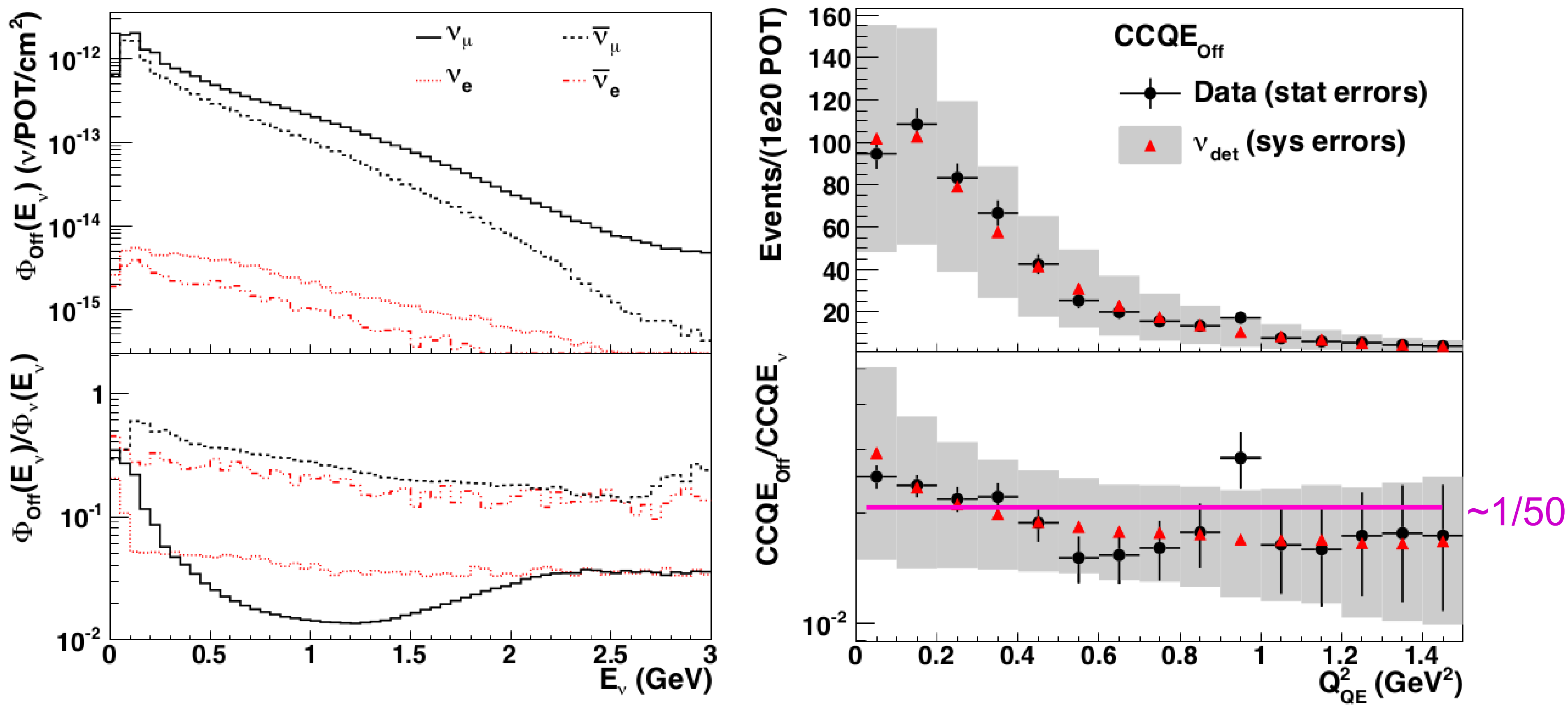
- Reduce ν production by steering beam to miss the target.
- Beam impacts on the beam dump
- Charged mesons absorbed in the steel beam dump before decaying → reduces the neutrino flux.



MiniBooNE target assembly



Neutrino flux reduction

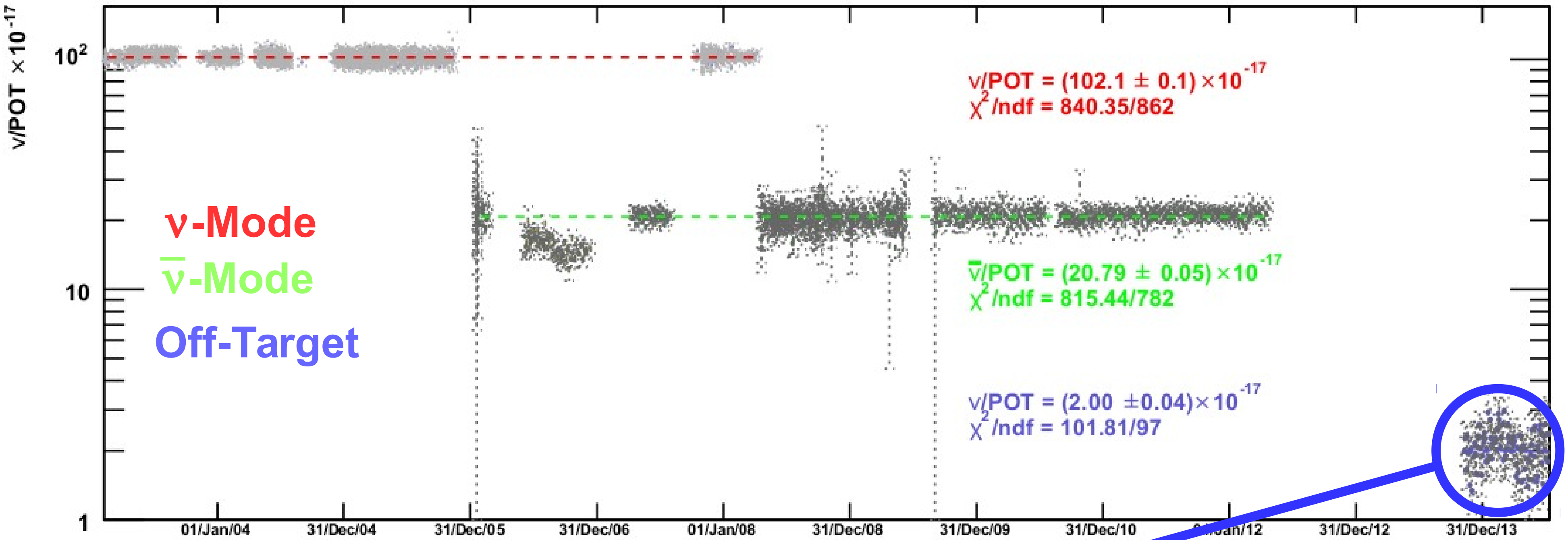


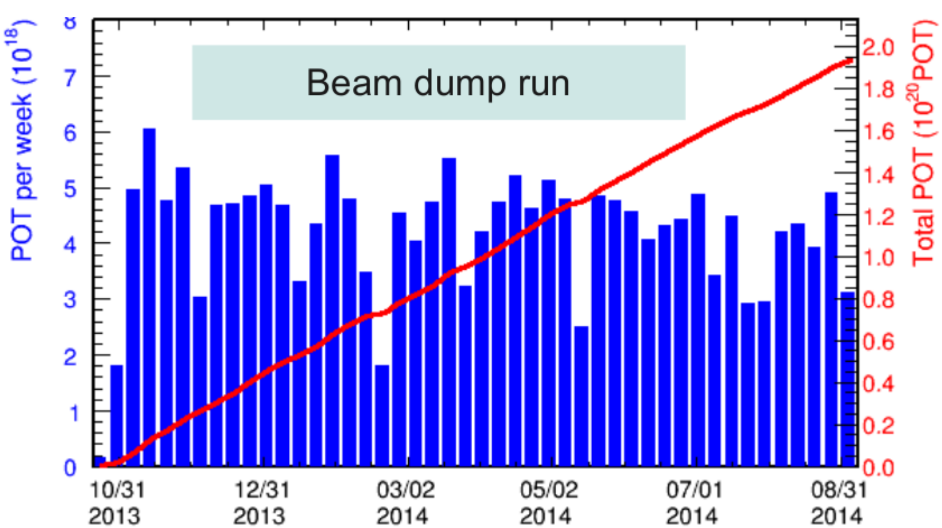
Off-Target flux: Φ_{off} = (1.19 ± 1.1)×10^{-11} ν/(POT · cm^2), $0.2 < E_\nu < 3$ GeV

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

- Event rate reduced by factor of ~50.

Off Target beam stability



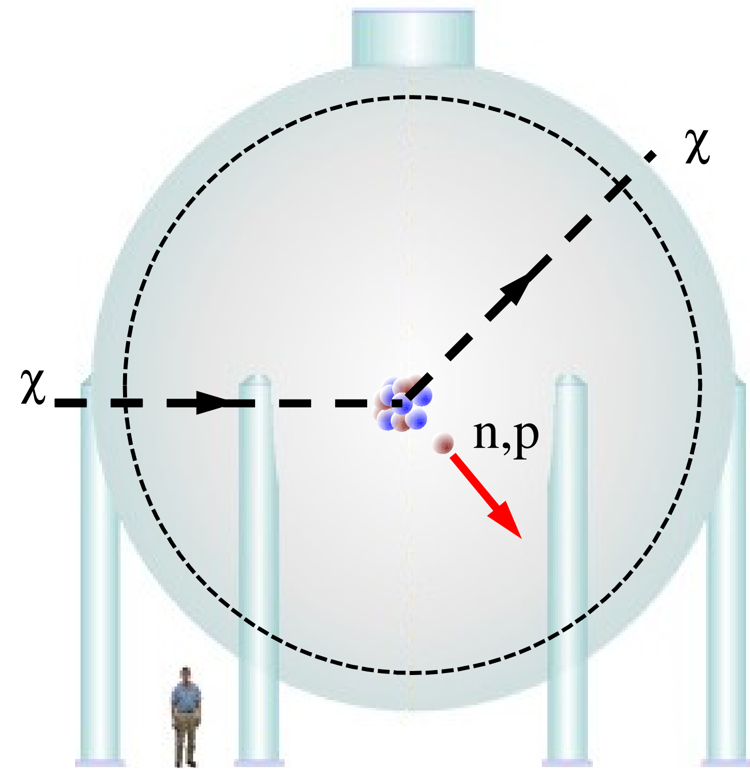


- Ran 9 months, Nov 2013 to Sep 2014, collected 1.86×10^{20} POT.
- ν/POT decreased by ~50 compared to ν Mode.

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

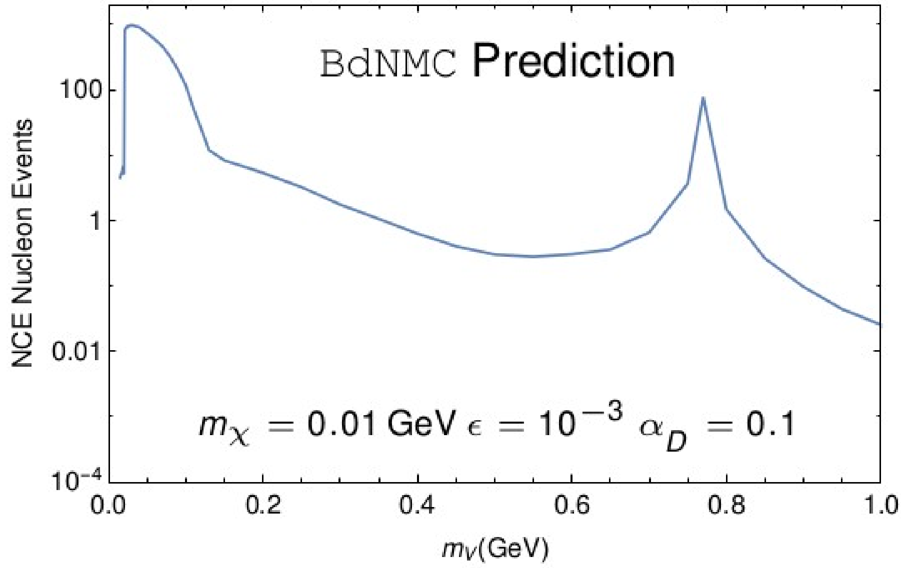


Based on the $\bar{\nu}$ NCE cross section analysis.

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

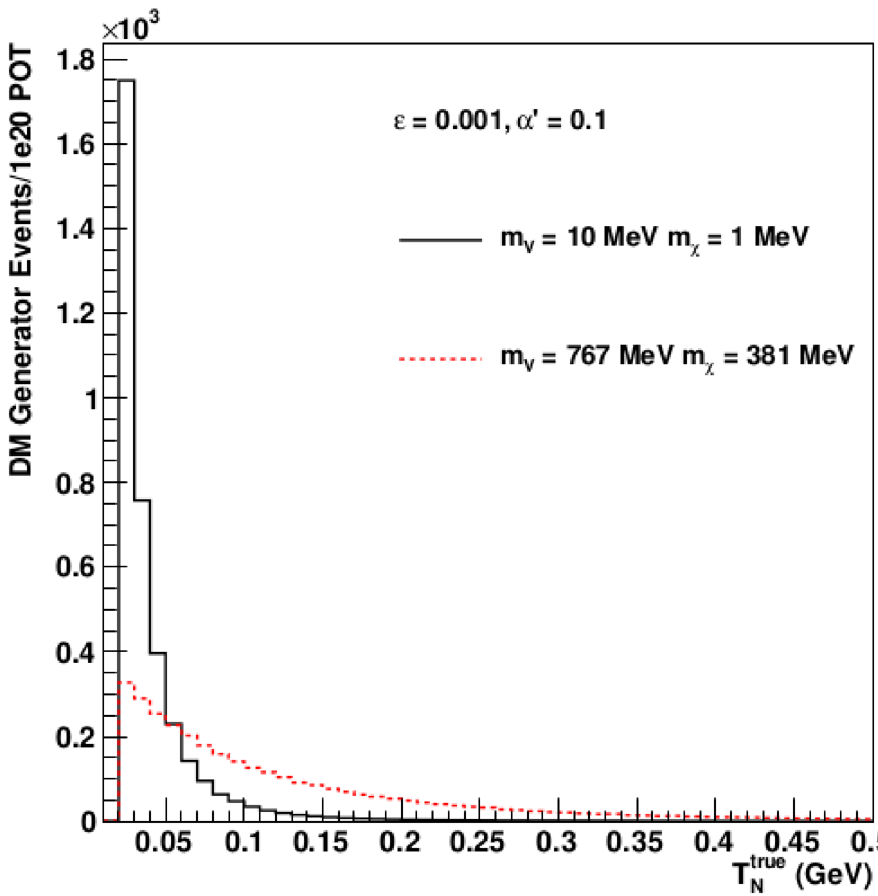
Dark Matter generator

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



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

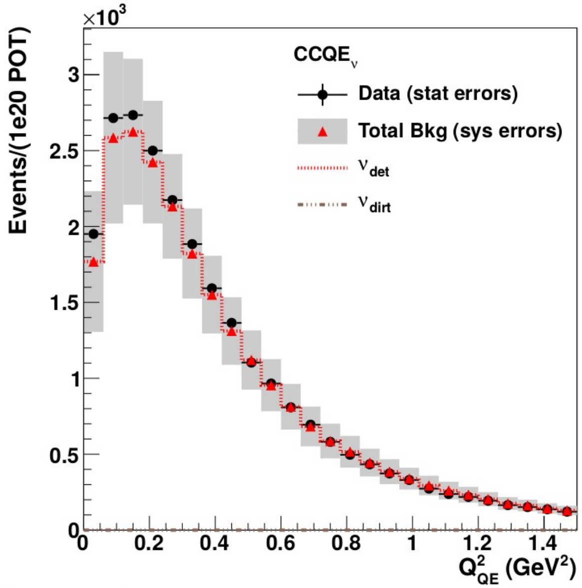
- π^0/η event lists from beam MC used to generate π^0 and η distributions.

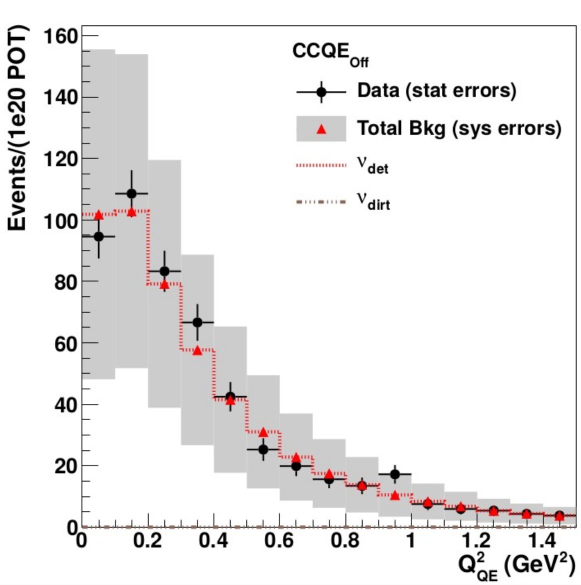


Fit strategy

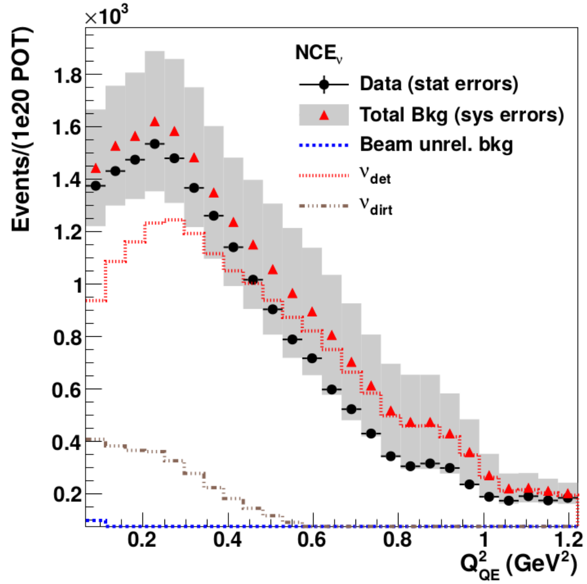
- Use 4 distributions:

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



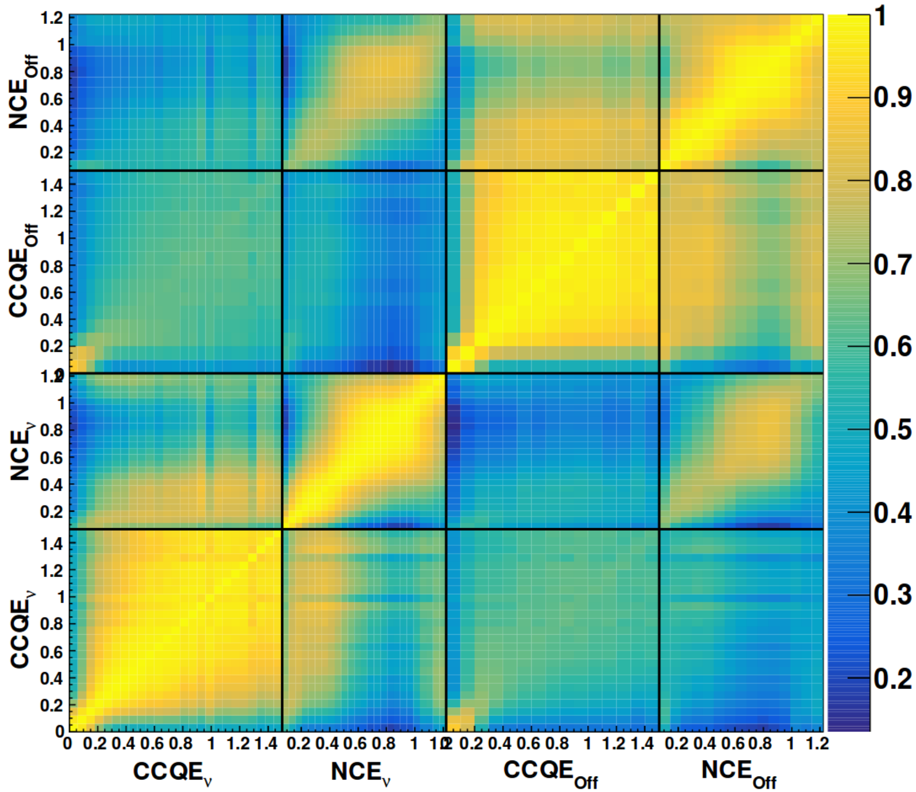


- CC ratios help reduce flux uncertainties.
- NC ratios help reduce neutrino cross section uncertainties.

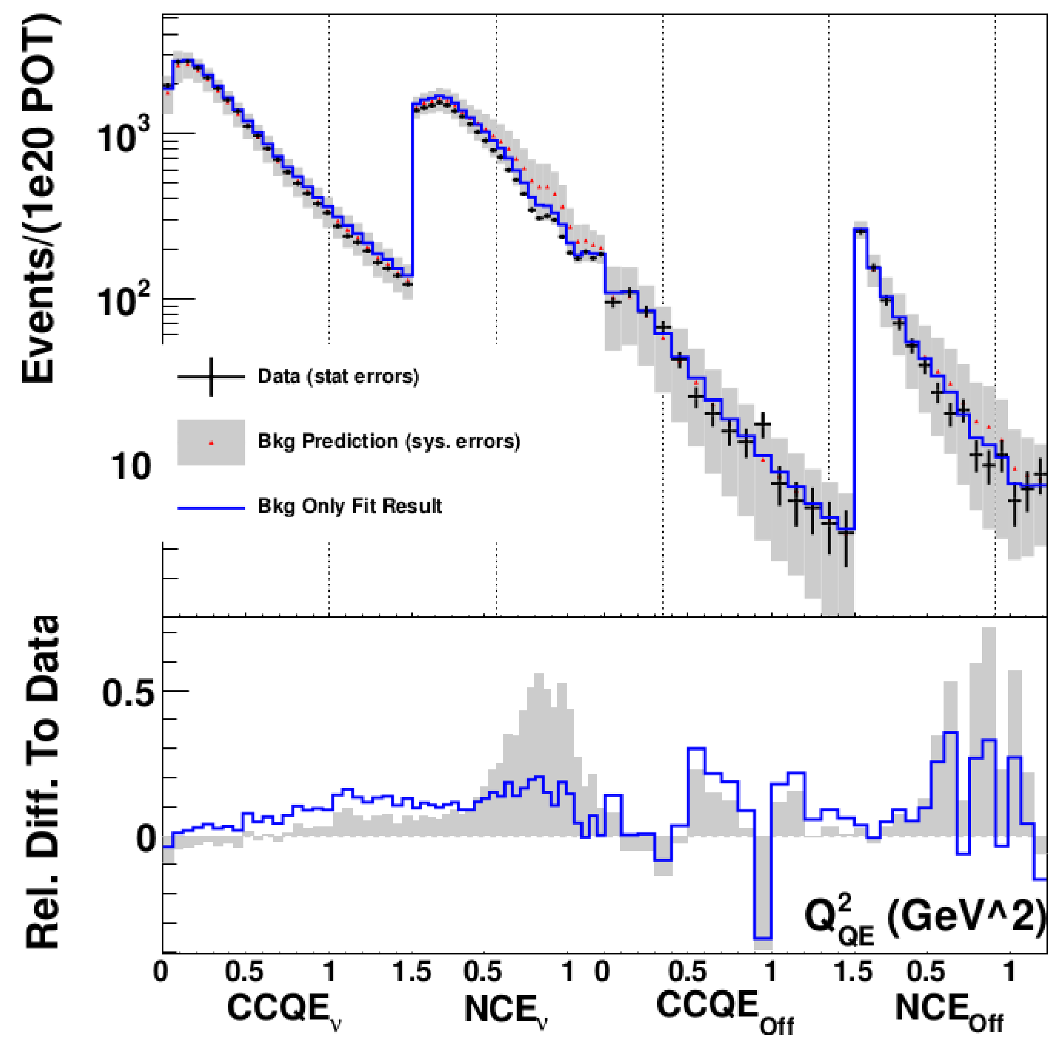


NCE_{Off} Signal

Simultaneous Fit



Covariance matrix



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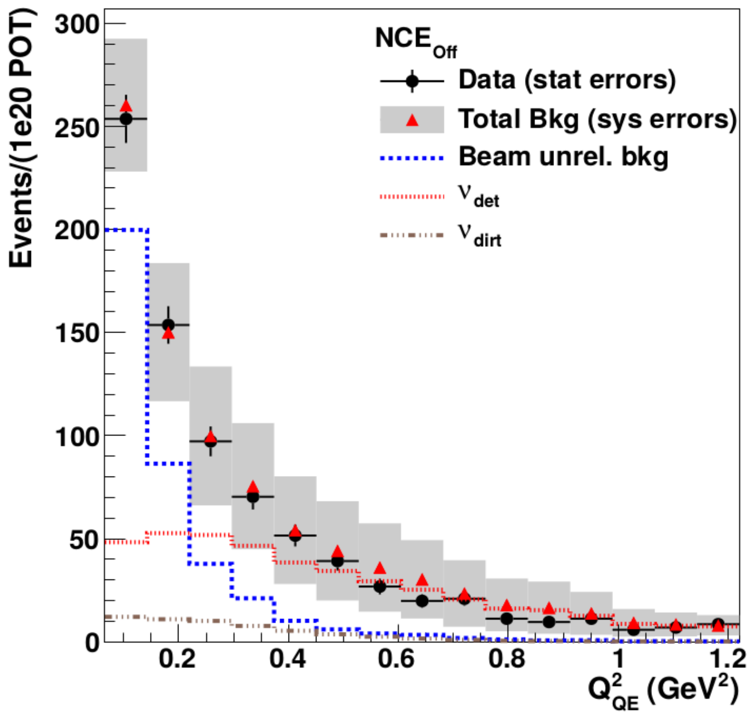
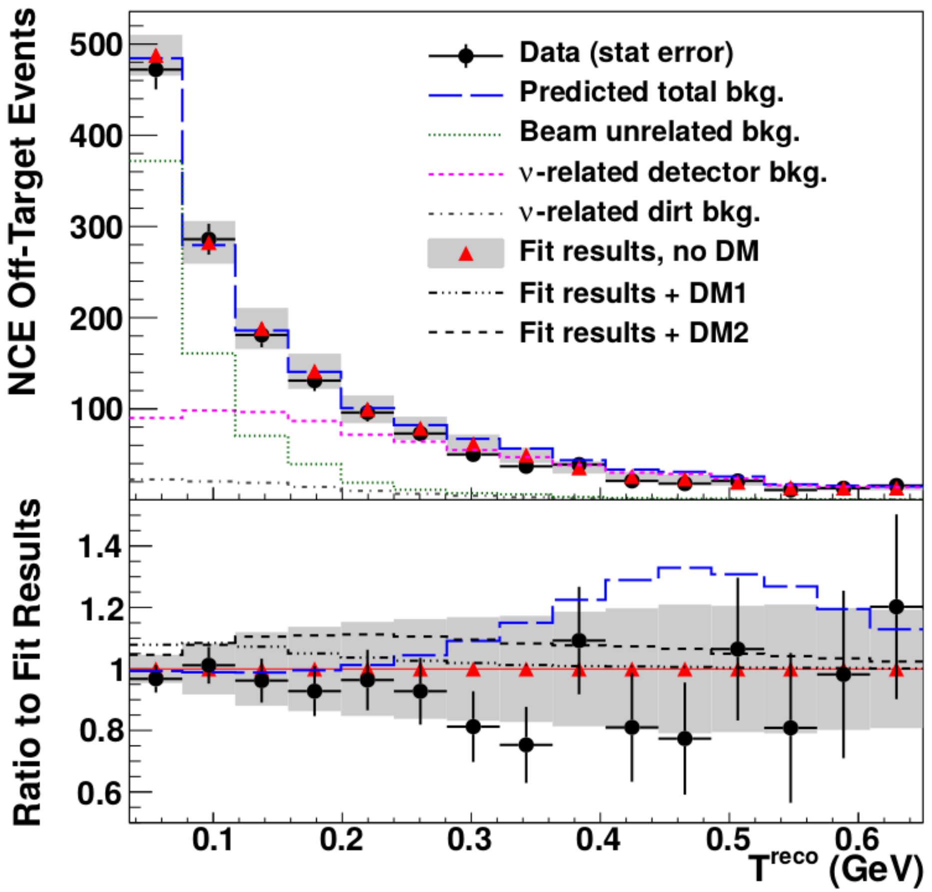
NCE_{Off} distribution

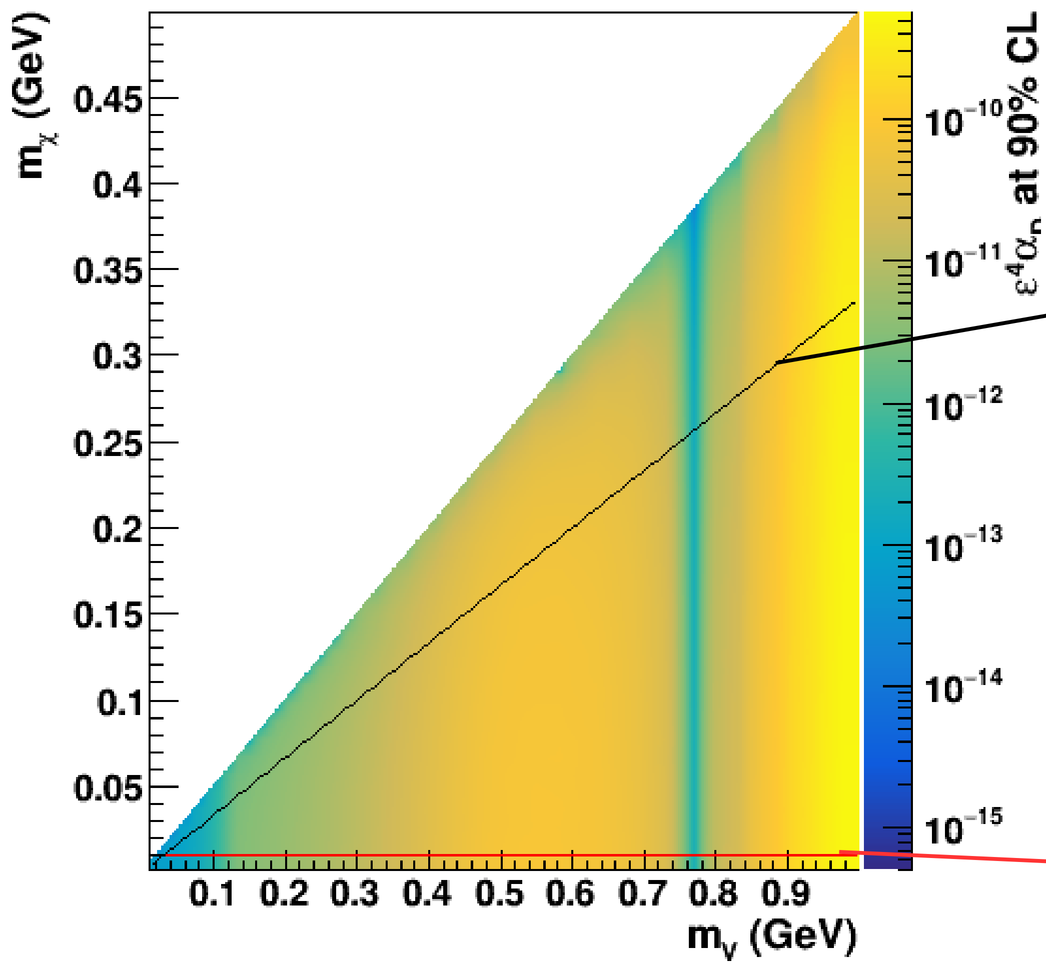


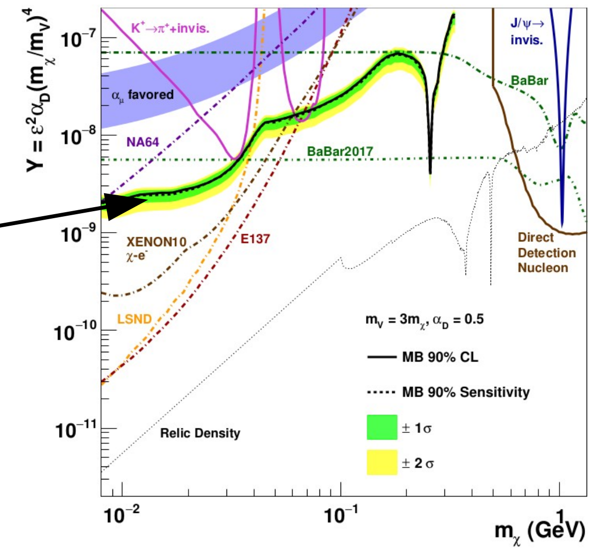


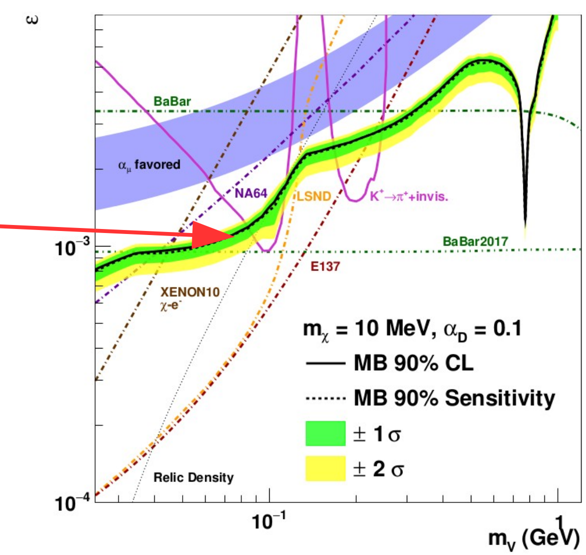
	#events	uncertainty
Beam unrel. bkg	697	
Beam rel: ν_{det} bkg	775	
Beam rel: ν_{dirt} bkg	107	
Total Bkg	1579	34% (pred. sys.)
Data	1465	3% (stat.)
Fit Results	1548	13% (fit effective error)

- Data consistent with background-only.
- Systematics dominated.
- Constrain samples reduce systematic error to 13%.

90% CL limits

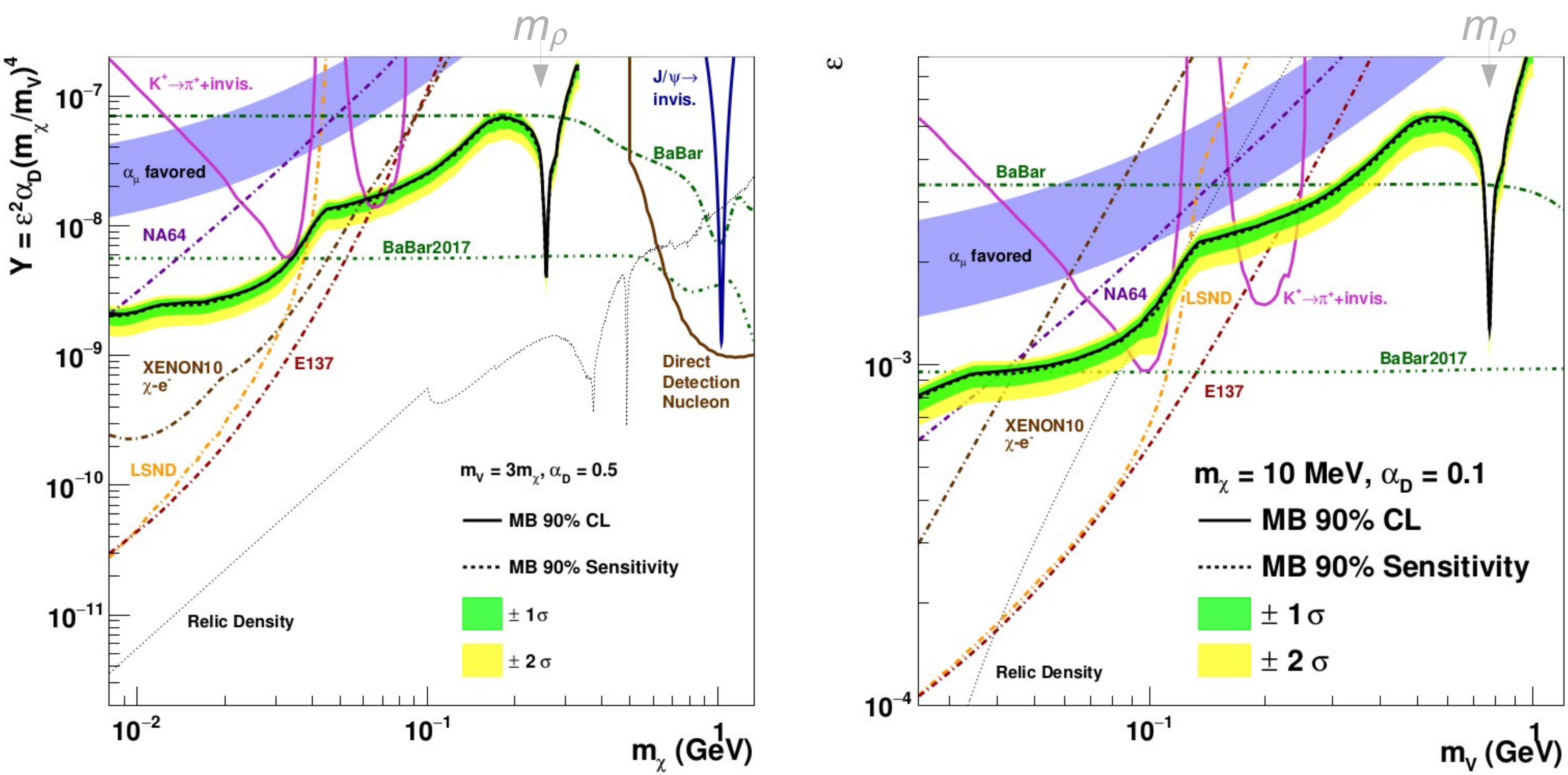






- Only considered on-shell decays ($m_V > 2m_\chi$)
- CL limit on $\boldsymbol{\varepsilon^4\alpha_D}$ for a given $\boldsymbol{m_V}$ and $\boldsymbol{m_\chi}$.
- Slice to compare to other experiments.

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 < m_χ < direct detection.

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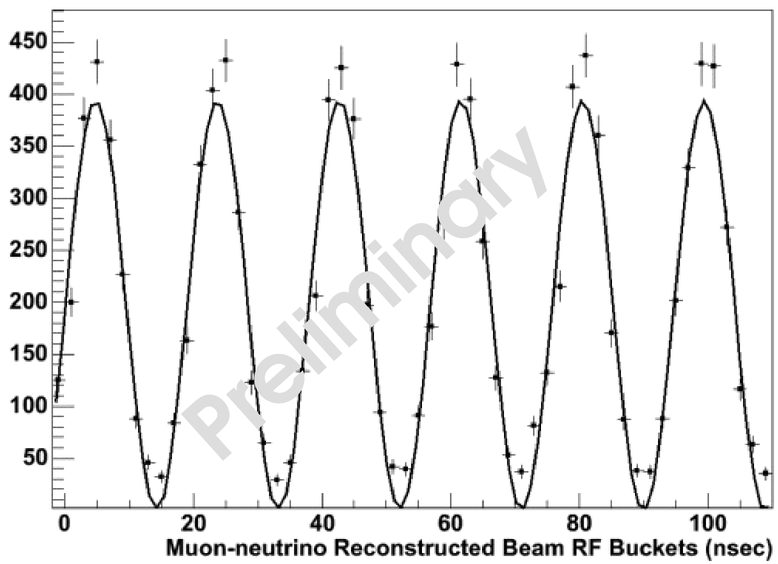
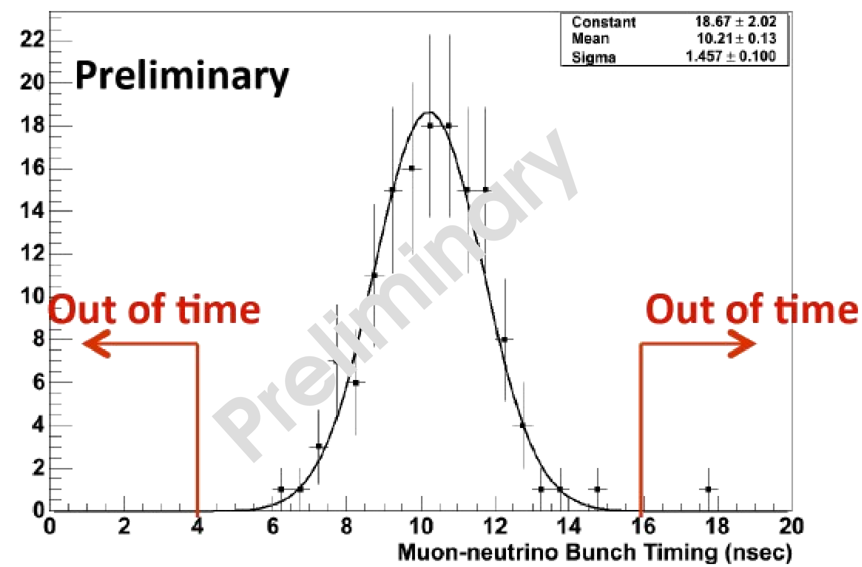
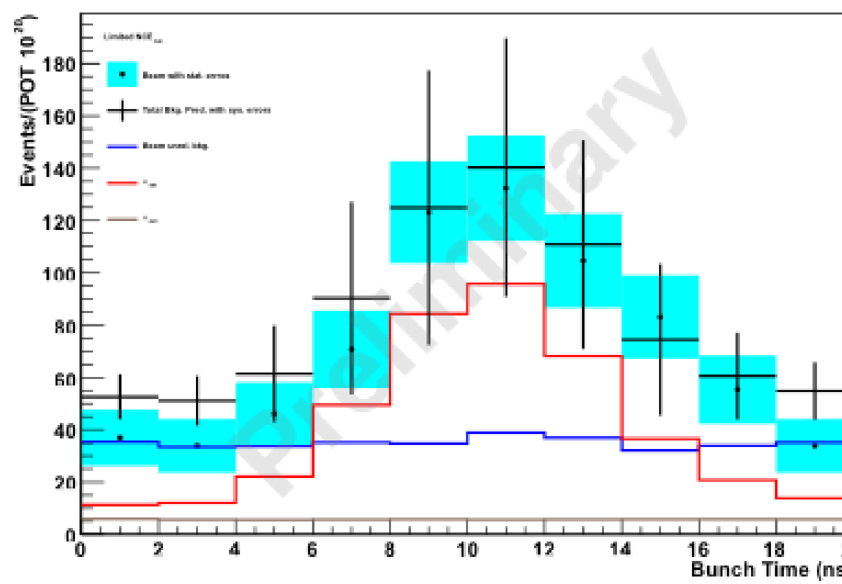
- Understand the Backgrounds
  - Used a decade worth of data to reduce systematic errors.
  - Large detector w/veto → reduce events from dirt around it.
  - Beam-unrelated backgrounds measured with 12 (2) Hz random trigger in off-target (ν) Mode.
- Nuclear physics must be considered
  - Final sensitivity affected by uncertainties from nuclear effects (eg. binding energy, Pauli blocking).
  - Honest sensitivity estimate must include a decent nuclear model.
- Correlations can be very helpful
  - Include sideband analyses (samples may be correlated)
  - Correlations → constrained systematic uncertainties in signal sample.

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-DM Elastic

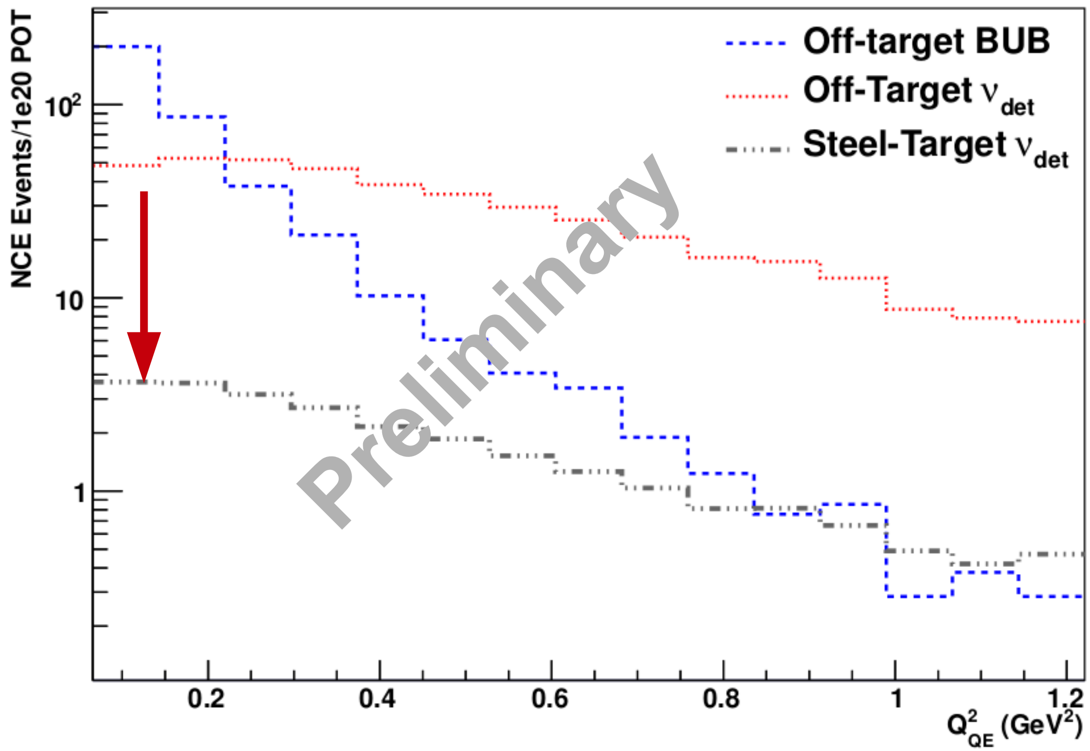
- MiniBooNE searched for $\nu_\mu \rightarrow \nu_e$ oscillations.
- Excellent electron tracker.
- $\nu_e + e \rightarrow \nu_e + e$
  is dominant background
  → clean SM prediction.
- Connected to low-energy excess from oscillation search.

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 "strobe" events.

Future: a dedicated beam dump

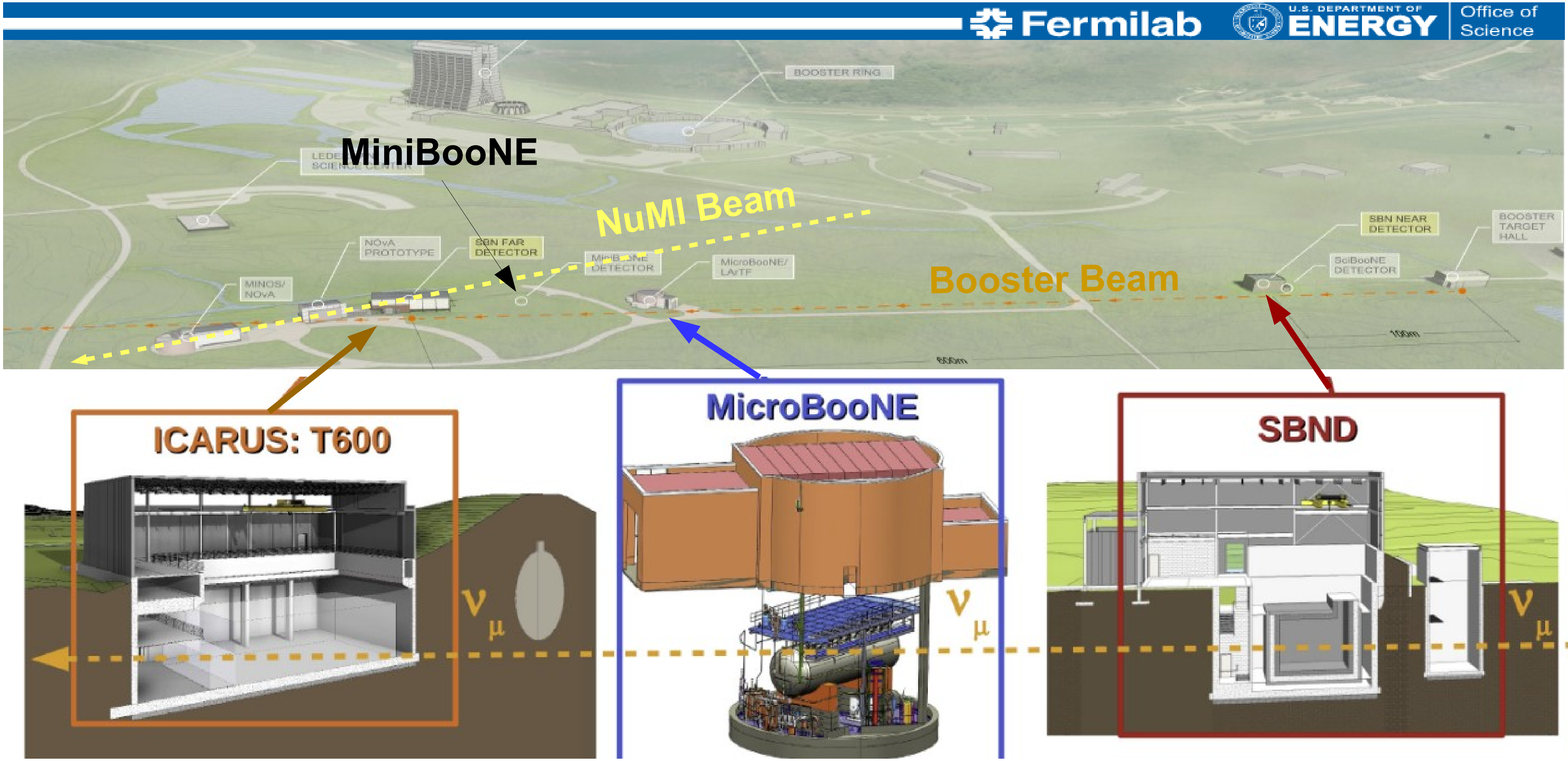
- Off-tgt mode ν's also from:
  - proton beam halo "scraping" against material
  - Proton interactions with air in the decay pipe
- Idea: *
  - remove BNB target and focusing horn.
  - Replace with dedicated steel dump at end of beam pipe.



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

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

Short Baseline Neutrino (SBN) program



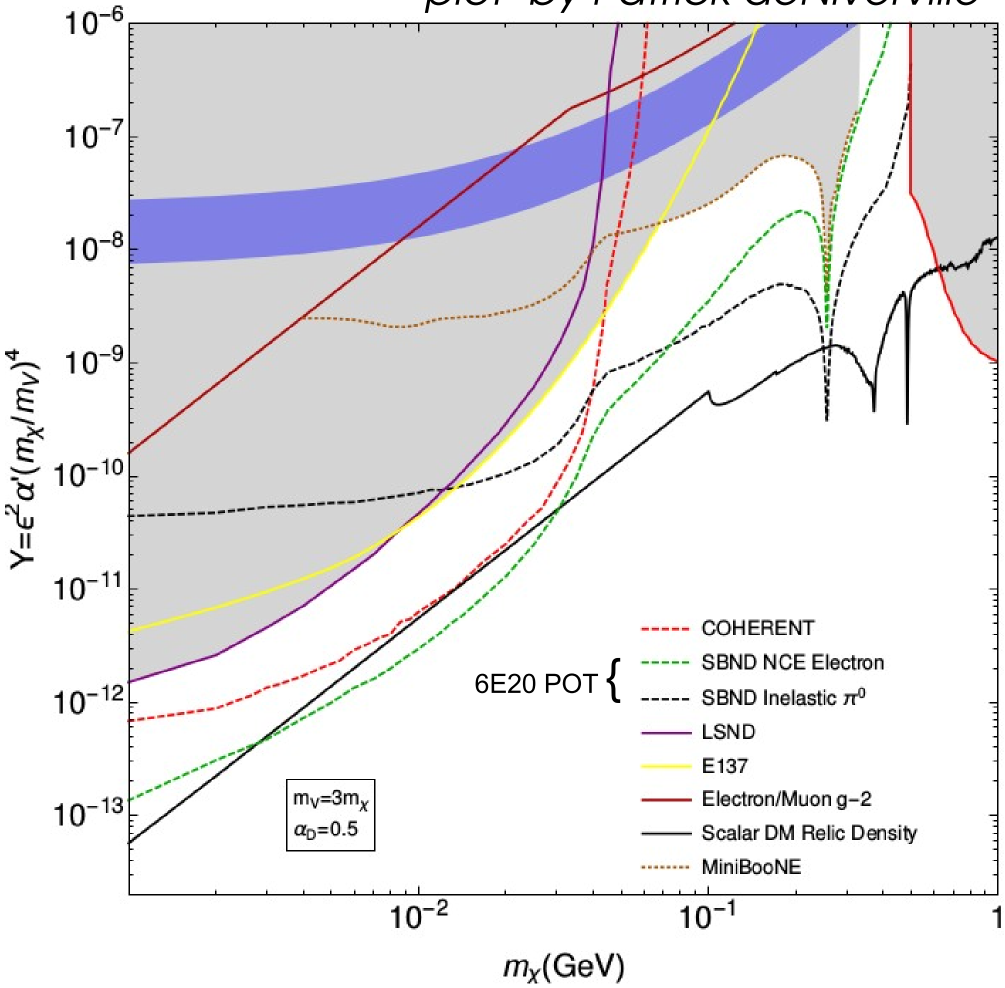
- Motivated by LSND/MiniBooNE to study ν oscillations. To begin operations in 2018.
- Short Baseline Near Detector (**SBND**) → Ideal for beam dump sub-GeV DM search.

DM search with SBND

e & π^0 channel

- SBDN closer to target ⇒ increased signal rate (~x9).
- Signal/Background estimates robust, learned from MB N-DM search.
- π^0 (*e*) good at high (low) masses - complementary to each other.
- Improve on current MiniBooNE limit by an order of magnitude.
- Require improved beam dump

plot by Patrick deNiverville



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- 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 uncorrelated backgrounds dominant.
- 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. (2017), arXiv:1702.2688 [hep-ex].

Backups

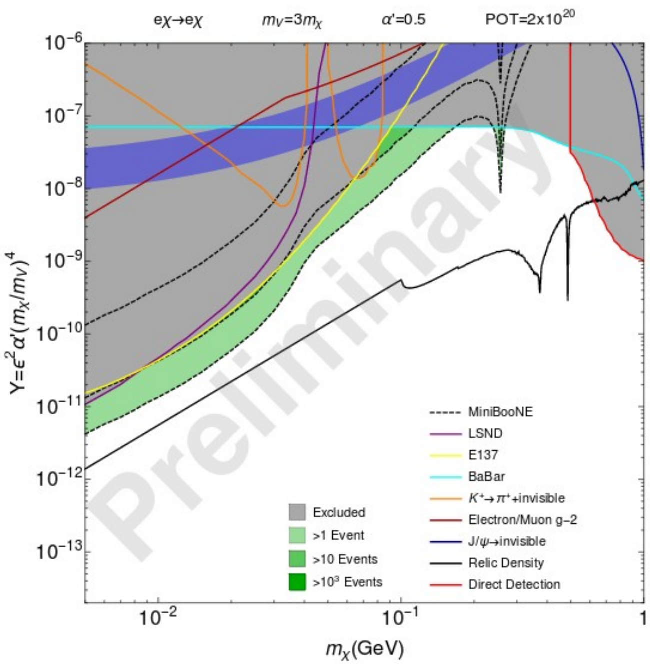
Previous beam dump / Fixed Target experiments – Proton Beams

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	0.32pA*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]**

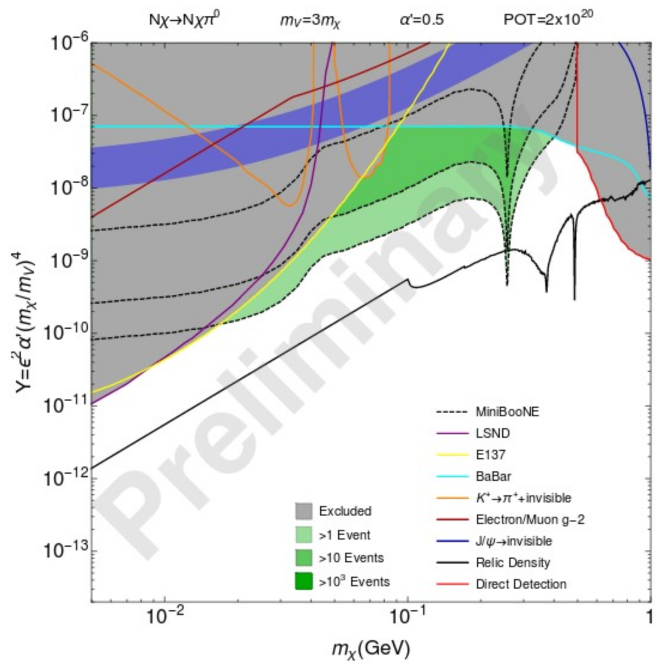
Table by R.T. Thornton, Indiana University Nuclear Physics Seminar, Nov. 21, 2014

Future MB analyses

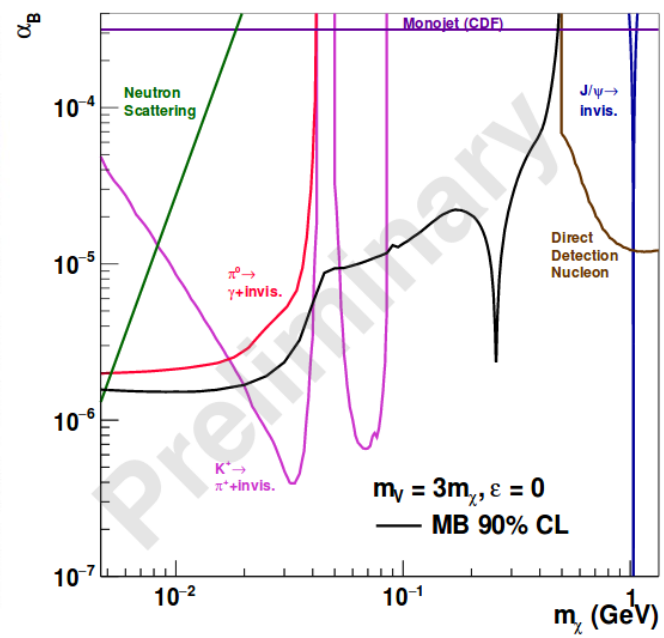
Electron Scattering



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)

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

$$D^{\mu} = \partial^{\mu} - ig_B q_B V_B^{\mu}$$

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

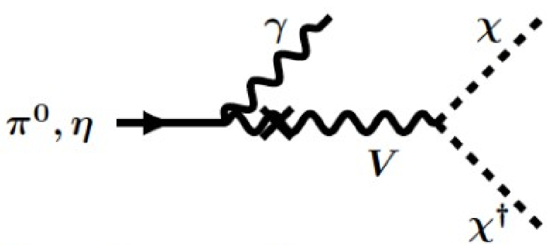
- 4 new parameters: $m_{\chi}, m_V, \alpha_B, q_B$
- $U(1)_B$ is "safe" - preserves approximate symmetries of SM (CP, P, flavor)
- Gauge anomalies can be canceled by new states at the weak scale

BdNMC

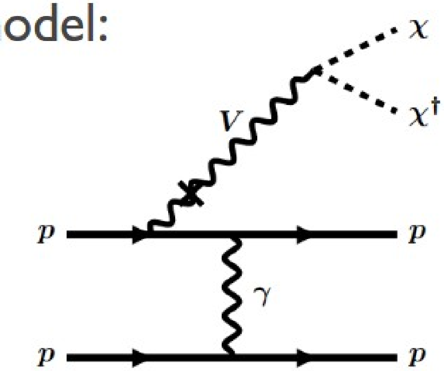
[deNivervile, Chen, Pospelov, Ritz]
https://github.com/pgdeniverville/BdNMC/releases

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

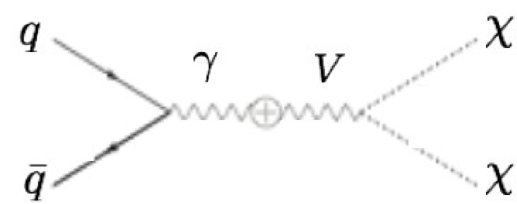
Detailed DM production model:



Neutral mesons decays

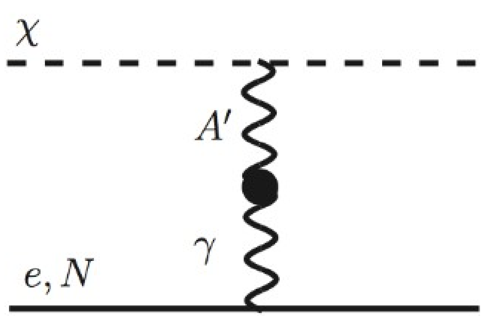


Bremsstrahlung + vector meson mixing

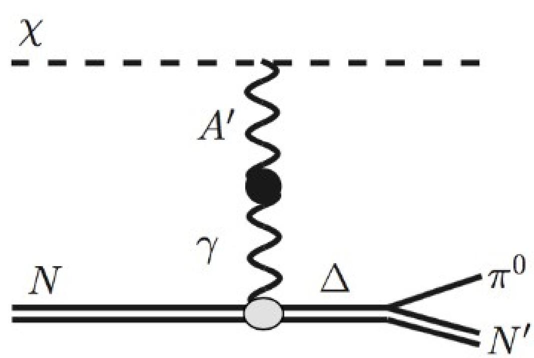


Direct production

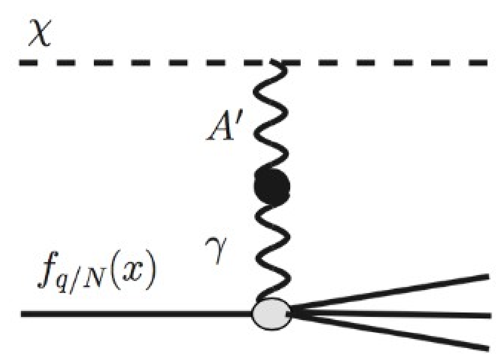
Several DM scattering processes included



Elastic NC nucleon or electron scattering



Inelastic NC neutral pion - like scattering



Deep Inelastic scattering