Latest Results from MiniBooNE

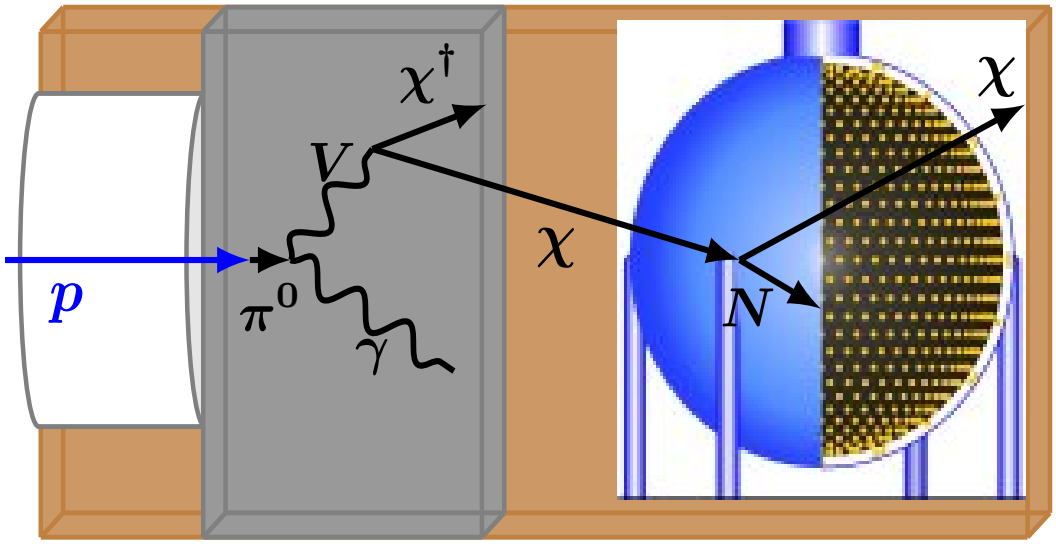
R. T. Thornton

On behalf of the MiniBooNE-DM Collaboration

For more information see:

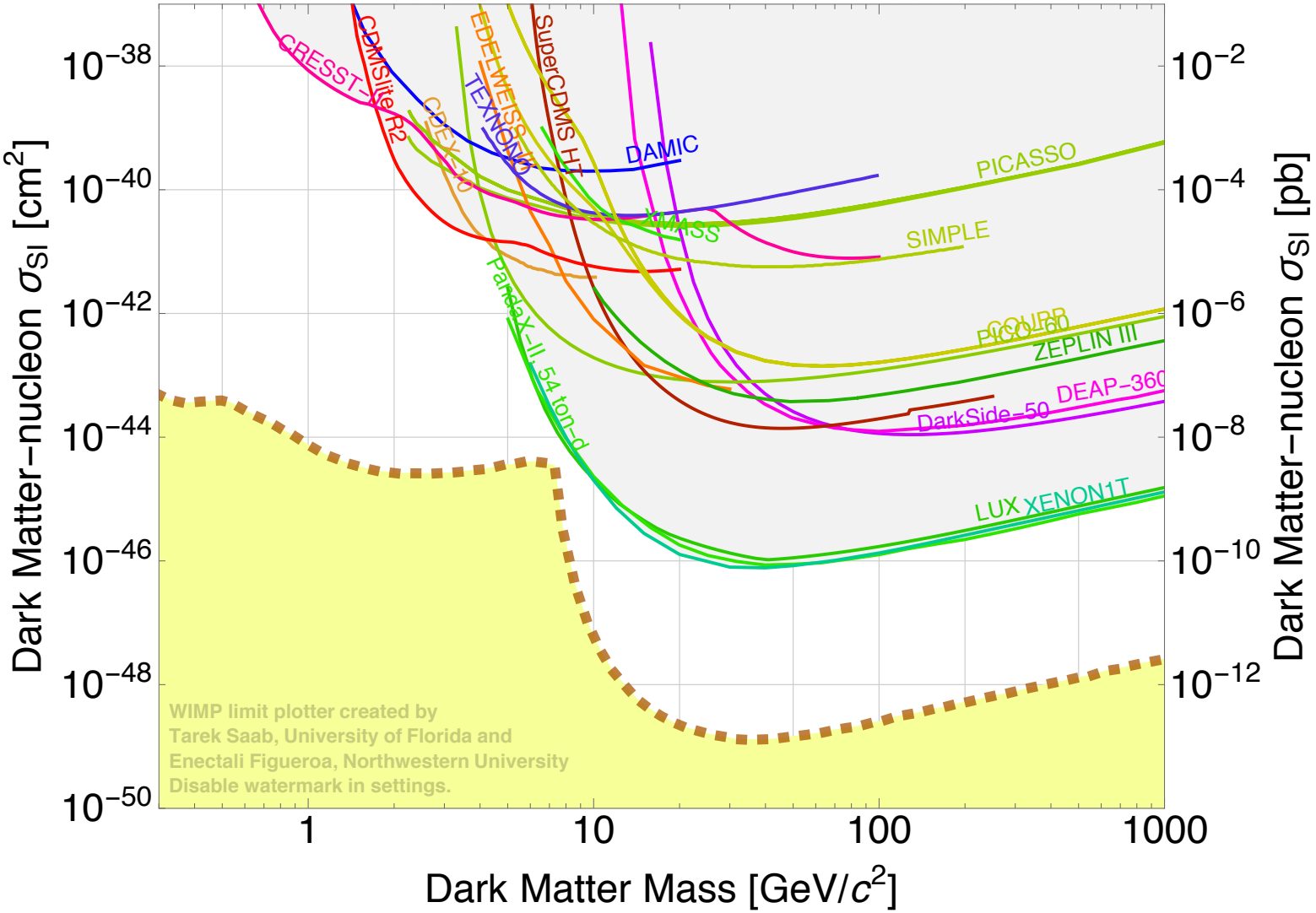
Dark Matter Search in Nucleon, Pion, and Electron Channels from a Proton Beam Dump with MiniBooNE

arXiv:1807.06137 – submitted to PRD



Los Alamos NATIONAL LABORATORY EST. 1943

Current Direct Detection Limits



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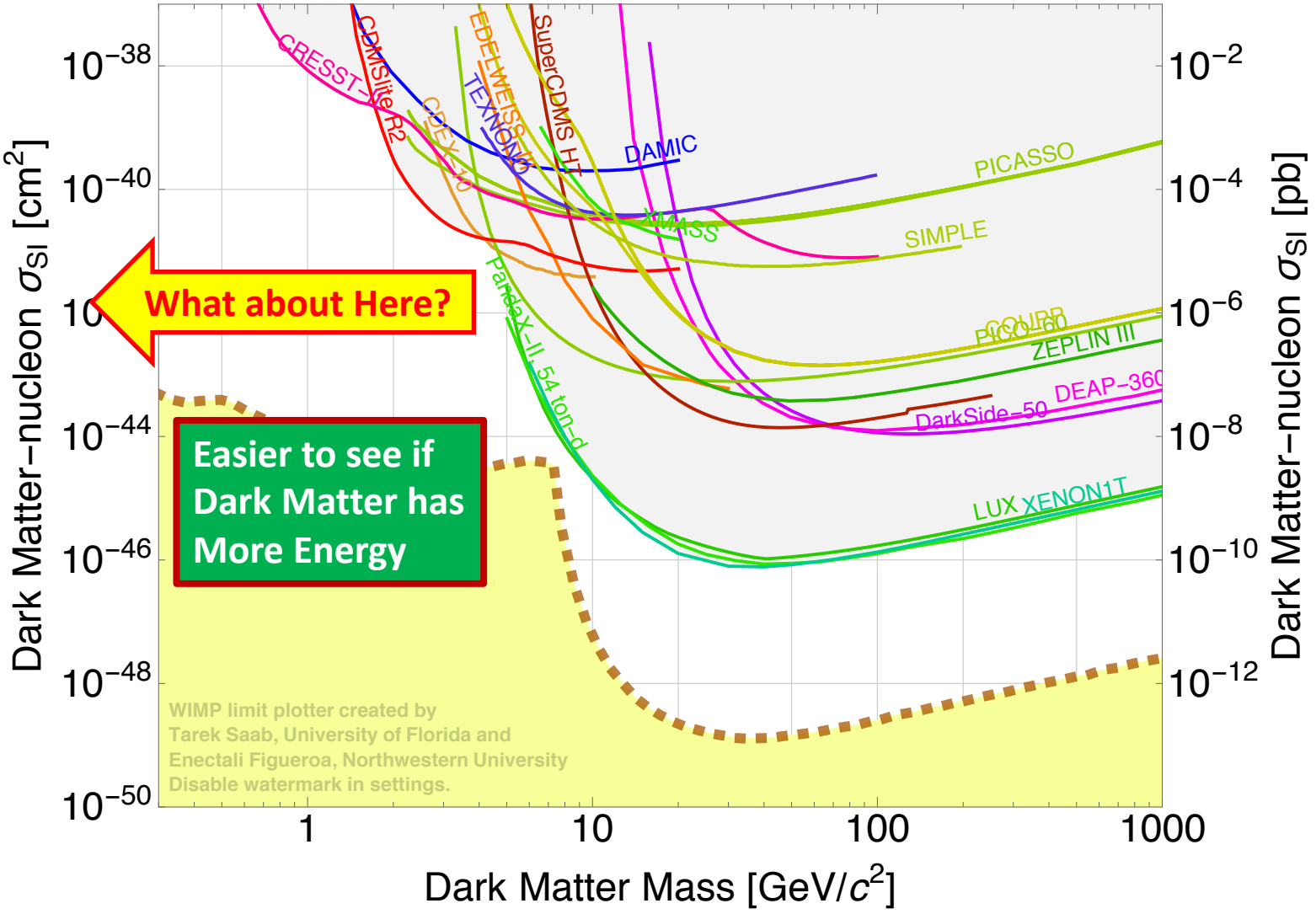
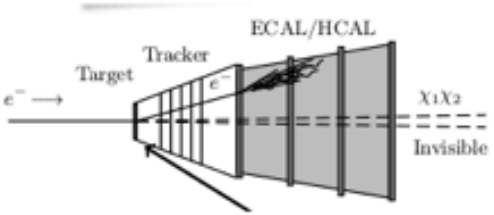


Use Accelerators To Increase Sensitivity to Lower Masses

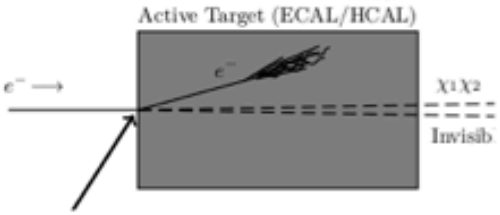
Missing mass

Resonance signal, rate gives coupling information

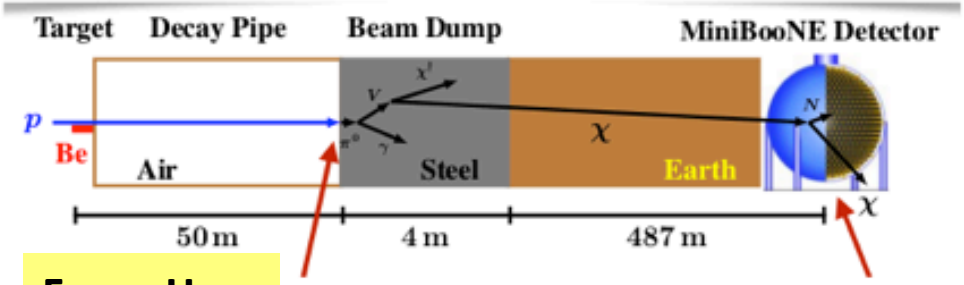
Missing energy / missing momentum



Best yield scaling with luminosity



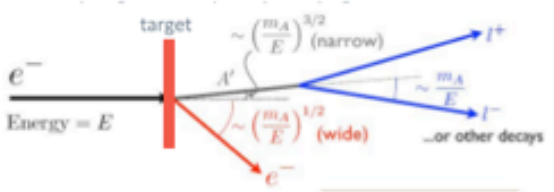
Proton / electron beam dump



Focus Here

Probes DM interaction twice

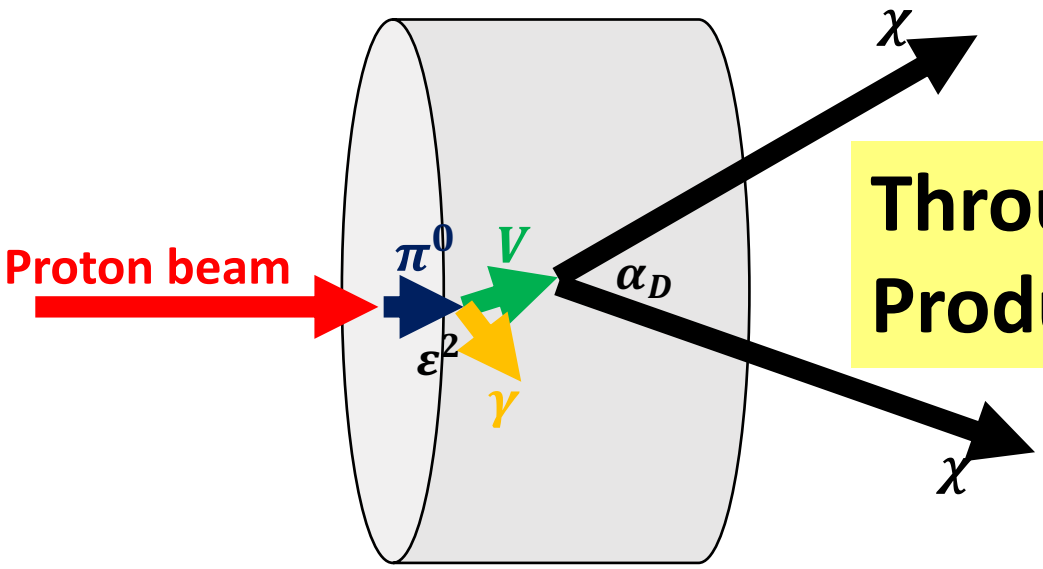
Searches for the mediator



Complementary to DM searches

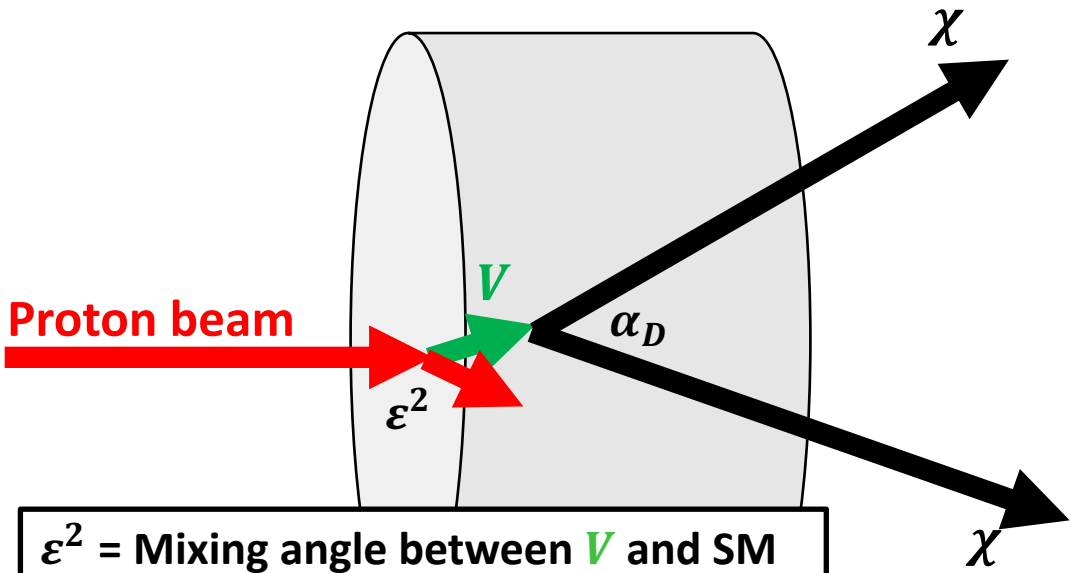
Production of Dark Matter

V = vector dark mediator
χ = scalar dark mater particle



Through Neutral Meson Production + Decay

Through Proton Bremsstrahlung

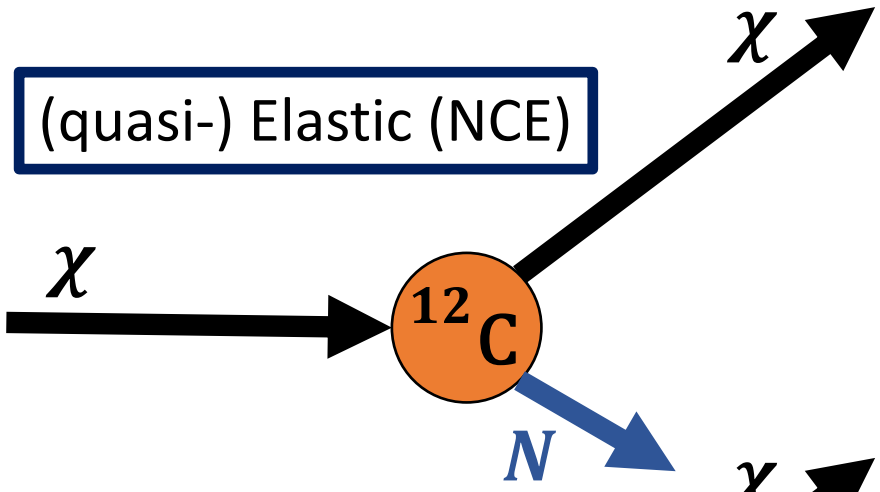


ε^2 = Mixing angle between V and SM
α_D = gauge coupling between V and χ

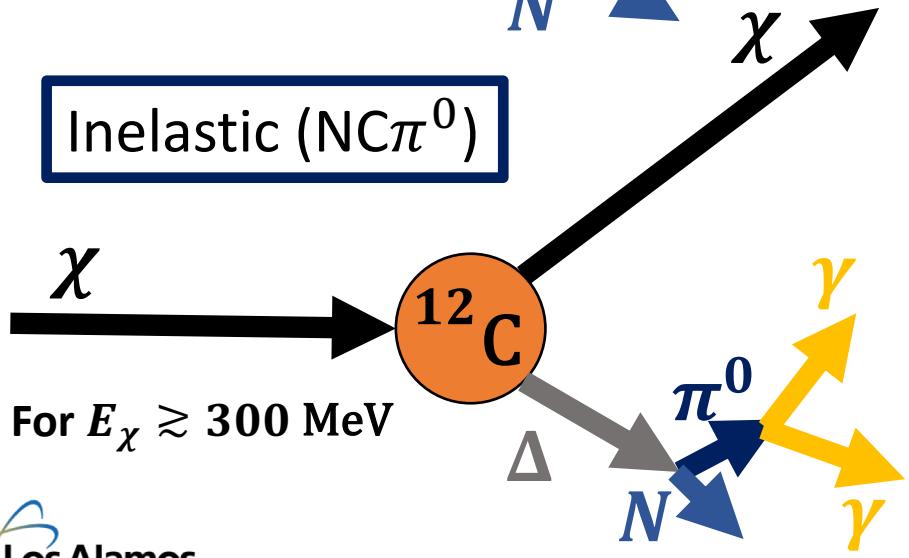
Dark Matter Interactions

Nucleons

(quasi-) Elastic (NCE)

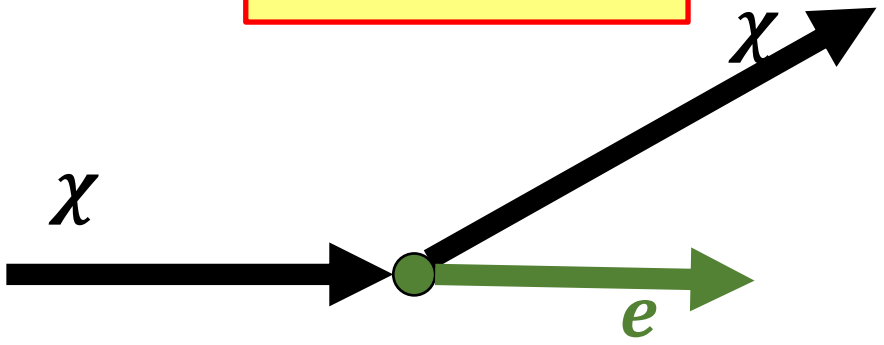


Inelastic (NCπ^0)



For $E_\chi \gtrsim 300$ MeV

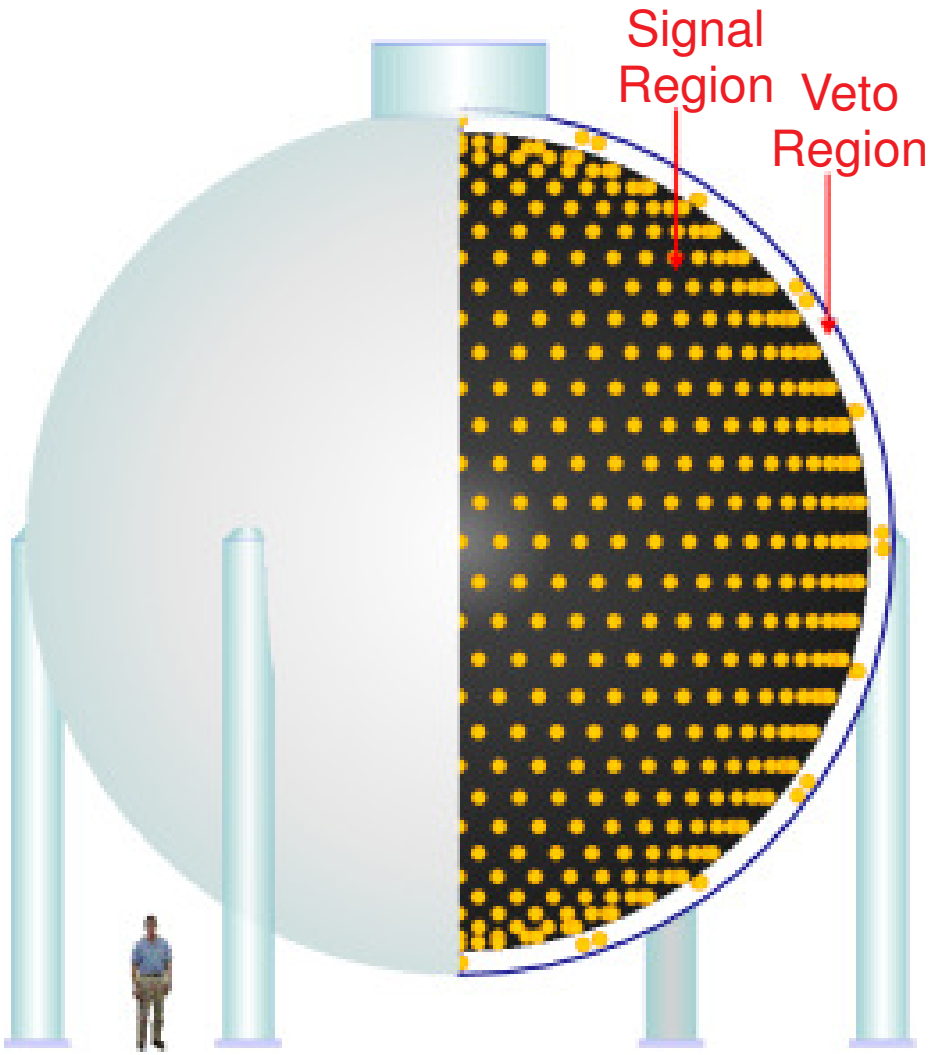
Electrons



- Interactions look just like neutrino interactions
- All interactions are neutral current ⇒ mediator is not charged
- Neutrino detectors are already designed to search for such interactions

The MiniBooNE Detector

- Cherenkov/Scintillation Detector
- 1280 inner, 240 veto PMTS
- Veto region helps reject backgrounds coming from the outside
- Designed to test LSND neutrino oscillation excess
- Has been running since 2002



Muons

- Long strait tracks
  → Sharp clear rings

Electrons

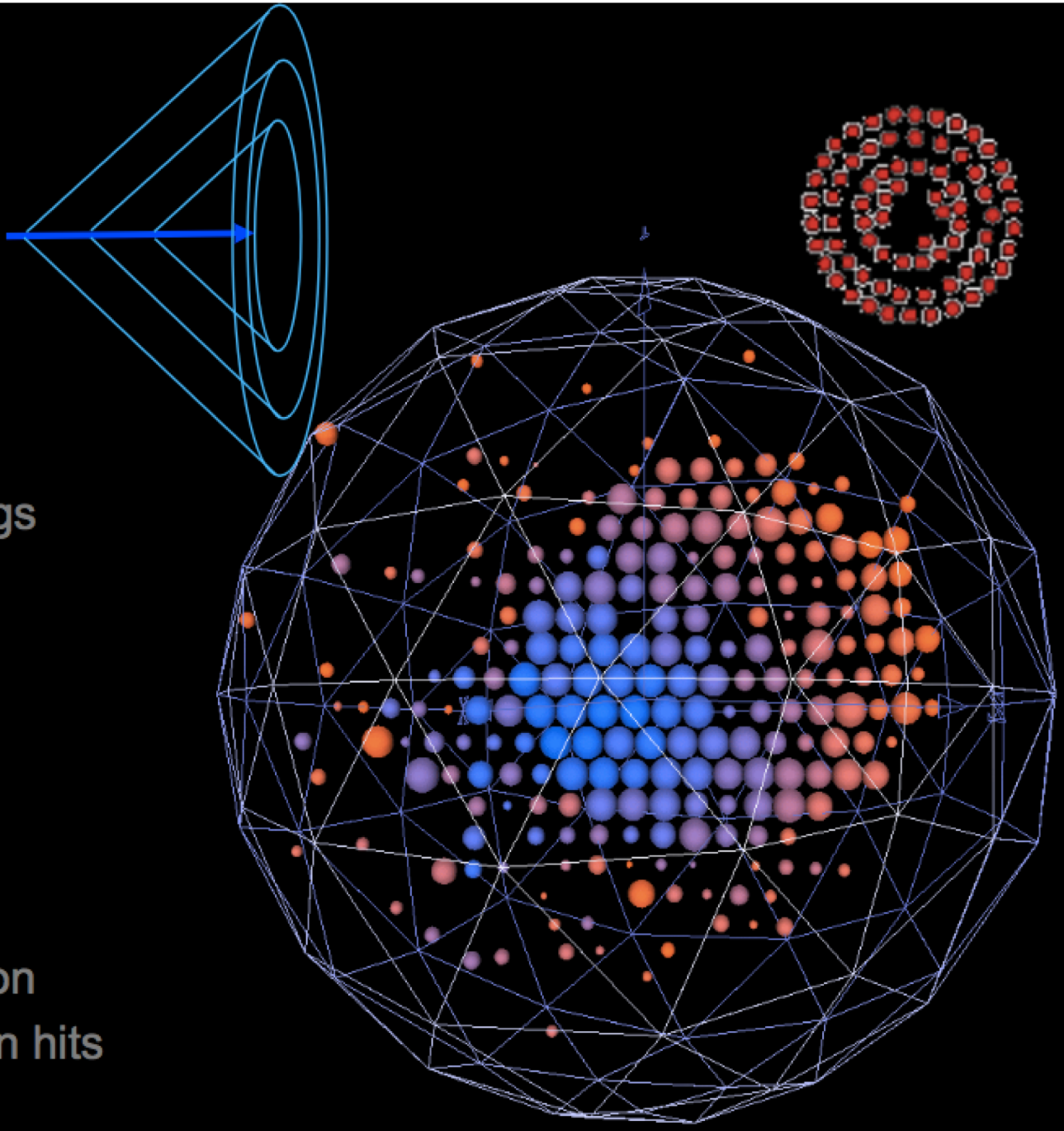
- Multiple scattering
- Radiative processes
  → Scattered fuzzy rings

Neutral pions

- Decays to 2 photons
  → Double fuzzy rings

NC elastic scattering

- No Cherenkov radiation
  → Isotropic scintillation hits



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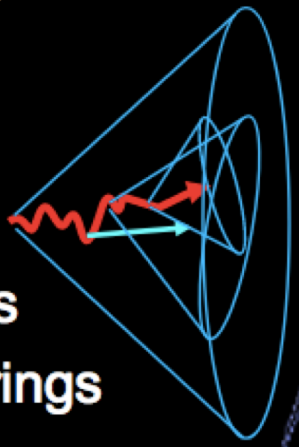

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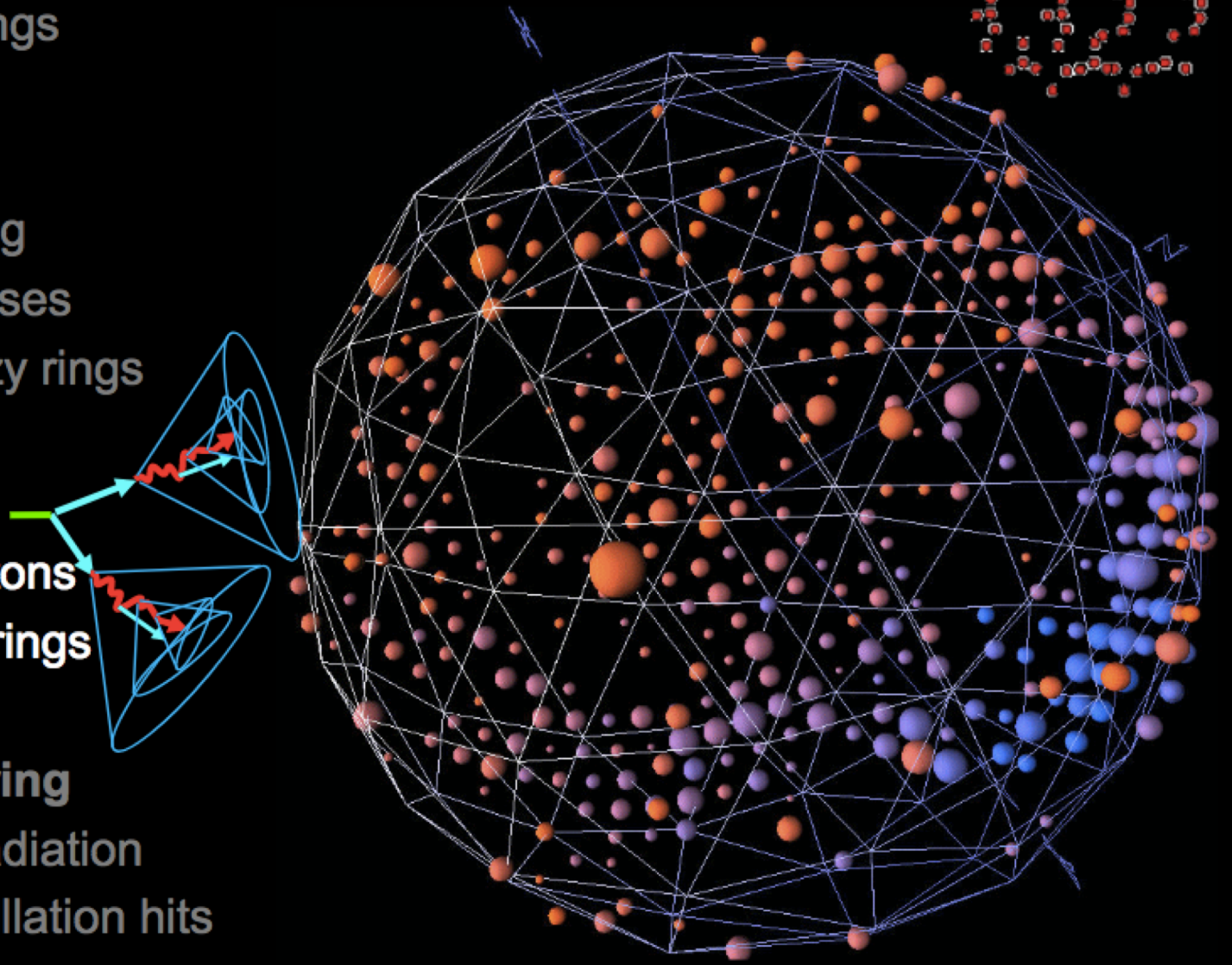

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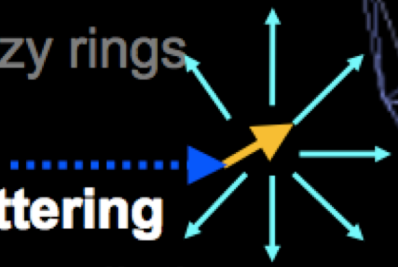

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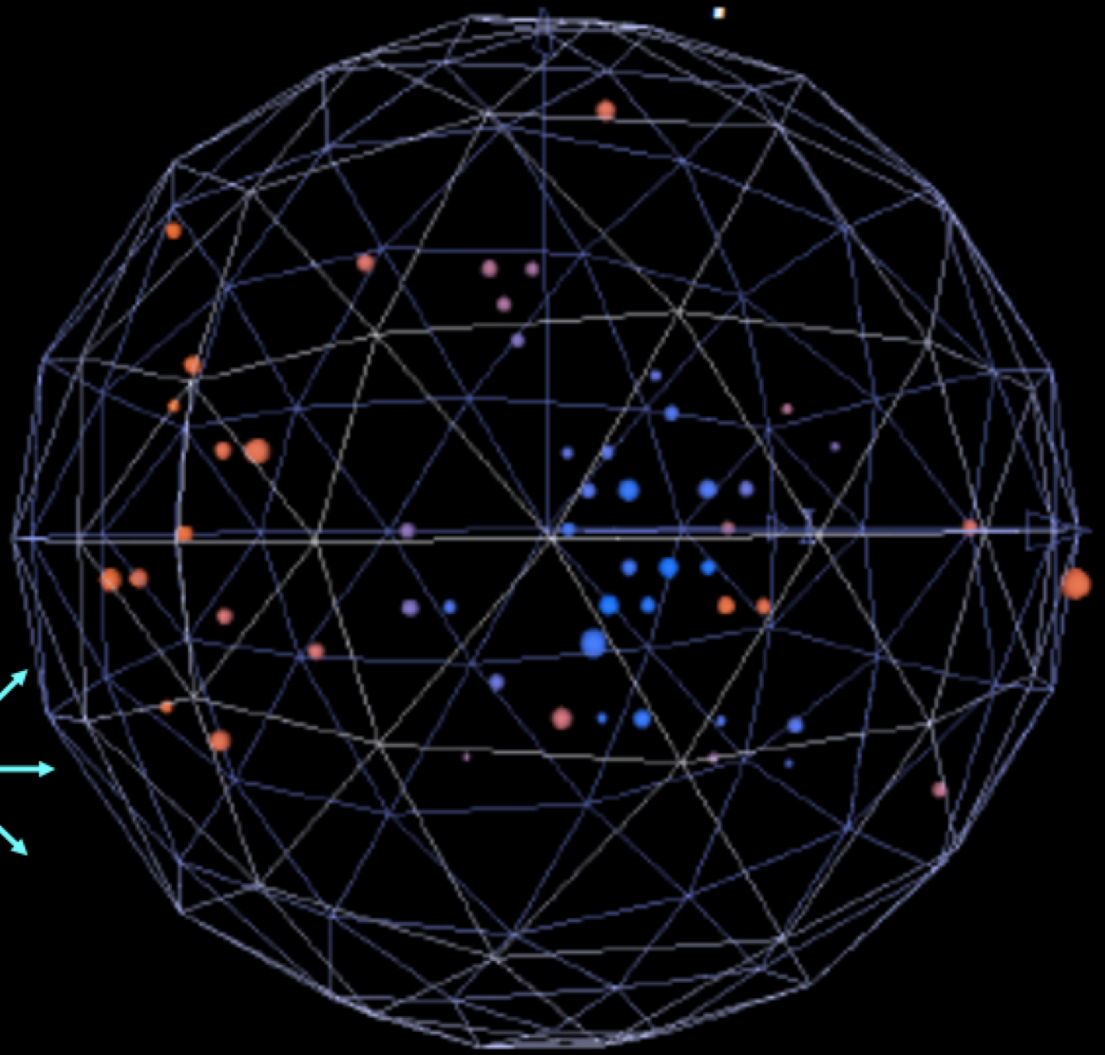
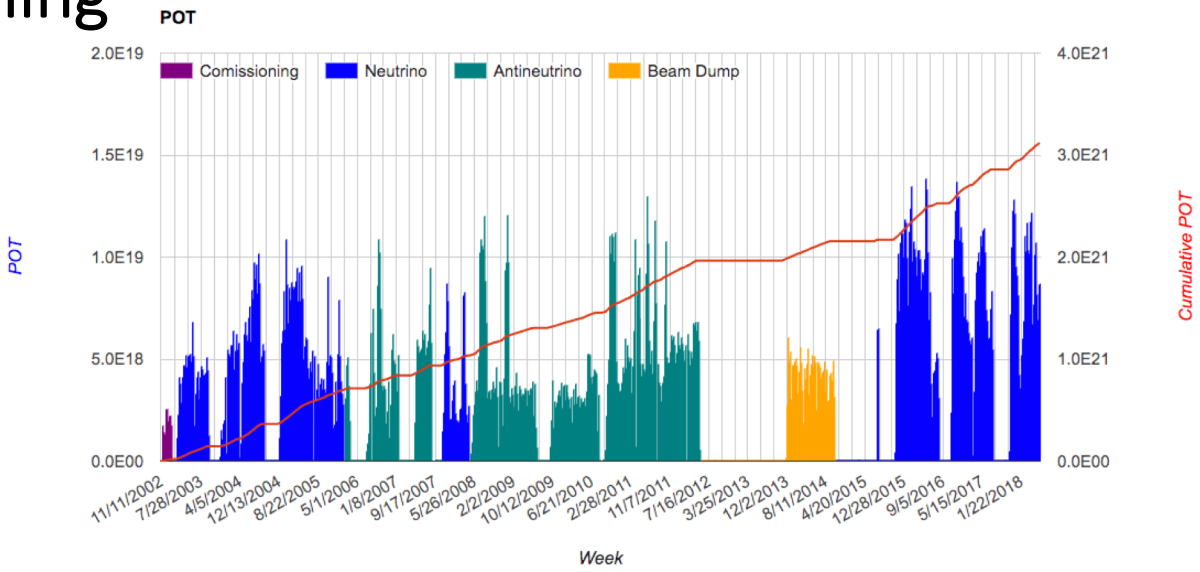
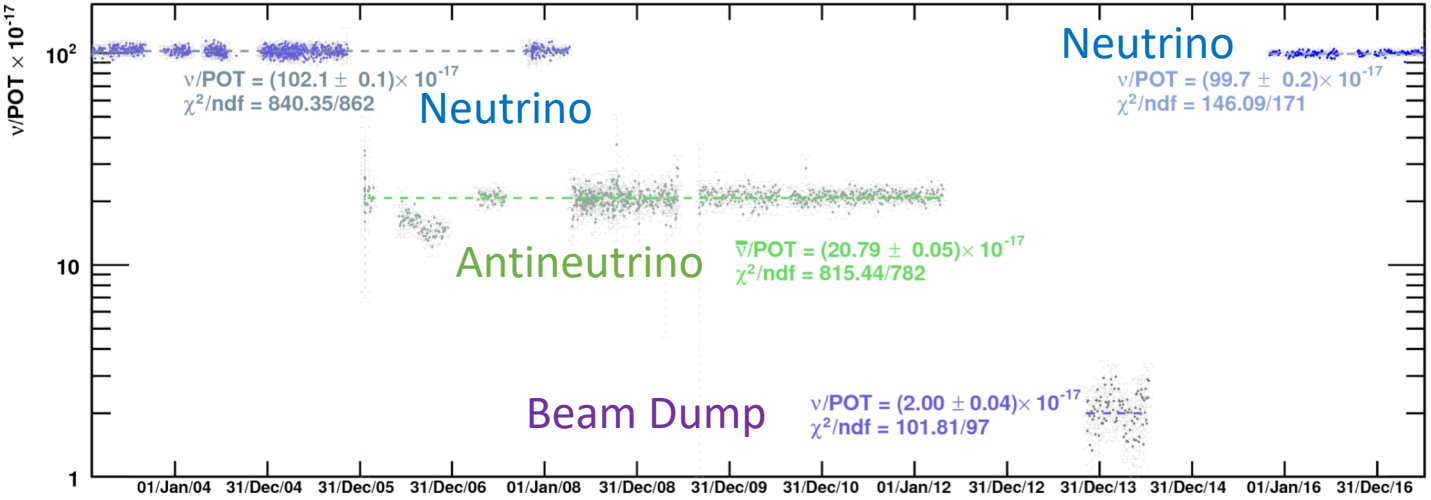


Booster Neutrino Beamline

15 years of running

- Accelerator has delivered more than 30×10^{20} proton-on-target (POT) for 3 different modes of running



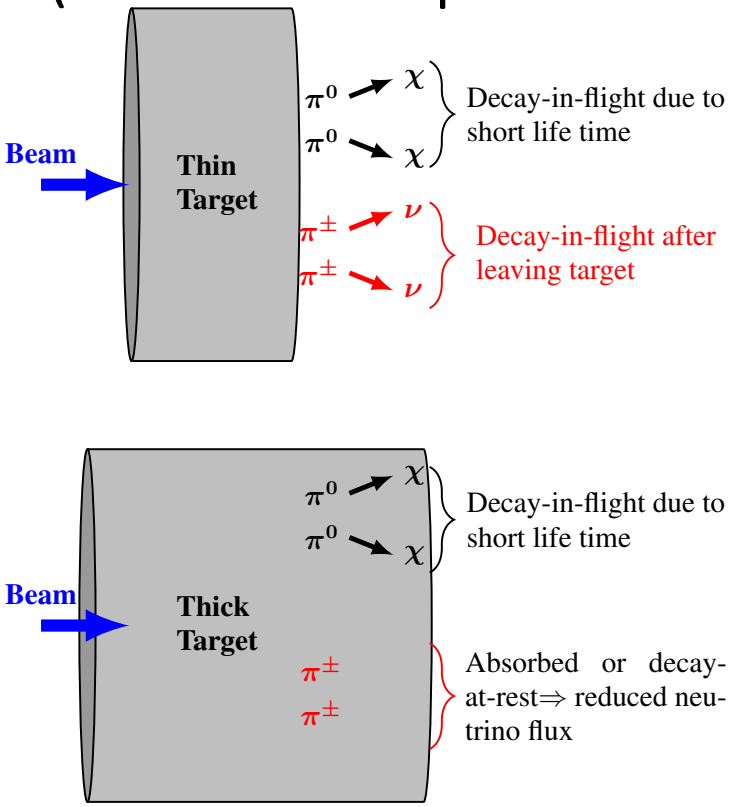


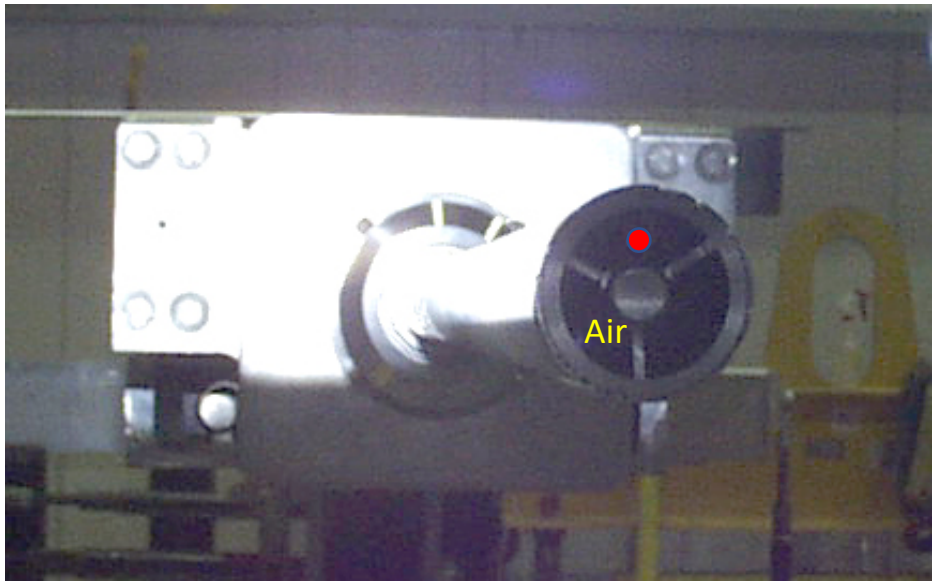
- Number of ν per POT
- Stable for ν Mode after ~8 years apart to within 2%

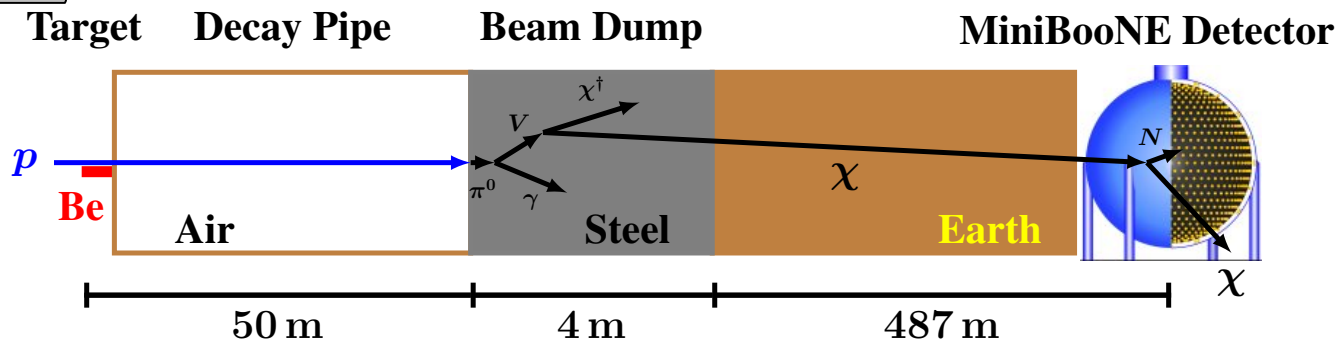
Beam-Dump Mode

(Nov 2012 – Sep 2013 1.86×10^{20} POT)

ν event rate in MiniBooNE decreased by a factor of 50 compared to ν Mode



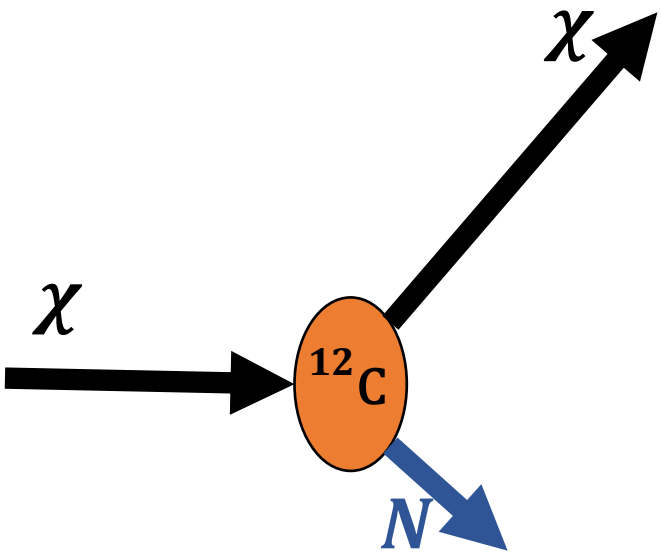


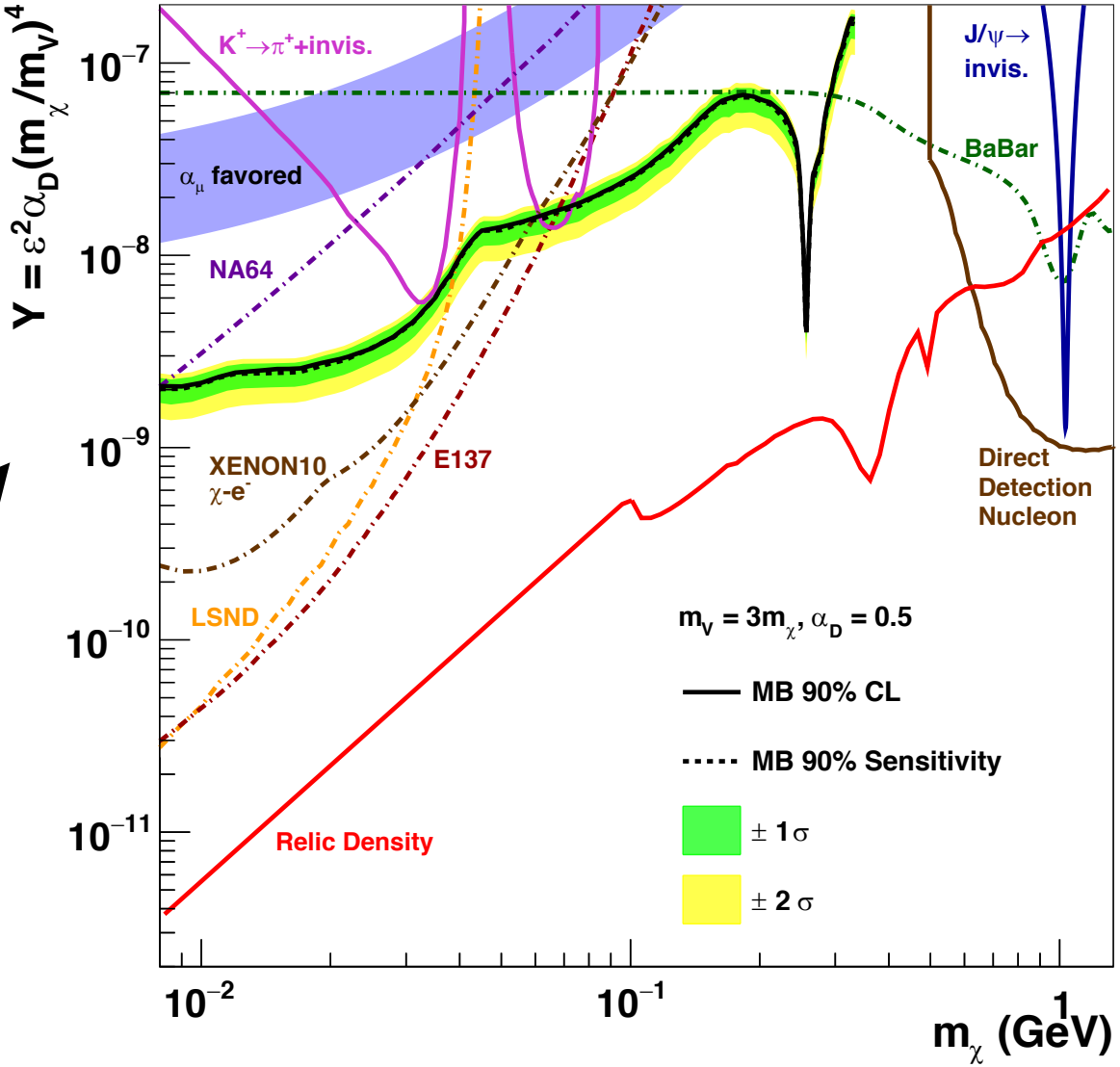


First Results: (quasi-) Elastic Scattering

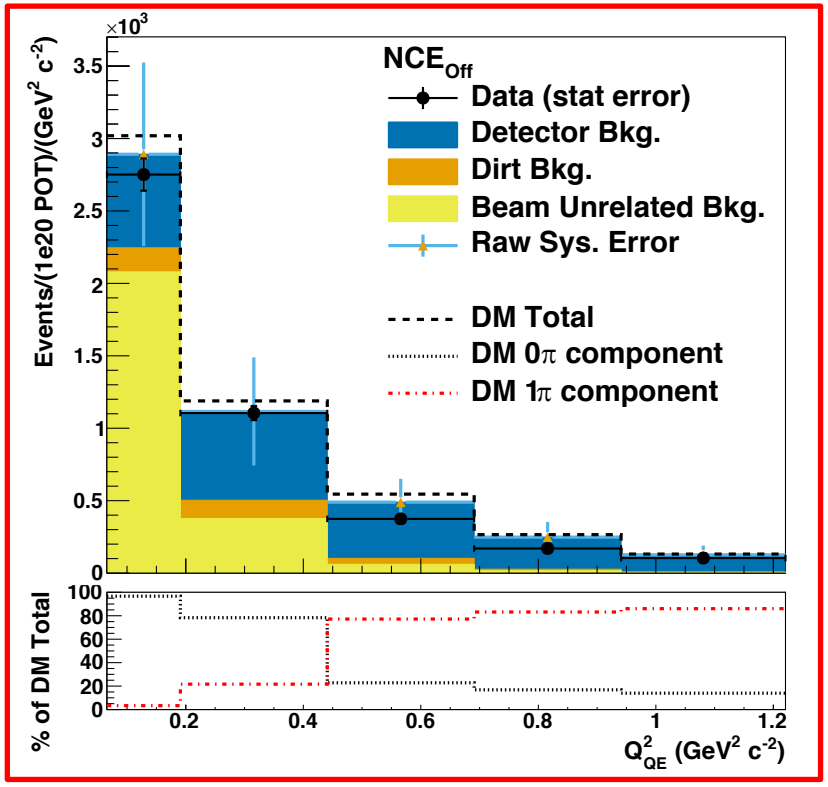
PRL 118, 221803 (2017) Editors' Suggestion

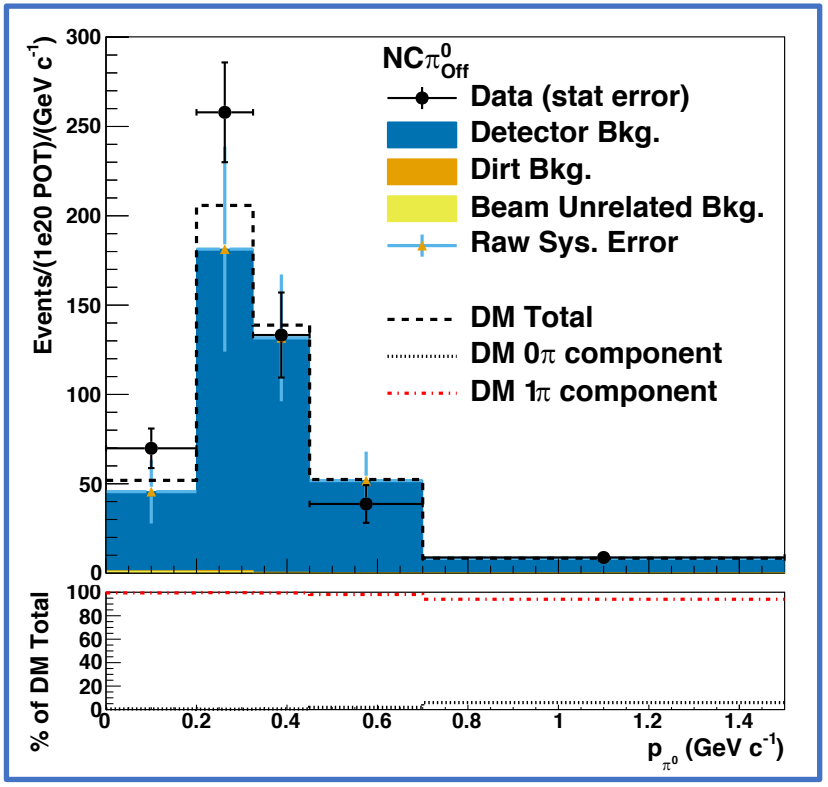
- First dedicated search for direct detection of accelerator-produced dark matter in a proton beamline
- $Y \propto$ DM annihilation cross section





New To Nucleon Analysis (Full Nucleon)





- **Neutral-Current elastic nucleon cut**
  - Large beam unrelated bkg. (BUB)
  - DM at high Q^2_{QE} has large % of true 1 π^0 sample
- **Neutral-Current single π^0 cut**
  - Reduced to almost no dirt and BUB

- Simultaneous fit of NCE and NCπ^0 cuts
- Constrained by ν and $\bar{\nu}$ data

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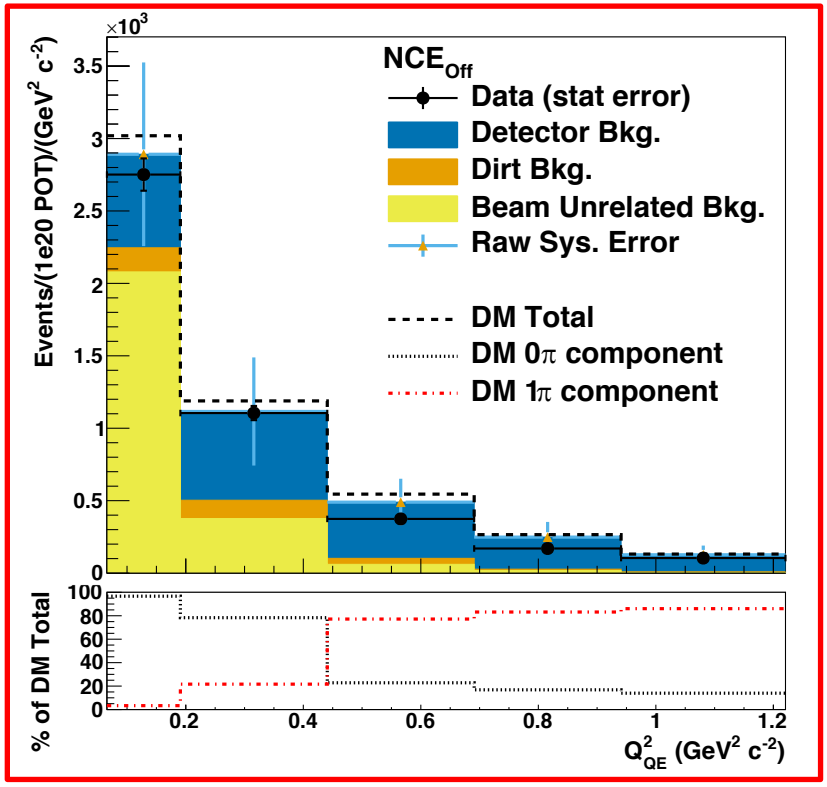

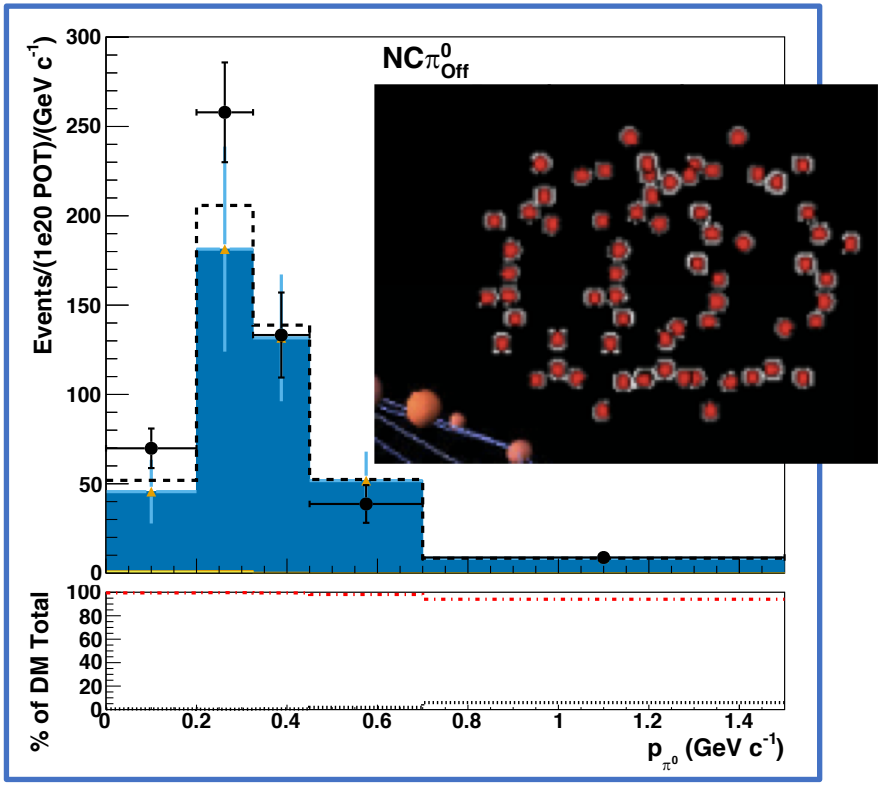

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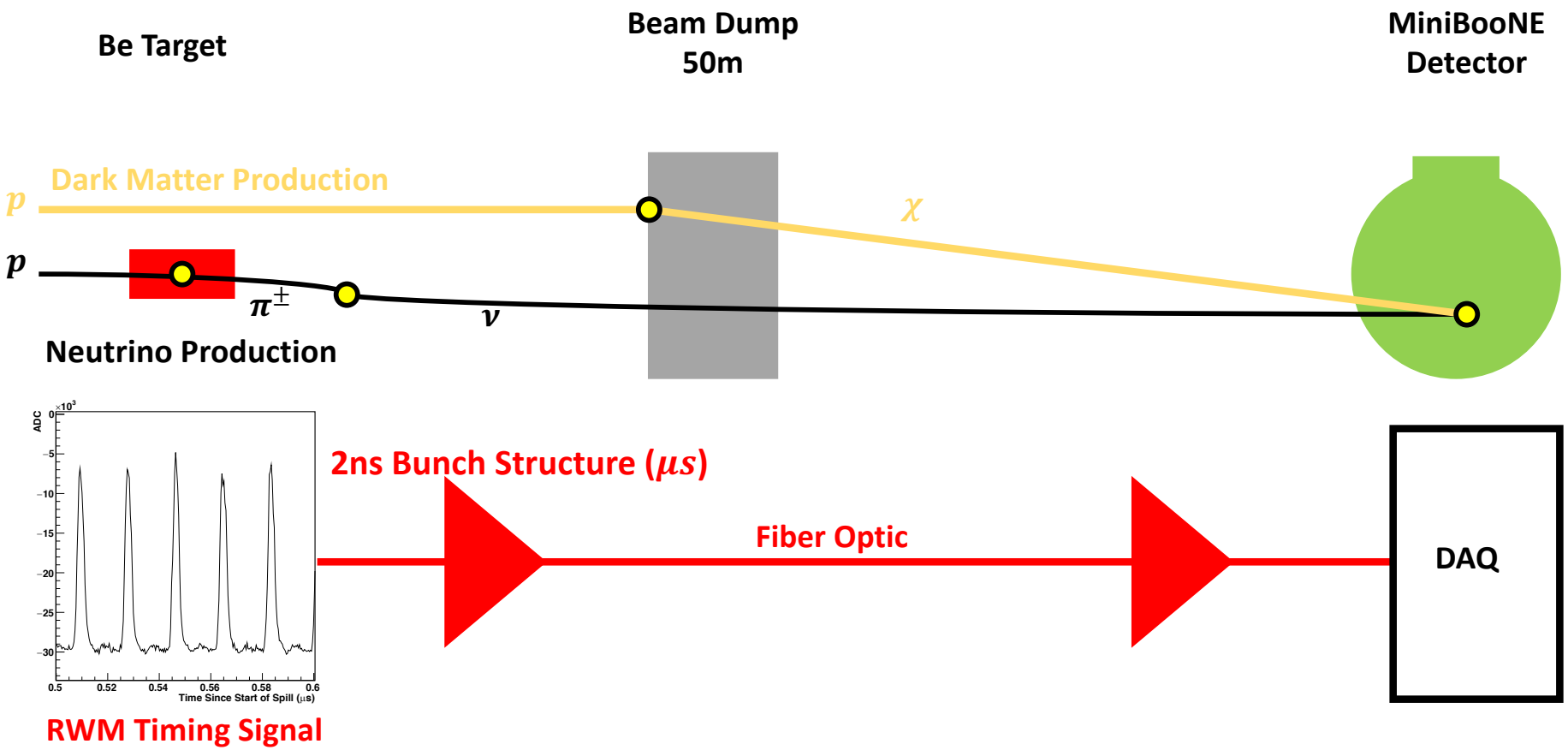
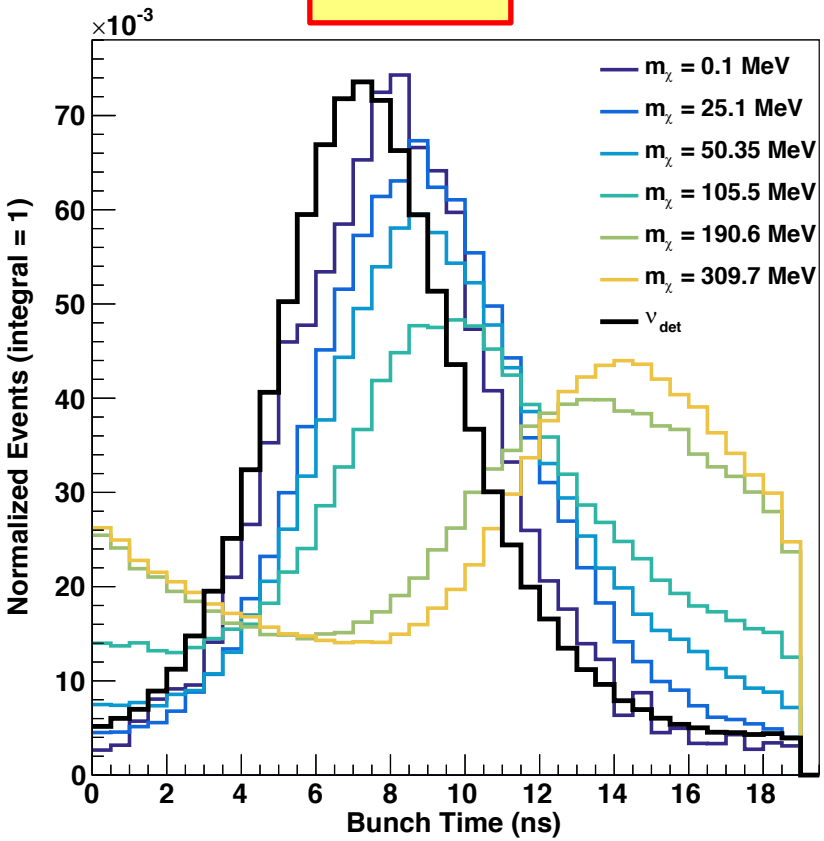
New To Nucleon Analysis ("Time-of-Flight")

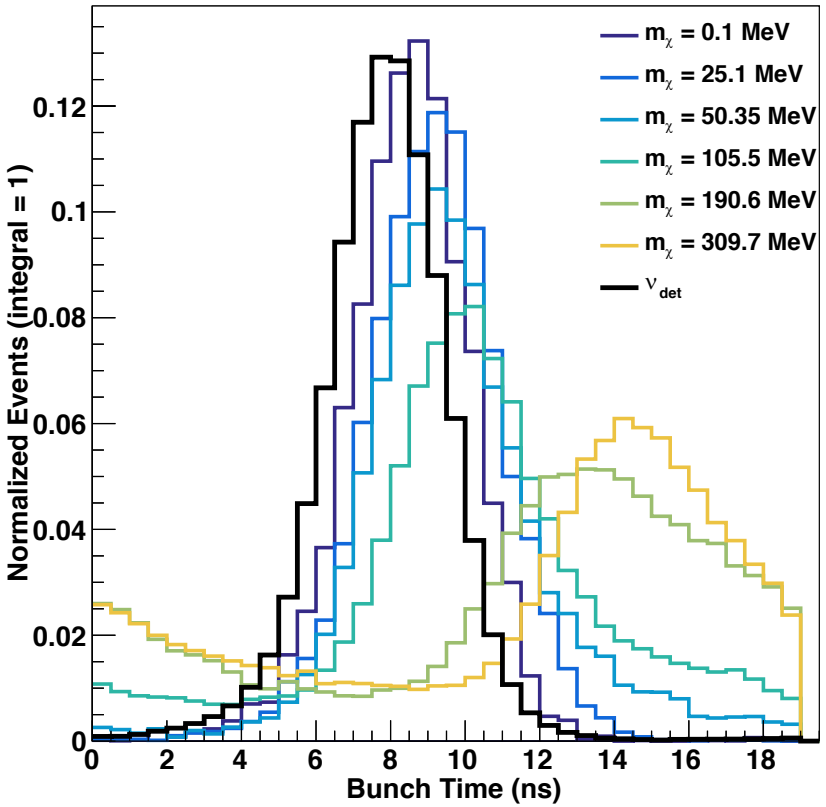


Comparing Time Distributions

NCE



NCπ^0

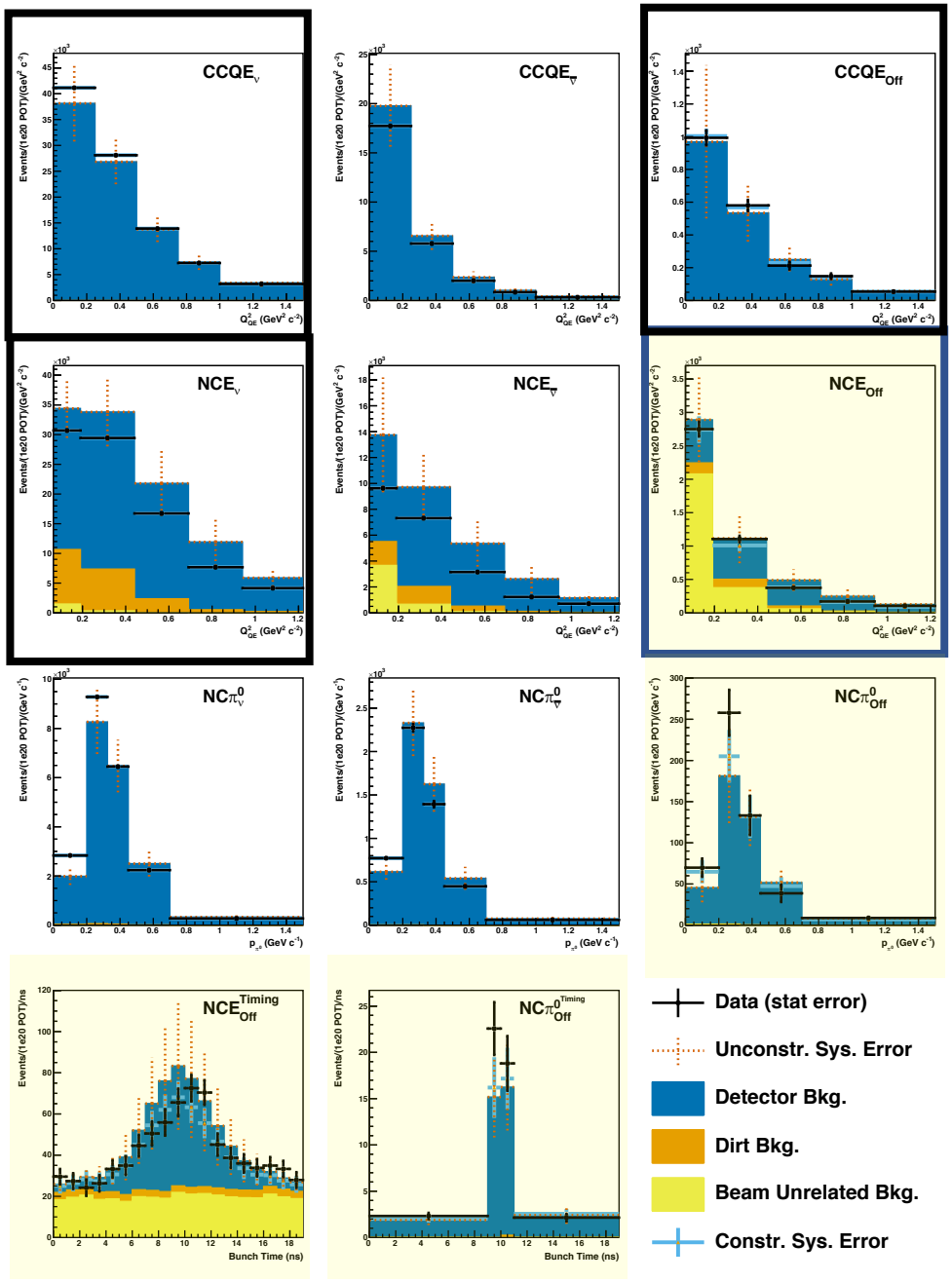


Dark matter could come later ⇒ Distort timing distribution

Distributions in Fit

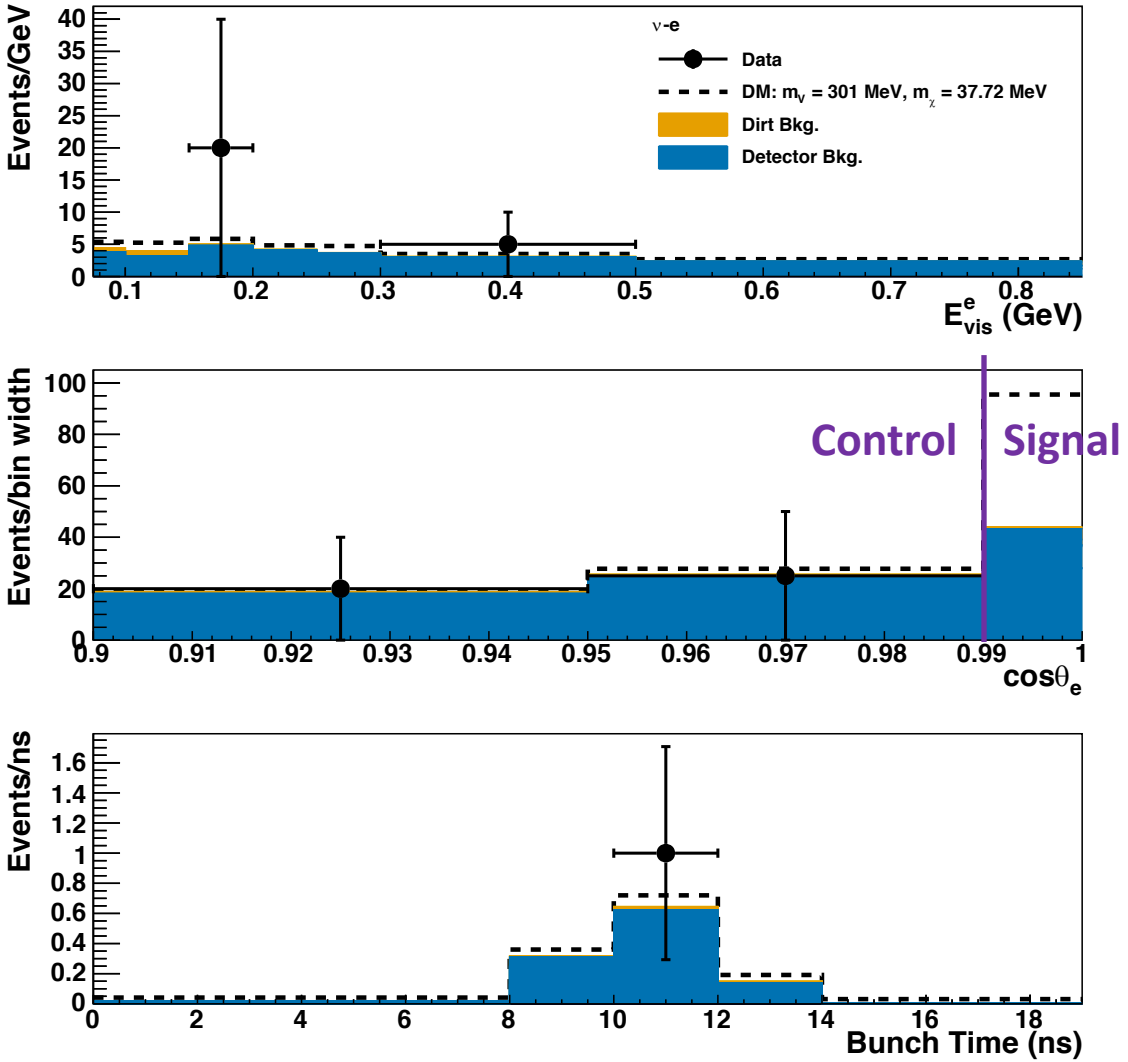
- Fit 11 Correlated Distributions
- Bold = in PRL
- Highlighted = Signal Channels

Neutrino CCQE	Antineutrino CCQE	**Off-Target CCQE**
Neutrino NCE	Antineutrino NCE	**Off-Target NCE**
Neutrino NCπ^0	Antineutrino NCπ^0	Off-Target NCπ^0
Off-Target NCE Timing	Off-Target NCπ^0 Timing	



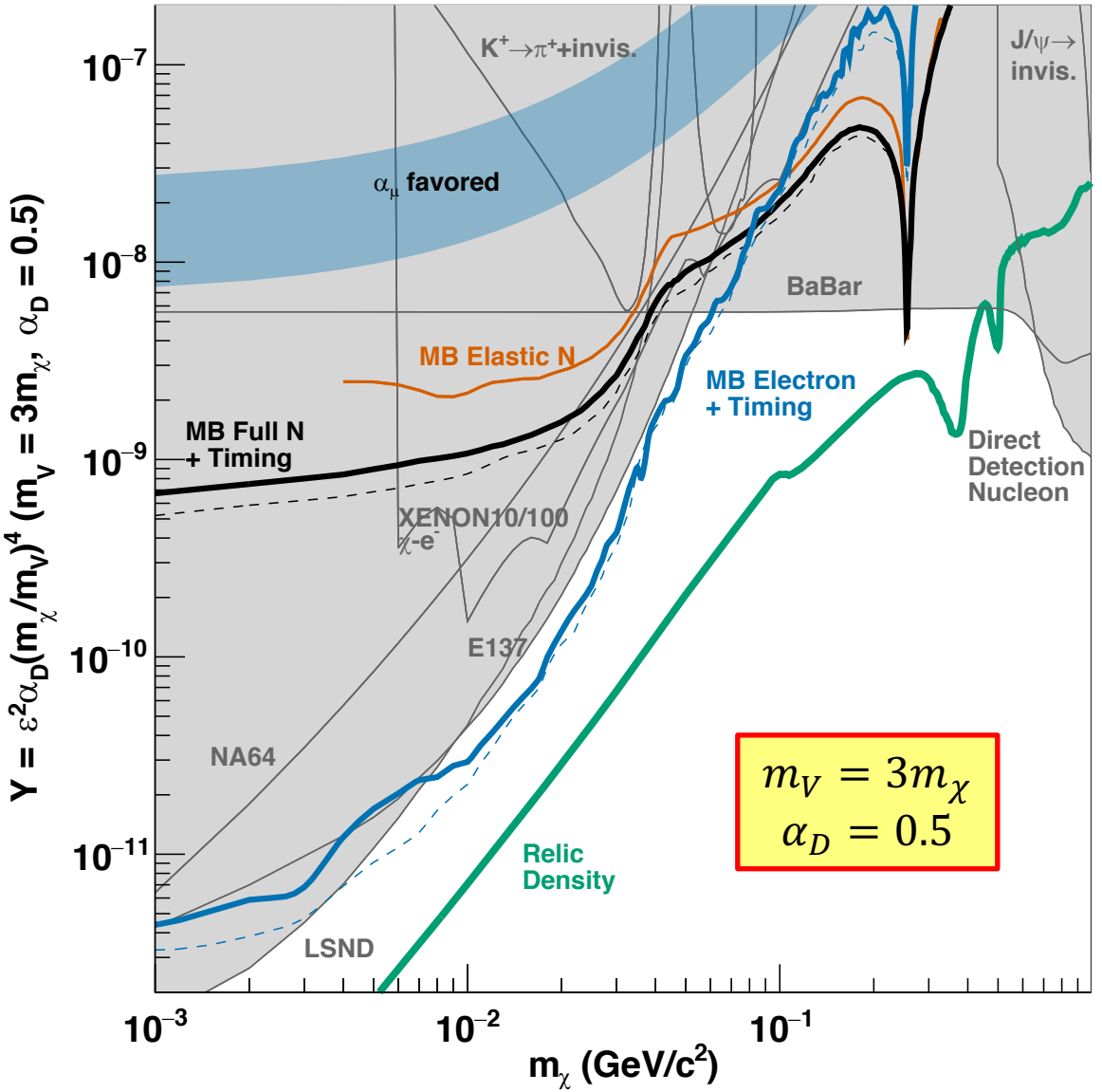
Electron Analysis

- Search for ν—electron neutral-current like interactions
- Outgoing electrons are very forward ($\cos\theta_e > 0.99$)
- Low Evis cut to remove Beam unrelated bkg.
- Beam related bkg. constrained by $0.9 \leq \cos\theta_e < 0.99$
- Statistical only fit in 3D
  - Evis
  - $\cos\theta_e$
  - Bunch Time



New 90% Confidence Limits

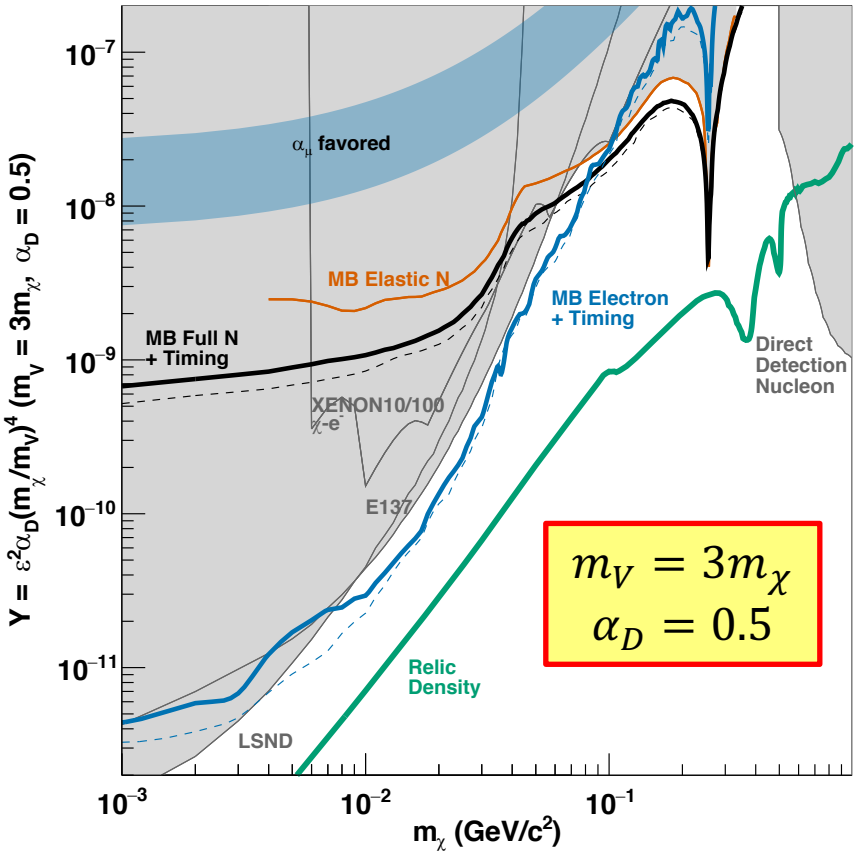
- No significant excess observed
- Results improved from 2017 PRL (MB Elastic N)
- Set world leading limits
- Sensitivity
  - Low mass ⇒ **Electron**
  - High mass ⇒ **Full N**
- ***arxiv:1807:06137 submitted to PRD***

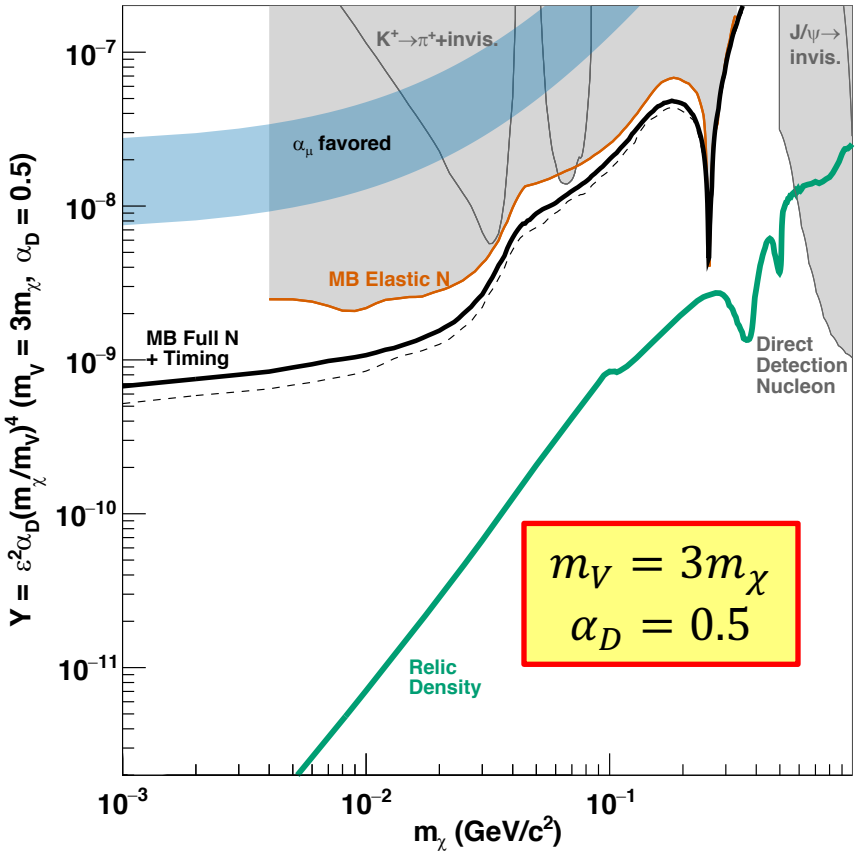


Various Looks

Direct detection

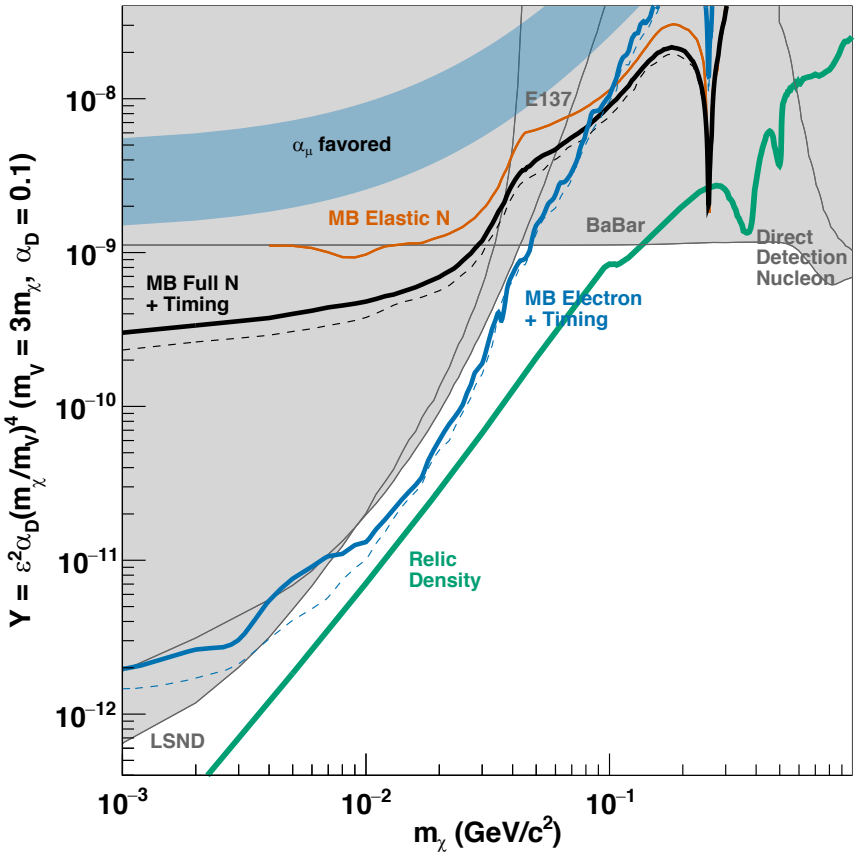
Does not require coupling to leptons



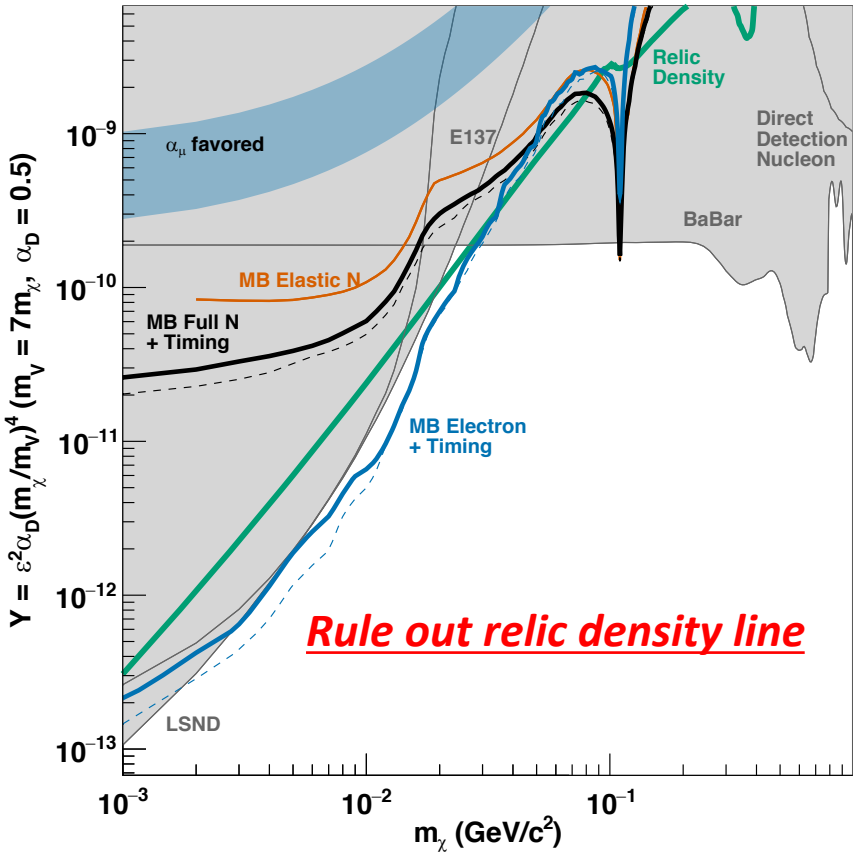


Various Looks (different slices)

$$m_V = 3m_\chi$$
$$\alpha_D = 0.1$$

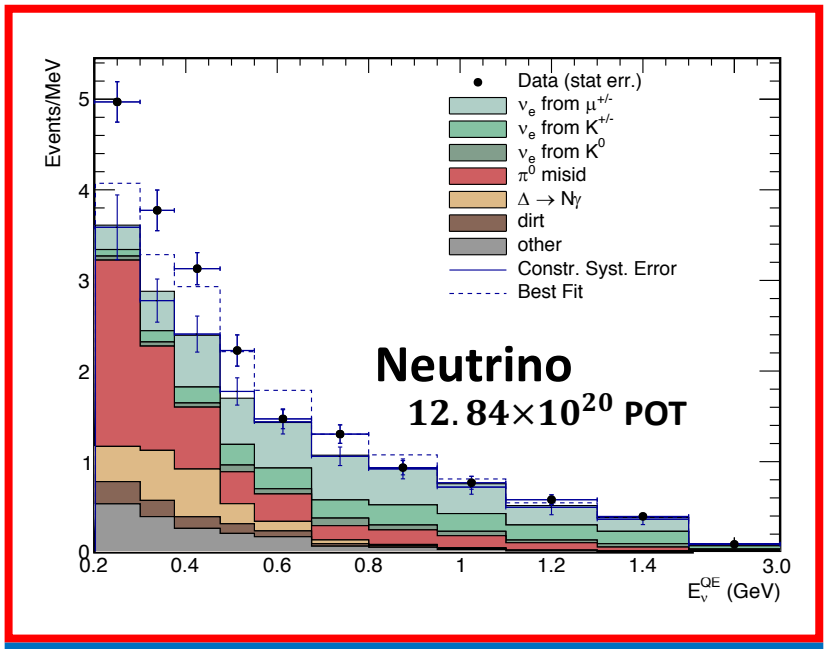


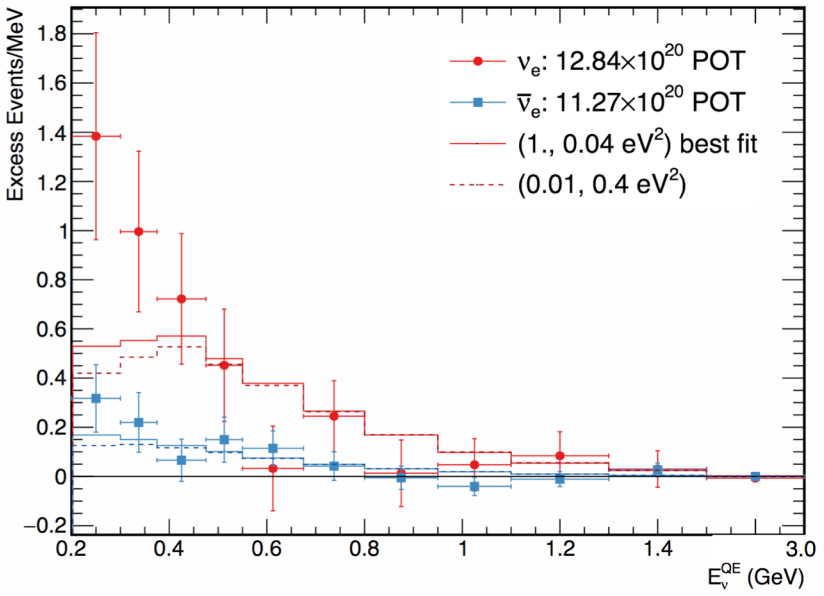
$$m_V = 7m_\chi$$
$$\alpha_D = 0.5$$

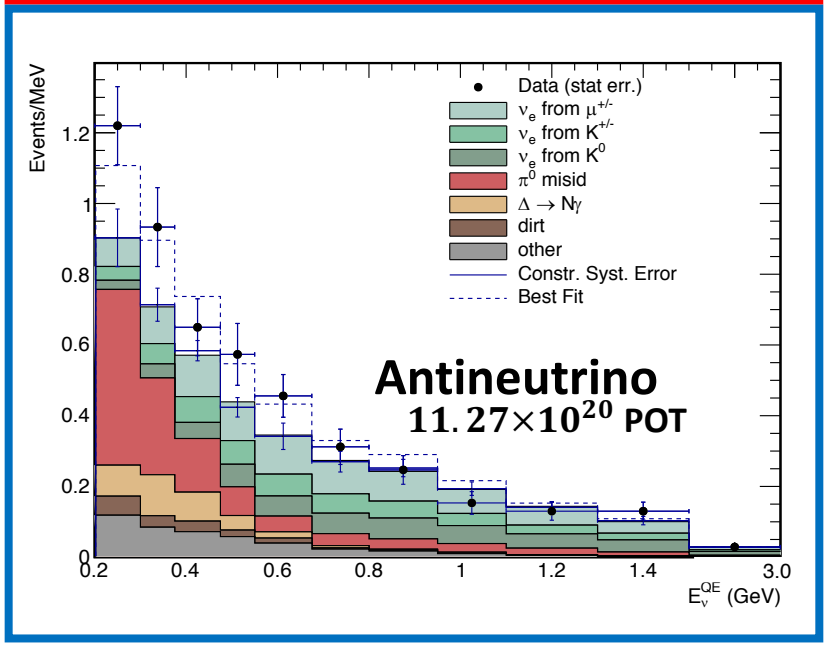


Neutrino Oscillation Analysis

	ν mode	$\bar{\nu}$ mode	Combined
Data	1959	478	2437
Unconstr. Background	1590.5	398.2	1988.7
Constr.	1577.8	398.7	1976.5
Excess	381.2 ± 85.2 4.5σ	79.3 ± 28.6 2.8σ	460.5 ± 99.0 4.7σ
0.26% (LSND) $\nu_\mu \rightarrow \nu_e$	463.1	100.0	563.1







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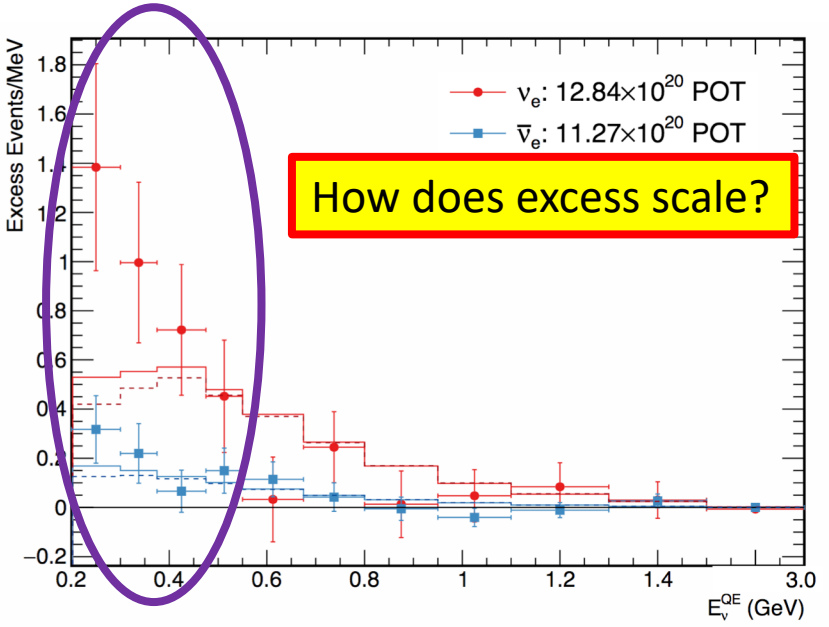
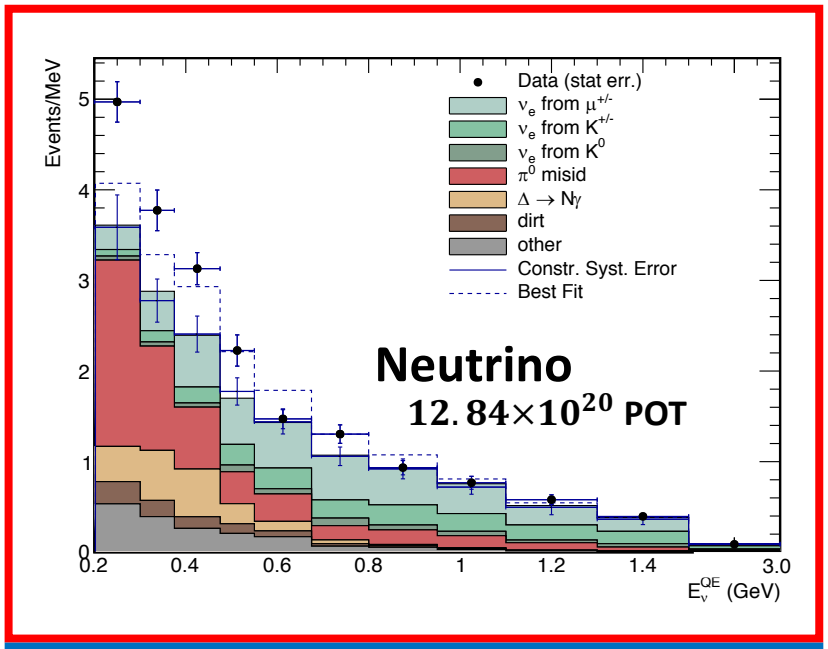
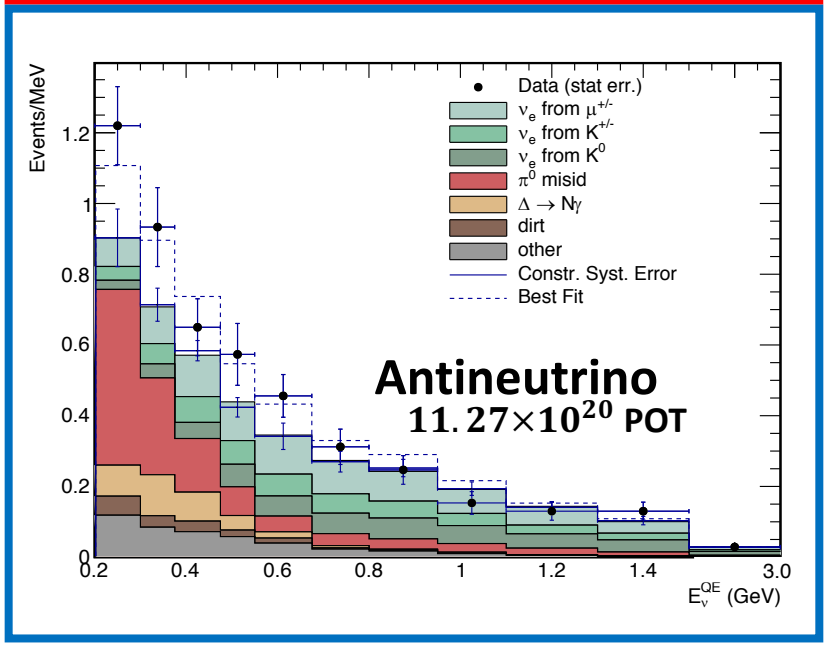
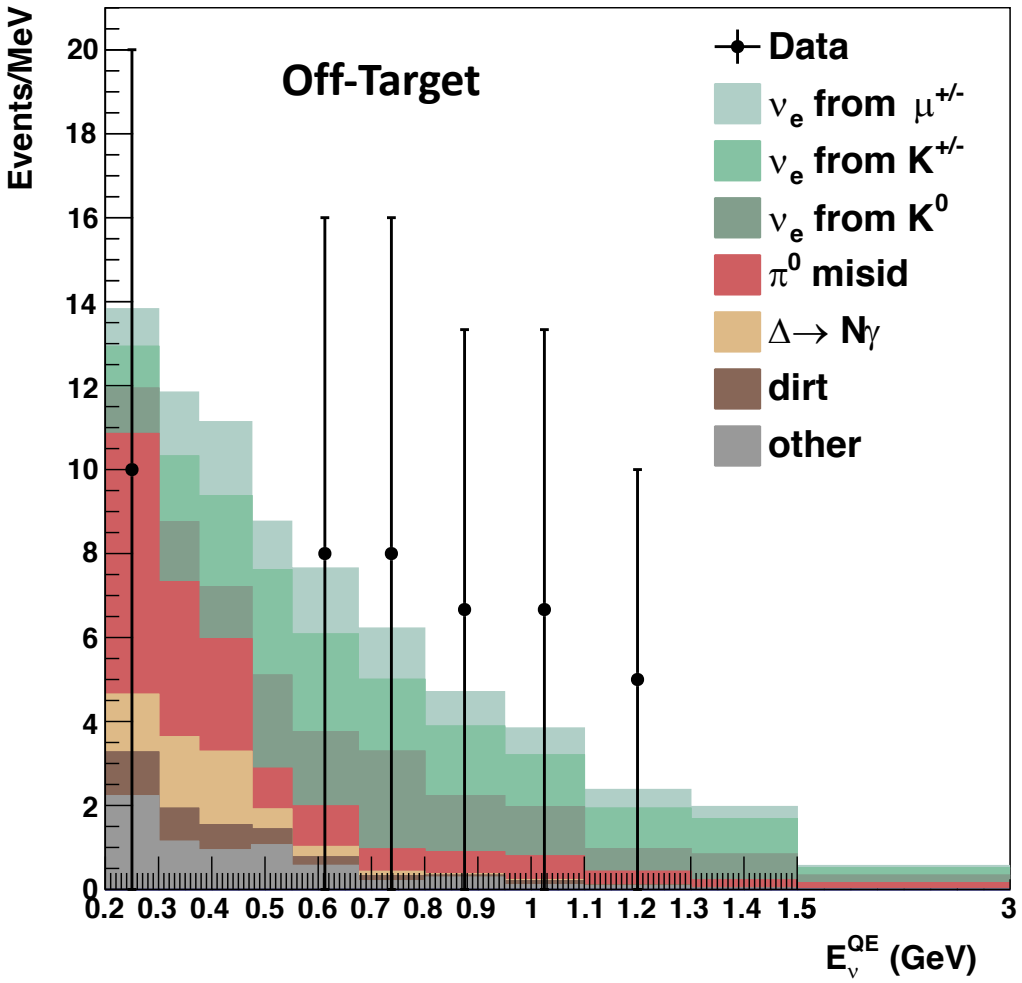






Checking if Excess Scales with only with POT

- Scale total combined excess to predict how many excess events expected for off-target running
- Expected 35.5 ± 7.4 excess events between 200 and 1250 MeV
- Measured -2.8 excess events
- Explanations that scale by only by POT instead of neutrino production are ruled out at 4.6σ



Summary

- Can use accelerators to help guide where to look for dark matter
- MiniBooNE/BNB was repurposed for a dark matter search
- First results were published in PRL (Editors Suggestions)
- Pi0 and Electron searches improved upon the first results (submitted to PRD) – new parameter space excluded
- Off-target run was able to rule out explanations of the oscillation excess that scale solely on number of POT

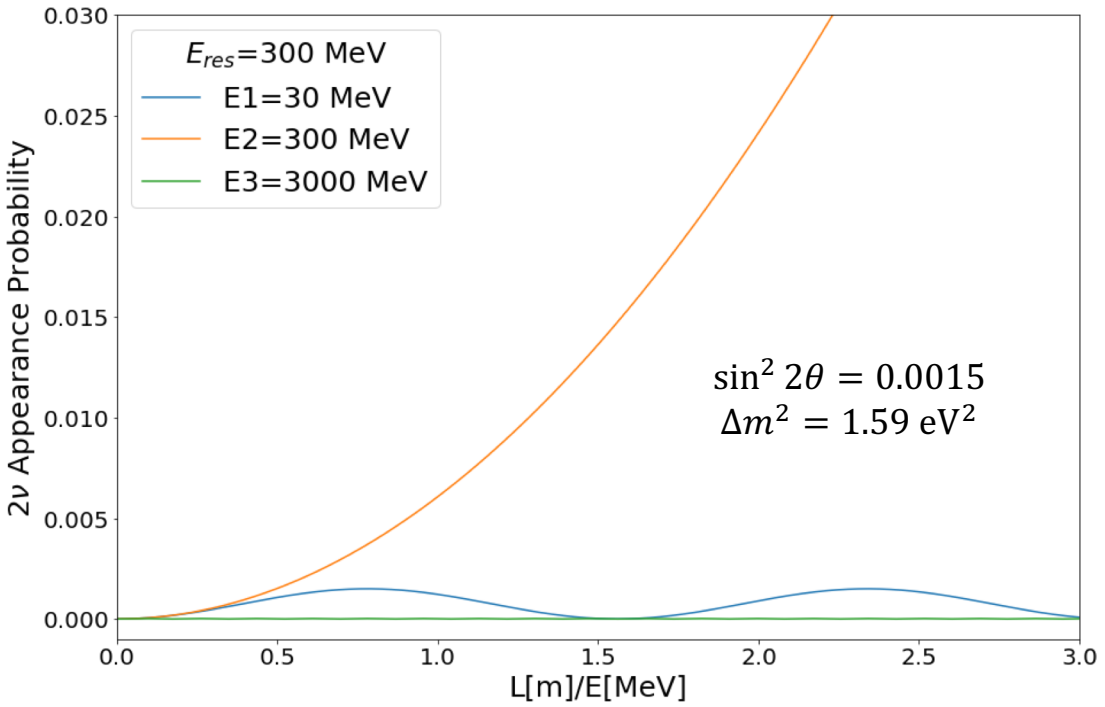
Extra Slides

Example of an Empirical Exotic Model: An MSW-Like Resonance

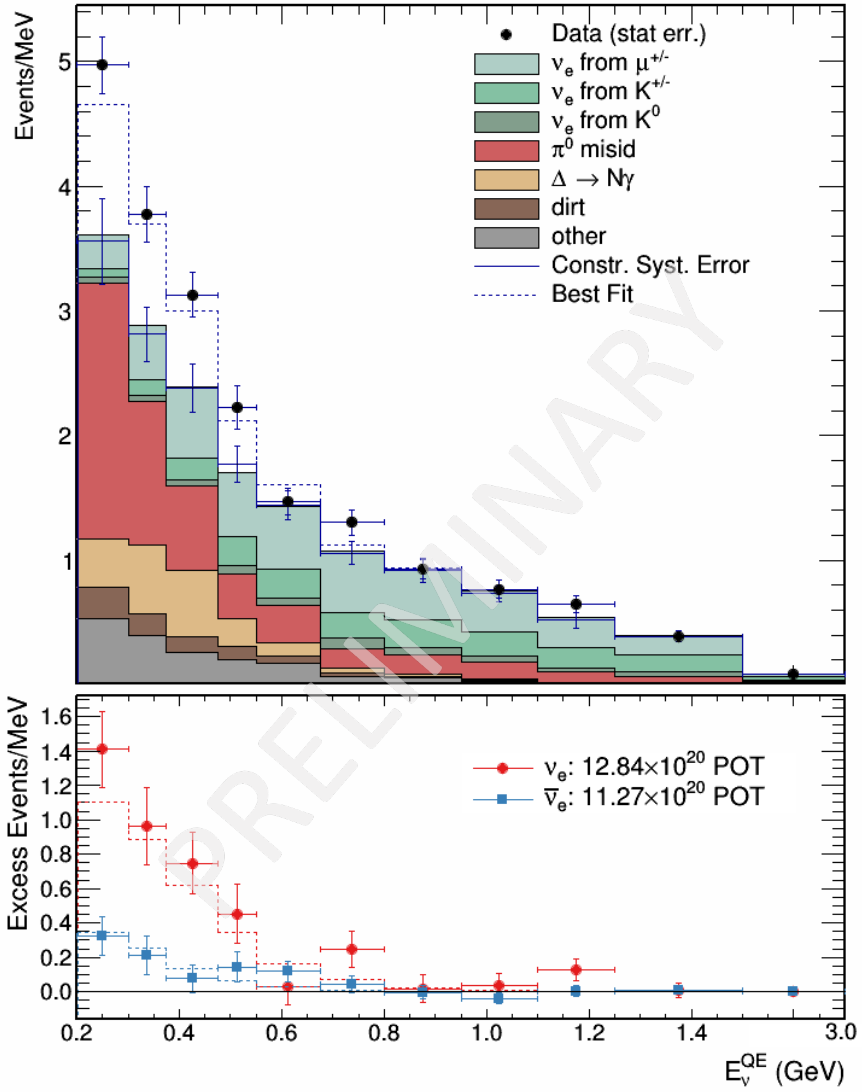
$$C = \sqrt{\cos^2 2\theta\,(1 - E/E_{res})^2 + \sin^2 2\theta}$$
$$\sin^2 2\theta_M = \sin^2 2\theta\,/C^2$$
$$\Delta m^2_M = C\Delta m^2$$

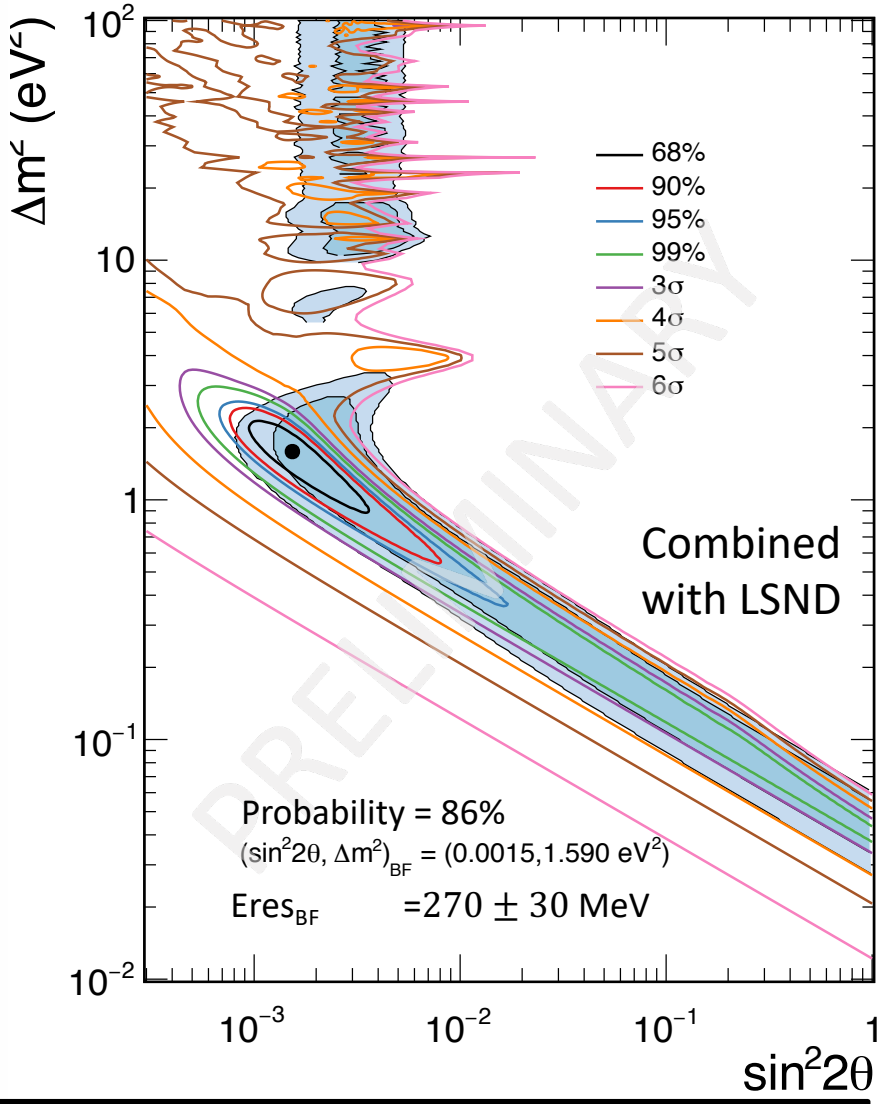
$$P(E \approx E_{res}, L) = \sin^2 2\theta_M \times \sin^2(1.267\Delta m^2_M L/E)$$
$$P(E \ll E_{res}, L) \approx \sin^2 2\theta \times \sin^2(1.267\Delta m^2 L/E)$$
$$P(E \gg E_{res}, L) \approx 0$$

Similar to:
arXiv:1712.08019
arXiv:1202.1024



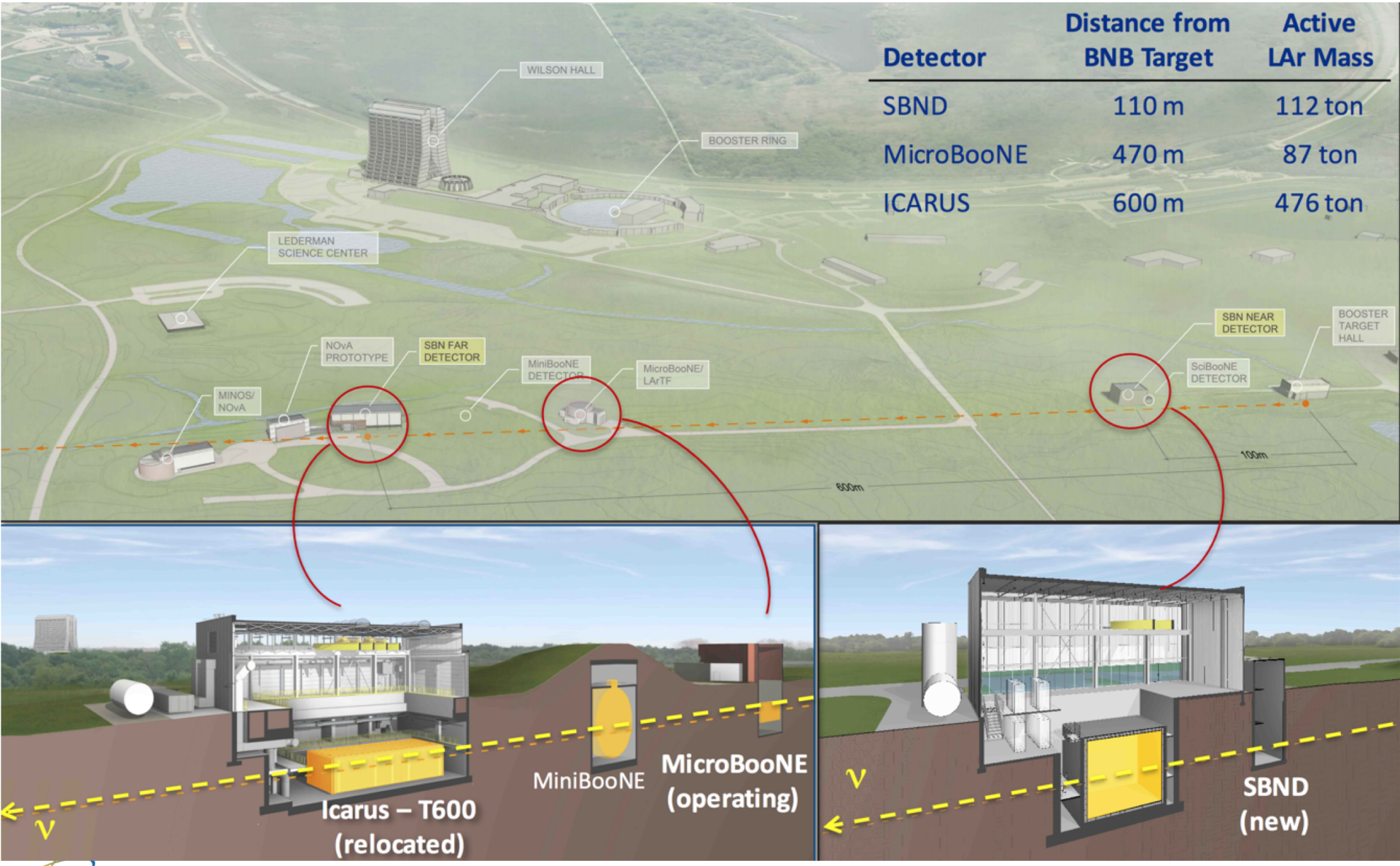
An MSW-Like Resonance Model





A more exotic model could provide a better fit to the MiniBooNE/LSND data

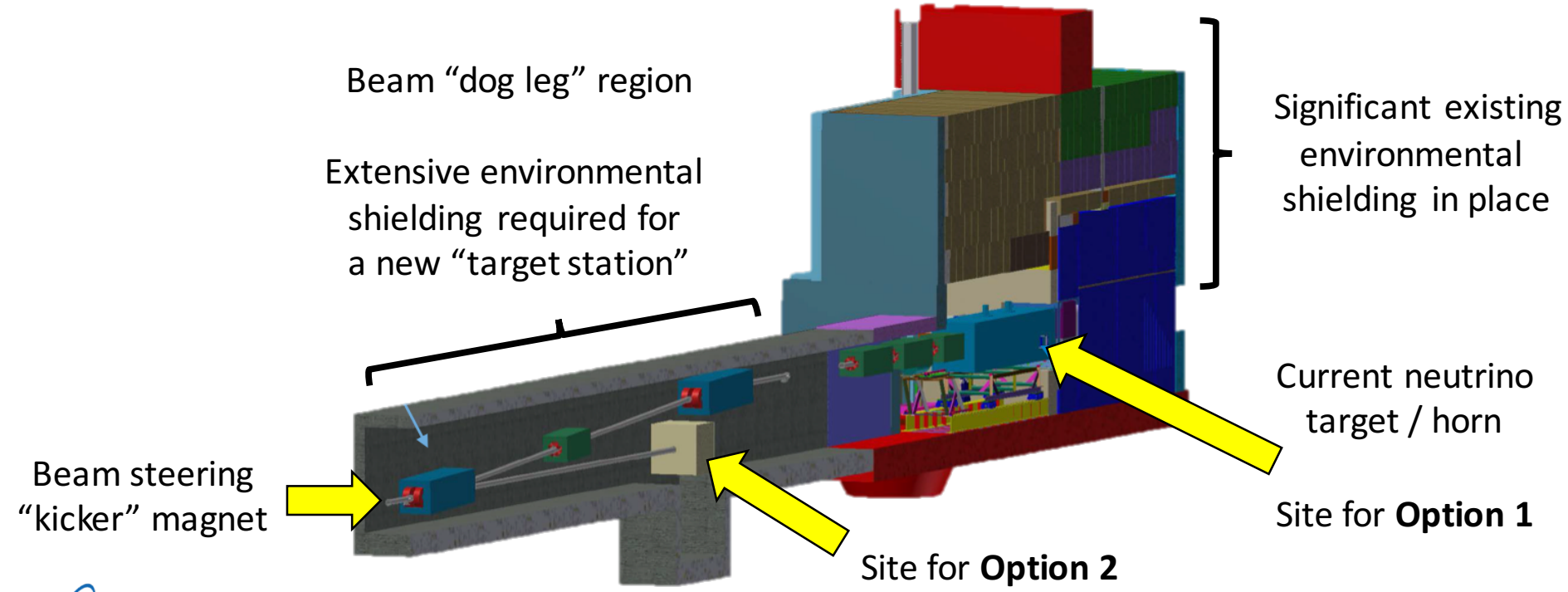
Short Baseline Neutrino Program



Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

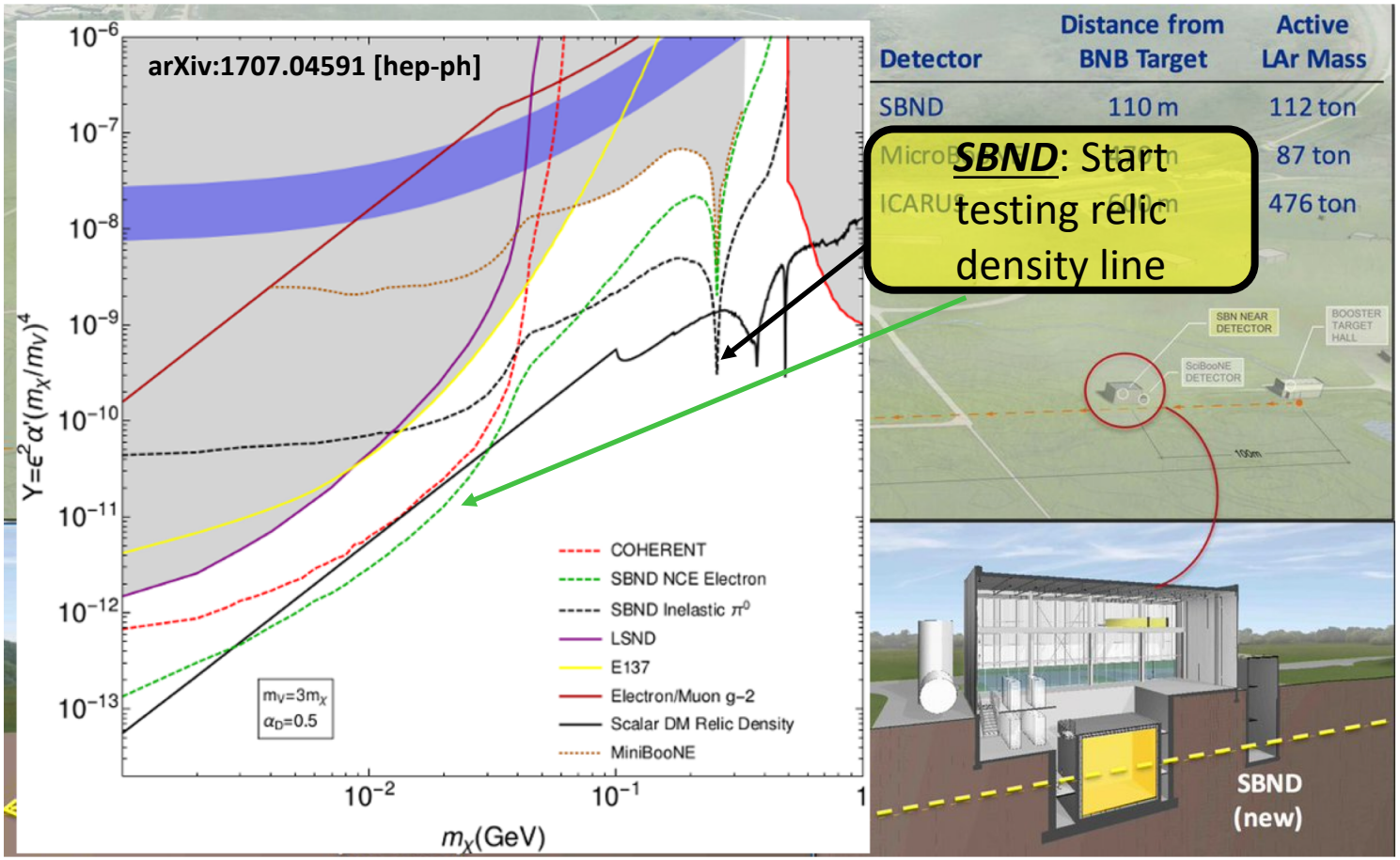
Dedicated SBN "Beam-Dump" Target (Expression of Interest to 2017 FNAL PAC)

- A dedicated SBN "beam-dump" target would decrease the ν rate by another factor of 20
- Adding an extra target to the BNB in the dog leg region would allow simultaneous ν/beam-dump running

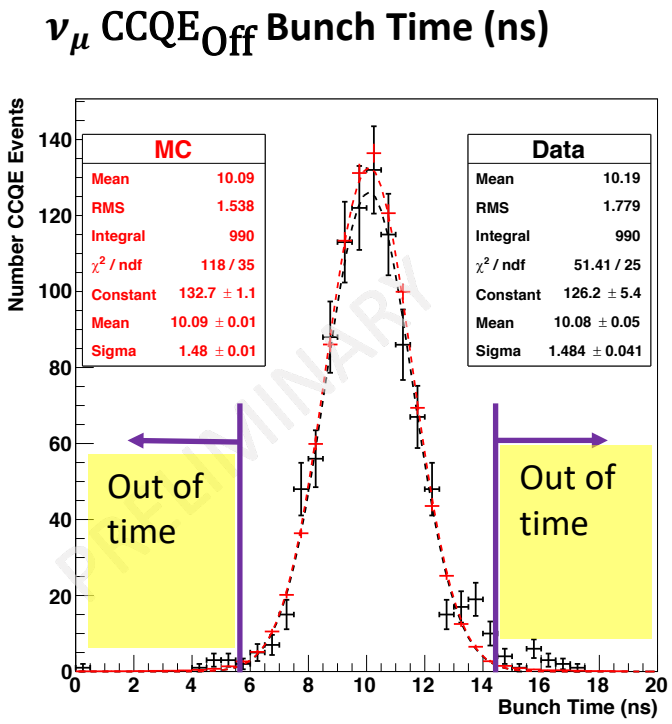


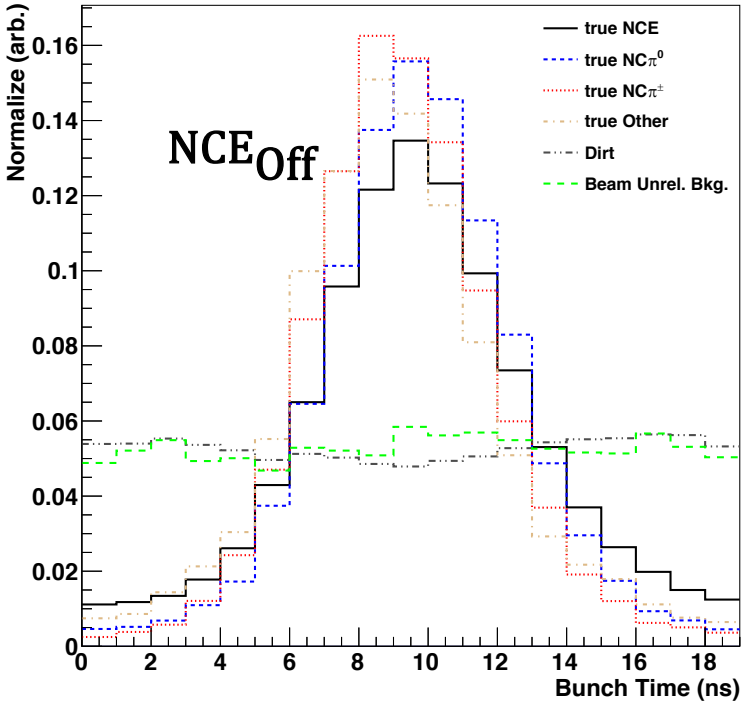
Dedicated SBN "Beam-Dump" Target (Expression of Interest to 2017 FNAL PAC)

- **Increase SBN physics output at low cost**
- Positive response from FNAL PAC, seeking DOE funding



New To Nucleon Analysis ("Time-of-Flight")





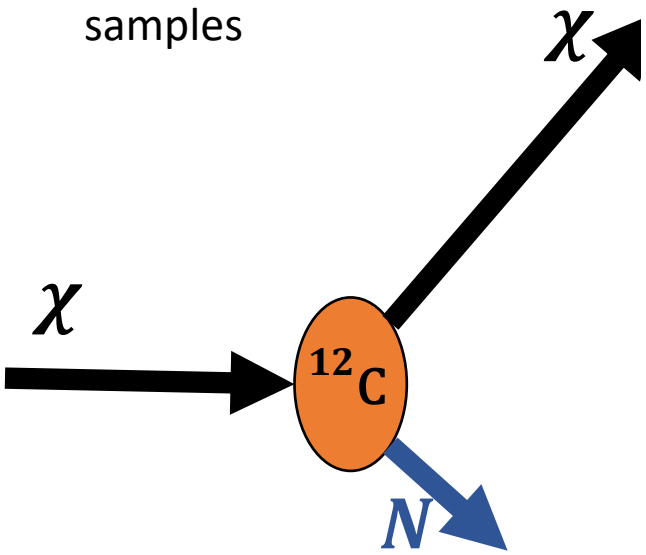
- **Time resolution of detector**
  - **Cherenkov ~1 ns**
  - **Scintillation ~4.5 ns**

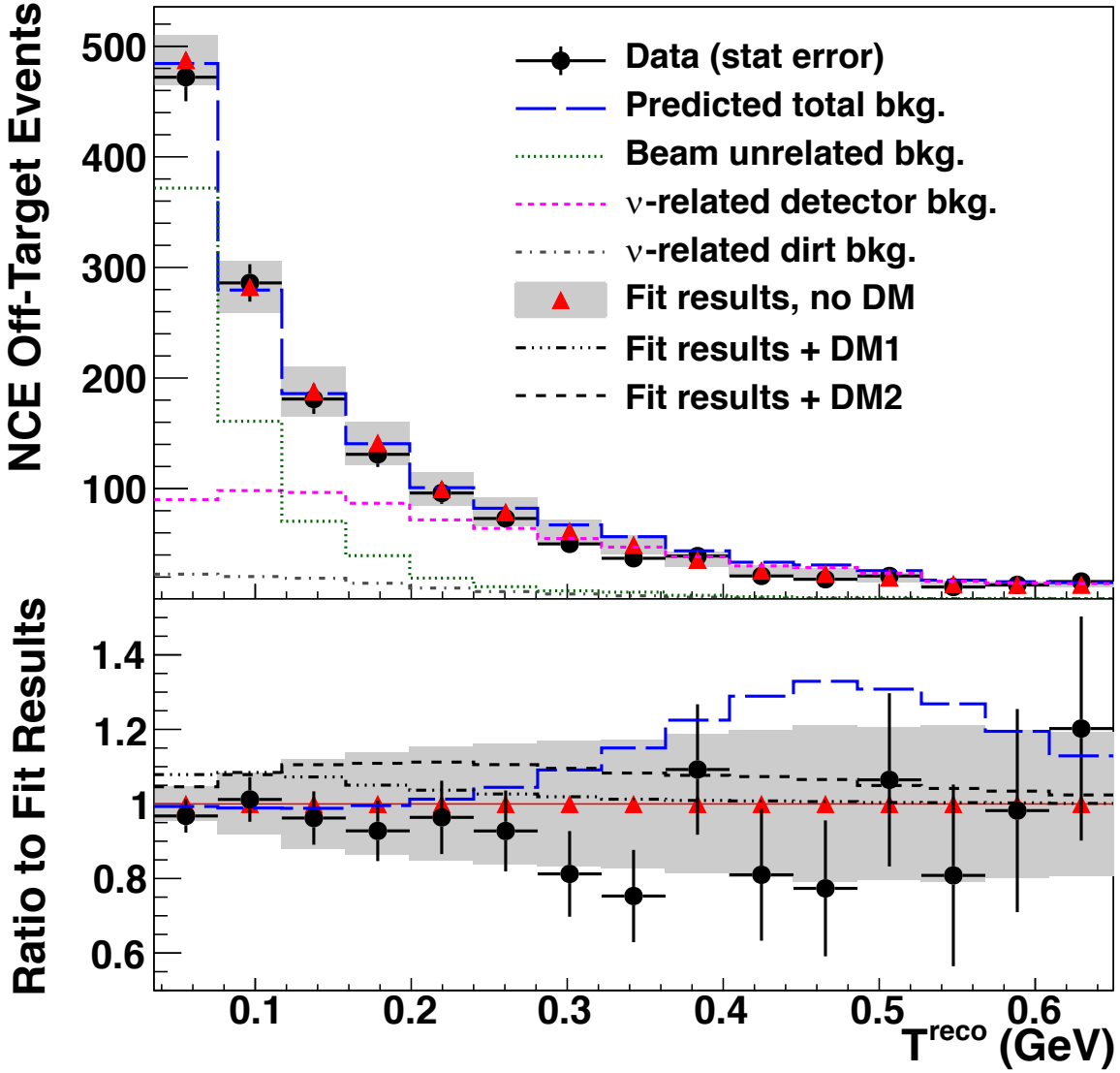
For Full N Analysis:
- **Fit in "energy" and time to increase sensitivity to heavier masses**

First Results: (quasi-) Elastic Scattering

PRL 118, 221803 (2017) Editors' Suggestion

- First dedicated search for direct detection of accelerator-produced dark matter in a proton beamline
- No excess observed
- Constrained by sideband samples

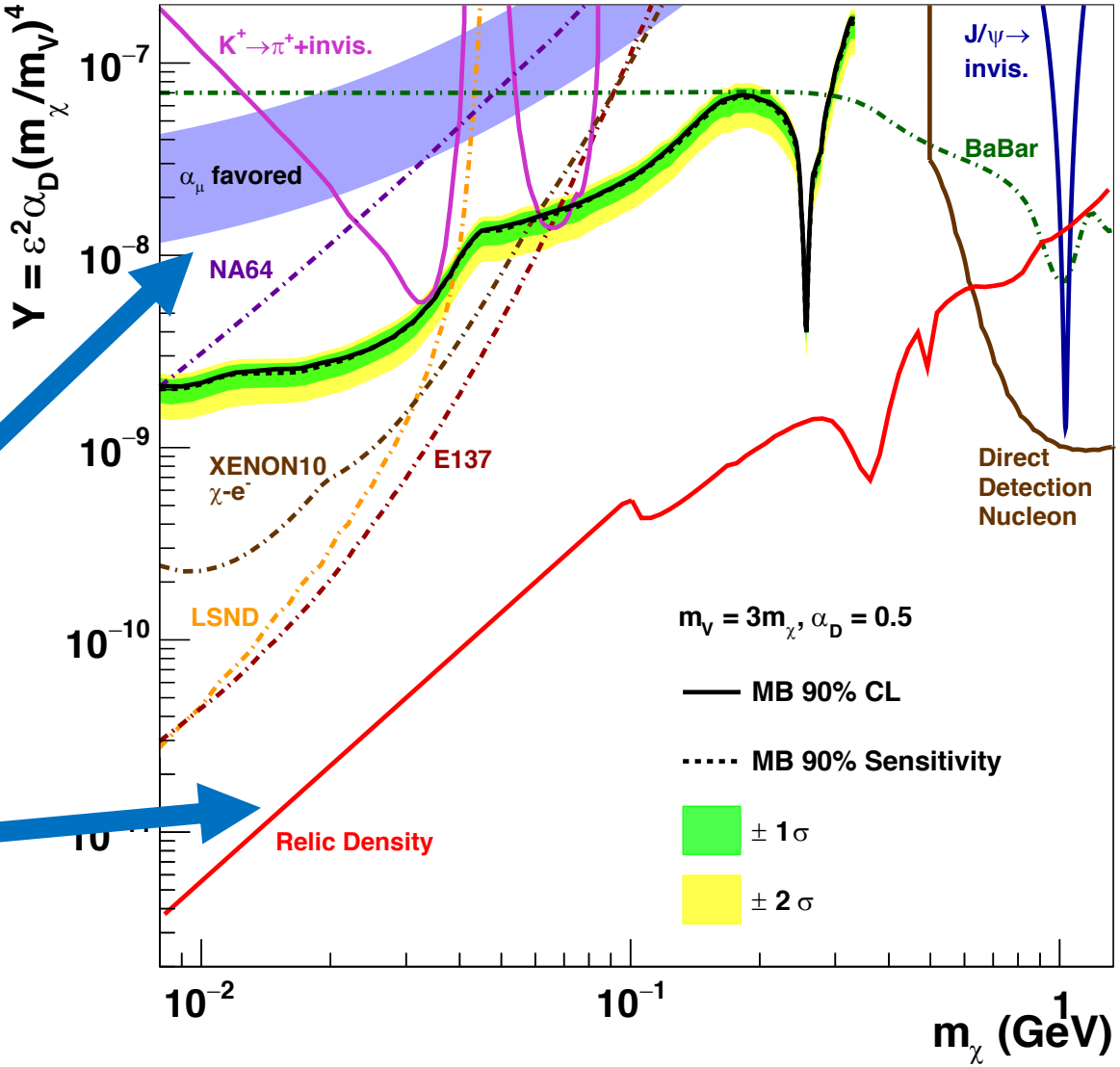




First Results: (quasi-) Elastic Scattering

PRL 118, 221803 (2017) Editors' Suggestion

- The goal was to test vector portal model interpretation of g-2 anomaly **(ruled out)**
- Where this model has to live to satisfy how much DM there is in the universe

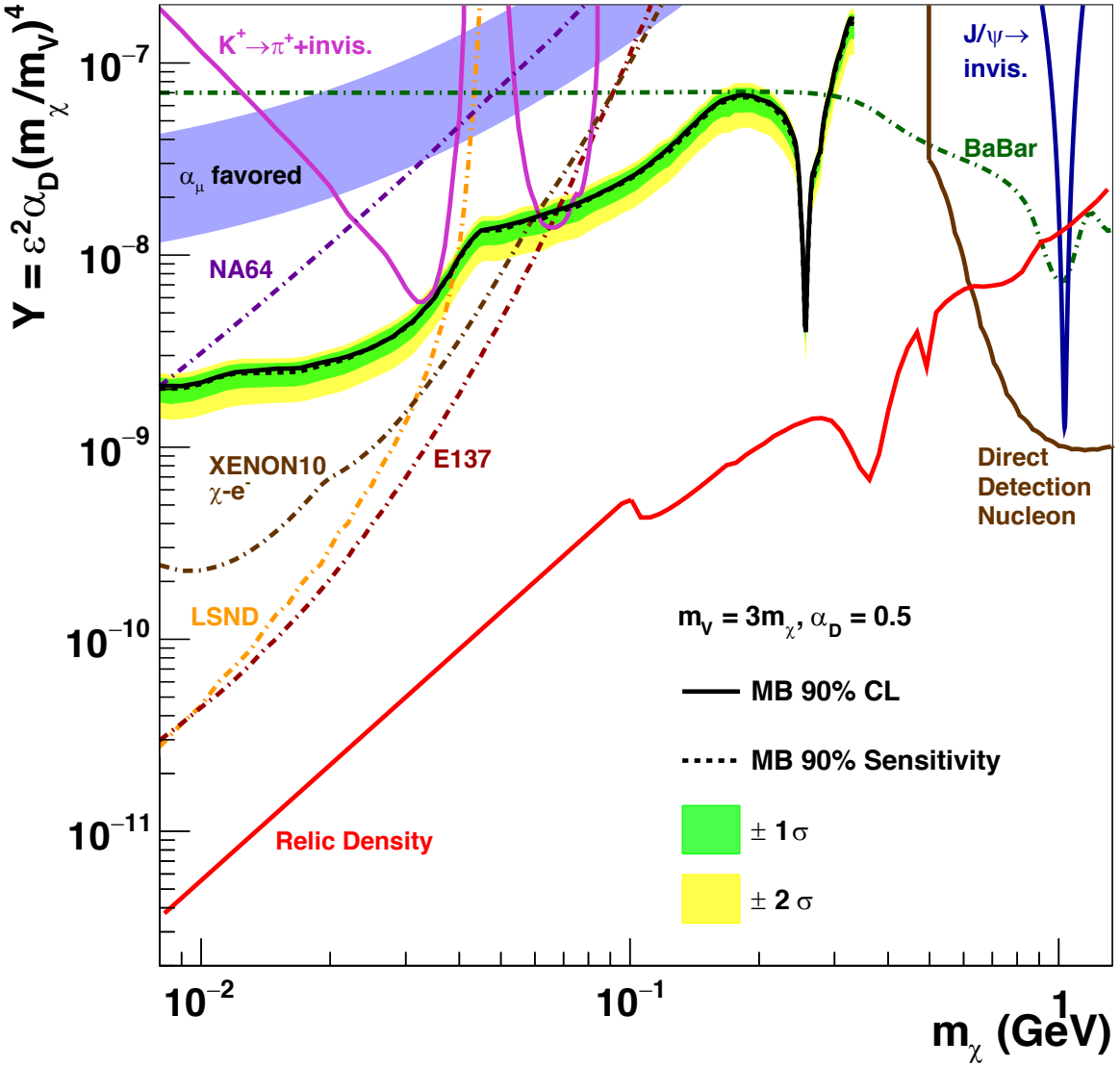


First Results: (quasi-) Elastic Scattering

PRL 118, 221803 (2017) Editors' Suggestion

MiniBooNE Result

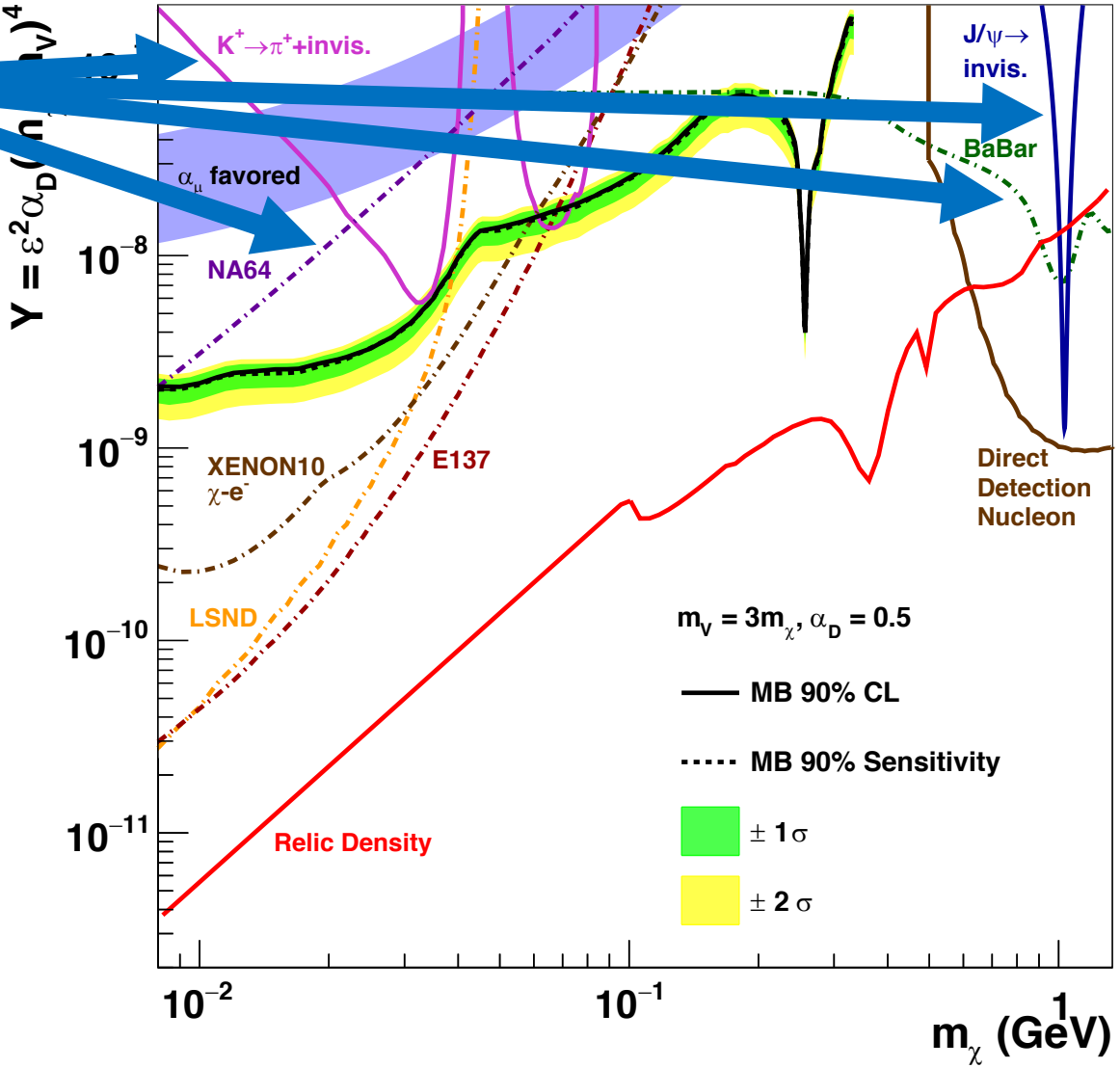
- Missing Mass/Energy Experiments ✗
- Direct Detection Experiments ✗
- Direct Detection from Electron/Proton Beam-dumps ✓
- Sensitive to models that weakly couple to leptons ✓



First Results: (quasi-) Elastic Scattering

PRL 118, 221803 (2017) Editors' Suggestion

- Missing Mass/Energy Experiments
- Direct Detection Experiments
- Direct Detection from Electron/Proton Beam-dumps
- Sensitive to models that weakly couple to leptons



First Results: (quasi-) Elastic Scattering

PRL 118, 221803 (2017) Editors' Suggestion

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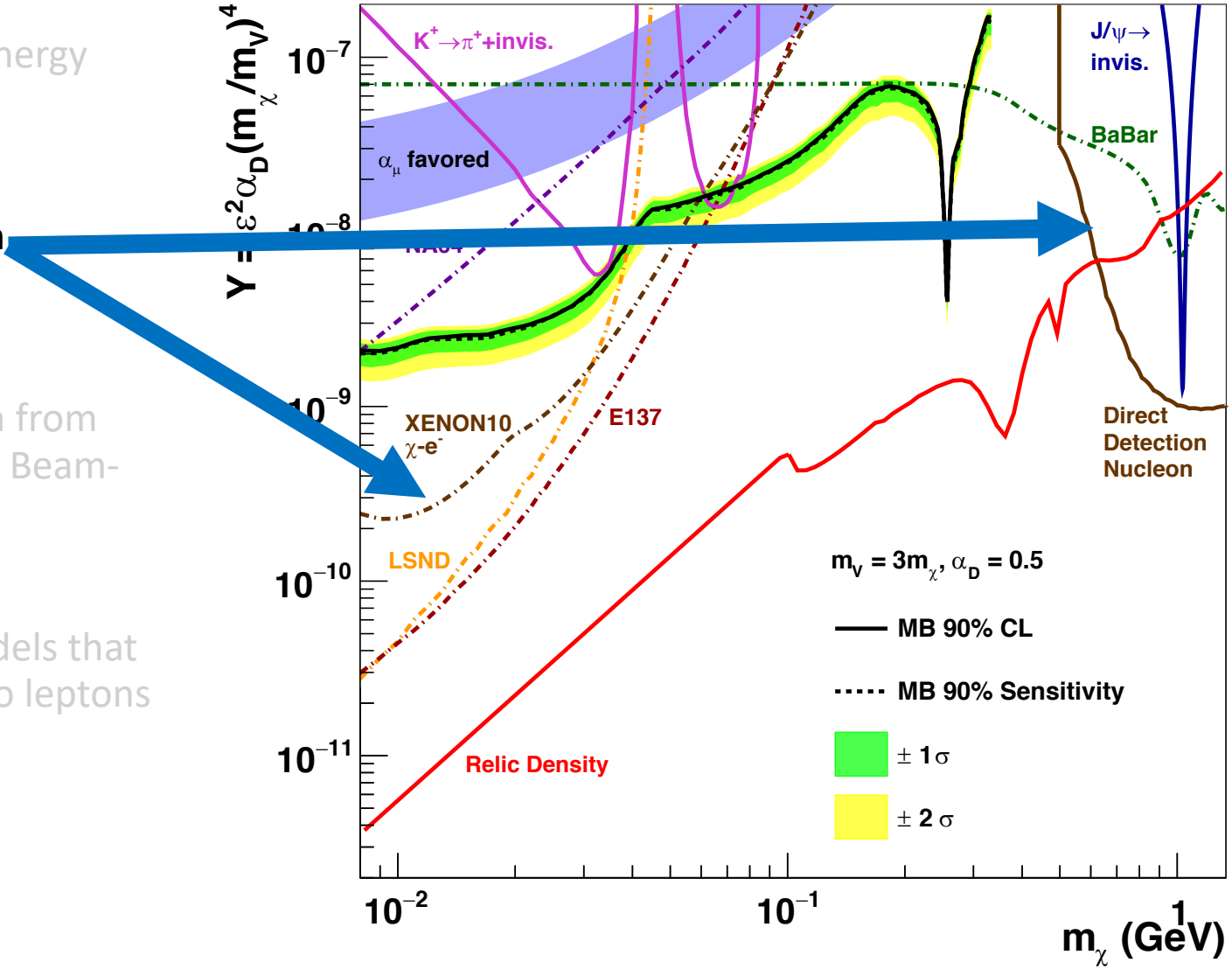

First Results: (quasi-) Elastic Scattering

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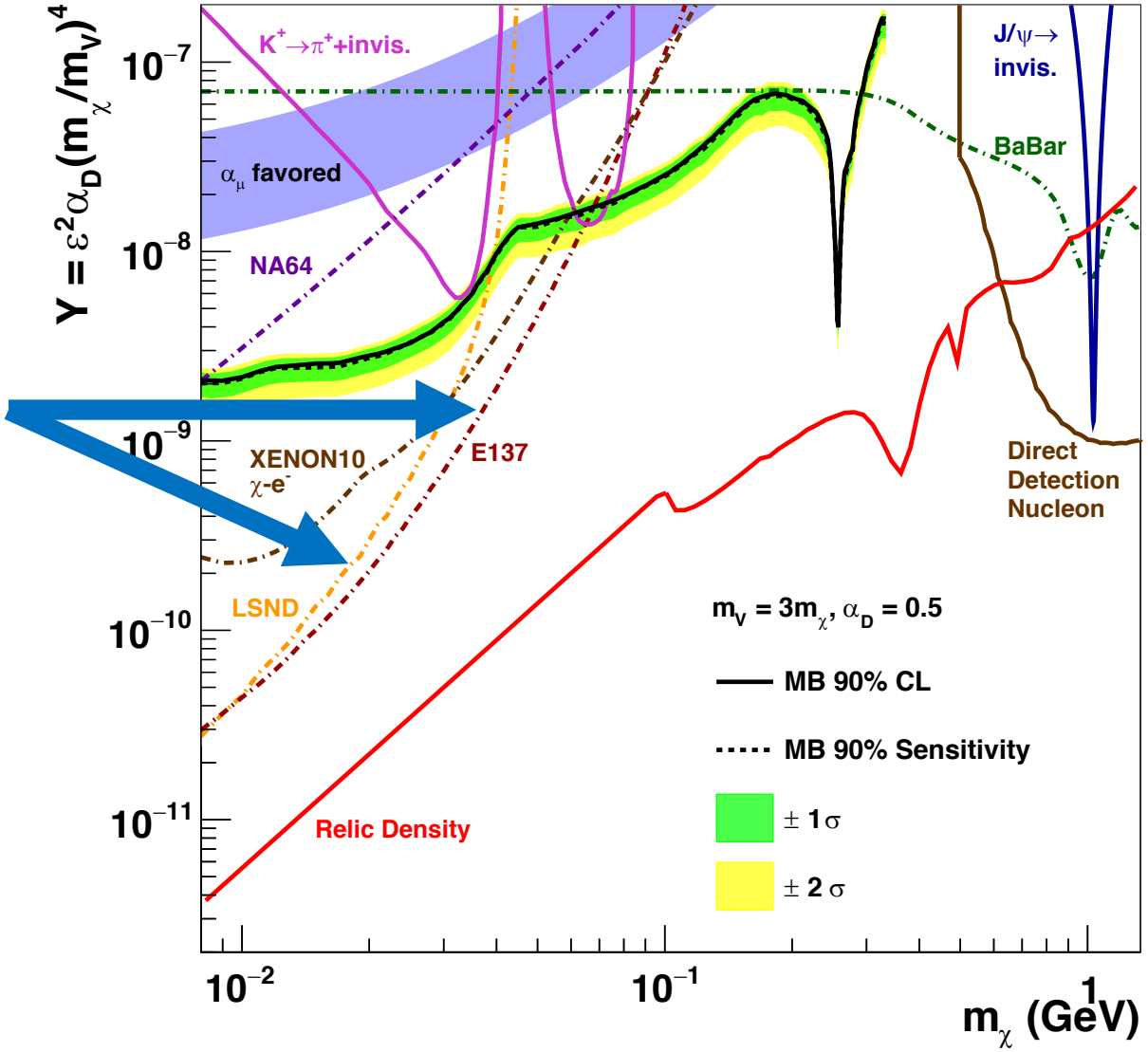

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