Light Mass WIMP Searches with a Neutrino Experiment:

The MiniBooNE Search

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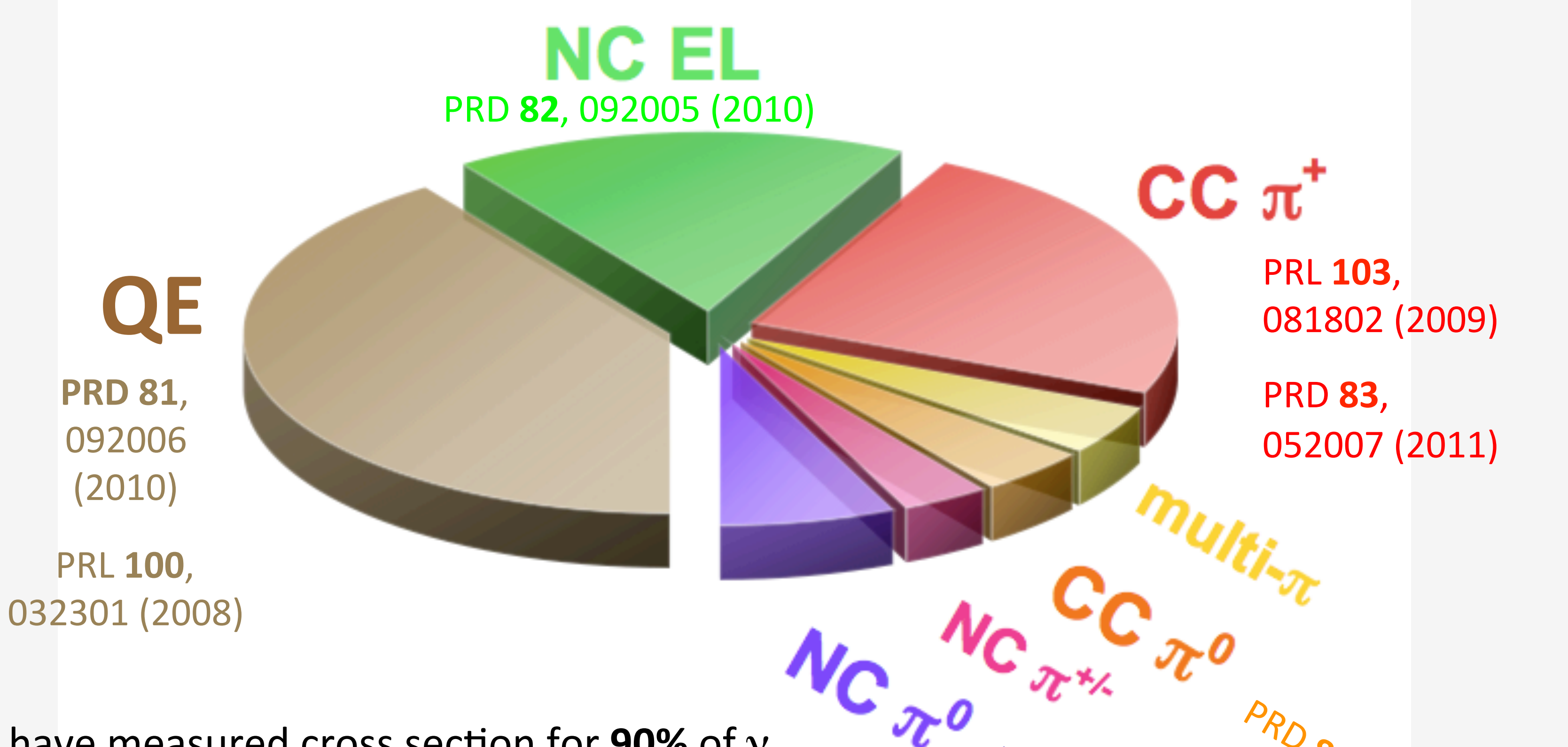
Outline

- Summary of 10 years of MiniBooNE neutrino/antineutrino running.
- The case for light mass WIMPs (<1 GeV) and how to produce them with protons beams.
  - neutrino experiments are good places to search for exotic particles.
- MiniBooNE WIMP detection methods, sensitivities and limits.
- The SNOWMASS process – motivating low mass WIMP searches at neutrino factories.
- Extended searches with the Main Injector (120 GeV protons), LBNE, Project X.
- FNAL accelerator complex commissioning and opportunity to perform a beam off target test run.
- Conclusions.

Ten Years of Successful MiniBooNE Running and Results!

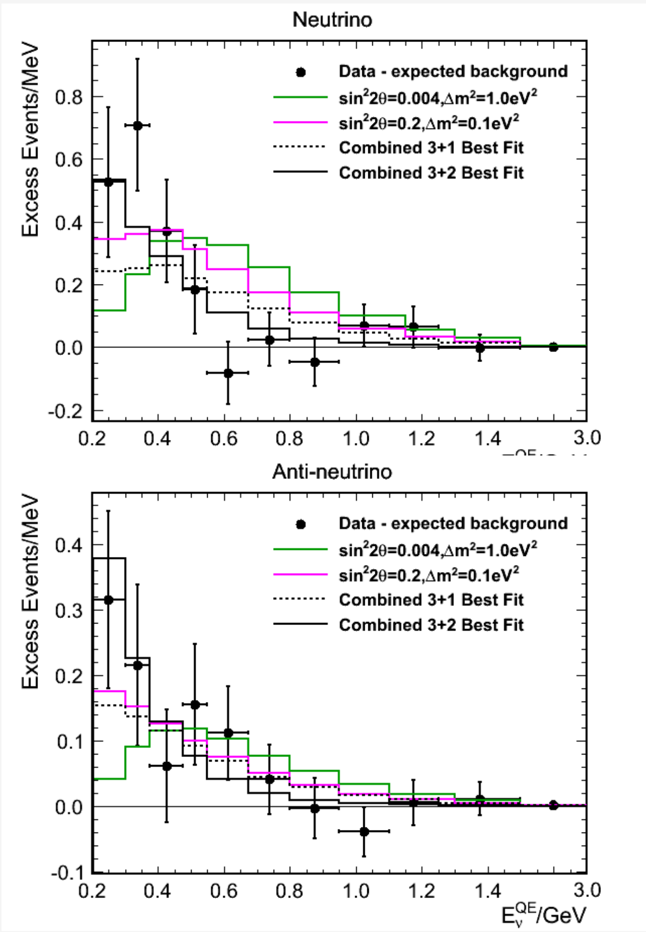
- Neutrino mode: 6.5E20 POT
- Antineutrino mode: 11.3E20 POT
- 10 oscillation papers
- 12 cross section and flux papers
- 1 detector and 1 supernova search paper
- 17 PhD thesis
- The experiment is well understood!

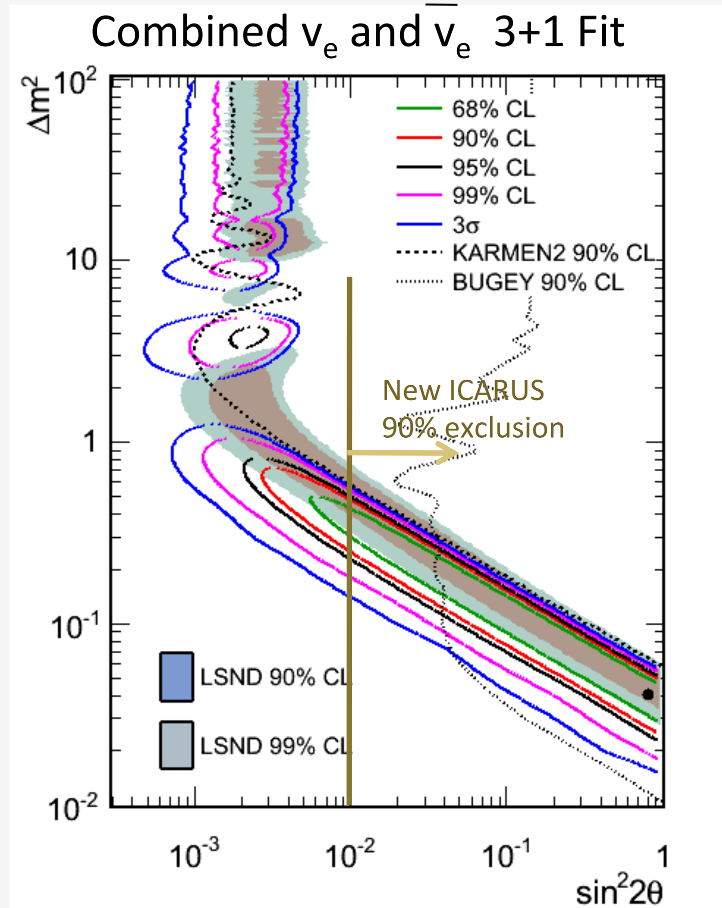
Ten Years of MiniBooNE Running: Cross Section Results (input to exotic searches)



- We have measured cross section for **90%** of ν interactions in MB. The detector is well understood!
- $\overline{\nu}$ results on CCQE and NC will be published soon.
- These results have motivate much new and needed theoretical work on neutrino nucleus scattering (> 540 citations)

Ten Years of MiniBooNE Running: Oscillation Results





- **Combined ν_e and $\bar{\nu}_e$ Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)**
- We fit for oscillations (3+1 – two neutrino model), and find consistency with LSND.
- However, with one detector, this is not proof of oscillations! Could some part of the e or γ excess be caused by a new background or other physics? **–need systematic checks**

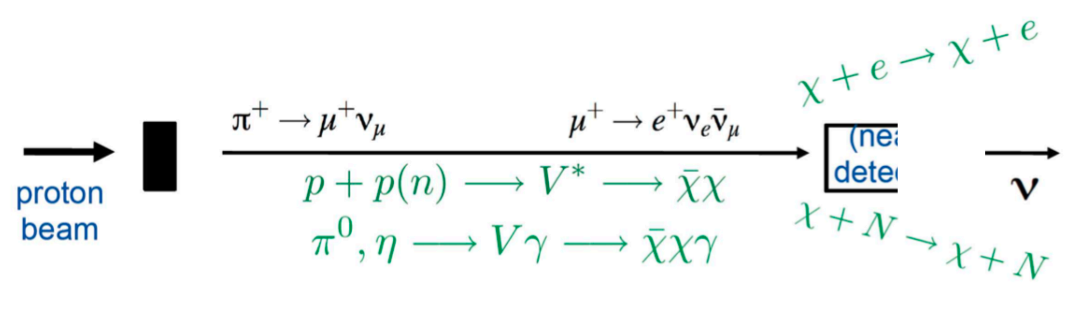
A New Idea: WIMP/Dark Sector Searches at MiniBooNE

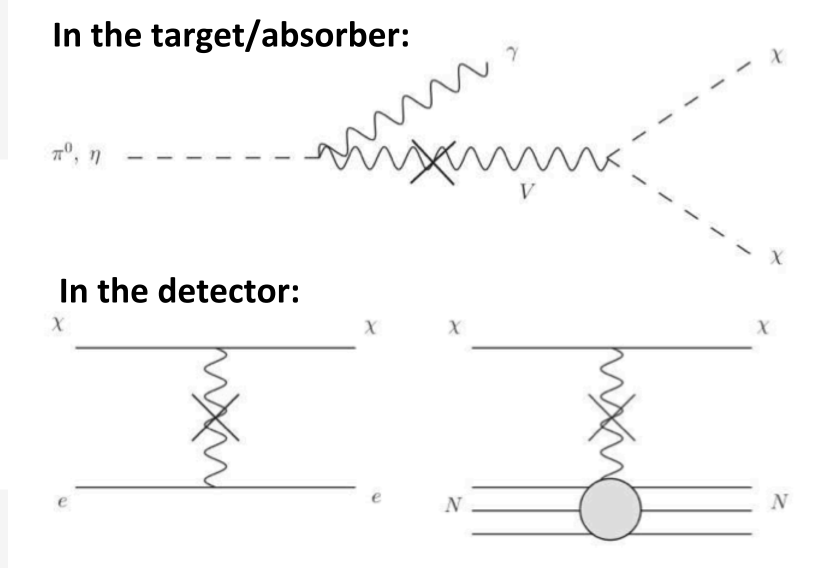
- Can WIMP Dark Matter be light (sub-GeV)?
- Yes! What are the constraints on such a scenario? What does a model look like?
- Consequences of the model for other observations, e.g. muon g-2.
- If WIMPs are light, how can MiniBooNE produce and detect them.
  – See Brian Batell's previous talk for theoretical setup.

Why are neutrino experiments (MiniBooNE) useful for new particle searches?

- Need a lots of protons on target: MiniBooNE has a total of ~$2x10^{21}$ @ E_{proton}= 8GeV.
- Detector needs to be close to source (for rate), but far enough away too minimize beam related backgrounds. MB is 500m from target.
- Massive detector (MB ~1 Kton oil).
- Good particle identification (MB reconstructs p, n, μ, e, γ).
- Good event reconstruction (for MB E_t > 20 MeV and absolute timing ~nsec).

Producing a Dark Matter Beam





Electron Elastic scattering

Nucleon Elastic scattering

- Monte Carlo Simulation of WIMP Production at MiniBooNE:
  - Use HARP-MiniBooNE Be target Sanford-Wang meson production model.
  - π^0 and η production errors range from 25% to 100%. More work to reduce these.
- Electrons and nucleon can be reconstructed in MiniBooNE with ~35% efficiency and ~10% energy resolution.
  - Nucleon systematic errors ~20% (cross section paper).
  - Electrons systematic errors ~12%, can make use of WIMP-electron forward scattering kinematics cosθ > 0.99 to reduce backgrounds by a factor of 100.

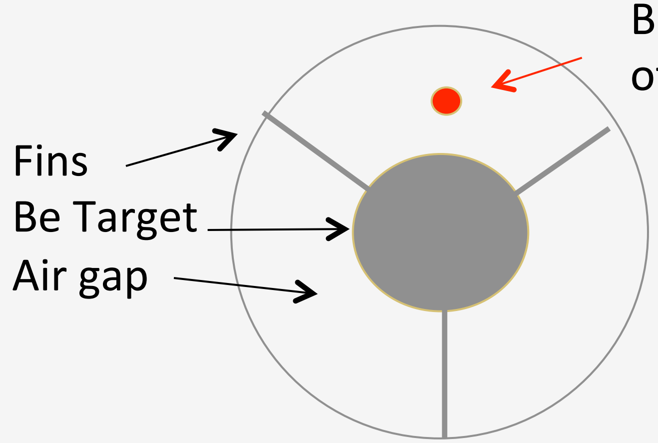
Enhancing the WIMP Search at MiniBooNE

- The WIMP scattering signal looks like neutrino nucleon or neutrino electron elastic scattering. Thus, neutrino interactions are the biggest background to these searches.
- We can employ a beam dump type method to significantly reduce charged meson decay, and hence the neutrino flux.

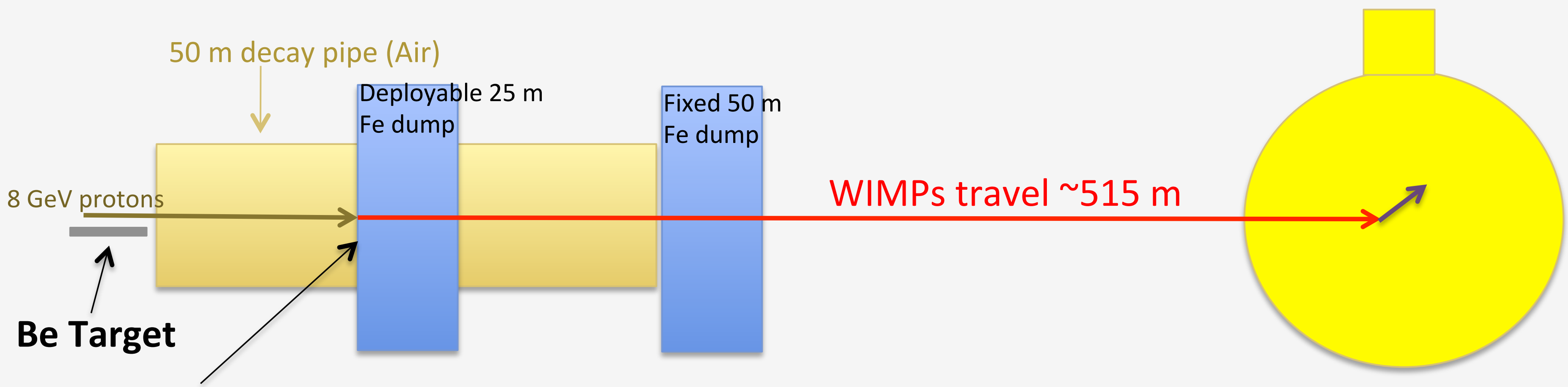
Beam Off Target Running

MB has the capability to steer the protons past the target and onto the 25m or 50m iron dump

Beam spot position in beam off target mode (~1 mm spread)



-Target is 1 cm diameter
-Air gap between target and horn inner conductor is ~1 cm

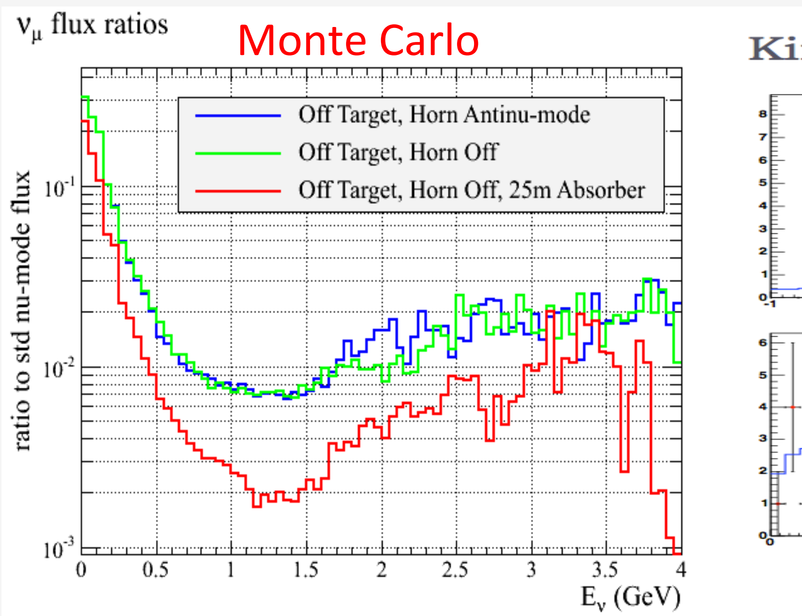


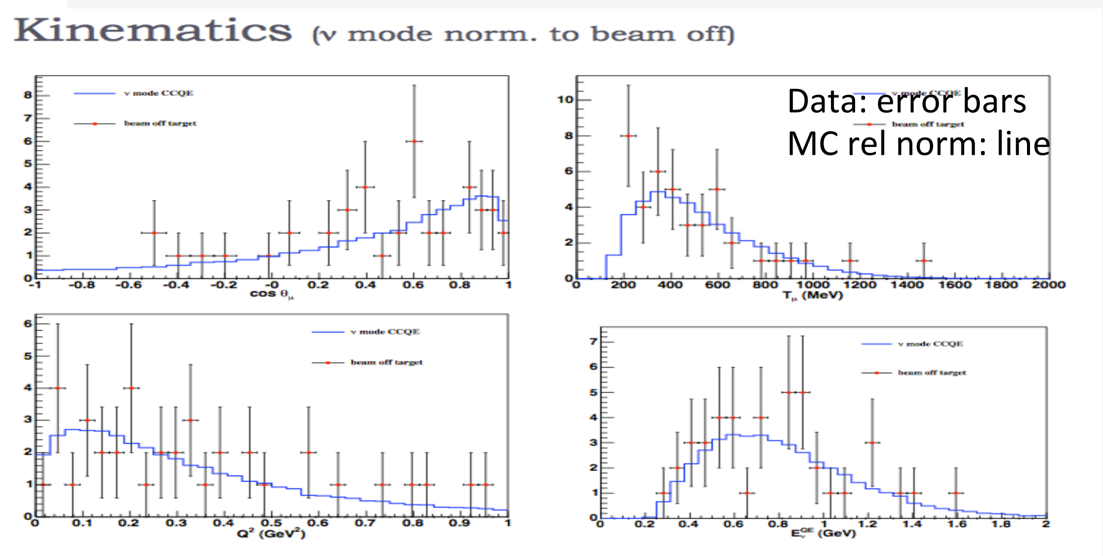
- π^0 and η produced by protons in the iron quickly decay producing WIMPs (χ)
- Charged mesons are absorbed in the iron before decaying, which significantly reduces the neutrino flux (still some production from proton-Air interactions). **Neutrino Flux reduction measured to be ~42 with 50m dump.**

Neutrino Rate Reduction with Beam Off Target Running (1 week test run)

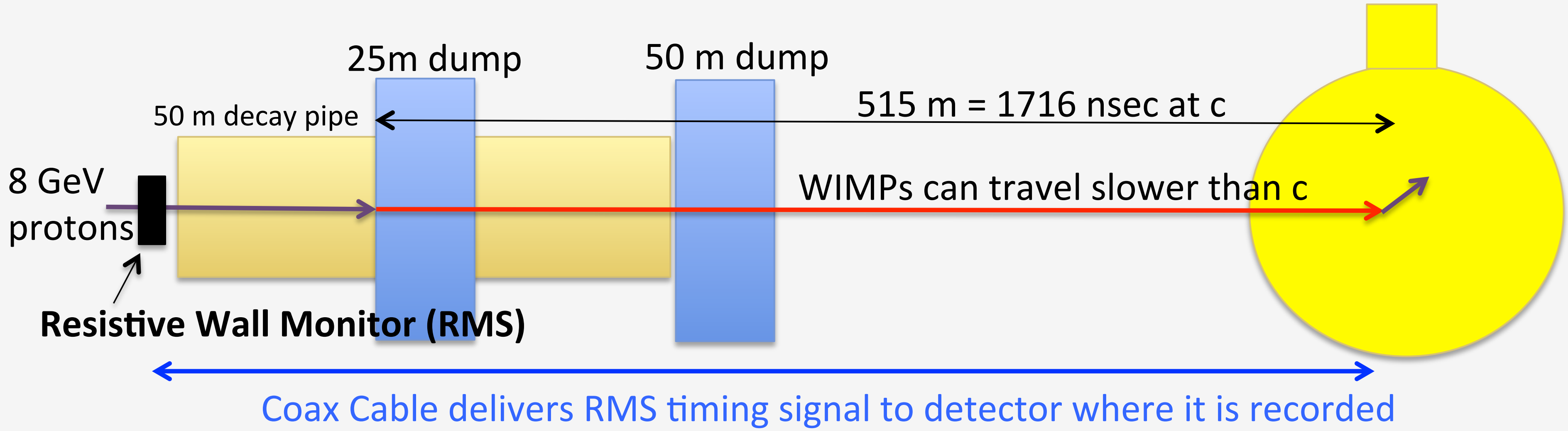
- Estimated neutrino rate reduction:
  - 50m absorber one week beam off target run (~5.54e18 POT): $(\text{events/POT})^{\nu\ \text{mode}}/(\text{events/POT})^{\text{beam off target}} = 42 \pm 7$ ← Data rate reduction
  - 50m MC: $(\text{events/POT})^{\nu\ \text{mode}}/(\text{events/POT})^{\text{beam off target}} = 36$
  - 25m MC: $(\text{events/POT})^{\nu\ \text{mode}}/(\text{events/POT})^{\text{beam off target}} = 72$

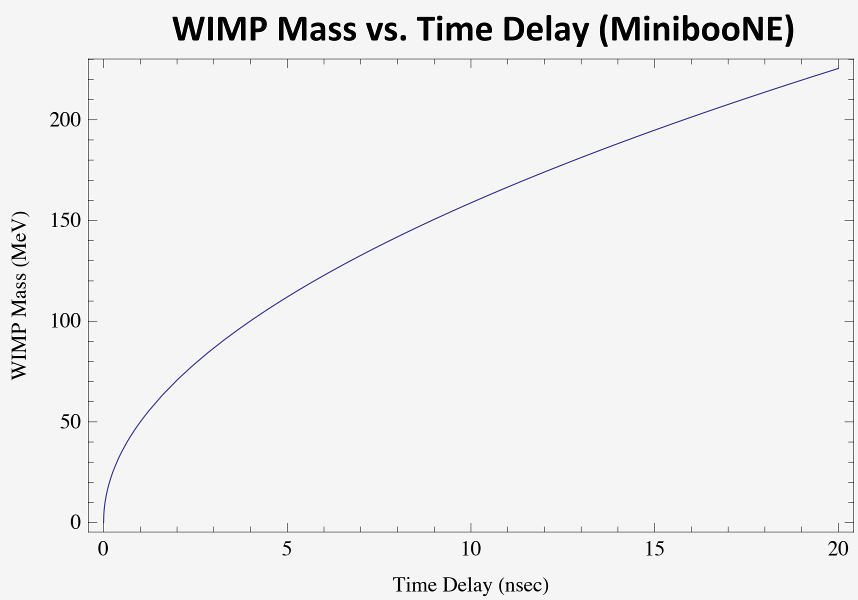
MC flux reduction



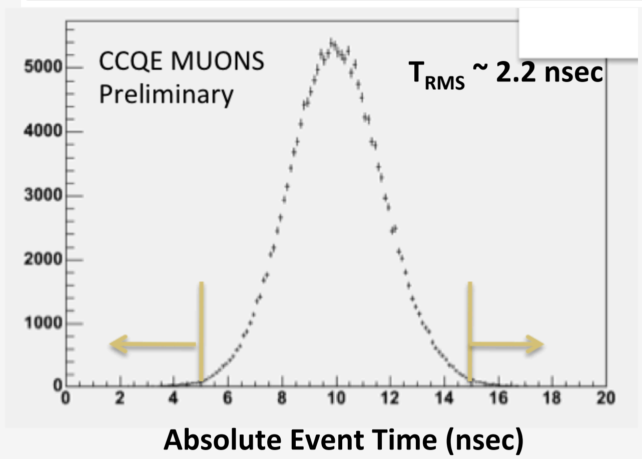


WIMP Time of Flight





Timing cut (nsec)	Background Reduction (%)	WIMP Velocity β	WIMP Mass (MeV)
3.0	90	0.9984	85
4.6	99	0.9974	108
5.9	99.9	0.9967	122



-Electrons timing will be similar to muons, while NC nucleon events twice as worse.

MiniBooNE Collaboration and Theory Group Proposes Beam Off Target Run to FNAL PAC (Nov 2012)

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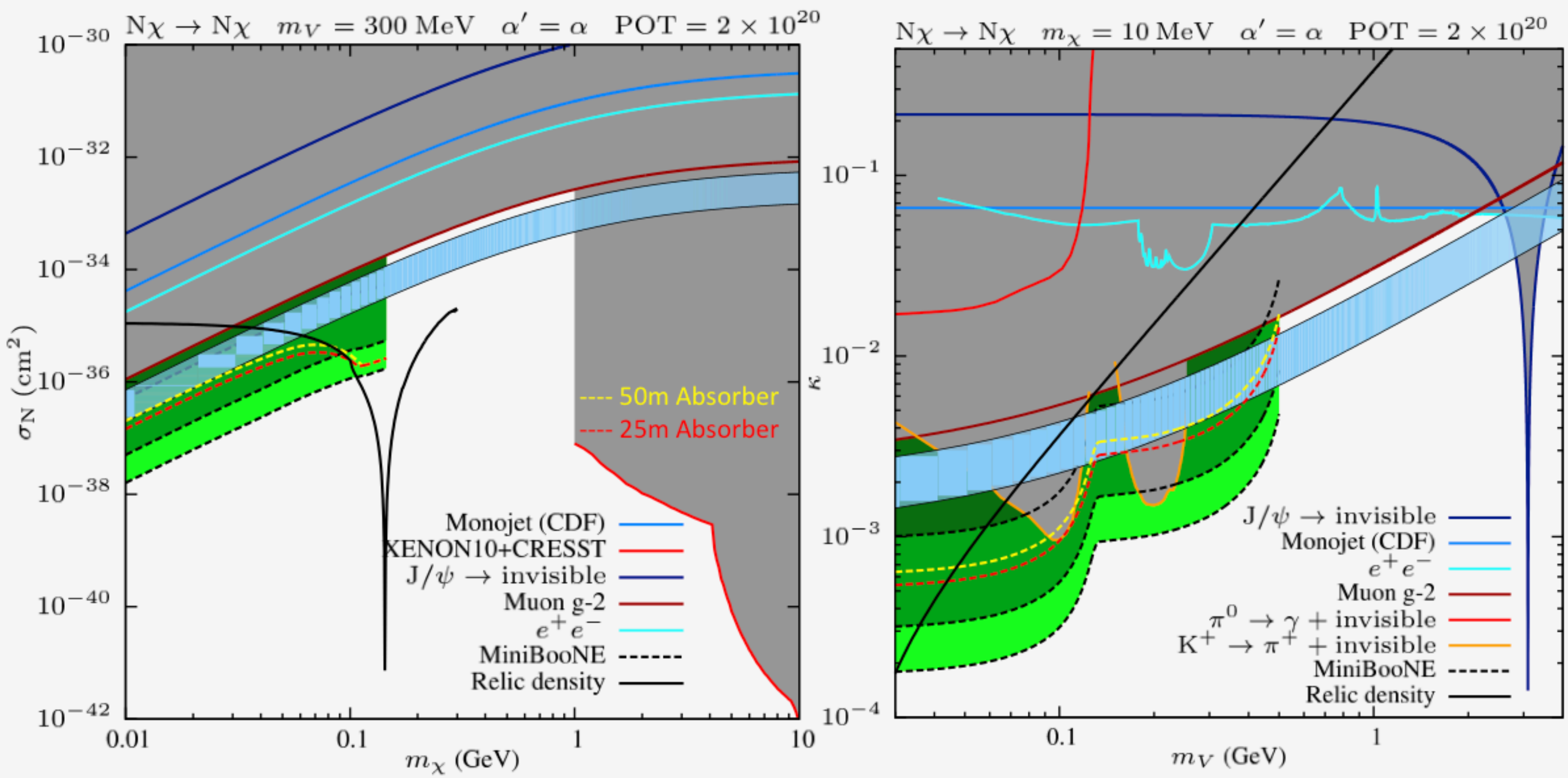
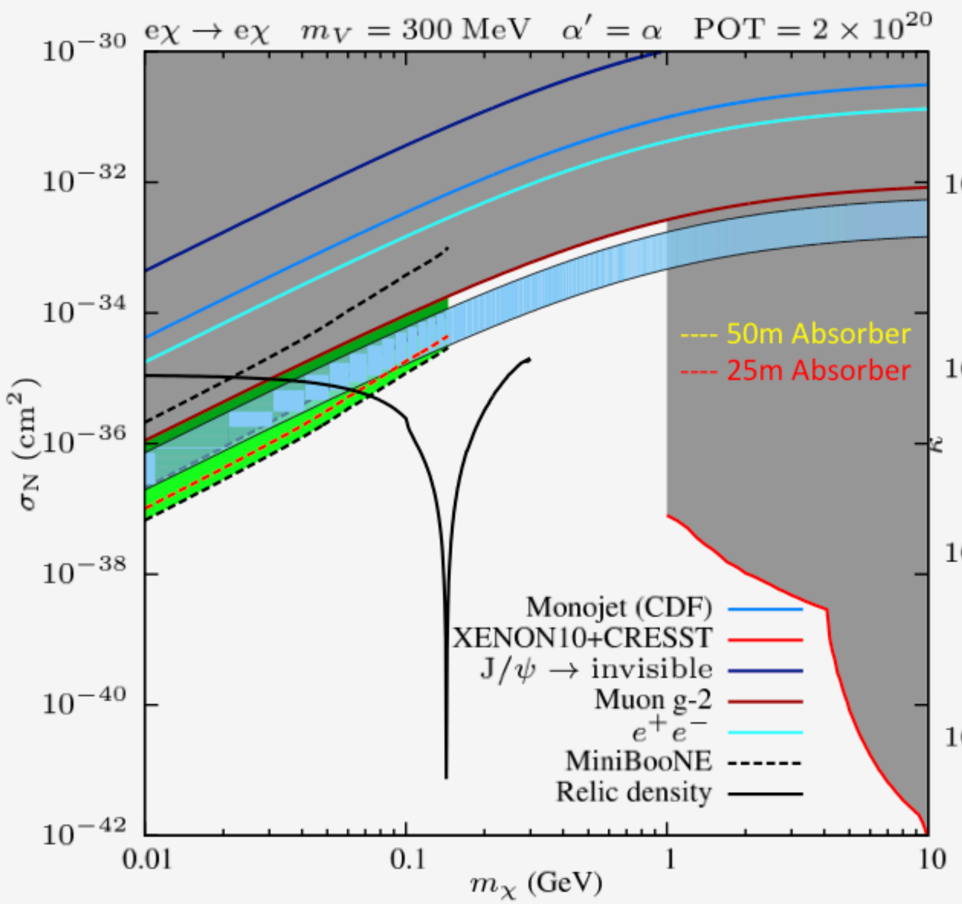
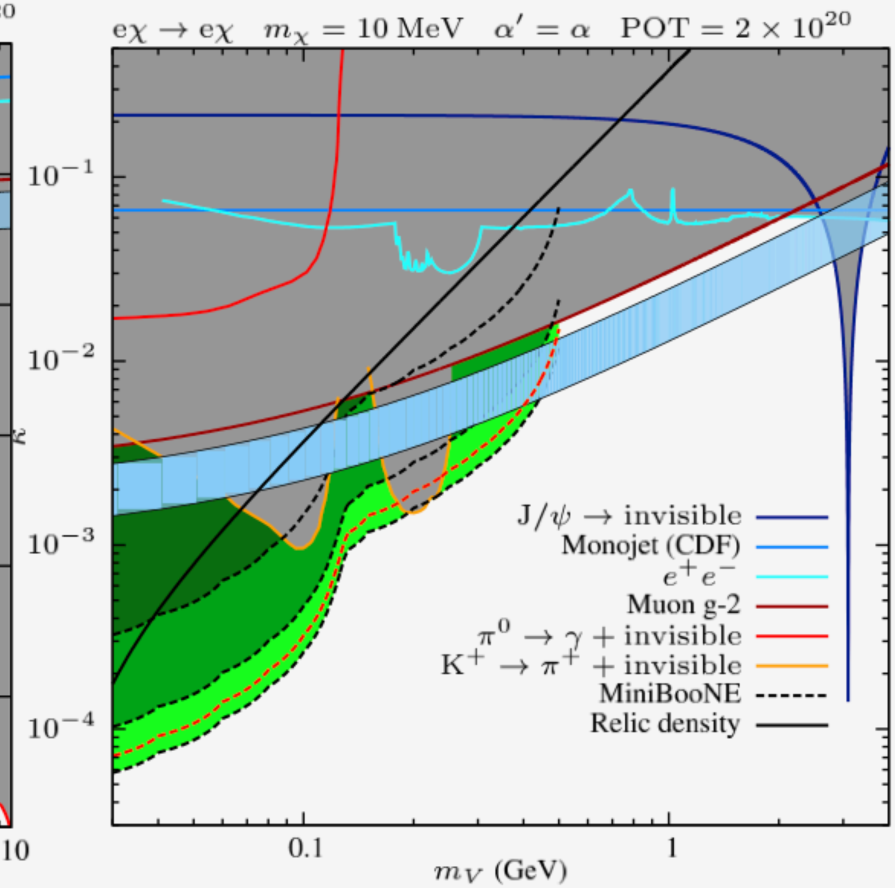
90% C.L. Sensitivities for WIMP-Nucleon Scattering: 2E20 POT Beam off Target and 25/50m Absorber Run



- Estimate 90% C.L. upper limits includes timing information.
- Can cover a significant part of the muon g-2 signal region.

90% C.L. Sensitivities for WIMP-Electron Scattering: 2E20 POT Beam off Target and 25/50m Absorber Run





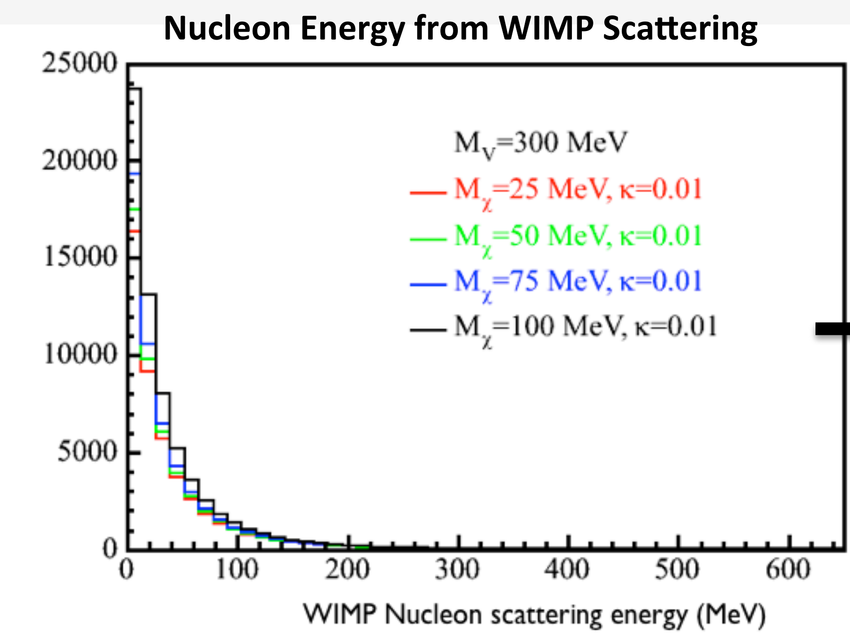
- Estimate 90% C.L. upper limits includes $\cos\theta_{beam}$ and timing info.
- Can cover a significant part of the muon g-2 signal region.

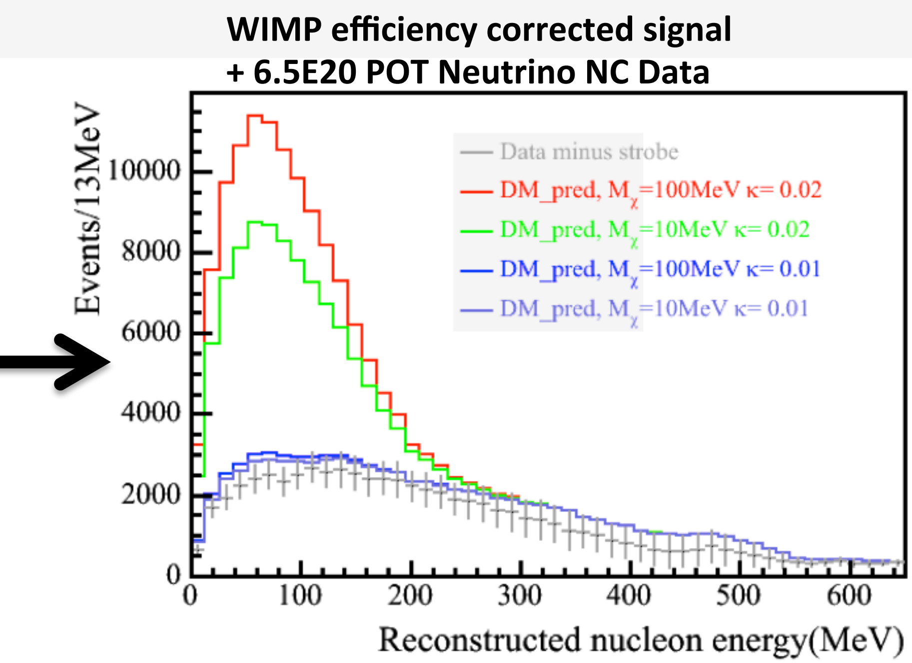
The MiniBooNE 2012 PAC Request

MiniBooNE request[illegible]nning to collect a total [illegible].0 $\times 10^{20}$ POT in beam off target mode and with the 25[illegible]bsorber deploye[illegible] [illegible]his will allow a powerful search for light mass WIMPs in a par[illegible]ter sp[illegible]hat overlaps with muon $g-2$ and cosmic relic density estimates. The [illegible]ment further requests that this beam be delivered in FY2013 and 2014 be[illegible] the [illegible]roBooNE experiment turns on.

- Search for low mass WIMP signals is compelling and explores uncharted territory.
- In the period before MicroBooNE turns on (~1 year), we put the idle Booster Neutrino Beamline (BNB) to good use that will produce publishable physics.
- Proposal rejected, physics was motivating but cited a lack of remaining collaboration strength, and not completing the WIMP scattering analysis on the current data sets.

Work Since the PAC Decision: Using Energy to Fit to the Neutrino NC Data



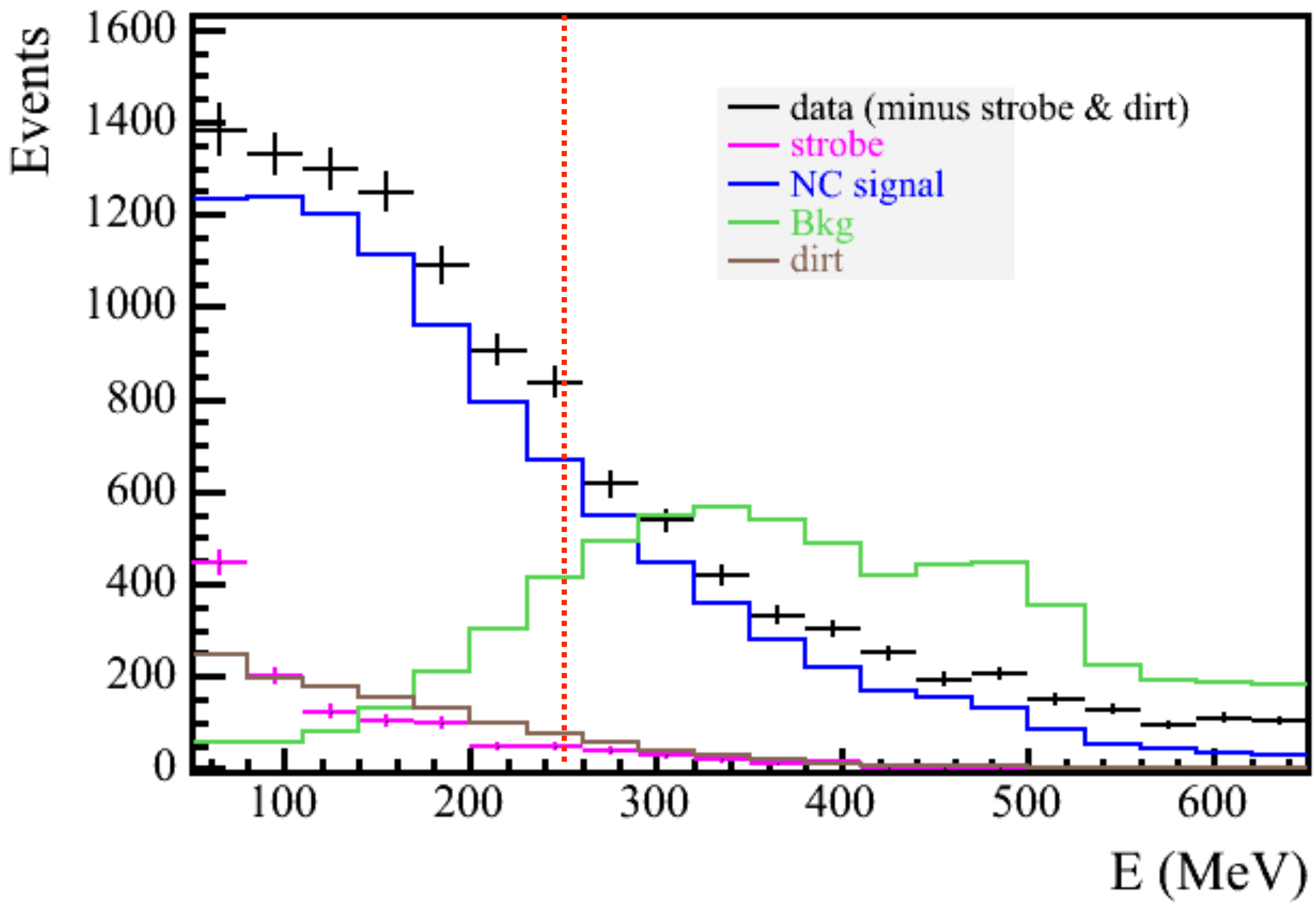


- Fit the WIMP template plus the neutrino background prediction to the NC data. Use full NC cross section error matrix.
- Most of the WIMP signal resides $E_{nucleon}$ < 200 MeV.
- Analysis done by MiniBooNE's Ranjan Dharmapalan (U. Alabama).

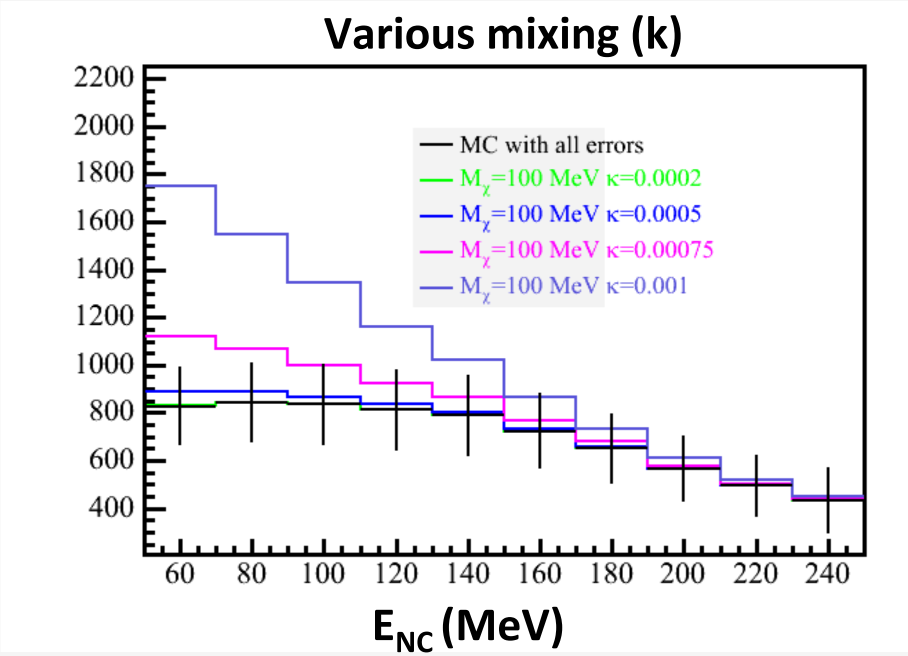
Nucleon Energy Cuts:

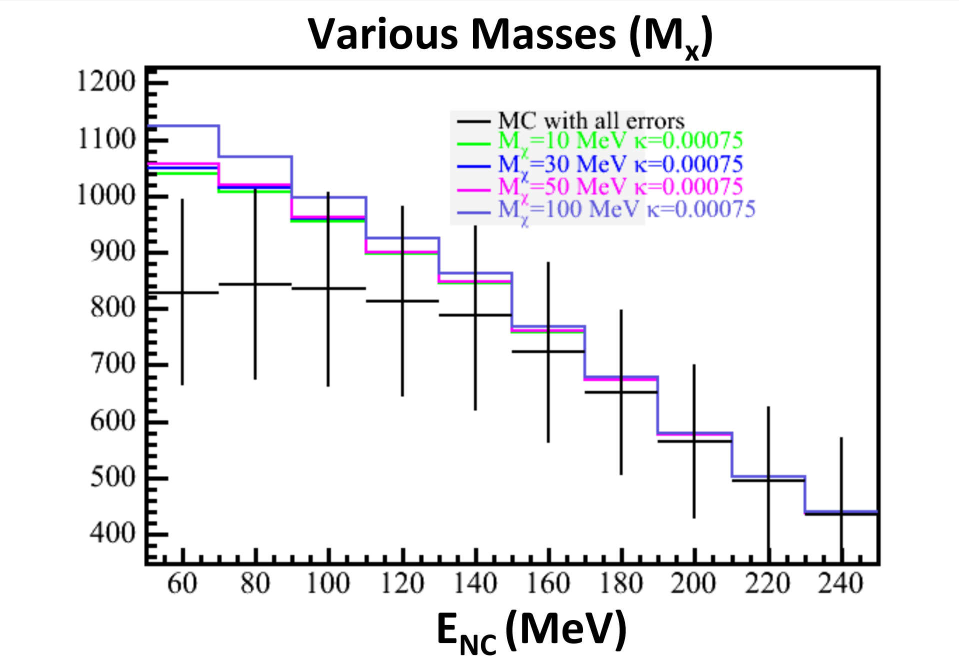
E_{NC} > 50 MeV reduce beam unrelated events

E_{NC} < 250 MeV reduce NC-bkg events



Nucleon Energy from WIMP Scattering



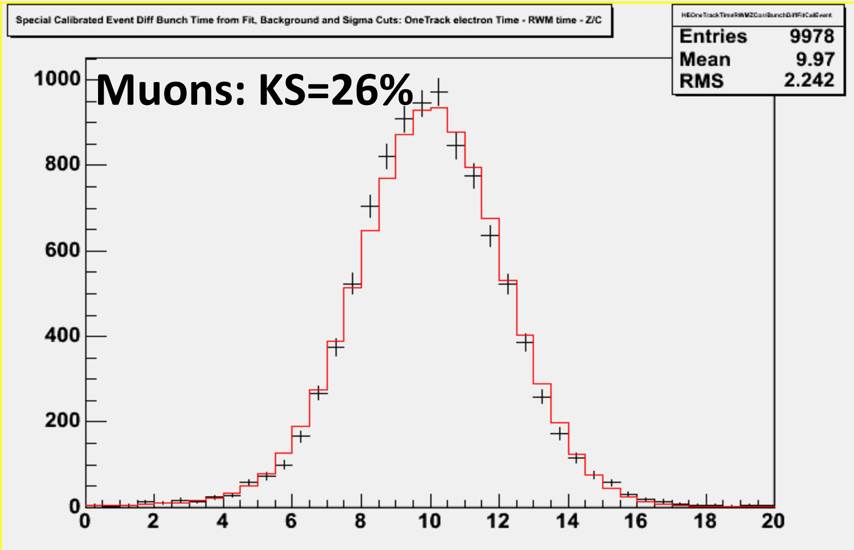


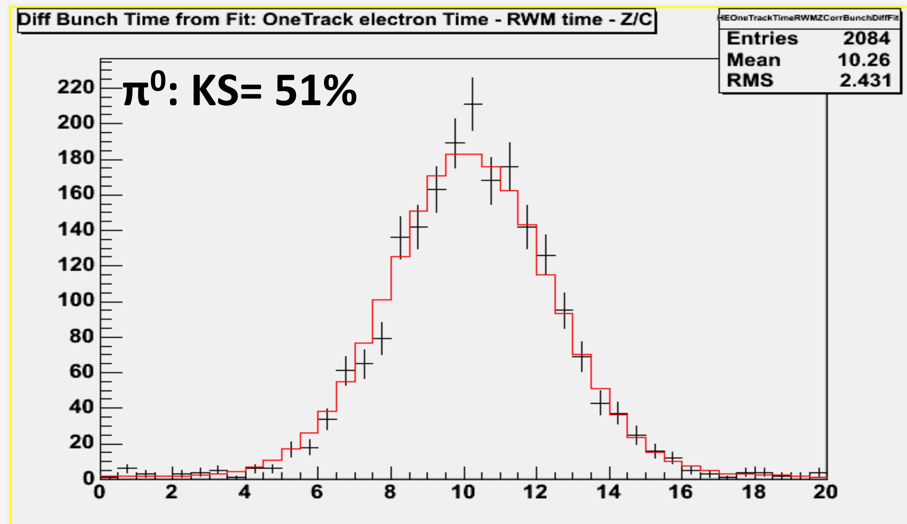
- Nucleon energy is mostly insensitive to WIMP mass and mixing strength
- WIMP-nucleon signal below 200 MeV.
- E > 50 MeV to reduce beam unrelated backgrounds that dominate a low energy.

Preliminary Time of Flight Analysis (Red full MC)

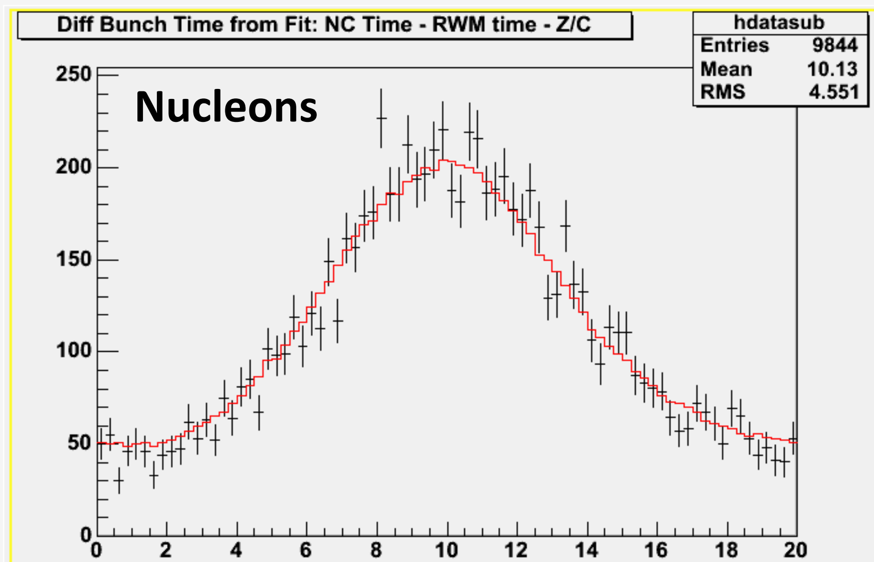
Muon/π^0 calibration-test samples – good agreement!

Electron/NC physics samples





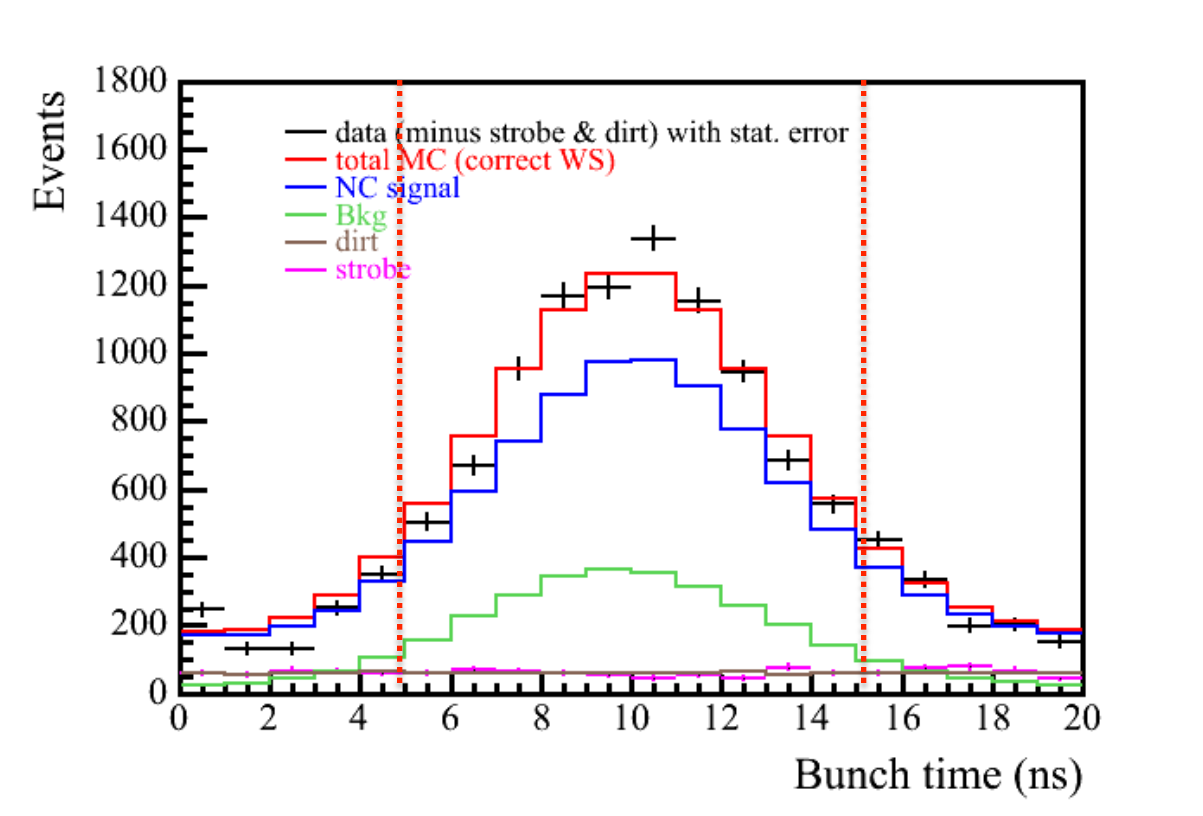
Electrons, work in progrss, ~2.2 nsec,
Will test electron/photon low energy excess hypothesis.



Bunch Time (nsec) **Bunch Time (nsec)**

Simplified NC Timing Analysis **(PRELIMINARY)**

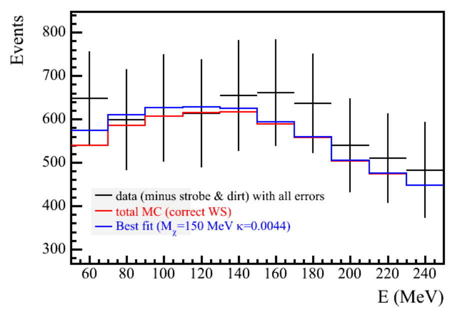
- In-Time (5-15nsec): NC + NC-bkg
- Out-Time(0-5 && 15-20 nsec): Dirt + Beam unrelated

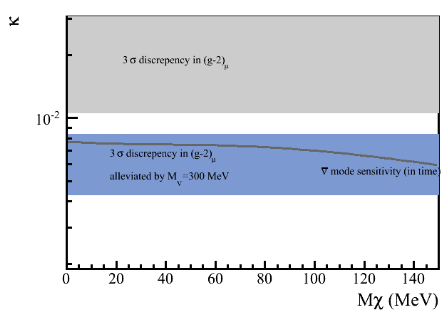


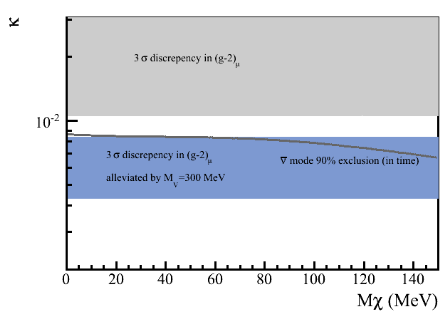
- WIMP Signal: In-Time: $M_x < 75$ MeV; Out-Time $M_x > 75$ MeV

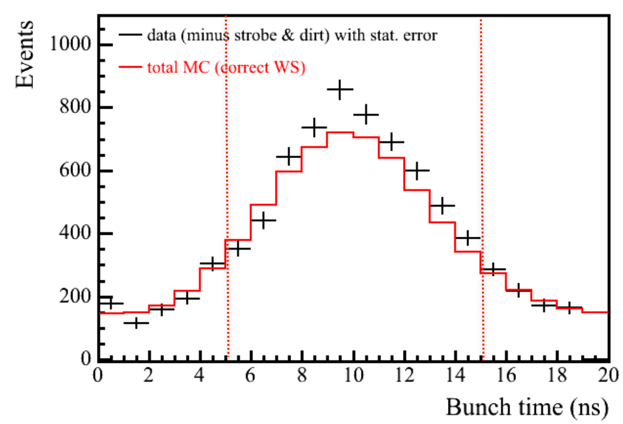
11.3E20 POT Antineutrino NC Sensitivity/ Limits 50<E<250MeV (**Preliminary**)

In Time







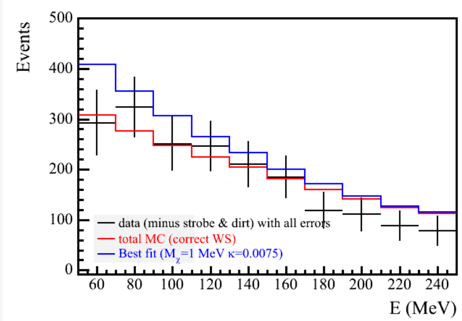


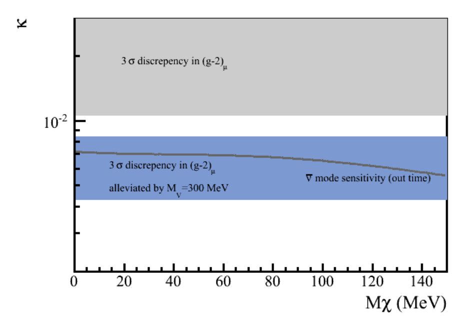
Fits with full stat and sys errors

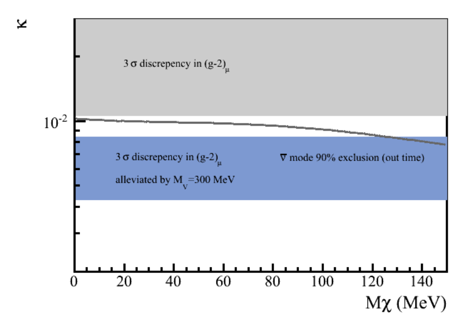
	InTime	OutTime
Data=	5969	1904
MC=	5535	1981
Diff=	434	-77
Error=	+/-1496	+/-576

Full NCE error matrix used, plus 25% WIMP production error.

Out of Time

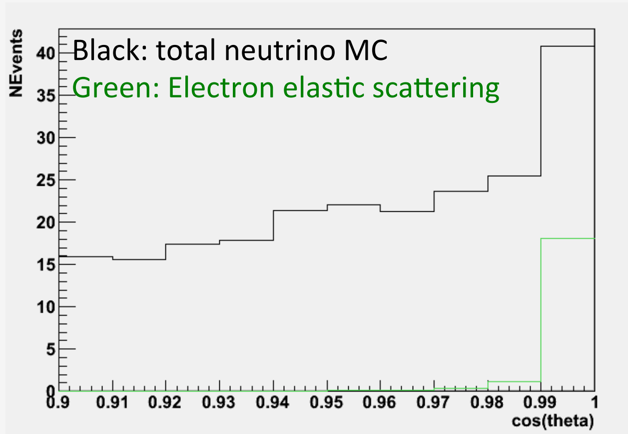






WIMP-Electron analysis will be much more sensitive!

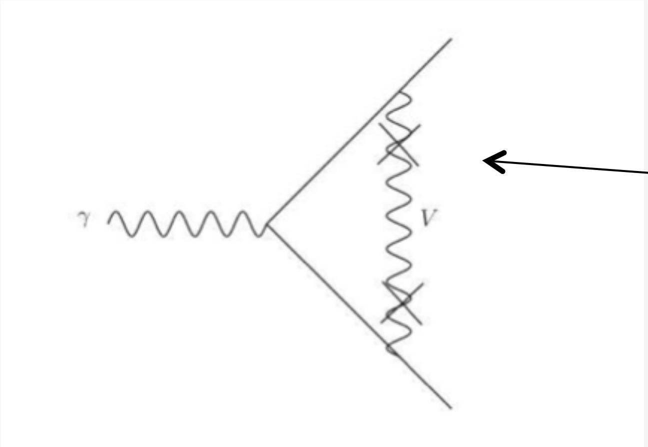
- $\cos\theta_{beam} < 0.99$ cut reduces backgrounds by x100



- Will cover entire g-2 region up to ~200 MeV.
- However, current energy threshold > 140 MeV, this needs to be reduced to > 50 MeV to improve sensitivity. Working on it!

SNOWMASS Process:
Model Consequences for Muon g-2

- Light kinetically mixed vector V that serves as a mediator in this model also contributes to the anomalous magnetic moment of SM fermions.
- This can explain the muon g-2 discrepancy.



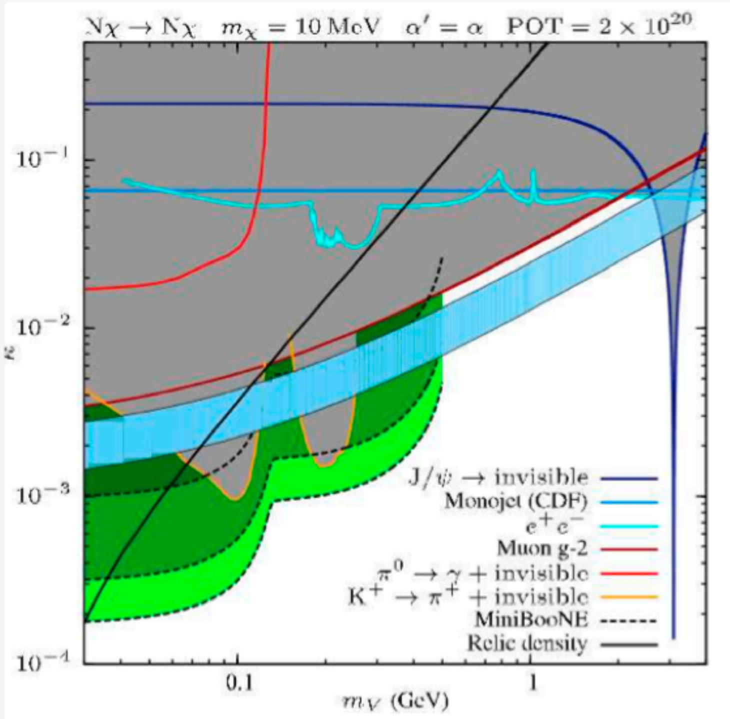
The crosses represent the kinetic mixing κ of the vector V with the photon

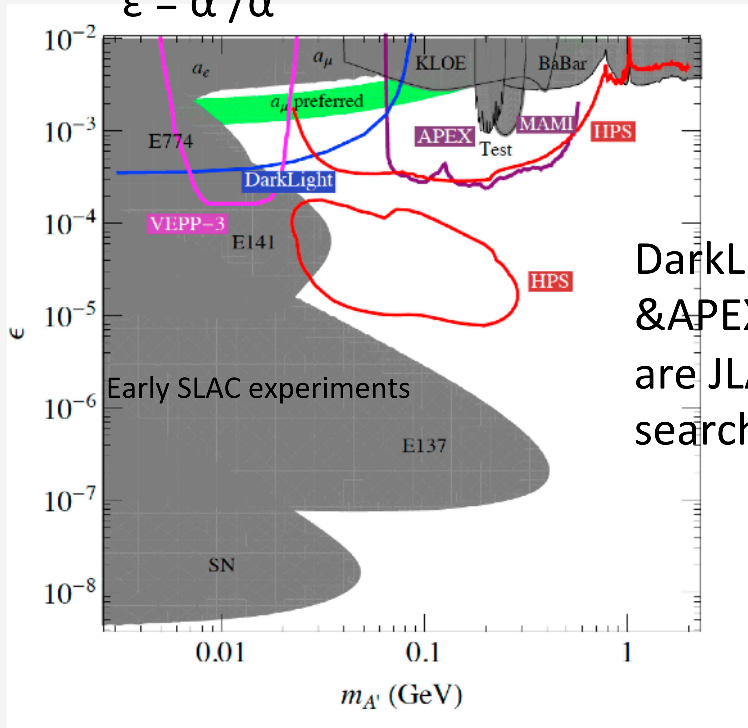
- Dark Sector models are gaining attention to explain g-2: See Bill Marciano's talk at the Argonne Intensity frontier workshop (2nd plenary talk). Being tested at JLAB, we can do it too!

Two Regimes for Light Mass WIMP Models:
We Need to Investigate both Regimes!

This was an important point we drove home at SNOWMASS…

$\varepsilon = \alpha'/\alpha$





DarkLight, HPS, &APEX are JLAB searches

$M_v > 2M_{wimp}$
$Br(V \rightarrow SM) \sim \kappa^2\alpha'/\alpha$
"Invisible V decay"

$M_v < 2M_{wimp}$
$Br(V \rightarrow SM) \sim O(1)$
"Visible V decay"

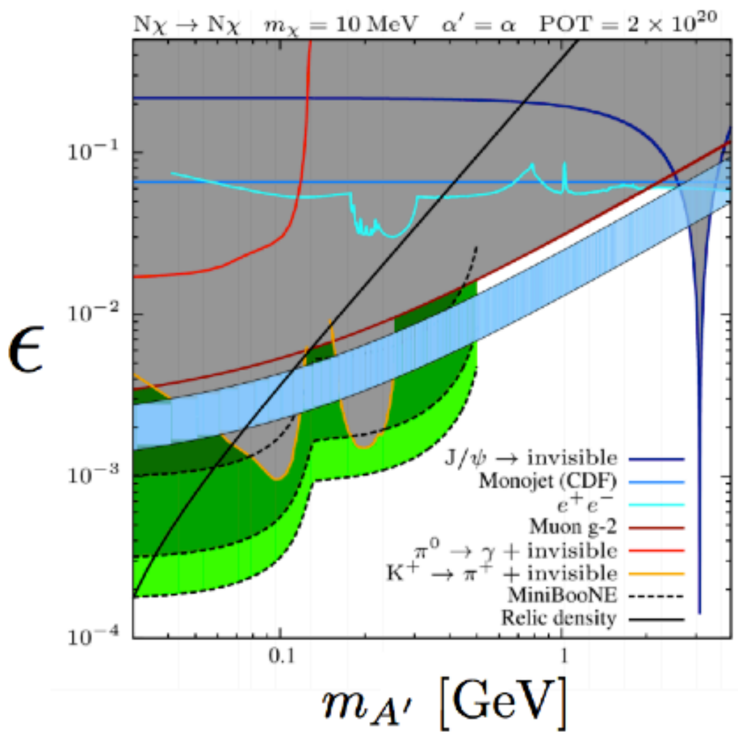
- Electron and Proton dump experiments compliment each other and extend the search for the hidden/dark sector!
- MB proton searches will be part of Intensity Frontier (IF5) Snomass and project X reports.
- JLAB actively looking into doing invisible V decay modes!

Quoting Joanne Hewitt's IF summary talk…"this is a no brainer!"

Proton–beam based searches

MiniBooNE proposal for sub-GeV DM search

Aguilar-Arevalo et.al. (MiniBooNE proposal)



e.g. $m_{\rm DM} = 10$ MeV

pioneering search for sub-GeV dark matter using a neutrino factory

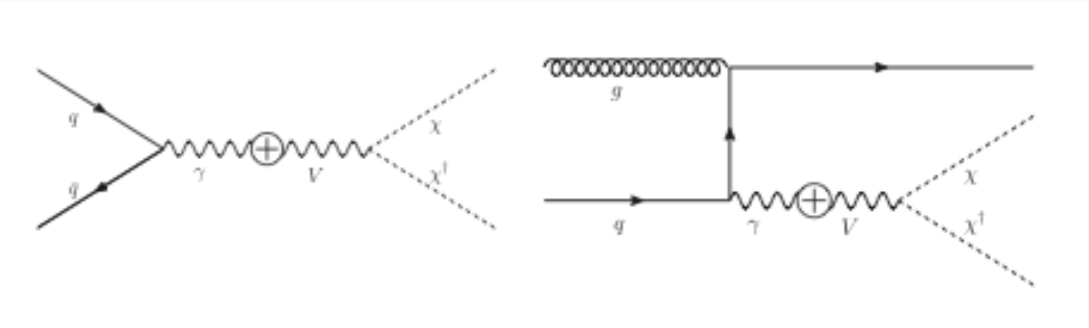
relatively inexpensive, no new facility

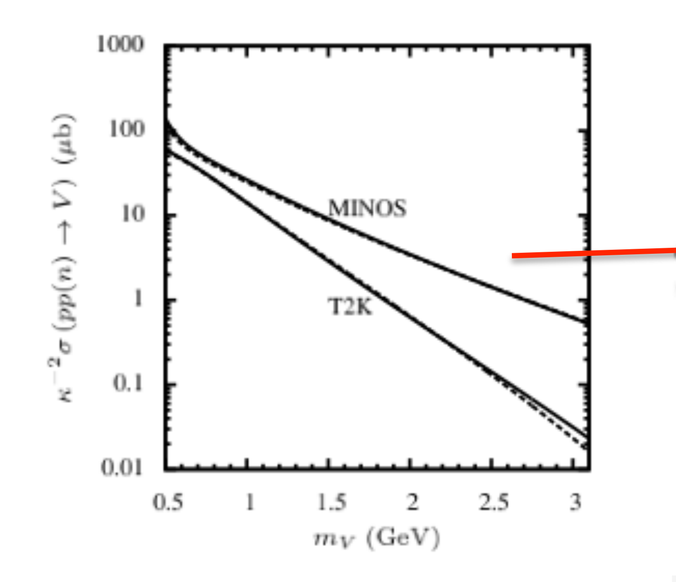
Essig

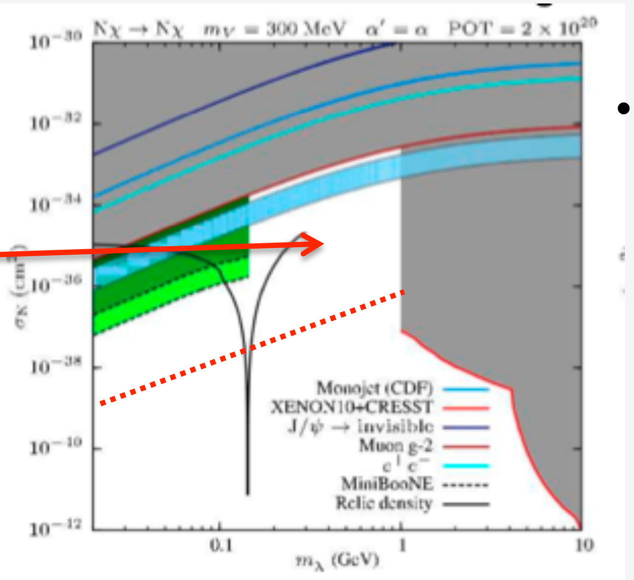
Proton beam DM searches written into the Project X Physics book and IF white paper.

Extending the WIMP search using the Main Injector (LBNE/Project X)

- With the higher energy protons (120 GeV), the direct production channel dominates.





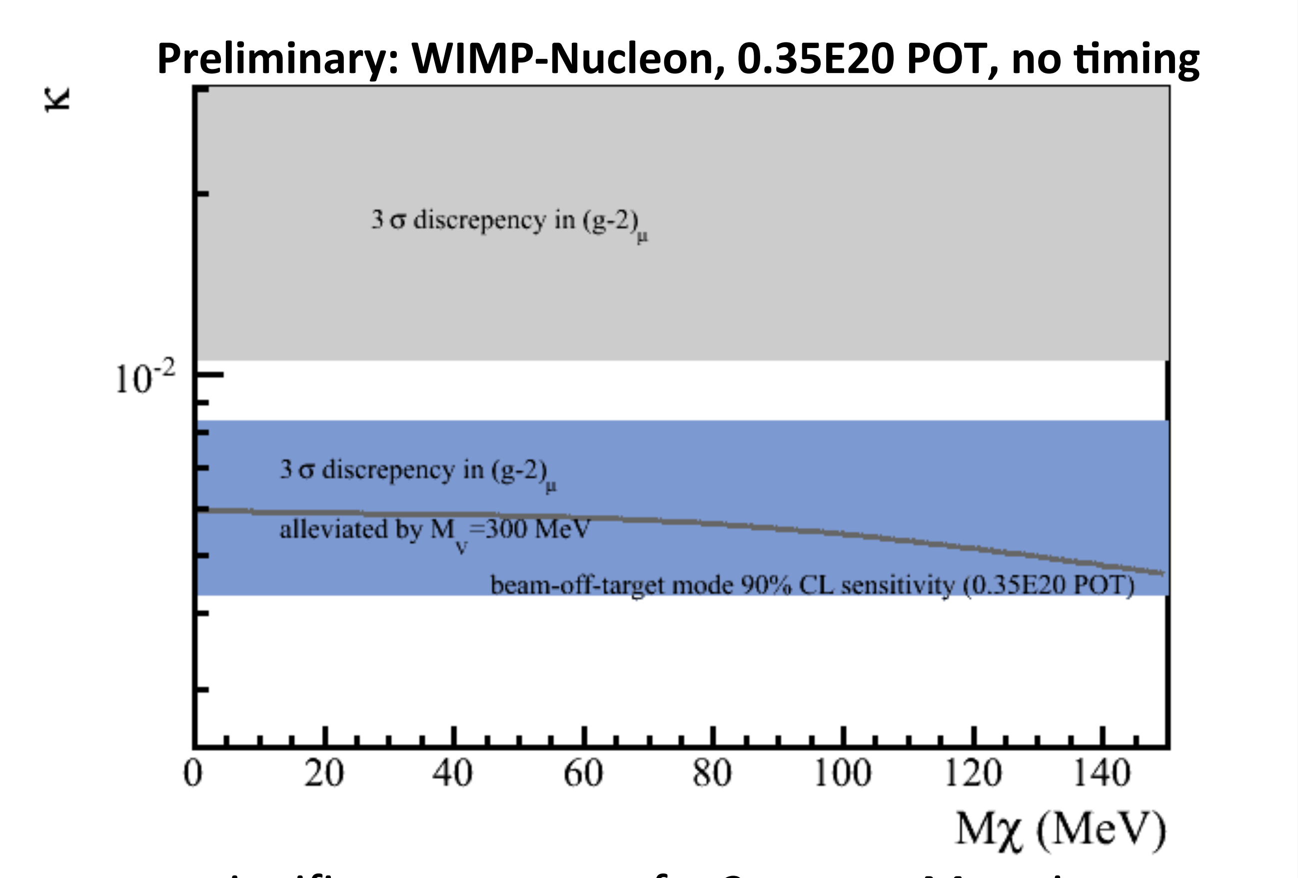


- With MI experiment we can fill in the M_x gap up to the direct detection experiments, and with project X can go lower in cross section!

A new opportunity presents itself: FNAL Beamline Commissioning

- Summer of 2013, FNAL is coming out of a long shutdown after major upgrades to the Booster and Main Injector which require months of commissioning, e.g. putting the protons on a beam dump.
  - What better beam dump than the BNB!!
- Can test BNB new beam line hardware.
- Can test analysis methods, develop a new/better PAC proposal.
- Recent analysis has demonstrated ~0.35E20 POT, which is only 2-3 months of running, can produce interesting limits.
- Recent discussions with FNAL management encouraging, after SNOWMASS they have given us **the green light to run.**
  - Aim to collect 0.35E20 POT in beam off target mode, maybe more…

What can we do with 0.35E20POT Beam off Target Running and the 50m Dump



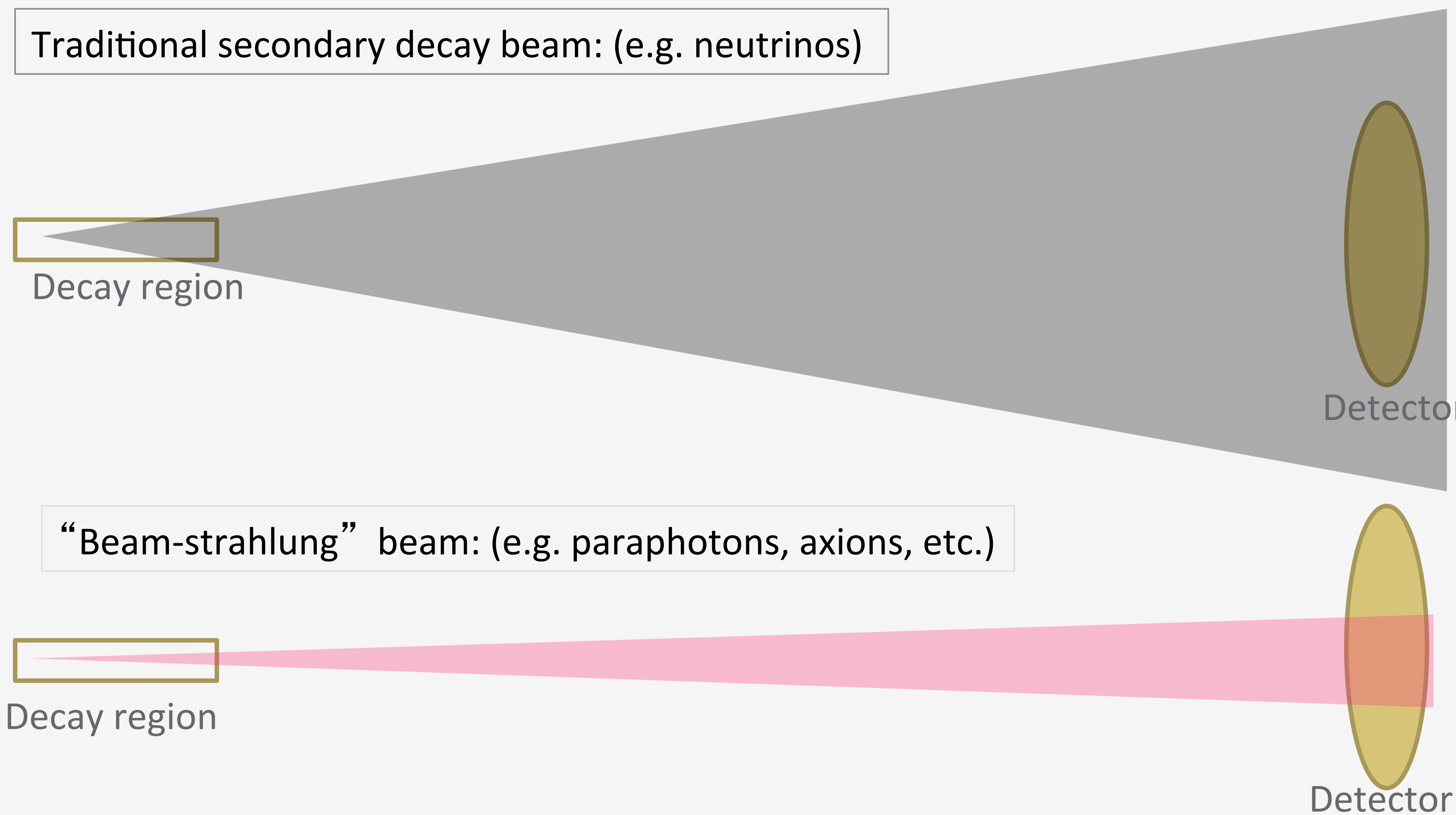
- Can cover a significant amount of g-2 space. More important, the run will allow us to test in detail the analysis assumptions and techniques and prove the methods are viable. If successful, physics publications will result and new proposals vigorously pursued!

Conclusions

- MiniBooNE has performed a detailed (but preliminary) WIMP-nucleon scattering analysis with the 11.3E20 POT antineutrino data. Limits include energy and timing information.
- A 2-3 month MiniBooNE beam off target run (0.35E20 POT) could result in relevant and interesting light WIMP limits (or possible signals??). **Run approved!**
  - Explores new regions of WIMP parameter space that are consistent with relic density estimates and g-2 anomaly. Will request more data!
- A successful MiniBooNE beam off target run can help motivate future beam dump experiments and Project X
  - Calculating sensitivities for MicroBooNE (LAr ~8 times less fiducial mass), might propose a beam off target run after 3yr neutrino run.
  - MI 120GeV proton dump experiment will have significantly better reach in WIMP mass and cross section.
  - **LBNE/Project X is a natural place to search for dark sector particles, this needs to be highlighted as a justification for the near detector/machine.**

BackUp Slides

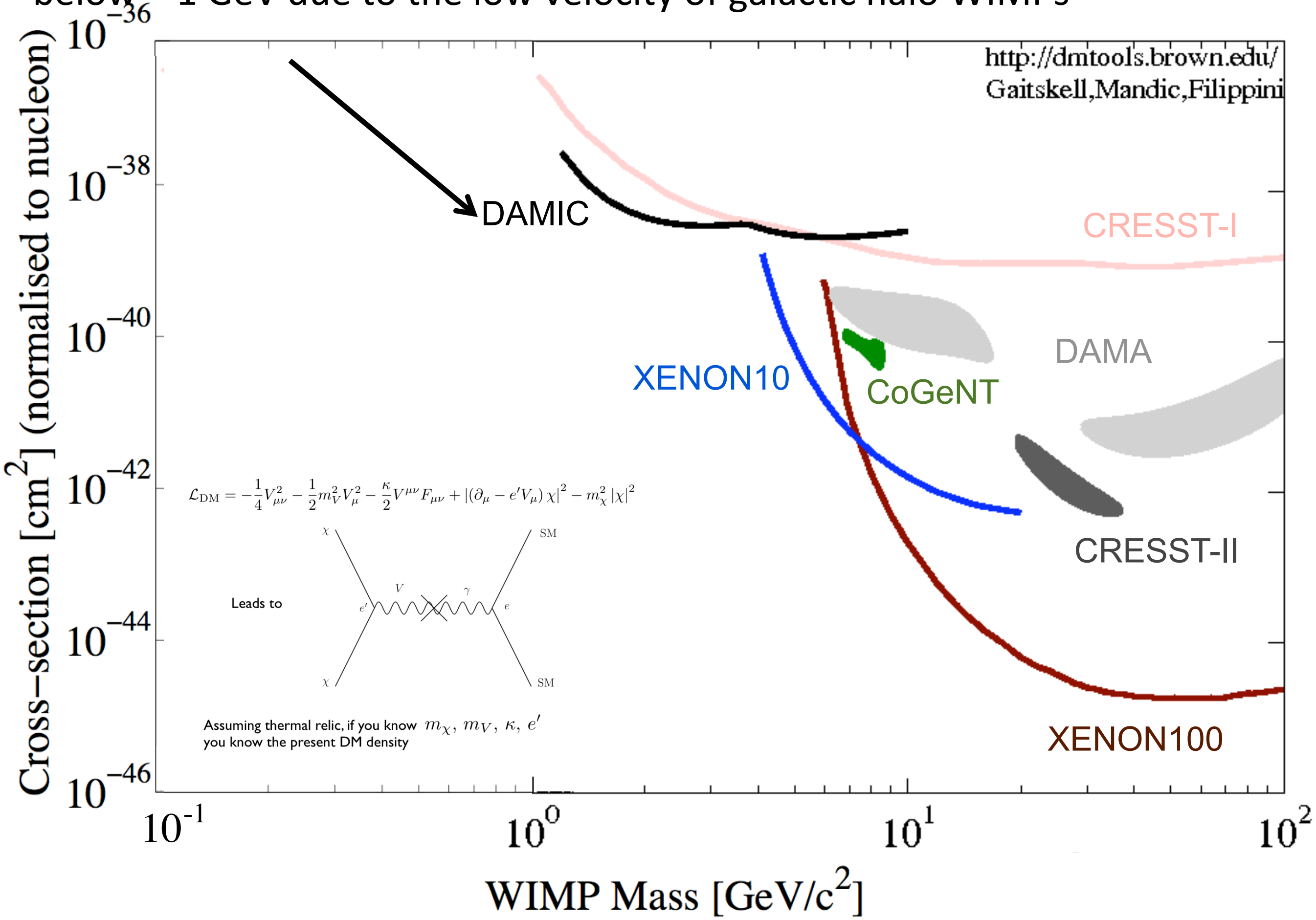
Beam-strahlung



The "brem-ed" particles will be tightly collimated around the incoming proton beam direction (<~0.5 mrad) and will either decay or scatter in the center of the detector (assuming on-axis beam!)

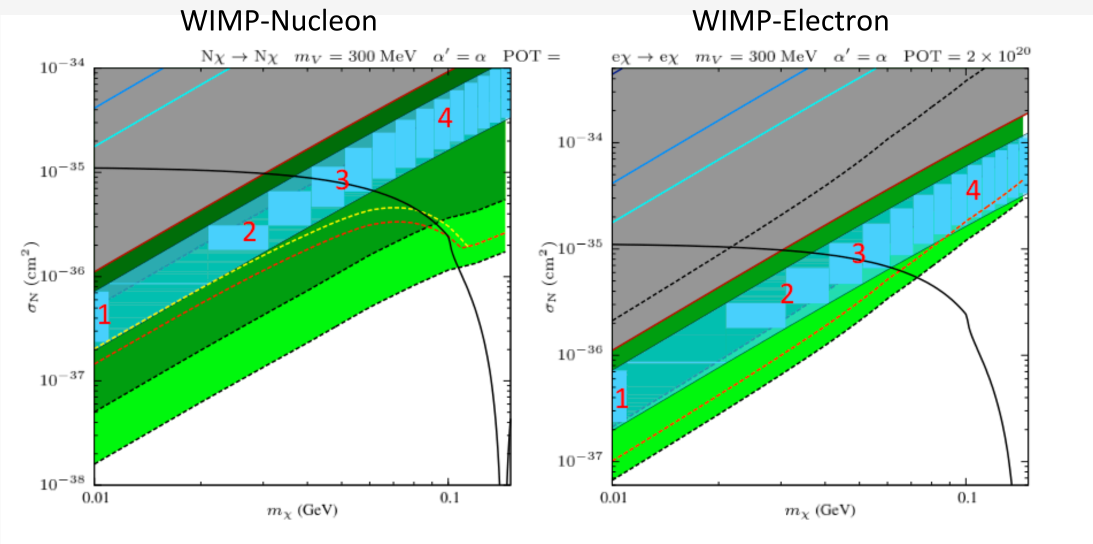
World Data on Low Mass Spin Independent WIMP Scattering

Traditional underground direct detection experiments run out of sensitivity below ~1 GeV due to the low velocity of galactic halo WIMPs



However, for low mass WIMPs (< 1 GeV) you need a new model to produce the right relic density!

Estimated WIMP Signal Significance:
2E20 POT Beam off Target and **25m** Absorber Run



- Signal, backgrounds and significance for various M_x and σ points in the g-2 band.
- g-2 band mostly covered at > 5σ

Pt.	Scattering Channel	Beam Mode (2.0×10^{20} POT)	WIMP mass (MeV)/ cross section (cm^2)	Signal	Background and Errors	Probability
1	Nucleon	25m	$10/4 \times 10^{-37}$	1859	350±66	$< 10^{-10}$
2	Nucleon	25m	$30/3 \times 10^{-36}$	1453	350±66	$< 10^{-10}$
3	Nucleon	25m	$50/8 \times 10^{-36}$	1326	203±40	$< 10^{-10}$
4	Nucleon	25m	$100/3 \times 10^{-35}$	1186	9.2±3.4	$< 10^{-10}$
1	Electron	25m	$10/4 \times 10^{-37}$	13.2	0.15	$< 10^{-10}$
2	Electron	25m	$30/3 \times 10^{-36}$	7.7	0.15	$\sim 10^{-9}$
3	Electron	25m	$50/8 \times 10^{-36}$	4.8	0.09	$\sim 10^{-6}$
4	Electron	25m	$100/3 \times 10^{-35}$	1.4	0.004	$\sim 10^{-3}$

Pt. 3 is overlap of g-2 and relic density