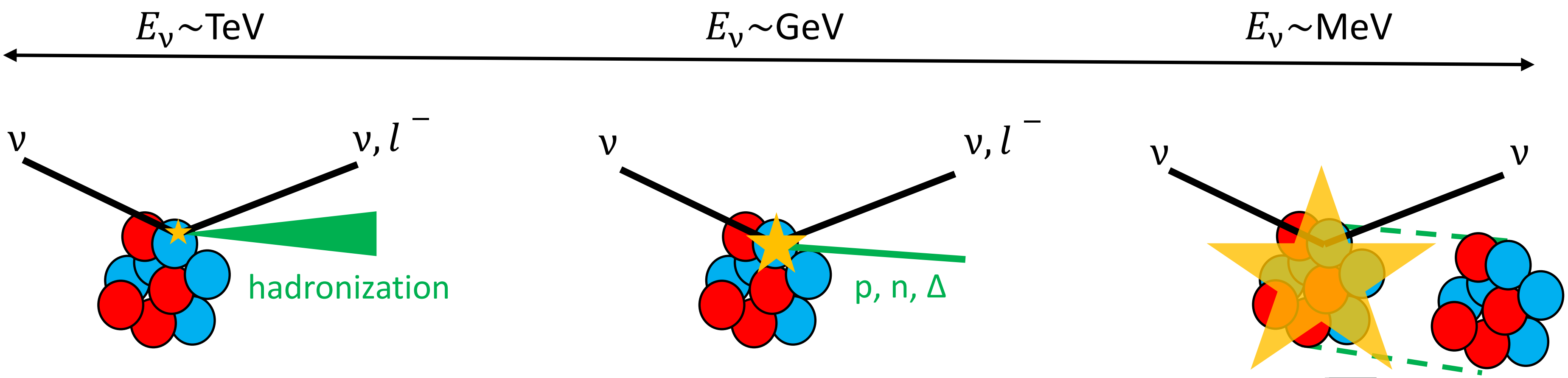
New CEvNS Results from the COHERENT CsI[Na] Detector

Dan Pershey (Duke University)
for the COHERENT Collaboration

Fermilab JETP Seminar, Dec 11, 2020

Neutrino Scattering with Nuclei



$\lambda = h/\sqrt{Q^2} \ll R_p$

Localized scattering on quarks with nuclear fragmentation e.g. NuTeV, MINERvA, DUNE

$\lambda = h/\sqrt{Q^2} \approx R_p$

Scattering on nucleons with nucleon emission e.g. NOvA, SBN, DUNE

$\lambda = h/\sqrt{Q^2} \gg R_p$

Elastic scattering on nuclei with Q^2 so low, nuclear state is unchanged

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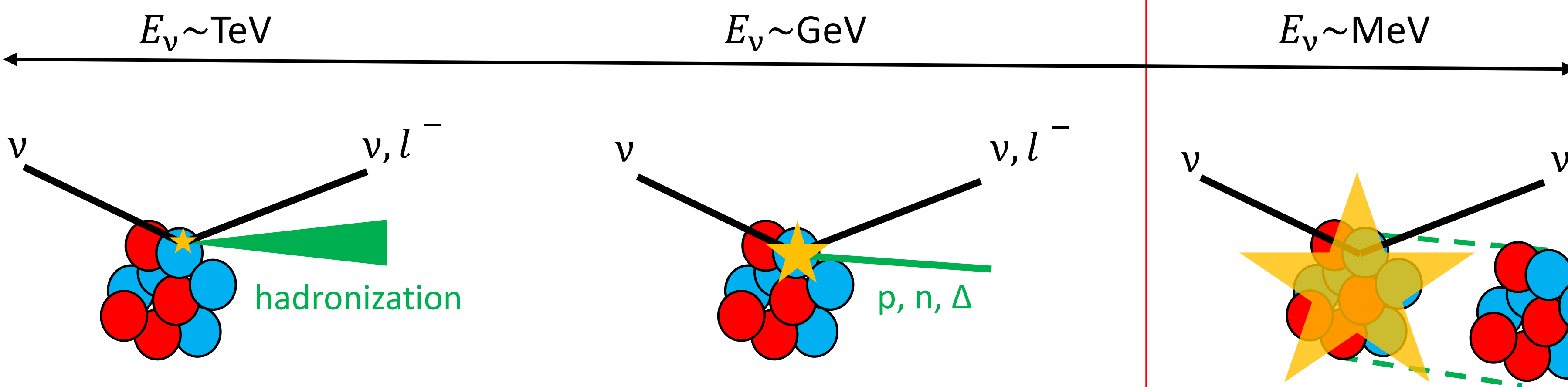

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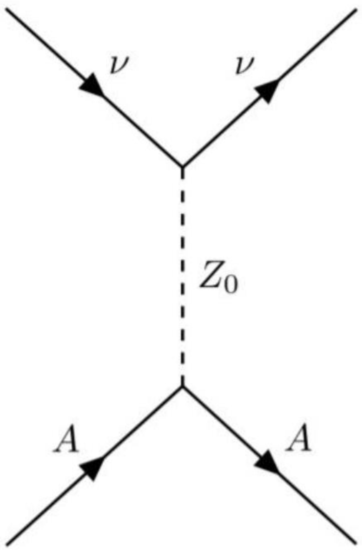
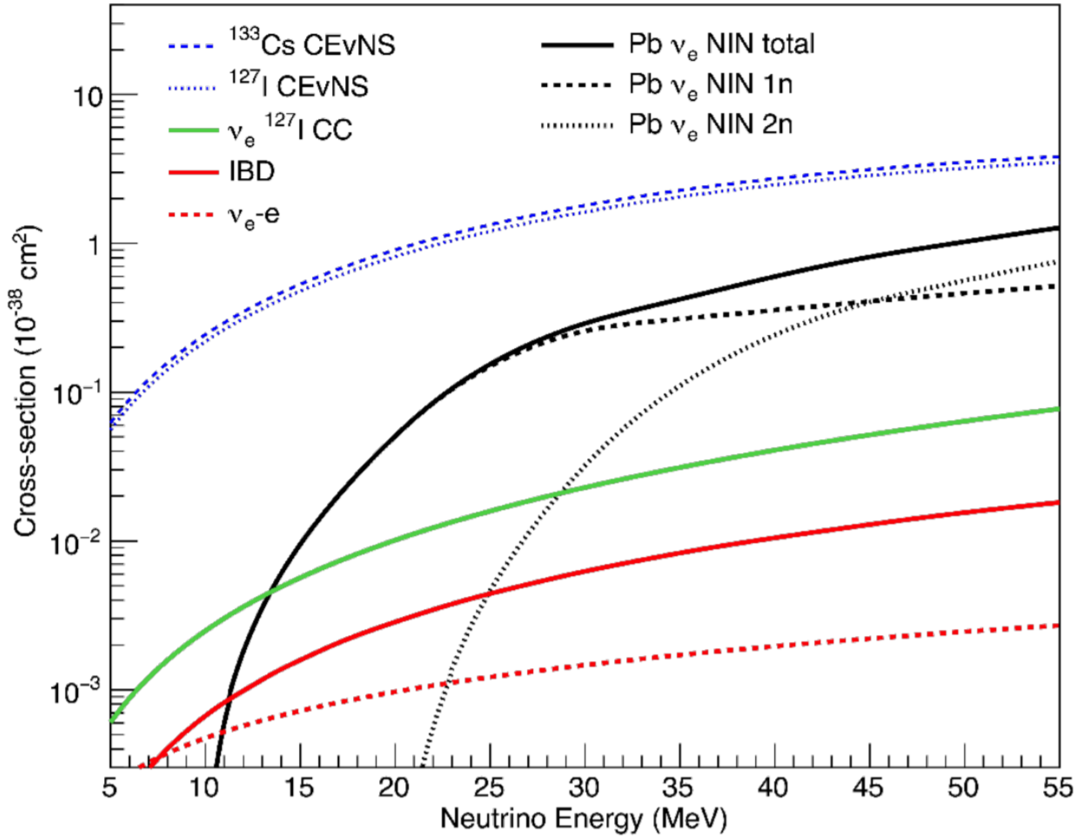
COHERENT measures coherent elastic neutrino-nucleus scattering (CEvNS) at neutrino energies 10-50 MeV

CEvNS Cross Section

CEvNS





- The process is coherent, which gives a large cross section, roughly scaling with the square of the number of neutrons

$$\sigma \approx \frac{G_F^2}{4\pi}(N-(1-4\sin^2\theta_W)Z)^2 E_\nu^2$$

- Very large cross section, compared to low-energy neutrino processes
  - Measurements within reach of kg-scale detectors

First measurement by COHERENT in 2017 with CsI[Na] – new, full-dataset results today

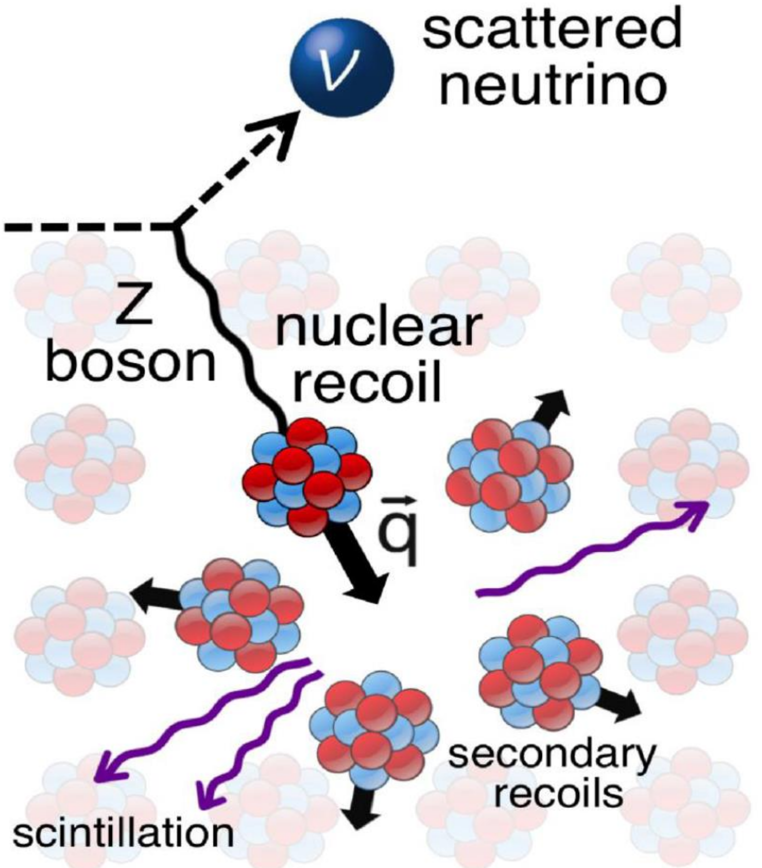
Nuclear Recoil Signature

- The struck nucleus acquires a small recoil energy
  - Max recoil energy is $2E_\nu^2/M$
  - Only 15 keV for CsI at 30 MeV

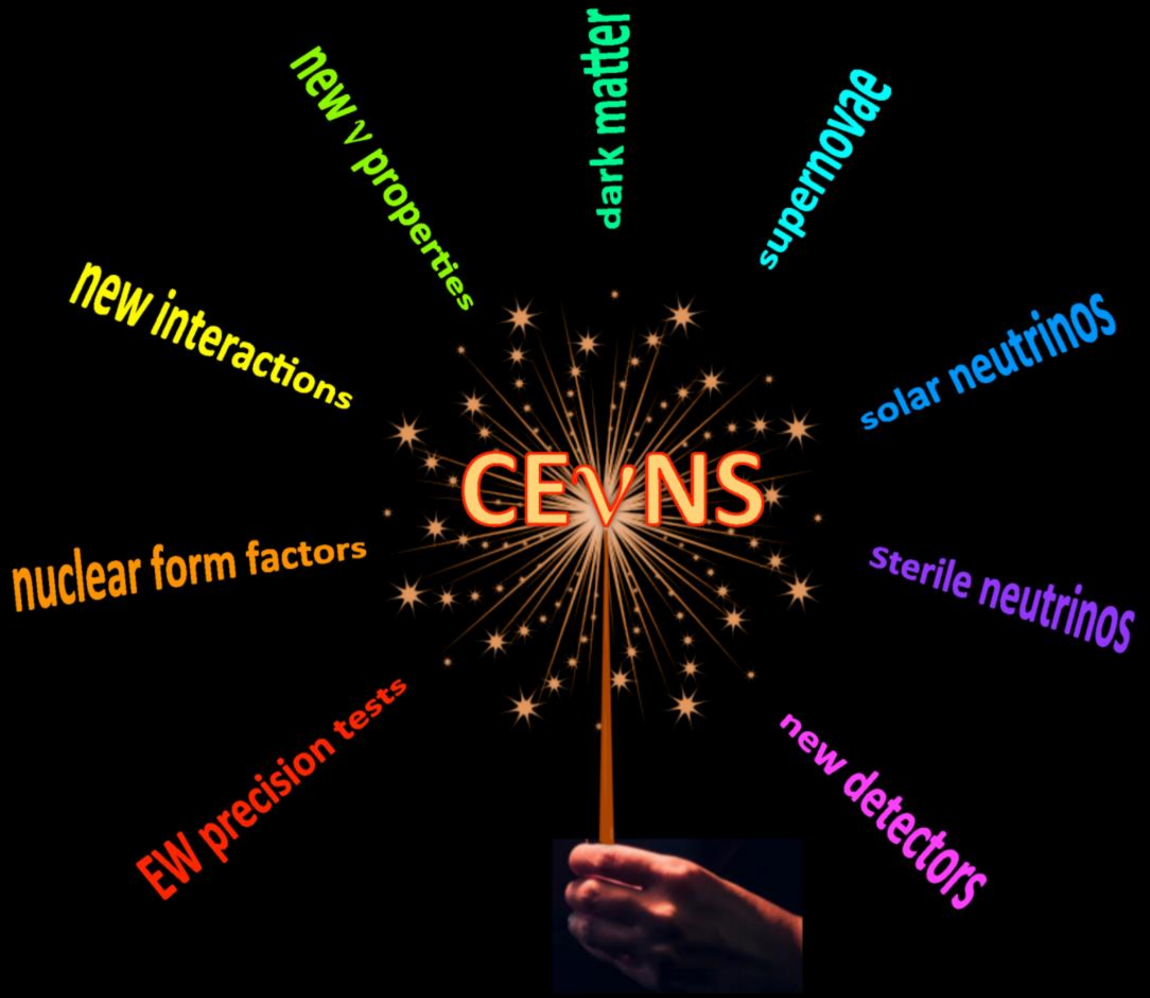
1: Need a detector with a very low threshold

- Recent advances in dark matter detection has made keV-scale thresholds possible

2: Will need to place detector in a large neutrino flux



Why measure CEνNS?



E Lisi, Neutrino 2018

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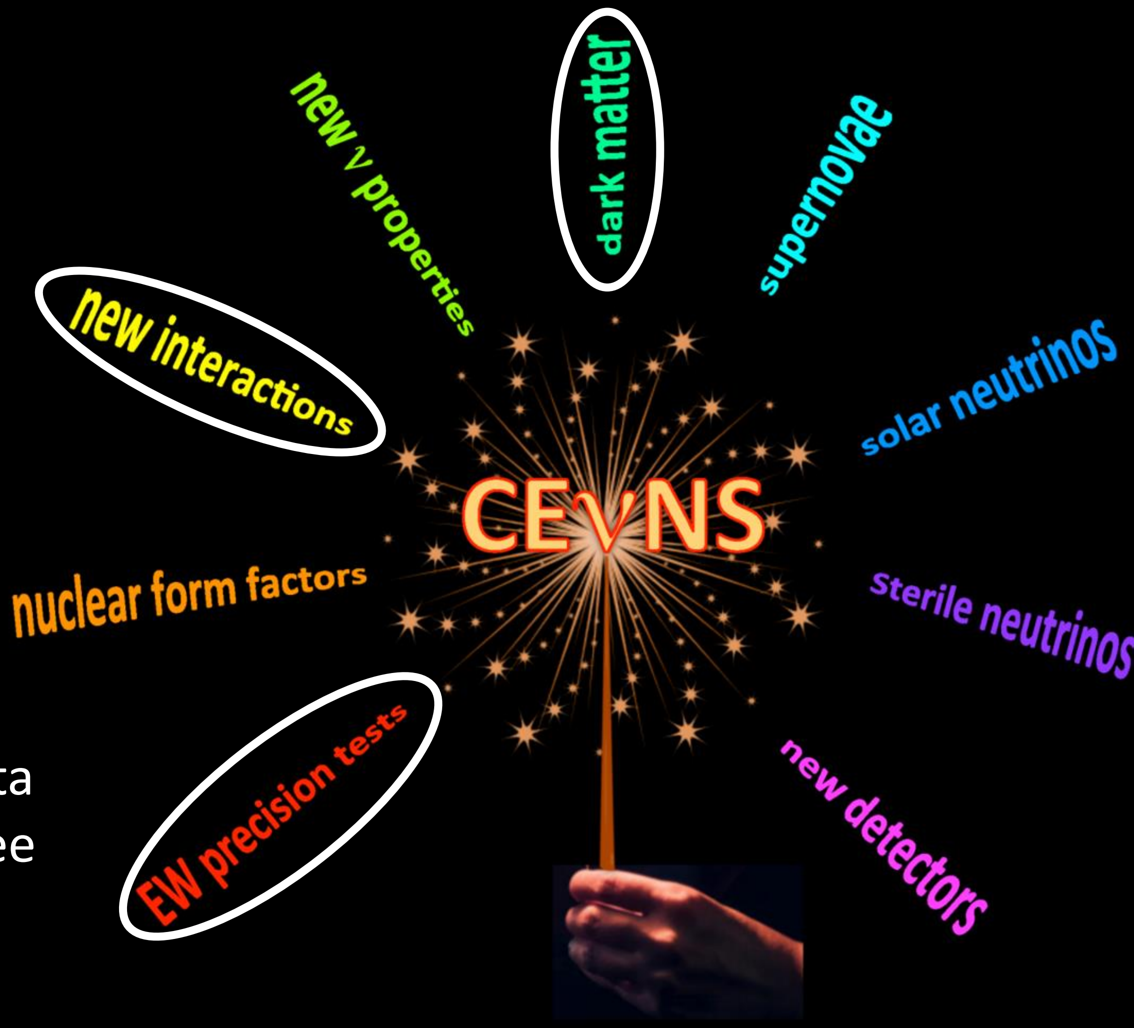


Will discuss COHERENT data applied to three BSM scenarios

E Lisi, Neutrino 2018

Searching for BSM Interactions with CEvNS

- CEvNS is sensitive to non-standard interactions (NSI) between neutrinos and quarks mediated by some heavy (> 50 MeV/c^2), undiscovered particle
- Generally parameterized by coupling constants: $\varepsilon^{N}_{\alpha\beta}$ $(\alpha, \beta \in e, \mu, \tau)$

$$\mathcal{L}^{NSI}_{\nu Hadron} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} \left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta\right] \left(\varepsilon^{qL}_{\alpha\beta} \left[\bar{q}\gamma_\mu (1-\gamma^5) q\right] + \varepsilon^{qR}_{\alpha\beta} \left[\bar{q}\gamma_\mu (1+\gamma^5) q\right]\right)$$

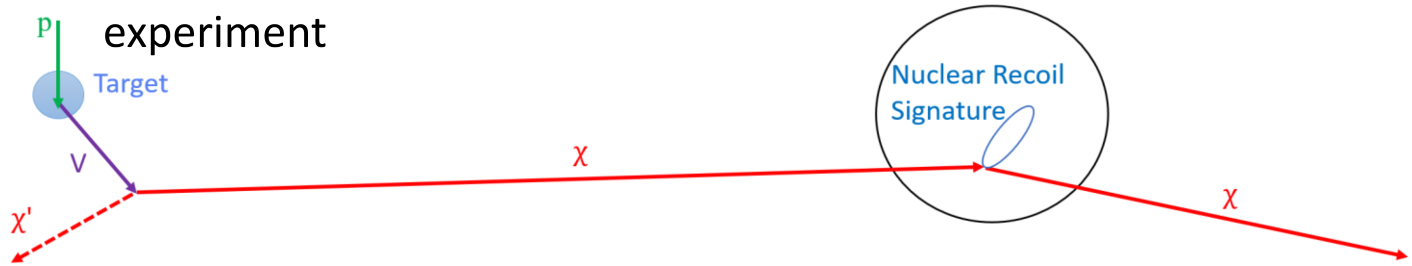
Barranco et al., JHEP 12 021 (2005)

- NSI scenarios would scale the observed CEvNS rate and several ε parameters are only constrained at ~ unity
  - ε_{ee} / $\varepsilon_{\mu\mu}$ / $\varepsilon_{\tau\tau}$ break flavor universality predicted by the standard model (at tree level)
  - $\varepsilon_{e\mu}$ / $\varepsilon_{e\tau}$ / $\varepsilon_{\mu\tau}$ change neutrino flavors

- NSI would affect our interpretation of neutrino oscillation data from long-baseline neutrino oscillation results from experiments like NOvA and DUNE which CEvNS data can resolve
  - CEvNS can resolve these measurements of the CP violating angle and neutrino mass ordering

Δm^2_{32}: Coloma et al., PRD 94 055005 (2017)
δ_{CP}: Denton et al., arXiv:2008.01110 (2020)
θ_{12}: Coloma et al., PRD 96 115007 (2017)

Searching for Dark Matter with CEvNS Detectors



- CEvNS detectors at accelerators are sensitive to hidden sector particles and can make competitive searches for 1 – 100 MeV mass WIMP candidates
- Huge number of proton-Hg collisions may produce portal particles (V) that mediate interactions between SM and hidden sector particles (χ)

Vector portal: $$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}V^{\mu\nu}F_{\mu\nu}$$

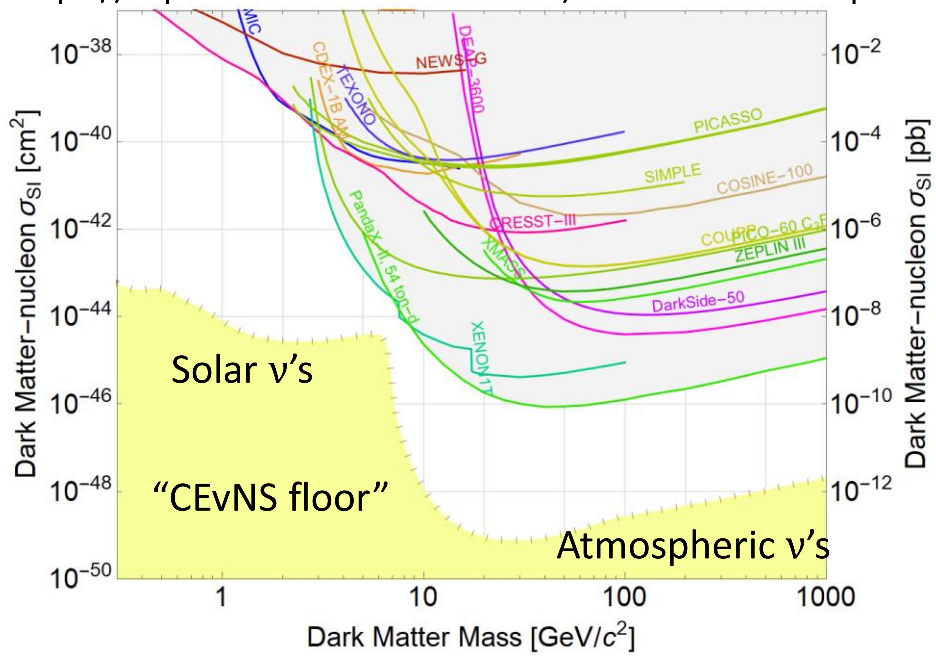
deNiverville et al., PRD 92 095005 (2015)
Dutta et al., PRL 124 121802 (2020)

- Such a particle makes an attractive dark matter candidate consistent with thermal freeze-out for masses below the Lee-Weinberg bound

COHERENT will test dark matter consistent with the astronomically observed concentration
Akimov et al., PRD 102 052007

Neutrino Physics with CEvNS in Dark Matter Detectors

https://supercdms.slac.stanford.edu/dark-matter-limit-plotter



- ❑ CEvNS are an ultimate background for dark matter detection experiments
- ❑ Cosmogenic sources of neutrinos can produce CEvNS in dark matter detectors – the CEvNS floor – and expected rates are not far from current sensitivities
  - Several experiments will soon see CEvNS from ^{8}B solar neutrinos
  - First search with expected sensitivity released this week from xenon1t: arXiv 2012.02846

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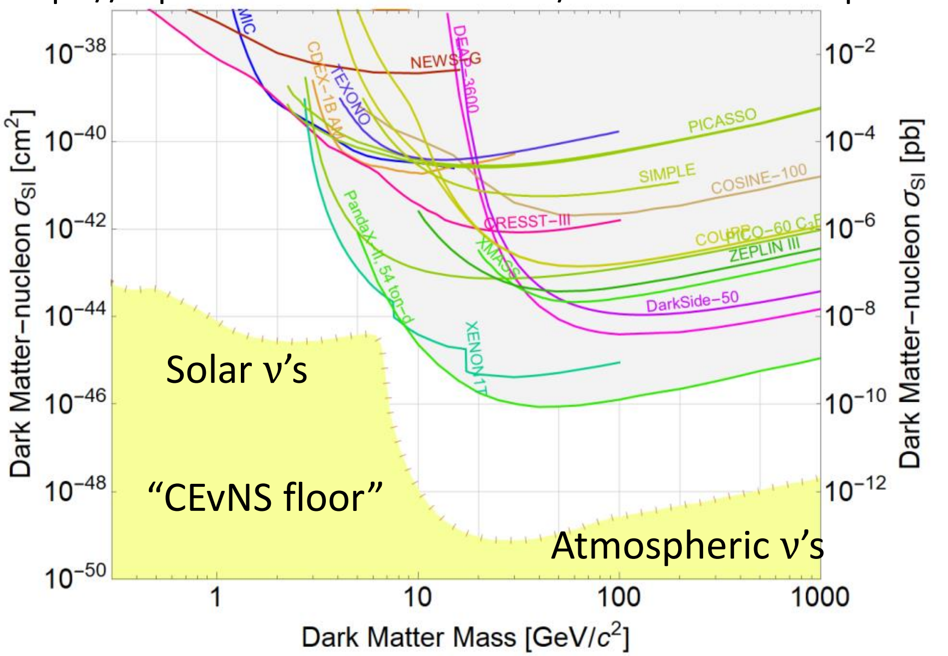
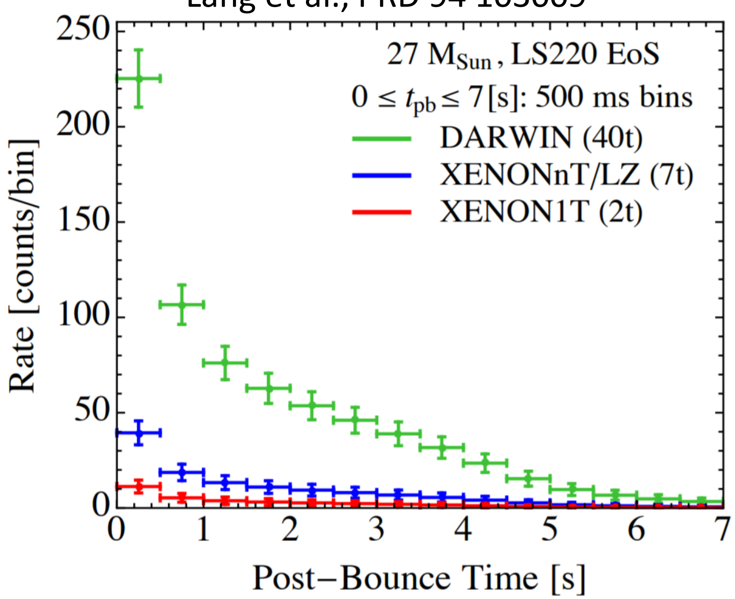


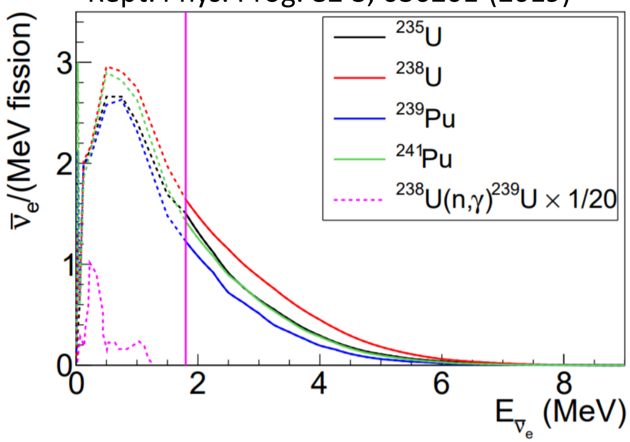
Lang et al., PRD 94 103009

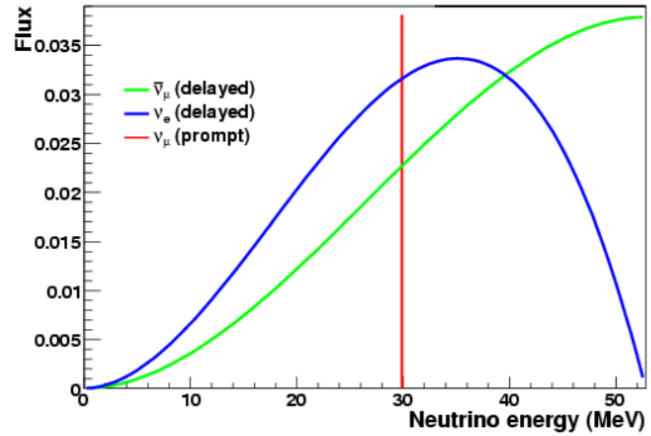


- ❑CEvNS will also be a detection channel for a burst of neutrinos from a supernova
- ❑E.g., DARWIN, a future Xe experiment expects to see several hundred CEvNS events for a typical galactic supernova
- ❑CEvNS is NC → sensitive to all flavors of flux which would help interpretation of data from DUNE and other experiments

High-flux Sources for Low-energy Neutrinos

Rept. Phys. Prog. 82 3, 036201 (2019)





❑ Nuclear reactors

- Very high flux: $\sim 2\times10^{20}\ \bar{\nu}_e$ / s — reactors win
- Maximum recoil energy for CsI: 1 keV
- Reactor-off data → in-situ background constraint

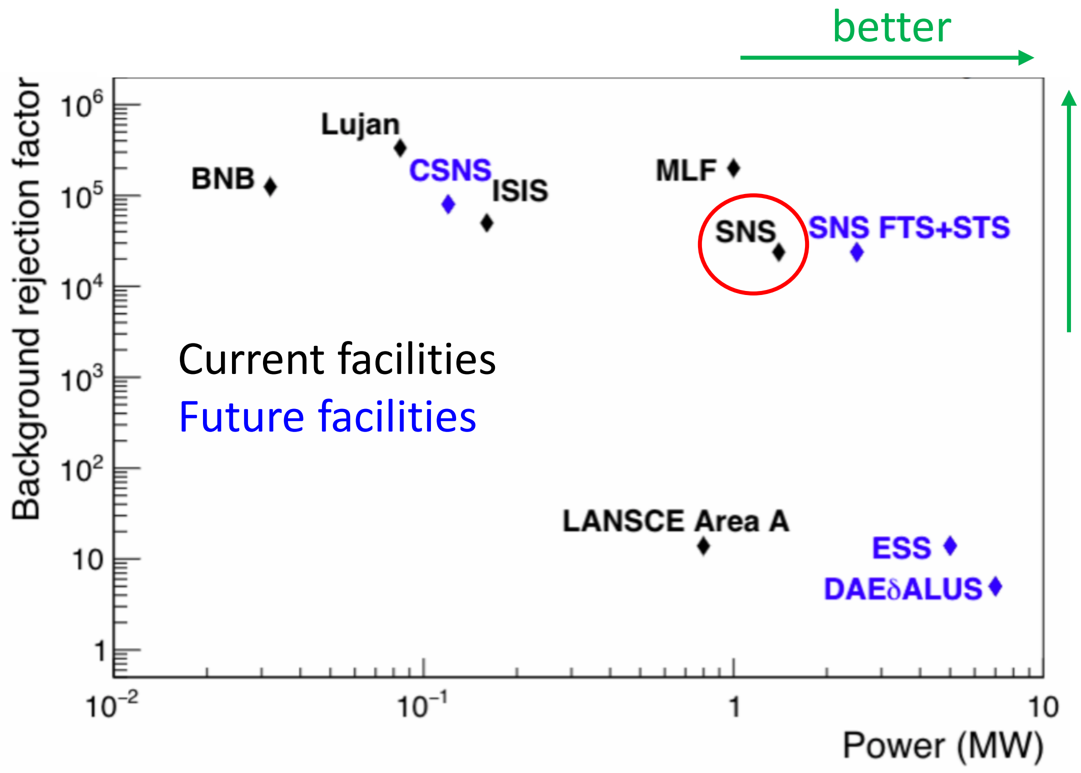
❑ Pion decay-at-rest (πDAR) at accelerators

- High flux: $\sim 3\times10^{14}\ \nu_\mu/\nu_e/\bar{\nu}_\mu$ / s
- Maximum recoil energy for CsI: 15 keV — πDAR wins
- Pulsed beam → in-situ background constraint

Fermilab collaboration

Coherent Captain Mills @

Selecting a πDAR Source



- For selecting a source, we want
  - High beam power → faster accumulation of signal
  - Low duty factor → improved background rejection through beam pulsing

- Move to the Spallation Neutron Source at ORNL
  - Upgrade will double beam power and construct second target station by 2028

The Spallation Neutron Source at ORNL
+ Neutrino

- 1.4 MW proton beam on mercury target at T_p = 1.01 GeV
- Pulse width is 340 ns FWHM at 60 Hz, reducing backgrounds by a factor of $\sim 3\times 10^4$ from beam pulsing

- Opportunistic neutrino program expands fundamental physics reach of the SNS

Future Beam Improvements at the SNS

- ❑ Two staged improvement to the beam

1: Proton Power Upgrade

- Increases the power of neutron beam 1.4 → 2.8 MW
- Feasibility of a second target station

2: Second Target Station

- Implements a second beamline at the accelerator

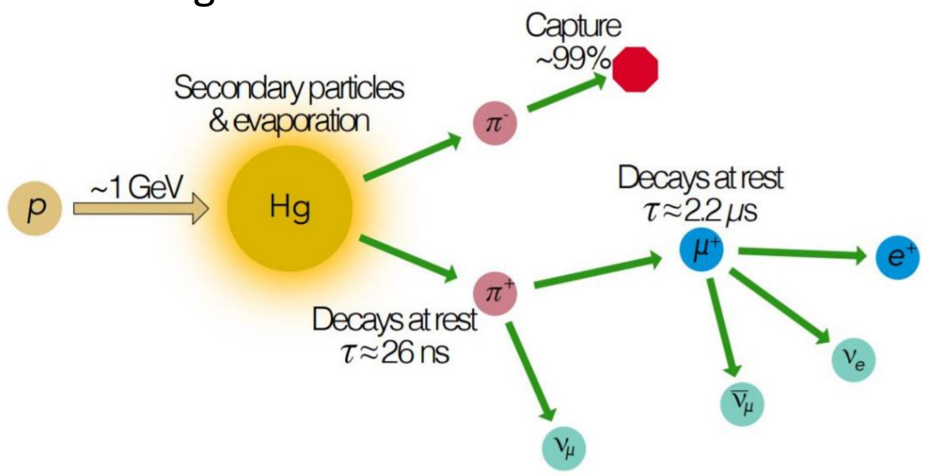
- ❑ Expected completion ≈2028
- ❑ Interest from the lab to design STS to accommodate a specialized detector hall for neutrino measurements capable of fitting a 10-t detector

Neutrino Flux at the SNS

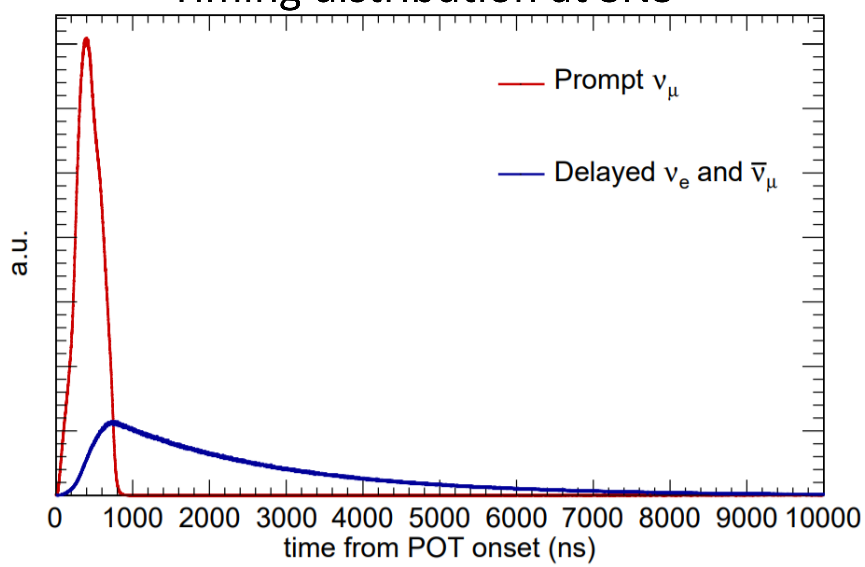
- Low energy pions are a natural by-product of SNS running
  - π^+ will stop and decay at rest

    $\pi^+ \rightarrow \mu^+ + \nu_\mu \quad : \tau = 26$ ns

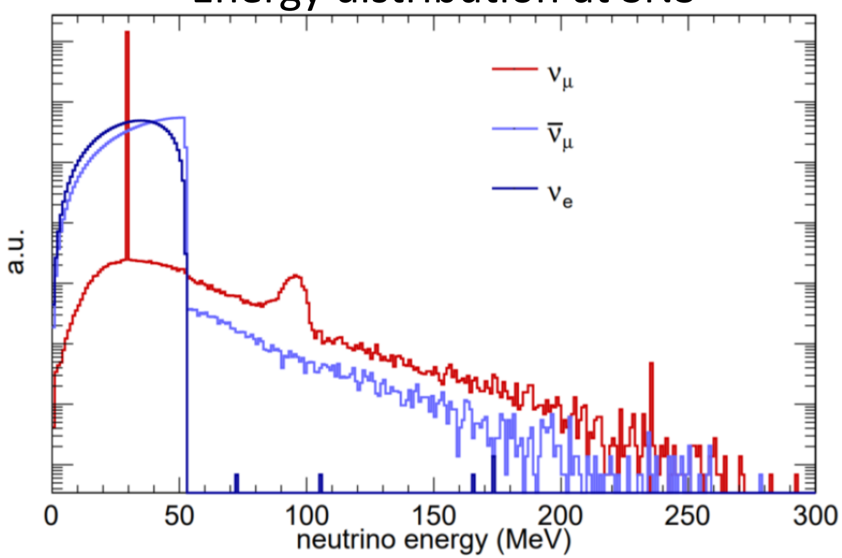
    $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad : \tau = 2200$ ns
  - Flux includes three flavors of neutrinos → can test flavor universality as a BSM signature
- Flux shape is very well known and very small contribution from decay in flight at the SNS



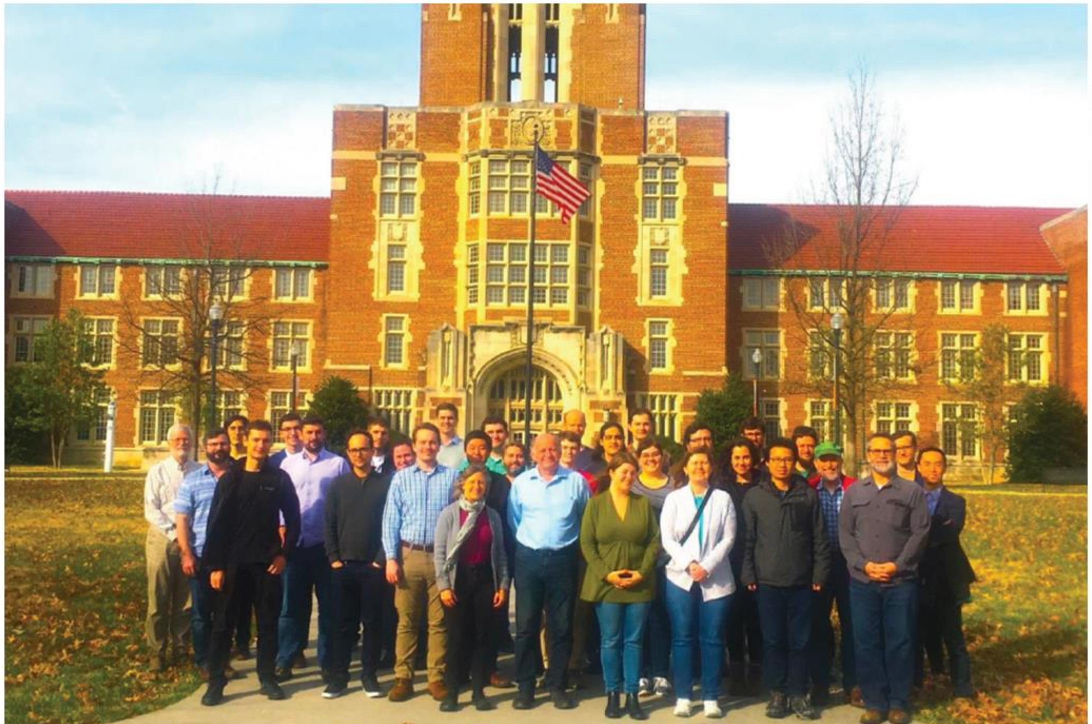
Timing distribution at SNS



Energy distribution at SNS

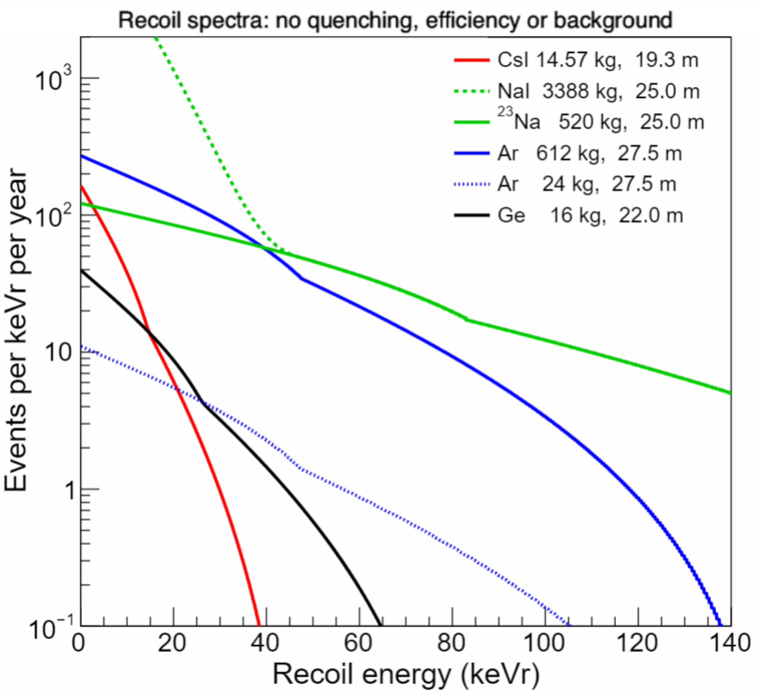


The COHERENT Collaboration at the SNS



COHERENT at the SNS

- Measure CEvNS with multiple nuclear targets test the coherent cross section scaling $\propto N^2$
- Key advantages of different detectors and joint fits of all COHERENT improves physics reach



Target	Technology	Fid. Mass (kg)	Threshold (keV_{nr})	Commissioning
CsI[Na]	Scintillation	14.6	6.5	2015
Liquid Ar	Scintillation only	24.4/610	20	2017/≈2023
Ge	Ionization	16	1-2	2021
NaI[Tl]	Scintillation	185/3000	13	2016/2021

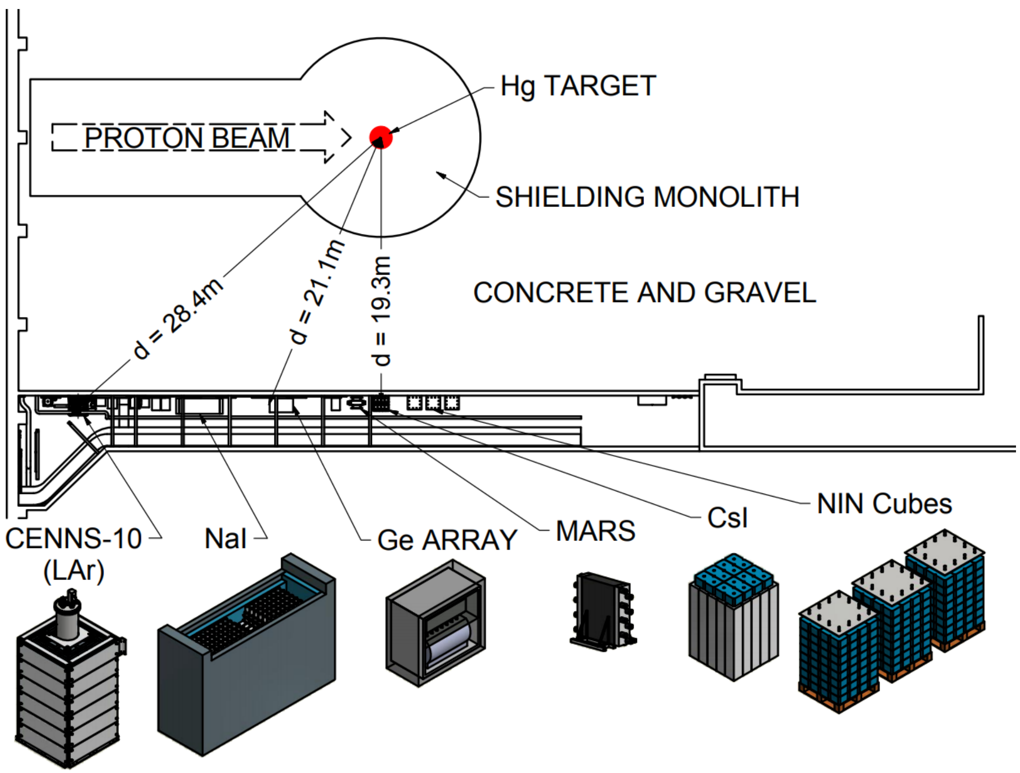
First result 2017
Science 357 6356
New results: this talk

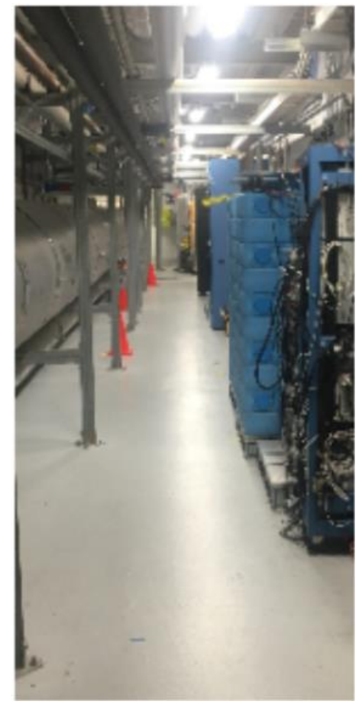
First result 2019
arXiv:2003.10630

Commissioning of two new detectors 2021

Managing Neutron Backgrounds at a Neutron Source

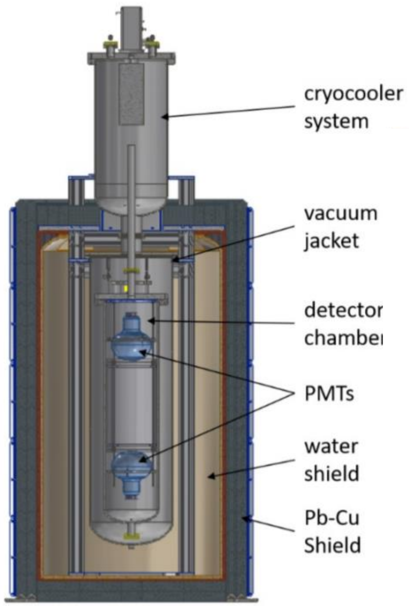
- ❑ The SNS does its job of making neutrons very well – where can we avoid them?
- ❑ While assessing the site, a basement hallway was discovered where the neutron flux was reduced by orders of magnitude to levels acceptable for CEvNS experiments
  - "Neutrino alley" was born



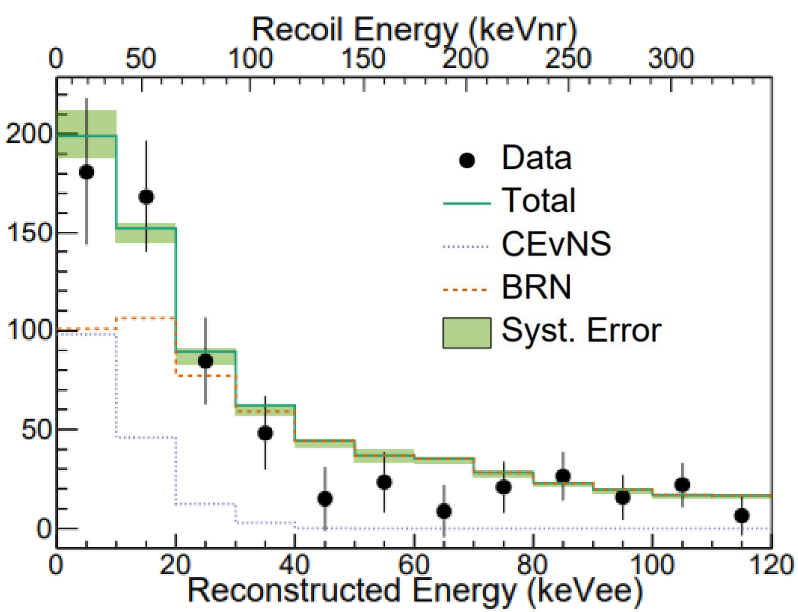


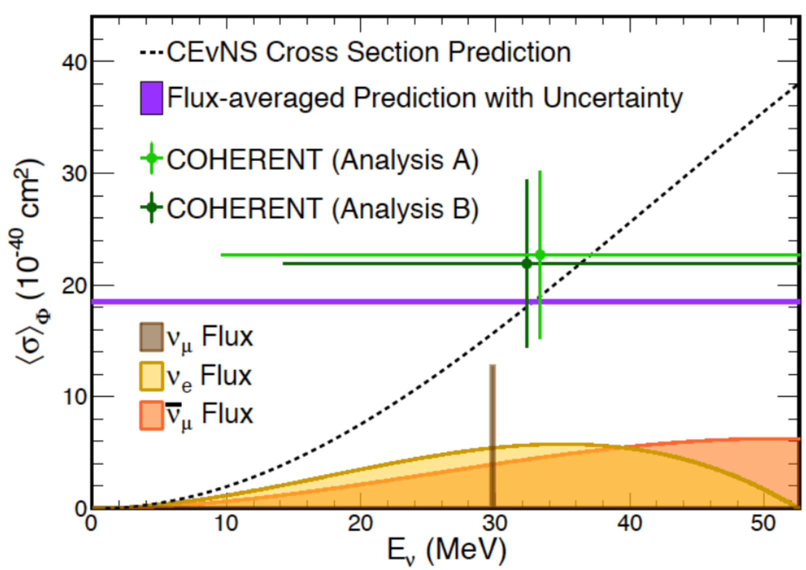
Looking down neutrino alley, just wide enough to deploy ton-scale detectors

COHERENT CEvNS Detection on ^{40}Ar



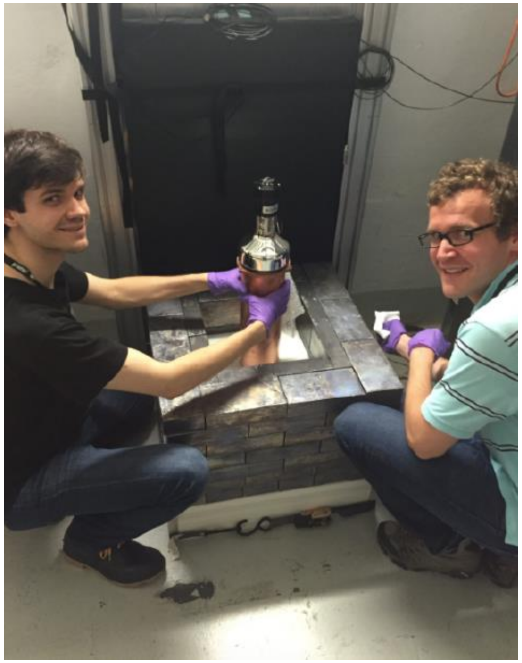
- CENNS-10 (aka. COH-Ar-10): 24.4-kg liquid argon scintillation calorimeter with a 20 keVnr threshold
  - Originally built by J. Yoo et al. at Fermilab for the lab CENNS effort
  - Upgraded in 2017 with TPB-coated PMT's and Teflon walls to increase light yield for CEvNS detection in neutrino alley
- CEvNS excess observed with 3.5σ evidence on argon
  - Second detection of CEvNS after COHERENT CsI[Na] detector
  - Fermilab JETP seminar by J. Zettlemoyer on Jan 10, 2020
  - Result: arXiv:2003.10630 (accepted to PRL)
  - Data release: arXiv:2006.12659
- Dataset has since increased by 2.6x → more CEvNS coming

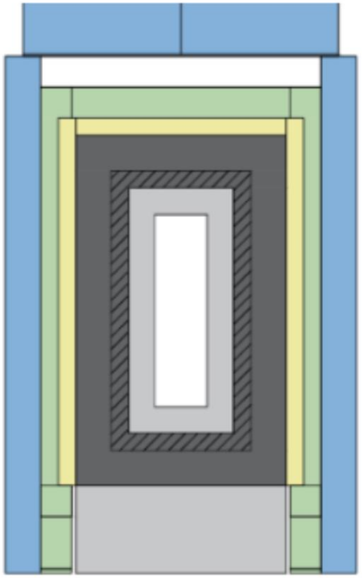




The COHERENT CsI[Na] Detector

A hand-held neutrino detector
– 14.6-kg CsI[Na] crystal
– Manufactured by Amcrys-H
– Single R877-100 PMT



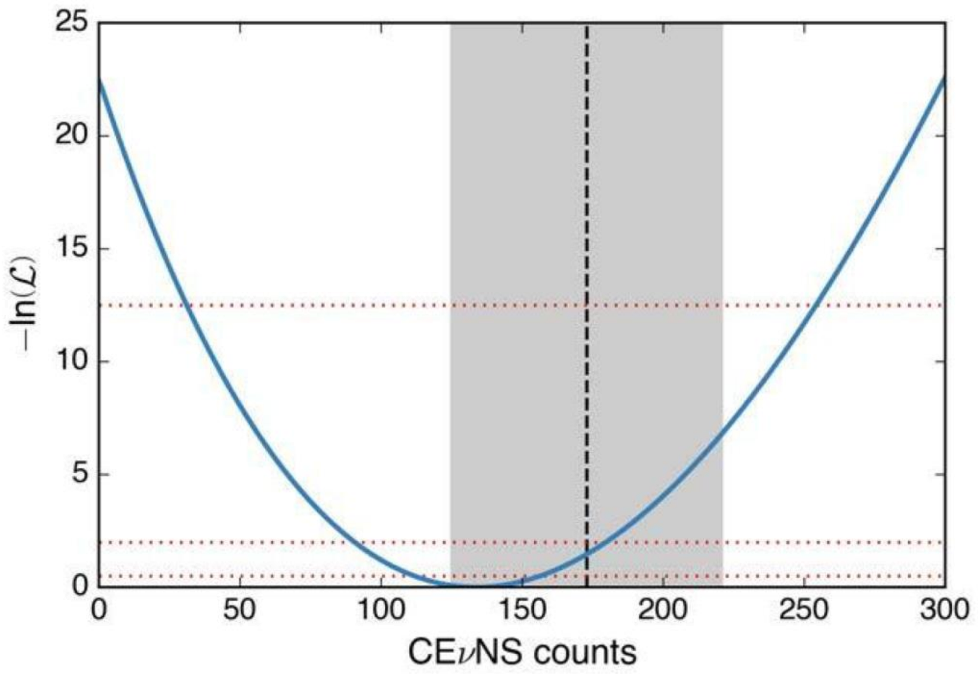


Shielding design

– Veto to tag cosmic events
– Lead to shield from gammas
– Water and plastic to moderate neutrons

Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3"	2"	4"	2"	4"
Colour					

First Observation of CEvNS with CsI[Na]



Made first observation of CEvNS
– Established the existence of CEvNS to 6.7σ
– 134 ± 22 CEvNS events
– 173 ± 48 CEvNS predicted

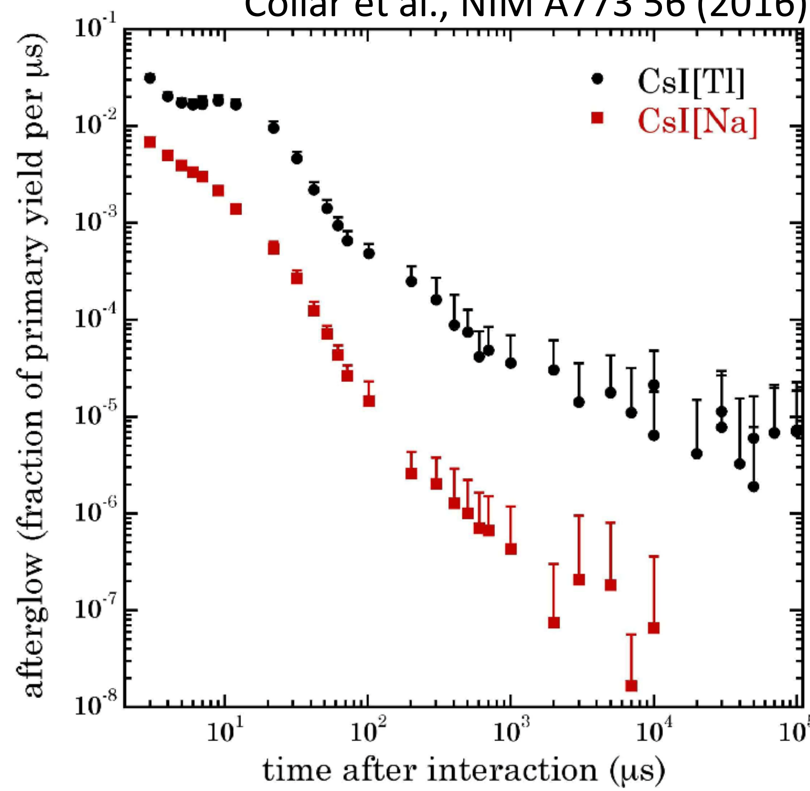
Dataset increased by 2.2x before decommissioning

Data released publicly, used to study
– neutrino NSI
– new forces
– neutrino magnetic moment
– $\sin^2\theta_W$ at low-Q^2
– neutrino charge radius
– Nuclear weak charge distribution
– dark matter searches + more

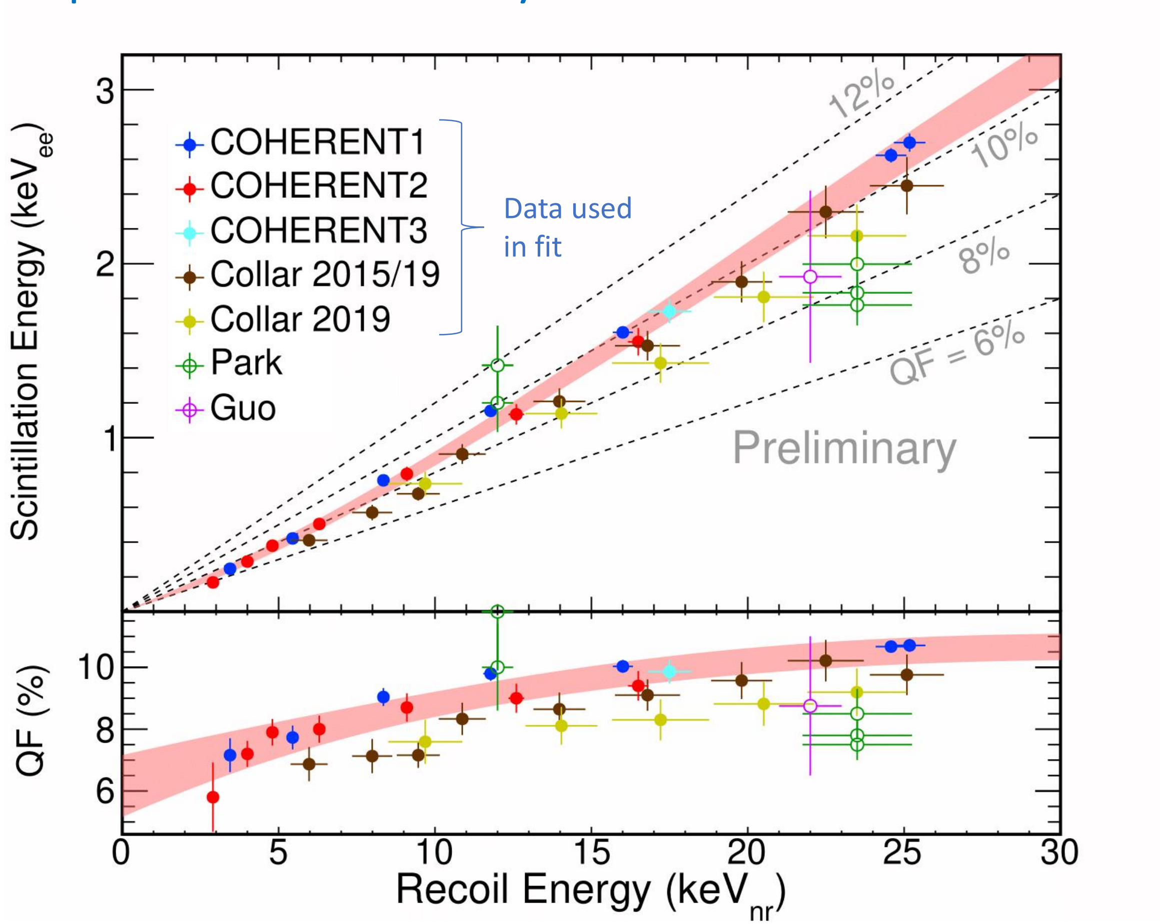
Timing of Scintillation in CsI[Na]

- CsI has a high light yield and low background, but afterglow photons can be troublesome
  - CsI can scintillate for up to 1 s following a large energy deposit within the crystal
- The afterglow rate in Na-doped CsI is low enough to allow a search for small, few keV nuclear recoils associated with CEvNS

Collar et al., NIM A773 56 (2016)

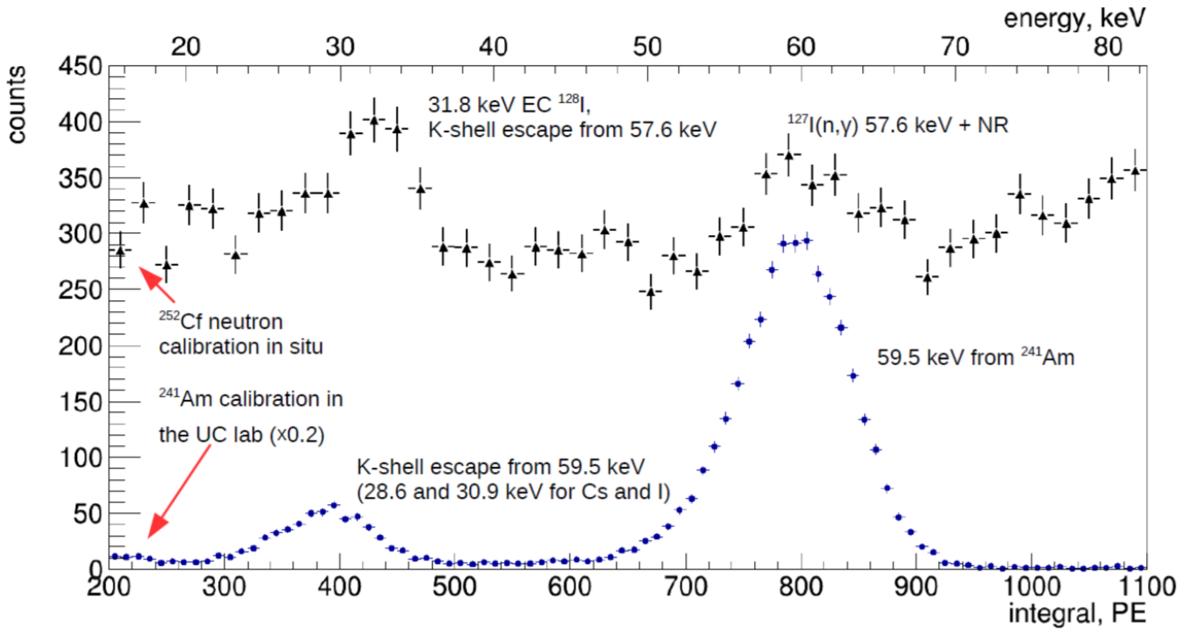


Scintillation Response of the Crystal to Nuclear Recoils



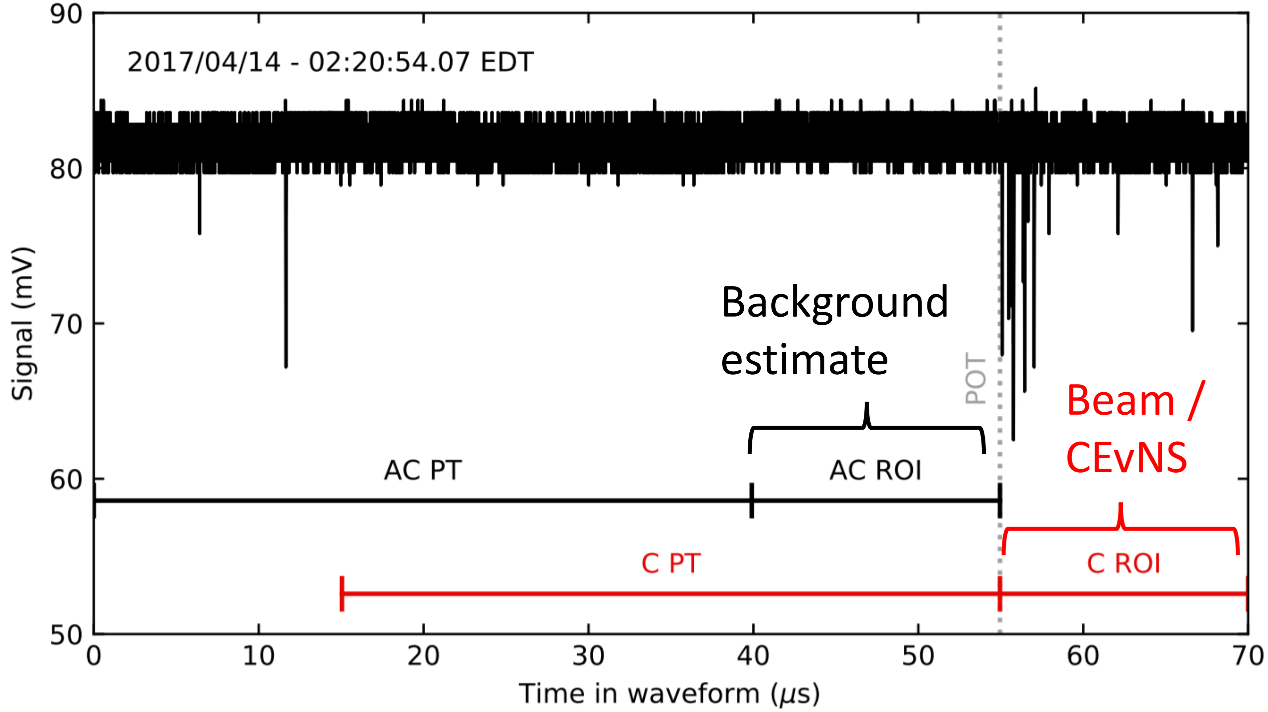
- ❑ Only a fraction of the struck nucleus's kinetic energy, E_{nr}, goes into scintillation energy, E_{ee}
- ❑ There are five separate measurements of the scintillation response using CsI[Na] grown by the same manufacturer used for our detector
  - Empirically model $E_{ee}(E_{nr})$ as a fourth order polynomial with $E_{ee}(0) = 0$ and fit to the global data

Calibrating the CsI[Na] Detector



- Detector calibrated
  - 59.5 keV gamma using ^{241}Am decay calibration source
  - 57.6 keV ^{127}I(n,γ) peak using a ^{252}Cf neutron source
- A 13.35 photon / keV light yield is achieved
  - LY uniformity across crystal shown to be everywhere within 3%
- Single PE charge monitored during data collection using accidental peaks

Waveform Reconstruction

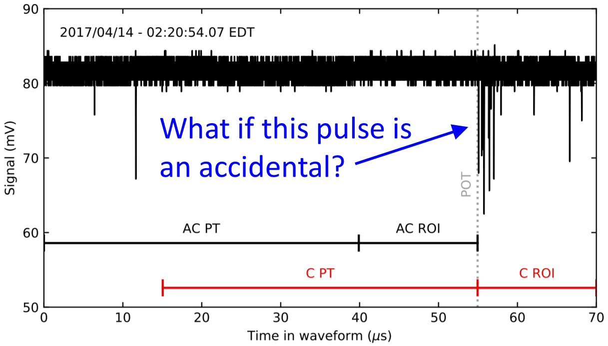


- Each waveform has a two regions-of-interest: coincident (C) with the beam and anticoincident (AC), immediately preceding the arrival of the beam
  - ROI is 15 μs
  - Each ROI has a 40 μs pretrace region to monitor scintillation activity in the crystal in real-time
  - Event begins with first reconstructed pulse in ROI and has a 3 μs integration window

- AC events give an unbiased in-situ estimate of steady state backgrounds in neutrino alley

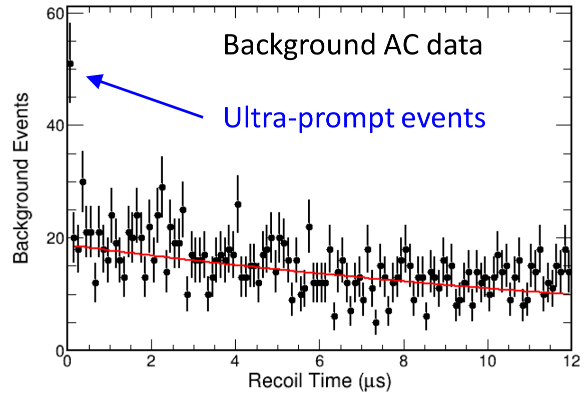
Mitigating Common Reco Pathologies and Background Events

Misidentified onset



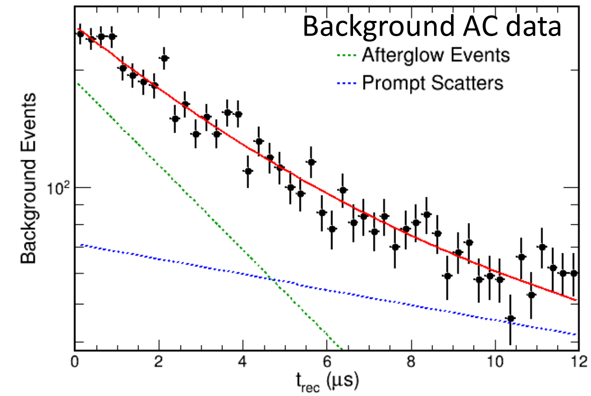
- ❑ Afterglow rate is high enough the first pulse found in the ROI may not be from a nuclear recoil
  - "Misidentified-onset events"
  - 6% of signal events
- ❑ Stray afterglow pulses also cause us to lose signal whose first pulse is ≥ 3 μs after the afterglow pulse
  - 2% of signal events
- ❑ Also implies the timing for signal and backgrounds should be exponential

Ultra-prompt background



- ❑ A background event starting in the tail-end of the pretrace can sneak into the waveform ROI
  - "Ultra-prompt events"
- ❑ Requiring no PE pulse in the final 0.2 μs of the pretrace reduces the background from ≈40 events to ≈1

Afterglow background



- ❑ Coincidence of afterglow pulses can fake an event
- ❑ Waveform simulation predicts these events to fall sharply in time and we see this behavior in data
- ❑ Simulation and beam-off data show afterglow events can be eliminated with a cut on the number of pulses reconstructed

Event Selection

Quality	Remove events with muon veto, PMT saturation, or digitizer overflow	Reject cosmic-induced events and require energy consistent with a low-energy recoil
Scintillation Activity	Reject waveforms with ≥ 6 PE pulses in pretrace	Reject events that occur when detector is especially bright
Ultra-prompt	No PE pulse in final 0.2 μs of pretrace	Reject events from the tail-end of the pretrace that sneak into the waveform ROI

Acceptance cuts reduce detector livetime, no cut on ROI and effect is measured in-situ during operations

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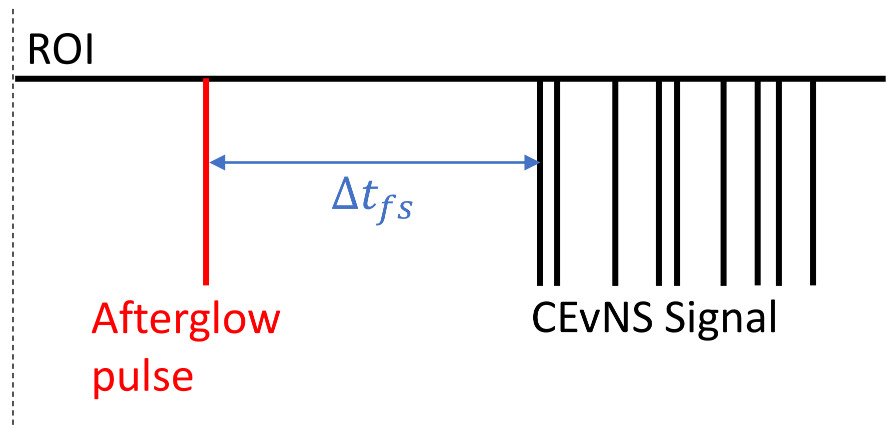

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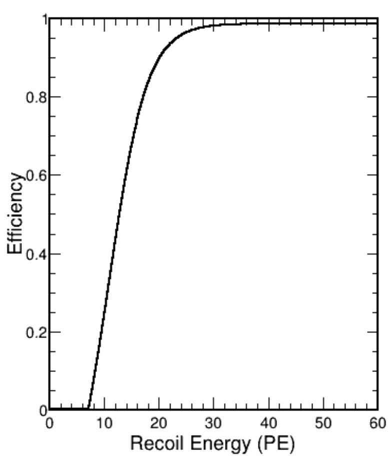
Afterglow	Require ≥ 9 pulses in ROI	Reject accidental coincidence of afterglow scintillation	Efficiency determined using ^{133}Ba calibration data of low-energy Compton electrons

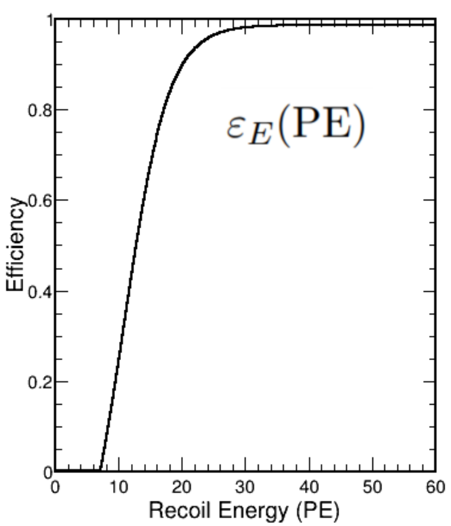


Threshold of ≈10 PE to reject afterglow background

CEvNS Selection Efficiency

- Our efficiency for detecting CEvNS recoils depends on both the recoil time and energy
- PE-dependence
  - Efficiency loss from rejection of afterglow-induced background
  - Determined with ^{133}Ba calibration data
- t-dependence
  - Misidentified onset and lost events are more common at late times
  - Calculated with data-driven simulation and validated with high-energy background data
- These two parts are uncorrelated and the 2D efficiency is a simple product

$$\varepsilon(\mathrm{PE}, t_{rec}) = \varepsilon_E(\mathrm{PE}) \times \varepsilon_t(t_{rec})$$



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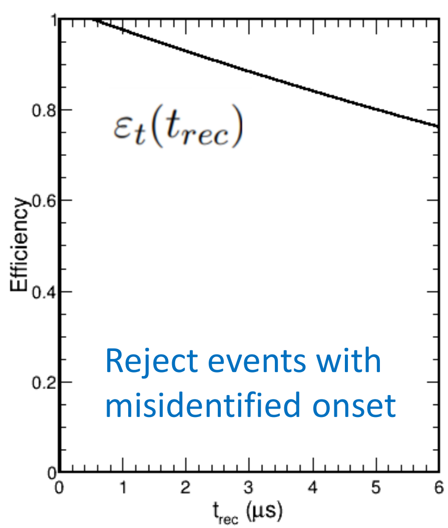

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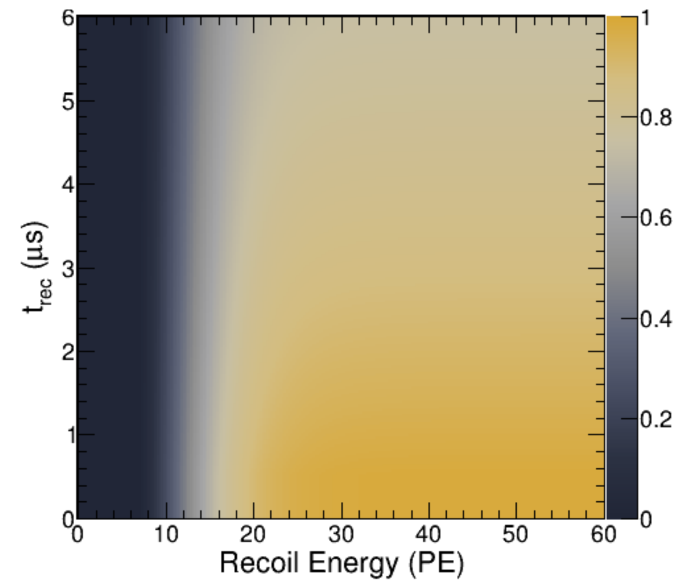
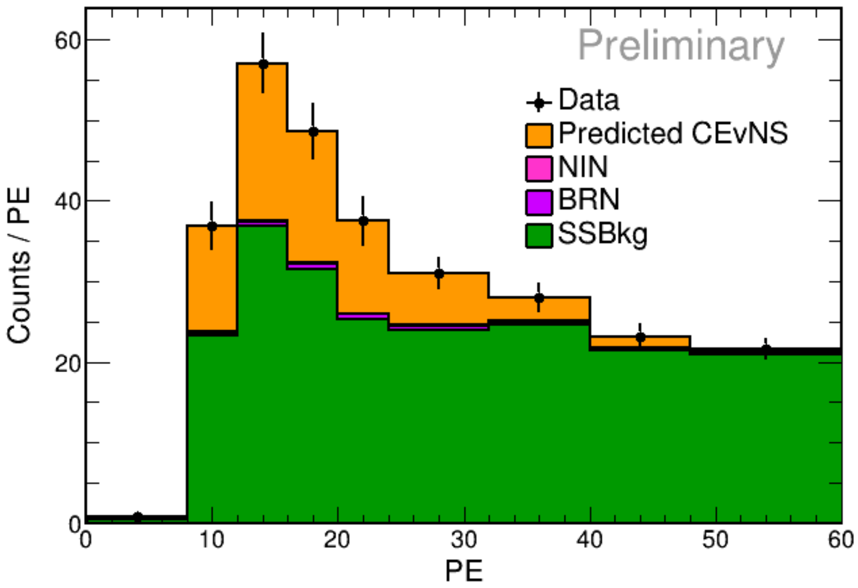
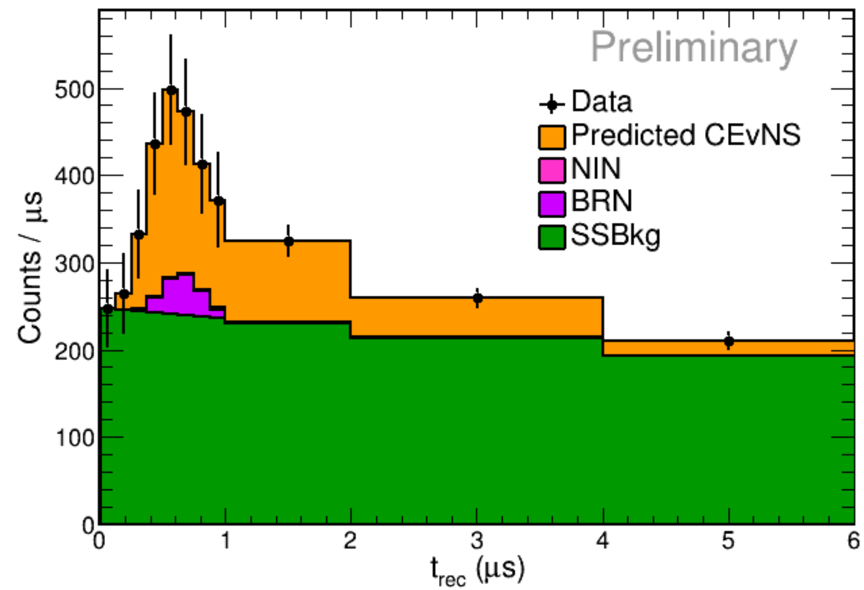


Expected CEvNS in Our Sample



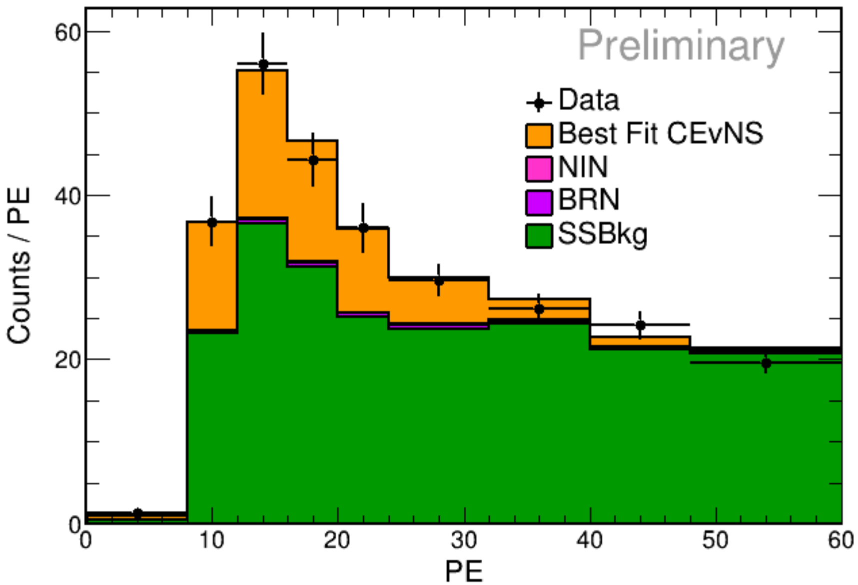


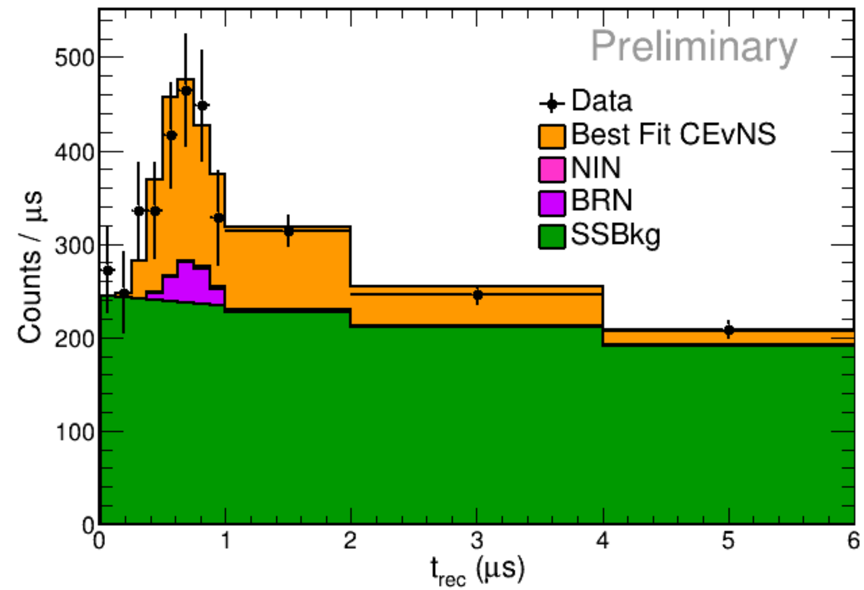
- Perform 2D likelihood fit in PE and t_{rec}
- Beam-unrelated steady-state background measured in-situ with beam out-of-time data
- Beam-related neutron backgrounds small, only 7% of the predicted CEvNS rate

Expected events

Steady-state background	1286
Beam-related neutrons	18
Neutrino-induced neutrons	6
CEvNS	333

Observed CEvNS



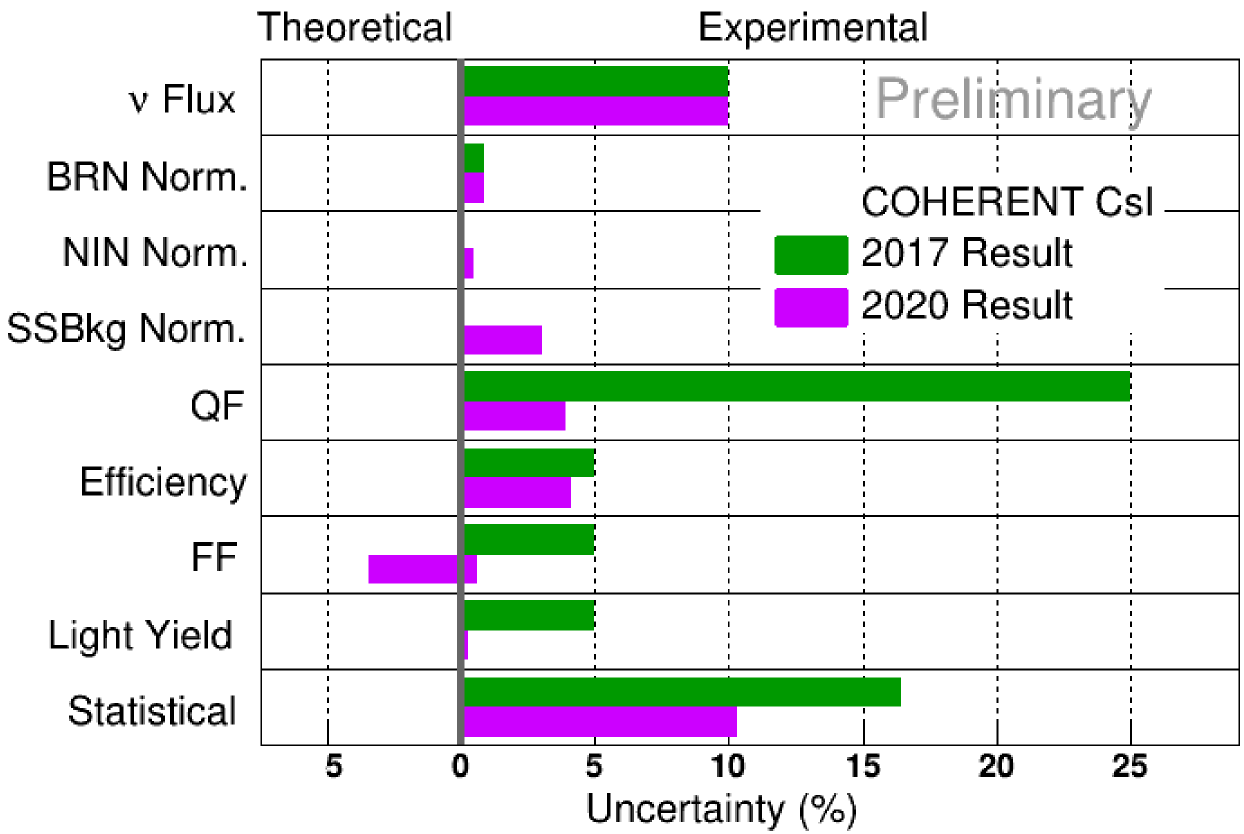


- Data in our CsI[Na] detector match our best-fit predicted spectra very well
- Best-fit CEvNS slightly low, but consistent with expected statistical error

Best fit results

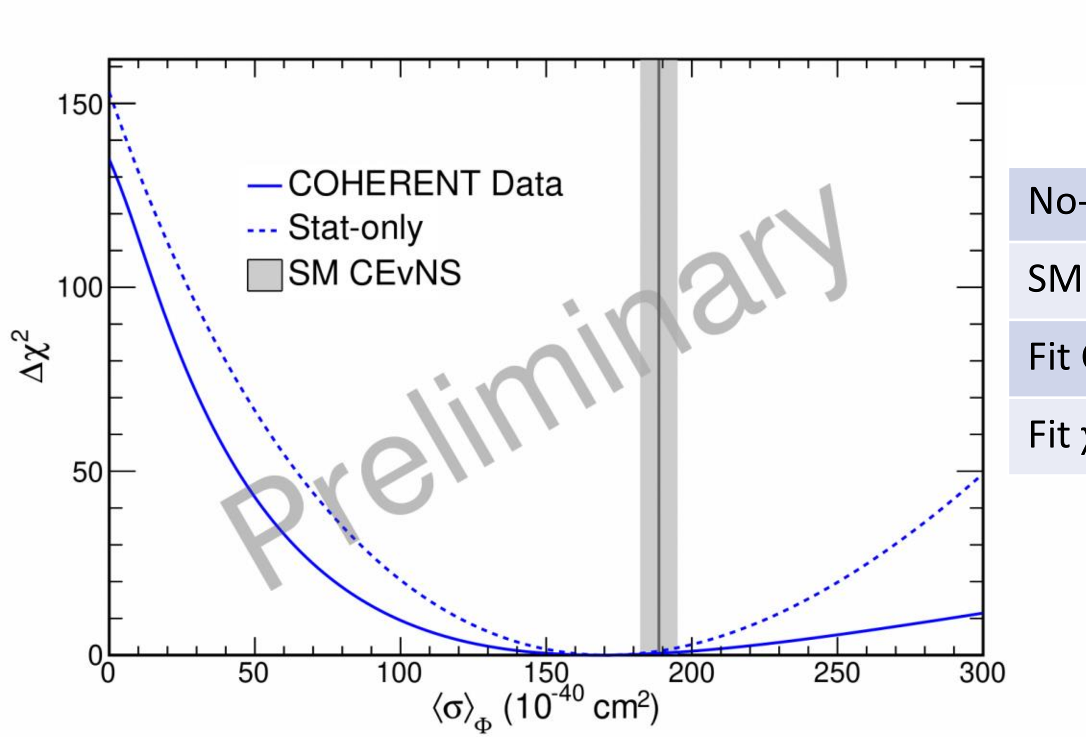
Steady-state background	1273
Beam-related neutrons	17
Neutrino-induced neutrons	5
CEvNS	306

Measurement Uncertainties



- Re-assessed all systematic uncertainties
- Huge improvement to QF error from newly available data, better model and fit strategy
- Neutrino flux normalization now dominates our cross section uncertainty
- Overall precision improves 33% → 16%

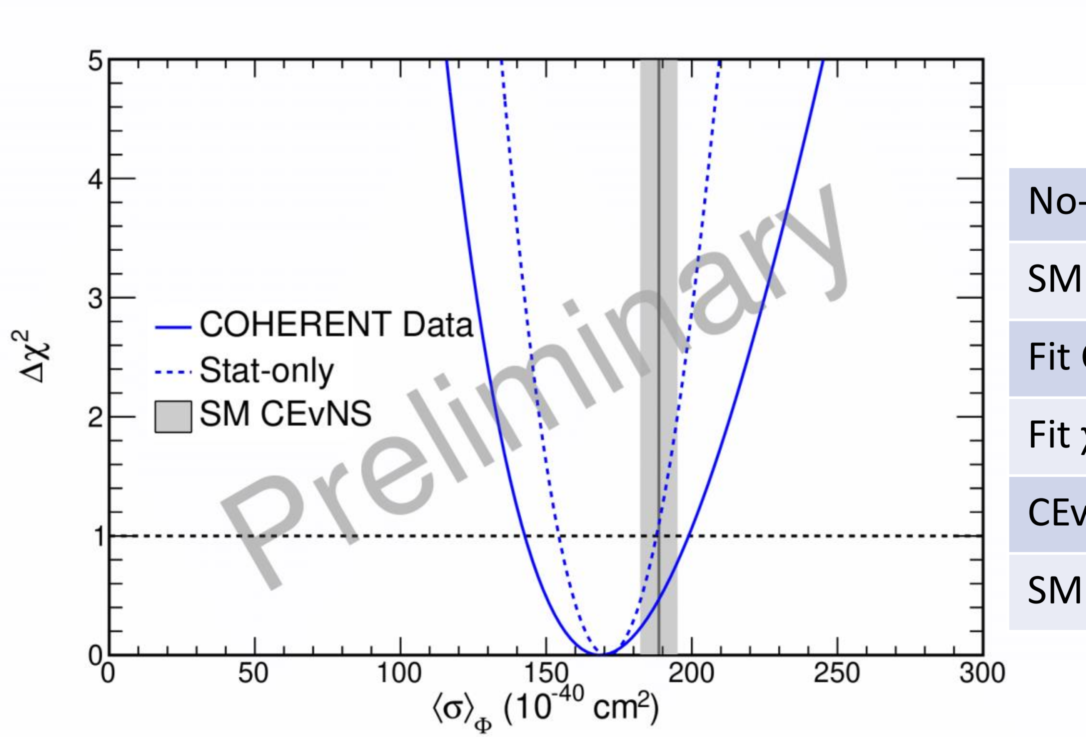
Measuring CEvNS Rate



No-CEvNS rejection	11.6 σ
SM CEvNS prediction	333 ± 11(th) ± 42(ex)
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98

- We again see CEvNS
- Best fit χ^2 is consistent with degrees of freedom
- We reject the no-CEvNS hypothesis at 11.6 σ
  - Can't read off the 1 σ error from this plot: moving towards precision measurements of CEvNS
  - No question CEvNS is there, let's do our best to measure it the cross section

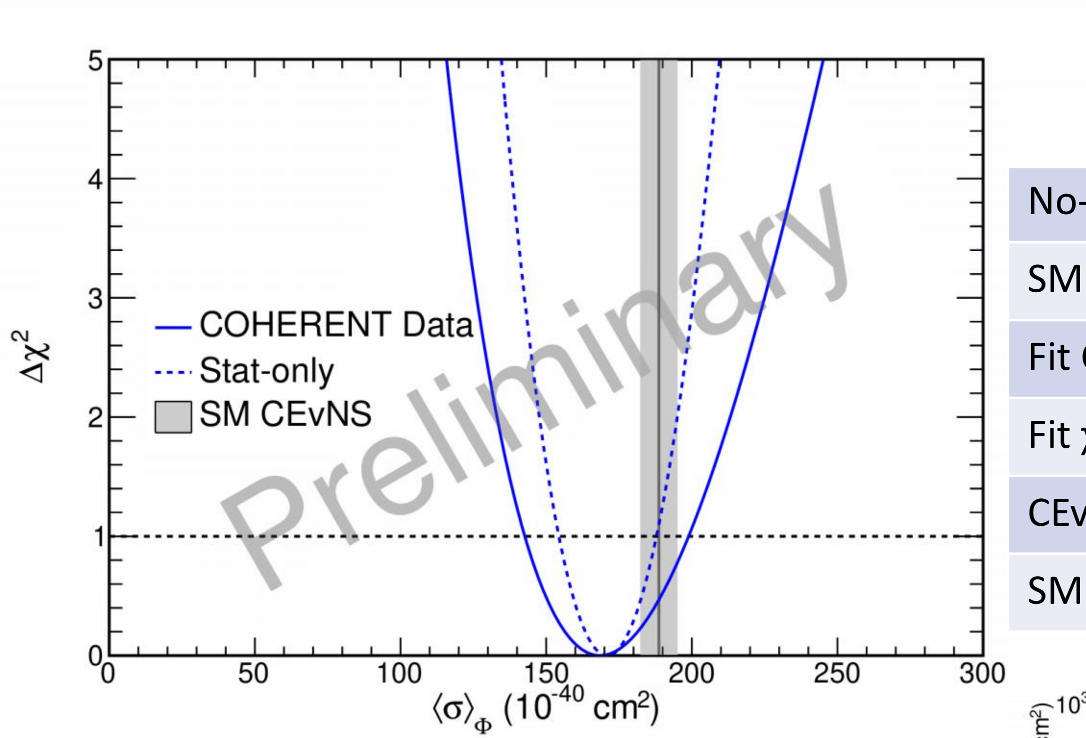
Determining the CEvNS Cross Section



No-CEvNS rejection	11.6 σ
SM CEvNS prediction	$333 \pm 11(\text{th}) \pm 42(\text{ex})$
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

- From the observed CEvNS rate, we calculate the flux-averaged cross section
  - Result is consistent with the standard model prediction to 1 σ

Determining the CEvNS Cross Section



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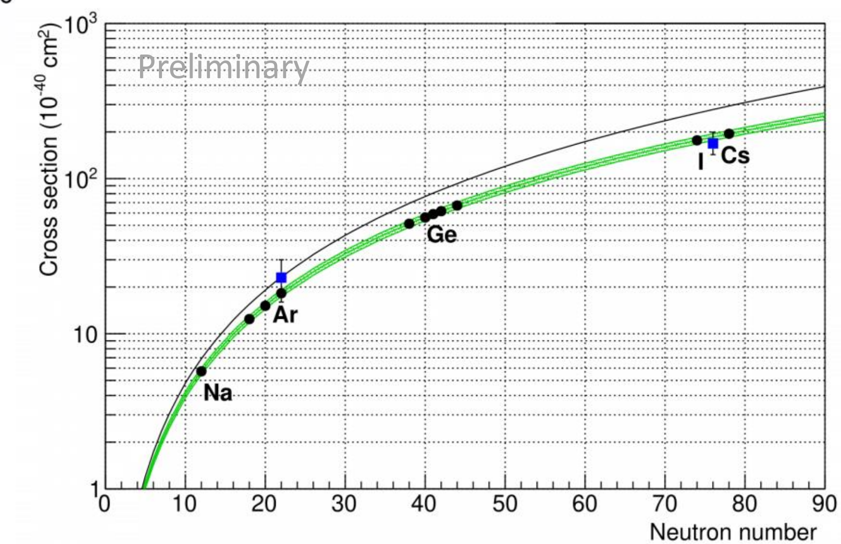
SM cross section	189 ± 6 × 10^{-40} cm^2

- From the observed CEvNS rate, we calculate the flux-averaged cross section
  - Result is consistent with the standard model prediction to 1 σ
- Observed cross section consistent with N^2 dependence

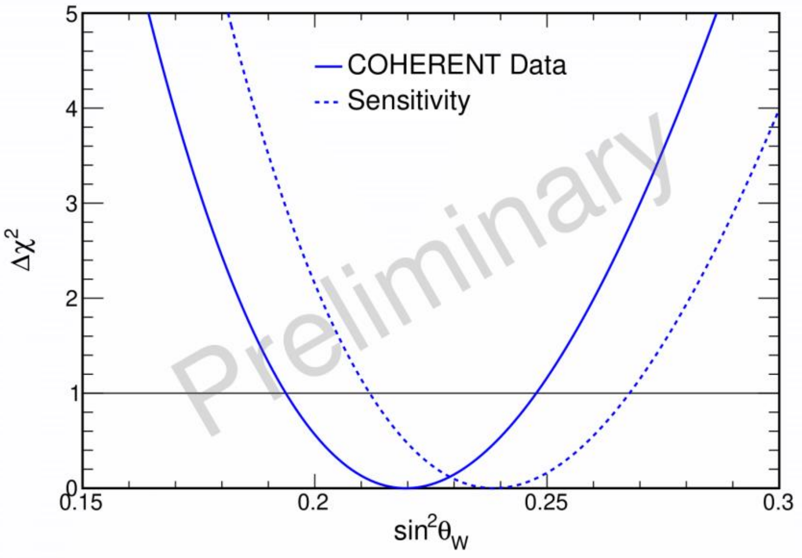


Measuring the Weak Mixing Angle

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{4\pi} Q_W^2 \left(1 - \frac{MT}{E_\nu^2} + \left(1 - \frac{T}{E_\nu}\right)^2\right)$$

$$Q_W = (1 - 4\sin^2\theta_W) Z F_Z(Q^2) - N F_N(Q^2)$$

- The expression for the weak charge gives CEvNS sensitivity to determine $\sin^2\theta_W$ at low-Q^2
  - $\sin^2\theta_W = 0.220^{+0.028}_{-0.027}$



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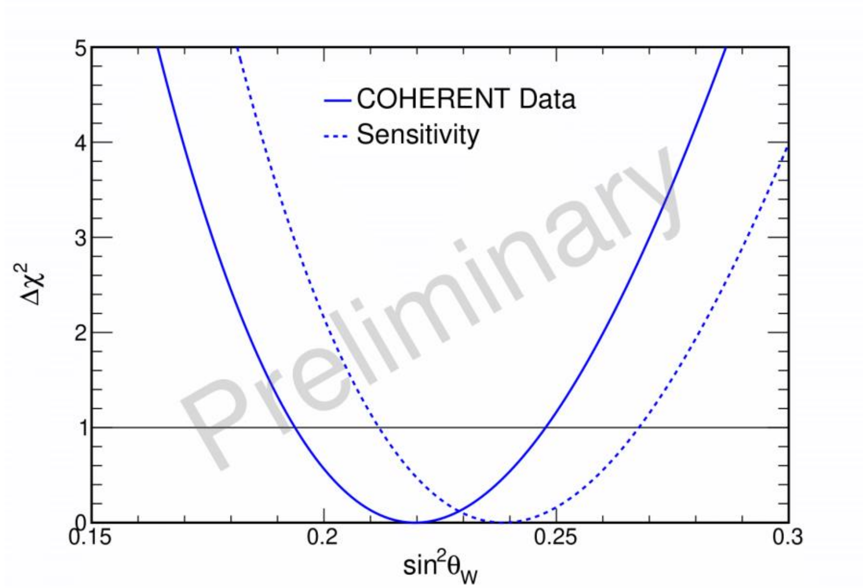
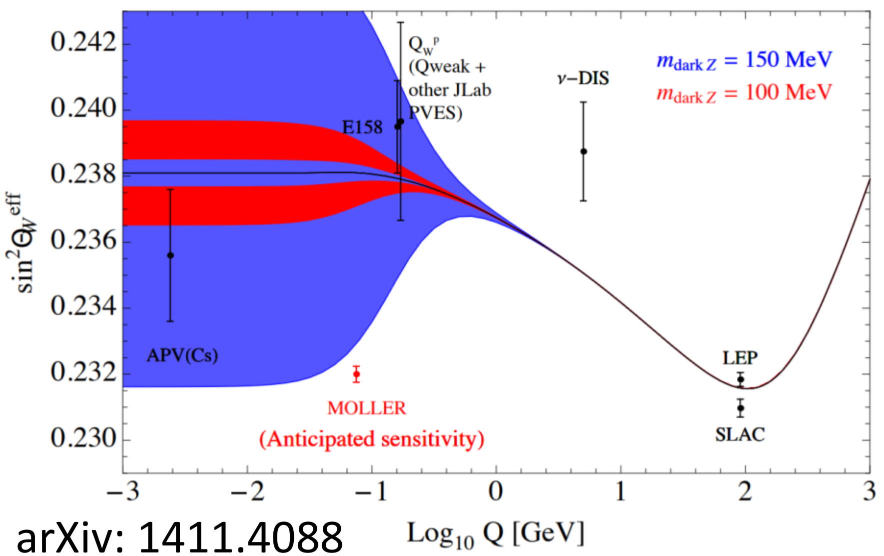
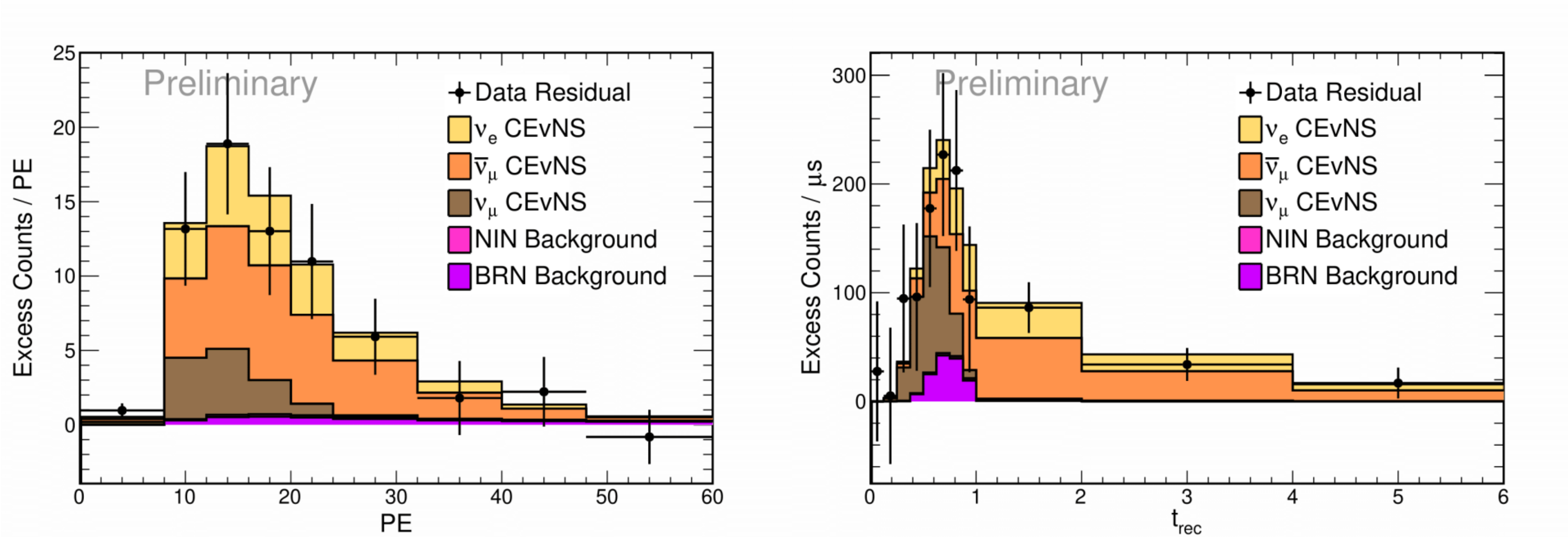




arXiv: 1411.4088

- Measurement not currently competitive, though will be with COHERENT plans for large datasets with improved uncertainties
- However, CEvNS already helpful!
  - Gives an experimental measure of nuclear structure important for APV measurements on ^{133}Cs Phys Rev D99 033010

CEvNS Spectra by Flux Component

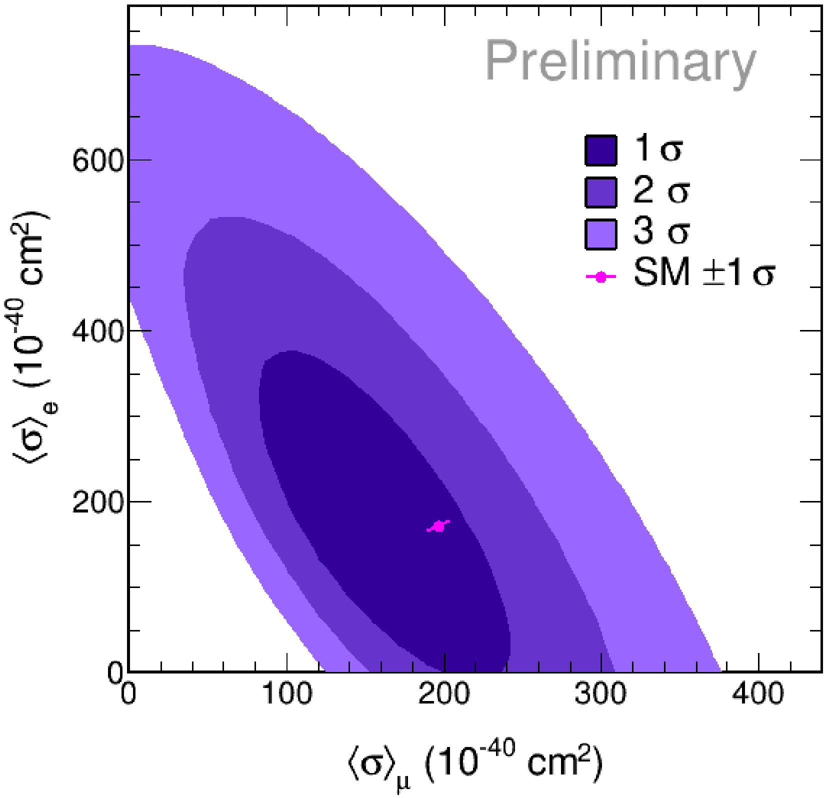


- At the SNS, CEvNS from ν_μ occur earlier than CEvNS from $\nu_e/\bar{\nu}_\mu$
- This is a lever arm for constraining CEvNS cross sections for different flavors separately
  - Advantage of spallation sources with beam width < muon lifetime
  - Now have collected enough exposure and understand our sample well enough to exploit this information, allowing precision measurements that exploit the SNS flux shape

- We measure the flavored CEvNS cross sections, $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$, to study CEvNS constraints of NSI
  - SM predicts flavor universality of the cross section at tree level
  - (There are small SM differences in $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$ cross sections which we account for)

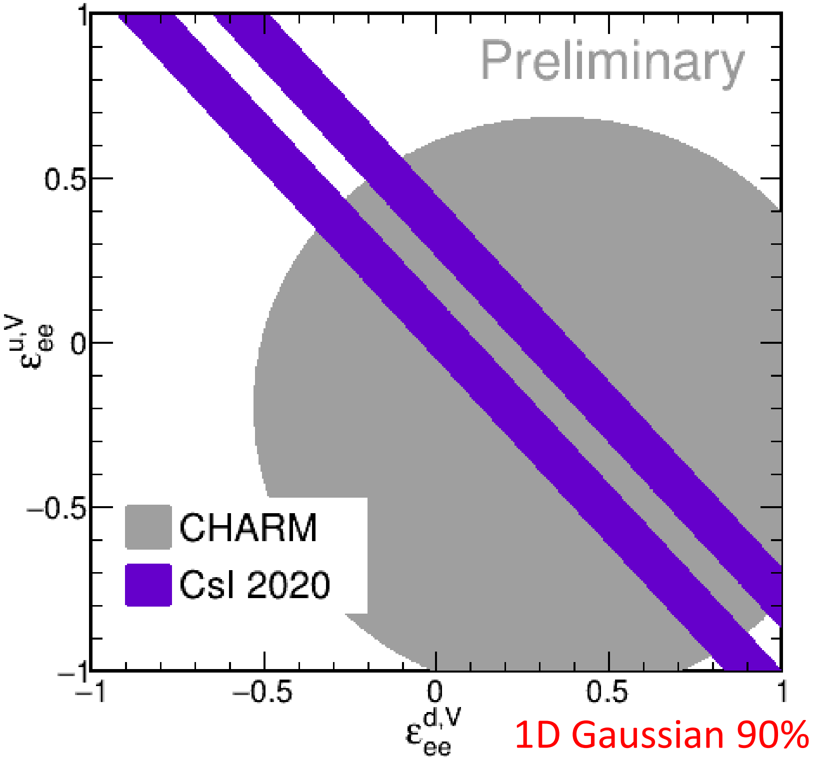
Flavored CEvNS Cross Section

- Allow for completely different $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$ as would be allowed in NSI scenarios
- ν_μ timing sheds light on the fraction of observed CEvNS that are from each flavor
- As in 1D CEvNS fit, the SM prediction is included within the 1 σ contour



COHERENT NSI Constraints

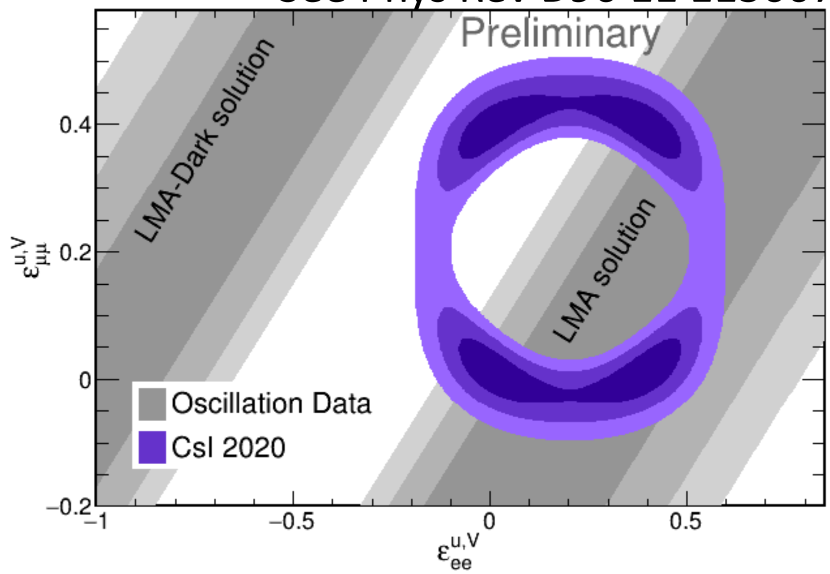
- Updated CsI data improves upon previous constraints
- Updated from 2017 result to include full spectral fit
- $\langle\sigma\rangle_{\mu}$ held fixed at SM prediction while $\langle\sigma\rangle_{e}$ floats freely



1D Gaussian 90% critical up-values

Interpreting Solar Neutrino Oscillation Data

See Phys Rev D96 11 115007

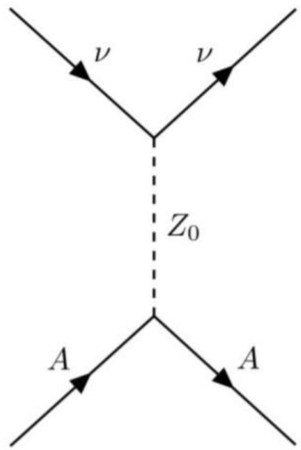


2D Gaussian 1/2/3σ critical up-values

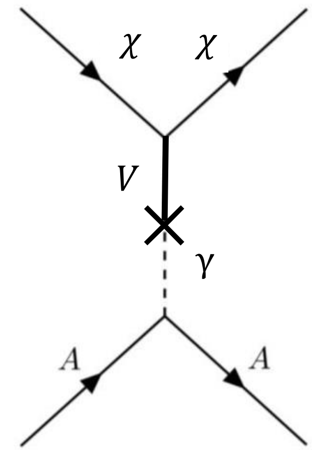
- Measurement of PMNS parameters with neutrino oscillation experiments can be confused in NSI scenarios
- In particular, there is ambiguity between the large mixing angle (LMA) solution to solar oscillations and the LMA-Dark dark model
  - Would flip the θ_{12} octant: $\theta_{12} \rightarrow \pi/2 - \theta_{12}$
- LMA-Dark would require non-zero $\varepsilon_{ee}^{u,V}$ and $\varepsilon_{\mu\mu}^{u,V}$, which we can test given with our flavored cross section result

DM Scattering in COHERENT Detectors

CEvNS



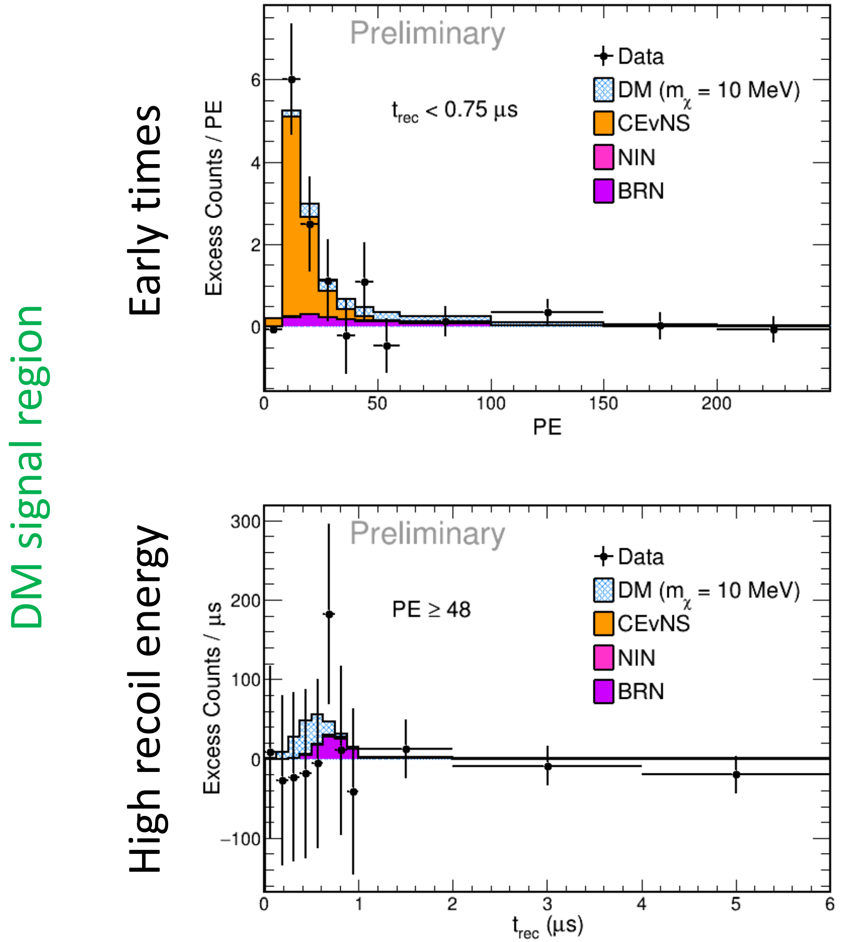
Coherent
dark matter-nucleus
elastic scattering



- Dark matter particles would produce nuclear recoil signatures, similar to CEvNS
- The cross section is similarly large and precisely calculable so that a dark matter detector sensitive to CEvNS may be competitive with much larger experiments
- Would be "prompt" – arriving coincident with the beam and would have a harder recoil spectrum than CEvNS as $V \rightarrow \chi\chi'$ happens in flight

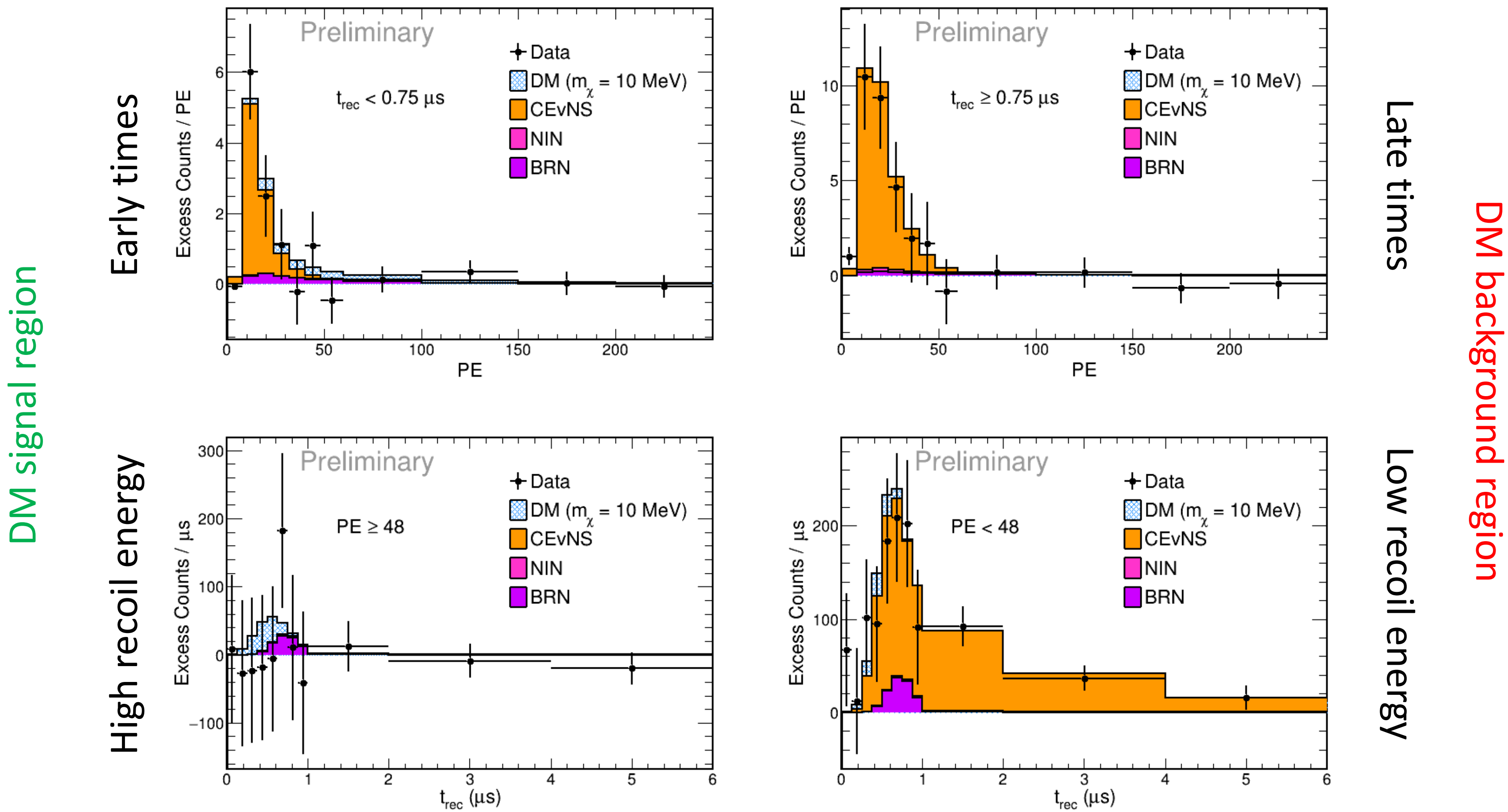
- DM scatters would be an additional component of our sample → can constrain with current CsI dataset

CsI Search for Dark Matter Particles at the SNS



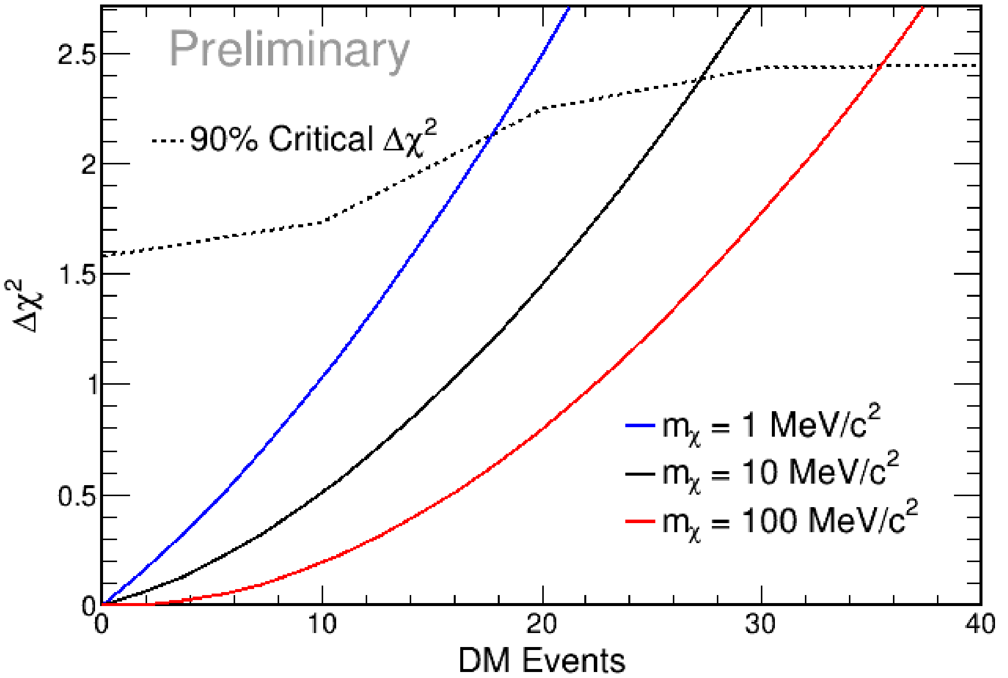
- Extend fit region to capture DM signal region: 60 < PE < 250 + t_{rec} < 0.75 μs

CsI Search for Dark Matter Particles at the SNS



- Extend fit region to capture DM signal region: 60 < PE < 250 + t_{rec} < 0.75 μs
  - DM background region used to constrain systematic uncertainty

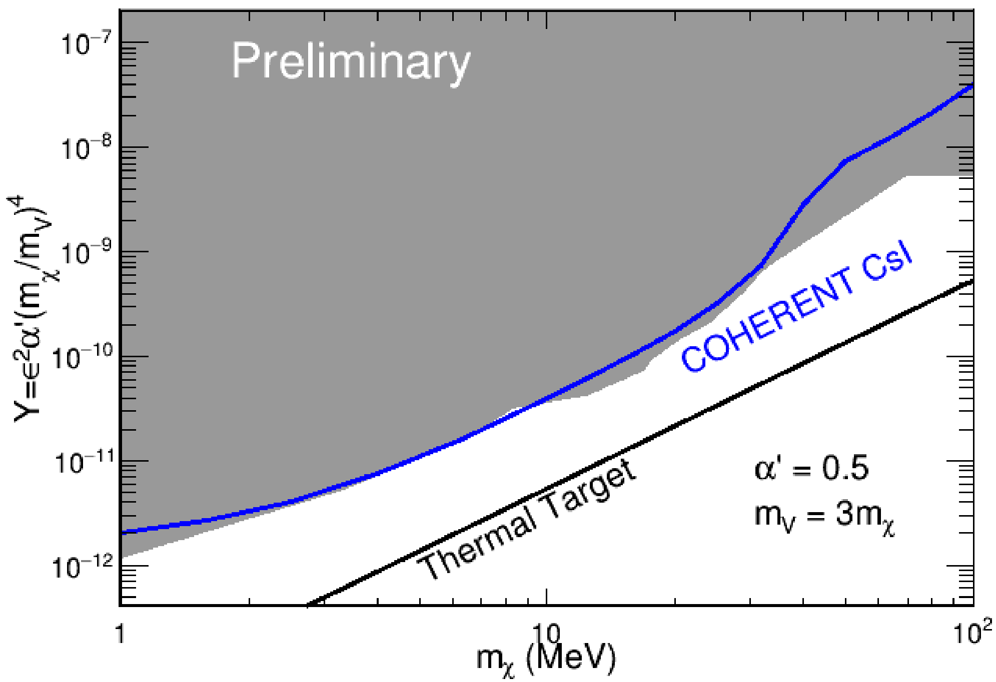
Constraining Dark Matter Event Rate



- We do not see evidence for dark matter at the SNS
- Since our limit is near a physical boundary $N_{DM} \geq 0$, we constructed critical $\Delta\chi^2$ values for different values of dark matter mass and event rate using the Feldman-Cousins procedure
  - Critical values shown to be independent of the dark matter mass

	1 MeV/c²	10 MeV/c²	100 MeV/c²
90% constraint on N_{DM}	< 18	< 27	< 35

DM Constraint with Our CsI Dataset



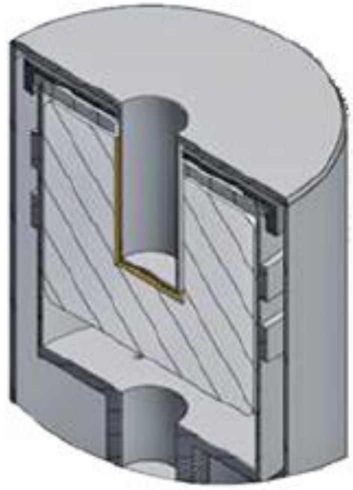
- At 90% confidence, observed data rejects parameter space competitive with other major constraints: NA64 / MiniBooNE / LSND / BaBar
  - Strongest constraint yet for $m_\chi \approx$ 7-9 MeV

- A small, 14.6 kg detector places successfully demonstrates the power of CEvNS detectors for direct detection sub-GeV WIMP detection

Ongoing COHERENT Activity at the SNS

NUBEs	2016	Scintillator encased in Pb/Fe, which is surrounded by water to moderate outside neutrons	Measure neutrino-induced neutron production cross sections on Pb and Fe which is a background to CEvNS detectors and a detection channel for supernova burst neutrinos for HALO
NaIνE	2016	185 kg of NaI scintillating crystals	Assess backgrounds for future NaI CEvNS detector, measure ^{127}I inelastic cross sections, a background for 0νββ searches with Xe
CENNS-10	2017	22.4 argon scintillating calorimeter	Continue physics data-taking, R&D for future CEvNS program with argon
MARS	2017	Scintillator covered with Gd paint to observe neutron captures	Mobile neutron flux calorimeter taking measurements throughout neutrino alley
Neutrino alley neutron measurements	2020	4 x 10 liter scintillator cells	Map the timing of the neutron flux through neutrino alley, determine how neutrons from the target hall are sneaking in

2021: Commissioning Two New CEvNS Nuclear Targets

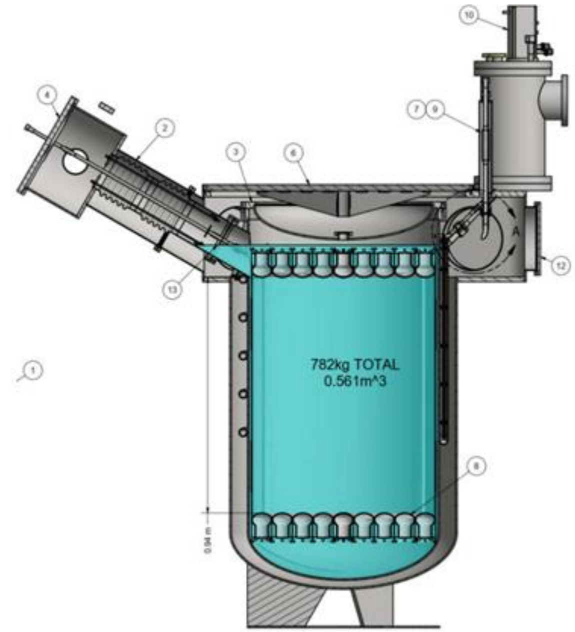


- 16 kg of low threshold Ge PPC detectors
  - COH-Ge-1
- Will collect 500+ CEvNS/yr at $E_{rec} > 0.3$ keV_{ee} with good energy resolution
- 3/8 detectors delivered, finalizing shielding design, commissioning expected early 2021

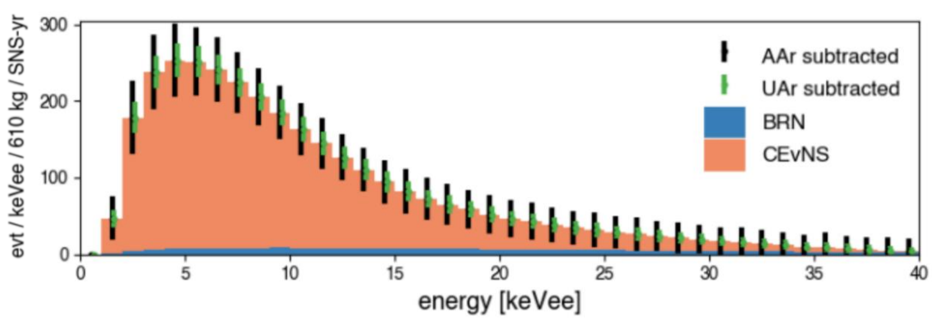
- Multi-ton detector of NaI scintillating crystals
  - COH-NaI-2
- 13 keV_{nr} threshold for CEvNS on ^{23}Na with background characterization from NaIvE
- Lightest nucleus yet studied by COHERENT

Future Argon Plans at the SNS

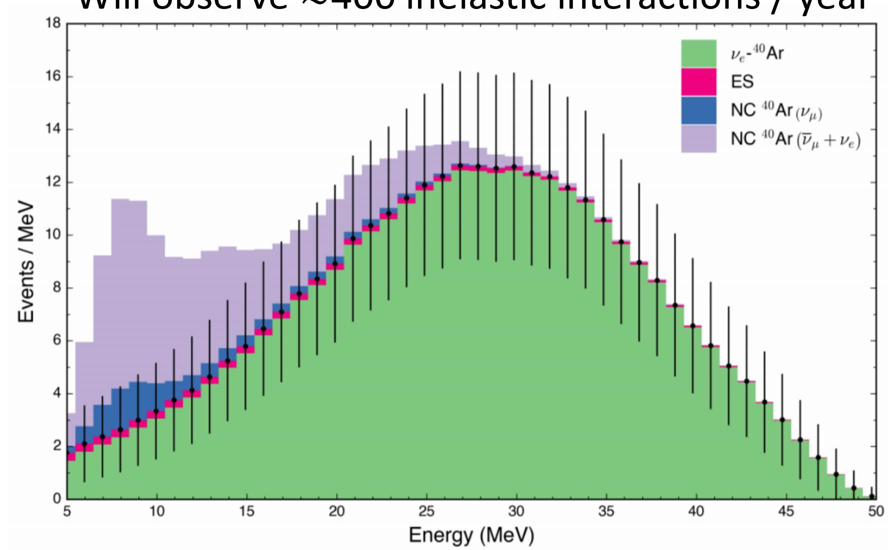
- CENNS-750 (aka. COH-Ar-750): O(1 ton) of LAr at SNS
- Using simulation tuned to our experience with CENNS-10 operations, we can achieve a 20 keV_{nr} threshold
- Working to secure ^{39}Ar-depleted argon mined from underground
- Great timing resolution and large mass gives powerful sensitivity to measuring flavored cross sections and searching for accelerator-produced dark matter
- Also sensitive to inelastic interactions which will reduced cross section uncertainties for for DUNE supernova / solar neutrino measurements



Will observe ≈3000 CEvNS / year

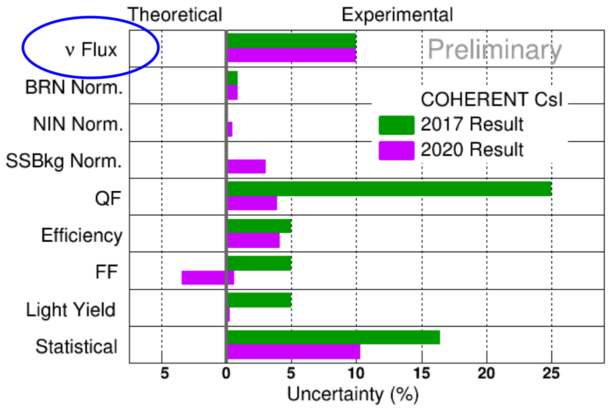


Will observe ≈400 inelastic interactions / year



Calibrating the Neutrino Flux at the SNS

Neutrino flux largest systematic uncertainty, will dominate error for future Ge and Ar results



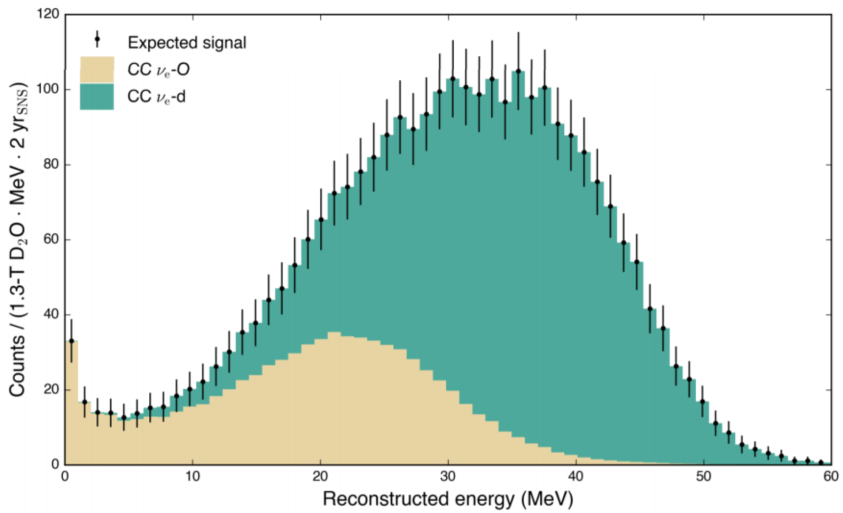
Proposed D2O detector can measure the SNS ν flux

Light collection with PMT's on one endcap

Heavy water fiducial volume in acrylic vessel

Already have D_2O on hand

- Why D2O? – the ν_e-d CC cross section is known to 2-3% from calculations
  - Use observed event rate to determine flux
  - Flux uncertainty of few % is achievable
- Has very significant impact on NSI parameter space we can probe
- Vital for competitive CEvNS $\sin^2 \theta_W$



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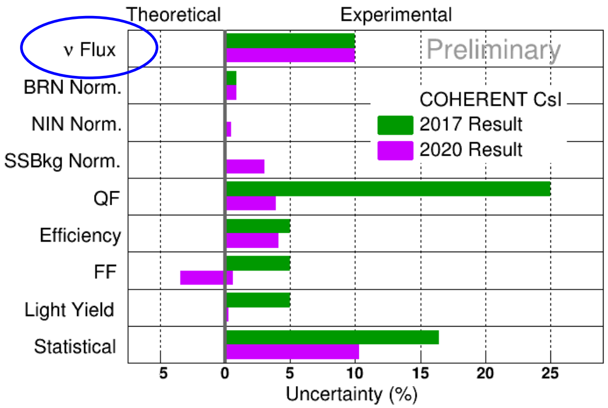


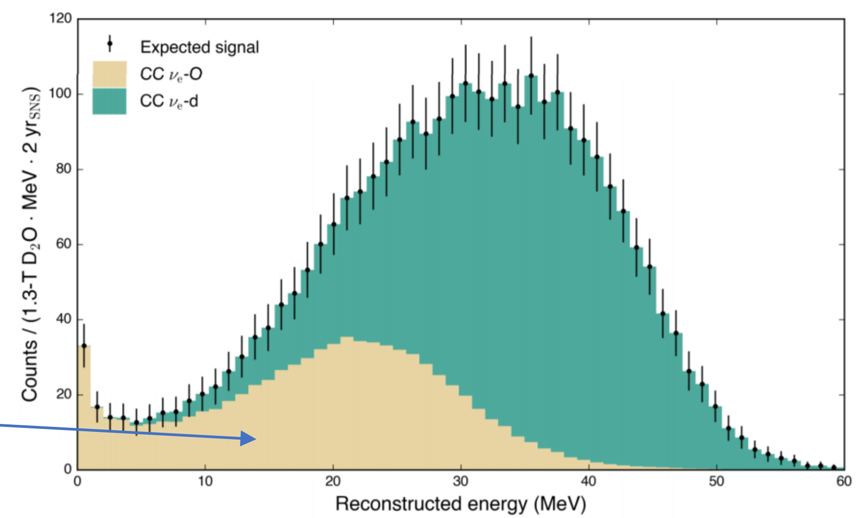
Proposed COH-D2O detector can measure the SNS ν flux

Light collection with PMT's on one endcap

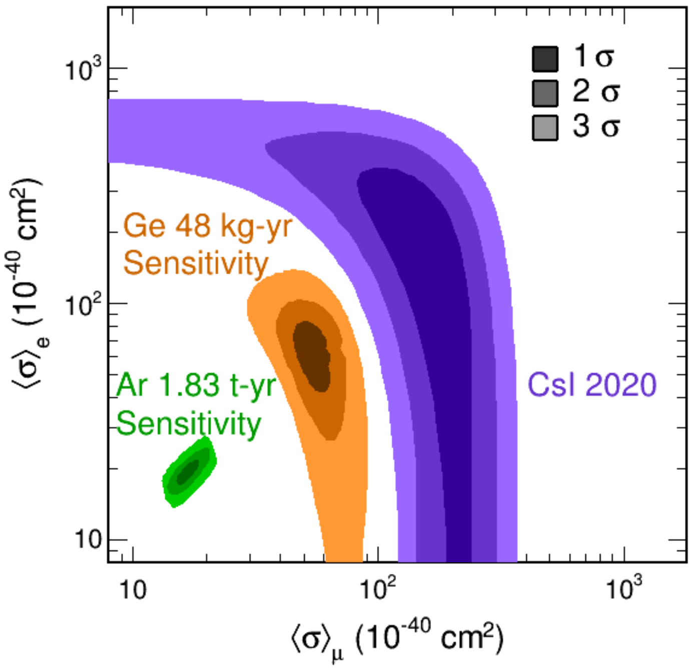
Heavy water fiducial volume in acrylic vessel

Already have D_2O on hand

- Why D2O? – the ν_e-d CC cross section is known to 2-3% from calculations
  - Use observed event rate to determine flux
  - Flux uncertainty of few % is achievable
- Has very significant impact on NSI parameter space we can probe
- Vital for competitive CEvNS $\sin^2 \theta_W$
- Also allows first measurement of ν_e CC on ^{16}O
  - Detection channel for supernova neutrinos – SK/HK



Future Sensitivity to NSI Scenarios



- Future COH-Ge-1 and COH-Ar-750 detectors will have significantly improved sensitivity to measuring flavored cross sections vital for aggressively probing NSI parameter space

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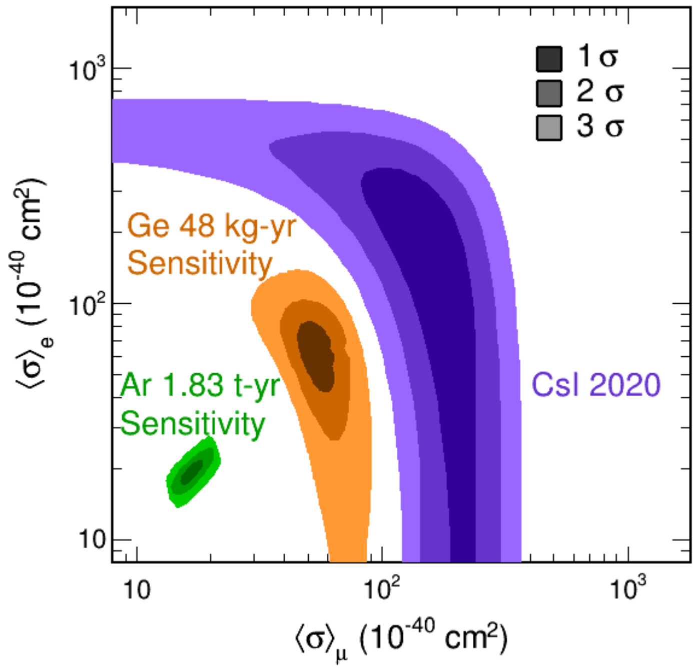
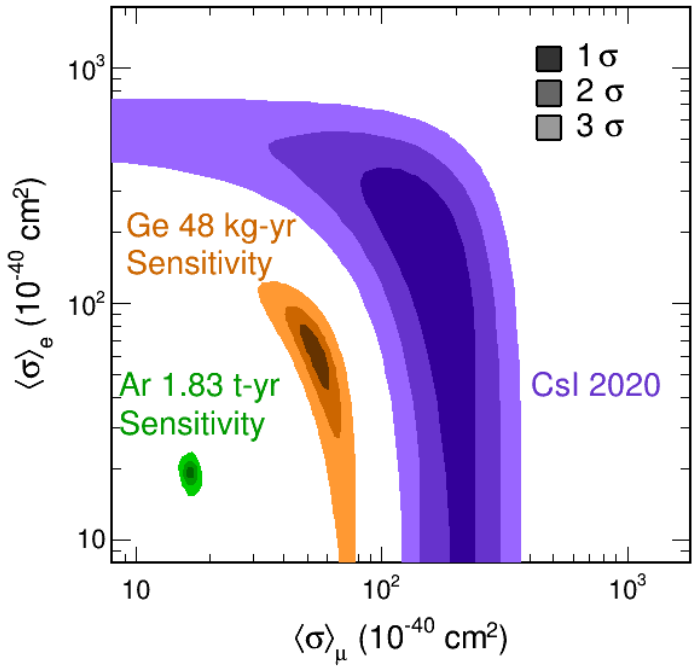


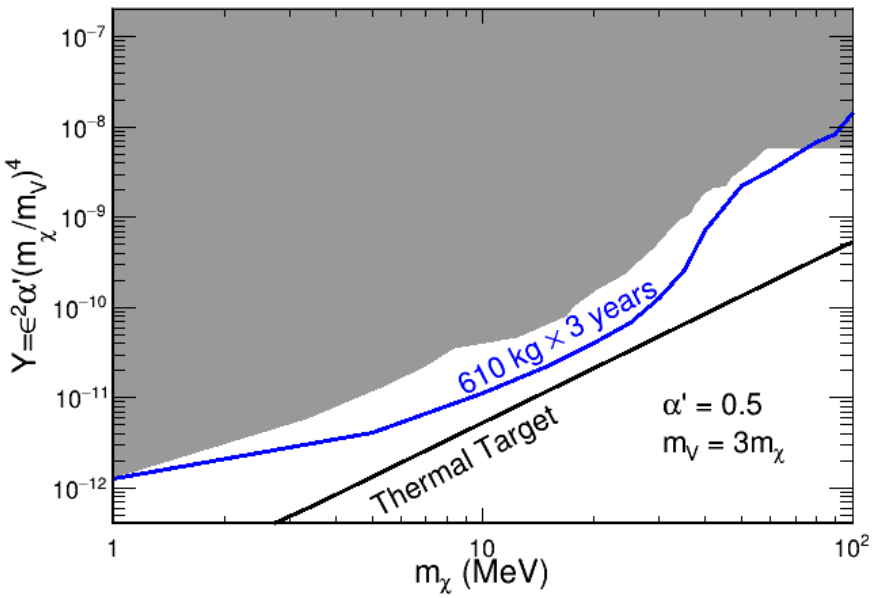
Sensitivity from D2O flux calibration



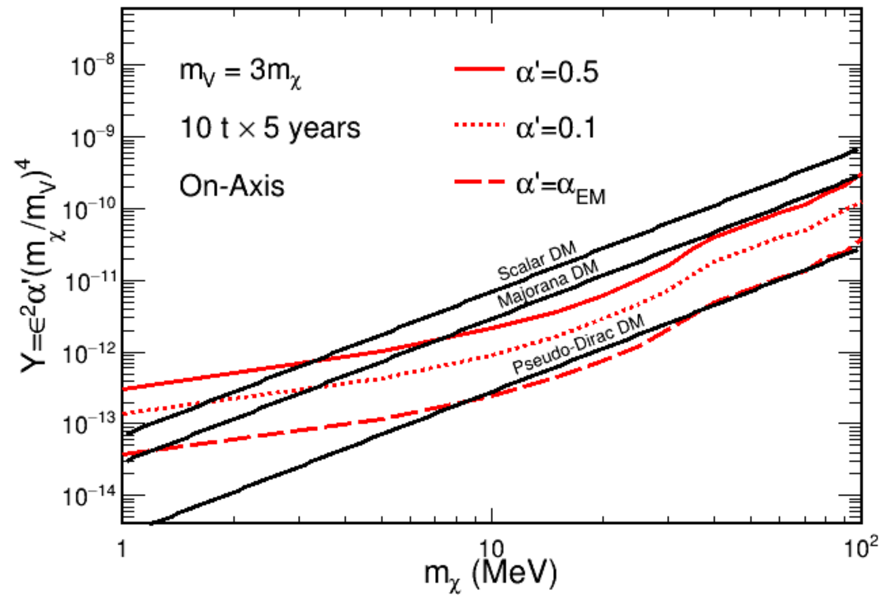
- Future COH-Ge-1 and COH-Ar-750 detectors will have significantly improved sensitivity to measuring flavored cross sections vital for aggressively probing NSI parameter space
- Both measurements limited by systematic error on neutrino flux – a D2O detector at the SNS would further increase power of future COHERENT detectors

Future Sensitivity to Dark Matter at the SNS

COH-Ar-750 Sensitivity



10-t Argon, on-axis at STS

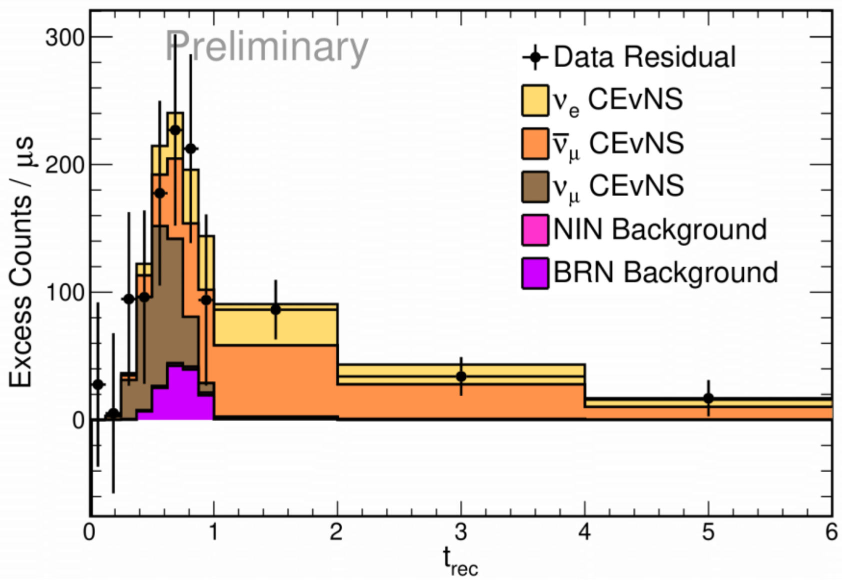


- Analysis techniques ensure that dark matter analysis will always remain statistically limited – scaling up detector size accompanied by similar gains in sensitivity PRD 102 052007 (2020)

- Our 14.6-kg CsI detector has already placed a leading bound for detecting sub-GeV dark matter which our large 610-kg Ar can improve further
- An on-axis detector at the SNS can rule out the thermal target line for scalar dark matter particles and test intriguing parameter space for Majorana or pseudo-Dirac dark matter

Summary

- New results from COHERENT are moving towards precision measurements of CEvNS exploiting multiple flavors and neutrino energies available in πDAR neutrino fluxes
- New analysis techniques allow for improved constraints on neutrino NSI and dark matter production at the SNS



- 2021 will be a productive year for COHERENT – commissioning detectors to measure CEvNS on Ge and Na and beginning construction on D2O detector – and plans to continue expanding in the following years capitalizing on ORNL investment in SNS beam upgrades

- Data-taking and commissioning of CEvNS detectors by other collaborations will soon expand our global understanding of CEvNS

Coherent Captain Mills @


COHERENT
SNS

The COHERENT Collaboration

COHERENT collaboration

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Collaboration Early Career Members

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Max Hughes
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Lara Blokland, UTK
Abasi Brown, NCCU

Former Postdocs


John Sparger
ORNL


Ivan Tolstukhin
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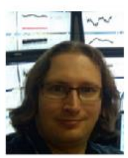
Mayra Cervantes
Duke


Josh Albert
IU


Dan Salvat
UW

Ph.D. Theses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U of Chicago
Tanaka Award 2020


Grayson Rich
TUNL-UNC
APS-DNP Award 2018


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Indiana University


Alex Khromov
MEPhI


Gleb Sinev
Duke


Dmitry Rudik
MEPhI


Jacob Zettlemoyer
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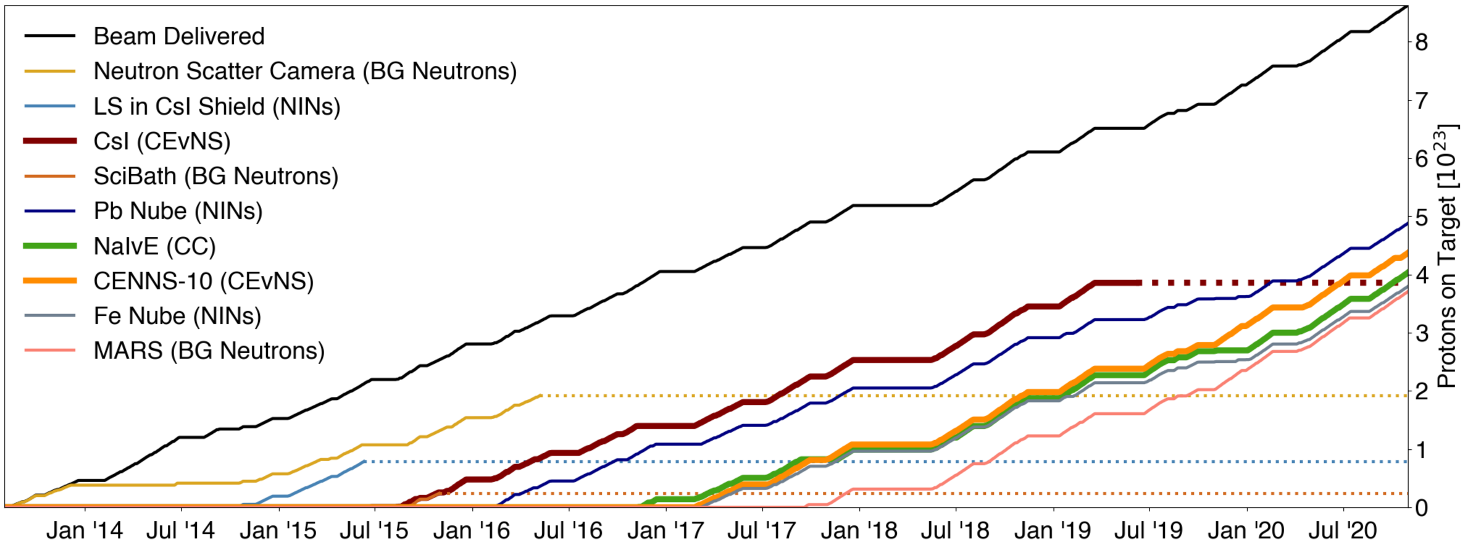
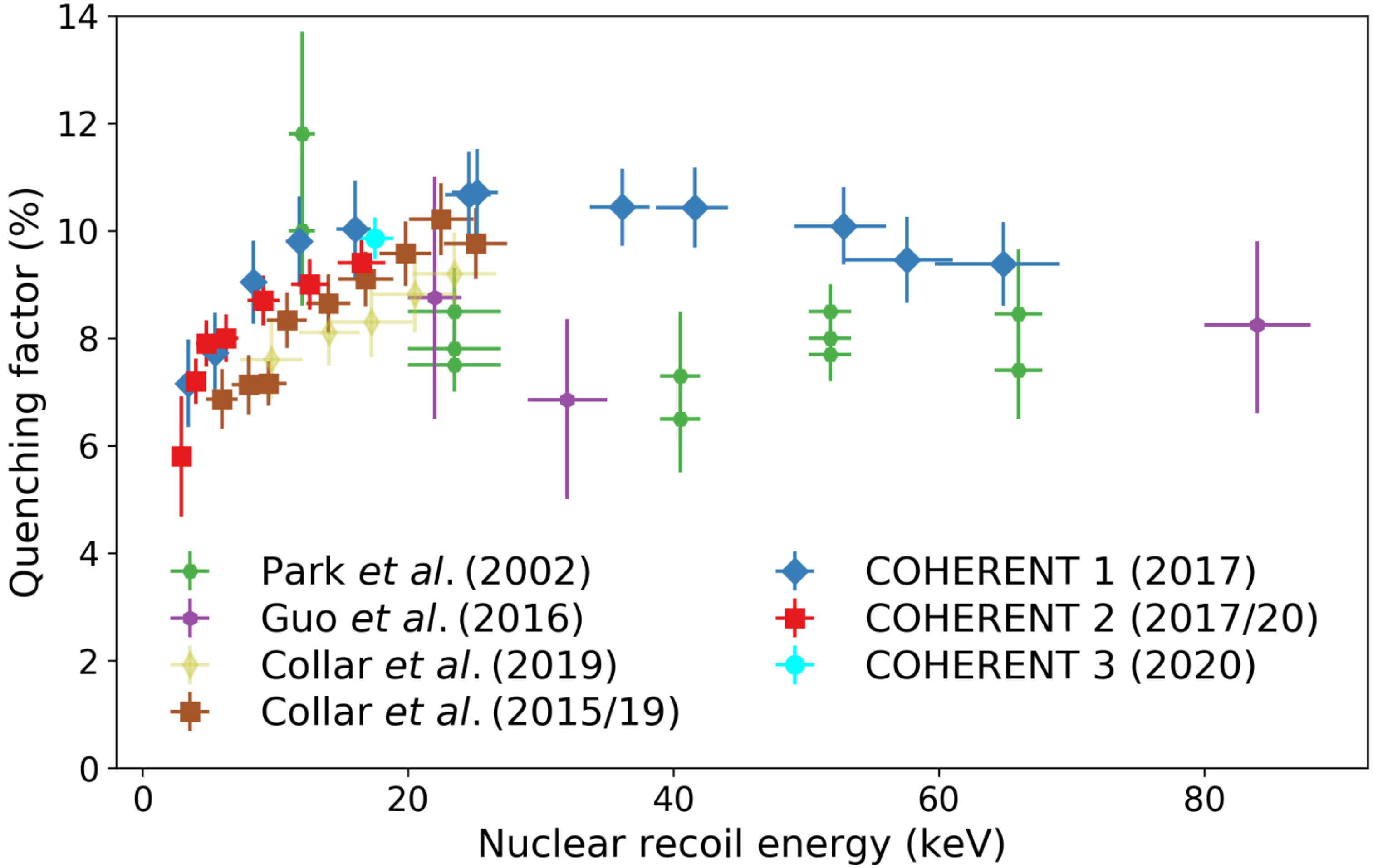
SNS Operations

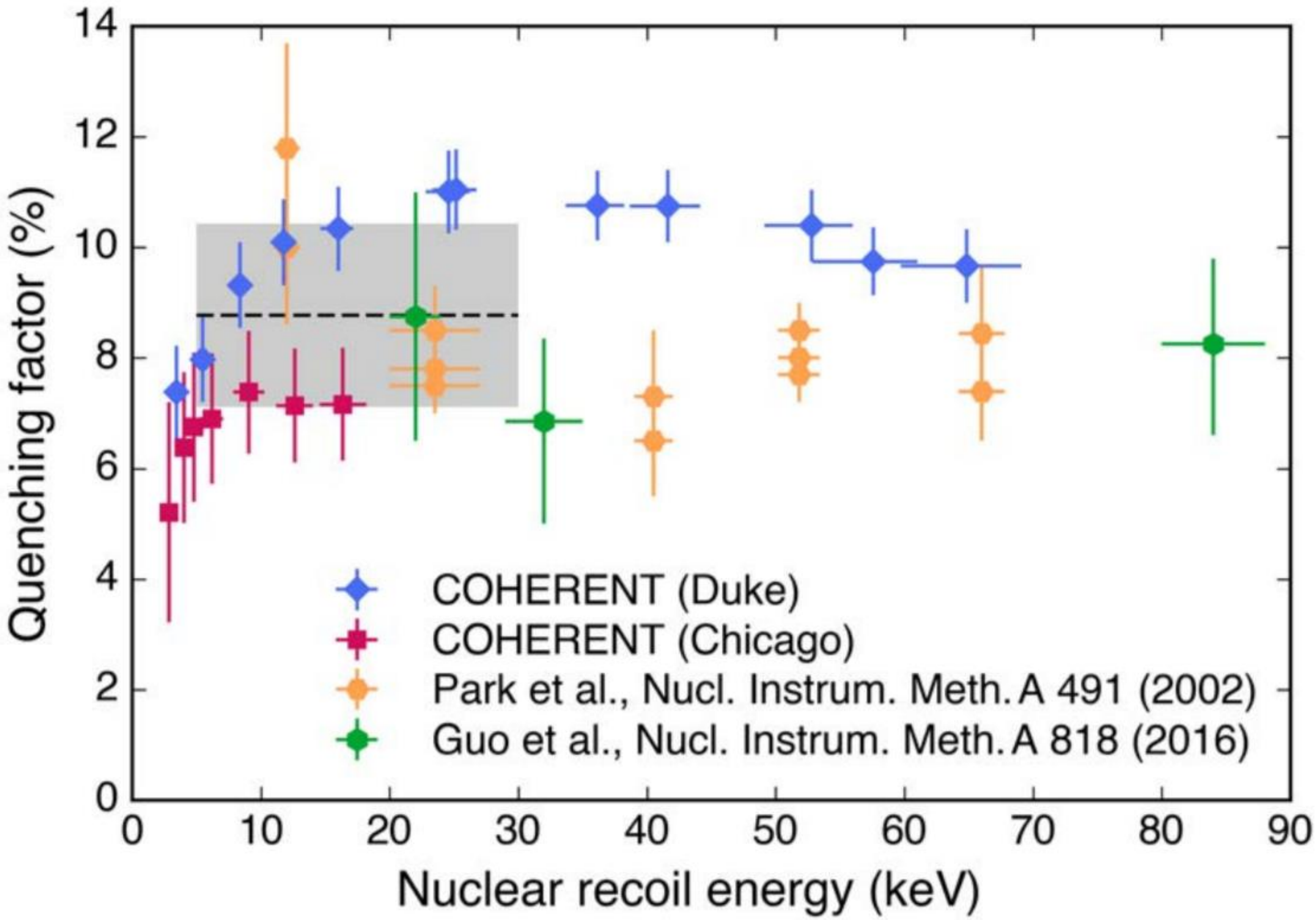


- SNS has delivered more than its projected protons-on-target with running up to 1.4 MW
- COHERENT continues to collect data in several subsystems within neutrino alley
- CsI detector decommissioned spring 2019, full CEvNS dataset has now been analyzed
  - More than double dataset of 2017 result (2.2x)

Global Quenching Factor Data for CsI[Na]

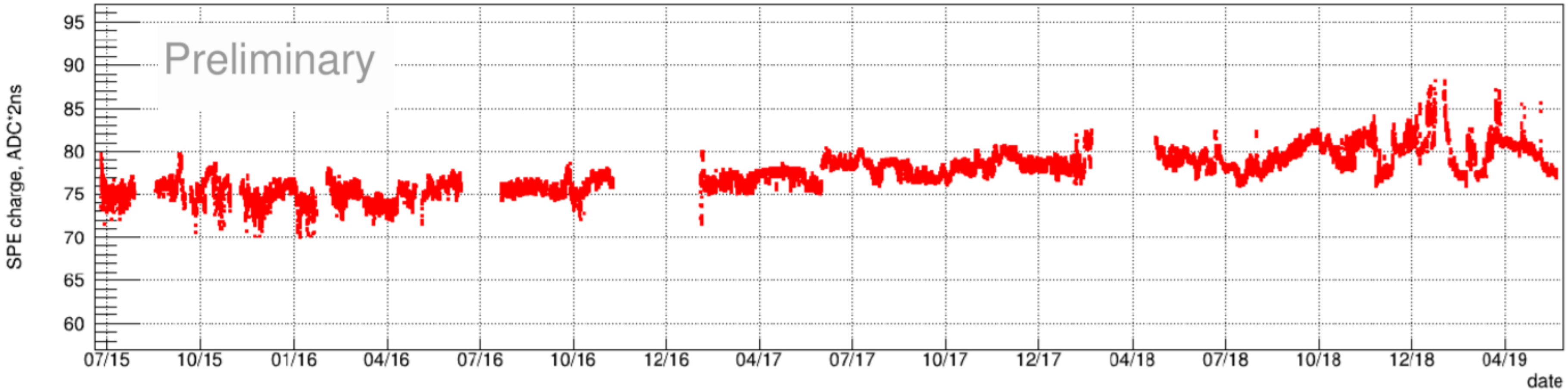


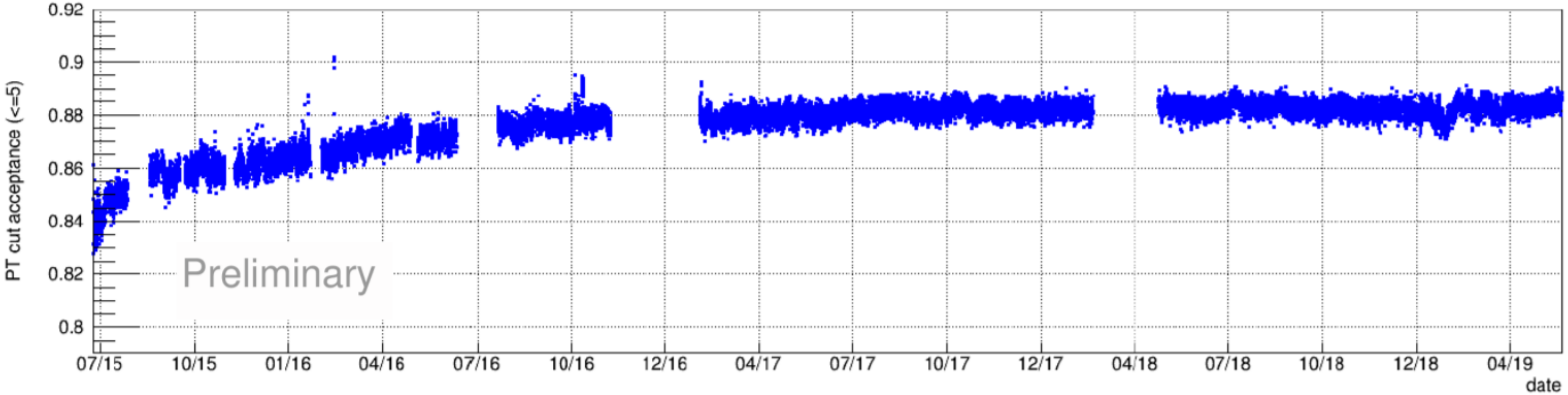
Quenching Factor Model Used in 2017 Result



- ❑ Constant QF model with large error to encompass energy dependence for all measurements

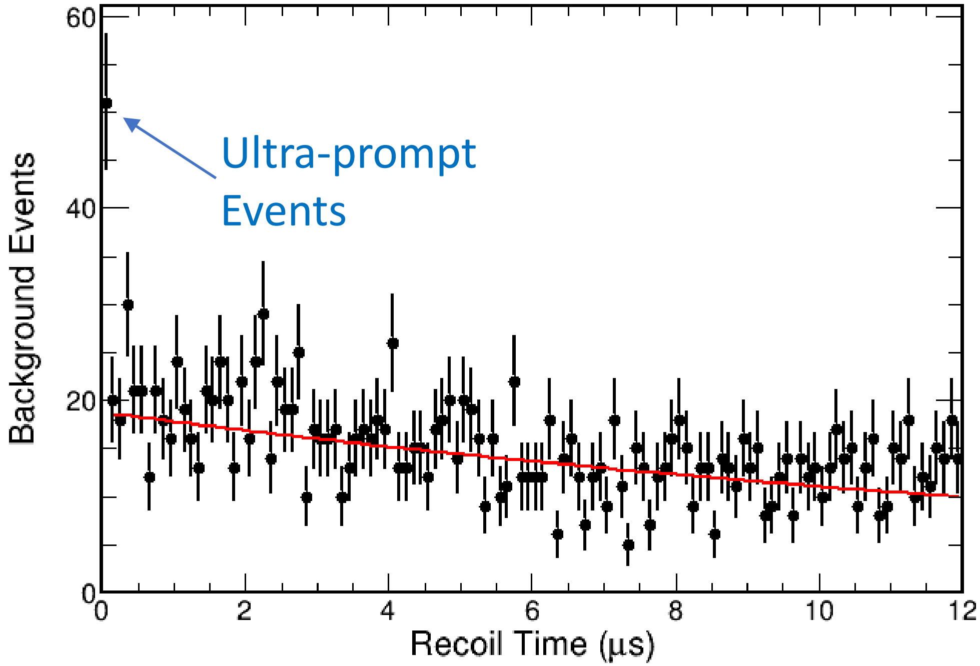
CsI Detector Stability





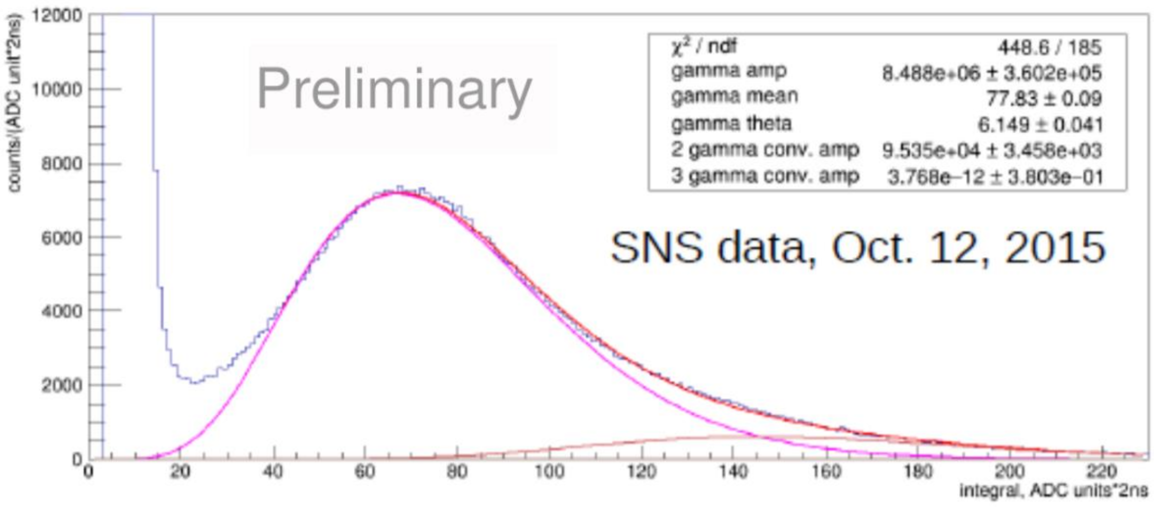
- ❑SPE charge drifts by ± 7% over detector operations which is accounted for within analysis
- ❑Acceptance is flat after one year, after initial increased afterglow rate has decayed

Removing Ultra-prompt Events



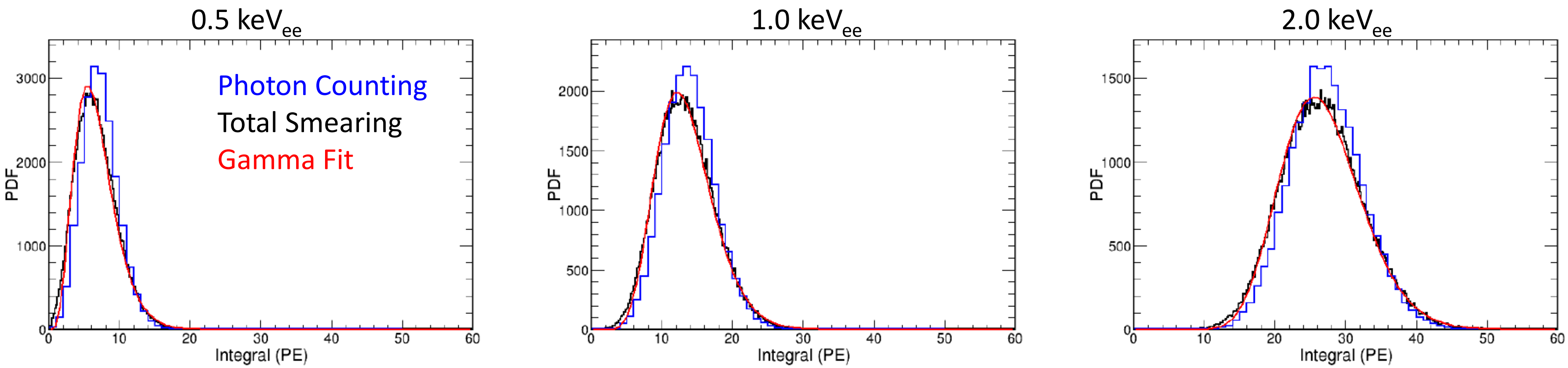
- ❑ Background events that begin in the tail-end of the AC region can sneak into the analysis C region and reconstruct within the first 0.1 μs of the ROI
- ❑ This background can be reduced from ≈40 events to ≈1 event by requiring no PE observed in the last 0.2 μs of the pretrace
  - Cut trained using waveform simulation and validated with effect on beam-off data

Single PE Shape



- We measure the single PE charge distribution during SNS conditions by integrating afterglow pulses
- High rate gives lets us monitor drifts in SPE charge on short timescales
- Width of the distribution is large, so we include smearing of single PE pulses in our energy smearing

Detector Smearing in CsI[Na]



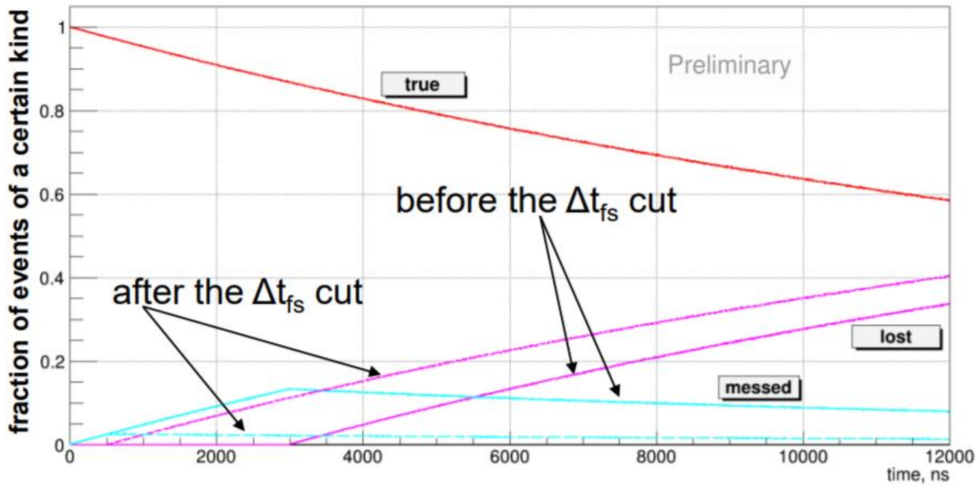
- We account for photon counting and the shape of the single PE charge distribution when determining energy smearing
- Our simulated smearing is non-Gaussian, fits well to a Gamma distribution

$$P(x) = \frac{(a(1+b))^{1+b}}{\Gamma(1+b)} x^b e^{-a(1+b)x} \qquad a = \frac{1}{x} \qquad b = 0.7157 \times x$$

x is LY × E$_{ee}$

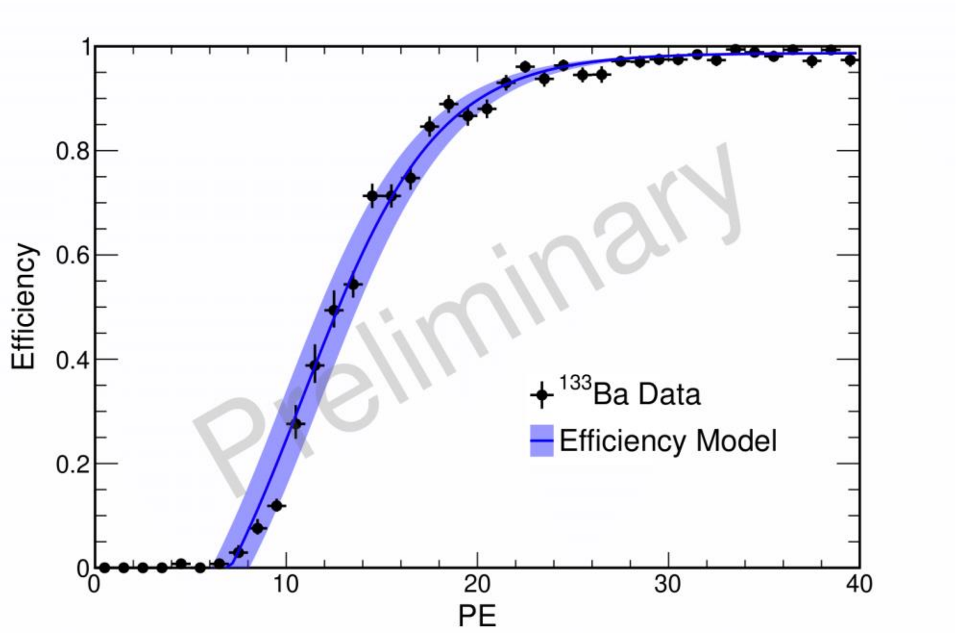
- Model shows degree of event smearing from absolute calibration of the SP charge has negligible effect on our result

Calculating Time Dependence of CEvNS Efficiency



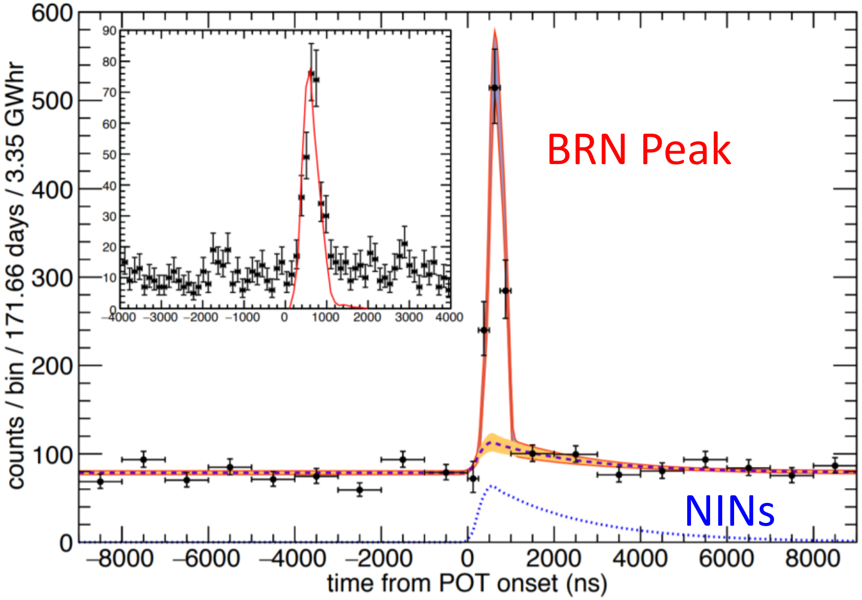
- ❑ We estimate the t-dependence of our efficiency using a data-driven simulation
  - Overlay a simulated CEvNS recoil on a beam out-of-time data waveform
  - Library of data waveforms give unbiased sampling of afterglow pulse distribution
- ❑ Properly reconstructed events fit very well to an exponential distribution
- ❑ We can reduce the fraction of misidentified onset events by a factor of 5 by the Δt_{fs} cut

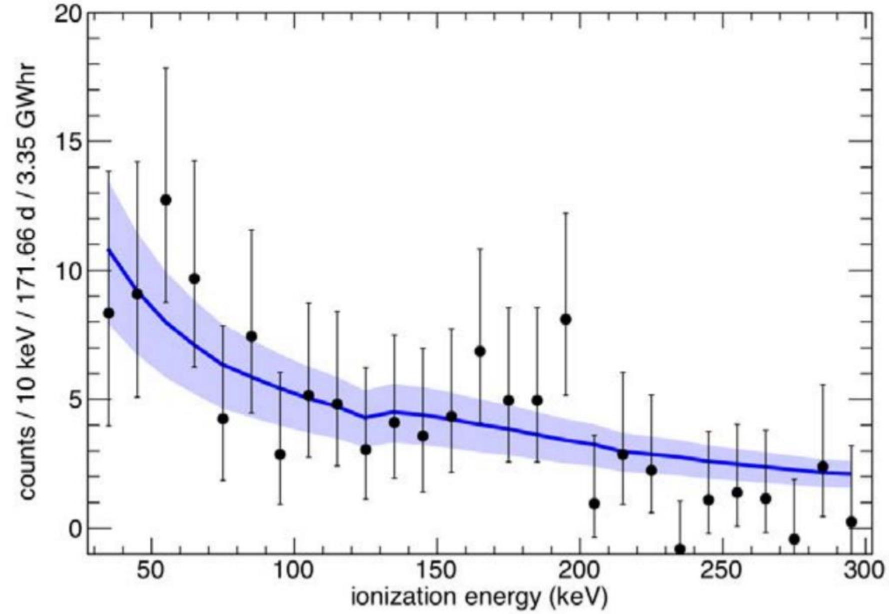
Efficiency Uncertainty



- Use same PCA strategy to determine an error band for our efficiency
- PE part of efficiency calibrated with ^{133}Ba data
- Almost all variance in the covariance matrix is explained by just the first eigenvector
  - Physically, this vector roughly equates to a change in the threshold by $\approx$1 PE

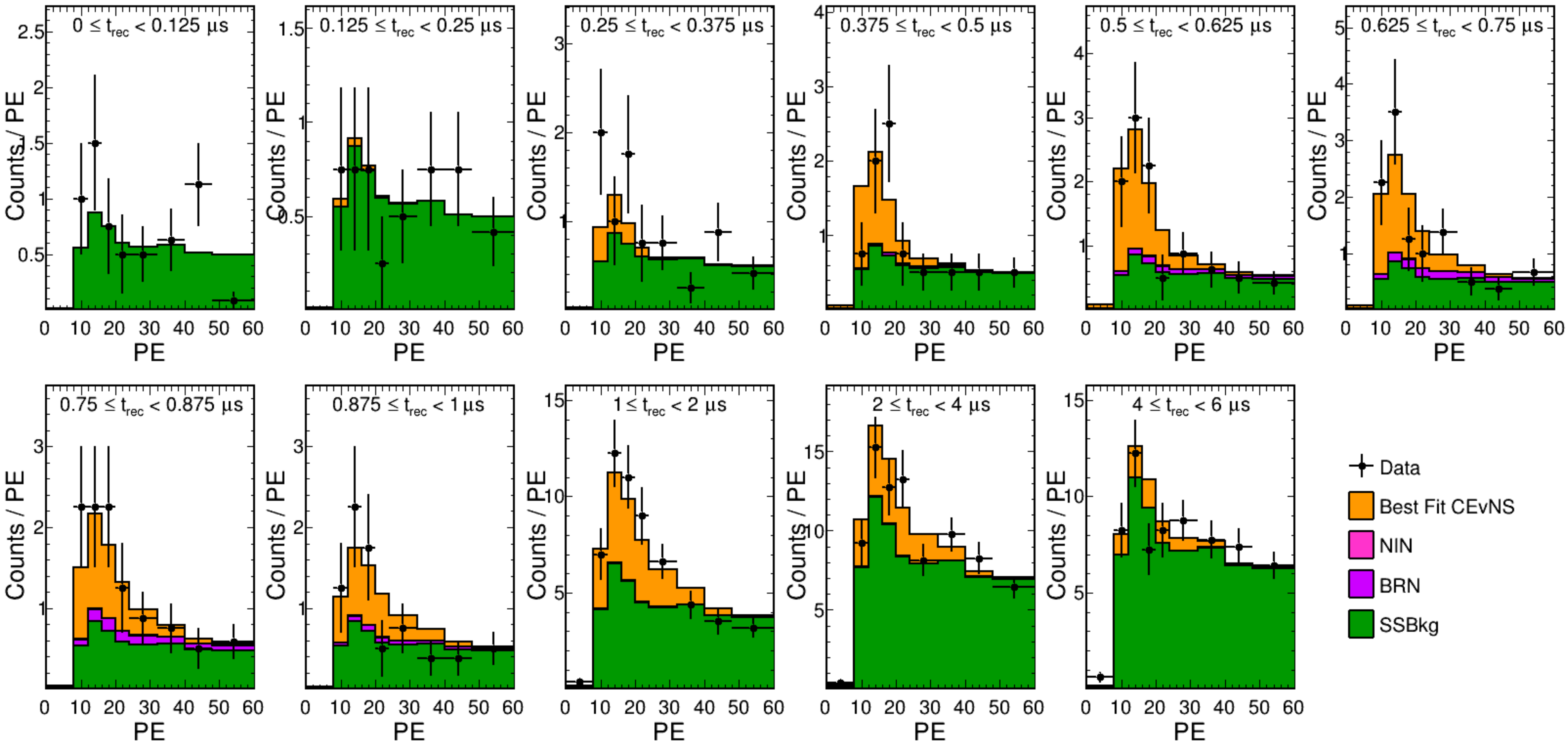
Neutron Backgrounds in CsI[Na]



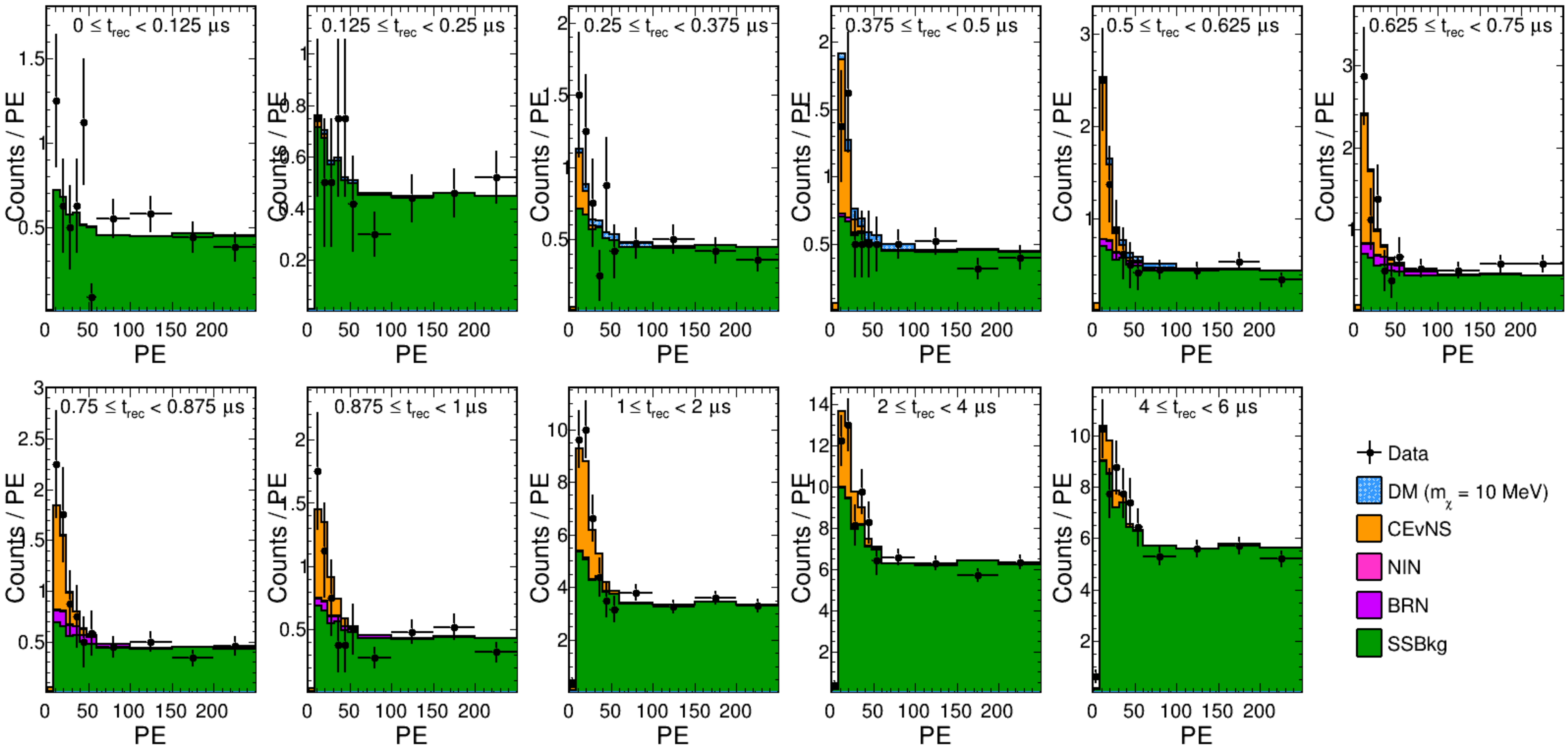


- ❑ Ran Eljen cell scintillator in CsI shielding to study neutron backgrounds in detector location
- ❑ Fit to timing data gives the relative ratio of BRN and NIN events with uncertainties
- ❑ MCNP simulation predicts the observed recoil distribution very well in the Eljen cells
- ❑ Ran observed neutrino flux through CsI simulation to determine analysis backgrounds
  - Together, only 7% of signal

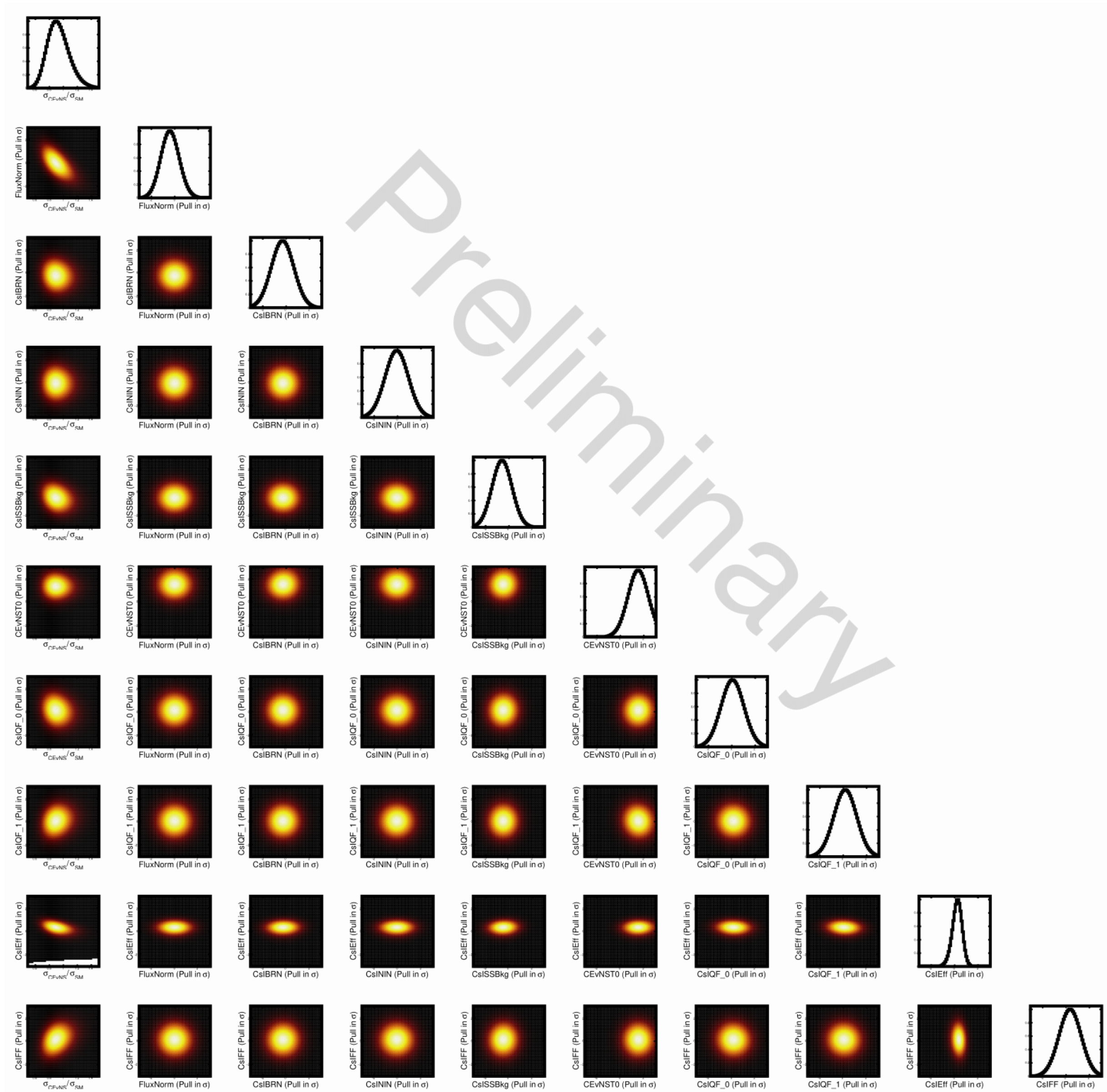
2D Spectra for CEvNS Measurement



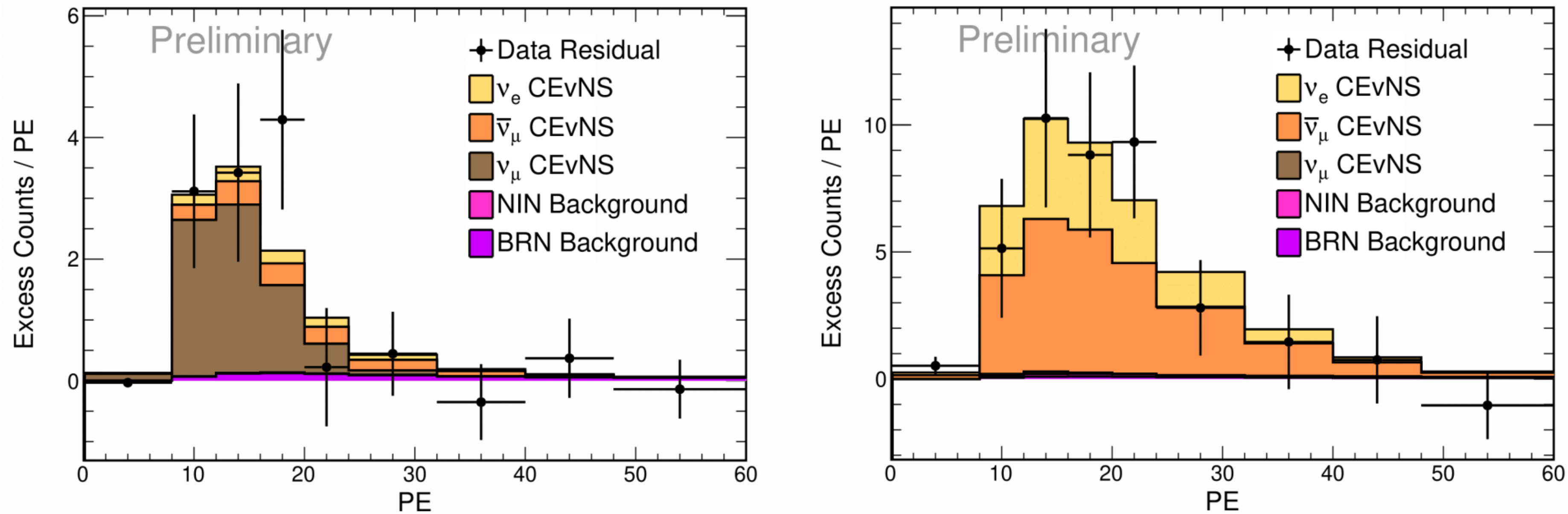
2D Spectra for Dark Matter Search



Fit Parameter Correlations



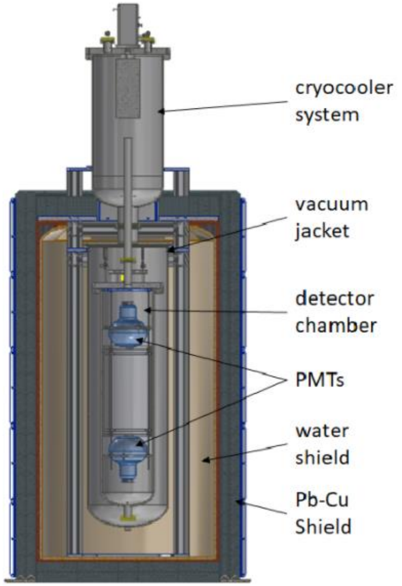
Counting Experiment-style Samples



- We can isolate CEvNS from different neutrino flavors by selecting different time regions
  - ν_μ: $0.125 < t_{rec} < 0.5$ μs
  - $\nu_e/\bar{\nu}_\mu$ $0.875 < t_{rec} < 4$ μs
- Apply global best fit to prediction for each sample
- Agreement of observed shape good test of our understanding of shape effects in our flux, quenching, and efficiency

Ongoing COHERENT Activity

- NUBEs studying NIN cross sections
- Supernovae neutrinos + CEvNS background
- Scintillator encased in Pb/Fe/Cu with water brick shielding



- CENNS-10
- CEvNS on LAr
- Dataset doubled since first result
- Continued physics data + R&D for future Ar program

- NaIvE: 185 kg NaI scintillator
- Measuring inelastics on ^{127}I for 0νββ searches
- Prototype future ton-scale CEvNS detector

- Neutron flux studies with portable MARS
- Scintillator covered with Gd paint to study captures