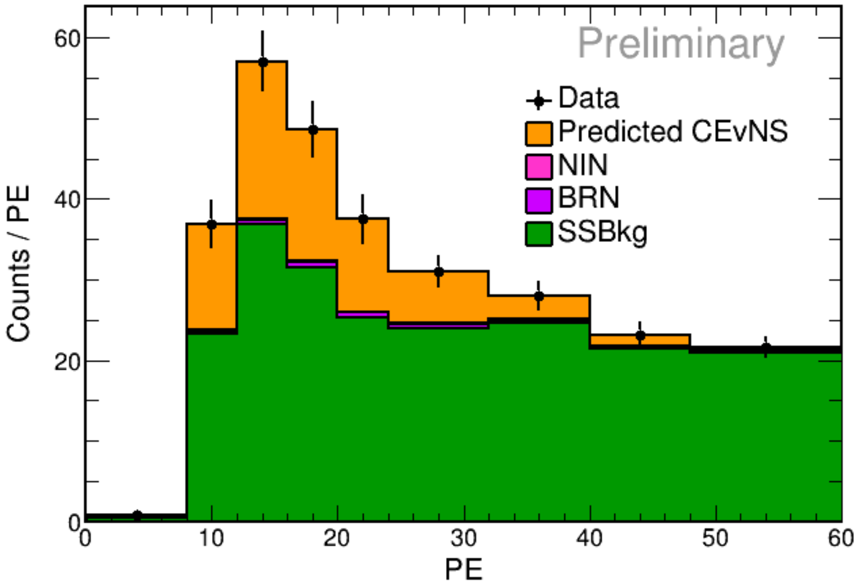
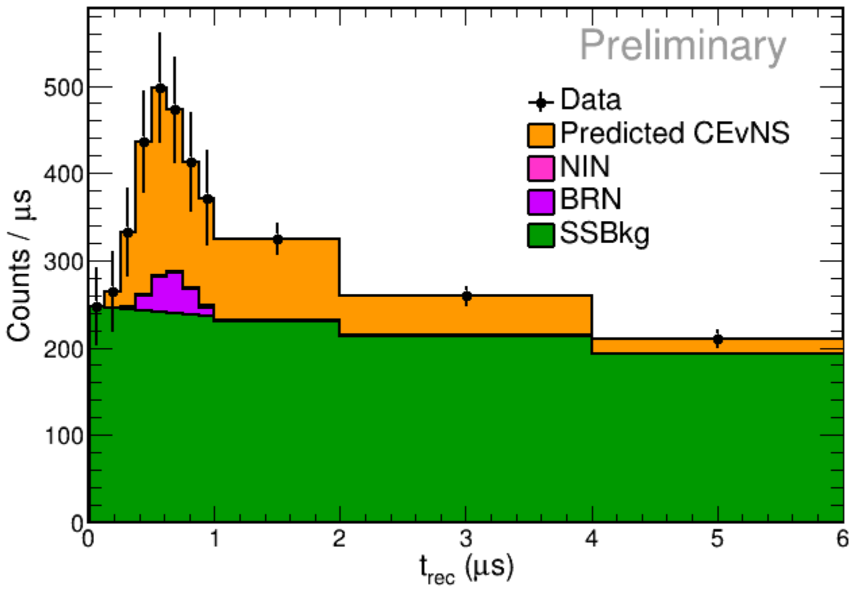
New Results from the COHERENT CsI[Na] Detector

Dan Pershey (Duke University)
for the COHERENT Collaboration

Magnificent CEvNS 2020, Nov 16, 2020

Expected CEvNS in CsI



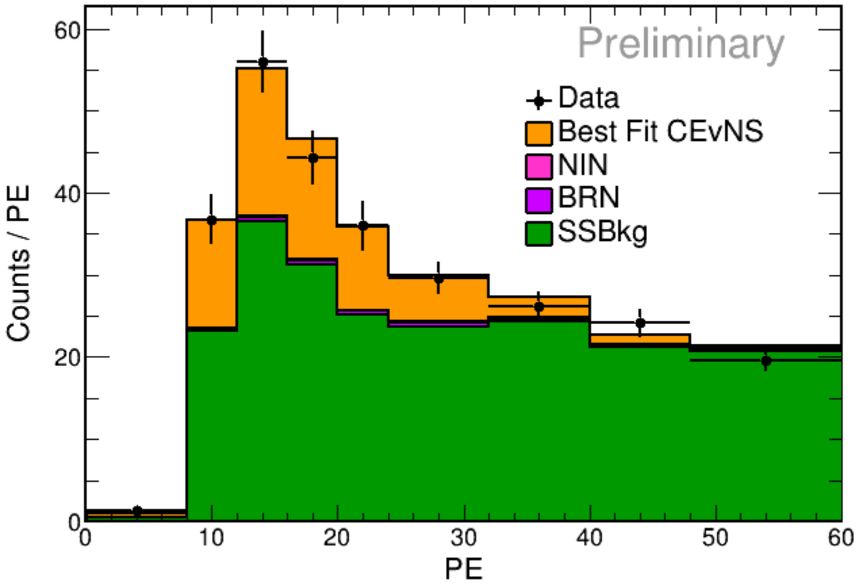


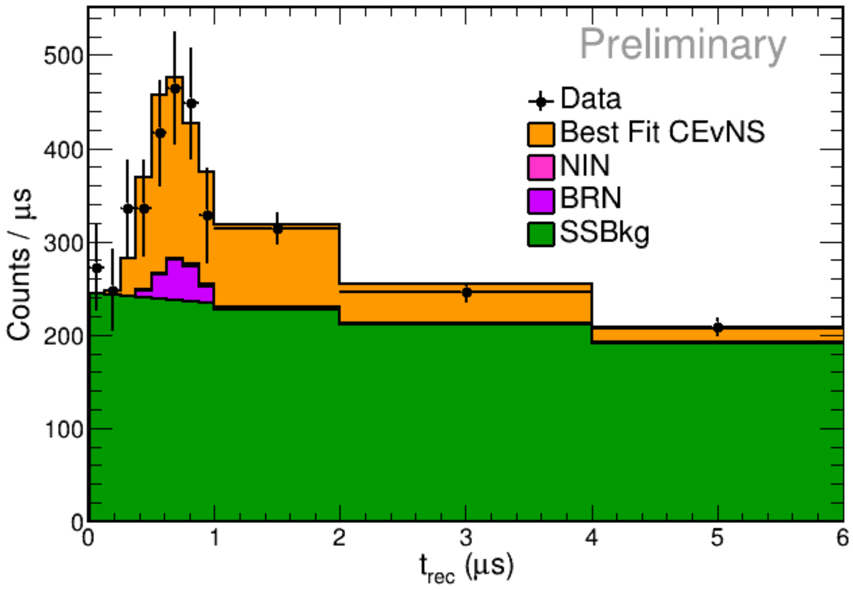
- ☐ Implemented many analysis improvements since first observation – see talk by A. Konovalov
  - Developed blind analysis to avoid biasing
- ☐ Perform 2D likelihood fit in PE and t_{rec}
- ☐ Beam-unrelated steady-state background measured in-situ with beam out-of-time data
- ☐ Beam-related neutron backgrounds small

Expected events

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

Observed CEvNS





Best fit results

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

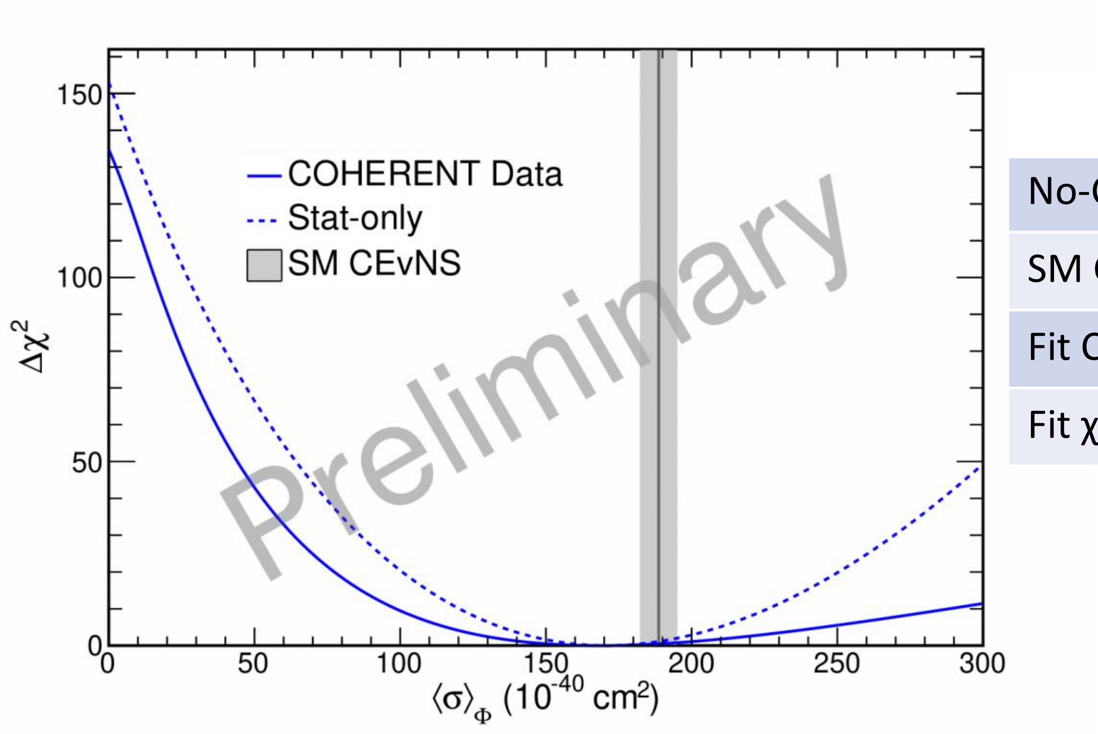
- ❑ Data in our CsI[Na] detector match our best-fit predicted spectra very well
- ❑ Best-fit CEvNS slightly low, but consistent with expected statistical error

Systematic Uncertainties

Uncertainty	Effect on CEvNS	Evaluation strategy
Neutrino Normalization	10%	Dominated by flux uncertainty
SSBkg Normalization	3.0%	Finite statistics for background estimate
BNR Normalization	0.9%	Fit error from neutron det. in CsI shielding
NIN Normalization	0.5%	Fit error from neutron det. in CsI shielding
Form Factor (R_n)	3.4%(theory) 0.6%(expt)	Theoretical uncertainty on nuclear structure
Quenching factor	3.6%	Fit to world QF data on CsI[Na] with our dopant concentration
CEvNS efficiency	4%	From ^{133}Ba calibration data – influences events near threshold

- All uncertainties appropriately account for shape effects
- Flux uncertainty larger than combined effect of all other systematics
- Form factor includes both a theoretical error and an experimental error
  - Changing R_n changes the cross section, and also our ability to measure it

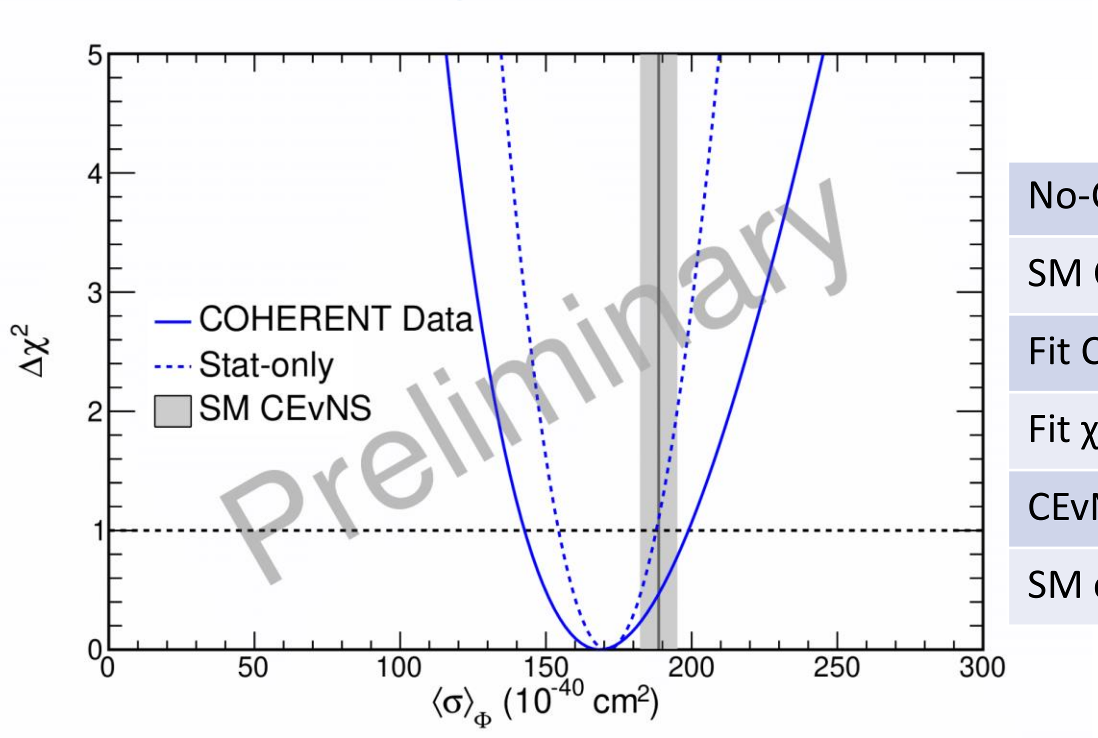
Measuring CEvNS Rate



No-CEvNS rejection	11.6 σ
SM CEvNS prediction	$333 \pm 11(\mathrm{th}) \pm 42(\mathrm{ex})$
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
  - No question it’s there, let’s focus on measuring the cross section

Determining the CEvNS Cross Section



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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 1σ

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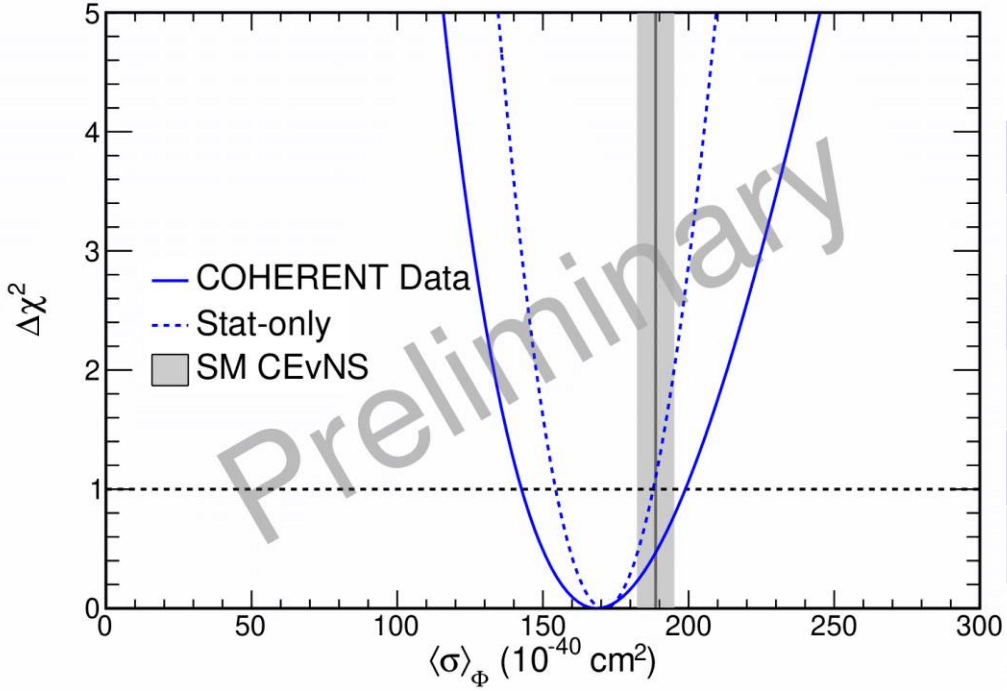

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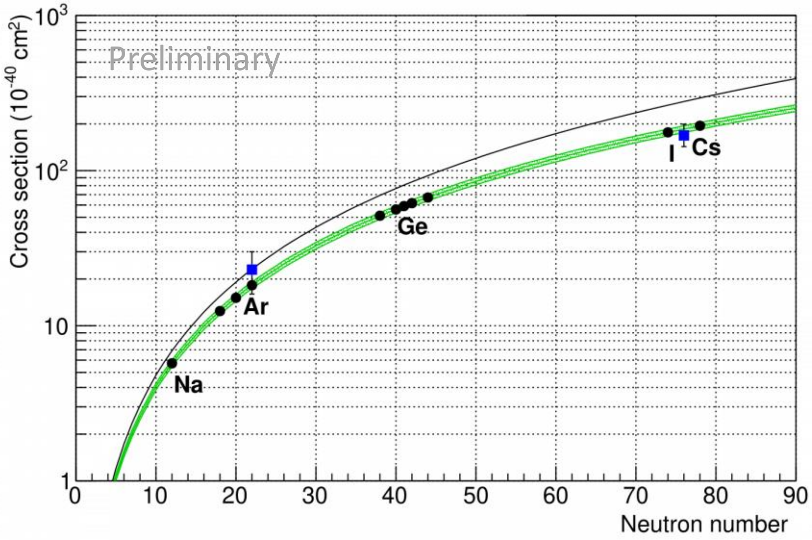
    - Result is consistent with the standard model prediction to 1σ
- ❑ Observed cross section consistent with N^2 dependence



Comparison with 2017 Result

- We've implemented several improvements to our analysis that affect how many CEvNS we reconstruct and our predicted event rate

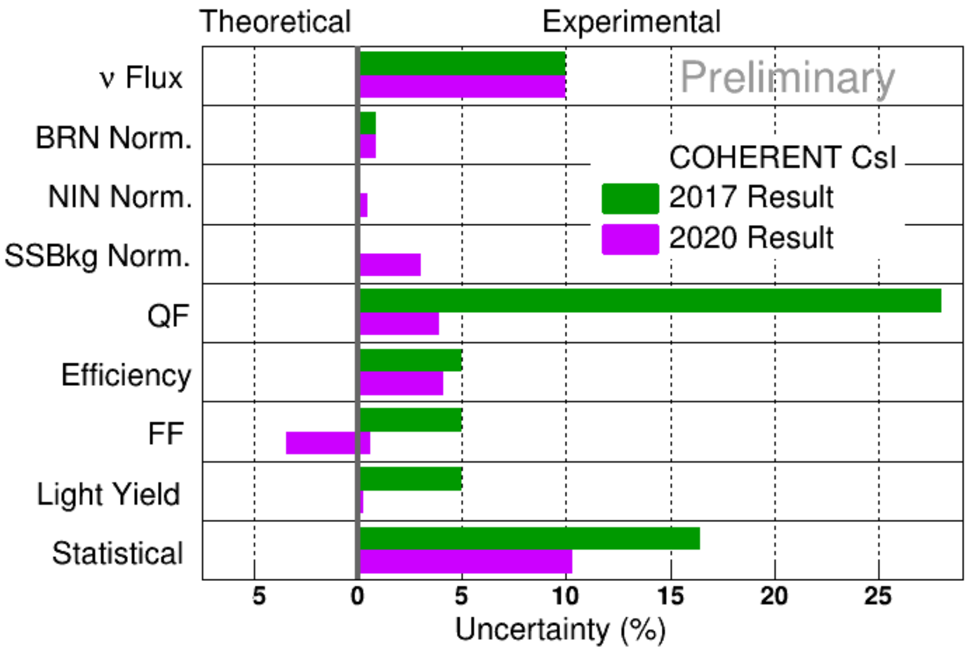
Risetime cuts mitigate this, but shape biases interpretation of data (NSI, etc)

Inferred from beam-on ac data stat error with this number

	Effect on N_{CEvNS} measured	Effect on Prediction
Time-dependence of efficiency		-2%
New QF model		-1%
New smearing model		-1%
Updates to CEvNS cross section model		-5%
Ultra-prompt events	-4%	
Beam-power determination	+7%	
Afterglow pileup events	-14%	
Total Effect	-11%	-9%

- In 2017, we saw 134 compared to an expectation of 173, but with new strategies, this ought to be closer to 119 observed vs 157 expected
  - Ratio 119/157 = 76% ± 16% (stat, correlated) ± 16% (stat, uncorrelated)
  - Consistent with new result (89% σ_{SM}) with the uncorrelated stat uncertainty

Improvements on Error Determination



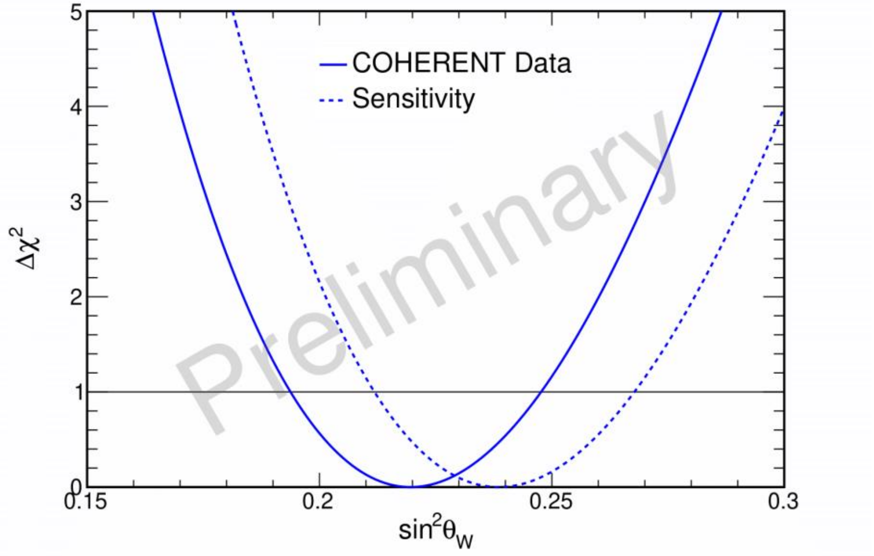
- ☐ Extensive to improve our understanding of quenching in CsI[Na] has dramatically reduced our overall systematic uncertainty: 28% → 13%
  - Driven by improved QF understanding – see talk by A. Konovalov
- ☐ Flux uncertainty now dominates the systematic uncertainty
- ☐ FF uncertainty has been factored into theoretical and experimental parts
  - Reducing Rn both increases σ_{SM} and our ability to measure $\sigma_{\mathrm{CE\nu NS}}$
- ☐ Reduced stat error from increased sample size

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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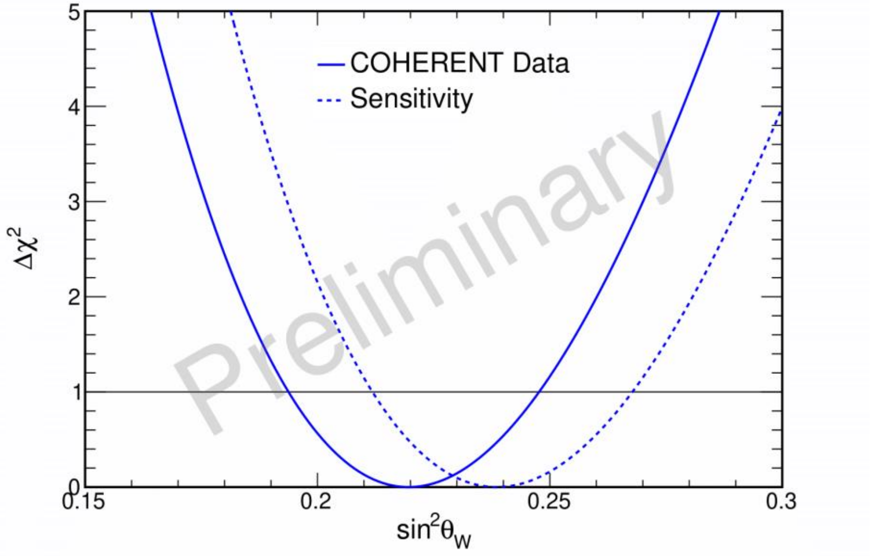
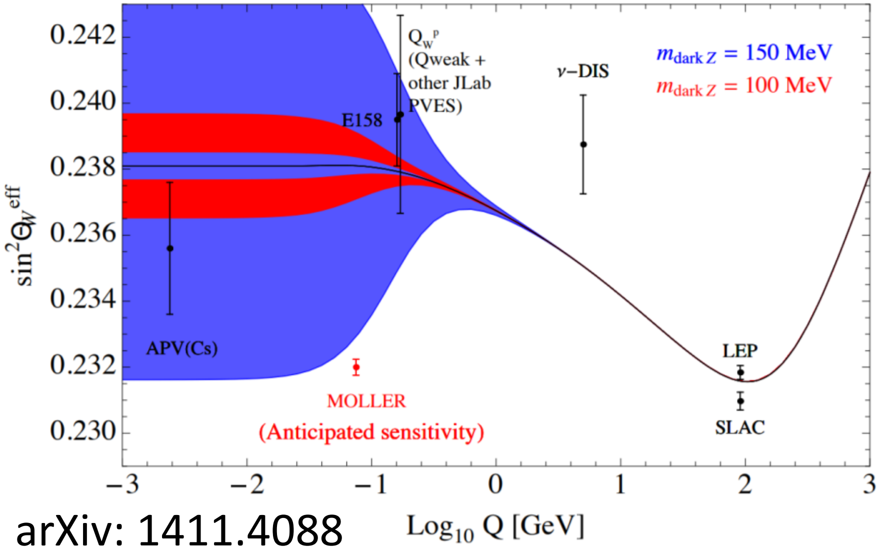




arXiv: 1411.4088

- ❑ 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

Probing Non-Standard Interactions with CEvNS

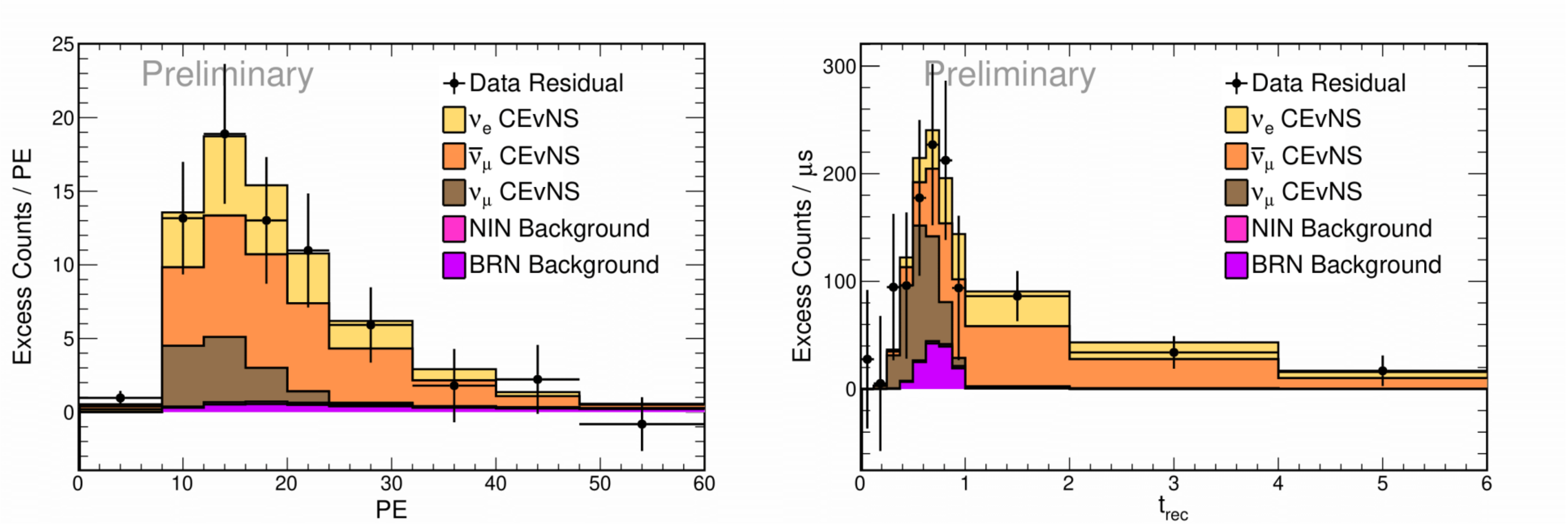
- Hypothesized interactions between neutrinos and quarks may be a consequence of some heavy, undiscovered vector mediator
- We can parameterize interactions by coupling constants: $\varepsilon^{N}_{\alpha\beta}$ $(\alpha, \beta \in e, \mu, \tau)$
- NSI scenarios would scale the physical cross section by adjusting the weak charge

$$Q^2_{w\alpha} \propto \sum_i \left\{ \left[Z_i (g_p^V + \varepsilon^p_{\alpha\alpha}) + N_i (g_n^V + \varepsilon^n_{\alpha\alpha}) \right]^2 + \sum_{\beta \neq \alpha} \left[Z_i \varepsilon^p_{\alpha\beta} + N_i \varepsilon^n_{\alpha\beta} \right]^2 \right\}$$

E.g. arXiv: 1907.00991

- Possible to choose NSI couplings so that $Q^2_{We} \neq Q^2_{W\mu} \neq Q^2_{W\tau}$
- The SNS flux has contributions from $\nu_\mu / \nu_e / \bar{\nu}_\mu$ so we are in principle sensitive to constraints on $Q^2_{W\mu}$ and Q^2_{We}
  - These can be treated as free parameters in NSI fits

CEvNS Spectra by Flux Component

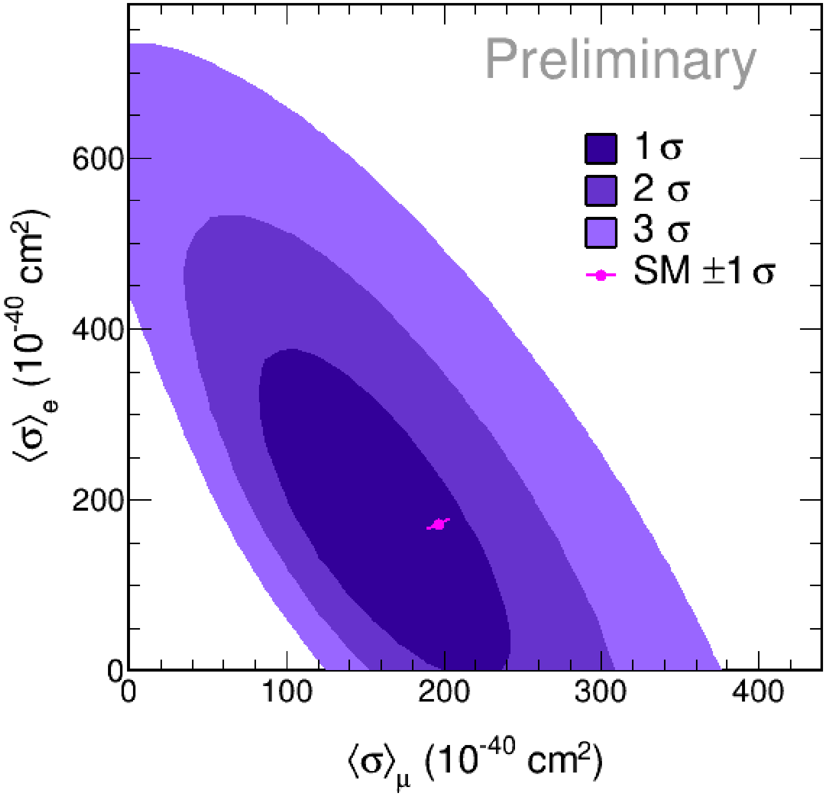


- ❑ At the SNS, CEvNS from ν_μ occur earlier than CEvNS from $\nu_e/\bar{\nu}_\mu$
- ❑ This is a lever arm for constraining $Q^2_{W\mu}$ and Q^2_{We} separately
  - Advantage of spallation sources with beam width < muon lifetime

- ❑ We measure the flavored CEvNS cross sections, $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$, to study CEvNS constraints of NSI
  - Small differences in SM $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$ cross sections taken into account

Flavored CEvNS Cross Section

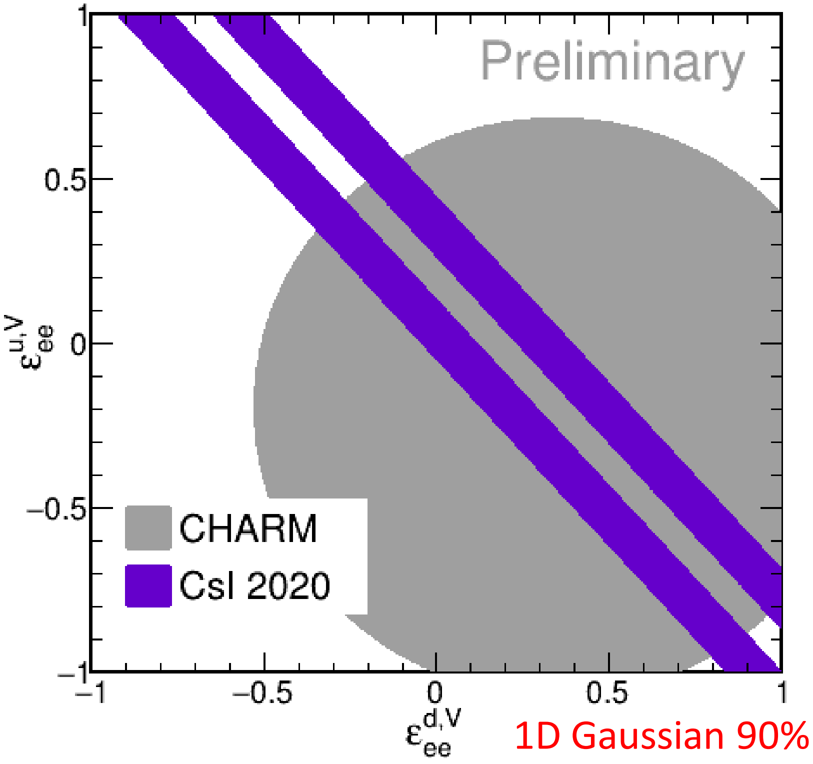
- ❑ Allow for completely different $\langle\sigma\rangle_\mu$ and $\langle\sigma\rangle_e$ as would be allowed in NSI scenarios
- ❑ ν_μ timing sheds light on the fraction of observed CEvNS that are from each flavor
- ❑ As in 1D CEvNS fit, the SM prediction is included within the 1 σ contour



COHERENT NSI Constraints

- ☐ Updated CsI data improves upon previous constraints

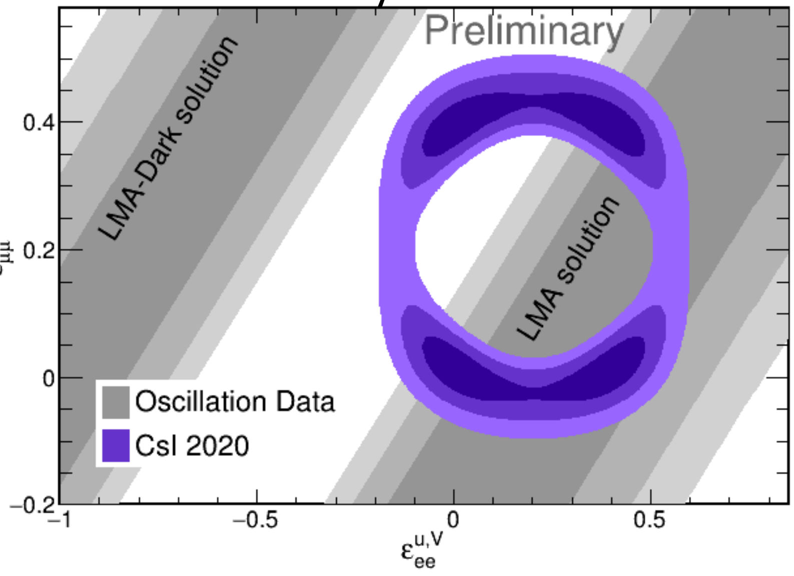
- ☐ Updated from 2017 result to include full spectral fit
- ☐ $\langle\sigma\rangle_\mu$ held fixed at SM prediction while $\langle\sigma\rangle_e$ floats freely



1D Gaussian 90% critical up-values

Interpreting Solar Neutrino Oscillation Data

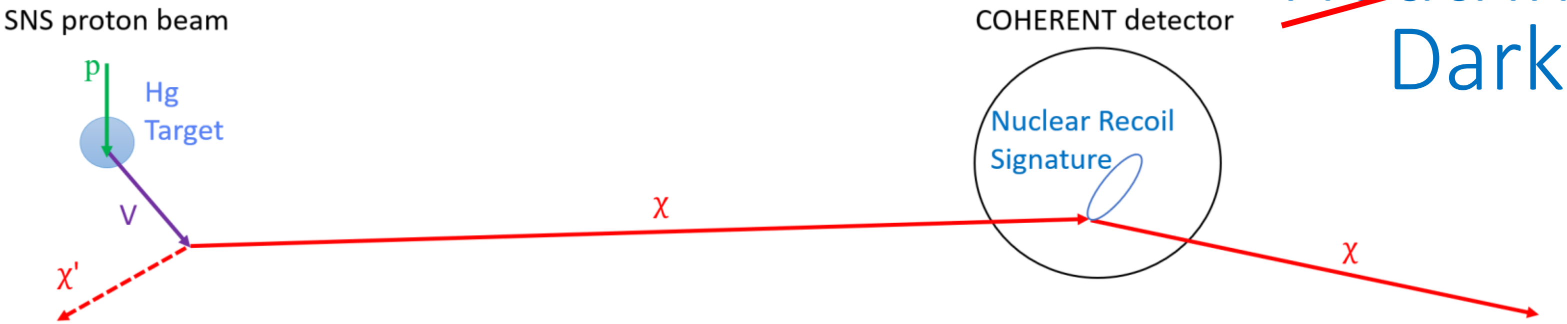
See Phys Rev D96 11 115007



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

Dark Matter at the Spallation ~~Neutron~~ Source
~~Neutrino~~
Dark Matter



- 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.,
Phys Rev **D92** 095005 (2015)
Dutta et al.,
PRL 124 121802

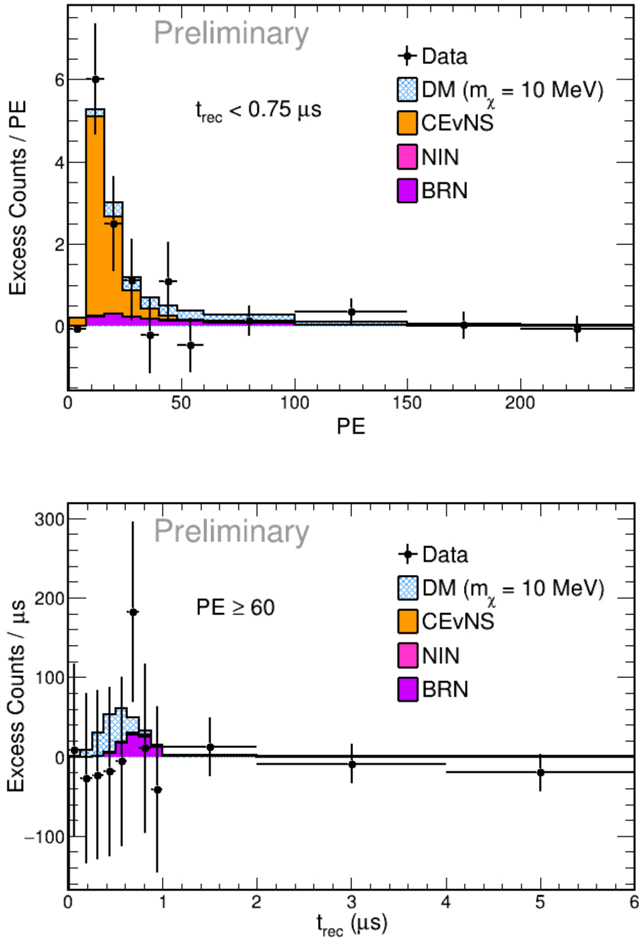
- Such a particle makes an attractive dark matter candidate consistent with thermal freeze-out for masses below the Lee-Weinberg bound
- DM scatters would be an additional component of our sample → can constrain with current CsI dataset
- Dark matter particles would produce nuclear recoil signatures similar to CEvNS, though at higher typical recoil and timed coincident with the beam

CsI Search for Dark Matter Particles at the SNS

DM signal region

Early times

High recoil energy



- Extend fit region to capture DM signal region: $60 < PE < 250 + t_{rec} < 0.75\ \mu s$

CsI Search for Dark Matter Particles at the SNS

DM signal region

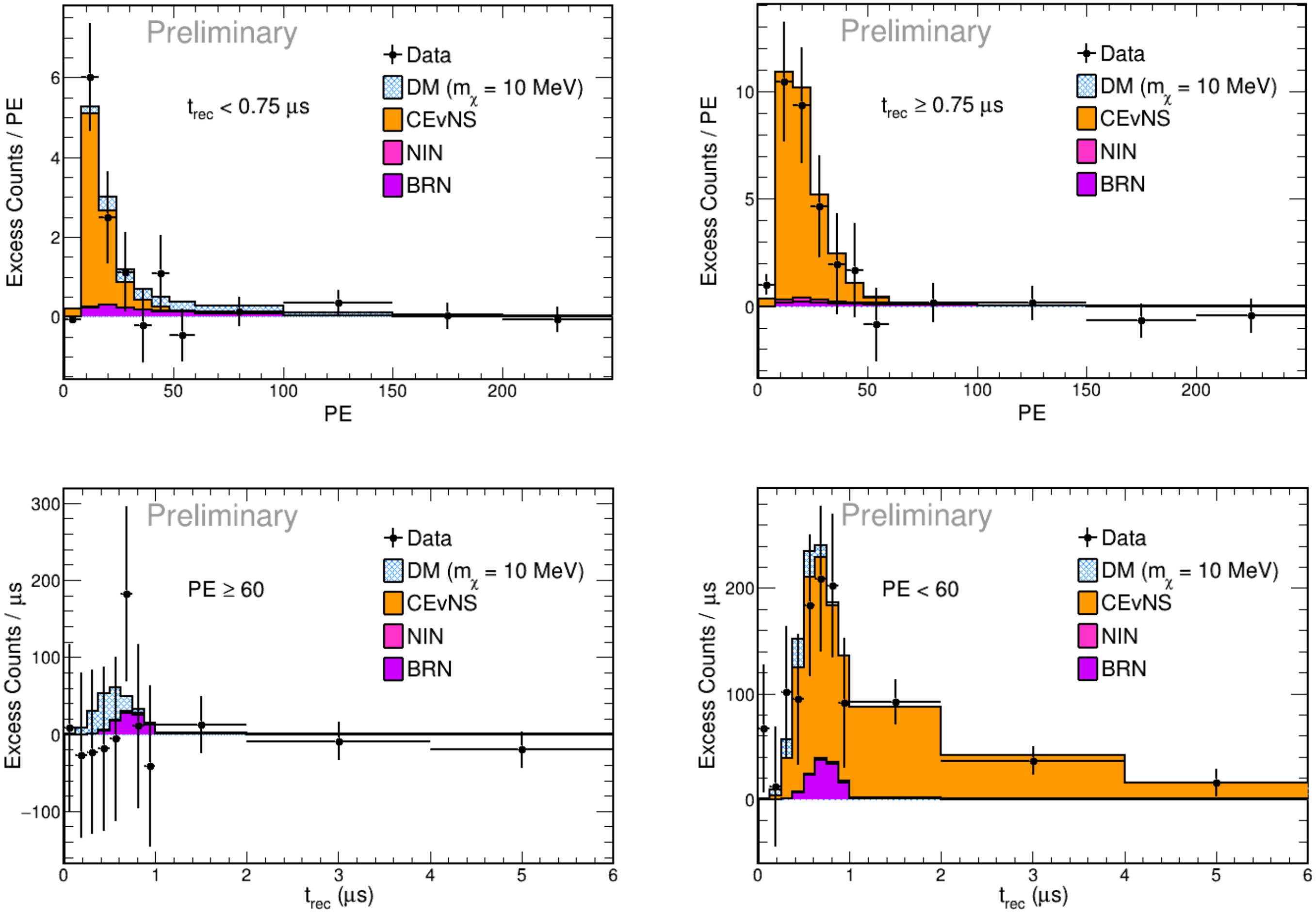
Early times

High recoil energy

Late times

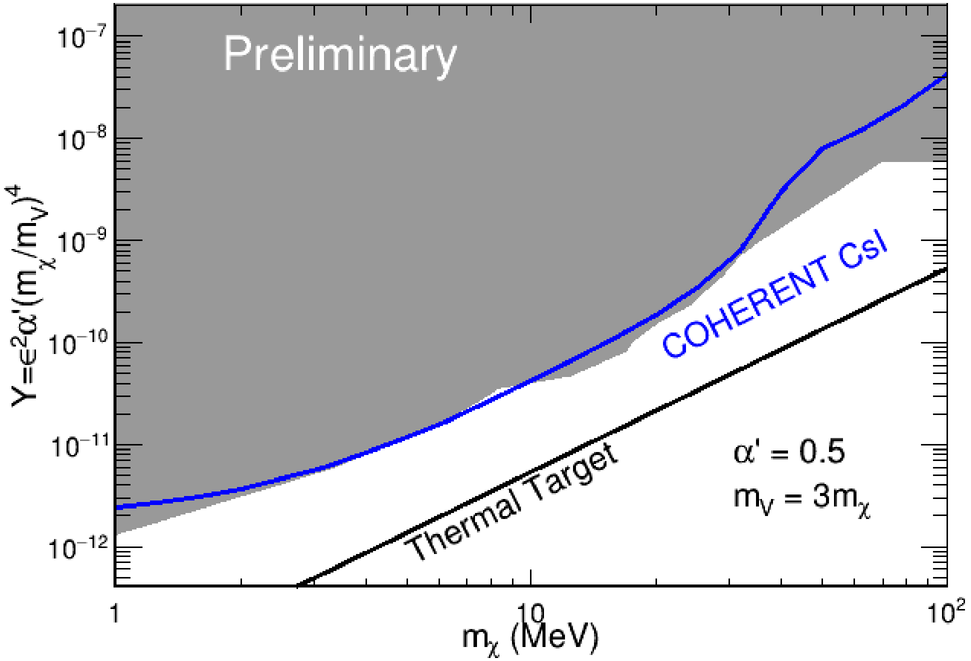
Low recoil energy

DM background region



- ☐ Extend fit region to capture DM signal region: $60 < PE < 250 + t_{rec} < 0.75$ µs
  - DM background region used to constrain systematic uncertainty
- ☐ With 2D fit, we find 0 best fit DM events, <22 DM events at 90% confidence

DM Constraint with CsI Data

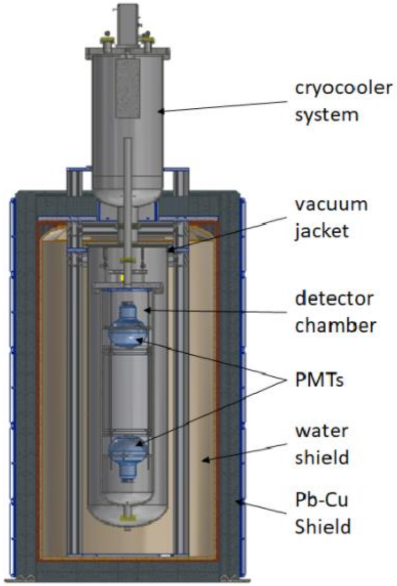


- ❑ At 90% confidence, observed data rejects parameter space competitive with other major constraints: NA64 / MiniBooNE / LSND / BaBar
  - Strongest constraint yet for $m_\chi \approx 9$ MeV

- ❑ A small, 14.6 kg detector places successfully demonstrates the power of CEvNS detectors for direct detection sub-GeV WIMP detection
- ❑ Bright future ahead with large detectors (see J. Daughhetee talk)

Ongoing COHERENT Activity

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



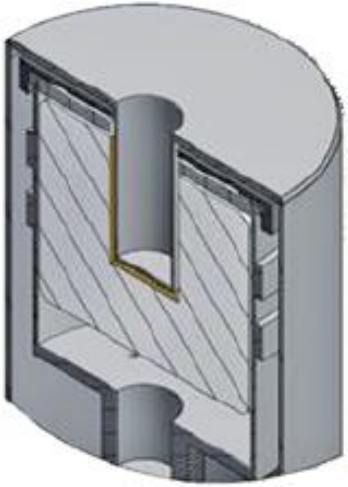
- CEvNS on LAr
- Dataset doubled since first result
- Continued physics data + R&D for future Ar program

- 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

2021: Commissioning Two CEvNS Detectors

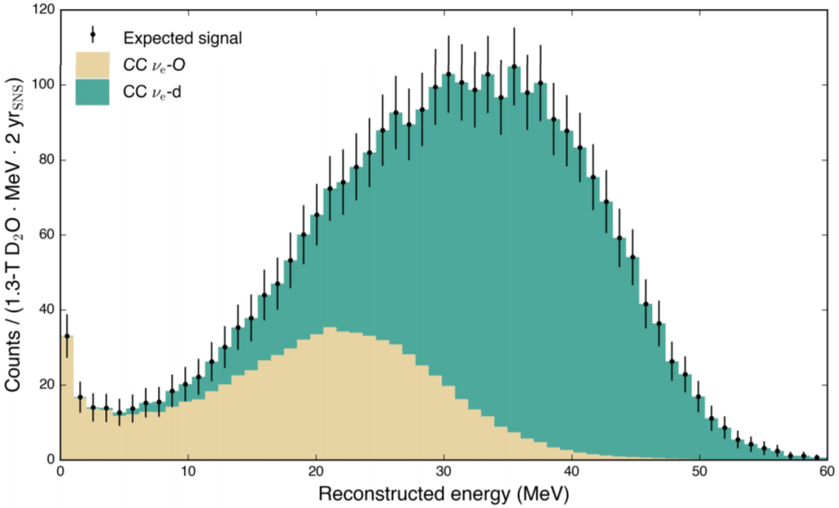
- ❑ 16 kg of low threshold Ge PPC detectors
- ❑ Will collect 500+ CEvNS/yr at $E_{rec} > 0.3$ keV$_{ee}$ with good energy resolution
- ❑ 2/8 detectors delivered, finalizing shielding design, commissioning expected early 2021



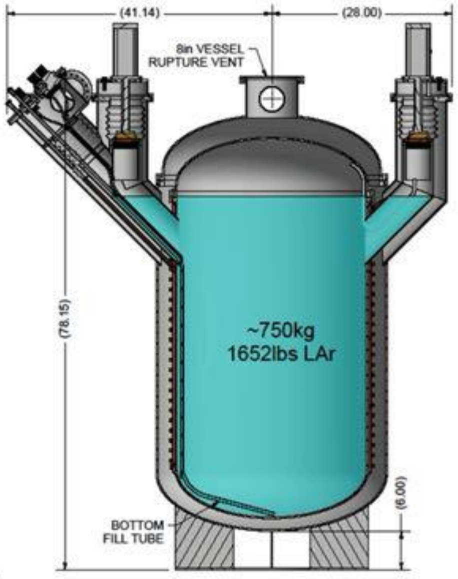
- ❑ Multi-ton detector of NaI scintillating crystals
- ❑ 13 keV$_{nr}$ threshold for CEvNS on ^{23}Na with background characterization from NaIvE
- ❑ Lightest nucleus yet studied by COHERENT

Future COHERENT Efforts

- D2O – calibrating SNS flux using well-known ν_e-d CC cross section
- Reduce flux uncertainty to few %
- Has very significant impact on NSI parameter space we can probe
- Vital for competitive CEvNS $\sin^2\theta_W$



- COHAr-750: O(1 ton) of LAr at SNS
- Experience from CENNS10 prototype
- Physics rich – see J. Daughhetee talk



+ CEvNS plans at the SNS second target station, very large detectors, and new detector ideas

Summary

- Analyzed full-dataset for CsI[Na] detector
  - Existence of CEvNS has been shown to > 11 σ, we now move towards precision measurements
- Measure a flux-averaged cross section $169^{+30}_{-26} \times 10^{-40}$ cm^2, consistent with the standard model
- We also measure the CEvNS cross section for each neutrino flavor independently which gives powerful constraints on NSI
- We've performed our first search for dark matter particles at the SNS giving a competitive measurement over two orders of dark matter mass

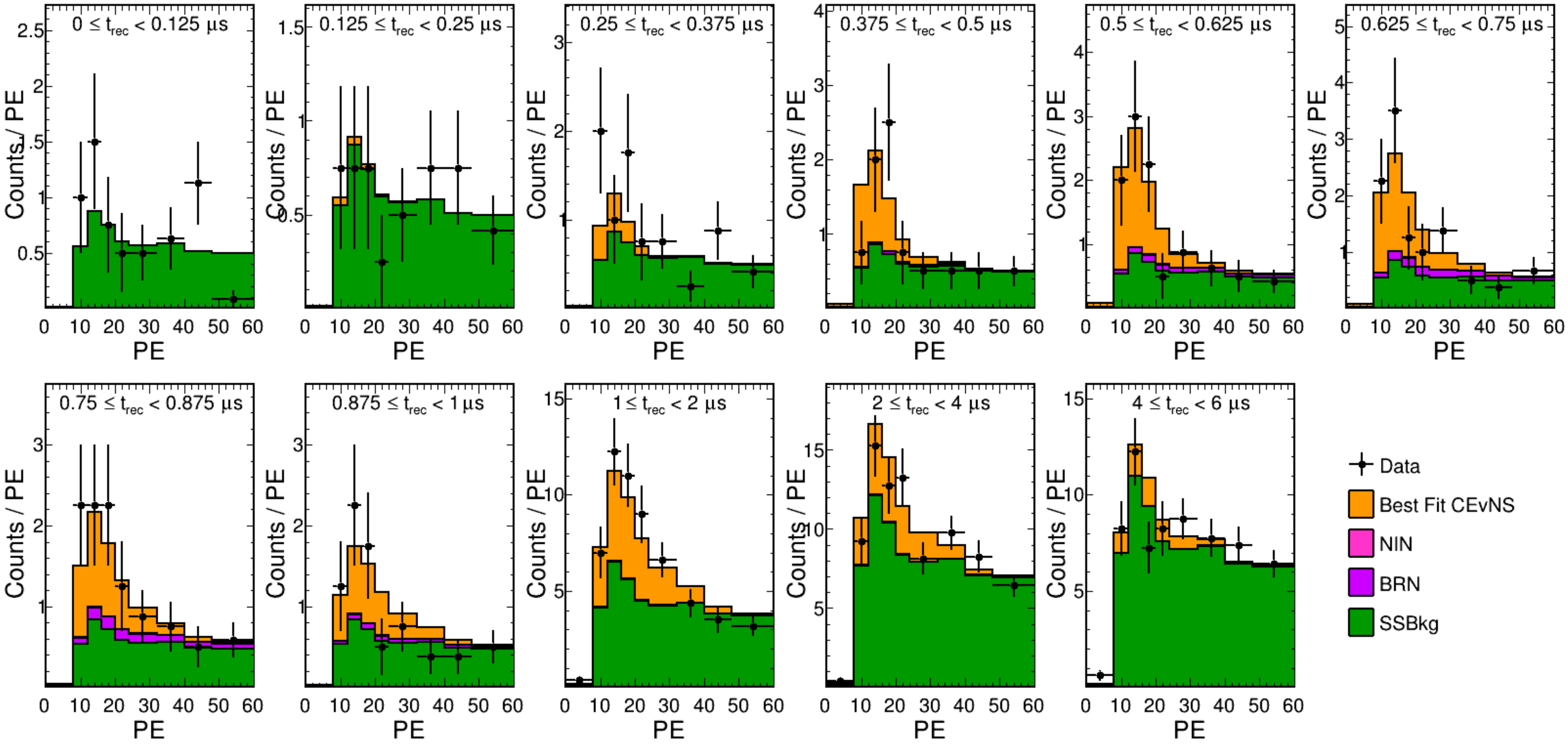
- Still early in our program – data-taking, deployment, and design ongoing

Thank you from the COHERENT collaboration!


COHERENT
COHERENT
SNS

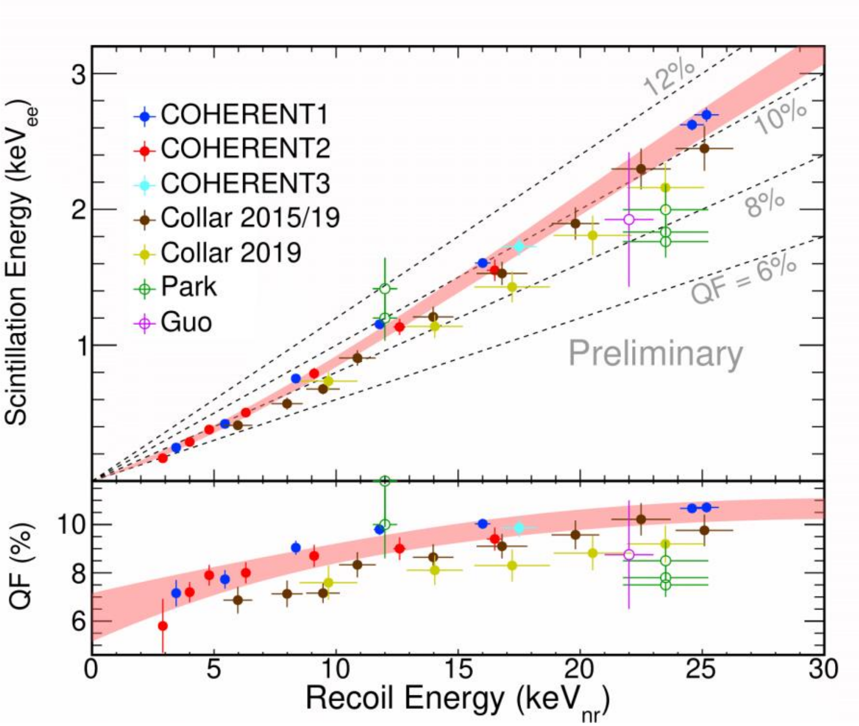
Backup

2D CEvNS Spectra

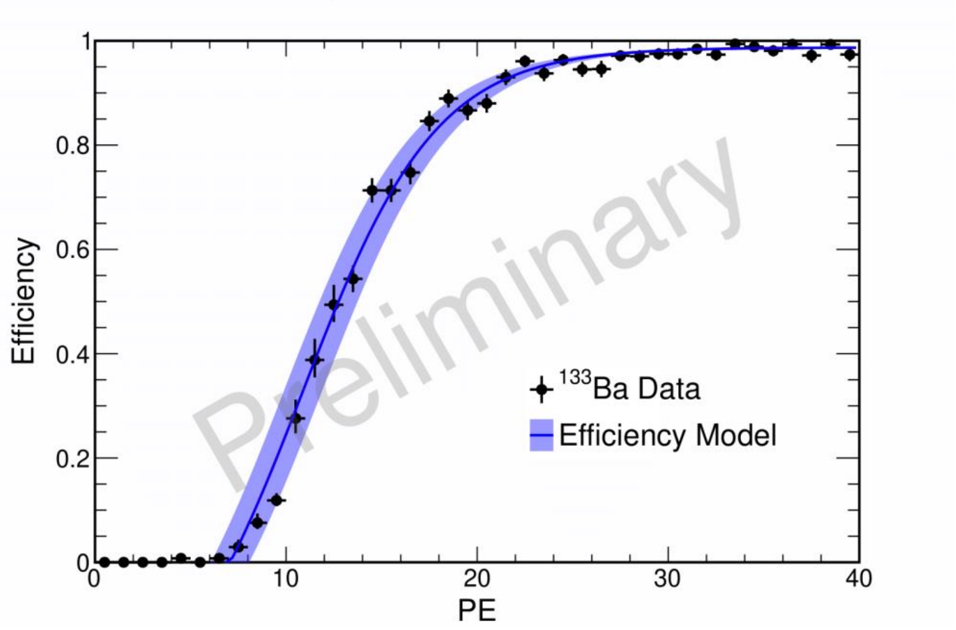


Quenching Factor Uncertainty

- To capture shape uncertainty on QF, fit to a 3rd degree polynomial
- Perform principal component analysis on covariance matrix to derive uncorrelated systematic parameters
- Two PCA nuisance parameters found to significantly bias results are included in our fit

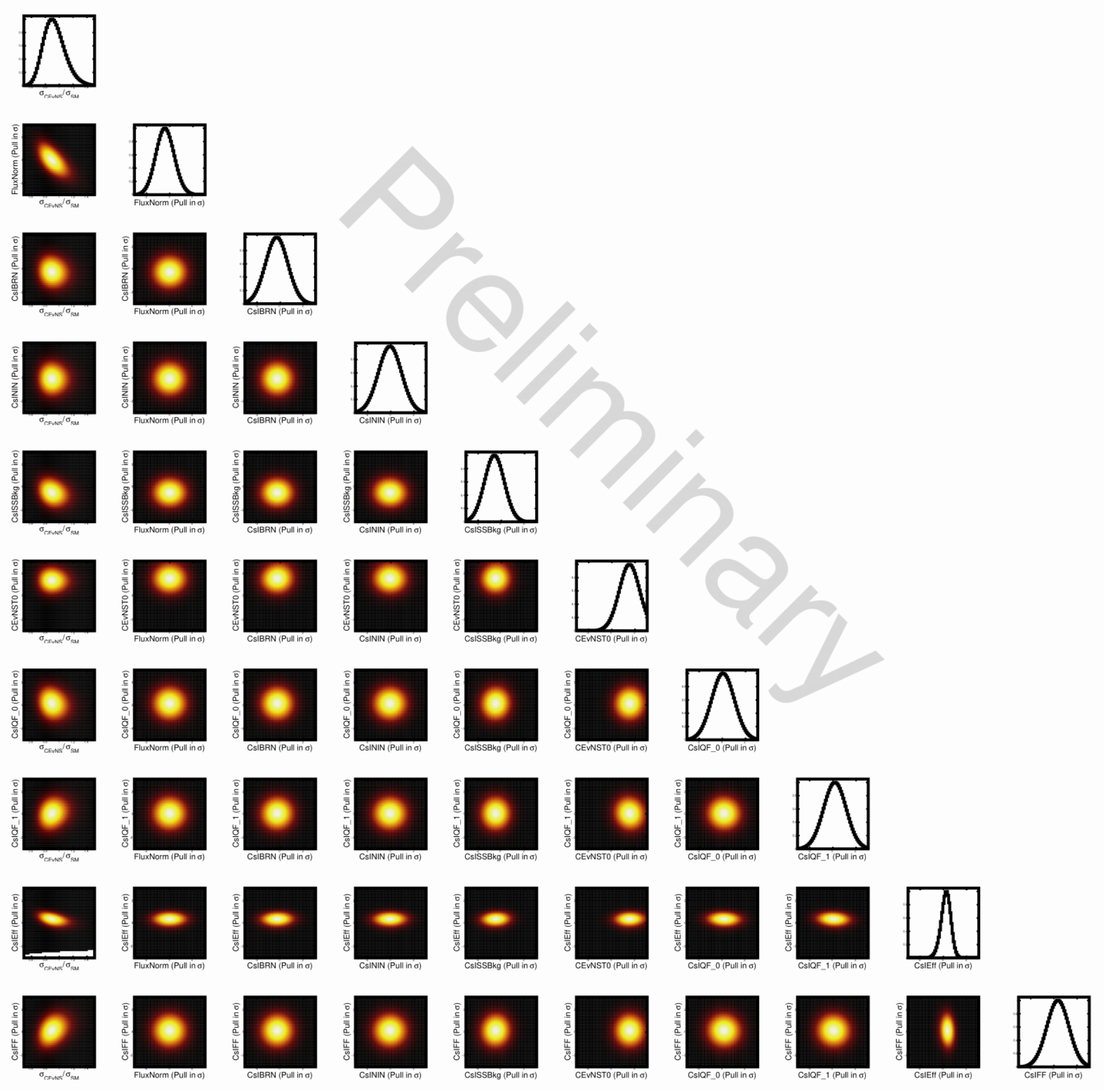


Efficiency Uncertainty

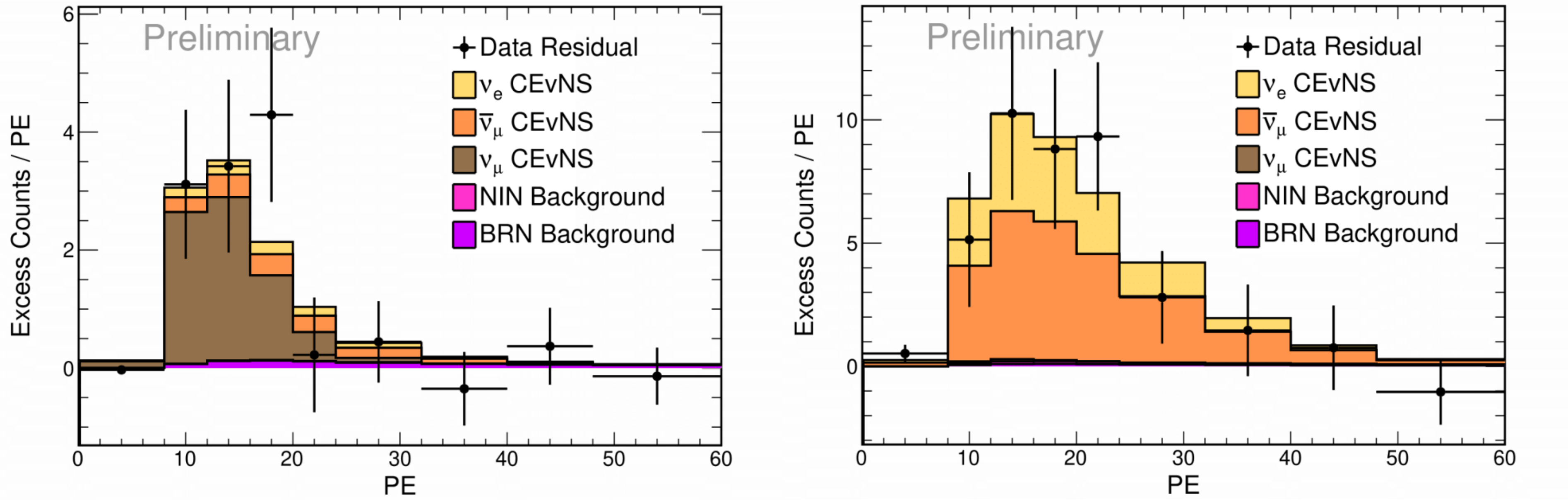


- ❑ Use same PCA strategy to determine an error band for our efficiency
- ❑ PE part of efficiency calibrated with ^{133}Ba data
- ❑ Almost all variance in the covariance matrix is explained by just the first eigenvector
  - Physically, this vector roughly equates to a change in the threshold by ≈1 PE

Fit Parameter Correlations



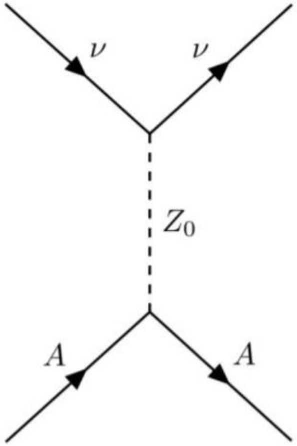
Counting Experiment-style Samples



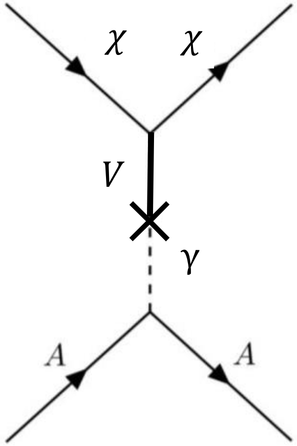
- We can isolate CEvNS from different neutrino flavors by selecting different time regions
  - ν_μ: $0.125 < t_{rec} < 0.5$ μs
  - $\nu_e/\bar{\nu}_\mu$ $0.875 < t_{rec} < 4$ μs
- Apply global best fit to prediction for each sample
- Agreement of observed shape good test of our understanding of shape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

DM Scattering in COHERENT Detectors

CEvNS:
at low Q^2, a neutrino may interact with an atom whose nucleons recoil in-phase, increasing the cross section



Dark Matter:
In these dark matter models, an analogous channel exists with a similarly enhanced cross section



- Detectors with a low-enough threshold to observe CEvNS would also be sensitive to coherent $\chi - A$ scattering
- 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 expect a harder recoil spectrum than CEvNS as $V \rightarrow \chi\chi'$ happens in flight

2D DM Search Spectra