Systematic Limitations of BSM Searches in Neutrino Experiments

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New Opportunities at the Next Generation Neutrino Experiments, UT Arlington, Apr 12-13, 2019

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April 12^{th}, 2019

Outline

To understand how best to integrate systematics into BSM searches at next gen. ν expts, one starts by examining the challenges faced by the current generation - a small sample is chosen for consideration:

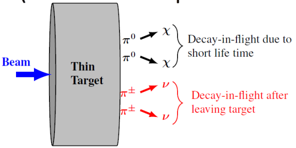
BSM Searches at Beam Dumps

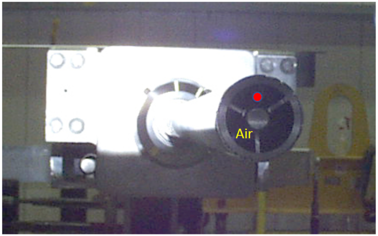
MiniBooNE DM Search

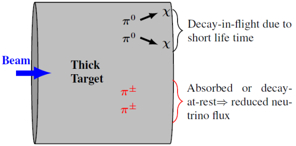
Beam-Dump Mode

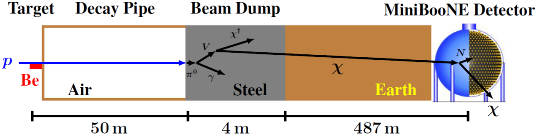
(Nov 2012 – Sep 2013 1.86×10^{20} POT)

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



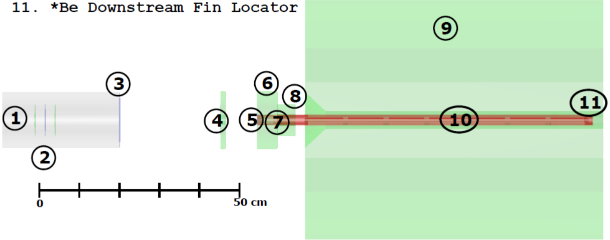






Systematic Challenges of Beam Dump Expts

1. *Vacuum Pipe
2. *MWTGT Al Foils and Wires
3. *Ti Window
4. *Al Target Back Plate
5. *Be Window
6. *Al Target Base Block
7. *Be Upstream Fin Locator
8. *Al Bellows Contact Assembly
9. Al Horn
10. Be Target, Fins and Outer Tube
11. *Be Downstream Fin Locator

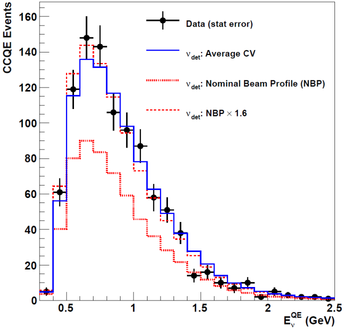


In off-target mode much more detailed simulation of material in beamline is required.

Systematic Challenges of Beam Dump Expts

		π^+	π^-
Off-Target meson/POT		2.48	2.36
Composition			
	Air	3.6%	3.0%
	Aluminum	0.2%	0.2%
	Beryllium	0.2%	0.2%
	Concrete	3.6%	4.1%
	Dolomite	0.1%	0.1%
	Steel	92.3%	92.4%
Neutrino Mode meson/POT		2.54	2.51
Composition			
	Air	1.7%	1.4%
	Aluminum	5.3%	5.2%
	Beryllium	29.5%	27.6%
	Concrete	28.0%	27.6%
	Dolomite	0.1%	0.2%
	Steel	35.4%	38.0%

MC sources of $\pi^\pm$

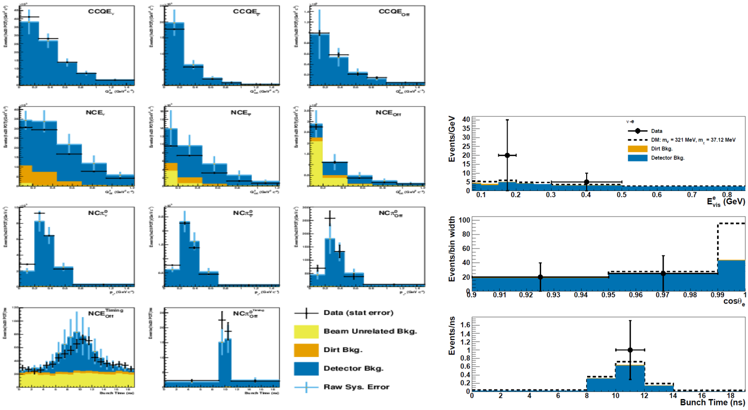


CCQE predicted vs data

Despite careful material accounting - prediction is 1.6× *lower* than CCQE data
Movement of proton beam angle within $\pm 2\sigma$ accounts for most of the discrepancy

Phys.Rev. D98 (2018) no.11, 112004

Results



DM signals would manifest as excess over prediction in NC (quasi)-elastic (NCE) or NC π^0 or $\nu - e$ scatter

No evidence for DM signal

Systematics summary for MB DM Search

TABLE V. The total unconstrained error broken down by source and distribution. The total constrained error for $\mathrm{NCE}_{\mathrm{Off}}$ is 6.4% and 11.0% for $\mathrm{NC}\pi^0{}_{\mathrm{Off}}$.

Distribution	Source unconstrained total uncertainty (%)				
	ν flux	cross section	detector model	total systematic	statistical
Neutrino Mode					
CCQE_ν	5.9	16.2	3.3	17.6	0.3
NCE_ν	5.5	12.7	13.6	19.5	0.3
$\mathrm{NC}\pi^0{}_\nu$	7.7	10.5	10.2	16.5	0.7
Anti-neutrino Mode					
$\mathrm{CCQE}_{\bar\nu}$	5.6	18.4	9.3	21.4	0.3
$\mathrm{NCE}_{\bar\nu}$	4.7	16.0	19.7	27.8	0.4
$\mathrm{NC}\pi^0{}_{\bar\nu}$	7.0	7.9	14.5	17.9	1
Off-Target					
$\mathrm{CCQE}_{\mathrm{Off}}$	32.8	17.9	3.0	37.5	3.2
$\mathrm{NCE}_{\mathrm{Off}}$	25.9	7.7	7.8	28.2	2.6
$\mathrm{NC}\pi^0{}_{\mathrm{Off}}$	26.7	10.0	10.3	30.3	9

***Unconstrained* uncertainties dominated by flux - but constrained uncerts dominated by detector,xsec**
Control data samples are v. important in reducing systs.

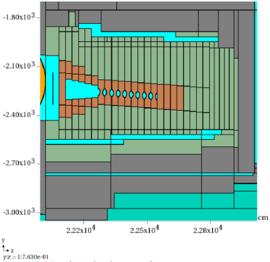
Phys.Rev. D98 (2018) no.11, 112004

LBNF Beam Design challenges for BSM searches

LBNF hadron absorber (beam dump) design at CD1R (2015) was not optimized - monitoring of tertiary beam muons difficult. Uniform absorber design developed in 2017-2018:

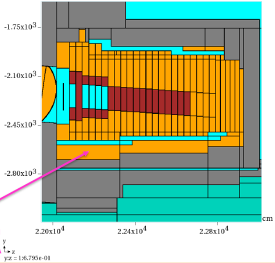
Ref. Hadron Absorber (RHA)

Non-uniformity, sculpting needed for RD



Uniform Hadron Abs (UHA)

No sculpting, larger uniform masks, larger core blocks (60”->67”), 1/16” windows on mask blocks – better for muon measurements



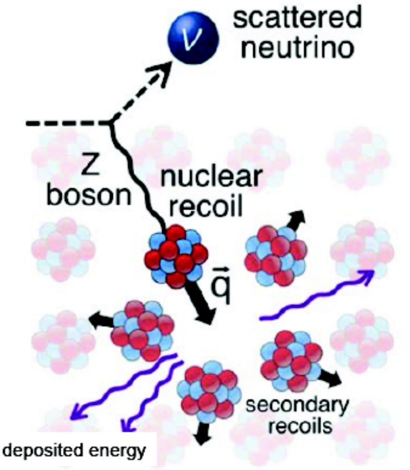
CFD simulation points to temperature reduction by 40% (89^{0}C) in the optimized design with UHA

2015 large gaps and non-uniformity in 2015 LBNF absorber would have introduced ***larger ν backgrounds*** **for DM searches.**
BSM using LBNF dump proponents *should get more involved in absorber redesign!*

Measurement of Coherent ν-Nucleus Scattering

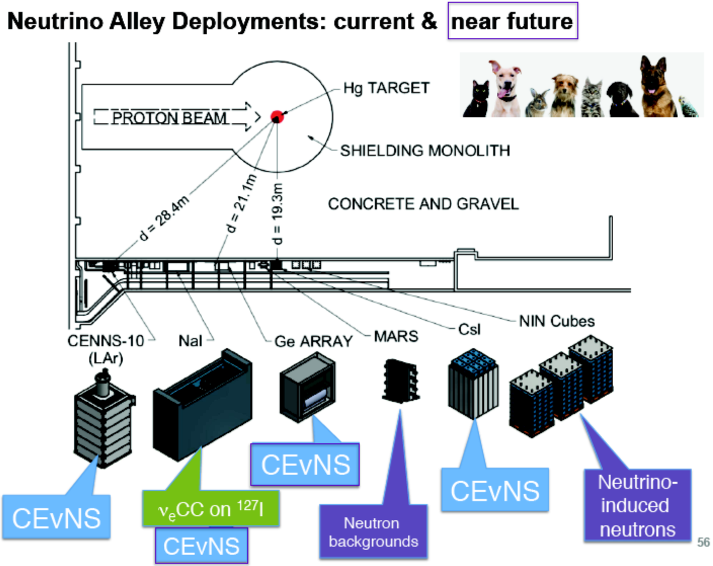
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



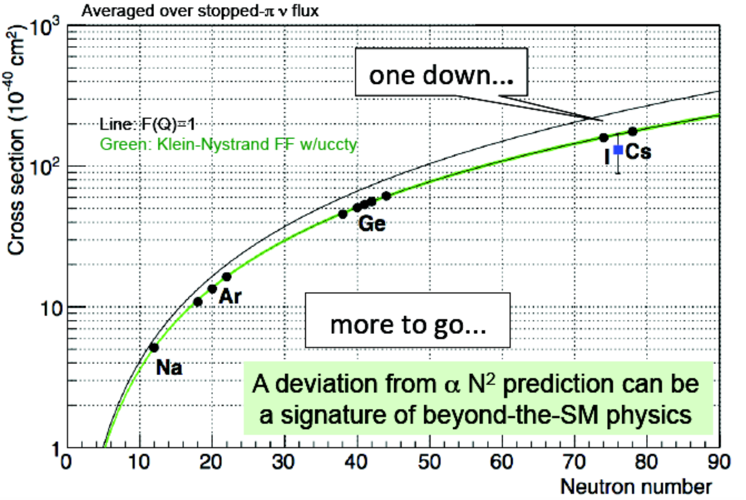
The COHERENT Experiment and Proposed Upgrades

slides from K. Scholberg



Searching for BSM with CEνNS

slides from K. Scholberg



COHERENT Systematics

Reducing systematic uncertainties

2017 CsI measurement

Uncertainties on signal and background predictions	
Event selection	5%
Quenching factor	25%
Flux	10%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

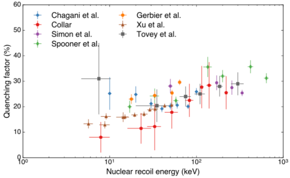
Dominant uncertainty (detector-dependent)

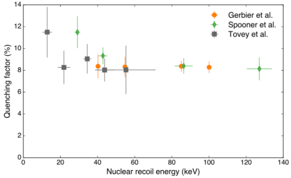
Next largest uncertainty (affects all detectors)

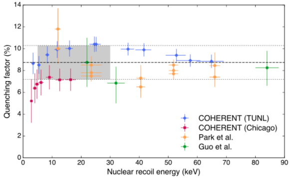
- ancillary quenching factor measurements are important for the physics program
- D_2O for flux normalization also planned

COHERENT Systematics

Program of independent measurements of quenching factors using sources or monochromatic neutron beams:





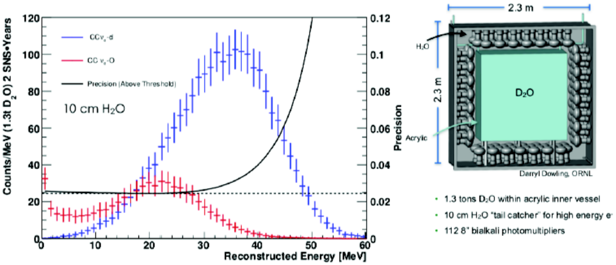


Reduction of detector systematics often requires precision ***independent*** **calibration measurements at external facilities**

COHERENT Systematics

Proposed D_2O detector:

Measurement Precision with 2 SNS years at 1.4 MW



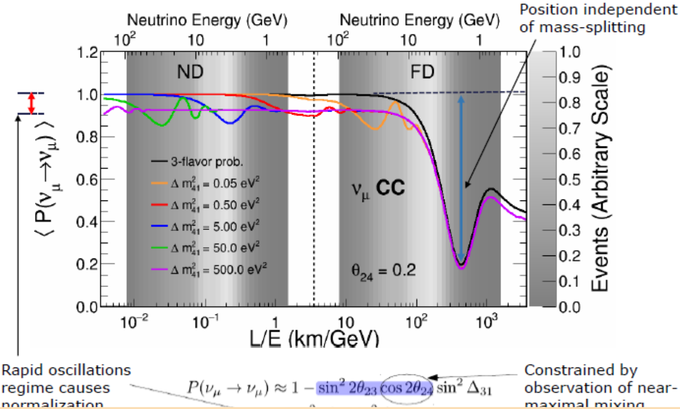
- 1.3 tons D_2O within acrylic inner vessel
- 10 cm H_2O "tail catcher" for high energy e-
- 112 8" bialkali photomultipliers

➔ ~few percent precision on flux normalization

In *many ν expts* **- precision ν flux measurements require** *independent measurements* **on D (and H)**

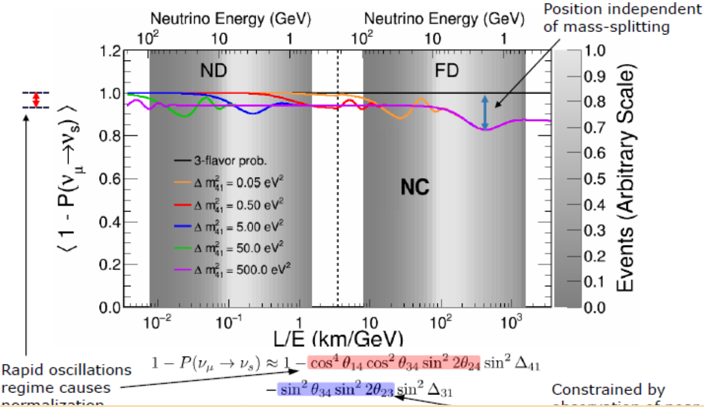
BSM Searches at Long Baseline Experiments

MINOS/MINOS+ Sterile Search



Long-baseline $\nu_\mu \to \nu_x$ expts with high intensity wide-band beams are *very sensitive interferometers*.
Combination of near/far, different detection channels (CC/NC) and different flavors of ν_x enable reduction of many correlated systs

MINOS/MINOS+ Sterile Search

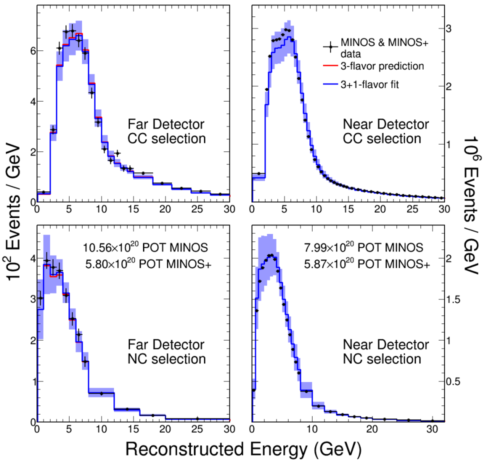


Long-baseline $\nu_\mu \to \nu_x$ expts with high intensity wide-band beams are *very sensitive interferometers*.

Combination of near/far, different detection channels (CC/NC) and different flavors of ν_x enable reduction of many correlated systs

MINOS/MINOS+ Sterile Search Results

Combination of low-energy $\sim 1-8$ GeV and medium-energy $\sim 4-20$ GeV beam running:

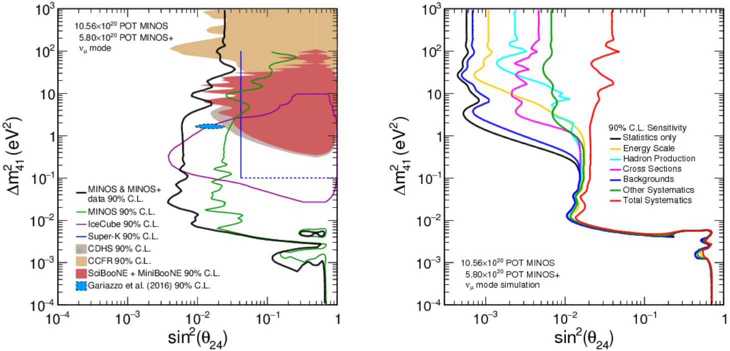


Simultaneous fit **to ND and FD distributions**

No evidence of deviation from 3-flavor

Phys.Rev.Lett. 122 (2019) no.9, 091803

MINOS/MINOS+ Sensitivities and Systematics



Significant sensitivity to 3+1 over *5 orders of magnitude in* $\boldsymbol{\Delta m^2}$. Higher $\boldsymbol{\Delta m^2_{41}}$ mass range (driven by ND) is more sensitive to systematics like target hadron production and cross-sections. Lower mass range (FD) statistical uncertainties dominate.

Phys.Rev.Lett. 122 (2019) no.9, 091803

MINOS/MINOS+ Sensitivities and Systematics

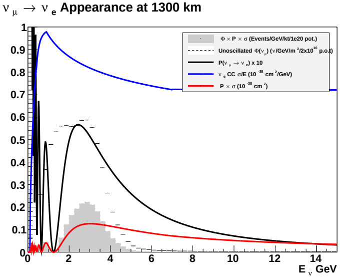
Uncertainty	Sensitivity to $\sin^2\theta_{24}$ at: $\Delta m^2_{41} = 1\,\mathrm{eV}^2$	$\Delta m^2_{41} = 1000\,\mathrm{eV}^2$
Statistics only	0.0008	0.0002
+Energy scale	0.0054	0.0003
+Hadron production	0.0131	0.0063
+Cross section	0.0138	0.0103
+Background	0.0141	0.0112
+Beam	0.0143	0.0128
+Other	0.0153	0.0165

Table I. The reduction in $\sin^2\theta_{24}$ exclusion sensitivity caused by accumulation of systematic sources at two values of Δm^2_{41}. The systematic uncertainty sources are given in Eq. (4).

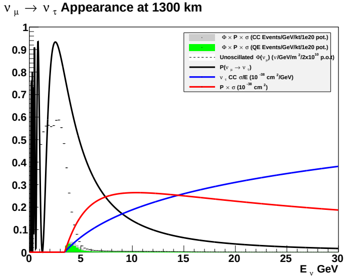
Systematics contribution to sensitivity vary with sterile mass scale.

Expanding LBL BSM Searches with DUNE

With a CPV optimized beam (low-energy):



$\nu_\mu \rightarrow \nu_e$ **290 CC events**



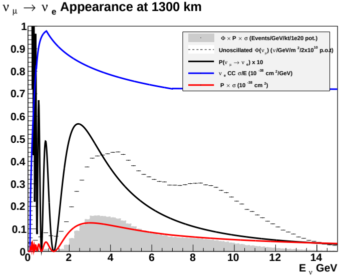
$\nu_\mu \rightarrow \nu_\tau$ **60 CC events**

DUNE will expand LBL BSM searches by adding FD ν_μ statistics and ν_e and ν_τ appearance signatures in FD *if running in medium energy tune is included in physics plan*

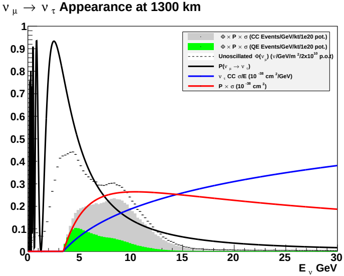
New systematics are introduced: ND is *not* **functionally identical to FD, EM as well as hadronic energy scale uncertainties, ν_τ xsec and acceptance uncertainties could reduce sensitivity to BSM**

Expanding LBL BSM Searches with DUNE

With a NuMI-like ME energy tune:



$\nu_\mu \to \nu_e$ CC 330 events



$\nu_\mu \to \nu_\tau$ CC 700 events

DUNE will expand LBL BSM searches by adding FD ν_μ statistics and ν_e and ν_τ appearance signatures in FD *if running in medium energy tune is included in physics plan*

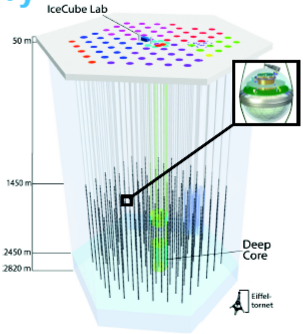
New systematics are introduced: ND is *not* functionally identical to FD, EM as well as hadronic energy scale uncertainties, ν_τ xsec and acceptance uncertainties could reduce sensitivity to BSM

BSM Searches with Atmospheric ν (IceCUBE)

IceCUBE Program

IceCube Neutrino Observatory

A pioneering multi-purpose detector



Astrophysics

- Discovery of astrophysical neutrinos
- First evidence for neutrino point source with TXS
- Key partner in multi-messenger landscape
- Cosmic rays with IceTop

Particle Physics

- Atmospheric neutrino oscillations
- Neutrino cross-sections at TeV-scale
- Exotic/BSM physics searches

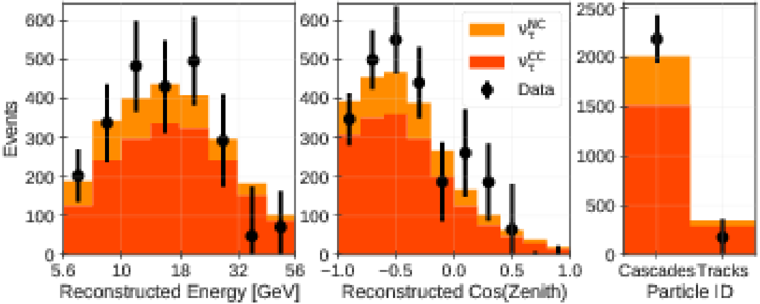
Earth science

- Glaciology
- Earth tomography

	Spacing [m] Horizontal	Spacing [m] Vertical	Energy threshold [GeV]
IceCube	125	17	~100
DeepCore	50	7	~5

IceCUBE ν_τ

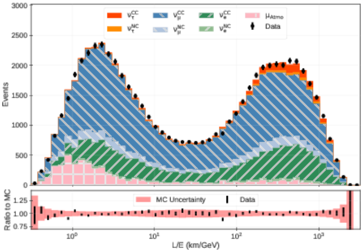
Data distrbutions with best-fit neutrino and muon backgrounds subtracted with simulated expected signal:

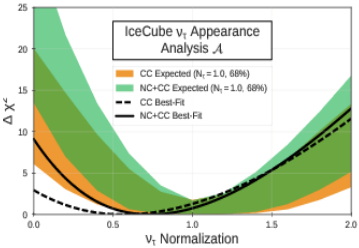


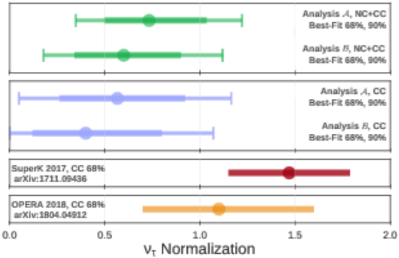
Combined NC+CC analysis. Good agreement between data and prediction - but even though signal statistics are large, background statistical uncertainties dominate

Some overlap with DUNE ν_τ appearance in range 5-10 GeV. Combination could improve BSM sensitivities

IceCUBE ν_τ





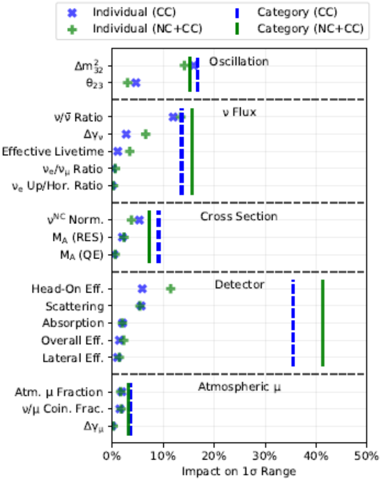


Current IceCUBE sensitivity on par with SuperK
Potential for improvements with upgrade.

IceCUBE ν_τ

Systematics nuisance parameters:

Parameter	Prior	Analysis $\mathcal{A}$ Best fit (CC+NC)	Analysis $\mathcal{A}$ Best fit (CC)	Analysis $\mathcal{B}$ Best fit (CC+NC)	Analysis $\mathcal{B}$ Best fit (CC)
Neutrino Flux & Cross Section:					
ν_e/ν_μ Ratio	1.0 ± 0.05	1.03	1.03	1.03	1.03
ν_e Up/Hor. Flux Ratio (σ)	0.0 ± 1.0	−0.19	−0.18	−0.25	−0.24
$\nu/\bar{\nu}$ Ratio (σ)	0.0 ± 1.0	−0.42	−0.33	0.01	0.04
$\Delta\gamma_\nu$ (Spectral Index)	0.0 ± 0.1	0.03	0.03	−0.05	−0.04
Effective Livetime (years)	-	2.21	2.24	2.45	2.46
M_A^{CCQE} (Quasi-Elastic) (GeV)	$0.99^{+0.248}_{-0.149}$	1.05	1.05	0.88	0.88
M_A^{res} (Resonance) (GeV)	1.12 ± 0.22	1.00	0.99	0.85	0.85
NC Normalization	1.0 ± 0.2	1.05	1.06	1.25	1.26
Oscillation:					
θ_{13} (°)	8.5 ± 0.21	-	-	8.5	8.5
θ_{23} (°)	-	49.8	50.2	46.1	45.9
Δm^2_{32} (10^{-3}eV^2)	-	2.53	2.56	2.38	2.34
Detector:					
Optical Eff., Overall (%)	100 ± 10	98.4	98.4	105	104
Optical Eff., Lateral (σ)	0.0 ± 1.0	0.49	0.48	−0.25	−0.27
Optical Eff., Head-on (a.u.)	-	−0.63	−0.64	−1.15	−1.22
Local Ice Model	-	-	-	0.02	0.07
Bulk Ice, Scattering (%)	100.0 ± 10	103.0	102.8	97.4	97.3
Bulk Ice, Absorption (%)	100.0 ± 10	101.5	101.7	102.1	101.9
Atmospheric Muons:					
Atm. μ Fraction (%)	-	8.1	8.0	4.6	4.6
$\Delta\gamma_\mu$ (μ Spectral Index, σ)	0.0 ± 1.0	0.15	0.15	-	-
Coincident $\nu + \mu$ Fraction	$0.0 + 0.1$	0.01	0.01	-	-
Measurement:					
ν_τ Normalization	-	0.73	0.57	0.59	0.43

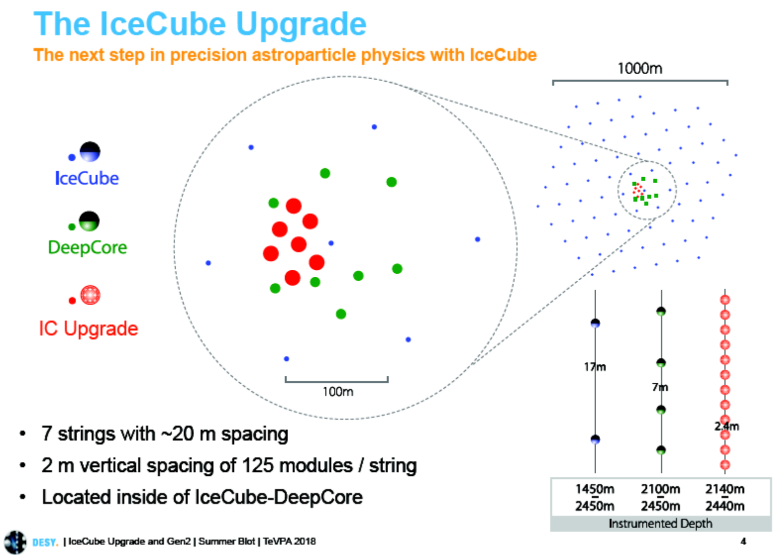


Detector systematics dominate - in particular optical model

Uncertainties on oscillation parameters Δm^2_{32} next largest (no external constraint?).

Phys. Rev. D99 (2019) no.3, 032007

IceCUBE Upgrades



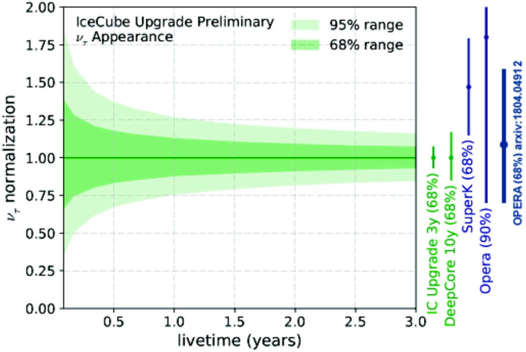
IceCUBE Upgrades

The IceCube Upgrade - Science

Precision atmospheric oscillation measurements

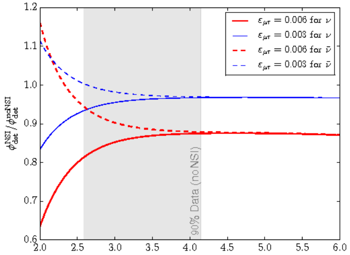
Similar physics program to DeepCore, just better!

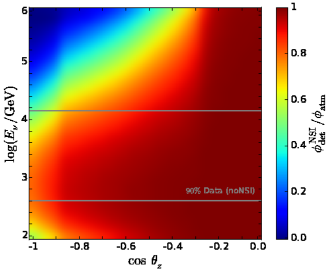
- Oscillations, non-standard interactions, sterile neutrinos, dark matter…

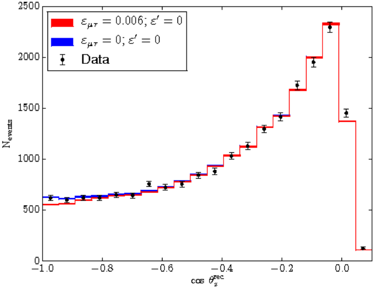


Projected sensitivities *do not* include reduced ice/OM systematics

Searches for NSI with IceCUBE







There is sensitivity for small values of $\epsilon_{\mu\tau} < 0.01$, but no evidence for NSI.

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Searches for NSI with IceCUBE

Fit parameters for this analysis for 4 different cosmic MC and hadronic models:

	HG-GH-H3a + QGSJET-II-4		HG-GH-H3a + SIBYLL2.3		ZS + QGSJET-II-4		ZS + SIBYLL2.3	
Parameter	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
$\varepsilon_{\mu\tau}$	-0.0004	0.0034	0.0001	0.0035	-0.0005	0.0036	-0.0002	0.0035
ε'	0.000	0.047	-0.003	0.045	0.002	0.046	0.001	0.046
N	1.013	0.056	0.911	0.051	1.257	0.066	1.123	0.063
π/K	1.078	0.084	1.059	0.080	1.073	0.080	1.067	0.083
$\Delta\gamma$	-0.050	0.013	-0.092	0.013	0.066	0.012	0.102	0.012
$\mathrm{DOM_{eff}}$	0.9869	0.0064	0.9863	0.0061	0.9910	0.0061	0.9885	0.0058
$\Delta m^2_{31}/10^{-3}$ [eV^2]	2.484	0.046	2.485	0.047	2.487	0.044	2.480	0.043
θ_{23} [°]	49.3	1.8	49.3	1.7	49.3	1.7	49.2	1.7

TABLE II. Mean value and standard deviation for the parameters and systematics of this analysis, for each of the four combinations of primary cosmic-ray flux and hadronic models.

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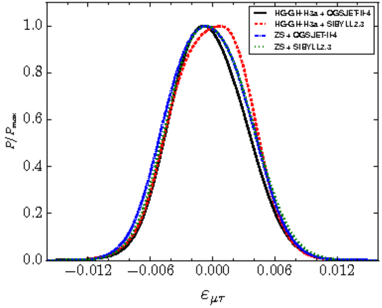
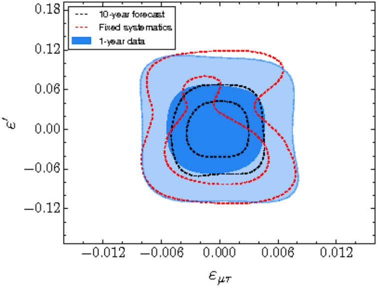
Uncertainties in cosmic MC and hadronization models introduce additional uncertainties to NSI sensitivities

Searches for NSI with IceCUBE

Posterior probabilities for $\epsilon_{\mu\tau}$ after marginalizing over all fit parameters for 4 choices of cosmic ray spectrum+hadronic models



68% and 95% contours when all nuisance parameters set to default value



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Uncertainties in cosmic MC and hadronization models introduce additional uncertainties to NSI sensitivities

Summary and Conclusions

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- **Searches for BSM and dark matter in ν experiments share many of the same uncertainties with the SM measurements of ν oscillations and properties: flux, detector, cross-sections**
- **Some uncertainties are unique to BSM searches e.g. beam dump geometries and materials for DM searches.**
- **Reduction of the dominant systematics on detector response and ν flux necessitate external calibration and measurements. For e.g flux measurements on D or H for accelerator based experiments, external measurments of hadronization for atm. expts, testbeam expts to calibrate detector response**

BSM signals that impact different signal samples - *particularly in the same experiment*- **enable more constraint on systematics and enhanced sensitivity.**