Fun with Low-Energy **Atmospheric Neutrinos**

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kjkelly@tamu.edu [1904.02751] and [2304.04689] with many great collaborators



• Why (low-energy) atmospheric neutrinos?

• CP-complementarity with atmospherics

Connections between atmospheric neutrinos and the solar cycle





Why (low-energy) atmospheric neutrinos?



New Regime of Detection

Grand Unified Neutrino Spectrum - Detected Fluxes





$\textbf{LEATM} \nu \text{ as a Background}$



Møller et al, [1804.03157]

O'Hare, [2109.03116]

1	
	10^{-43}
	10^{-44}
	10^{-45} 9
	10 ⁻⁴⁶
	10^{-47}
	10^{-48}
	12
	10
	8
	6
	4
	2



$\textbf{LEATM} \nu \text{ as a Background}$



Møller et al, [1804.03157]

O'Hare, [2109.03116]



CP Violation with Atmospherics [1904.02751] — with P.A.N. Machado, I. Martinez-Soler, S. Parke, Y.F. Perez-Gonzalez



CP Violation in Atmospheric Neutrinos

<u>CP-violating term in (vacuum) oscillation probability:</u>

$$P_{CP} = -8J_r \sin \delta_C$$













So, why haven't we done this already?



Especially at low energies, the correlation between the incoming neutrino direction and the outgoing (visible) particles' direction is muddled.

Best atmospheric measurements to date come from Super-Kamiokande, but water has a Cherenkov threshold for protons of $\sim 1.4 \text{ GeV KE}$, so lower-energy protons go undetected.







So, why haven't we done this already?



Solution — Liquid Argon TPCs. Capable of particle detection and ID to significantly lower energies.

ArgoNeuT identified proton candidates down to 21 MeV of kinetic energy.





Direction/Energy Reconstruction in LArTPCs



KJK et al [2110.00003]



Reconstruction (1D)



Event Rates in 400 kt-yr

 $N_e - \text{CC-1p0}\pi, \, \delta_{\text{CP}} = 3\pi/2$

	1.		I	I	I	I	I	I		I			1.									
		-10.64	10.46	10.41	10.58	11.89	11.69	10.25	9.29	8.65	5.94 -			0.65	-0.48	-0.21	-0.90	-0.58	-0.08	0.00	0.00	0.00
	0.8	-23.05	22.69	22.29	22.55	25.13	24.67	21.74	19.82	18.62	12.52-		0.8	1.45	-1.07	-0.55	-1.90	-1.25	-0.22	-0.02	0.00	0.00
	0.0	-31.70	31.60	30.40	30.48	33.56	32.88	29.15	26.77	25.54	16.46-		0.0	2.31	-1.54	-0.89	-2.69	-1.75	-0.40	-0.05	-0.01	0.00
eV]	0.6	-41.31	41.87	39.39	39.20	42.40	41.54	37.09	34.25	33.25	20.66-		0.6	3.17	-2.26	-1.45	-3.60	-2.54	-0.72	-0.13	-0.03	-0.01
ep [G6		-52.42	54.44	50.28	49.83	52.97	51.79	46.55	43.06	42.58	25.99-	ep [G	0.0	4.74	-3.45	-2.29	-4.70	-3.38	-1.16	-0.28	-0.08	-0.03 -
$E_{ m d}$	0.4	-64.65	69.05	62.87	61.91	64.35	62.92	57.06	52.88	53.21	31.81-	$E_{\rm d}$	0.4	6.28	-4.90	-3.37		-4.85	-2.09	-0.67	-0.21	-0.09 -
		-73.38	80.29	72.35	70.86	72.03	70.29	64.34	59.90	60.89	35.18-		0.4	3.75		-4.66			-3.24	-1.39	-0.54	-0.23 -
	0.2	-60.23	72.28	65.72	63.93	63.64	61.83	56.87	53.13	53.88	29.99-		0.2	6.14		-4.69	-5.56	-5.33	-3.42	-1.89	-0.91	-0.41 -
		-26.46	33.38	30.69	30.30	29.79	28.70	26.18	24.14	23.97	13.07-		0.2	1.08	-2.92	-2.46	-2.54	-2.54	-1.87	-1.17	-0.65	-0.32 -
	_	10).8-0).6-0).4-0	0.2 0). 0.	.2 0.	4 0.	6 0.	.8 1			1().8-().6-().4-0).2 0). ().	2 0.	4 0.	6 0.8
	$\cos heta_z$						$\cos \theta_z$															

KJK et al [1904.02751] (PRL Supplemental Material)

 $\Delta N_e - CC - 1p0\pi$, $\delta_{CP} = 3\pi/4$





Event Rates in 400 kt-yr

 $N_e - CC - 1p0\pi, \, \delta_{CP} = 3\pi/2$

	1										
	1.	-10.64	10.46	10.41	10.58	11.89	11.69	10.25	9.29	8.65	5.9
	0.8	-23.05	22.69	22.29	22.55	25.13	24.67	21.74	19.82	18.62	12.
		-31.70	31.60	30.40	30.48	33.56	32.88	29.15	26.77	25.54	16.
[Ve	0.6	-41.31	41.87	39.39	39.20	42.40	41.54	37.09	34.25	33.25	20.
ep [Ge		-52.42	54.44	50.28	49.83	52.97	51.79	46.55	43.06	42.58	25.
$E_{\mathrm{d}\epsilon}$	0.4	-64.65	69.05	62.87	61.91	64.35	62.92	57.06	52.88	53.21	31.
		-73.38	80.29	72.35	70.86	72.03	70.29	64.34	59.90	60.89	35.
		-60.23	72.28	65.72	63.93	63.64	61.83	56.87	53.13	53.88	29.
	0.2	-26.46	33.38	30.69	30.30	29.79	28.70	26.18	24.14	23.97	13.
	_	1().8-().6–0).4-(0.2 0). 0.	.2 0.	4 0.	6 0.	8
	$\cos \theta_z$										

KJK et al [1904.02751] (PRL Supplemental Material)

 $\Delta N_e - CC - 1p0\pi, \delta_{CP} = 3\pi/4$ -0.65 -0.48 -0.21 -0.90-0.58-0.080.000.000.00-1.45 -1.07 -0.55 -1.90 -1.25 -0.22 -0.020.000.000.8-2.31 -1.54 -0.89 -2.69 -1.75 -0.40 -0.05 -0.010.00-3.17 -2.26 -1.45 -3.60 -2.54 -0.72 -0.13 -0.03 -0.01[GeV] 0.6-4.74 -3.45 -2.29 -4.70 -3.38 -1.16 -0.28 -0.08 -0.03 -0.01 E_{dep} -6.28 -4.90 -3.37 -6.05 -4.85 -2.09 -0.67 -0.21 -0.09 -0.04^{-1} 0.4-3.75 **-7.19 -4.66 -6.88 -6.08 -3.24 -1.39 -0.54 -0.23 -0.11** -6.14 -8.55-4.69 -5.56 -5.33 -3.42 -1.89 -0.91 -0.41 -0.170.2-1.08 -2.92 -2.46 -2.54 -2.54 -1.87 -1.17 -0.65 -0.32 -0.13^{-1} -1. -0.8 - 0.6 - 0.4 - 0.2 0. 0.2 0.4 0.6 0.8 1. 1.

 $\cos \theta_z$







Measuring CP Violation

<u>Goal</u>: determine the measurement capability of 10 years' (400 kt-yr) data collection with DUNE, contrasted with beam measurements

Details:

Simulate neutrino-argon interactions with event generators

Use realistic atmospheric fluxes (Honda et al 1502.03916)

Account for uncertainties of atmospheric neutrino fluxes $\Phi_{\alpha}(E) = \Phi_{\alpha,0} f_{\alpha}(E) \left(\frac{E}{E_0}\right)^r$ 40% normalization, 5% e/µ ratio, 2% nu/nubar ratio, ± 0.2 spectral distortion coefficient

Realistic LArTPC capabilities $\Delta p = 5\%$, 5%, 10%, $\Delta \theta = 5^{\circ}$, 5°, 10°, for e, µ, p, K_p = 30 MeV

Classify events by final state topology (number of protons)





Contrast with HK Projections





Connections to the Solar Cycle [2304.04689] — with P.A.N. Machado, **Nityasa Mishra**, L. Strigari, and **Yi Zhuang**





Magnetic fields & **Cosmic Rays**

Downward-going neutrino flux at a location is tied to the rigidity of the magnetic field there —lower rigidity means that lower-energy protons can contribute to the neutrino flux at that location

Lower-energy CRs – more variance over the course of the solar cycle (11 years)

S \mathcal{O} \sim



Up-vs. Down-going Fluxes





JUNO

Downward-going flux at each detector location won't oscillate (much) and can vary a lot depending on latitude



Up-vs. Down-going Fluxes

Upward-going flux comes from a huge range of latitudes/longitudes, and is subject to oscillations



JUNO

OUNA

Downward-going flux at each detector location won't oscillate (much) and can vary a lot depending on latitude



Up-vs. Down-going Fluxes

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JUNO

DUNA

Downward-going flux at each detector location won't oscillate (much) and can vary a lot depending on latitude

Is this effect measurable? Is it robust if we consider different oscillation parameters, etc.?

Uncertainty on oscillation parameters (today's knowledge): NuFit









Fluxes at Detector Locations





Fluxes at Detector Locations





Fluxes at Detector Locations







Event-rate Modulation

Significant modulation in each dataset. HK sees largest statistics, but smallest predicted fractional modulation.

> 2.0σ HK: DUNE: 4.8σ JUNO: 2.0σ





Up/Down Ratio

Thick line: median expectation as solar cycle varies.

Shaded regions: variance of oscillation parameters given *current* knowledge

	JUN
1.7 1.6 1.5	
0.80	JUN
0.75	
0.65)
	1.7 1.6 1.5 0.80 0.75 0.75



Up/Down Ratio

Thick line: median expectation as solar cycle varies.

Shaded regions: variance of oscillation parameters given *current* knowledge

1.55	
1.50	
1.45	HK
0.82	
0.79	
0.76	
0.73	HK
()
	1.55 1.50 1.45 0.82 0.79 0.73



Up/Down Ratio

Thick line: median expectation as solar cycle varies.

Shaded regions: variance of oscillation parameters given *current* knowledge

	0.85	
	0.80	
JUIO	0.75	
	0.70	
LVer		
NWO	0.48	DUN
	0.46	
	0.44	
	0.42	
	()



Three Comparisons



Combined measurement in three detectors — strong evidence for connection between atmospheric neutrinos and solar cycle variance









Conclusions













Thresholds, etc., for Particle Reconstruction

Table 1. Assumptions of DUNE Far Detector reconstruction and identification capability that enter our analysis.

Particle	Minimum K.E.	Angular Uncertainty	Energy Uncertainty
Proton	30 MeV	10°	10%
Pion	30 MeV	10°	10%
Λ	30 MeV	10°	10%
μ^{\pm}	5 MeV	2°	5%
e^{\pm}	10 MeV	2°	5%







KJK et al [1904.02751] (PRL Supplemental Material)







1.2

Earth Tomography & Parametric Resonances KJK et al [2110.00003] $\rho = \{11, 5, 3\} \text{ g cm}^{-3}$



 L/R_{\oplus}



Effect of Matter Density Profile Shape





Neutrino Tomography with Atmospherics



Compare with IceCube (utilizing HE absorption) — Donini et al [1803.05901]

KJK et al [2110.00003]



Measuring the Earth's Mass





KJK et al [2110.00003]



