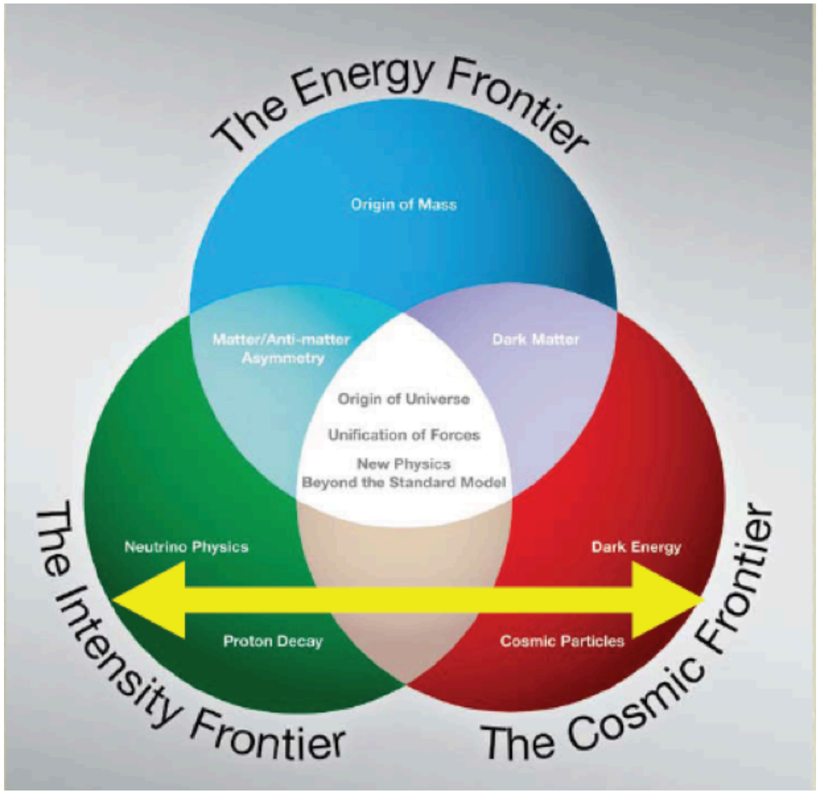
Instrumentation at the
Intensity Frontier

R. Svoboda, ANL, January 2013

THE UNIVERSITY OF CALIFORNIA
DAVIS

What the heck is the Intensity Frontier?

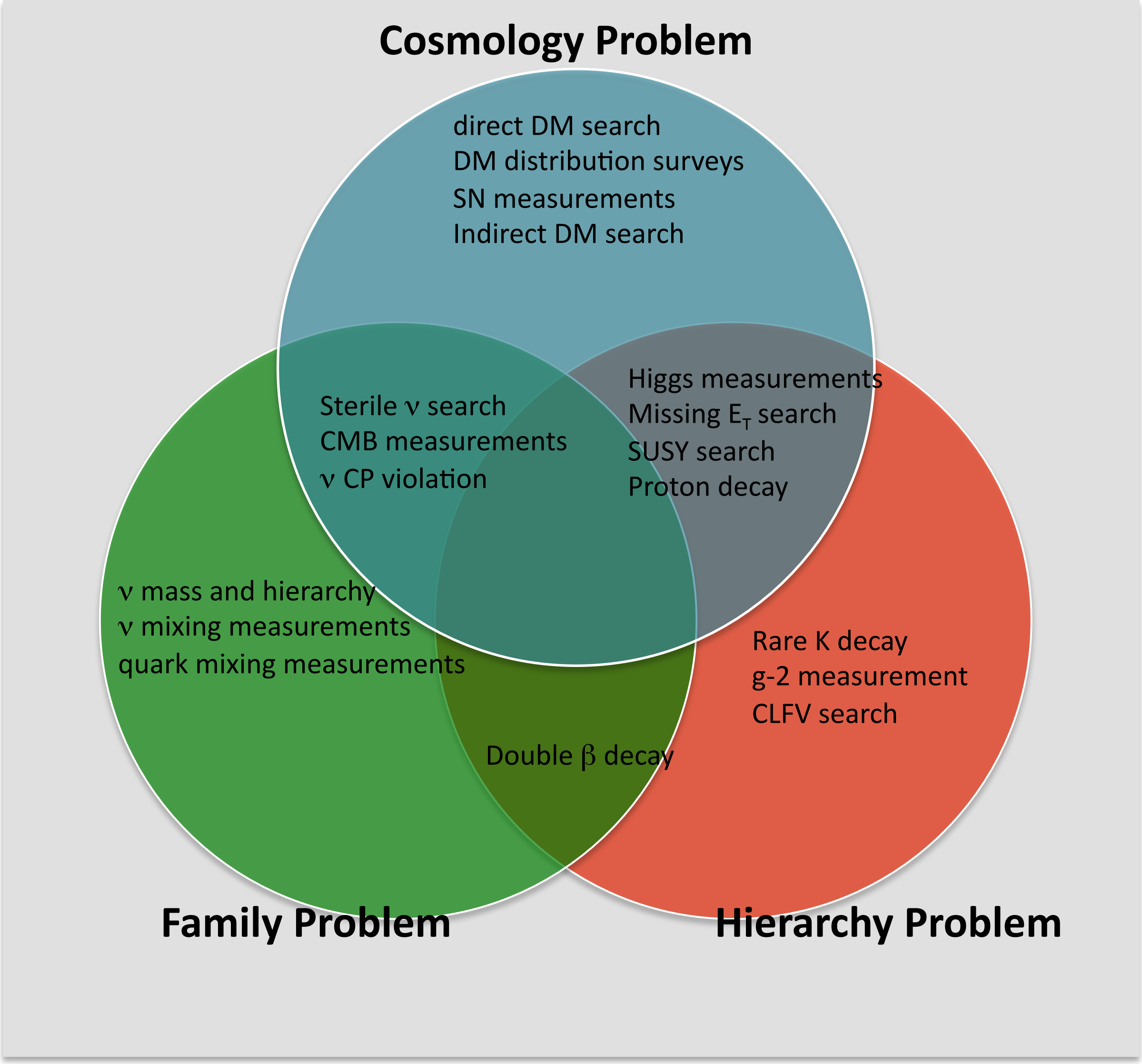


- The 2008 P5 report came up with a plan for U.S. particle physics
- In addition to the "Energy Frontier", there would also be a "Cosmic Frontier" and an "Intensity Frontier"
- These categories based on **experimental technique** rather than **science**.
- Useful, but sometimes leads to confusion due to **MIXING**

Classification by "Big Problems"

- **Hierarchy Problem:** How do particles interact with each other? Why does the vacuum not have infinite energy? How are the forces of nature related?
- **Family Problem:** Why are there only three types of lepton and quarks? Why do they experience different interactions? Are there really only three?
- **Cosmology Problem:** Why is the universe accelerating in it's expansion? What is the nature of the dark matter? What is the final fate of the universe?

Let's try this basis just for fun



Cosmology Problem

direct DM search
DM distribution surveys
SN measurements
Indirect DM search

Sterile ν search
CMB measurements
ν CP violation

Higgs measurements
Missing E_T search
SUSY search
Proton decay

ν mass and hierarchy
ν mixing measurements
quark mixing measurements

Rare K decay
g-2 measurement
CLFV search

Double β decay

Family Problem

Hierarchy Problem

Add your favorite experiment here.

I'm going to look at instrumentation needs for the **Intensity Frontier** in this basis in order to link more directly with the science.

What limits Intensity Frontier Measurements?

- As name implies, **intensity of particle source** is a major consideration. This can sometimes be compensated by **large detectors**. In this case, **cost** is typically the limiting factor. Examples include LBL ν experiments, proton decay experiments
- **Background rejection** is also a limiting factor in many cases. This can come from inadequate tracking, intrinsic energy resolution, insufficient information to separate background from signal. Examples include $0\nu2\beta$ decay experiments, CLFV experiments, rare K decay experiments, diffuse SN flux detection experiments.
- **Source characterization** is also a common theme, but instrumentation is often not key here.

Intensity Frontier: Hierarchy Problem

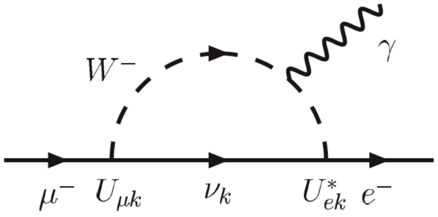
- Charged Lepton Flavor Violation Experiments:

  e.g. MEG, Mu2e
- Rare K decay experiments: e.g. ORCA
- Proton Decay experiments: e.g. Hyper-Kamiokande, LBNE Phase II, LENA
- B mixing and CP violation experiments: e.g. Belle II
- g-2 experiments: e.g. g-2

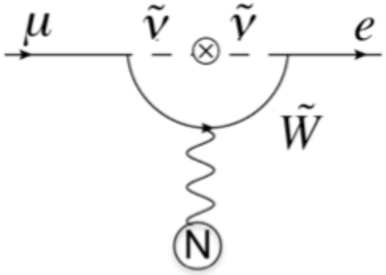
Search for rare processes as a manifestation of new loop diagrams or exchange particles.

Example: CLFV

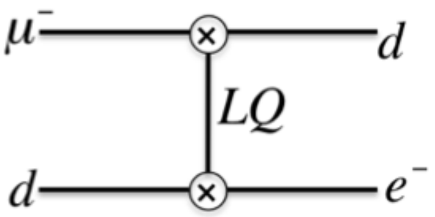
$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54},$$



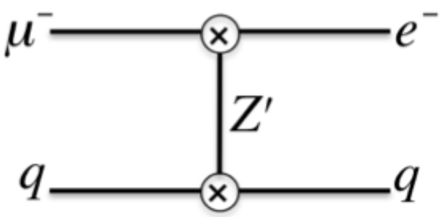
The SM process for μ→eγ is GIM suppressed, such that it depends on the tiny mass differences between neutrinos. This is much smaller than can be realistically detected. Thus any enhanced rate must come from new physics, such as new particles in exchange or loop diagrams. Some of these (like SUSY) would impact the Hierarchy Problem via allowing GIM-like cancellations in the vacuum.



SUSY



Leptoquarks



FCNC with Z'

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum \bar{q}_L\gamma^\mu q_L\right),$$

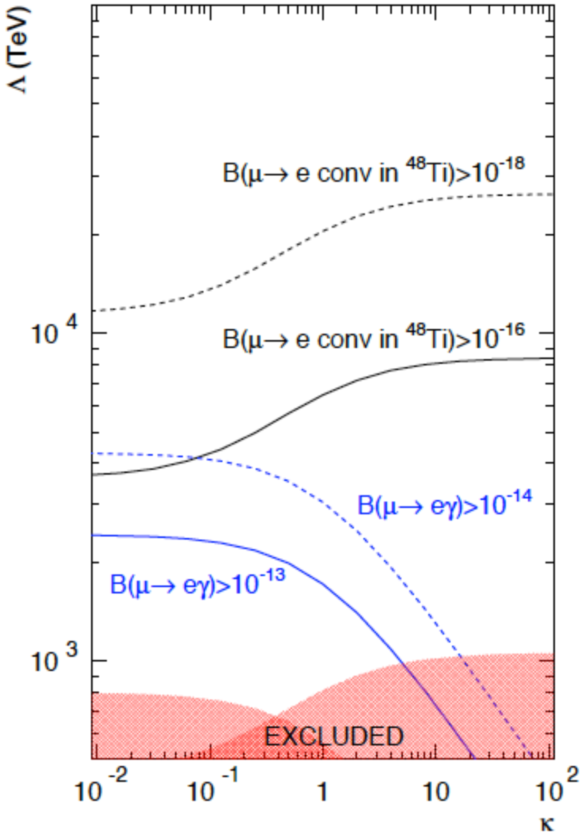
Mu2e Proposal

A generic CLFV Lagrangian has a magnetic-dipole like process and a four-fermion like process. The parameter κ is a convenient knob for their relative Rates

$\mu \to e\gamma$ and $\mu A \to eA$ have different sensitivity

If sensitivities can be extended to the 10^{-18} range, mass scales in the range of 10^4 TeV could be explored.

Current MEG limit on $\mu^+ \to e^+\gamma$: $<2.4\times10^{-12}$ @90% c.l.
PRL 107 171801 (2011)

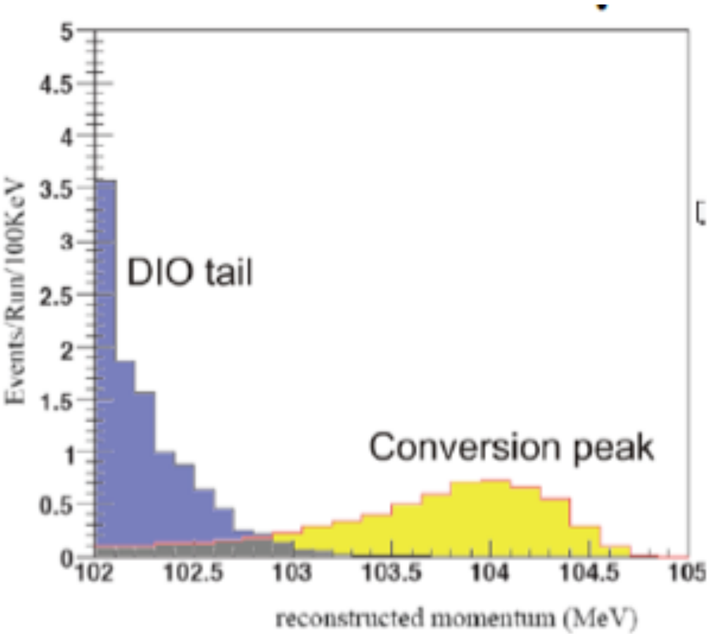


Mu2e proposal

Current Mu2e goal:

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + (A,Z) \to e^- + (A,Z)\right)}{\Gamma\left(\mu^- + (A,Z) \to e^- + (A,Z-1)\right)} \le 6\times10^{-17} \ @\ 90\%\ CL$$

What are limiting factors for CLFV?

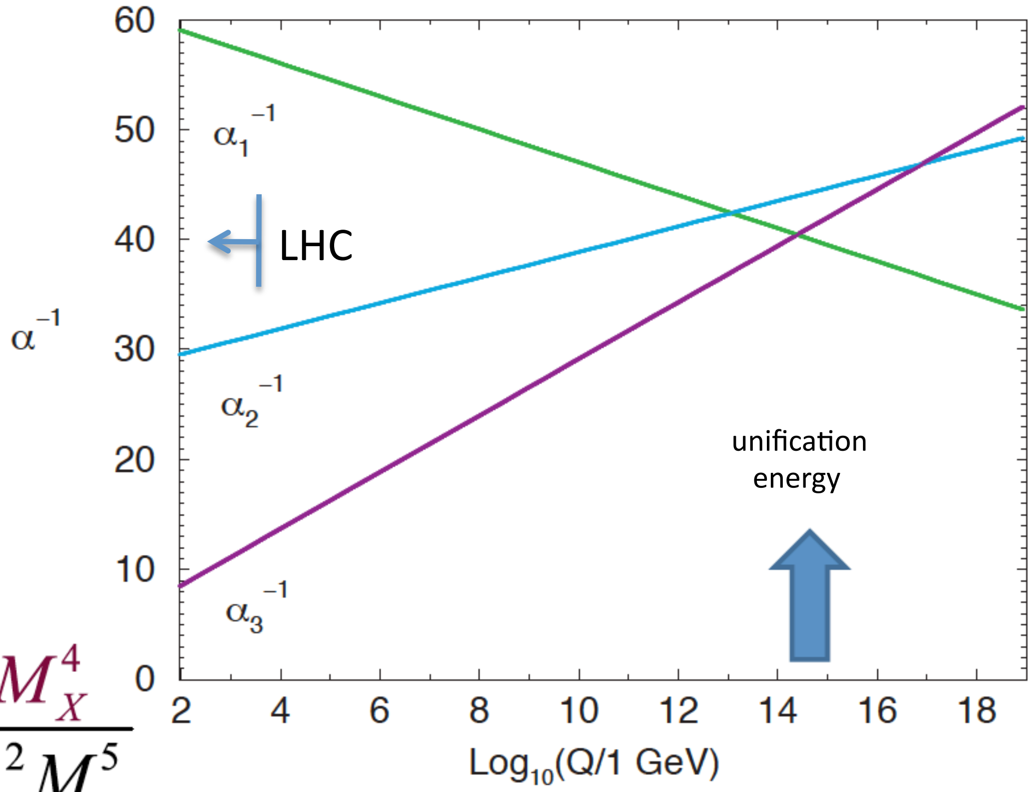


The Decay In Orbit (DIO) tail overlaps with the conversion peak, thus making energy resolution a major concern for future experiments.

- **Tracking**: requirement of precision tracking with very low (<<1% X_o) mass to reject backgrounds
- **Intensity**: high rates imply need for low latency and resistance to radiation damage
- There are similar concerns for **rare K decay and g-2 experiments**. In all cases, detailed studies are required for non-trivial trade-offs.

Another Example: Proton Decay

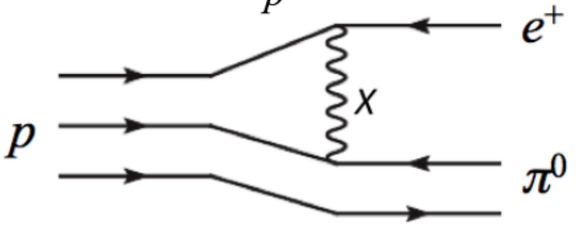
Gauge Coupling Unification



Three of the four
forces of nature
are thought to become
similar in strength
at very high energies –
far above any conceivable
accelerator

Simple unification
theory ruled
out by data – proton
decay is an effective way
to test such theories

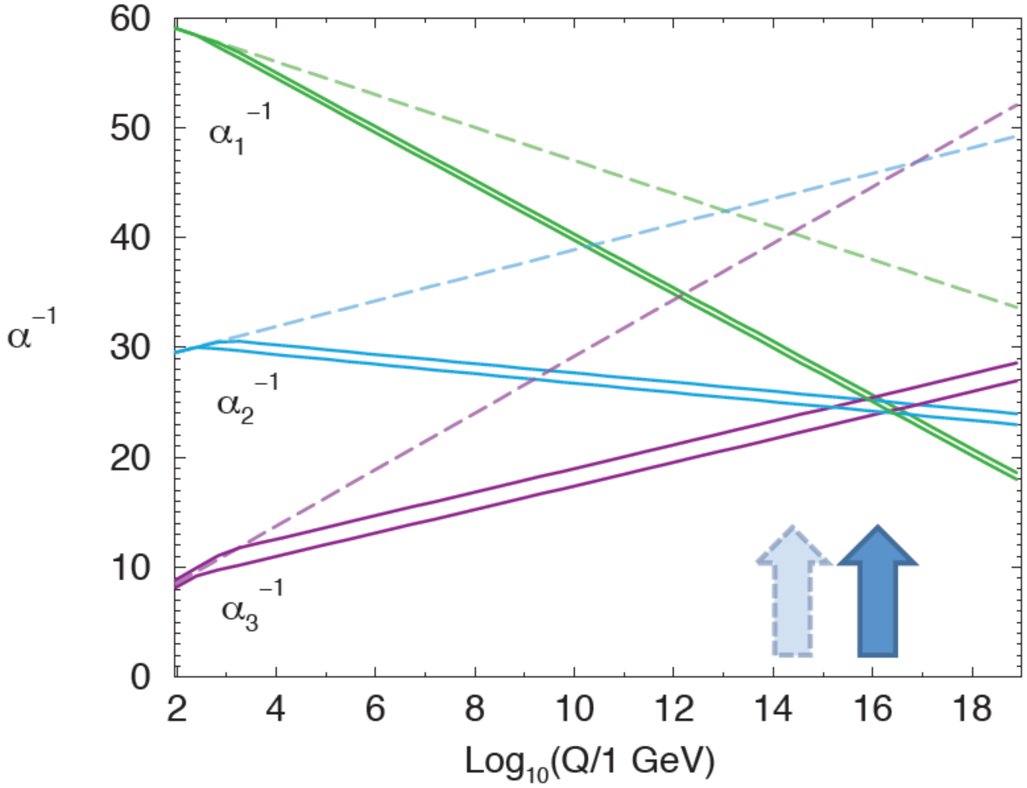
$$\tau \approx \frac{M_X^4}{\alpha^2 M_p^5}$$



$$\tau(e^+\pi^0) = 4.5\times 10^{29\pm 1.7}\ years\ \text{(predicted)}$$

>1.3x10^{34} years (Super-K)

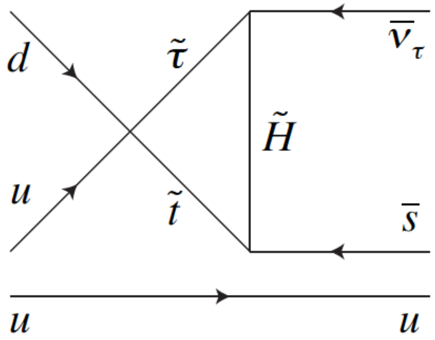
New theories (e.g. SUSY) can push up unification scale



Unification scale pushed up…

$$\tau(e^+\pi^0) \approx 10^{35-38} \text{ years}$$

>4.0x10^{33} years (Super-K)



$p \rightarrow K^+\nu$

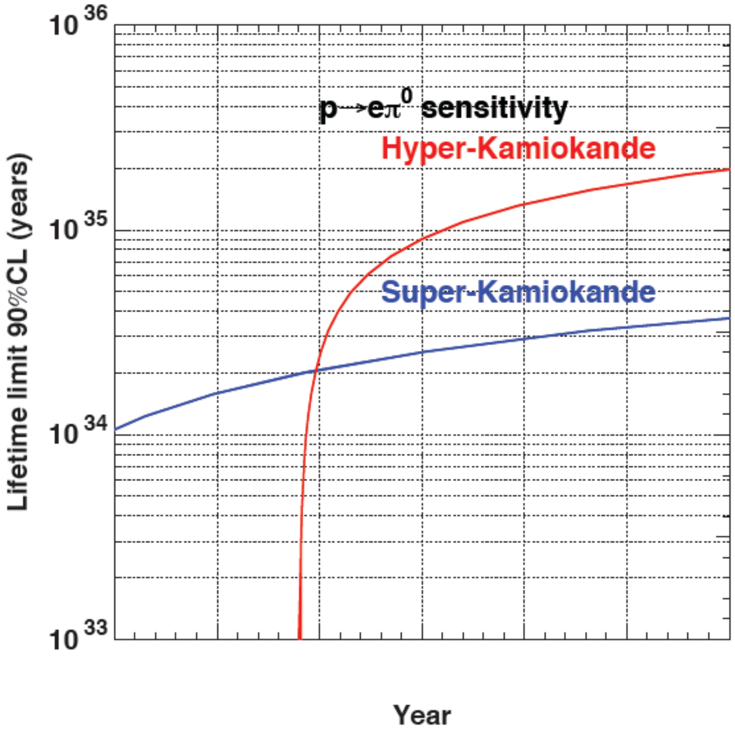
Example of a possible proton decay through supersymmetric particles.

Observation of virtual processes like proton decay is another way to access physics at these energies

What are the limiting factors?

- **Size of detector**: for real progress, detectors in the 0.1-1.0 megaton range are needed. This is mainly constrained by **cost**. Cheaper photosensors, water-based scintillator, cheaper liquid argon TPC fabrication.
- **Background reduction:** In future water Cherenkov experiments, backgrounds from complex atmospheric neutrino interactions are expected to be a factor. **Neutron tagging** is likely to be a key to reducing these.

$p \rightarrow e^{+}\pi^{0}$



	ε x B_{meson}	BKG (/Mtonyr)	BG (/yr)
IMB3	0.48	26	0.087
KAM-I	0.53	<15	<0.015
KAM-II	0.45	<8	<0.008
Super-K	0.44	2.1	0.047

Efficiency dominated by nuclear effects.
Background dominated by resolution.

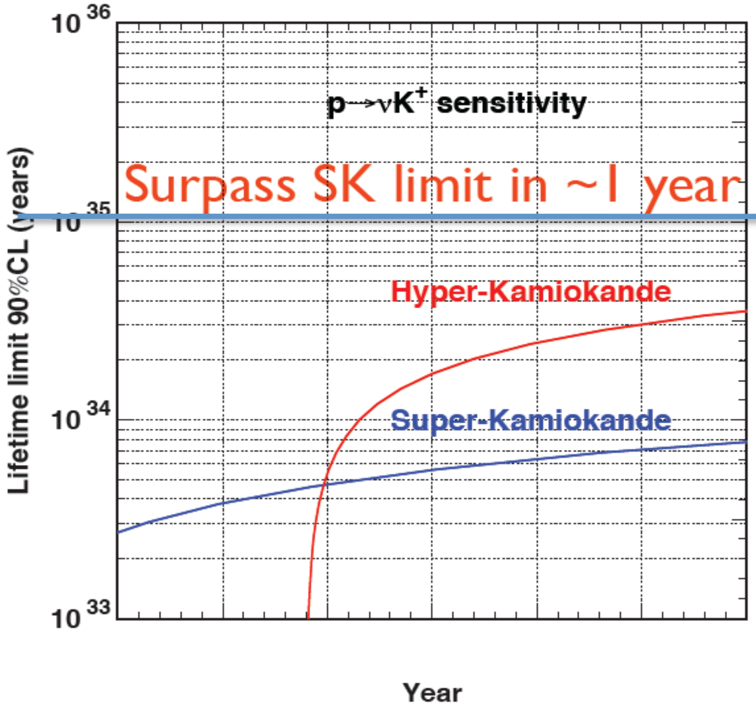
Calculated Background: 2.1 +/- 0.9 ev/Mton/yr

Measured: 1.63 (+0.42/-0.33 stat) (+0.45/-0.51 syst.) ev/Mton/yr

About 80% of proton decays in water should not have a neutron in the final state, whereas it is expected that the neutron multiplicity from proton-decay like atmospheric neutrino events is >1.

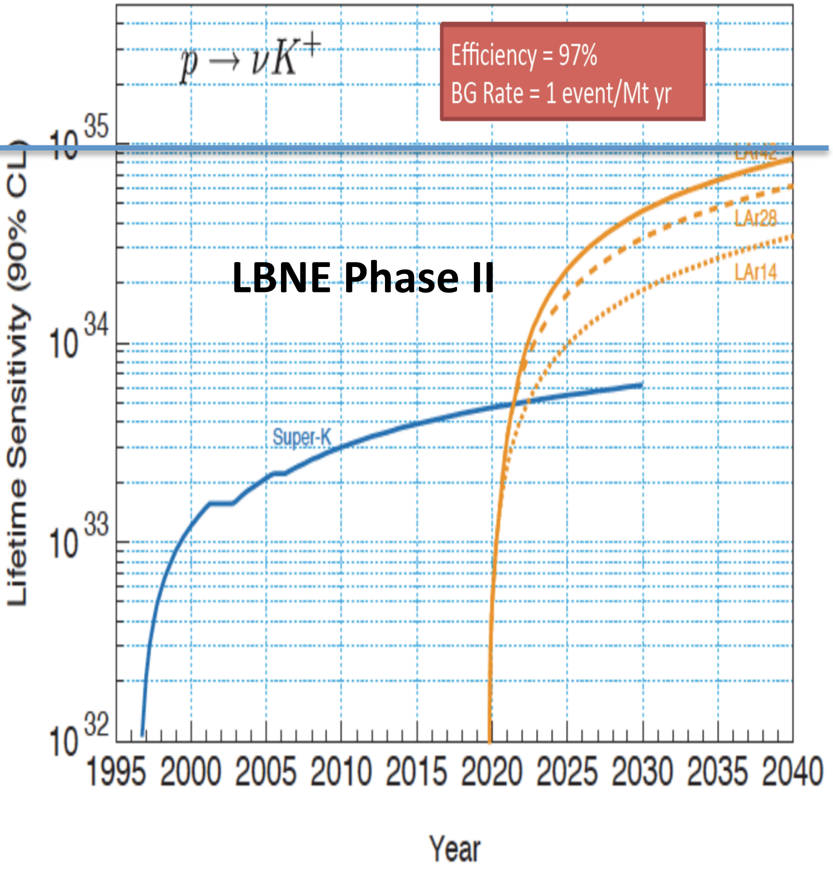
$p \to \nu K^+$

For this mode, development of **large liquid argon TPC** (i.e. low cost per kton located underground) would be effective. Large (>50 kton) low-cost liquid scintillation detectors would have similar sensitivity to 28 ktons liquid argon. **Water-based scintillator** development would have a dramatic impact on cost.



Surpass SK limit in ~1 year

Hyper-K limited by the fact that the K+ is below Cherenkov threshold



LBNE Phase II

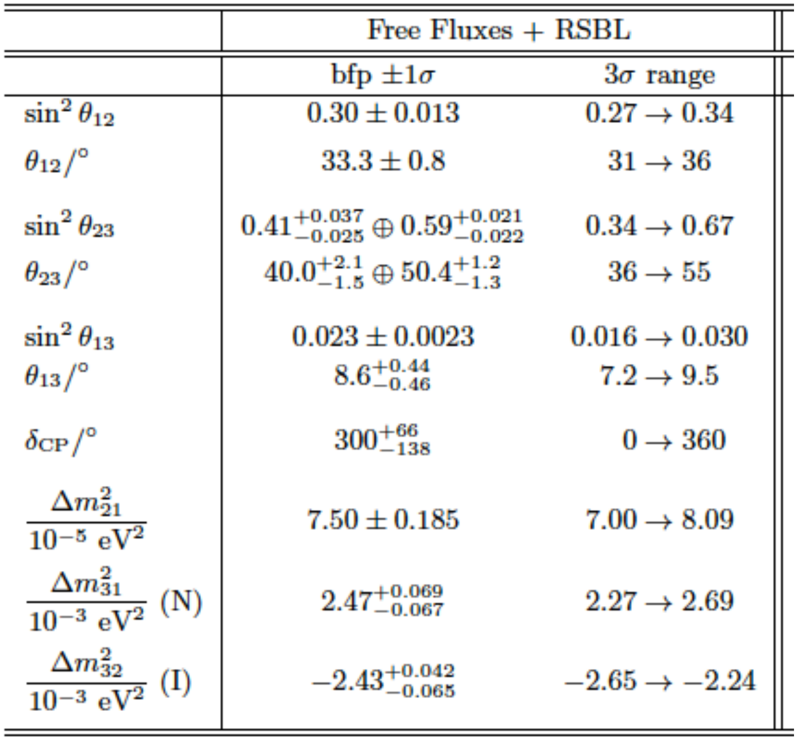
Intensity Frontier: Family Problem

- Neutrino mass ordering: e.g. LBNE, Hyper-Kamiokande, INO, ICE CUBE upgrade
- Majorana or Dirac neutrinos: e.g. EXO, Majorana, SNO+, KamLAND-Zen upgrades, …
- Neutrino CP violation: e.g. LBNE, Hyper-Kamiokande
- Sterile neutrino experiments: e.g. μBooNE, OscSNS, new reactor and source experiments,

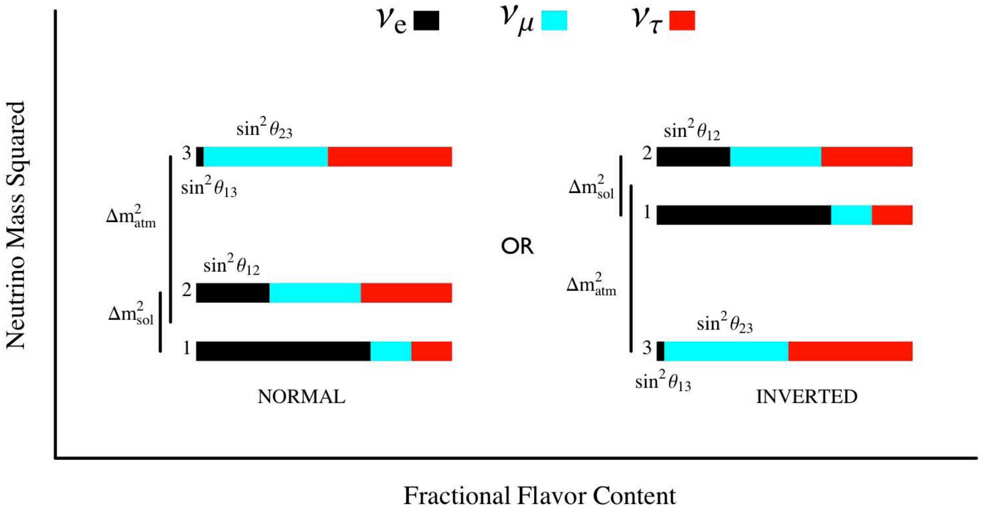
Progress in Neutrino Physics

We now have a good understanding of many (but not all) of the parameters associated with neutrino mass and mixing.

In some sense, neutrinos are the **easiest** family to study. They are a fertile ground for thinking about the Family Problem



	Free Fluxes + RSBL	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$
$\delta_{\rm CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	7.50 ± 0.185	$7.00 \to 8.09$
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \rm eV^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \rm eV^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$

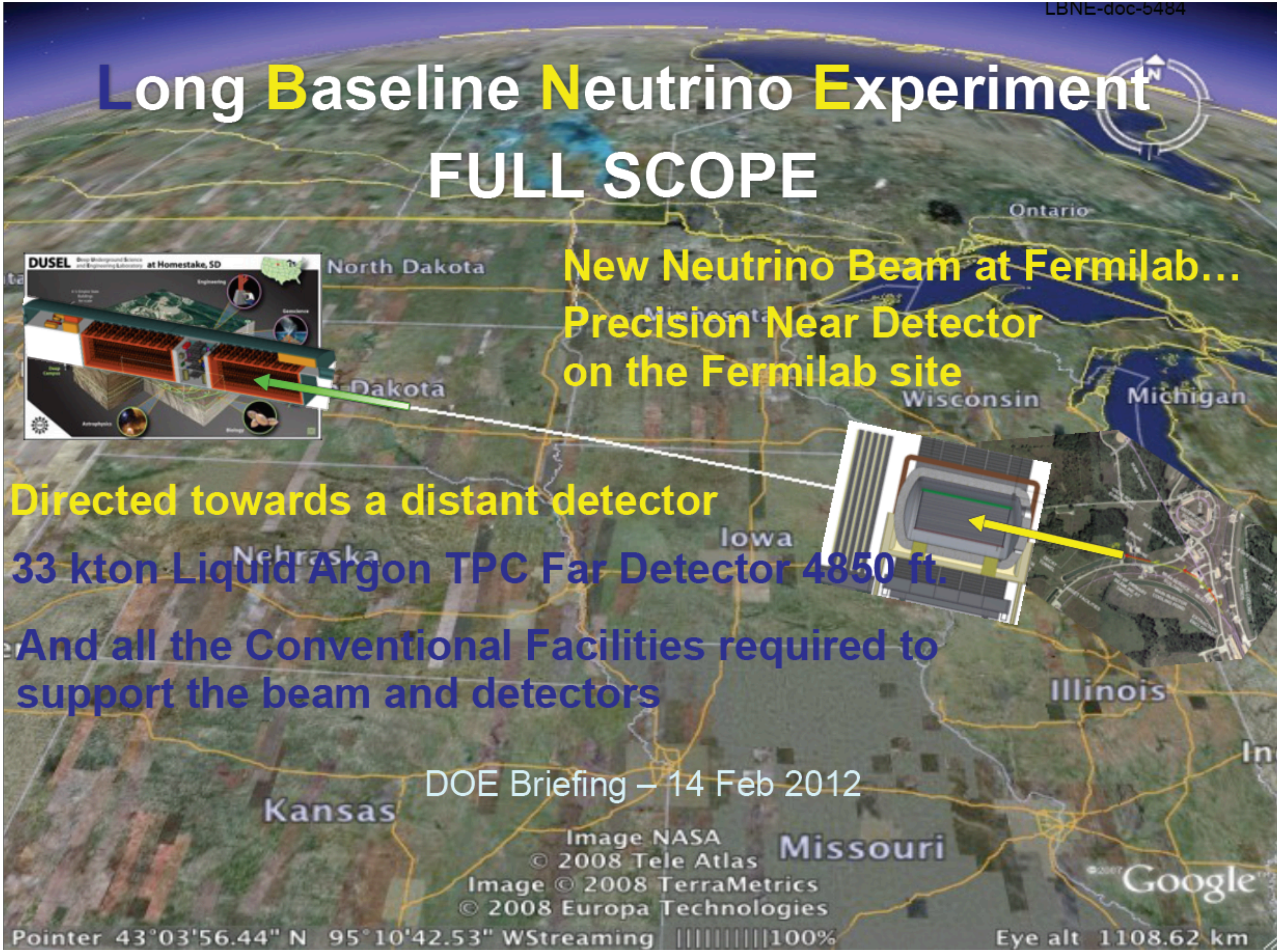


Example: LBNE Phase II

- LBNE Phase I is currently planned as a 10 kton liquid argon TPC on the surface with minimal beam monitoring.
- Phase II would be a **larger** (~40 kton) far detector **underground** and a highly-capable near detector.
- Contributions from international partners could **accelerate** Phase II, along with providing a near detector.

Long Baseline Neutrino Experiment

FULL SCOPE



New Neutrino Beam at Fermilab…

Precision Near Detector on the Fermilab site

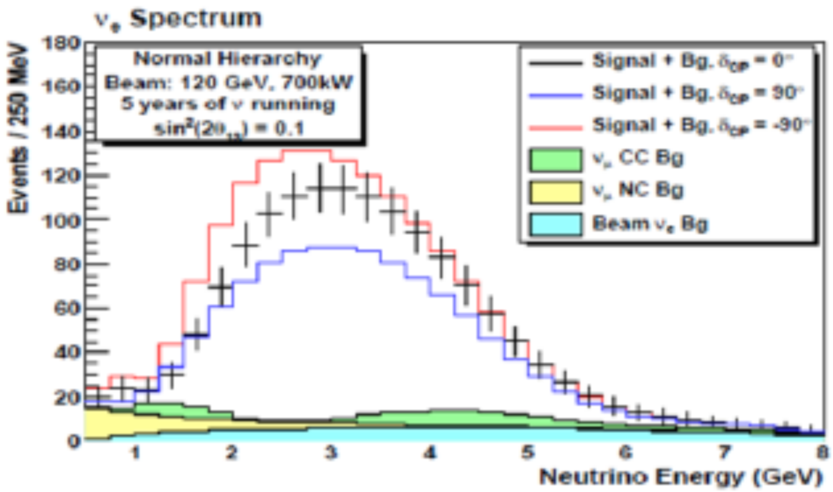
Directed towards a distant detector

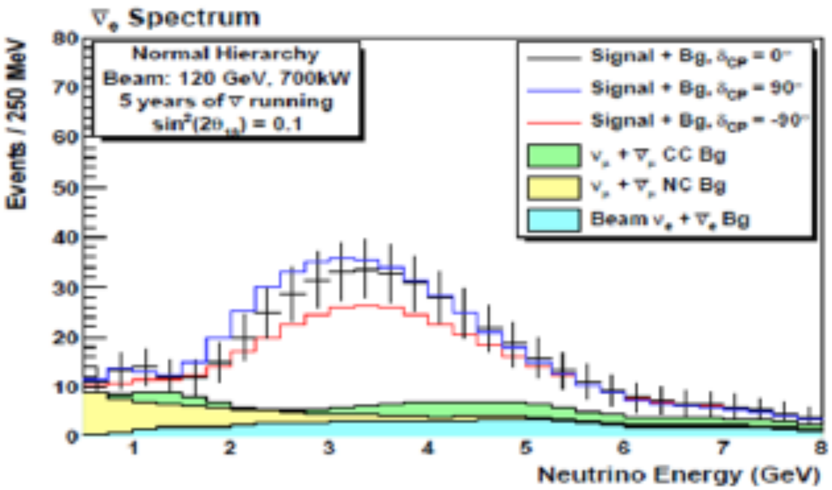
33 kton Liquid Argon TPC Far Detector 4850 ft.

And all the Conventional Facilities required to support the beam and detectors

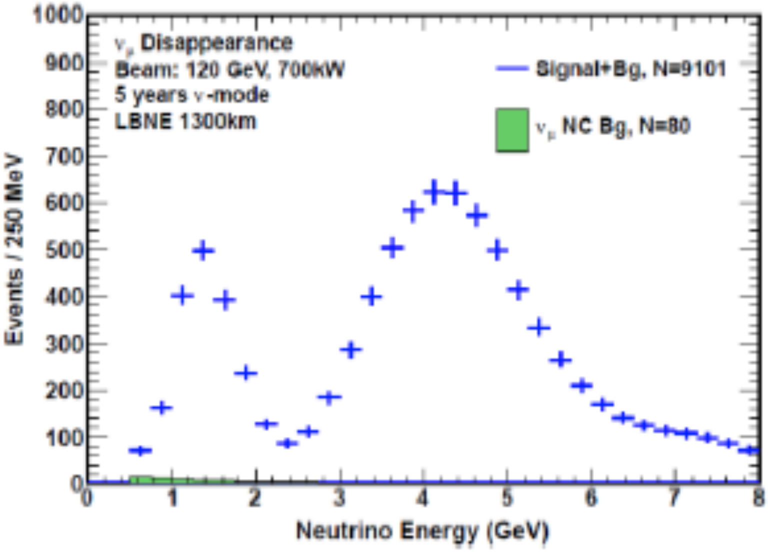
DOE Briefing – 14 Feb 2012

LBNE Phase II Spectra





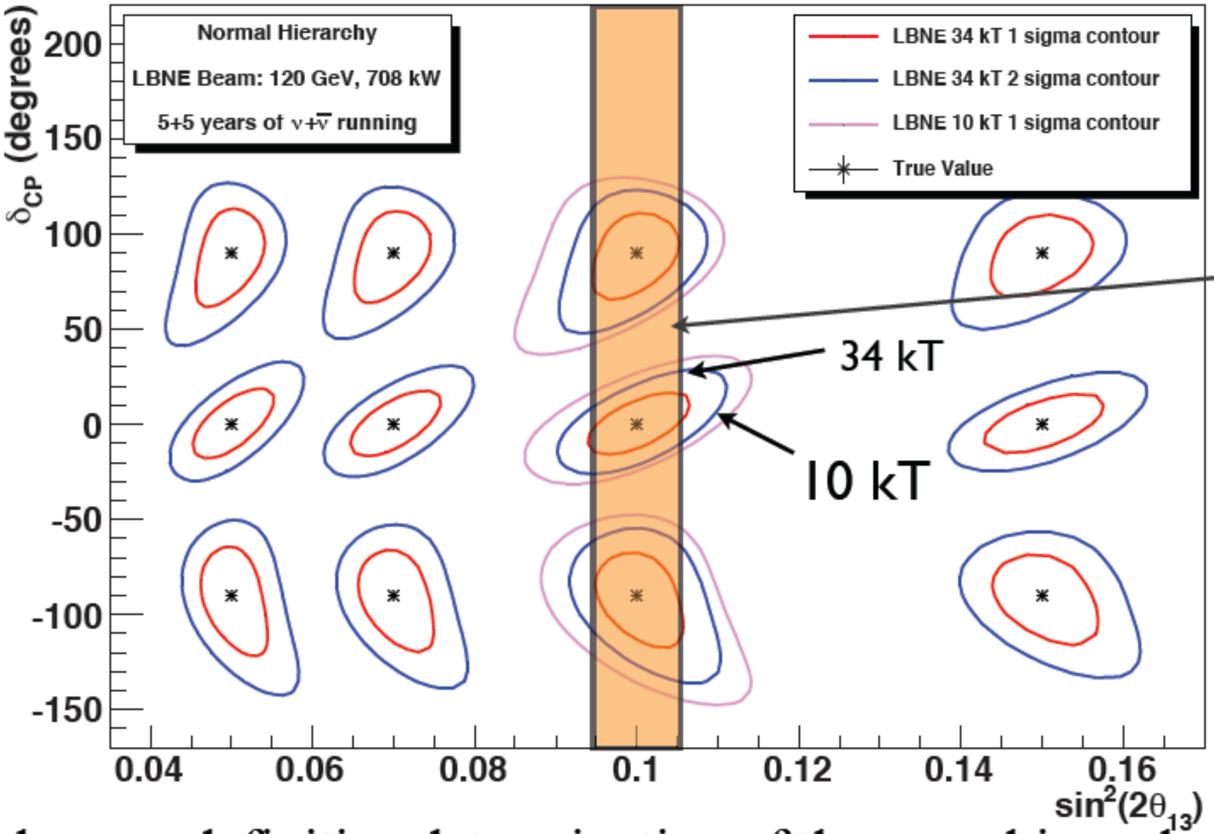
34 ktons in the existing 700 KW Beam. Project X would improve statistics ~factor of 3 for same running time.



LBNE Parameter measurement

Phase I versus Phase II

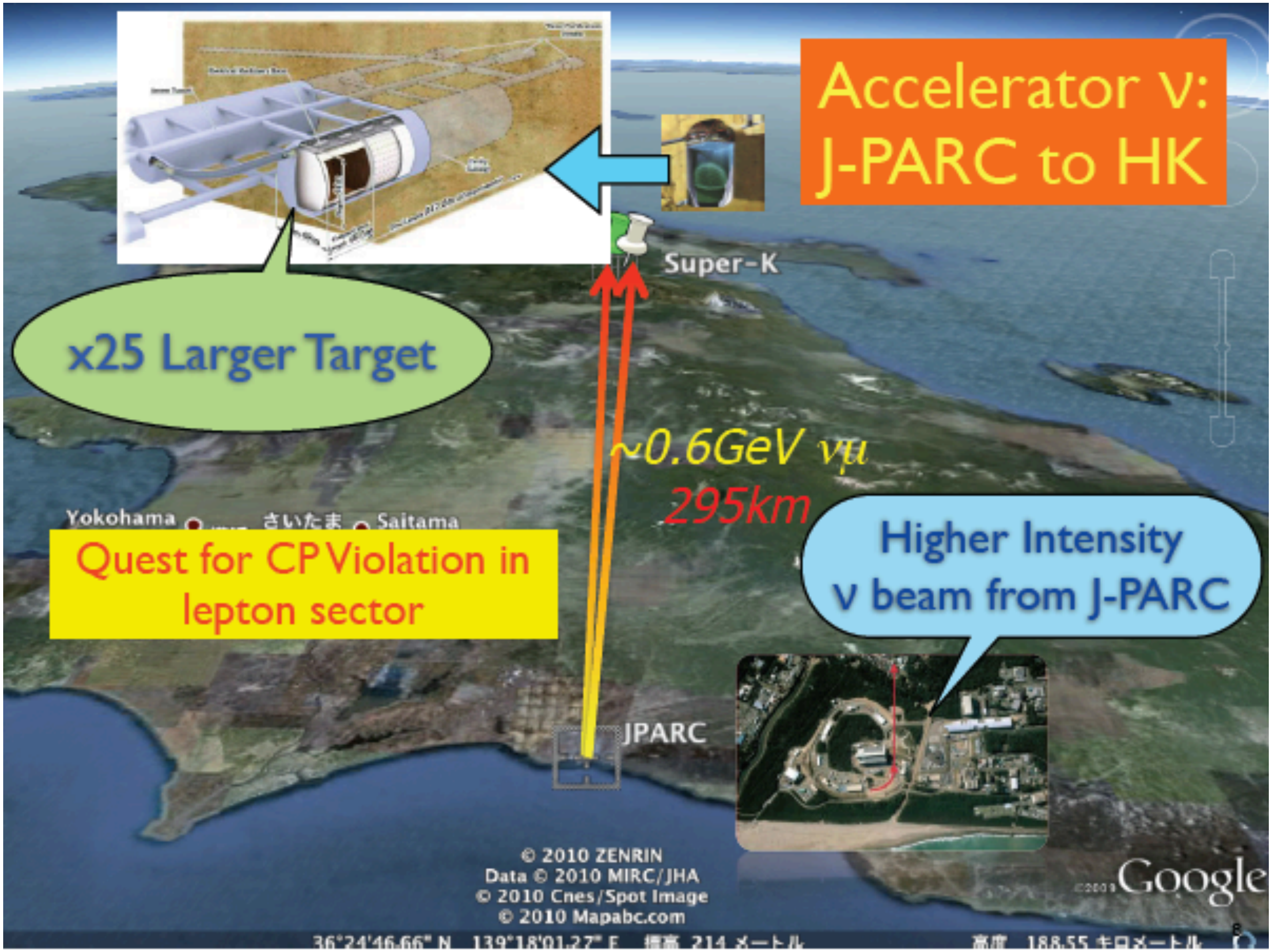
Phase I ν_e(anti-ν_e) ~50 (~20) events per year with >50% modulation



Expected final 1 sigma error from reactors (centered on 0.1)

- LBNE will have a definitive determination of the mass hierarchy.
- LBNE will have a measurement of the phase and θ_{13} with no ambiguities.
- The phase measurement will range from ±20 to ±30 deg for Phase I when combined with reactor data.
- Parameter measurement will continue to improve with statistics.

Example: Hyper-Kamiokande



Accelerator ν: J-PARC to HK

x25 Larger Target

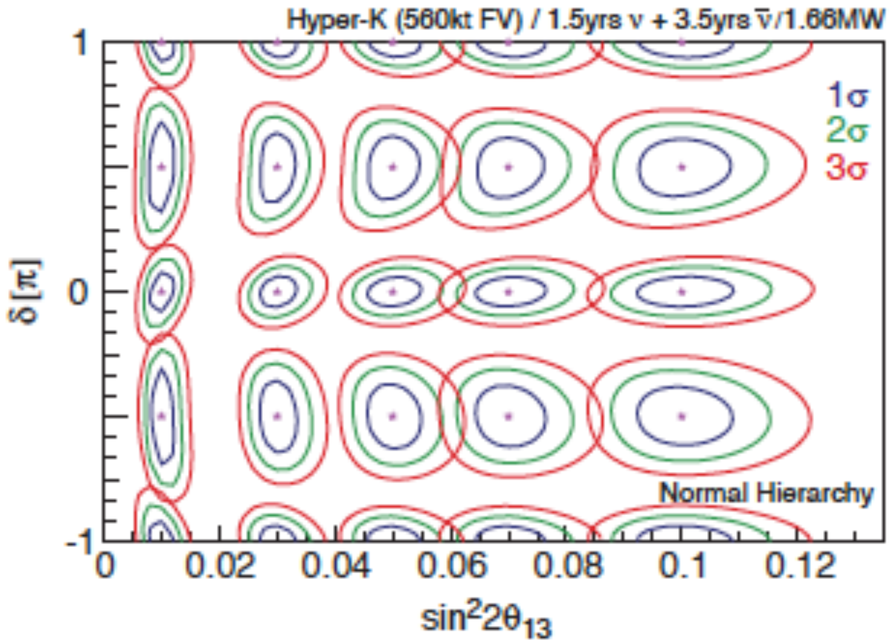
~0.6GeV νμ

295km

Quest for CP Violation in lepton sector

Higher Intensity ν beam from J-PARC

Hyper-K Parameter Measurement



Note: This is 560 ktons fiducial running five years with a 1.66 MW beam. It Assumes the mass hierarchy is known from other experiments or from ten years of of Hyper-K atmospheric neutrino Measurements. (from HK LOI)

What are limiting factors?

- **LBNE Phase II:** Cheaper cost/kton for the far detector TPC and deep depth. No one single cost driver, but some key items include cold electronics, low-cost light collection systems, cheaper cryogenics and purification.
- **Hyper-Kamiokande**: 10^4 PMTs would be > \$200M. Cheaper photosensors needed. Picosecond timing could also improve sensitivity. Neutron tagging could improve flavor separation.

Example: EXO and nEXO ("Next EXO")

Latest EXO results: arXiv:1205.5608

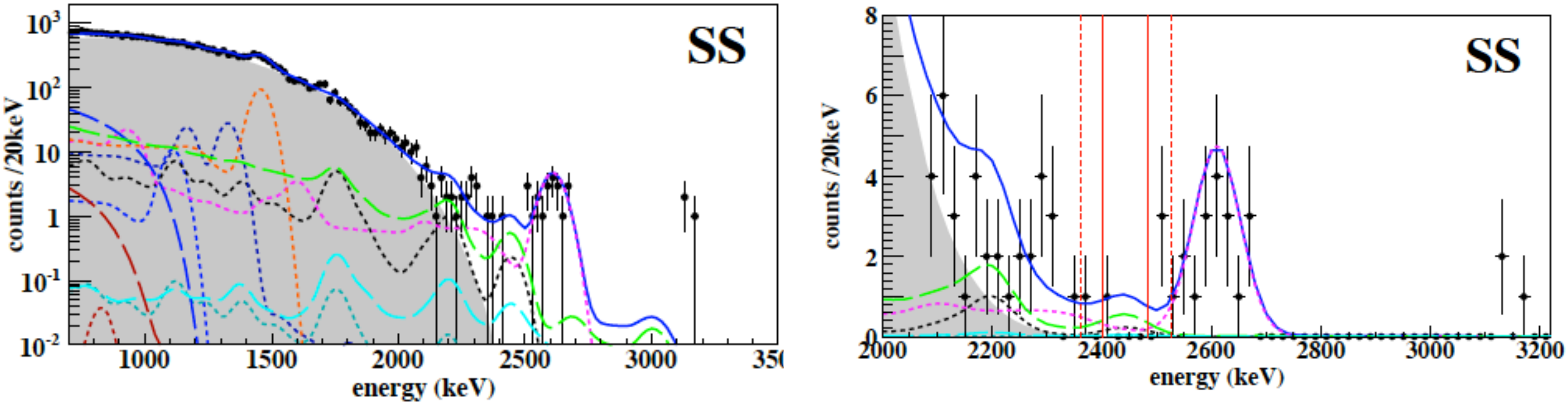
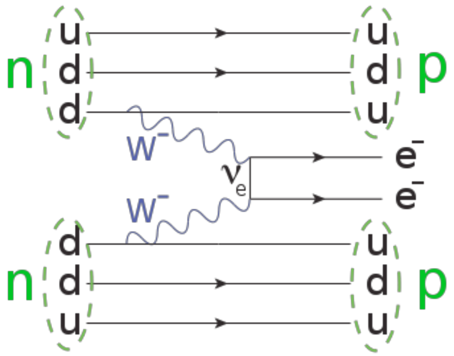
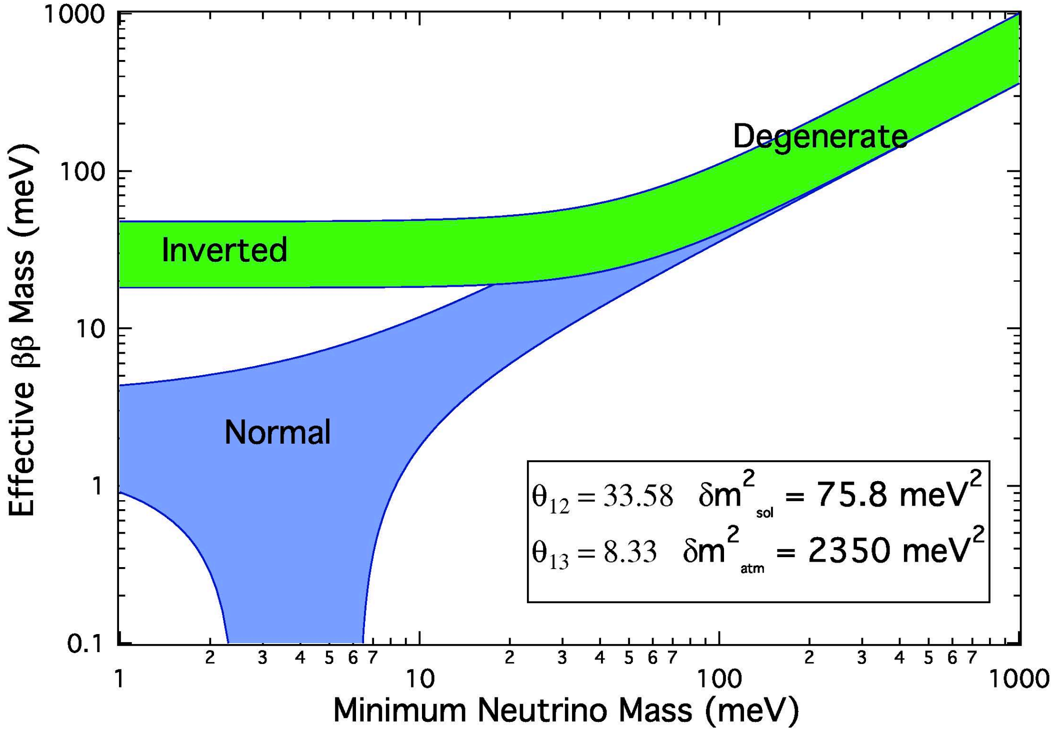


FIG. 4: MS (top) and SS (bottom) energy spectra. The best fit line (solid blue) is shown. The background components are $2\nu\beta\beta$ (grey region), ^{40}K (dotted orange), ^{60}Co (dotted dark blue), ^{222}Rn in the cryostat-lead air-gap (long-dashed green), ^{238}U in the TPC vessel (dotted black), ^{232}Th in the TPC vessel (dotted magenta), ^{214}Bi on the cathode (long-dashed cyan), ^{222}Rn outside of the field cage (dotted dark cyan), ^{222}Rn in active xenon (long-dashed brown), ^{135}Xe (long-dashed blue) and ^{54}Mn (dotted brown). The last bin on the right includes overflows (none in the SS spectrum).

136-Xe Q for 0ν2βDK is 2458 keV (see red ROI above). ENERGY RESOLUTION is a key factor in sensitivity.



Observation of zero neutrino double beta decay would show that neutrinos are Majorana in nature.
the rate is dependent upon the absolute neutrino mass and the mass hierarchy.



The current generation is probing
The top of the "IH" region with
100 kg scale experiments. 1-10 ton
Experiments are needed to completely
cover the green area.

Note relationship to MH experiments!

(From S.Elliott, arXiv:1203.1070)

Intensity Frontier: Cosmology Problem

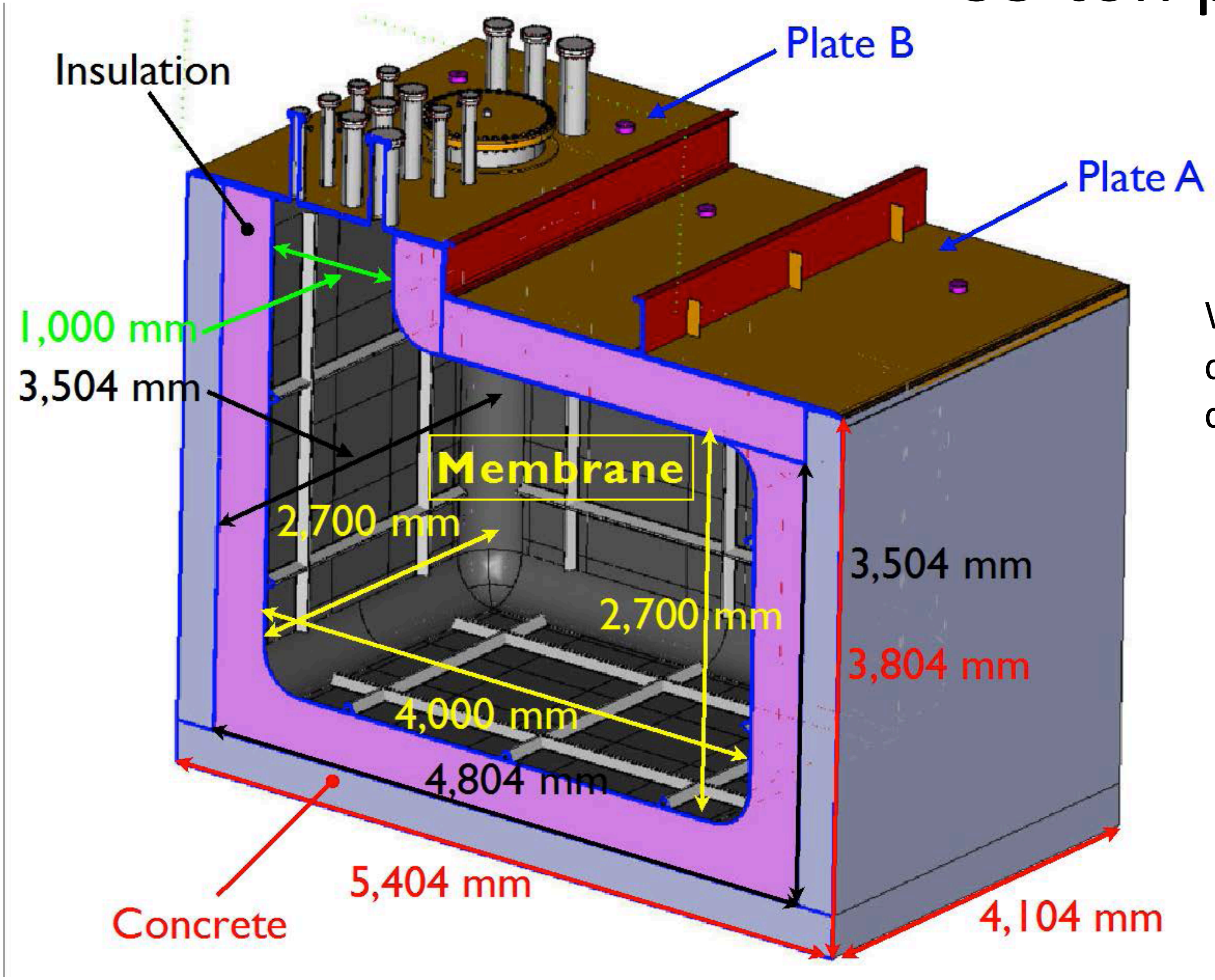
- Indirect DM detection: e.g. ICE CUBE upgrades, Hyper-Kamiokande, LBNE Phase II
- Galactic SN detection: e.g. Hyper-Kamiokande, LBNE Phase II, SNO+, WATCHMAN,…
- Diffuse SN detection: e.g. upgraded Super-Kamiokande

Conclusions

- The technologies used in the IF vary widely, as experiments have very different approaches to the same scientific problems
- Although we divide the field into "technique" frontiers, we should keep in mind the real scientific questions.

Backup Slides

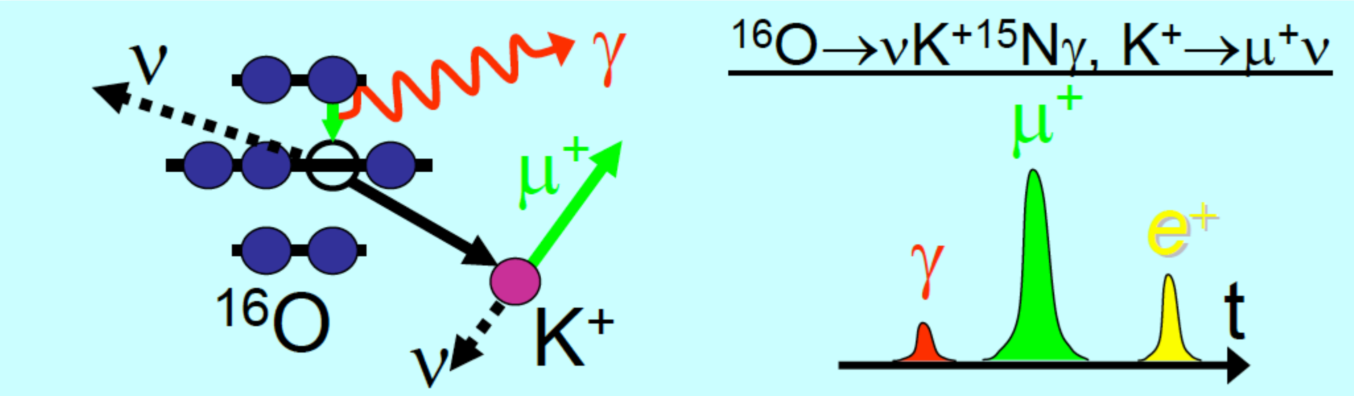
35 ton prototype

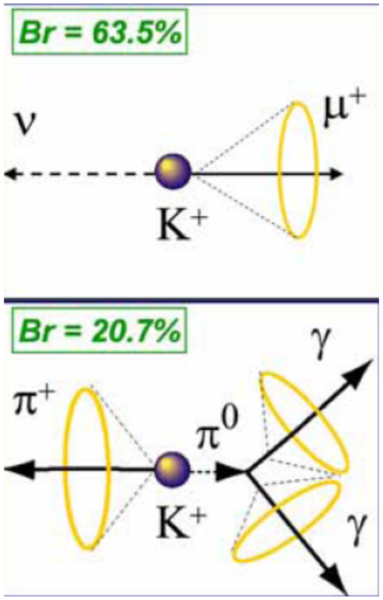


Will allow prototype deployment of many detector components

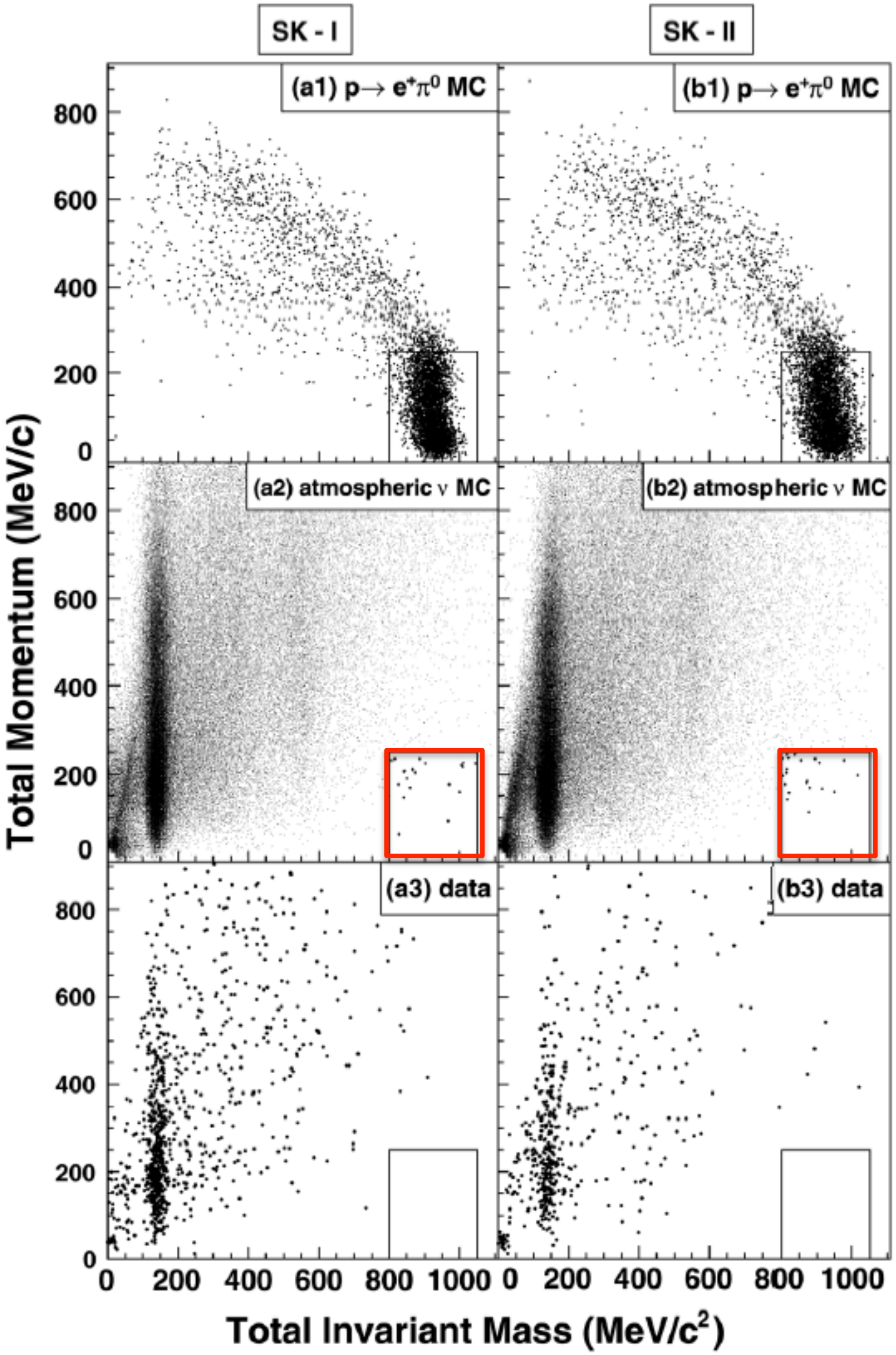
$p \to \bar{\nu} K^+$

- K^+ below Cherenkov threshold is 560 MeV/c. Super-Kamiokande detects K^+ daughters plus nuclear de-excitation tag. A triple coincidence, but low efficiency.





Mode	effxB.R.	Background(/Mton/yr)
$K^+ \to \mu\nu$	36.0%	2000
$K^+ \to \mu\nu + \gamma$	7.2%	1.7
$K^+ \to \pi^+\pi^0$	6.2%	4.7



- background is from atmospheric neutrino interactions
- Estimate that this is dominated by CC (81%), with 51% of these 1+ pion production (PRL 102, 2009)
- How many background events will have one or more neutrons, either from initial interaction, FSI in nucleus, or nuclear de-excitation?
- **Discussions ongoing about a low-energy neutrino beam experiment.**

Will Proton Decay Result in Neutrons?

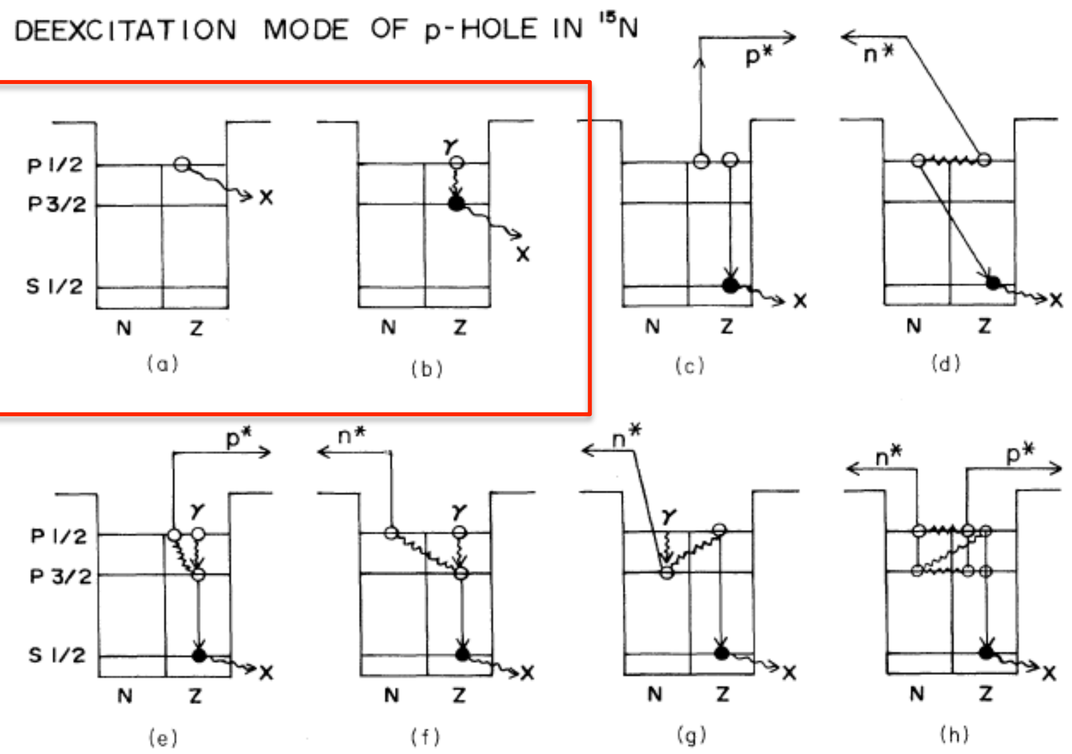


FIG. 1. Deexcitation scheme of a proton hole produced by proton decay ($p \to x$) in ^{16}O. N and Z stand for neutron and proton shells, respectively. p^* and n^* are protons and neutrons emitted into the continuum region.

0556-2813/93/48(3)/1442(3)/$06.00 48 1442

Neutrons from Proton Decay in Water

- 2/10 of protons are free protons. No neutrons.
- 2/10 of protons are in $P_{1/2}$ shell. If they decay nucleus is already in the ground state. No neutrons
- 4/10 of protons are in $P_{3/2}$ shell. If they decay then a $P_{1/2}$ proton will drop down, giving a 6 MeV gamma. No neutrons. (Ejiri gives 94% B.R. for this)
- **~80% of proton decays should give neutrons only indirectly from FSI.** (such FSI usually makes them undetectable anyway) This is fairly model independent. Ejiri's more detailed estimate gives 81%
- Similar numbers for neutron decay.

The prompt 6.32 MeV gamma ray branching ratio of 41% comes from a study of de-excitation of 15-N following a proton decay. This same study predicts inclusive neutron de-excitation branching ratio of ~8%. Most proton decays should not have neutrons. (0.08*0.8 = 6.4%)

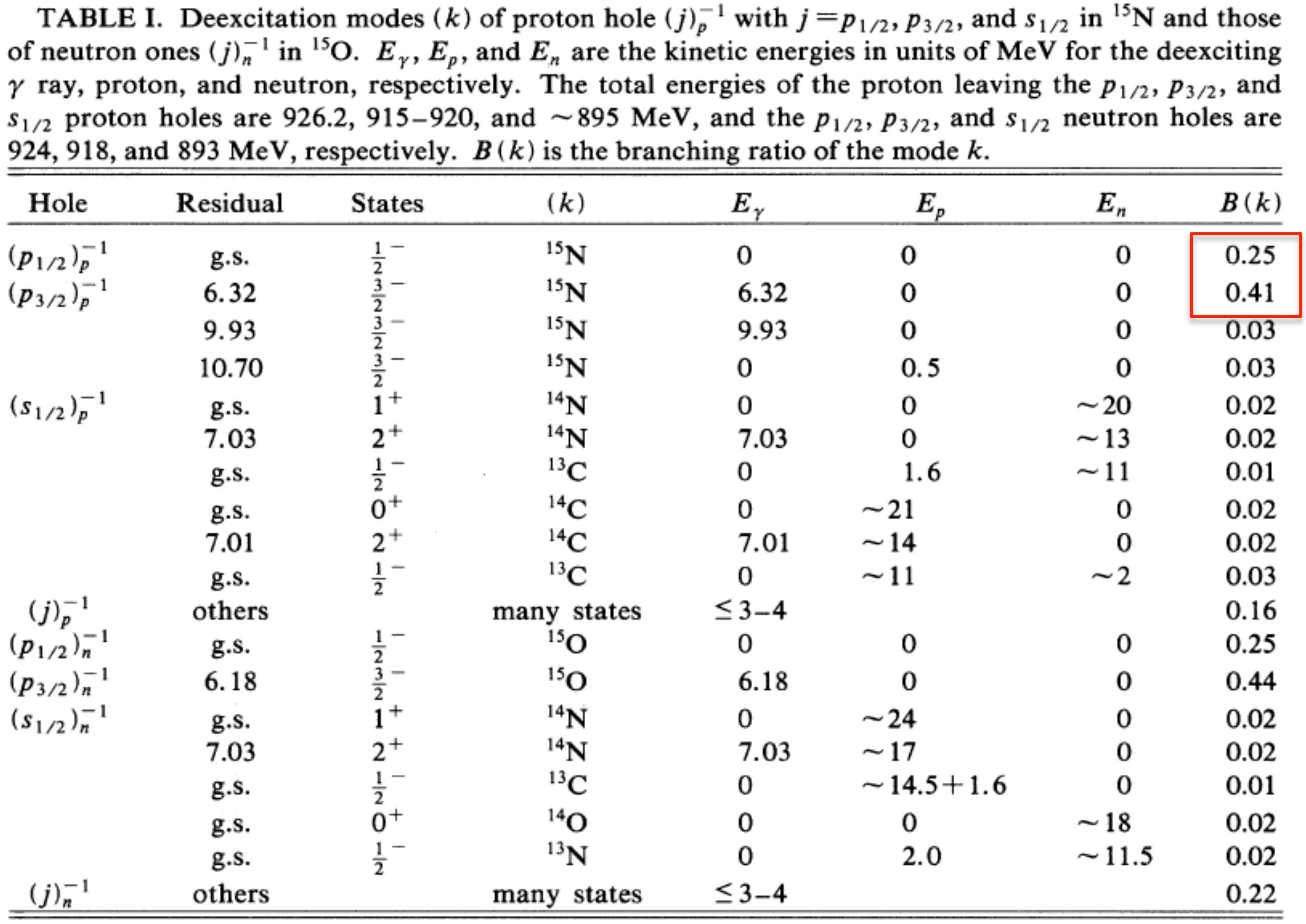


TABLE I. Deexcitation modes (k) of proton hole $(j)_p^{-1}$ with $j = p_{1/2}, p_{3/2}$, and $s_{1/2}$ in ^{15}N and those of neutron ones $(j)_n^{-1}$ in ^{15}O. E_γ, E_p, and E_n are the kinetic energies in units of MeV for the deexciting γ ray, proton, and neutron, respectively. The total energies of the proton leaving the $p_{1/2}$, $p_{3/2}$, and $s_{1/2}$ proton holes are 926.2, 915–920, and ~895 MeV, and the $p_{1/2}$, $p_{3/2}$, and $s_{1/2}$ neutron holes are 924, 918, and 893 MeV, respectively. $B(k)$ is the branching ratio of the mode k.

Hole	Residual	States	(k)	E_γ	E_p	E_n	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}N	0	0	0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	^{15}N	6.32	0	0	0.41
	9.93	$\frac{3}{2}^-$	^{15}N	9.93	0	0	0.03
	10.70	$\frac{3}{2}^-$	^{15}N	0	0.5	0	0.03
$(s_{1/2})_p^{-1}$	g.s.	1^+	^{14}N	0	0	~20	0.02
	7.03	2^+	^{14}N	7.03	0	~13	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	1.6	~11	0.01
	g.s.	0^+	^{14}C	0	~21	0	0.02
	7.01	2^+	^{14}C	7.01	~14	0	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	~11	~2	0.03
$(j)_p^{-1}$	others		many states	≤3–4			0.16
$(p_{1/2})_n^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}O	0	0	0	0.25
$(p_{3/2})_n^{-1}$	6.18	$\frac{3}{2}^-$	^{15}O	6.18	0	0	0.44
$(s_{1/2})_n^{-1}$	g.s.	1^+	^{14}N	0	~24	0	0.02
	7.03	2^+	^{14}N	7.03	~17	0	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	~14.5+1.6	0	0.01
	g.s.	0^+	^{14}O	0	0	~18	0.02
	g.s.	$\frac{1}{2}^-$	^{13}N	0	2.0	~11.5	0.02
$(j)_n^{-1}$	others		many states	≤3–4			0.22

H.Ejiri
PRC 48 (1993)

What Other Modes are Good for LAr? (2)

		Super-K Water Ch.		LAr (generic)	
	Mode	Efficiency	BG Rate (/Mt y)	Efficiency	BG Rate (/Mt y)
B-L	$e^+\pi^0$	45%	2	45%	1
	ν K^+	16%	7	**97%**	**1**
	μ+ K^0	10%	5-10	**47%**	**<2**
B+L	μ^- π^+ K^+	?	?	**97%**	**1**
	e^- K^+	10%	3	**96%**	**<2**
ΔB=2	n nbar	12%	260	**?**	**?**

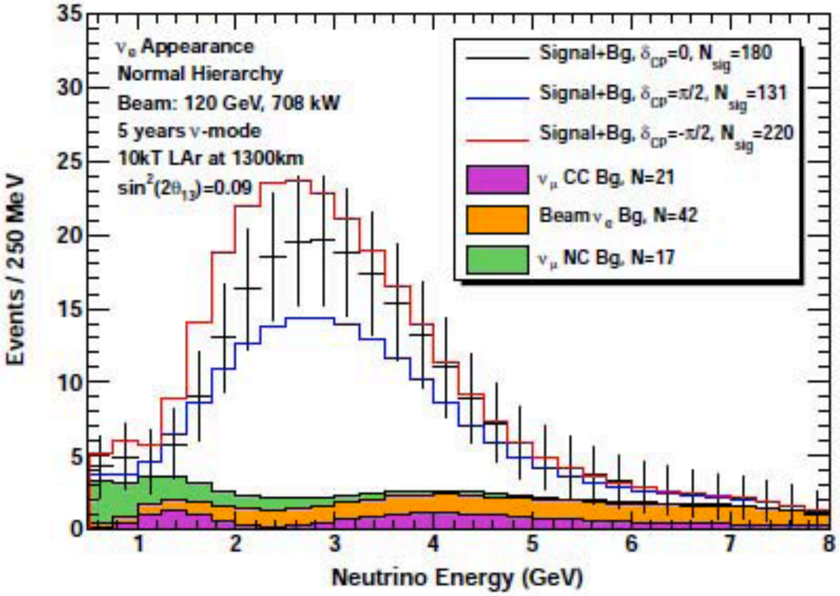
Rough and unofficial
SK efficiency & BG – ETK

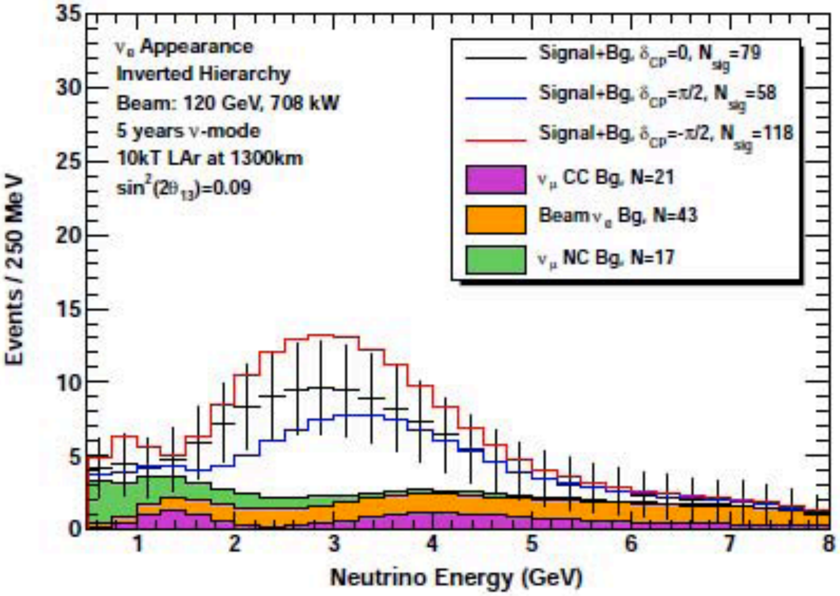
A. Bueno et al.
hep-ph/0701101

estimates from Ed Kearns

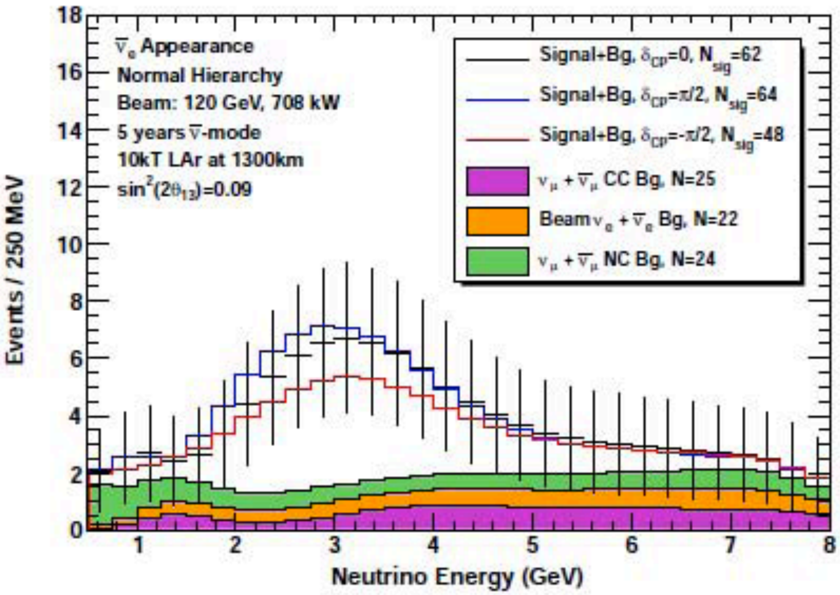
Costs after Reconfiguration

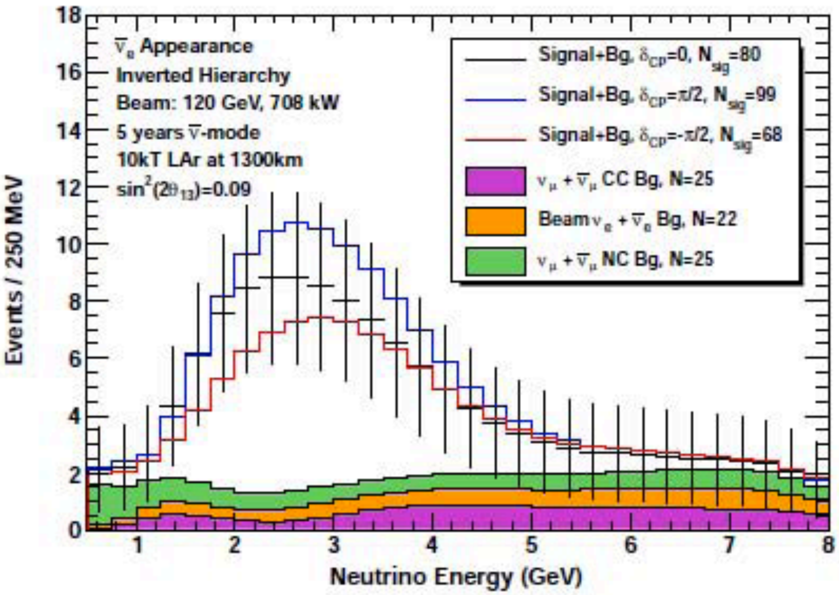
Scope	Cost (TPC)
LBNE 34 kTon@4850L and near detector	$1.440B
LBNE Phase I, 10 kTon surface	$0.789B
+Place Underground	$0.924B
+ Near Detector	$1.054B

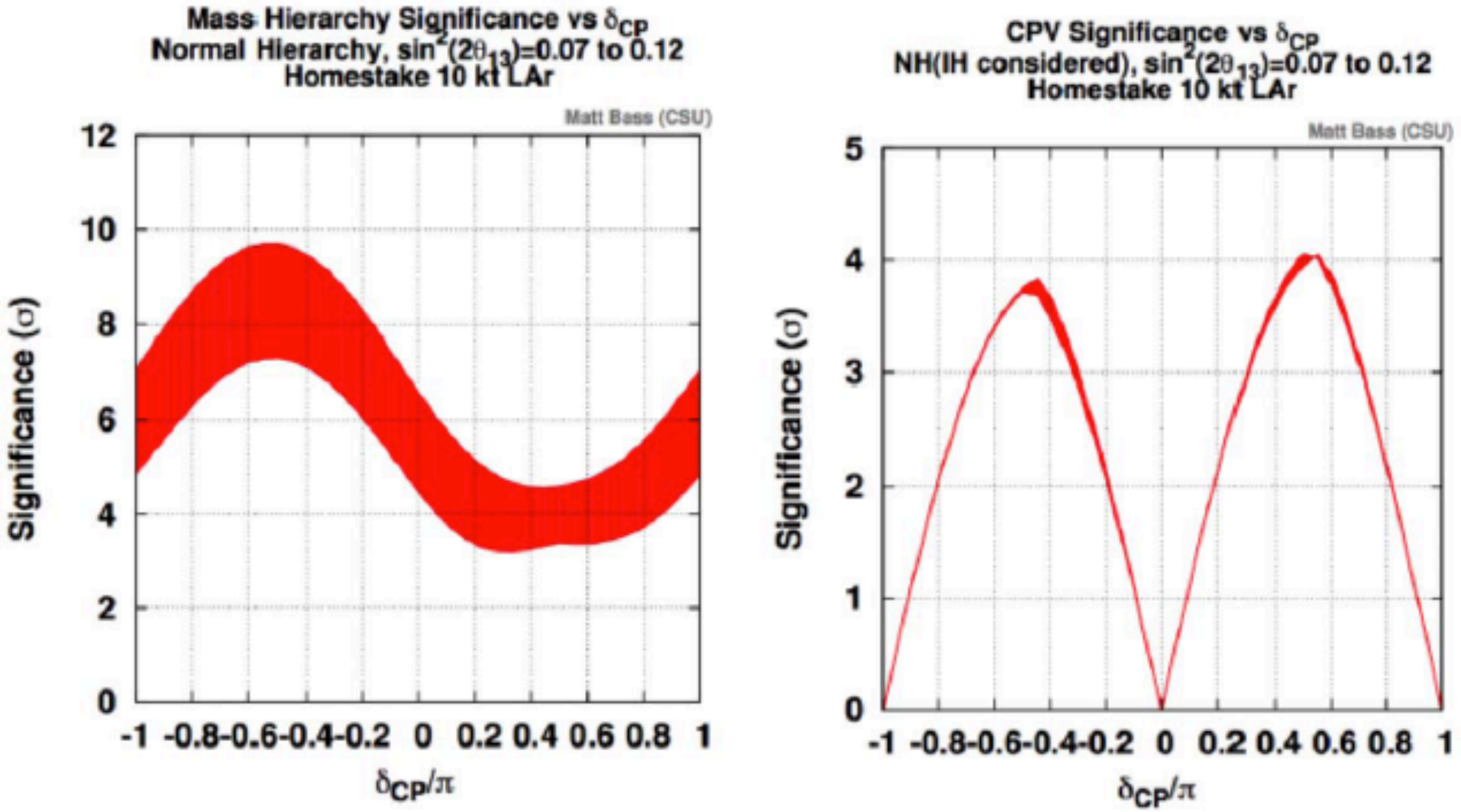




LBNE 10 ktons Phase I






Mass Hierarchy Significance vs δ_{CP}
Normal Hierarchy, $\sin^2(2\theta_{13})$=0.07 to 0.12
Homestake 10 kt LAr

CPV Significance vs δ_{CP}
NH(IH considered), $\sin^2(2\theta_{13})$=0.07 to 0.12
Homestake 10 kt LAr

Figure 15. Significance for determining the hierarchy (left) and CP violation (right) as a function of δ_{CP} for the first phase of LBNE, leveraging the knowledge that will have been gained from NOvA and T2K beforehand. Projections are for 5+5 years of 700 kW $\nu + \bar{\nu}$ of a 10 kton fiducial mass LAr TPC at Homestake combined with anticipated results from NOvA (3+3 years at 700 kW) and T2K ($5x10^{21}$ POT or ~6 years). The bands indicates the change in significance when the assumed value of $\sin^2 2\theta_{13}$ is varied from 0.07 to 0.12, corresponding to roughly a $\pm 2\sigma$ variation relative to the latest results presented by Daya Bay at Neutrino 2012.