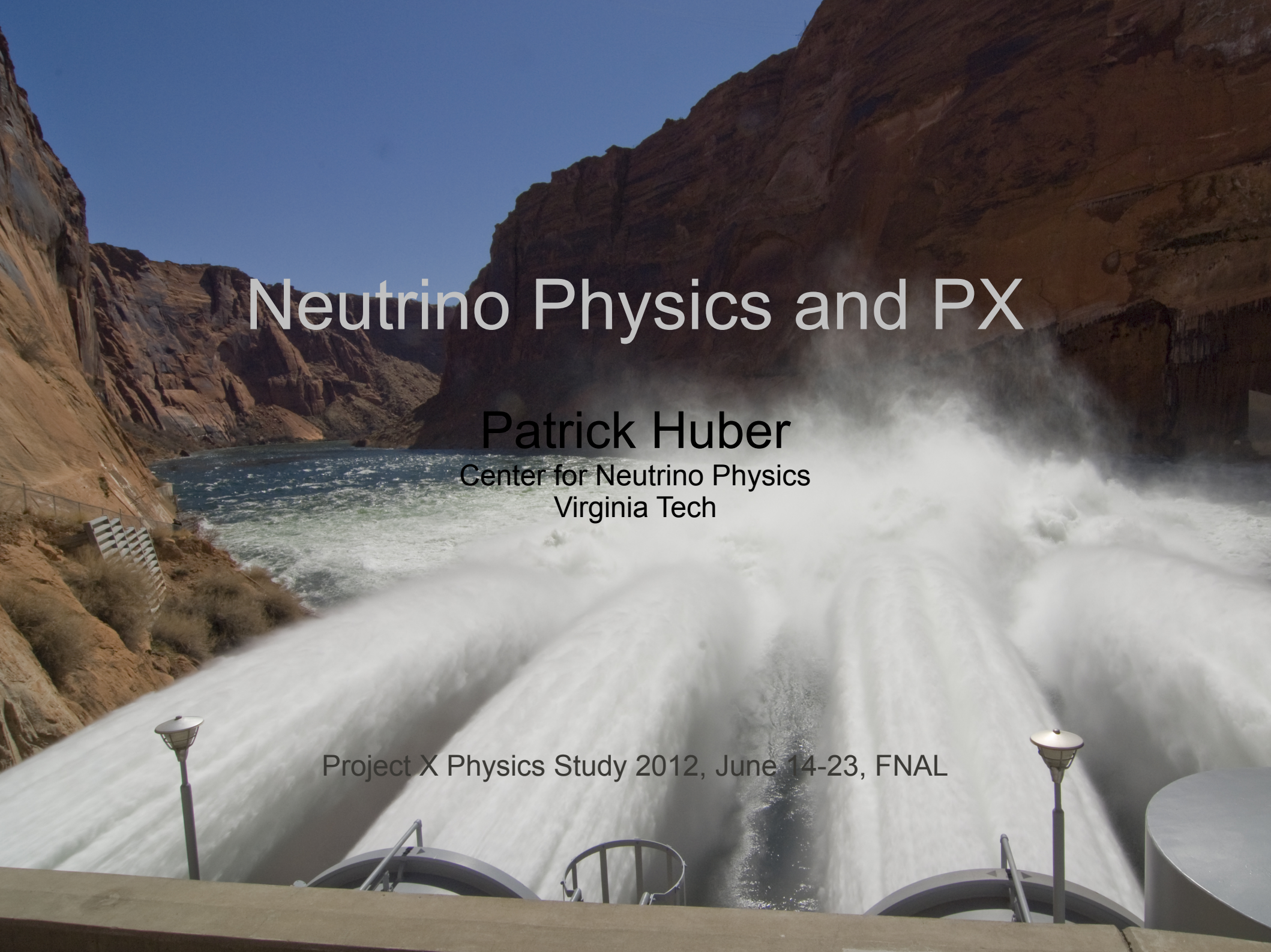
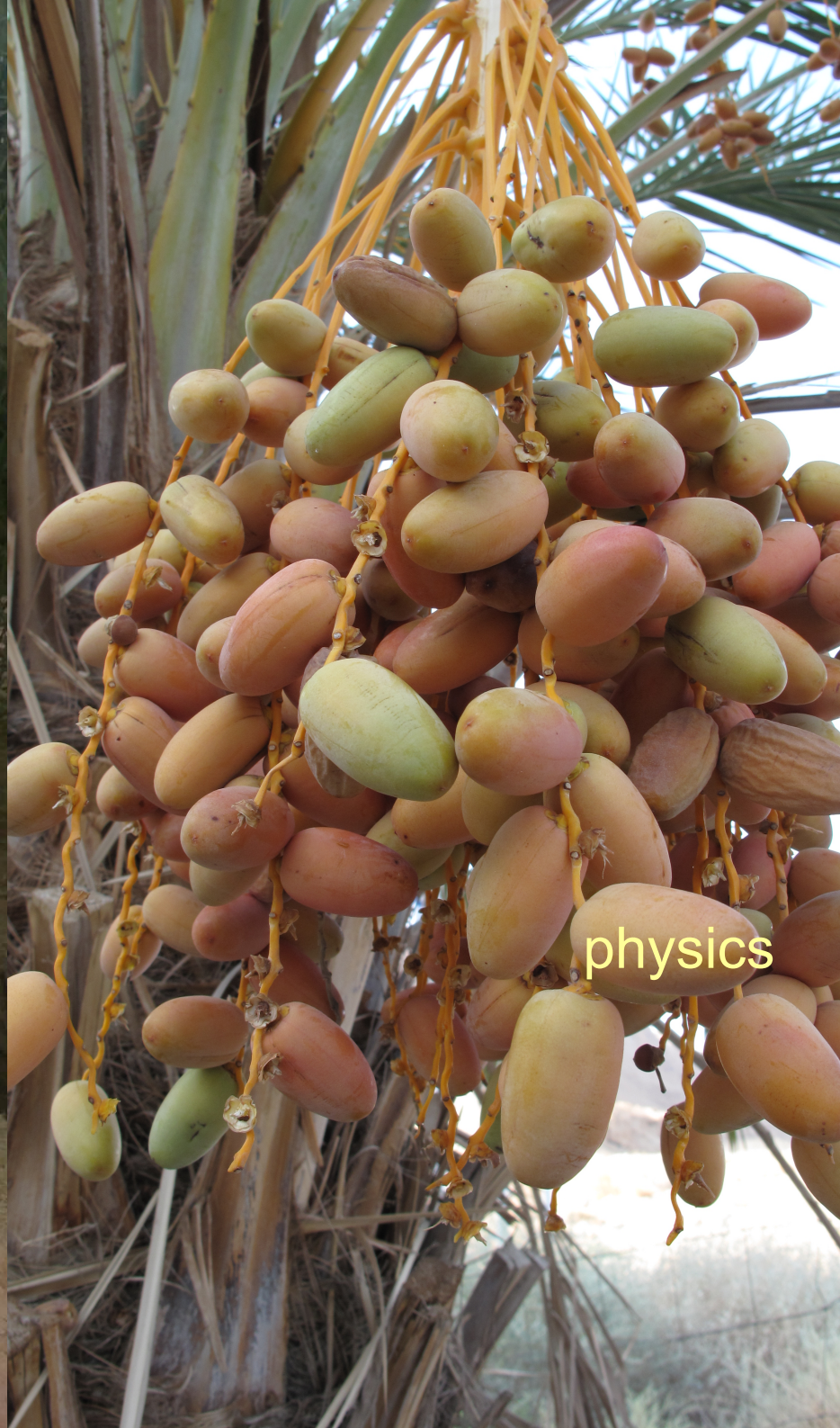


Neutrino Physics and PX

Patrick Huber
Center for Neutrino Physics
Virginia Tech

Project X Physics Study 2012, June 14-23, FNAL

An analogy...



Sterile neutrinos - SBL anomalies

- There is a great deal of interest in sterile neutrinos lately

  Workshop on Beyond Three Family Neutrino Oscillations, LNGS, April 2011
  Short-Baseline Neutrino Workshop, Fermilab, May 2011
  Sterile Neutrinos at the Crossroads Workshop, Virginia Tech, Sept. 2011
  Future Short Baseline Neutrino Experiments −Needs & Options, Fermilab, March 2012
  Light Sterile Neutrinos: A White Paper, arXiv:1204.5379, April 2012

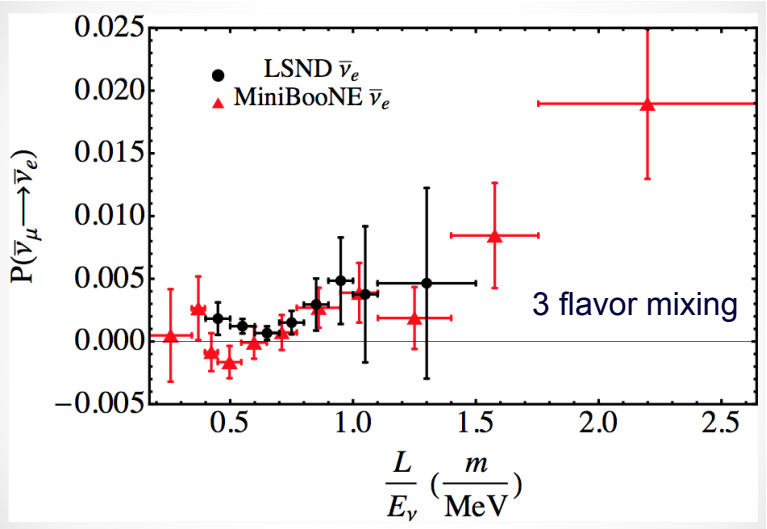
- There are many hints of sterile neutrinos in particle physics: LSND, MiniBooNE ν, Gallium, Reactor Flux

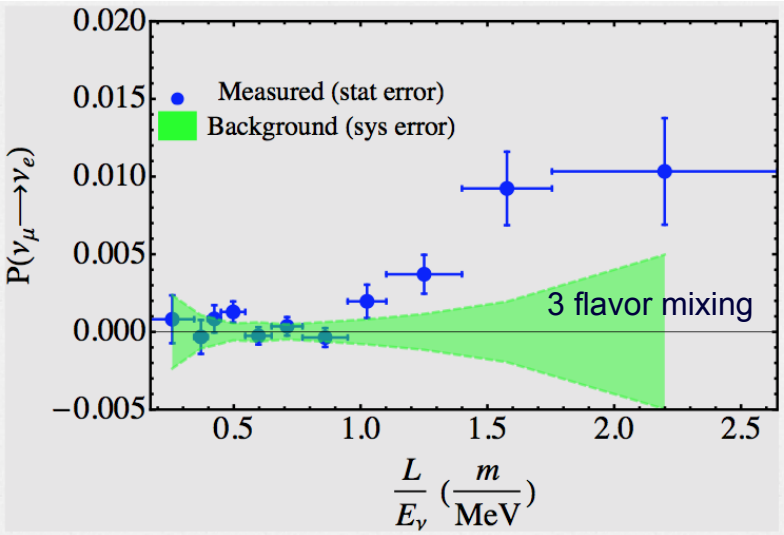
- There are many null or ambiguous results as well: KARMEN, Bugey, MiniBooNE ν, Accelerator Disappearance

- There are several proposals/concepts for new, hopefully definitive tests of the $\Delta m \sim 1\ \mathrm{eV}^2$ sterile neutrino hypothesis.

Courtesy J. Link

LSND & MiniBooNE





An excess of events above background seen by LSND (>3σ) + MiniBooNE (3σ), corresponding to a transition probability O(0.003).

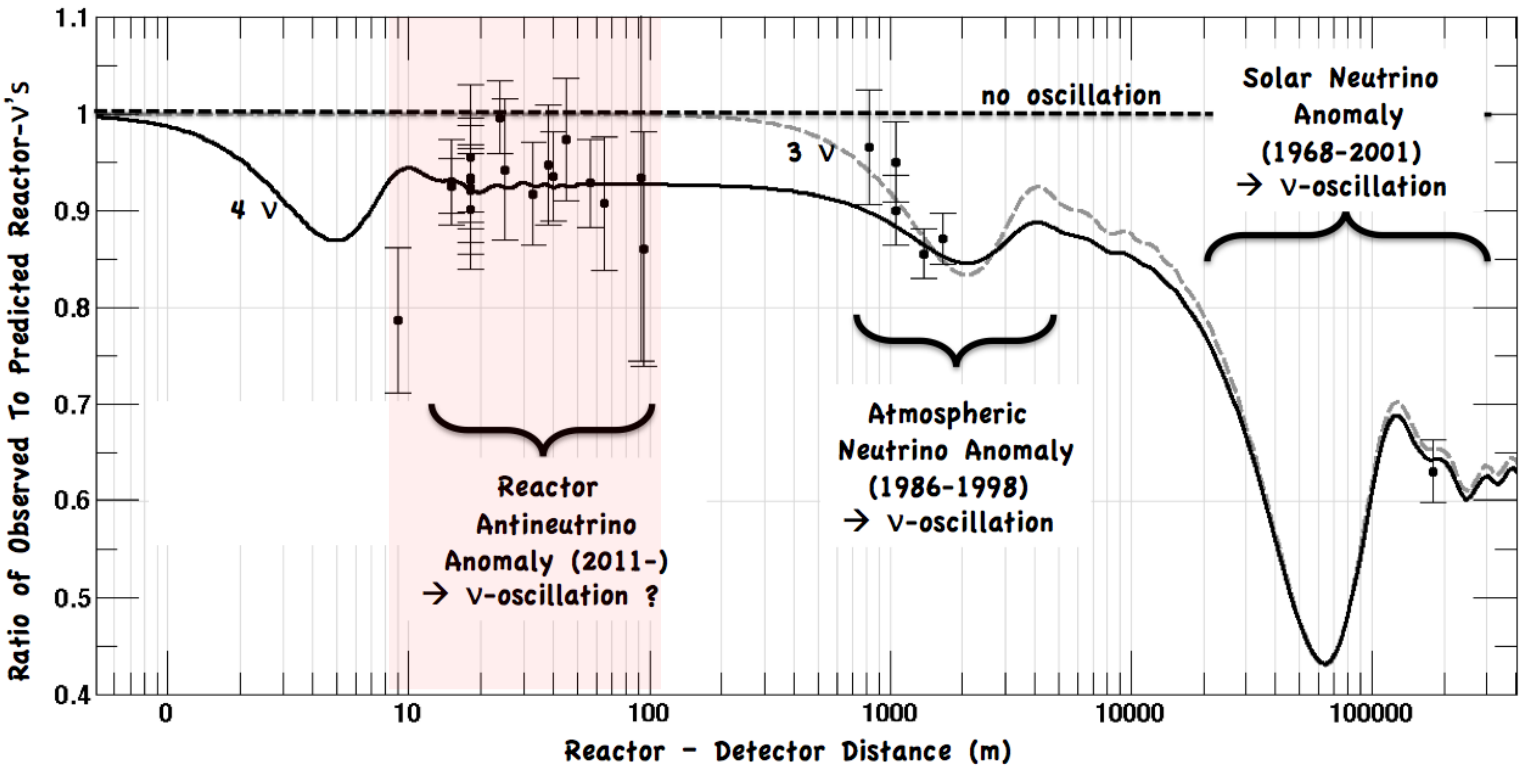
An ~3σ excess of events above background seen by MiniBooNE at low neutrino energies (E < 0.5 GeV) . At higher energies data consistent with background.

The combined ν + ν MiniBooNE excess = 240.3±34.5±52.6 events (3.8σ).

Courtesy S. Geer

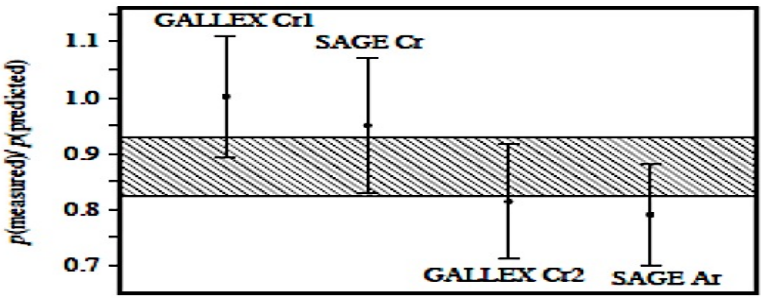
REACTOR ANOMALY

New analysis of the reactor anti-neutrino spectrum has increased the expected flux by 3%, neutron life time decreased and non-equilibrium corrections combine to a 6% effect



Gallium anomaly

SAGE, PRC 73 (2006) 045805



R=0.86+-0.05

SAGE, PRC 73 (2006) 045805
arXiv:nucl-ex/0512041

The solar radiochemical detectors GALLEX and SAGE used intense ^{51}Cr and ^{37}Ar electron-capture neutrino sources to "calibrate" the ν_eGa cross section.

The average ratio of measurement to theory:

R=0.86±0.05 (Bahcall)

R=0.76 $^{+0.09}_{-0.08}$ (Haxton)

Courtesy S. Geer

Sterile neutrino white paper

~200 authors, >250 pages, >700 references

For more information see the *Light Sterile Neutrinos: A White Paper* (arXiv:1204.5379 [hep-ph])

Outline:

1. Theory and Motivation (editors Barenboim & Rodejohann)
2. Astrophysical Evidence (Abazajian & Wong)
3. Evidence from Oscillation Experiments (Koop & Louis)
4. Global Picture (Lasserre & Schwetz)
5. Requirements for Future Experiments (Fleming & Formaggio)
6. Appendix: Possible Future Experiments (Huber & Link)

Written from an international perspective for an audience including *both* the scientific community and funding agencies.

Visit http://cnp.phys.vt.edu/white_paper/

Courtesy J. Link

SBL focus group

A new Short-Baseline experiment at Fermilab is well motivated and is necessary to definitively resolve the LSND/MiniBooNE tensions with three-flavor mixing:

1. A new experiment to search for anti-$\nu_\mu \rightarrow$ anti-ν_e and/or $\nu_e \rightarrow \nu_\mu$ transitions. The experiment should be capable of <u>both</u> excluding sterile neutrinos over the entire allowed LSND/MiniBooNE parameter space with a significance of at least 5s, and of discovering sterile neutrinos if they exist within this region of parameter space, also with a significance of at least 5σ.

2. The new experiment be pursued as vigorously as is practical.

SBL focus group

We note that LOIs have been written for several interesting options for a new short-baseline experiment at Fermilab:

3. The Focus Group recommends there be a call for proposals for a new short-baseline experiment that can be evaluated by the PAC at one time, and that the evaluation be on a timescale that is as fast as is practical. The criteria for evaluating the proposals should include:

- The ability to discover, or exclude (at 5s), sterile neutrinos over the entire parameter space indicated by the LSND and MiniBooNE results.
- The expected statistical and systematic uncertainties, and the uncertainty on those uncertainties.
- The possible upgrade path that might be followed IF there were a discovery.

SBL focus group

If sterile neutrinos are discovered, the SBL program be further expanded to include additional experiments capable of exploring as many flavor transitions as practical over the appropriate *L/E* range.

4. The Focus Group recommends that in the advent of a sterile neutrino discovery, either at Fermilab or elsewhere, the Fermilab short-baseline program be further expanded to include one or more additional experiments capable of exploring as many flavor transitions as practical over the appropriate *L/E* range. Indeed it seems likely, in this scenario, that the short-baseline program would become, for an extended period of time, a flagship of the domestic accelerator based program.

The neutrino cross-section & flux knowledge needed for any given proposed experiment depend on the experimental details & the energy range .

5. The impact of cross-section and flux uncertainties on the sensitivity of any proposed new short-baseline experiment should be spelled out in the proposal, together with an assessment of the need for new cross-section and/or particle production measurements beyond those currently planned.

SBL focus group

The currently planned beam power at 8 GeV is not obviously competitive with multi-GeV beam powers at J-PARC and CERN.

6. A study to understand better the potential for increasing the beam power at 8 GeV, and the resulting neutrino beam intensity, should be undertaken.

This would help ensure that upgrades to the complex do not unnecessarily limit the laboratory's options in response to a discovery, and that options for increasing the intensity of future Booster Neutrino Beam experiments are well understood.

If these recommendations are followed there would be new SBL experiment at FNAL which has results prior to PX phase I

Most likely, there will be a worldwide effort to address the sterile neutrino question by a wide variety of techniques, many of which do not rely on accelerators or are underground (isoDAR, LSND reloaded, new reactor experiments, radioactive source experiments ...)

Therefore, PX phase I would be needed to do precision studies of sterile neutrinos or no SBL physics at all

Not obvious that pion decay based beams with 1% nu_e background provide the required systematics control to study a 0.1% effect with precision (see BooNE+ talk)

Limitations of pion decay based beams

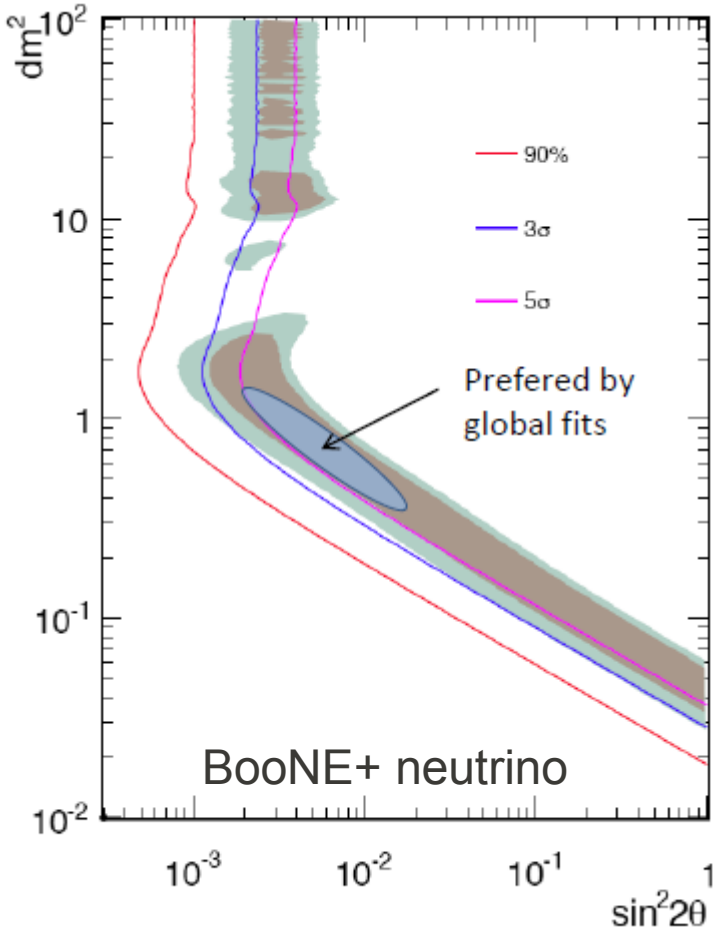
MiniBooNE uncertainties

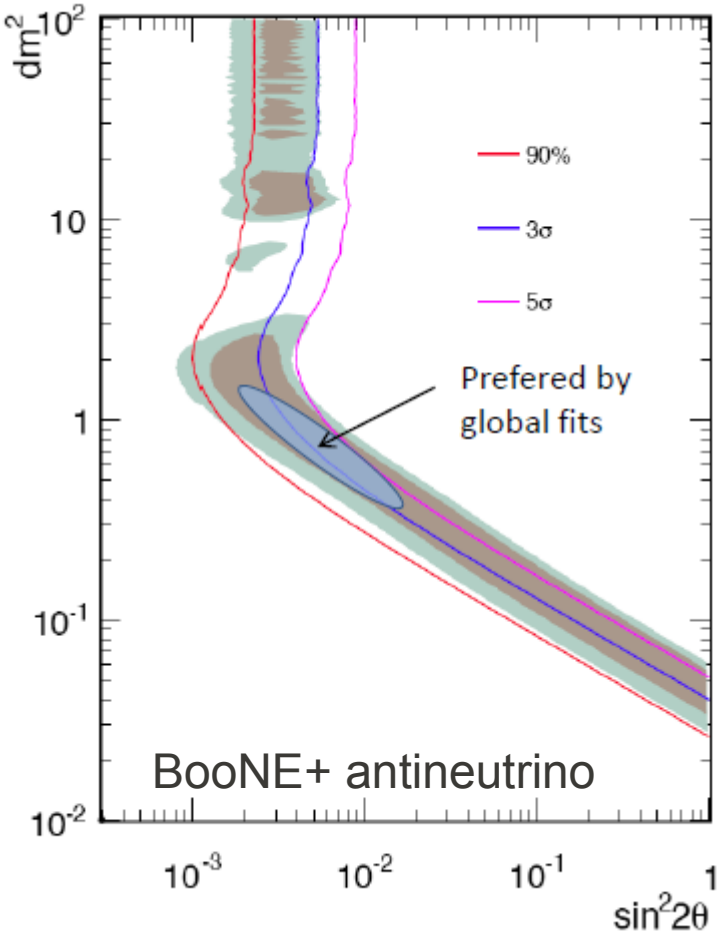
Uncertainty (%)	200-475 MeV	475-1100 MeV
π+	0.4	0.8
π-	3.1	2.5
K+	0.7	1.4
K-	0.5	1.2
K0	1.9	5.3
Target and beam models	1.6	2.9
Cross sections	6.4	12.7
NC π0 yield	1.5	1.4
Hadronic interactions	0.4	0.2
Dirt	1	0.5
Electronics&DAQ model	4.2	4.3
Optical Model	8.2	3.1
Total	12.1%	15.4%

- Unconstrained nuebar background uncertainties
- Biggest contributors
  - Detector response
  - Cross sections

Z. Pavlovic

Limitations of pion decay based beams





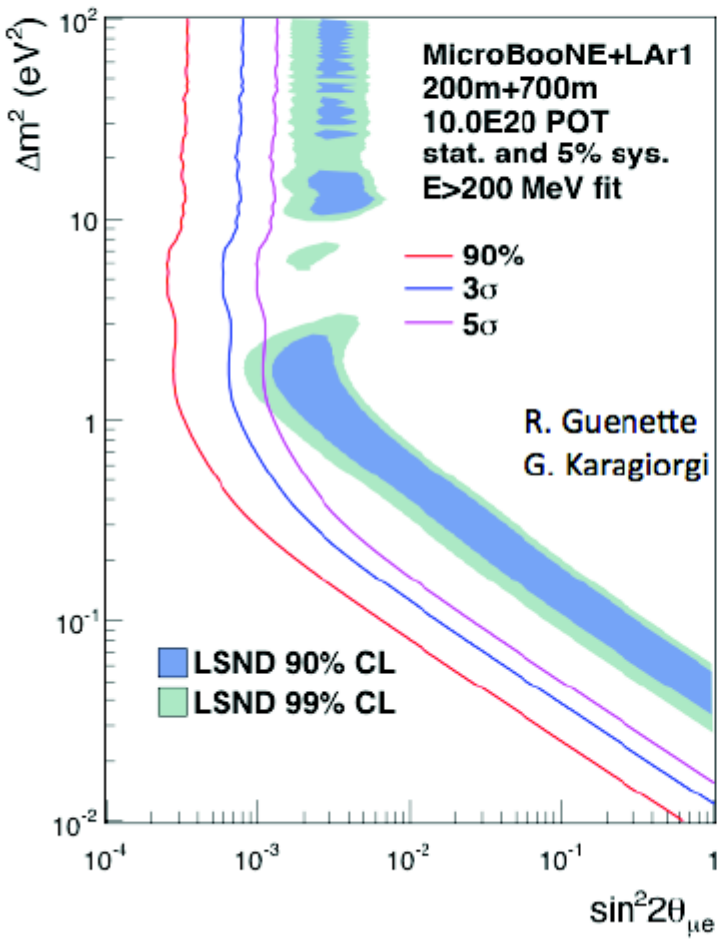
Not obvious that large increase in statistics will alleviate systematics issue (see also talk by J. Grange)

Z. Pavlovic

Another way to use the same beam

LAr1 sensitivity* to MiniBooNE anti-neutrino anomaly

MicroBooNE at 200m and LAr1 at 700m



10.0E20 POT: ~5 years with present running conditions

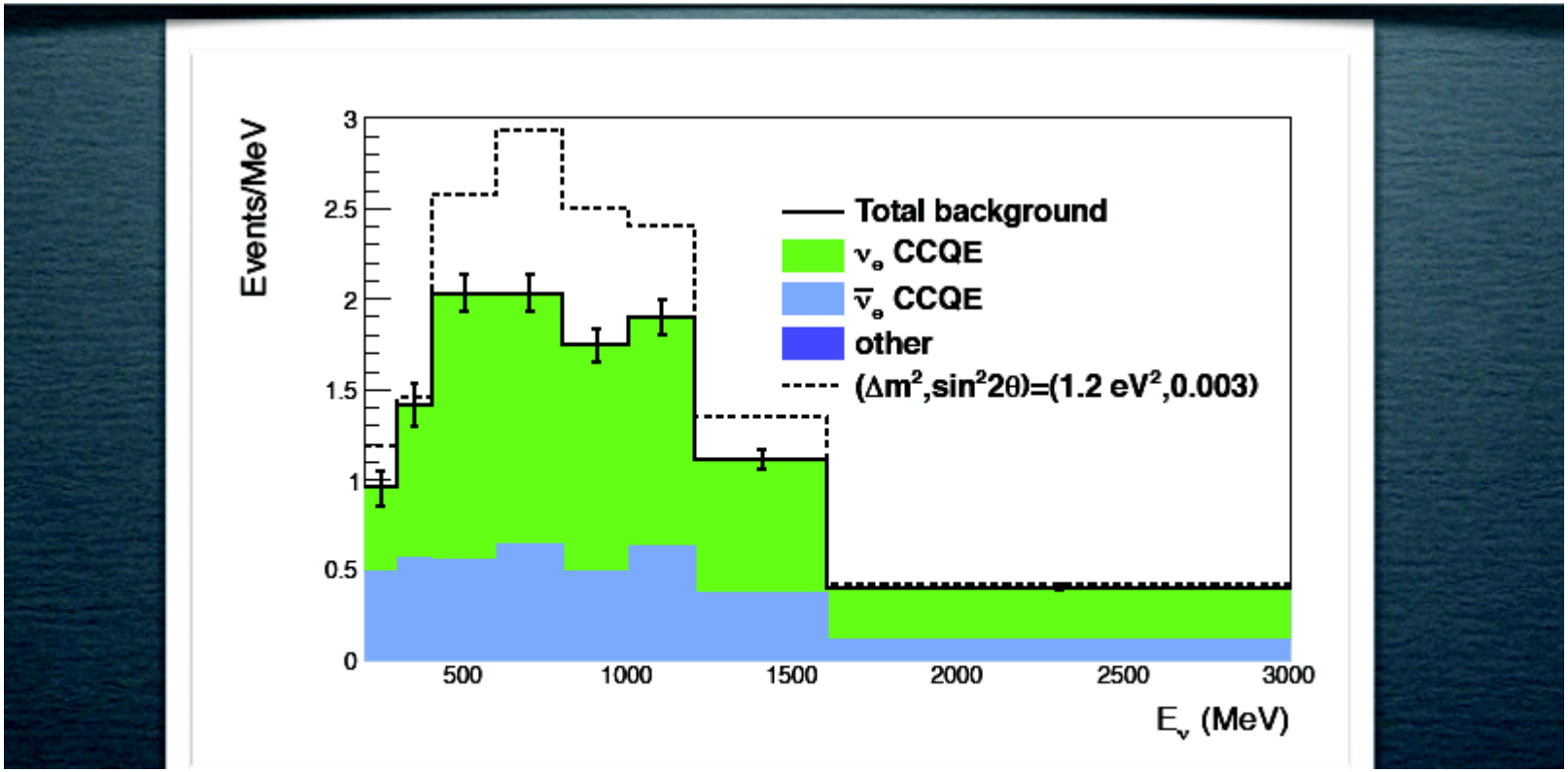
Fiducial volumes assumed for MicroBooNE and LAr1 are 61 t and ~1 kt respectively.

* 3+1 neutrino model

F. Cavanna

Another way to use the same beam

Intrinsic ν_e	Intrinsic $\bar{\nu}_e$	LSND Best Fit $\nu+\bar{\nu}$	ν_μ	$\bar{\nu}_\mu$
200-3000 MeV	200-3000 MeV	200-3000 MeV	200-2000 MeV	200-3000 MeV
1,895	894	257+434	130,126	217,059

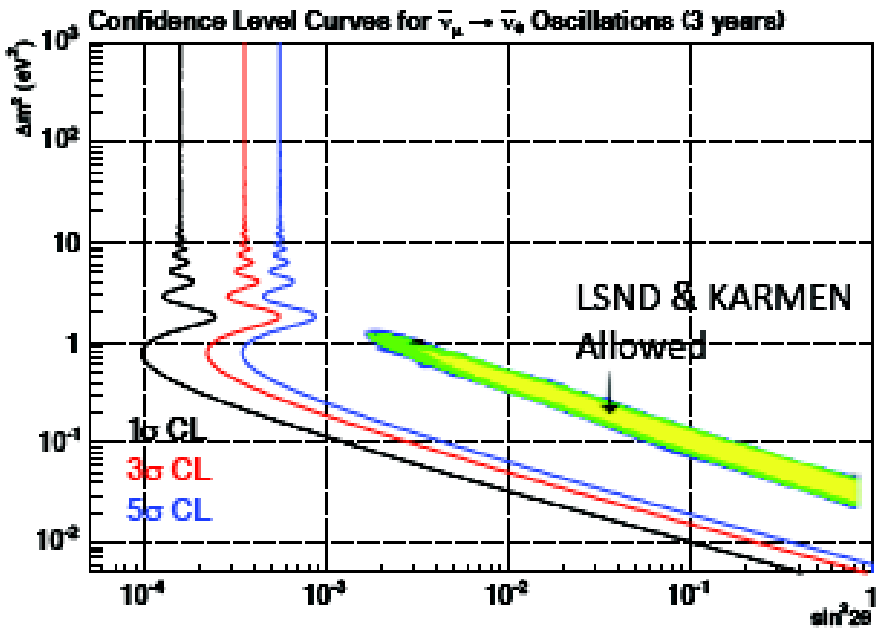


F. Cavanna

DAR/OscSNS/OscFNAL

OscSNS Event Rates at 60m

Channel	Events/year
ν_e C -> e^- N_{gs}	4650
ν_e C -> e^- N^*	2247
ν_μ C -> ν_μ $C^*(15.11)$	1463
ν C -> ν $C^*(15.11)$	6322
ν_e e^- -> ν_e e^-	1320
ν_μ e^- -> ν_μ e^-	450
100% $\bar{\nu}_\mu$ -> $\bar{\nu}_e$, $\bar{\nu}_e$ p -> e^+ n	99,275
0.4% $\bar{\nu}_\mu$ -> $\bar{\nu}_e$, $\bar{\nu}_e$ p -> e^+ n	397



Requires a 1MW proton beam with low duty cycle

W. Louis

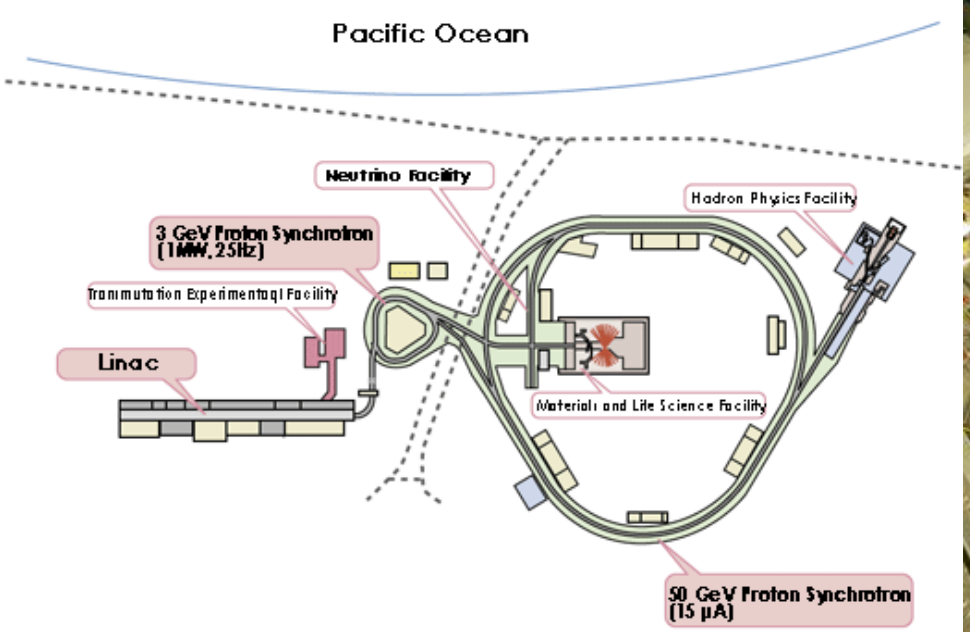
Spallation sources around the globe

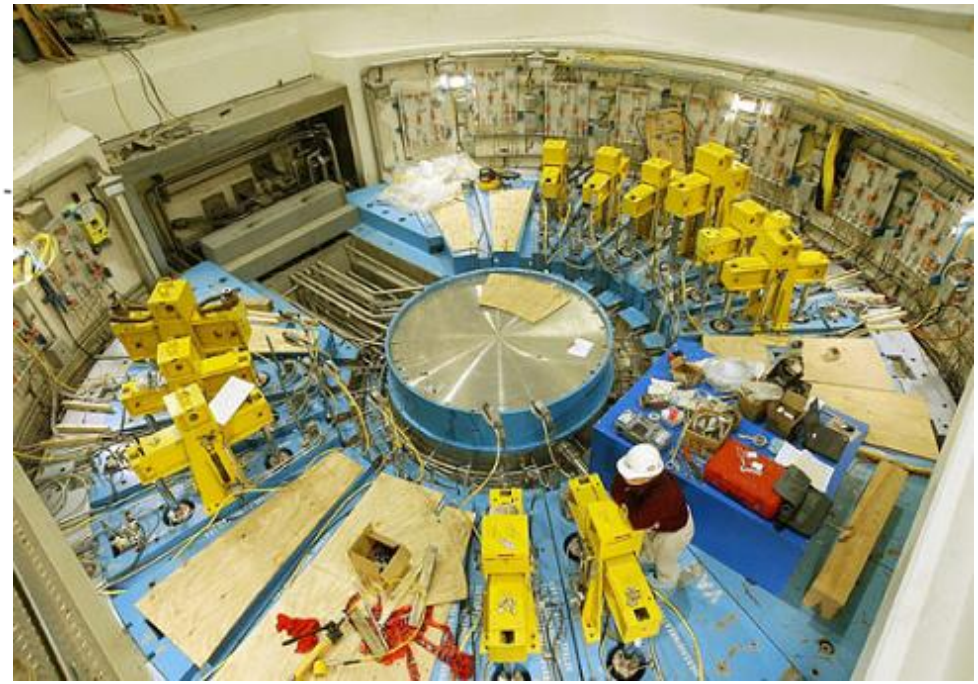
Neutrino experiment can be run parasitically

Small & rel. cheap experiment

Timescale is critical

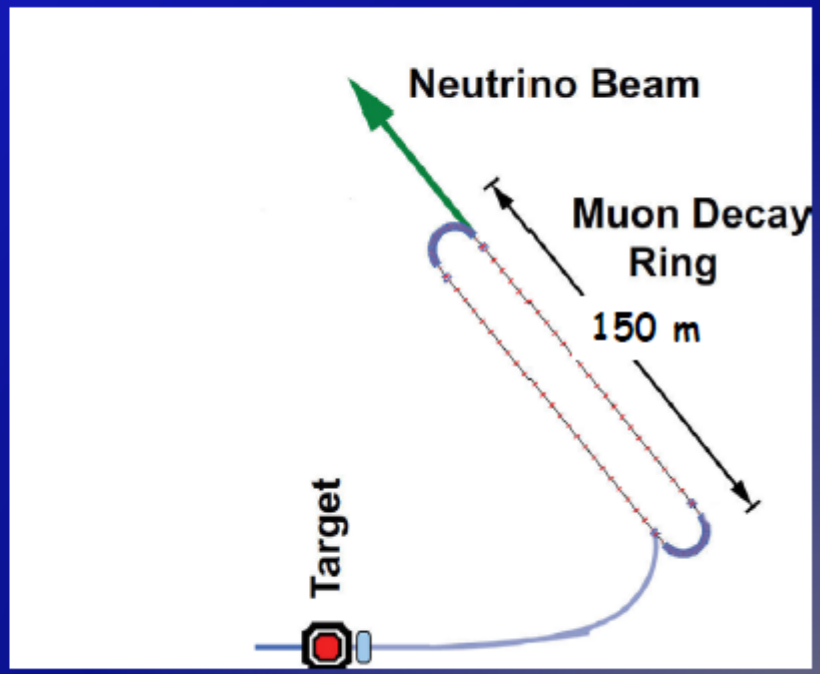
OscFNAL neither cheap nor timely





nuSTORM

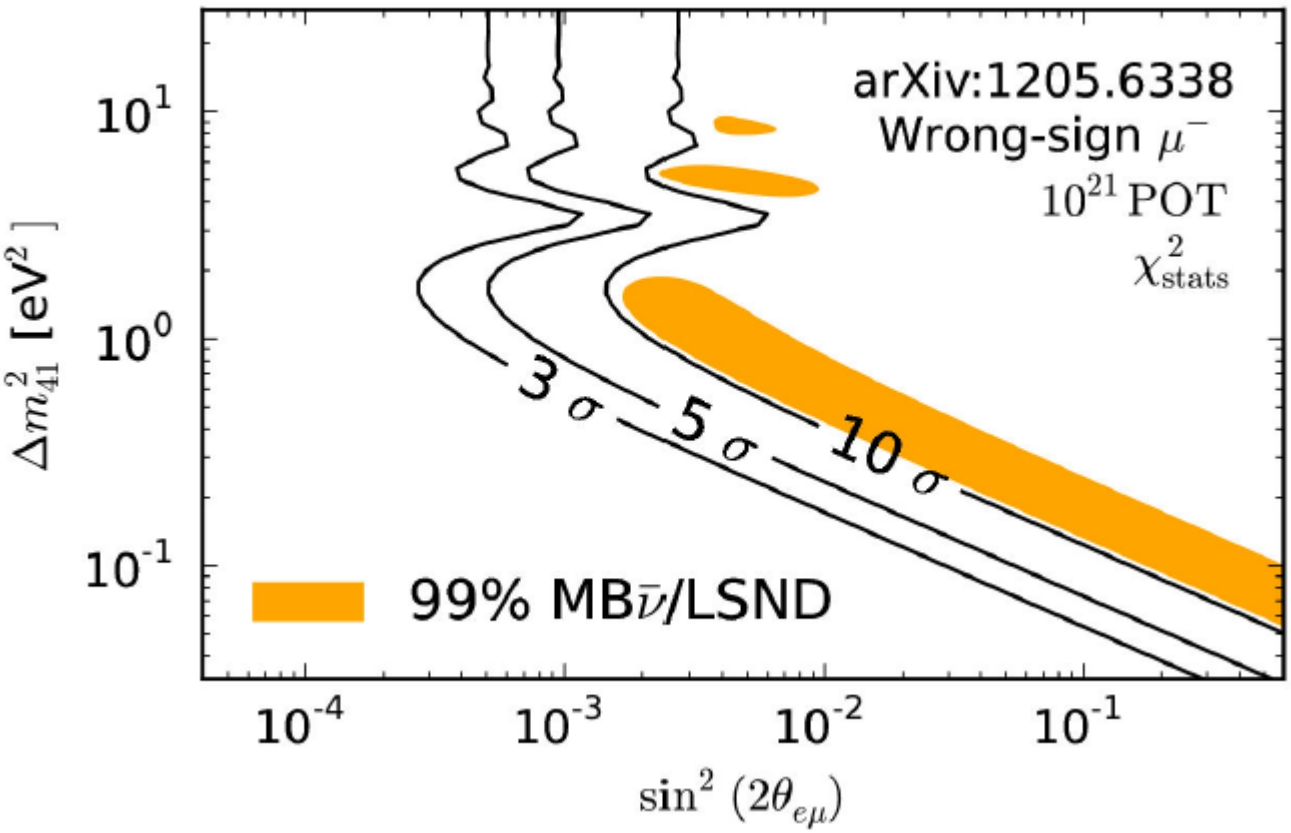
- 100 kW Target Station
  - Assume 60 GeV proton
    - Fermilab PIP era
  - Be target
    - Optimization on-going
  - Li Lens or horn collection after target
- Collection/transport channel
  - Two options
    - Stochastic injection of π
    - Kicker with $\pi \rightarrow \mu$ decay channel
    - At present NOT considering simultaneous collection of both signs
- Decay ring
  - Large aperture FODO
  - Racetrack FFAG
  - Instrumentation
    - BCTs, mag-Spec in arc, polarimeter



A. Bross

nuSTORM

Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421



νSTORM :

- Delivers on the physics for the study of sterile ν
  - Offering a new approach to the production of ν beams setting a 10 σ benchmark to confirm/exclude LSND/MiniBooNE ν-bar data
- Can add significantly to our knowledge of ν cross-sections, particularly for ν_e interactions
- Provides an accelerator technology test bed
- Provides a powerful ν detector test facility

A. Bross

nuSTORM

- NuSTORM is the only accelerator based proposal which has a clear upgrade path (and will not run into systematics) if sterile neutrinos are discovered
- PX, especially at 8 GeV, would allow, together with improvements of muon capture and front end to boost luminosity by 1-3 orders of magnitude

LBL – what we want to learn

In the context of long baseline neutrino experiments

- δ_{CP}
- mass hierarchy
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?
- New physics?

It is very difficult to rank those measurements in their relative importance

Given the current state of the theory of neutrinos we can not say with confidence that any one quantity is more fundamental than any other.

Large θ_{13} – implications

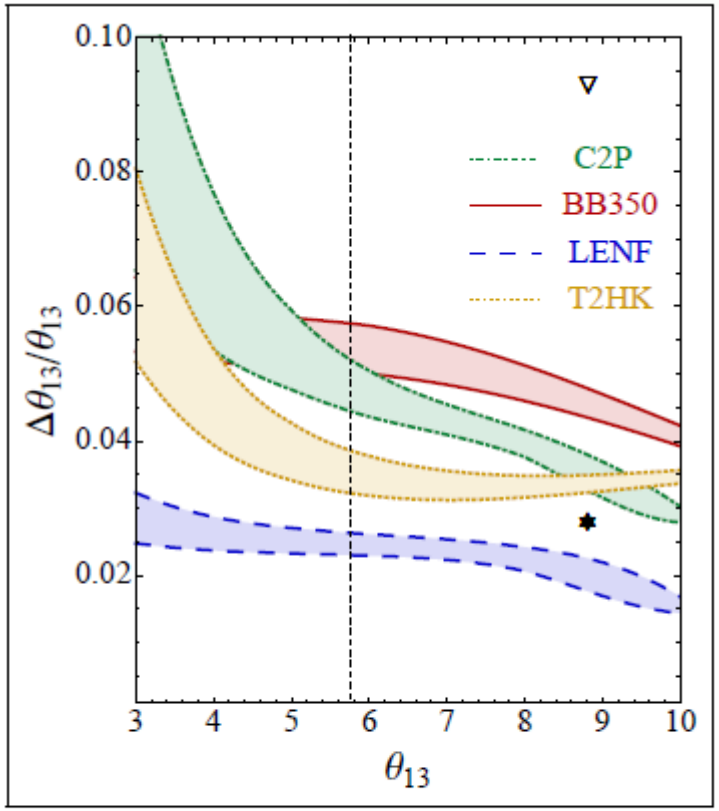
The Daya Bay result is

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\mathrm{stat}) \pm 0.005(\mathrm{syst}) \,,$$

which translates into a more than 5 σ exclusion of $\theta_{13} = 0$, confirmed by RENO. What are the implications for future facilities?

In general, this raises the following questions

- Will the mass hierarchy have been determined?
- Are new experiments beyond NOνA and T2K necessary?
- Are superbeams sufficient?



P. Coloma, A. Donini, E. Fernandez-Martinez, P. Hernandez, arXiv:1203.5651

FAPP θ_{13} will be known to very high accuracy

At $\sin^2 2\theta_{13} = 0.1$ the measurement error at T2K will be 10%

At $\sin^2 2\theta_{13} = 0.1$ the measurement error at Daya Bay will be <5%

Can beams improve this result? – not any time soon

Mass hierarchy from existing experiments

- **The scenario**
  - NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)
  - T2K continues running at 22.5 kton × 700 kW for another 6 years (to 2025)
  - NOνA achieves a further 20% sensitivity gain through analysis improvements
  - T2K achieves a further 10% sensitivity gain through analysis improvements

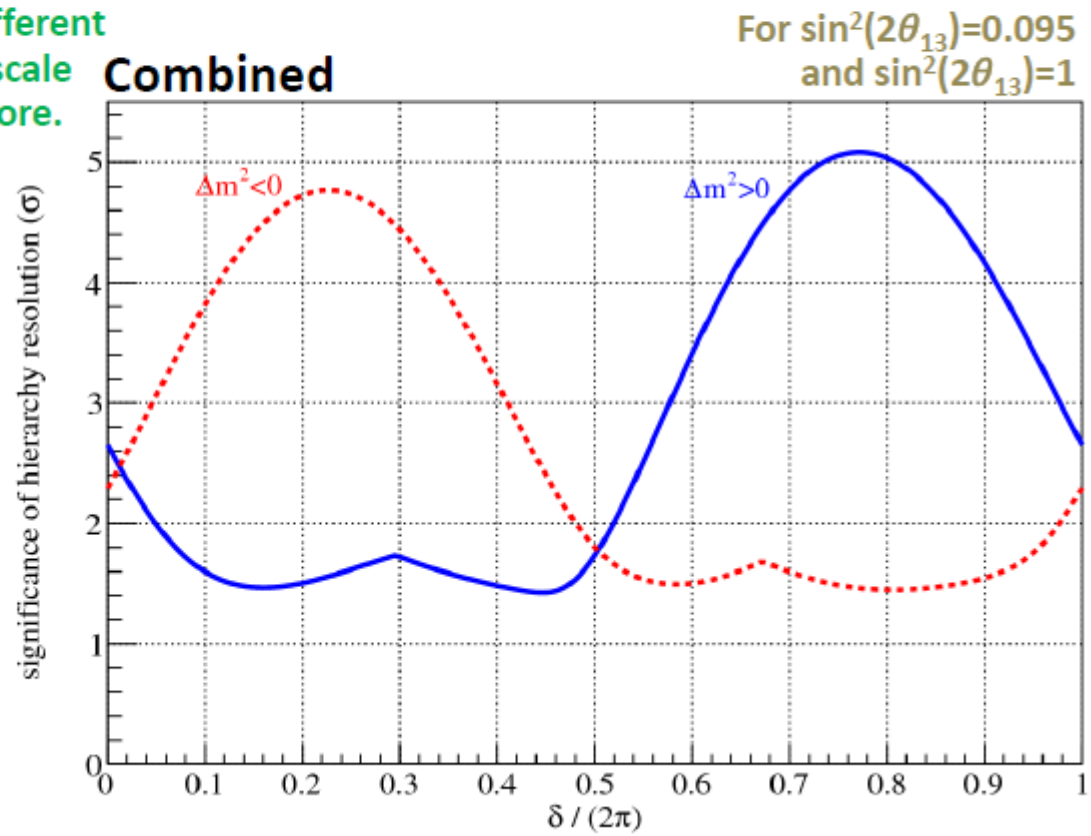
Note: different vertical scale than before.

Raw hierarchy sensitivity
maximal mixing scenario

Best: 5.1σ

53% of δ range: >2σ
40% of δ range: >3σ

Everything >1.4σ: a good start.



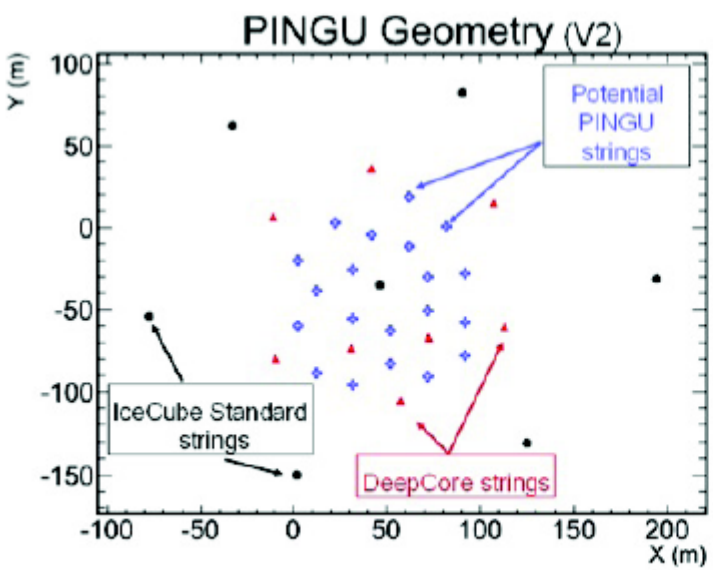
R. Patterson

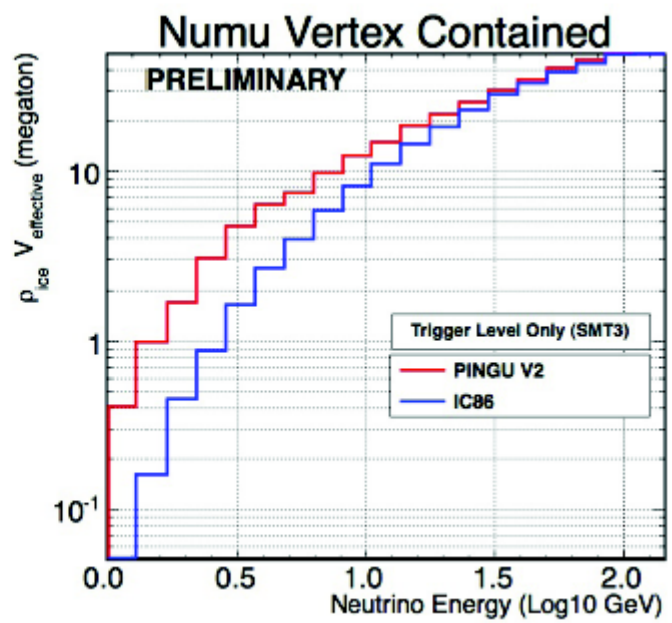
Mass hierarchy from atmospheric neutrinos

PINGU

- Phased IceCube Next-Generation Upgrade
- Add 20 strings with ~1000 optical modules inside the Deep Core region (~500PMT)
- Expected energy threshold near 1 GeV

- ~$25-30 million
- 2 years deployment
- White paper Fall 2012
- full proposal 2013
- R&D for further infill to reach below GeV range





I. Mociuou

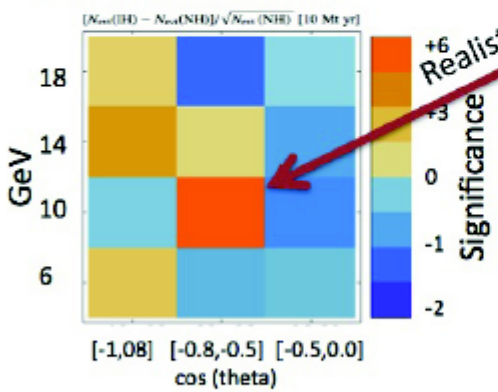
Mass hierarchy from atmospheric neutrinos

Mass hierarchy

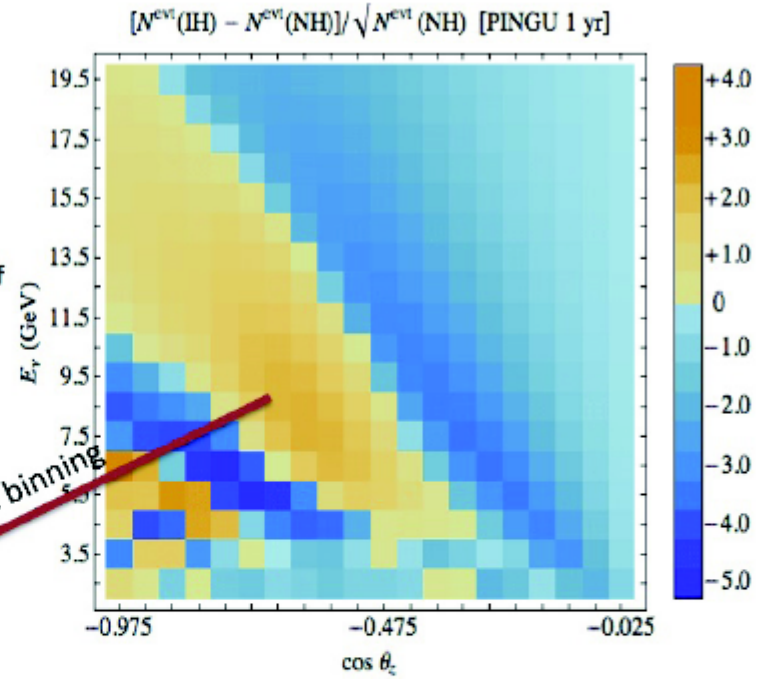
Figure and Analysis from:
Akhmedov, Razzaque, Smirnov, arXiv: 1205.7071

- Expected significance for observed number of events for IH vs NH are shown in energy vs. zenith plot
- If required energy and directional resolution is achievable:

  → high statistical significance



Realistic binning



Conclusion (Akhmedov et al.):
"Our preliminary estimates show that after 5 years of PINGU 20 operation the significance of the determination of the hierarchy can range from 3 to 11 (without taking into account parameter degeneracy), depending on the accuracy of reconstruction of neutrino energy and direction."

Assumed above:

Energy resolution: 4 GeV,
Angular resolution: 0.3 in cos(theta)
Exposure: 10 Mt yr

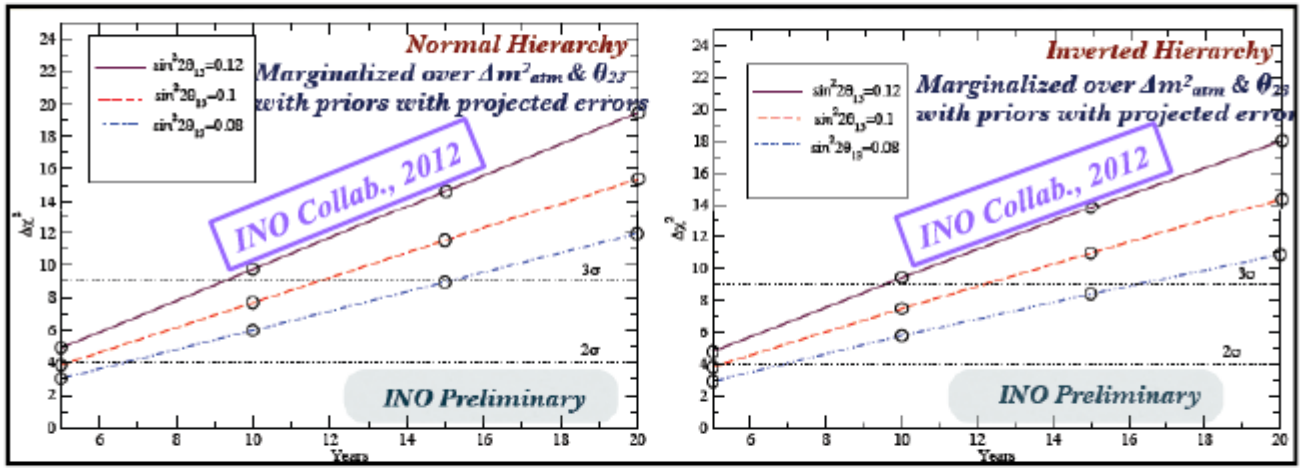
- very general analysis, many details missing
- DIS only
- full analysis: likely better outcome!

I. Mociuou

Mass hierarchy from atmospheric neutrinos

Mass Hierarchy with INO-ICAL

Events generated using Nuance & ICAL resolution in E and $\cos\theta_{zenith}$

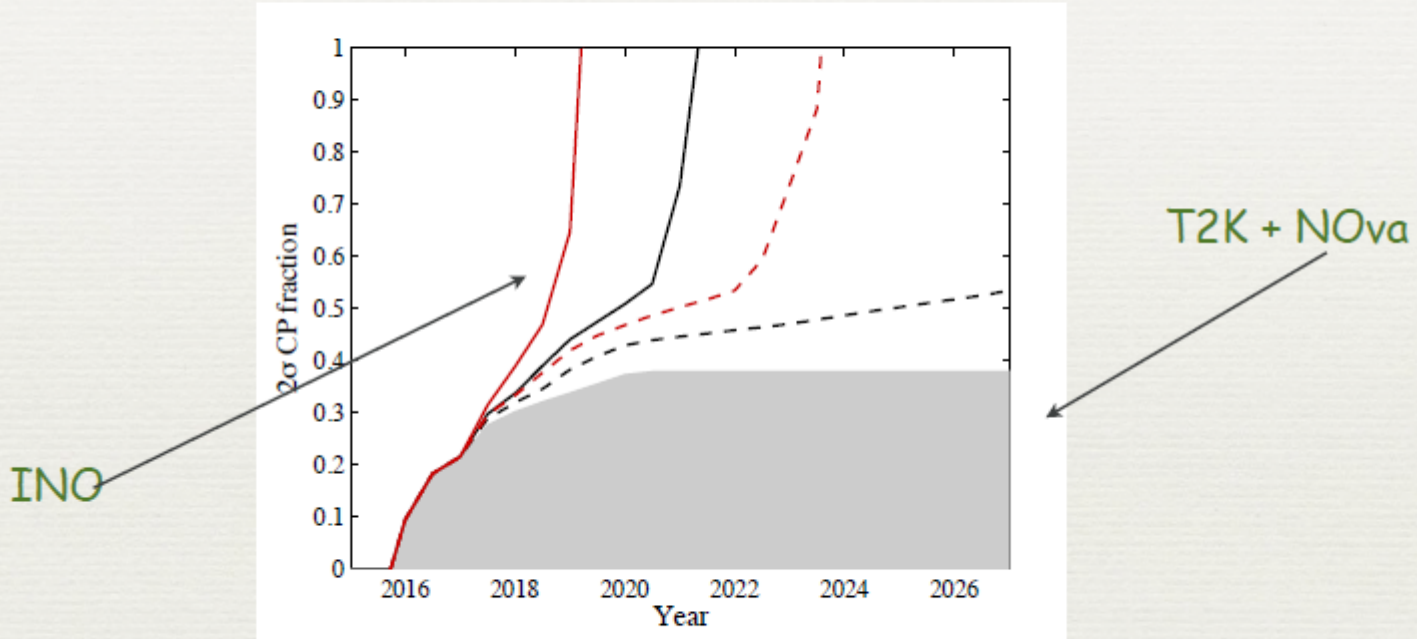


~2σ sensitivity for $\sin^2\theta_{23}$ = 0.5, $\sin^2 2\theta_{13}$ = 0.1 by 2022 (5 yrs)
~2.7σ sensitivity for $\sin^2\theta_{23}$ = 0.5, $\sin^2 2\theta_{13}$ = 0.1 by 2027 (10 yrs)

B. Choudhary

Mass hierarchy from atmospheric neutrinos

Earlier studies have shown the power of combining LBL + ATM data to maximize the physics output.....



Blennow and Schwetz
arXiv 1203.3388

Also a magnetized Lar TPC has been discussed

R. Gandhi

Mass hierarchy

- Given the large value of theta13 mass hierarchy can be done in many different ways
- This is just a small selection of possibilities, others are Daya Bay 2, HK atmospheric data,...
- It seems to be the general opinion that mass hierarchy will be determined w/o a new long baseline experiment
- I share this assessment

BSM – new interactions

Interference of amplitudes

A.F. ,C. Lunardini, PRD (2006)

$$P(\nu_\mu \to \nu_e) \simeq \left| G_1 \sin\theta_{23} \frac{\exp(i\Delta_1 L) - 1}{\Delta_1} - G_2 \cos\theta_{23} \frac{\exp(i\Delta_2 L) - 1}{\Delta_2} \right|^2 ,$$

$$G_1 \simeq \sqrt{2} G_F N_e |\epsilon_{e\tau}| e^{i\delta_\nu} \cos\theta_{23} + \Delta \sin 2\theta_{13} e^{i\delta},$$

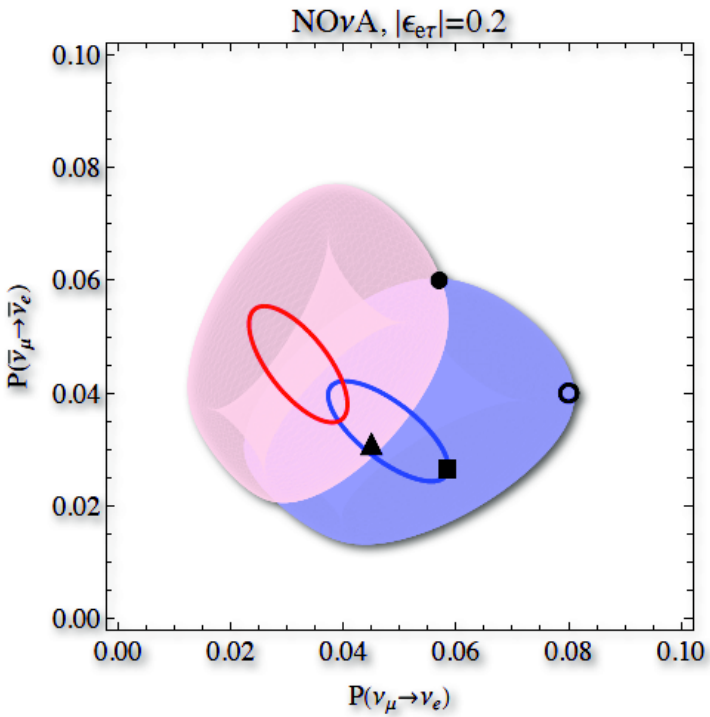
$$G_2 \simeq \sqrt{2} G_F N_e |\epsilon_{e\tau}| e^{i\delta_\nu} \sin\theta_{23} - \Delta_\odot \sin 2\theta_{12}.$$

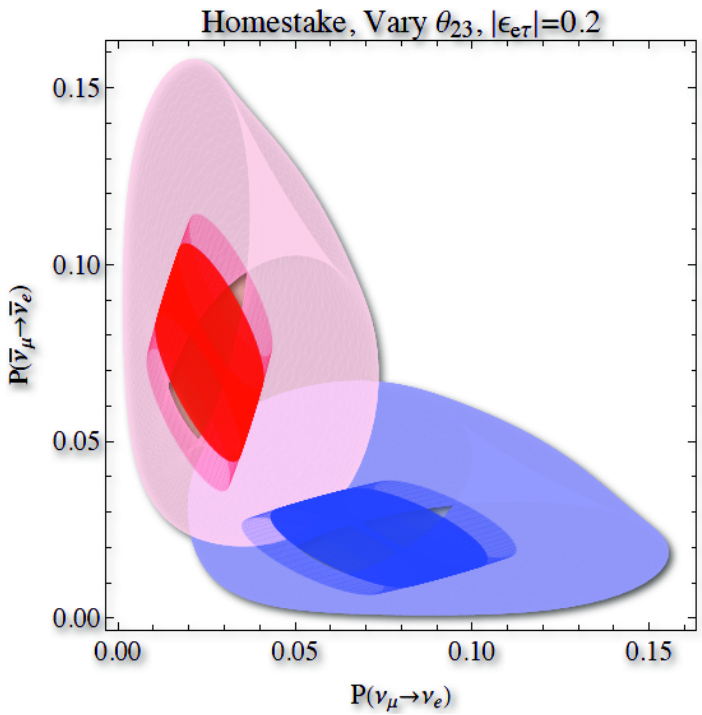
- Two channels, solar and atmospheric; NSI amplitude appears in both

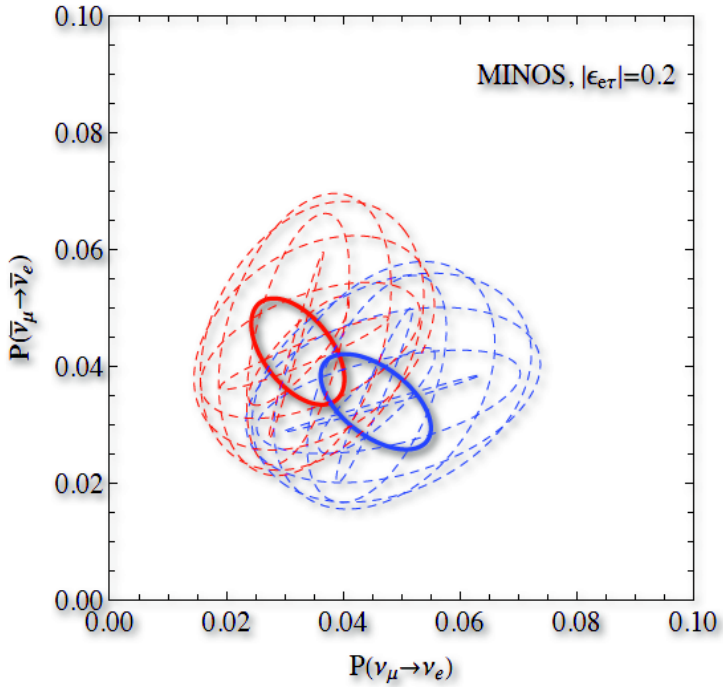
Interference of the large theta13 term with the NSI term dramatically enhances the sensitivity!

A. Friedland

BSM – new interactions







Combination of baseline and energies
Key to resolve degeneracies

A. Friedland

BSM – new interactions

Example: NC NSI in the μ–τ sector

Two-flavor calculation leads to

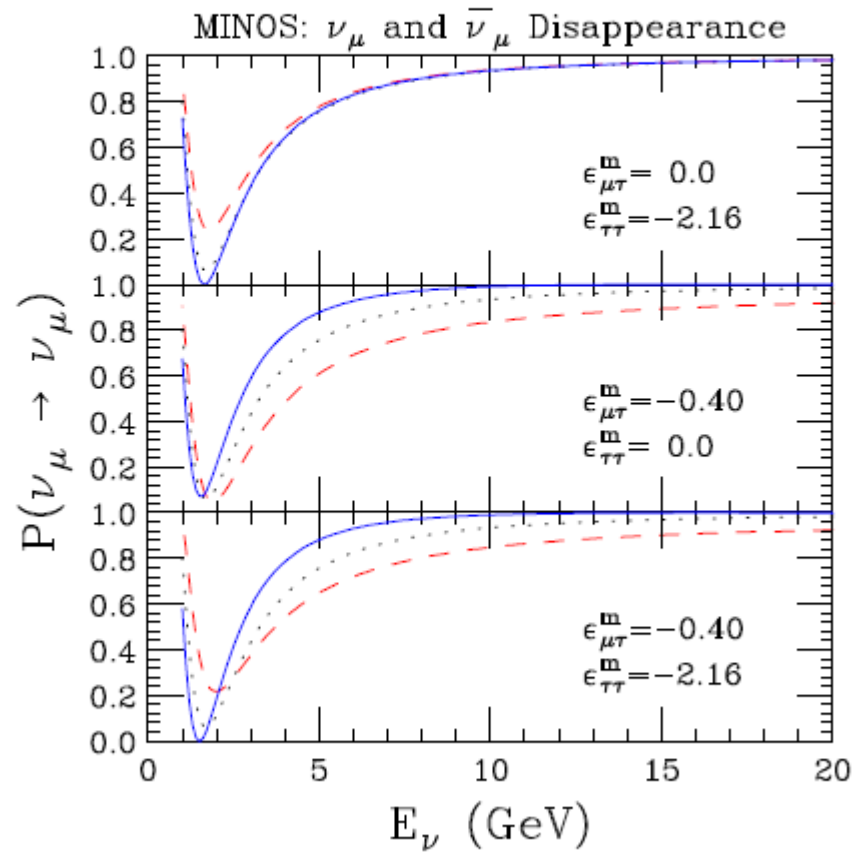
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_N \sin^2\left(\frac{\Delta m_N^2 L}{4E}\right)$$

with

$$\Delta m_N^2 = \left[(\Delta m_{32}^2 \cos 2\theta_{23} + \epsilon_{\tau\tau} A)^2 + |\Delta m_{32}^2 \sin 2\theta_{23} + 2\epsilon_{\mu\tau} A|^2\right]$$

$$\sin^2 2\theta_N = |\Delta m_{32}^2 \sin 2\theta_{23} + 2\epsilon_{\mu\tau} A|^2 / \Delta m_N^4 ,$$

and $A = A = 2\sqrt{2} G_F n_e E$. (we set $\epsilon_{\mu\mu} = 0$ since flavor-universal terms can be subtracted from V)

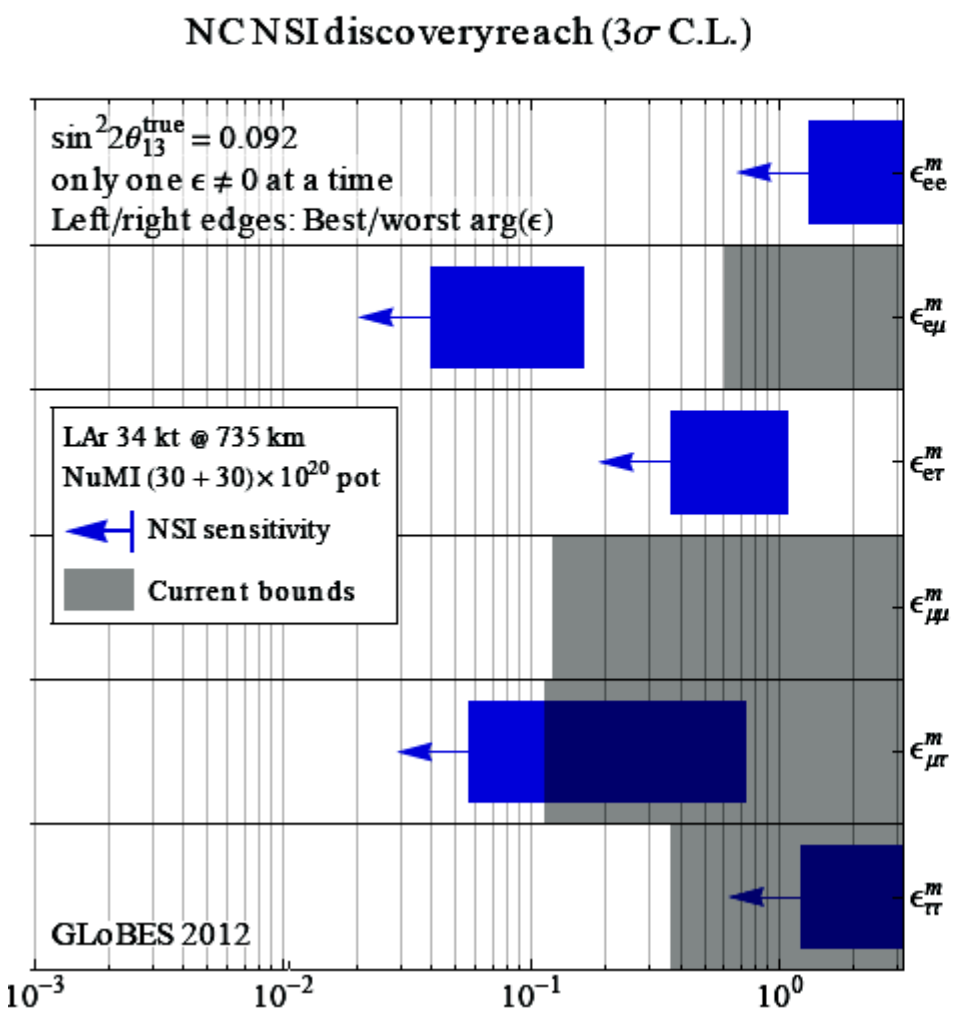


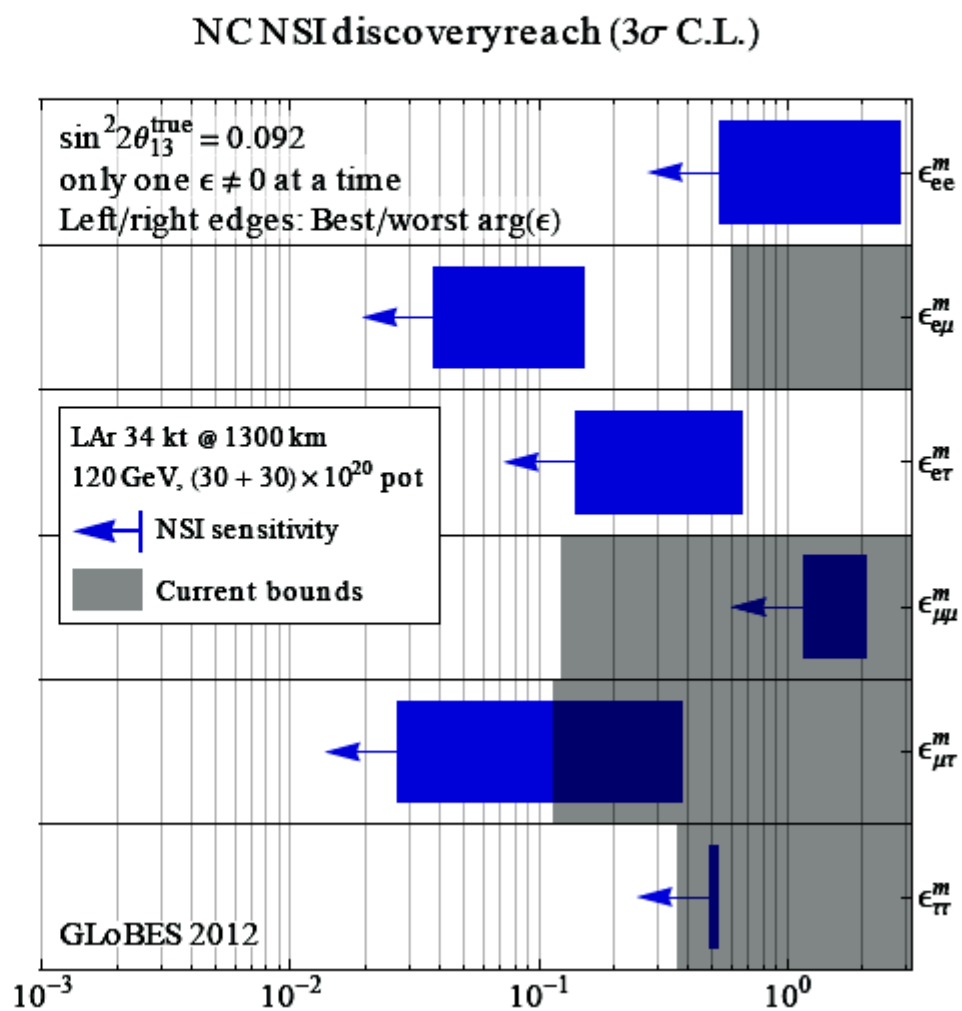
JK Machado Parke 2010

J. Kopp

BSM – new interactions

Discovery reach in super-MINOS and mini-LBNE

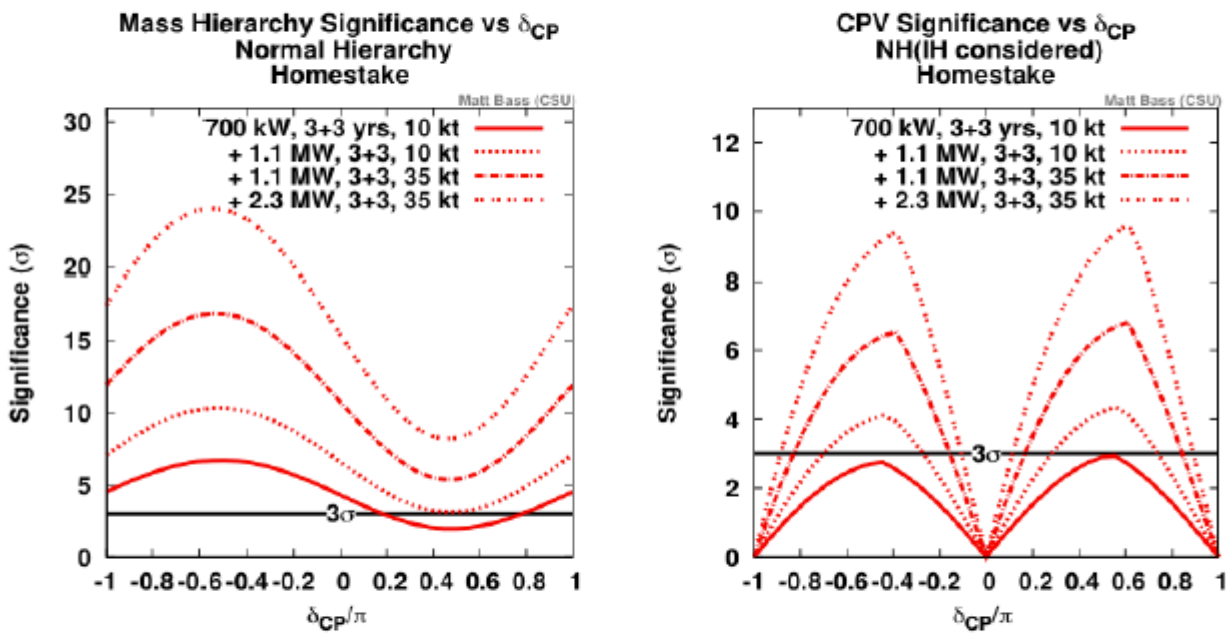




J. Kopp

LBNE + PX

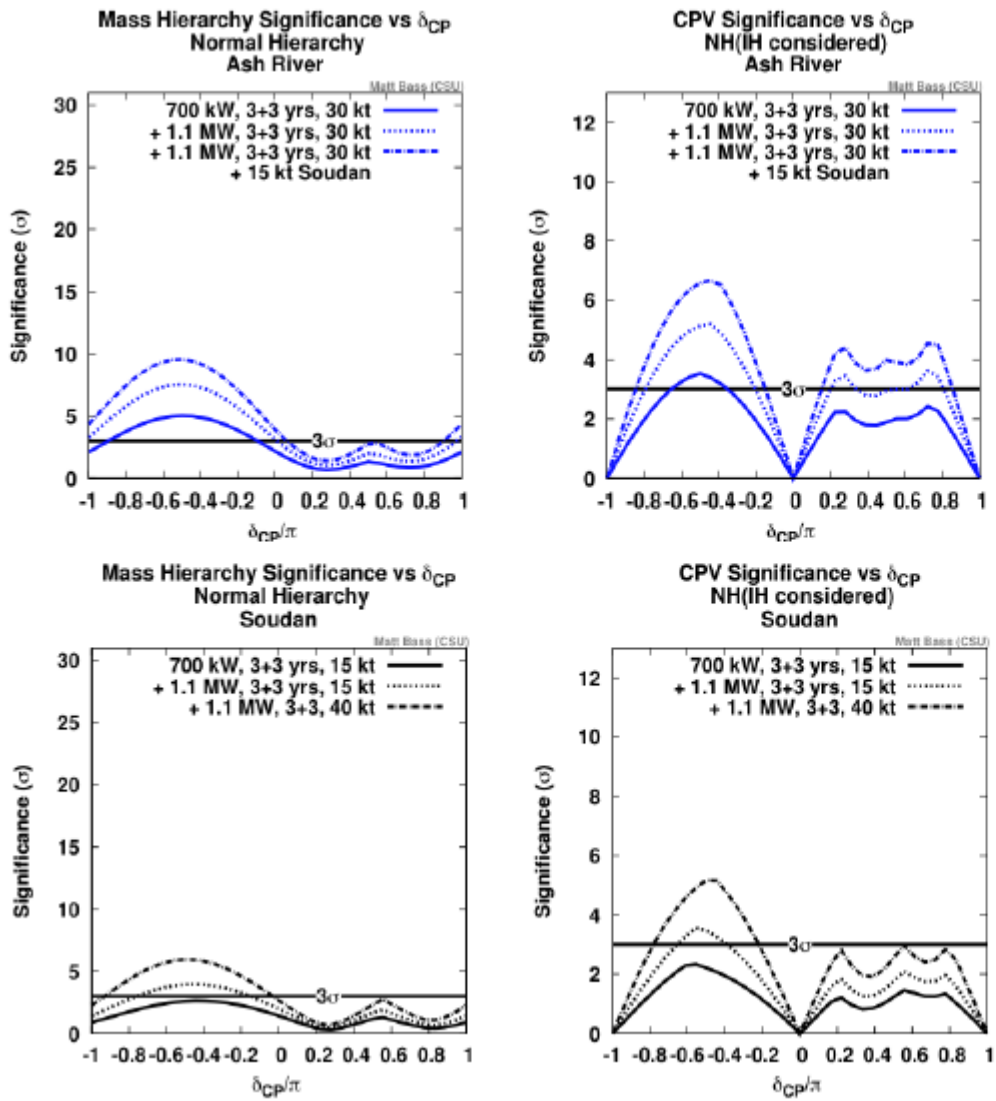
LBNE Phase 2 + Project X Stage 1



- Stage 1 of PX increases the MI beam power to MW range
- LBNE/Homestake Phase 2 + PX Phase 1 = **Discovery (>5σ) CPV**

Z. Isvan

LBNE + PX



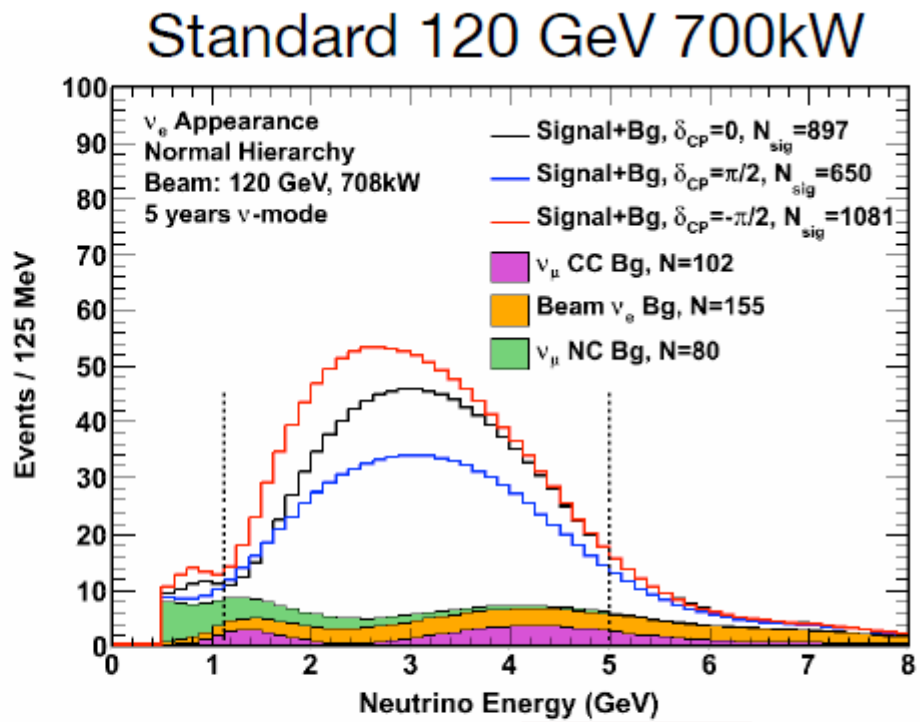
- LBNE/Ash River (30kT) Phase 2 + PX Phase 1 = **Evidence (>3σ) CPV**
- LBNE/Soudan (15-40kT) Phase 2 + PX Phase 1 = **< 3σ CPV even with Project X Stage 1**

Z. Isvan

LBNE + PX

- Stage 2 will allow MW-power lower energy beams
- Can we gain low energy flux (at long baselines) by going to lower energies?
- This can populate the second maximum and improve the signal/background in the CPV-sensitive region.
- Consider 30, 60, 90 GeV energies and 1MW beam power
- Separation power figure of merit:

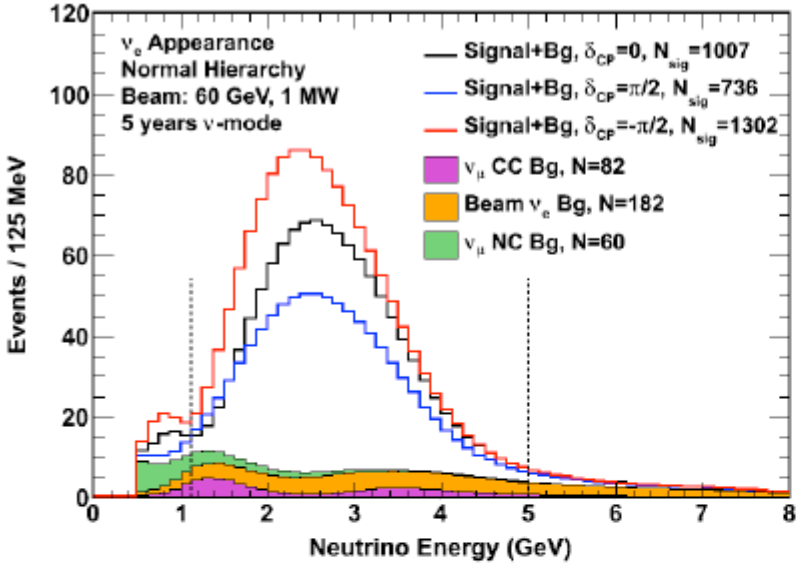
$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 23.5$$

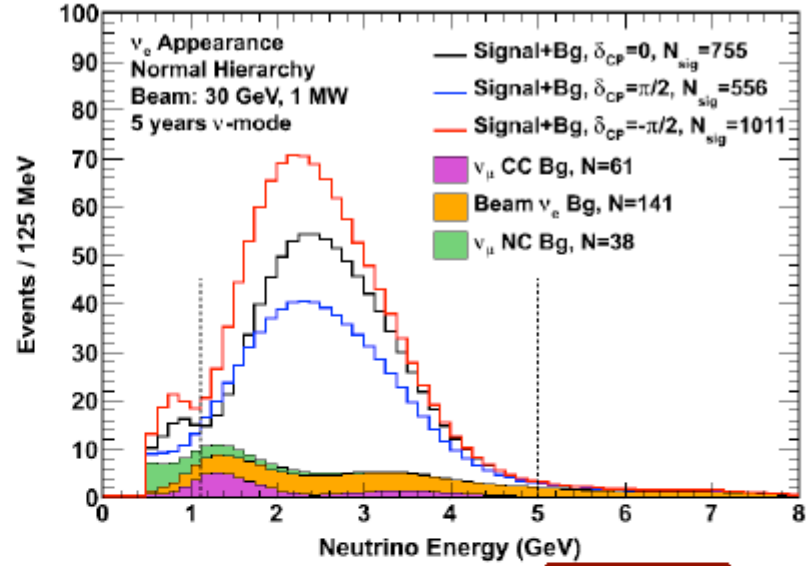


δ_{CP}	N	N_{second}	N_{first}	$N/\sqrt{B}$	$N_{second}/\sqrt{B}$	$N_{first}/\sqrt{B}$
0	897	14	817	48.86	2.27	57.34
$\pi/2$	650	5	597	35.41	0.81	41.90
$-\pi/2$	1081	24	994	58.89	3.89	69.77

Z. Isvan

LBNE + PX





δ_{CP}	N	N_{second}	N_{first}	$N/\sqrt{B}$	$N_{second}/\sqrt{B}$	$N_{first}/\sqrt{B}$
0	1007	26	955	55.94	3.92	64.83
$\pi/2$	736	10	707	40.89	1.51	47.99
$-\pi/2$	1302	45	1231	72.33	6.78	83.57

$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 31.4$$

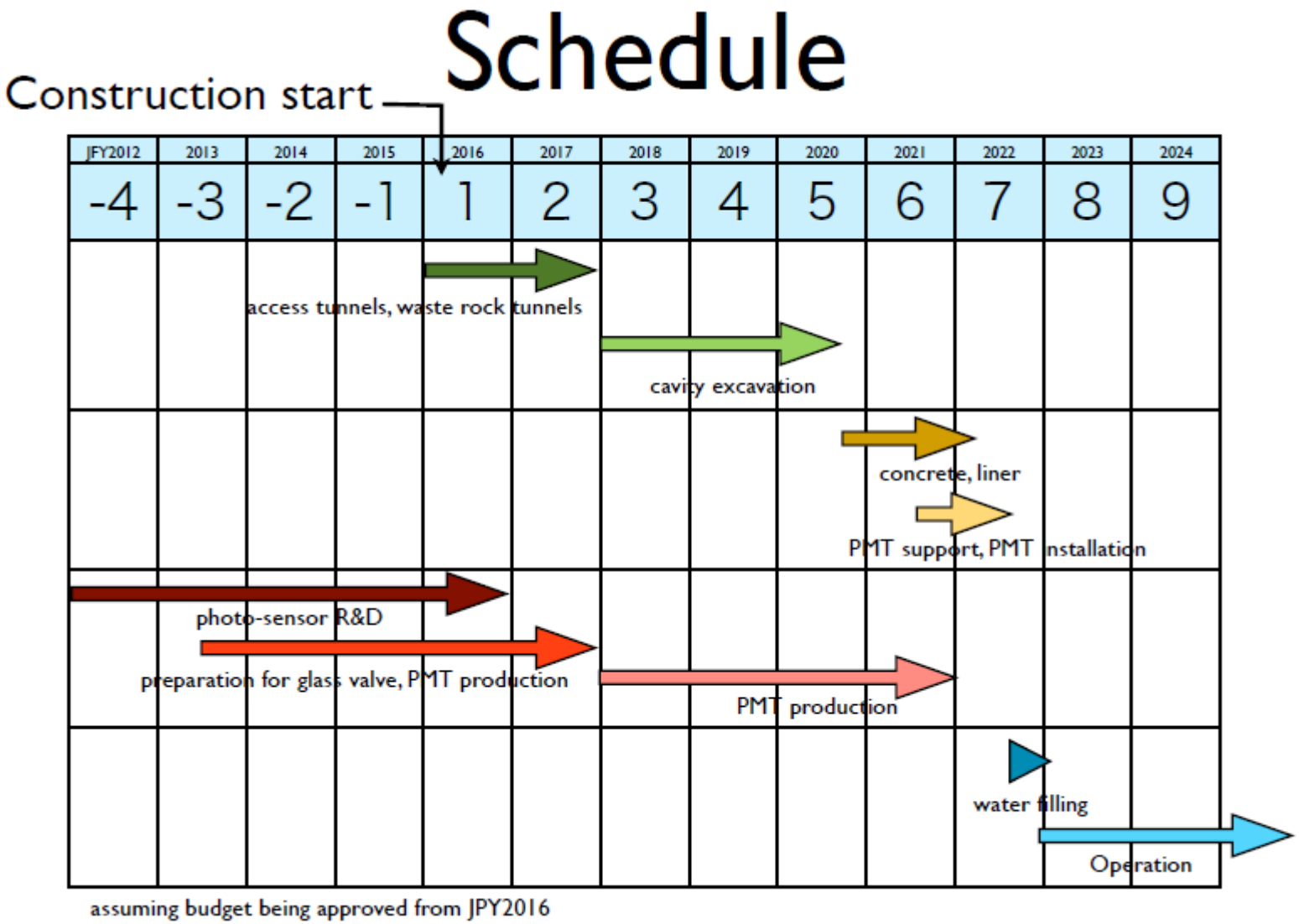
δ_{CP}	N	N_{second}	N_{first}	$N/\sqrt{B}$	$N_{second}/\sqrt{B}$	$N_{first}/\sqrt{B}$
0	755	30	716	48.74	4.93	55.08
$\pi/2$	556	11	538	35.89	1.81	41.38
$-\pi/2$	1011	51	951	65.26	8.38	73.15

$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 29.4$$

- Can do better CPV than 120 GeV with the same amount of running
- Technical: High density graphite target inserted into horn 1 unlike standard NuMI LE at z=-30cm

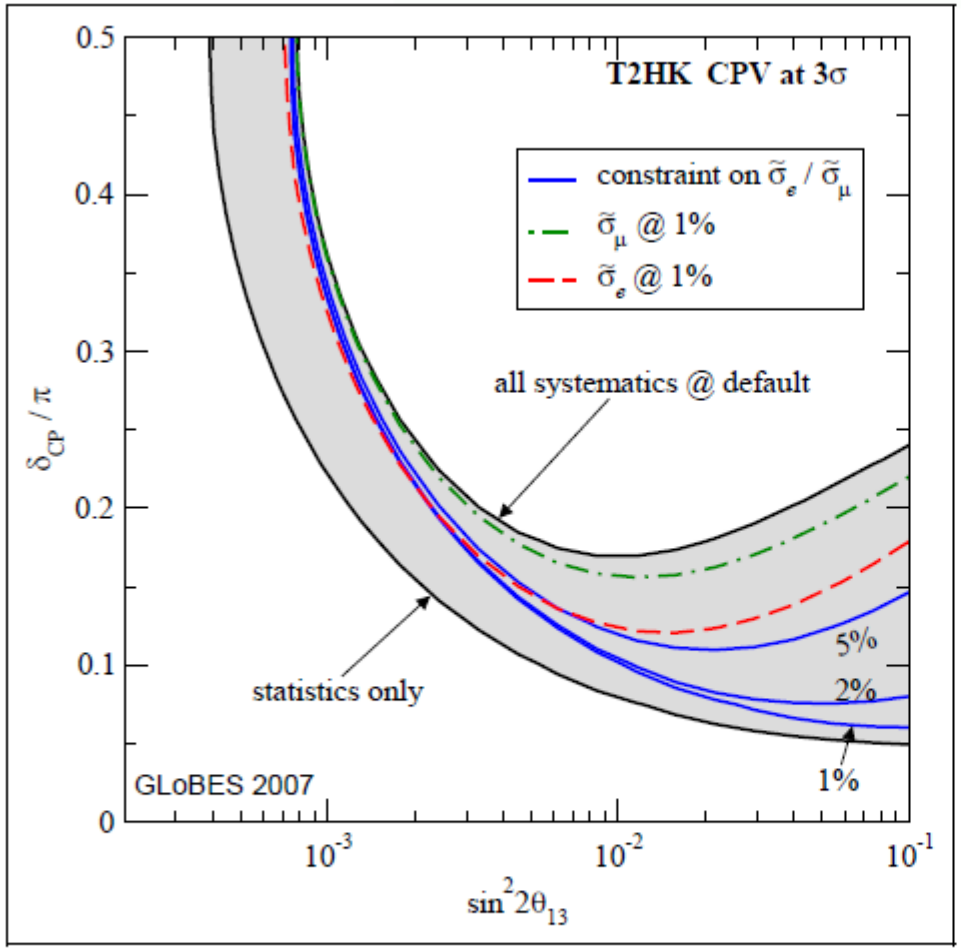
Z. Isvan

T2HK



M. Shiozawa

ν_e/ν_μ x-sections



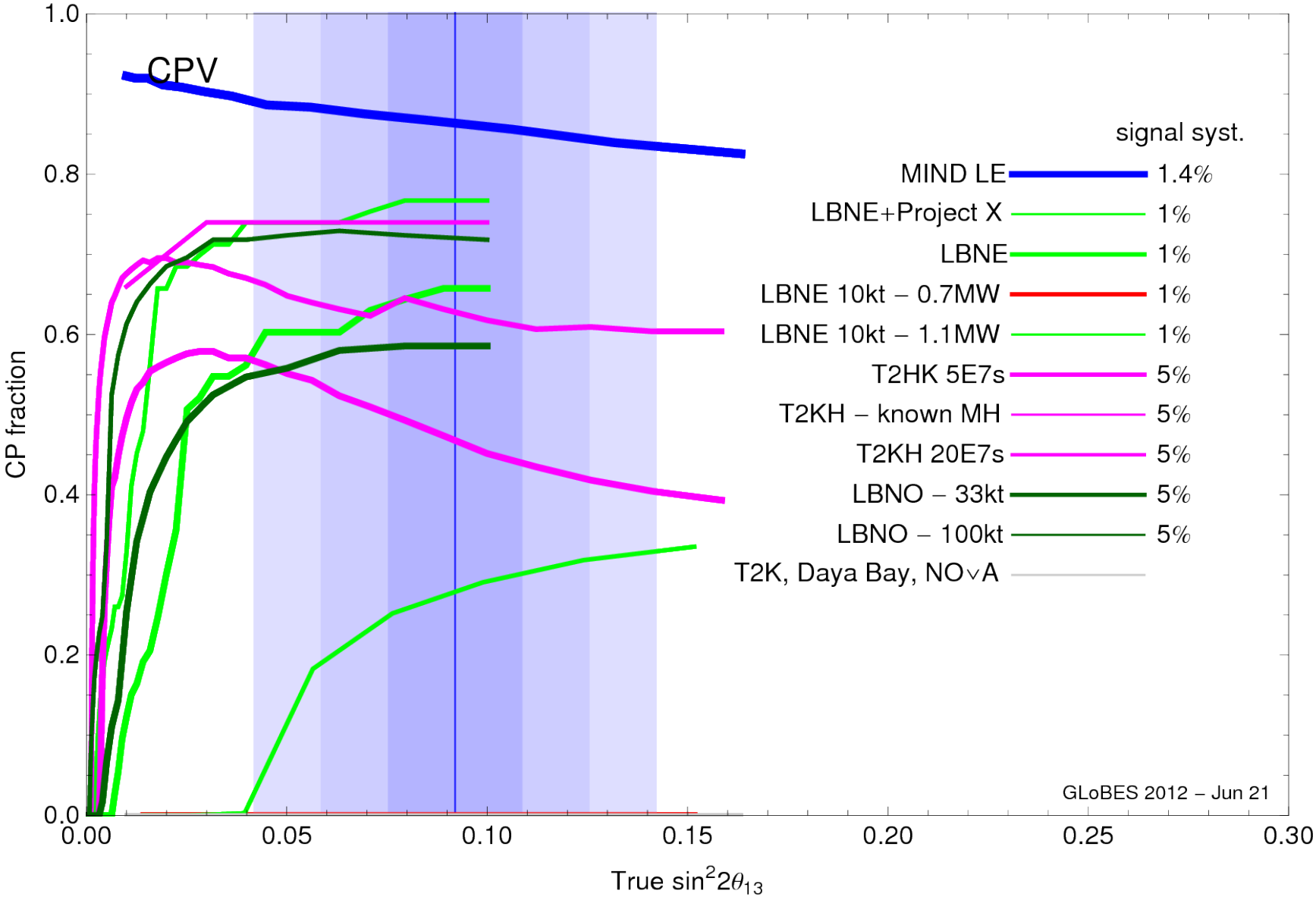
PH, M. Mezzetto, T. Schwetz
arXiv:0711.2950

Appearance experiments using a (nearly) flavor pure beam can not rely on a near detector to predict the signal at the far site!

Large θ_{13} most difficult region.

nuSTORM!

CP violation sensitivities



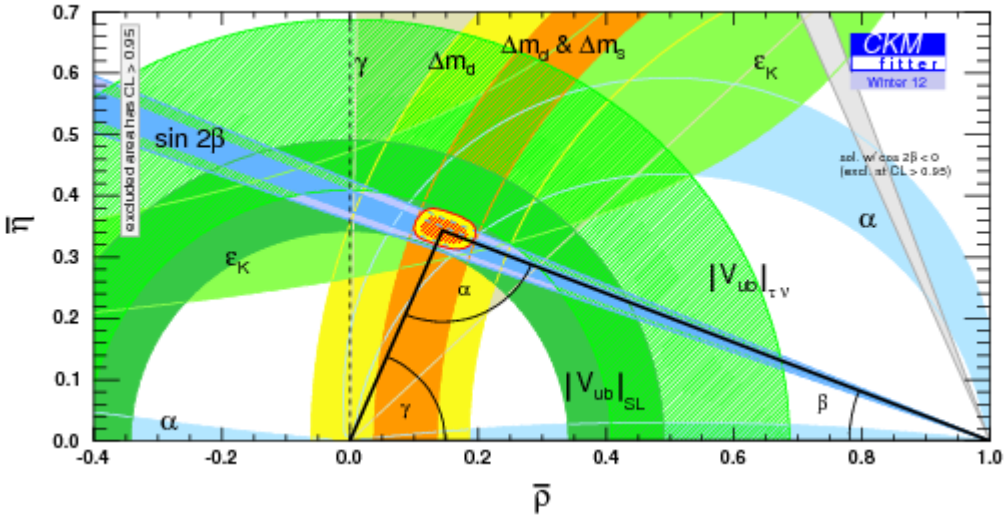
Is this the right metric?

How to compare facilities?

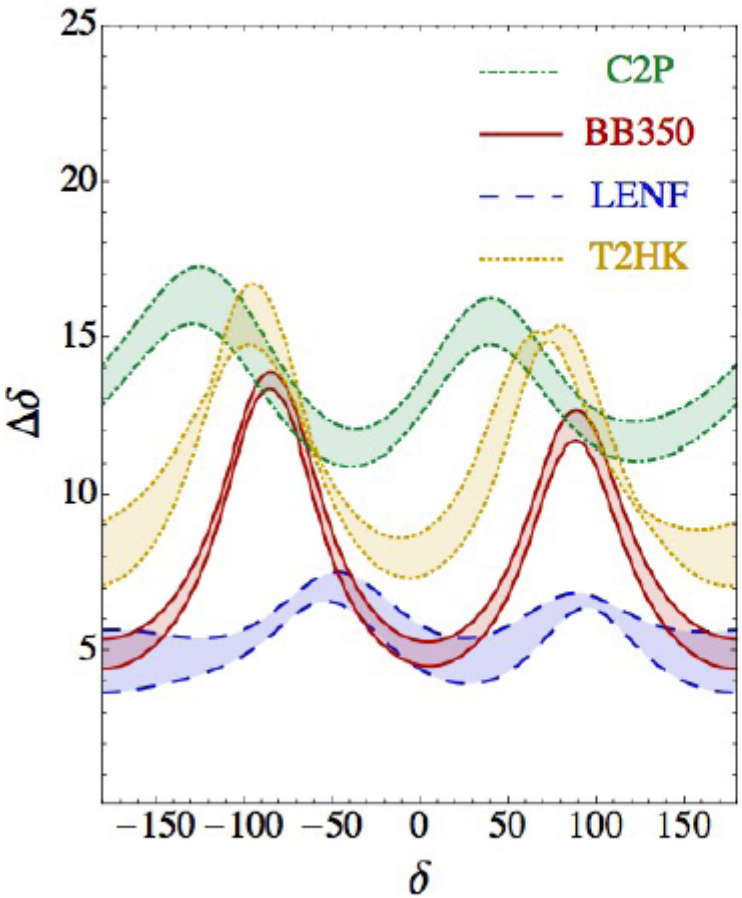
- Th13 is measured
- Mass hierarchy likely will be determined

I will use CP precision as figure of merit

- Experimentally most challenging – high bar
- Directly related to constraints on the unitarity triangle
- Most susceptible to new physics



Precision

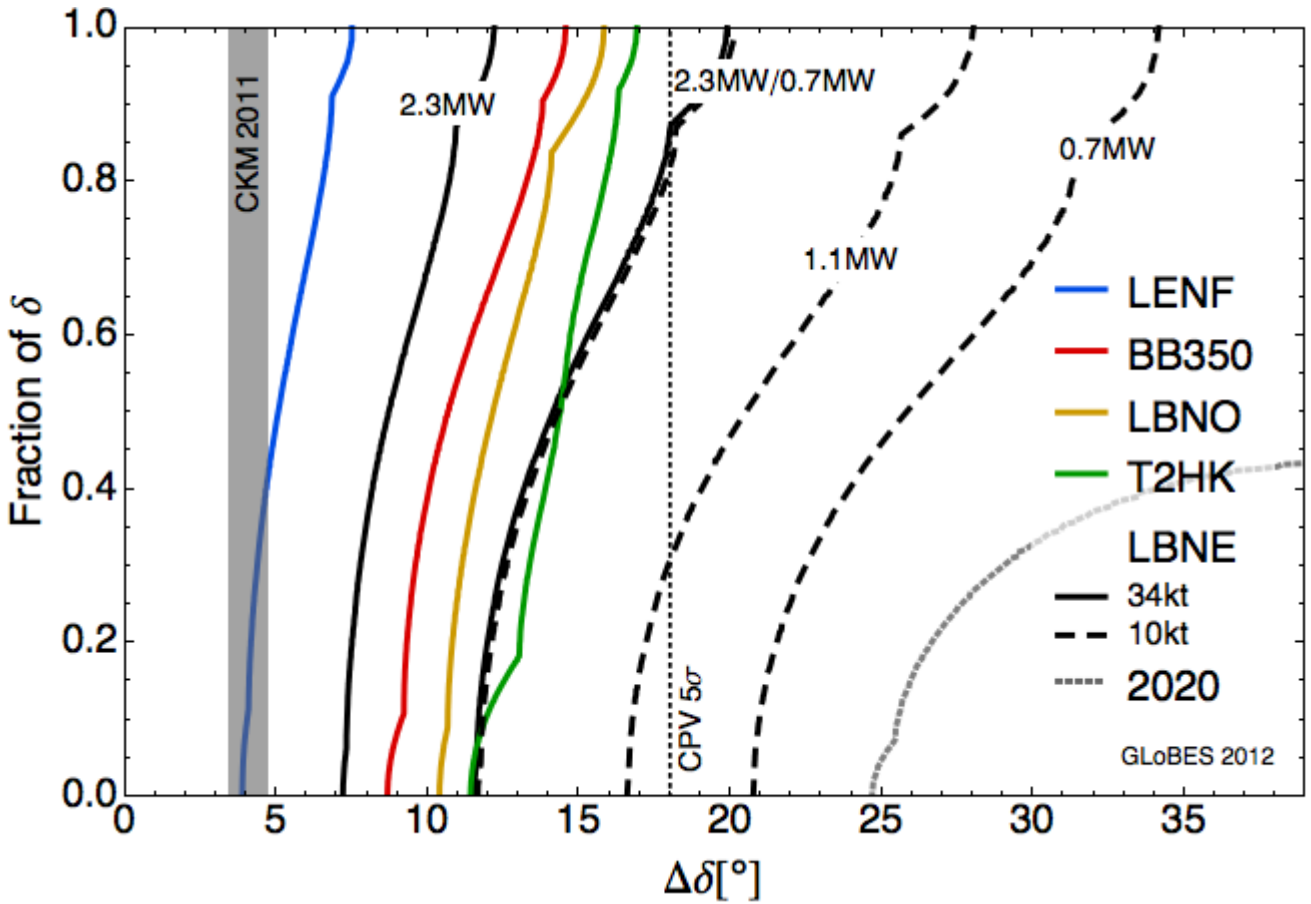


very different behaviour for all facilities

Coloma, Donini, Fernández-Martínez, Hernández, 1203.5651 [hep-ph]

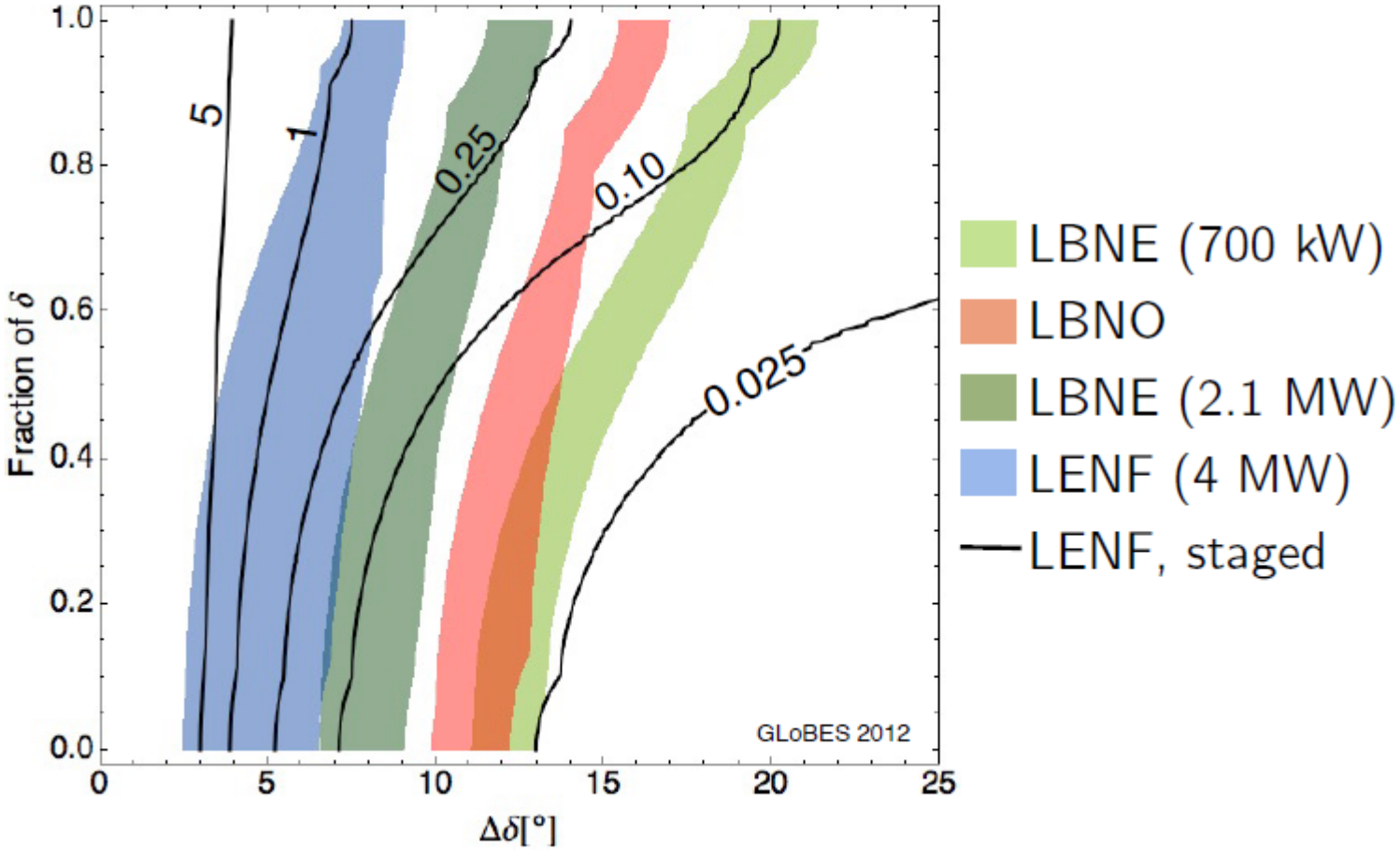
P. Coloma

CP precision – global picture



P. Coloma

Staged approach for a NF



P. Coloma

Summary

SBL

- On PX timescale there is either a discovery or this is no longer a priority
- If discovery more intensity alone will not be sufficient
- Systematics will be limiting factor for traditional pion decay in flight sources
- High intensity at low energy to help DAR (still meaningful in PX era?) and/or nuSTORM

LBL

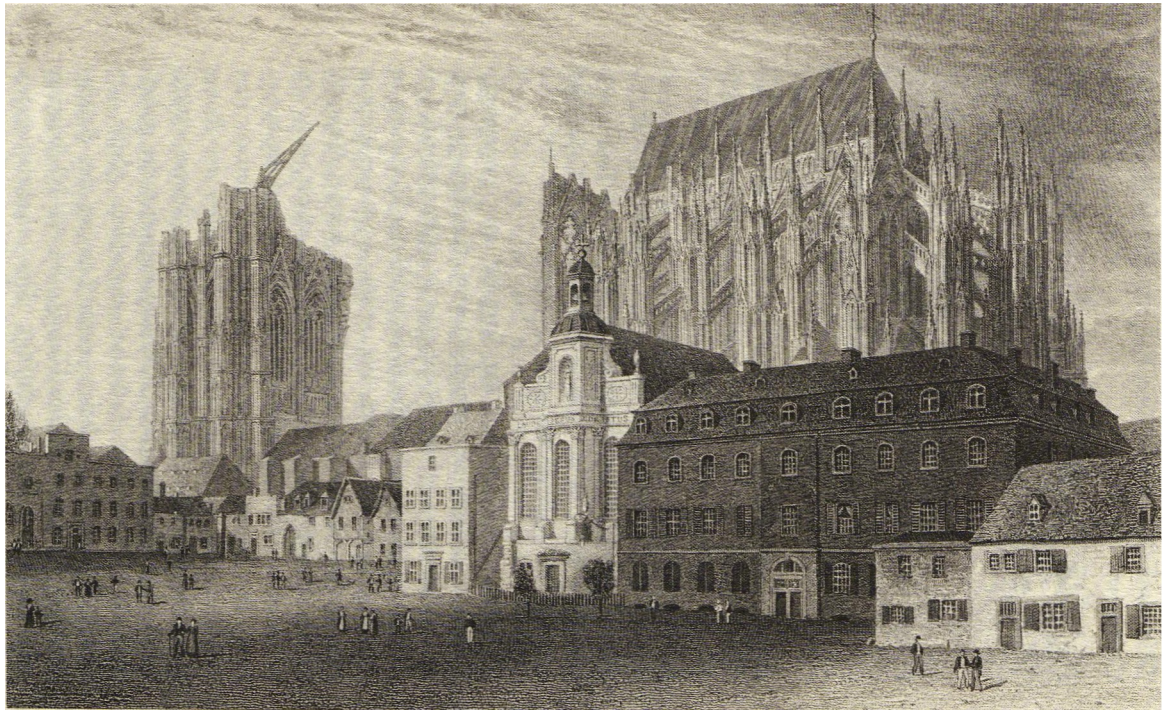
- Mass hierarchy likely measured
- Maybe indications for delta_CP
- Need for precision
- Competitiveness w.r. to global program (even for full LBNE)?
- PX most useful in connection with phase 2 of LBNE.
- Is this most effective way of enhancing LBNE?

A tale from German history and personal comment

Konrad von Hochstaden
Archbishop of Cologne

August 15, 1248 A.D.
Konrad inaugurated a civil engineering project
to build a Gothic cathedral...

His successors ran out of funding in 1473 A.D.



Project status 1824 A.D.

The community (= citizens of Cologne) managed to raise 2/3 of the funds required, about $1B in today's currency, and construction resumed

On August 24, 1880 A.D. the cathedral was finished,
a mere 632 years after inception of the project...

No doubt – this is a magnificent cathedral.

Maybe, we should consider something more along these lines...

which eventually will grow to be able to use the protons, Project X provides