NuFact 2013

Summary

Karol Lang
University of Texas at Austin
August 24, 2013
Confession

Past Workshop

2000 UCBerkeley Monterey California USA
2001 Tsukuba Japan
2002 Imperial College London UK http://www.hep.ph.ic.ac.uk/NuFact02/
2004 Osaka University Japan
2005 INFN Frascati Italy http://www.lnf.infn.it/conference/2005/nufact05/
2006 UC Irvine California USA
2007 University of Okoyama Japan http://fphy.hep.okayama-u.ac.jp/nufact07/
2008 University of Valencia Spain http://ific.uv.es/nufact08/
2009 IIT and Fermilab Chicago USA http://nufact09.iit.edu/
2010 Tata Institute Mumbai India http://www.tifr.res.in/~nufact2010/
2011 Geneva Switzerland http://NUFACT11.unige.ch
2012 Jefferson Lab http://www.jlab.org/conferences/nufact12/

... I have not been the most attentive student... but:

“You can observe a lot by just watching.” (Yogi Berra)
Summary of ...

- WG1 – neutrino oscillations
- WG2 – neutrino-nucleon scattering
- WG3 – accelerator physics
- WG4 – Muon physics
- Plenaries
- IHEP visit
- Coffee breaks
- Posters
- Chitchats
Summary of ...

- WG1 – neutrino oscillations
- WG2 – neutrino-nucleon scattering
- WG3 – accelerator physics
- WG4 – Muon physics

- Plenaries
- IHEP visit
- Coffee breaks
- Posters
- Chitchats

NuFact2013 Agenda

8/24/13

K. Lang, U. of Texas at Austin: Summary
$\nu$ masses beyond the SM: tree level

$2 \times 2 = 1 + 3$

SU(2) xU(1)$_{\text{em}}$ inv.

Belen Gavela
Neutrinos lighter because Majorana?
Neutrino Mass

normal hierarchy

inverted hierarchy

\[ \Delta m_{\text{sol}}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2 \]

\[ \Delta m_{\text{atm}}^2 \sim 2.4 \times 10^{-3} \text{ eV}^2 \]
IBD Prompt Spectrum

Spectrum distortion consistent with oscillation. Errors are statistical only.
Shape and mass splitting

Rate and Spectral Analysis

$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$

$|\Delta m_{ee}^2| = 2.59^{+0.19}_{-0.20} \times 10^{-3} \text{(eV}^2)\text{)}$

$\chi^2 / NDF = 162.7 / 153$

$\sin^2 \Delta_{ee} = \cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}$

$\Delta m_{32}^2 = 2.54^{+0.19}_{-0.20} \times 10^{-3} \text{(eV}^2)\text{)}$ (Normal Mass Hierarchy)

$\Delta m_{23}^2 = 2.64^{+0.19}_{-0.20} \times 10^{-3} \text{(eV}^2)\text{)}$ (Inverted Mass Hierarchy)

- Far vs. near relative measurement. [Absolute rate is not constrained.]
- Consistent results obtained by independent analyses, different reactor flux models.
- Result consistent with $|\Delta m_{\mu\mu}^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3} \text{(eV}^2)\text{)}$ result from MINOS.
Summary

**Dava Bay**
\[
\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}
\]
\[
|\Delta m^2_{ee}| = (2.59^{+0.19}_{-0.20}) \times 10^{-3} \text{ eV}^2
\]

**RENO**
\[
\sin^2 2\theta_{13} = 0.100 \pm 0.010 \text{(stat)} \pm 0.015 \text{(sys)}
\]

**Double Chooz**
\[
\sin^2 2\theta_{13} = 0.109 \pm 0.030 \text{(stat)} \pm 0.025 \text{(sys)}
\]
\[
\sin^2 2\theta_{13} = 0.097 \pm 0.034 \text{(stat)} \pm 0.034 \text{(sys)}
\]

Electron neutrino contains 2 mass-splittings (3 mass states) and the large splitting agrees with that measured from muon neutrinos.

Accelerator experiments:
- normal,
- inverted, \( \delta_{CP} = 0, \theta_{23} = 45^\circ \)

Reactor experiments:
- rate only, rate+shape, n-Gd, n-H

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Steve Ketell
Brookhaven National Lab
NuFact 2013, IHEP, Beijing

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<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reference</th>
</tr>
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<td>Solar+KamLand</td>
<td>[1106.5028]</td>
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<td>MINOS</td>
<td>[1108.0015]</td>
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<td>T2K 6 Events</td>
<td>[1106.2822]</td>
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<td>DC 101 Days</td>
<td>[1112.6353]</td>
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<tr>
<td>Daya Bay 55 Days</td>
<td>[1203.1669]</td>
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<tr>
<td>RENO 229 Days</td>
<td>[1204.5026]</td>
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<td>T2K 11 Events</td>
<td>[ICHEP2012]</td>
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<td>DC 228 Days</td>
<td>[1207.5632]</td>
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<td>Daya Bay 139 Days</td>
<td>[1210.6327]</td>
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<tr>
<td>DC n-H Analysis</td>
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<tr>
<td>RENO 416 Days</td>
<td>[NuTe2013]</td>
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<td>T2K 11 Events</td>
<td>[1304.0841]</td>
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<td>DC RRM Analysis</td>
<td>[1305.2734]</td>
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<tr>
<td>T2K 28 Events</td>
<td>[EPS2013]</td>
</tr>
<tr>
<td>Daya Bay 217 Days</td>
<td>[NuFact2013]</td>
</tr>
</tbody>
</table>
BEPCII/BESIII: Operational since 2009

A high lumi. $e^+e^-$ collider at the $\tau$-c energy region
Mass Hierarchy by Reactor neutrinos

\[ F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E) \]

\[ P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32} \]

\[ P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \]

\[ P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \]

\[ P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \]

\[ \Delta_{21} \ll \Delta_{31} \approx \Delta_{32} \]

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022
L. Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009

Precision energy spectrum measurement: Looking for interference between \( P_{31} \) and \( P_{32} \) → relative measurement
More Photoelectrons -- PMT

SBA photocathode

MCP PMT with reflection photocathode at bottom

20" + 8" PMT
8" PMT better timing

Miao HE
Institute of High Energy Physics, Beijing
China Superbeam Facility

A possible detector: JUNO detector (distance between CSNS and JUNO: ~150 km)
The next questions

→ Which $\theta_{23}$ octant?
→ What is the mass hierarchy?
→ Is CP Violated in the neutrino sector?

→ Are neutrinos Majorana type?
→ Are there (light) sterile neutrinos?

→ and then there are even more fundamental issues:
  
  neutrino mass,
  hierarchy problem,
  baryon asymmetry,
  leptogenesis,
  dark matter
  inflation,
  ...

\begin{center}
\textbf{Mixing matrices}
Quarks
\[ |U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix} \]
Neutrinos
\[ |U_{\nu}| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \]
\end{center}
CUORICINO
NEMO-3
EXO-200
KamLAND-Zen
GERDA

\[ \langle m_{\beta\beta} \rangle = 140 - 930 \text{ meV} \]
Probing the Inverted Mass Hierarchy?
Post-Planck... Ade et al. [Planck] 2013

ΛCDM + neutrino mass (7 parameters)

- WMAP (9 years)
- W9 + ACT
- Planck + WMAP Polarisation

\[ \sum m_\nu < 0.66 \text{ eV (95\% C.L.)} \]

Best CMB-only bound

- W7 + matter power spectrum + HST \( H_0 \)
- Planck + WP + (ACT \( \ell > 1000 \) + SPT \( \ell > 2000 \)) + baryon acoustic oscillations

\[ \sum m_\nu < 0.25 \text{ eV (95\% C.L.)} \]

Best minimal bound

Formally similar to the pre-Planck best minimal bound, but arguably less prone to issues of nonlinearities.
Many Exciting New Experiments and Pro-

- Reactor $\bar{\nu}_e$ Disappearance:
  - Nucifer (OSIRIS, Saclay), Stereo (ILL, Grenoble) [arXiv:1204.5379]
  - DANSS (Kalinin Nuclear Power Plant, Russia) [arXiv:1304.3696], POSEIDON (PIK, Gatchina, Russia) [arXiv:1204.2449]
  - SCRAAM (San Onofre, California) [arXiv:1204.5379]
  - CARR (China Advanced Research Reactor) [arXiv:1303.0607]
  - Neutrino-4 (SM-3, Dimitrovgrad, Russia), SOLID (BR2, Belgium), Hanaro (Korea) [D. Lhuillier, EPSHEP 2013]

- Radioactive Source $\nu_e$ and $\bar{\nu}_e$ Disappearance:
  - SOX (Borexino, Gran Sasso, Italy) [arXiv:1304.7721]
  - CeLAND ($^{144}$Ce@KamLAND, Japan) [arXiv:1107.2335]
  - SAGE (Baksan, Russia) [arXiv:1006.2103]
  - IsoDAR (DAEδALUS, USA) [arXiv:1210.4454, arXiv:1307.2949]
  - SNO+, Daya Bay, RENO [T. Lasserre, Neutrino 2012]

- Accelerator $\nu_\mu \rightarrow (\neg) \nu_e$ Appearance:
  - nuSTORM [arXiv:1308.0494]
  - OscSNS (Oak Ridge, USA) [arXiv:1305.4189, arXiv:1307.7097]
• cLFV forbidden in the **Standard Model** with vanishing neutrino masses

• extremely suppressed in the SM extension with neutrino oscillation

  • example: $BR(\mu \rightarrow e\gamma) \approx 10^{-50}$ not measurable by any experiment

$$\Gamma(\mu \rightarrow e\gamma) \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \left( \frac{\alpha}{2\pi} \right) \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2}{M_W^2} \right)$$

$\mu$ – decay \hspace{1cm} $\gamma$ – vertex \hspace{1cm} $\nu$ – oscillation

$$\approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{3\alpha}{32\pi} \left( \frac{\Delta m_{23}^2 s_{13} c_{13} s_{23}^2}{M_W^2} \right)^2$$

$\Rightarrow \mu \rightarrow e\gamma$ as a **clean probe** of **new physics** beyond the Standard Model
cLFV zoology

Several cLFV (and $\mu$ physics) processes sensitive to New Physics

Lepton anomalous decay

complementary processes to define the nature of NP

Anomalous magnetic moment
The coolest picture
Inspiration and Aspiration

- The level of agreement between the measurements is often misinterpreted.
- Allowed region is much larger if NP is included in the fit, more parameters, which changes the fit completely.
- $\mathcal{O}(20\%)$ NP contributions to most loop processes (FCNS) are still allowed.
- Need experimental precision and theoretical cleanliness to increase NP sensitivity.

Talk by Z. Ligeti at Snowmass-on-Mississipi, July-Aug 2013
The PMNS Fitter

- Framework for global fit with deeply involved from all current experiments (not just likelihood surface, but systematic contributions).

- "Bayesian Analysis Toolkit" (BAT based on Bayes’ theorem and MCMC) is used as backbone.

- Using MINOS data to test framework (by comparing with MINOS published results.)

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Frederik Beaujean
Max-Planck-Institut für Physik

Son Gao
University of Texas at Austin

Alexandre Sousa
University of Cincinnati

Viet Nus, December 21, 2012
The Energy Frontier

- Origin of Mass
- Dark Matter

The Intensity Frontier

- Matter/Antimatter Asymmetry
- Origin of Universe
- New Physics Beyond the Standard Model
- Cosmic Particles

The Cosmic Frontier

- Neutrino Physics
- Unification of Forces
- Proton Decay
- Dark Energy
Summary of Snowmass 2013

André de Gouvêa
Northwestern University

- Nu1: Neutrino Oscillations and the Three-Flavor Paradigm (Mary Bishai, Karsten Heeger, Patrick Huber);
- Nu2: The Nature of the Neutrino: Majorana vs. Dirac (Steve Elliott, Lisa Kaufman);
- Nu3: Absolute Neutrino Mass (Hamish Robertson, Ben Monreal);
- Nu4: Neutrino Interactions (Jorge Morfin, Rex Tayloe);
- Nu5: Anomalies and New New Physics (Boris Kayser, Jon Link);
- Nu6: Astrophysical and Cosmological Neutrinos (Kara Hoffman, Cecilia Lunardini, Nikolai Tolich);
- Nu7: Neutrinos and Society (José Alonso, Adam Bernstein).
LBNE + Project X (1.1-2.3 MW) = Comprehensive Global Science Program

- Long-range program in tandem with near detector neutrino interactions and non-accelerator physics

With 80 GeV MI protons source
LBNE Design Status

LBNE has a well-developed design for the complete project:

- Neutrino beam at Fermilab for 700 kW operation, upgradeable to 2.3 MW
- Highly-capable near neutrino detector on the Fermilab site
- 34 kt fiducial mass LAr far detector at
  - A baseline of 1300 km
  - A depth of 4300 m.w.e. at the Sanford Underground Research Facility (SURF) in the former Homestake Mine in Lead, South Dakota
The most popular plot

A NEW plot – THANKS to Pilar!
Sum rules

\[ \theta_{12} = 35^\circ + \theta_{13} \cos \delta \]
\[ \theta_{12} = 32^\circ + \theta_{13} \cos \delta \]
\[ \theta_{23} = 45^\circ + \sqrt{2} \theta_{13} \cos \delta \]
\[ \theta_{23} = 45^\circ - 1/\sqrt{2} \theta_{13} \cos \delta \]
\[ \theta_{12} = 45^\circ + \theta_{13} \cos \delta \]

Antusch, King

3 \sigma resolution of 15° distance requires 5° error. NB – smaller error on \( \theta_{12} \) requires dedicated experiment like JUNO
Physics of GeV $\nu$–N Interactions

1. Cross section models for all exclusive $\nu$-nucleon interaction channels (elastics, resonance productions, DIS ...)

2. Models of nucleons within the nucleus (Relativist Fermi Gas, spectral functions, nucleon correlations, ...)

3. Final state interaction models which alter the hadronic final state (rescattering, absorption, charge exchange, ...)

David Schmitz, UChicago
NuFact 2013, 19-24 August, 2013
CERN, a success story

Staged approach

Multi-purpose
“If you don't know where you are going, you might wind up someplace else.”  
Yogi Berra
# Staged Physics Program

<table>
<thead>
<tr>
<th>Program:</th>
<th>NOvA + Proton Improvement Plan</th>
<th>Stage-1: 1 GeV CW Linac driving Booster &amp; Muon, n/edm programs</th>
<th>Stage-2: Upgrade to 3 GeV CW Linac</th>
<th>Stage-3: Project X RDR</th>
<th>Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW</th>
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<tbody>
<tr>
<td>MI neutrinos</td>
<td>470-700 kW**</td>
<td>515-1200 kW**</td>
<td>1200 kW</td>
<td>2450 kW</td>
<td>2450-4000 kW</td>
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<tr>
<td>8 GeV Neutrinos</td>
<td>15 kW + 0-50 kW**</td>
<td>0-42 kW* + 0-90 kW**</td>
<td>0-84 kW*</td>
<td>0-172 kW*</td>
<td>3000 kW</td>
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<td>8 GeV Muon program e.g. (g-2), Mu2e-1</td>
<td>20 kW</td>
<td>0-20 kW*</td>
<td>0-20 kW*</td>
<td>0-172 kW*</td>
<td>1000 kW</td>
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<td>1-3 GeV Muon program e.g. Mu2e-2</td>
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<td>80 kW</td>
<td>1000 kW</td>
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<td>Kaon Program</td>
<td>0-30 kW** (&lt;30% df from MI)</td>
<td>0-75 kW** (&lt;45% df from MI)</td>
<td>1100 kW</td>
<td>1870 kW</td>
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<td># Programs:</td>
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<td>9</td>
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<td>Total max power:</td>
<td>735 kW</td>
<td>2222 kW</td>
<td>4284 kW</td>
<td>6492 kW</td>
<td>11870 kW</td>
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</table>

HEPAP Subpanel, February 2013
Reference Design
Staging

1 MW @ 1 GeV
3 MW @ 3 GeV
0.2 MW @ 8 GeV
2 MW @ 60-120 GeV
>6 MW Total
The U.S. Muon Accelerator Program

Neutrino Factory

Proton Driver
- Accumulator
- Compressor
- Hg-Jet Target Capture Sol.

Target
- Front End
- Decay Channel
- Buncher
- Phase Rotator
- 4D Cooler

Decay: 0.2–1.2 GeV
Luminosity: 5 GeV
Length: ~0.35 km

Accelerators:
- Linac, RLA or FFAG

μ Storage Ring
- 1.2 – 5 GeV

ν Factory Goal:
- O(10^{21}) μ/yr within the accelerator acceptance

μ-Collider Goals:
- 126 GeV ⇒ ~14,000 Higgs/yr
- Multi-TeV ⇒ Lumi > 10^{34} cm^{-2}s^{-1}

Muon Collider

Proton Driver
- Accumulator
- Compressor
- Hg-Jet Target Capture Sol.

Target
- Front End
- Decay Channel
- Buncher
- Phase Rotator

Cooling:
- 6D Cooling
- μ^+
- μ^−
- Bunch
- Merge
- Cooling
- Final Cooling

Acceleration:
- Linac, RLA or FFAG, RCS

Collider Ring
- E_{com} = 126 GeV
- 1.5 TeV
- 3 TeV

Mark A. Palmer

NUFACT 2013 - Beijing, China
August 21, 2013

K. Lang, U. of Texas at Austin: Summary
LBNE
To Far Detector in Sanford (1300km)
Buncher/
Accumulator
Rings & Target
Linac + RLA
SC 325MHz
to ~5 GeV
5 GeV
NF Decay Ring:
ν
s to Sanford
Front End + 4D
RLA to 63 GeV +
300m Higgs Factory
ν
STORM + Muon Beam
R&D Facility
Later upgradable to a
Muon Collider with
Tevatron size at 6 TeV
Project X
Stage III
Project X
Stage I
Project X
Stage II
1500
0
1500

J.P. Delahaye
NuFACT13 (August 21, 2013)

Mark Palmer
Jean-Pierre Delahaye
The Muon Accelerator Program

By the end of this decade:

- To deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider and/or a next-generation neutrino beam facility

As well as...

- To explore the path towards a facility that can provide cutting edge performance at both the Intensity Frontier and the Energy Frontier

- To validate the concepts that would enable the Fermilab accelerator complex to support these goals
Neutrino Factory target baseline: free mercury jet
- see WG3 talk tomorrow by Kirk McDonald

Baseline target system for a Neutrino Factory

But a liquid mercury target presents many challenges, e.g. interaction of mercury jet with dump, handling, disposal etc

MERIT mercury jet experiment at CERN demonstrated suppression of beam induced ‘splash’ with magnetic field
Conclusion

• Through the end of this decade, the primary goal of MAP is demonstrating the feasibility of key concepts needed for a neutrino factory and muon collider

⇒ Thus enabling an informed decision on the path forward for the HEP community

A promising R&D program is in progress!
Forget about

- CERN resources are fully challenged by LHC upgrades
- As a matter of fact the latest neutrino beam line fully funded by CERN had been WANF (Chorus, Nomad), more than 20 years ago. (CNGS had been funded by the largest part by external funding agencies, mainly INFN).
- The neutrino physics community is not converging to a single project and sometimes the different projects conflict.

Four large scale projects with high priority

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. **CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.**

- Full cost for a comprehensive accelerator based neutrino facility is large. Ideas for such facilities are being developed in Japan, the US and Europe.
- Consideration should include the physics potential from non-accelerator neutrino programme: i.e. sterile neutrino and mass hierarchy.
- Optimising the European contribution for neutrino physics vis a vie the European ambition of high energy frontier.
Workers of the world, unite!

Proletarier aller Länder vereinigt Euch!

Пролетарии всех стран, соединяйтесь!
http://www.fnal.gov/directorate/icfa/neutrino_panel.html

Top page only at the moment. Site will go “live” Monday 26Aug13.
The neutrino (Super) beam

Primary proton beam on target

Focusing the pions with a magnetic device

Decay volume

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]
Conclusions-1

- A conventional neutrino beam with an increasing beam power towards the multi-MW range remains the primary tool for the further study of neutrino oscillations

- The EUROnu design study concluded that practical solutions exists for the target and horn

- Several aspects (target, horn cooling) require further prototyping to validate these solutions

- The devil is in the details: strips, cooling system, piping, remote replacement system

- The target system remain the primary area for further investigations towards feasibility

- The horn system has the potential for boosted performances
INO Facilities at Pottipuram

New kid on the block!

50 kton ICAL Neutrino Detector
Funding Balance .... “The 1% Tax”

- What is the right balance between funding to support the needs of specific projects and funding to support generic detector development?
- What if 1% of the OHEP budget were set aside for the development of potentially transformative technologies?
- What technologies could be developed?
US HEP Funding

DOE Office of Science and HEP Funding (M$)

Discovery science is not a high priority

Energy independence and economic competitiveness are

HEP is funding is likely to remain flat at best

"$800M is not exactly chicken feed"
J. Hewett, Summary Intensity Frontier Snowmass on the Mississippi From Formaggio and Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012
Bruno Pontecorvo (1913-1993)

Born Aug 22, 1913

- Solar neutrinos
  $^{37}\text{Cl (ν, }e^-\text{)}^{37}\text{Ar (inverse beta)}$
- Different ν flavors, 1957
- Neutrino oscillations
- Accelerator produced ν beams
  $\pi \rightarrow \mu + ν, \ K \rightarrow \mu + ν$
- Sterile neutrinos
- ...(and much more)
◆ This is a memorable NuFact
◆ Unforgettable hospitality
◆ Well organized and smoothly run!

◆ THANKS to all!

◆ My special thanks to Miao He
Bon voyage!

再 见

zai jian