# PHYS 5326 – Lecture #8

*Wednesday, Feb. 21, 2007*
*Dr. Jae Yu*

1. Short Base Line Experiments
2. Future Neutrino Oscillation Projects
3. Local Gauge Invariance and Introduction of Massless Vector Gauge Field

# Short Baseline Experiments

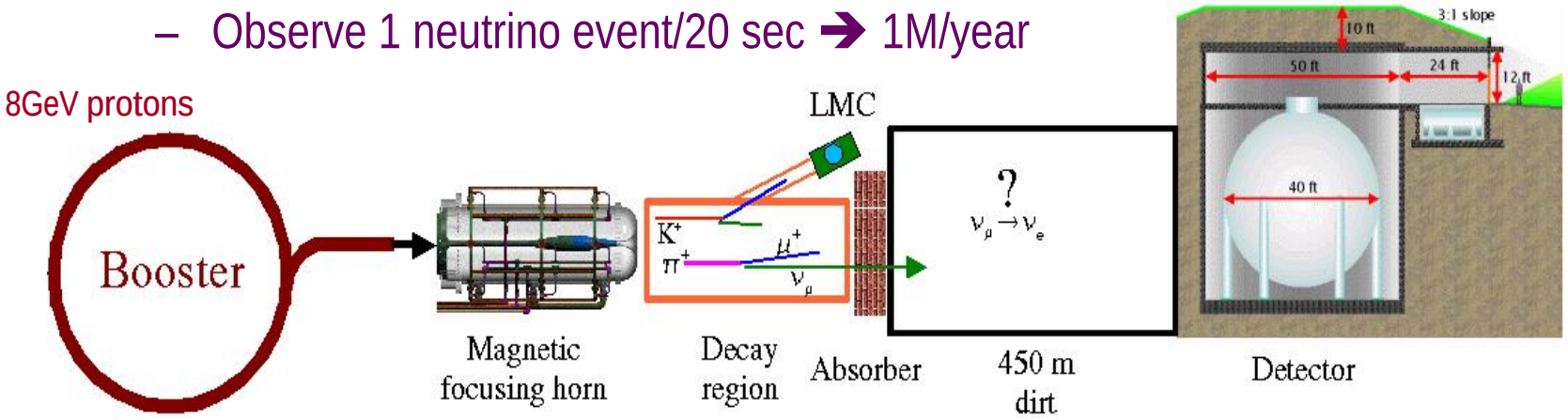
- Baseline less than a few km
- Neutrino energies need to be low

$$P\left(\nu_\mu \to \nu_e\right) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

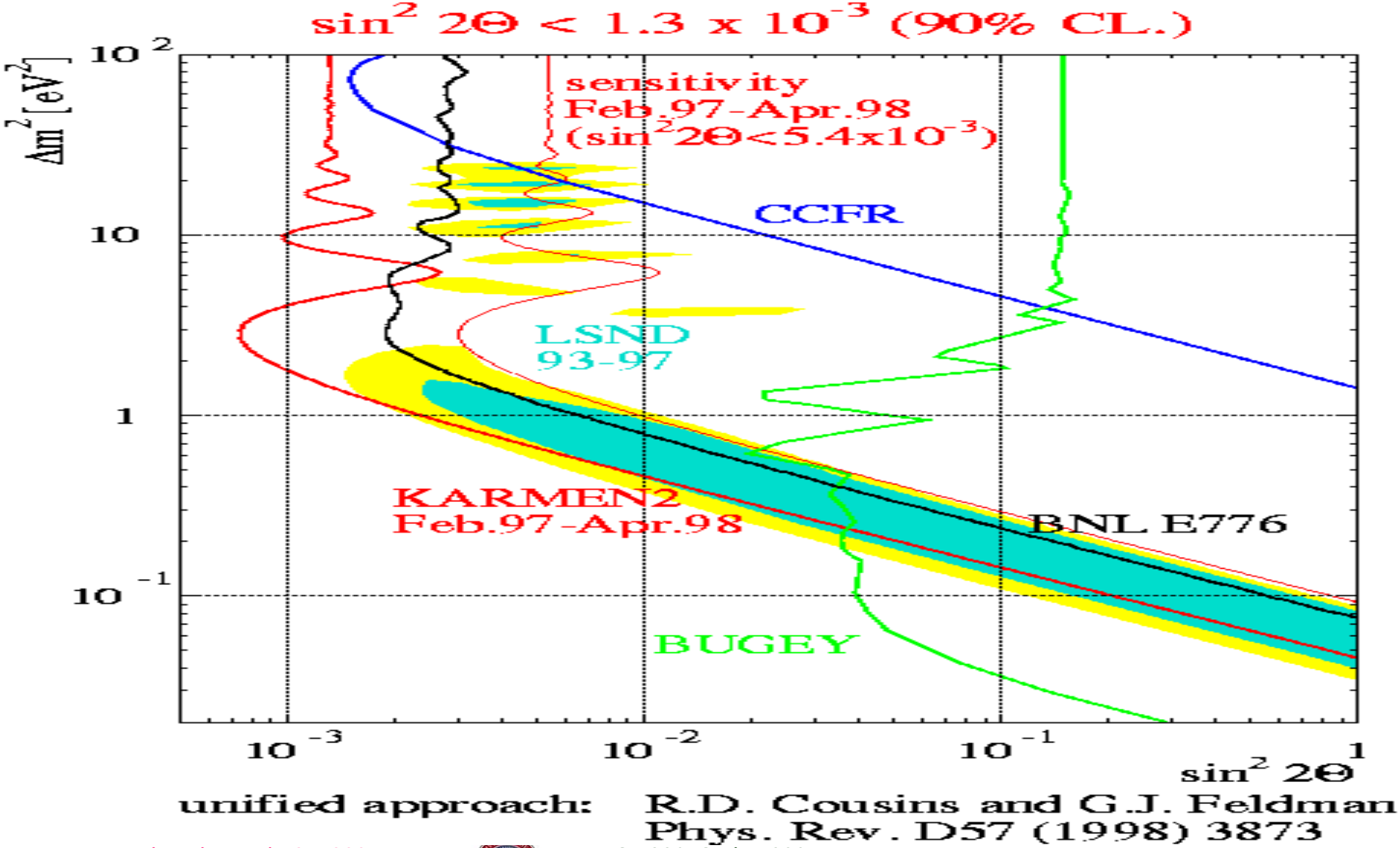
- Experiments and laboratories
  - CERN, Geneva: NOMAD, CHORUS,
  - Fermilab: BooNE, COSMOS (rejected)
  - Los Alamos: LSND (Completed)
  - Rutherford, UK: KARMEN
  - Oak Ridge: ORLanD (Using spallation neutrino source)

# MiniBooNE (Booster Neutrino Experiment)

- A short base line experiment
- Goal: To investigate the signal from LSND on $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at $\Delta m^2 \sim 1 eV^2$
  - A bit contradictory to Super-K results
  - Measure oscillation properties
- Uses 8GeV protons from Fermilab's Booster on a target embedded in a Horn magnet
- Started commissioning in 2003 and is taking data now
- Use Cerenkov light in a liquid scintillator detector
  - 40ft sphere with 800 tons of mineral oil and 1520 PMT's
  - Observe 1 neutrino event/20 sec ➔ 1M/year



# KARMEN Results




unified approach: R.D. Cousins and G.J. Feldman Phys. Rev. D57 (1998) 3873

# Summary of $\nu_\tau$ Appearance Experiments

Neutrino oscillation data page - Microsoft Internet Explorer provided by America Online - [Working Offline]

File Edit View Favorites Tools Help

Address D:\UTA\Classes\5326-spring03\Lectures\Wee of Mar. 3\Neutrino oscillation data page.htm Go Links

| Experiment | Location | Source | Baseline | Observation | Status | Years |
|---|---|---|---|---|---|---|
| E531 | Fermilab | accelerator | 949 m | no osc | finished | 86 |
| CHORUS | Cern | SPS | 820 m | no osc | scanning and analyzing data | 1994-1997- |
| Nomad | Cern | SPS | 820 m | no osc | analyzing data | 1995-1998 |
| OPERA | Gran Sasso | Cern | 740 km | | proposed | 2005- |
| TOSCA | Cern | SPS | | | rejected | - |

Internet

# Summary of $\nu_e$ Appearance Experiments

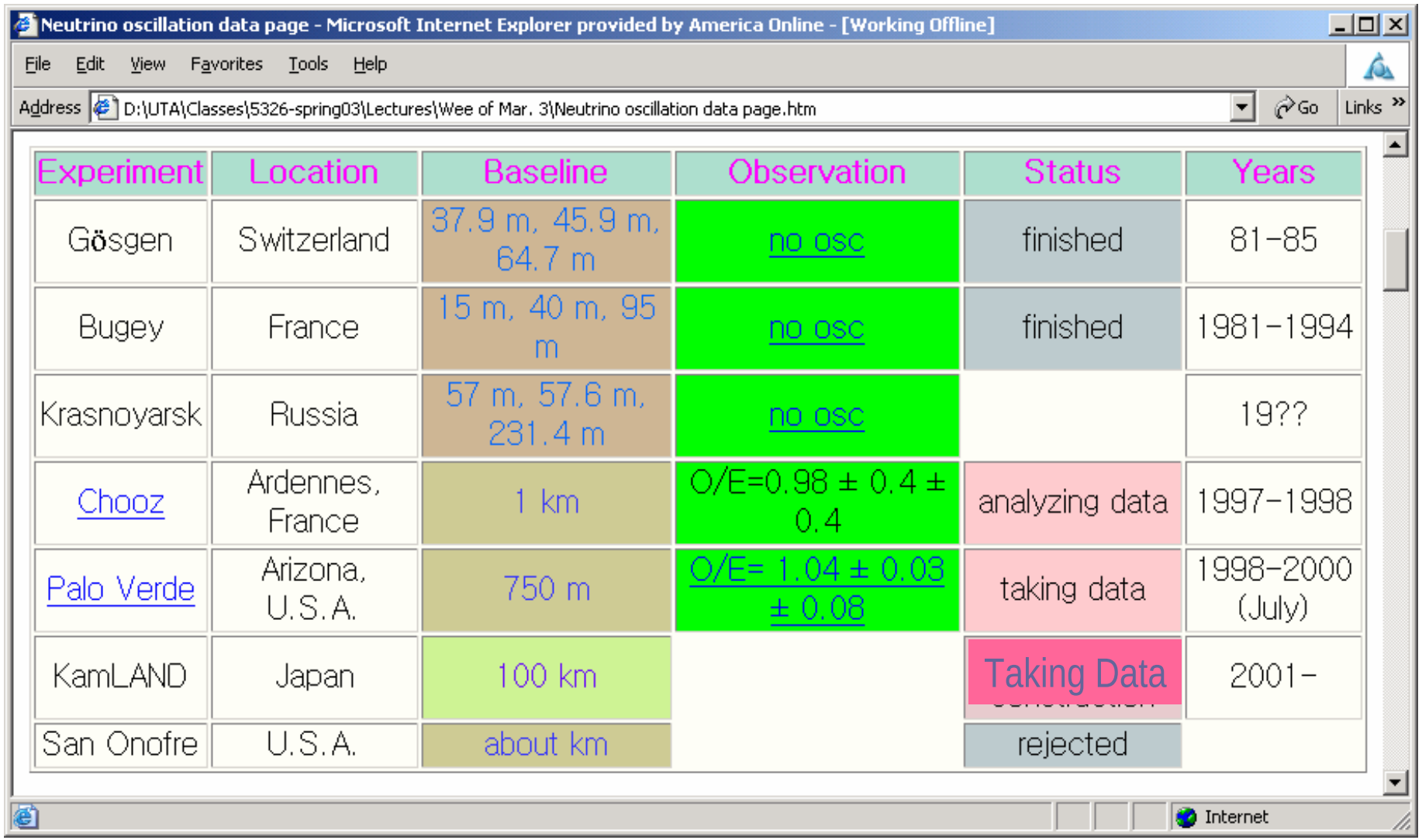
Neutrino oscillation data page - Microsoft Internet Explorer provided by America Online - [Working Offline]

File Edit View Favorites Tools Help

Address D:\UTA\Classes\5326-spring03\Lectures\Wee of Mar. 3\Neutrino oscillation data page.htm Go Links

| Experiment | Location | Source | Baseline | Observation | Status | Years |
|---|---|---|---|---|---|---|
| BEBC | Cern | SPS | | no osc | finished | - 1986? |
| CCFR | Fermilab | Tevatron | 0.9 km to 1.4 km | no osc | taking data (?) | 1990? - |
| E776 | BNL | AGS | 1 km | no osc | finished | 85-86 |
| LSND | Los Alamos | LAMPF proton beam | 30 m | excess of $\bar{\nu}_e$: 40 ± 9 $\nu_e$: 18 ± 7 | completed | 1994-1998 |
| Karmen | Rutherford | ISIS proton beam | 18 m | no osc | taking data | 1994-2001 |
| Nomad | Cern | SPS | 820 m | no osc | analyzing data | 1995-1998 |
| K2K | Kamioka | KEK beam | 250 km | | taking data | 1999- |
| Minos | Soudan mine, MS | Main Injector at Fermilab | 730 km | | under construction | 2004- |
| miniBooNE | Fermilab | Fermilab Booster | 0.5 km/ 1 km | | Taking Data | 2003- |
| NOE | Gran Sasso | Cern | 732 km | | merged to Icanoe | |
| Icanoe | Gran Sasso | Cern | 732 km | | proposed | about 2005 |
| Cosmos | Fermilab | Main Injector | 1 km | | rejected | |

# $\nu_e$ Disappearance Experiments




| Experiment | Location | Baseline | Observation | Status | Years |
|---|---|---|---|---|---|
| Gösgen | Switzerland | 37.9 m, 45.9 m, 64.7 m | no osc | finished | 81-85 |
| Bugey | France | 15 m, 40 m, 95 m | no osc | finished | 1981-1994 |
| Krasnoyarsk | Russia | 57 m, 57.6 m, 231.4 m | no osc | | 19?? |
| Chooz | Ardennes, France | 1 km | O/E=0.98 ± 0.4 ± 0.4 | analyzing data | 1997-1998 |
| Palo Verde | Arizona, U.S.A. | 750 m | O/E= 1.04 ± 0.03 ± 0.08 | taking data | 1998-2000 (July) |
| KamLAND | Japan | 100 km | | Taking Data | 2001- |
| San Onofre | U.S.A. | about km | | rejected | |

# What do we know now?

- We clearly know neutrinos oscillate ➔ Neutrinos have masses
- It seems that there are three allowed regions of parameters ($\sin^2 2\theta$ and $\Delta m^2$) that the current data seem to point
  - LSND ~1eV$^2$; Super-K ~ $10^{-3}$ eV$^2$, Solar (LMA) ~ $10^{-5}$ eV$^2$
  - There are at least three flavors participating in oscillation
  - $\sin^2 2\theta_{23} \sim 1$ at 90% confidence level
  - $|\Delta m_{32}^2| \sim 2\times10^{-3}$ eV$^2$
  - $\Delta m_{21}^2 \sim 2\times10^{-3}$ eV$^2$ (If LMA confirmed)
  - $\sin^2 2\theta_{12} \sim 0.87$ at 90% confidence level (if LMA confirmed)
  - $\sin^2 2\theta_{13} < O(0.1)$

# What do we not know?

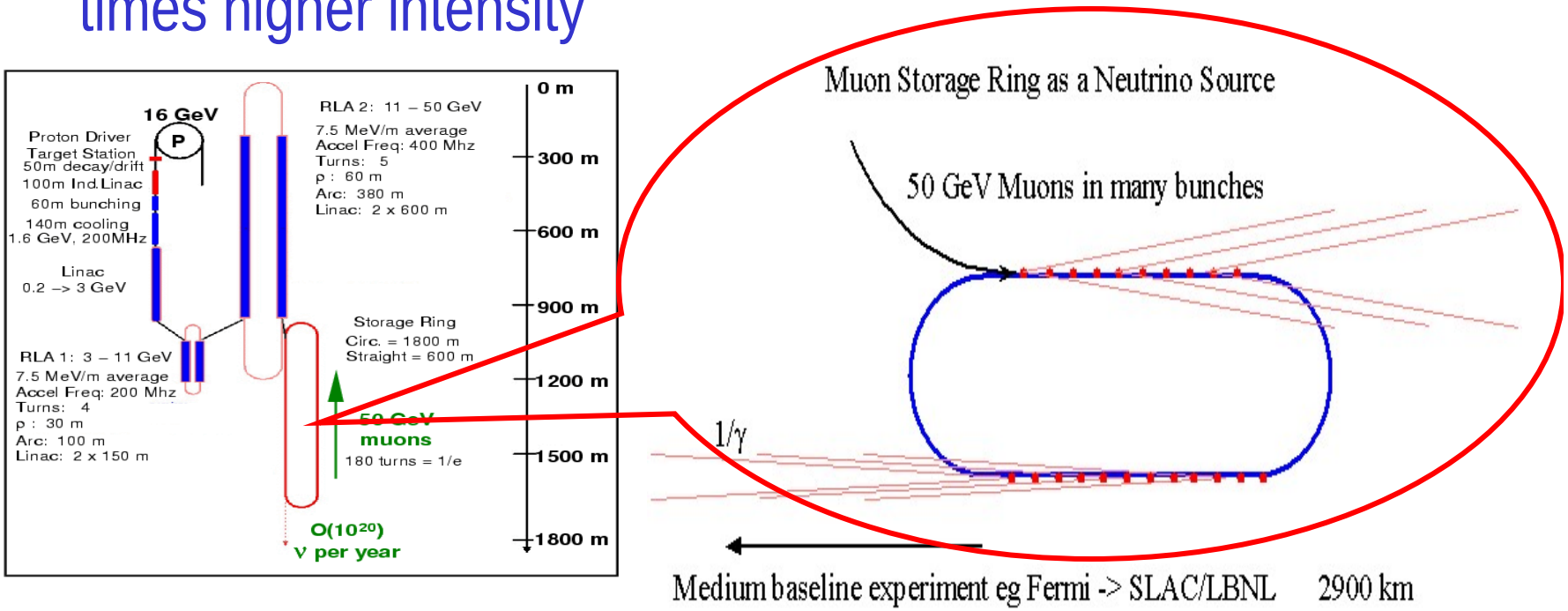
- Does 3-flavor mixing provide right framework?
  - For CP–violating oscillation, additional neutrino flavors, neutrino decay, etc?
- How many flavors of neutrinos do we have?
- Is $\sin^2 2\theta_{13}$ 0 or small?
- What is the sign of $\Delta m_{32}$?
  - What are the configuration of neutrino masses?
  - What are the actual masses of neutrinos mass eigenstates?
- What are the matter effects?
- Is $\sin^2 2\theta_{23} = 1$?
- While there are a lot of questions and measurements need to be performed, neutrino oscillation provides an exciting new area in HEP.

# Other Future Projects

- It is practically accepted that there are neutrino oscillations
  - Many new models are being thought to explain this
- Goals of these experiments are to measure specifics of neutrino oscillations
  - Mixing angles
  - Matter effects
  - Other types of neutrinos, etc
- BNL Neutrino Working Group Accelerator Experiment
- Reactor experiments ( $\bar{\nu}_e \rightarrow \bar{\nu}_e$ )
  - Braidwood Reactor Experiment
  - Daya Bay Reactor Experiment
  - Diablo Canyon Reactor Experiment
  - KASKA Reactor Experiment
  - Kr2Det Reactor Experiment
  - Reno Experiment

# Future: Neutrino Factory

- Spin-off of a muon collider research
  - One a hot, summer day at BNL, the idea of neutrino storage ring popped up
- Future facility using muon storage ring, providing well understood neutrino beam ($\nu_\mu$ and $\nu_e$) at about $10^6$ times higher intensity



# Useful Links for Neutrinos Oscillations

- General summary: http://www.nu.to.infn.it/
- http://www.hep.anl.gov/ndk/hypertext/nuindustry.html
- http://www.ps.uci.edu/~superk/oscillation.html
- http://wwwlapp.in2p3.fr/neutrinos/ankes.html