Superbeams

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What is a Superbeam?

- Neutrino beam made directly from pion decay.
- Magnetically (horn) focused secondary beam.
- Driven by a high-power proton beam.
  - What is “high-power”? 0.5 MW? 2 MW? 4 MW? Seems to be in the eye of the beholder.
  - Current state of the art: ~0.4 MW
  - Beams in the 1-2 MW range are on the drawing board.
  - >>2 MW becomes a real challenge.
- Technical challenge is not just beam power, but also total integrated protons on target and rep rate.
  => Easier to deal with high beam power at higher beam energy.
Why Continue to Use Superbeams

• They are simple and direct …
  … neutrino beam is merely a tertiary beam, not a quarternary beam, as in a neutrino factory.

• They are an incremental extension of a well-developed and well-understood method of making a $\nu$ beam.

• They make a pretty good $\nu_\mu$ beam $\geq 98\%$ pure.
  (But not so good for $\bar{\nu}_\mu$, no good at all for $\nu_e$.)

• Versatile in terms of energy spectrum, depending on:
  - proton beam energy
  - horn system properties
  - target placement
  - decay pipe dimensions
  - off-axis angle
Limitations of Superbeams

- Intrinsically broad-band beam, whose spectrum cannot be crisply controlled.
- Difficult to know the spectrum and absolute flux to high precision – dependent on modeling.
- Intrinsic $\nu_e$ contamination from K and $\mu$ decays – hard to get below $\sim 1\%$ level.
- Intrinsic “wrong-sign” contamination, especially in $\bar{\nu}_\mu$ beam, especially in the high energy part of the spectrum where horn focusing system is less important.
- Long high-energy tail beyond region of interest for oscillation physics can generate background at lower energy (depending on detector capabilities).
Why Continue to Use Superbeams

• We have not yet reached the limits of superbeams:
  - x5~10 in beam power is feasible relative to the current state of the art (0.3-0.4 kW).
  - Modest improvements are still possible in control of spectrum and $\nu_\mu$ ($\bar{\nu}_\mu$) purity.
  - Modest improvements are still possible in measurement and understanding of spectrum and $\nu_\mu$ ($\bar{\nu}_\mu$) purity.

=> There is still a lot of important physics we can do using superbeams. They are the workhorse of neutrino physics and are likely to remain so for a long time.
Optimization (L, E, etc) of the setup

- Optimization strongly depends on physics goals.
- For LBNE, we want to measure $\theta_{13}$, $\delta$, and sign($\Delta m_{32}^2$) all in one experiment. This requires:
  - Baseline long enough to separate CP and matter effects on $\nu / \bar{\nu}$ oscillation asymmetry for $\sin^2 2\theta_{13} \geq 0.01$
    $\Rightarrow L \geq 1300$ km.
  - Baseline short enough that matter asymmetry does not too strongly dominate over CP asymmetry.
    $\Rightarrow L \leq 2000$ km (softer limit than for $L_{\text{min}}$)
  - Broad band beam covering the 1$^{\text{st}}$ and if possible 2$^{\text{nd}}$ oscillation maximum.
    $\Rightarrow$ on-axis beam; $E_{\text{max}} \approx 2.5$ GeV.
- We judge that 1300 km is nearly optimal for $\sin^2 2\theta_{13} \geq 0.01$
Optimization (L, E, etc) of the setup

Additional consideration:

- Longer baseline puts 1\textsuperscript{st} and 2\textsuperscript{nd} oscillation maxima at higher energy => easier to access both. (larger cross-sections, weaker nuclear effects.)
The total asymmetry is naively:

\[ A_{total} = A_{CP} + A_{matter} \text{ or } 1.0 \]
The Total Asymmetry at 3000km

When matter asymmetries start to dominate measuring $\delta_{cp}$ becomes more difficult.
$\theta_{13}$, Mass Hierarchy and CP Sensitivities vs. Distance

1300 km represents a near optimal compromise among sensitivity to $\theta_{13}$, $\delta$, and mass hierarchy.
For $\delta > 0$, sensitivity is best for $L = 1300\sim1600$ km.

For $\delta < 0$, sensitivity is best for $L = 1000\sim1300$ km.

(Opposite pattern with sign of $\delta$ for inverted hierarchy)

$\Rightarrow$ 1300 km looks like optimal distance.

G. Rameika

CP/matter effect ambiguity at small $\theta_{13}$, could be helped by better coverage at 2$^{nd}$ oscillation max
Other Possible Approach

- Perform narrow-band experiments at several different energies and baselines with different sensitivities to CP and matter effects.
  - Matter effect is less at important at 2\textsuperscript{nd} oscillation max, or for shorter baseline.
  - T2K and NOvA are complementary in this regard.
Does the optimization change for large $\theta_{13}$?

- Optimization described above is good for $\sin^2 2\theta_{13} \geq 0.01$.
- The question should be how the optimization would change for small $\theta_{13}$?
  
  => Would need the greater precision of neutrino factory beam to sort out the $\theta_{13}$ sector.

- But superbeams can search for non-zero $\theta_{13}$ down to at least $\sin^2 2\theta_{13} \geq 10^{-3}$, if the $\nu_e$ component can be well measured.
  
  => May need to do this before trying to justify large expense of building a neutrino factory.