Physics reach of neutrino beta beams

J. B., D. Casper, J.J. Gómez-Cadenas, P. Hernández, F. Sánchez

And lots of inputs from Mats Lindroos

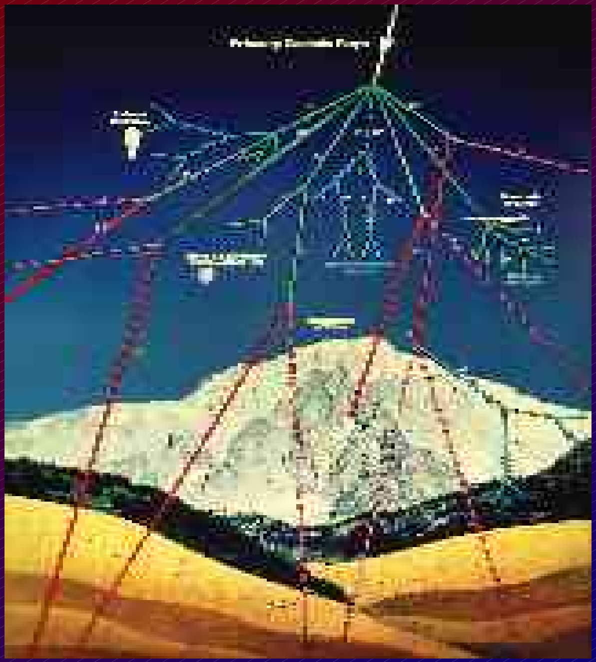
Jordi Burguet-Castell

Benasque – 21 Jul. 2004

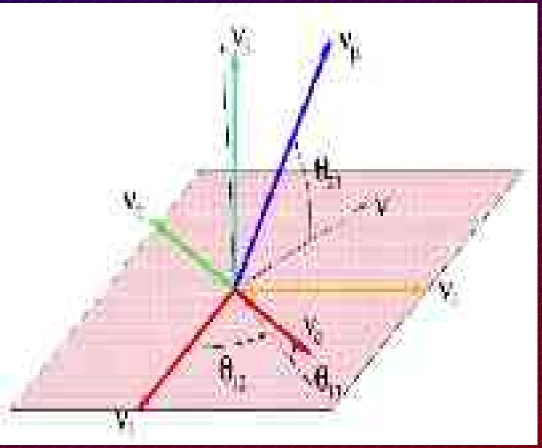
Physics reach of neutrino beta beams

- Motivation
- What is a β-beam?
- What can you expect from it?
- Variations on the idea
- Fluxes, x-sections, eff, bg and all that
- Sensitivity
- What is its current status?
- Conclusion

Motivation



Spectacular results in atmospheric, solar, reactor and long-baseline neutrino experiments in recent years can be economically accommodated in the SM with neutrino masses and a three neutrino mixing matrix:



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\underbrace{\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}}_{\text{Atmospheric and 1st generation of long baseline exp.}}\underbrace{\begin{pmatrix}c_{13}&0&s_{13}e^{i\delta}\\0&1&0\\-s_{13}e^{-i\delta}&0&c_{13}\end{pmatrix}}_{\text{2nd generation of long baseline exp.}}\underbrace{\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}}_{\text{Solar and reactor exp.}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric and 1st generation of long baseline exp.

2nd generation of long baseline exp.

Solar and reactor exp.

$c_{ij}\equiv\cos(\theta_{ij})$

$s_{ij}\equiv\sin(\theta_{ij})$

Motivation

What we **KNOW**

$$\theta_{12} \simeq 35^0 \quad \Delta m^2_{12} \simeq 7\times 10^{-5}\, eV^2 \qquad \Delta m^2_{ij} \equiv m^2_j - m^2_i$$

$$\theta_{23} \simeq 45^0 \quad |\Delta m^2_{23}| \simeq 2.5\times 10^{-3}\, eV^2$$

What we **DON'T KNOW**

$$\theta_{13} \quad \delta \quad sign(\Delta m^2_{23})$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Their measurement requires high-precision oscillation experiments

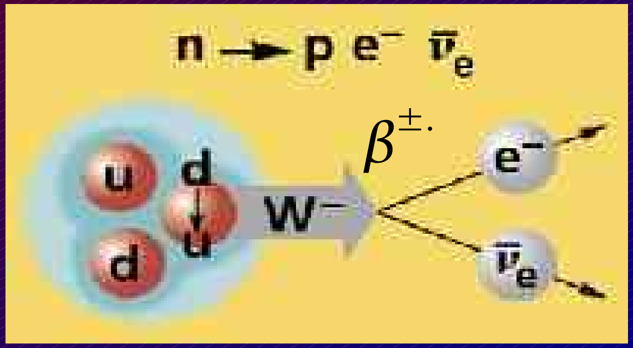
A few proposals on the market:

- **Superbeams** (very intense conventional neutrino beams)
- Improved **reactor experiments**
- **Neutrino factories** (neutrino beams from boosted-muon decays)

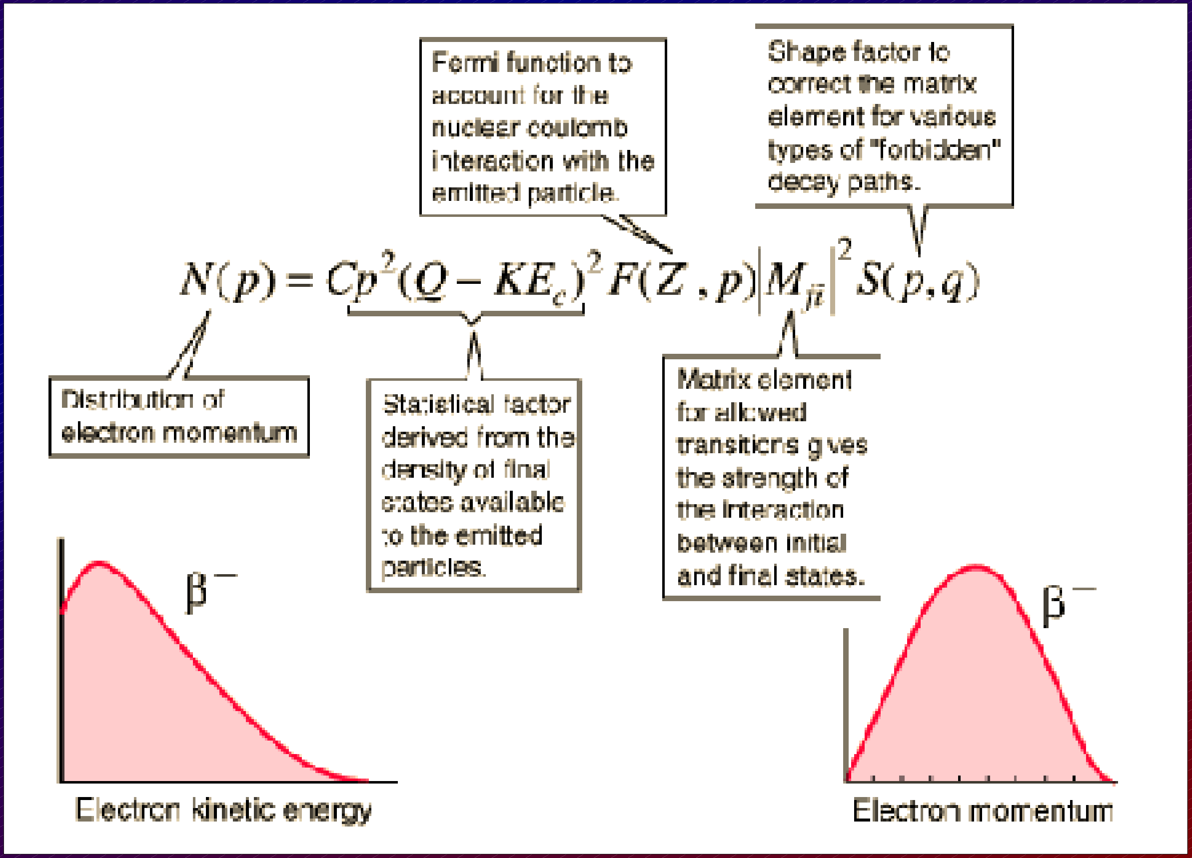
And now comes a “new” one: **β-beams**

What is a β-beam?

Some nucleae with an excess of neutrons (protons) decay emitting an electron and antineutrino (positron and neutrino) in what is called β^- decay (β^+ decay).



The beta decay has a very precisely known energy distribution



What is a β-beam?

So, an idea:

Accelerate beta-unstable ions, let them decay in storage ring pointed at far detector.

Two candidates:

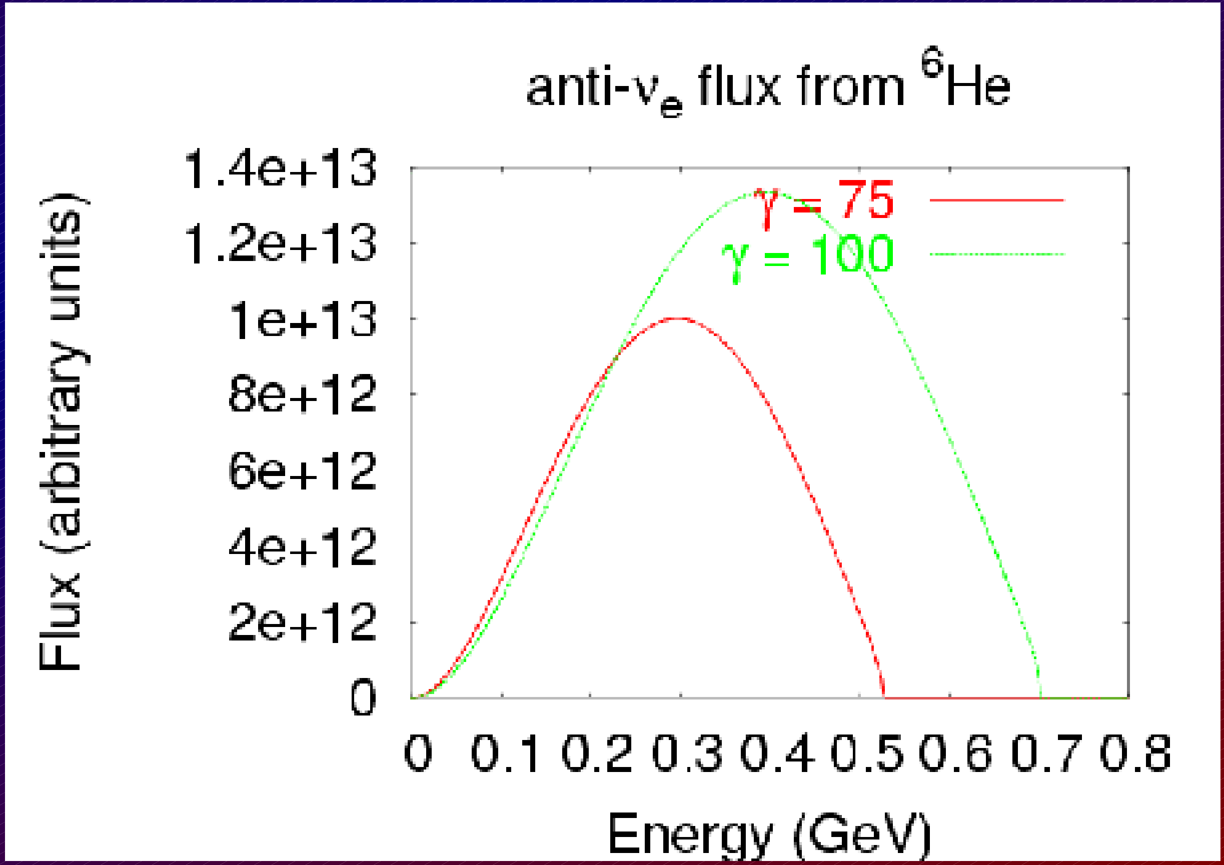
$$^{6}He \rightarrow \bar{\nu}_e \quad (\beta^-)$$

$$^{18}Ne \rightarrow \nu_e \quad (\beta^+)$$

Produce a beam with

- **Single flavor**
- **Spectrum exactly known**
- Known intensity
- Focused

P. Zucchelli, Phy. Lett. B 532

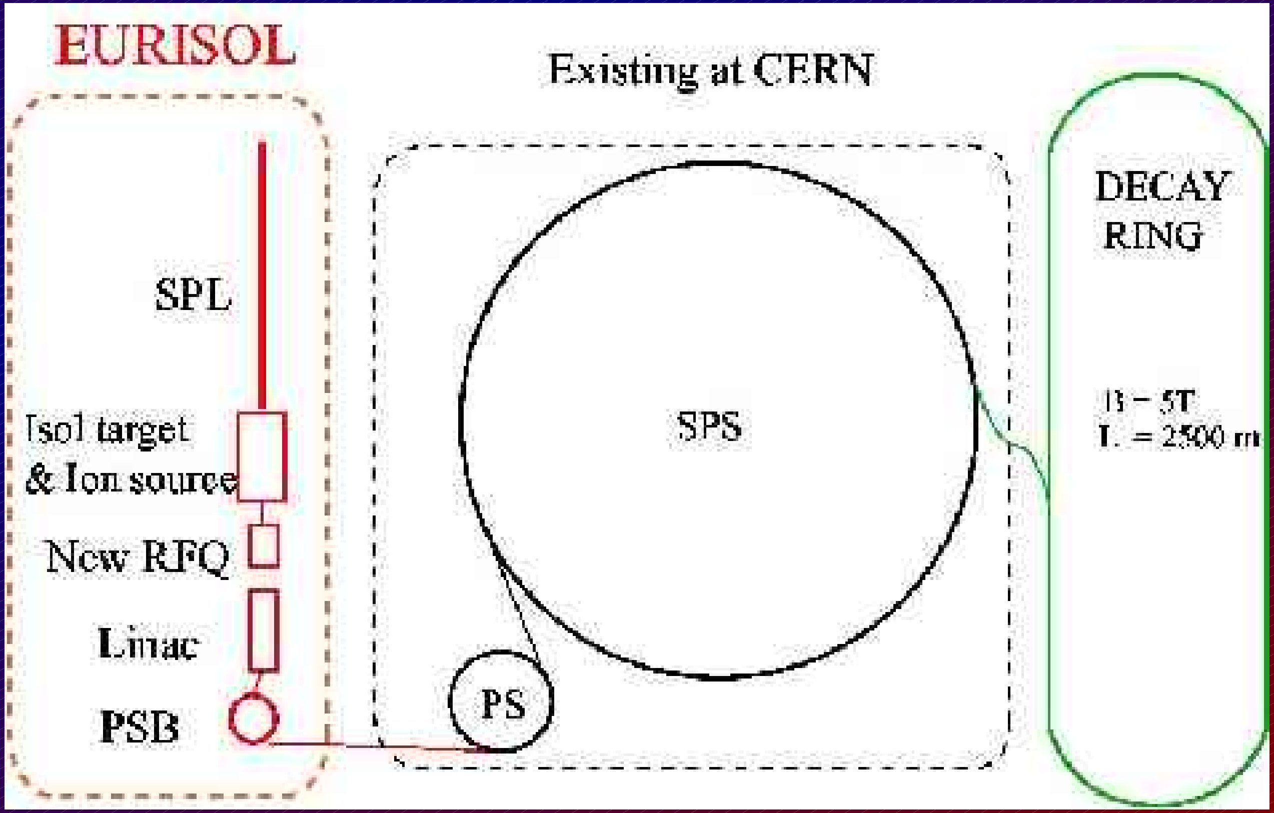


How can it be implemented?

M. Lindroos already told us this morning!

Just a brief recall:

- Ions produced at EURISOL
- Accelerated by the SPS
- Stored in a storage ring, straight sections point to detector



How does it make its work?

For each polarity (^{6}He and ^{18}Ne), there are 2 channels:

For instance... $^{18}Ne \rightarrow \nu_e \ldots$

$\nu_e \rightarrow \nu_\mu \rightarrow \mu^-$. Appearance
Most sensitive channel to $\theta_{13}, \delta, sign(\Delta m^2_{23})$

$$
\begin{aligned}
P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} &= s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{13} L}{2}\right) && \text{“atmospheric”} \\
&+ c^2_{23} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) && \text{“solar”} \\
&+ J \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right) \frac{\Delta_{12} L}{2} \sin\left(\frac{\Delta_{13} L}{2}\right) && \text{“interference”}
\end{aligned}
$$

$\nu_e \rightarrow \nu_e \rightarrow e^-$. Disappearance
Less sensitive, but it can help too

What can you expect from β-beams?

Most wanted **missing pieces** of the

eam help?

Let's see how the oscillation probability depends on these parameters

Are neutrinos **D**

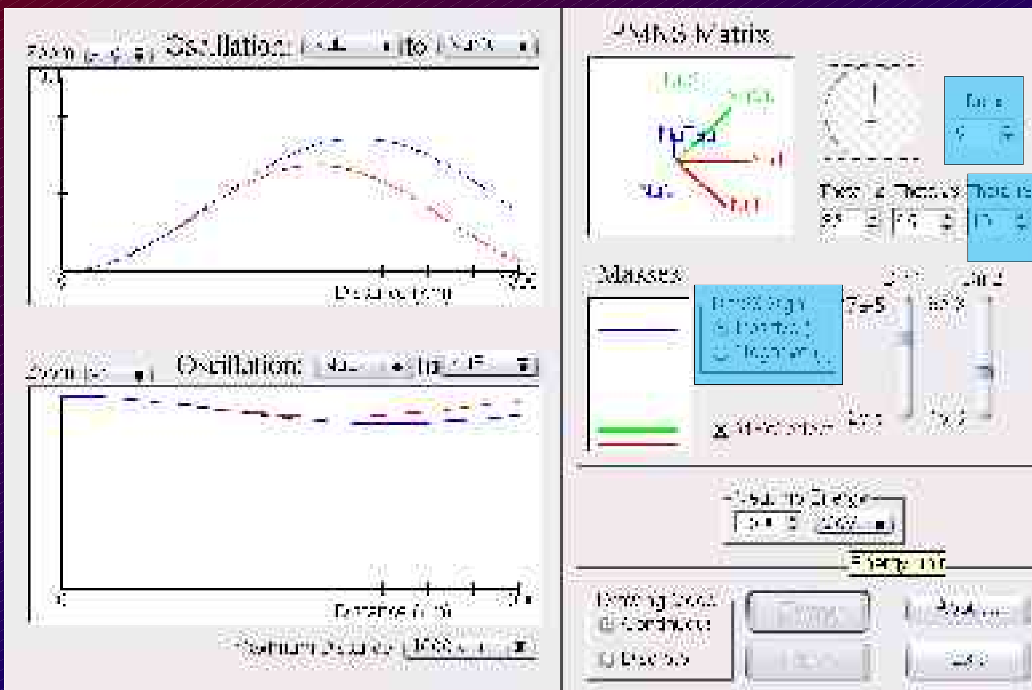
etector may)

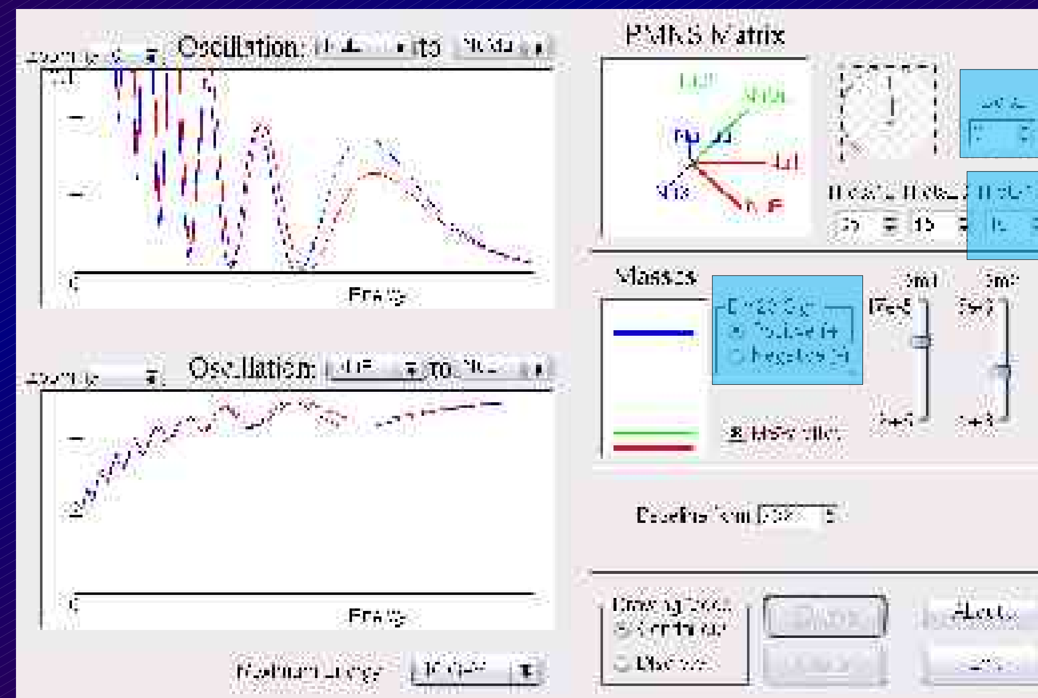
θ_{13} ► Sure!

δ ► Good chances

Mass hierarchy $sign(\Delta m^2_{23})$ ► Yes with newly proposed setups

$$\theta_{13} \qquad \delta \qquad sign(\Delta m^2_{23}) \quad \ldots$$





I hope you are convinced that we are sensitive to them!

How does it fit among other neutrino experiments?

Characteristics

- It is a long baseline accelerator-based neutrino experiment

  its water detector can be used for atmospherics and proton decay too.
- The beam is composed of pure ν_e or $\bar{\nu}_e$

  unlike any other accelerator experiment!
- The beta-spectrum is well known, so systematics are very low

  similar to the NuFact case, different from everything else
- Beyond superbeams and improved reactor experiments

  and at high gammas, even *competitive with the Neutrino Factory!*
- Feasible, but may need a massive water ckov UNO-like and/or an improvement of CERN's SPS
- For timescale, around 2015?

One idea, several variations

There are a few different interesting setups for a betabeam:

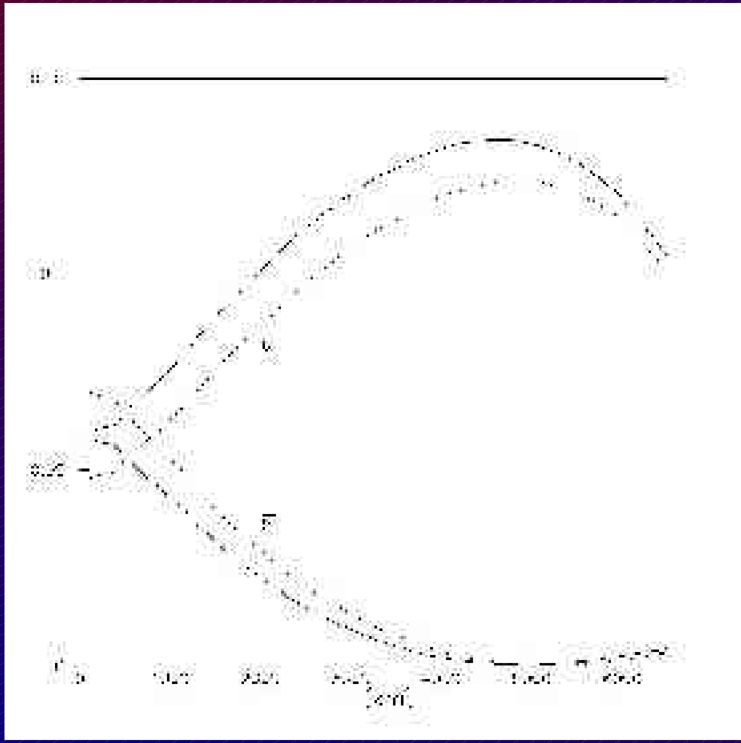
- **Low energy**: $\gamma = 60$ for ^{6}He and $\gamma = 100$ for ^{18}Ne with L = 130 km (CERN-Fréjus)
- **Medium energy**: $\gamma = 350$ for ^{6}He and $\gamma = 580$ for ^{18}Ne with L = 732 km (CERN-Gran Sasso w/ refurbished SPS or with LHC, or better by ramping the fills; FNAL-Soudan)
- **High energy**: $\gamma = 1500$ for ^{6}He and $\gamma = 2500$ for ^{18}Ne with L = 3000 km (CERN-Canary Islands w/ LHC)

Though it seems that you don‘t need different γ anymore...

Going far, increasing energy

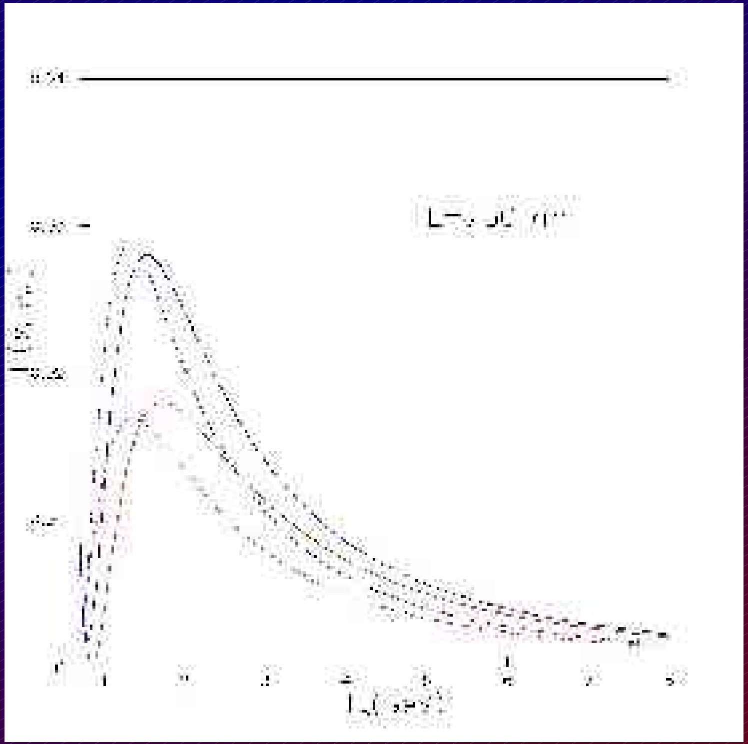
1. The rates increase linearly with <E$_\nu$> at fixed <E$_\nu$>/L

2. At long distances the measurement of the mass hierarchy is possible



$P(\nu_e \to \nu_\mu), P(\overline{\nu}_e \to \overline{\nu}_\mu)$
as a function of the baseline, for:
$E/L = |\Delta m^2_{23}|/2\pi, \theta_{13} = 8^0, \delta = 0^0, 90^0$

3. Increased neutrino energy enhances the energy dependence of oscillation signals



$P(\nu_e \to \nu_\mu), P(\overline{\nu}_e \to \overline{\nu}_\mu)$
as a function of the energy, for:
$\theta_{13} = 6^0, \delta = 40^0$

Simulation

Just a brief reminder of what one works with.

Observables:

flux　cross-section　oscillation probability

$$N_{i,p} = \int_{E_i}^{E_i+\Delta E} \epsilon(E_\nu)\,\phi_{\nu(\bar{\nu})}(E_\nu)\,\sigma_{\nu(\bar{\nu})}(E_\nu)\,P_{\nu(\bar{\nu})}(E_\nu, \theta_{13}, \delta, \ldots)\,dE$$

different energy bins whenever possible

polarity: ν_e, ν_e

Chi square:

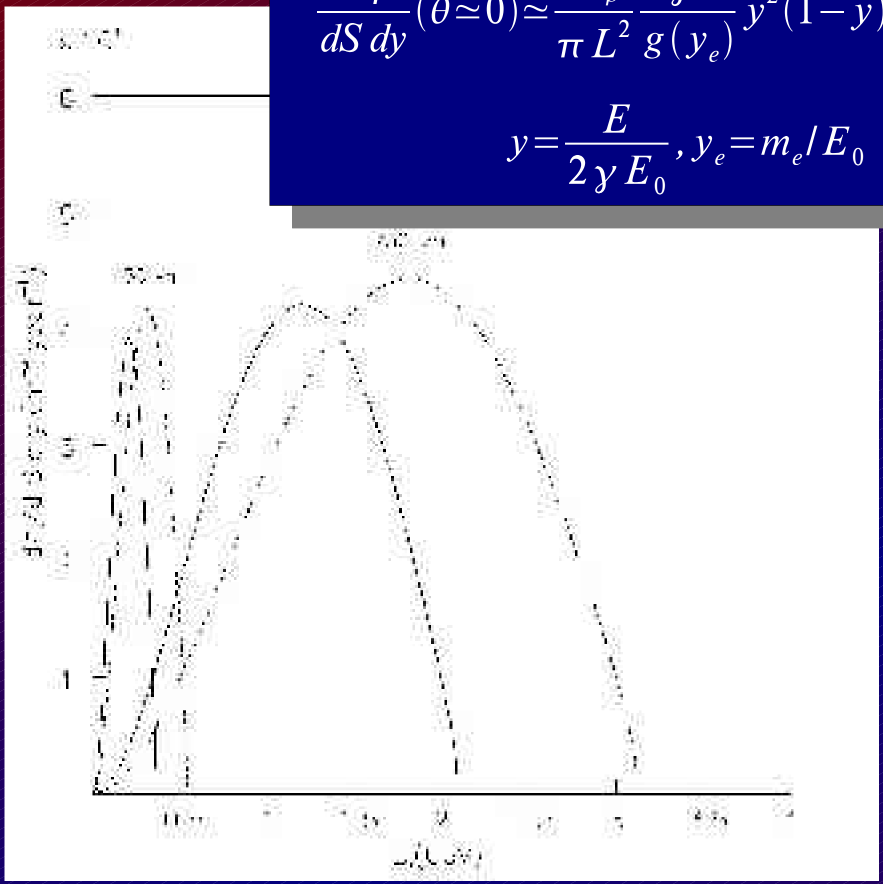
oscillation parameters

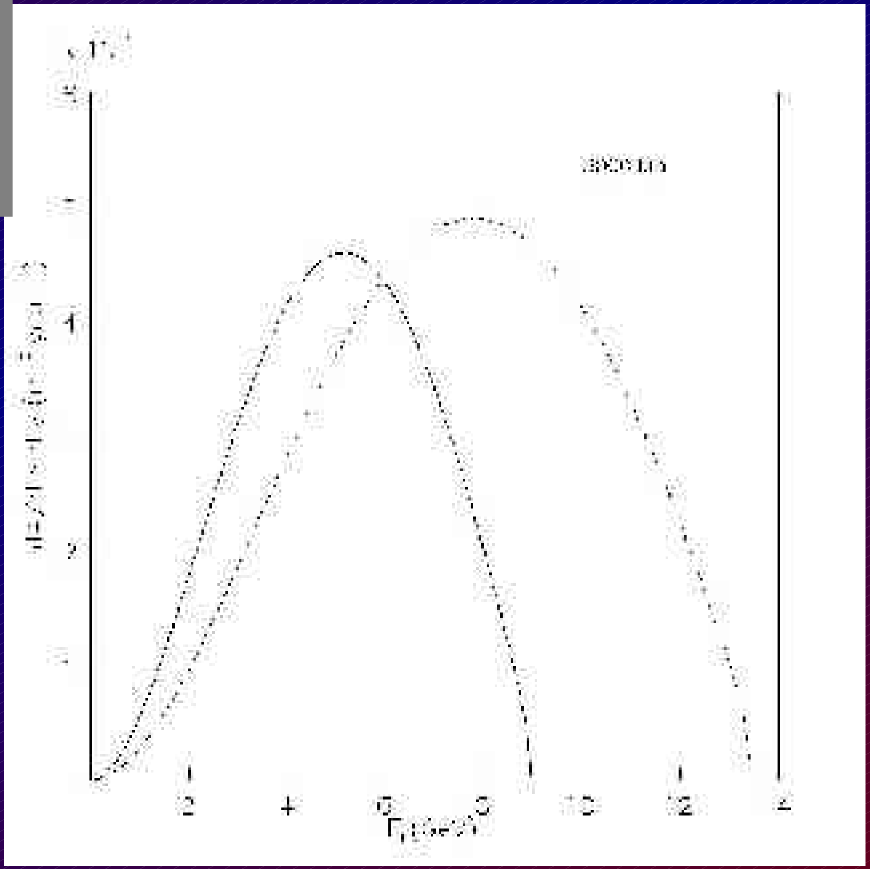
$$\chi^2(\alpha) = \sum_{i,p} \frac{(N_{i,p} - N_{i,p}(\alpha))^2}{\sigma_{i,p}^2}$$

Fluxes

$$\frac{d\phi}{dS\,dy}(\theta \simeq 0) \simeq \frac{N_\beta}{\pi L^2}\frac{\gamma^2}{g(y_e)}\,y^2(1-y)\sqrt{(1-y)^2-y_e^2}$$

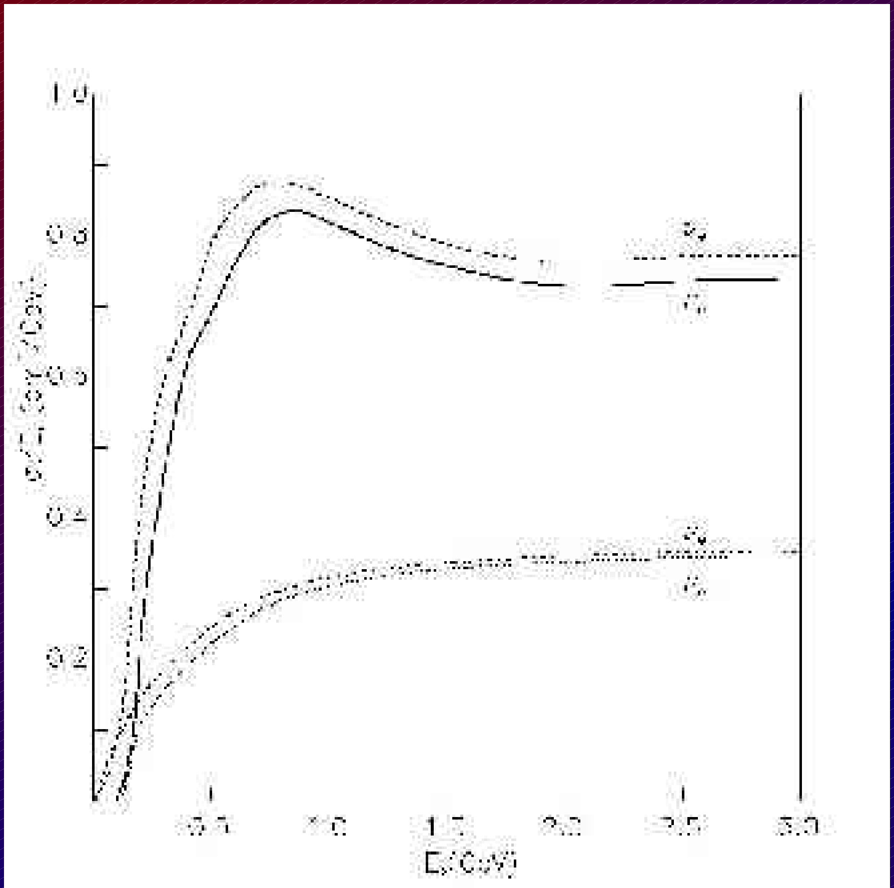
$$y=\frac{E}{2\gamma E_0},\; y_e=m_e/E_0$$



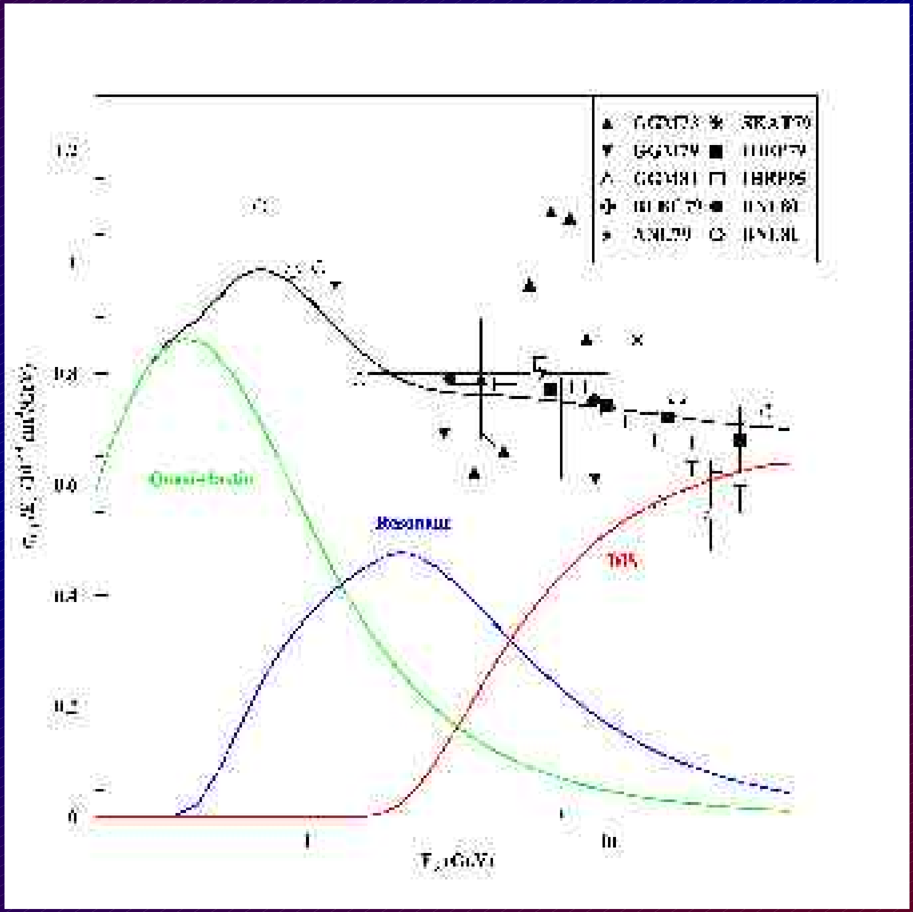


Like for the neutrino factory, fluxes are known very accurately, and the ν_μ ($\bar{\nu}_\mu$) appearance signal has no beam background (and *you don't even need charge discrimination*, there is only one flavor!)

Cross sections

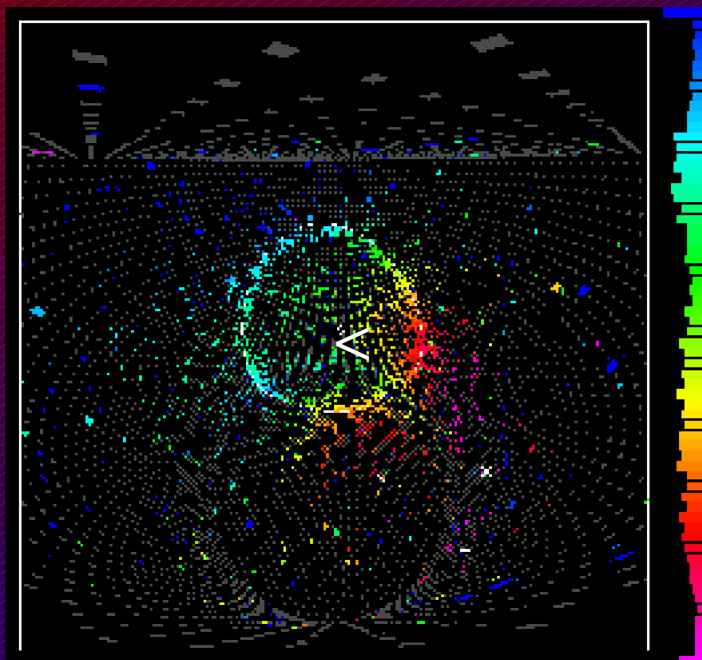


Cross section per nucleon for an isoscalar target, divided by the energy in GeV

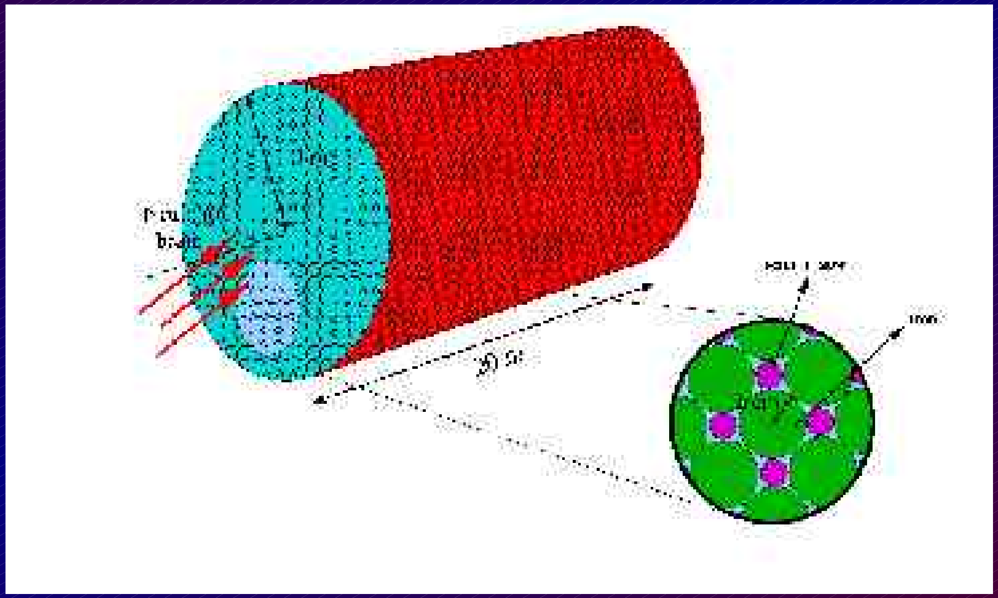


Different contributions to the cross section. At low energy QE events are dominant, at high energy deep inelastic dominates, and for the intermediate setup all 3 terms contribute significantly

Detectors



Massive water Cherenkov detectors offer excellent particle ID and good energy resolution for $E \lesssim 1.5$ GeV.



For $E \sim 10$ GeV deep inelastic CC and NC are dominant. **Massive tracking calorimeters** are the best option.

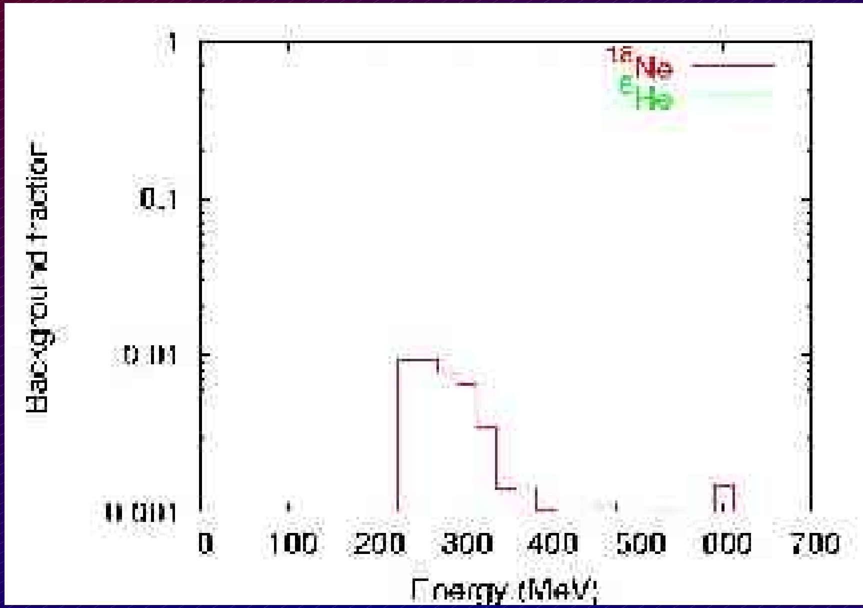
For concreteness:

UNO-like, 400 kton fid. mass

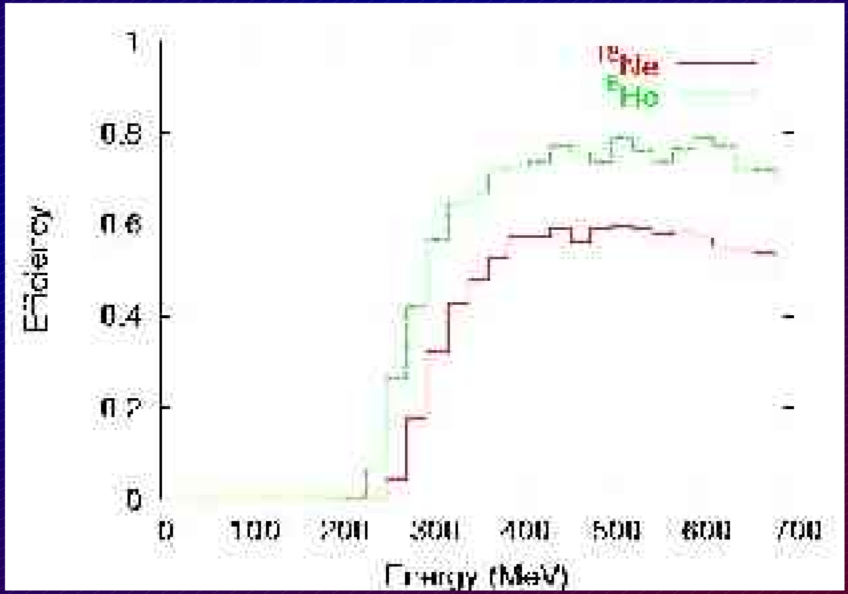
NuFact-like, 40 kton

Backgrounds and Eff, low energy

For fully-contained, single ring, muon-like events...



Almost no background (a few NC)

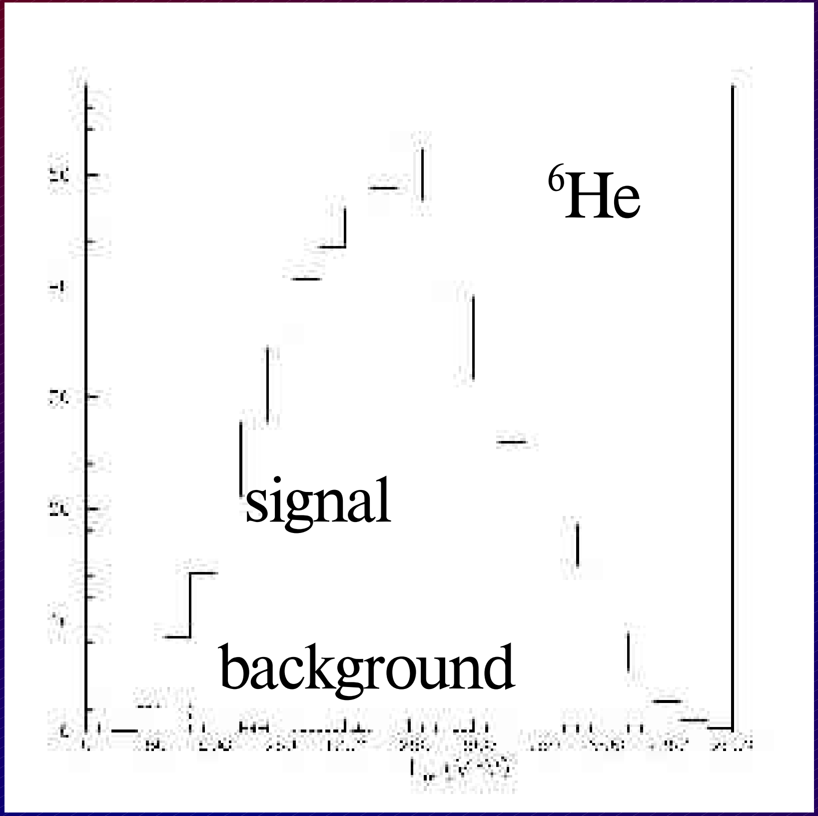


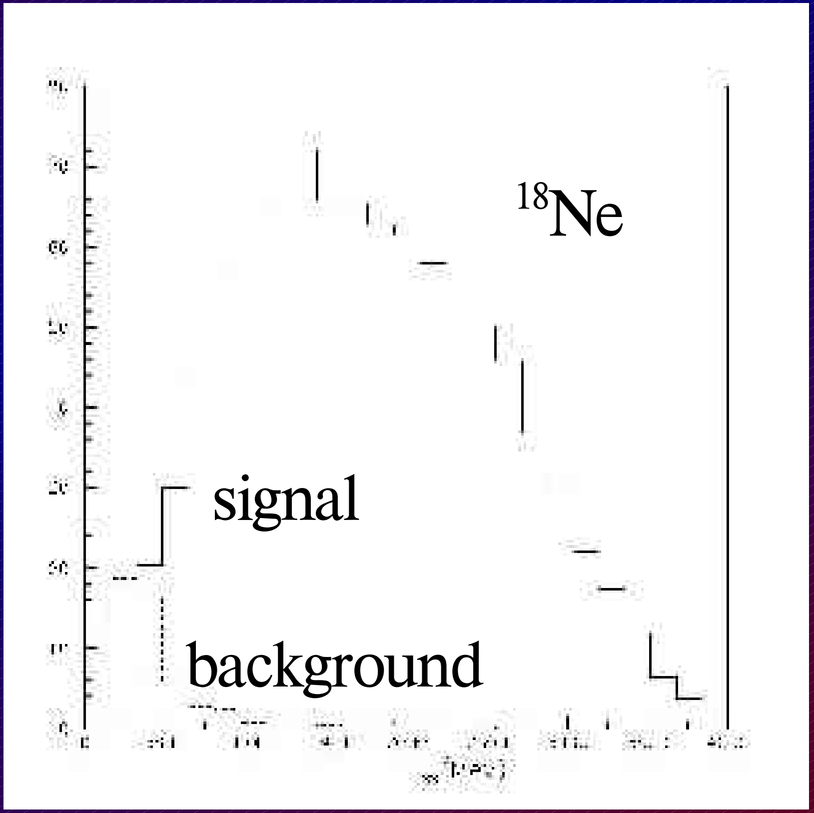
Large eff, but drops below 300 MeV

Also, event energy information washed out by fermi motion, so not possible to do energy binning to get spectral information

Backgrounds and Eff, medium energy

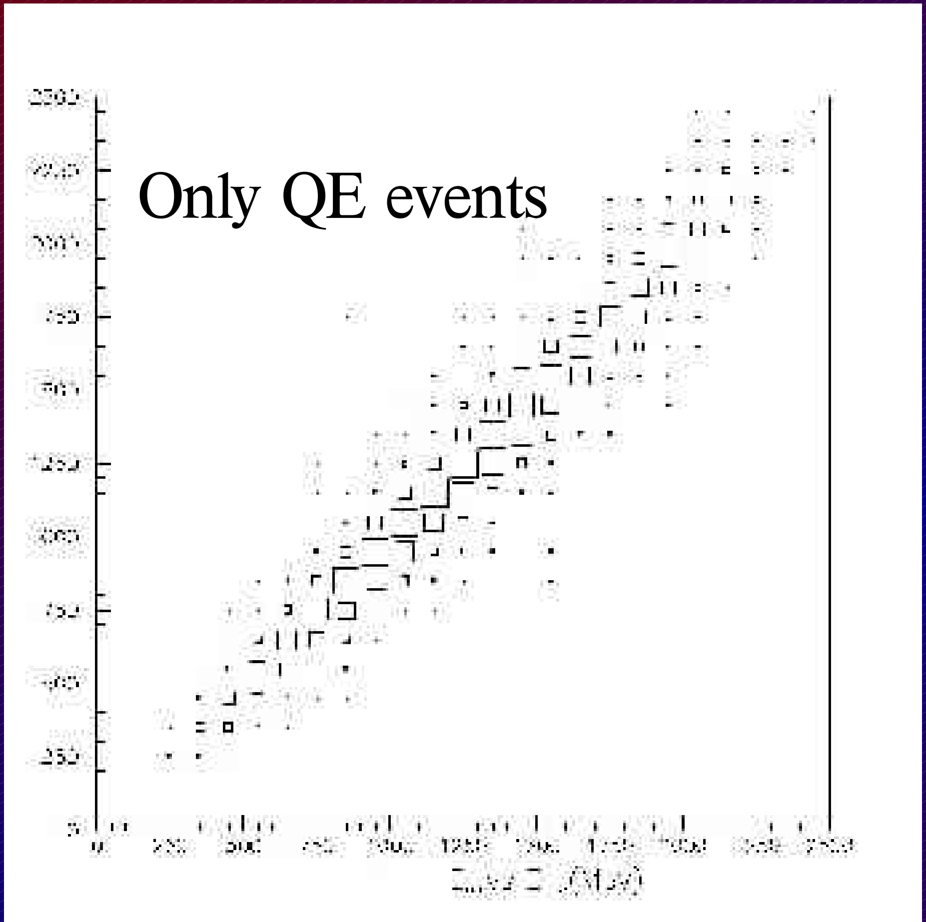
Reconstructed spectrum for signal and background

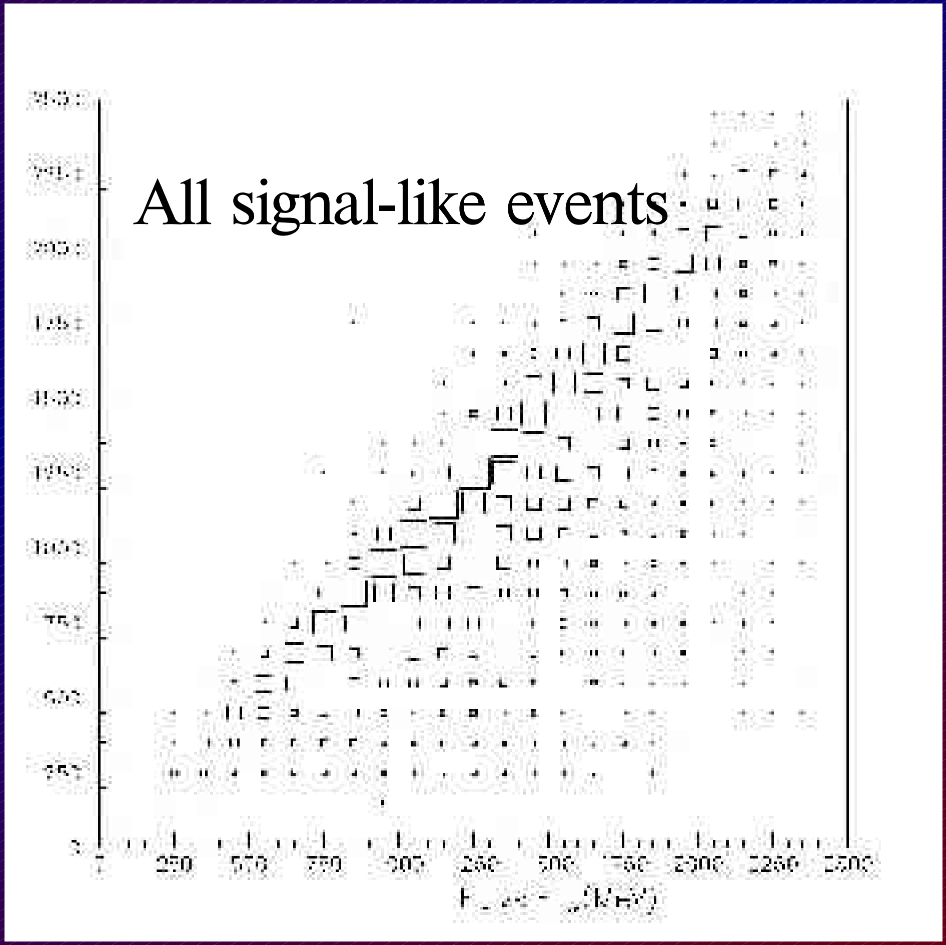




Backgrounds tend to cluster at low energies (can be cutted too)

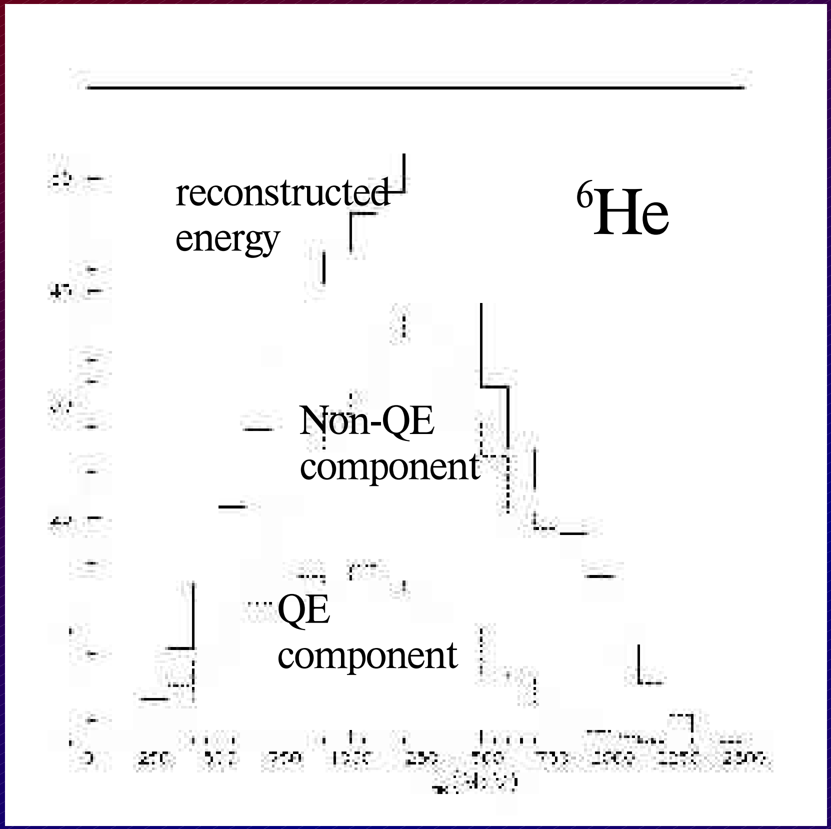
Energy reconstruction, medium energy

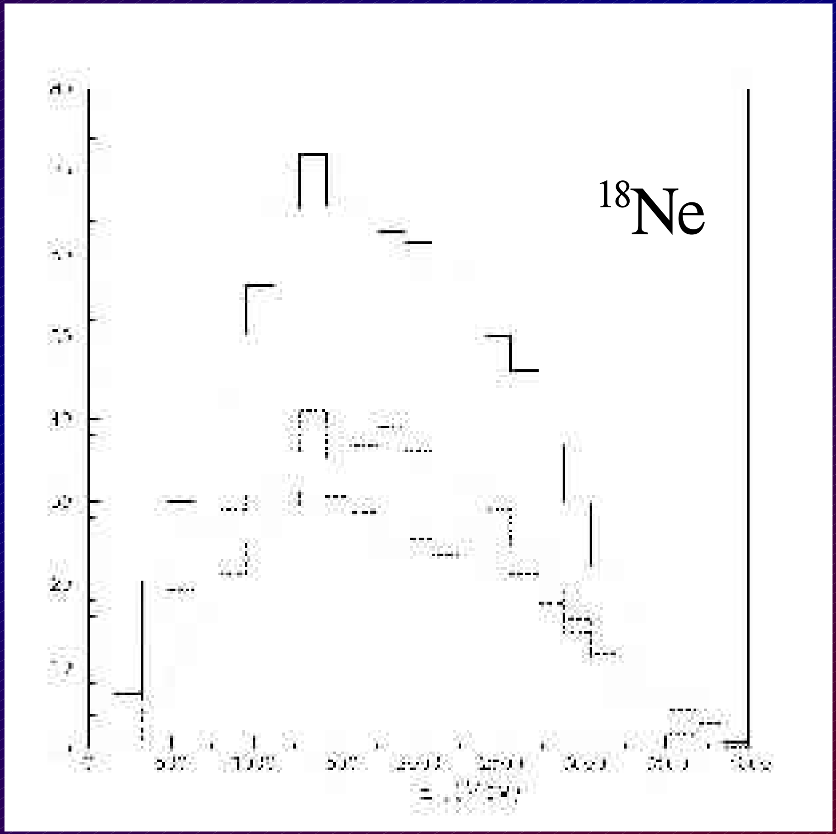




Energy reconstruction is done assuming QE interaction.
Distorsions due to sizeable non-QE events taken into account with migration matrices

Backgrounds and Eff, high energy



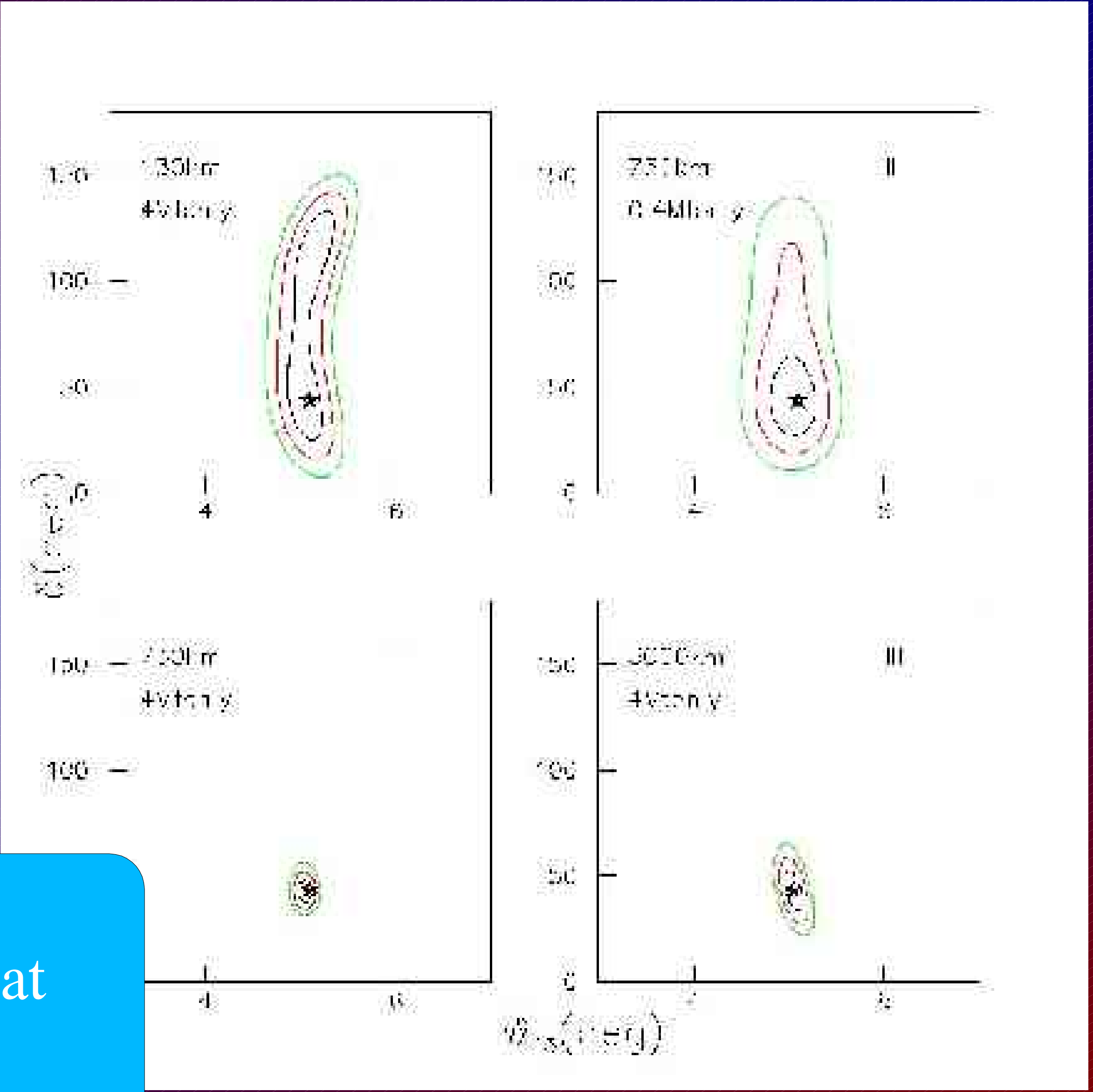


For high energy the best option to reconstruct the energy is to use a tracking calorimeter.

Finding θ_{13} and δ

Simultaneous measurement of θ_{13} and δ is affected by correlations and the intrinsic degeneracy.

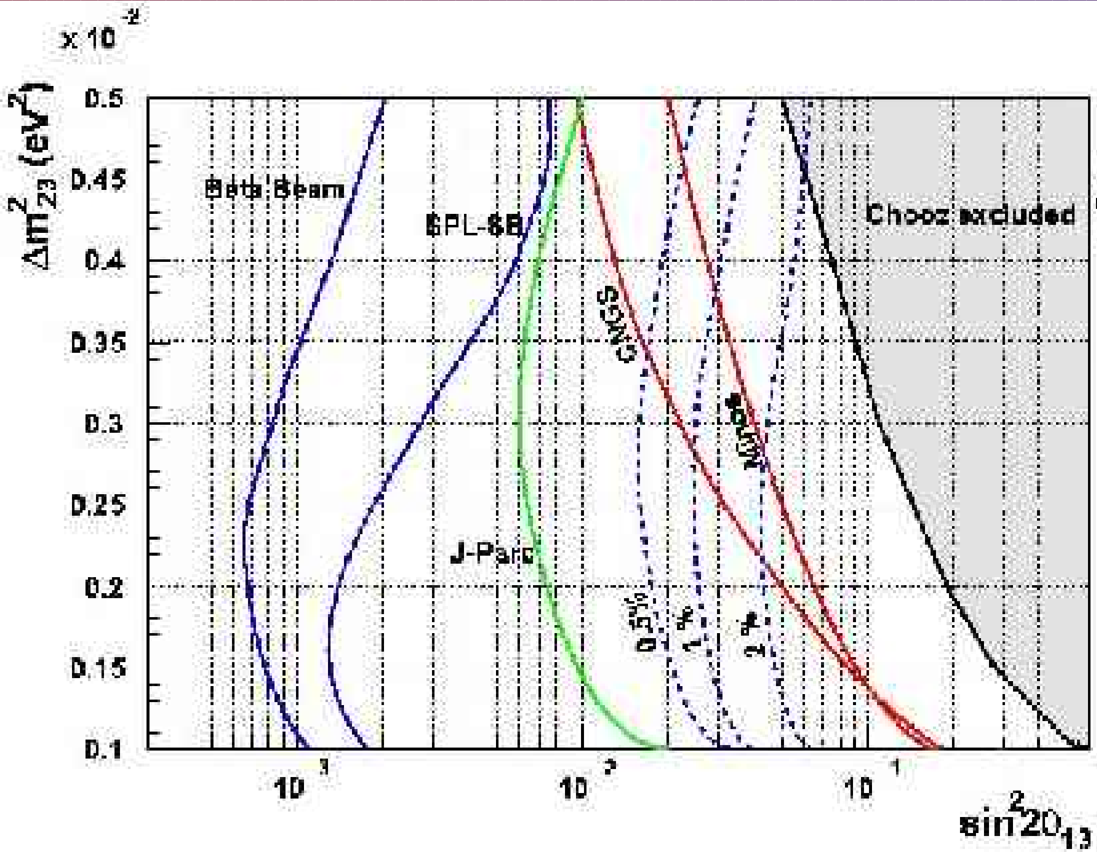
To resolve them one can combine experiments or exploit the energy dependence if possible.

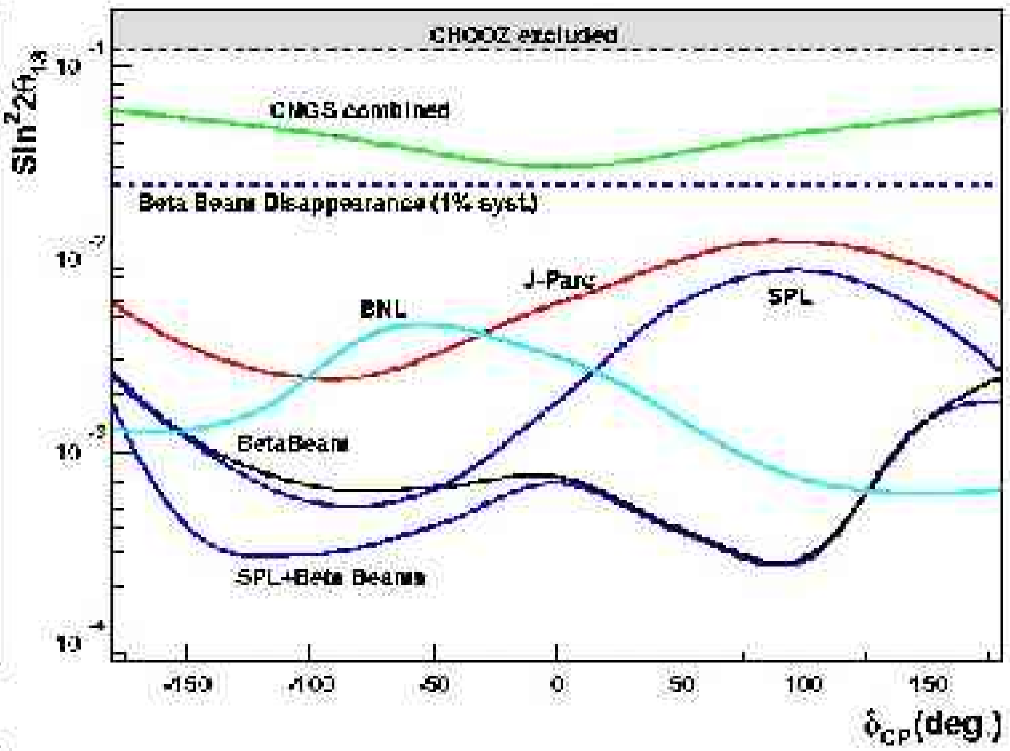


Let's have a look at how it works

Sensitivity to θ_{13}

J. Bouchez, M. Lindroos, M. Mezzetto
hep-ex/0310059



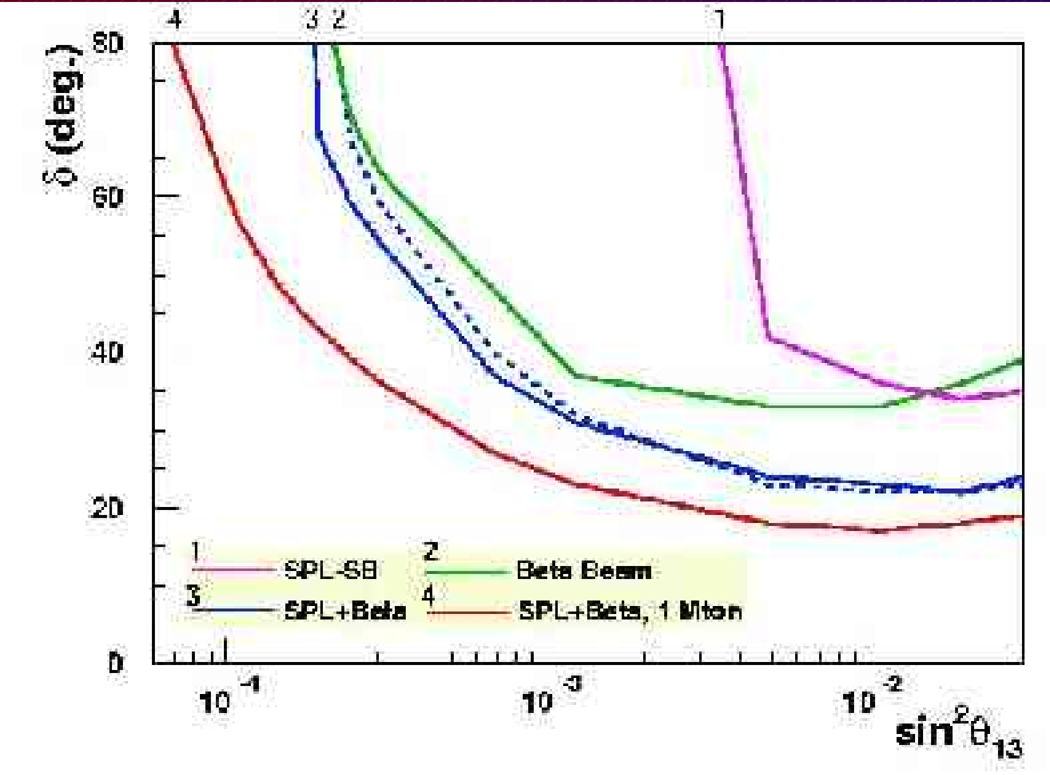


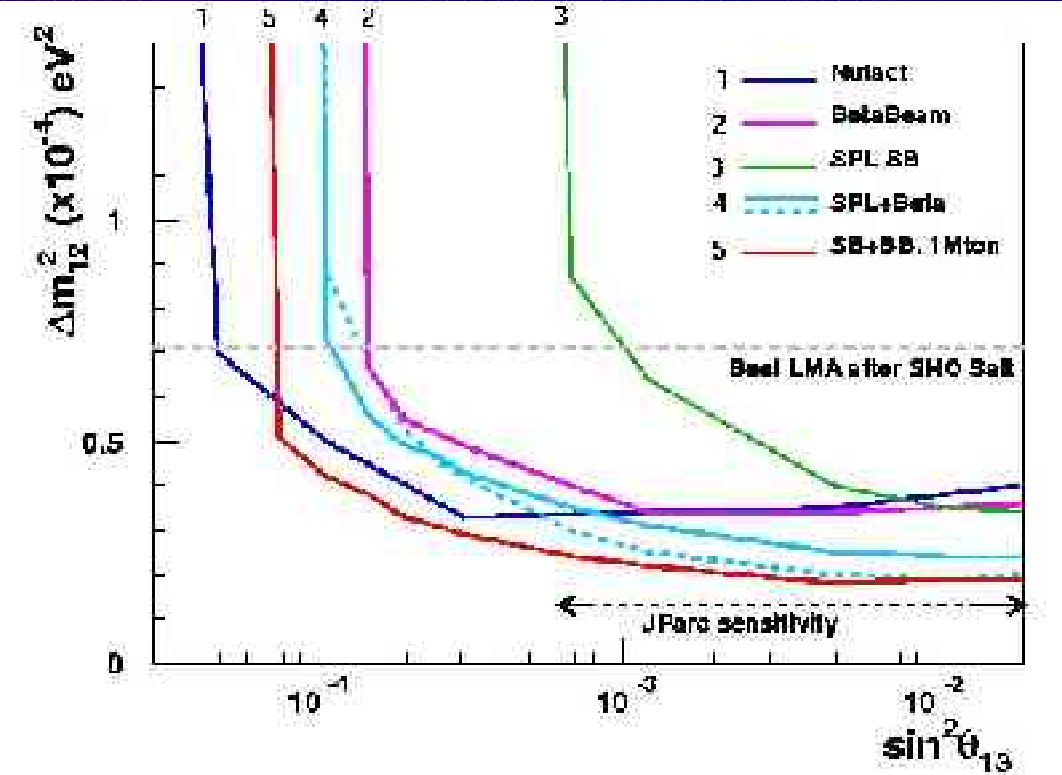
90% CL sensitivity to θ_{13}, disappearance channel

Setup I

Appearance channel
Sensitivity as a function of δ

Sensitivity to θ_{13} and δ



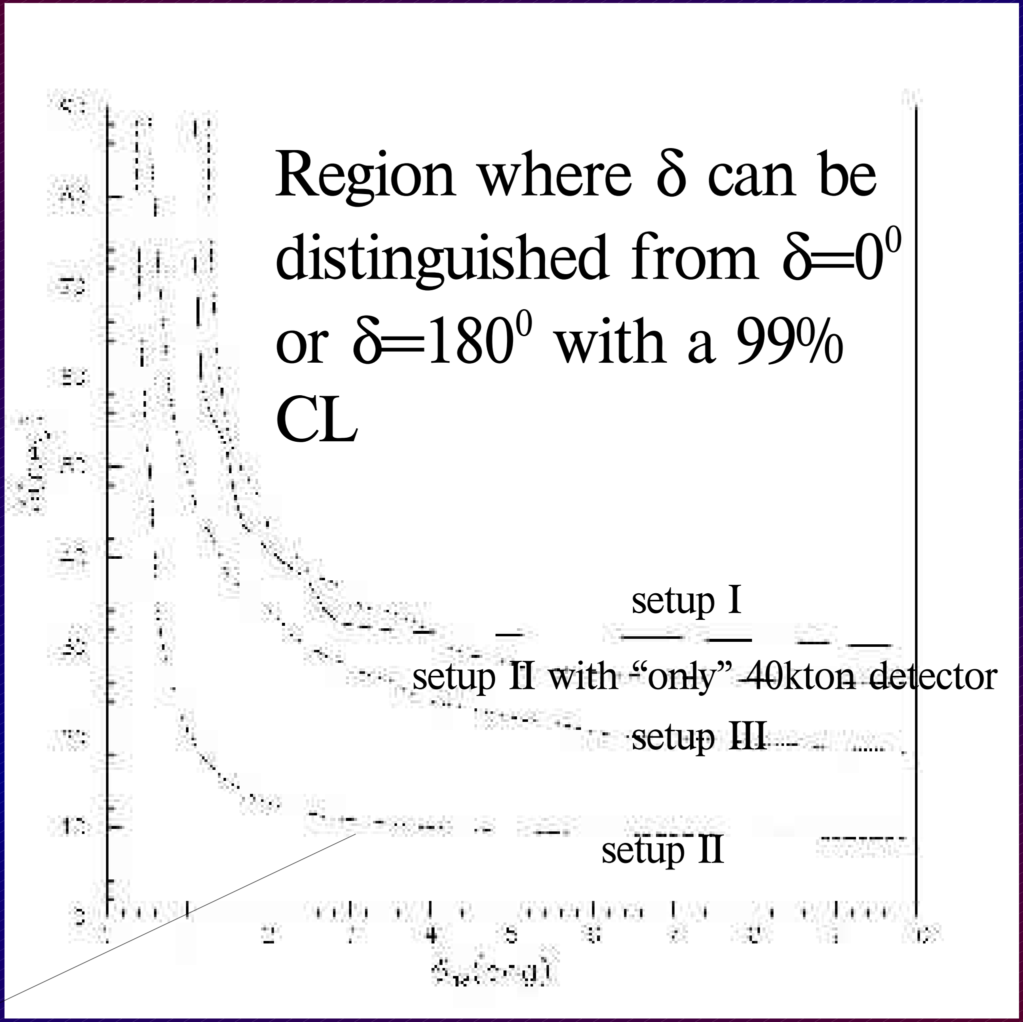


99% CL sensitivity to δ

This corresponds to setup I

J. Bouchez, M. Lindroos, M. Mezzetto
hep-ex/0310059

Sensitivity to θ_{13} and δ



UNO-like detector for medium energy
is competitive with a neutrino factory!

$\Delta m^2_{23} = 2.5\times 10^{-3}\, eV^2, \theta_{23} = 45^0, \Delta m^2_{12} = 7\times 10^{-4}\, eV^2, \theta_{12} = 35^0$

Finding the sign of Δm^2_{23}

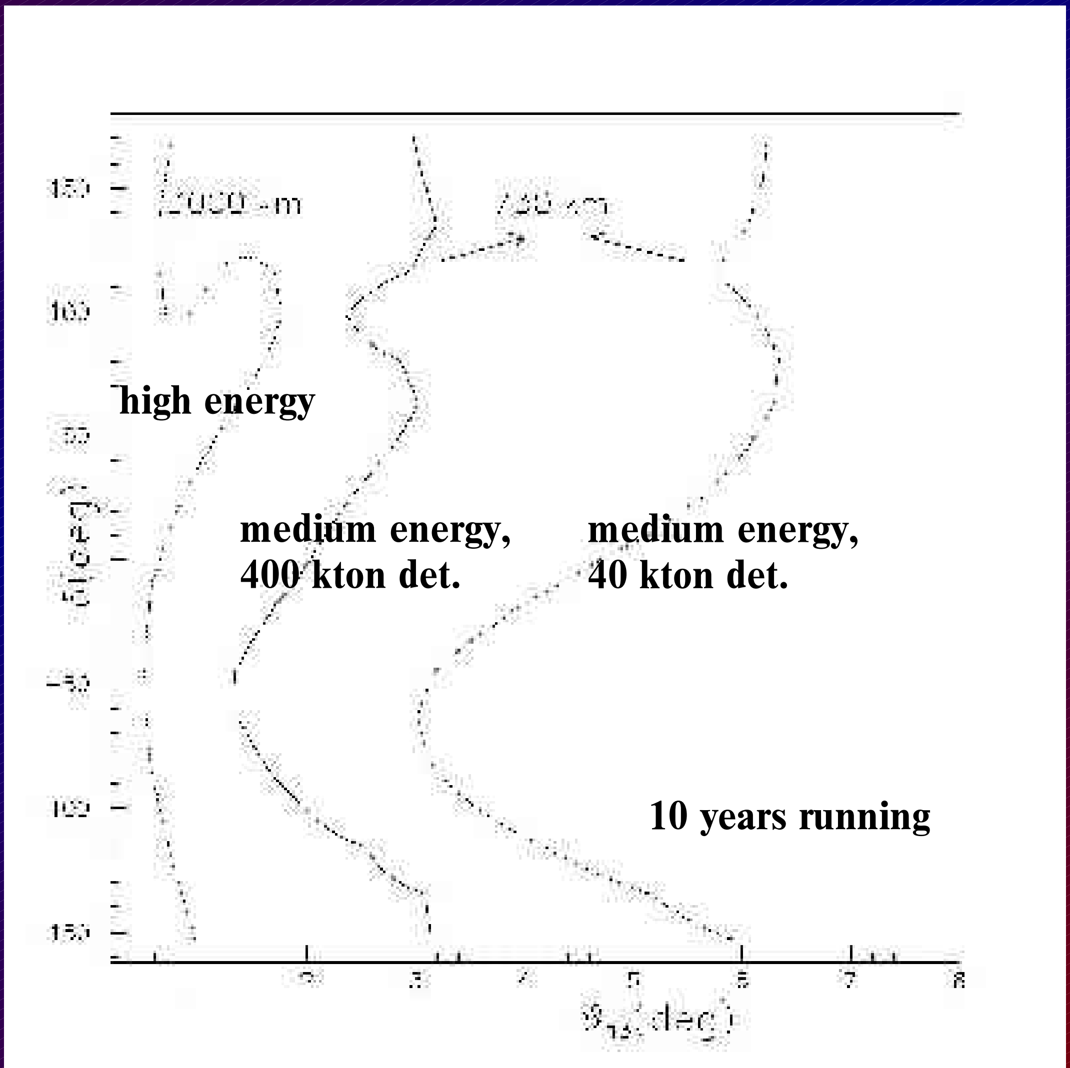
The sign is essential to determine the structure of the neutrino mass matrix.

It cannot be measured in oscillations in vacuum.

↓

Matter effects need to be sizeable

For this, going to higher energies and longer distances gets more sensitivity (but remember, at the cost of sensitivity to δ)



Regions where the sign can be measured at 99% CL.

How you can do even better

To cancel correlations and degeneracies there are more options available:

- Combine with a SPL superbeam
- Combine between different β-beam setups?
- Use the silver channel $\nu_e \rightarrow \nu_\tau$

They might actually change which is the best setup, though the medium-energy options seems hard to beat.

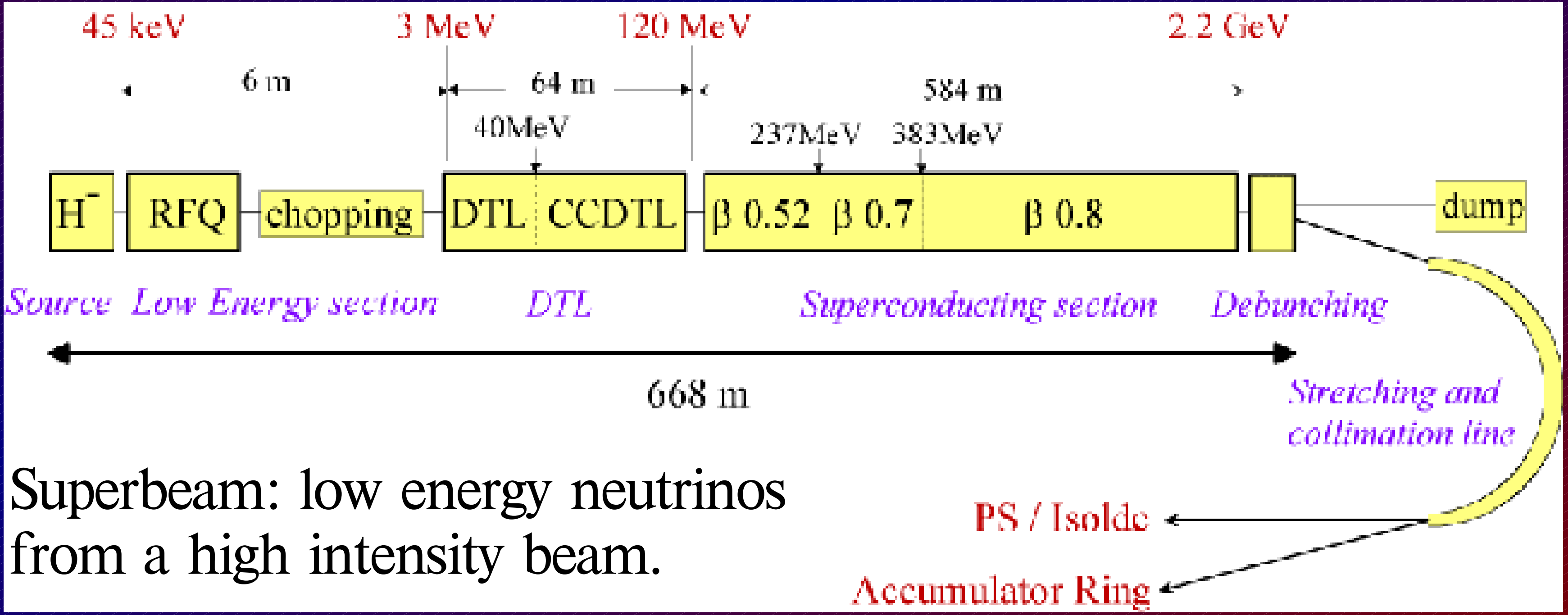
Combination with SPL Superbeam

- The Beta-Beam needs the SPL as injector, but consumes at most ~3% of the SPL protons

- Possibility to search for CP, T and CPT

	SPL	Beta-beam
	$\pi^{+} \rightarrow \nu_\mu$	$^{6}He \rightarrow \bar{\nu}_e$
	$\pi^{-} \rightarrow \bar{\nu}_\mu$	$^{18}Ne \rightarrow \nu_e$

CP	$P(\nu_e \rightarrow \nu_\mu)$ vs. $P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$
T	$P(\nu_e \rightarrow \nu_\mu)$ vs. $P(\nu_\mu \rightarrow \nu_e)$
CPT	$P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$ vs. $P(\nu_\mu \rightarrow \nu_e)$



Superbeam: low energy neutrinos from a high intensity beam.

What is its current status?

- Still a full treatment of systematics to be done
- Letter of Intent after Moriond 2003 workshop
- Got 10 M€ from the EU to produce a design study!

Conclusions

- A β-beam with $\gamma \sim 500$ is a very nice machine, tuned to measure θ_{13}, δ and find the mass hierarchy.
- The physics reach of the β-beam is much more promising than previously thought... it may even compete with the neutrino factory! (and it is *much* cheaper).
- However, all systematic errors should be included in a fair comparison of the β-beam with the neutrino factory (TO DO).
- Combinations with an SPL superbeam offer even better perspectives.
- The interest of the idea has been recognized and a design study is going to be done.