Neutrino Oscillation Physics with a Beta Beam

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Fermilab Theory Seminar,
3rd of August, 2006

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- The Neutrino Puzzle
- The Experimental Challenge
- The Beta Beam concept
- Detector performance
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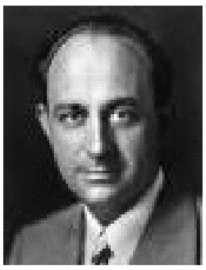
- Conclusions

1 – The Neutrino Puzzle

Born a desperate remedy to save energy conservation, neutrinos have turned out to play a key role in modern particle physics.

The most fascinating particle

- 'Invisible' particle postulated by Pauli to save energy conservation



- Only a chiral gauge charge

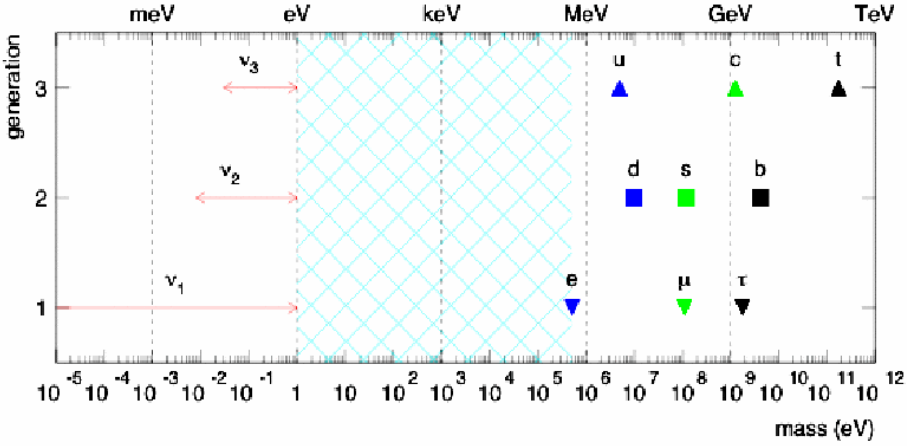
- Only particle that can be its own antiparticle

- The least massive of all

- Key to understanding weak interactions

Neutrino masses

- Atmospheric, solar, reactor and long baseline neutrino oscillation experiments have spectacularly shown us that neutrinos are massive.



…but extremely light…

Fundamental questions

- What are the neutrino masses? Why so small?
- Majorana or Dirac? Is L conserved?
- Are there only 3 neutrinos?
- Is there leptonic CP violation?
- What can neutrinos tell us about the Universe?
  - Bariogenesis
  - Dark matter
  - Large scale structure
  - Astrophysical sources

Neutrino masses in the SM

- The other helicity states:
  - At least 3 new fundamental Weyl fields without any charge:

Most general renormalizable lagrangian

$$\delta \mathcal{L}_m^\nu = \overline{L}_L \, \lambda_\nu \, \Phi \, \mathrm{N}_R + \underbrace{\frac{1}{2} \mathrm{N}_R^T \, \mathrm{C} \, \mathrm{M} \, \mathrm{N}_R + h.c.}_{\text{L violating}}$$

  - What is the new physics scale M?
    - M = 0 ⇔ Dirac neutrino masses ⇔ L conserved
    - M ≠ 0 ⇔ N_R Majorana ⇔ L violated
      - M » v ? → decoupling physics
      - M ~ v ? → new sector around the corner

Neutrino masses in the SM

- A more general alternative:

Neutrino masses generated by heavy hidden sector:

$$\mathcal{L}_{eff}^{d=5} = \frac{1}{2} \mathrm{L}_L^T \, \mathrm{C} \, \Phi^T \left(\lambda_\nu \frac{1}{\mathrm{M}} \lambda_\nu^T \right) \Phi \, \mathrm{L}_L + \ldots$$

(Such as the previous case with M » v)

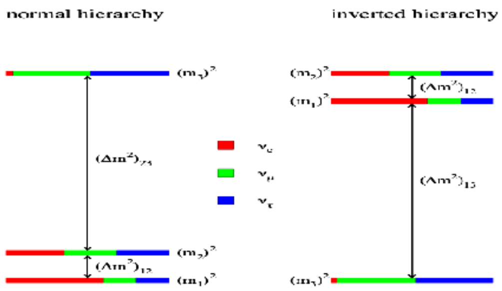
See-saw model

Standard 3 neutrino scenario

- Whatever the mechanism for neutrino mass generation (see-saw or more complicated physics), at low energies the neutrino mass matrix can be described in terms of 9 new parameters:

Masses	Angles	CP phases
m_1, m_2, m_3	$\theta_{12}, \theta_{23}, \theta_{13}$	$\delta, \alpha_1, \alpha_2$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{NMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

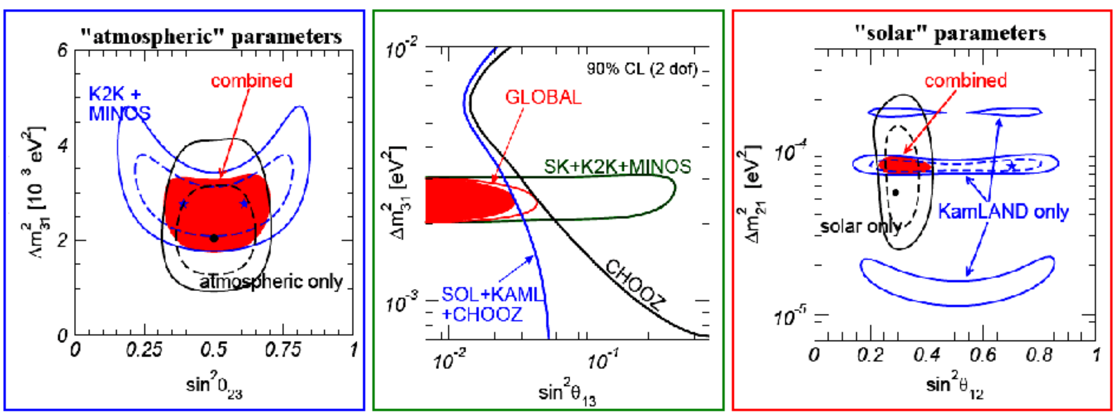


Standard 3 neutrino scenario

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

Atmospheric — Solar

- What we know:



T. Schwetz, hep-ph/0606060

Standard 3 neutrino scenario

$$V_{NMS}^{Dirac} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}}$$

- However:
  - –Not much known about θ_{13}…
  - –Is θ_{23} maximal?
  - –CP violation: $\delta, \alpha_1, \alpha_2$
  - –What is the absolute mass scale?
  - –Normal or inverted hierarchy?

Since discovered, neutrinos have taken us further and further in our understanding of the SM…

And still they offer to take us beyond…

2 – The Experimental Challenge

> "Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos"
>
> Sir Arthur Eddington, 1939

- The obvious next step in the field of ν Physics is the measurement of the unknown parameters:
  - θ_{13}
  - δ
  - Mass hierarchy
  - θ_{23} octant
  - Absolute masses
  - α_1, α_2
  - Majorana or Dirac
- Together with a more precise determination of the known ones:
  - Unitarity of the PMNS matrix
  - Is θ_{23} maximal?
  - Need to solve correlations!

New symmetries?
More Neutrinos?
New Physics!!

Oscillation $0\nu\beta\beta$, $\beta\beta$, Cosmology $0\nu\beta\beta$

Channel Tuning

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{k>j} \mathrm{Re}[W_{\alpha\beta}^{jk}]\,\sin^2\left(\frac{\Delta m_{jk}^2 L}{4E}\right) \pm \quad \to \text{CP conserving}$$

$$\pm\; 2\sum_{k>j} \mathrm{Im}[W_{\alpha\beta}^{jk}]\,\sin\left(\frac{\Delta m_{jk}^2 L}{2E}\right) \quad \to \text{CP violating}$$

with $W_{\alpha\beta}^{jk} \equiv U_{\alpha j}\, U_{\alpha k}^{*}\, U_{\beta j}^{*}\, U_{\beta k}$

- The sensitivity of a channel to a specific parametter can be enhanced by tuning the ratio E/L.
- For the measurement of the unknowns, the best choice is to stay at $E/L \approx \Delta m^2_{atm}$

Channel Tuning

- At $E/L \sim |\Delta m^2_{23}|$:

Unknowns:

Channel:	θ_{13}	δ	hierarchy	θ_{23} octant
$e \leftrightarrow e$	☹	–	– / ☹	–
$e \leftrightarrow \mu$	☺	☺	– / ☺	☺
$e \leftrightarrow \tau$	☺	☺	– / ☺	☺
$\mu \leftrightarrow \mu$	☹	☹	😐	☹
$\mu \leftrightarrow \tau$	☹	☹	😐	☹

☺ ~ 1   😐 ~ ε ☹ ~ ε^2

ε ≡ small parameters: θ_{13}, $\Delta m^2_{12}/\Delta m^2_{23}$

Channel Tuning

- At $E/L \sim |\Delta m^2_{23}|$:

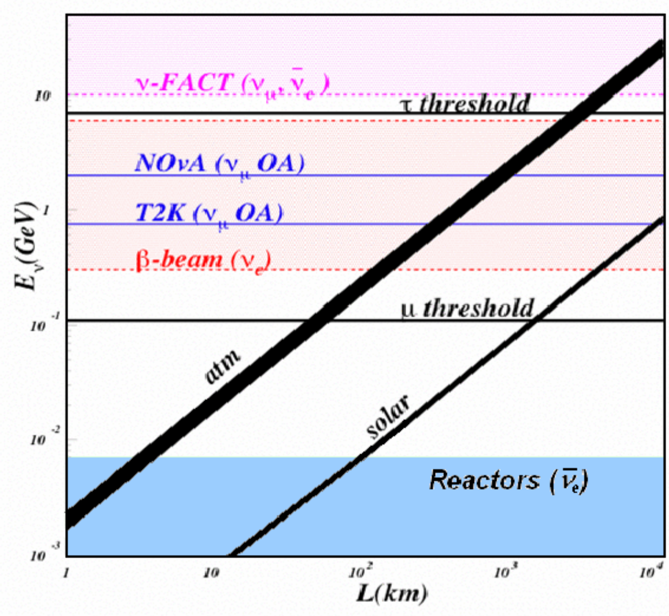
Knowns:

Channel:	$\sin^2 2\theta_{23}$	$\lvert\Delta m^2_{23}\rvert$	$\sin^2 2\theta_{12}$	Δm^2_{12}
$e \leftrightarrow e$	–	☹	☹	☹
$e \leftrightarrow \mu$	☺	☺	☺	☺
$e \leftrightarrow \tau$	☺	☺	☺	☺
$\mu \leftrightarrow \mu$	☺	☺	☹	☹
$\mu \leftrightarrow \tau$	☺	☺	☹	☹

☺ ~ 1 😐 $\sim \varepsilon$ ☹ $\sim \varepsilon^2$

ε ≡ small parameters: $\theta_{13}, \Delta m^2_{12}/\Delta m^2_{23}$

Channel Tuning

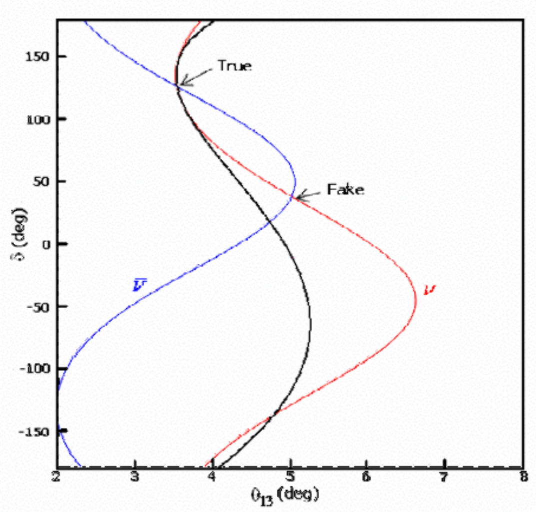


Correlation and degeneracies

- Intrinsic degeneracy:

Burguet-Castell et al, hep-ph/0103258

  - Keeping E/L fixed:
    - Curve of solutions for ν and $\bar{\nu}$ each.
    - They intersect at the "true" value of (θ_{13}, δ), but also at another "fake" one.
  - Changing E/L:
    - Different set of curves, intersecting the others only at the "true" value.

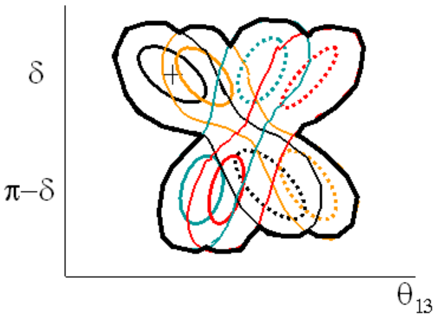


Assuming we know the mass hierarchy and the true θ_{23} octant

Correlation and degeneracies

- Discrete degeneracies:

Minakata, Nunokawa, hep-ph/0108085
Barger et al, hep-ph/0112119



2 intrinsic degeneracies
x 2 possible ν hierarchies
x 2 possible θ_{23} octants

= 1 true solution + 7 clones!!

- Each color belongs to a different space.
- Intrinsic fake solution and its clones  depend strongly on E/L ratio (unlike the clones of the true solution ).
-  greatly increase the errors, particularly for δ.

Correlation and degeneracies

- Discrete degeneracies:

Minakata, Nunokawa, hep-ph/0108085
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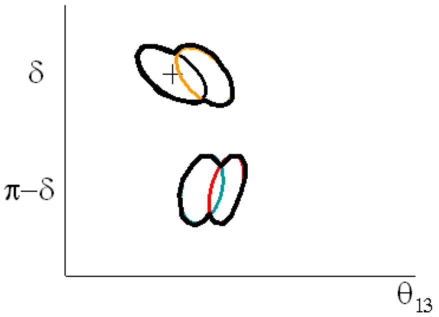

2 intrinsic degeneracies
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= 1 true solution + 7 clones!!

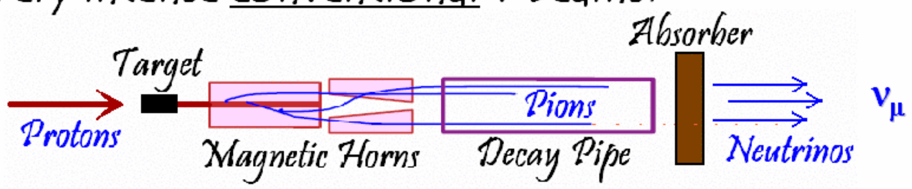
- Each color belongs to a different space.
- Intrinsic fake solution and its clones depend strongly on E/L ratio (unlike the clones of the true solution).
- greatly increase the errors, particularly for δ.

The experimental challenge

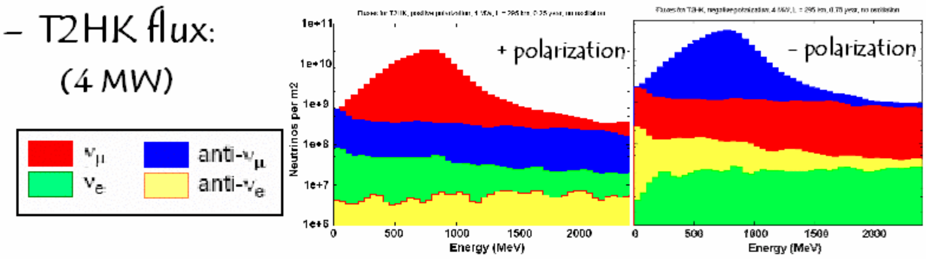
- Need for precision measurements of very small oscillation probabilities at $E/L \approx \Delta m^2_{atm}$:
  - High Statistics:
    - Very intense beams
    - Very large detectors
  - Low Systematics:
    - Well-known beams
    - Control of detector systematics
- Proposed beams:
  - Superbeams
  - ν-Factories
  - Beta beams

Superbeams (coming soon!)

- Very intense conventional ν beams:



- Off-axis to reduce ν_e contamination
  - T2HK flux:
    (4 MW)



Mostly ν_μ …but contamination still present
(particularly wrong-sign)

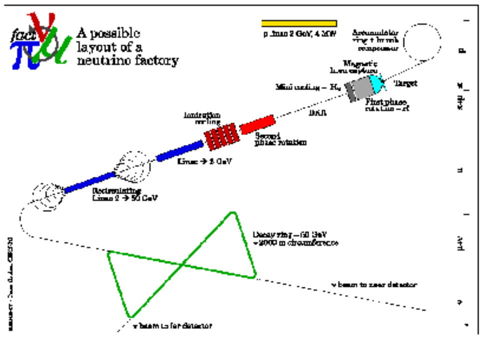
Superbeams (coming soon!)

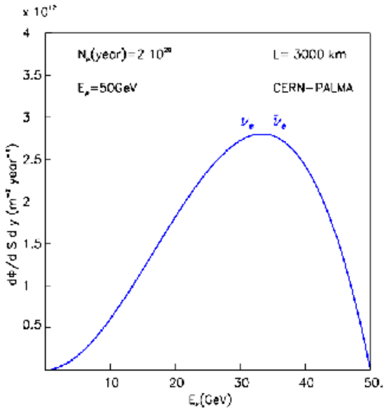
- Channels:
  - Golden: $\nu_\mu \to \nu_e \quad (\bar{\nu}_\mu \to \bar{\nu}_e)$ ▪ Signal: detected e±
  - Disappearance: $\nu_\mu \to \nu_\mu \quad (\bar{\nu}_\mu \to \bar{\nu}_\mu)$ ▪ Signal: detected μ±
- 2 of them in the near future! (hopefully)
  - T2K (Japan)
  - NOνA (here at Fermilab)
- Caveats:
  - Sensitivity limited by beam systematics
    (flavour and sign contamination)

ν-Factories (next generation!)

- Very intense and pure $\nu_\mu / \bar{\nu}_e$ or $\bar{\nu}_\mu / \nu_e$ beams from muon decay:

$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$
$$\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$$





- Flux spectrum and composition known to very high precision

$$\left.\frac{d\Phi}{dS\,dy}\right|_{\theta=0} \simeq \frac{N_\mu}{\pi L^2}\; 12\; \gamma^2\, y^2\, (1-y) \qquad y = \frac{E}{E_\mu}$$

ν-Factories (next generation!)

- Channels:
  - Golden: $\bar{\nu}_e \to \bar{\nu}_\mu \quad (\nu_e \to \nu_\mu)$ ■ Signal: wrong-sign μ
  - Silver: $\bar{\nu}_e \to \bar{\nu}_\tau \quad (\nu_e \to \nu_\tau)$ ■ Signal: detected τ±
  - Disappearance: $\nu_\mu \to \nu_\mu \quad (\bar{\nu}_\mu \to \bar{\nu}_\mu)$ ■ Signal: right-sign μ

  ➔ Access to most interesting channels!

Magnetized detector required

- Caveats:
  - Technical challenge, requiring lots of R&D
  - Cost issues

- It is believed by many to be the ultimate facility…

3 - The Beta Beam Concept

N H
ELSEVIER
Physics Letters B 532 (2002) 166–172
PHYSICS LETTERS B
www.elsevier.com/locate/npe

A novel concept for a $\bar{\nu}_e/\nu_e$ neutrino factory: the beta-beam

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CERN, Geneva, Switzerland

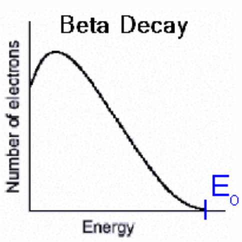
Received 3 July 2001; received in revised form 8 February 2002; accepted 7 March 2002
Editor: L. Rolandi

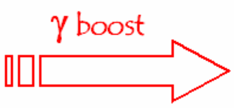
Abstract

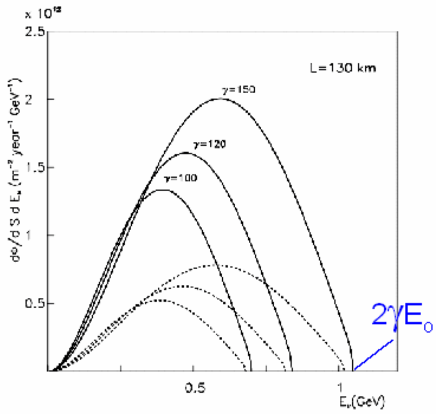
The evolution of neutrino physics demands new schemes to produce intense, collimated and pure neutrino beams. The current neutrino factory concept implies the production, collection, and storage of muons to produce beams of muon and electron neutrinos at equal intensities at the same time. Research and development addressing its feasibility are ongoing. In the current Letter, a new neutrino factory concept is proposed that could possibly achieve beams of high intensity, known energy spectrum and a single neutrino flavour (electron–antineutrino or electron–neutrino). The scheme relies on existing technology.

Beta Beam:

- Very intense and pure ν_e (or $\bar{\nu}_e$) beam from boosted β–radiactive ions.
- Flux spectrum and composition know to very high precision.







$$\left.\frac{d\Phi}{dS\,dy}\right|_{\theta=0} \simeq N_\beta \frac{\gamma^2}{\pi L^2} \frac{y^2\,(1-y)}{g(y_e)} \sqrt{(1-y)^2 - y_e^2}$$

$$y = \frac{E}{2\gamma E_0} \qquad y_e = \frac{m_e}{E_0}$$

Beta Beam:

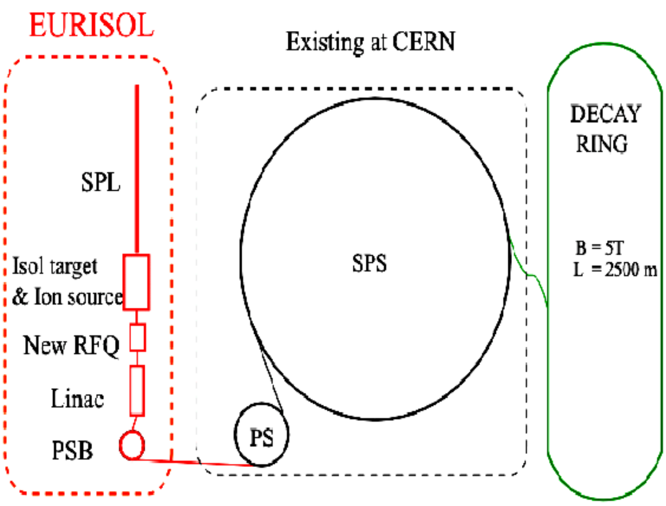
- Channels:
  - Golden: $\nu_e \to \nu_\mu \quad \left(\bar{\nu}_e \to \bar{\nu}_\mu\right)$ ▪ Signal: detected μ ±
  - Disappearance: $\nu_e \to \nu_e \quad \left(\bar{\nu}_e \to \bar{\nu}_e\right)$ ▪ Signal: detected e ±

- No need to detect the charge:
  - Only one type of neutrino

- Caveats:
  - No access to ν_μ disappearance.
  - Technical challenge $\Rightarrow$ R&D

The Beta Beam's birth

- Original idea:



The Beta Beam's birth

- Baseline scenario:
  - Ions: $\begin{cases} {}^{6}He^{++} \rightarrow {}^{6}Li^{+++} + e^{-} + \bar{\nu}_e \\ {}^{18}Ne^{10+} \rightarrow {}^{18}F^{9+} + e^{+} + \nu_e \end{cases}$
  - L = 130 km (CERN to Frejus)
  - Boost: $\begin{cases} \gamma = 60 \text{ for } {}^{6}He \\ \gamma = 100 \text{ for } {}^{18}Ne \end{cases}$
  - Detector: Megaton Water Cherenkov

M.Mezzetto et al, J. Phys. G.29, 2003

…growing up…

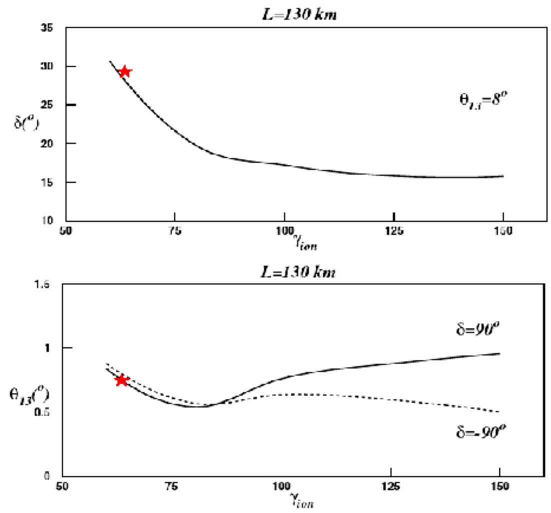
- However it soon became clear that those settings were not optimal:
  - A large part of the neutrinos, particularly for ^{6}He, were under the muon threshold
  - Poor energy dependence $\Rightarrow$ Not good for degeneracies
- Moving to higher gammas and baselines:
  - Flux $\propto \left(\frac{\gamma}{L}\right)^2$
  - $\sigma \propto \gamma$

$\Rightarrow$
- Signal grows at least linearly with γ
- Energy dependence increases
- Matter effects increase

Burguet-Castell et al, hep-ph/0312068

…growing up…

- CERN scenario:
  - For the Frejus baseline:



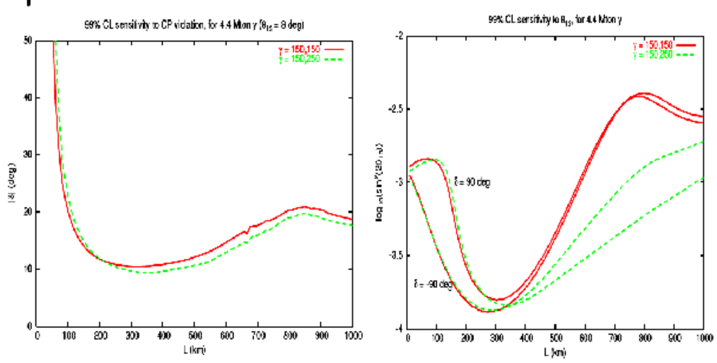
Optimal boost turns out to be:

γ = 100 ~ 120
(for both ions)

Burguet-Castell, Casper, E.C., Gomez-Cadenas, Hernandez, hep-ph/0503021

…growing up…

- CERN scenario:
  - But changing the baseline allows us to reach the full potential of the SPS:
    - SPS maximum boost: γ = 150/250
    - Optimal baseline: ~ 300 km



Burguet-Castell, Casper, E.C., Gomez-Cadenas, Hernandez, hep-ph/0503021

…and moving out

- What if we do not restrict ourselves to the CERN baseline scenario? What's the optimal β–beam? How good could it be?
- SPS is not the only choice:

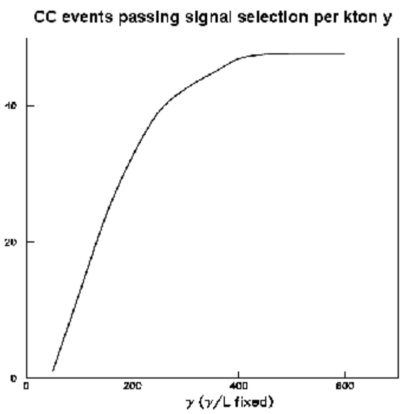
Refurbished SPS
γ_{max} = 350/580
(might be necessary for LHC upgrades!)

LHC
γ_{max} = 2488/4158

Tevatron
γ_{max} = 350/580

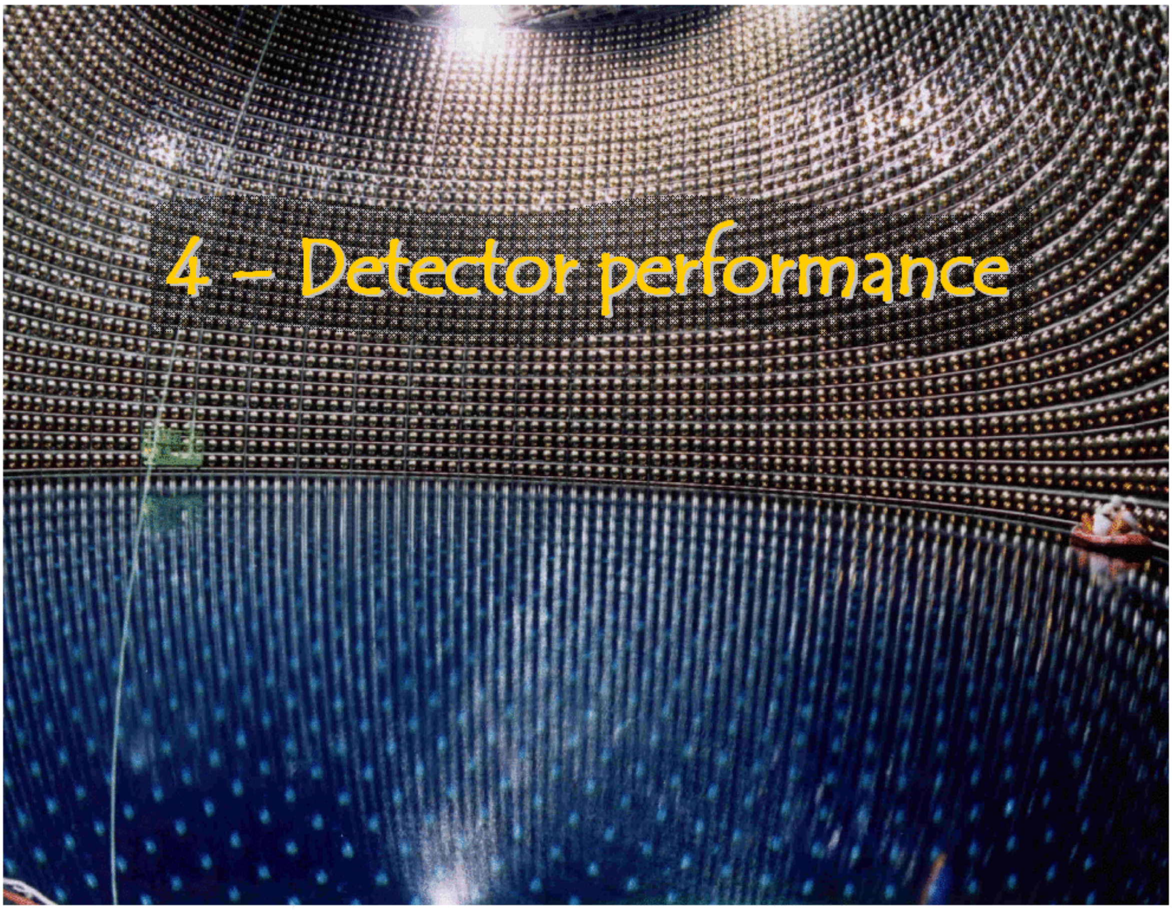
…and moving out

- If we stick to Water Cherenkov technology:
  - Maximum boost: $\gamma \sim 350$
    Afterwards:
    - Non-elastic cross section begins to dominate…
    - Single-pion background increases…
  - Optimal distance: L ~ 700 km
    (atm. peak)



CERN to Canfranc or Gran Sasso
Fermilab to Soudan

Burguet-Castell et al, hep-ph/0312068



Why a Water Cherenkov Detector?

- For β-beams, unlike ν-Factories, we don't need to be able to tell the charge of the detected fermion.
- We know how to make Water Cherenkovs.
  - They've already told us a lot about neutrino oscillations!
- They are versatile:
  - atmospherics, proton decay, supernova…
- Water is cheap!
  - Detectors at least 10 times more massive than for any other technology…

Why not … 20 x  ≈ 1 Megaton!

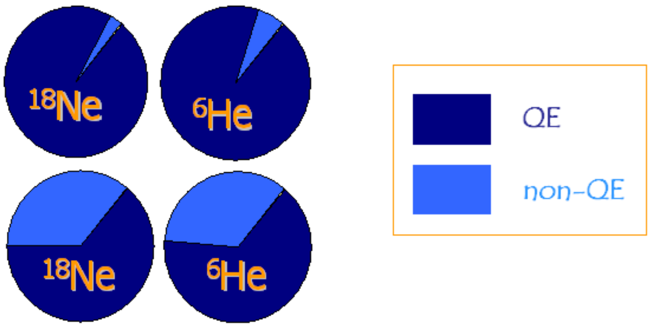
Studies on different detectors

- Scintillator a la NOvA — Huber et al, hep-ph/0506237
- Iron calorimeter — Donini et al, hep-ph/0604229

- Better intrinsic performance for high γ option
- …But not enough to compensate mass difference

Signal Issues

- Intrinsic energy resolution (Fermi motion)
- For a Water Cherenkov, energy reconstruction is done assuming QE dynamics…
  - For γ = 100:
  - For γ = 350:



But energy migrations can be studied and accounted for from Monte Carlo simulations

Background Issues

- Atmospheric background:
  - Extremely large!
  - To deal with it:
    - Directional cuts
    - End point of spectrum
    - Minimum energy cut
    - Bunching of the parent ions

Negligible

Around 100 times less significant than intrinsic bkg

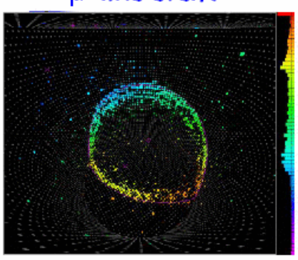
- Intrinsic background:
  - From the miss-id'ed electrons.
  - To deal with it:
    - ID cut
    - Michel e- cut

Let's take a closer look…

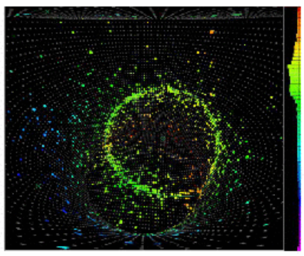
Signal/Background discrimination

- <u>P-ID cut:</u> μ/e separation

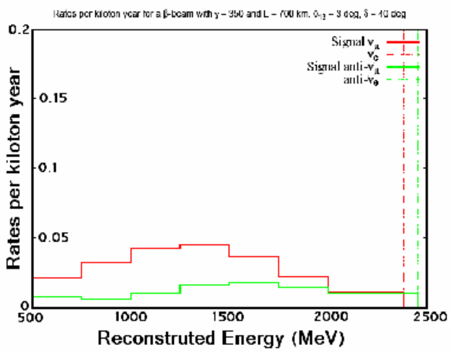
μ-like event



e-like event

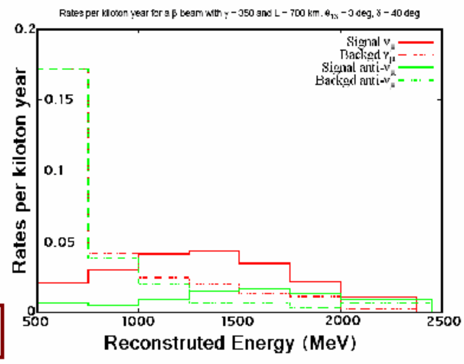


High-γ β-beam after fiducial cuts:



P-ID cut

$(\theta_{13} = 3^o)$



Signal/Background discrimination

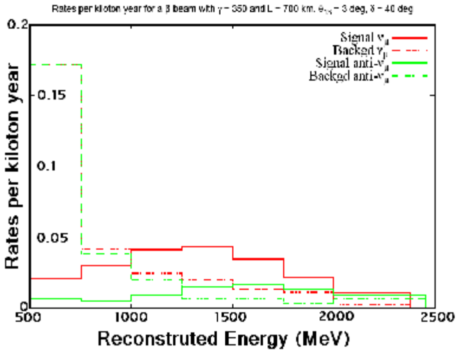
- Michel e- cut: μ/e,π separation:

$$\boxed{\mu^-} \rightarrow \nu_\mu + \boxed{e^-} + \bar{\nu}_e$$

Signal

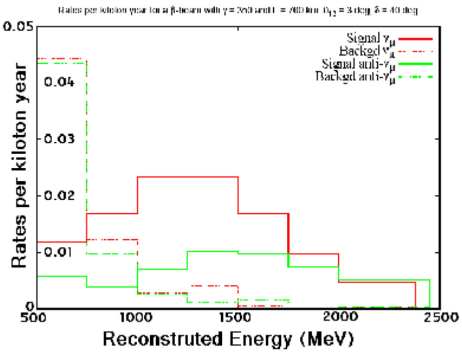
Michel e-
(Observation of
a delayed ring)

High-γ β-beam after P-ID cut:



Delayed ring cut

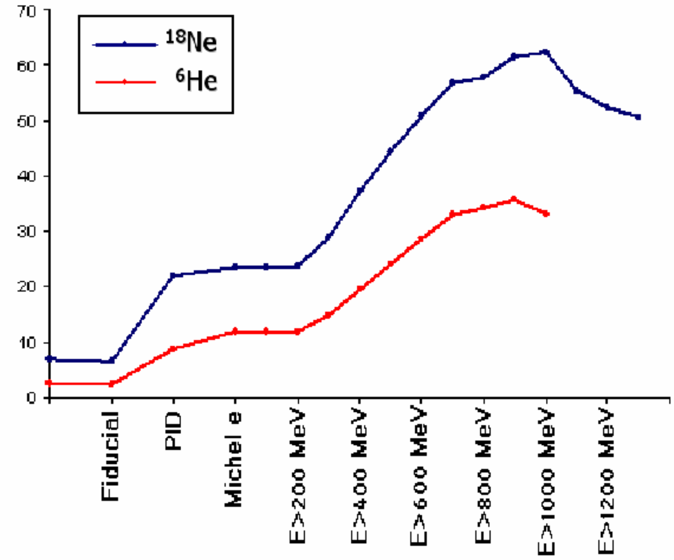
($\theta_{13} = 3^o$)



Signal to noise ratio

signal / sqrt(bkgnd)

($\theta_{13} = 3^o$)



High-γ β-beam

Assumptions:

- Atmospheric and solar parameters: G.L. Fogli hep-ph/0506083

$$\begin{cases} \Delta m^2_{12} = 7.9\times10^{-5}\ \mathrm{eV}^2 \\ \theta_{12} = 33^\circ \\ \Delta m^2_{23} = \begin{cases} 2.4\times10^{-3}\ \mathrm{eV}^2 \\ -2.45\times10^{-3}\ \mathrm{eV}^2 \end{cases} \\ \theta_{23} = \begin{cases} 41.5^\circ \\ 48.5^\circ \end{cases} \end{cases}$$

- Total run time: 5+5 years

- Intensities: $\begin{cases} 2.9\times10^{18}\ {}^{6}\mathrm{He}\ \text{decays per year} \\ 1.1\times10^{18}\ {}^{18}\mathrm{Ne}\ \text{decays per year} \end{cases}$

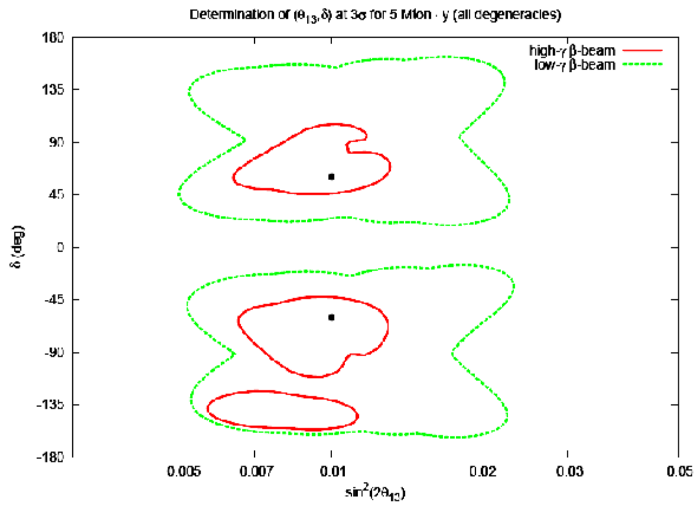
- 500 kton fiducial mass Water Cherenkov detector

- Systematic errors:
  - Signal global norm. (fiducial vol.) 5%
  - Background global norm. 10%
  - ν to ν xsection ratio 1%

Looking for θ_{13} and δ

Region of the θ_{13} – δ plane where we can expect, at 3σ or better, the real values of θ_{13} and δ.

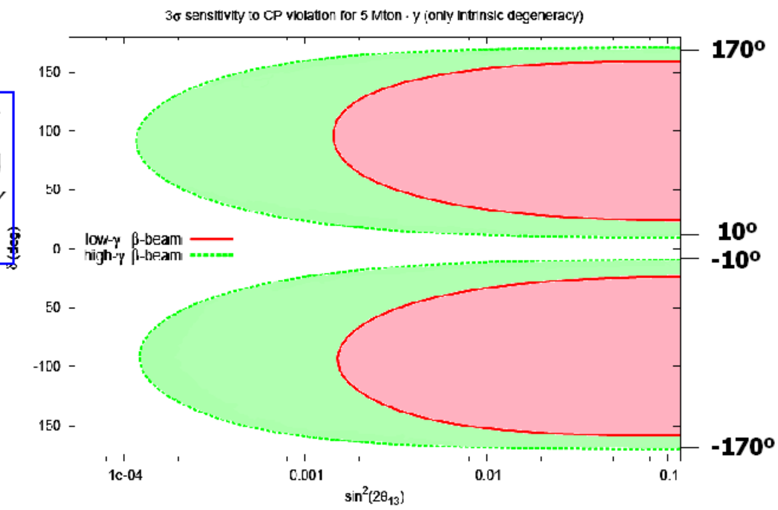
(The actual true values used to calculate the plot are indicated with black dots)



Looking for CP-vio

Region of the θ_{13} – δ plane where we can establish, at 3σ or better, that there is CP vio.

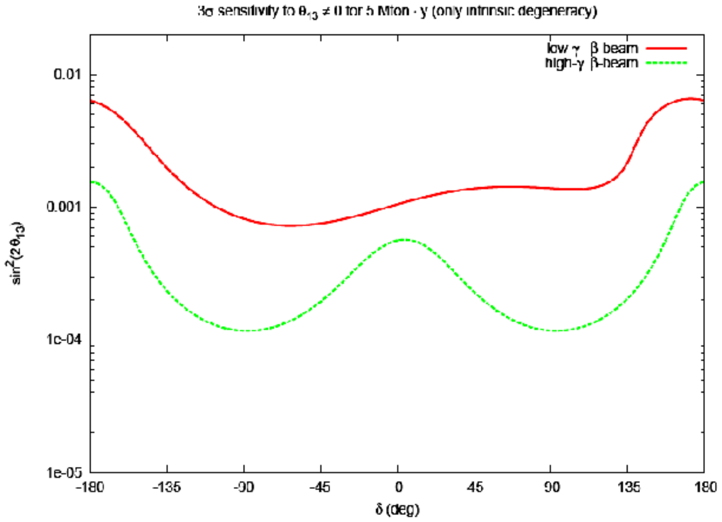
We can distinguish "true" δ from non-CP-violating δ (0° and 180°), for *any* best fit value of θ_{13}



E.C, hep-ph/0607008

Looking for θ_{13}

Region of the θ_{13} – δ plane where we can establish, at 3σ or better, that $\theta_{13} \neq 0$.

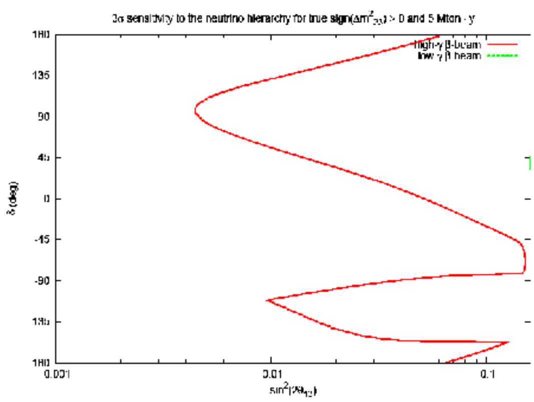


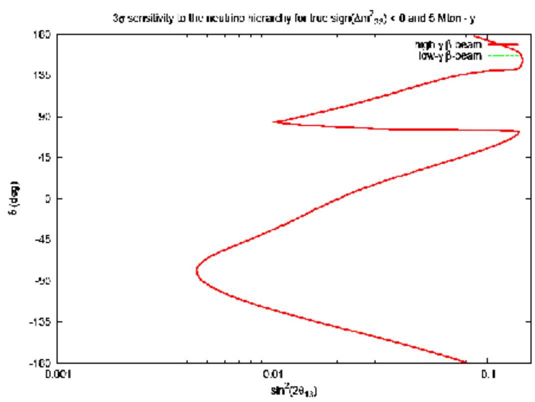
E.C, hep-ph/0607008

Looking for the mass hierarchy

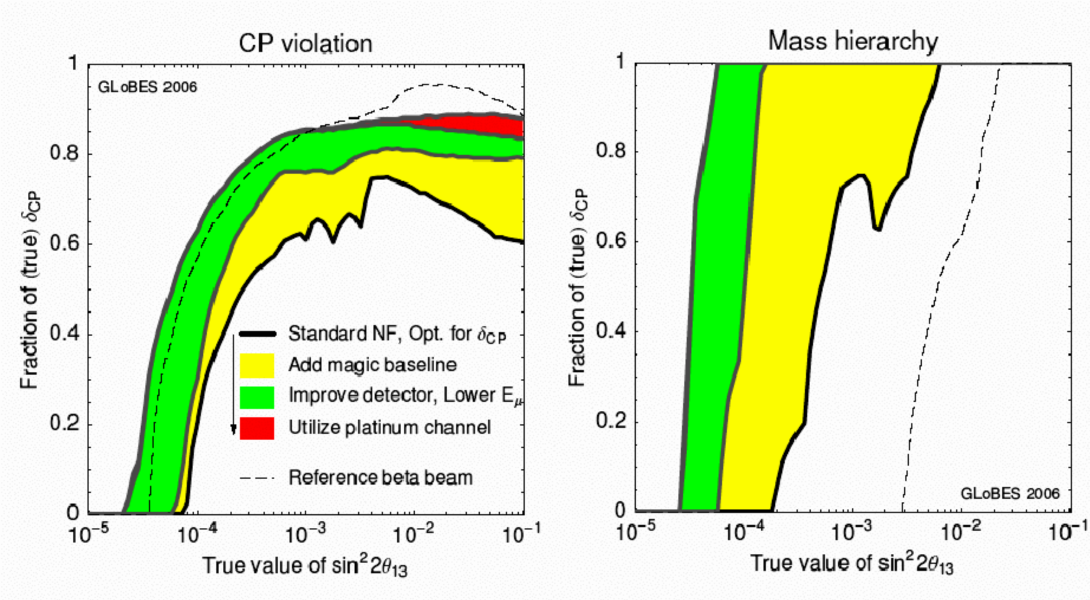
Region of the θ_{13} – δ plane where we can establish, at $3\ \sigma$ or better, the sign of Δm^2_{23}.

We can distinguish the *true* sign from the *wrong* one for *any* best fit value of δ *and* θ_{13}





High-γ β-beam vs ν-Factory



Plots from P. Huber et al, hep-ph/0606119

Changing the ions

- Ions with larger E_0 (and similar q/m ratio) have been proposed: Rubbia et al, hep-ph/0602032

$^{8}Li^{3+}$, $^{8}B^{5+}$

Higher energies for same γ

- "High γ–like" β-beam at less powerful accelerators… … say, the Main Injector at Fermilab, maybe?

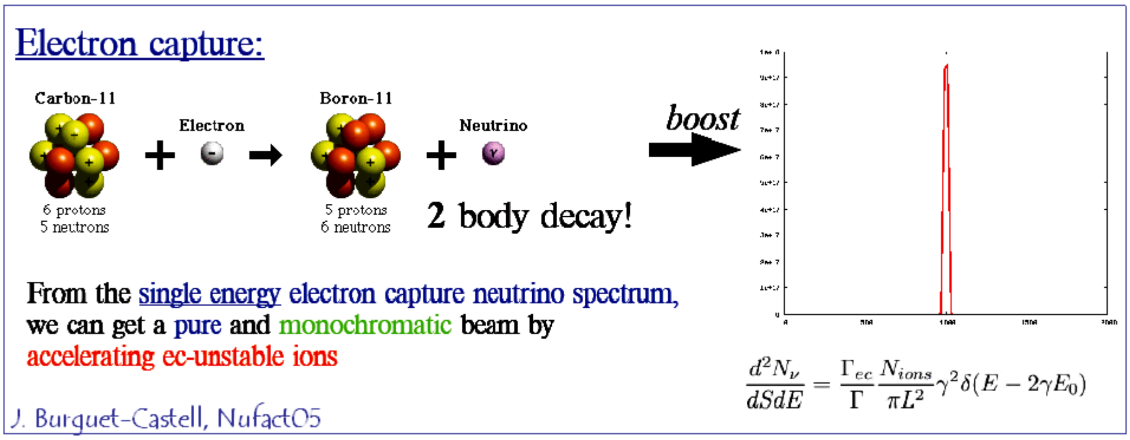
- Combination with He and Ne to solve degeneracies

A. Donini, E. Fernandez-Martinez, hep-ph/0603261

e^- capture beams

- A very interesting idea:

J. Bernabeu et al, hep-ph/0602032



– Monoenergetic neutrino beams!

e^- capture beams

- Advantages:
  - All neutrinos at the energy of interest — Not wasted flux
  - Energy of interest can be changed — ⇒ Solving degeneracies
  - Extremely low detector backgrounds — (energy reconstruction)
- Caveats:
  - No anti-neutrino beams — combination with a β^--beam?
  - Technical feasibility not clear yet

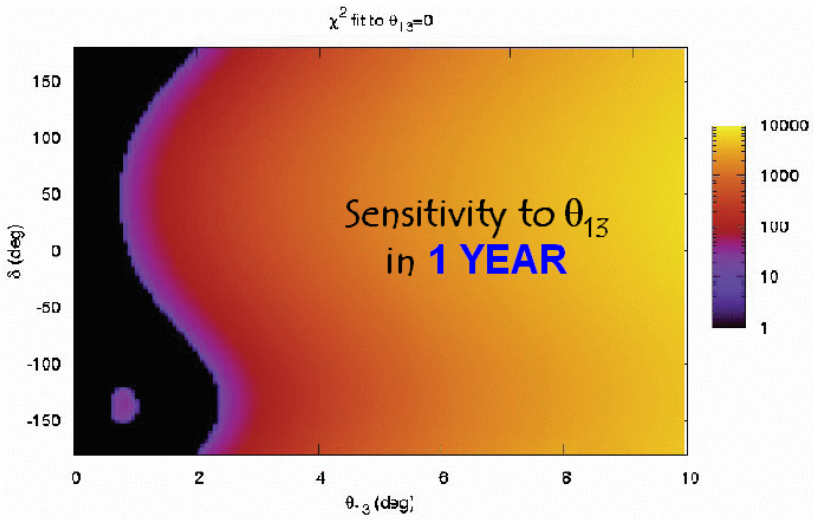
If flux similar to β^+-beam, it would clearly <u>outperform</u> it

e^- capture beams

- Performance

Assuming:

- 10^{18} ions/year
- L = 130 km
- γ = 90/195
- Megaton W. Chkov



Plot: J. Burguet-Castell @ Nufact 05

Beta Beam:

- Elegant idea of using beta decay to produce pure ν_e (ν_e) beams.
- Most likely at energies beneath the τ–threshold:
  - Golden channel $\nu_e \rightarrow \nu_\mu$
  - ν_e disappearance (not very useful)
- No charge discrimination needed:
  - Water Cherenkov detector (massive and versatile)

Beta Beam:

- It has grown into a serious competitor of the ν-Factory as the "ultimate neutrino oscillation experiment":

–Comparable sensitivities to θ_{13} and δ

–Some sensitivity to the hierarchy, although not comparable:

- shorter baseline
- only golden channel

–Not so good for the 'known' sector of the PMSN matrix:

- Needs Atmospheric + T2K data

Beta Beam:

- It has grown into a serious competitor of the ν-Factory as the "ultimate neutrino oscillation experiment":

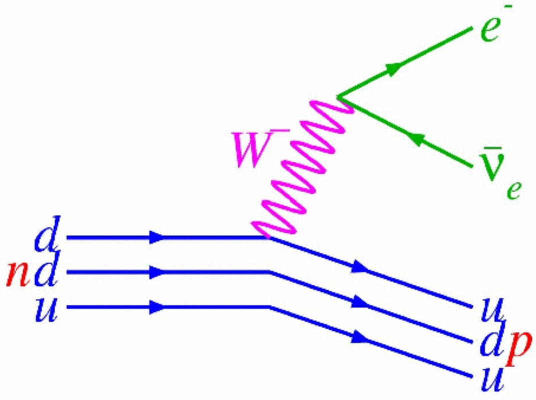
Bottom line:

– Given current global assumptions, their performances are comparable

– Technical progress will probably be the key to the final choice:

- Fluxes
- Mton Water Cherenkov Facility ?
- Muon collider ?

– … Not to mention political and economic issues…



Beta decay gave the first word...

...may it also give the last one?