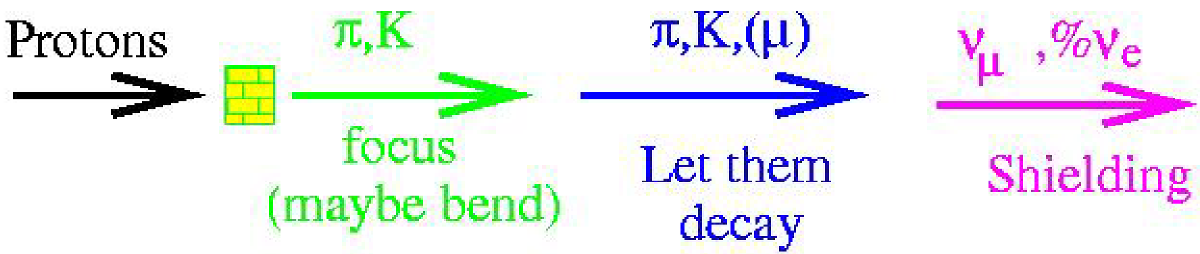
Future neutrino beams(>2015): β-beams and Neutrino Factories

Pasquale Migliozzi

Why conventional ν beams are not adequate to precision measurements of the PMNS matrix?

Working principle of a conventional neutrino beam



- High energy protons (O(10 GeV) to O(100 GeV) are sent onto a target (typically Be, graphite) where π and K are produced copiously
- π^+/K^+ (π^-/K^-) are focused and π^-/K^- (π^+/K^+) are defocused in order to obtain a ν_μ (anti-ν_μ) beam through a magnetic lens system
- Focused hadrons are let decay into a "decay tunnel" to produce neutrinos of the wanted flavor (and not only)
- A shielding is put at the end of the decay tunnel in order to absorb charged particles associated with the neutrino beam (this step is only true for exps located very close (L<1km) to the neutrino source)

Problems with conventional neutrino beams in predicting fluxes and composition (I)

- Description of the proton beam
- Particle yield in the p-Target interaction
- Description of the focusing system
- Description of the particle trajectories after the focusing system (important to extrapolate from the decay point to the detector location)

Problems with conventional neutrino beams in predicting fluxes and composition (II)

Use standard MC simulation : Geant, Fluka, Mars to full simulate target production + beamline (SLOW)

Use dedicated parametrizations for secondary production in target (Sanford-Wang, Malensek, BMPT .... based on available data (Na56/SPY, ...)) + simulation of beamline (FAST)

Secondary components -> needs better knowledge of hadron production in the target

More data needed on hadroproduction

Two possible solutions

- NOMAD approach (no close detector)
- One (or even more) detector(s) approach (near to far extrapolation)

Systematic uncertainties

- Uncertainty on the yields of particles from p-Be interactions
- Uncertainty on the yields of particles interactions other than p-Be
- Proton interactions downstream of the Be target
- Reinteractions in the Be target and downstream of the target
- Position and angular divergence of p beam
- Magnetic field in the horn and the reflector
- Inaccuracies in the simulation of the beam line elements
- Misalignment of the beam line elements

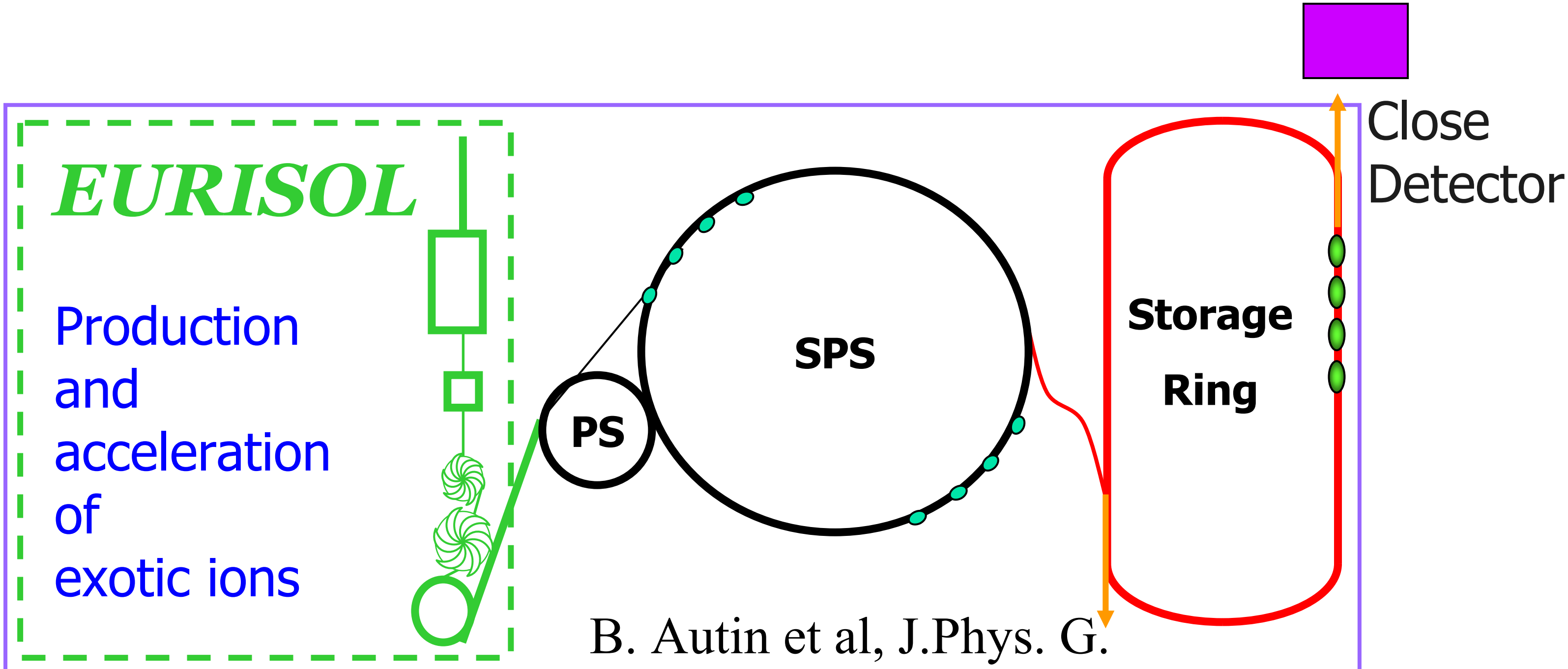
The BETA-BEAM

The BB was born in 2001 when P. Zucchelli put forward the idea to produce pure (anti-)ν_e beam from the decay of radioactive ions

1. Produce a radioactive ion with a short beta-decay lifetime
2. Accelerate the ion in a conventional way (PS) to "high" energy
3. Store the ion in a decay ring with straight sections
4. By its β–decay, ν_e (anti-ν_e) will be produced

- SINGLE flavour (ν_e)
- Known spectrum/intensity
- Focussed ($1/\gamma$)
- The energy depends on the ion γ

Baseline Scenario at CERN



B. Autin et al, J.Phys. G.

One of the possible scenarios :

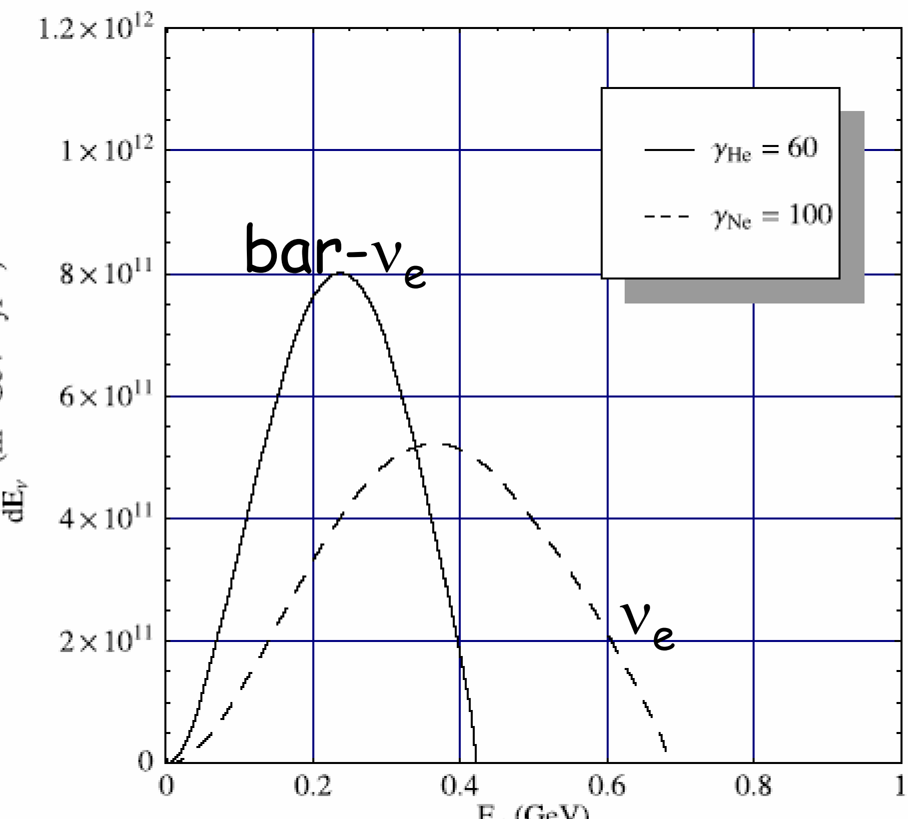
UNO

CP VIOLATION,
PROTON DECAY
SUPERNOVA ν.

BB fluxes at Fréjus location

$\gamma(^6\mathrm{He}) = 60$ $\gamma(^{18}\mathrm{Ne}) = 100$

<E>=230 MeV <E>=370 MeV



All ^{18}Ne decay modes are accounted for

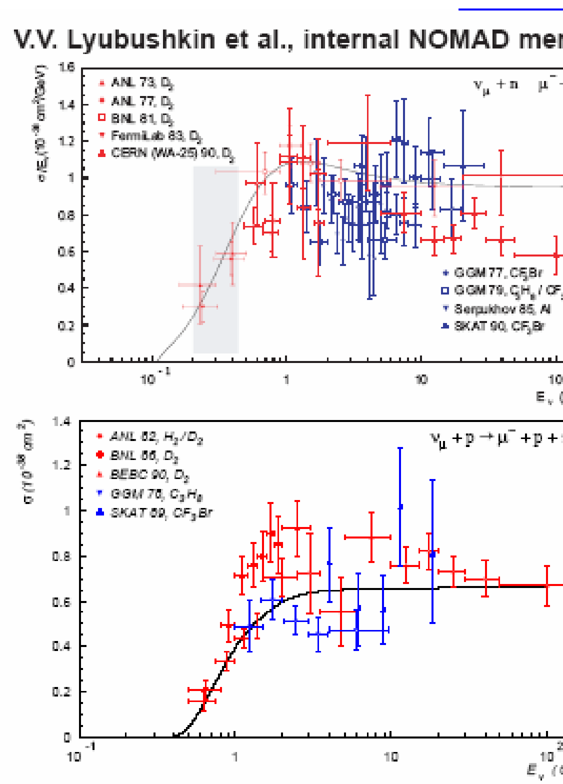
Element	End-Point (MeV)	Decay Fraction
^{18}Ne	34.114	92.1%
	23.699	7.7%
	17.106	0.2%
^{6}He	35.078	100%

A $m_e \neq 0$ is considered, unlike in hep-ex/0310059 Although it seems negligible, this has a strong impact on the expected rate due to the strong cross-section suppression at small energies.

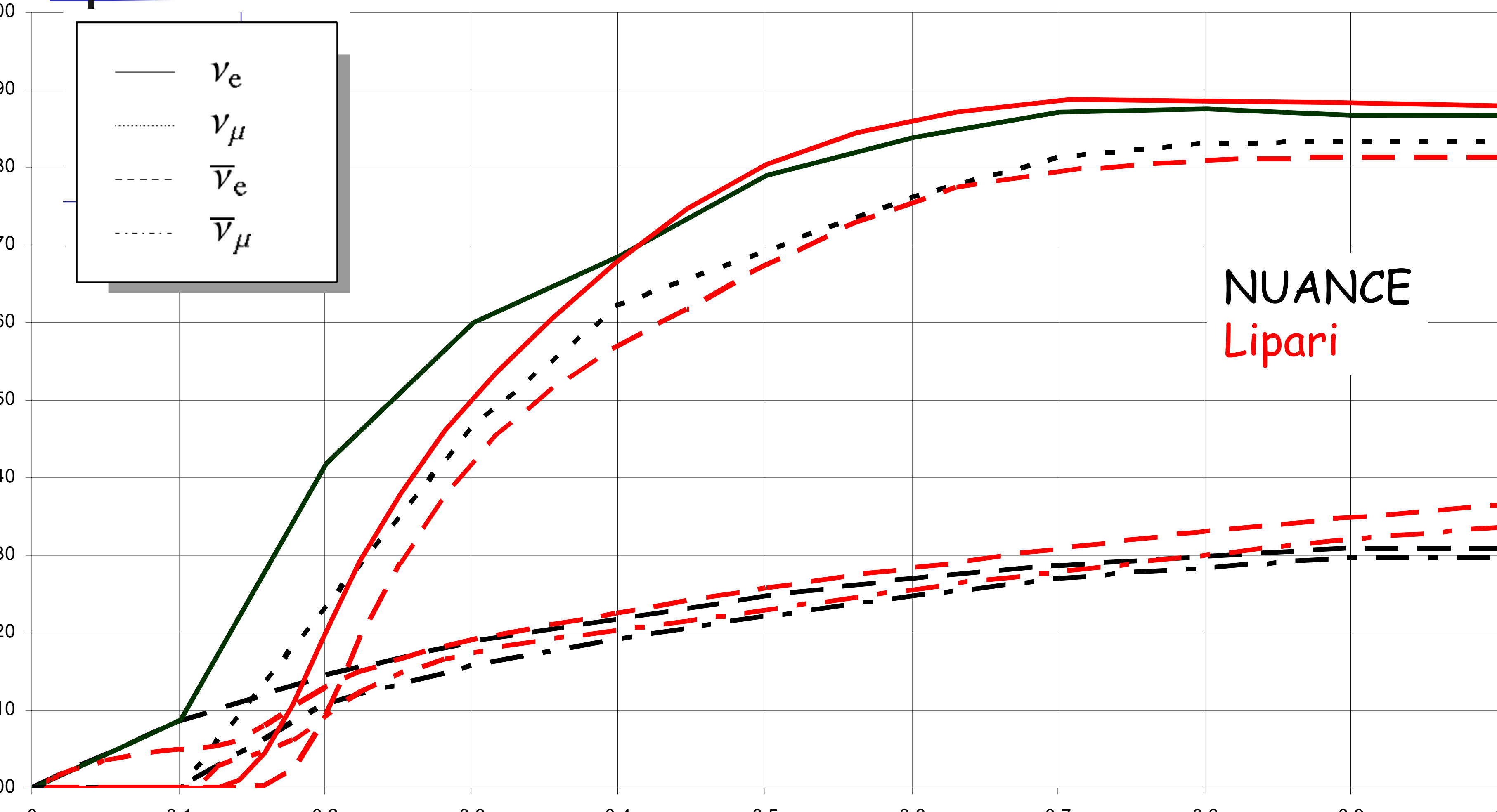
Rate(m_e=0) smaller than 20% wrt Rate($m_e \neq 0$)!

The cross-section problem

- The present knowledge of neutrino and anti-neutrino cross-sections is rather poor below 1 GeV (see plot)
- On top of that, the few available data are not on water
  - Very difficult the extrapolation from different nuclei due to nuclear effects
- Therefore, it is not astonishing that different calculations can differ up to a factor 2
- In the following we compare two calculations on water: NUANCE and one from P. Lipari (adopted in this work)



Cross-section comparison



Target values for the decay ring

^{6}Helium^{2+}

- In Decay ring: 1.0x10^{14} ions
- Energy: 139 GeV/u
- Rel. gamma: 150
- Rigidity: 1500 Tm

^{18}Neon^{10+} (single target)

- In decay ring: 4.5x10^{12} ions
- Energy: 55 GeV/u
- Rel. gamma: 60
- Rigidity: 335 Tm

- The neutrino beam at the experiment should have the "time stamp" of the circulating beam in the decay ring.
- The beam has to be concentrated to as few and as short bunches as possible to maximize the number of ions/nanosecond. (background suppression), aim for a duty factor of 10^{-4}

Why high γ BB?

- statistics increases linearly with E (cross section) → increase rates (very important for anti-neutrinos)
- longer baseline → enhance matter effects → possibility to measure the sign of Δm^2_{13}
- increase the energy → easier to measure the spectral information in the oscillation signal → important to reduce the intrinsic degeneracies
- Atmospheric background becomes negligible (this is a major background source in the low energy option) → the bunching of the ions is not more a crucial issue

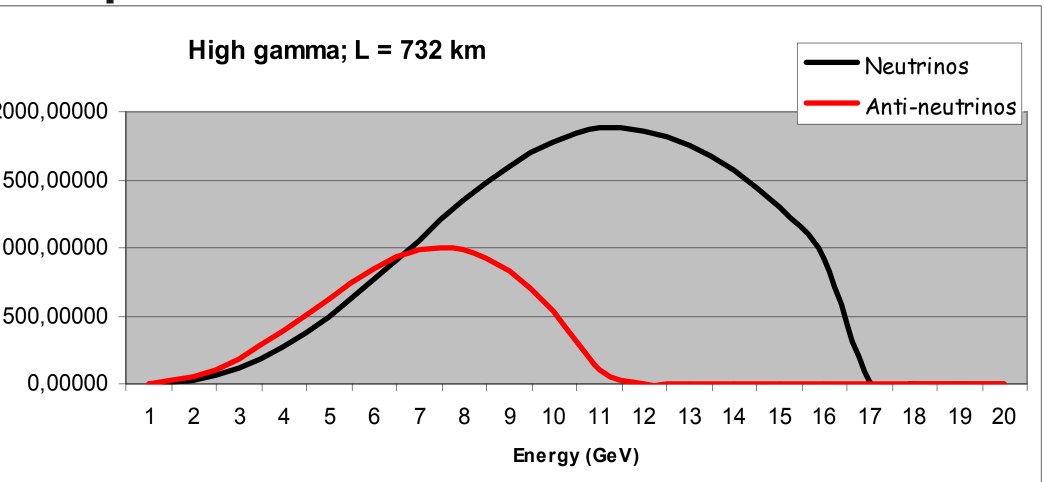
Which γ's?

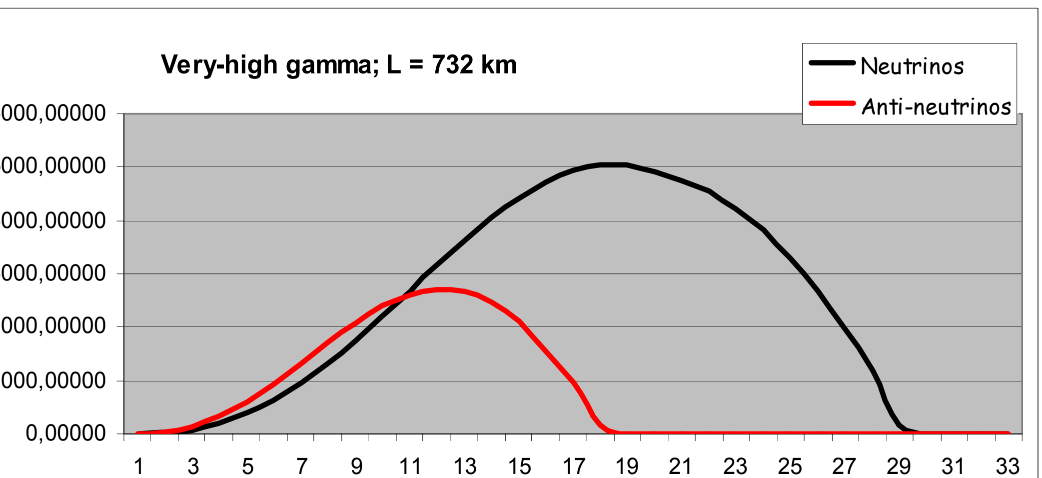
- Use a refurbished SPS with super-conducting magnets to accelerate ions
  - Maximum γ~600
- Use the LHC to accelerate ions
  - Up to γ~2488 for ^{6}He and 4158 for ^{18}Ne

Machine	Proton kinetic energy (GeV)	$\gamma(p)$	$\gamma(^6He^{2+})$	$\gamma(^{18}Ne^{10+})$
FNAL Booster	8	9.5	3.3	5.4
Main Injector	150	161	64	89
Tevatron	980	1045	349	581
BNL Booster	2	3.1	1.4	1.9
AGS	30	34	11	19
RHIC	250	268	89	149

In the US (see talk of S.Geer and APS meeting @ Snowmass, 28-30 Jun 04)

BB fluxes at higher γ values





- Cross-sections are not an issue anymore (E_ν > 1 GeV)
- Megatonne water Cerenkov detectors are not need anymore
- $\nu_e \rightarrow \nu_\tau$ becomes possible
- More challenging from the accelerator point of view

EURISOL Design Study

- **Total budget is 33293300 (9161900 from EU)**
- **Start date:** 1 January 2005
- **Objective:** TDR for end of 2008
- **Objective: TDR enabling the Nuclear physics and Neutrino physics communities to take a decision about a future facility**
- **2009:** Fix site and apply for EU construction project

Beta-beam task

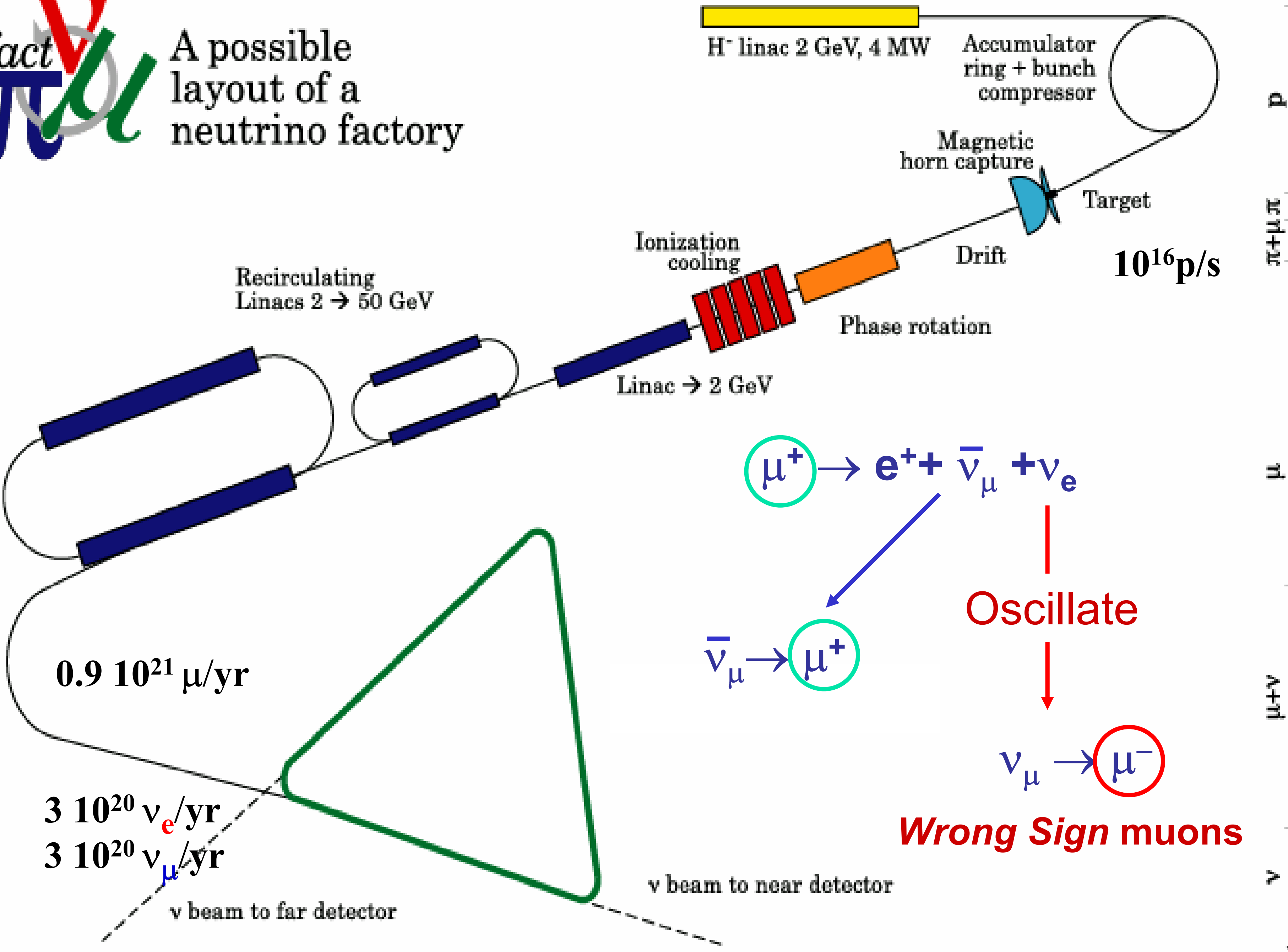
- **Objective:** Study all components of a beta-beam facility above 100 MeV/u
- **Deliverable:** Conceptual Design Report (CDR) for a beta-beam facility
- **Participating institutes:** CERN, CEA, IN2P3, CLRC-RAL, GSI, MSL-Stockholm
- **Parameter group to define the conceptual design and follow the evolution of the beta-beam facility:** Higher intensities and higher gamma

Neutrino Factories

- The ultimate tool for probing neutrino oscillation, based on muon decays (NOT π DECAY !!!)
  - Enormous luminosity
  - Exceptional purity
  - Perfect knowledge of spectrum
  - Flavor of initial neutrino tagged by charge
- Caveats:
  - Technical challenges to muon acceleration
  - Cost

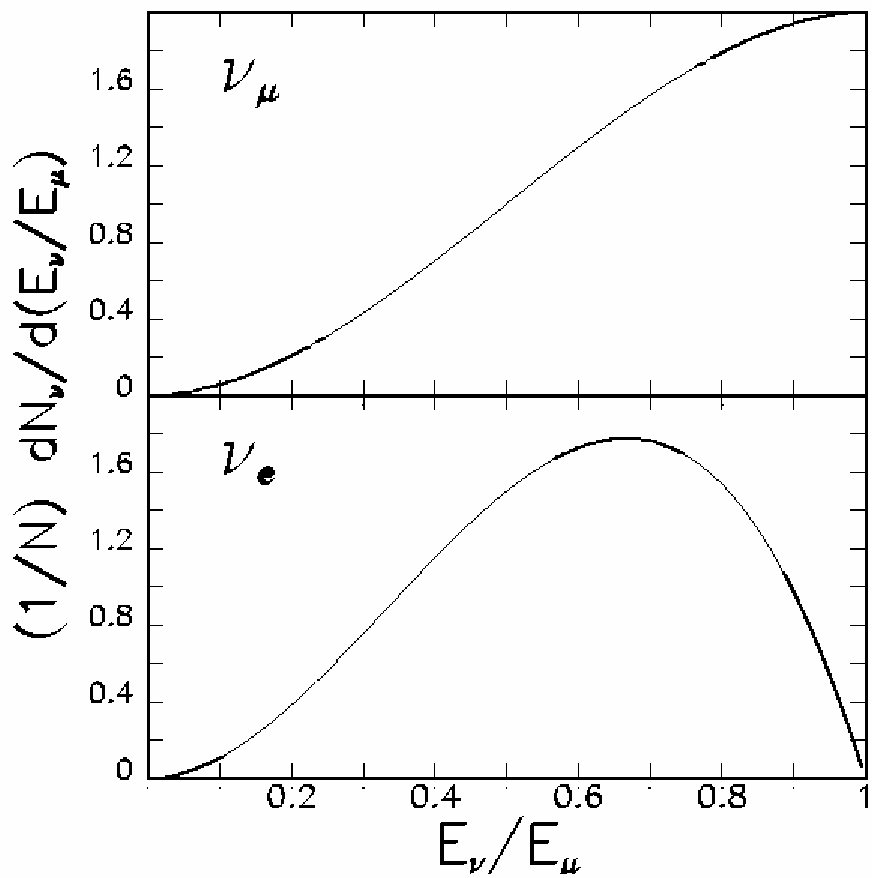
- Proton drivers
- Targetry
- Particle production measurements
- RF manipulation
- Cooling
- Muon acceleration

A possible layout of a neutrino factory



Advantages of Muon Storage Ring

- Both ν_e and ν_μ species in beam:
  - A way to get well understood, high-intensity source of ν_e's
    $\nu_e \rightarrow \nu_\tau$ or $\nu_e \rightarrow \nu_\mu$
- High intensity allows:
  - Probe small mixing angles
- Long distances
  - Start to see earth matter effects for oscillations involving ν_e's
  - Reach solar neutrino region with accelerator beams



Comparison with Conventional ν Beam

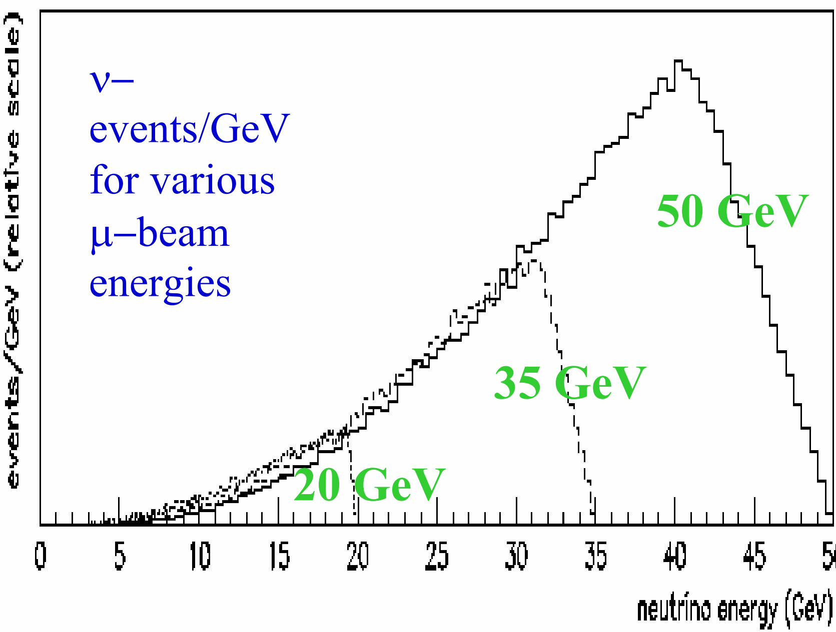
Experiment (L = 732 km)	CC Rates (per kt–yr) ν_μ	$\bar{\nu}_e$
MINOS (WBB)		
Low Energy	458	1.3
Medium Energy	1439	0.9
High Energy	3207	0.9
μ–ring		
10 GeV	2200	1300
20 GeV	18 000	11 000
50 GeV	2.9×10^5	1.8×10^5
250 GeV	3.6×10^7	2.3×10^7

Rate $\sim E^3$

ν - Factory Beam Parameters

High Rate Beam:

- 10^{20} - 10^{21} muon decays/yr
- ν rates higher than conventional beams for $E_{storage}$ > ~20 GeV
- Rate in detector $\propto E^3 \Rightarrow$ High storage ring energy ~ 50 GeV



Measurement Uncertainties at Neutrino Factory

In general, MUCH SMALLER than Conventional Beams

Flux Uncertainties come from:

- current of muons in the ring
- divergence of muon beam
- Energy
- Polarization (usually unpolarized)

- Cross Section Issues
  - Energies are higher, in DIS regime
  - Energy resolution good (>10GeV
  - ν production of charged particles well-modeled—less important

At least 4 phases of Long Baseline experiments

2001

2010

2015

10^{-1}

10^{-2}

10^{-3}

1) 2001-2010. K2K, Opera, Icarus, Minos.

Optimized to confirm the SuperK evidence of oscillation of atmospheric neutrinos through ν_μ disappearance or ν_τ appearance. They will have limited potential in measuring oscillation parameters. Not optimized for ν_e appearance (θ_{13} discovery).

2) 2009-2015. T2K (approved), Noνa, Double Chooz. Optimized to measure θ_{13} (Chooz $\times$ 20) through ν_e appearance or ν_e disappearance. Precision measure of the atmospheric parameters (1 % level). Tiny discovery potential for CP phase δ, even combining their results.

?????

Parameters to Measure

Atmospheric: Δm^2_{23} ☑ θ_{23} ☑

Solar: Δm^2_{12} ☑ θ_{12} ☑

θ_{13} ☐

δ_{CP} ☐

Mass hierarchy ☐

Possible scenarios after first results of the planned experiments and implications

- θ_{13} is so small ($< 3°$, $\sin^2 2\theta_{13} \leq 0.01$) that all give null result
  - We need a "cheap" experiment to probe $\sin^2 2\theta_{13}$ values down to $O(0.001 - 0.0001)$
- θ_{13} is larger than 3° ($\sin^2 2\theta_{13} \geq 0.01$)
  - We need an experiment (or more than one) to
    - Measure θ_{13} more precisely
    - Discover δ (if not done yet) or precisely measure it
    - Measure the sign of Δm^2_{13}
    - Measure θ_{23} (is it $\neq 45°$?)
- NB Independently of the scenario the worsening of the experimental sensitivity due to the eightfold degeneracy has to be taken into account

How to exploit high γ BB?

- Phase I exps give null result
  - See hep-ph/0405081 for a cheap and extremely sensitive to θ_{13} experiment
- Phase I discover θ_{13}
  - See Nucl.Phys.B695:217-240,2004 for possible setups to search for δ
  - New ideas

A proposal for a cheap experiment

Signal: an excess of horizontal muons in coincidence with the beam spill (possible thanks to the BB flavour composition)

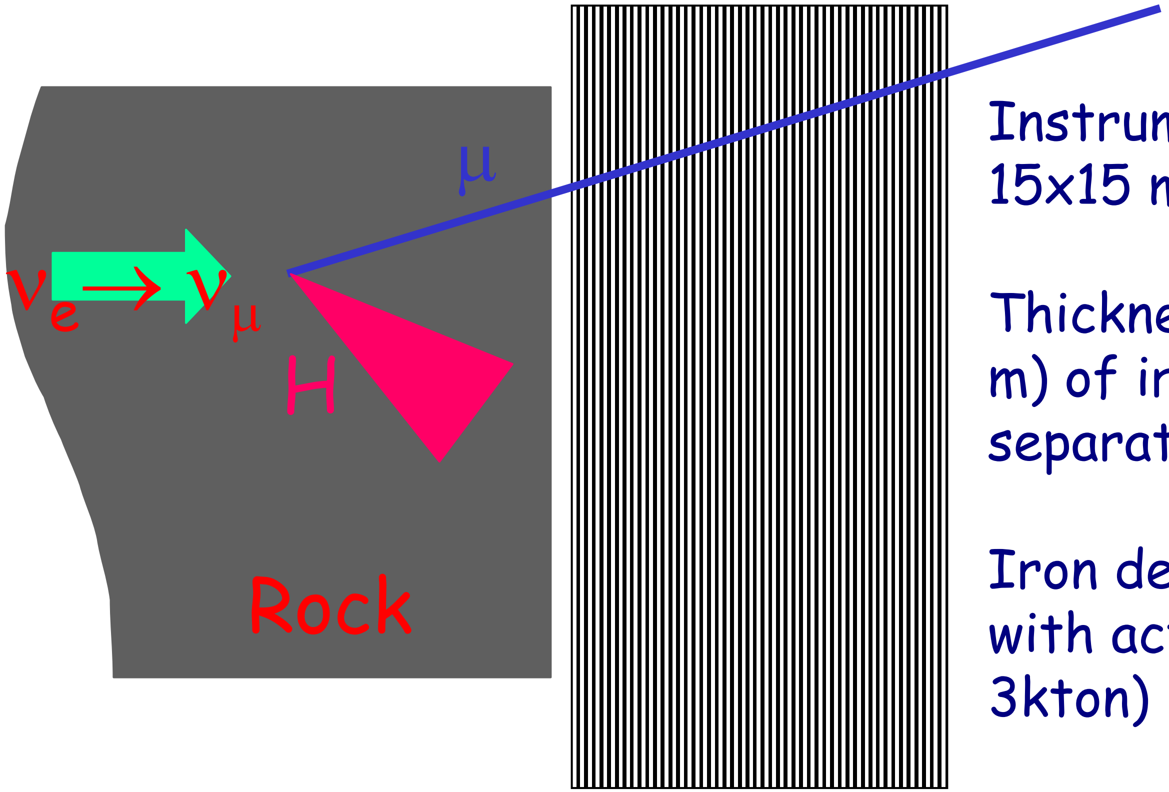
- ✓ Number of unoscillated events: increase linearly with E
- ✓ Range of muons: increase linearly with E as well. The effective volume of rock contributing to the statistics increase linearly with E
- ✓ The cost of the detector increase with the surface and not with the volume

We gain a quadratic increase of the sensitivity if we increase γ and we reduce the detector cost by order of magnitudes!

We loose the possibility to fully reconstruct the events

P.M. F. Terranova, A. Marotta, M. Spinetti hep-ph/0405081

Schematic view of the detector



Instrumented surface: 15x15 m^2 (one LNGS Hall)

Thickness: at least 8λ_I (1.5 m) of iron for a good π/μ separation

Iron detector interleaved with active trackers (about 3kton)

A possible scenario: BB from CERN to Gran Sasso

- A cavern already exists at GS, but
  - Too small to host 40 kton WC or LAr detectors
  - On peak exp requires $E_\nu \sim$ 1-2 GeV (γ= 350/580) $\Rightarrow$ too small to efficiently exploit iron detectors
- What happens if we consider $\gamma > 1000$ (i.e. off-peak experiment)?
  - The oscillation probability decreases as γ^{-2}
  - The flux increases as γ^2
  - The cross-section and the effective rock volume increase both as γ
  - Matter effects cancel out at leading order even if the baseline is large

$\Rightarrow$ We recover the quadratic increase of sensitivity but we test now CP-even terms and no matter effects

Event rate

Beam assumptions

1.1×10^{18} decays per year of ^{18}Ne
2.9×10^{18} decays per year of ^{6}He

Applied cuts

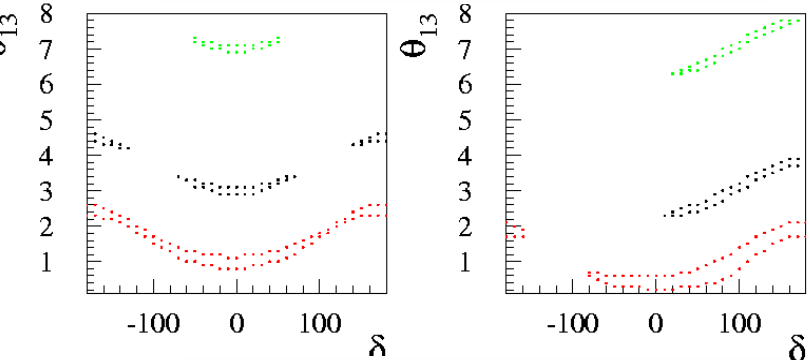
2 GeV energy cut in a 20° cone

00 % oscillated events/year:
$.3\times10^{4}$ (ν_e @ γ=2500)
$.0\times10^{4}$ (anti ν_e @ γ=1500)
$.9\times10^{5}$ (ν_e @ γ=4158)
$.1\times10^{5}$ (anti ν_e @ γ=2488)

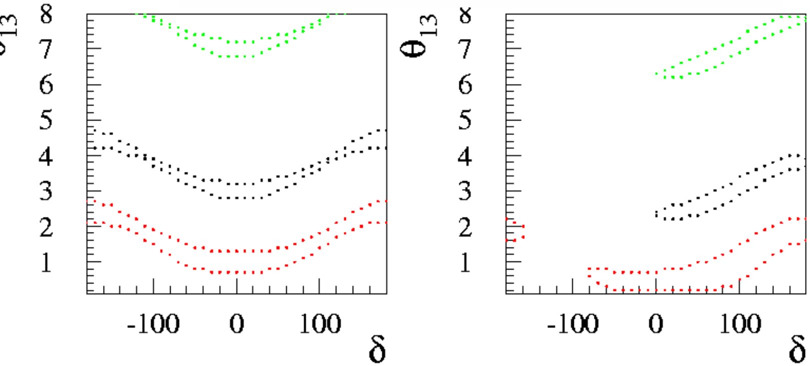
Detector	γ	$\nu_e \to \nu_\mu$	π	μ	charm
$B = 0$ T	2500 (ν_e)	1.5	0.5	11.6	20.2
$B = 0$ T	1500 ($\bar{\nu}_e$)	0.8	0.02	3.5	1.5
$B = 0$ T	4158 (ν_e)	4.9	4.6	153.4	357.1
$B = 0$ T	2488 ($\bar{\nu}_e$)	3.2	0.3	15.4	37.1
$B \sim 1$ T	2500 (ν_e)	1.5	0.2	5.8	0.2
$B \sim 1$ T	1500 ($\bar{\nu}_e$)	0.8	0.01	1.8	0.01
$B \sim 1$ T	4158 (ν_e)	4.9	1.8	64.8	3.6
$B \sim 1$ T	2488 ($\bar{\nu}_e$)	3.2	0.1	7.8	0.4

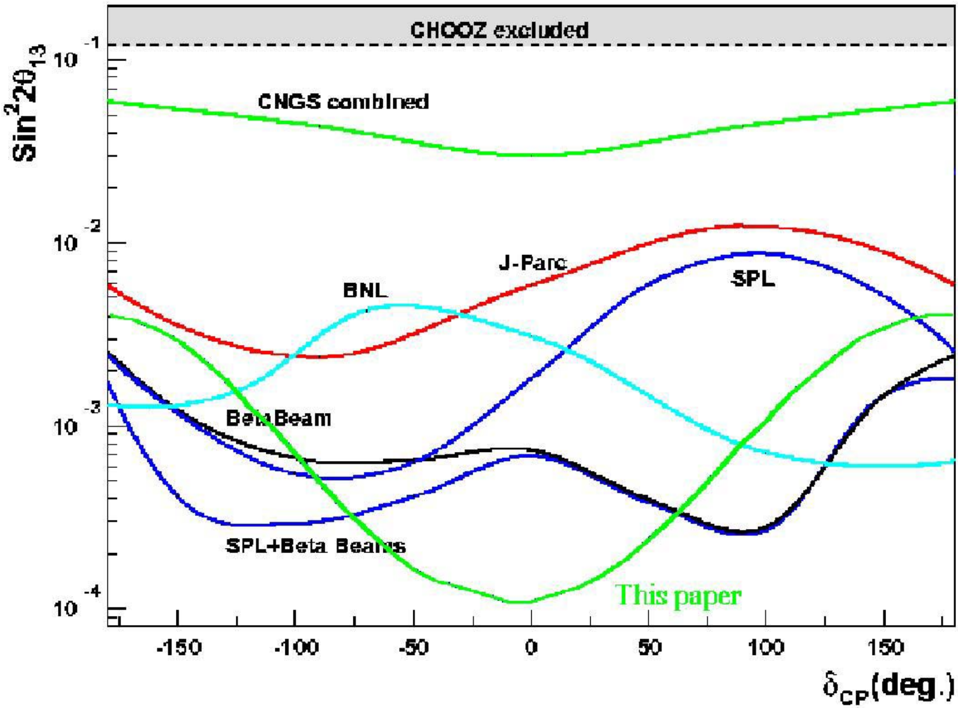
Sensitivity of a "massless" detector located 730 km from a (very)high-γ BB

$$\gamma = 4158(\nu_e)/2488(\bar{\nu}_e)$$



$$\gamma = 2500(\nu_e)/1500(\bar{\nu}_e)$$

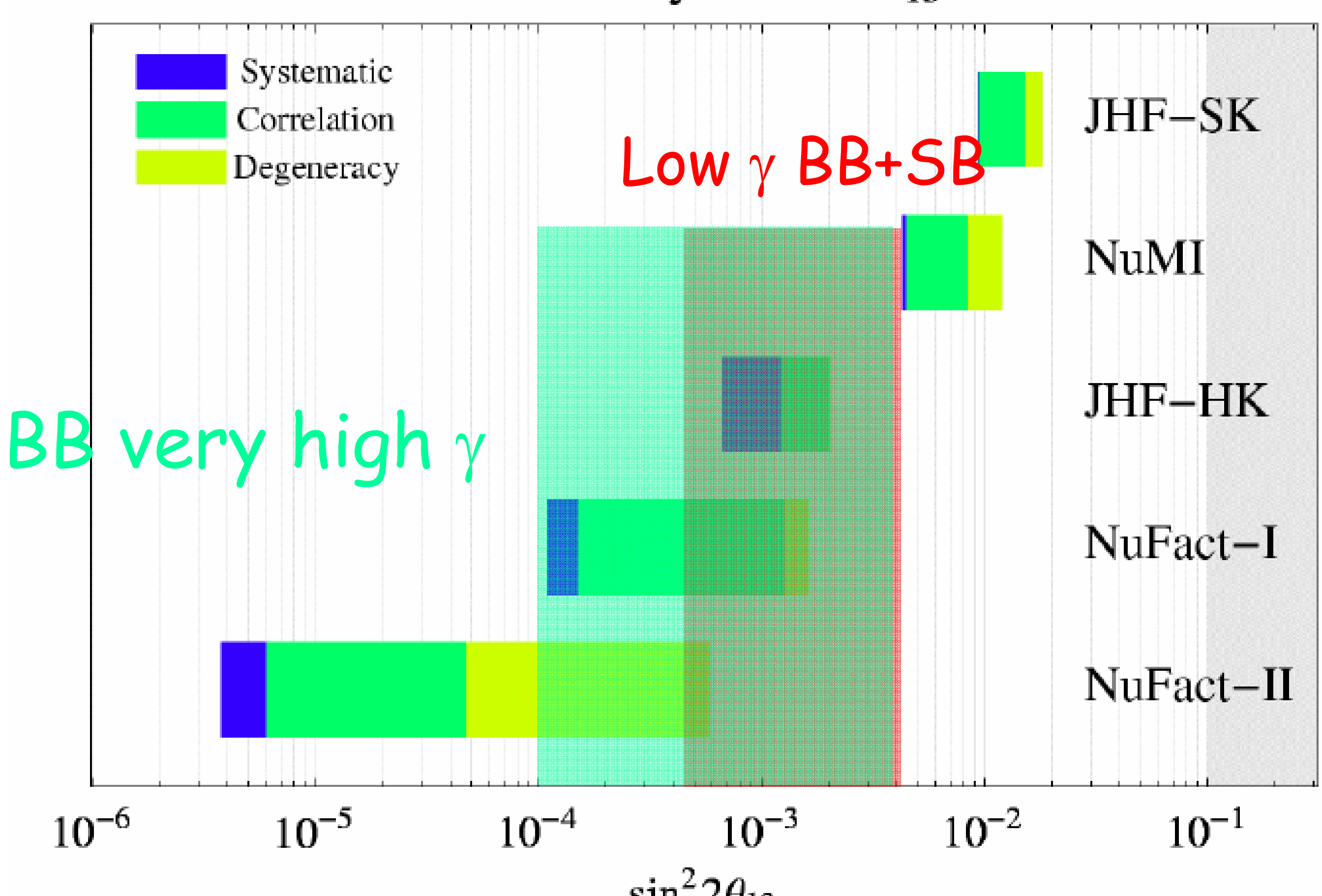




test $\sin^2 2\theta_{13}$ values down to 10^{-3}-10^{-4}!!!

Comparison of very-high γ BB with some of future projects

In case of null result very difficult to build new facilities!



Two setups studied for the medium/high γ options

- Medium (350) and high (1500) γ for medium (730 km) and far (3000 km) baselines
- Water detector (UNO) like; 1 Mton mass. Includes full simulation of efficiencies and backgrounds (only statistical study for high gamma option)
- Running time 10 years
- Full analysis (including the eightfold degeneracy, all systematics on cross-sections, detector, beam, performance at small θ_{13}, etc.) still to be done

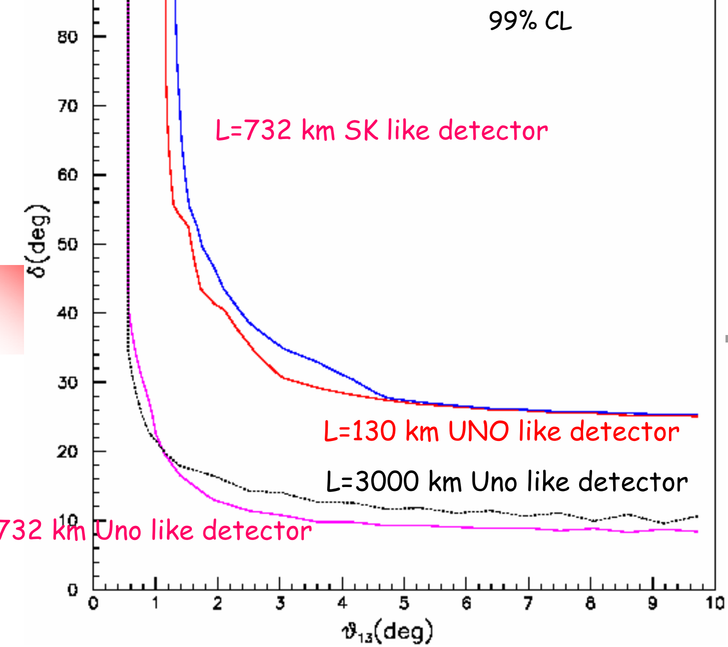
Results

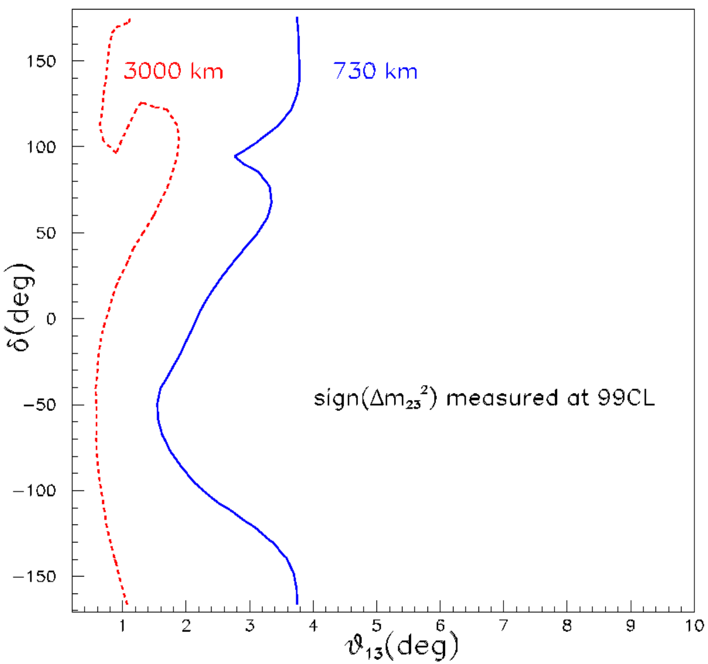
4 Mton/y WC detector @ 3000 km
γ=1550 (^{6}He) / 2500 (^{18}Ne)

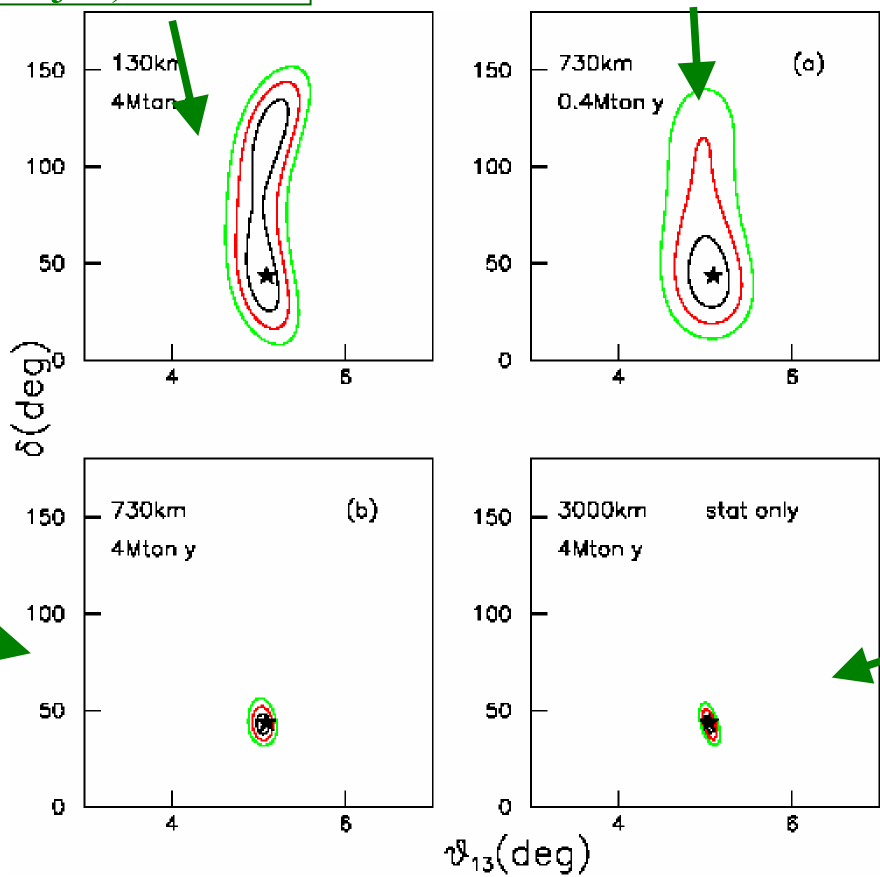
4 Mton/y WC @ 730 km
γ=350 (^{6}He) / 580 (^{18}Ne)

Baseline option
(Frejus)

40 Kton/y WC @ 730 km
γ=350 (^{6}He) / 580 (^{18}Ne)







J.Burguet-Castell et al., Nucl Phys B695:217-240 2004

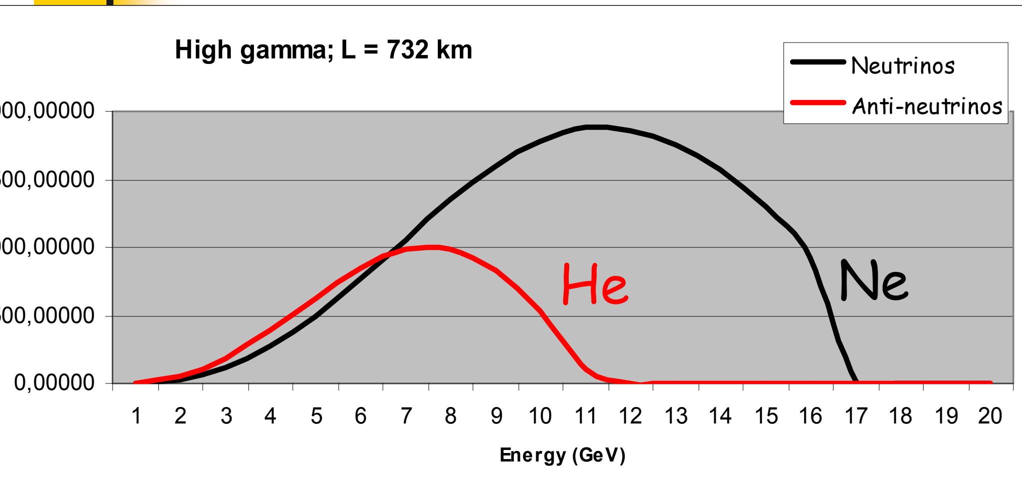
Comments

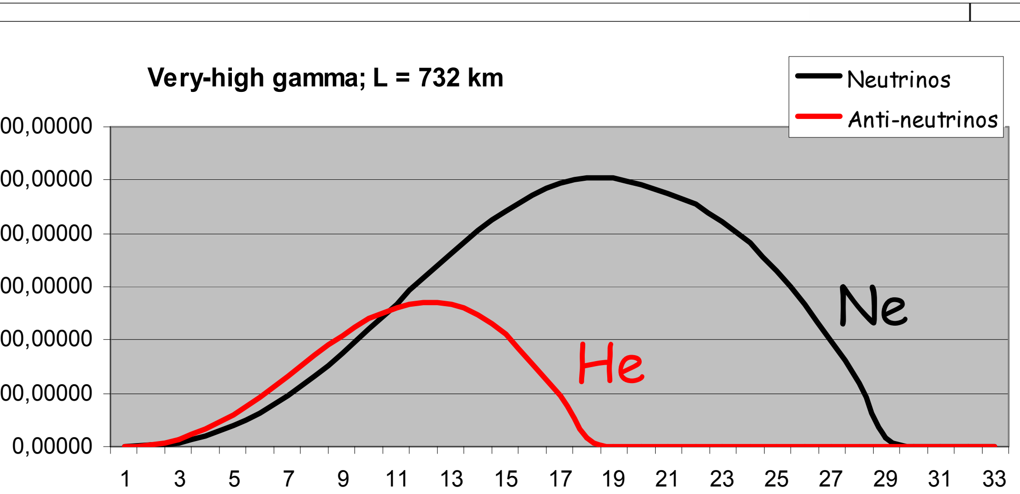
- The idea of medium/(very) high-γ BB is very appealing
- Whatever γ (medium, high, very-high) we consider its performance is better than the low one
- The medium scenario has been put forward in Nucl.Phys.B695:217-240,2004 to measure θ_{13}, δ and the sign of Δm^2_{13}, but more studies are needed to fully exploit its potential (i.e. the θ_{23} ambiguity)
- However, we think this is not the optimal solution
  - It foresees the construction of a 1 Mton detector!
  - There are no place in the world able to host it
  - It is very expensive, so to risky to build if phase I exps give null results
- The optimal solution is the very-high γ scenario
  - In case of null result of phase I exps it allows a cheap investigation of very small values of $\sin^2 2\theta_{13}$ (see hep-ph/0405081)
  - In case of positive result of phase I exps it allows a complete study of the PMNS matrix through different channels, see next slides for details
  - On top of that it makes possible the usage of magnetized calorimeters which are smaller (40 kton -> about 10^4 m^3) than WC detectors (1 Mton -> about 10^6 m^3) $\rightarrow$ cheaper (easier) civil engineer costs

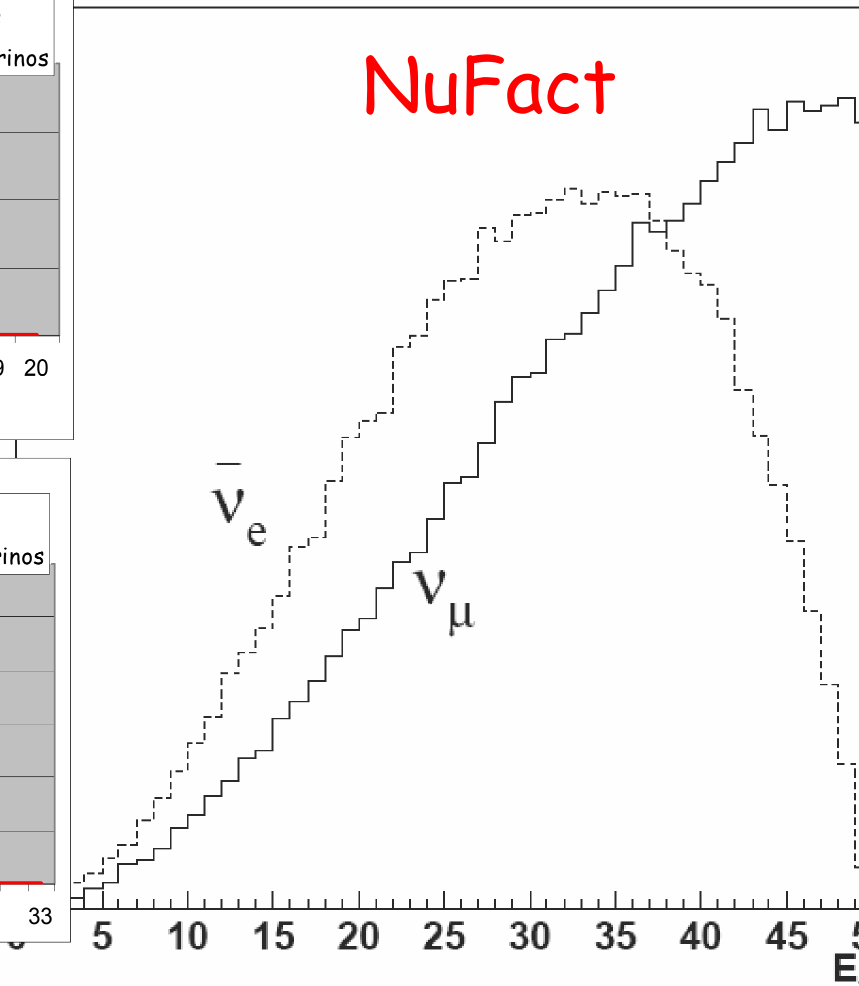
Preliminary studies/ideas on how to use the very-high γ BB

A. Donini, PM, S. Rigolin, …

BB vs NuFact spectra







Expected rates (1ktonx1year)

	NuFact		BB	
	ν_e	anti-ν_μ	ν_e	anti-ν_e
L=730 km	**296×10^3**	**176×10^3**	**---**	**---**
L=730 km γ=2500/1500	---	---	17×10^3	5.5×10^3
L=730 km γ=4158/2488	**---**	**---**	**77×10^3**	**25×10^3**
L=3000 km	**18×10^3**	**11×10^3**	**---**	**---**
L=3000 km γ=2500/1500	---	---	1.0×10^3	0.3×10^3
L=3000 km γ=4158/2488	**---**	**---**	**4.6×10^3**	**1.5×10^3**

NB There is less than a factor 10 difference in the #evts

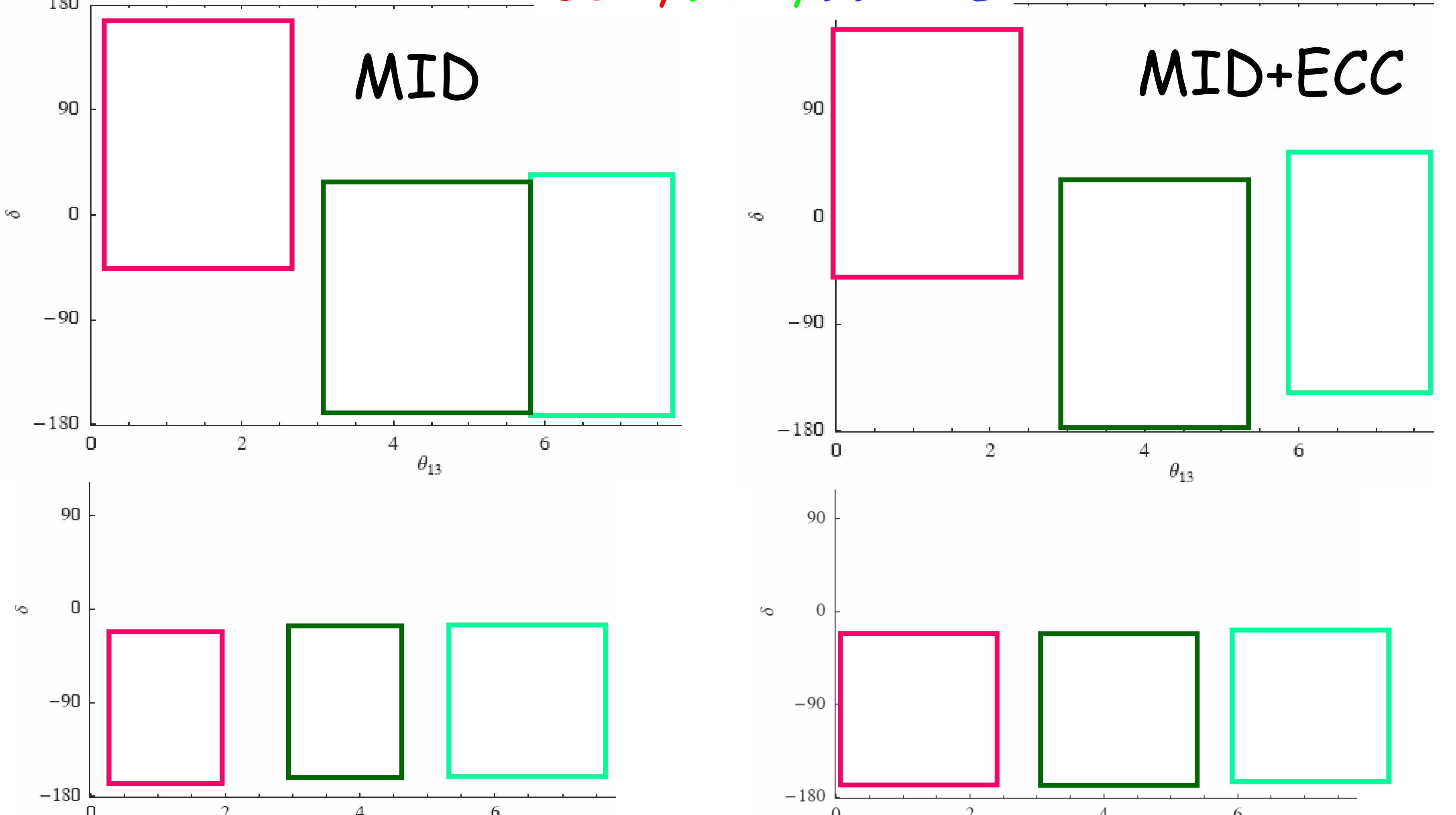
BB allows simultaneous run with ν and anti-ν, while NuFact does not

Potentiality of a very-high γ BB

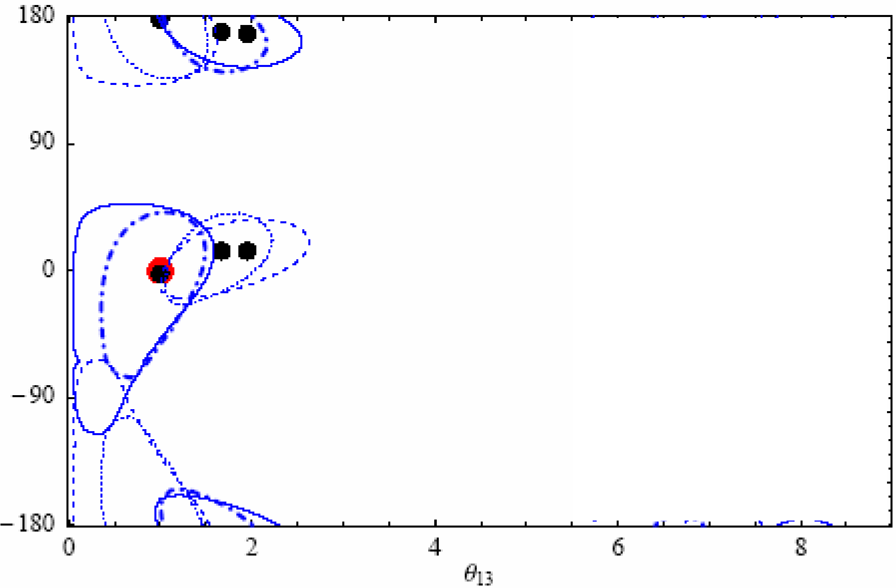
- Simultaneous search for $\nu_e \rightarrow \nu_\mu$ (golden) and $\nu_e \rightarrow \nu_\tau$ (silver) channels
  - This combination is highly efficient in removing the intrinsic and the sign degeneracy (see A.Donini, D.Meloni, P.Migliozzi Nucl.Phys.B646:321-349,2002)
- Simultaneous search for ν and anti-ν channels (i.e. 1 year BB $\equiv$ 2 years NuFact)
- Detectors: 40kton magnetized iron detector (MID) at 3000km; ≥5kton ECC detector at 730km
- The physics potential of this setup is currently under study as well as its comparison with a NuFact

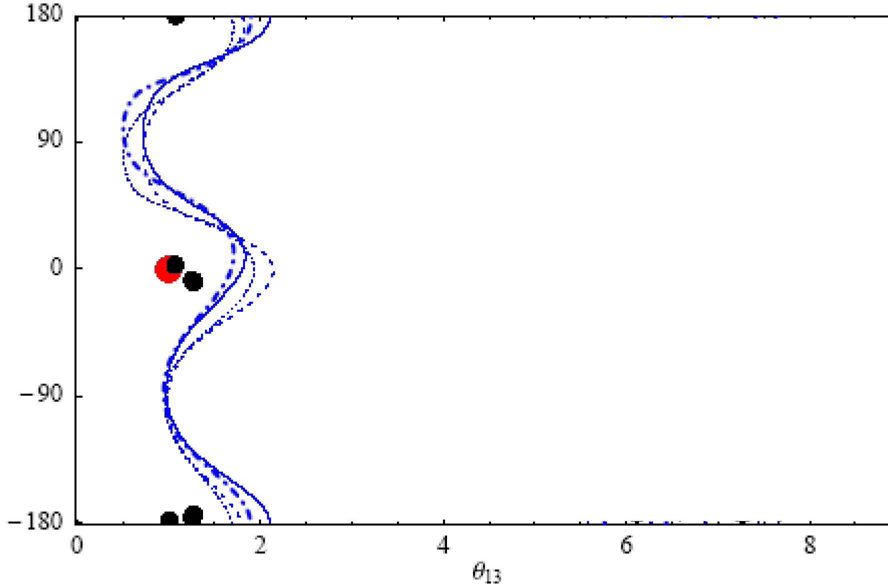
Very preliminary results at a high-γ BB with golden plus silver channels

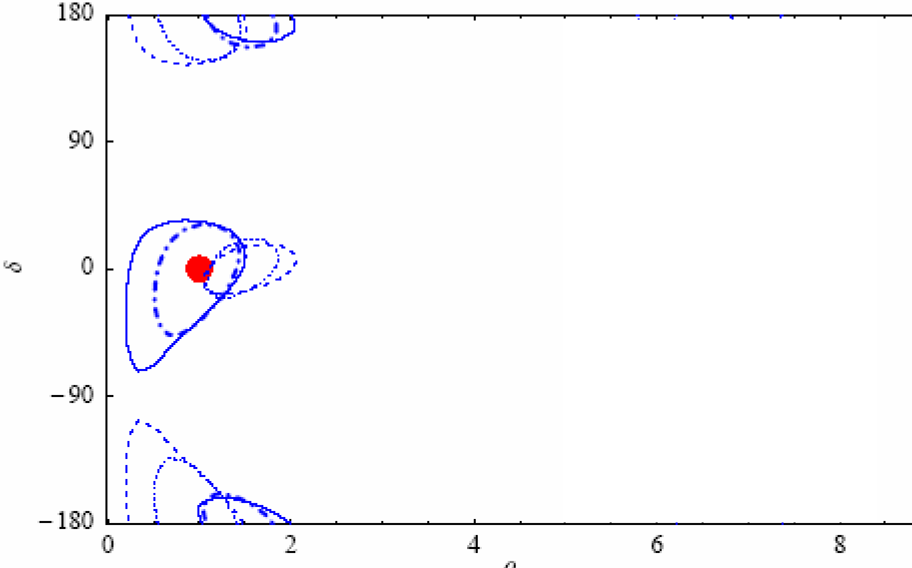
68%, 90%, 99% CL



Parameter extraction in presence of signal (II) with a low γ BB plus a SB







Continuous line: intrinsic degeneracy

Dashed line: sign ambiguity

Dot-dashed line: octant ambiguity

Dotted line: mixed ambiguity

Solving all degeneracy's needs "gold, silver and water"

The Detectors Setup

50 GeV Neutrino Factory located at CERN
Three detectors of different design:

- 40 Kton Magnetized iron detector (MID)
  $L = 2810$ Km (Canary Islands)

  A. Cervera *et al.*,
  Nucl. Instr. Meth. A 451 (2000) 123; NuFact99, Lyon
- 400 Kton Water Cherenkov (WC)
  $L = 130$ Km (Frejus)

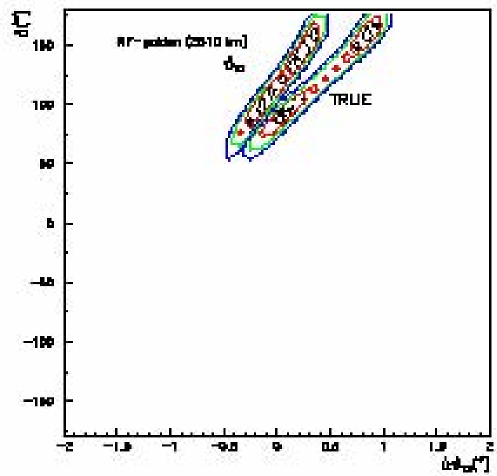
  A. Blondel *et al.*,
  Nucl. Instr. Meth. A 503 (2001) 173; NuFact01, Tsukuba
- 4 Kton Emulsion Cloud Chamber (ECC)
  $L = 732$ Km (Gran Sasso) or $L = 2810$ Km

  D. Autiero *et al.*, hep-ph/0305185; NuFact03, New York

One detector

Consider the NuFact golden channel:
best option for one detector, with baseline $L = 2810$
(no sign degeneracies for $\theta_{13} \geq 1^\circ$).
A. Cervera *et al.*, hep-ph/0002108

- 40 Kton MID



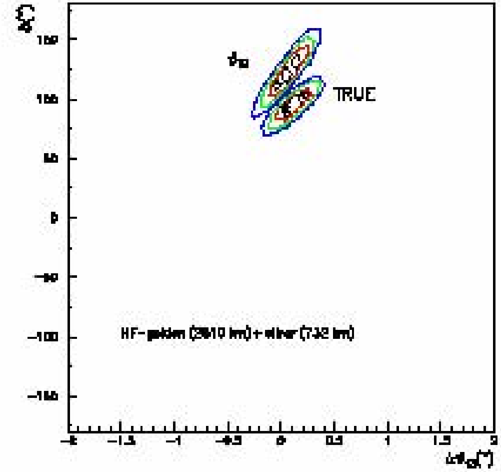
$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$

Two detectors

You can now add a second detector.
We can take advantage of the NuFact silver channel...

A. Donini *et al.*, hep-ph/0206034

- 40 Kton MID
- 4 Kton ECC



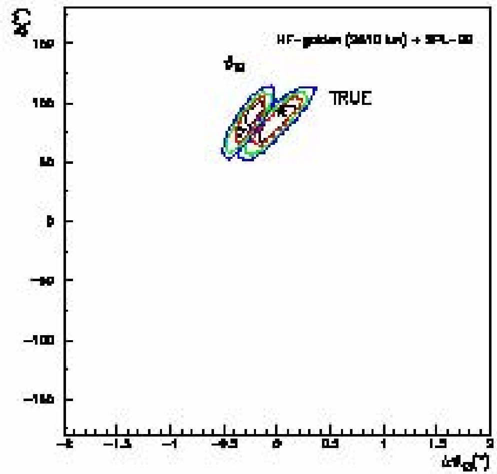
$$\bar{\theta}_{13} = 2^\circ \ \bar{\delta} = 90^\circ$$

Two detectors

... or of the Superbeam-driven water Cherenkov.

J. Burguet-Castell *et al.*, hep-ph/0207080

- 40 Kton MID
- 400 Kton WC



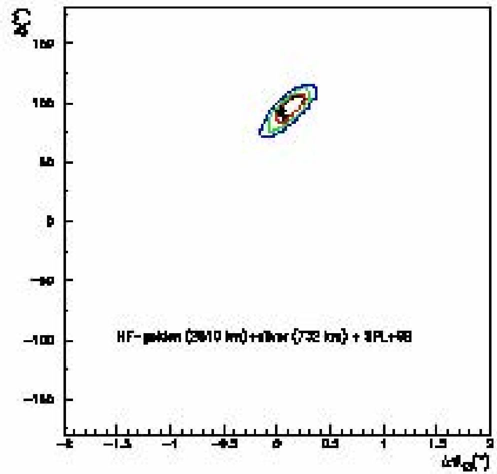
$$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$$

The Three Detectors

However, the very best possibility is
to combine the three detectors in their FULL GLORY.

.... Halleluja....

- 40 Kton MID
- 4 Kton ECC
- 400 Kton WC



$$\bar{\theta}_{13} = 2^\circ \ \bar{\delta} = 90^\circ$$

Sensitivity limits

Statement:
All degeneracies solved for $\theta_{13} \geq 1^\circ$
$(\sin^2 2\theta_{13} \geq 0.001)$

However, three comments are in order:

- 4 Kton ECC: statistical limit at $\sim 1^\circ$
(P. Migliozzi's talk and hep-ph/0305185)
- 40 Kton MID: effect of systematics?
(P. Migliozzi's talk and hep-ph/0305185)
- 400 Kton WC: can we reduce its mass?
how this affects our results?

A conservative statement:
All degeneracies solved for $\theta_{13} > 1^\circ$