High-Q, gamma = 100 Beta Beam at LNGS

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From the work:
P. Coloma, A. Donini, P. Migliozzi, *L. S. L.*, F. Terranova
arXiv:1004.3773v2 [hep-ph]

Beyond CNGS...

LHC data-taking started

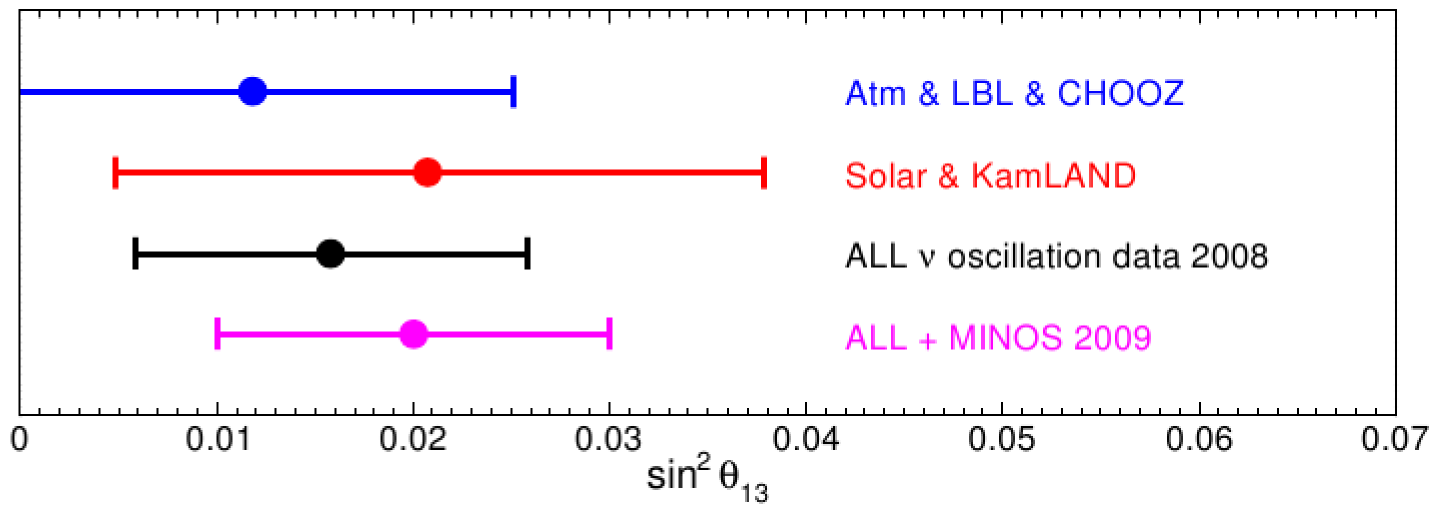
Clearly, unless of major early results by LHC, **possible upgrades for the LHC** physics (SLHC, Double-LHC) are not seen strictly necessary for forthcoming years and they have to face with the **high costs** to be afforded

All upgrades studied for **next generation neutrino physics** are expensive too and reaching the desired performances is still a challenge

This is true in terms of:
- accelerators and storage rings for neutrino **production**
- extension or construction of big **underground sites**
- technology and mass of the most far **detector**

Hints of $\theta_{13} > 0$

From global neutrino analysis from 2009 data

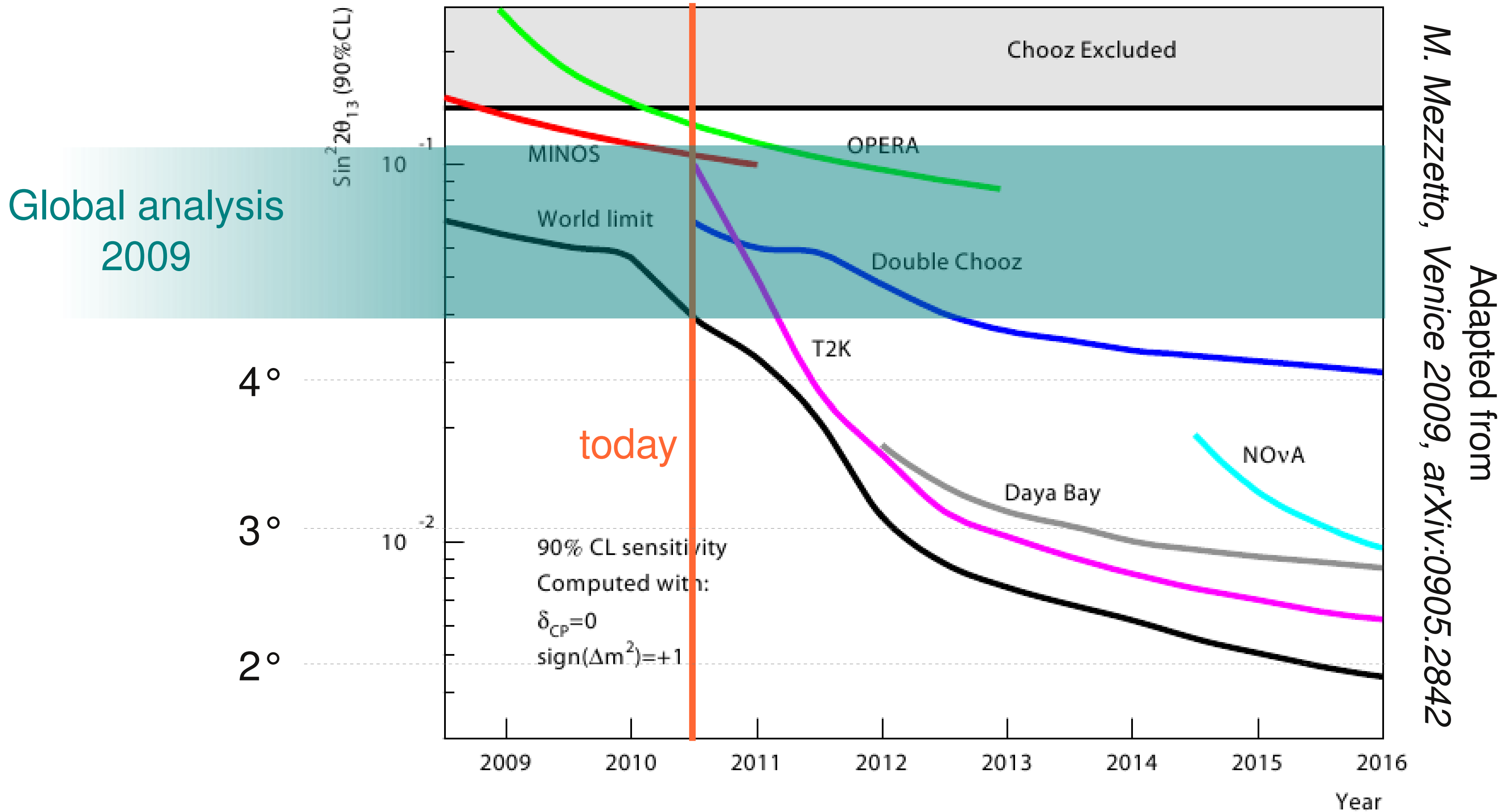


G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A.M. Rotunno, Venice 2009, Neutrino Telescopes arXiv:0905.3549 [hep-ph]

$$\sin^2\theta_{13} \simeq 0.02 \pm 0.01$$

$\theta_{13} = [5.7°, 10°]$, possible $\theta_{13} > 0$ 2σ hint

Timescale is short for an European facility



If combined analysis hints are confirmed by the present generation experiments (T2K and reactors), a θ_{13} > 2-3° measurement would allow to measure CP violation with next upgrades of already existing facilities

Standard and novel neutrino sources

Standard beams: p → π,K → ν

Upgrading existing beams (Super-Beams, CNGS upgrades, ...), long timescale

Neutrino factories: μ → ν

Very high luminosity, completely new infrastructures, very long timescale

Beta beams: unstable isotopes → ν

New infrastructures: ions production facility, (possible) SPS upgrade, ions decay ring. The development and the interaction among them is challenging.
Timescale depends on the number of planned upgrades, which In turn depends on beam properties

Beta beam – original design

Ion isotope production with ISOL techniques

SPS as **terminal booster** γ up to ~450 Z/A

Used ions: ^{6}He (Q=3.51 MeV), ^{18}Ne (Q=3.41 MeV)

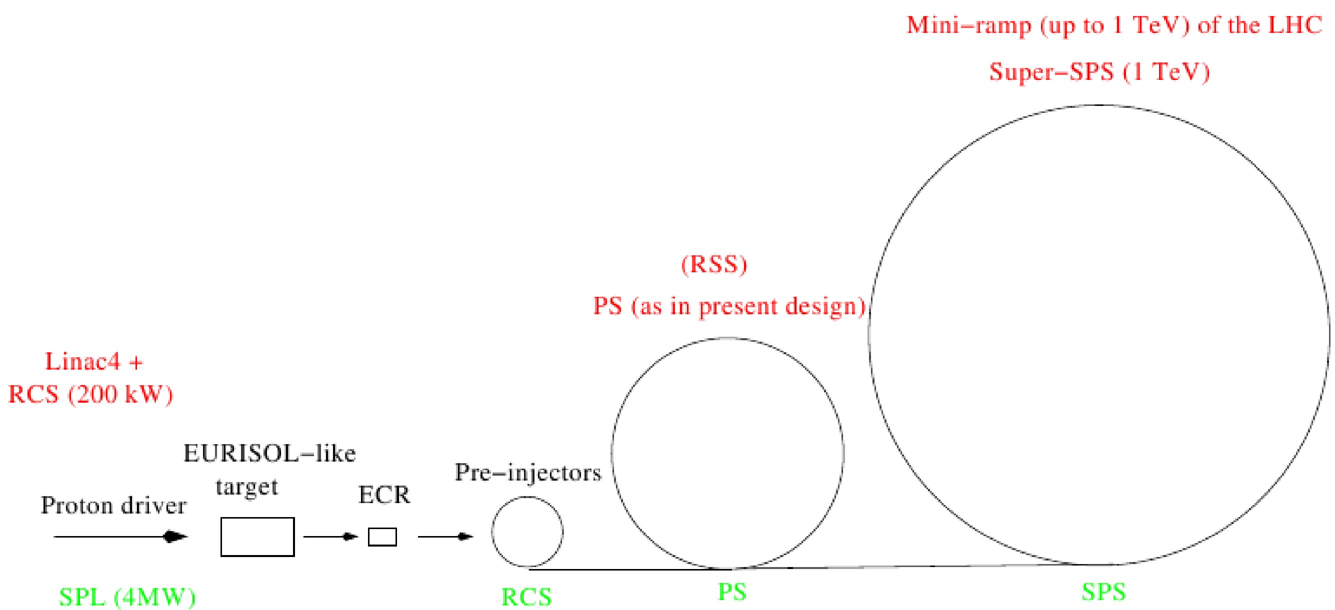
We get a neutrino energy (~γQ) < 0.5 GeV (^{6}He), < 0.9 GeV (^{18}Ne)

Short baseline
Huge low density detectors
Large underground infrastructures

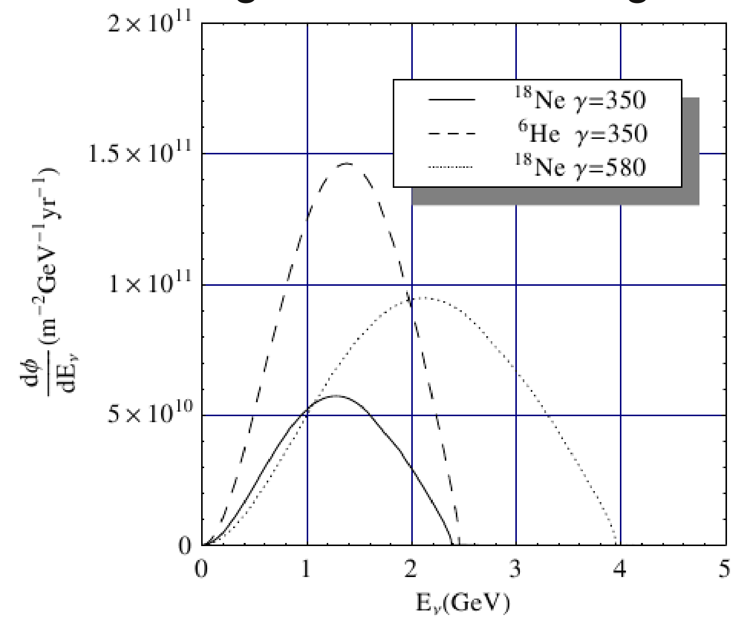
Beta beam – an investigated possible option

Ion isotope production with ISOL techniques, low Q-ions (^{6}He and ^{18}Ne)

"Super-SPS" as **terminal booster** (1 TeV) γ up to 350 for ^{6}He and ^{18}Ne

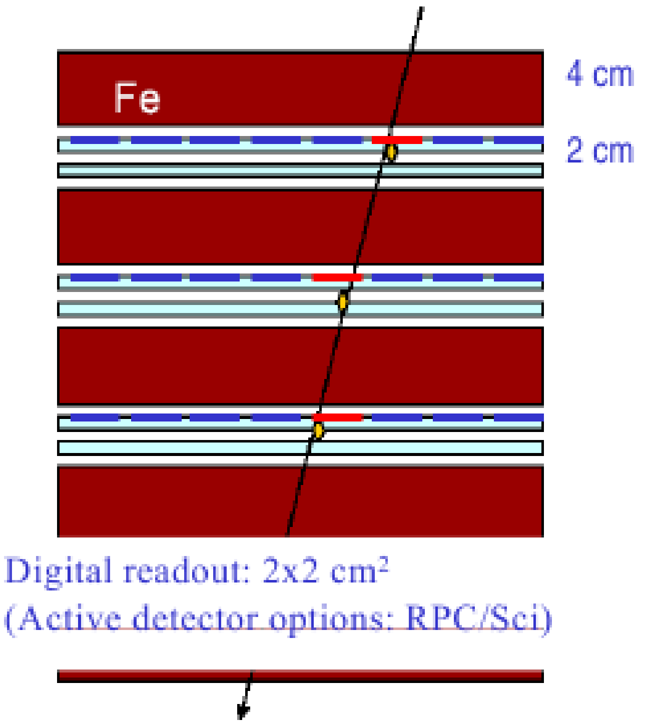


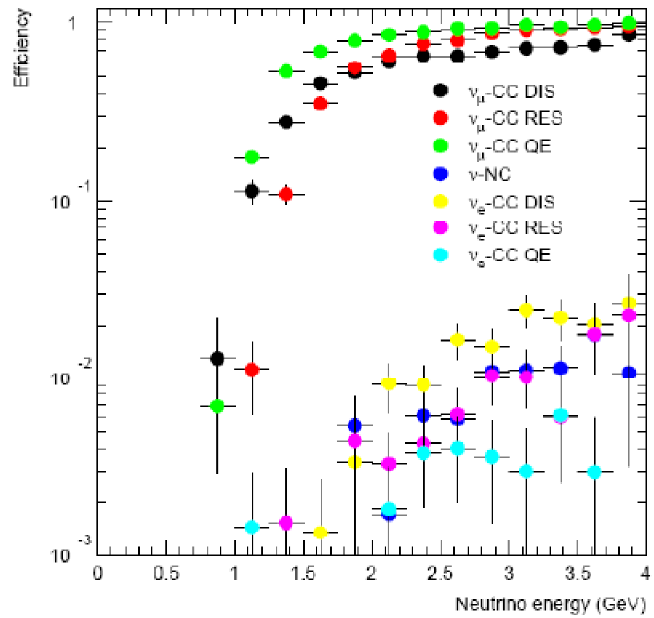
Higher neutrino energies



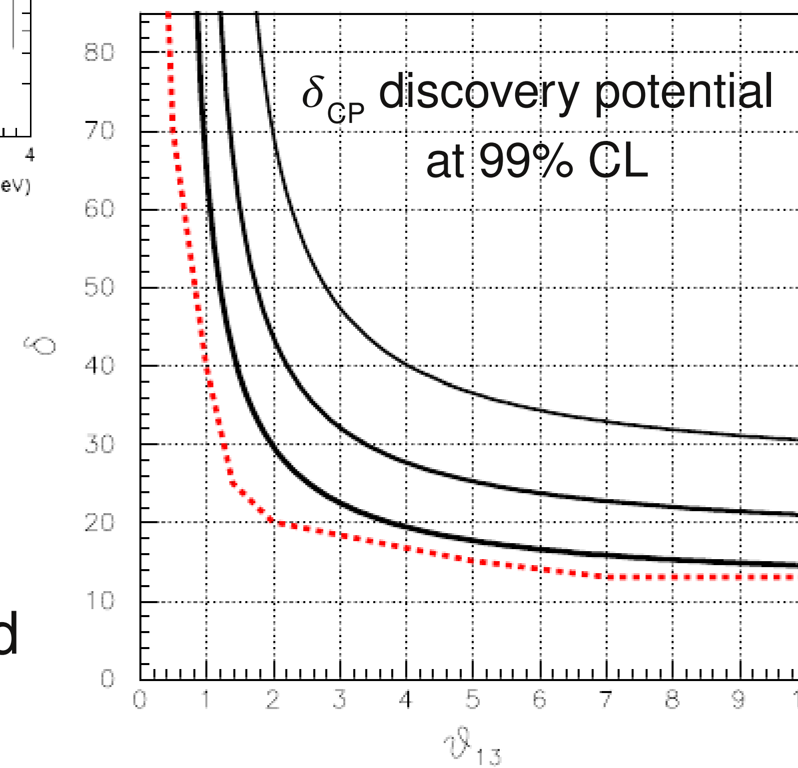
Enough energy to consider:
- high density detectors
- longer baselines (e.g. CERN to Gran Sasso distance)

Low-Q beta beam – performances





40 kton
iron detector



Low-Q high γ beta beams can be very effective to probe θ_{13} and δ_{CP} parameters

Unfortunately, the need of an **SPS upgrade** and the technical challenges for a **long decay ring** (**luminosity** far from the baseline) make this option still far to be considered a reality

A. Donini et al. Eur. Phys. J. C48 (2006) 787, [arXiv:hep-ph/0604229]

The high-Q beta beam option

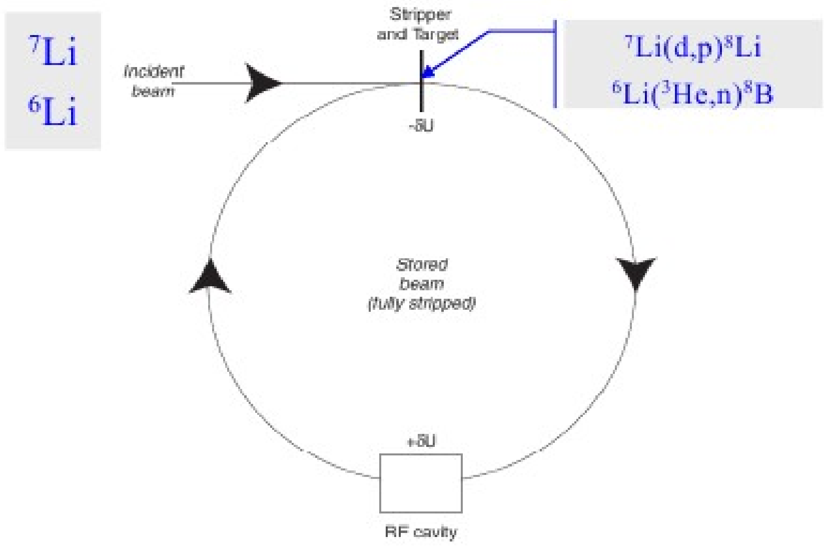
None of the previous challenges have to be faced
if we employ **isotopes with higher Q** and γ = 100
like ^{8}Li ($\overline{\nu}_e$) and ^{8}B (ν_e)

Why was this option not considered at the beginning?

Roughly, the number *N* of neutrino events is proportional to: $N \simeq \frac{N_\beta(\gamma)\cdot\gamma}{Q}$
(N_β = number of useful ion decays per year)

Clearly, reducing γ and increasing *Q* is counterproductive

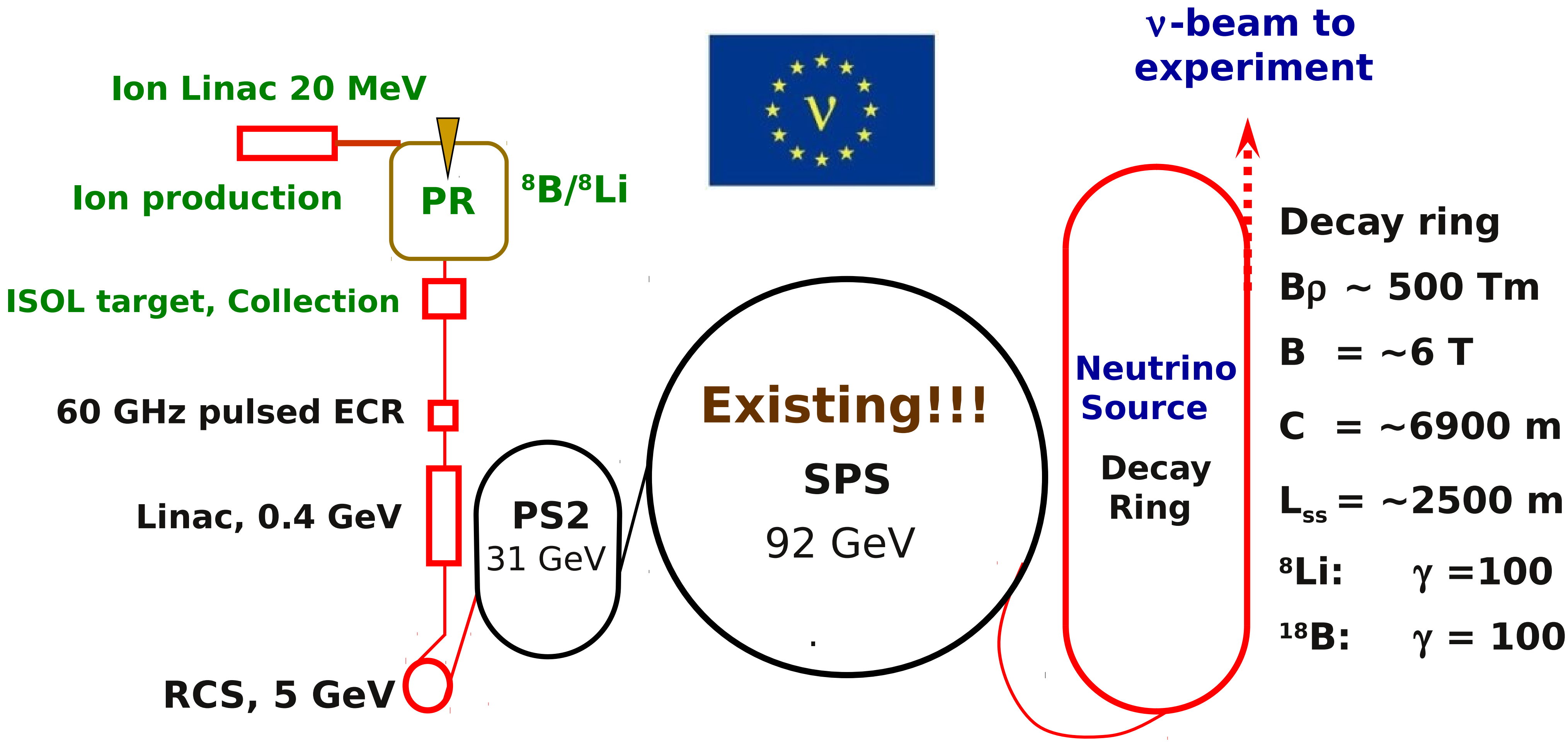
Why is this option now considered?



Non standard techniques to produce low-Z,
high-Q ions show that high rates can be reached

[Rubbia et al., NIM A 568 (2006) 475;
Mori, NIM A562 (2006) 591]

Beta beam scenario EUROnu, FP7



From E. Wildner, Nufact09

A configuration exploiting at most existing facilities

Facility based on:
- ^{8}Li and ^{8}B ions
- boosted by a PS upgrade (PS2)
- accelerated by the present SPS
- neutrinos produced by decay ring
- pointing to Gran Sasso Laboratories

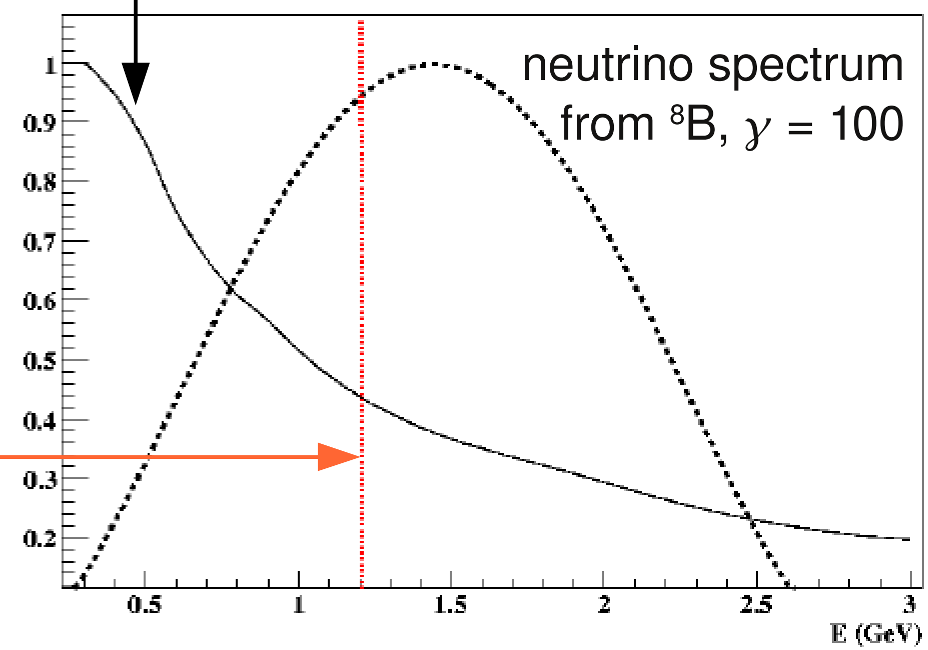
$\sigma^{QE}_{CC}/\sigma_{CC}(E_\nu)$

It allows to use detectors capable to identify not only **QE topologies** (Water Cherenkov) detectors, but also **DIS and resonances** (liquid scintillators, LAr TPC, iron calorimeters)

The idea behind:

Muon energy to reach a range in iron larger than 4.6 interaction lengths

Pion punch-through contamination < 10^{-2}



Physics performances

CP discovery potential **sgn(Δm^2_{23}) reach**	as function of	**$\sin^2(2\theta_{13})$, δ_{CP}** **Beam flux intensities**

Considered baseline for ^8B and ^8Li fluxes is
$F_0 = 3 \times 10^{18}$ useful ion decays per year

Iron calorimeter detector mass considered is 100 kton
Distance = 732 km (CERN to LNGS)

Data taking duration: 5 + 5 years

Sensitivity to the CP-violating phase

as a function of flux intensities

and for several δ_{CP},θ_{13} scenarios

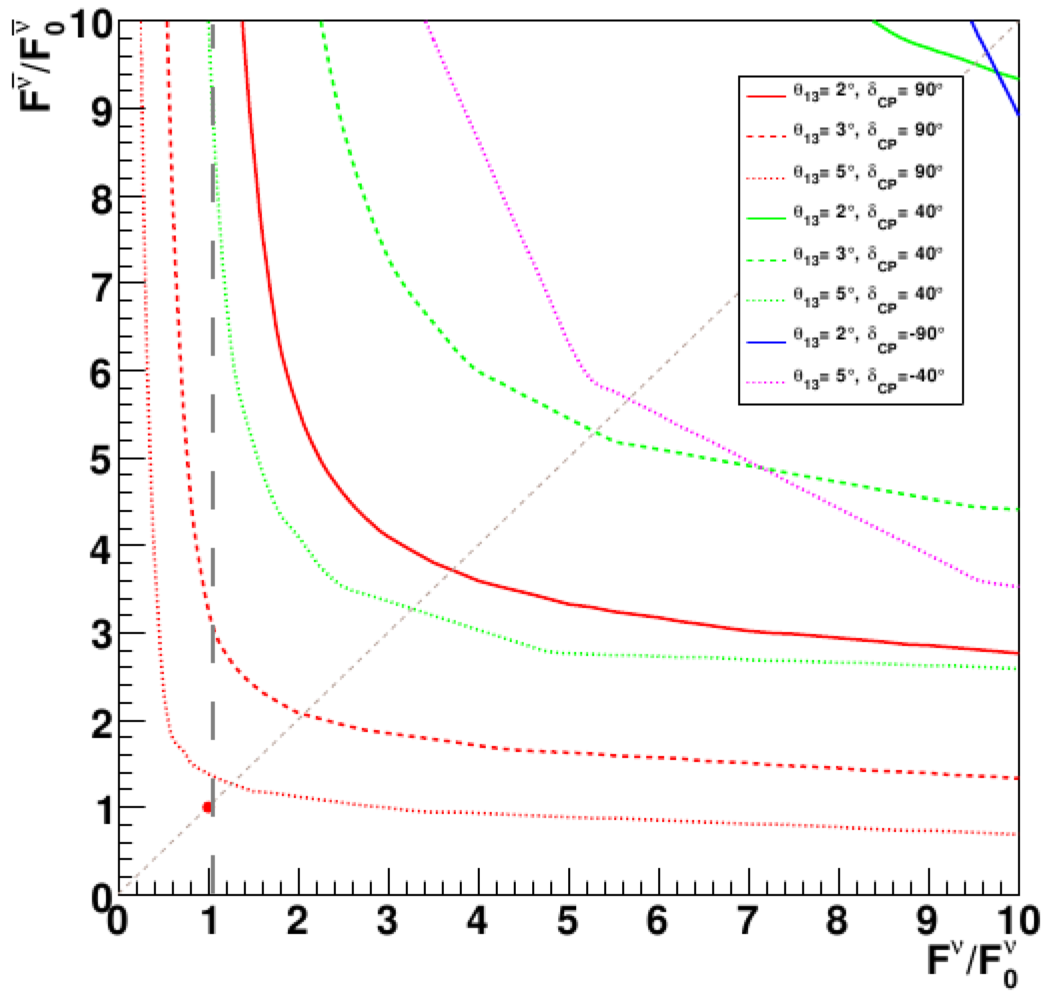
Even with maximal CP violation ($|\delta_{CP}| = 90°$) and $\theta_{13} = 5°$ the baseline (●) cannot establish CP violation

Maximal CP violation can be established for:

$\theta_{13} = 5°$ if $F^{\bar{\nu}} = 1.4\ F_0$

$\theta_{13} = 3°$ if $F^{\bar{\nu}} = 3\ F_0$

F^{ν} can be fixed to the baseline F_0



Note: for negative deltas, $\theta_{13} = 2°$ is inside the flux window, but $\theta_{13} = 3°$ not: this is due to the "π-transit" effect

Sensitivity to the CP-violating phase

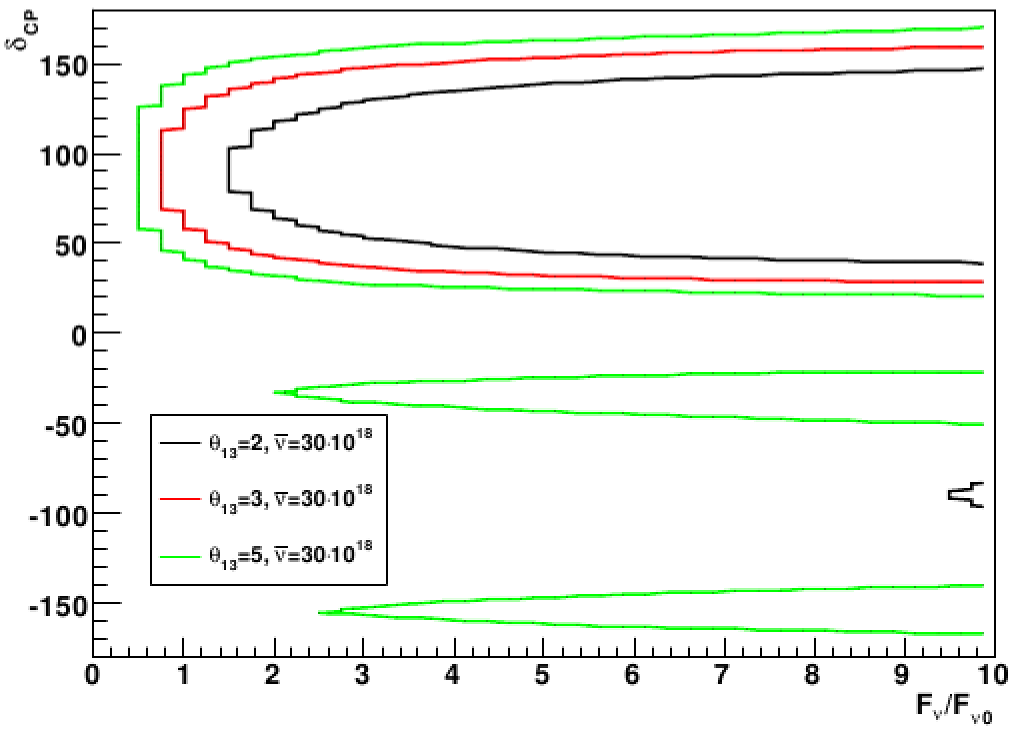
as a function of neutrino flux and δ_{CP}

and for several θ_{13} values

$\theta_{13} = 2°, 3°, 5°$

Anti-neutrino flux is fixed to $F^{\bar{\nu}} = 10\ F_0$

CP-discovering quite poor for $\delta_{CP} < 0$



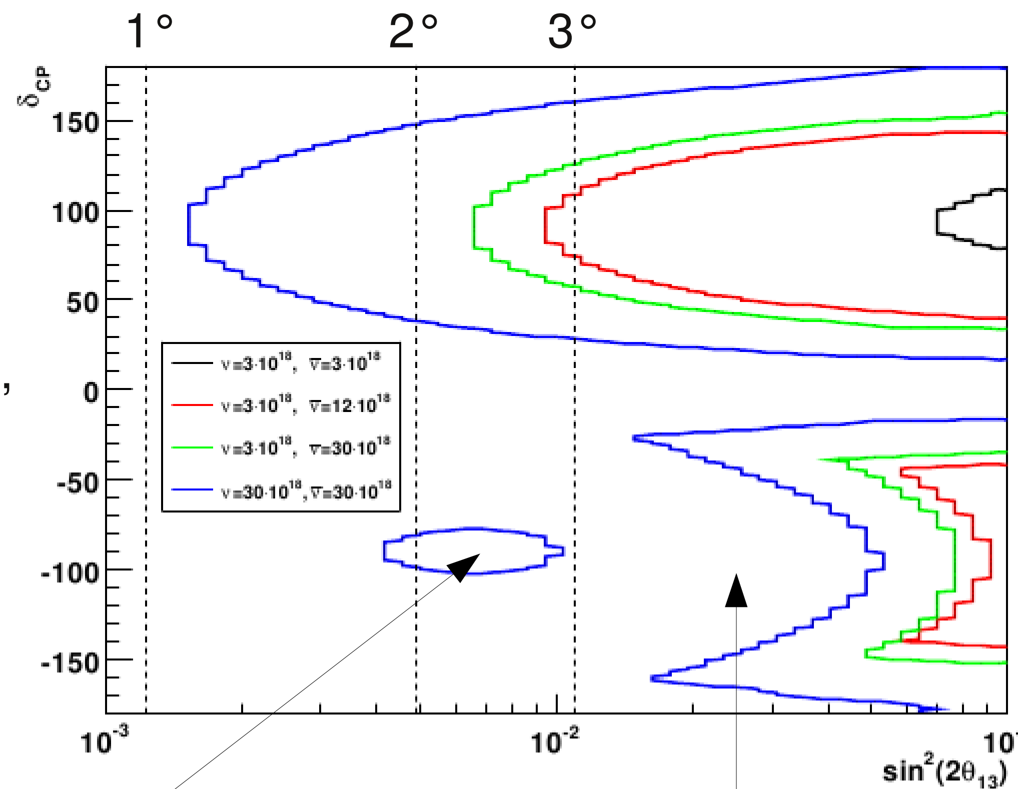
Sensitivity to the CP-violating phase

as a function of θ_{13},δ_{CP} values

and for several fluxes combinations

1) baseline
2) $\overline{\nu}$ flux increased by 4: great improvement
3) $\overline{\nu}$ flux further increased ($10F_0$): poor improvement
4) ν flux increased by 10: great improvement

After increasing anti-neutrino flux by a factor ~4, we cannot improve so much unless we don't increase neutrino flux as well



With $F^{\overline{\nu}}$ = 3 x 10^{19}, F^{ν} = 6 x 10^{18} and if θ_{13} > 3°, then a δ_{CP}>0 can be measured in 60% of the parameter space

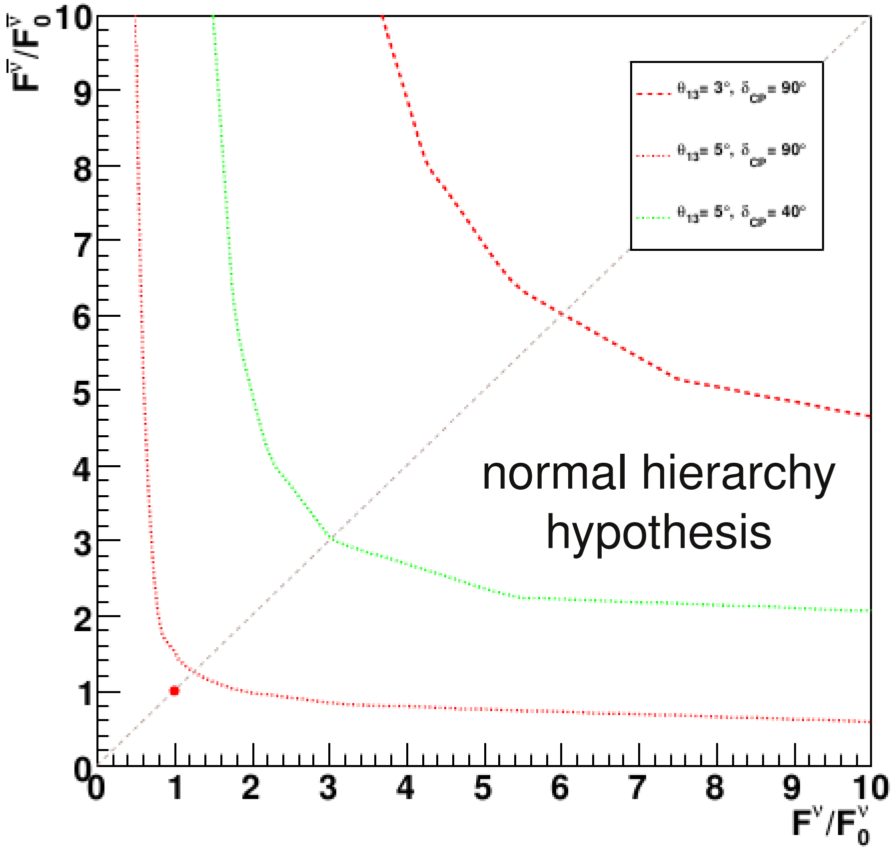
CP-violation sensitivity reappears at smaller θ_{13} values

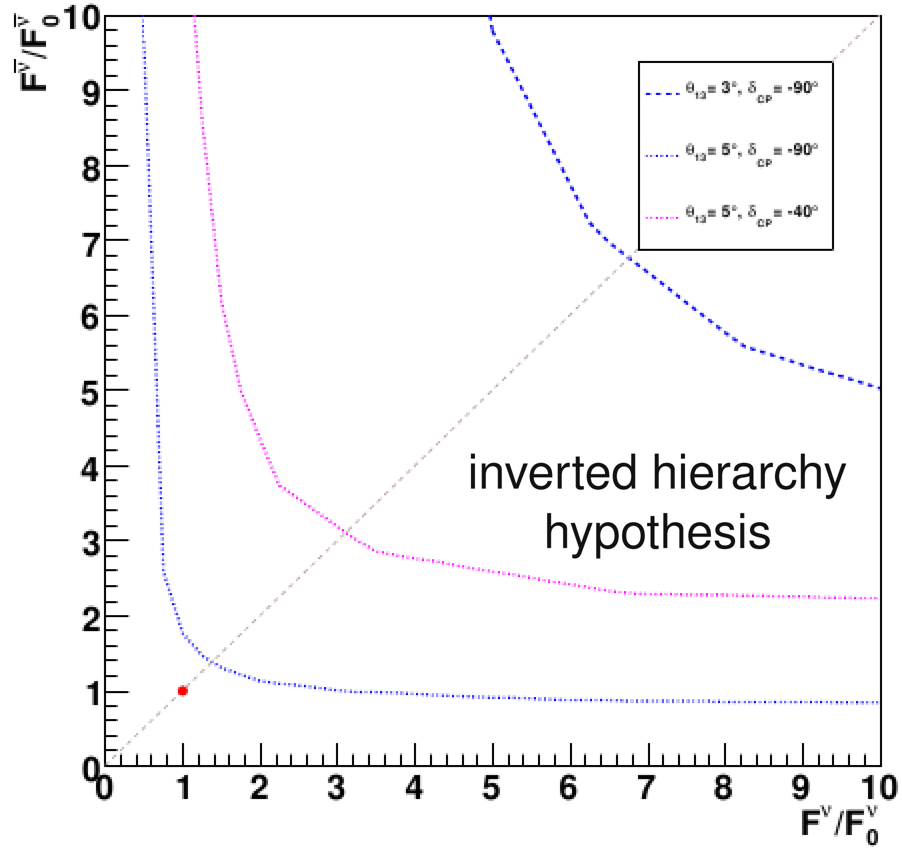
"π-transit" effect: sign clones moves to a CP-conserving region of δ space

Sensitivity to the neutrino mass hierarchy

as a function of flux intensities

and for several δ_{CP},θ_{13} scenarios





Sensitive to the mass hierarchy if:

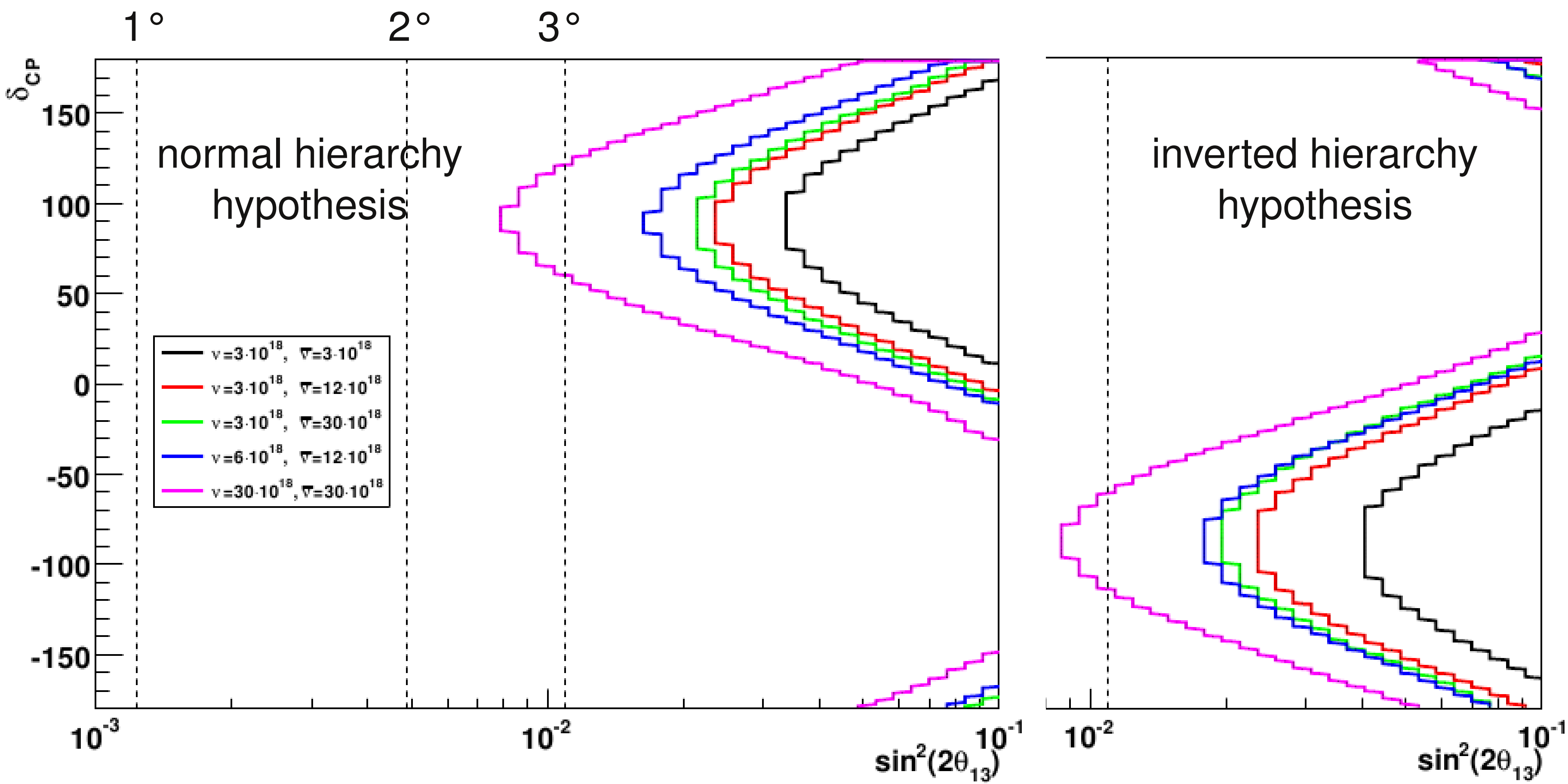
$\theta_{13} > 5°$, $\delta_{CP} = 90°$ (normal hierarchy) or -90° (inverted hierarchy)

with fluxes $F^{\bar{\nu}} = 1.5\ F_0$ and $F^{\nu} = F_0$

Sensitivity to the neutrino mass hierarchy

as a function of θ_{13},δ_{CP} values

and for several fluxes combinations



Matter effect not dominant: sensitivity only in small part of the parameter space.
Opposite sgn(Δm^2_{23}) determines an opposite sensitivity of sgn(δ_{CP})

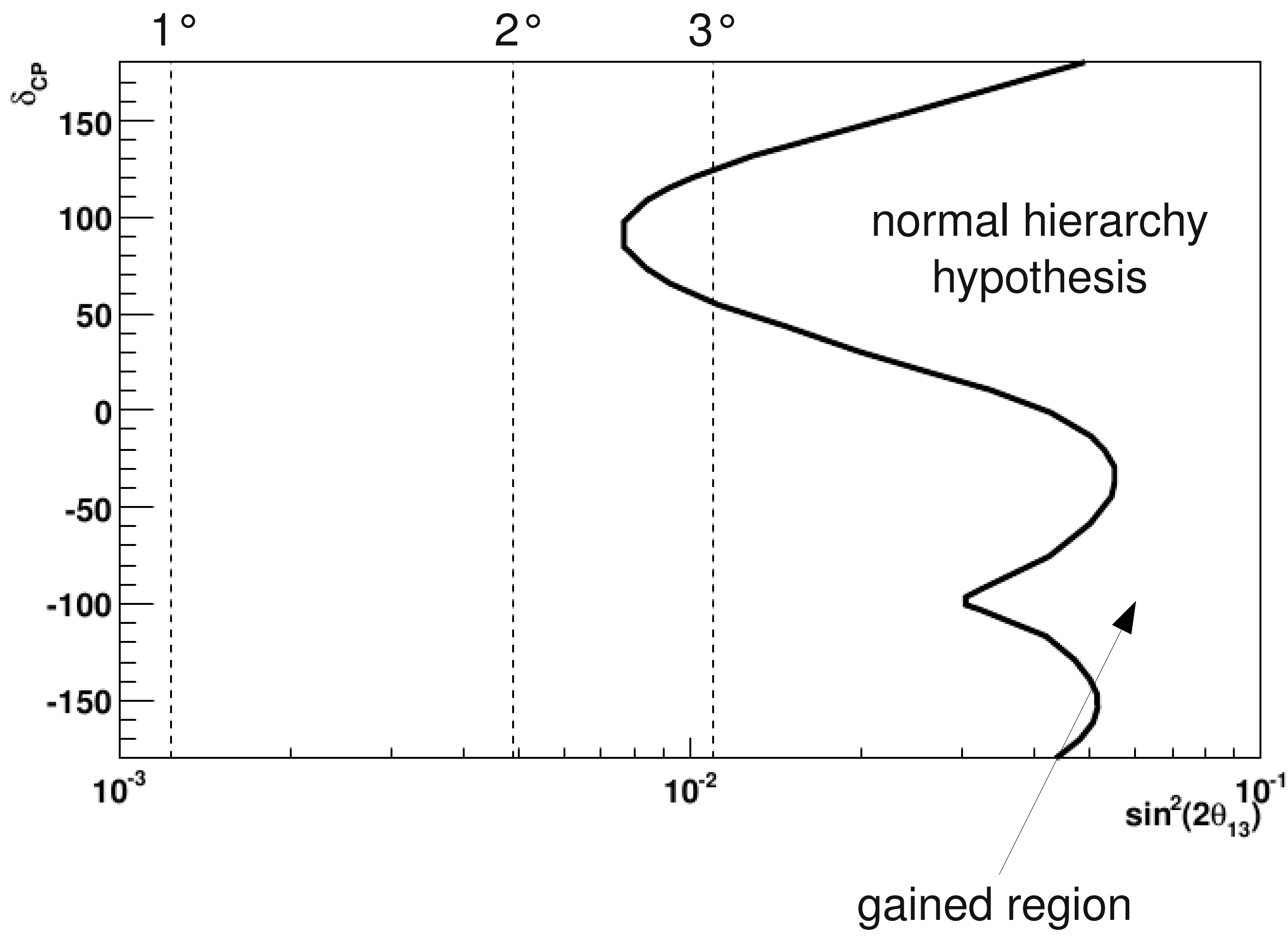
Sensitivity to the neutrino mass hierarchy

With a **magnetized iron detector**, a combined analysis between **Beta beam** and **atmospheric neutrinos** can improve the sensitivity on the mass hierarchy (as noted in *A. Donini et al., Eur. Phys. J. C 53 (2008) 599*)

With the present setup and with:

$F^{\bar{\nu}} = F^{\nu} = 10\ F_0$

we gain sensitivity also at $\delta_{CP} < 0$ starting from $\sin^2(2\theta_{13}) \sim 3 \times 10^{-2}$



Conclusions

In the present work (*P. Coloma, A. Donini, P. Migliozzi, L. Scotto Lavina, F. Terranova, arXiv:1004.3773v2 [hep-ph]*), we consider a **Beta beam** setup which leverages at most present European infrastructures.

It is based on PS2 upgrade, SPS accelerator and uses high-Q ions with γ = 100. Neutrinos are sent toward Gran Sasso laboratories. The far detector is an iron detector of 100 kton mass.

A flux of $6\text{x}10^{18}$ ^{8}B (still challenging) and $3\text{x}10^{19}$ ^{8}Li (feasible) useful decays per year are needed to:

- observe **CP violation** in a large fraction of the parameter space (60%), if $\theta_{13} > 3°$. The θ_{13} range is the one where T2K can give positive signal. The sensitivity is deteriorated at $\delta_{CP} < 0$ because of the "π-transit" effect

- be sensitive to the **neutrino mass hierarchy** up to $\theta_{13} \sim 4°$, for positive (negative) δ_{CP} values for normal (inverted) hierarchy. In the non-sensitive parameter area, a **combination with atmospheric data** collected during the Beta beam run by the same magnetized detector further improves such a sensitivity to $\theta_{13} \sim 6°$

Of course, reaching such a fluxes is the most challenging task