A minimal Beta Beam with high-Q ions to address CP violation in the leptonic sector

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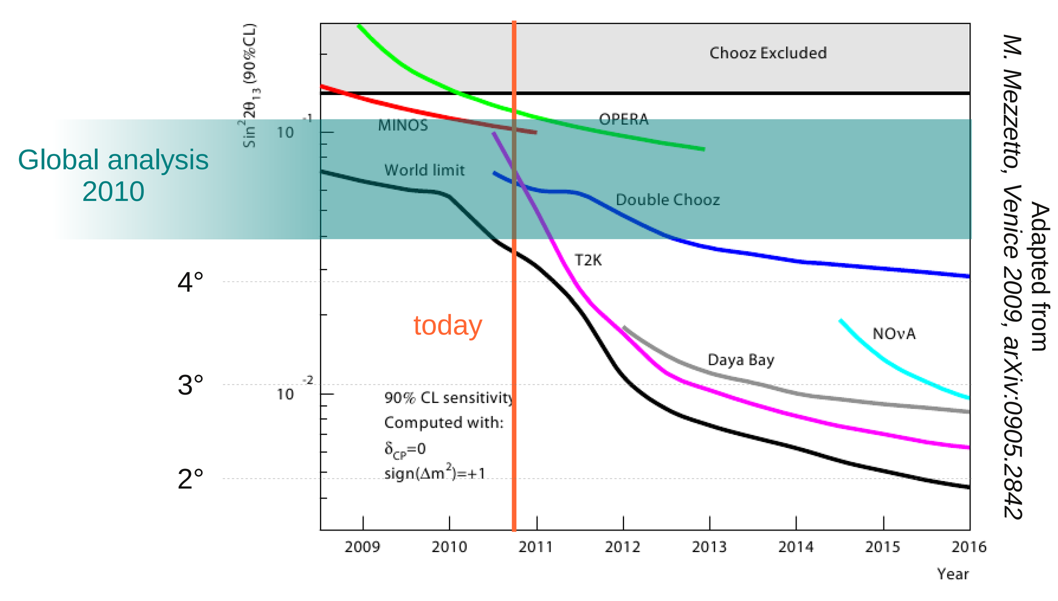
We consider a Beta Beam setup that tries to leverage at most existing European facilities: i.e. a setup that takes advantage of facilities at CERN to boost high-Q ions (^{8}Li and ^{8}B) aiming at a far detector located at L = 732 Km in the Gran Sasso Underground Laboratory. The average neutrino energy for ^{8}Li and ^{8}B ions boosted at $\gamma \sim 100$ is in the range $E_\nu \in [1, 2]$ GeV, high enough to use a large iron detector of the MINOS type at the far site. We perform, then, a study of the neutrino and antineutrino fluxes needed to measure a CP-violating phase δ in a significant part of the parameter space. In particular, for $\theta_{13} \geq 3°$, if an antineutrino flux of 3×10^{19} useful ^{8}Li decays per year is achievable, we find that δ can be measured in 60% of the parameter space with 3×10^{18} useful ^{8}B decays per year.

Status of θ_{13} search



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

Possible beta beam designs

Original design: low-Q isotopes

Ion isotope production with ISOL techniques

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

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

Neutrino energy ($\sim\gamma Q$) < 0.5 GeV (^{6}He), < 0.9 GeV (^{18}Ne)

Short baseline
Huge low density detectors
Large underground infrastructures

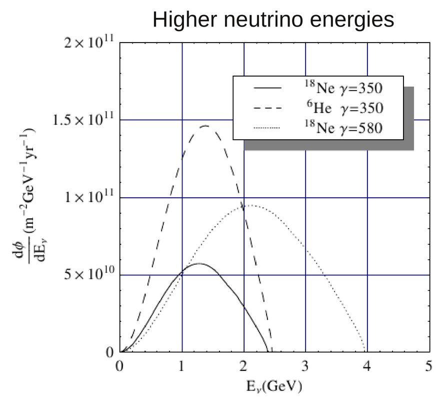
An investigated possible option

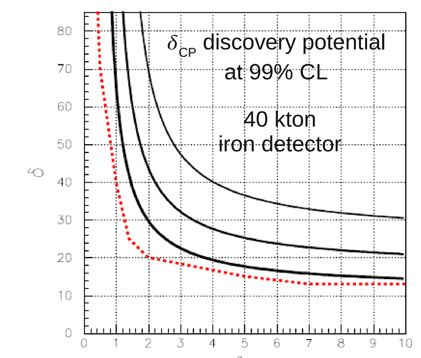
Ion isotope production with ISOL techniques

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

"Super-SPS" as **terminal booster** (1 TeV) γ up to 350

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





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

The high-Q beta beam option

A configuration exploiting at most existing facilities

Isotopes with higher Q like ^{8}Li ($\bar{\nu}_e$) and ^{8}B (ν_e) and γ = 100

Why was this option not considered at the beginning?

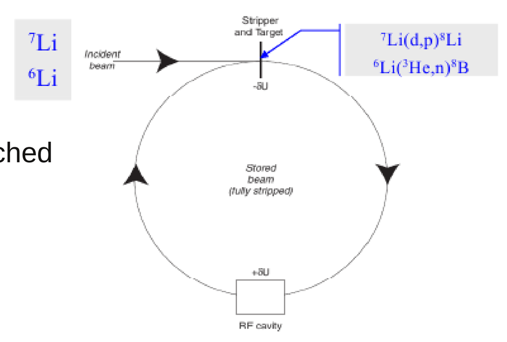
Roughly, the number N of neutrino events is proportional to: $N \simeq \frac{N_\beta(\gamma)\cdot\gamma}{Q}$
(N_β = number of useful ion decays per year)

Clearly, reducing γ and increasing Q is counterproductive

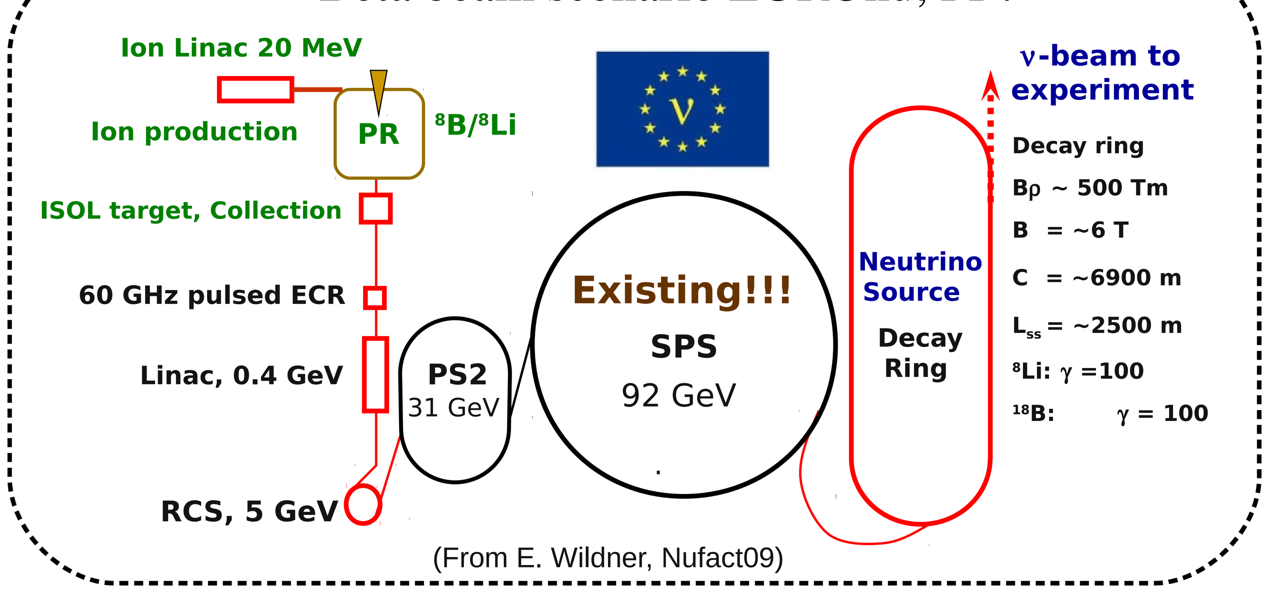
Why is this option now considered?

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)

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

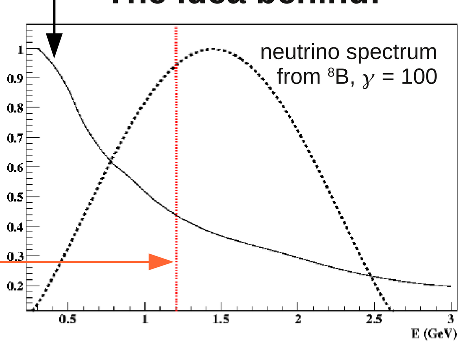
$\sigma_{CC}^{QE}/\sigma_{CC}(E_\nu)$

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

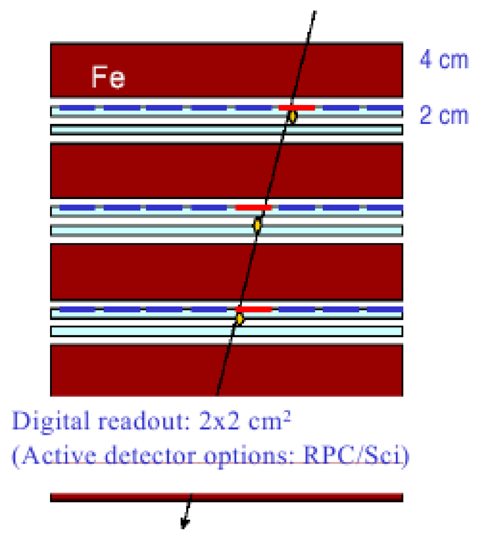
CP discovery potential	as function of	**$\sin^2(2\theta_{13})$, δ_{CP}**
sgn(Δm^2_{23}) reach		**Beam flux intensities**

Considered **baseline** for ^{8}B and ^{8}Li 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)

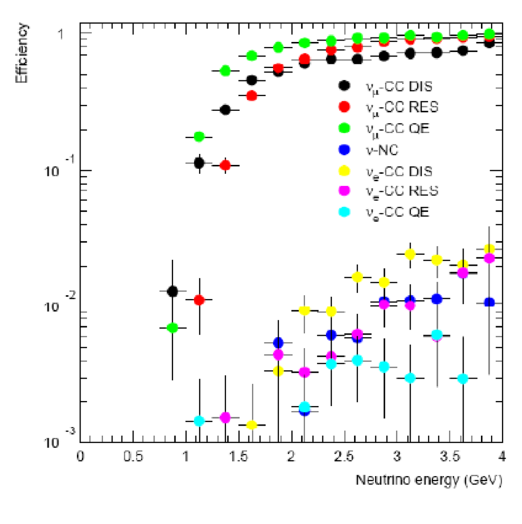
Data taking duration: 5 + 5 years

The detector



Digital readout: 2x2 cm²
(Active detector options: RPC/Sci)

100 kton
iron detector



Sensitivity to the CP-violating phase

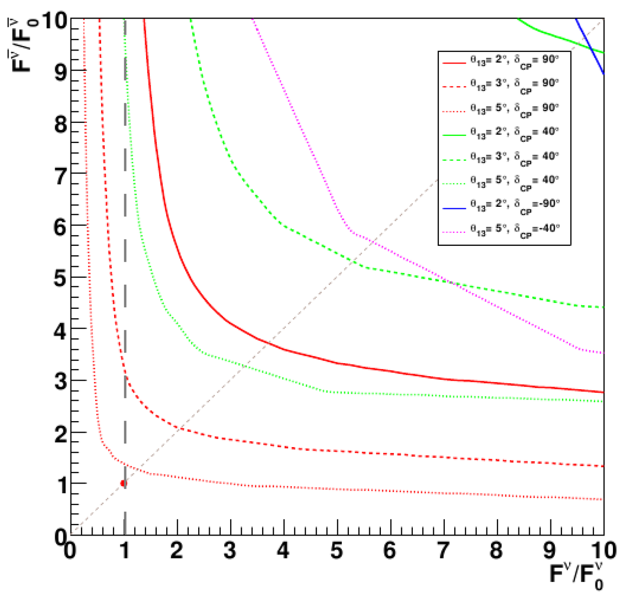
as a function of flux intensities
and for several δ_{CP},θ_{13} scenarios

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

Maximal CP violation can be established for:

θ_{13} = 5° if $F^{\bar{\nu}}$ = 1.4 F_0
θ_{13} = 3° if $F^{\bar{\nu}}$ = 3 F_0

F^ν can be fixed to the baseline F_0



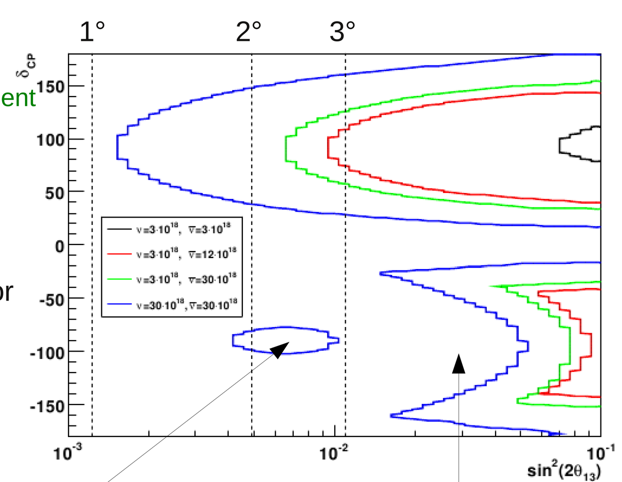
Note: for negative deltas, θ_{13} = 2° is inside the flux window, but θ_{13} = 3° not: this is due to the "π-transit" effect

as a function of θ_{13},δ_{CP} values
and for several fluxes combinations

1) baseline
2) $\bar{\nu}$ flux increased by 4: great improvement
3) $\bar{\nu}$ 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 $F^{\bar{\nu}} = 3 \times 10^{19}$, $F^\nu = 3 \times 10^{18}$ and if θ_{13} > 3°, then a δ_{CP}>0 can be measured in 60% of the parameter space

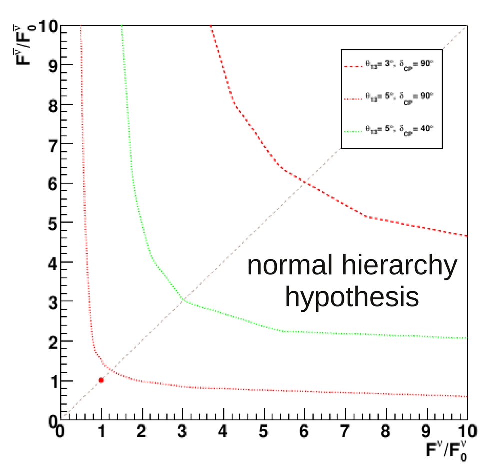


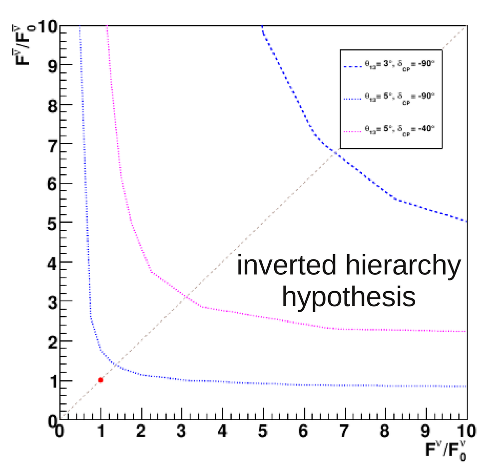
CP-violation sensitivity reappears at smaller θ_{13} values

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

Sensitivity to the neutrino mass hierarchy

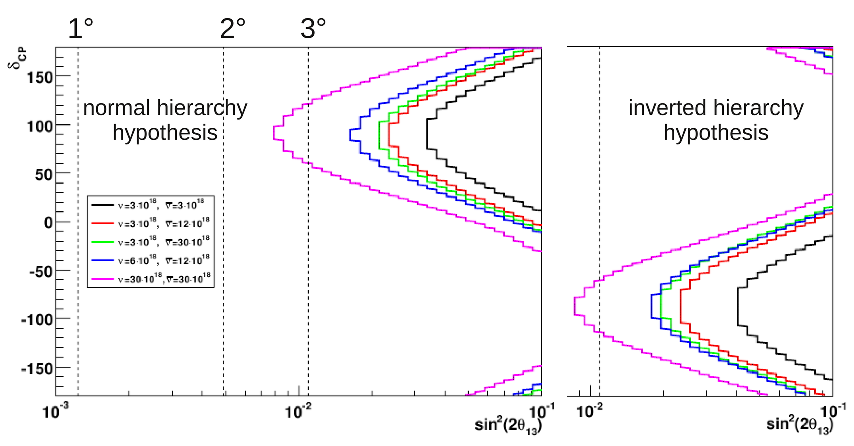
as a function of flux intensities
and for several δ_{CP},θ_{13} scenarios





Sensitive to the mass hierarchy if:
θ_{13} > 5°, δ_{CP} = 90° (normal hierarchy) or -90° (inverted hierarchy)
with fluxes $F^{\bar{\nu}}$ = 1.5 F_0 and F^ν = F_0

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})

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 δ_{CP} < 0 starting from $\sin^2(2\theta_{13}) \sim 3 \times 10^{-2}$