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““Future neutrino oscillation experiments "

- Super Beams
- Beta Beams
- Neutrino Factories
- Comparisons

δm^2_{12} ☑ SOLARS+KAMLAND $\delta m^2_{12} = (7.9 \pm 0.7)\ 10^{-5}\ eV^2$

θ_{12} ☑ SOLARS+KAMLAND $\sin^2(2\theta_{12}) = 0.82 \pm 0.055$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} $_{23}$ ☑ ATMOSPHERICS $\delta m^2 = (2.4 \pm 0.4)\ 10^{-3}\ eV^2$

θ_{23} ☑ ATMOSPHERICS $\sin^2(2\theta_{23}) > 0.95$

θ_{13} ☐ CHOOZ LIMIT $\sin^2 2\theta_{13} < 14^0$

LSND/Steriles ☐

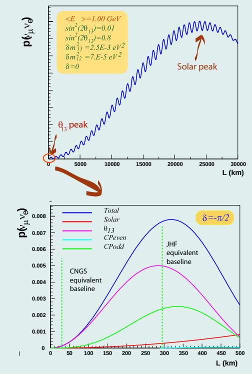
δ_{CP} ☐

Mass hierarchy ☐

Σm_ν ☐ BETA DECAY END POINT $\Sigma m_\nu < 6.6$ eV

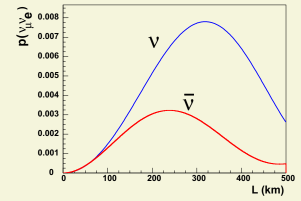
Dirac/Majorana ☐

Sub leading $\nu_\mu - \nu_e$ oscillations



$$
\begin{aligned}
p(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m^2_{13} L}{4E} \times \left[1 \pm \frac{2a}{\Delta m^2_{13}}(1-2s^2_{13})\right] && \theta_{13}\ \text{dri} \\
& + 8c^2_{13} s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m^2_{23} L}{4E} \sin \frac{\Delta m^2_{13} L}{4E} \sin \frac{\Delta m^2_{12} L}{4E} && \text{CPev} \\
& \mp 8c^2_{13} c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m^2_{23} L}{4E} \sin \frac{\Delta m^2_{13} L}{4E} \sin \frac{\Delta m^2_{12} L}{4E} && \text{CPodd} \\
& + 4s^2_{12} c^2_{13} \{ c^2_{13} c^2_{23} + s^2_{12} s^2_{23} s^2_{13} - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta \} \sin \frac{\Delta m^2_{12} L}{4E} && \text{solar driven} \\
& \mp 8c^2_{12} s^2_{13} s^2_{23} \cos \frac{\Delta m^2_{23} L}{4E} \sin \frac{\Delta m^2_{13} L}{4E} \frac{aL}{4E} (1-2s^2_{13}) && \text{matter effect (CP odd)}
\end{aligned}
$$

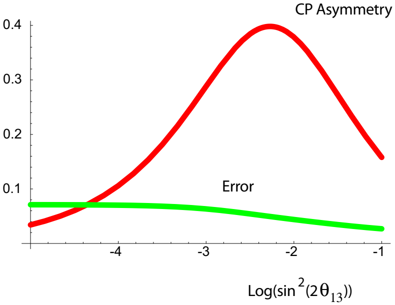
θ_{13} discovery requires a signal ($\propto \sin^2 2\theta_{13}$) greater than the solar driven probability



Leptonic CP discovery requires
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \neq 0$$

Measuring Leptonic CP violation

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$



LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

Measuring Leptonic CP violation

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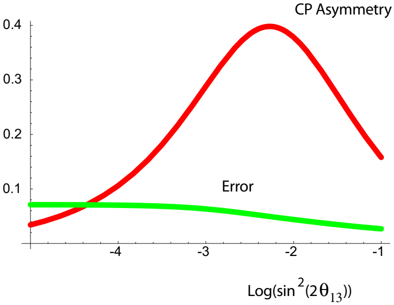

LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) ⇒ "short" Long Baseline experiments**

Measuring Leptonic CP violation

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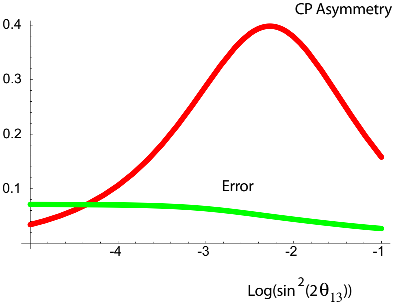
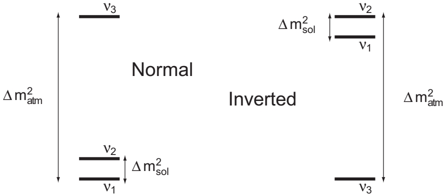


LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) ⇒ ”short“ Long Baseline experiments**
- Statistics and systematics play different roles at different values of $\theta_{13} \Rightarrow$ impossible to optimize the experiment without a prior knowledge of θ_{13}
- Contrary to the common belief, the highest values of θ_{13} are not the easiest condition for LCPV discovery

Measuring mass hierarchy

An internal degree of freedom of neutrino masses is the sign of Δm^2_{31}: $\mathrm{sign}(\Delta m^2_{23})$.



This parameter decides how mass eigenstates are coupled to flavor eigenstates with important consequencies to direct neutrino mass and double beta decay experiments.

Neutrino Oscillations in Matter

$$
\begin{gathered}
P_{\theta_{13}} = \sin^2(2\theta_{13})\sin\theta_{23}{}^2 \sin^2((\hat{A}-1)\hat{\Delta})/(\hat{A}-1)^2; \\
p_{\sin\delta} = \alpha\sin(2\theta_{13})\zeta\sin\delta\sin(L\hat{\Delta})\sin(\hat{A}\hat{\Delta})\sin((1-\hat{A})\hat{\Delta})/((1-\hat{A})\hat{A}); \\
p_{\cos\delta} = \alpha\sin(2\theta_{13})\zeta\cos\delta\cos\hat{\Delta}\sin(\hat{A}\hat{\Delta})\sin(1-\hat{A}\hat{\Delta})/((1-\hat{A})\hat{A}); \\
p_{\mathrm{solar}} = \alpha^2\cos\theta_{23}{}^2\sin^2 2\theta_{12}\sin^2(\hat{A}\hat{\Delta})/\hat{A}^2;
\end{gathered}
$$

$\alpha = \mathrm{Abs}(\Delta m^2_{21}/\Delta m^2_{31})$; $\hat{\Delta} = \frac{L\Delta m^2_{31}}{4E}$ $\zeta = \cos\theta_{13}\ \sin 2\theta_{12}\sin 2\theta_{23}$
$\boldsymbol{\hat{A} = \pm a/\Delta m^2_{31}}$; $a = 7.6\cdot 10^{-5}\rho\cdot E_\nu(GeV)$ $\quad \rho = \text{matter density } (\mathrm{g\,cm^{-3}})$
The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{23})$

Matter effects require long “long baselines"

Neutrino Oscillations in Matter

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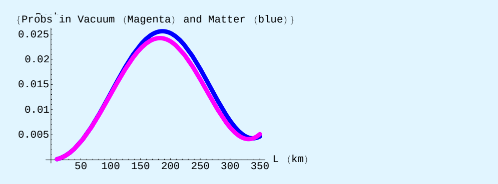
Matter effects require long "long baselines"

$\boldsymbol{E_\nu = 0.35\mathrm{GeV}\ L \simeq 130\ \mathrm{km}}$



Neutrino Oscillations in Matter

$$P_{\theta_{13}} = \sin^2(2\theta_{13})\sin\theta_{23}{}^2\,\sin^2((\hat{A}-1)\hat{\Delta})/(\hat{A}-1)^2;$$
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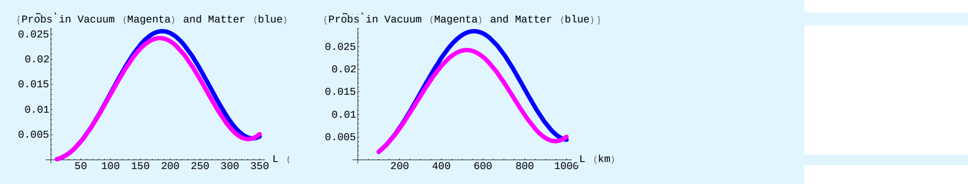
Matter effects require long "long baselines"

$E_\nu = 0.35\mathrm{GeV}$ $L \simeq 130$ km **$E_\nu = 1\mathrm{GeV}$ $L \simeq 500$ km**



Neutrino Oscillations in Matter

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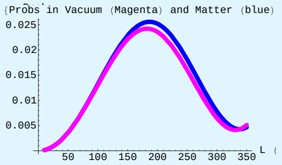
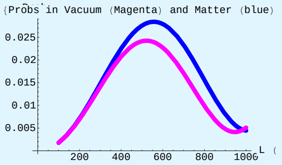
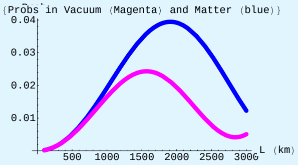
Matter effects require long "long baselines"

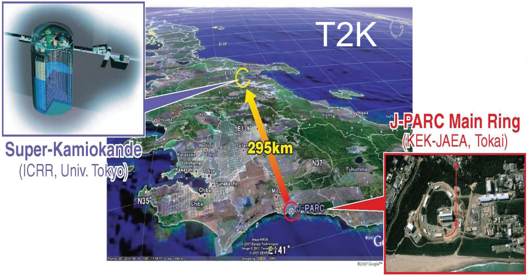
$\boldsymbol{E_\nu = 0.35\mathrm{GeV}\ L \simeq 130\ \mathrm{km}}$ $\boldsymbol{E_\nu = 1\mathrm{GeV}\ L \simeq 500\ \mathrm{km}}$ $\boldsymbol{E_\nu = 3\mathrm{GeV}\ L \simeq 1500\ \mathrm{km}}$

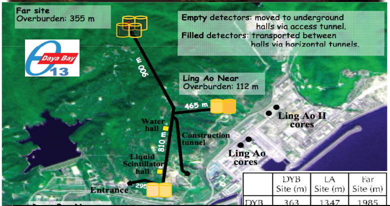






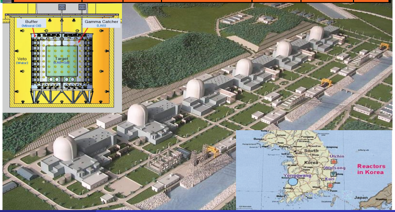
Double Chooz

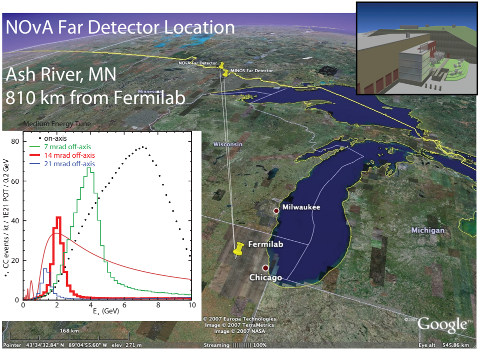




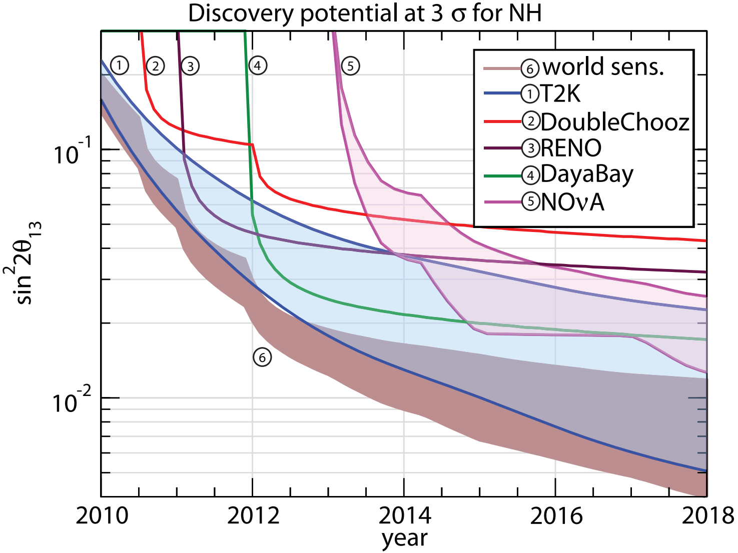
	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985

	Location	Thermal Power	Distances Near/Far (m)	Depth (mwe)	Target Mass (tons)	Cost
RENO	Korea	17.3 GW	290/1380	120/450	16/16 ton	~10M$



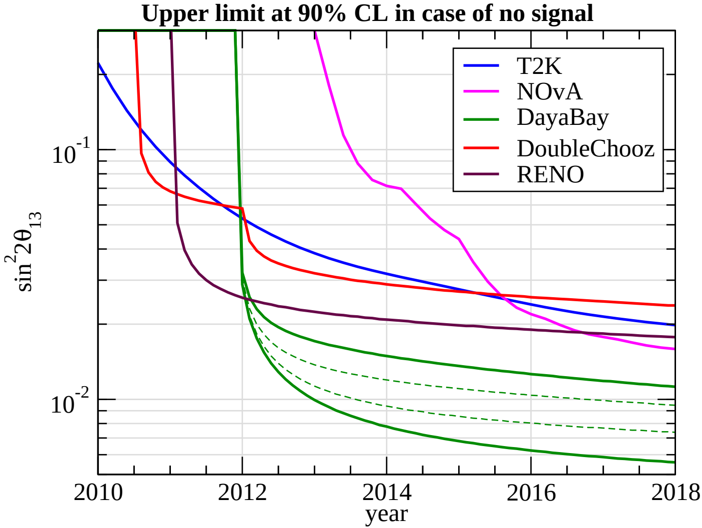


Status after this generation of LBL experiments: θ_{13}


From M.M. and T. Schwetz, arXiv:1003.5800

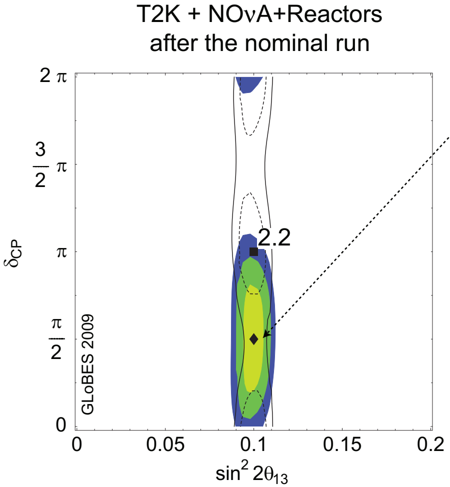
Discovery potential is not sensitivity . . . .

again mrom M.M. and T. Schwetz, arXiv:1003.5800



Status after this generation of LBL experiments: CPV

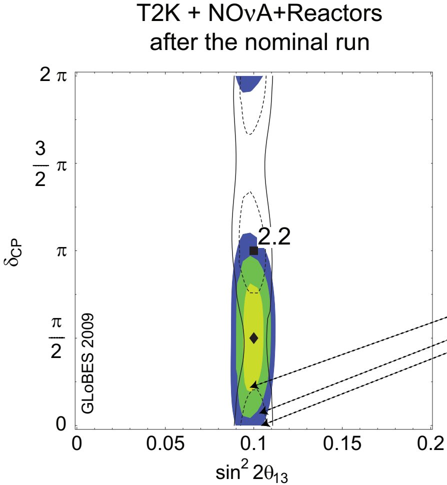
From P. Huber et al., JHEP 0911:044,2009.



1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

Status after this generation of LBL experiments: CPV

From P. Huber et al., JHEP 0911:044,2009.



1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

Status after this generation of LBL experiments: CPV

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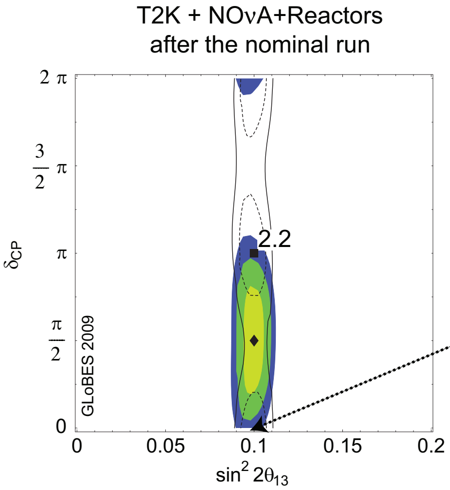


1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

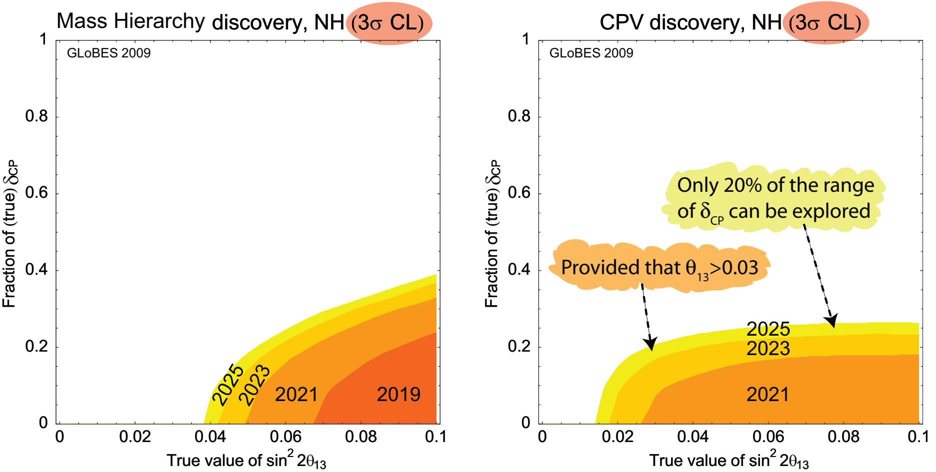
2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

3) Null CP is compatible with data already at 2σ

Status after accelerator upgrades

From P. Huber et al., JHEP 0911:044,2009.

Prediction of sensitivity including a **fully optimized global run** (antineutrinos in T2K and NOνA) and **full upgrade of the accelerators**: 1.6 MW at J-PARC and 2.4 MW at FNAL (Project-X)



Only 20% of the range of δ_{CP} can be explored

Provided that $\theta_{13}>0.03$

Status after accelerator upgrades

From P. Huber et al., JHEP 0911:044,2009.

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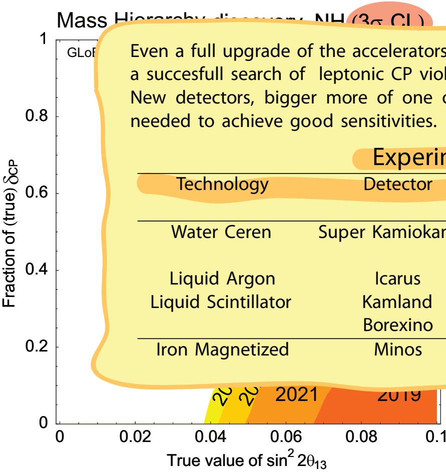

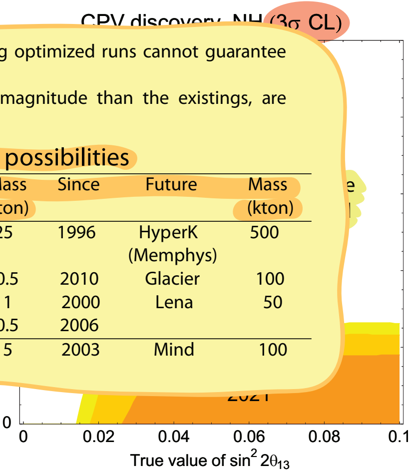

Even a full upgrade of the accelerators and long optimized runs cannot guarantee a succesfull search of leptonic CP violation.

New detectors, bigger more of one order of magnitude than the existings, are needed to achieve good sensitivities.

Experimental possibilities

Technology	Detector	Mass (kton)	Since	Future	Mass (kton)
Water Ceren	Super Kamiokande	25	1996	HyperK (Memphys)	500
Liquid Argon	Icarus	0.5	2010	Glacier	100
Liquid Scintillator	Kamland	1	2000	Lena	50
	Borexino	0.5	2006		
Iron Magnetized	Minos	5	2003	Mind	100

The SuperBeam way

Upgrade existing or future accelerators to several MW power and build WC detectors 10 × Super Kamiokande or 300 × Icarus

- **Japan.**
  J-Parc: 0.75 ⇒ 2 MW + Super Kamiokande ⇒ Hyper Kamiokande (500 kton fiducial: 20 × bigger). Also considered a 100 kton liquid argon detector.
- **USA.**
  FNAL: Project X to a 3 × 100 kton water Cherenkov detectors (or $3-6\times$ 20kton liquid argon) at Dusel, $L\sim 1300$ km.
- **Europe**
  10×CNGS ⇒ off-axis CNGS fired on a 20-100 kton liquid argon detector
  - 4 MW SPL fired on 500 kton water Cherenkov (Memphys) at Frejus at 130 km
  - 2 MW PS2 fired on 100 kton liquid Argon (Glacier) at Phyasalmi (Finland) at 2288 km

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CNGS exists, but cannot be upgraded to the needed intensities

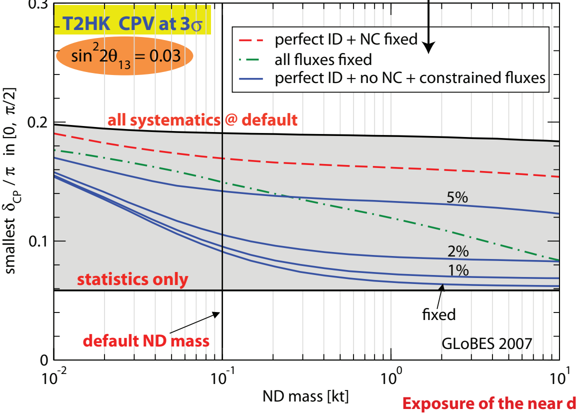
HP-SPL R&D is funded at CERN, PS2 so far not.

Next to statistics: systematic errors

From Huber, MM, Schwetz, JHEP 0803:021,2008

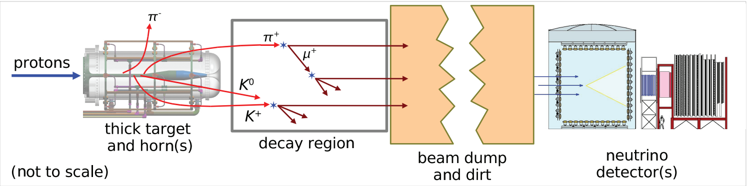
The main limiting factor for future searches of leptonic CP violation will be statistics, next the not perfect knowledge of the neutrino beam fluxes

Some hypothesis about near detector performances and ancillary data by hadroproduction experiments



Exposure of the near detector

Conventional neutrino beams are going to hit their ultimate limitations.



In a **conventional neutrino beam**, neutrinos are produced SECONDARY particle decays (mostly pions and kaons).
Given the short life time of the pions ($2.6 \cdot 10^{-8}$s), they can only be focused (and charge selected) by means of magnetic horns. Then they are let to decay in a decay tunnel, short enough to prevent most of the muon decays.

- Besides the main component (ν_μ) at least 3 other neutrino flavors are present ($\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$), generated by wrong sign pions, kaons and muon decays. $\nu_e$contamination is a background for θ_{13} and δ, $\overline{\nu}_\mu$contamination dilutes any CP asymmetry.
- Hard to predict the details of the neutrino beam starting from the primary proton beam, the problems being on the secondary particle production side.

All these limitations are overcome if secondary particles become primary

Collect, focus and accelerate the neutrino parents at a given energy. This is impossible within the pion lifetime, but can be tempted within the muon lifetime **(Neutrino Factories)** or within some radioactive ion lifetime **(Beta Beams)**:

- Just one flavor in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the γ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by γ.

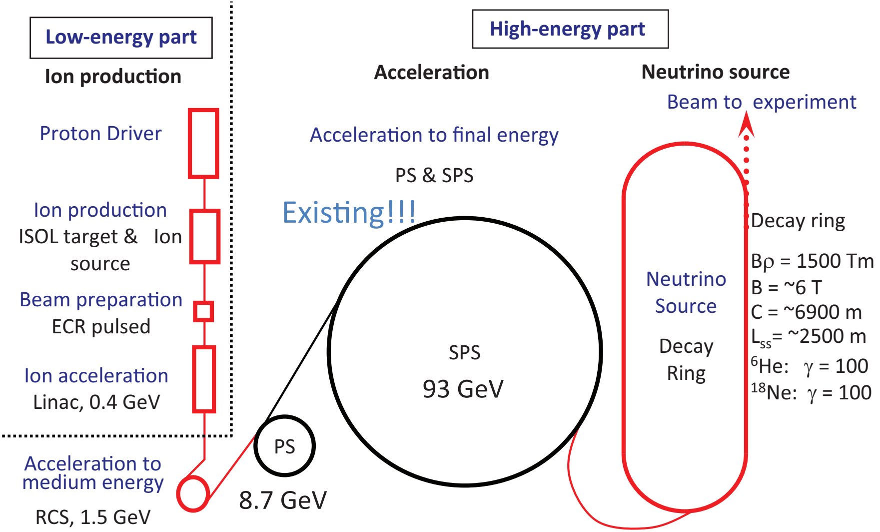
Distinctive features of Beta Beams

. . . for the limitations see tiny notes in the next slides . . .

- Don't need a magnetized detector ⇒ make use of next generation megaton water Cerenkov detectors or 100 kton liquid argons.
- Can re-use part of the CERN accelerator complex (this can be seen as a limitation)
- Synergies with Nuclear Physics (share an intense radioactive ion source), SPL Super Beam (two neutrino beams in the same detector), atmospheric neutrinos (physics case of both beams greatly enhanced by this synergy).
- An evolving concept with several interesting possible upgrades.

Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

M. Lindroos M. Mezzetto, “Beta Beams”, Imperial College Press, 2009



Low-energy part

Ion production

Proton Driver

Ion production
ISOL target & Ion source

Beam preparation
ECR pulsed

Ion acceleration
Linac, 0.4 GeV

Acceleration to medium energy

RCS, 1.5 GeV

High-energy part

Acceleration

Acceleration to final energy

PS & SPS

Existing!!!

PS

8.7 GeV

SPS

93 GeV

Neutrino source

Beam to experiment

Neutrino Source

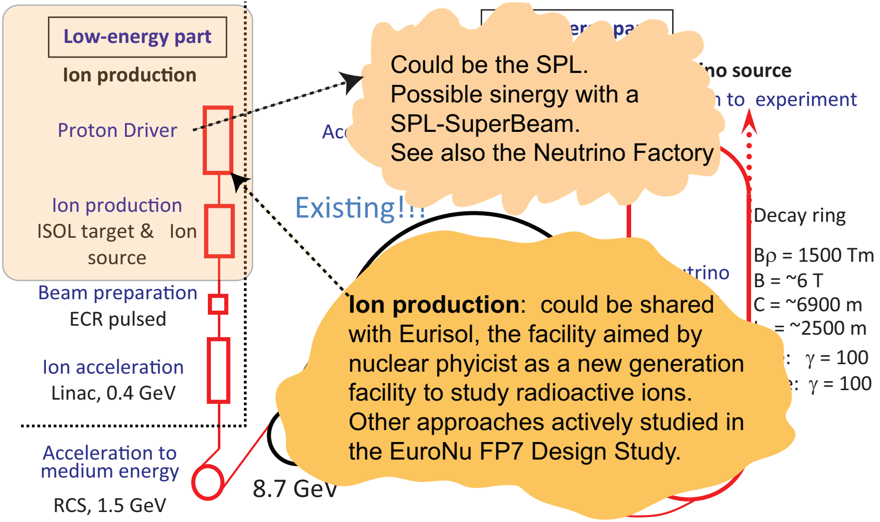
Decay Ring

Decay ring

$B\rho$ = 1500 Tm
B = ~6 T
C = ~6900 m
L_{ss}= ~2500 m
^{6}He: γ = 100
^{18}Ne: γ = 100

Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

M. Lindroos M. Mezzetto, “Beta Beams”, Imperial College Press, 2009



Could be the SPL.
Possible sinergy with a SPL-SuperBeam.
See also the Neutrino Factory

Ion production: could be shared with Eurisol, the facility aimed by nuclear phyicist as a new generation facility to study radioactive ions.
Other approaches actively studied in the EuroNu FP7 Design Study.

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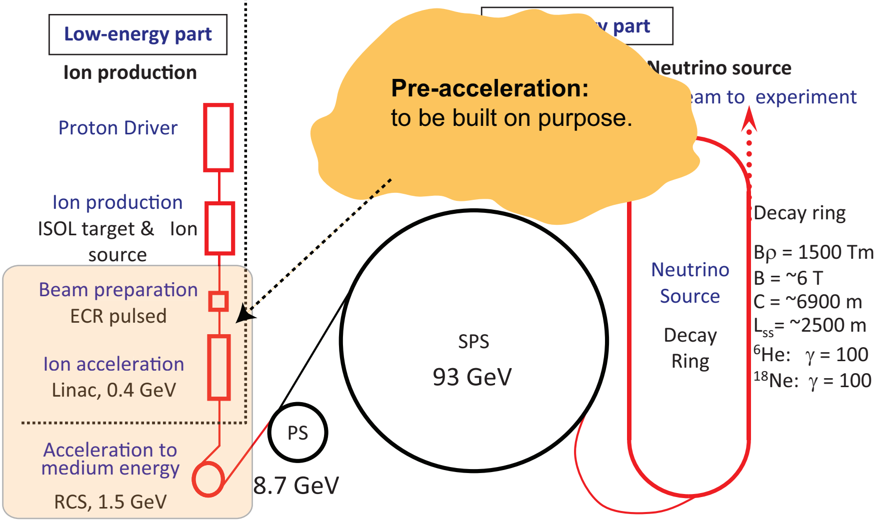

Low-energy part

Ion production

Proton Driver

Ion production

ISOL target & Ion source

Beam preparation

ECR pulsed

Ion acceleration

Linac, 0.4 GeV

Acceleration to medium energy

RCS, 1.5 GeV

Pre-acceleration:
to be built on purpose.

y part

Neutrino source

eam to experiment

Neutrino Source

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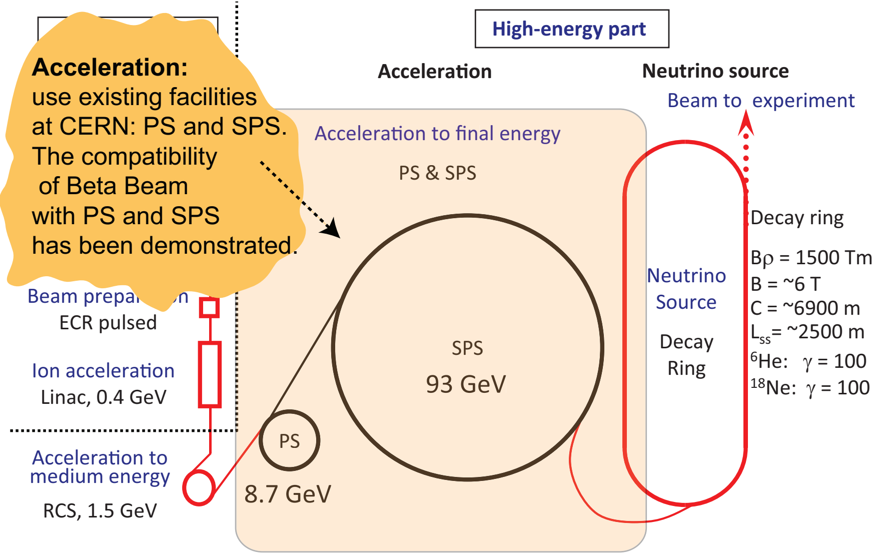

Acceleration:
use existing facilities
at CERN: PS and SPS.
The compatibility
of Beta Beam
with PS and SPS
has been demonstrated.

High-energy part

Acceleration

Neutrino source

Beam to experiment

Acceleration to final energy

PS & SPS

SPS

93 GeV

PS

8.7 GeV

Beam prepa n

ECR pulsed

Ion acceleration

Linac, 0.4 GeV

Acceleration to medium energy

RCS, 1.5 GeV

Neutrino Source

Decay Ring

Decay ring

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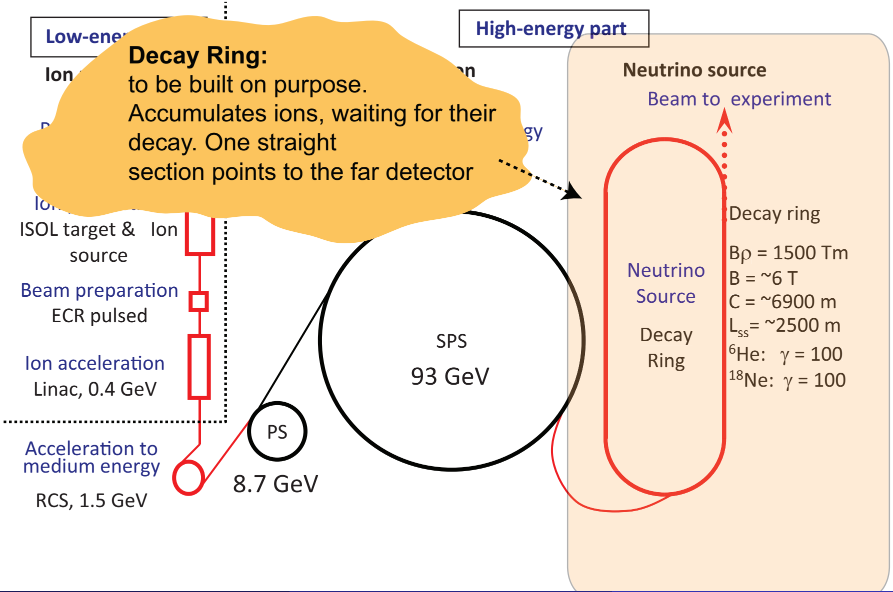

Decay Ring:
to be built on purpose.
Accumulates ions, waiting for their decay. One straight section points to the far detector

Low-ene

Ion

n

High-energy part

gy

Io

ISOL target & Ion source

Beam preparation
ECR pulsed

Ion acceleration
Linac, 0.4 GeV

Acceleration to medium energy
RCS, 1.5 GeV

PS
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SPS
93 GeV

Neutrino source

Beam to experiment

Neutrino Source

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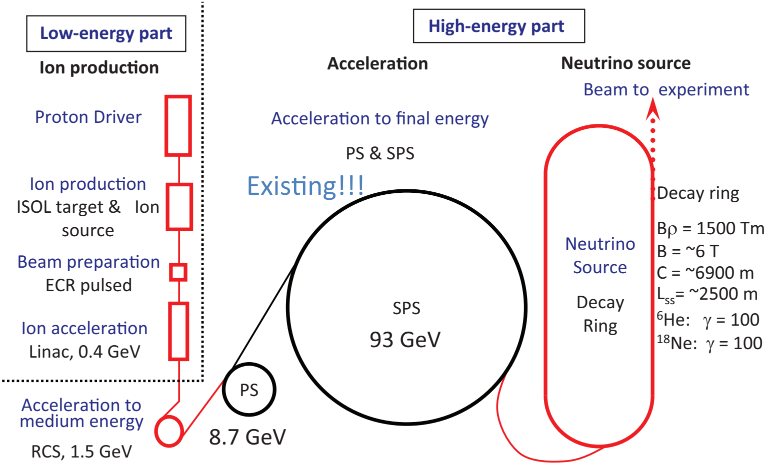


- $\overline{\nu}_e$ generated by He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year.
- ν_e generated by Ne^{18}, 100 μA, $\Rightarrow 1.1 \cdot 10^{18}$ ion decays/straight session/year.

Some scaling laws in Beta Beams

β^+ emitters			β^- emitters		
Ion	$Q_{\rm eff}$ (MeV)	Z/A	Ion	$Q_{\rm eff}$ (MeV)	Z/A
^{18}Ne	3.30	5/9	^{6}He	3.508	1/3
^{8}B	13.92	5/8	^{8}Li	12.96	3/8

- Proton accelerators can accelerate ions up to Z/A × the proton energy.
- Lorentz boost: end point of neutrino energy $\Rightarrow 2\gamma Q$
- In the CM neutrinos are emitted isotropically $\Rightarrow$ neutrino beam from accelerated ions gets more collimated $\propto \gamma^2$
- Merit factor for an experiment at the atmospheric oscillation maximum: $\boxed{\mathcal{M} = \frac{\gamma}{Q}}$
- Ion lifetime must be:
  - As long as possible: to avoid ion decays during acceleration
  - As short as possible: to avoid to accumulate too many ions in the decay ring

$\Rightarrow$ optimal window: lifetimes around 1 s.

- Decay ring length scales $\propto \gamma$, following the magnetic rigidity of the ions.
- Two body decay kinematics : going off-axis the neutrino energy changes (feature used in some ECB setup and in the low energy setup)

Beta Beam baseline scenario

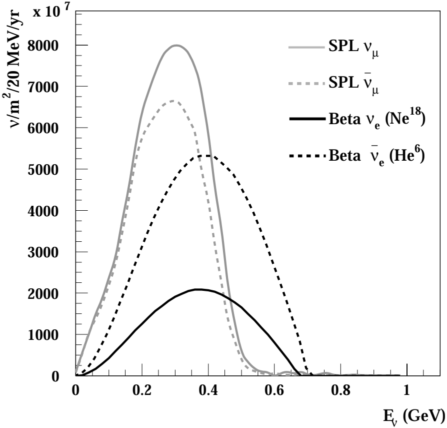
Boundary conditions:

- CERN SPS can accelerate $^{6}\mathrm{He}$ up to $\gamma = 150 \Rightarrow E_\nu \simeq 0.5\,GeV$ $\Rightarrow$ baselines within 300 km.
- The only viable candidate to host a megaton detector is Frejus lab, 130 km away from CERN

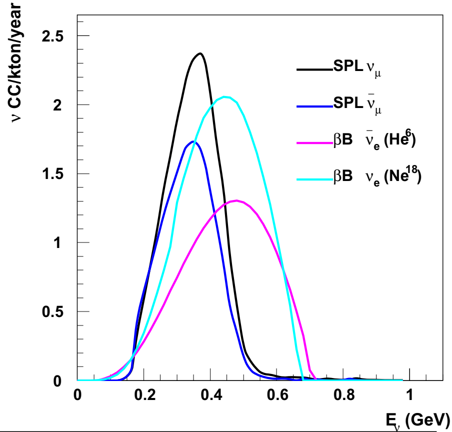
Optimal γ: $\gamma = 100$.

This is the option studied by the Eurisol design study and now by the EuroNu design study

Yearly Fluxes



CC rates, 440 kton/yr



	Fluxes @ 130 km $\nu/m^2/yr$	$\langle E_\nu \rangle$ (GeV)	CC rate (no osc) events/kton/yr	$\langle E_\nu \rangle$ (GeV)	Years	Integrated events (4400 kton/yr)
SPL Super Beam						
ν_μ	$11.80 \cdot 10^{11}$	0.29	121.7	0.36	2	107127
$\overline{\nu}_\mu$	$9.66 \cdot 10^{11}$	0.28	23.1	0.35	8	81164
Beta Beam						
$\overline{\nu}_e(\gamma = 100)$	$10.92 \cdot 10^{11}$	0.40	46.0	0.46	5	101262
$\nu_e(\gamma = 100)$	$4.06 \cdot 10^{11}$	0.38	65.4	0.44	5	143887

Beta Beam sensitivities as computed with Jacques

from: J. Bouchez, M. Lindroos, M.M, AIP Conf. Proc., 2004, 721, hep-ex/0310059

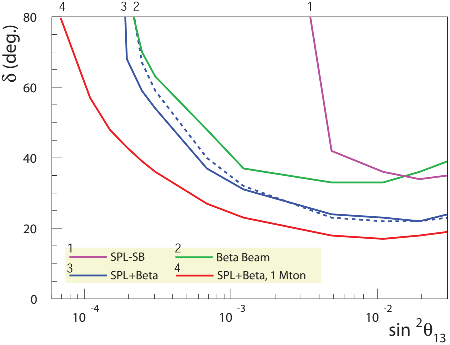
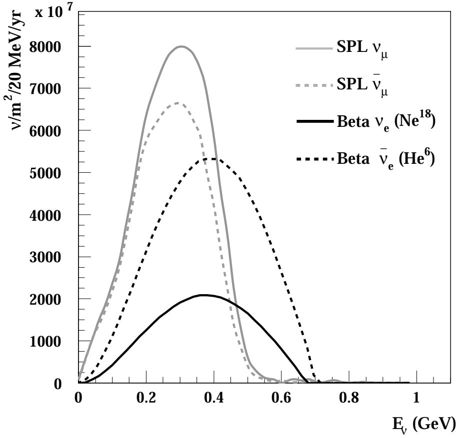


FIGURE 6. δ discovery potential (3σ) as function of θ_{13}. Dotted line are sensitivities computed for sign(Δm^2)=-1

The Beta Beam - SPL Super Beam synergy

MM, Nucl. Phys. Proc. Suppl. **149** (2005) 179.

Yearly Fluxes



A Beta Beam has the same energy spectrum than the SPL SuperBeams and consumes 5% of the SPL protons.

The two beams could be fired to the same detector ⇒ LCPV searches through CP and T channels (with the possibility of using just neutrinos).

Access to CPTV direct searches.

Cross measurement of signal cross section in the close detectors

The synergy with atmospheric neutrinos

P. Huber et al., Phys. Rev. D 71, 053006 (2005): Combining Long Baseline data with atmospheric neutrinos (that come for free in the megaton detector):

- Degeneracies can be canceled, allowing for better performances in θ_{13} and LCPV searches
- The neutrino mass hierarchy can be measured
- The θ_{23} octant can be determined.

The main reasons are:

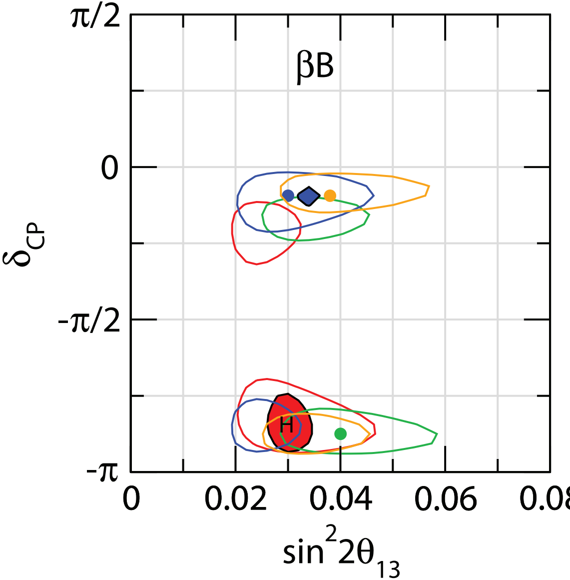
- **Octant** e-like events in the Sub-GeV data is $\propto \cos^2 \theta_{23}$
- **Sign** e-like events in the Multi-GeV data, thanks to matter effects, especially for zenith angles corresponding to neutrino trajectories crossing the mantle and core where a resonantly enhancement occurs.

NOTE: LBL and atmospherics are a true synergy. They add to each other much more that a simple gain in statistics. Atmospherics alone could not measure the hierarchy, the octant, θ_{13} and LCPV. While the Beta Beam at short baselines could not measure the hierarchy as well as the octant.

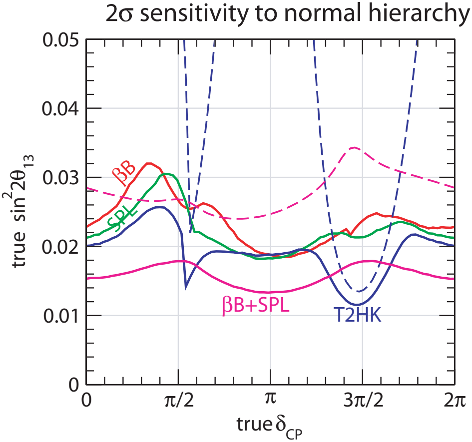
Synergy with atm. neutrinos: degeneracy removal

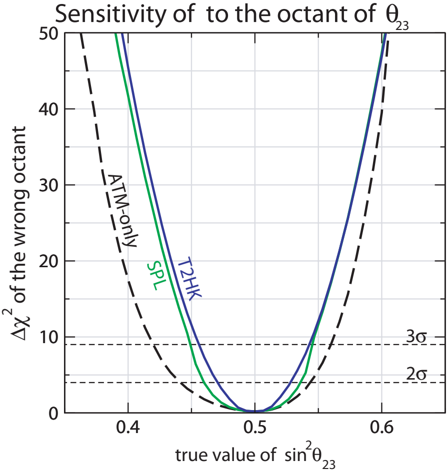
J.E.Campagne, M.Maltoni, M.M., T.Schwetz, JHEP **0704** (2007) 003

The red region is what is left after the atmospheric analysis.
Note how degeneracies were not influencing LCPV sensitivity too much.



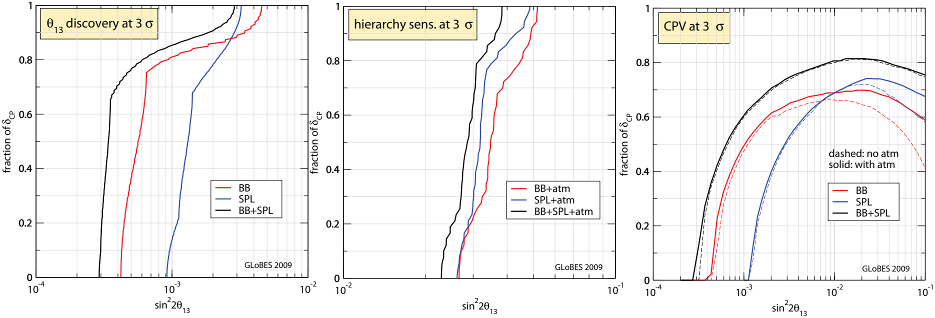
Beta Beam plus atmo: determining mass hierarchy and the octant





Updated sensitivities of SPL, BB and SPL+BB

From J.E.Campagne, M. Maltoni, M.M., T.Schwetz, hep-ph/0603172



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  - The injection ring proposed by C. Rubbia (C. Rubbia et al.,NIM A **568** (2006) 475), now actively studied in the EuroNu WP4 package, could match the ion production, but apparently the PS-SPS chain cannot digest all those ions.

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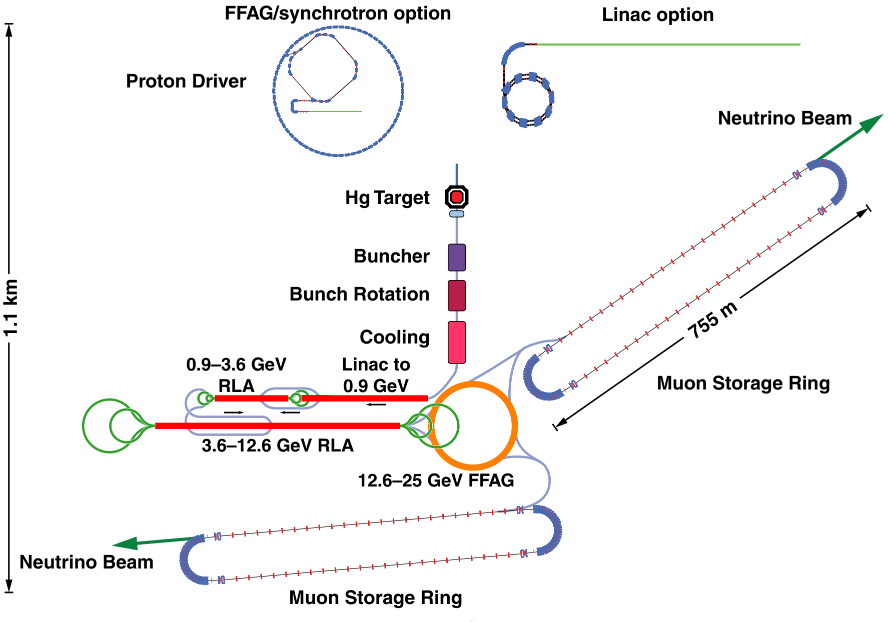
- **Electron capture Beta Beams**: monochromatic neutrino beams, a very attractive option
  - They require long lived, high-A, far from the stability valley ions, r$\Rightarrow$ challenging R&D to match the needed fluxes.

Layout of a Neutrino Factory



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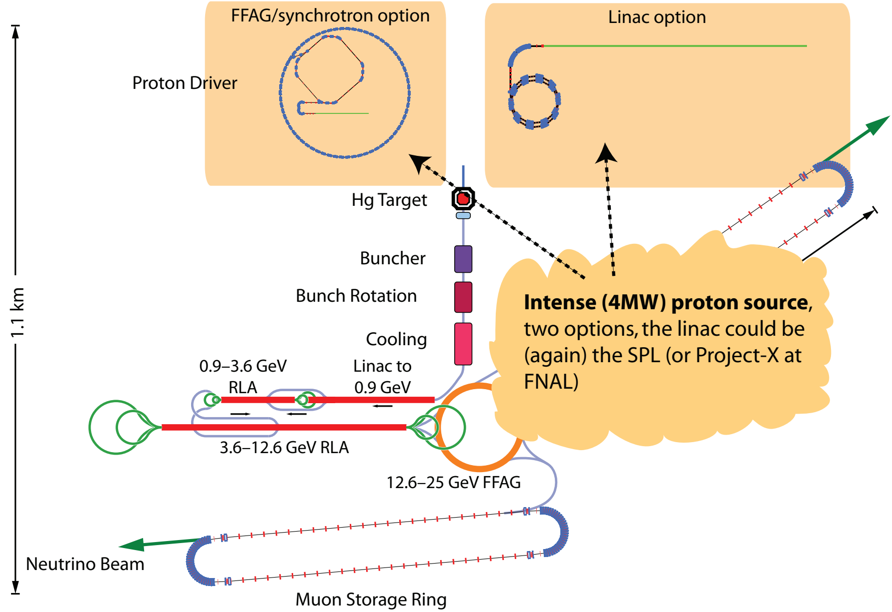

Intense (4MW) proton source, two options, the linac could be (again) the SPL (or Project-X at FNAL)

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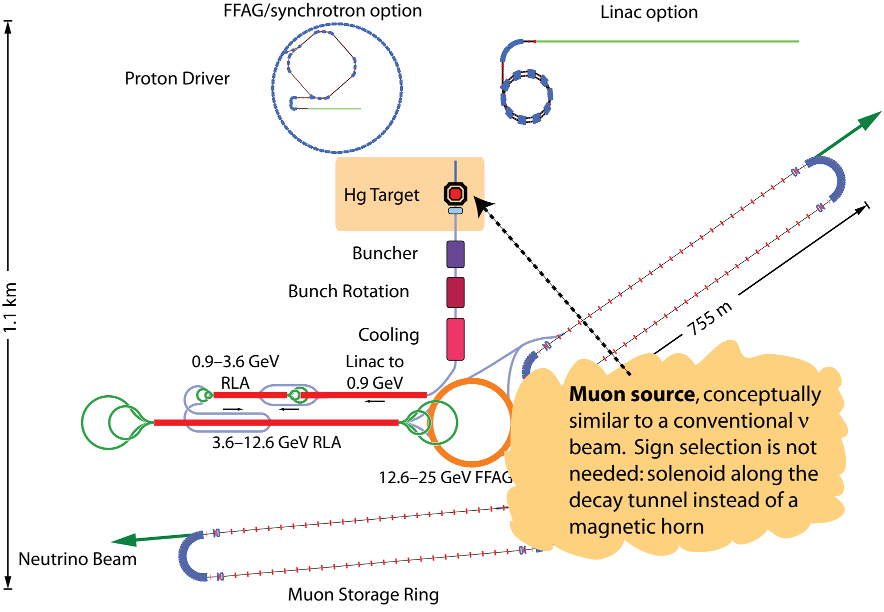
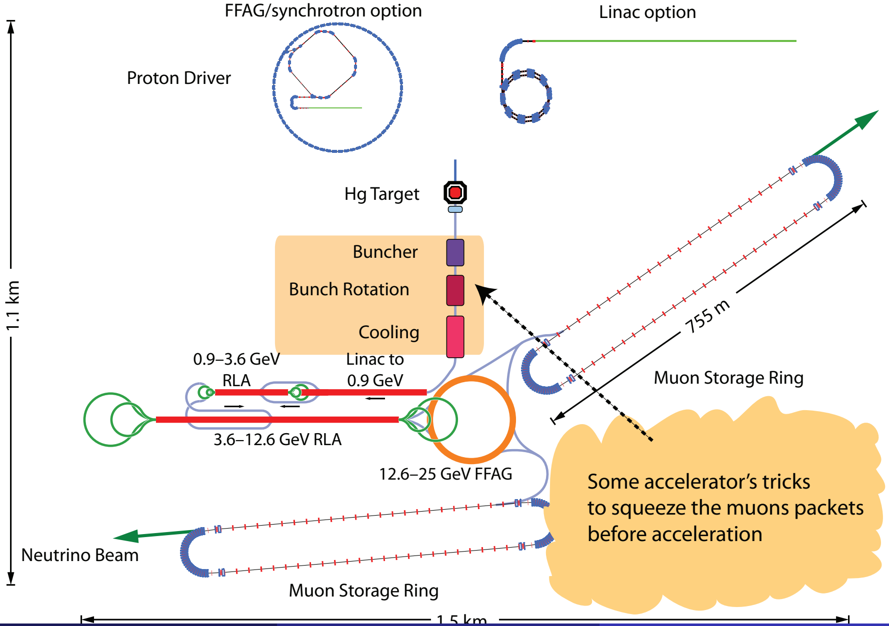


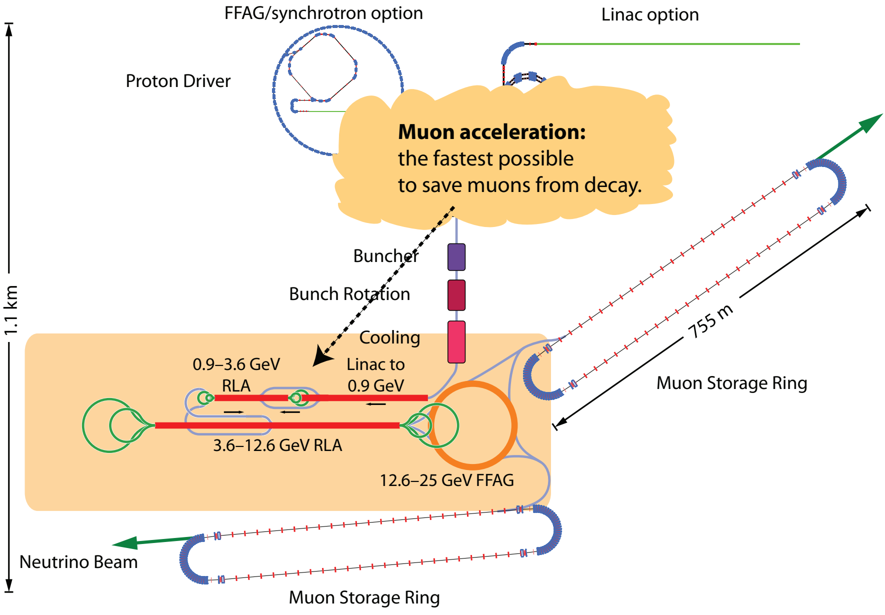
Muon source, conceptually similar to a conventional ν beam. Sign selection is not needed: solenoid along the decay tunnel instead of a magnetic horn

Layout of a Neutrino Factory



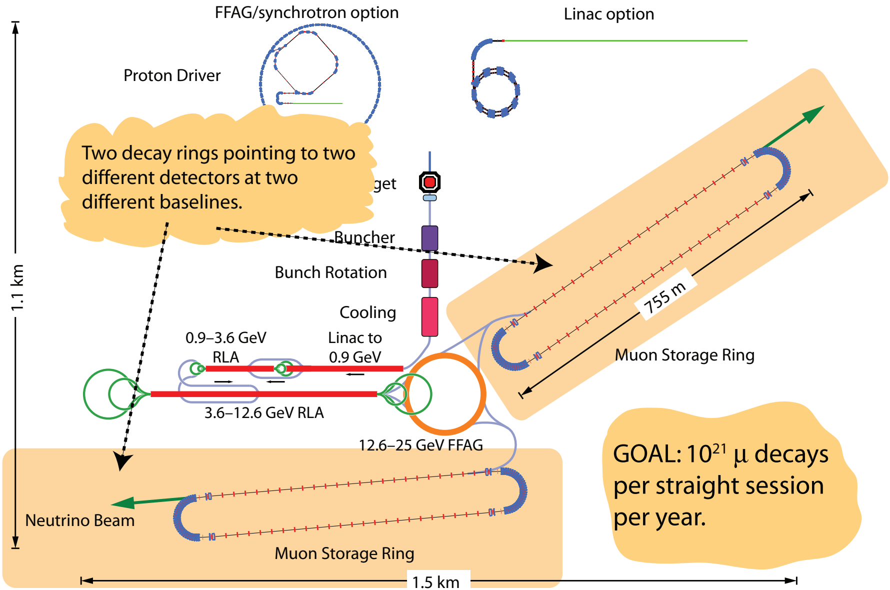
Some accelerator's tricks to squeeze the muons packets before acceleration

Layout of a Neutrino Factory



Muon acceleration:
the fastest possible
to save muons from decay.

Layout of a Neutrino Factory

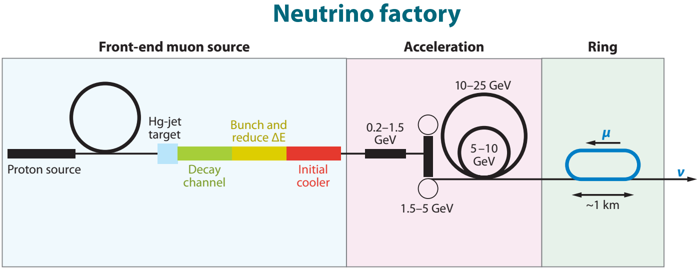


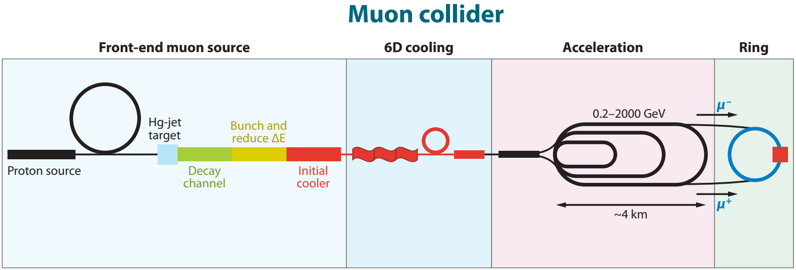
Two decay rings pointing to two different detectors at two different baselines.

GOAL: 10^{21} μ decays per straight session per year.

Neutrino Factory as a first stage of a Muon Collider

From S. Geer, Ann.Rev.Nucl.Part.Sci.59:347-365,2009.





Oscillation signals at the neutrino factory

μ^- (μ^+) decay in (ν_μ, $\overline{\nu}_e$) (($\overline{\nu}_\mu$, ν_e)).

Golden channel: search for $\nu_e \rightarrow \nu_\mu$ ($\overline{\nu}_e \rightarrow \overline{\nu}_\mu$) transitions by detecting wrong sign muons.
Default detector: 40-100 kton iron magnetized calorimeter (Minos like)

Silver channel: search for $\nu_e \rightarrow \nu_\tau$ transitions by detecting ν_τ appearance.
Ideal detectors: 4× Opera or 20 Kton LAr detector.

Sensitivity Comparison

Based to arXiv:1005.3146, the EuroNu midterm physics report

WBB: Fermilab to Dusel, 1 MW for ν running, proton energy: 120 GeV, 2 MW for $\overline{\nu}$ running (5+5 yr), 100 kton liquid argon detector, according to Barger et al, Phys. Rev. D76:053005, 2007 (hep-ph/0703029). This setup is different from the proposed LBNE experiment.

T2KK: J-Parc ν beam running at 4 MW. 270 kton WC detector at Kamioka (295 km) and 270 kton WC detector in Korea (1050 km), Barger et al, Phys. Rev. D76:053005, 2007 (hep-ph/0703029).

PS2-Slanic CERN-PS2 SuperBeam fired to 100 kton LAr detector at Slanic, as computed by A. Rubbia, arXiv:1003.1921.

SPL: Neutrino beam from CERN-SPL running at 3.5 GeV, 4 MW. 440 kton WC detector at Frejus (130 km). Campagne et al. JHEP **0704** (2007) 003 (hep-ph/0603172).

Beta Beam $\gamma = 100$ Eurisol Beta Beam to Frejus (440 kton WC detector). Campagne et al. JHEP **0704** (2007) 003 (hep-ph/0603172).

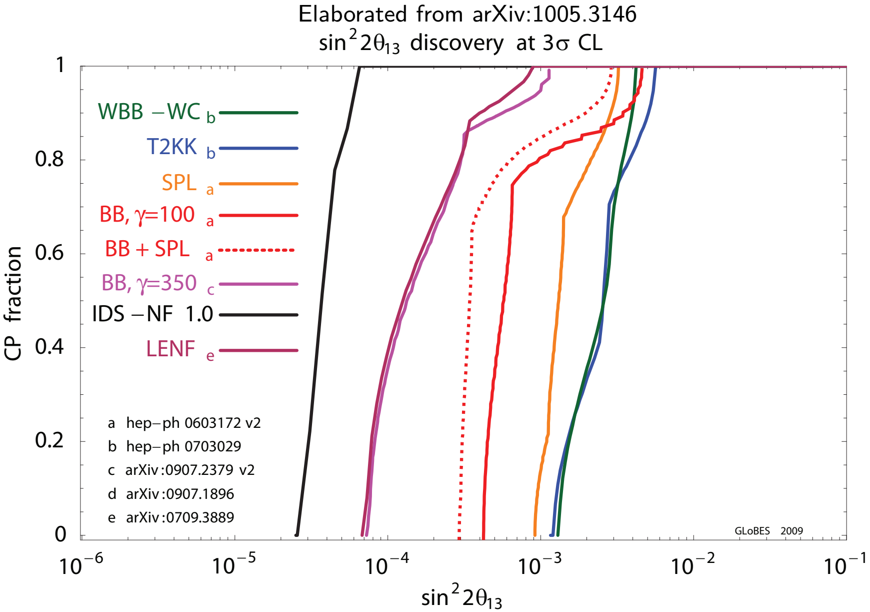
Beta Beam + SPL The combination of the above two.

Beta Beam $\gamma = 350$ Beta Beam at $\gamma = 350$, running $^{6}\mathrm{He}$ and $^{18}\mathrm{Ne}$ at the same decay rates as the Eurosol Beta Beam. WC detector of 500 kton at Canfranc (650 km). S. Choubey et al., JHEP 0912:020,2009 (arXiv:0907.2379)

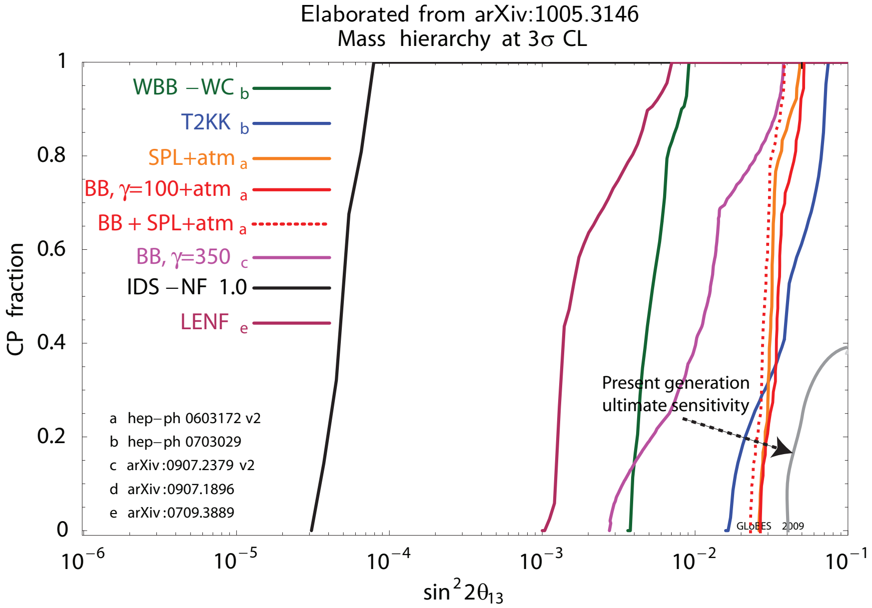
Low Energy Neutrino Factory (LENF) Neutrino Factory running at 4.12 GeV delivering 10^{21} muon decays/year for each sign, 30 kton Noνa like detector, fully magnetized (!) at 1480 km (Fermilab-Henderson mine). A. Bross et al, Phys.Rev.D77:093012,2008. (arXiv:0709.3889)

IDS 1.0 Neutrino Factory 25 GeV neutrino factory delivering $0.5 \cdot 10^{21}$ muon decays/year for each sign, a 50 kton iron magnetized detector and a 10 kton Emulsion Cloud Chamber, at 4000 km and a 50 kton iron magnetized detector at 7500 km.

Sensitivity Comparison: θ_{13}

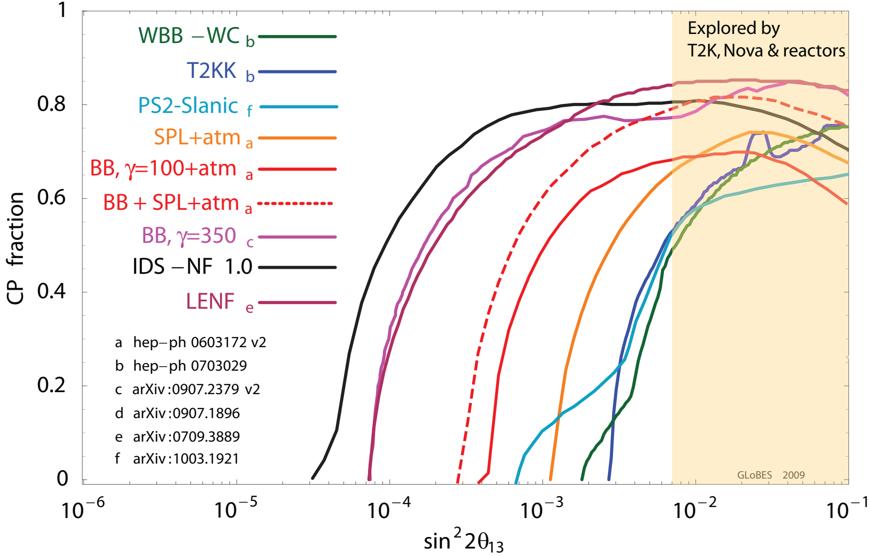


Sensitivity Comparison: $\mathrm{sign}(\Delta m^2_{23})$



Sensitivity Comparison: LCPV

Elaborated from arXiv:1005.3146
CP violation at 3σ CL



Conclusions

- We have several different possible strategies to attack Leptonic CP violation searches.
- Super Beams could reach a 3σ sensitivity in case of moderately large values of θ_{13} . In this case they could be the fastest way to initiate LCPV searches. Not for free.
- Innovative concepts like beta beams and neutrino factories can guarantee higher sensitivities. More important, they can be upgraded to allow for future searches like non-standard neutrino interactions, checks of the unitarity triangle, searches of CPT violation.
- A Beta Beam setup can make use of existing CERN infrastructures like the PS and the SPS. The injector side can be shared with nuclear physicists (Eurisol). The far detector is the same detector aimed for proton decay searches and astrophysics (Laguna). Under this perspective a super beam built around the SPL could offer very interesting synergies.
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- **Most of the developments in this field in Europe happened thanks to the illuminated collaboration of Jacques Bouchez.**