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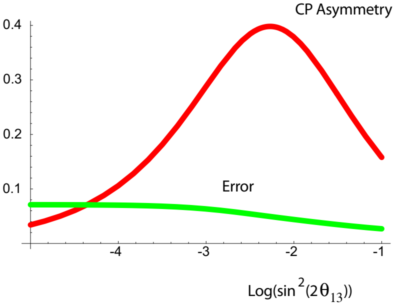
“The case of short long-baselines"

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.

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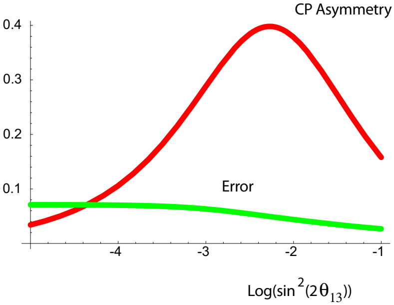

LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

- **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**

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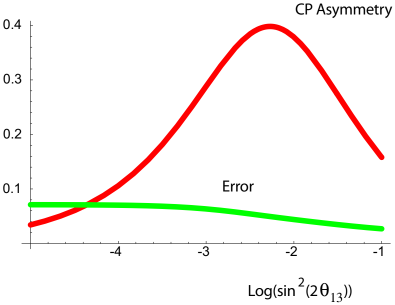

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- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) ⇒ "short" Long Baseline experiments**
- Statistics and systematics play different roles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

Neutrino Oscillations in Matter

$$P_{\theta_{13}} = \sin^2(2\theta_{13})\sin\theta_{23}{}^2 \sin^2((\hat{A}-1)\hat{\Delta})/(\hat{A}-1)^2;$$
$$p_{\sin\delta} = \alpha\sin(2\theta_{13})\zeta\sin\delta\sin(L\hat{\Delta})\sin(\hat{A}\hat{\Delta})\sin((1-\hat{A})\hat{\Delta})/((1-\hat{A})\hat{A});$$
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$\alpha = \mathrm{Abs}(\Delta m^2_{21}/\Delta m^2_{31})$; $\hat{\Delta} = \frac{L\Delta m^2_{31}}{4E}$ $\zeta = \cos\theta_{13}\ \sin 2\theta_{12}\sin 2\theta_{23}$
$\boldsymbol{\hat{A} = \pm a/\Delta m^2_{31}}$; $a = 7.6\cdot 10^{-5}\rho\cdot E_\nu(GeV)$ $\quad\rho = \mathrm{matter\ density}\ (\mathrm{g\,cm^{-3}})$
The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{23})$

Matter effects require long “long baselines"

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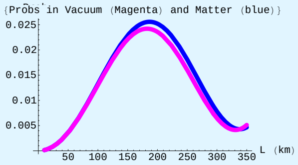
Matter effects require long "long baselines"

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



Neutrino Oscillations in Matter

$$
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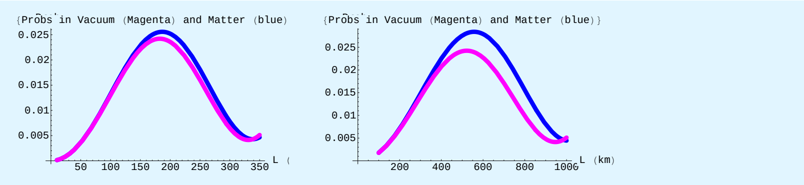
Matter effects require long "long baselines"

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



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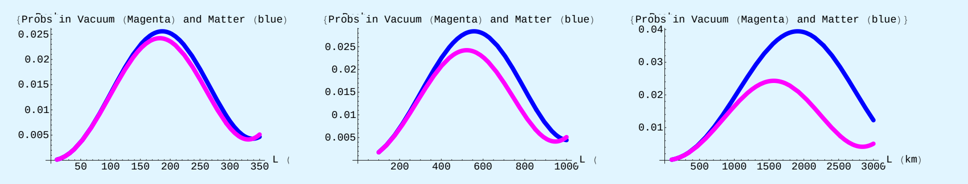
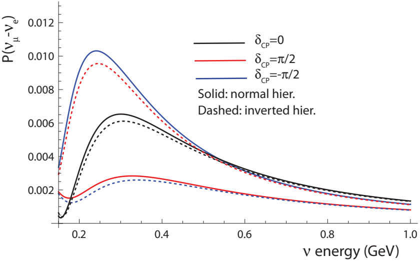
Matter effects require long "long baselines"

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



CPV vs. mass hierarchy

At 130 km matter effects are negligible. Inverse hierarchy solutions are very similar to direct hierarchy (changing sign of $\delta_{\mathrm{CP}}$is equivalent of change of $\mathrm{sign}(\Delta m^2_{23})$sign) $\Rightarrow$ No degeneracies for CP searches but no sensitivity on mass hierarchy.



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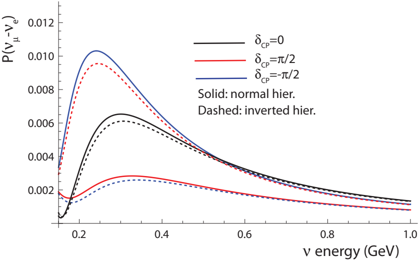
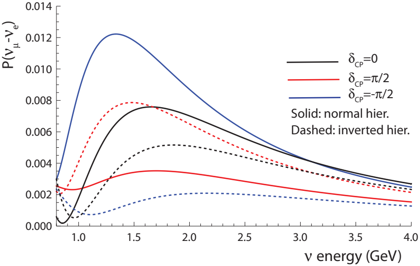


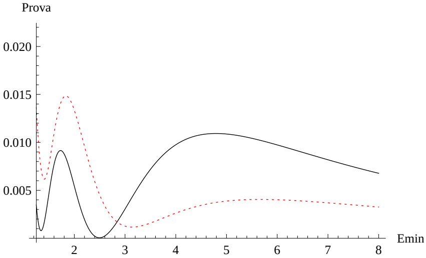
At 730 km matter effects are sizable. Probabilities differ.

Note however as the normal hierarchy $\delta_{\rm CP} = 0$ probability is very similar to inverse hierarchy $\delta_{\rm CP} = \pi/2$, $\Rightarrow$ very difficult to experimentally disentangle the two.



CPV vs. mass hierarchy

At 2500 km the two probabilities are more different and their the second oscillation maximum behaviour is very much different.



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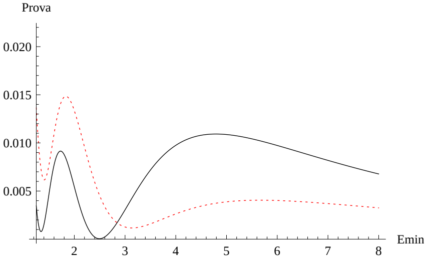
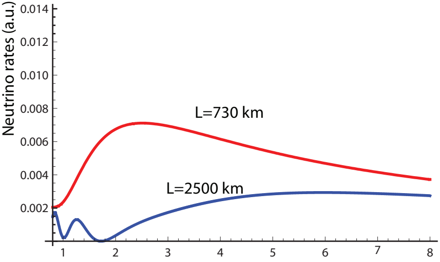
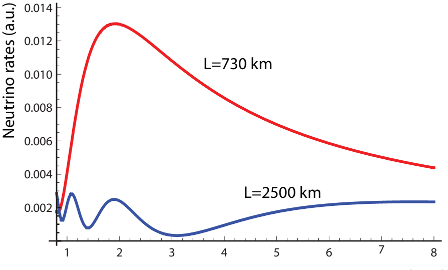


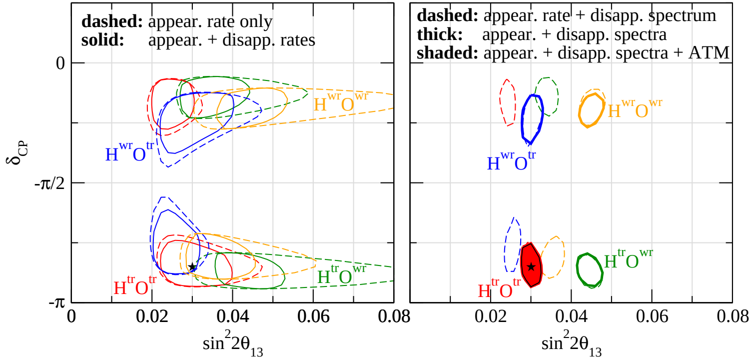
Any price for that? Of course yes. Fluxes go like $1/L^2$, $\Rightarrow$ ten time less flux at 2500 km. Partially recoverd by the rise of cross sections: $\sigma \propto E$ and the MSW resonance (if in the lucky hierarchy). Let's compare interaction rates $I \propto P \times \sigma \times L^{-2}$





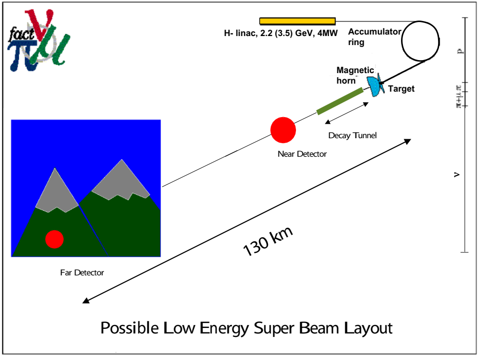
Degeneracies don't affect CPV sensitivity at short baselines

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



Resolving degeneracies in SPL by successively using the appearance rate measurement, disappearance channel rate and spectrum, spectral information in the appearance channel, and atmospheric neutrinos. Allowed regions in $\sin^2 2\theta_{13}$ and δ_{CP} are shown at 95% CL, and $\mathrm{H}^{\mathrm{tr/wr}}(\mathrm{O}^{\mathrm{tr/wr}})$ refers to solutions with the true/wrong mass hierarchy (octant of θ_{23}). The true parameter values are $\delta_{\mathrm{CP}} = -0.85\pi$, $\sin^2 2\theta_{13} = 0.03$, $\sin^2 \theta_{23} = 0.6$. The running time is $(2\nu + 8\bar{\nu})$ yrs.

SuperBeams - SPL ν beam at CERN

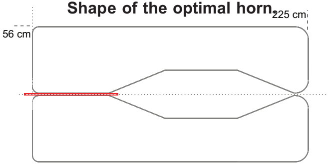


Possible Low Energy Super Beam Layout

- A 3.5 GeV, 4MW Linac: the SPL.
- A target station capable of managing the 4 MW proton beam. R&D required.
- A conventional neutrino beam optics capable to survive to the beam power, the radiation and the mercury. Already prototyped.
- Up to here is the first stage of a neutrino factory complex.
- A sophisticated close detector to precisely measure signal and backgrounds.
- A megaton class detector under the Frejus, L=130 km: Memphys.

SPL revised (A. Longhin, paper in preparation)

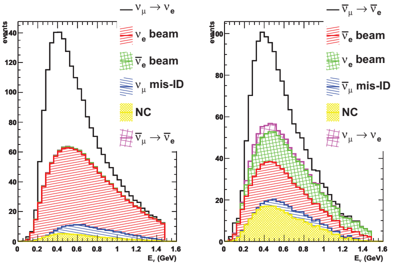
Shape of the optimal horn



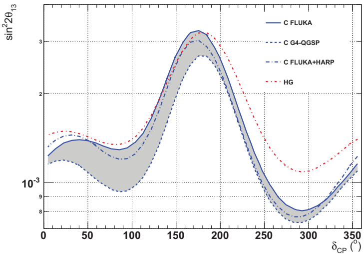
L_1	58.9	$r_1 = r_2$	10.8
L_2	46.8	R_1	1.2
L_3	60.3	$R_1 + R_2 + R_3$	56.2
L_4	47.5	$R_1 + R_2$	20.3
L_5	1.08	z_0^{tg}	-6.8
L^{tg}	78	R^{tg}	1.5
L^{tun}	2500	R^{tun}	200

Parameters of the optimized system expressed in cm.

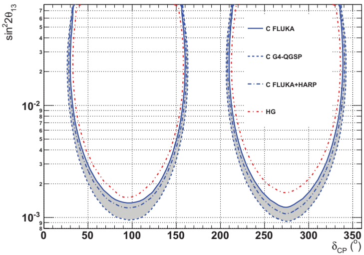
Event rates in MEMPHYS for $\sin^2 2\theta_{13}$ = 0 01 and δ_{CP} = 0.



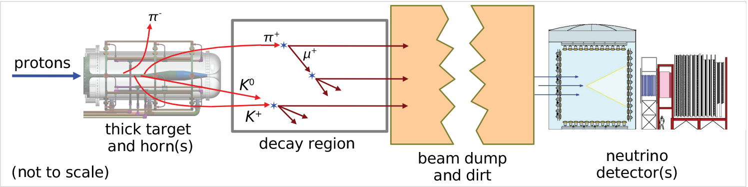
θ_{13} discovery at 3 σ ($\Delta\chi^2$ = 9). 5% sys.



CP violation discovery at 3 σ ($\Delta\chi^2$ = 9). 5% sys.



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.

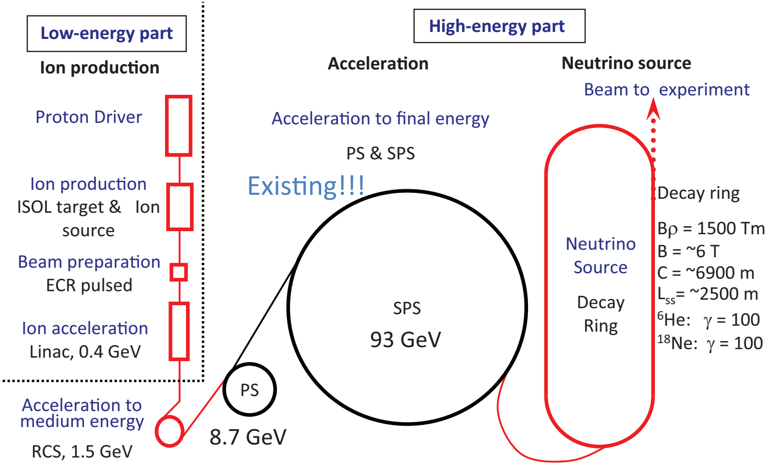
Distinctive features of Beta Beams

…limitations exist but aren't too much discussed in the following …

- Don't need a magnetized detector $\Rightarrow$ 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: $\gamma = 100$
^{18}Ne: $\gamma = 100$

- $\overline{\nu}_e$ generated by $He^6 \Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year.
- ν_e generated by $Ne^{18} \Rightarrow 1.1 \cdot 10^{18}$ 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 ⇒ neutrino beam from accelerated ions gets more collimated $\propto \gamma^2$
- Merit factor for an experiment at the atmospheric oscillation maximum: $\boldsymbol{\mathcal{M} = \frac{\gamma}{Q}}$
- 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

  ⇒ 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

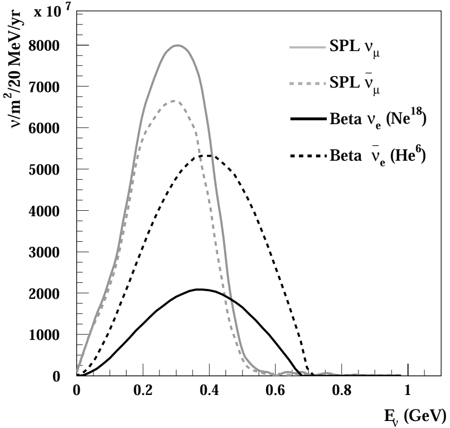
Boundary conditions:

- 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

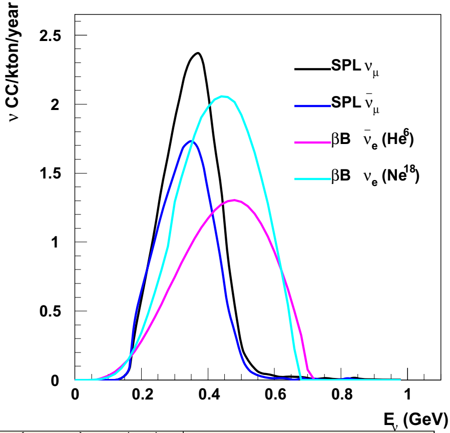
Optimal γ: $\gamma = 100$.

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
$\bar{\nu}_\mu$	$9.66 \cdot 10^{11}$	0.28	23.1	0.35	8	81164
Beta Beam						
$\bar{\nu}_e(\gamma = 100)$	$10.92 \cdot 10^{11}$	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

The Beta Beam - SPL Super Beam synergy

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

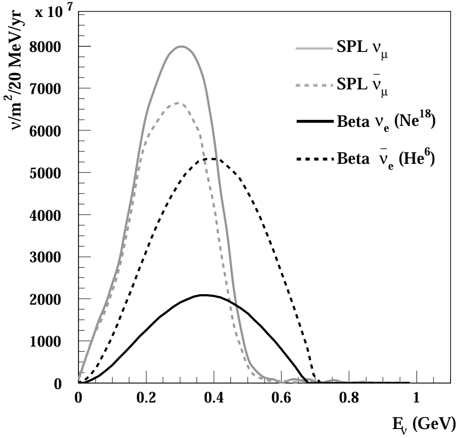
A Beta Beam has the same energy spectrum than the SPL SuperBeams and consumes 5% of the SPL protons.

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

Yearly Fluxes



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:

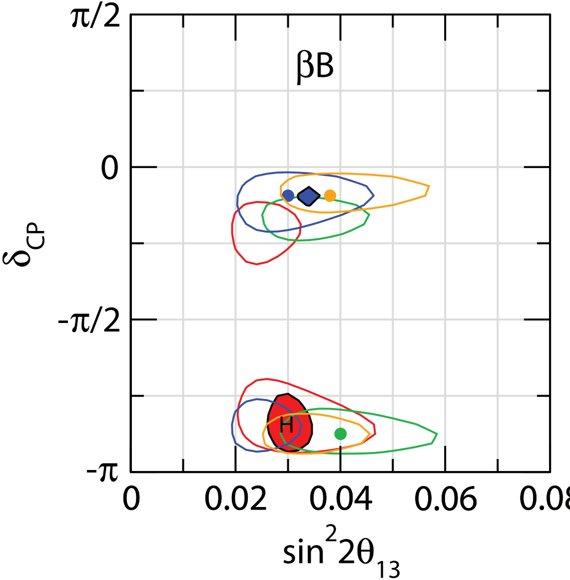
- **Octant** e-like events in the Sub-GeV data is $\propto \cos^2\theta_{23}$
- **Sign** e-like events in the Multi-GeV data, thanks to matter effects, especially for zenith angles corresponding to neutrino trajectories crossing the mantle and core where a resonantly enhancement occurs.

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.

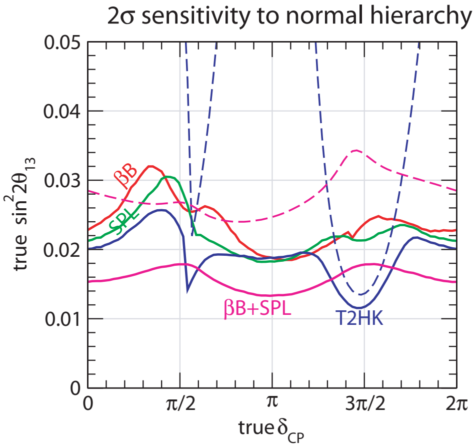
Synergy with atm. neutrinos: degeneracy removal

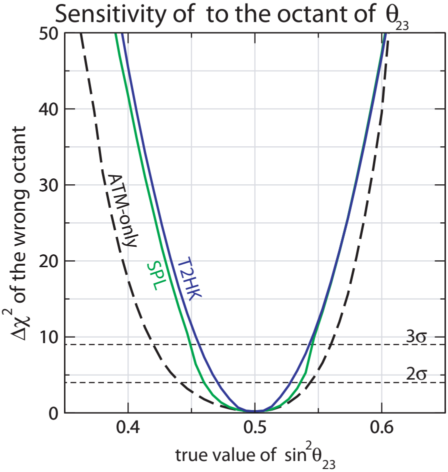
J.E.Campagne, M.Maltoni, M.M., T.Schwetz, JHEP **0704** (2007) 003

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



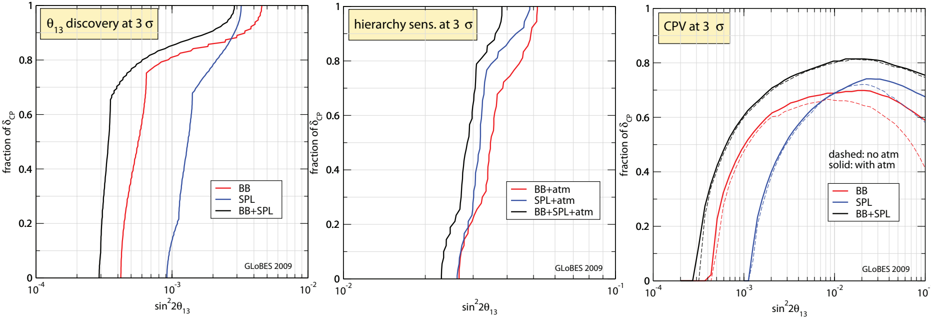
Beta Beam plus atmo: determining mass hierarchy and the octant





Updated sensitivities of SPL, BB and SPL+BB

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



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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.

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).

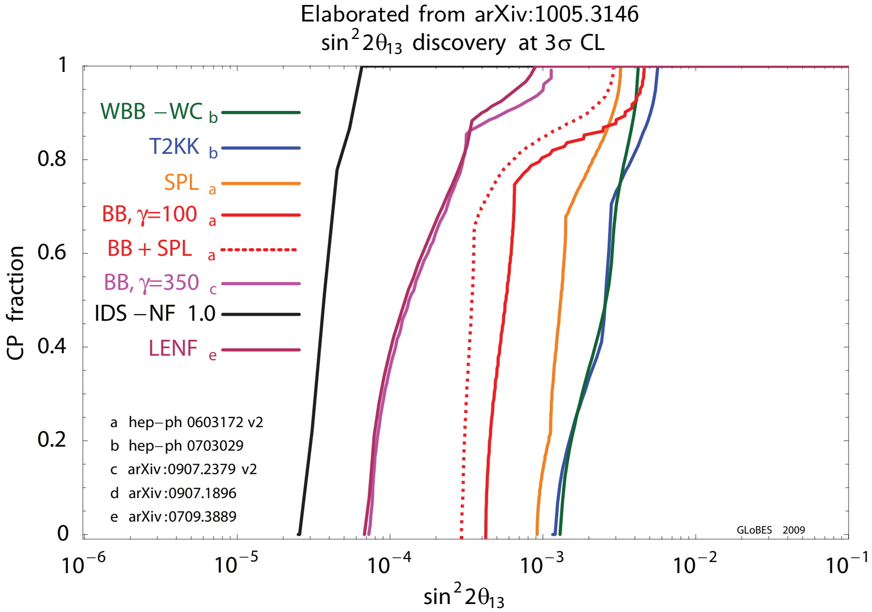
Beta Beam + SPL The combination of the above two.

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)

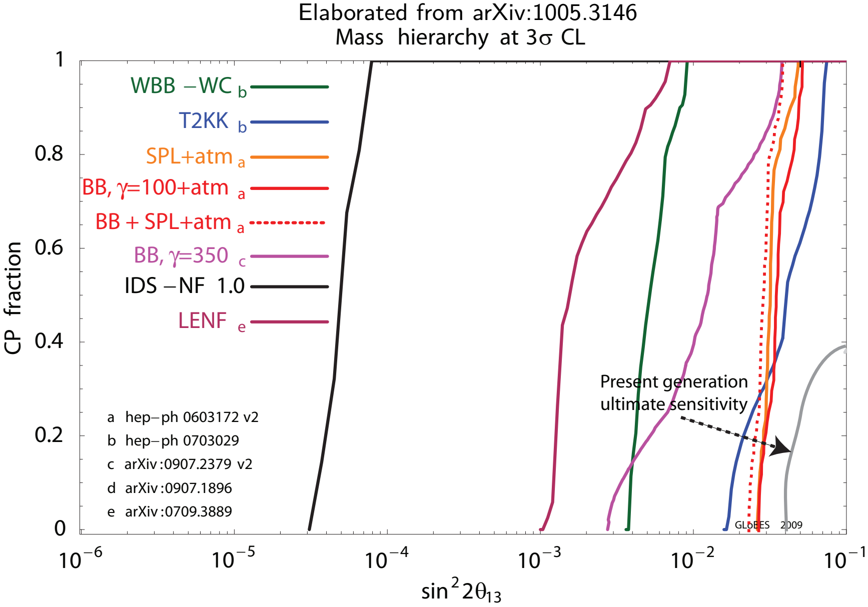
Low Energy Neutrino Factory (LENF) Neutrino Factory running at 4.12 GeV delivering 10^{21} muon decays/year for each sign, 30 kton Noνa like detector, fully magnetized (!) at 1480 km (Fermilab-Henderson mine). A. Bross et al, Phys.Rev.D77:093012,2008. (arXiv:0709.3889)

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}

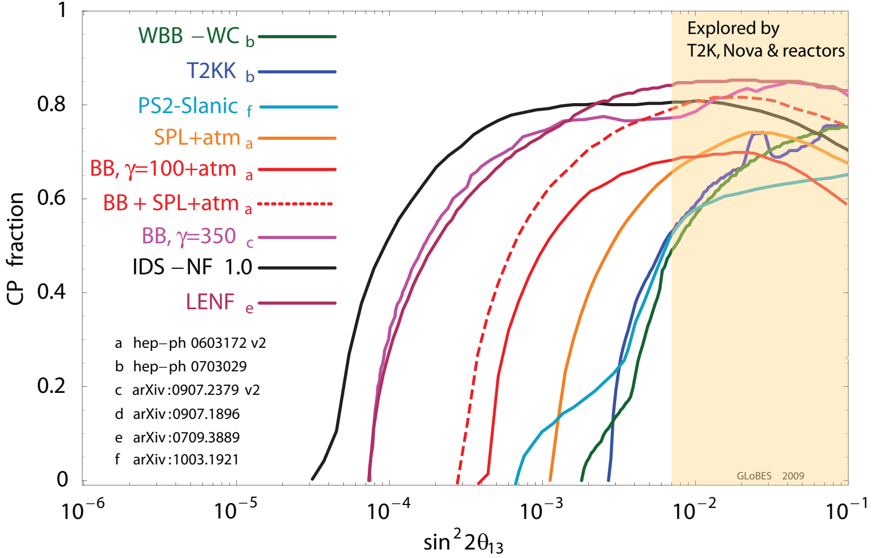


Sensitivity Comparison: $\mathrm{sign}(\Delta m^2_{23})$



Sensitivity Comparison: LCPV

Elaborated from arXiv:1005.3146
CP violation at 3σ CL



Conclusions

- Short Long-Baselines offer the cleanest possible setup for Leptonic CP Violation studies.
- They have almost null sensitivity to mass hierarchy, that can be partially compensated by a combined analysis with the atmospheric neutrinos.
- The CERN-Frejus scenario could offer a staged approach where a SuperBeam built over the Beta Beam injector (the SPL) can already provide a powerful setup.
- The innovative concept of Beta Beams 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.