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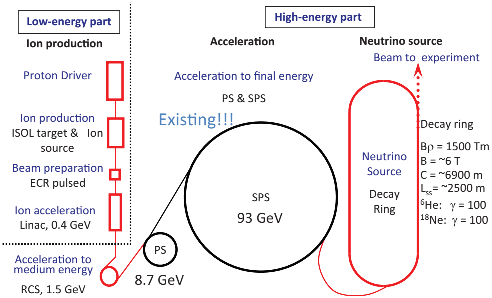
“Beta Beams: the physics case "



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

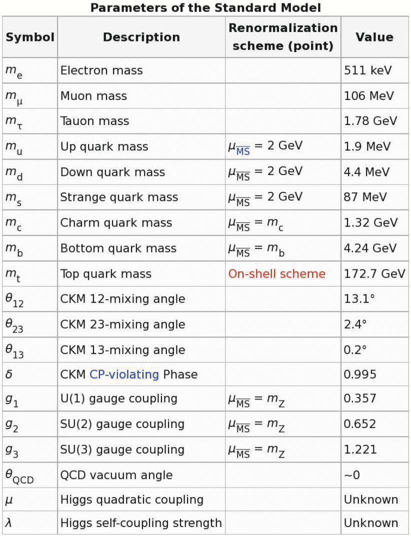
Neutrino source

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

- Introduction
- General principles of a Beta Beam
- Strategies for a Beta Beam experiment
- Sensitivities
- Future options
- Comparison with other setups.



Parameters of the Standard Model

Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		106 MeV
m_τ	Tauon mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}} = 2$ GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}} = 2$ GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}} = 2$ GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
μ	Higgs quadratic coupling		Unknown
λ	Higgs self-coupling strength		Unknown

Parameters added after neutrino oscillations

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$m_{\nu e}$	Electron neutrino mass	Unknown
$m_{\nu\mu}$	Muon neutrino mass	Unknown
$m_{\nu\tau}$	Tau neutrino mass	Unknown
θ_{12}	MNSP 12 – mix angle	34.4^0
θ_{23}	MNSP 23 – mix angle	45.0^0
θ_{13}	MNSP 13 – mix angle	Unknown
δ	MNSP CP-violating phase	Unknown
Higgs scheme	Higgs mechanism for neutrino masses	Unknown (See –Saw?)

Δm^2_{12}= 7.6 10^{-5} eV^2
Δm^2_{23}= 2.4 10^{-3} eV^2
Sign(Δm^2_{23}): Unknown
Absolute scale: Unknown

To be measured by Long Baseline neutrino oscillation experiments

δm^2_{12} ☑

SOLARS+KAMLAND

$\delta m^2_{12} = (7.9 +/- 0.7)\ 10^{-5} eV^2$

θ_{12} ☑

SOLARS+KAMLAND

$\sin^2(2\theta_{12}) = 0.82 +/- 0.055$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} $_{23}$ ☑

ATMOSPHERICS

$\delta m^2 = (2.4 +/- 0.4)\ 10^{-3}\ eV^2$

θ_{23} ☑

ATMOSPHERICS

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

$\theta\ 13$ ☐

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

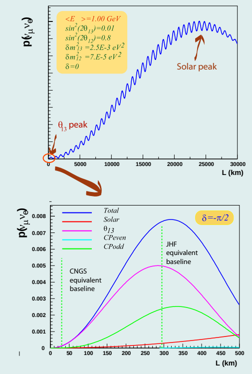
$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right] \qquad \theta_{13} \text{ dri}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \text{CPev}$$

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\} \sin\frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

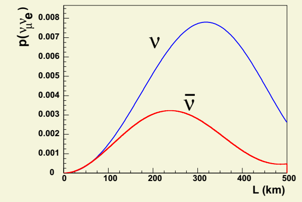
$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1-2s_{13}^2) \qquad \text{matter effect (CP odd)}$$



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

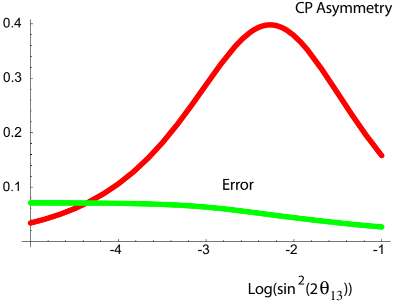
Leptonic CP discovery requires

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



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.

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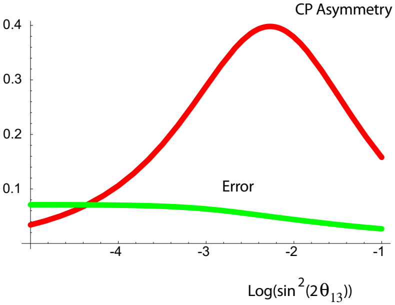

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- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) ⇒ "short" Long Baseline experiments**

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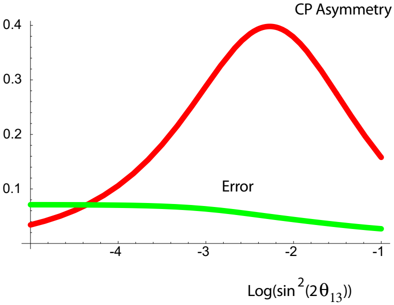
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$

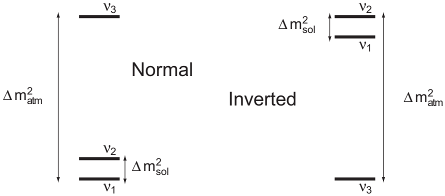


LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

- **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

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

$\alpha = \mathrm{Abs}(\Delta m^2_{21}/\Delta m^2_{31})$; $\hat{\Delta} = \frac{L\Delta m^2_{31}}{4E}$ $\zeta = \cos\theta_{13}\ \sin 2\theta_{12}\sin 2\theta_{23}$

$\boldsymbol{\hat{A} = \pm a/\Delta m^2_{31}}$; $a = 7.6\cdot 10^{-5}\rho\cdot E_\nu(GeV)$ $\rho = \text{matter density } (\mathrm{g\,cm^{-3}})$

The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{23})$

Matter effects require long "long baselines"

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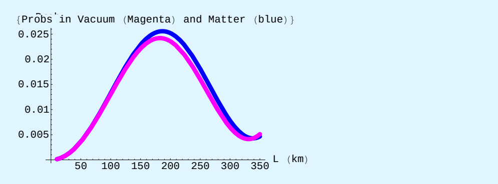
Matter effects require long "long baselines"

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



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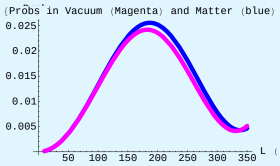
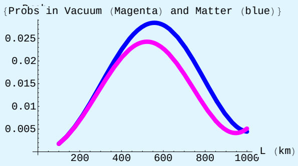
The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{23})$

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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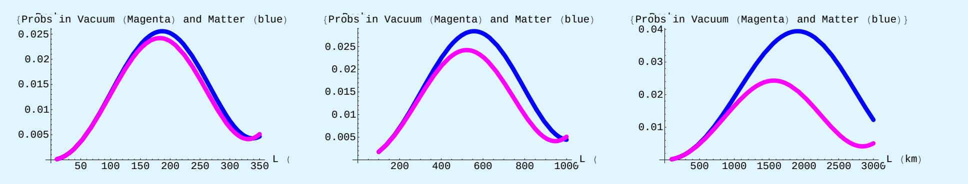
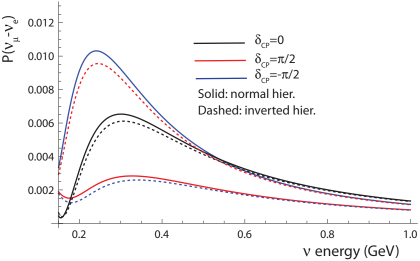
Matter effects require long “long baselines”

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



CPV vs. mass hierarchy

At 130 km matter effects are negligible. Inverse hierarchy solutions are very similar to direct hierarchy (changing sign of $\delta_{\rm CP}$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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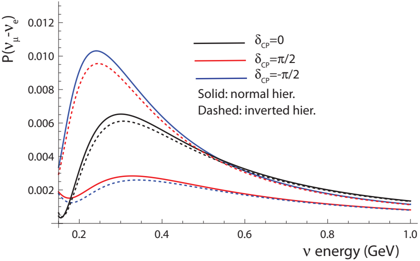
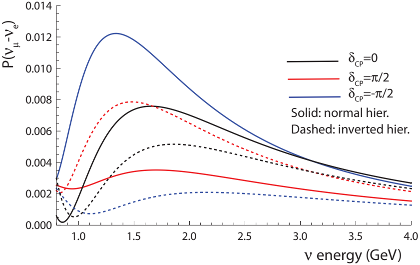


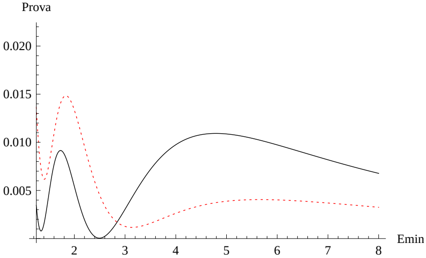
At 730 km matter effects are sizable. Probabilities differ.

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

Let's move at 2500 km where the matter effects are bigger. Note how the two probabilities are more different and note how their behaviour is very much different at the second oscillation maximum.



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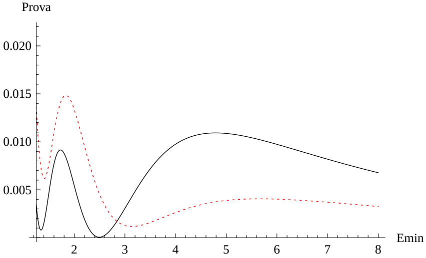
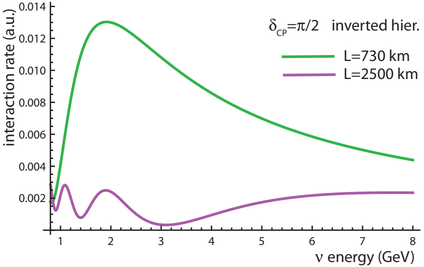


Do we pay a price for that? Of course yes. Fluxes go like $1/L^2$, $\Rightarrow$ ten time less flux at 2500 km. Partially compensated by the rise of cross sections: $\sigma \propto E$. Lets compare interaction rates $I \propto P \times \sigma \times L^{-2}$



The synergy with atmospheric neutrinos

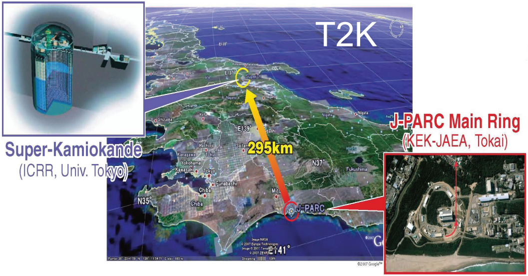
P. Huber et al., Phys. Rev. D 71, 053006 (2005): Combining Long Baseline data with atmospheric neutrinos (that come for free in the megaton detector):

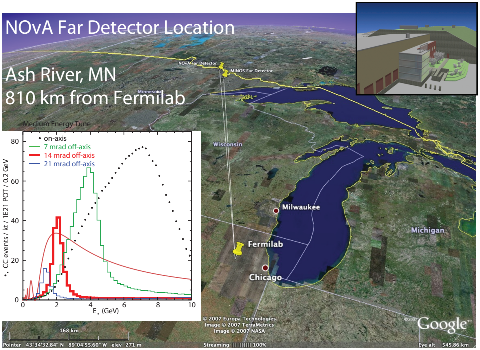
- Degeneracies can be canceled, allowing for better performances in θ_{13} and LCPV searches
- The neutrino mass hierarchy can be measured
- The θ_{23} octant can be determined.

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.

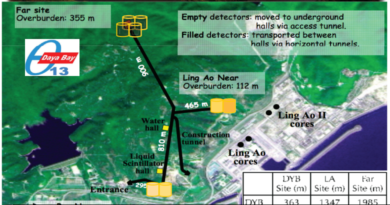




Double Chooz

Near site:
L ~ 280 m (~ 80 mwe)

Far Site :
L = 1 050 m in preparation
~ 300 mwe



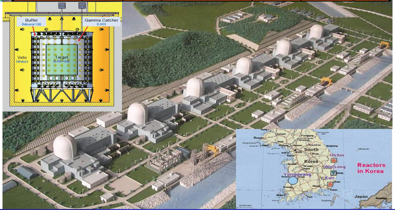
Far site
Overburden: 355 m

Empty detectors: moved to underground halls via access tunnel.
Filled detectors: transported between halls via horizontal tunnels.

Ling Ao Near
Overburden: 112 m

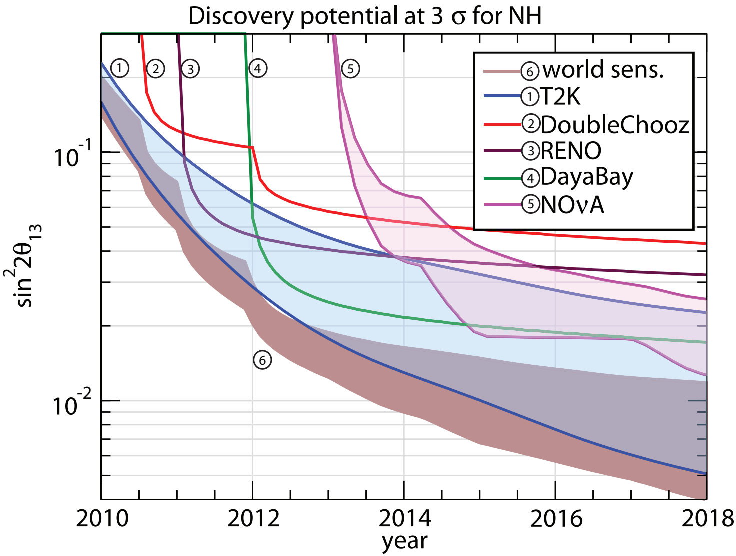
	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985

	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$



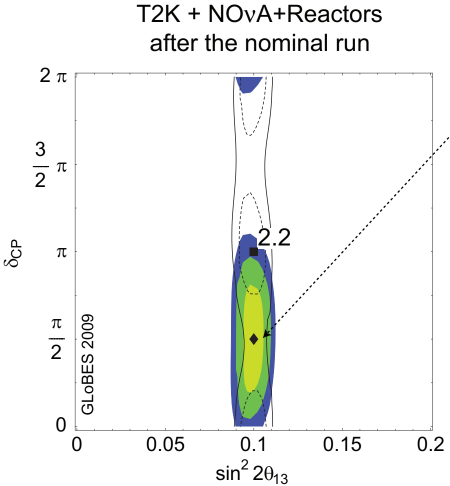
Status after this generation of LBL experiments: θ_{13}

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



Status after this generation of LBL experiments: CPV

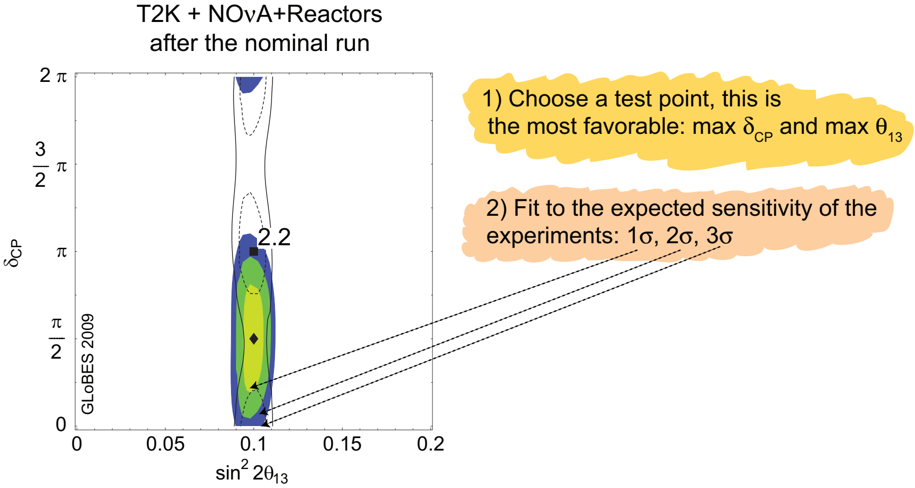
From P. Huber et al., JHEP 0911:044,2009.



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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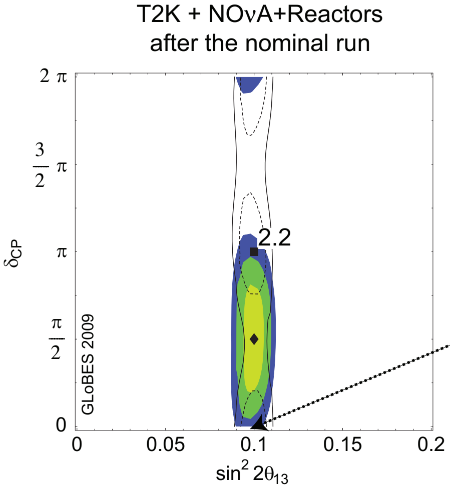


1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

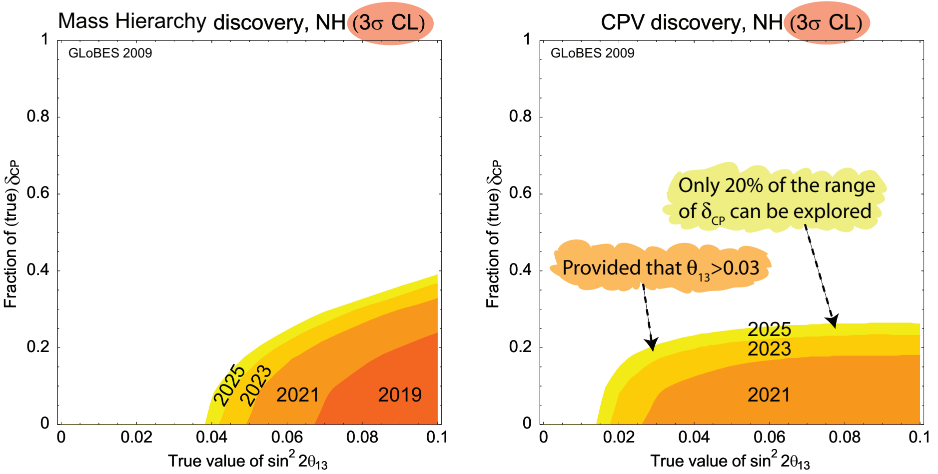
2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

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)



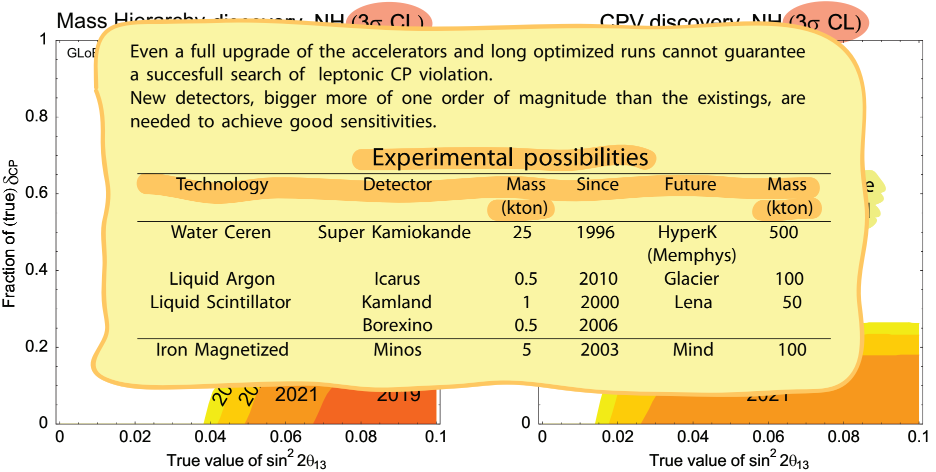
Only 20% of the range of δ_{CP} can be explored

Provided that θ_{13}>0.03

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)



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

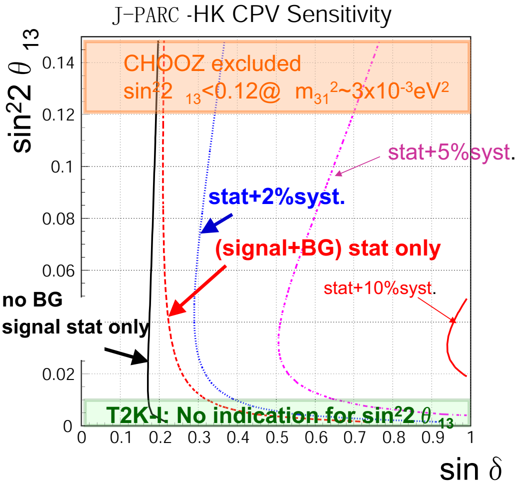
Technology	Detector	Mass (kton)	Since	Future	Mass (kton)
Water Ceren	Super Kamiokande	25	1996	HyperK (Memphys)	500
Liquid Argon	Icarus	0.5	2010	Glacier	100
Liquid Scintillator	Kamland	1	2000	Lena	50
	Borexino	0.5	2006		
Iron Magnetized	Minos	5	2003	Mind	100

Systematic errors

They could completely destroy leptonic CP violation sensitivity.

Default value are often 5% for SuperBeams, 2% for Neutrino Factory and 2-5% for Beta Beams.

Are
them realistic goals? Are close detectors powerful enough?



The general problem of close detectors in a SB experiment

SuperBeams

$$N^{\rm far}_{\rm events} = \left(\sigma_{\nu_e}\epsilon_{\nu_e}P_{\nu_\mu\nu_e} + \sigma^{\rm NC}_{\nu_\mu}\epsilon_{\rm NC} + \sigma^{\rm CC}_{\nu_\mu}\epsilon_{\rm CC}P_{\nu_\mu\nu_\mu}\right)\phi_{\nu_\mu} + \sigma^{\rm CC}_{\nu_e}\epsilon_{\nu_e}\phi_{\nu_e}$$

$$N^{\rm close}_{\rm events} = \left(\sigma^{\rm NC}_{\nu_\mu}\epsilon'_{\rm NC} + \sigma^{\rm CC}_{\nu_\mu}\epsilon'_{\rm CC}\right)\phi'_{\nu_\mu} + \sigma^{\rm CC}_{\nu_e}\epsilon_{\nu_e}\phi'_{\nu_e}$$

- The close detector measures the product of fluxes × cross section × efficiency
- Reduced $\nu_e$flux: small statistics to determine the cross section
- NC backgrounds must be separated from beam ν_e.

Beta Beams

$$N^{\rm far}_{\rm events} = \left(\sigma_{\nu_\mu}\epsilon_{\nu_\mu}P_{\nu_e\nu_\mu} + \sigma^{\rm NC}_{\nu_e}\epsilon_{\rm NC} + \sigma^{\rm CC}_{\nu_e}\epsilon_{\rm CC}P_{\nu_e\nu_e}\right)\phi_{\nu_e}$$

$$N^{\rm close}_{\rm events} = \left(\sigma^{\rm NC}_{\nu_e}\epsilon'_{\rm NC} + \sigma^{\rm CC}_{\nu_e}\epsilon'_{\rm CC}\right)\phi_{\nu_e}$$

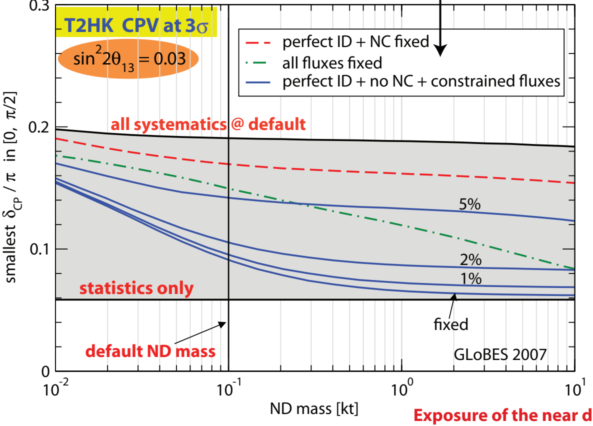
Flux known at priori, no intrinsic contamination (direct measure of NC backgrounds), no problems with the close-far extrapolation BUT no events to measure signal (ν_μ) cross sections.

Systematic errors and their pulls

Computed for T2HK sensitivity on LCPV at $\sin^2 2\theta_{13} = 0.03$

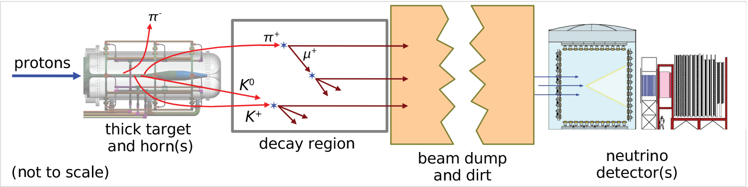
From P. Huber, MM, T. Schwetz, JHEP **0803** (2008) 021 [arXiv:0711.2950 [hep-ph]].

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.

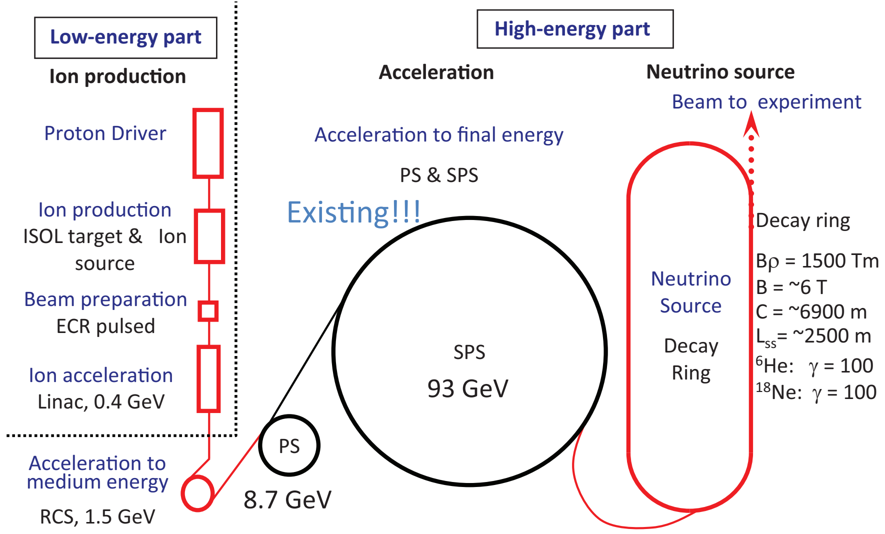
Distinctive features of Beta Beams

. . . 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

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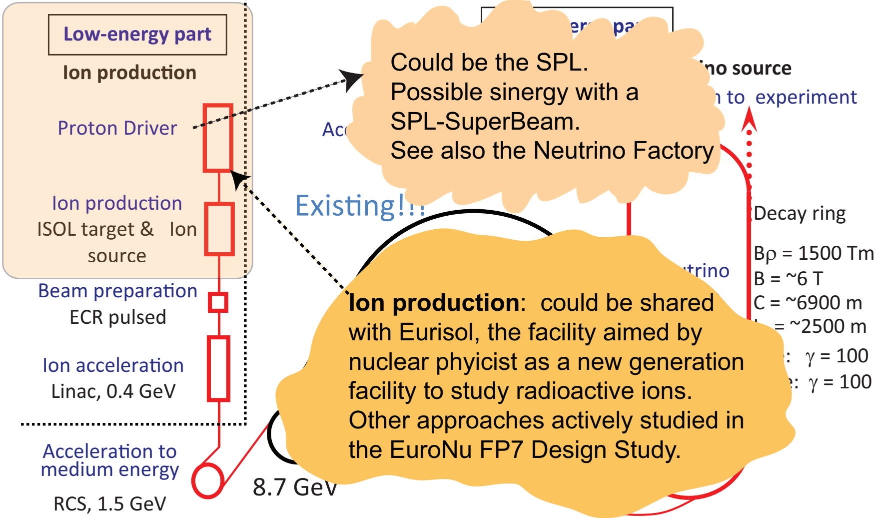

Could be the SPL.
Possible sinergy with a SPL-SuperBeam.
See also the Neutrino Factory

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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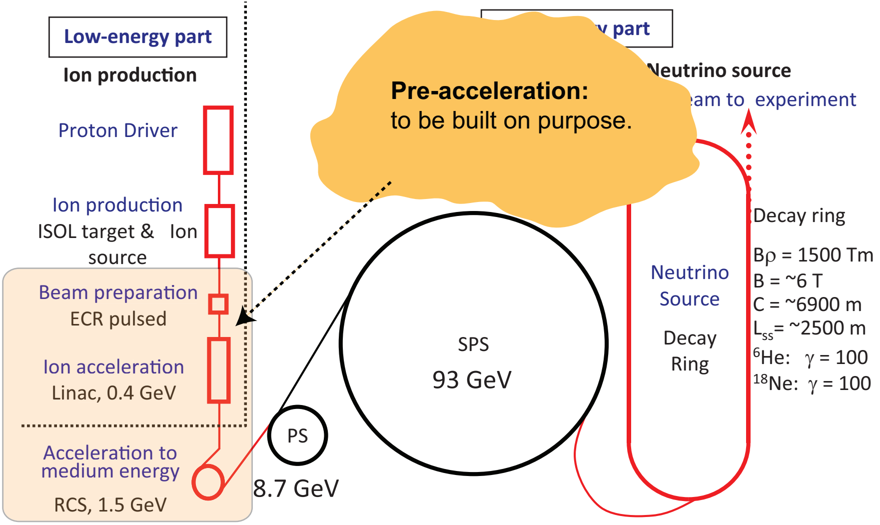

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Ion production
ISOL target & Ion source

Beam preparation
ECR pulsed

Ion acceleration
Linac, 0.4 GeV

Acceleration to medium energy
RCS, 1.5 GeV

PS
8.7 GeV

SPS
93 GeV

Pre-acceleration:
to be built on purpose.

part

Neutrino source

eam to experiment

Neutrino Source

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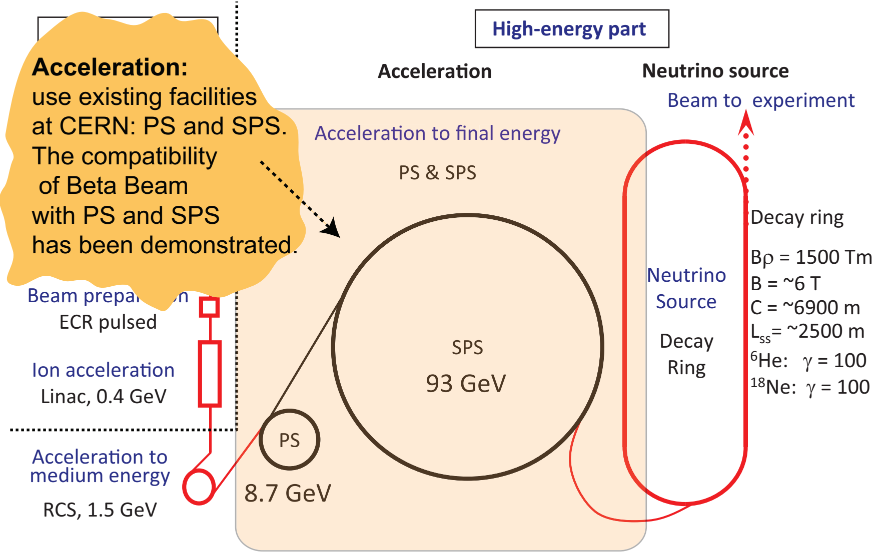

Acceleration:
use existing facilities
at CERN: PS and SPS.
The compatibility
of Beta Beam
with PS and SPS
has been demonstrated.

Decay ring

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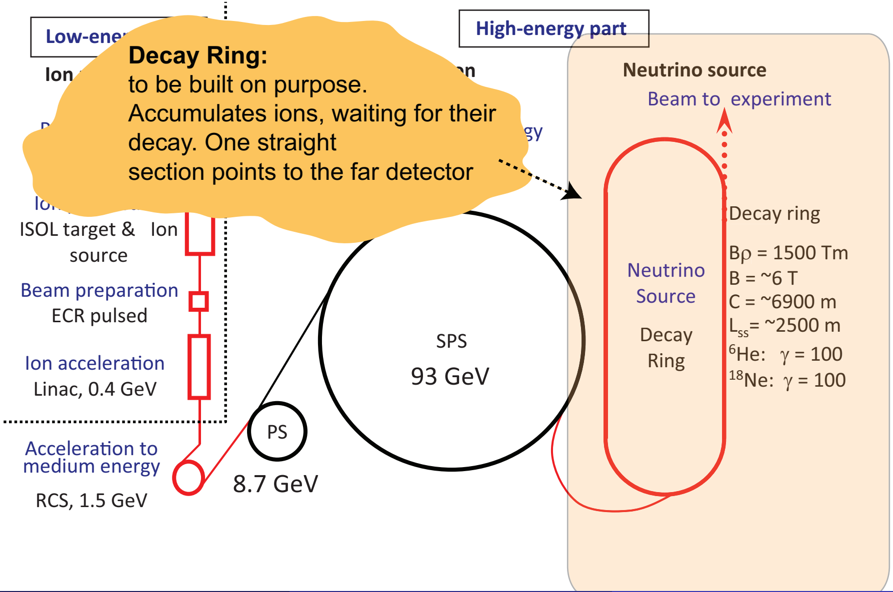

Decay Ring:
to be built on purpose.
Accumulates ions, waiting for their decay. One straight section points to the far detector

High-energy part

Neutrino source

Beam to experiment

Decay ring

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

Neutrino Source

Decay Ring

SPS
93 GeV

PS
8.7 GeV

ISOL target & Ion source

Beam preparation
ECR pulsed

Ion acceleration
Linac, 0.4 GeV

Acceleration to medium energy
RCS, 1.5 GeV

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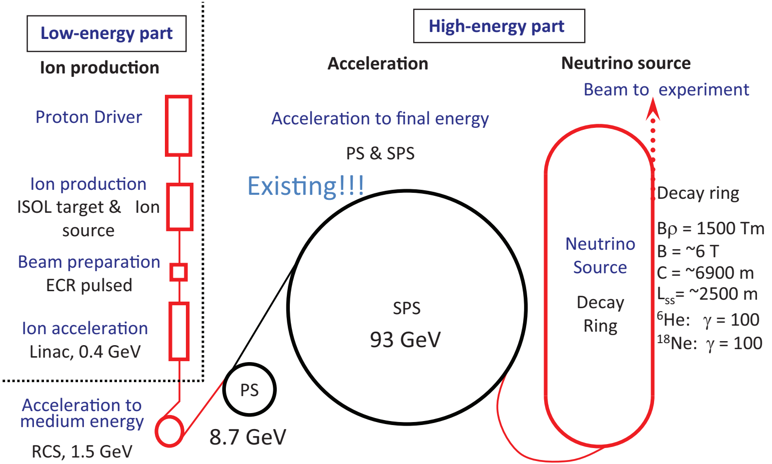

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Acceleration

Acceleration to final energy

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Existing!!!

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Beam to experiment

Neutrino Source

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Decay ring

$B\rho$ = 1500 Tm
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^{6}He: $\gamma = 100$
^{18}Ne: $\gamma = 100$

- $\overline{\nu}_e$ 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.

Possible β^- emitters ($\bar{\nu}_e$)

Isotope	Z	A	A/Z	$T_{1/2}$	$Q_{\beta\ (gs>gs)}$	$Q_{\beta\ eff.}$	$E_{\beta\ av.}$	$E_{\nu\ av.}$	<E_LAB> (MeV)
				s	MeV	MeV	MeV	MeV	(@ 450 GeV/p)
6He	2	6	3.0	0.807	3.5	3.5	1.57	1.94	582
8He	2	8	4.0	0.119	10.7	9.1	4.35	4.80	1079
8Li	3	8	2.7	0.838	16.0	13.0	6.24	6.72	2268
9Li	3	9	3.0	0.178	13.6	11.9	5.73	6.20	1860
11Be	4	11	2.8	13.81	11.5	9.8	4.65	5.11	1671
15C	6	15	2.5	2.449	9.8	6.4	2.87	3.55	1279
16C	6	16	2.7	0.747	8.0	4.5	2.05	2.46	830
16N	7	16	2.3	7.13	10.4	5.9	4.59	1.33	525
17N	7	17	2.4	4.173	8.7	3.8	1.71	2.10	779
18N	7	18	2.6	0.624	13.9	8.0	5.33	2.67	933
23Ne	10	23	2.3	37.24	4.4	4.2	1.90	2.31	904
25Ne	10	25	2.5	0.602	7.3	6.9	3.18	3.73	1344
25Na	11	25	2.3	59.1	3.8	3.4	1.51	1.90	750
26Na	11	26	2.4	1.072	9.3	7.2	3.34	3.81	1450

From P..Zucchelli talk at Nufact 03. Table compiled by U. Koster

Possible β^+ emitters (ν_e)

Isotope	Z	A	A/Z	$T_{1/2}$	$Q_{\beta\ (gs>gs)}$	$Q_{\beta\ eff.}$	$E_{\beta\ av.}$	$E_{\nu\ av.}$	<E_LAB> (MeV)
				s	MeV	MeV	MeV	MeV	(@450 GeV/p)
8B	5	8	1.6	0.77	17.0	13.9	6.55	7.37	4145
10C	6	10	1.7	19.3	2.6	1.9	0.81	1.08	585
14O	8	14	1.8	70.6	4.1	1.8	0.78	1.05	538
15O	8	15	1.9	122.2	1.7	1.7	0.74	1.00	479
18Ne	10	18	1.8	1.67	3.4	3.4	1.50	1.86	930
19Ne	10	19	1.9	17.34	2.2	2.2	0.96	1.25	594
21Na	11	21	1.9	22.49	2.5	2.5	1.10	1.41	662
33Ar	18	33	1.8	0.173	10.6	8.2	3.97	4.19	2058
34Ar	18	34	1.9	0.845	5.0	5.0	2.29	2.67	1270
35Ar	18	35	1.9	1.775	4.9	4.9	2.27	2.65	1227
37K	19	37	1.9	1.226	5.1	5.1	2.35	2.72	1259
80Rb	37	80	2.2	34	4.7	4.5	2.04	2.48	1031

From P..Zucchelli talk at Nufact 03. Table compiled by U. Koster

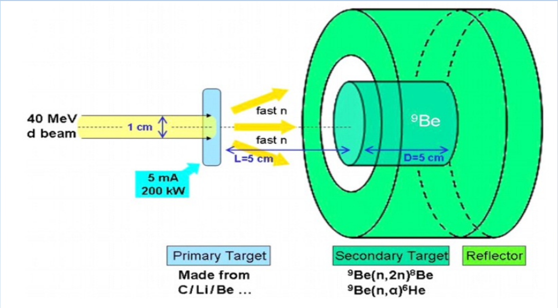
Some scaling laws in Beta Beams

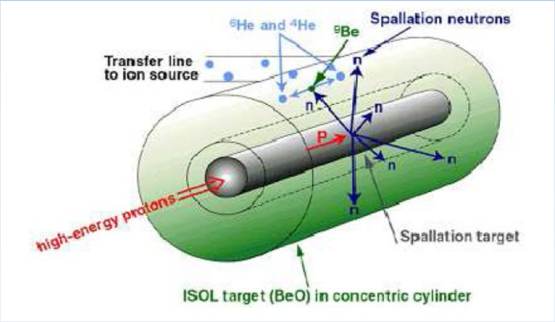
β^+ emitters			β^- emitters		
Ion	$Q_{\rm eff}$ (MeV)	Z/A	Ion	$Q_{\rm eff}$ (MeV)	Z/A
^{18}Ne	3.30	5/9	^{6}He	3.508	1/3
^{8}B	13.92	5/8	^{8}Li	12.96	3/8

- 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)

Production of ^{6}He ions for beta beams

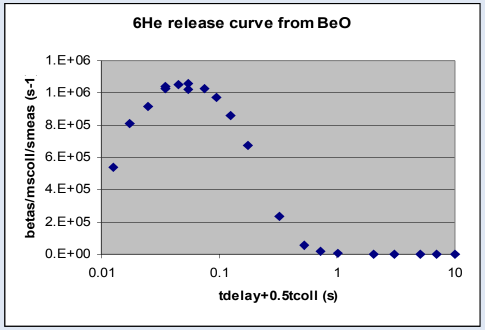




M. Hass et al

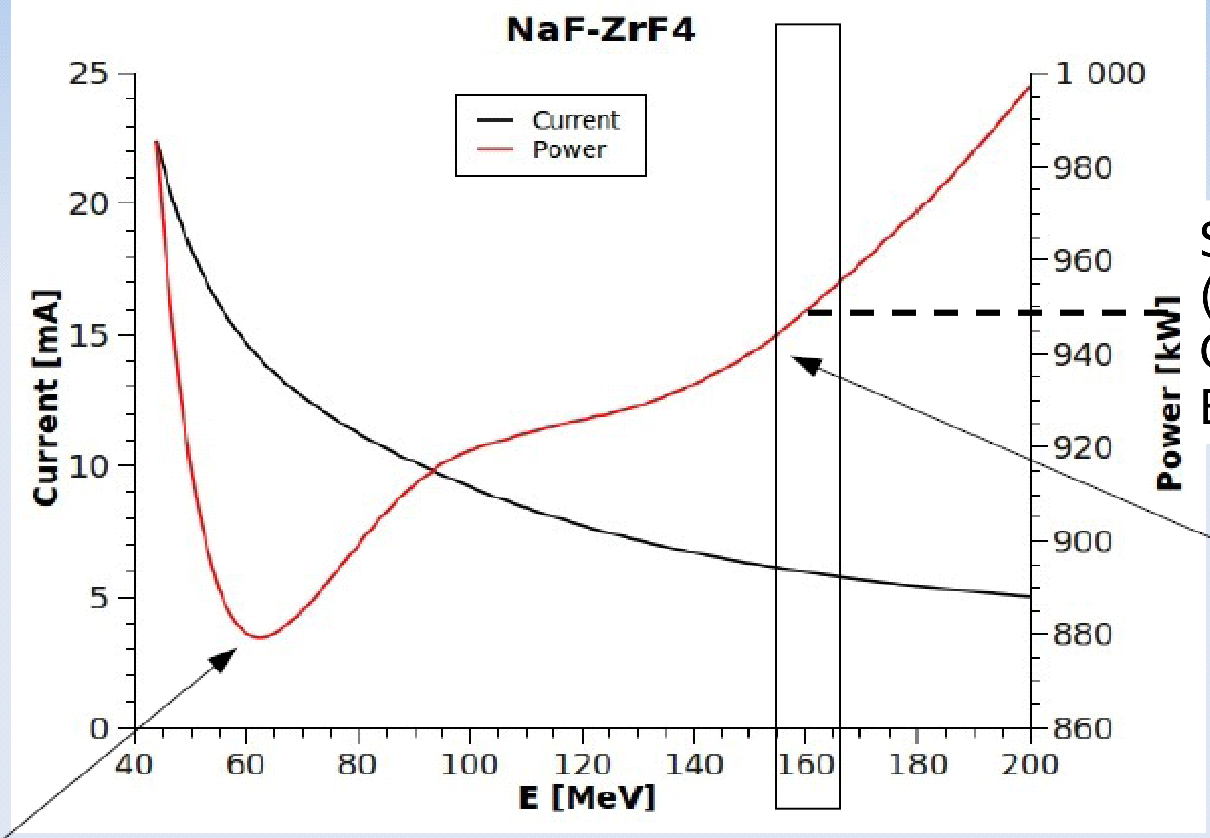
10^{14} ^{6}He/s 200 kW, 2 GeV proton beam in-target production. 50 – 90% extraction efficiency from realistic big targets
(reduced scale experiment doe at CERN-ISOLDE to confirm these numbers; Weizmann, GANIL and CERN collaboration).

Numbers have now been carefully checked. 1 kW of 1-2 GeV protons produces more ^{6}He than 1 kW of 40 MeV deuterons.



Production of ^{18}Ne ions for beta beams

The beam current and power for a constant yield 10^{13} ^{18}Ne/s



Sub MW target
(ca 700kW in target)
Challenging,
But within reach

Upgraded
LINAC 4

6mA, 160MeV

Lowest power

EUROnu week in Strasbourg - IPHC

P. Valko - CERN

Where do we stand for BaseLine ion production for beta beams

- ^{6}He
  Can be produced with *(a variant of)* SPL 200kW, 2 GeV Linac : synergies with a future Radioactive Ion Beam facility at CERN (light EURISOL or super-ISOLDE).
- ^{18}Ne
  Could be produced with upgraded Linac4. This project is stopped at present.

Beta Beam baseline scenario

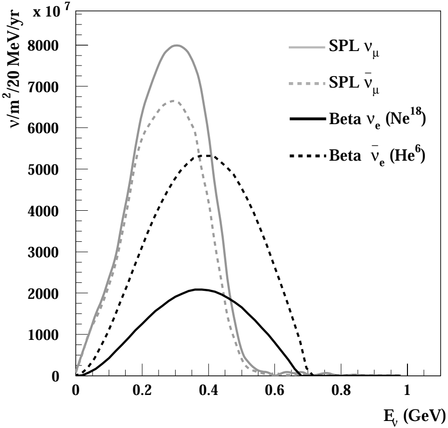
Boundary conditions:

- 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

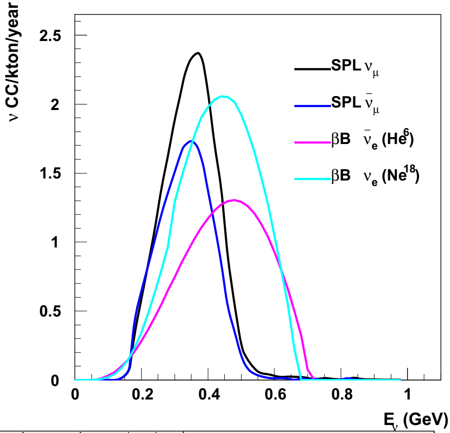
Optimal γ: $\gamma = 100$.

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

Experimental strategy

Beta Beam signal is $\nu_\mu$appearance.
To profit of the no-background beam, detector backgrounds should be taken at minimum:

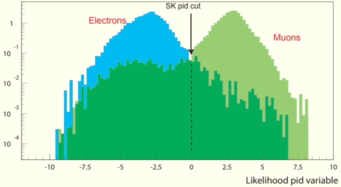
- ν_e events mis-identified as ν_μ events
- Charged pions from NC and NC-like ν_e interactions mis-identified as muons.
- Atmospheric neutrinos

As described in the following, background reduction will not rely on kinematical cuts.

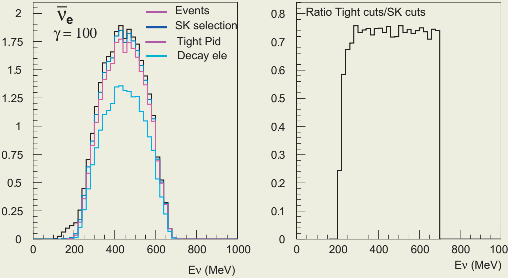
Particle identification and signal efficiency

Electron/muon misidentification must be suppressed much more than in standard SK analysis to guarantee a negligible background level.

Pid in SK is performed through a Likelihood, *Pid* > 0 identifies muons. Use *Pid* > 1



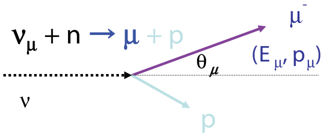
To further suppress electron background ask for the signal of the Michel electron from μ decay. Final efficiency for positive muons. Negative muons have an efficiency smaller by $\sim 22\%$ because they can be absorbed before decaying. **Electron mis-identification suppressed to $\sim 10^{-5}$.**



Energy reconstruction for beam neutrinos

Slide of K. Nishikawa

Select single ring events and assume they are Quasi Elastic

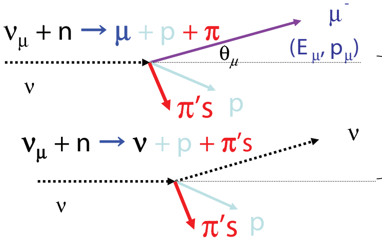


- ✧ **CC QE**
  - ✧ can reconstruct $E_\nu \leftarrow (\theta_\mu, p_\mu)$

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

$\delta E \sim 60$ MeV $\delta E/E \sim 10\%$

Single ring non Quasi Elastic are badly measured

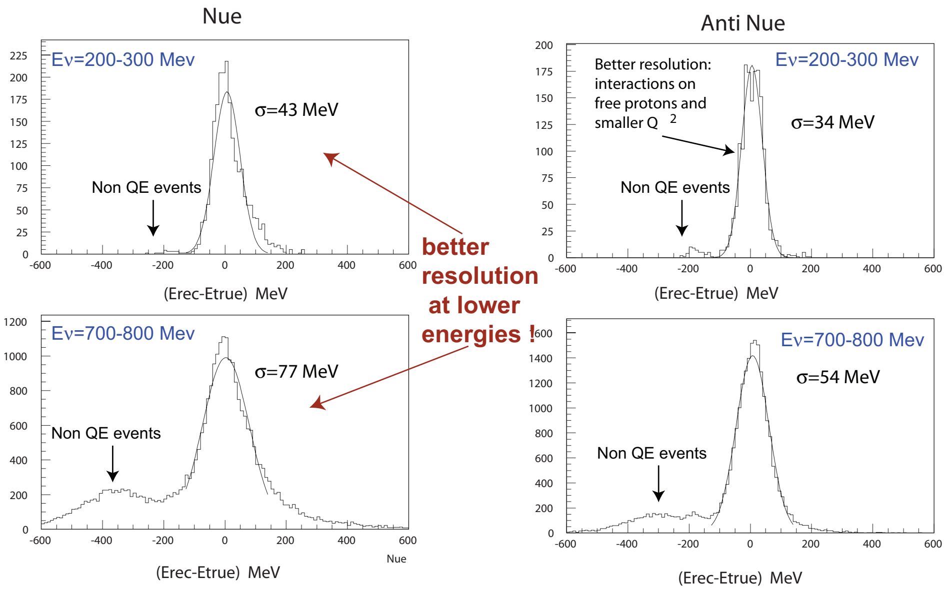


✧ bkg. for E_ν measurement

High energy part

✧ bkg.for e-appearance

Goodness of energy reconstruction



Nue

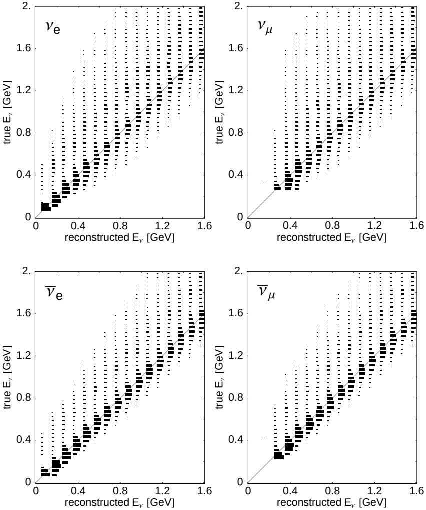
Anti Nue

Better resolution: interactions on free protons and smaller Q^2

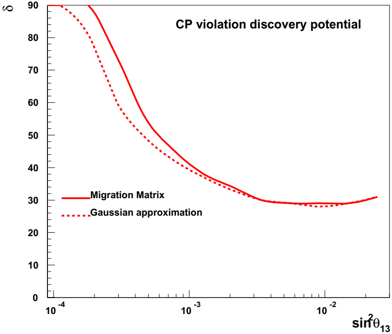
better resolution at lower energies !

Migration Matrixes

A gaussian assumption for energy resolution is a too crude approximation



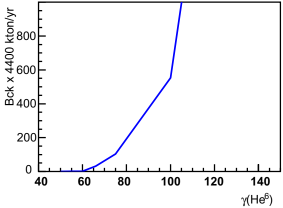
BB, $\gamma = 100$



The pion background

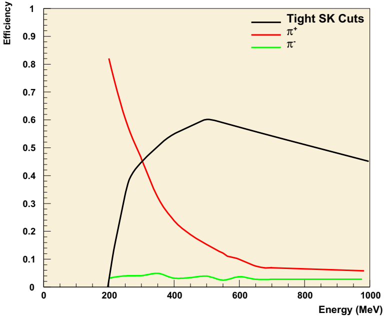
The pions generated in NC events can fake the muon signal.
They are the main concern at high gammas.

Pion backgrounds as function of γ

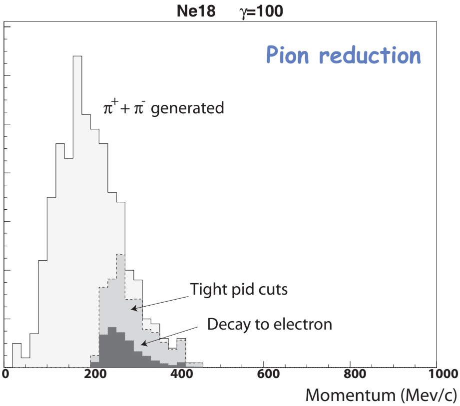


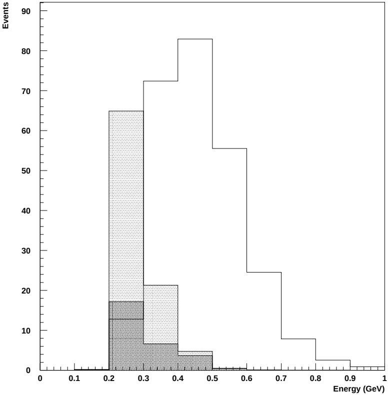
To estimate these backgrounds

- Generate CC and NC events with Nuance
- Count events with a pion and no other track above the Čerenkov threshold (single ring events)
- Apply the tight pid cuts of SuperKamiokande
- Follow pions in water (Geant 3.21) to compute the probability for $\pi \to \mu \to e$.
- Reconstruct the neutrino energy from the survived pions treating them as the signal muons



The pion background (cont.)





A very important cross check

ChizueIshihara,arXiv:0912.1002v2

Beta Beam signals and backgrounds recalculated with theSuperKamiokande analysis tools: full simulation and full reconstruction.

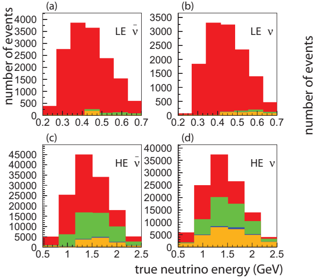


Figure 3: The final sample neutrino true energy distributions for each beam type, in case of $\sin^2 2\theta_{13} = 0.15$. The different event types are shown in different colors as shown right side.

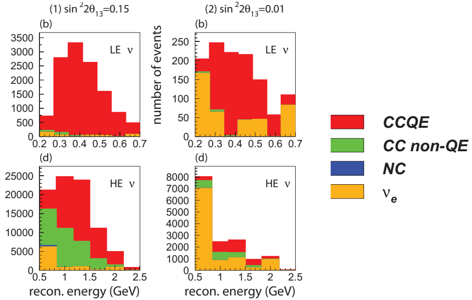


Figure 4: (1) are the reconstructed energy distributions in case of $\sin^2 2\theta_{13} = 0.15$. (2) are in case of $\sin^2 2\theta_{13} = 0.01$.

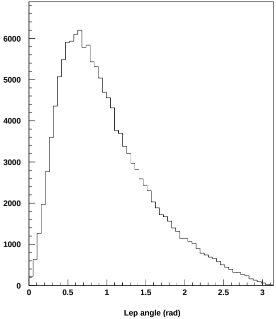
Atmospheric neutrino background

Why are they dangerous?

Atmospheric neutrinos come in two flavors: ν_e and ν_μ so they can fake any signal.

Their energy spectrum fully covers Beta Beam spectrum.

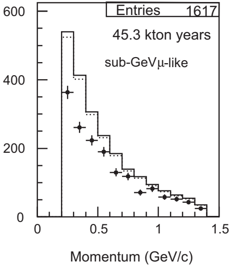
They don't necessary come from the decay ring, but outgoing lepton direction is loosely correlated with the neutrino energy direction in QE events.



The only viable tool to keep them at a negligible rate is to keep very short the live time of the neutrino beam. This is a tight requirement for the Beta Beam accelerator complex.

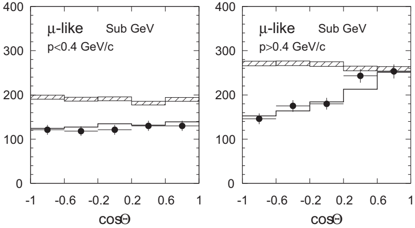
Question: why atmospherics are not a great concern at T2K phase 1, that has much smaller signal neutrino fluxes?

Atmospheric neutrino background

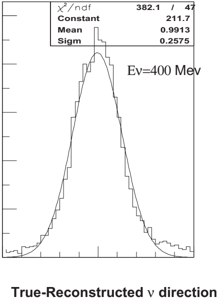


Sub-GeV μ-like events in SK integrated over the solid angle. 45.3 kton year exposure

Sub-GeV μ-like events zenithal distribution



Event direction resolution at 400 MeV. Take $\pm 2\sigma$ as acceptance, equivalent to $\pm 40°$. Solid angle reduced to 1/8

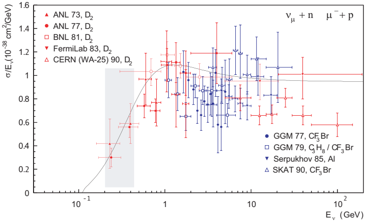


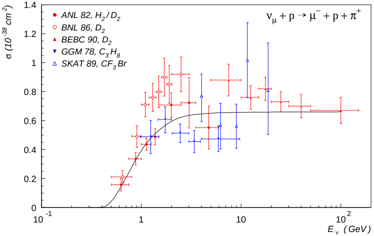
Kamioka to Frejus flux correction: + 20%

Signal efficiency with respect to standard SK algorithms: 54% (flat in energy)

A duty cycle of 1% would keep the atmospheric background rate below the pion bkg rate (Eurisol DS duty cycle: 0.45%).

The cross sections problem





Neutrino cross-sections are poorly measured around 300 MeV.
Nuclear effects are very important at these energies.
No surprise that different MonteCarlo codes predict rates with a 50% spread.

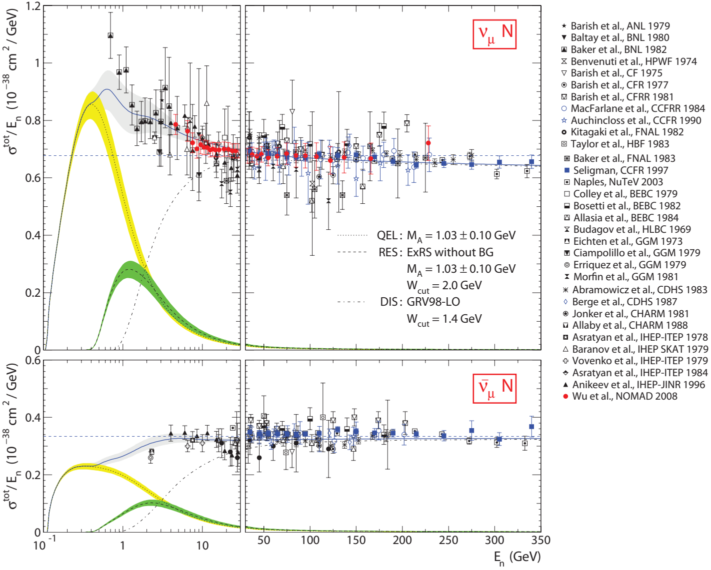
On the other hand: Beta Beam is the ideal place where to measure neutrino cross sections

- Neutrino flux and spectrum are completely defined by the parent ion characteristics and by the Lorentz boost γ.
- Just one neutrino flavour in the beam.
- You can scan different γ values starting from below the Δ production threshold.
- A close detector can then measure neutrino cross sections with unprecedent precision.

A systematic error ranging from 2% to 5% both in signal and backgrounds is used in the following

Neutrino Cross Sections

From: NOMAD Collaboration, Eur. Phys. J. C **63** (2009) 355 [arXiv:0812.4543 [hep-ex]].



Oscillation signals

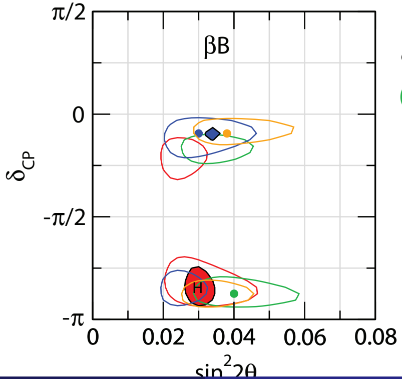
From J.E.Campagne, M. Maltoni, M.M., T.Schwetz, hep-ph/0603172, revised

	βB		SPL		T2HK	
	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$
appearance ν						
background	113		600		1017	
$\sin^2 2\theta_{13} = 0$	24		41		84	
$\sin^2 2\theta_{13} = 10^{-3}$	66	76	93	10	181	18
$\sin^2 2\theta_{13} = 10^{-2}$	285	314	387	126	754	240
appearance $\overline{\nu}$						
background	127		500		1428	
$\sin^2 2\theta_{13} = 0$	23		36		90	
$\sin^2 2\theta_{13} = 10^{-3}$	64	10	74	104	188	261
$\sin^2 2\theta_{13} = 10^{-2}$	271	100	297	390	746	977

How to extract θ_{13} and δ_{CP}

The problem is not that simple

- The 3 ν oscillation formula contains all the mixing matrix parameters and Δm^2. The parameters already measured do have errors that will influence the extraction of the unknown parameters.
- Several parameters still unknown: θ_{13} , δ_{CP}, sign(Δm^2) (hierarchy), the octant of θ_{23}. Different combinations of the above unknowns can fit the same data: ⇒ **The eightfold degeneracy**



95% CL regions for the $(H^{tr}O^{tr})$, $(H^{tr}O^{wr})$, $(H^{wr}O^{tr})$, $(H^{wr}O^{wr})$ solutions

$\delta=-0.85\,\pi$
$\sin^2(2\theta_{13})=0.03$
$\sin^2(2\theta_{23})=0.6$

How to extract θ_{13} and $\delta_{\rm CP}$

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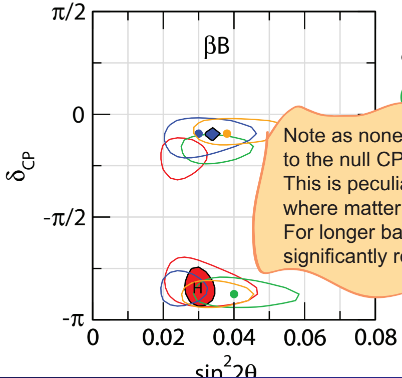


95% CL regions for the $(H^{tr}O^{tr})$, $(H^{tr}O^{wr})$, $(H^{wr}O^{tr})$, $(H^{wr}O^{wr})$

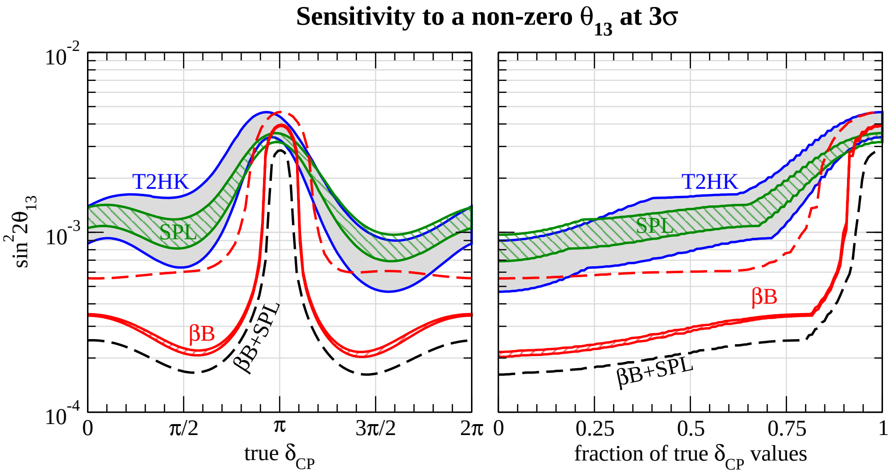
Note as none of the fake solutions goes closer to the null CP line: sensitivity is not affected. This is peculiar of “short” long baseline exp. where matter effects are negligible.
For longer baselines fake solutions tend to significantly reduce sensitivity.

$\sin^2(2\theta_{23})=0.6$

Degeneracies (cont.)

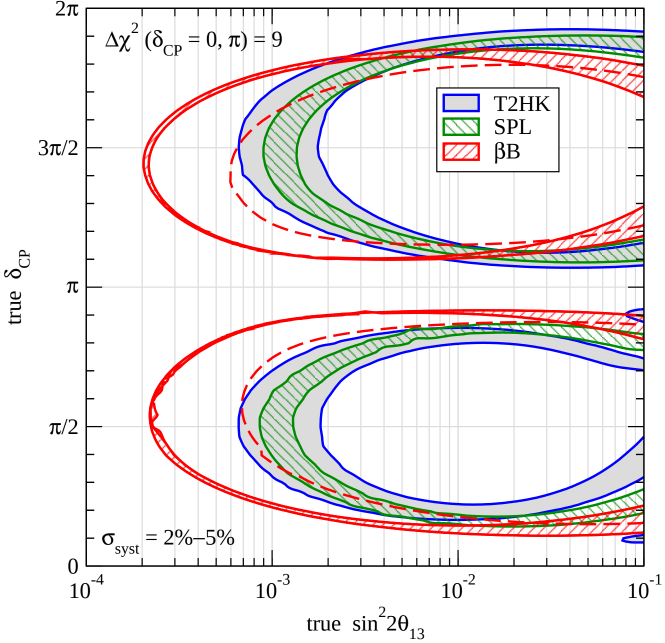
To solve degeneracies:

- A single experiment, single channel, can't get rid of degeneracies.
- The combination of different channels in the same detector can solve degeneracies, i.e. first a second oscillation maximum measurement in LBNE or at Okinoshima.
- Different signals in the same detector can also do the job, i.e. beta beams and atmospheric neutrinos.
- A third possibility is to combine the information of different detectors along the same neutrino beam, as exploited by several proposed neutrino factory configurations.
- Of course the combination of the above combinations can also measure all the unknown parameters: can we define an optimal strategy?



Line width: 2% and 5% systematic errors.

Sensitivity to CP violation at 3σ



Additional signals at the Frejus detector.

Can the θ_{13} and LCPV searches be improved?
Two pathways explored so far. In order of comparison:

- Fire a conventional neutrino beam (the SPL-SuperBeam) to the same detector.
- Combine BB information with the atmospheric neutrinos that the megaton detector will record for free

P.S. Also ν_e disappearance could help in determining θ_{13} and in removing degeneracies (it's the same channel of reactor experiments). However it would help if systematic errors could be pushed below 0.5%. At present 2% seems to be the ultimate level of systematics for a Beta Beam. You should consider that is very unpractical to build a close detector IDENTICAL to the far detector.

The Beta Beam - SPL Super Beam synergy

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

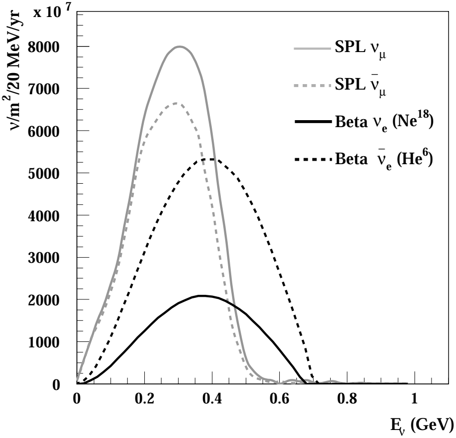
A Beta Beam has the same energy spectrum than the SPL SuperBeams and consumes 5% of the SPL protons.

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:

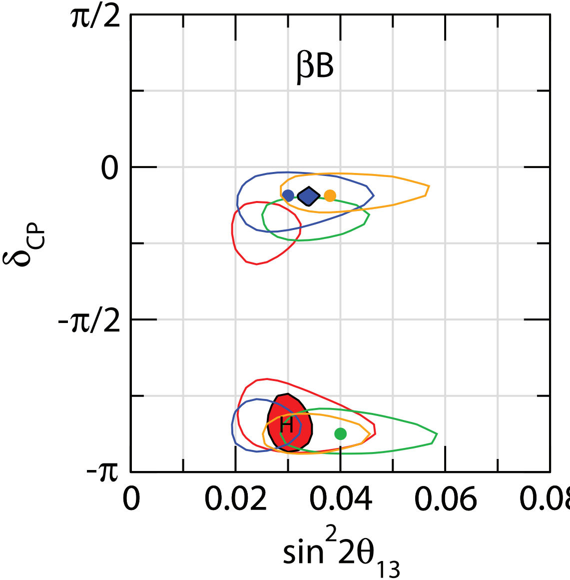
- **Octant** e-like events in the Sub-GeV data is $\propto \cos^2 \theta_{23}$
- **Sign** e-like events in the Multi-GeV data, thanks to matter effects, especially for zenith angles corresponding to neutrino trajectories crossing the mantle and core where a resonantly enhancement occurs.

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.

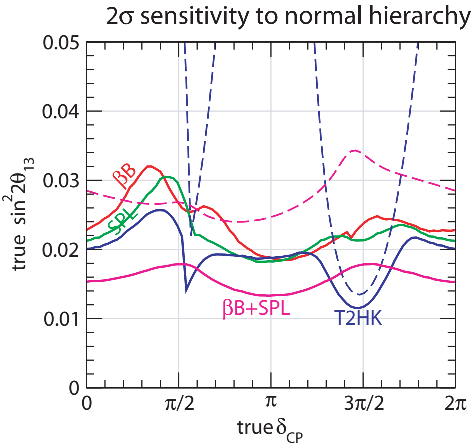
Synergy with atm. neutrinos: degeneracy removal

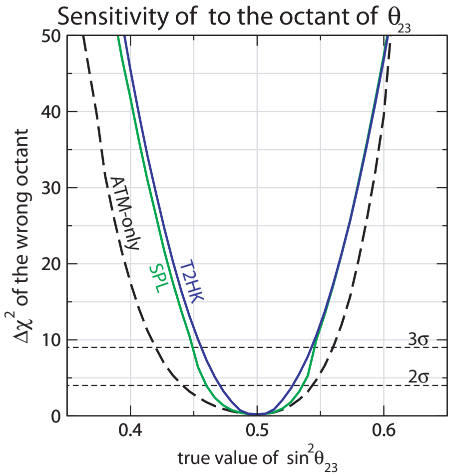
J.E.Campagne, M.Maltoni, M.M., T.Schwetz, JHEP **0704** (2007) 003

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



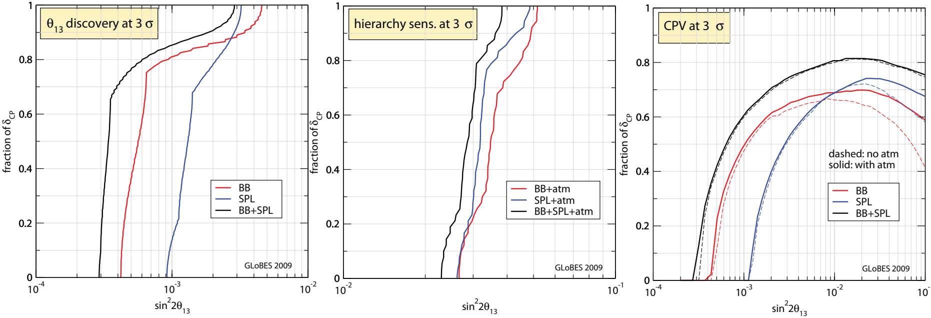
Beta Beam plus atmo: determining mass hierarchy and the octant





Updated sensitivities of SPL, BB and SPL+BB

Courtesy of T. Schwetz, 5% systematics.



Ways to improve beta-beam performances

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Ways to have more neutrinos in the far detector

1. More ions
2. Higher γ

Other Beta Beam options

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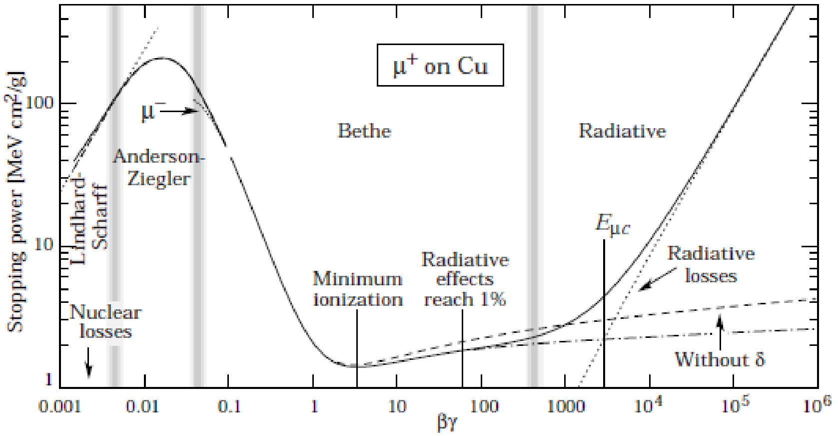
- **Electron capture Beta Beams**: monochromatic neutrino beams, a very attractive option
  - They require long lived, high-A, far from the stability valley ions, r$\Rightarrow$ challenging R&D to match the needed fluxes.

Ionization cooling

C.Rubbia et al, NIM A 568 (2006) 475–487

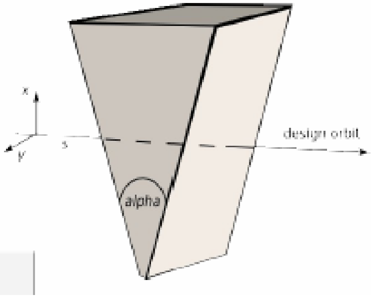
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$



- Only longitudinal component recovered in RF cavities
  → Transverse emittance shrinks

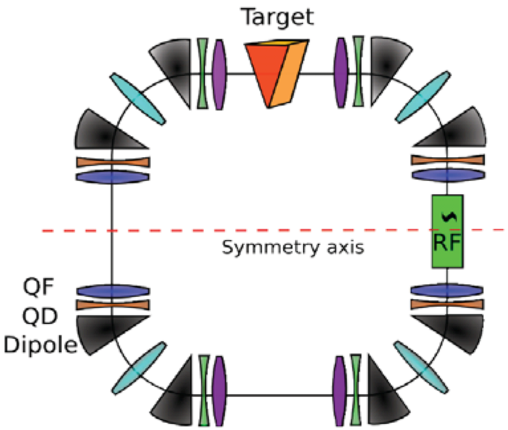
- Cooling in 6D
  - (dE/ds) ~ β^{-2} smaller at higher energies → cooling not effective in longitudinal
  - need coupling between transverse and longitudinal:
    → Dispersion & wedge-shaped target

Faster ions will travel on an outer orbit and see a larger target thickness → they will get more (dE/ds)



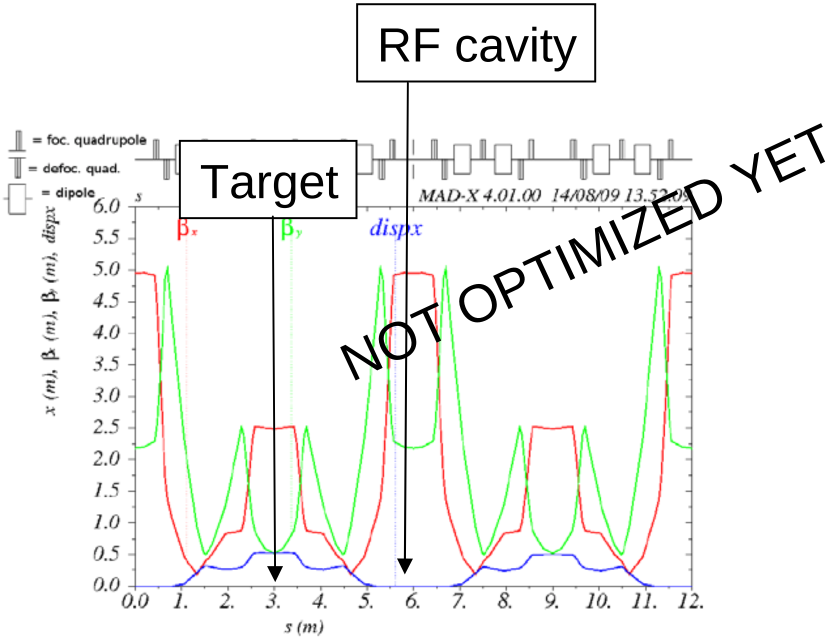
Target:
width @ closed orbit = 5 cm
t = 0.289 mg/cm^2
If angle = 20^o → D_x> 24 cm

Preliminary lattice



***M. Schaumann**, CERN-THESIS-2009-128*

Particle		^{7}Li
Energy	E_c	25 MeV
Relativistic gamma	γ_r	1.00383
Beam rigidity	$B\rho$	0.636 T m
Transition γ	γ_t	3.58
Tune	$Q_{x,y}$	2.58, 1.63
Natural chromaticity	$Q'_{x,y}$	-3.67, -3.58
β @ target	$\beta^*_{x,y}$	2.62 m, 0.35 m
Dispersion @ target	$D^*_{x,y}$	0.523 m, 0 m
Target thickness	t_0	0.27 mg/cm^2
	n_t	10^{19} atoms/cm^2
Energy losses @ target	E_{BB}	~ 0.30 MeV


RF cavity

Target

NOT OPTIMIZED YET

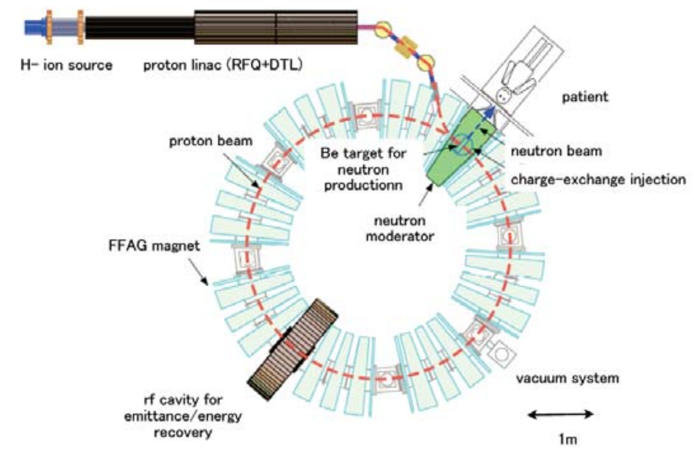
- C=12m
- normal-conducting magnets

- Capacitive loaded RF cavity
- Charge-exchange injection Li^{+1}

FFAG-ERIT @ KURRI (Osaka)

FFAG and Ionization Cooling:
Y.Mori, NIM A 562 (2006) 591

Schematic layout of FFAG-ERIT



K.Okabe et al, IPAC10, EPAC08,...

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).

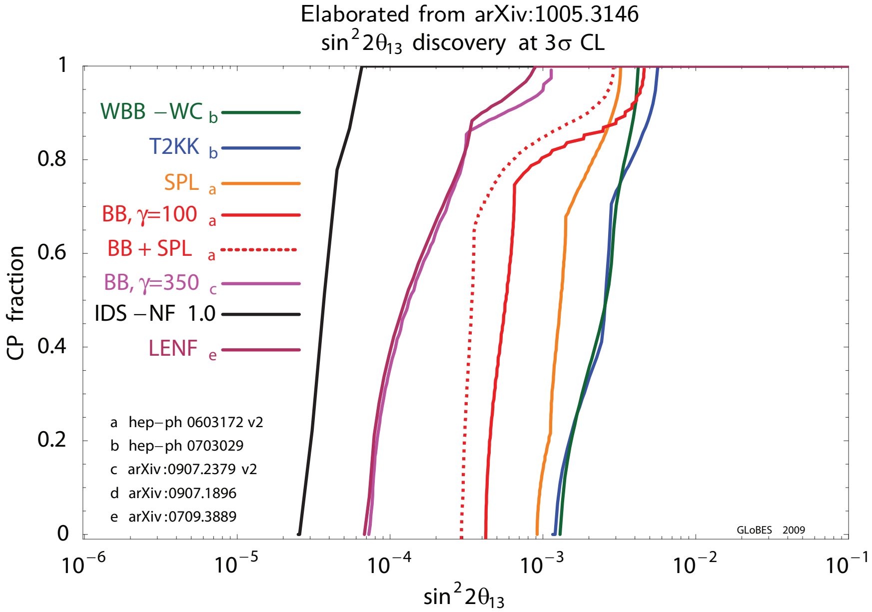
Beta Beam + SPL The combination of the above two.

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)

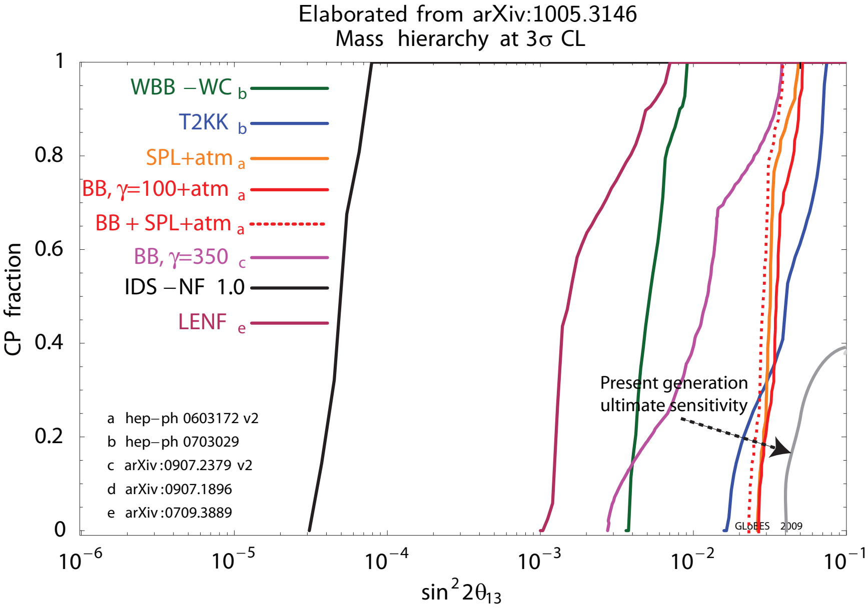
Low Energy Neutrino Factory (LENF) Neutrino Factory running at 4.12 GeV delivering 10^{21} muon decays/year for each sign, 30 kton Noνa like detector, fully magnetized (!) at 1480 km (Fermilab-Henderson mine). A. Bross et al, Phys.Rev.D77:093012,2008. (arXiv:0709.3889)

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.

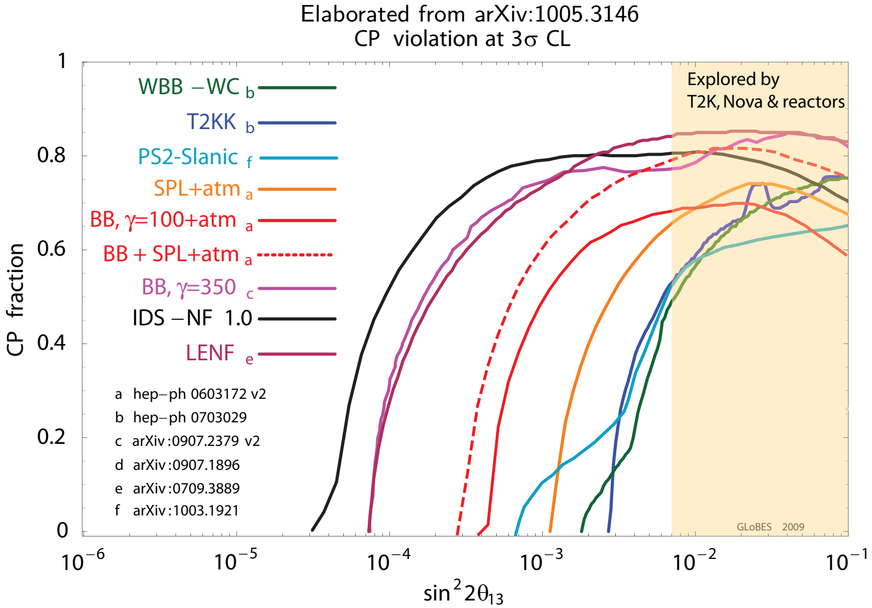
Sensitivity Comparison: θ_{13}



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



Sensitivity Comparison: LCPV



Sensitivity Comparison: LCPV

Additional Slides

Conclusions

- Neutrino oscillations have many foundamental results to offer, and maybe unexpected surprises. Certainly not for free.
- Future experiments will probably require innovative instruments rather than brute force.
- Beta Beams are a realistic possibility solving most of the bottlenecks of conventional neutrino beams.
- They require anyway R&D and manpower, so far they are funded only by EU funds.
- There are several very interesting develoments of the Beta Beams concept that can allow interesting future upgrades.