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“ Future CP violation searches in the lepton sector, accelerator based ”

- **Introduction**
- **Super Beams**
- **Beta Beams**
- **Neutrino Factories**

A bottom-up perspective.

International Workshop on “Fundamental Symmetries: from nuclei and neutrinos to the Universe”,

ECT* Trento, 25 - 29 June 2007

Introduction

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Near future neutrino oscillations experiments: T2K, Double Chooz (Noνa, Daya Bay), will not be enough to exhaust neutrino oscillations searches: they will be unable to unambiguously measure mass hierarchy and leptonic CP violation, whatever value of θ_{13} .

A new generation of neutrino oscillation experiments will be needed. It could be based again on conventional neutrino beams (SuperBeams) or on neutrino beams of new concept: Beta Beams and/or Neutrino Factories.

Europe it could be the site of next to next generation experiments.

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Europe it could be the site of next to next generation experiments.

A list of frequently asked questions:

- Shouldn't we wait to know θ_{13} before proposing these facilities?
- Is it possible to design an optimal facility for a simultaneous measure of θ_{13} , δ_{CP} and $\mathrm{sign}(\Delta m^2)$?
- Is it possible to design an optimal facility for leptonic CP violation searches regardless of the value of θ_{13} ?
- Do we have a clear picture of the R&D, timescales, costs and performances of the proposed new facilities?
- Is it Europe big and coherent enough to propose one of the new facilities?

Most of the neutrino oscillation parameters are waiting to be measured

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} ✓ ATMOSPHERICS $\delta m^2_{23} = (2.4 +/- 0.4)\ 10^{-3}\ eV^2$

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

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

LSND/Steriles

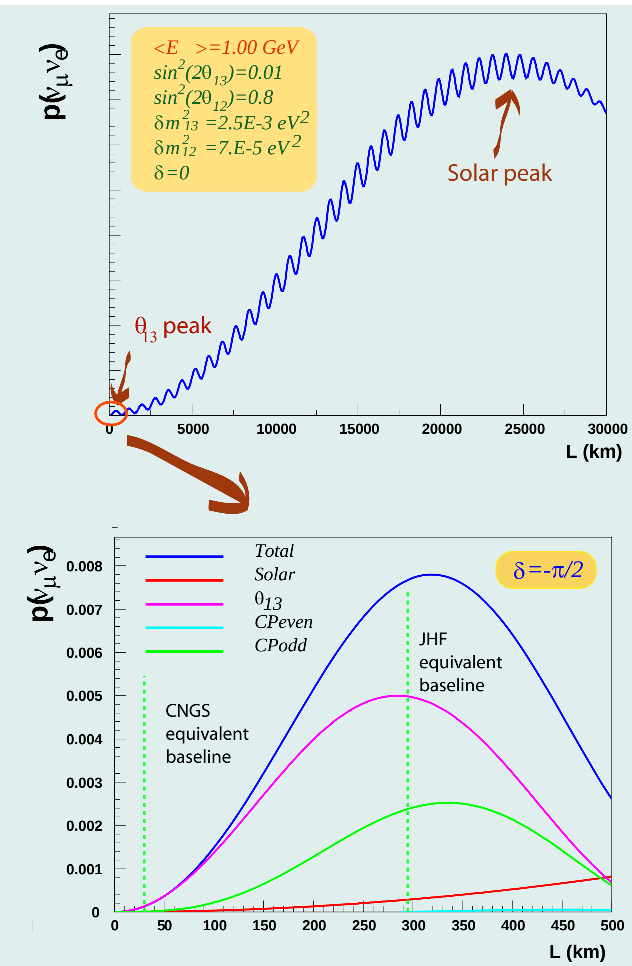
δ_{CP}

Mass hierarchy

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

Dirac/Majorana

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



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

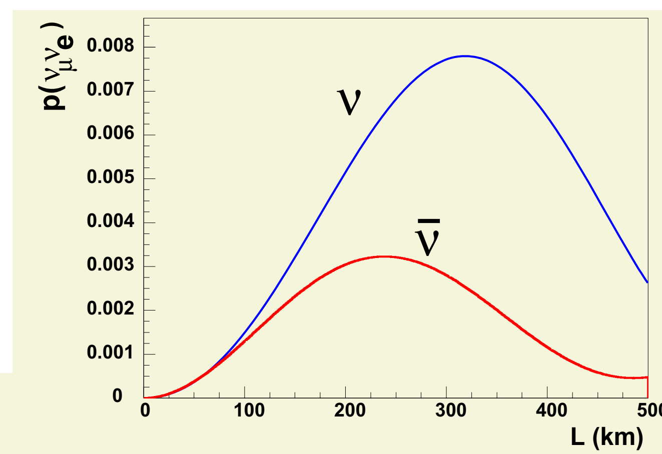
$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \text{ CPeven}$$

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

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

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

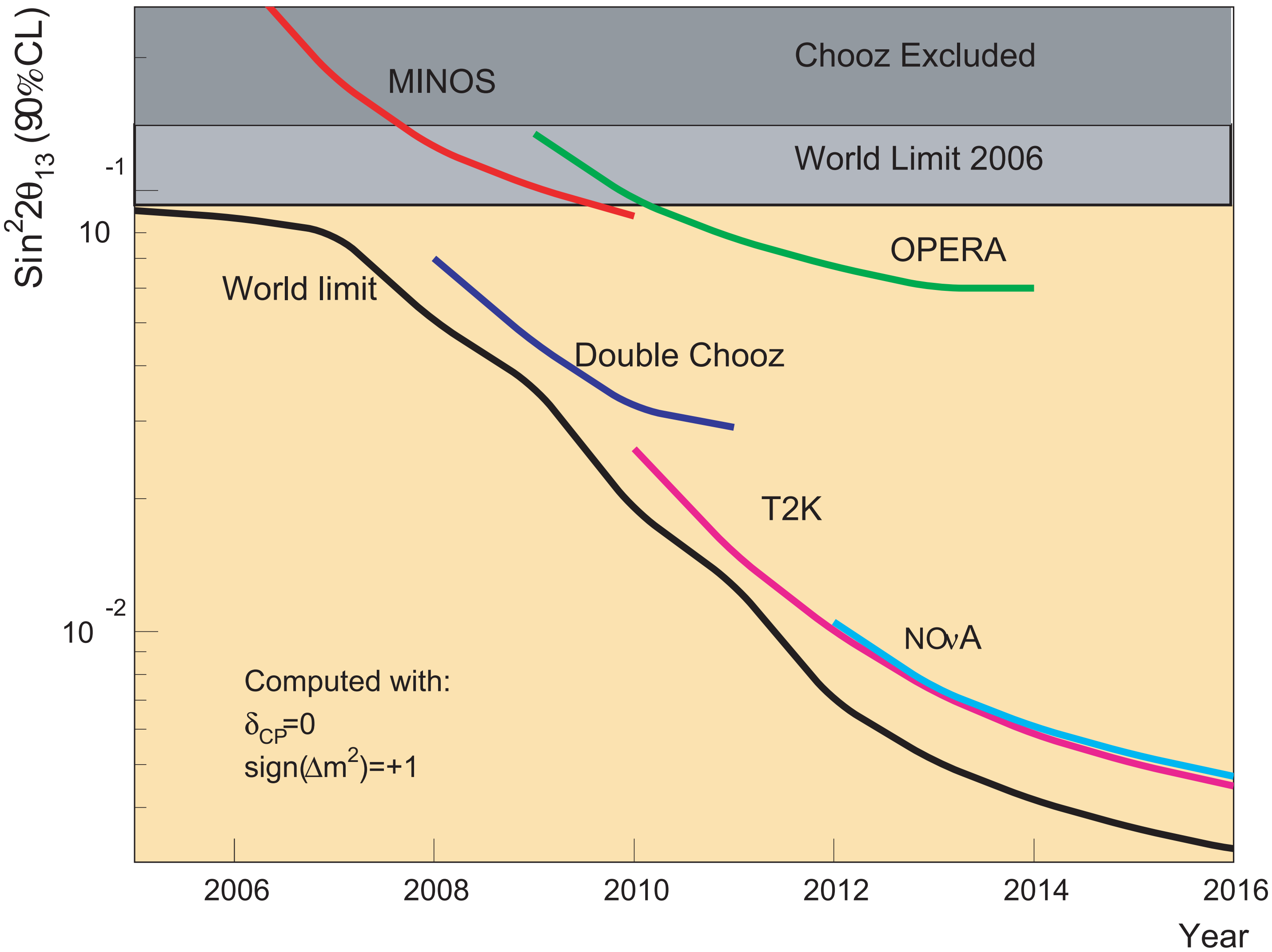
θ_{13} discovery requires total probability ($\propto \sin^2 2\theta_{13}$) greater than solar driven probability



Leptonic CP discovery requires

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

Status after the first and second generation: θ_{13}



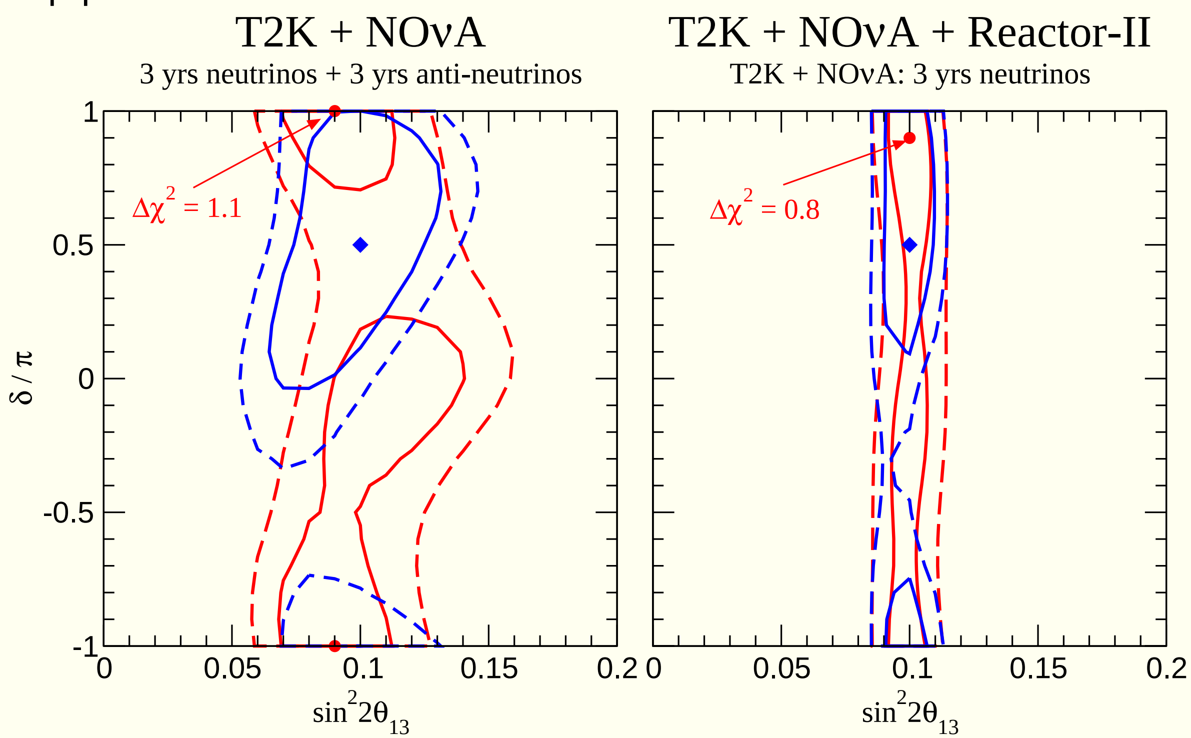
T2K: Start in 2009, latest default beam power curve.

NOνA: Start in 2011, 20 kton, $6 \cdot 10^{20}$ pot/yr

Status after the first and second generation: δ_{CP}

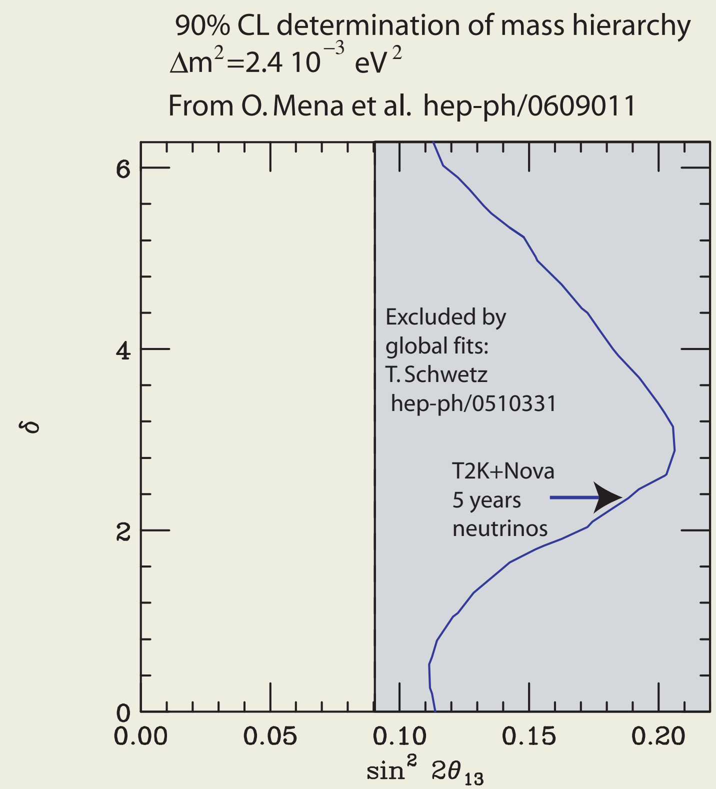
No hope to see any CP signal at 3σ

From P. Huber, M. Lindner, M. Rolinec, T. Schwetz and W. Winter, hep-ph/0412133.



(dotted lines: 3σ, solid are 90%CL)

. . . and mass hierarchy



To address leptonic CP violation: improve of at least one order of magnitude the sensitivity of $\sin^2 2\theta_{13}$; two order of magnitudes more neutrinos !!!

The SuperBeam way

Proposals based on upgrades of existing facilities:

- T2K $\Rightarrow$ T2HK or T2KK
- Noνa $\Rightarrow$ Super Noνa
- CNGS $\Rightarrow$ off-axis CNGS fired on a gigantic liquid argon detector
- AGS Brookhaven $\Rightarrow$ wide band beam fired on a gigantic water Cerenkov detector.

Proposals based on new facilities

- CERN-SPL SuperBeam

SuperBeams - J-PARC phase 2 (T2HK)

Upgrade the proton driver from 0.75 MW to 4 MW

Upgrade SuperKamiokande by a factor $\sim 20 \Longrightarrow$ HyperKamiokande

Both upgrades are necessary to address leptonic CP searches.

The detector would have valuable physics potential in proton decay, SN neutrinos, solar neutrinos.

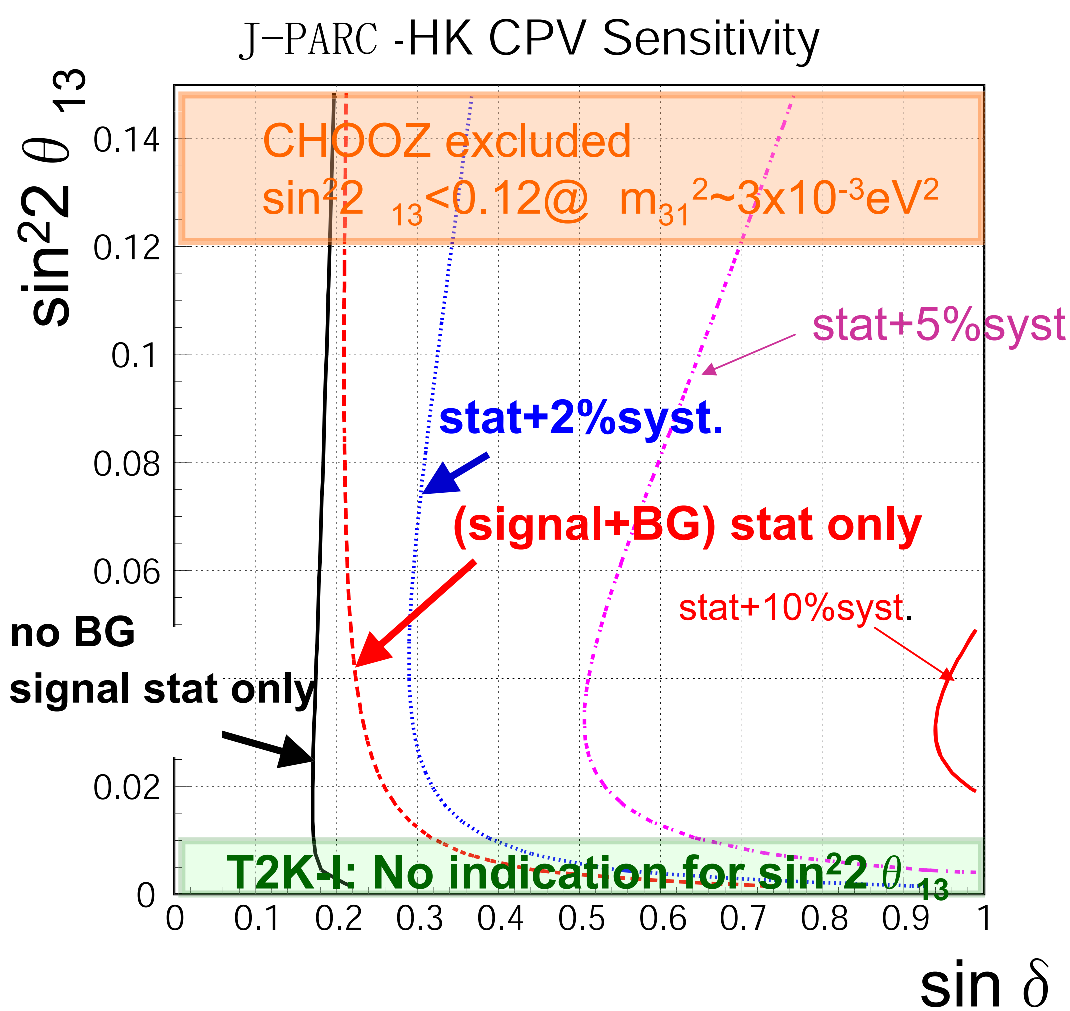
Its cost: ~ 0.5 G$

Systematics at 2% are difficult

4 MW at 50 GeV/c are difficult

Targetry and optics at 4 MW are difficult and will probably require some compromise

T. Kobayashi, J.Phys.G29:1493(2003)



The MODULAr project

- First study of off-axis CNGS to a liquid argon detector by A. Meregaglia and A. Rubbia, JHEP **0611** (2006) 032
- MODULAr is a LoI by the ICARUS collaboration: B. Baibussinov *et al.*, arXiv:0704.1422 [hep-ph].

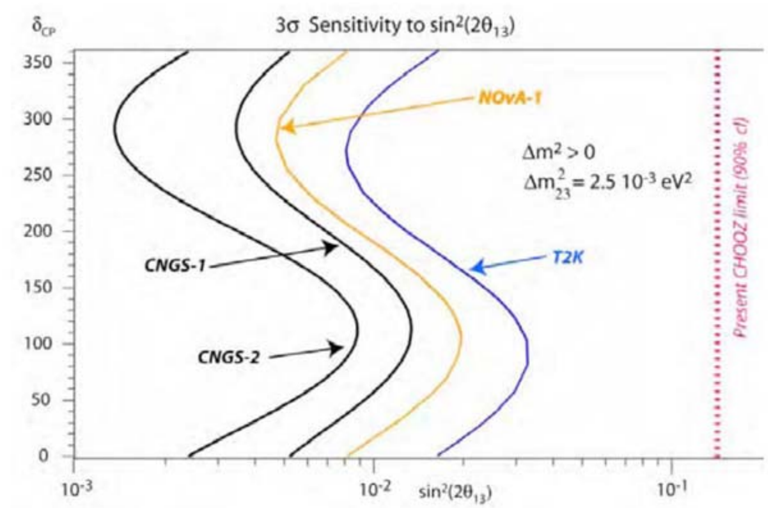
– Have $1.2 \cdot 10^{20}$ pot/yr at the CNGS (about 3 times more than today).

– Design a new opticts (actually cloned by the NuMI optics) to reduce the mean neutrino energy below 10 GeV.

– Dig a new cavern, shallow depth, at the baseline of 732 km, 10 km off-axis CNGS direction.

– Install a 20 kton liquid argon detector.

– Additional details by the recent Cryodet2 workshop at LNGS: `http://cryodet.lngs.infn.it/`



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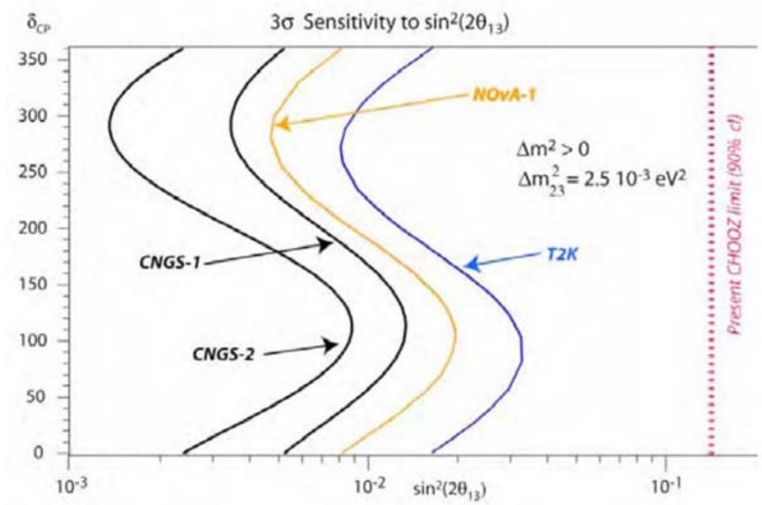
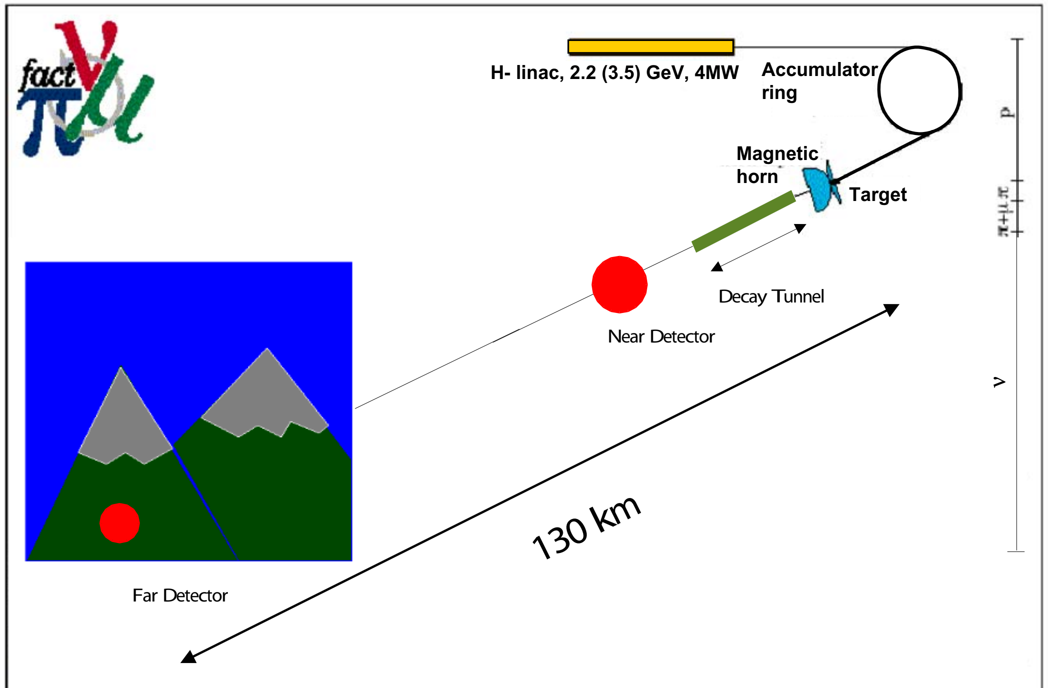


- For the proton capabilities of the CNGS see M. Meddahi and E. Shaposhnikova, "Analysis of the maximum potential proton flux to CNGS", CERN-AB-2007-013-PAF, 01 Apr 2007.

  $1.2 \cdot 10^20$ pot/yr requires hardware upgrades of the SPS injection chain and the suppression of the fixed target experiments at CERN.
- According to A. Meregaglia and A. Rubbia a CP sensitivity comparable with T2HK can be reached with $4.2 \cdot 10^{20}$ pot/yr and a 100 kton liquid argon detector.

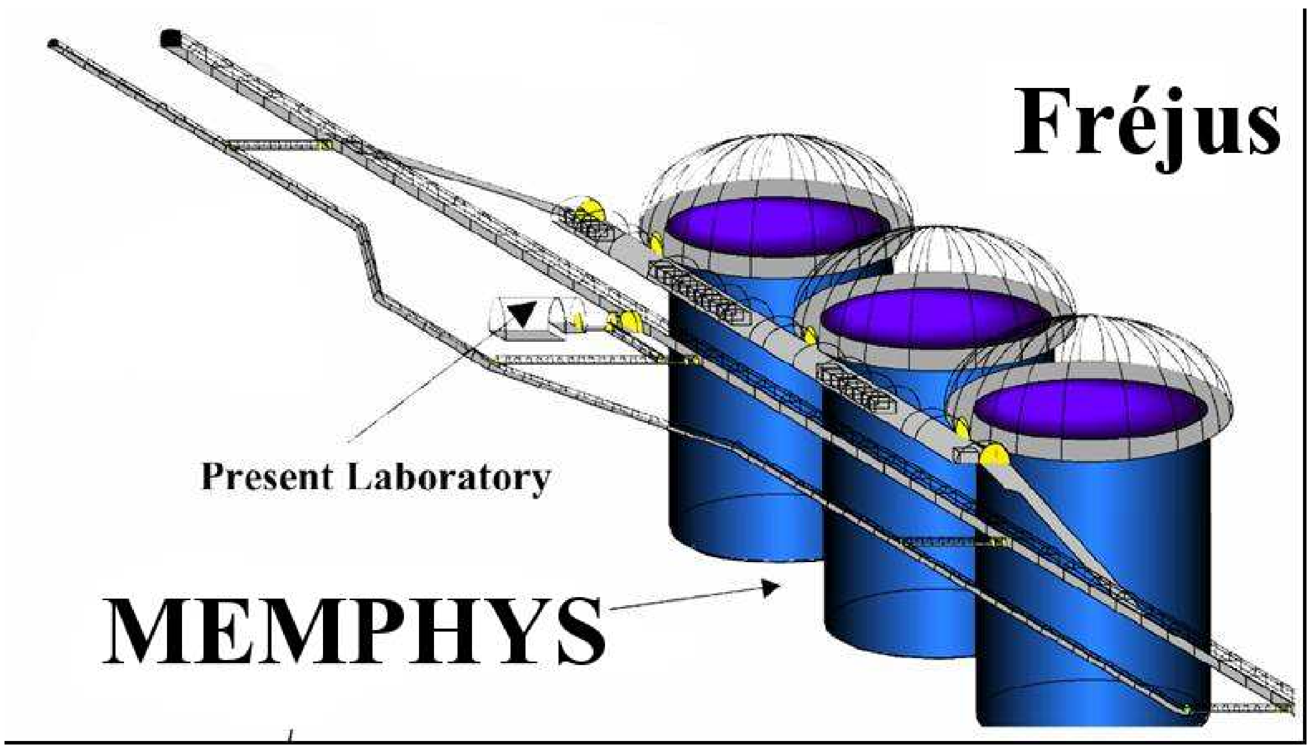
SuperBeams - SPL ν beam at CERN



Possible Low Energy Super Beam Layout

- A 3.5 GeV, 4MW Linac: the SPL.
- A liquid mercury target station capable to manage 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 measure at 2% signal and backgrounds.
- A megaton class detector under the Frejus, L=130 km: Memphys.

The Memphys detector (hep-ex/0607026)



In the middle of the Frejus tunnel at a depth of 4800 m.w.e a preliminary investigation shows the feasibility to excavate up to five shafts of about 250,000 m^3 each ($\Phi = 65\,m$, full height=80 m).

Fiducial of 3 shafts: 440 kton.

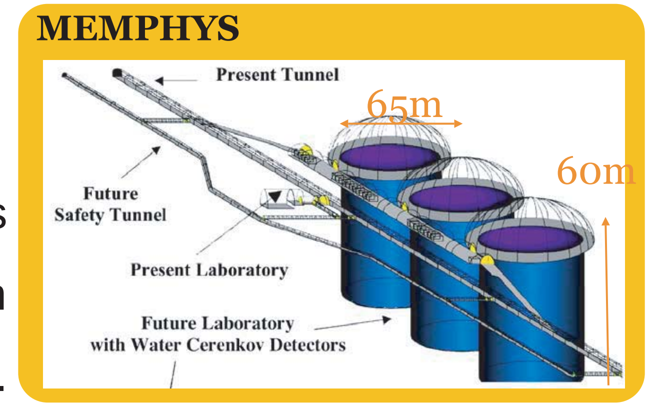
30% coverage by using 12“ PMT's from Photonis, 81k per shaft (with the same photostatistics of SuperKamiokande with 40% coverage)

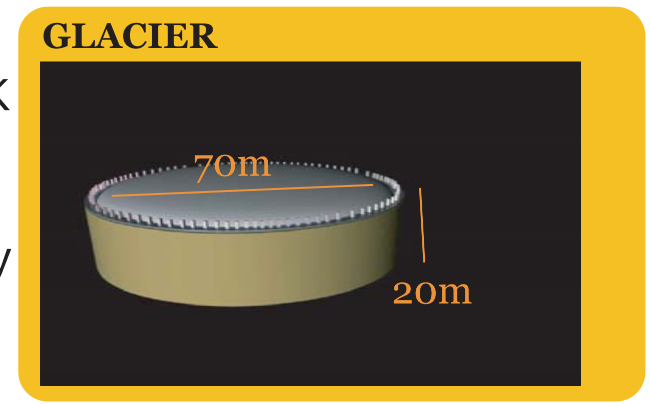
Laguna (arXiv:0705.0116 [hep-ph])

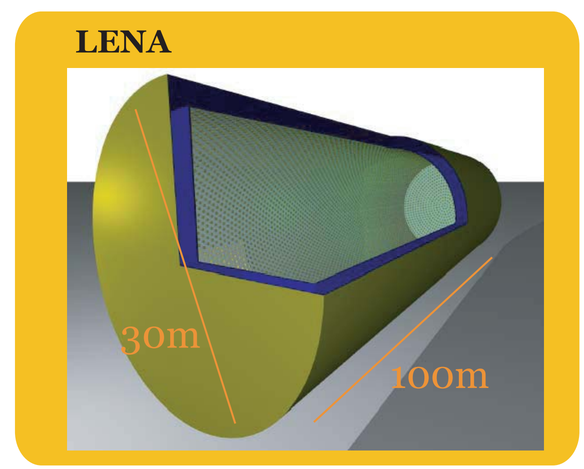
A coordinated European effort aimed towards conceptual designs for European large underground detectors.Physics focus: proton decay, low energy neutrino astronomy, long baseline neutrino beam. Three detection techniques are currently investigated:

- Water Cerenkov imaging, ~ 500 kton, with synergy with HK (Japan) and UNO (USA).
- Liquid argon time-projection chamber, ~ 100 kton. Technology pioneered in Europe by the ICARUS R&D programme.
- Liquid scintillator, ~ 50 kton connected to Borexino R&D programme

Feasibility studies for site excavation are mandatory to build the required infrastructure ho host these very large detectors, also under contrlled cost boundaries.
A request to a European FP7 Design Study has been submitted.







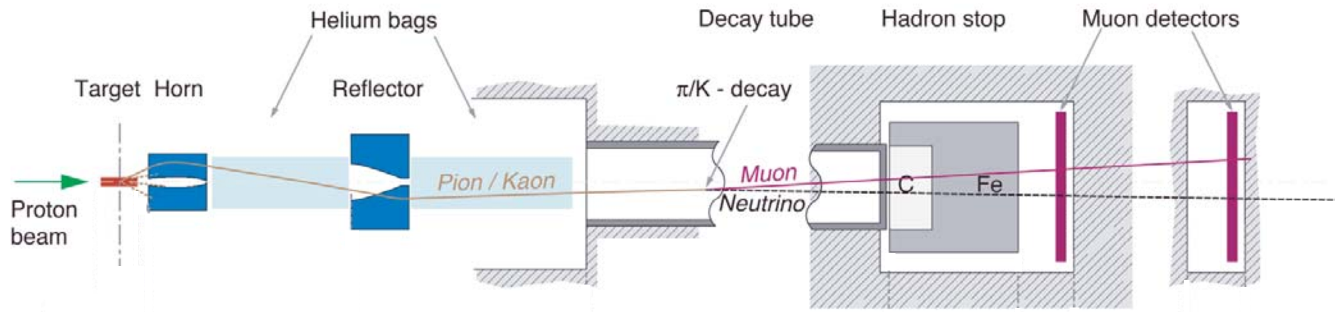
The merits of the "short baselines"

- Absolutely negligible matter effects: the cleanest possible environment for direct leptonic CP violation and θ_{13} searches.
- Almost all the events are quasi elastics: very reduced problems from the QE-not QE ratios.
- Energy shape it's not a problem, a reasonable binning can be achieved (see later slides).
- In principle the same energy of a SPS based beta beam. The two beams could be fired to the same detector.

On the other hand

- Mass hierarchy cannot be directly measured. A not trivial sensitivity on $\mathrm{sign}(\Delta m^2)$ can however been recovered combining accelerator neutrino signals with the atmospherics' (see later slides).
- Small cross sections, loosely known and with important influence of nuclear effects.

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.
- Difficult to tune the energy of the beam in case of ongoing optimizations.

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)**:

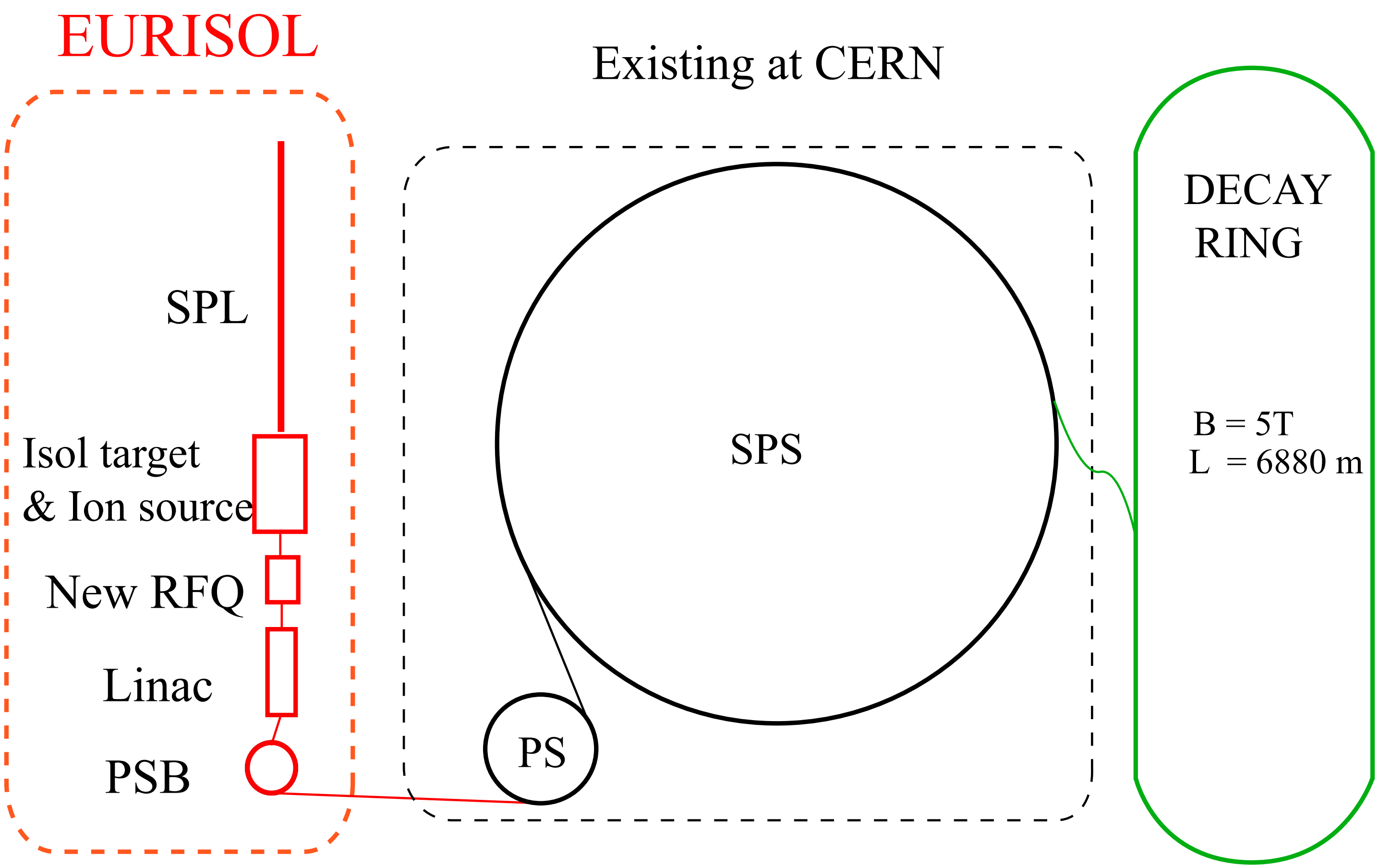
- Just one flavor in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the γ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by γ.

The full ^{6}He flux MonteCarlo code

```
Function Flux(E)
Data Endp/3.5078/
Data Decays /2.9E18/
ye=me/EndP
c ...For ge(ye) see hep-ph0312068
ge=0.0300615
2gE0=2*gamma*EndP
c ...  Kinematical Limits
If(E.gt.(1-ye)*2gE0)THEN
   Flux=0.
   Return
Endif
c ...Here is the Flux
Flux=Decays*gamma**2/(pi*L**2*ge)*(E**2*(2gE0-E))/
+ 2gE0**4*Sqrt((1-E/2gE0)**2-ye**2)
Return
```

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

M. Lindroos et al., see http://beta-beam.web.ch/beta-beam

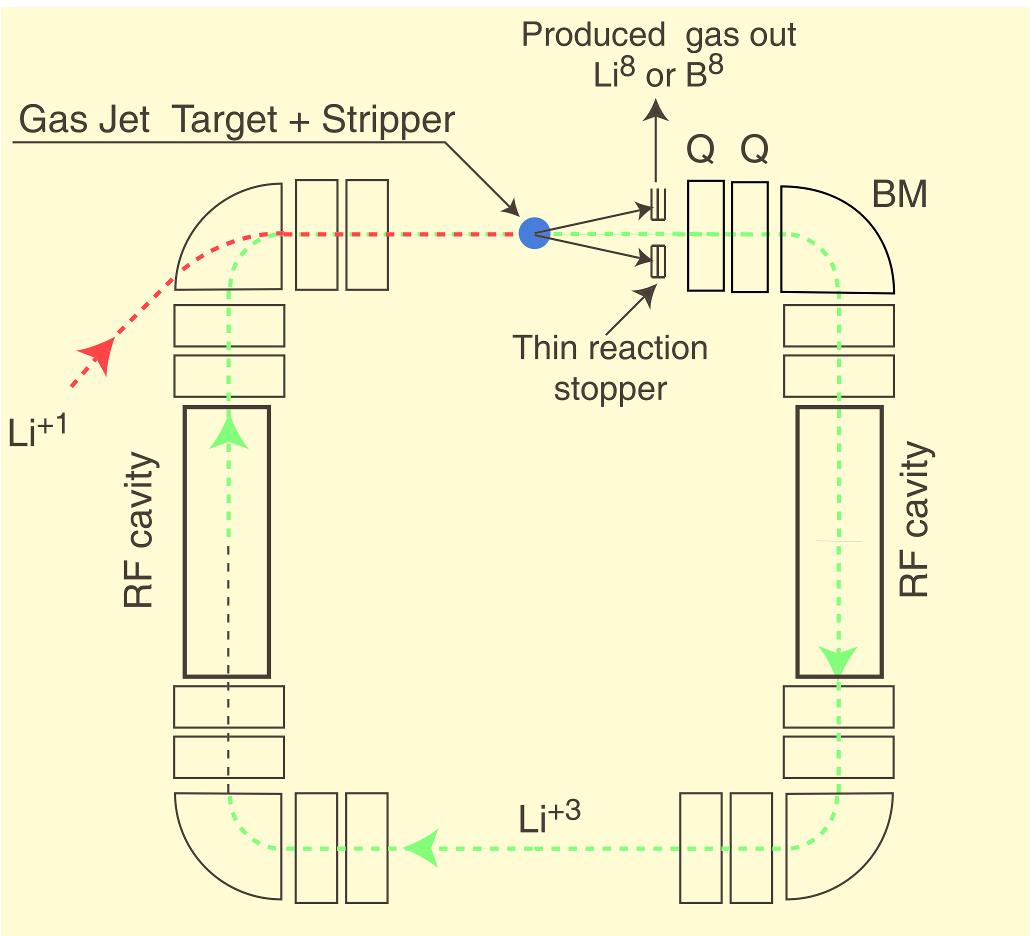


- 1 ISOL target to produce He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 1.1 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.
- These fluxes apply if the two ions are run separately

Exciting new ideas about radioactive ion production

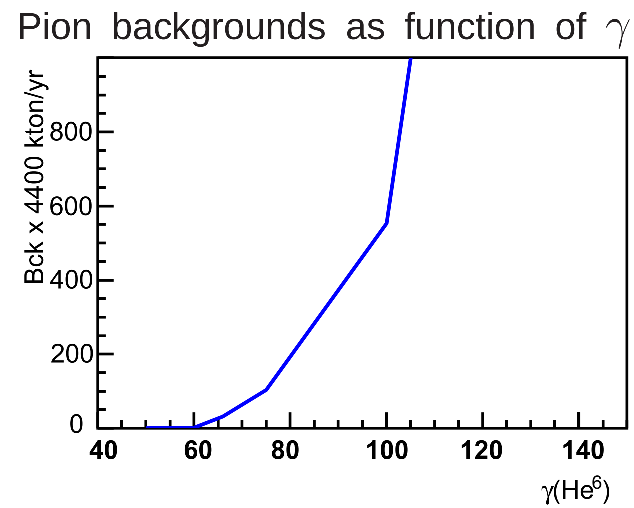
C. Rubbia et al., hep-ph/0602032

C. Rubbia hep-ph/0609235

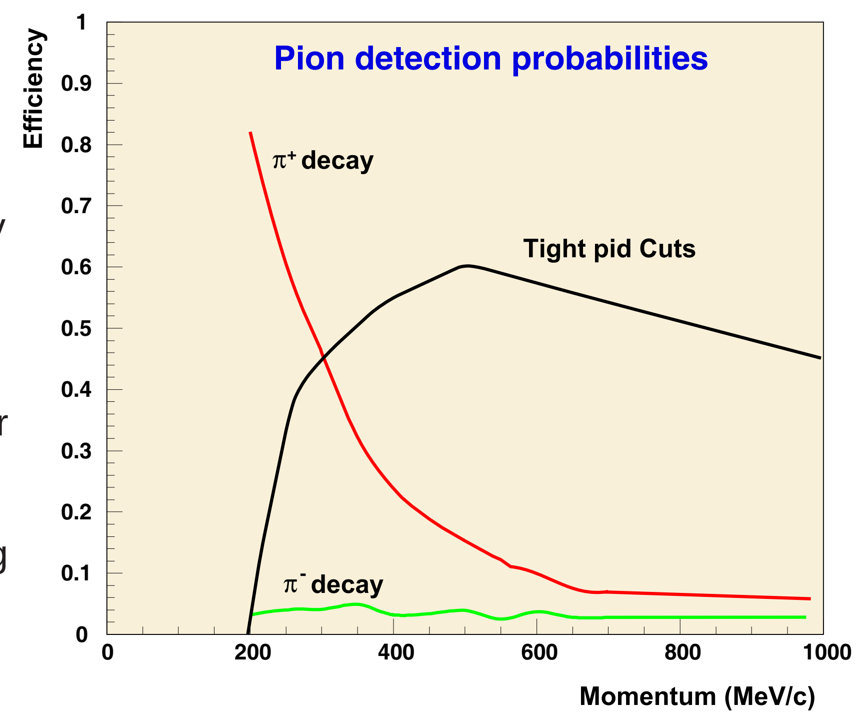


- It could deliver up to two order of magnitudes more radioactive ions than the Eurisol targets.
- ^{8}B and ^{8}Li have a Q factor about 8 times larger than ^{6}He and ^{18}Ne, allowing higher neutrino energies for the same γ value (on the other hand for the same neutrino energy the relative flux is lower by $1/\gamma$ due to the smaller Lorenz boost.)
- They have a more favorable Z/A factor, allowing for higher γ at the same accelerator.
- If realistic, this production method could bring to a completely different Beta Beam optimization scheme.

The pion background: a potential Beta Beam killer?



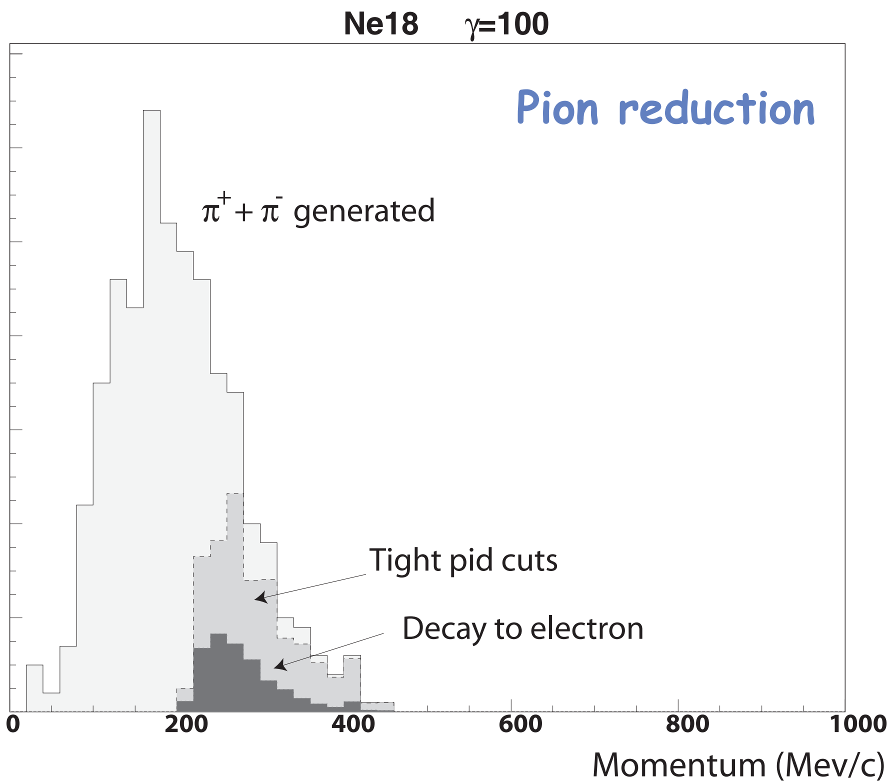
The pions generated in NC events can fake the muon signal. **They are the main concern.**



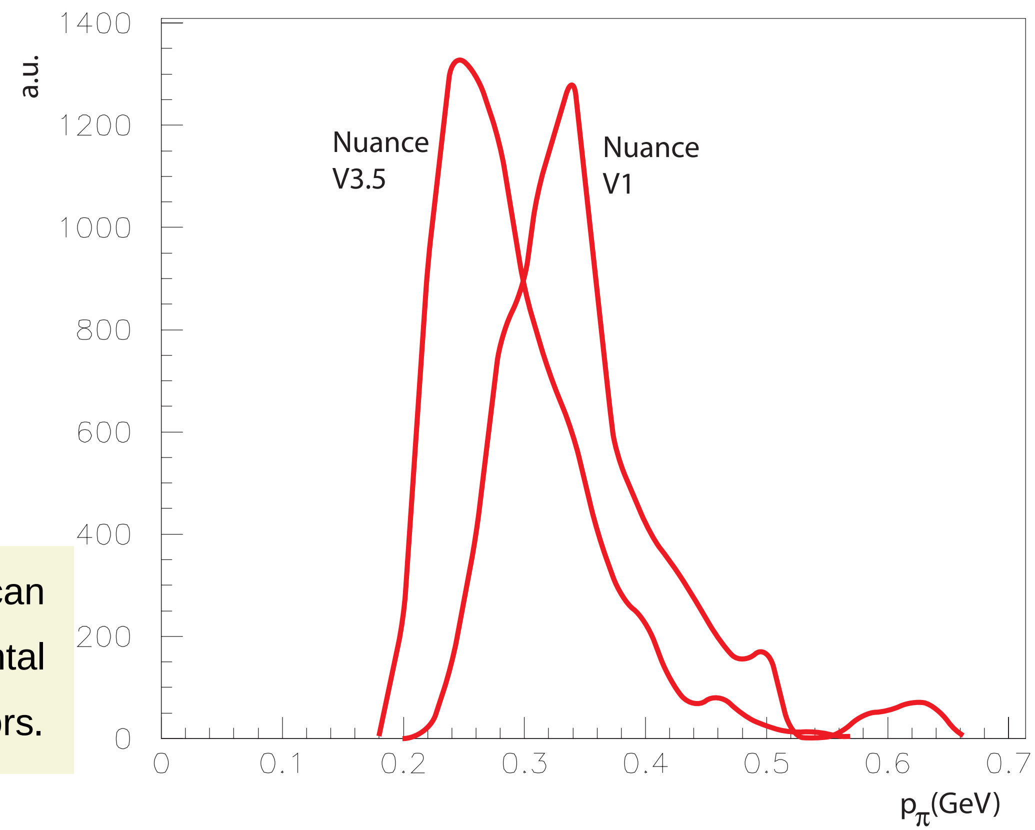
To estimate these backgrounds

- 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 particle identification 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.)



	Ne18			He6		
	ν_μ	π^+	π^-	$\overline{\nu}_\mu$	π^+	π^-
generated	133078	560	334	113631	673	400
pid	105923	202	102	83419	241	119
decay	67888	106	8	67727	121	7



Pion production cross sections and nuclear effects can heavily change these numbers and the overall experimental sensitivity. Potentially the worst source of systematic errors.

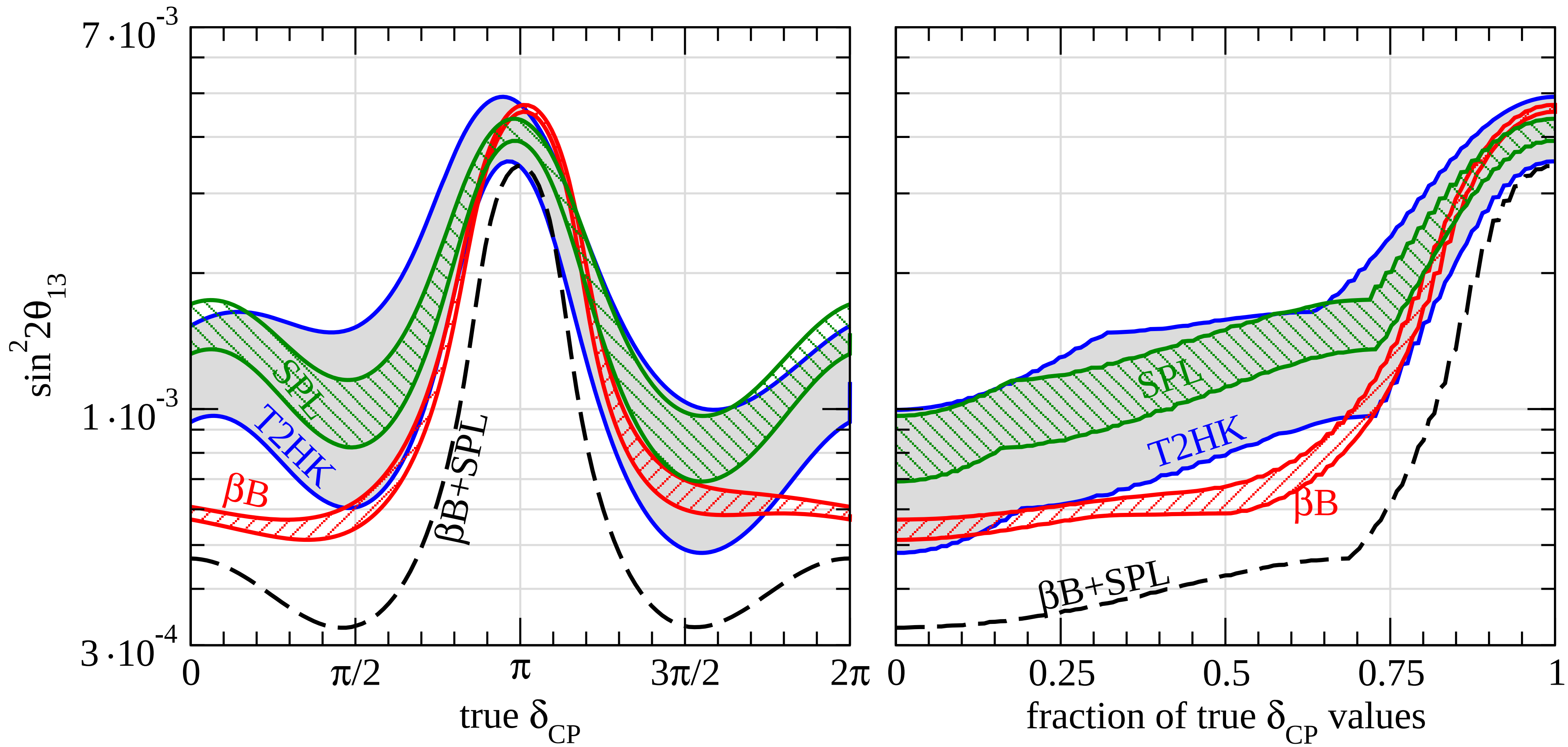
Oscillation signals

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

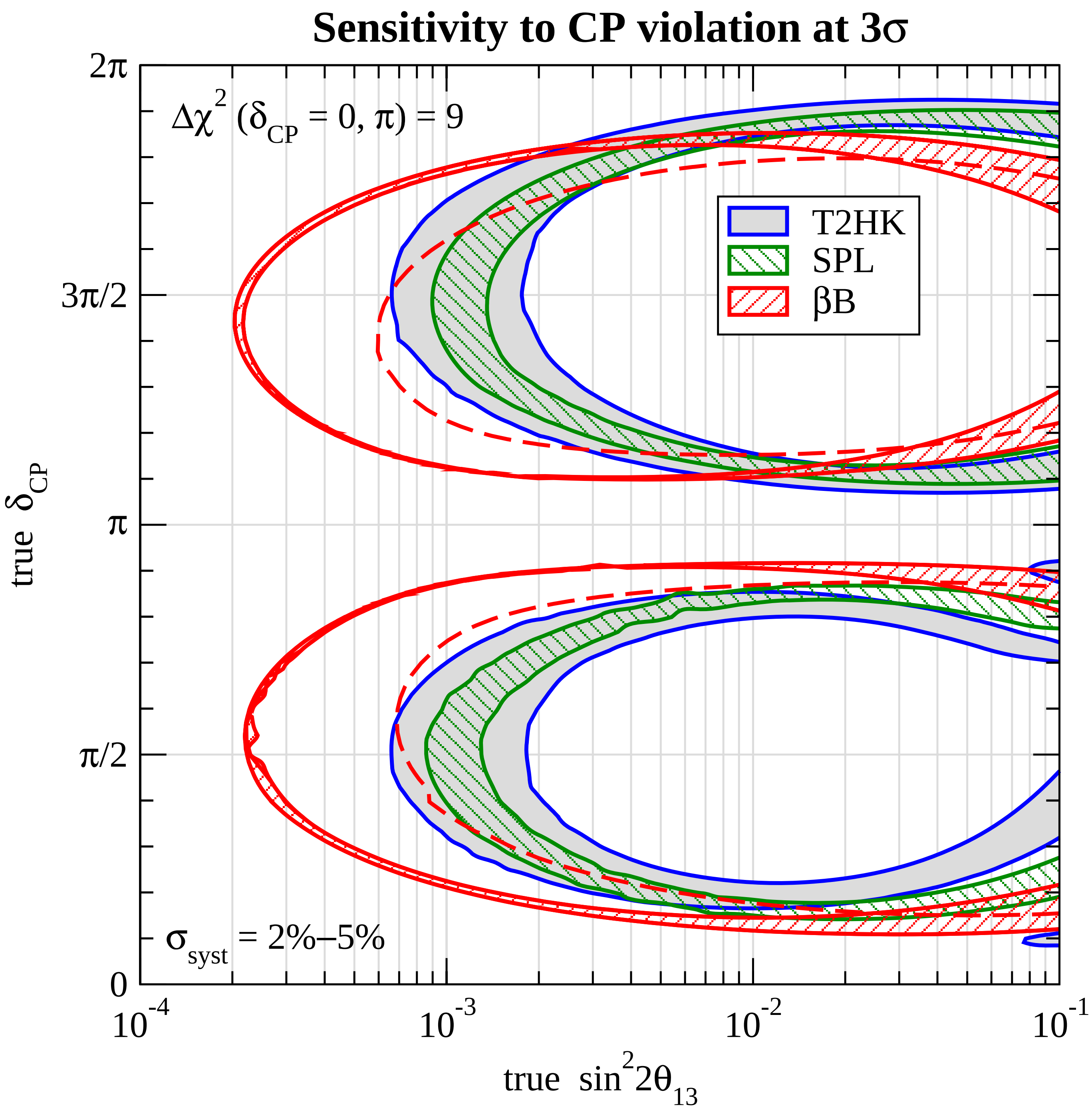
	βB		SPL		T2HK	
	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$
appearance ν						
background	143		600		1017	
$\sin^2 2\theta_{13} = 0$	25		41		84	
$\sin^2 2\theta_{13} = 10^{-3}$	72	81	93	10	181	18
$\sin^2 2\theta_{13} = 10^{-2}$	310	339	387	126	754	240
appearance $\bar{\nu}$						
background	157		500		1428	
$\sin^2 2\theta_{13} = 0$	30		36		90	
$\sin^2 2\theta_{13} = 10^{-3}$	82	12	74	104	188	261
$\sin^2 2\theta_{13} = 10^{-2}$	346	125	297	390	746	977

Computed with $\Delta m^2_{31} = +2.4 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{21} = 7.9 \times 10^{-5}\ \mathrm{eV}^2$, $\sin^2\theta_{12} = 0.3$. with an accuracy of 10% for θ_{12}, θ_{23}, Δm^2_{31}, and 4% for Δm^2_{21} at 1σ.

3σ discovery of a non-zero θ_{13}



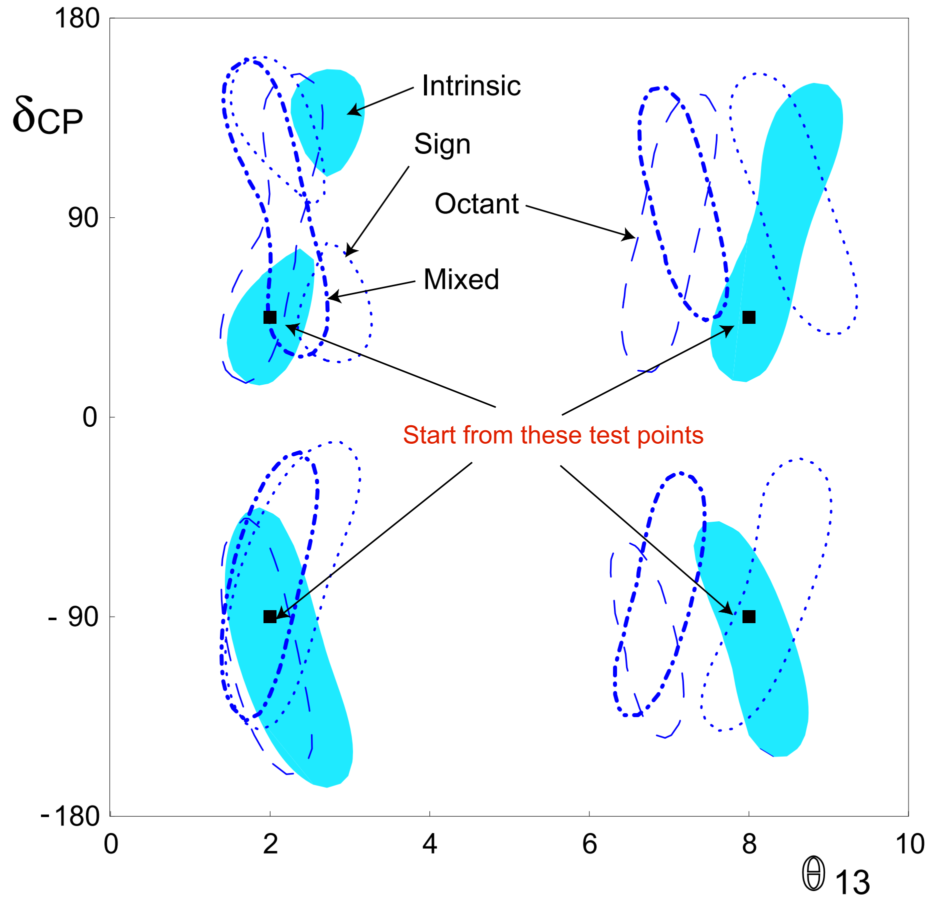
Line width: 2% and 5% systematic errors.


Sensitivity to CP violation at 3σ
Δχ² (δ_CP = 0, π) = 9
T2HK
SPL
βB
σ_syst = 2%–5%
2π
3π/2
π
π/2
0
true δ_CP
10^-4
10^-3
10^-2
10^-1
true sin²2θ_13

The degeneracy problem

The sub-leading $\nu_\mu \rightarrow \nu_e$formula leaves room for clone solutions of the fit to θ_{13} and $\delta_{\rm CP}$. The eightfold degeneracies arise from

- $\mathbf{sign(\Delta m^2)}$. Changing $\mathrm{sign}(\Delta m^2)$ the $P(\nu_\mu \rightarrow \nu_e)$terms $\propto$ $\sin(\Delta m^2_{23})$ change sign. Two separate solutions can be created by $(\theta_{13}, \delta_{\rm CP}, \mathrm{sign}(\Delta m^2))$ and by $(\theta_{13}', \delta_{\rm CP}', -\mathrm{sign}(\Delta m^2))$.
- $\boldsymbol{\pi/2 - \theta_{23}}$ (octant) . ν_μ disappearance measures $\sin^2 2\theta_{23}$ but some terms in the oscillation formula depend from $\sin\theta_{23}$ .At present the experimental best fit is $\sin^2 2\theta_{23} = 1$ allowing no ambiguity, but the experimental not excluded values smaller than unity allow for a twofold $\pi/2 - \theta_{23}$ ambiguity.
- **Mixed** The product of the above two



These eightfold discrete degeneracies (or twofold in case $\sin^2 2\theta_{23} \simeq 1$) can be solved by combining information of different experiments running at different energies or looking to different processes (i.e. combining $\nu_\mu \rightarrow \nu_e$ transitions with $\nu_e$disappearance or with $\nu_e \rightarrow \nu_\tau$ transitions). A single experiment cannot solve all these degeneracies by itself.

The synergy with atmospheric neutrinos

P. Huber et al., hep-ph/0501037: 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.

In the following sensitivities of the Beta Beam combined with the atmospherics are taken from J.E.Campagne, M.Maltoni, M.M., T.Schwetz, hep-ph/0603172

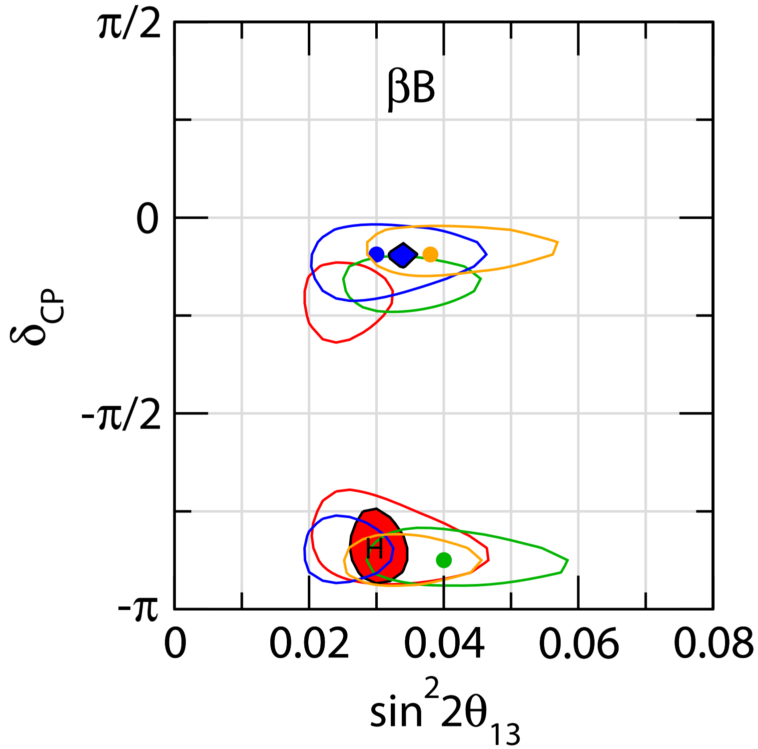
Beta Beam plus atmospherics: degeneracy removal

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

The red region is what is left after the atmospheric analysis.

Note how degeneracies were not influencing LCPV sensitivity too much.

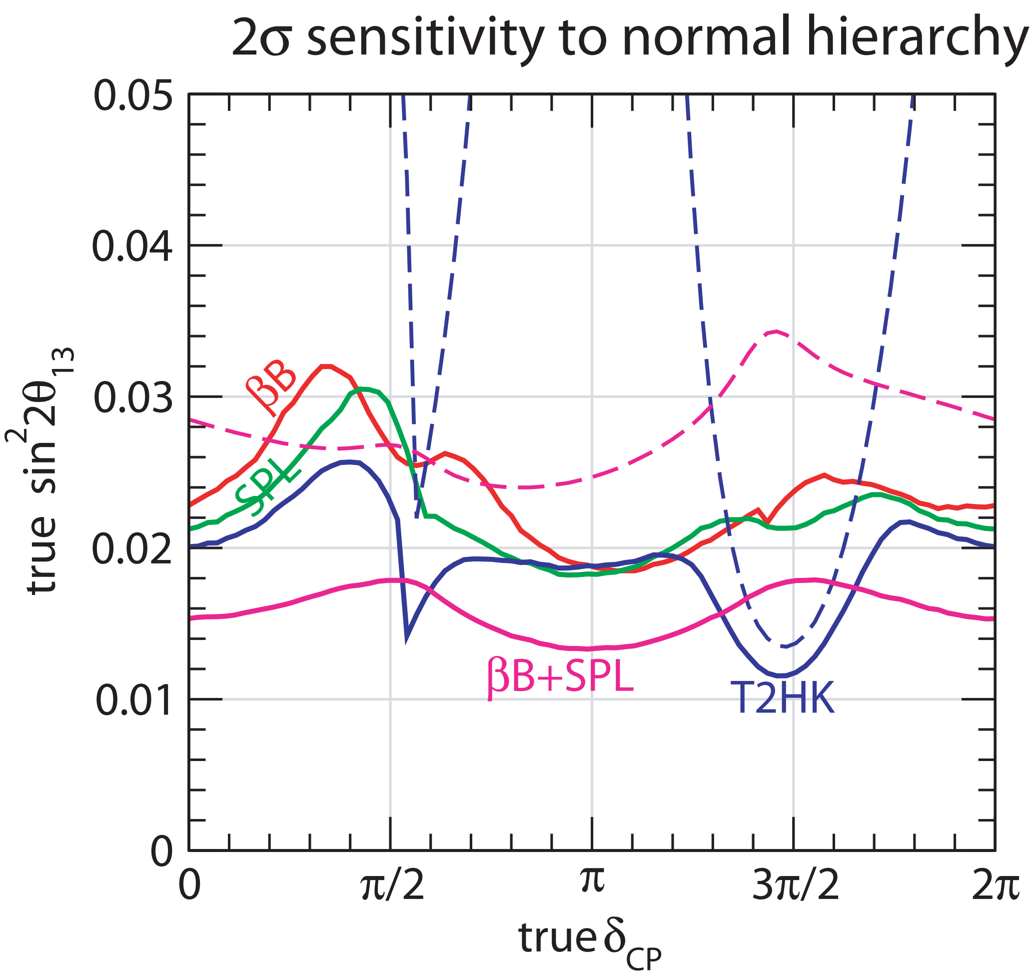
95% CL regions for the $(H^{tr}O^{tr})$, $(H^{tr}O^{wr})$, $(H^{wr}O^{tr})$, $(H^{wr}O^{wr})$ solutions

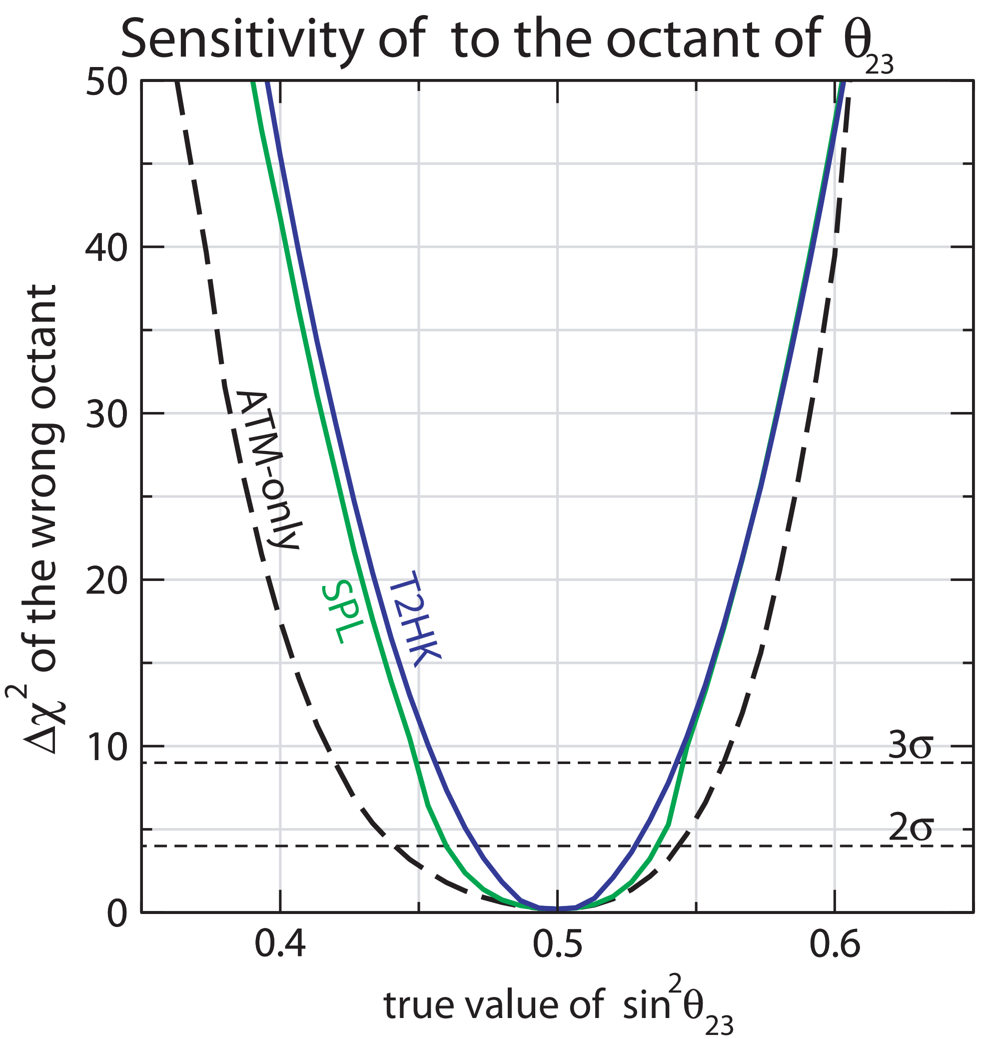


δ=-0.85 π
$\sin^2(2\theta_{13})$=0.03
$\sin^2(2\theta_{23})$=0.6

Beta Beam plus atmospherics: determining mass hierarchy and the octant

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





The high energy options

Several papers explored the physics potential of higher energy beta beams, showing how the experimental sensitivities can be improved if a higher energy accelerator than the SPS could be used (performances shown in later slides):

- J. Burguet-Castell et al., Nucl. Phys. B **695**, 217 (2004), Nucl. Phys. B 725, 306 (2005) ($\gamma = 150, 350$)
- F. Terranova et al., Eur. Phys. J. C **38** (2004) 69: $\gamma = 2500, \gamma = 4158$
- P. Huber, M. Lindner, M. Rolinec and W. Winter, Phys. Rev. D 73,053002 (with a discussion of fluxes vs. γ).
- S. Agarwalla, S. Choubey, A. Raychaudhuri, hep-ph/0610332

- Need a proton machine of 1 TeV energy (LHC cannot be used at such high fluxes)
- Assume the same ion decay rates of the SPS option.
- The decay ring length rises linearly with γ

Electron capture beams

Radioactive ions can produce neutrinos also through electron capture.

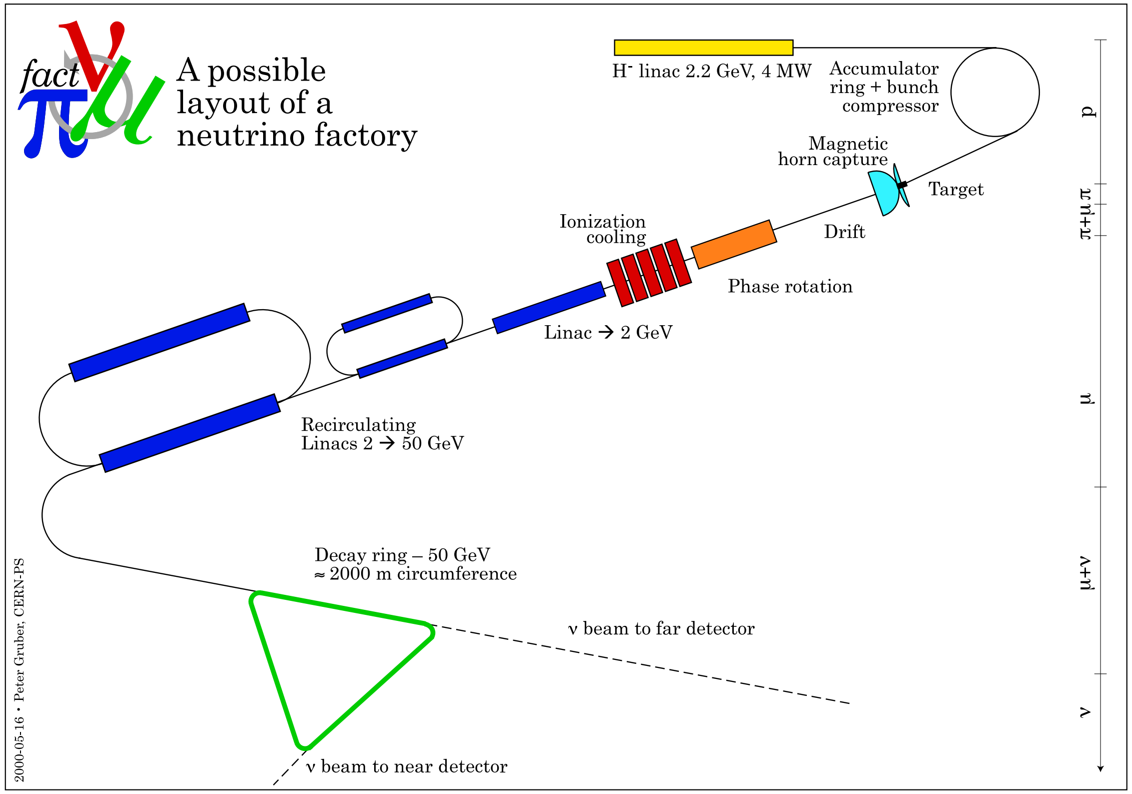
Monochromatic, single flavor neutrino beams!

- J. Bernabeu, J. Burguet-Castell, C. Espinoza and M. Lindroos, hep-ph/0505054
- J. Sato, hep-ph/0503144. M. Rolinec and J. Sato, hep-ph/0612148.

- The same complex could run either beta or electron capture beams.
- No way to have $\overline{\nu}_e$ beams.
- Ions should be partially (and not fully) stripped. Technologically challenging.
- Ion candidates are much heavier than beta candidates and have longer lifetimes (more difficult to stack them in the decay ring)

The basic concept of a neutrino factory (the CERN scheme)

- High power (4 MW) proton beam onto a liquid mercury target.
- System for collection of the produced pions and their decay products, the muons.
- Energy spread and transverse emittance have to be reduced: "phase rotation" and ionization cooling
- Acceleration of the muon beam with a LINAC and Recirculating Linear Accelerators.
- Muons are injected into a storage ring (decay ring), where they decay in long straight sections in order to deliver the desired neutrino beams.
- **GOAL: $\sim\ 10^{21}\ \mu$ decays per straight section per year**



Oscillation signals at the neutrino factory

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

Golden channel: search for $\nu_e \longrightarrow \nu_\mu$ ($\overline{\nu}_e \longrightarrow \overline{\nu}_\mu$) transitions by detecting wrong sign muons.

Default detector: 40-100 kton iron magnetized calorimeter (Minos like)

Silver channel: search for $\nu_e \longrightarrow \nu_\tau$ transitions by detecting ν_τ appearance.

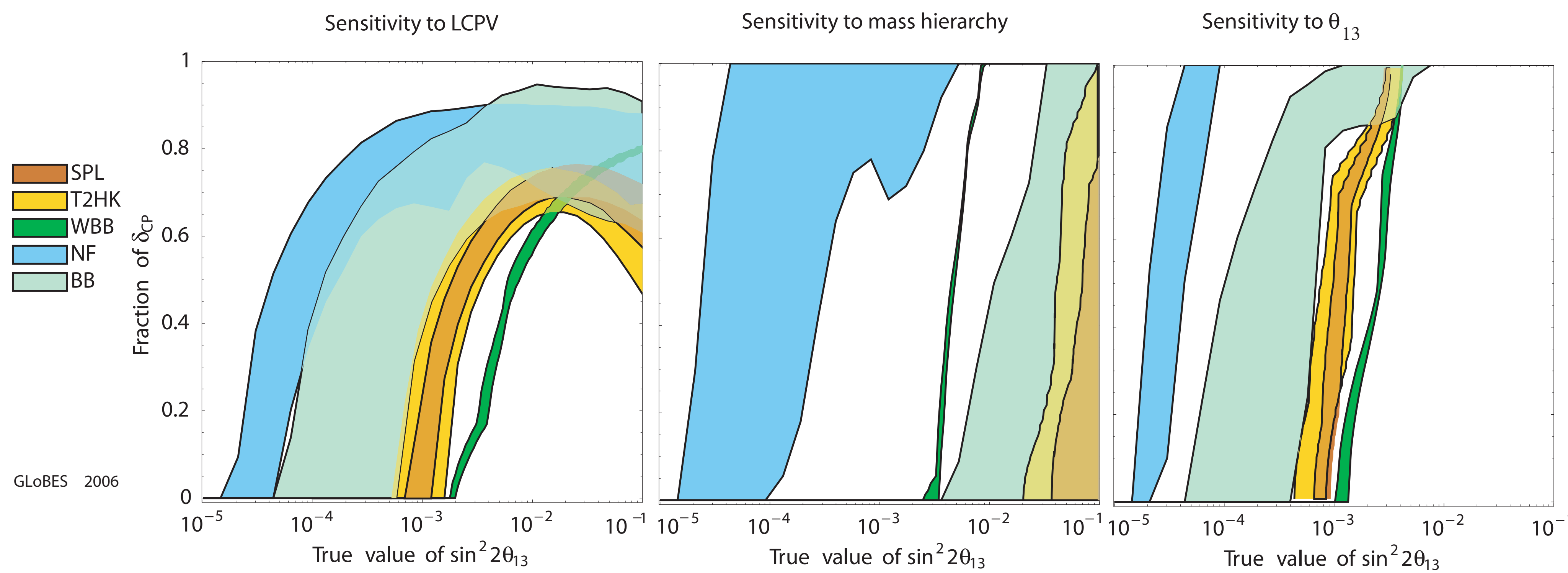
Ideal detectors: $4\times$ Opera or 10 Kton LAr detector.

All these detectors can be accomodate at LNGS.
Ideal baseline for a 50 GeV Neutrino Factory is ~ 3000 km.

ISS and European design study.

ISS stands for International Scoping study, an international effort started about 2 years ago to fully establish the possibilities and the physics potential of future neutrino beam facilities. The final document will be ready soon. Next ISS plenary meeting: CERN 29-30 March.

The neutrino phyisics community has produced a EU FP7 request for a design study of future neutrino beam facilities: EuroNu.



Line widths reflect different assumptions on machine configuration, fluxes, detector performances and systematic errors.

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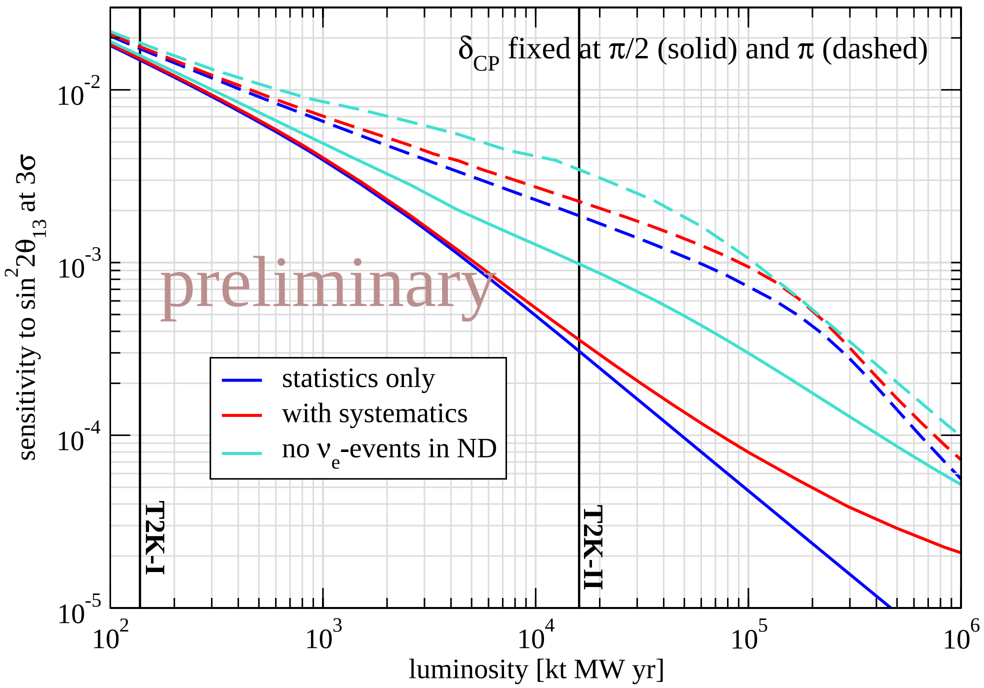
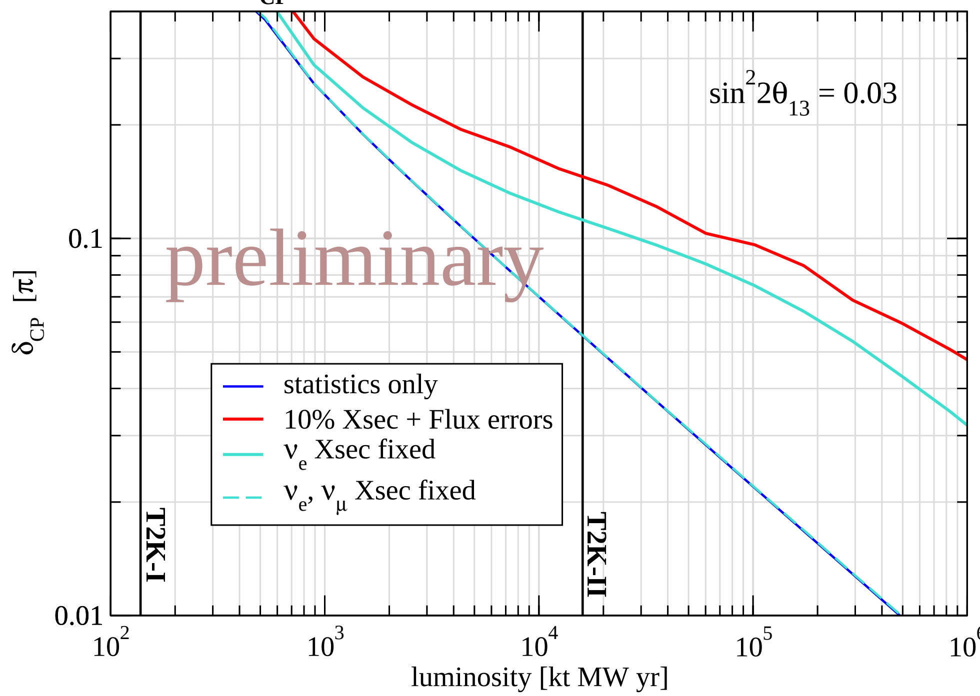
Developments in this field are up to now a bottom-up process, driven by the foundamental importance of neutrino oscillations and the enthusiasm of neutrino physicists.

Backup Slides

Effects of systematic errors

Preliminary results of a study of P. Huber, M.M. and T. Schwetz



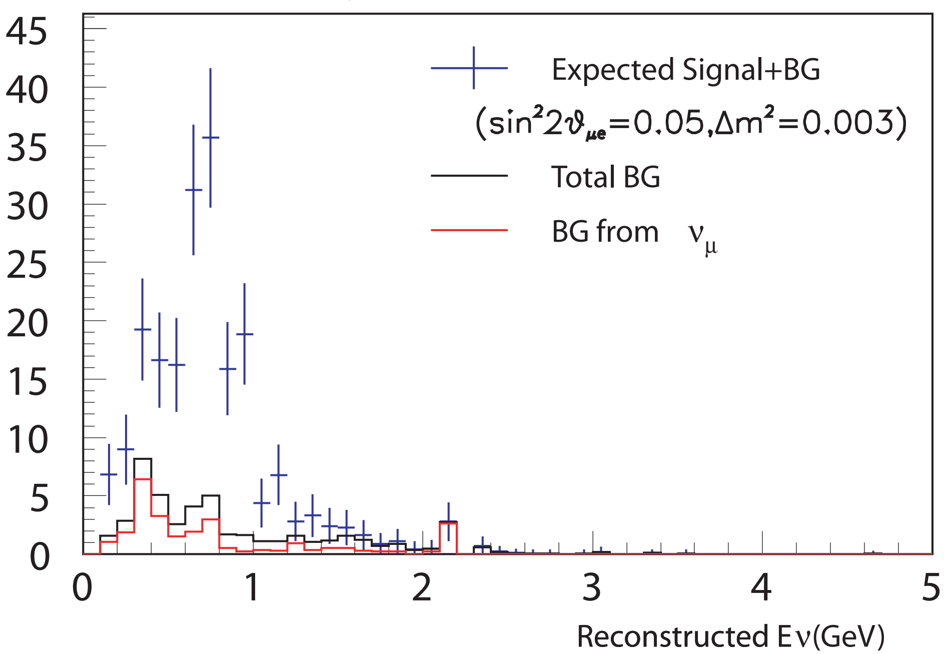


$\nu_e - \nu_e$ oscillations

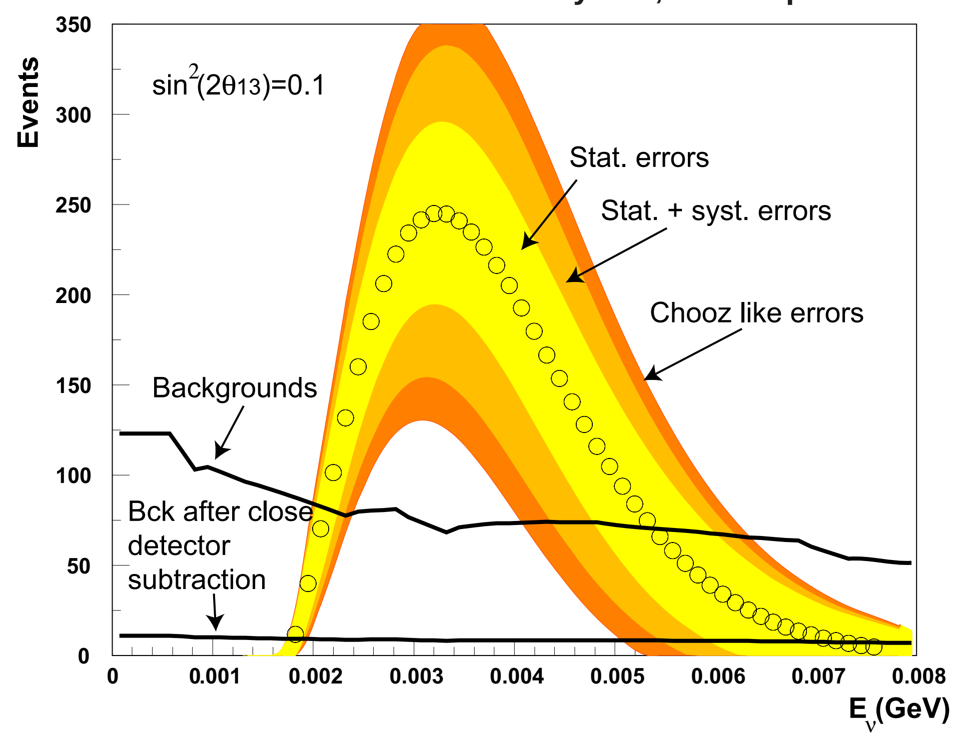
$$1 - P_{\bar{e}\bar{e}} \simeq \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E) + (\Delta m^2_{21}/\Delta m^2_{31})^2)\,(\Delta m^2_{31} L/4E)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$

- Much simpler connection between $P_{\bar{e}\bar{e}}$ and θ_{13}, no interference with $\delta_{\rm CP}$ and $\text{sign}(\Delta m^2)$.
- No way to directly measure leptonic CP violation and mass hierarchy.
- Truly complementary to the accelerator experiments.
- Disappearance experiments: systematic errors dominate over statistics.

T2K appearance signal in 5 years, from hep-ex/0106019



Double Chooz FAR-Near difference in 5 years, from hep-ex/0606025



Evolution of the Double Chooz sensitivity

Start the operation of the **far detector**, 10 m3, at t0. With no close detector, systematics dominate.

Start the operations of an identical **close detector** after 1.5 yrs. Reactors flux is identical in the two detectors. Systematics reduced.

Triple Chooz: put in operation a 200 ton far detector in a already existing cavern. Experimental sensitivity improved. See JHEP 605 (2006) 72

Time 0: scheduled to be 2008