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# “ Performances of Beta Beams at $\gamma = 100$ and Combination with Atmospheric Neutrino Data”

**This talk basically updates results of J.E.Campagne, M. Maltoni, M.M., T.Schwetz, hep-ph/0603172.**

**The analysis is powered by two great public domain tools: Nuance and Globes.**

Nufact 06, UCI, August 24-30, 2006.

## Beta Beam fluxes

This work assumes 5.8 and 2.2 $10^{18}$ decays/year for $^{6}\mathrm{He}$ and $^{18}\mathrm{Ne}$ respectively.

These intensities have been used in all the papers published so far about Beta Beam performancies, starting from the original P. Zucchelli paper.

Eurisol DS group fluxes are $2.9 \cdot 10^{18}$ useful $^{6}\mathrm{He}$ decays/year and $1.1 \cdot 10^{18}$ useful $^{18}\mathrm{Ne}$ decays/year.

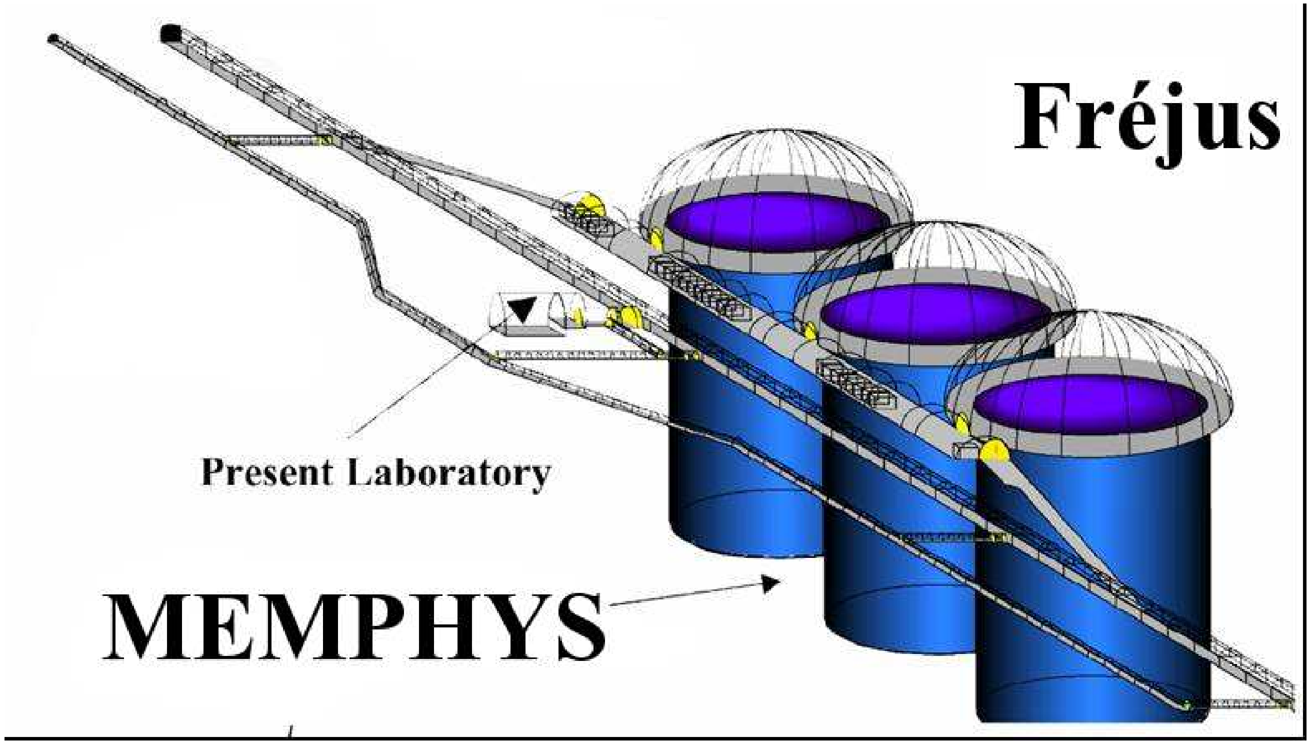
These are computed keeping PS and SPS as they are today.

By no mean they can be considered the ultimate Beta Beam fluxes.

To reach 2.2 and 5.8 (and perhaps more) the accelerator complex must be upgraded, possible solutions are delineated in M. Lindroos: “Possible ways of increasing the number of (anti-)neutrinos from the EURISOL Beta Beam facility”; EURISOL DS/TASK12/TN-05-02 (2005).

Furthermore the duty cycle bound so far imposed to the Beta Beam can be relaxed (see next slides).

## The Memphys detector (hep-ex/0607026)




In the middle of the Frjus 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)

## A new description of the Beta Beam experiment

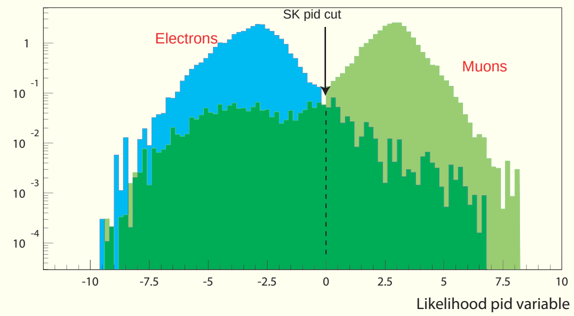
**With respect to Nufact05 and to J.E.Campagne, M. Maltoni, M.M., T.Schwetz, hep-ph/0603172.**

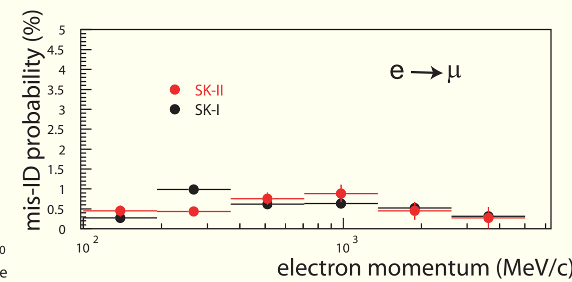
- A slightly different definition of particle identification.
- A more accurate description of energy reconstruction, with a more aggressive energy binning.
- New definition of migration matrixes.
- Pion and atmospherics background recomputed with Nuance 3.5 (they were computed with Nuance 1.0)

# 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.

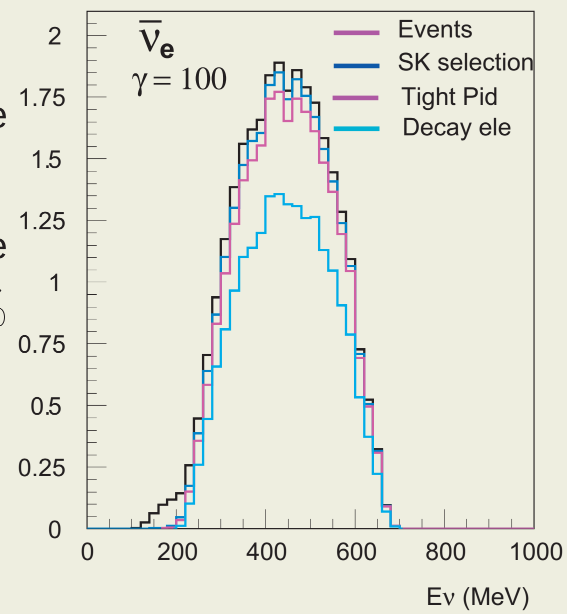


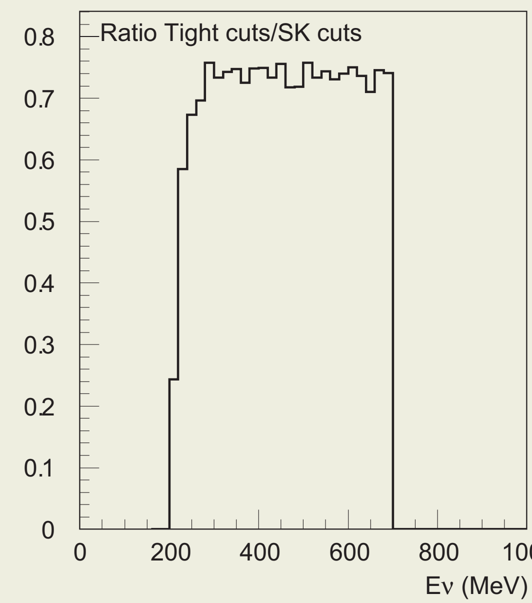




To further suppress electron background ask for the signal of the Michel electron from $\mu$ decay.

Final efficiency for positive muons $\sim 75\%$. Negative muons have an efficiency smaller by $\sim 22\%$ because they can be absorbed before decaying.

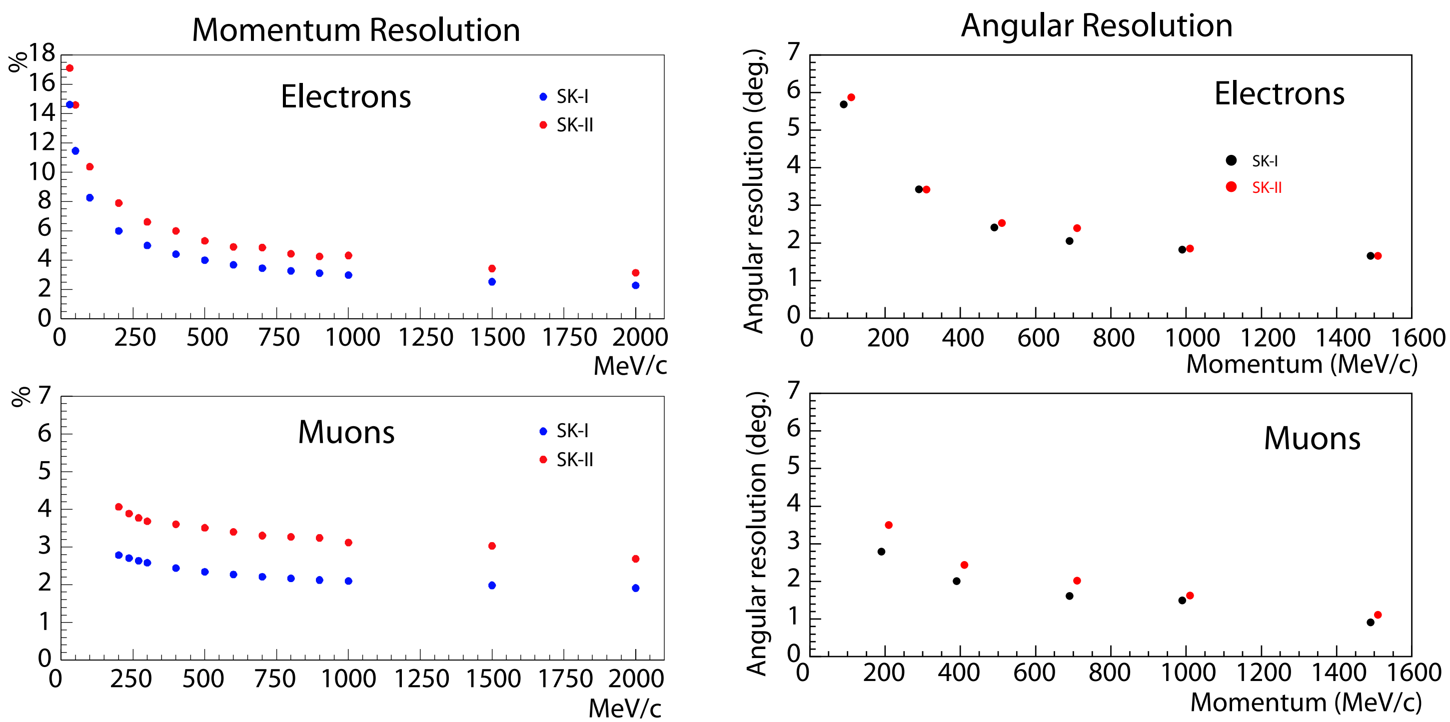
**Electron mis-identification suppressed to $\sim 10^{-5}$.**



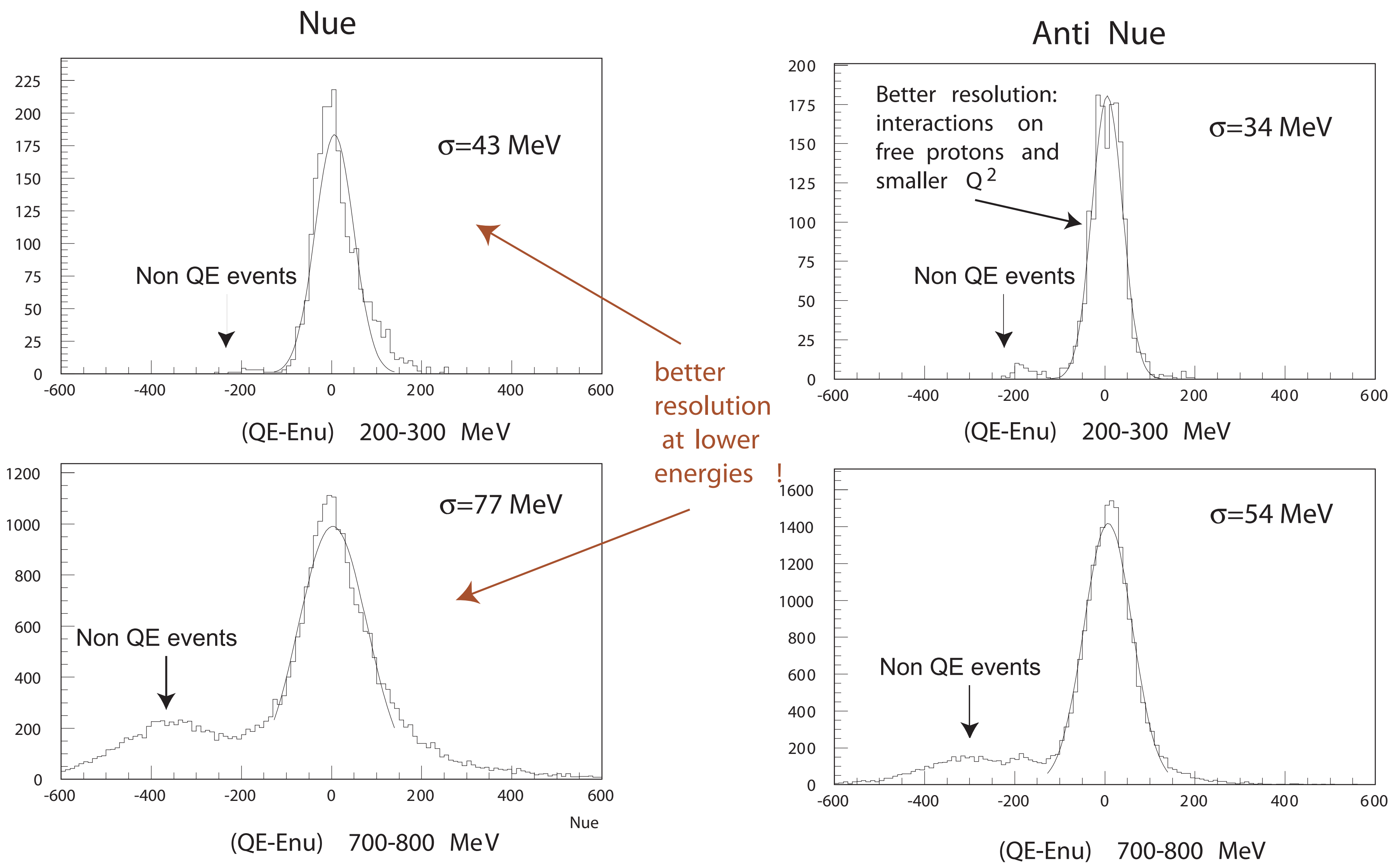
# Reconstructing neutrino energy

- Generate neutrino events following Beta Beam fluxes with Nuance
- Smear momentum and angular reconstruction with the SuperKamiokande functions.




- Reconstruct neutrino energy following the two body Quasi Elastic kinematics

# Neutrino energy reconstruction (QE kinematics)

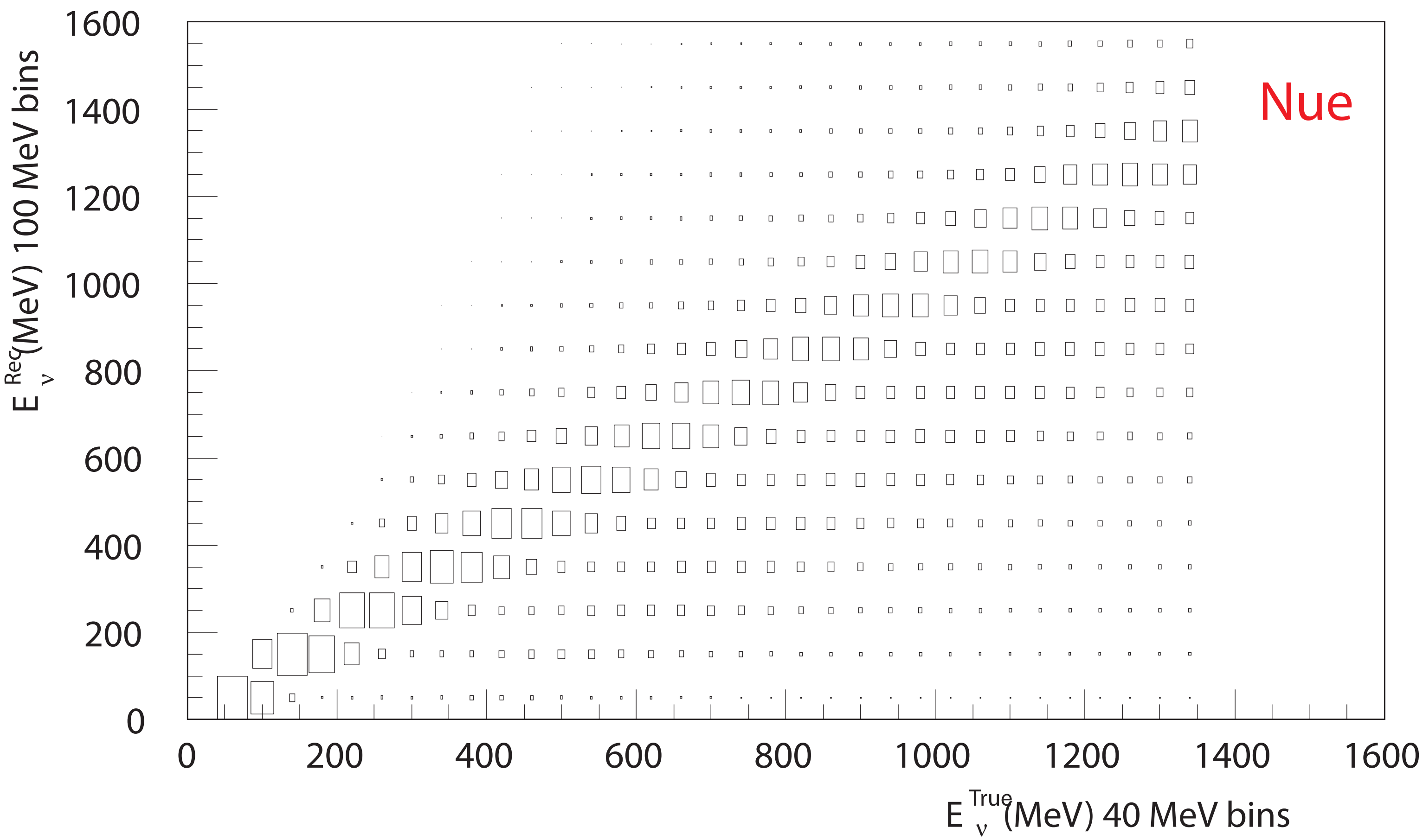



**Below 0.5 GeV the energy resolution is optimal and the non QE contamination negligible.**

# Migration matrices

Energy resolution is not necessarily gaussian. Better if it is described by a migration matrix. We use 4 migration matrixes for $\nu_e, \overline{\nu}_e, \nu_\mu$ and $\overline{\nu}_\mu$.

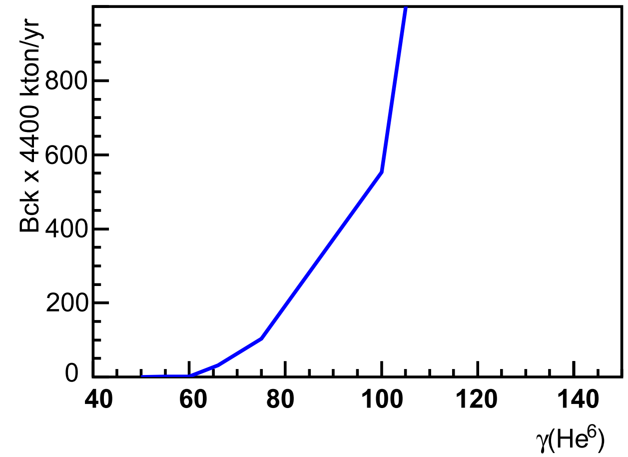
Migration Matrix (4 matrixes for nue, numu and anti's)



# The pion background

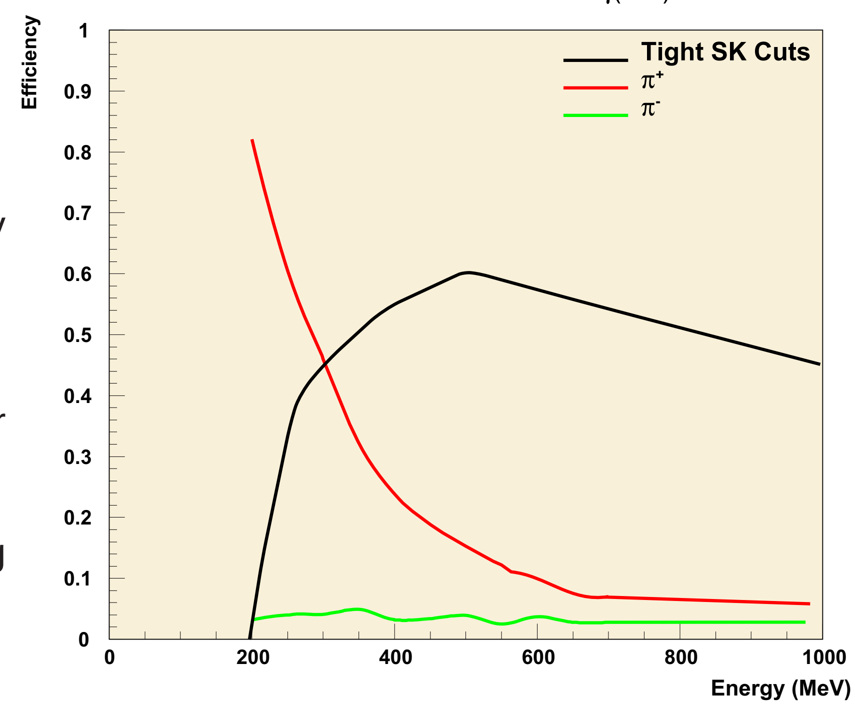
The pions generated in NC events can fake the muon signal.
**They are the main concern at high gammas.**

Pion backgrounds as function of $\gamma$

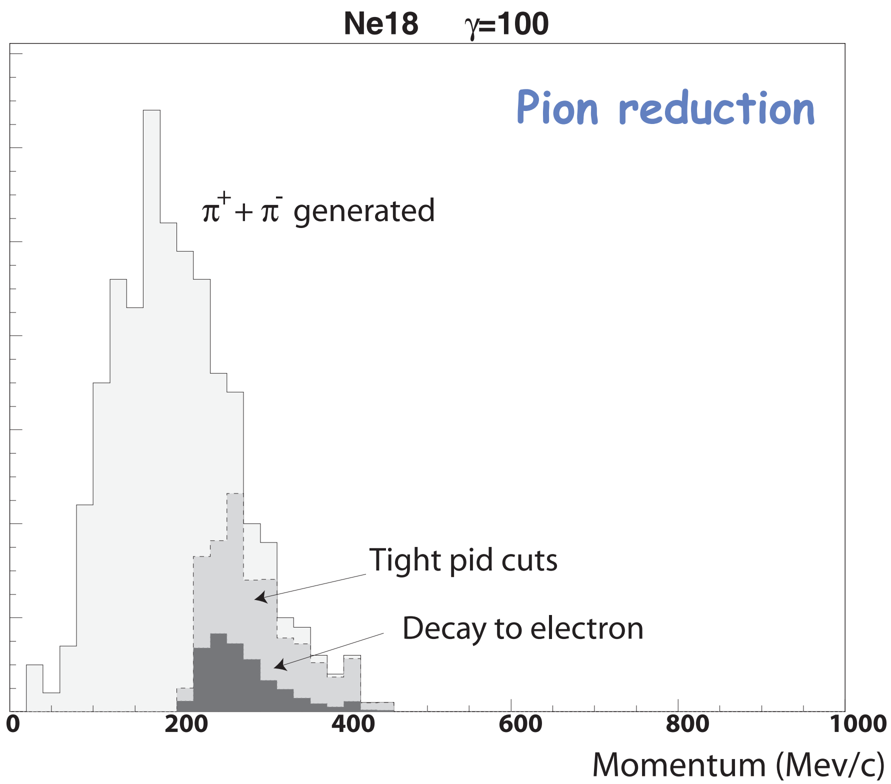



To estimate these backgrounds

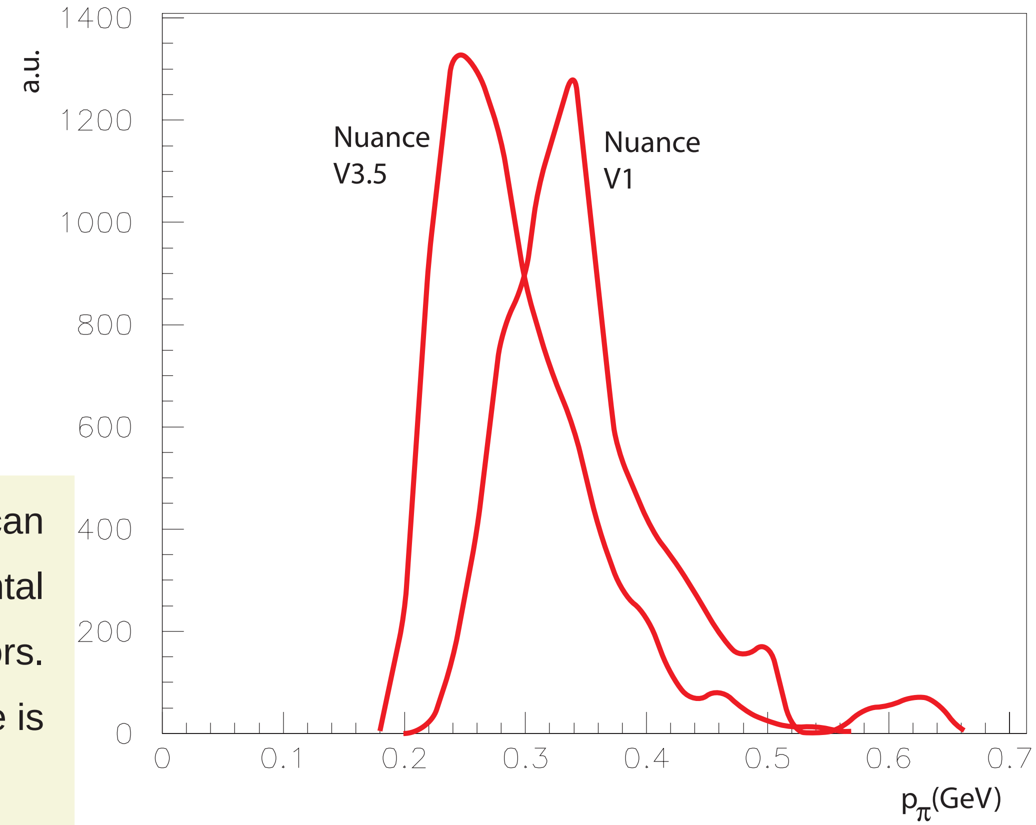
- Generate CC and NC events with Nuance
- Count events with a pion and no other track above the Čerenkov threshold (single ring events)
- Apply the particle identification cuts of SuperKamiokande
- Follow pions in water (Geant 3.21) to compute the probability for $\pi \rightarrow \mu \rightarrow e$.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



# The pion background (cont.)




| | Ne18 | | | He6 | | |
|---|---|---|---|---|---|---|
| | $\nu_\mu$ | $\pi^+$ | $\pi^-$ | $\overline{\nu}_\mu$ | $\pi^+$ | $\pi^-$ |
| 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. A cross-check of these background rates with E. Couche is ongoing.

## Atmospheric neutrino background

- Generate with Nuance atmospheric neutrinos in the Memphys fiducial
- Apply the tight particle identification cuts.
- Reconstruct them with the QE algorithm assuming they are coming from CERN.
- Accept them in the energy and direction window of the BB events:
- Apply the baseline BB duty cycle: $2.2 \cdot 10^{-3}$

The final rate is 5 background events/year (in a solar year, Beta Beam should run about 1/3 of this period)

**Considering that the pion background is of the order of 20 events/year, the duty cycle of the Beta Beam can be raised by a factor 5 at least without sizeable losses in the overall sensitivities.**

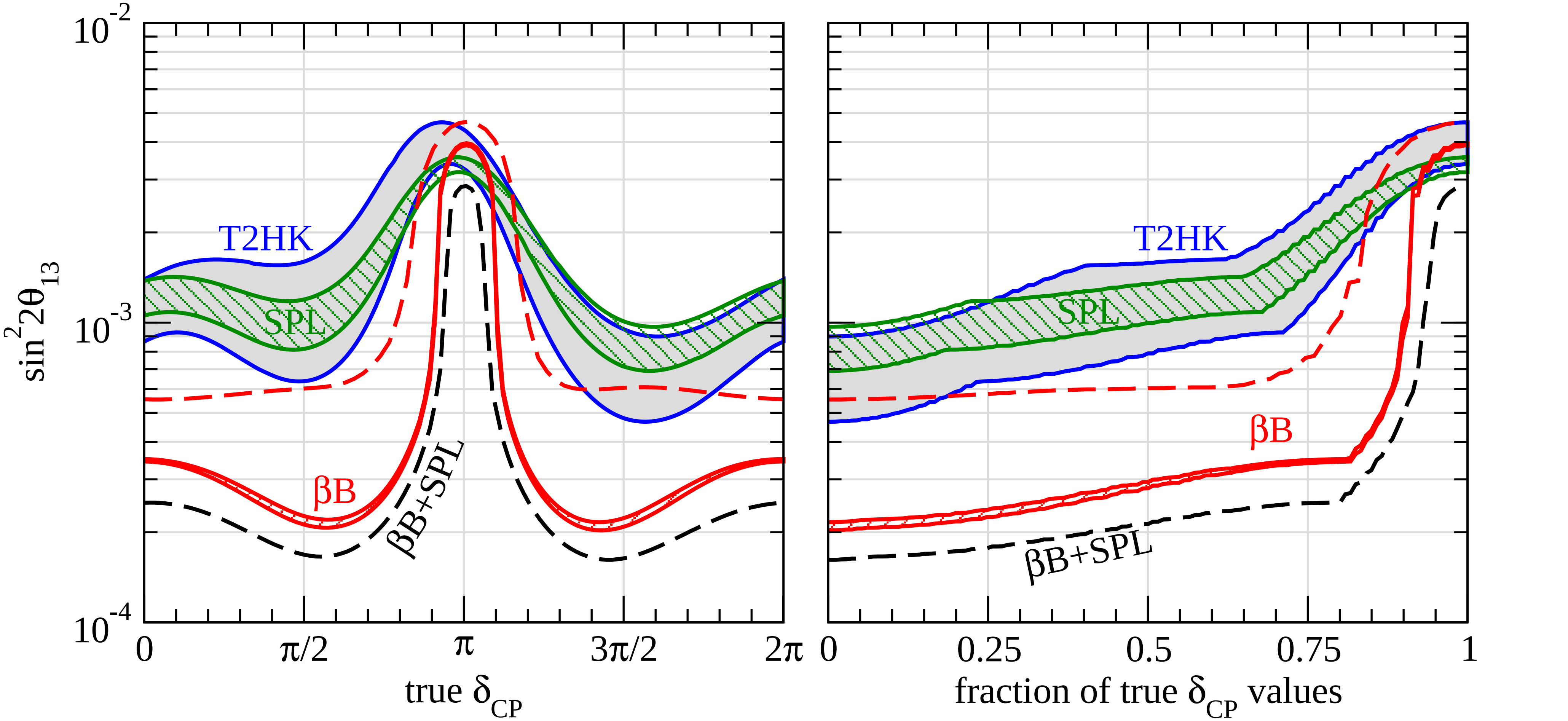
# Oscillation signals

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 $\nu$ | | | | | | |
| background | 143 | | 600 | | 1017 | |
| $\sin^2 2\theta_{13}=0$ | 25 | | 41 | | 84 | |
| $\sin^2 2\theta_{13}=10^{-3}$ | 72 | 77 | 93 | 10 | 181 | 18 |
| $\sin^2 2\theta_{13}=10^{-2}$ | 310 | 327 | 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 | 75 | 74 | 104 | 188 | 261 |
| $\sin^2 2\theta_{13}=10^{-2}$ | 346 | 325 | 297 | 390 | 746 | 977 |

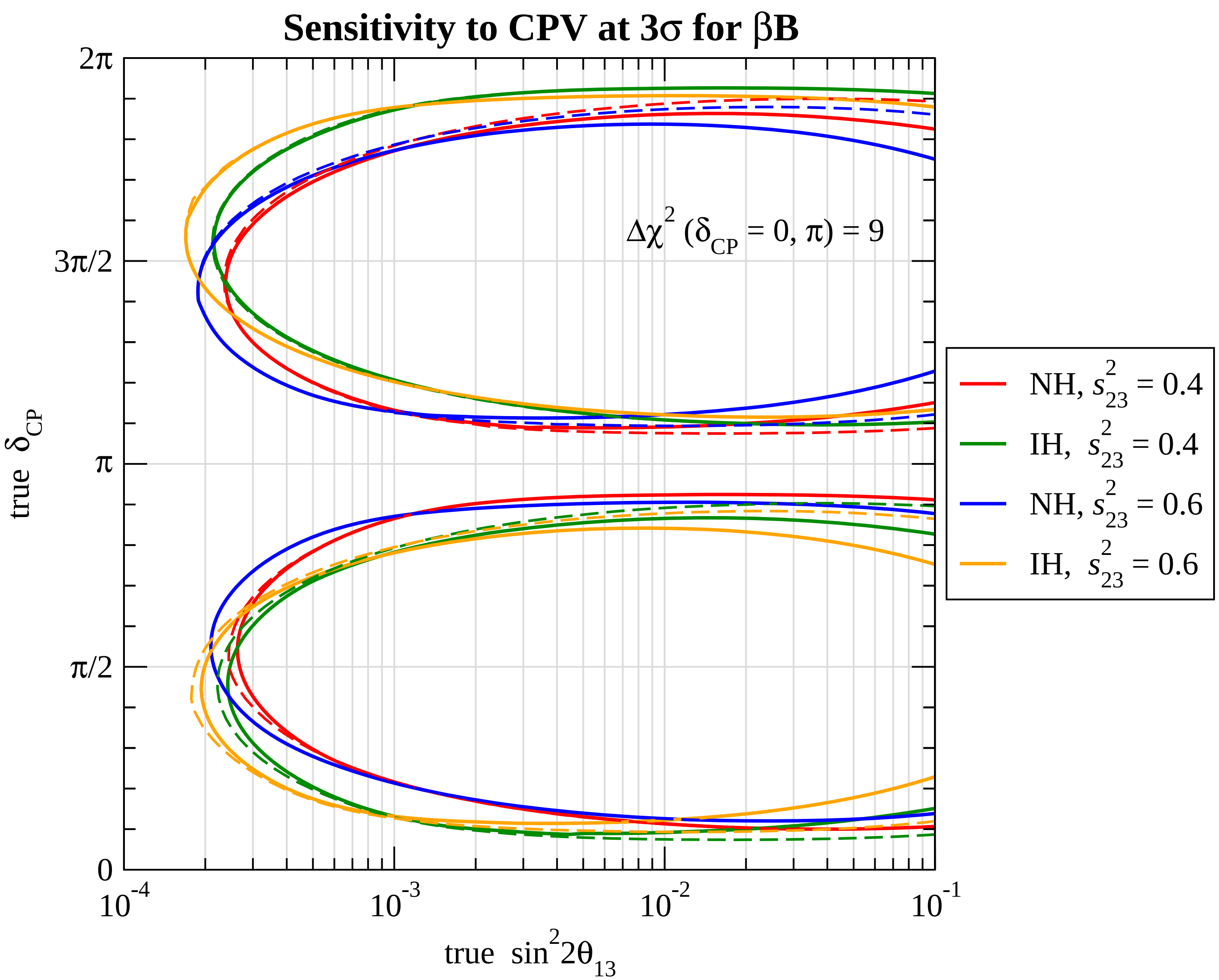
Computed with $\Delta m^2_{31} = +2.4 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{21} = 7.9 \times 10^{-5}\ \mathrm{eV}^2$, $\sin^2\theta_{12} = 0.3$. with an accuracy of 10% for $\theta_{12}$, $\theta_{23}$, $\Delta m^2_{31}$, and 4% for $\Delta m^2_{21}$ at $1\sigma$.

# Sensitivity to a non-zero $\theta_{13}$ at $3\sigma$

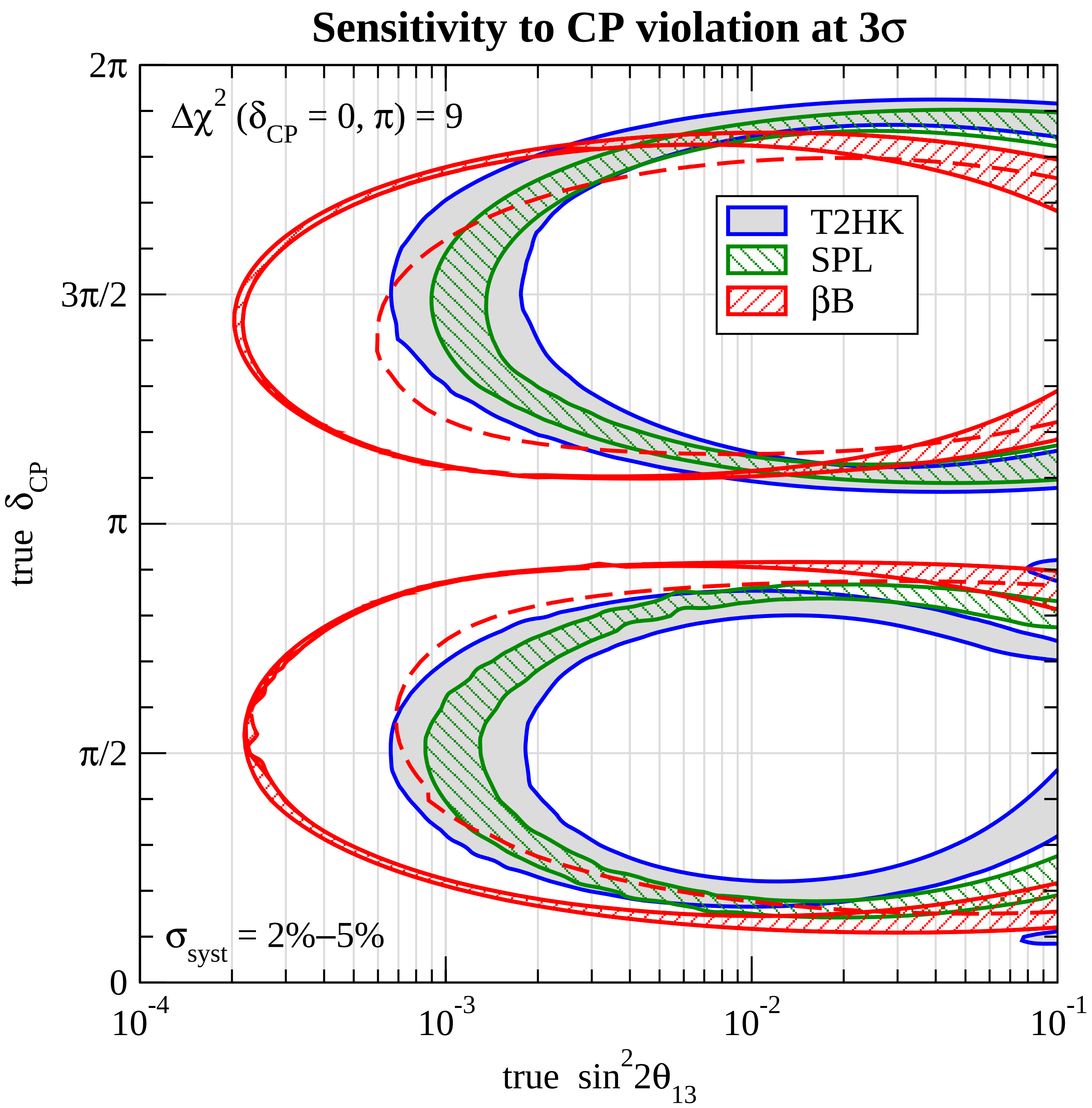



Dashed red line: Nufact 05 Beta Beam performances. Line width: 2% and 5% systematic errors.

# Sensitivity to CPV at 3σ for βB




Computed for all the possible combinations of the unknown octant and $\mathrm{sign}(\Delta m^2)$. Dashed curves are sensitivities computed not taking into account degeneracies.


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 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 $\theta_{13}$ and LCPV searches
- The neutrino mass hierarchy can be measured
- The $\theta_{23}$ 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, $\theta_{13}$ and LCPV. While the Beta Beam at short baselines could not measure the hierarchy as well as the octant.

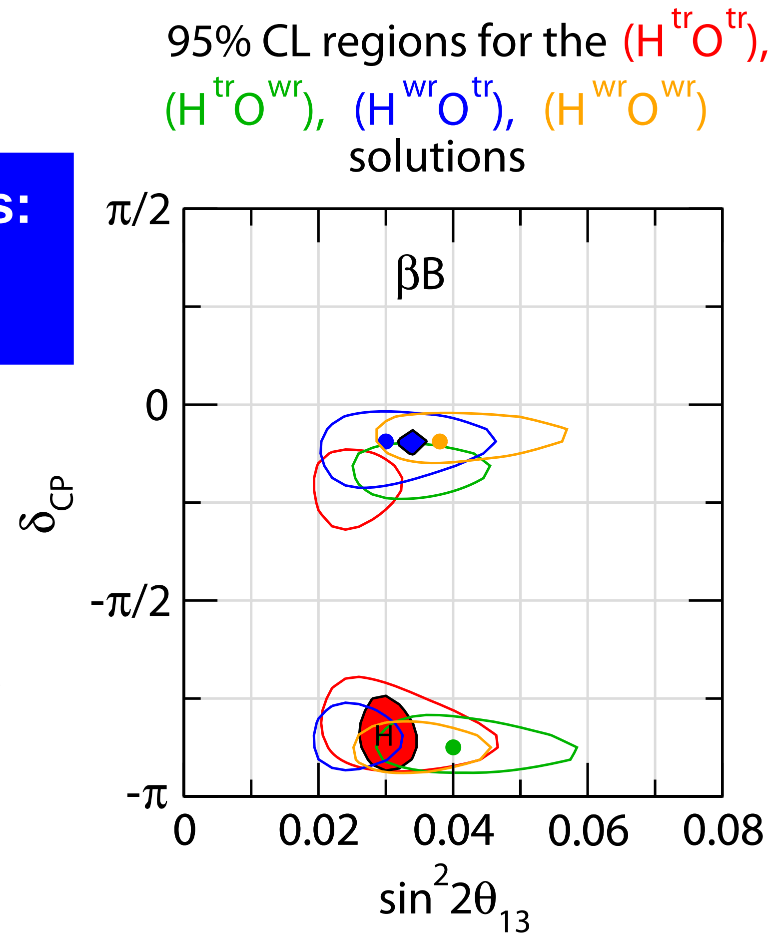
In the following sensitivities of the Beta Beam combined with the atmospherics are taken from J.E.Campagne, M.Maltoni, M.M., T.Schwetz, hep-ph/0603172 in its latest version, not yet released.

## Beta Beam plus atmospherics: degeneracy removal

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

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

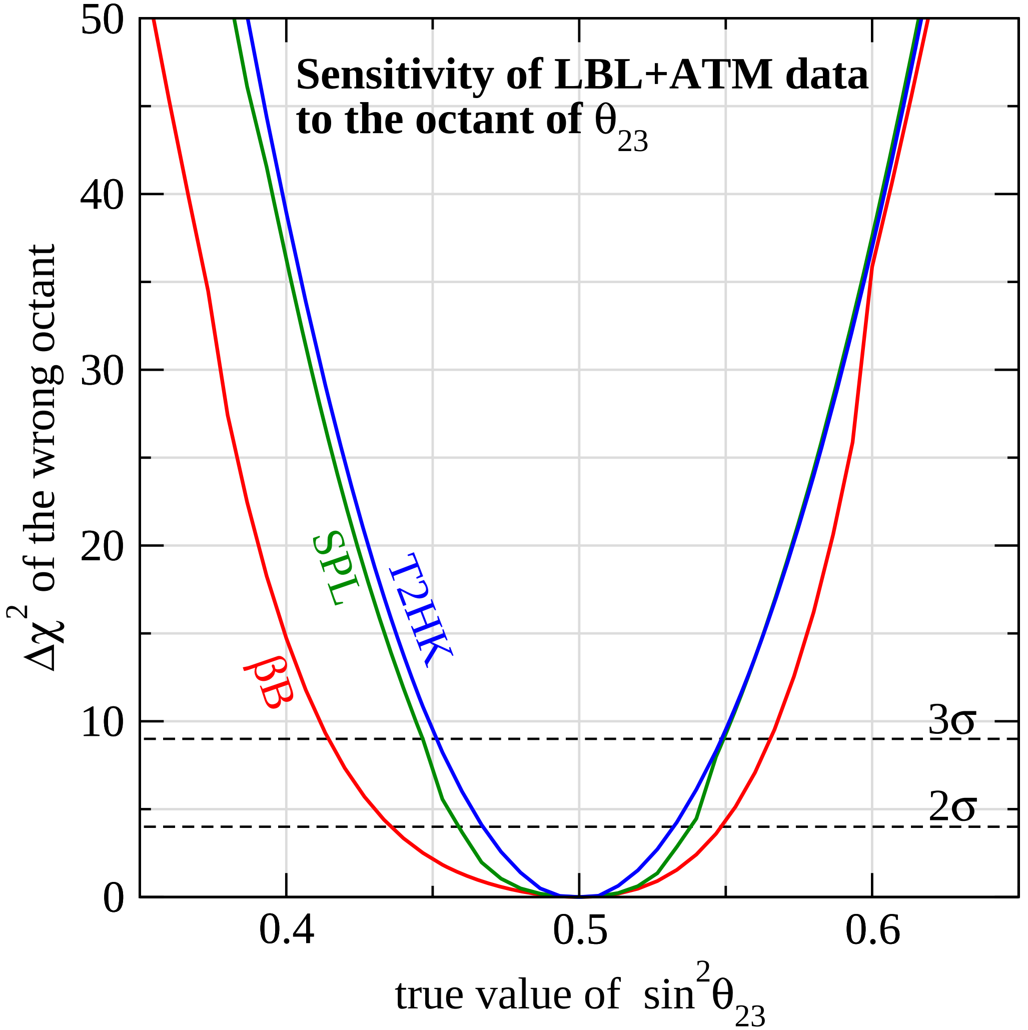
Note how degeneracies were not influencing LCPV sensitivity too much.




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

# Beta Beam plus atmospherics: determining the octant

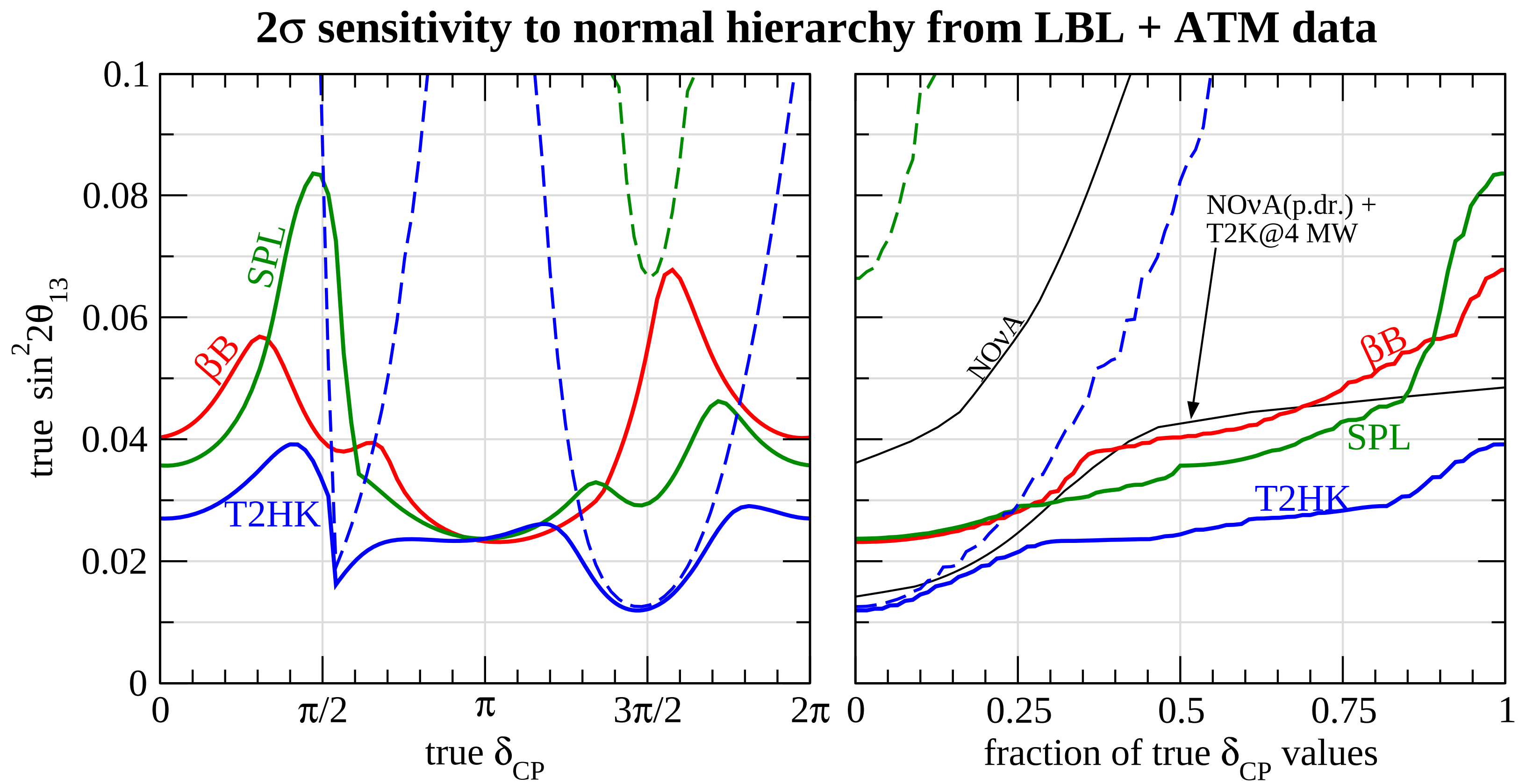
From: J.E.Campagne, M.Maltoni, M.M., T.Schwetz, hep-ph/0603172, revised




Computed for $\theta_{13}$ =0. Though the Beta Beam has practically no sensitivity to $\theta_{23}$ and the precision on $\theta_{23}$ from the Beta Beam is very poor, together with atmospheric data it can provide non-trivial information on the octant.

# Beta Beam plus atmospherics: determining the mass hierarchy.

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



## Conclusions (I)

- In a slow process, we are learning how to get the most from Beta Beams (no experience on $\nu_e \rightarrow \nu_\mu$ searches before).
- The duty cycle of the Beta Beam can be safely raised by a factor 5.
- The new Beta Beams description shows sizable better performances, but indicates that the pion background needs particular attention.
- By combining Beta Beams signals with atmospheric neutrinos all the degeneracies can be removed and hierarchy and octant measured provided that $\sin^2 2\theta_{13}$ is bigger than about 0.04.

## Conclusions (II)

$\gamma = 100$ performances vary very much with the input fluxes.

So far they have been normalized to conservative fluxes that by no mean can considered the ultimate possible fluxes in a Beta Beam.

The relevance of the input fluxes can be appreciated in this plot of LCPV sensitivity, where the higher input fluxes are fixed to match the CC rate at the far detector assumed for the high energy Beta Beams.