Physics with a Neutrino Factory Complex

-- Principles

-- Neutrino Oscillations

-- Other Physics and muon collider

-- R&D in Europe and elsewhere (-->Helmut Haseroth)

This summarizes the work of several 100 authors who recently published
'ECFA/CERN studies of a European Neutrino Factory Complex'
CERN 2004-002 ECFA/04/230
+
The US-based Muon Collaboration (S. Geer & R. Palmer et al)
+
The ECFA BENE Working groups (The CERN MMW workshop)

Where are we?

1. We know that there are three families of active, light neutrinos *(LEP)*
2. Solar neutrino oscillations are established *(Homestake+Gallium+Kam+SK+SNO+KamLAND)*
3. Atmospheric (ν_{μ} –>) oscillations are established *(IMB+Kam+SK+Macro+Sudan+K2K)*
4. At that frequency, electron neutrino oscillations are small *(CHOOZ)*

This allows a consistent picture with 3-family oscillations

$\theta_{12} \sim 30^0$ $\Delta m_{12}^2 \sim 7\ 10^{-5} eV^2$ $\theta_{23} \sim 45^0$ $\Delta m_{23}{}^2 \sim 2.5\ 10^{-3} eV^2$ $\theta_{13} <\sim 10^0$

with several unknown parameters θ_{13}, δ, mass hierarchy

Where do we go?

leptonic CP & T violations

=> an exciting experimental program for at least 25 years *)

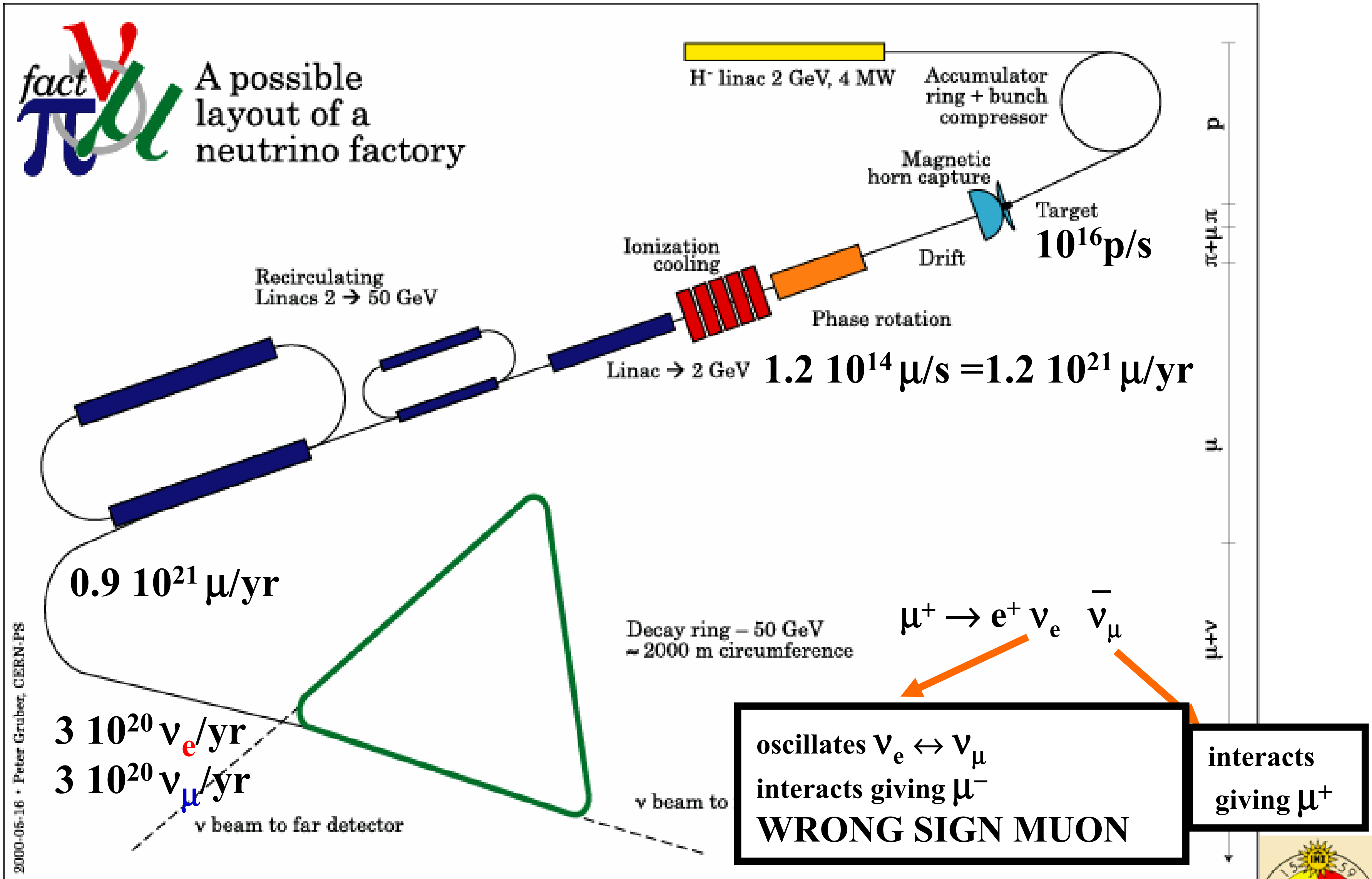
*)to set the scale: CP violation in quarks was discovered in 1964
and there is still an important program (K0pi0, B-factories, Neutron EDM, LHCb, BTeV….)
to go on for >>10 years…i.e. a total of >50 yrs.
and we have not discovered leptonic CP yet!

5. *LSND ? (→ miniBooNe)*
This result is not consistent with three families of neutrinos oscillating, and is not supported (nor is it completely contradicted) by other experiments.

If confirmed, this would be even more exciting

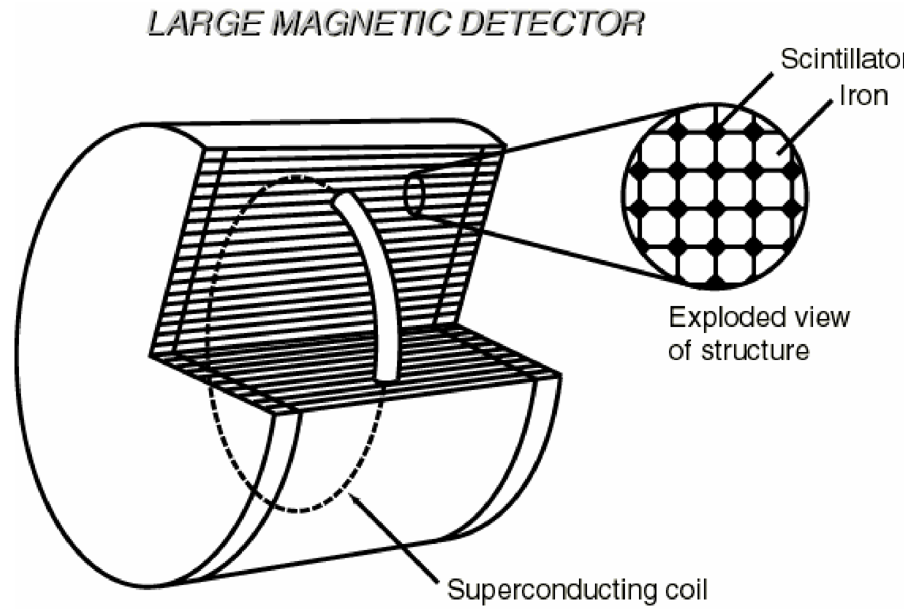
See *Barger et al PRD 63 033002*

-- Neutrino Factory --
CERN layout



Detector

Cervera et al



Dimension: radius 10 m, length 20 m
Mass: 40 kt iron, 500 t scintillator

- Iron calorimeter
- Magnetized
  - Charge discrimination
  - B = 1 T
- R = 10 m, L = 20 m
- Fiducial mass = 40 kT

Also: L Arg detector: magnetized ICARUS *Bueno et al*

Wrong sign muons, electrons, taus and NC evts *->

Events for 1 year

Baseline	$\bar{\nu}_\mu$ CC	ν_e CC	ν_μ signal ($\sin^2\theta_{13}=0.01$)
732 Km	3.5×10^7	5.9×10^7	1.1×10^5
3500 Km	1.2×10^6	2.4×10^6	1.0×10^5

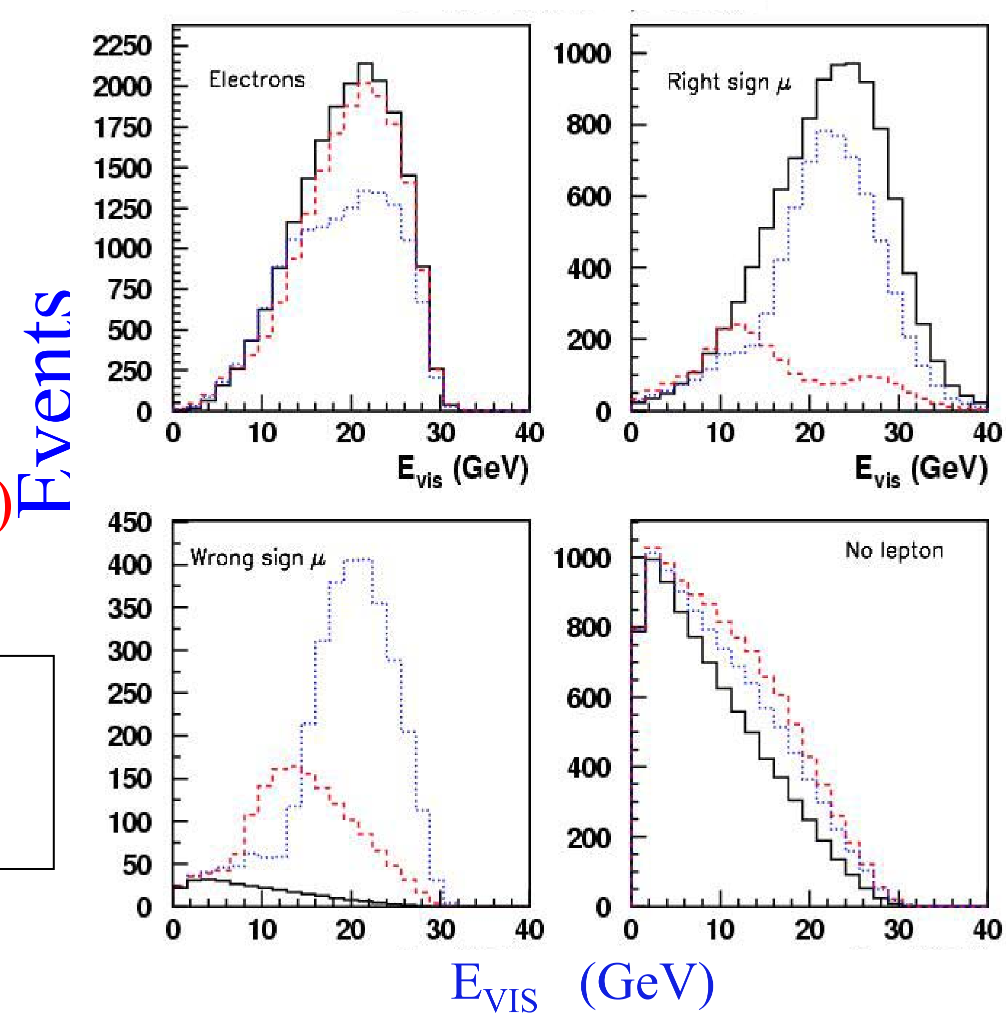
CF ν_e signal at J-PARC =40

Oscillation parameters can be extracted using energy distributions

Simulated distributions for a 10kt LAr detector at L = 7400 km from a 30 GeV nu-factory with 10^{21} μ^+ decays.

- a) right-sign muons
- b) wrong-sign muons
- c) electrons/positrons
- d) positive τ-leptons
- e) negative τ -leptons
- f) no leptons

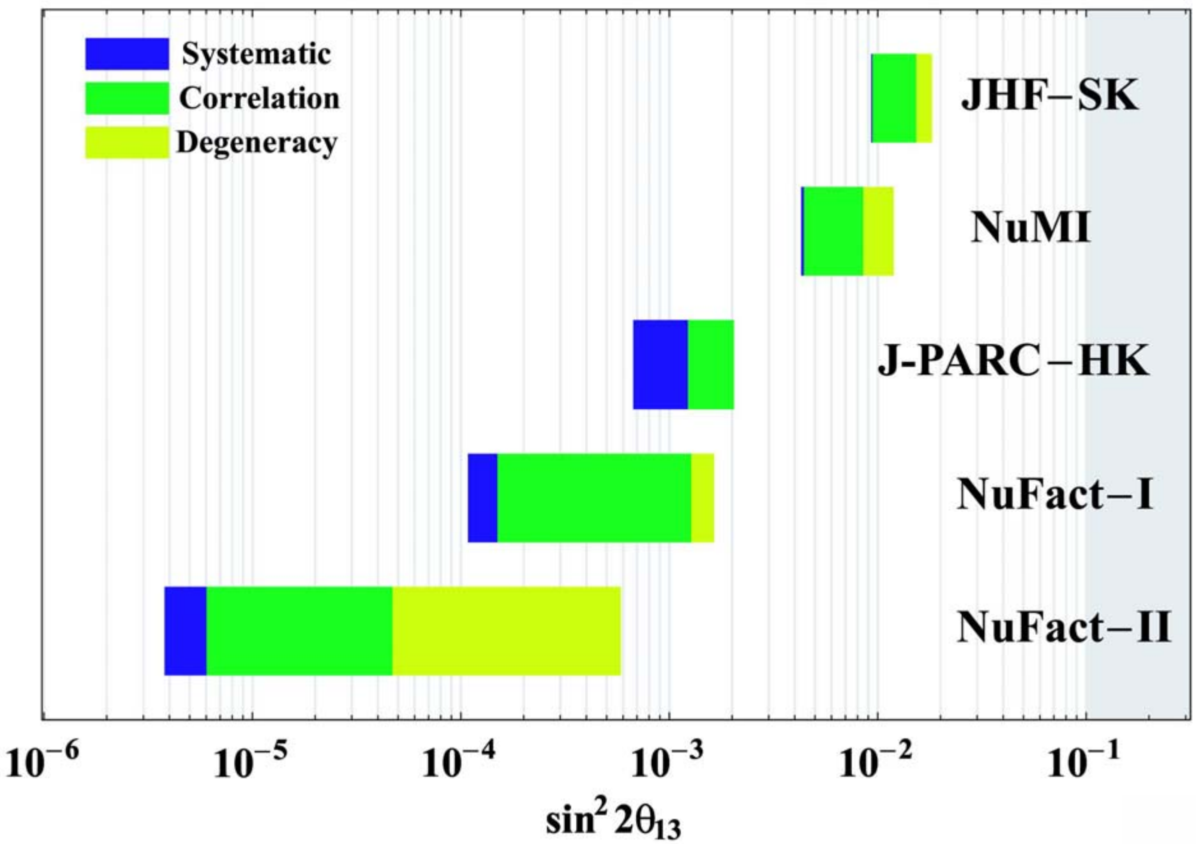
X2 (μ^+ stored and μ^- stored)



Bueno, Campanelli, Rubbia; hep-ph/0005007

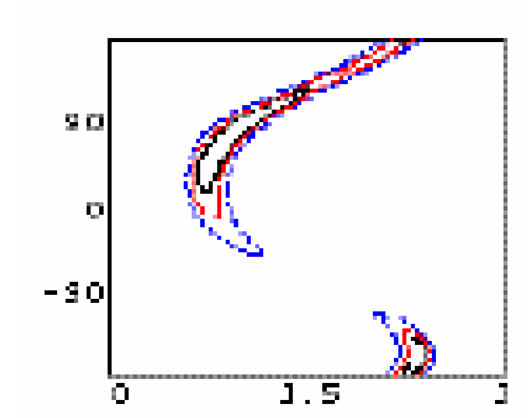
Note: $\nu_e \to \nu_\tau$ is specially important (Ambiguity resolution & Unitarity test): ***Gomez-Cadenas et al.***

Sensitivity to $\sin^2 2\theta_{13}$ *Linder et al.*



θ_{13} in degrees

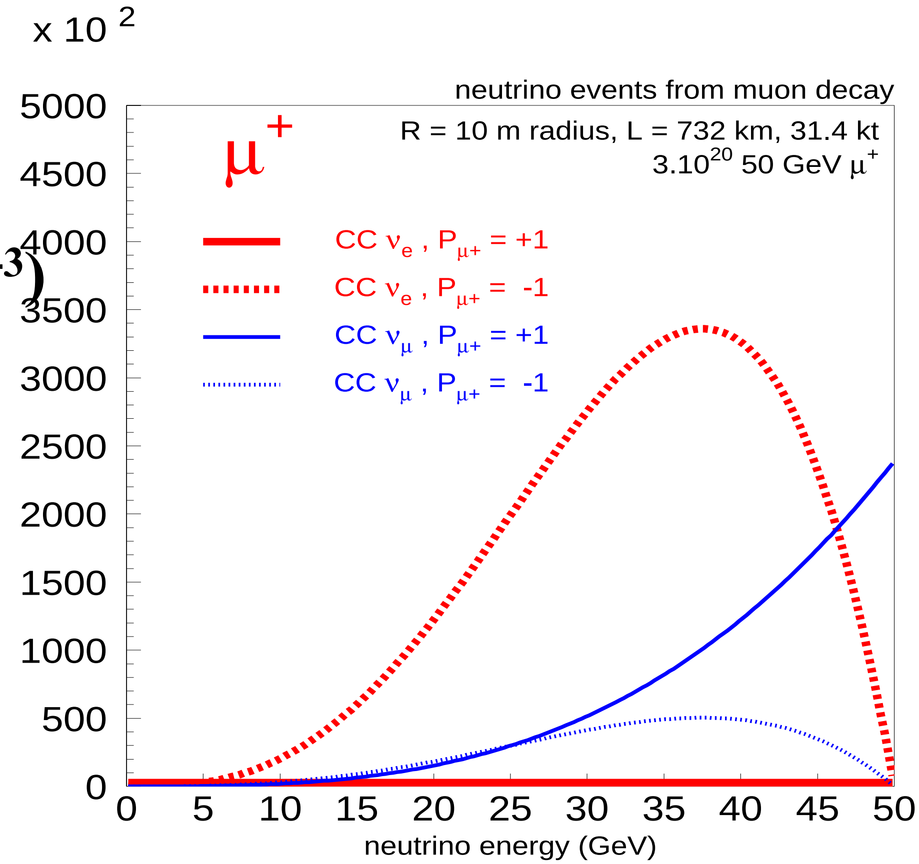
δ



Above plot obtained with Golden channel, one sign only and one distance. Emphasizes very low systematics, and degeneracies

Neutrino fluxes $\mu^+ \to e^+ \nu_e \nu_\mu$

ν_μ/ν_e ratio reversed by switching μ^+/μ^-
ν_e ν_μ spectra are different
No high energy tail.



Very well known flux (aim is 10^{-3})

- absolute flux measured from muon current
 or by $\nu_\mu e^- \to \mu^- \nu_e$ in near expt.

-- in **triangle ring**,
muon polarization precesses and averages out
(**preferred**, -> calib of energy, energy spread)

-- $E\&\sigma_E$ calibration from muon spin precession

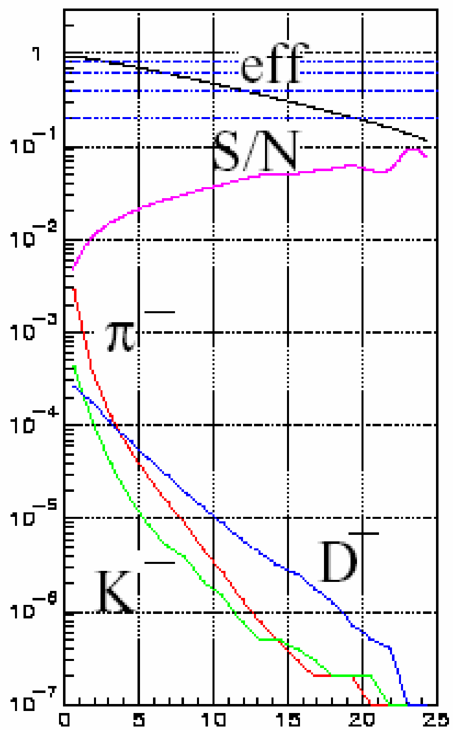
-- angular divergence: small effect if $\theta < 0.2/\gamma$,
can be monitored

-- in **Bow-tie ring,**
muon polarization stays constant, no precession
 20% easy -> 40% hard
 Must be measured!!!! (precision?)
Physics gain not large

μ polarization controls ν_e flux:

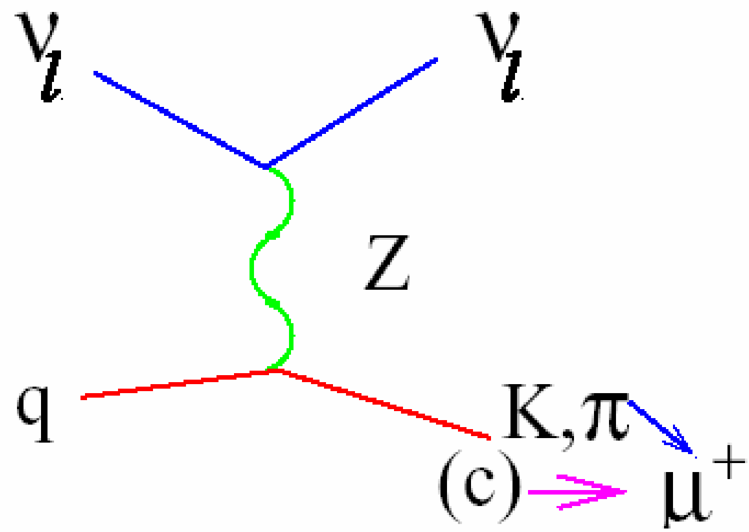
μ^+ -X> ν_e in forward direction

- Backgrounds at $\leq 10^{-4}$ level, not few $\times 10^{-3}$



momentum cut (GeV)

Cervera *et al*, Nucl.Phys.**B579** 17,2000



Momentum cut on muon easily removes backgrounds

CP asymmetries

compare $\nu_e \to \nu_\mu$ to $\bar{\nu}_e \to \bar{\nu}_\mu$ probabilities

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = \sin^2\theta_{23}\sin^2 2\,\theta_{13}\left(\frac{\Delta m^2_{23}}{B_\pm}\right)^2 \sin^2 B_\pm L$$

with $B_\pm \equiv \sqrt{(\Delta m^2_{23}\cos 2\,\theta_{13} \pm \mu)^2 + (\Delta m^2_{23}\sin 2\,\theta_{13})^2}$

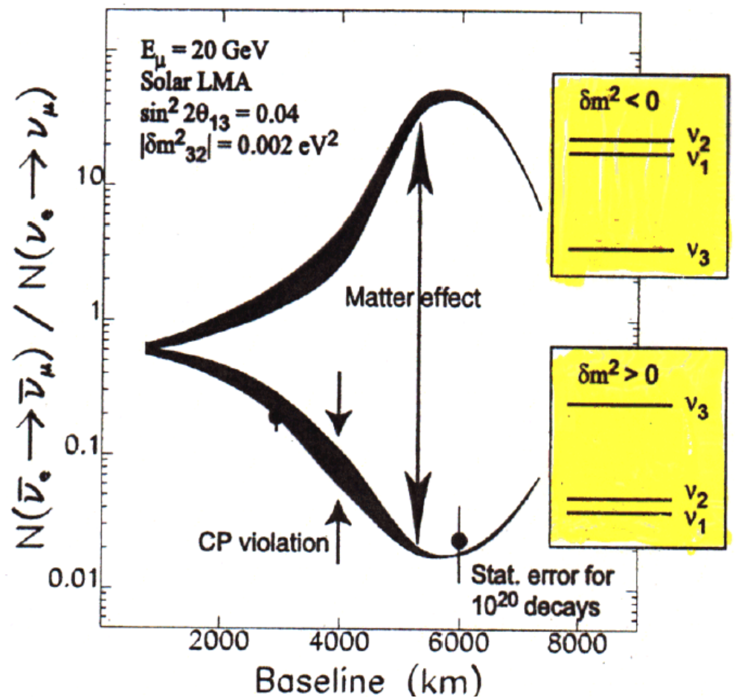
μ is prop. to matter density, positive for neutrinos, negative for antineutrinos

$$A = \frac{\mu^- / \nu_e - \mu^+ / \bar{\nu}_e}{\mu^- / \nu_e + \mu^+ / \bar{\nu}_e}$$

HUGE effect for distance around 6000 km!!

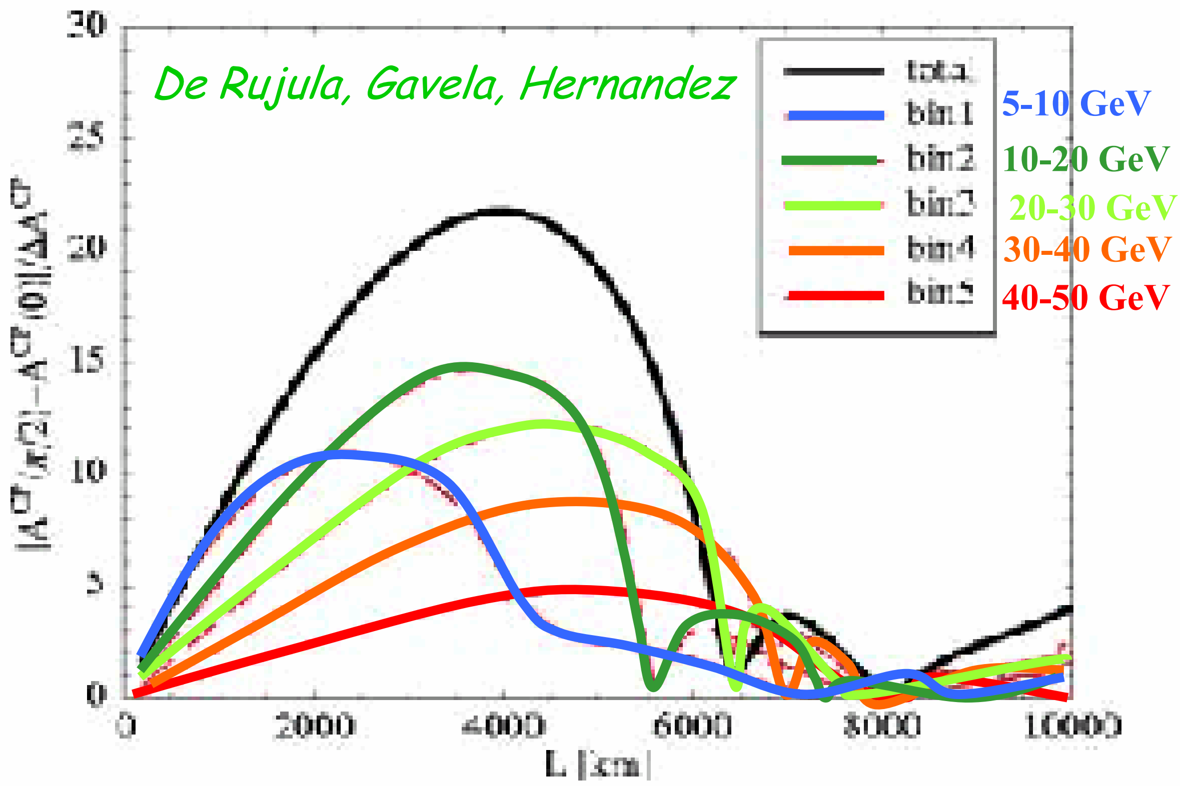
Resonance around 12 GeV when

$$\Delta m^2_{23}\cos 2\theta_{13} \pm \mu = 0$$



CP violation (ctd)

Matter effect must be subtracted. One believes this can be done with uncertainty Of order 2%. Also spectrum of matter effect and CP violation is different
⇒It is important to subtract in bins of measured energy.
⇒knowledge of spectrum is essential here!



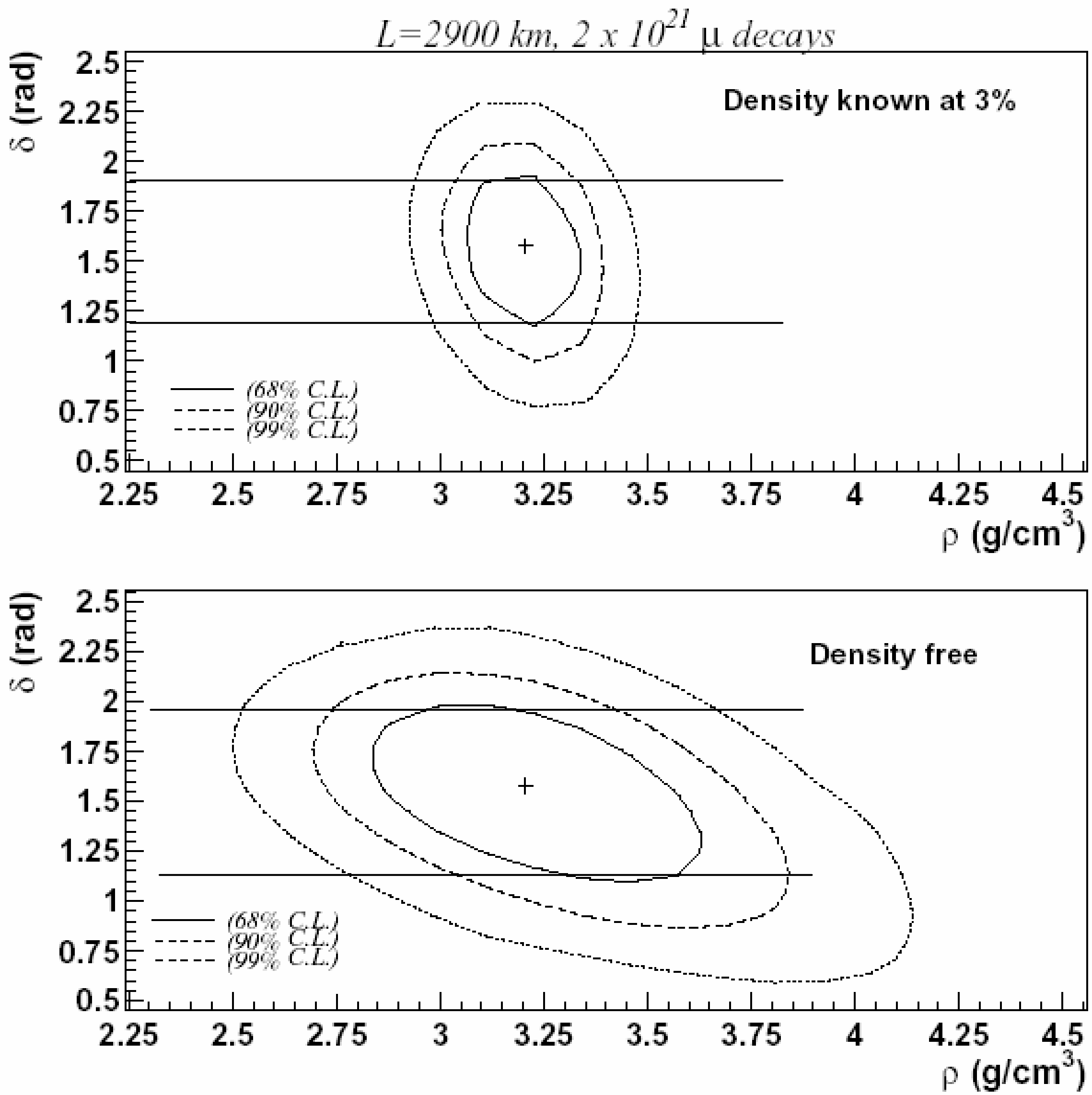
40 kton L M D
50 GeV nufact
5 yrs $10^{21}\mu$ /yr

In fact, 20-30 GeV
Is enough!

Best distance is
2500-3500 km

e.g. Fermilab or BNL
-> west coast or …

Bueno, Campanelli, Rubbia hep-ph/0005-007



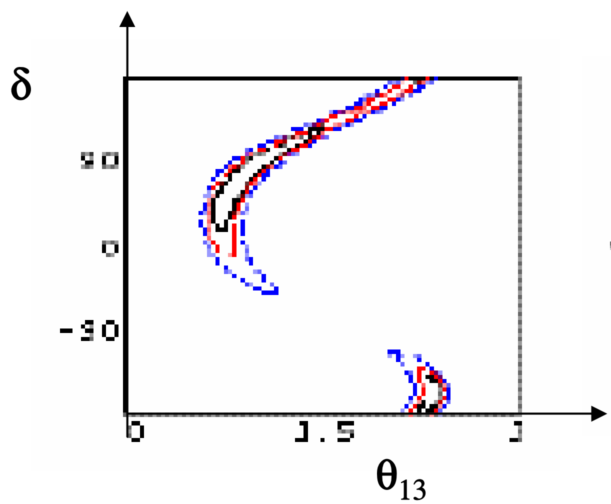
Silver channel at neutrino factory

A. Donini et al
hep-ph/0206034
ROMA-1336/02

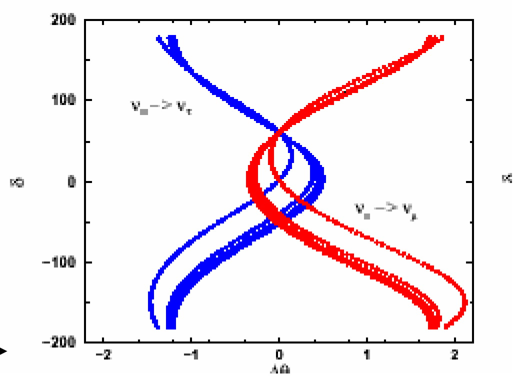
High energy neutrinos at NuFact allow observation of $\nu_e \rightarrow \nu_\tau$
(wrong sign muons with missing energy and P⊥). UNIQUE

Liquid Argon or OPERA-like detector at 732 or 3000 km.

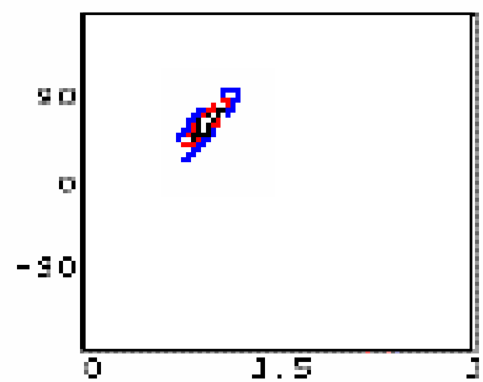
Since the sinδ dependence has opposite sign with the wrong sign muons, this solves ambiguities that will invariably appear if only wrong sign muons are used.



ambiguities with only wrong sign muons (3500 km)



equal event number curves muon vs taus



associating taus to muons (no efficencies, but only OPERA mass) studies on-going

- The Eightfold Degeneracy in (θ_{13}, δ) Measure (Barger01,Burguet02)

e.g. Rigolin, Donini, Meloni

$$\boxed{N_i^{\pm}(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct}) = N_i^{\pm}(\theta_{13}, \delta; s_{atm}, s_{oct})}$$

One has to solve ALL the following systems of equations:

intrinsic ambiguity

$$N_i^{\pm}(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct}) = N_i^{\pm}(\theta_{13}, \delta; s_{atm} = \bar{s}_{atm}, s_{oct} = \bar{s}_{oct})$$

sign ambiguity

$$N_i^{\pm}(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct}) = N_i^{\pm}(\theta_{13}, \delta; s_{atm} = -\bar{s}_{atm}, s_{oct} = \bar{s}_{oct})$$

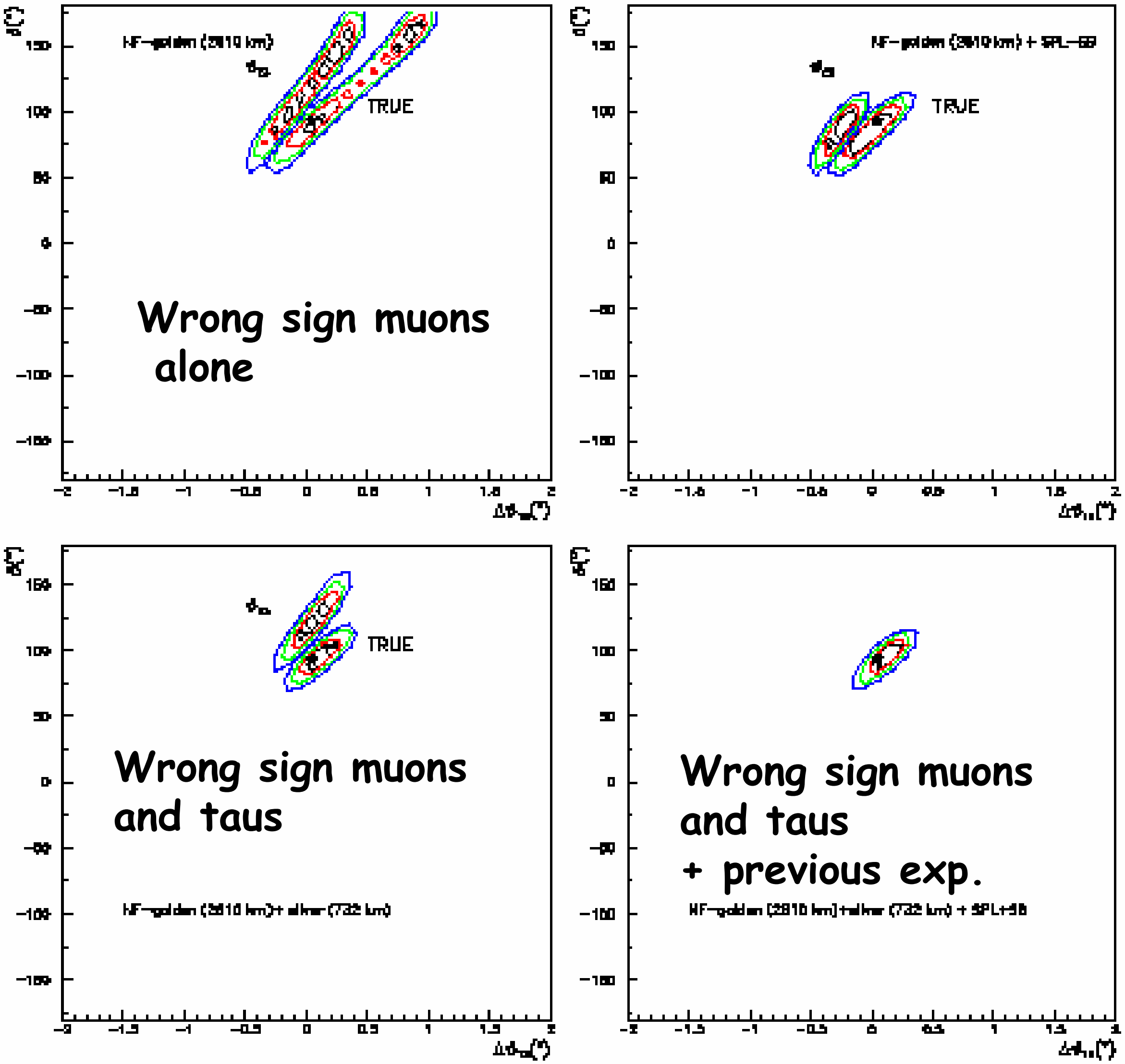
octant ambiguity

$$N_i^{\pm}(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct}) = N_i^{\pm}(\theta_{13}, \delta; s_{atm} = \bar{s}_{atm}, s_{oct} = -\bar{s}_{oct})$$

mixed ambiguity

$$N_i^{\pm}(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct}) = N_i^{\pm}(\theta_{13}, \delta; s_{atm} = -\bar{s}_{atm}, s_{oct} = -\bar{s}_{oct})$$

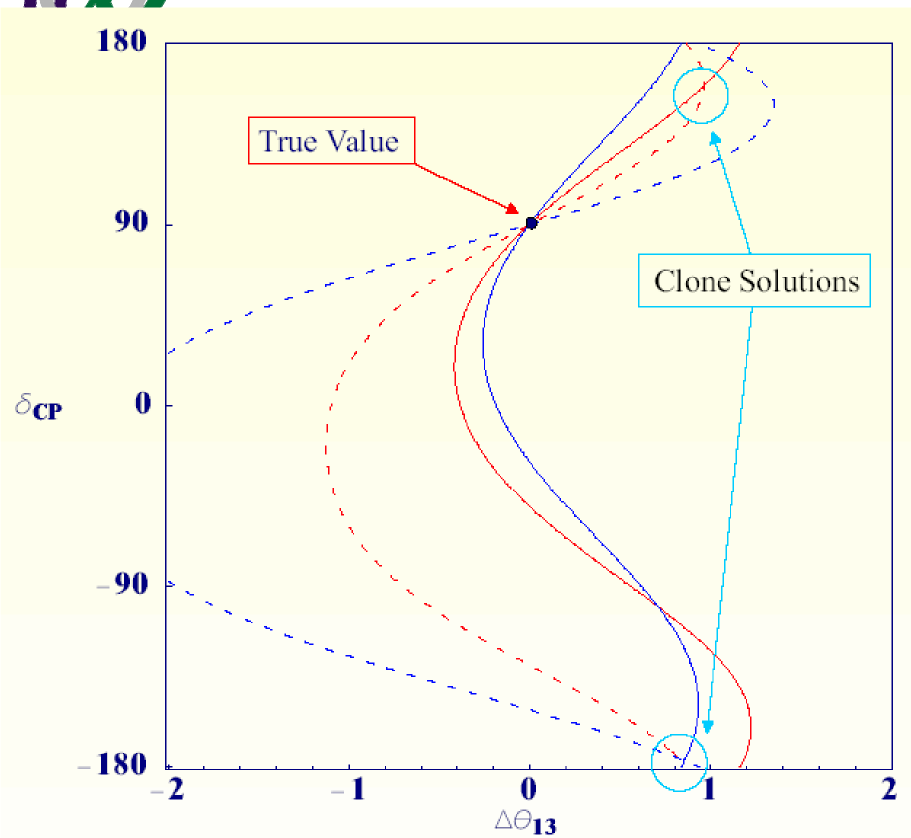
From Donini, NuFact03: There were even ambiguities with the neutrino factory:

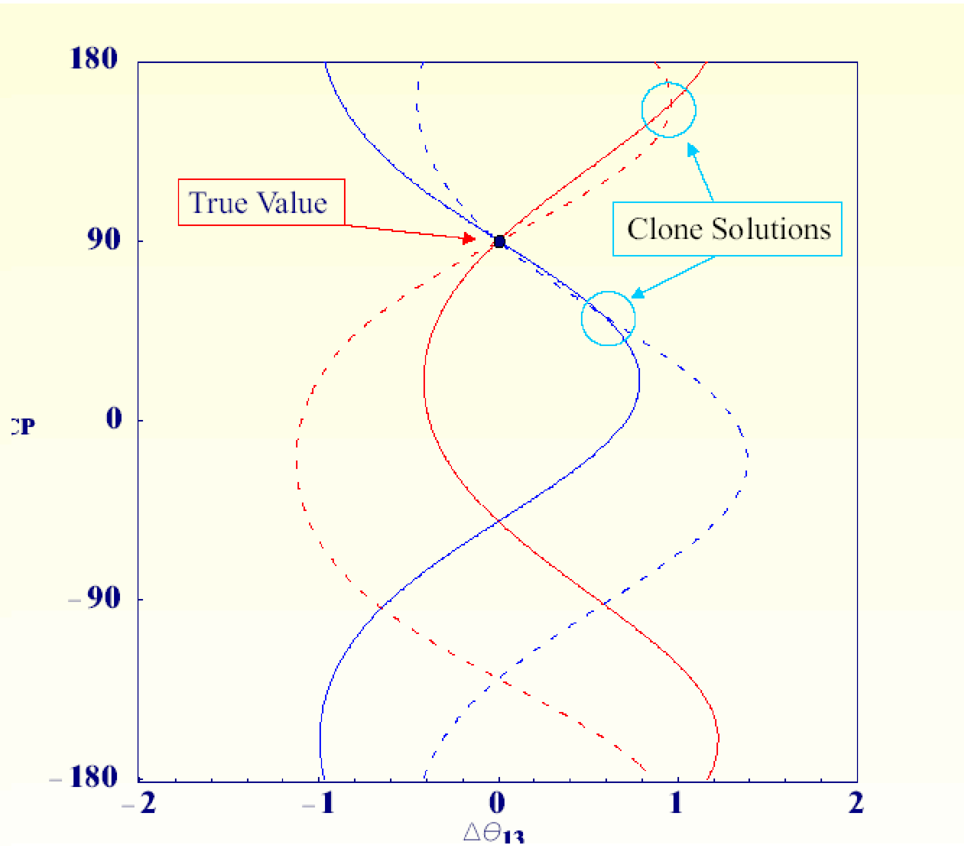


Getting to ultimate precision means combining data from several channels:

- Wrong-sign muons
- $\nu_e \to \nu_\tau$
- Conventional Beams

hep-ph/0310014





red vs blue = different baselines

red vs blue = muons and taus

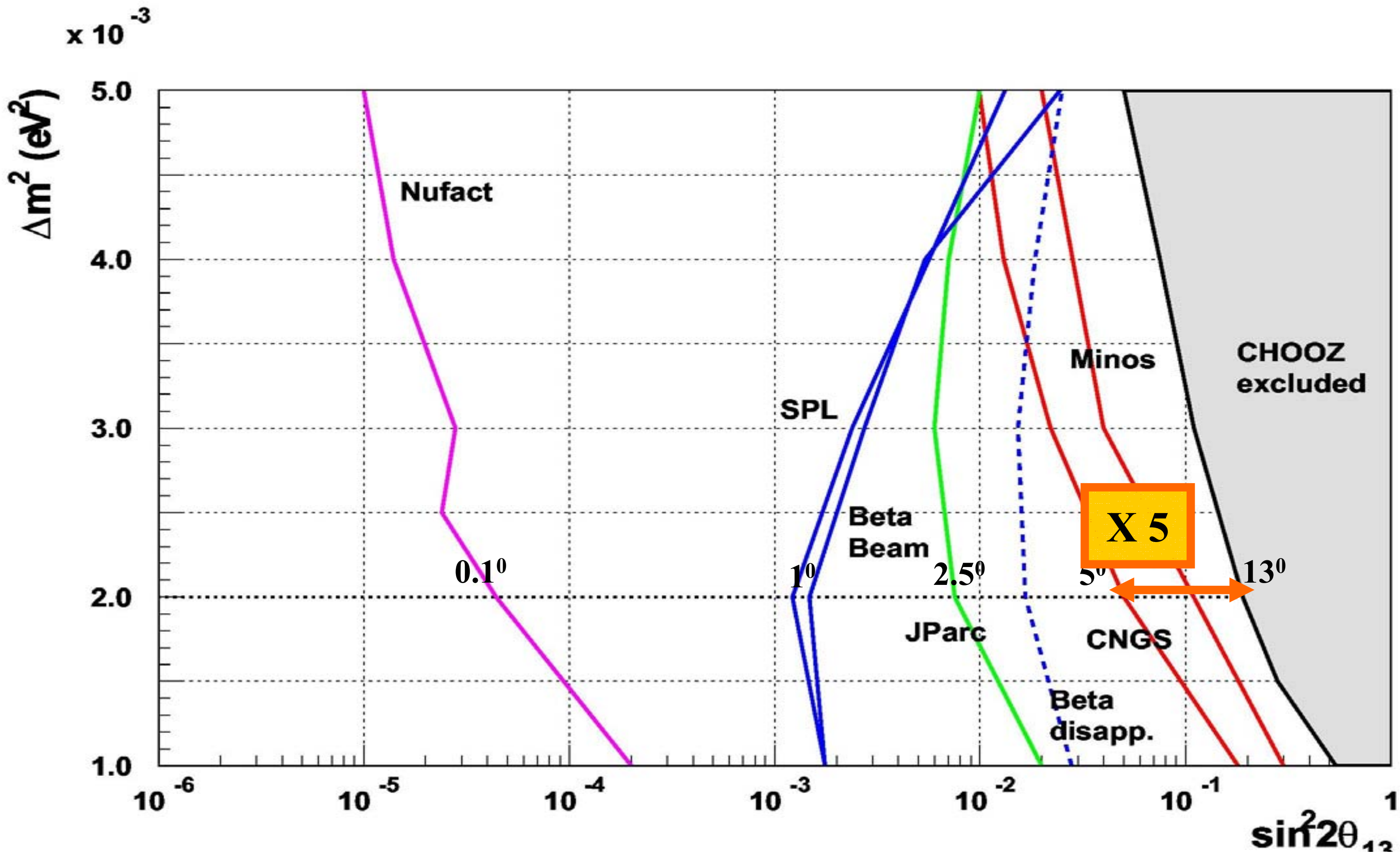
dashed vs <u>line</u> = different energy bin
(most powerful is
around matter resonance @ ~12 GeV)

Conclusion:

Neutrino Factory has many handles on the problem (muon sign + Gold + Silver + different baselines + binning in energy *(Aoki)*) thanks to high energy!

"It could in principle solve many of the clones for θ_{13} down to 1^0 The most difficult one is the octant clone which will require a dedicated analysis" *(Rigolin)*

Where will this get us…



Mezzetto

comparison of reach in the oscillations; right to left:

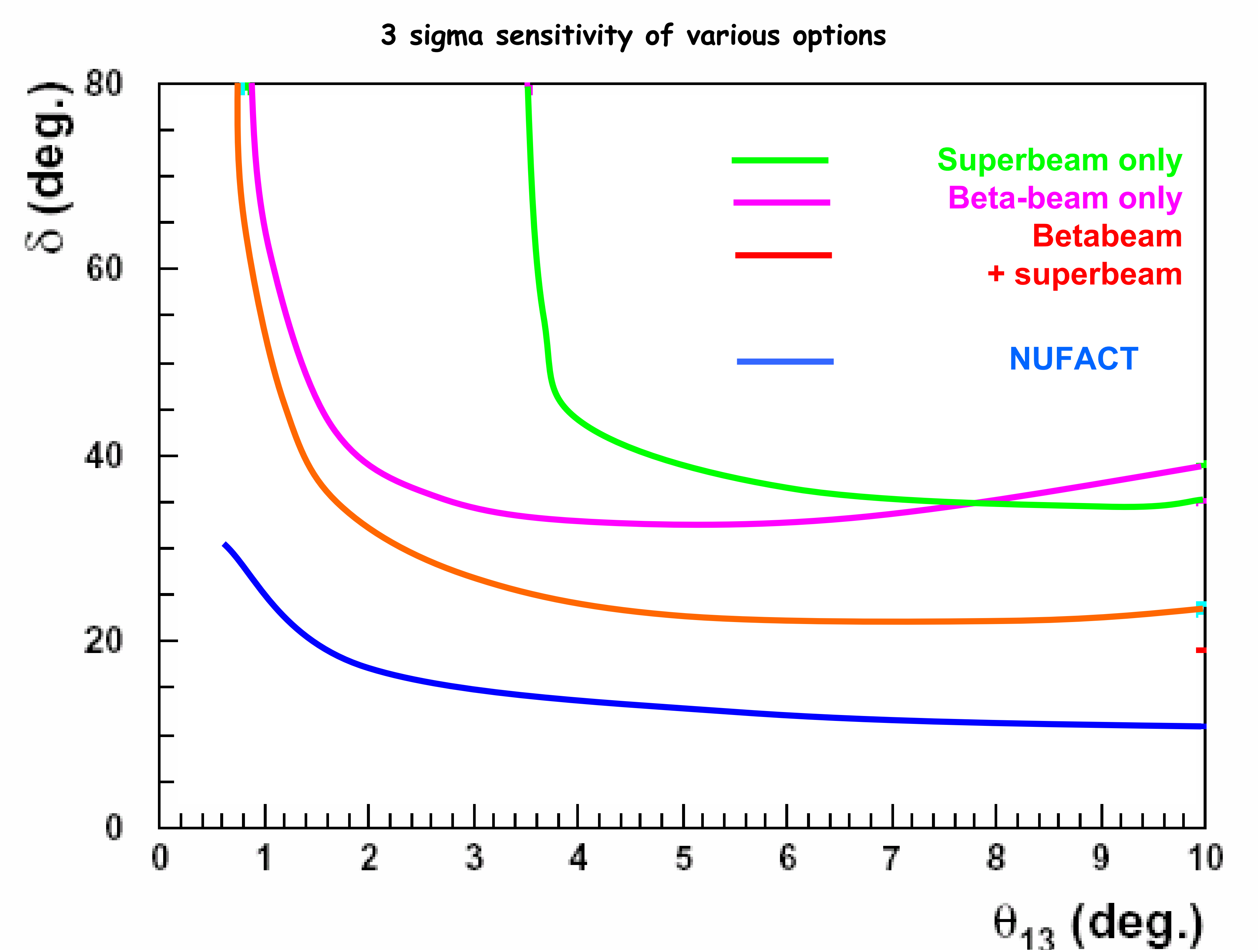
present limit from the CHOOZ experiment,

expected sensitivity from the MINOS experiment, CNGS (OPERA+ICARUS)

0.75 MW JHF to super Kamiokande with an off-axis narrow-band beam,

Superbeam: 4 MW CERN-SPL to a 400 kt water Cerenkov@ Fréjus (J-PARC phase II similar)

Neutrino Factory with 40 kton large magnetic detector.



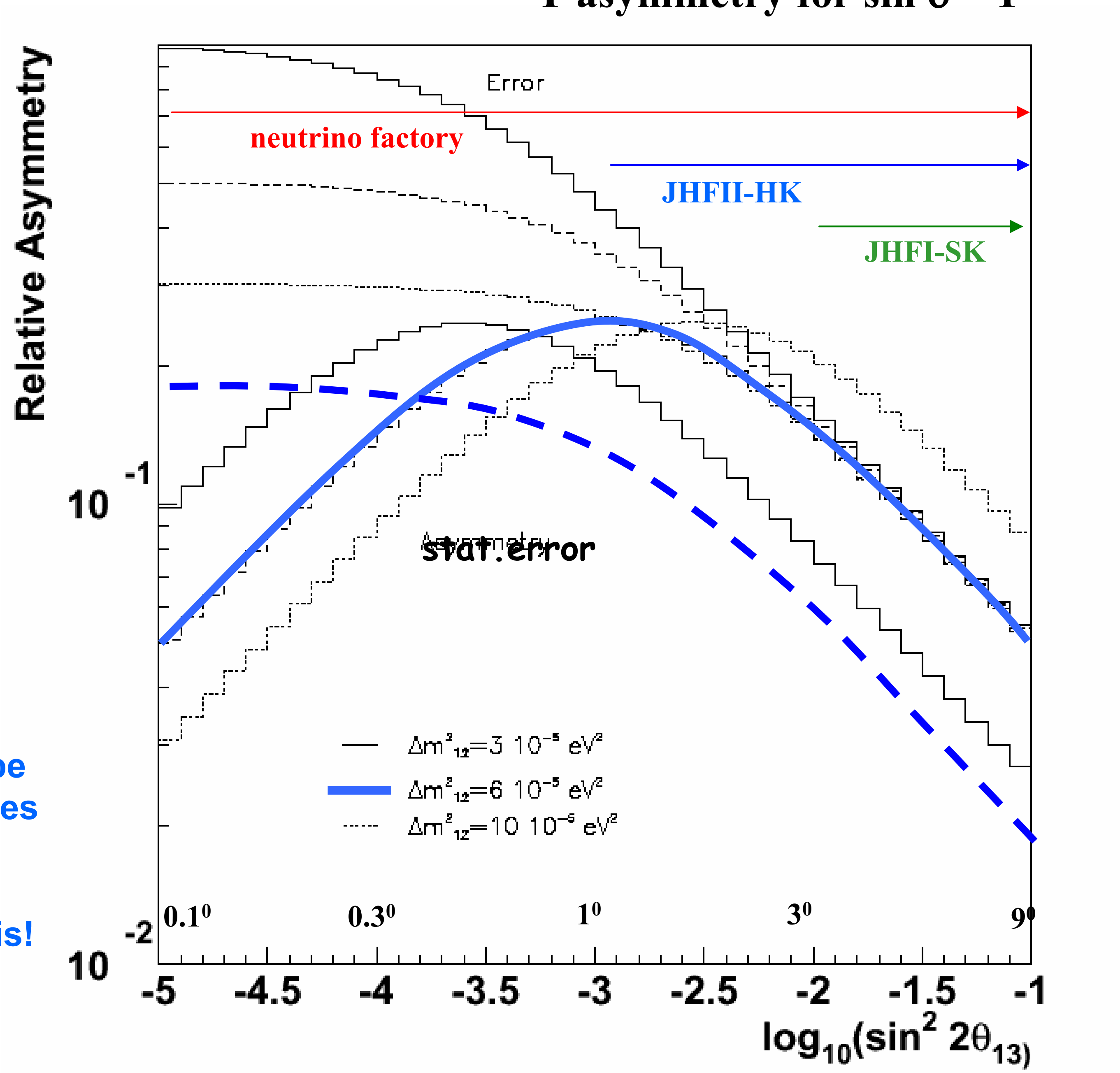
3 sigma sensitivity of various options
δ (deg.)
θ13 (deg.)
Superbeam only
Beta-beam only
Betabeam
+ superbeam
NUFACT
0
20
40
60
80
0
1
2
3
4
5
6
7
8
9
10

!

asymmetry is
a few %
and requires
excellent
flux normalization
(neutrino fact., beta beam
or
off axis beam with
not-too-near
near detector)

NOTE:
This is at first maximum!
Sensitivity at low values of θ_{13} is better for short baselines, sensitivity at large values of θ_{13} may be better for longer baselines (2d max or 3d max.)
This would desserve a more systematic analysis!

T asymmetry for sin δ = 1



Other physics opportunities at a ν-factory complex

<u>Related to high intensity</u>

Could begin as soon as SPL/accumulator is build:

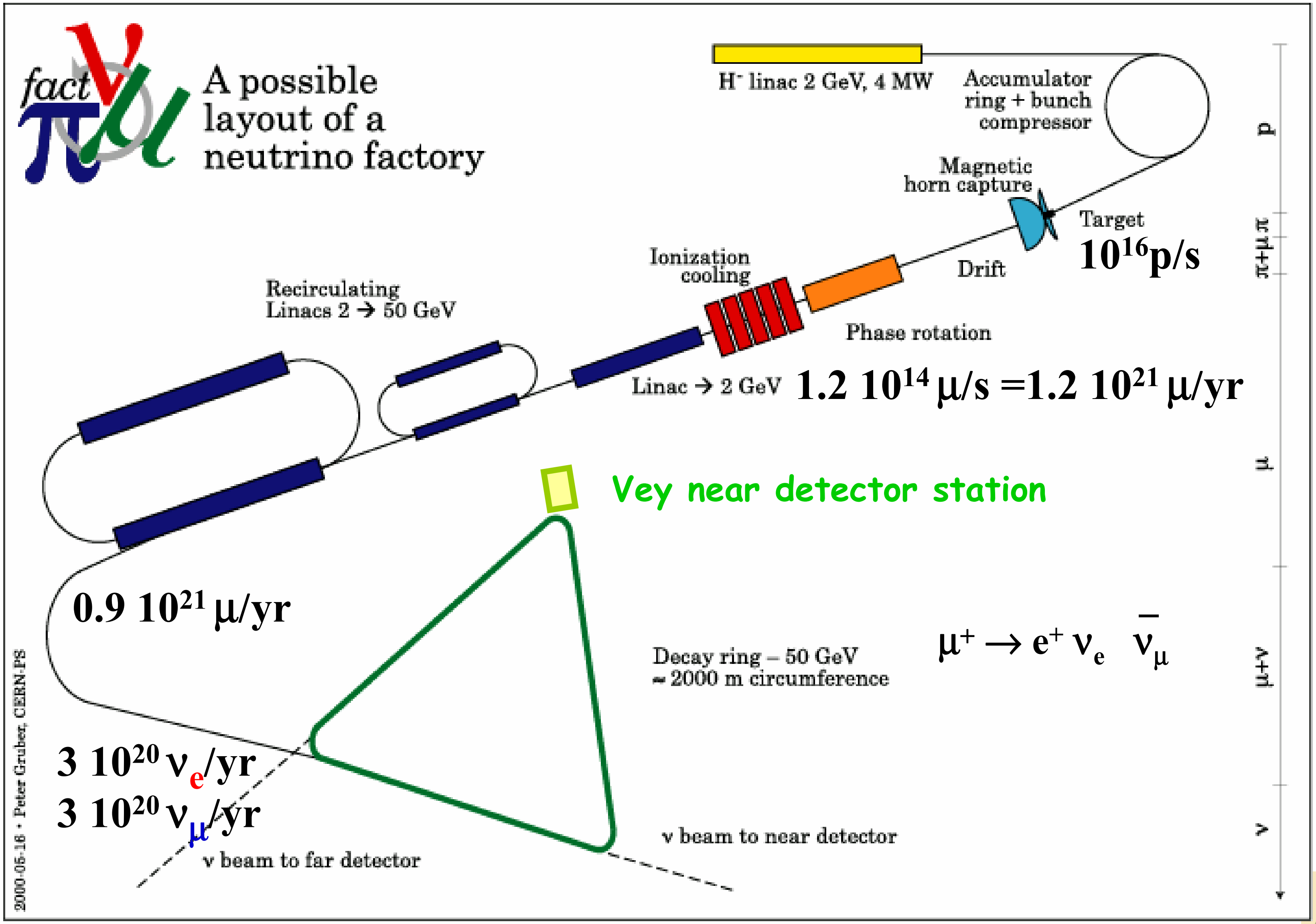
-High intensity low energy muon experiments
-- rare muon decays and muon conversion (lepton Flavor violation)
-- G_F, g-2, edm, muonic atoms, $e^+ \mu^- \leftrightarrow e^- \mu^+$
--> design of target stations and beamlines needed.

- 2d generation ISOLDE (Radioactive nuclei)
-- extend understanding of nuclei outside valley of stability
-- muonic atoms with rare nuclei(?)

if a sufficient fraction of the protons can be accelerated to E>15 GeV:
-High intensity hadron experiments
-- rare K decays (e.g.$K \to \pi^0 \nu \nu$)

In parallel to long baseline neutrino experiments:
-short baseline neutrino experiments (standard fluxes X10^4)
-- DIS on various materials and targets, charm production
-- NC/CC -> m_W (10-20 MeV) $\nu_\mu e \to \nu_\mu e$ & $\nu_e e \to \nu_e e$ -> $\sin^2\theta_W^{eff}$ (2.10^{-4})
--> design of beamline + detectors needed

-- Neutrino Factory --
Short baseline Physics



At the end of the straight sections, the fluxes are gigantic, in a very small area:

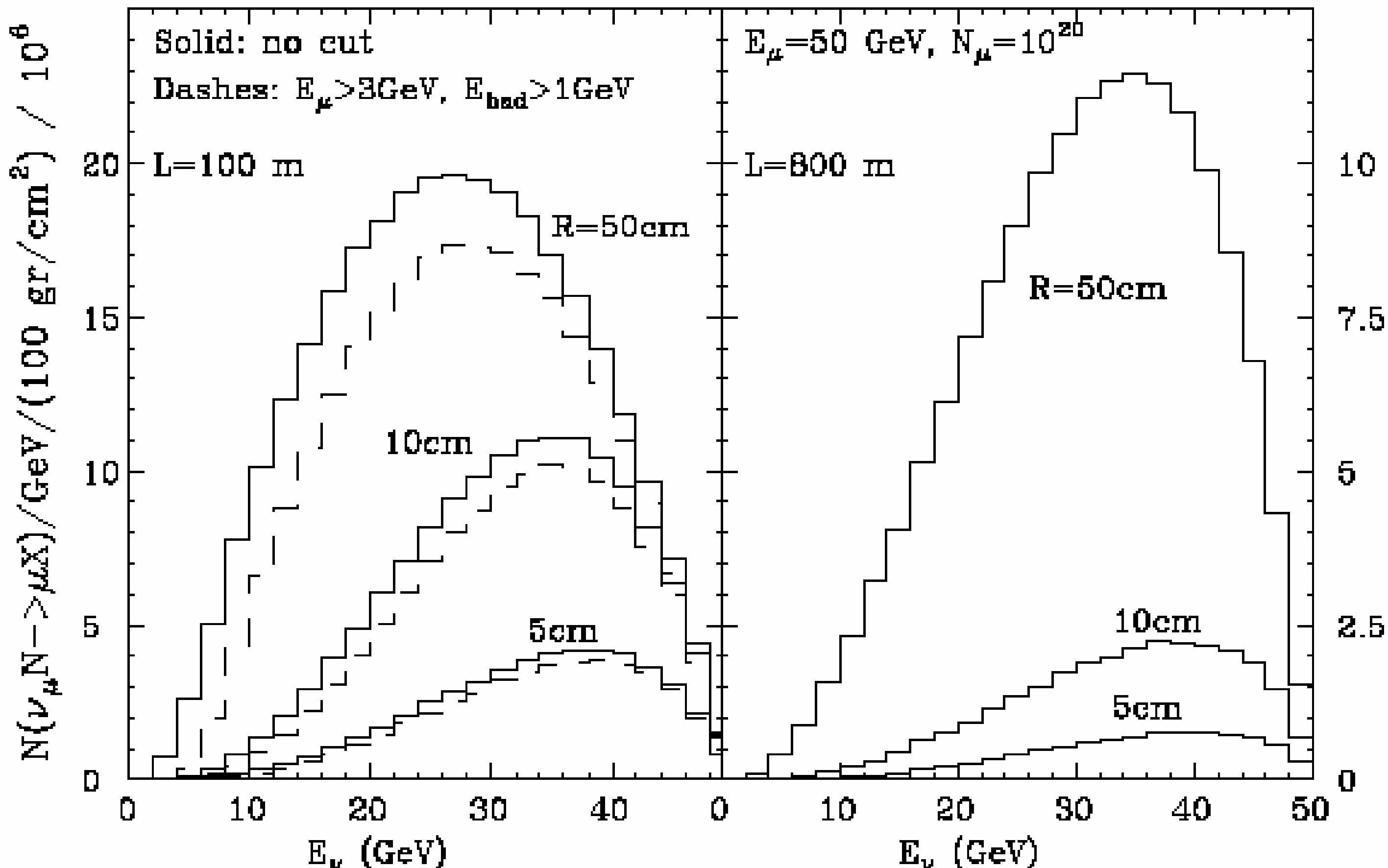
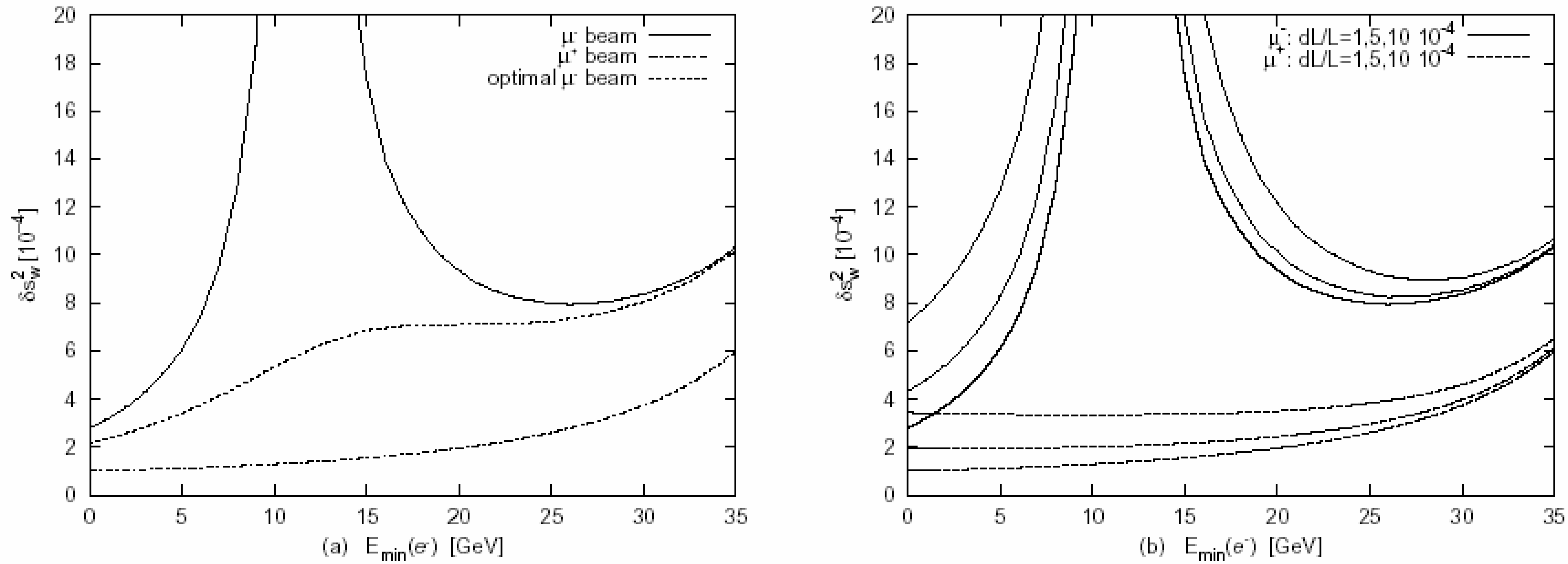


Fig. 2: CC event rates, in units of 10^6, as function of Lab-frame neutrino spectra, for several detector and beam configurations. The dashed lines on the left include cuts on the final-state muon ($E_\mu > 3$ GeV) and on the final-state hadronic energy ($E_{had} >$ 1 GeV). The solid lines have no energy-threshold cuts applied. The three set of curves correpsond to different detector radiuses (50, 10 and 5 cm, from top to bottom).

$\sin^2\theta_W$ FROM ELASTIC $e-\nu$

preset best: $\sin^2\theta_W = 0.2324 \pm 0.0058(\mathrm{stat}) \pm 0.0059(\mathrm{syst})$ (CHARMII, 1994)

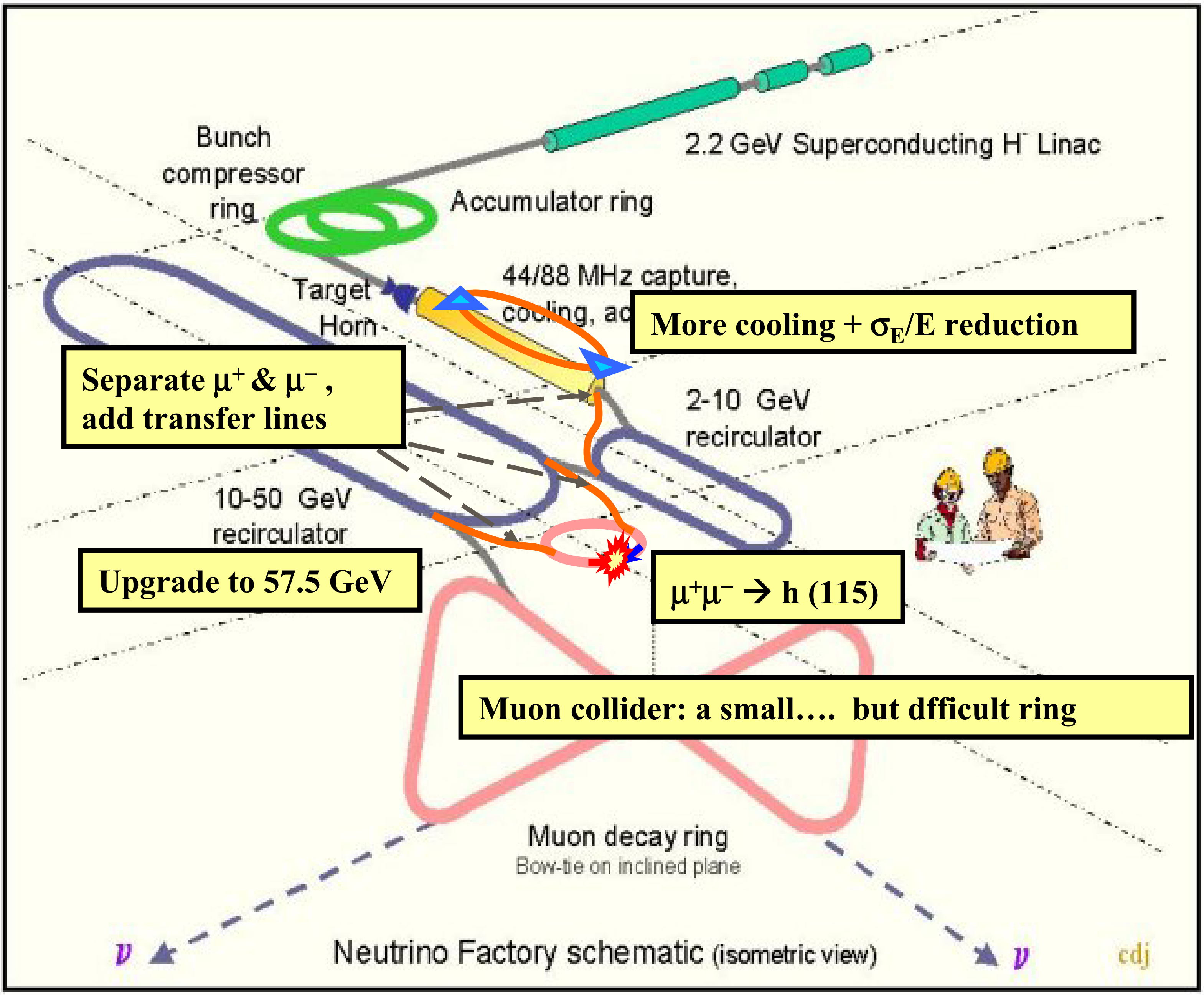
UNCERTAINTIES AT THE ν FACTORY: $(\times 10^{-4})$



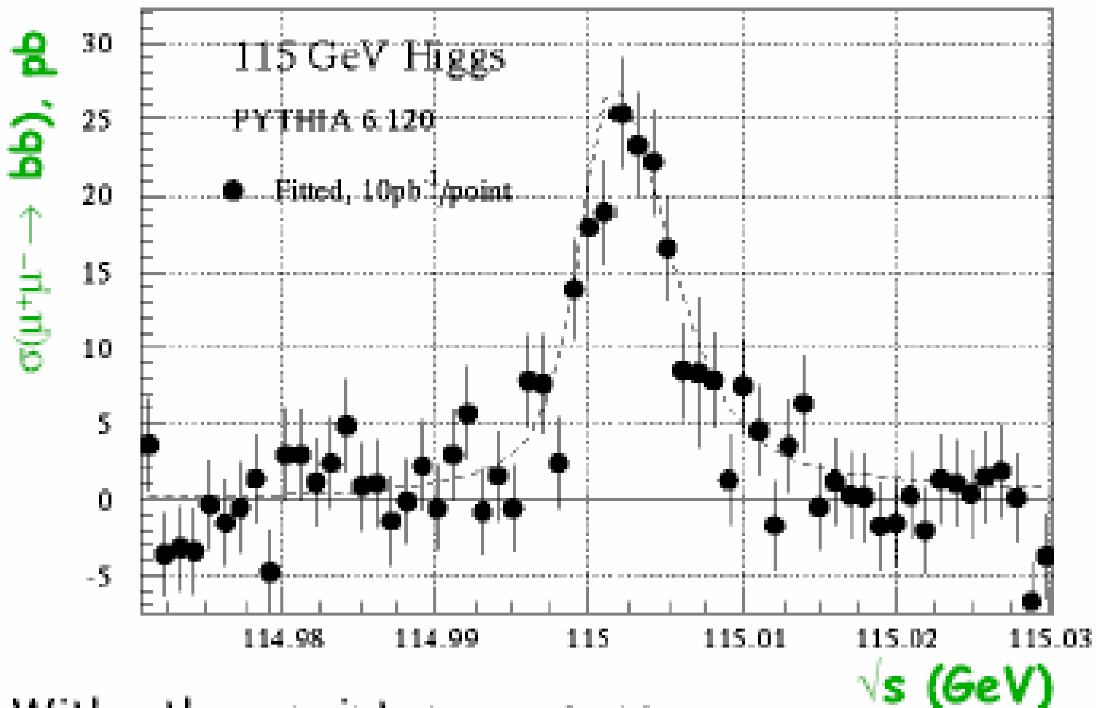
STAT. UNCERTAINTY **SYST. LUMI. UNCERTAINTY**

- **SIGNAL: FORWARD e TRACK WITH NO HADRONS, $E > E_{min}$**
- **BACKGROUND: QUASIELASTIC $\nu - p$ SCATTERING, REMOVE WITH p_T CUT**

From neutrino factory to Higgs collider



With an irrealistic 10 pb^{-1} / MeV scan:



With a three-point energy scan:

Observable	With 100 pb^{-1}	With 2.5 fb^{-1}
Mass	± 0.1 MeV/c^2	± 0.05 MeV/c^2
Width	± 0.5 MeV	± 0.1 MeV
σ_{peak}	± 1 pb	± 0.2 pb

Statistics limited !

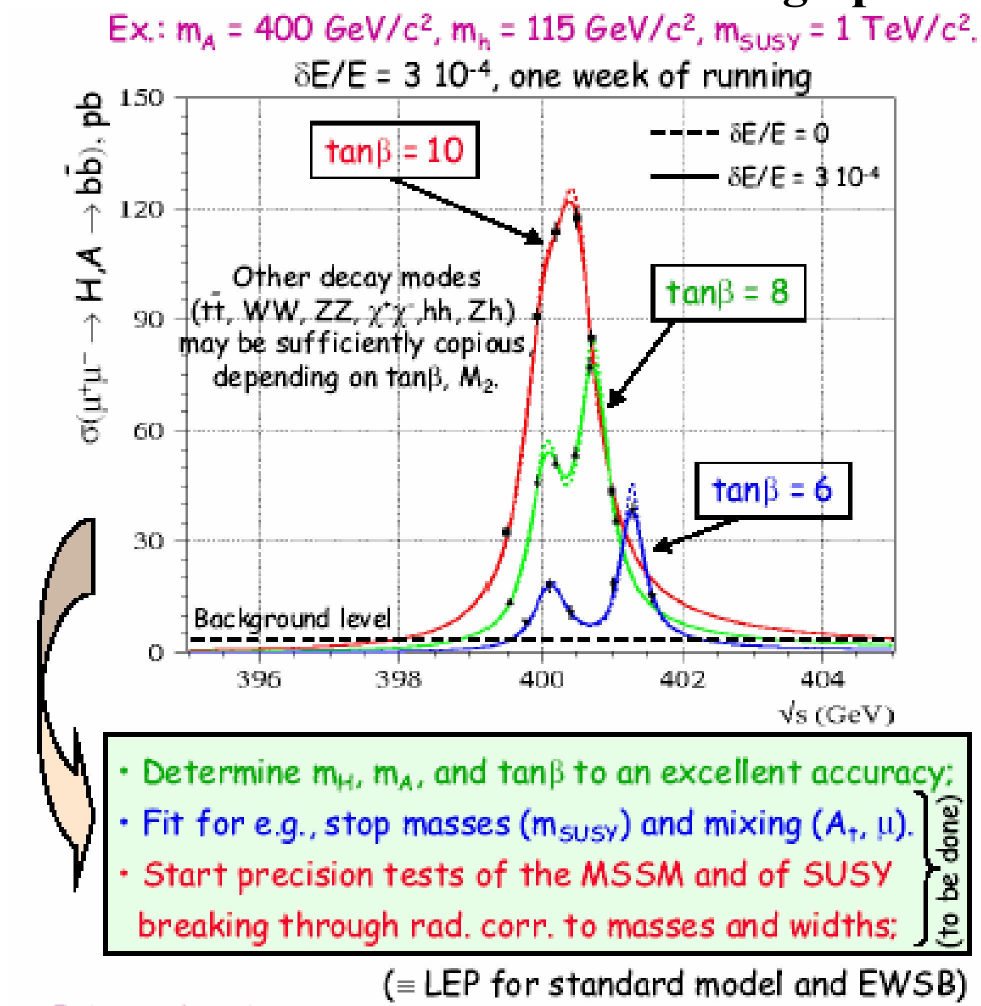
Still to be tried:

A scan in δE/E

Higgs Factory #2: $\mu^+ \mu^- \rightarrow$ H, A

SUSY and 2DHM predict two neutral heavy Higgs with masses close to each other and to the charged Higgs, with different CP number, and decay modes.

Cross-sections are large. Determine masses & widths to high precision.



Telling H from A:
bb and tt cross-sections
(also: hh, WW, ZZ…..)

investigate CP violating
H/A interference.

$$$$$ ... COST ... $$$$$

USA, Europe, Japan have each their scheme for Nu-Fact.
Only one has been costed, US 'study II' and estimated (2001) ~2B$.
The aim of the R&D is also to understand if one could reduce cost in half.

System	Sum ($M)	Others[a] ($M)	Total ($M)	Reconciliation[b] (FY00 $M)
Proton Driver	167.6	16.8	184.4	179.9
Target Systems	91.6	9.2	100.8	98.3
Decay Channel	4.6	0.5	5.1	5.0
Induction Linacs	319.1	31.9	351.0	342.4
Bunching	68.6	6.9	75.5	73.6
Cooling Channel	317.0	31.7	348.7	340.2
Pre-accel. linac	188.9	18.9	207.8	202.7
RLA	355.5	35.5	391.0	381.5
Storage Ring	107.4	10.7	118.1	115.2
Site Utilities	126.9	12.7	139.6	136.2
Totals	1,747.2	174.8	1,922.0	1,875.0

+ detector: MINOS * 10 = about 300 M€ or M$

Neutrino Factory CAN be done.....but it is too expensive as is.

Aim of R&D: ascertain challenges can be met + cut cost in half.

$$$$$ ... COST ... $$$$$

Why we are optimistic:

	Study 2	Now	Factor
PHASE ROTATION			
Beam Line (m)	328	166	51 %
Acceleration (m)	269	35	13 %
Acc Type	Induction	Warm RF	
COOLING			
Beam Line (m)	108	51	47 %
Acceleration (m)	74	34	46 %
Absorbers	Liquid Hydrogen	Solid Li or LiH	
ACCELERATION			
Beam Line (m)	3261	≈ 700	≈ 21 %
Tun Length	1494	≈ 700	≈ 47 %
Acc Length	288	≈ 130	≈ 45 %

In the previous design ~ ¾ of the cost came from these 3 equally expensive sub-systems.

New design has similar performance to Study 2 performance and keeps both μ^+ and μ^- !
(RF phase rotation)

NUFACT 2004: cost can be reduced by at least 1/3
= proton driver + 1 B €

==>the Neutrino Factory is not so far in the future after all….

S. Geer: We are working towards a "World Design Study" with an emphasis on cost reduction.

Conclusions

1. The Neutrino Factory remains the most powerful tool imagined so far to study neutrino oscillations

Unique: High energy $\nu_e \rightarrow \nu_\mu$ *and* $\nu_e \rightarrow \nu_\tau$ transitions
at large θ_{13} has the precision
at small θ_{13} has the sensitivity

2. The complex offers many other possibilities

3. It is a step towards muon colliders

4. There are good hopes to reduce the cost significantly thus making it an excellent option for CERN in the years 2011-2020

5. Regional and International R&D on components and R&D experiments are being performed by an enthusiastic and motivated community
(rate of progress is seriously slowed by funding constraints, however)

6. Opportunities exist in Europe:
HI proton driver, (SPL@CERN)
Target experiment @ CERN
Collector development @LAL-CERN
MICE @ RAL