food for thought: (simple)

what result would one get if one measured the mass of a ν_e (in K-capture for instance)?

what result would one get if one measured the mass of a ν_μ (in pion decay)?

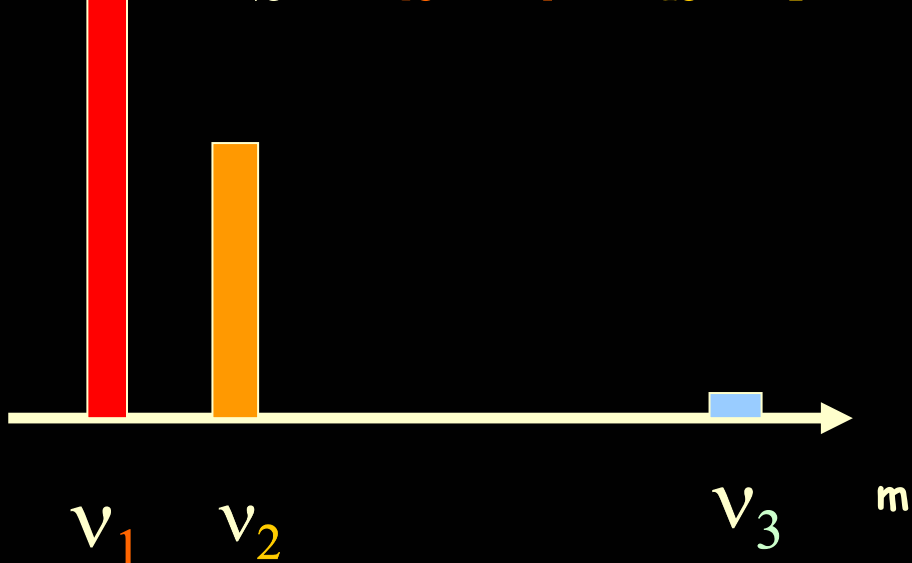
Is energy conserved when neutrinos oscillate?

ν_e

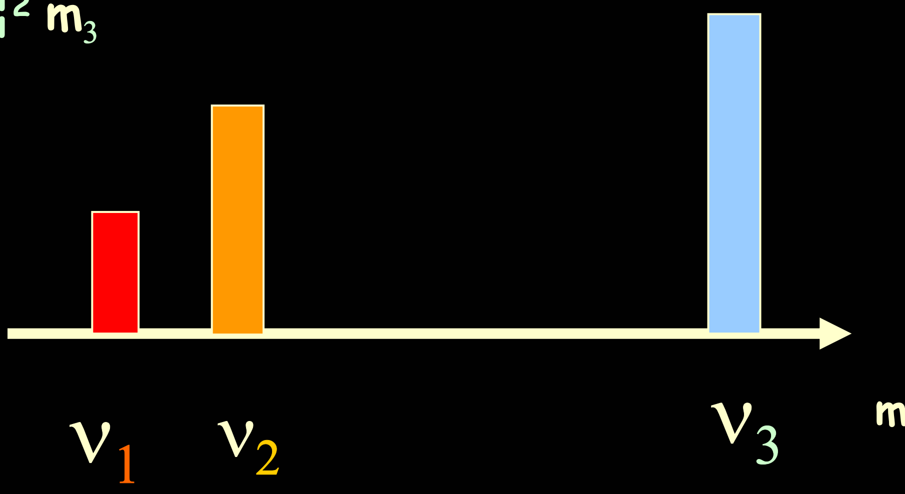
on mesure une distribution de masses avec
trois valeurs possibles ayant les prob.

$|U_{1e}|^2$ $|U_{2e}|^2$ $|U_{3e}|^2$

$\langle m_{\nu e} \rangle = |U_{1e}|^2 \, m_1 + |U_{2e}|^2 \, m_2 + |U_{3e}|^2 \, m_3$



ν_μ



Is energy conserved when neutrinos oscillate?

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = U_{1e}\,|\nu_1\rangle\ \exp(i E_1 t) + U_{2e}\,|\nu_2\rangle\ \exp(i E_2 t) + U_{3e}\,|\nu_3\rangle\ \exp(i E_3 t)$$

$P(\nu_1) = |U_{1e}|^2$

$P(\nu_2) = |U_{2e}|^2$

$P(\nu_3) = |U_{3e}|^2$

sont conservées durant la propagation

Future Neutrino Experiments

neutrinoless double beta decay
oscillations and search for CP vioaltion
- road map
- Reactor experiments
- T2K

Future facilities and their challenges
- Neutrino factory physics
- Proton drivers
- Target and Collection
- Neutrino Factory challenges
  - muon cooling
  - acceleration (FFAGs)
- Beta-Beam challenges

See NUFACT04 site:
http://www-kuno.phys.sci.osaka-u.ac.jp/~enufact04/
http://muonstoragerings.cern.ch

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

$\theta_{12} \sim 30^0$ $\Delta m_{12}^2 \sim 8\ 10^{-5} eV^2$ $\theta_{23} \sim 45^0$ $\Delta m_{23}{}^2 \sim 2.5\ 10^{-3} eV^2$ $\theta_{13} <\sim 10^0$

with several unknown parameters $\theta_{13,}$ 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.

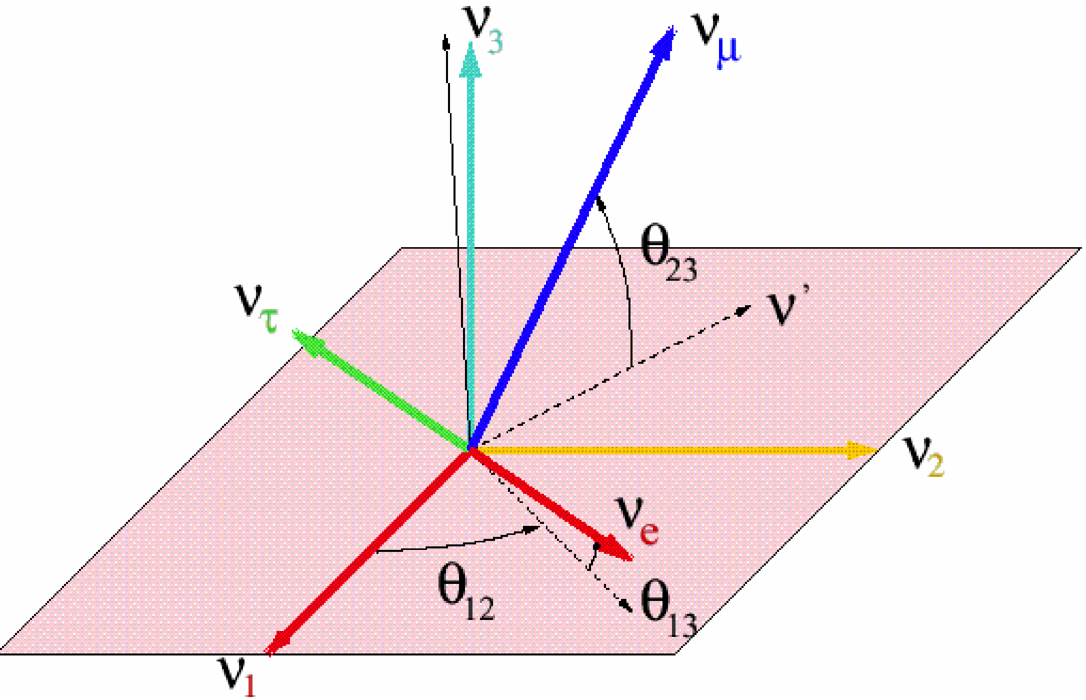
and we have not discovered leptonic CP yet!

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.

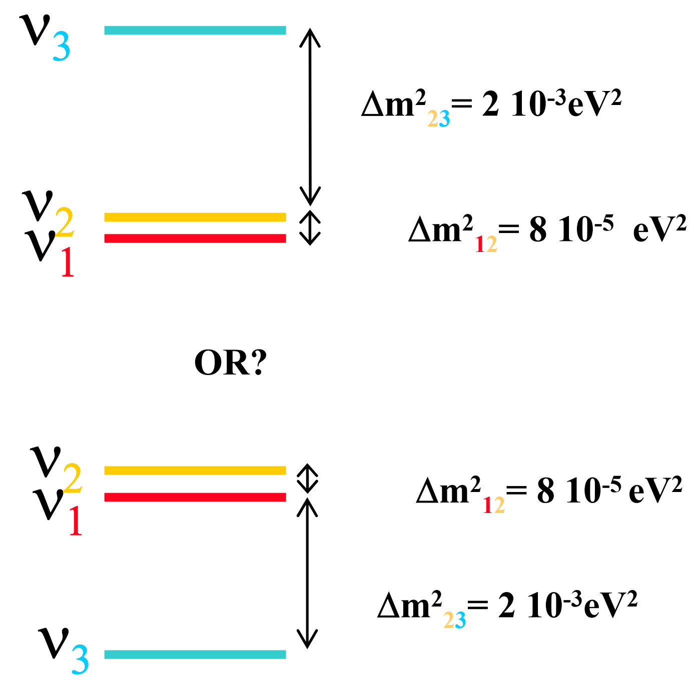
If confirmed, this would be even more exciting

See *Barger et al PRD 63 033002*

The neutrino mixing matrix: 3 angles and a phase δ



θ_{23} (atmospheric) = 45^0 , θ_{12} (solar) = 32^0 , θ_{13} (Chooz) < 13^0

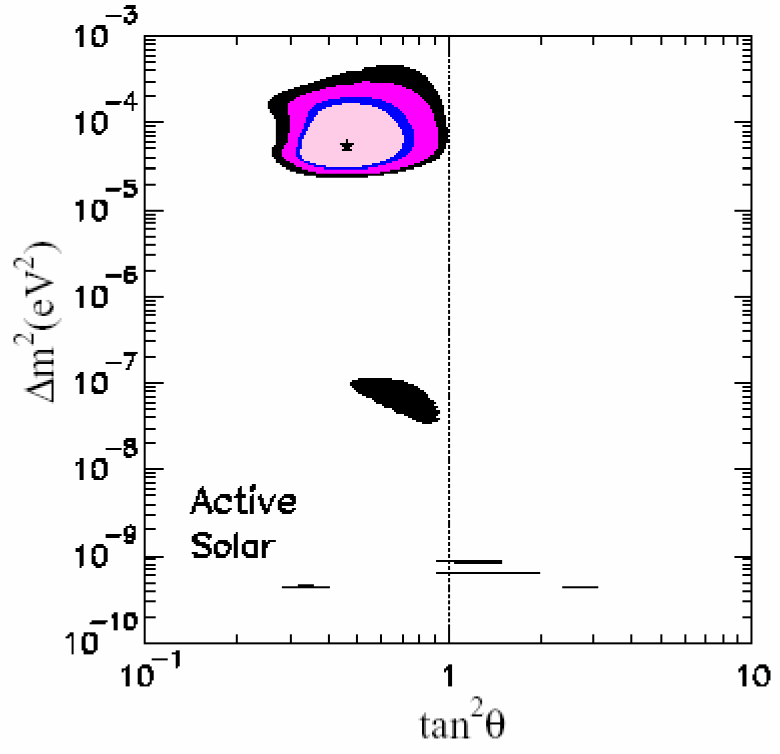


$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

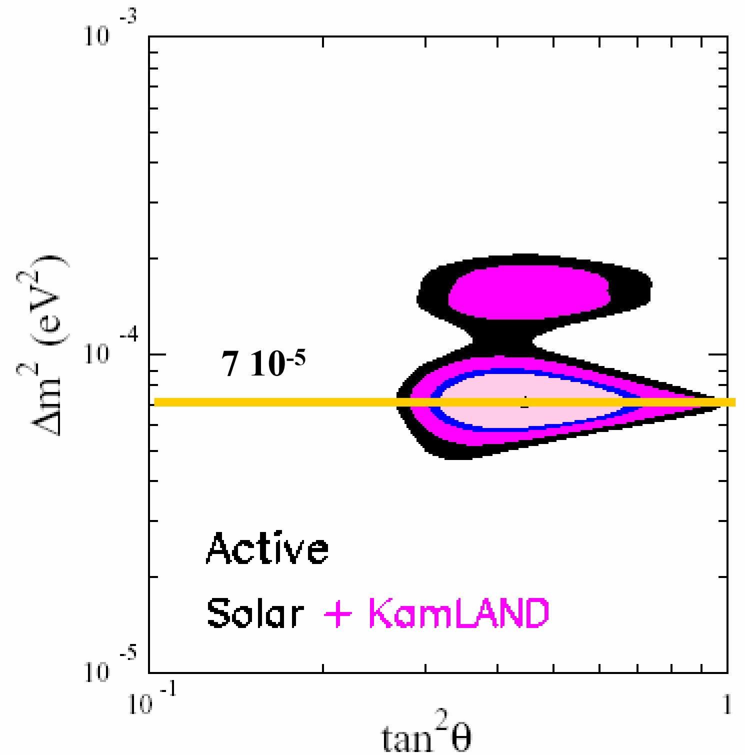
Unknown or poorly known even after approved program:
θ_{13} , phase δ , sign of Δm^2_{13}

Prerequisite for CP violation in neutrinos: Solar LMA solution

Before KamLAND

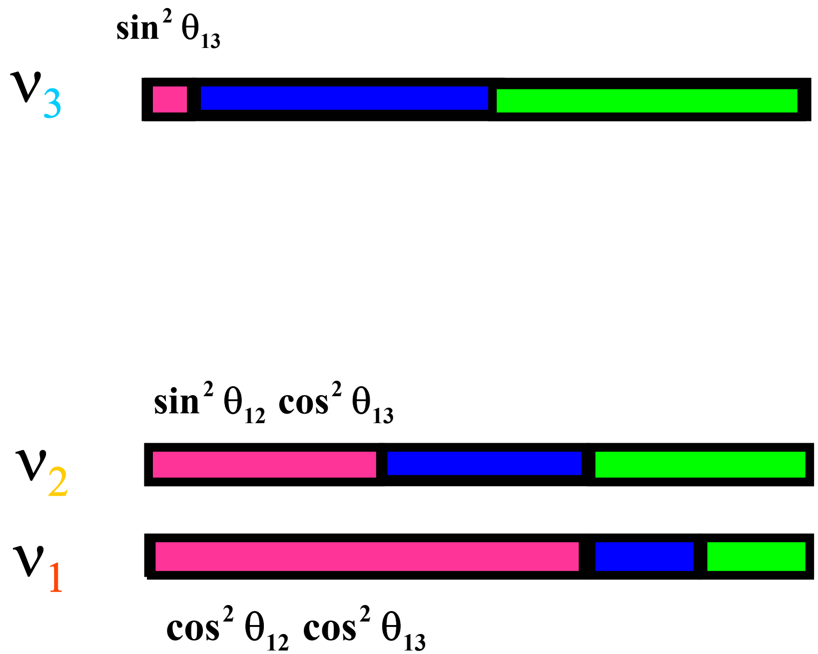


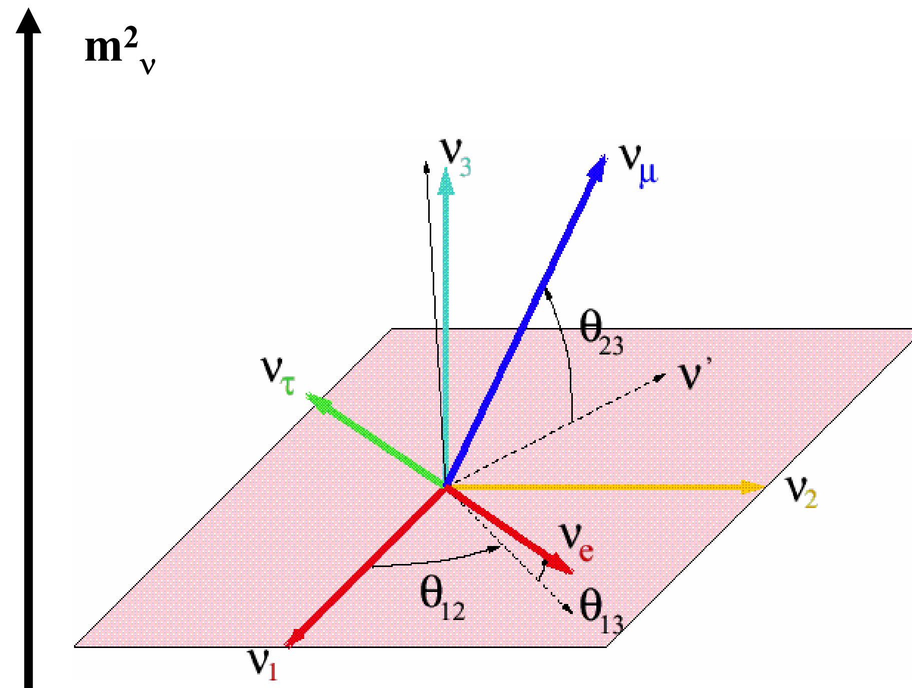
After KamLAND



This will be confirmed and Δm^2_{12} measured precisely by KAMLAND and maybe Borexino in next 2-4 yrs

neutrino mixing (LMA, natural hierarchy)





$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

ν_e is a (quantum) mix of

ν_1 (majority, 65%) and ν_2 (minority 30%)

with a small admixture of ν_3 (< 13%) (CHOOZ)

Neutrinos have mass and mix

This is NOT the Standard Model

why cant we just add masses to neutrinos?

Majorana neutrinos $\nu_i = \overline{\nu}_i$

or

Dirac neutrinos? $\nu_i \neq \overline{\nu}_i$

e+ $\neq$ e- since Charge(e+) = – Charge(e-).
But neutrinos may not carry any conserved charge-like quantum number.
There is NO experimetal evidence or theoretical need for a conserved Lepton Number L as
L(ν) = L(l-) = -L(ν) = -L(l+) = 1

then, nothing distinguishes ν_i **from** $\overline{\nu}_i$ **!**

violation of fermion number….

Adding masses to the Stadard model neutrino 'simply' by adding a Dirac mass term

$$m_D \nu_L \overline{\nu}_R$$

implies adding a right-handed neutrino.

No SM symmetry prevents adding then a term like

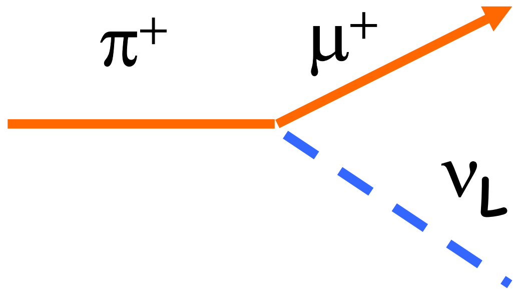
$$m_M \overline{\nu_R^{c}} \nu_R$$

and this simply means that a neutrino turns into a antineutrino (the charge conjugate of a right handed antineutrino is a left handed neutrino!)

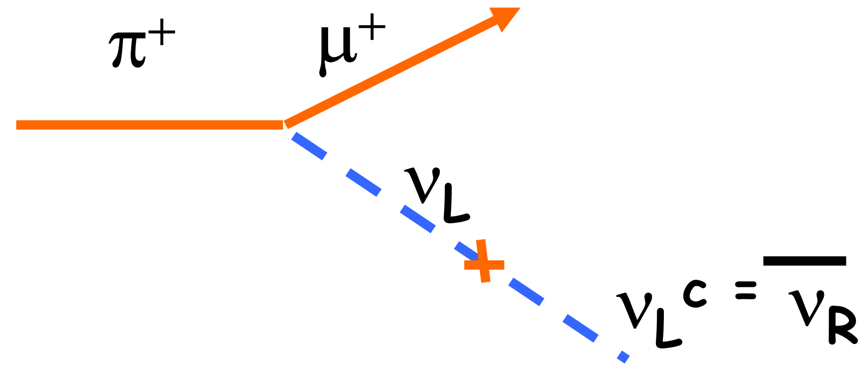
this does not violate spin conservation since a left handed field has a component of the opposite helicity (and vice versa)

$\nu_L \approx \nu_- + \nu_+ \, m/E$

Pion decay with massive neutrinos



$+$



1

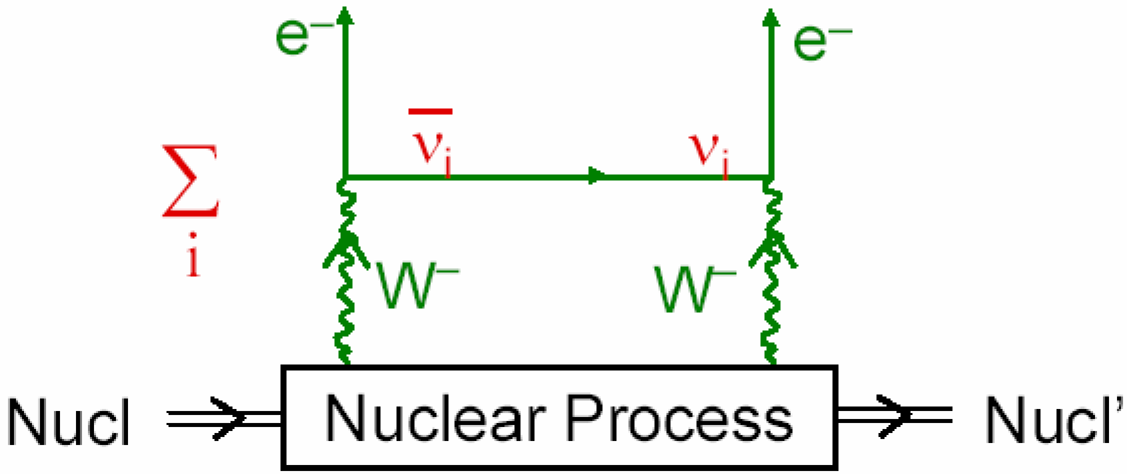
$$(m_\nu / E)^2$$

$$(.05/30\ 10^6)^2 = 10^{-18}$$

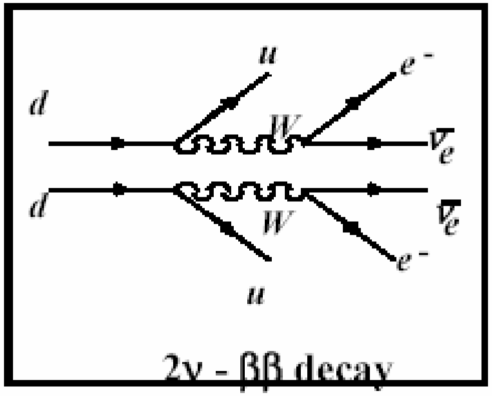
no problem, but not observable

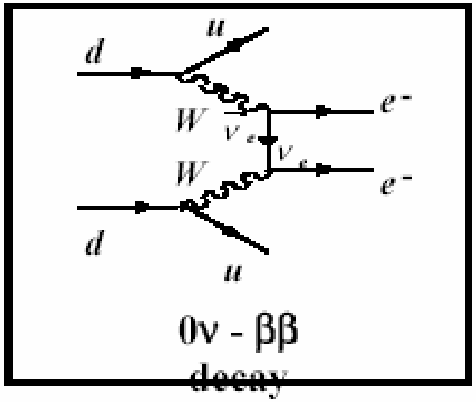
The Idea That Can Work —

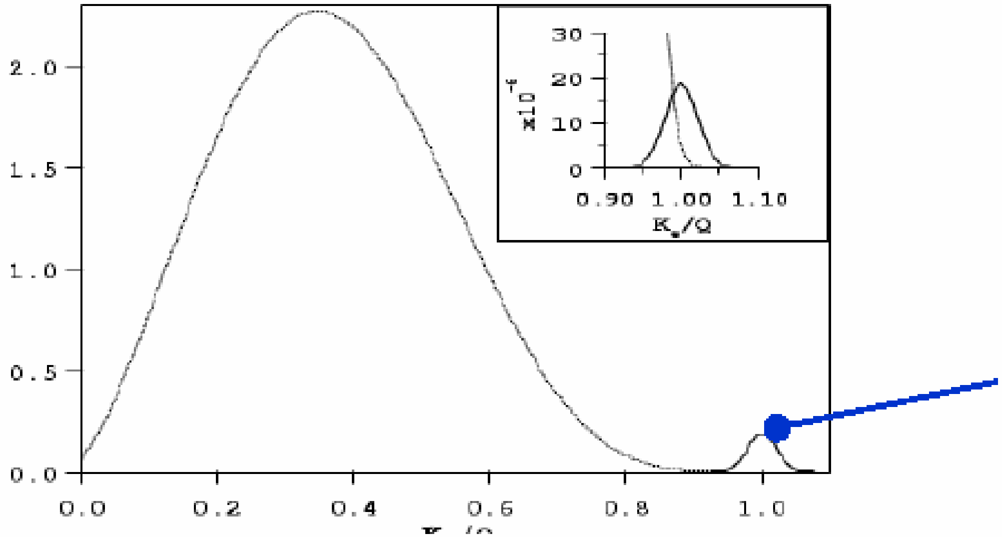
Neutrinoless Double Beta Decay [$0\nu\beta\beta$]



By avoiding competition, this process can cope with the small neutrino masses.







Two neutrino ββ decay has been detected in ten nuclei also into exited states

Three Neutrino Mixing

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\,\nu_{j\mathrm{L}}\ .$$

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

- U - $n \times n$ unitary:

		n	2	3	4
mixing angles:	$\frac{1}{2}n(n-1)$		1	3	6
CP-violating phases:					
• ν_j- Dirac:	$\frac{1}{2}(n-1)(n-2)$		0	1	3
• ν_j- Majorana:	$\frac{1}{2}n(n-1)$		1	3	6

$n = 3$: 1 Dirac and
2 additional CP-violating phases, Majorana phases

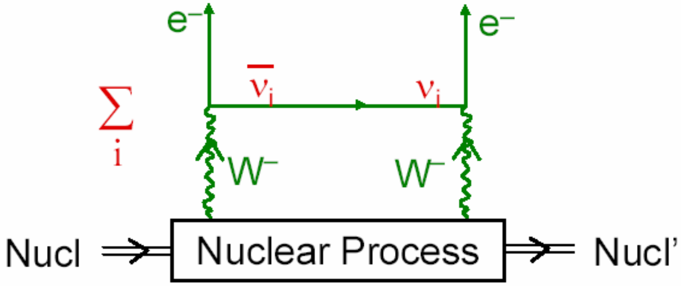
S.M. Bilenky, J. Hosek, S.T.P.,1980;
J. Schechter, J.W.F. Valle,1980;
M. Doi, T. Kotani, E. Takasugi,1981

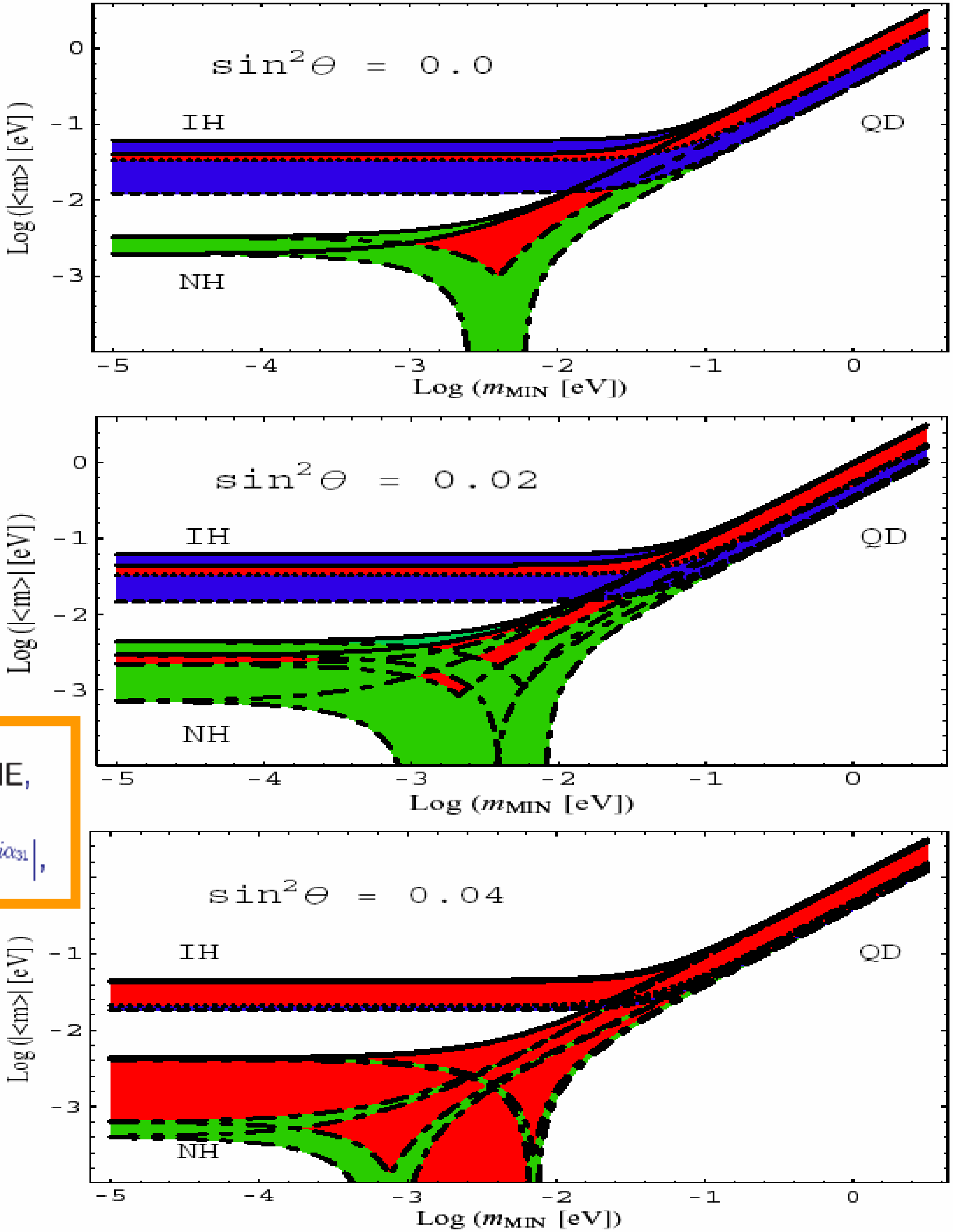
$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix} \qquad (4)$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \qquad (5)$$

$A(\beta\beta)_{0\nu} \sim \langle m \rangle$ M(A,Z), M(A,Z) - NME,

$$|\langle m \rangle| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2\, e^{i\alpha_{21}} + m_3 |U_{e3}|^2\, e^{i\alpha_{31}} \right|,$$

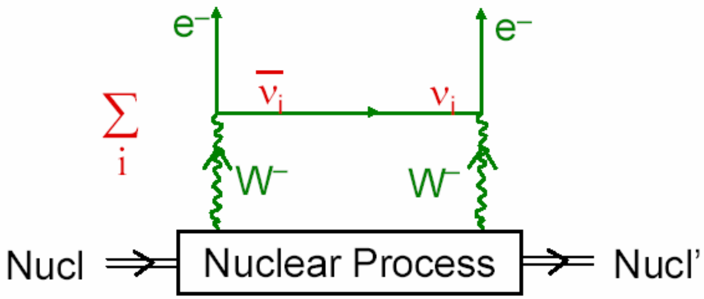




ce que mesure le $0\nu\beta\beta$ est <m> :

$A(\beta\beta)_{0\nu} \sim <m>$ M(A,Z), M(A,Z) - NME,

$$|<m>| = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2\, e^{i\alpha_{21}} + m_3|U_{e3}|^2\, e^{i\alpha_{31}}|,$$



$$(G_F)^4$$

Experimental approach

Geochemical experiments

^{82}Se = > ^{82}Kr, ^{96}Zr = > ^{96}Mo (?) , ^{128}Te = > ^{128}Xe (non confirmed), ^{130}Te = > ^{130}Te

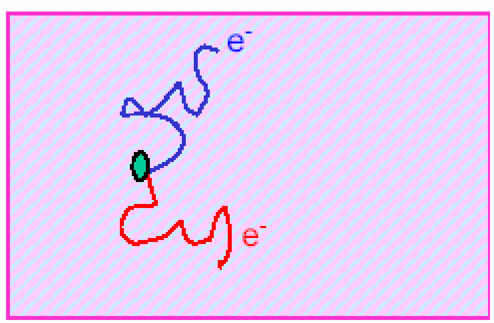
Radiochemical experiments

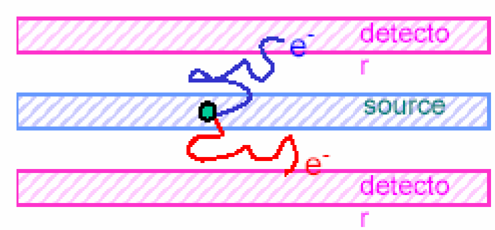
^{238}U = > ^{238}Pu (non confirmed)

Direct experiments

Source = detector (calorimetric)

Source ≠ detector





Source ≠ Detector

Summary of the most recent 2 ν experiments : **2νββ**

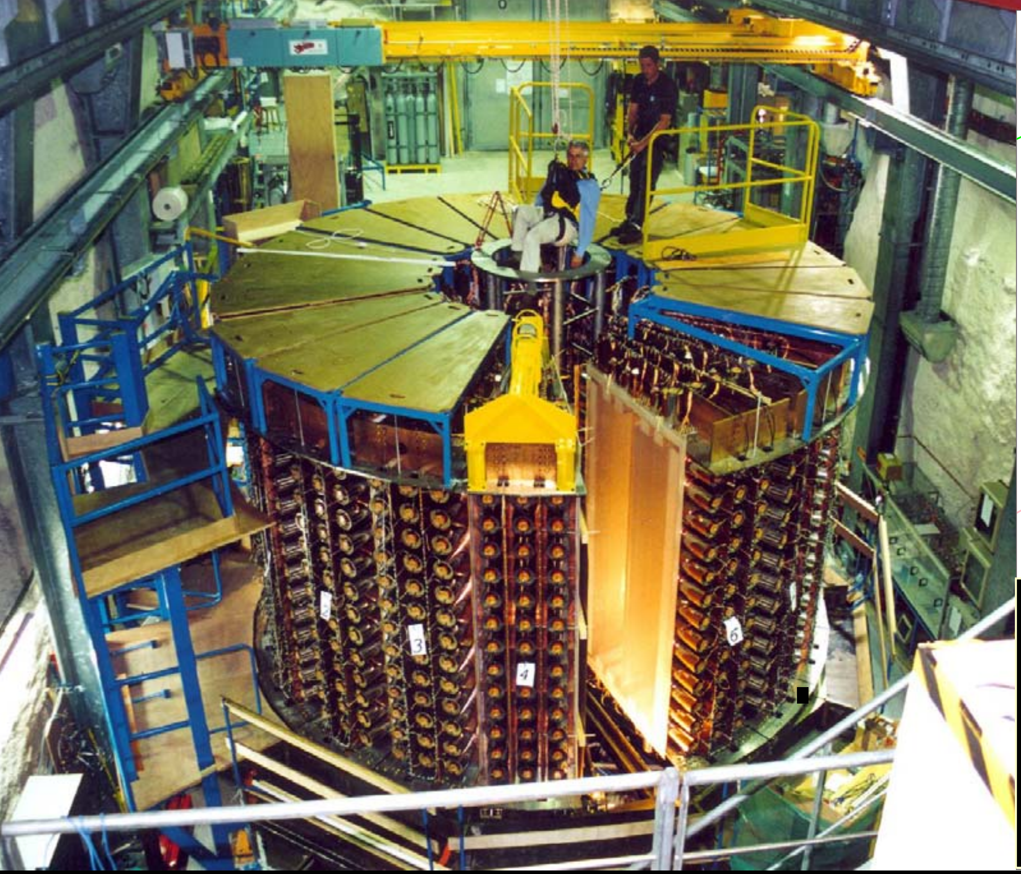
Isotope	$\tau_{1/2}^{2\nu}$(y) [measured]	$\tau_{1/2}^{2\nu}$(y)[calculated]
^{48}Ca	$(4.2\ ^{+2.1}_{-1.0}) \times 10^{19}$	6×10^{18} - 5×10^{20}
^{76}Ge	$(1.42\ ^{+0.09}_{-0.07}) \times 10^{21}$	7×10^{19} - 6×10^{22}
^{82}Se	$(0.9 \pm 0.1) \times 10^{20}$	3×10^{18} - 6×10^{21}
^{96}Zr	$(2.1^{+0.8}_{-0.4}) \times 10^{19}$	3×10^{17} - 6×10^{20}
^{100}Mo	$(8.0 \pm 0.7) \times 10^{18}$	1×10^{17} - 2×10^{22}
^{100}Mo(0^{+*})	$(6.8 \pm 1.2) \times 10^{20}$	5×10^{19} - 2×10^{21}
^{116}Cd	$(3.3\ ^{+0.4}_{-0.3}) \times 10^{19}$	3×10^{18} - 2×10^{21}
^{128}Te	$(2.5 \pm 0.4) \times 10^{24}$	9×10^{22} - 3×10^{25}
^{130}Te	$(0.9 \pm 0.15) \times 10^{21}$	2×10^{19} - 7×10^{20}
^{150}Nd	$(7.0 \pm 1.7) \times 10^{18}$	6×10^{16} - 4×10^{20}
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$	1.2×10^{19}

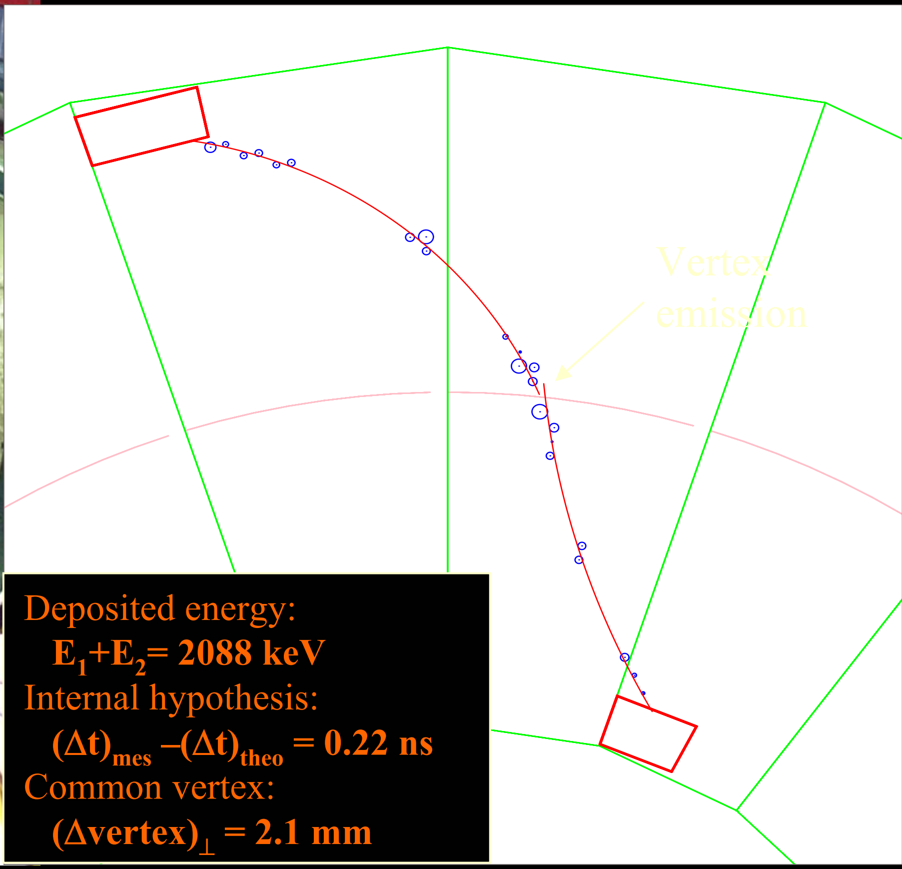
Summary of the most sensitive neutrinoless ββ experiments

0νββ

Experim	Isotope	$\tau_{1/2}^{0\nu}$ (y)	m^*_{ee} (eV)	Range m_{ee}
Heidelberg – Moscow 2001	^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35	< 0.3 – 2.5
IGEX 2002		$> 1.57 \times 10^{25}$	< 0.38	< 0.3 – 2.5
Mi DBD – ν 2002	^{130}Te	$> 2.1 \times 10^{23}$	< 1.5	< 0.9 – 2.1
Bernatowicz et al. 1993 (GEO)	^{128}Te^{geo}	$> 7.7 \times 10^{24}$	< 1.0	< 1.0 – 4.4
Belli et al. 2003	^{136}Xe	$> 1.2 \times 10^{24}$	< 1.0	< 0.8 – 2.4
Bizzeti et al. 2003	^{116}Cd	$> 1.7 \times 10^{23}$	< 1.7	< 1.6 – 5.5
Ejiri et al. 2001	^{100}Mo	$> 5.5 \times 10^{22}$	< 4.8	< 1.4 - 256
Osawa I. et al. 2002	^{48}Ca	$> 1.8 \times 10^{22}$	< 6.0	

* Staudt, Muto, Klapdor-Kleingrothaus Europh. Lett 13 (1990)





NEMO

Criteria to select ββ events:

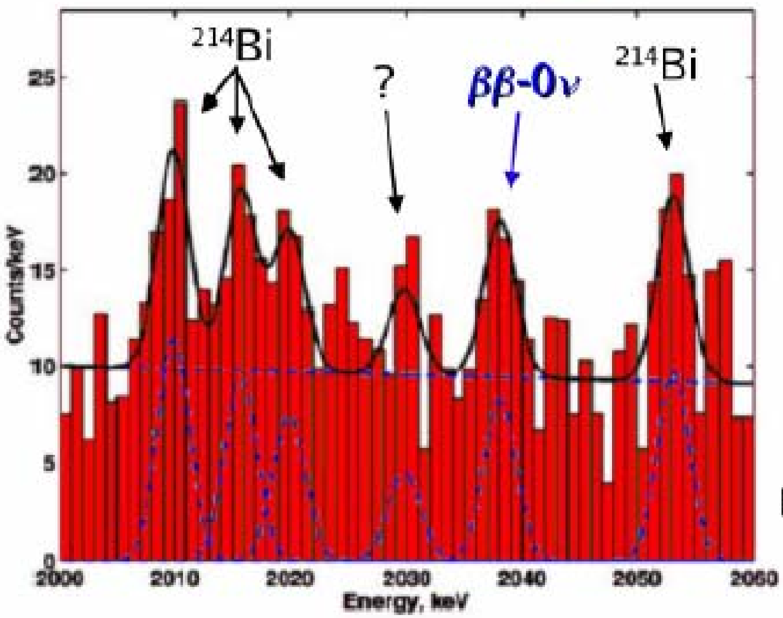
- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex

- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track (^{214}Bi rejection)

evenement 2νββ typique

Heidelberg-Moscow exp.: evidence for $\beta\beta$-0ν of ^{76}Ge

- best exploitation of the Ge detector technique proposed by E. Fiorini in 1960
  - longest running experiment (13 years) with largest exposure (71.7 kg×y)
  - Status-of-the-art for low background techniques and for enriched Ge detectors
  - reference for all last generation $\beta\beta$-0ν experiments



1990 – 2003 data, all 5 detectors

exposure = 71.7 kg×y

$$\tau_{1/2}^{0\nu} = 1.2\times10^{25} \text{ years}$$

$$\langle m_\nu \rangle = 0.44 \text{ eV}$$

H.V.Klapdor-Kleingrothaus *et al.*, Phys. Lett. B 586 (2004) 198

- still, community **does not fully accept the result**, because:
  - signal is indeed **too faint** (4 σ) to be *blindly* accepted: people still find some weak points in the published analysis
  - presence of **not understood peaks** around the signal and with *similar* significance
  - impossibility to check an **energy window larger** than the published one
- **nevertheless any future $\beta\beta$-0ν experiment will have to cope with this result**

$0\nu\beta\beta$ CONC LUSIONS

- Present limits (or indication) are at the level of a fraction of eV for <m>, neutrino oscillations demand a few 10 meV sensitivities, namely an improvement of an order of magnitude or two

- sensitivity on <m > depends linearly on nuclear matrix element and on the square root of the inverse of the limit on half-life

- if no evidence is observed limit on lifetime depend linearly on isotopic abundance, and on the square root of the mass, the measurement time and the inverse of the energy resolution and of the background

one needs to :
- increase the isotopic abundance (expensive,slow,careful to the background)
- increase the mass (expensive and technically complicated)
- increase the time of measurement (tedious)
- Increase the energy resolution (already at the level of a few keV)
- Decrease the background (already at ~ 0.1 counts-1 keV-1 kg-1 y-1)

Searches on neutrinoless double beta decay are a multidiscipInary challenge for an experimentalist involving astroparticle and nuclear physics, material science cosmochronology, low radioactivity etc.

Road Map

A Experiments to find θ_{13} :

search for $\nu_\mu \rightarrow \nu_e$

--in conventional ν_μ beam (MINOS, ICARUS/OPERA)

limitations: NC π^0 background, intrinsic ν_e component in beam

-- in reactor experiments

--Off-axis beam (JPARC-SK, off axis NUMI) or

--Low Energy Superbeam (BNL → Homestake, SPL →Fréjus)

B Precision experiments to find CP violation

-- or to search further if θ_{13} is too small

-- beta-beam 6 ++ 6 +++ − − and $^{18}Ne^{10+} \rightarrow {}^{18}F^{9+}\ \nu_e\ e^+$

-- Neutrino factory with muon decay storage ring

− and $\mu^- \rightarrow e^-\ \bar{\nu}_e\ \nu_\mu$

fraction thereof will exist .

Roadmap

Where do we stand?

Where do we go?

Which way do we chose?

Shortest?

Cheapest?

Fastest?

Taking into account practicalities or politics?

Oscillation maximum $1.27\,\Delta m^2\ L / E = \pi/2$

Atmospheric $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$ — $L = 500$ km @ 1 GeV
Solar $\Delta m^2 = 7\ 10^{-5}\ eV^2$ — $L = 18000$ km @ 1 GeV

Consequences of 3-family oscillations:

I There will be $\nu_\mu \leftrightarrow \nu_e$ **and** $\nu_\tau \leftrightarrow \nu_e$ **oscillation at** L_{atm}

$P(\nu_\mu \leftrightarrow \nu_e)_{max} =\sim \frac{1}{2}\sin^2 2\theta_{13}$ +… (small)

II There will be CP or T violation

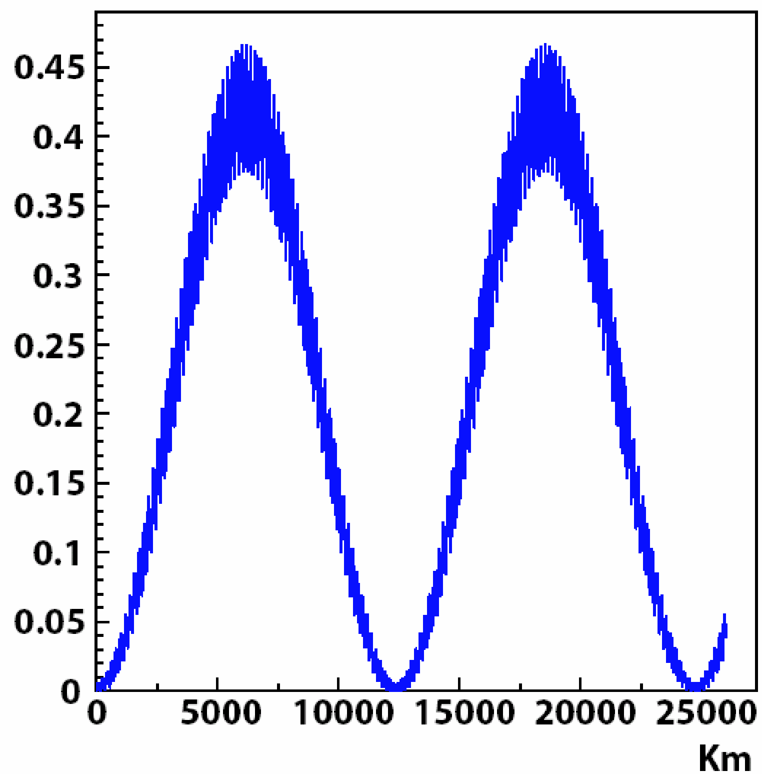
CP: $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P(\nu_\mu \leftrightarrow \nu_e)$

T : $P(\nu_\mu \leftrightarrow \nu_e) \neq P(\nu_e \leftrightarrow \nu_\mu)$

III we do not know if the neutrino ν_1 **which contains more** ν_e
is the lightest one (natural?)
or not.

Oscillations of 250 MeV neutrinos;

$P(\nu_\mu \leftrightarrow \nu_e)$



$$P(\nu_e \to \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\ \sin\delta$$

$$P(\bar{\nu}_e \to \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2\,A\,S\ \sin\delta$$

$$\frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} = A_{CP}\ \alpha\ \frac{\sin\delta\ \ \sin(\Delta m^2_{12} L/4E)\ \ \sin\theta_{12}}{\sin\theta_{13} + \text{solar term}\ldots}$$

… need large values of sin θ_{12}, Δm^2_{12} (LMA) but *not* large $\sin^2\theta_{13}$

… need APPEARANCE … $P(\nu_e \to \nu_e)$ is time reversal symmetric (reactors or sun are out)

… can be large (30%) for suppressed channel (one small angle vs two large)

at wavelength at which 'solar' = 'atmospheric' and for $\nu_e \to \nu_\mu$, ν_τ

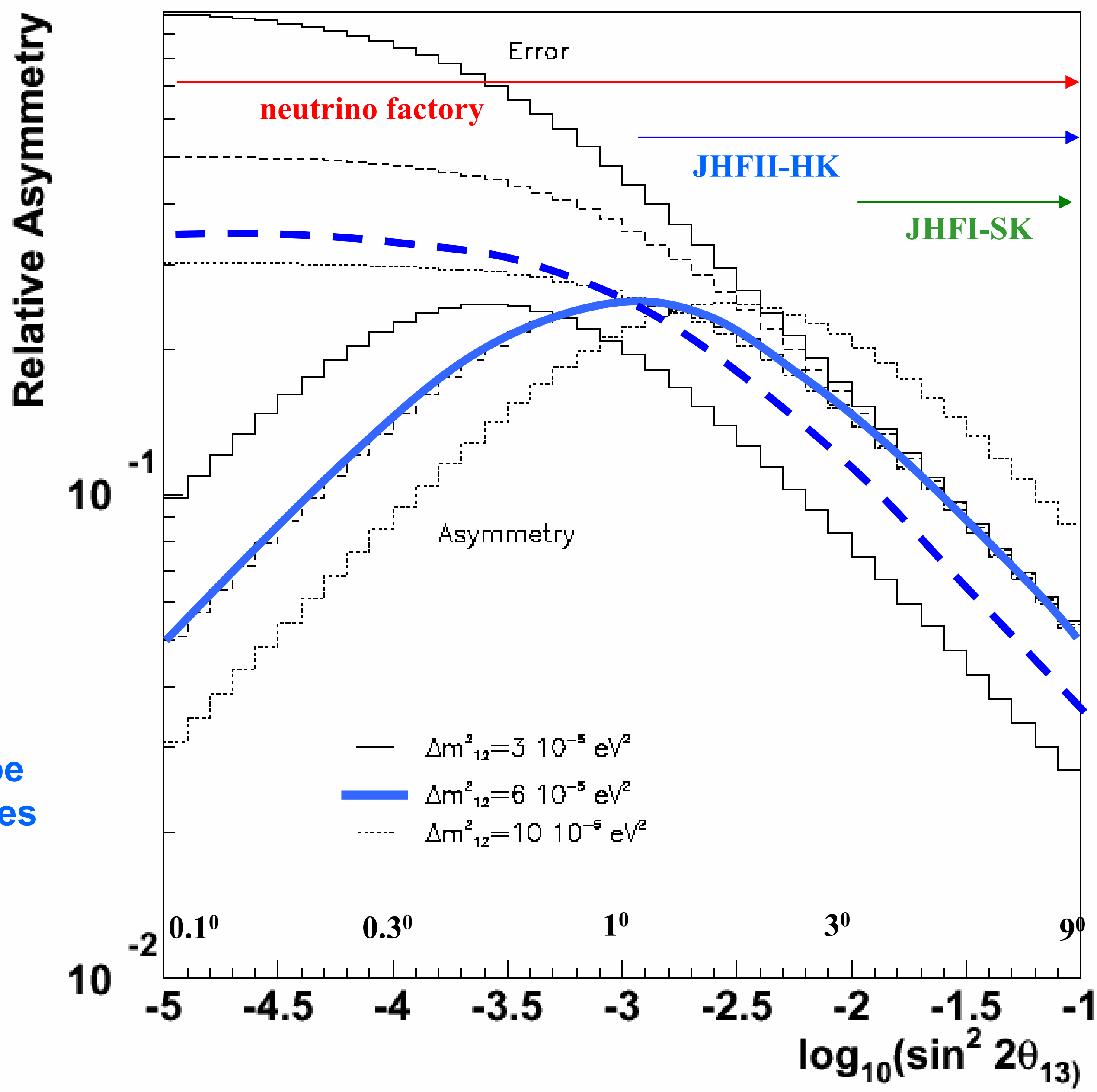
… asymmetry is opposite for $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$

T asymmetry for sin $\delta = 1$

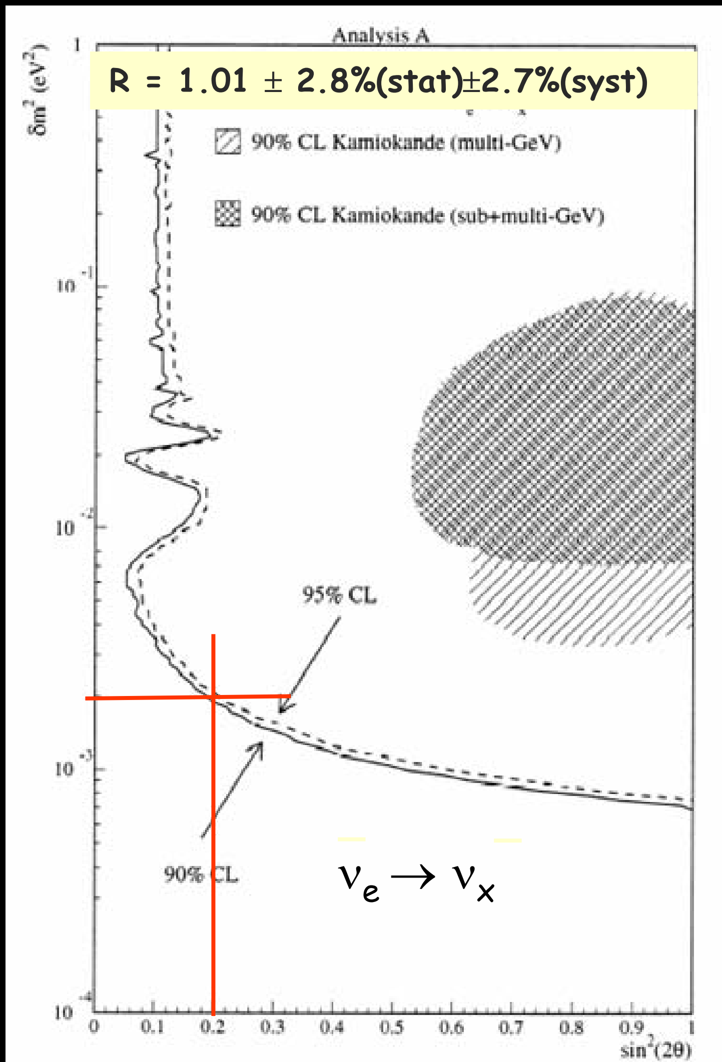
!

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

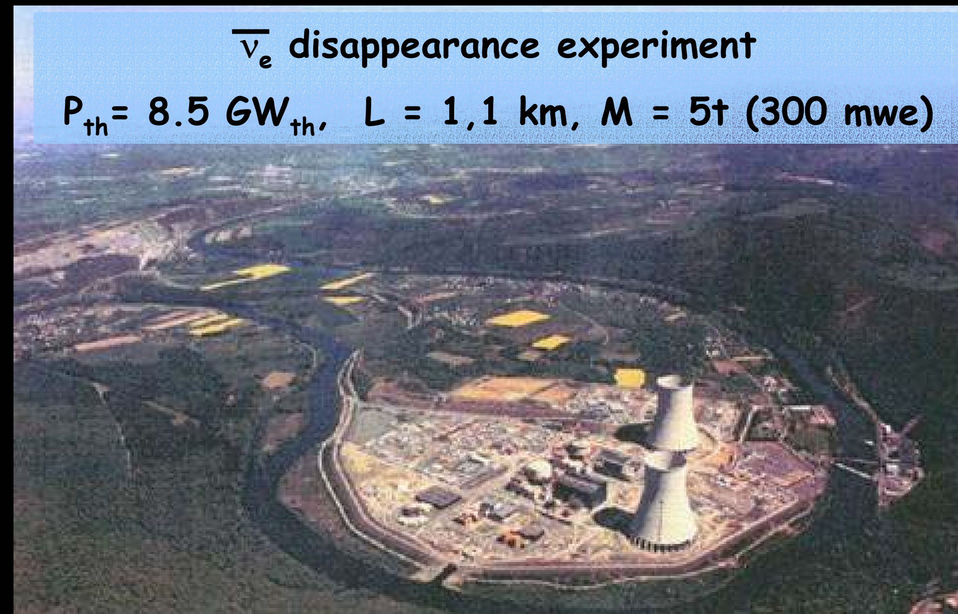
NOTE:
This is at first maximum!
Sensitivity at low values of θ_{13} is better for short baselines, sensitivity at large values of θ_{13} may be better for longer baselines (2d max or 3d max.)
This would desserve a more careful analysis!

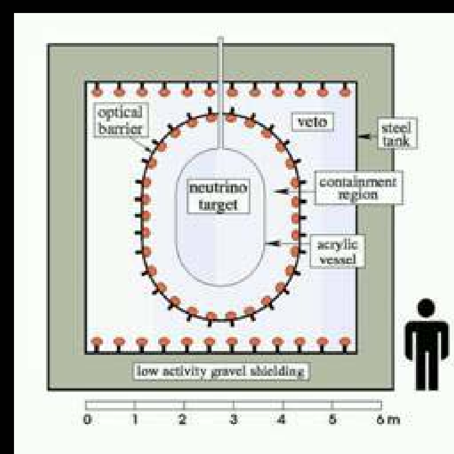


θ_{13} : Best current constraint: CHOOZ



M. Apollonio et. al., Eur.Phys.J. C27 (2003) 331-374





World best constraint !

@Δm^2_{atm}=2 10^{-3} eV^2

$\sin^2(2\theta_{13})$<0.2

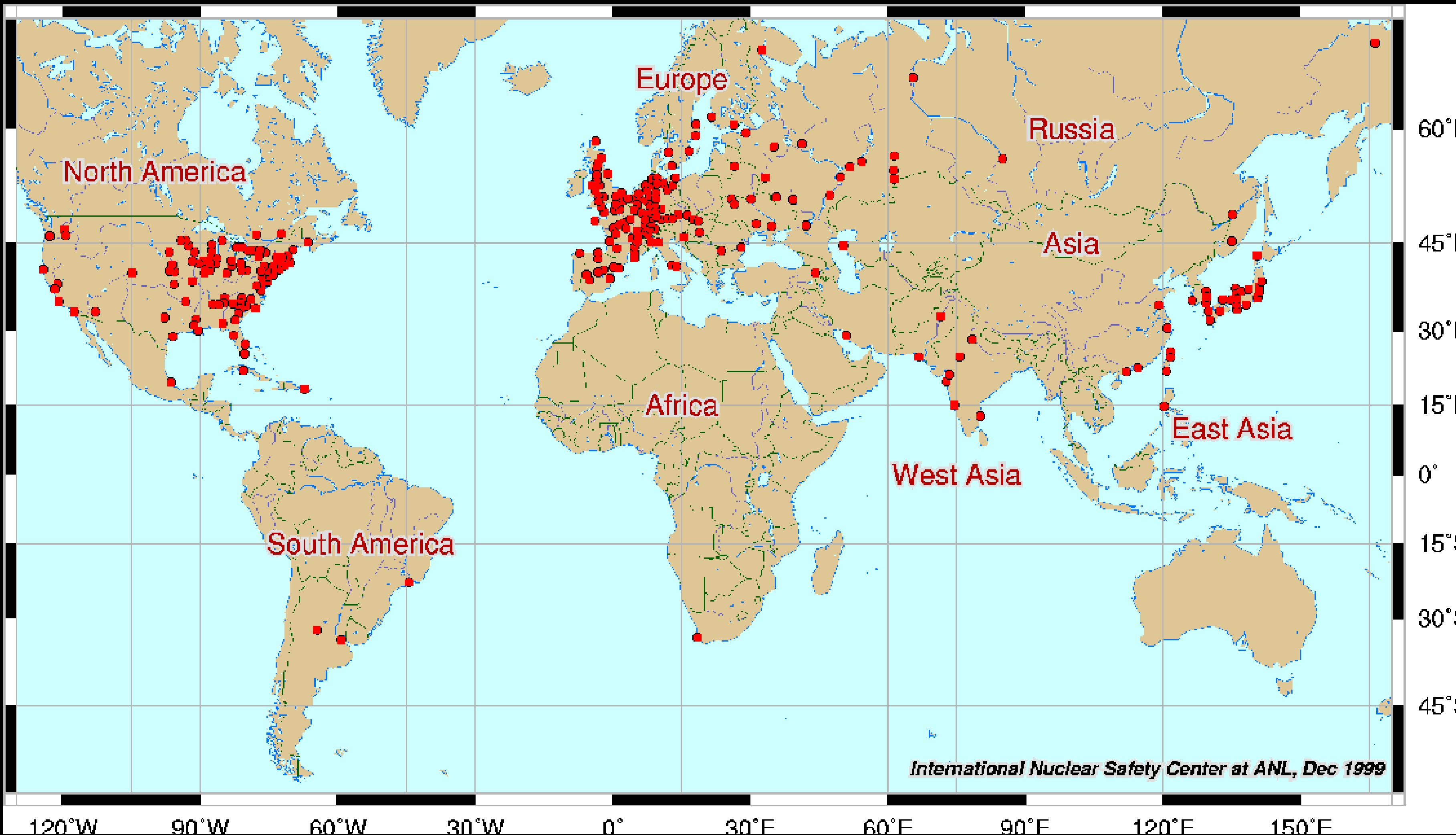
(90% C.L)

Improving CHOOZ is difficult …

@CHOOZ: R = 1.01 ± 2.8%(stat)±2.7%(syst)

- **Statistics**
  - ✓ Increase luminosity $L = \Delta t \times P(GW_{th}) \times N_p(target)$
  - ✓ Increase fiducial volume & exposure
  - ✓ ~2700 events in CHOOZ but >40,000 for the next experiment → $\sigma < 0.5\%$
- **Experimental error**
  - ✓ 2 detectors → cancel neutrino flux and cross section syst. uncertainty [~2%]
  - ✓ Identical detectors → decrease detector systematic uncertainties [<1%]
  - ✓ Movable VS non movable detectors : cross calibration, but error might be increased ?
- **Backgrounds** (S/N~25 in CHOOZ ; Goal S/N >100 in the new experiment)
  - ✓ Uncorrelated background (meast in-situ) – Correlated backgrounds (μ induced)
  - ✓ Underground site required: >300 m.w.e for the far site to improve CHOOZ
  - ✓ S/N equivalent for Near and Far detector (near detector could be shallower)
  - ✓ Reactor ON/OFF measurement → 1, 2, 4, or up to 7 reactor cores ?

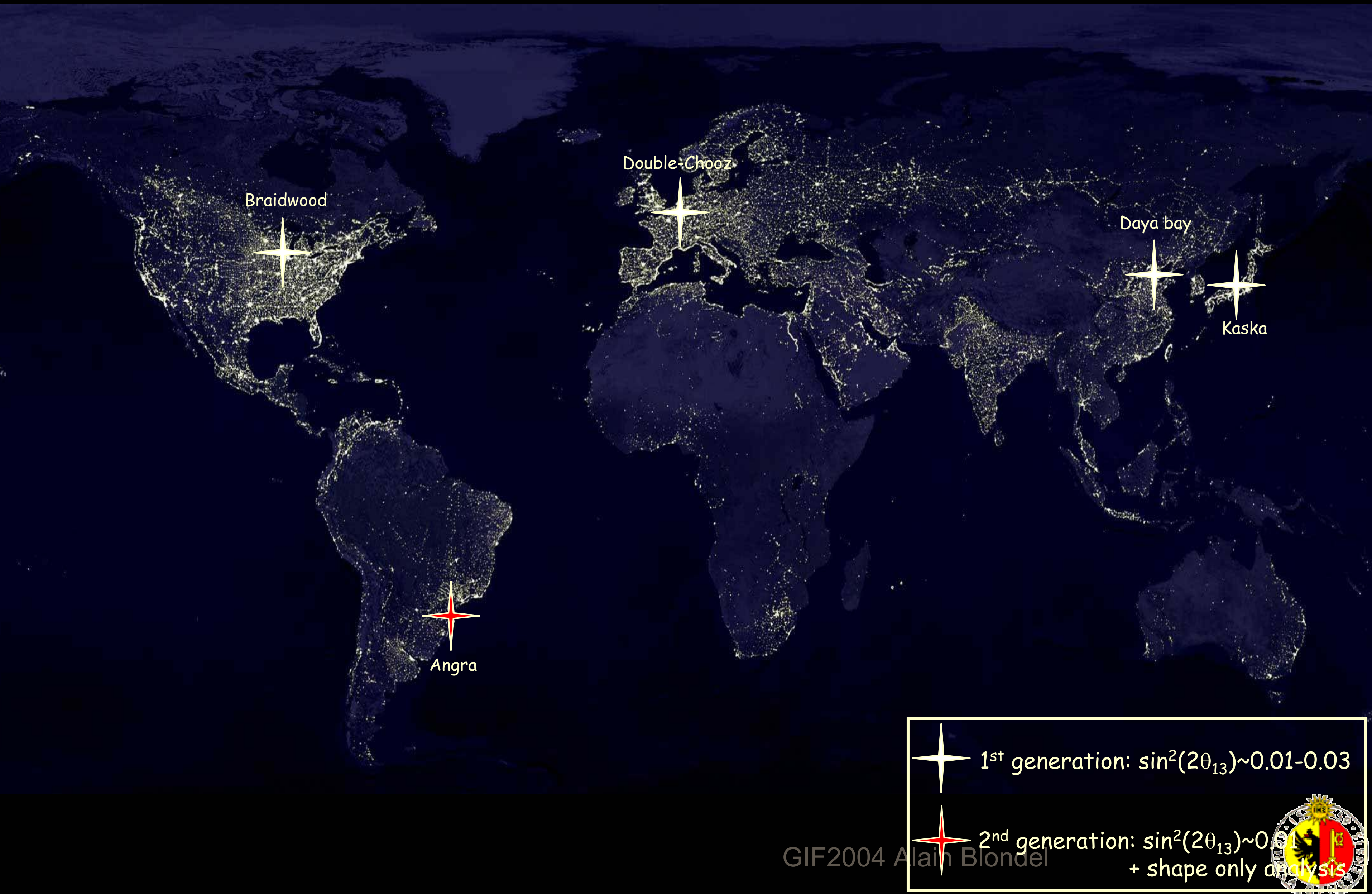
Nuclear reactors in the world



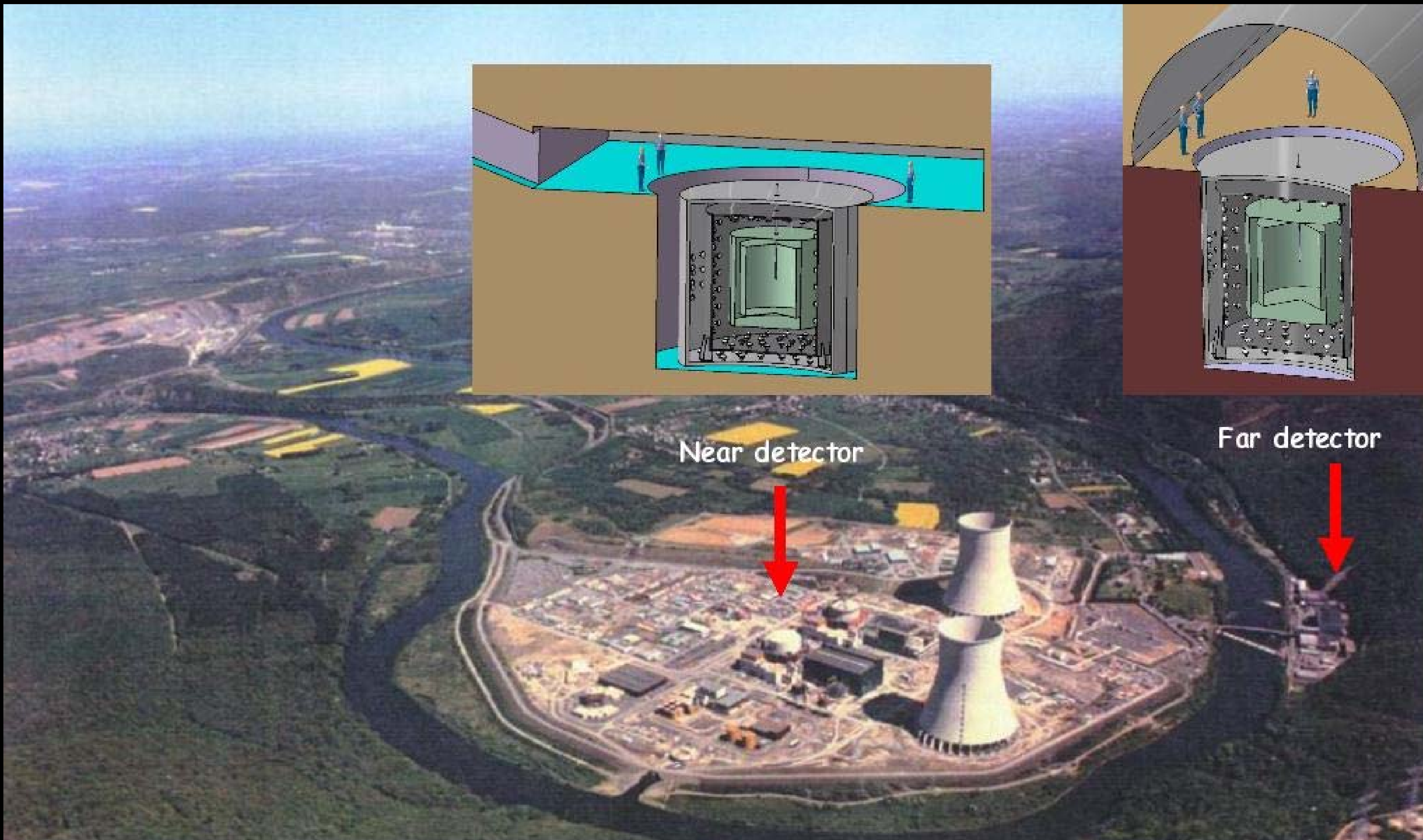
Which site for the experiment ?

One reactor complex
Two underground cavities @0.1-1 km & ~1-2 km

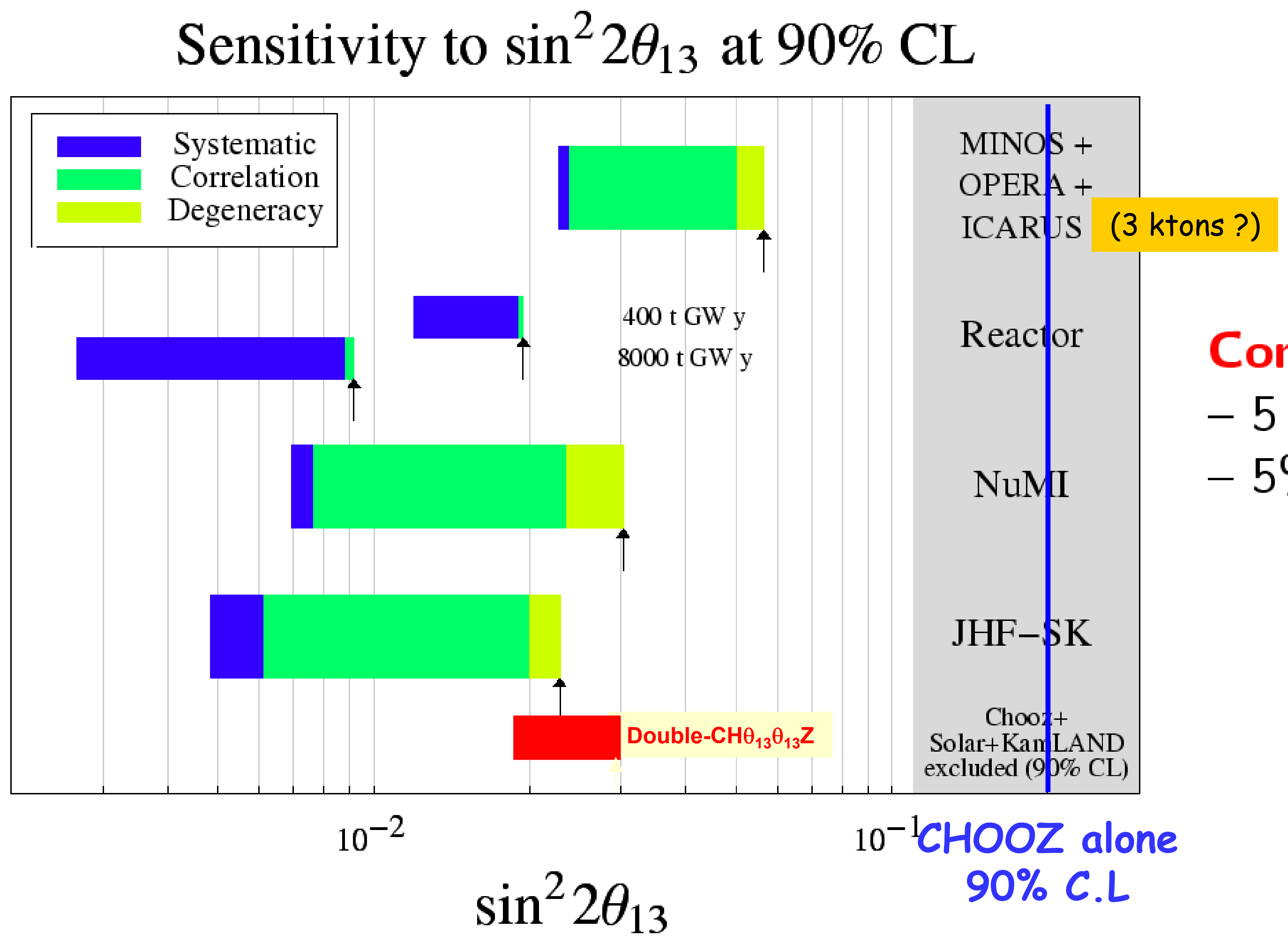
Current proposals



Double-Chooz (France)



$\sin^2(2\theta_{13})$ at LBL & reactors



@Δm^2=2.0 10^{-3} eV^2

Compare:

– 5 years each
– 5% flux uncertainty

Huber, Lindner, Schwetz & Winter ('extremum' of projection of the χ^2 manifold on the $\sin^2(2\theta_{13})$ axis)

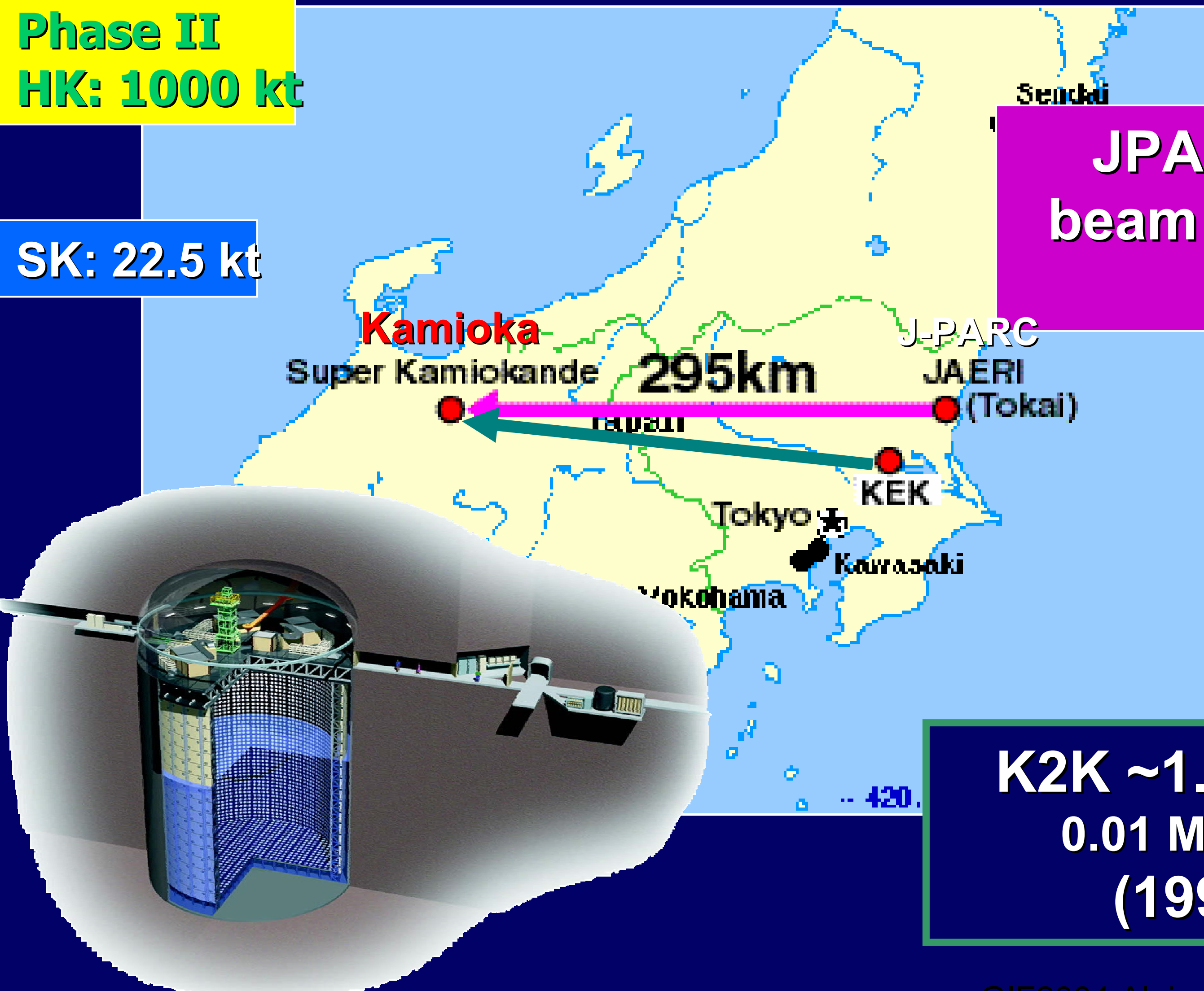
T2K

Phase II
HK: 1000 kt

Phase II:
4 MW upgrade

SK: 22.5 kt

JPARC-ν ~0.6GeV ν
beam 0.75 MW 50 GeV PS

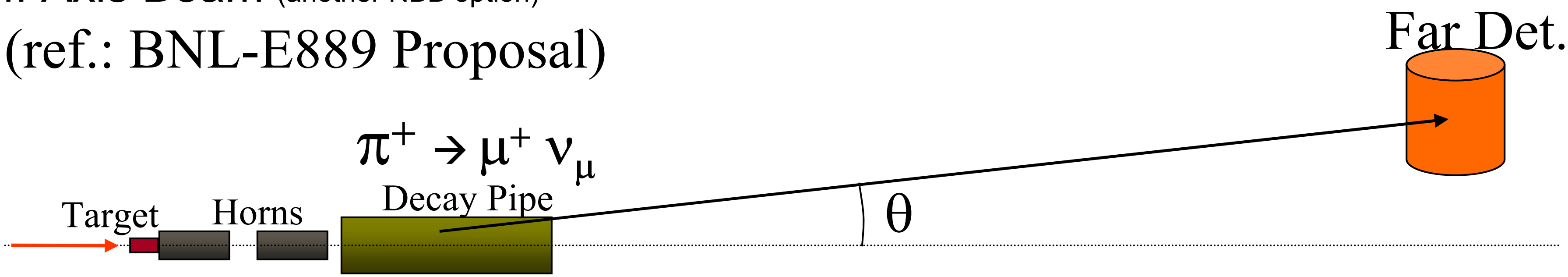


K2K ~1.2 GeV ν beam
0.01 MW 12 GeV PS
(1999 →2005)


T2K
Tokai-to-Kamioka Neutrino Project
at J-PARC

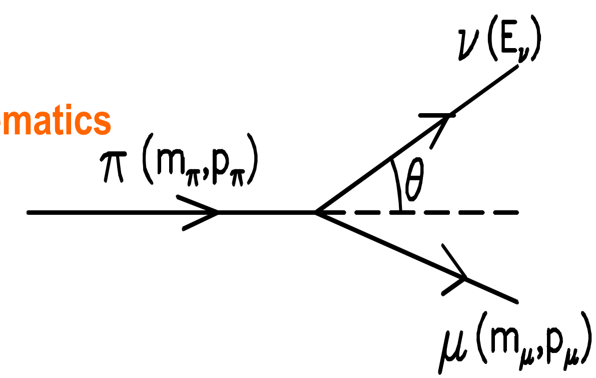
Off Axis Beam (another NBB option)

(ref.: BNL-E889 Proposal)

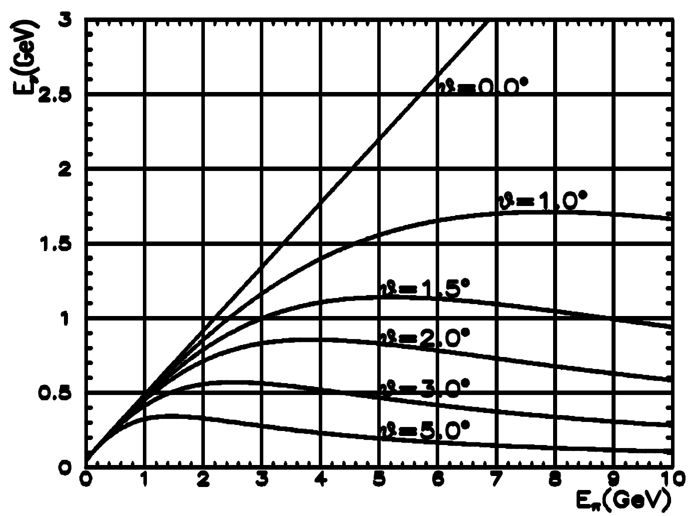


WBB w/ intentionally misaligned beam line from det. axis

Decay Kinematics

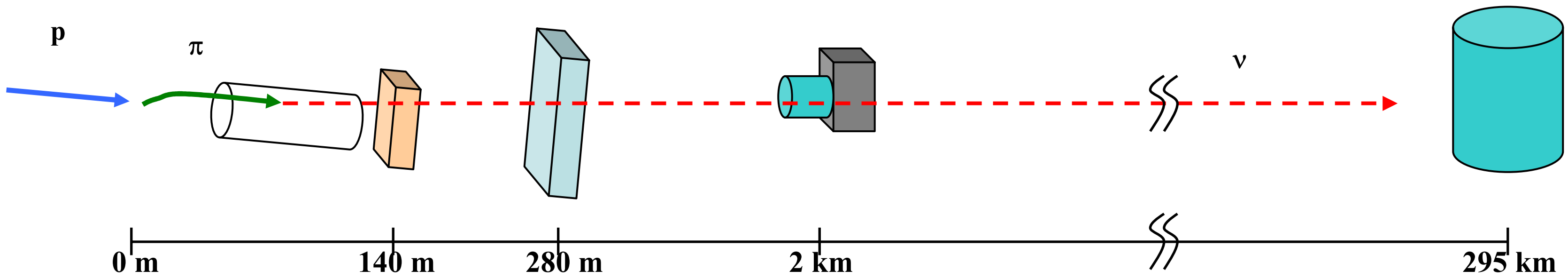


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

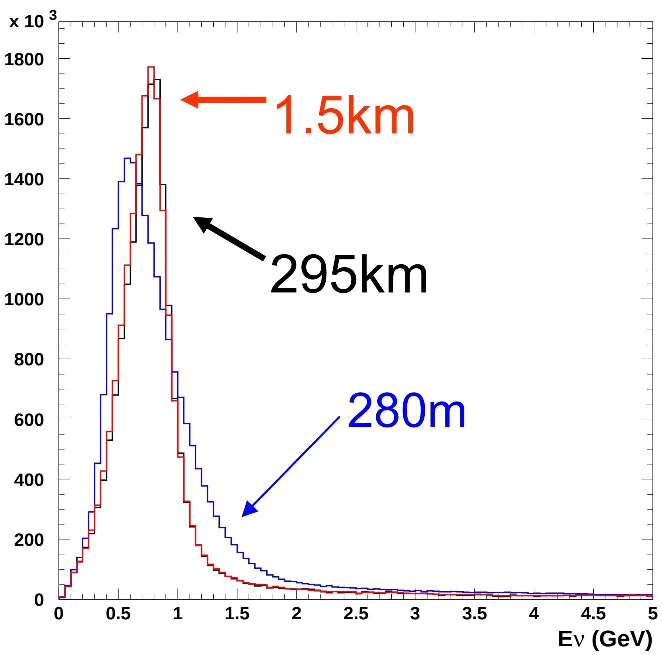


- Quasi Monochromatic Beam
- x2~3 intense than NBB

The (J-PARC-ν) T2K Beamline



Neutrino spectra at diff. dist



Problem with water Cerenkov:

not very sensitive to details of interactions.

Either 280 m or 2 km would be good locations for a very fine grained neutrino detector

=> Need 10-50 tons fiducial or so @ 2km
200-500 kg fid @ 280m

The T2K experimental programme

Disappearance

1. improve measurement of Δm^2_{13} (after MINOS, CNGS)
2. improve measurement of $\sin^2 2\theta_{12}$

These require good knowledge of

-- flux shape

-- absolute energy scale,

-- experimental energy resolution.

Here the fact that the 2km flux is much similar to the SK flux than at 280 m is clearly an argument in favor of 2km detector location.

3. Appearance search for $\nu_\mu \leftrightarrow \nu_e$ oscillation $\Rightarrow$ θ_{13}

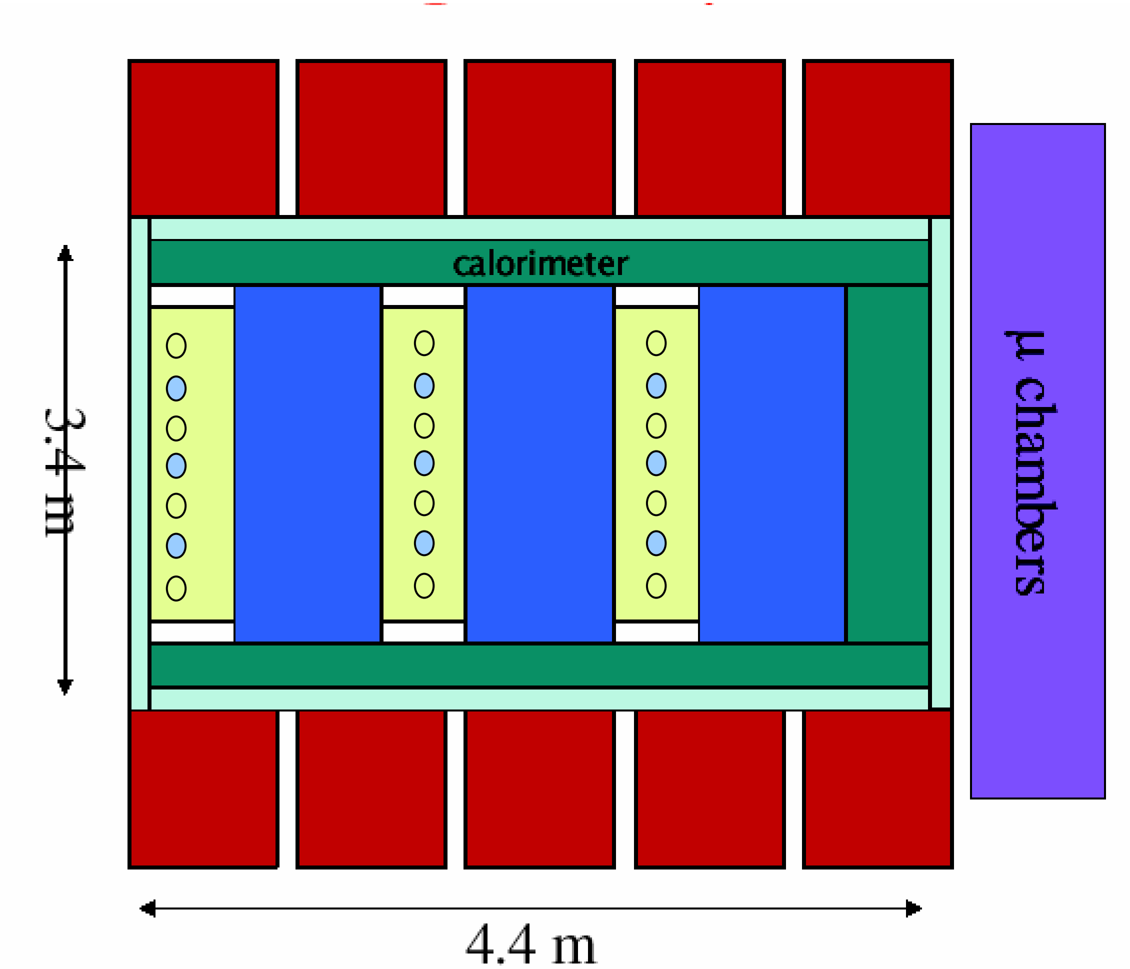
This is probably the highest priority measurement

Appearance experiment. The main problem here is the understanding of the backgrounds from anything that produces or mimics an electromagnetic shower.

- beam ν_e from K and mu decay
- π^0
- pions and secondary interactions etc…

loverre, sanchez, radicioni

The present 280 m detector concept



suggested detectors:

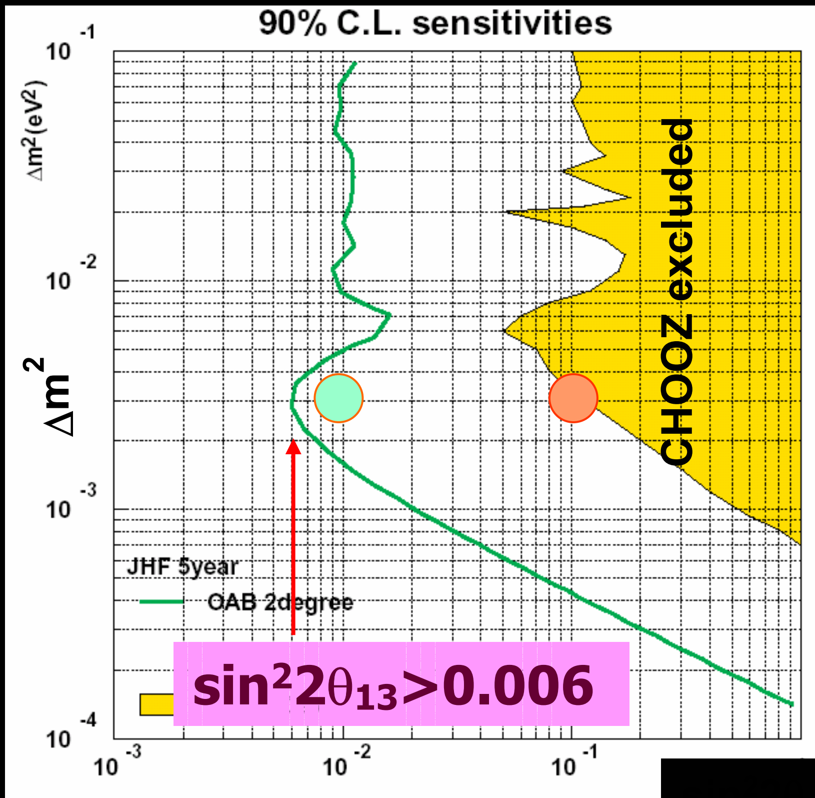
water targets

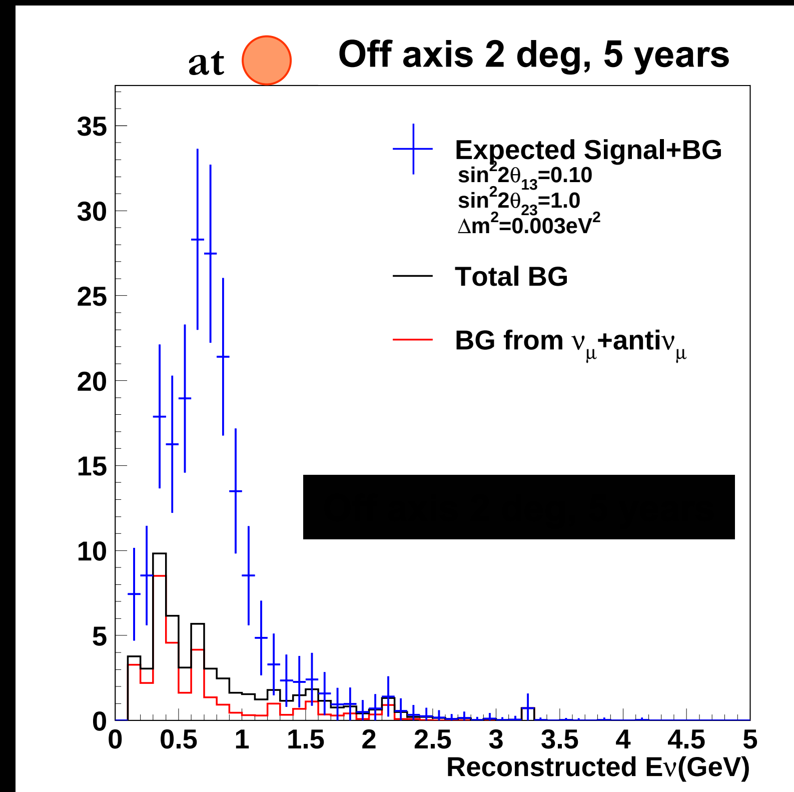
empty targets

Target -SCInt BARs
2.7x2.7 m²
45 cm thick pack
1 X0

Pack of tracking chambers
2.9x2.9 m²

ν_e appearance : θ_{13}





$\sin^2 2\theta_{13}$	Estimated background in Super-K					Signal (~40% eff.)	Signal + BG
	ν_μ (NC π^0)	ν_e beam	$\bar{\nu}_\mu$	$\bar{\nu}_e$	total		
0.1	12.0	10.7	1.7	0.5	24.9	114.6	139.5
0.01	12.0	10.7	1.7	0.5	24.9	11.5	36.4

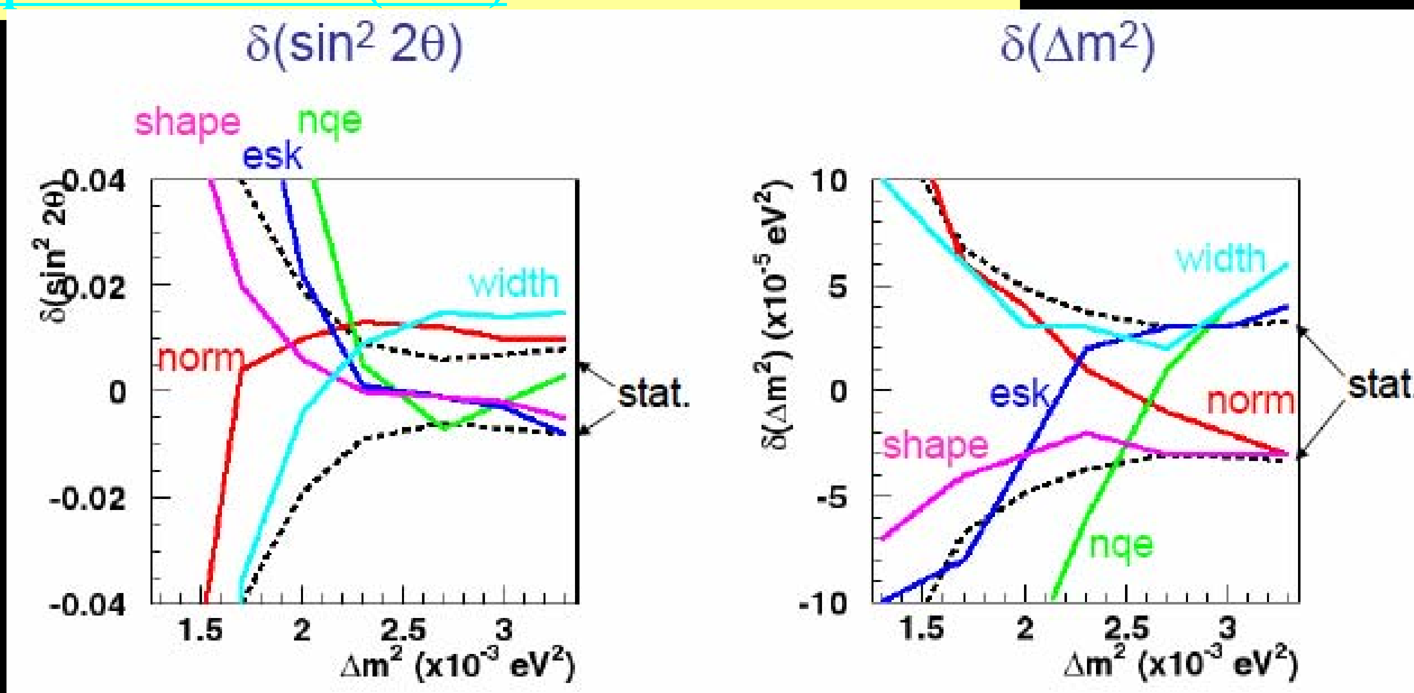
Precision measurement of θ_{23} , Δm^2_{23} possible systematic errors and phase-1 stat.

- Systematic errors
  - normalization (10%.→5%(K2K))
  - non-qe/qe ratio (20% (to be measured))
  - E scale (4% (K2K 3%))
  - Spectrum shape (Fluka/MARS →(Near D.))
  - Spectrum width (10%)

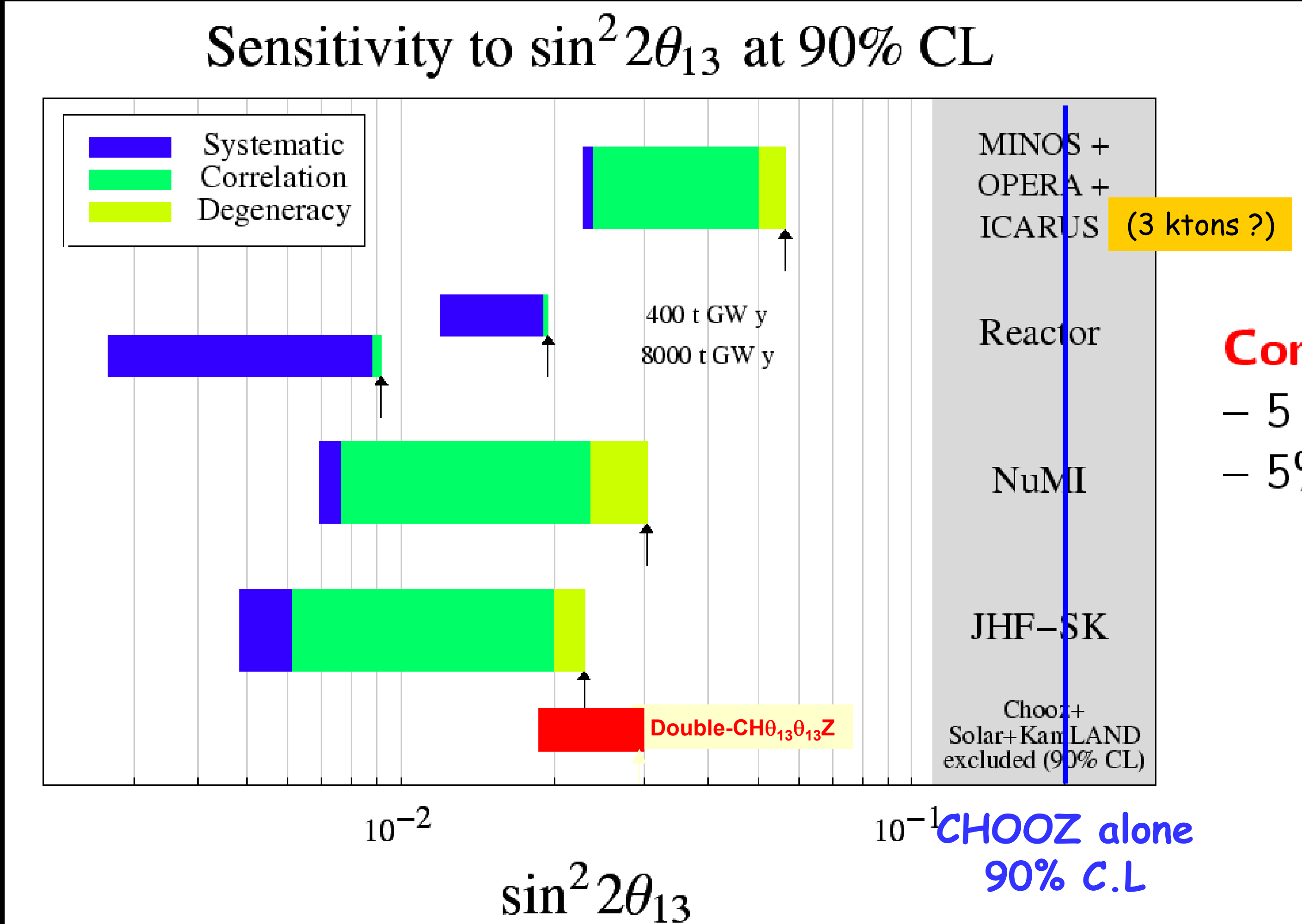
OA2.5°

$\delta(\sin^2 2\theta_{23}) \sim 0.01$

$\delta(\Delta m^2_{23}) < 1 \times 10^{-4}\ \mathrm{eV}^2$



$\sin^2(2\theta_{13})$ at LBL & reactors



@Δm^2=2.0 10^{-3} eV^2

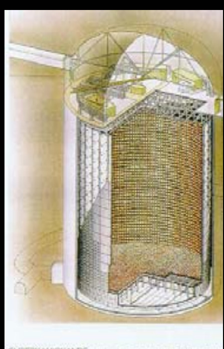
Compare:

- 5 years each
- 5% flux uncertainty

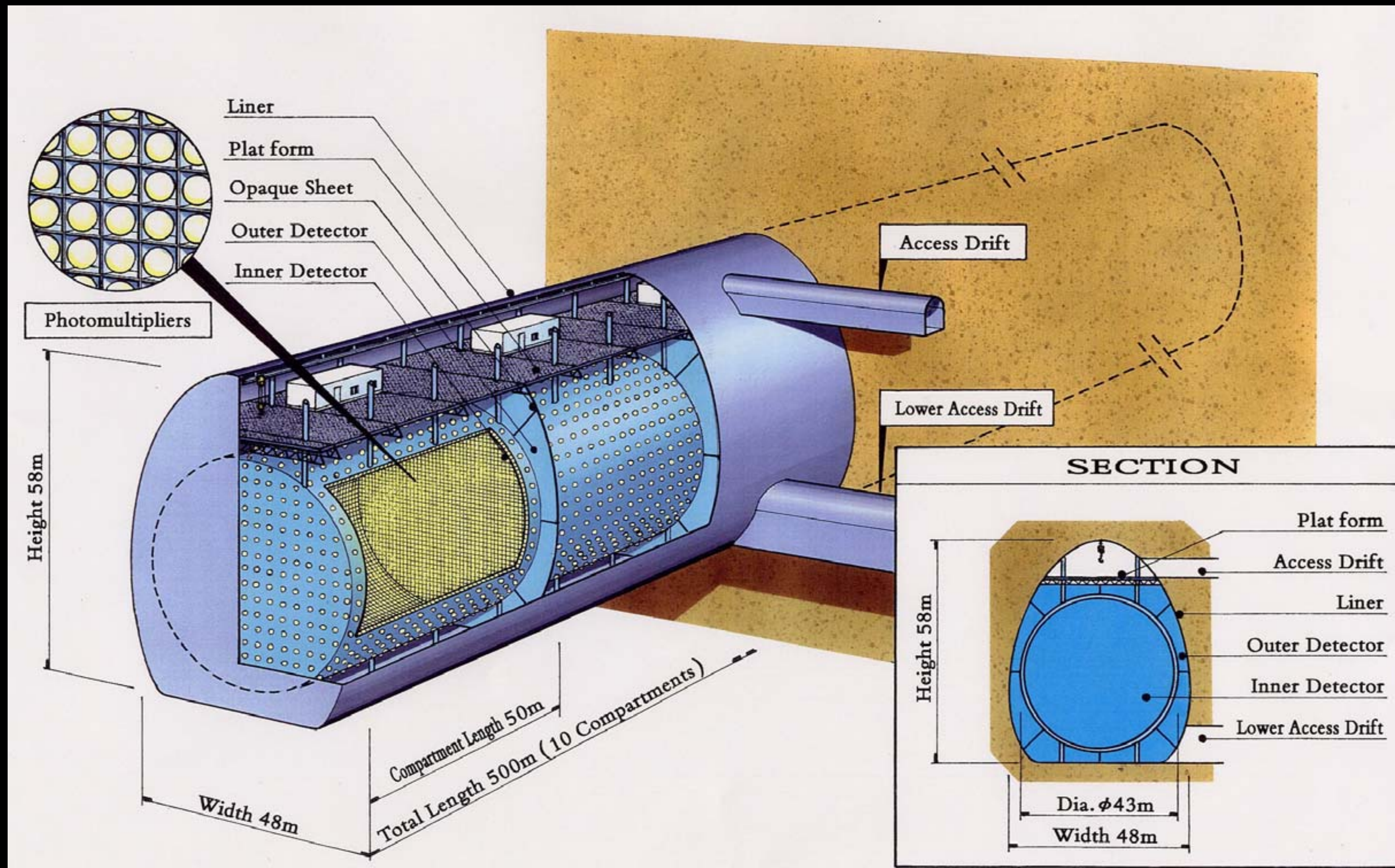
Huber, Lindner, Schwetz & Winter ('extremum' of projection of the χ^2 manifold on the $\sin^2(2\theta_{13})$ axis)

Schematic drawing of Hyper-Kamiokande

Super-K



40m



1 Mton (fiducial) volume: Total Length 400m (8 Compartments)

Other major goal: improve proton decay reach

Supernovae until Andromedes, etc…

Excavation will not start until 2011

Beta beam Challenges

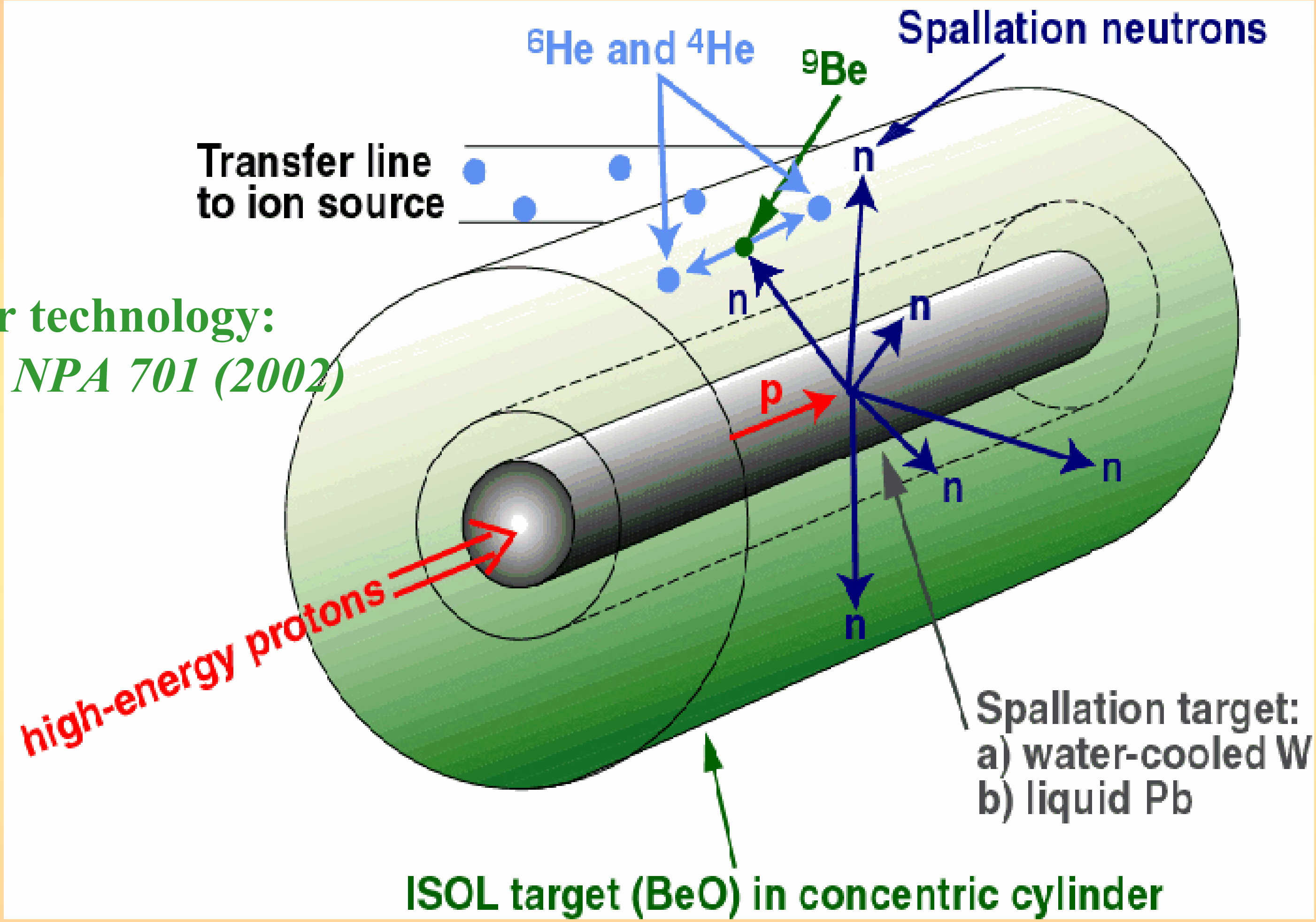
1. Intense production of ions, in particular β^+ emitters (^{18}Ne)

2. Clean acceleration: life time is much longer than muons but the decays produce activation in the rings

3. Stacking in the storage ring to ensure low duty cycle to distinguish beam events from atmospheric neutrinos

^{6}He production by ^{9}Be(n,a)

Converter technology:
(*J. Nolen, NPA 701 (2002) 312c)*



Layout very similar to planned EURISOL converter target aiming for 10^{15} fissions per s.

Production of β^+ emitters

Spallation of close-by target nuclides:

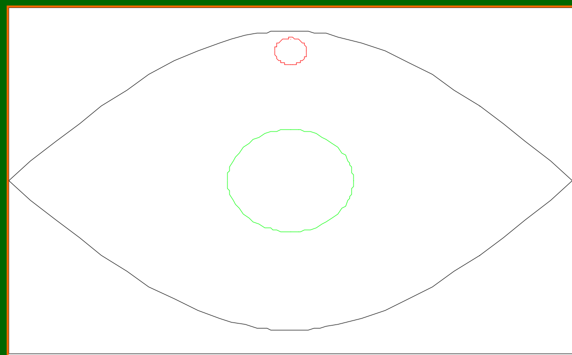
^{18,19}Ne from MgO and ^{34,35}Ar in CaO

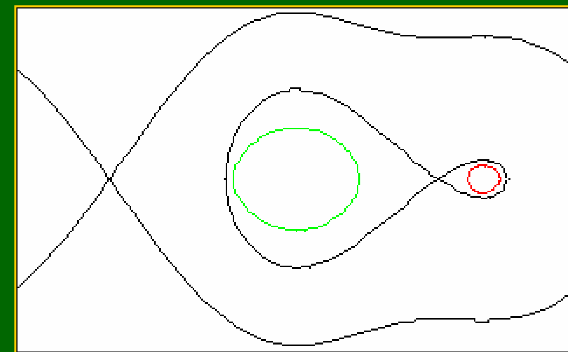
Production rate for ^{18}Ne is 1×10^{12} s^{-1} (with 2.2 GeV 100 μA proton beam, cross-sections of some mb and a 1 m long oxide target of 10% theoretical density)

^{19}Ne can be produced with one order of magnitude higher intensity but the half life is 17 seconds!

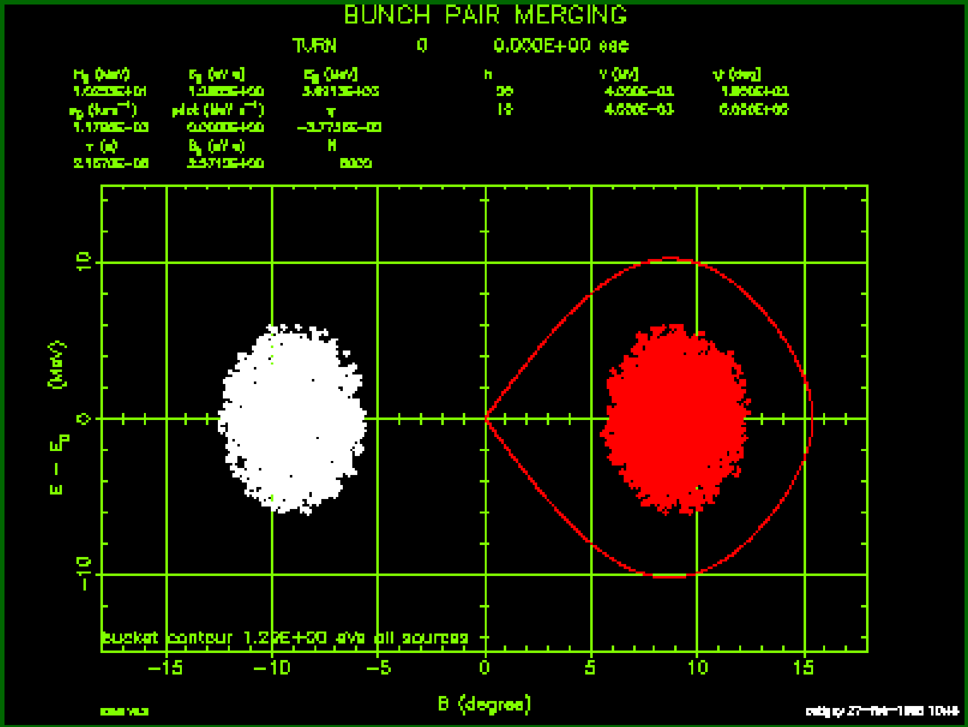
A PULSED souce could be realized by ECR (P.Sortais Moriond 2003)

STACKING is necessary to ensure duty cycle less than 10^{-3}



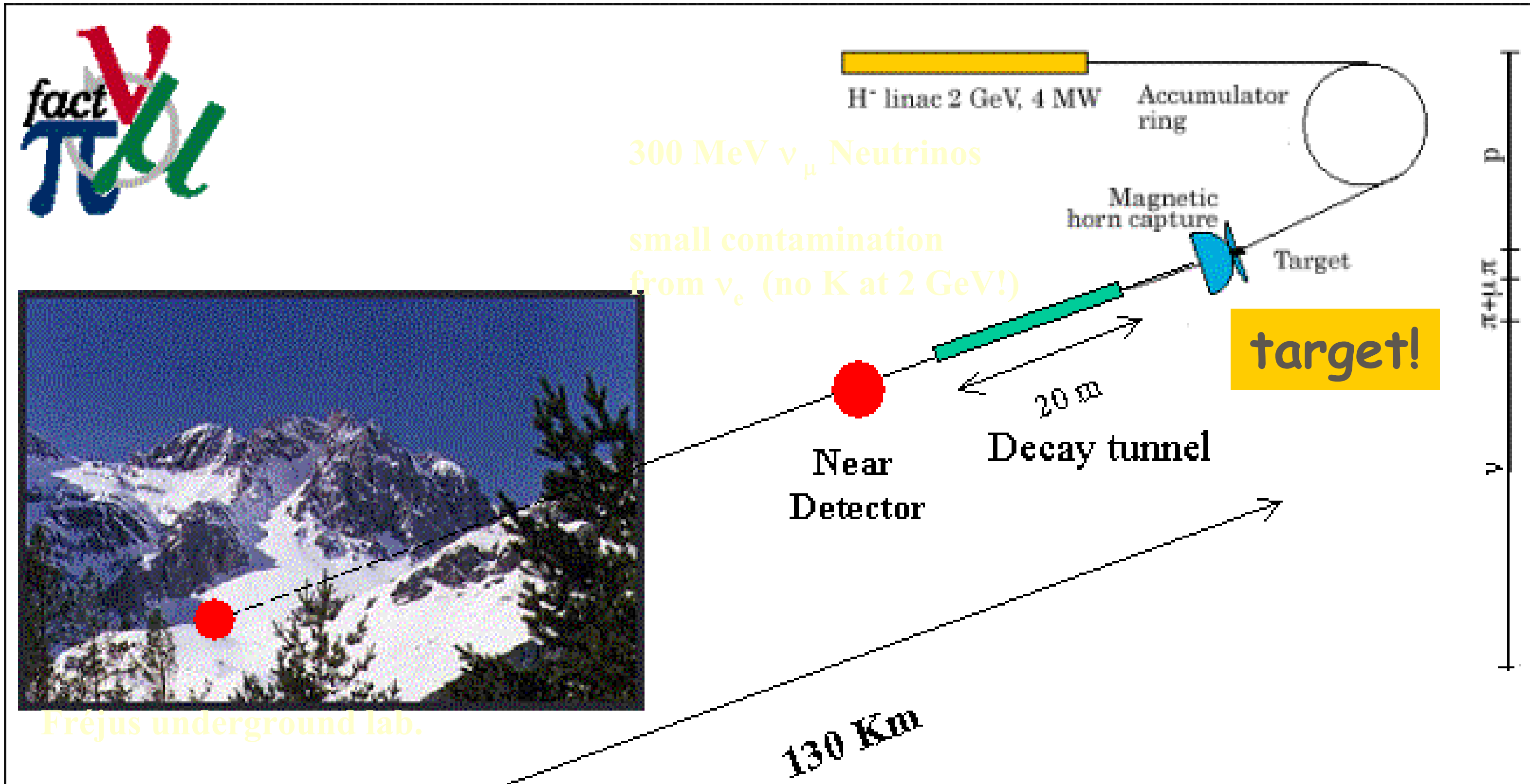


inject off energy
(using e.g.
dispersive section)



Going beyond…
Example: a series of facilities envisaged for CERN

CERN-SPL-based Neutrino SUPERBEAM

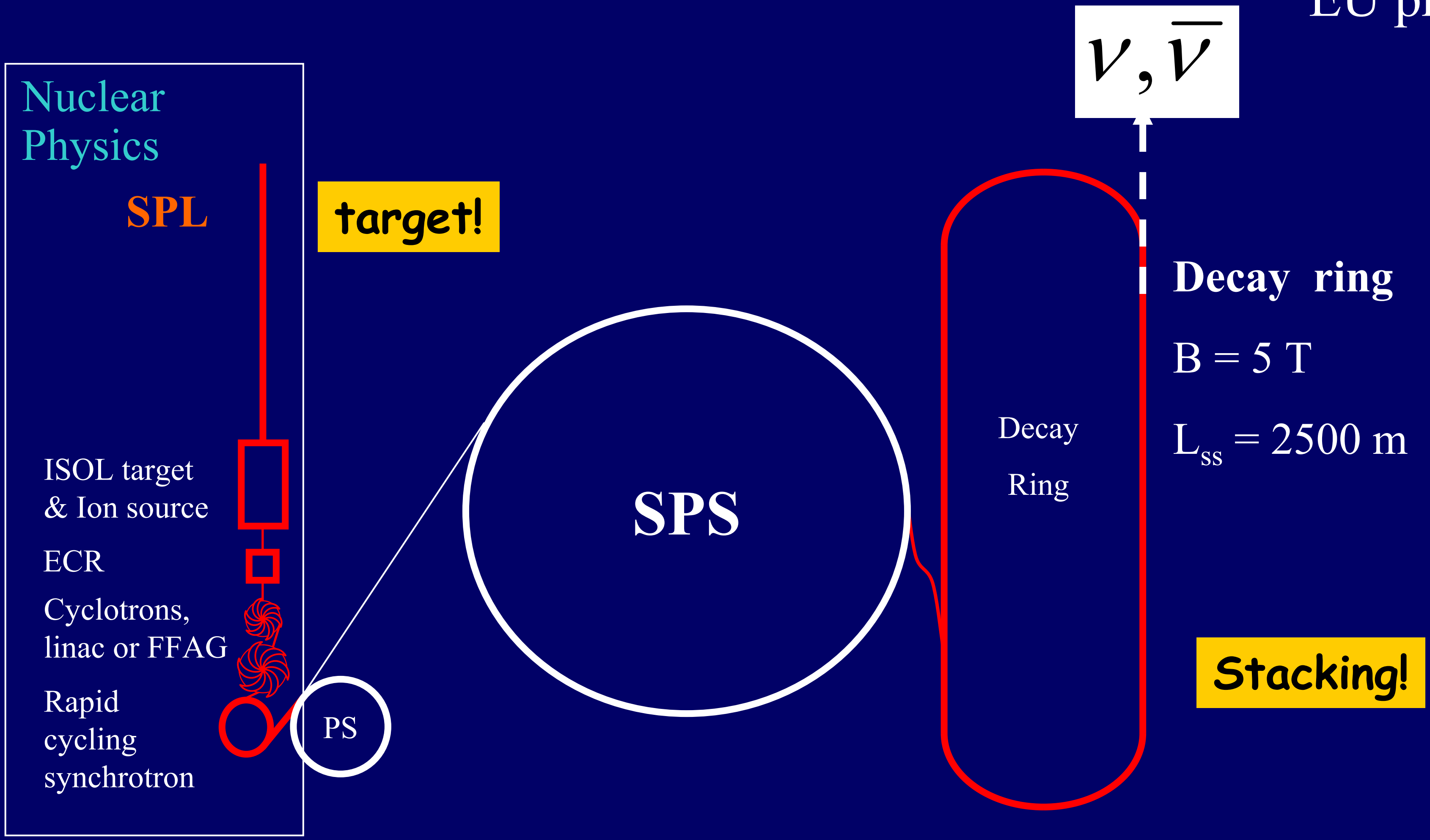


A large underground water Cerenkov (400 kton) UNO/HyperK or/and a large L.Arg detector.
also : proton decay search, supernovae events solar and atmospheric neutrinos. Performance similar to J-PARC II
There is a window of opportunity for digging the cavern stating in 2008 (safety tunnel in Frejus)

CERN: β-beam baseline scenario

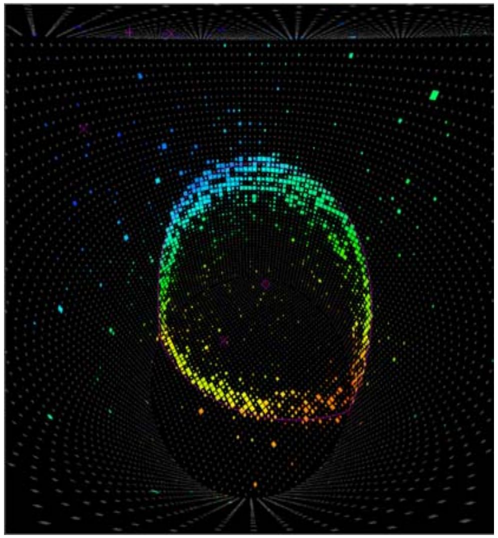
neutrinos of E_{max}=~600MeV

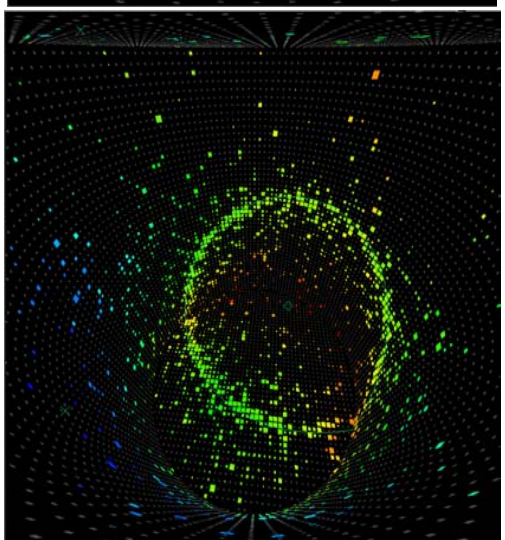
EU pride..



Same detectors as Superbeam !

Combination of beta beam with low energy super beam





Unique to CERN:

need few 100 GeV accelerator (PS + SPS will do!)
experience in radioactive beams at ISOLDE

many unknowns: what is the duty factor that can be achieved? (needs < 10^{-3})

combines CP and T violation tests

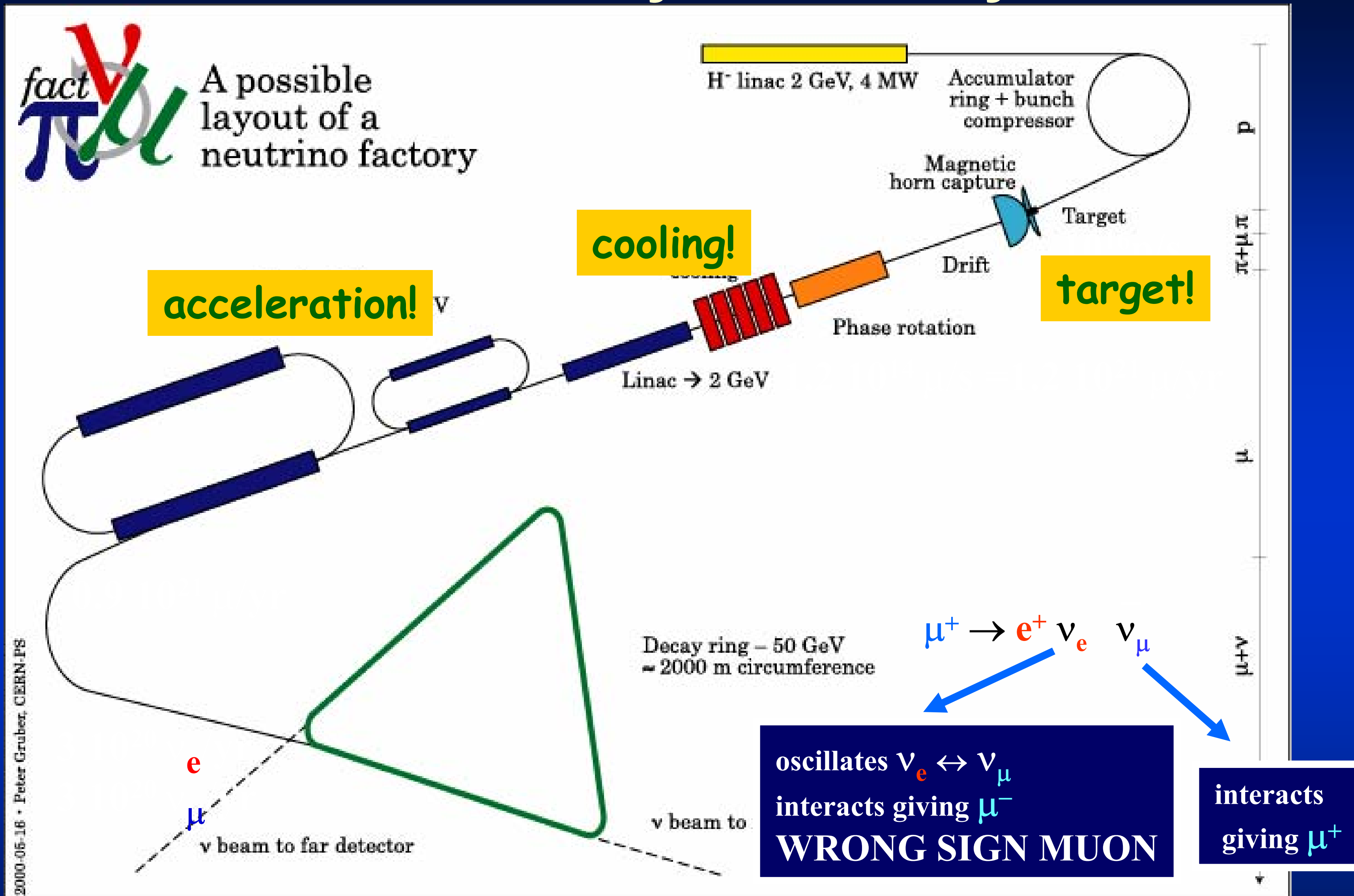
$\nu_e \rightarrow \nu_\mu$ (β+) **(T)** $\nu_\mu \rightarrow \nu_e$ (π^+)

(CP)

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ (β-) **(T)** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (π^-)

Can this work???? **theoretical studies now on beta beam**
+ SPL target and horn R&D → design study together with EURISOL

-- Neutrino Factory -- CERN layout --



Golden MEASUREMENTS at ν- FACTORY

$$\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$$

$\bar{\nu}_e \longrightarrow \bar{\nu}_\mu$ is the golden measurement at Nufact:
appearance of wrong-sign muons

$$\mu^- \rightarrow \nu_\mu \quad \bar{\nu}_e \quad e^-$$

$$\downarrow$$

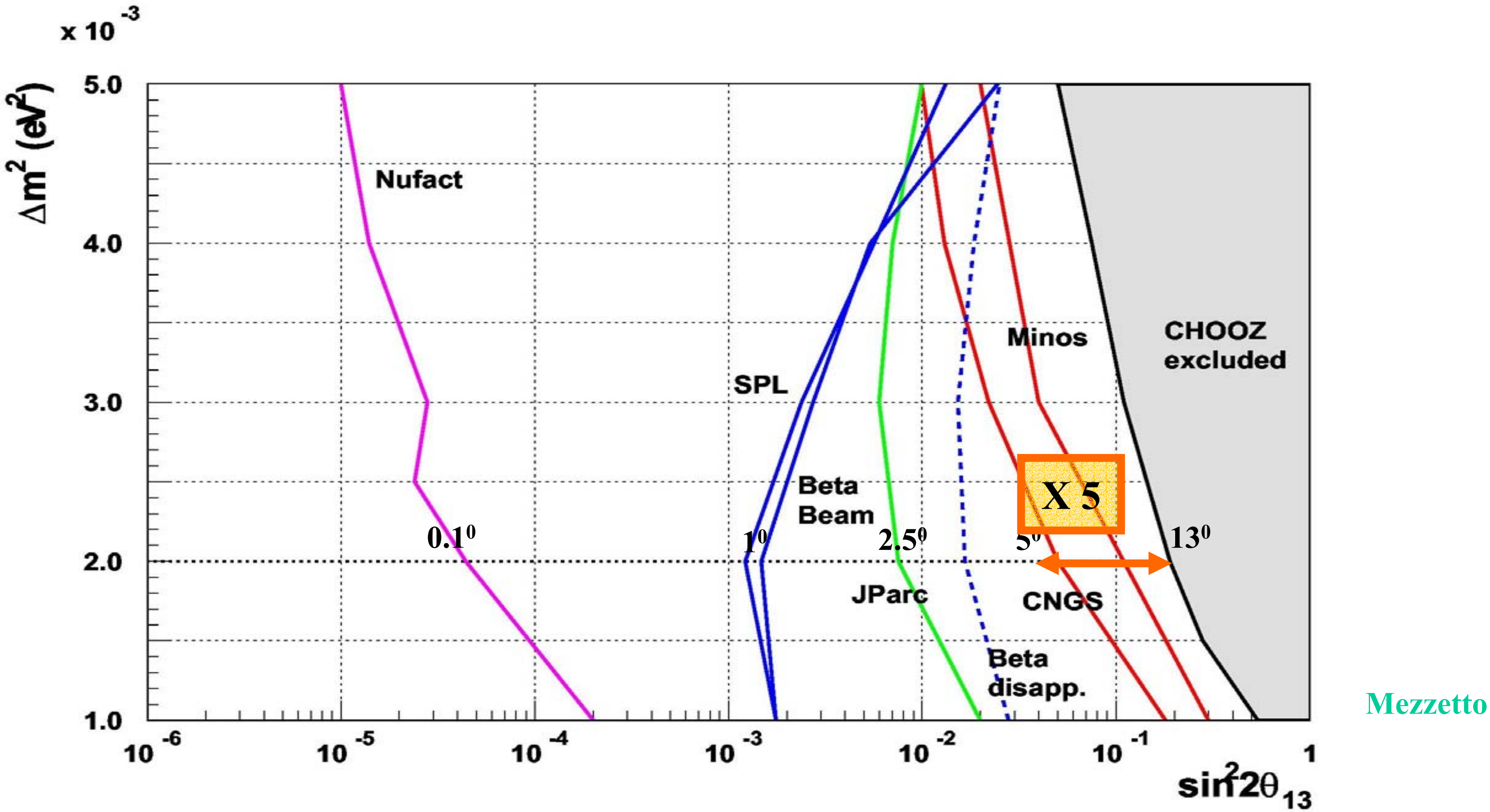
$$\bar{\nu}_\mu \quad \rightarrow \mu^+$$

$$\mu^+ \rightarrow \bar{\nu}_\mu \quad \nu_e \quad e^+$$

$$\downarrow$$

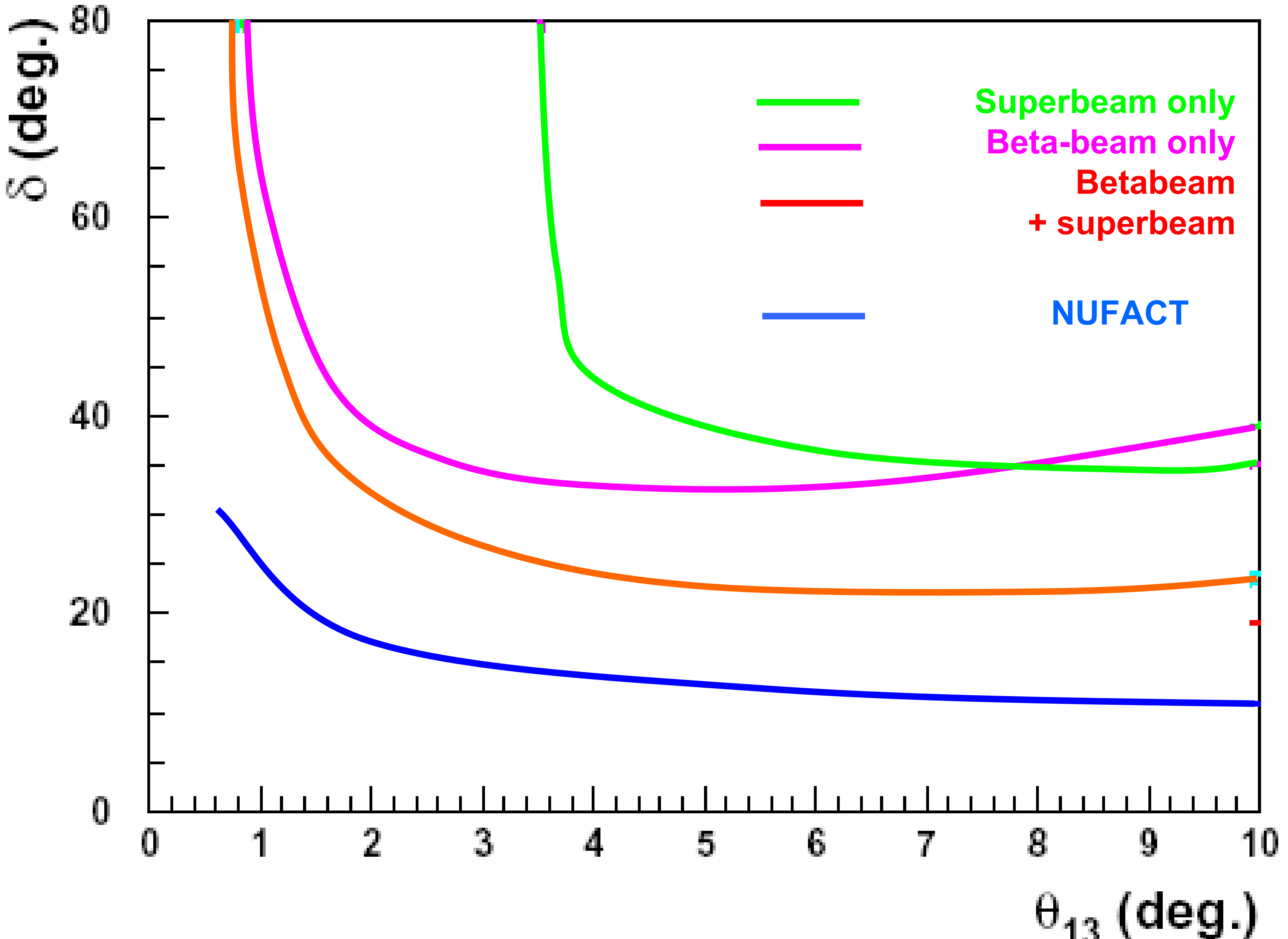
$$\nu_\mu \quad \rightarrow \mu^-$$

Where will this get us…

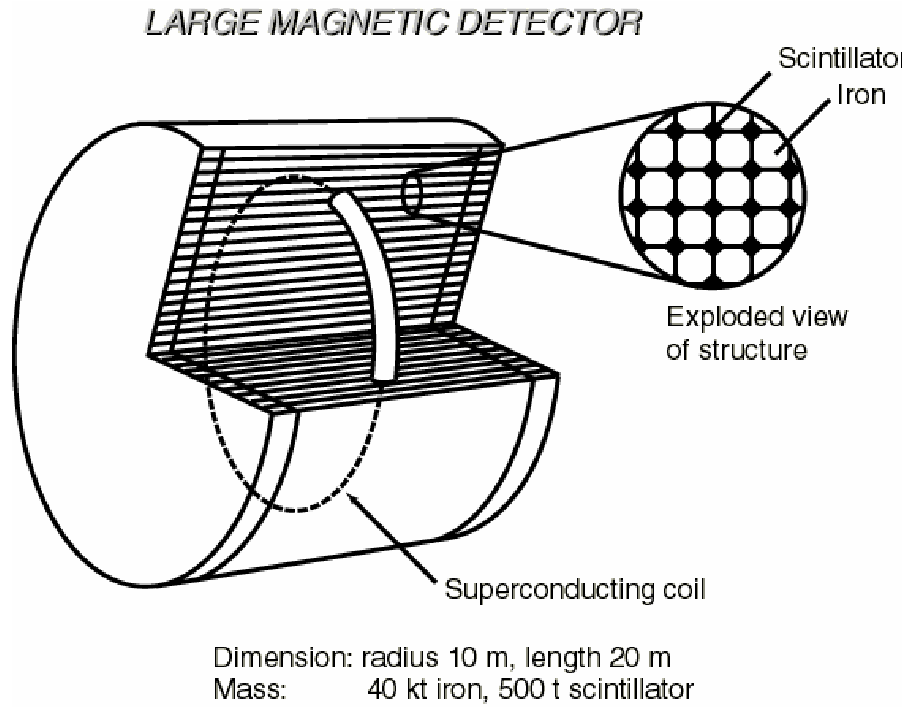


comparison of reach in the oscillations; right to left:
present limit from the CHOOZ experiment,
expected sensitivity from the MINOS experiment, CNGS (OPERA+ICARUS)
0.75 MW JHF to super Kamiokande with an off-axis narrow-band beam,
Superbeam: 4 MW CERN-SPL to a 400 kton water Cerenkov in Fréjus (J-PARC phase II similar)
from a Neutrino Factory with 40 kton large magnetic detector.

3 sigma sensitivity of various options



Detector



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

Also: L Arg detector: magnetized ICARUS
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	(J-PARC I→ SK = 40)
3500 Km	1.2×10^6	2.4×10^6	1.0×10^5	

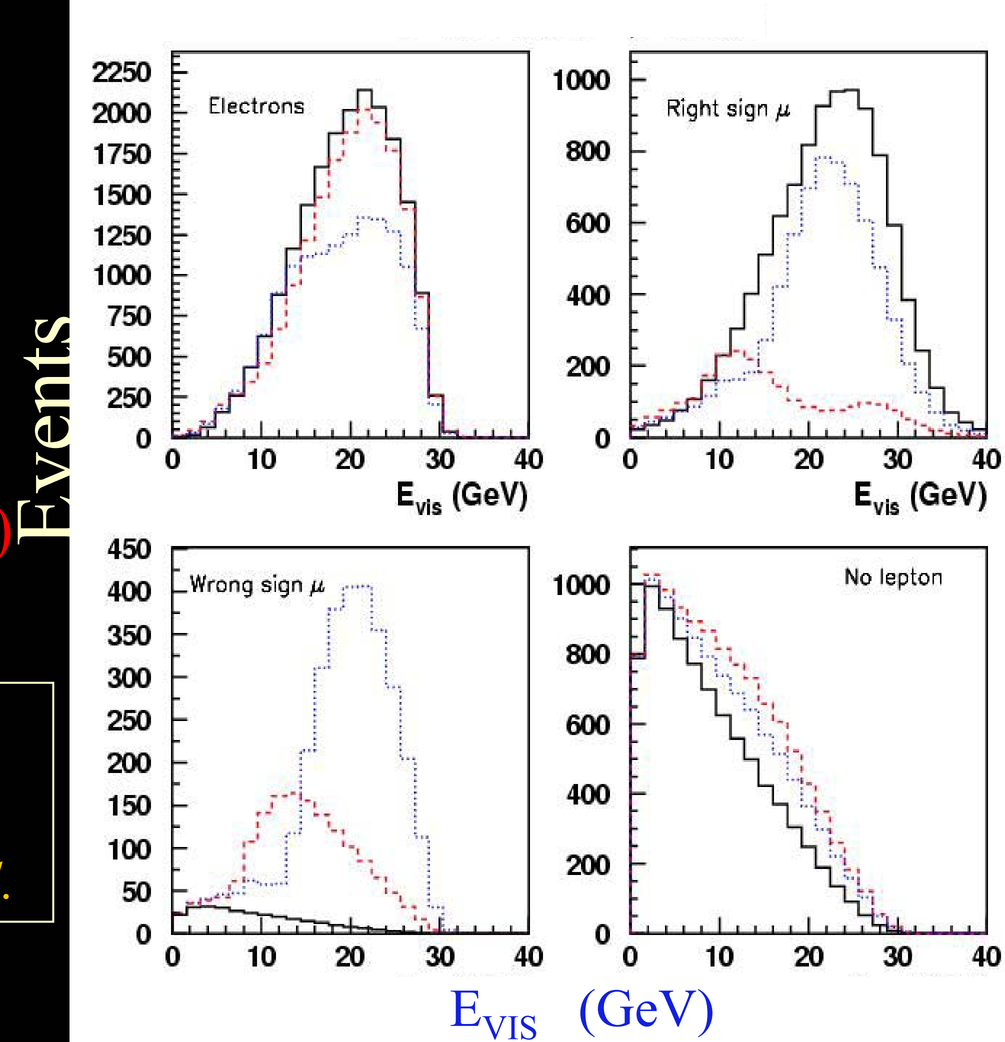
Oscillation parameters can be extracted using energy distributions

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

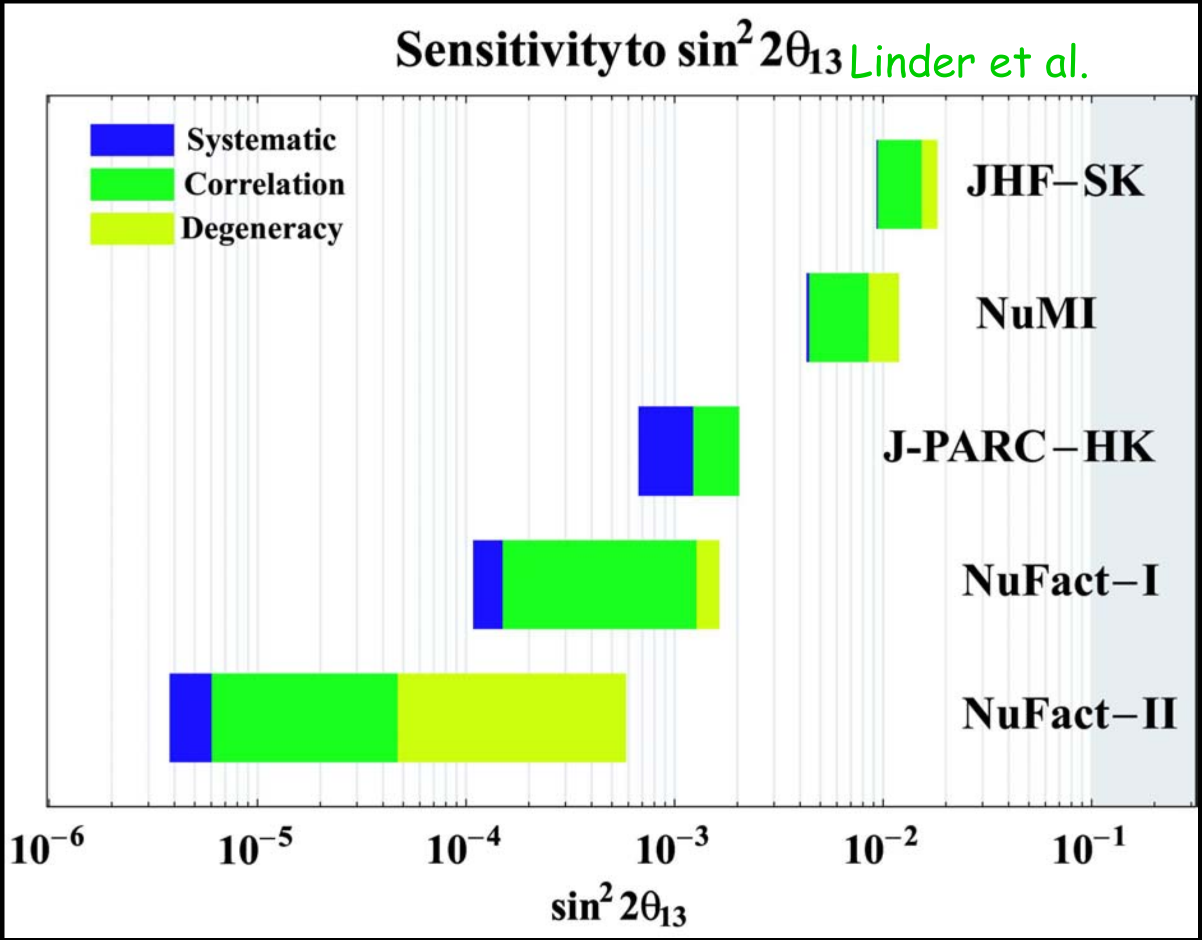
X2 (μ^+ stored and μ^- stored)

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

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



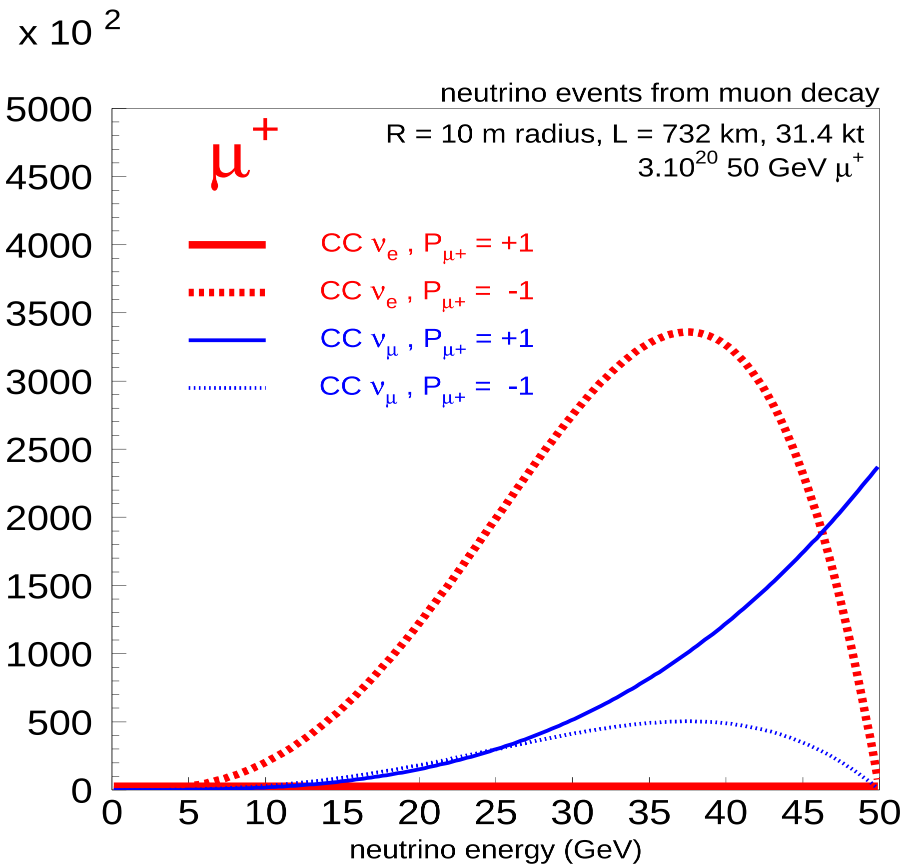
Bueno, Campanelli, Rubbia; hep-ph/0005007



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

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

ν_μ/ν_e ratio reversed by switching μ^+/μ^-
$\nu_e\ \nu_\mu$ spectra are different
No high energy tail.



Very well known flux ($\pm 10^{-3}$)

-- E&σ_E calibration from muon spin precession

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

-

- from muon current

or by $\nu_\mu e^- \rightarrow \mu^- \nu_e$ in near expt.

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

Similar comments apply to beta beam, except spin 0
→ Energy and energy spread have to be obtained from the properties of the storage ring
(Trajectories, RF volts and frequency, etc…)

μ polarization controls ν_e flux:

μ^+ -X> ν_e in forward direction

Muon Polarization

muons are born longitudinally polarized in pion decay (~18%)
depolarization is small (Fernow &Gallardo)

effects in electric and magnetic fields is (mostly) described by spin tune:

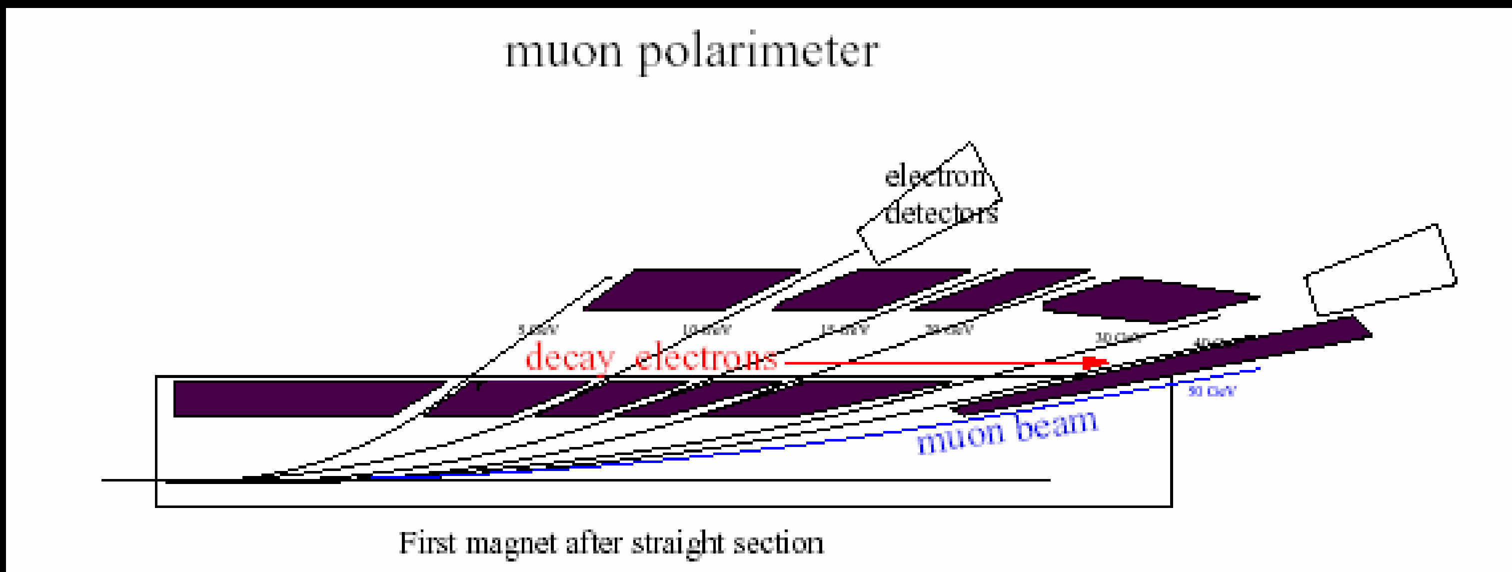
$$\nu = a_\mu \gamma = \frac{g_\mu - 2}{2} \frac{\mathrm{E_{beam}}}{m_\mu} = \frac{\mathrm{E_{beam}(GeV)}}{90.6223(6)}$$

which is small: at each kick θ of a 200 MeV/c muon the polarization is kicked by $\nu.\theta = 0.002\ \theta$

in the high energy storage ring polarization precesses. Interestingly $\nu = 0.5$ for a beam energy of 45.3112 GeV: at that energy it flips at each turn. (NB This is roughly half the Z mass…!)

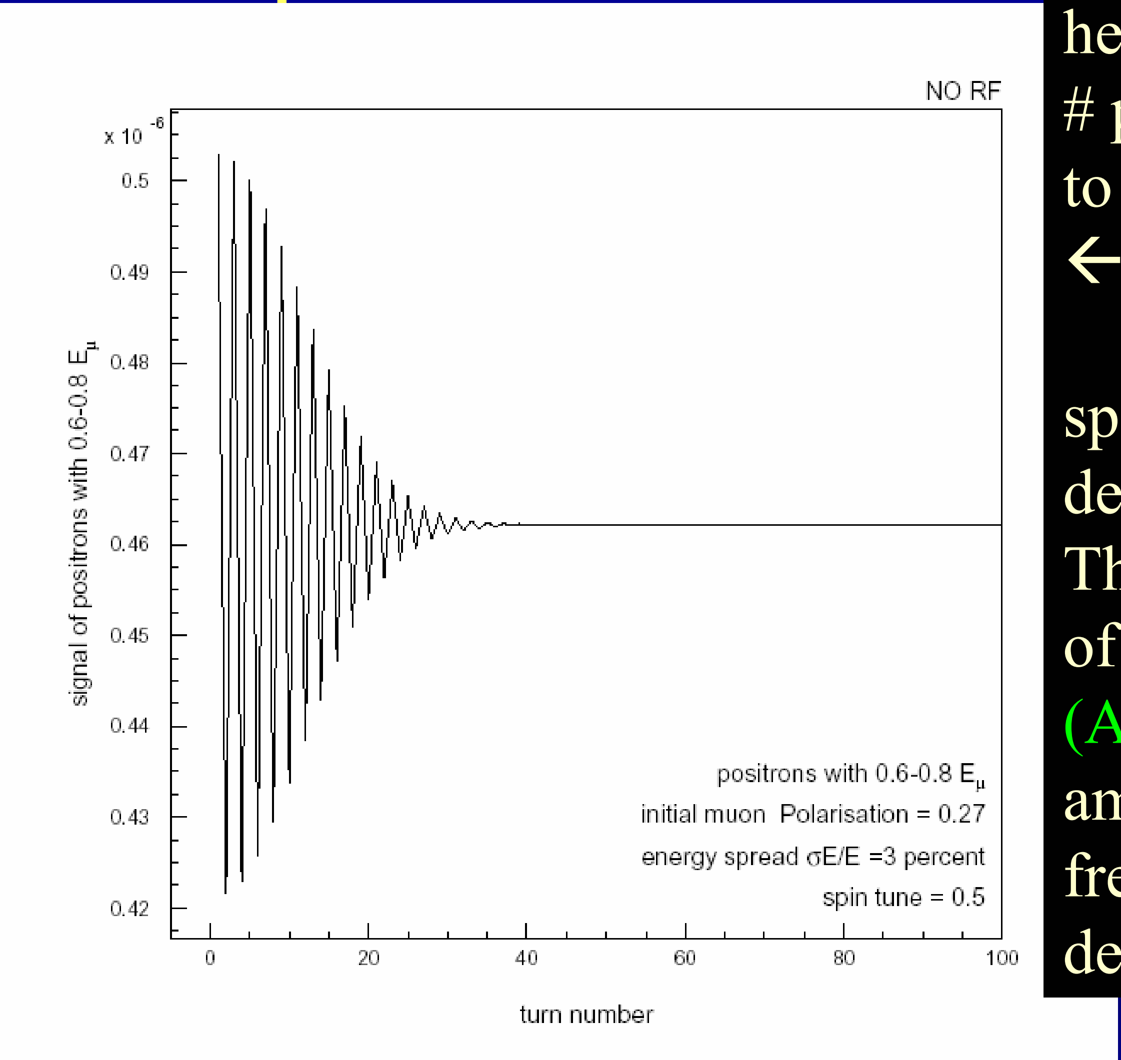
Muon Polarization

muon polarization is too small to be very useful for physics (AB, Campanelli) but it must be monitored.
In addition it is precious for energy calibration (Raja&Tollestrup, AB)



a muon polarimeter would perform the momentum analysis of the decay electrons at the end of a straight section.
Because of parity violation in muon decay the ratio of high energy to low energy electrons is a good polarization monitor.

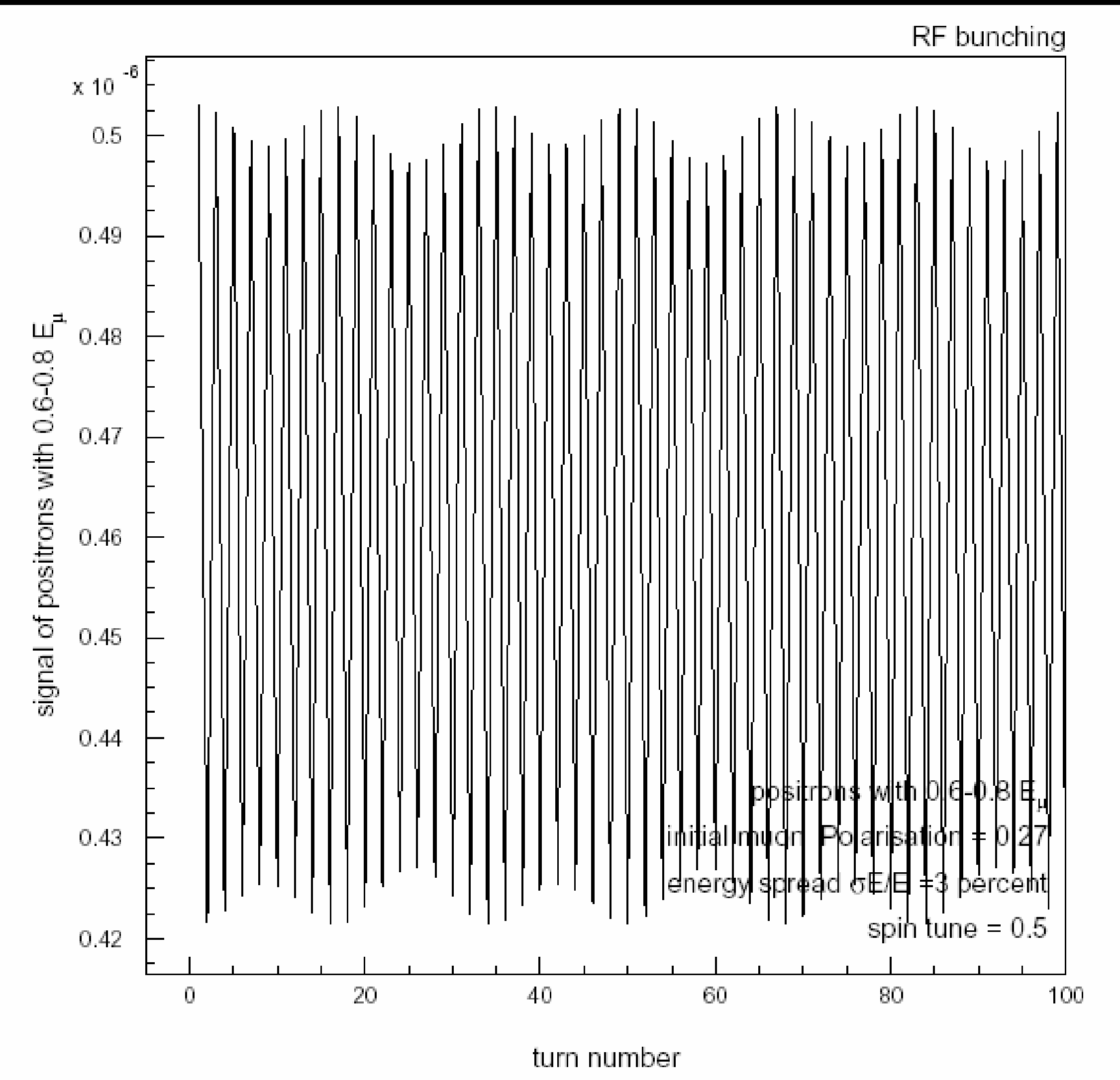
muon polarization



here is the ratio of
positons with E in [0.6-0.8] E_μ
to number of muons in the ring.
← There is no RF in the ring.

spin precession and
depolarization are clearly visible
This is the Fourier Transform
of the muon energy spectrum
(AB)
amplitude=> **polarization**
frequency => **energy**
decay => **energy spread.**

➔ $\Delta E/E$ and $\sigma E/E$ to 10^{-6}
➔ polarization to a few percent.



If there is RF in the storage ring to keep the muons bunched, depolarization is suppressed.
(synchrotron oscillations)

Even in this case,
the muon polarization,
averaged over ~500 turns
is very small
($<<0.18/500 = 410^{-4}$)
and will be monitored.

muon polarization: triangle or bow-tie?

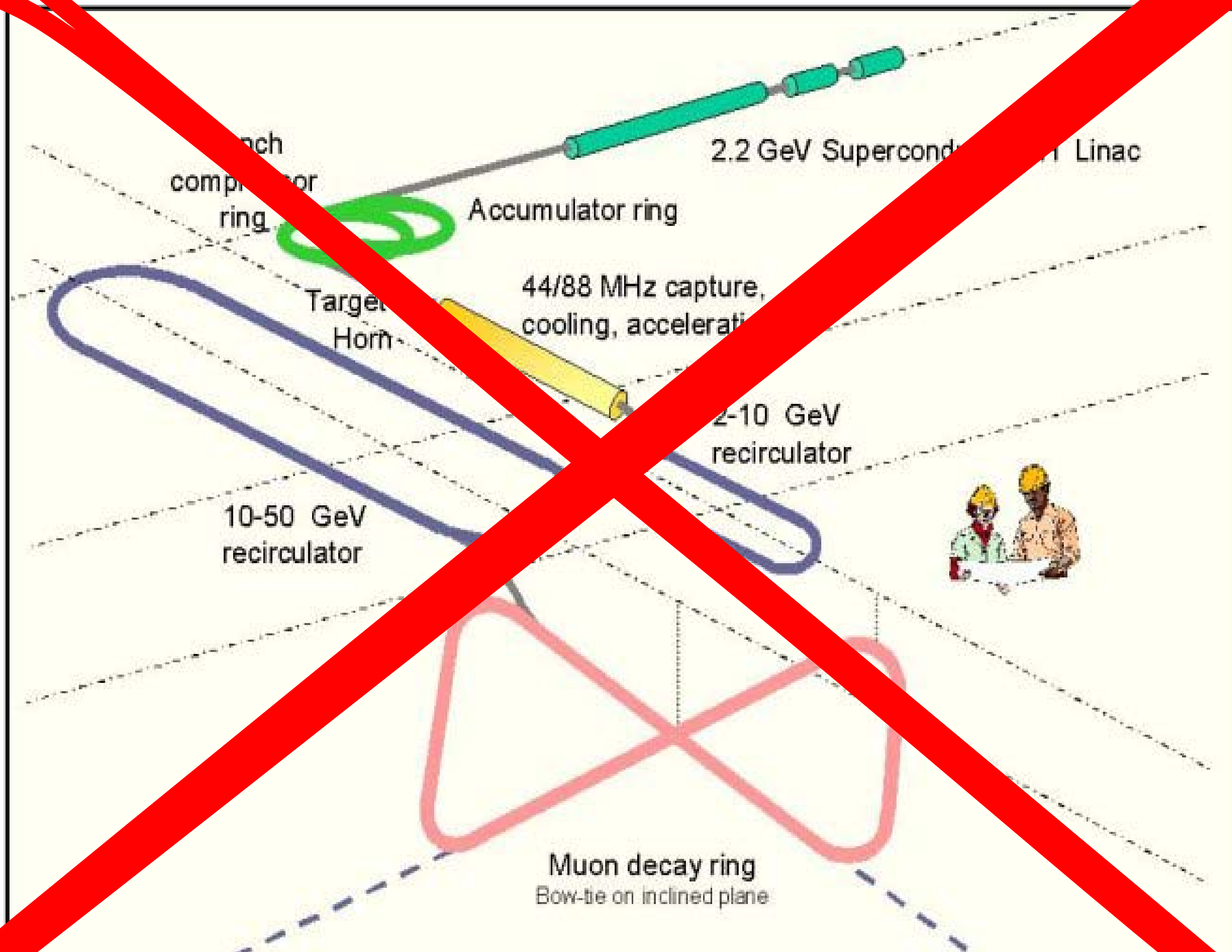
This was true for a race track or triangle decay ring, in which polarization precesses.

A bow-tie has been suggested to avoid this spin precession and depolarization (net bend is zero, so muon polarization does not precess either)

This has several inconveniences:
-- P is different for the two straights (who shall be pleased?)
-- P cannot be reversed
-- E and $\sigma(E)$ can no longer be measured
-- in order to know the flux to 0.1% on must know P to 0.1% and this is hard!

end of the bow tie.

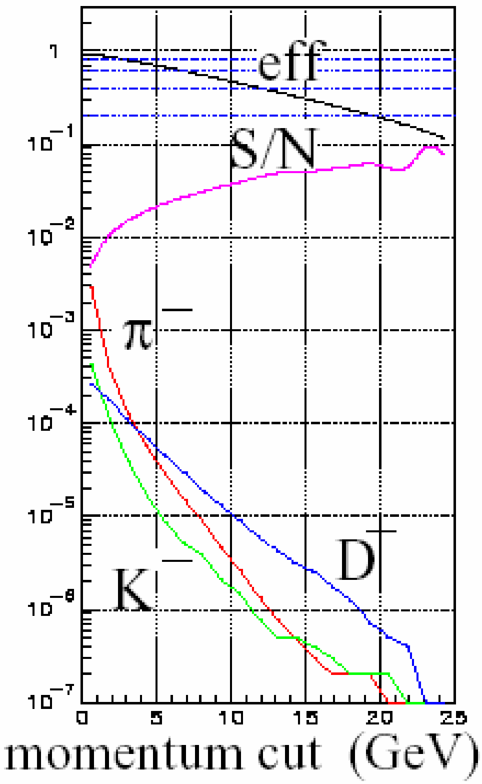
CERN baseline scenario



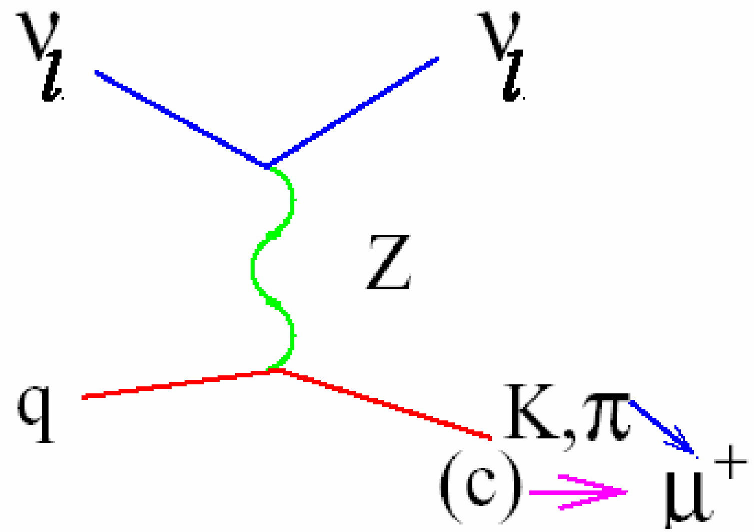
Neutrino Factory schematic (isometric view)

Very small systematics in neutirno factory come from low background

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



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



Momentum cut on muon easily removes backgrounds

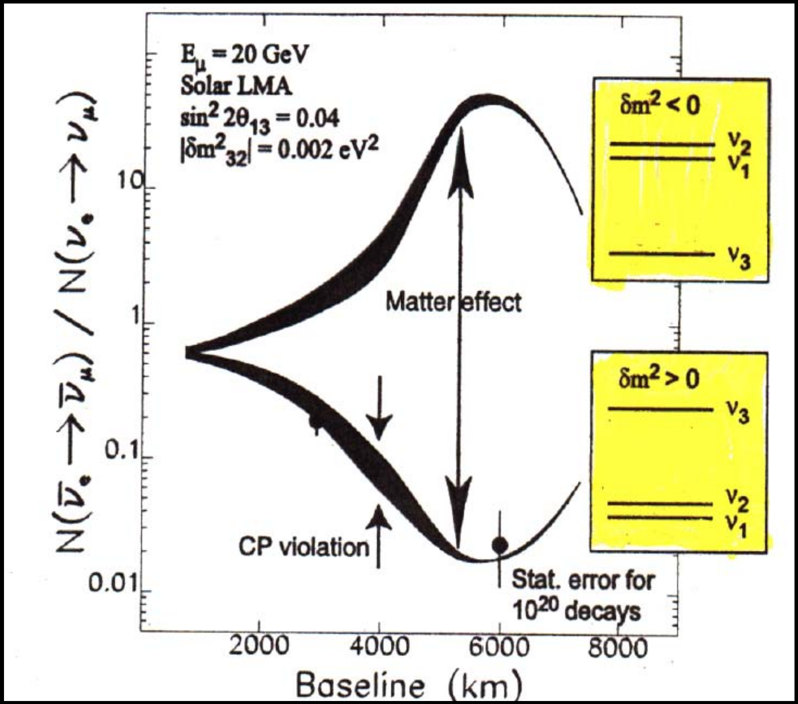
to be investigated:
the lowest possible momentum cut for specific events (Quasi-elastics)

CP asymmetries
compare $\nu_e \rightarrow \nu_\mu$ to $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ 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



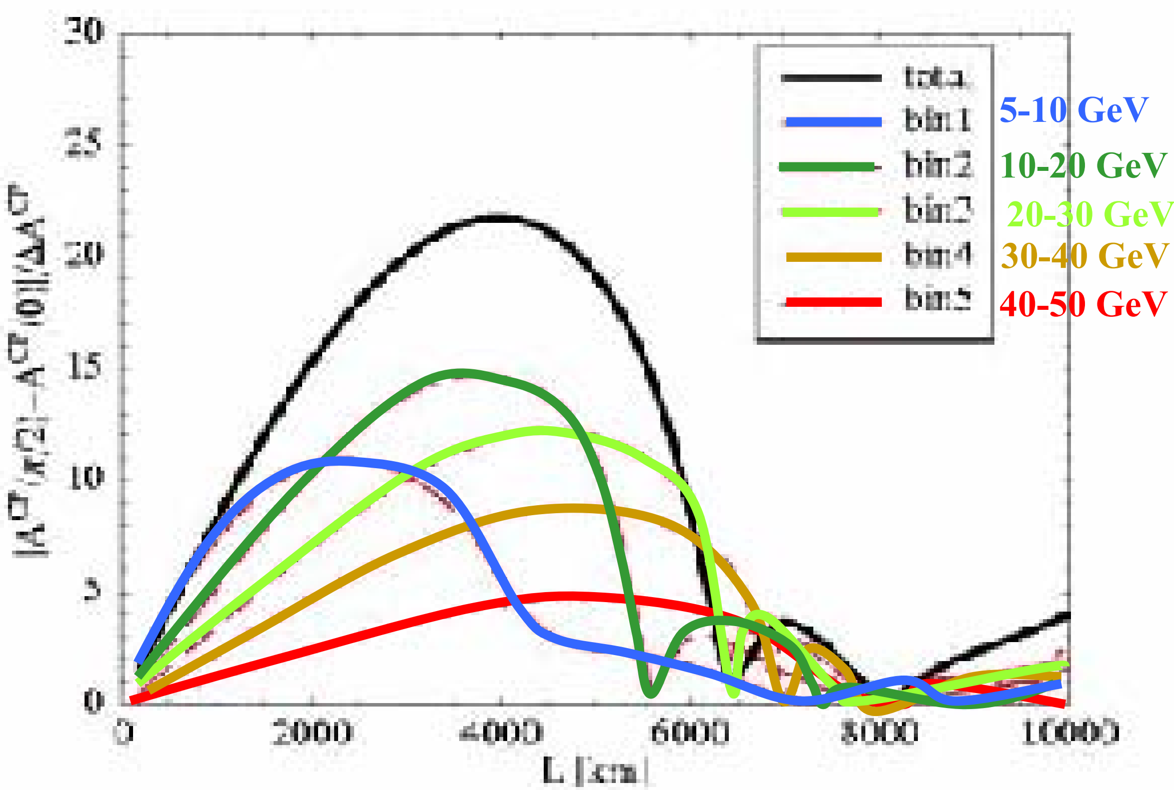
HUGE effect for distance around 6000 km!!

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

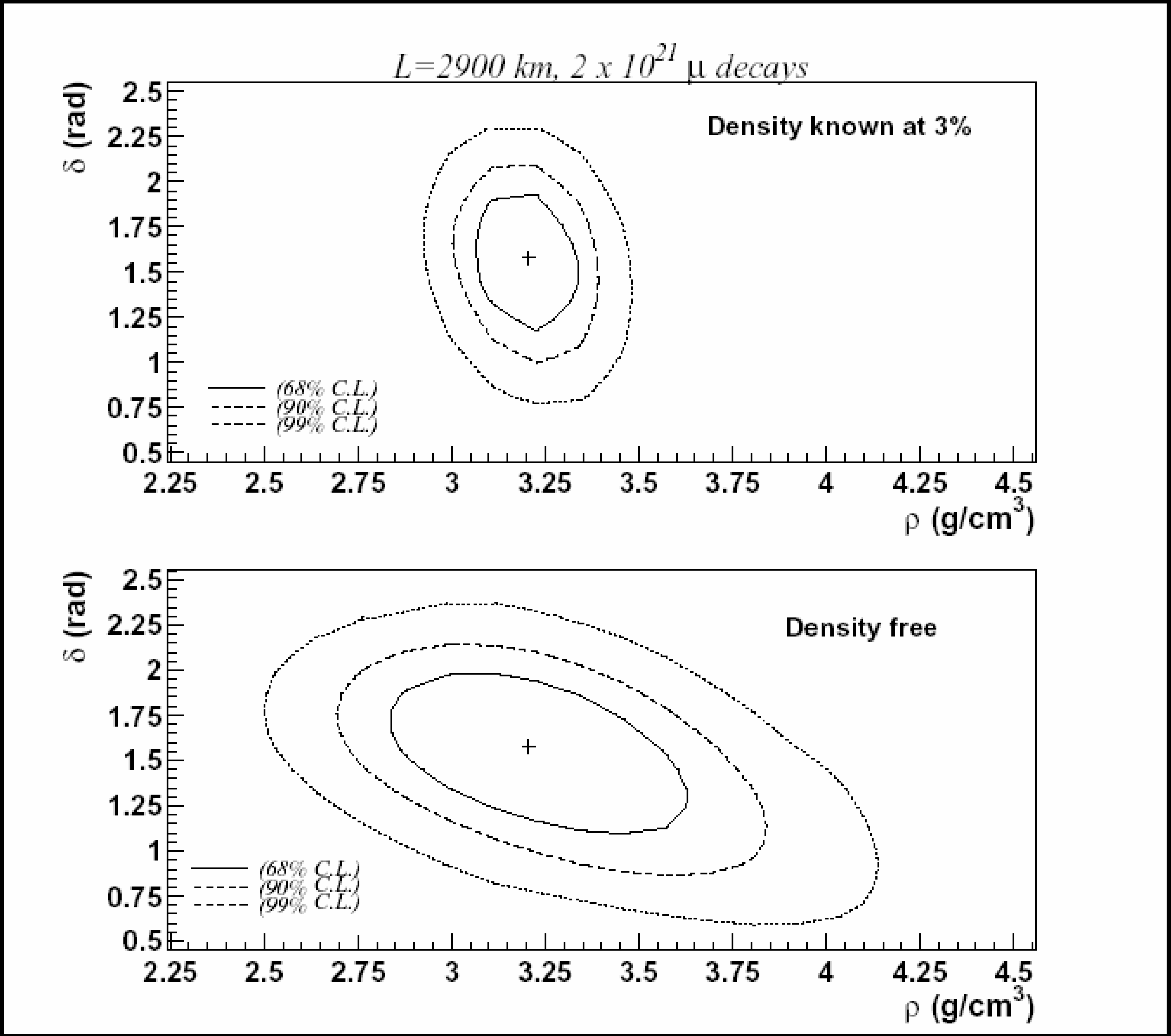
In fact, 20-30 GeV Is enough!

Best distance is 2500-3500 km

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

Where do you prefer to take shifts?

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



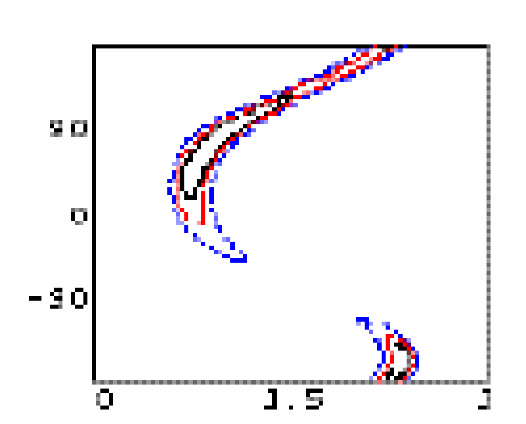
Silver channel at neutrino factory

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

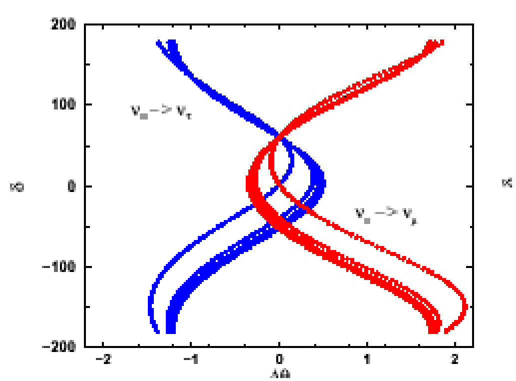
High energy neutrinos at NuFact allow observation of $\nu_e \rightarrow \nu_\tau$
(wrong sign muons with missing energy and P⊥). UNIQUE

Liquid Argon or OPERA-like detector at 3000 km.

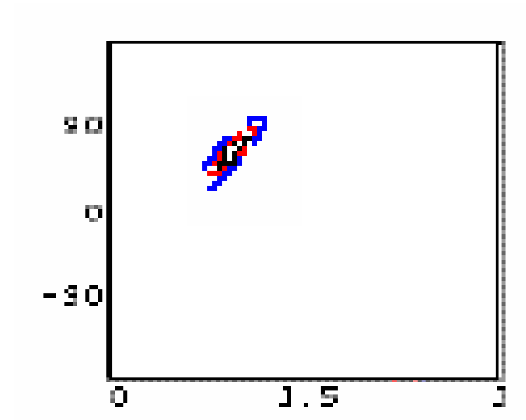
Since the sinδ dependence has opposite sign with the wrong sign muons, this solves ambiguities that will invariably appear if only wrong sign muons are used.



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

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

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

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

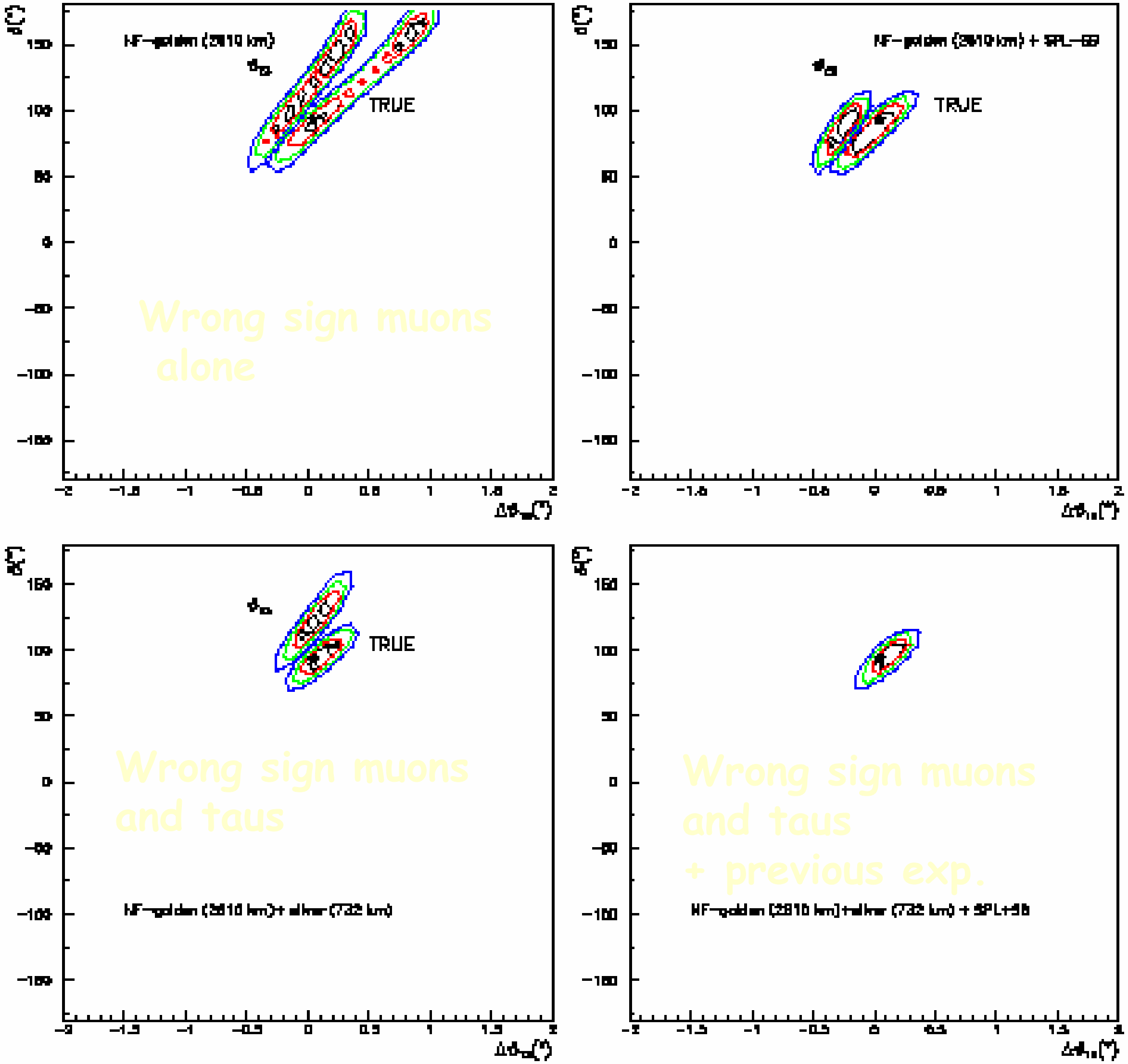
octant ambiguity

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

mixed ambiguity

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

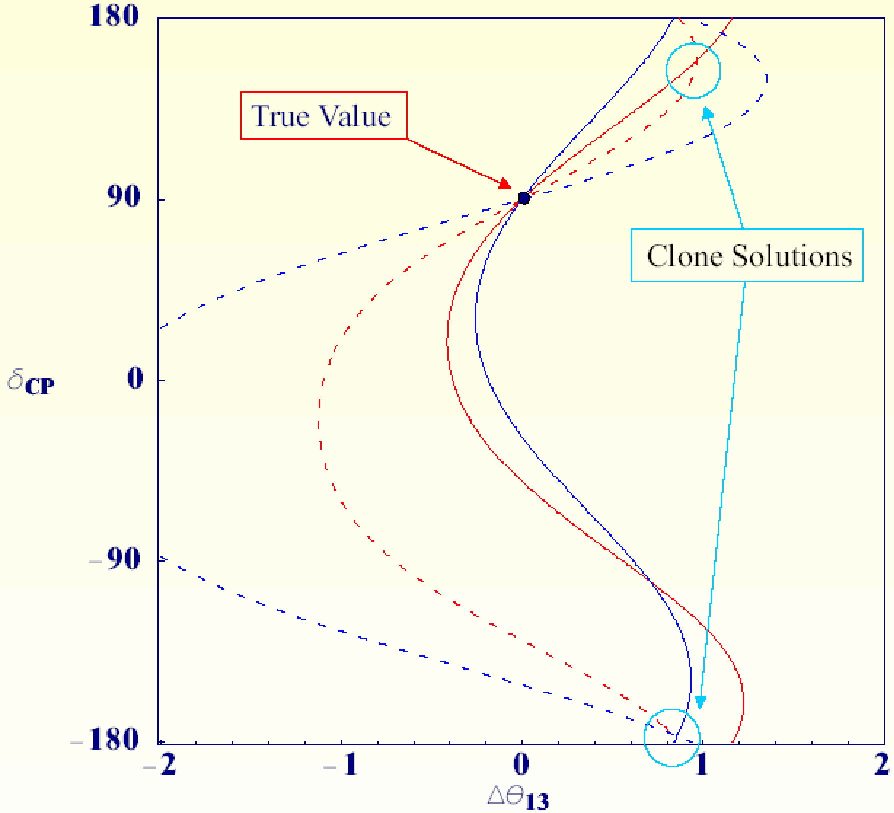
From Donini, NuFact03: There were even ambiguities with the neutrino factory:

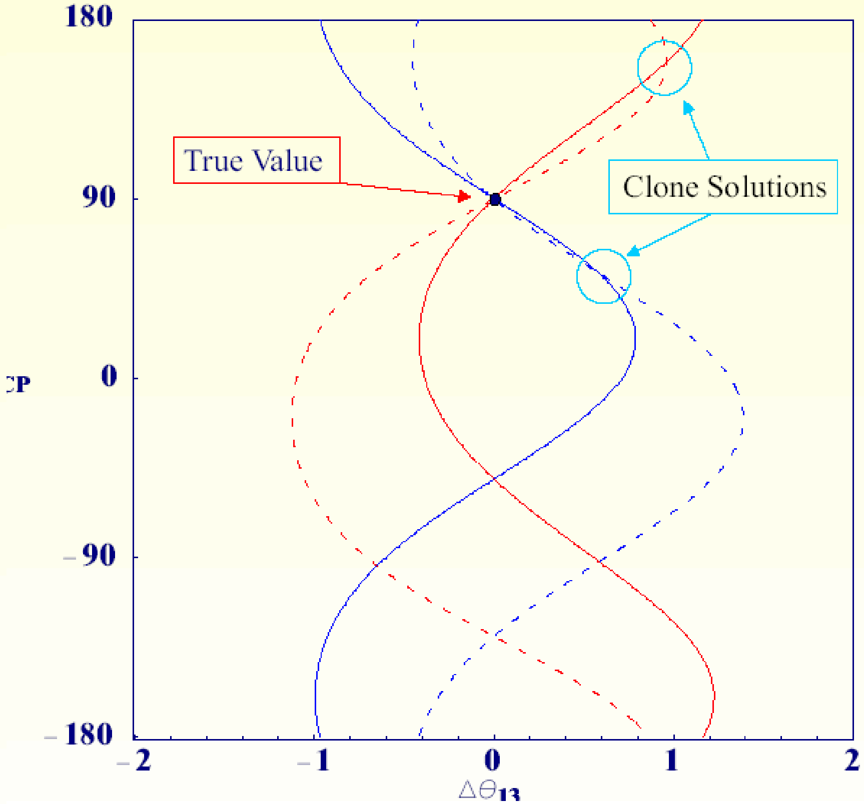


Getting to ultimate precision means combining data from several channels:

- Wrong-sign muons
- $\nu_e \rightarrow \nu_\tau$
- 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)
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)***

Fermilab Proton Driver
8 GeV Superconducting Linac

Basic concept inspired by the observation (by Bill Foster) that $/GeV for SCRF has fallen dramatically

⇒ Consider a solution in which H^- beam is accelerated to 8 GeV in a superconducting linac and injected directly into the Main Injector

Attractions of a superconducting linac:

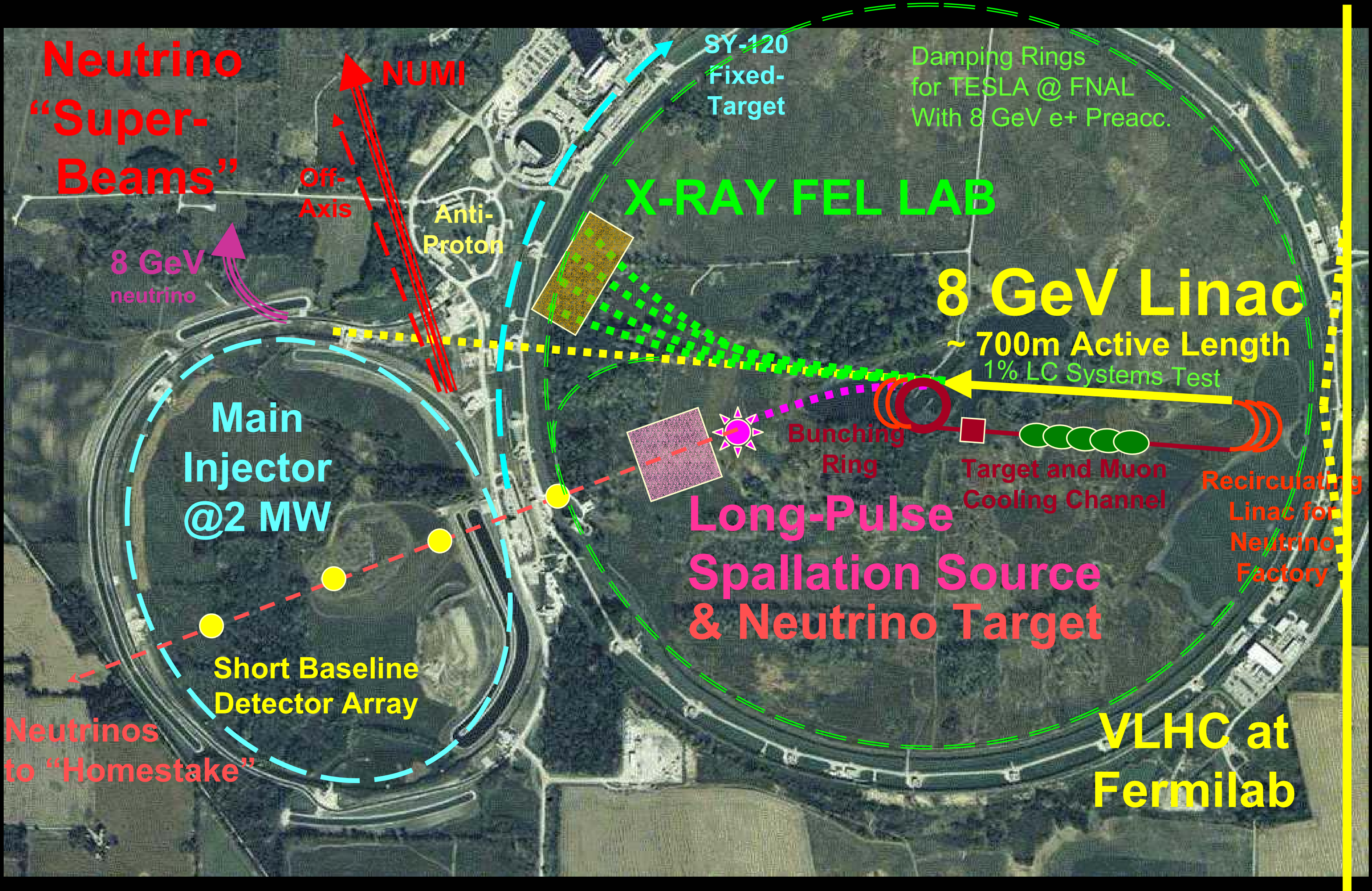
- Many components exist (few parts to design vs. new synchrotron)
  - Copy SNS, RIA, & AccSys Linac up to 1.2 GeV
  - **"TESLA" Cryo modules from 1.2 → 8 GeV**
- Smaller emittance than a synchrotron
- High beam power simultaneously at 8 & 120 GeV
  - Plus, high beam power (2 MW) over entire 40-120 GeV range
- Flexibility for the future

Issues:

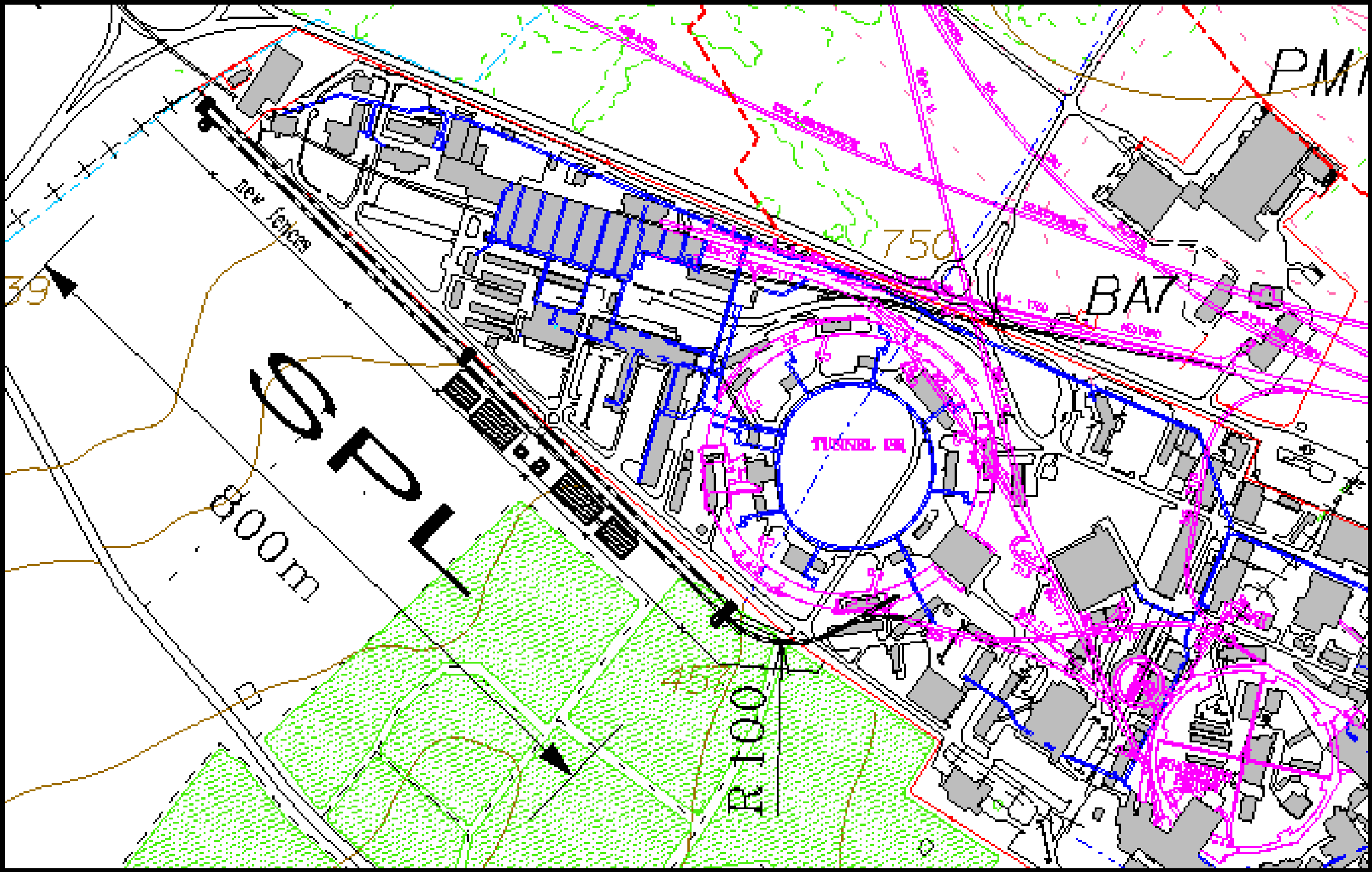
- **Uncontrolled H^- stripping**
- **Halo formation and control**
- **Cost**

Fermilab Proton Driver

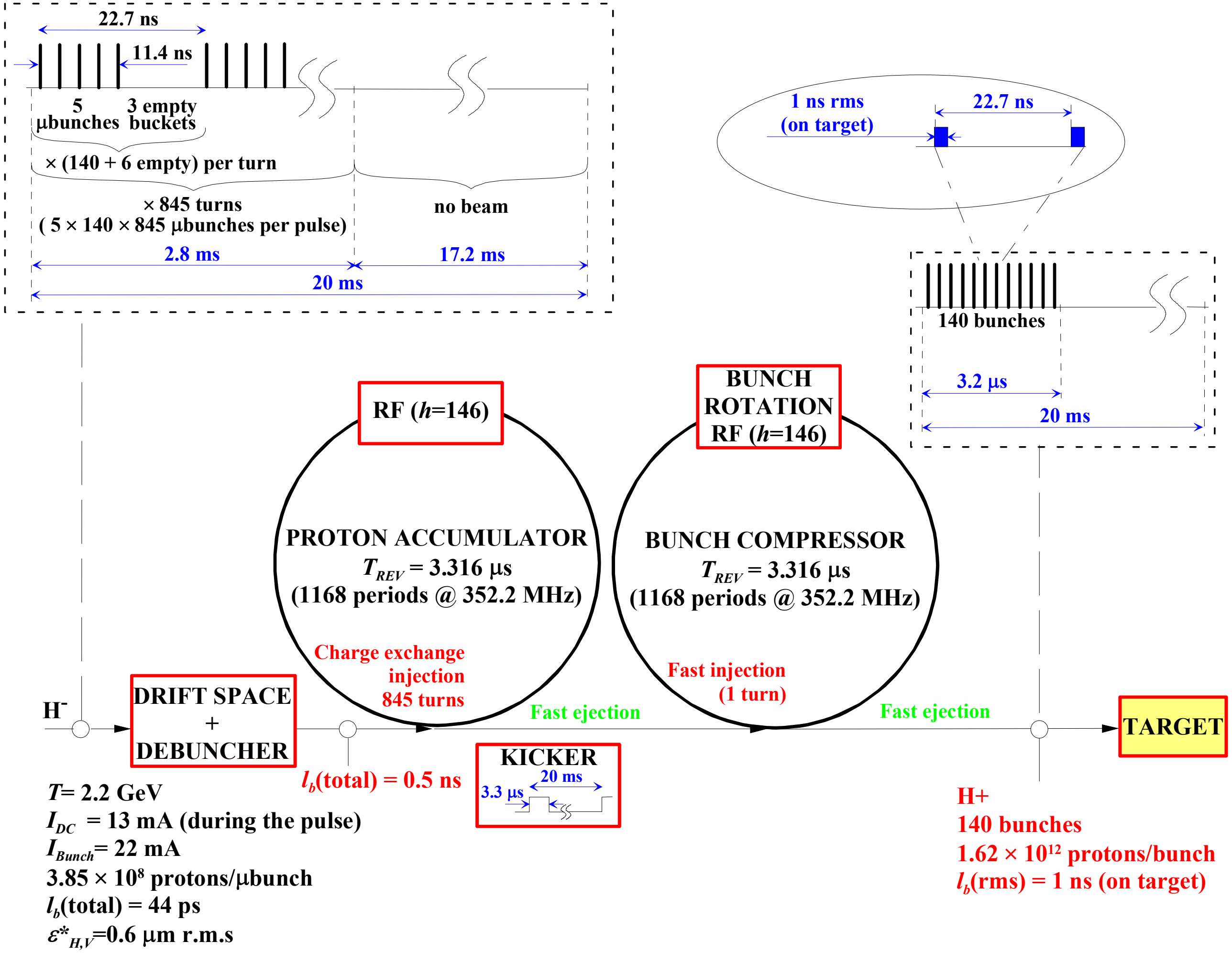
8 GeV SC Linac: Other possible missions (from the mind of Bill Foster)



SPL layout



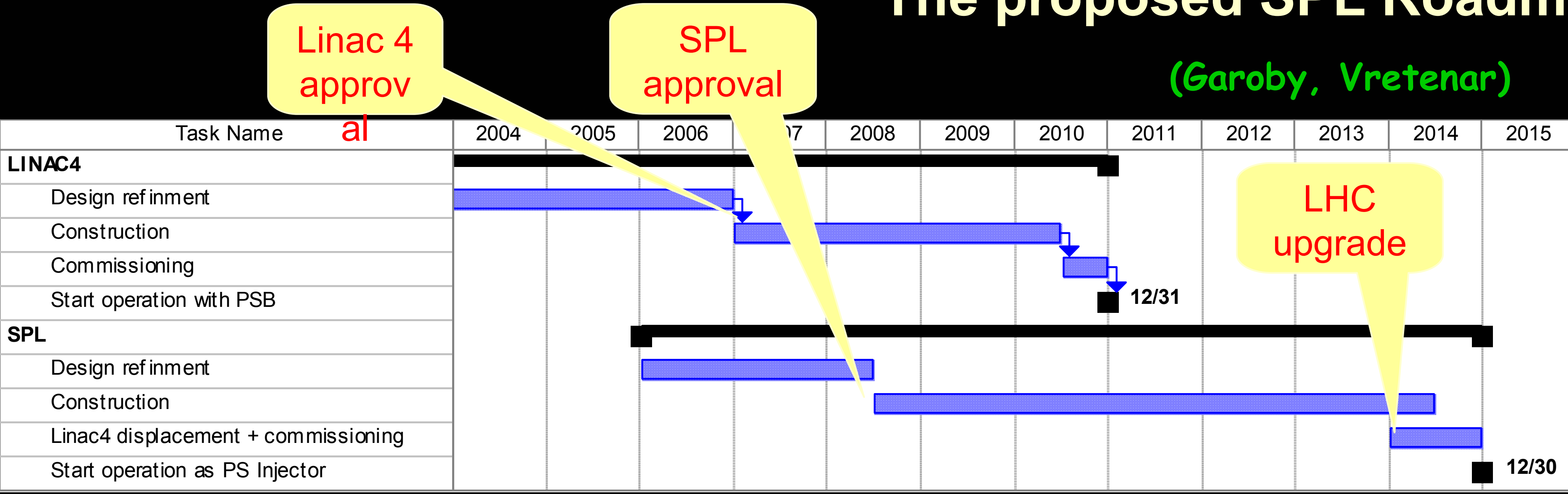
Accumulator and Compressor



Parameter	Value	Unit
Mean beam power	4	MW
Kinetic energy	2.2	GeV
Repetiton rate	50	Hz
Pulse duration	3.3	µs
Number of bunches	140	
Pulse intensity	2.27×10^{14}	p/pulse
Bunch spacing (Bunch frequency)	22.7 (44)	ns (MHz)
Bunch length (σ)	1	ns
Relative momentum spread (σ)	5×10^{-3}	
Norm. horizontal emittance (σ)	50	µm.rad

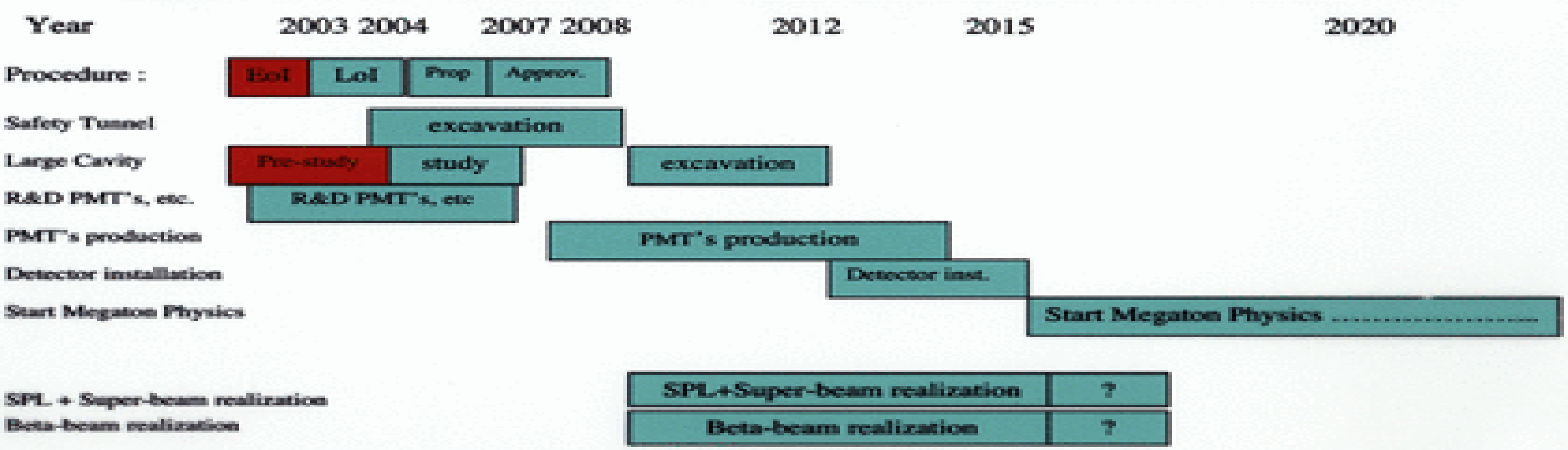
The proposed SPL Roadmap

(Garoby, Vretenar)



18

5) An « Optimal » schedule for a Megaton Physics Project in Europe



High intensity proton accelerators pose many challenges but certainly one of the most critical one is the

Target !

Typical Dimensions: L $\approx$ 30 cm, R $\approx$ 1 cm

$\rightarrow$ 4 MW of protons (i.e. 40 000 light bulbs!) into a big cigar….

it would immediately go to smoke.

Liquid Mercury Target R&D

Experiment @BNL and @CERN

Speed of Hg disruption

Max $v_{\perp} \approx 20$ m/s measured

$v_{//} \approx 3$ m/s

(design calls for 20m/s)

E951 Mercury run
4-25-2001

file #: jet-data-10-movie.gif

grid size: 1 cm
field of view: 13.2 cm x 13.2 cm

frame rate: 1 ms
exposure time: 150 ns

proton energy: 24 GeV
# of particles: 3.8 TP

1 cm

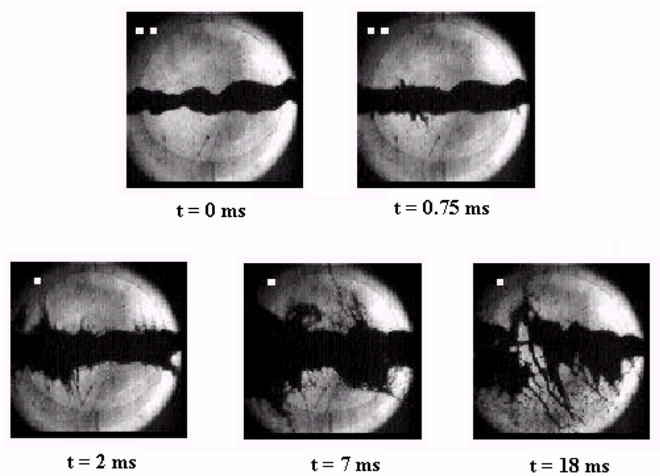
Protons

jet remains intact for more than 20 microseconds.

Target: Hg jet tests

E951

- 1 cm
- v=2.5 cm/s
- 24 GeV 4 TP p beam
- No B field

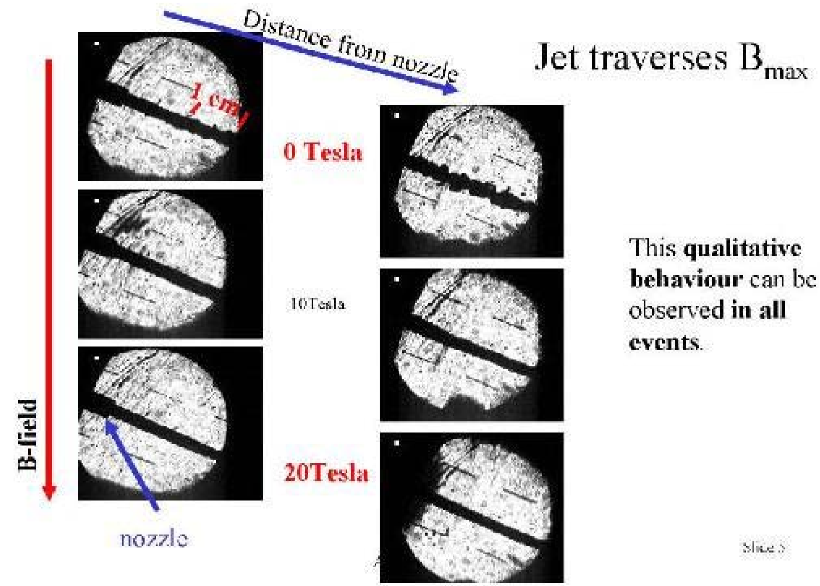


Hg jet dispersal properties :

- proportional to beam intensity
- velocities ~½ times that of “confined thimble” target
- largely transverse to the jet axis
- delayed 40 ms

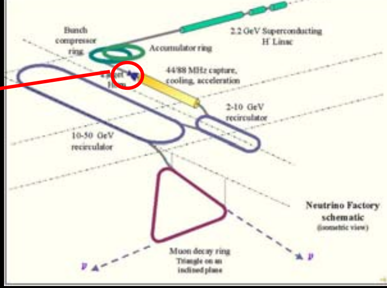
CERN/Grenoble

- 4 mm
- v=12 m/s
- No p beam
- 0,10,20T B field



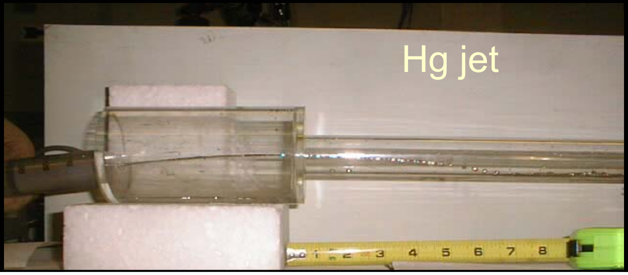
- The Hg jet is stabilized by the 20 T B field
- Minimal jet deflection for 100 mrad angle of entry
- Jet velocity reduced upon entry to B field

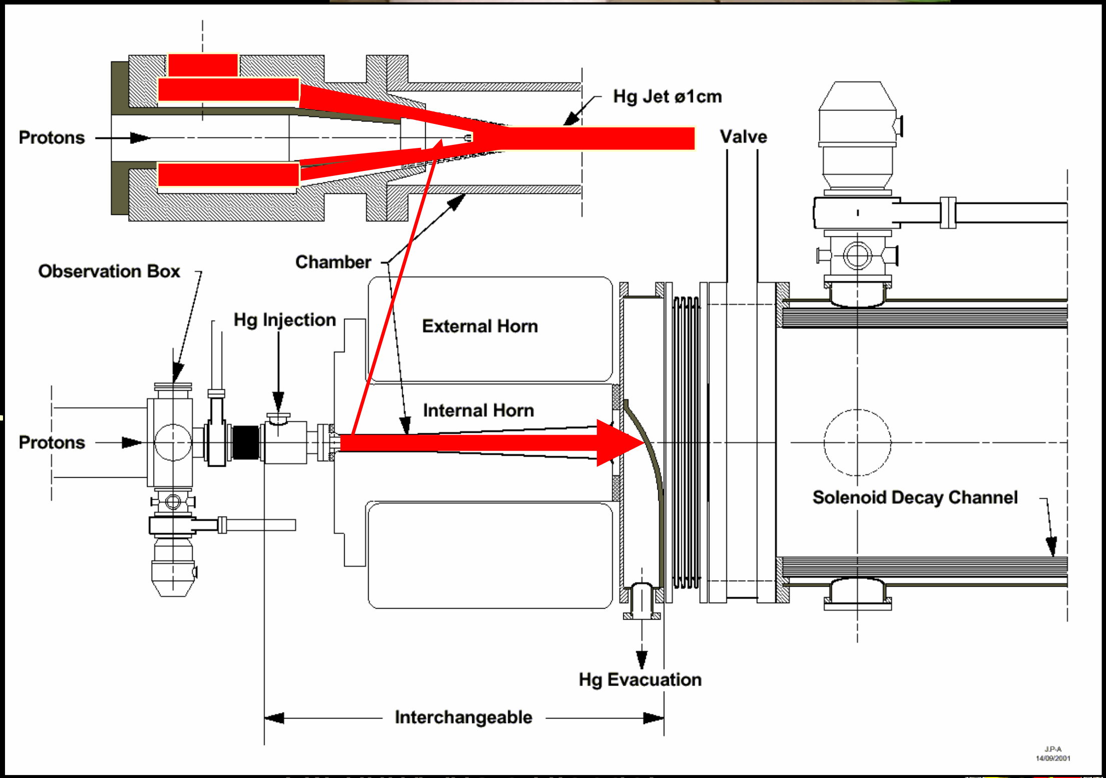
Target & collection



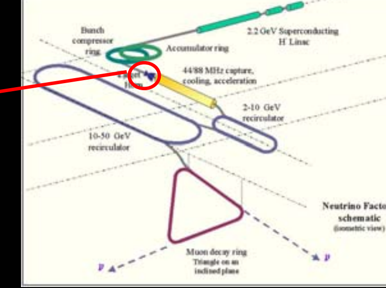
- Achieve intense muon beams by maximizing production of π+ <u>and</u> π-
- Soft pion production
  - HARP cross-section results awaited!
  - High Z material
- High magnetic field
- Sustain high power

- Superbeam or Neutrino Fact Targetry concept:
- Hg jet p-converter target
- Pion focusing horn

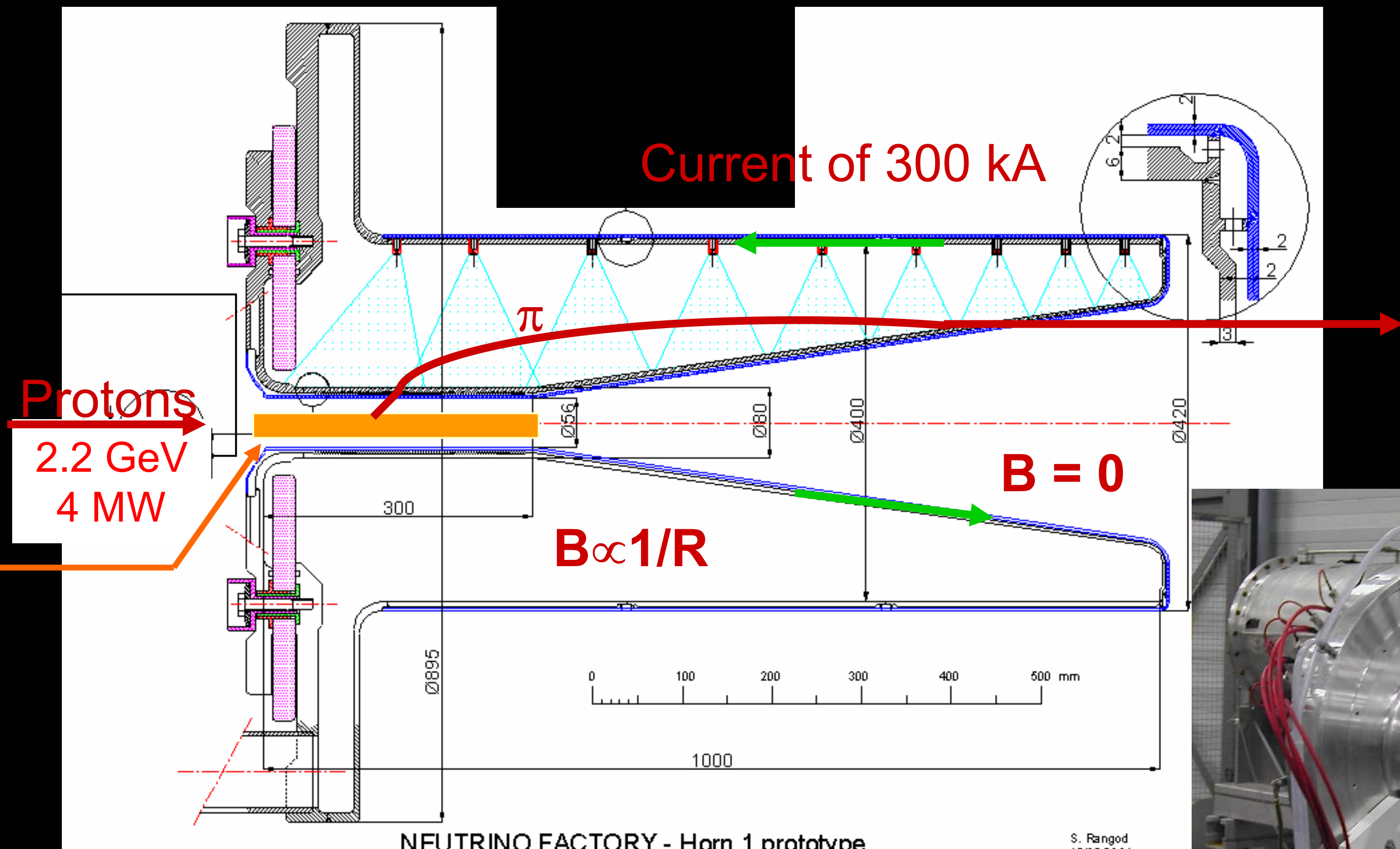




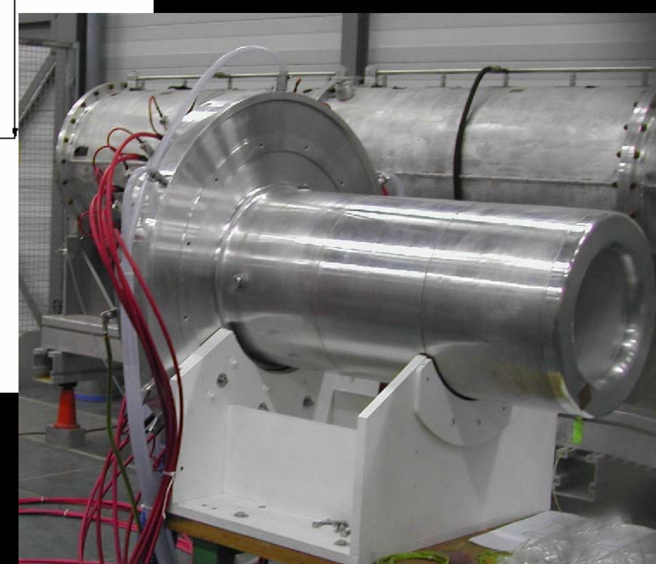
Target & collection



The CERN magnetic horn for pion collection

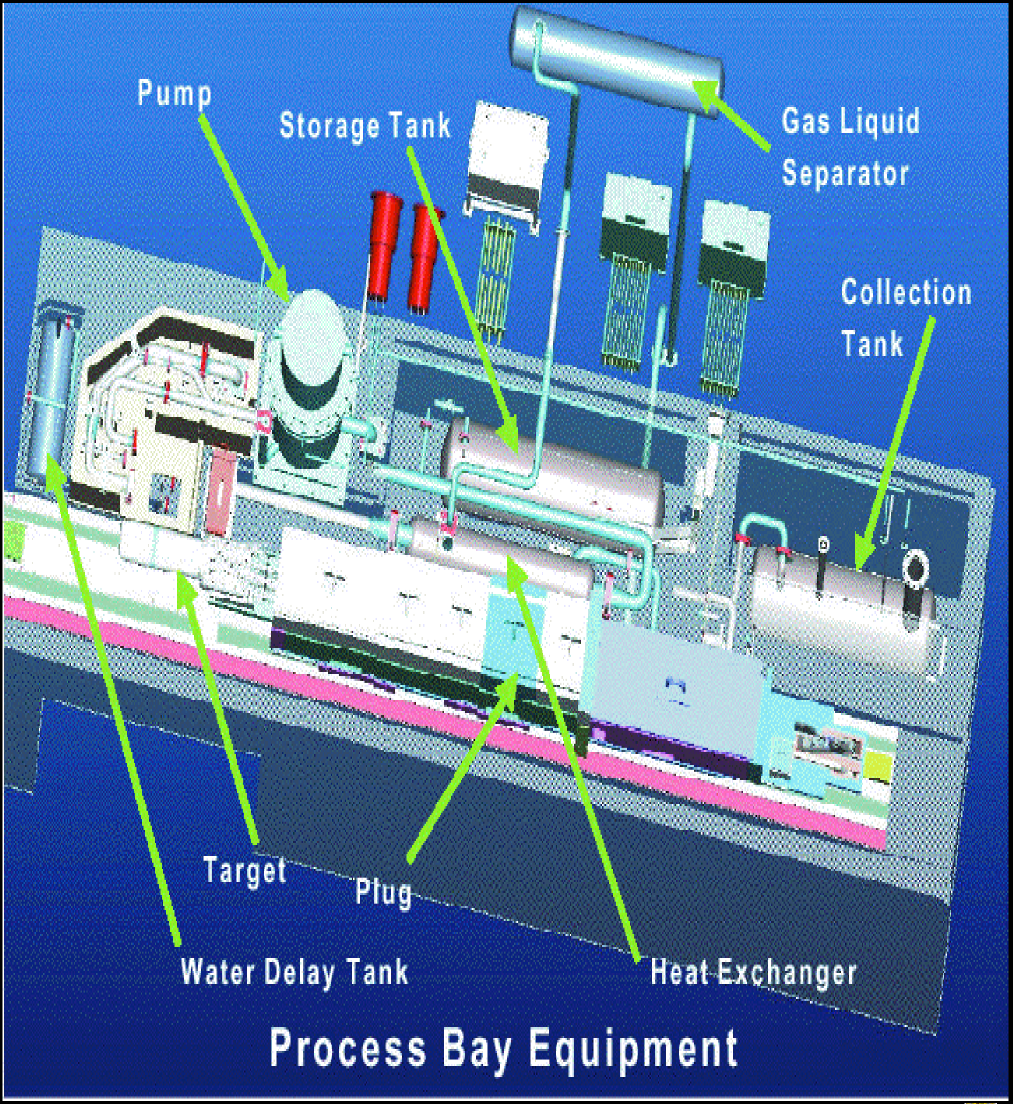


Prototype built at CERN

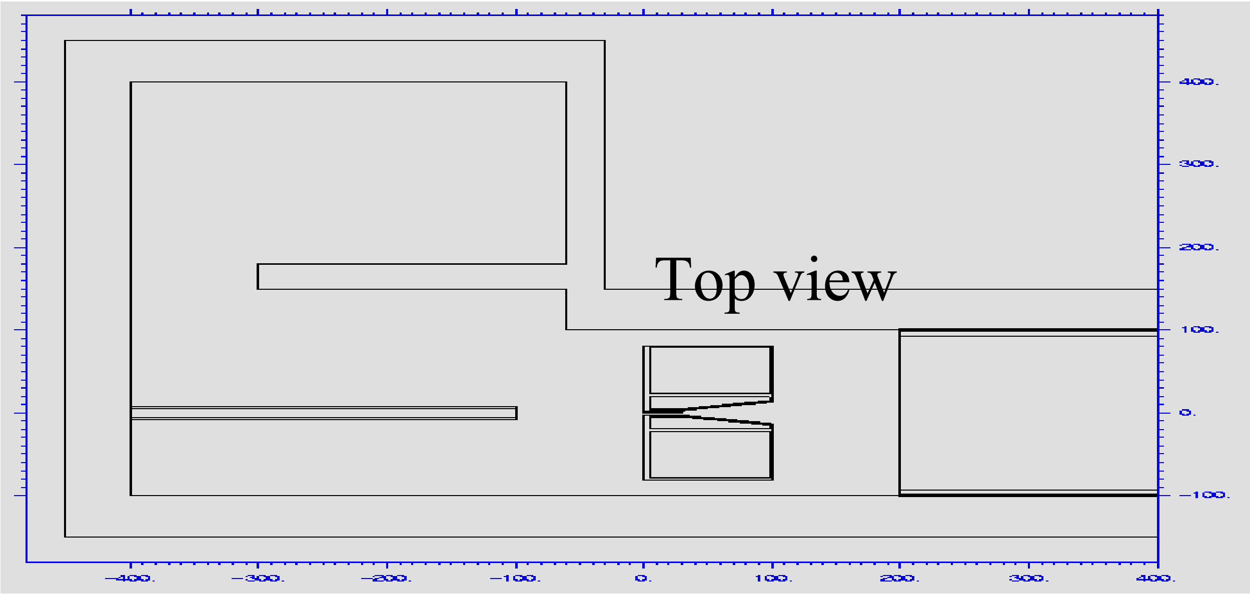


Hg-jet system

Power absorbed in Hg-jet	1 MW
Operating pressure	100 Bar
Flow rate	2 t/m
Jet speed	30 m/s
Jet diameter	10 mm
Temperature	
- Inlet to target 30° C	
- Exit from target	100° C
Total Hg inventory	10 t
Pump power	50 kW



The target station



The facility consists of a target, two horns and a decay tunnel. It is shielded by 50 cm thick walls of concrete and is embedded in the rock.

Silari

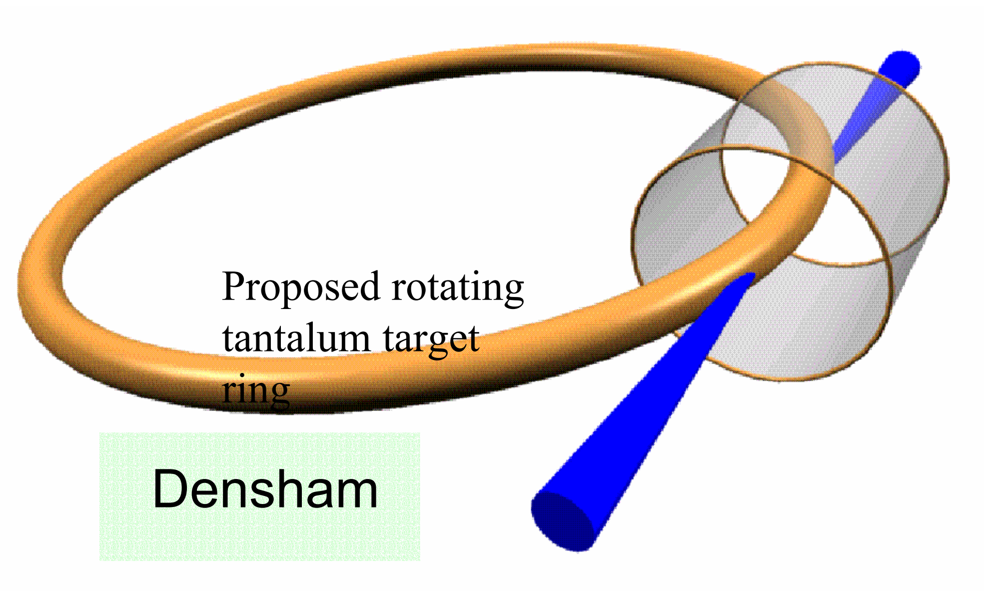
Many difficulties: enormous power density

⇒ lifetime problems

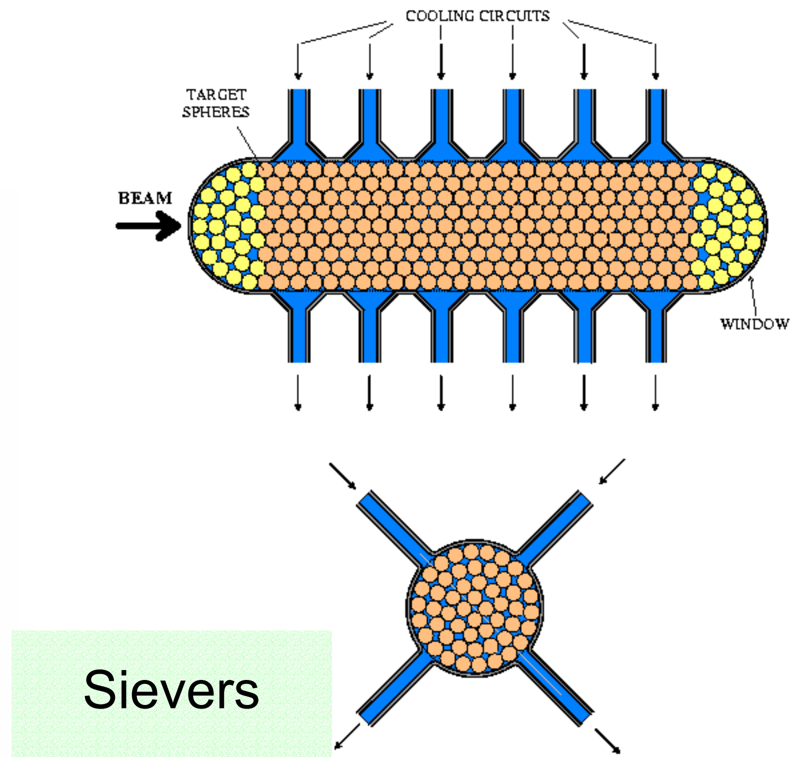
pion capture

Replace target between bunches:

Liquid mercury jet or rotating solid target



Stationary target:



Target & collection

Proposal to test a 10m/s Hg Jet in a 15T Solenoid with an Intense Proton Beam

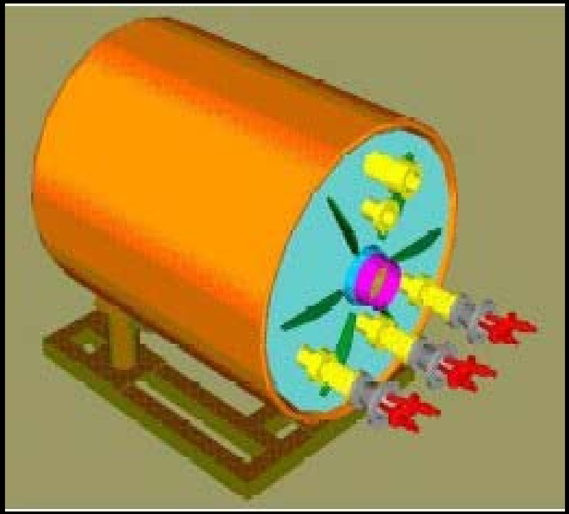
CERN-INTC-2003-033
INTC-I-049
26 April 2004

A Proposal to
the ISOLDE and Neutron Time-of-Flight Experiments Committee

Studies of a Target System for a 4-MW, 24-GeV Proton Beam

J. Roger J. Bennett[1], Luca Bruno[2], Chris J. Densham[1], Paul V. Drumm[1], T. Robert Edgecock[1], Tony A. Gabriel[3], John R. Haines[3], Helmut Haseroth[2], Yoshinari Hayato[4], Steven J. Kahn[5], Jacques Lettry[2], Changguo Lu[6], Hans Ludewig[5], Harold G. Kirk[5], Kirk T. McDonald[6], Robert B. Palmer[5], Yarema Prykarpatskyy[5], Nicholas Simos[5], Roman V. Samulyak[5], Peter H. Thieberger[5], Koji Yoshimura[4]

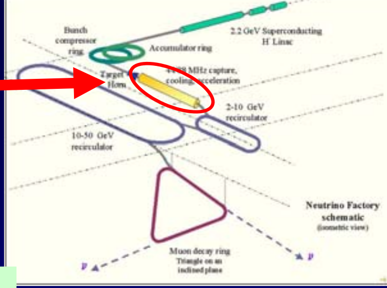
Spokespersons: H.G. Kirk, K.T. McDonald
Local Contact: H. Haseroth



Participating Institutions
1) RAL
2) CERN
3) KEK
4) BNL
5) ORNL
6) Princeton University

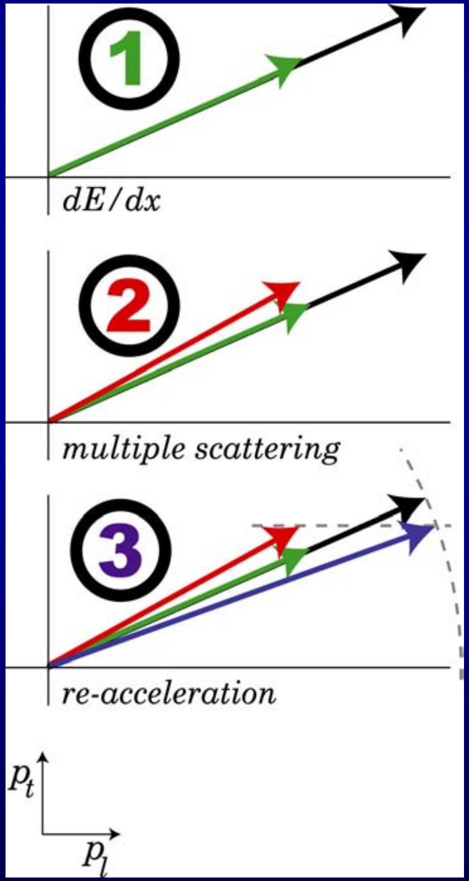
aim:
Installation and commissioning at CERN by April 2006

Muon ionization cooling



A novel method for $\mu+$ and $\mu-$ is needed: ionization cooling

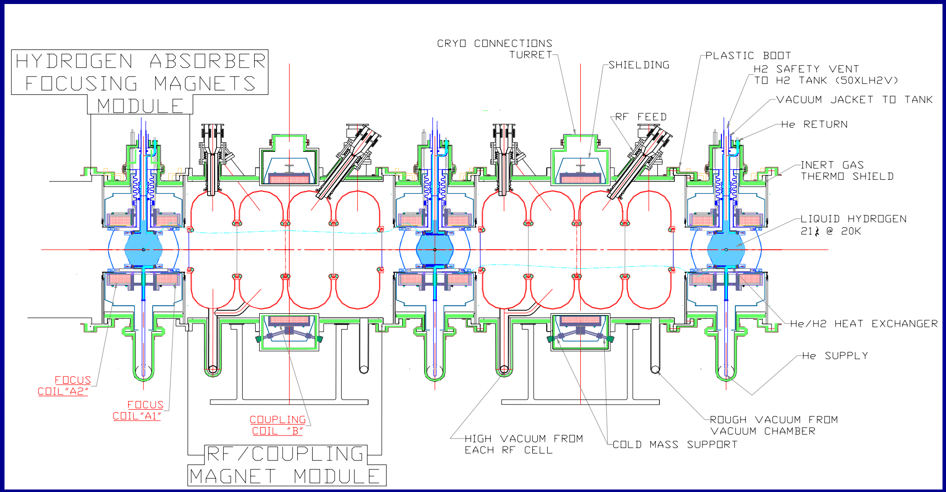
principle



reduce p_t and p_l with as little heating as possible: Hydrogen!

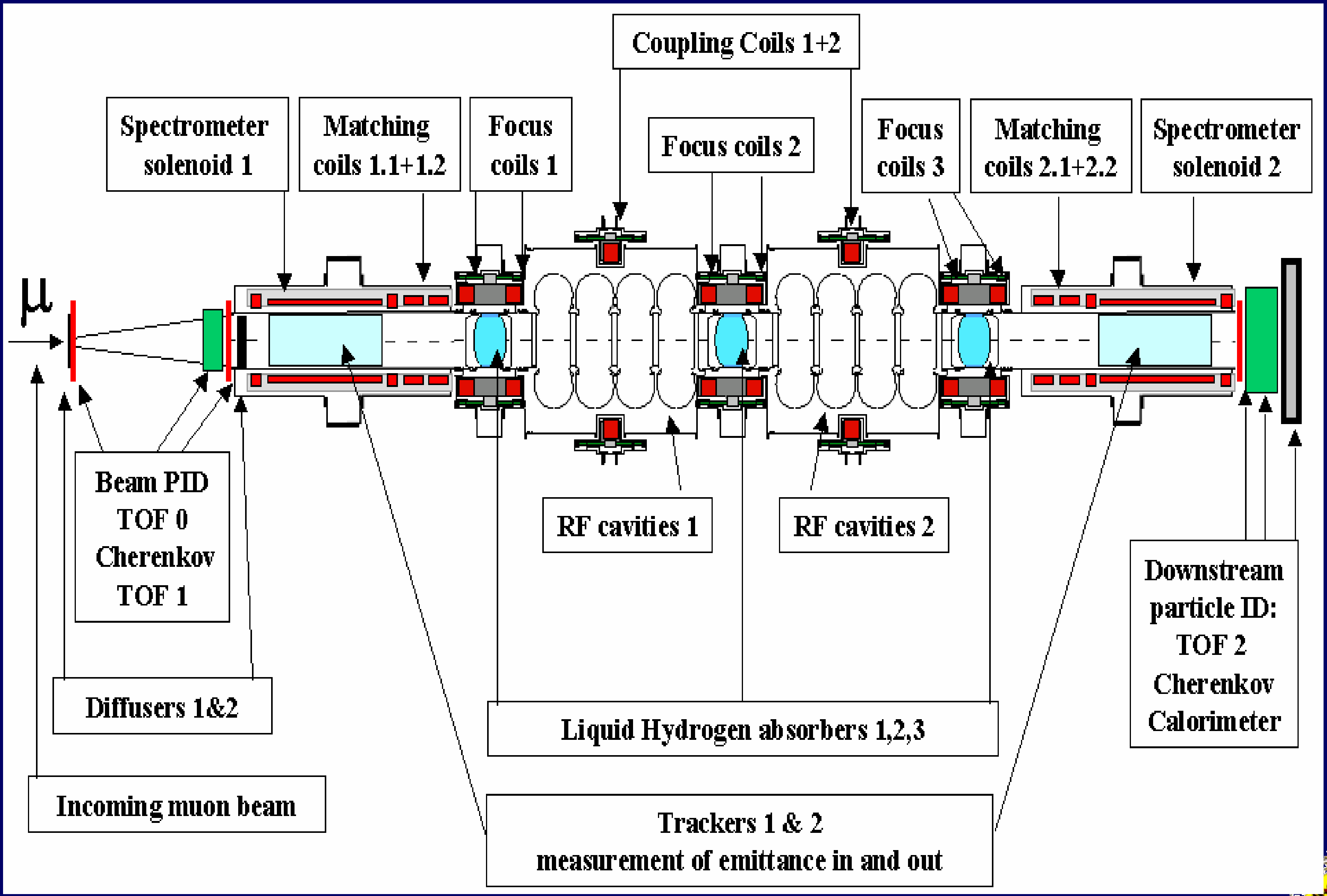
increase p_l fast acceleration

reality (simplified)

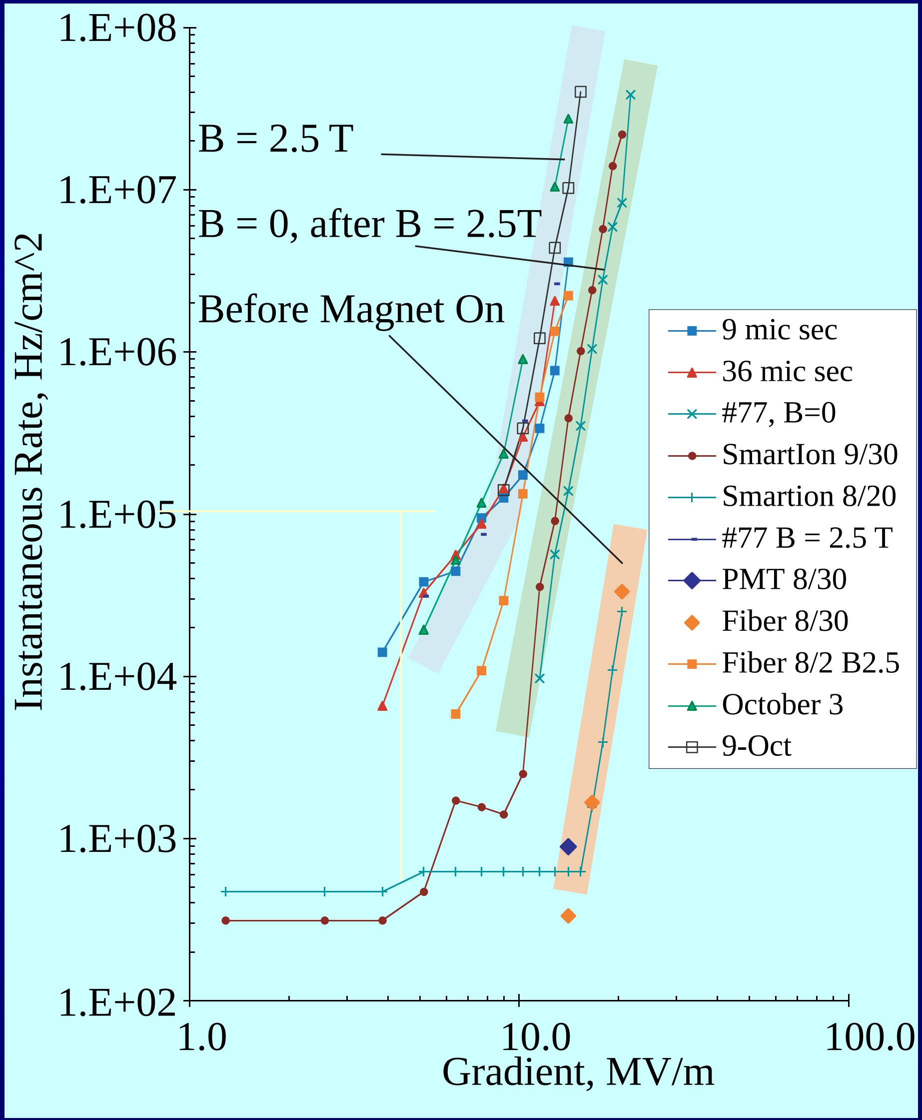


Never realized in practice !
A realistic prototype should be built and proven to be adequate to the Neutrino Factory requirements.

MICE setup: cooling + diagnostics

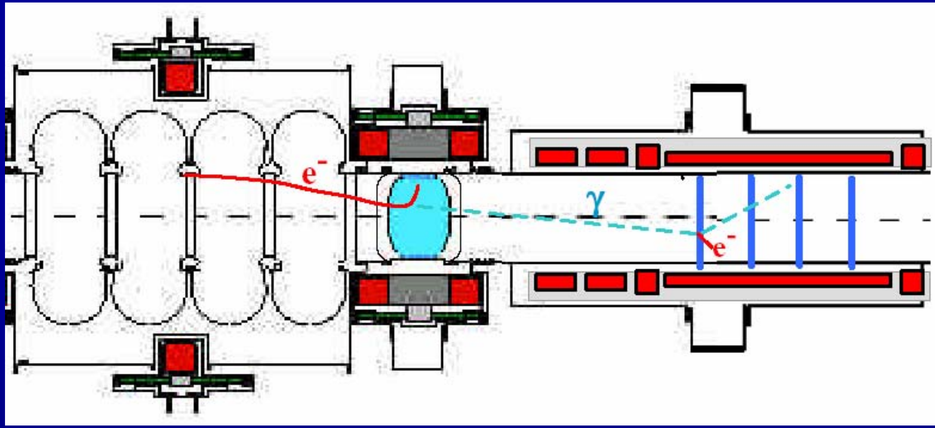


Operation of RF cavities at high gradient in magnetic field



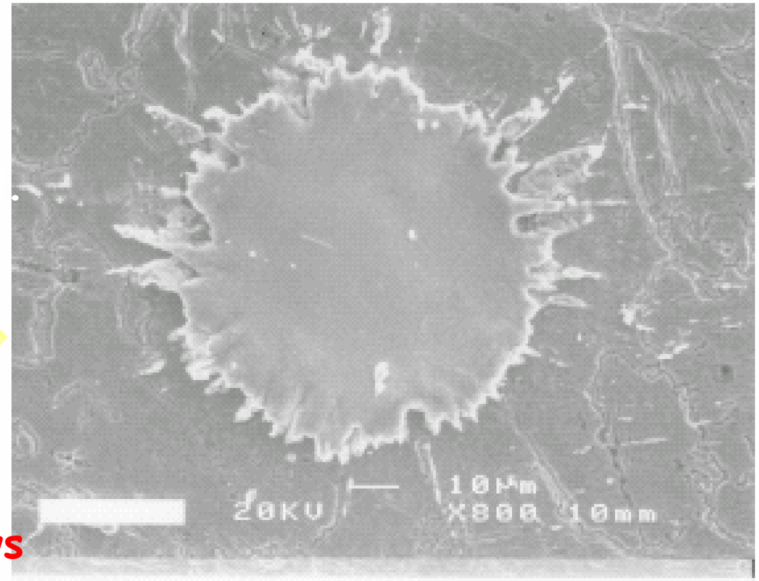
Dark current backgrounds measured on a 805 MHz cavity in magnetic field! with a 1mm scintillating fiber at d=O(1m)

This will be also a source of backgrounds for MICE:

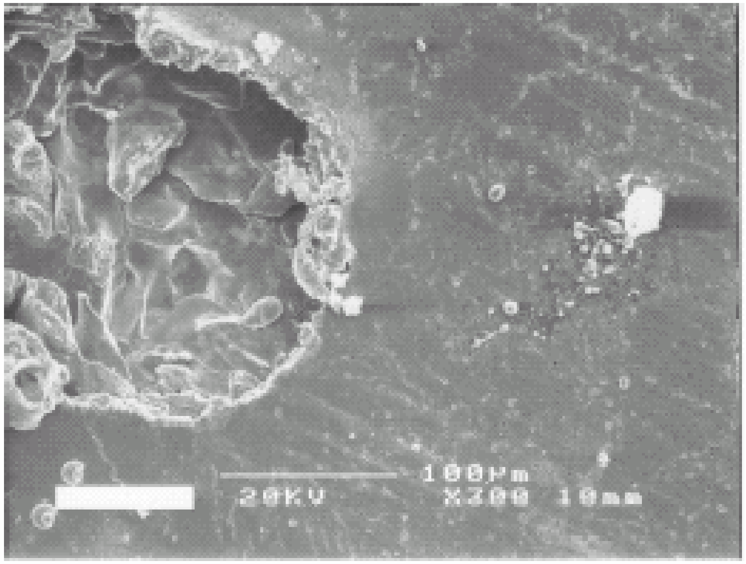


RF cavity (800 MHz) at Fermilab
being pushed to its limits (35 MV/m)
to study dark current emission in magnetic
field. Sees clear enhancement due to B field.
Various diagnostics methods
photographic paper, scintillating fibers
Microscope ------→
BCT and solid state counters
have demonstrated this and allowed precise
measurements
Real cavities will be equipped with Be windows
which do not show sign of being pitted
contrary to Cu

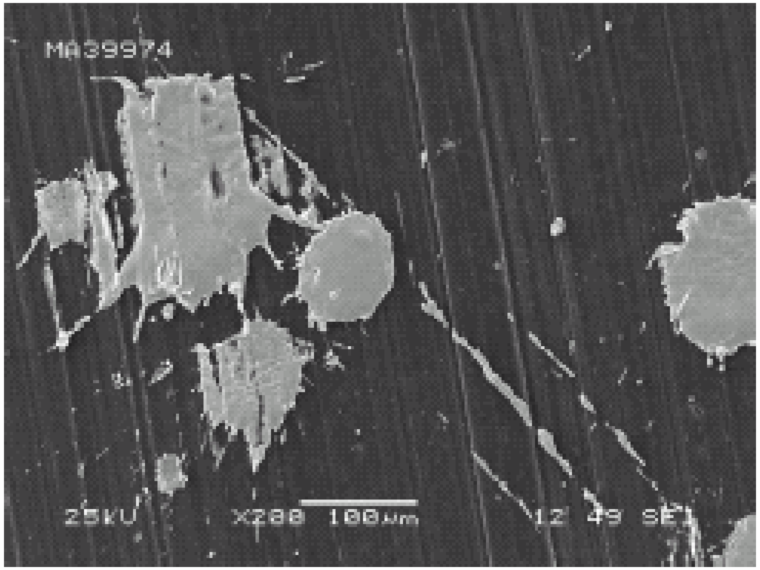
Pillbox cavity: Cu plate



Copper windows were pitted.



Cu splashes on the Be window.



MICE cooling channel R&D

The challenge:
Thin windows +
safety regulations

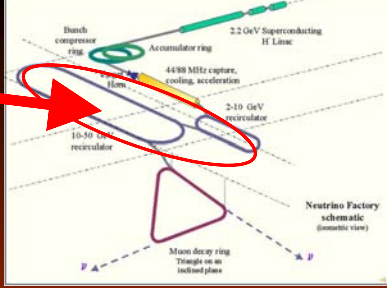
LH_2 window
(IIT, NIU, ICAR)

RF module
(Berkeley, Los Alamos, CERN, RAL)

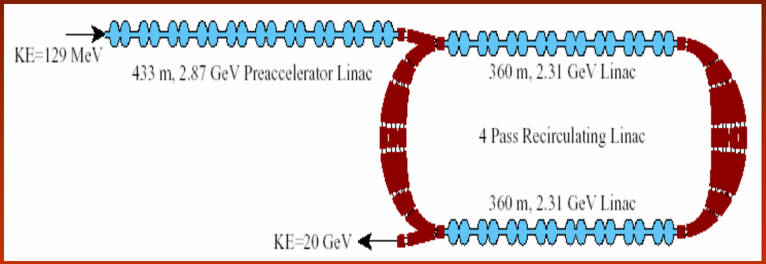
First cavity

Be window to minimize thickness

Muon acceleration



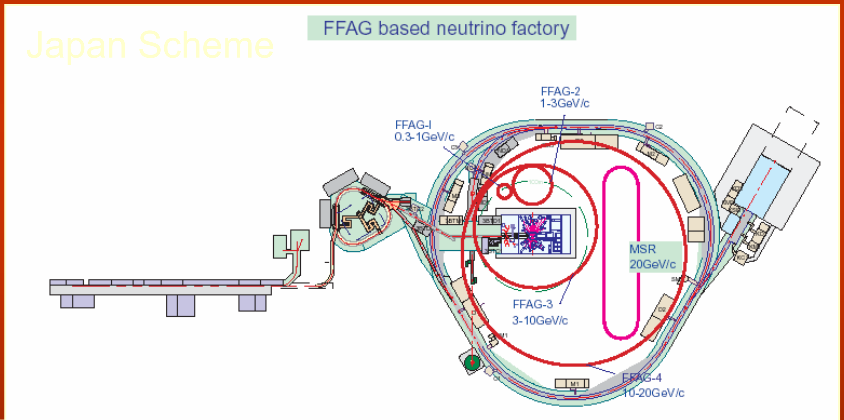
Previous accelerator scheme:
LINAC + Recirculating Linear Accelerator (RLA)
Very costly and rigid use.

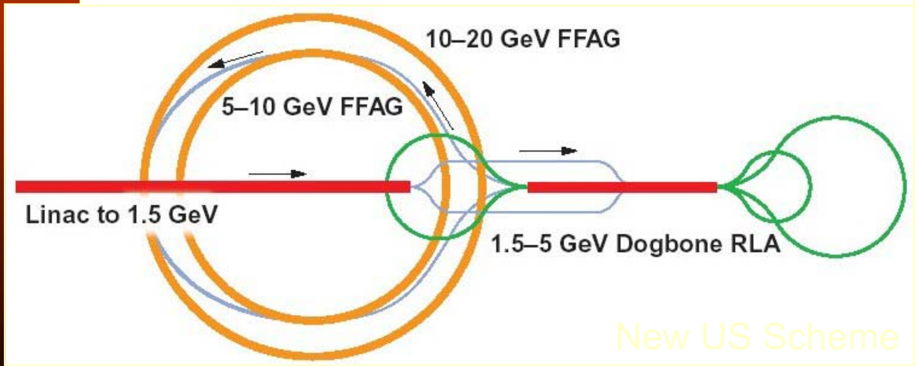


Proposed solution:

Fixed Field Alternating Gradient (FFAG). a new type of accelerator with B-field shaped as r^k

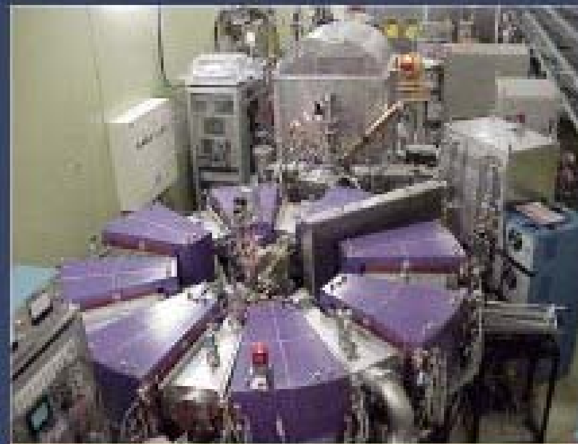
-->particles can be kept and accelerated over a range of energies of ~factor 3.





Muon acceleration: FFAG

Much progress in Japan with the development and demonstration of large acceptance FFAG accelerators



0.5-MeV Proton FFAG
POP at KEK

150-MeV Proton FFAG
Under construction at KEK

- Latest ideas in US have lead to the invention of a new type of FFAG ("non-scaling FFAG")
  - interesting for more than just Neutrino Factories (e.g. from SPL to 20 GeV?)
  - require a demonstration experiment (PRISM, electron prototype)

➔ Perhaps US & Japanese concepts are merging to produce something better ??

\$\$\$\$\$ ... 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 solutions 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 €

MAYBE 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.*

Other physics opportunities at a ν-factory complex

Related to high intensity

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, $e^+ \mu^- \text{<->} e^- \mu^+$

--> 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:

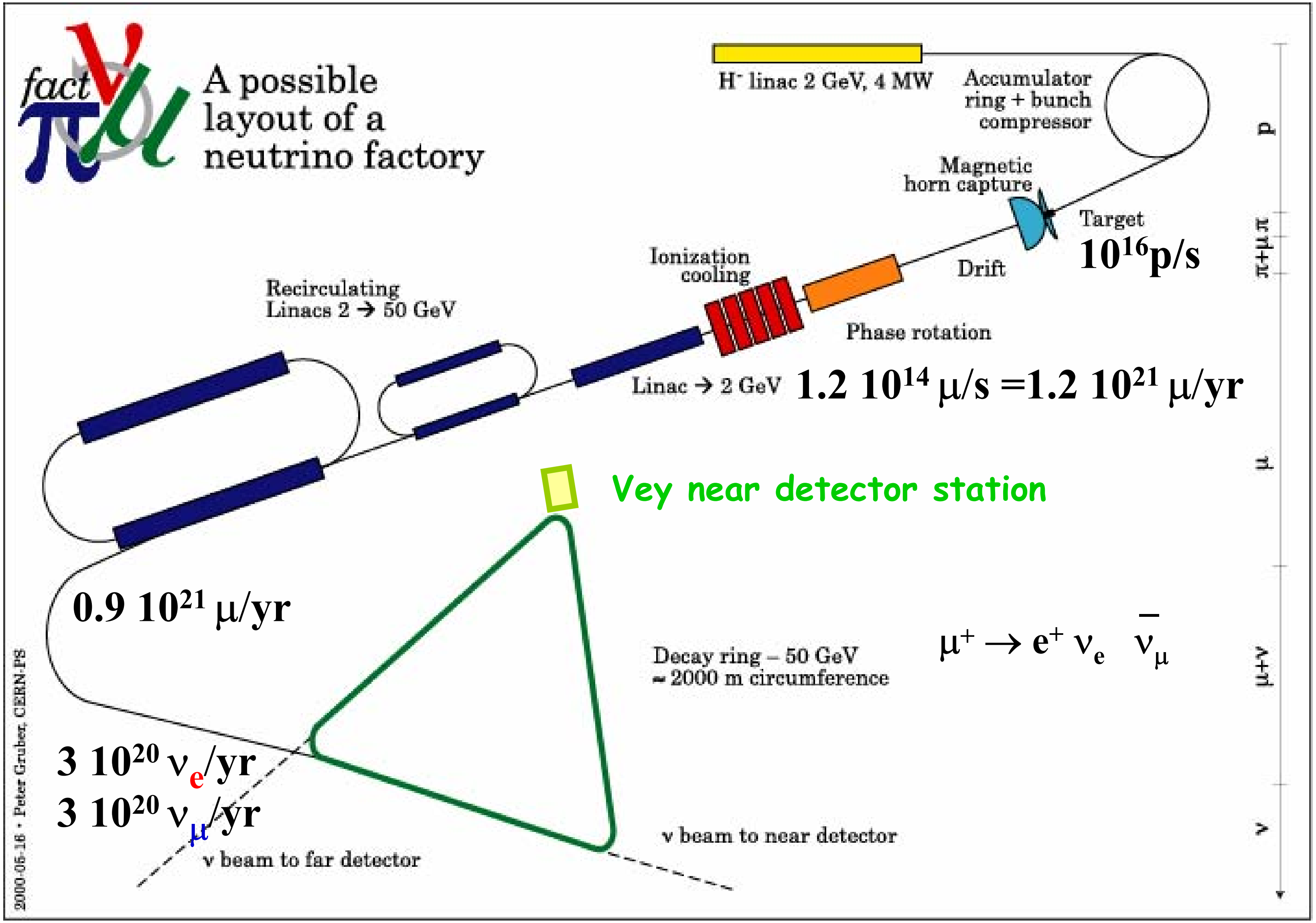
-short baseline neutrino experiments (standard fluxes $X10^4$)

-- 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:

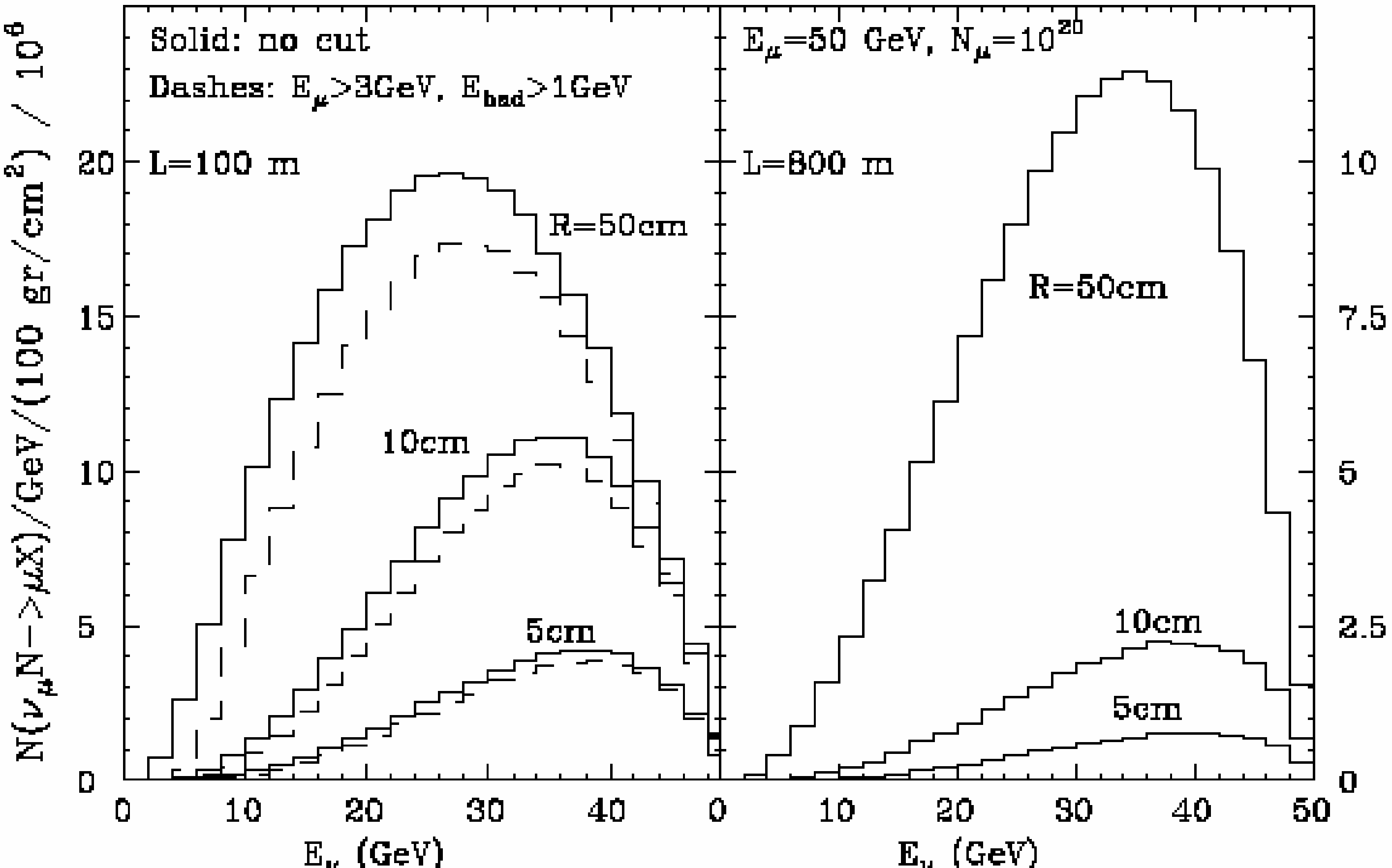
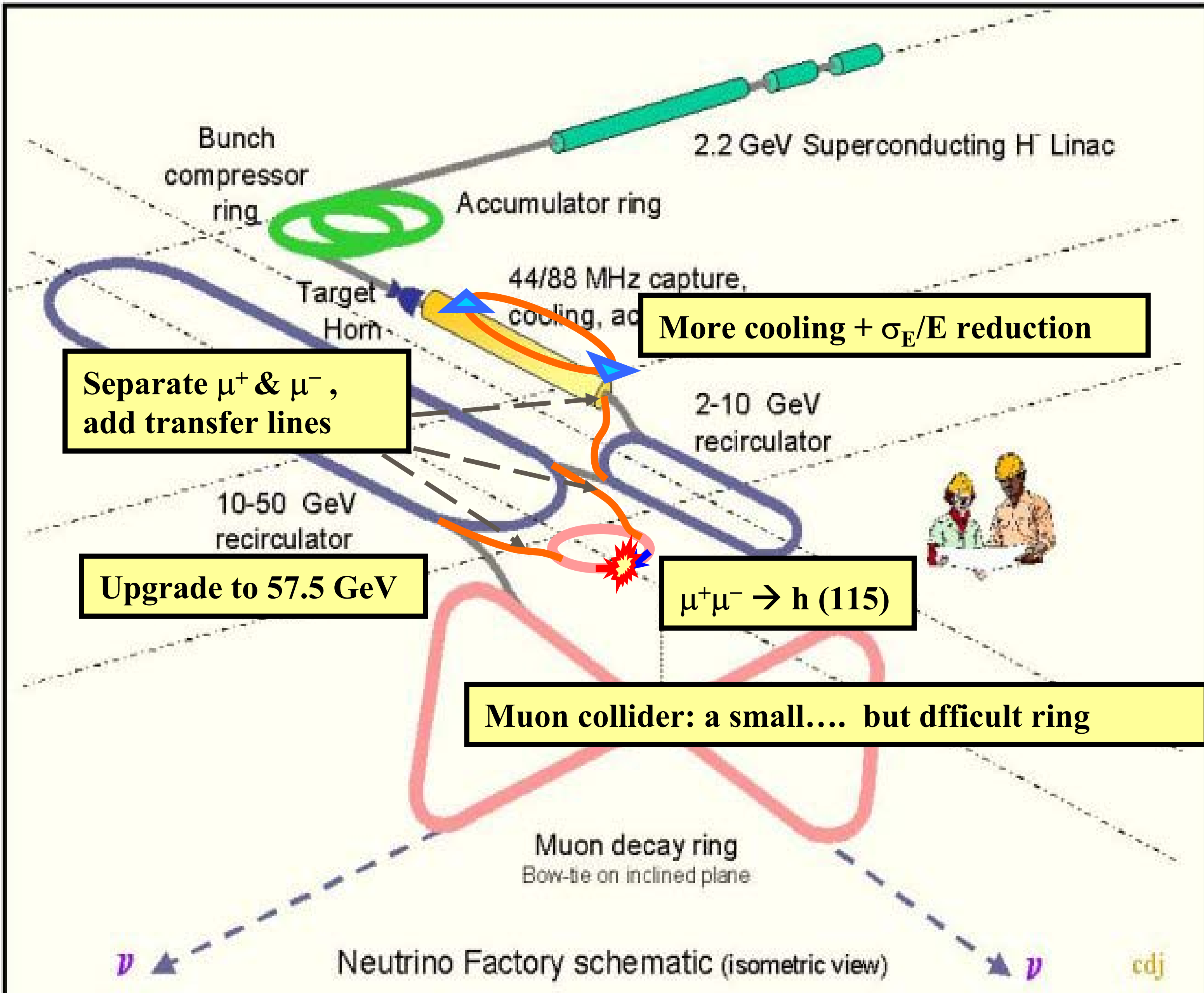


Fig. 2: CC event rates, in units of 10^6, as function of Lab-frame neutrino spectra, for several detector and beam confi gurations. The dashed lines on the left include cuts on the fi nal-state muon ($E_\mu > 3$ GeV) and on the fi nal-state hadronic energy ($E_{had} >$ 1 GeV). The solid lines have no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

From neutrino factory to Higgs collider



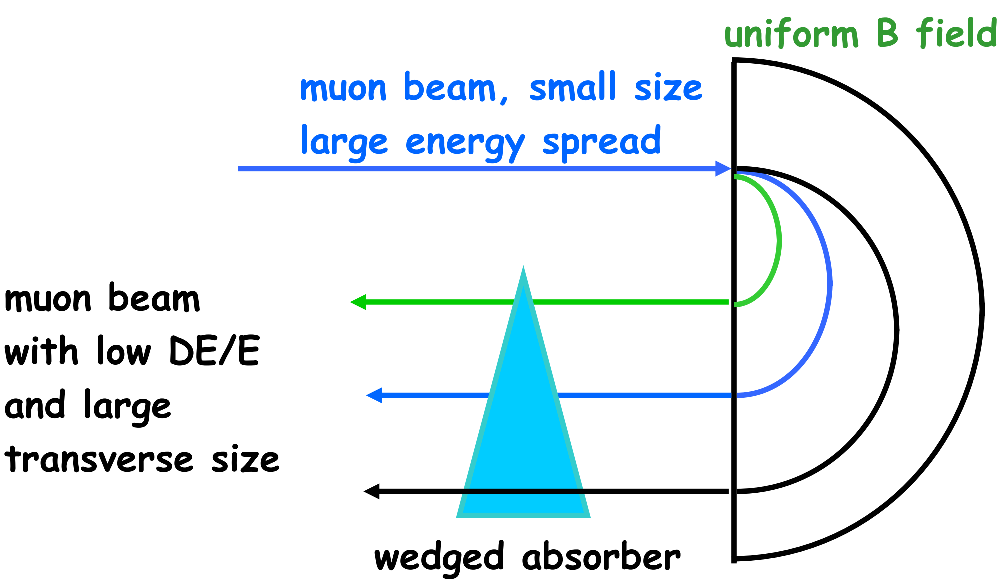
challenges of μ μ collider

$$N_{events} = \mathcal{L}.\sigma \qquad \mathcal{L} = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y}$$

Now needs not only muons but also a very small beam.

From neutrino factory to muon collider
-- keep both signs of muons
-- much more trasverse cooling
-- much better reduction of energy spread
→ ring cooler?
trade off between energy spread and transverse beam size:

f = repetition rate (frequency of crossings
N1 particles in each bunch of beam 1
N2 particles in each bunch of beam 2
$\pi \sigma_x \sigma_y$: area of beam ellipse.



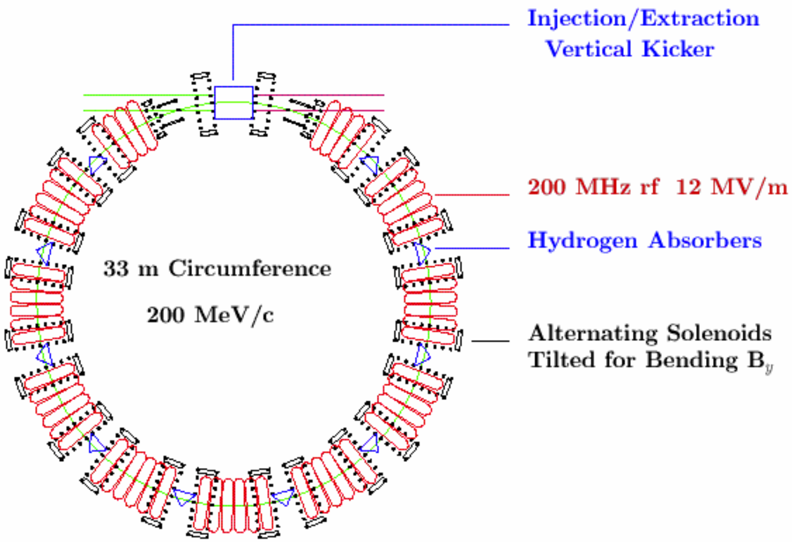
With a 4 MW proton driver; repetition rate 15 Hz:

$\delta E/E$ (%)	0.12	0.01	0.003
$\sigma_{x,y}$ (μm)	86	196	294
L ($cm^{-2}s^{-1}$)	1.2 10^{32}	2.2 10^{31}	1.0 10^{31}
$\int Ldt$/year	1.2 fb^{-1}	220 pb^{-1}	100 pb^{-1}

With 20 MW → 2.5 fb^{-1} ?

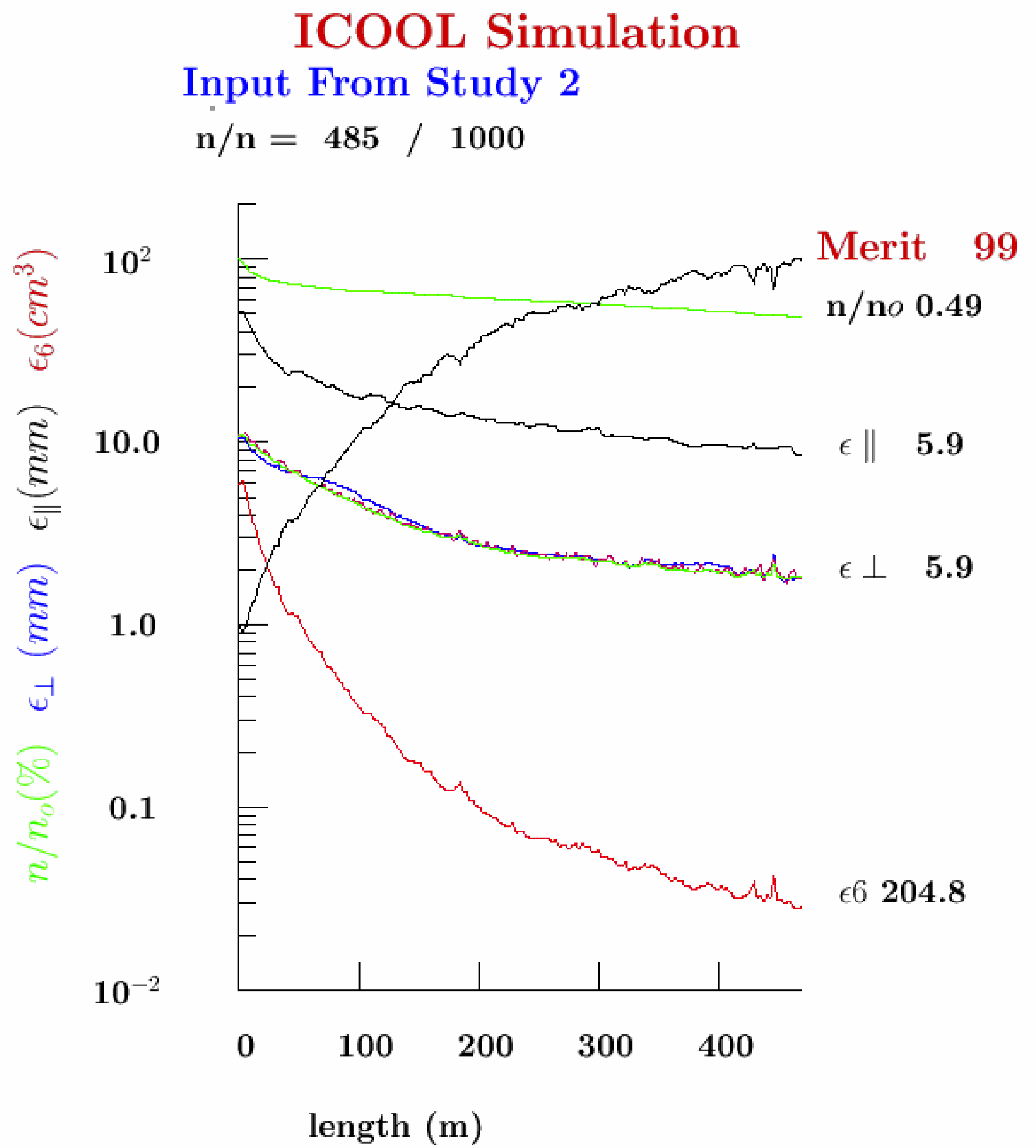
COOLING RINGS

Two goals: 1) Reduce hardware expense on cooling channel
2) Combine with energy spread reduction (longitudinal and transverse cooling)



Simple but Sinful:

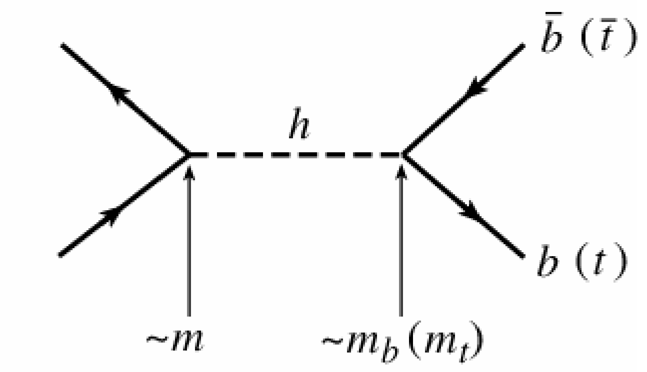
- Rf in dispersive location



major problem: Kickers

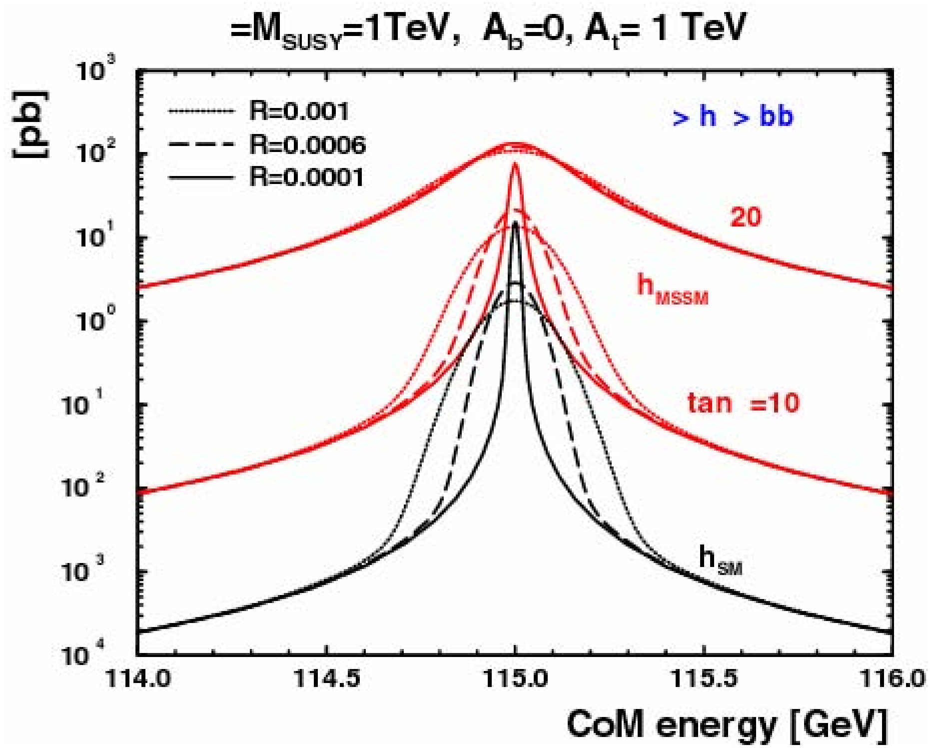
(Same problem occurs in Japanese acceleration scheme with FFAG)

Higgs factory $\mu^+ \mu^- \rightarrow h(115)$



- S-channel production of Higgs is unique feature of Muon collider
- no beamstrahlung or Synch. Rad., g-2 precession

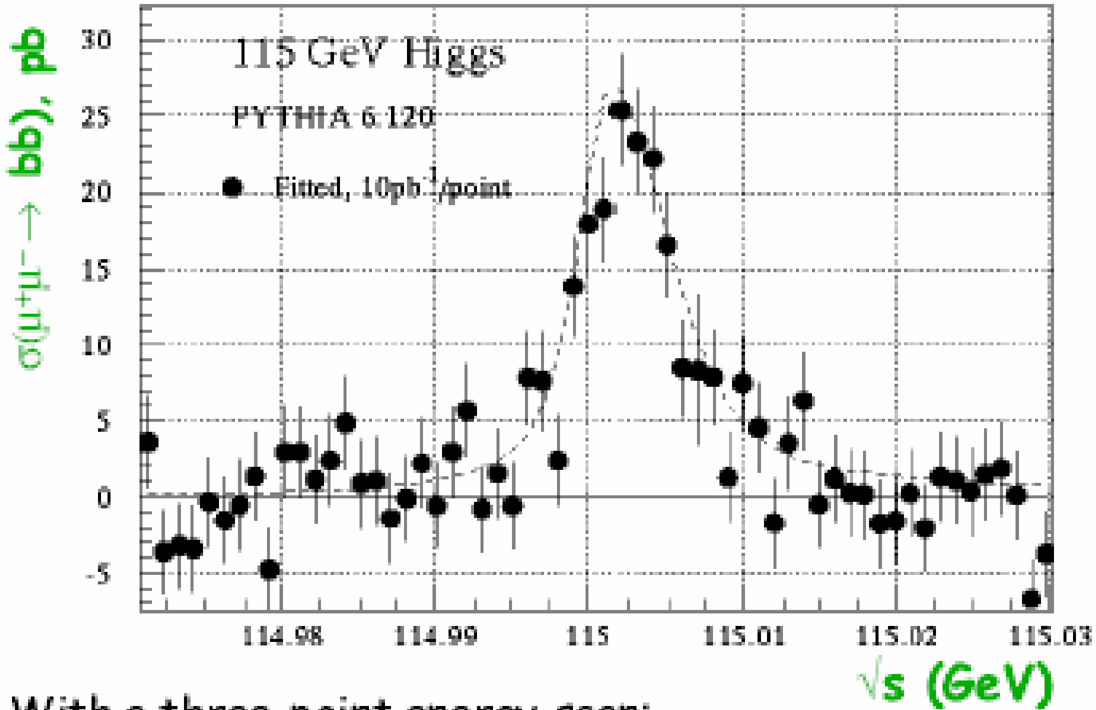
=> outstanding energy calibration (OK) and resolution R=ΔE/E (needs ideas and R&D, however!)



Δm_h=0.1 MeV
$\Delta\Gamma_h$=0.3 MeV
$\Delta\, \sigma_{h\to bb} / \sigma_h$ = 1%

very stringent constraints on Higgs couplings (μ,τ,b)

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	$\pm$ 0.1 MeV/c^2	$\pm$ 0.05 MeV/c^2
Width	$\pm$ 0.5 MeV	$\pm$ 0.1 MeV
σ_{peak}	$\pm$ 1 pb	$\pm$ 0.2 pb

Statistics limited !

Still to be tried:

A scan in $\delta E/E$

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.

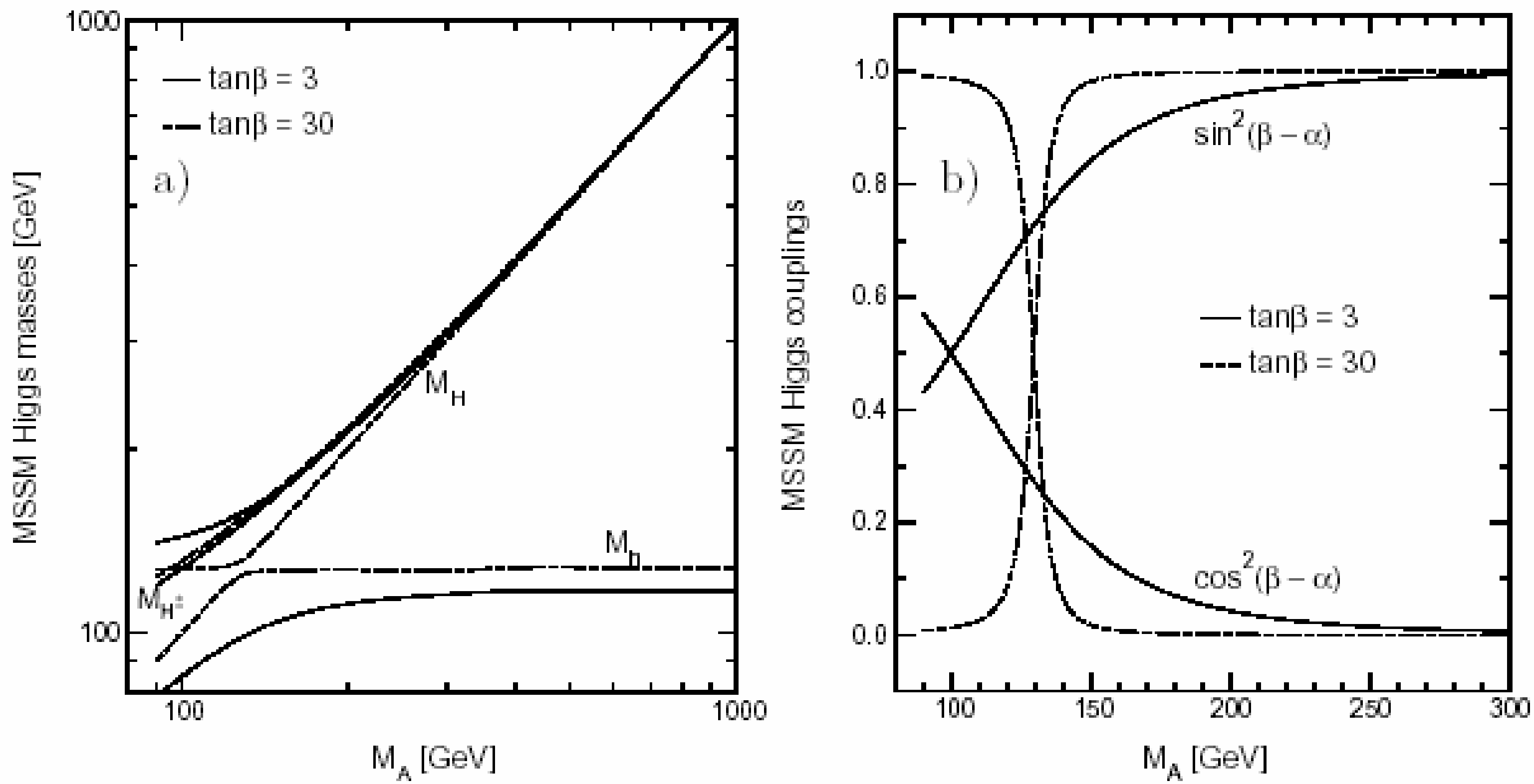
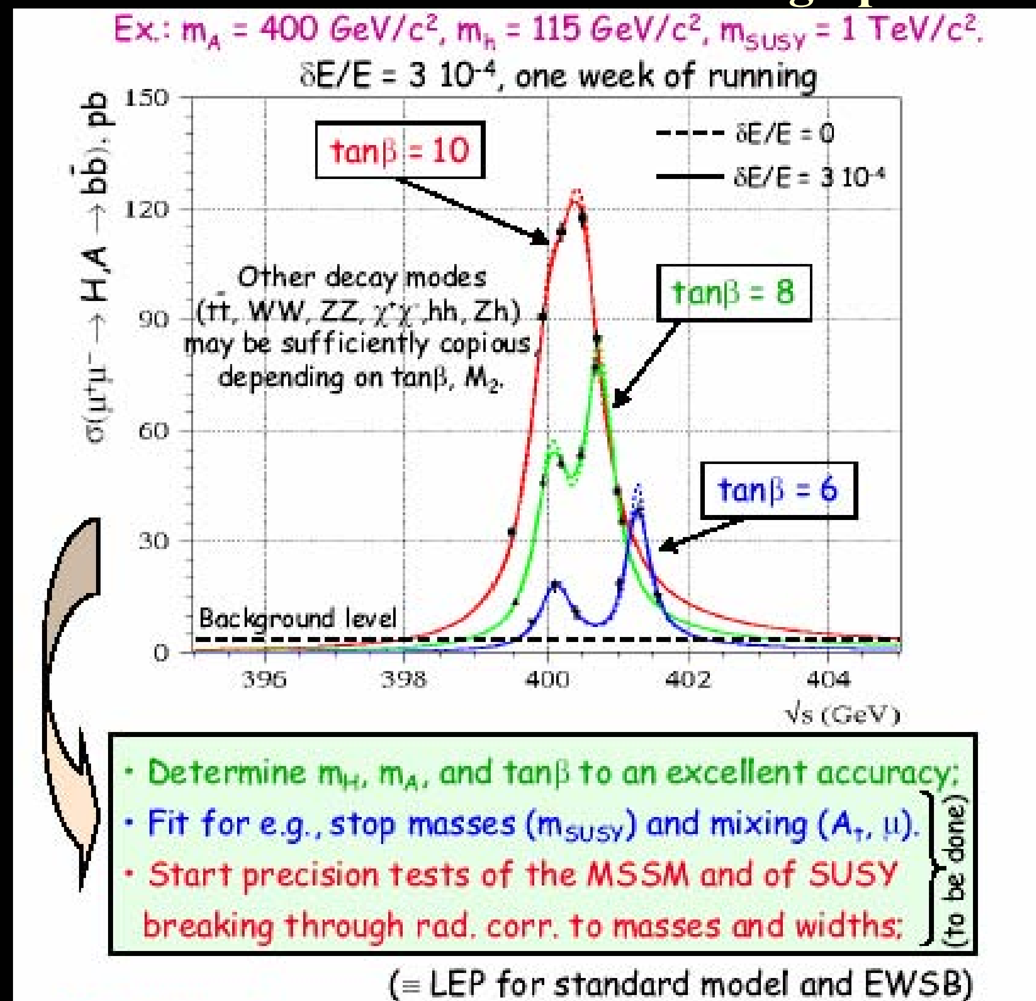


Figure 2.1.6: *The masses of the Higgs bosons in the MSSM (a) and their squared couplings to the gauge bosons (b) for two representative values of* $\tan\beta$ *= 3 and 30 [29].*

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.

Summary

The (long) road towards leptonic CP violation has begun.

Reactor and off axis experiments are being proposed/funded/approved to establish the value of θ_{13}

(Double CHOOZ, T2K,NOVA …) will come to fruition in 5- 15 years

to measure CP violation and matter effects, as well as testing unitarity and possible non-standard scenarios will require PRECISION! --> neutrinos from stored beams

These pose considerable challenges to accelerator and detector builders!

Enthusiastic R&D is ongoing, and a lot has already been accomplished (despite all the difficulties related to funding) -- much more is needed!

Many of these facilities offer other a large range of physics interests ranging from nuclear physics to rare muon decay and neutrinos -- AND… LHC upgrade…

The long term goal, LEPTONIC CP VIOLATION, makes the effort highly worthwhile

And… this is the first step towards muon colliders!