the
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international centre for theoretical physics

SMR.1508 - 25

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

PHYSICS OF FUTURE ACCELERATOR EXPERIMENTS

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Physics at future accelerator experiments

1. The questions that we ask and the energy scales at which we think they happen

2. Physics of the known fermions: Neutrino physcs
   the issues in neutrino experiments neutrino factories

2.' physics involving the GUT scale:proton decay

3. physics of the electroweak and nearby energy scale
   LHC
   the future lepton colliders

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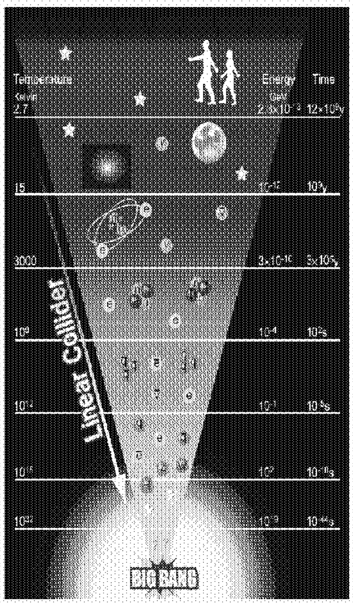
Fundamental questions in elementary particle physics

- What are the elementary constituents of matter?
- What are forces acting between them?
- How did the Universe begin and evolve?

$$d = 10^{-16}\,\text{cm} \leftrightarrow E = 10^{3}\,\text{GeV} = 1\,\text{TeV} \leftrightarrow T = 10^{16}\,\text{K} \leftrightarrow t = 10^{-12}\,\text{sec}$$



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Our current understanding =
The Standard Model **of**
elementary particle physics

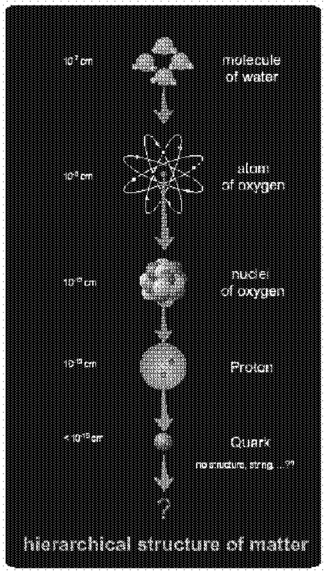
Matter :

quark	
u	d
c	s
t	b

lepton	
e	ν_e
μ	ν_μ
τ	ν_τ

Forces: gauge force

		Electro-weak force		
Forces	Strong force	Electro-magnetic force	Weak force	Gravity
Exchanged particles	Gluon	Photon	W,Z bosons	Graviton
Magnitude	1	0.01	10[illegible]	10[illegible]
	Nuclei Hadron Nuclear fusion Solar energy	Molecule, Atom Electronics Synchrotron rad. Aurora	Neutron decay Nuclei decay Neutrino Geothermy	Gravitation Galaxy Black Hole Stellar [illegible]



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Developments of the Standard Model (SM)

	quark	lepton	gauge principle	Higgs mechanism (Mass generation)
	u,d,s	**e,μ,ν**	**photon**	
1970		**" Proposal of the Standard Model "**		
	charm (SPEAR,AGS)	τ (SPEAR)		
1980	**bottom** (FNAL)		**gluon** (PETRA); **W, Z bosons** ($Sp\bar{p}S$)	
1990	**top** (TEVATRON)		**gluon-coupling** (TRISTAN); **gauge-interaction** (SLC, LEP)	
2000	**KM mechanism for CP violation** (KEKB, PEP-II)			**No experimental confirmation**

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•Unification

Supersymmetric grand unified theory, Superstring.

•Neutrino mass

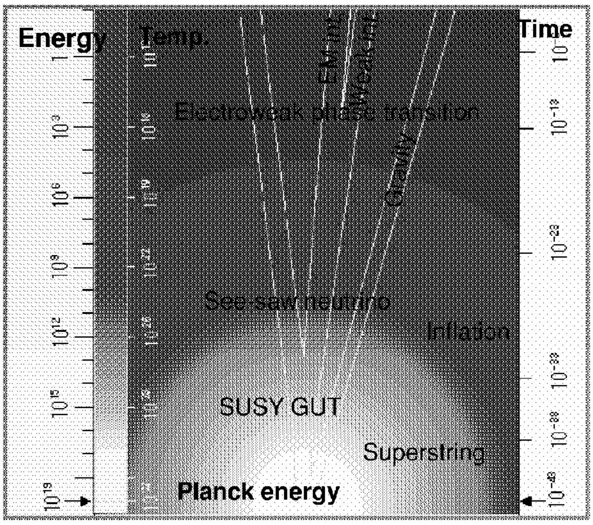
SuperKamokande, Cl,Ga, exp, K2K, SNO, KamLAND, ...

•Cosmology

Dark matter, Baryogenesis, Inflation,...

↓

Need a higher energy than 100 GeV.



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The Energy quest: pp or p$\bar{p}$ colliders

accelerator	date	E_{cm}	E_{cm} effective
ISR	1971	62GeV	~8GeV
sp$\bar{p}$s	1982	540 GeV	~90 GeV
TeVatron	1987	2 TeV	~350 GeV
LHC	2007	14 TeV	~2 TeV

factor 225 in 36 years
factor 2 in every 4.3 years (almost the same, a little faster)
discoveries: large Pt, W and Z boson, top quark

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The Energy quest: high intensity fixed target proton acc

accelerator	date	E_{cm}	E_{cm} effective
Bevatron	1955	4	~2 GeV
PS (BNL, CERN, etc..)	1959	7.5	~4 GeV
SPS	1976	28 GeV	~10 GeV
TeVatron	1972-1990	63 GeV	~15 GeV

factor 15 in 35 years: not the way to high energy!
discoveries: antiproton, many resonances, K^0 oscillations, CP violation, all three neutrinos, Neutral Currents, J/ψ, Υ, quark model, etc.. etc...

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The Energy quest: e+e- colliders

accelerator	date	E_{cm}	E_{cm} effective
e+e- ring SPEAR	1974	8 GeV	8 GeV
e+e- ring PETRA	1979	40 GeV	40 GeV
e+e- lin. SLC	1987	90 GeV	90 GeV
e+e- ring LEPI	1989	100 GeV	100 GeV
e+e- ring LEPII	1996	200 GeV	200 GeV
e+e- lin. WorldLC	201X	800 GeV	800 GeV

22 years for a factor 25 .... when will we reach 10^{15} GeV?

A. 220 years or so, if it is a factor 2 every so many(5) years.

B. And this involve a lot of R&D on accelerators.

discoveries: J/ψ & charmonia, gluon, tau lepton
precise measurements of b-system (still at it with b factories)
and of the Z and W boson! Best limit on the Higgs so far.

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Physics with accelerators can be broadly devided in two classes

1. physics at the present energy frontier
presently: the Electroweak scale and the Higgs boson (generation of W and Z masses)

2. precise measurements of properties of already known particles/interactions
(K, B, muon, neutrinos, tests of QED, SM, QCD)
Neutrinos are, today, the most interesting because their mass
(and mixing process) seem to originate in very high energies (see-saw mwchanism)

These lectures will begin with a novel type of accelerator that is being developped conceptually now: neutrino sources with storage rings

➔ neutrino factory and beta beams

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neutrino definitions

the electron neutrino is present in association with an electron (e.g. beta decay)

the muon neutrino is present in association with a muon (pion decay)

the tau neutrino is present in association with a tau ($W \to \tau\nu$ decay)

these flavor-neutrinos are not (as we know now) quantum states of well defined mass (neutrino mixing)

the mass-neutrino with the highest electron neutrino content is called ν_1

the mass-neutrino with the next-to-highest electron neutrino content is ν_2

the mass-neutrino with the smallest electron neutrino content is called ν_3

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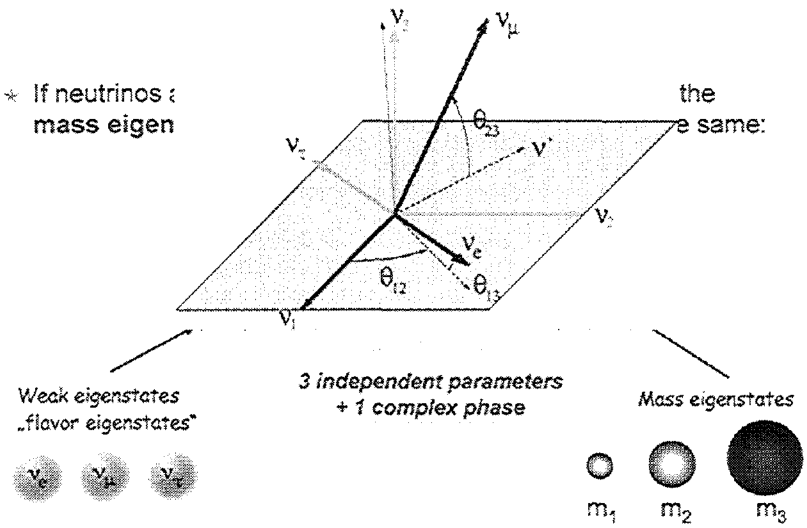
Lepton Sector Mixing

⋆ If neutrinos … the mass eigen… …e same:



Pontecorvo 1957

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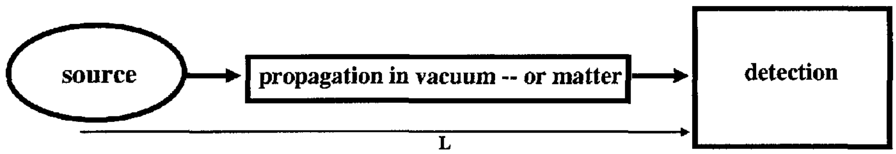
Neutrino Oscillations (Quantum Mechanics lesson 5)



weak interaction produces 'flavour' neutrinos

e.g. pion decay $\pi \to \mu\nu$

$|\nu_\mu\rangle = \alpha|\nu_1\rangle + \beta|\nu_2\rangle + \gamma|\nu_3\rangle$

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = \alpha|\nu_1\rangle \exp(i E_1 t) + \beta|\nu_2\rangle \exp(i E_2 t) + \gamma|\nu_3\rangle \exp(i E_3 t)$$

t = proper time ∝ L/E

weak interaction: (CC)

$\nu_\mu N \to \mu^- X$

or $\nu_e N \to e^- X$

or $\nu_\tau N \to \tau^- X$

$$P(\mu \to e) = |\langle \nu_e | \nu(t)\rangle|^2$$

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Oscillation Probability

- The case with two neutrinos:
  - →A mixing angle: θ
  - →A mass difference:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\Delta m^2 = m_2^2 - m_1^2$$

- The oscillation probability is:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

where L = distance between source and detector
E = neutrino energy

Hamiltonian= E = sqrt($p^2 + m^2$ ***) = p +*** $m^2 / 2p$
for a given momentum, eigenstate of propagation in free space are the mass eigenstates!

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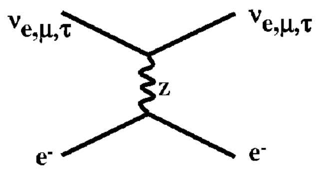
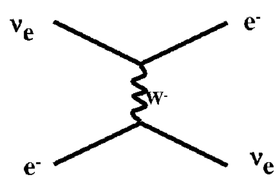
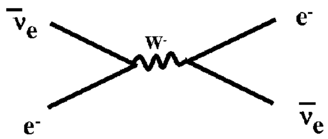
To complicate things further:
matter effects
elastic scattering of (anti) neutrinos on electrons



all neutrinos and anti neutrinos do this equally



only electron neutrinos



only electron anti- neutrinos

These processes add a forward amplitude to the Hamiltonian, which is proportional to the number of elecrons encountered to the Fermi constant and to the neutrio energy.
The Z exchange is diagonal in the 3-neutrino space
this does not change the eigenstates
The W exchange is only there for electron neutrinos
It has opposite sign for neutrinos and anti-neutrinos (s vs t-channel exchange)

$D = \pm 2\sqrt{2}\, G_F n_e E_\nu$ **THIS GENERATES A FALSE CP VIOLATION**

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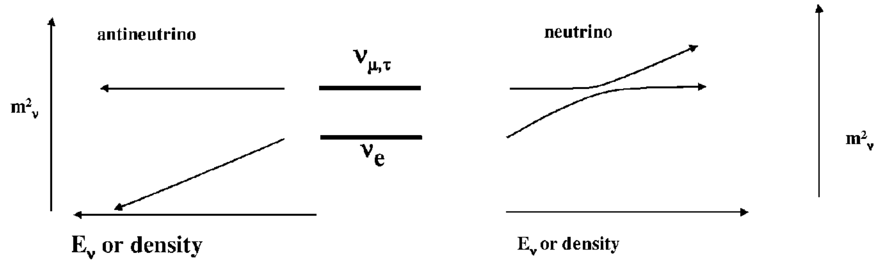
$$D = \pm 2\sqrt{2}\, G_F\, n_e E_\nu$$

$$\mathbf{H}_{\text{flavour base}} = U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} D & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

This is how YOU can solve this problem: write the matrix, diagonalize, and evolve using, $i\frac{\partial\psi}{\partial t} = H\psi$

This has the effect of modifying the eigenstates of propagation!
Mixing angle and energy levels are modified, this can even lead to level-crossing. ***MSW effect***



oscillation is further suppressed | **resonance… enhances oscillation**

oscillation is **enhanced** for **neutrinos if $\Delta m^2_{1x} > 0$**, and suppressed for antineutrinos
oscillation is **enhanced** for **antineutrinos if $\Delta m^2_{1x} < 0$**, and suppressed for neutrinos

since **T asymmetry** uses neutrinos it **is not affected**

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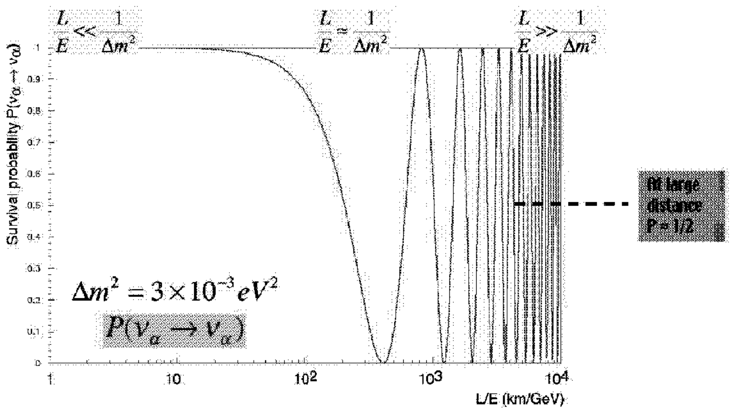
Oscillation Phenomena



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General framework:

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 neutrino (ν_μ –>) oscillations are established *(IMB+Kam+SK+Macro+Sudan)*
4. At that frequency, electron neutrino oscillations are small *(CHOOZ)*

This allows a consistent picture with 3-family oscillations
preferred:
LMA: θ_{12} ~30^0 $\Delta m_{12}{}^2$~7 $10^{-5}eV^2$, θ_{23} ~45^0 $\Delta m_{23}{}^2$~ ±2.5 $10^{-3}eV^2$, θ_{13} <~ 10^0
with several unknown parameters
=> an exciting experimental program for at least 25 years *)
including **leptonic CP & T violations**

5. There is indication of possible higher frequency oscillation (LSND) to be confirmed (miniBooNe)
This is not consistent with three families of neutrinos oscillating, and is not supported
(nor is it completely contradicted) by other experiments.
(Case of an unlikely scenario which hangs on only one not-so-convincing experimental result)
If confirmed, this would be even more exciting

(I will not explore this here, but this has been done. See *Barger et al PRD 63 033002*)

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

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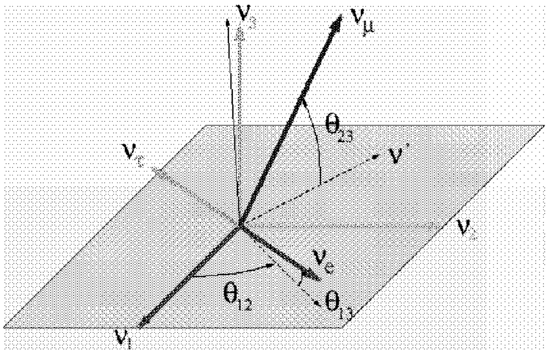
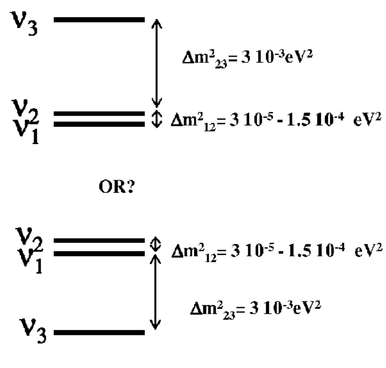
The neutrino mixing matrix: 3 angles and a phase δ



θ_{23} (atmospheric) = 45^0, θ_{12} (solar) = 30^0, 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}

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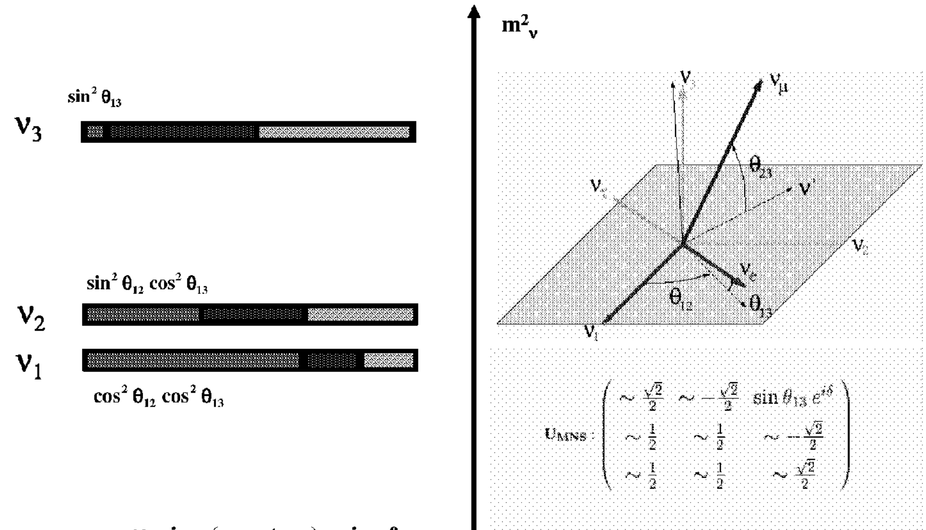
neutrino mixing (LMA, natural hierarchy)



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)

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

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

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

... need large values of $\sin\theta_{12}$, Δm^2_{12} (LMA) but *not* large $\sin^2\theta_{13}$
... need APPEARANCE ... $P(\nu_e \rightarrow \nu_e)$ 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 $\nu_e \rightarrow \nu_\mu$, ν_τ
... asymmetry is opposite for $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$

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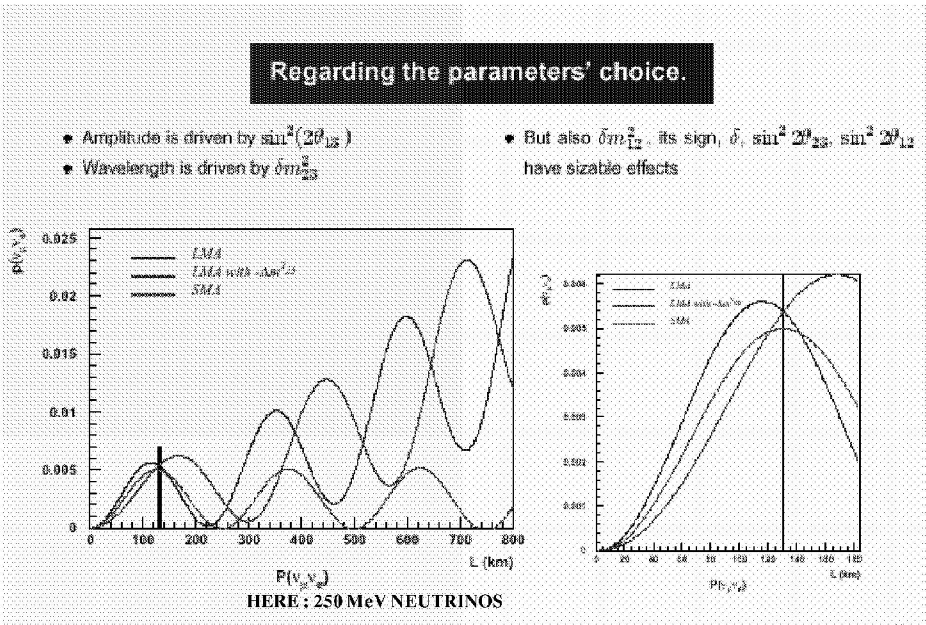

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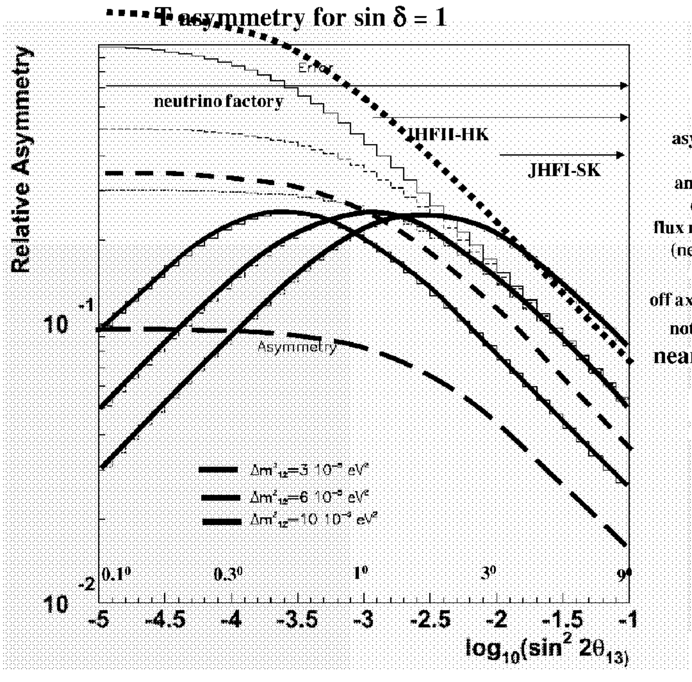

!
asymmetry is a few % and requires excellent flux normalization (neutrino fact. or off axis beam with not-too-near near detector)
!

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Road Map

Experiments to find θ_{13} :

1. **search for $\nu_\mu \to \nu_e$ in conventional ν_μ beam (ICARUS, MINOS)**
   limitations: NC π^0 background, intrinsic ν_e component in beam
2. **Off-axis beam (JHF-SK, off axis NUMI, off axis CNGS) or**
3. **Low Energy Superbeam**

Experiments to find CP violation or to search further if θ_{13} is too small

1. **Neutrino factory with muon storage ring**
   $\mu^+ \to e^+ \nu_e \ \bar{\nu}_\mu$ and $\mu^- \to e^- \bar{\nu}_e \ \nu_\mu$
2. **beta-beam** $\quad {}^6He^{++} \to {}^6Li^{+++} \bar{\nu}_e e^- \qquad {}^{18}_{10}Ne \to {}^{18}_{9}F \nu_e e^+$

fraction thereof will exist.

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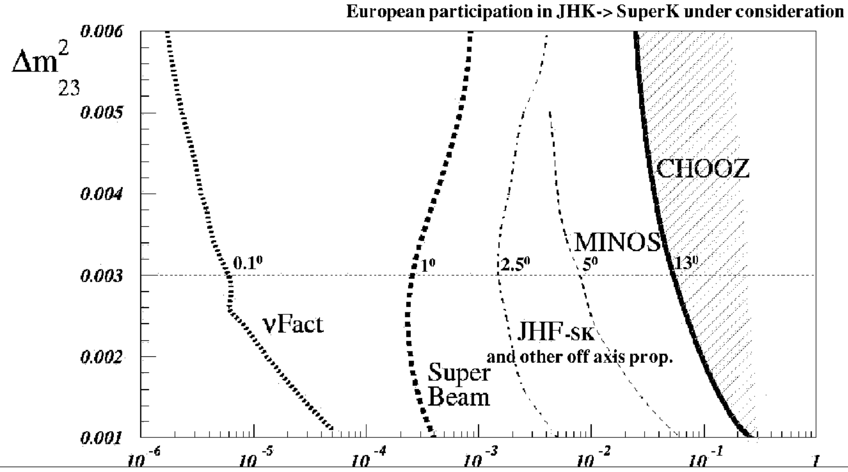
Where will this get us...

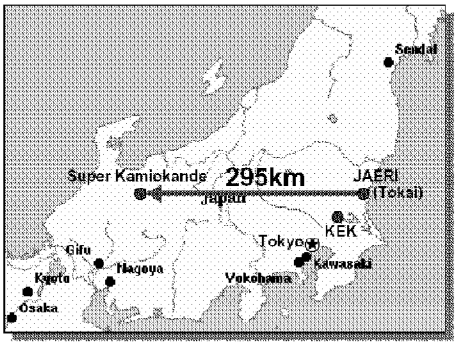
European participation in JHK-> SuperK under consideration



comparison of reach in the oscillations; right to left:
present limit from the CHOOZ experiment,
expected sensitivity from the MINOS experiment,
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
from a Neutrino Factory with 40 kton large magnetic detector. INCLUDING SYSTEMATICS

JHF → Super-Kamiokande

- 295 km baseline
- JHF approved
- neutrino beam under discussion but set as first priority by international committee
- Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent e/μ ID -- 10^{-3}
  - Additional π^0/e ID -- 10^{-2}
  - (for $E_\nu \sim$ 500 MeV- 1 GeV)
- Matter effects small
- need near detector
- European collaboration forming (UK(5)-Italy(5)-Saclay-Gva-SP(2))



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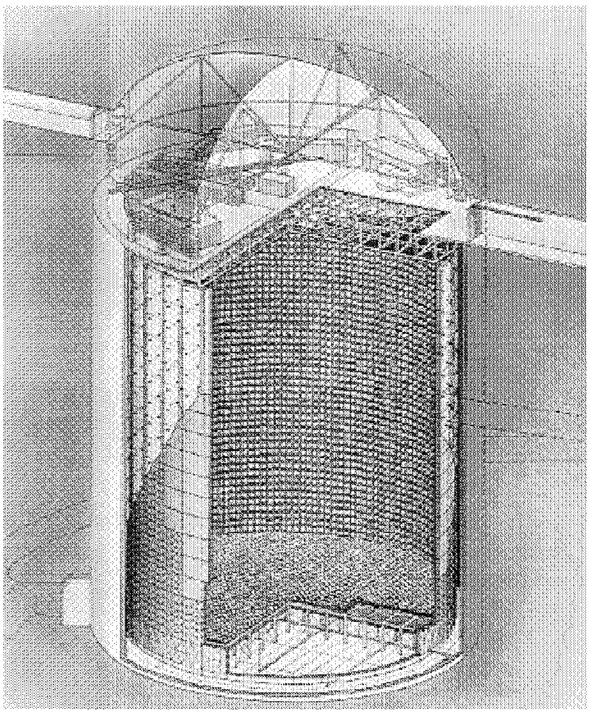
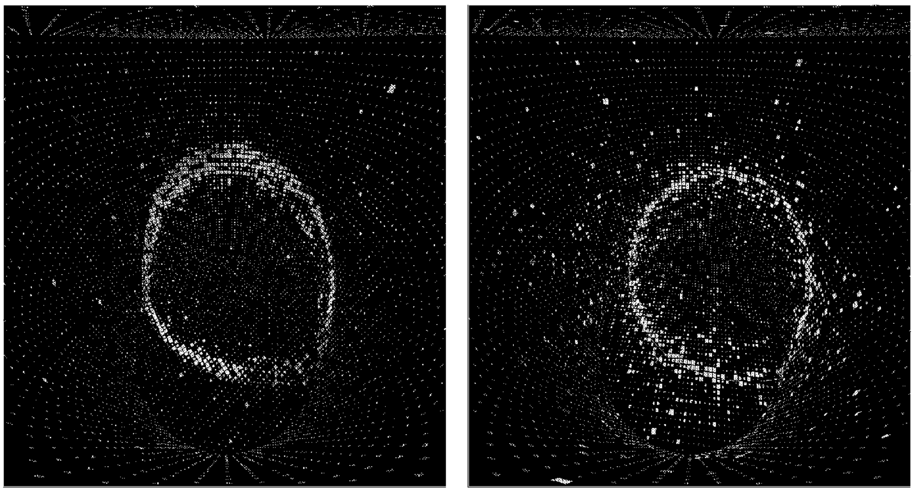
Detector Phase I:
the Super Kamiokande Detector



μ/e Background Rejection

e/mu separation directly related to granularity of coverage.
Limit is around 10^{-3} (mu decay in flight) SKII coverage OKOK, less maybe possible



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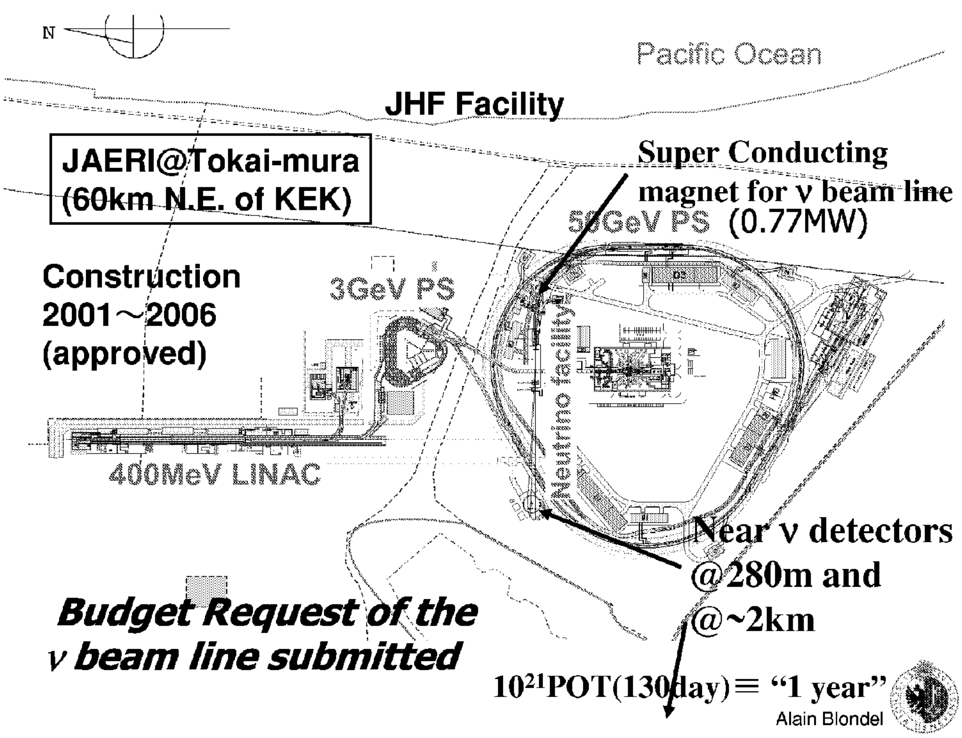

10^{21}POT(130day)≡ "1 year"

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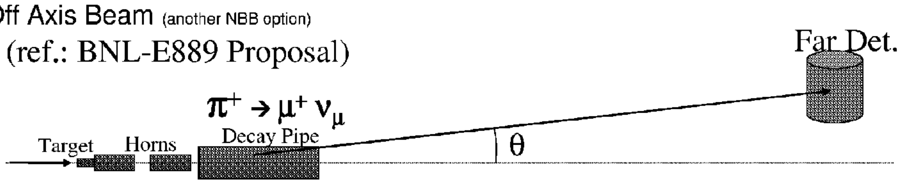
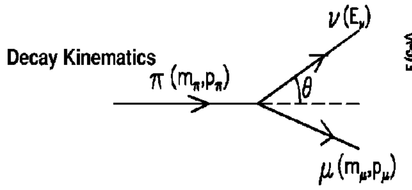
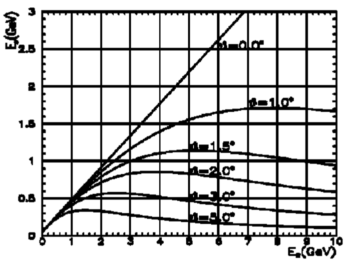
Off Axis Beam (another NBB option)
(ref.: BNL-E889 Proposal)



WBB w/ intentionally mi saligned beam line from det. axi s



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



◆**Quasi Monochromatic Beam**
◆**x2~3 intense than NBB**

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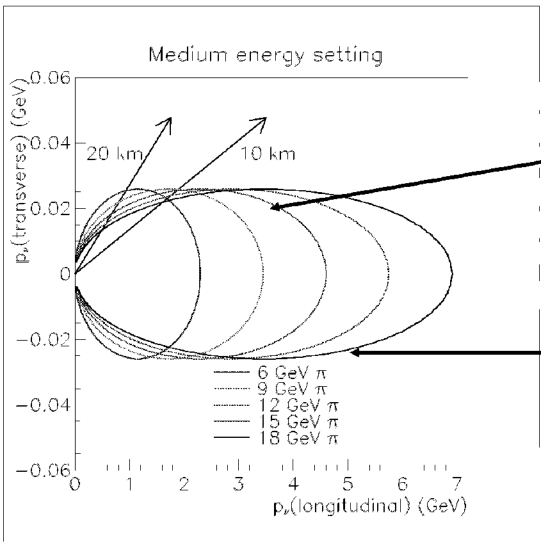
Two body decay kinematics:case of 734 km (NUMI)



At this angle, 15 mrad, energy of produced neutrinos is 1.5-2 GeV for all pion energies ➔ very intense, narrow band beam

'On axis': $E_\nu = 0.43 E_\pi$

$$p_L = \gamma(p^* \cos\theta^* + \beta E^*)$$
$$p_T = p^* \sin\theta^*$$

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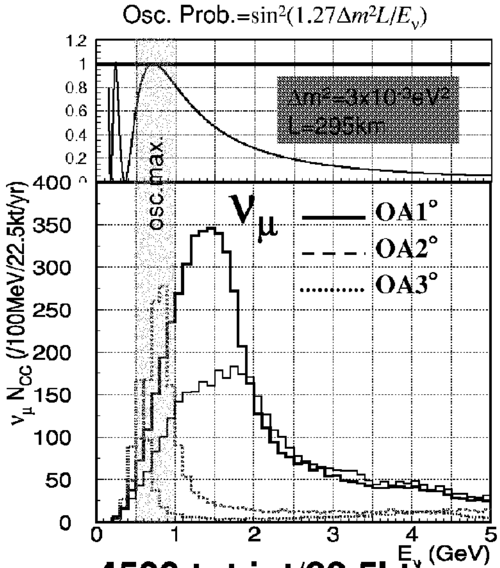
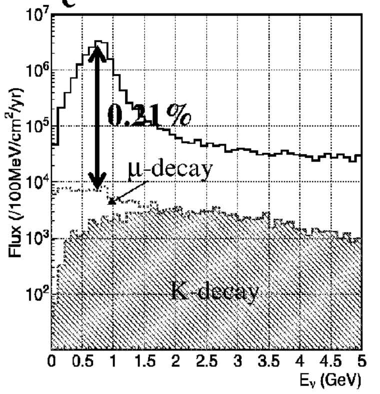
Expected spectrum



ν_e contamination



~4500 tot int/22.5kt/yr
~3000 CC int/22.5kt/yr

Very small ν_e/ν_μ @ ν_μ peak

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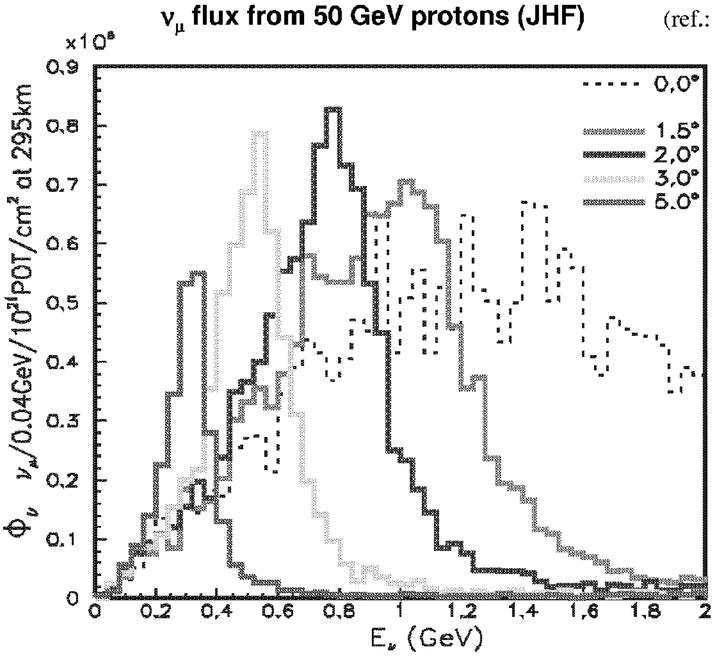
High intensity narrow band beam: Off-axis (OA) beam

ν_μ flux from 50 GeV protons (JHF) (ref.: BNL-E889 Proposal)



Increase statistics @ osc. max.

Decrease bkg from HE tail

Tunable by varying beam angle (or: detector position?)

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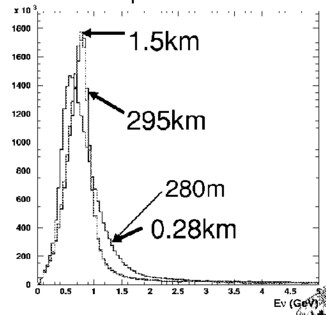
Detectors at near site

- **Muon monitors @ ~140m**
  - Behind the beam dump
  - Fast (spill-by-spill) monitoring of beam direction/intensity
- **First Front detector** "Neutrino monitor" @280m
  - Intensity/direction
  - Neutrino interactions
- **Second Front Detector @ ~2km**
  - **Almost same E_ν spectrum as for SK**
  - Absolute neutrino spectrum
  - Precise estimation of background
  - **Investigating possible sites**

Neutrino spectra at diff. dist



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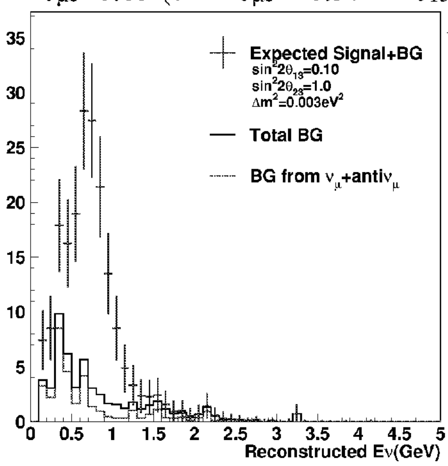
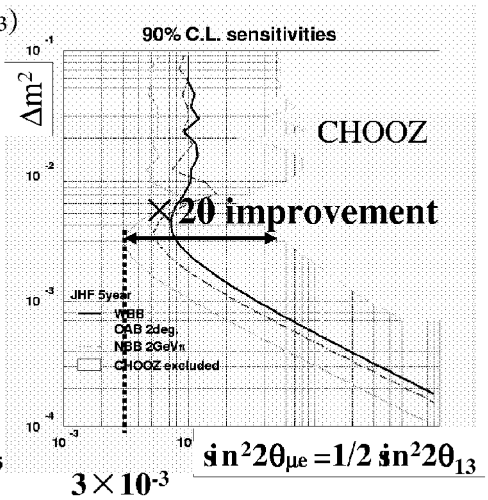
ν_e appearance (continue)

$\sin^2 2\theta_{\mu e} = 0.05$ ($\sin^2 2\theta_{\mu e} \equiv 0.5 \sin^2 2\theta_{13}$)





$\sin^2 2\theta_{13} < 0.006$ (90% C.L.)

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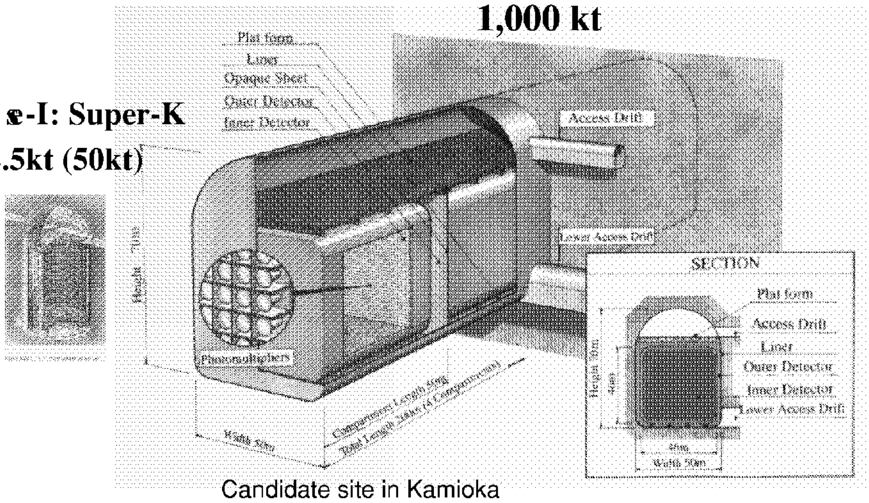
Far detector in second phase

Phase-II: Hyper-K 1,000 kt

Phase-I: Super-K 22.5kt (50kt)



Candidate site in Kamioka

Other major goal: improve proton decay reach

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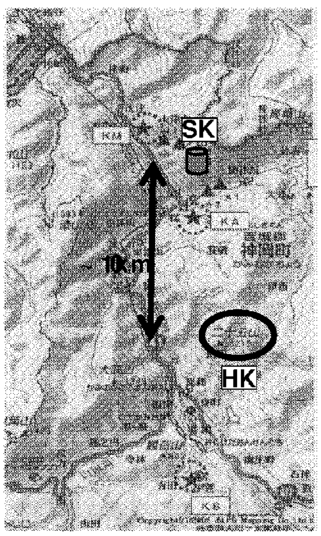
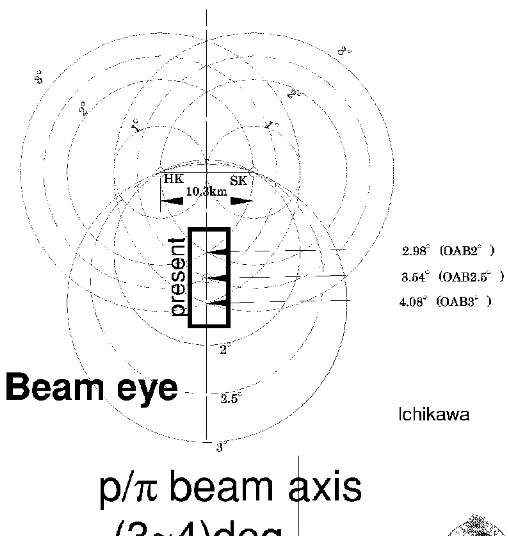
Decay pipe common for SK/HK

Possible site for Hyper-K





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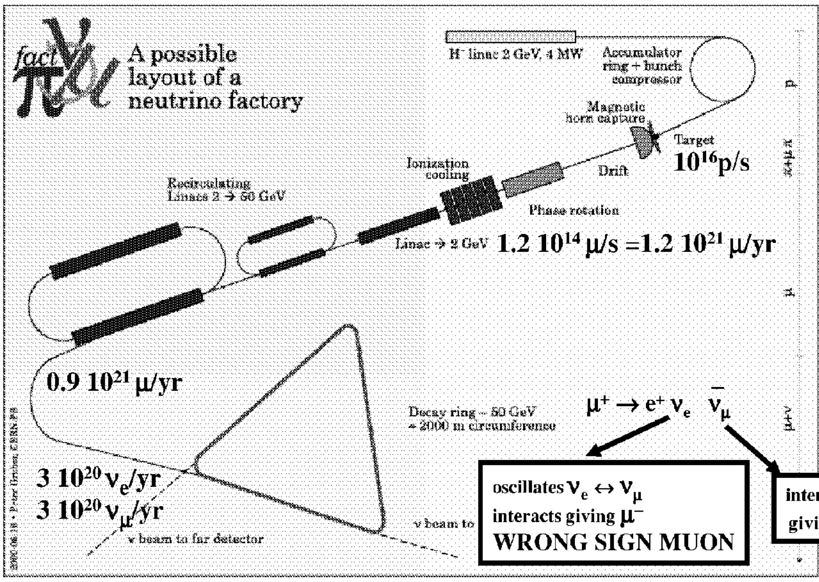
-- Neutrino Factory --
CERN layout



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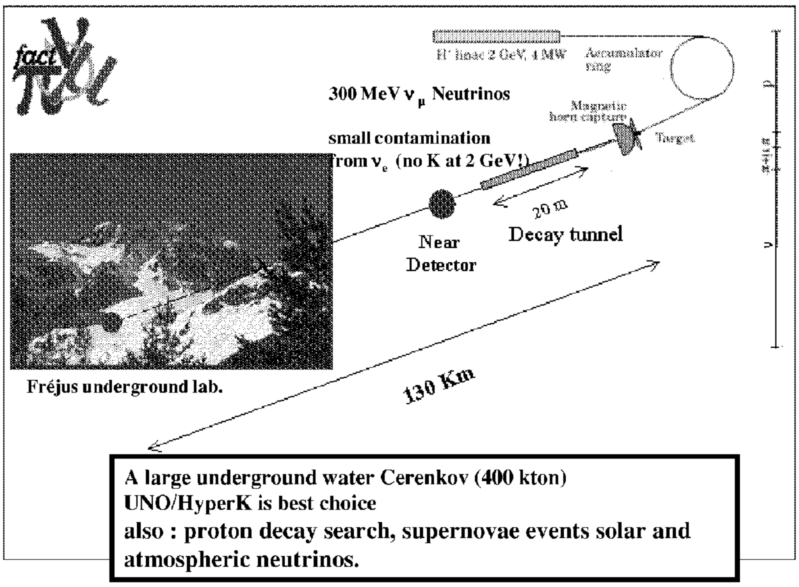
Possible step 0: Neutrino SUPERBEAM



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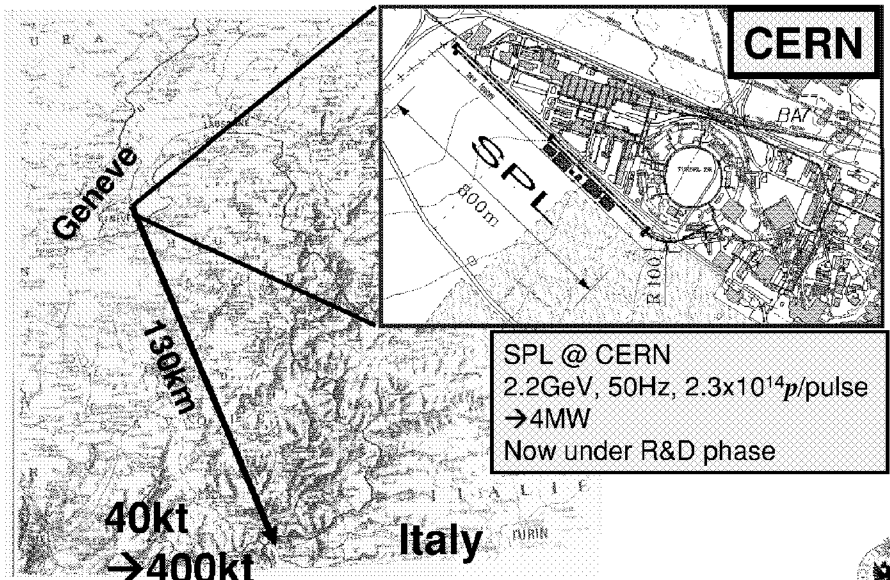
Europe: SPL→Furejus



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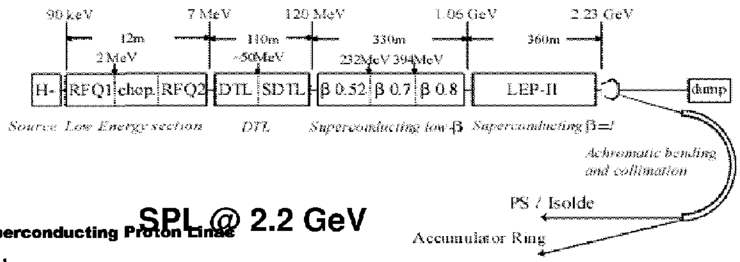

SPL @ 2.2 GeV

Superconducting Proton Linac

- High power
  - LINAC @ 4 MW
  - Rep. Rate 50 Hz
  - 2.27 10^{14} p/pulse spaced by 22.7 nsec (44 MHz)
- Reuse of LEPII cavities or cryostat (LEP IS NOT DEAD)
- Single turn μ injection in storage ring (2000 m):
  - proton burst < 6 μs → Linac 2.8 ms
  - duty cycle for neutrino beam →**Accumulator Needed**

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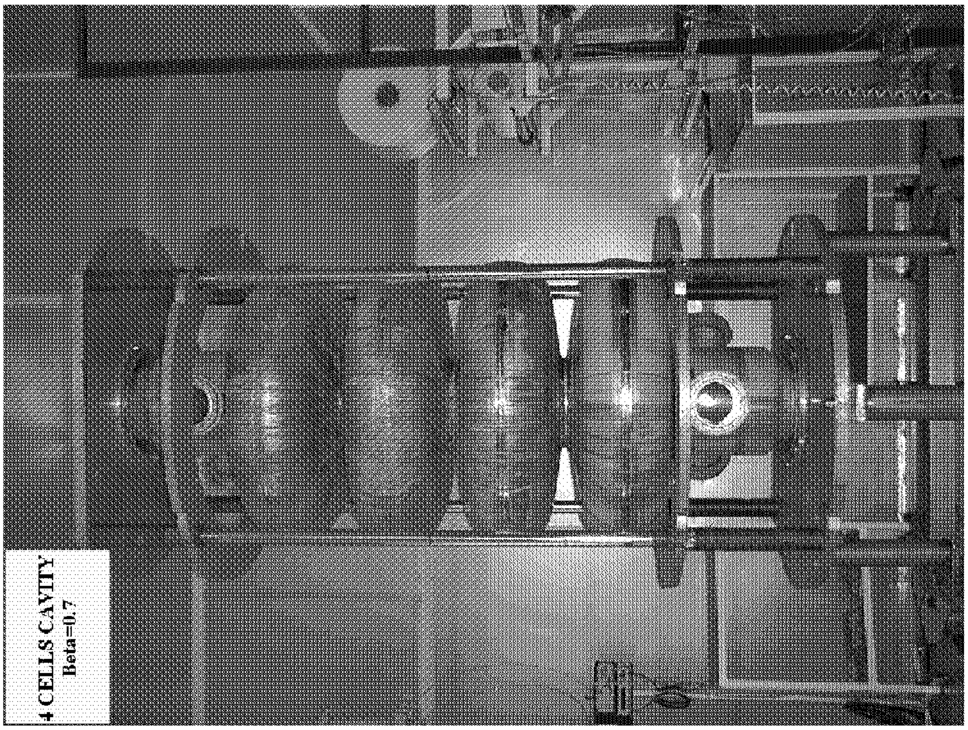
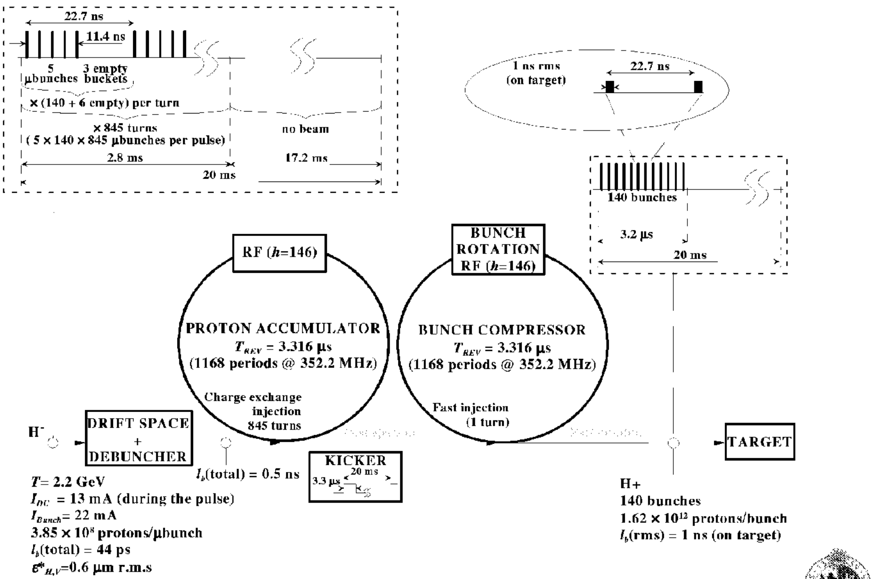


Accumulator compressor scheme



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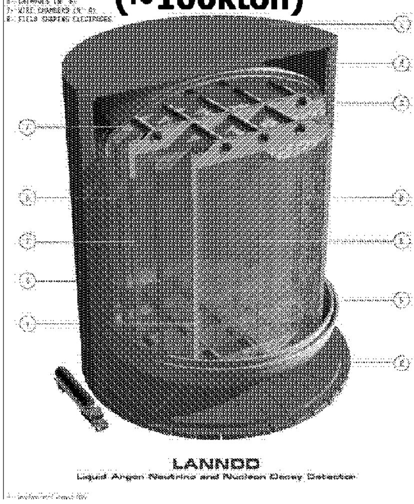
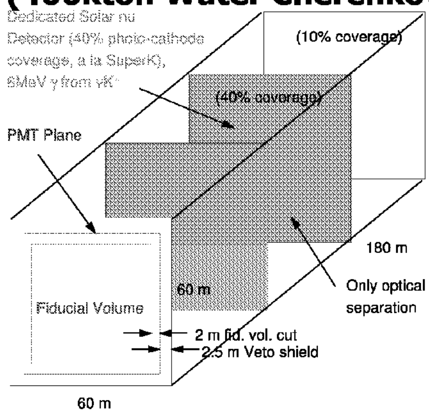
Detectors

Liquid Ar TPC (~100kton)



UNO (400kton Water Cherenkov)



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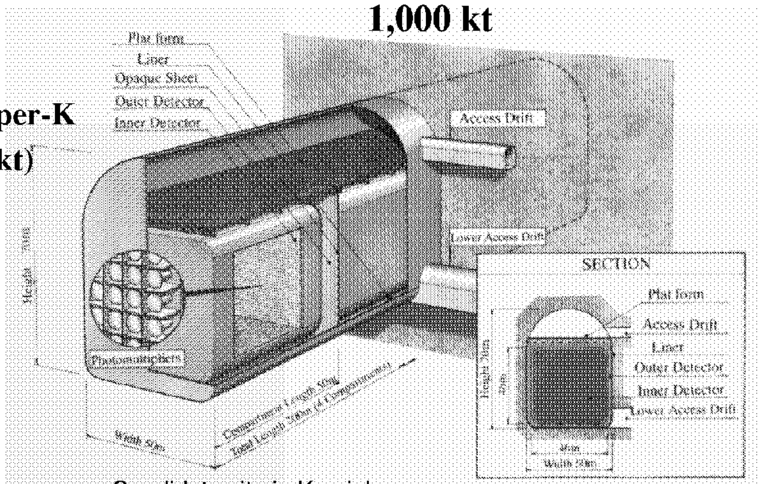
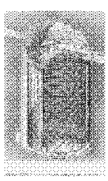
Far detector in second phase

limit to the size of large underground Water Cherenkov detectors will be given by the difficulties of excavation. Max width is about 50-60 meters.=> increase high&length

Phase-II: Hyper-K
1,000 kt



Phase-I: Super-K
22.5kt (50kt)



Candidate site in Kamioka

Other major goal: improve proton decay reach

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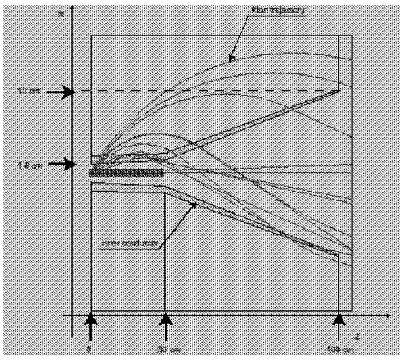
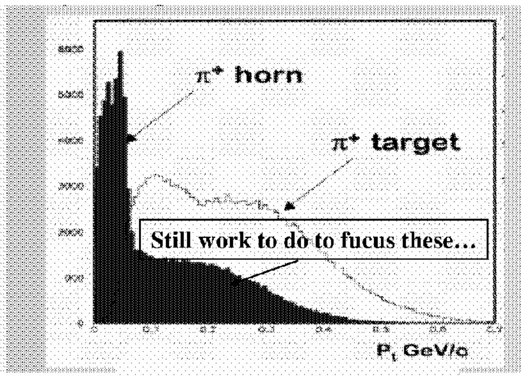
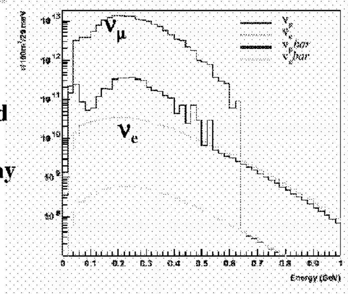
SPL neutrino beam





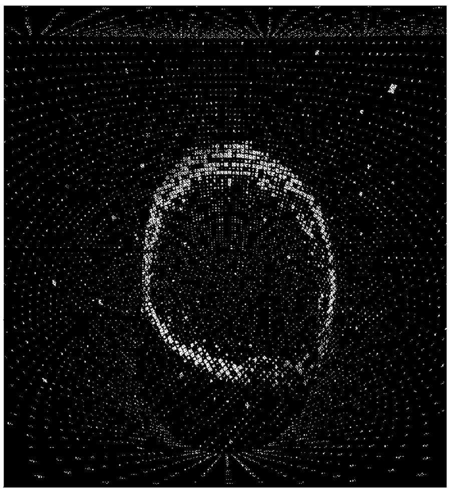


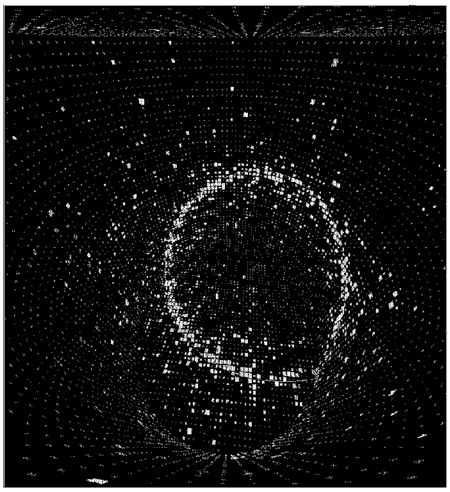
* At 2 GeV, K production is very small
⇒Bkg of from ν_e in the beam is small and dominated by muon decay
This can be tailored by varying the length of the decay tunnel and reduced to 0.3-0.4 % (all spectrum)

* this is a low energy beam ($<E_\nu>$ = 300 MeV)

μ/e Background Rejection

e/mu separation directly related to granularity of coverage.
Limit is around 10^{-3} (mu decay in flight) SKII coverage OKOK, less maybe possible





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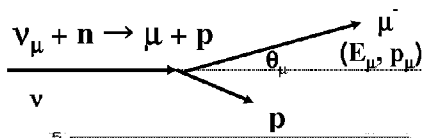
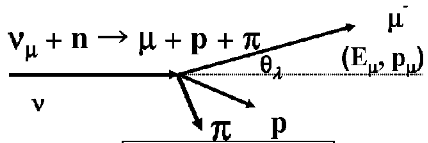
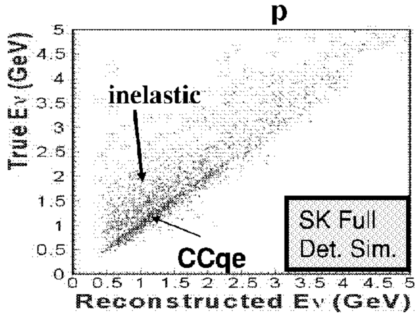
E_ν reconstruction < 1GeV region

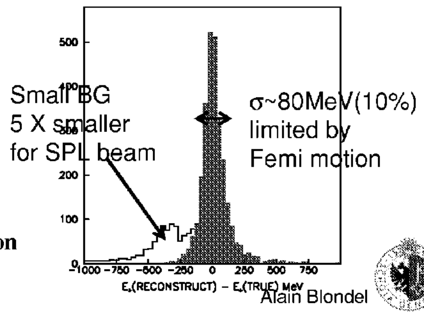
CC quasi elastic reaction $\Leftrightarrow$ $E_\nu = \dfrac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$





Inelastic (BG)





Energy can be well reconstructed =>Bkg reduction
⇒precise measurement of osc. params
⇒ SENSITIVITY SIMILAR TO JHF-> HyperK

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BETA Beam

new idea by P. Zucchelli

produce $^6He^{++}$, store, accelerate (100 GeV/u), store

$$^6He^{++} \rightarrow {}^6Li^{+++}\ \bar{\nu}_e\ e^-$$

Q=3.5078 MeV T/2 = 0.8067 s
pure anti-ν_e beam at ≈ 600 MeV

or:

$$^{18}_{10}Ne \rightarrow {}^{18}_{9}F\ \nu_e\ e^+$$

pure ν_e beam at ≈ 600 MeV

oscillation signal: appearance of low energy muons
no opposite charge neutrinos=> no need for magnetic detectors
little matter effects at these energies
water Cerenkov excellent for this too, same as for Superbeam.
seems feasible; but cost unknown so far.
Critical: duty cycle.

A nice * idea to be followed up!**

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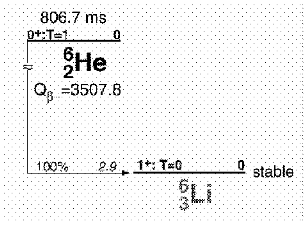
Anti-Neutrino Source



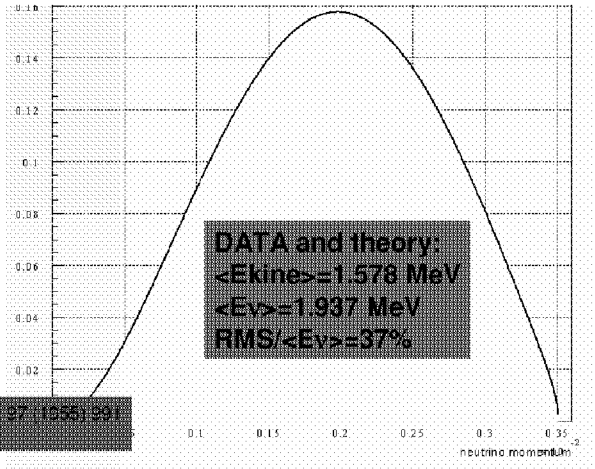
Consider $^{6}He^{++} \to {}^{6}Li^{+++}\ \overline{\nu}_e\ e^-$

$E_0 \approx 3.5078$ MeV   T/2 ≈ 0.8067 s

1. The ion is spinless, and therefore decays at rest are isotropic.

2. It can be produced at high rates, I.e. 5E13 ^{6}He/s

3. The neutrino spectrum is known on the basis of the electron spectrum.



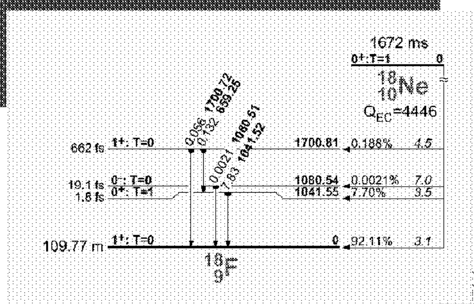
B.M. Rustand and S.L. Ruby, Phys.Rev. 97 (1955) 991
B.W. Ridley Nucl.Phys. 25 (1961) 483

Neutrino Source

Possible neutrino emitter candidate:^{18}Ne

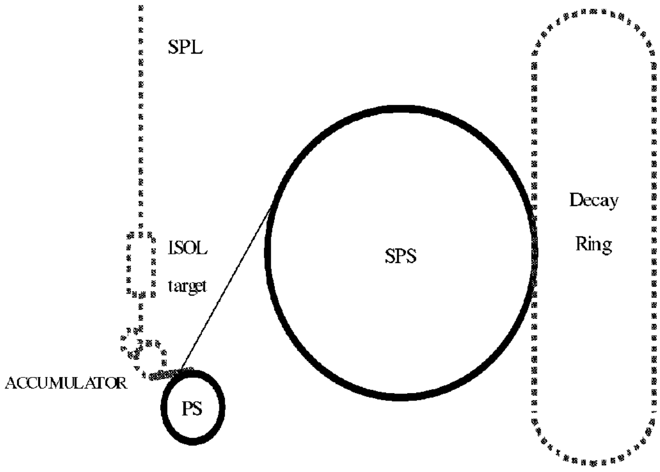
The same technology used in the production of ^{6}He is limited in the ^{18}Ne case to 10^{12} ions/s.
Dedicated R&D should increase this figure.
Use this intensity as reference.

Issues:
MgO less refractory.
heat dissipation



Beta Beam

(P. Zucchelli)



M. Lindroos et al.

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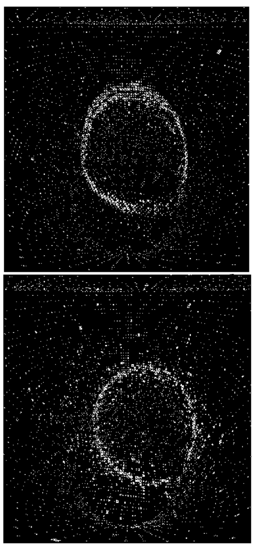
Combination of beta beam with low energy super beam



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 revue at NUFACT02 (1-6 July 2002)

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Superbeam & Beta Beam cost estimates

Educated guess on possible costs	USD/CHF	1.60
UNO	**960**	MCHF
SUPERBEAM LINE	100	MCHF
SPL	300	MCHF
PS UPGR.	**100**	MCHF
SOURCE (EURISOL), STORAGE RING	**100**	MCHF
SPS	**5**	MCHF
DECAY RING CIVIL ENG.	**400**	MCHF
DECAY RING OPTICS	**100**	MCHF
TOTAL (MCHF)	**2065**	MCHF
TOTAL (MUSD)	**1291**	MUSD
INCREMENTAL COST (MCHF)	**705**	MCHF
INCREMENTAL COST (MUSD)	**441**	MUSD

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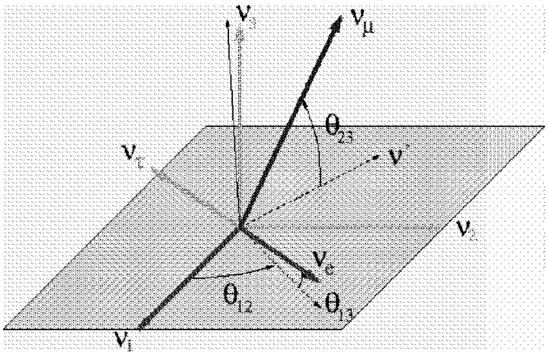
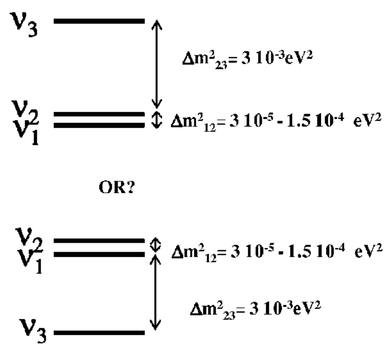
The neutrino mixing matrix: 3 angles and a phase δ



θ_{23} (atmospheric) = 45^0, θ_{12} (solar) = 30^0, 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}

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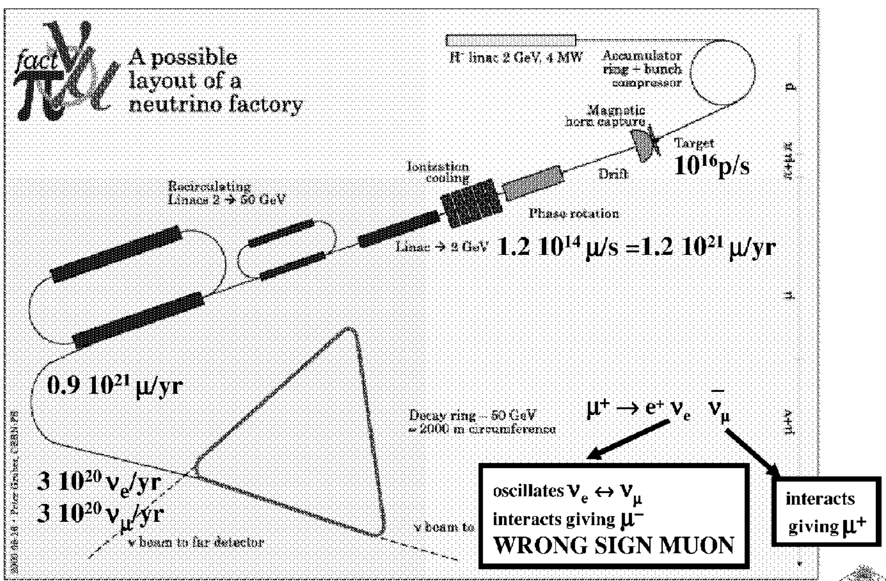
-- Neutrino Factory -- CERN layout



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Scaling laws

Event numbers in a neutrino beam (at long distance the beam is much larger than the detector)

N_events = σ [cm^2] Φ [ν/cm^2] A[cm^2] L[cm] d[g/cm^3] . $\mathcal{N}_{Avogadro}$ [nucleons/g]

σ ~= 0.7 10^{-38} E_ν [GeV] cm^2/GeV scales with energy E

flux scales as $1/\theta^2 L^2 \sim E^2_{parent}/L^2$

➔number of events scales as E^3_{parent}/L^2

Oscillation goes as sin^2 (1.27 Δm^2 L/E) this scales as L^2/E^2 in the first oscillation. (note L^2 dependence goes – for signal!)

Events -- and sensitivity in absence of background -- go like E_{parent}

In case of background, sensitivity goes like $S/\sqrt{B}$ and B goes like E^3/L^2

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

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 ($\pm 10^{-3}$)

-- E&σ_E calibration from muon spin precession

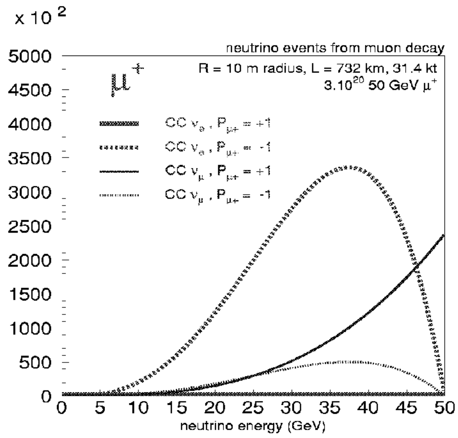
-- angular divergence: small effect if $\theta < 0.2/\gamma$,

-

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

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

-- in Bow-tie ring,
muon polarization stays constant, no precession
20% easy -> 40% hard
Must be measured!!!! (precision?)



μ polarization controls ν_e flux:

μ^+ -X> ν_e in forward direction

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

Expected Physics outcome of a Long base Line program at a Neutrino factory

High energy ν_e essential & unique

- **Measurements of**
  θ_{13}, θ_{23} with precision of 10^{-3} or limit at about 10^{-6}
  Δm_{13} with relative precision of 1%
- **establish matter effect -> sign of Δm_{13}**
- **Will be sensitive to CP violation over the whole Large Mixing Angle solution of the Solar neutrinos (now established)**
- **(50 KT, 5 years, 10^{21} muons per year stored, 3000 km)**

Golden MEASUREMENTS at ν- FACTORY

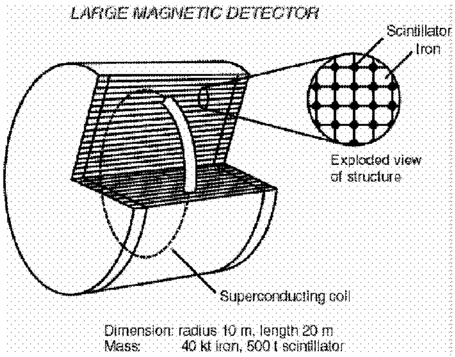
$$\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$$

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

$$\mu^- \to \nu_\mu \quad \bar{\nu}_e \quad e^-$$
$$\downarrow$$
$$\bar{\nu}_\mu \to \mu^+$$
$$\mu^+ \to \bar{\nu}_\mu \quad \nu_e \quad e^+$$
$$\downarrow$$
$$\nu_\mu \to \mu^-$$

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
3500 Km	1.2×10^6	2.4×10^6	1.0×10^5

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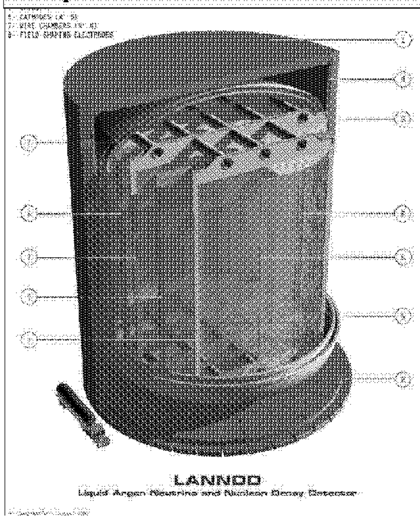
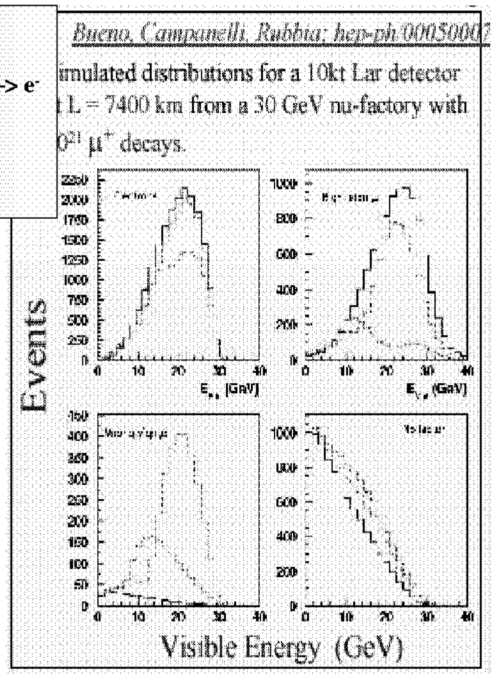
6 classes of events

right sign muon	$\bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+$
electron/positron	$\bar{\nu}_\mu \to \bar{\nu}_e \to e^+$ or $\nu_e \to \nu_e \to e^-$
wrong sign muon	$\nu_e \to \nu_\mu \to \mu^-$
right sign tau	$\bar{\nu}_\mu \to \bar{\nu}_\tau \to \tau^+ \to \mu^+ \nu\nu$
wrong sign tau	$\nu_e \to \nu_\tau \to \tau^- \to \mu^- \nu\nu$
no lepton	NC & other taus





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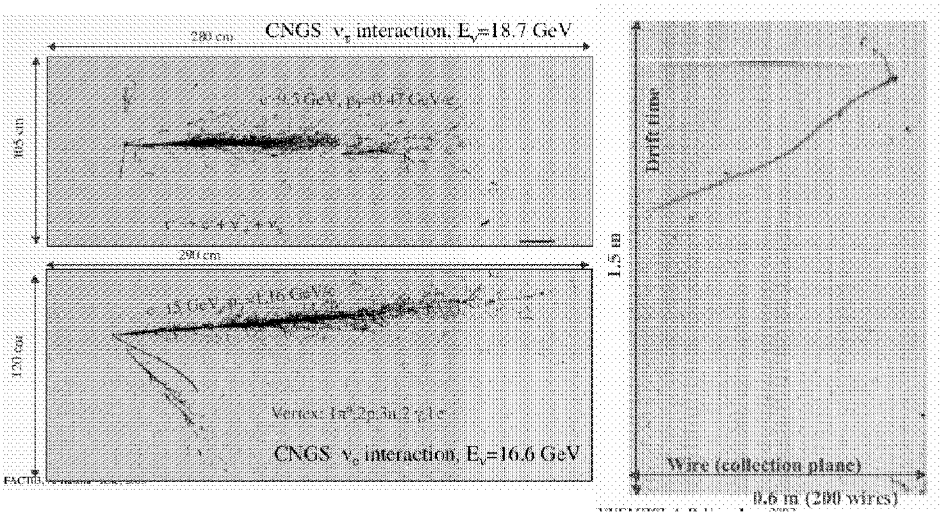
ICARUS



NB: additional potential wrt magnetized iron calorimeter:
tau detection ,sign of *low* energy electrons, if magnetized.
May redefine the optimal parameters of neutrino factory

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Advantages of Liquid argon detector:
see everything charged →extraordinary amount of information
excellent pattern recognition
for limited magnetic field (about 0.5-1 T) can tell charge of muons down to low energy
can also tell the charge of low energy electrons (E<~2 GeV)

Limitations:
-- which mass can be reasonably build with a magnetic field?
-- at which cost?
-- safety issues in an underground environment?
-- decay background on wrong sign muons will be larger.

Interesting R&D ahead...

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Event rates

$N_{\mu^+,\mu^-} = 10^{21}/y$, $M_{fid} = 40$ KTon y, $E_\mu = 50 GeV$

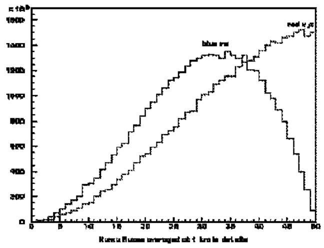
μ^- beam

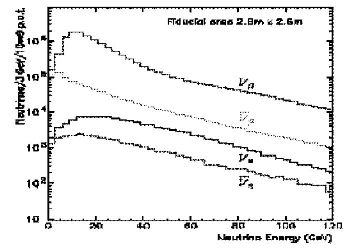
Baseline	$\bar{\nu}_e$ CC	ν_μ CC	$\mu^+(10^\circ)$	$\mu^+(0.5^\circ)$
732 Km	$3 \cdot 10^7$	$6.9 \cdot 10^7$	$1.7 \cdot 10^4$	44
3500 Km	$1.3 \cdot 10^6$	$3 \cdot 10^6$	$7 \cdot 10^3$	15
7332 Km	$3 \cdot 10^5$	$6.9 \cdot 10^5$	$2.8 \cdot 10^2$	1

μ^+ beam

Baseline	ν_e CC	$\bar{\nu}_\mu$ CC	$\mu^-(10^\circ)$	$\mu^-(0.5^\circ)$
732 Km	$5.9 \cdot 10^7$	$3.5 \cdot 10^7$	$3.6 \cdot 10^4$	94
3500 Km	$2.5 \cdot 10^6$	$1.5 \cdot 10^6$	$3.1 \cdot 10^4$	85
7332 Km	$5.9 \cdot 10^5$	$3.5 \cdot 10^5$	$1.2 \cdot 10^4$	39

NB: oscillation signal is nearly indept of distance





conventional neutrino beam from π, K decay: long high energy tail, Bkg from ν_e and NC events

NUFACT = 100 X CNGS with 2 Flavours,

No high energy tail to produce NC with π^0

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Signal Rates & Signal/Background

Note: backgrounds for $\nu_e \rightarrow \nu_\mu$ measurements (wrong-sign muon appearance) are much easier to suppress than backgrounds to $\nu_\mu \rightarrow \nu_e$ measurements (electron appearance).

Many groups have calculated signal & background rates. Recent example
Hubner, Lindner & Winter; hep-ph/0204352

JHF-SK: Beam = 0.75 MW, M_{fid} = 22.5 kt, T = 5 yrs
JHF-HK: Beam = 4 MW, M_{fid} = 1000 kt, T = 8 yrs
Entry-Level NUFACT: Beam = 1×10^{19} decays/yr, M_{fid} = 100 kt, T = 5 yrs
High-Performance NUFACT: Beam = 2.6×10^{20} decays/yr, M_{fid} = 100 kt, T = 8 yrs

$\Delta m_{32}^2 = 0.003\ eV^2$, $\Delta m_{21}^2 = 3.7\times10^{-5}\ eV^2$, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{12} = 0.8$, $\delta = 0$

	Superbeams		Neutrino Factories	
	JHF-SK	JHF-HK	Entry Level	High Performance
Signal	140	13000	1500	65000
Background	23	2200	4.2	180
S/B	6		360	

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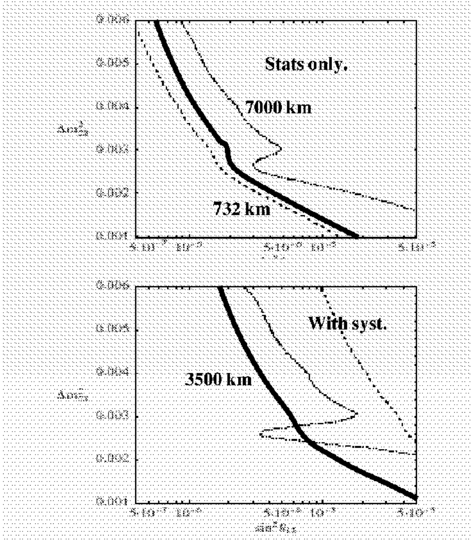
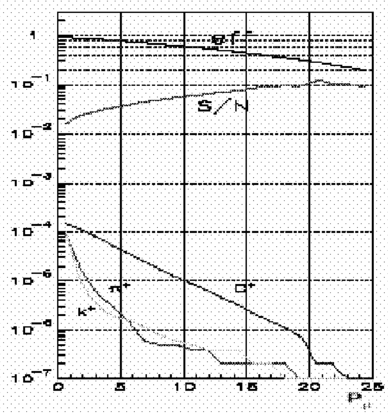
Sensitivity to $\sin^2\theta_{13}$



$N_{\mu^+\mu^-} = 10^{21}$/year, $M_{det} = 40$ KTon year

Appearance of wrong sign muons.
Background very low in dense detector
(mostly comes from very inelastic charm production)
Can be kept at a few 10^{-5} level by cuts on
Muon momentum, Pt, and Pt w.r.t. hadronic shower

N_{CC} events



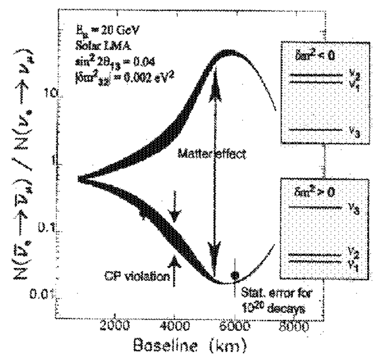
CP asymmetries
compare $\nu_e \to \nu_\mu$ to $\bar{\nu}_e \to \bar{\nu}_\mu$ probabilities

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

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

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

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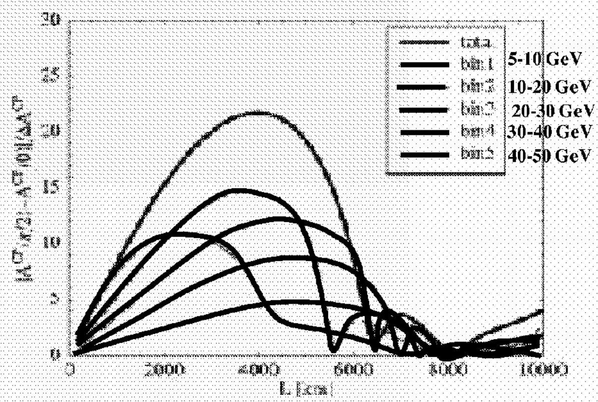
CP violation (ctd)

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 ...

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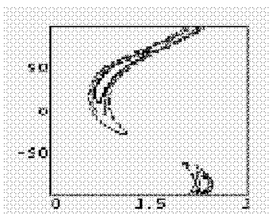
Silver channel at neutrino factory

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

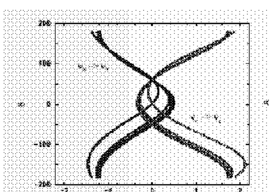
High energy neutrinos at NuFact allow observation of $\nu_e \rightarrow \nu_\tau$
(wrong sign muons with missing energy and P⊥). UNIQUE

Liquid Argon or OPERA-like detector at 3000 km.

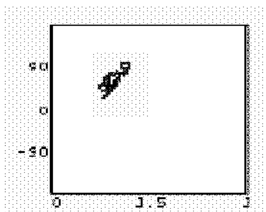
Since the sinδ dependence has opposite sign with the wrong sign muons, this solves ambiguities that will invariably appear if only wrong sign muons are used.



ambiguities with only wrong sign muons (3500 km)



equal event number curves muon vs taus



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

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Why do we believe that the neutrino fluxes can be determined to +- 10^{-3} at a Neutrino Factory?

Flux Control and Resulting Constraints on the Decay Ring Design

source: M. Apollonio et al,
OSCILLATION PHYSICS WITH A NEUTRINO FACTORY
arXiv: hep-ph/0210192 v1 13 Oct 2002

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why?

In the high intensity scenario

- the event rates in the far detector are above 10^9·/yr/Mton

➔precision measurement of the mixing angle and mass differences.

2. the event rates in the near detectors are at the level of 10^8/yr/kg

➔ precision measurements of total cross-sections
➔ structure functions
➔ SM tests etc…

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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 i s10^{-3})

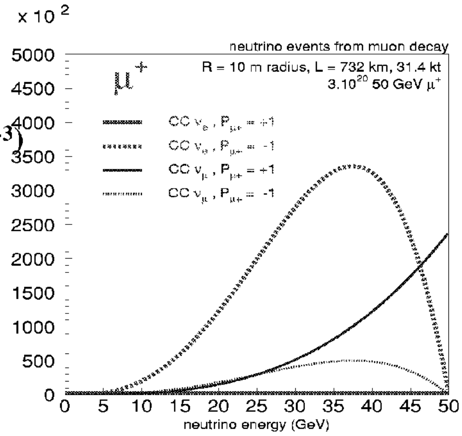
- absolute flux measured from muon current
 or by $\nu_\mu e^- \to \mu^- \nu_e$ in near expt.

-- 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?)



μ polarization controls ν_e flux:

$\overrightarrow{\mu^+}$ -X> $\overleftarrow{\nu_e}$ **in forward direction**

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System where one stores a beam of decaying particles
Neutrino Factory, (and Beta Beam?)
⇨potential for excellent neutrino flux control

Main parameters to MONITOR

1. Total number of muons circulating in the ring,
2. muon beam polarisation,
3. muon beam energy and energy spread,
4. muon beam angle and angular divergence.
5. Theory of μ decay, including radiative effects

Beam shape parameters are crucial for:
 the measurement of oscillation length (i.e.Δm^2)
Absolute normalisation is essential for
 the measurement of the mixing angles.
The relative normalisation of the two muon charges crucial for:
 CP asymmetries.

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Absolute number of muons in the ring: maybe the most difficult?

Total beam current: Beam Current Transformer

-- difficulties:

1. presence of decay electrons in the ring?

Keil CERN-NUFACT Note 54 (2000), showed that the electrons are swept in the arcs and destroyed. Since the lifetime is 200 turns, the maximum fraction of electrons is $0.3/200 = 1.6\ 10^{-3}$ at the ***end*** *of a straight section, much less at the entrance of it.*

→ Monitor should be placed at entrance of straight section.

2. absolute calibration? 10^{-3} difficult, not impossible.

3. the most practical way to cross-normalize μ^+ vs μ^- fluxes

alternative: count the electrons at the exist of a straight.

this has a nice feature of counting the decays!

the acceptance of the monitor (see polarimeter later) is tricky

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Absolute normalisation (ctd)

-- Near detector will measure product of flux X cross-section

-- better: $\nu_\mu e^- \rightarrow \mu^- \nu_e$ in a dedicated near detector.

type of detector:
ring imagind water cerenkov,
LA detector,
pressurized gas detector.

small mass is enough as rates are high but cross-section is quite small. (10^4 ev/kg/yr. →need 100 kg.)
Main problem is determination of fiducial mass.
This provides an absolute normalization of the flux in the same way as bhabha scattering in e+e- colliders.

Limitations: threshold (11 GeV) & only for μ^- stored beam

alternative is $\nu_x e^- \rightarrow \nu_x e^-$ (assumes SM)

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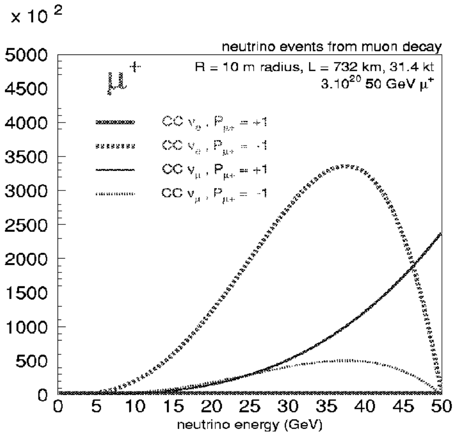
Muon polarization



Has a large effect on the flux!
ν_e flux varies by 100% when P goes from -1 to +1

μ polarization controls ν_e flux:
$\overrightarrow{\mu^+}$ -X> $\overleftarrow{\nu_e}$ in forward direction

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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:

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

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.

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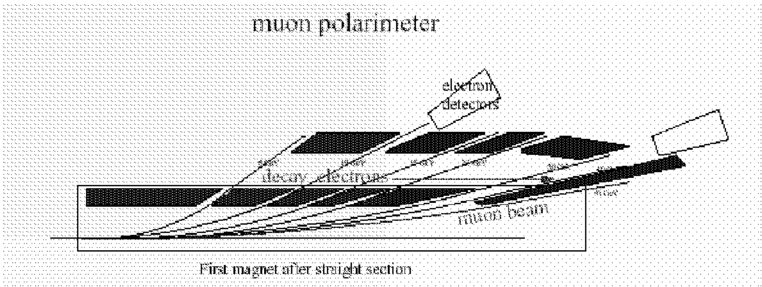
Muon Polarization

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.

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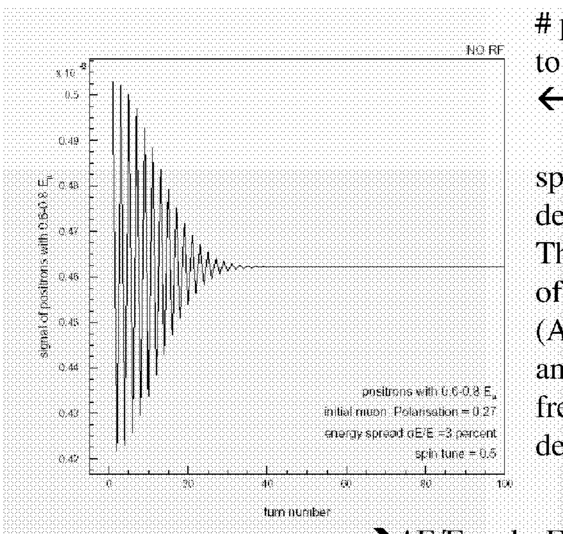
muon polarization



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.

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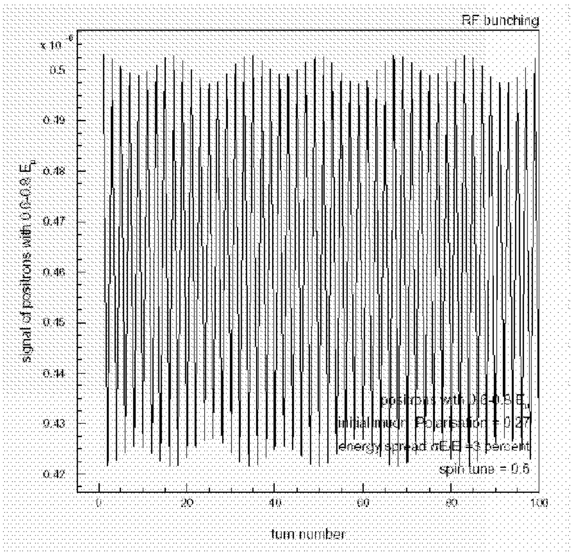


If there is RF in the storage ring to keep the muons bunched, depolarization is suppressed. (synchrotron oscillations)

Even in this case, the muon polarization, averaged over ~500 turns is very small ($<<0.18/500 = 4 10^{-4}$) and will be monitored.

muon polarization: triangle or bow-tie?

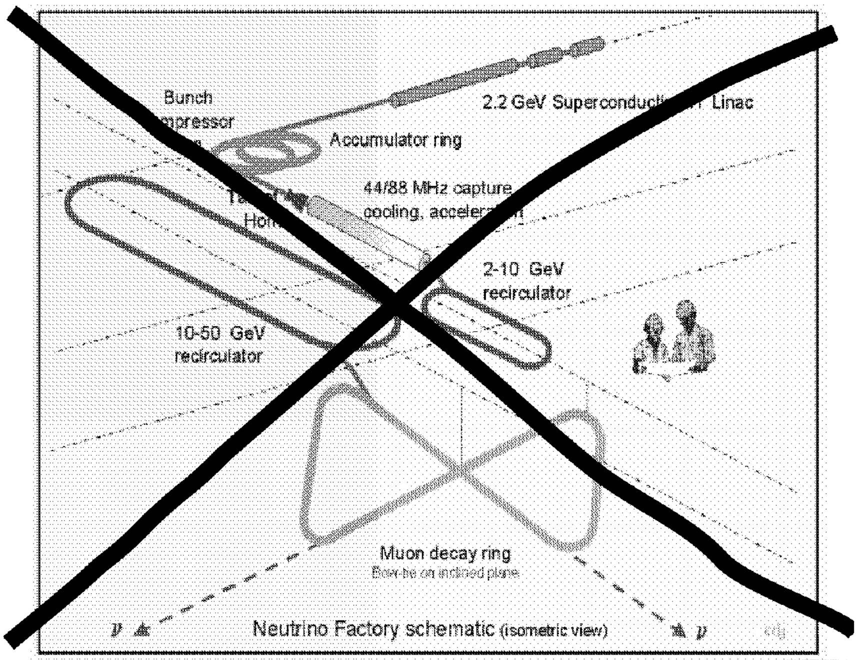
This was true for a race track or triangle decay ring, in which polarization precesses.

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 inconvenients:
-- P is different for the two straights (who shall be pleased?)
-- P cannot be reversed
-- E and σ(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



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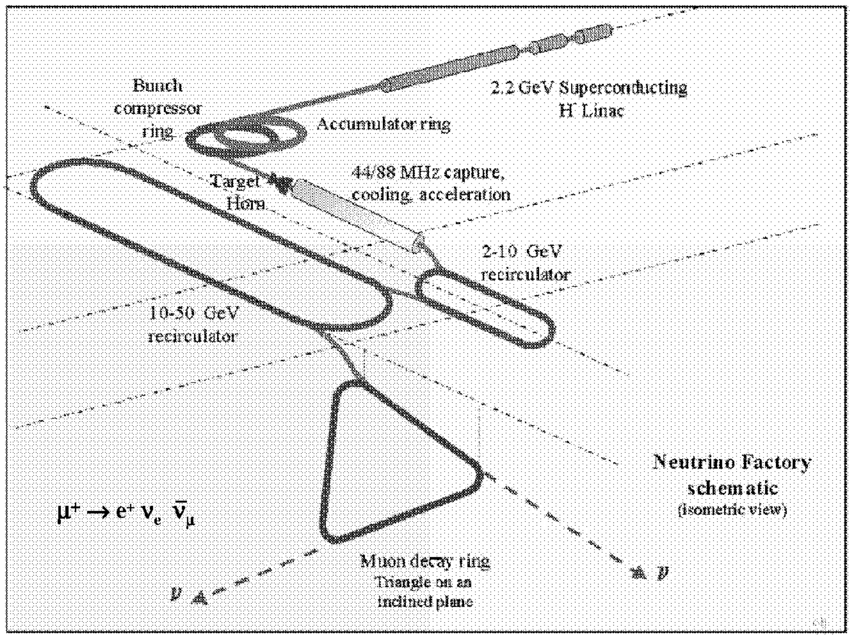

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Angular divergence

If the muons have transverse momentum comparable to that of muon decay (50 MeV) the neutrino beam will be seriously degraded this corresponds to $\sigma(\theta) = 0.5\ m_\mu / E_\mu$ ➔

in order for the effect of beam divergence to affect the flux by less than a few 10^{-3} beam divergence must be very small.

I. Papadopoulos has calculated the effect.

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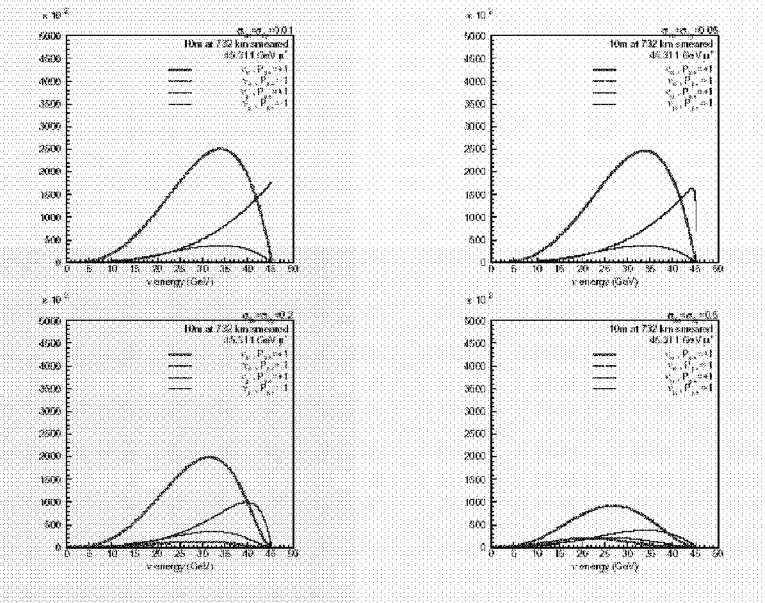
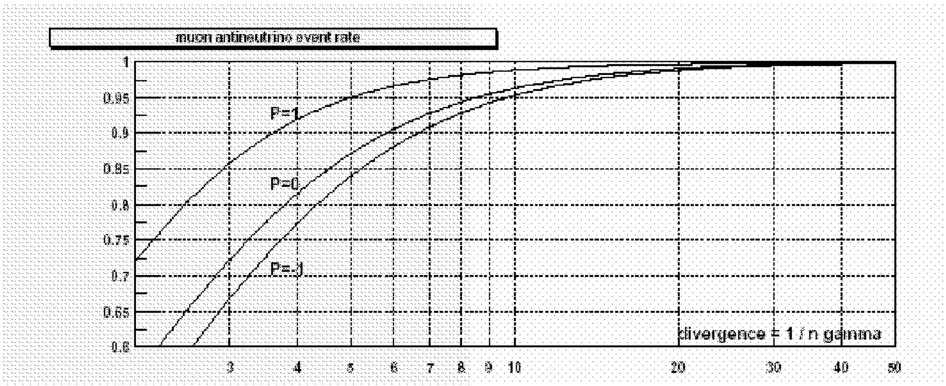


Fig. 34: *Neutrino event spectra for different beam divergences: Upper left: $\sigma\theta_x = \sigma\theta_y = 0.01\ m_\mu/E_\mu$; upper right: $\sigma\theta_x = \sigma\theta_y = 0.05\ m_\mu/E_\mu$; lower left: $\sigma\theta_x = \sigma\theta_y = 0.2\ m_\mu/E_\mu$; lower right: $\sigma\theta_x = \sigma\theta_y = 0.5\ m_\mu/E_\mu$. It is clear that beam divergence results in a loss of events, and in a sizeable distortion of the spectra and of their*



divergence of 0.1/γ keeps 95% of the original flux.
Straight section with this property were designed for the US Study II and by Keil

Divergence MUST be measured.

A gas Cerenkov device to measure the beam emittance was devised by Piteira.
Various efects were considered (optical aberrations, heating of gas, multiple scattering, etc…and concluded that the divergence is easier to measure the bigger it is so that this should not be a problem)

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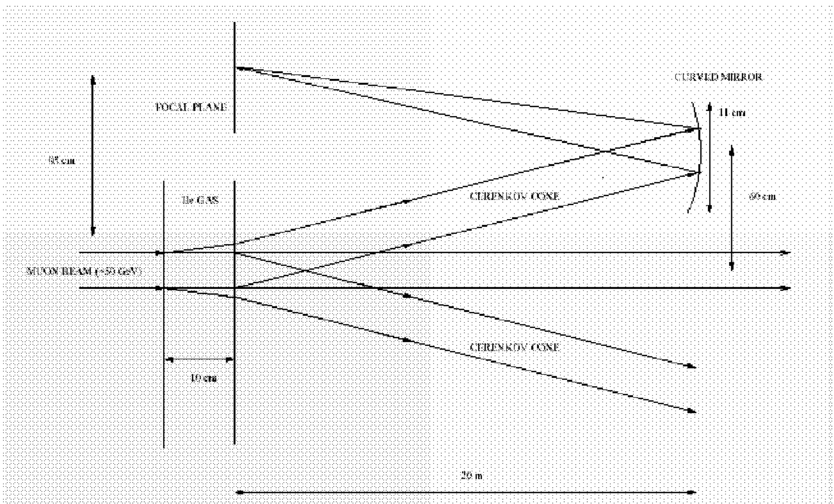

Schematic of a muon beam divergence measurement device. A low-pressure He gas volume is contained by windows (one of which must be transparent) within a straight section of the the muon decay ring. The Cerenkov light is collected by a parallel to point optics in the direction of interest, so as to provide an image of the angular distribution of particles in the focal plane.

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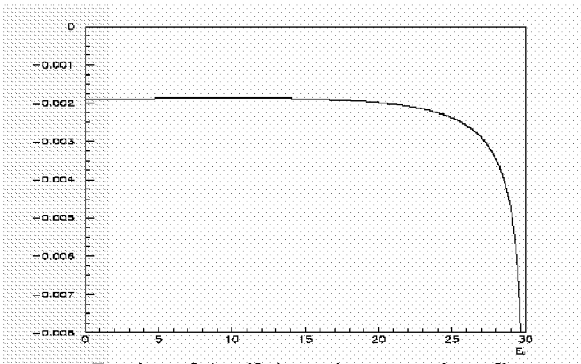
Radiative effects



Ratio of 1st/0th order neutrino flux

Radiative effects
by Broncano & Mena

Dominated by the presence of a photon in the final state, which reduces the energy of the neutrino and thus the flux in forward direction.
(the total number of neutrinos emitted is constant of course)

Effect is –0.4% with a slight distortion of the end-point.
Error is small fraction thereof.

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Conclusions I

Main parameters to MONITOR

1. Total number of muons circulating in the ring,
   BCT, near detector for purely leptonic processes
2. muon beam polarisation,
   polarimeter
3. muon beam energy and energy spread,
   race-track or triangle. NO BOW-TIE!
   +polarimeter
4. muon beam angle and angular divergence.
   straight section design
   +beam divergence monitors e.g. Cerenkov
5. Theory of μ decay, including radiative effects
   OK

Yes, we believe that the neutrino flux can be monitored to 10^{-3} IF
+ design of accelerator foresees sufficient diagnostics.
+ quite a lot of work to do to design and simulate these diagnostics

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Conclusions II: and the Beta-beam?

Main parameters to MONITOR

1. Total number of ions circulating in the ring,
   BCT, near detector for purely leptonic processes
2. ion beam polarisation, NO they are spin 0!→ no problem
3. ion beam energy and energy spread,
   no polarization -- need magnetic field measurement.
   precision required a few 10-4 (evt. rate goes like E^{3})
4. ion beam angle and angular divergence.
   beam divergence monitor e.g. Cerenkov
5. Theory of ion decay, including radiative effects
   To be done

neutrino flux can probably be monitored to 10^{-3}

– somewhat more difficult than for muons, but not impossible.

provided:

+ design of accelerator foresees sufficient diagnostics.
+ quite a lot of work to do to design and simulate these diagnostics.

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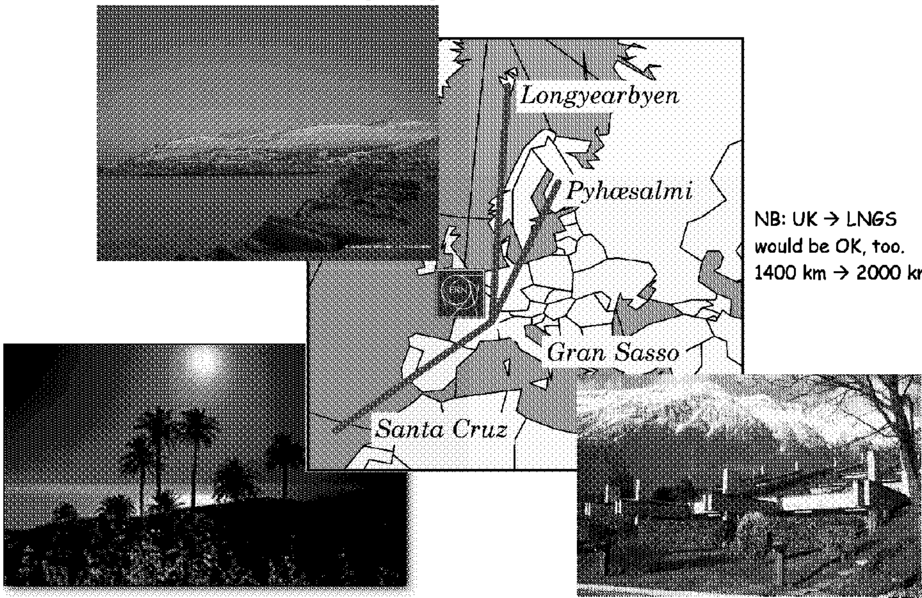
Where do you prefer to take shifts?



NB: UK → LNGS would be OK, too. 1400 km → 2000 km)

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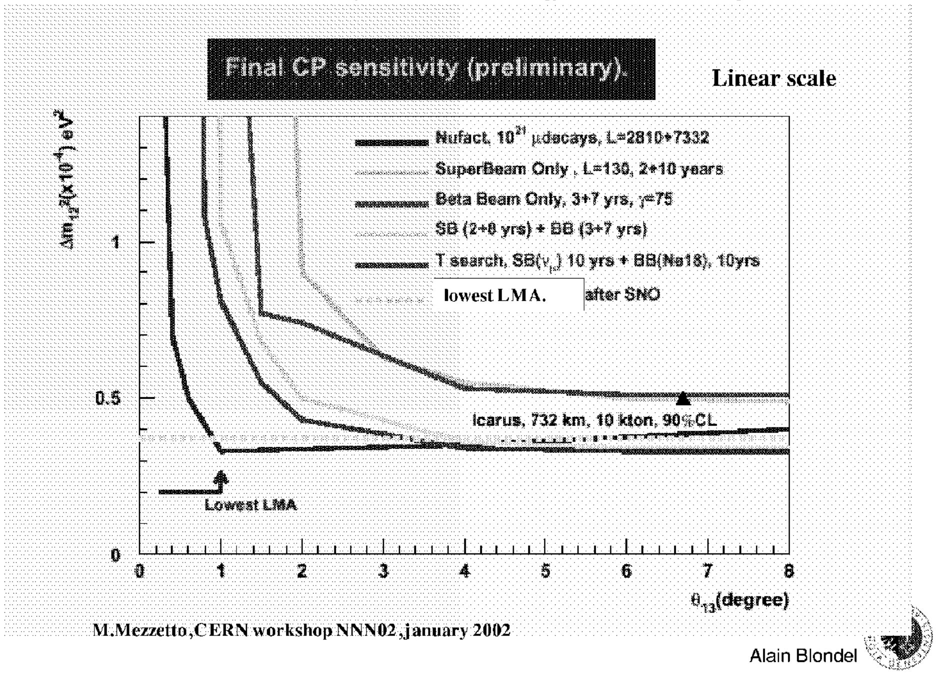
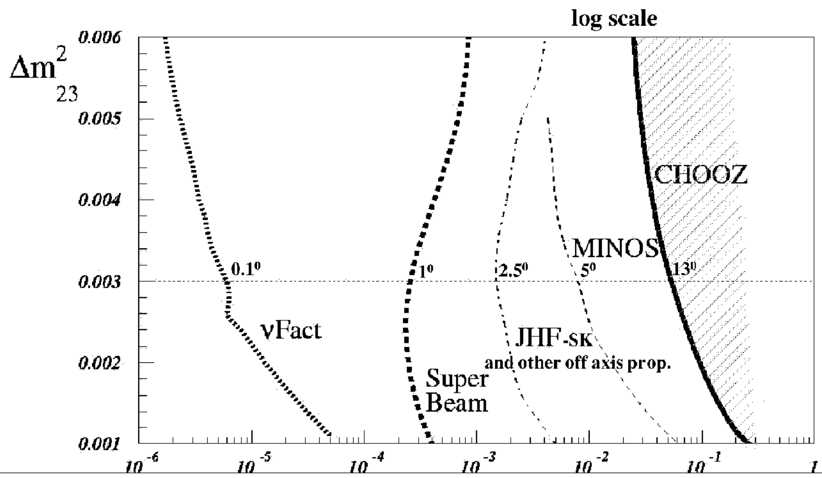
Combination of Beta beam and superbeam is in the same ballpark of performance as neutrino factory ...
(bewrare of systematics for low Energy neutrino events,though)



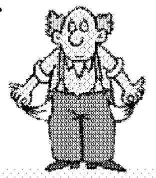
Superbeam gets us quite a ways...



comparison of reach in the oscillations; right to left:
present limit from the CHOOZ experiment,
expected sensitivity from the MINOS experiment,
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
from a Neutrino Factory with 40 kton large magnetic detector. INCLUDING SYSTEMATICS

Last question: about financing?

⌘ For the time being our situation is not so good....



BUT..... Some ideas are developing...

hep-ph/0111247
TUM-HEP-440/01

Could One Find Petroleum Using Neutrino Oscillations in Matter?

Tommy Ohlsson[a,*] and Walter Winter[a,†]

[a]*Institut für Theoretische Physik, Physik-Department, Technische Universität München, James-Franck-Straße, 85748 Garching bei München, Germany*

(Dated: November 20, 2001)

It is now widely believed in neutrino physics that neutrino oscillations are influenced by the presence of matter, modifying the energy spectrum produced by a neutrino beam traversing the Earth. Here, we will discuss the reverse problem, i.e., what could be learned about the Earth's interior from a single neutrino baseline energy spectrum, especially about the Earth's mantle. In the end of the paper, we will finally investigate if one could really find petroleum using this method.

PACS numbers: 14.60.Lm, 13.15.+g, 91.35.-x

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Conclusions

Neutrinos have mass and they mix.

This is a NEW FORCE, (beyond the SM)
that could also generate proton decay
the baryon asymmetry of the universe,
$\mu \to e\,\gamma$
....

A Neutrino Factory Complex (and in a first step a high intensity superbeam) would offer the possibility to discover leptonic CP violation and to measure the mass and mixing properties of neutrinos very precisely.
Would offer a very versatile physics program on the side as well

We know that such a machines/detectors can be build and work.
Cost would be too high today and techniques have never been tested in practice.

Requires R&D! Target/MICE Ascertain designs and find new ideas.
Will follow also carefully beta-beam + super-beam combination
Detector ideas are based on today's detectors MINOS, SUPERK, ICARUS, OPERA + R&D for size

Following ECFA recommendations, a coordinated effort is being build in Europe (and across the world), goals and priorities set -- we will get there!

we are living an exciting time

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LECTURE 3

Towards a Neutrino Factory Complex

1. European R&D towards neutrino factory
   proton accelerator
   target
   muon cooling experiment MICE

2. Other physics around a neutrino factory
   stopped muons
   high intensity neutrino scattering

3. Towards muon colliders
   Higgs factory and CP violation

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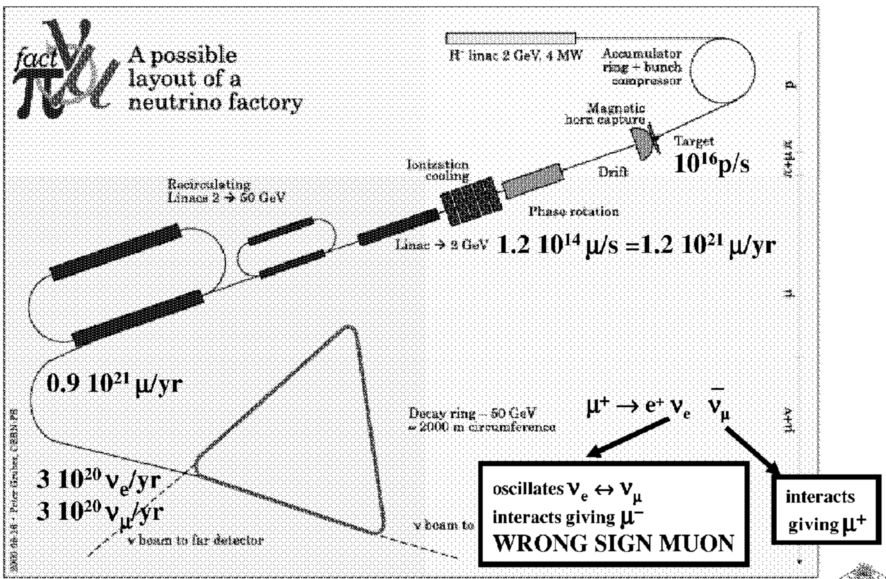
-- Neutrino Factory -- CERN layout



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Neutrino Factory studies and R&D

USA,Europe,Japan have each their scheme. Only one has been costed,US study II:

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: ascertain challenges can be met + cut cost in half.

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EMCOG (European Muon Concertation and Over sight Group FIRST SET OF BASIC GOALS

The long-term goal is to have a Conceptual Design Report for a European Neutrino Factory Complex by the time of JHF & LHC start-up, so that, by that date, this would be a valid option for the future of CERN.

An earlier construction for the proton driver (SPL + accumulator & compressor rings) is conceivable and, of course, highly desirable.
The SPL, targetry and horn R&D have therefore to be given the highest priority.

Cooling is on the critical path for the neutrino factory itself; there is a consensus that a cooling experiment is a necessity.

The emphasis should be the definition of practical experimental projects with a duration of 2-5 years. Such projects can be seen in the following four areas:

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1. High intensity proton driver. Activities on the front end are ongoing in many laboratories in Europe, in particular at CERN, CEA, IN2P3, INFN and GSI. Progressive installation of a high intensity injector and of a linear accelerator up to 120 MeV at CERN (R. Garoby et al) would have immediate rewards in the increase of intensity for the CERN fixed target program and for LHC operation. GSI.... EMCOG will invite a specific report on the status of the studies and a proposal for the implementation process.

2. Target studies
. This experimental program is already well underway with liquid metal jet studies. Goal: explore synergies among the following parties involved: CERN, Lausanne, Megapie at PSI, EURISOL, etc...

3. Horn studies.
A first horn prototype has been built and is being equipped for pulsing at low intensity.
5 year program to reach high intensity, high rep rate pulsing, and study the radiation resistance of horns. Optimisation of horn shape. Explore synergies between CERN, IN2P3 Orsay, PSI (for material research and fatigue under high stress in radiation environment)

4. MICE. A collaboration towards and International cooling experiment has been established with the muon collaboration in United States and Japanese groups. There is a large interest from European groups in this experiment. Following the submission of a letter of Intent to PSI and RAL, the collaboration has been encouraged to prepare a full proposal at RAL, with technical help fro RAL. PSI offers a solenoid muon beam line and CERN, which as already made large initial contributions in the concept of the experiment, could earmark some very precious hardware that could be recuperated. A summary of the requests should be presented by the collaboration.

It is noted that the first three items are also essential for a possible initial neutrino program with a high intensity low energy conventional neutrino beam (superbeam).

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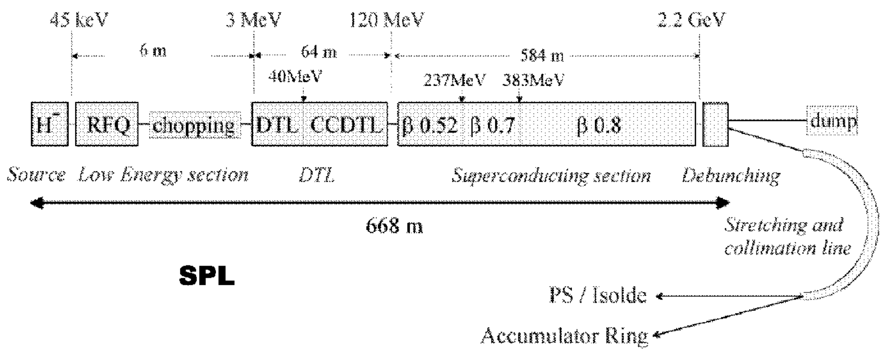
Proton Drivers

- **For CERN, two possibilities:**



Uses LEP RF system

(capable of >20 MW ....)

a CW machine, needs accumulators

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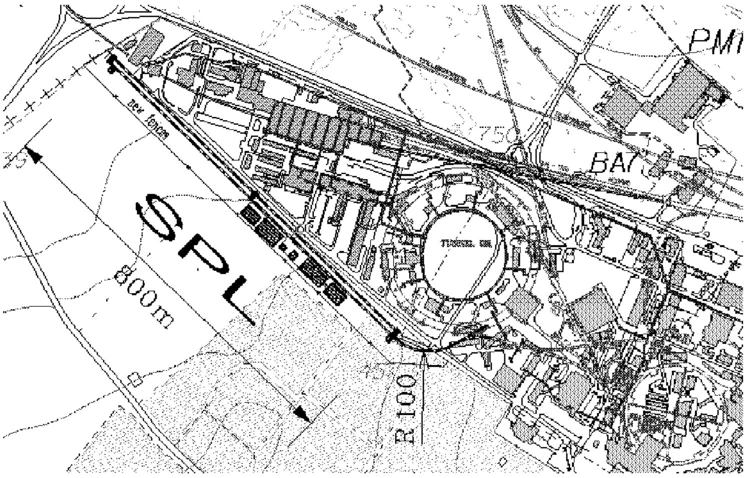
SPL layout on the CERN site (top view)



R. Garoby muon week 24-10-2000

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A very potent machine indeed!

SPL power consumption

	NOMINAL (PULSED @ 75 Hz)	CONTINUOUS BEAM
Mean beam power	4 MW	24 MW
Electrical power consumption:		
- RF (mean RF power)	24MW (12 MW)	64 MW (32 MW)
- Cryogenics (cooling power at 4.5 K)	8 MW (32 kW)	20 MW (75 kW)
- Cooling & ventilation	2 MW	6 MW
- Other & general services	4 MW	5 MW
Total electrical power consumption:	38 MW	95 MW

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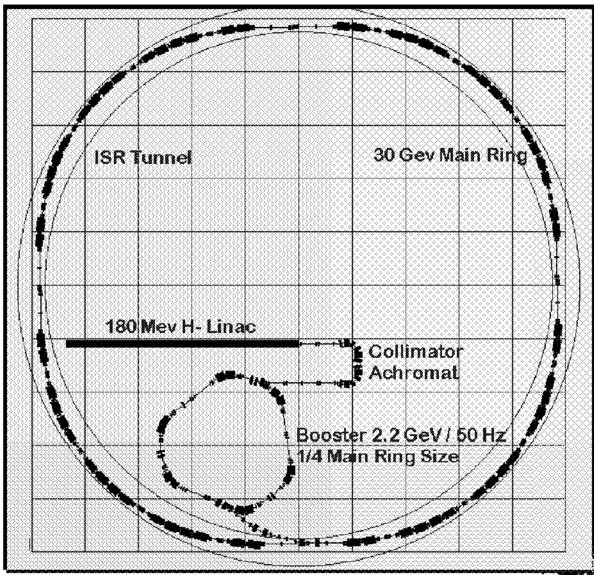
Proton Drivers

30 GeV Rapid Cycling Synchrotron in the ISR tunnel



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Proton Drivers

Cost comparison

PDAC		RCS	
	MCHF		MCHF
SPL	350	Linac	110
Accumulator	63	Booster RCS	88
Compressor	50	Driver	233
TOTAL	463	*TOTAL*	431

Schönauer

SPL: **driver for a conventional superbeam to Frejus**
driver for β-beams
R&D already started with CEA

RCS: **replacement for PS**

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NUFACT R&D: Target station

⌘ Target:

- Dimension: L ≈ 30 cm, R ≈ 1 cm
- → **4 MW proton beam into an expensive cigar…**
- → High Z → small size good for optics
- → Liquid → easy to replace ($v_{//} \approx 20$ m/s) → Mercury

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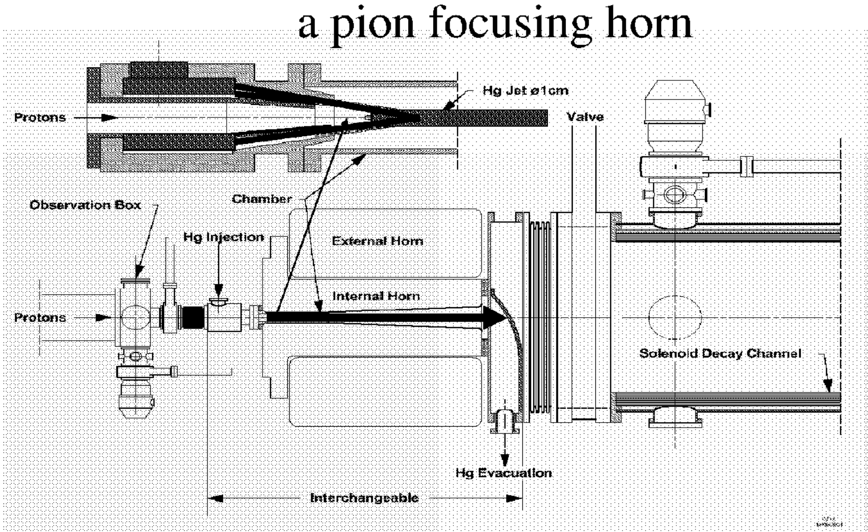
Hg-jet p-converter target with a pion focusing horn



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NUFACT R&D: Target station

Experiment @BNL and @CERN

- Speed of Hg disruption
- Max $v_{\perp} \approx 20$ m/s measured
- $v_{//} \approx 3$ m/s
- jet remains intact for more than 20 microseconds.

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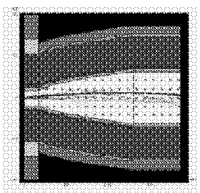
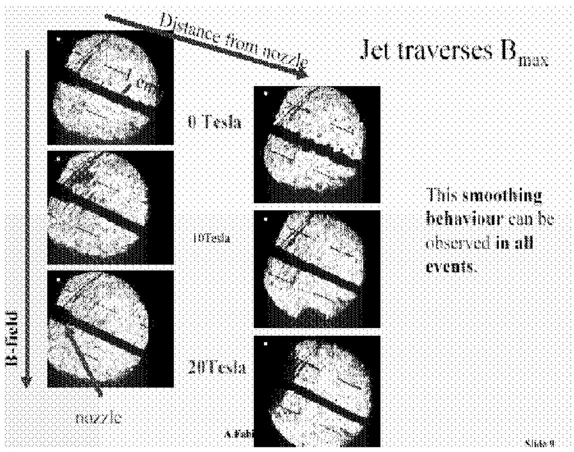
US scheme:
jet is inside a very high field tapered solenoid (20 T max)





this was tested at the Laboratoire de Champs Intenses (Grenoble)

A. Fabich et al– CERN-BNL-Grenoble

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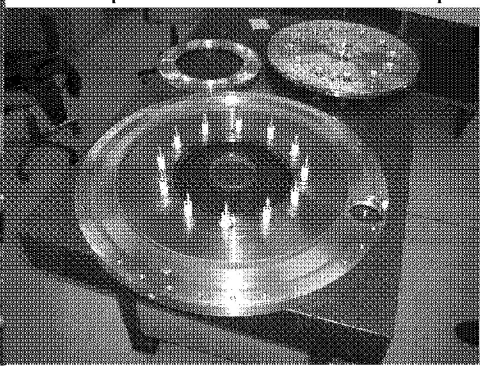
HORN STUDIES

horn is built at CERN
mechanical properties measured
(can it be pulsed at 350 KA and 50 Hz?
important for basic choice of proton driver)

This is the neutrino factory horn,
SPL-superbeam one will have different shape.



J.-M. Maugain,....(S.Gilardoni,UNiGe) et al

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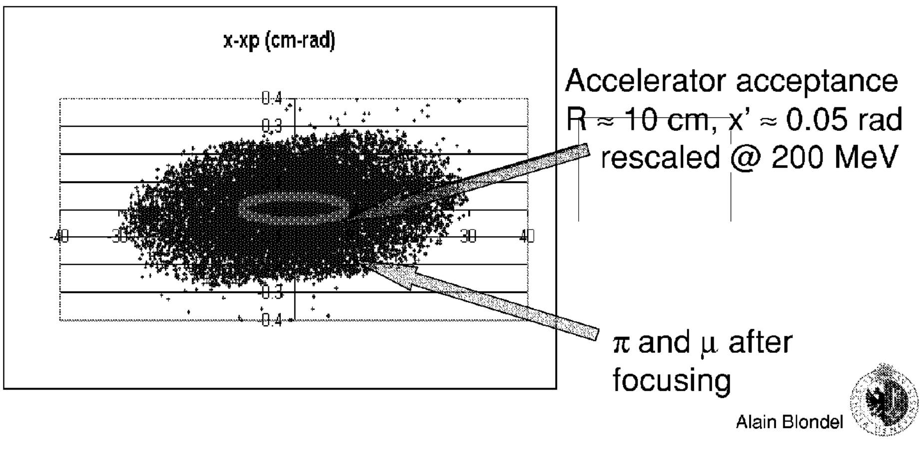
NUFACT R&D; Cooling

⌘ Problem: $\mu \rightarrow$ Beam pipe radius of storage ring

$P_{\perp}$ or x' and x reduction needed: COOLING



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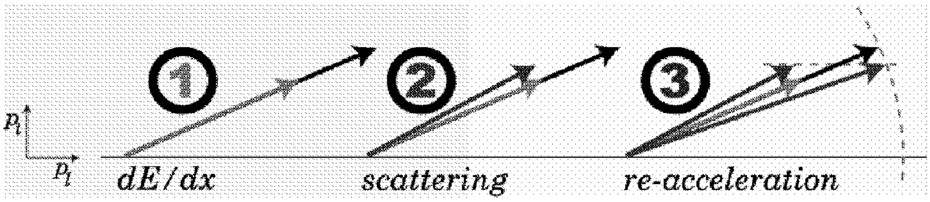
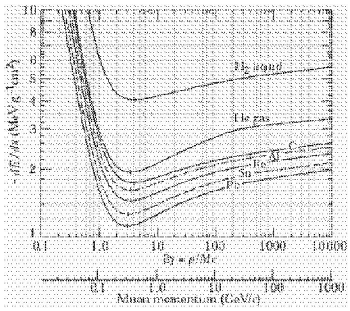
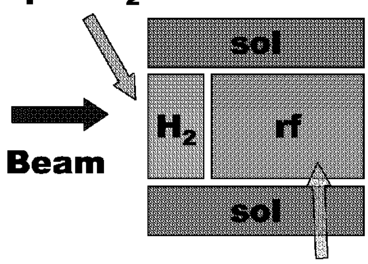
Ionization Cooling : the principle





Liquid H_2: dE/dx



RF restores only $P_{//}$

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What muon cooling buys

MUON Yield without and with Cooling

	NOCOOL	with cooling
long. emittance	0.05 eVs	0.05 eVs
rotation	6.7×10^{19}	6.7×10^{19}
44 MHz	6.8×10^{19}	
88 MHz	7.3×10^{19}	1.2×10^{21}
176 MHz	5.5×10^{19}	1.0×10^{21}

exact gain depends on relative amont of phase rotation (monochromatization vs cooling trade off)

cooling of minimum ionizing muons has never been realized in practice
involves RF cavities, Liquid Hydrogen absorbers, all in magnetic field
designs similar in EU and US Nufact concepts

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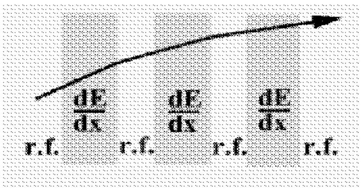
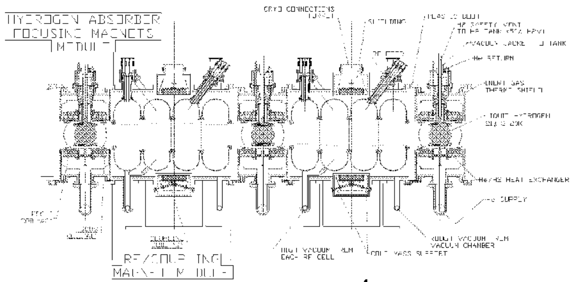
IONIZATION COOLING

principle: | **reality (simplified)**



this will surely work..!



....maybe...

A delicate technology and integration problem
⇒ Need to build a realistic prototype and verify that it works (i.e. cools a beam)

Difficulty: affordable prototype of cooling section only cools beam by 10%, while standard emittance measurements barely achieve this precision.

Solution: measure the beam particle-by-particle
state-of-the-art particle physics instrumentation will test state-of-the-art accelerator technology.

⇒RF Noise??

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An International Muon Ionization Cooling Experiment

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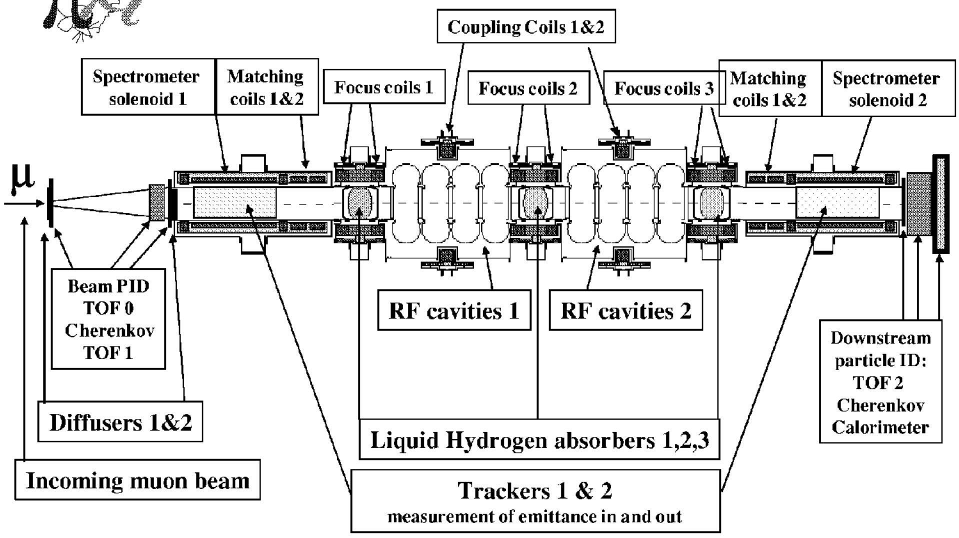
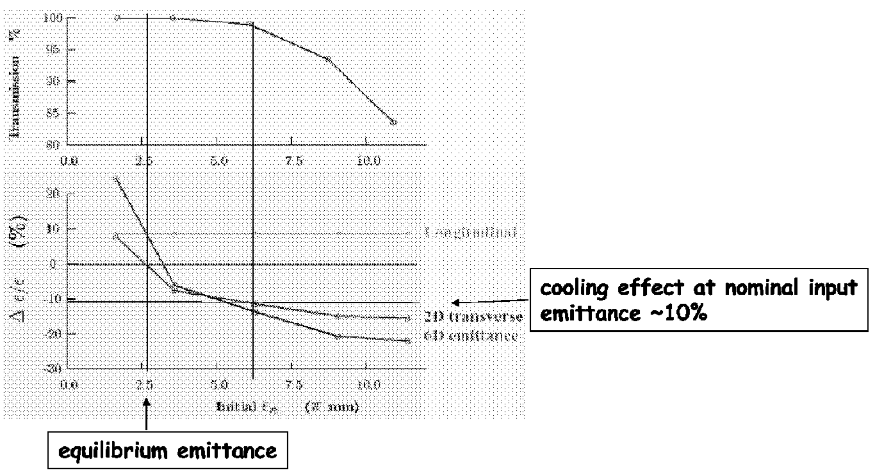
10% cooling of 200 MeV/c muons requires ~ 20 MV of RF
<u>single particle measurements</u> =>
measurement precision can be as good as $\Delta(\varepsilon_{out}/\varepsilon_{in}) = 10^{-3}$
never done before either....



Quantities to be measured in a cooling experiment



curves for 23 MV, 3 full absorbers, particles on crest

Emittance measurement

Each spectrometer measures 6 parameters per particle
x y t
$x' = dx/dz = P_x/P_z$ $y' = dy/dz = P_y/P_z$ $t' = dt/dz = E/P_z$

Determines, for an ensemble (sample) of N particles, the moments:
Averages <x> <y> etc...
Second moments: variance(x) $\sigma_x^2 = \langle x^2 - \langle x \rangle^2 \rangle$ etc...
covariance(x) $\sigma_{xy} = \langle x.y - \langle x \rangle \langle y \rangle \rangle$

Covariance matrix

$$M = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xt} & \sigma_{xx'} & \sigma_{xy'} & \sigma_{xt'} \\ \ldots & \sigma_y^2 & \ldots & \ldots & \ldots & \sigma_{yt'} \\ \ldots & \ldots & \sigma_t^2 & \ldots & \ldots & \sigma_{tt'} \\ \ldots & \ldots & \ldots & \sigma_{x'}^2 & \ldots & \sigma_{x't'} \\ \ldots & \ldots & \ldots & \ldots & \sigma_{y'}^2 & \sigma_{y't'} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \sigma_{t'}^2 \end{pmatrix}$$

Getting at e.g. $\sigma_{xt'}$ is essentially impossible with multiparticle bunch measurements

Evaluate emittance with:

$$\varepsilon^{6D} = \sqrt{\det(M_{xytx'y't'})}$$

$$\varepsilon^{4D} = \sqrt{\det(M_{xyx'y'})} = \varepsilon_\perp^2$$

Compare ε^{in} with ε^{out}

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requirements on spectrometer system:

1. must be sure particles considered are muons throughout
   1.a reject incoming e, p, π
   => TOF 2 stations 10 m flight with 70 ps resolution
   1.b reject outgoing e => Cerenkov + Calorimeter

2. measure 6 particle parameters
   i.e. x,y,t, p_x/p_z , p_y/p_z , E/p_z

3. measure widths and correlations ...
   resolution in all parameters must be better than 10% of width at equilibrium emittance (correction less than 1%)
   $\sigma^2_{meas} = \sigma^2_{true} + \sigma^2_{res} = \sigma^2_{true} [1 + (\sigma_{res}/\sigma_{true})^2]$

4. robust against noise from RF cavities

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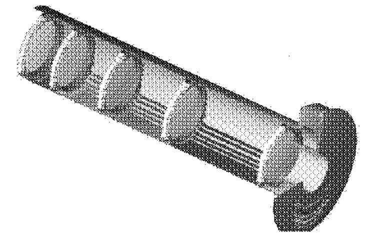
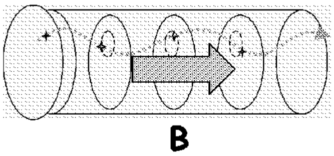
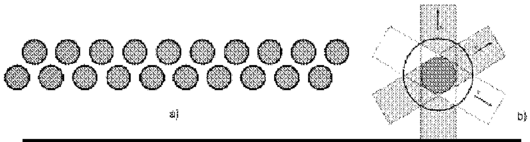
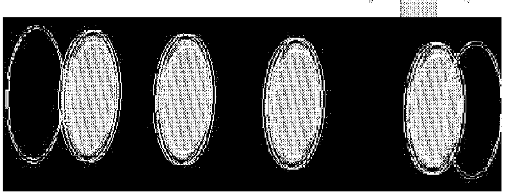
tracking in a solenoid:









SIMULATIONS:

LOI: DWARF4.0 by P.Janot: a fast simulation including dE/dx & MS (ad-hoc)

Proposal: G4MICE: Geant 4 application including everything including noise
(long term FOUNDATION FOR MICE software)

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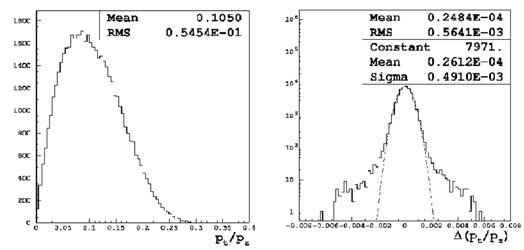
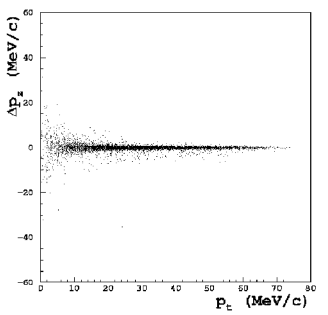
RESULTS

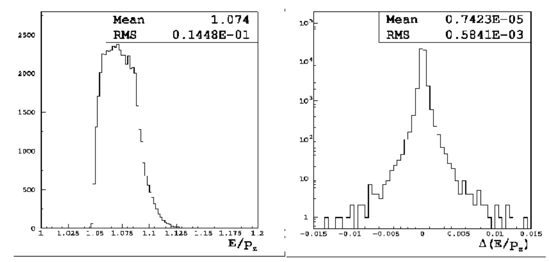
TRANSVERSE MOMENTUM RESOLUTION σ_{pt} = 110 keV



P_z resolution degrades at low p_t :



resolution in E/P_z is much better behaved



measurement rms is 4% of beam rms

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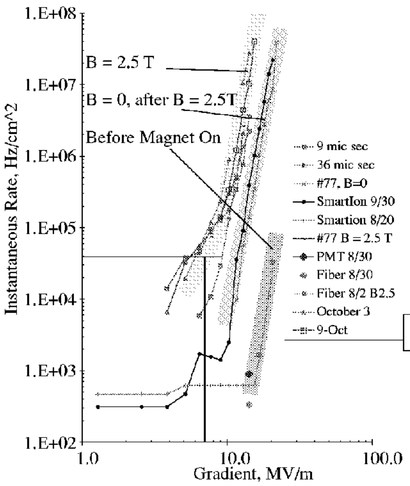
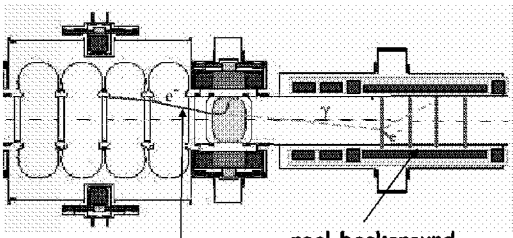
Backgrounds





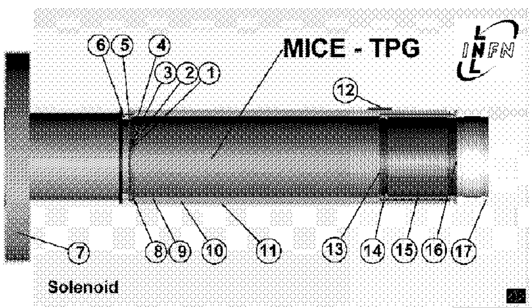
measured dark currents

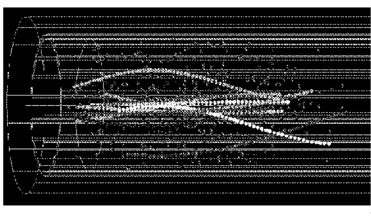
real background reduced by factor
L/X0(H2) . L/X0(det)
0.07 0.0026

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

Extrapolation to MICE (201 MHz):
scale rates as (area.energy) X 100
and apply above reduction factor 2 10^{-4}

4 10^4 Hz/cm^2 @ 8 MV/m @805 MHz
$\Rightarrow$0.8 kHz/cm^2 per sci-fi
$\Rightarrow$ 500 kHz/plane
! within $\pm$ one order of magnitude !





at noise rate similar to that simulated for fibers, no difficulty finding tracks and measuring them.

resolution somewhat better than sci-fi (which is good enough)

difficulty: nobody knows the effect of RF photons on the GEM themselves
tests in 2003, decision October 2003

International Muon Ionization Cooling Experiment

Steering committee:
A. Blondel* (University of Geneva) H. Haseroth (CERN**) R. Edgecock (Rutherford Appleton Laboratory)
Y. Kuno (Osaka University)
S. Geer (FNAL) D. Kaplan (Illinois Institute of Technology) M. Zisman (Lawrence Berkeley Laboratory)
* convener for one year (June 2001-2002)

Conveners of Technical teams:
a) Concept development and simulations: Alessandra Lombardi (CERN **) Panagiotis Spentzouris (FNAL) Robert B Palmer (BNL)
b) Hydrogen absorbers: Shigeru Ishimoto (KEK) Mary-Anne Cummings (Northern Illinois)
c) RF cavities and power sources Bob Rimmer (LBNL) Roland Garoby (CERN**)
d) Magnets Mike Green (LBNL) Jean-Michel Rey (CEA Saclay)
e) Particle detectors Vittorio Palladino (INFN Napoli) Alan Bross (FNAL)
f) Beam lines Rob Edgecock (RAL) Claude Petitjean (PSI)
g) RF radiation Jim Norem (Argonne) Ed McKigney (IC London)

Participating institutes
INFN Bari INFN Milano INFN Padova INFN Napoli INFN LNF Frascati Roma
INFN Trieste INFN Legnaro INFN Roma I Roma II Roma III
Rutherford Appleton Laboratory University of Oxford Imperial College London
DAPNIA, CEA Saclay
Louvain La Neuve
NESTOR institute University of Athens Hellenic Open University
CERN** (H. Haseroth)
** only some limited simulation work and lend of used or refurbished equipment
University of Geneva University of Zurich ETH Zurich PSI
KEK Osaka University
Argonne National Laboratory Brookhaven National Laboratory Fermi National Accelerator Laboratory
Lawrence Berkeley National Laboratory University of California Los Angeles University of Mississippi
University of Indiana/ U.C. Riverside, Princeton University
University of Illinois University of Chicago – Enrico Fermi Institute
Michigan State University Northern Illinois University
Illinois Institute of Technology

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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, $e^+ \mu^- \langle\text{-}\rangle e^- \mu^+$
--> 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-> $\pi^0 \nu \nu$)

In parallel to long baseline neutrino experiments:
-short baseline neutrino experiments (standard fluxes X10⁴)
-- DIS on various materials and targets, charm production
-- NC/CC -> m_W (10-20 MeV) $\nu_\mu e \rightarrow \nu_\mu e$ & $\nu_e e \rightarrow \nu_e e$ -> $\sin^2\theta_W^{eff}$ (2.10^{-4})
--> design of beamline + detectors needed

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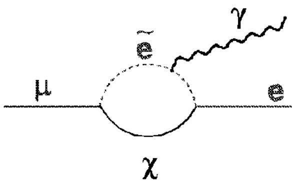
http://wwwth.cern.ch/stoppedmuons/stoppedmuons.html
Gian Giudice et al

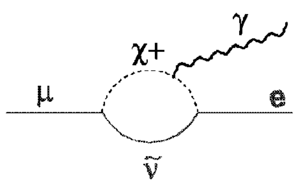
Rare muon decays

Lepton flavor violating processes $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu^- N \rightarrow e^- N$
observation of any of these decays would be
A MAJOR DISCOVERY

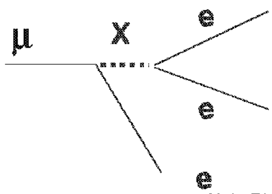
From mixed neutrino loops: completely negligible rates (10^{-50})

Rate in vicinity of observability due to SUSY loops





Or new (e.g RPV) interactions
-- four-fermion operators



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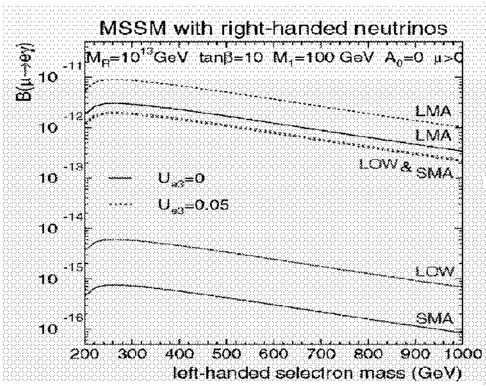
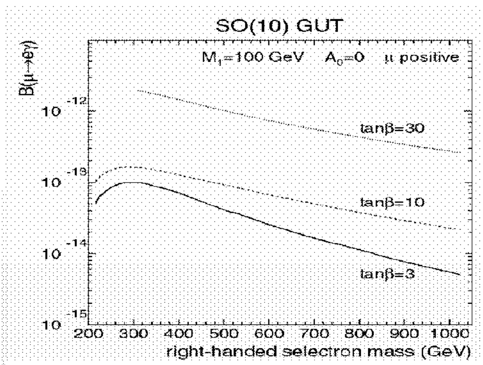
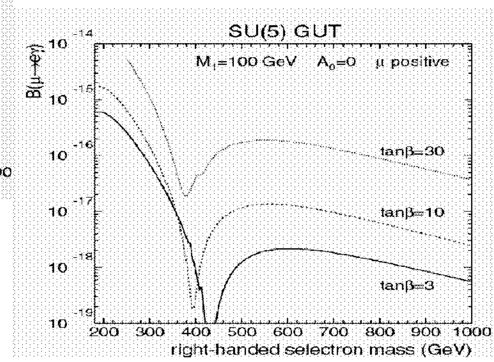
Rates for $\mu \rightarrow e\gamma$







Message: it is difficult in SUSY to avoid $\mu \rightarrow e\gamma$ at a rate visible in the next generations of expts. (PSI MEG should go to a few 10^{-14})

Present lines of thought for High Intensity Low Energy muon beams

PSI already has 1 MW DC beam of 590 MeV protons
with 5%λ_I target for muons. How can one do 1000 times better?

DC beams ($\mu \rightarrow e\gamma$, $\mu \rightarrow eee$)

1. **Thin inner target in proton accumulator**
   advantages: very efficient use of proton beam, point source
   difficulties: - can target take the heat?
   - creates high-radiation area inside ring 20 - 120

2. **Or Use full DC SPL 24 MW with thin muon target 20**

   + solenoid collection $(1/.16)^2 = 40$
   + better experiments ?

Pulsed beam ($\mu^- N \rightarrow e^- N$)

1. **Use proton beam from buncher**
2. **Use muons at the end of cooling channel!**

--> need now conceptual design of target station and muon beams

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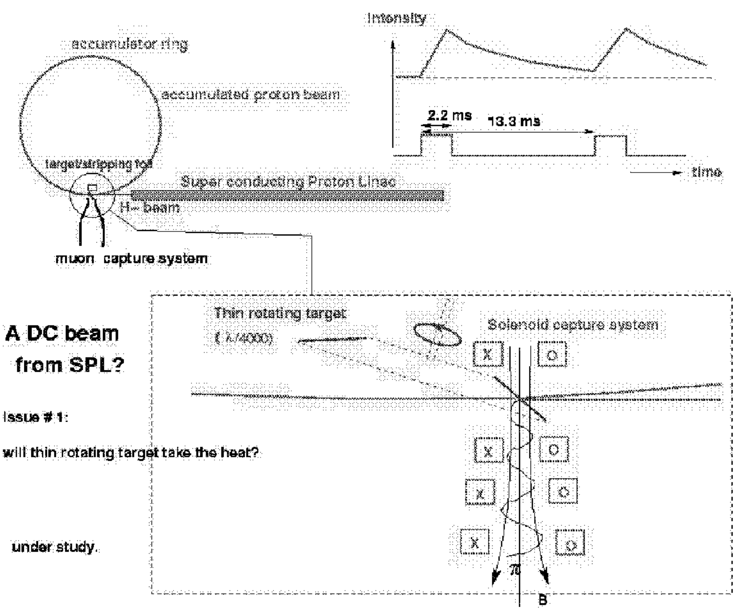

A DC beam from SPL?

Issue # 1:

will thin rotating target take the heat?

under study.

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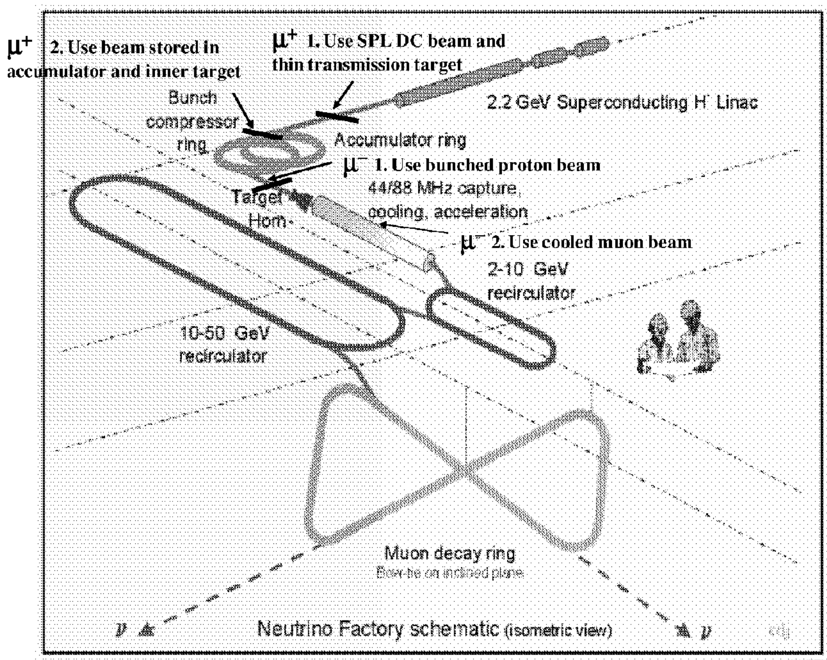
Thoughts for muon targets in neutrino factory complex



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Neutrino scattering experiments

Event rates very high.
High energy + small ring preferred

M. Mangano et al have evaluated in realistic way performance of possible experiments.

=> detector must measure scattered μ as well as e

Big gains of precision in
- -- DIS structure functions
- -- nuclear effects,
- -- Higher twist effects
- -- QCD fits
- -- Polarised structure functions
  (neutrinos ARE polarised! Polarised targets)

ELECTROWEAK STUDIES
- -- NC/CC (efficient electron ID crucial here!)
- -- $\nu_\mu e \rightarrow \nu_\mu e$ & $\nu_e e \rightarrow \nu_e e$ -> $\sin^2\theta_w^{eff}$ ($\pm 2.10^{-4}$)

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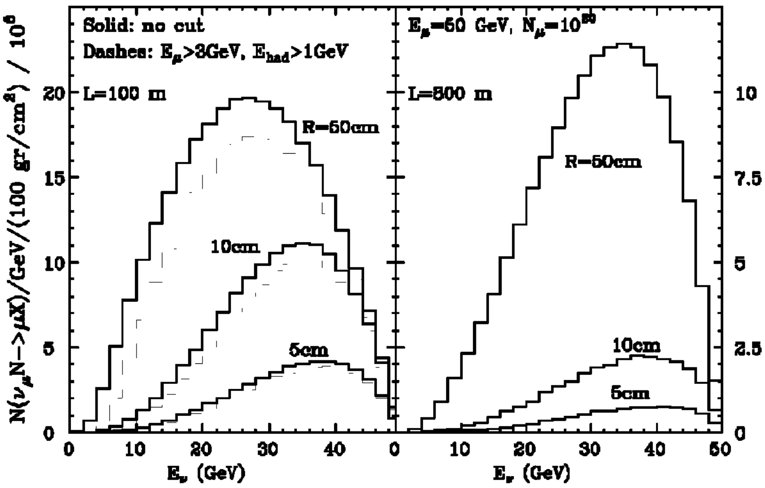
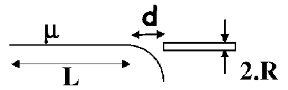
Neutrino fluxes at near-by detectors



Set-up:



Integrated event rates 2.10^8/kg/year
prefer small ring, short straight-sections

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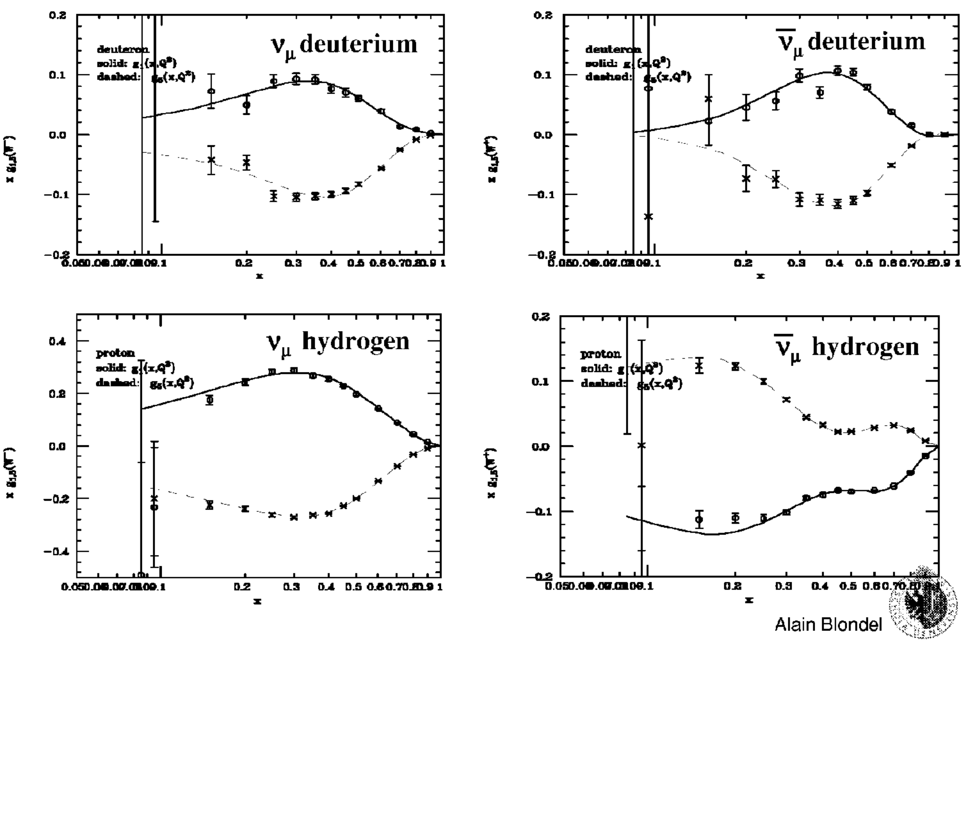
Sort out nucleon spin structure



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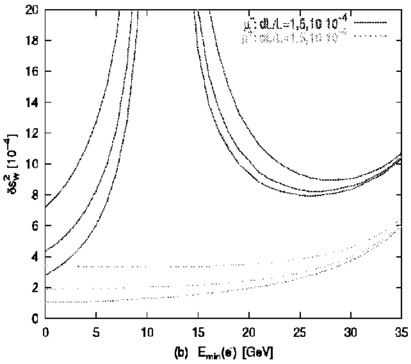
Precision physics with neutrinos

=> $\nu_\mu e \rightarrow \nu_\mu e$ & $\nu_e e \rightarrow \nu_e e$

10^7 events/year in L=20m R=20 cm
liq. scintillator detector
μ^+ beam much better. ->



flux normalization crucial.
$\Delta\Phi/\Phi = 10^{-3}$ allows $\Delta\sin^2\theta_w^{eff} = \pm 2.10^{-4}$

Noted: $\nu_\mu e \rightarrow \mu^- \nu_e$ provides
absolute normalization of μ^-beam w 10^8 evts/yr
(carry over to μ^+ beam?)

Accept e above E_{min}

=> νN (NC/CC-> m_W) under study

Beyond ν-factory

<u>Step 1 towards muon collider(s)</u>

Higgs and top factories

benefit from Higgs couplings ($\sigma_{higgs} \alpha\ m^2$)
and superior energy calibration/resolution
ideal for m_h= 115 GeV/c^2 !
and for study of Susy Higgses H,A
(masses, widths, couplings and CP violation)
--> experimental feasibility needed (backgrounds, efficiencies,etc.)

Energy frontier (synergy with CLIC studies) why muons?

muon collider is not a new idea (Skrinsky 1971)
but it involves considerable difficulties.
Why would one want to do this?

Muons charateristics:	With respect to e^+e^- colliders
A. Muons are <u>leptons</u>	
• Collisions to the full energy; • Low and well-known physics backgrounds.	=
B. Muons are <u>heavy</u>	
• No synchrotron radiation: Small collider rings;	+
• No beamstrahlung: Energy resolution can be excellent;	+++
• Large coupling to Higgs bosons: $\mu^+\mu^- \to$ h, A, H cross section sizeable.	+++
C. Muons are <u>polarized</u> ($\pi^\pm$ decays) **and they <u>decay</u>**	
• Infinitely precise energy calibration: Precise study of resonances (and of thresholds).	+++

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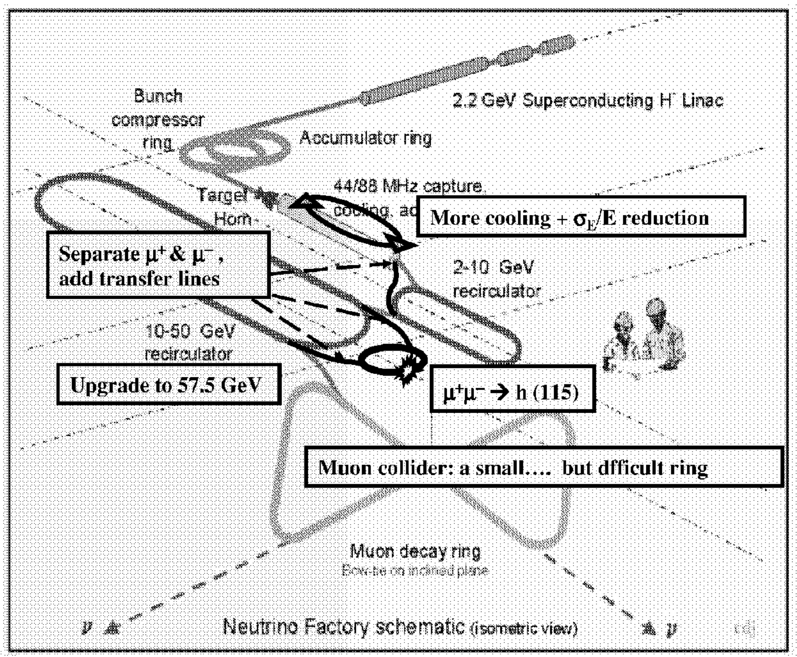
From neutrino factory to Higgs collider



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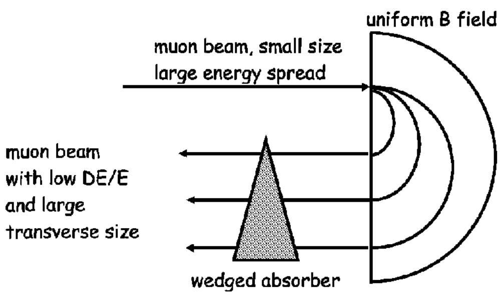
challenges of $\mu\mu$ collider

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

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} ?

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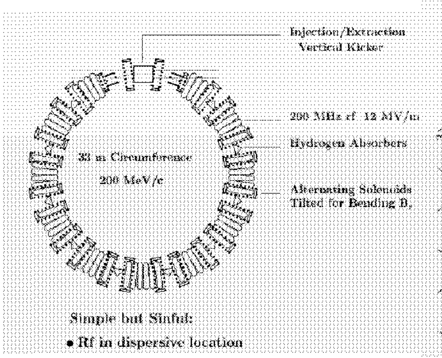
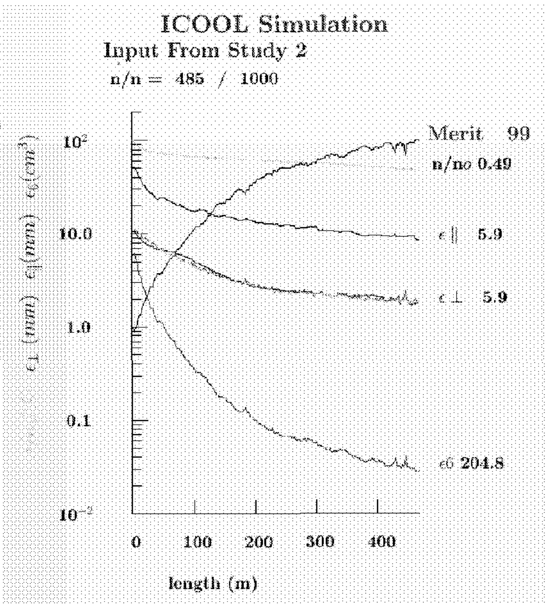
COOLING RINGS

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

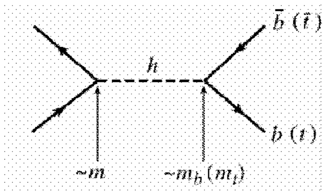




major problem: Kickers

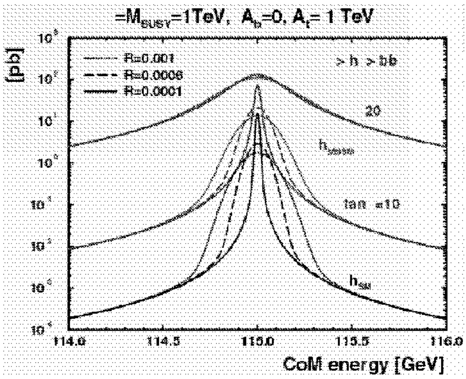
(Same problem occurs in Japanese acceleration scheme with FFAG)

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=DE/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)

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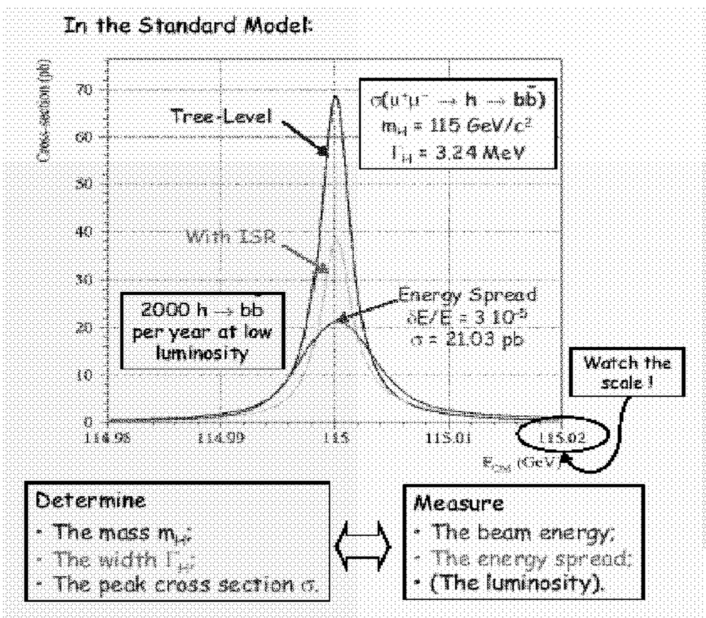
The Higgs Line Shape



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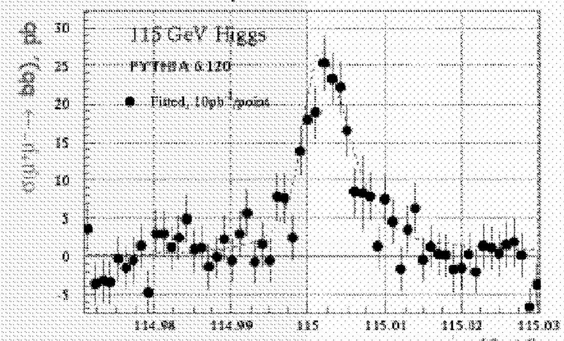
With an irrealistic 10 pb^{-1} / MeV scan:



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 $\delta E/E$

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Higgs Factory #2: $\mu^+ \mu^- \to$ 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.

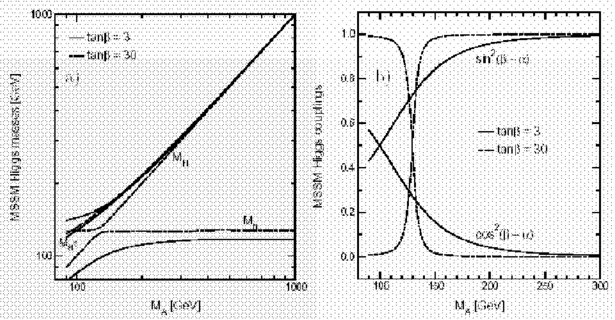

Figure 2.1.6: *The masses of the Higgs bosons in the MSSM (a) and their squared couplings to the gauge bosons (b) for two representative values of* $\tan\beta = 3$ *and* 30 [ ].

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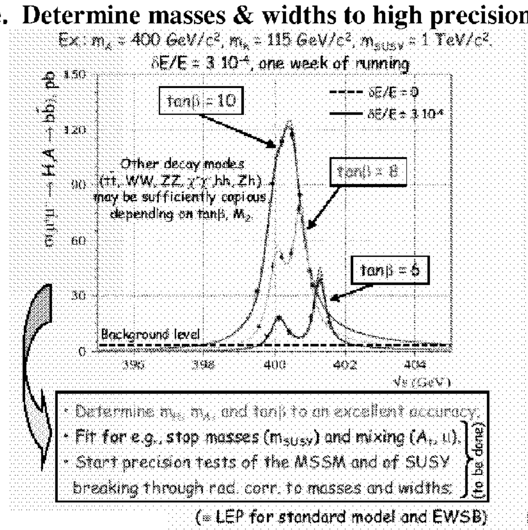
Higgs Factory #2: $\mu^+ \mu^- \to H, A$

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.....)



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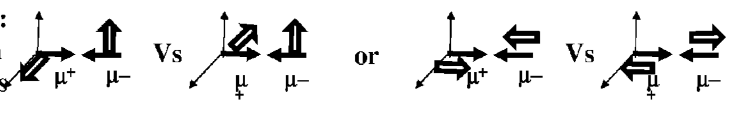
CP violation in Higgs sector

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ a \end{pmatrix} = M \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \text{(if CP conserved)} \begin{pmatrix} h \\ A \\ H \end{pmatrix}$$

Effects are very small in SM, MSSM (loops), but could be larger in general

M= 3X3 matrix of Higgses with different CP numbers

Light Higgs: polarization asymmetries



Heavy Higgs: any mixing/interference between H and A => CP violation
Interference or "wrong decays"-> *CP violation* look for A->hh, for instance.

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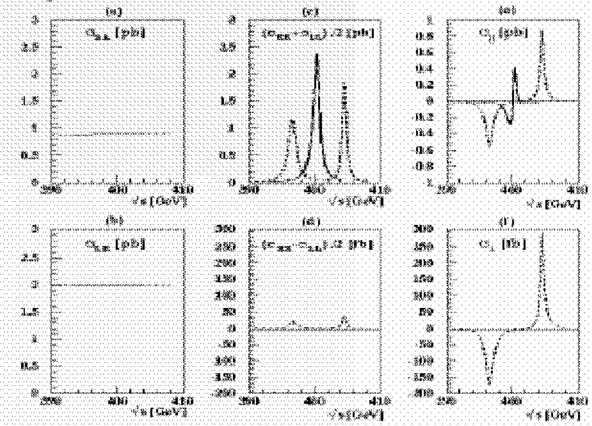
- SUSY parameters (e.g., A_t and μ) may have phases, which lead to CP violation in the Higgs sector and H/A mixing.
- Muon polarization (even partial) allows to measure CP sensitive cross sections: σ_{LL}, σ_{RR}, σ_{LR}, σ_{RL}, $\sigma_{//}$, σ_T.
- Nonzero values for σ_{RR} - σ_{LL} or σ_T come from nonzero phases of the MSSM parameters.

e.g., for $\tan\beta = 3$, $|A_t| = |\mu| = 1$ TeV, $m_{H^+} = 400$ GeV:



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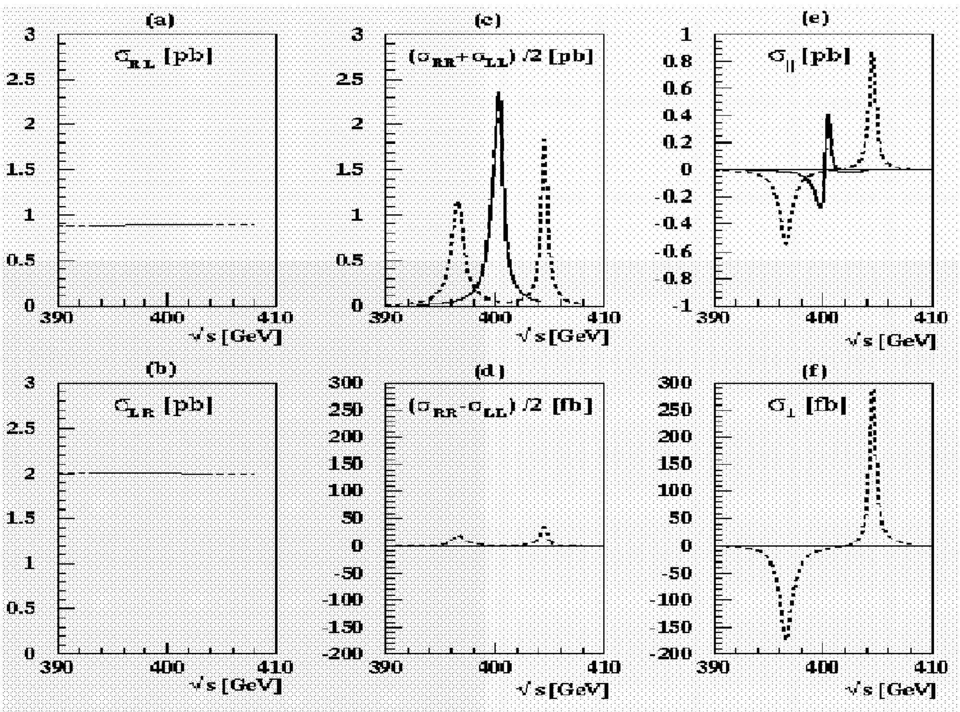

Much to do!

-- R&D for long baseline detectors

-- target stations & beam designs for stopped muon physics

-- beam design for near-by neutrino physics

-- nufact target tests (collection system must be integrated)

-- cooling test facility

-- etc etc

project has many facets; ideal to European competence

world wide:
communication takes place already (NUFACT series) MICE is international, etc…

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Conclusions

NuFact Complex addresses essential physics issues that will not be addressed by High Energy colliders (LHC, NLC/Tesla):
- **-- lepton number violation (ν–mixing, rare muon&K decays)**
- **-- new CP violation phenomena (neutrinos, Higgses)**

and offers a large variety of physics opportunities and synergies
- **-- high intensity neutrino physics**
- **-- nuclear physics (muonic atoms, radioactive nuclei, etc..)**

AN ATTRACTIVE OPTION FOR EUROPE AFTER LHC
Studies have become considerably more concrete over the last year thanks to an active and motivated community

There is a scheme for a NuFact that seems well adapted for CERN. Much work remains to be done to ascertain performance and.. Simply learn how a muon machine could work

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