PARTICLE PHYSICS alongside LHC

Alain Blondel
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Recently a big CERN Yellow Report was published

'ECFA/CERN studies of a European Neutrino Factory Complex'
CERN 2004-002 ECFA/04/230

several 100 authors
-- neutrino factory (the accelerator)
incl beta-beam and low energy, SPL based, superbeam
-- Oscillation physics
incl. beta-beam and superbeam
-- physics with low energy muon beams (SPL)
-- High energy neutrino interactions (Short Baseline @ Neutrino Factory)
-- Kaon physics (requires E>~16 GeV proton driver)
-- muon collider and Higgs Factory

and a large Workshop was held

Workshop on

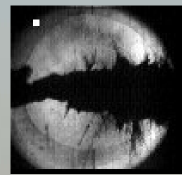
PHYSICS

WITH A

MULTI-MW PROTON SOURCE

CERN, Geneva, May 25-27, 2004

The workshop explores both the short- and long-term opportunities for particle and nuclear physics offered by a multi-MW proton source such as a proton linear accelerator or a rapid-cycling synchrotron.
This source would provide Muon and Electron Neutrino beams of unprecedented intensity, superior slow Muon and possibly Kaon facilities, as well as a world-leading Radioactive Ion Beam facility for Nuclear, Astro- and fundamental physics.



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http://physicsatmwatt.web.cern.ch/physicsatmwatt/

PHYSICS with a high intensity (4 MW) proton driver

1. LHC intensity upgrade

2. neutrino oscillations
-- superbeam
-- betabeam
-- neutrino factory

3. neutrino interactions

4. low energy muon beams and… muon collider

5. Kaon physics

6. Nuclear physics

7. Applied sciences (medicine, transmutation, materials,etc)

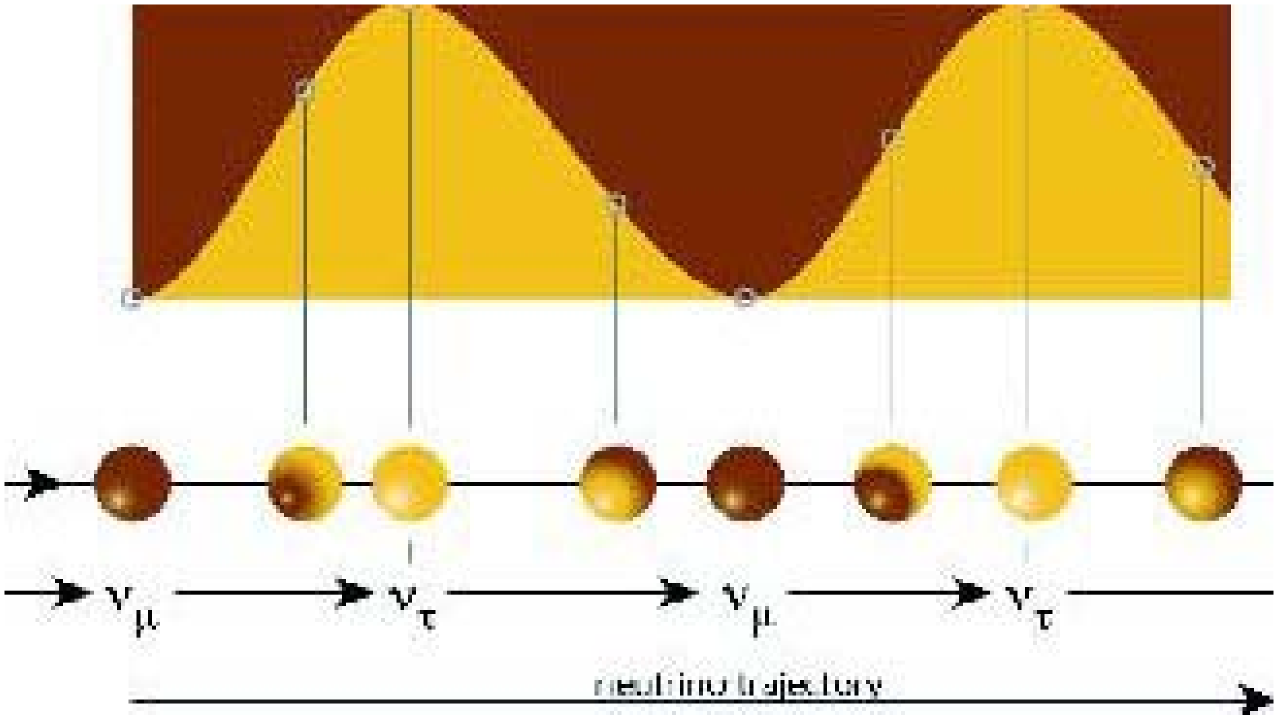
Interesting project – and CERN would be a good place for it

Neutrino Oscillations

After many years (since 1968!) it was established in 1998
that neutrinos change flavor when travelling through space.

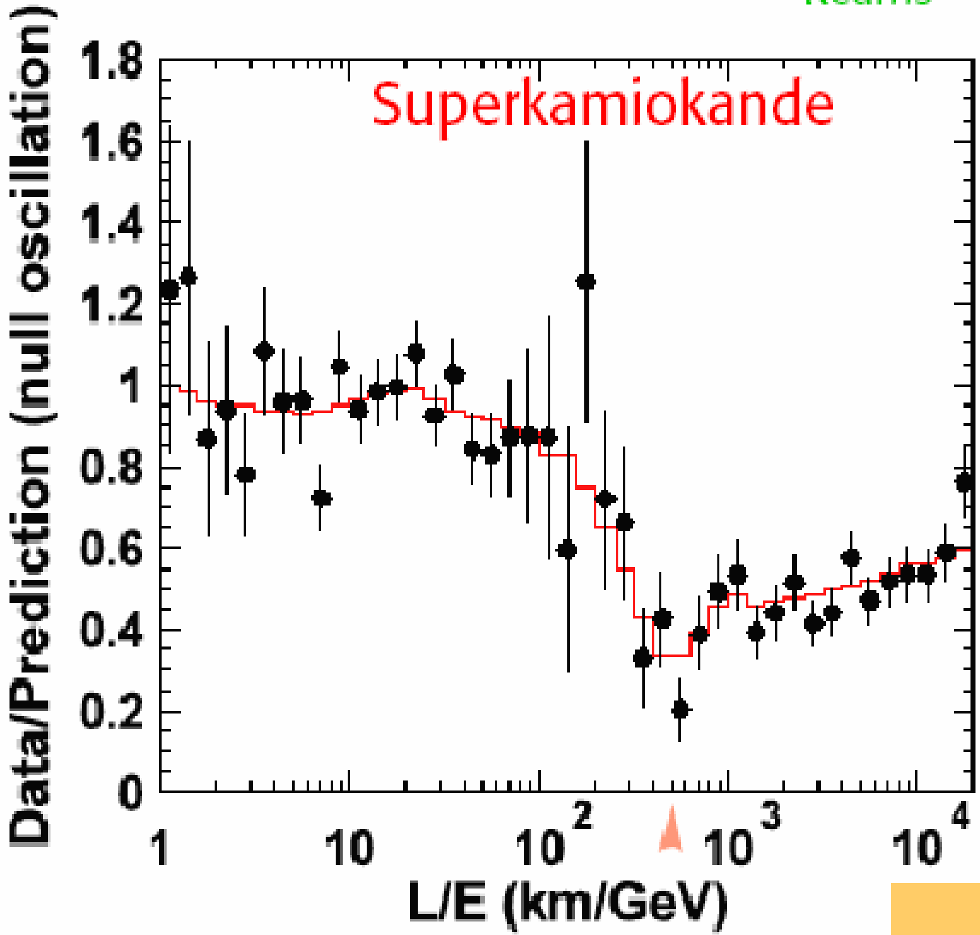
First observation: solar neutrinos ! (150 000 000 km)
Second observation: neutrinos produced in the atmosphere and going through the earth. (13000 km)
Recent observation 2003 (exp. K2K, KAMLAND ~200 km)
with accelerator or reactor neutrinos

Observation of a quantum phenomenon over distances of hundred to millions of km!



Atmospheric neutrinos: SuperKamiokande L/E analysis

Kearns



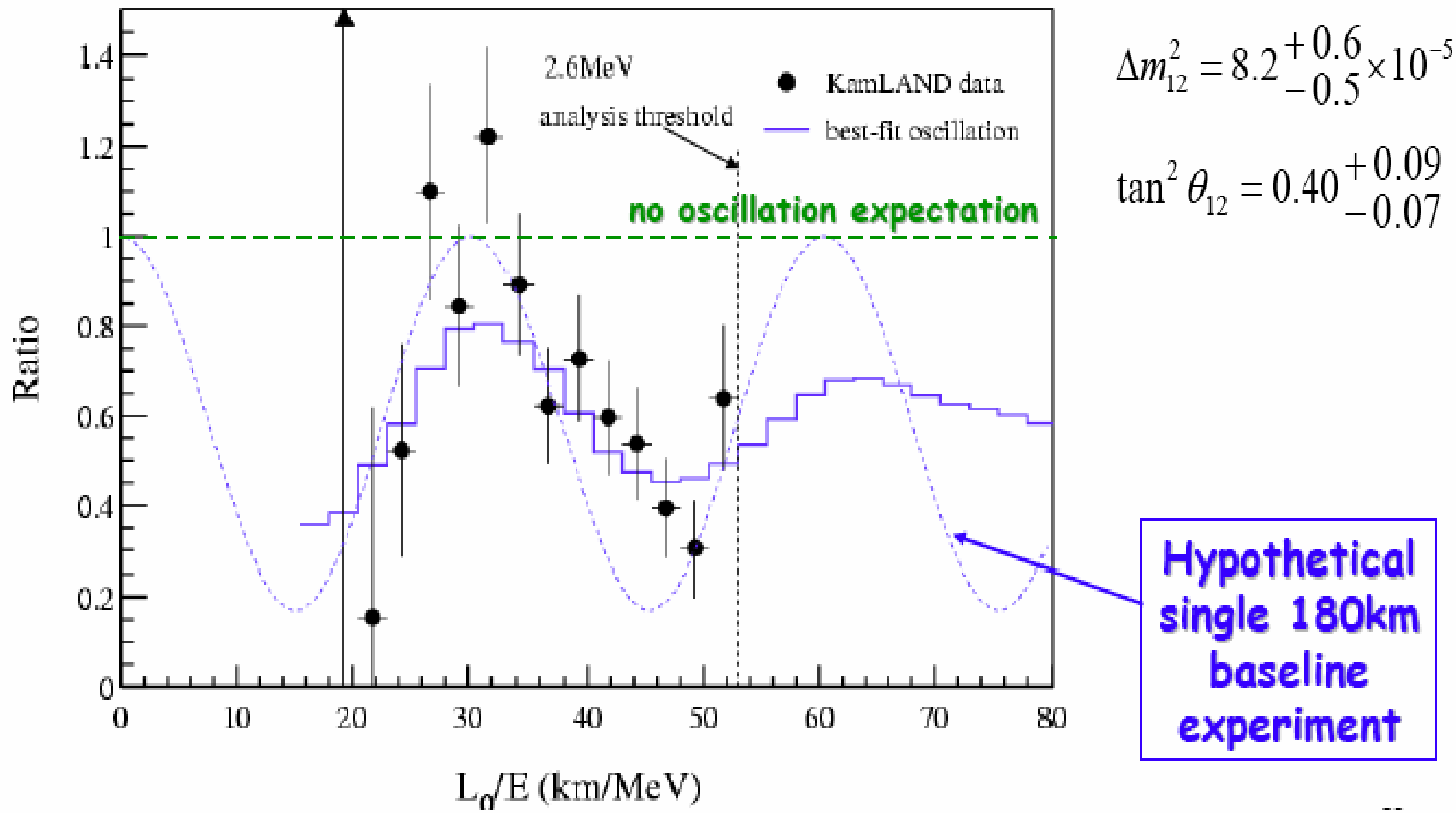
Atmospheric "wavelenght"

oscillation dip seen at ~500 km/GeV

KamLAND "L"/E distribution: direct look at oscillations

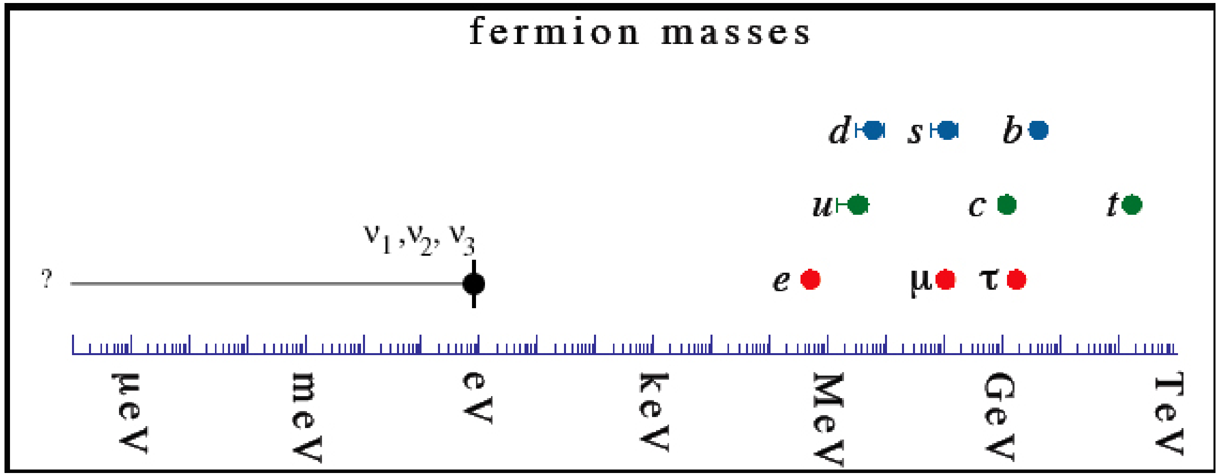
Solar "wavelenght" about 30 times longer

Gratta



$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$

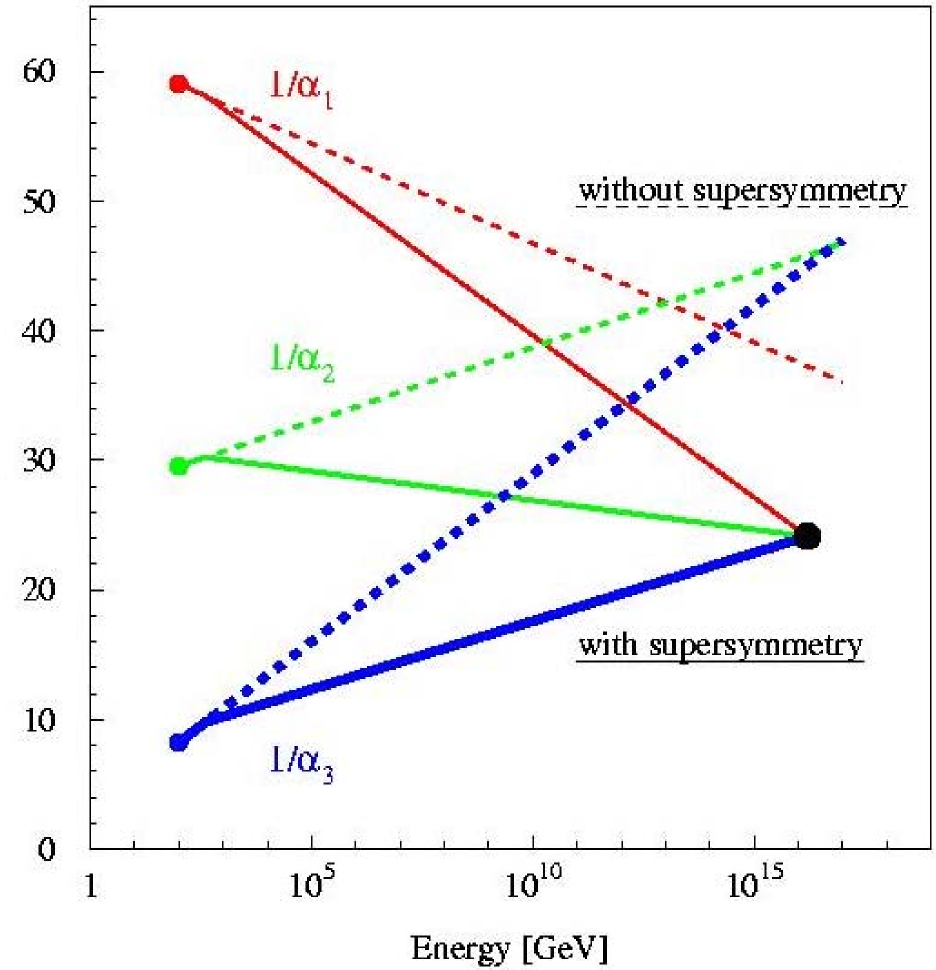


The mass spectrum of the elementary particles. Neutrinos are 10^{12} times lighter than other elementary fermions. The hierarchy of this spectrum remains a puzzle of particle physics.

Most attractive wisdom: the see-saw mwchanism,
the neutrinos are very light because they are low-lying states
in a split doublet with heavy neutrinos of mass scale interestingly
similar to the grand unification scale.

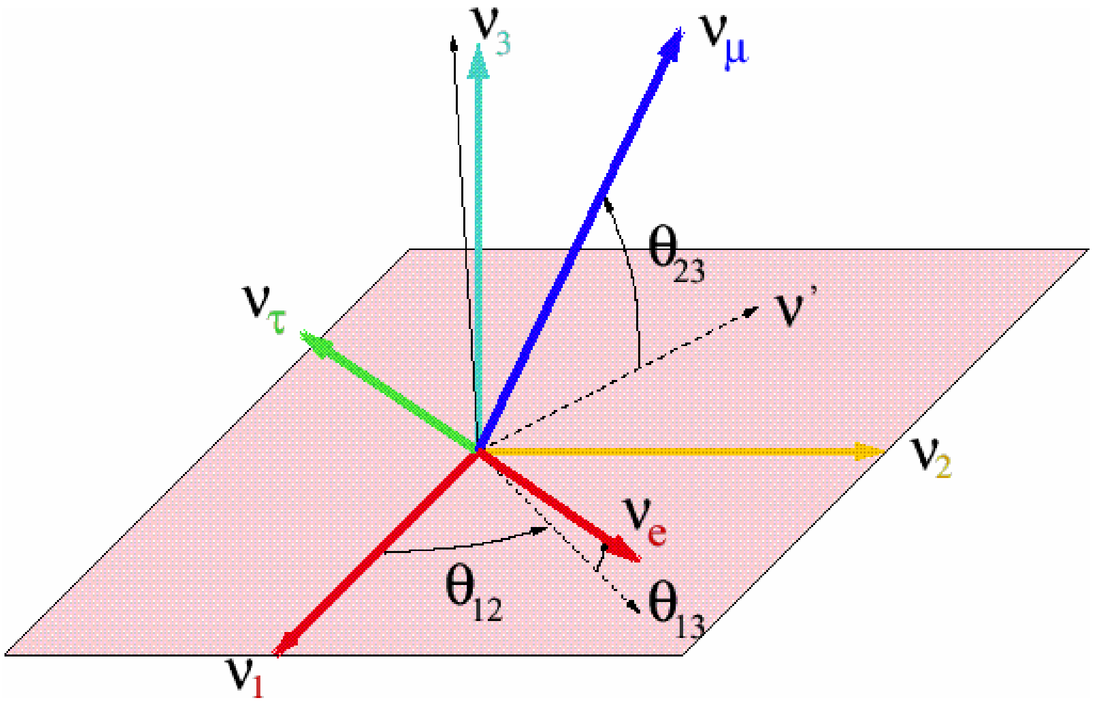
$m_{\nu.} M = \langle v \rangle^2$ with $\langle v \rangle \sim= m_{top} = 174$ GeV, $m_{\nu.} = O(10^{-2})$ eV

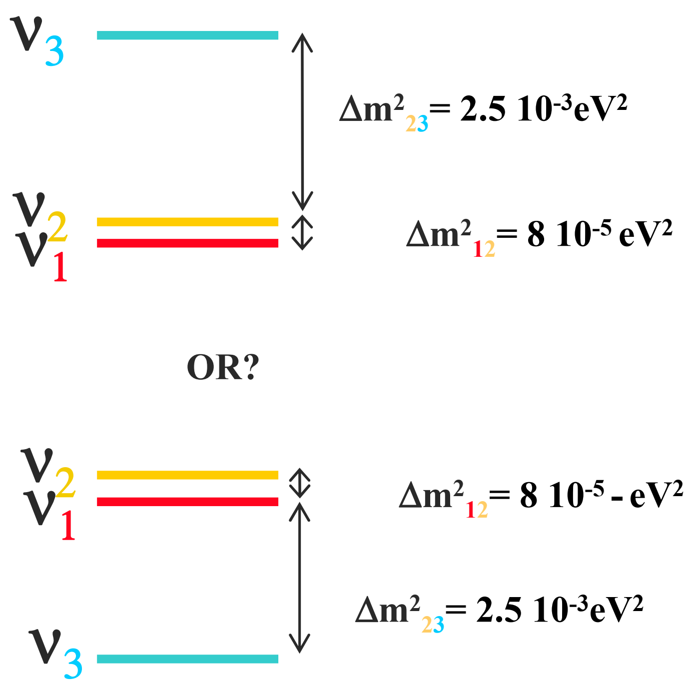
==> $M \sim 10^{15}$ GeV



60
50
40
30
20
10
0
1
10^5
10^{10}
10^{15}
Energy [GeV]
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
without supersymmetry
with supersymmetry

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

θ_{13} , phase δ , sign of Δm_{13}^{2}

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

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

Solar $\Delta m^2 = 8\ 10^{-5}\ eV^2$ $L = 16000$km @ 1 GeV

Consequences of 3-family oscillations:

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

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

II There will be CP or T violation

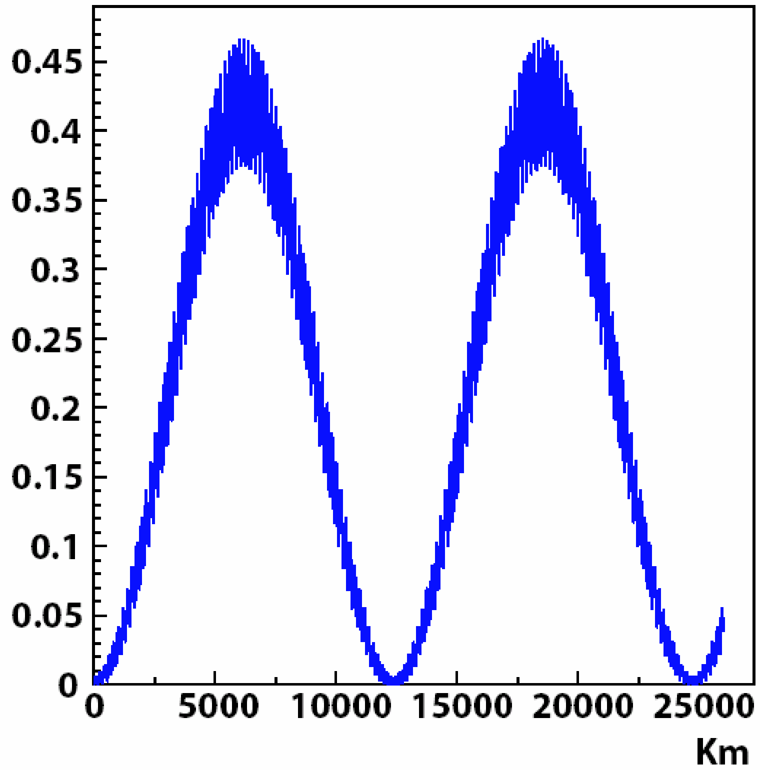
CP: $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P(\nu_\mu \leftrightarrow \nu_e)$

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

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

Oscillations of 250 MeV neutrinos;

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



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

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

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

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

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

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

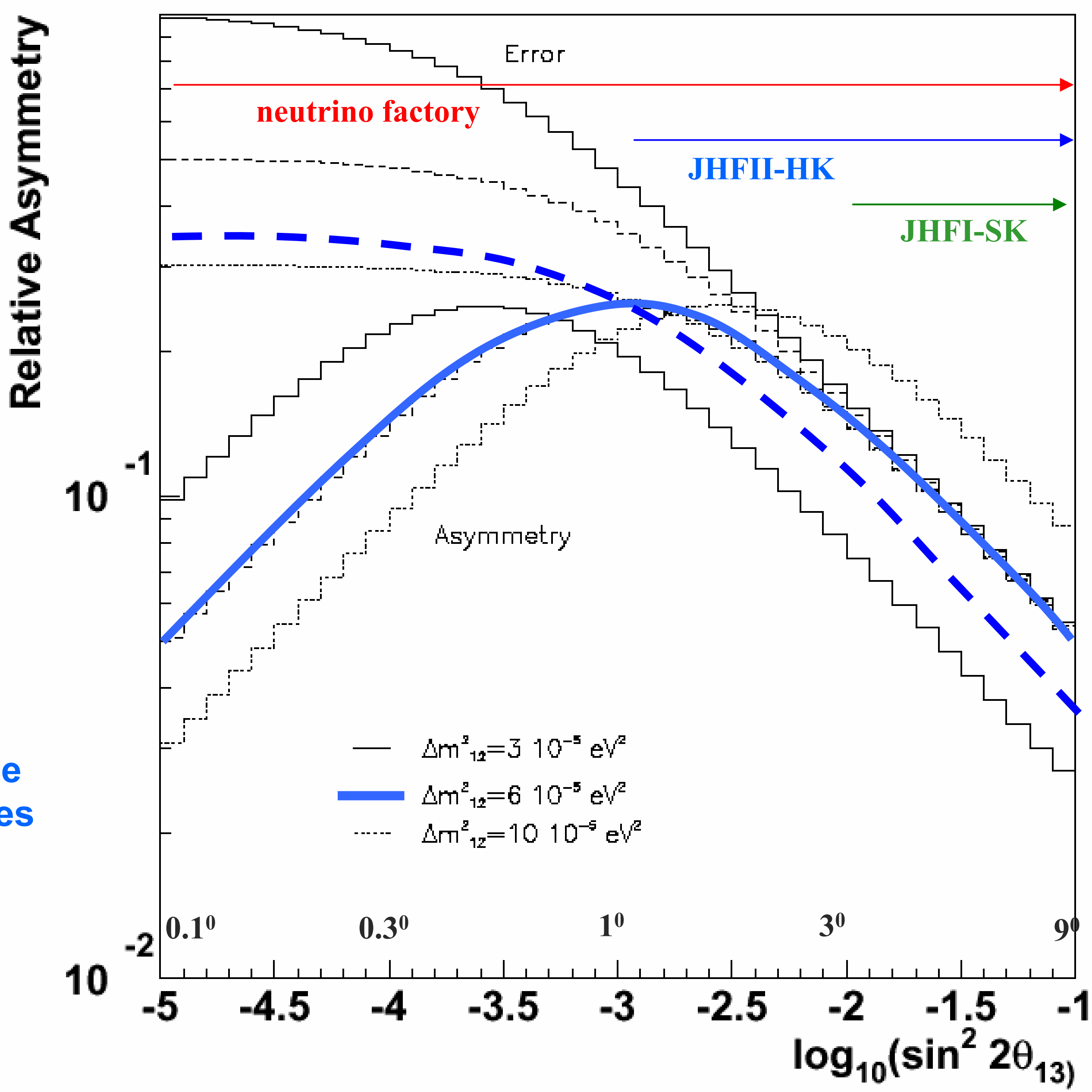
at wavelength at which 'solar' = 'atmospheric' and for $\nu_e \to \nu_\mu$, ν_τ

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

T asymmetry for sin δ = 1

!

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



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

LEPTONIC T , CP VIOLATION

The baryon asymmetry in the Universe… requires CP or T violation.

That of the quarks is not enough!

Perhaps there was —

$$\Gamma[N(\text{Heavy Majorana}) \to \ell^- + \text{Higgs}^+]$$
$$\neq \Gamma[N(\text{Heavy Majorana}) \to \ell^+ + \text{Higgs}^-].$$

Boris Kayser

This leptonic asymmetry would in turn generate baryon asymmetry.
(energies typical of the particles that would be exchanged in Baryon decay $10^{11\text{-}15}$ GeV or so)

NB this is CP asymmetry for the Heavy Majorana Neutrinos

1. **we don't know if neutrinos are Majorana particles**
2. **The CP phases that enter are those of the heavy neutrinos, not the light ones.**

Nevertheless: leptonic CP violation *may be* the reason why we exist…
lets look for it!

Road Map

Experiments to find θ_{13} :

1. **search for $\nu_\mu \to \nu_e$ in conventional ν_μ beam (MINOS, ICARUS/OPERA)**
   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 (BNL → Homestake, SPL →Fréjus)**

Precision experiments to find CP violation

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

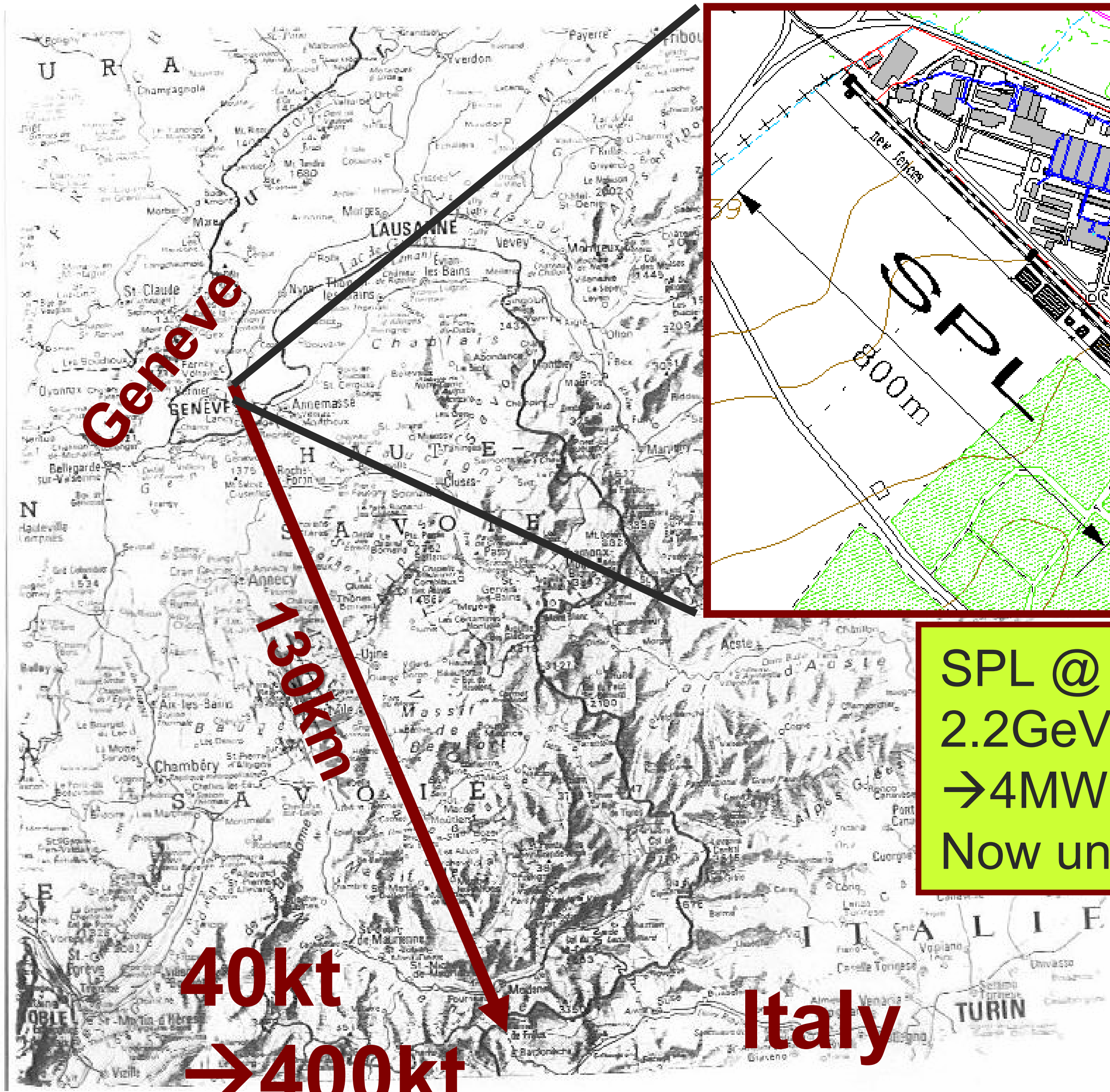
1. **beta-beam** $^{6}He^{++} \to {}^{6}Li^{+++}\ \bar{\nu}_e\ e^-$ **and** $^{18}Ne^{10+} \to {}^{18}F^{9+}\ \nu_e\ e^+$

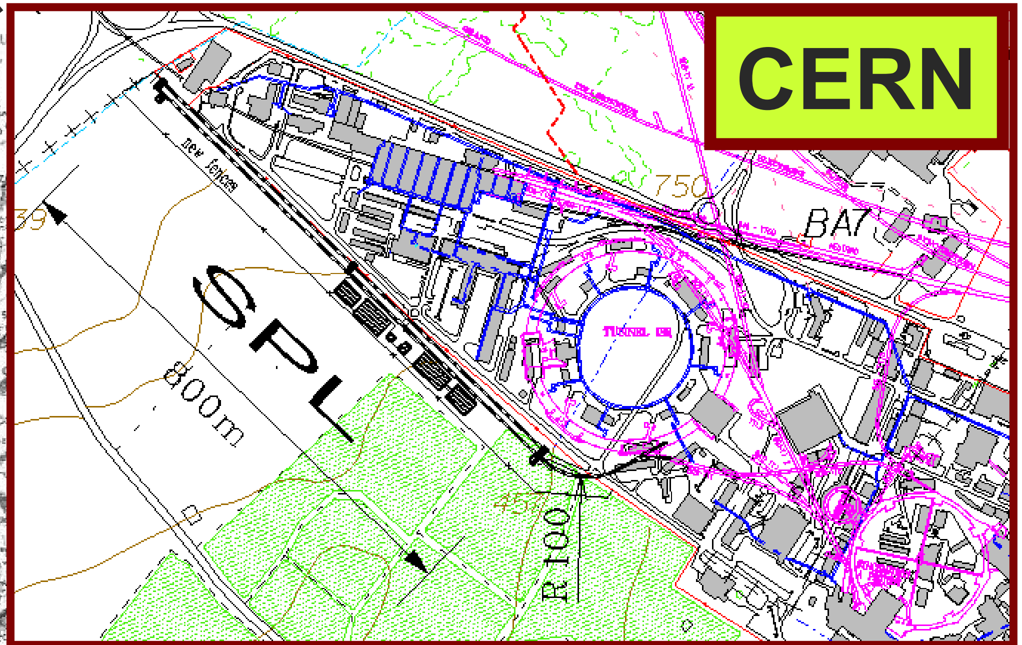
2. **Neutrino factory with muon storage ring**

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

fraction thereof will exist .

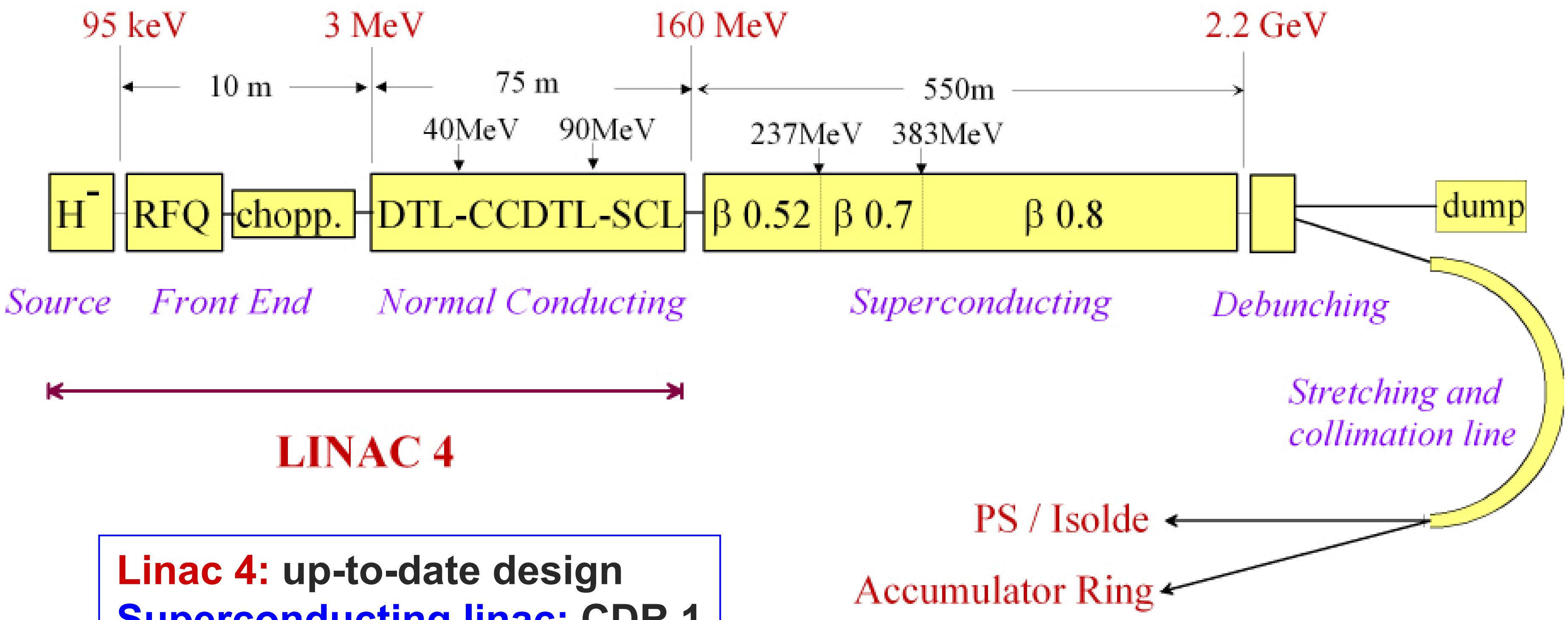
Europe: SPL→Frejus





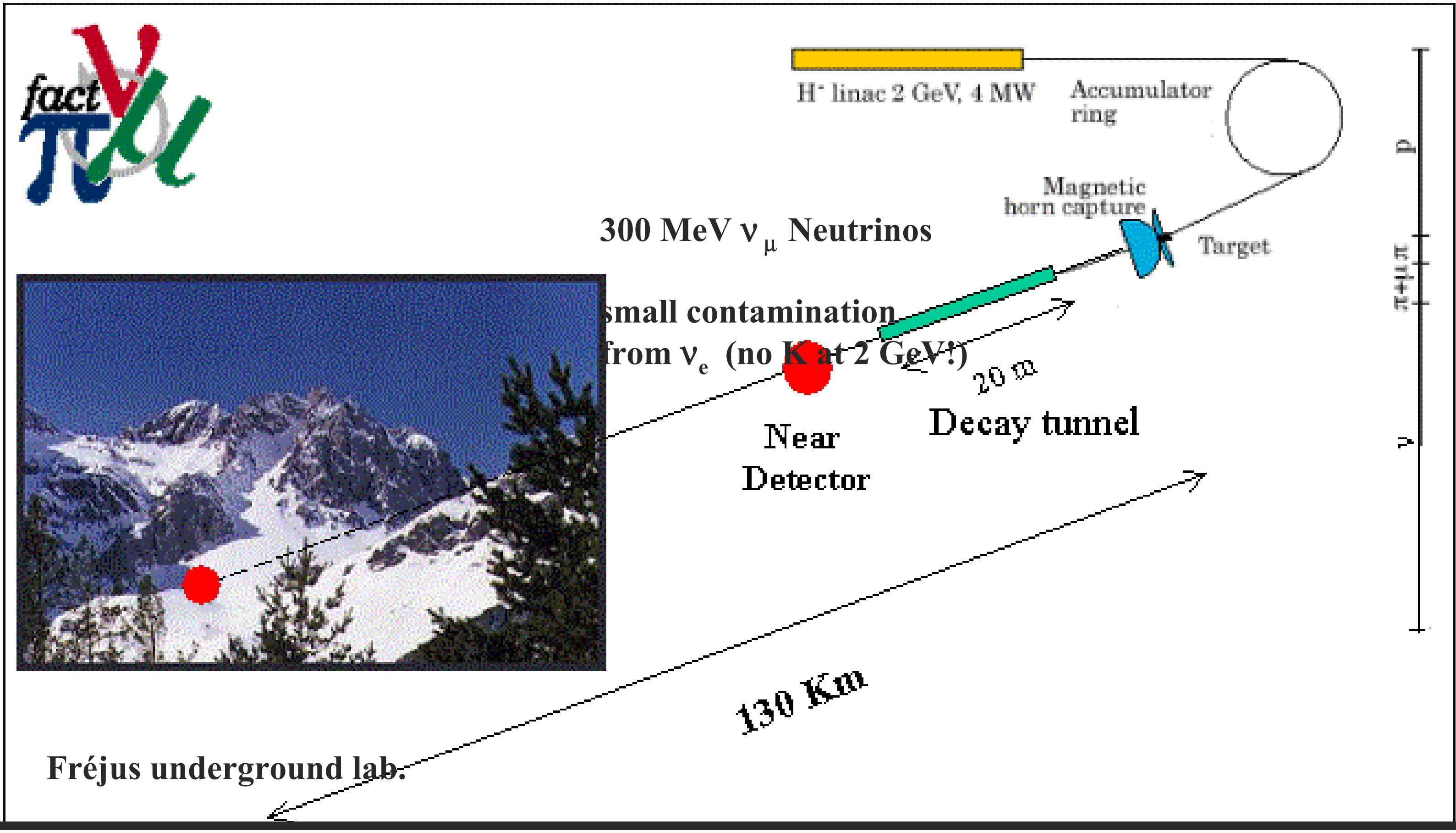
SPL @ CERN
2.2GeV, 50Hz, 2.3x10^{14} p/pulse
→4MW
Now under R&D phase

SPL block diagram (CDR-1)



Linac 4: up-to-date design
Superconducting linac: CDR 1

Possible step 0: Neutrino SUPERBEAM



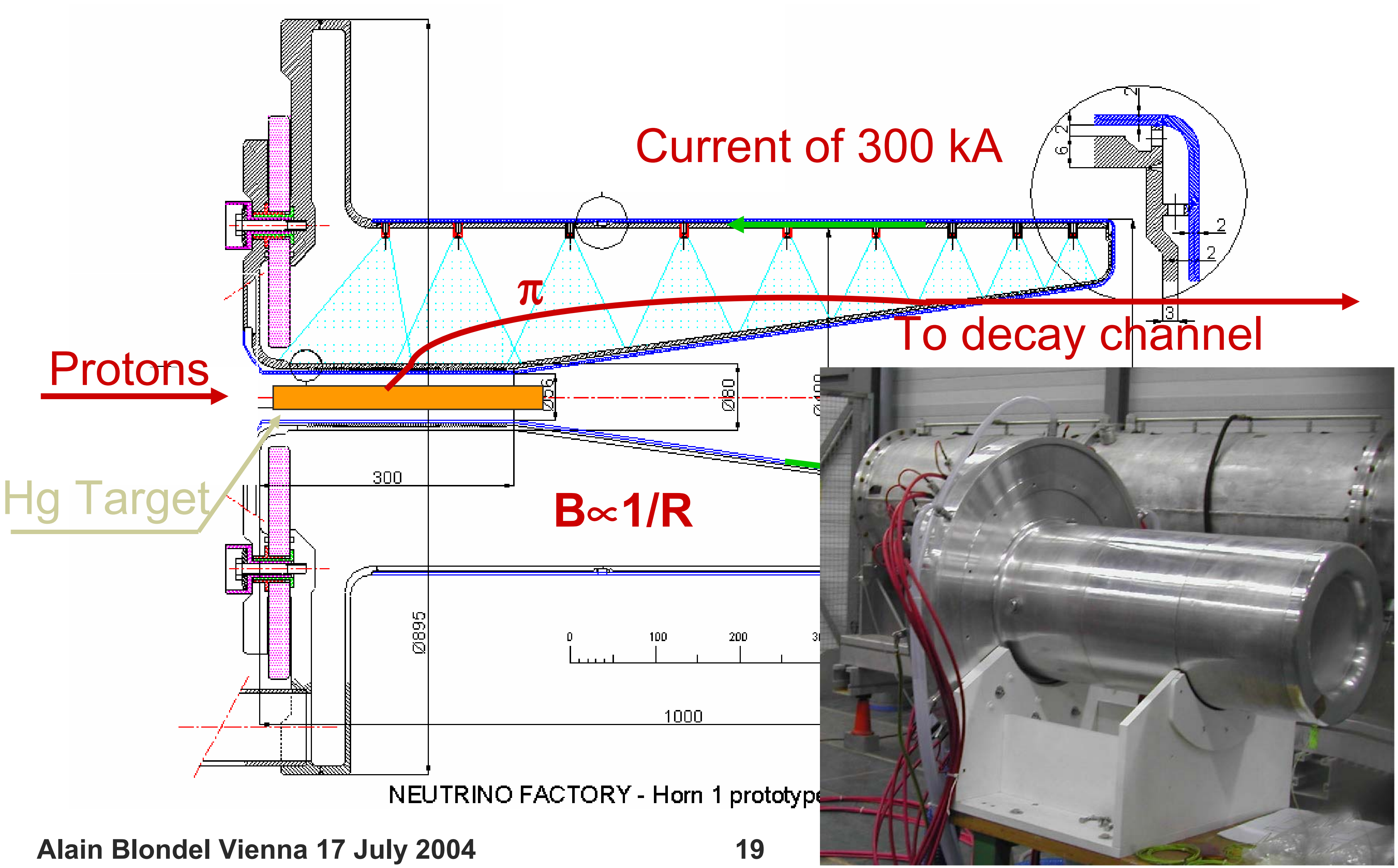
A large underground water Cerenkov (400 kton) UNO/HyperK or/and a large L.Arg detector.

also : proton decay search, supernovae events solar and atmospheric neutrinos. Performance similar to J-PARC II

There is a window of opportunity for digging the cavern stating in 2008/9 (safety tunnel in Frejus)

Agreement has been signed between IN2P3/CEA/INFN to study this

Magnetic horn prototype



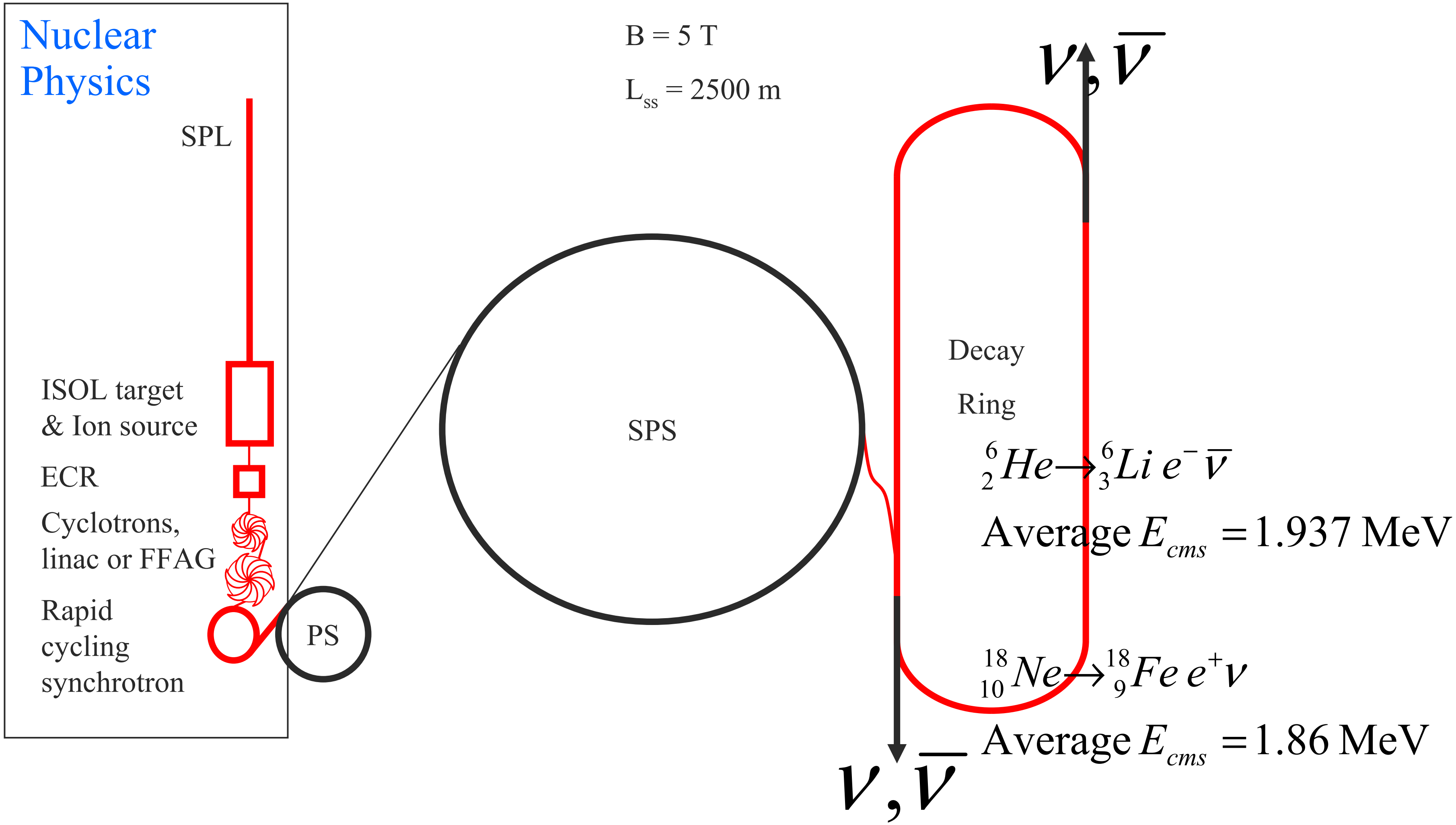
β-beam

Decay ring

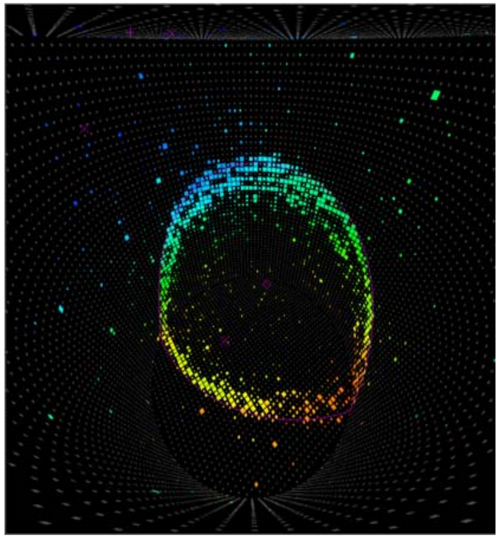
Brho = 1500 Tm

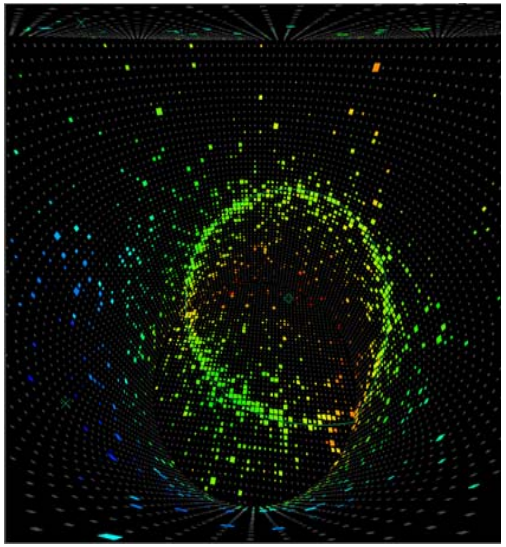
B = 5 T

L_{ss} = 2500 m



Combination of beta beam with low energy super beam





Unique to CERN:

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

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

combines CP and T violation tests

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

(CP)

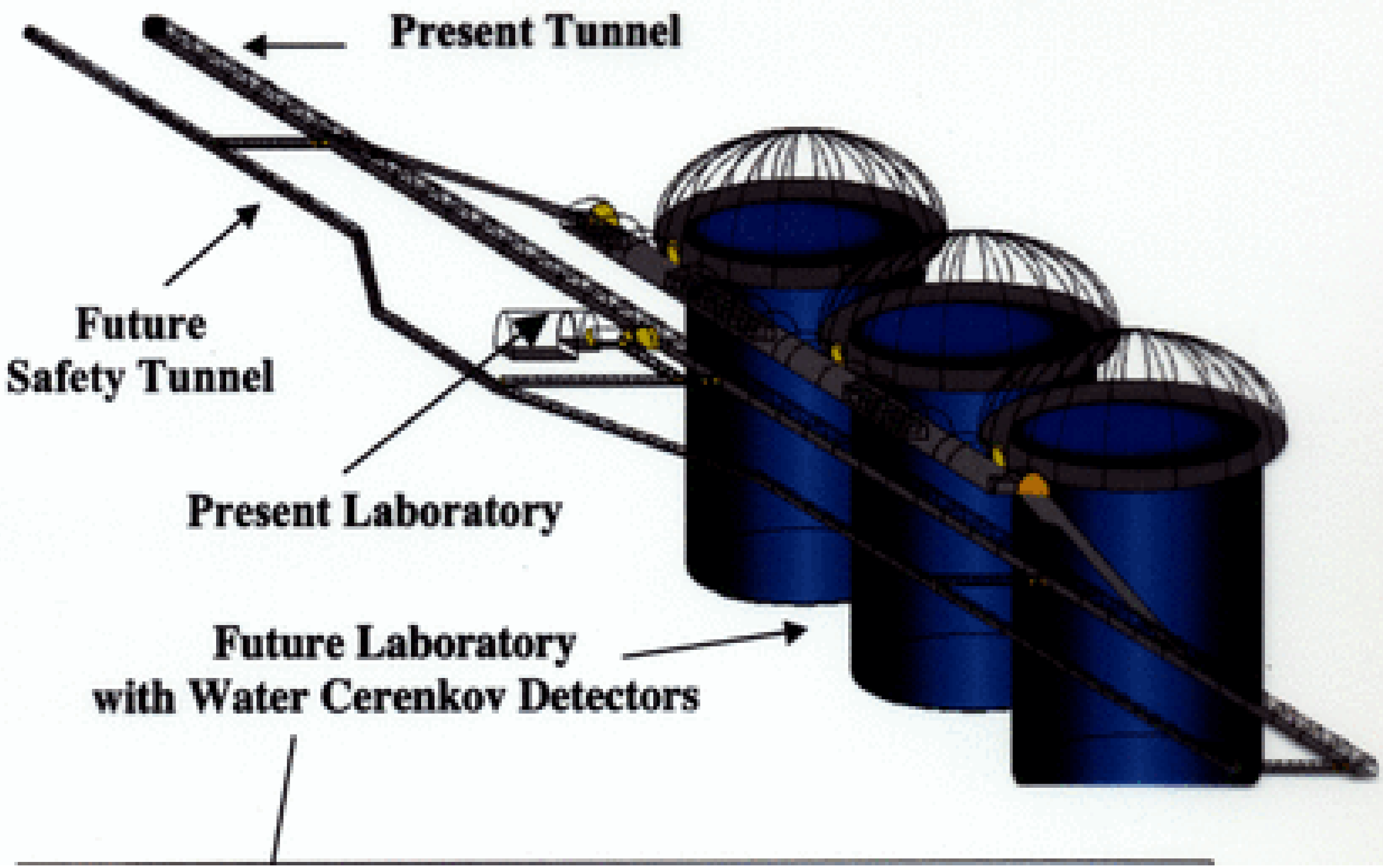
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ (β-) **(T)** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (π^-)

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

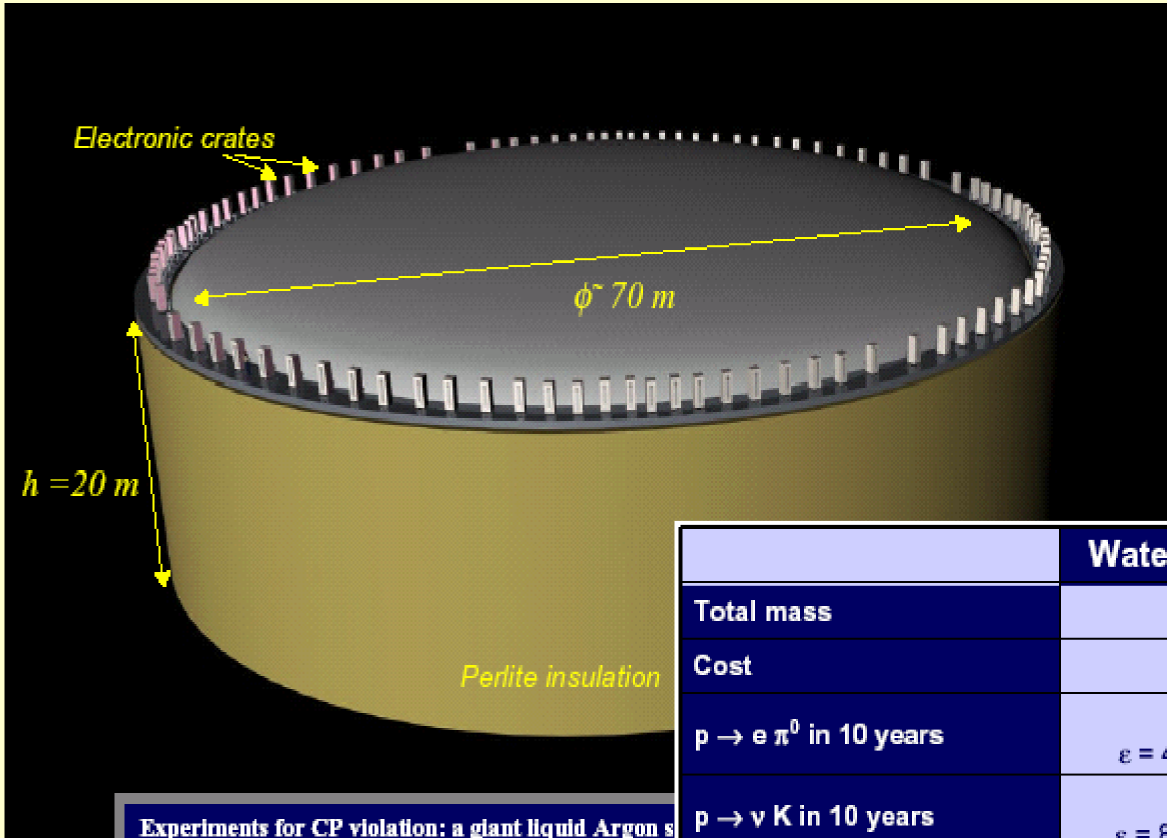
2) Components of the Project

L. Mosca

-> a **very large Laboratory** to allow the installation of a **Megaton**-scale **Cerenkov** Detector (≈ 10^6 m^3)



100 kton liquid Argon TPC detector



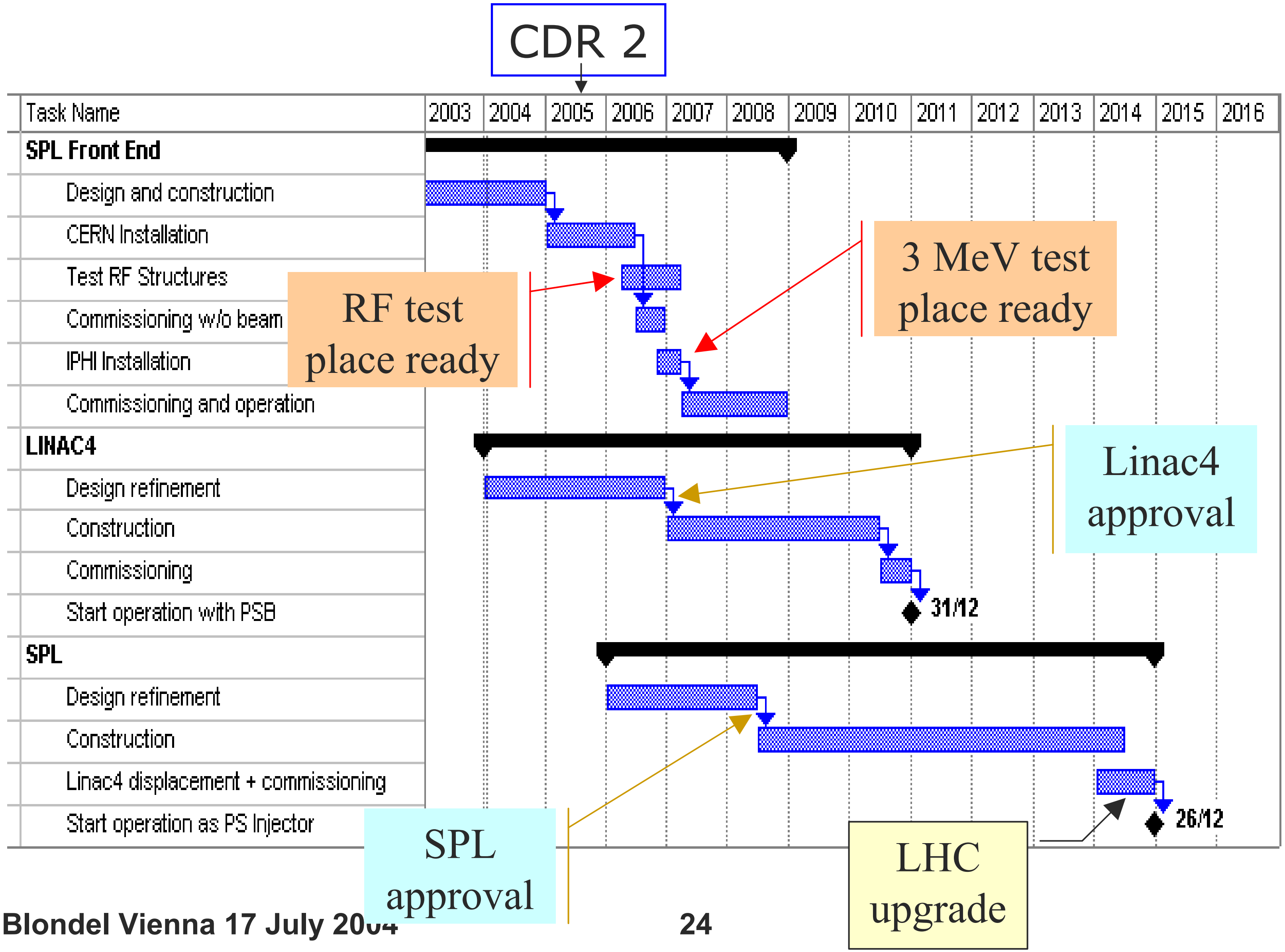
Experiments for CP violation: a giant liquid Argon s
A.Rubbia, Proc. II Int. Workshop on Neutrinos i

Liquid Argon TPC
Adequate for Super beam
beta beam
AND neutrino factory
Network proposed for R&D
But is it always better?
Ereditato Rubbia

	Water Cerenkov (UNO)	Liquid Argon TPC
Total mass	650 kton	100 kton
Cost	~ 500 M$	Under evaluation
$p \to e\,\pi^0$ in 10 years	10^{35} years ε = 43%, ~ 30 BG events	3×10^{34} years ε = 45%, 1 BG event
$p \to \nu\,K$ in 10 years	2×10^{34} years ε = 8.6%, ~ 57 BG events	8×10^{34} years ε = 97%, 1 BG event
$p \to \mu\,\pi\,K$ in 10 years	No	8×10^{34} years ε = 98%, 1 BG event
SN cool off @ 10 kpc	194000 (mostly $\overline{\nu}_e p \to e^+ n$)	38500 (all flavors) (64000 if NH-L mixing)
SN in Andromeda	40 events	7 (12 if NH-L mixing)
SN burst @ 10 kpc	~ 330 ν-e elastic scattering	380 ν_e CC (flavor sensitive)
SN relic	Yes	Yes
Atmospheric neutrinos	60000 events/year	10000 events/year
Solar neutrinos	E_e > 7 MeV (central module)	324000 events/year E_e > 5 MeV

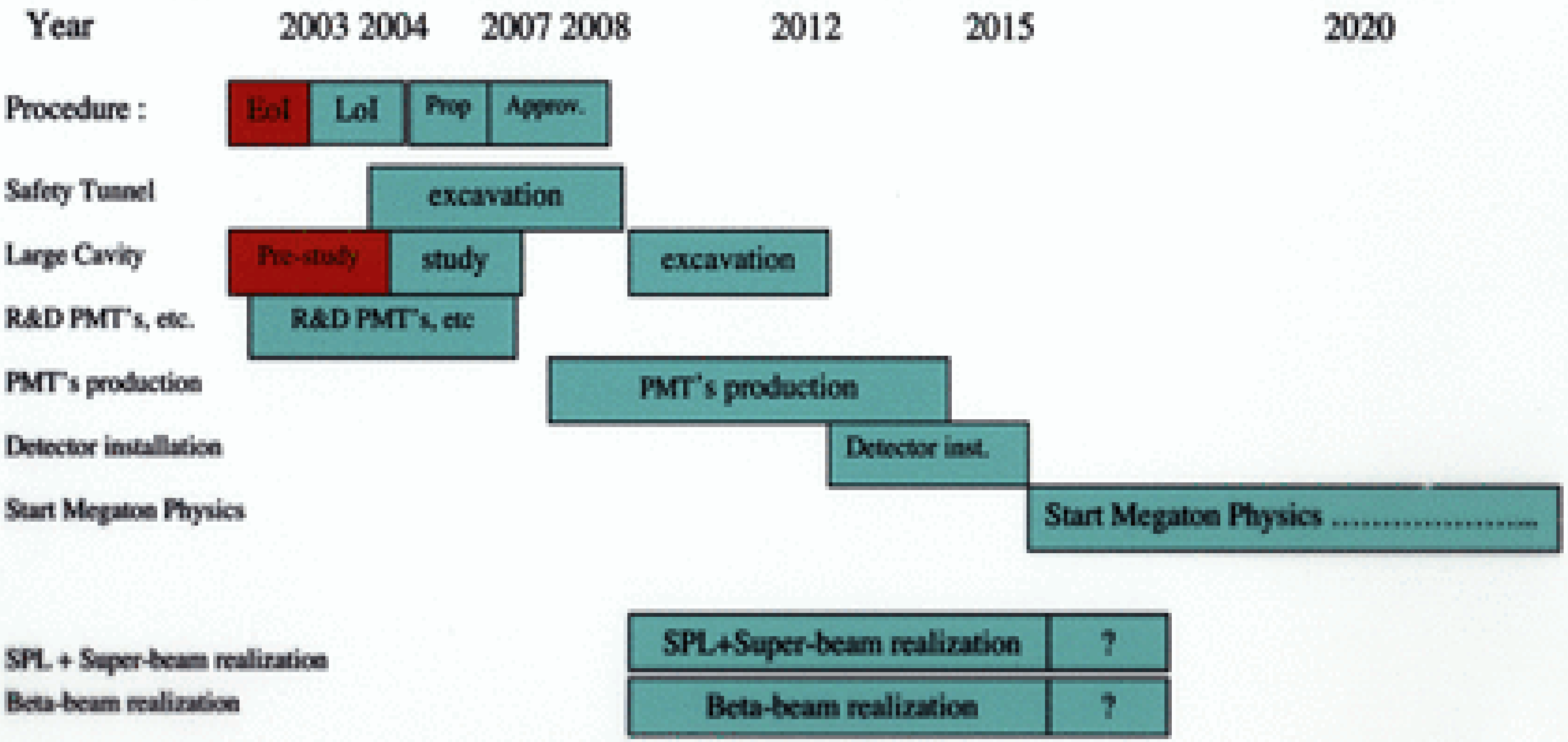
Possible planning

if the SPL is firmly supported…



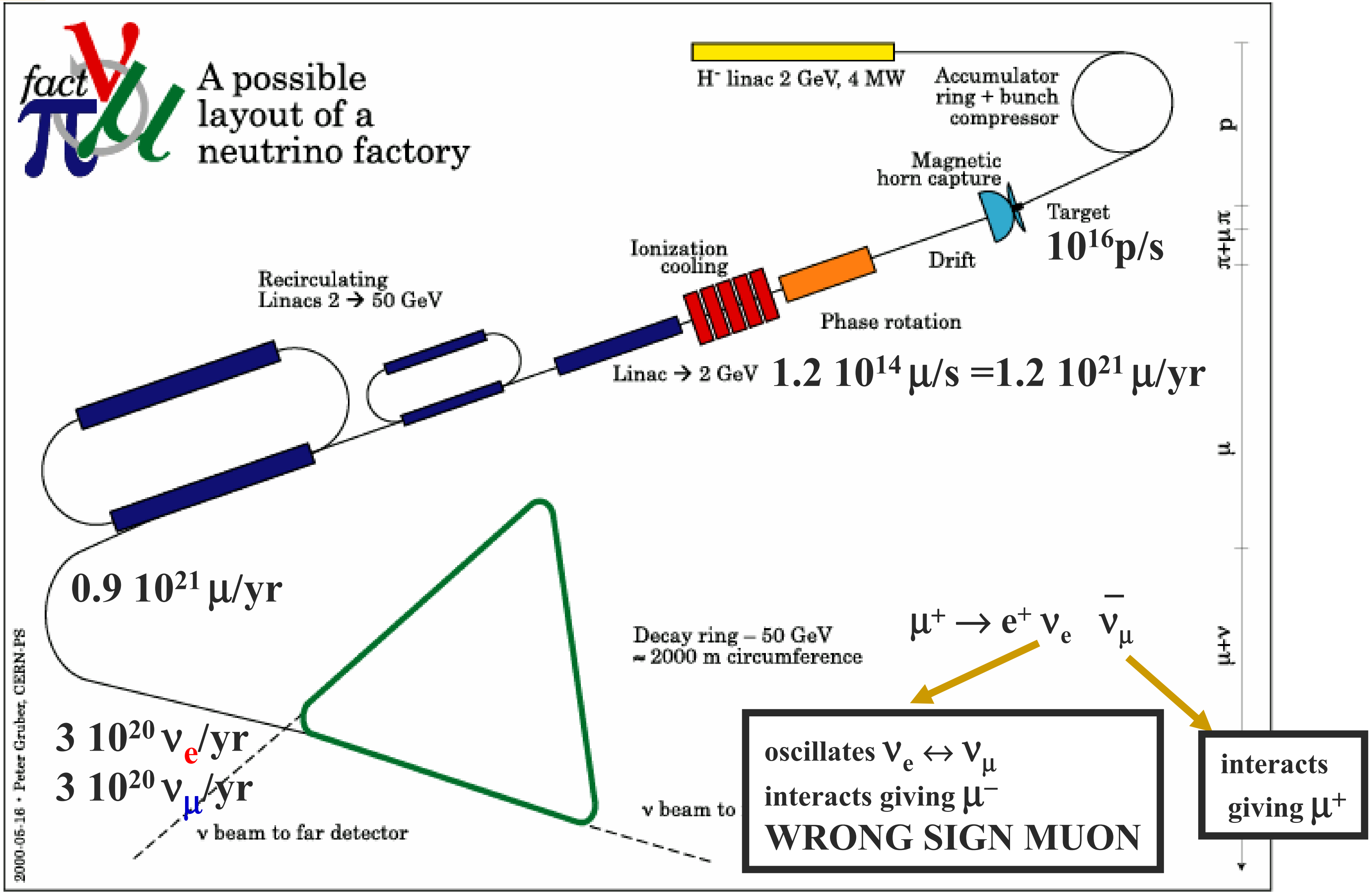
L. Mosca

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



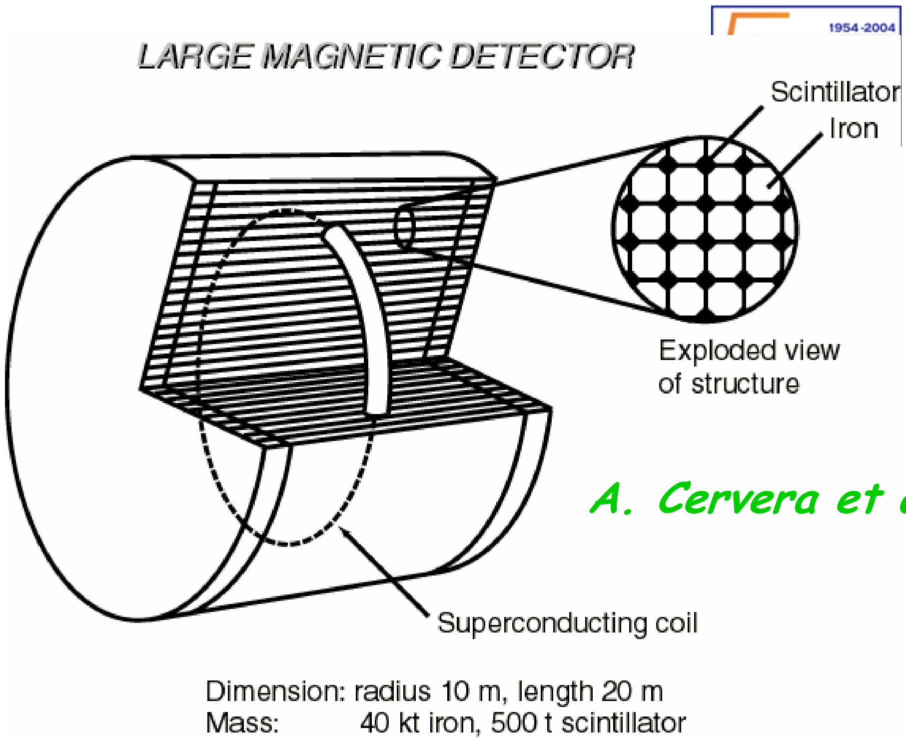
This fits very well!

-- Neutrino Factory -- CERN layout



Detector

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



A. Cervera et al

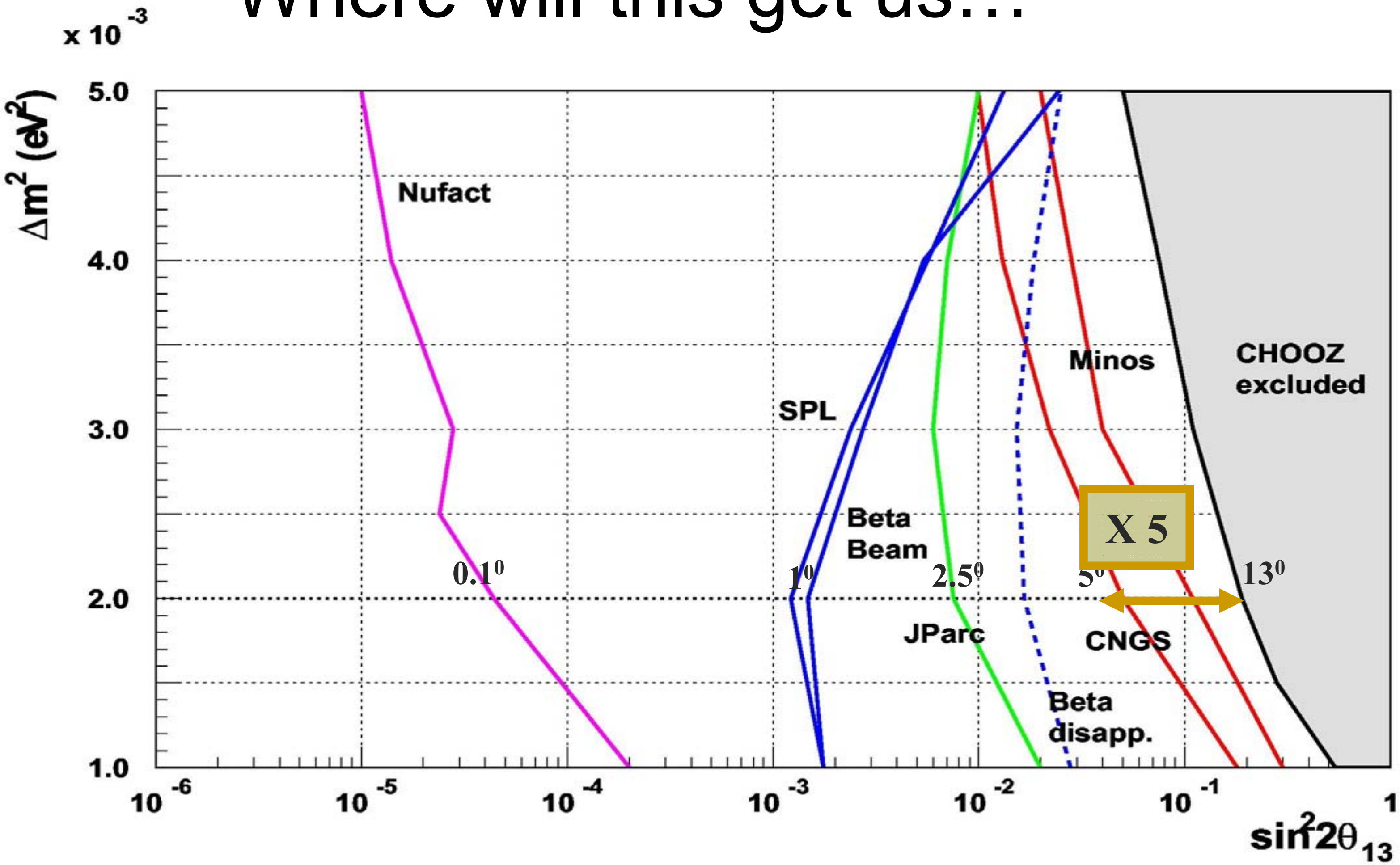
Also: L Arg detector: magnetized ICARUS
Wrong sign muons, electrons, taus and NC evts *(Bueno Campanelli Rubbia*

Events for 1 year

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

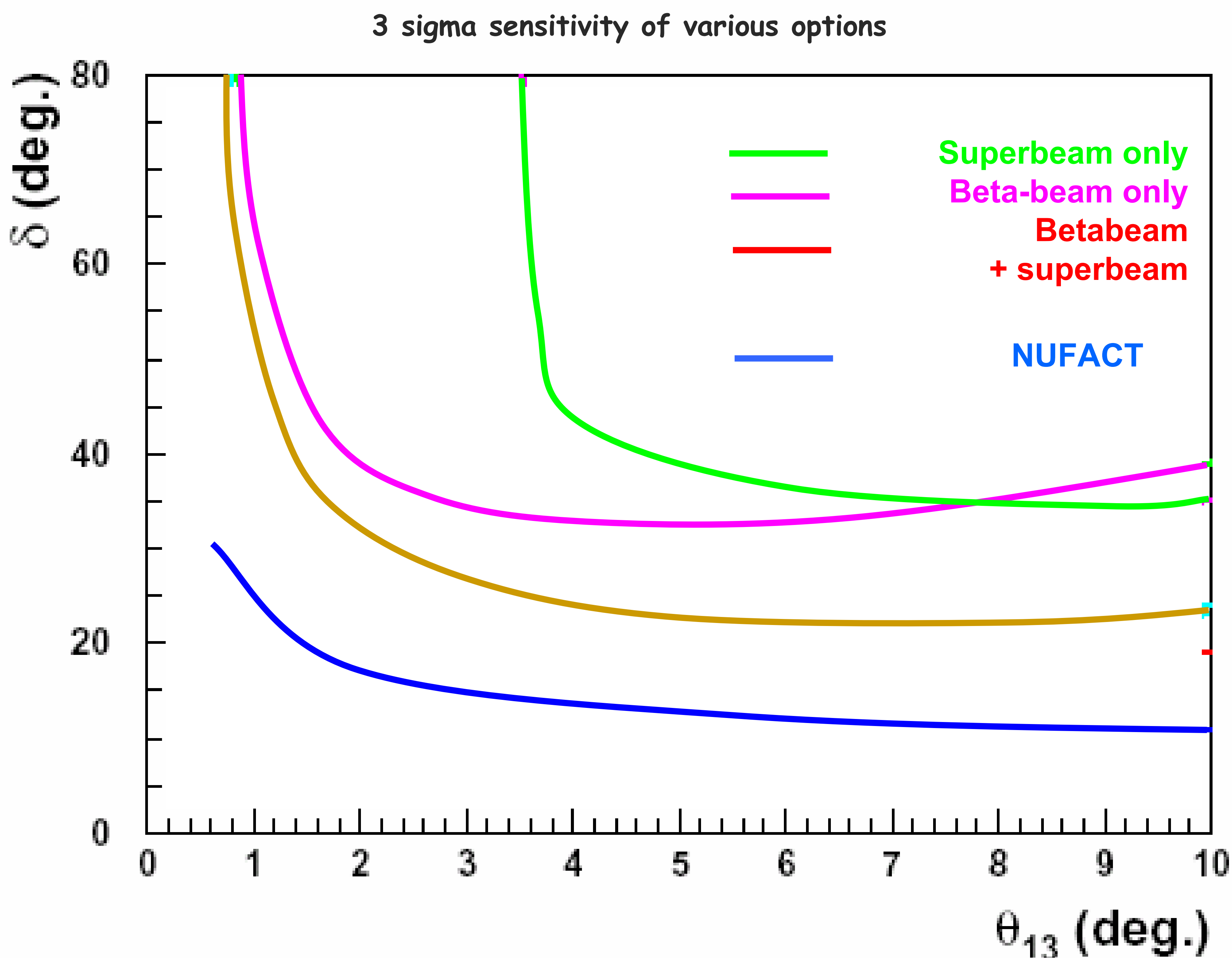
CF ν_e signal at J-PARC =40

Where will this get us…



Mezzetto

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


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

Conclusions (neutrino)

There is a baseline scenario for future neutrino facilities in Europe (basis for discussion and progress)

--SPL + accumulator+target station and Low energy WBB give a superbeam aimed at very large underground detector(s) (WC and/or Larg) which has other applications (N decay and astronophysical neutrinos)

-- possibly (easier if Eurisol choses CERN as host) a betabeam facility which has the nice feature to use the same detector!

-- the long term goal is a neutrino factory. Performance is superior and there is firm hope to reduce the cost substantially!

-- R&D on critical items should proceed:

proton driver, accumulator, targets & target station, collection, muon cooling

detectors: photo-detectors, liquid argon.. & caverns

Accelerator R&D

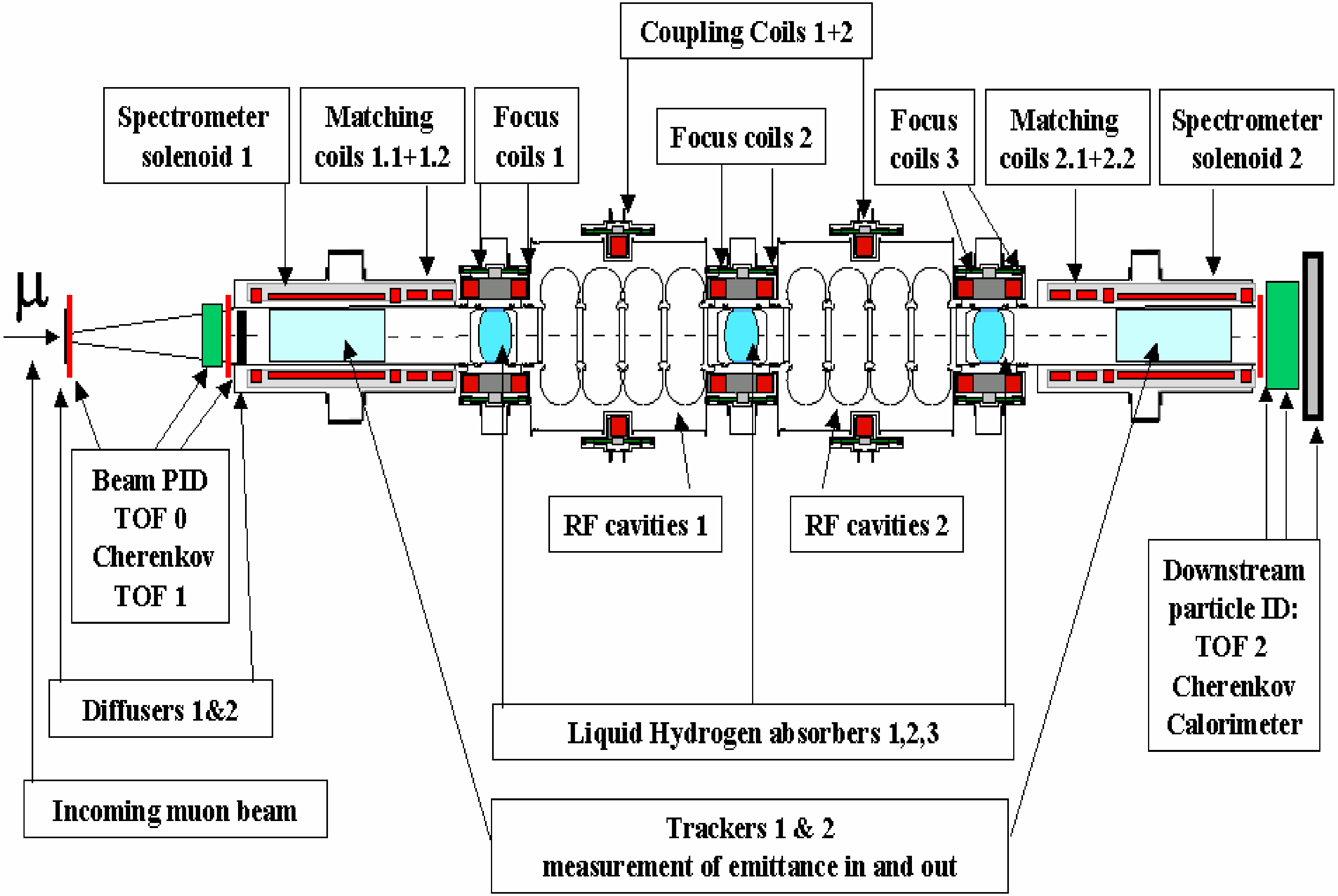
--SPL and beta-beam studies are being funded (a few M€ over 5 years) via FP6 EU programme (CARE and EURISOL) and ISTC (EU-FSU), as well as generic neutrino physics studies (BENE 0.5 M€/5yrs)

-- neutrino superbeam and Neutrino Factory design study in preparation

-- Muon cooling experiment supported by UK and international collaboration (not quite there yet)

-- in general effort has suffered from 'LHC budget crisis' in 2001, but is recovering

MICE setup: cooling + diagnostics



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.

S. Geer:

We are working towards a “World Design Study” with an emphasis on cost reduction.

Why we are optimistic/enthusiastic – US perspective:

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

Note: In the Study 2 design roughly ¾ of the cost came from these 3 roughly equally expensive sub-systems.

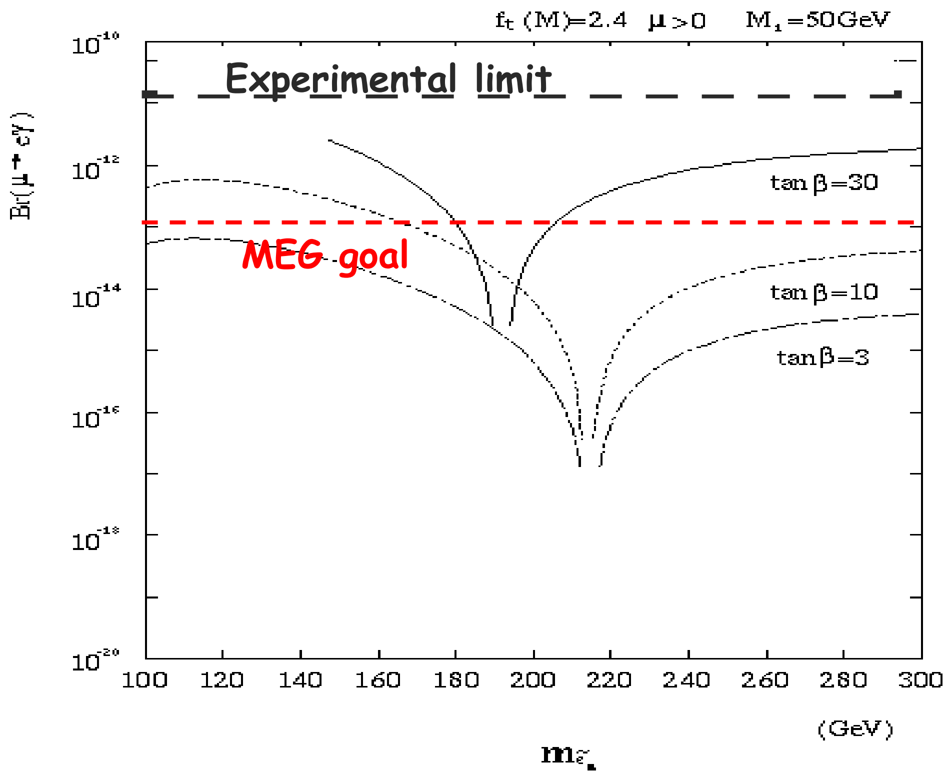
New design has similar performance to Study 2 performance but keeps both μ^+ and μ^- !

Good hope for improvement in performance ad reduction of cost!

The SPL + accumulator offers opportunities in muon physics
High intensity
Flexible time structure

μ –> eγ or μ –> eee (DC beam)
or μ N–> eN' (Bunched beam)
offer sensitivity to SUSY effects.
Great to investigate
even after LHC discovery of SUSY!

- Also:
-- Precise measurements of muon lifetime (G_F)
-- High precision experiments mesuring the carachteristics of the normal muon decay
-- g-2 and EDM
-- and synergies with nuclear physics (muonic and anti.p atoms)

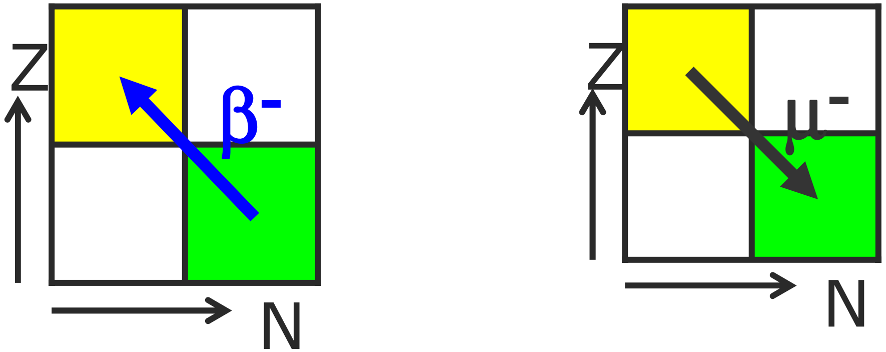


Aysto, Jungmann

Nuclear muon capture

- follows naturally muonic atom formation

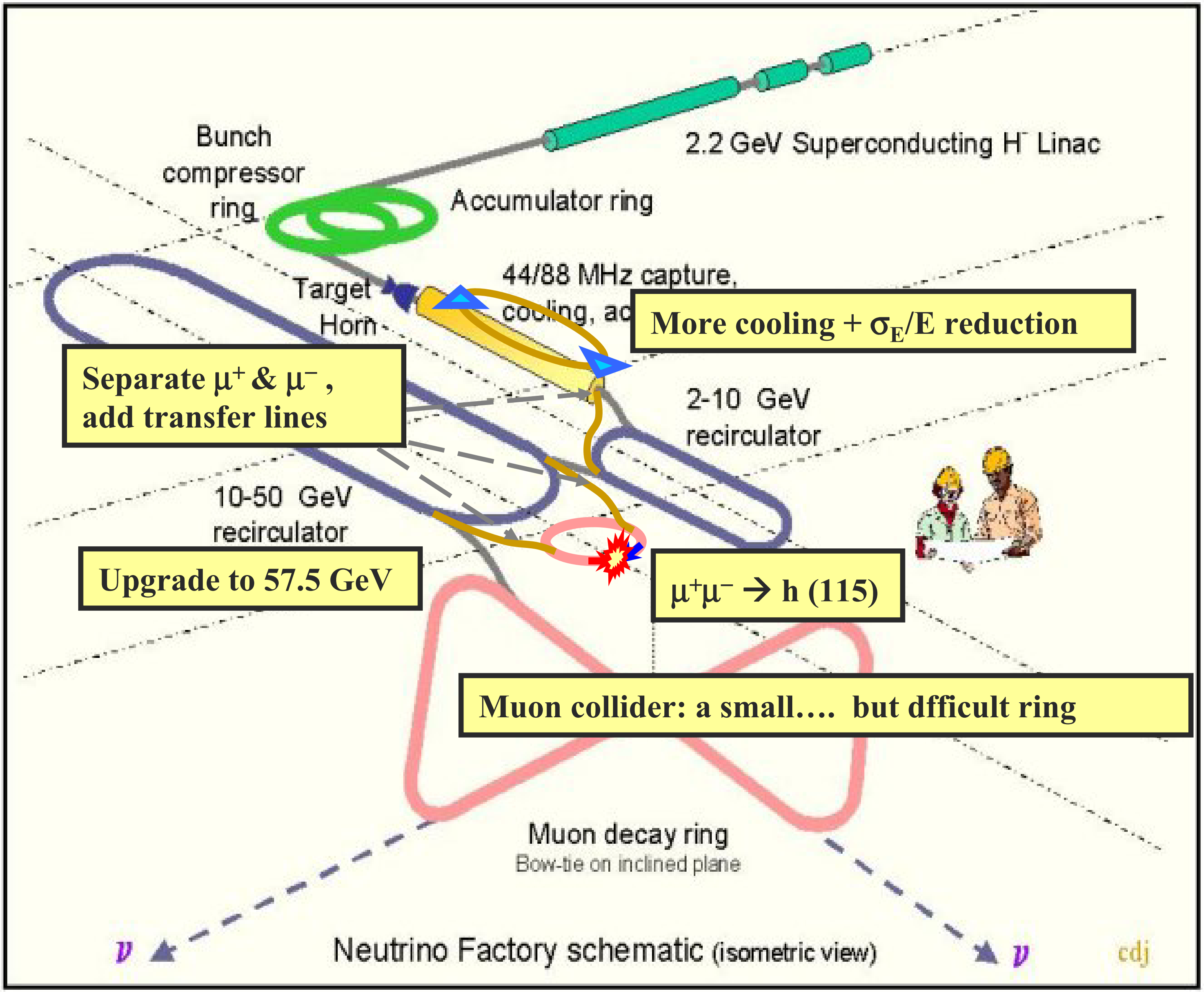
- "inverse β⁻ decay" $^{A}_{Z}X + \mu^- \rightarrow {}_{Z-1}^{\;\;A}X + \nu_\mu$



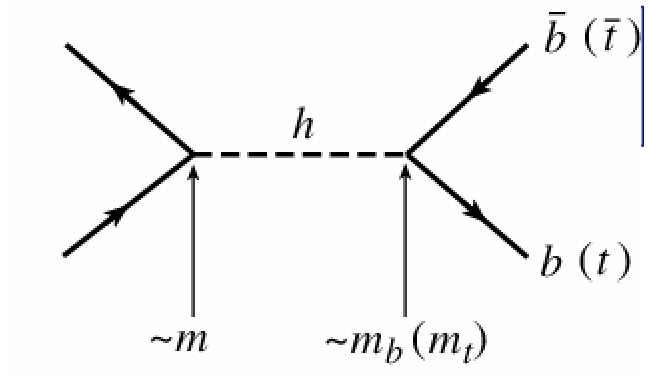
- capture rates can tell something about nuclear structure
  E. Kolbe et al., Eur. Phys. J. A 11 (2001) 39
- produces exotic nuclei at high excitation energy
  → structure up to several 10 MeV
- several multipoles excited → medium spin states
- renormalization of g_A in nuclear medium

- Nuclear astrophysics, ν scattering (supernova), ν post-processing, …
- Neutrino physics

From neutrino factory to Higgs collider

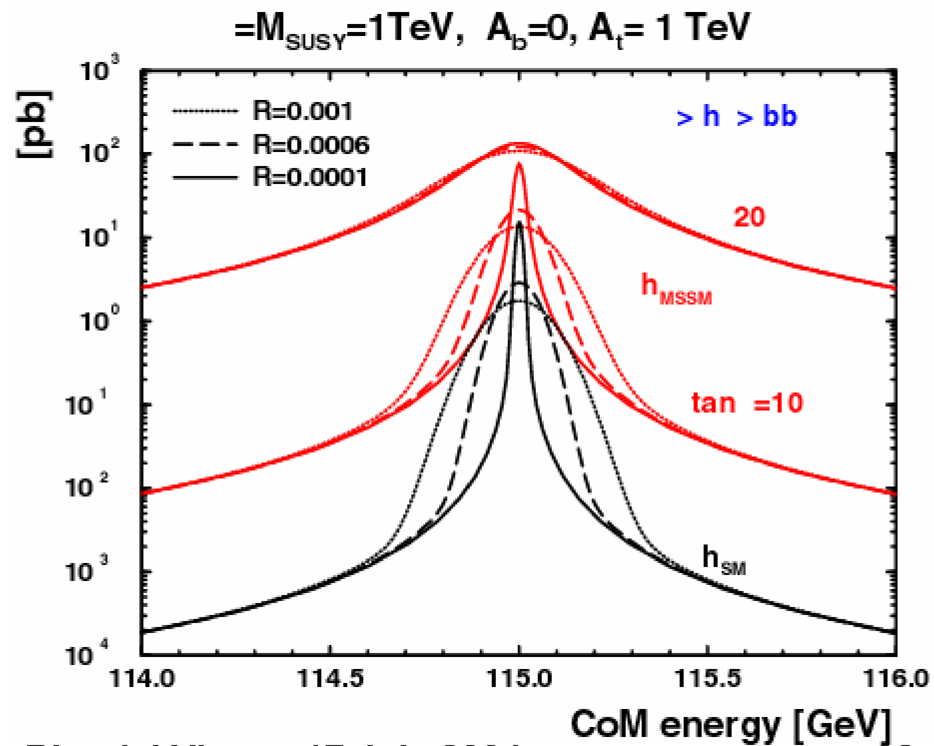


Higgs factory $\mu^+ \mu^- \rightarrow h(115)$



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

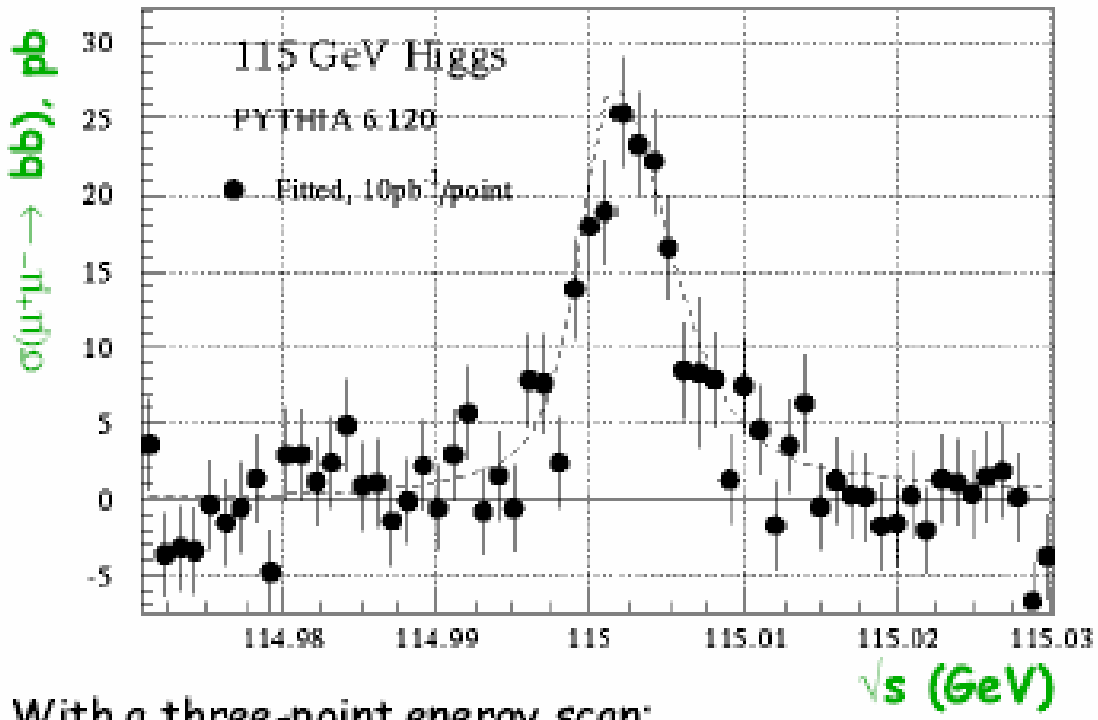
=> outstanding energy calibration (OK) and resolution R=ΔE/E (needs ideas and R&D, however!)



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

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

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



With a three-point energy scan:

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

Statistics limited !

Still to be tried:

A scan in $\delta E/E$

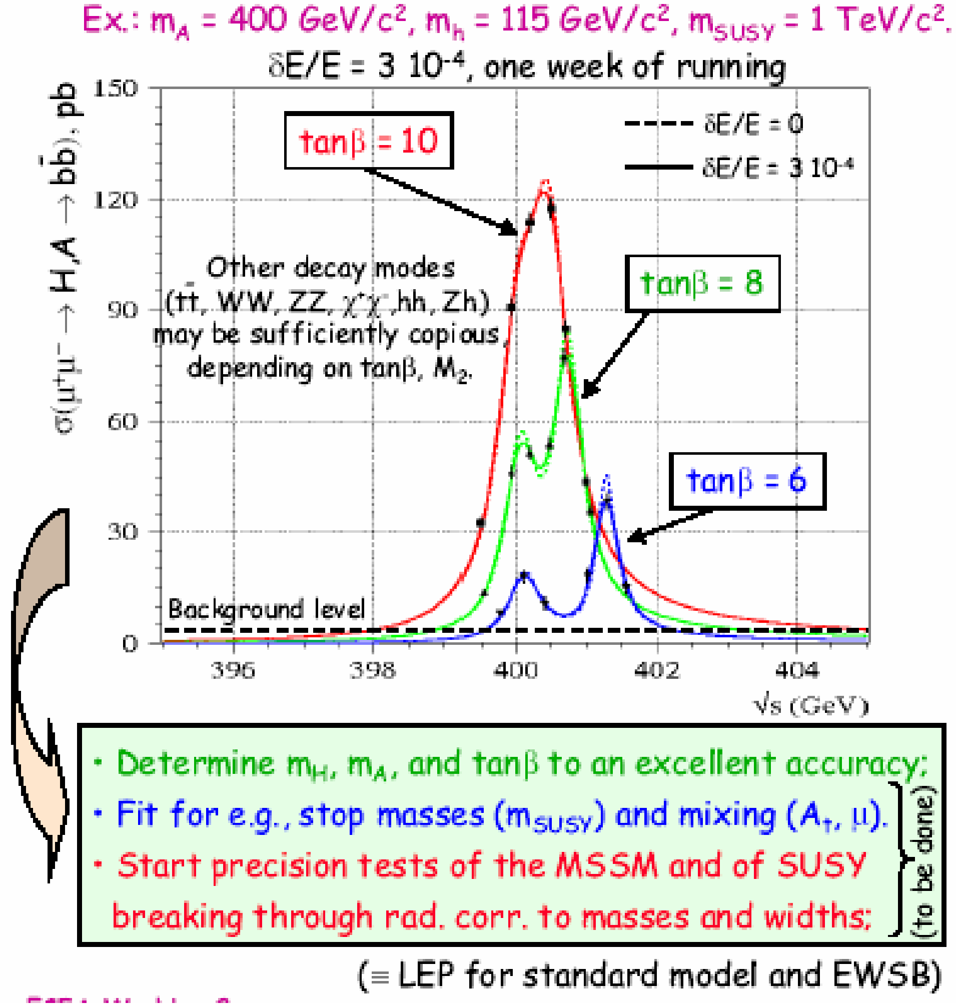
Higgs Factory #2: $\mu^+\mu^- \to$ H, A

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…..)

investigate CP violating H/A interference.



Conclusions

-- There is a strong and diverse physics programme at a high intensity proton source
-- This has been recognized in Japan (J-PARC) and
is being explored now at Fermilab as well (8 GeV Linac based on SCRF)
-- SC linac seems to have the largest potential in terms of power and flexibility.

-- The leading particle physics case is Neutrino Oscillation with the aim of discovery and study of Leptonic CP violation.
This physics is complementary to (and cannot be addressed at)
the high energy frontier (LHC and Lepton Collider)
There is a baseline scenario for this, delivering cutting edge results if the timeline can be held.
Neutrino Factory has the ultimate physics reach and should be kept in the line.
-- Ressources are needed for Accelerator and Detector R&D,
both within european and world wide collaboration.

-- There are also fundamental particle physics measurements in Muon physics, neutrino interactions, Kaon physics that would benefit from such a complex
-- The synergy with nuclear physics (EURISOL) seems a unique opportunity