Novel Ideas and R&D for High Intensity Neutrino Beams

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EPAC 2004, Lucerne

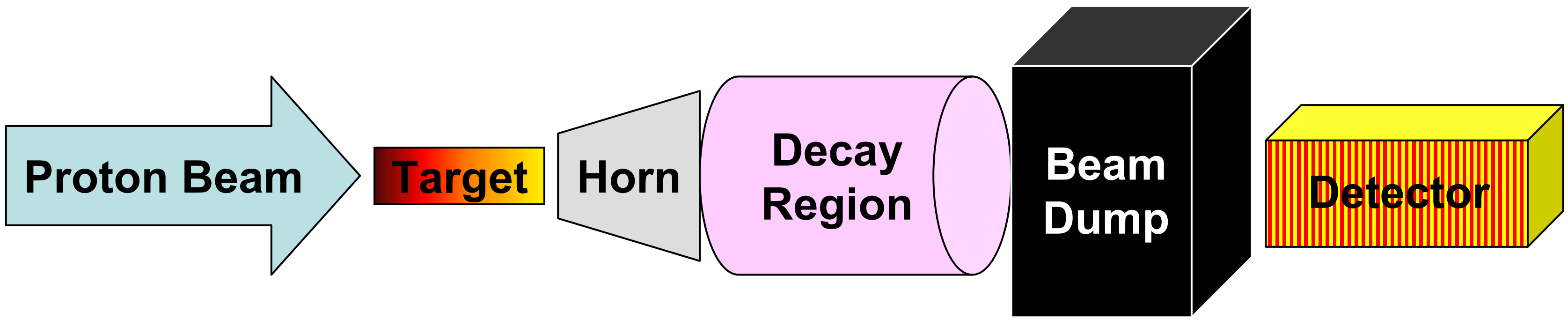
Outline

- Conventional Neutrino Beams
- Neutrino Phenomenology
- Existing and planned neutrino beams
- "Off Axis" and "Super" neutrino beams
- Factories
- Summary

- Acknowledgement
  - There is an enormous amount of work being done by the 300+ accelerator and particle physicists who make the "NuFACT" community. I acknowledge their dedication, enthusiasm and inventiveness

- Apology
  - Most of the topics mentioned in this talk, and many that are not, are each worth at least half an hour to do full justice. Apologies to those whose work is not mentioned, or mentioned-but-not-adequately-discussed.
  - I have tried to acknowledge sources of material where possible.

Conventional Neutrino Beams



- **Main components**
  - Proton Beam
    - Energy, Intensity, frequency
  - Target
  - Horn (focussing)
  - Decay Region
  - Beam Dump
  - Detector

Note

For any (class of) experiment

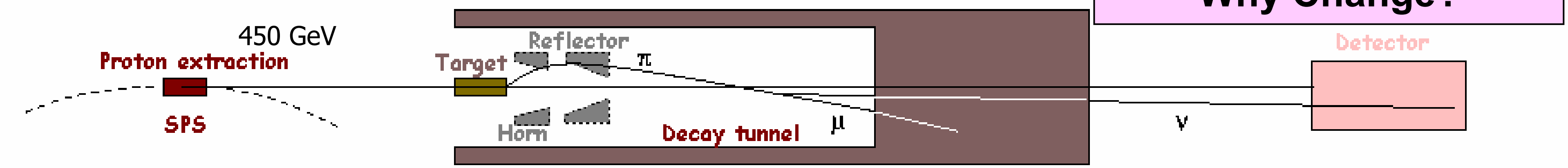
$$N_{ev} \propto P \times M \; (\times E_{\nu})$$

P: Beam Power; M: Target Mass; E_{ν}: Neutrino Energy

Example of a Neutrino Beam

West Area Neutrino Facility at CERN SPS

Why Change?



CHORUS, NOMAD

Wide Band Beam

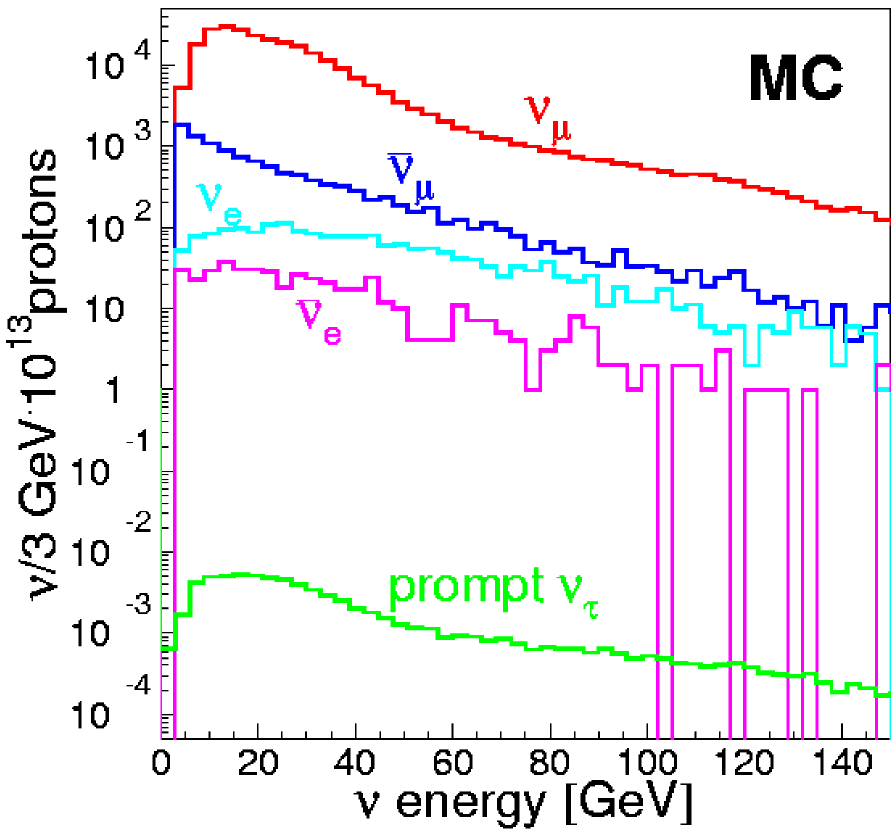
- 5.06×10^{19} POTs (1994-1997)
- $\langle E\nu_\mu \rangle \sim 27$ GeV
- $\langle L \rangle \sim 0.6$ km

  $\langle L \rangle / \langle E \rangle \sim 2 \times 10^{-2}$ km/GeV

  $\rightarrow \Delta m^2 > 1$ eV^2

- Prompt ν_τ : negligible

~10^{12} neutrinos



J Panman, Neutrino 2004

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… because Neutrino Physics has changed!!!

- **1950’s and early 60’s**
  - Nature (and existence) of the neutrino
    - (Reines & Cowan, Lederman, Schwartz and Steinberger)
- **Late 1960s, 1970s, 1980s**
  - Structure of the nucleon
    - F_2, xF_3 etc
  - Structure of the weak current
    - Neutral currents, $sin_2\theta_w$ etc
- **Now, and future**
  - Nature of the neutrino
    - Neutrino Mass and Neutrino Oscillations
    - Standard Model assumption of massless neutrinos is *wrong!*
      - Note: difficult to add neutrino mass to SM *a la Higgs*
      - Lack of Charge → additional mass-like (Majorana) terms
- **New Physics at last!!!!**

New facilities allow old physics to be done much better

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Neutrino Mixing

Atmospheric | **3G** | **solar** | **Majorana**

$$U_{MNS} = \begin{bmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{bmatrix} \otimes \begin{bmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{bmatrix} \otimes \begin{bmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{bmatrix} \otimes \begin{bmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{bmatrix} \otimes \begin{bmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{bmatrix}$$

Parameters of neutrino oscillation

1 absolute mass scale	m_{ν_e}
2 squared mass differences	Δm^2_{12} , Δm^2_{23} $\begin{cases} \Delta m^2_{ij} = m_j^2 - m_i^2 \\ \Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21} \end{cases}$
3 mixing angles	θ_{12} , θ_{23} , θ_{13}
1 phase	δ (always $\sin\theta_{13}e^{i\delta}$)
2 Majorana phases	α, β

Matter-antimatter asymmetry

What do we know?

$$\left|\Delta m_{32}^2\right| = (2.3^{+0.35}_{-0.45}) \times 10^{-3}\,\mathrm{eV}^2$$

$$\theta_{23} = \left(46.1^{+4.1}_{-5.1}\right)^\circ$$

$$\Delta m_{21}^2 = (6.9^{+0.75}_{-0.40}) \times 10^{-5}\,\mathrm{eV}^2$$

$$\theta_{12} = \left(33.2^{+1.8}_{-1.6}\right)^\circ$$

$$\theta_{13} < 11^\circ$$

$$Sign\left(\Delta m_{32}^2\right) \text{ unknown}$$

$$\delta, \alpha, \beta \text{ unknown}$$

Maltoni et al, hep-ph/04051272

$$U_{MNS} \cong \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \sim 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Ignores LSND – wait for MiniBooNE

'tri-bi-maximal'
Perkins, Harrison & Scott

$$U_{CKM} \cong \begin{pmatrix} 1 & .2 & .003 \\ -.2 & 1 & .04 \\ .007 & -.04 & 1 \end{pmatrix}$$

absolute mass scale ? Less than ~ few eV (electron neutrino)

Measuring the Parameters

$$P(\nu_\mu \Rightarrow \nu_e) = \quad 4c_{13}^2 s_{12}^2 (c_{12}^2 c_{23}^2) \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$4c_{13}^2 s_{12}^2 (c_{12}^2 c_{23}^2 - s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13} \boxed{\cos\delta}) \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12}c_{23} \boxed{\cos\delta} - s_{12}s_{13}s_{23}) \cos\left(\frac{\Delta m_{32}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$+ 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)\left(1 + (1 - 2s_{13}^2)\frac{2a}{\Delta m_{31}^2}\right)$$

$$\nu_\mu \Rightarrow \bar{\nu}_\mu \quad \Leftrightarrow \quad a \Rightarrow -a$$

$$- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\left(\frac{\Delta m_{32}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\left(\frac{\Delta m_{32}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)(1 - 2s_{13}^2)\frac{aL}{4E}$$

$a = 2\sqrt{2}\, G_F n_e E_\nu = 7.6\ 10^{-5}\ \rho\ E$

Where is the electron density ; ρ is the density (g/cm³) ; E is the neutrino energy (GeV)

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

(Richter: hep-ph/0008222)

What to Measure?

Neutrinos

ν_e disappearance

$\nu_e \rightarrow \nu_\mu$ appearance

$\nu_e \rightarrow \nu_\tau$ appearance

ν_μ disappearance

$\nu_\mu \rightarrow \nu_e$ appearance

$\nu_\mu \rightarrow \nu_\tau$ appearance

… and the corresponding antineutrino interactions

Note: the beam requirements for these experiments are:

high intensity	known flux
known spectrum	known composition (preferably no background)

ν_e disappearance

Non-accelerator!

- Reactor experiments
  – (almost) pure anti-electron neutrinos
  – Flux and spectrum determined by the power curve
  – Existing experiments (Chooz, Palo Verde, KAMLAND) use a single detector
  – Experiments currently planned use 2 detectors
    - ~200m to measure the spectrum and flux, and ~1000m to measure the spectral distortion due to oscillations
    - Given good measurements of Δm_{12}^2 and θ_{12}, measures or constrains θ_{13}.

The need for long baselines

$$P_{Oscillation} \approx (\text{Sines \& Cosines})\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

$$\Rightarrow \tfrac{1}{4}\lambda = \frac{2\pi E}{\Delta m_{ij}^2}$$

$$\approx \frac{0.8E}{\Delta m_{ij}^2} \quad [E \text{ in GeV}; \Delta m_{ij}^2 \text{ in eV}^2; L \text{ in km}]$$

$$\tfrac{1}{4}\lambda_{12} \approx 11\times 10^3\, E \text{ km}$$

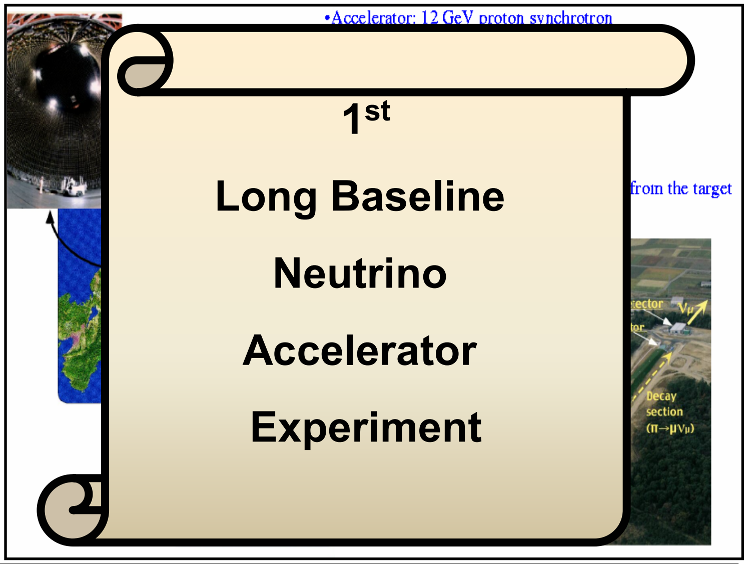
$$\tfrac{1}{4}\lambda_{23} \approx 0.3\times 10^3\, E \text{ km}$$

Means neutrino beams >1000 times more intense!

Well matched to the dimensions of the earth!

Running Experiments

K2K



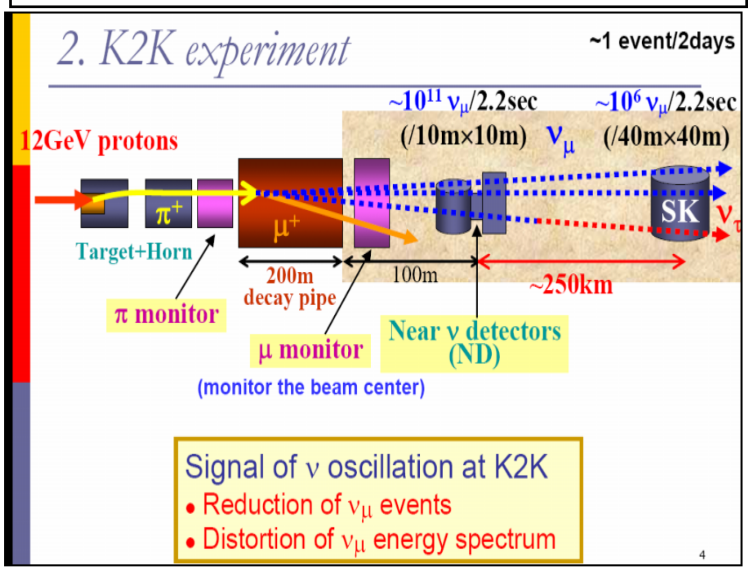
1^{st}

Long Baseline

Neutrino

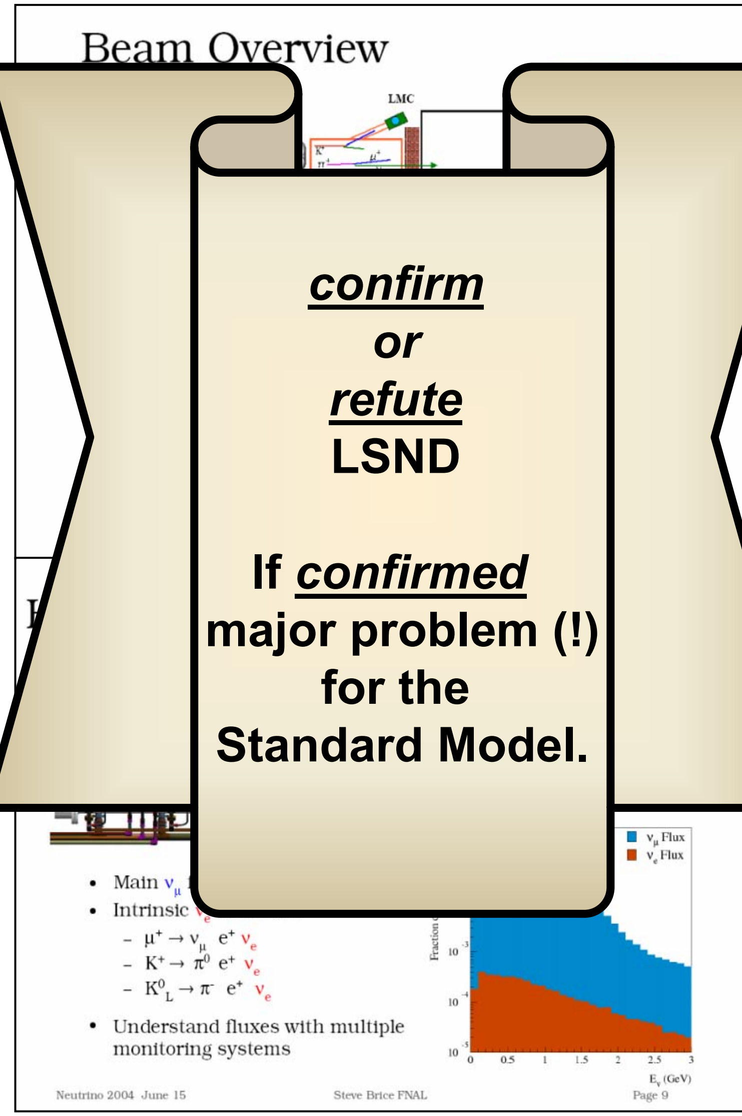
Accelerator

Experiment



T Nakaya, Neutrino 2004

MiniBooNE



confirm

or

refute

LSND

If *confirmed*

major problem (!)

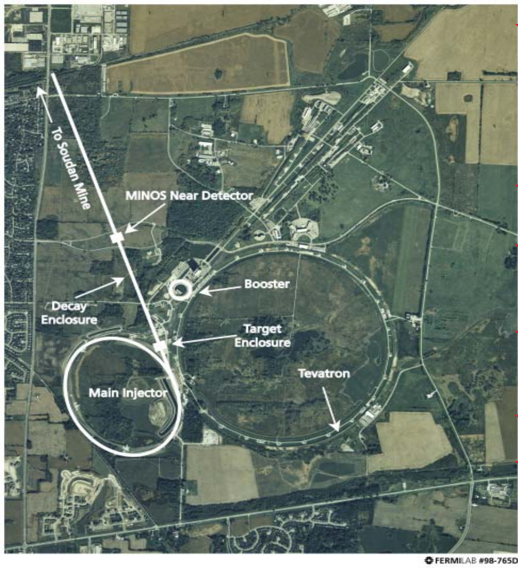
for the

Standard Model.

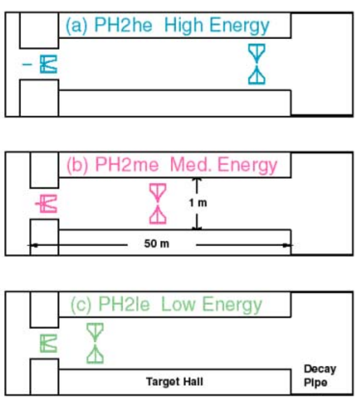
S Brice, Neutrino 2004

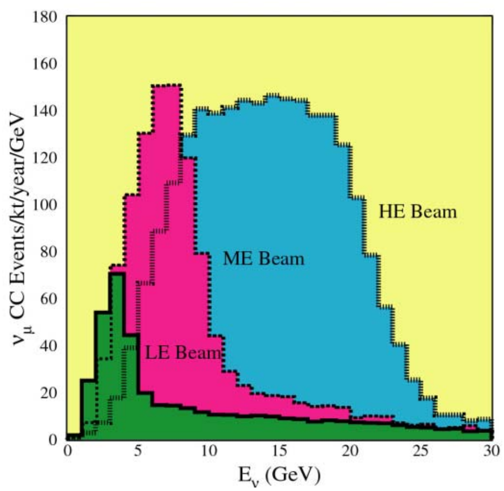
Experiments under construction

NuMI / MINOS



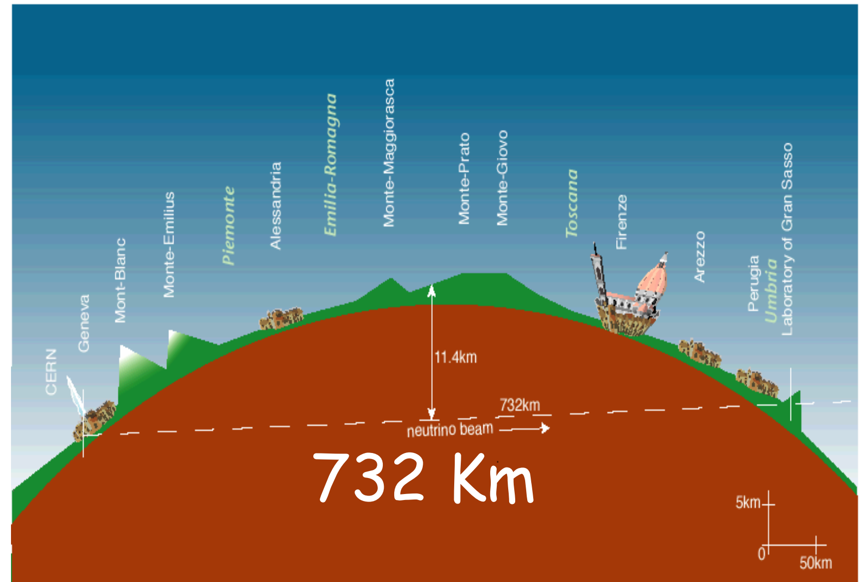
- 120 GeV protons from the MAIN INJECTOR in a single turn (8.7μs)
- 1.9 s cycle time
- *i.e.* ν beam `on' for 8.7μs every 1.9 s
- 2.5×10^{13} protons/pulse
- 0.3 MW on target !
- Initial intensity
  - 2.5×10^{20} protons/year



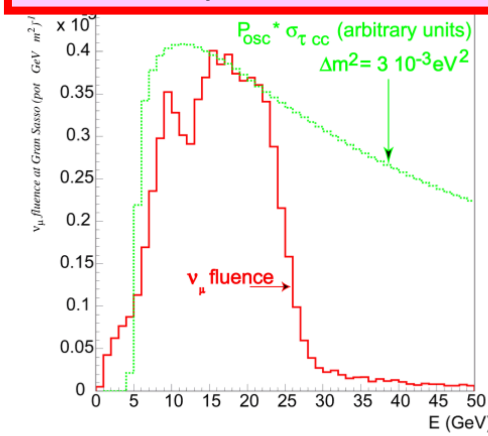


M Thomson, Neutrino 2004

CNGS

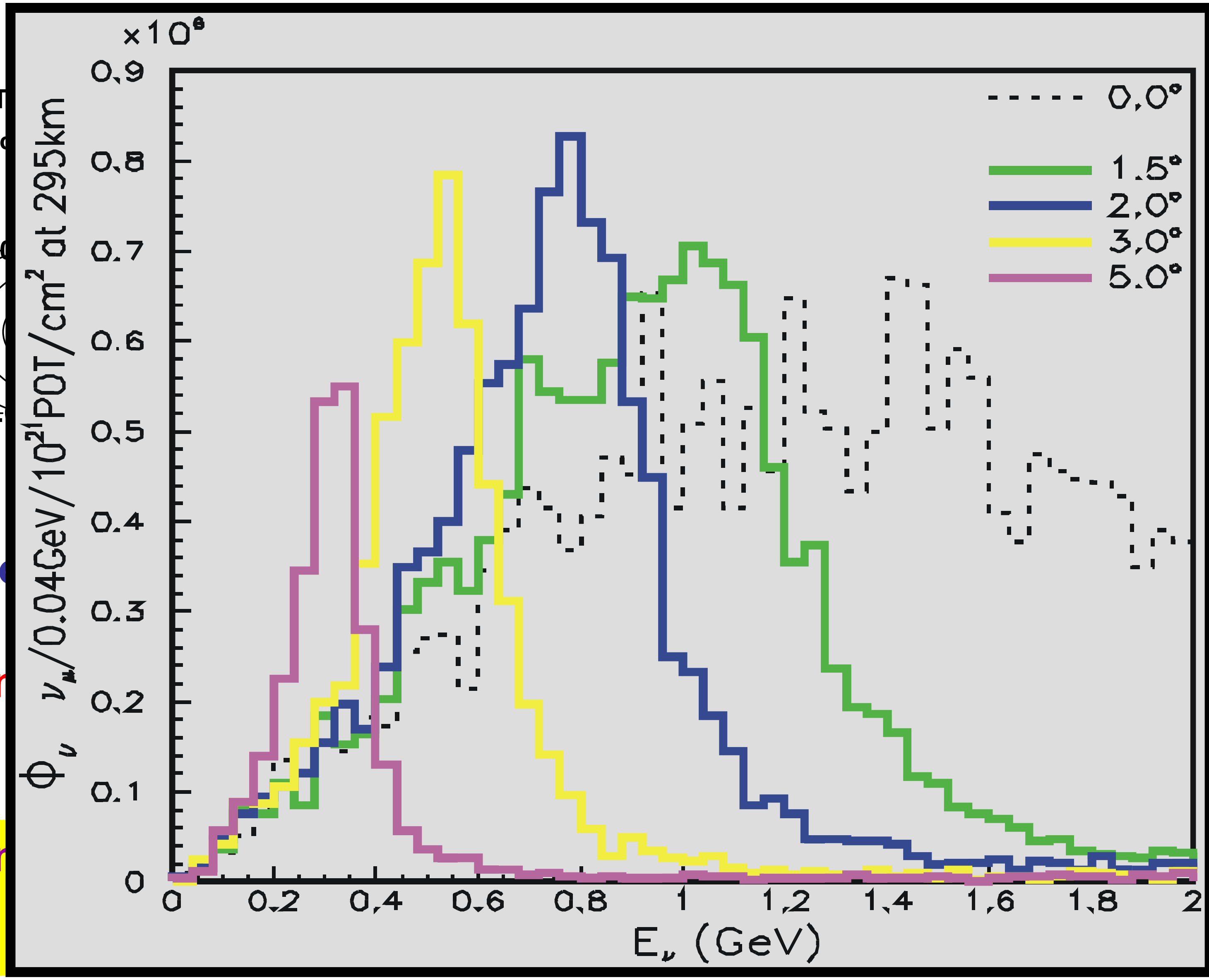


ν_τ appearance!!



D Autiero, Neutrino 2004

The “Off Axis” trick



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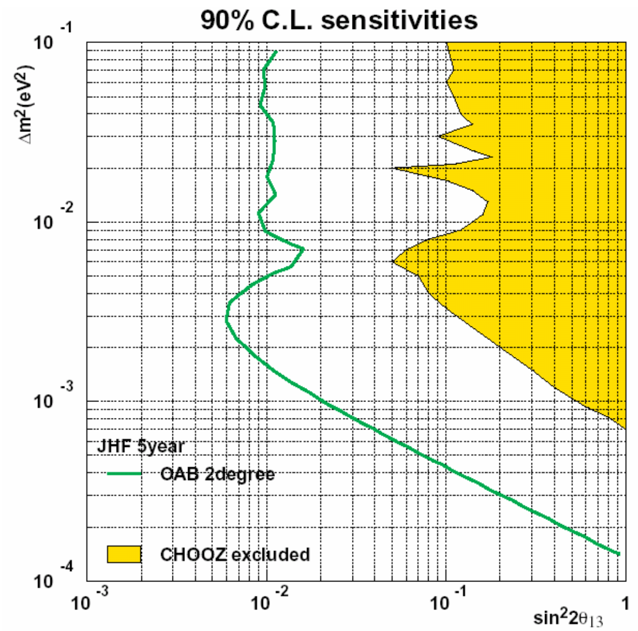
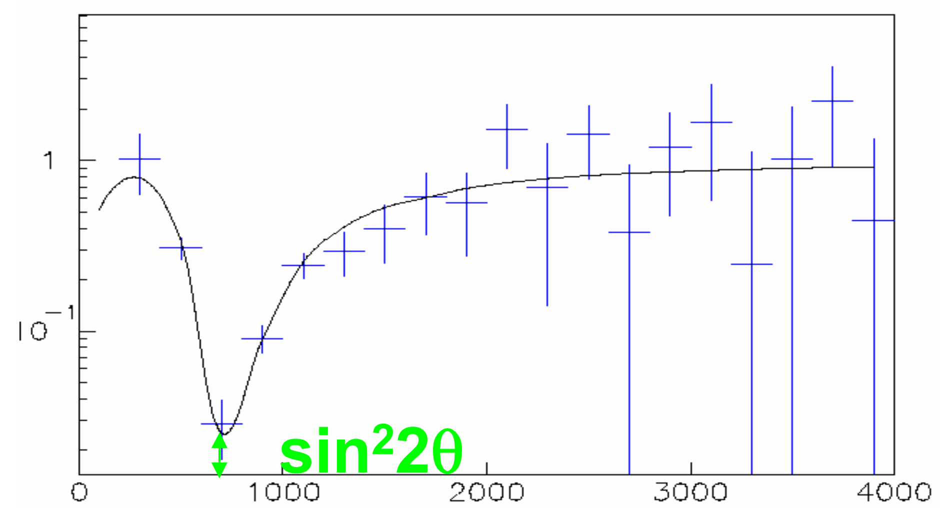
D. Beavis et al., “Long Baseline Neutrino Oscillation Experiment, E889, Physics Design Report,” BNL-52459, (1995)

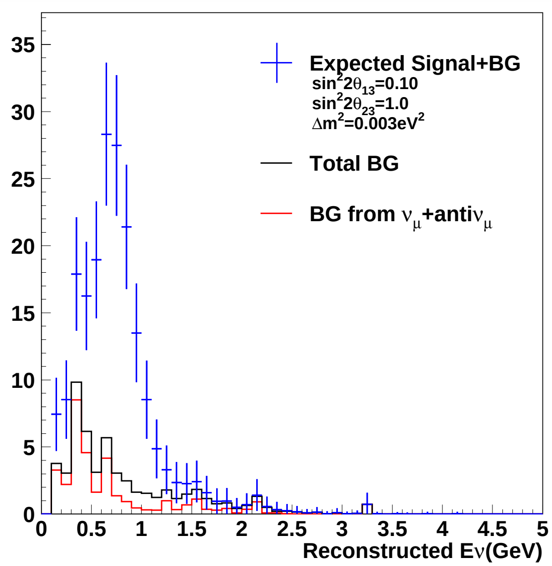
Proposals

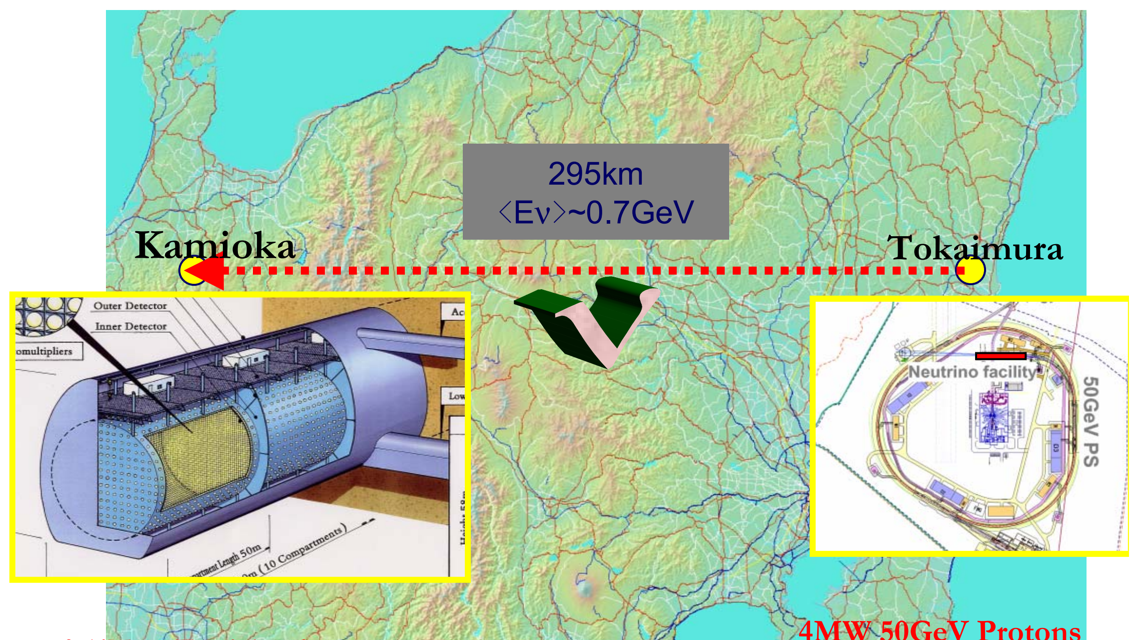
- T2K (Tokai [J-PARC] to SuperKamiokande)
  - Under construction
- NOVA (Fermilab to “somewhere near MINOS”)
  - Under consideration
- C2GT (CERN [CNGS] to Gulf of Taranto)
  - Being worked upon
- BNL
  - Proposal in preparation

T2K



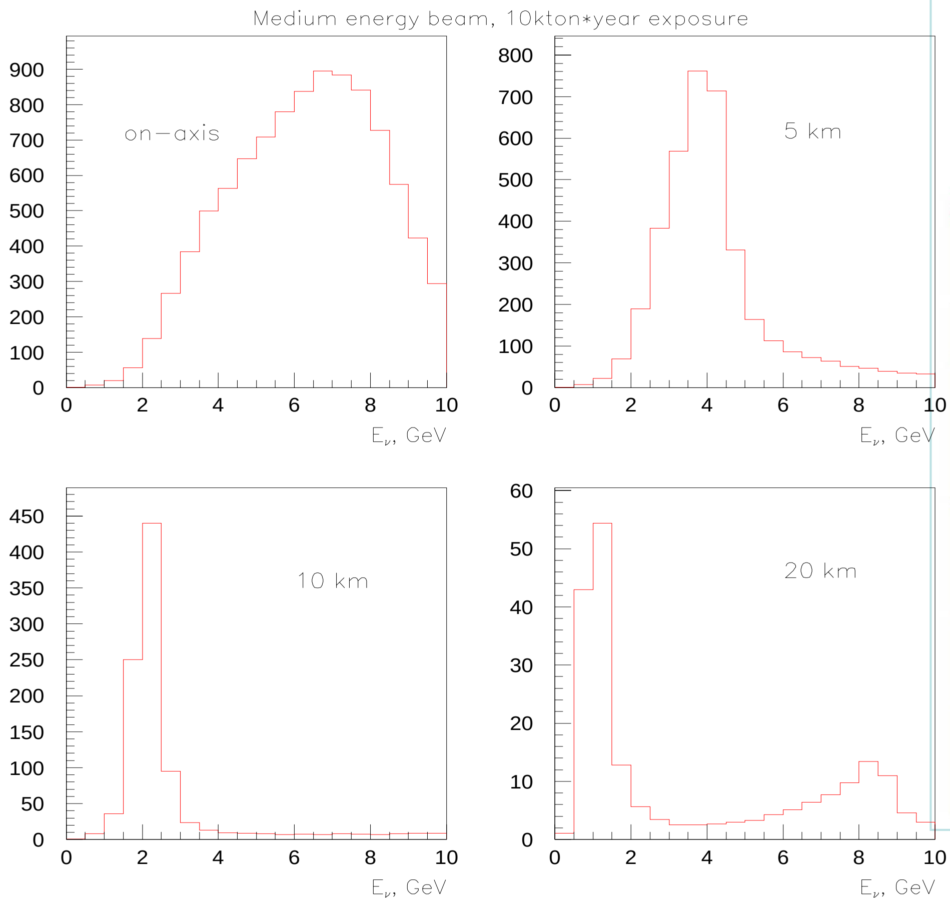


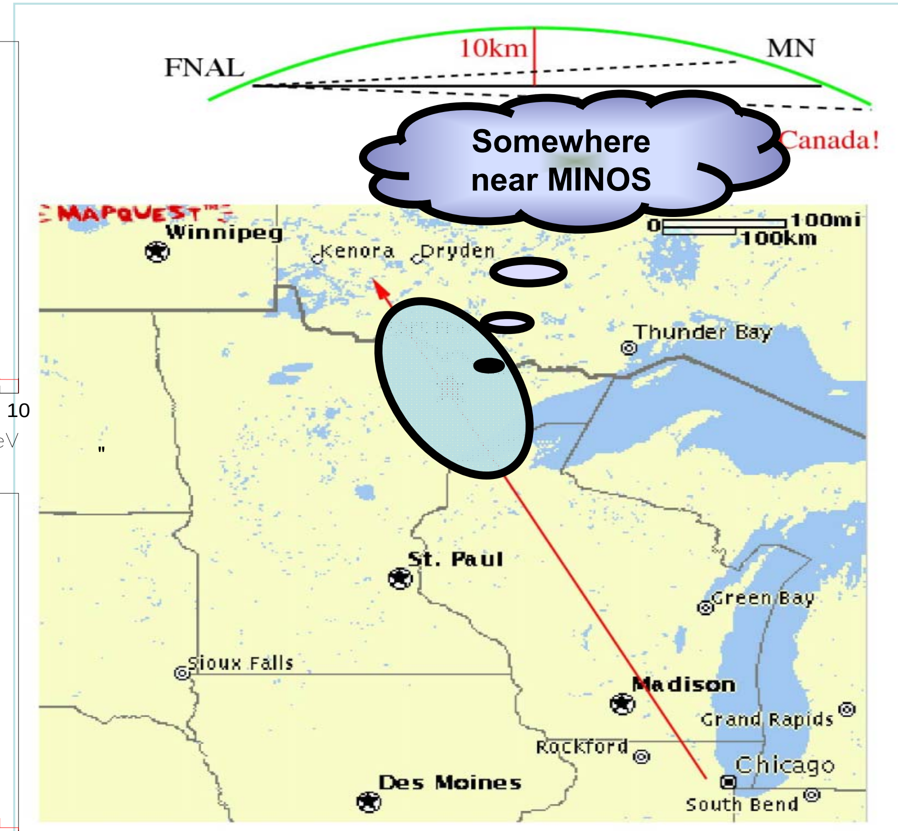




M ShiozawaNuFACT03

NuMI Off Axis



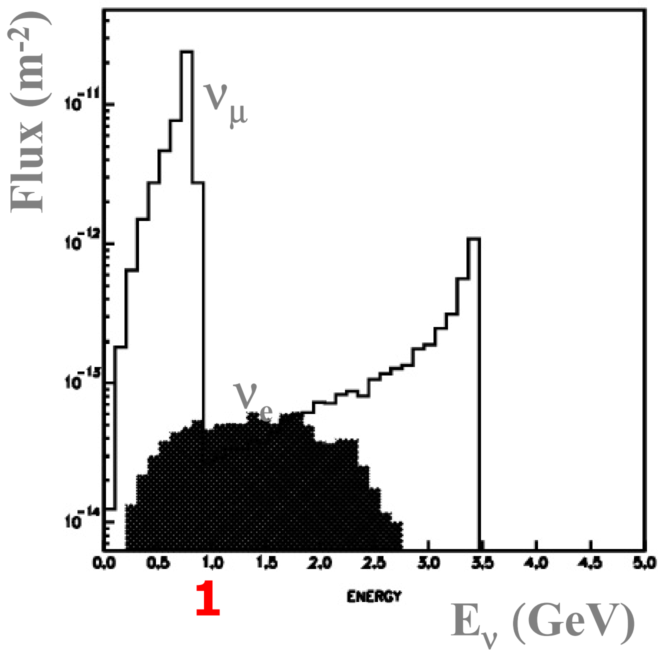


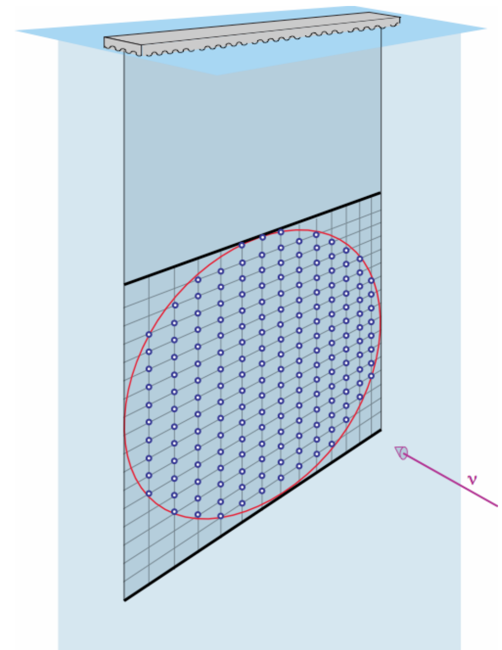
- ~ 2 GeV energy :
  - Below τ threshold
  - Relatively high rates per proton, especially for antineutrinos
- Matter effects to differentiate mass hierarchies
- Baselines 700 – 1000 km

Michael, NuFACT03

C2GT (CNGS to Gulf of Taranto)

F.Dydak et.al.





- **OA-CNGS**
- **Movable underwater Cherenkov det. (r=150m), 2Mt fid vol, L=1,200~1,600km**
- **~5,000 $\nu\mu$ CC/year**
- **Disappearance & Appearance**
- **$\sin^2 2\theta_{13}$~0.008 @90%**
- **Technology to be established** **(underwater, light collection, LE PID,…)**

“SuperBeams”

“conventional beams with better proton drivers”

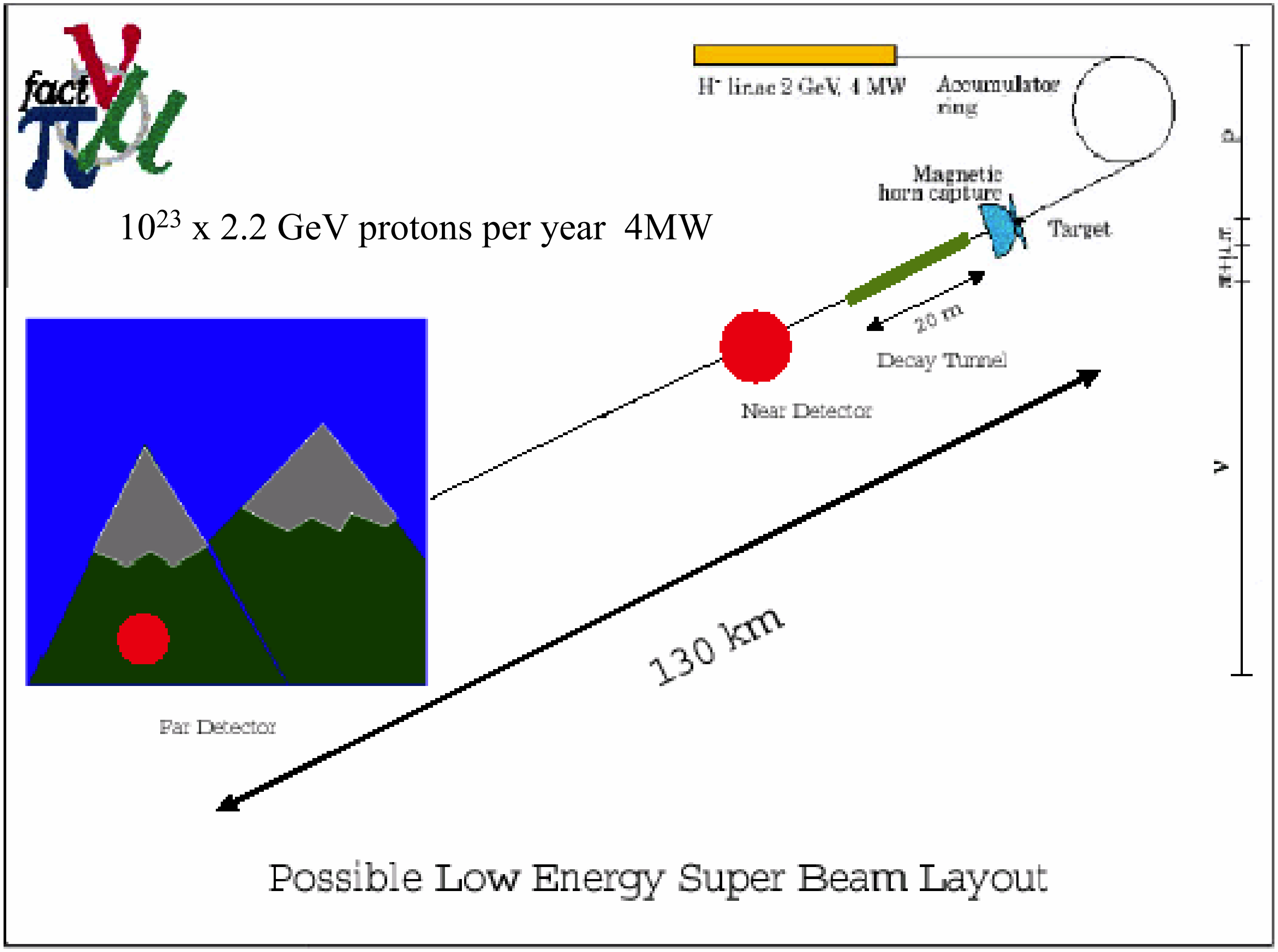
Notes:

1. Original motivation: How much can be done with just the front end of a neutrino factory?

2. Many other uses for high power proton drivers

CERN → Frejus

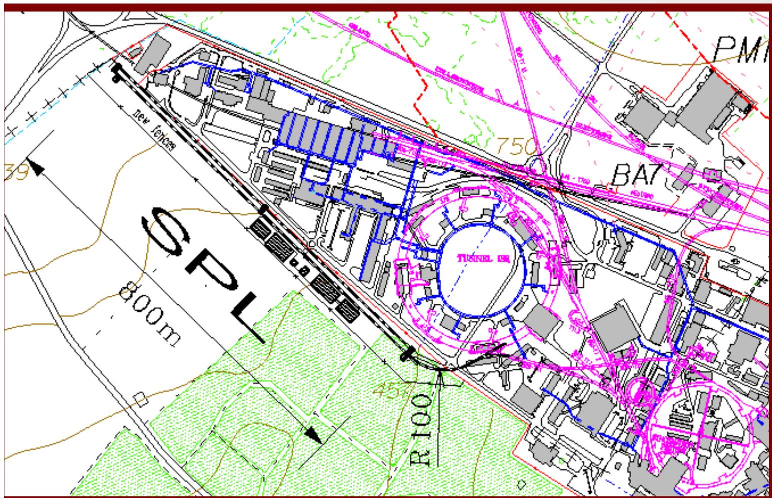
“Super-K”
~50 kT
or
“UNO”
~500 kT
water

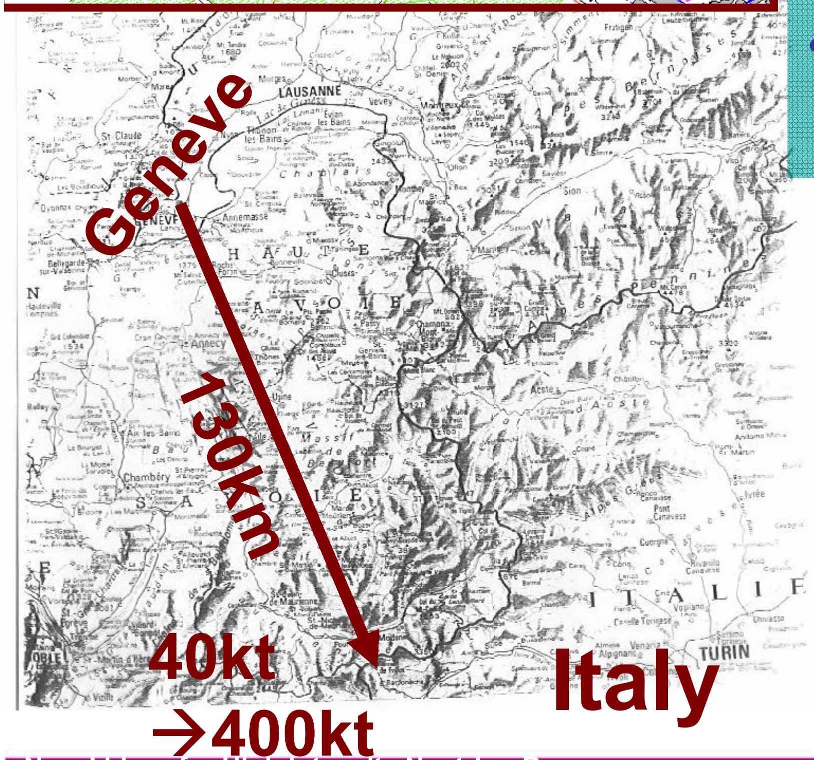


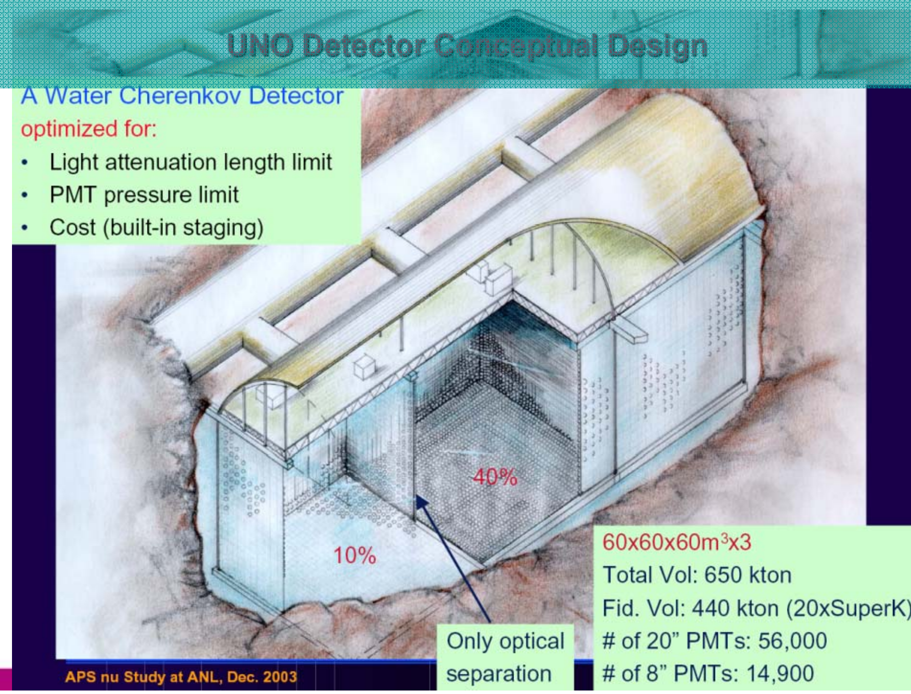
Mezzetto, NuFACT03

CERN → Frejus

- 4MW 2.2GeV Superconducting Proton Linac (SPL) @ CERN
- Low energy wide band (E_ν~0.3GeV)
- L=130km
- Water Cherenkov 40→ 400kt (UNO)
- ~18,000 ν_μ CC/year/400kt
- θ_{13}, CPV
- Small matter effect
- SPL in R&D, UNO in conceptual design

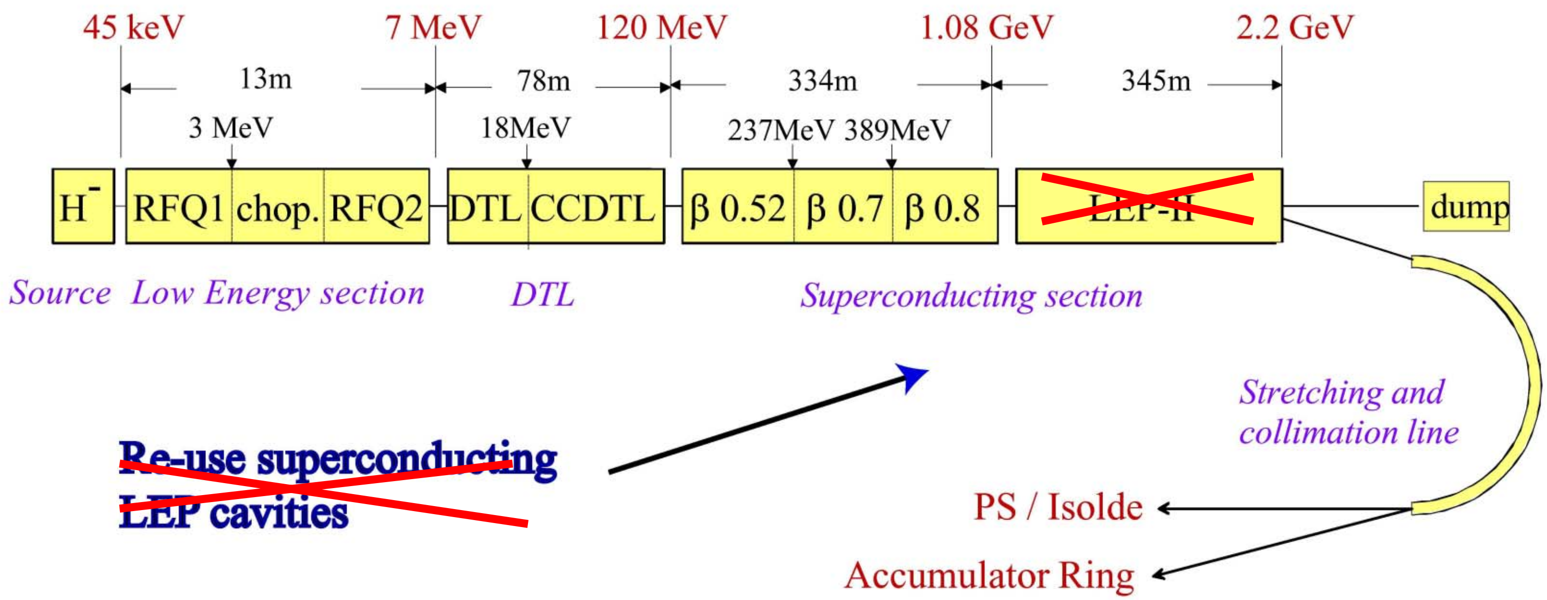






SPL

MW-Linac: SPL (Superconducting Proton Linac)



EKIN = 2.2 GeV
Power = 4 MW
Protons/s = 10^{16}

→ **10^{23} protons/year**

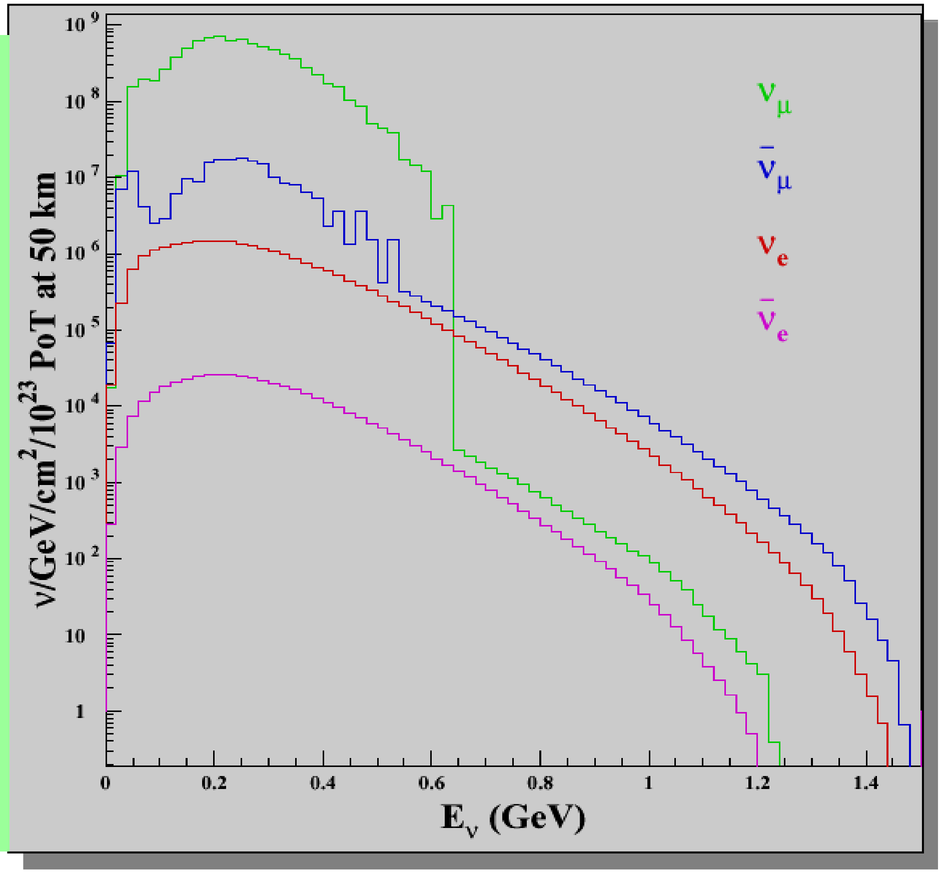
M. Mezzetto, *"Physics Potential of SPL part I: Super Beam"*, NUFACT02, London, 1-6 July 2002 4

Mezzetto, NuFACT03

Fluxes for SPL beam

Flux intensities at 50 km from the target

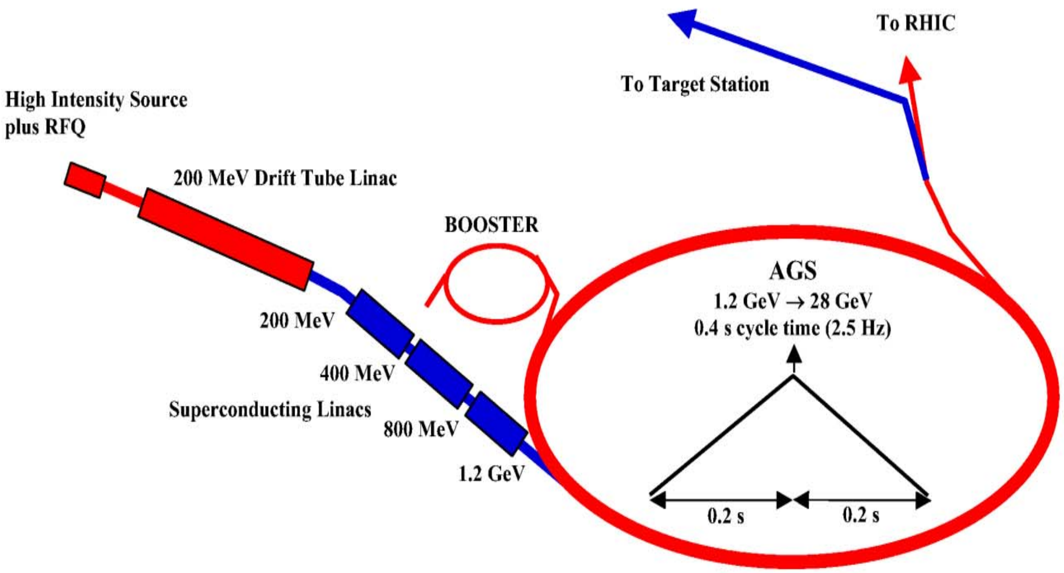
Flavour	Absolute Flux ($/10^{23}$pot / m^2)	Rel. Flux (%)	E (GeV)
ν_μ	$3.2 \cdot 10^{12}$	100	0.27
$\bar{\nu}_\mu$	$2.2 \cdot 10^{10}$	1.6	0.28
ν_e	$5.2 \cdot 10^{9}$	0.67	0.32
$\bar{\nu}_e$	$1.2 \cdot 10^{8}$	0.004	0.29



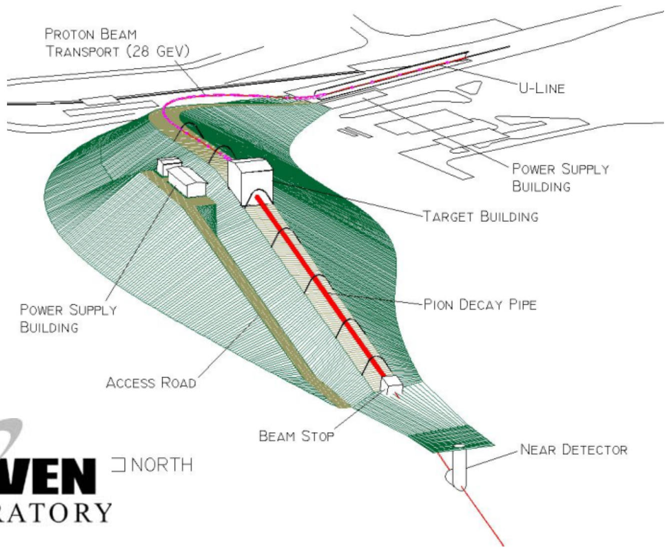
- Low energy wide band beam
- Less NC π^0 BG for ν_e search

Mezzetto, NuFACT03

BNL to ???



28 GeV protons, 1 MW beam power
500 kT Water Cherenkov detector
5 10^7 sec of running,
Conventional Horn based beam



BROOKHAVEN NATIONAL LABORATORY

(Ref: Diwan et al., PRD68, 012002, 2003)

Fermilab Proton Driver (PD)

8 GeV synchrotron option
- **Original concept (May 2002, Fermilab-TM-2169)**
- **Large aperture (100x150mm) magnets**
- **LINAC 400MeV → 600MeV**
- **MI cycle time 1.87s → 1.53s**

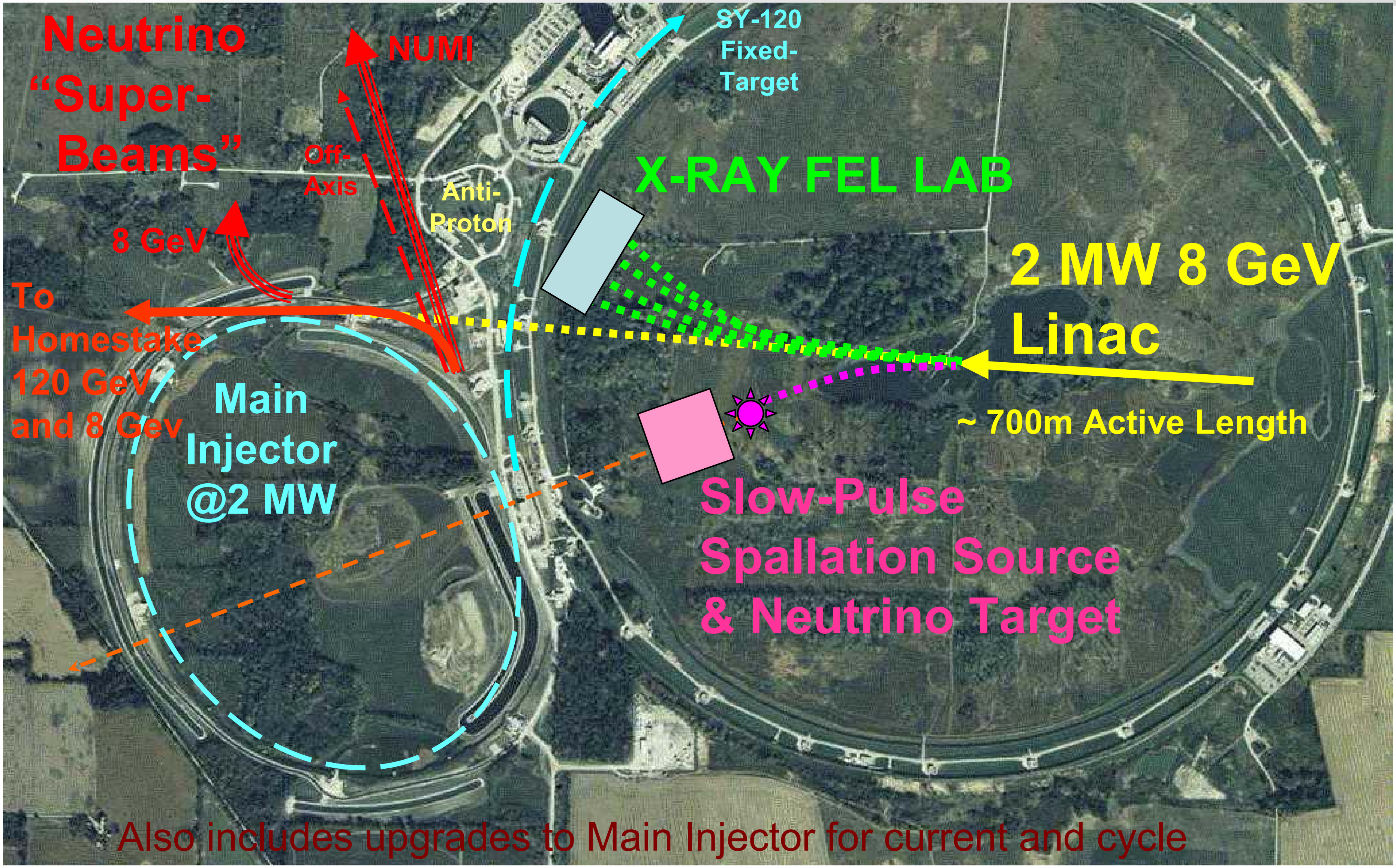
➔ **Net results : MI power of 1.9MW**

8 GeV superconducting linac
- **Recent study**
- **Direct injection**
  - **2MW @ 8GeV & 40~120GeV(MI)**
- **Future flexibility**
- **Issue: Cost?**

Increase MI power by x5~6 (2MW)
→ Improve MINOS & NOνA sensitivities

B.Foster and D.Michael, BNL-APS SB WS Mar.04

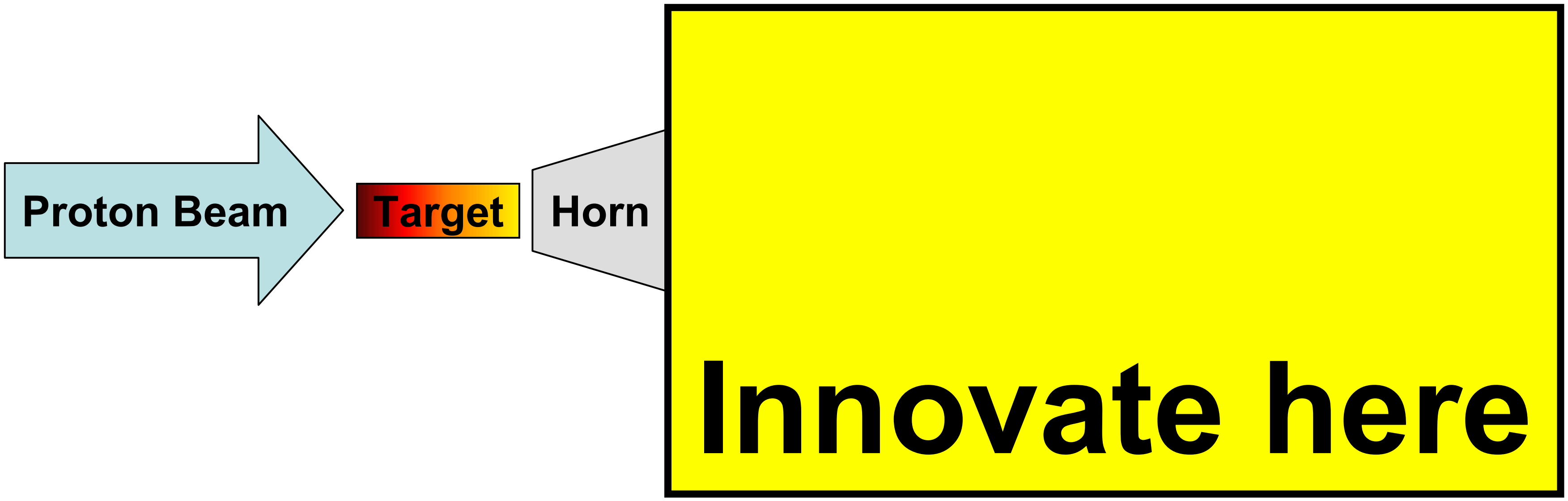
Potential Flexibility of LINAC



B.Foster and D.Michael, BNL-APS SB WS Mar.04

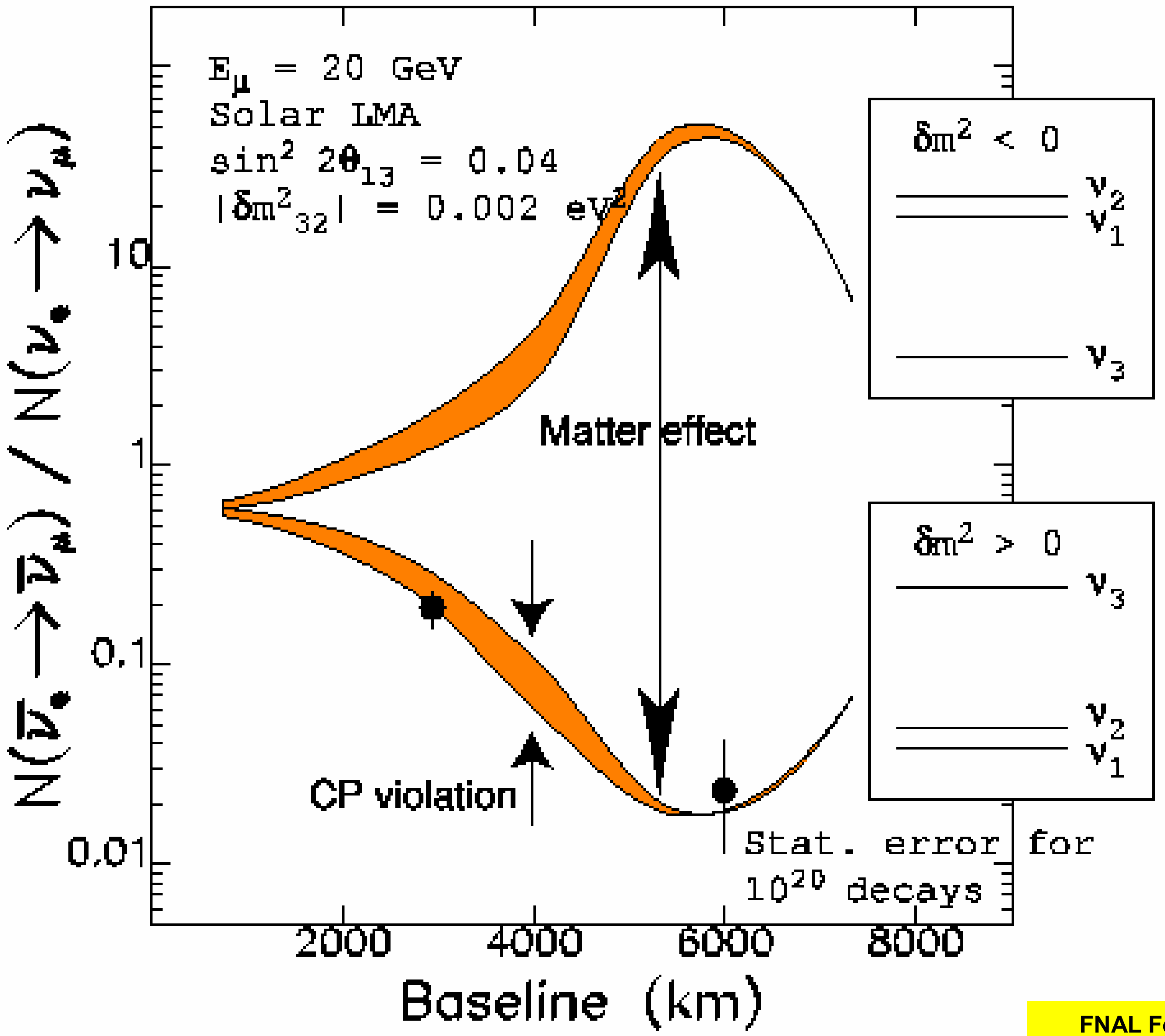
New kinds of Neutrino Beam

Neutrinos NOT from π decay!



- Generate the neutrino beams from unstable particles in storage rings with long straight sections

CP-violation



FNAL Feasability Study 1

The Neutrino Factory

CPV: > 10^{20} muon decays

Conventional ν beams

- π,μ & K decay
- Some flavour selectivity
- Contamination

Reactor ν beams

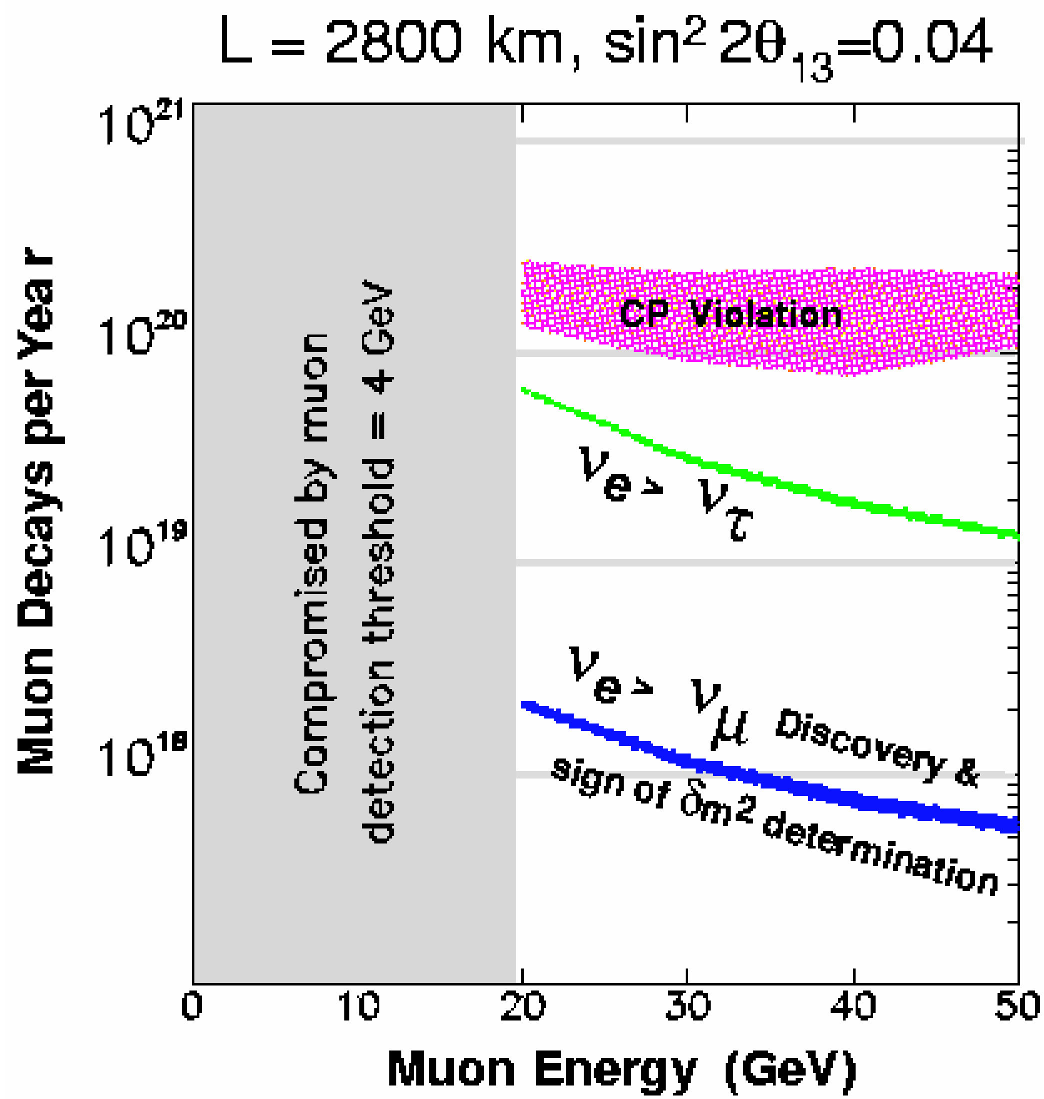
- Pure ν_e
- Huge Fluxes
- Very low energy (MeV)

Super Conventional ν beams

- π, (& some μ) decay
- Flavour selectivity (ν_μ)
- Low Contamination at E<200MeV

The Neutrino Factory

- β beams



FNAL Feasibility Study 1

β-beam ($\nu_e \rightarrow \nu_\mu$ appearance)

- **Need E_{ν_e} > 100 MeV**
  - Conventional (high energy) neutrino beams
    - Come from K decays
    - small fraction of beam
- **New idea (Zucchelli)**
  - β beams
    - Pure electron (anti) neutrino beams

    from

    accelerated radioactive ions

Possible β^+ emitters (ν_e)

Isotope	Z	A	A/Z	$T_{1/2}$	$Q_{\beta\ (gs>gs)}$	$Q_{\beta\ eff.}$	$E_{\beta\ av.}$	$E_{\nu\ av.}$	<E_LAB> (MeV)
				s	MeV	MeV	MeV	MeV	(@450 GeV/p)
8B	5	8	1.6	0.77	17.0	13.9	6.55	7.37	4145
10C	6	10	1.7	19.3	2.6	1.9	0.81	1.08	585
14O	8	14	1.8	70.6	4.1	1.8	0.78	1.05	538
15O	8	15	1.9	122.2	1.7	1.7	0.74	1.00	479
18Ne	10	18	1.8	1.67	3.4	3.4	1.50	1.86	930
19Ne	10	19	1.9	17.34	2.2	2.2	0.96	1.25	594
21Na	11	21	1.9	22.49	2.5	2.5	1.10	1.41	662
33Ar	18	33	1.8	0.173	10.6	8.2	3.97	4.19	2058
34Ar	18	34	1.9	0.845	5.0	5.0	2.29	2.67	1270
35Ar	18	35	1.9	1.775	4.9	4.9	2.27	2.65	1227
37K	19	37	1.9	1.226	5.1	5.1	2.35	2.72	1259
80Rb	37	80	2.2	34	4.7	4.5	2.04	2.48	1031

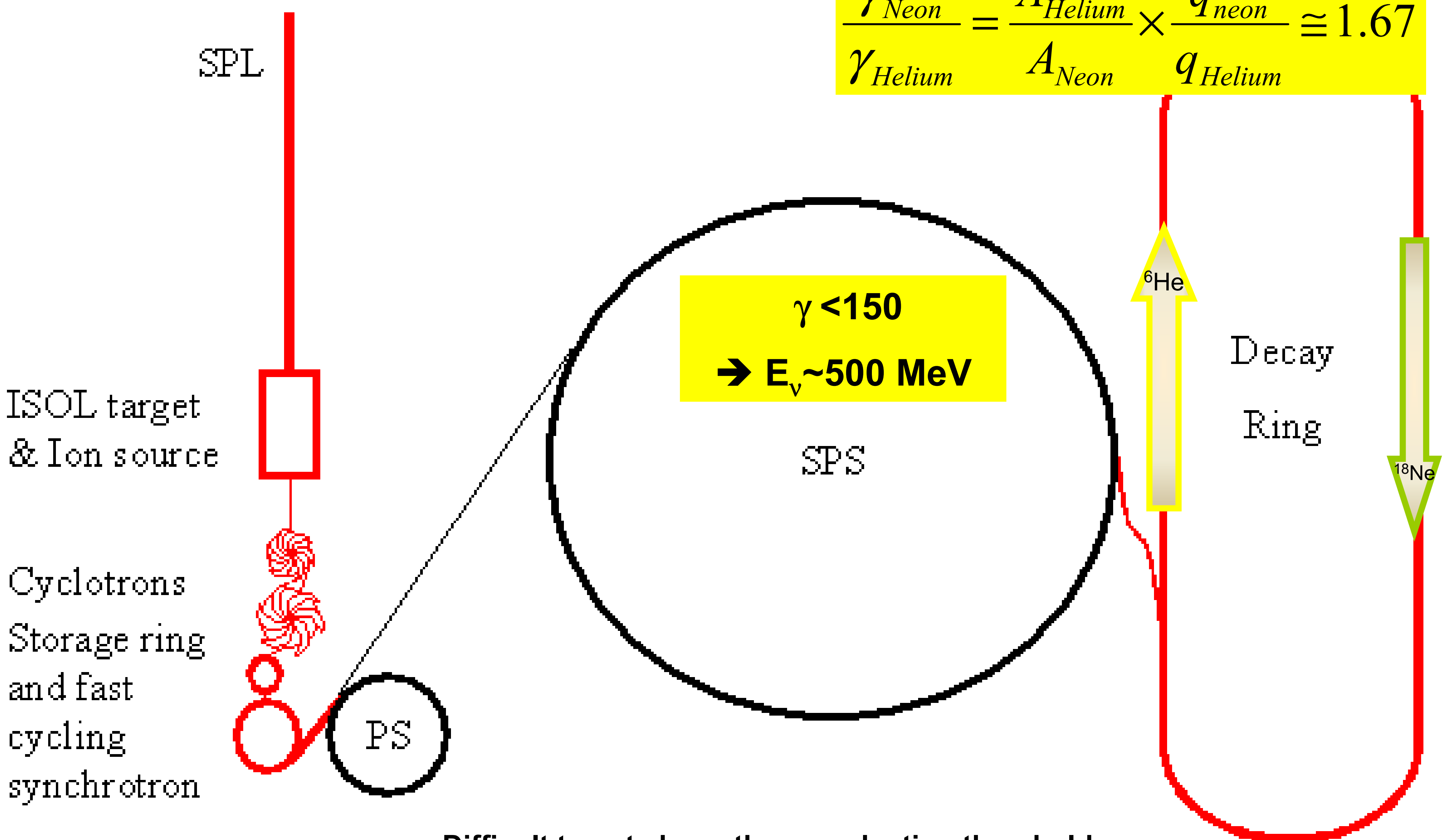
Possible β^- emitters ($\bar{\nu}_e$)

Isotope	Z	A	A/Z	$T_{1/2}$	$Q_{\beta\ (gs>gs)}$	$Q_{\beta\ eff.}$	$E_{\beta\ av.}$	$E_{\nu\ av.}$	<E_LAB> (MeV)
				s	MeV	MeV	MeV	MeV	(@ 450 GeV/p)
6He	2	6	3.0	0.807	3.5	3.5	1.57	1.94	582
8He	2	8	4.0	0.119	10.7	9.1	4.35	4.80	1079
8Li	3	8	2.7	0.838	16.0	13.0	6.24	6.72	2268
9Li	3	9	3.0	0.178	13.6	11.9	5.73	6.20	1860
11Be	4	11	2.8	13.81	11.5	9.8	4.65	5.11	1671
15C	6	15	2.5	2.449	9.8	6.4	2.87	3.55	1279
16C	6	16	2.7	0.747	8.0	4.5	2.05	2.46	830
16N	7	16	2.3	7.13	10.4	5.9	4.59	1.33	525
17N	7	17	2.4	4.173	8.7	3.8	1.71	2.10	779
18N	7	18	2.6	0.624	13.9	8.0	5.33	2.67	933
23Ne	10	23	2.3	37.24	4.4	4.2	1.90	2.31	904
25Ne	10	25	2.5	0.602	7.3	6.9	3.18	3.73	1344
25Na	11	25	2.3	59.1	3.8	3.4	1.51	1.90	750
26Na	11	26	2.4	1.072	9.3	7.2	3.34	3.81	1450

Bouchez, NuFACT03

β-beam

$$\frac{\gamma_{Neon}}{\gamma_{Helium}} = \frac{A_{Helium}}{A_{Neon}} \times \frac{q_{neon}}{q_{Helium}} \cong 1.67$$



Difficult to get above the τ production threshold

Intensities

$\bar{\nu}_e$ ^{6}He

- From ECR source
  - 2.0×10^{13} ions per second
- PS after acceleration:
  - 1.0×10^{13} ions per batch
- SPS after acceleration:
  - 0.9×10^{13} ions per batch
- Decay ring:
  - 2.0×10^{14} ions
- 50 % losses
  - 10^{14} ions in four 10ns

ν_e ^{18}Ne

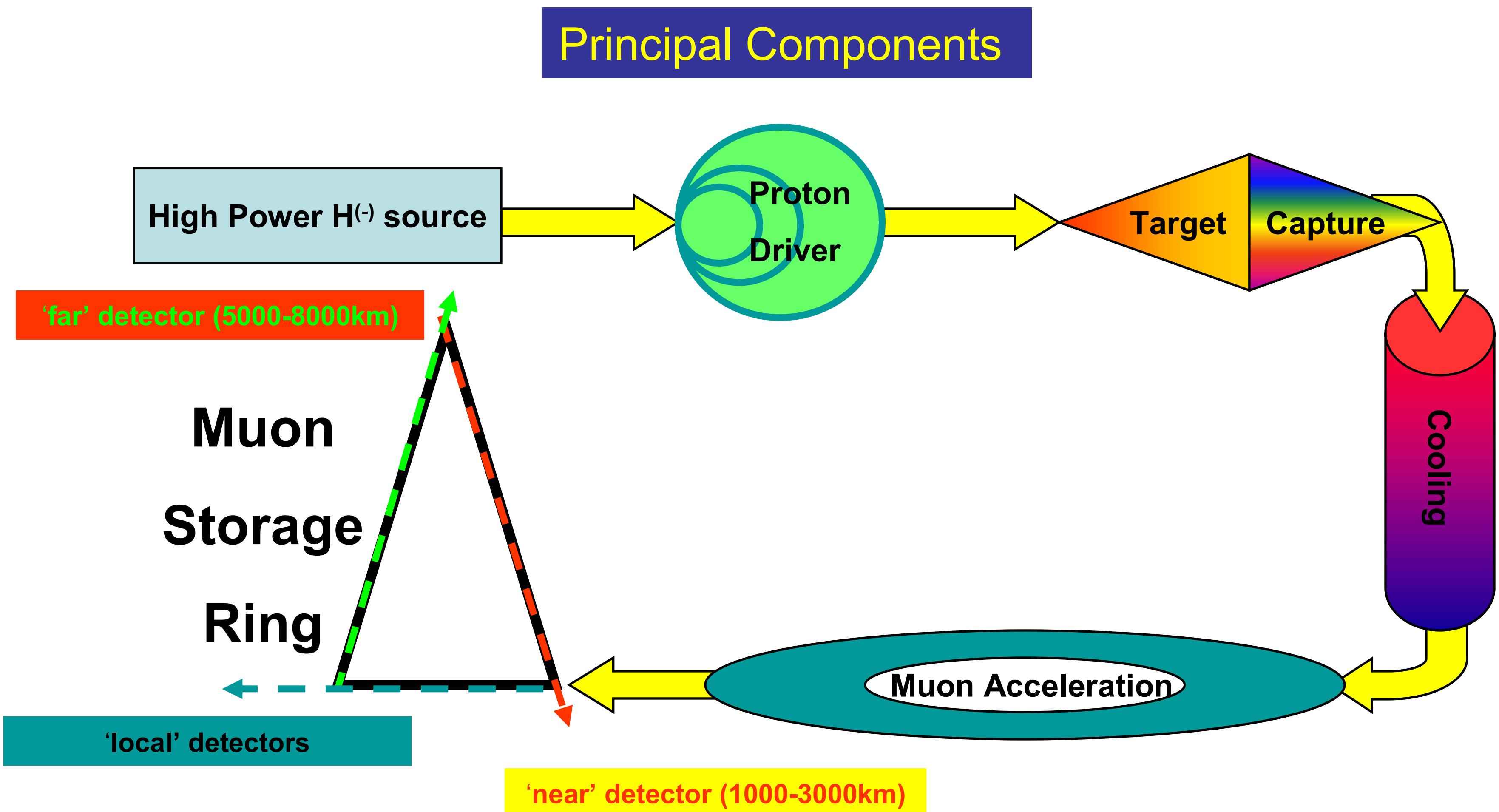
- From ECR source:
  - 0.8×10^{11} ions per second
- PS after acceleration
  - 5.2×10^{11} ions per batch
- SPS after acceleration
  - 4.9×10^{11} ions per batch
- Decay ring:
  - 9.1×10^{12} ions
- 50 % losses:
  - 5×10^{12} ions in four 10 ns
- FOR 3 ISOL targets
  - 1.3×10^{13} ions

Bouchez

Electron Cyclotron Resonance

A Neutrino Factory is …

… an accelerator complex designed to produce >10^{20} muon decays per year directed at a detector thousands of km away

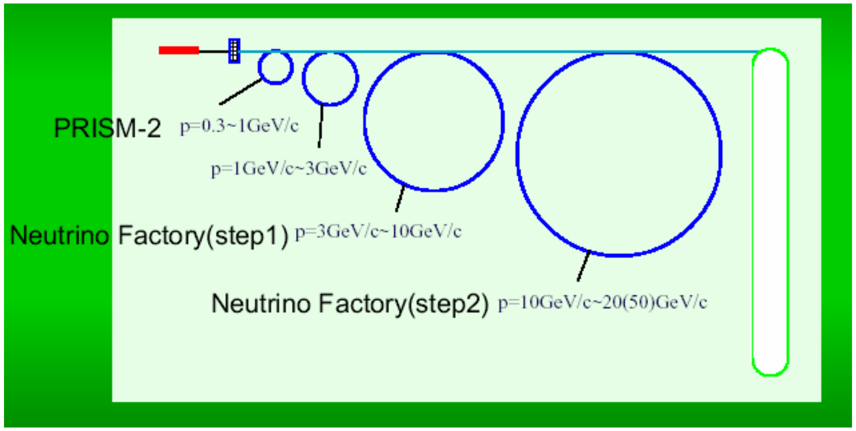


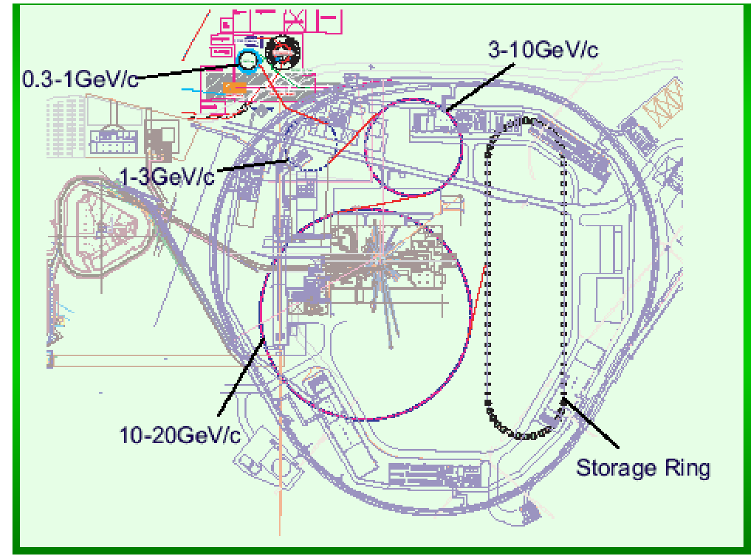
Neutrino Factory Challenges

- Parameters
  - Need to know that θ_{13} is not zero
    - Other parameters well known to fix (E_{μ},L)
- Technology
  - Proton driver
    - RCS or LINAC?
  - Proton energy?
    - HARP, E910, MIPP
  - Target
    - MW beam power
      - Mercury, solid, liquid-cooled, pellet, …
  - Pion/muon collection and/or cooling
    - Magnetic Horns or Solenoids?
    - Phase Rotators, FFAG's, cooling?
  - RF and acceleration
    - RLA's or FFAG's?
  - Muon Storage Ring
    - Racetrack, triangular or bow-tie
    - Conventional or FFAG?

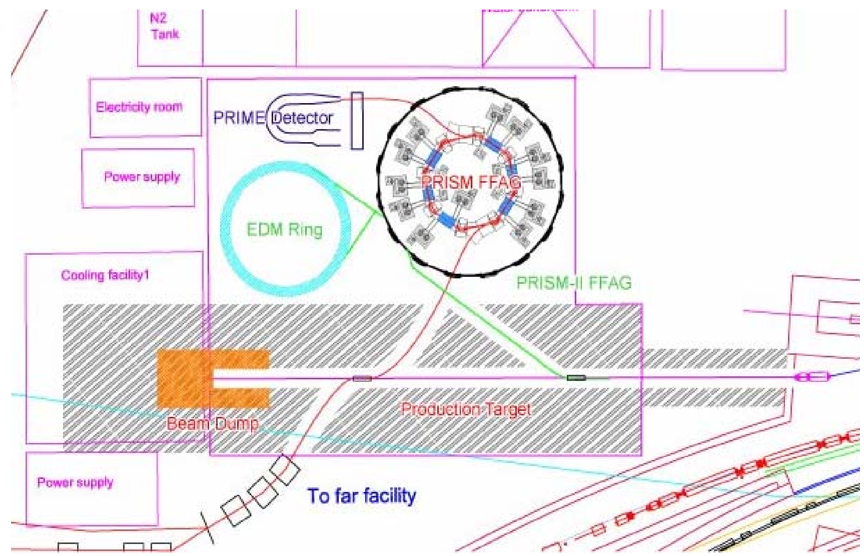
- Other uses of high power protons & muons?

The FFAG model





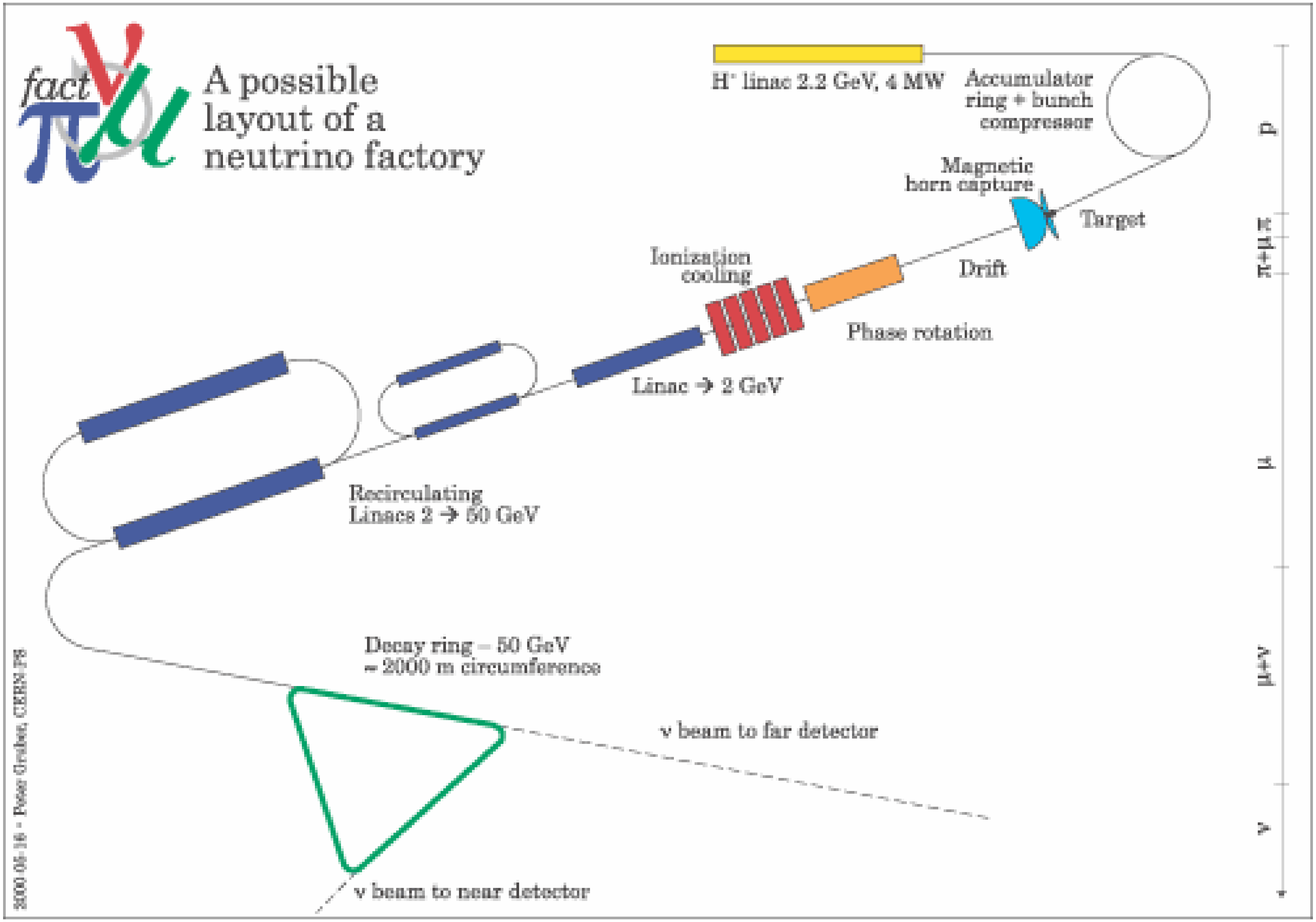
- **High Power Proton Driver**
  - **Muon g-2**
- **Muon Factory (PRISM)**
  - **Muon LFV**
- **Muon Factory-II (PRISM-II)**
  - **Muon EDM**
- **Neutrino Factory**
  - **Based on 1 MW proton beam**
- **Neutrino Factory-II**
  - **Based on 4.4 MW proton beam**



After Y Kuno

CCLRC

Another Neutrino Factory



Key Challenges

Targets

- ~ same power as SNS targets
  - Open
  - Small
    - See previous talk

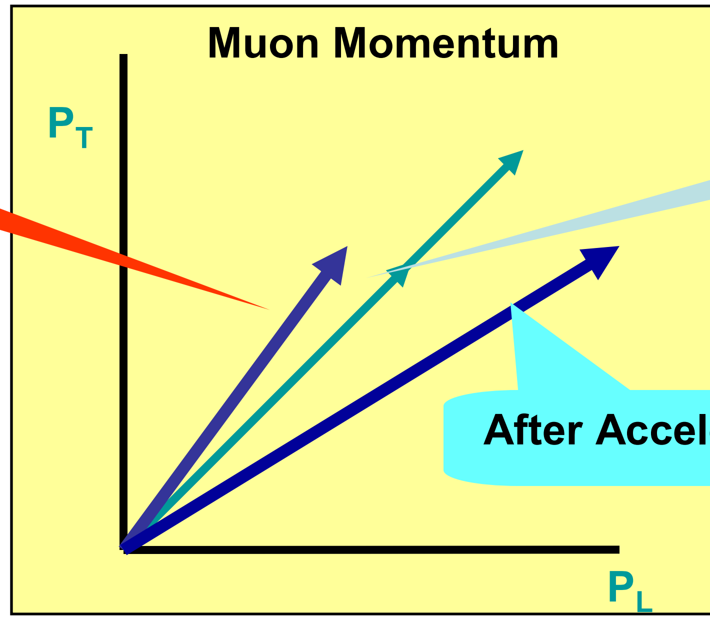
Muon Cooling

- Certainly needed for a muon collider
- Almost certainly needed for a neutrino factory
  - (combined FFAG/cooling or ring-coolers?)

Ionization Cooling

After Multiple Scattering

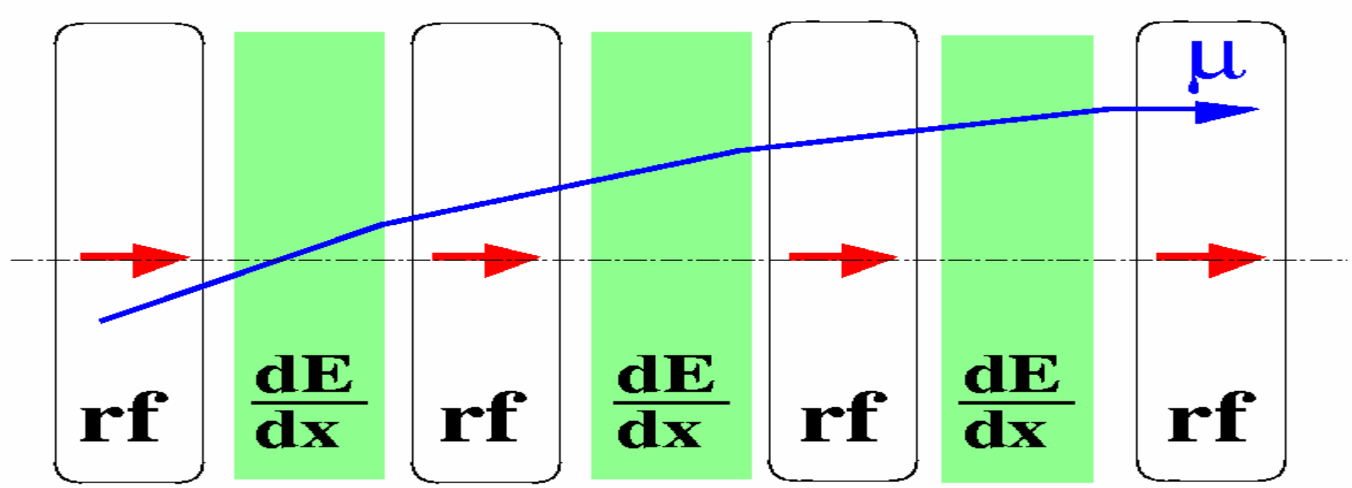
$$\frac{d\varepsilon_n}{ds} = \frac{\beta_\perp}{\beta^3 m_\mu c^2 X_0 E_\mu}\frac{dE_\mu}{ds}$$



After ionisation energy loss

$$\frac{d\varepsilon_n}{ds} = -\frac{\varepsilon_n}{\beta^2 E_\mu}\frac{dE_\mu}{ds}$$

After Acceleration

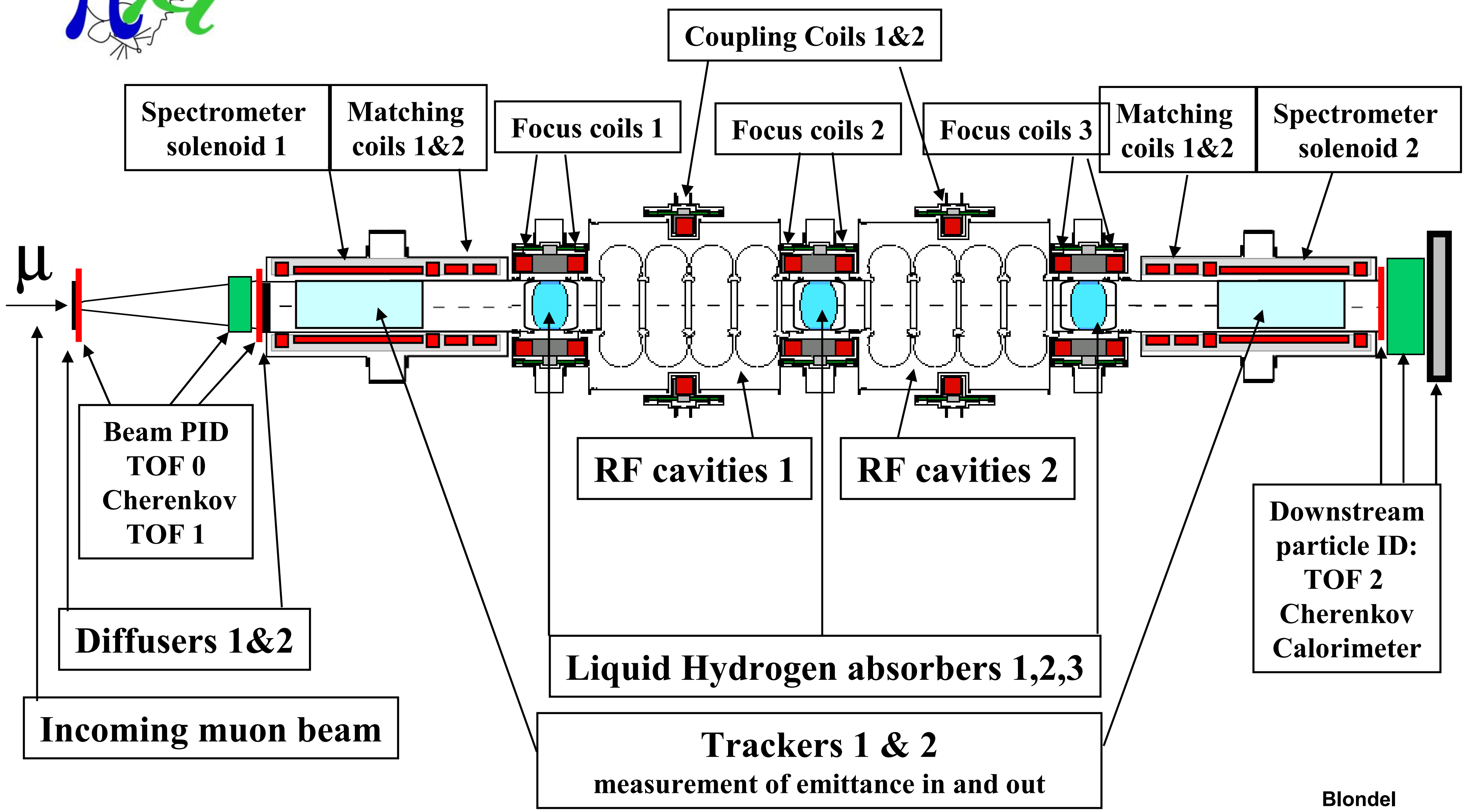


10% cooling of 200 MeV/c muons requires ~ 20 MV of RF

single particle measurements =>

measurement precision can be as good as $\Delta (\varepsilon_{out}/\varepsilon_{in}) = 10^{-3}$

never done before either….

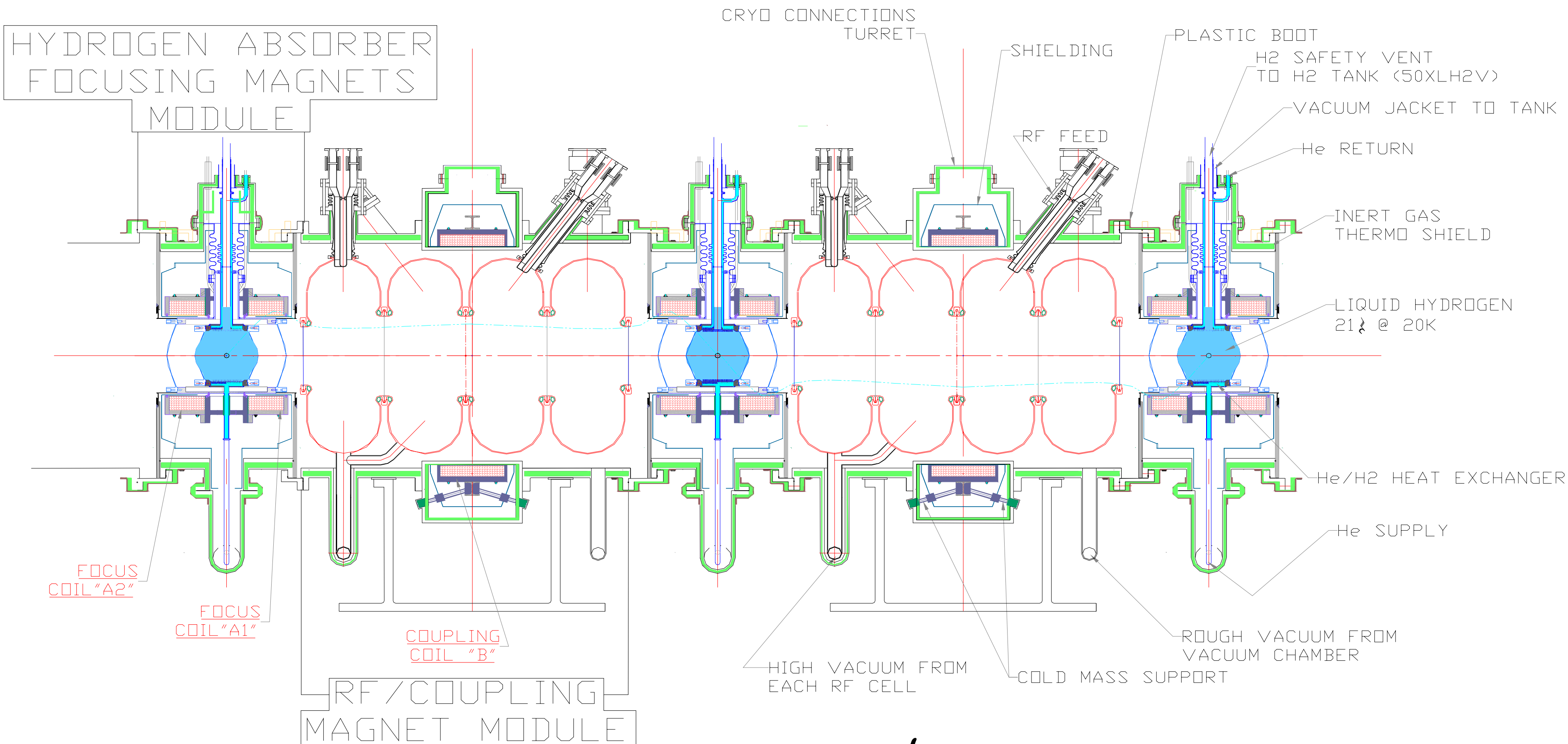


Blondel

CCLRC

… after engineering …

reality (simplified)

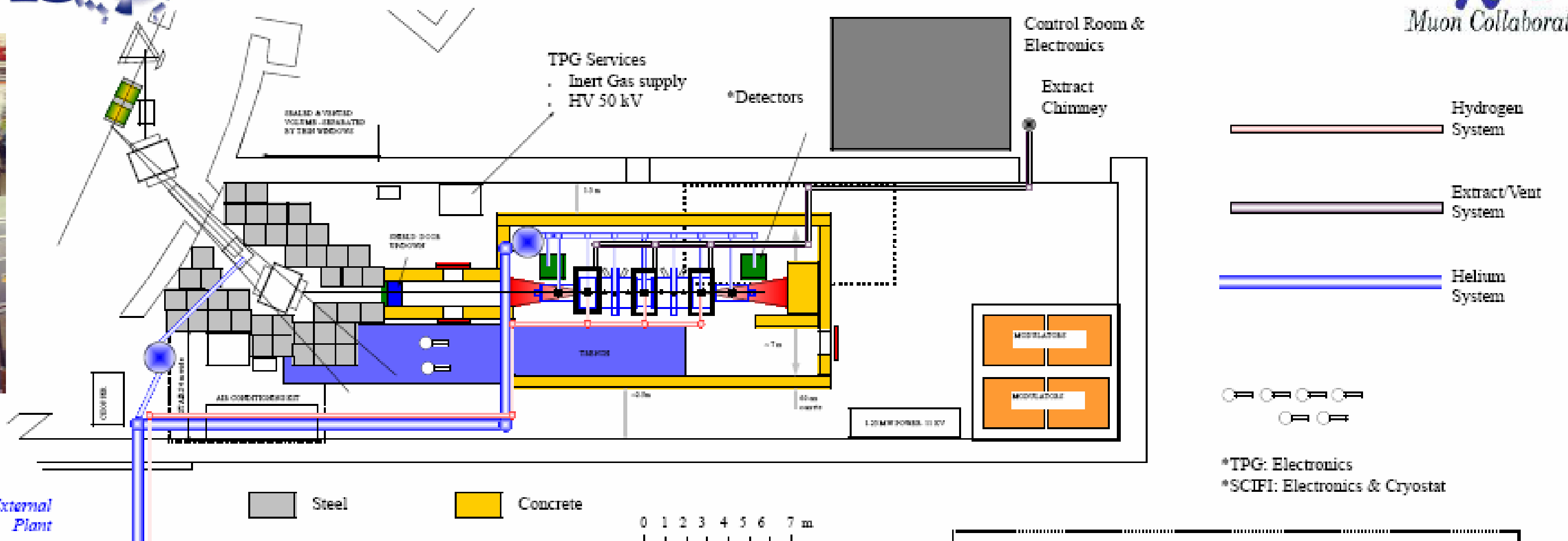


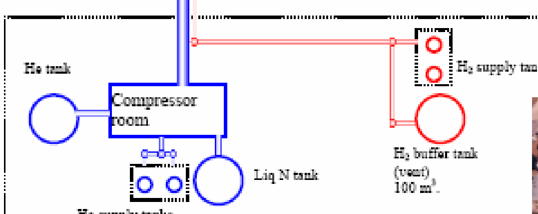
….maybe…

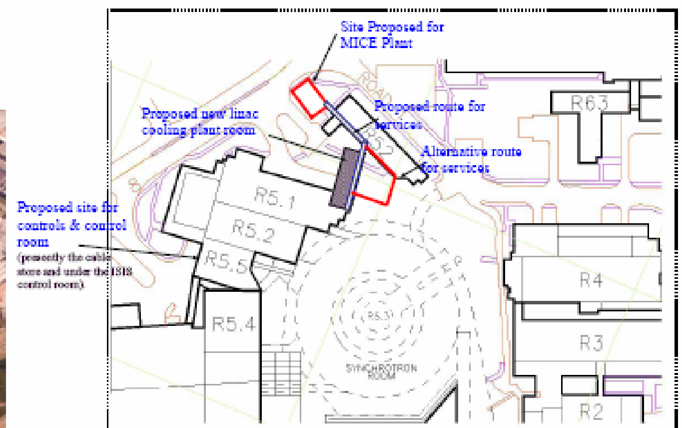
Blondel

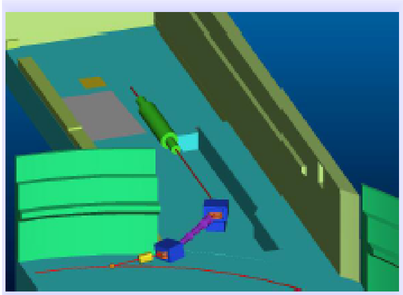
Proposal

Muon Ionization Cooling Experiment





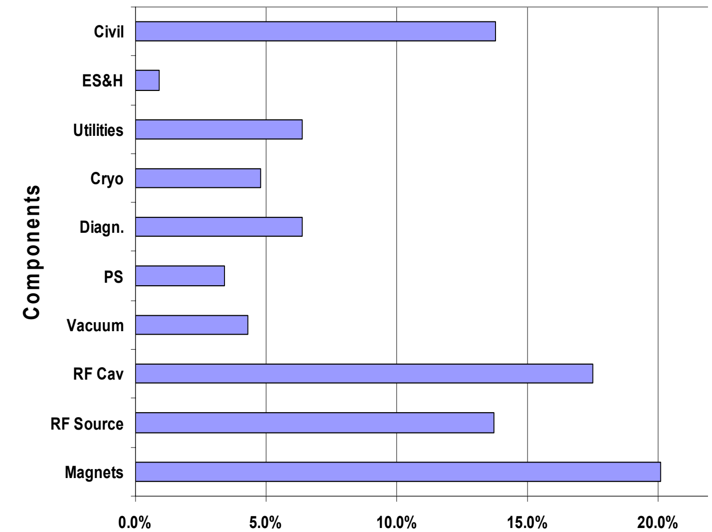


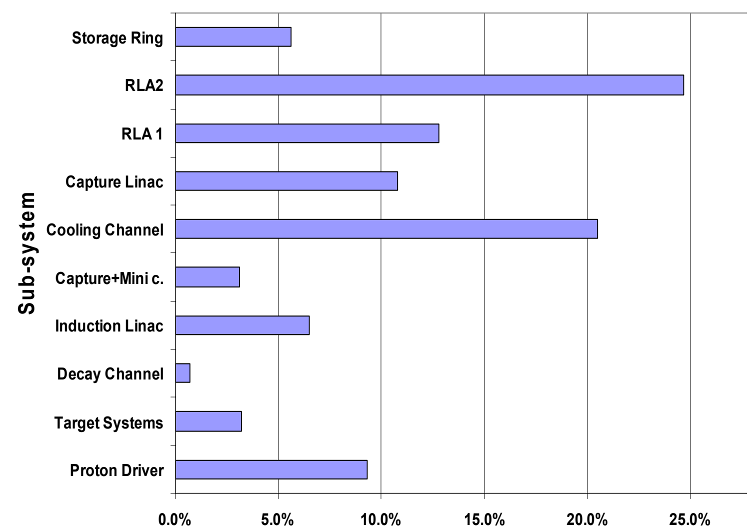


at the Rutherford Appleton Laboratory

Neutrino Factory R&D

- High Power proton drivers
  - MW power, ns pulses
- RF
  - 30% of the cost?
- Cooling
  - How much? (20% of the cost?)
- RLA or FFAG?
  - Which is cheaper?

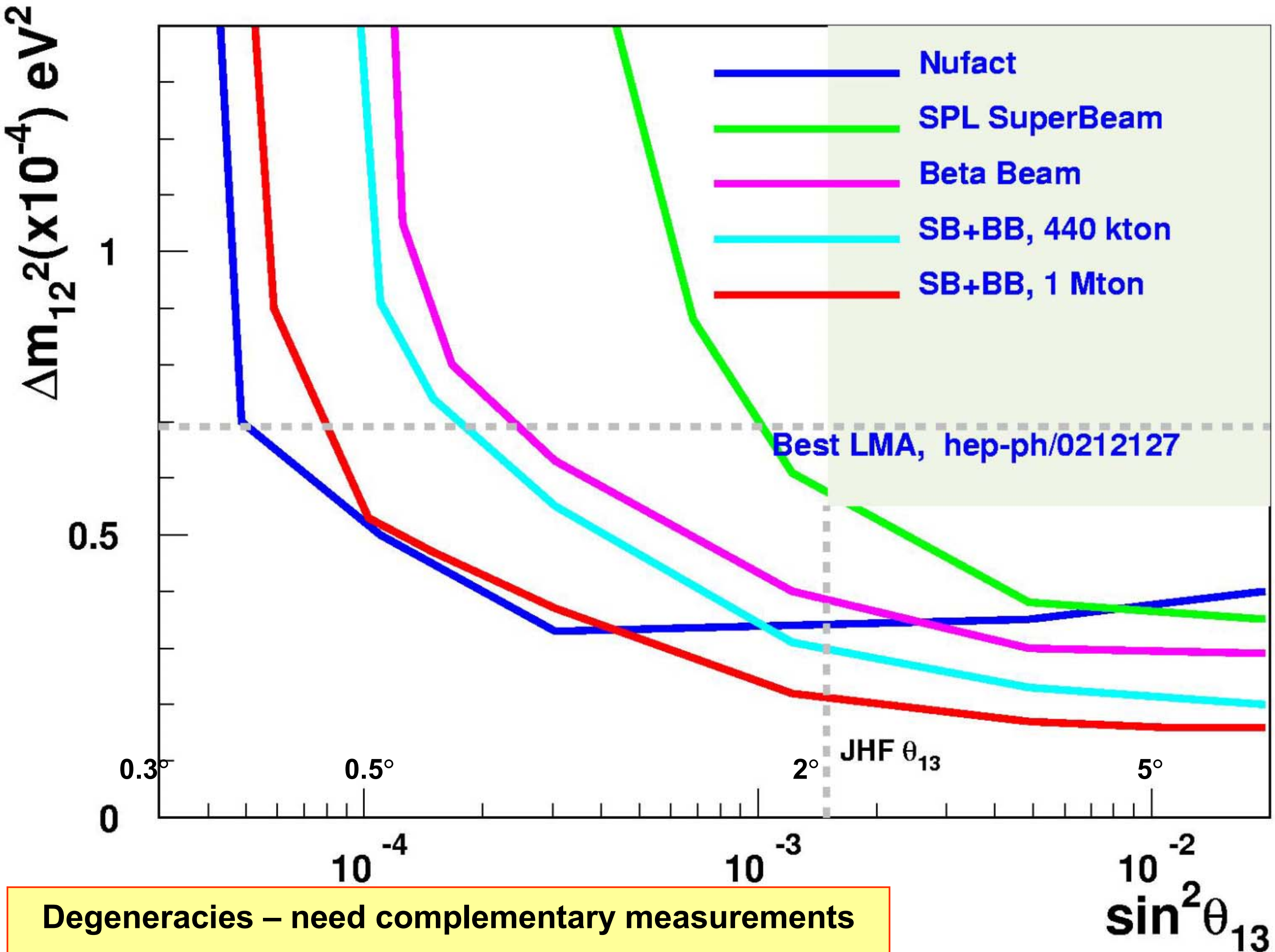




BNL Feasability Study 2

CP sensitivity

domain of 99% CL effect for maximal CP violation



Degeneracies – need complementary measurements

(baselines, energies, flavours, channels)

Bouchez