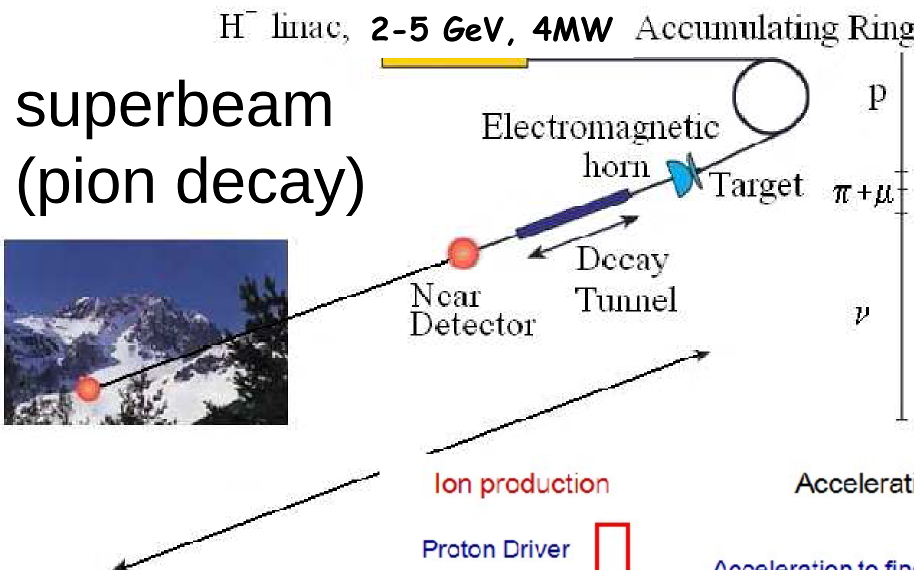
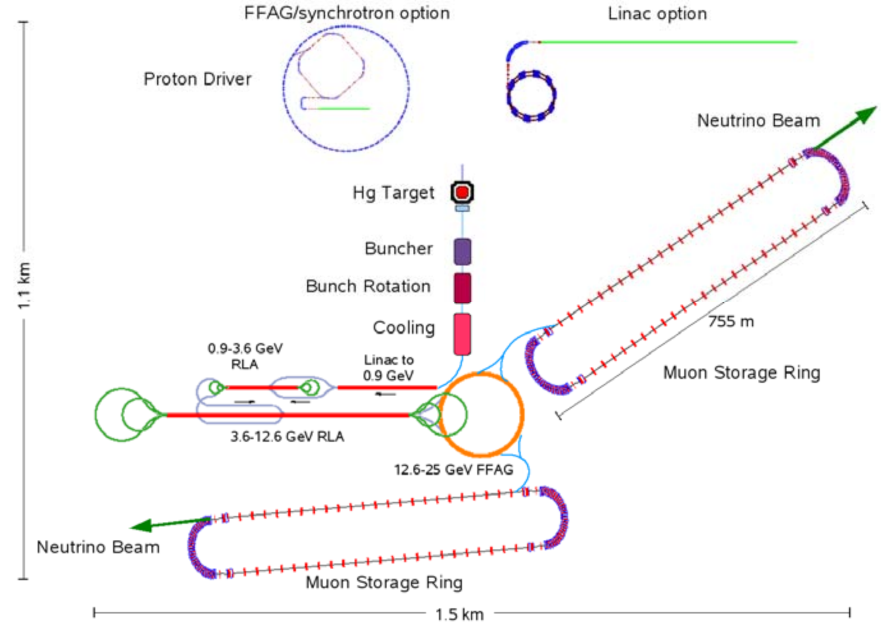
Requirements on Proton Driver for Future Neutrino Facilities

Superbeam	Beam Power
Beta-beam	Beam Energy
Muon beams	Time structure
Neutrino factory	Others (target infrastructure etc..)

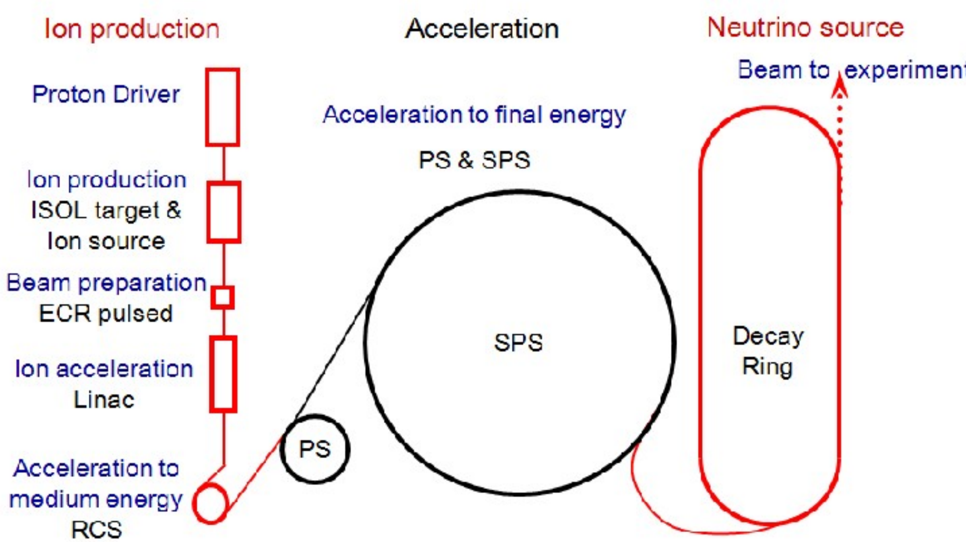
EUROν

superbeam
(pion decay)





Neutrino Factory
(muon decay)



Beta-beam
ion decay ^{6}He, ^{18}Ne or ^{8}Be, ^{8}Li

CE

key question for us:
can any of this be at CERN?

Super beam

$\pi \rightarrow \mu\ \nu_\mu$

There exist several superbeam projects in the world.

CNGS 400 GeV protons, Fast extraction, Ev= 25 GeV 400 kW on axis,
OPERA far detector at 730 km
Limitations at ca 1MW, near detector?

T2K: 30 GeV protons, 0.75 MW Fast extraction (5 microsecond@ 0.3Hz)
off axis 2.5 degrees -> Ev=700 MeV 50 (22 fid.) kton WC detector at 300km;
Future 1.66 MW by 2016 consider 500 kton WC far detector or Liq. Argon
at distances up to 1000km

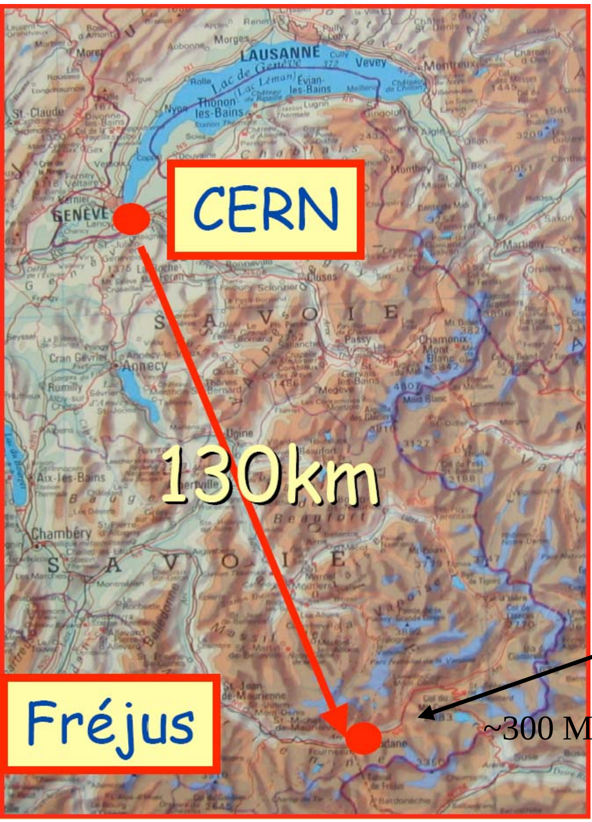
FNAL (NUMI) 125 GeV protons 0.4MW fast extraction
Present LE beam at ~2 GeV 730 km MINOS detector
Off axis beam at 1.5 GeV TASD 15kton detector NOVA at 890 km
Future project to DUSEL

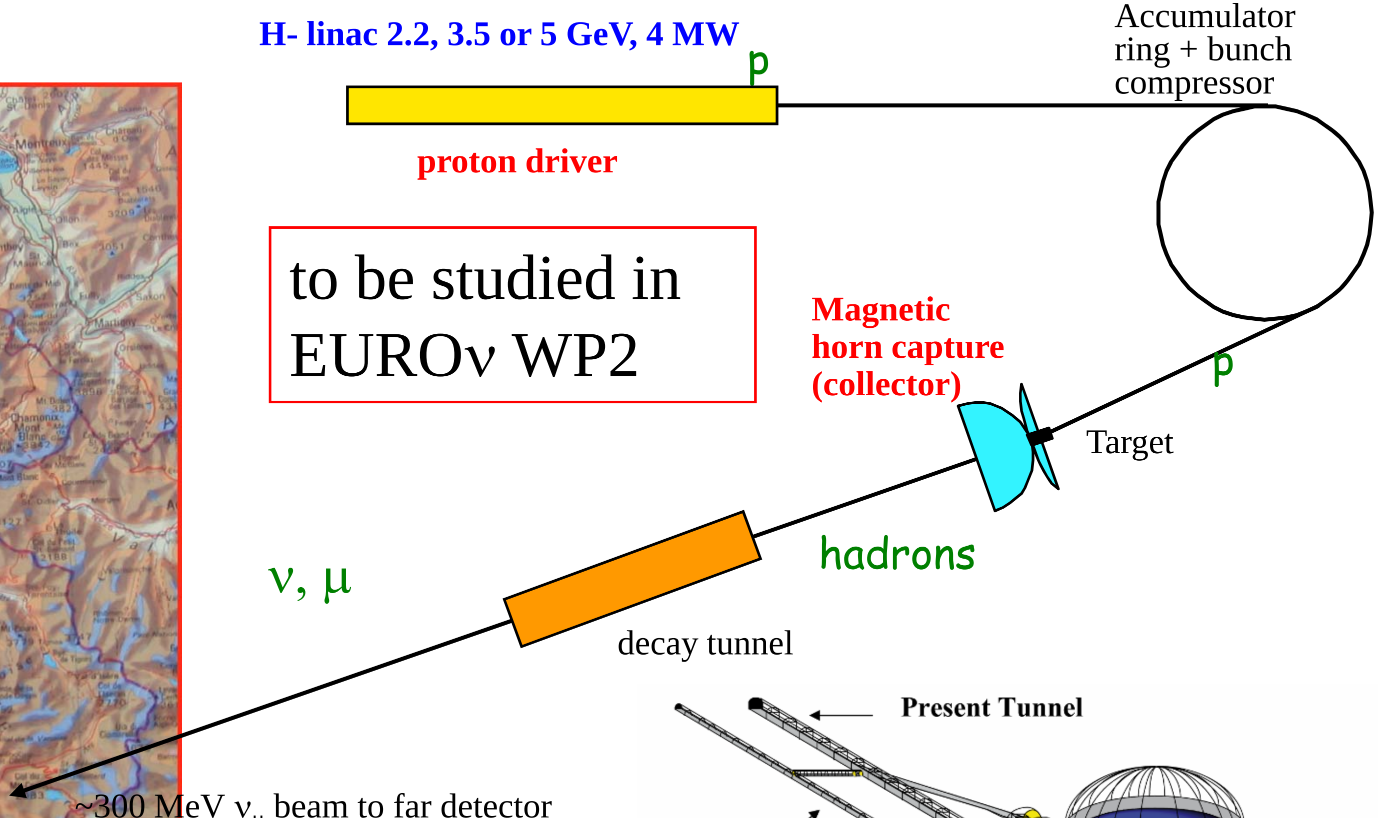
Comment: at sub GeV Energy, fast extraction is necessary (D.C.$<10^{-5}$)
for rejection of cosmic background and atmospheric neutrinos which are ~50% ν_e

To go beyond: several MW beam power, energy related to baseline,
Duty cycle must be $<10^{-4}$.

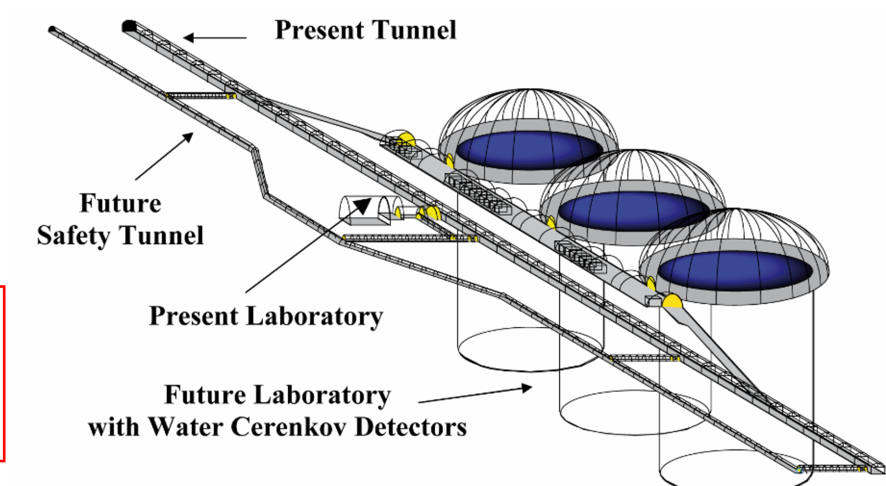
Beam composition monitoring and near detector station are crucial.

SPL Super-Beam Project





to be studied in EUROν WP2



to be studied by LAGUNA

SUPERBEAM at SPL? 50 Hz 4 MW 4-5 GeV LINAC

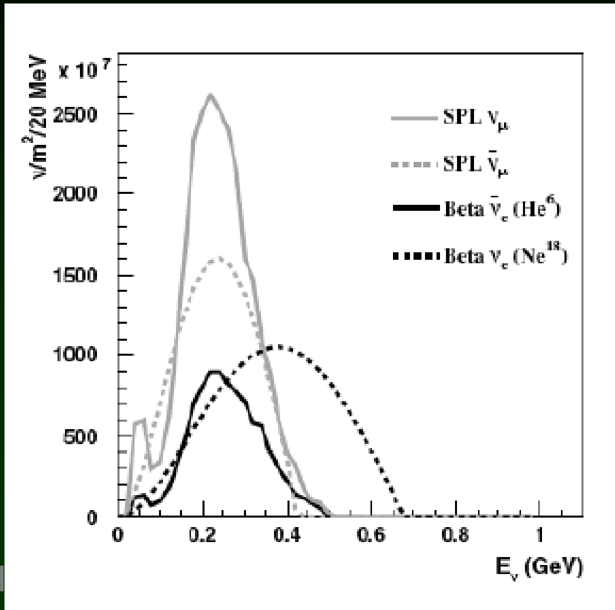
High beam power required (~4MW or more if possible)

Short duty cycle => accumulator ring is necessary

Pulsed Magnetic horns require duty cycle typically <10-3 (thermal constraint)
At 50 Hz operation this requires beam delivery within <20 microseconds.

Single Target? Liquid Hg target difficult to integrate in horn. Solid/powder target?

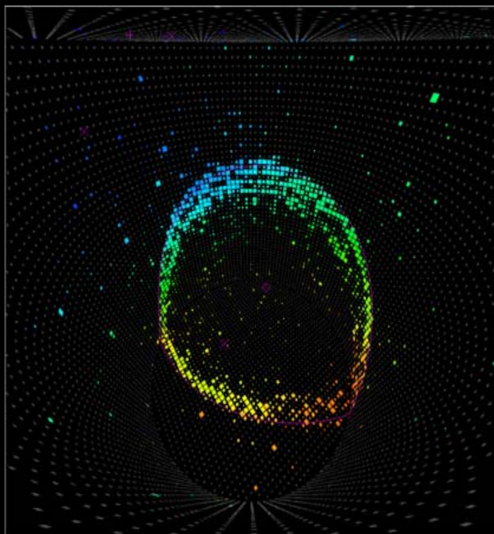
Proton Beam energy?
On axis pion decay Neutrino energy is typically < 10-15% of proton beam energy
SPL superbeam=> 400-500 MeV neutrino beam energy.
This is a good energy for the Water Cherenkov also
in search of proton decay.

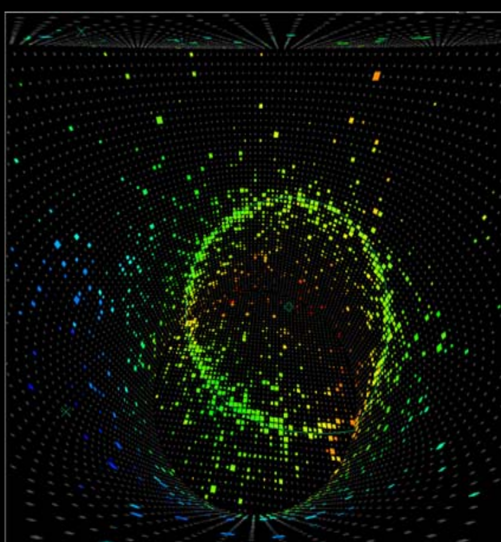


First oscillation maximum is situated at <250 km.
Second oscillation maximum at < 750 km.
(useful if $\sin^2 2\theta_{13}$ is small?)

Probably not very interesting if considered in isolation.
Advocated to be Interesting/important/necessary
if considered in conjunction to beta-beam.

Combination of beta beam with super beam





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^-)

in addition, one beam provides cross-sections and topologies for the other in the near detector

Beta-beams

$$^{6}He \rightarrow {}^{6}Li\, e^{-} \overline{\nu}_{e} \qquad {}^{18}Ne \rightarrow {}^{18}Fe^{+} \nu_{e}$$

Aimed:
He 2.9 10^{18} (2.0 10^{13}/s)
Ne 1.1 10^{18} (2.0 10^{13}/s)

Original concept for the ion production is based on the SPL:
succesful for ^{6}He, well established production mechanism
Spallation production of ^{6}He on a BeO target from a powerful proton source (~200 kw per target station)

For ^{18}Ne initial considerations using the same technique lead to a deficit of a factor > 10 wrt to physics demands. (8 10^{11}/s).
Direct production using high power ^{3}He gun under study.

With SPS as final accelerator, typical maximal energy for (anti) neutrinos is 400-600 MeV (i.e. can be matched to the SPL superbeam)

➔EUROnu DS will investigate new production mechanisms using high Q isotopes: ^{8}Li, ^{8}B (C. Rubbia et al) which are less demanding on the proton source.
Higher energy neutrinos (factor 4-5) but correspondingly higher number of ions will be required for same event rates. Flux goes as $1/Q^2$ and cross-section as Q.

Exciting possibility also with e-capture ions (Dy for instance) N+e-> N'+ν_e which produce monochromatic electron neutrino beams.
Spallation production; really needs high power SPL.

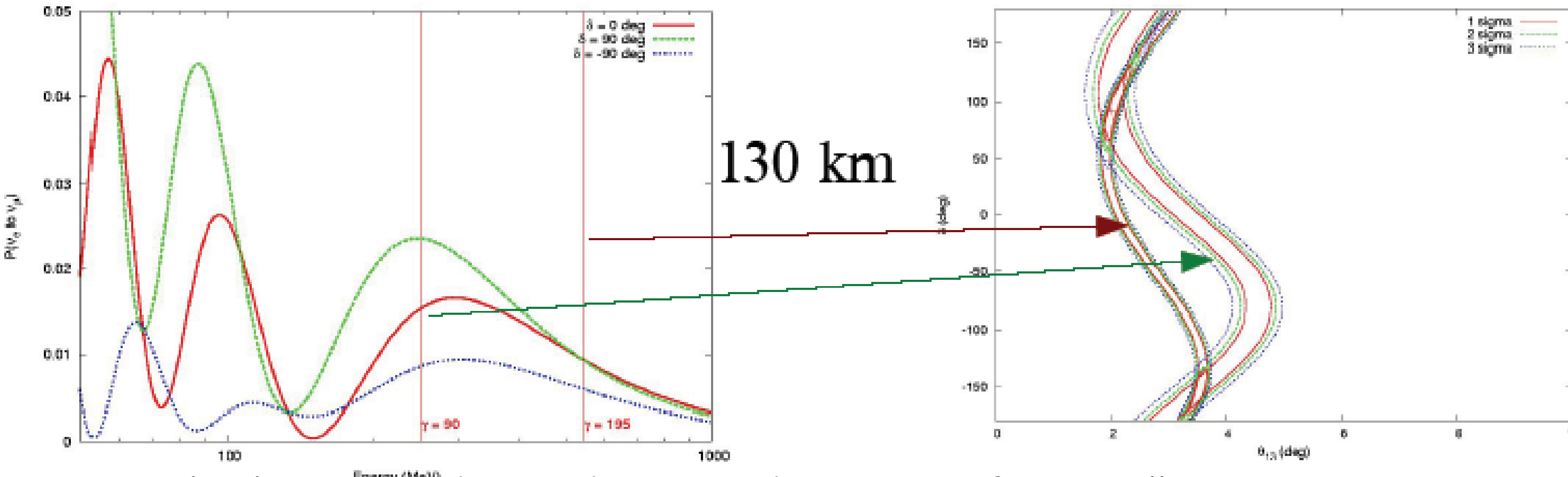
These new ion production schemes are object of the EUROnu design study.

A monochromatic neutrino beam

Electron Capture:

$N+e^- \rightarrow N'+\nu_e$

Decay	$T_{1/2}$	BR_ν	EC/ν	I^{β}_{EC}	B(GT)	E_{GR}	Γ_{GR}	Q_{EC}	E_ν	ΔE_ν
$^{148}Dy \rightarrow {}^{148}Tb^*$	3.1 m	1	0.96	0.96	0.46	620		2682	2062	
$^{150}Dy \rightarrow {}^{150}Tb^*$	7.2 m	0.64	1	1	0.32	397		1794	1397	
$^{152}Tm2^- \rightarrow {}^{152}E_T^*$	8.0 s	1	0.45	0.50	0.48	4300	520	8700	4400	520
$^{150}Ho2^- \rightarrow {}^{150}Dy^*$	72 s	1	0.77	0.56	0.25	4400	400	7400	3000	400



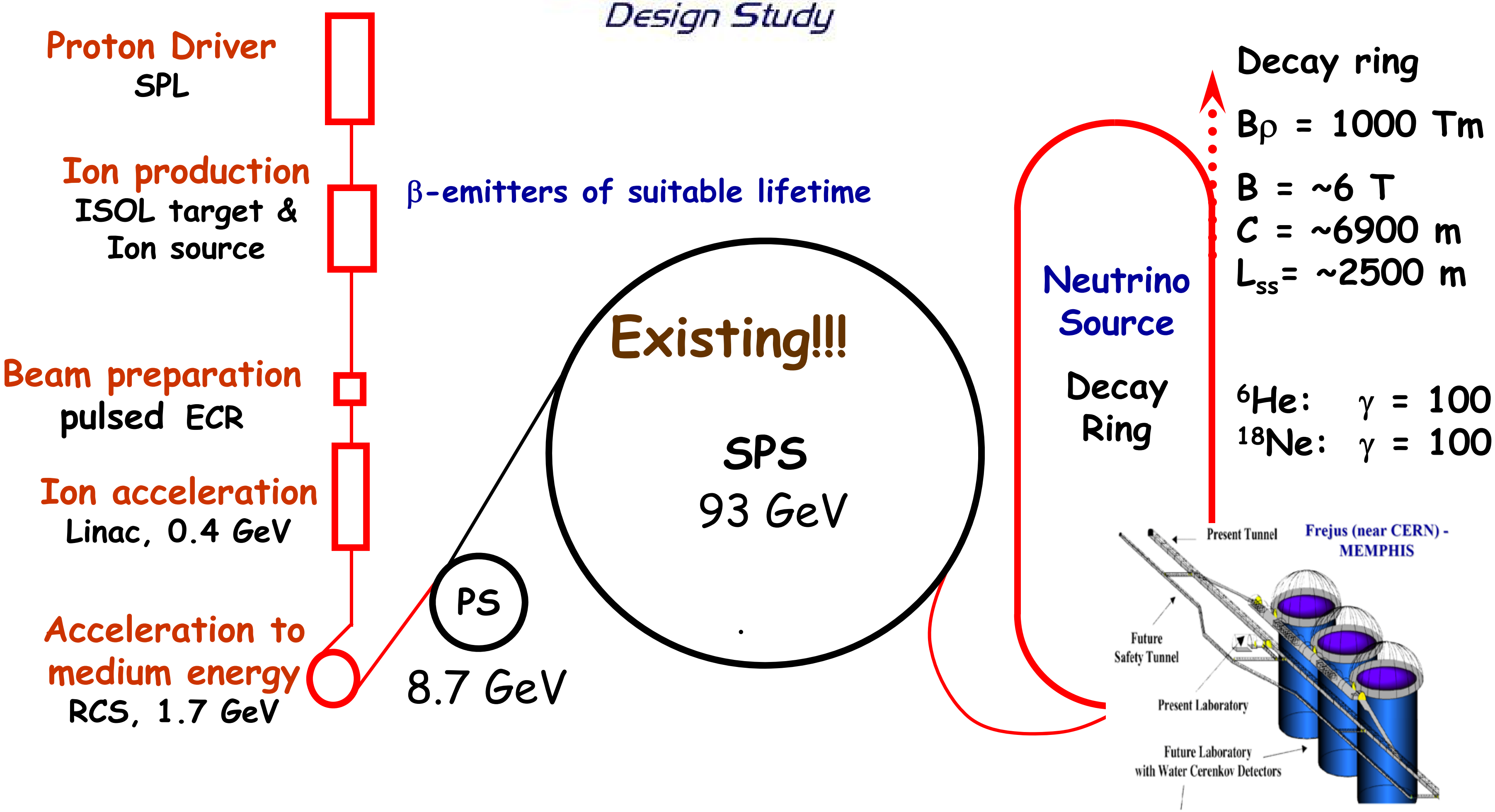
This has been advocated as a good way to perform oscillation measurements…

Unfortunately the decay rate of these isotopes is very long,
and the number of stored ions correspondingly lower
==> intensities likely to be too small for oscillation experiments.

Tunable monochromatic beam for cross-section measts in near detector!

Recall of Beta Beam scenario, EURISOL

EURISOL Design Study



Detector in the Frejus tunnel

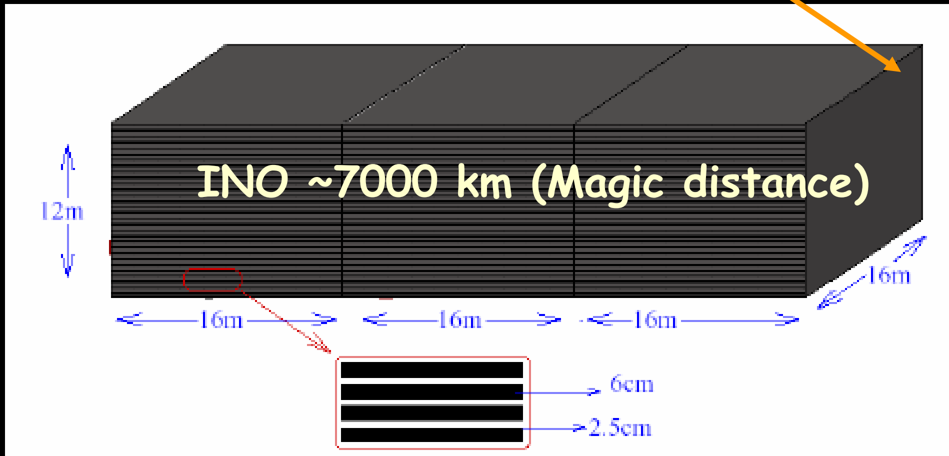
Neutrino Factory

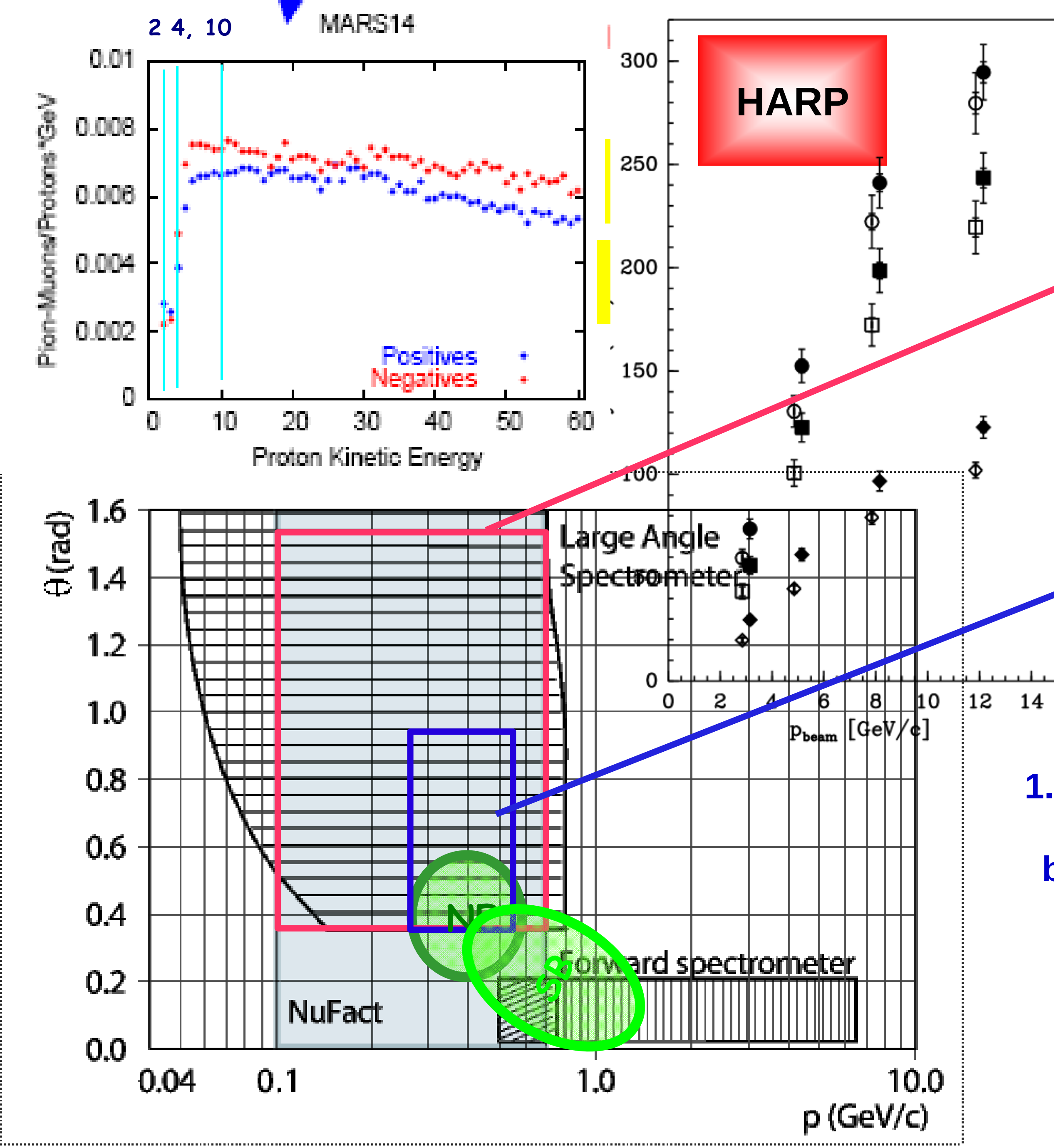
(see Mike Zisman's talk)
Requirement is bunches of 1-3 ns.
For SPL this requires accumulator and compressor

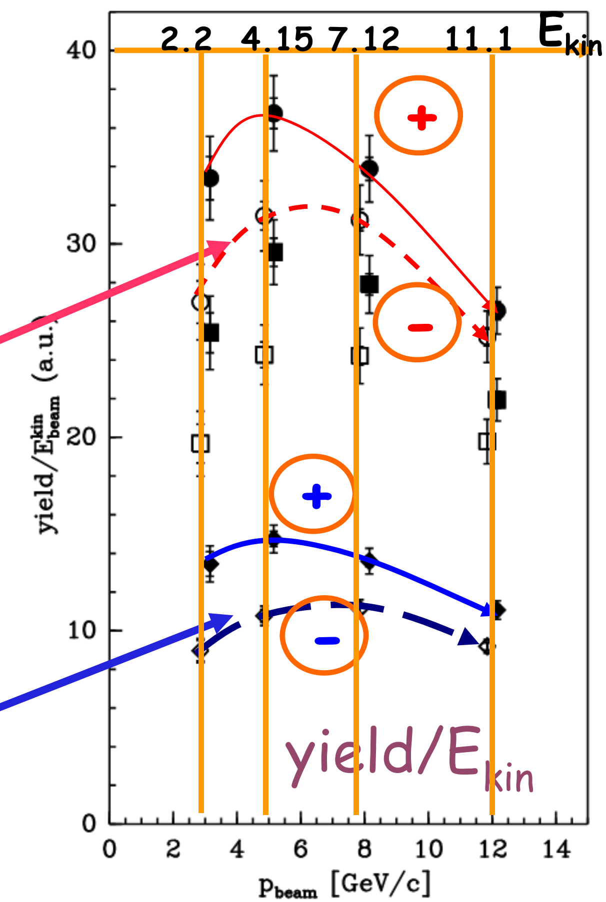
Target concept demonstrated with MERIT
Needed: target environment study – can a 4MW target station be located here?
(i.e. CERN -- or elsewhere)

Proton (kinetic) energy 10 ± 5 GeV
SPL at lower limit but good enough.
Question of MARS prediction validity

Part of
Laguna study







1. HARP does not support very sharp drop given by MARS between 4 and 2 GeV kinetic.
2. BUT: HARP angular acceptance does not cover well low-angle+low-energy particles. Missing region between large angle and forward analysis.

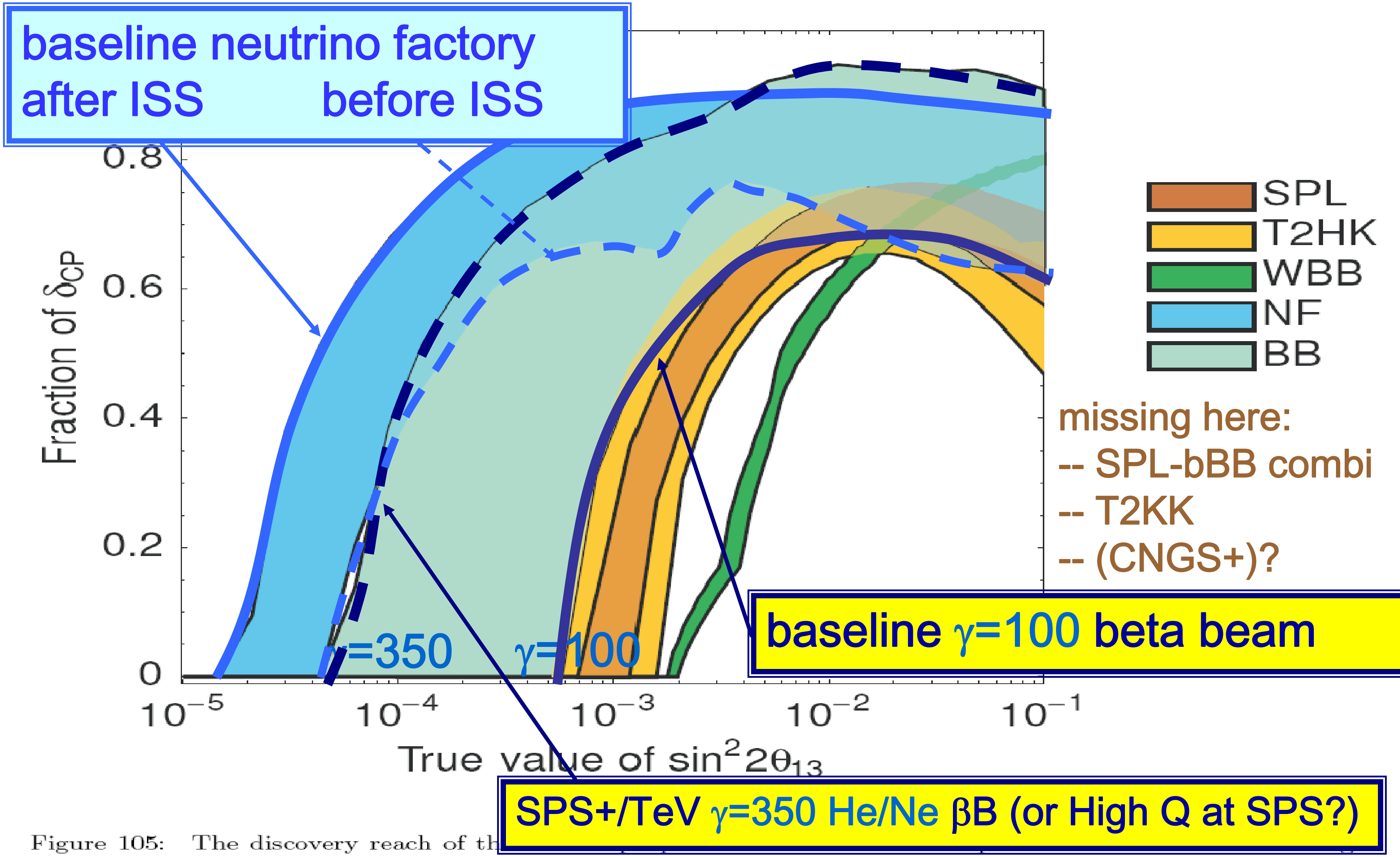


Figure 105: The discovery reach of th… of the bands, $\delta = 0$ and $\delta = \pi$ can be excluded at the 3σ confidence level. The discovery limits are shown as a function of the fraction of all possible values of the true value of the CP phase δ ('Fraction of δ_{CP}') and the true value of $\sin^2 2\theta_{13}$. The right-hand edges of the bands correspond to the conservative set-ups while the left-hand edges correspond to the optimised set-ups, as described in the text. The discovery reach of the SPL super-beam is shown as the orange band, that of T2HK … ent as the green band. The discovery reach of … actory discovery reach is shown as the blue band.

Need to include other T2K-'futures' in these plots

Muon beams for rare muon decay physics

Rare decays searches: $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+ee$, $\mu^- N \to e^- N$ are sensitive probes of Models with FCNC's. (SU-SY in particular). Very fundamental experiments!

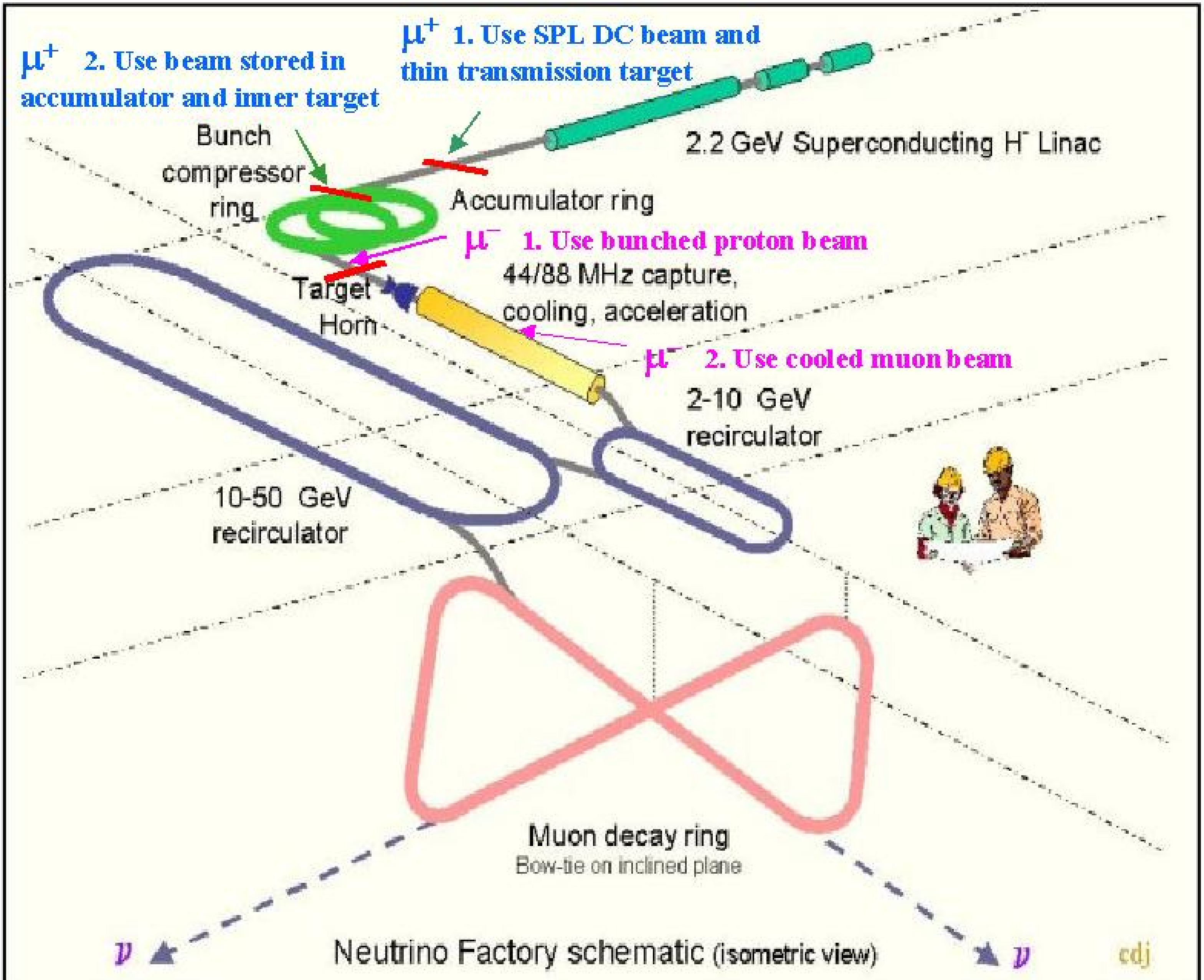
Leading experiment $\mu \to e\gamma$, MEG at PSI aims at 10^{-13} sensitivity.
1.5 MW proton beam at 590 MeV, 4% transmission target, surface muons.
(PSI Main user of protons is spallation source SINQ and low energy neutron source)

Can one gain 3 orders of magnitude over MEG?
Progress needed both on detector side and on beam intensity.

As was pointed out in early studies the SPL with accumulator ring provides (using an internal target of completely open design)
a very convenient DC beam for DC muon production. $\mu+ \to e+\gamma$, $\mu+ \to e+ee$,

It can also provide en excellent pulsed proton beam with short pulses using a target on the neutrino beam transfer line or its own fast extraction beam line.
$\mu\text{-}N \to e\text{-}N$

No succesful idea (yet) to use the muons from the neutrino factory front end.



μ+ 1. Use SPL DC beam and thin transmission target
μ+ 2. Use beam stored in accumulator and inner target
Bunch compressor ring
2.2 GeV Superconducting H- Linac
Accumulator ring
μ− 1. Use bunched proton beam
Target
Horn
44/88 MHz capture, cooling, acceleration
μ− 2. Use cooled muon beam
2-10 GeV recirculator
10-50 GeV recirculator
Muon decay ring
Bow-tie on inclined plane
ν
ν
Neutrino Factory schematic (isometric view)
cdj

Conclusions -- outlook

A programme of precision neutrino oscillation physics, leading to such a major discovery as the observation of leptonic CP violation, would be an appropriate, exciting, high-level goal for CERN. (POFPA)

Three main options are considered

-- superbeam (possibly in combination with)
-- betabeam (of same E_ν)
-- neutrino factory

These machine all require a high power proton driver; requirements on it have been established.

The SPL as required for the LHC upgrade – provided it can be upgraded to high power ca >= 4MW, can fullfill requirements for NUFACT, Superbeam, beta-beam and rare muon decays.

Quite a few questions remain that should be further developped at the workshop on

European Strategy for Neutrino physics -- 1-3 oct09 @cern

SPARES

The accelerator experiments will need to publish a quantity like $P(\nu_\mu \to \nu_e)\{L, E_\nu\}$

Typical measurement:

$$\frac{\{ N\text{"}(\nu_e N \to e X)\text{"}_{cuts} - Bkg \} \text{ (far det.)}}{\{ N\text{"}(\nu_\mu N \to \mu X)\text{"}_{other\ cuts} - Bkg \} \text{ (near det.)}} \times \frac{\Phi_{Near}}{\Phi_{Far}} \times \frac{\sigma(\nu_\mu N \to \mu X)_{other\ cuts}}{\sigma(\nu_e N \to e X)_{cuts}}$$

Thus, knowledge of $\sigma(\nu_\mu N) / \sigma(\nu_e N)$ will be necessary -- within cuts! --

--> physics understanding + implementation in Monte Carlo.

Even with assumption of lepton universality this is not a completely easy task

Lepton mass effect X nuclear effects --> uncertainties

Radioactive ion production rates

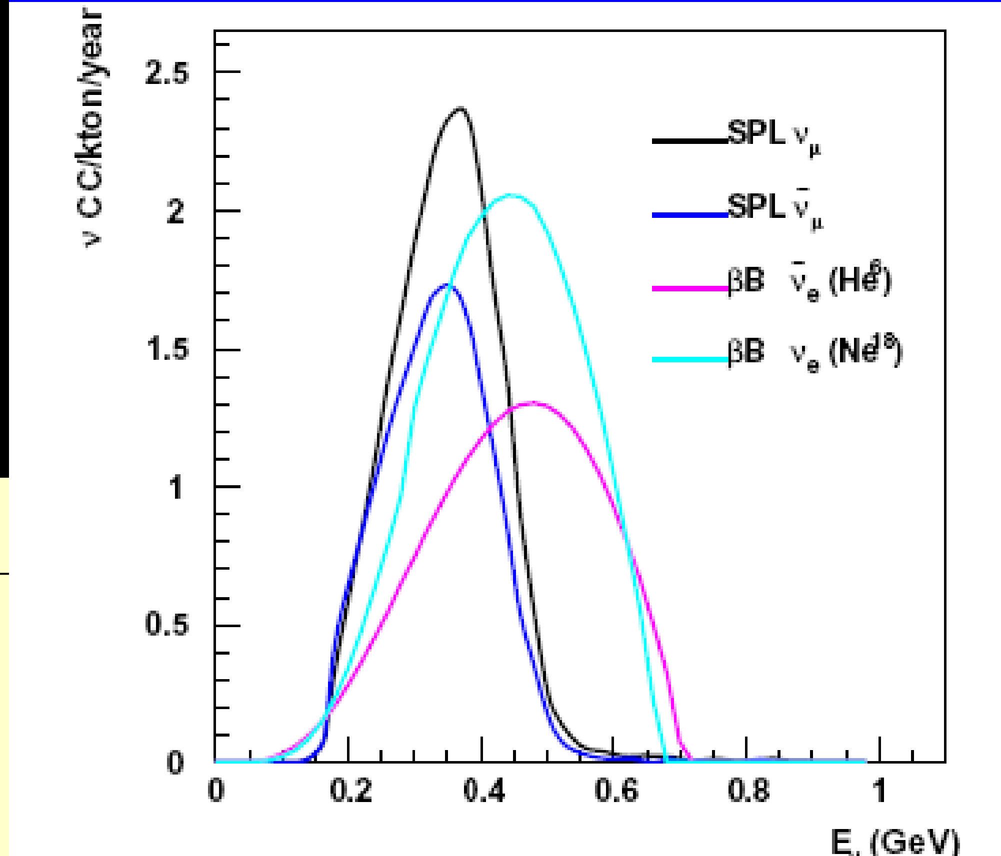
- ISOL method at 1-2 GeV (200 kW)
  - >1 10^{13} ^{6}He per second
  - <8 10^{11} ^{18}Ne per second
  - Studied within EURISOL
- Direct production
  - >1 10^{13} (?) ^{6}He per second
  - 1 10^{13} ^{18}Ne per second
  - ^{8}Li ?
  - Studied at LLN, Soreq, WI and GANIL
- Production ring
  - 10^{14} (?) ^{8}Li
  - >10^{13} (?) ^{8}B
  - **Will be studied within EUROν**

Aimed:
He 2.9 10^{18} (2.0 10^{13}/s)
Ne 1.1 10^{18} (2.0 10^{13}/s)

Courtesy M. Lindroos

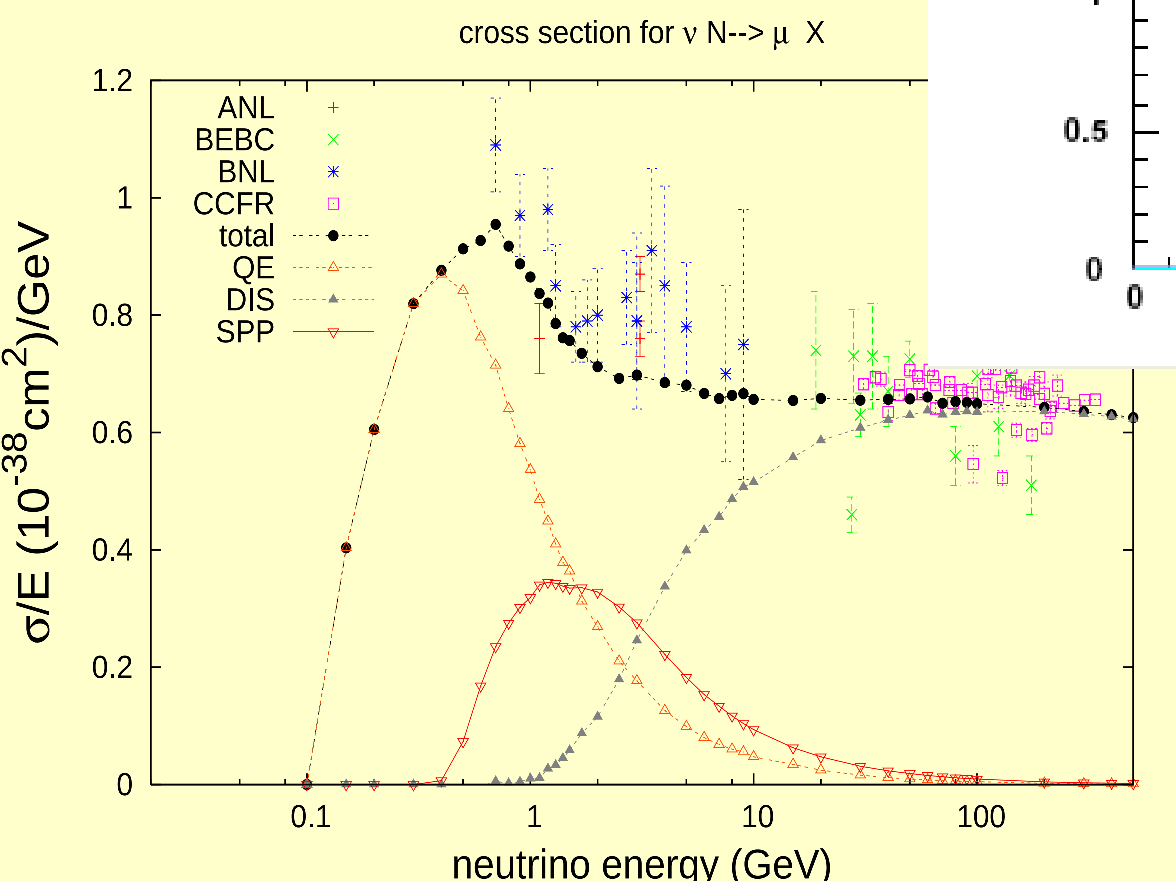
N.B. Nuclear Physics has limited interest in those elements ->> Production rates not pushed!

Averaged yearly CC rates in a 10 years run for CP



3.5 GeV SPL

$\gamma = 100$ β–**beam**

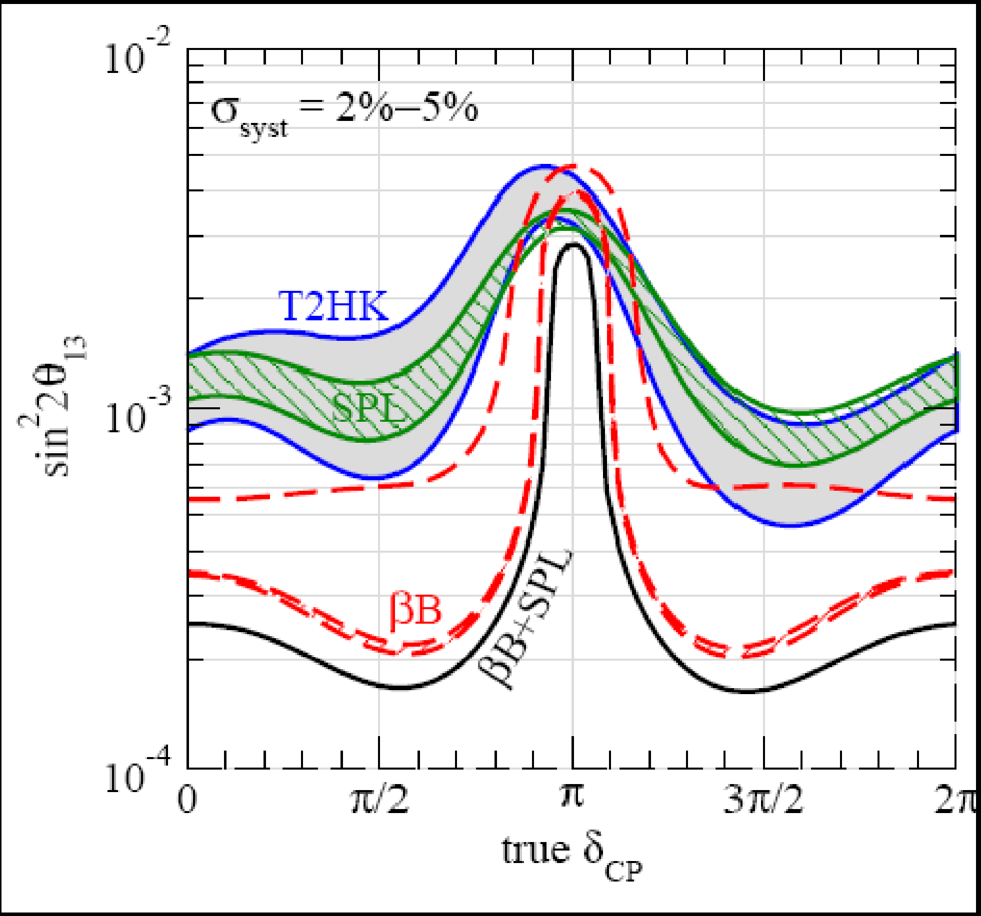


-- low proton energy:
no Kaons → ν_e background is low
--region below pion threshold
(low bkg from pions)

but:
low event rate and
uncertainties on cross-sections

3σ sensitivity to $\sin^2 2\theta_{13}$

10 year exposure



issues:

-- ^{18}Ne flux?
-- low energy
--> cross-section accuracy? (assume 2%)
-- energy reconstruction OK
-- near detector concept?

sensitivity $\sin^2 2\theta_{13}$ ~2-5 10^{-4}

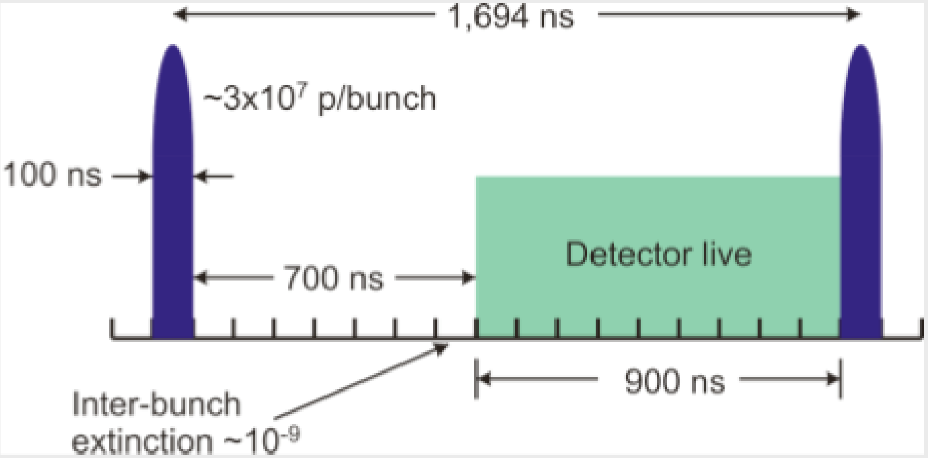
combine SPL(3.5 GeV) + βB
==> improves sensitivity by T violation!

J-E. Campagne et al. hep/ph0603172

Pulsed Beam Structure

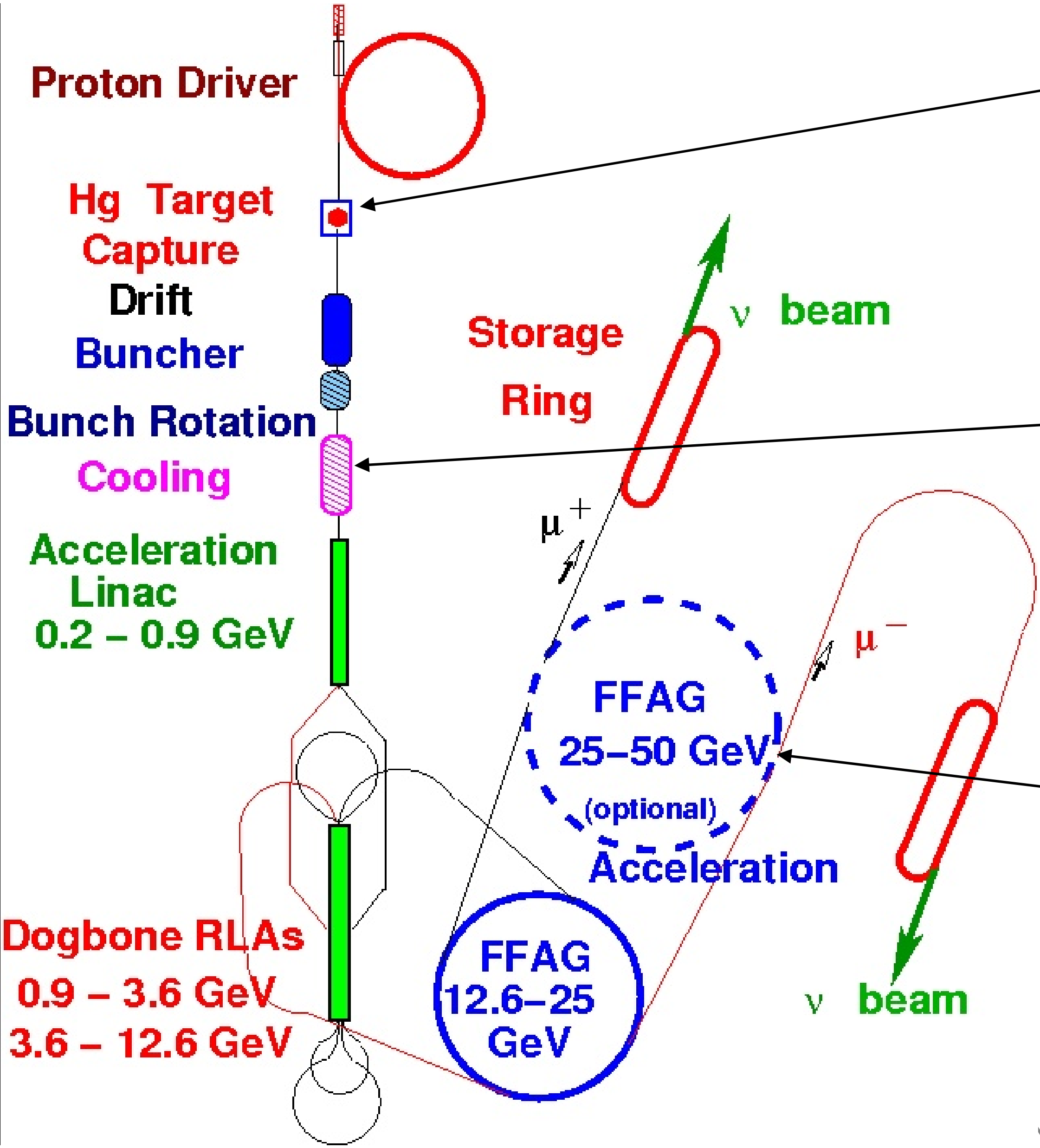
- Tied to prompt rate and machine: FNAL "perfect"
- Want pulse duration << τ_{μ}^{Al} , pulse separation ≈ τ_{μ}^{Al}
  - FNAL Debuncher has circumference 1.7μsec !
- Extinction between pulses < 10^{-9} needed

  = # protons out of pulse/# protons in pulse



- 10^{-9} based on simulation of prompt backgrounds

Major challenges tackled by R&D expts



High-power target
- 4MW
- good transmission

MERIT experiment (CERN)

Fast muon cooling

MICE experiment (RAL)

Fast, large aperture accelerator (FFAG)

EMMA (Daresbury)

ISS baseline,
(storage rings not to scale)

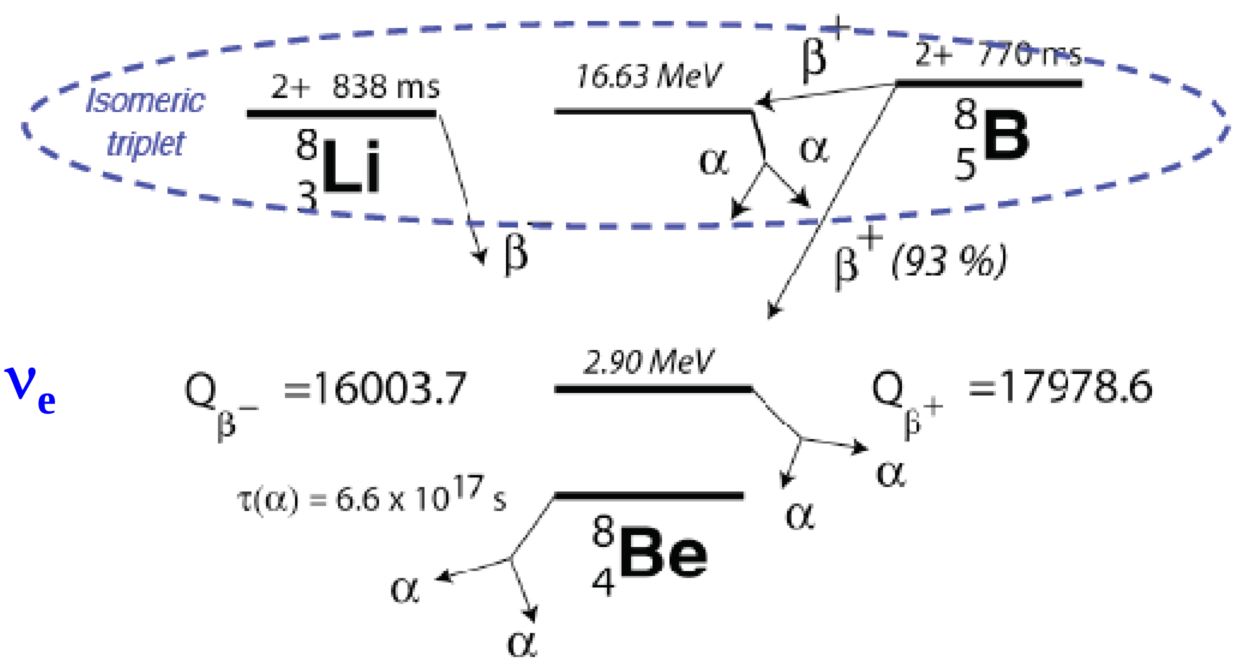
Better beta beams:

main weakness of He/He beta-beam is low energy
(450 GeV proton equiv. storage ring produces 600 MeV neutrinos)

Solution 1: Higher γ (Hernandez et al)
Use SPS+ (1 TeV) or tevatron ==> reach γ= 350 expensive!

Solution 2: use higher Q isotopes (C.Rubbia)

$^8B \to {}^8Be\ e^+\ \nu_e$
or
$^8Li \to {}^8Be\ e^-$ anti- ν_e



A possible solution to the ion production shortage:

Direct production in a small storage ring,
filled [Gas + RF cavity] for ionization cooling

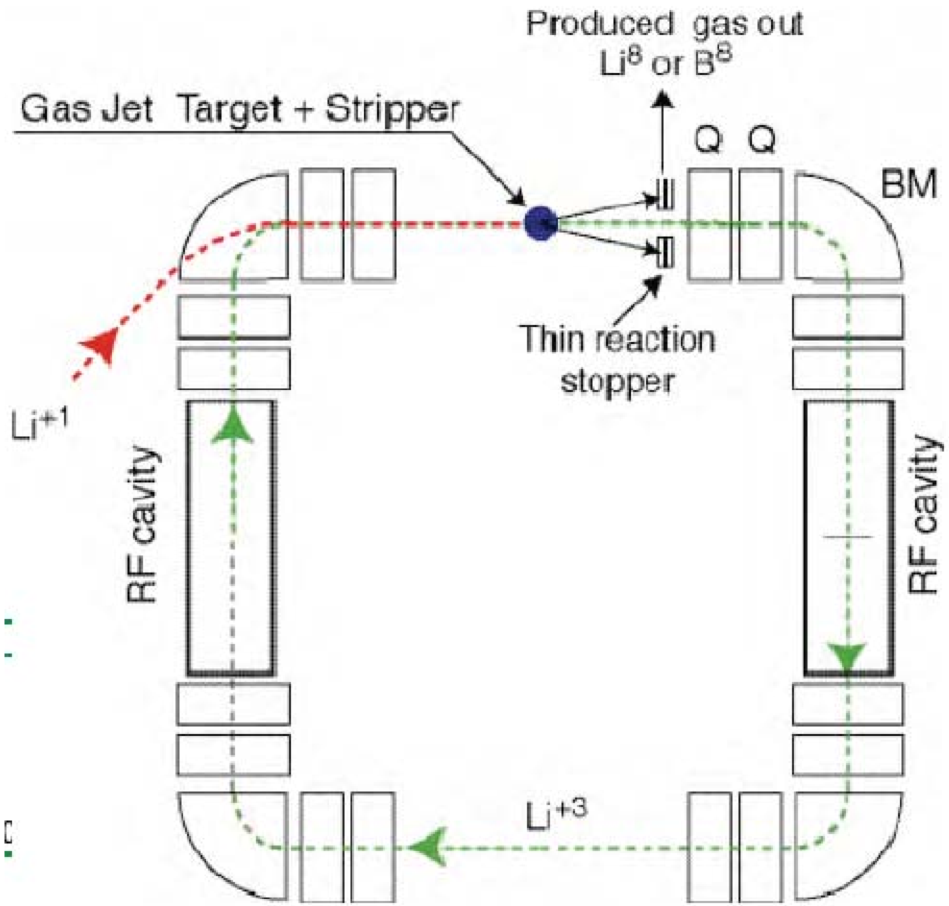
For ^{8}B or ^{8}Li production,
strip-inject ^{6}Li / ^{7}Li beam,
collide with gas jet (D_2 or ^{3}He)

$$Li^{7} + d \rightarrow Li^{8} + p$$

$$Li^{6} + He^{3} \rightarrow B^{8} + n$$

reaction products are ejected and collected

goal: >~ 10^{21} ions per year



Advantages of $^{8}B^{5+}$ (ν_e Q=18MeV) or $^{8}Li^{3+}$ (anti-ν_e Q=16MeV) vs ^{18}Ne, ^{6}He (Q~=3 MeV)

The storage ring rigidity is considerably lower for a given E_ν
==> for ~1 GeV end point beam
for $^{8}B^{5+}$: 45 GeV proton equiv. storage ring
for $^{8}Li^{3+}$: 75 GeV proton equiv. storage ring

Two ways to see it:
1. Beta-beams to Fréjus (E_{max} =600 MeV) could be accelerated with PS2 into a 50 GeV proton-equivalent storage ring (save €)
2. Beta beams of both polarities up to end-point energy of ~6 GeV can be produced with the CERN SPS (up to 2000km baseline)

A new flurry of opportunities