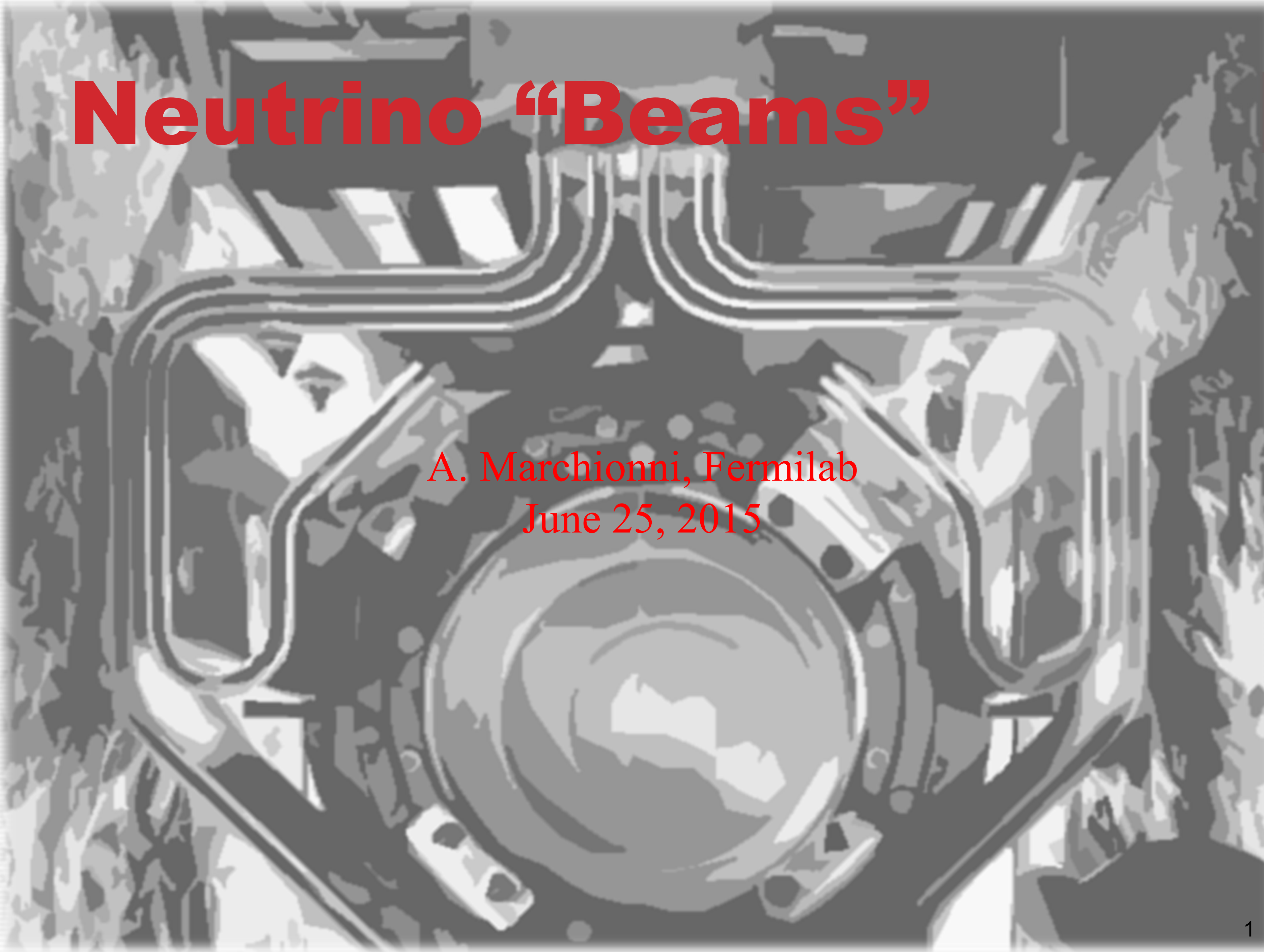
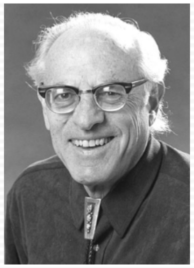


Neutrino "Beams"

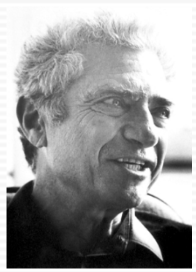
A. Marchionni, Fermilab
June 25, 2015

The Nobel ν prizes

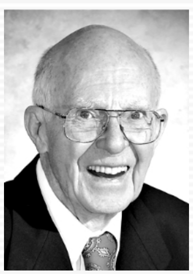


Physics 1995
FREDERICK REINES
for the detection of the neutrino (1953-1956)



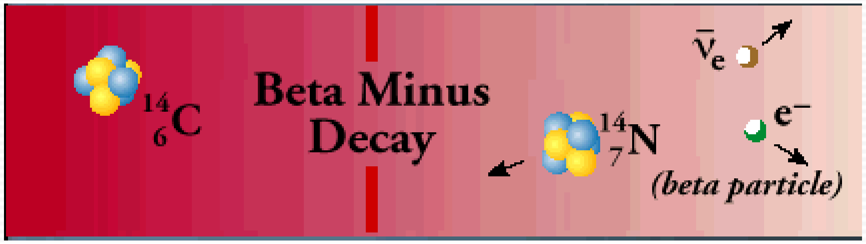


Physics 1988
LEON M LEDERMAN, MELVIN SCHWARTZ and JACK STEINBERGER
for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino (1962)



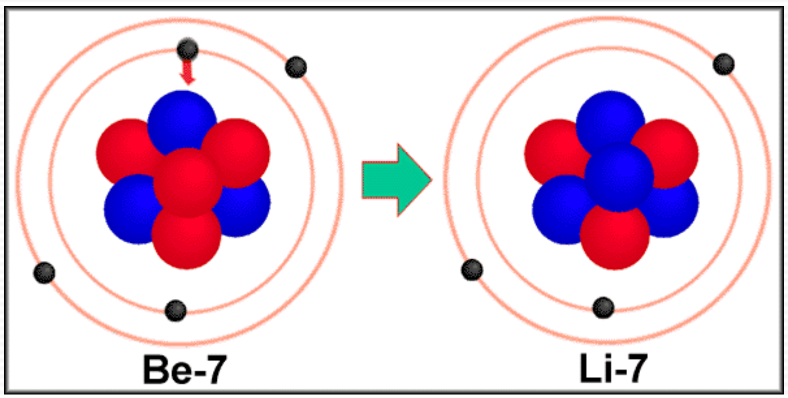

Physics 2002
RAYMOND DAVIS Jr. and MASATOSHI KOSHIBA
for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos
Homestake (1970-1995), Kamiokande (1983), Kamiokande-II (1985), Super-Kamiokande (1996)

Beta Decay



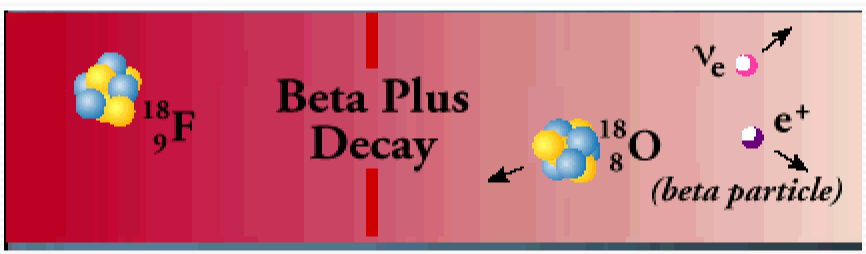
$$^{A}_{Z}\{P\} \rightarrow \, ^{A}_{(Z+1)}\{D\} + e^- + \bar{\nu}$$

$$M(Z,A) > M((Z+1),A) + m_e$$



Electron capture (EC)

$$e^- + \, ^{A}_{Z}\{P\} \rightarrow \, ^{A}_{(Z-1)}\{D\} + \nu$$



$$^{A}_{Z}\{P\} \rightarrow \, ^{A}_{(Z-1)}\{D\} + e^+ + \nu$$

$$M(Z,A) > M((Z-1),A) + m_e$$

A few beta decay examples

Parent Nucleus	Parent E(level)	Parent Jπ	Parent $T_{1/2}$	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus	
$^{1}_{0}$Nn	0.0	1/2+	613.9 s *6*	β^-: 100 %	782.347*1*	$^{1}_{1}$H	Decay Scheme

Beta-:

Energy (keV)	End-point energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
301.37	782.3470 *10*	100 %	0.301

$$n \rightarrow p\, e^- \bar{\nu}_e \qquad (100\%\ \beta^-)$$

Parent Nucleus	Parent E(level)	Parent Jπ	Parent $T_{1/2}$	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus	
$^{3}_{1}$H	0.0	1/2+	12.32 y *2*	β^-: 100 %	18.590*2*	$^{3}_{2}$He	Decay Scheme

Beta-:

Energy (keV)	End-point energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
5.69 *4*	18.5900 *20*	100 %	0.00569

Tritium decay (100% β^-)

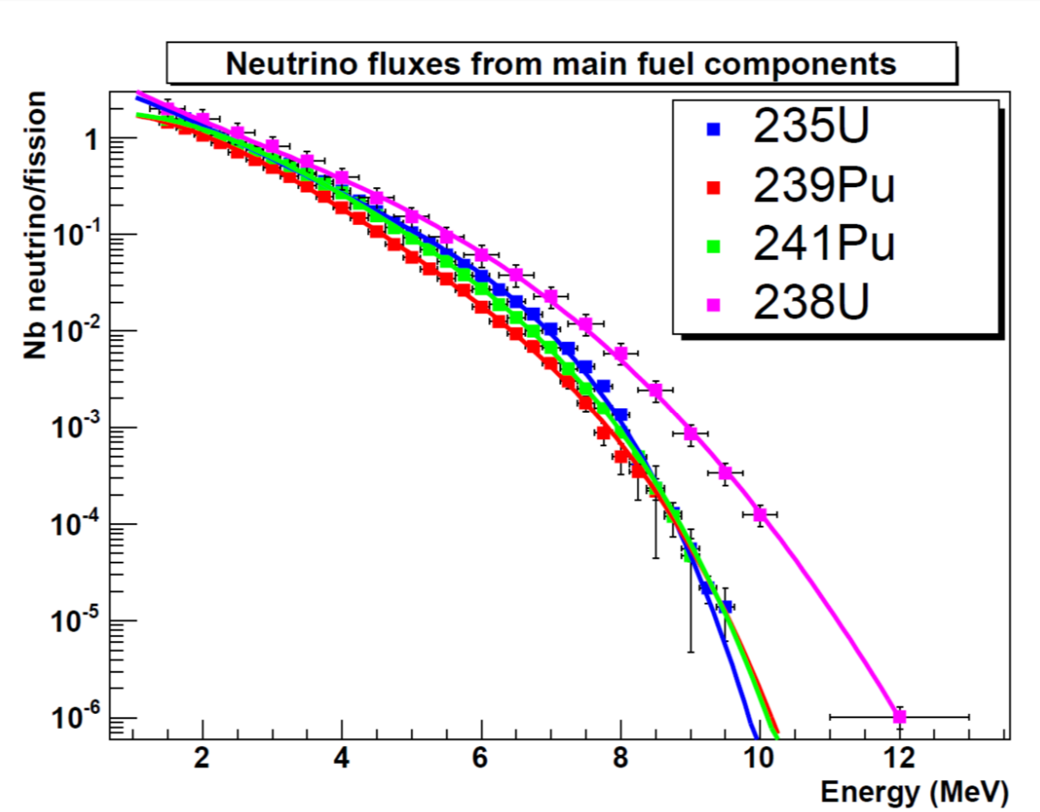
Parent Nucleus	Parent E(level)	Parent Jπ	Parent $T_{1/2}$	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus	
$^{7}_{4}$Be	0.0	3/2-	53.22 d *6*	ε: 100 %	861.815*18*	$^{7}_{3}$Li	Decay Scheme

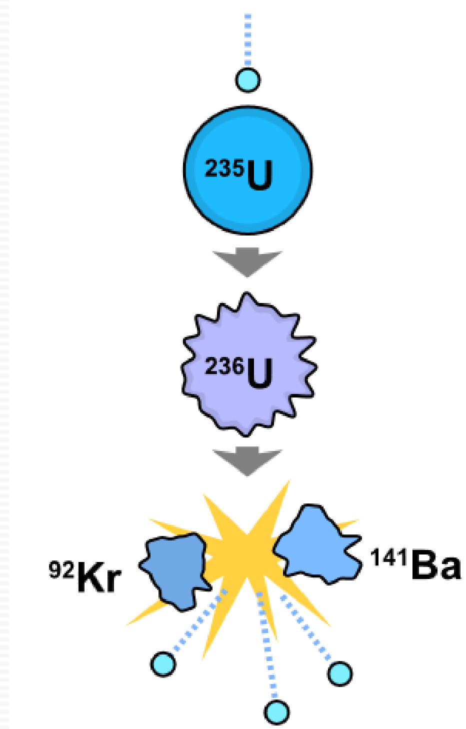
Gamma and X-ray radiation:

Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
477.6035 *20*	10.44 % *4*	0.04986 *19*

^{7}Be decay (100% EC)

Reactor anti-neutrinos

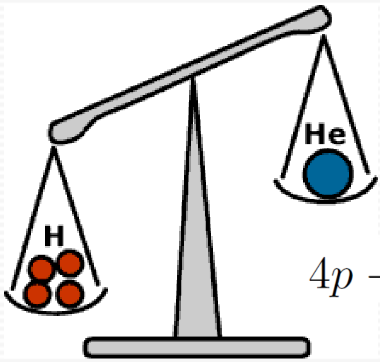




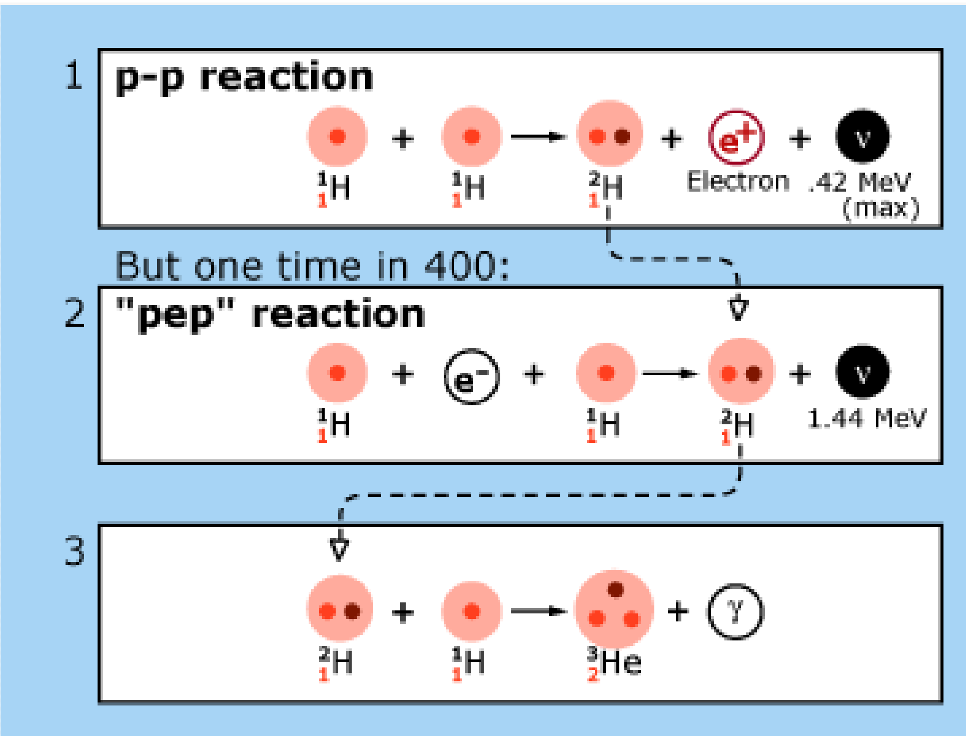
The spectrum is a sum over beta decays of fragments produced in the thermal neutron induced fission

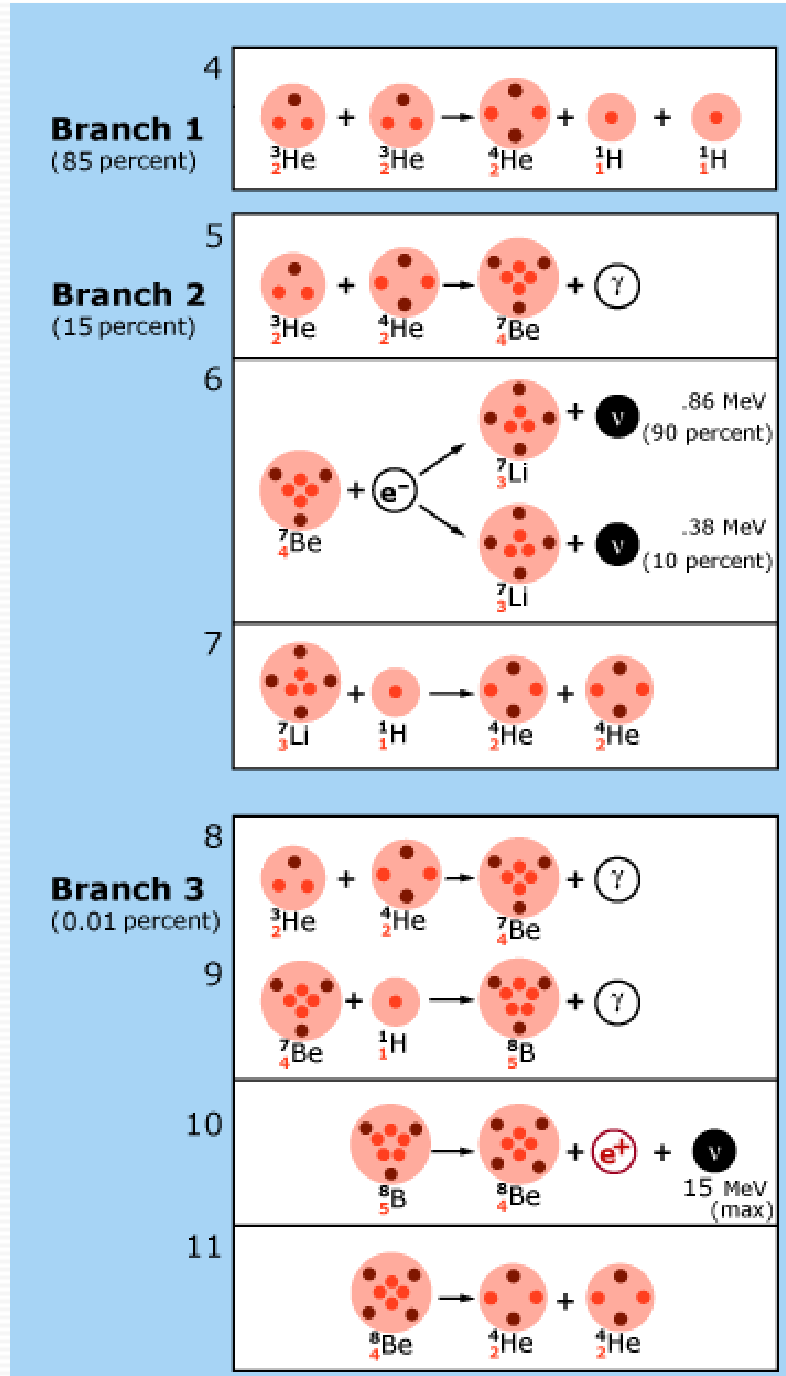
	Mean energy per fission (MeV)	Refueling cycle beginning	Refueling cycle end
^{235}U	201.7 ± 0.6	60.5 %	45.0 %
^{238}U	205.0 ± 0.9	7.7 %	8.3 %
^{239}Pu	210.0 ± 0.9	27.2 %	38.8 %
^{241}Pu	212.4 ± 1.0	4.6 %	7.9 %

Energy Production in Stars



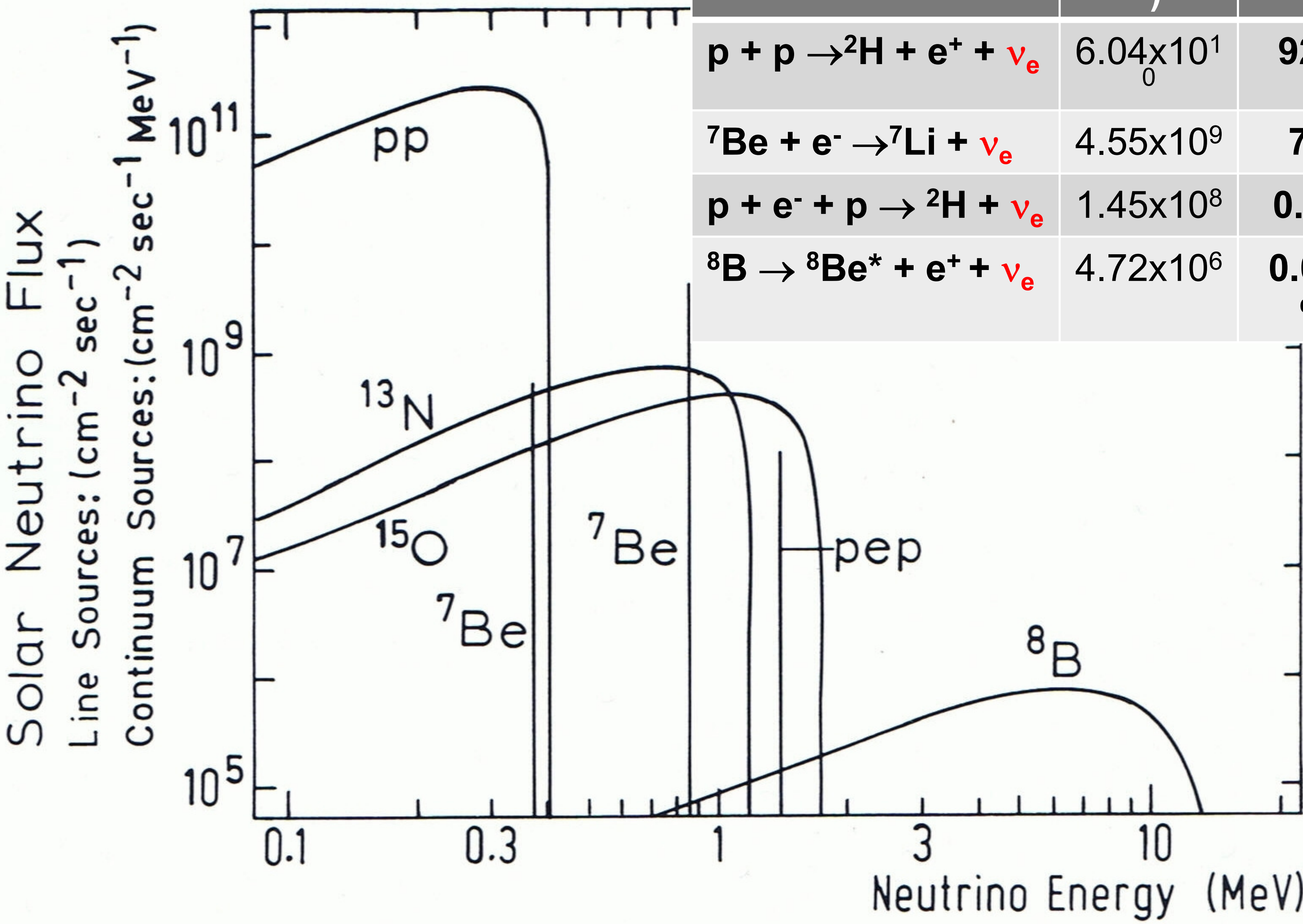
$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 24.7\,\mathrm{MeV}$$





Solar Neutrinos

Reaction	ν flux ($cm^{-2}\ s^{-1}$)	% total ν flux
$p + p \rightarrow {}^2H + e^+ + \nu_e$	6.04×10^{10}	**92%**
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	4.55×10^9	**7%**
$p + e^- + p \rightarrow {}^2H + \nu_e$	1.45×10^8	**0.2%**
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	4.72×10^6	**0.007 %**

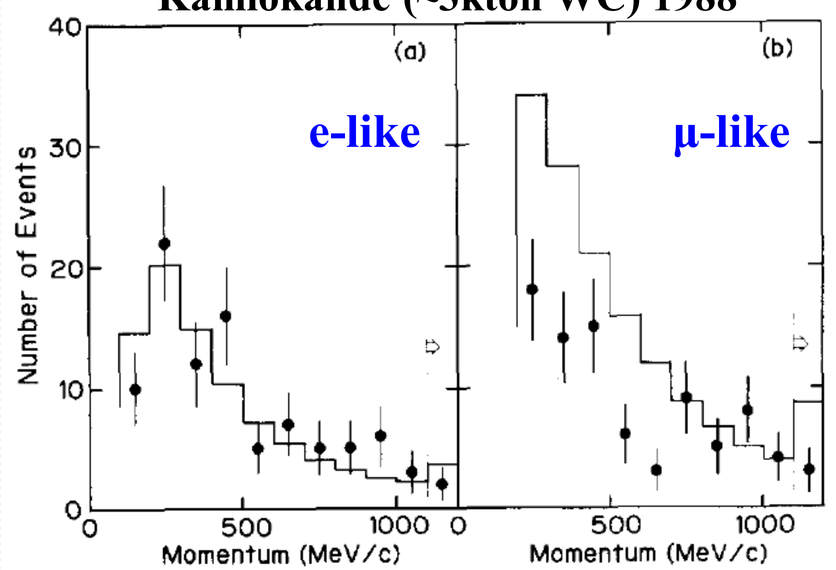


Atmospheric neutrinos

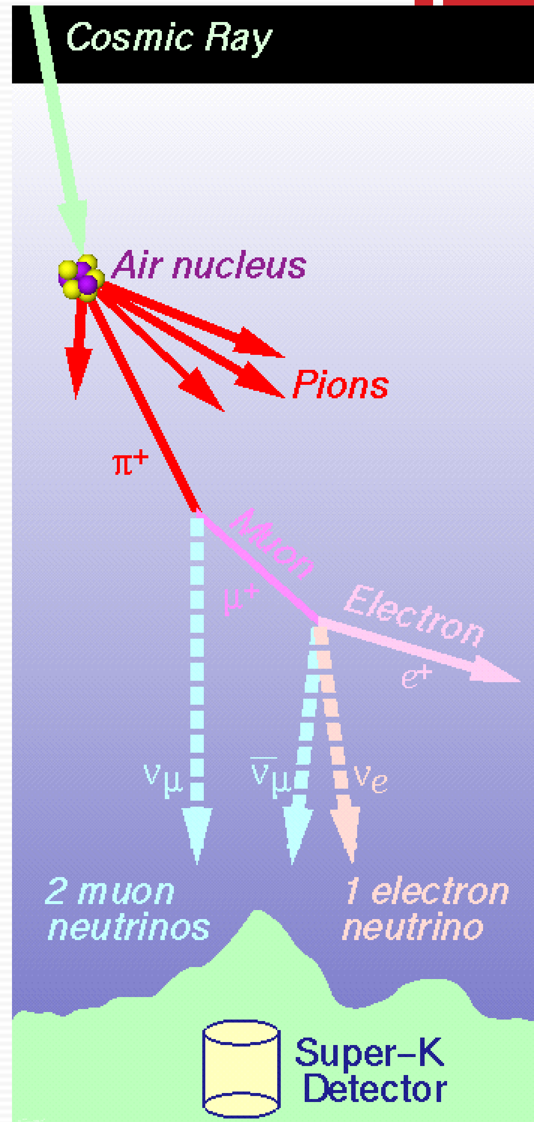
T.Kajita, Y. Totsuka Rev. Mod. Phys. 73 (2001) 85

- **First atmospheric ν neutrino experiments in the 1960s**, deep underground (~8000 mwe). Measured ν events occurring in the rock and crossing the detector. Particles traversing the detectors almost horizontally (or upward going) were atmospheric ν's
  - **Kolar Gold Field (KGF) in South India**
  - **East Rand Proprietary Mine in South Africa**
- From the **early 1980s, several proton decay experiments** began operation. Background to proton decay were atmospheric ν's. These experiments were the first to observe fully contained events
  - **KGF, NUSEX, IMB, KAMIOKANDE, HPW, FREJUS**

Kamiokande (~3kton WC) 1988



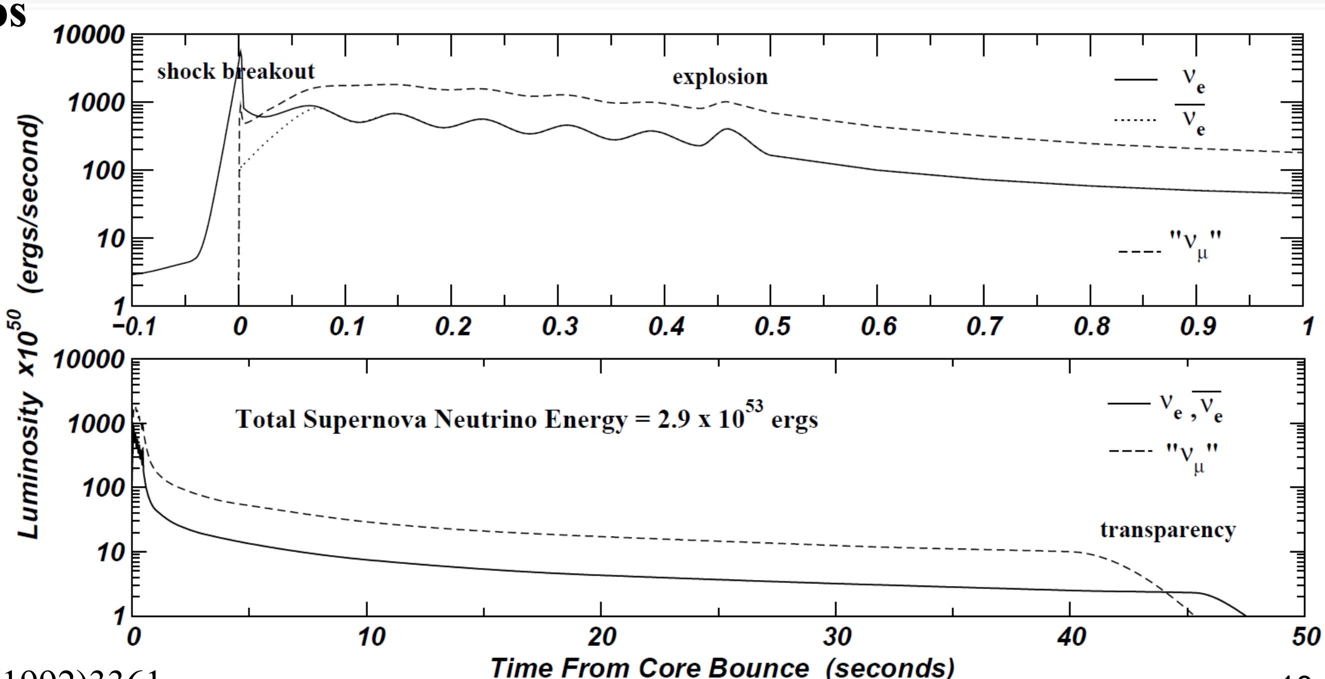
?



What kind of neutrinos am I going to get in a Supernova explosion?

Supernova model

- **Type II supernova**: a massive star when the pressure from fusion reactions can not support the gravitational pressure of the outer regions
- an **inward collapse** proceeds until the central density reaches nuclear density
    - **in this collapse phase electron capture on protons produces a sharp burst of ν_e**
- then a bounce occurs (outward shock wave), causing an **explosion**, aided by energy deposited by neutrinos created in the collapsing core
    - **neutrinos and antineutrinos** are produced in the wake of the shock wave
- up **to 99 % of the roughly 10^{53} ergs** of energy released in type II supernova is carried away **by neutrinos**



A. Burrows et al., Phys. Rev. D45(1992)3361

Producing neutrinos with accelerator produced particles I

μ

$$J = \frac{1}{2}$$

Mass $m = 0.1134289267 \pm 0.0000000029$ u
Mass $m = 105.6583715 \pm 0.0000035$ MeV
Mean life $\tau = (2.1969811 \pm 0.0000022) \times 10^{-6}$ s
$\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$
$c\tau = 658.6384$ m

$e^- \overline{\nu}_e \nu_\mu$	$\approx 100\%$

$\pi^\pm$

$$I^G(J^P) = 1^-(0^-)$$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\mu^+ \nu_\mu$	[b]	(99.98770 ± 0.00004) %
$\mu^+ \nu_\mu \gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$
$e^+ \nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$
$e^+ \nu_e \gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$

Producing neutrinos with accelerator produced particles II

$K^{\pm}$

$$I(J^P) = \tfrac{1}{2}(0^-)$$

Mass $m = 493.677 \pm 0.016$ MeV [u] (S = 2.8)
Mean life $\tau = (1.2380 \pm 0.0021) \times 10^{-8}$ s (S = 1.9)
$c\tau = 3.712$ m

$e^+ \nu_e$	$(1.581 \pm 0.007) \times 10^{-5}$
$\mu^+ \nu_\mu$	(63.55 ± 0.11) %
$\pi^0 e^+ \nu_e$ Called K^+_{e3}.	(5.07 ± 0.04) %
$\pi^0 \mu^+ \nu_\mu$ Called $K^+_{\mu3}$.	(3.353 ± 0.034) %

K^0_L

$$I(J^P) = \tfrac{1}{2}(0^-)$$

Mean life $\tau = (5.116 \pm 0.021) \times 10^{-8}$ s (S = 1.1)
$c\tau = 15.34$ m

Semileptonic modes

$\pi^{\pm} e^{\mp} \nu_e$ Called K^0_{e3}.	[gg]	(40.55 ± 0.11) %
$\pi^{\pm} \mu^{\mp} \nu_\mu$ Called $K^0_{\mu3}$.	[gg]	(27.04 ± 0.07) %

Producing neutrinos with accelerator produced particles III

$D_s^\pm$ $I(J^P) = 0(0^-)$

Mass $m = 1968.30 \pm 0.11$ MeV (S = 1.1)

$m_{D_s^\pm} - m_{D^\pm} = 98.69 \pm 0.05$ MeV

Mean life $\tau = (500 \pm 7) \times 10^{-15}$ s (S = 1.3)

$c\tau = 149.9\ \mu$m

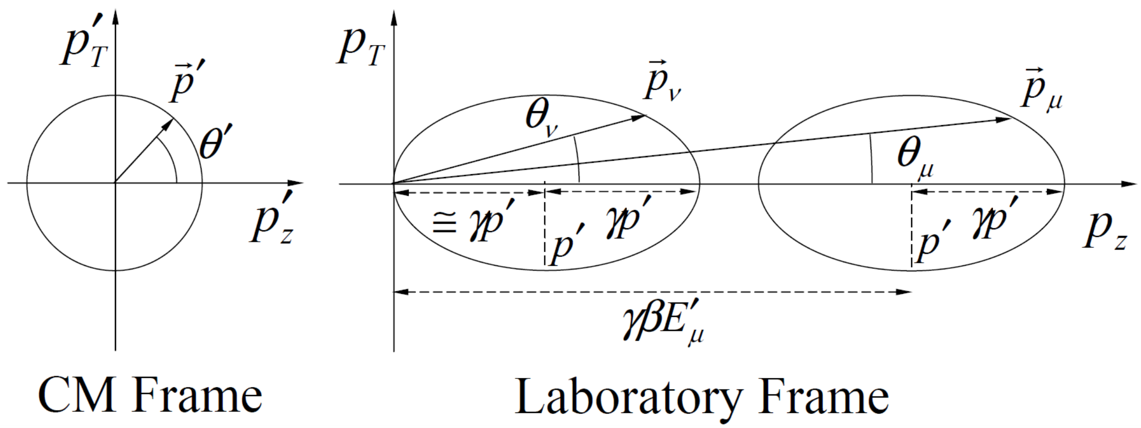
$e^+ \nu_e$	$< 8.3 \times 10^{-5}$
$\mu^+ \nu_\mu$	$(5.56 \pm 0.25) \times 10^{-3}$
$\tau^+ \nu_\tau$	(5.54 ± 0.24) %

… + leptonic/semileptonic decays of $D^0/D^\pm$ and $B^0/B^\pm$

2 body decay kinematics I

S. Kopp, Phys. Rept. 439 (2007) 101

$\pi^+ \rightarrow \mu^+ \nu_\mu$ 99.988% $\quad\quad$ $K^+ \rightarrow \mu^+ \nu_\mu$ 63.5%



$$\frac{(p_z - \beta\gamma E')^2}{\gamma^2 p'^2} + \frac{p_T^2}{p'^2} = 1$$

$$\gamma \tan\theta = \frac{\sin\theta'}{\cos\theta' + (\beta/\beta')}$$

where β′ = p′/E′ is the daughter velocity in the CM frame (=1 for ν and =0.28 or 0.91 for μ in π or K decays)

⇒ $\theta_\nu^{\max} \approx 1/\gamma \quad\quad \theta_\mu^{\max} \approx \beta'/\gamma$

If no focusing of π is employed, π diverge from the target with a typical angle

$$\theta_\pi \approx p_T/p_\pi \approx \langle p_T \rangle / p = 280\text{MeV}/p_\pi = 2/\gamma$$

which is larger than the typical angle of neutrinos from π decay, so important to correct

2 body decay kinematics II

S. Kopp, Phys. Rept. 439 (2007) 101

$$E_\nu \underset{\beta \approx 1}{\approx} \frac{(1-(m_\mu / m_{(\pi,K)})^2 E_{(\pi,K)}}{(1+\gamma^2 \tan^2\theta_\nu)} \underset{\theta_\nu << 1}{\cong} \frac{(1-(m_\mu / m_{(\pi,K)})^2 E_{(\pi,K)}}{(1+\gamma^2 \theta_\nu^2)}$$

$$1-(m_\mu / m_\pi)^2 = 42.7\%$$

$$1-(m_\mu / m_K)^2 = 95.4\%$$

Angular distribution of neutrinos in the Lab frame

$$\frac{dP}{d\Omega} \underset{\beta \approx 1}{\approx} \frac{1}{4\pi} \frac{4\gamma^2(1+\tan^2\theta_\nu)^{3/2}}{(1+\gamma^2\tan^2\theta_\nu)^2} \underset{\theta_\nu << 1}{\cong} \frac{1}{4\pi}\left(\frac{2\gamma}{1+\gamma^2\theta_\nu^2}\right)^2$$

Flux of neutrinos at a given decay angle θ with respect to the π direction

$$\Phi_\nu = \frac{A}{4\pi z^2}\left(\frac{2\gamma}{1+\gamma^2\vartheta^2}\right)^2$$

A = size of the detector
z = distance from the π decay point

The first concepts for an accelerator-based ν beam - I

Electron and muon neutrinos

$$\frac{R(\mu \to e\gamma)}{R(\mu \to e\nu\bar{\nu})} < 10^{-8} \quad (\text{in} \sim 1960) \quad \textbf{Why?}$$

Are ν_e (emitted in β decay) **and ν_μ** (emitted in π→μ decay) **identical particles?**

Is $\bar{\nu}_\mu + p \to e^+ + n$ happening?

- Use a high energy accelerator and dump the beam on a target
  - it is possible to achieve a beam of $\bar{\nu}_\mu$ particles from μ^+ decay at rest with practically no admixture of $\bar{\nu}_e$ (μ^- are absorbed)

The LSND strategy…

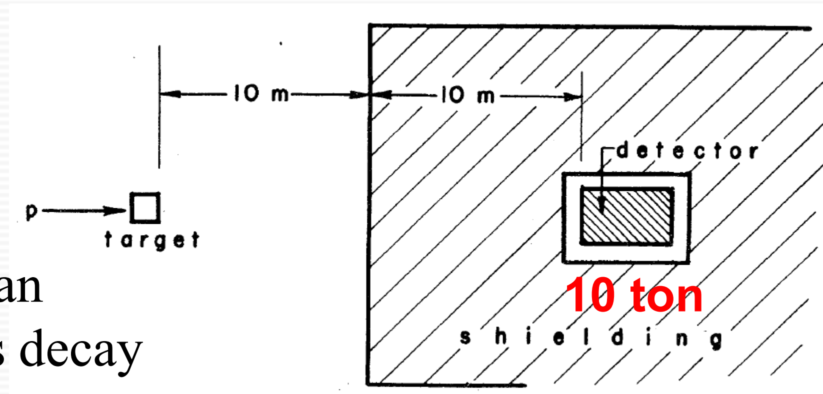
B. Pontecorvo, Sov. Phys. JETP 37 (1960) 1236

The first concepts for an accelerator-based ν beam - II

Is it possible to use high energy ν's to study weak interactions?

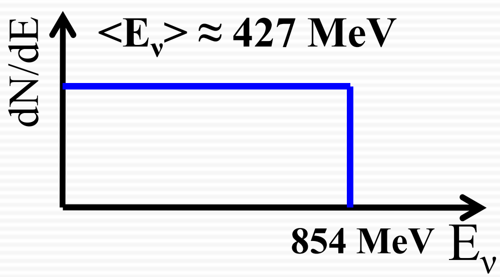
5 x 10^{12} 3 GeV protons, 10 ton detector

- I = # protons/unit time
- I/10 π´s with $E_\pi \geq 2$ GeV in ~2 steradians
- 10 m decay length, 10 m shielding
- 1 cm^2 detector @ 20 m → 2.5 x 10^{-7} steradian
- $c\tau_\pi = 7.8$ m → $\gamma c\tau_{2GeV\pi} \approx 110$ m → 10% π's decay



$$\nu / s / cm^2 = \left(\frac{1}{10} I\right)\left(\frac{1}{4}\times 10^{-6}\right)\left(\frac{1}{10}\right)\left(\frac{1}{2}\right) \cong 1\times 10^{-9} I$$

$\sigma \sim 10^{-38}$ cm^2



$\pi^+ \rightarrow \mu^+ \nu$, assume 2 GeV π

$(dN/dE)_\nu$ is flat in the lab system: decay angular distribution in the π rest frame is isotropic and energy independent from decay angle

$$\nu \text{ int.} / s = (10^7)(6\times 10^{23})(10^{-9} I)\sigma = 6\times 10^{21} I\sigma$$

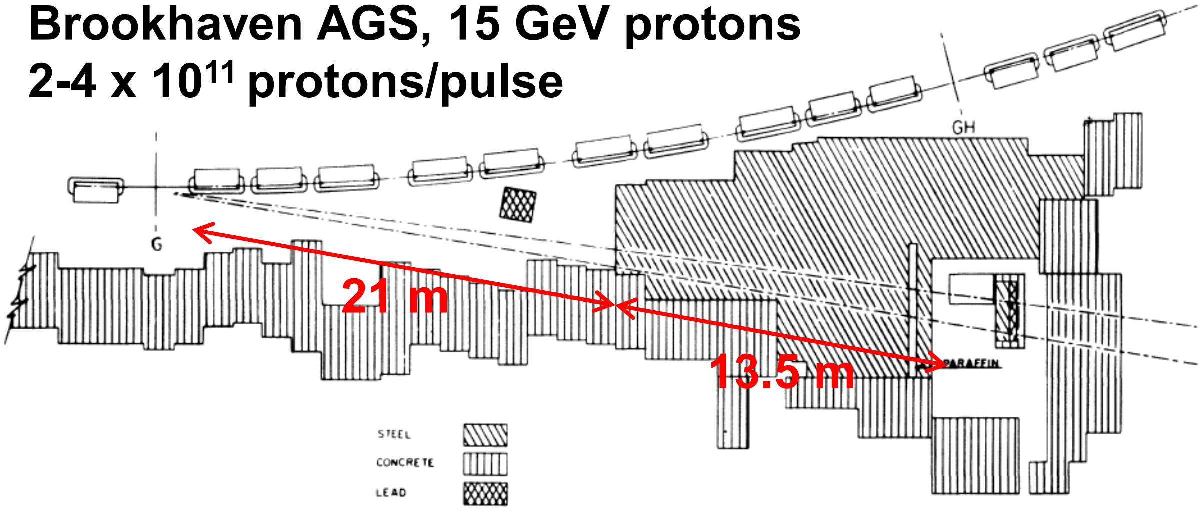
⇨ **~1 ν int./hour**

Yes!

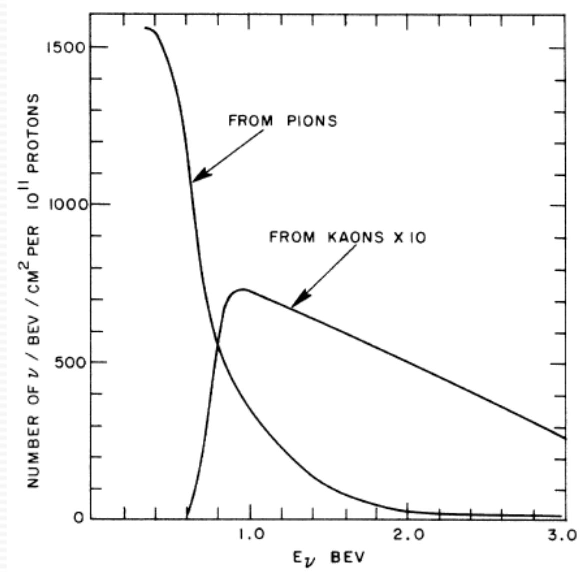
M. Schwartz, Phys. Rev. Lett. 4 (1960) 306

The first ν beam… at BNL, and the discovery of $\nu_e \neq \nu_\mu$

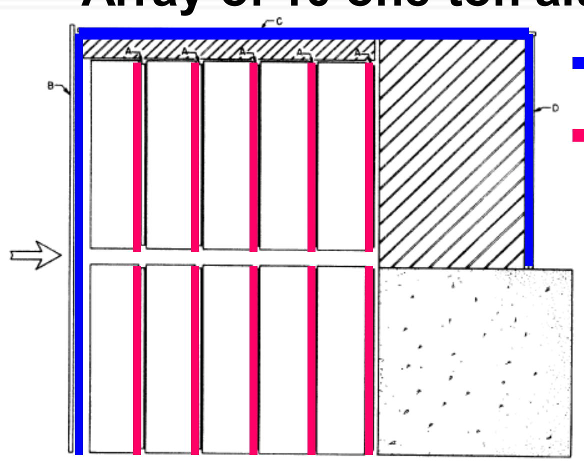
Brookhaven AGS, 15 GeV protons
2-4 x 10^{11} protons/pulse



ν's from π and K decays



Array of 10 one-ton aluminum spark chambers



anti-coincidence slabs

triggering slabs

Exposure of 3.48 x 10^{17} protons

- 34 single μ, p_μ > 300 MeV
- 22 'vertex' events
- 6 'shower' events, not consistent with μ's

G. Danby et al., Phys. Rev. Lett. 9 (1962) 36

The first concept of a horn

Divergent beams of charged particles can be made nearly parallel by a magnetic horn that is analogous to an internally reflecting conical surface in geometrical optics

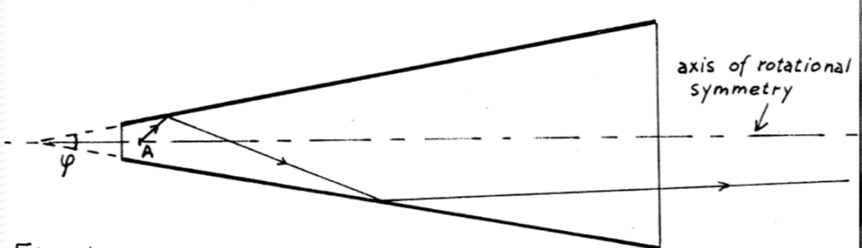


Fig. 1

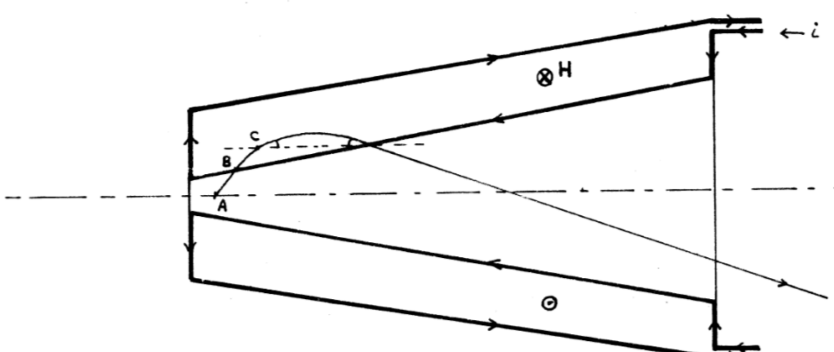
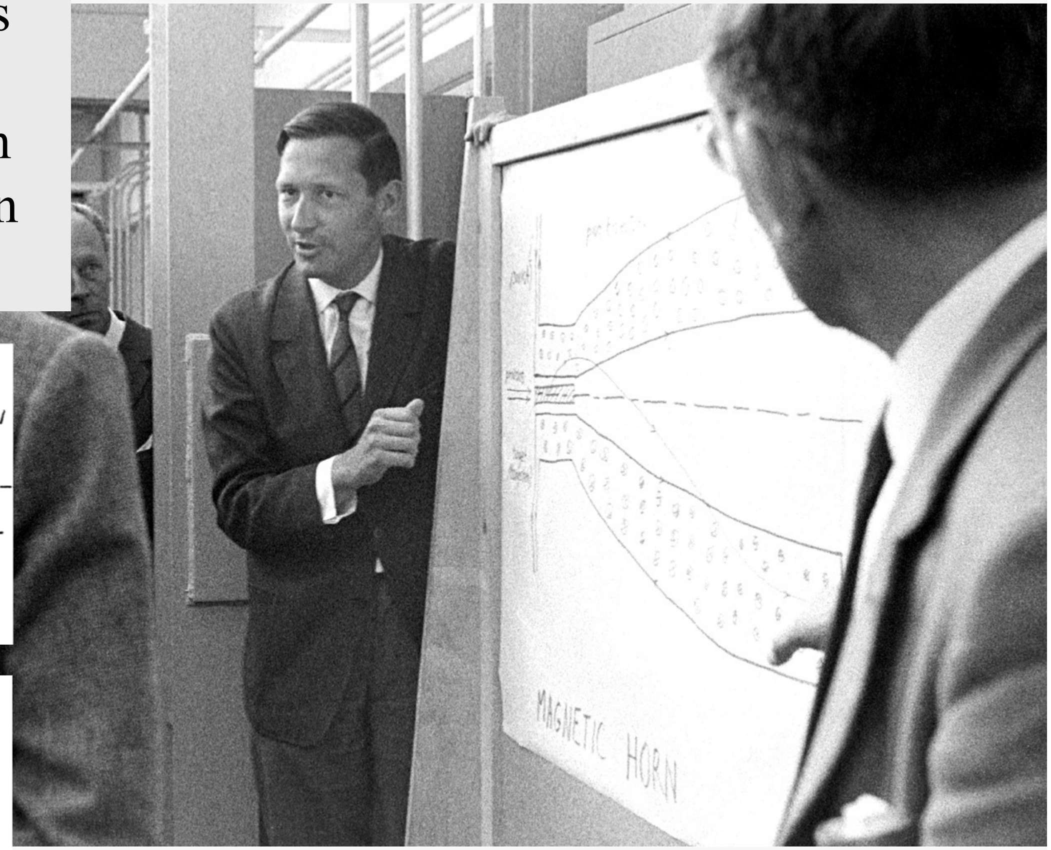


Fig. 2



S. van der Meer
A directive device for charged particle and its use in an enhanced neutrino beam
CERN 61-7

Development of the first ν beam at CERN PS

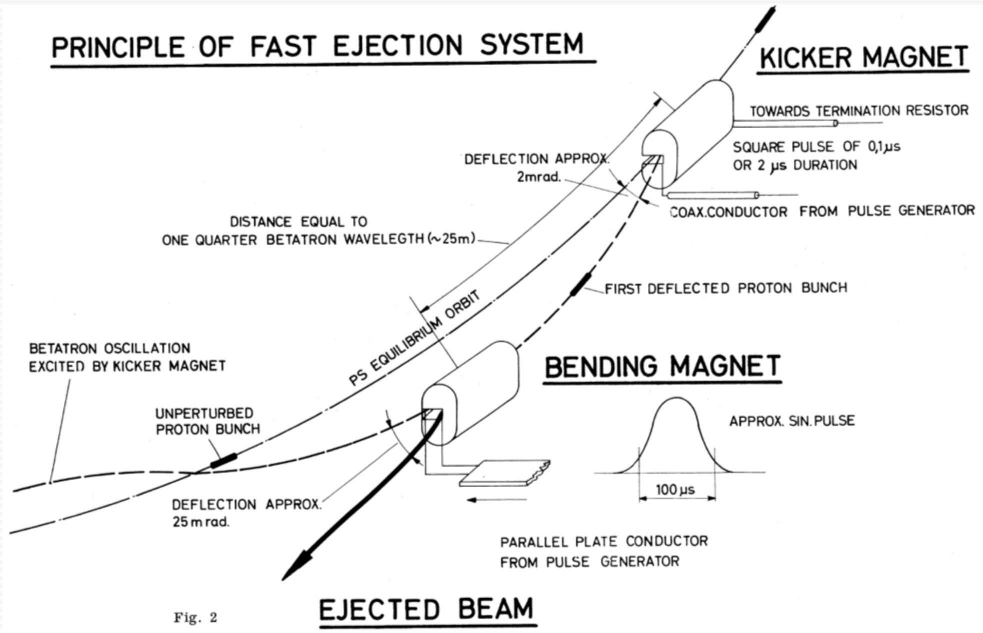
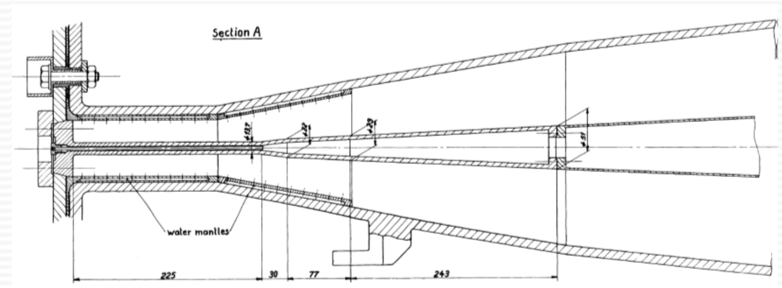
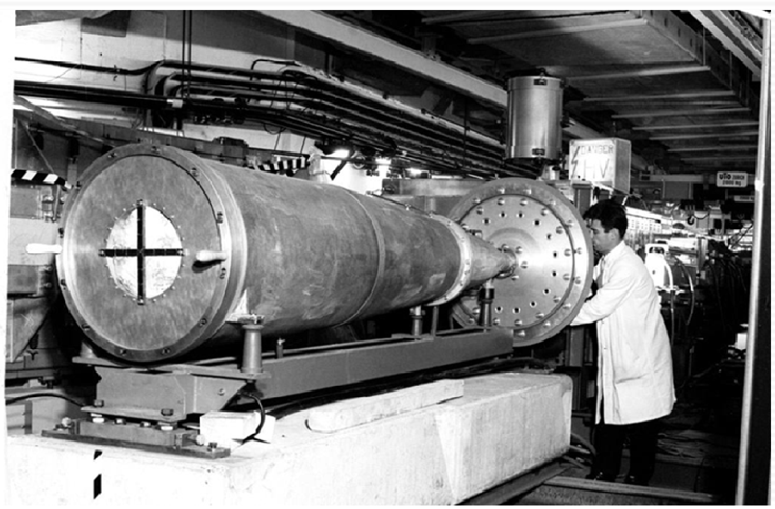


Fig. 2

- 300 kA current, of ~180 μs half-sine wave duration
- cooled between pulses by spraying demineralized water on it

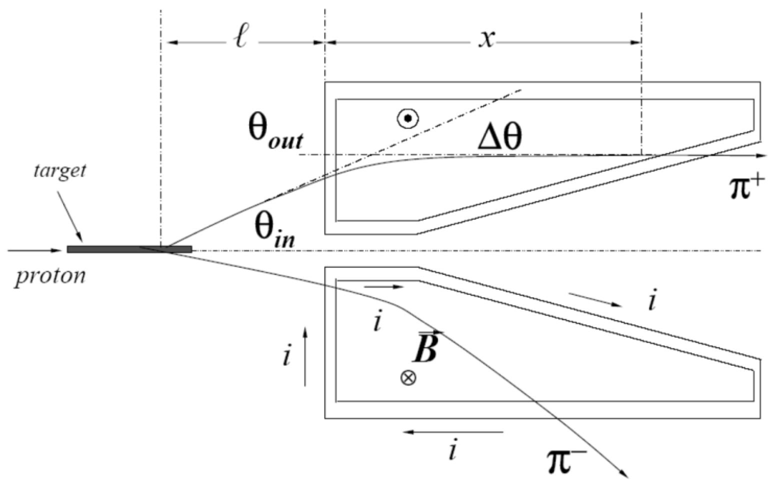


M. Giesch et al., NIM 20 (1963) 58

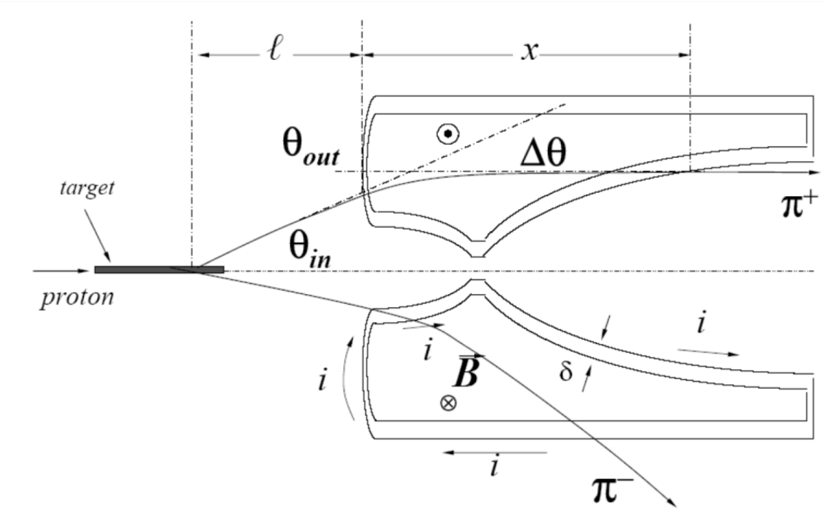


- inner conductor shape calculated to give nearly exact focusing after 1 reflection only for all particle momenta produced at an angle corresponding to maximum production
- developed "fast ejection" scheme to extract beam in 2.1 μs

Focusing devices (Horns)

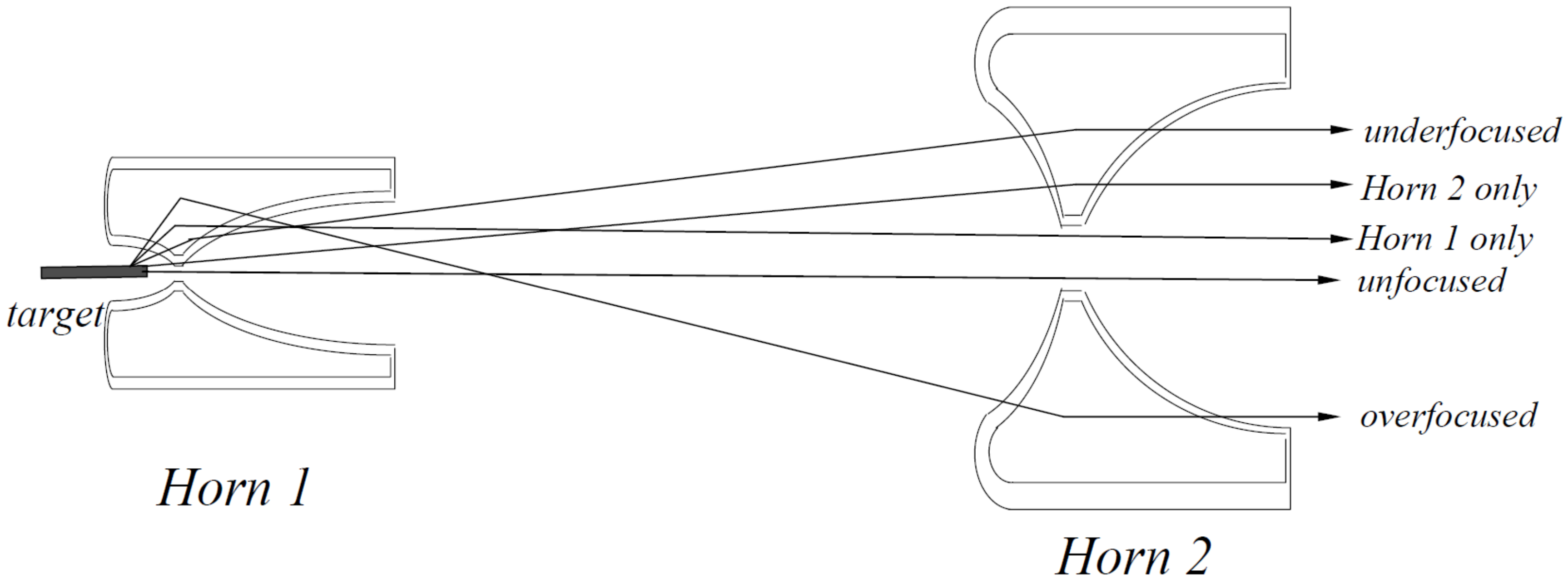


Focuses all momenta of a given sign for a given angle of pion into the horn. It produces a broad band beam.



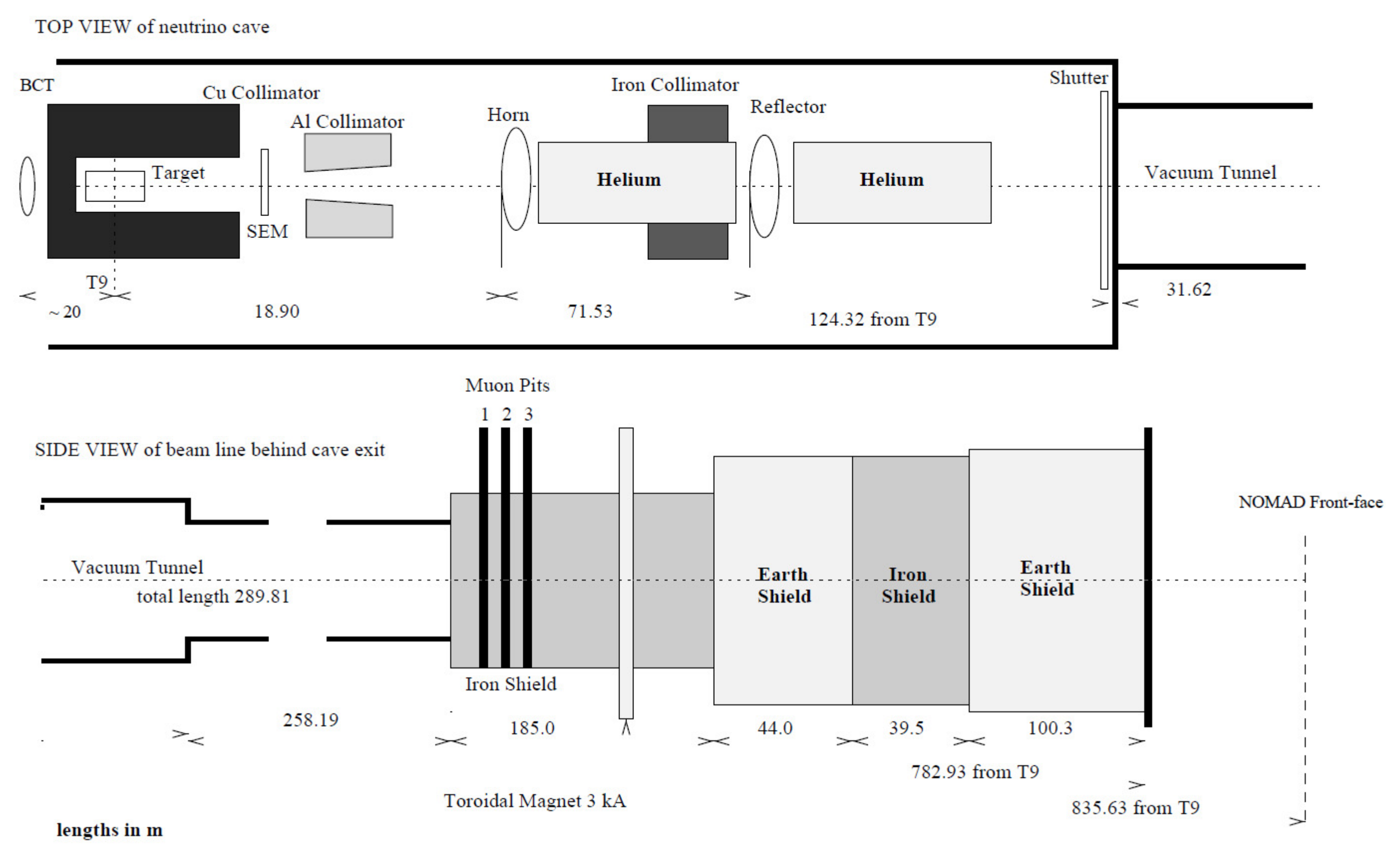
With a parabolic shaped horn inner conductor, the horn behaves like a lens (p_t kick proportional to the distance from the axis), with a focal length proportional to the momentum

Multi-horn systems



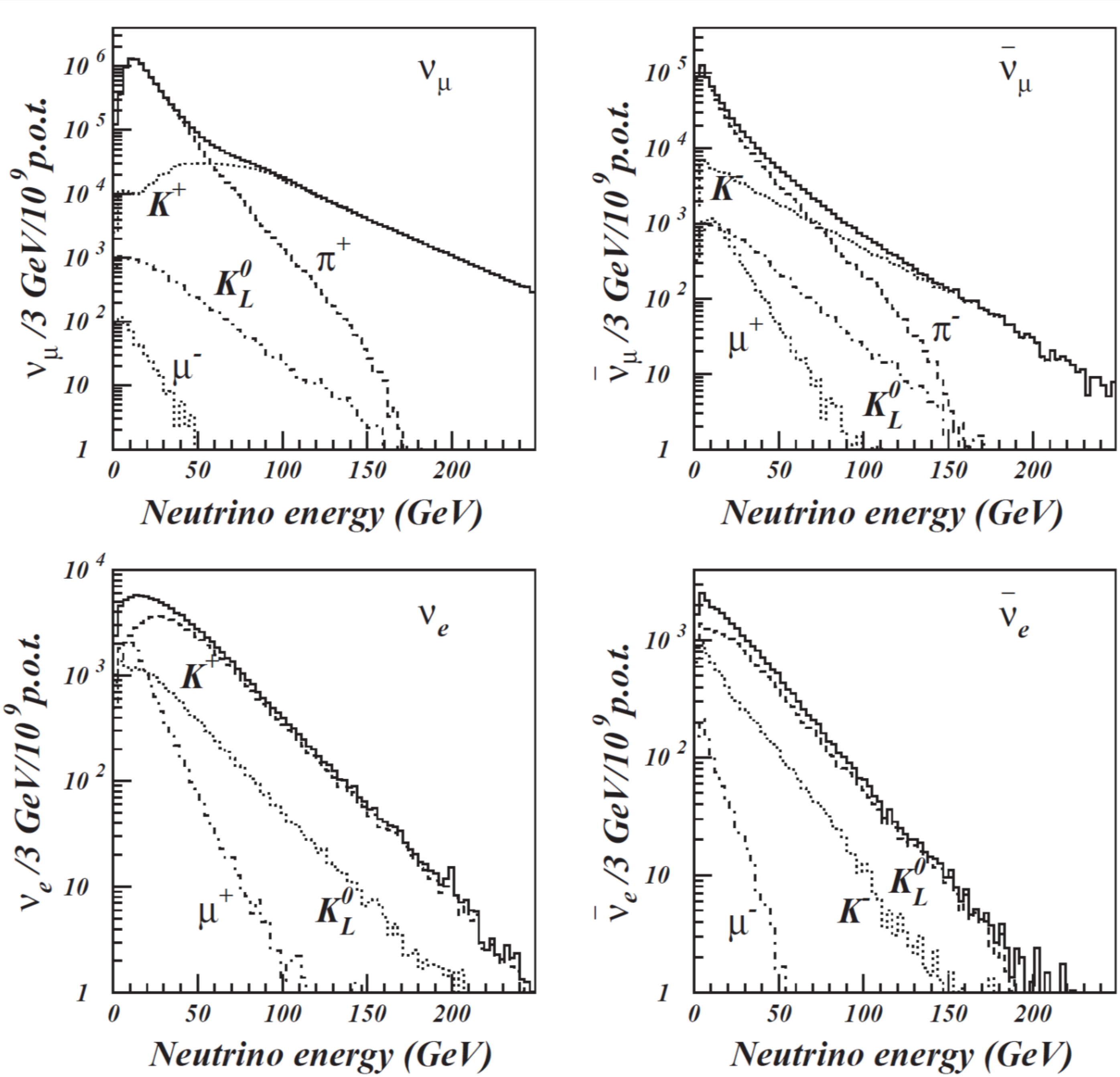
Short-baseline Neutrino Beams

The CERN WANF ν beam



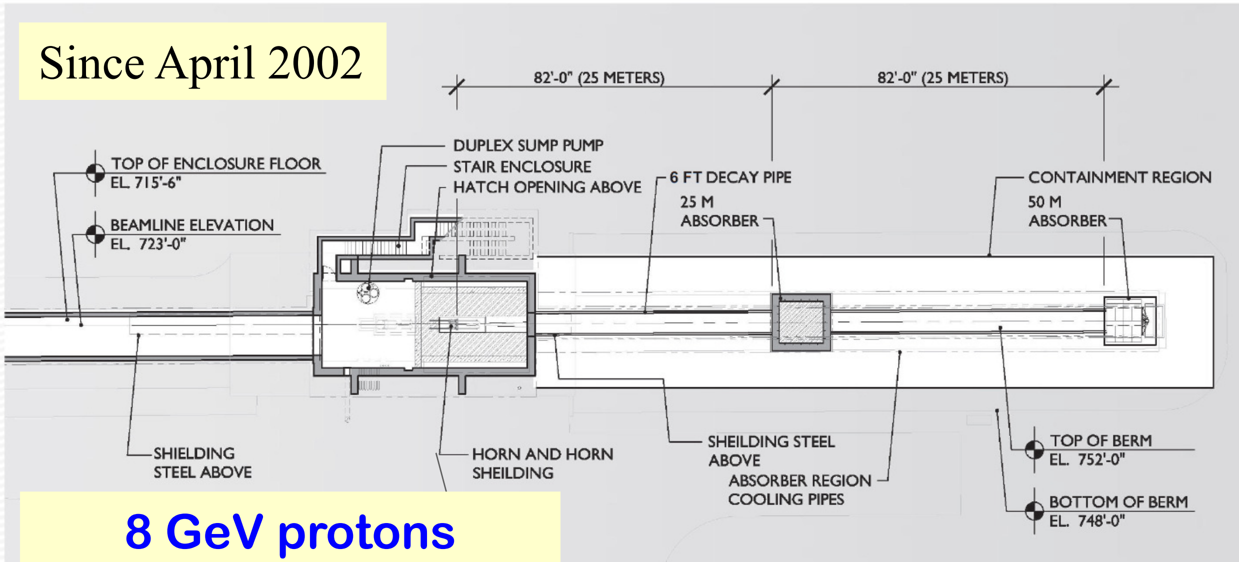
- **450 GeV protons impinging on a beryllium target**
- protons are extracted in two 4 ms long spills separated by 2.6 s
- **the target is made up by 11 beryllium rods, 10 cm long and 3 mm in diameter, separated by 9 cm gaps**

The NOMAD Neutrino Beam



The FNAL Booster ν beam

Since April 2002

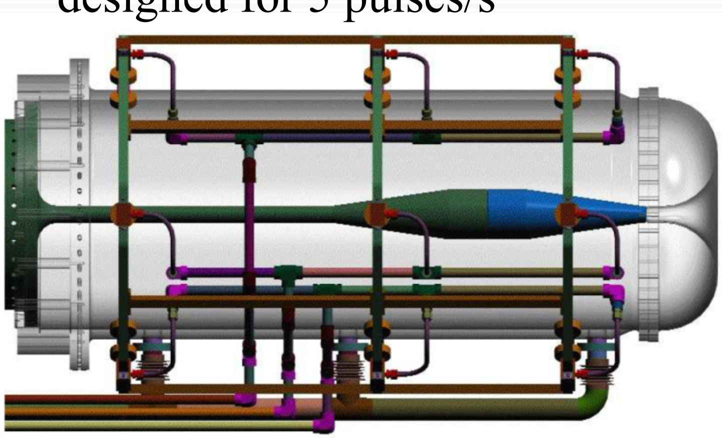


8 GeV protons from FNAL Booster

Beryllium target

7 rods 10.2 cm long, 0.96 cm Ø

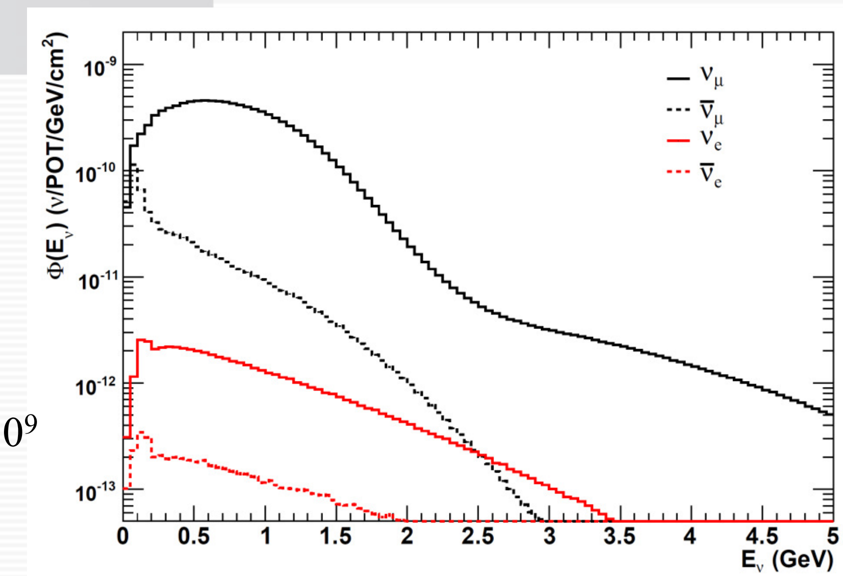
172 kA @ 15 Hz
designed for 5 pulses/s



Horn pulses

1^{st} horn: 97×10^6

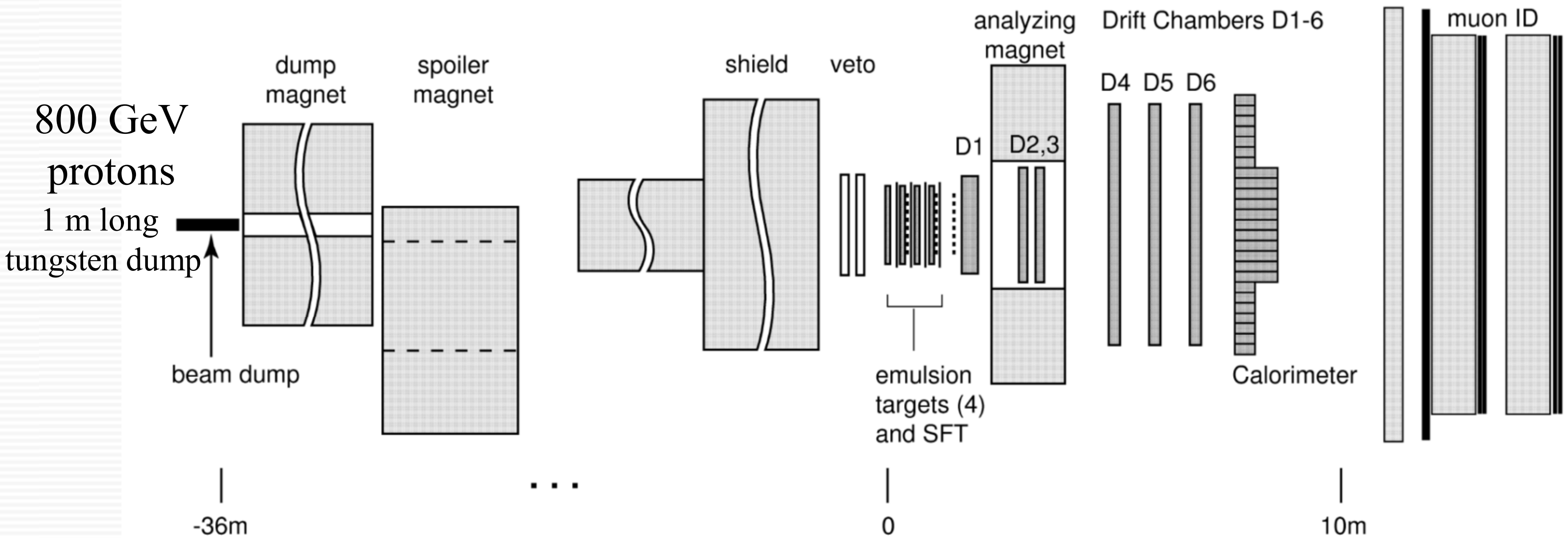
2^{nd} horn: $\sim 0.3 \times 10^9$

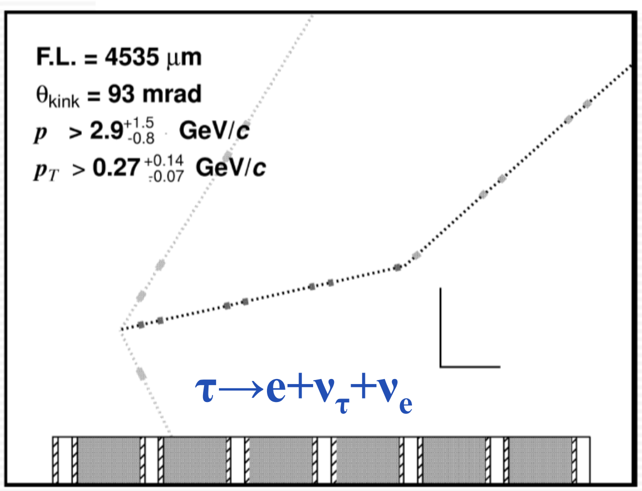


The beam dump experiments

- **'beam dump' experiments: an intense beam of high energy protons is absorbed in a thick, dense target**
- **motivation: discover new particles and new effects**
- **sensitive to short lived particles, down to small cross section, whose decay modes include neutrinos in the final state**
  - provided the first evidence of charm production in hadronic interactions
  - measurement of the ratio of electron- to muon-neutrino rates as a test of e-μ universality (BEBC, CDHS, CHARM, FFMOW)
- **sensitive to "other" penetrating particles…**
  - Search for Dark Matter with MiniBooNE: recently running BNB with off-axis beam

DONUT: the discovery of ν_τ





9 ν_τ events with an estimated background of 1.5 events

K. Kodama et al., Phys. Lett. B 504 (2001) 218

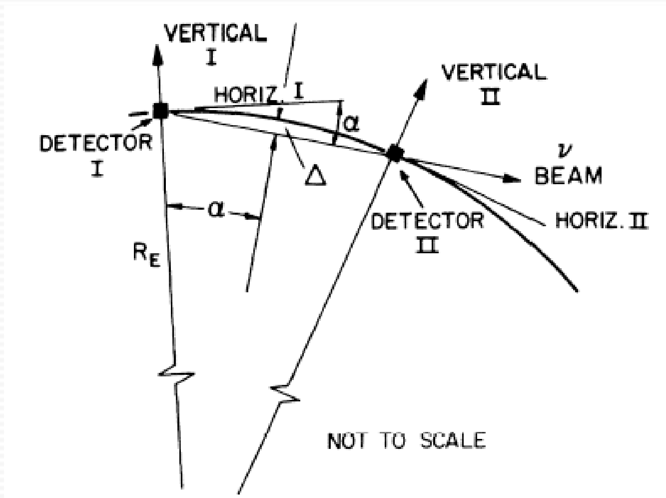
Can I do a neutrino experiment at LHC?

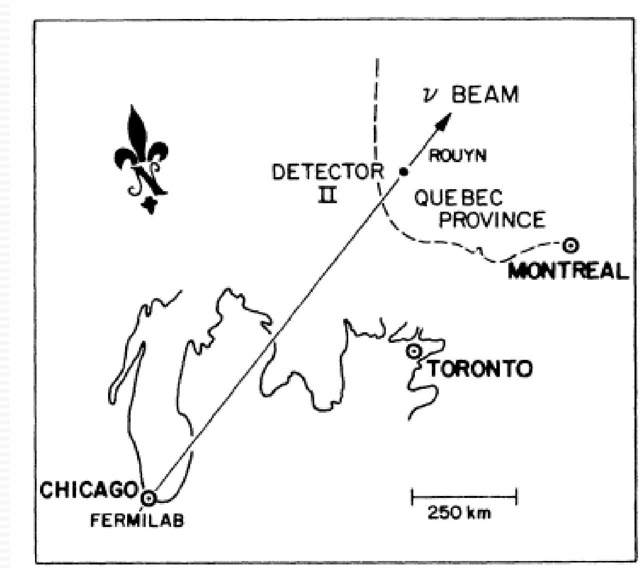
a. conventional neutrino beam by extracting the LHC proton beam
b. neutrino beam from interactions of the proton beam on an internal gas-jet target
c. neutrino beam from extracted proton beam in a beam dump
d. neutrino beam from pp interactions at the interaction points

Long-baseline Neutrino Beams

A.K. Mann, H. Primakoff **"Neutrino oscillations and the number of neutrino types"**, Phys.Rev. D 15 (1977) 655

The first idea for a long baseline ν beam





L= 1000 km, α=78 mrad, Δ=19 km

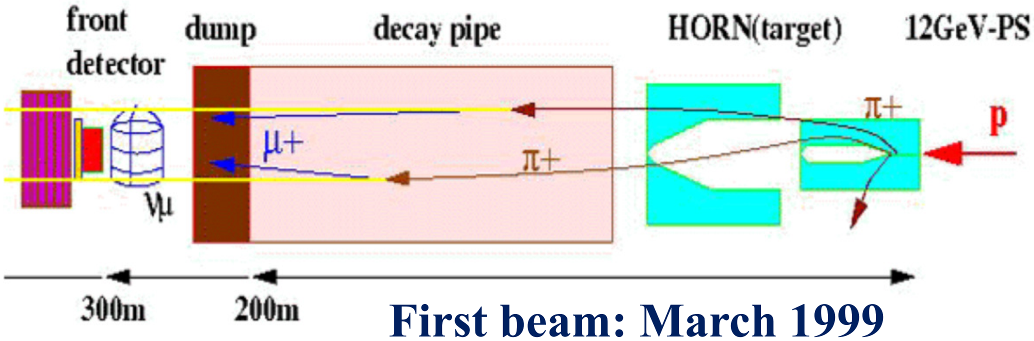
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$

Δm^2 in eV^2, L/E in km/GeV

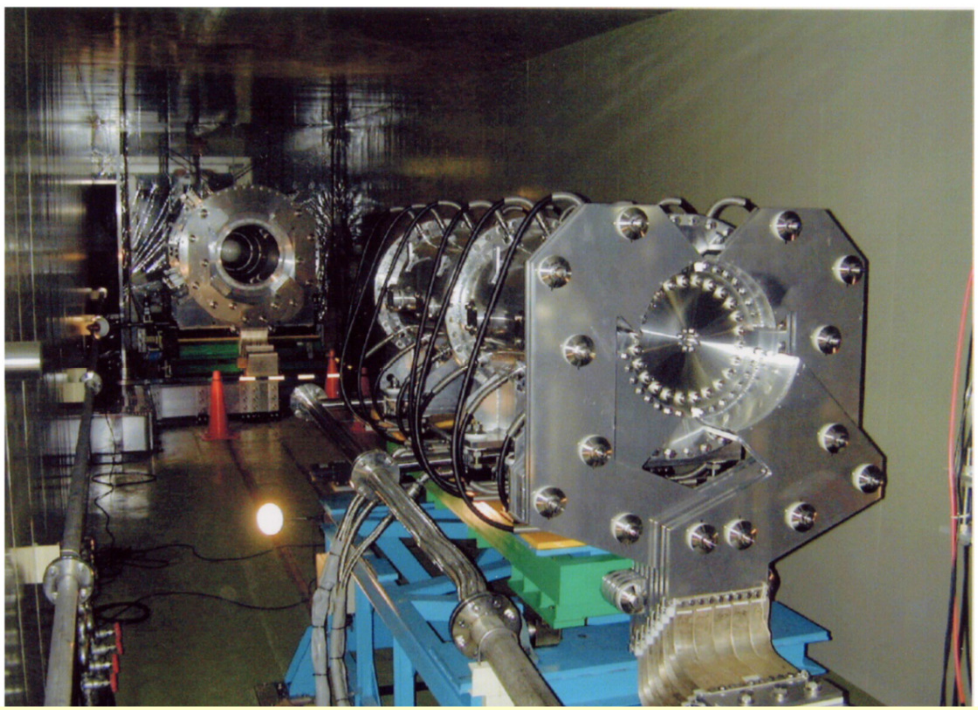
"None of our speculations on the lower limit of the oscillation length at $p_\nu \leq 20$ GeV appears to be significantly larger than the distance between the accelerator and the distant detector (1000 km)"

"It is perhaps worth mentioning again that any actual neutrino-oscillation phenomenon might conceivably provide another means of observing CP violation"

The KEK ν beam



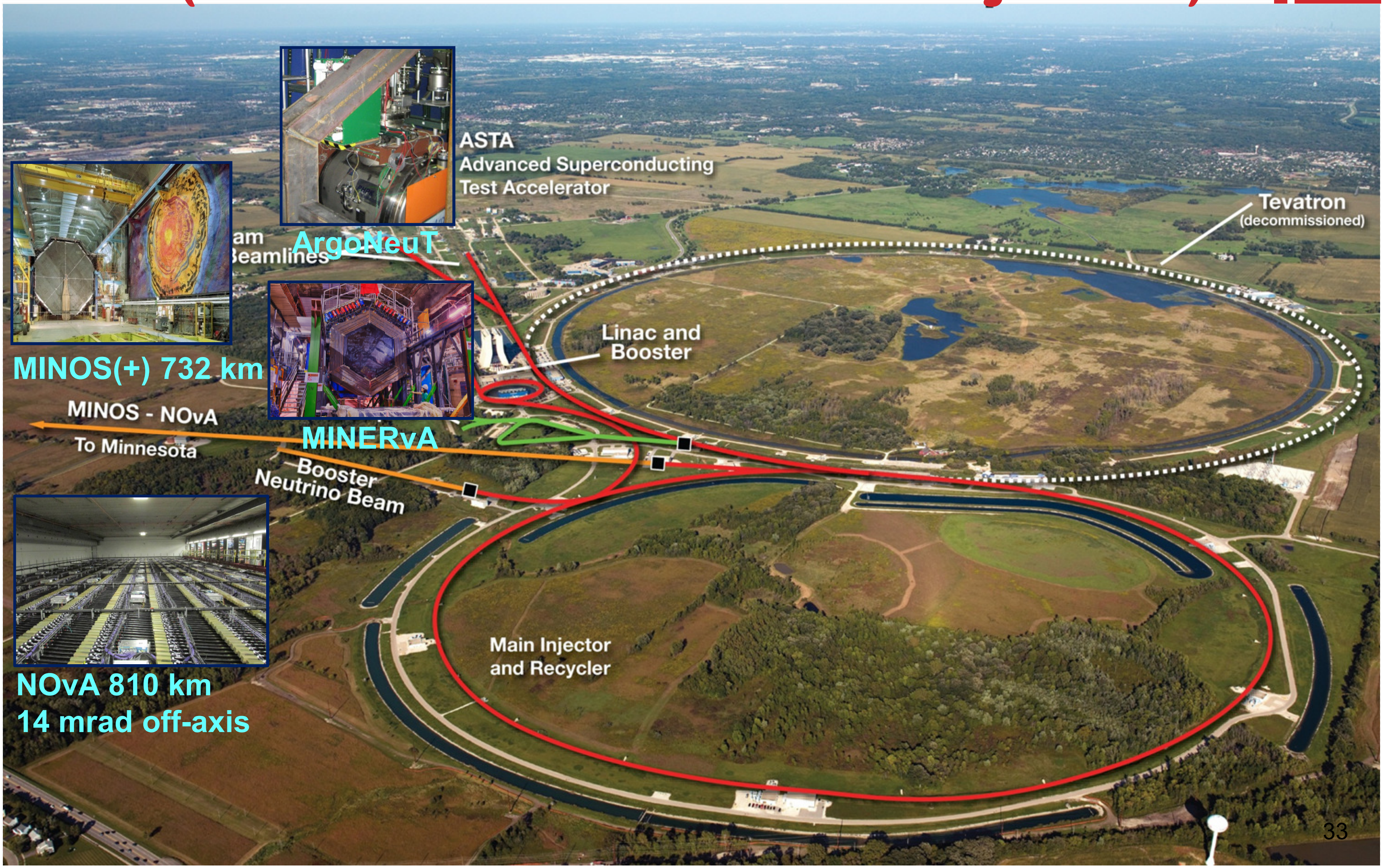
First beam: March 1999



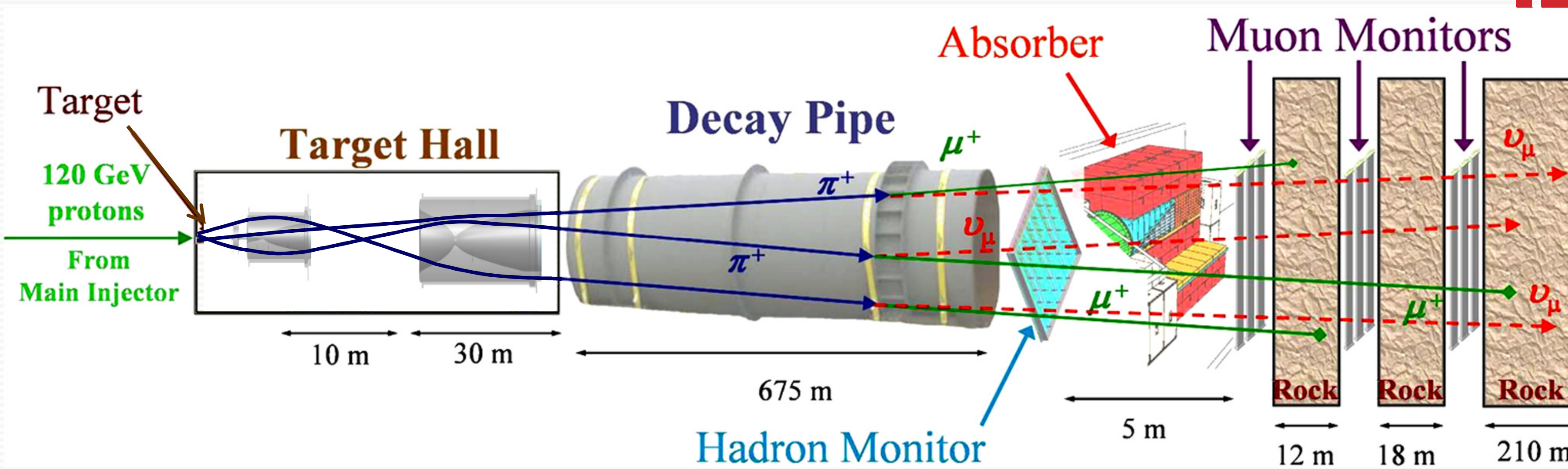
- Two Horns (Collector & Reflector).
- Built-in Target in Collector
- 250kA Operation
- 10M Excitation with 30mmφTarget
- Transformer near-by
- 200m Decay Volume filled with He.

From KEK to Super-Kamiokande (250 km)

Experiments on the NuMI line (Neutrinos at the Main Injector)

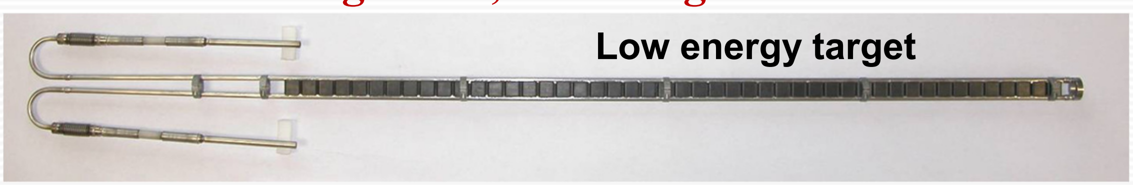


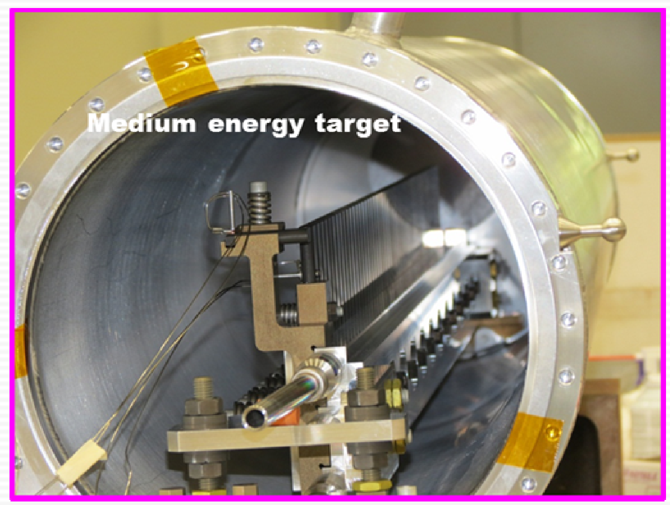
The NuMI ν beam



Water-cooled segmented graphite target

- 47 2.0 cm segments; total length of 95.4 cm

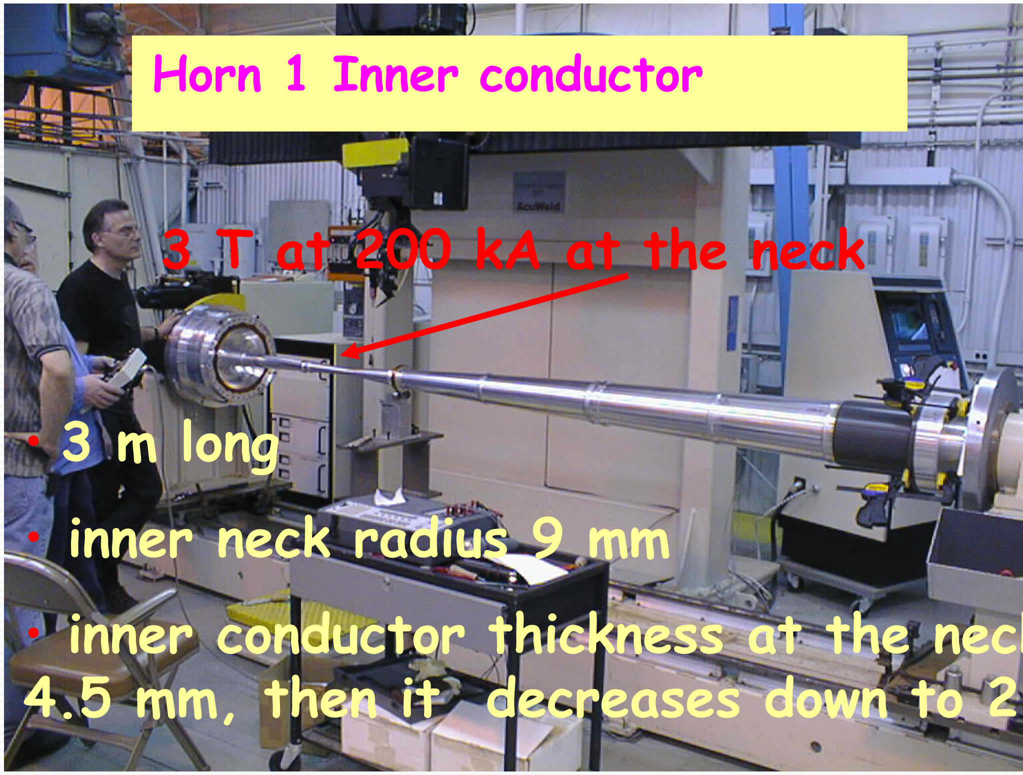


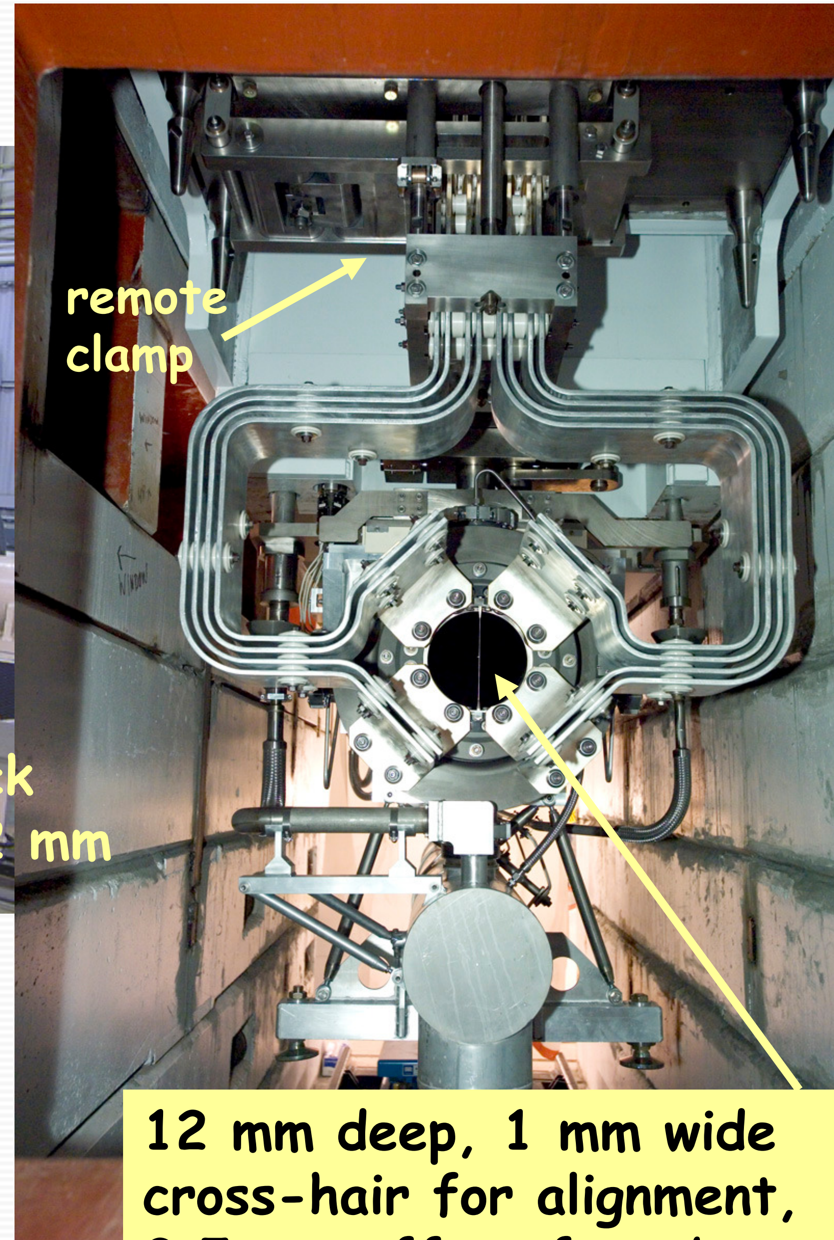


2 parabolic horns carrying

- Up to 200 kA current provides up to 3T fields
- Target can be remotely positioned up to 2.5m upstream of the first horn to change beam energy

NuMI Horn 1

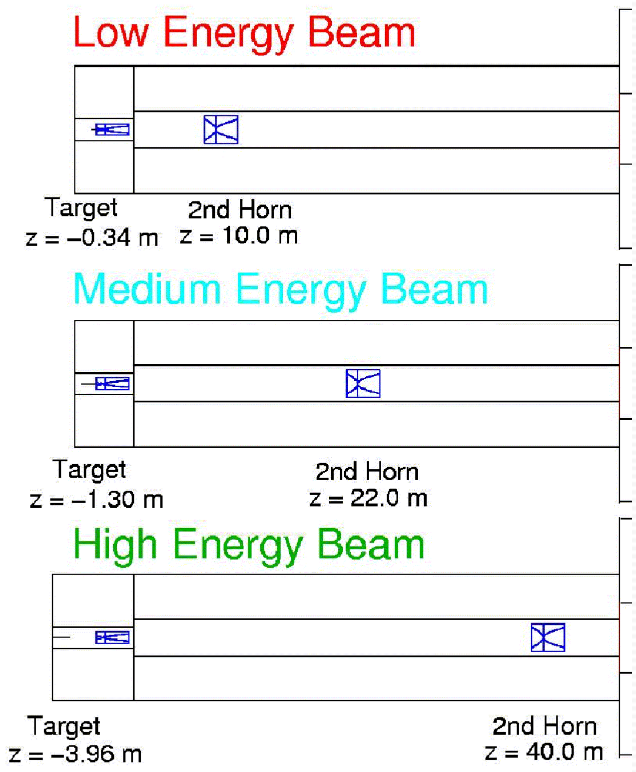




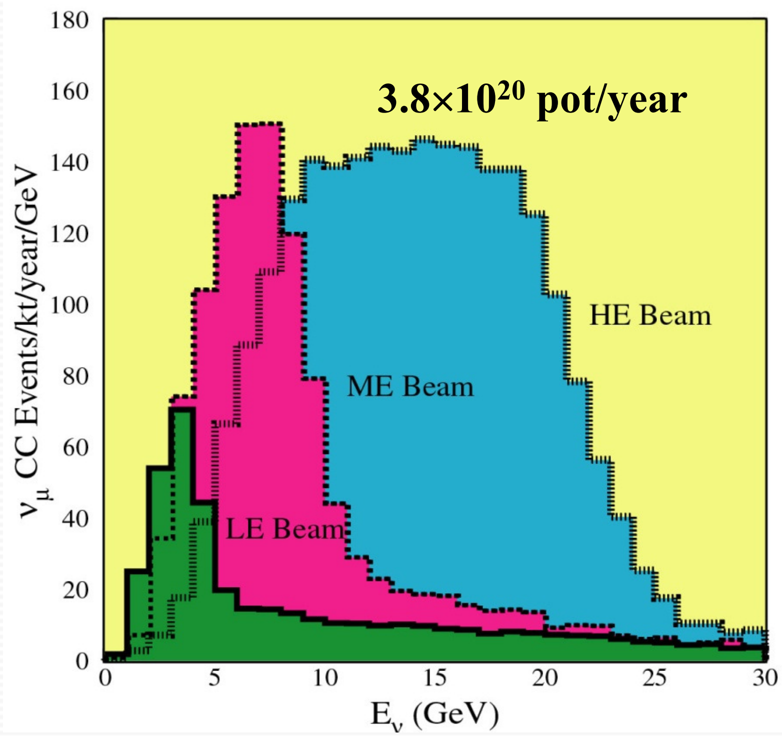
12 mm deep, 1 mm wide cross-hair for alignment, 2.5 mm offset from beam center

- Made of Aluminum 6061
- Outer conductor anodized (corrosion, insulation)
- Inner conductor nickel plated (corrosion, fatigue)

NuMI: variable energy beam

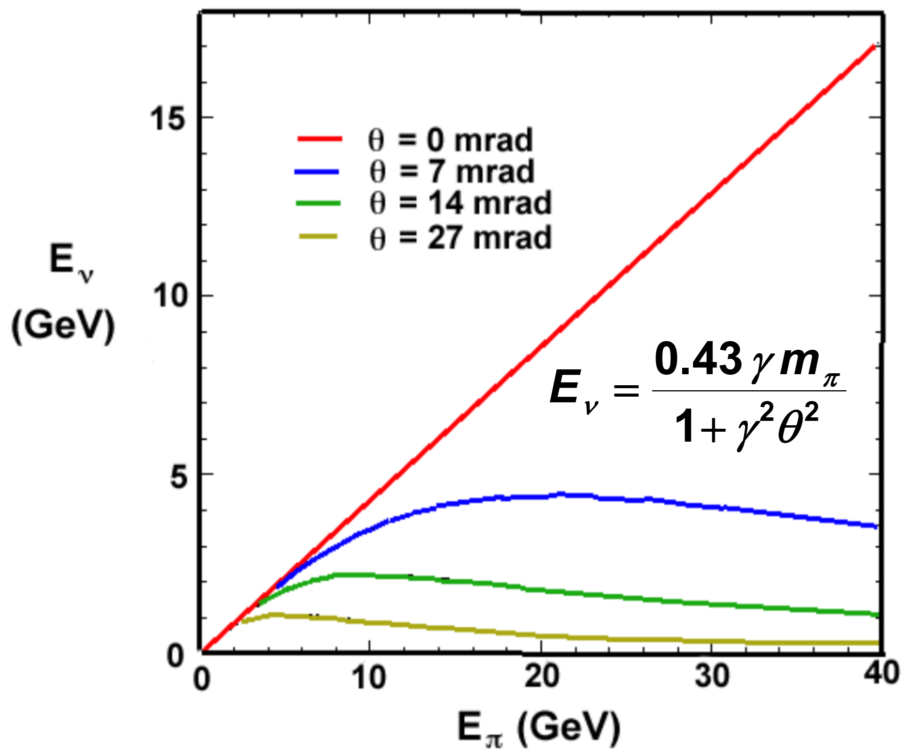


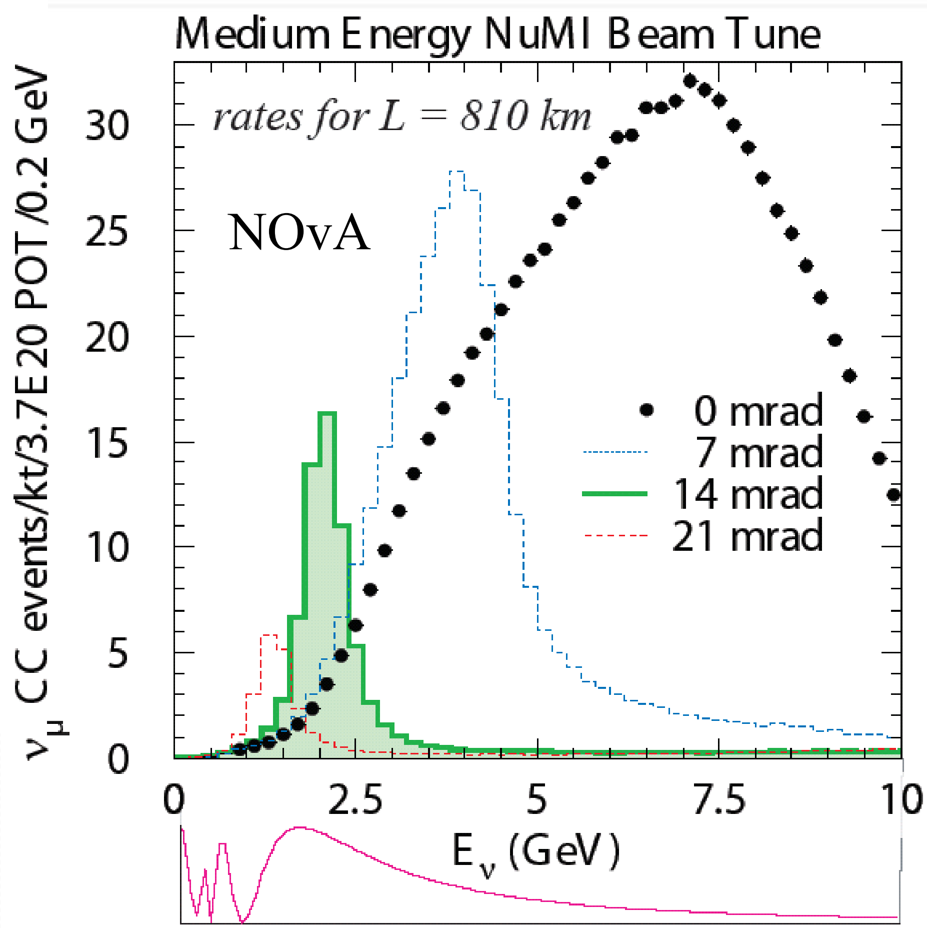
Far detector event spectra



- **Fully optimized spectra for each energy are obtained by moving the target and the 2nd horn, but most of the effect is due to the position of the target**
- **in LE configuration, 2/3 of the target length is positioned inside the 1st horn**

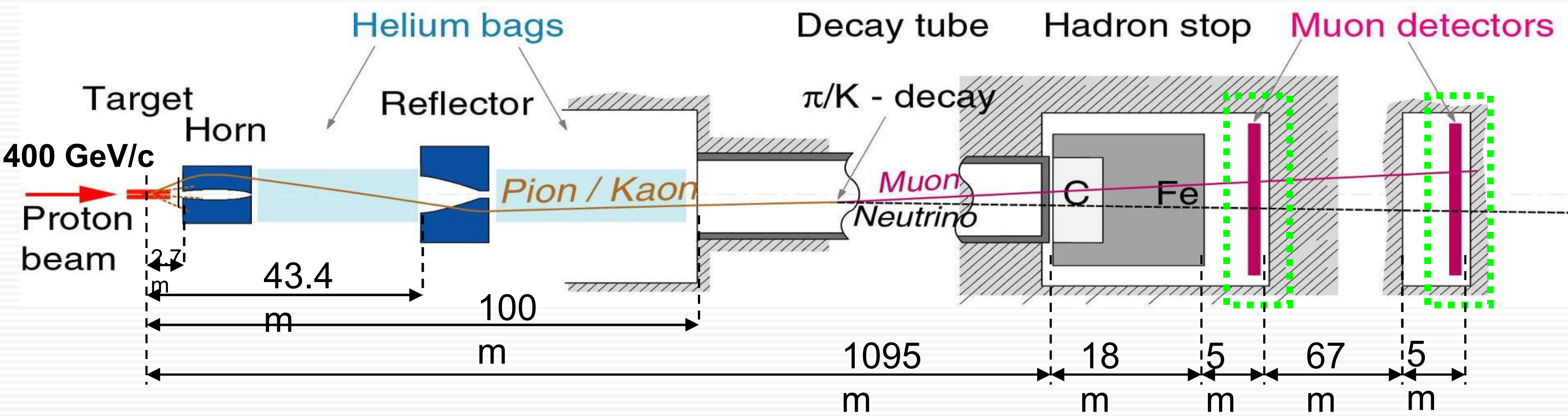
Neutrino beam configurations: on axis, off-axis



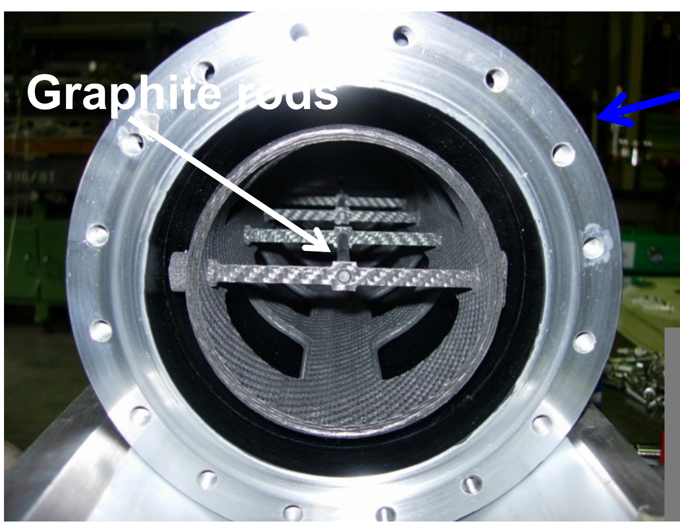


For a given θ≠0, a large range of pion energies contributes to a small range of neutrino energies

The CNGS ν beam

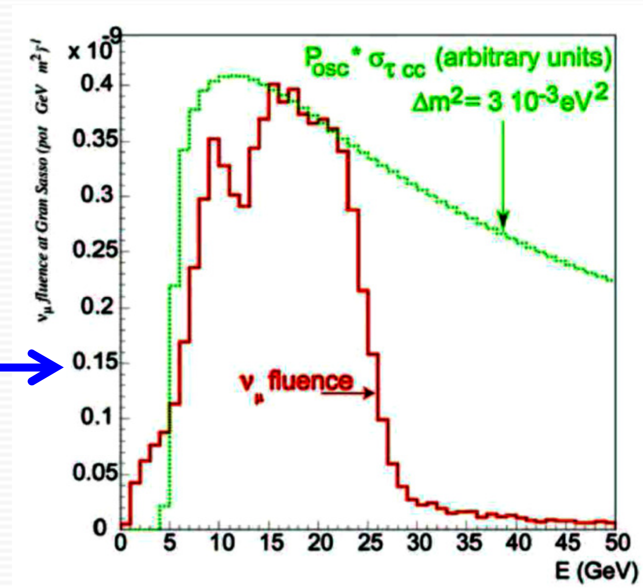


13 graphite rods, 10 mm long, 5 mm Ø
in He atmosphere

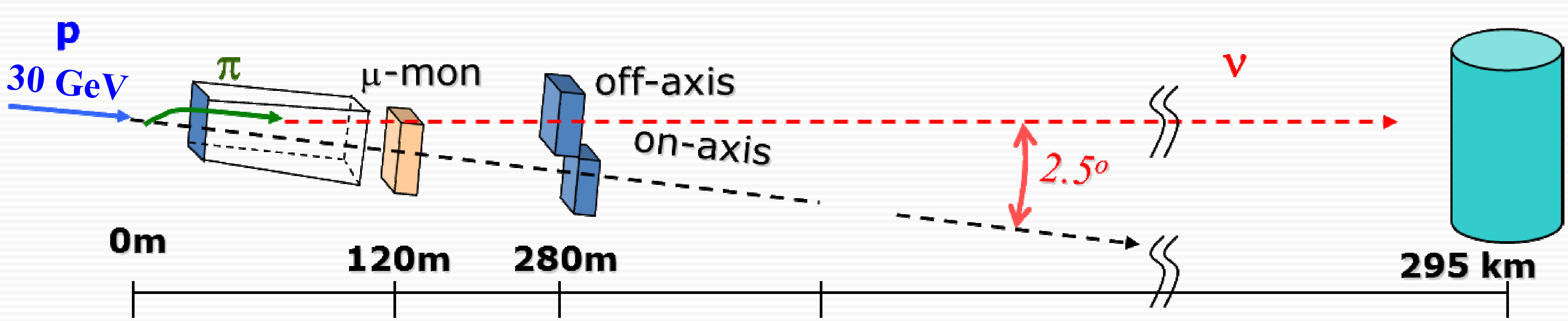


Target configuration for high energy beam

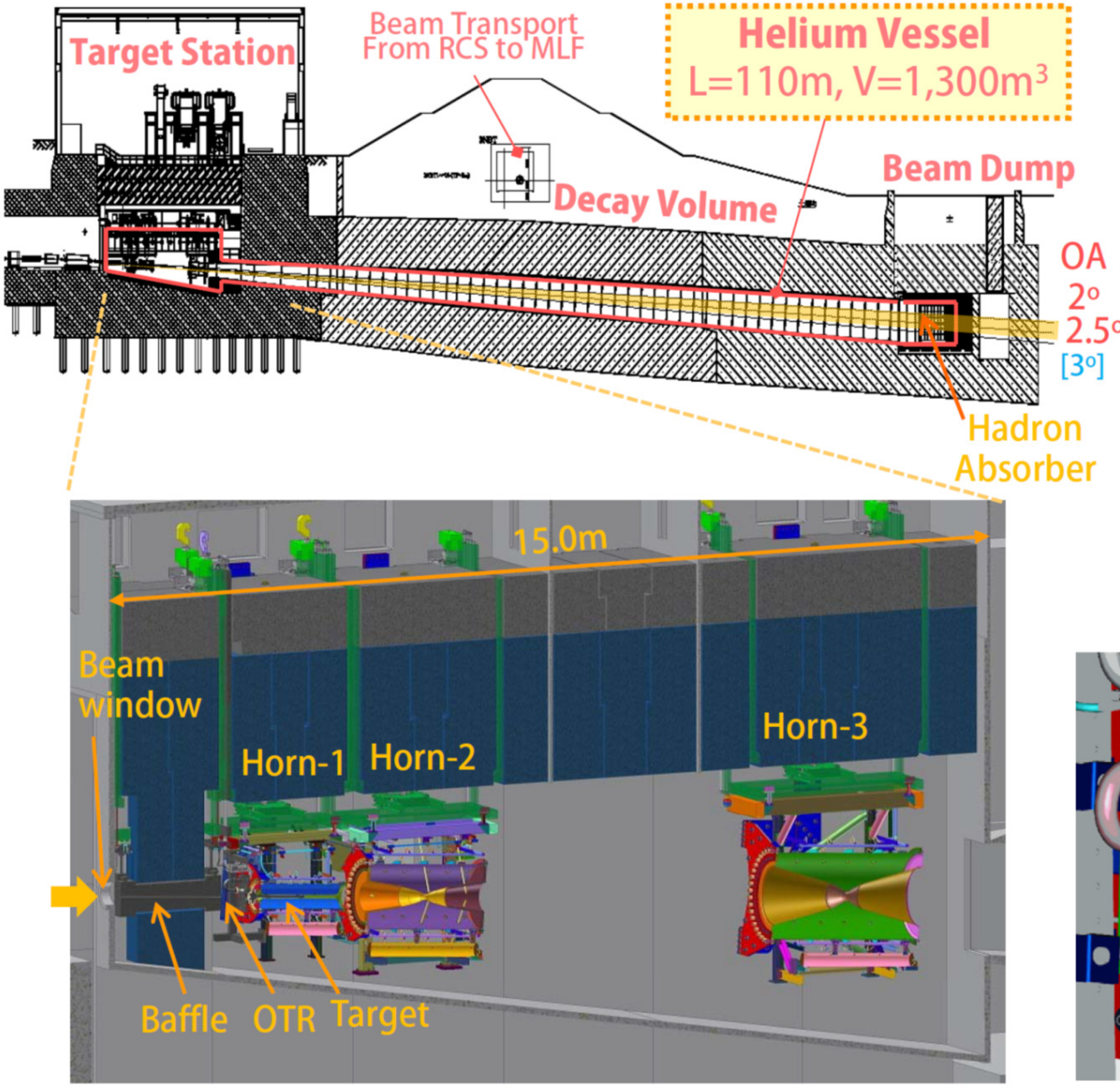
$T_{graphite}$ ~ 990 ˚C
$T_{C\text{-}C}$ ~ 375 ˚C
T_{He} ~ 365 ˚C

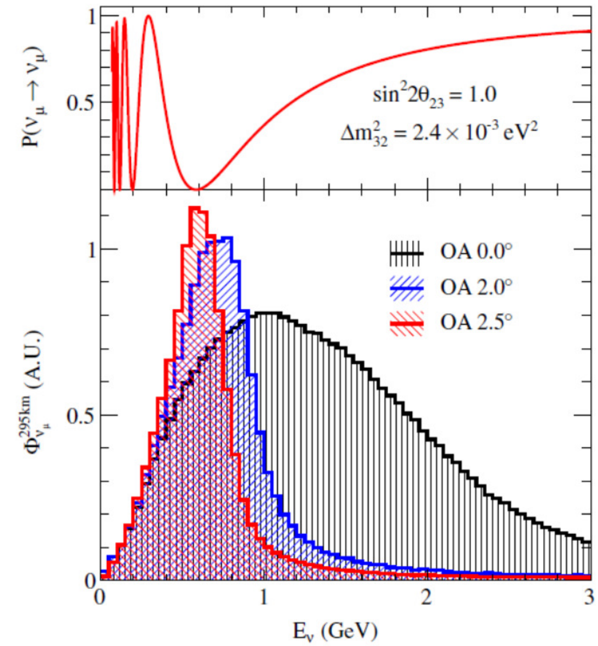


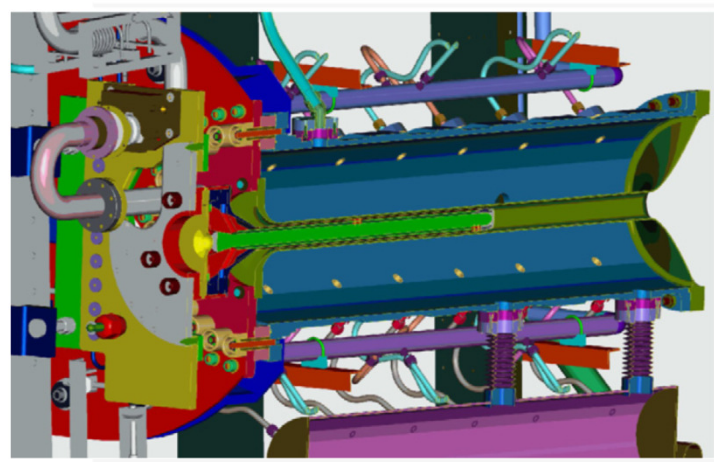
Tokai-to-Kamioka (T2K) experiment



The J-PARC ν beam

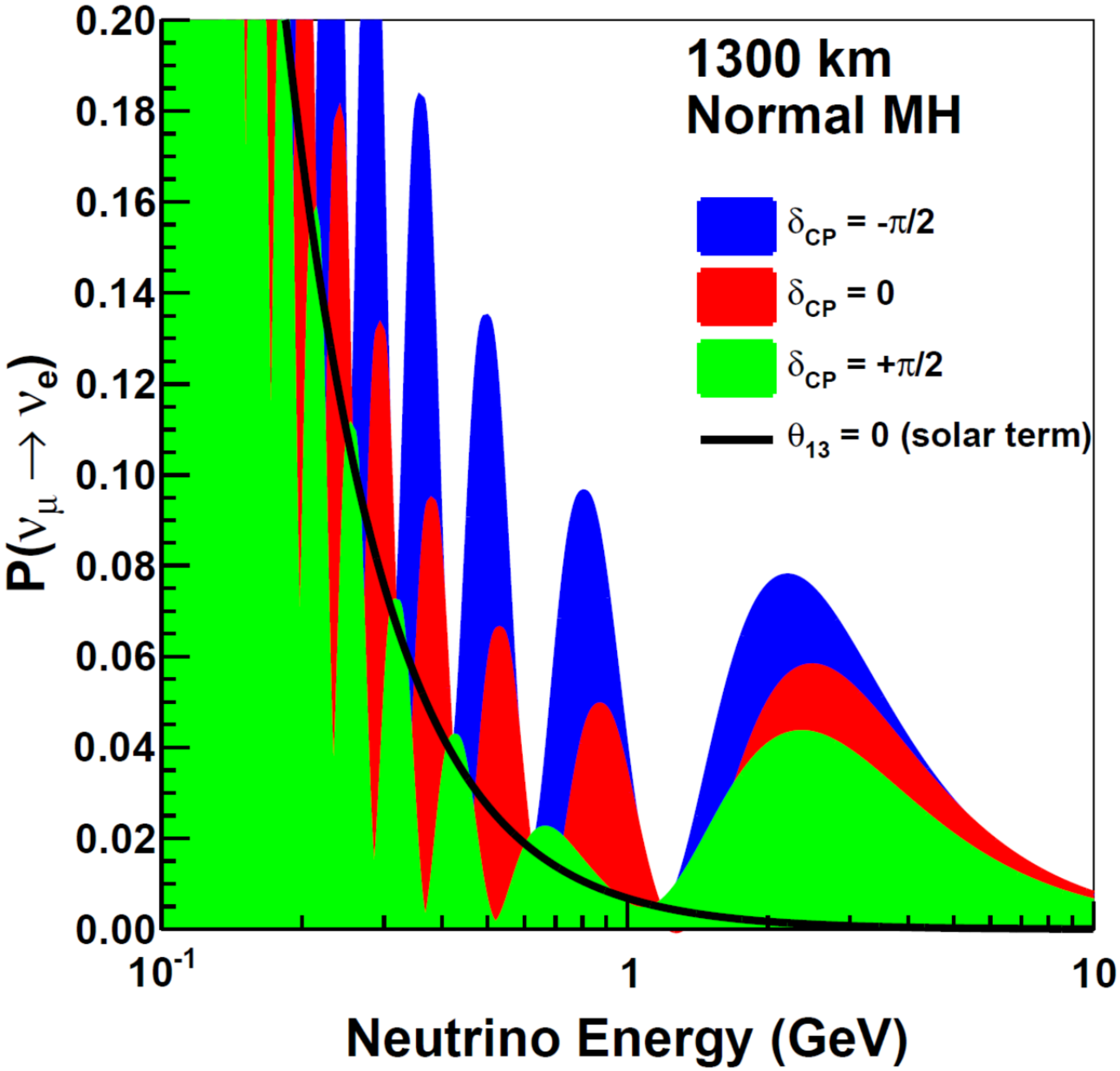




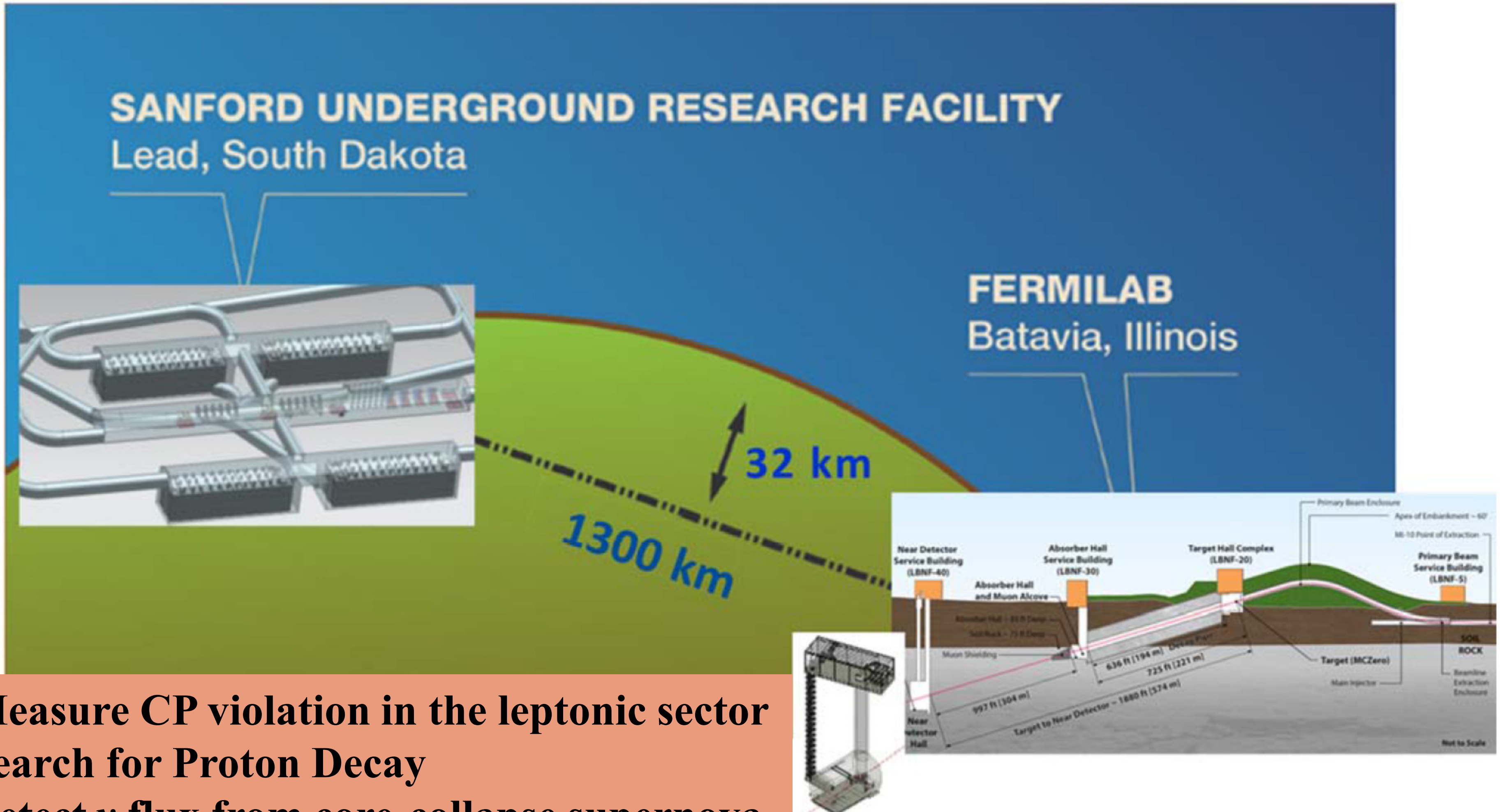


How to get a neutrino beam containing a large fraction of ν_τ (>10%) in order to study charged current ν_τ interactions?

The sub-leading ν_μ oscillation



DEEP UNDERGROUND NEUTRINO EXPERIMENT

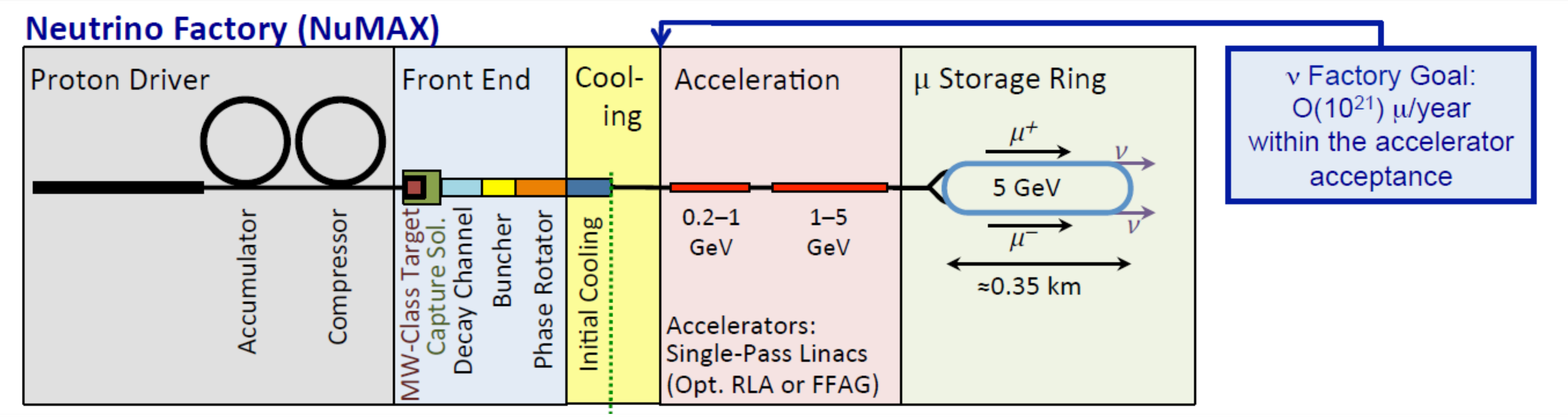


Measure CP violation in the leptonic sector
Search for Proton Decay
Detect ν flux from core-collapse supernova

What else?

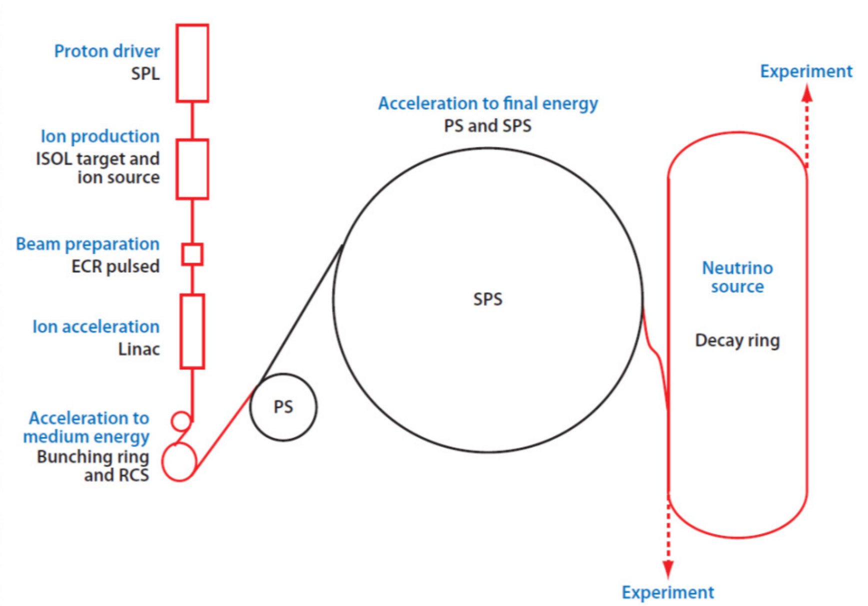
http://map.fnal.gov/

- Neutrino Factory
  - neutrinos from μ decays!



What else??

M. Lindroos, M. Mezzetto, Ann. Rev. Nucl. Part. Sci 60 (2010)299



Beta Beams!

Accelerate ions to ≥ 500 MeV/nucleon

Isotope	Method	Rate within reach (ions s^{-1})
^{18}Ne	ISOL at 1 GeV and 200 kW	$<8 \times 10^{11}$
^{6}He	ISOL converter at 1 GeV and 200 kW	$<5 \times 10^{13}$
^{18}Ne	Direct production through ^{16}O(^{3}He,n)^{18}Ne	$<1 \times 10^{13}$
^{6}He	ISOL converter at 40-MeV deuterons and 80 kW	$<6 \times 10^{13}$
^{8}Li	Production ring through ^{7}Li(d,p)^{8}Li	$<1 \times 10^{14}$

$\langle E_\nu \rangle$

β^+, 1.52 MeV

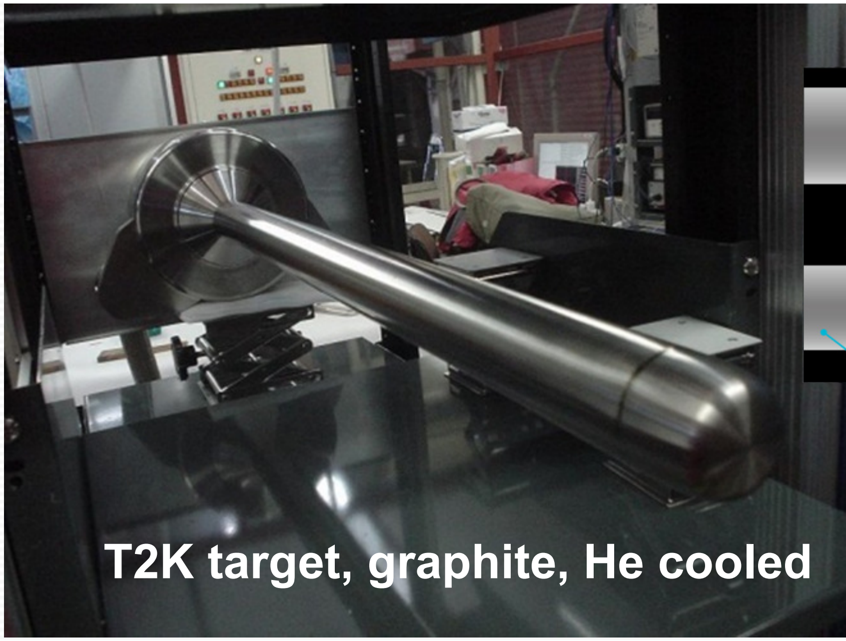
β^-, 1.94 MeV

β^-, 6.72 MeV

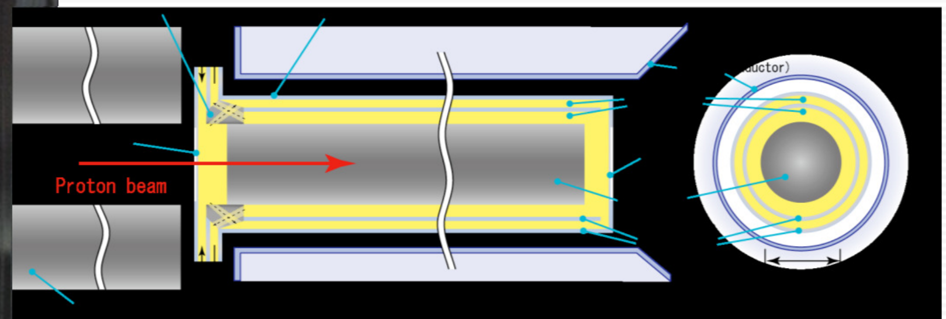
When you think neutrino beams,… think out of the box!

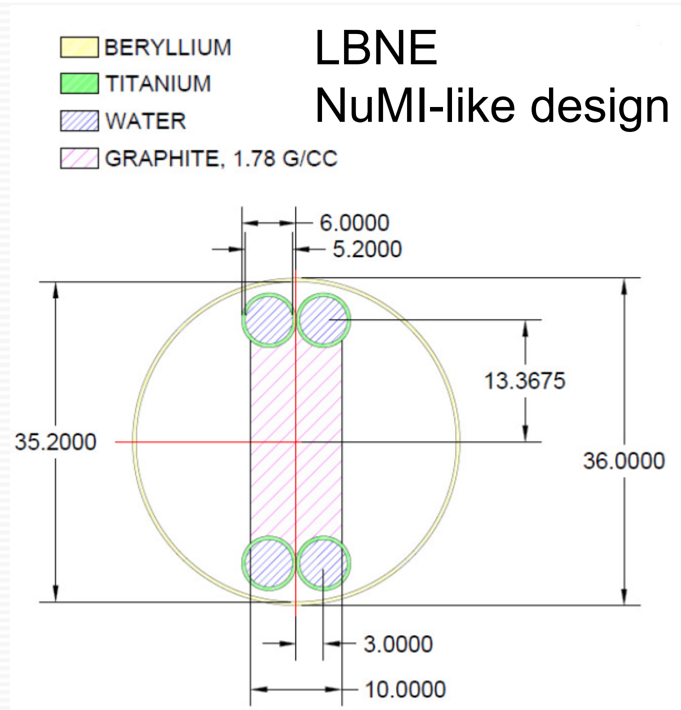
It's easier to get $2B for a good idea than $1B for a bad one!

High power targets

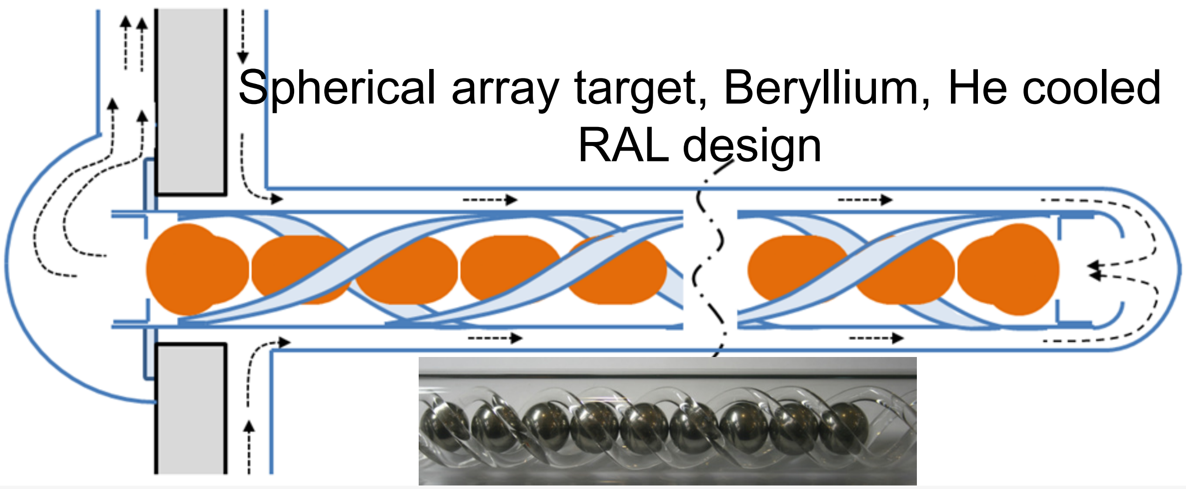


T2K target, graphite, He cooled





LBNE
NuMI-like design



Spherical array target, Beryllium, He cooled
RAL design