Neutrino Beams

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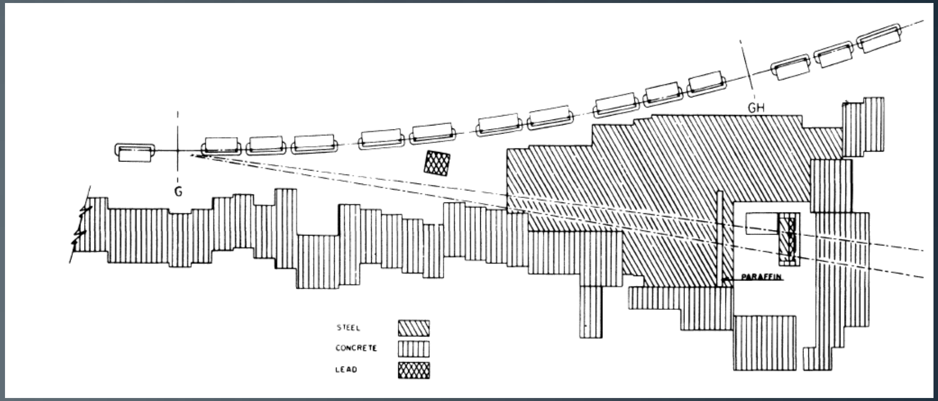
Fermilab
Nufact 2012
JLAB/William and Mary

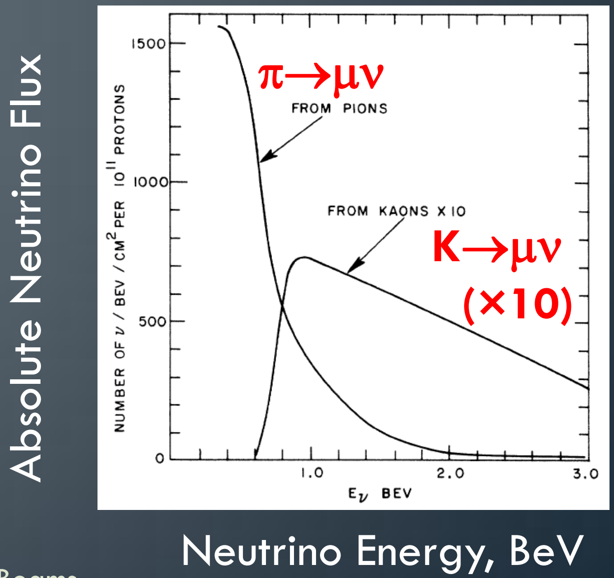
Outline

- Historic Note: First Accelerator-based Neutrino Beam
- Neutrino beams, 50 years later
  - Current Accelerator-based Neutrino Beams
- Predicting neutrino fluxes, 50 years later
- Moving beyond pion decays
  - Beta-beams
  - Muon Storage Rings
- Conclusions

First Neutrino Beam: AGS at Brookhaven

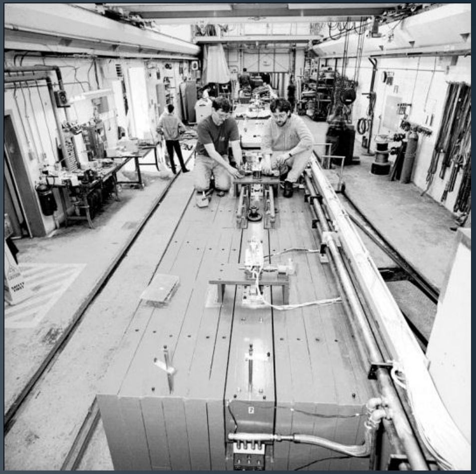
- Phys. Rev. Lett. 9, 36–44 (1962), published 50 years ago this month
- 15 "BeV protons striking 3" thick Be target, 21m long "decay region"
- Dominant Reaction: $\pi, K \rightarrow \mu\nu$
- Detector at 44.5m from neutrino target, 23.5m of steel
- Goal was to see if there were any muon-like events, signaling presence of muon flavor in neutrinos produced in $\pi, K \rightarrow \mu\nu$ decays
- 34 single muon events, predict 5 cosmic ray background events
- Neutrino Flux Uncertainty: 30%

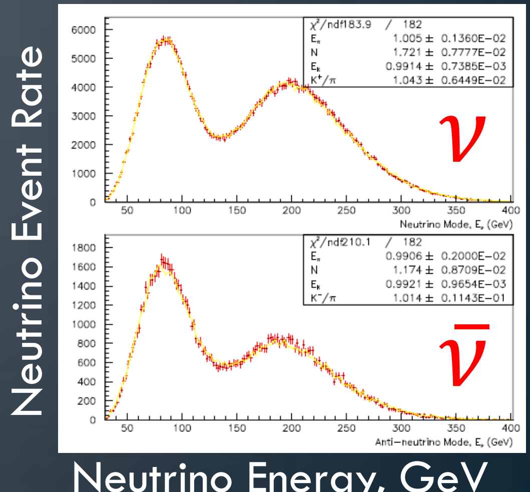




Changing goals, changing beamlines

- As goals of neutrino experiments changed, beamlines changed
  - First Neutral Current Measurements
  - Neutrino Scattering to measure Structure Functions
  - Precision Measurements of Weak Mixing Angle (See Sign Selected Quad Triplet Assembly at right)
- Constant need to increase protons on target
- Through 1998, constant need to increase neutrino energy (see ν energies of 10-200GeV at NuTeV)
- Advent of atmospheric and solar neutrino oscillation discovery pushes field back to low neutrino energies and higher intensities





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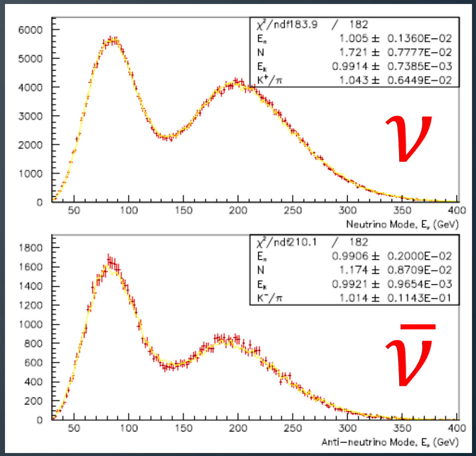
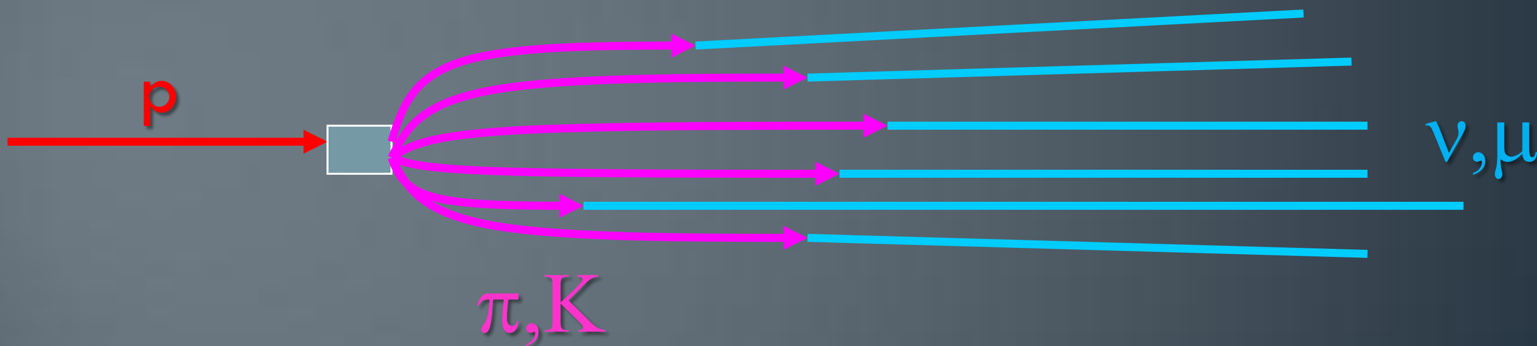


Anatomy of a "Conventional" Neutrino Beam

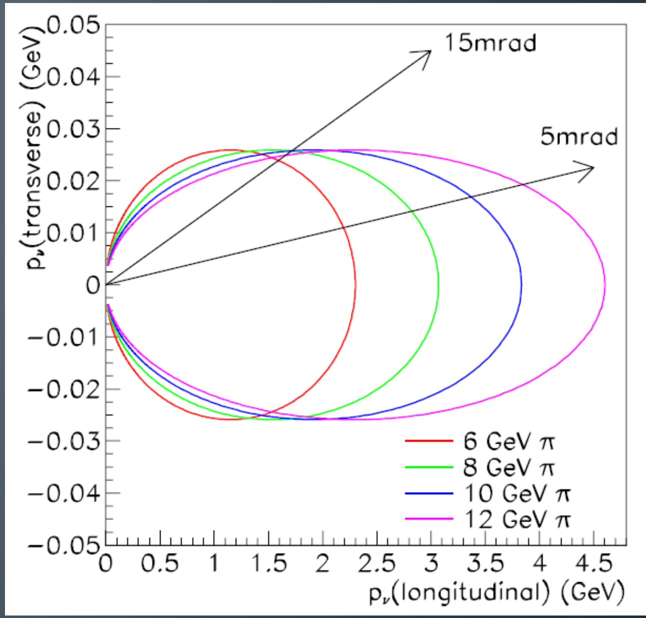
- Protons on a target produce pions and kaons
- Pions and Kaons are focused with magnetic horn towards long decay region



- Want to maximize π,K$\rightarrow\mu\nu_\mu$ decays for highest ν_μ fluxes
- First oscillation goals with accelerator beams:
  - Confirm oscillations, both with $\nu_\mu\rightarrow\nu_\tau$ appearance and ν_μ disappearance

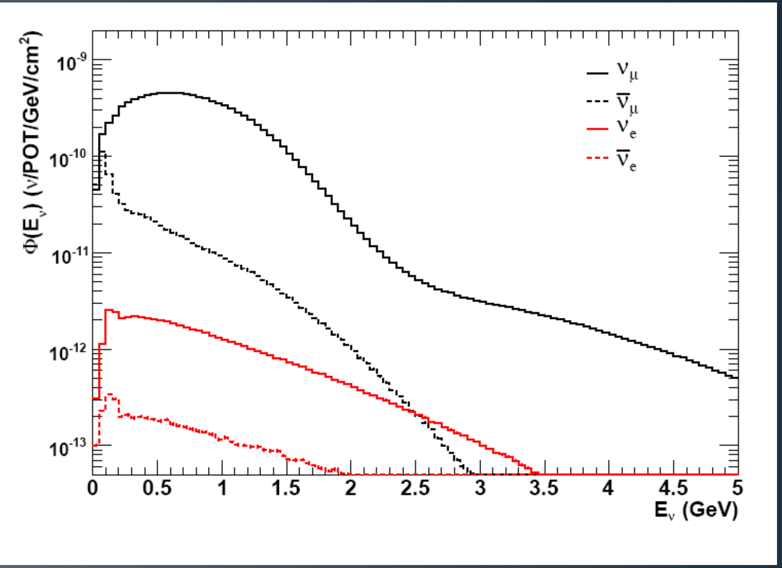
New Physics Goals, New Beamline Choices

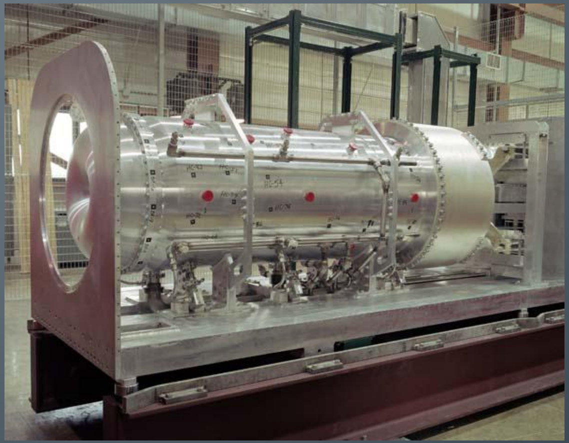
- New Goals:
  - Precision measurement of $\nu_\mu \rightarrow \nu_e$ appearance (neutrinos and antineutrinos)
  - Understanding low energy neutrino interactions in nuclei to get to precision
- Causes some strange design choices
  - Very short decay volumes: don't even let all the pions decay, to minimize muon decays
  - Off axis neutrino beams: aim pions and kaons AWAY from detector
    - Ref: D. Beavis et al, BNL No. 52459, 4/95
    - T2K and NOvA both use this



MiniBooNE Beamline

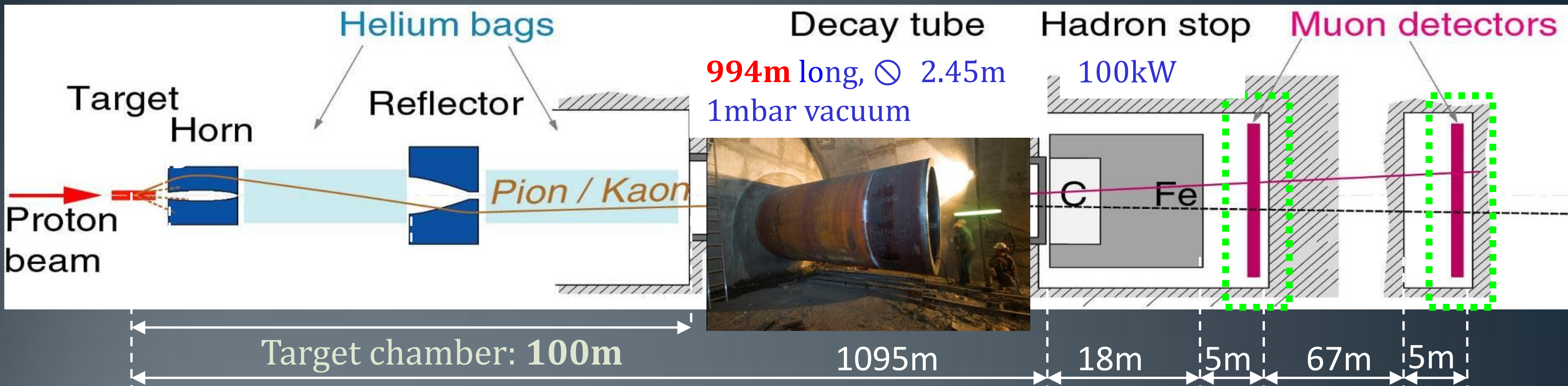
- 8 GeV protons, Beryllium target, one horn, short decay pipe
  - Enclosures for SciBooNE and MiniBooNE detectors
- Produces broad band of ν_μ events centered at ~1.4GeV
- Designed for $\nu_\mu \rightarrow \nu_e$ oscillations
- Flux prediction using HARP hadron production data





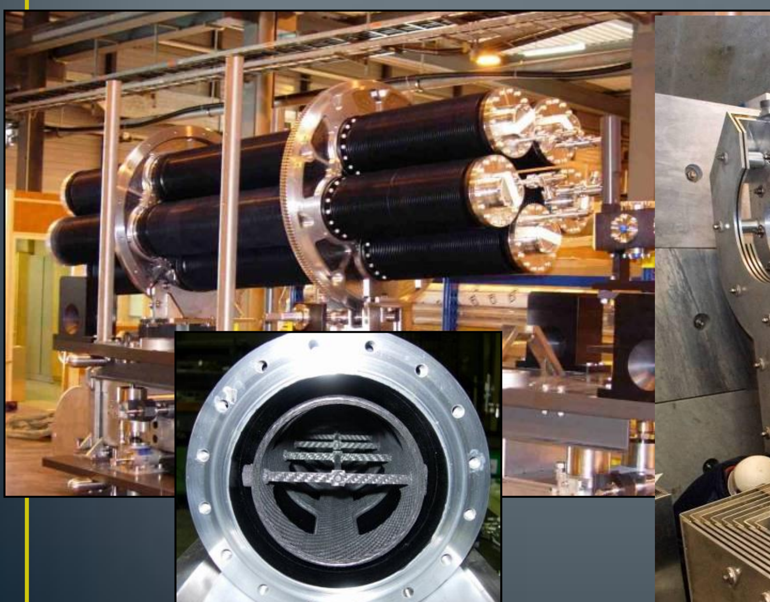
481Million Horn pulses over last 10 years
170kA@15Hz

CNGS Neutrino Beamline

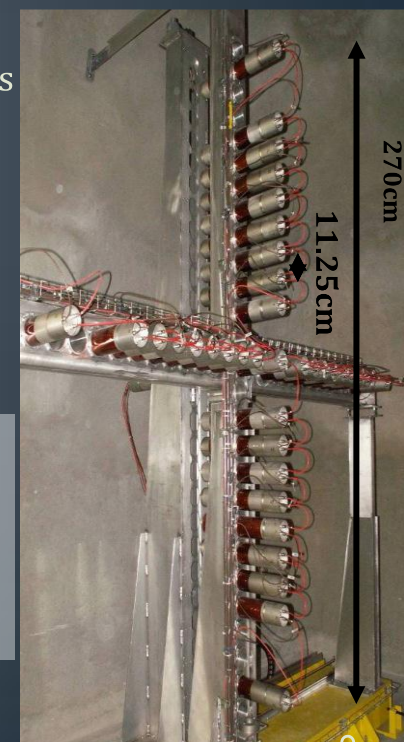


1 Target unit: 13 graphite rods 10cm
1 Magazine: 1 unit used, 4 in situ spares

Muon detectors:
2x41 LHC type BLMs

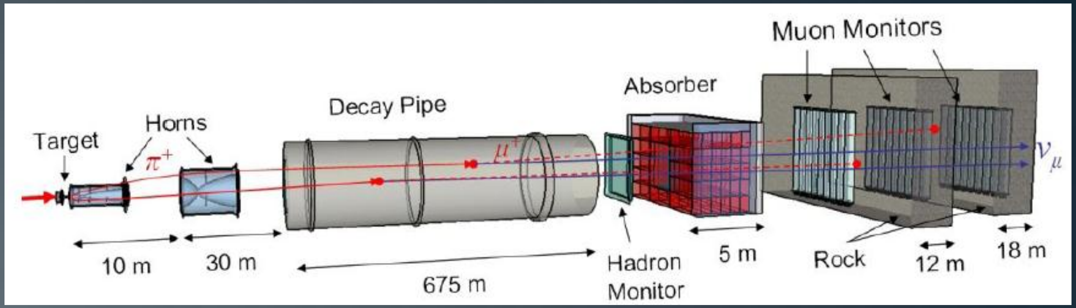


2 HORNS:
7m long, 150/180kA pulsed
Water cooled
Remote polarity change
1.8mm inner conductor

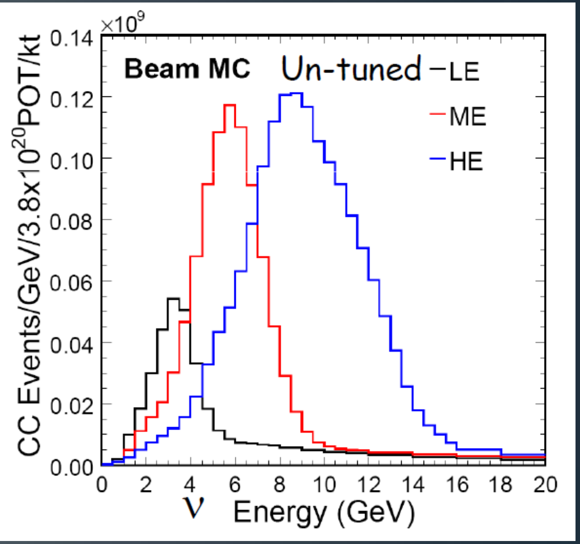


Figures courtesy E. Gschwendtner

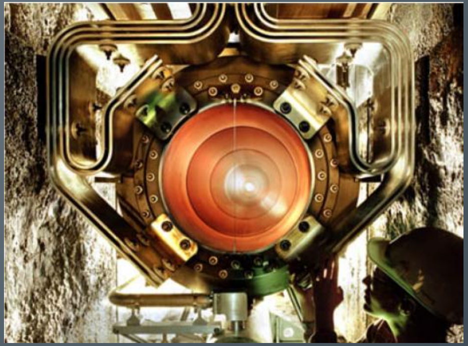
NuMI Beamline



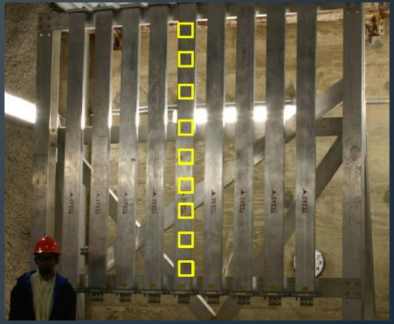
- 120GeV protons, Graphite target,
- Operating since 2005, over 1.4×10^{21} POT
- Flexible enough to produce peak energies from 3.5 to 10GeV
- Three planes of μ monitors, one hadron monitor at downstream end of decay pipe



NuMI Target

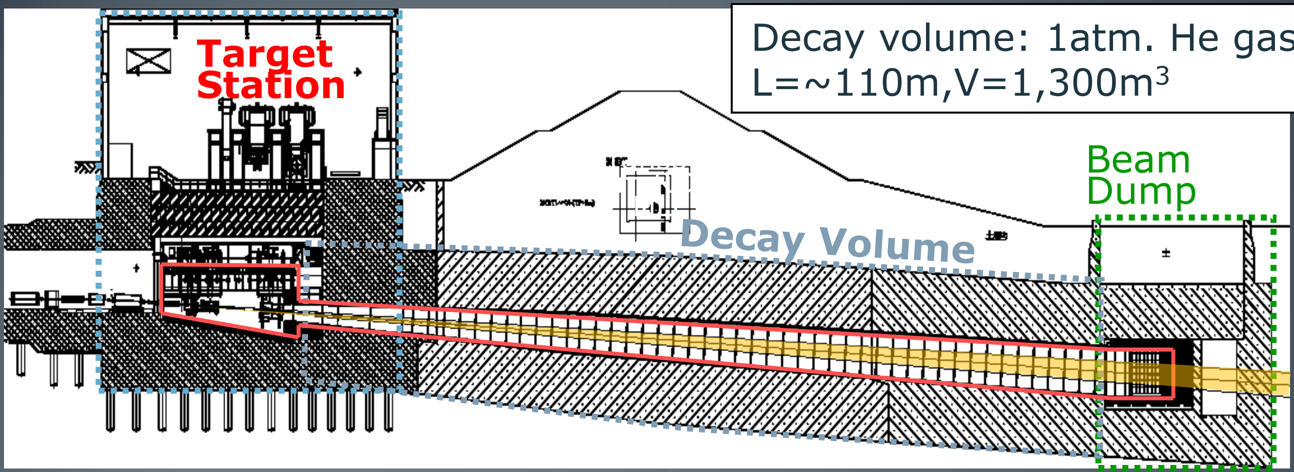


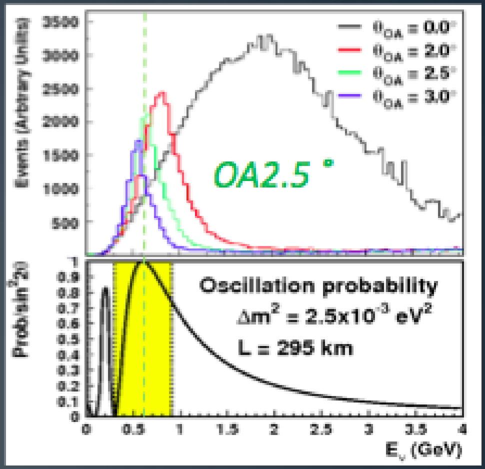
Horn 1

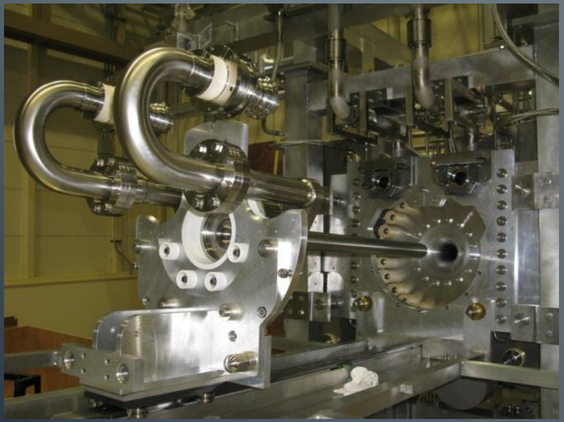


1 of 3 Muon Monitors

T2K Beamline







Target and horn 1

horn 3

Decay Volume

2 technologies for muon monitoring

Figures courtesy T. Ishida

Survey of Conventional Beams

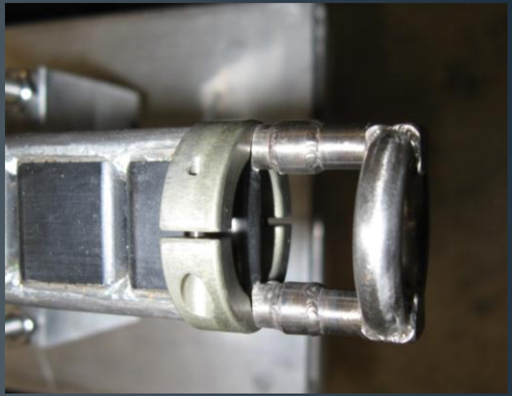
Name	Length of run (years)	Max proton Power (kW)	$\int$(protons on target) ($\times 10^{18}$)	Proton Energy (GeV)	Decay Pipe Length (m)	# horns
AGS ν beam	*<1*	*tiny*	*0.35*	*15*	*21*	*0*
NuTeV	*1.5*	*tiny*	*3*	*800*	*400*	*0 (Quad Triplet)*
Booster ν Beam	10	50	1980	9	50	1
NuMI	7	350	1571	120	675	2
CNGS	6	480	152	400	1095	2
T2K	1.5	200	301	30	110	3

References

- AGS: **Phys. Rev. Lett. 9, 36–44 (1962)**
- NuTeV: G. Zeller, APS 2000 and FNAL-TM-2040
- CNGS: Edda Gschwendtner, CERN 2nd Neutrino Town Meeting May 14-16, 2012
- NuMI: Howard Budd, May 7 2012 Fermilab All Experimenter's Meeting
- MiniBooNE: Zarko Pavlovic, May 7 2012 Fermilab All Experimenter's Meeting
  - (http://www.fnal.gov/directorate/program_planning/all_experimenters_meetings/index.html)
- T2K:
  - H. Hakuno, NBI 2010, "Overview of T2K Facility"
  - T. Ishida, Nufact 2012

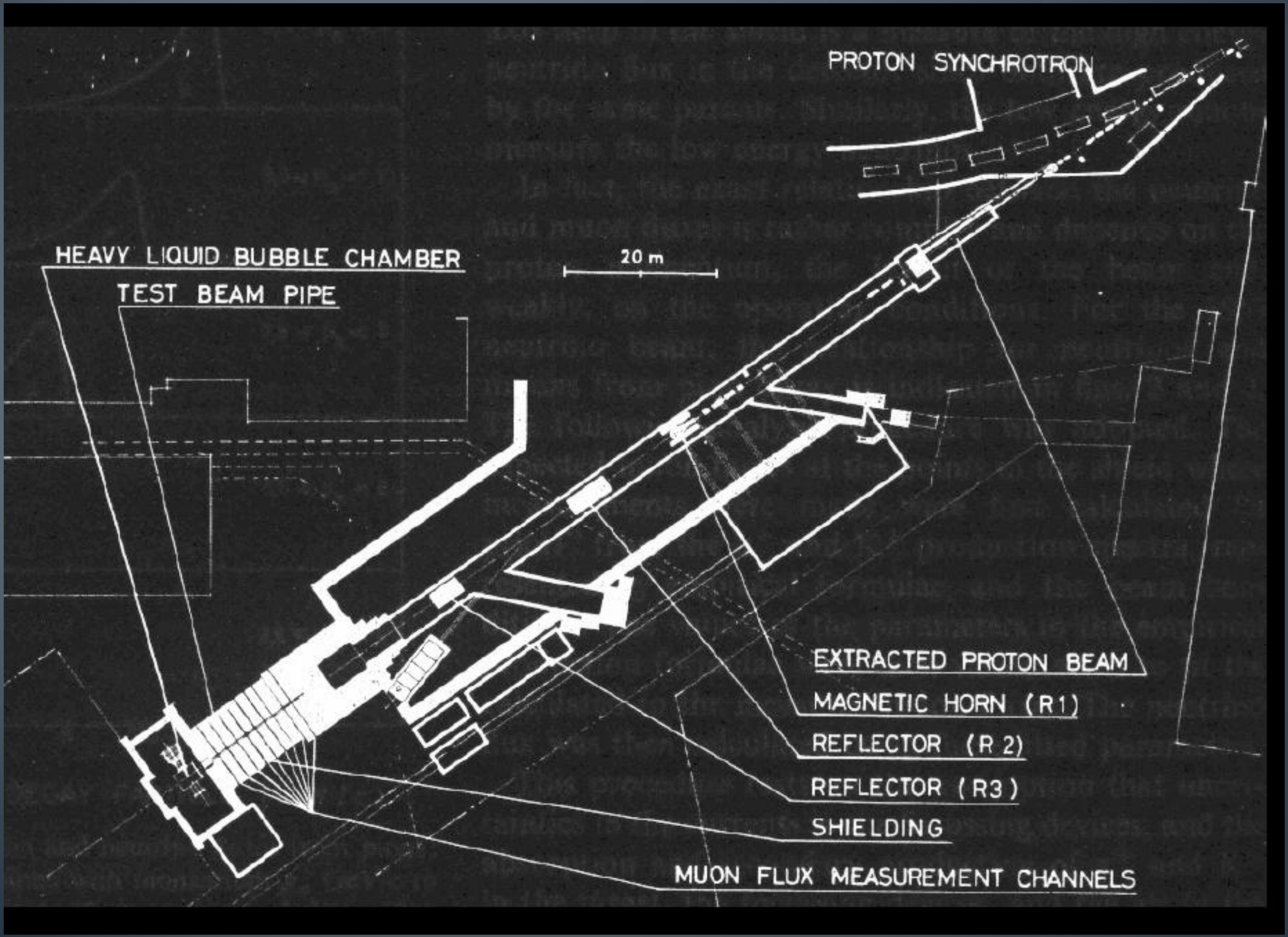
Lessons learned from operating pion beams

- Think VERY carefully about how you cool your target
- Don't assume you have enough shielding around your electronics
- Be sure to add enough instrumentation so you can figure out if/how something broke
- Think VERY carefully about how you cool your horns!
- Beware of the air that leaves your target hall, it's probably hotter than you think
- Need to design in remote handling of all components
- Don't expect the flux in your TDR to be what you see when the beam turns on…



Superbeam Neutrino Flux Predictions

Flux Monitoring at PS Beamline at CERN



- Beamline from Gargamelle Experiment:
- Discovery of Neutral Currents
- Count number of muon monitor planes
- Typical uncertainty ~20%

Slide courtesy Sacha Kopp

How well do we know the flux now?

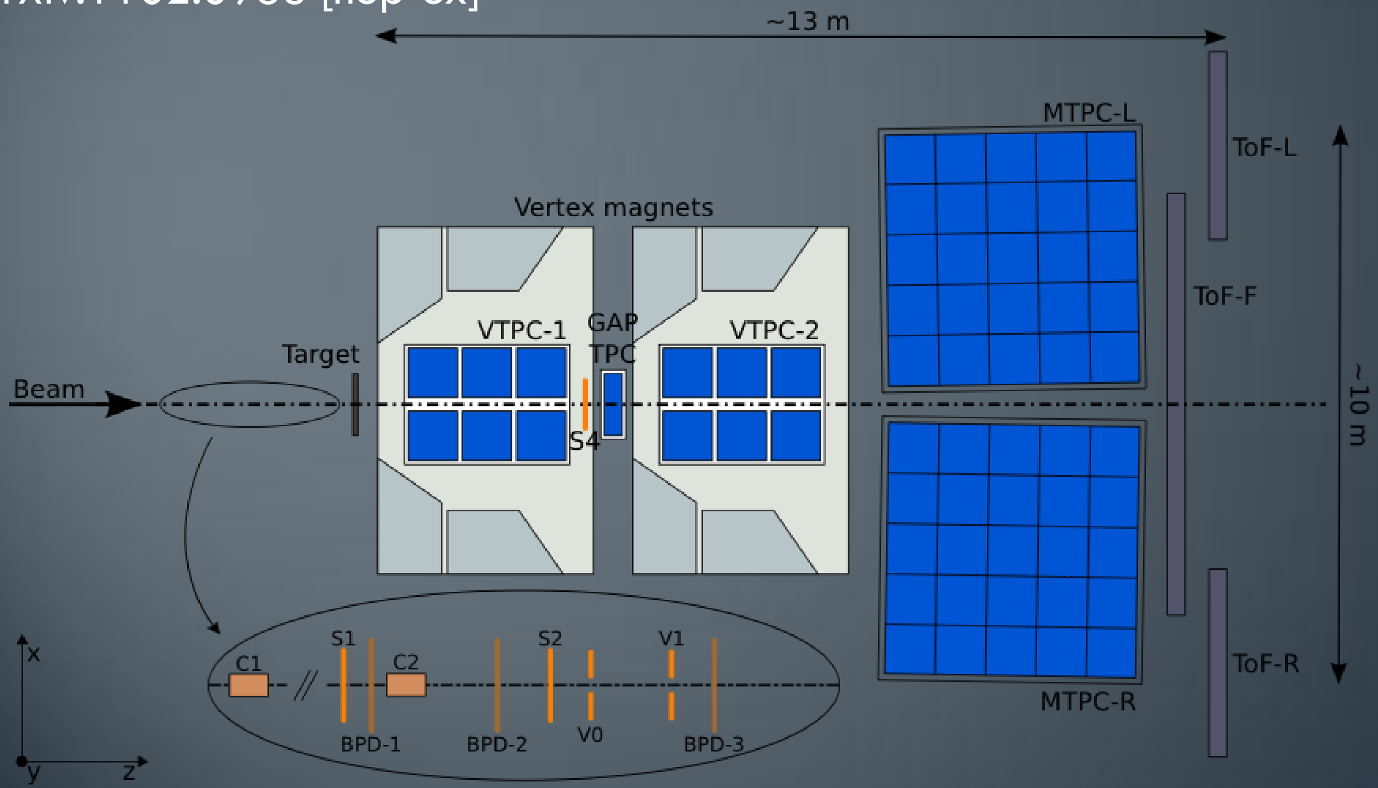
- Recall: AGS ν experiment knew its flux to 30%,
- Ingredients to flux prediction from upstream to downstream:
  - Proton Dynamics (number of protons on target, spot size, beam scraping)
  - Hadron production off target
    - Need measurements on both thin and thick targets, preferably at similar energy
  - Horn current, position, angle measurements
- HADRON PRODUCTION most important of these!
- Need to do dedicated hadron production experiments
  - HARP: 8GeV protons on Be (MiniBooNE)
  - NA49: 158GeV protons on thin C (NuMI)
  - MIPP: 120GeV protons on thick C target (NuMI)
  - NA61/SHINE: 31GeV protons on thick and thin C (T2K)

NA61/SHINE

Designed to do Heavy Ion Measurements

Has also done thin and thick target measurements for T2K

N.Abgrall et al., Phys.Rev.C 84, 034604 (2011)
arXiv:1102.0983 [hep-ex]



TPCs as main tracking devices

2 dipole magnets with max bending power of 9 Tm

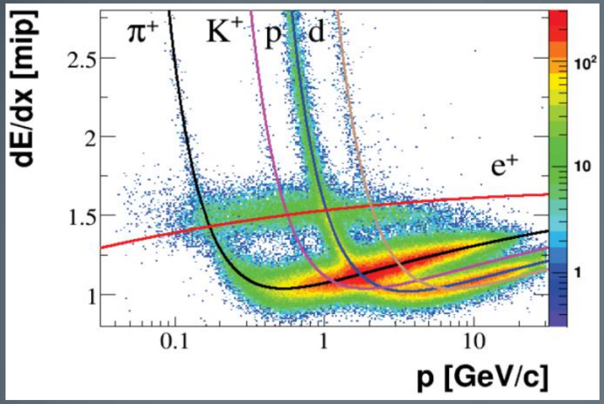
New ToF-F array to fully cover T2K acceptance

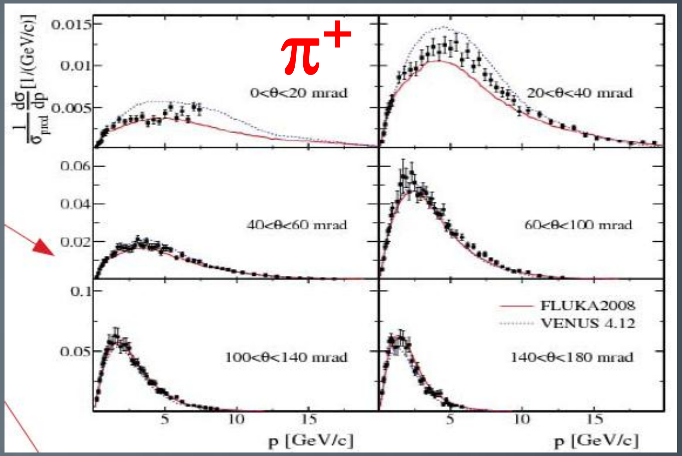
High momentum resolution

Good particle identification

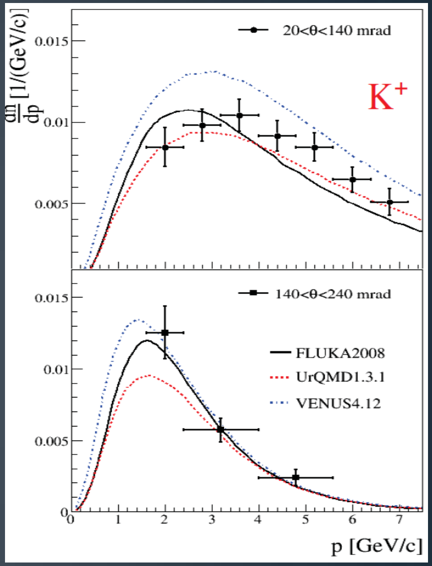
Graphics courtesy B. Popov

SHINE performance, results, impact





PRC 84 (2011) 034604



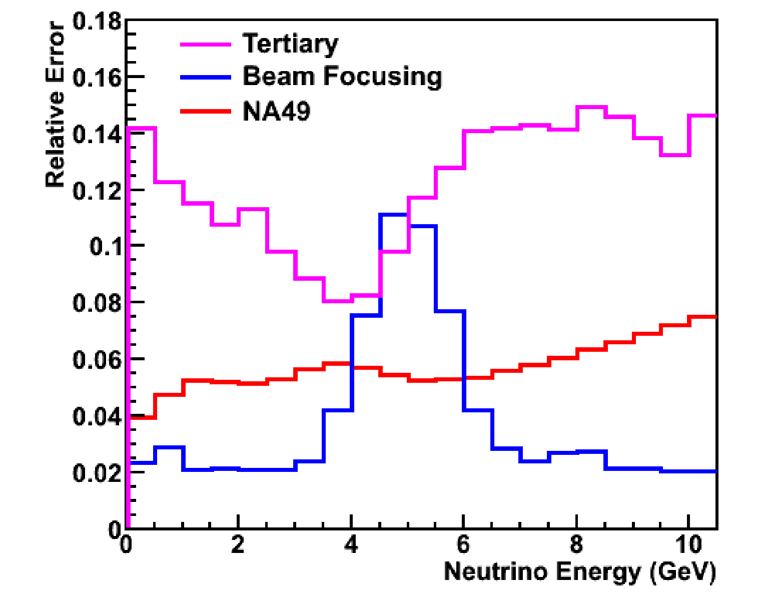
PRC 85 (2012) 035210

Ongoing work to incorporate hadron production experiments in flux predictions:
Example: NuMI at 120GeV, needs hadron production for protons *up to* 120GeV
See L. Aliaga at NuFact, Wednesday

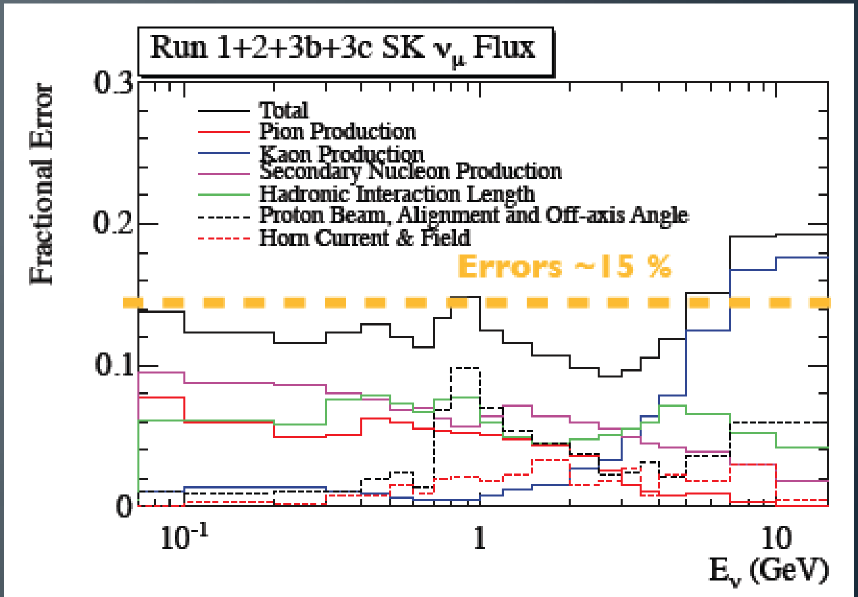
Graphics courtesy B. Popov

Current State of the Art Flux Predictions

- See talks at NuFact for the complete story:
  - Wednesday, 2PM: talks by Aliaga, Murphy
- But in 50 years we've gone from 30% uncertainties to ~15% uncertainties, while improving protons on target by 6000



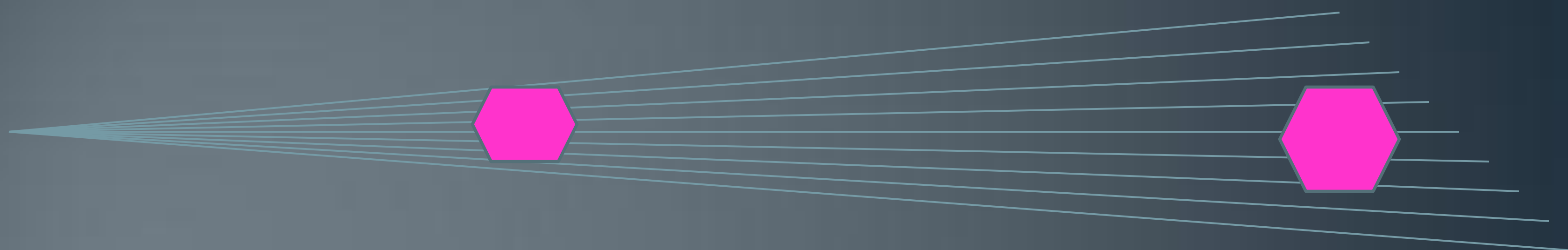
MINERvA, M. Kordosky, FNAL W&C June 2012



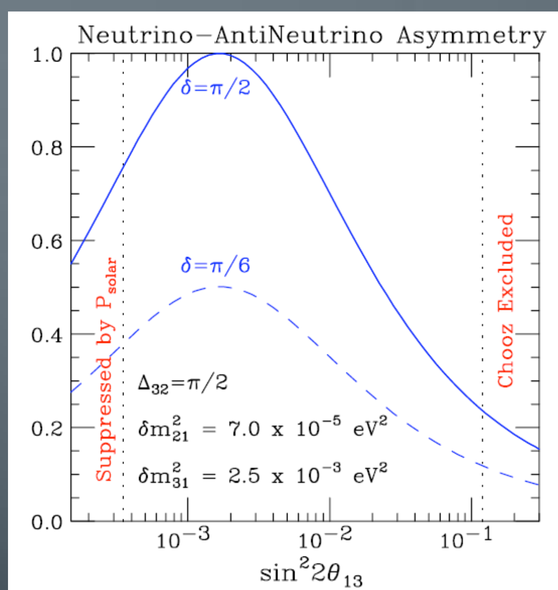
T2K, T. Nakaya, Neutrino 2012

How can we measure oscillation probabilities if we only know our fluxes to 15-20%?

- Two detector experiments, flux uncertainties partially cancel



$$\frac{P(\nu) - P(\bar{\nu})}{P(\nu) + P(\bar{\nu})}$$

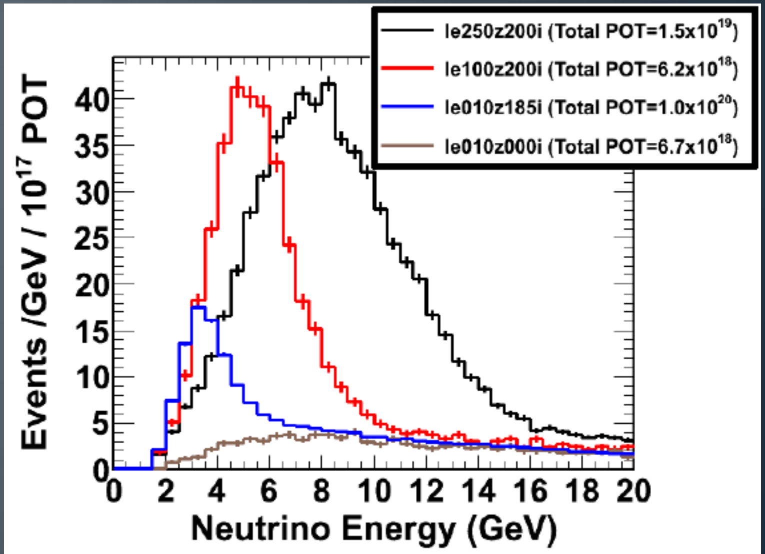


S. Parke, INSS 2009

Beware, CP violation searches for large θ_{13} require much better knowledge of both flux and cross sections!

Next Steps for better understanding of fluxes

- New collaboration between FNAL-based ν experiments and SHINE, goal to take data with NuMI target (with proton energies relevant for NuMI and LBNE)
- Understanding NuMI better:
  - Constraints from special in situ runs in modified beam optics
  - Constraints from muon monitor data with scans of horn current
  - Trying to get the most out of "low nu" events to constrain flux *(see plenary talk by A. Bodek, 7/25)*



MINERvA, M. Kordosky, FNAL W&C 6/2012

Next Steps for SuperBeams

Next Steps, Fermilab

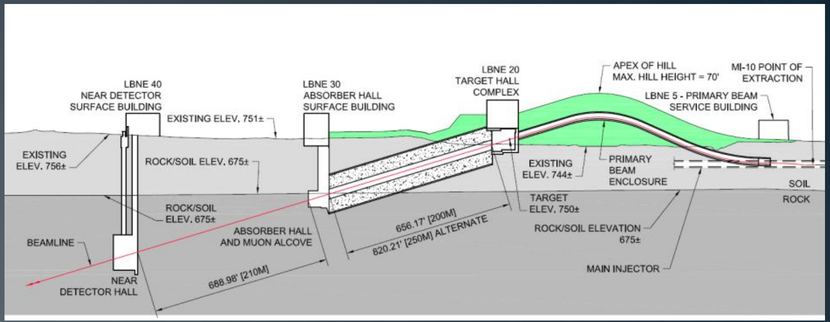
- NuMI currently undergoing upgrade to enable 700kW instead of 350kW
- Proton Improvement Plan at FNAL to allow simultaneous NOvA and MicroBooNE running
- FNAL is designing new beamline for LBNE experiment
  - Peak neutrino energy comparable to NuMI Low Energy Beam
  - New beamline optimized for:
    - Less ν_e contamination
    - Longer Baseline (steeper decay region)
- In Longer term, FNAL is developing plan for 2MW proton source: Project X

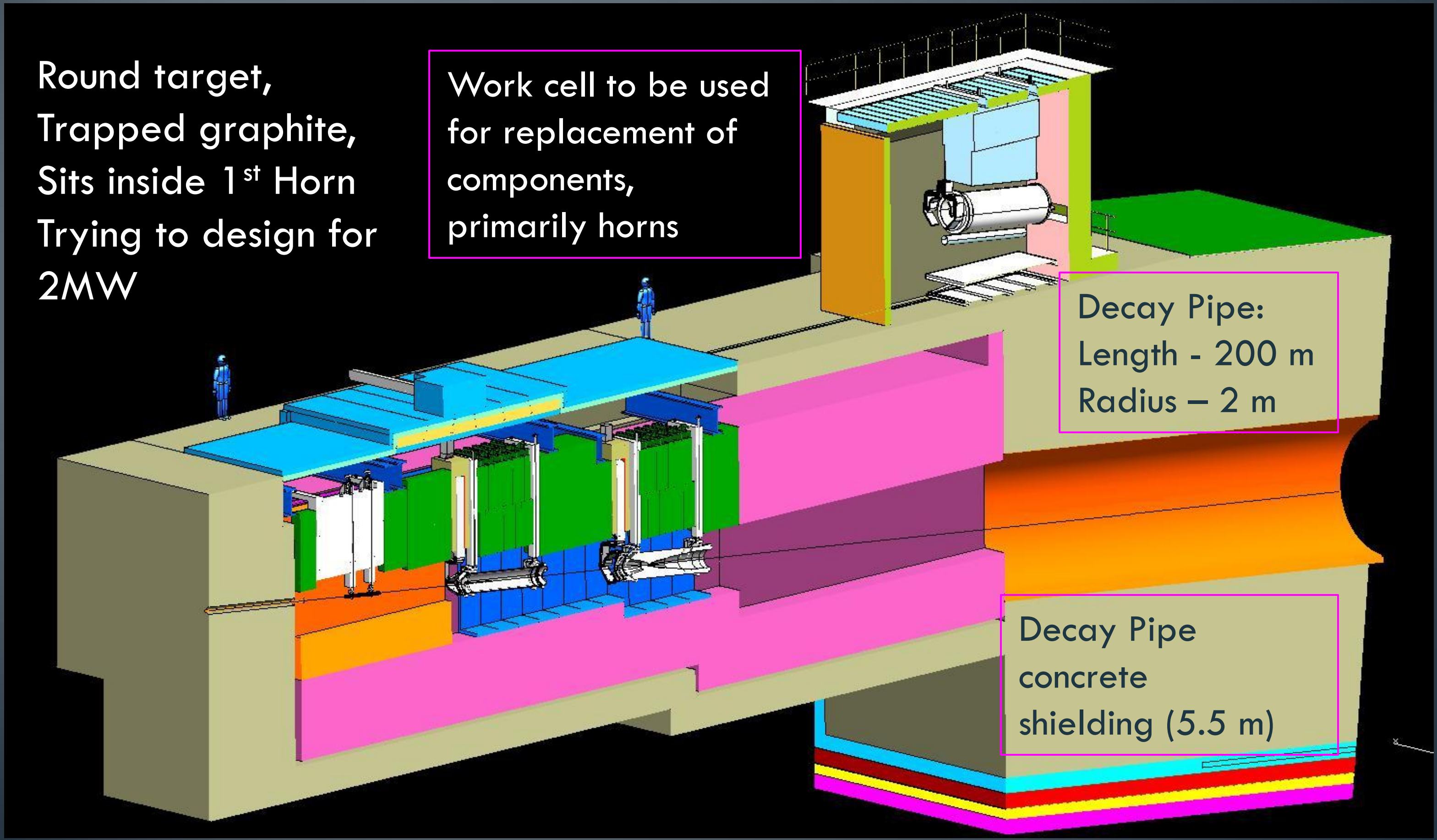
Next Steps, CERN and JPARC

- JPARC neutrino facility is working on improvements to get from 200kW to 700kW: improve losses, air handling *(Ishida, 7/24)*
- Longer term plans: JPARC at 2MW
  - Current secondary beamline is already designed to accept 2MW
- High power proton source at CERN
  - Considering neutrino beam to Pyhasalmi
  - Considering also short baseline experiment to address sterile neutrino oscillations (detectors at 300m, 1100m, 1600m, all on CERN site)

- For next steps at all three of these labs, need to understand high power targets before getting to 2MW

LBNE Beamline Design





Round target,
Trapped graphite,
Sits inside 1st Horn
Trying to design for
2MW

Work cell to be used for replacement of components, primarily horns

Decay Pipe:
Length - 200 m
Radius – 2 m

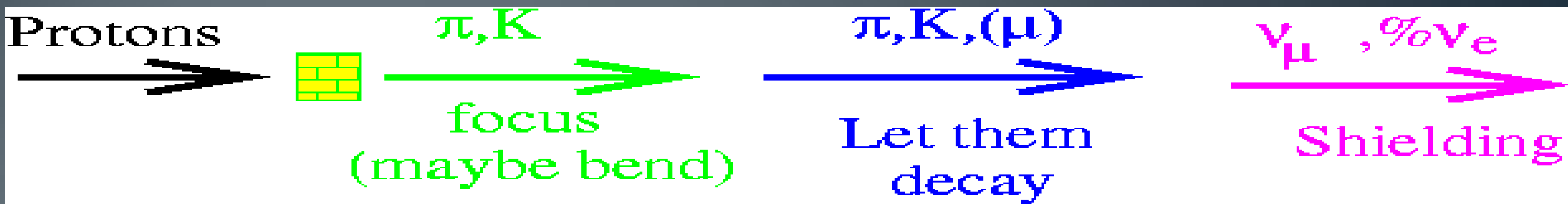
Decay Pipe concrete shielding (5.5 m)

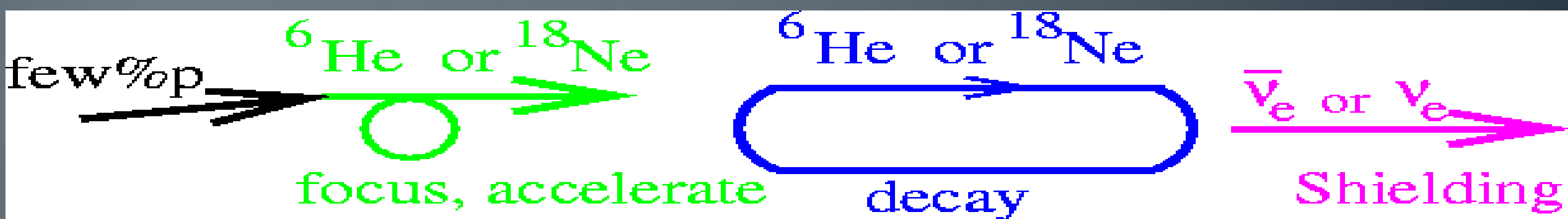
See also J. Strait, 7/26 plenary talk

V. Papadimitriou, LBNE Reconfiguration workshop
April 2012

Moving beyond pion decays…

Different ways to make neutrino beam





For each of these beams,
ν flux (Φ) is related to boost of parent particle (γ)

$$\Phi_\upsilon \propto \gamma^2$$
$$\sigma \propto \gamma$$

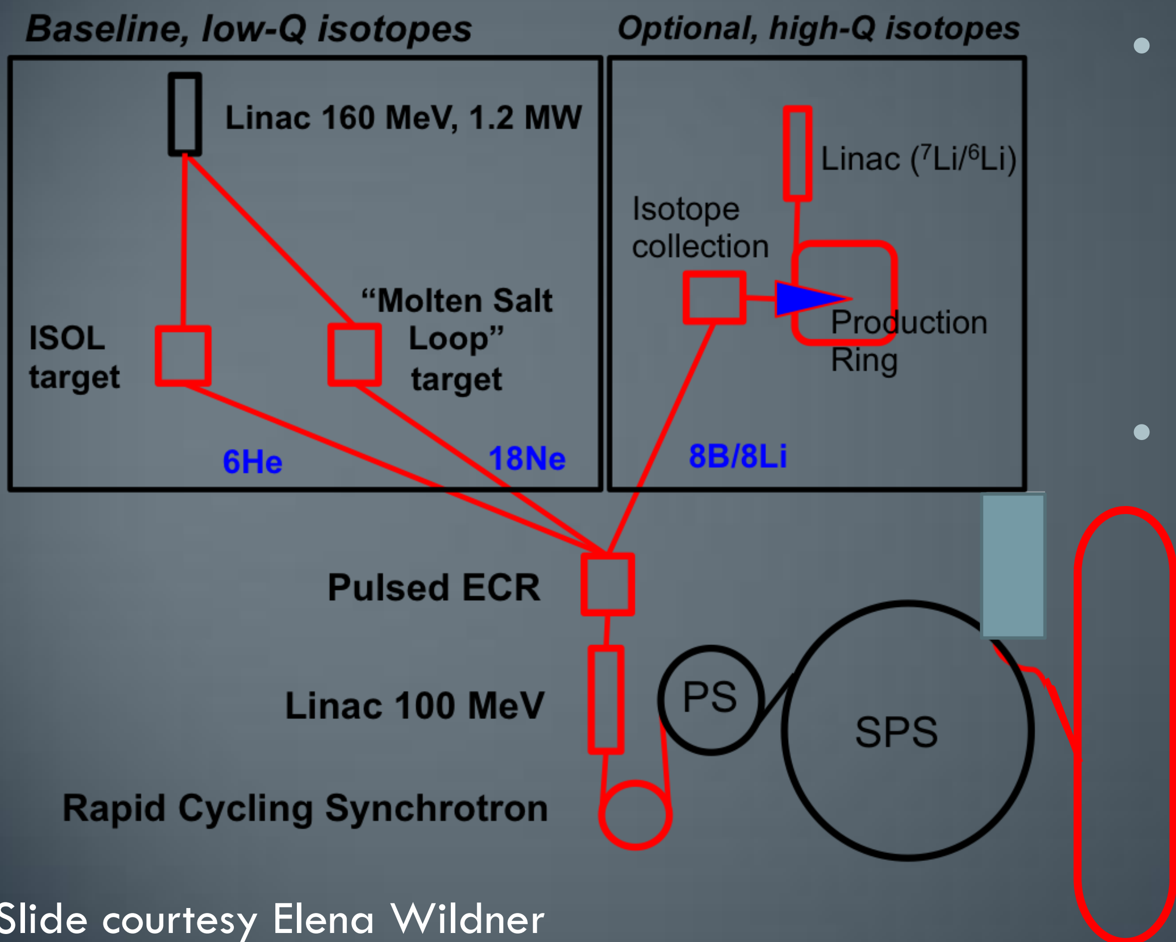
Beta-beam Basics

- Tale of two isotopes: one makes neutrinos, the other makes anti-neutrinos
- The good news:
  - This is the purest beam you could possibly ask for
  - If you can measure the current of the ions in the ring you know your absolute neutrino flux, spectra is also perfectly known
- The bad news:
  - It's hard to get enough ions in the ring to make the experiment worthwhile
  - The neutrino energies are low because Q of the decay is low

$$ {}^{6}_{2}\mathrm{He}^{++} \rightarrow {}^{6}_{3}\mathrm{Li}^{+++}\mathrm{e}^{-}\bar{\nu}_{\mathrm{e}} $$

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

CERN Concept for Beta Beam, 2012



- Ingredients
  - Proton Driver
  - ISOL or molten salt target
  - Ion Source
- Options
  - Low-Q version (^{6}He, ^{18}Ne)
  - High-Q decays: ^{8}Li, ^{8}B)

Slide courtesy Elena Wildner

Decay Ring: Bρ ~ 500 Tm, B = ~7 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

Recent Beta-beam Progress

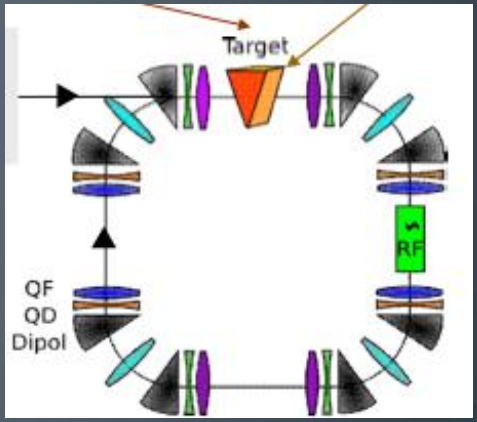
- Molten salt loop experiment to produce ^{18}Ne at CERN ISOLDE
  - experiments at CERN & LPSC (Grenoble)
  - Experiments with static target give expected results
  - ^{18}Ne production rate estimated to 1×10^{13} ions/s (dc) for 960 kW on target

Aachen Univ., GSI, CERN

- Production Target
  - Production of ^{8}B and ^{8}Li, C. Rubbia, EUROnu proposal
  - Start with supersonic gas jet target, stripper and absorber

$^{7}Li(d,p)^{8}Li$
$^{6}Li(^{3}He,n)^{8}B$

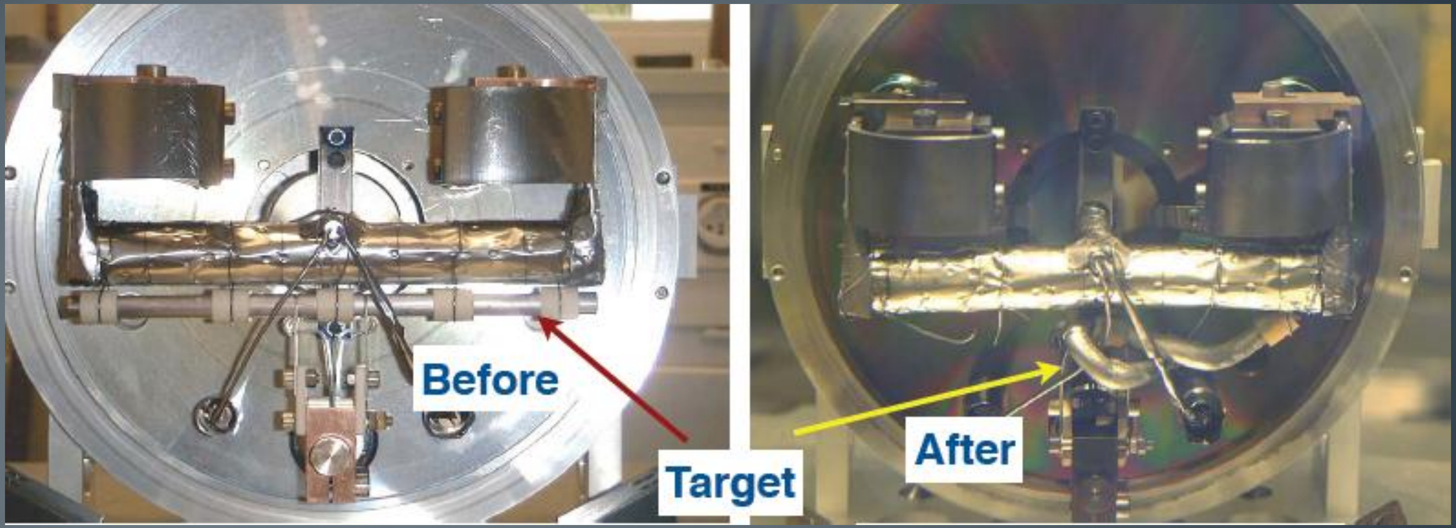
^{7}Li
^{6}Li



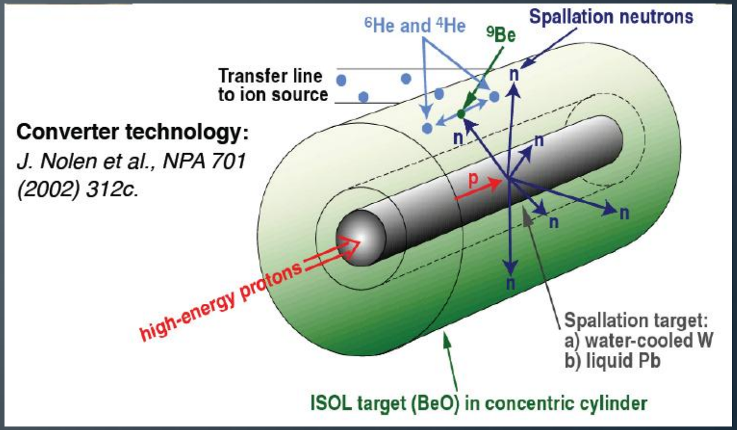
- Cross section measurement done (INFN, Legnaro)
- Collection device constructed (UCL, Louvain la Neuve)
  - ^{8}Li is collected , ^{8}B (highly reactive): need bound state to be extracted from target

Slide courtesy Elena Wildner

Beta-beam: not just powerpoint



2×10^{18} integrated intensity
In shots of 3×10^{13} at 1.4GeV
1 pulse 2.2μs long



Slide courtesy S. Gilardoni

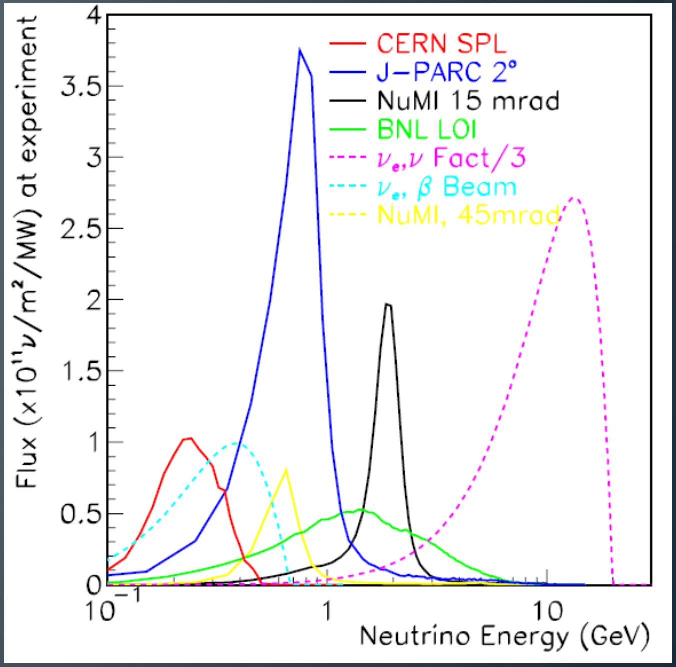
Neutrino Factory Basics:

- One "parent" neutrino beam, two flavors available

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

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

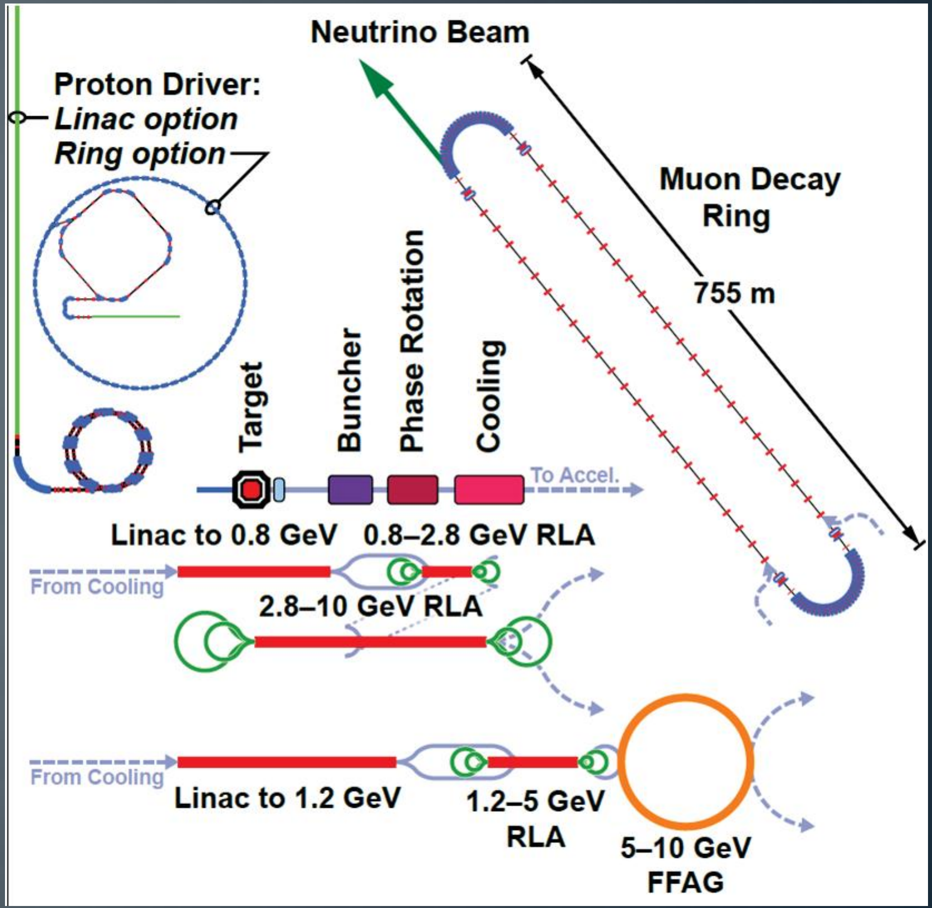
- Good news:
  - Final state lepton charge identification tells you flavor of interacting neutrino
  - Very high fluxes if you are willing to go to high muon energies
  - Extremely good knowledge of ν_e and ν_μ flux from current in μ storage ring
- Bad news:
  - Need magnetized detector



Old plot, conclusions still valid!

Neutrino Factory Concept

- Ingredients:
  - Proton Driver (see Superbeams)
  - Target, Capture and Decay (MERIT)
    - Need to create pions, keep the muons they become
  - Bunching and Phase Rotation
    - Start with wide energy range at one time, change to narrow energy range but long bunch length
  - Cooling
    - Need to reduce transverse emittance (MICE)
  - Decay Ring
    - Store for ~1000 turns, decays in long straight sections make the ν beam



See K.Long, 6/27 plenary talk

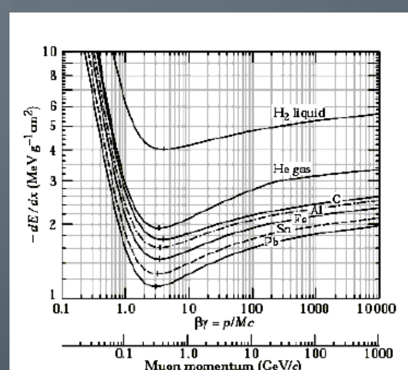
Ionization Cooling

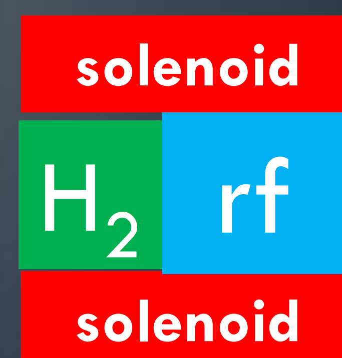
- How can you cool a beam that is decaying at 2.2μsec?

Use Solid LiH or Liquid H_2 for steps 1+2

RF restores only parallel momentum, energy is constant

"Simple" application of Bethe-Bloch

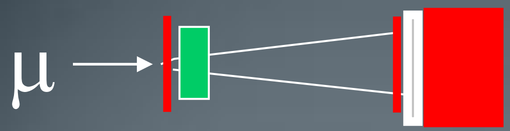




S. Gilardoni, INSS 2012

MICE: test of Ionization Cooling

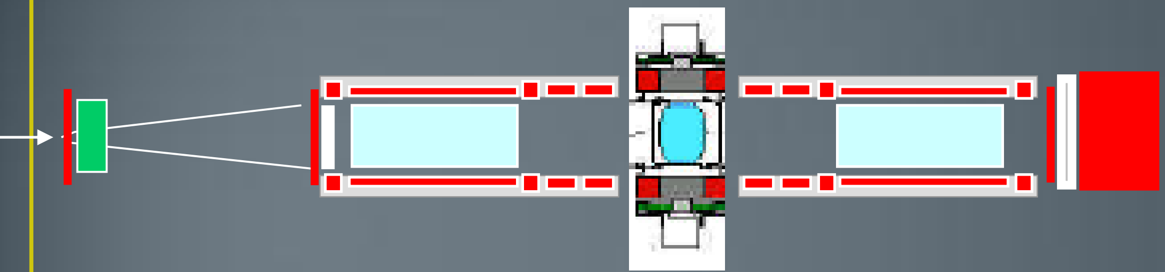
Run date:



STEP I

COMPLETED

EMR run Feb 2013

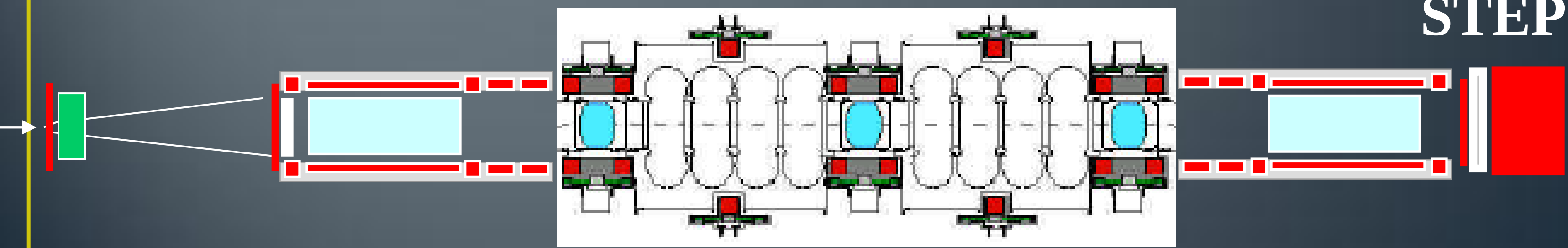


STEP IV

Q2 2013
till
Q2 2014

Under construction:

STEP VI

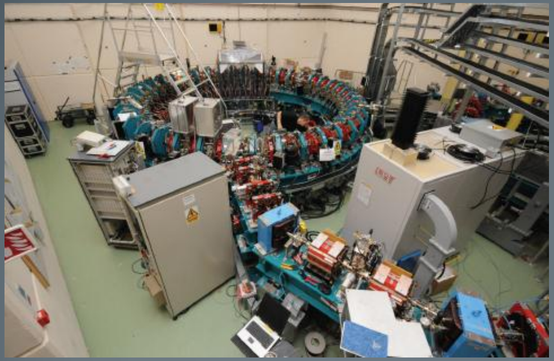


Slide courtesy Alain Blondel

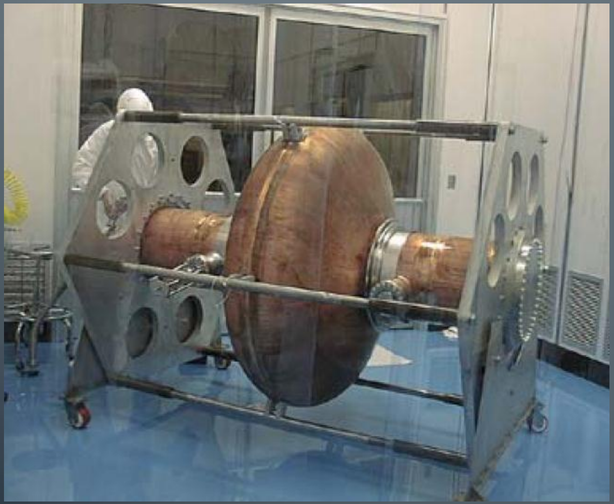
NB: target date 2016

Neutrino Factory: not just powerpoint

EMMA at Rutherford:
Fixed Field Alternating Gradient

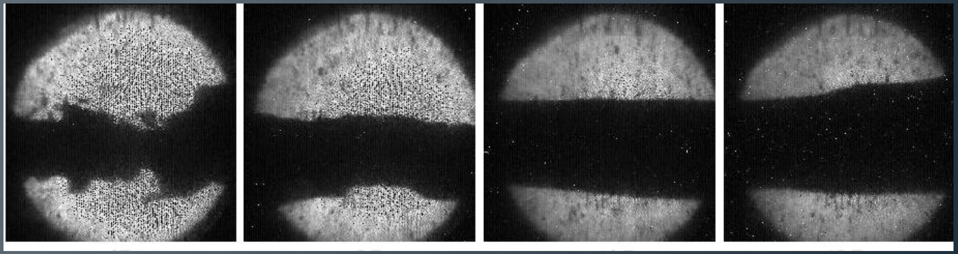


Superconducting RF cavity at CERN



S. Gilardoni, INSS 2012

MERIT Experiment at CERN:
mercury jet in 4MW proton beam



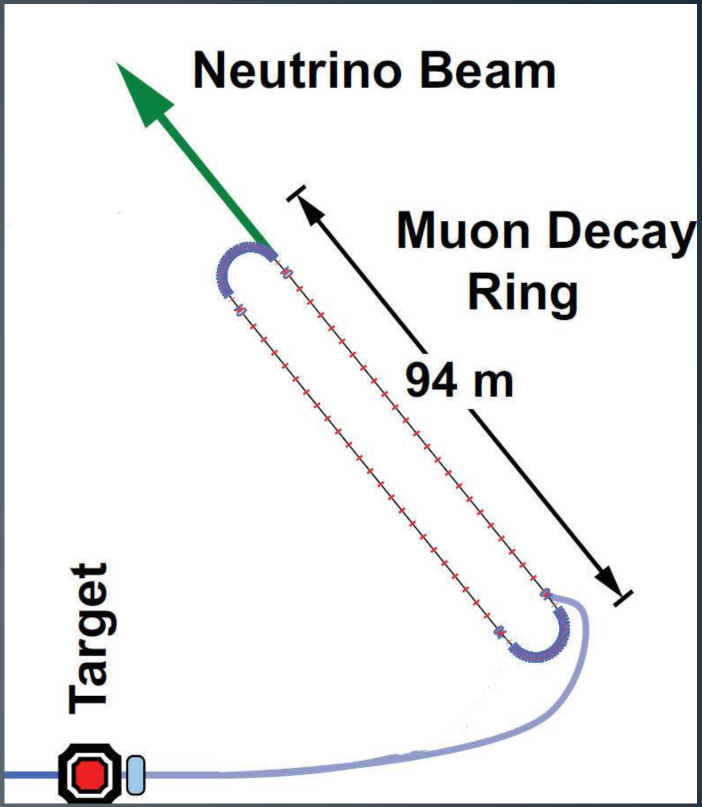
0T 5T 10T 15T

What is the first step in putting all this together for an experiment?

νSTORM

- Short baseline oscillation physics
- ν cross section measurements
- 100 kW Target Station
  - Assume 60 GeV proton
  - Ta target
    - Optimization on-going
  - Horn collection after target
    - Li lens has also been explored
- Collection/transport channel
  - Two options
    - Stochastic injection of π
    - Kicker with $\pi \rightarrow \mu$ decay channel
    - At present **NOT** considering simultaneous collection of both signs
- Decay ring
  - Large aperture FODO
  - Racetrack FFAG

Alan Bross, FNAL PAC 6/2012, and NuFact 7/26



Decay ring: 3.8 GeV/c ± 10% momentum acceptance, circumference = 350 m

Detector similar to MINOS: 1-2cm Fe plates, magnetized, plus extruded scintillator plus SiPM's

Conclusions

- 50 years of accelerator-based neutrino beams have taught us a lot about particle physics
  - Neutral Currents and the Weak Mixing Angle
  - Structure Functions
  - Precision measurements of Neutrino Oscillations
- We've also learned a lot about dealing with high power proton sources
- We have more to learn about understanding our neutrino fluxes to get to cross sections and the next steps in oscillations
- Promising ideas for new beam techniques to get to ultimate precision we need