# Neutrino Beams

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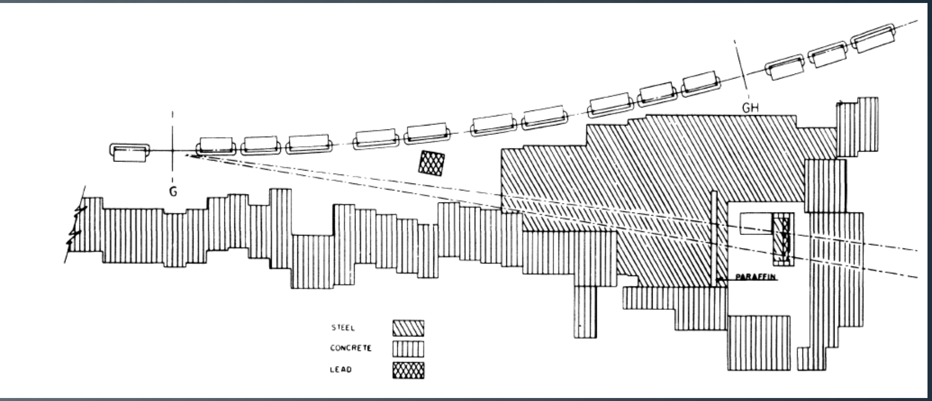
Nufact 2012
JLAB/William and Mary

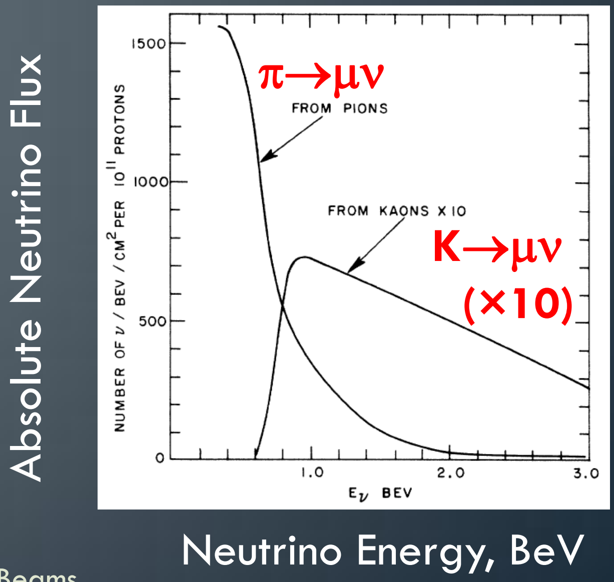
# Outline

- 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

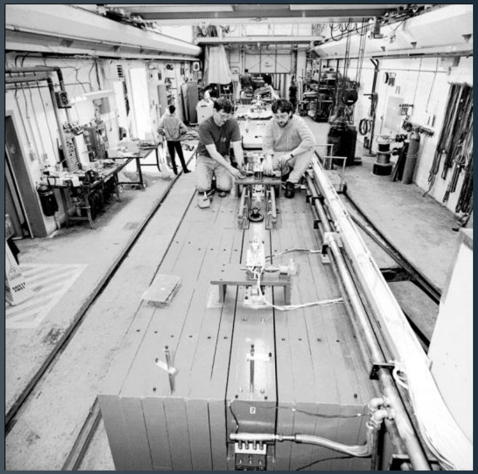
- Phys. Rev. Lett. 9, 36–44 (1962), published 50 years ago this month
- 15 "BeV protons striking 3" thick Be target, 21m long "decay region"
- Dominant Reaction: $\pi,K\rightarrow\mu\nu$
- Detector at 44.5m from neutrino target, 23.5m of steel
- Goal was to see if there were any muon-like events, signaling 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%

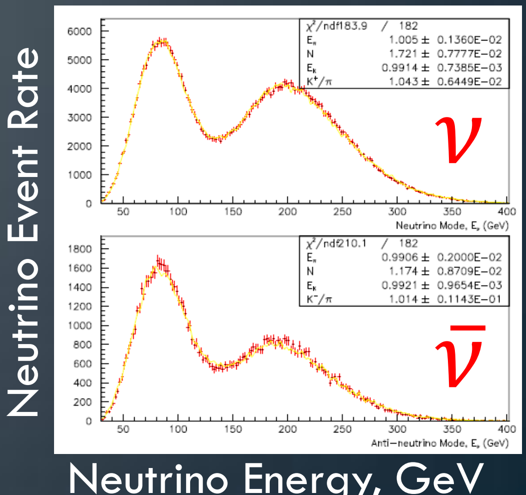


# Changing goals, changing beamlines

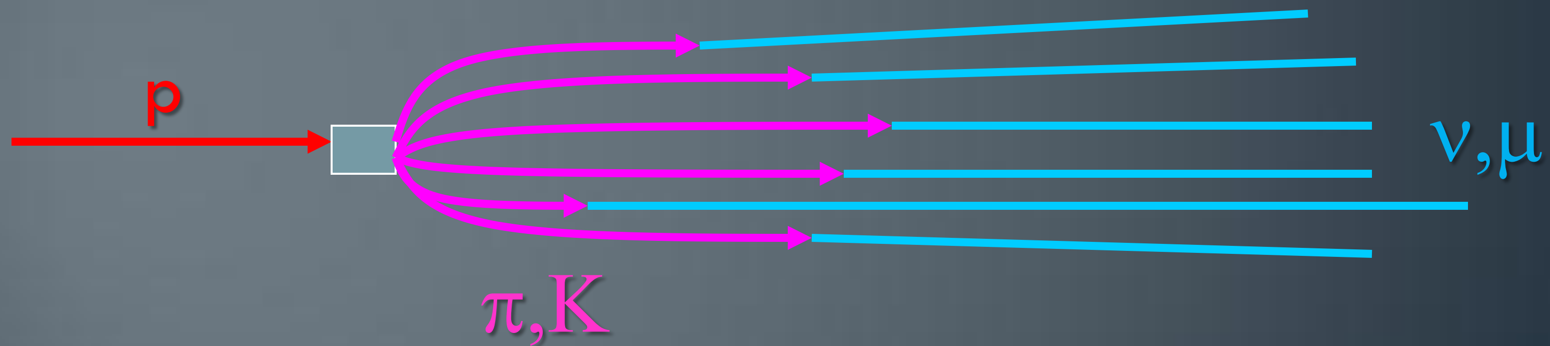
- As goals of neutrino experiments changed, beamlines changed
  - First Neutral Current Measurements
  - Neutrino Scattering to measure Structure Functions
  - Precision Measurements of Weak Mixing Angle (See Sign Selected Quad Triplet Assembly at right)
- Constant need to increase protons on target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





# Anatomy of a "Conventional" Neutrino Beam

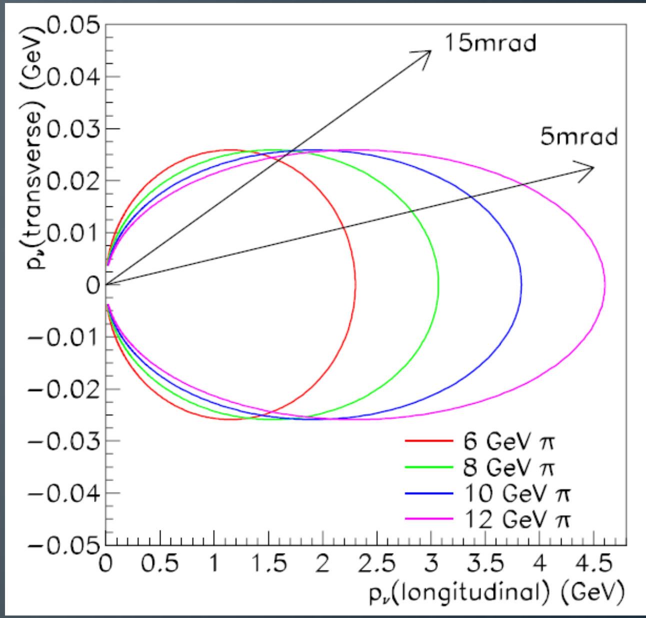
- Protons on a target produce pions and kaons
- Pions and Kaons are focused with magnetic horn towards long decay region




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

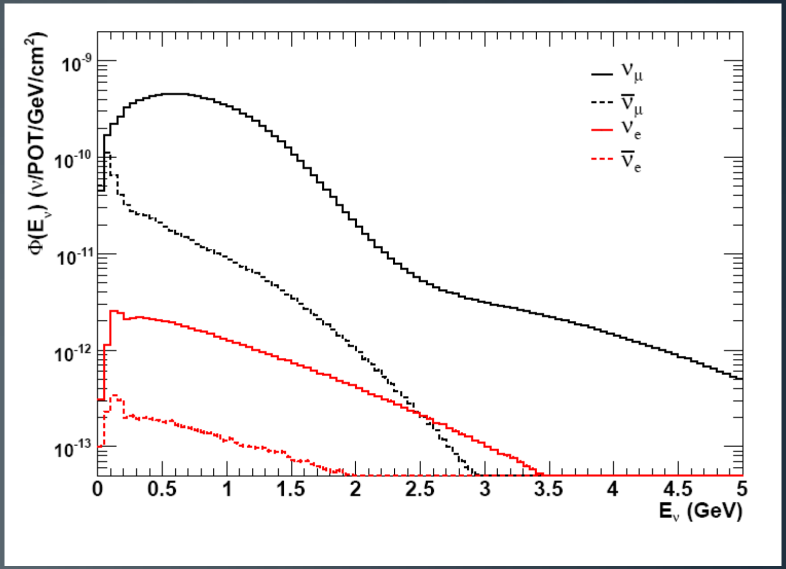
# New Physics Goals, New Beamline Choices

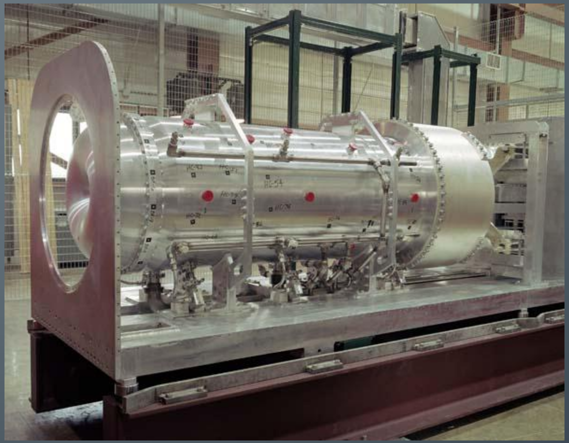
- New Goals:
  - Precision measurement of $\nu_\mu \rightarrow \nu_e$ appearance (neutrinos and antineutrinos)
  - Understanding low energy neutrino interactions in nuclei to get to precision
- Causes some strange design choices
  - Very short decay volumes: don't even let all the pions decay, to minimize 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

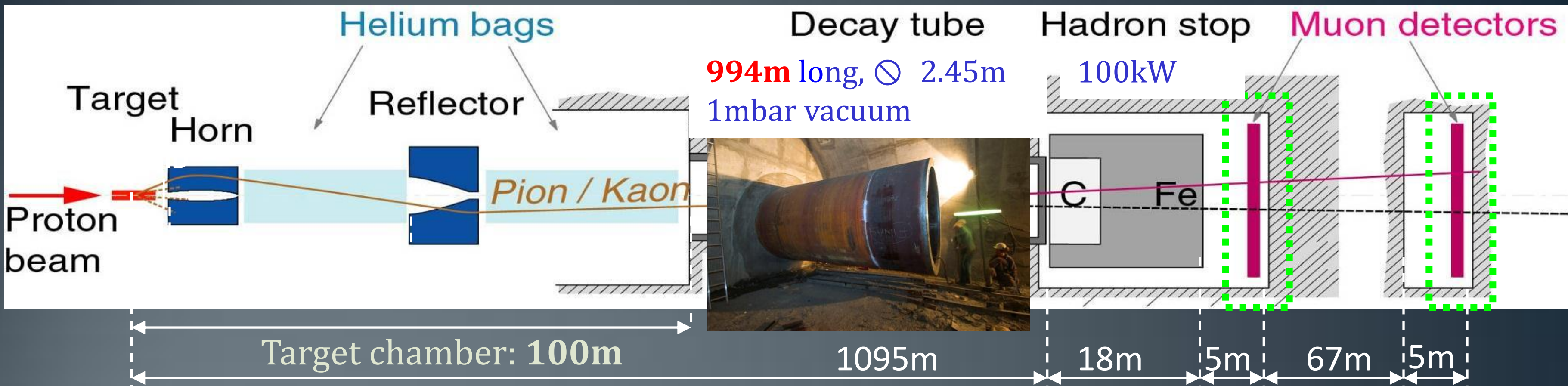
- 8 GeV protons, Beryllium target, one horn, short decay pipe
  - Enclosures for SciBooNE and MiniBooNE detectors
- Produces broad band of $\nu_\mu$ events centered at ~1.4GeV
- Designed for $\nu_\mu \rightarrow \nu_e$ oscillations
- Flux prediction using HARP hadron production data



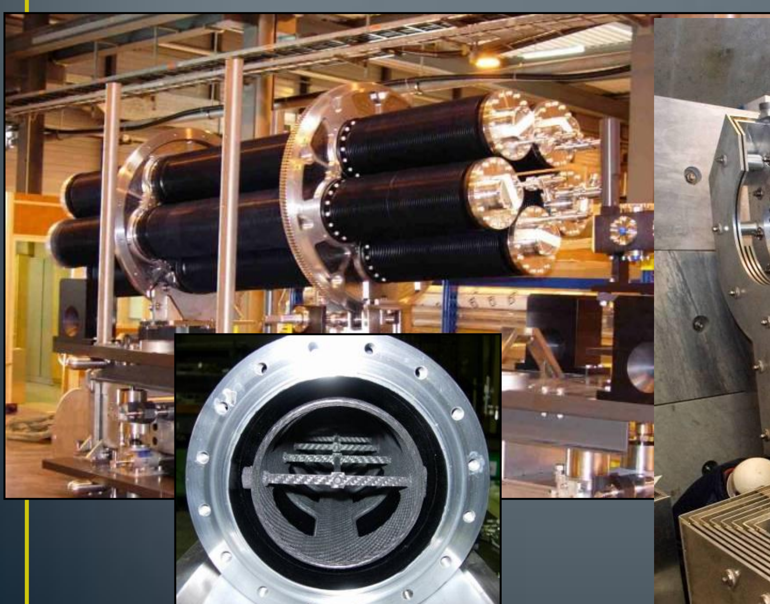
481Million Horn pulses over last 10 years 170kA@15Hz

# CNGS Neutrino Beamline

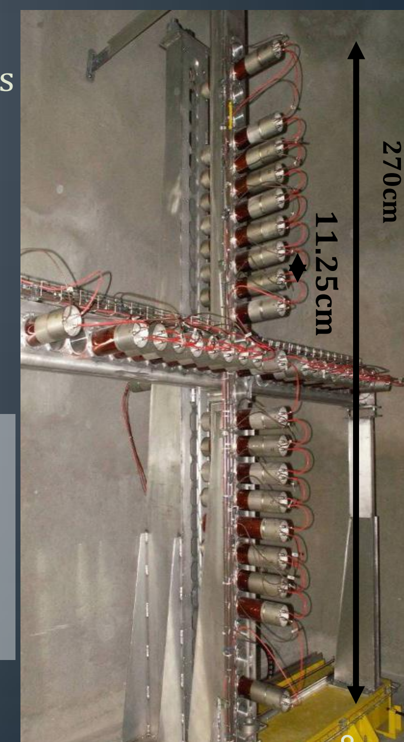



1 Target unit: 13 graphite rods 10cm
1 Magazine: 1 unit used, 4 in situ spares

Muon detectors:
2x41 LHC type BLMs



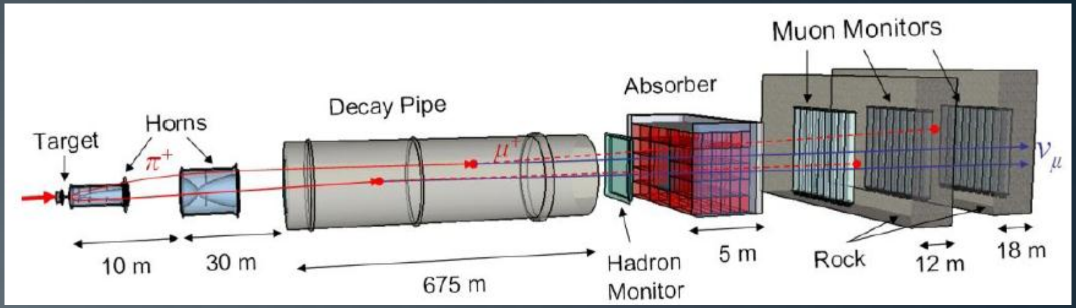
2 HORNS:
7m long, 150/180kA pulsed
Water cooled
Remote polarity change
1.8mm inner conductor



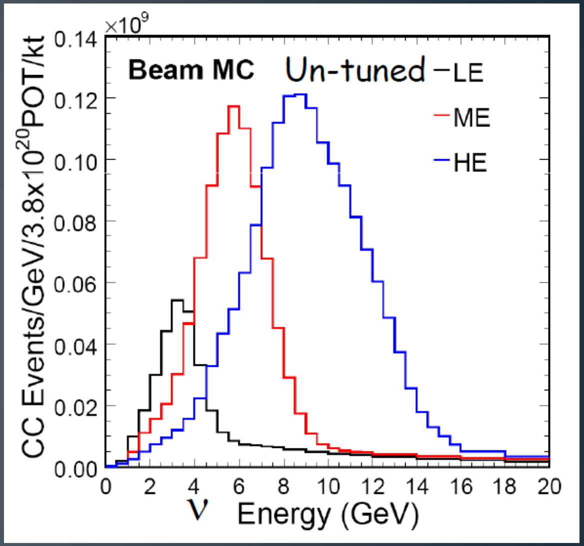



*Figures courtesy E. Gschwendtner*

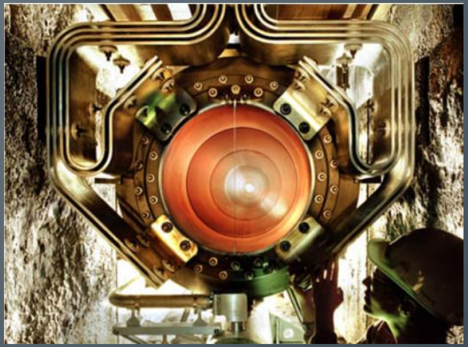
# NuMI Beamline



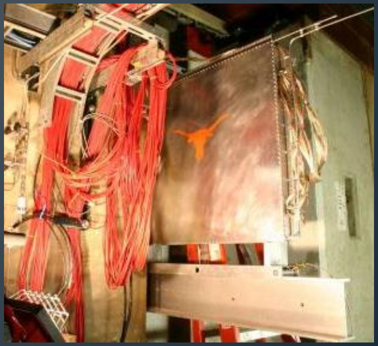

- 120GeV protons, Graphite target,
- Operating since 2005, over $1.4 \times 10^{21}$ POT
- Flexible enough to produce peak energies from 3.5 to 10GeV
- Three planes of μ monitors, one hadron monitor at downstream end of decay pipe




NuMI Target

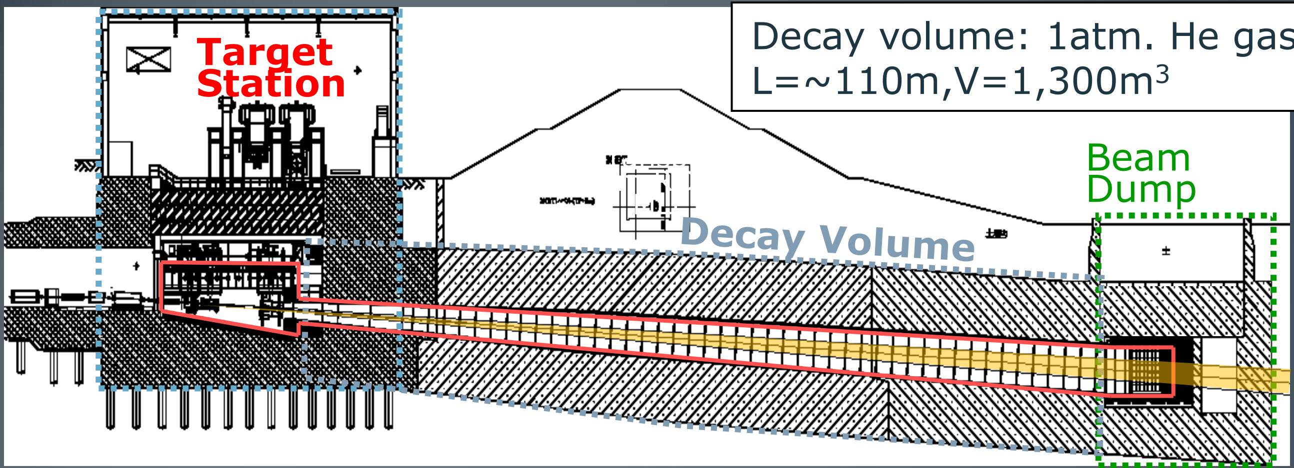


Horn 1

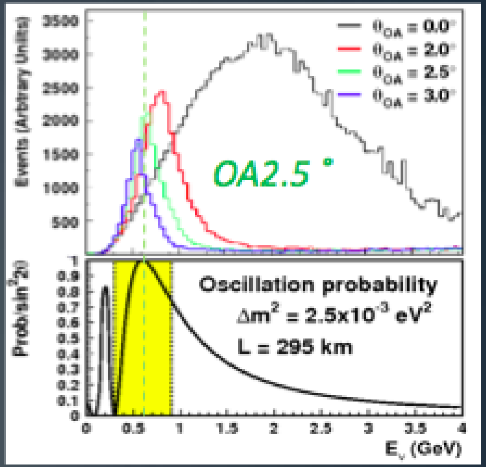


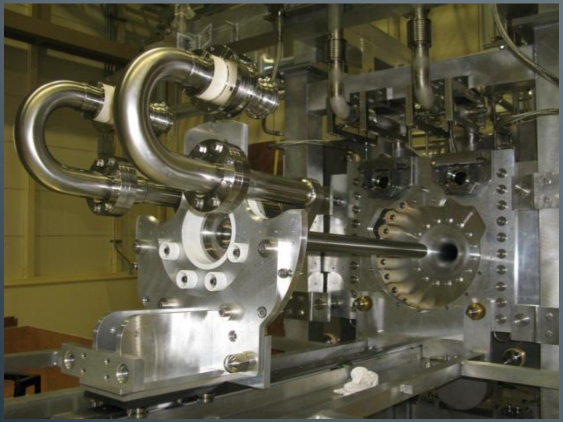
Hadron Monitor

# T2K Beamline




Decay volume: 1atm. He gas
L=~110m,V=1,300m$^3$



Target and horn 1

horn 3

Decay Volume

2 technologies for muon monitoring

*Figures courtesy T. Ishida*

# Survey of Conventional Beams

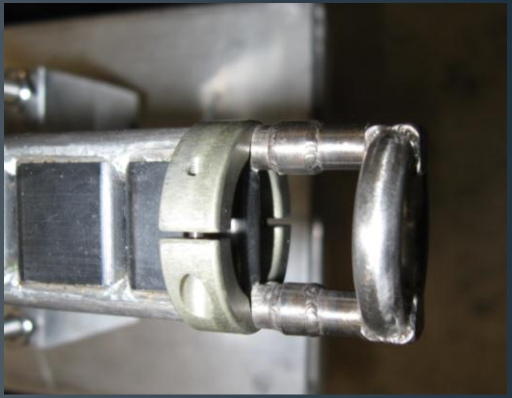
| Name | Length of run (years) | Max proton Power (kW) | $\int$(protons on target) ($\times 10^{18}$ ) | Proton Energy (GeV) | Decay Pipe Length (m) | # horns |
|---|---|---|---|---|---|---|
| *AGS $\nu$ beam* | *<1* | *tiny* | *0.35* | *15* | *21* | *0* |
| *NuTeV* | *1.5* | *tiny* | *3* | *800* | *400* | *0 (Quad Triplet)* |
| Booster $\nu$ 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
- 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

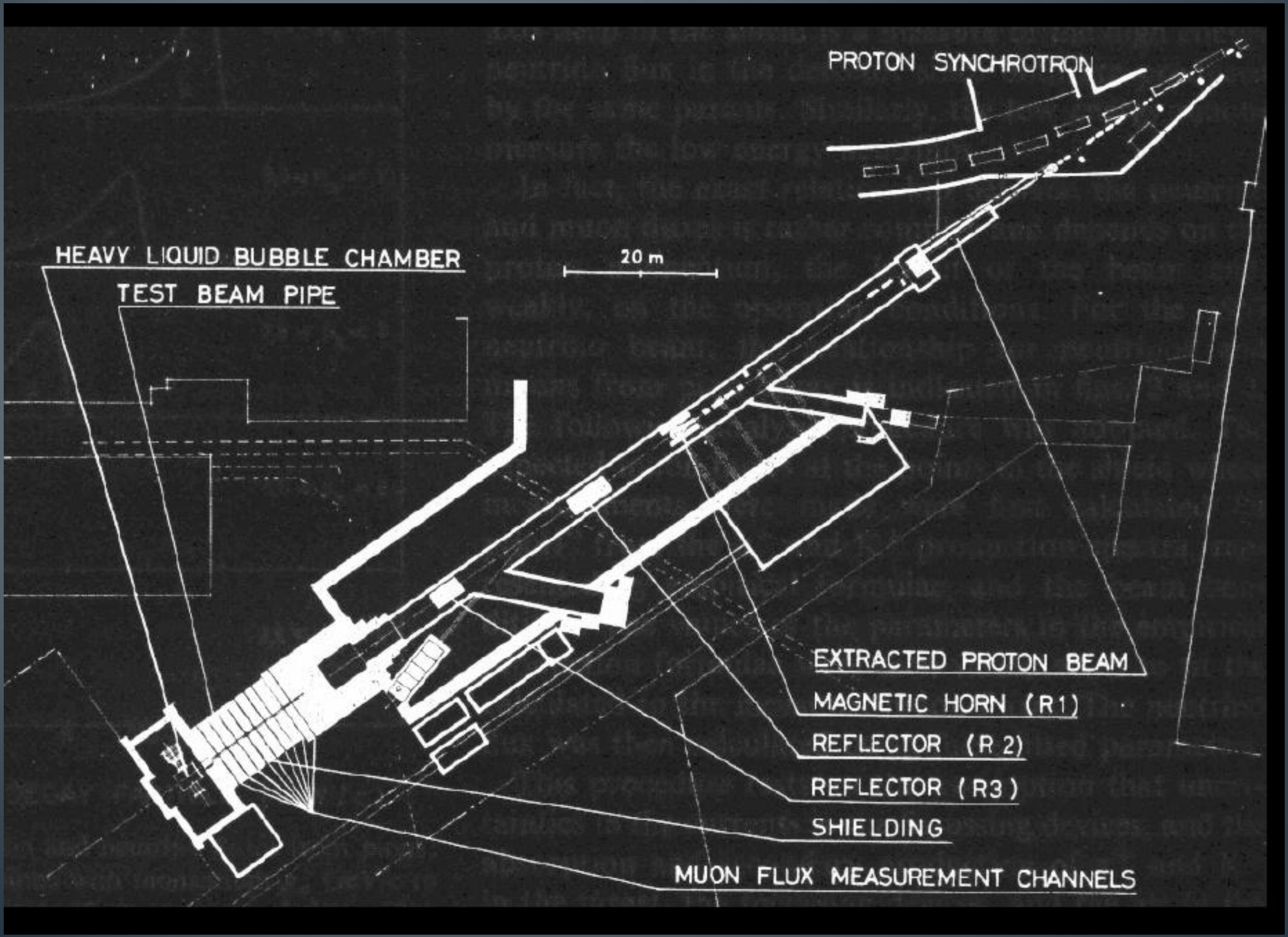
# Lessons learned from operating pion beams

- 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)

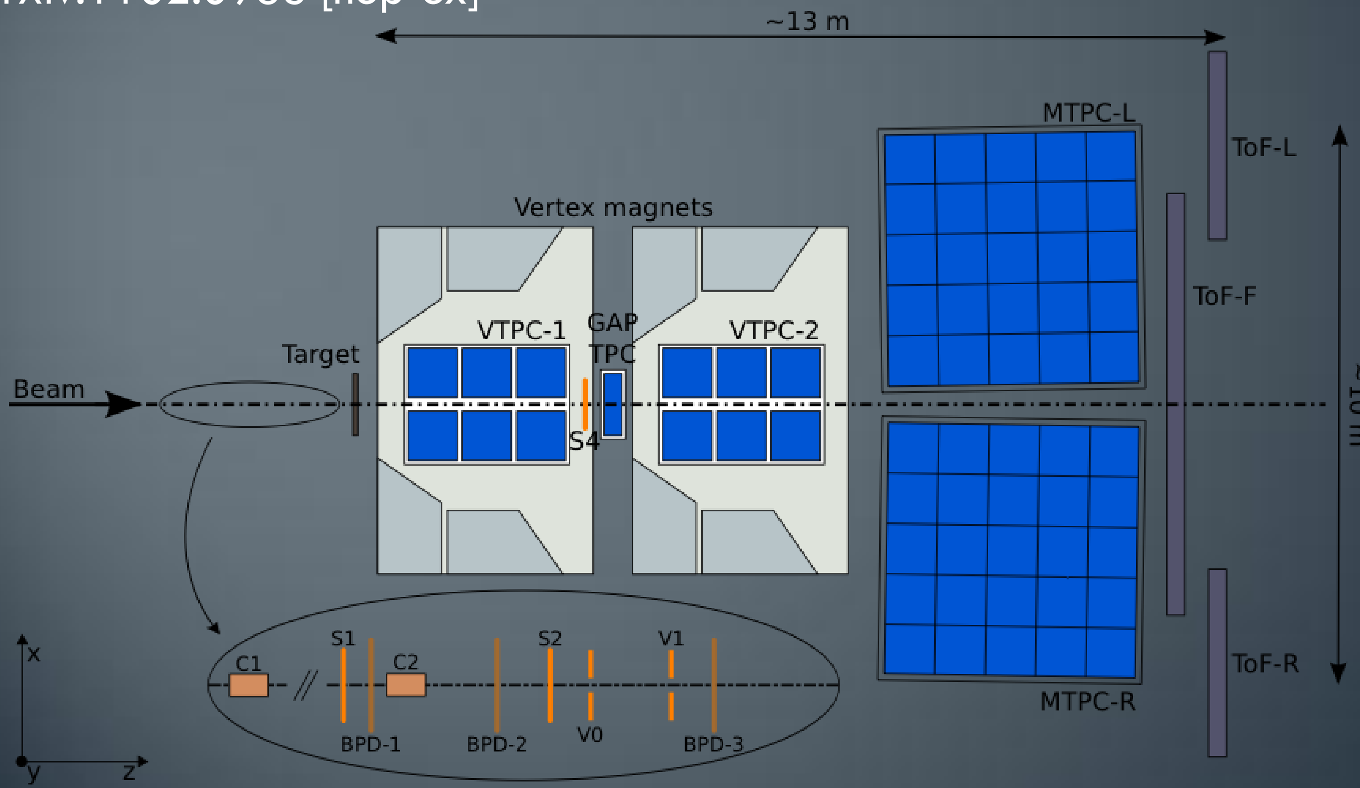
# NA61/SHINE

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

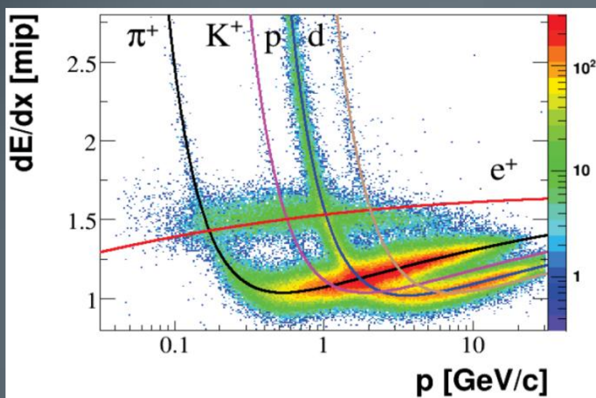
New ToF-F array to fully cover T2K acceptance

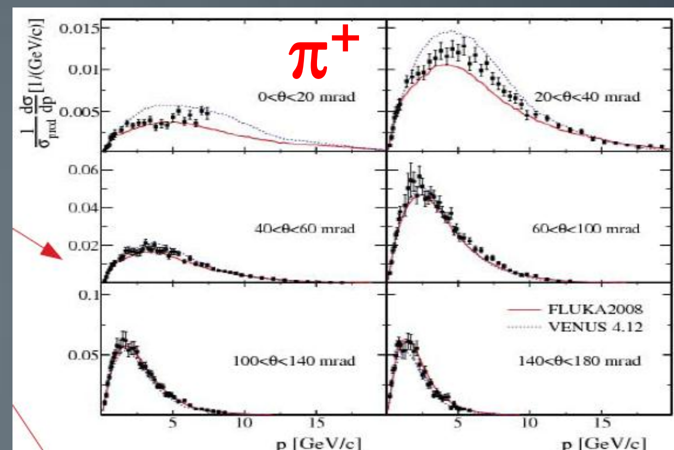
High momentum resolution

Good particle identification

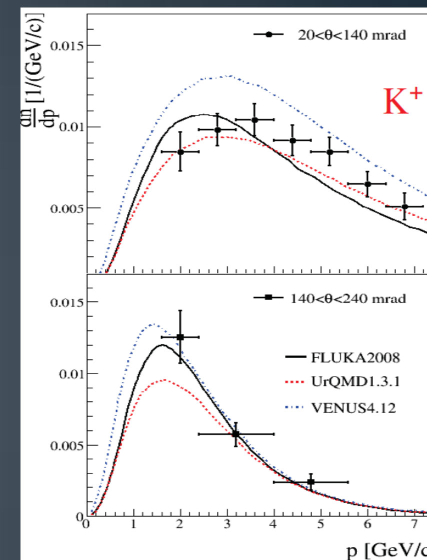
Graphics courtesy B. Popov

# SHINE performance, results, impact




[PRC 84 (2011) 034604]



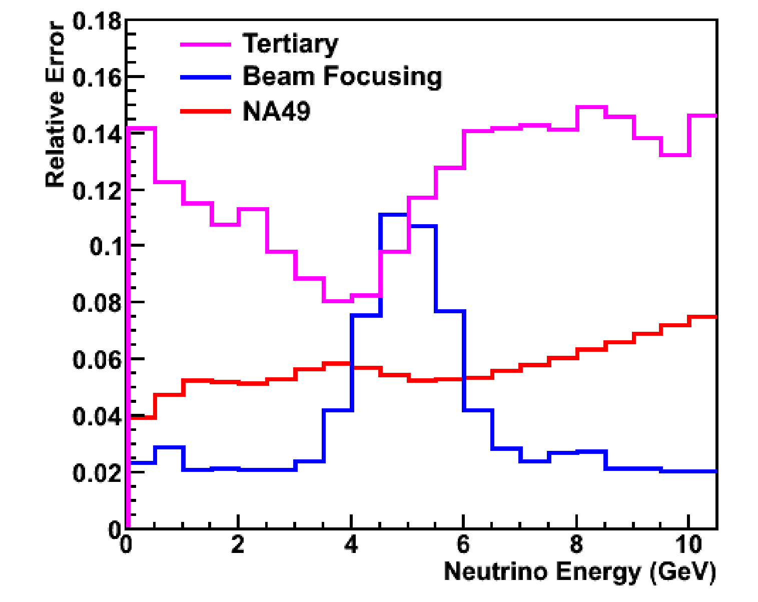

[PRC 85 (2012) 035210]

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

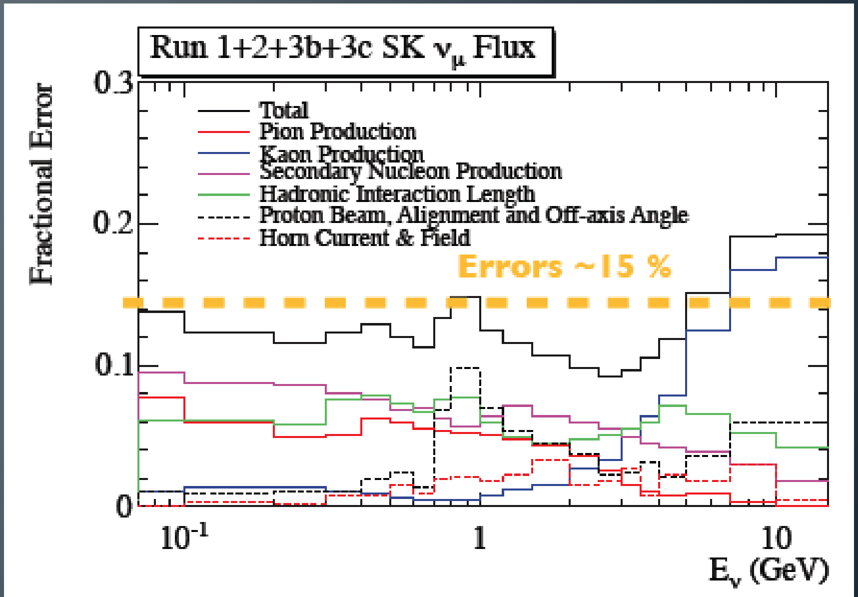
*Graphics courtesy B. Popov*

# 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



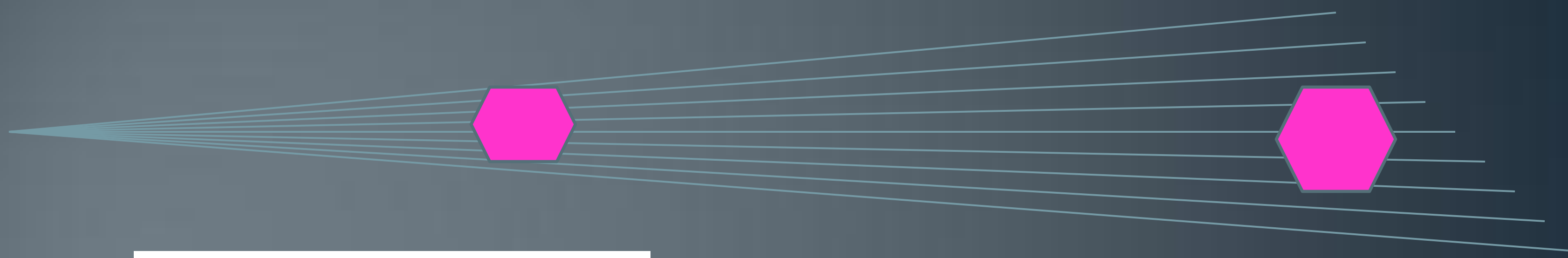

MINERvA, M. Kordosky, FNAL W&C June 2012



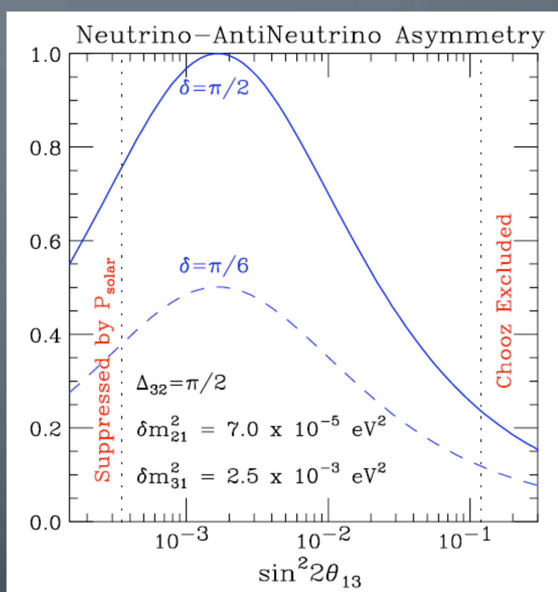

T2K, T. Nakaya, Neutrino 2012

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

- Two detector experiments, flux uncertainties partially cancel



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

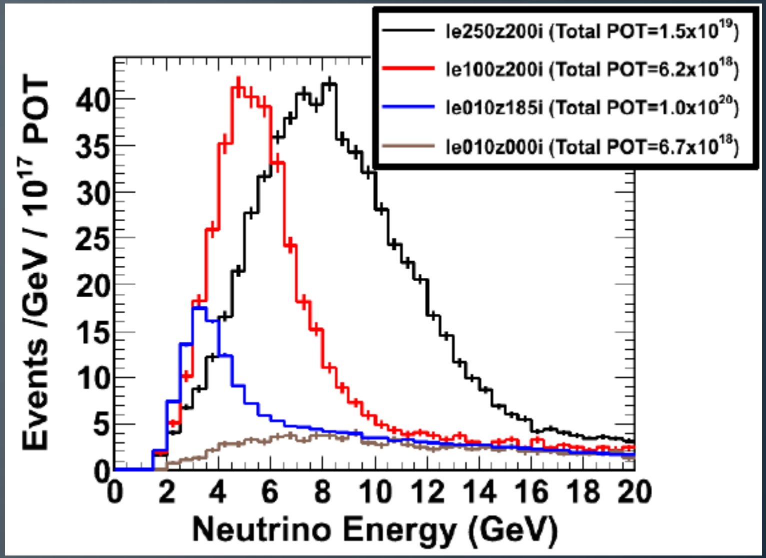



*S. Parke, INSS 2009*

Beware, CP violation searches for large $\theta_{13}$ 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

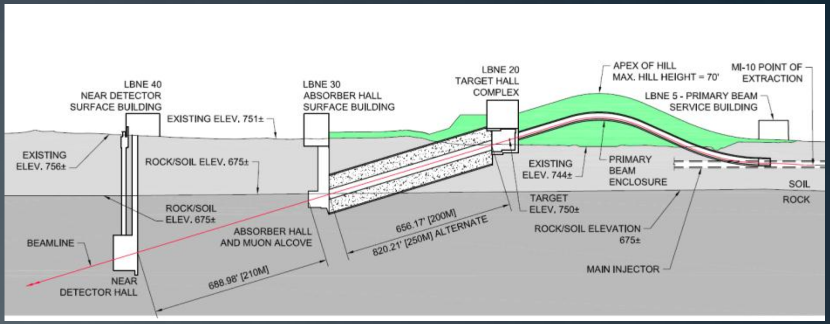
- NuMI currently undergoing upgrade to enable 700kW instead of 350kW
- Proton Improvement Plan at FNAL to allow simultaneous NOvA and MicroBooNE running
- FNAL is designing new beamline for LBNE experiment
  - Peak neutrino energy comparable to NuMI Low Energy Beam
  - New beamline optimized for:
  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

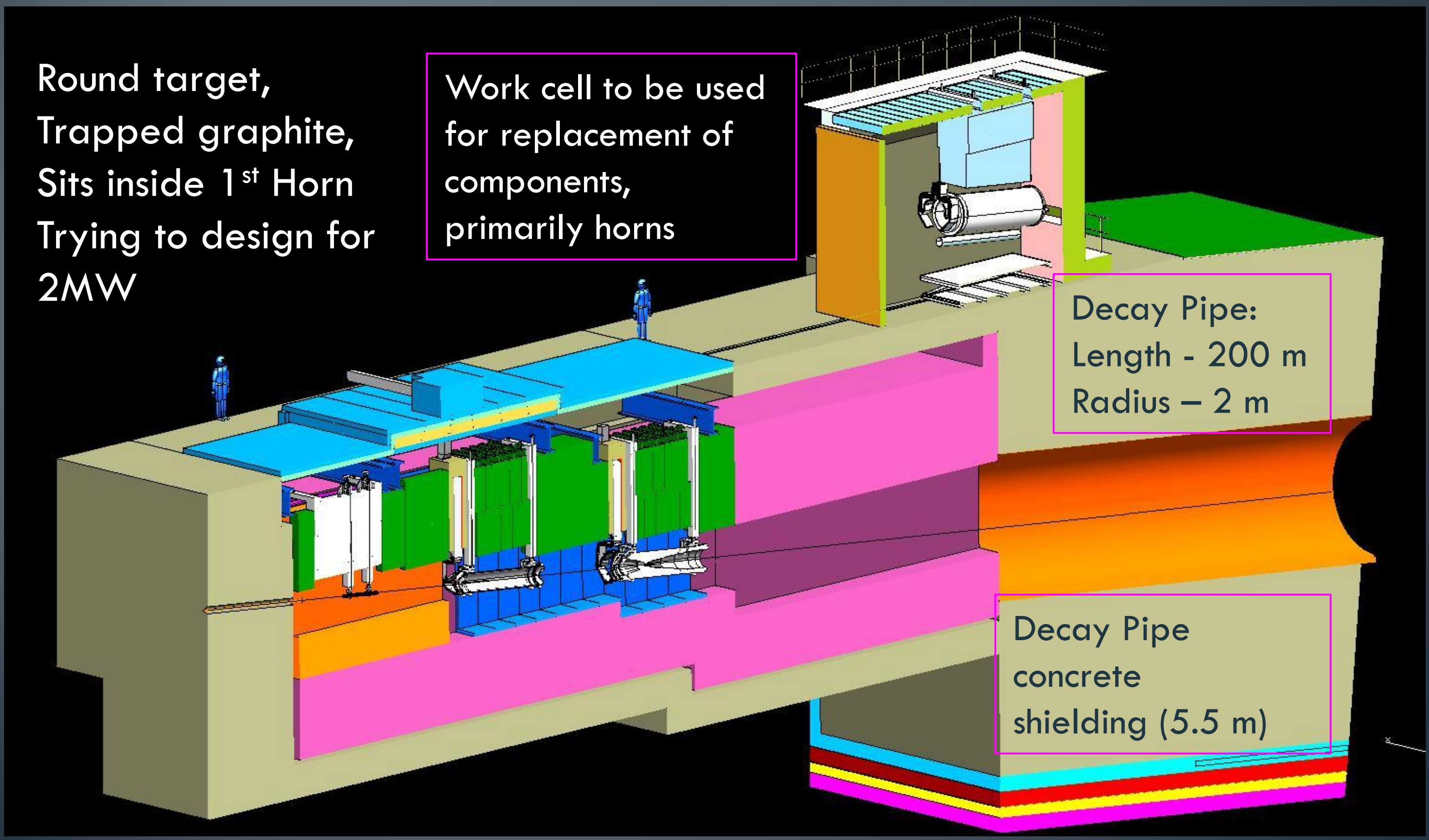
# Next Steps, CERN and JPARC

- 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

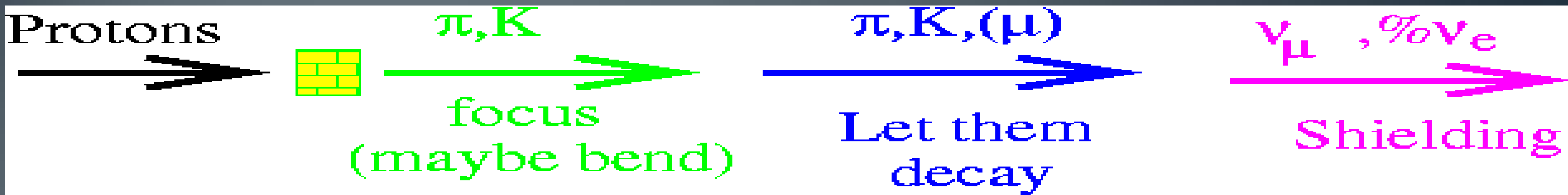
Decay Pipe concrete shielding (5.5 m)

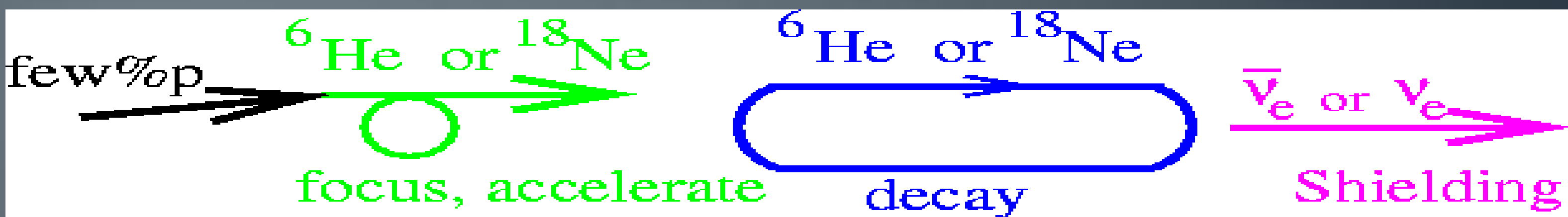
V. Papadimitriou, LBNE Reconfiguration workshop
April 2012

*See also J. Strait, 7/26 plenary talk*

# 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)

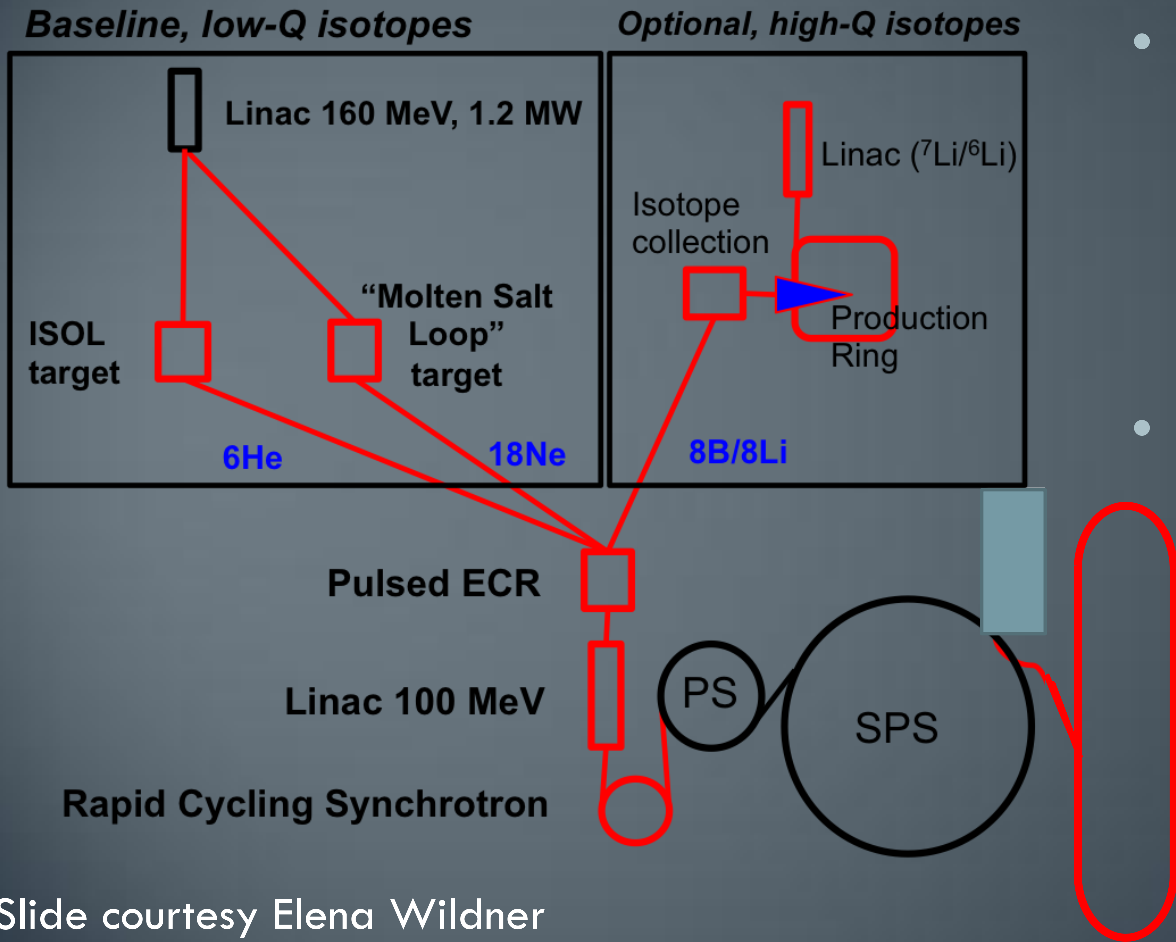
$$\Phi_\upsilon \propto \gamma^2$$
$$\sigma \propto \gamma$$

# 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

$$ {}^{6}_{2}\mathrm{He}^{++} \rightarrow {}^{6}_{3}\mathrm{Li}^{+++} e^{-} \bar{\nu}_{e} $$
$$ {}^{18}_{10}\mathrm{Ne} \rightarrow {}^{18}_{9}\mathrm{F}e^{+} \nu_{e} $$

# 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

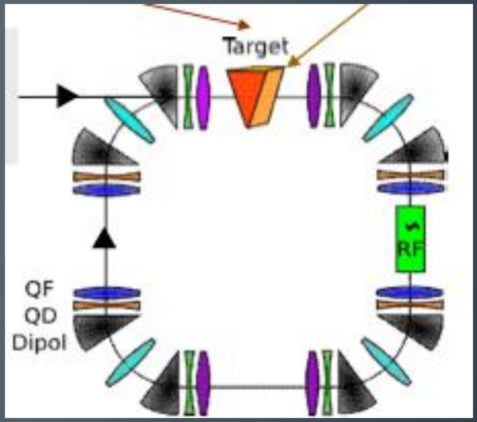
- Molten salt loop experiment to produce $^{18}$Ne at CERN ISOLDE
  - experiments at CERN & LPSC (Grenoble)
  - Experiments with static target give expected results
  - $^{18}$Ne production rate estimated to 1 x$10^{13}$ ions/s (dc) for 960 kW on target

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

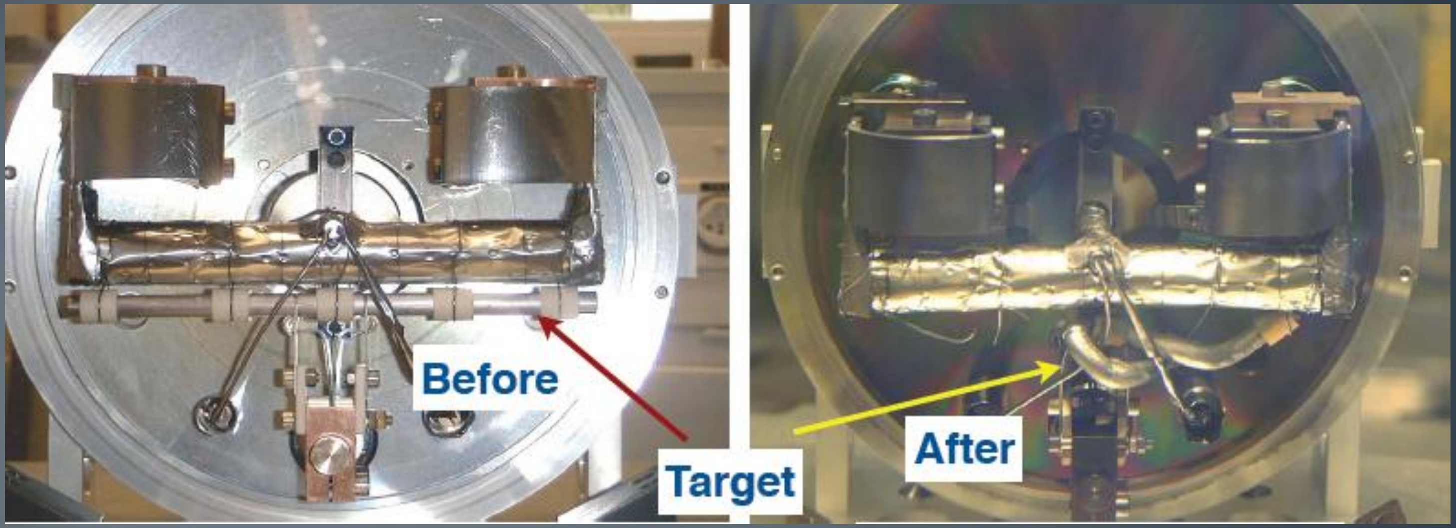
$^{7}$Li
$^{6}$Li



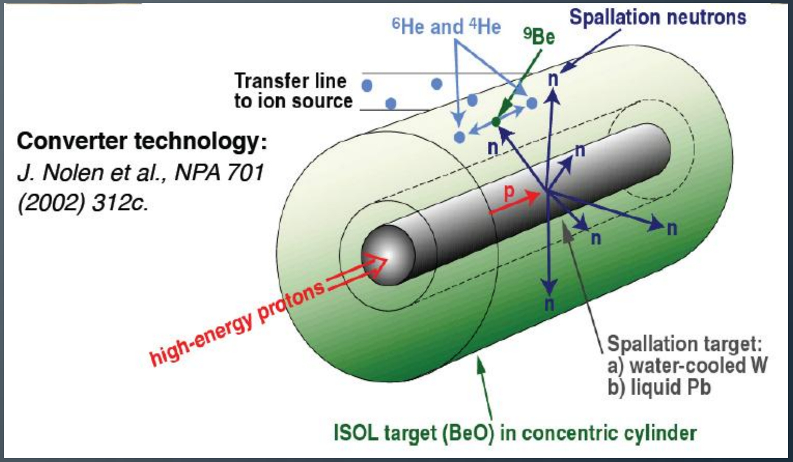

- Cross section measurement done (INFN, Legnaro)
- Collection device constructed (UCL, Louvain la Neuve)
  - $^{8}$Li is collected , $^{8}$B (highly reactive): need bound state to be extracted from target

Slide courtesy Elena Wildner

# Beta-beam: not just powerpoint




$2\times10^{18}$ integrated intensity
In shots of $3\times10^{13}$ at 1.4GeV
1 pulse 2.2μs long




Slide courtesy S. Gilardoni

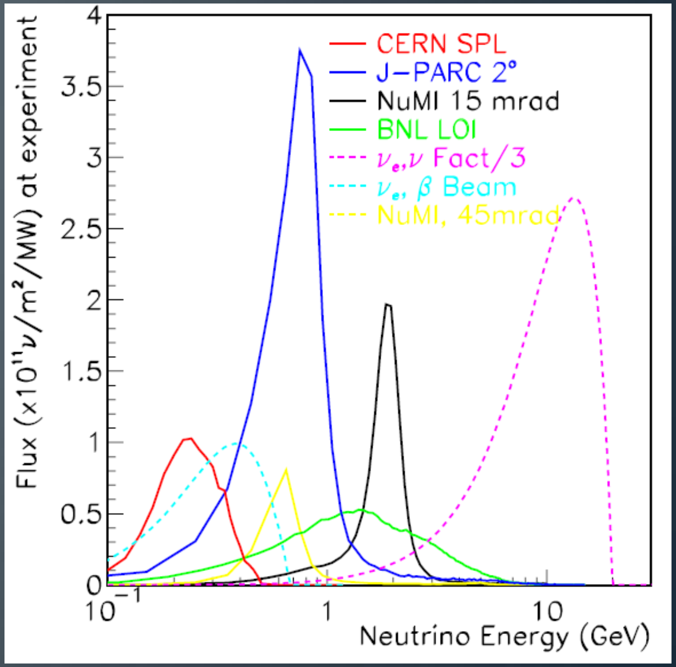
# Neutrino Factory Basics:

- One "parent" neutrino beam, two flavors available

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

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

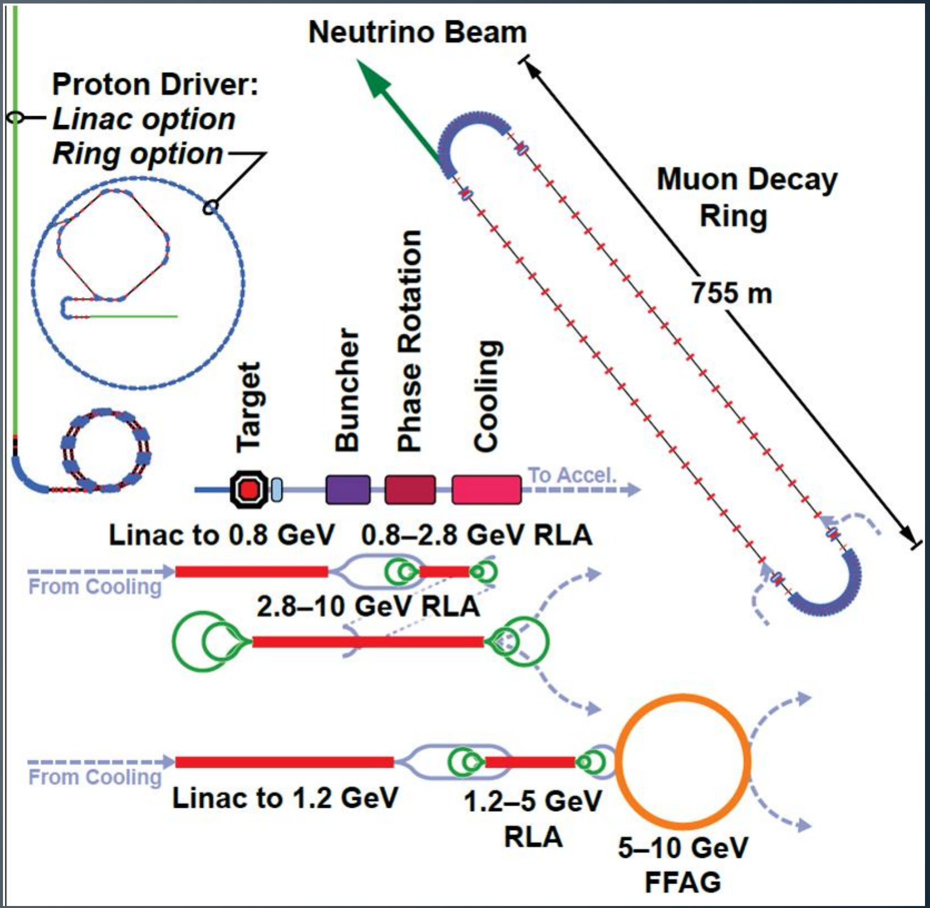
- Good news:
  - Final state lepton charge identification tells you flavor of interacting neutrino
  - Very high fluxes if you are willing to go to high muon energies
  - Extremely good knowledge of $\nu_e$ and $\nu_\mu$ flux from current in $\mu$ storage ring
- Bad news:
  - Need magnetized detector




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*

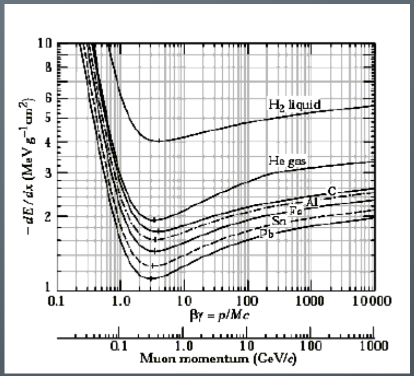
# Ionization Cooling

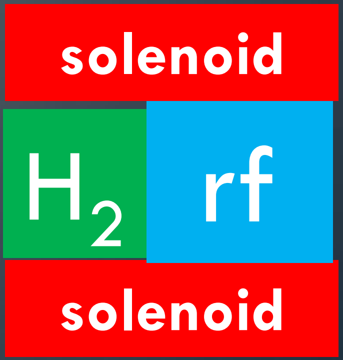
- How can you cool a beam that is decaying at 2.2μsec?


Use Solid LiH or Liquid $H_2$ for steps 1+2

RF restores only parallel momentum, energy is constant

“Simple” application of Bethe-Bloch

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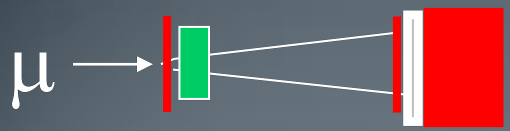
# MICE: test of Ionization Cooling

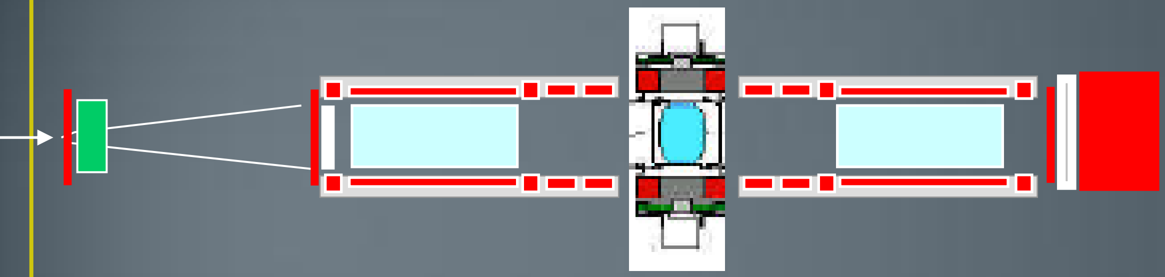
Run date:




STEP I

COMPLETED

EMR run Feb 2013

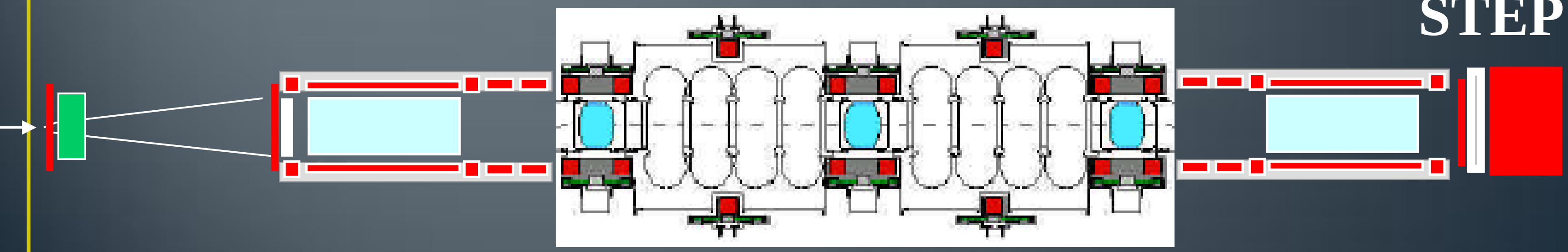


STEP IV

Q2 2013
till
Q2 2014

Under construction:

STEP VI

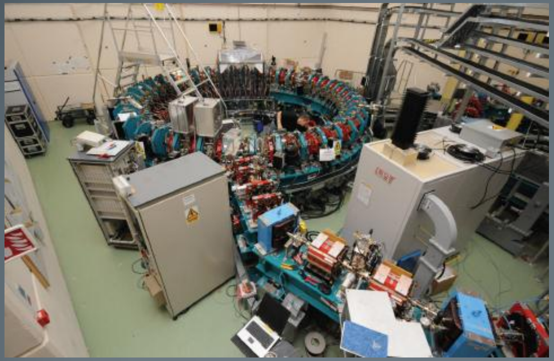


Slide courtesy Alain Blondel

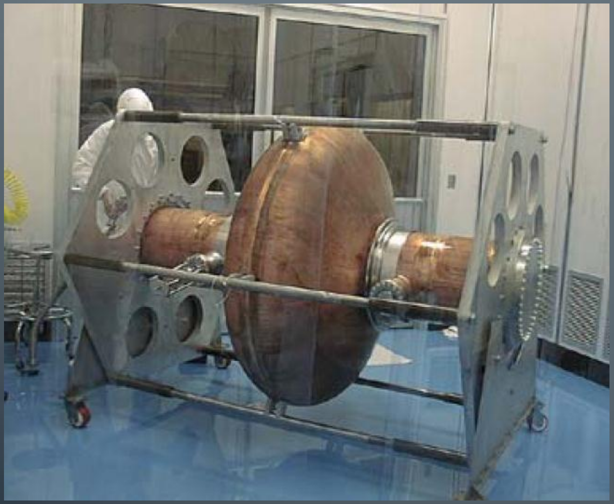
NB: target date 2016

# Neutrino Factory: not just powerpoint

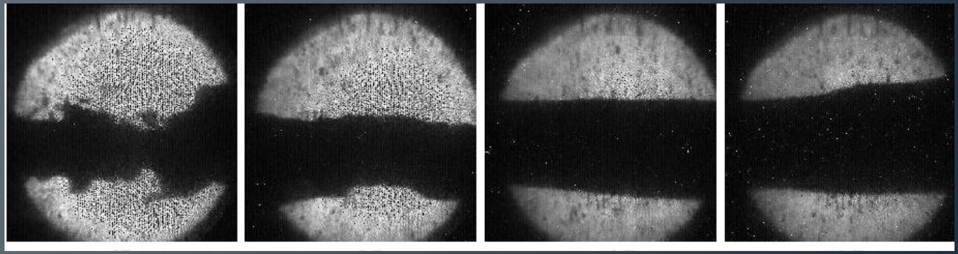
EMMA at Rutherford:
Fixed Field Alternating Gradient



Superconducting RF cavity at CERN



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



0T 5T 10T 15T

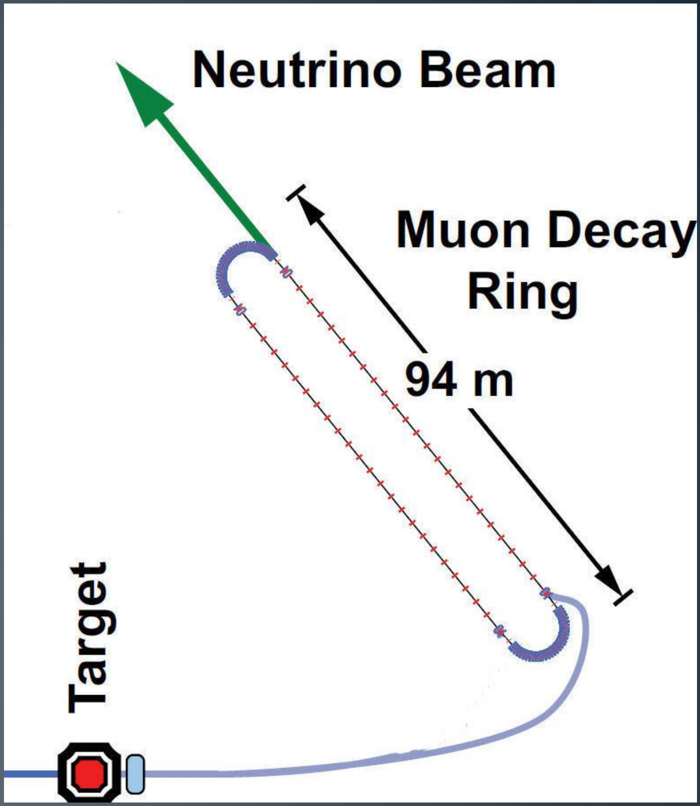
What is the first step in putting all this together for an experiment?

S. Gilardoni, INSS 2012

# 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