Accelerator-based Neutrino Beams

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Fermilab Neutrino Division

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ICTS Understanding The Universe with
Neutrinos Summer School

Fermilab

Please Note…

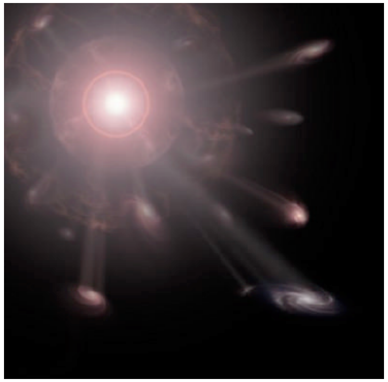
- I sincerely apologize that I cannot be there in person to meet and talk with you all!
- Since this is a school:
  - I have some questions throughout my slides that I would like you to answer afterward.
  - Please send me at least 1 follow-up question after each lecture. I will answer at least 1 question from each of you and post them in Slack (#flux-and-xsec-exp).
  - You may send me questions either via email (jpaley@fnal.gov) or Slack (@Jon Paley)

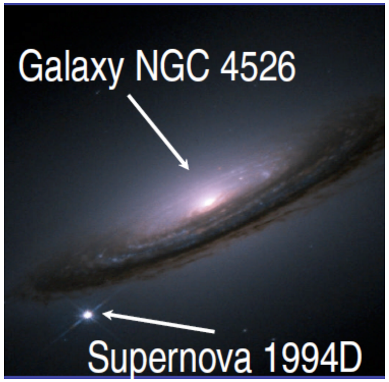
Outline

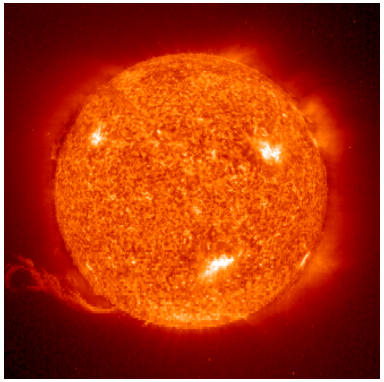
- Neutrino beams: the why and the how
- Neutrino flux uncertainties: hadron production and beam focusing
- Constraining the flux:
  - In-situ measurements
  - Ex-situ measurements
- Future Prospects

Why Neutrino Beams?

- Nature is kind and provides lots of sources of neutrinos across many orders of magnitude of energy. Reactors are a great source too!







Swiss Chard - has more potassium than bananas!

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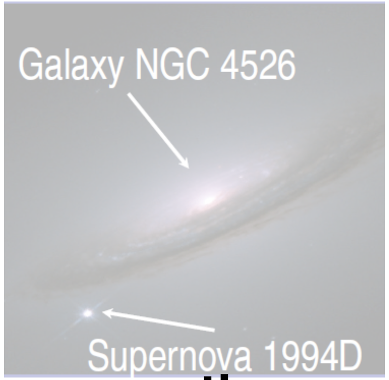
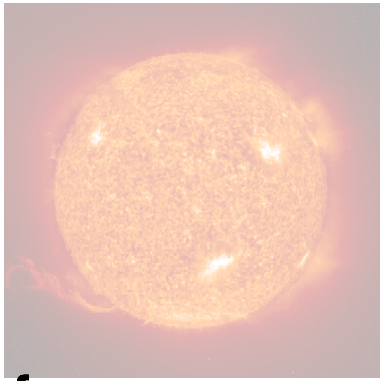
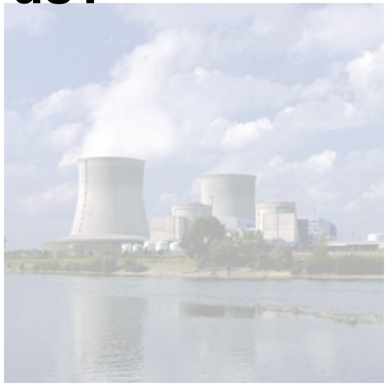




What are some other sources of neutrinos that Nature provides us?

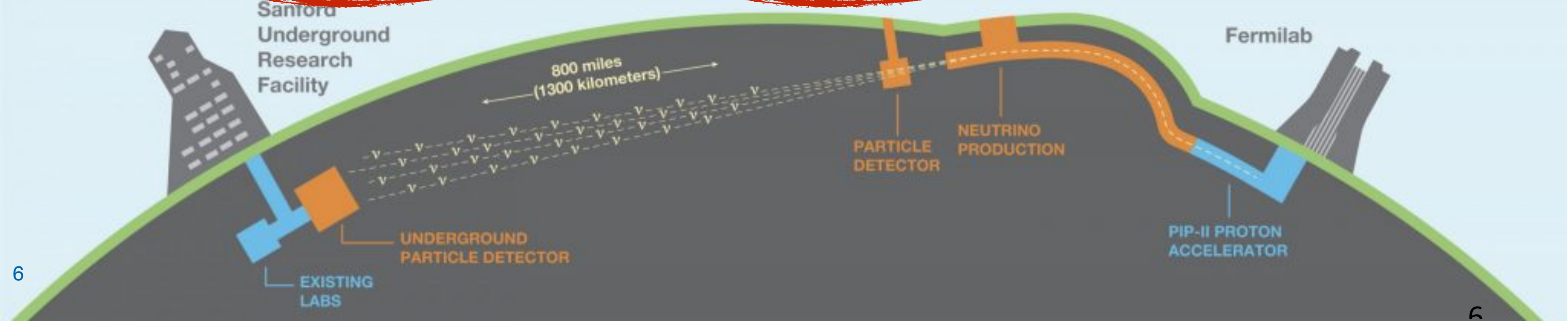
Swiss Chard - has more potassium than bananas!



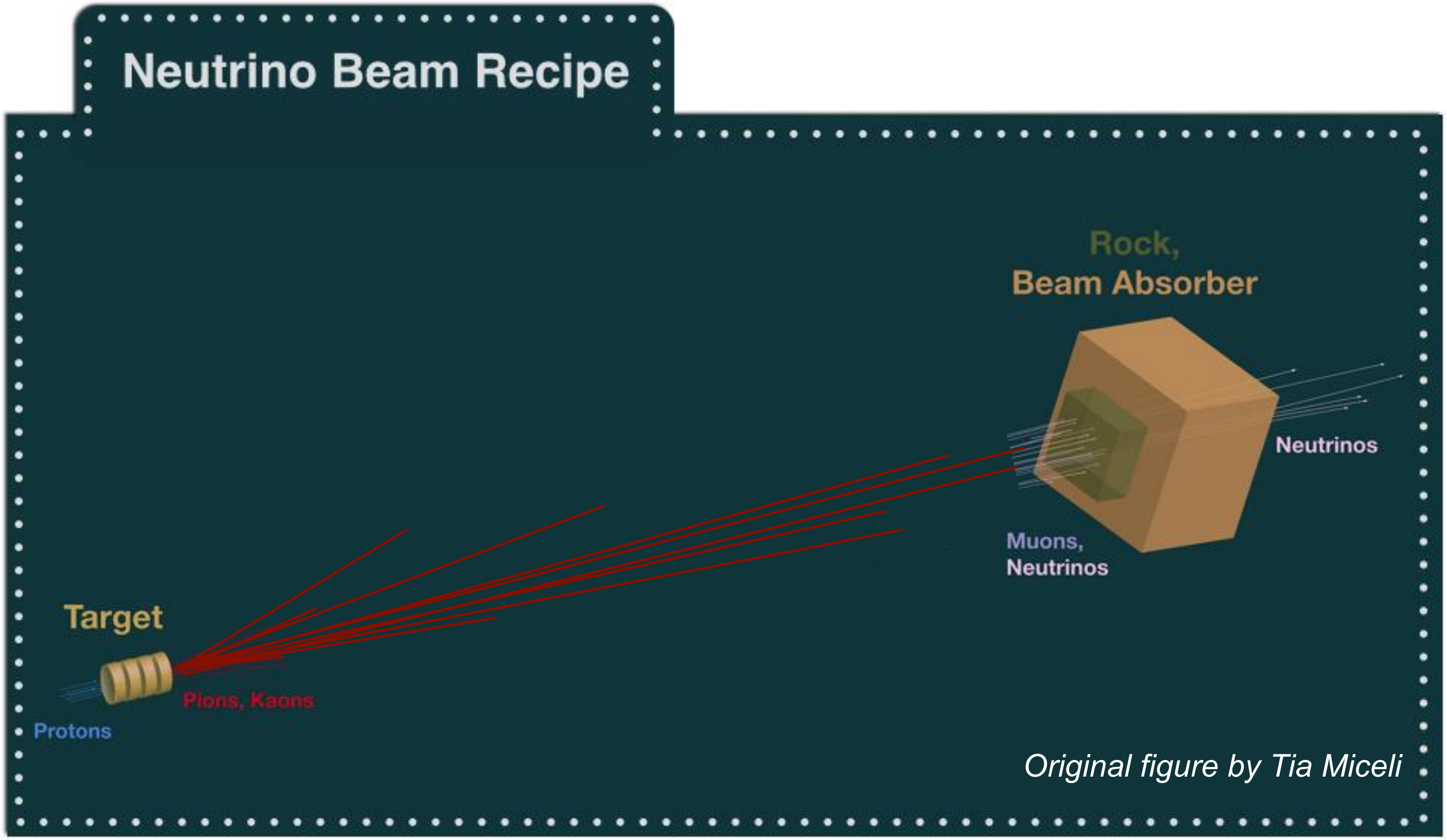
Why Neutrino Beams?

- Nature is kind and provides lots of sources of neutrinos across many orders of magnitude of energy. Reactors are a great source too!
- But we can't really control what we get. Beams offer control over neutrino energies, direction and time.
- It's relatively "easy" to produce GeV-scale energy beams of ν_μ's on Earth. These are great for studying neutrino oscillations and neutrino scattering, both of which offer possibilities for the discovery of BSM.

$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{Atmospheric, Accelerator} \\ P(\nu_\mu \to \nu_\mu)}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix}}_{\substack{\text{Reactor, Accelerator} \\ P(\nu_{\mu,e} \to \nu_e)}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{Solar, Reactor} \\ P(\nu_e \to \nu_e)}}$$



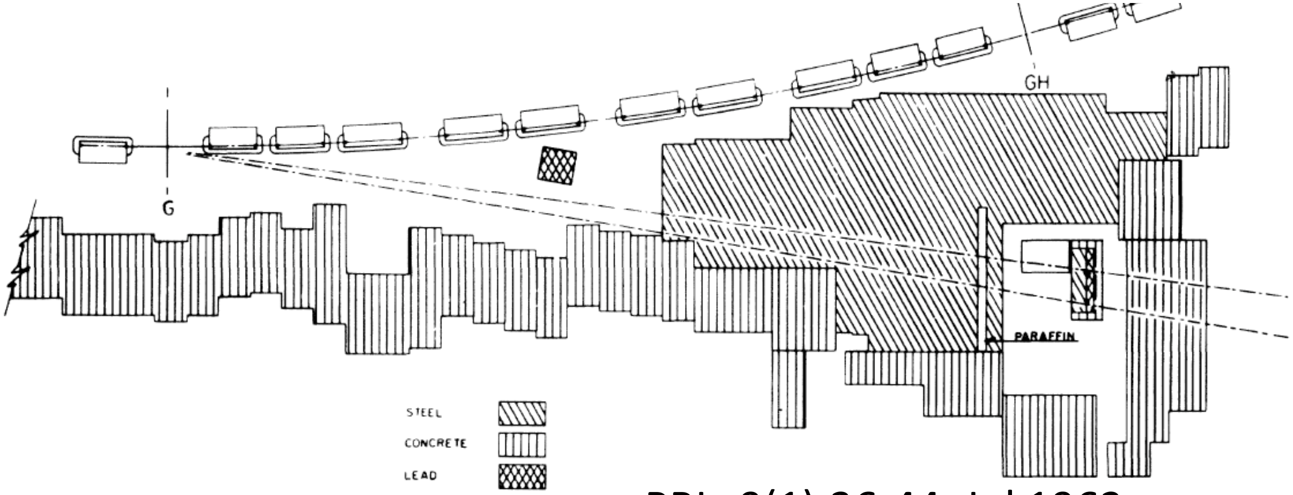
How to Make a Neutrino Beam



Original figure by Tia Miceli

- Smash high-energy proton into a target (graphite, beryllium), creating showers of hadrons including pions and kaons.
- Pions and kaons decay, leaving muons and neutrinos. Muons are then absorbed, leaving a beam of neutrinos.

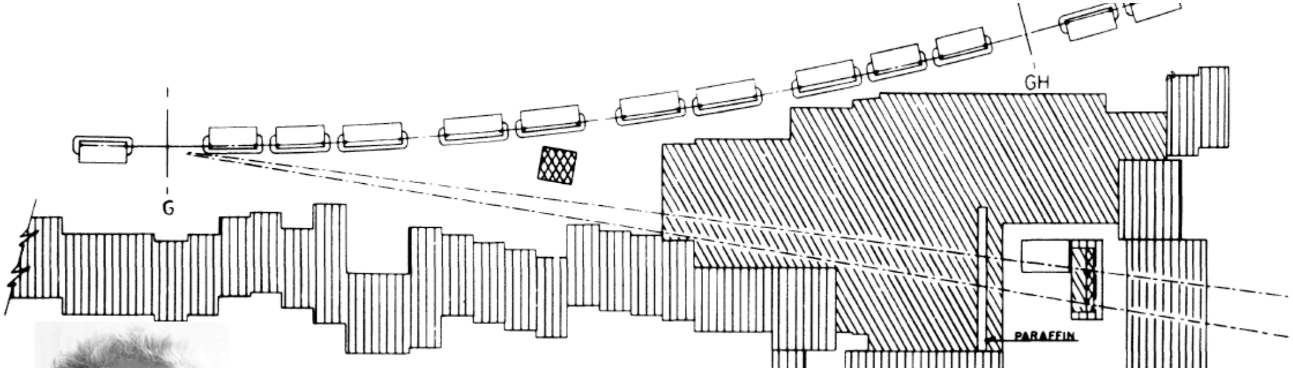
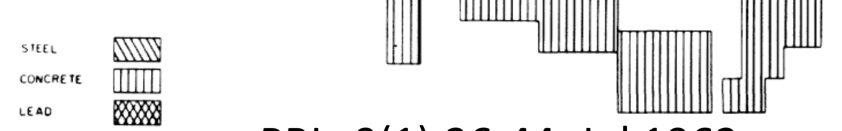
How to Make a Neutrino Beam



PRL, 9(1):36-44, Jul 1962

- First accelerator-based neutrino beam: Brookhaven, 1962
- 15 GeV proton beam struck Be target, producing secondary hadrons (mostly π's)
- π's decay to neutrinos and muons. Muons are stopped in an absorber.
- Neutrinos interact in detector (spark chamber) to produce electrons and muons.

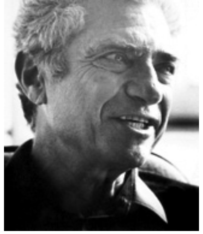
How to Make a Neutrino Beam

PRL, 9(1):36-44, Jul 1962

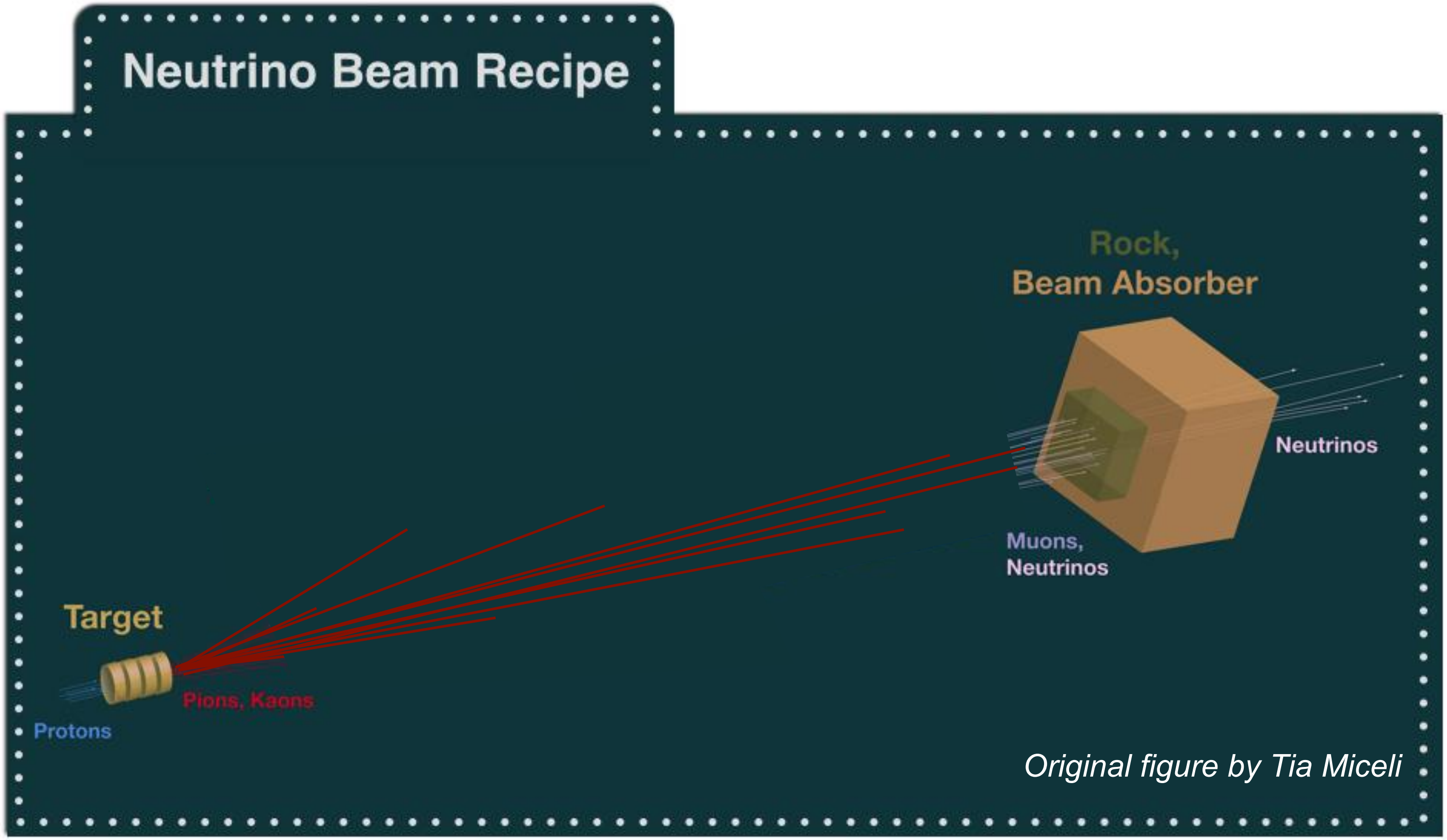

Leon Lederman


Melvin Schwartz


Jack Steinberger

- First accelerator-based neutrino beam: Brookhaven, 1962
- 15 GeV proton beam struck Be target, producing secondary hadrons (mostly π's)
- π's decay to neutrinos and muons. Muons are stopped in an absorber.
- Neutrinos interact in detector (spark chamber) to produce electrons and muons.
- **Led to the discovery of the muon neutrino!**

How to Make a Neutrino Beam



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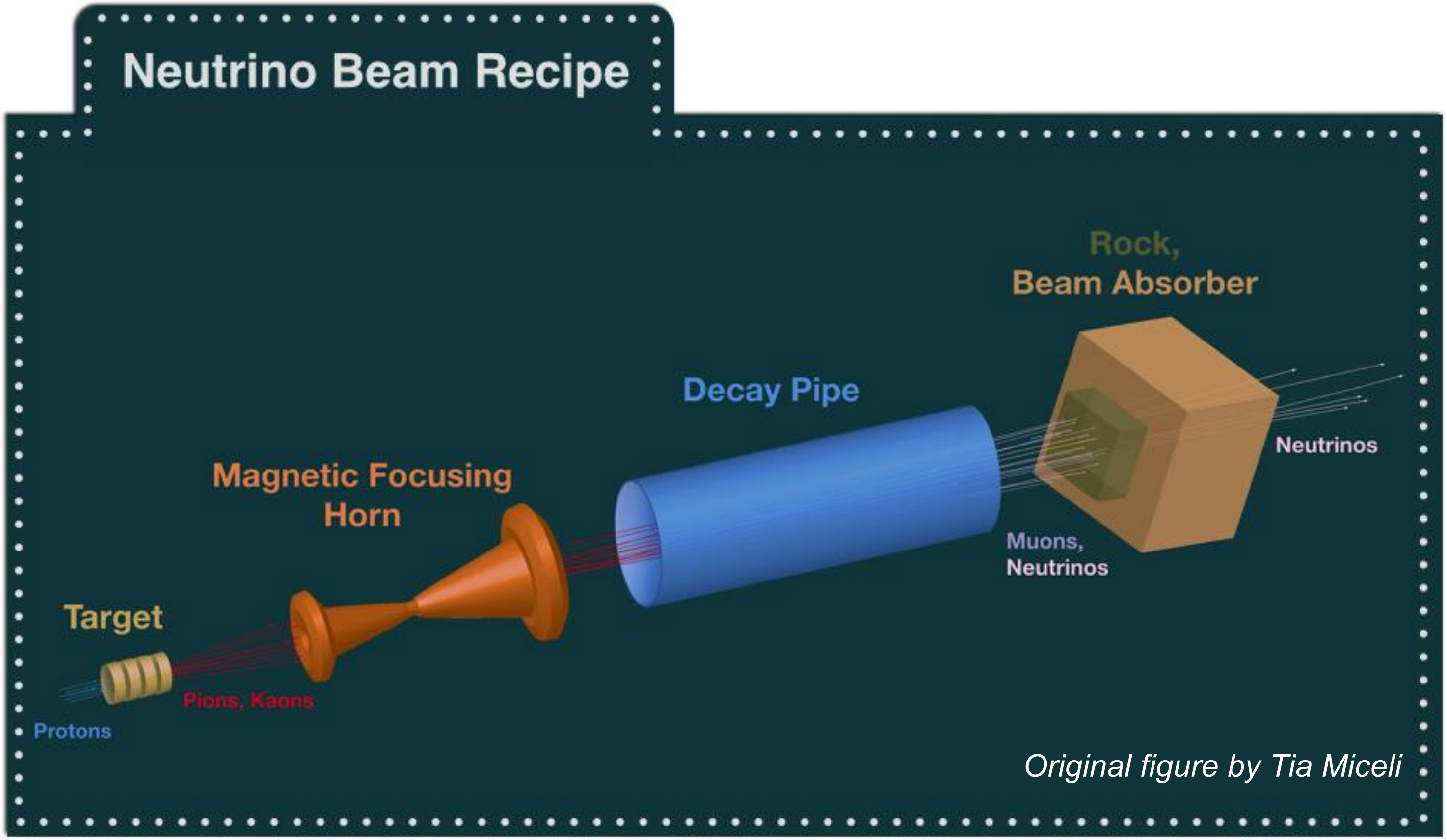
- Modern-day beams function on the same principle, but with some improvements:

How to Make a Neutrino Beam

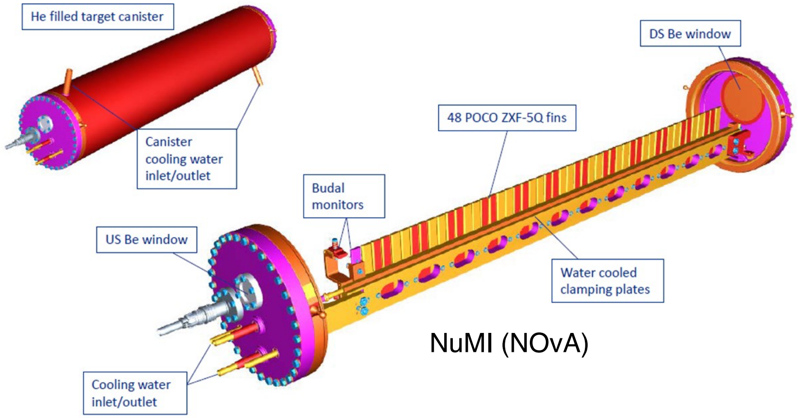


Original figure by Tia Miceli

- Modern-day beams function on the same principle, but with some improvements:
  - Magnetic focusing horns used to increase overall flux by 6x, and select + or - hadrons (creating a beam purity of 95% neutrinos or anti-neutrinos). **Why is purity useful?**
  - Long decay pipe to allow more hadrons to decay. Often filled with helium. **Why?**

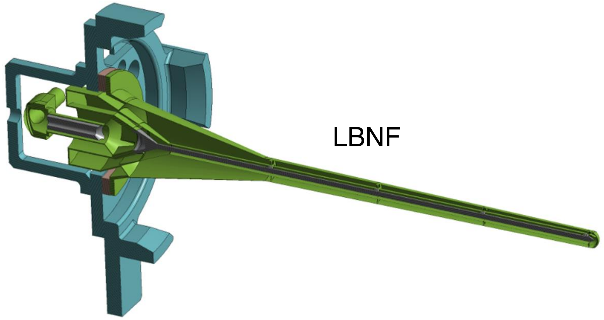
Neutrino Production Targets


BNB



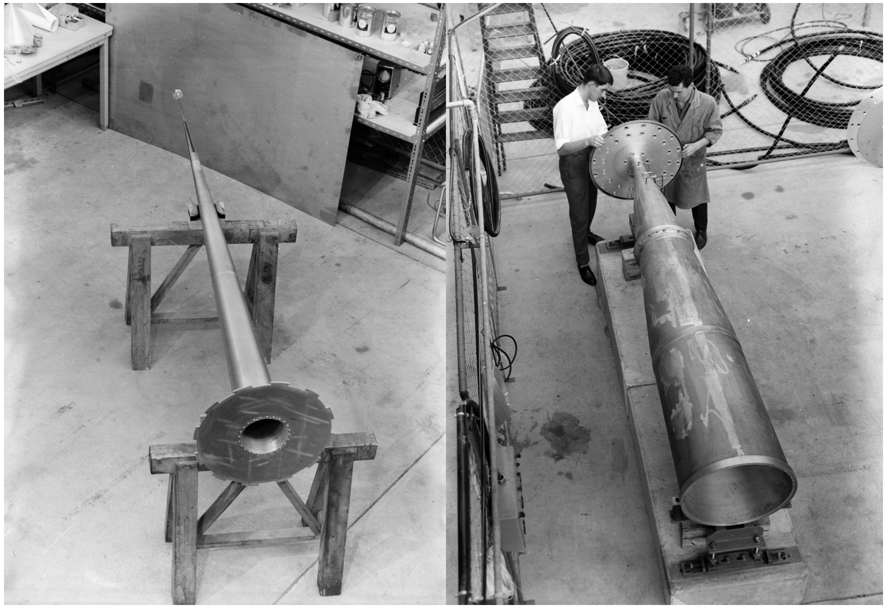
NuMI (NOvA)

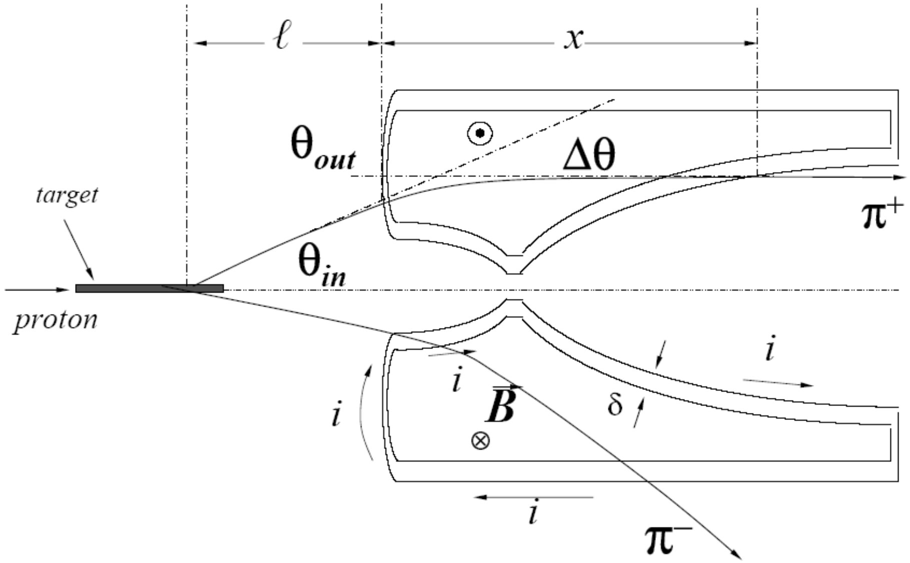

T2K (replica)


LBNF

- Targets are long (~2 interaction lengths) to maximize production of pions.
- Targets are “thin” and sometimes segmented (with gaps) to make it easier for pions to escape.
- Many other considerations for materials and design: high thermal conductivity, melting point well above operating temperature, mechanical stability, etc.

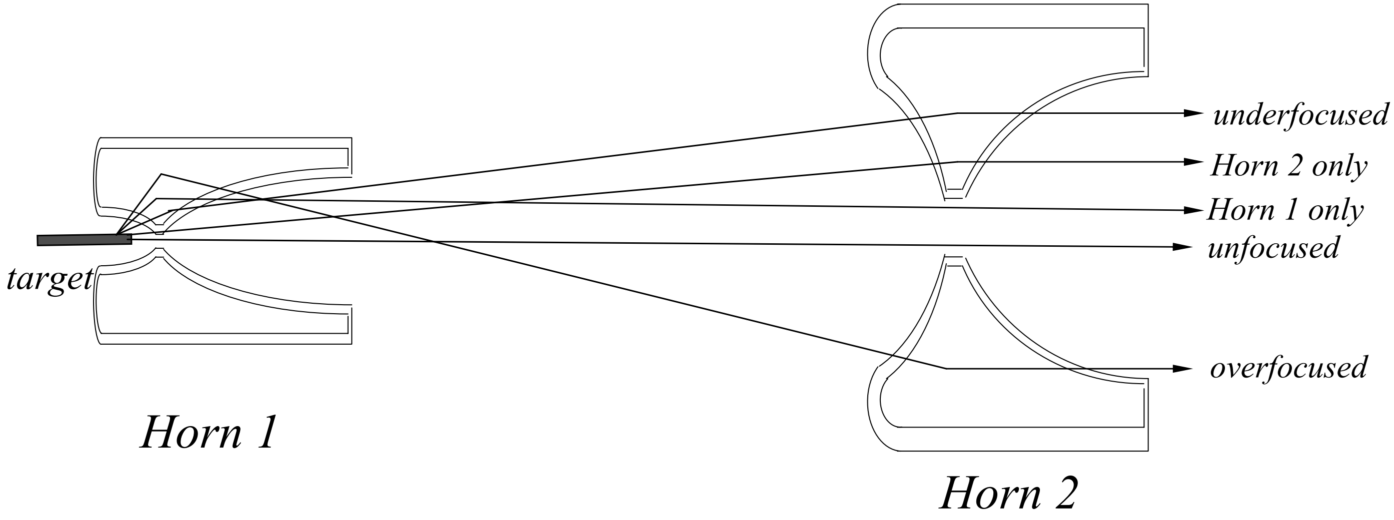
Focusing Horn Systems





- Concept of magnetic focusing horn developed in 1961 by van der Meer. Current flows along the length of a cone producing a toroidal fields that focuses positive [negative] particles, and defocuses the opposite sign.
- Results in large increase in neutrino flux, as well as a [anti-]neutrino beam. Purity is critical for CP-violation searches (hopefully measurements!). **Why?**

Focusing Horn Systems



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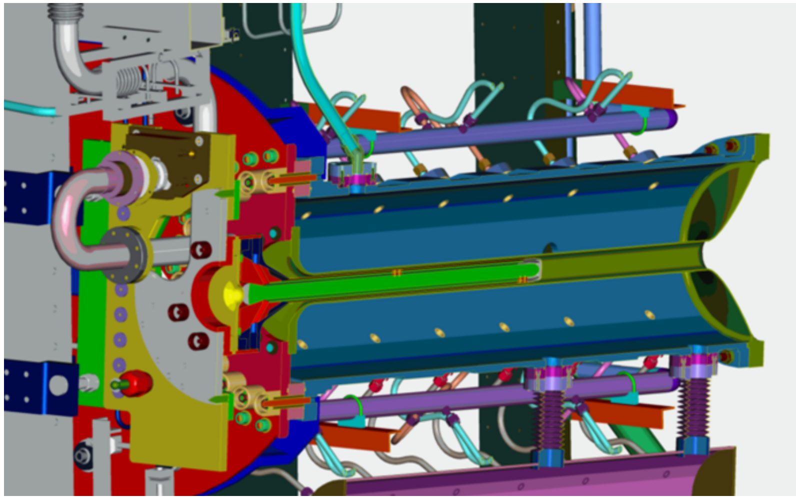
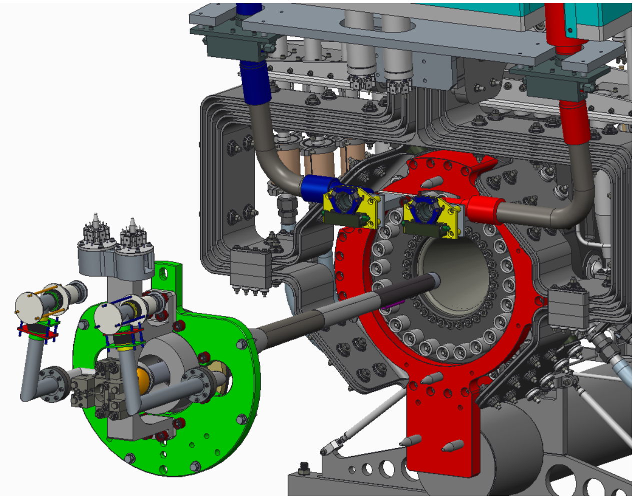
- Results in large increase in neutrino flux, as well as a [anti-]neutrino beam. Purity is critical for CP-violation searches (hopefully measurements!)
- Multi-horn configurations are common, the additional horns capture mesons that are under- or over-focused.

Integrated Target and Horn Assemblies

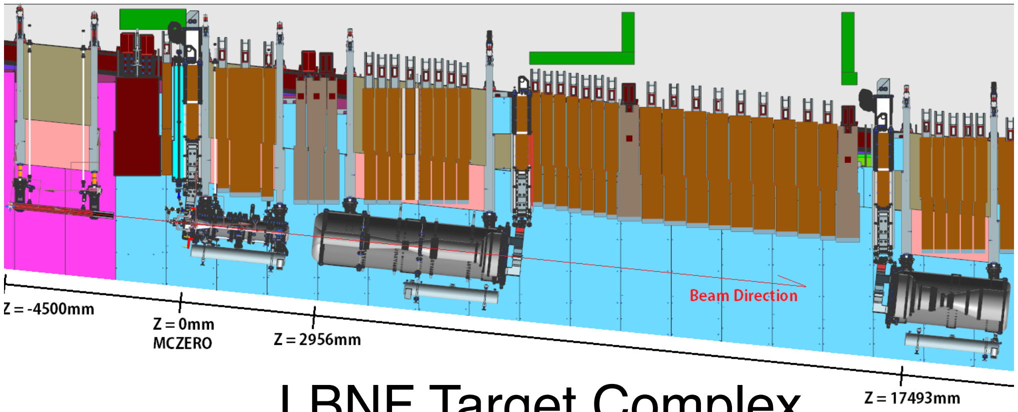


T2K Target and Horn



LBNF Target + Horn A

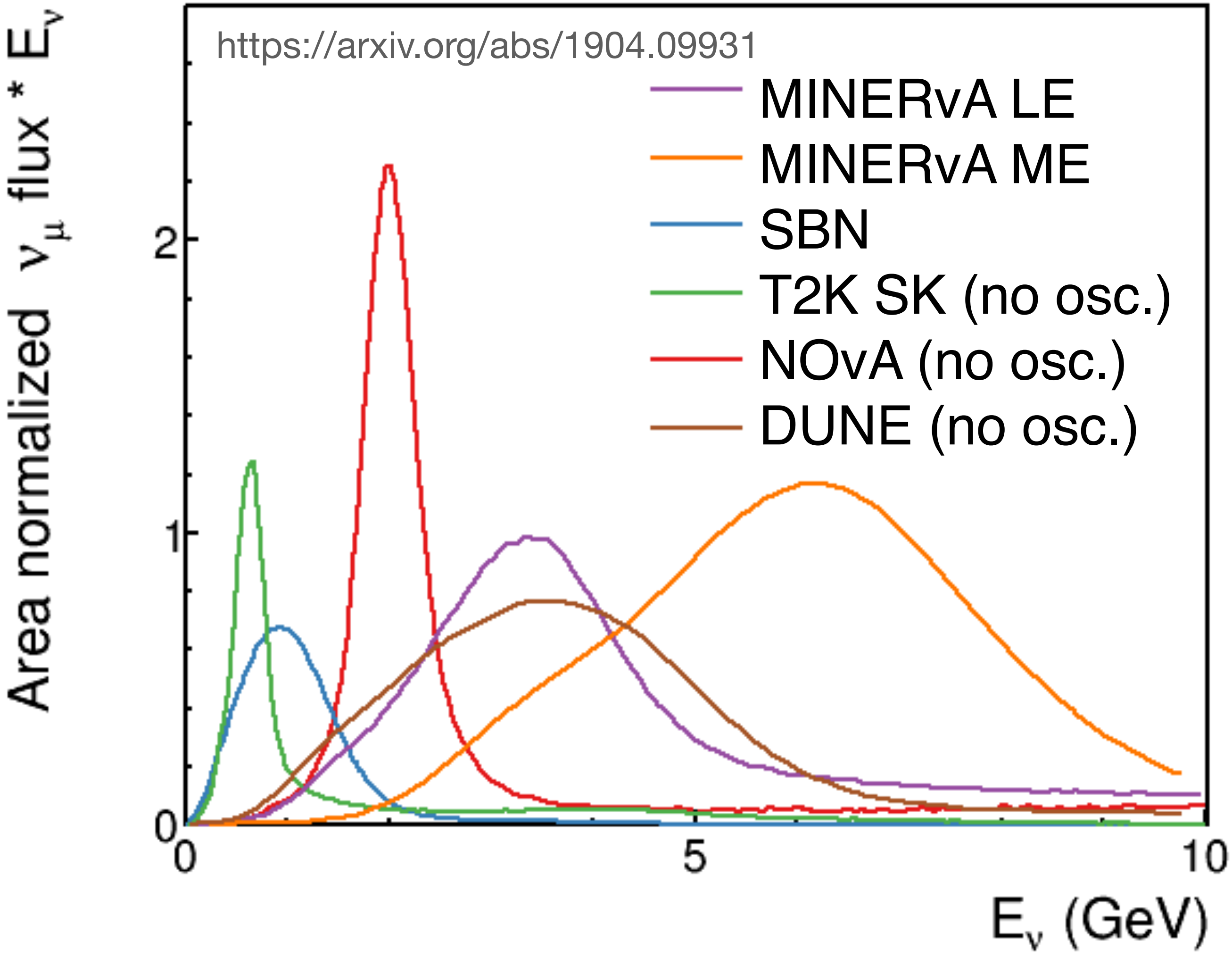
- Target is often put inside or very close the first focusing horn.
- Careful consideration is needed for support structure and remote handling for removal and replacement of all elements.



LBNF Target Complex

Neutrino Flux Predictions and Uncertainties

Modern-Day Accelerator-based Neutrino Fluxes

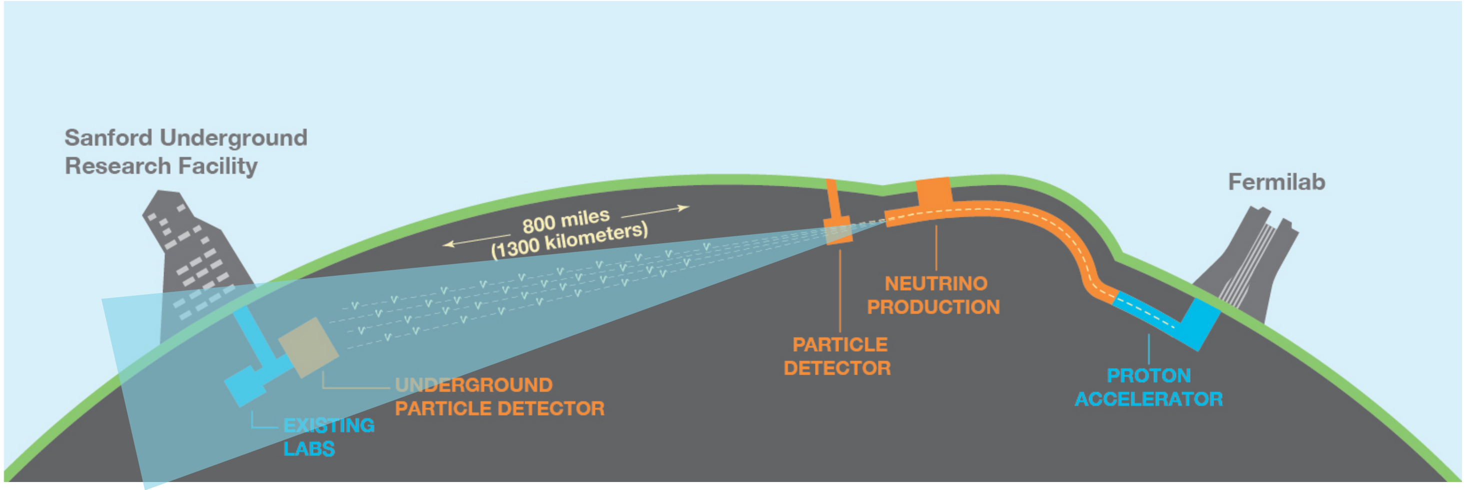


- Neutrino beams are typically “designed for the baseline”.
  - T2K/HK: 250km baseline, energy peaks around 600 MeV.
  - NOvA and DUNE have baselines that are O(1000 km).
  - **Question: Why is the SBN peak so low?**
- Note: T2K and NOvA both have their detectors off-axis experiments. **Why?**

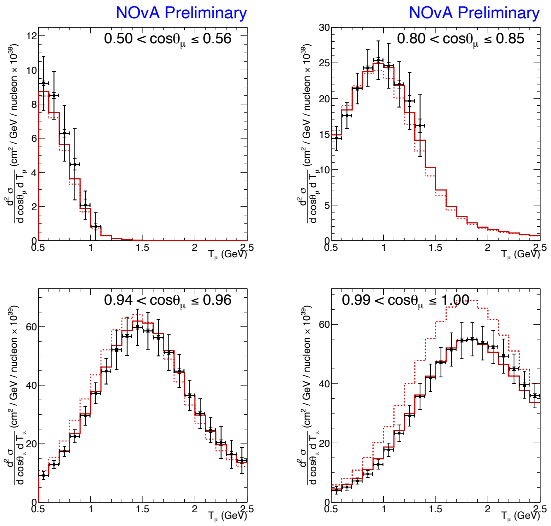
Neutrino Oscillations and the Role of Flux

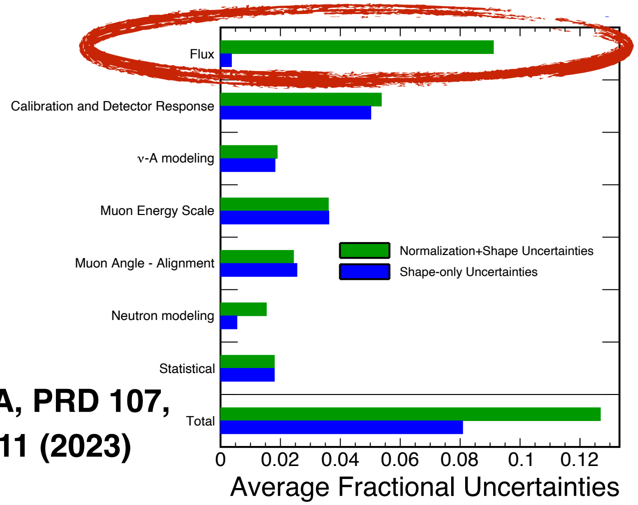
$$N_\nu^{\mathrm{obs}}(E_\nu^{\mathrm{reco}}) \sim \vec{U}(E_\nu^{\mathrm{true}} \to E_\nu^{\mathrm{reco}})\Big(\Phi(E_\nu^{\mathrm{true}}) \times \sigma(E_\nu^{\mathrm{true}}) \times \epsilon(E_\nu^{\mathrm{true}}) \times P^{\mathrm{osc}}(E_\nu^{\mathrm{true}})\Big)$$

- In an ideal experiment, the flux, cross section and efficiencies of the near and far detectors would simply “cancel” in the ND/FD ratio.
- But reality:
  - The ND typically sees a “line source” of neutrinos, whereas the FD sees a “point source”. So the fluxes are not the same even in the absence of oscillations!
  - The acceptance and performance of the ND is often different from the FD, so the efficiencies are different, and they typically depend on neutrino energy. The efficiency corrections rely on a reliable flux model.

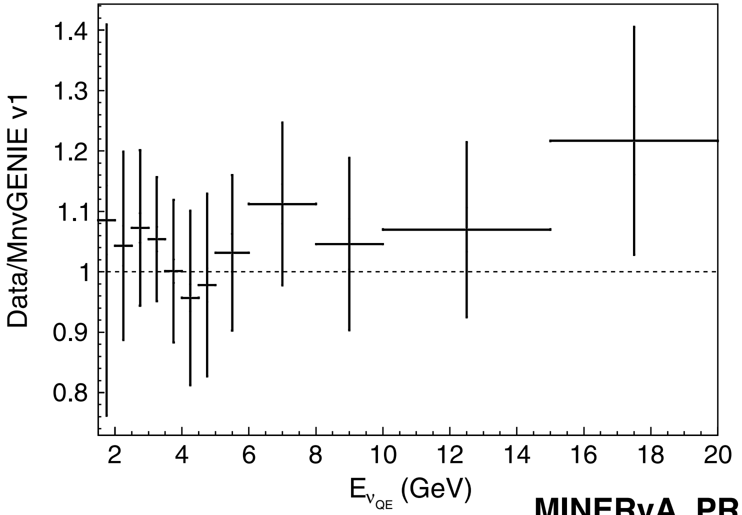


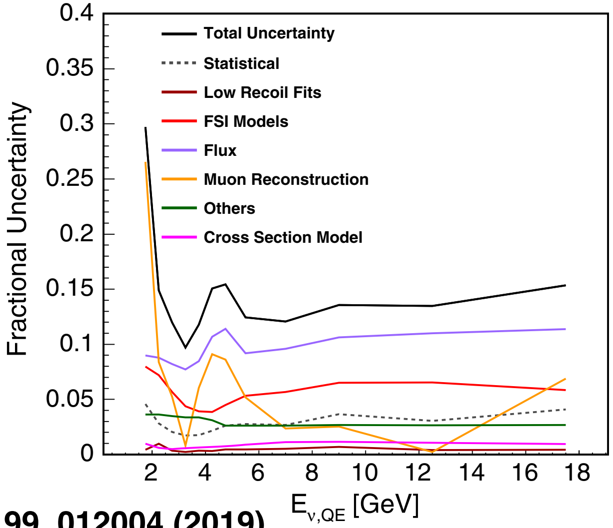
Impact of Neutrino Flux Uncertainties





NOvA, PRD 107, 052011 (2023)

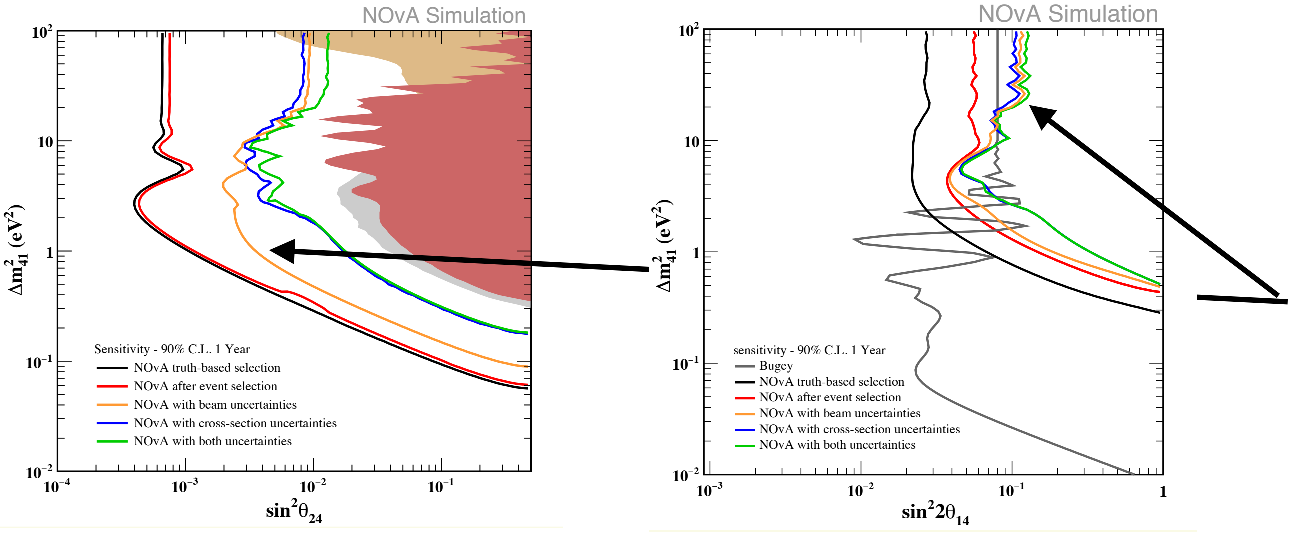




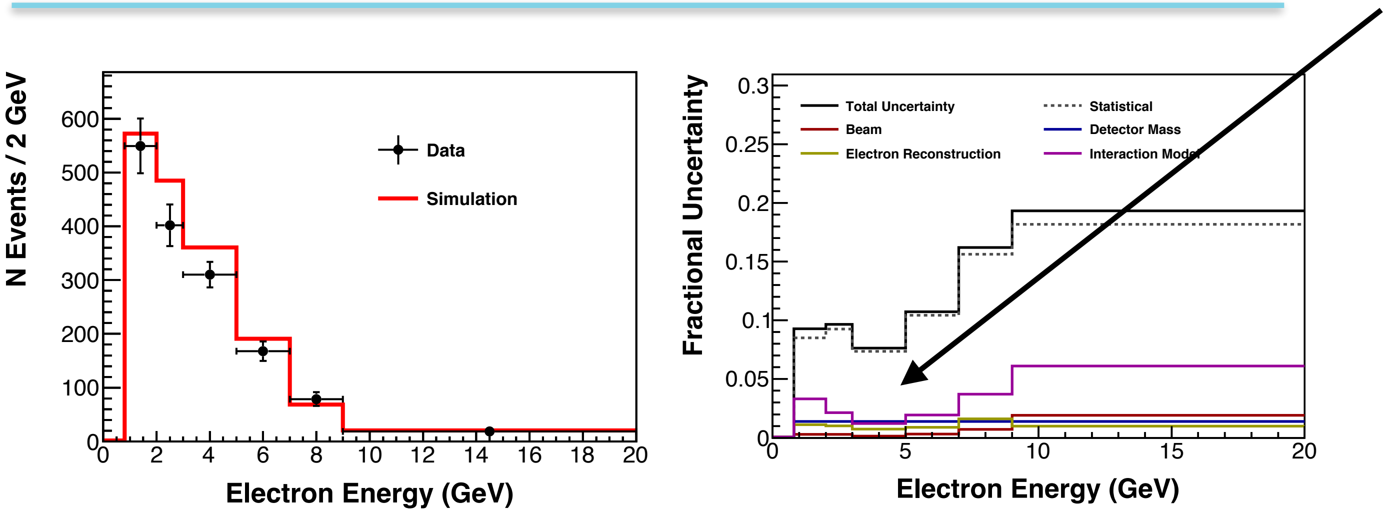
MINERvA, PRD 99, 012004 (2019)

- Flux is a limiting systematic for all neutrino cross section measurements by current experiments.
- Current measurements are being used to tune neutrino scattering models.
- Uncertainties in these models impact the sensitivity of the future DUNE physics program.

Impact of Neutrino Flux Uncertainties



- Flux is a limiting systematic for nearly all single-detector measurement.
- Single-detector searches for sterile neutrinos are severely limited by flux uncertainties.
- Percent-level ν-e scattering measurements can also be used to constrain “new ν” physics, eg NSI, ν magnetic moments, etc. But again these constraints will be limited by flux uncertainties.



MINERvA, PRD 100, 092001 (2019)

Why Don’t We Just Measure the Flux?

- Easier said than done!
- We don’t know the energy of the incident neutrino in our interactions. We have to infer it by reconstructing the energy. Even with our best detectors (eg, LArTPCs), this introduces some model-dependence.
- Since we $N_{obs} \approx \Phi \times \sigma$ in our detectors, we must rely on cross sections that are already well known to extract the flux. The best candidate for this is ν-e scattering.
  - This is a very rare process, and can really only be measured well for energies in the GeV region. It takes time (in many cases years) to collect and analyze the data.
  - Provides a constraint on the total rate, but limited constraints on the shape of the flux.
- It is important to have strong a-priori constraints on the flux when we first turn the beam on. If we see something unexpected in our detectors, we want to minimize the possible causes, and “flux” could be one of them.
- So, we rely very heavily on a-priori flux predictions, based on simulations of all of the [complicated] components: target + horn + decay pipe…

The Role of Simulation

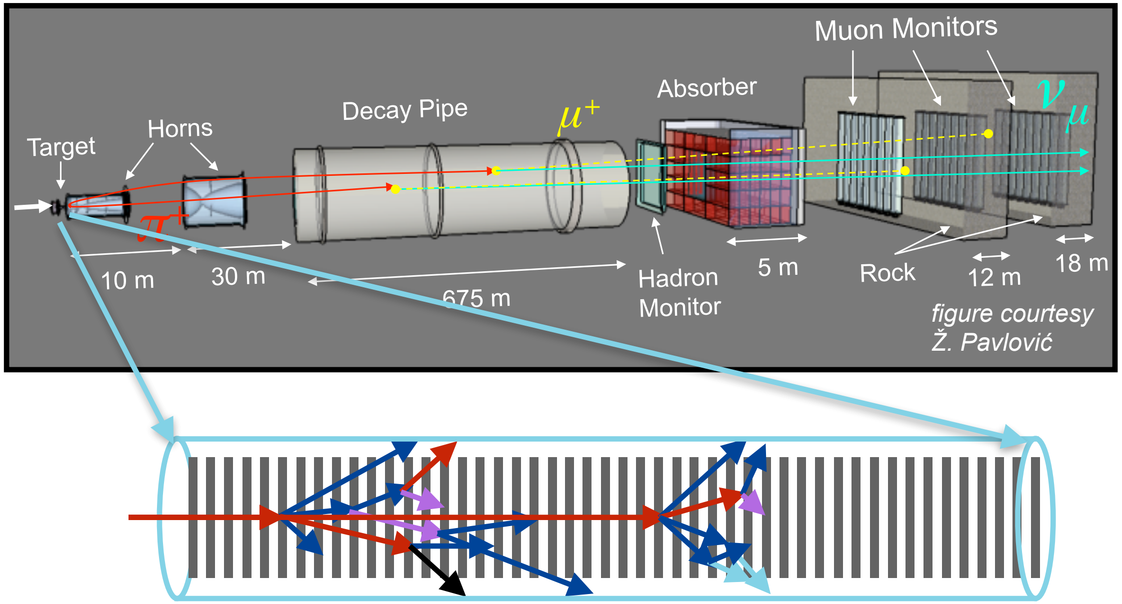
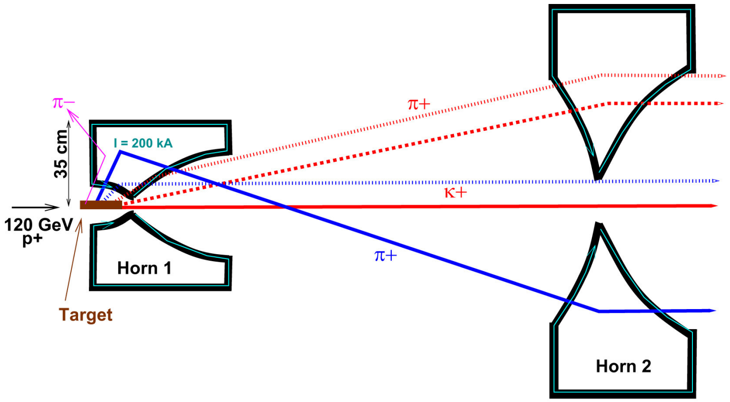
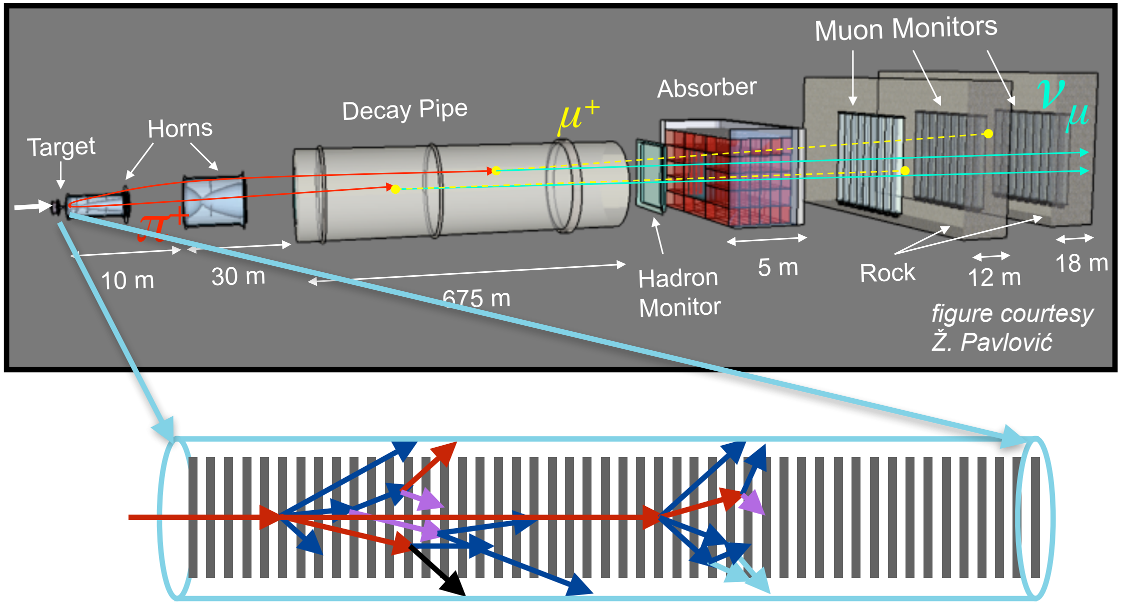


figure courtesy Ž. Pavlović



- Simulations use the production cross section for p, π, K hitting a broad range of nuclear targets across a broad range of energies. Eg, particles of all energies up to the beam energy interact in the production target (C or Be), focusing horns (aluminum), and lots of other material (water, Ti, Fe, He, rock, etc.).
- Simulations also need very detailed descriptions of the target and focusing horn geometry, and the focusing magnetic field as a function of position and time.

The Role of Simulation



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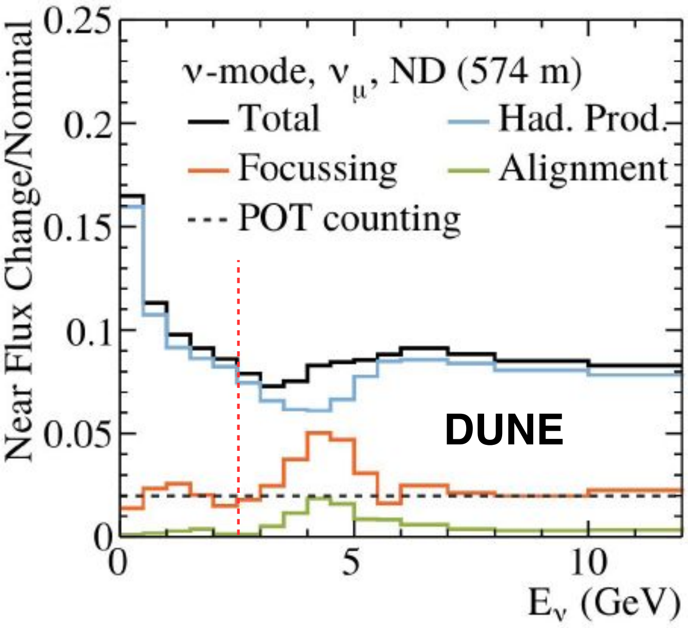

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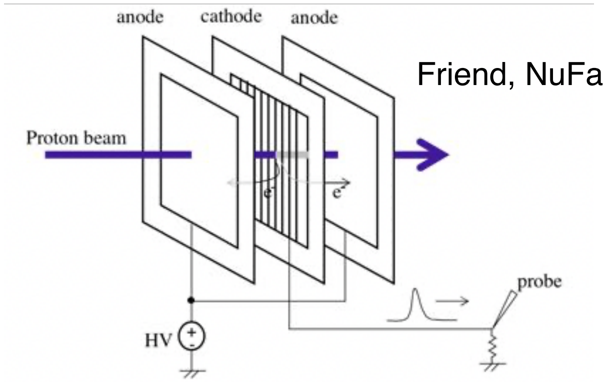
- Simulations also need very detailed descriptions of the target and focusing horn geometry, and the focusing magnetic field as a function of position and time.
- **Two sources of uncertainty in these predictions: hadron production (HP) and beam focusing. HP uncertainties are currently dominant.**

In-Situ Constraints

Primary Beam Monitoring

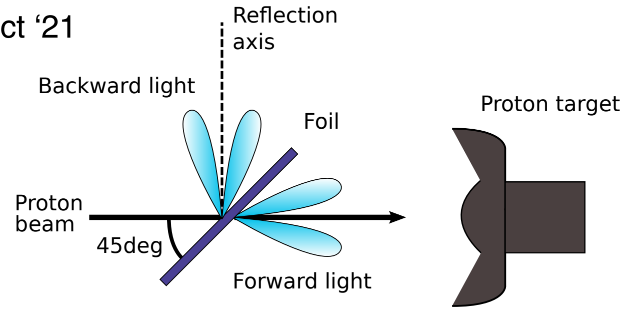
Segmented Secondary Emission Monitor (SSEM)



Friend, NuFact '21

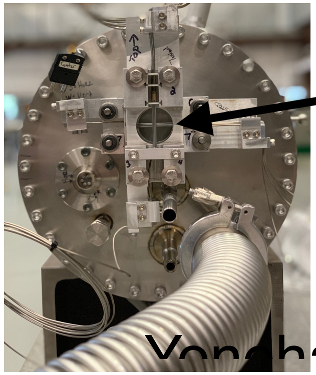
- Used at both J-PARC and FNAL
- Secondary electrons emitted from segmented cathode plane when struck by primary proton are collected on anode planes. Planes are 5 μm Ti foils.
- Cathode current read out, digitized and recorded to extract beam profile.

Optical Transition Radiation (OTR) Monitor



- Used at J-PARC
- OTR produced when charged particles travel between two materials with different dielectric constants.
- Image of the backward light captured by a rad-hard camera in low-rad area.

Target Position Thermometer (TPT)



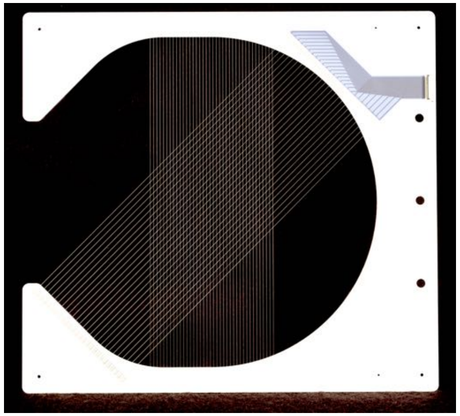
Yonehara

- Used at NuMI
- Proton beam heats up thin Be horizontal and vertical wires connected to thermocouples.
- Resolution and stability < 0.1 mm.

Primary Beam Monitoring Upgrades (J-PARC)

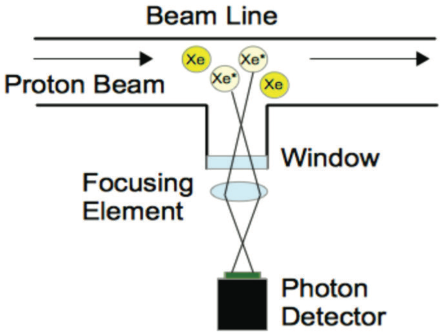
Friend, NuFact ‘21

Wire Secondary Emission Monitor (WSEM)



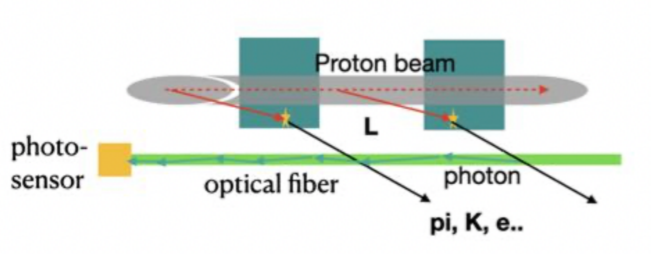
- Uses twined 25 um Ti wires
- Less material than foil-based detectors.
- C-shape allows monitor to be moved in/out of beam during beam operations.
- Developed in collaboration with Fermilab.

Beam Induced Fluorescence (BIF) Monitor



- Locally degrade vacuum level, inject gas (N_2).
- Fluorescence from de-excitation of gas molecules excited by protons passing through.
- Non-destructive, can be used to continuously monitor beam.

Optical Beam Loss Monitor (O-BLM)

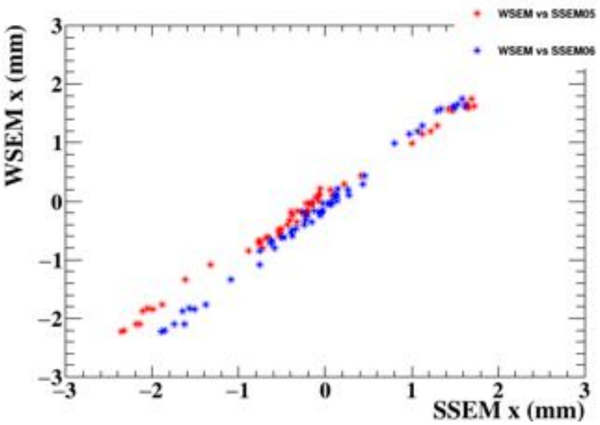


- Beam-induced signal on optical fiber running alongside the beam from lost beam particles.
- Precise timing information can be used to localize point of beam loss.
- Few channels needed to monitor entire beamline.

Primary Beam Monitoring Upgrades (J-PARC)

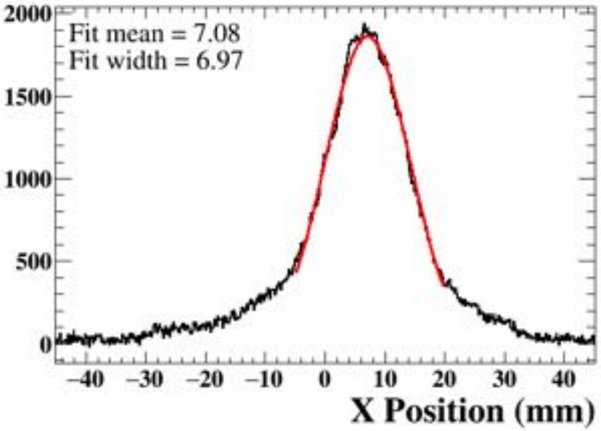
Friend, NuFact '21

Wire Secondary Emission Monitor (WSEM)



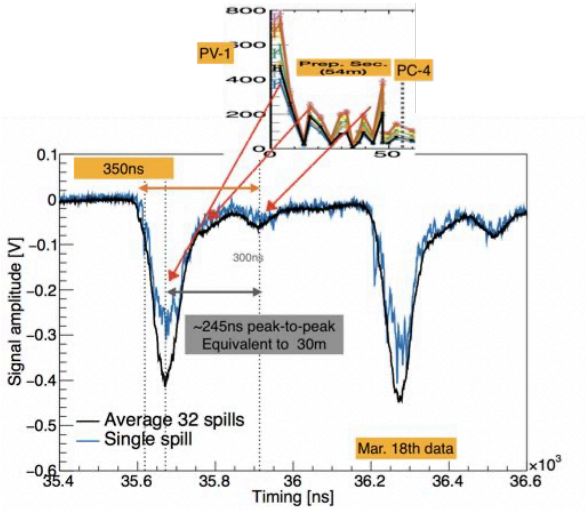
- Shown to have same resolution as SSEMs.
- Beam loss < 10x that of SSEMs.
- Stable operations since 2018, plan to install more in the near future.

Beam Induced Fluorescence (BIF) Monitor



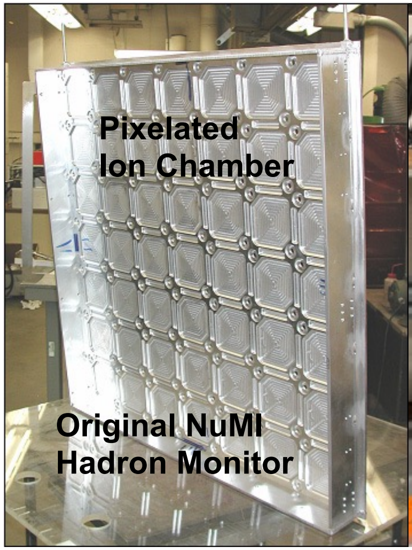
- Prototype successfully tested in 2020/21.
- Plans to upgrade system with 2-stage micro-channel plate detector (increase gain by 10^3)
- Also studying system with MPPC+fibers.

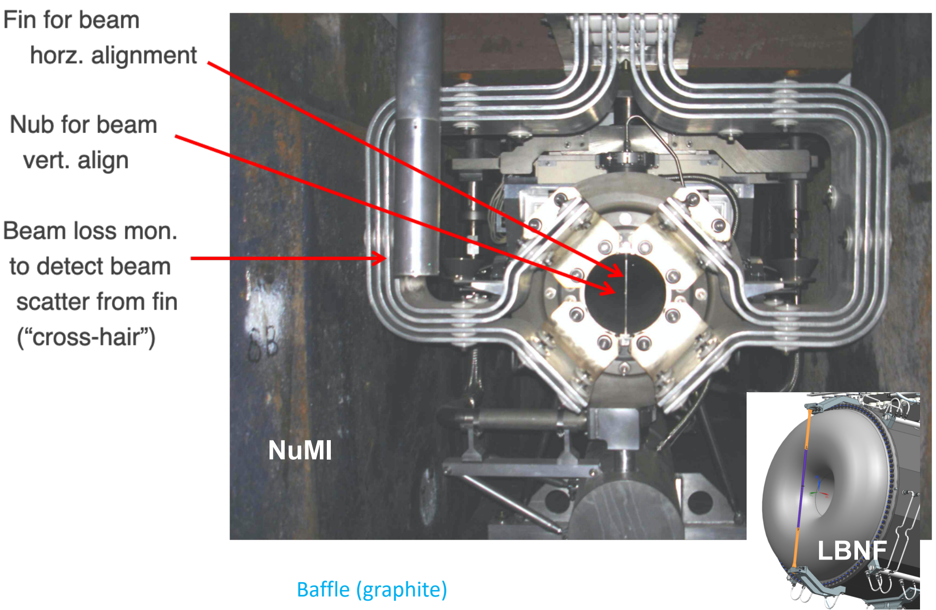
Optical Beam Loss Monitor (O-BLM)



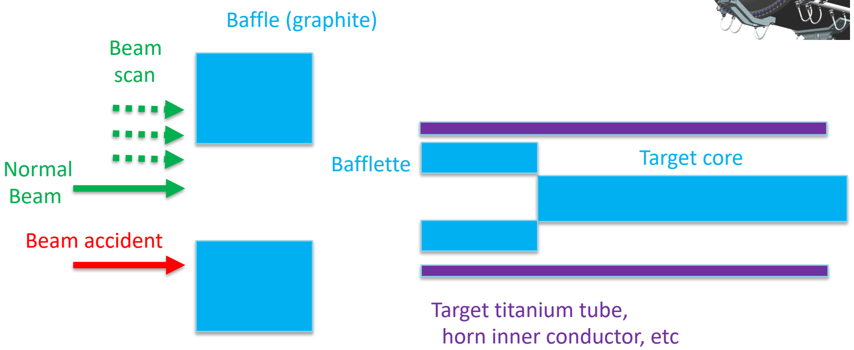
- Installed in 2021, covered 91m of beamline with only 3 channels.
- Plot above shows mapping of O-BLM timing to different points along the beamline.

Target and Horn Alignment



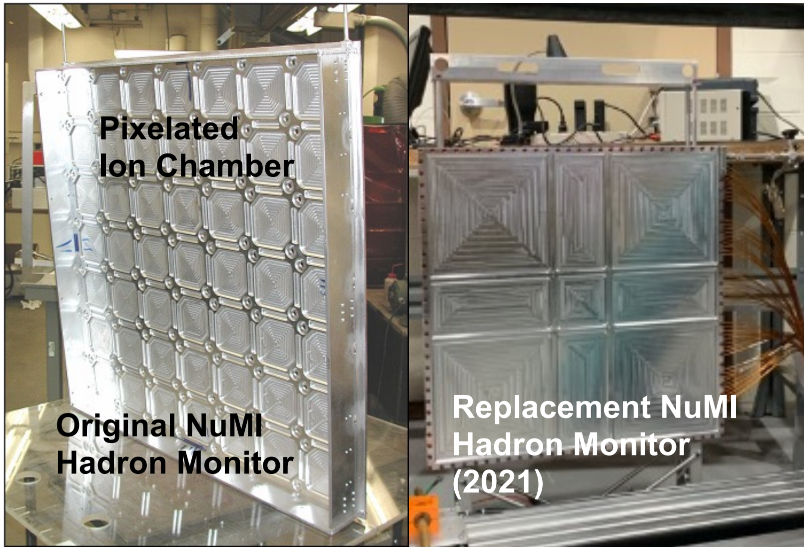


- Target and horns positions are determined via a beam scan across known features and measuring the scattering rate with different detectors:
  - Hadron monitor (misnomer, not really a monitor) located at end of decay pipe
  - Beam loss monitors

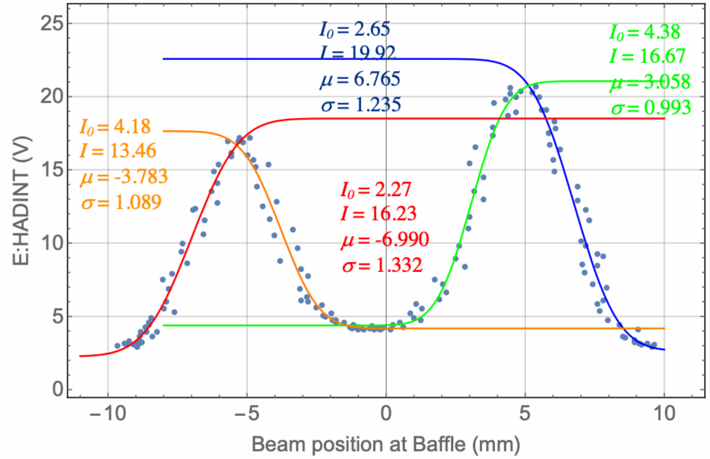


Baffle protects target utilities and horn from mis-steered beam. Bafflette protects decay pipe windows and absorber. Also use bafflette for alignment.

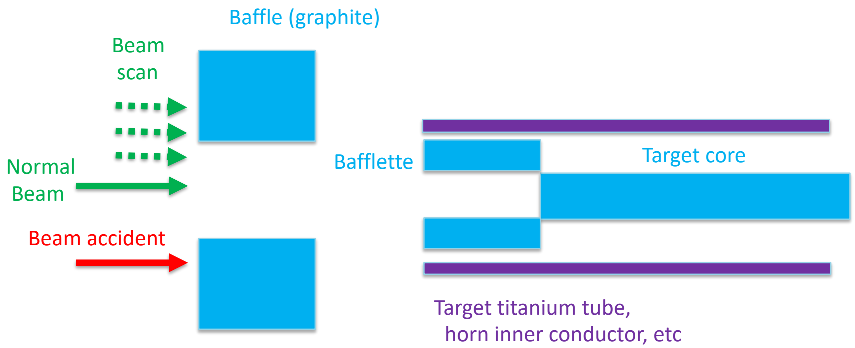
Target and Horn Alignment



- Target and horns positions are determined via a beam scan across known features and measuring the scattering rate with different detectors:
  - Hadron monitor (misnomer, not really a monitor) located at end of decay pipe
  - Beam loss monitors

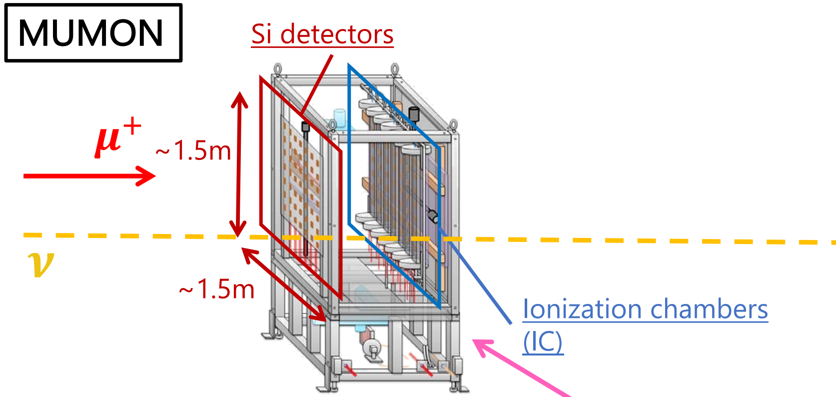


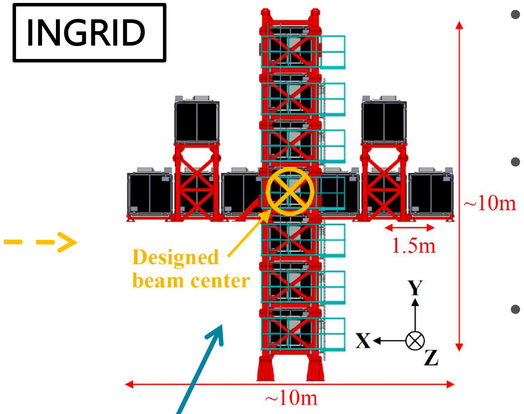
Baffle = -0.113 mm
Target = -0.362 mm

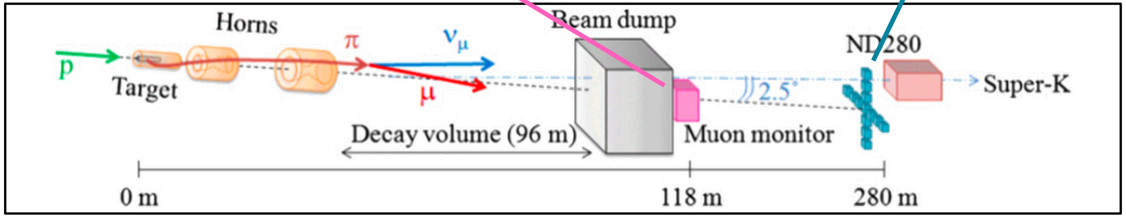


Baffle protects target utilities and horn from mis-steered beam. Bafflette protects decay pipe windows and absorber. Also use bafflette for alignment.

Muon and Neutrino Monitoring







- Ionization chambers used at both J-PARC and Fermilab to monitor the muon beam.
- J-PARC also has an array of Si PIN photodiodes to measure the muon beam profile.
- J-PARC uses the INGRID on-axis neutrino detector to monitor the muon-neutrino beam profile.
- No on-axis neutrino beam monitor at NuMI. DUNE will have one.

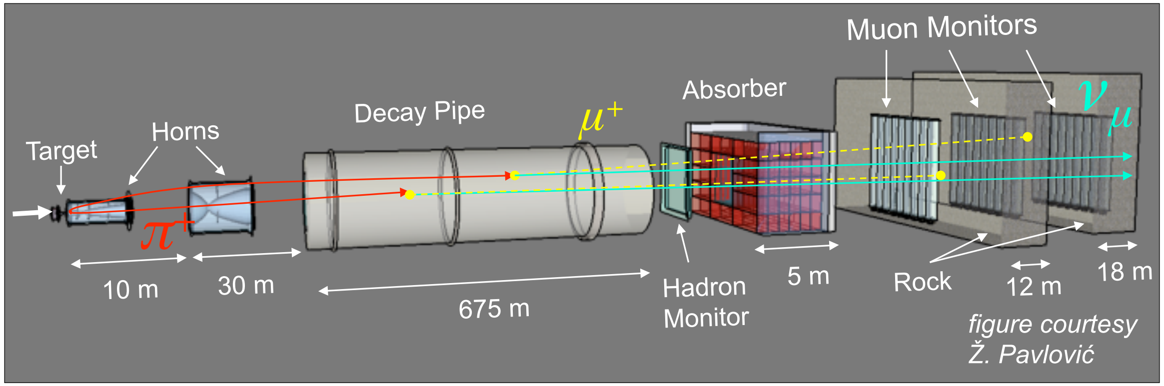
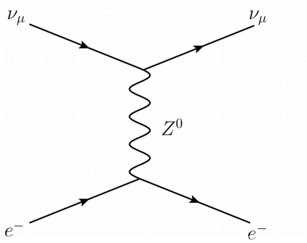


figure courtesy Ž. Pavlović

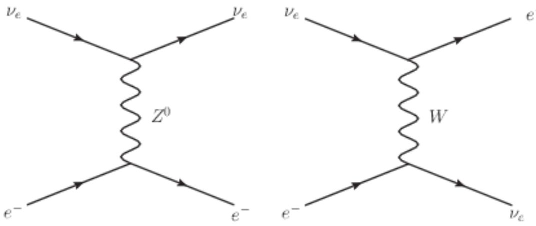
9x9 Ionization Chamber Pixels

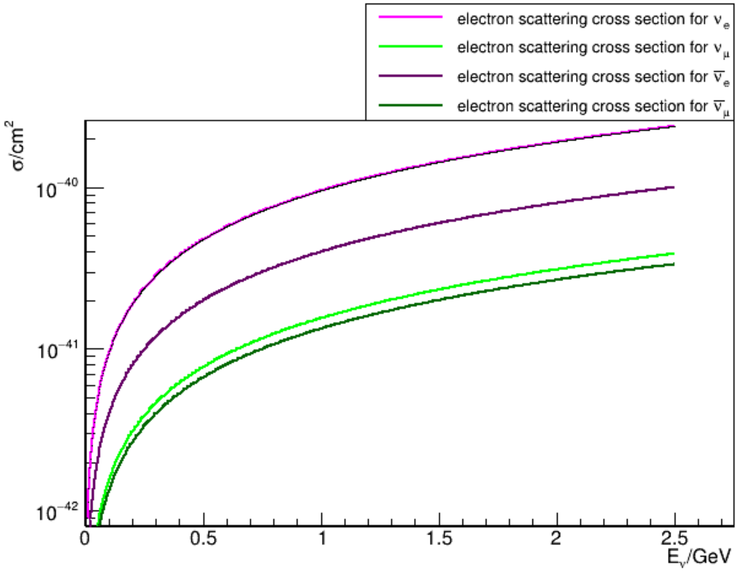
Neutrino-electron scattering

$$\nu_\mu + e^- \xrightarrow{\text{NC}} \nu_\mu + e^-$$



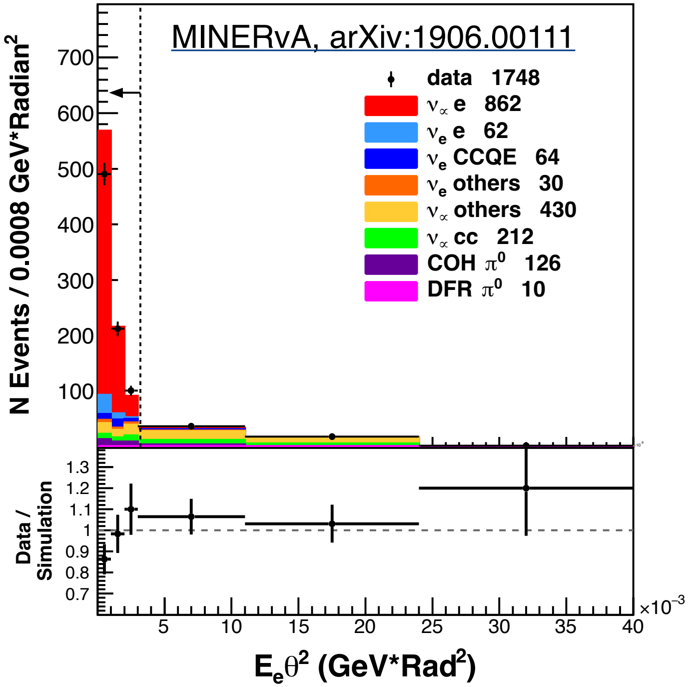
$$\nu_e + e^- \xrightarrow{\text{NC + CC}} \nu_e + e^-$$





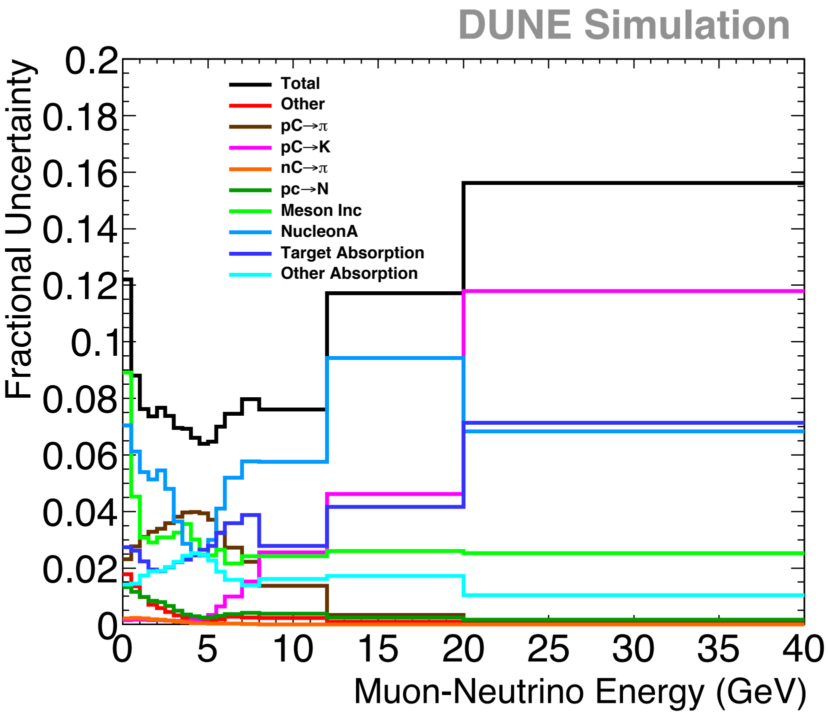
$$1 - \cos\theta_e = \frac{m_e(1-y)}{E_e}$$

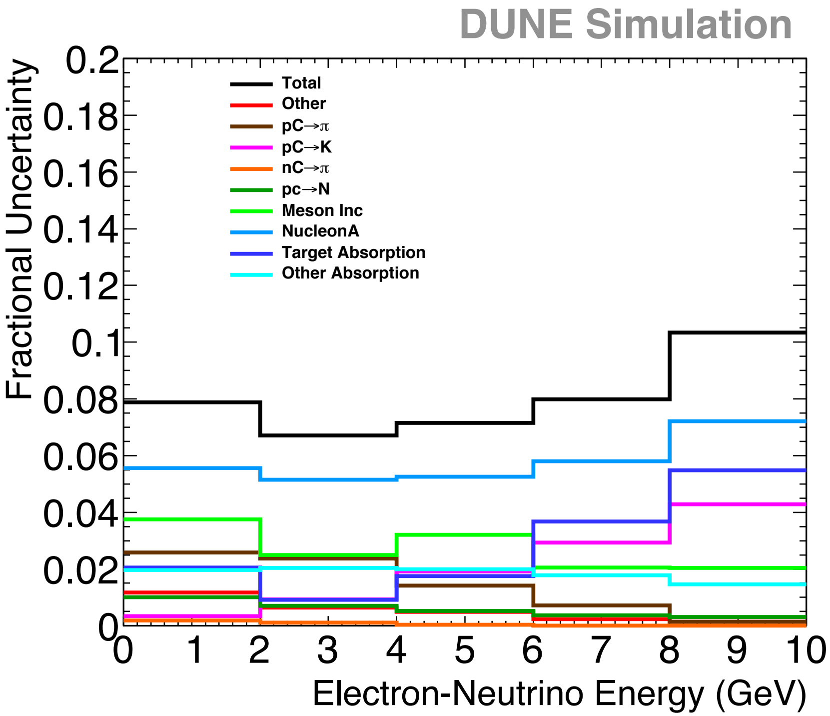
- A purely leptonic process, the theoretical uncertainty is ~1%
- Signature is a very forward-going electron only in the final state.
- In principle, a measurement of the electron angle gives a measurement of the neutrino energy.
- Note that the cross section is tiny, about 1/1000 that of the CC cross section!
- Provides a constraint on the total flux (all neutrinos and anti-neutrinos).
- MINERvA has used this to reduce their flux uncertainty to ~3.5%. DUNE expects to achieve 2%.



Ex-Situ Constraints

Neutrino Flux Uncertainties



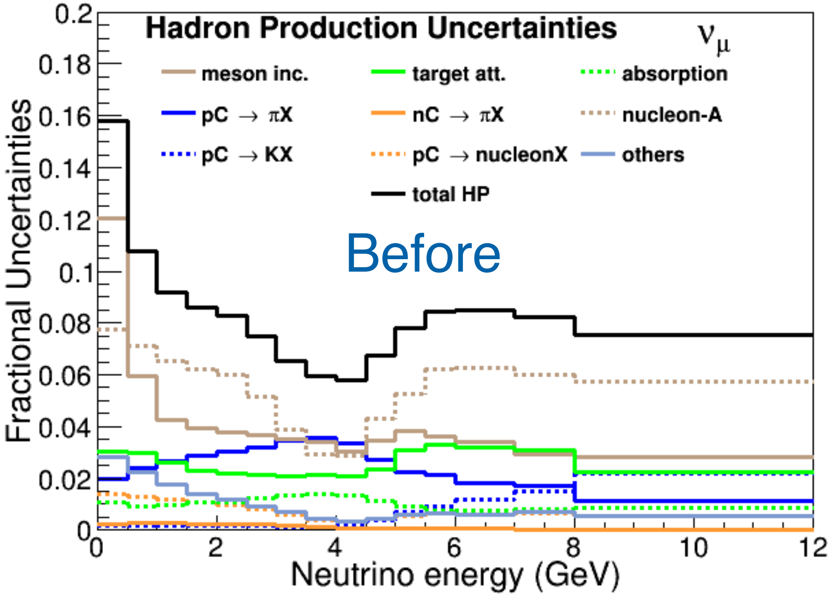


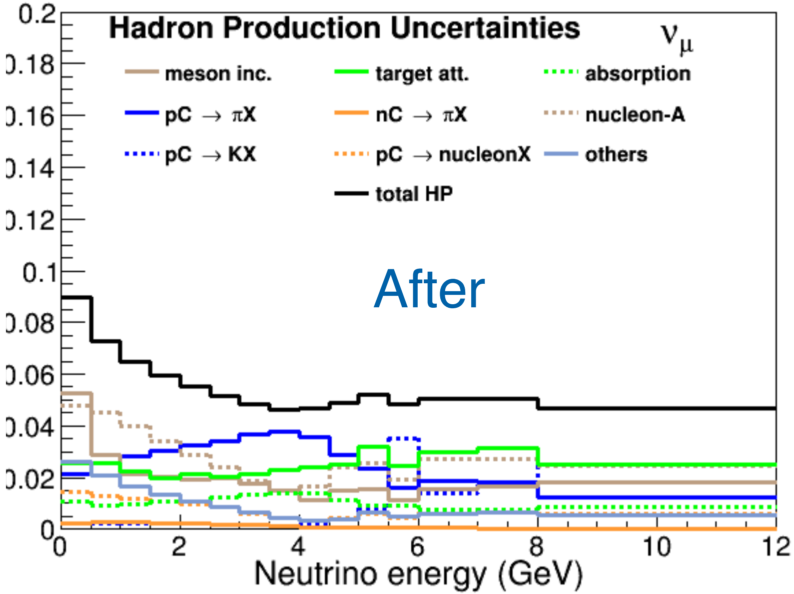
- Dominant flux uncertainties come from 40% xsec uncertainties on interactions in the target and horns that have never been measured (or have large uncertainties/spread).
- Lack of proton and pion scattering data at lower beam energies.
- **Reduction of flux uncertainties improves physics reach of most near detector analyses (cross-sections and BSM searches), and any non-3-flavor (PMNS) oscillation analysis.**
- **New hadron production measurements support the oscillation program by increasing confidence in the a-priori flux predictions and ND measurements.**

Hadron Production Uncertainties - Can we do better?

- Reasonably achievable uncertainty reduction:
  - No improvement for π production where ≲ 5% measurements already exist
  - 10% uncertainty for K absorption (currently 60-90% for p<4 GeV/c, 12% for p>4 GeV/c)
  - 10% on quasi-elastic interactions (down from 40%)
  - 10% on p,π,K + C[Fe,Al] —> p + X (down from 40%)
  - 20% on p,π,K + C[Fe,Al] —> K± + X (down from 40%)

Not covered by current data

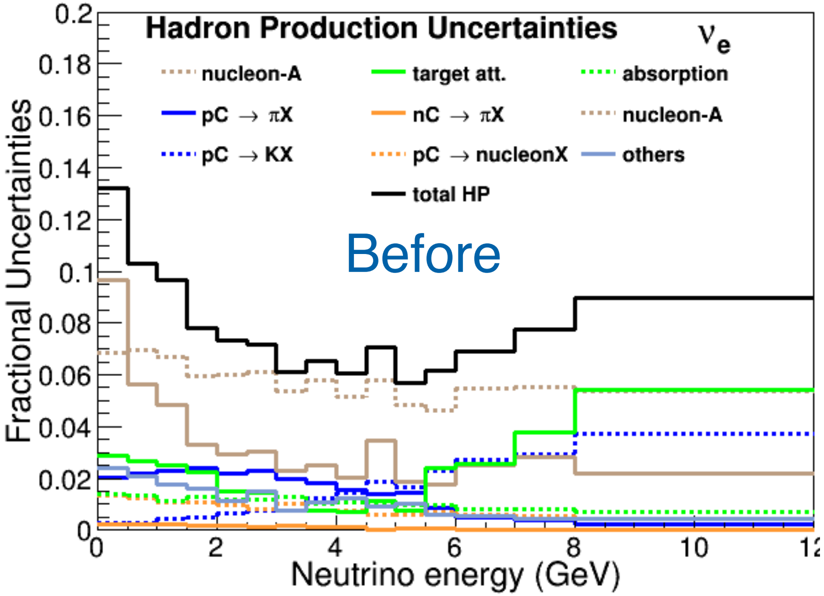


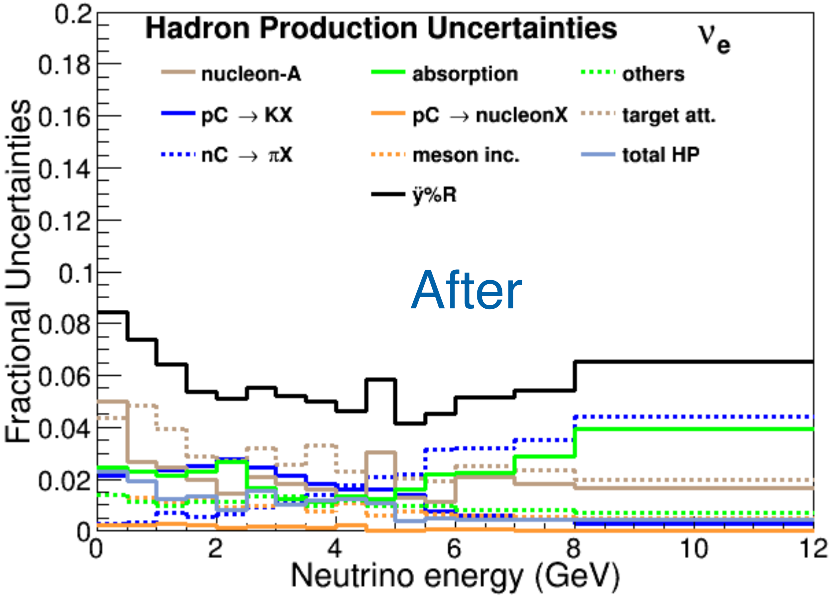


Note: flux uncertainties determined by EMPHATIC, not DUNE

Hadron Production Uncertainties - Can we do better?

- Similar observations for the electron-neutrino flux.

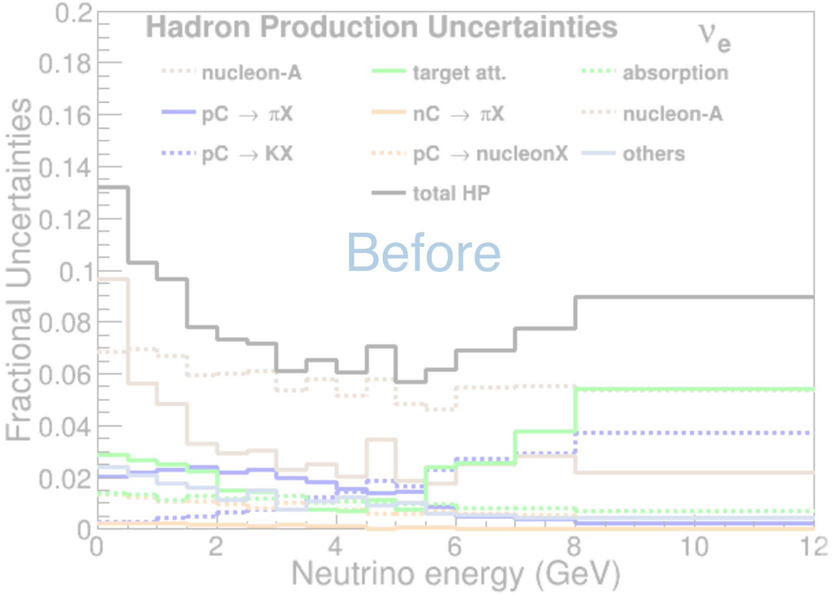


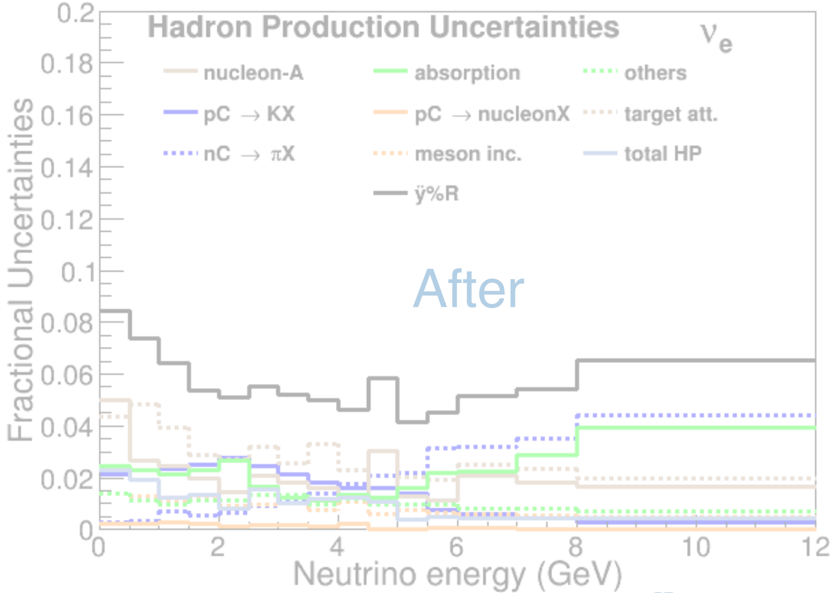


Note: flux uncertainties determined by EMPHATIC, not DUNE

Hadron Production Uncertainties - Can we do better?

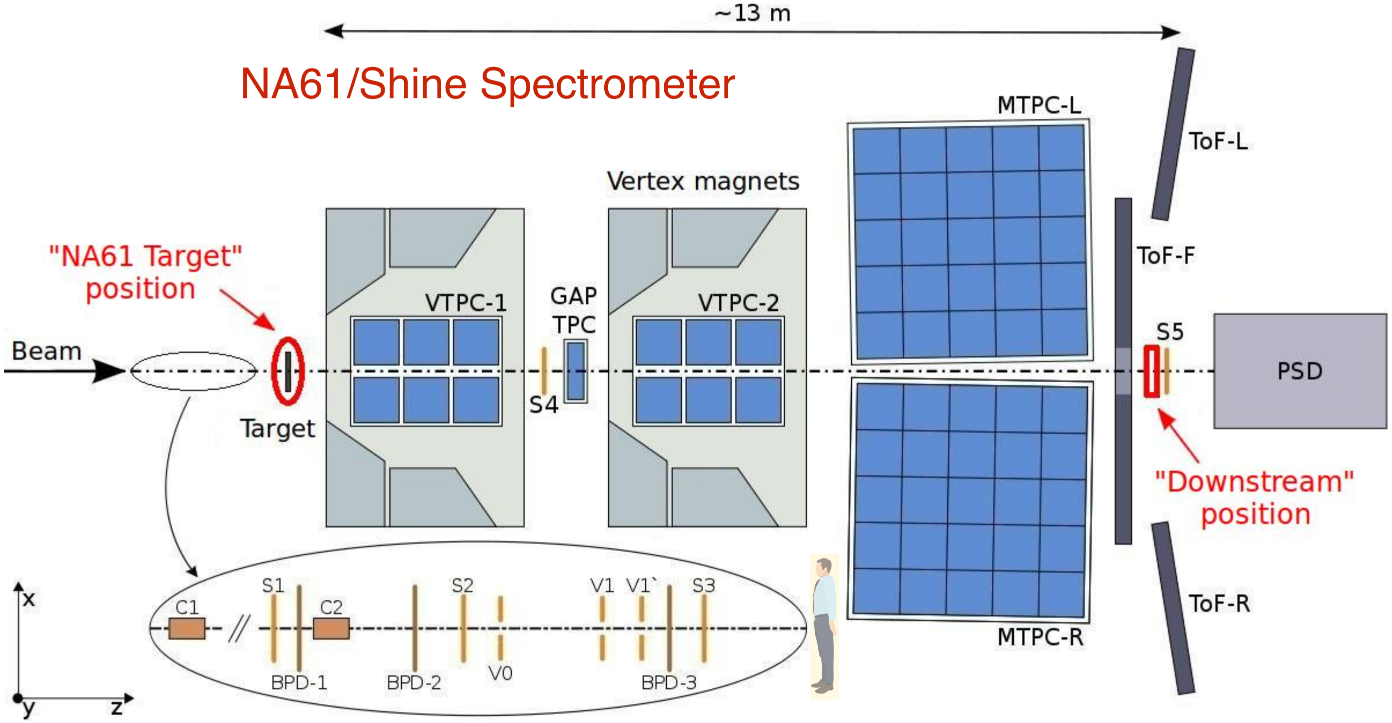
Note: we care about more than just reducing uncertainties! Many of the interactions we have to simulate in the target and horns are unconstrained by external data. New data will give us a more ROBUST flux prediction.





Note: flux uncertainties determined by EMPHATIC, not DUNE

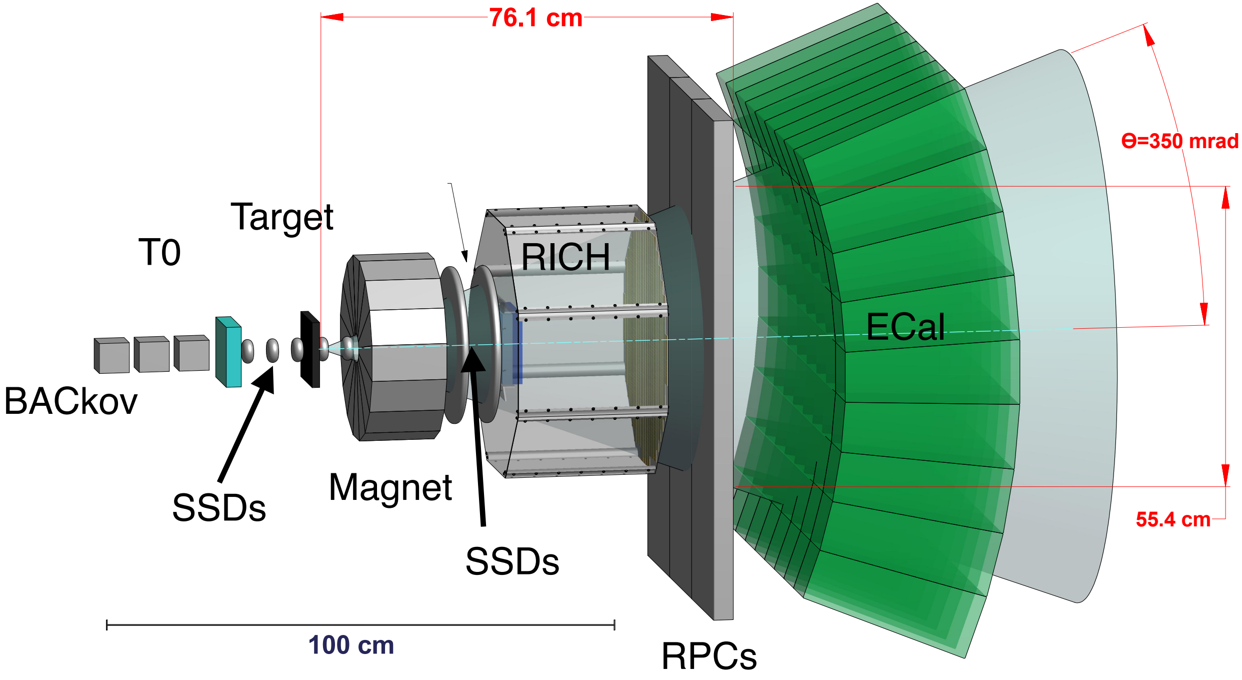
Hadron Production - A Global Effort



- The NA61/SHINE experiment at CERN: high-acceptance spectrometer with dE/dx and ToF measurements to identify particles. Designed for beam momenta p > 20 GeV/c, but they are hoping to re-arrange their beamline in order to collect data for p < 15 GeV/c.
- Operational for 15+ years.
- **Capable of measuring particle spectra produced in long neutrino targets.**

EMPHATIC

- **E**xperiment to **M**easure the **P**roduction of **H**adrons **At** a **T**est beam **I**n **C**hicagoland
  - Uses the FNAL Test Beam Facility (FTBF) (eg, MTest)
  - Table-top size experiment, focused on hadron production measurements with p_{beam} < 15 GeV/c, but will also make measurements with beam from 20-120 GeV/c.
- Ultimate design:
  - 350 mrad acceptance, compact size reduces overall cost
  - high-rate DAQ, precision tracking and timing
- International collaboration, with involvement of experts from NOvA/ DUNE/SBN and SK/T2K/ HK.



EMPHATIC

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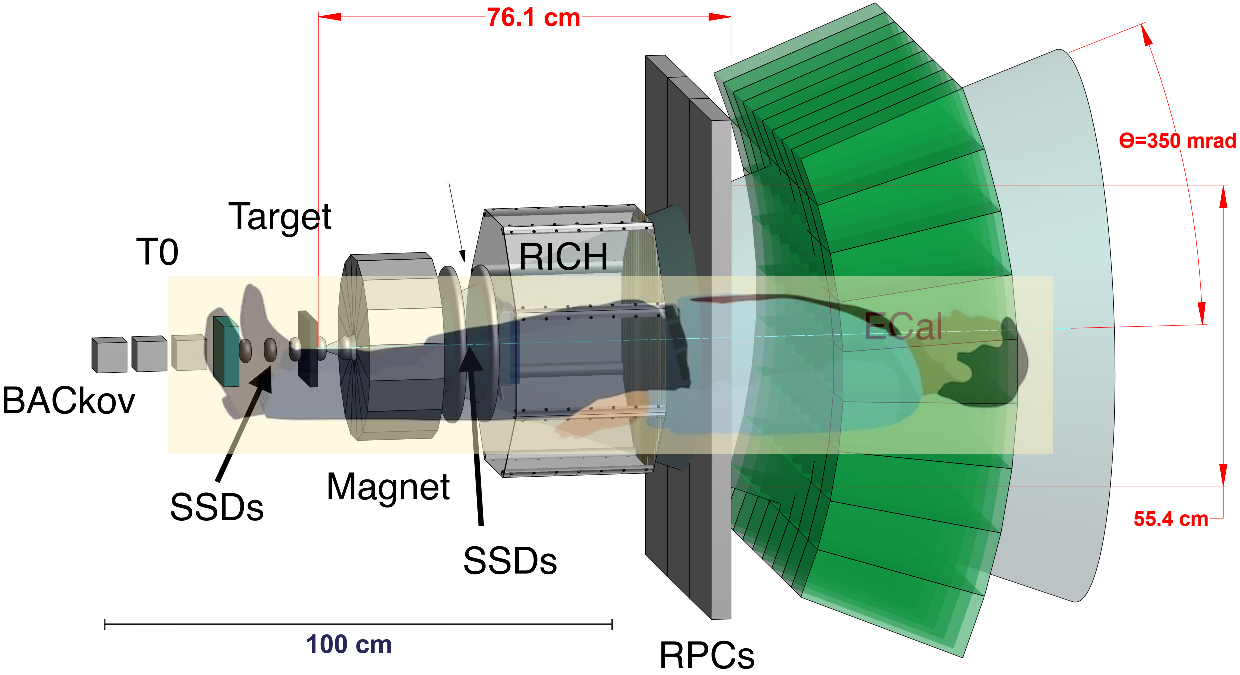
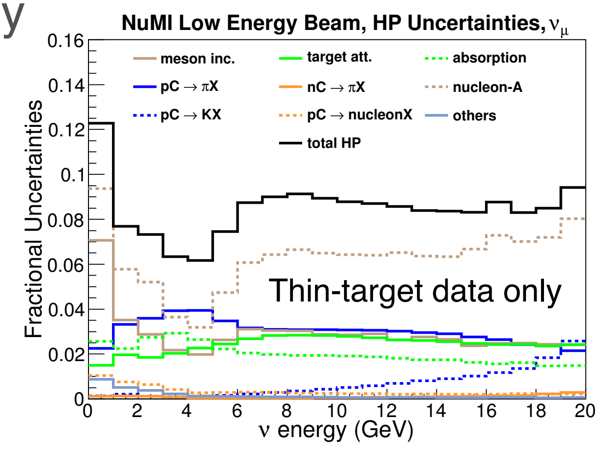


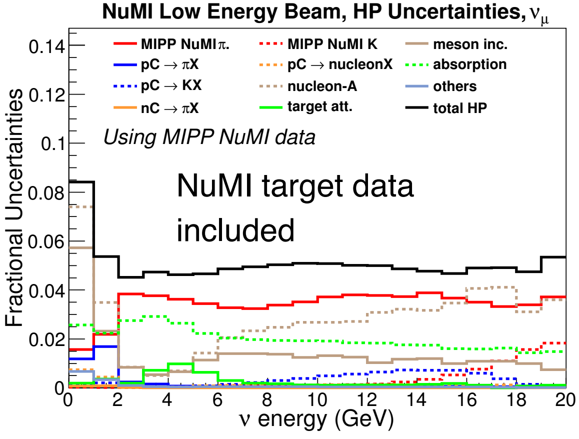
Future Prospects

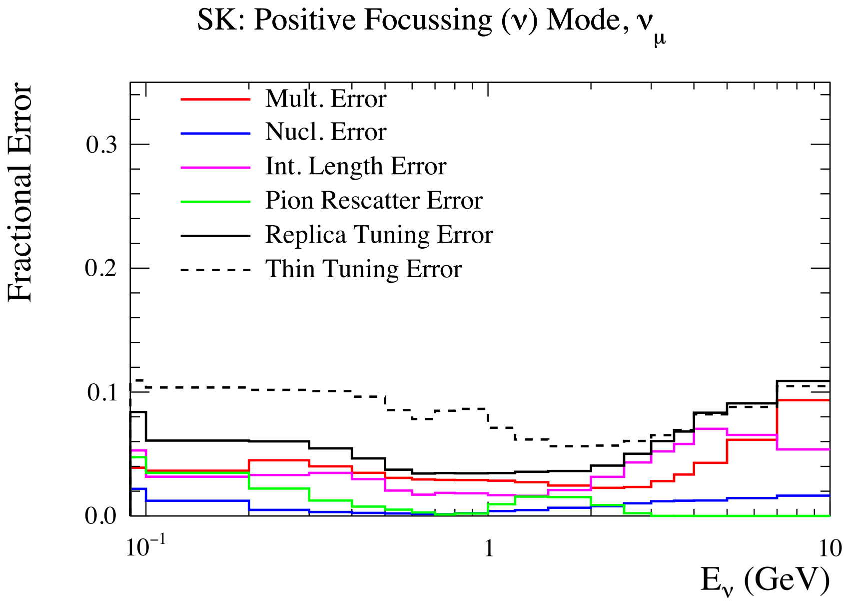
Neutrino Production Target Measurements

- Thin-target measurements are extremely useful and generally necessary for improved flux predictions (atmospheric neutrinos too!)
- Measurements by MIPP and NA61/SHINE of hadron production off real (or replica) targets can further reduce the HP uncertainties by nearly a factor of 2.
- NA61/SHINE has collected data using a replica NOvA-era NuMI target, and plans to collect data with a **prototype LBNF target next year. It is also considering collecting data at lower beam momenta in a couple of years.**

From L. Aliaga, Ph.D. thesis

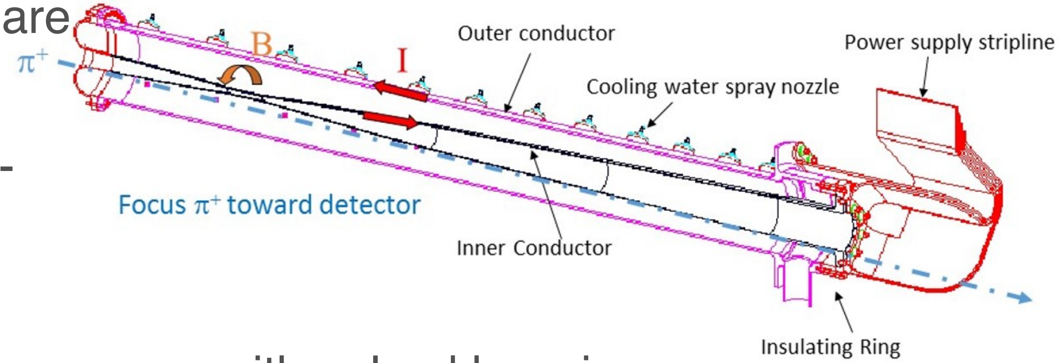




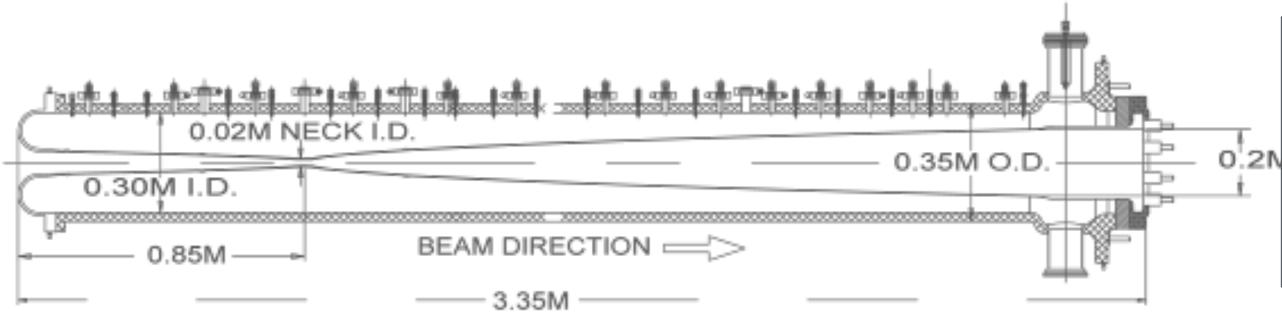


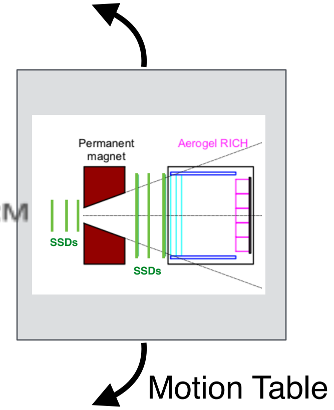
EMPHATIC Phase 2 - Beyond Target HP Uncertainties

- Put EMPHATIC Phase 1 spectrometer on a motion table downstream of spare NuMI horn and target.
- Minimal goal is to measure charged-particle spectrum downstream of target+horn.



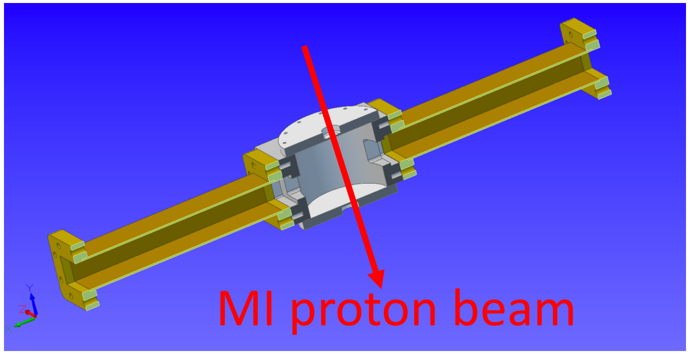
- Power supply also available; hope to measure with pulsed horn in the future.
- Establishes program to address questions re: HP in horns and modeling of horn geometry and magnetic field.



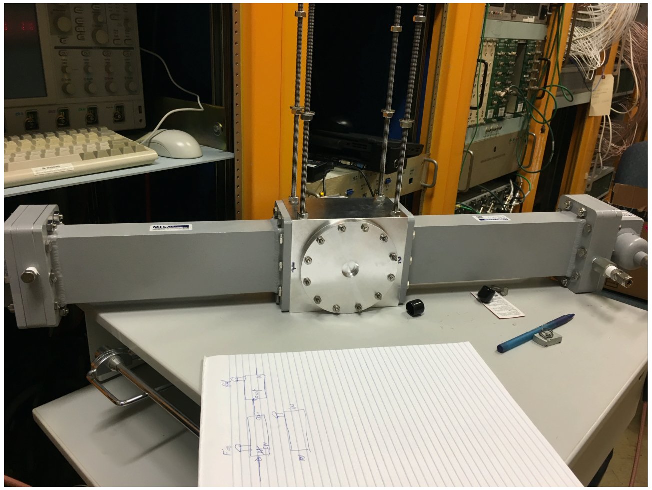


Motion Table

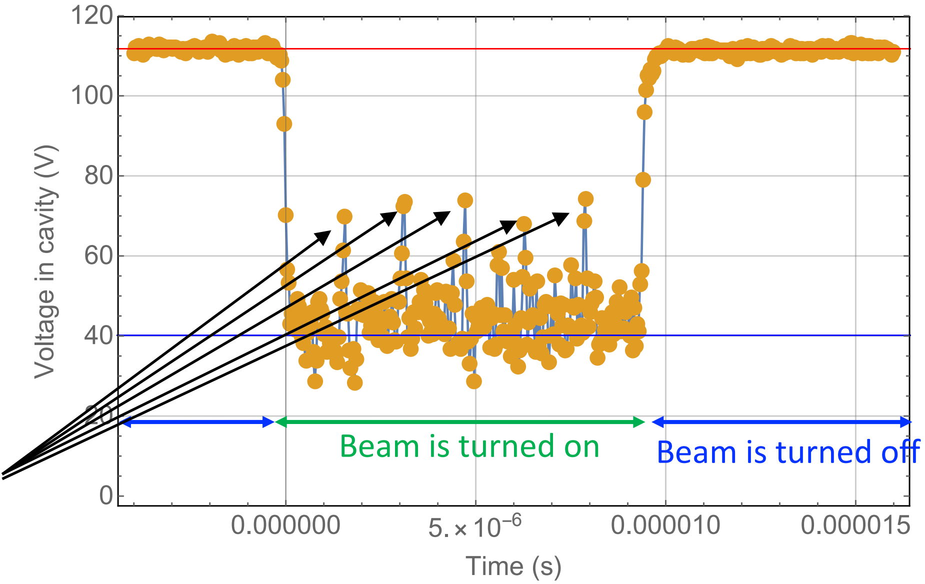
Improved Monitoring of Hadrons Downstream of the Target



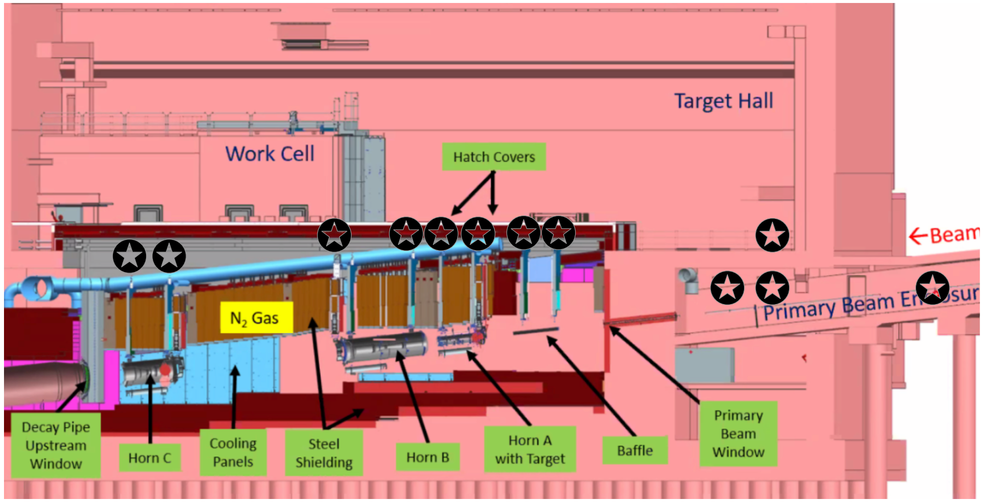
Yonehara, NBI 2019

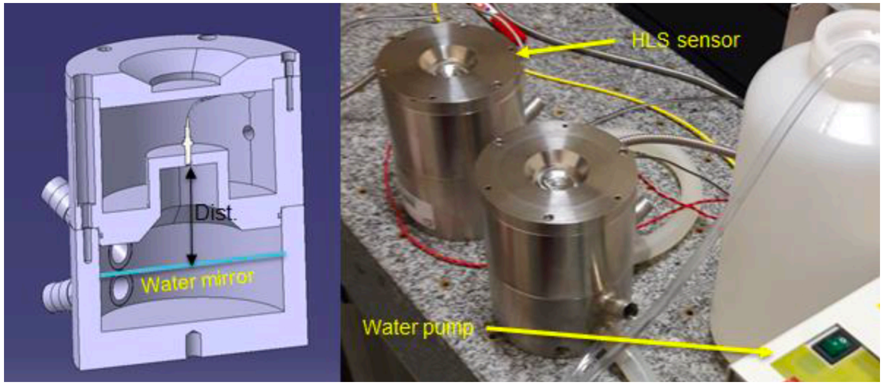


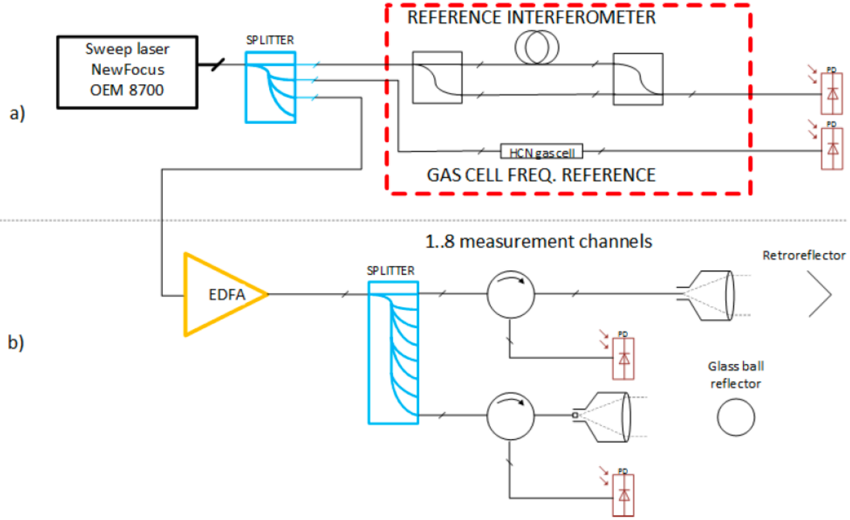
- Measure amount of ionization gas plasma in an RF resonator by measuring gas permittivity which is proportional to the intensity of charged particles passing through: $\varepsilon = \varepsilon_r + i\varepsilon_i$
- Detector is rad-hard.
- Proof-of-principle test in 2019 using Fermilab Main Injector 120 GeV protons.
- Five peaks shows the six (6) Main Injector batch structure!



Monitoring The Horn Positions

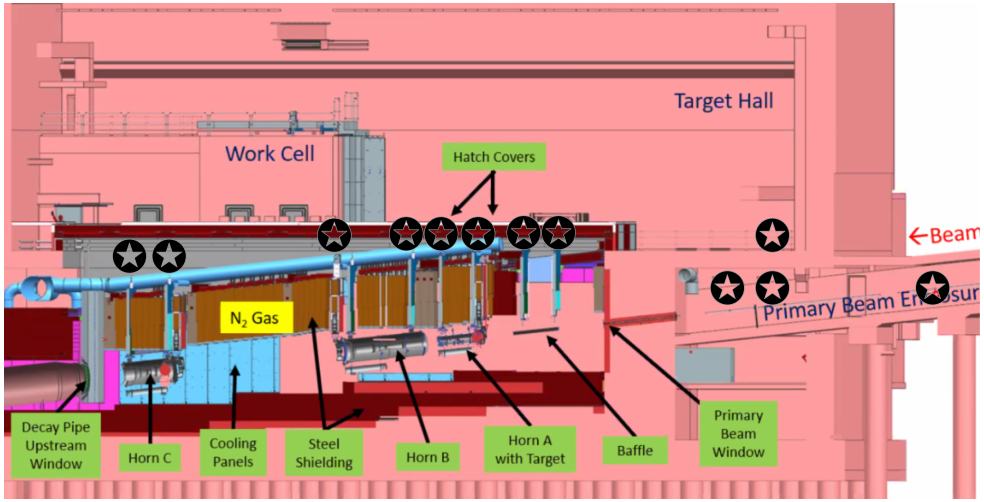


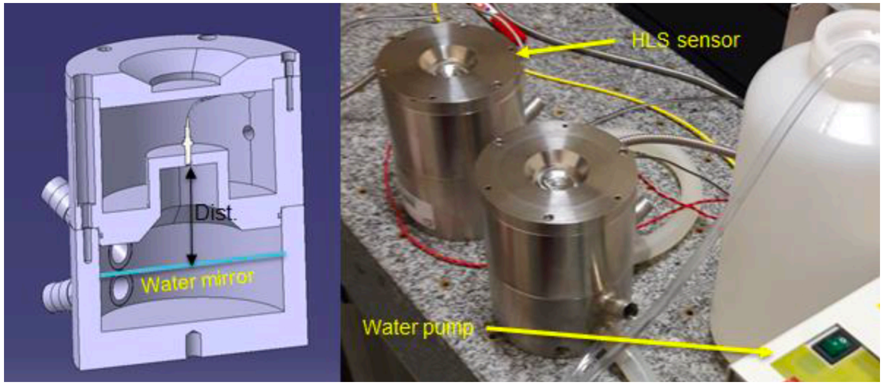


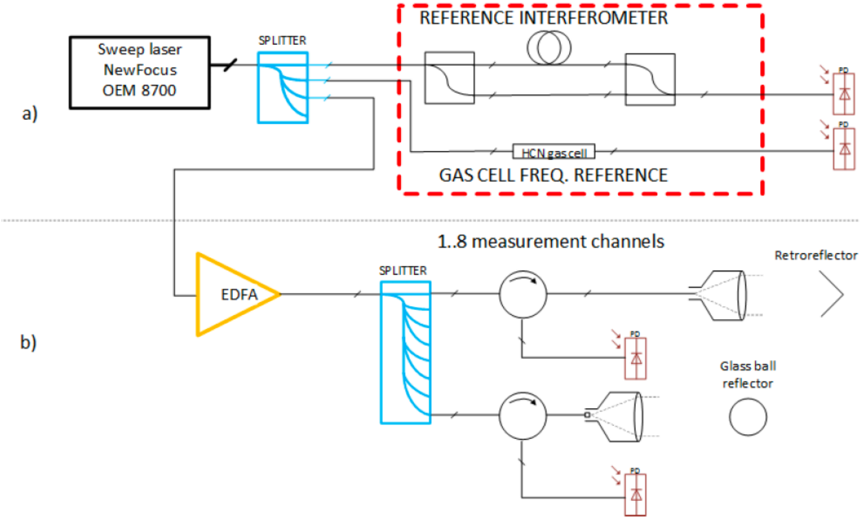


- Want independent measurement of height of all relevant beam components, especially the horns.
- System based on CERN’s hydrostatic leveling sensor for HL-LHC.
- Sensors connected by water pipe/tubing. Change in height of a sensor results in change in height of water.

Monitoring The Horn Positions

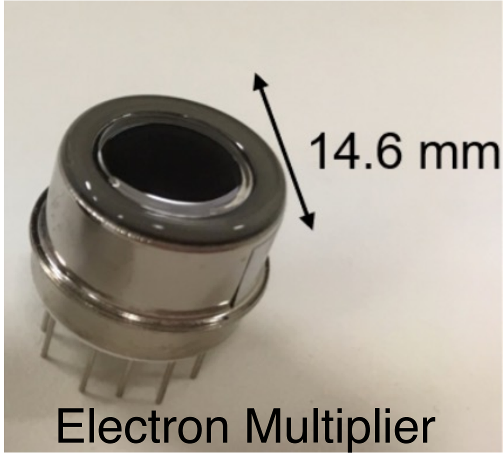




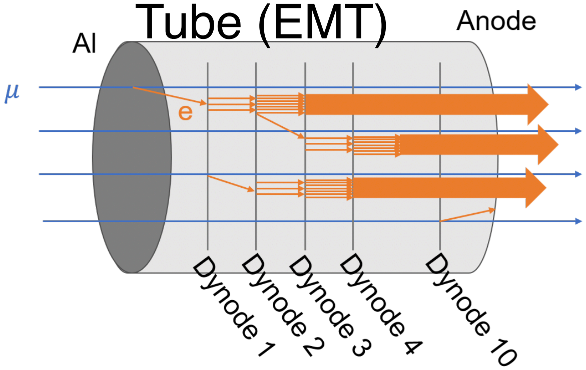


- Frequency scanning interferometry: part of light is reflected back from water surface, creating “beat” frequency signal in interferometer FFT spectrum.
- Measurement uncertainty < 5 μm.
- Prototype design nearly complete.
- Prototype tests will begin in early 2022.

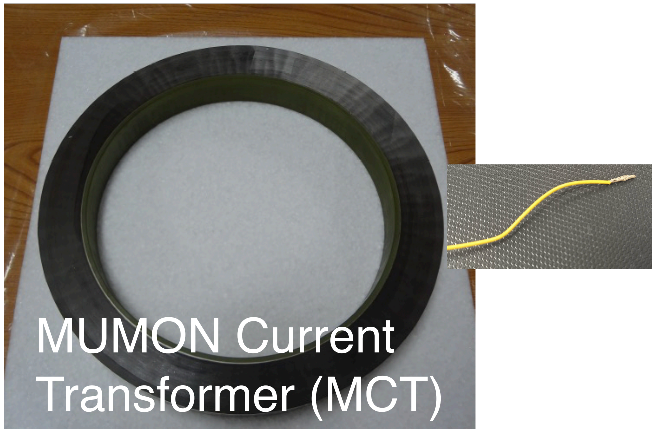
R&D for Improved Muon Monitoring



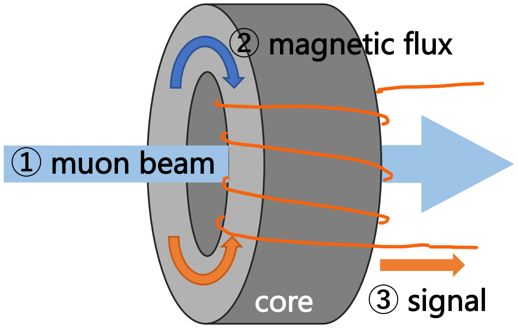
Electron Multiplier Tube (EMT)



Nakamura, NuFact '21



MUMON Current Transformer (MCT)



- EMTs are like PMTs but photocathode has been replaced with aluminum-coated surface. Electron beam tests have shown EMTs maintain stability to within 3% for at least 100 days at 1.3 MW, and have a sufficiently linear response.
- MCTs are a simple design, require no power, and are rad-hard. Muons passing through core of MCT induce a current in the wrapped coil. Current is proportional to muon beam flux.

R&D for Improved Muon Monitoring

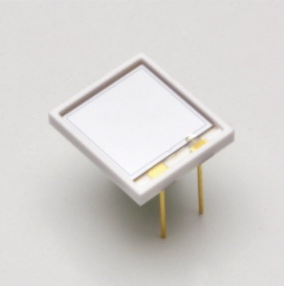
Nakamura, NuFact ‘21

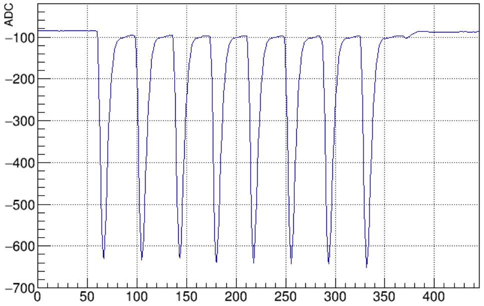
Neutrino mode

Anti-neutrino mode

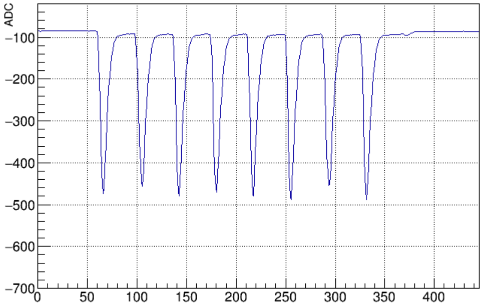
data

Si detector



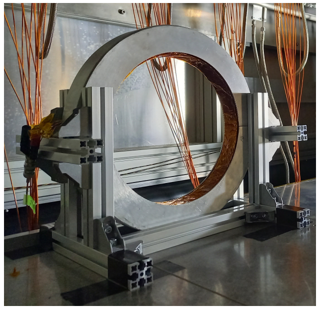


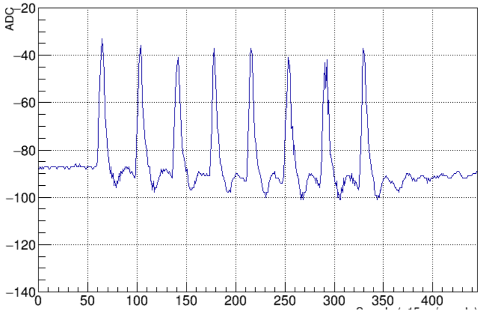
Sample (~15ns/sample)



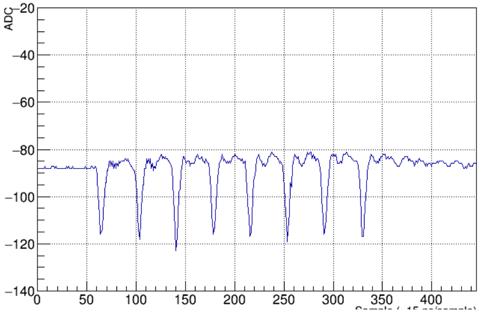
Sample (~15ns/sample)

MCT





Sample (~15ns/sample)



Sample (~15ns/sample)

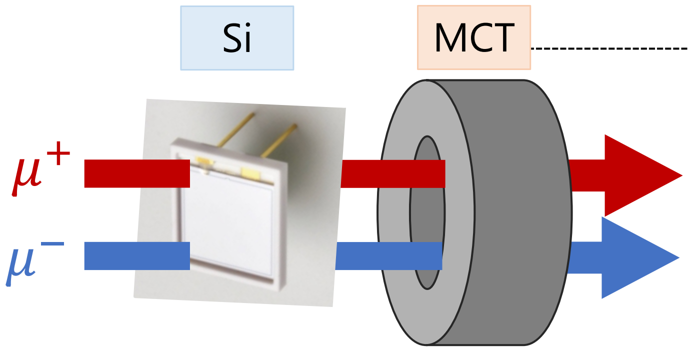
The MCT signal was flipped in neutrino and anti-neutrino modes.

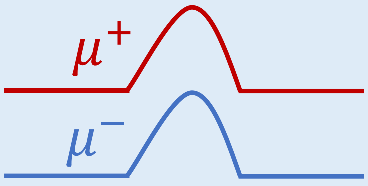
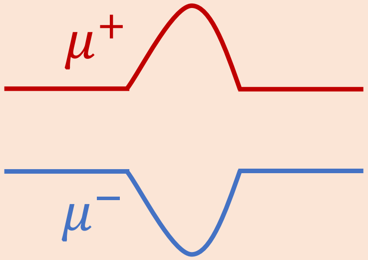
→ First observation of the muon polarity change at MUMON!

Future task: estimate the number of particles passing through the MCT using the signal.

R&D for Improved Muon Monitoring

Nakamura, NuFact ‘21



	Si detector or EMT	MCT
Features	When a particle with a charge of the opposite sign passes through…	
	Response independent from the sign of the charged particles	Response depend on the sign of the charged particles
		
Signal size	Proportional to the sum of μ^+ and μ^-	Proportional to the difference between μ^+ and μ^-
	Signal = $\alpha(N_+ + N_-)$	Signal = $\beta(N_+ - N_-)$

- Sign of current in MCT depends on sign of charged particles!
- Combining information from both could be used to constrain the wrong-sign component of the [anti-]neutrino beam.
- Studies are underway to determine sensitivity of measurements using this approach.

Summary

- Flux never “just cancels” in 2-detector neutrino oscillation experiments. Flux uncertainties are a limiting systematic on many single-detector measurements and searches for BSM.
- The primary, secondary (muons) and tertiary (neutrino) beams are all measured and monitored in real-time to provide in-situ constraints on the beam.
- Ex-situ measurements of hadron scattering and production off both thin- and thick-targets are critical to constraining the flux.
- New hadron production data are needed to further reduce neutrino flux uncertainties, enabling precision cross section measurements and more sensitive searches for BSM.