Constraining Accelerator-Based Neutrino Flux Predictions and Uncertainties

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Fermilab Neutrino Division

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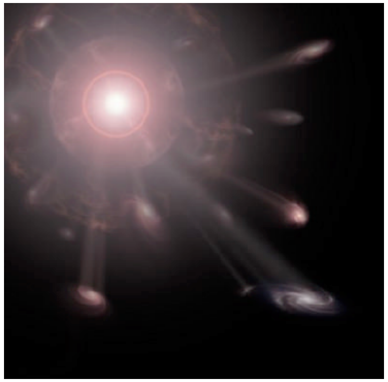
NuFact @ Argonne

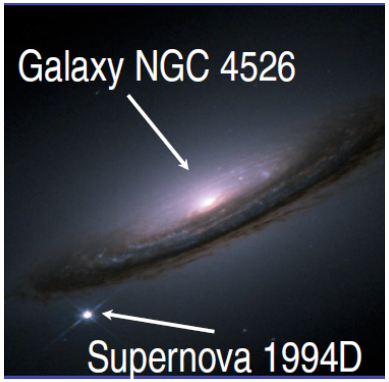
Outline

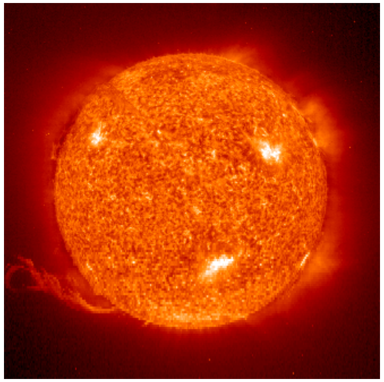
- Overview of neutrino sources and beams
- Why neutrino flux predictions matter
- Where do neutrino flux uncertainties come from
- How we constrain flux and uncertainties
  - In-situ measurements
  - Ex-situ measurements
- Future Prospects

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!

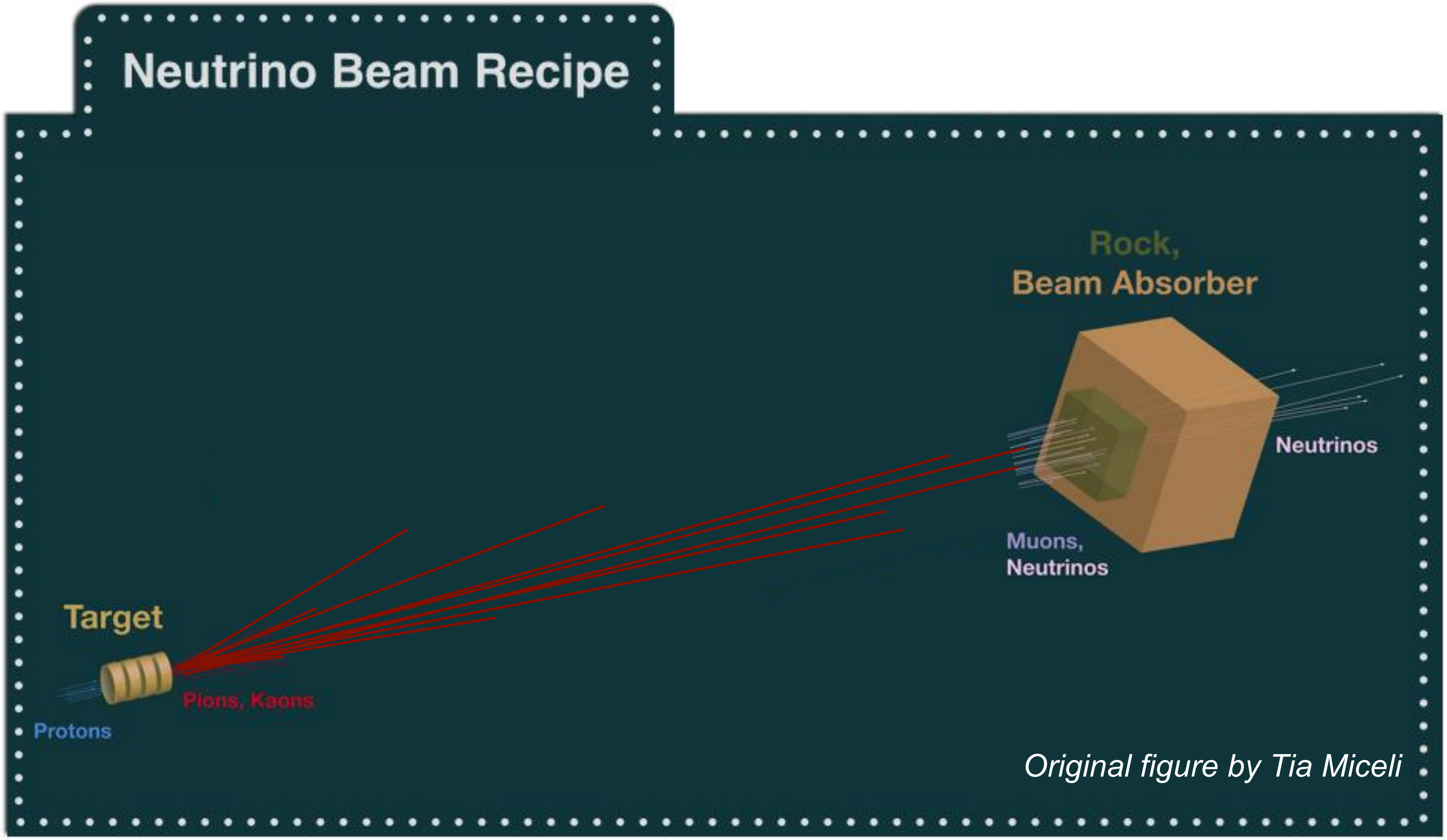






Swiss Chard - has more potassium than bananas!

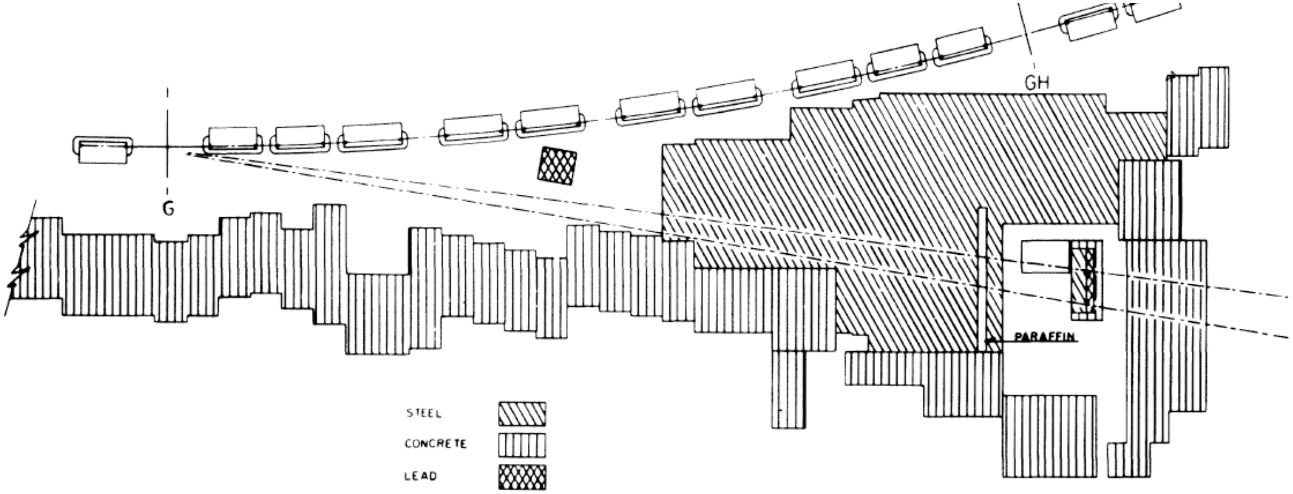
How to Make a Neutrino Beam



Original figure by Tia Miceli

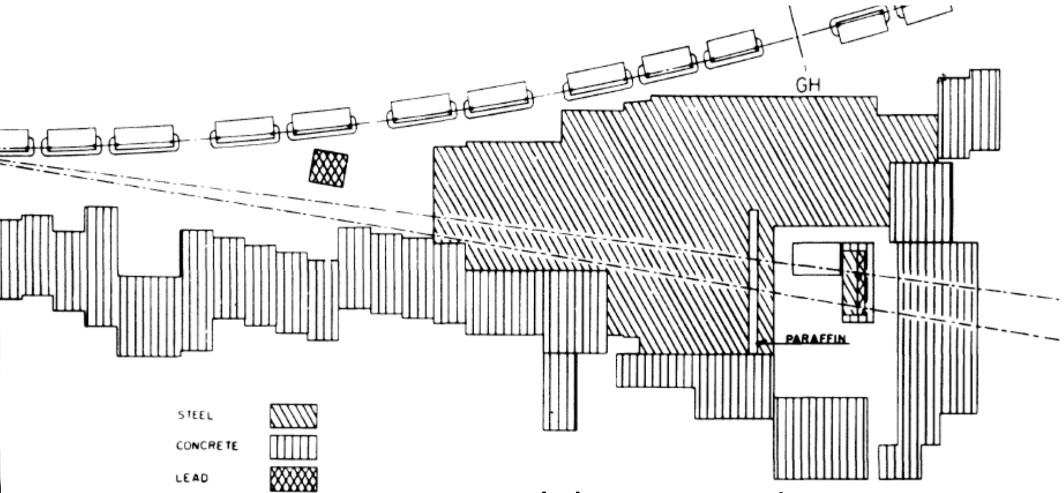
- Smash high-energy proton into a target (graphite, beryllium), creating showers of hadrons including pions and kaons.
- Pions and kaons decay, leaving muons and neutrinos. Muons are then absorbed, leaving a beam of neutrinos.

How to Make a Neutrino Beam



- 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

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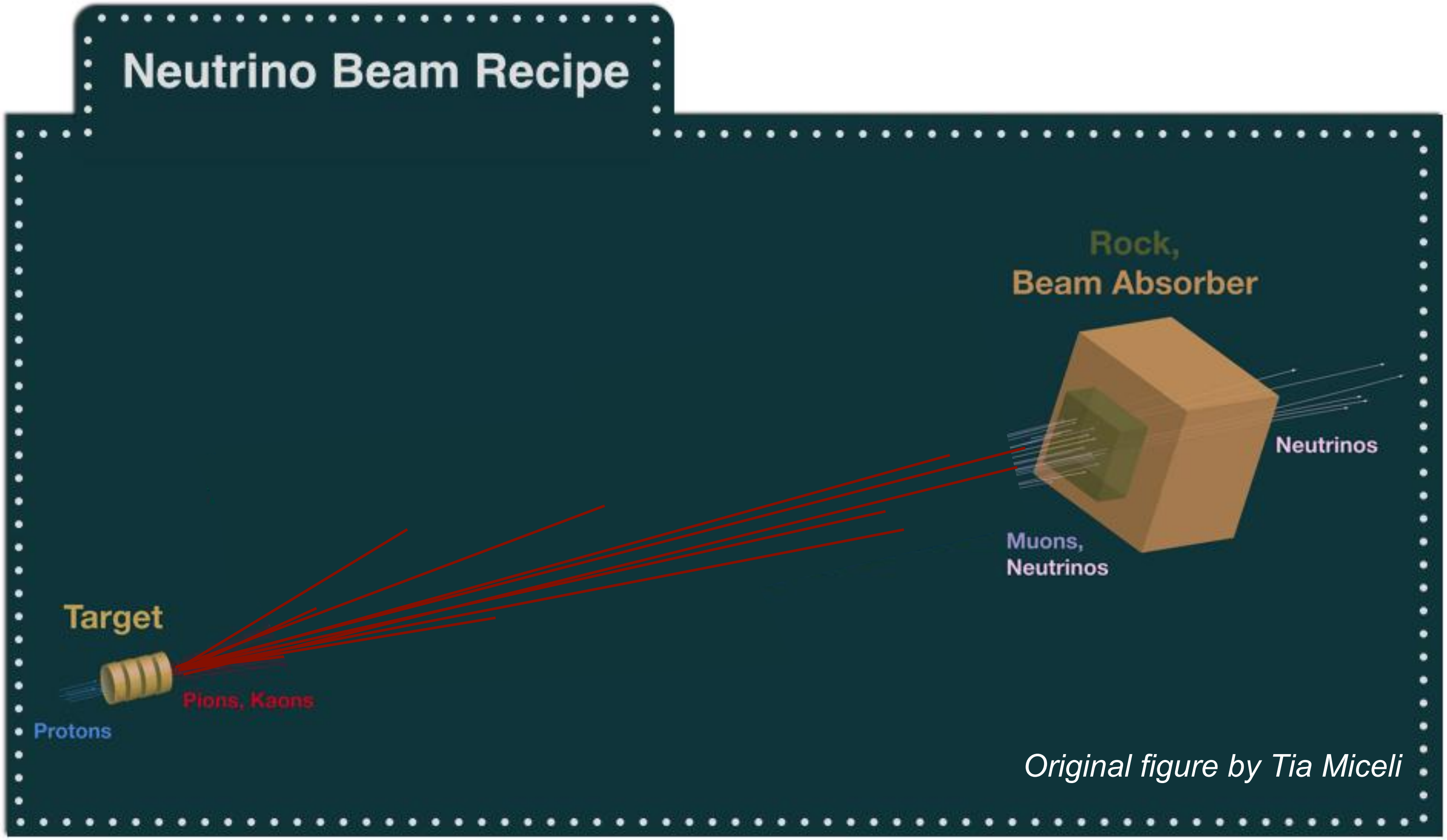
- 15 GeV proton beam struck Be target, producing secondary hadrons (mostly π's)
- π's decay to neutrinos and muons. Muons are stopped in an absorber.
- Neutrinos interact in detector (spark chamber) to produce electrons and muons.
- **Led to the discovery of the muon neutrino!**

How to Make a Neutrino Beam



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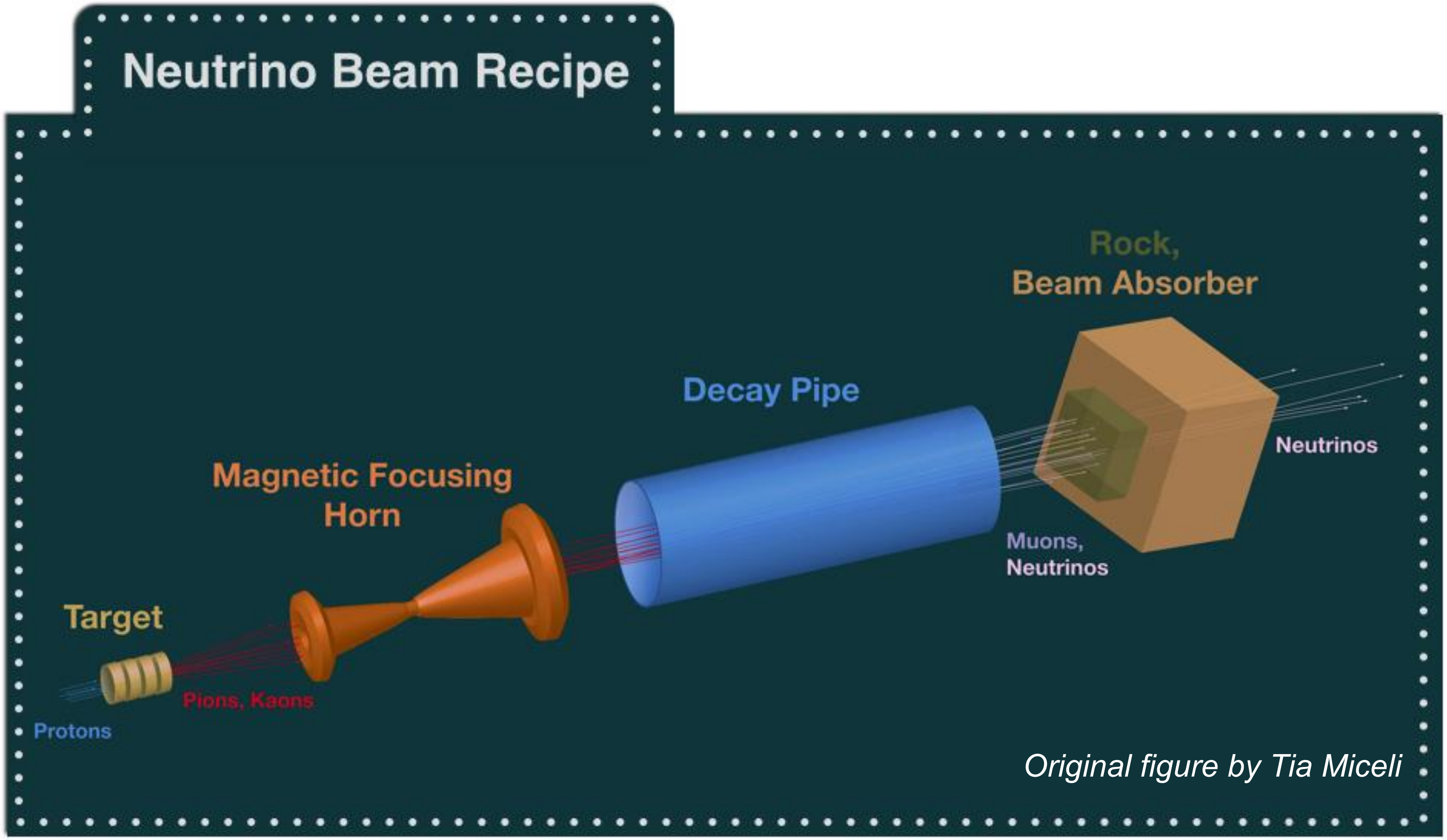
How to Make a Neutrino Beam

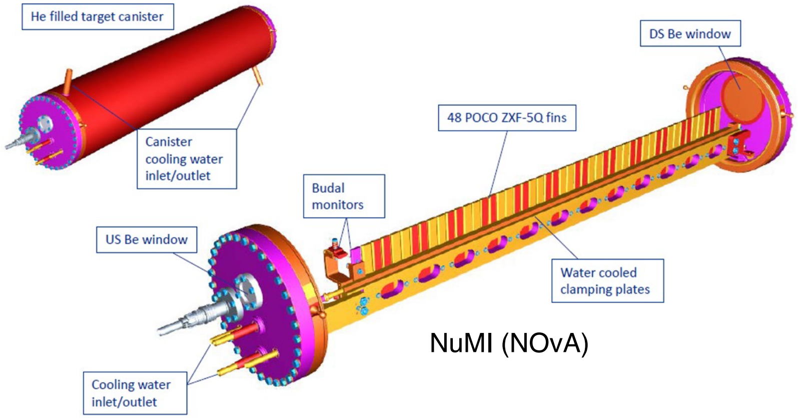


Original figure by Tia Miceli

- 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% muon neutrinos or anti-muon neutrinos).
  - Long decay pipe to allow more hadrons to decay. Often filled with helium.

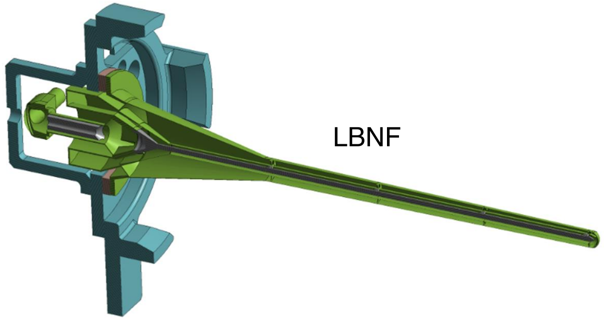
Neutrino Production Targets


BNB



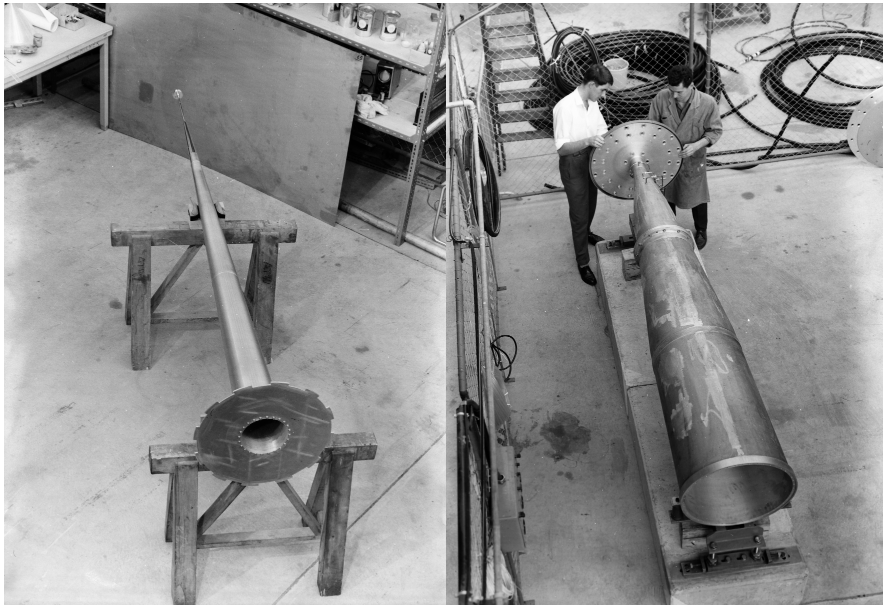
NuMI (NOvA)

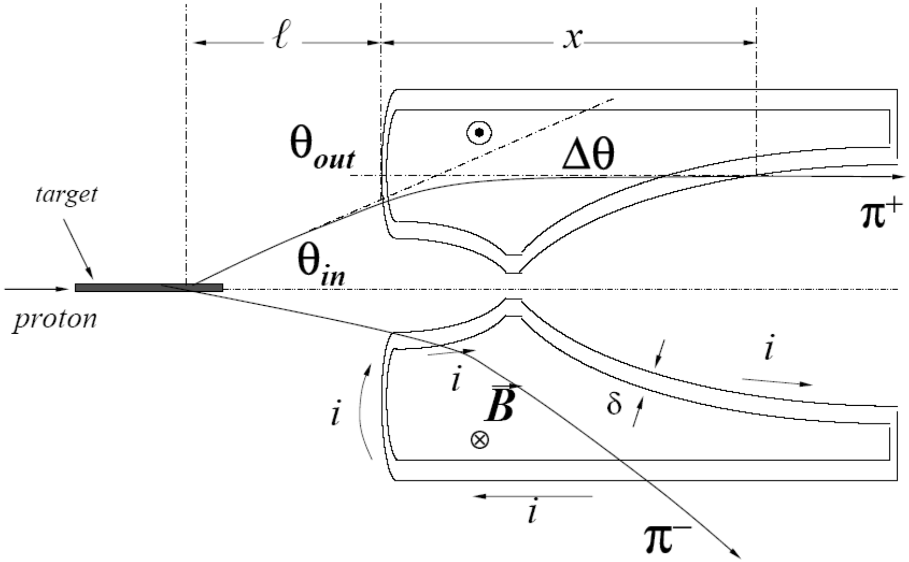

T2K (replica)


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.

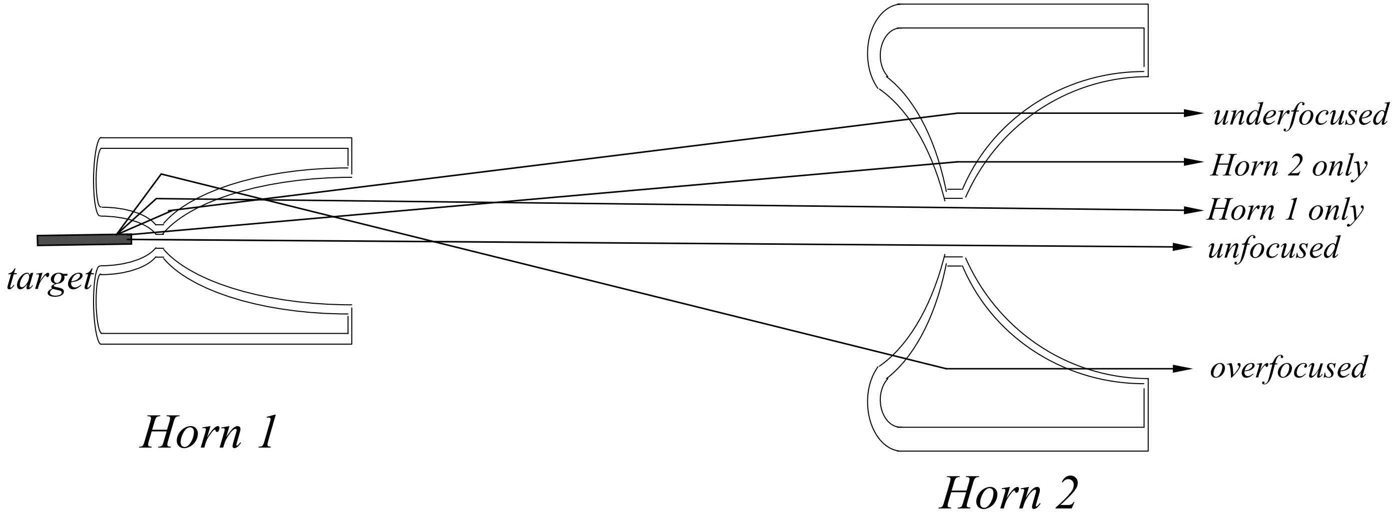
Focusing Horn Systems





- 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!).

Focusing Horn Systems



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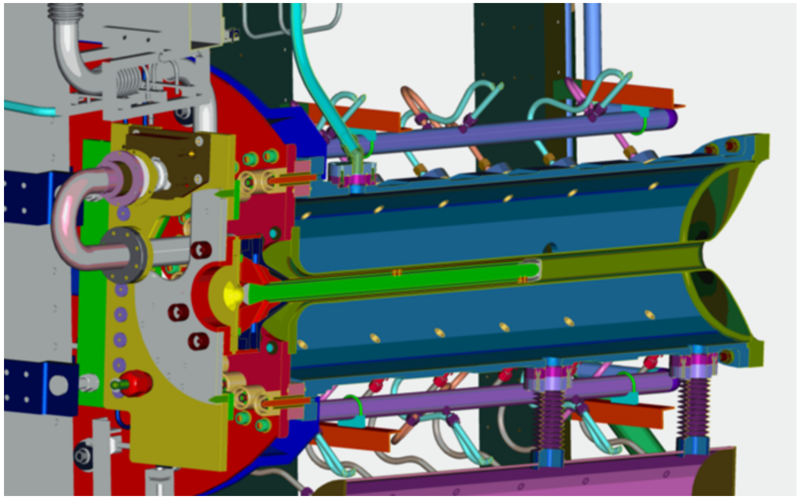
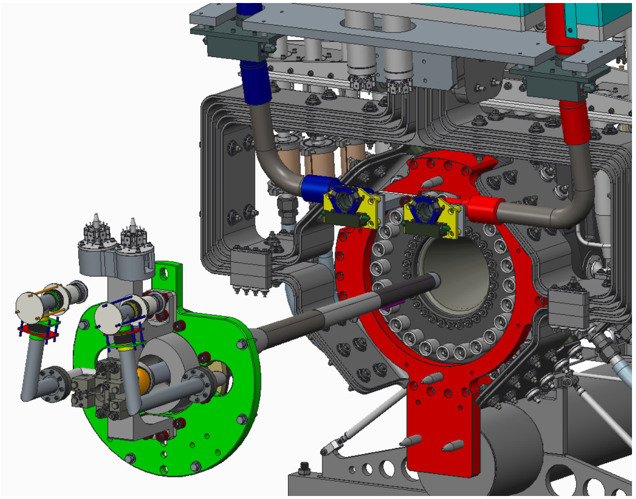
- Multi-horn configurations are common, the additional horns capture mesons that are under- or over-focused.

Integrated Target and Horn Assemblies

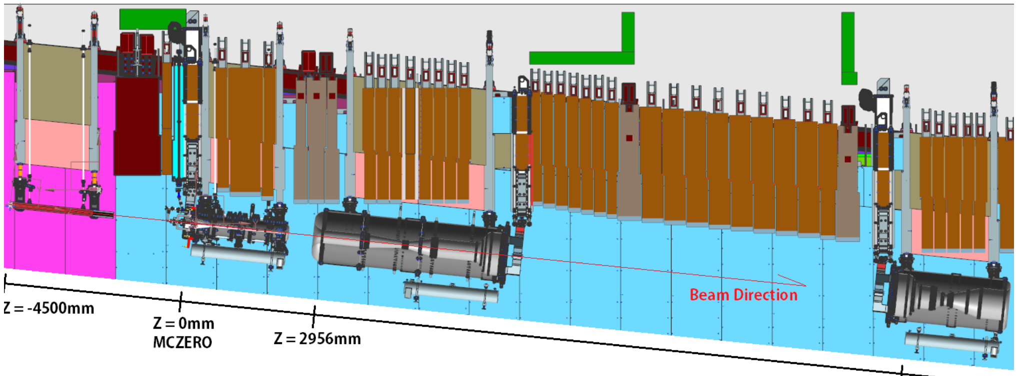


T2K Target and Horn



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.



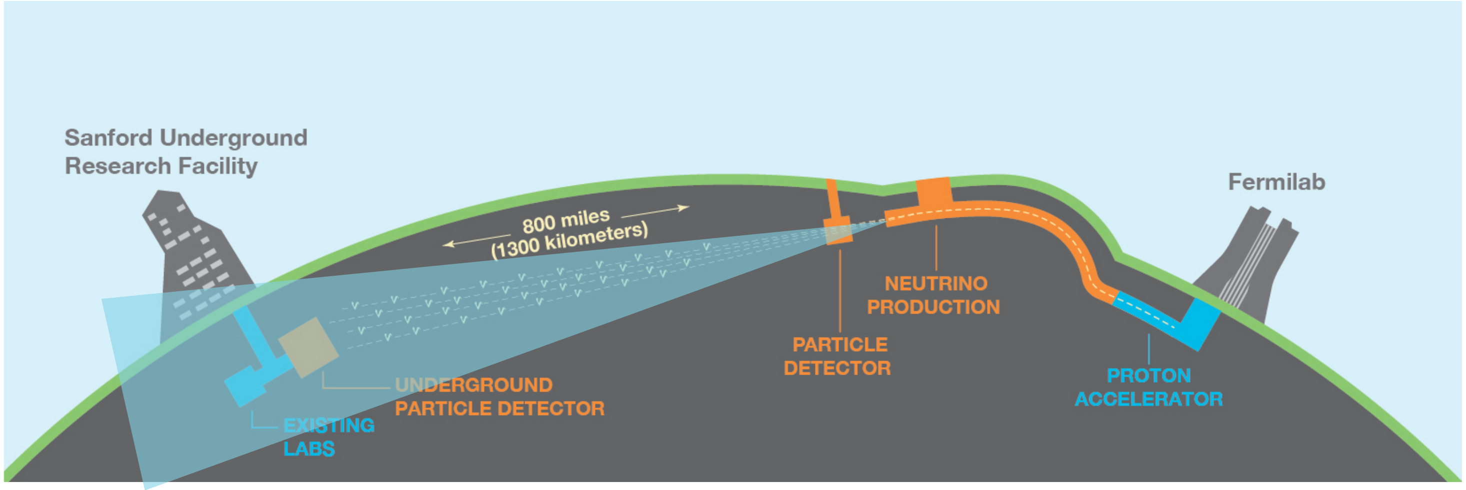
LBNF Target Complex

Neutrino Flux Predictions and Uncertainties

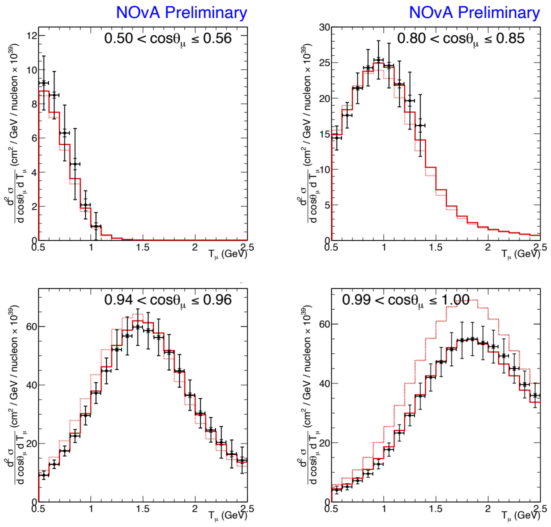
Neutrino Oscillations and the Role of Flux

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

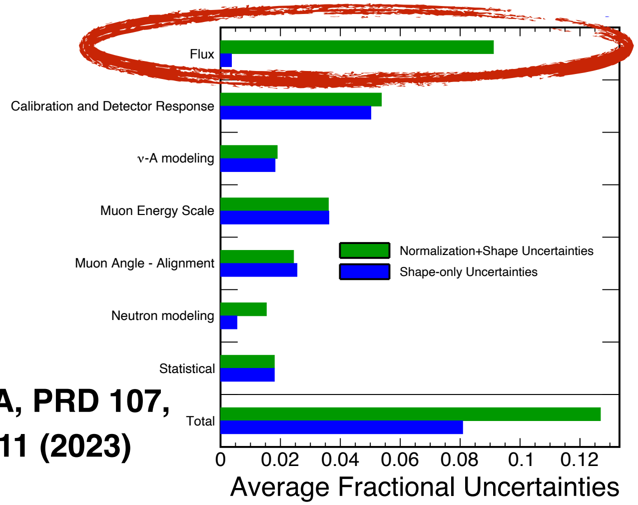
- In an ideal experiment, the flux, cross section and efficiencies of the near and far detectors would simply “cancel” in the ND/FD ratio.
- But reality:
  - The ND typically sees a “line source” of neutrinos, whereas the FD sees a “point source”. So the fluxes are not the same even in the absence of 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.



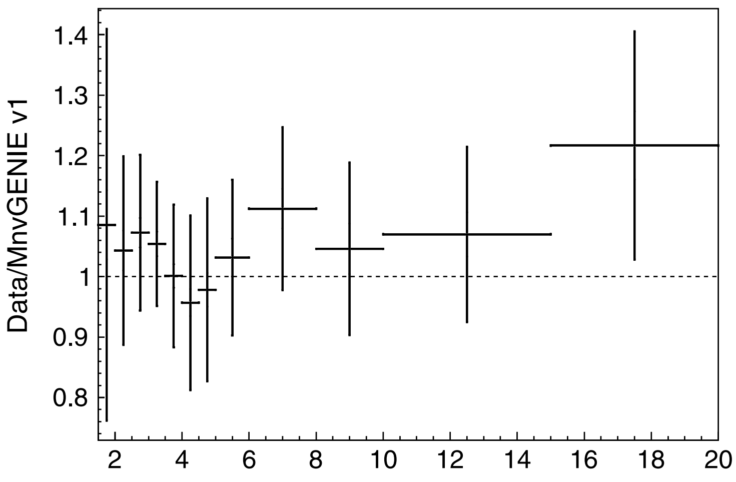
Impact of Neutrino Flux Uncertainties

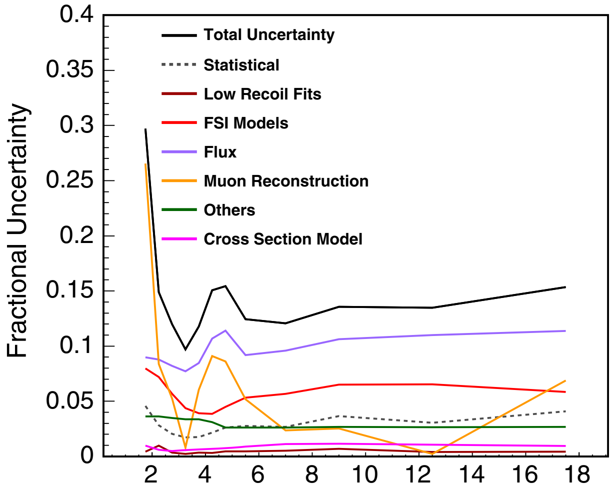


NOvA, PRD 107, 052011 (2023)



- Flux is often a limiting systematic for all neutrino cross section measurements.
- Current measurements are being used to tune neutrino scattering models.
- Uncertainties in these models impact the strategies and sensitivities of future neutrino experiments.





MINERvA, PRD 99, 012004 (2019)

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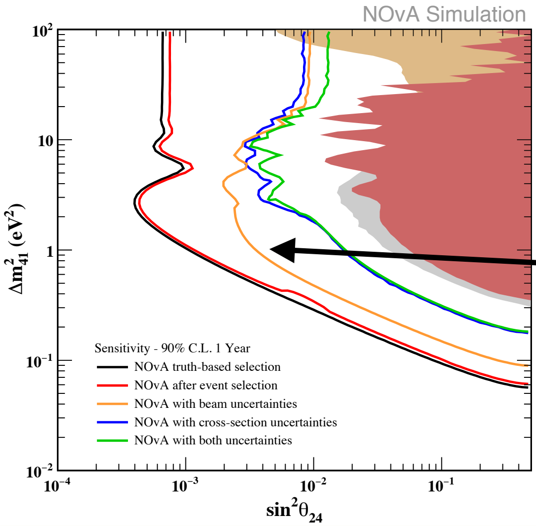
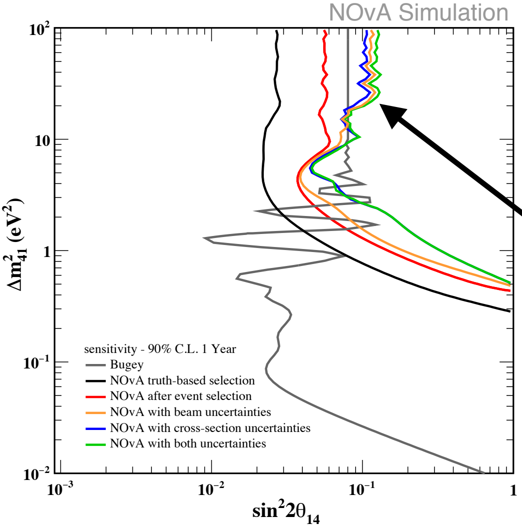
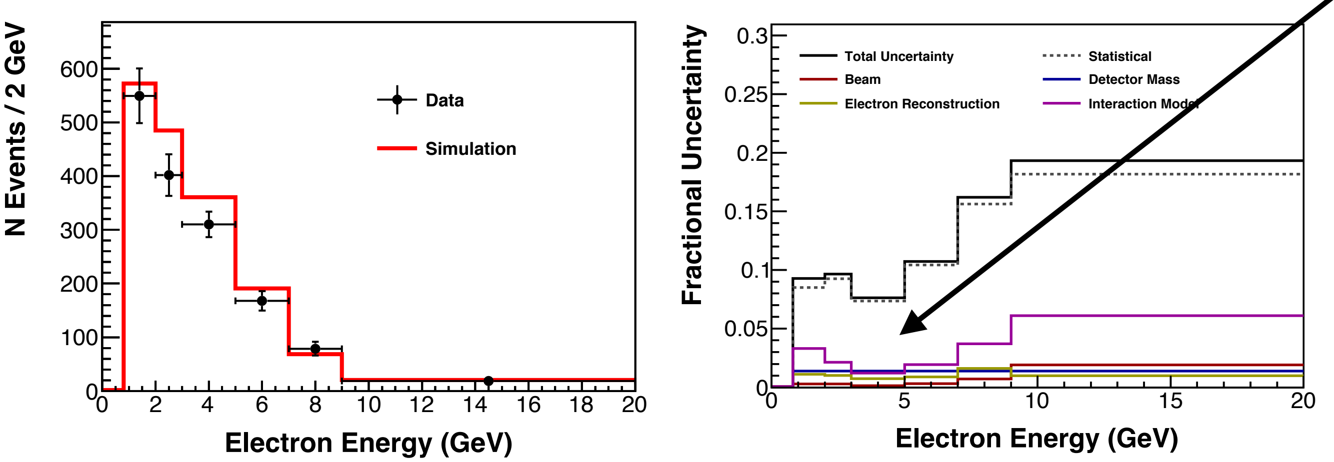




- Flux is a limiting systematic for nearly all single-detector measurement.
- Single-detector searches for sterile neutrinos are severely limited by flux uncertainties.
- Neutrino scattering measurements can also be used to constrain “new ν” physics, eg NSI, ν magnetic moments, etc. But again these constraints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



MINERvA, PRD 100, 092001 (2019)

The Role of Simulation

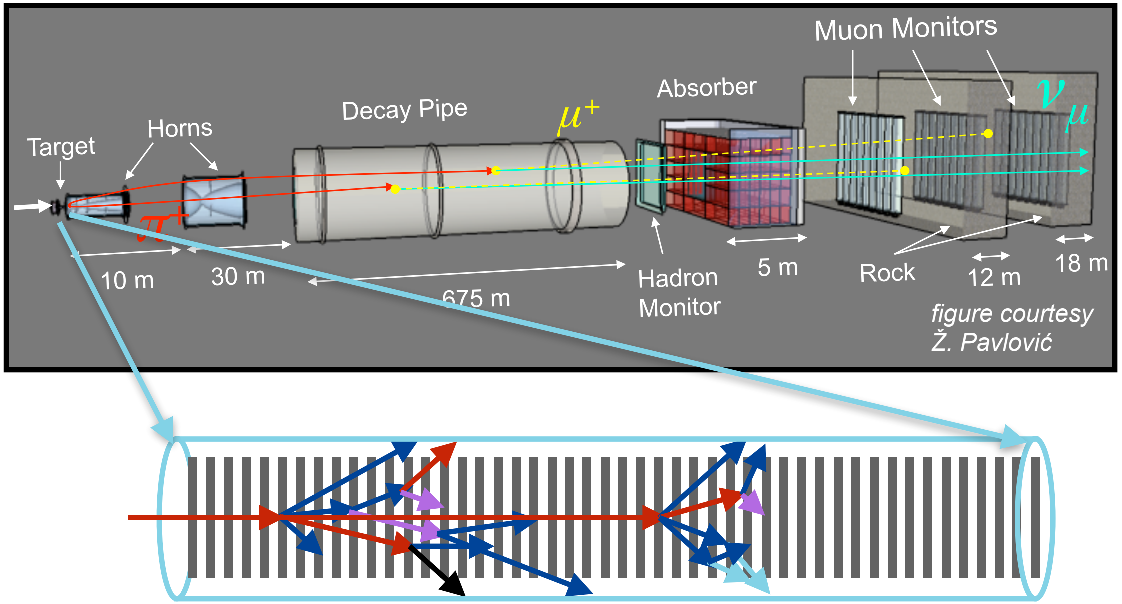
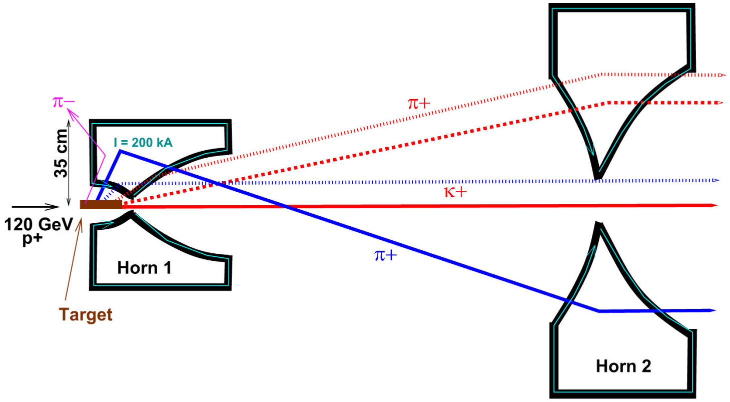


figure courtesy Ž. Pavlović



- Simulations use the production cross section for p, π, K hitting a broad range of nuclear targets across a broad range of energies. Beamline materials include C, Be, Al, H2O, 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.

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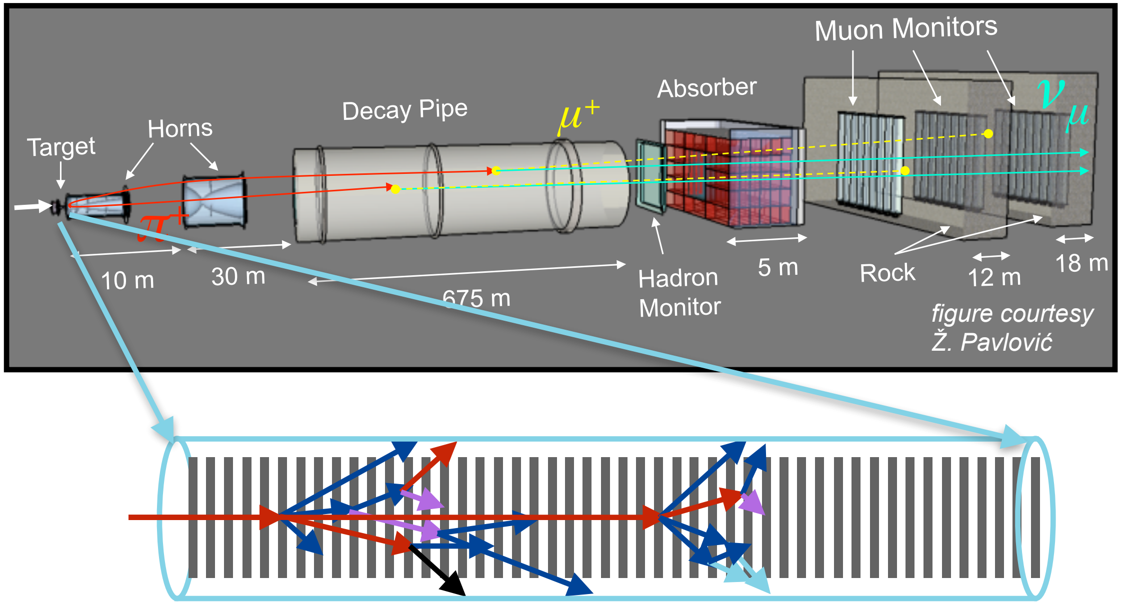

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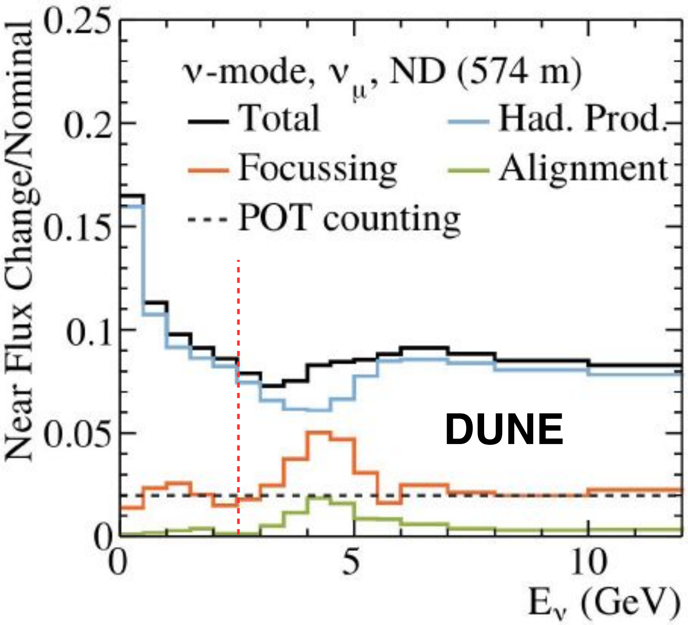

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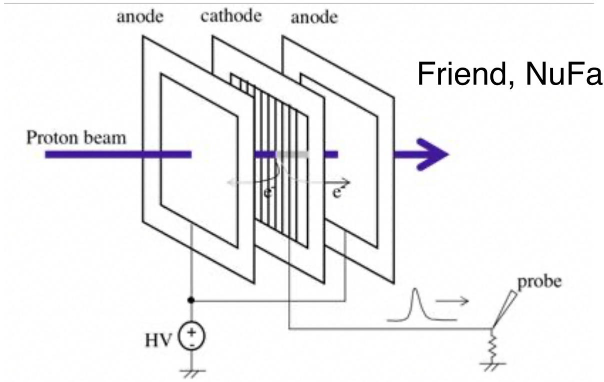
- Simulations also need very detailed descriptions of the target and focusing horn geometry, and the focusing magnetic field as a function of position and time.
- **Two sources of uncertainty in these predictions: hadron production (HP) and beam focusing. HP uncertainties are currently dominant, but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

In-Situ Constraints

Primary Beam Monitoring

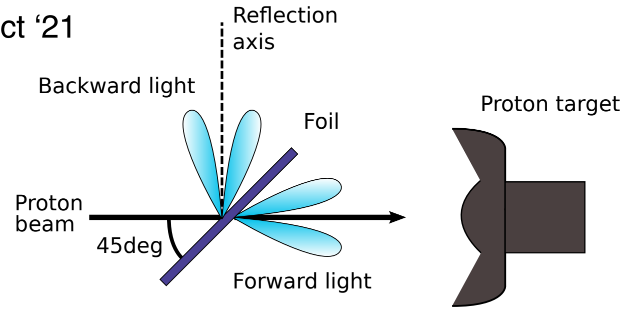
Segmented Secondary Emission Monitor (SSEM)



Friend, NuFact '21

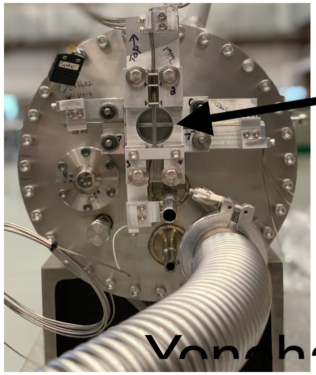
- Used at both J-PARC and FNAL
- Secondary electrons emitted from segmented cathode plane when struck by primary proton are collected on anode planes. Planes are 5 µm Ti foils.
- Cathode current read out, digitized and recorded to extract beam profile.

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.

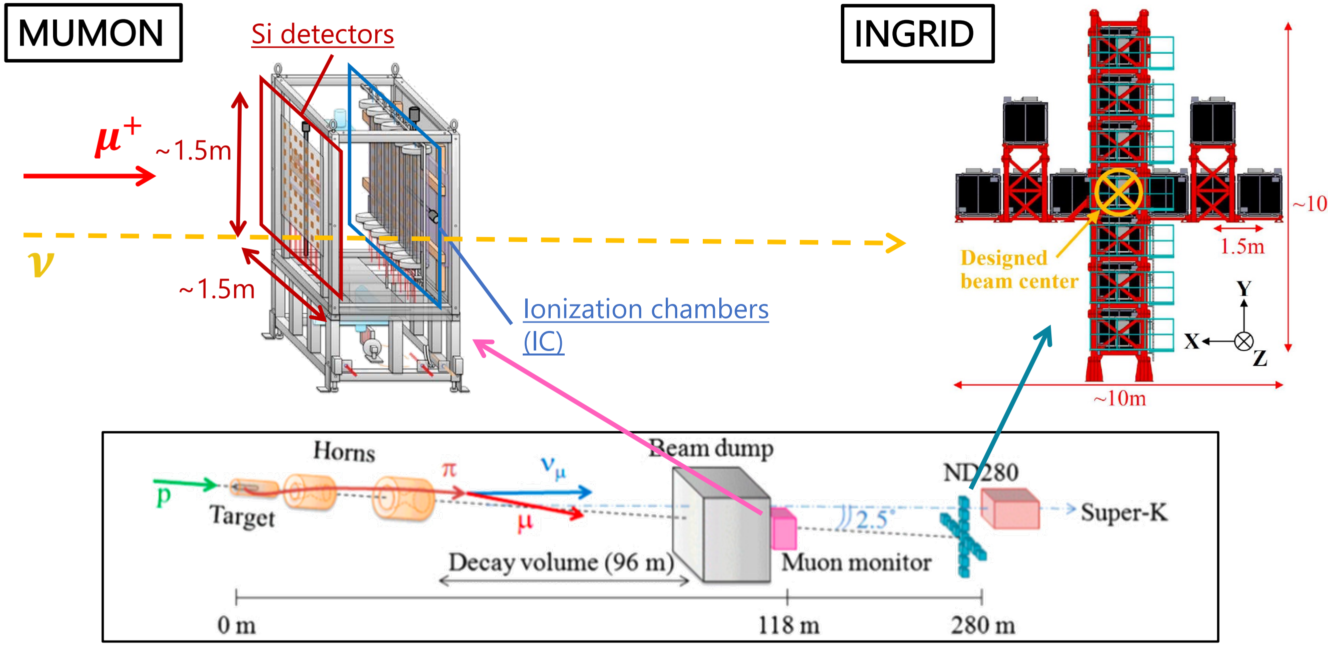
Target Position Thermometer (TPT)



3+3
Be wires
&
Thermo-couples

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

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.

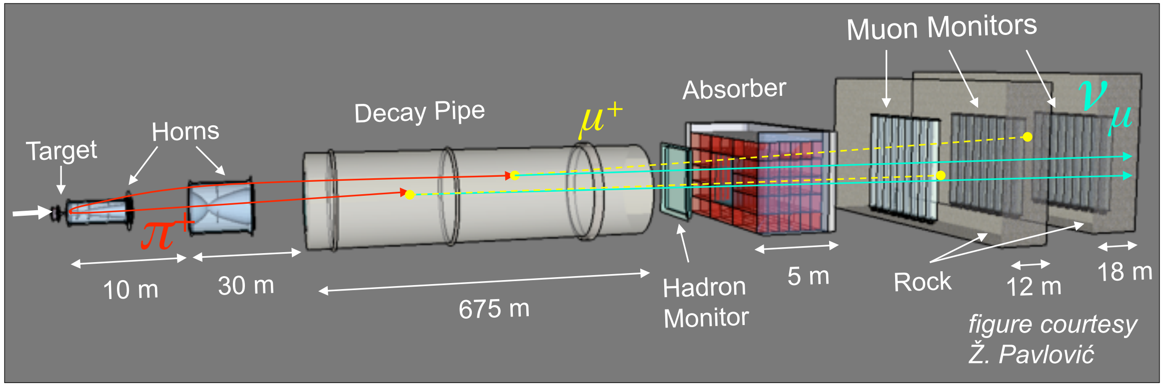
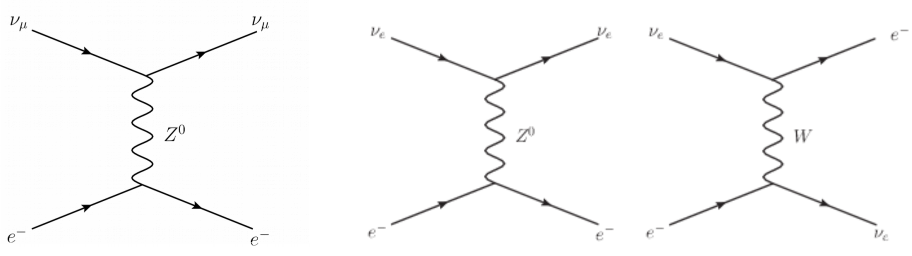


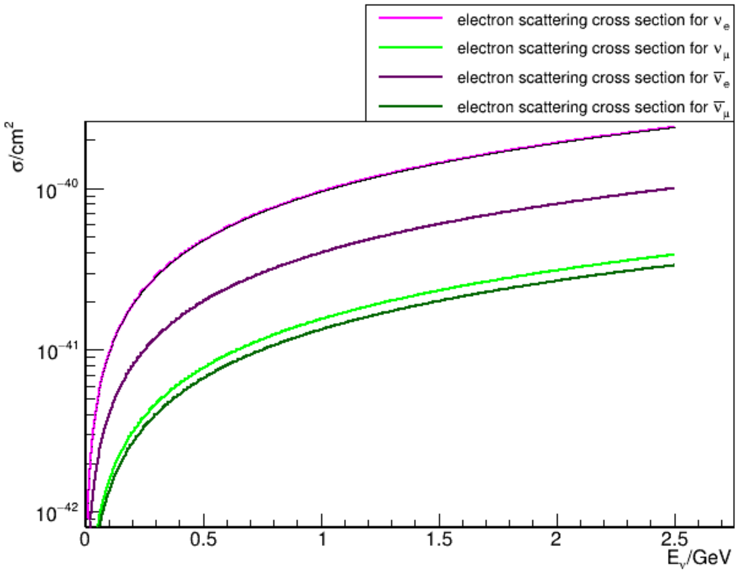
figure courtesy Ž. Pavlović

Neutrino-electron scattering

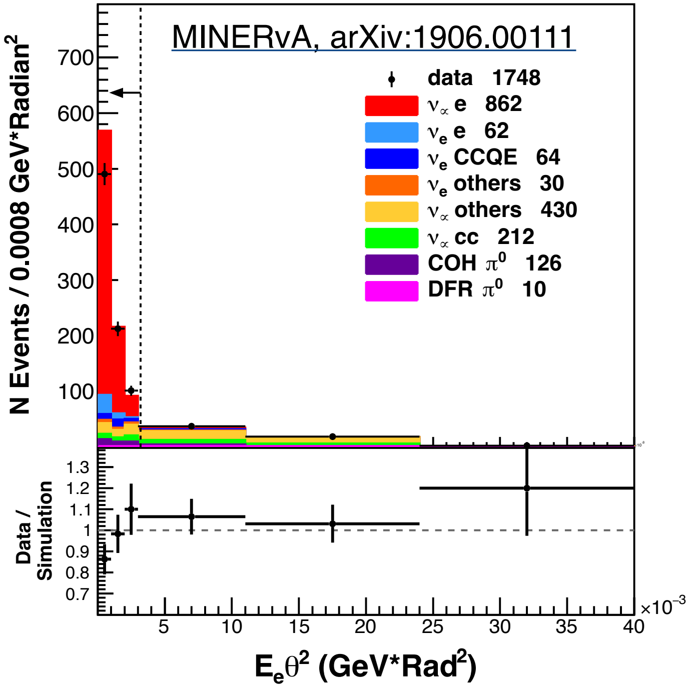
$$\nu_\mu + e^- \xrightarrow{\text{NC}} \nu_\mu + e^- \qquad \nu_e + e^- \xrightarrow{\text{NC + CC}} \nu_e + e^-$$



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

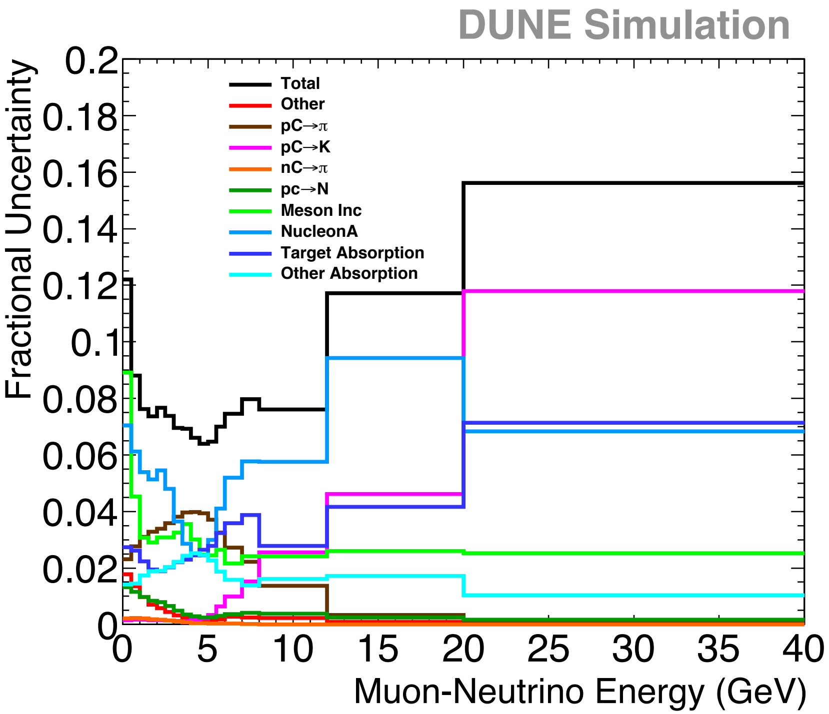


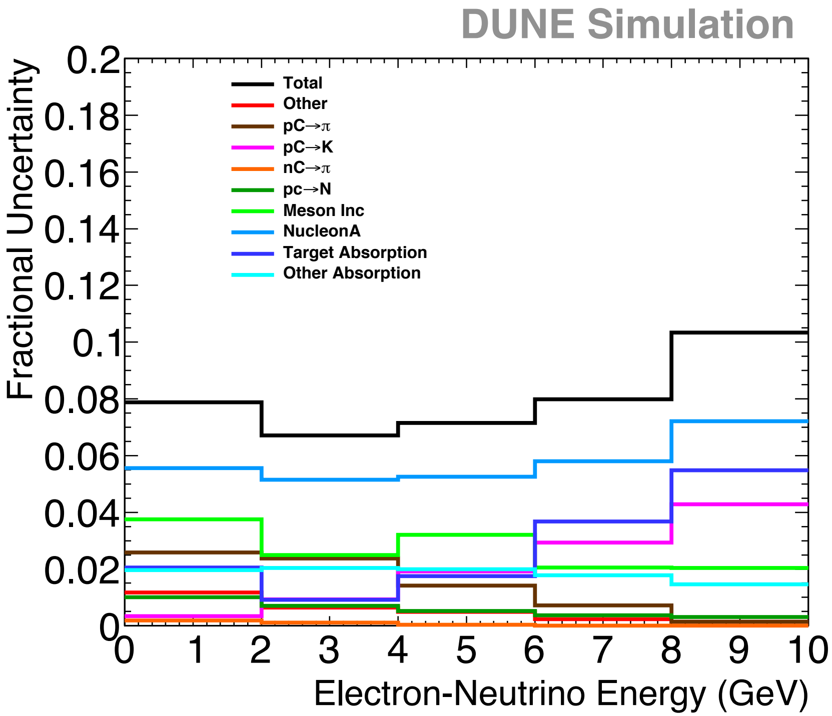
- A purely leptonic process, the theoretical uncertainty is ~1%
- Signature is a very forward-going electron only in the final state.
- In principle, a measurement of the electron angle gives a measurement of the neutrino energy.
- Note that the cross section is tiny, about 1/1000 that of the CC cross 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



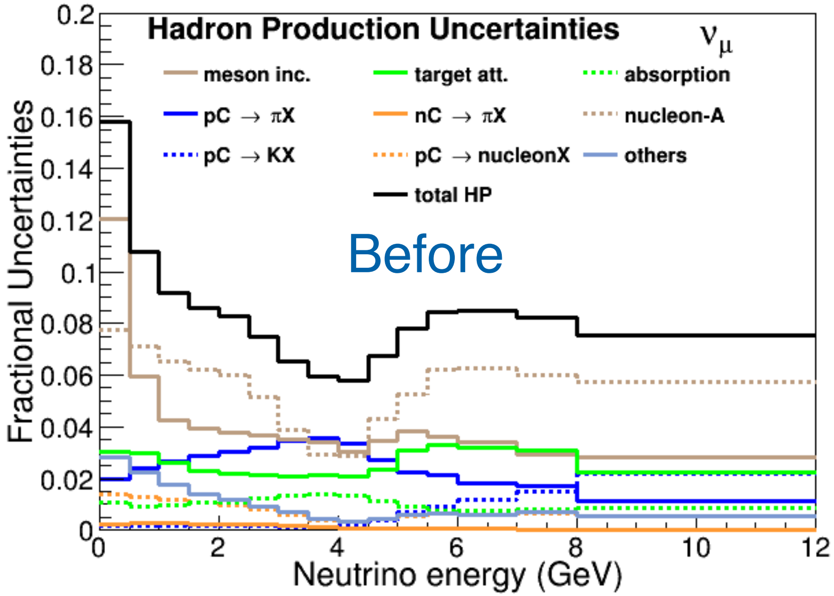


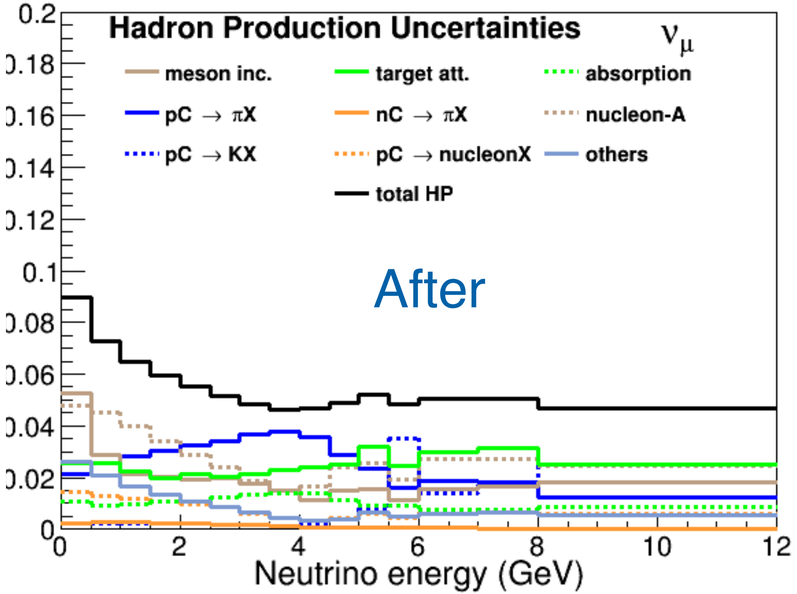
- Dominant flux uncertainties come from 40% xsec uncertainties on interactions in the target and horns that have never been measured (or have large uncertainties/spread).
- Lack of proton and pion scattering data at lower beam energies.
- **Reduction of flux uncertainties improves physics reach of most 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

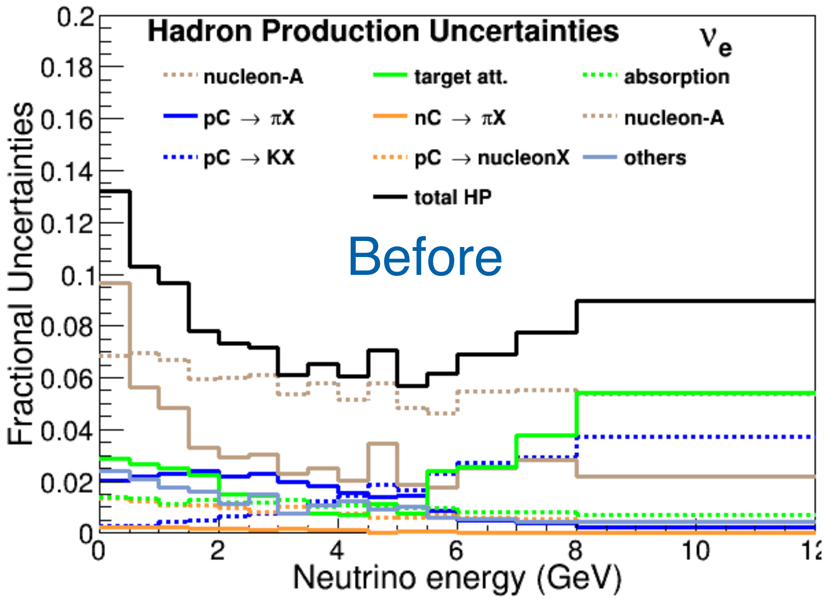


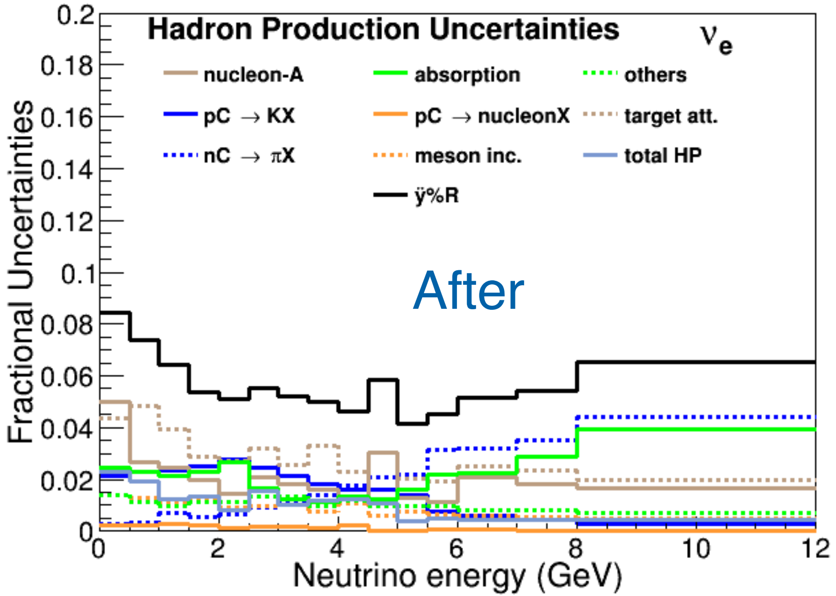


Note: flux uncertainties determined by EMPHATIC, not DUNE

Hadron Production Uncertainties - Can we do better?

- Similar observations for the electron-neutrino flux.





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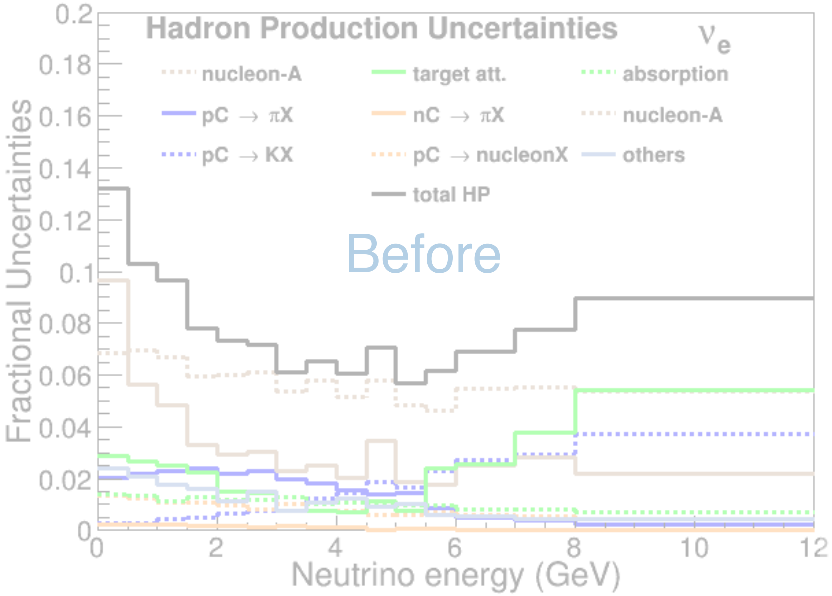
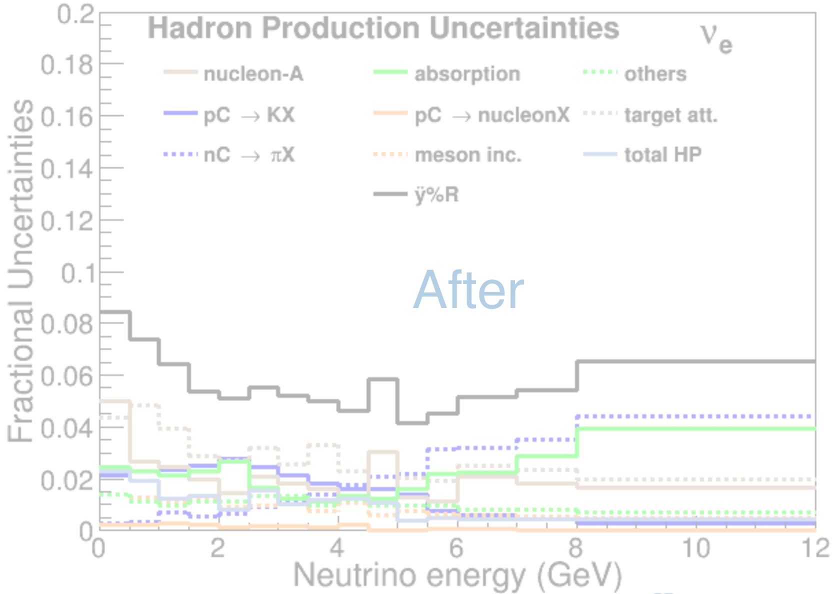
Hadron Production Uncertainties - Can we do better?

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.





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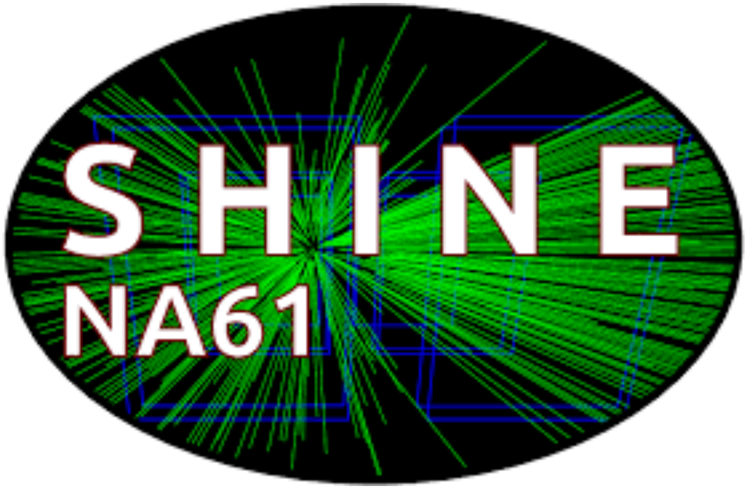
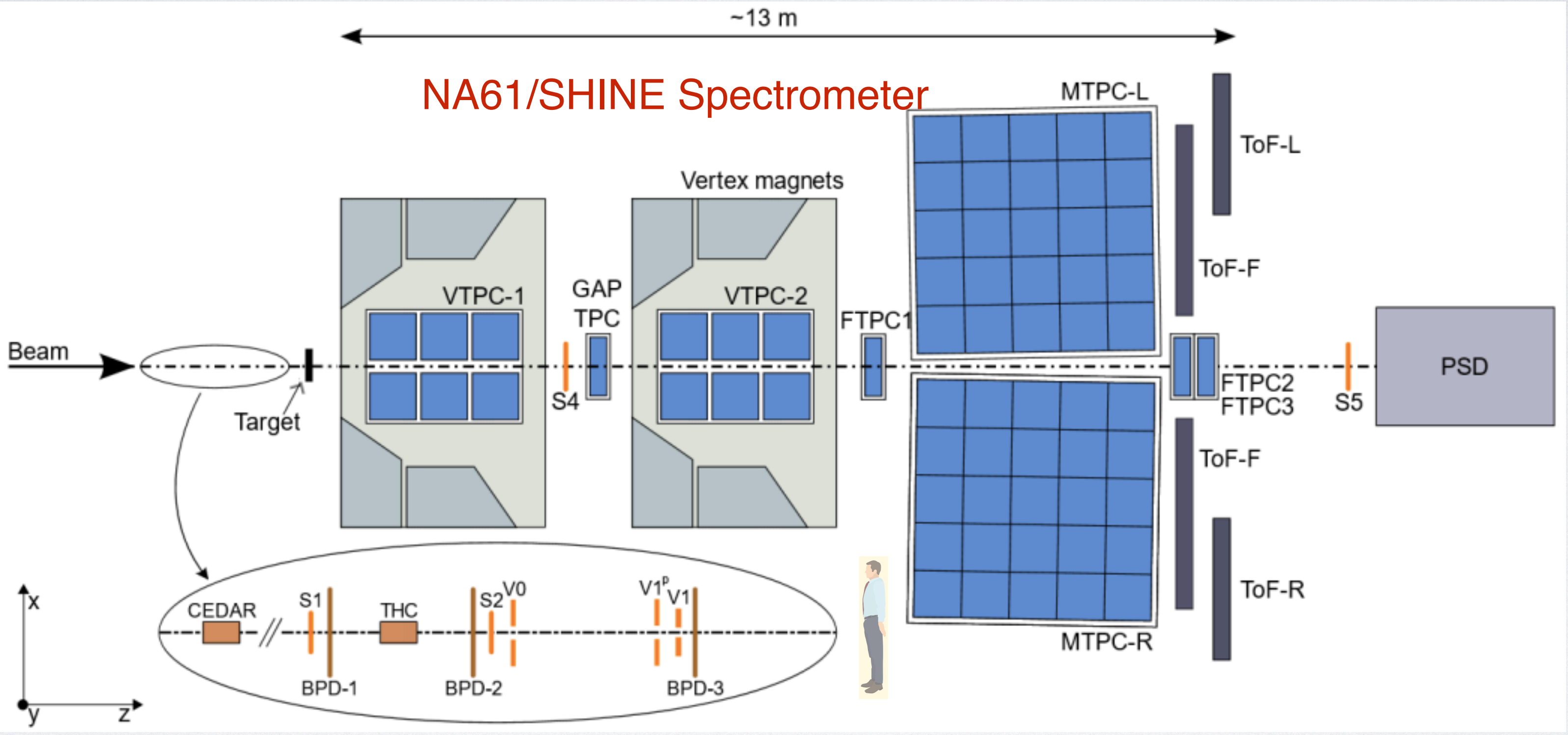
Hadron Production - A Global Effort

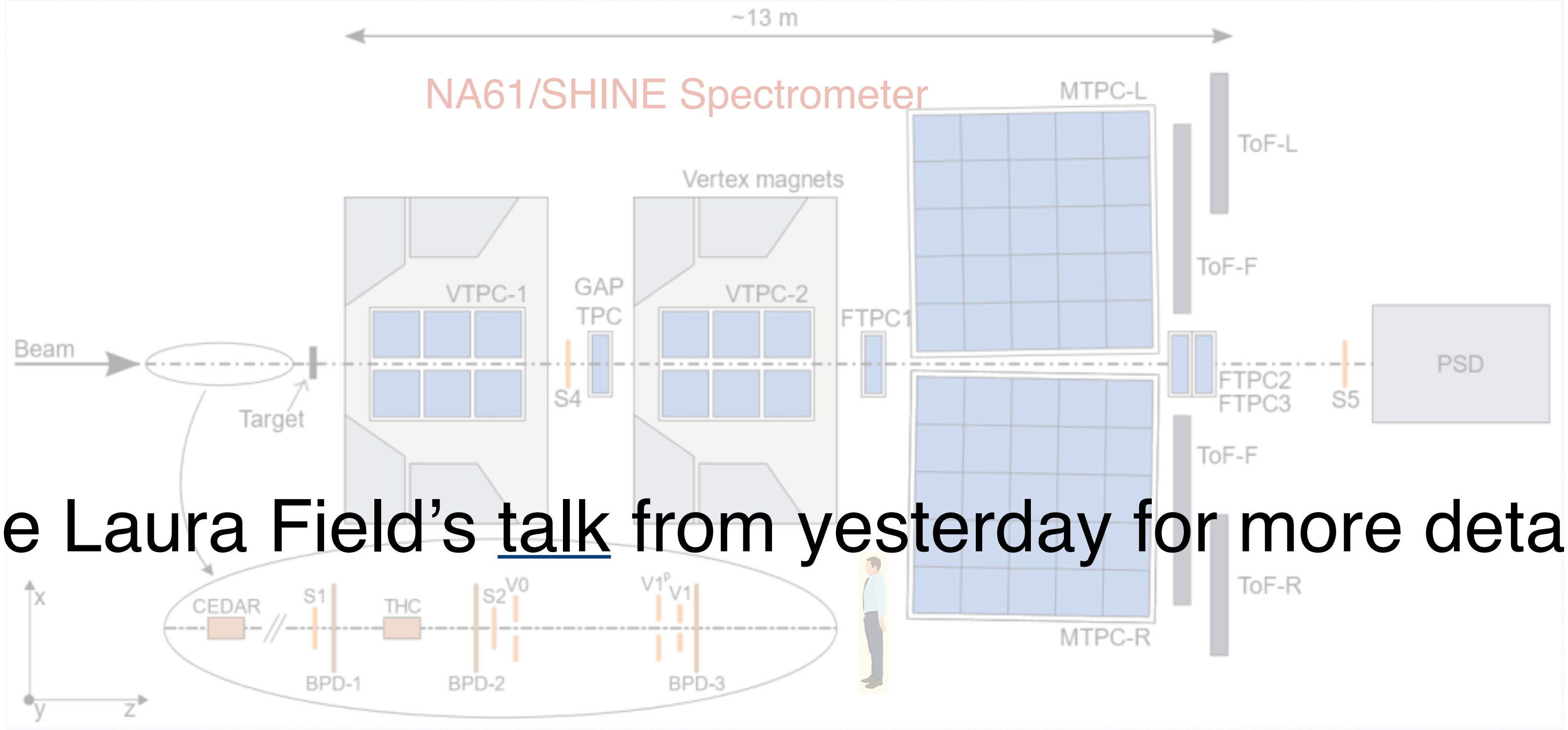


NA61/SHINE



- 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.
- First phase began in 2006.
- Capable of measuring particle spectra produced in long neutrino targets.

NA61/SHINE



See Laura Field's talk from yesterday for more details

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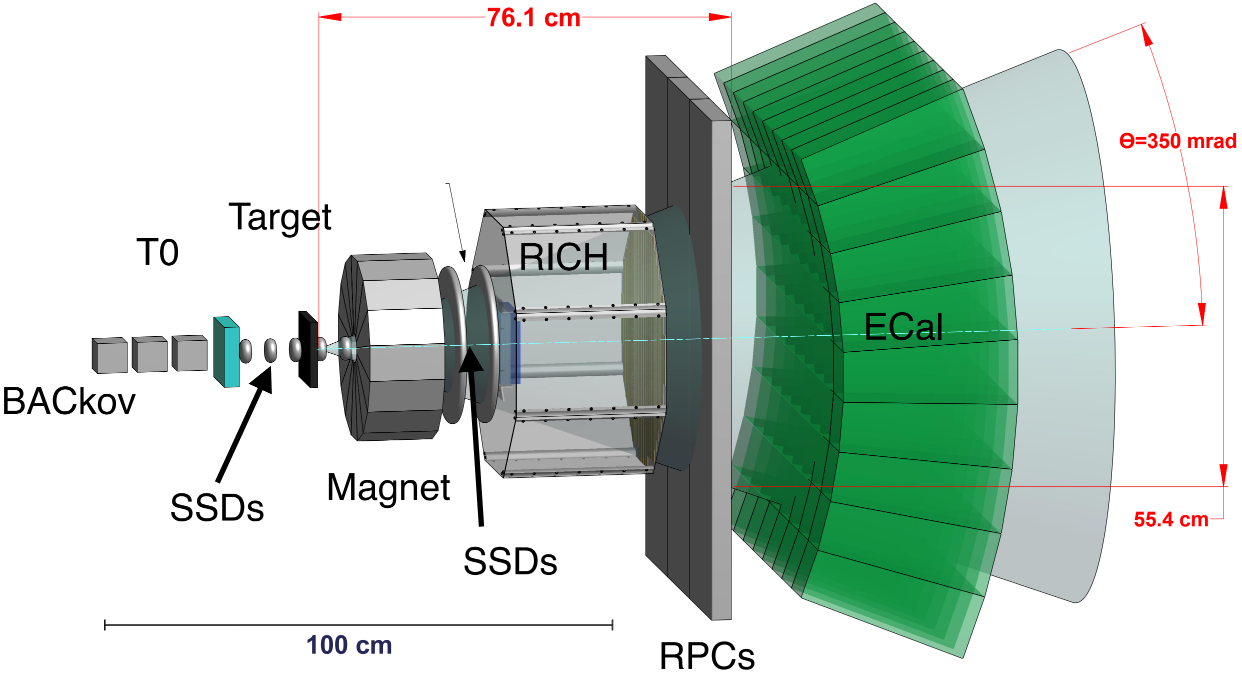
EMPHATIC

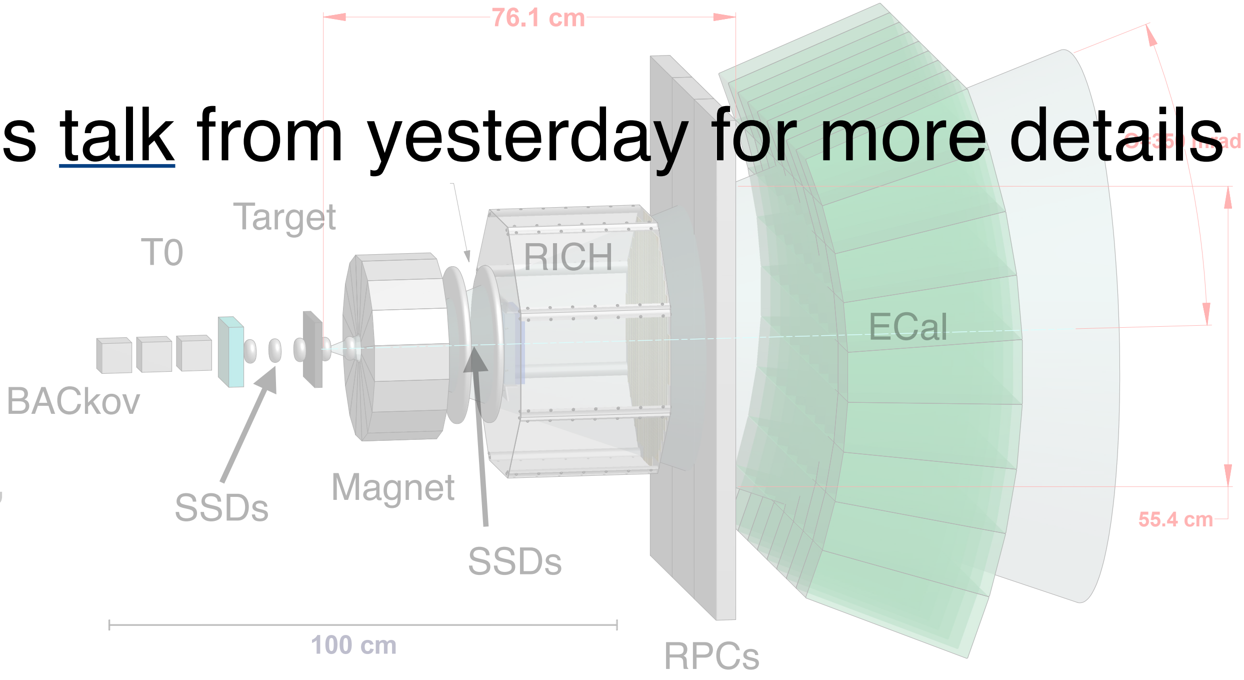
- **E**xperiment to **M**easure the **P**roduction of **H**adrons **At** a **T**est beam **I**n **C**hicagoland
  - Uses the FNAL Test Beam Facility (FTBF) (eg, MTest)
  - Table-top size experiment, focused on hadron production measurements with $p_{beam} < 15$ GeV/c, but will also make measurements 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

- **E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t 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.

See Robert Chirco’s talk from yesterday for more details



Hadron Production - A Global Effort

SHINE
NA61

EMPHATIC

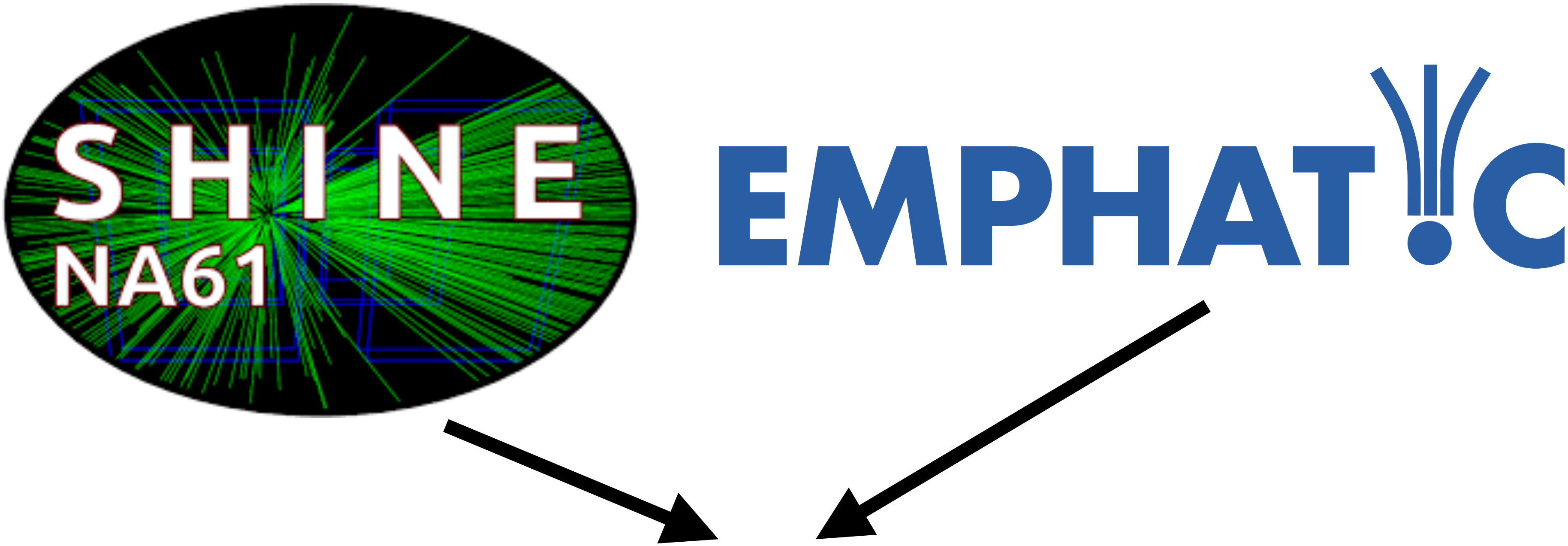
Complementary

Hadron Production - A Global Effort

Complementary

- Experiments (and collaborations) are very different in size and strategy
- NA61/SHINE is large (13m), can measure secondary particles out to 10s of GeV/c, excels at measurements at high pT and has a rich program of physics measurements that include those needed by heavy ion and neutrino experiments
- EMPHATIC is table-top (1.5m), designed to measure secondary particles only to ~15 GeV/c, has excellent forward-momentum measurement capabilities and is solely focused on measurements needed by neutrino experiments

Hadron Production - A Global Effort



PPFX

(And similar for Japanese experiments)

Applying HP Data to Simulations

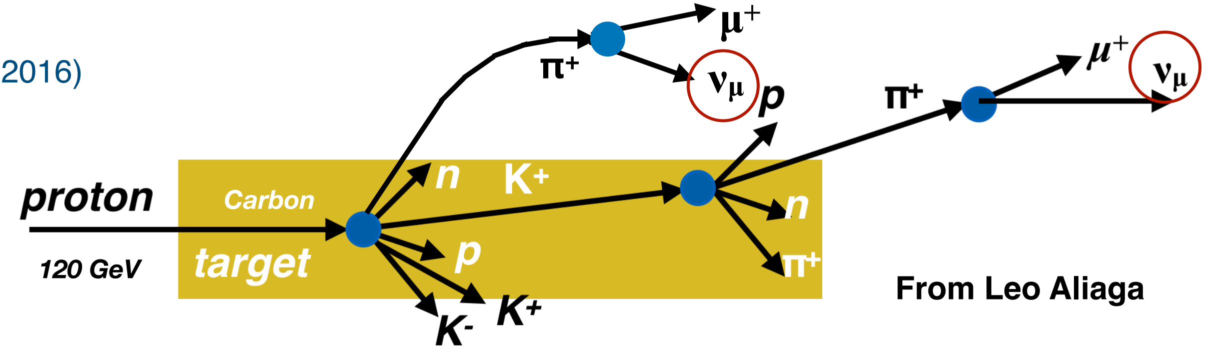
Package to Predict the Flux (PPFX)

For NuMI, we implement this procedure in the code called ***P****ackage to* ***P****redict the* ***F****lu****X*** *(PPFX)*

MINERvA, Phys. Rev. D 94, 092005 (2016)

$$w(p_{prod}, \theta_{prod}, E_{inc}, A) = \frac{[\frac{dn}{dp}]data}{[\frac{dn}{dp}]MC}$$

Correction per interacting particle, material and outgoing hadron



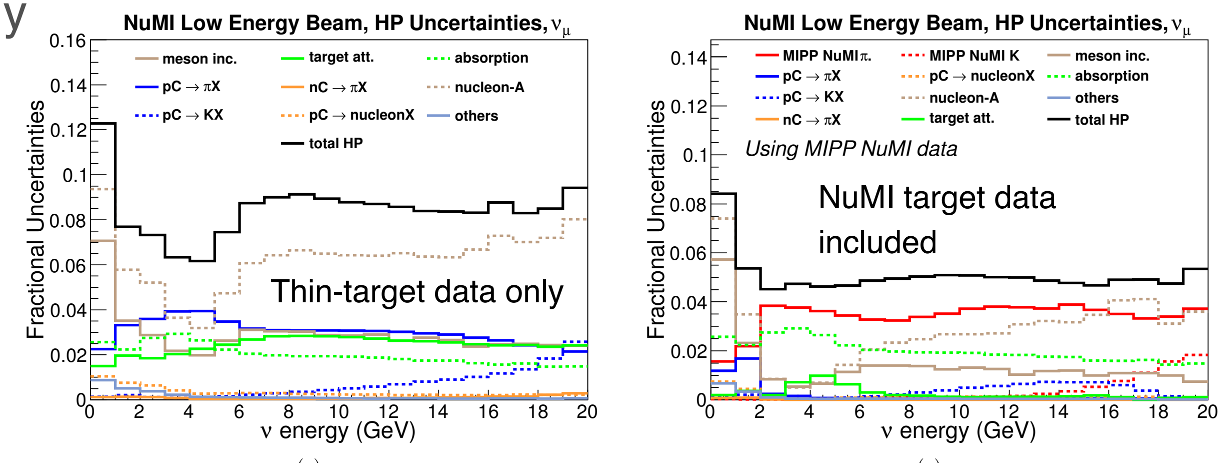
From Leo Aliaga

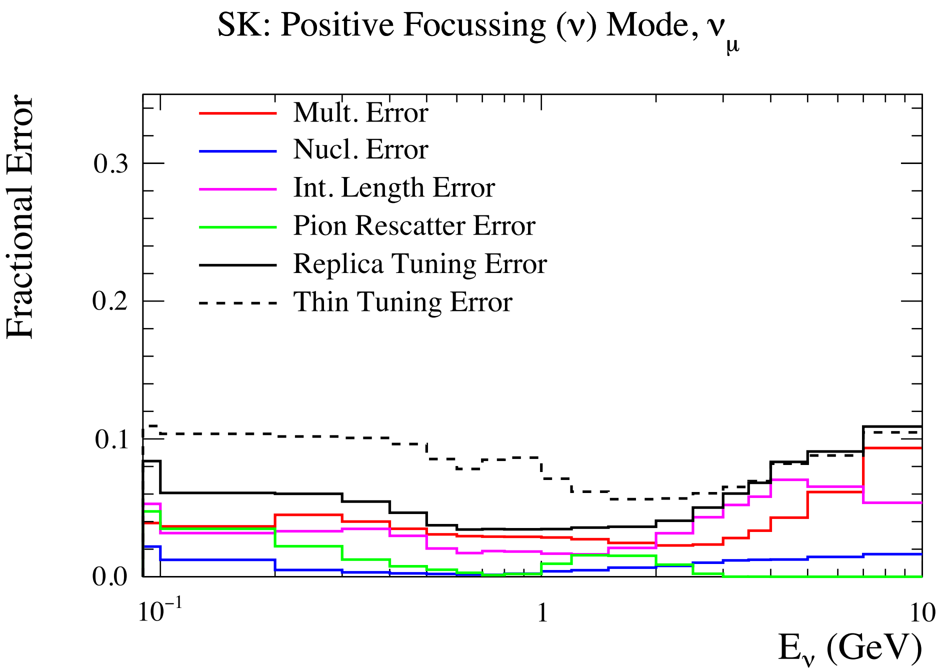
- Particles are given a weight (Data/MC) depending on the details of the interaction that produced them
- Correlated uncertainties are properly propagated
- End result is a new central-value prediction of the neutrino flux AND uncertainties based on external HP measurements

Neutrino Production Target Measurements

- Thin-target measurements are extremely useful and generally necessary for improved flux predictions (atmospheric neutrinos too!)
- HP measurements off actual or replica targets enable re-weighting only particles coming off the target… much simpler!
- NA61/SHINE measurements of T2K target reduced flux uncertainty to ~5%.
- Most of the remaining uncertainty comes from scattering in the horns and other beamline material.

From L. Aliaga, Ph.D. thesis

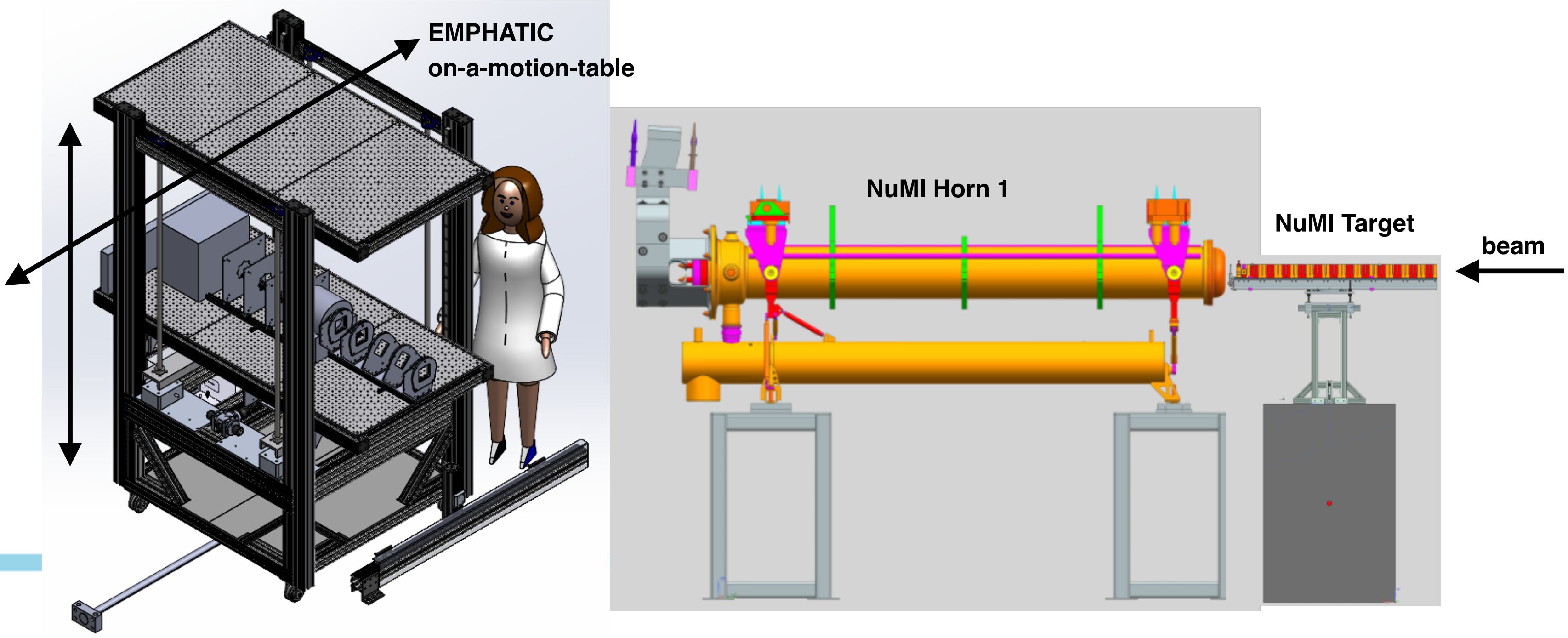




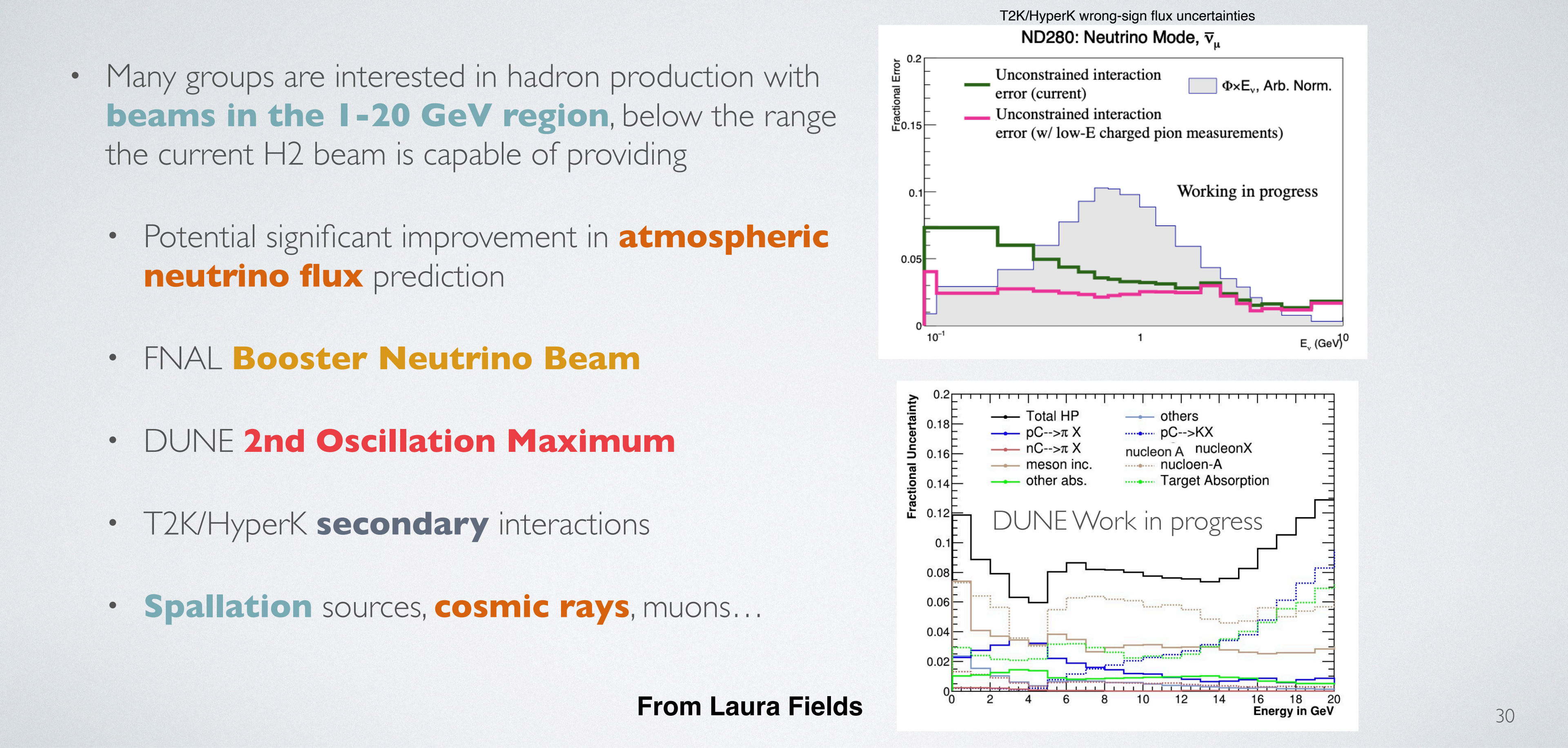
Future Prospects

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 AND [unpowered] horn.
- Power supply also available; funds required to operate with pulsed horn in the future.
- Establishes program to address questions re: HP in horns and modeling of horn geometry and magnetic field.



NA61/SHINE Low-Energy Beam



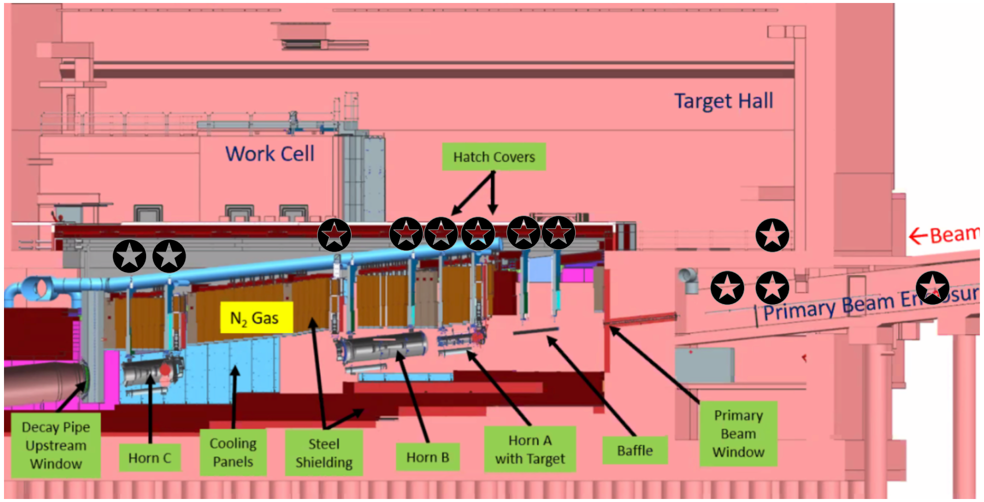
- Many groups are interested in hadron production with **beams in the 1-20 GeV region**, below the range the current H2 beam is capable of providing
  - Potential significant improvement in **atmospheric neutrino flux** prediction
  - FNAL **Booster Neutrino Beam**
  - DUNE **2nd Oscillation Maximum**
  - T2K/HyperK **secondary** interactions
  - **Spallation** sources, **cosmic rays**, muons…

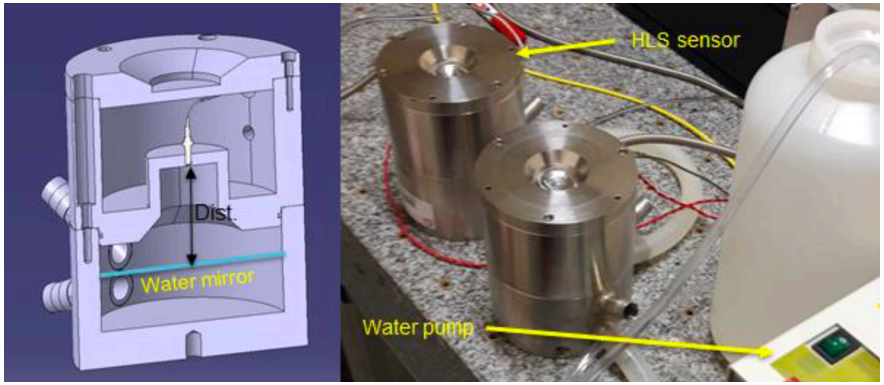
From Laura Fields

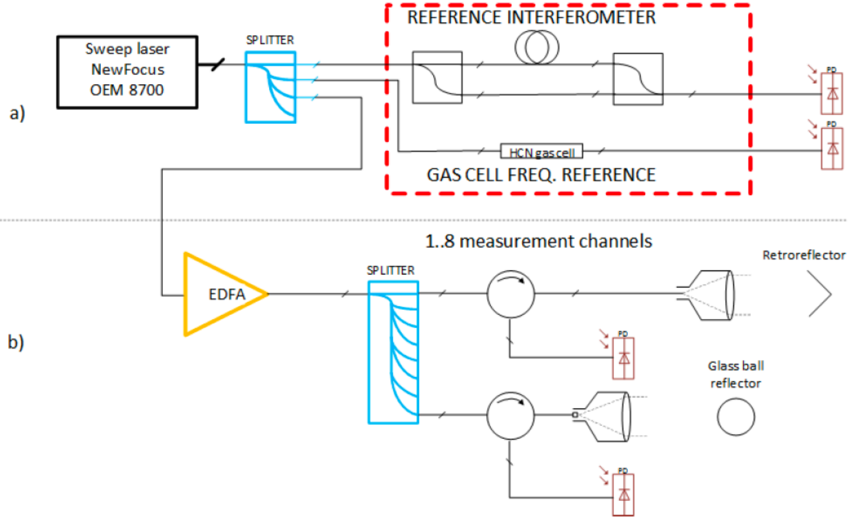
T2K/HyperK wrong-sign flux uncertainties

- NA61/SHINE Collaboration is pursuing modifications to their beam line to enable these measurements.

Monitoring The Horn Positions







- Want independent measurement of height of all relevant beam components, especially the horns.
- Sensors connected by water pipe/tubing. Change in height of a sensor results in change in height of water.
- Frequency scanning interferometry: part of light is reflected back from water surface, creating “beat” frequency signal in interferometer FFT spectrum.
- Measurement uncertainty < 5 μm.

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. Many improvements and new detectors have recently been implemented and/or are being planned at J-PARC and Fermilab beamlines.
- Ex-situ measurements of hadron scattering and production off both thin- and thick-targets are critical to constraining the flux.
- Measurements of the hadron spectrum downstream of the focusing horn would constrain both hadron production and beam focusing uncertainties.
- New data will be coming from NA61/SHINE and EMPHATIC, improving our flux predictions and uncertainties in both current and near-future experiments.
- Stay tuned, or better yet, have some fun by joining the effort!