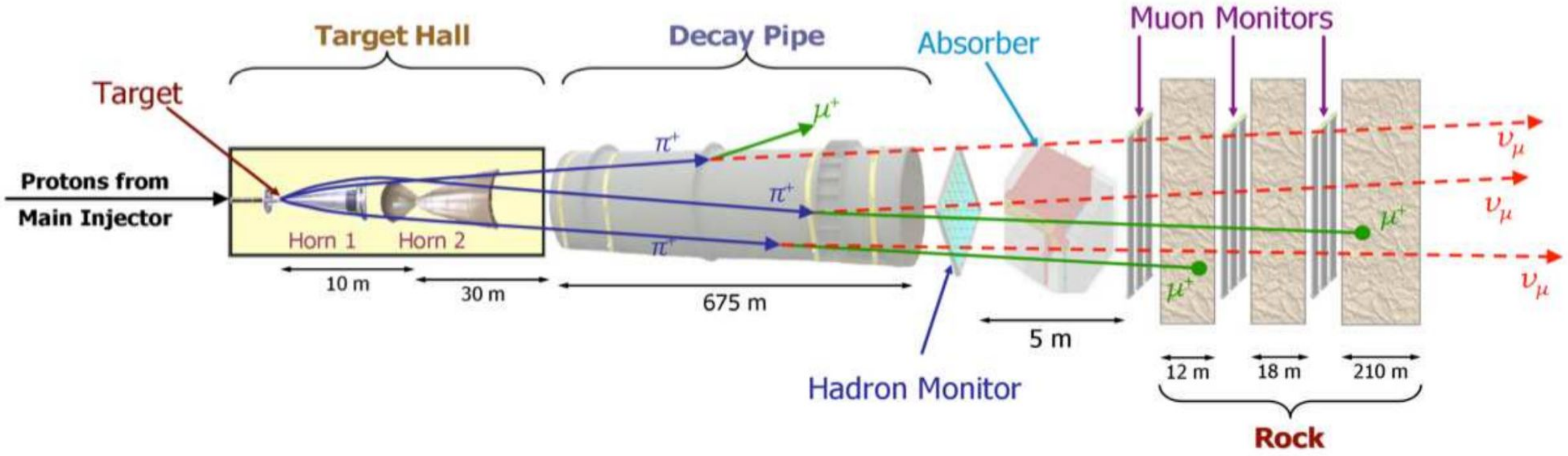
# Hadron Production Experiments

**Lu Ren**

University of Colorado Boulder

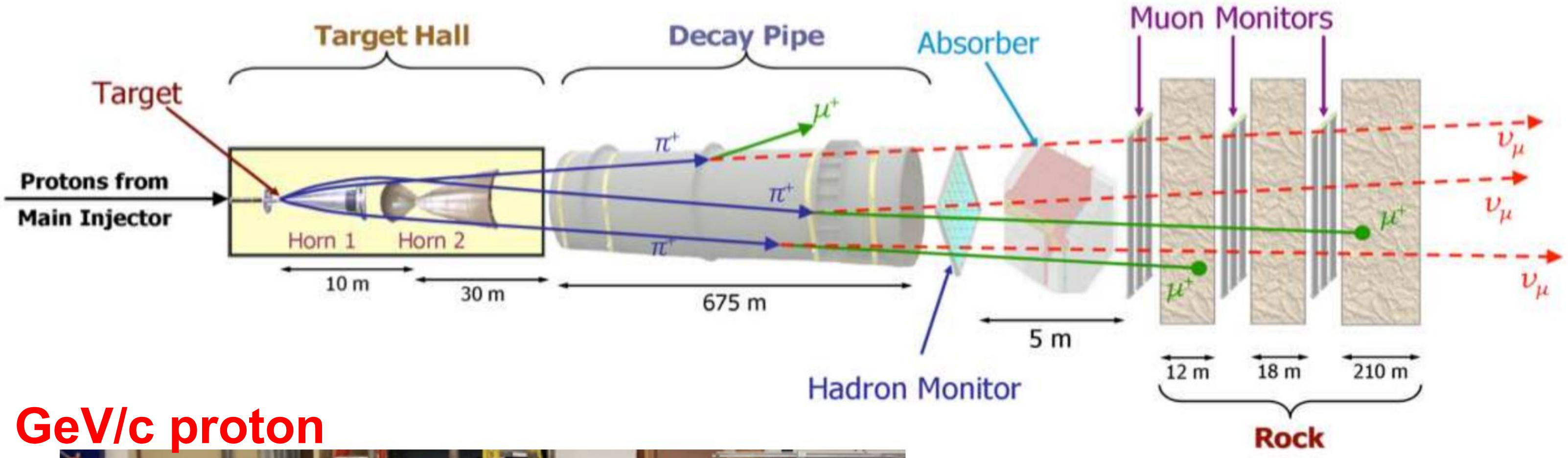
# How to Make a Neutrino Beam




Neutrinos at the Main Injector (NuMI) beam

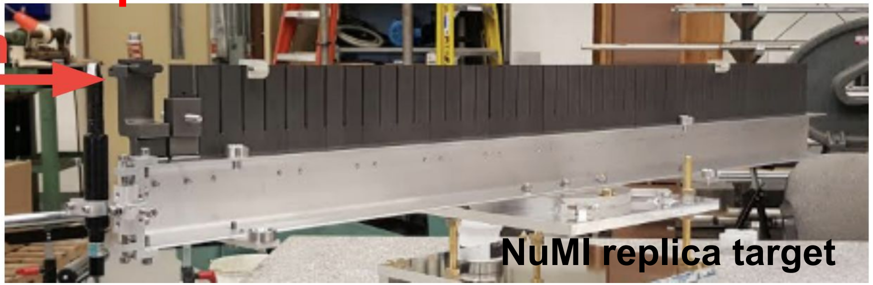
*P. Adamson et. al., Nucl. Instrum. Meth. A806, 279 (2016)*

# How to Make a Neutrino Beam



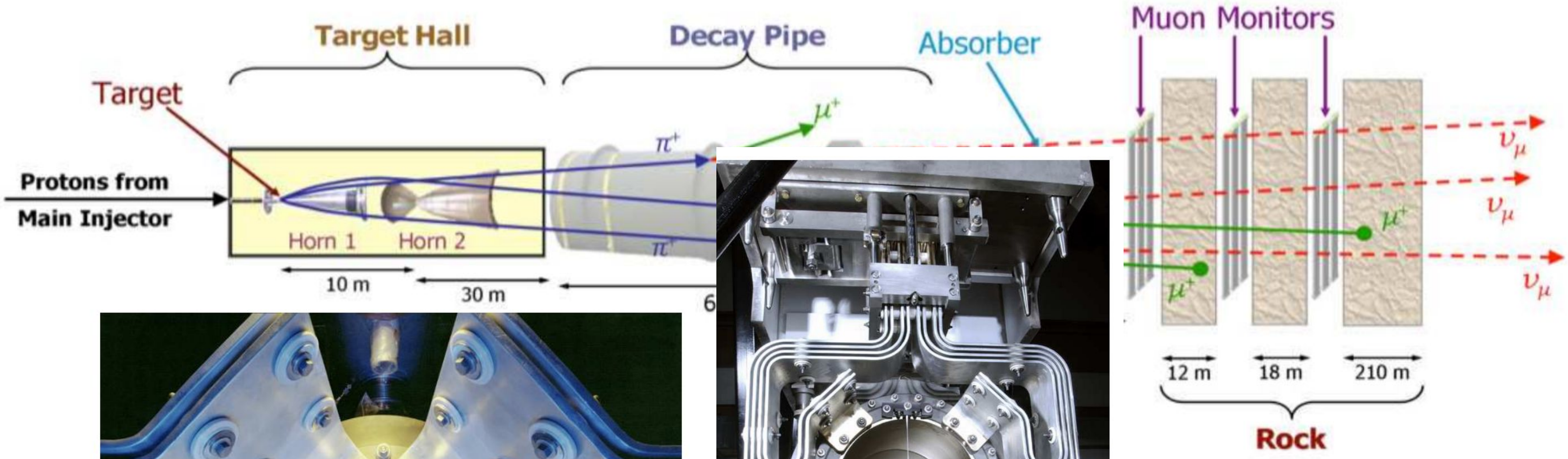

120 GeV/c proton

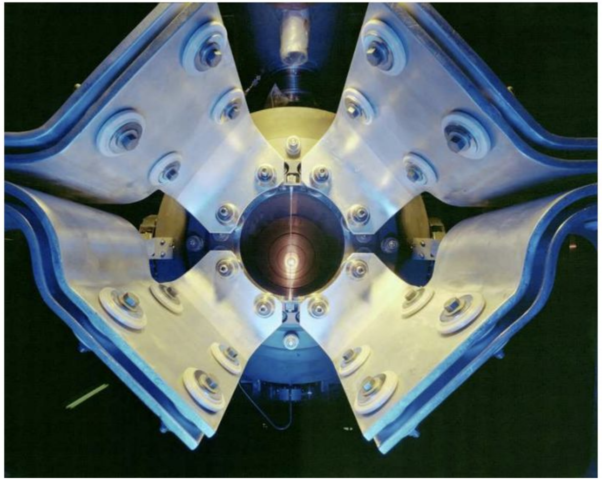
Beam

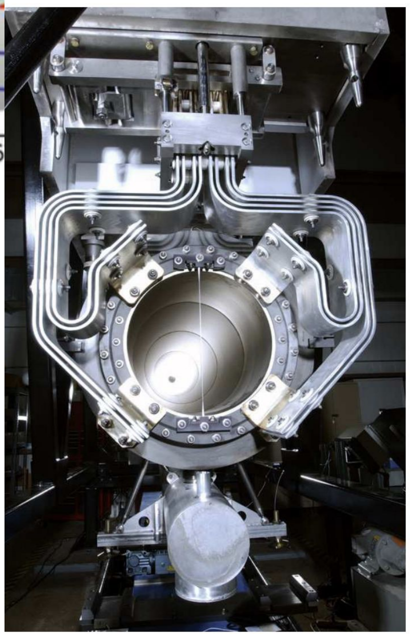



*P. Adamson et. al., Nucl. Instrum. Meth. A806, 279 (2016)*

# How to Make a Neutrino Beam

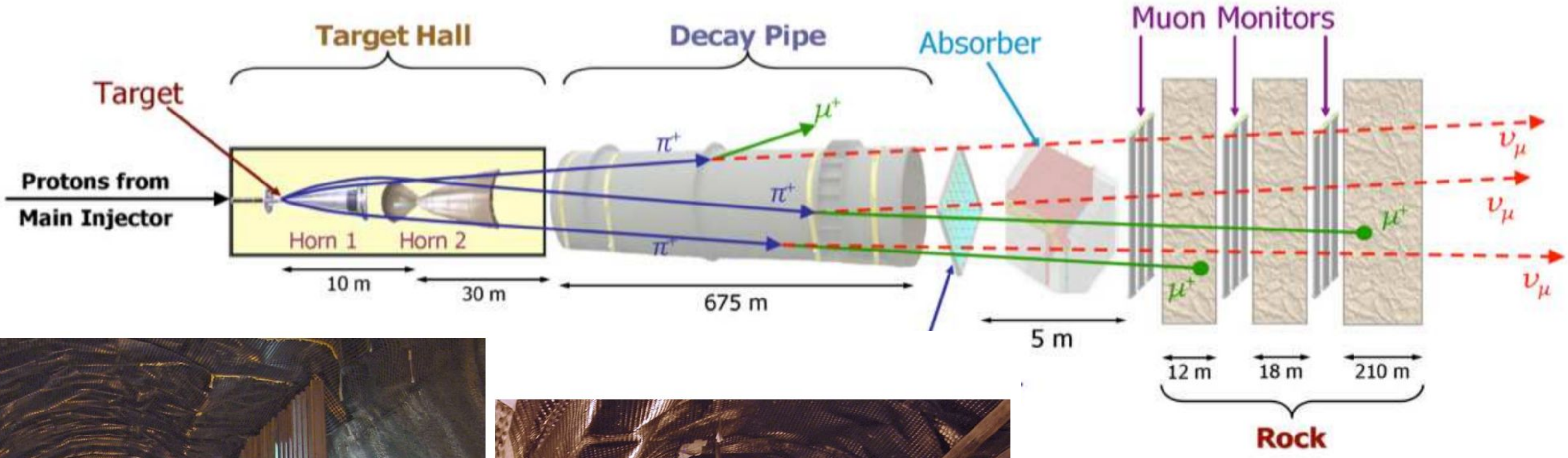




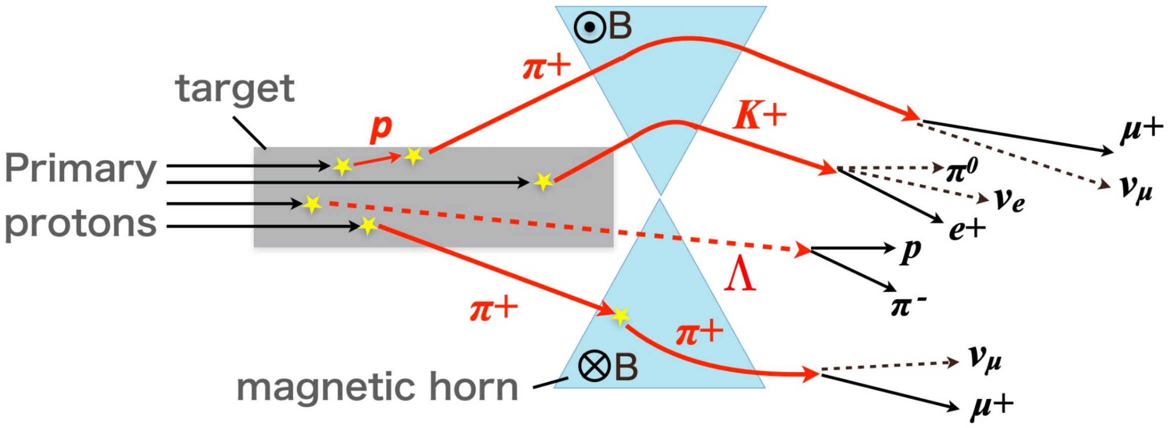
*P. Adamson et. al., Nucl. Instrum. Meth. A806, 279 (2016)*

# How to Make a Neutrino Beam



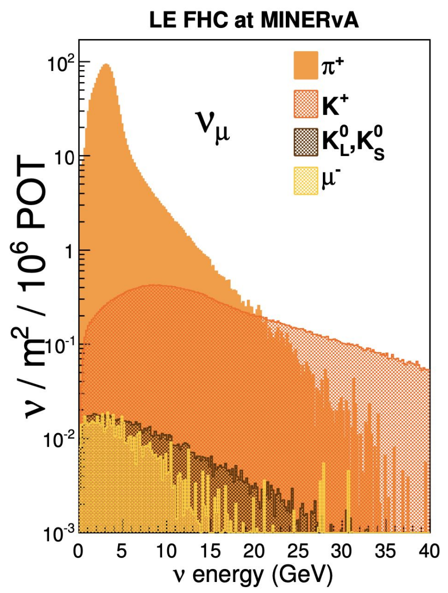

# How to Model a Neutrino Beam

- Neutrinos come from
  - Pions and kaons from primary proton-carbon interactions (p + C)
  - Secondary interactions of protons, pions in the target (hadrons + C/Be)
  - Secondary interactions with horn (hadrons + X)

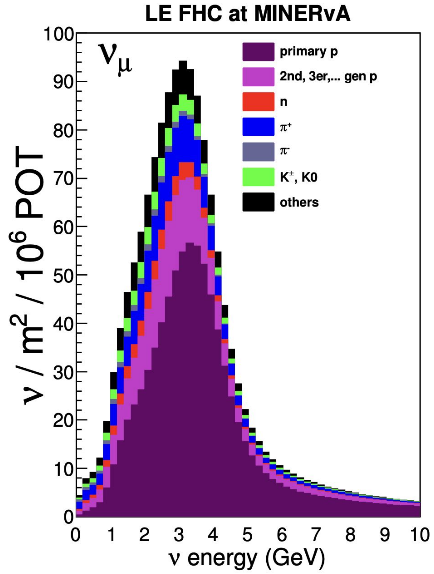


# How to Model a Neutrino Beam

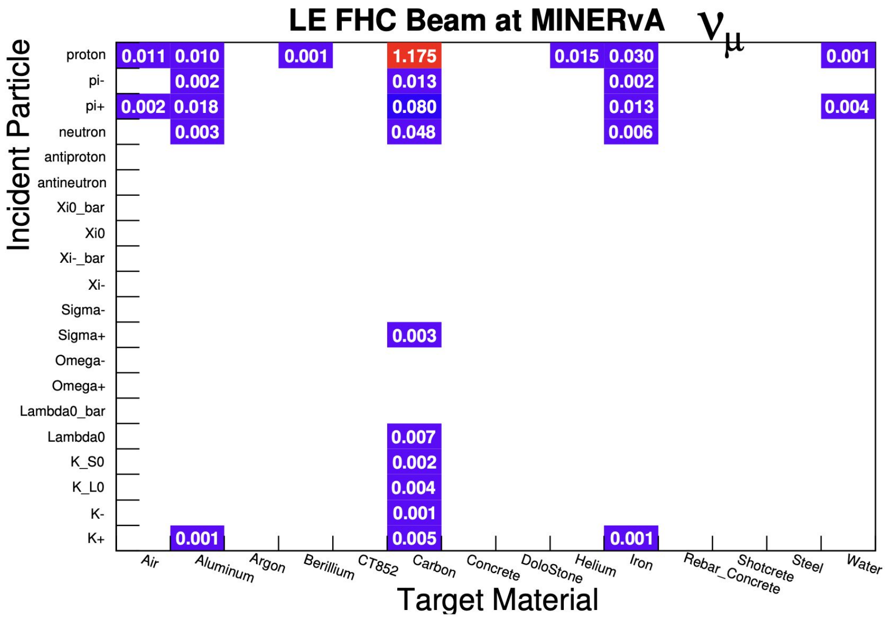
- Low-Energy mode Forward-Horn-Current NuMI beam at MINERvA




Parent




Grandparent

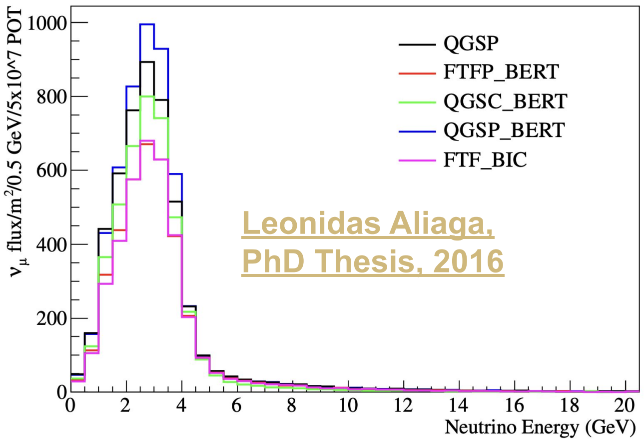



Incident particle vs material

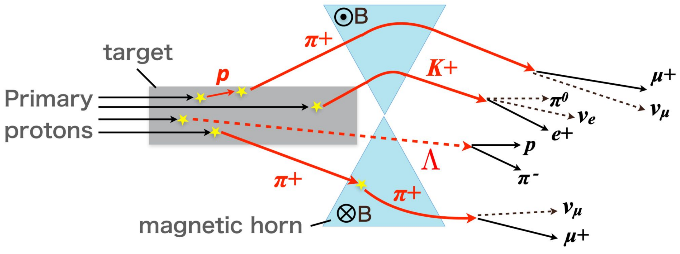
[Leonidas Aliaga, PhD Thesis, 2016]

# How to Model a Neutrino Beam

- Neutrino flux simulation relies on the hadronic interaction models used in MC event generators
  - i.e. FLUKA or GEANT4
  - Very large uncertainty (>20%)
- Important to have constraints on the hadronic processes
  - Proton-target interaction
  - Secondary interactions

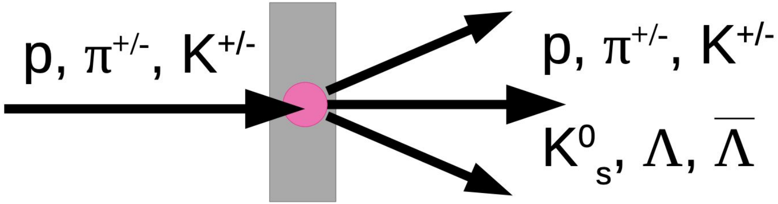


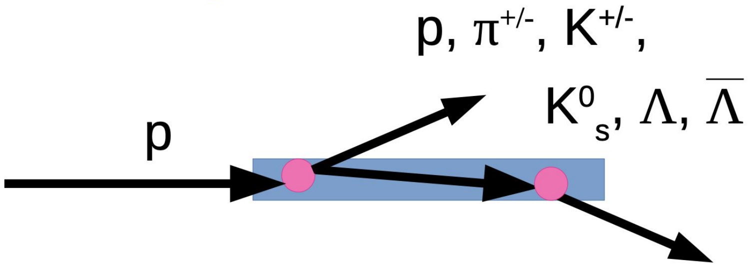

Leonidas Aliaga, PhD Thesis, 2016



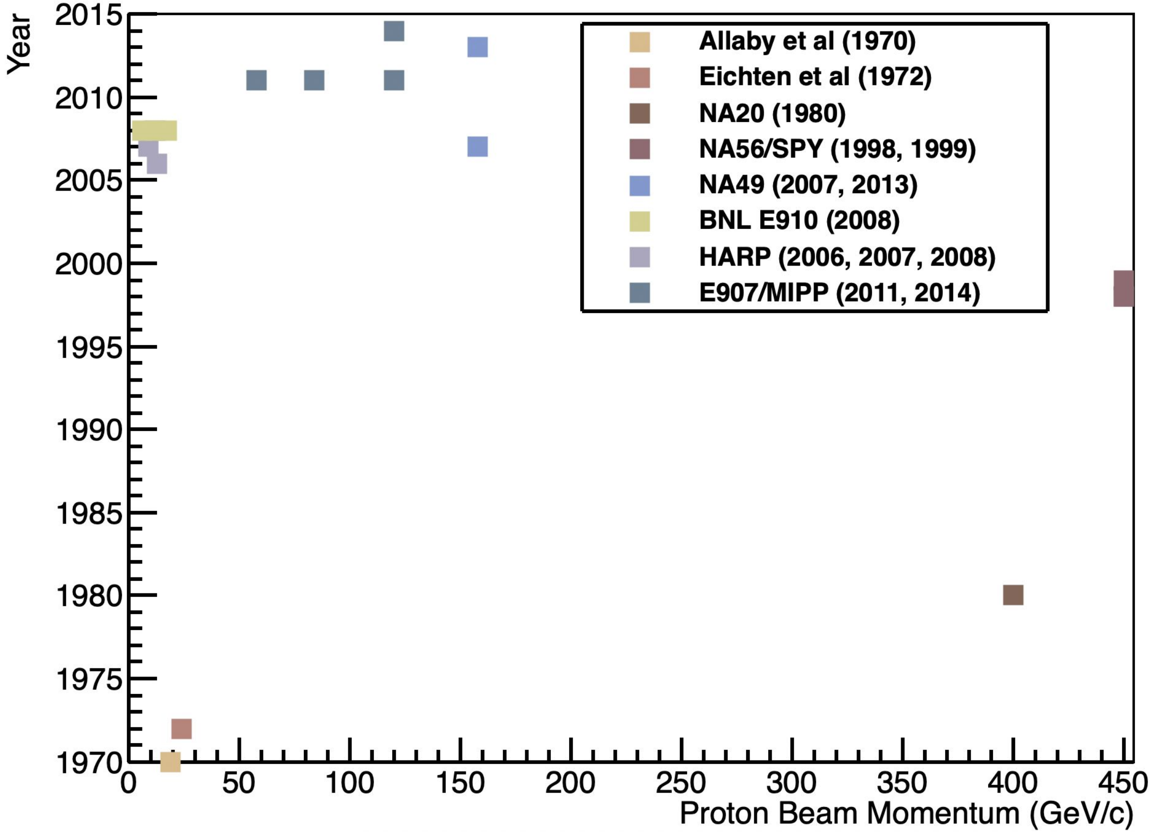
# Hadron Production Measurements

- Thin-target measurements
  - Total, inelastic and production cross sections
  - Charged and neutral hadron yields from primary and secondary interactions
  - Input to reweight flux simulations
- Replica-target measurements
  - Differential production yield measurements from the surface of the target
  - Beam survival probability
  - Input to reweight flux simulations
  - Input to understand beam attenuation

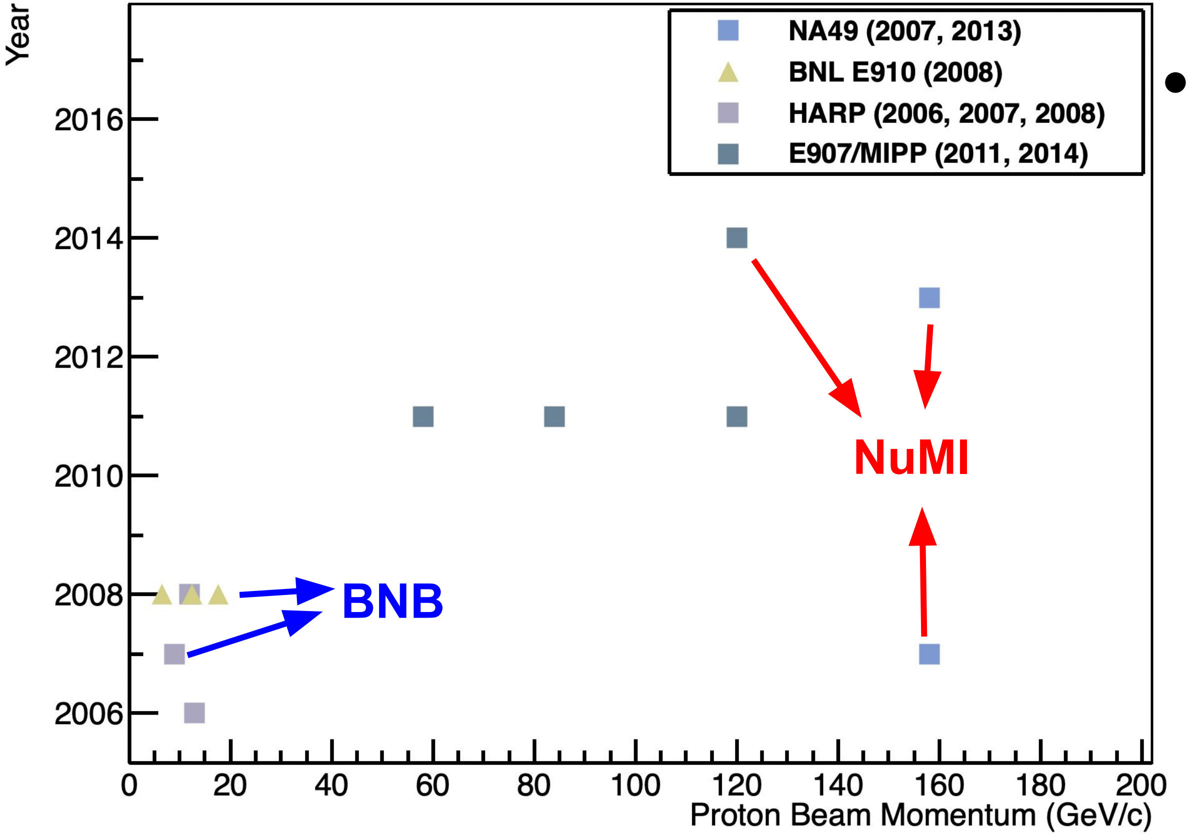


# Previous Hadron Production Experiments

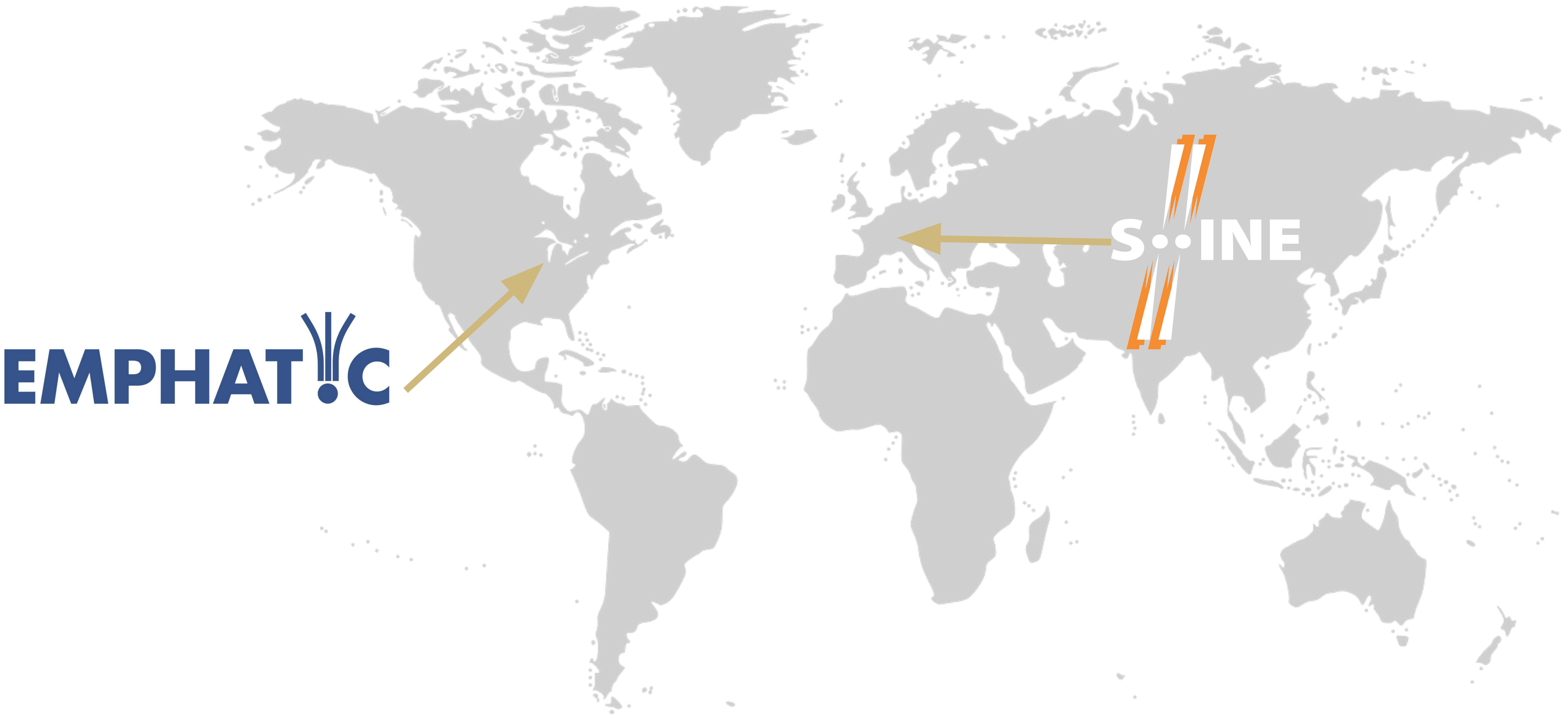


# Previous Hadron Production Experiments

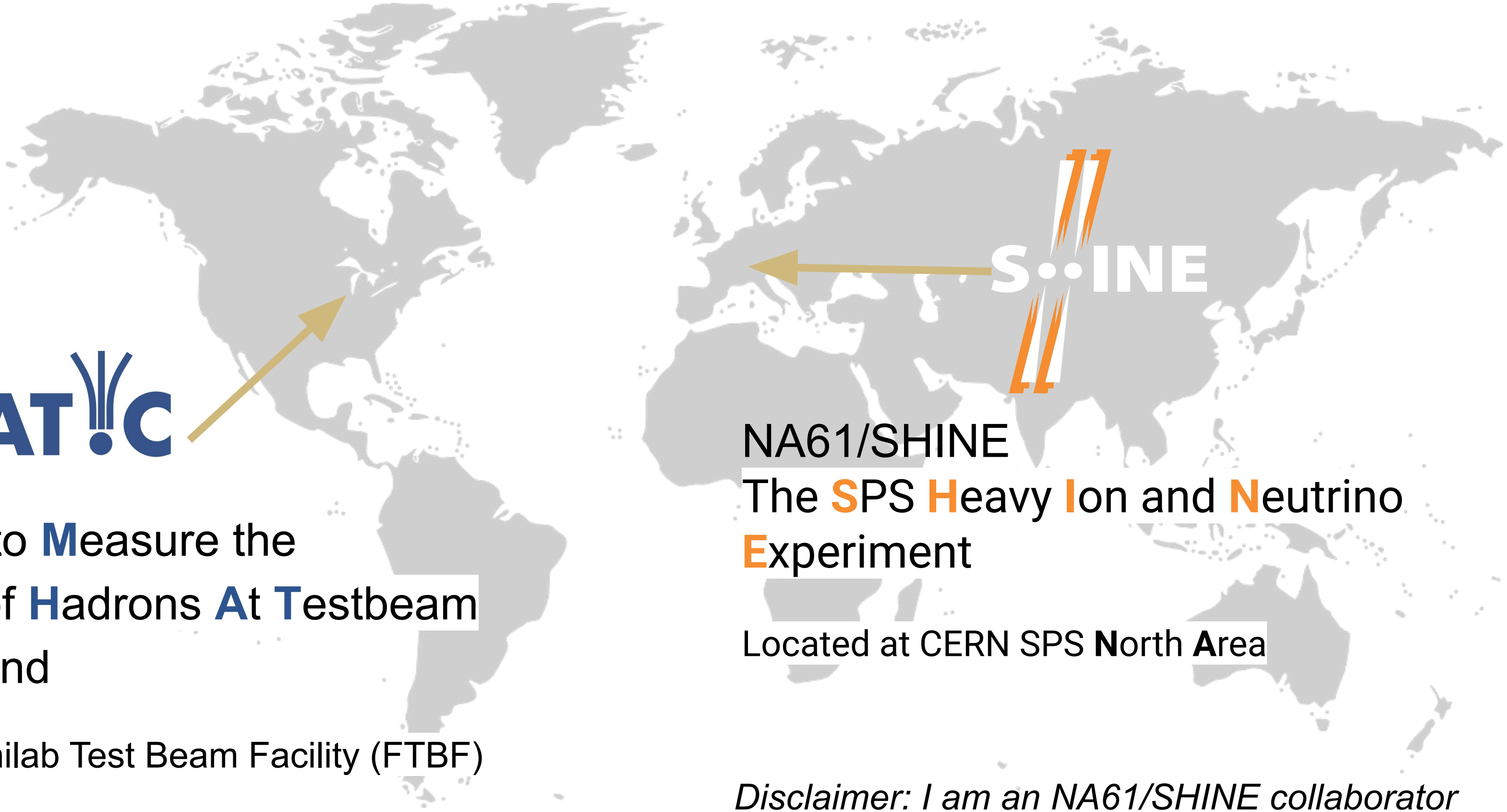



- Implemented in neutrino flux prediction
  - NuMI
    - NA49 (thin C target)
    - MIPP (NuMI spare target)
  - Booster Neutrino Beam (BNB)
    - HARP (thin Be target)
    - BNL E910 (thin Be target)

# Current Hadron Production Experiments



# Current Hadron Production Experiments



EMPHATIC

**E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t **T**estbeam **I**n **C**hicagoland

Located at Fermilab Test Beam Facility (FTBF)

SHINE

NA61/SHINE
The **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment

Located at CERN SPS **N**orth **A**rea

*Disclaimer: I am an NA61/SHINE collaborator*

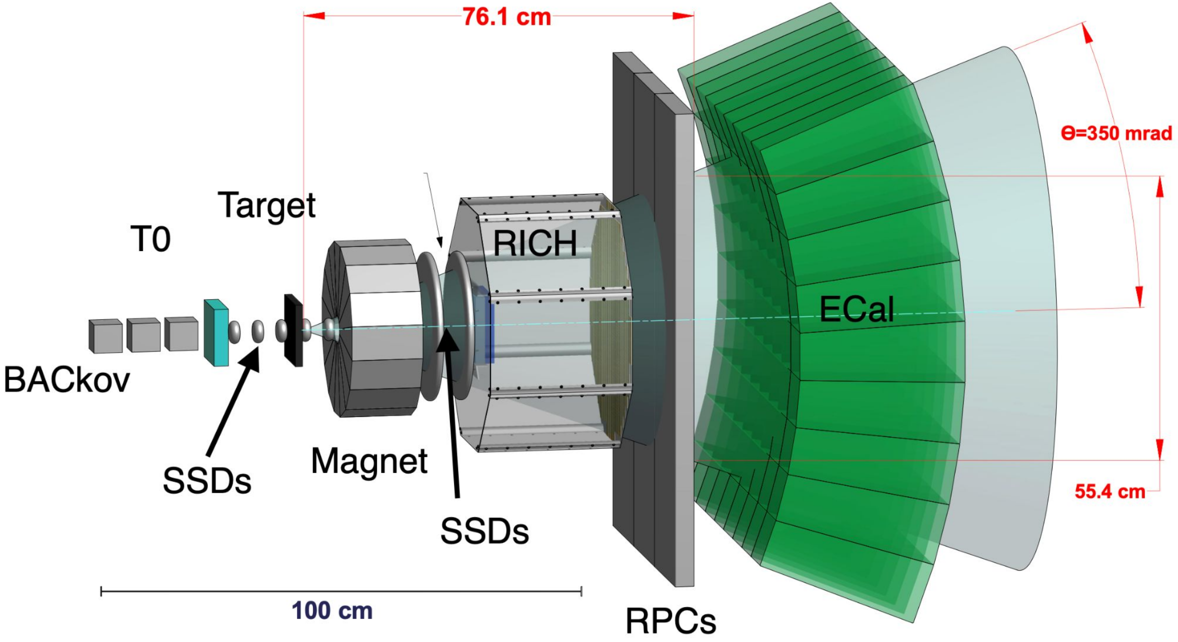
# Overview

- International collaboration from 25 institutions in 4 countries

# Overview

EMPHATIC

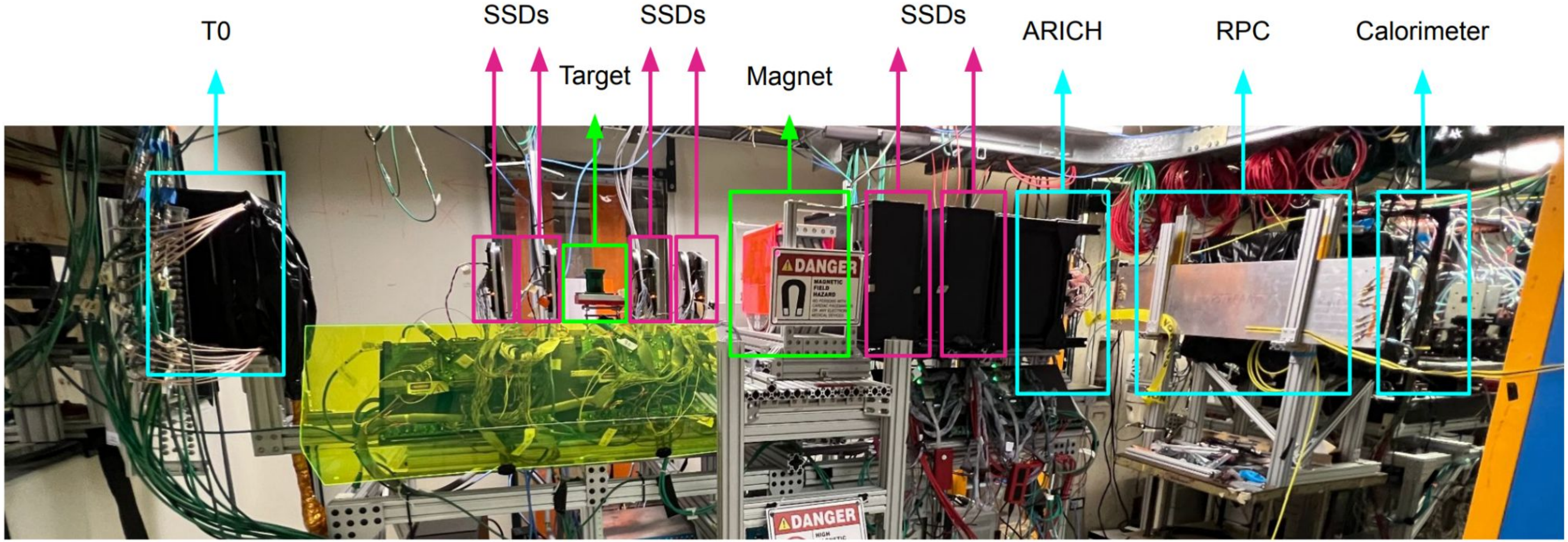
- Ultimate Design
  - 350 mrad acceptance
  - PID up to 18 GeV/c
- Timeline
  - Phase 0
    - 2018
  - Phase 1
    - 2022 - 2023
  - Phase 2
    - 2024 - 2025




arxiv: 1912.08841

# Layout

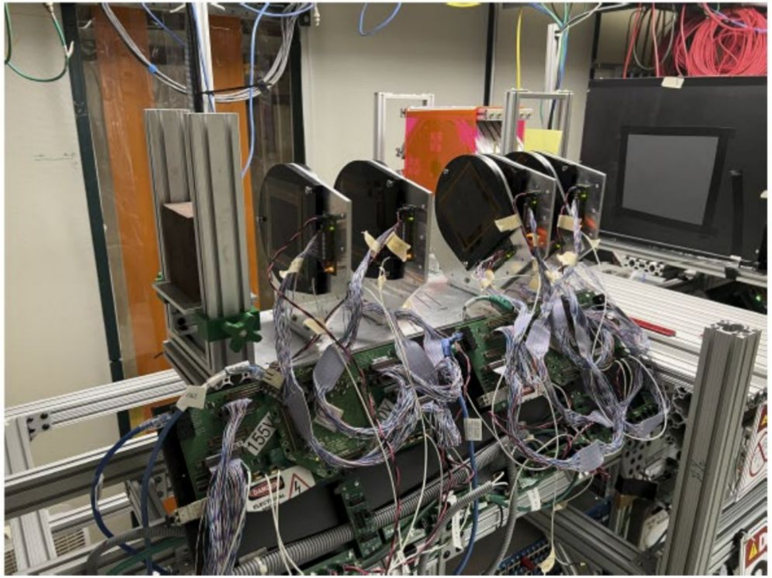
- Fermilab FTBF (2 - 120 GeV/c)
- Table-top experiment (detectors fit within 4 meters)
- Smaller versions of the Magnet, RICH, and ECal used in Phase 1
  - ≤ 100 mrad acceptance, PID up to 8 GeV/c

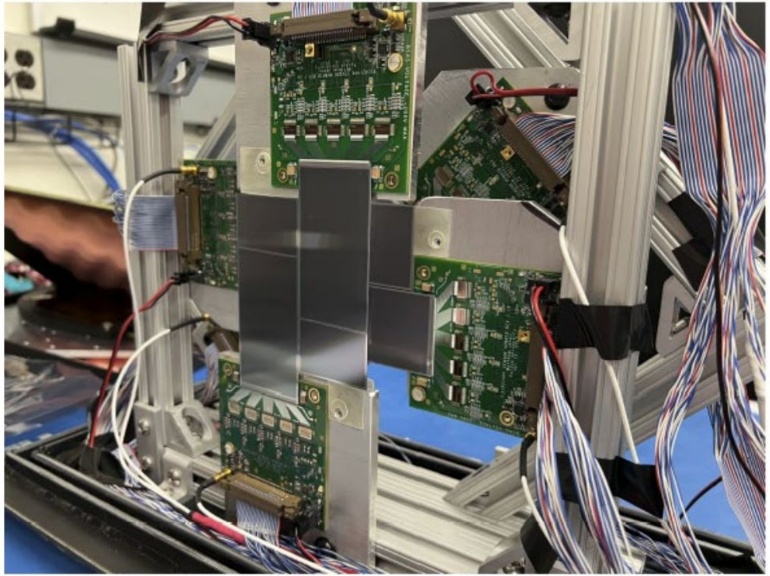


# SSDs

EMPHATIC

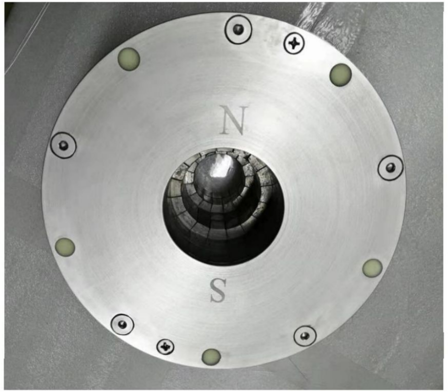
- Silicon Strip Detectors provided by FTBF
- Upstream and downstream of target
- Tracking of charged particles
- 60 μm pitch and ~10 μm spatial resolution

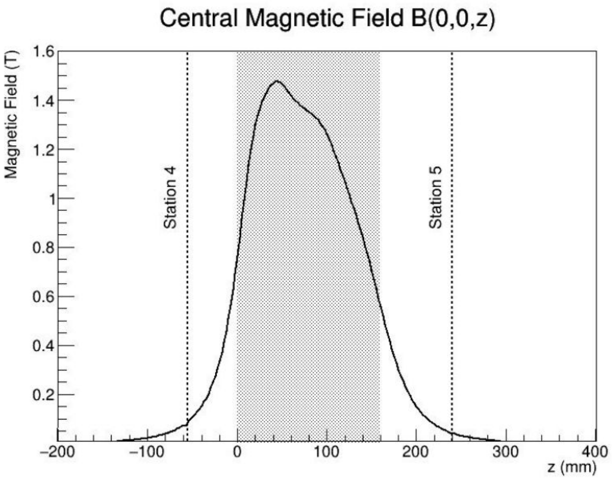


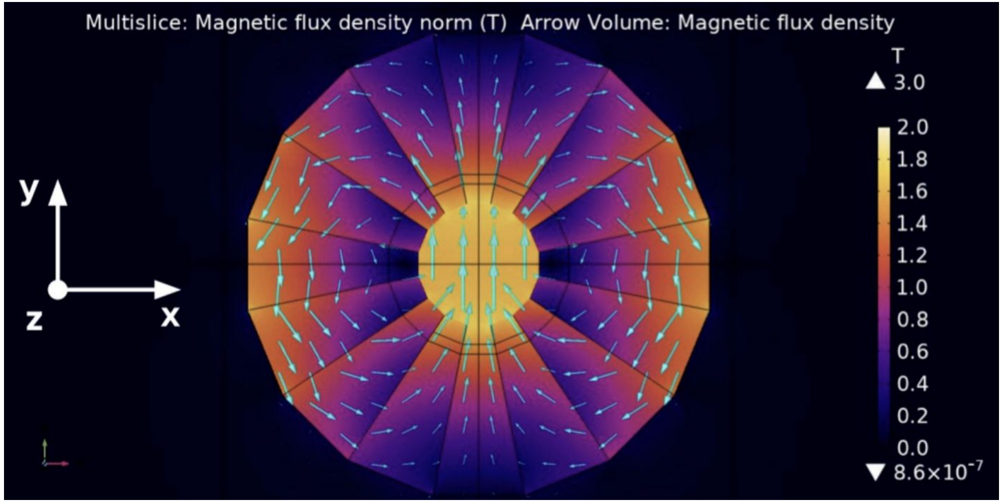


# Magnet

- prototype small-aperture compact magnet
  - 3-layer cylindrical Halbach dipole with 48 N52 Neodymium magnets
  - 3D measured map of the field available where B max = 1.44 T

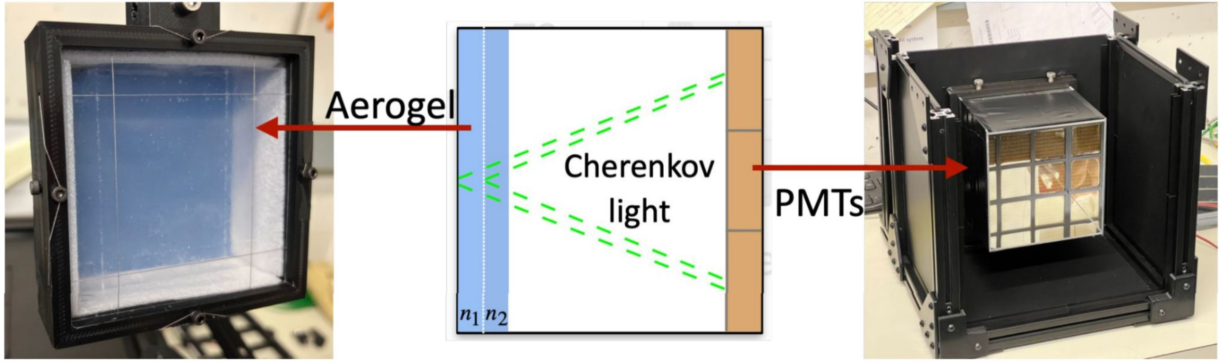


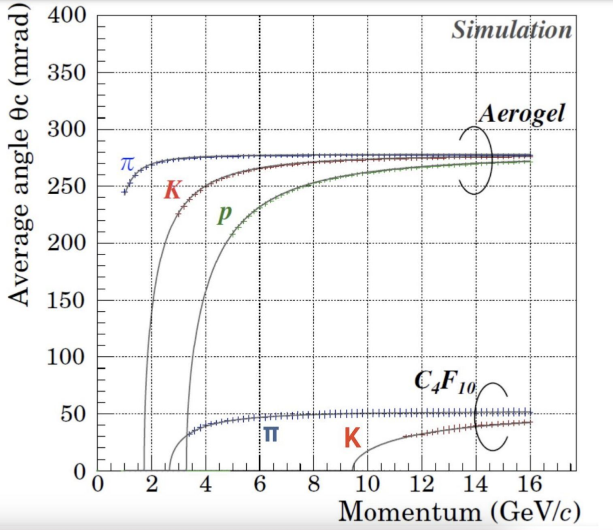



# ARICH

- Aerogel Ring Imaging CHerenkov
- Prototype ARICH with 150 mrad acceptance
- 2 layers of aerogel
- Aerogels with lower indices of refraction (n1=1.02, n2=1.03)
- Expect to achieve better than 2σ π/K separation at 7 GeV/c

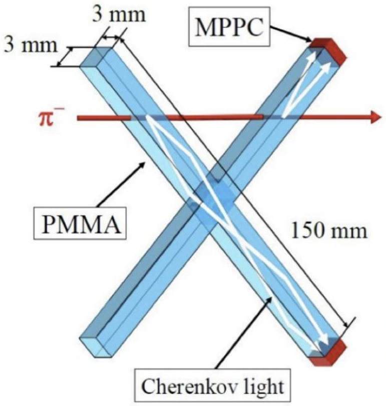


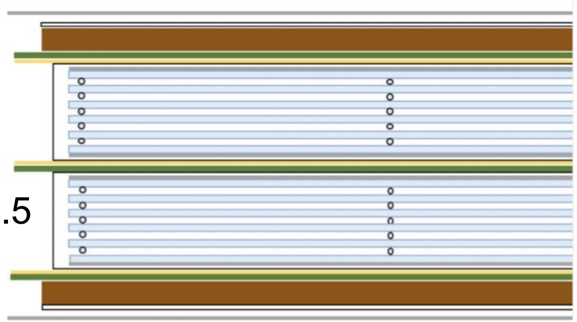
# Time of Flight system

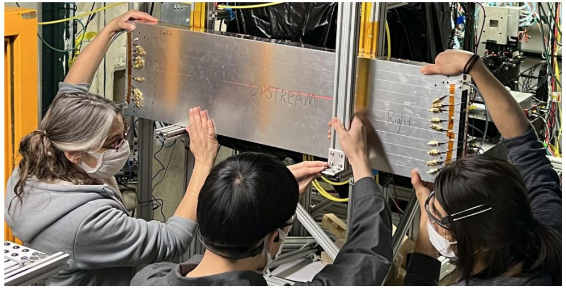
EMPHATIC

- T0
  - X-shaped acrylic Cherenkov layered detector
  - Upstream-most, time of incident beam particle
- Resistive Plate Chamber (RPC)
  - Measure time of secondary particles downstream
- Time of Flight (ToF)
  - Combined timing resolution expectation: ~ 70 ps
  - Particle separation up to ~1.5 GeV/c



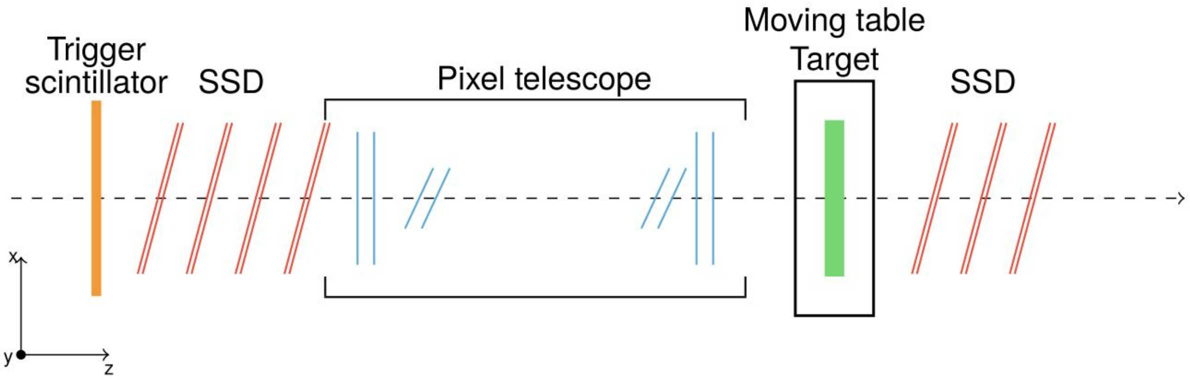

PMMA: poly(methyl methacrylate)
MPPC: multi-pixel photon counter (SiPM)





# EMPHATIC Run Plan

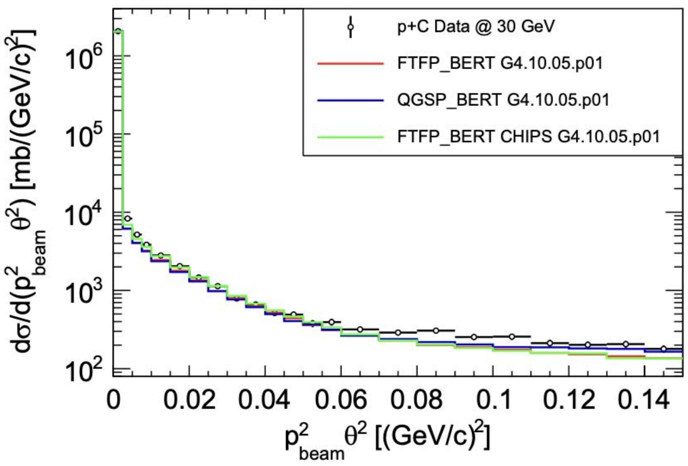
- Phase 0 (2018)
  - Proof of principle (0-20 mrad)
  - No spectrometer

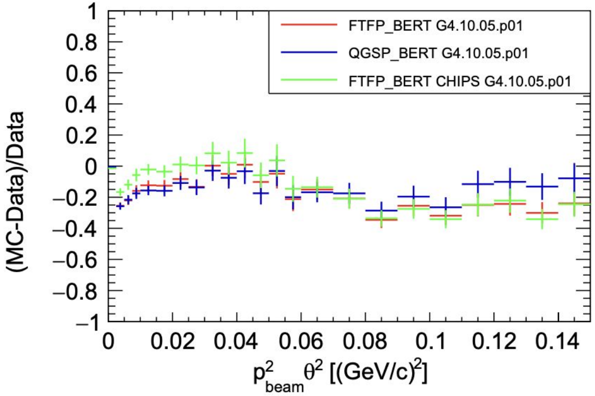


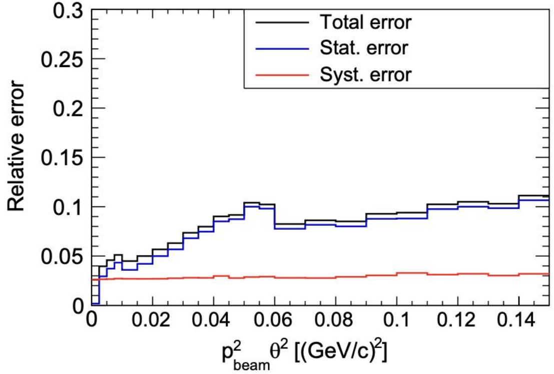

PRD 106 112008 (2022)

# EMPHATIC Run Plan

- Phase 0 (2018)
  - Proof of principle (0-20 mrad)
  - No spectrometer
  - Total cross section measurements in forward scattering
    - Beam
      - Proton at 20, 31, 60, 120 GeV/c
    - Target:
      - Carbon
      - Iron
      - Aluminum



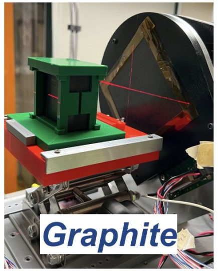



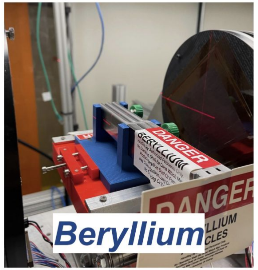




PRD 106 112008 (2022)

# EMPHATIC Run Plan

- Phase 0 (2018)
  - Proof of principle (0-20 mrad)
- Phase 1 (2022-2023)
  - 100 mrad acceptance spectrometer
  - During the 6-week data-taking, collected over 250 million triggers

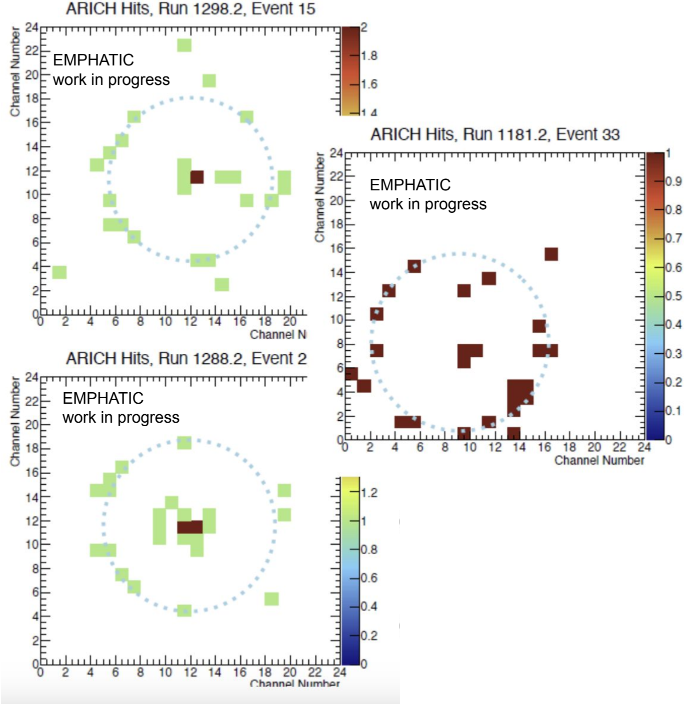


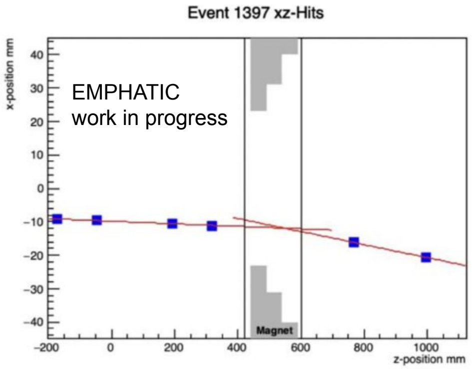





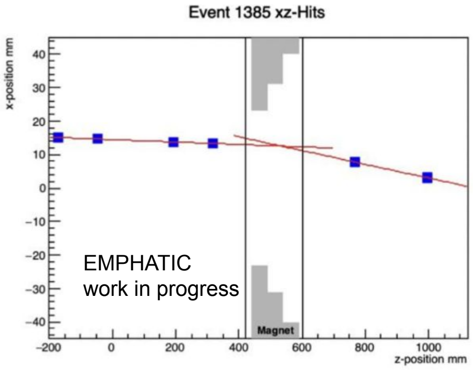
| Target | Beam Mom (GeV/c) | #Triggers | Target | Beam Mom (GeV/c) | #Triggers |
|---|---|---|---|---|---|
| Graphite | 120 | 2.5M | Beryllium | -4 | 11M |
| | 4 | 11M | | 4 | 11M |
| | -4 | 11M | | 8 | 13M |
| | -8 | 38M | CH2 | -20 | 14M |
| | -12 | 18M | | -8 | 6.5M |
| | 20 | 12M | | -4 | 3M |
| | -20 | 14M | H2O | -4 | 10M |
| | 30 | 23M | | 4 | 10M |
| | | | | -20 | 5.6M |

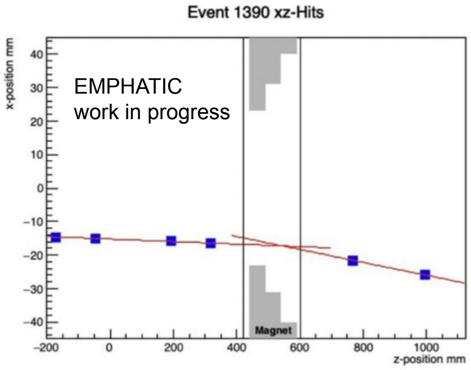
# Phase 1 data



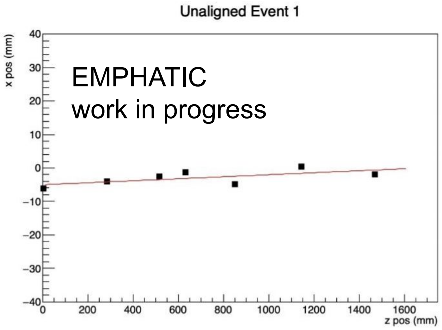

- 4 GeV Pion
  - XZ-plane
  - Saw bending tracks
- Cherenkov rings

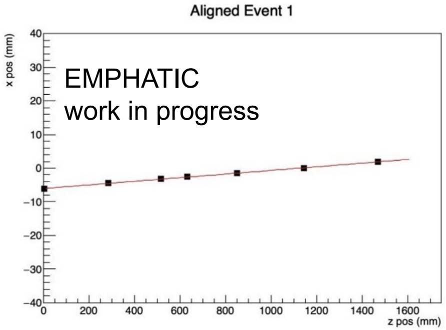


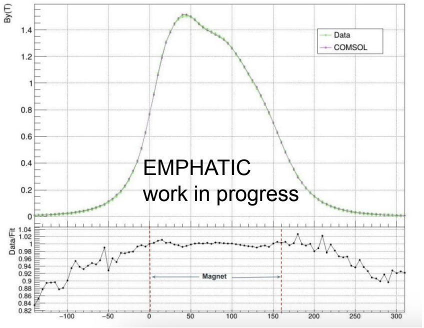



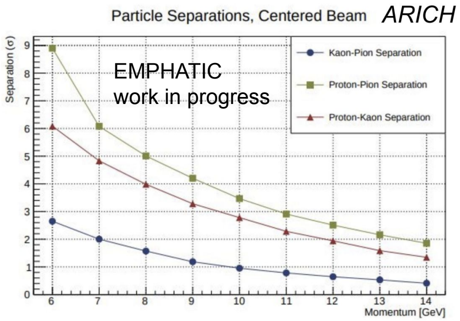
# Phase 1 data

EMPHATIC



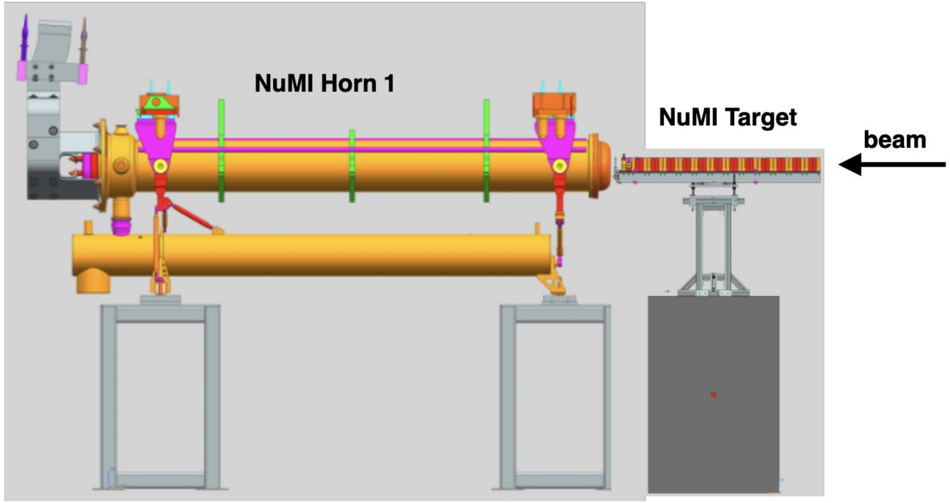




- Working on detector alignment and calibration
- Developing an extensive map of the magnetic field region of the spectrometer
- Developing PID algorithms (ARICH)
- Writing analysis infrastructure (CAFs)

# EMPHATIC Run Plan

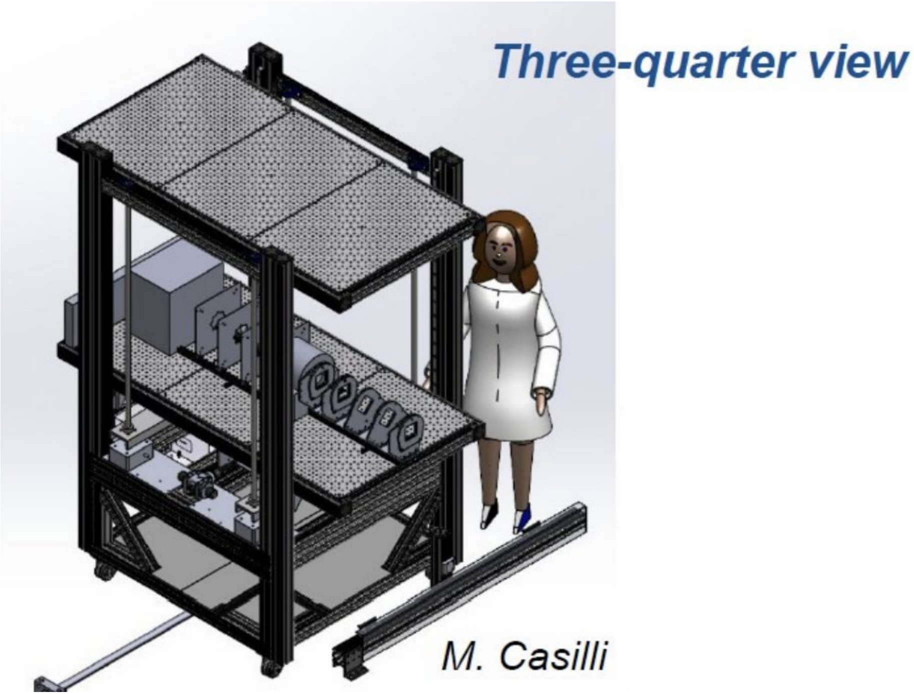
- Phase 0 (2018)
  - Proof of principle (0-20 mrad)
- Phase 1 (2022-2023)
  - 100 mrad acceptance spectrometer
- Phase 2 (2024-2025)
  - Make measurement of charged-particle spectrum downstream with spare NuMI target and unpowered horn
  - More thin-target measurements



# EMPHATIC Run Plan

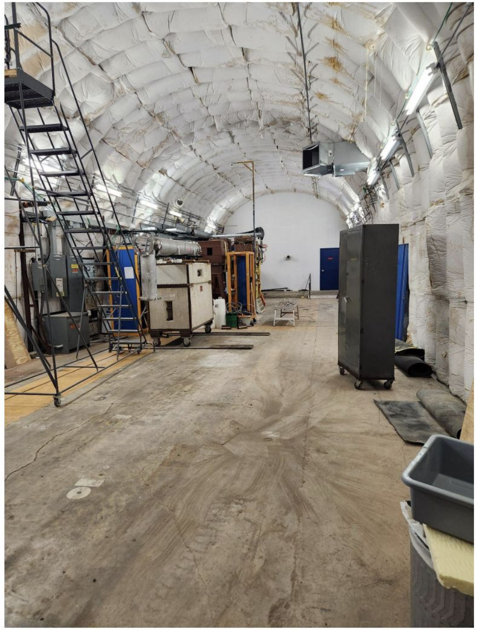
EMPHATIC

- Phase 0 (2018)
  - Proof of principle (0-20 mrad)
- Phase 1 (2022-2023)
  - 100 mrad acceptance spectrometer
- Phase 2 (2024-2025)
  - Make measurement of charged-particle spectrum downstream with spare NuMI target and unpowered horn
  - More thin-target measurements
  - Put the EMPHATIC Phase 1 spectrometer on a motion table that will sweep through the acceptance of the horn

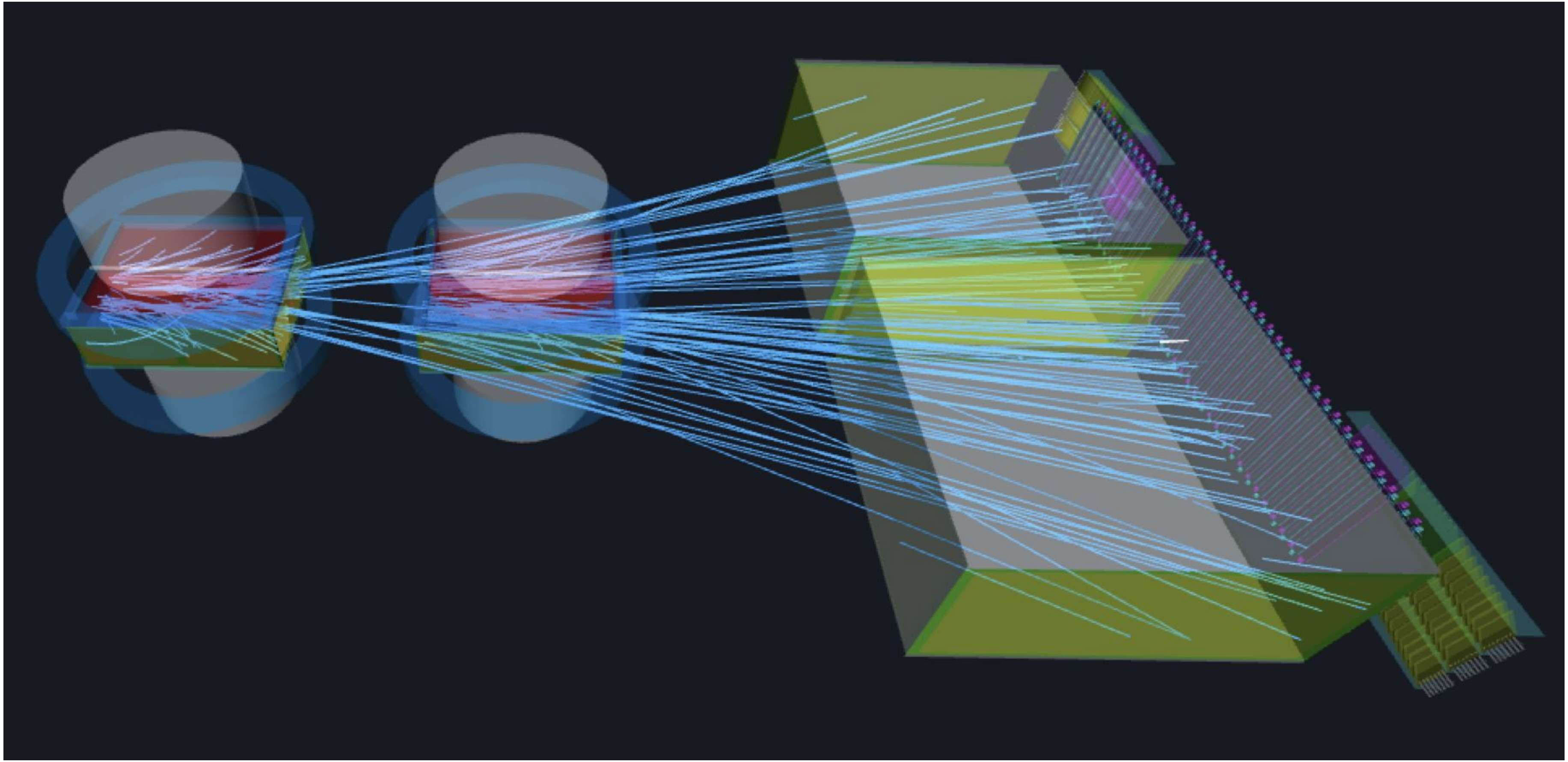


# EMPHATIC Run Plan

- Phase 0 (2018)
  - Proof of principle (0-20 mrad)
- Phase 1 (2022-2023)
  - 100 mrad acceptance spectrometer
- Phase 2 (2024-2025)
  - Installation started last week
  - New home at MCenter
  - Plan to take data this fall/winter
- Future upgrades under consideration



# NA61/SHINE



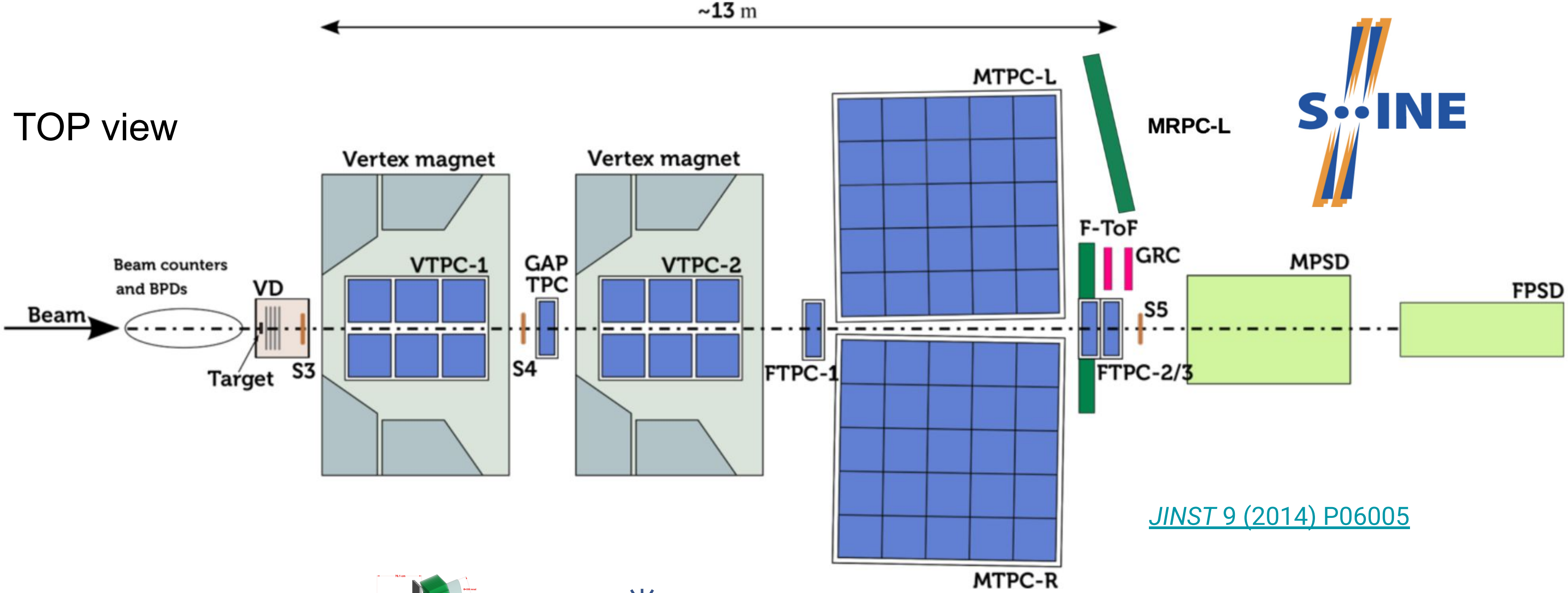
# NA61/SHINE

- Beam (13 - 350 GeV/c)
  - Primary proton beam from CERN SPS
  - Secondary beam of proton, kaon, pion, etc.
- Physics program
  - Heavy ions
  - Cosmic-ray production
  - **Hadron production for neutrino beams**
- International collaboration of 37 institutions
  - 9 of them work on the neutrino program

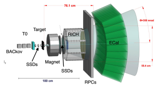

ELTE EÖTVÖS LORÁND UNIVERSITY
LPNHE PARIS
岡山大学 OKAYAMA UNIVERSITY
KEK
UNIVERSITY OF NOTRE DAME
University of Colorado Boulder
University of Pittsburgh
Fermilab
WARWICK

# NA61/SHINE Detector

TOP view



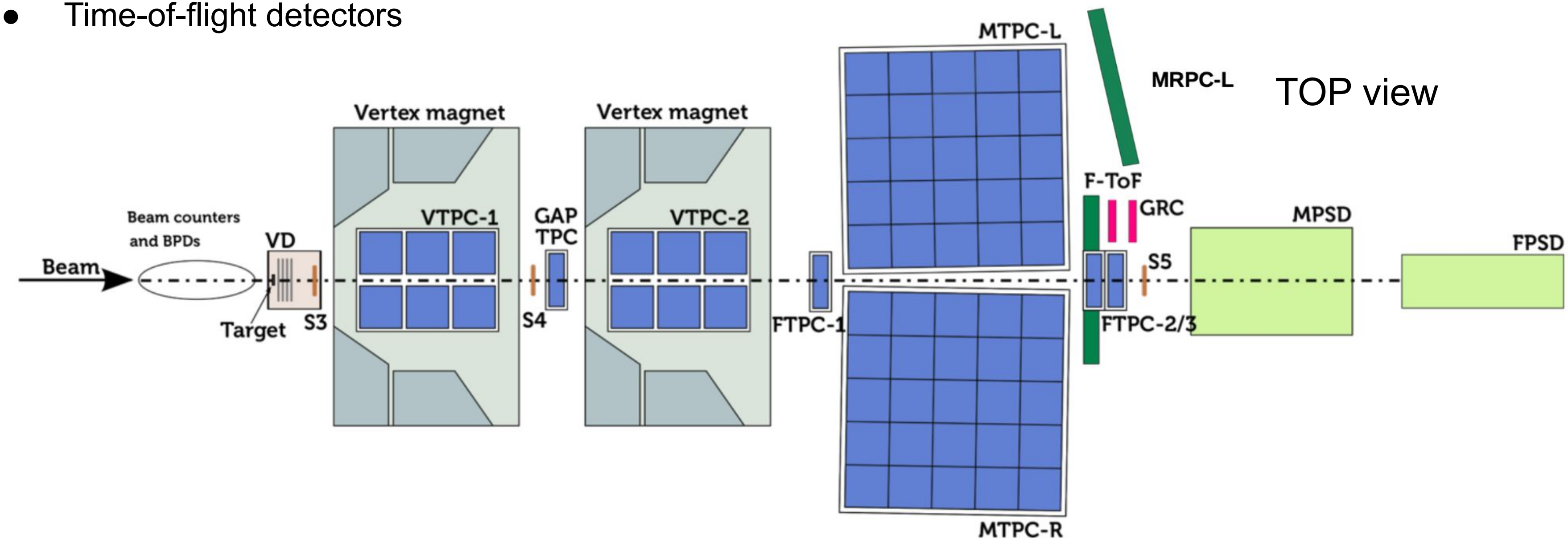

[JINST 9 (2014) P06005](#)



EMPHATIC

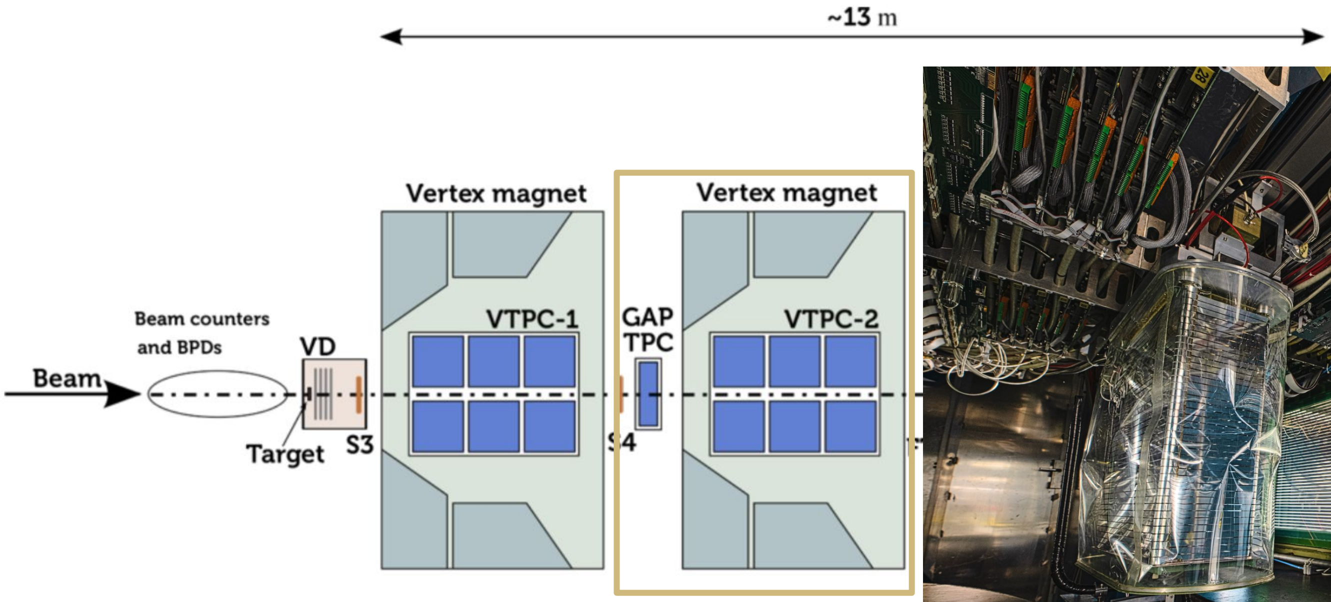
# NA61/SHINE Detector

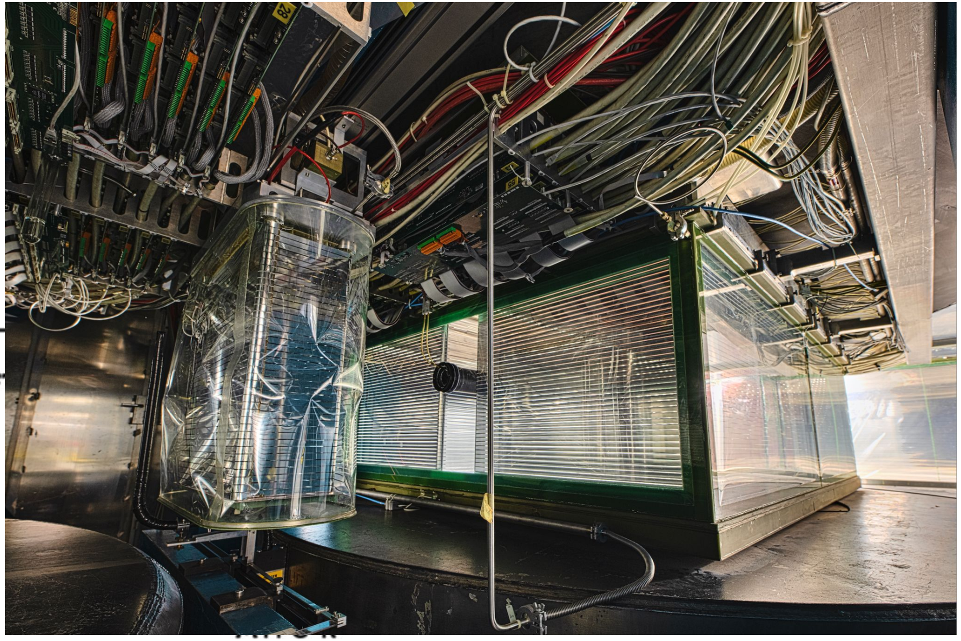
- 8 Time Projection Chambers (TPCs)
- Two superconducting magnets
- Time-of-flight detectors



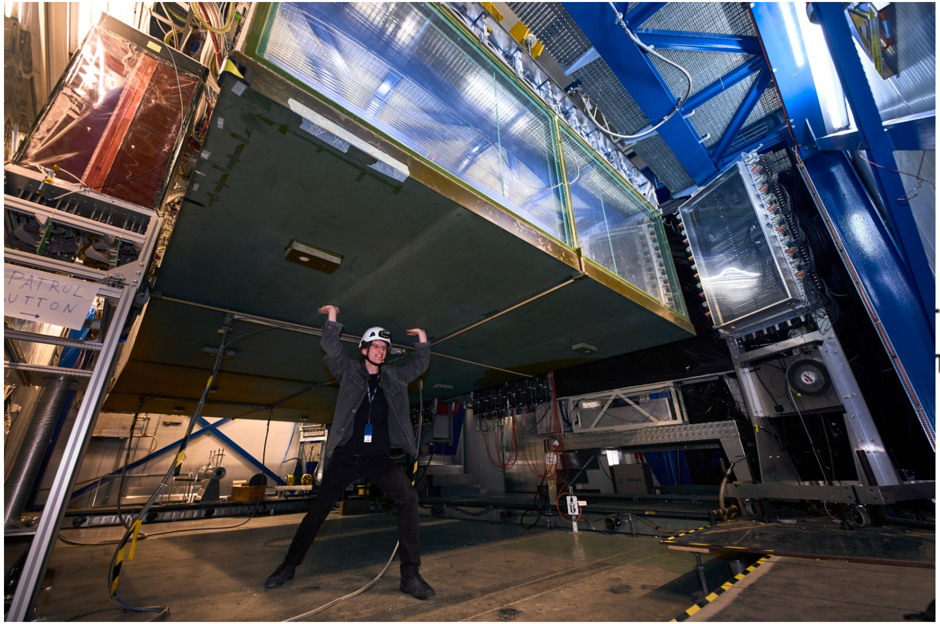

- Projectile Spectator Detectors (PSDs)
- Major detector upgrade finalized in 2022

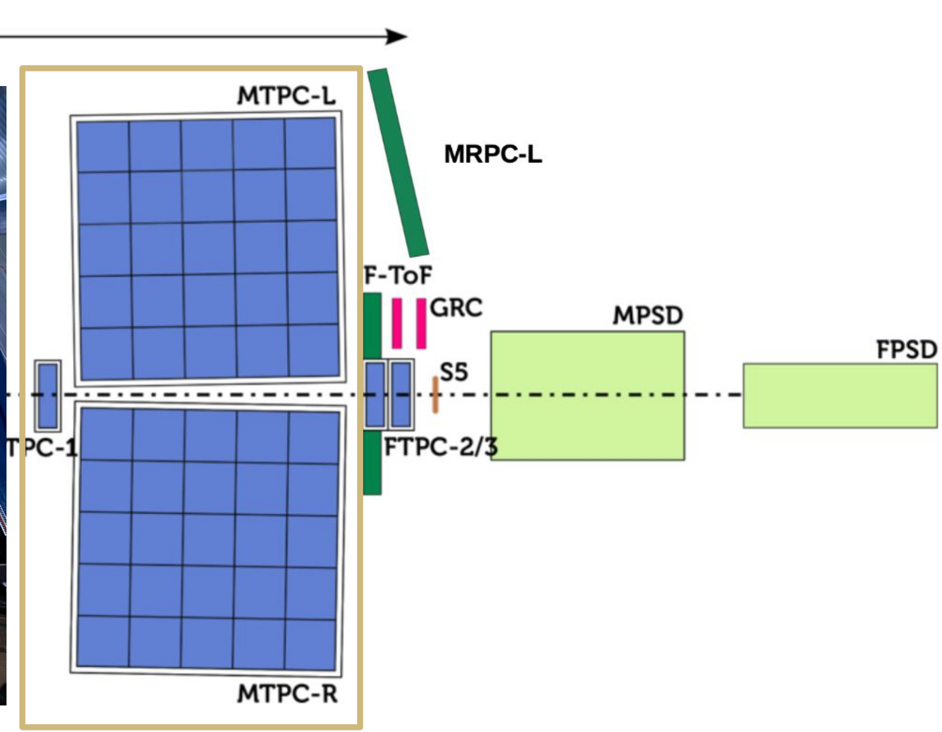
# NA61/SHINE Detector



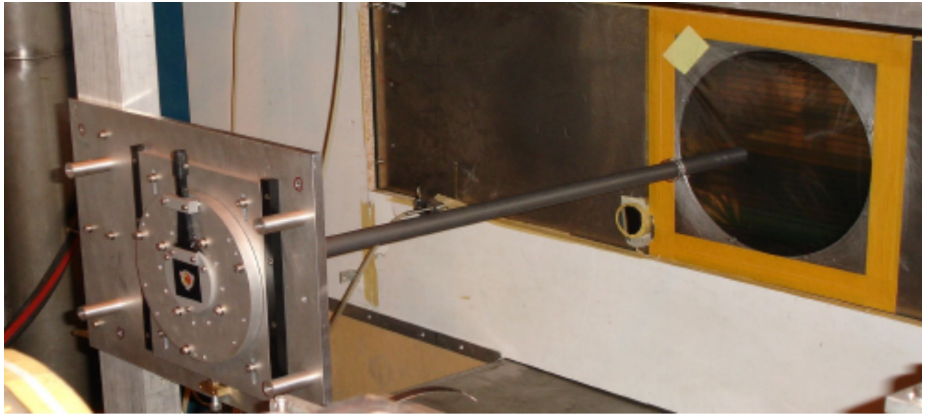
# NA61/SHINE Detector

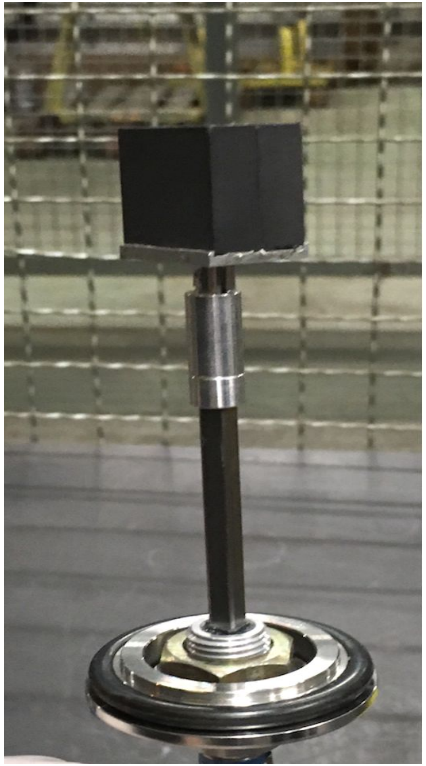


# Measurements for the T2K Experiment

- 2007 - 2010
- Proton + carbon @ 31 GeV/c
- Targets
  - Thin:   2 cm graphite target
  - Thick: 90 cm replica graphite target



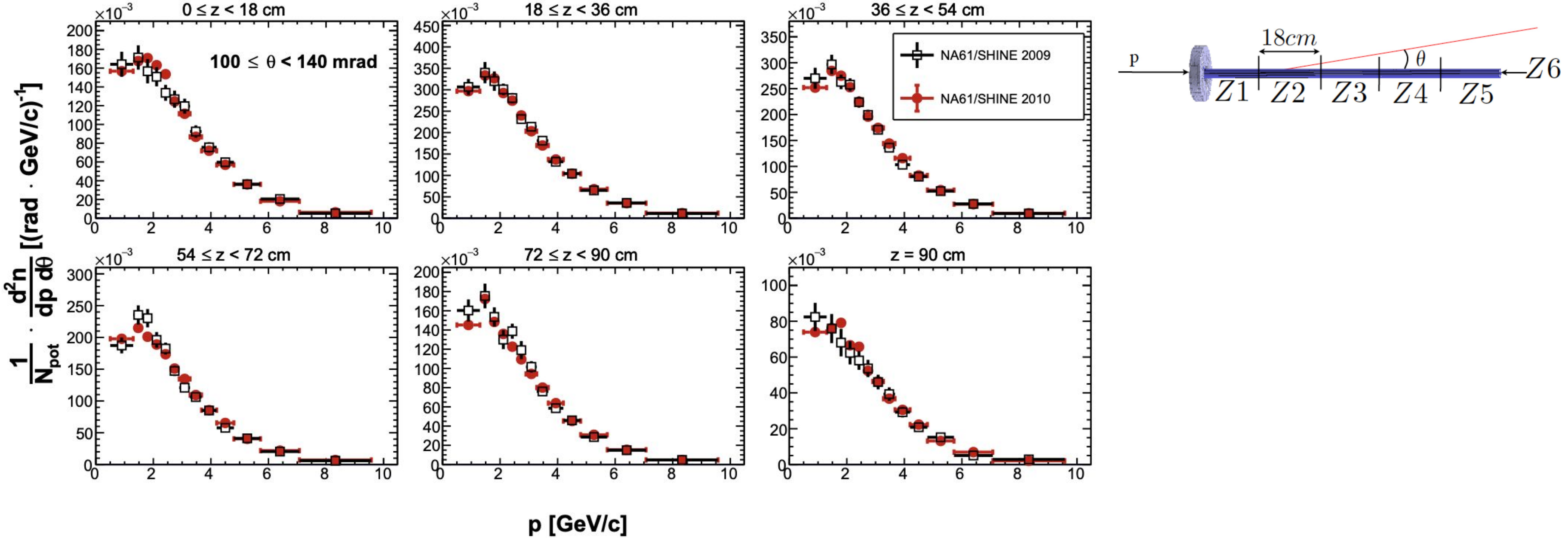


# Thin Target Measurements for T2K

- Thin target: 31 GeV/c proton on 2 cm graphite target
  - Total cross-section and $\pi^{+/-}$ spectra measurements (Phys. Rev. C84 (2011) 034604)
  - $K^{+}$ spectra measurement (Phys. Rev. C85 (2012) 035210)
  - $K^{0}_{S}$ and $\Lambda^{0}$ spectra measurements (Phys. Rev. C89 (2014) 025205)
  - Total cross-section and $\pi^{+/-}$, $K^{+/-}$, p, $K^{0}_{S}$, and $\Lambda^{0}$ spectra measurements (Eur. Phys. J. C76 (2016) 84)
- Replica target: 31 GeV/c proton on 90 cm replica graphite target
  - Methodology, $\pi^{+/-}$ yield measurement (Nucl. Instrum. Meth. A701 (2013) 99-114)
  - $\pi^{+/-}$ yield measurement (Eur. Phys. J. C76 (2016) 617)
  - $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79 100 (2019))
  - p beam survival probability measurement (Phys. Rev. D103 012006 (2021))

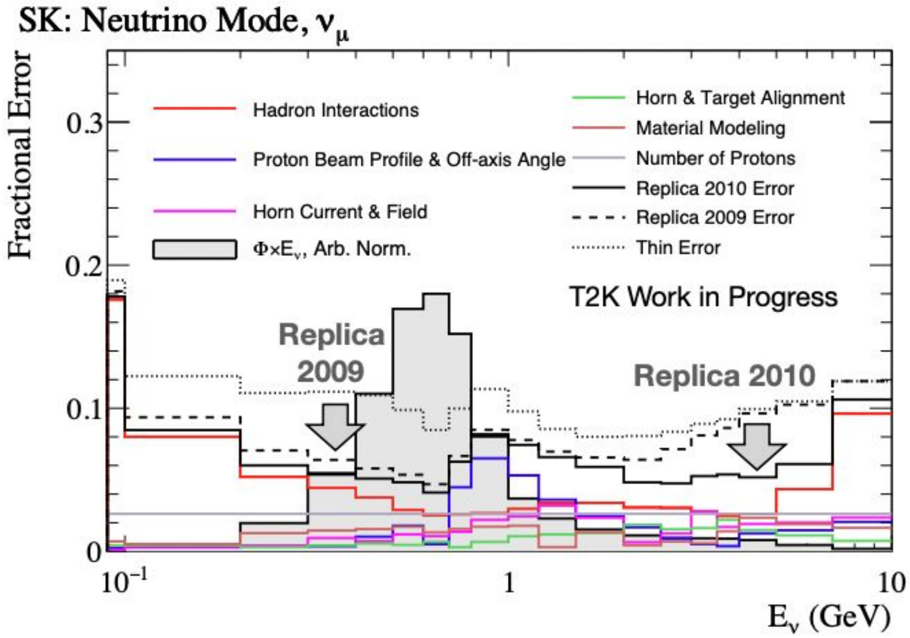
# Thick Target Measurements for T2K

- Replica target: 31 GeV/c proton on 90 cm replica graphite target
  - 2009 data: $\pi^{+/-}$ yield measurement (Eur. Phys. J. C76 (2016) 617)
  - **2010 data: $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79 100 (2019))**



# Effect on T2K Flux Uncertainty

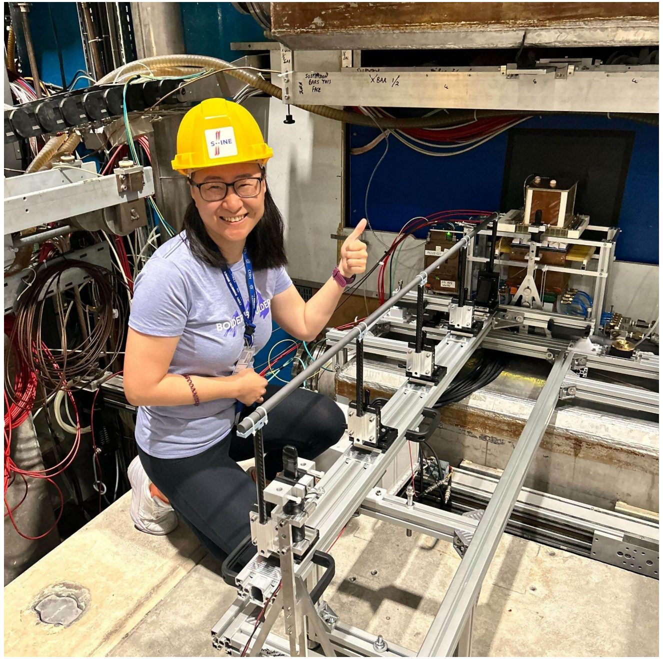
- Improved T2K flux uncertainty down to ~5%
- More replica target data collected in 2022
  - 18 times 2010 statistics
  - Being calibrated
  - Measure high-momentum kaon yields




[Lukas Berns, NBI 2019]

# Measurements for NuMI Experiments and DUNE

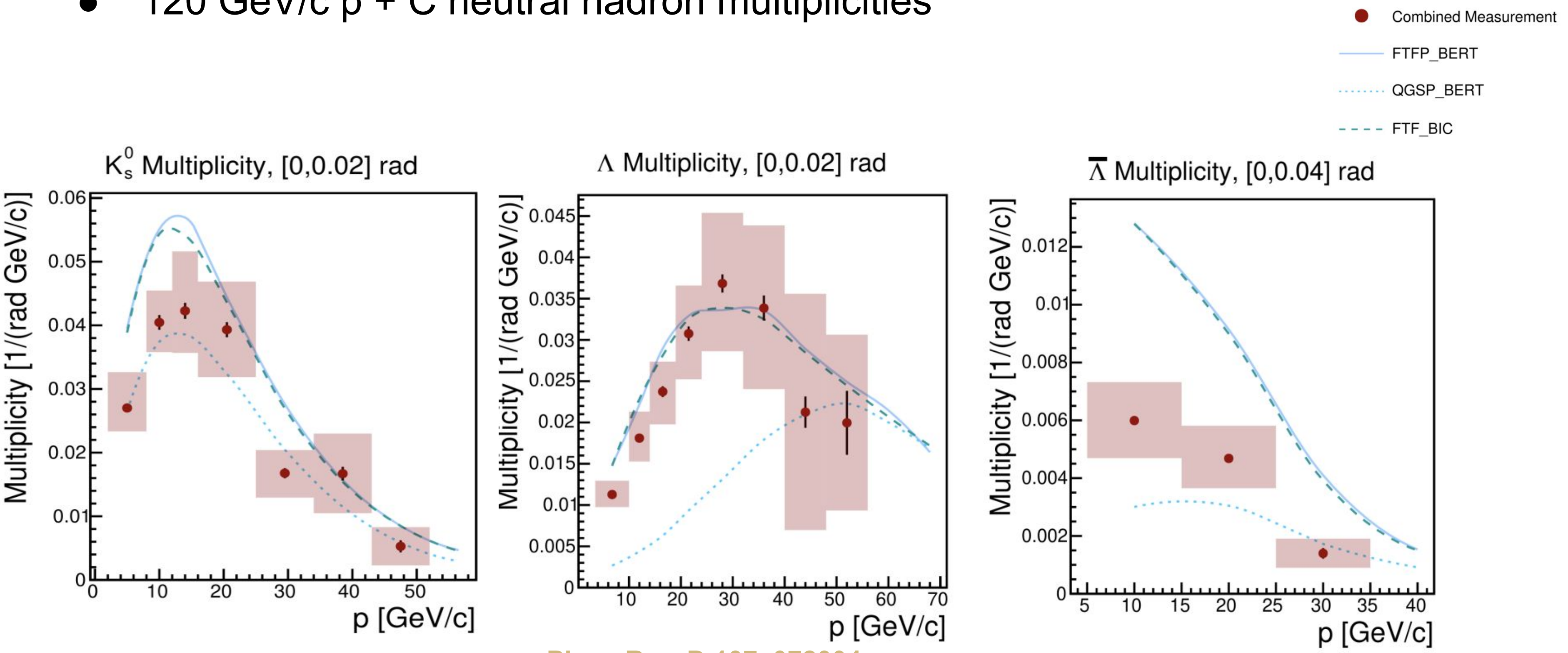
- 2015 - 2018, 2023-2025
- Beam
  - Proton at 120 GeV/c
  - Proton at  60, 90 GeV/c
  - Pion at 60 GeV/c
  - Kaon at 60 GeV/c
- Target
  - Thin (1.5 cm)
    - Carbon
    - Titanium
    - Beryllium
    - Aluminum
  - Thick
    - NuMI replica
    - LBNF/DUNE prototype (high density)
    - LBNF/DUNE prototype (low density, *proposed for 2025*)



LBNF/DUNE prototype target at NA61
July 2024

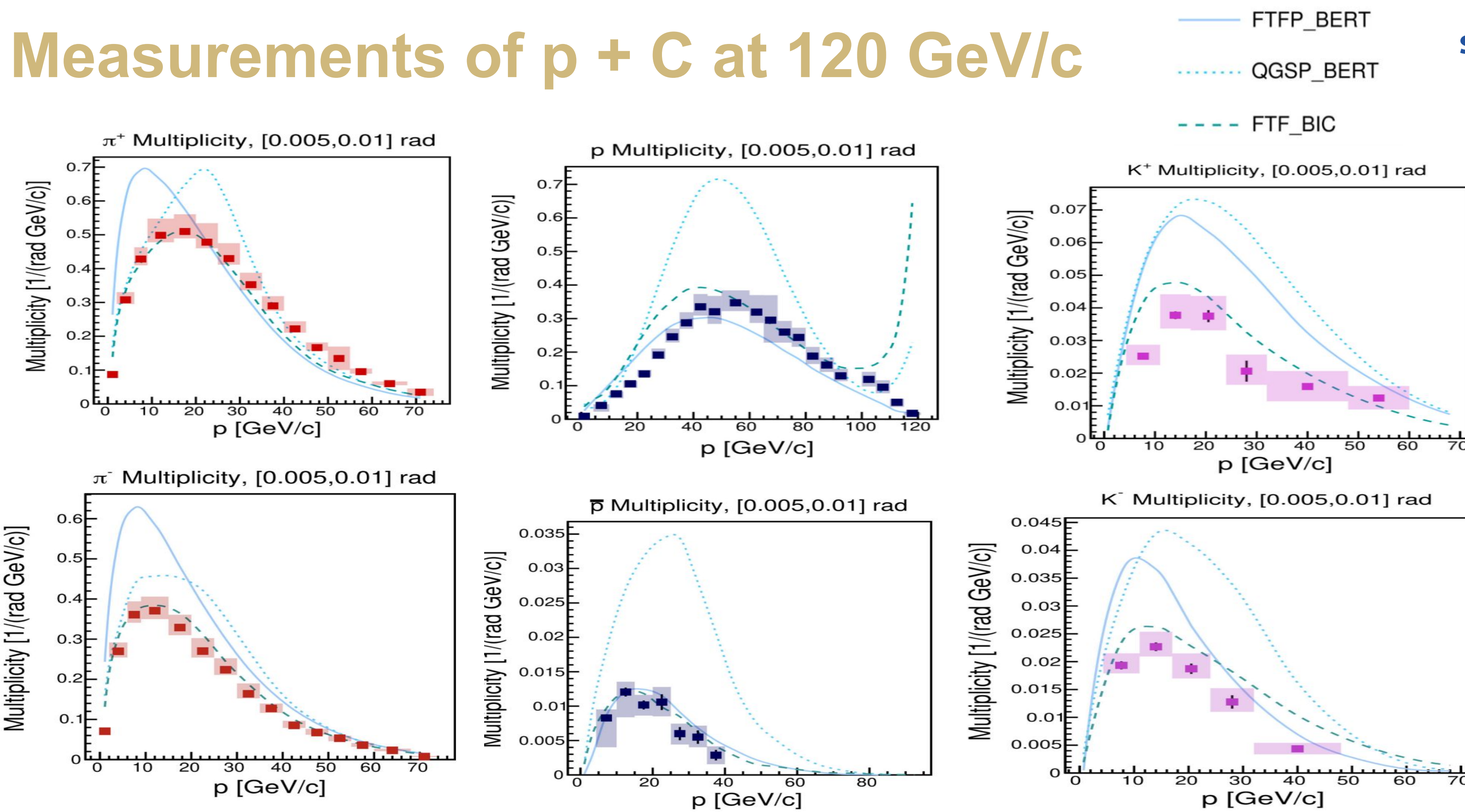
# Measurements of p + C at 120 GeV/c

- 120 GeV/c p + C neutral hadron multiplicities



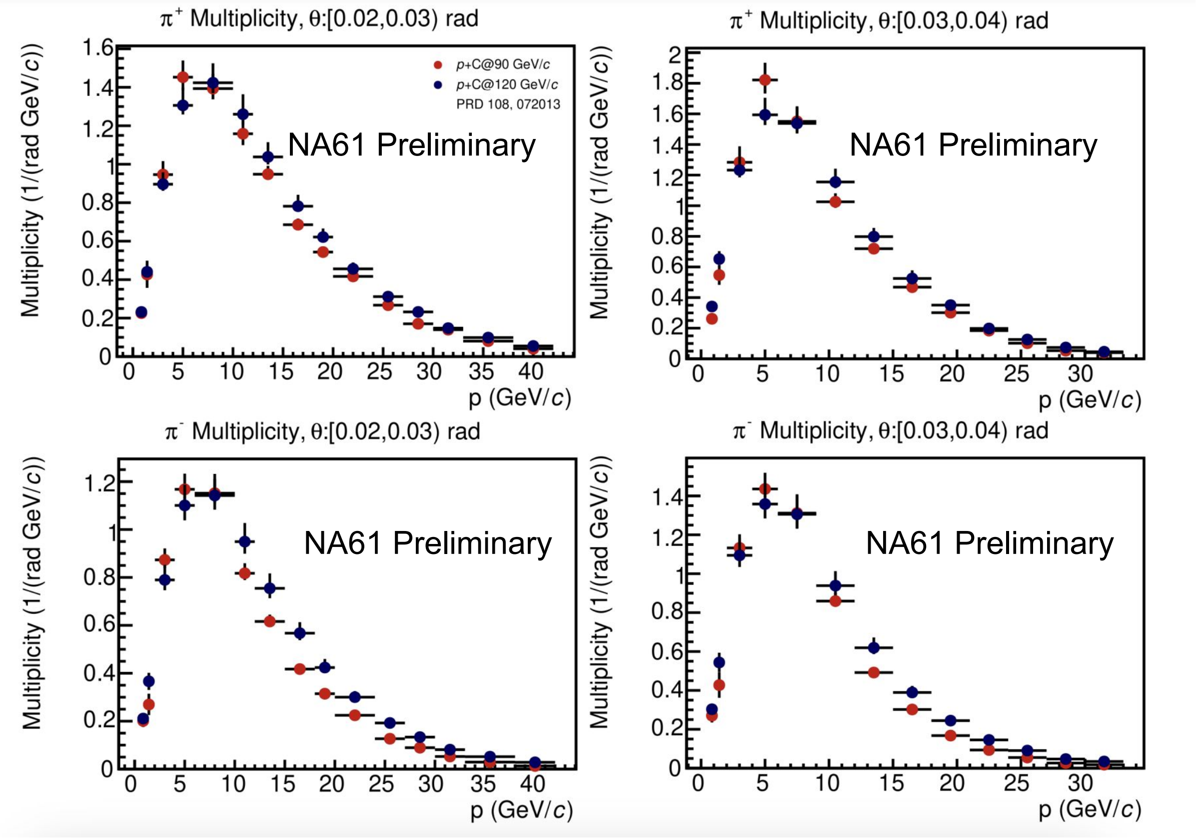

Phys. Rev. D 107, 072004

# Measurements of p + C at 120 GeV/c




Phys.Rev.D 108 (2023) 072013

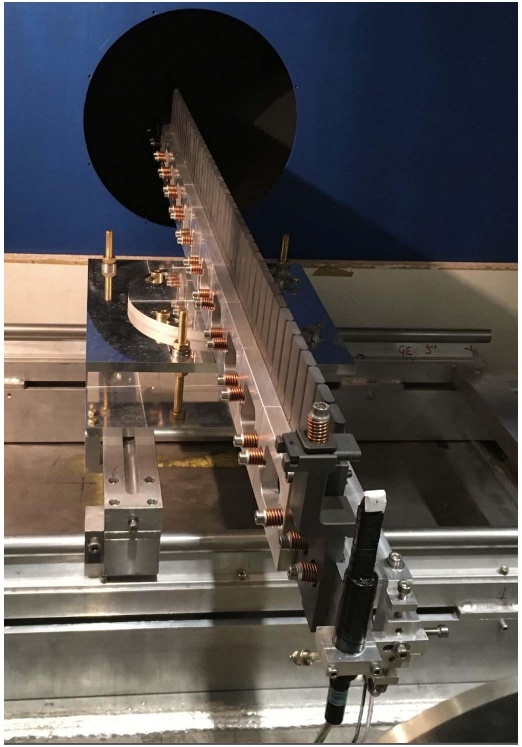
# Measurements of p + C at 90 GeV/c




- Paper being submitted to PRD
  - Neutral and charged hadron multiplicities
- Momentum scaling of proton-carbon interactions
  - p + C at 60 GeV/c coming soon

# Measurements with NuMI Replica Target

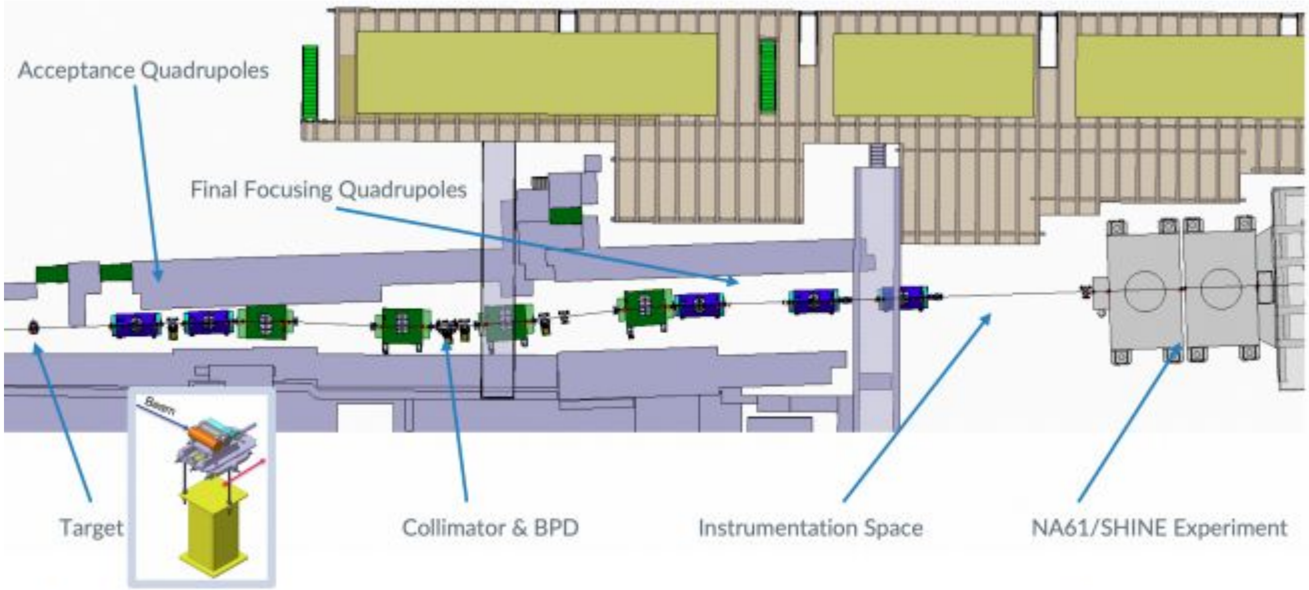
- 18 million events collected in 2018
- Proton at 120 GeV/c
- Main challenge
    - Complicated target geometry
- Calibration near complete
- Measurement of differential hadron production yields underway



NuMI replica target
“target in” at NA61

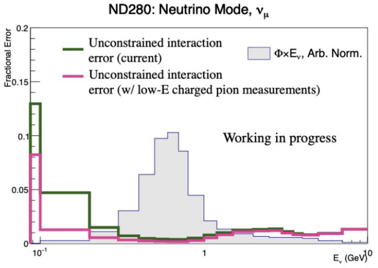
# Future Prospects (2026 - )

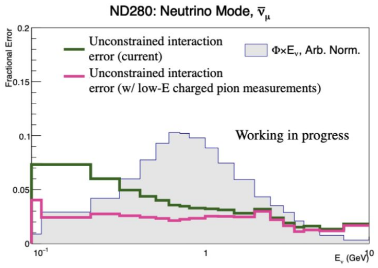
- A low-energy (2-13 GeV/c) beam design has been completed
- Beam may be available before/after CERN's Long Shutdown 3 (LS3)

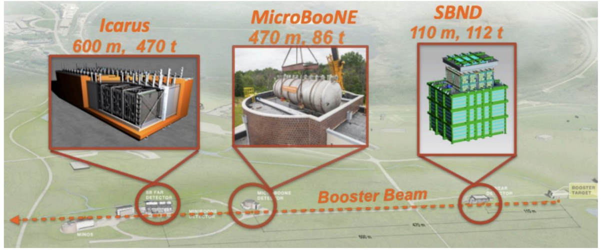


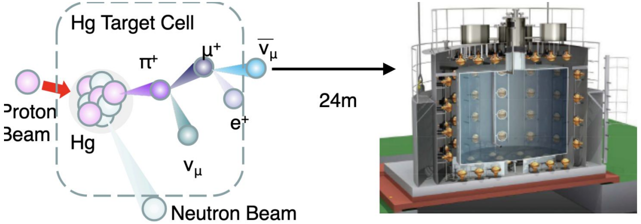
# Physics Cases for the Low-energy Beam

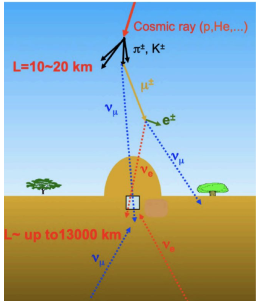
- Accelerator-based neutrino experiments
  - T2K, Hyper-K (pion at 2 GeV, 8 GeV)
  - LBNF/DUNE
  - Short-baseline Neutrino Program (proton at 8 GeV)
- Atmospheric neutrino experiments
  - sub-GeV neutrinos at Super-K, Hyper-K, DUNE
- Spallation neutron source neutrino experiments
  - JSNS$^2$ (proton at 3 GeV)
  - COHERENT (proton <2 GeV)
- Muon experiments
  - COMET (proton at 8 GeV, etc)
- …

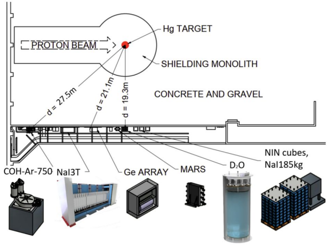


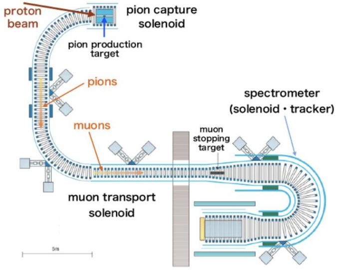



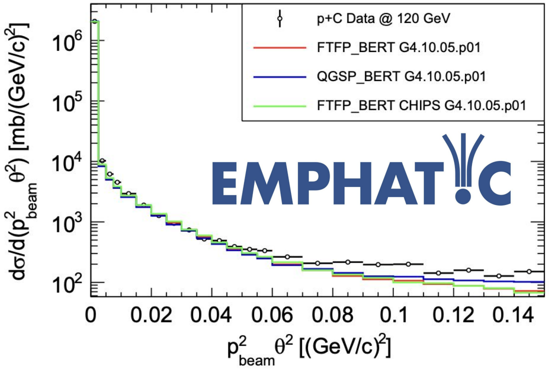



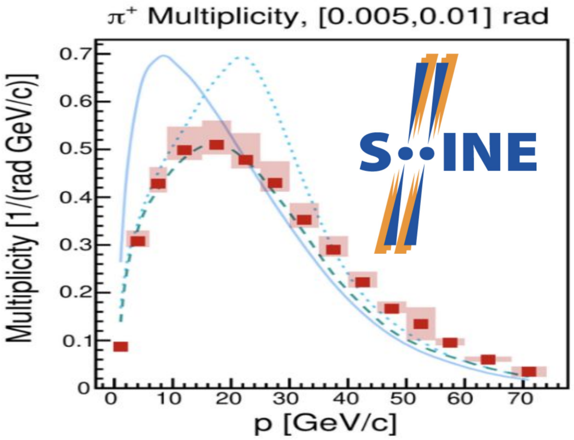



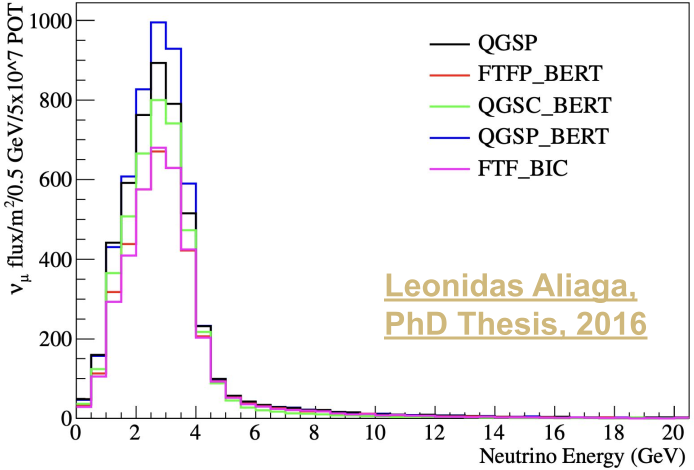



# How will Hadron Production Data be Applied?



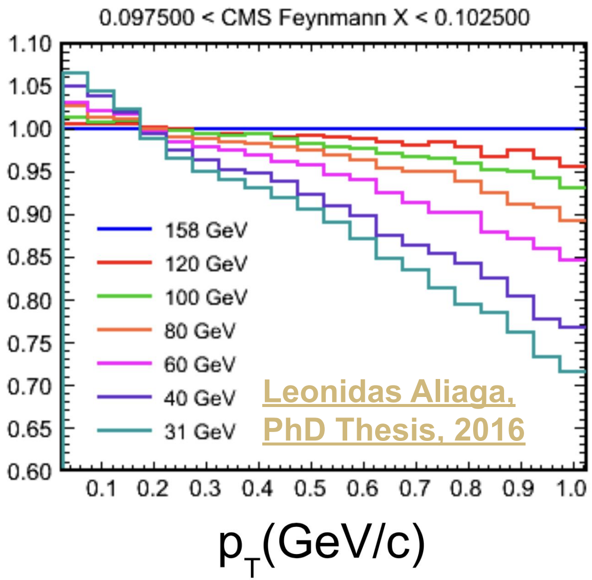




[Leonidas Aliaga, PhD Thesis, 2016]

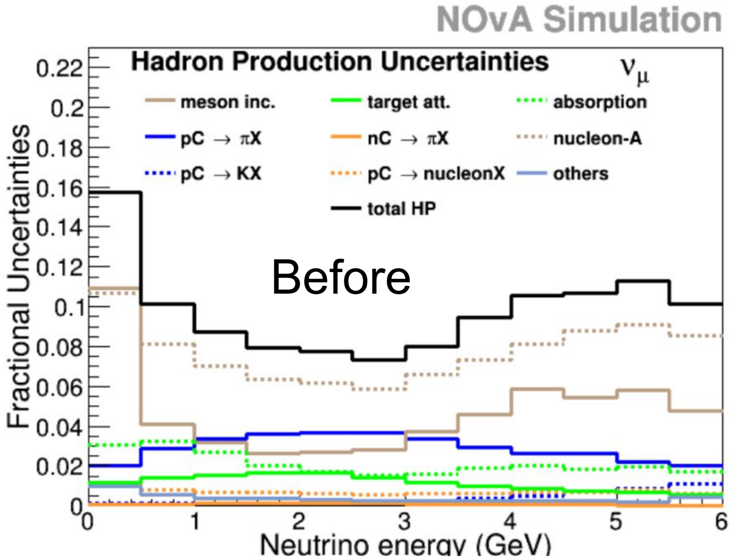
# NuMI experiments and DUNE

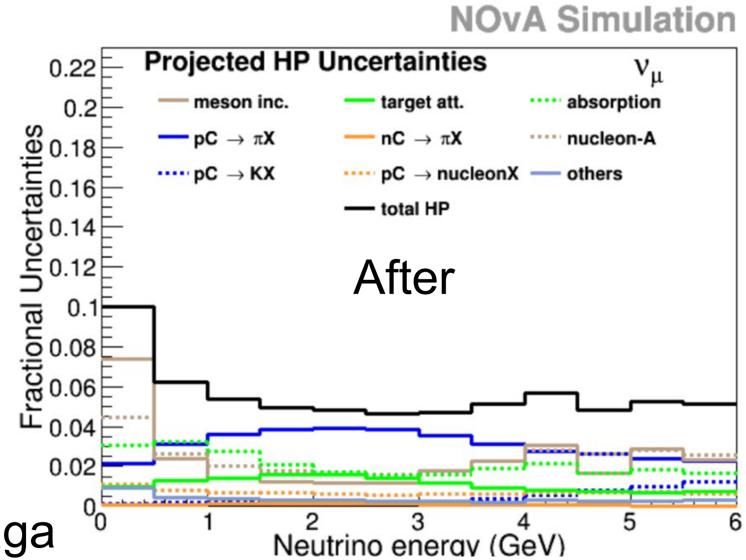
- Package to Predict Flux (PPFX):
    - Experiment-independent neutrino flux determination package for the NuMI beam *(MINERvA Collaboration, Phys. Rev. D 94, 092005, Leonidas Aliaga Soplin, PhD thesis)*
    - Provides hadron production corrections and propagates uncertainties
    - Uses external hadron production data
        - Currently use mainly NA49 p + C @ 158 GeV/c
            - Scaled to lower momenta using FLUKA



# Possible Flux Uncertainty Reduction

- Effect of reducing hadron production uncertainty
  - K absorption: 60-90% → 10%
  - QE interactions: 40% → 10%
  - p,π,K + C[Fe,Al] -> p X: 40% → 10%
  - p,π,K + C[Fe,Al] -> K+- X: 40% → 20%
- NA61/SHINE p + C at 120 GeV/c has been added
  - Final validation ongoing
  - Stay tuned!

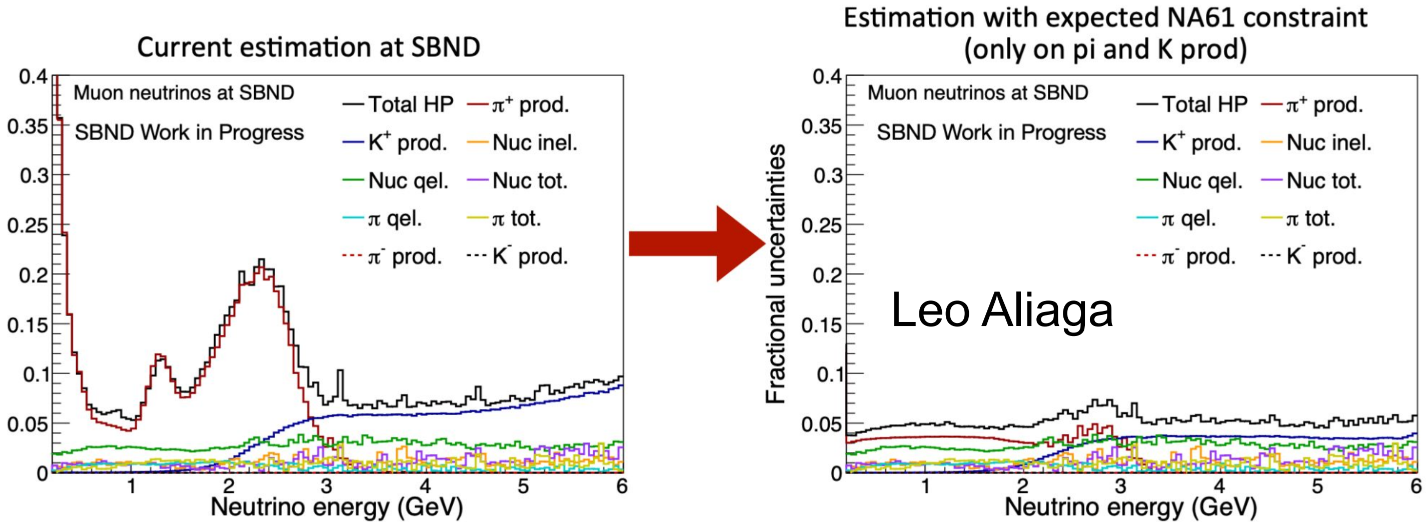



Leo Aliaga

# Booster Neutrino Beam (BNB)

- 8.9 GeV/c proton on Be
- SBND
  - Re-evaluating BNB flux uncertainties from the MiniBooNE era
  - Constructing a new framework to calculate precise flux uncertainties, incorporating current and future data
- Potential impact of NA61/SHINE data



# Takeaways

- Measurements of hadron production are critical to constraining the neutrino flux
- EMPHATIC and NA61/SHINE are two complementary hadron production experiments
- Both aim to improve flux predictions for current and future
  - Accelerator-based neutrino experiments
  - Atmospheric neutrino experiments
  - Spallation neutron source neutrino experiments
- With more new results available, both are working on improving flux predictions and uncertainties in current and future experiments
- **We both welcome new collaborators!**

SHINE

EMPHATIC


# Thank you!

U.S. DEPARTMENT OF ENERGY | Office of Science

# Backup

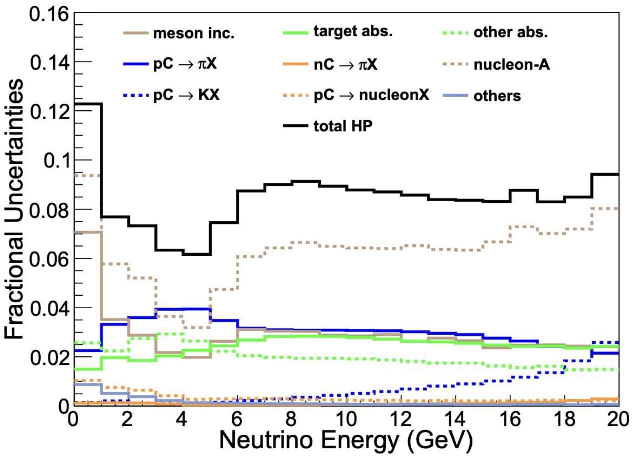
# Data available in PPFX

- Thin target experiments
  - Inelastic cross section
    - Belletini, Denisov, etc. cross sections of pC, πC, πAl etc
    - NA49: pC @ 158 GeV
    - NA61 pC @ 31 GeV
  - Hadron Production
    - Barton: pC → π ±X @ 100 GeV xF > 0.3
    - NA49: pC → π ±X @ 158 GeV xF < 0.5
    - NA49: pC → n(p)X @ 158 GeV for xF < 0.95
    - NA49: pC → K ±X @ 158 GeV for xF < 0.2
    - NA61: pC → π ±X @ 31 GeV
    - MIPP: π/K from pC at 120 GeV for pZ > 20GeV/c
- Thick targets experiments (off by default)
  - MIPP: proton on a spare NuMI target at 120 GeV
    - π ± up to 80 GeV/c.
    - K/π for > 20 GeV/c.

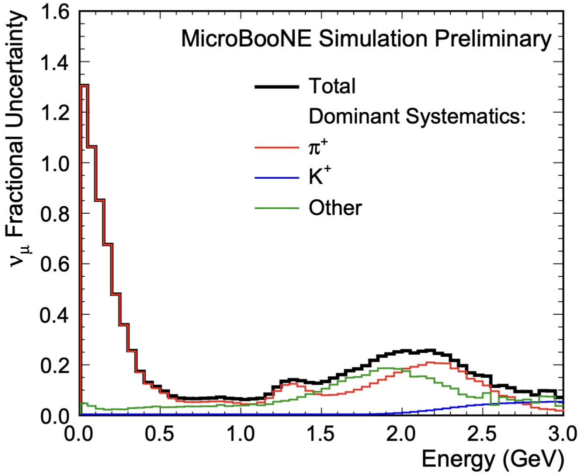
*Detailed descriptions in Section 4.3.-4.5 of Leo's [thesis](thesis))*

# Flux Uncertainty

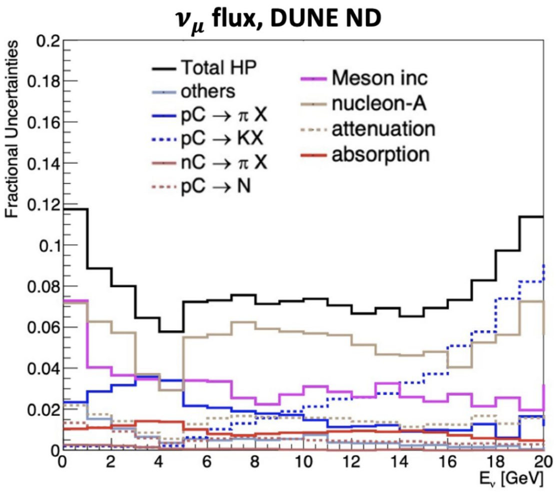
- Neutrino flux uncertainty limits the precision of measurements in all accelerator-based neutrino experiments




MINERvA at NuMI beamline




MicroBooNE at Booster Neutrino Beam




Nilay Bostan, Neutrino 2022

# Nucleon-A

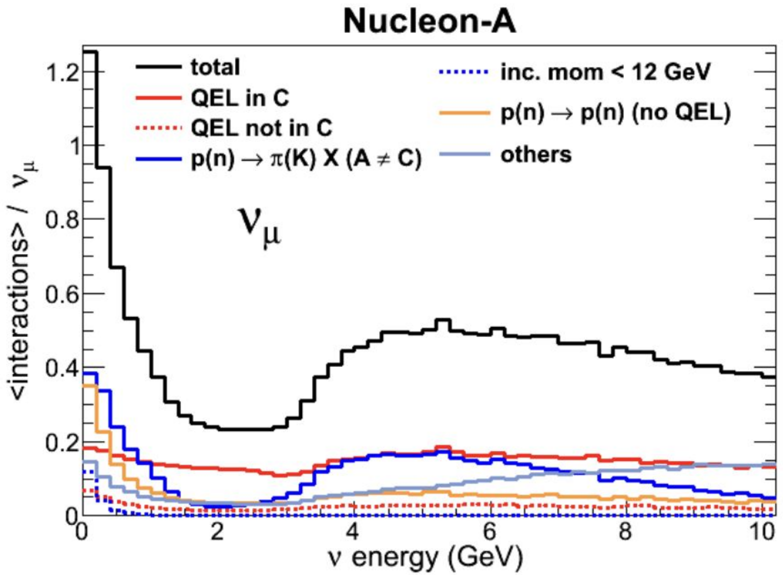
» **Quasi-elastic interactions**, selected as $x_F > 0.95$

- We assign a 40% uncertainty

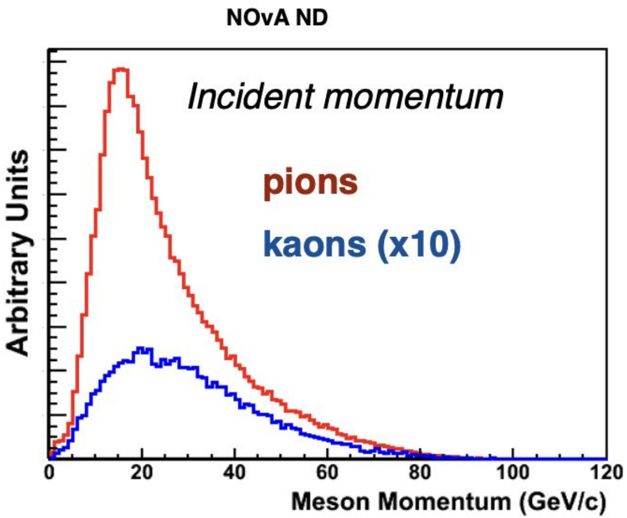
» **Extension of NA49**.

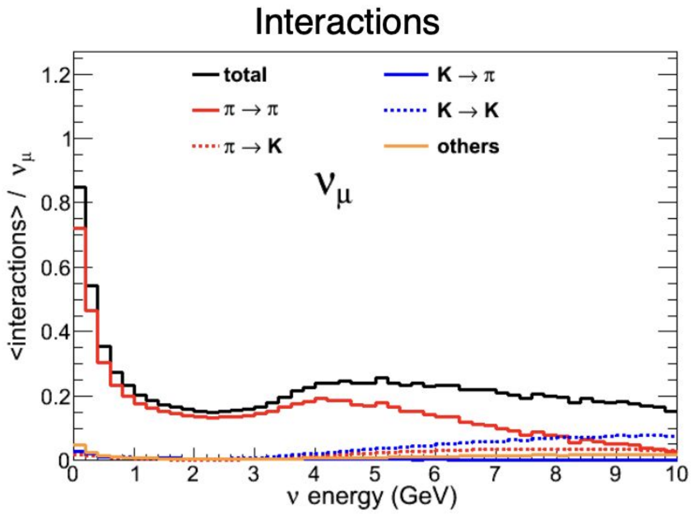
- We extend NA49 to other materials than carbon adding an additional uncertainty.

- Additional uncertainty is calculated by looking at: $K^0$ and $\Lambda^0$ production at 300 GeV in Skubic and check with Barton at 100 GeV.



# Incident meson

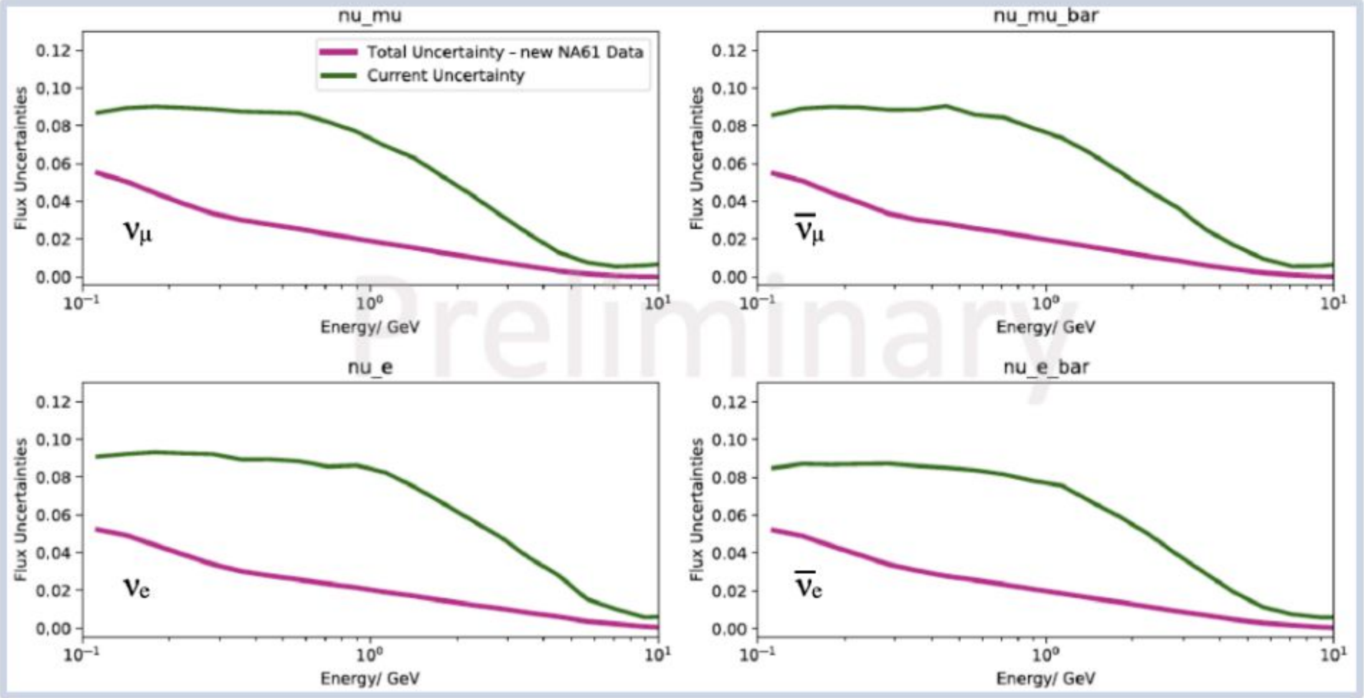



Main contribution from $\pi \longrightarrow \pi$ in the whole neutrino energy spectrum

# Atmospheric neutrino

if we have data for lower energy $\mathrm{p} + \mathrm{N} \rightarrow \pi^{\pm} + X$ interactions (down to a few GeV)




SPSC-M-793
(Plots by L. Cook)