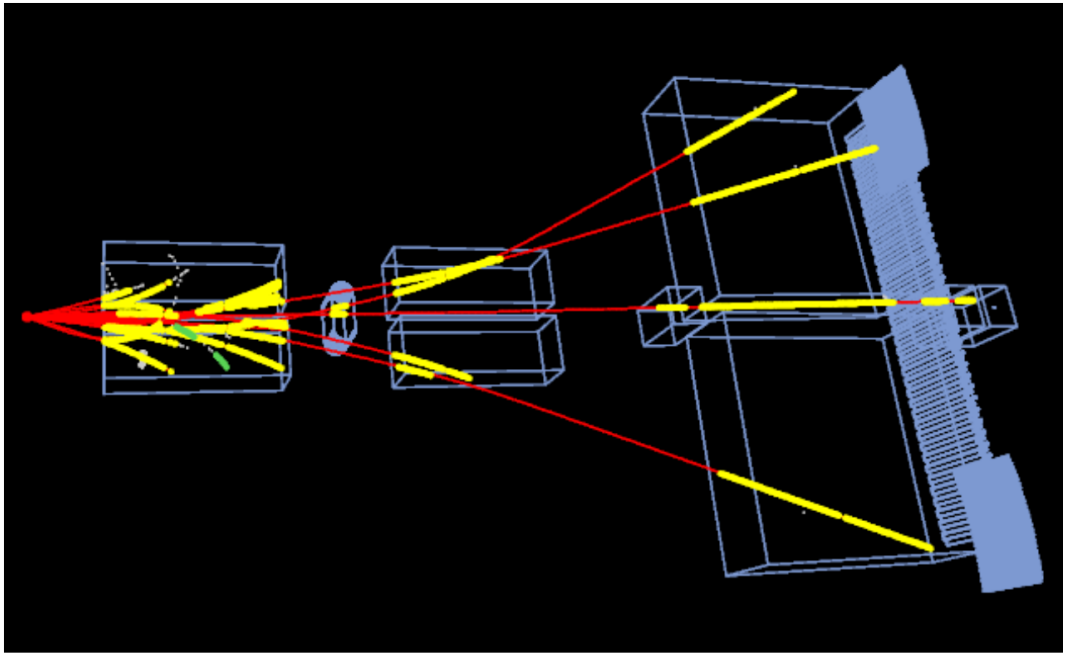
Recent Results: Hadron Production Measurements at NA61/SHINE



Brant Rumberger
University of Colorado Boulder

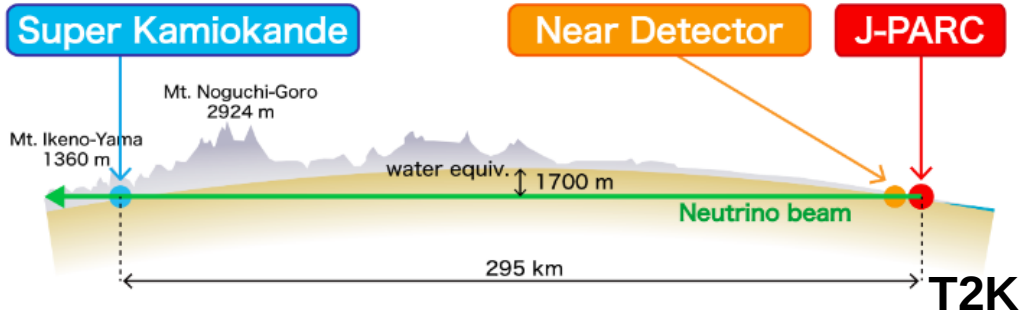
XIX International Workshop on Neutrino Telescopes
2/19/21

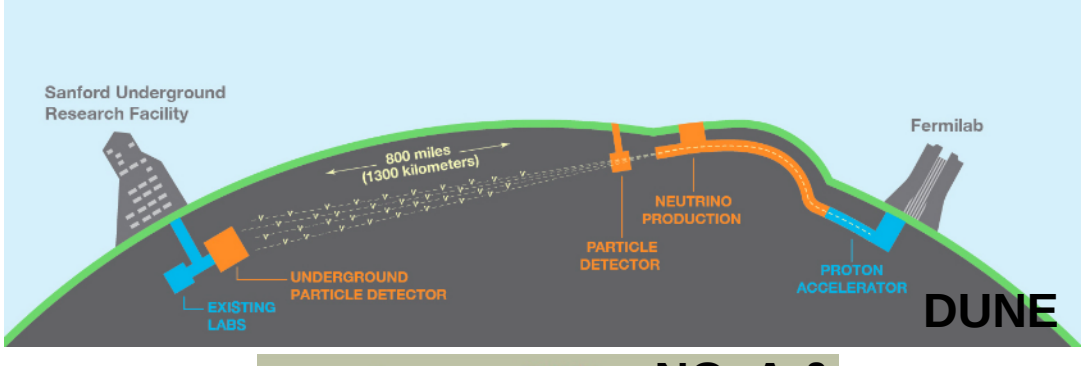
Overview

- Long-Baseline Neutrino Oscillation Experiments
- Neutrino Beam Flux Uncertainties
- NA61/SHINE
- Current Measurements
- Recent & Upcoming Results
- Upgrades & Future Measurements

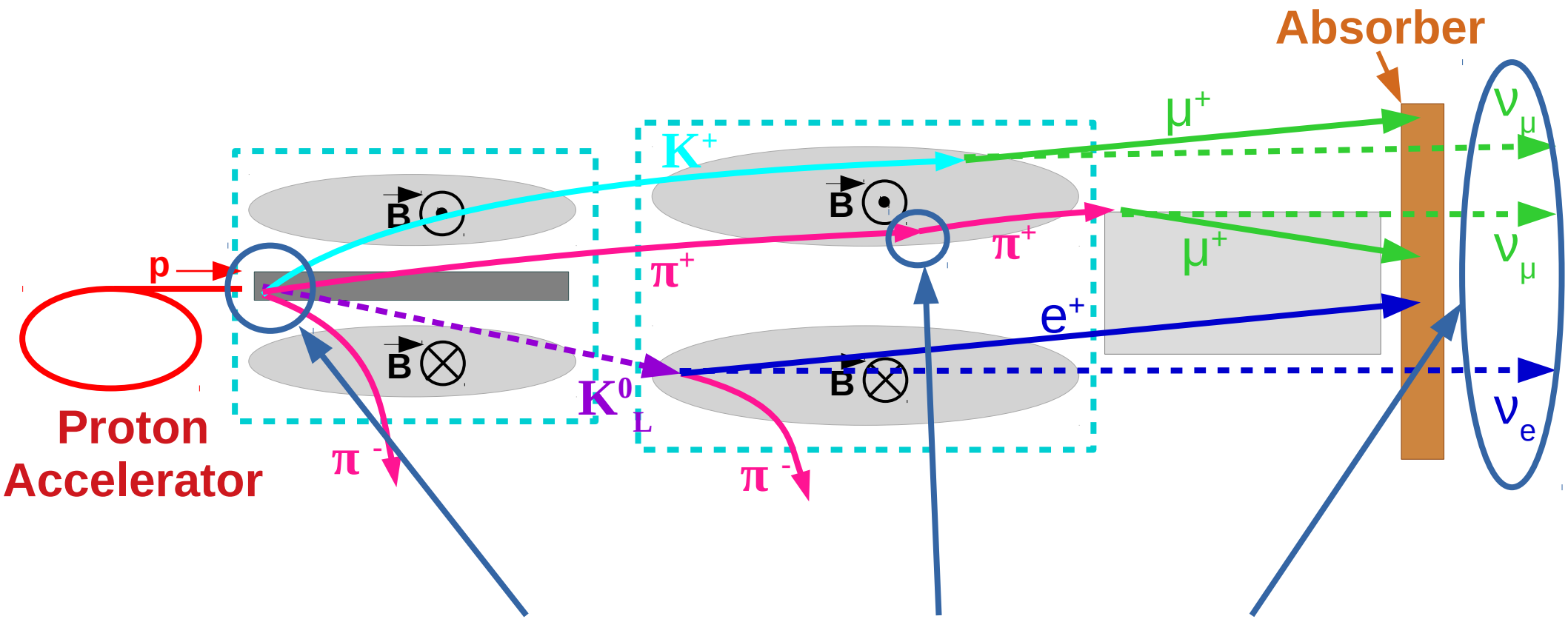
Long-Baseline Neutrino Oscillation Experiments

- Many prominent results over the past several years
- Active LB experiments:
  - T2K, NOvA, ...
- Future LB experiments:
  - DUNE, Hyper-K, …
  - Focus: Discovery & **precise neutrino oscillation parameter measurement**
- Future experiments require tight control of systematic uncertainties





Neutrino Beam Flux Uncertainties

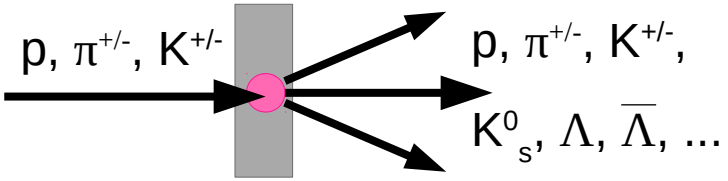


Neutrino beam content depends on primary & secondary hadron production in target & horns

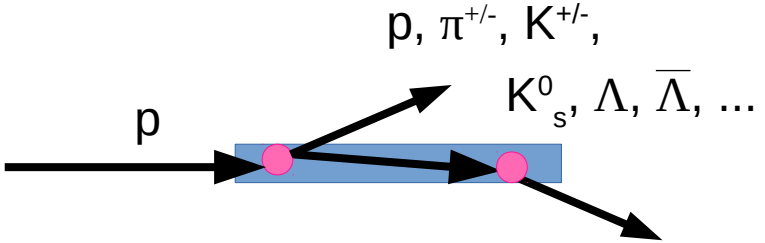
No constraint data:
Large uncertainty!

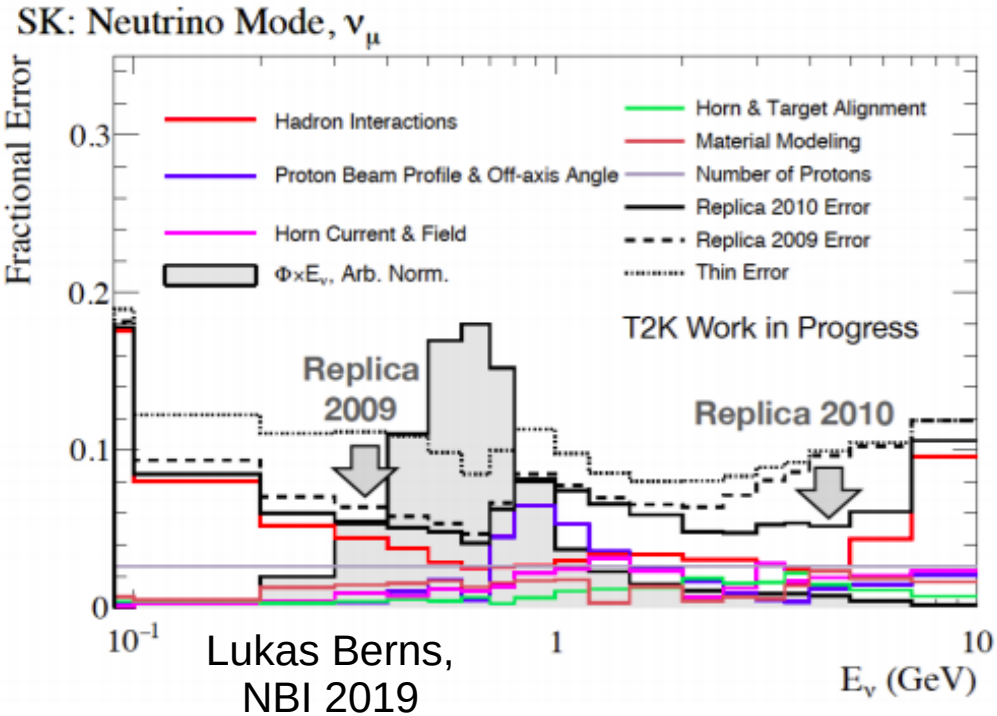
Reducing Flux Uncertainty: Hadron Production Measurements

Thin-Target Measurements



Replica-Target Measurements



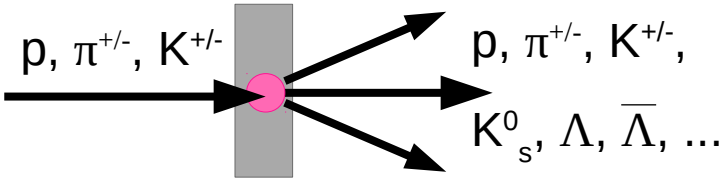


Beam reactions:

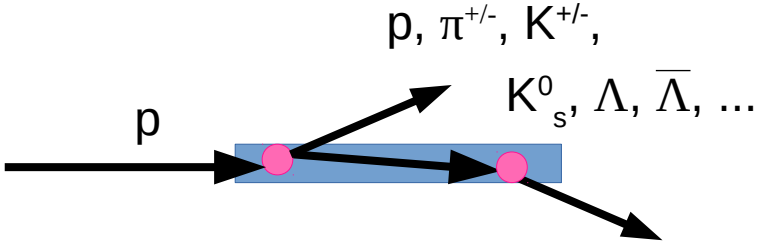
- T2K: 31 GeV/c protons on carbon
- NuMI: 120 GeV/c protons on carbon

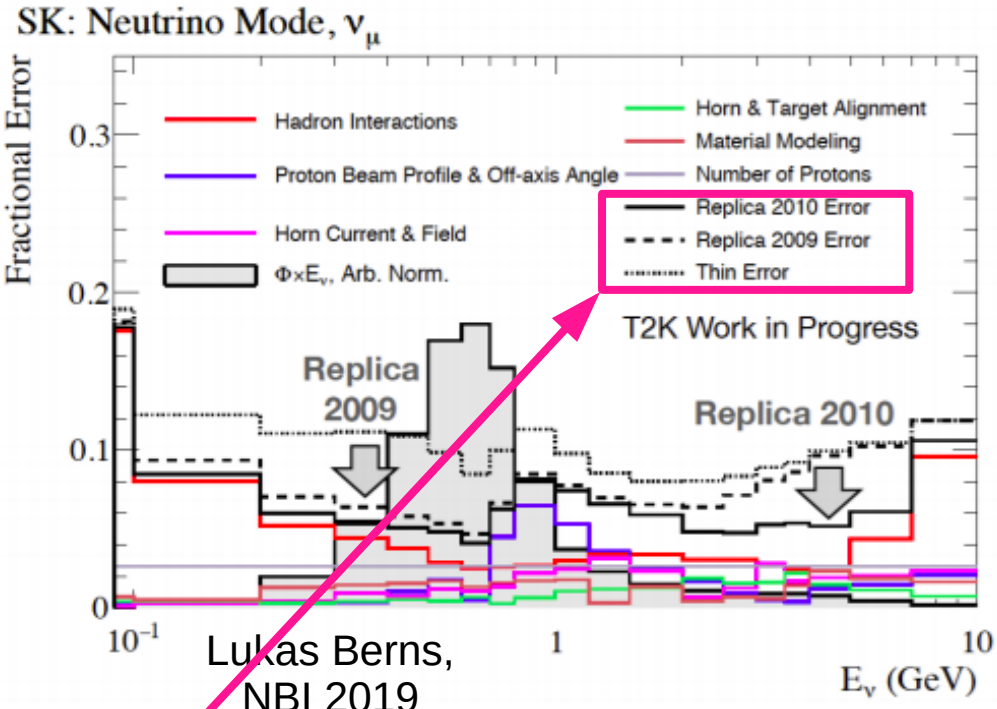
Reducing Flux Uncertainty: Hadron Production Measurements

Thin-Target Measurements



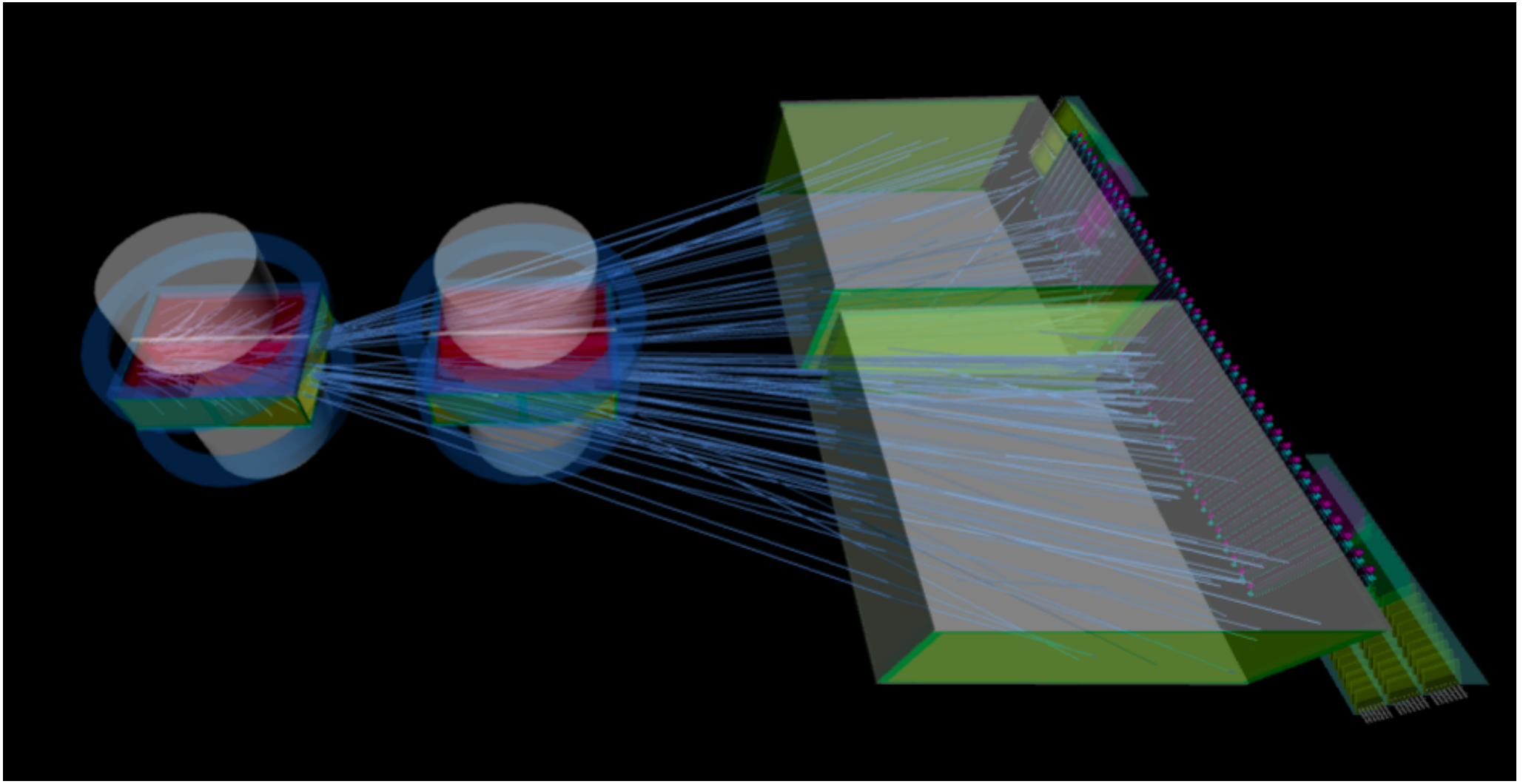
Replica-Target Measurements





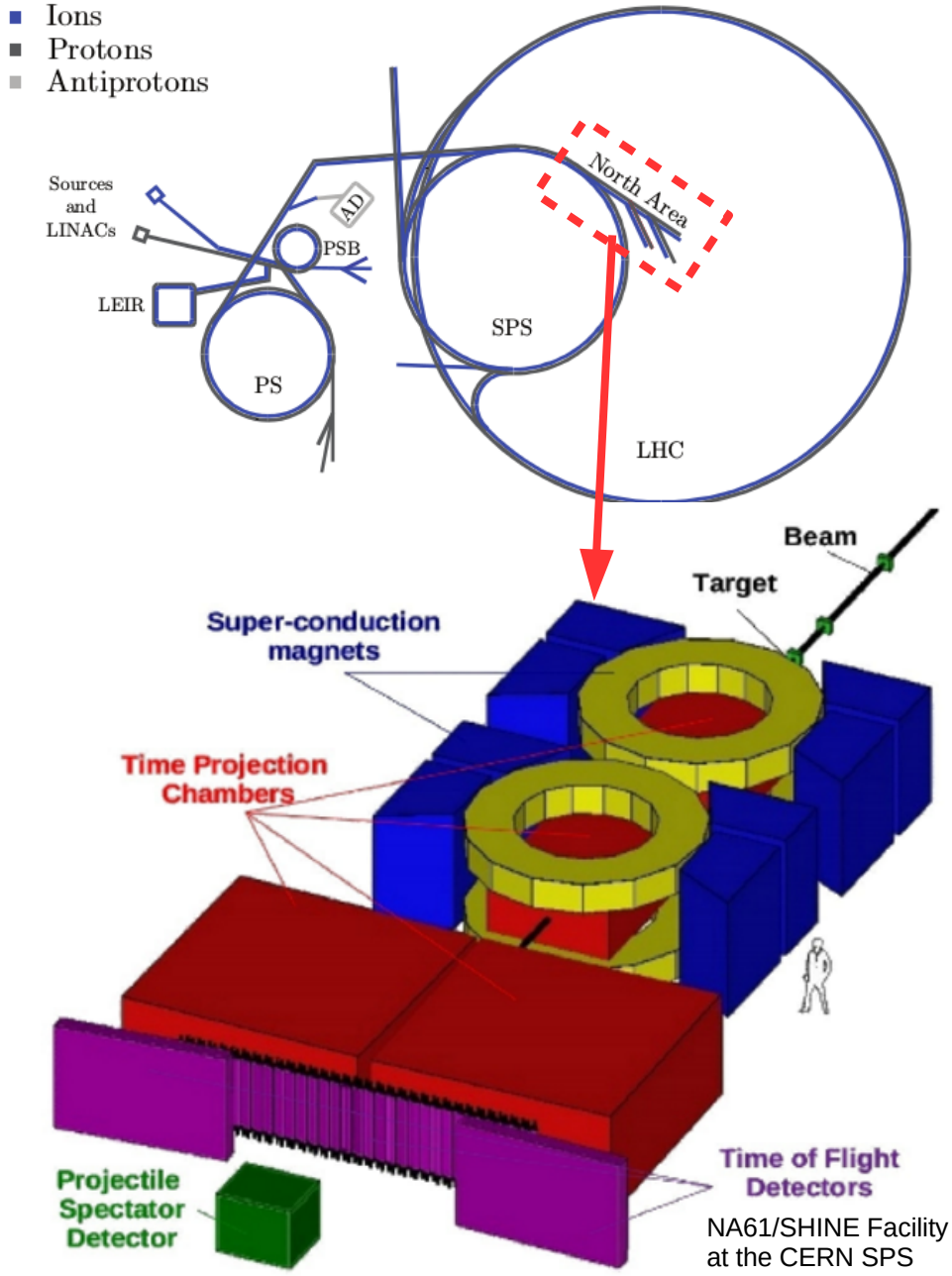
NA61/SHINE Data

NA61 / SHINE



NA61 / SHINE

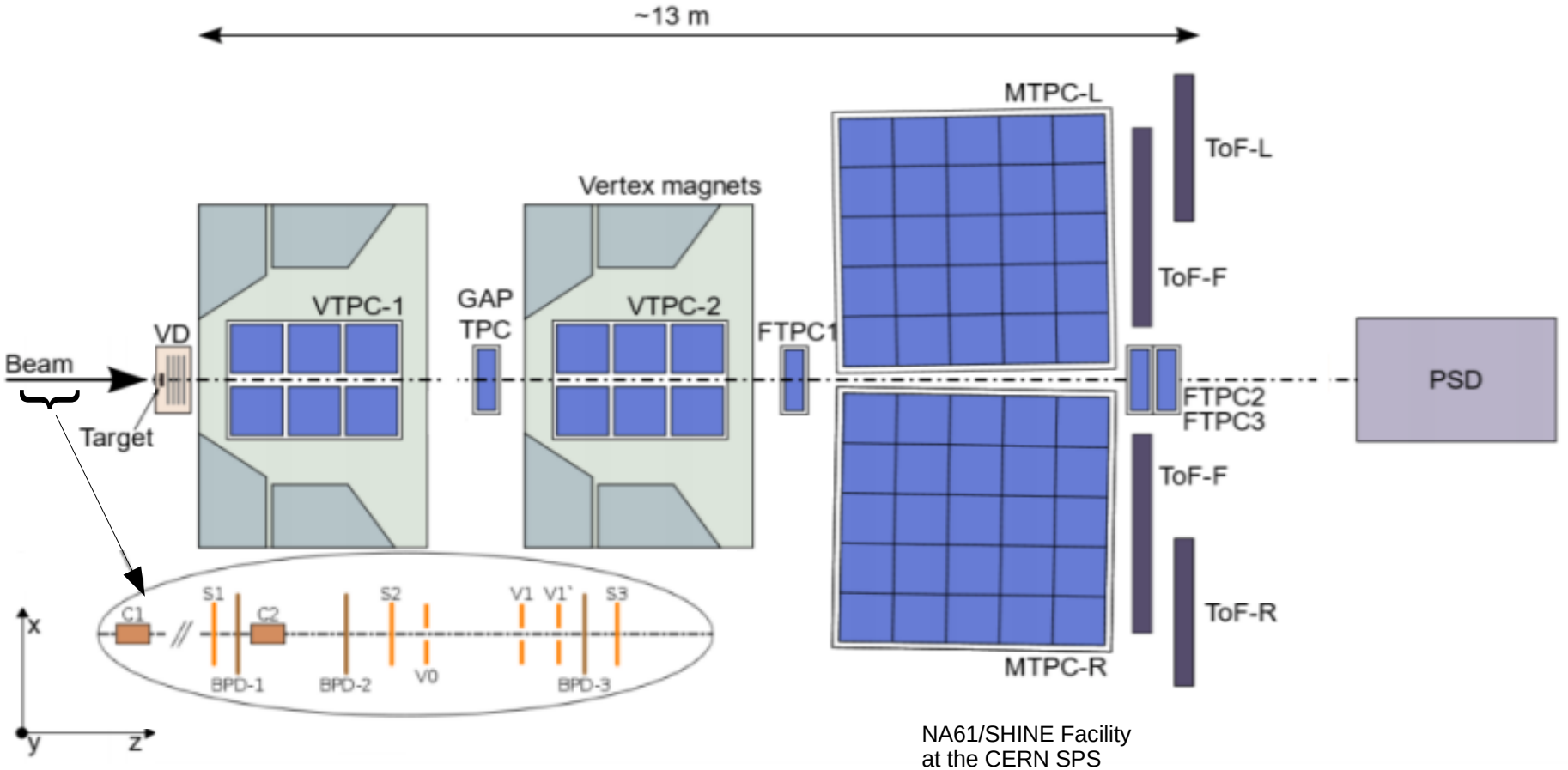
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Multi-faceted physics program
  - Heavy ions
  - Cosmic-ray physics
  - Neutrino flux constraint measurements
- Beam options:
  - Primary 400 GeV/c protons
  - Secondary p, $K^{+/-}$, $\pi^{+/-}$, 13 - 350 GeV/c
- Target options:
  - Thin (~2 cm) targets, any material
  - Neutrino experiment replica targets



NA61/SHINE Facility at the CERN SPS

NA61/SHINE Detector

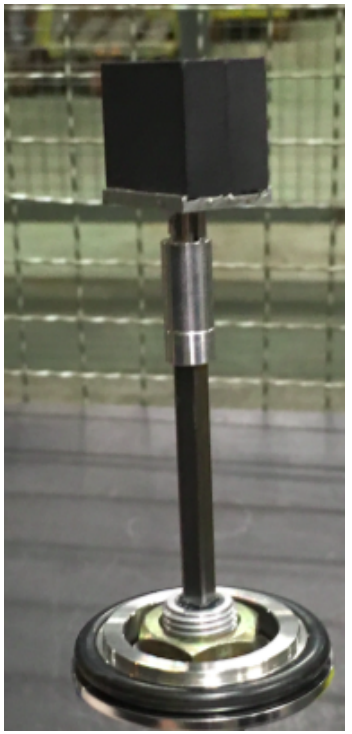
- 8 Time Projection Chambers: 3D tracking, dE/dx measurement (5 + 3 new)
- 2 superconducting magnets: momentum determination
- Cerenkov detectors: beam particle identification
- 3 Time-Of-Flight walls: mass determination
- 3 beam position detectors
- Projectile Spectator Detector (PSD): forward calorimeter

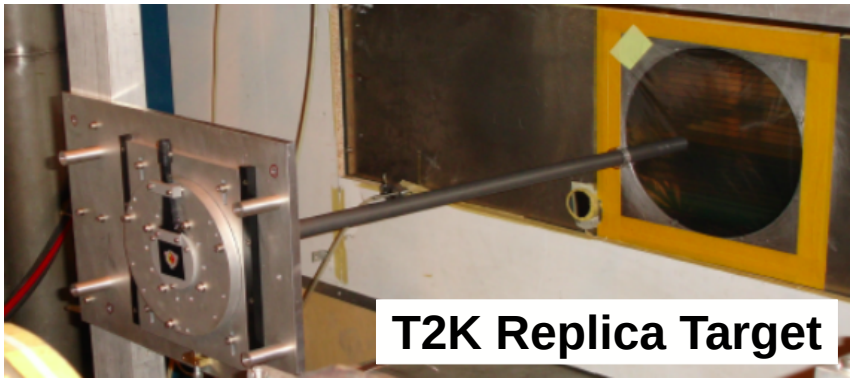


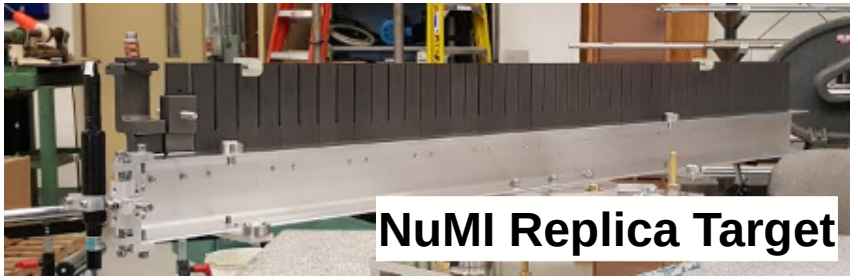
NA61/SHINE Facility
at the CERN SPS

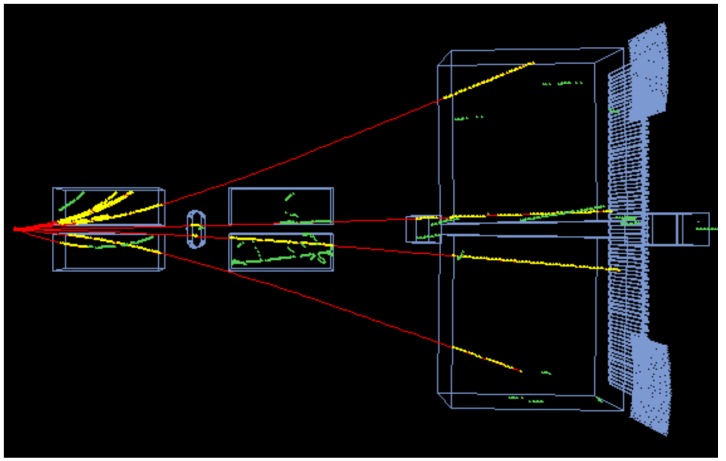
NA61/SHINE Capabilities for Neutrino Experiment Measurements

- Thin target measurements
  - Target materials (C, Be, etc)
  - Horn materials (Al, Fe)
- Replica target measurements
  - T2K (90 cm)
  - NuMI Medium Energy (123 cm)



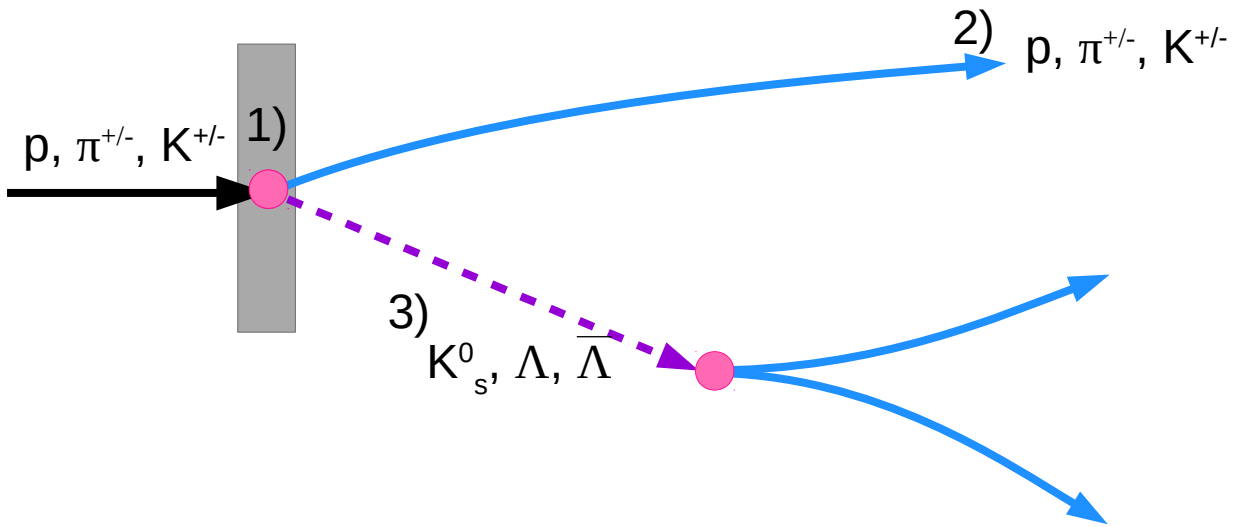






Recent Analysis Results: Thin Target Reactions

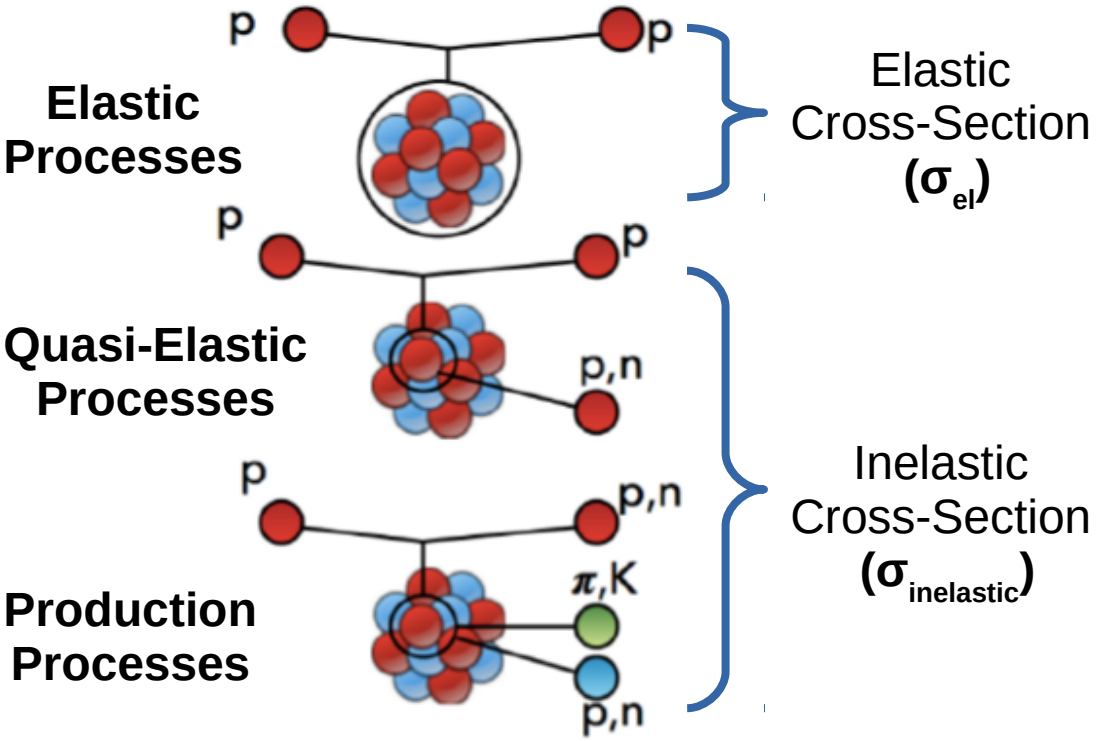
1) Total / inelastic / production cross-sections
2) Charged hadron yields
3) Neutral hadron yields



Thin-Target Results: Cross-Section

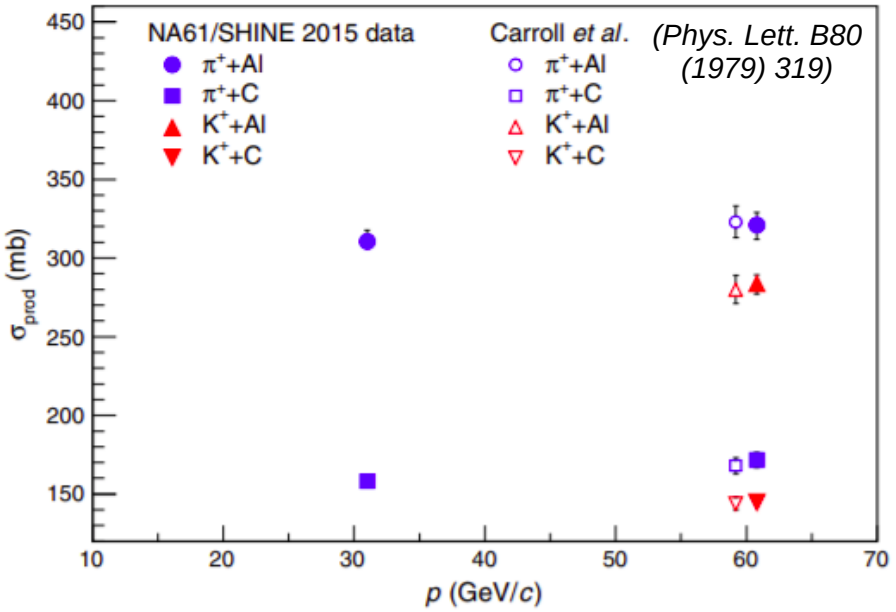
$$\sigma_{inelastic} = \sigma_{total} - \sigma_{elastic}$$

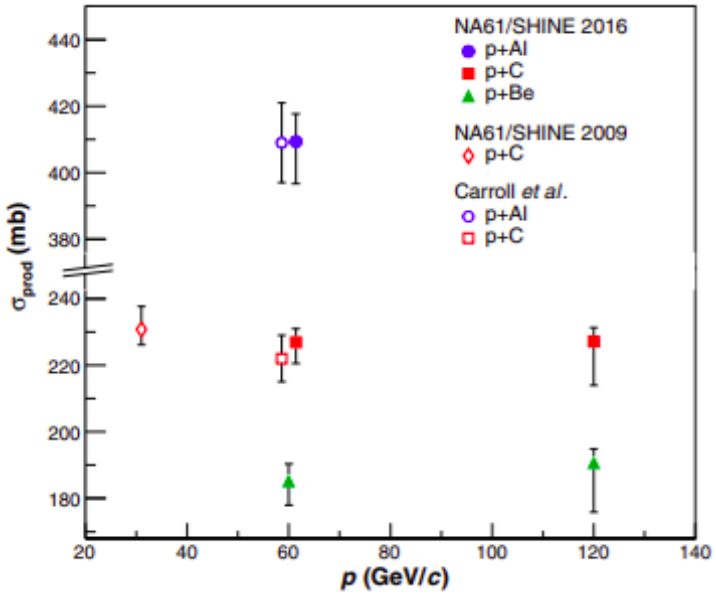
$$\sigma_{production} = \sigma_{inelastic} - \sigma_{QE}$$

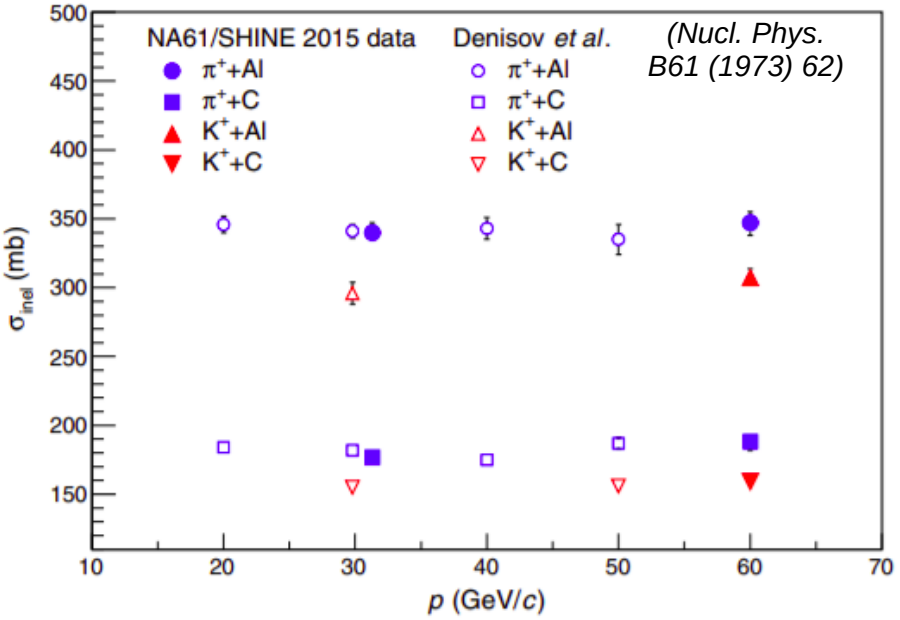


Thin Target Results: Cross-Section

- Inelastic & production cross-section measurements
- Improved precision compared to existing measurements (where available)
- Used to weight hadron production to correct neutrino flux predictions
- **Phys. Rev. D 98, 052001 (2018):**
  - π^+ on C, Al (31 & 60 GeV/c)
  - π^+ on Be (60 GeV/c)
  - K^+ on C, Al (60 GeV/c)
- **Phys. Rev. D 100, 112001 (2019):**
  - p on C, Be (60 & 120 GeV/c)
  - p on Al (60 GeV/c)

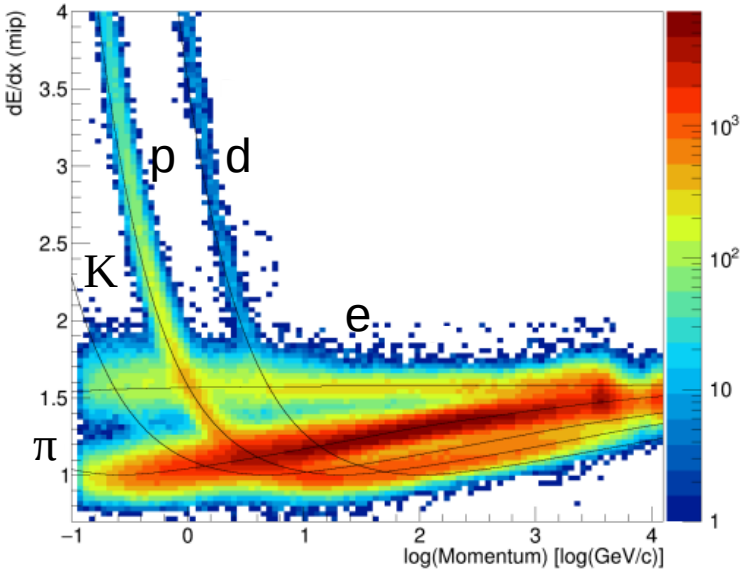




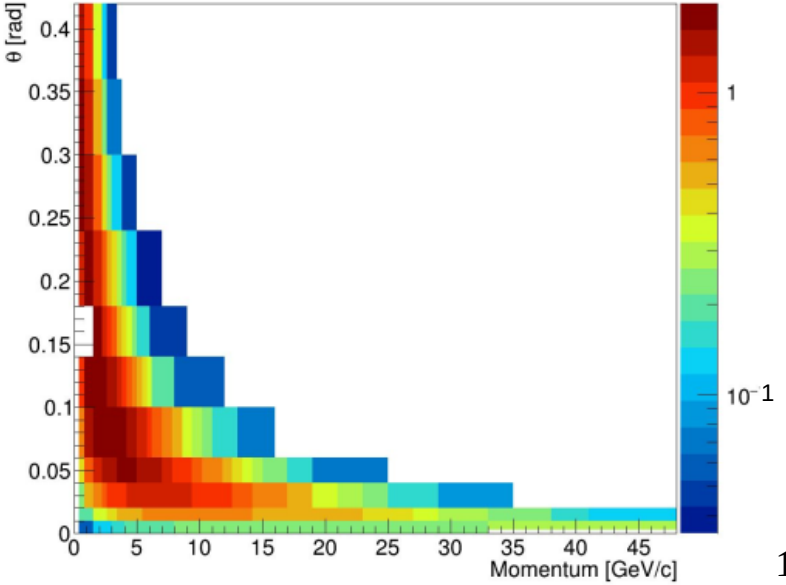


Thin Target Results: Charged Hadron Yield

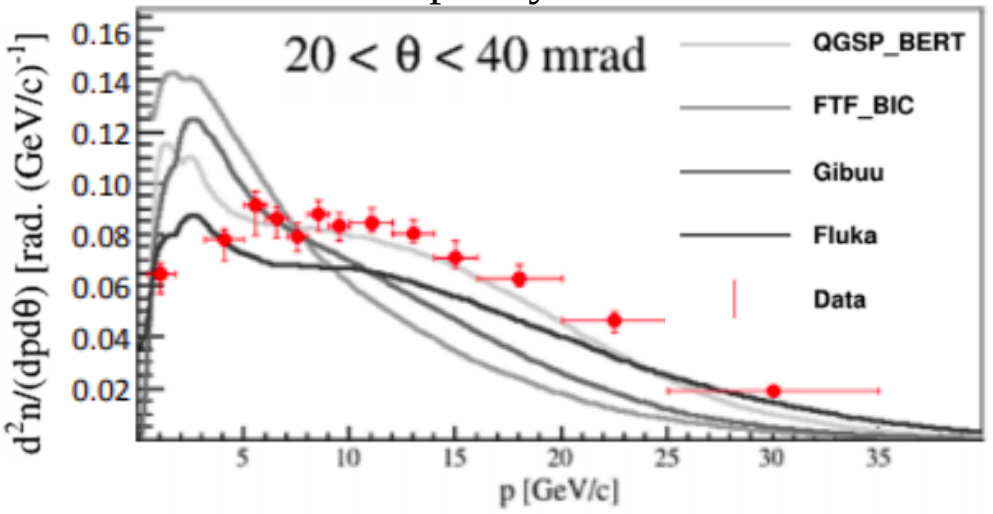
- Obtain ID of produced particles using track momentum & dE/dx
- Charged tracks binned for analysis
- dE/dx fit performed in each bin
- Resulting multiplicities obtained for [p,θ] bins
- Used to improve hadron production models



π^+ Yield: π^+ C, 60 GeV/c



Proton Multiplicity: π^+ C 60 GeV/c

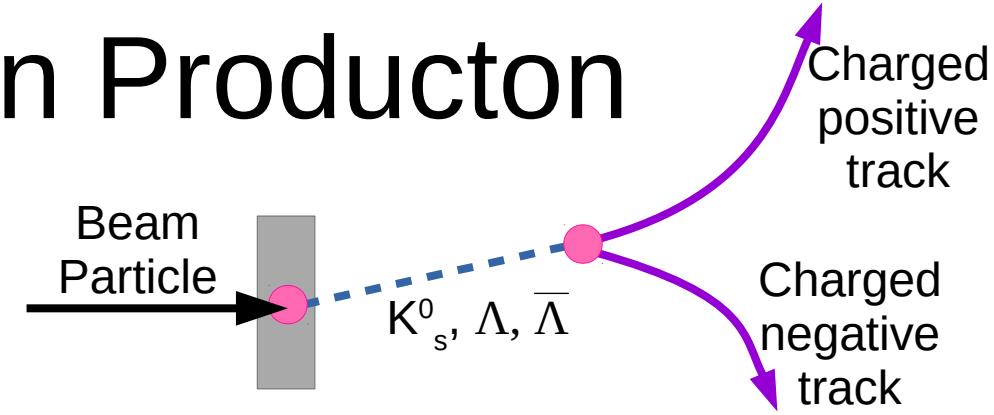


Phys. Rev. D100, 112004 (2019)

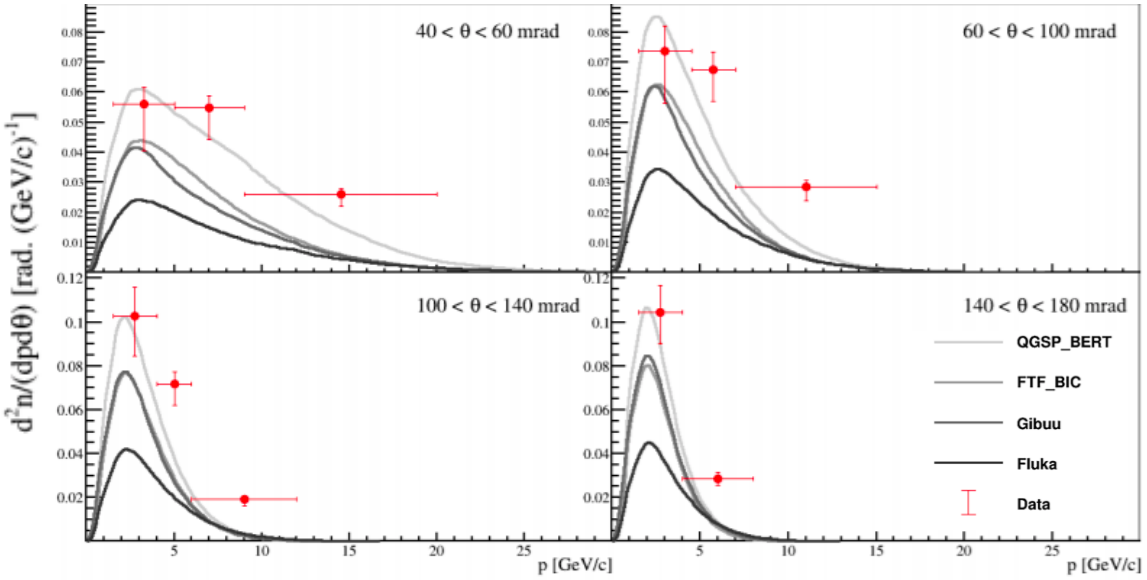
S. Johnson, Ph.D Thesis, 2019

Thin Target Results: Neutral Hadron Producton

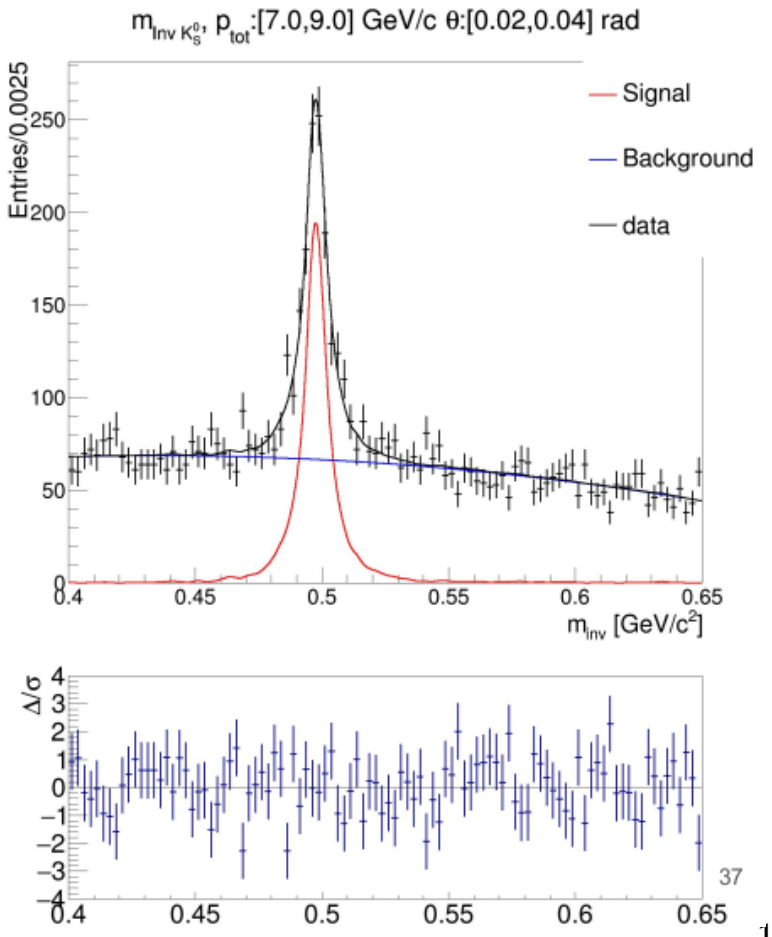
- Select + / - track pairs with small distance of closest approach
- Calculate invariant mass
- Fit signal for neutral particle yield



Λ Multiplicity: π^+ C 60 GeV/c



Phys. Rev. D100, 112004 (2019)



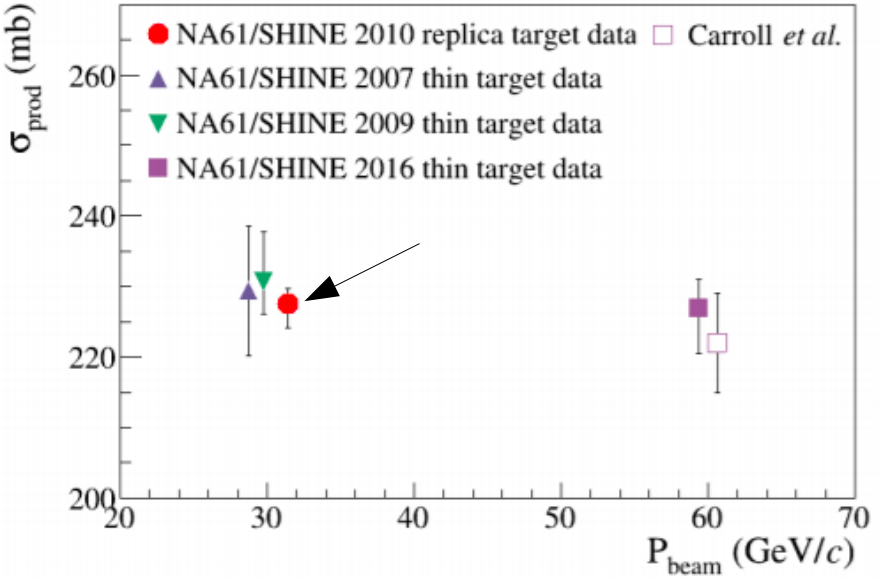
Recent Results

- Thin-target π^++C and π^++Be at 60 GeV/c
  - Differential yield measurements for charged & neutral hadrons
  - Phys. Rev. D 100, 112001 (2 Dec 2019)
- p+T2K replica target at 31 GeV/c (with high magnetic field)
  - Proton beam survival probability for measurement of production cross-section
  - Phys. Rev. D 103, 012006 (12 Jan 2021)
- Thin-target p+C and p+Al at 60 GeV/c
  - Differential yield measurements for charged & neutral hadrons
  - Preliminary results released, paper forthcoming
- p+C at 120 GeV/c coming soon

T2K Replica Target Production Cross-Section

- Production cross-section measured via beam attenuation in 90-cm T2K Replica Target
- Full magnetic field setting used for improved measurement of elastic and quasi-elastic protons
- Result consistent with 31 GeV/c proton-carbon thin-target measurement
  - Improved overall precision
- Will help reduce T2K flux prediction uncertainty

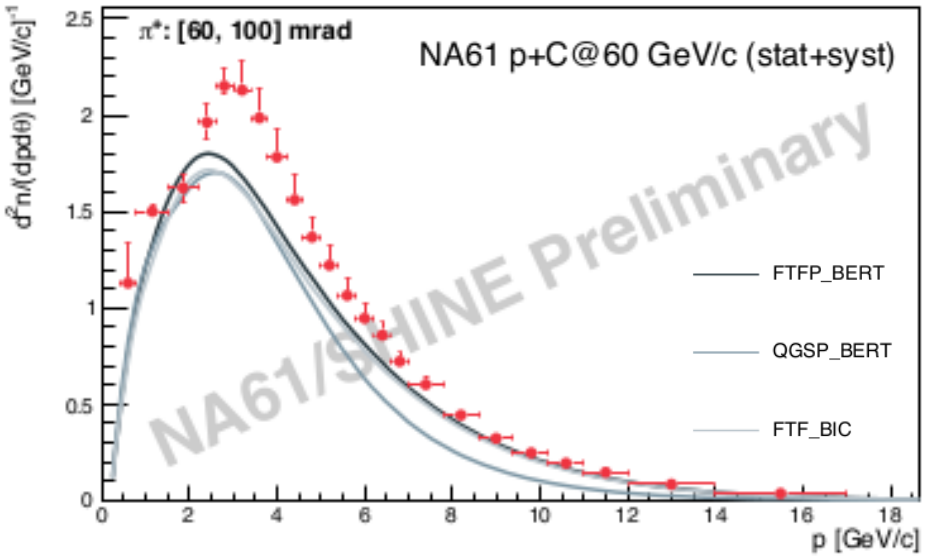
T2K Replica Target

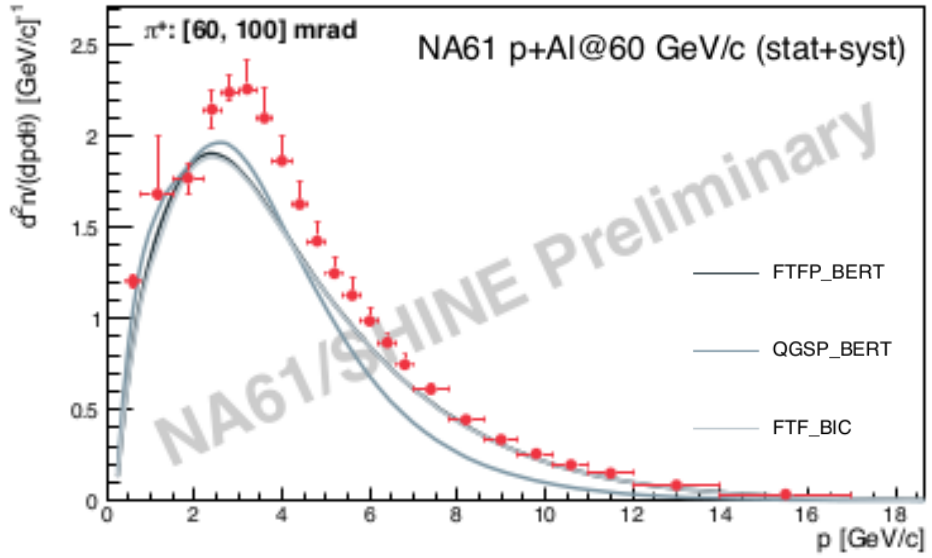


Phys. Rev. D 103, 012006 (12 Jan. 2021)

60 GeV/c Proton-Carbon & Proton-Aluminum Spectra

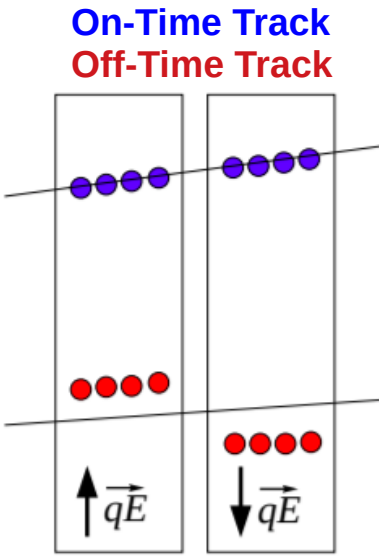
- Preliminary multiplicity spectra released for two additional 60 GeV/c proton thin-target reactions
  - Paper forthcoming
- Neutral particle spectra:
  - K^0_s, Λ, $\overline{\Lambda}$
- Charged particle spectra:
  - $\pi^{+/-}$, $p/\overline{p}$, $K^{+/-}$
- Resulting spectra will allow for material scaling studies & model refinement

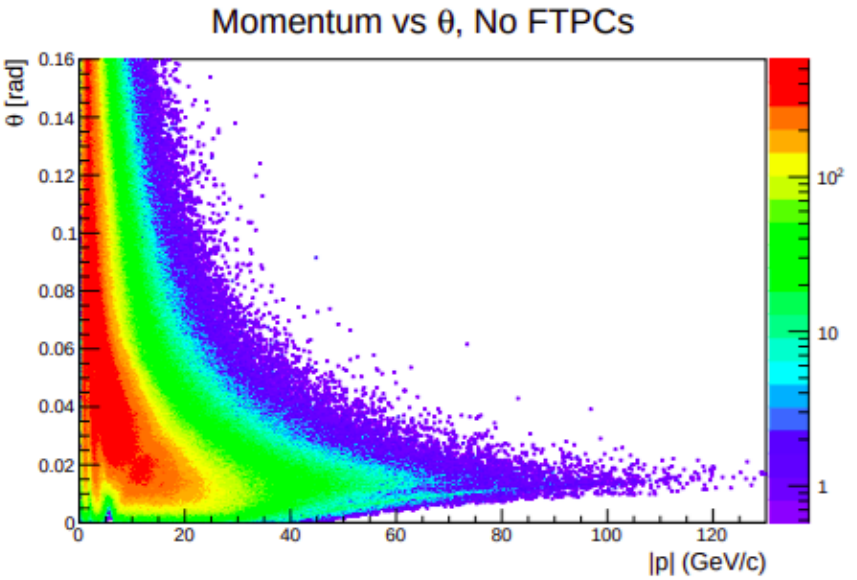


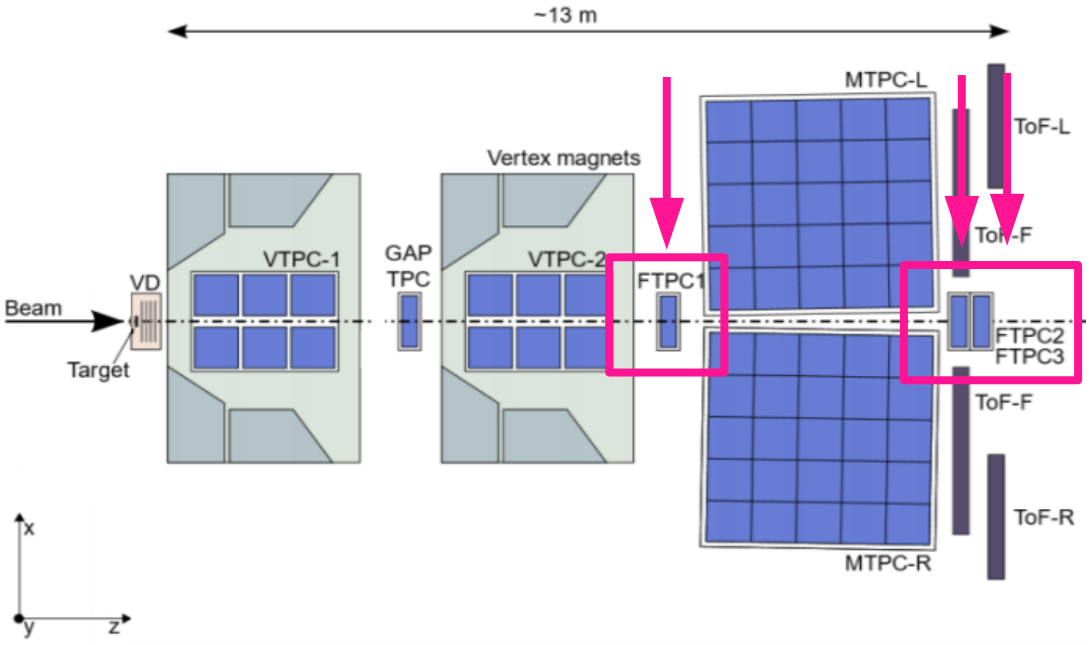


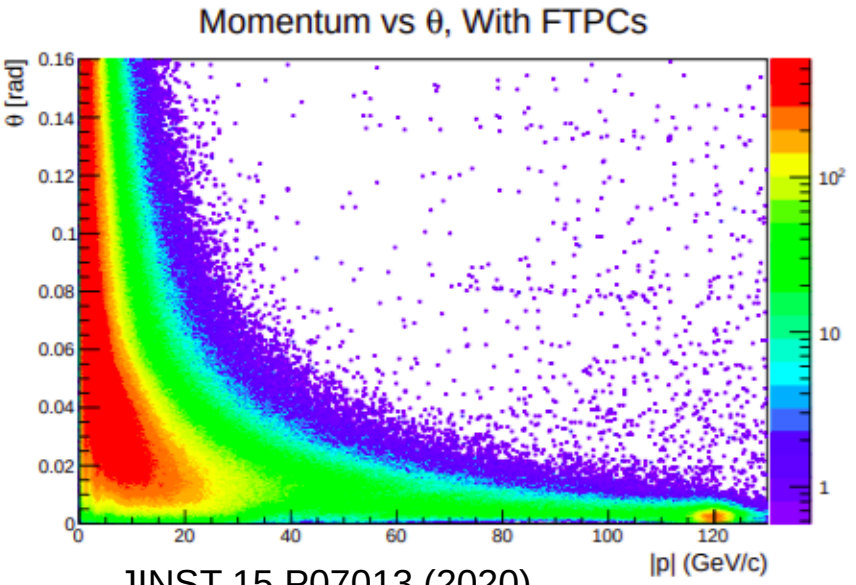
Closing the Forward Acceptance Gap

- Detector upgrade in 2017 significantly increased forward acceptance
- Forward Time Projection Chambers **(FTPCs)**
- Novel tandem field cage design for out-of-time track rejection
  - **JINST 15 P07013 (2020)**





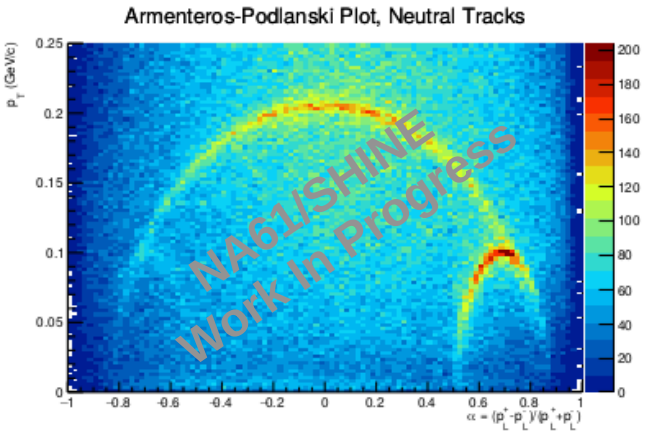


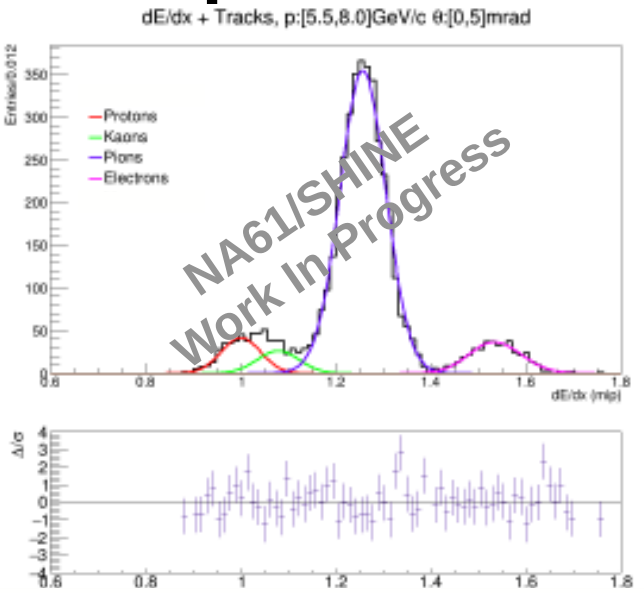


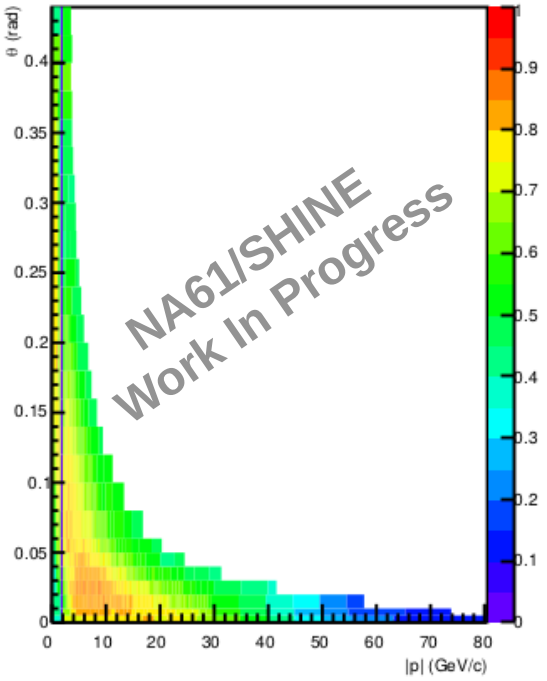
JINST 15 P07013 (2020)

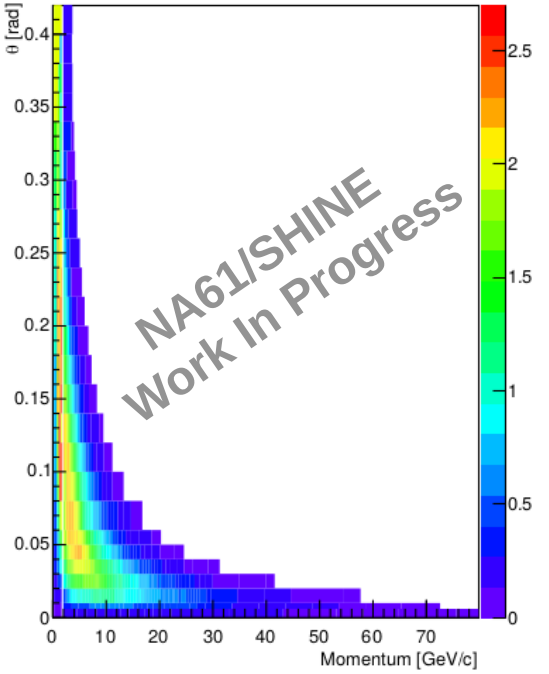
120 GeV/c Proton-Carbon Spectra

- Mature analysis of 2017 120 GeV/c proton-carbon dataset
- Data taken with improved forward detector acceptance
- Neutral particle spectra:
  - K^0_s, Λ, $\overline{\Lambda}$
- Charged particle spectra:
  - $\pi^{+/-}$, $p/\overline{p}$, $K^{+/-}$
- NuMI beam energy & target material



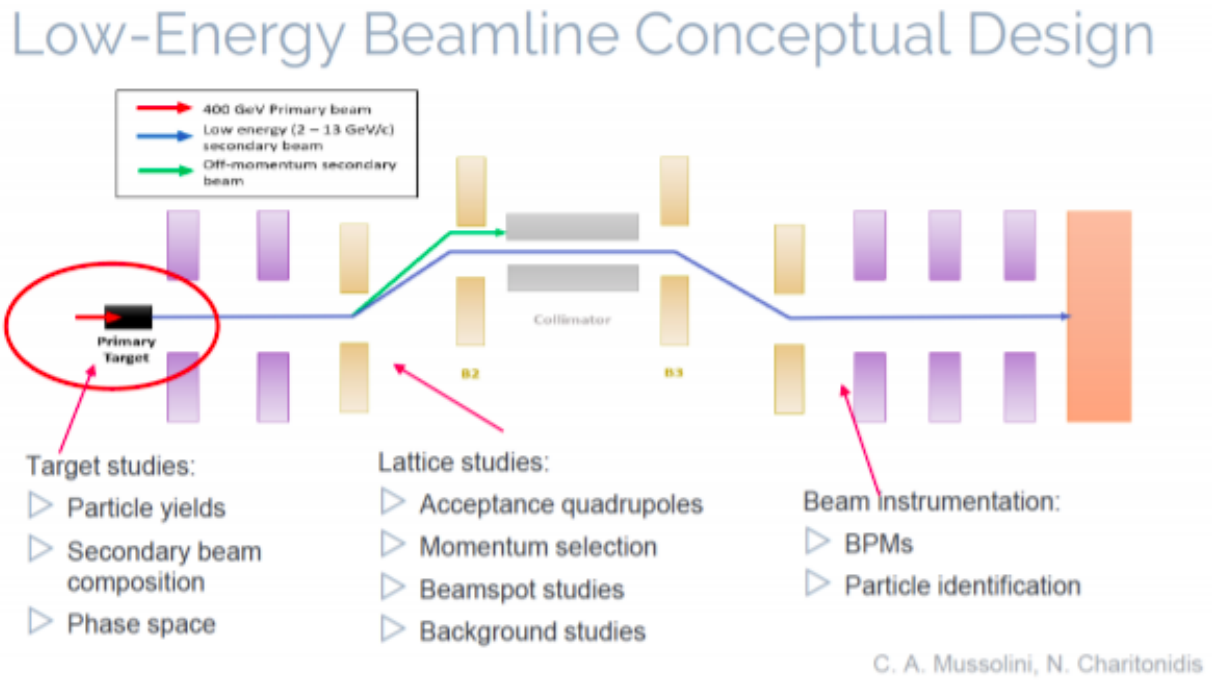






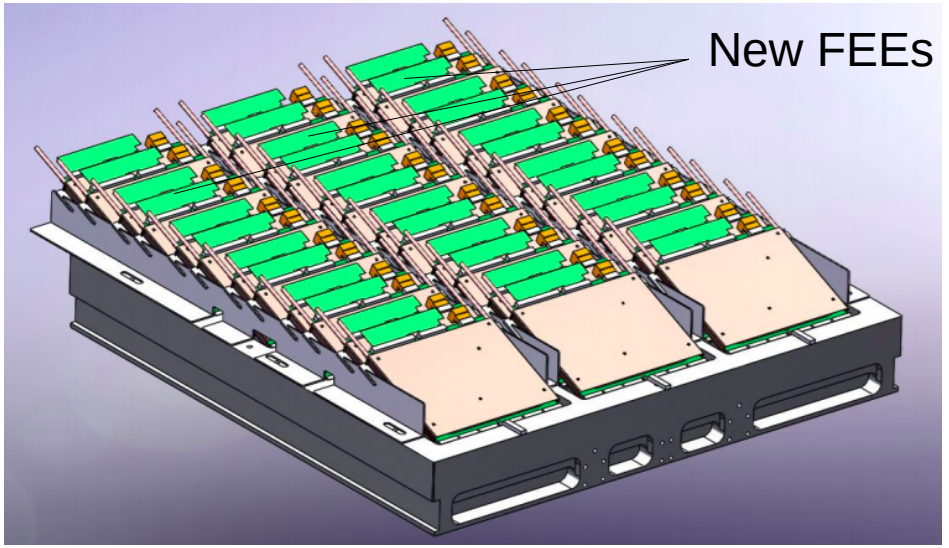
Lowering Incident Beam Energy

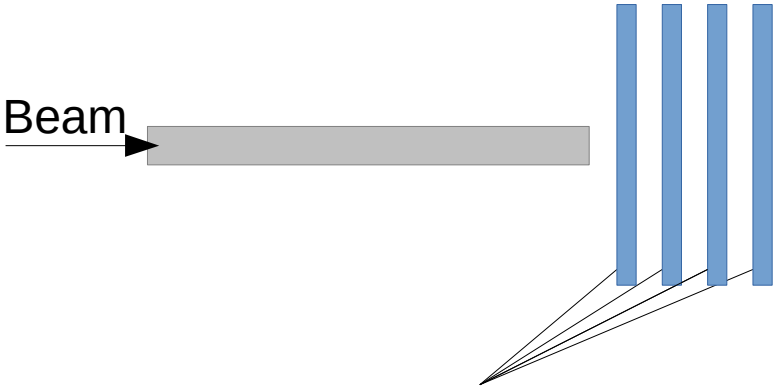
- Plans for tertiary beam delivery to NA61 would deliver 1 - 20 GeV/c beam
- Relevant energy range for:
  - FNAL SBN (8 GeV/c p+Be)
  - Spallation neutrinos (1-3 GeV/c p+Hg)
  - T2K/H-K low-momentum hadronic interactions (1 – 5 GeV/c)
- Beamline currently in conceptual design phase
- Data taking could begin in 2023-2024
- See Low Energy Workshop slides:
  - https://indico.cern.ch/event/973899/



Upgrade Plans & 2021 Runs

- Major upgrades underway at NA61/SHINE
- DAQ upgrade: ~100 Hz → ~ 1KHz event rate
- TPC front-end electronics replacement: ALICE front-ends
- mRPC upgrade of ToF walls
- Long-target tracker possibilities being explored
- Beam commissioning planned for Summer & Fall 2021
- **Request for resuming neutrino data taking in Fall 2021**





Additional tracking planes directly downstream of target

Summary

- Neutrino beam flux is a leading systematic uncertainty for long-baseline neutrino experiments
- NA61/SHINE facility capable of taking relevant data to constrain neutrino flux
- Thin target & replica target results for several pertinent reactions published & used for oscillation analysis
- DUNE replica target data will hopefully be taken when design is finalized
- **Stay tuned!**

Thanks!

Thanks to the entire NA61 collaboration!

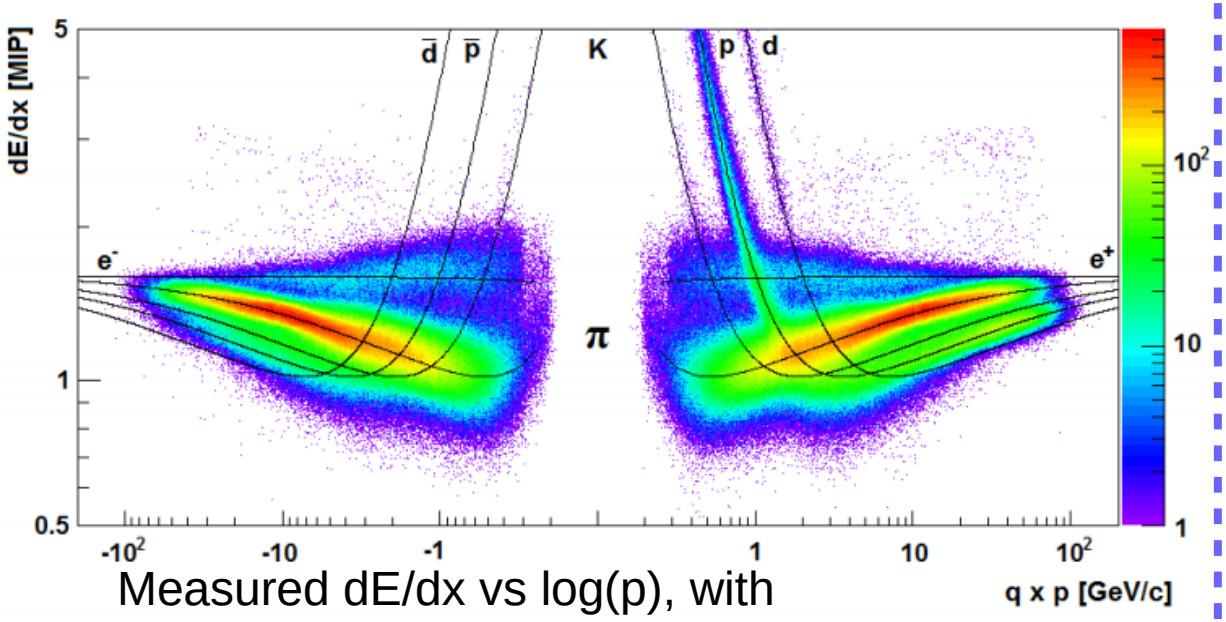
Funded by the US Dept. of Energy

U.S. DEPARTMENT OF ENERGY | Office of Science

BACKUP

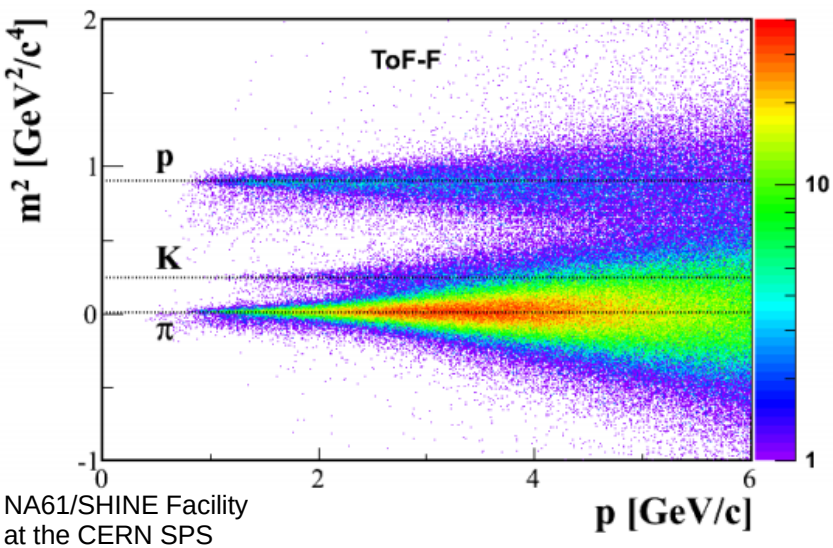
Particle Identification in NA61

- Performed via specific energy loss and time-of-flight analyses
- dE/dx: Sample charge deposited in detector along particle trajectory
  - Estimate mean dE/dx for each track
- TOF: Difference between trigger time and TOF scintillator hit time
  - Need high-precision scintillator hit time measurements (~100 ps)



Measured dE/dx vs log(p), with parameterized Bethe-Bloch curves overlayed:

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



NA61/SHINE Facility at the CERN SPS

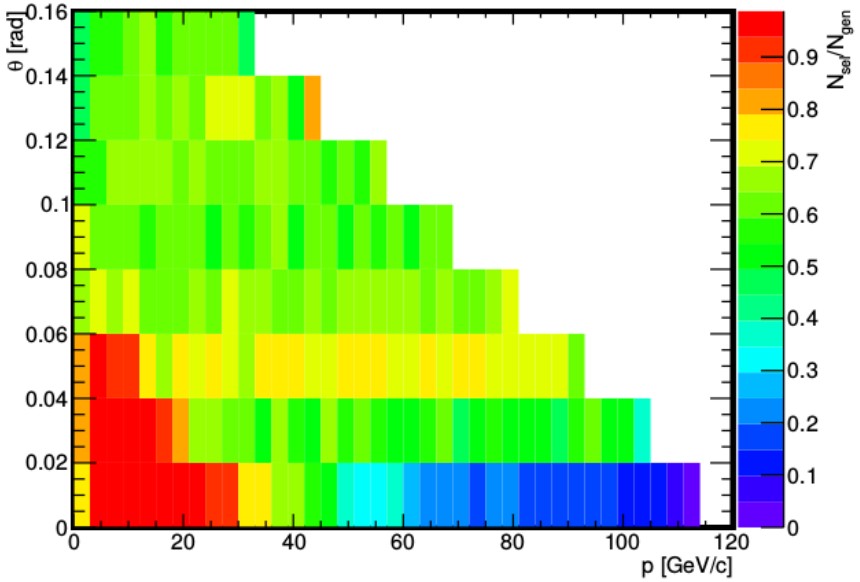
Measured mass from time-of-flight:

$$m^2 = p^2 \left(\frac{c^2\, tof^2}{l^2} - 1 \right)$$

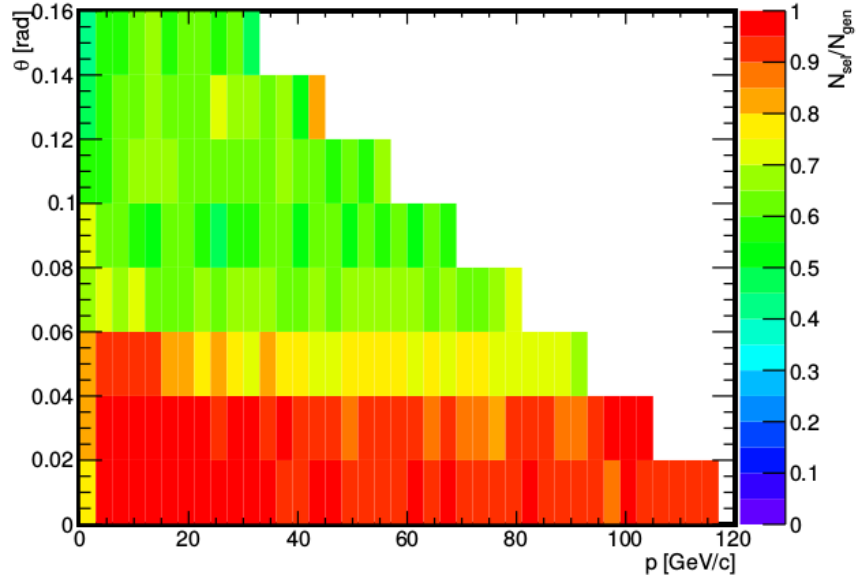
Additional Phase Space Coverage with FTPCs

NA61 Acceptance (120 GeV/c p+C)

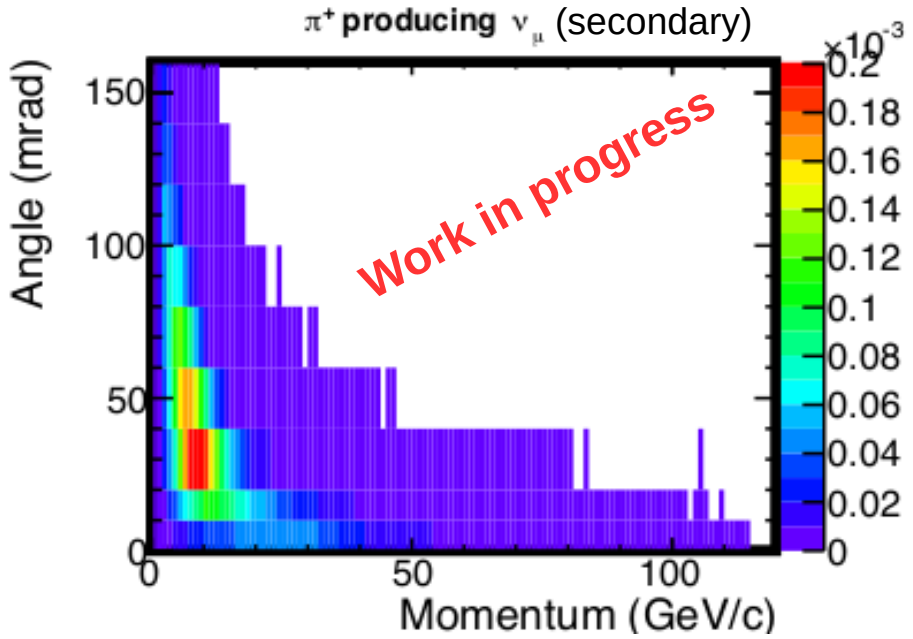
Old Acceptance (Pre-FTPCs)

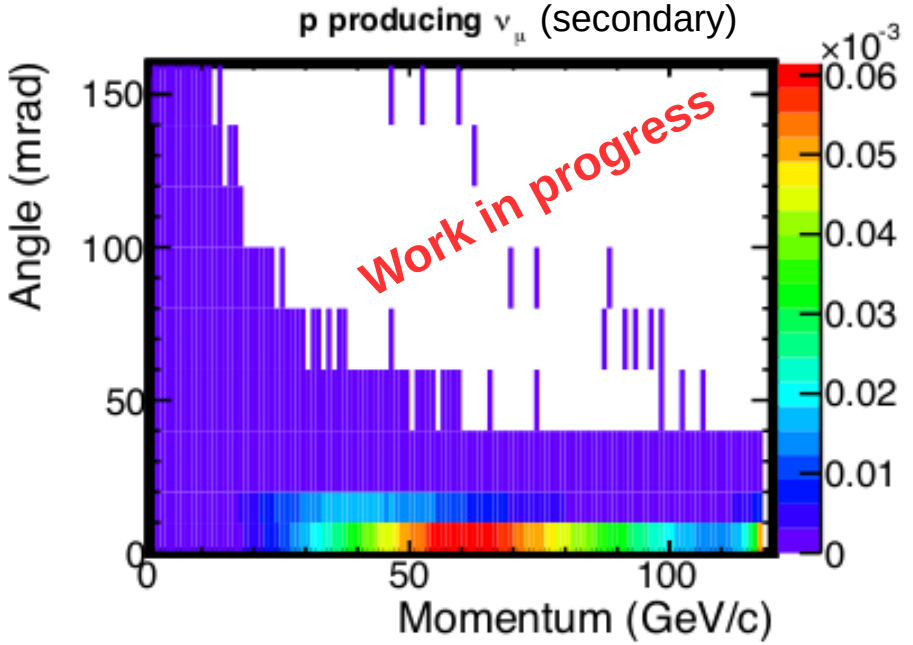


New Acceptance With FTPCs

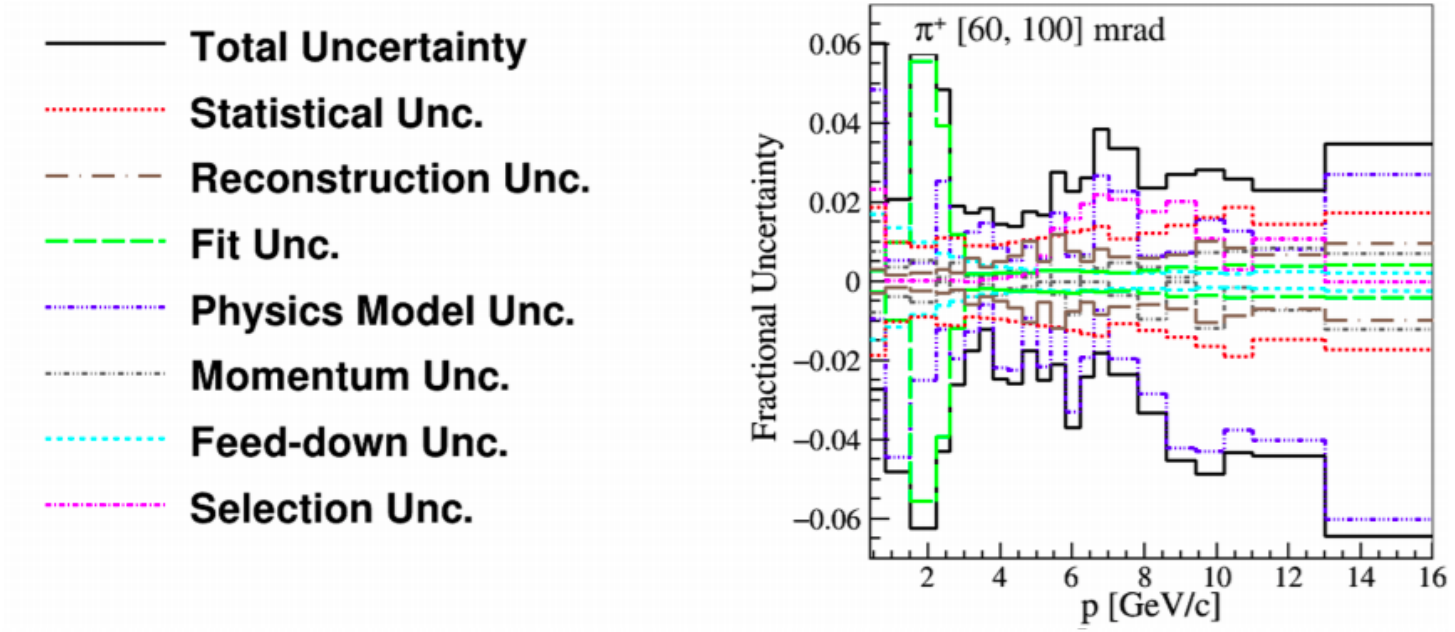


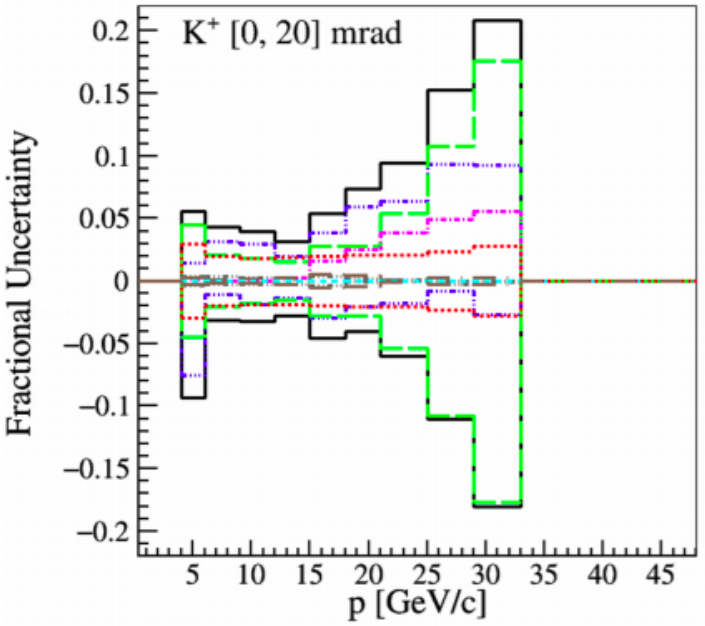
Example DUNE Neutrino Flux Contributors (120 GeV/c proton beam)

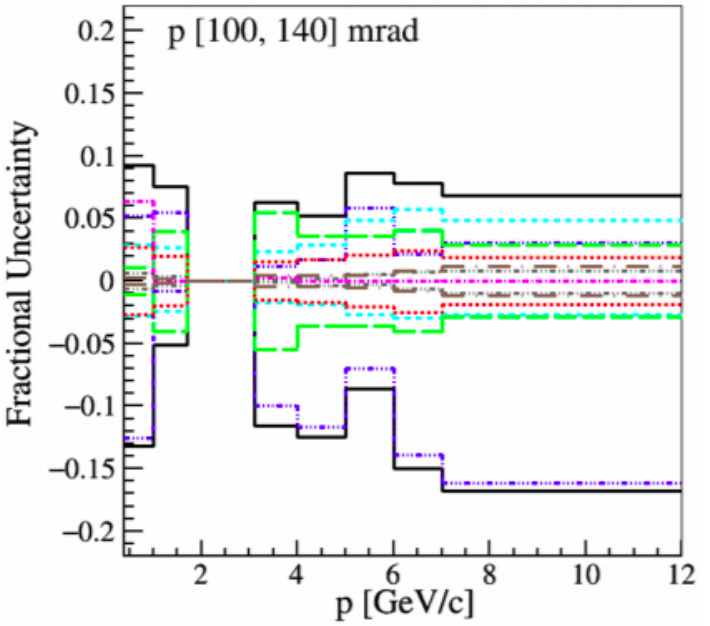




Thin-Target Results: Systematic Uncertainties



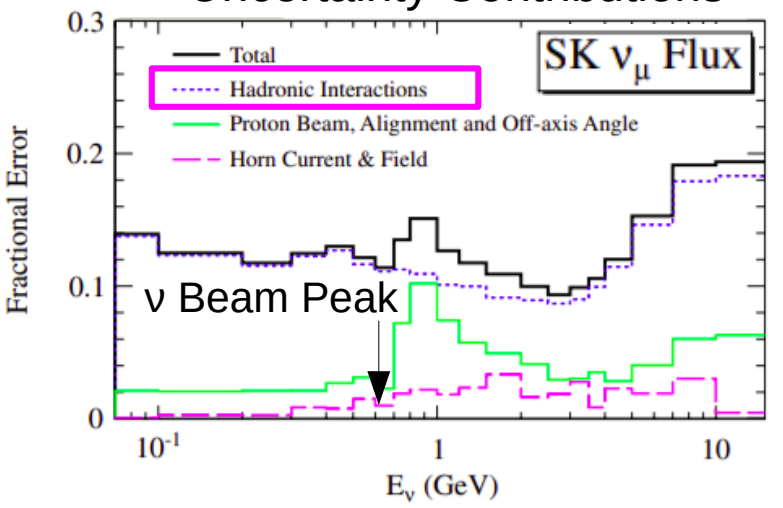




Neutrino Beam Flux Uncertainty

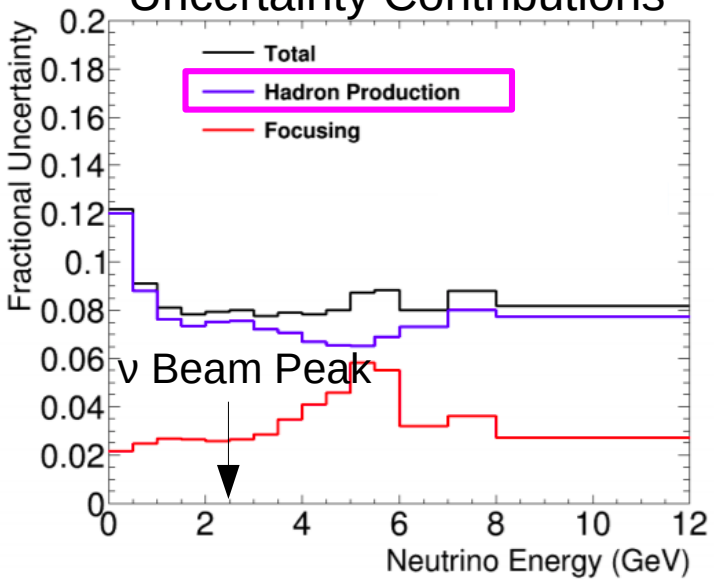
- Uncertainties on beam flux result in
  - Uncertainties on cross-section measurements
  - Uncertainties on oscillation parameter measurements
- Without **any** constraint data, hadron production uncertainty very large (20% – 50%)
- With current experimental data, uncertainties can still be as large as 8 – 12%

T2K Far Detector Flux Uncertainty Contributions



Phys. Rev. D 87, 012001 (2013)

DUNE Far Detector Flux Uncertainty Contributions



L. Fields, NA61
Beyond 2020 Workshop