Constraining Accelerator-based Neutrino Flux: The NA61/SHINE neutrino physics program

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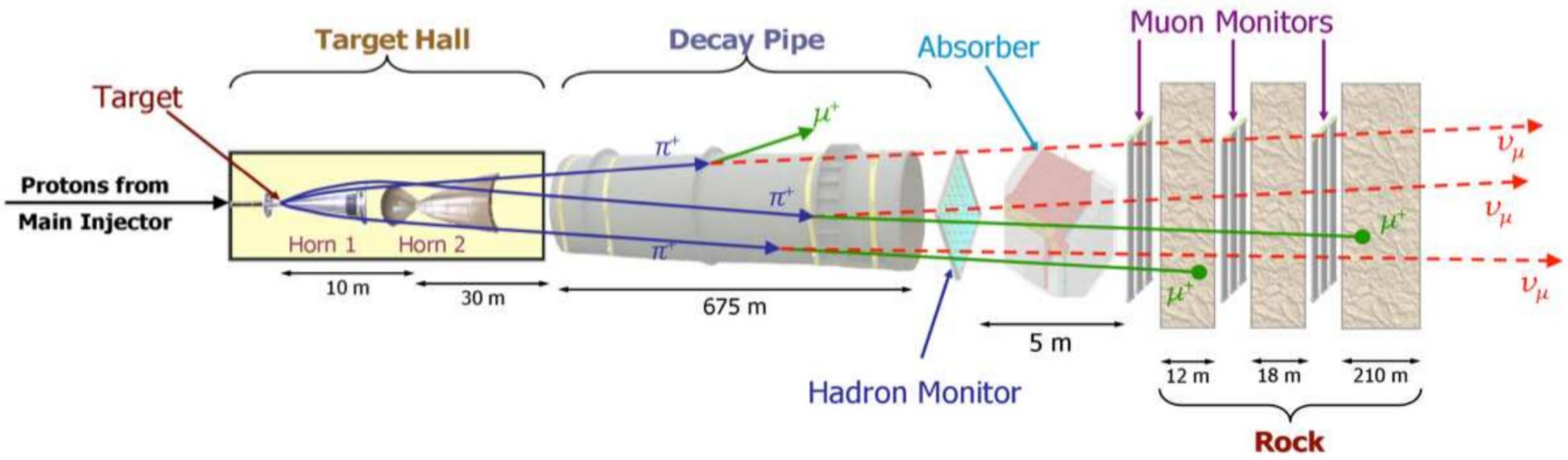
Outline

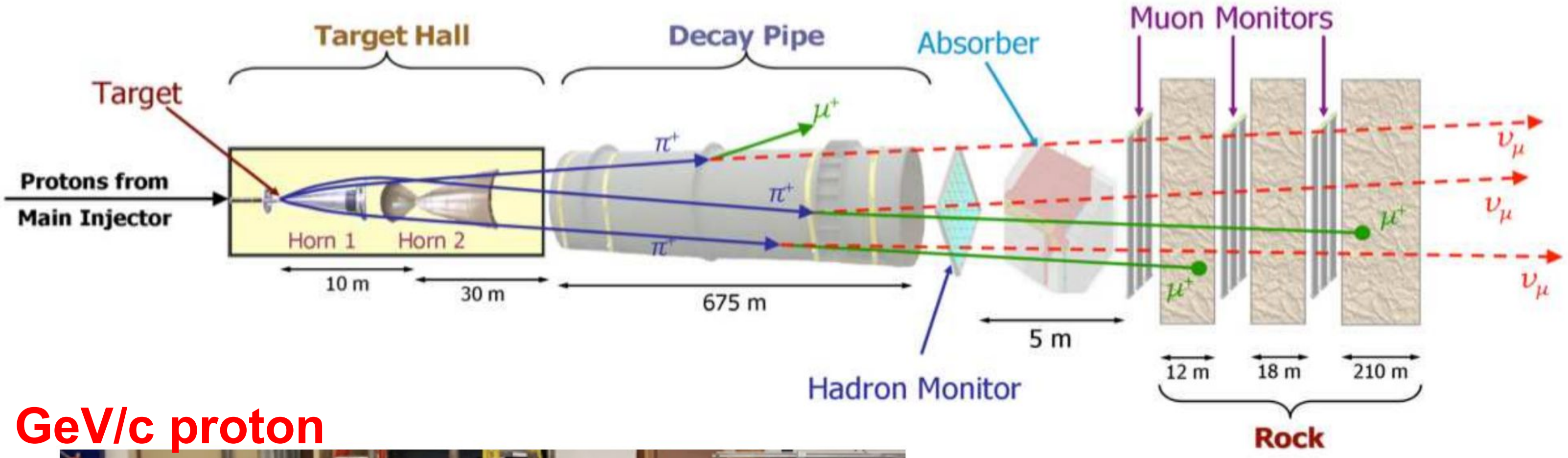
- Neutrino flux and hadron production uncertainty
- Introduction to NA61/SHINE
- Measurements for T2K
- Measurements for Fermilab experiments
- Current effort
- Future plans

How to Make a Neutrino Beam



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

How to Make a Neutrino Beam



120 GeV/c proton

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

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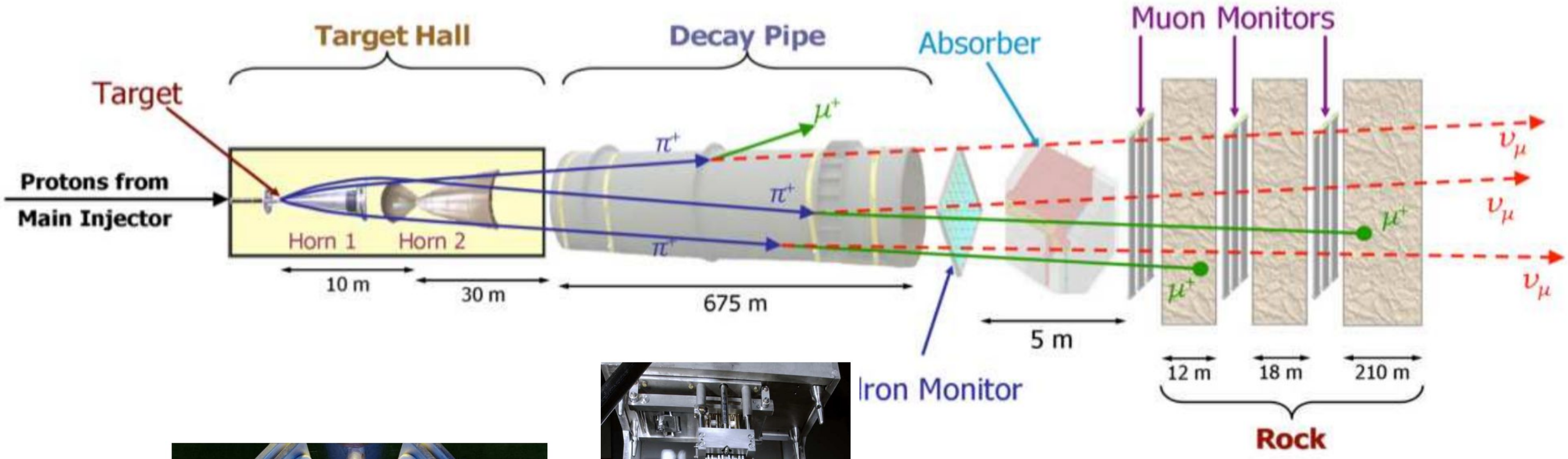

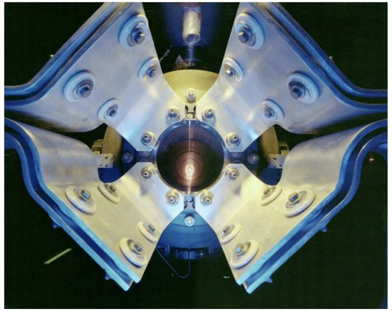

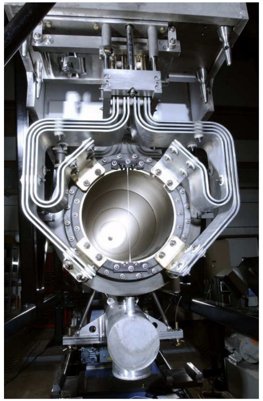

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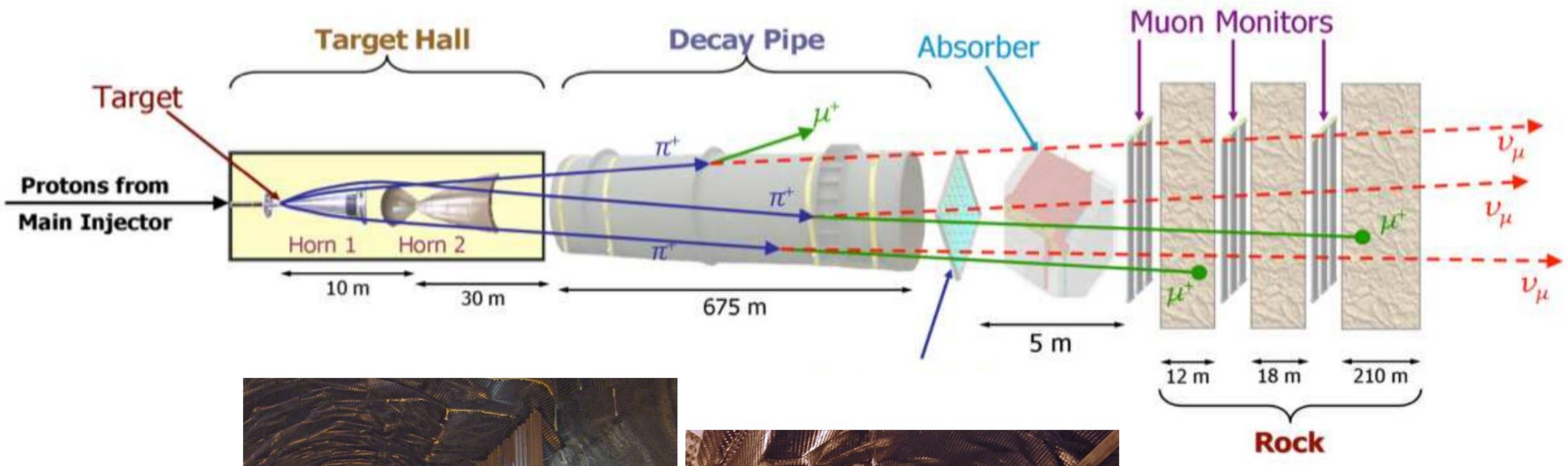

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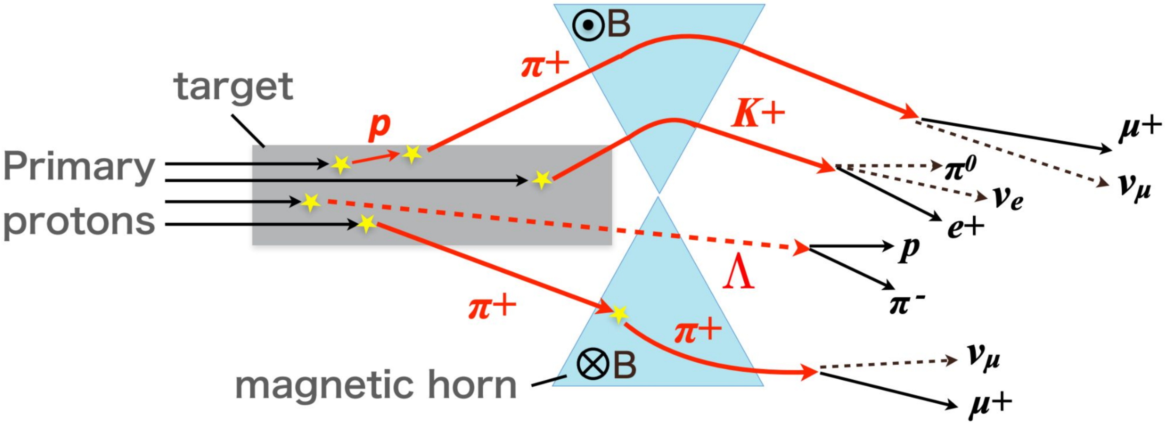
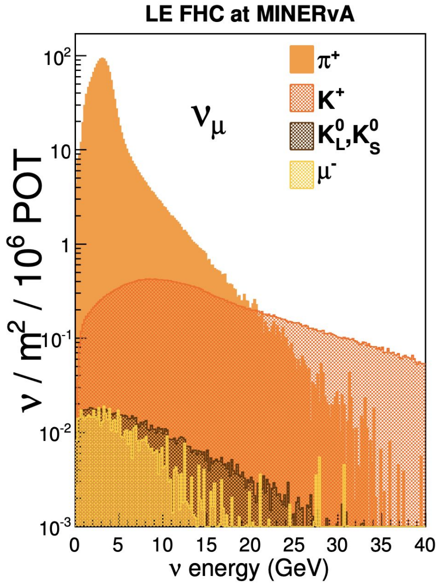
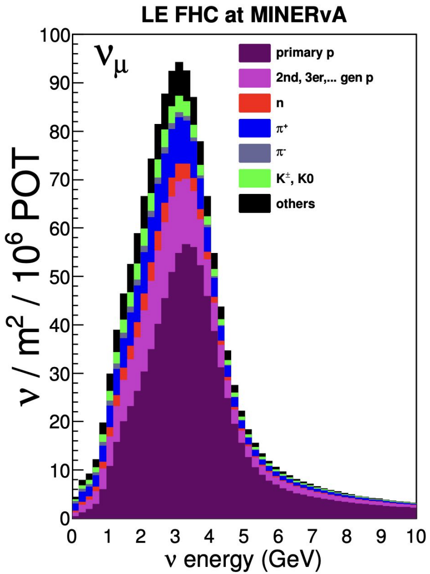


- Neutrinos come from
  - Pions and kaons from primary proton-carbon interactions (p + C)
  - Secondary interactions of protons, pions in the target (hadrons + C/Be)
  - Secondary interactions with horn (hadrons + X)

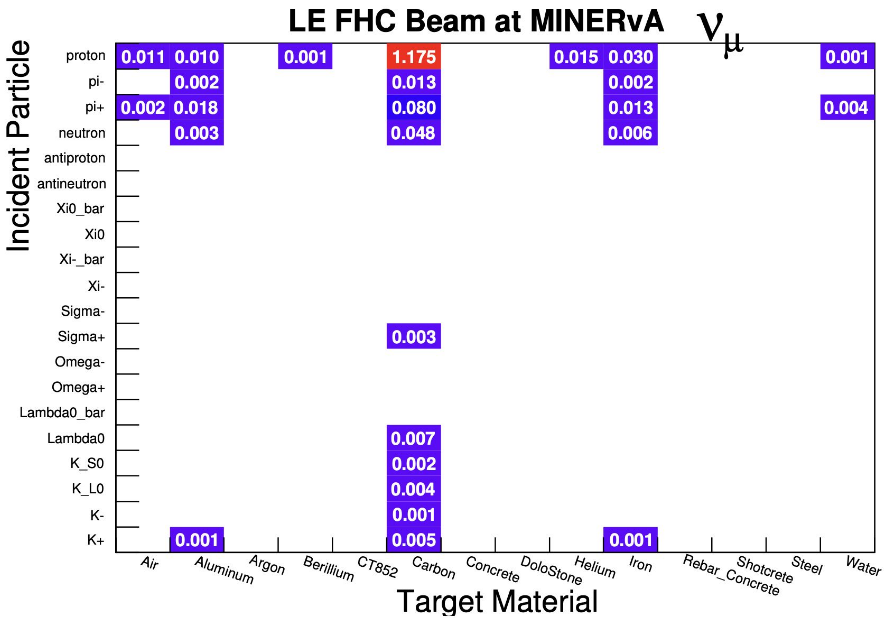
How to Model a Neutrino Beam



Parent



Grandparent

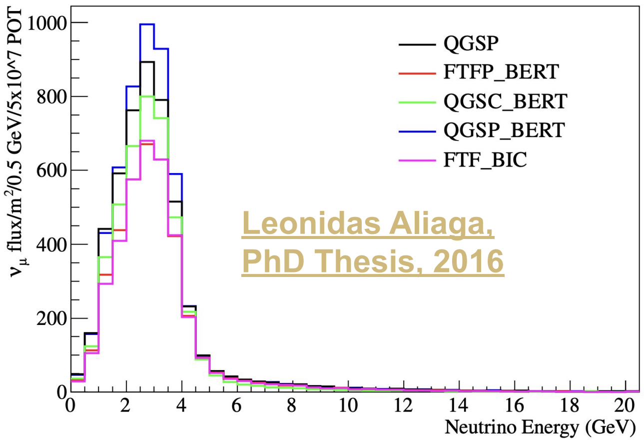


Incident particle vs material

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



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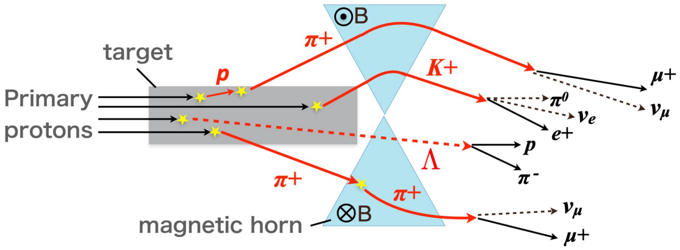
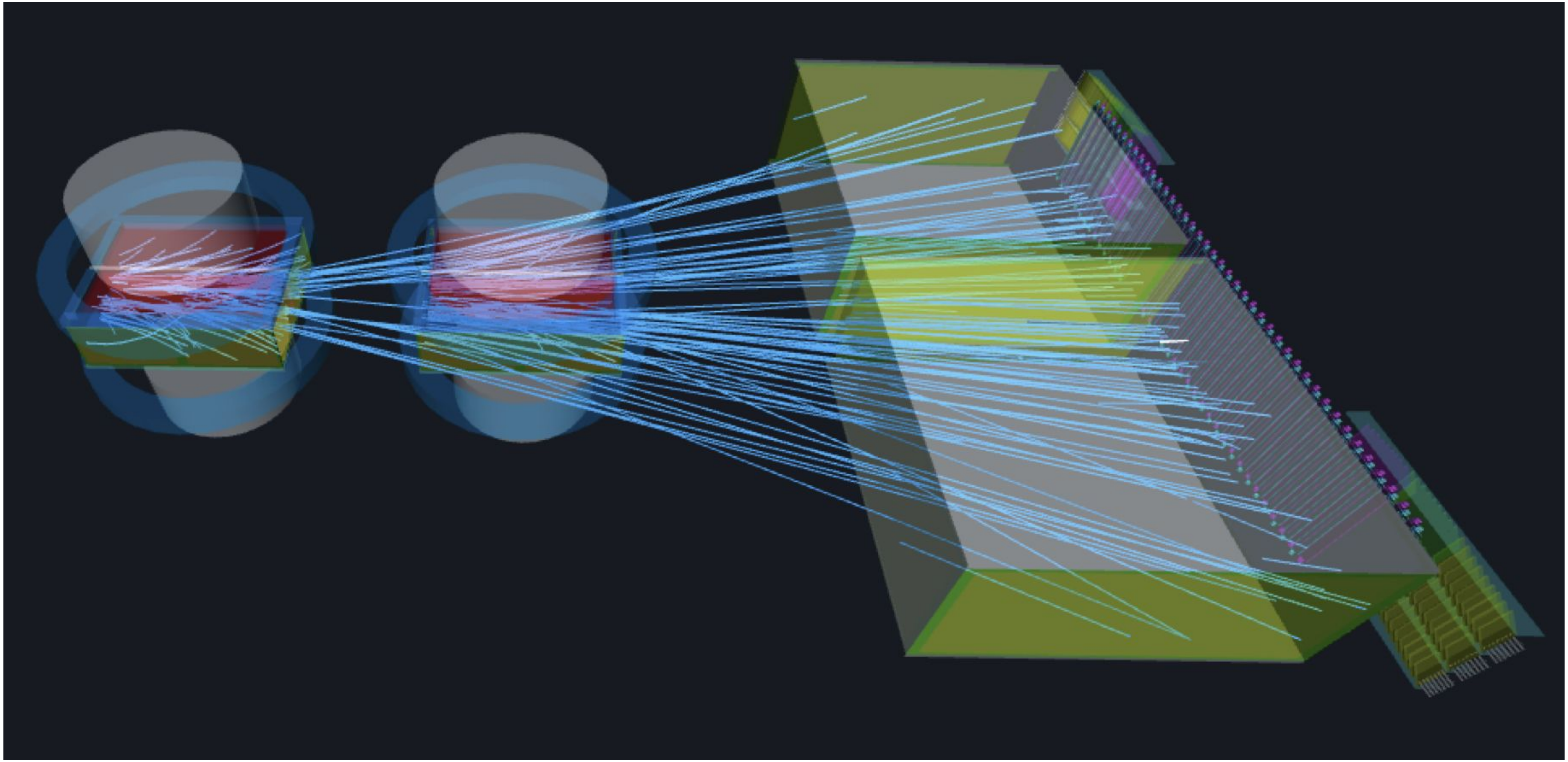
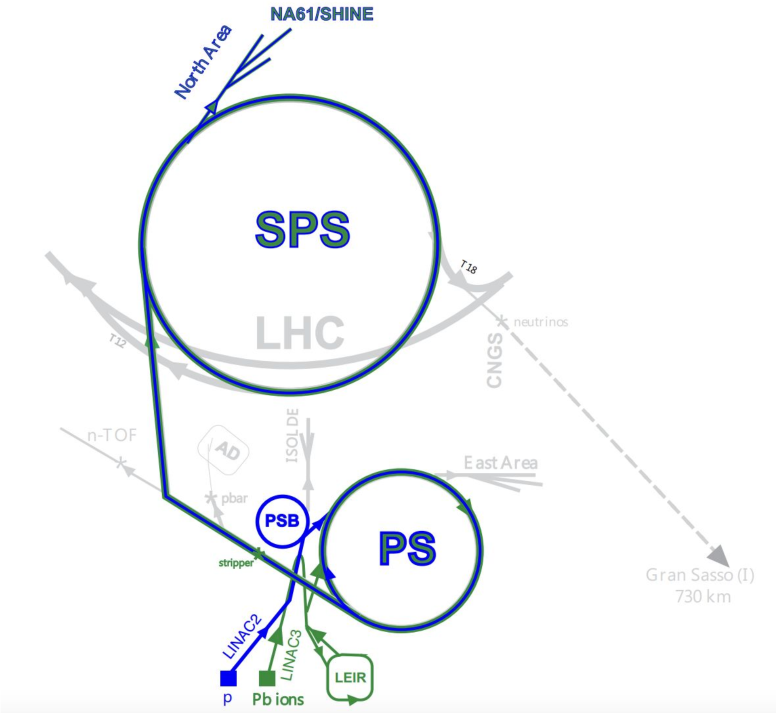


Introduction to NA61/SHINE



NA61/SHINE

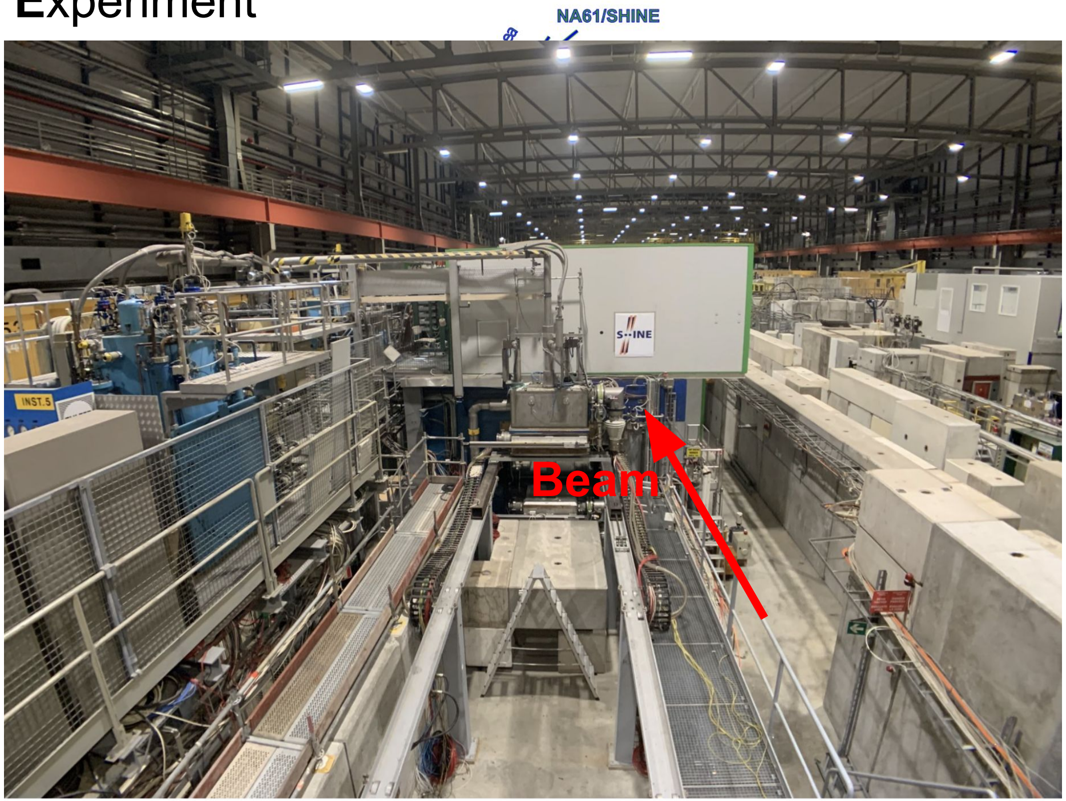
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment



JINST 9 (2014) P06005

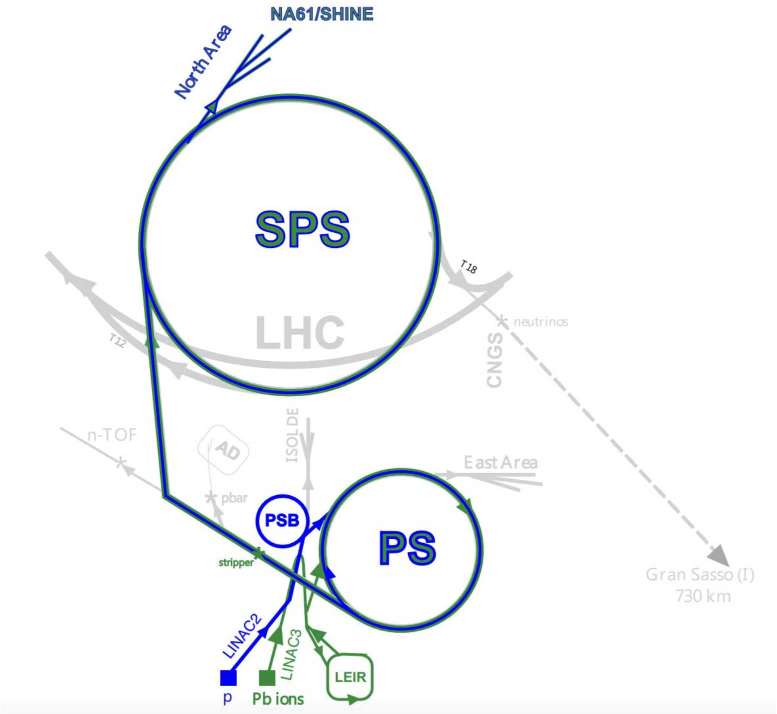
NA61/SHINE

- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Beam



NA61/SHINE

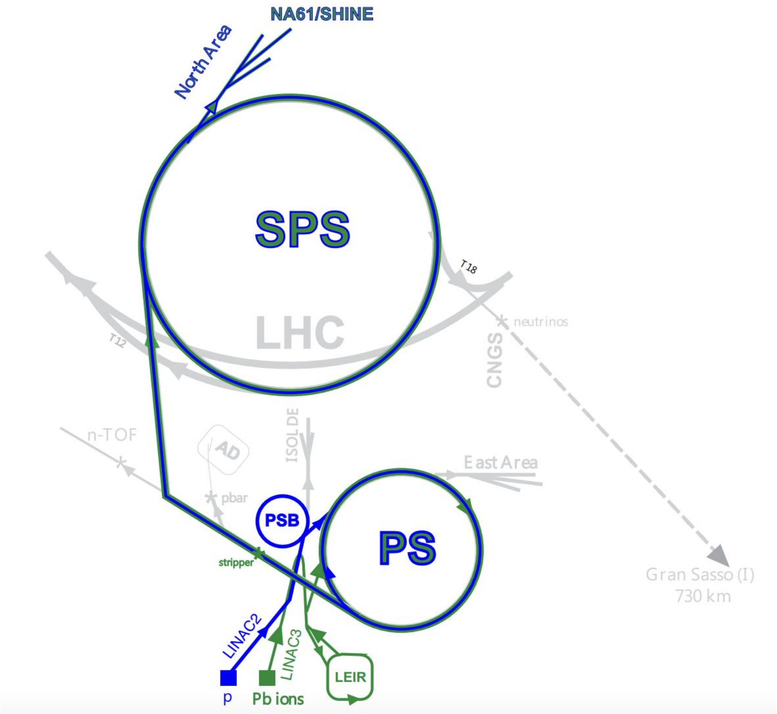
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Beam
  - Primary proton beam from CERN SPS
  - Secondary beam of proton, kaon, pion, etc.



JINST 9 (2014) P06005

NA61/SHINE

- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Beam
  - 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**

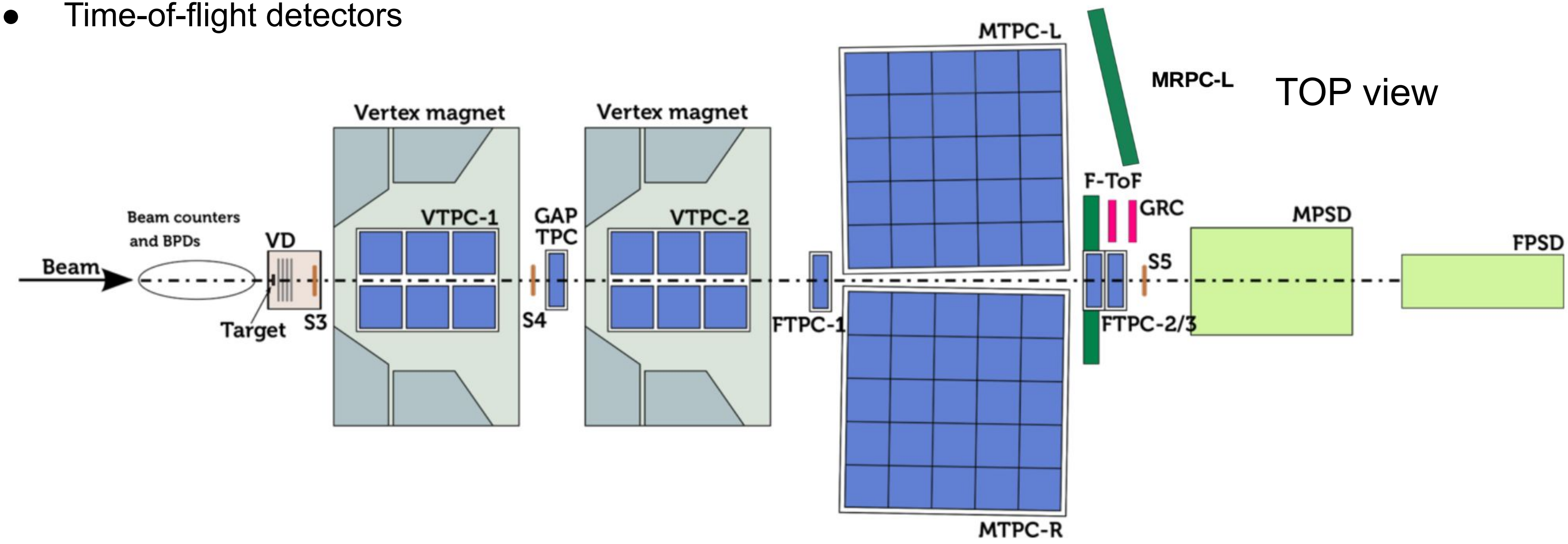


JINST 9 (2014) P06005

NA61/SHINE Detector

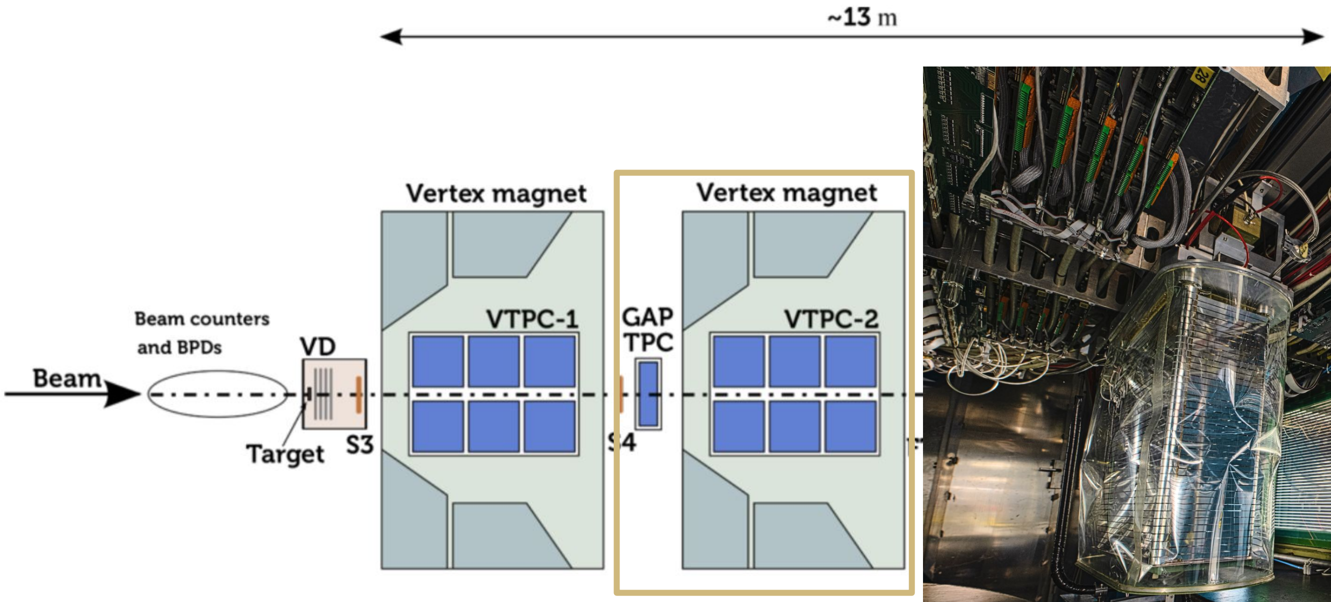
- 8 Time Projection Chambers (TPCs)
- Two superconducting magnets
- Time-of-flight detectors

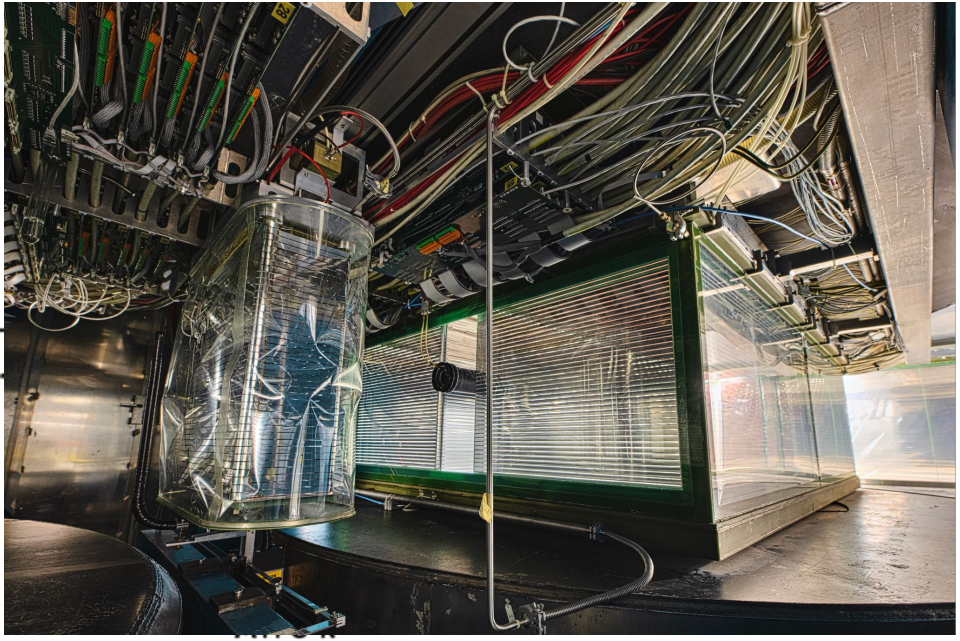
TOP view



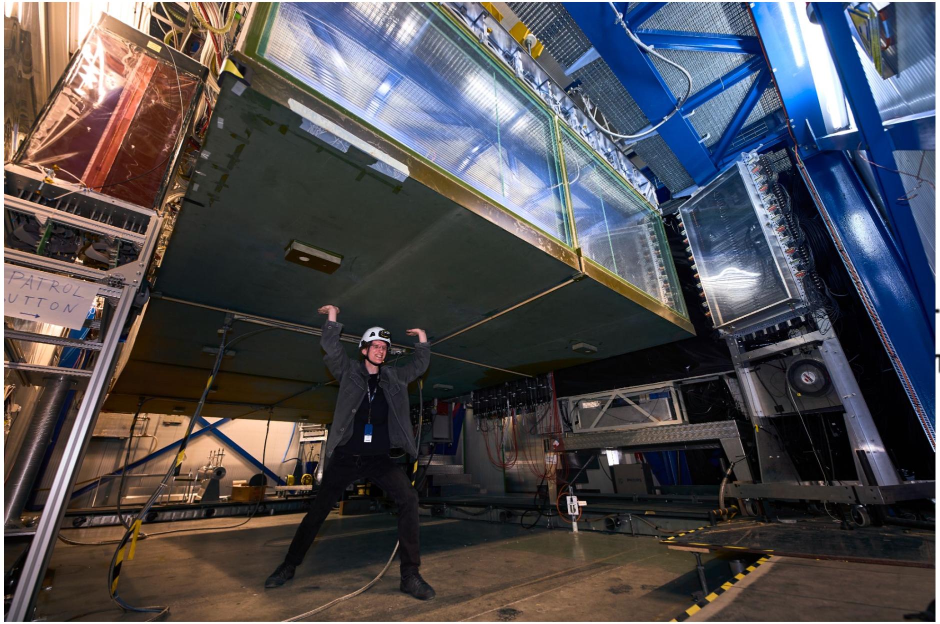
- Projectile Spectator Detectors (PSDs)
- Major detector upgrade finalized in 2022

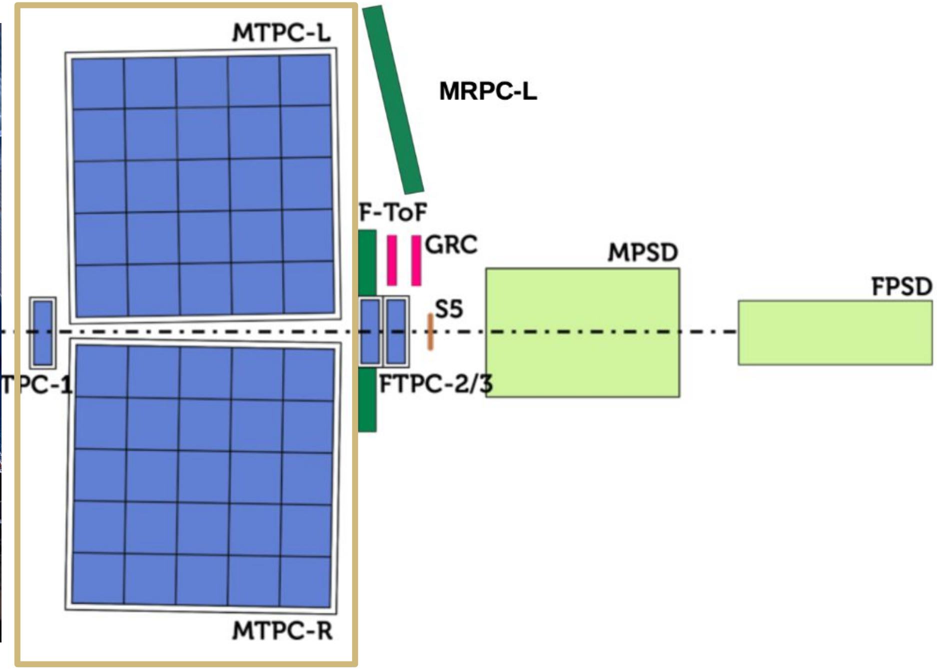
NA61/SHINE Detector





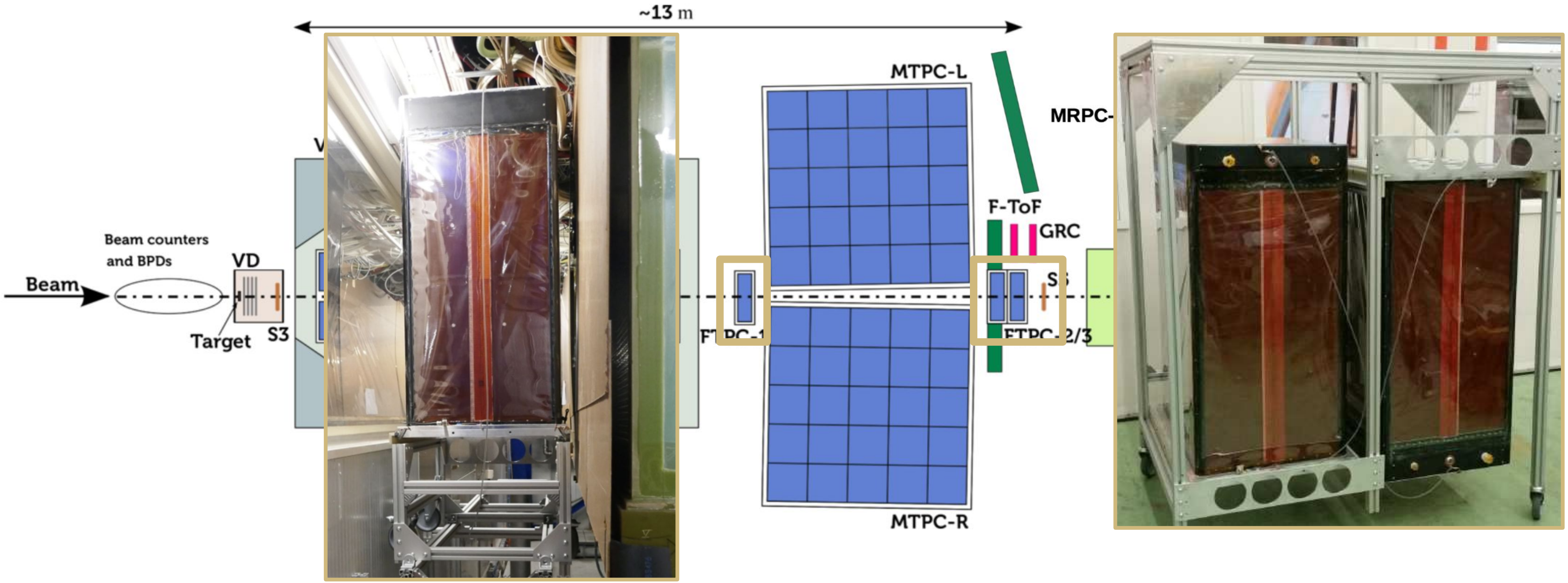
NA61/SHINE Detector





NA61/SHINE Detector

- Three Forward-TPCs (FTPCs) were built in 2015 - 2017
- Including in data taking since 2017

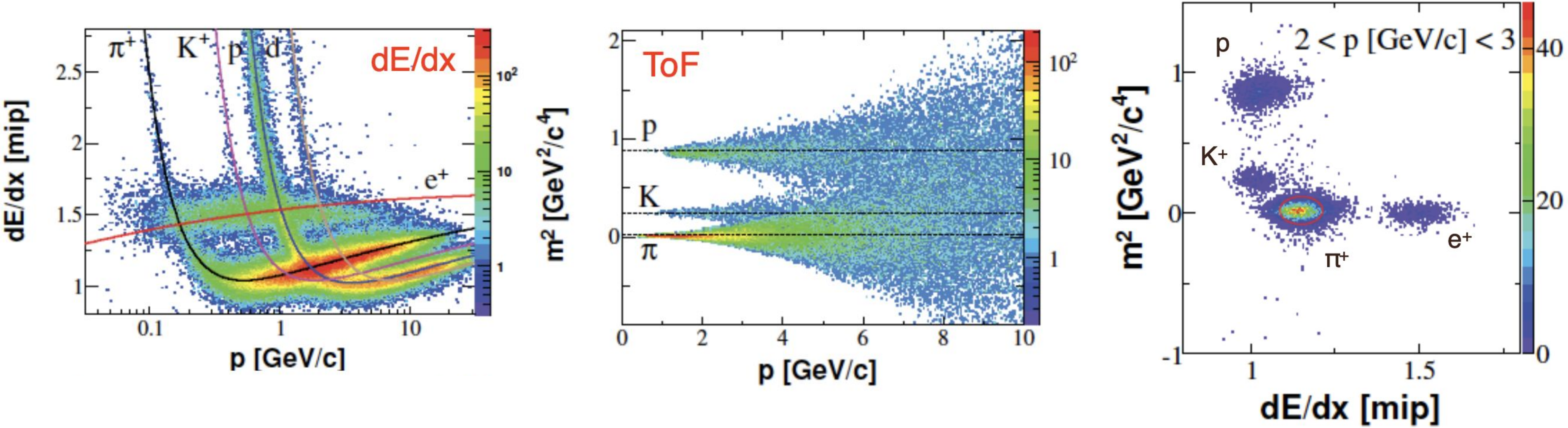


Major Upgrade (2019-2022)

- **Replacement of old TPC electronics with system from ALICE**
- **New trigger/DAQ, combined with new electronics, gives a major upgrade in data collection rate (~100 Hz → ~1 kHz)**
- New silicon vertex detector for open charm studies
- RPC-based replacement for TOF-L/R walls
- New beam position detectors
- New forward Projectile Spectator Detector module, reconfiguration of existing detector

Particle Identification

- Use dE/dx in TPCs for higher momentum
- Transitions to TOF at lower momentum



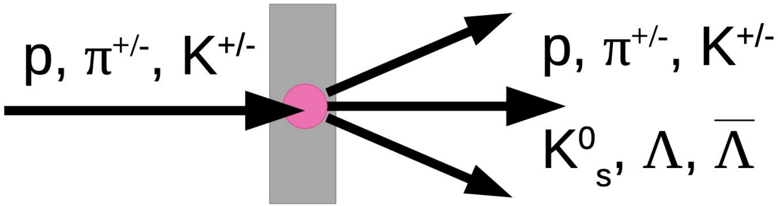
The Neutrino Program at NA61/SHINE

- Dedicated hadron production measurements for long-baseline oscillation neutrino experiments
  - J-PARC, NuMI, LBNF, …
- Main collaborators
  - Eötvös Loránd University, Budapest, Hungary
  - LPNHE, Sorbonne University, CNRS/IN2P3, Paris, France
  - Okayama University, Japan
  - KEK, Japan
  - University of Notre Dame, Notre Dame, USA
  - University of Colorado, Boulder, USA
  - University of Pittsburgh, Pittsburgh, USA
  - Fermilab, Batavia, USA

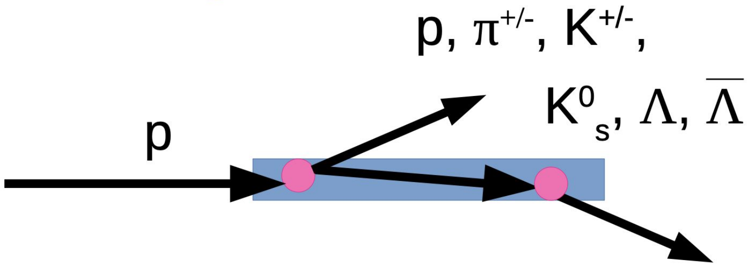
2007 - 2010 **T2K**	Long Shutdown (LS) 1	**2015 - 2018** **FNAL**	LS2	**2022 - 2025** **T2K, DUNE**	LS3	**2027 -** **?**

Hadron Production Measurements

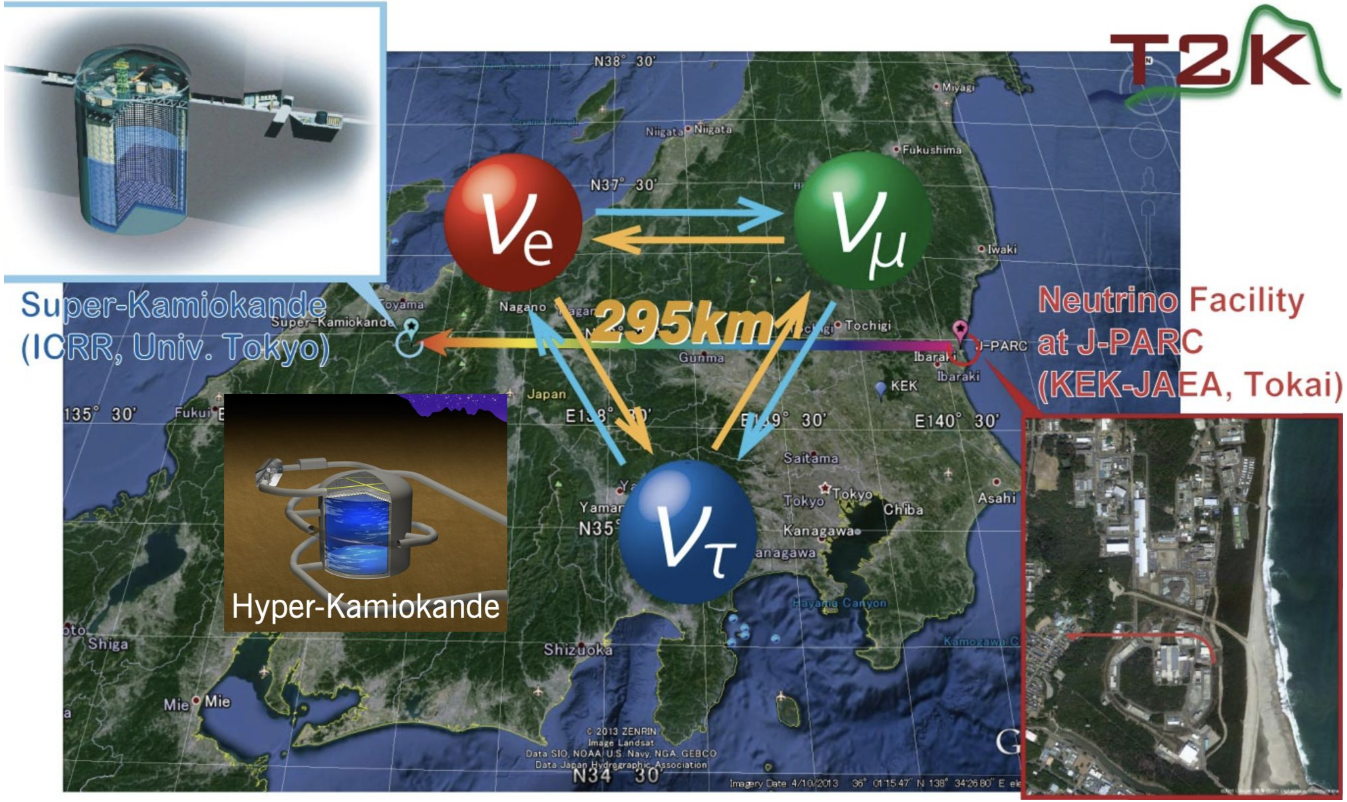
- Thin-target measurements
  - Total, inelastic and production cross sections
  - Charged and neutral hadron yields from primary and secondary interactions
  - Input to reweight flux simulations



- 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

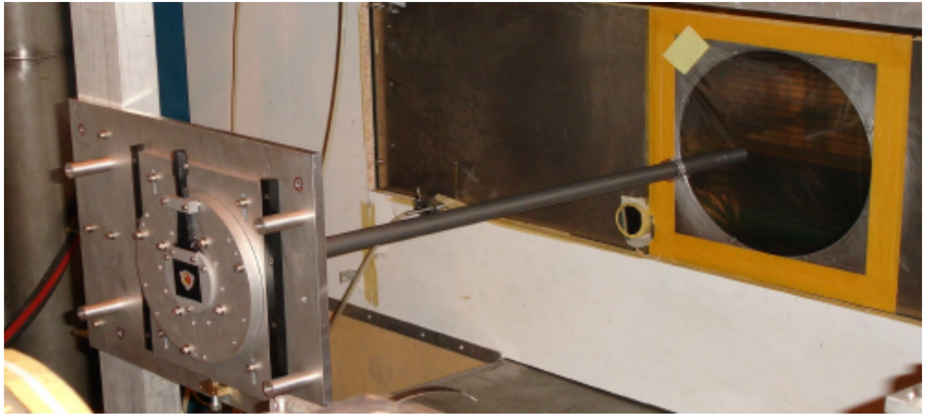


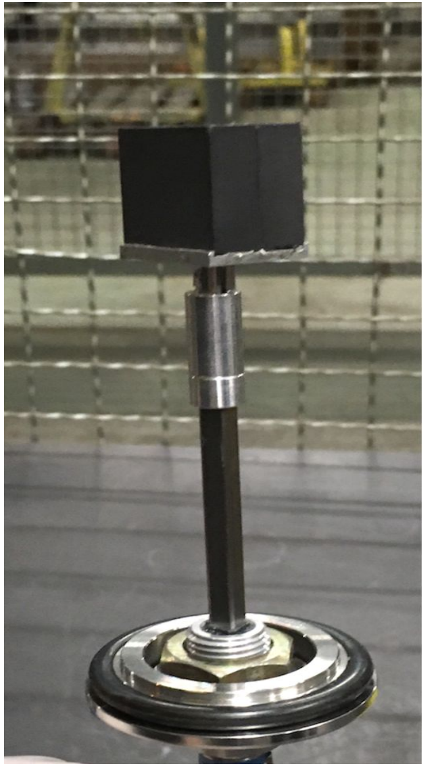
Measurements for the T2K Experiment



Measurements for the T2K Experiment

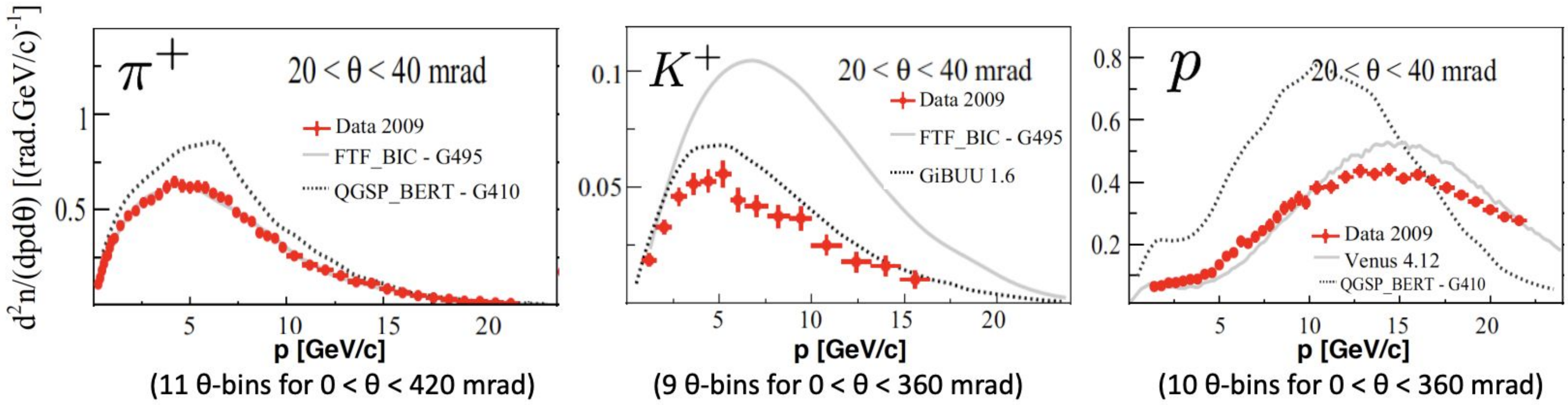
- 2007 - 2010
- Proton + carbon @ 31 GeV/c
- Targets
  - Thin: 2 cm graphite target
  - Thick: 90 cm replica graphite target





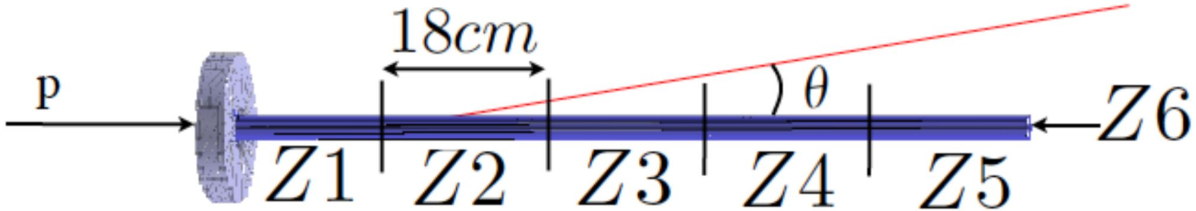
Thin Target Measurements for T2K

- 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 Λ^0 spectra measurements (Phys. Rev. C89 (2014) 025205)
  - **Total cross-section and $\pi^{+/-}$, $K^{+/-}$, p, K^0_S, and Λ^0 spectra measurements (Eur. Phys. J. C76 (2016) 84)**



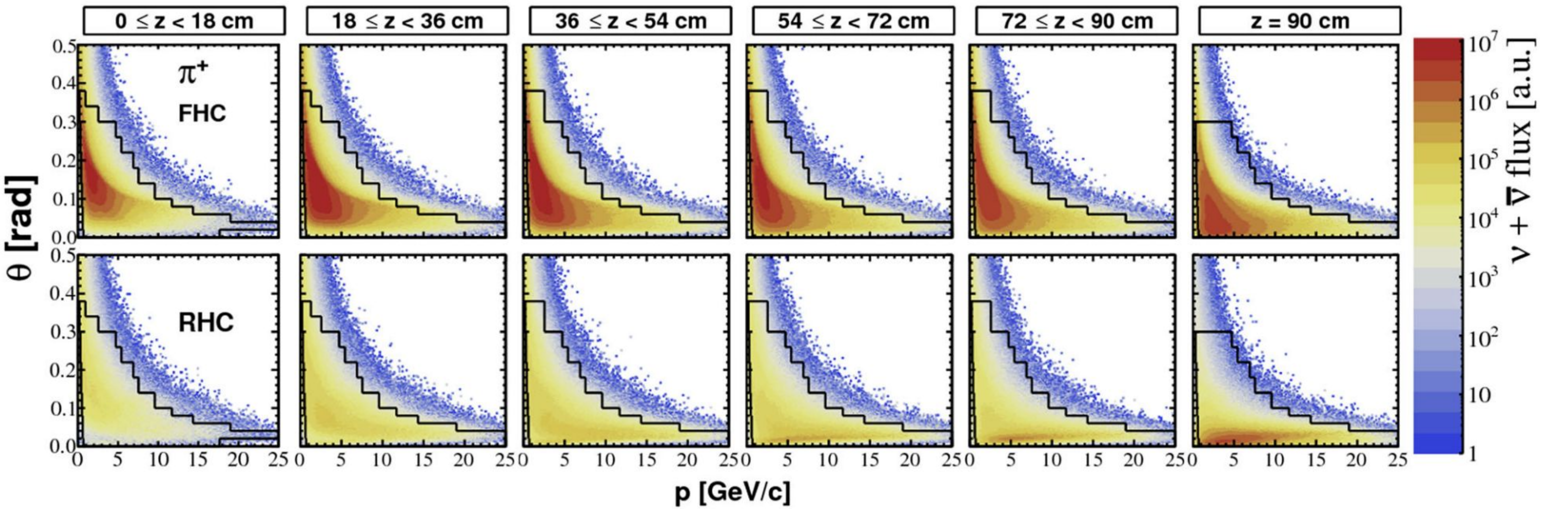
Thick Target Measurements for T2K

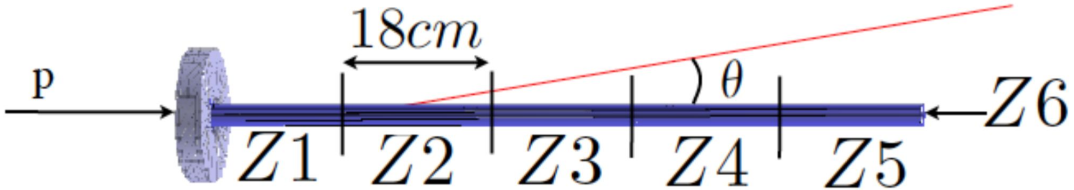
- Replica target: 31 GeV/c proton on 90 cm replica graphite target
  - Methodology, $\pi^{+/-}$ yield measurement (Nucl. Instrum. Meth. A701 (2013) 99-114)
  - $\pi^{+/-}$ yield measurement (Eur. Phys. J. C76 (2016) 617)
  - $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79 100 (2019))
  - p beam survival probability measurement (Phys. Rev. D103 012006 (2021))



Thick Target Measurements for T2K

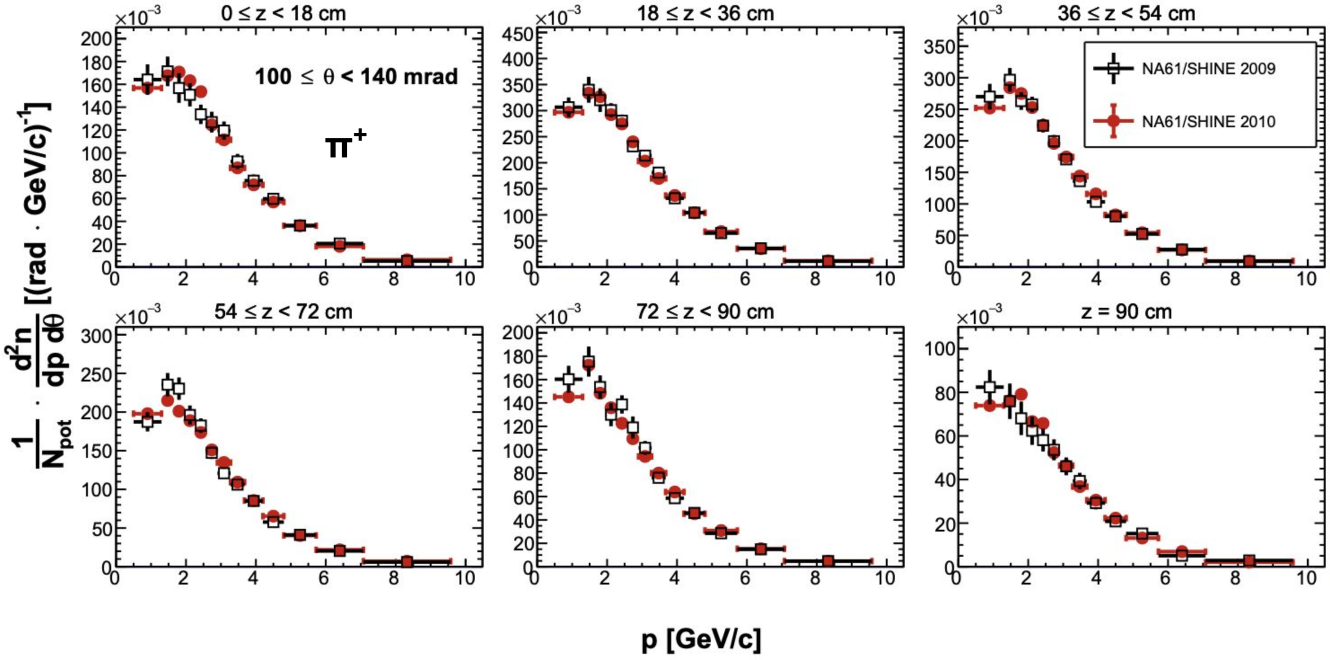
- Phase space of the charged hadrons coming from the T2K target surface that contribute to the (anti)neutrino fluxes





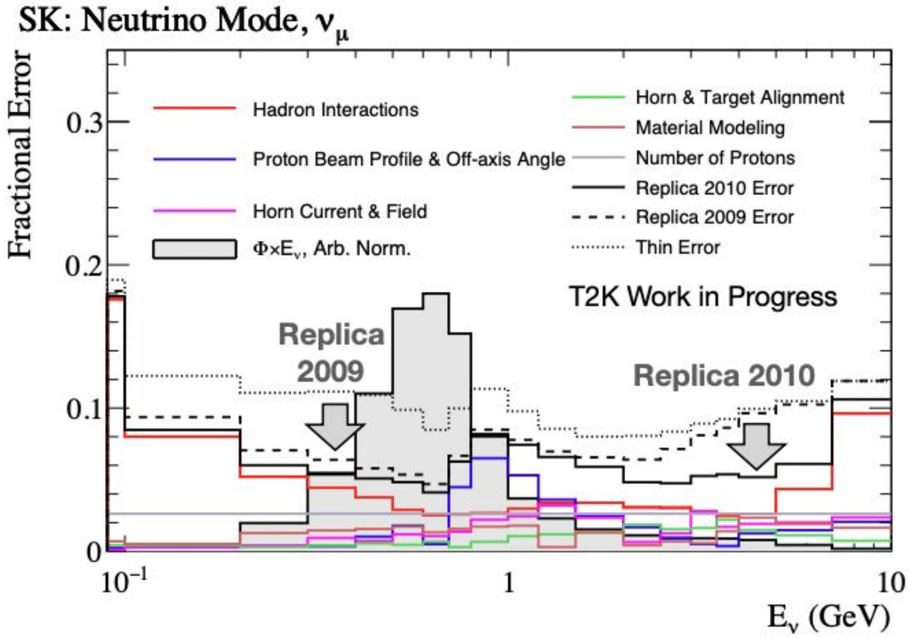
Thick Target Measurements for T2K

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



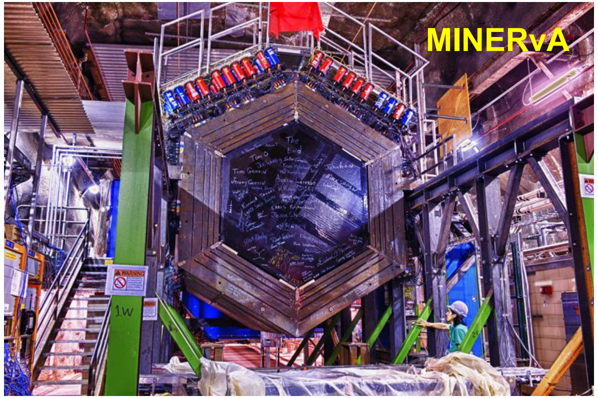
Effect on T2K Flux Uncertainty

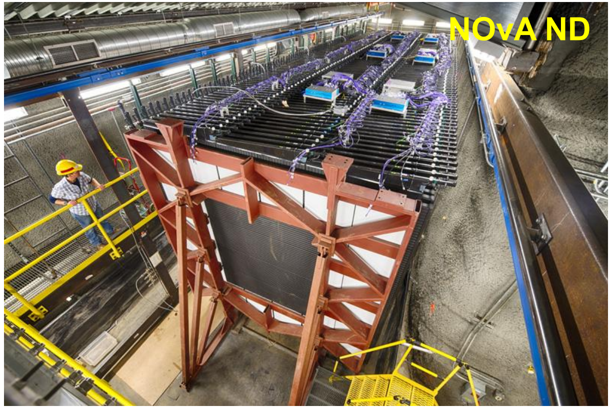
- Improved T2K flux uncertainty down to ~5%
- More replica target data collected in 2022
  - 18 times 2010 statistics
  - Being calibrated
  - Measure high-momentum kaon yields

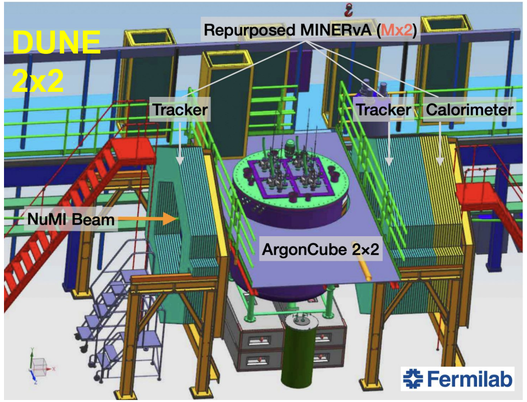


Lukas Berns, NBI 2019

Measurements for Fermilab Experiments

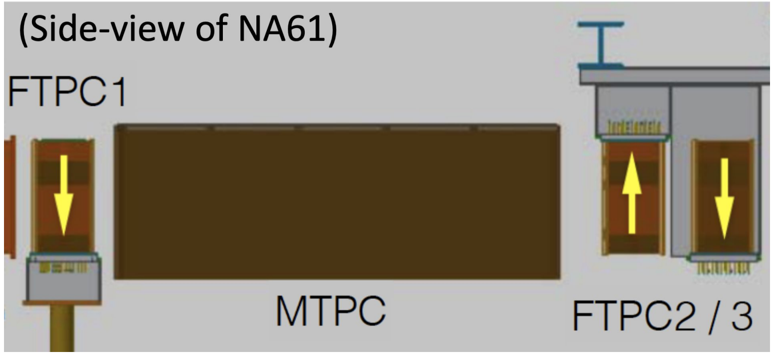


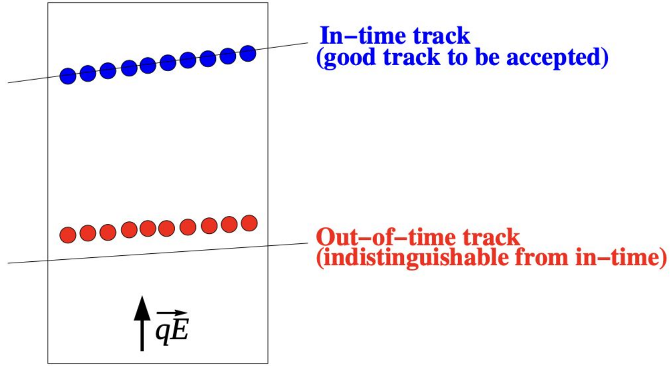


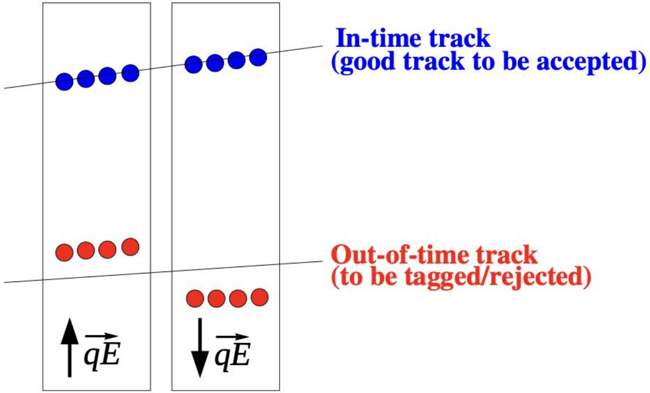


FTPCs

- Needed for higher momentum proton
- A “Tandem TPC” concept
- Beam off-time background rejection



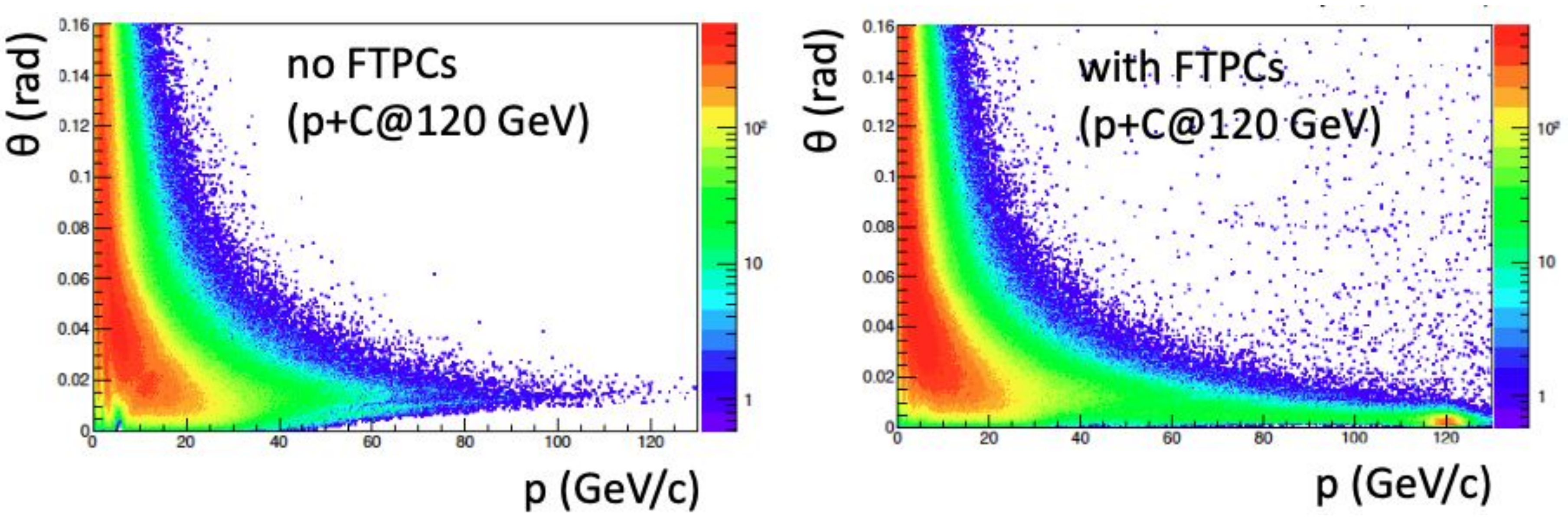




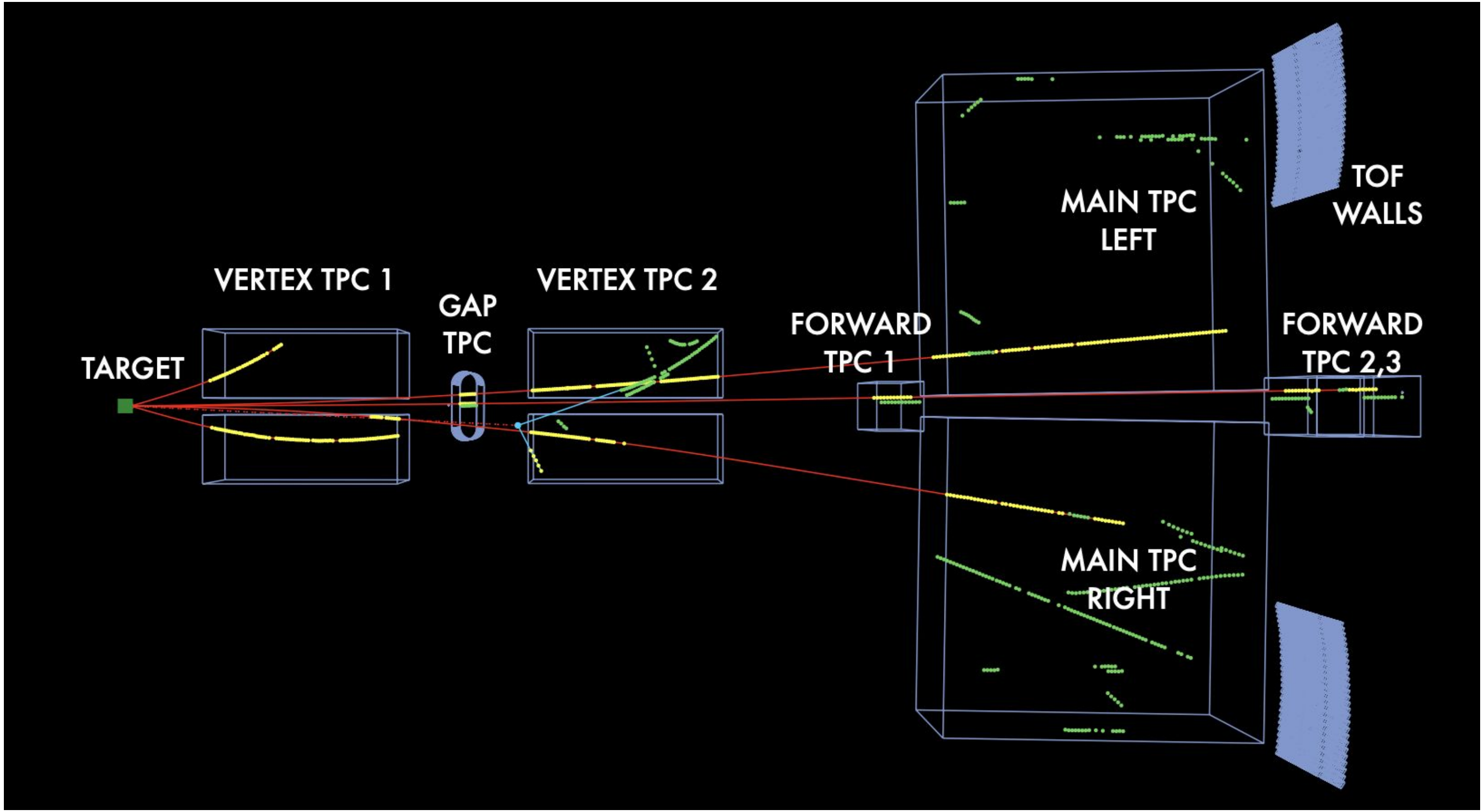
JINST 15 (2020) 07, P07013

FTPCs

- Greatly improved the acceptance in the forward region

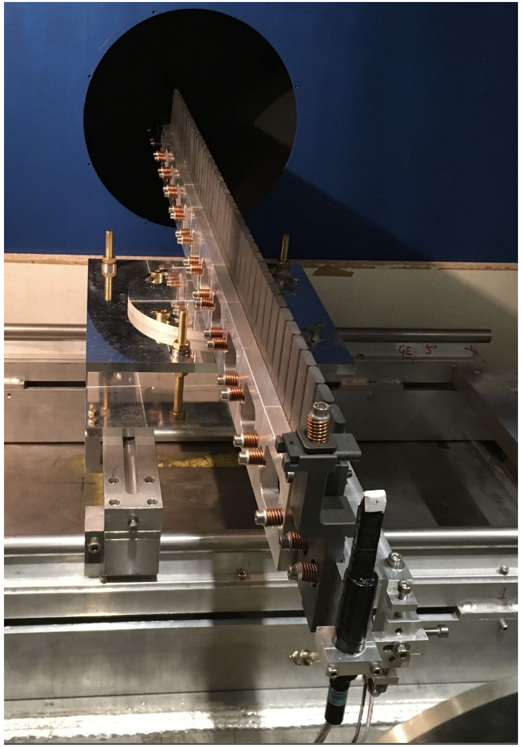


Event Display of 120 GeV/c proton + C



Measurements for Fermilab Experiments

- 2015 - 2017, 2023
- Beam
  - Proton at 120 GeV/c (primary)
  - Proton at 60, 90 GeV/c (secondary)
  - Pion at 60 GeV/c (secondary)
  - Kaon at 60 GeV/c (secondary)
- Target
  - Thin (1.5 cm)
    - Carbon
    - Titanium
    - Beryllium
    - Aluminum
  - Thick
    - NuMI replica



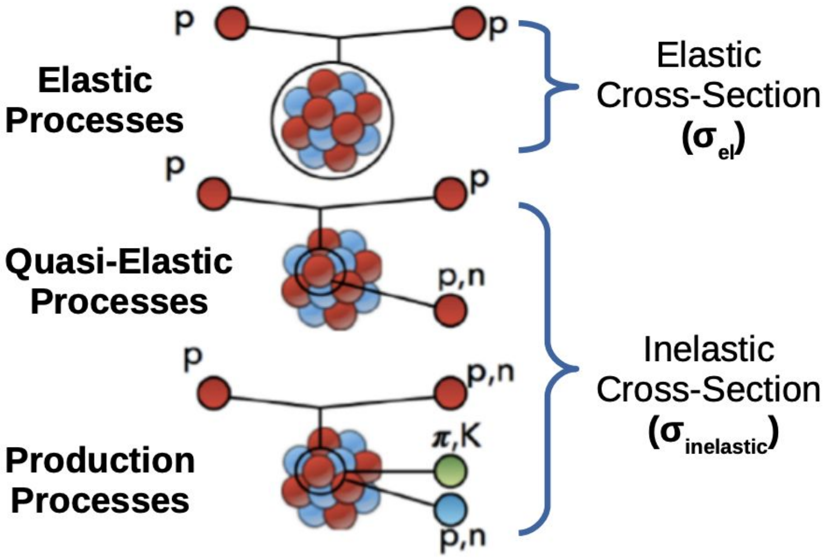
NuMI target in at NA61

Production and Inelastic Cross Section Measurements

- Production and inelastic cross sections of protons on carbon, beryllium, and aluminum targets at 60 GeV/c and 120 GeV/c

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

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



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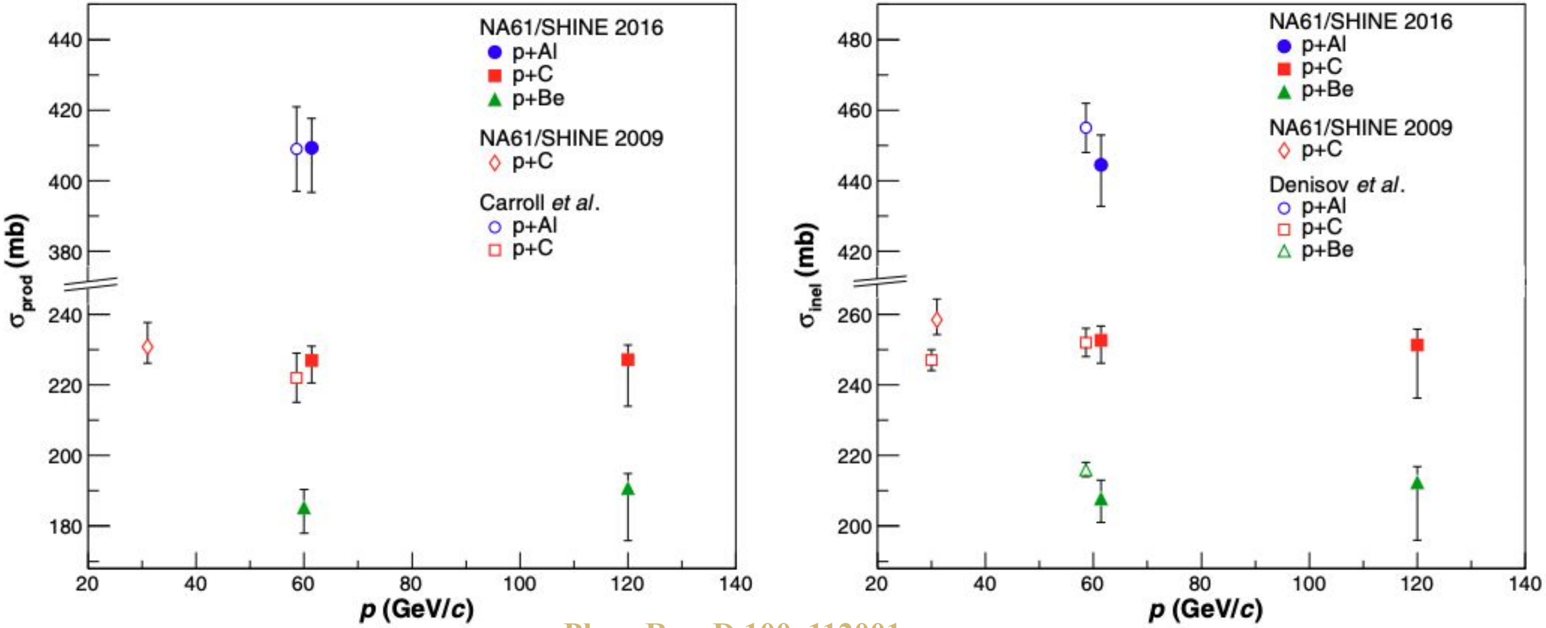
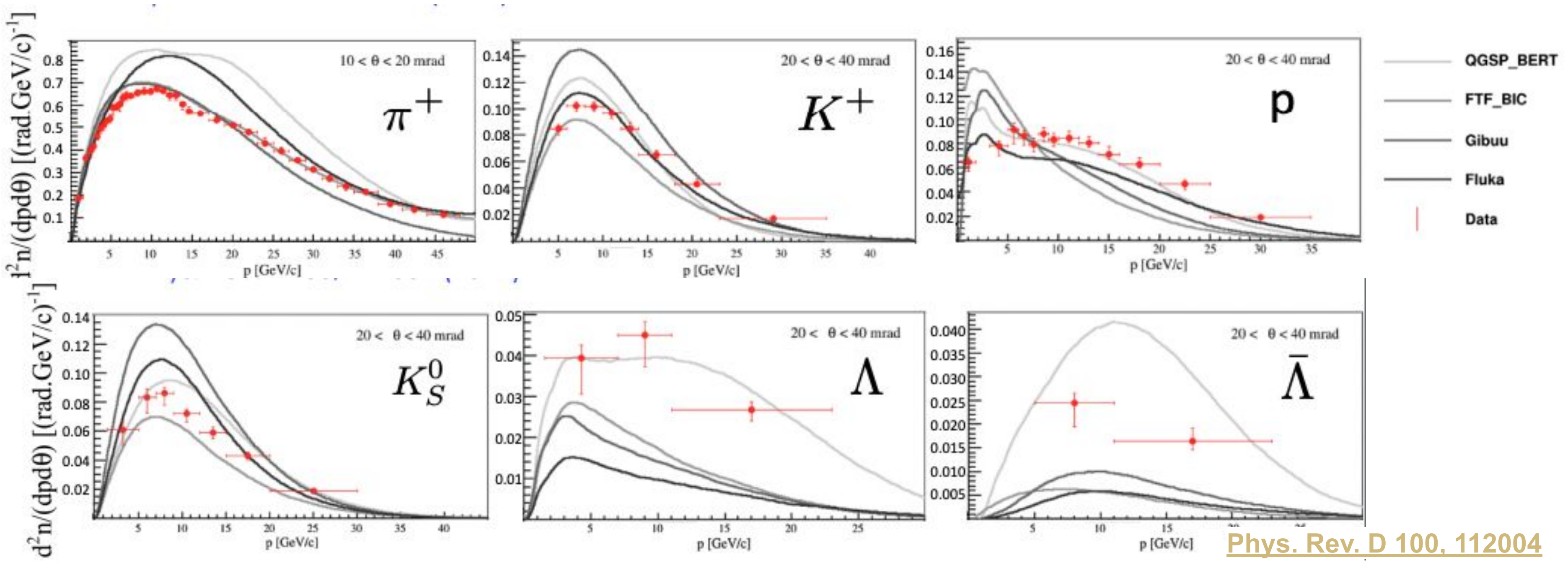


Phys. Rev. D 100, 112001

Measurements of π^+ + C/Be at 60 GeV/c

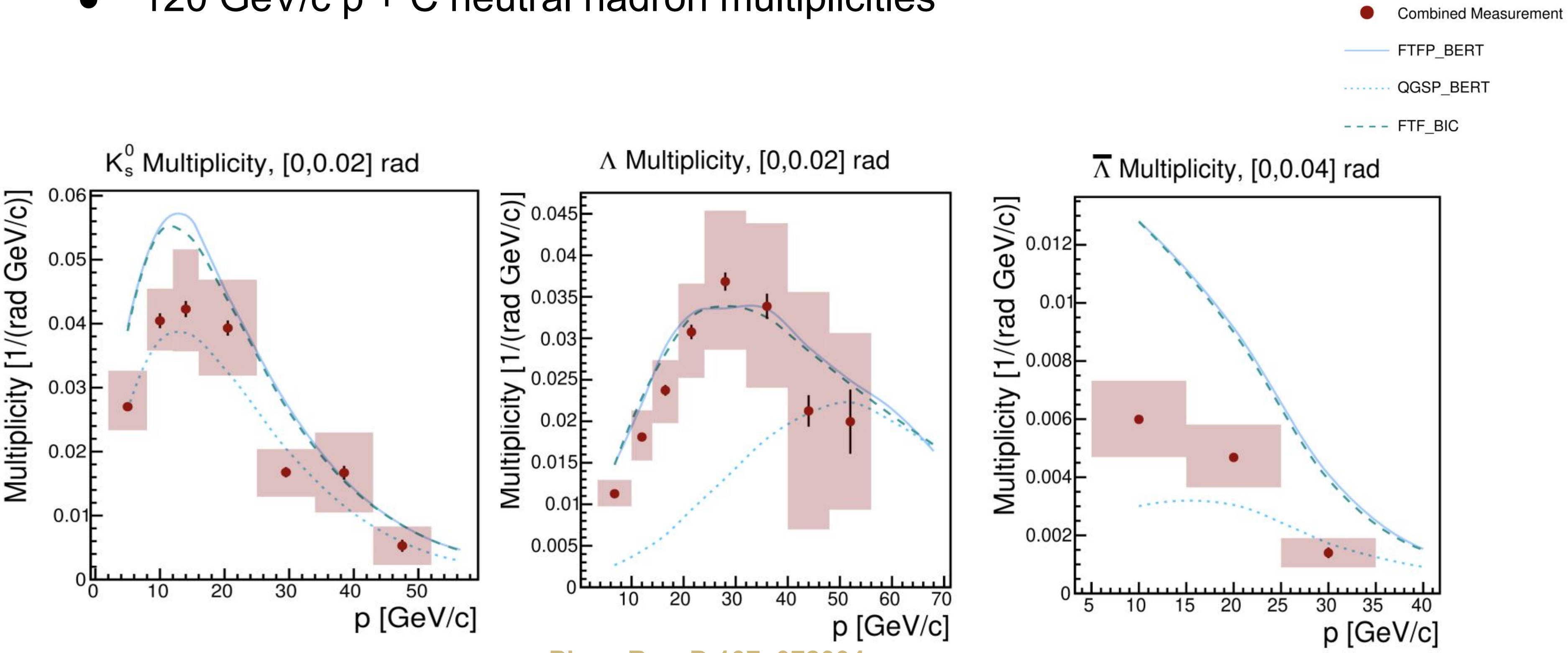
- Production and inelastic cross sections for π^+ + C/Be at 60 GeV/c
- Differential cross sections of π^-, π^+, K^-, K^+, protons, K^0_S, Λ and anti-Λ



Phys. Rev. D 100, 112004

Measurements of p + C at 120 GeV/c

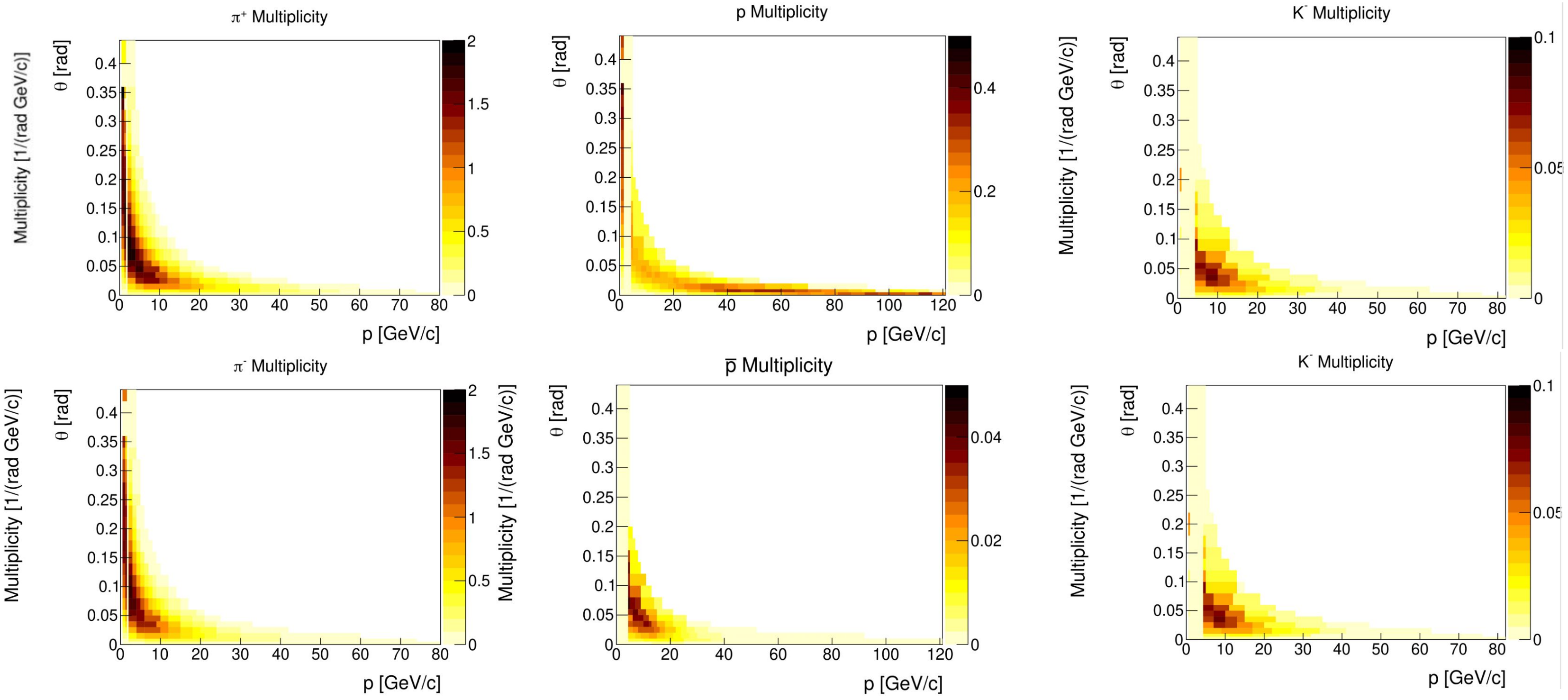
- 120 GeV/c p + C neutral hadron multiplicities



Phys. Rev. D 107, 072004

Measurements of p + C at 120 GeV/c

- 120 GeV/c p + C charged hadron multiplicities (Including FTPCs for the first time)



[Phys.Rev.D 108 (2023) 072013]()

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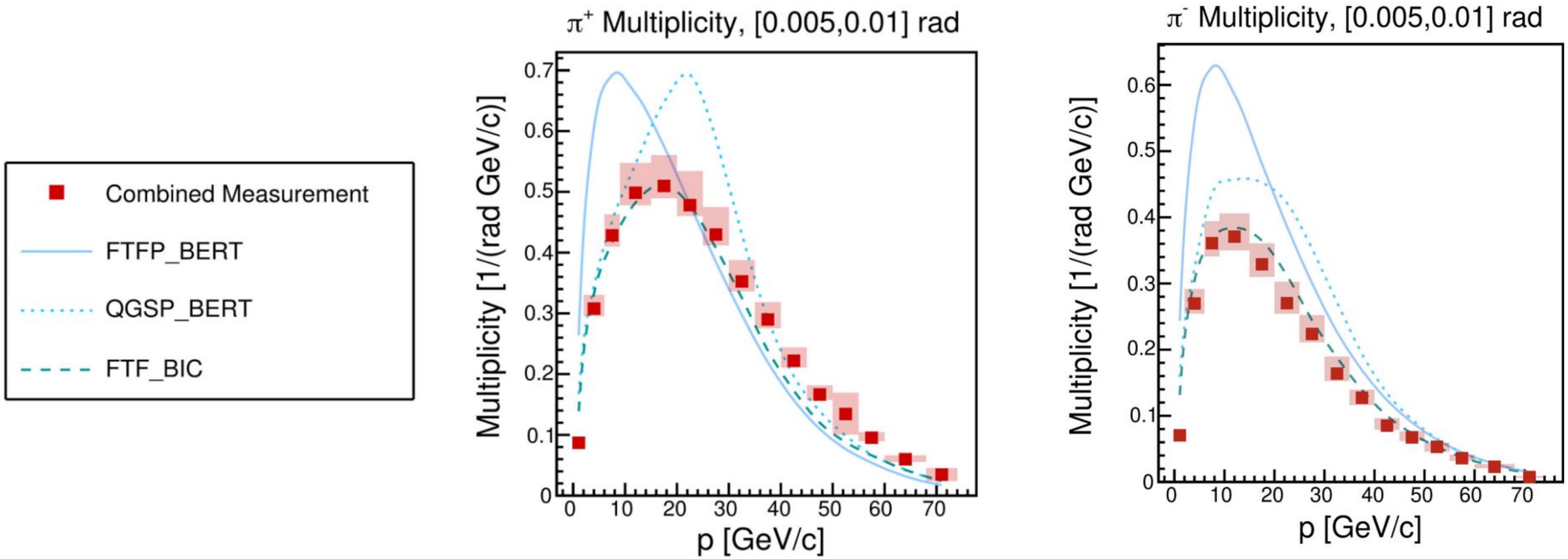

Phys.Rev.D 108 (2023) 072013

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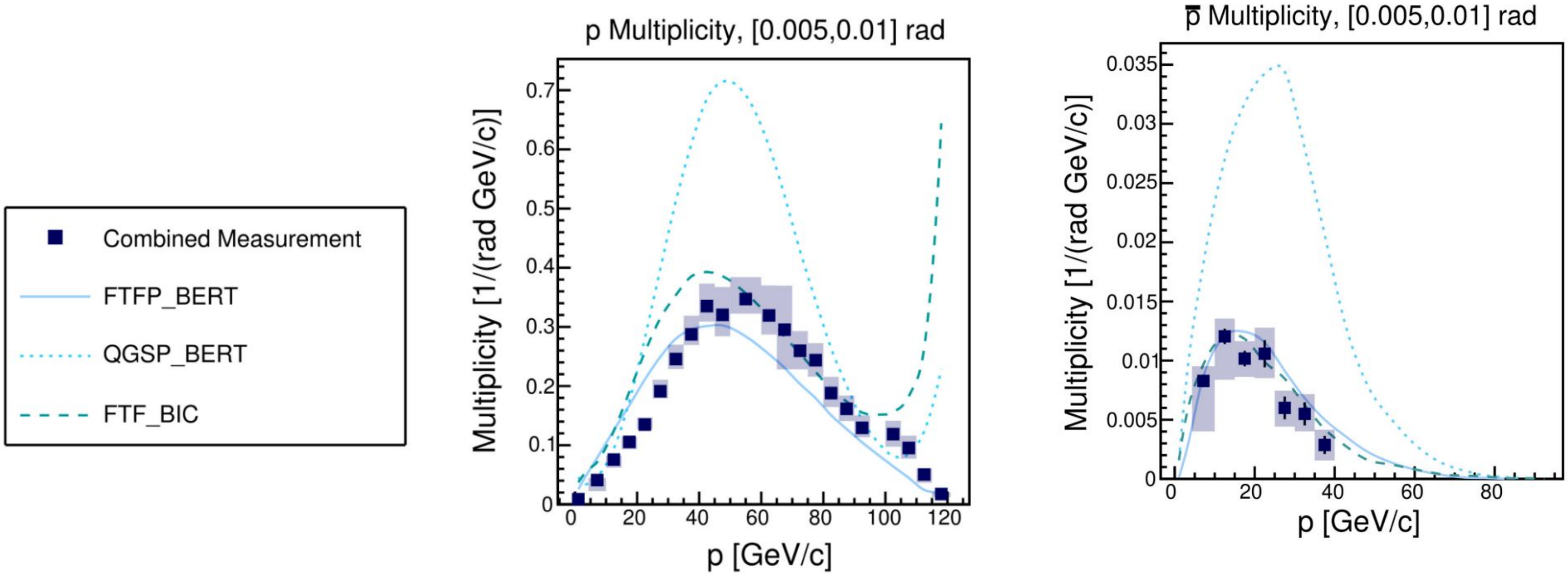

Phys.Rev.D 108 (2023) 072013

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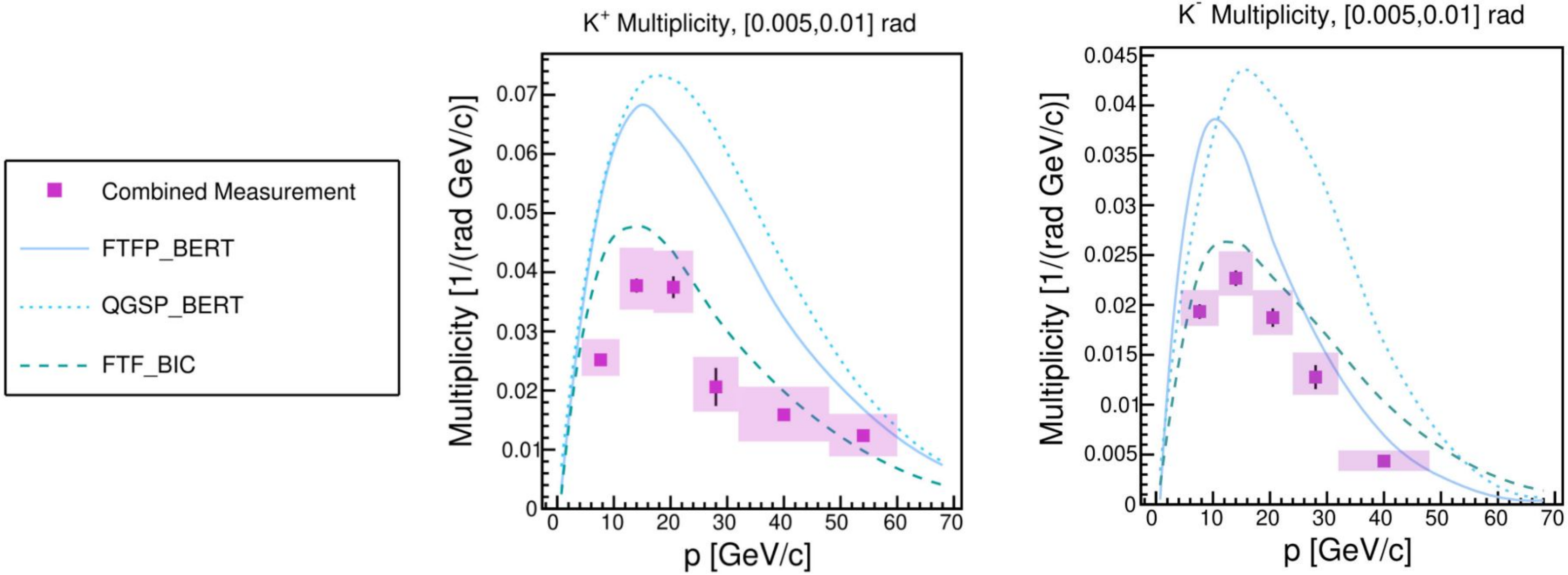
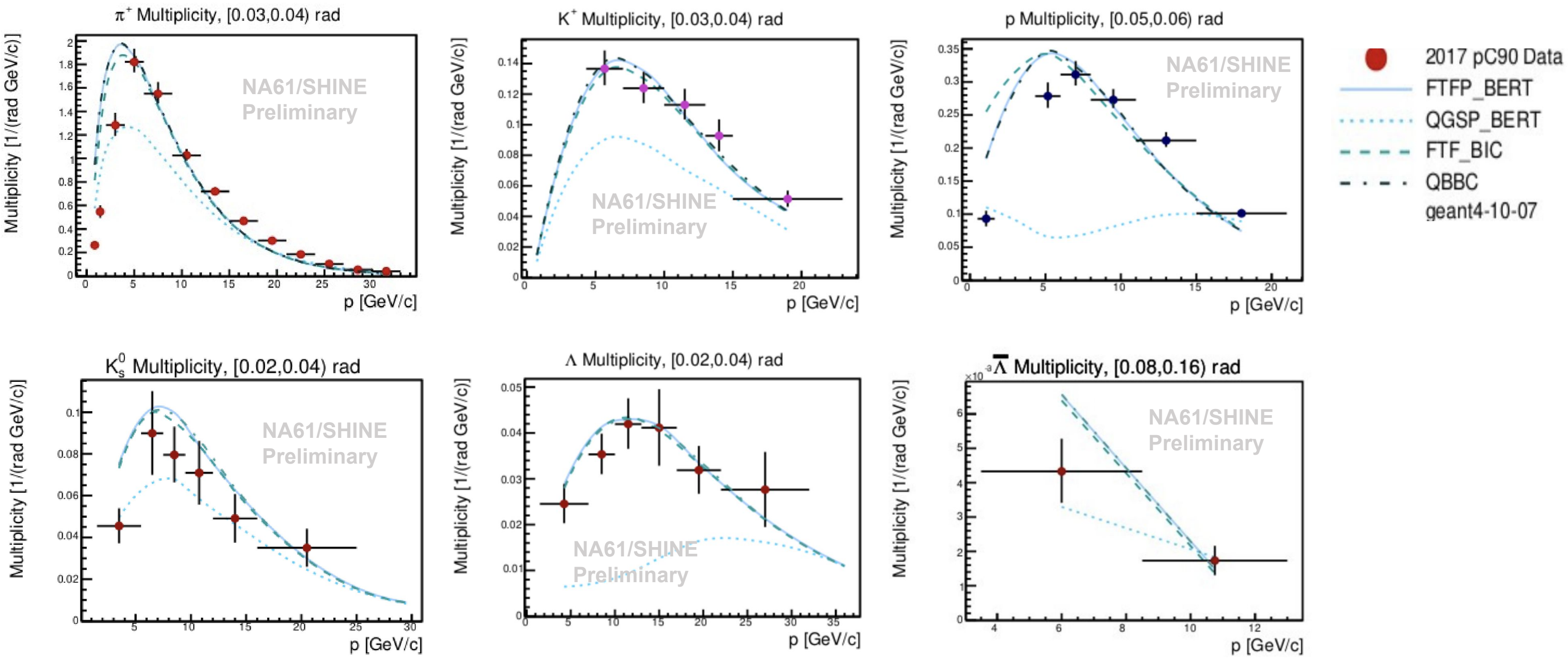


[Phys.Rev.D 108 (2023) 072013]

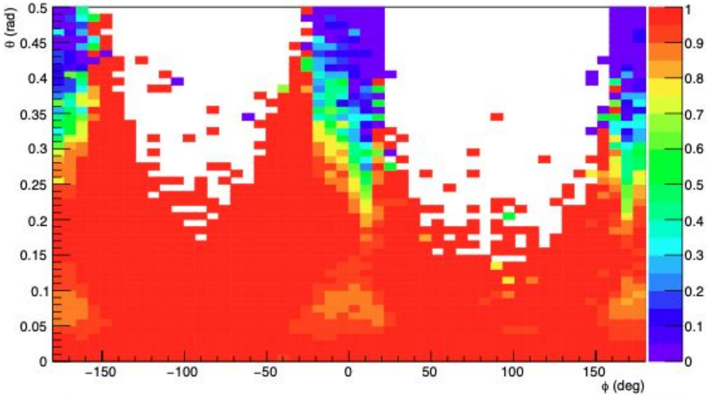
Measurements of p + C at 90 GeV/c

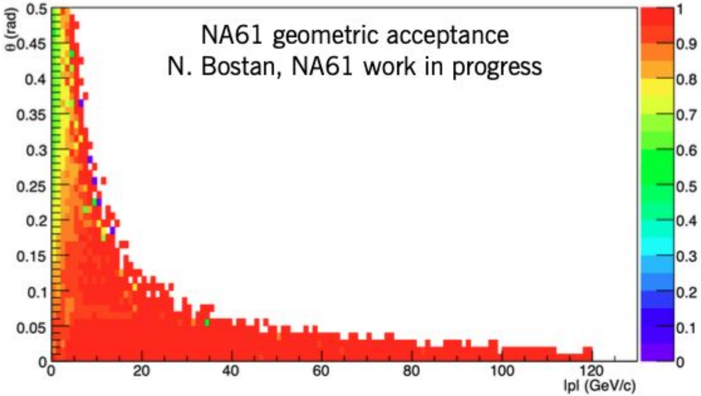


- Similar measurements using 60 GeV/c p + C data are ongoing

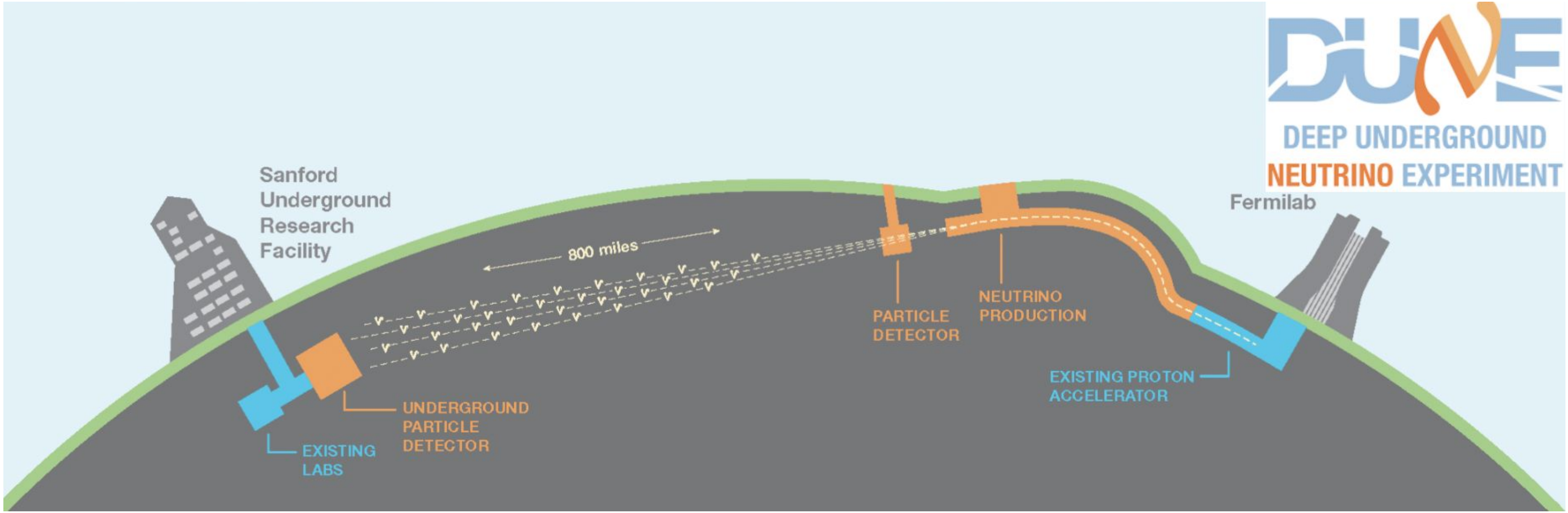
Measurements with NuMI Replica Target

- High statistics dataset collection in 2018
- Proton at 120 GeV/c
- Calibration is underway
- Main challenge
  - Complicated target geometry
  - Asymmetry in ϕ
- Measurement of differential hadron production
  - In similar way as T2K replica target measurement



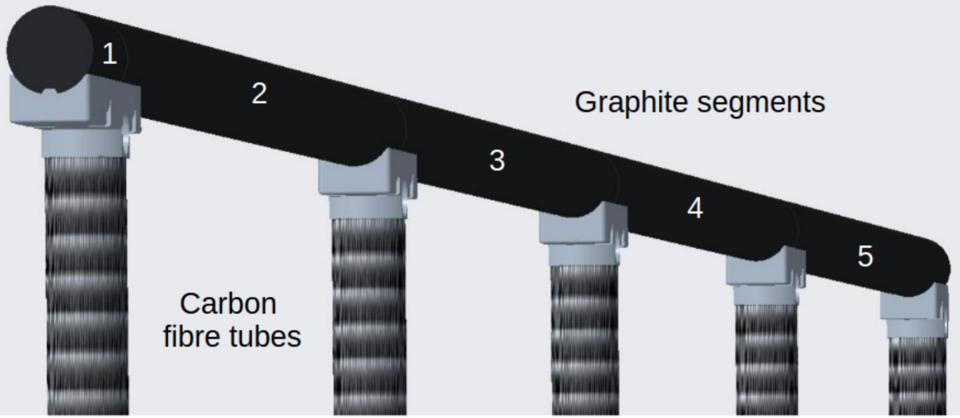


Measurements for the DUNE



Data-taking with LBNF/DUNE Prototype Target

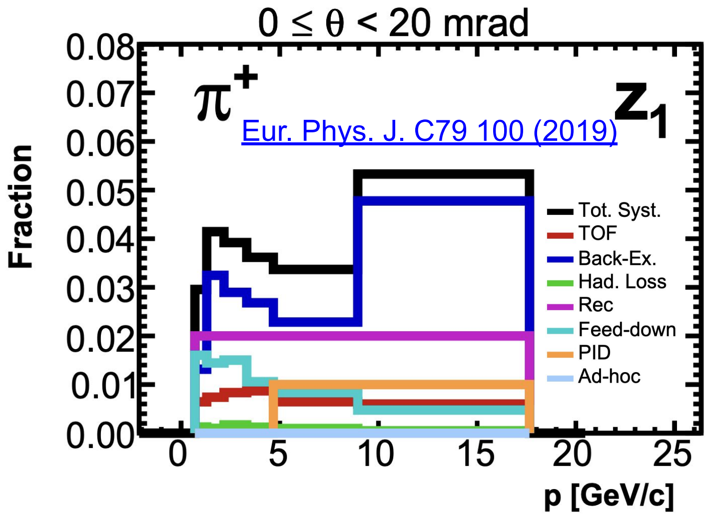
- Data-taking planned in July 2024
- Partial target data-taking in 2025
- 120 GeV/c proton beam
- 1.5-m long LBNF/DUNE prototype target
- Measurement of differential hadron production yields

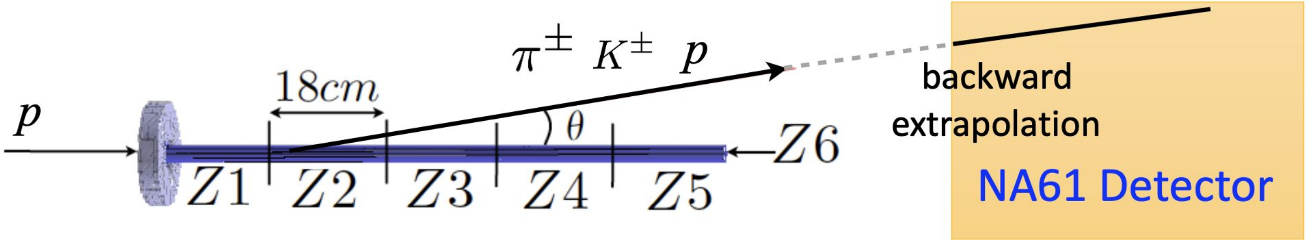


Data-taking with LBNF/DUNE Prototype Target

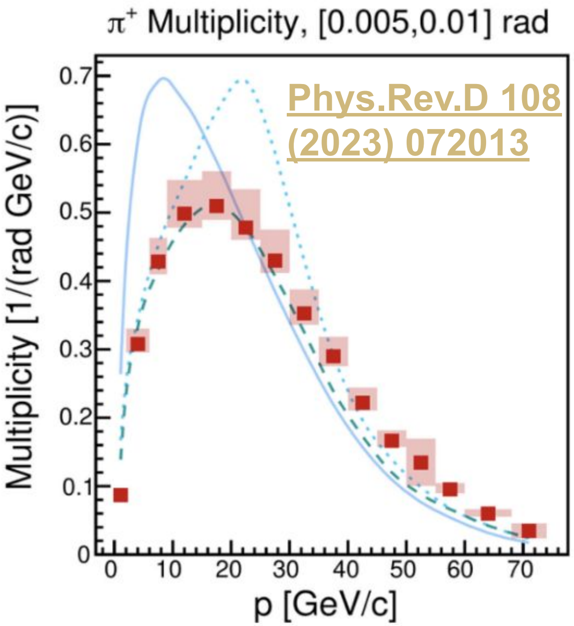
- Leading systematic uncertainty in the T2K replica target measurement is **extrapolation of shallow-angle tracks backward to the target surface**

- Long Target Tracker under development at KFKI/ Wigner in Budapest

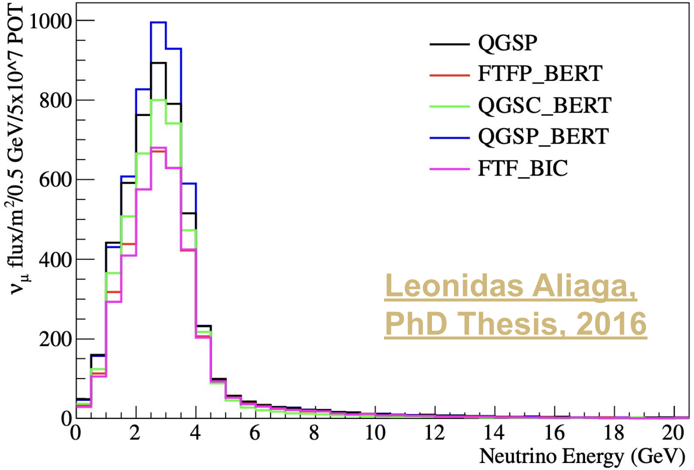




How will NA61/SHINE Results be Applied?



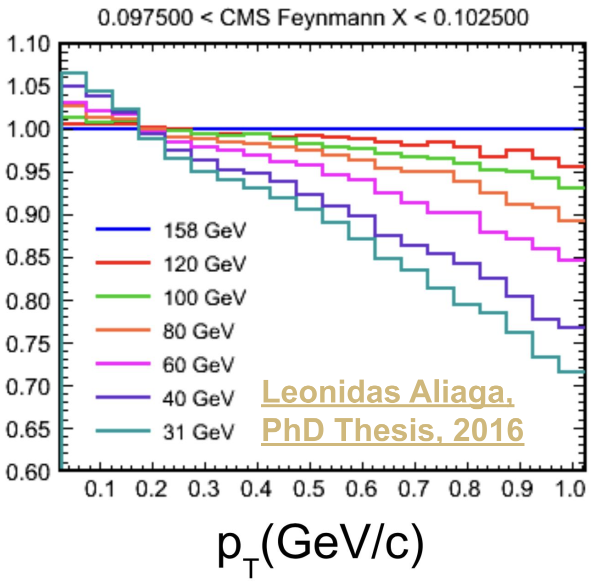
Phys.Rev.D 108 (2023) 072013



Leonidas Aliaga, PhD Thesis, 2016

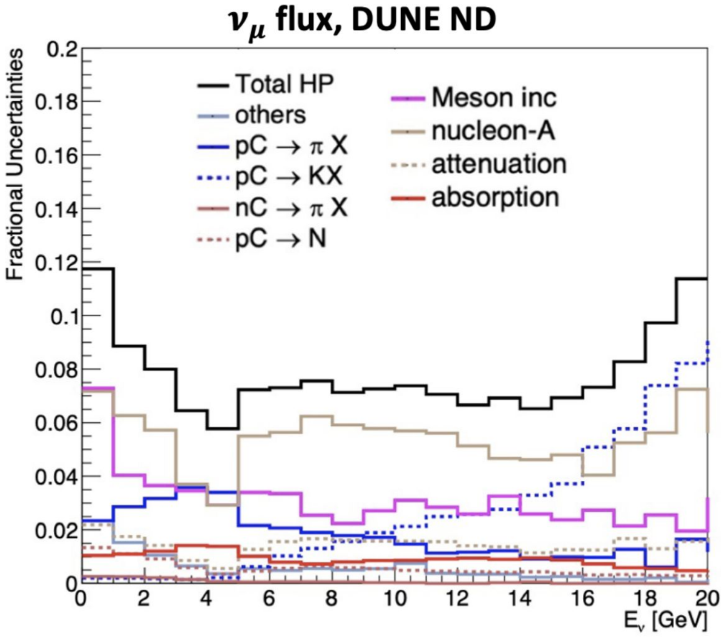
Package to Predict Flux (PPFX)

- 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 propagate uncertainties
  - Uses external hadron production data
    - Mainly NA49 p + C @ 158 GeV/c
      - Scaled to lower momenta using FLUKA
- Both charged and neutral measurements of NA61/SHINE proton + carbon @ 120 GeV/c data are being added in PPFX



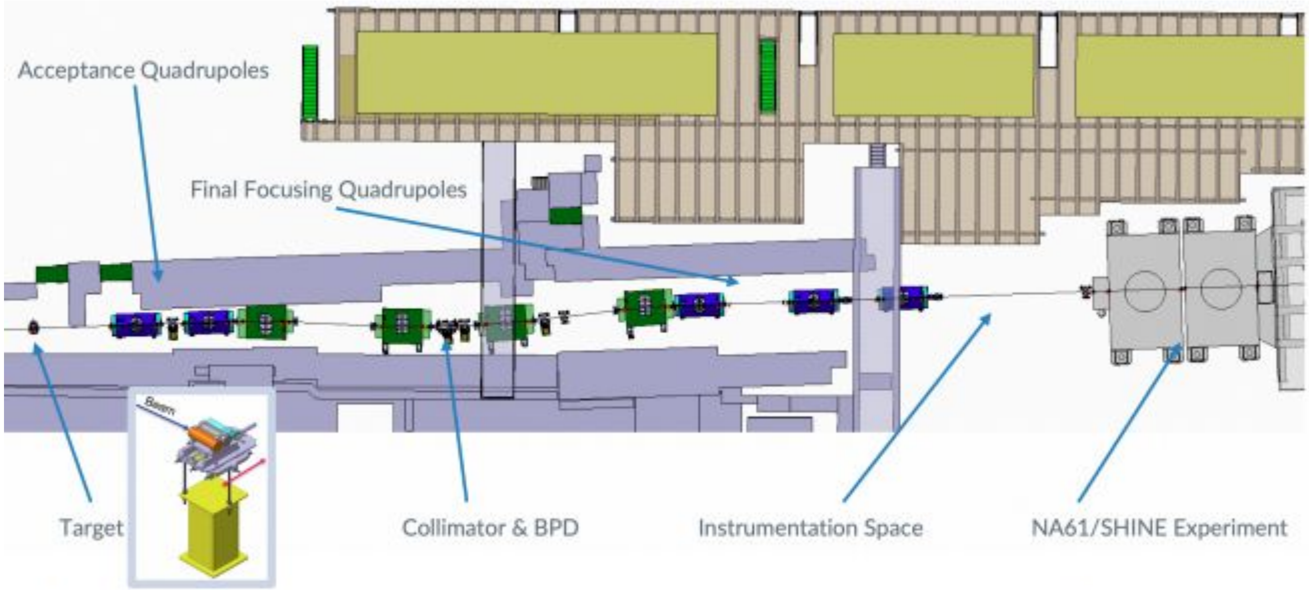
DUNE Near Detector Flux Uncertainty

- Hadron production uncertainty that will be covered by NA61/SHINE
  - Pion production (proton + carbon)
  - Kaon production (proton + carbon)
  - Pion production (neutron + carbon)
  - Nucleon production (proton + carbon)
  - Nucleon incident interactions
- Please expect the updated flux uncertainty in the coming months!



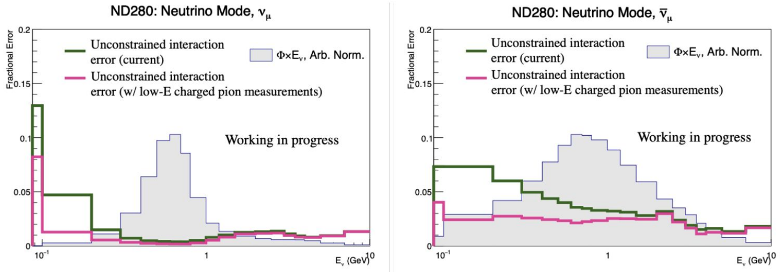
Post-LS3 (2027-)

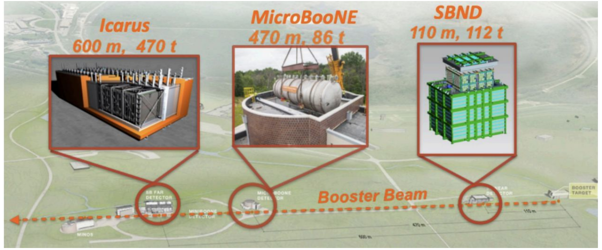
- A low-energy (2-13 GeV/c) beam designed by CERN beam group
- Beam may be available after CERN's Long Shutdown 3 (LS3)

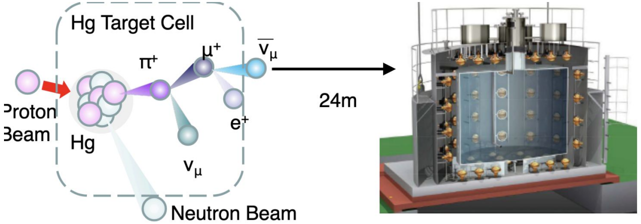


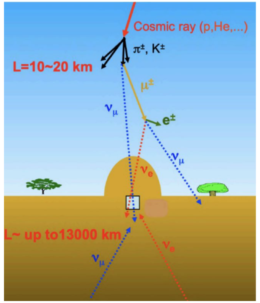
Physics Motivations of the Low-energy Beam

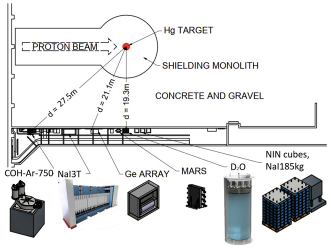
- Accelerator-based neutrino experiments
  - T2K, Hyper-K (pion at 2 GeV, 8 GeV)
  - LBNF/DUNE
  - Short-baseline Neutrino Program (proton at 8 GeV)
- Atmospheric neutrino experiments
  - sub-GeV neutrinos at Super-K, Hyper-K, DUNE
- Spallation neutron source neutrino experiments
  - JSNS^2 (proton at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

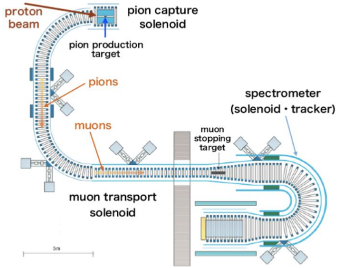






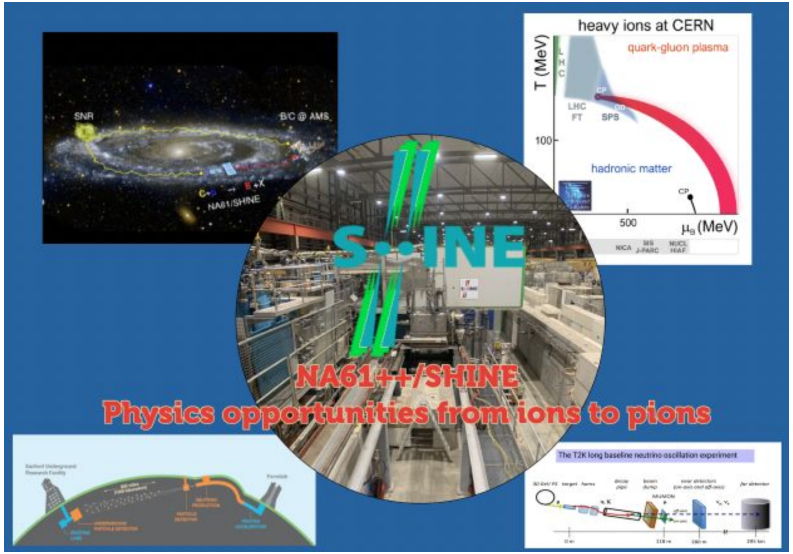






NA61++/SHINE

- Workshop focused on the physics program for the NA61/SHINE after LS3
  - https://indico.cern.ch/event/1174830/
- We are still seeking new ideas and new collaborators.



Summary

- NA61/SHINE provides unique hadron production measurements to support the accelerator-based neutrino experiments
  - Greatly reduced T2K flux uncertainty
  - Recent results will benefit neutrino experiments at Fermilab
- DUNE prototype target data taking planned this year
- Many exciting opportunities after LS3 (2027-)
- **We welcome new collaborators!**

Thank you!

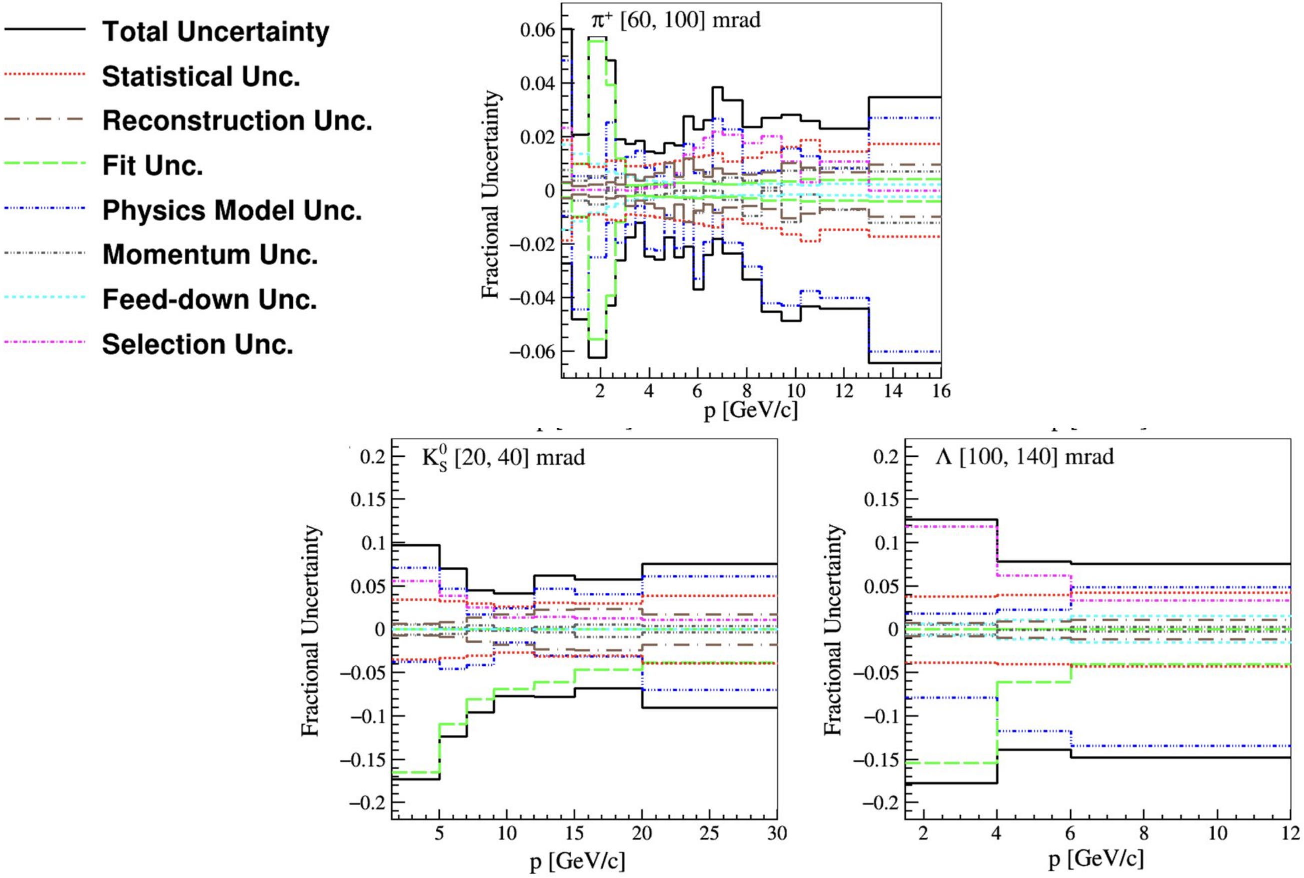
Backup

Total XSec Uncertainty

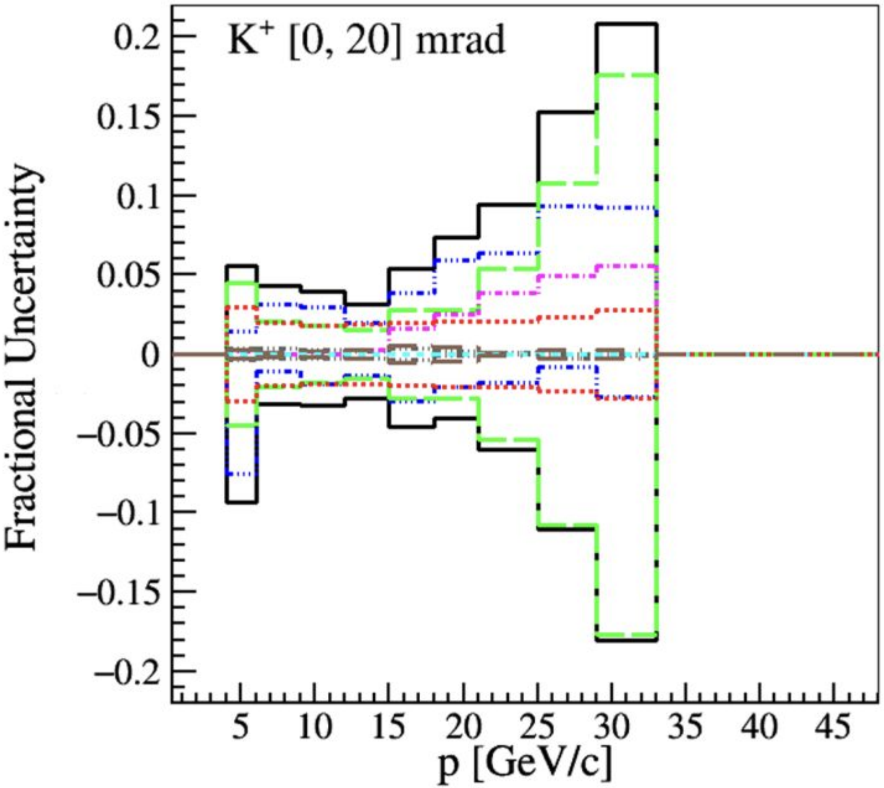
Interaction	p (GeV/c)	Production cross section (mb)					
		σ_{prod}	Δ_{stat}	Δ_{syst}	Δ_{model}	Δ_{total}	$\frac{\sigma_{prod}}{\sigma_{G4}}$
p + C	60	226.9	±3.1	$\pm^{2.6}_{2.9}$	$\pm^{0.2}_{4.8}$	$\pm^{4.1}_{6.4}$	1.05
p + Be	60	185.3	±4.9	$\pm^{1.1}_{1.5}$	$\pm^{0.0}_{5.2}$	$\pm^{5.0}_{7.3}$	1.03
p + Al	60	409.3	±7.8	$\pm^{3.0}_{5.1}$	$\pm^{0.2}_{8.4}$	$\pm^{8.4}_{12.5}$	1.05
p + C	120	227.1	±3.4	$\pm^{2.5}_{3.5}$	$\pm^{0.0}_{12.2}$	$\pm^{4.2}_{13.1}$	1.07
p + Be	120	190.8	±3.7	$\pm^{1.7}_{1.8}$	$\pm^{0.1}_{14.3}$	$\pm^{4.1}_{14.9}$	1.04

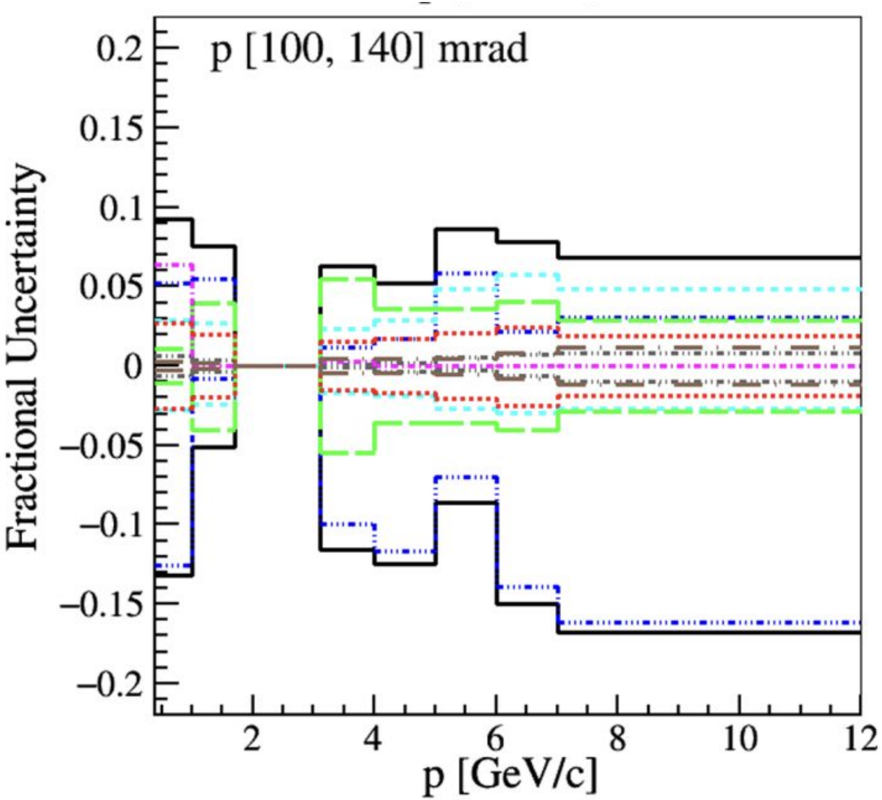
Interaction	p (GeV/c)	Inelastic cross section (mb)					
		σ_{inel}	Δ_{stat}	Δ_{syst}	Δ_{model}	Δ_{total}	$\frac{\sigma_{inel}}{\sigma_{G4}}$
p + C	60	252.6	±3.2	$\pm^{2.5}_{2.9}$	$\pm^{0.0}_{4.8}$	$\pm^{4.1}_{6.5}$	1.05
p + Be	60	207.8	±5.0	$\pm^{1.2}_{1.4}$	$\pm^{0.0}_{4.3}$	$\pm^{5.1}_{6.7}$	1.03
p + Al	60	444.5	±7.9	$\pm^{3.0}_{5.1}$	$\pm^{0.0}_{7.0}$	$\pm^{8.5}_{11.7}$	1.05
p + C	120	251.3	±3.6	$\pm^{2.7}_{3.7}$	$\pm^{0.0}_{14.1}$	$\pm^{4.5}_{15.0}$	1.06
p + Be	120	212.5	±3.9	$\pm^{1.9}_{1.8}$	$\pm^{0.2}_{16.0}$	$\pm^{4.3}_{16.6}$	1.04

Pion @ 60 Uncertainty



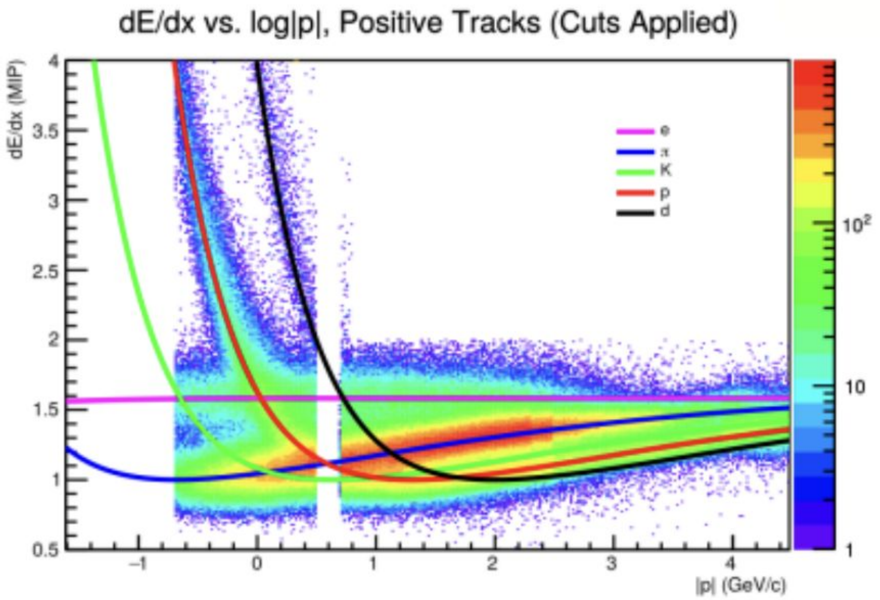
Pion @ 60 Uncertainty

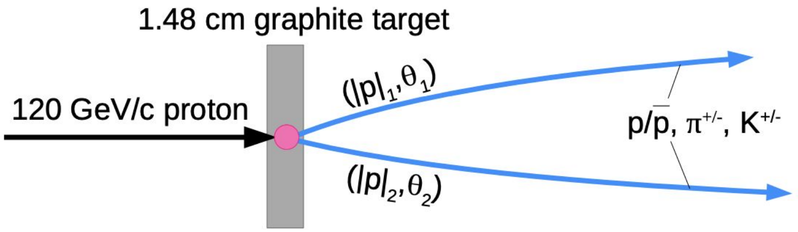




Charged Analysis

- In each kinematic bin, likelihood-based dE/dx fit performed to track dE/dx distribution
- Result: Fraction of e+/- , π+/- , K+/-, p/p, D+/- in each kinematic bin
  - Positive and negative tracks fit simultaneously in order to constrain calibration parameters
- Total number of each species used to calculate identified multiplicity in each bin





Charged Analysis

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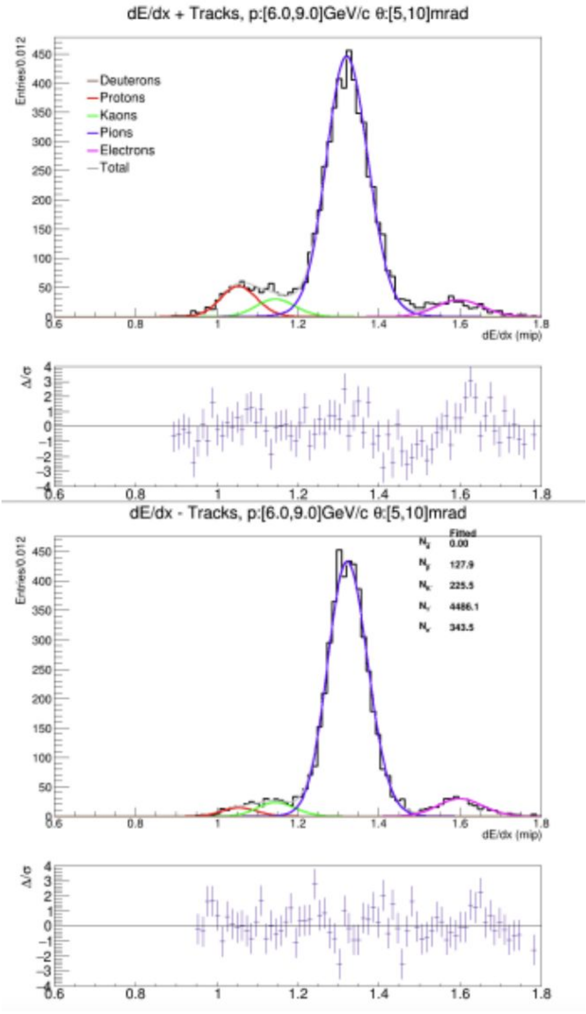
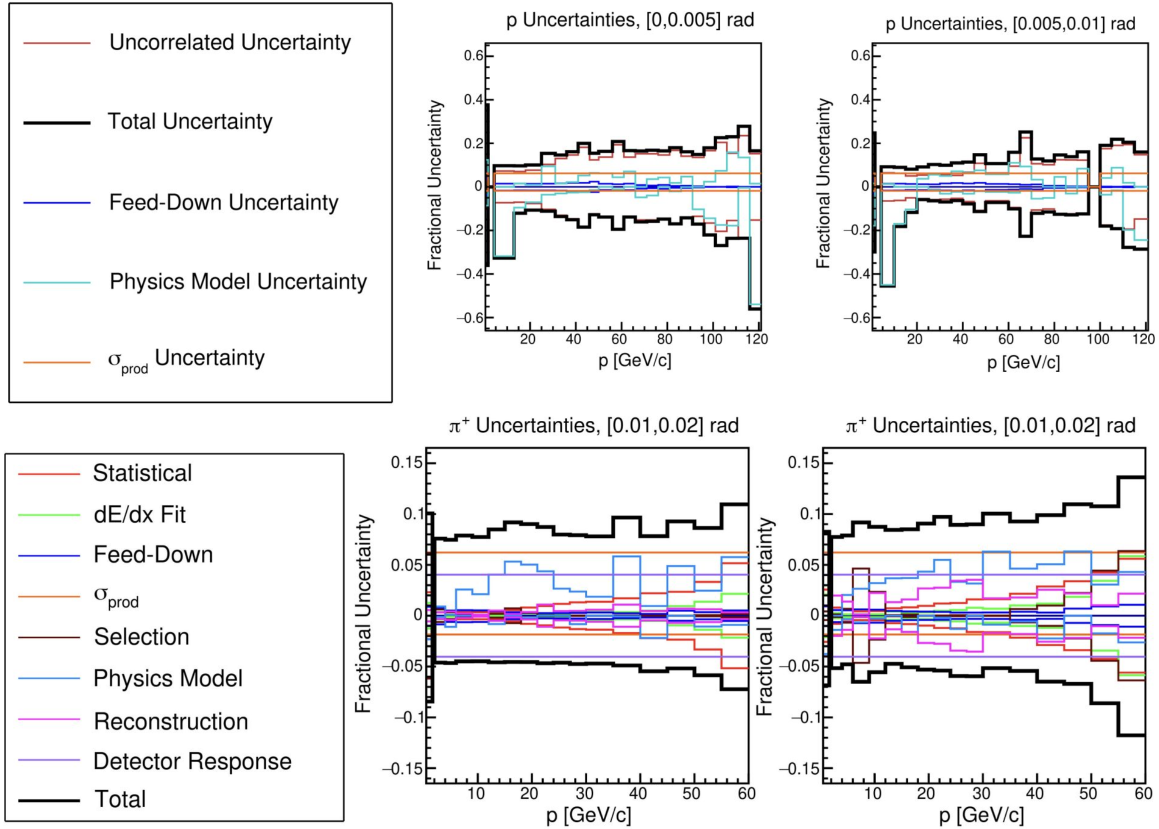
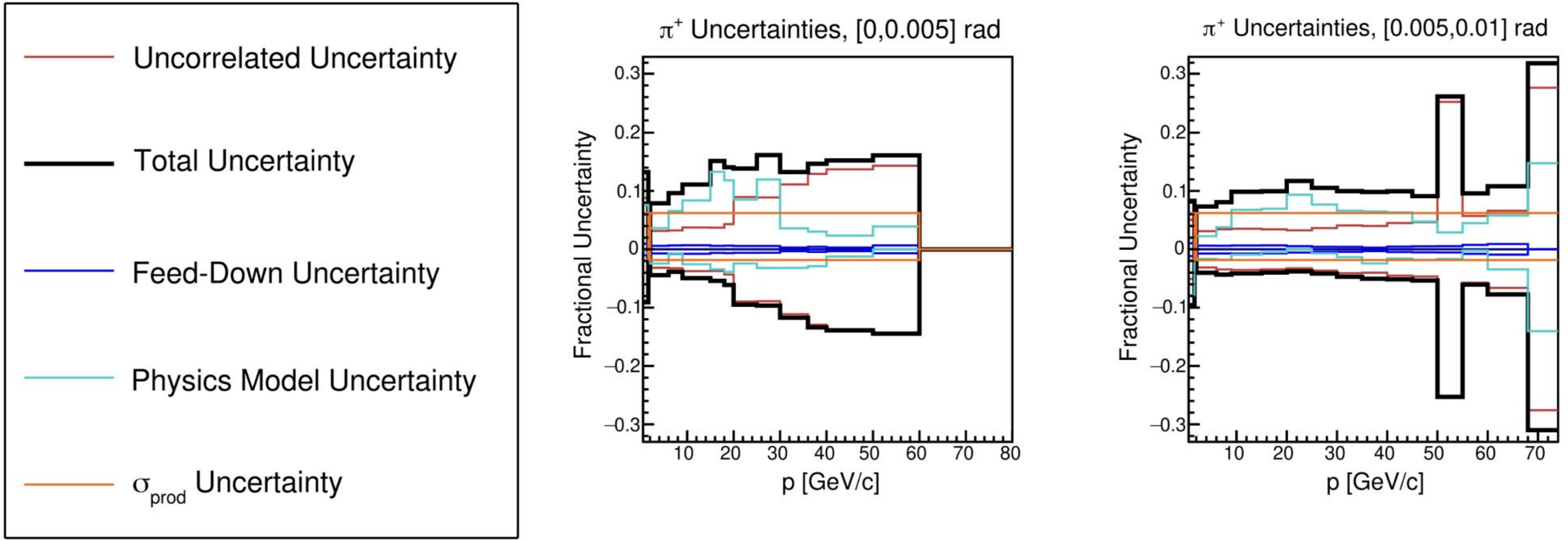


Uncertainty of pC120 Charged Analysis

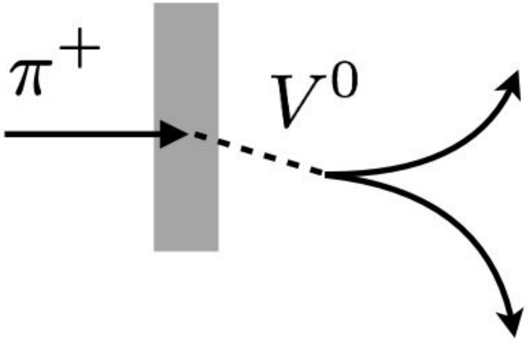


Uncertainty of pC120 Charged Analysis



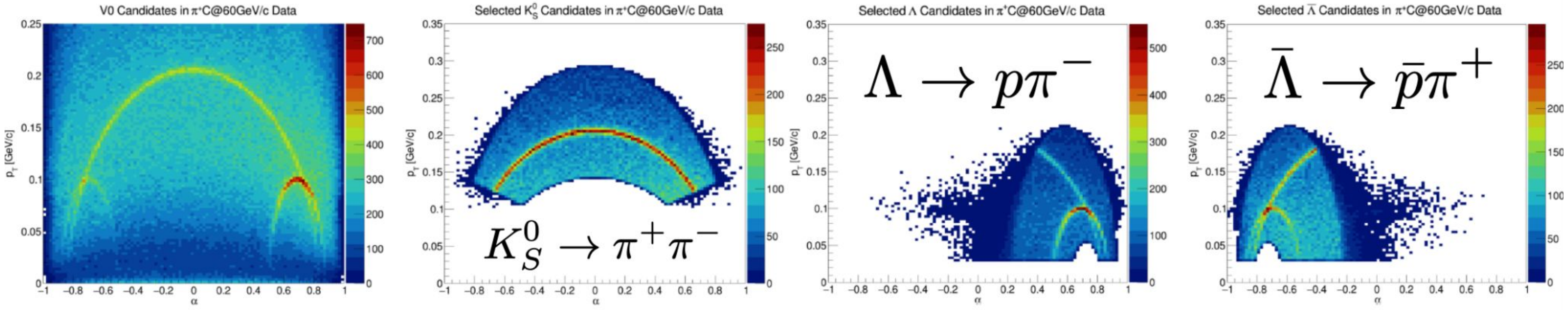
V0 analysis

- Reconstruct collection of V0 candidates using V0 finder & fitter algorithms
- Calculate neutral kinematics using decay product assumption
- Improve purity of V0 sample by applying selection cuts
- Fit invariant mass distributions for signal yield
- Calculate & apply bin-by-bin Monte Carlo corrections
- Calculate multiplicities



V0 analysis

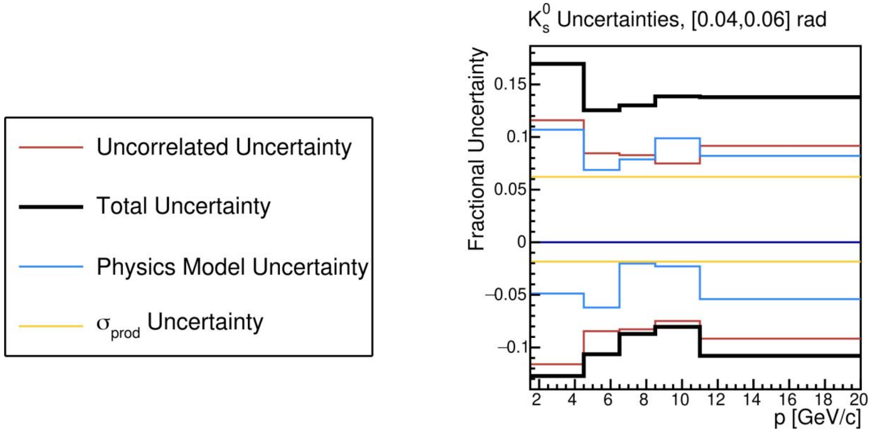
- The Armenteros-Podolansky distribution

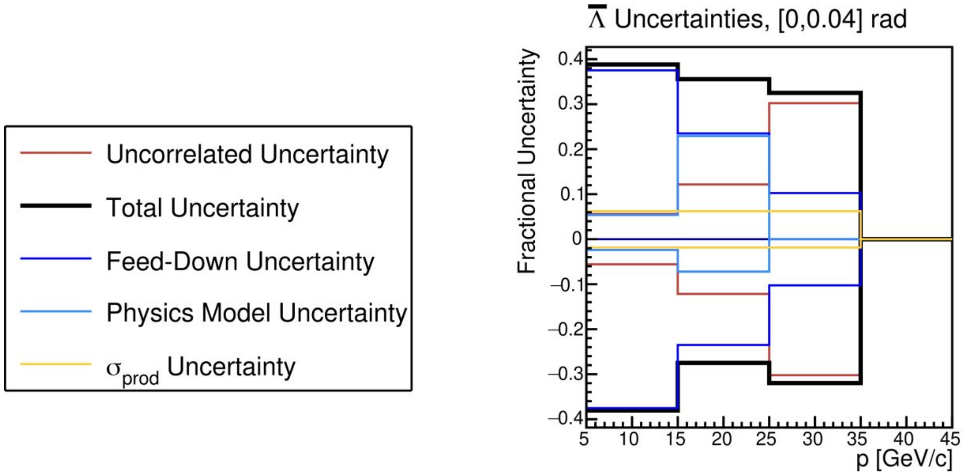


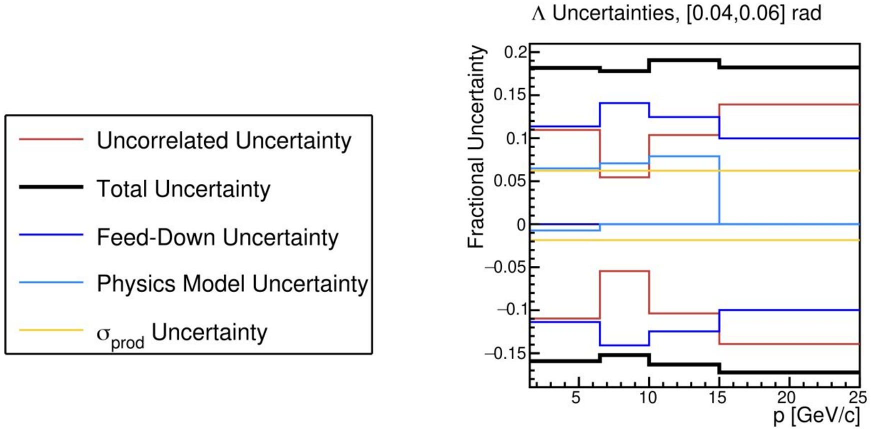
X-axis: $\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$ (Asymmetry in the longitudinal momenta of the child tracks with respect to the V^0 track)

Y-axis: p_T (Transverse momenta of V^0 track)

Uncertainty of pC120 Neutral Analysis



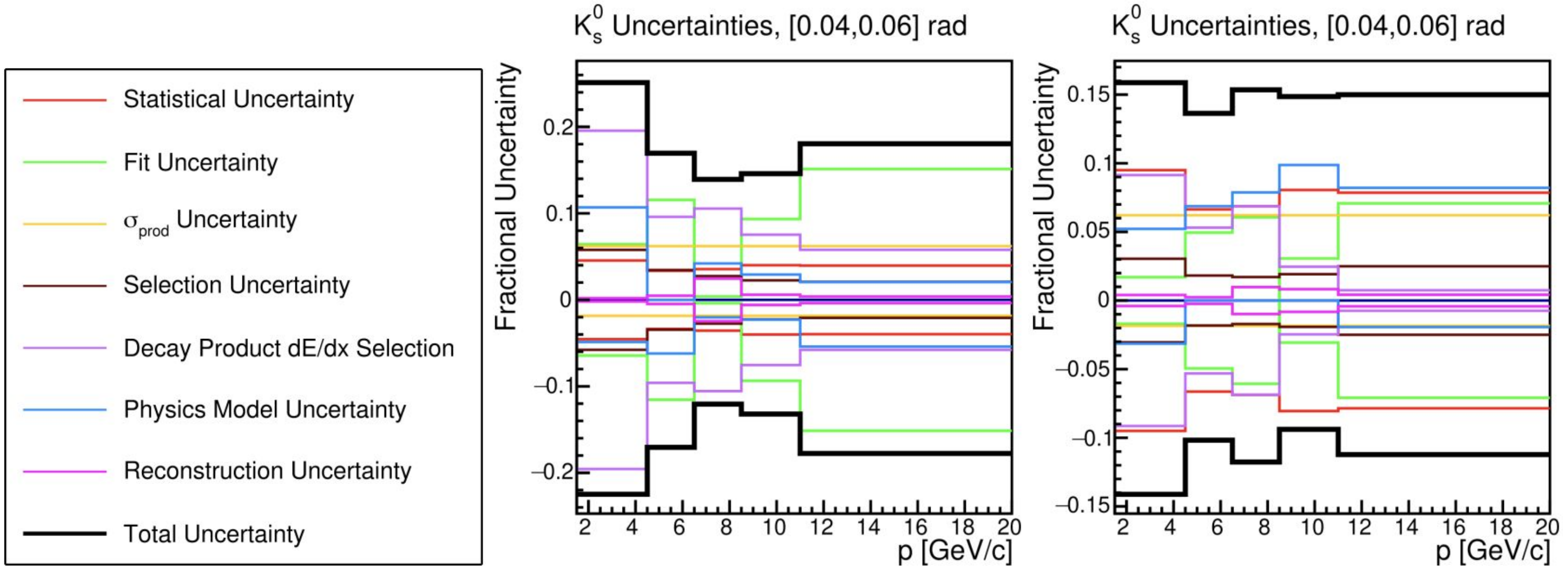




Uncorrelated:
statistical uncertainty, invariant mass fit uncertainty, decay product dE/dx selection uncertainty, reconstruction uncertainty, and V 0 selection uncertainty

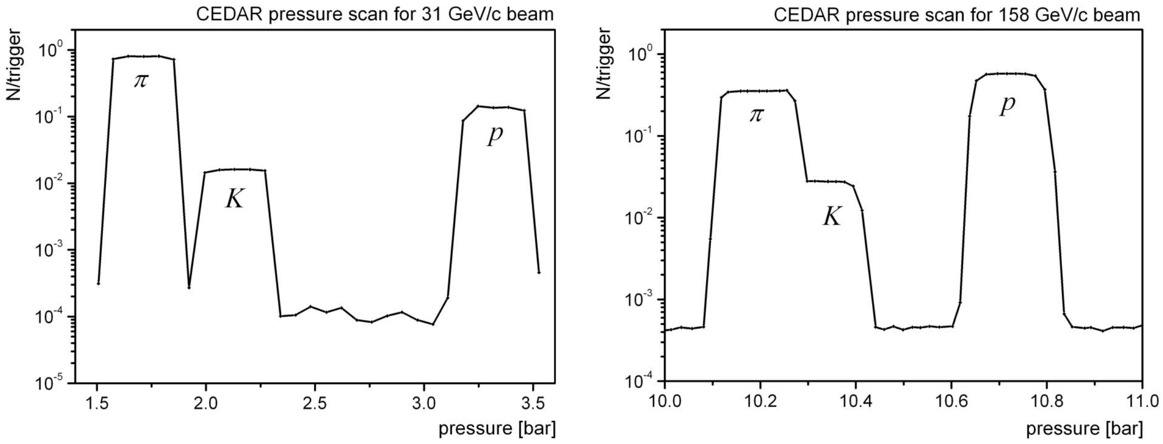
Uncertainty of pC120 Neutral Analysis

$$m_{\text{combined}} = \frac{\frac{m_1}{\sigma_1^2} + \frac{m_2}{\sigma_2^2}}{\frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2}}$$



CEDAR

- Cherenkov Differential Counter with Achromatic Ring Focus (CEDAR) counter
  - Uses a gas as radiator, Helium for beam momenta higher than 60 GeV/c and Nitrogen for lower momenta
  - Sophisticated optical system that collects and focuses the Cherenkov photons onto the plane of a diaphragm whose opening can be tuned
  - For a given gas pressure, such as to allow only the photons from the wanted species to pass through and get detected by the 8 PMTs of the counter



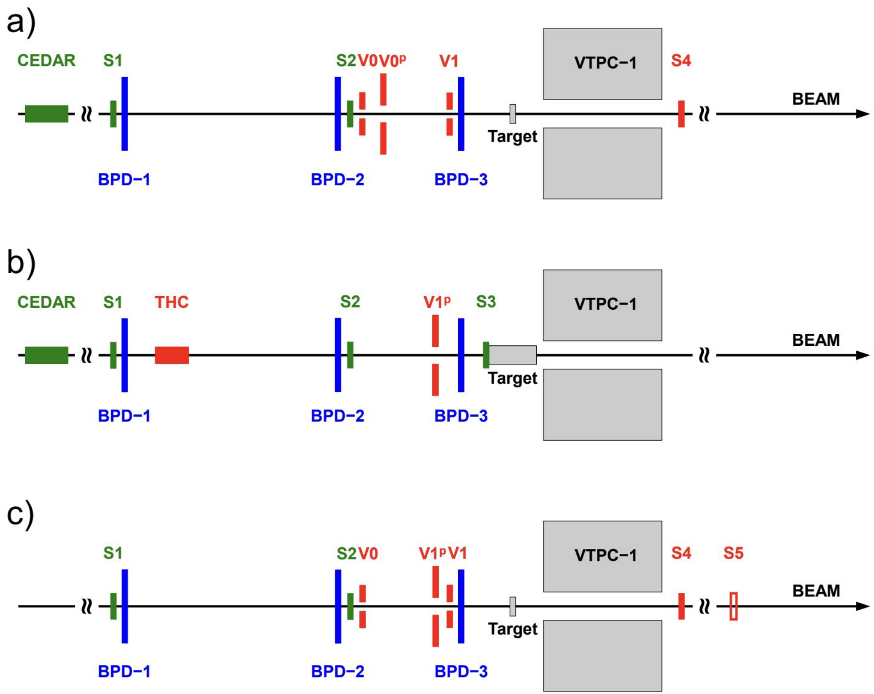
TPCs

	VTPC-1	VTPC-2	MTPC-L/R	GAP-TPC
size (L×W×H) [cm]	250 × 200 × 98	250 × 200 × 98	390 × 390 × 180	30 × 81.5 × 70
No. of pads/TPC	26 886	27 648	63 360	672
Pad size [mm]	3.5 × 28(16)	3.5 × 28	3.6 × 40, 5.5 × 40	4 × 28
Drift length [cm]	66.60	66.60	111.74	58.97
Drift velocity [cm/μs]	1.4	1.4	2.3	1.3
Drift field [V/cm]	195	195	170	173
Drift voltage [kV]	13	13	19	10.2
gas mixture	Ar/CO_2 (90/10)	Ar/CO_2 (90/10)	Ar/CO_2 (95/5)	Ar/CO_2 (90/10)
# of sectors	2 × 3	2 × 3	5 × 5	1
# of padrows	72	72	90	7
# of pads/padrow	192	192	192, 128	96

Beam Counters

- T1 (identified beam): S1*S2*V1_bar*CED6
- T2 (beam interaction): T1*S4_bar
- T3 (unidentified beam): S1*S2*V1_bar
- T4 (unidentified interaction): T3*S4_bar

detector	dimensions [mm]	hole [mm]	position [m]	material budget $[\%\lambda_I]$	$[\%X_0]$
S1	$60\times60\times5$		-36.42	0.635	1.175
S2	$\phi=28\times2$		-14.42	0.254	0.470
S3	$\phi=26\times5$		-6.58	0.635	1.175
S4	$\phi=20\times5$		-2.11	0.635	1.175
S5	$\phi=20\times5$		9.80	0.635	1.175
V0	$\phi=80\times10$	$\phi=10$	-14.16		
$V0^p$	$300\times300\times10$	$\phi=20$	$\approx$ -14		
V1	$100\times100\times10$	$\phi=8$	-6.72		
$V1^p$	$300\times300\times10$	$\phi=20$	-6.74		
A	$150\times5\times15$		$\approx$ -146	1.904	3.526
Z	$160\times40\times2.5$		-13.81	0.562	2.034
BPD-1	$48\times48\times32.6$		-36.20	0.025	0.070
BPD-2	$48\times48\times32.6$		-14.90	0.025	0.070
BPD-3	$48\times48\times32.6$		-6.70	0.025	0.070
Typical thin target position			-5.81		



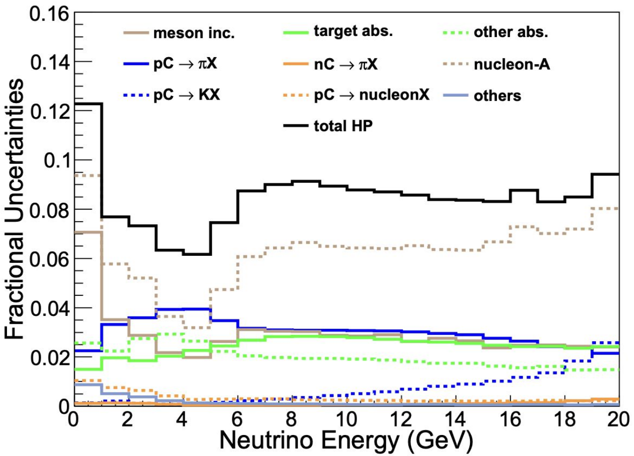
Data available in PPFX

- 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.

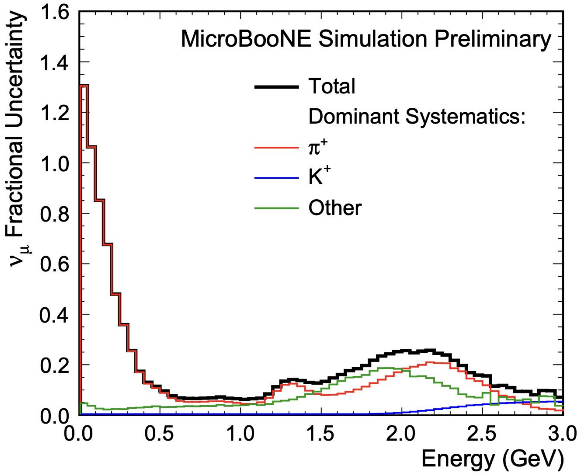
Detailed descriptions in Section 4.3.-4.5 of Leo's thesis)

Flux Uncertainty

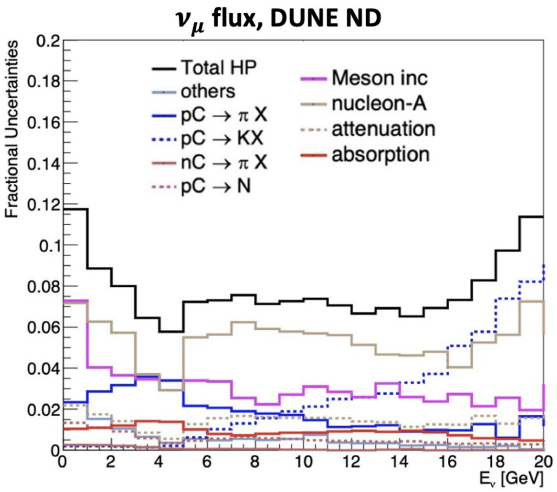
- Neutrino flux uncertainty limits the precision of measurements in all accelerator-based neutrino experiments



MINERvA at NuMI beamline



MicroBooNE at Booster Neutrino Beam



Nilay Bostan, Neutrino 2022

Nucleon-A

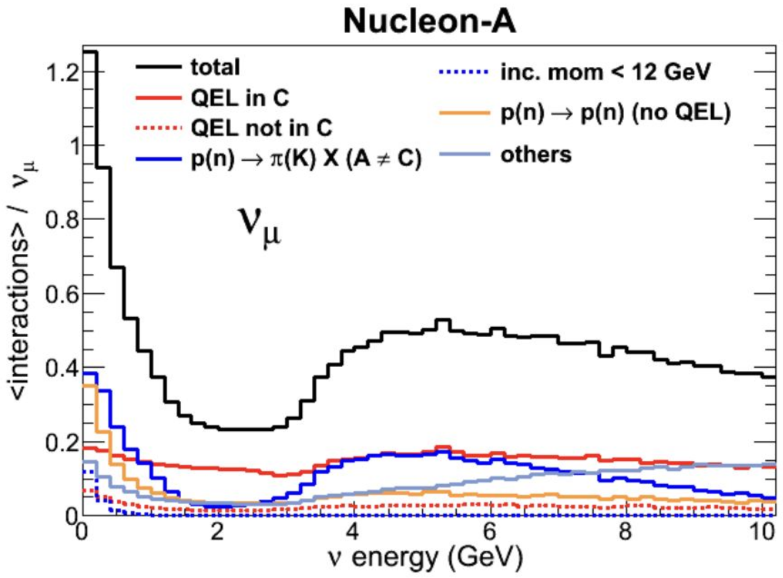
» **Quasi-elastic interactions**, selected as $x_F > 0.95$

- We assign a 40% uncertainty

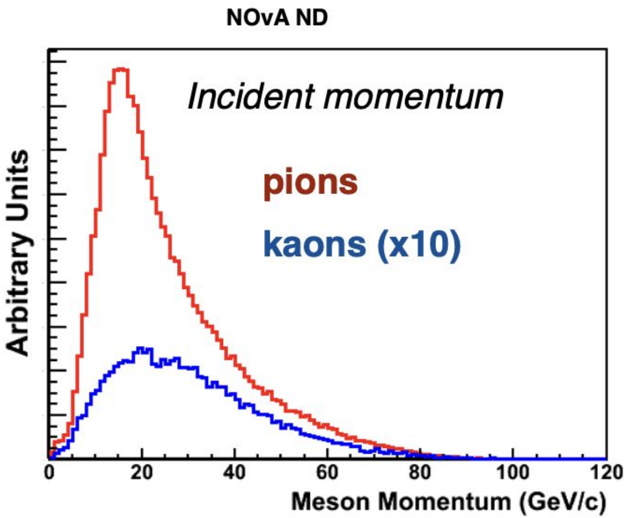
» **Extension of NA49**.

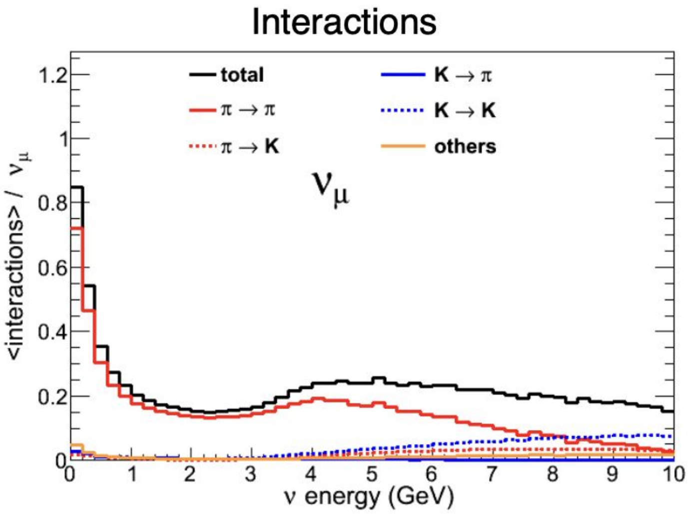
- We extend NA49 to other materials than carbon adding an additional uncertainty.

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



Incident meson

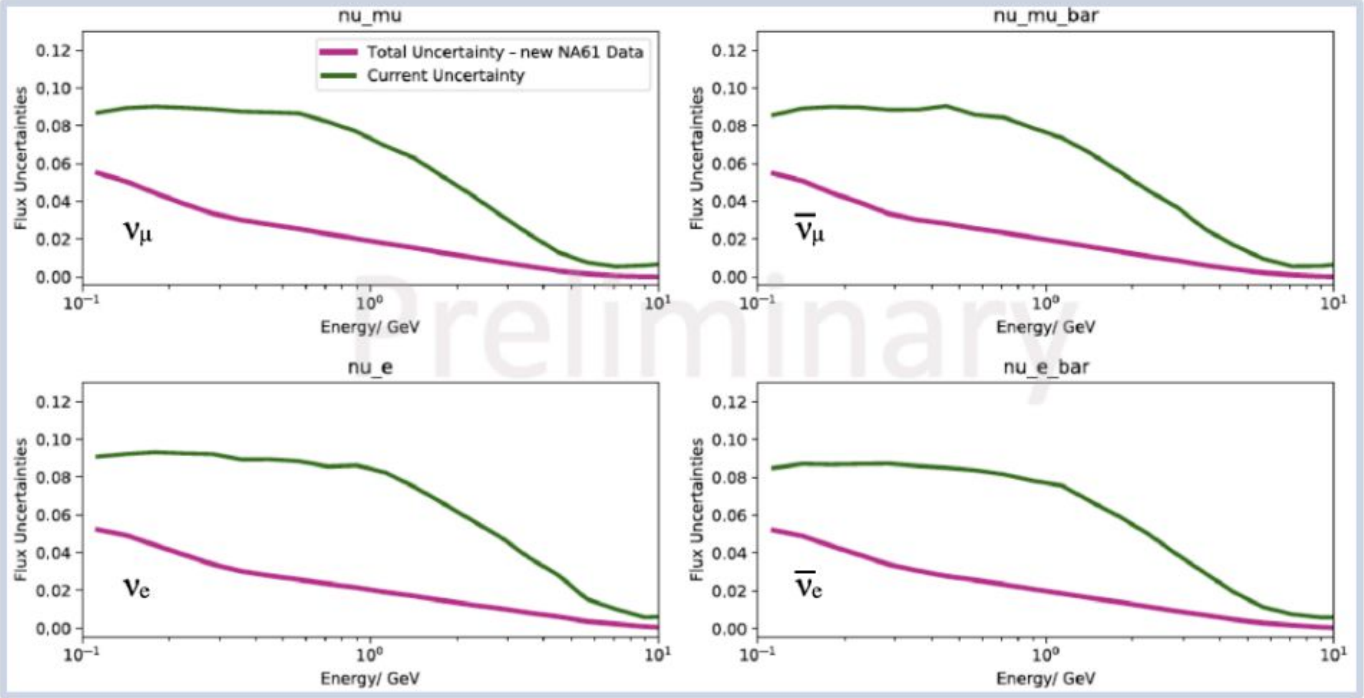




Main contribution from π ⟶ π in the whole neutrino energy spectrum

Atmospheric neutrino

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



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