NA61/SHINE Hadron Production Measurements

Andrew Olivier
On behalf of the NA61/SHINE collaboration
April 16, 2024

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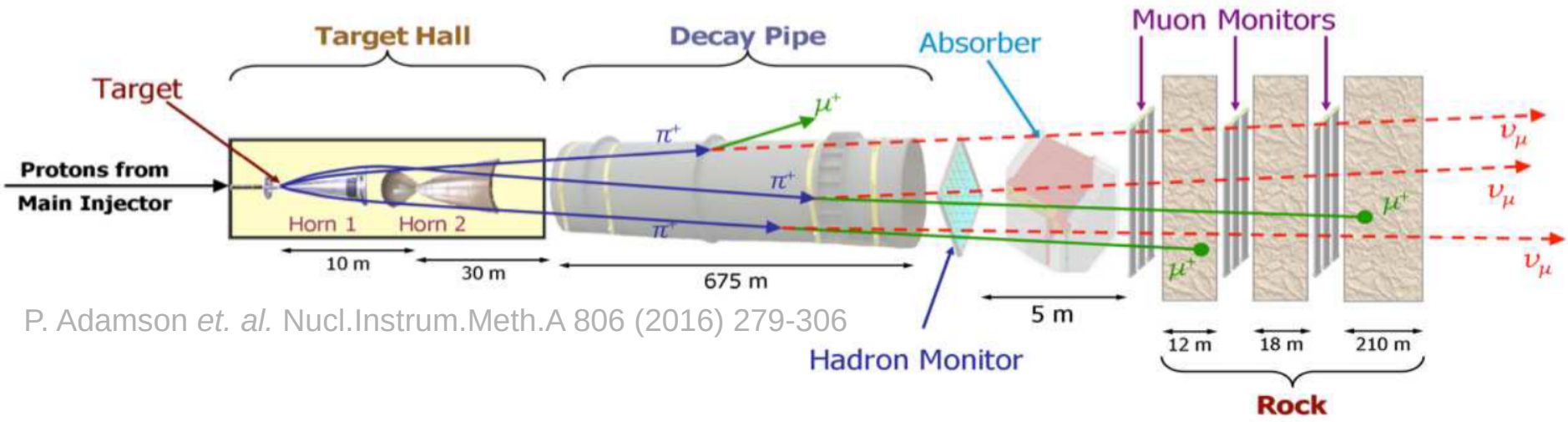
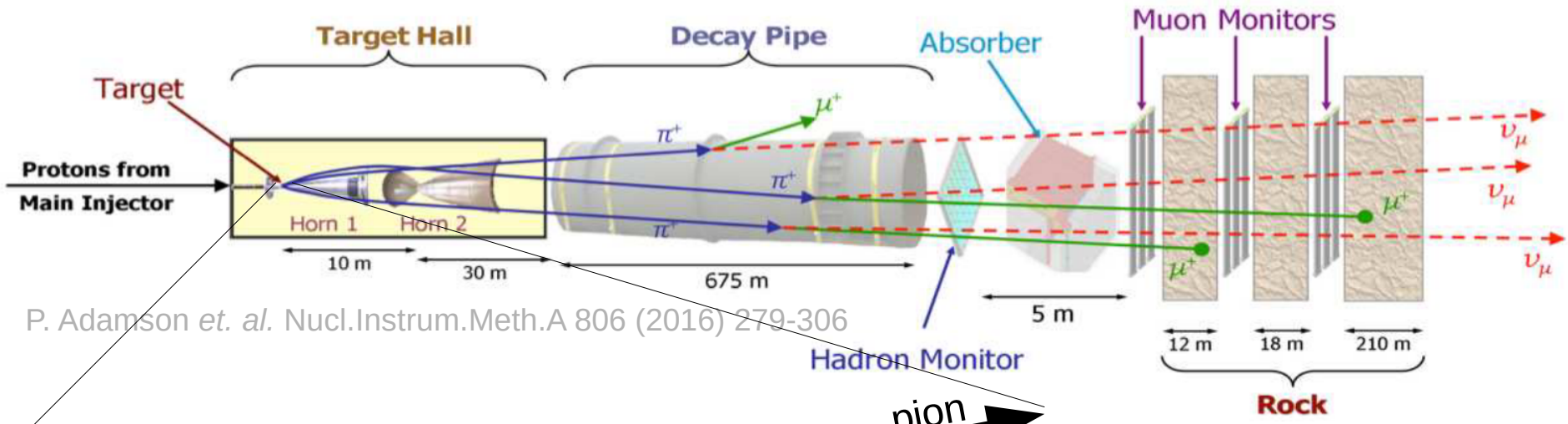
Neutrino Beams



P. Adamson *et. al.* Nucl.Instrum.Meth.A 806 (2016) 279-306

- Current conventional neutrino beams produced by:
  - Intense proton beam hits target
  - Pions and kaons produced
  - Charged mesons focused with magnetic horns
  - Mesons decay to charged leptons and neutrinos

Neutrino Beam Simulation



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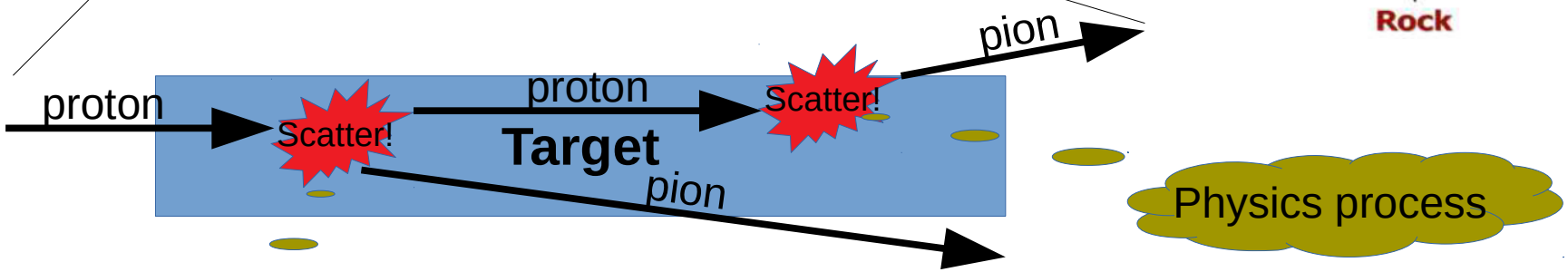

- Physics process:
  - Cross section → mean free path
  - Particles produced
  - Kinematics

Neutrino Beam Simulation

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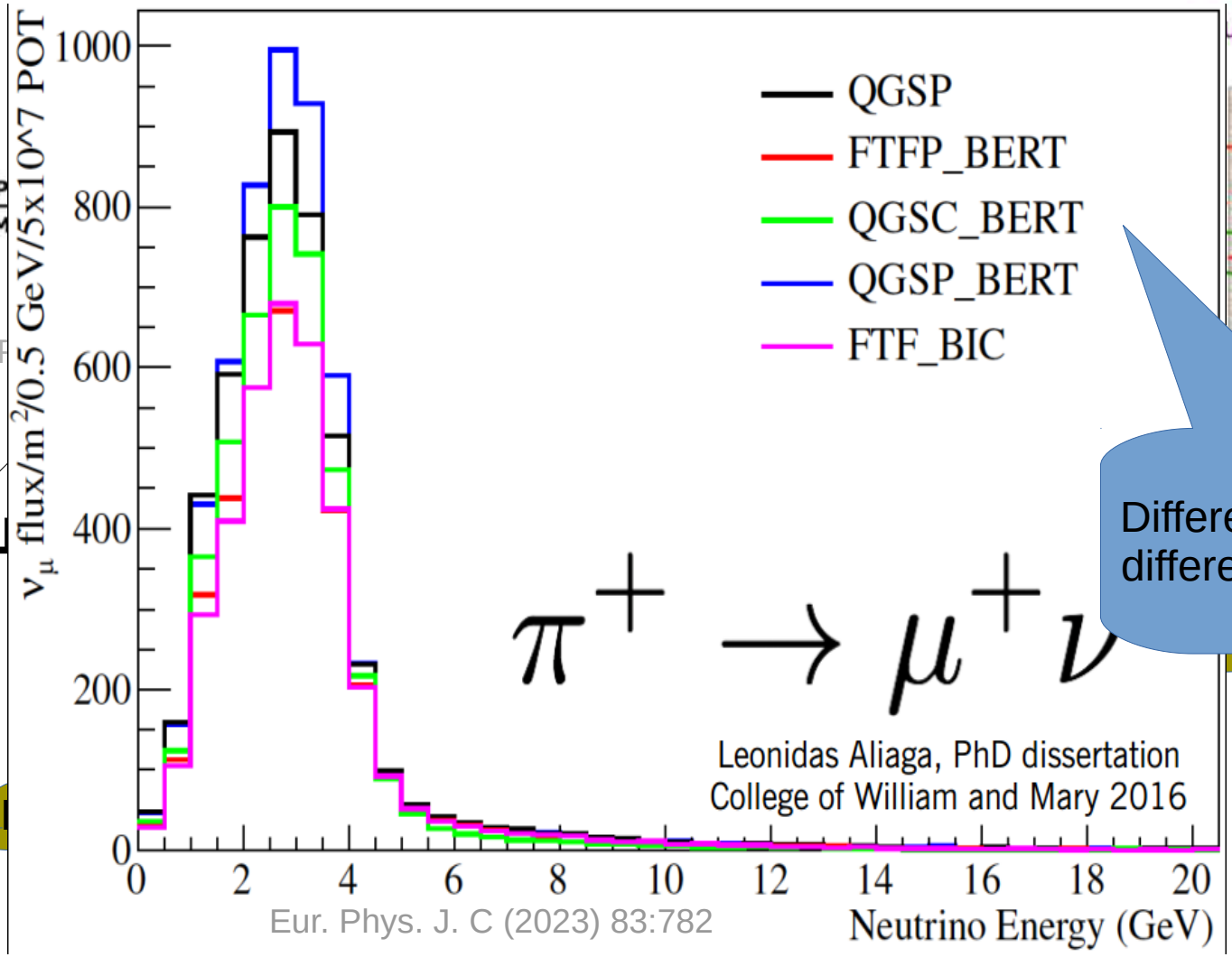
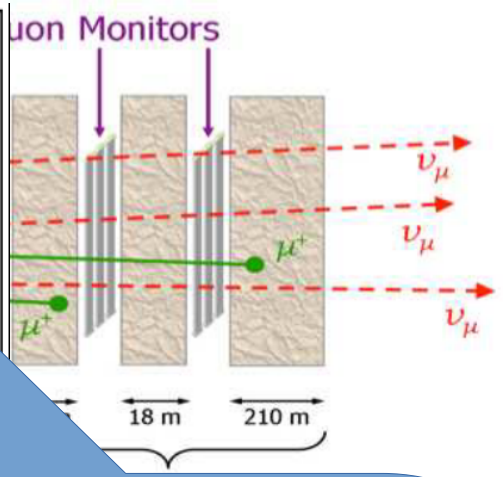


Eur. Phys. J. C (2023) 83:782



Different **cross sections** = different **beam** predictions!

path

- Kinematics

Hadron Production Experiments

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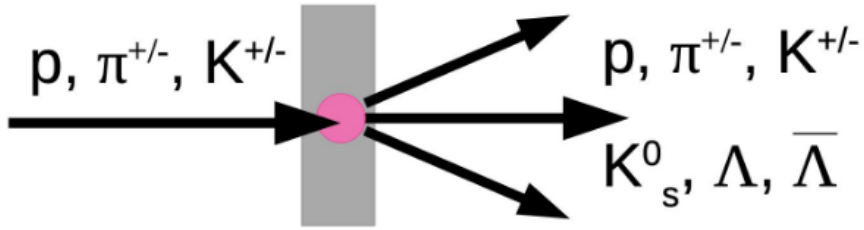
- Measure inputs to “physics process”
- Thin target
  - Proton on Carbon, etc.
  - Inelastic and production cross sections
  - Differential production yields
  - Tune e.g. GEANT models
- Replica target
  - Proton on e.g. replica NuMI target
  - Differential production yields for each species
  - Directly predict particle rates from target



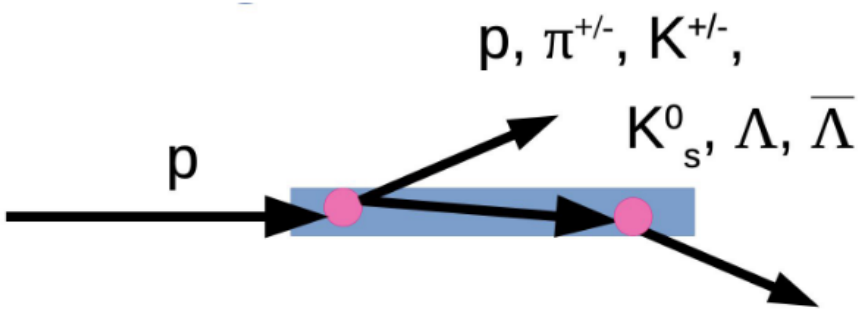
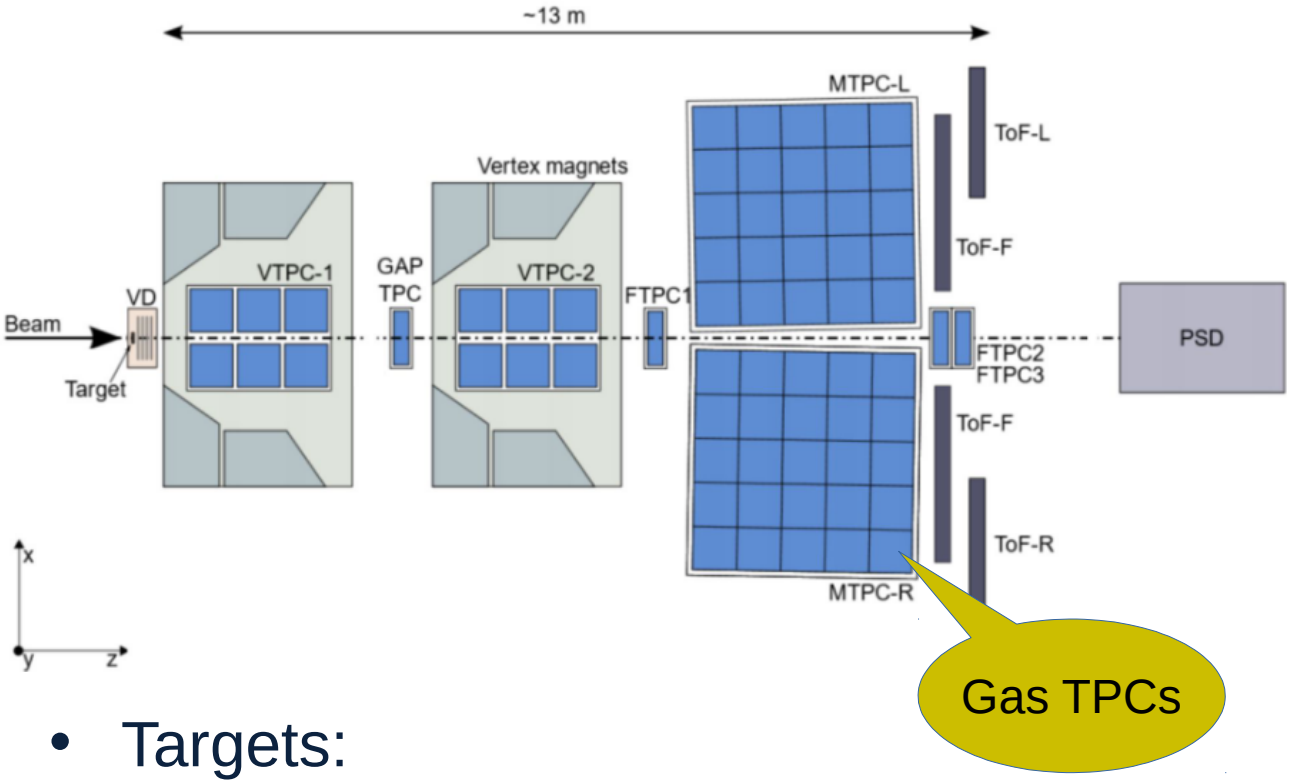


Figure: Yoshikazu Nagai

NA61/SHINE

- SPS Heavy Ion and Neutrino Experiment
- Detector: magnetized tracking spectrometer
- Beam:
  - Protons from CERN SPS
  - Pions, kaons, etc.
  - Energy: 20-400 GeV/c



- Targets:
  - Thin targets: carbon, Al, Be, etc.
  - Thick target: T2K, NuMI, DUNE

Where is NA61/SHINE?

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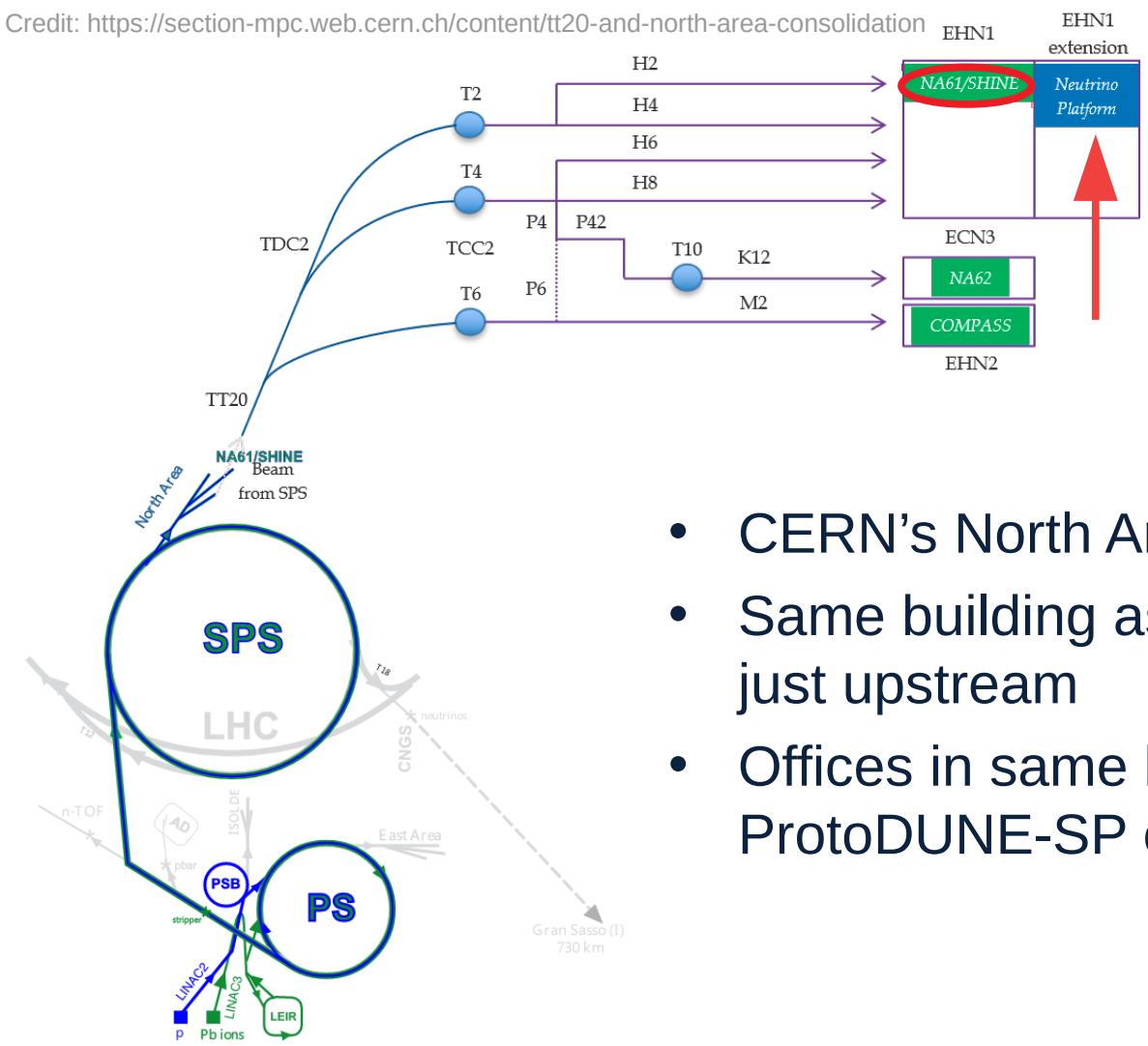
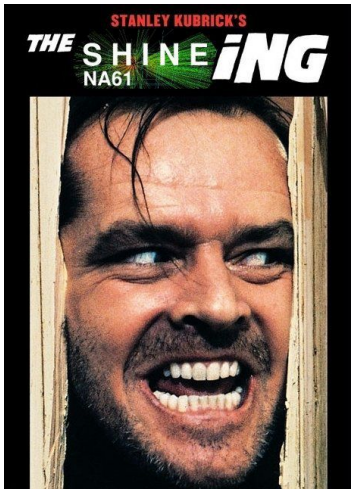
Credit: https://section-mpc.web.cern.ch/content/tt20-and-north-area-consolidation





- CERN's North Area = Prevessin site
- Same building as ProtoDUNEs and just upstream
- Offices in same building as old ProtoDUNE-SP offices

JINST 9 (2014) P06005

Heavy Ion Experiment

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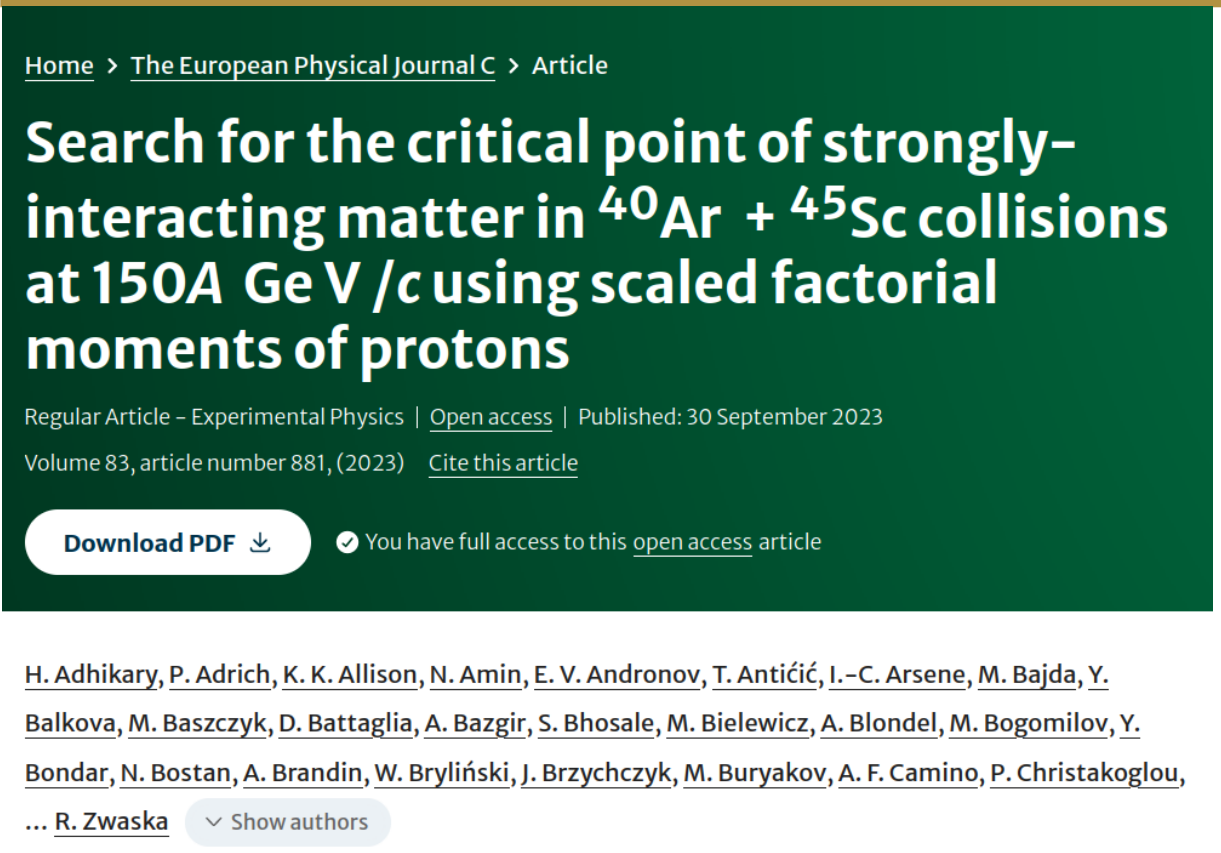

Home › The European Physical Journal C › Article

Search for the critical point of strongly-interacting matter in ^{40}Ar + ^{45}Sc collisions at 150A Ge V/c using scaled factorial moments of protons

Regular Article - Experimental Physics | Open access | Published: 30 September 2023

Volume 83, article number 881, (2023) Cite this article

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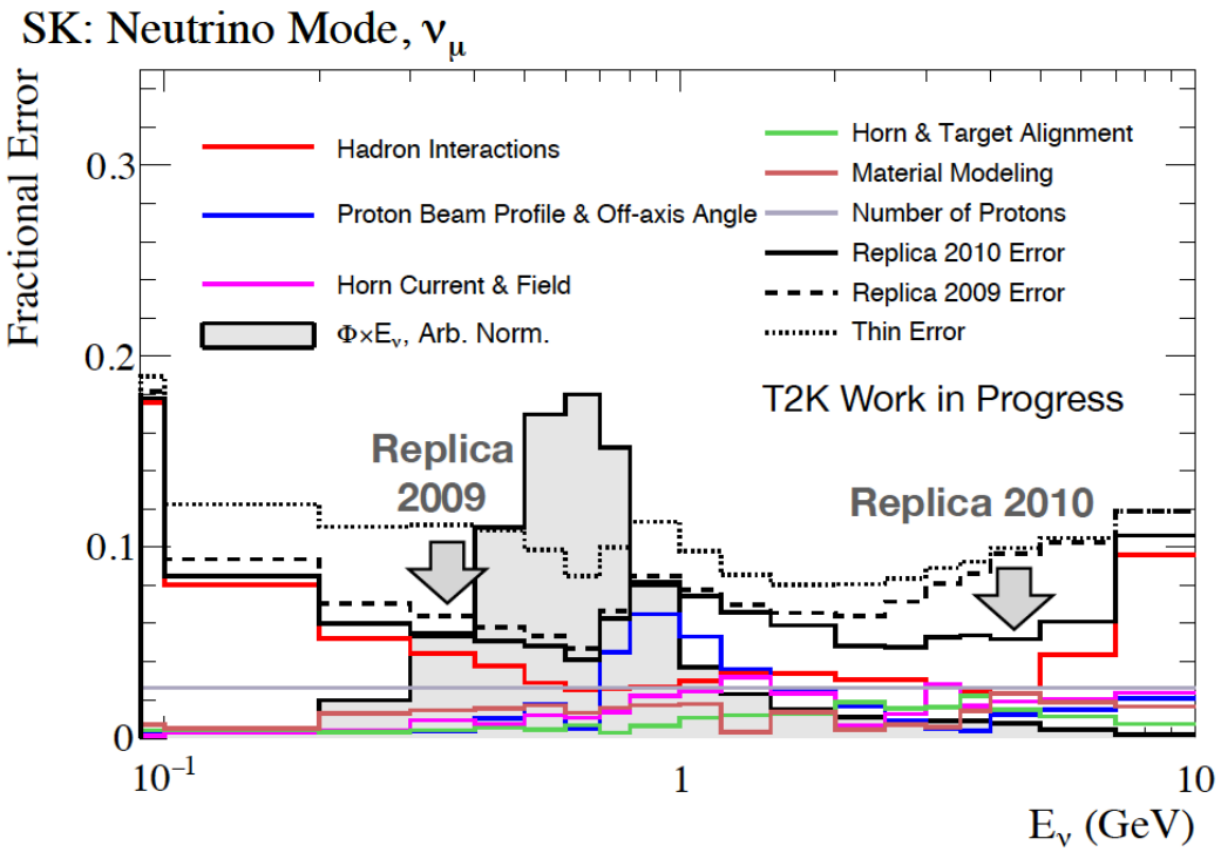
H. Adhikary, P. Adrich, K. K. Allison, N. Amin, E. V. Andronov, T. Antićić, I.-C. Arsene, M. Bajda, Y. Balkova, M. Baszczyk, D. Battaglia, A. Bazgir, S. Bhosale, M. Bielewicz, A. Blondel, M. Bogomilov, Y. Bondar, N. Bostan, A. Brandin, W. Bryliński, J. Brzychczyk, M. Buryakov, A. F. Camino, P. Christakoglou, ... R. Zwaska Show authors

- NA61/SHINE's other main topic is **heavy ion** physics
- Also great at measuring hadron production for neutrino and cosmic ray physics
- Very important to support this collaboration for beam modeling!

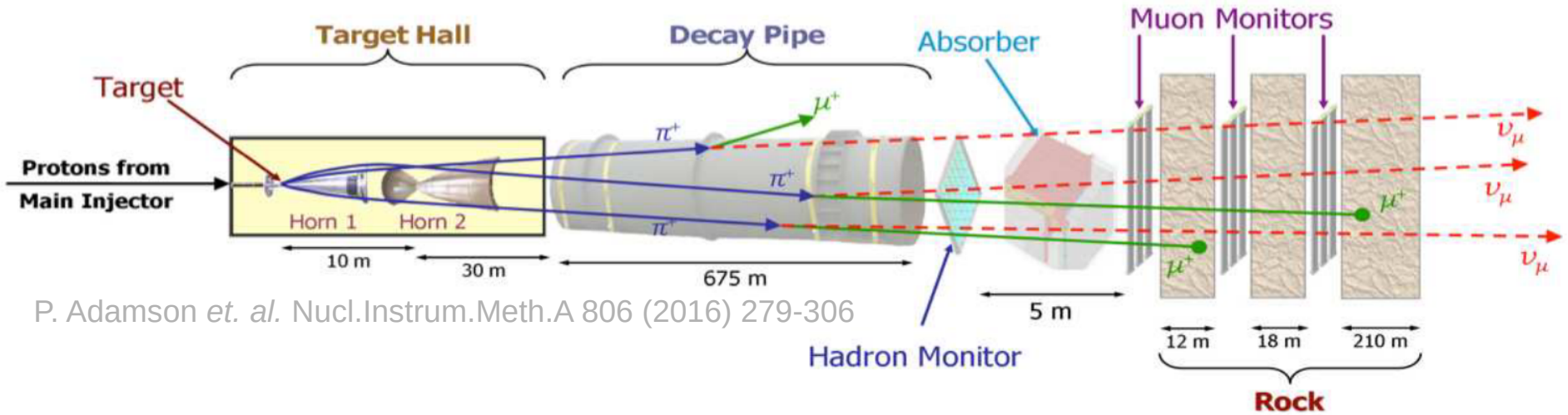
Impact on T2K



Credit: E. D. Zimmerman seminar 2024

- First application of NA61 data to a neutrino experiment
- Dedicated simulation tuning to NA61 data
- Two iterations:
  - Thin target data: tune physics processes
  - “Long target”: tune outgoing hadron multiplicity to replica target data

Example: NuMI through PPFX



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- Package to Predict the FluX predicts neutrino flux given:
  - Protons
  - Horn geometry
  - **GEANT cross section models: NA61 improves this!**
- **NA61 measurements translated to NOvA results through PPFX**

PPFX

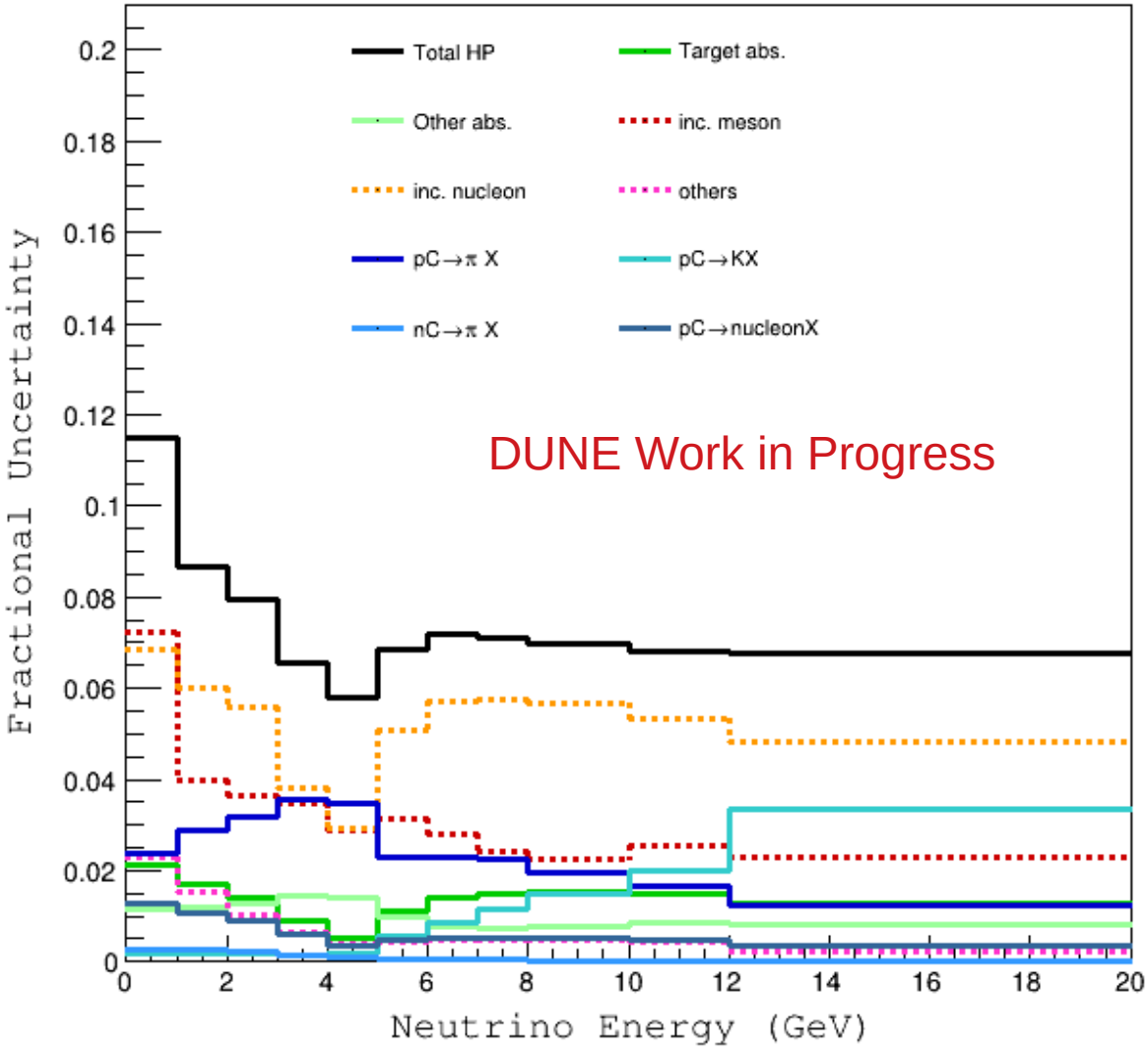

Figure: Ian D. Kotler

- Near detector hadron production uncertainties
- Solid lines: cross sections covered by existing data from e.g. NA49
- Incident nucleon: cross sections not yet covered by data
- NA61 reduces “incident nucleon” by:
  - covering more phase space than NA49
  - Reporting covariance

Our Hadron Production Measurements

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- p+C@120 GeV/c
  - Charged: p, pi, and K *Phys.Rev.D* 108 (2023) 072013
  - Neutral: K0s and lambdas *Phys.Rev.D* 107 (2023) 7, 072004
- p+T2K@31 GeV/c
  - Charged p, pi, K, neutral K, and lambdas *Eur.Phys.J.C* 76 (2016) 2, 84
  - Differential Pi+/- yields *Eur.Phys.J.C* 76 (2016) 11, 617
  - Charged p, pi, and K *Eur.Phys.J.C* 79 (2019) 2, 100
- p+C@31 GeV/c
  - K+: *Phys.Rev.C* 85 (2012) 035210
  - Neutral K0s and lambdas *Phys.Rev.C* 89 (2014) 2, 025205
  - Production cross section and differential yields for p, pi, K, K^0, and lambdas *Phys.Rev.D* 103 (2021) 1, 012006
- Pi and K on thin target
  - C and Al at 60 GeV/c and 31 GeV/c: *Phys.Rev.D* 98 (2018) 5, 052001
  - C and Be at 60 GeV/c: *Phys.Rev.D* 100 (2019) 11, 112004
- Protons on thin target
  - Production and inelastic cross sections on C, Be, Al at 60 GeV/c and 120 GeV/c: *Phys.Rev.D* 100 (2019) 11, 112001

Recent Measurements

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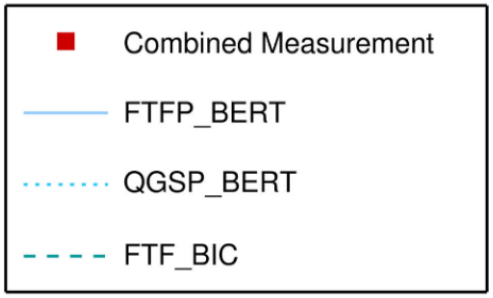
- p+C@120 GeV/c
  - Thin target cross sections
  - Charged: pi, p, and K

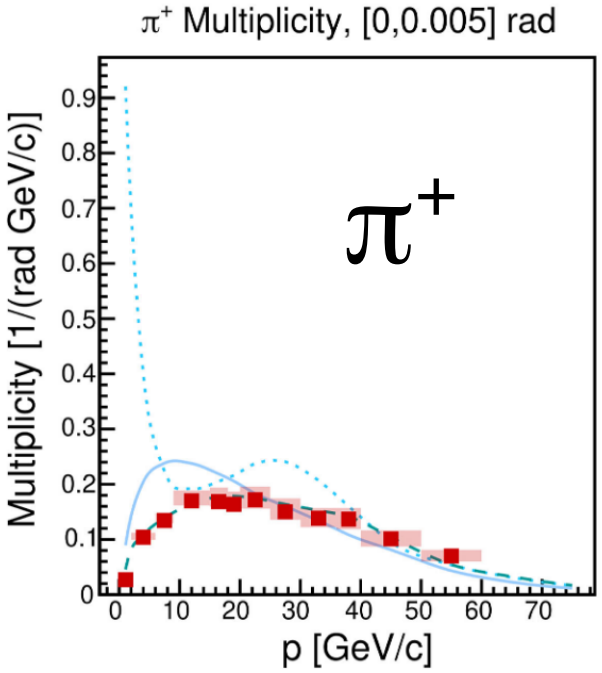
    Measurements of π^+, π^-, p, $\bar{p}$, K^+ and K^- production in 120 GeV/c p + C interactions
    NA61/SHINE Collaboration • H. Adhikary (Jan Kochanowski U.) et al.
    e-Print: 2306.02961 [hep-ex]
    DOI: 10.1103/PhysRevD.108.072013 (publication)
    Published in: Phys.Rev.D 108 (2023), 072013
  - Neutral: K^0 and lambdas

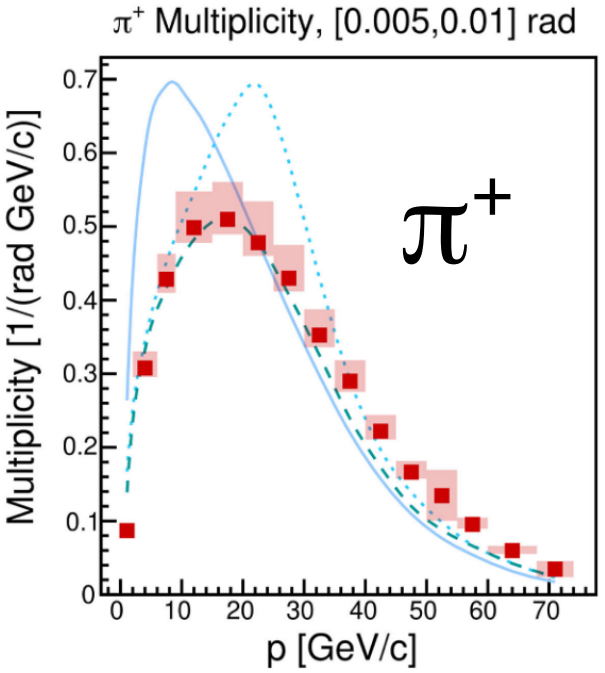
    Measurements of K^0_S, Λ, and $\bar{\Lambda}$ production in 120 GeV/c p+C interactions
    NA61/SHINE Collaboration • H. Adhikary (Jan Kochanowski U., Kielce (main)) et al.
    e-Print: 2211.00183 [hep-ex]
    DOI: 10.1103/PhysRevD.107.072004 (publication)
    Published in: Phys.Rev.D 107 (2023) 7, 072004
- p+C@90 GeV/c
  - Charged pi, p, and K; neutral K^0 and lambdas

    Publication in preparation

p+C@120 GeV/c







- Phys.Rev.D 108 (2023), 072013
- $\pi^{+/-}$, protons, $K^{+/-}$, and antiprotons on carbon at 120 GeV/c
- 20x statistics in new 2023 data

Forward TPCs

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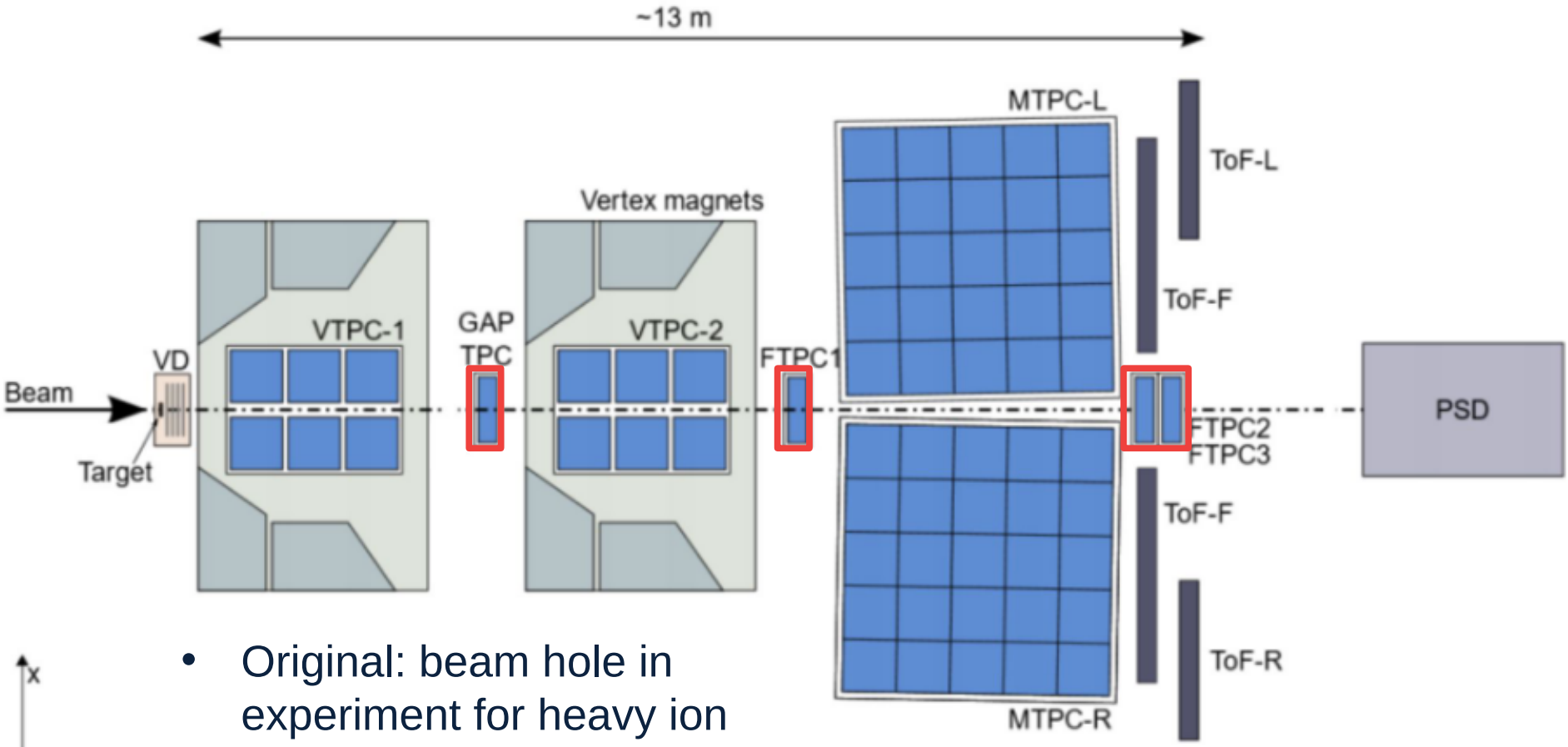
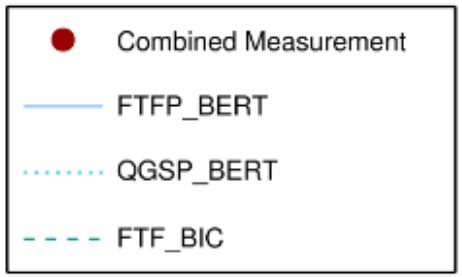
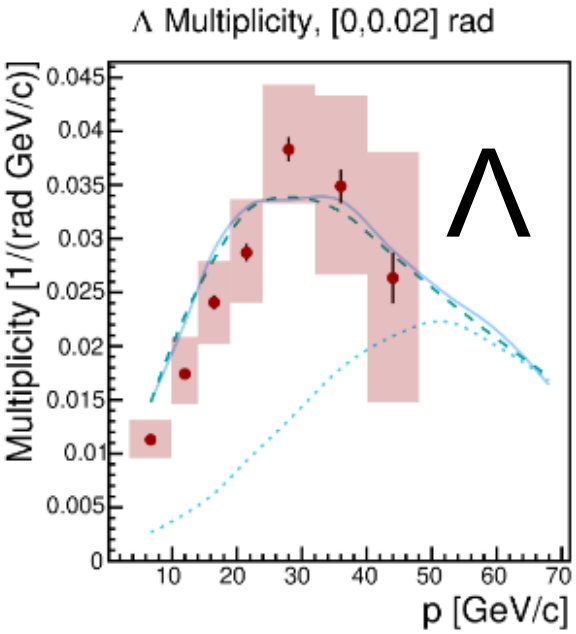
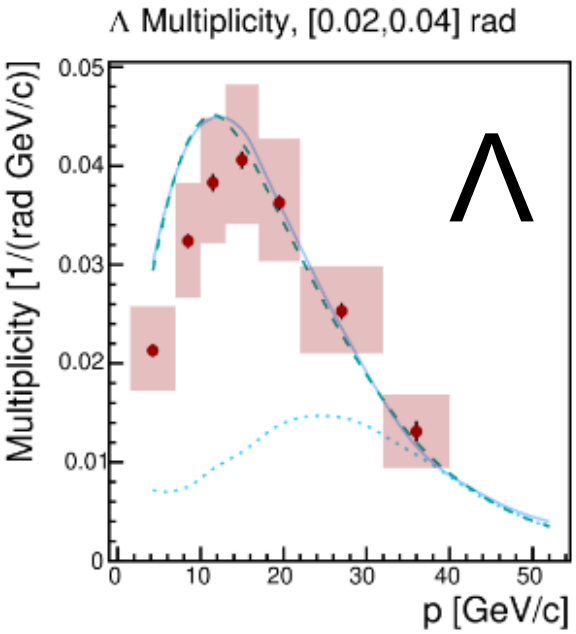


- Original: beam hole in experiment for heavy ion physics
- New forward-phase-space TPCs for NuMI data

p+C@120 GeV/c

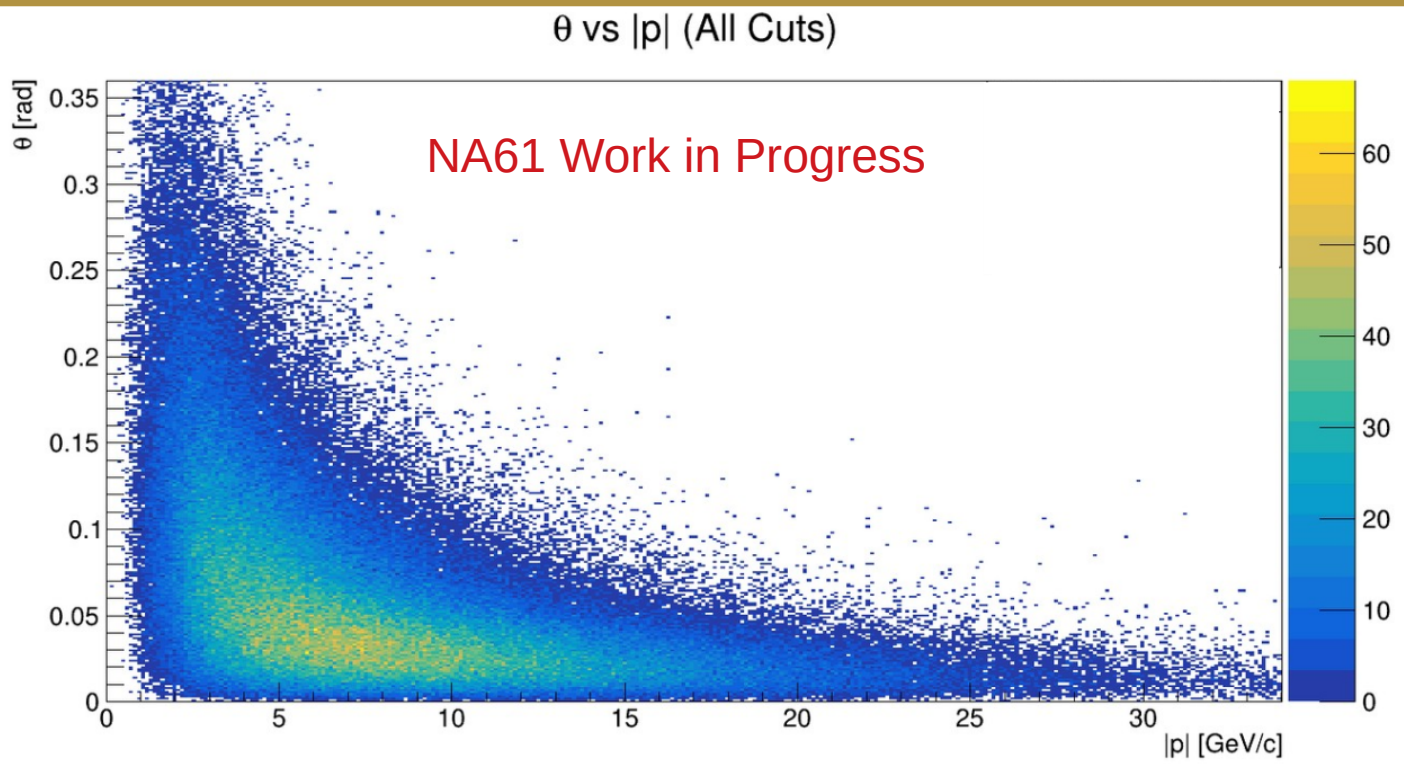






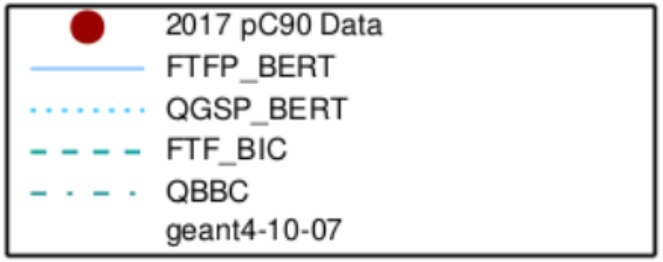
- Phys.Rev.D 107 (2023) 7, 072004
- K^0_S and lambdas on carbon at 120 GeV/c
- Different models agree in different regions of phase space

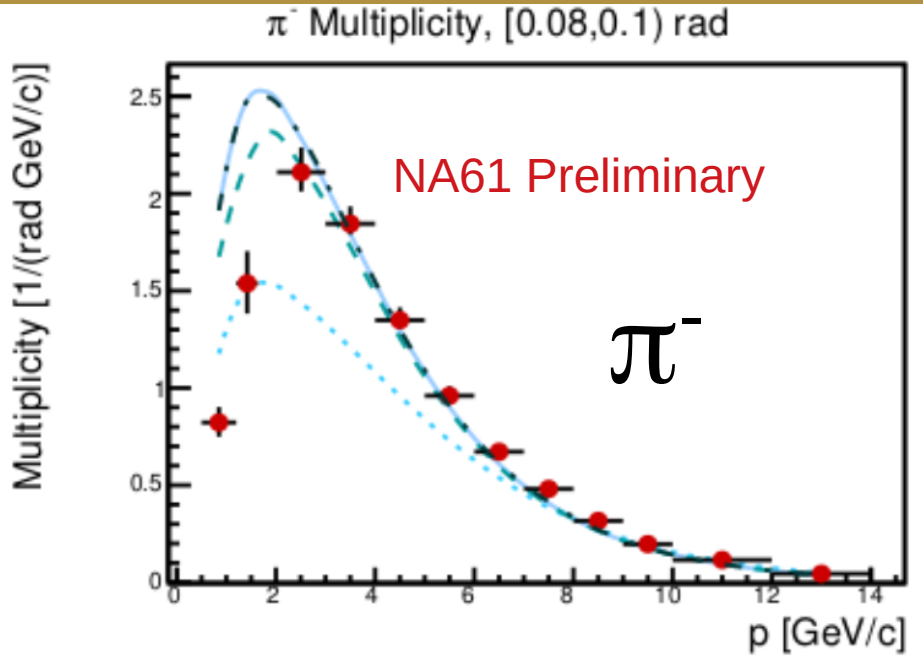
p+C@90 GeV/c

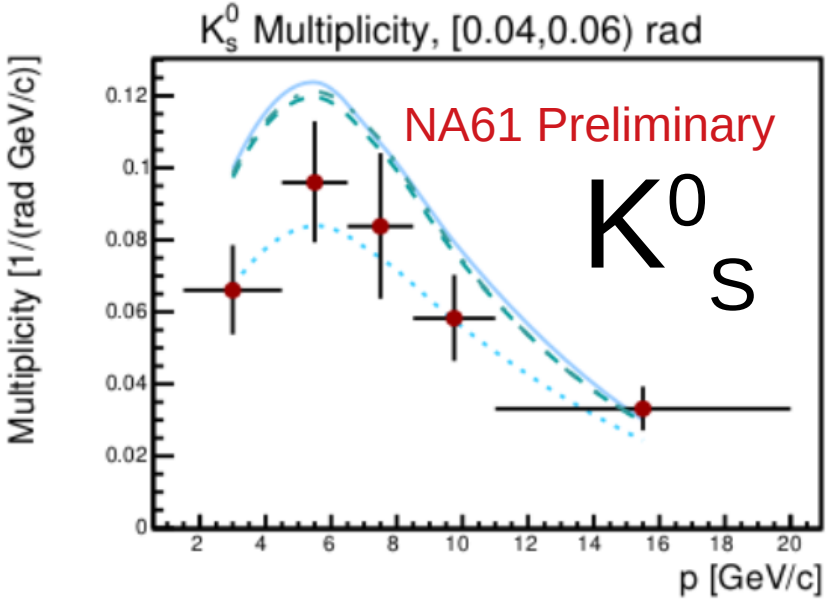


- Above: K^0_S phase space coverage
- Secondary interactions in target system lead to hadrons of all energies below beam energy
- Important to measure intermediate energies to test scaling

p+C@90 GeV/c





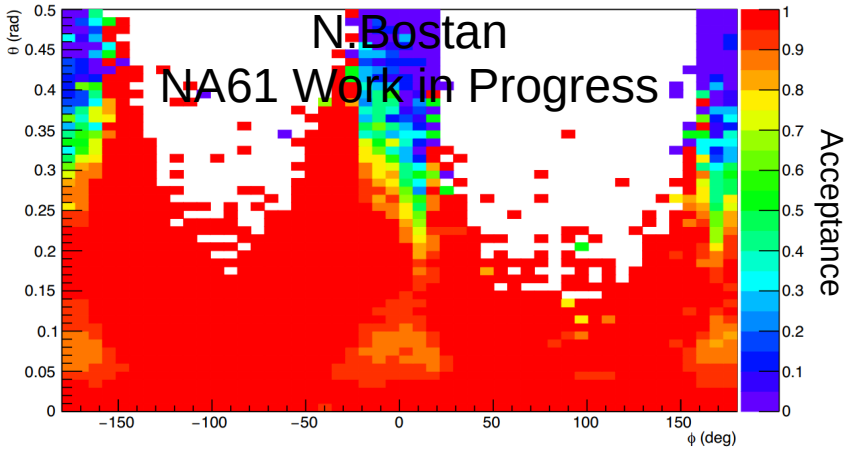


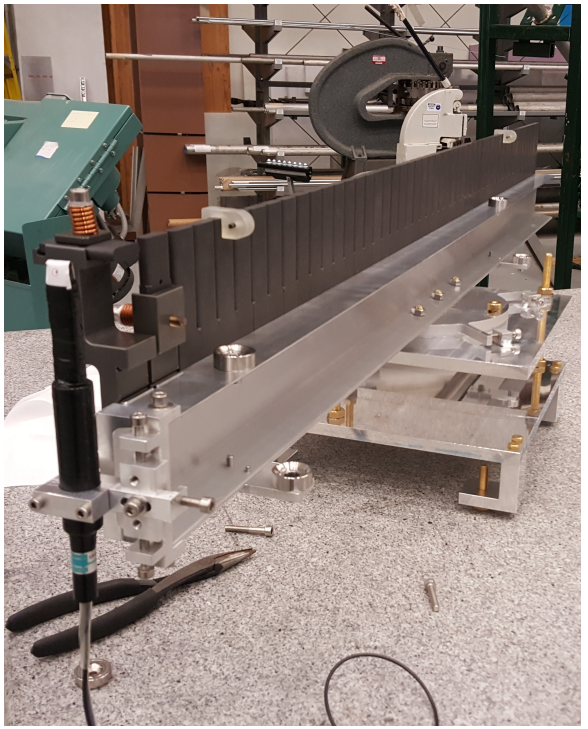
- Publication in preparation
- Charged and neutral multiplicities
- Fills in gaps between T2K and NuMI energies for e.g. secondary proton scattering inside NuMI target

Planned Measurements

- p+C@60 GeV/c
  - Charged
  - Neutral
- p+NOvA@120 GeV/c
  - Charged
  - Neutral
- **p+DUNE@120/c GeV: Summer 2024**
- Lower energy beam

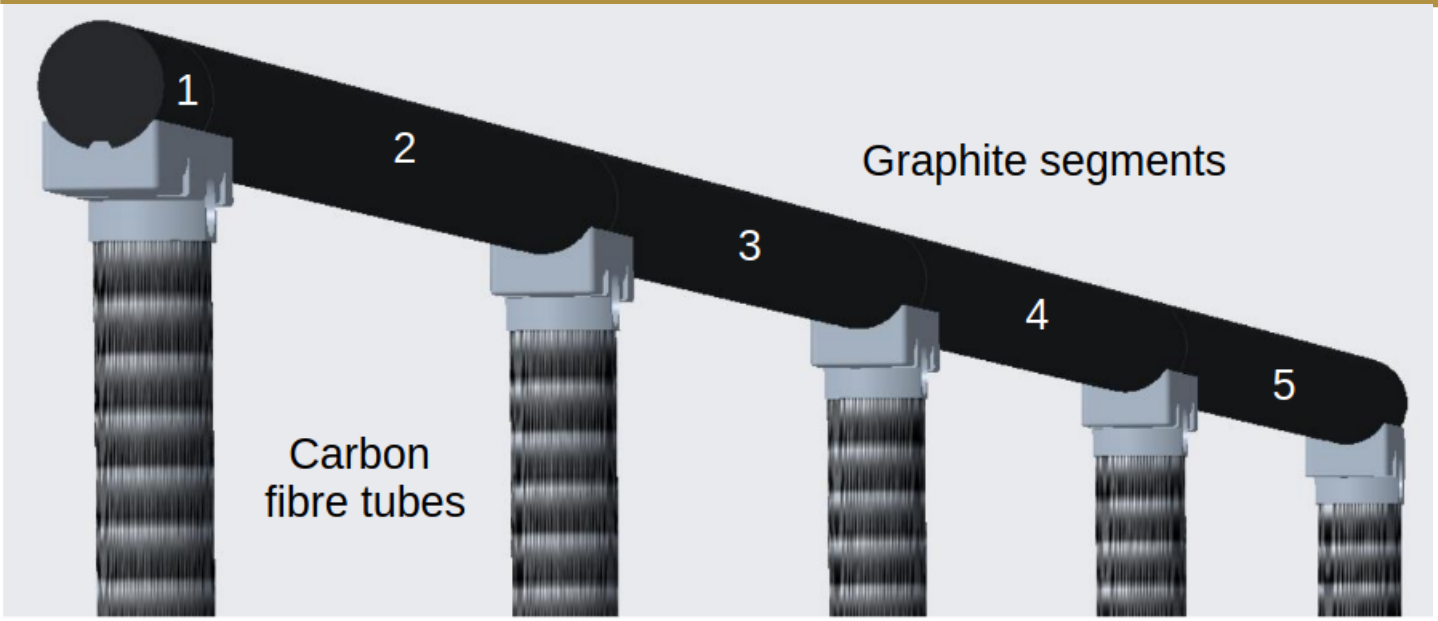
NuMI Analysis Progress





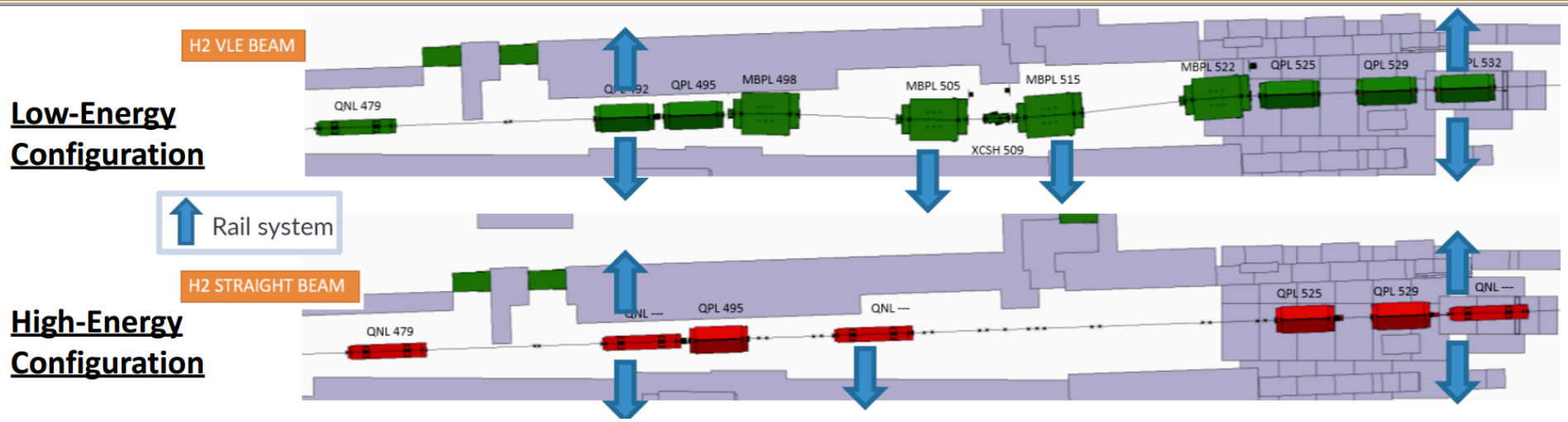
- “Long target” analysis for NuMI experiments
- 120 GeV/c protons on spare NuMI target
- Data collected in 2018
- Planning separate charged and neutral particle papers
- Currently calibrating

DUNE Target Plans



- DUNE prototype target coming to NA61 in 2024
- Same measurements as NuMI
  - Particle multiplicity
  - 120 GeV/c protons

Very Low Energy Beam



- Goal: extend beam coverage down from 20 GeV/c to 2 GeV/c
- Outcome:
  - Hadron production measurements for BNB
  - Atmospheric neutrinos at SuperK
  - Additional hadron production measurements for T2K and HyperK
  - Hadron production for DUNE second oscillation maximum
- **New collaborators welcome**

Thank you

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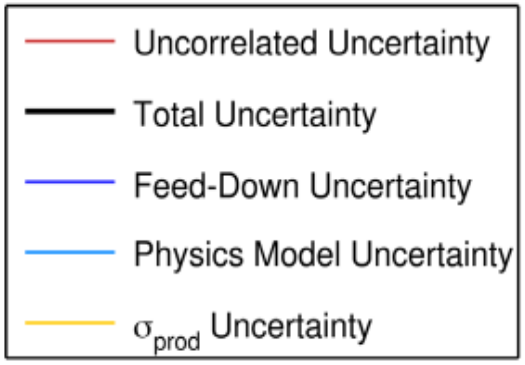
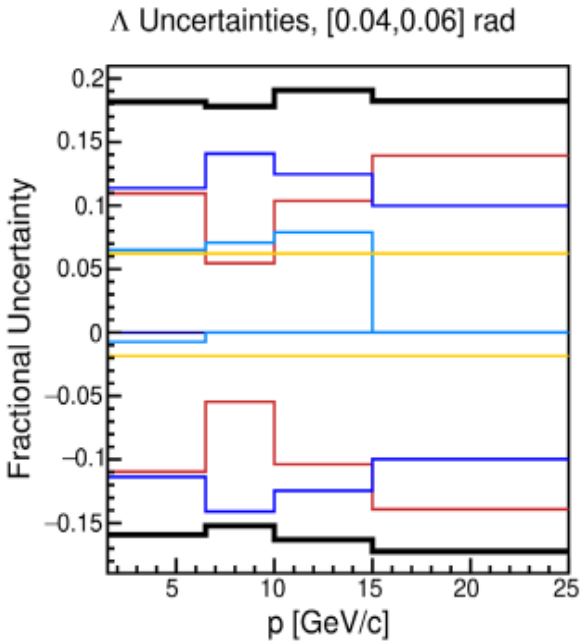
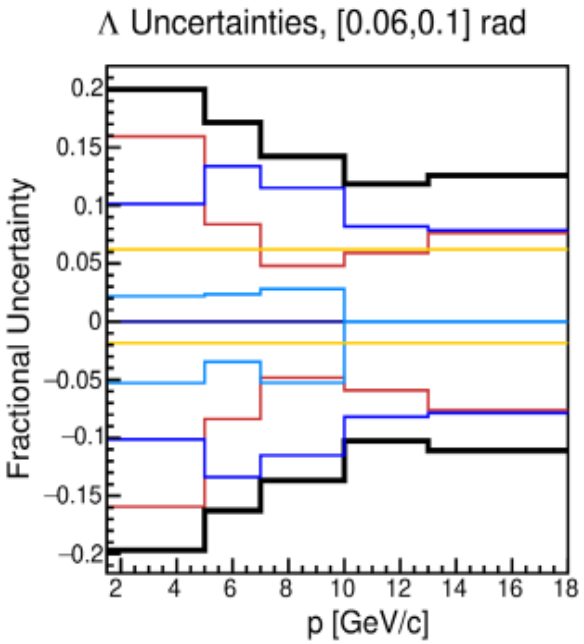
Lambda Uncertainties

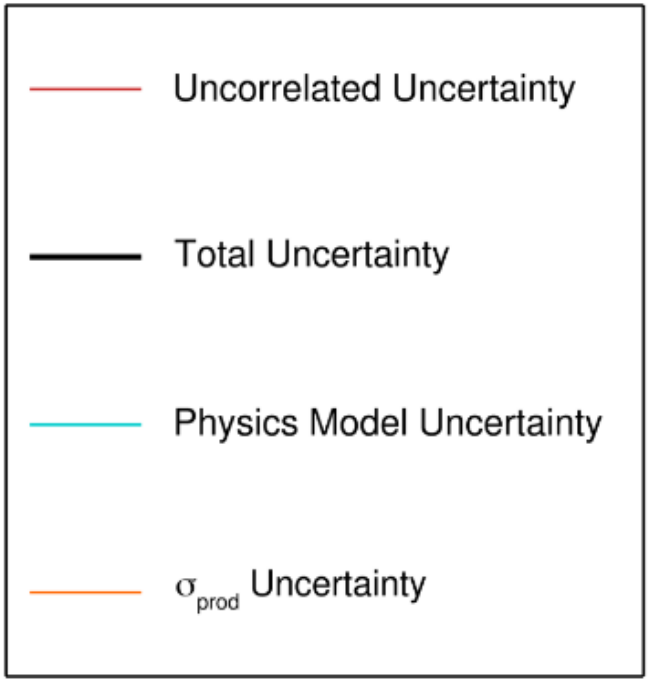


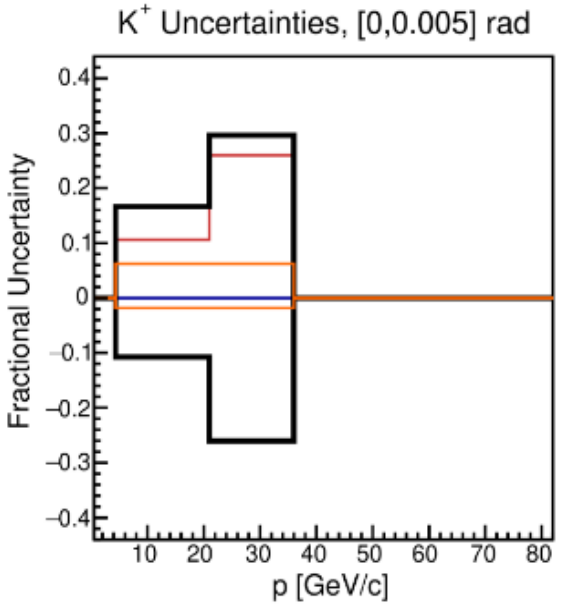


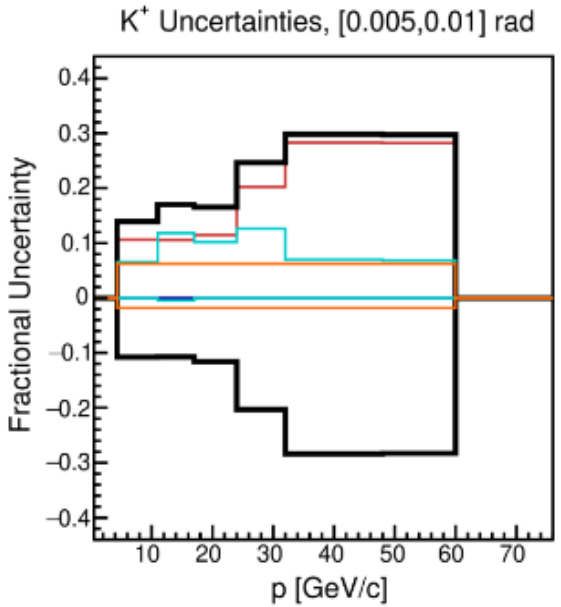


- Phys.Rev.D 107 (2023) 7, 072004
- K0S and lambdas on carbon at 120 GeV/c

Recent Measurements







- Phys.Rev.D 108 (2023), 072013
- K+/-, protons, and antiprotons on carbon at 120 GeV/c