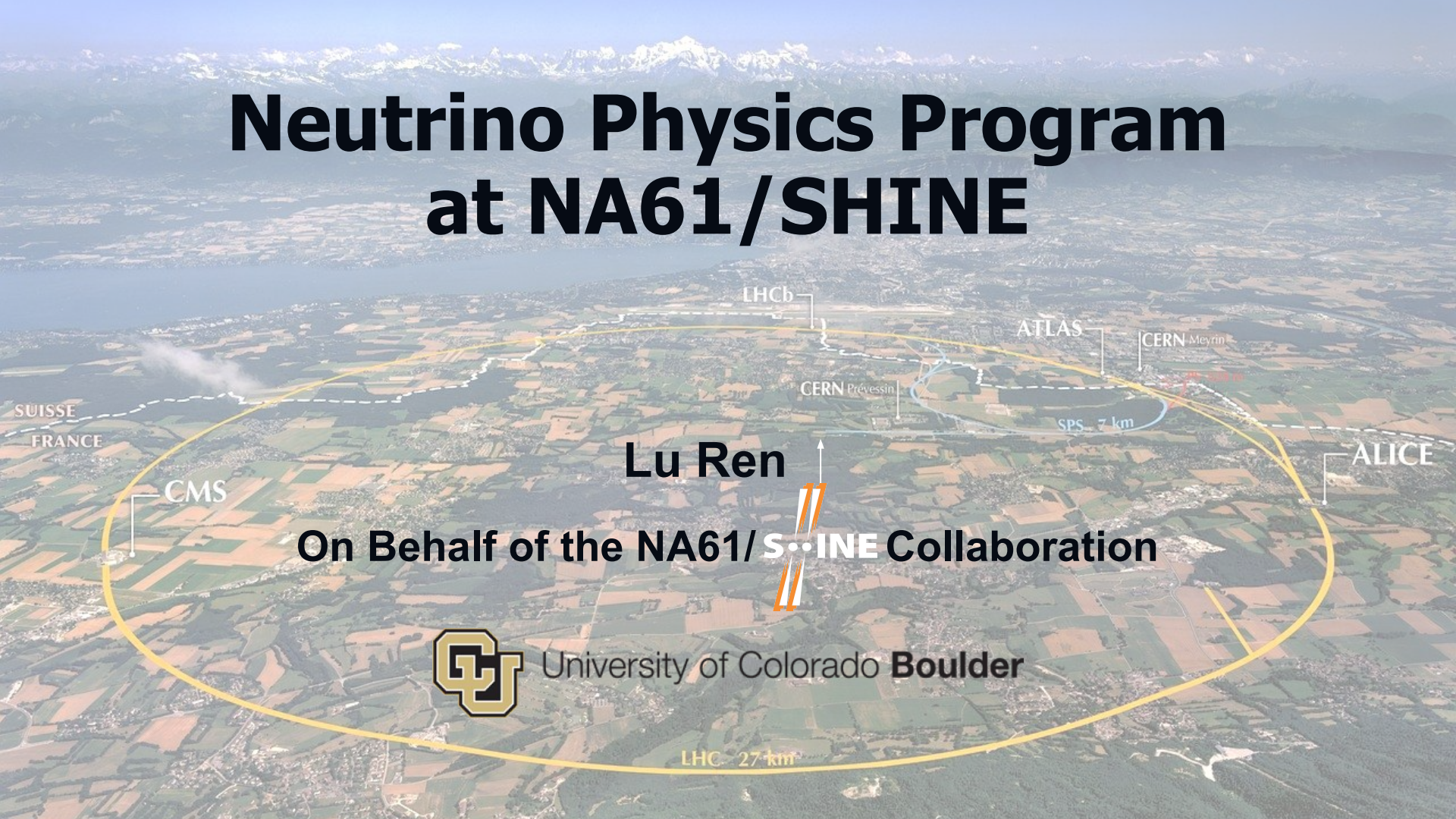
Neutrino Physics Program at NA61/SHINE



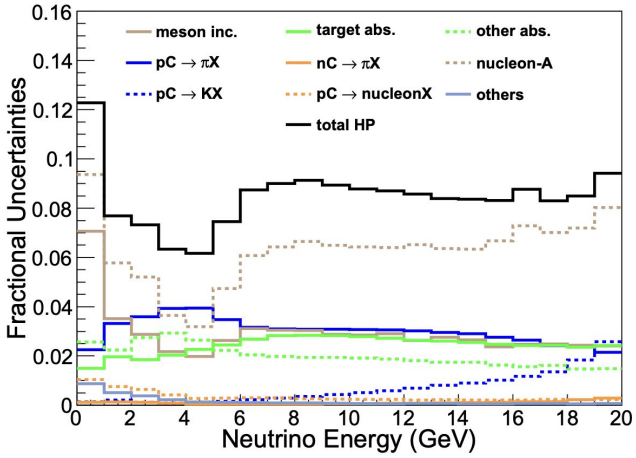
Lu Ren

On Behalf of the NA61/SHINE Collaboration

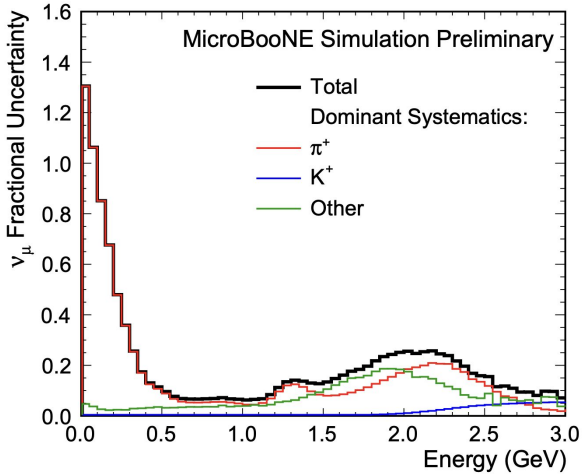
University of Colorado **Boulder**

Flux Uncertainty

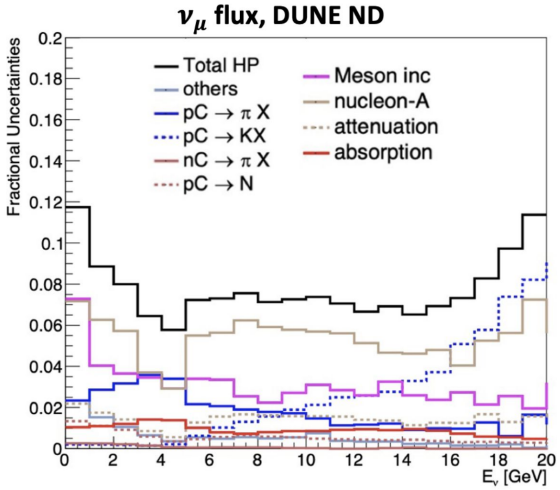
- Neutrino flux uncertainty limits the precision of measurements in all accelerator-based neutrino experiments



MINERvA at NuMI beamline



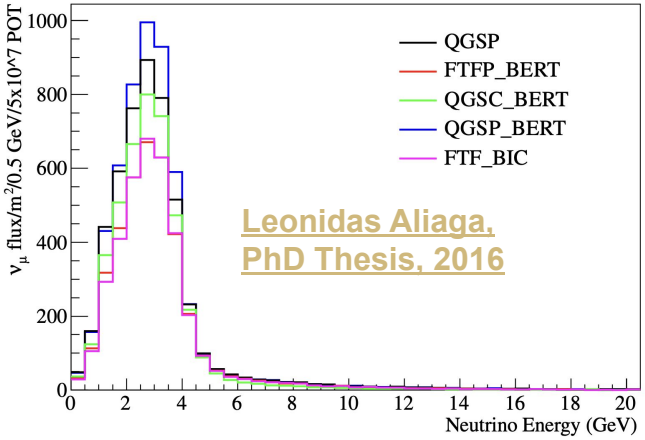
MicroBooNE at Booster Neutrino Beam

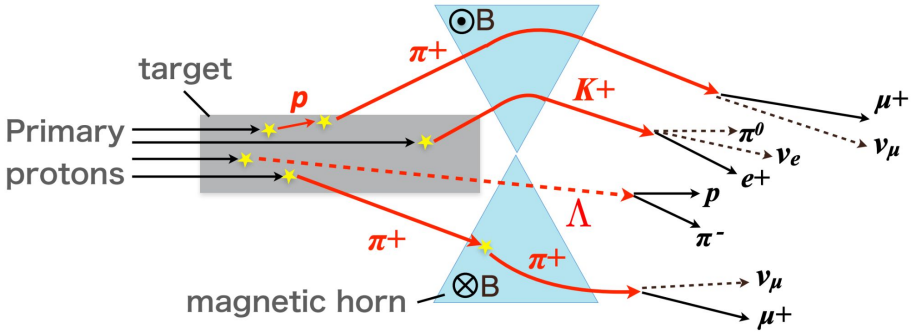


Nilay Bostan, Neutrino 2022

Why Hadron Production Measurements?

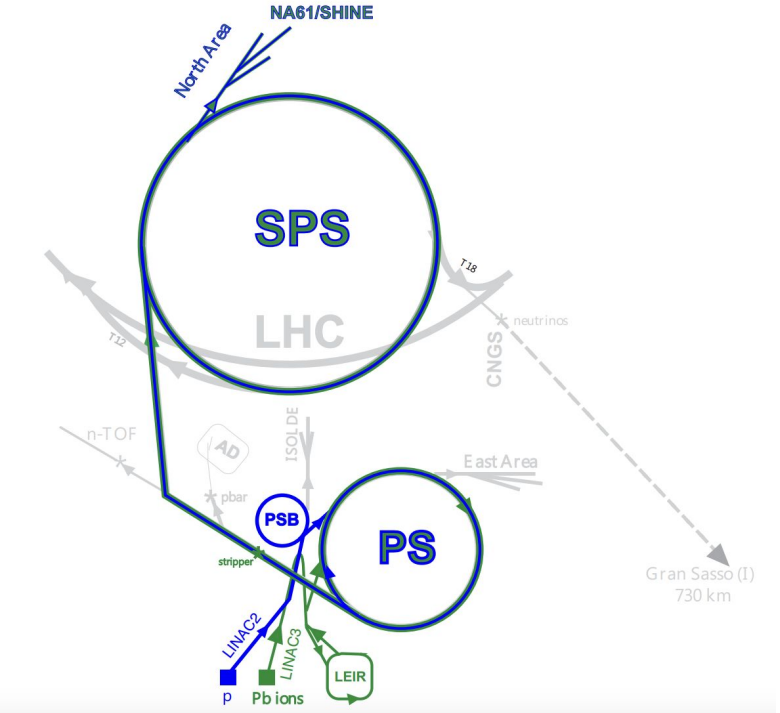
- Neutrino flux simulation relies on the hadronic interaction models used in FLUKA or GEANT4
  - Very large uncertainty (>20%)
- Important to have constraints on the hadronic processes
  - Proton-target interaction
  - Secondary interactions





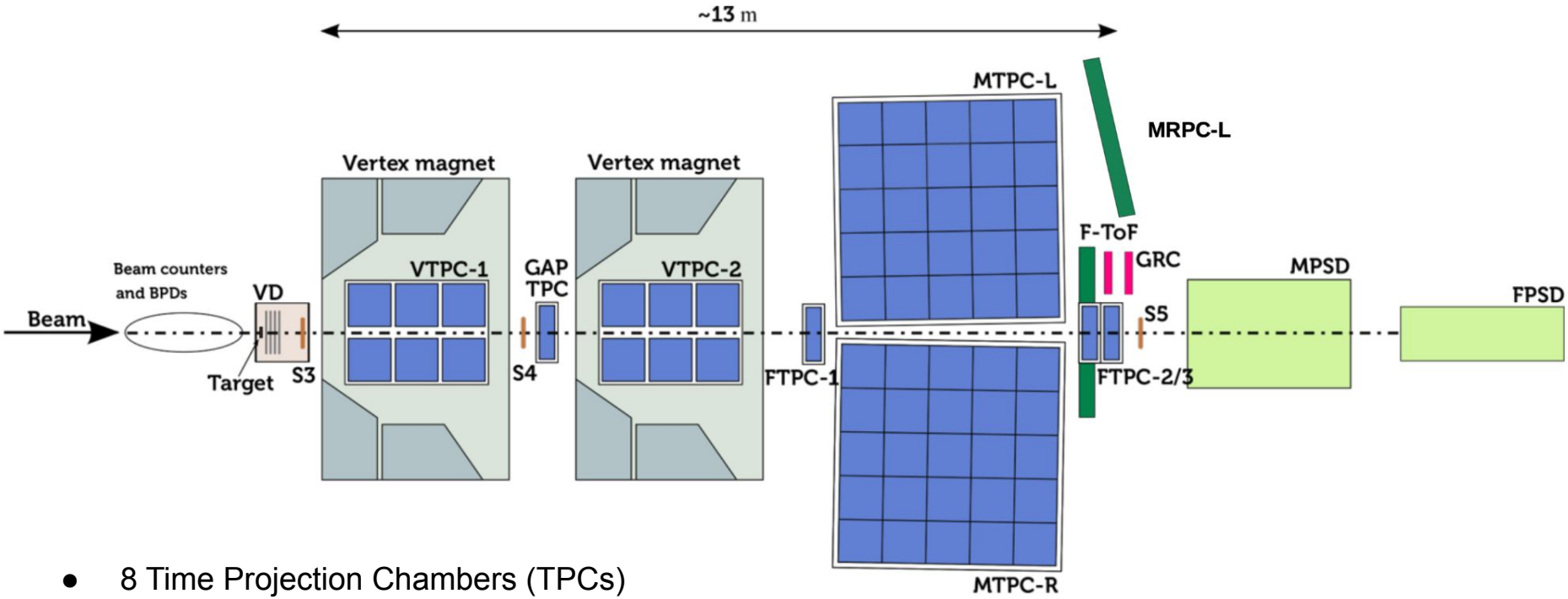
NA61/SHINE

- **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

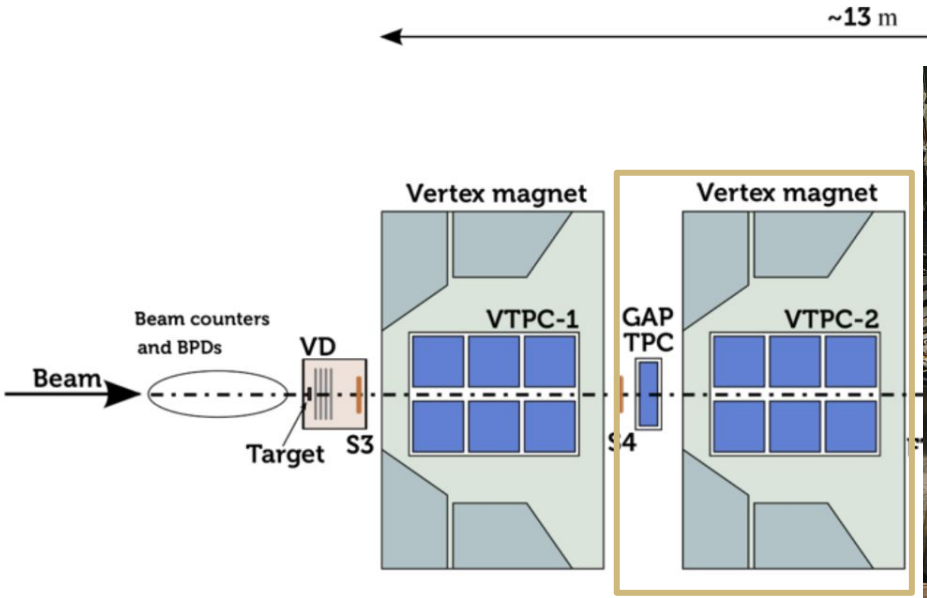
NA61/SHINE Detector

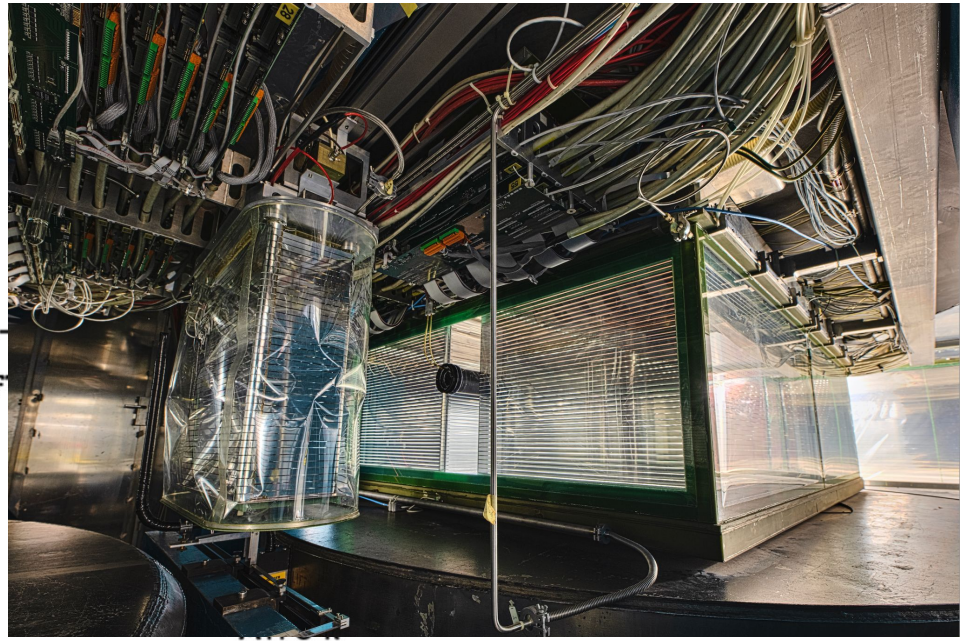


- 8 Time Projection Chambers (TPCs)
- Two superconducting magnets
- Time-of-flight detectors

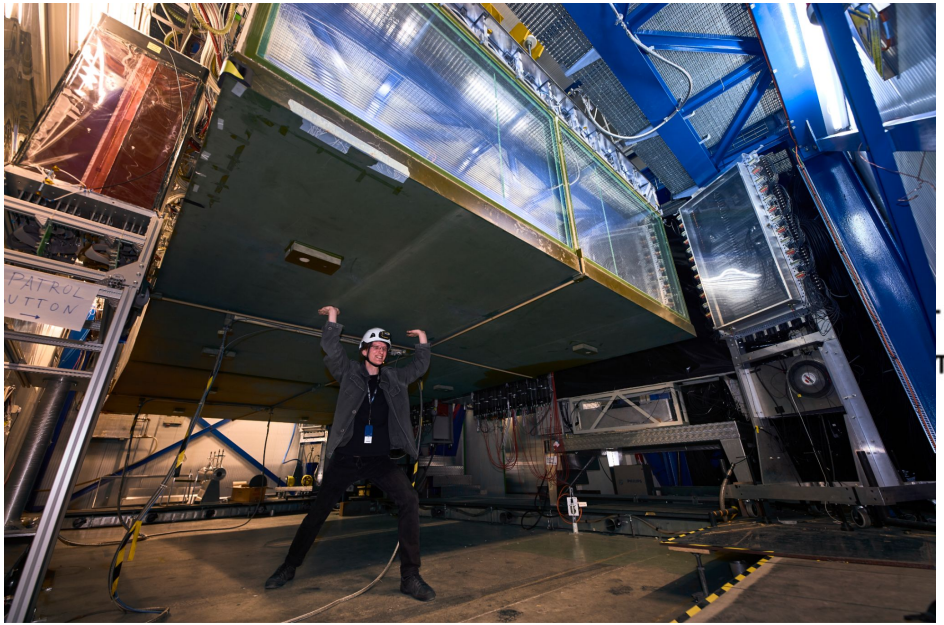
- Projectile Spectator Detectors (PSDs)
- Major detector upgrade finalized in 2022

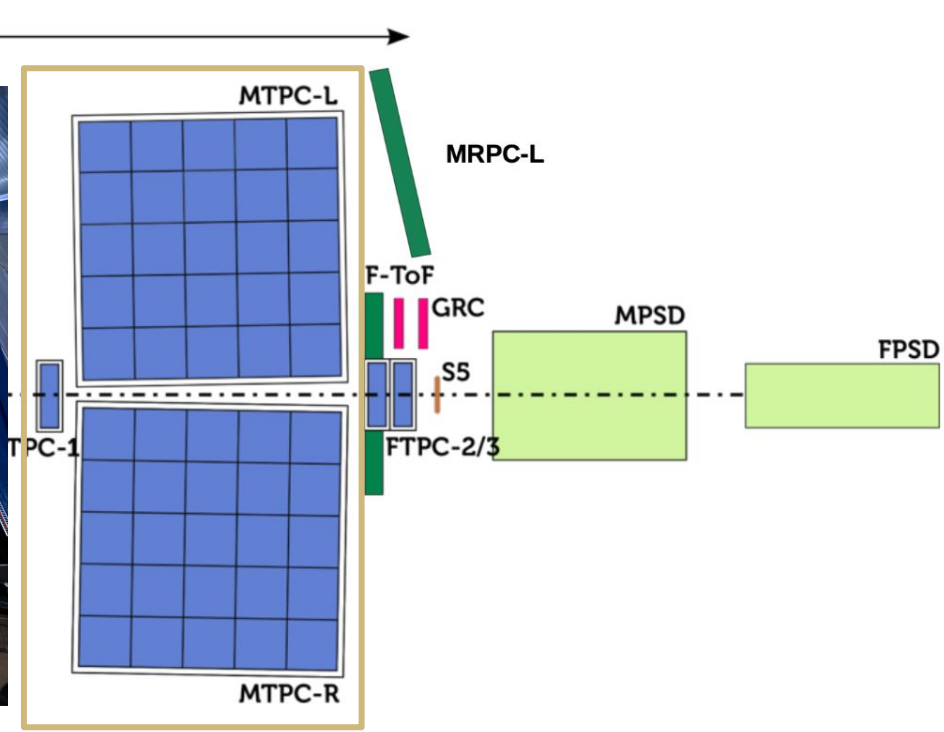
NA61/SHINE Detector



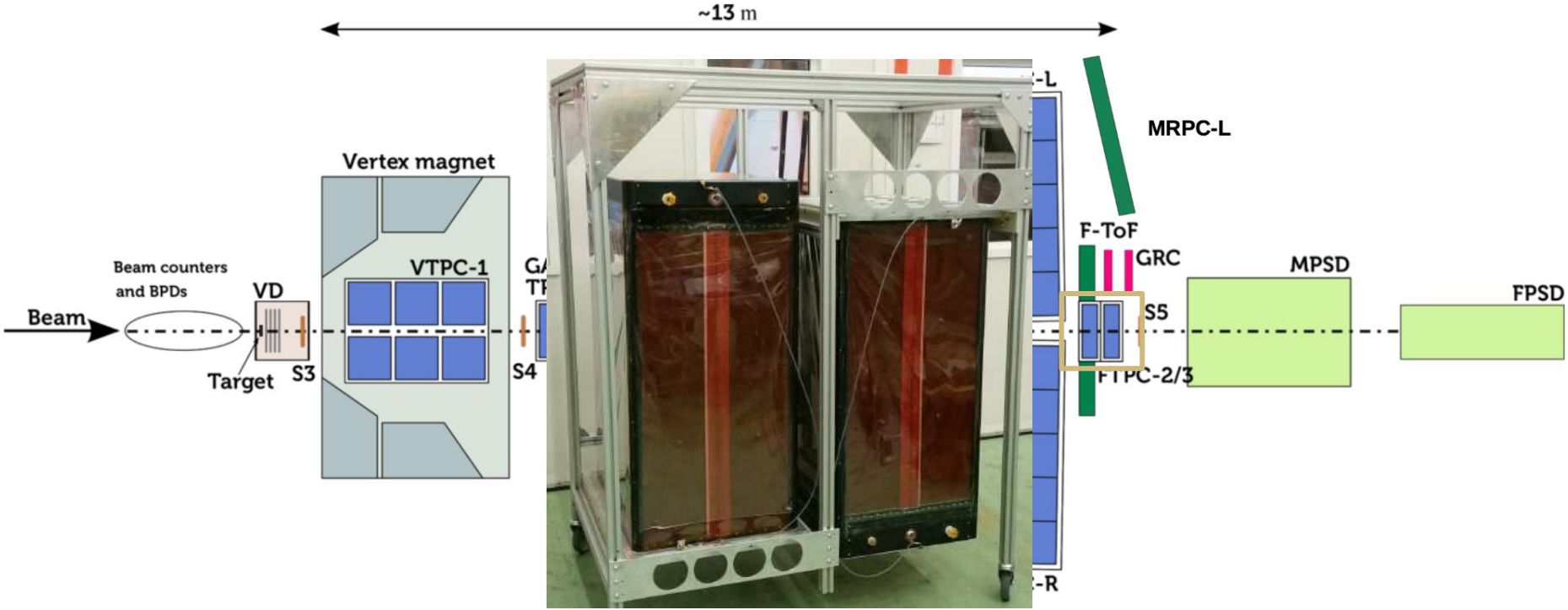


NA61/SHINE Detector



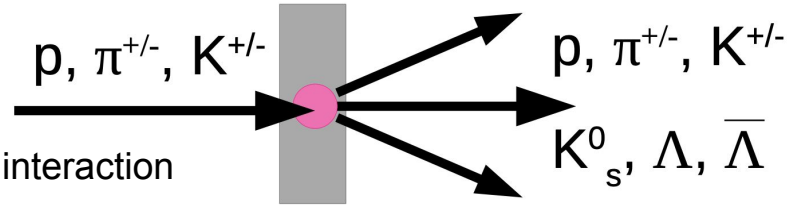


NA61/SHINE Detector

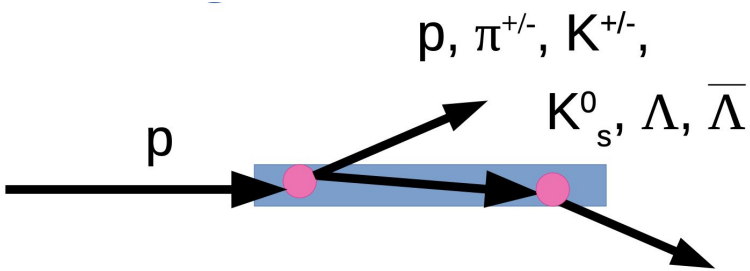


Hadron Production Measurements

- Thin-target measurements
  - Total, inelastic and production cross sections
  - Charged and neutral hadron yields from primary interaction
  - 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



NA61 Data Taking for Neutrino Experiments

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

	2 cm Carbon	T2K replica	1.5 cm Carbon	Al	Be	Ti	NuMI replica	LBNF replica
31 GeV/c	p, π^-	p						
60 GeV/c			p, K, π^+	p, π^+	p, π^+	p, K		
90 GeV/c			p					
120 GeV/c			p		p	p	p	p*
8 GeV/c					p*			

* Proposed

2007 - 2010

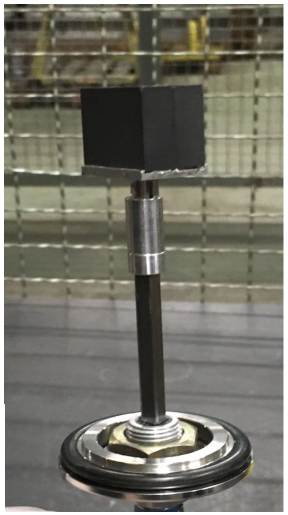
2007 - 2010 T2K	Long Shutdown (LS) 1	2015 - 2018 FNAL	LS2	2022 - 2025 T2K, DUNE, etc.	LS3	2027 - ?

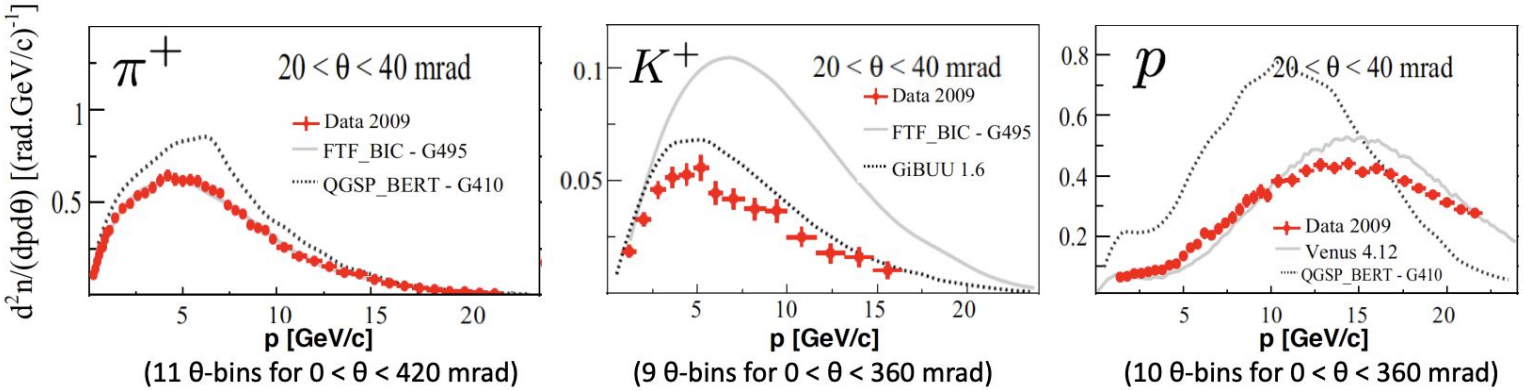
	2 cm Carbon	T2K replica	1.5 cm Carbon	Al	Be	Ti	NuMI replica	LBNF replica
31 GeV/c	p, π^-	p						
60 GeV/c			p, K, π^+	p, π^+	p, π^+	p, K		
90 GeV/c			p					
120 GeV/c			p		p	p	p	p*
8 GeV/c					p*			

* Proposed

Thin Target Measurements for T2K

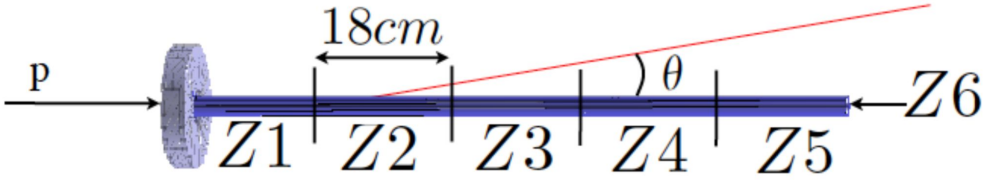
- Thin target: 31 GeV/c proton on 2 cm graphite target
  - Total cross-section and $\pi^{+/-}$ spectra measurements (Phys. Rev. C84 (2011) 034604)
  - K^+ spectra measurement (Phys. Rev. C85 (2012) 035210)
  - K^0_S and Λ^0 spectra measurements (Phys. Rev. C89 (2014) 025205)
  - **Total cross-section and $\pi^{+/-}$, p, K^0_S, and Λ^0 spectra measurements (Eur. Phys. J. C76 (2016) 84)**

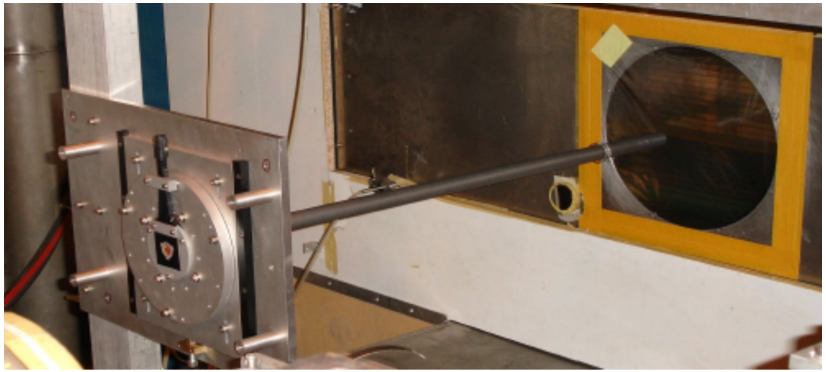




Thick Target Measurements for T2K

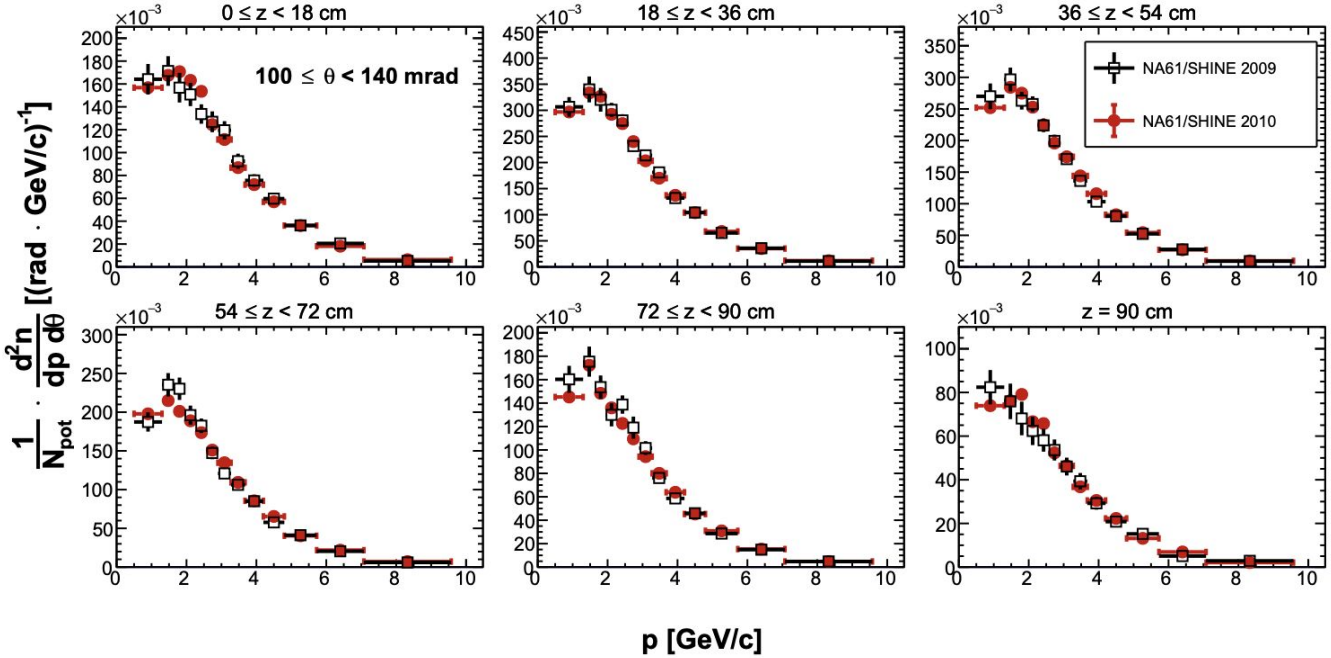
- Replica target: 31 GeV/c proton on 90 cm replica graphite target
  - Methodology, $\pi^{+/-}$ yield measurement (Nucl. Instrum. Meth. A701 (2013) 99-114)
  - $\pi^{+/-}$ yield measurement (Eur. Phys. J. C76 (2016) 617)
  - $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79 100 (2019))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





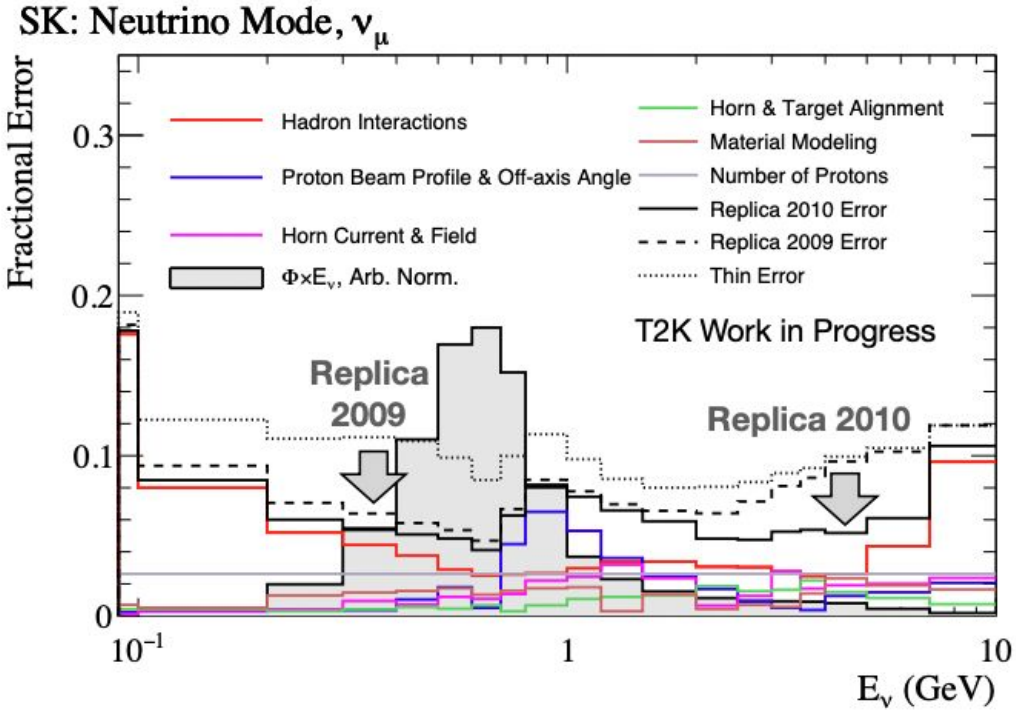
Thick Target Measurements for T2K

- 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%



Lukas Berns, NBI 2019

2015 - 2018

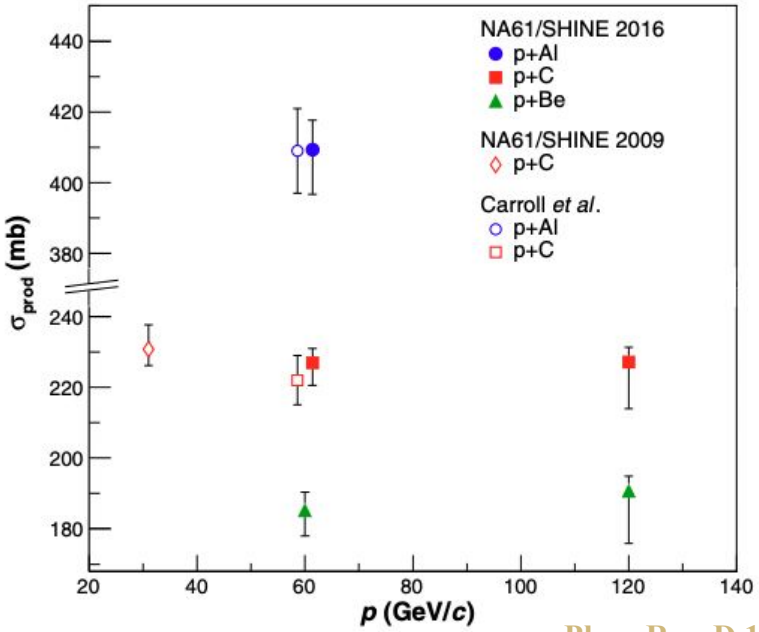
2007 - 2010 T2K	Long Shutdown (LS) 1	2015 - 2018 FNAL	LS2	2022 - 2025 T2K, DUNE, etc.	LS3	2027 - ?

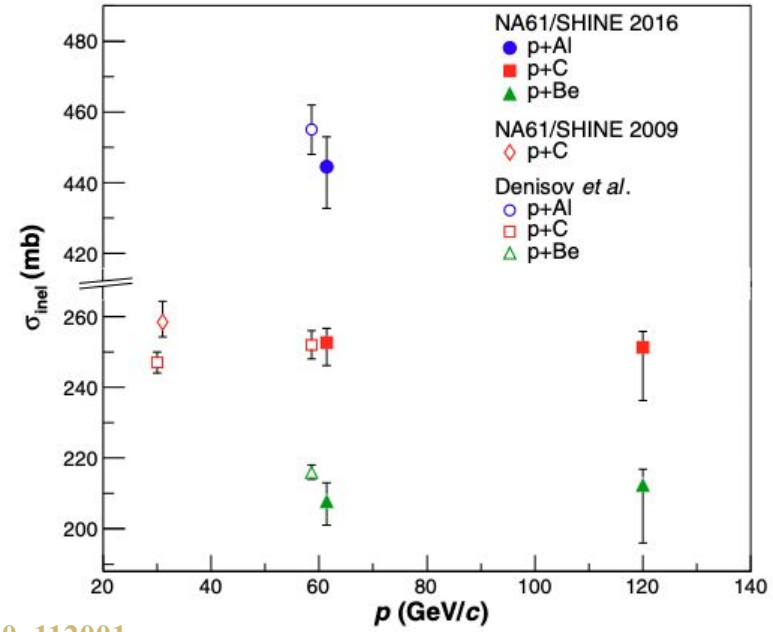
	2 cm Carbon	T2K replica	1.5 cm Carbon	Al	Be	Ti	NuMI replica	LBNF replica
31 GeV/c	p, π^-	p						
60 GeV/c			p, K, π^+	p, π^+	p, π^+	p, K		
90 GeV/c			p					
120 GeV/c			p		p	p	p	p*
8 GeV/c					p*			

* Proposed

Thin Target Measurements for FNAL Experiments

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

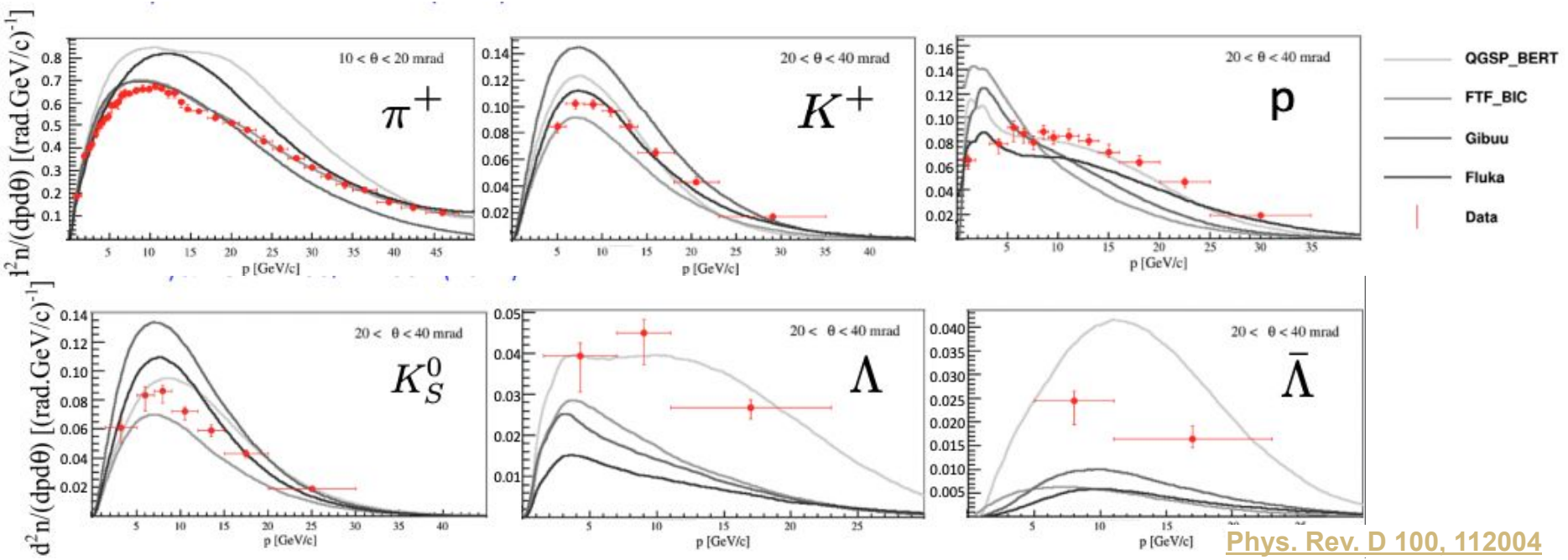




Phys. Rev. D 100, 112001

Thin Target Measurements for FNAL Experiments

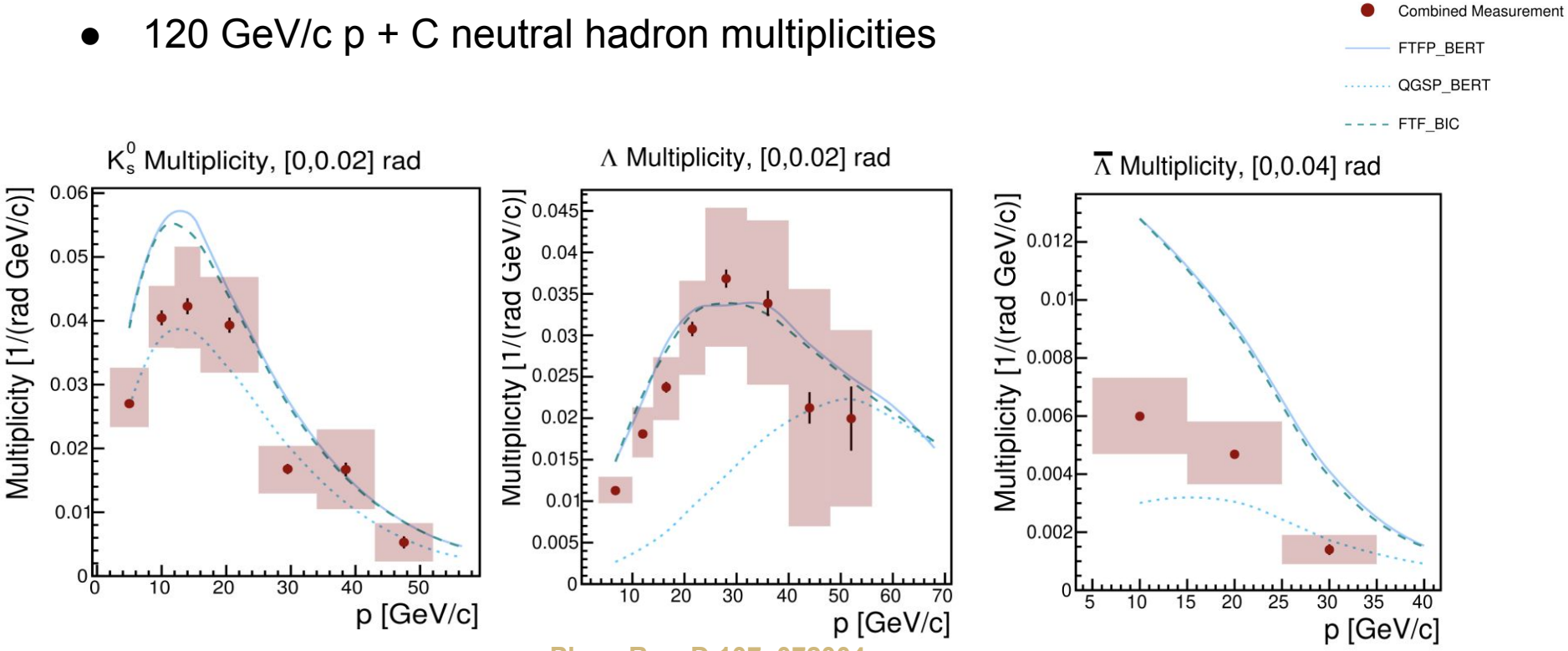
- Production and inelastic cross sections for π^+ + C/Be at 60 GeV/c
- Differential cross sections of π^-, π^+, K^-, K^+, protons, K^0_S, Λ and anti-Λ



Phys. Rev. D 100, 112004

Thin Target Measurements for FNAL Experiments

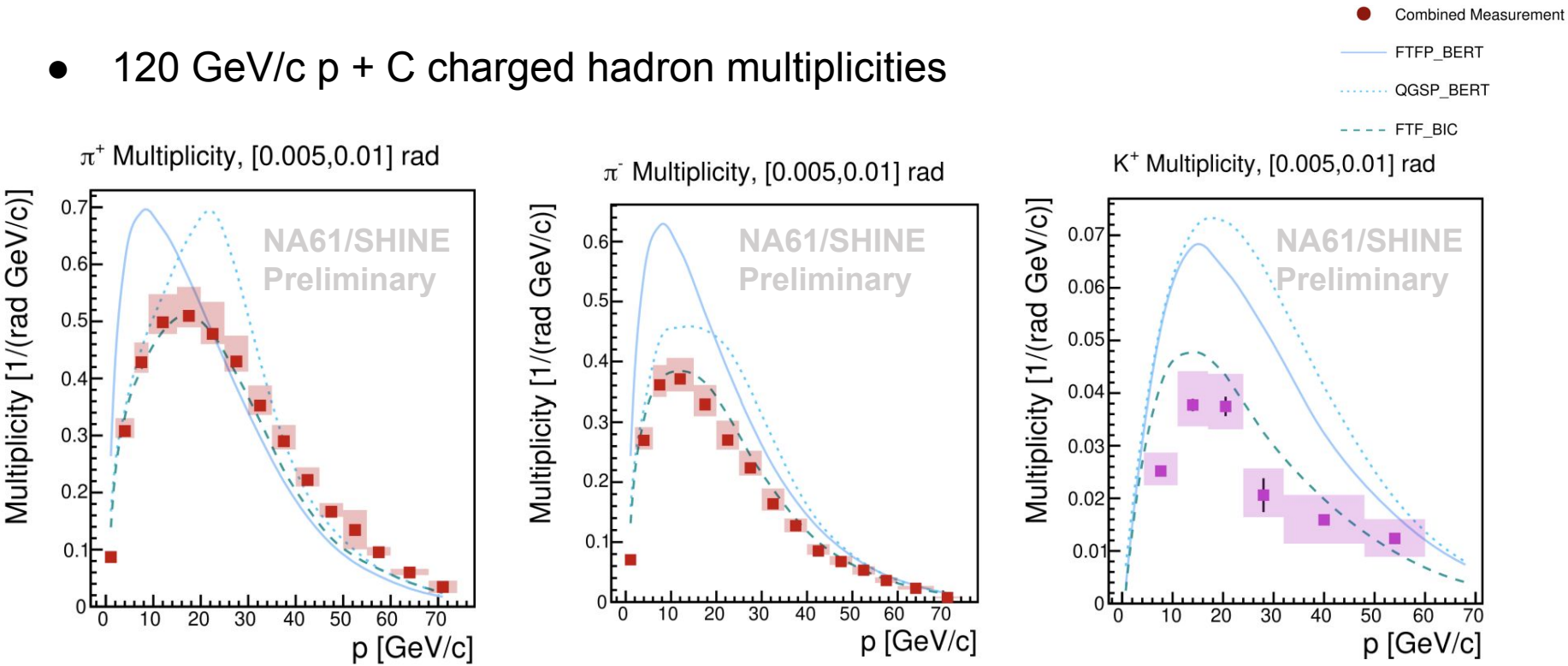
- 120 GeV/c p + C neutral hadron multiplicities



Phys. Rev. D 107, 072004

Thin Target Measurements for FNAL Experiments

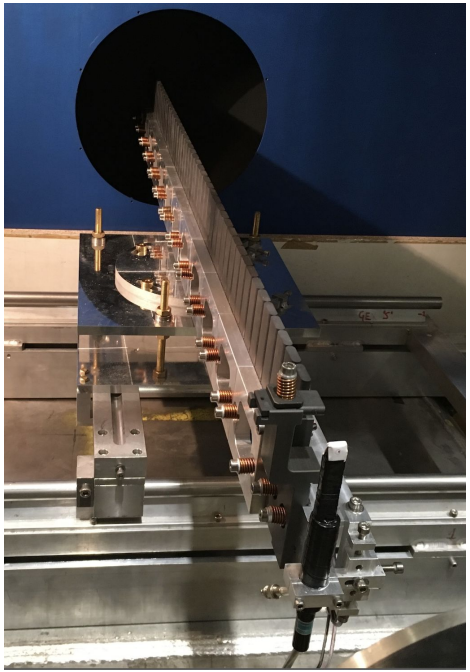
- 120 GeV/c p + C charged hadron multiplicities



arXiv:2306.02961

Ongoing Analyses for FNAL Experiments

- 60 GeV/c p + C charged and neutral hadron multiplicities
- 90 GeV/c p + C charged and neutral hadron multiplicities
- 120 GeV/c p + NuMI replica target data analysis
- Implementing 120 GeV/c p + C results into PPFX
    - Could be used by all NuMI experiments and DUNE



2022 - 2025

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

	2 cm Carbon	T2K replica	1.5 cm Carbon	Al	Be	Ti	NuMI replica	LBNF replica
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60 GeV/c			p, K, π^+	p, π^+	p, π^+	p, K		
90 GeV/c			p					
120 GeV/c			p		p	p	p	p*
8 GeV/c					p*			

* Proposed

2022 - 2025

- 31 GeV/c protons on T2K replica target (2022)
  - 18 times more statistics than 12 years ago, being calibrated
- 60 GeV/c kaon on thin graphite target and 120 GeV/c proton on thin titanium target (2023)
- 120 GeV/c proton on LBNF/DUNE prototype target (2024)
- A new tertiary low-energy (2-13 GeV/c) beamline (2025 - beyond LS3)
  - Measurements for the booster beam at Fermilab
  - Secondary interaction at T2K
  - Low-energy neutrinos from spallation sources (i.e. JSNS^2)
  - Understanding the production of atmospheric neutrinos

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 foreseen in the coming year
- Low-energy beamline being proposed and studied
- ***We welcome new collaborators!***

U.S. DEPARTMENT OF ENERGY | Office of Science

Thank you!