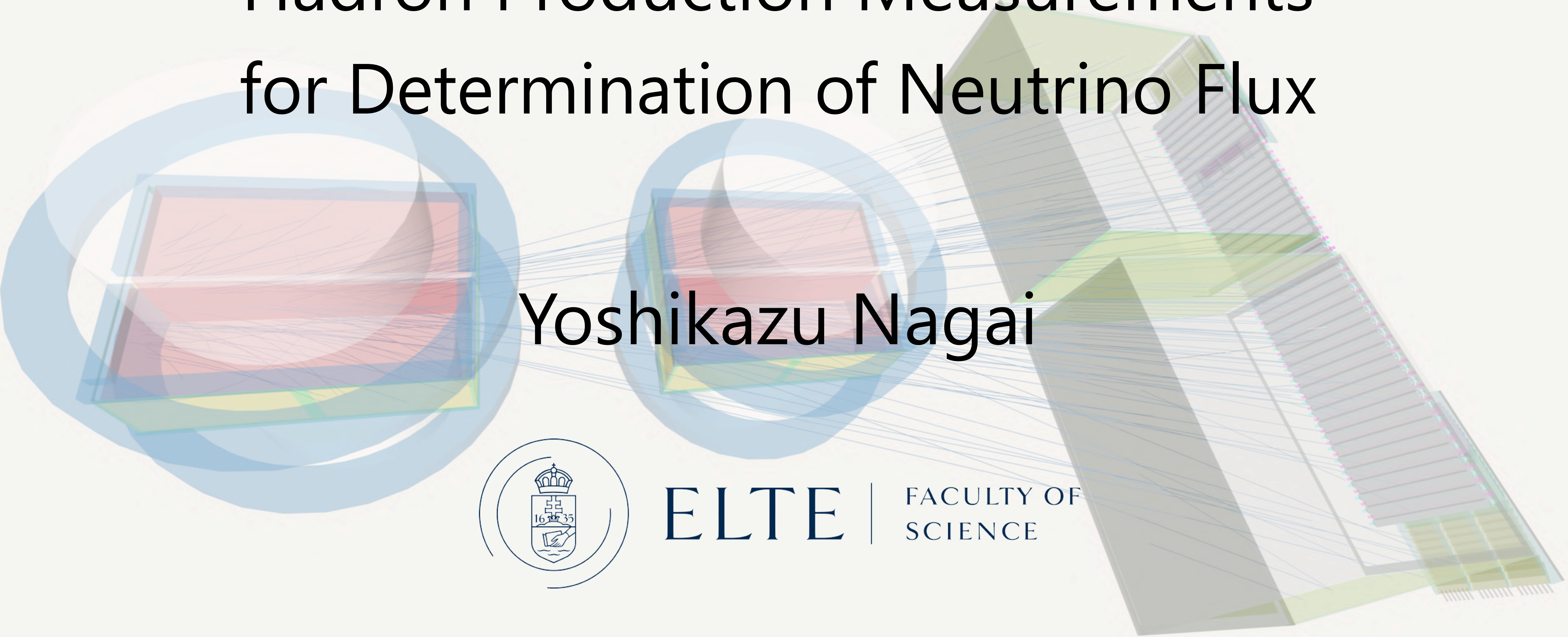
figure credit: the NA61/SHINE collaboration
(http://shine3d.web.cern.ch/shine3d)

Hadron Production Measurements for Determination of Neutrino Flux



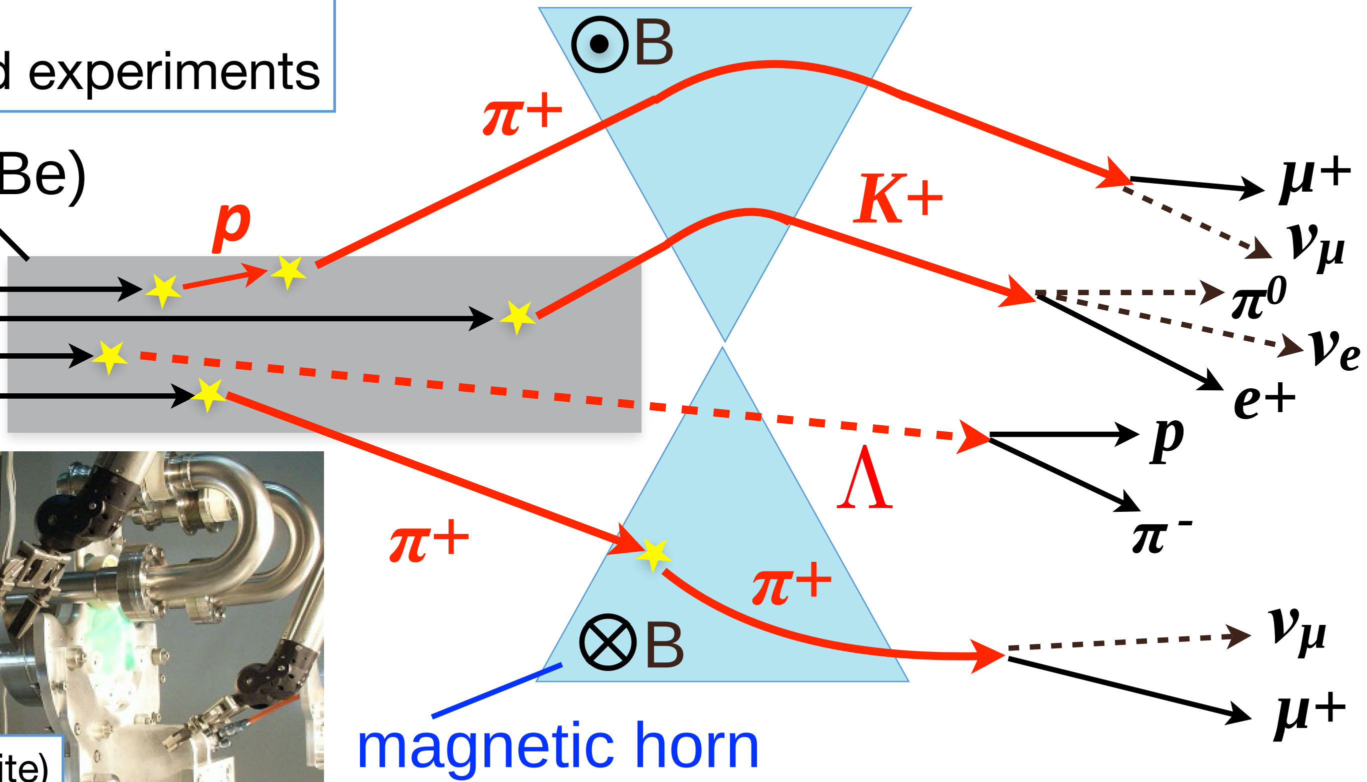
Yoshikazu Nagai

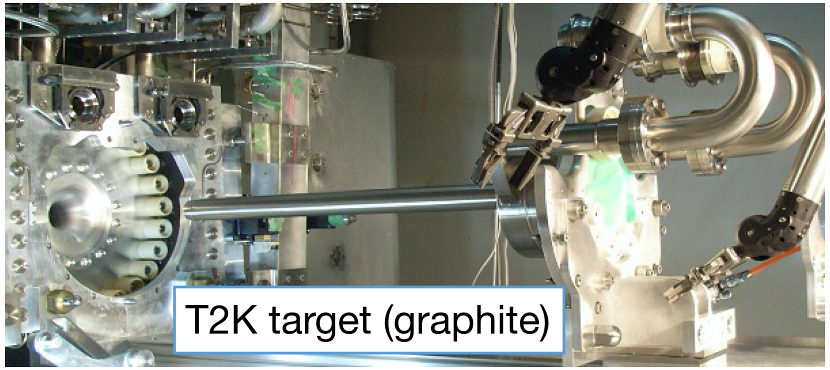
ELTE | FACULTY OF SCIENCE

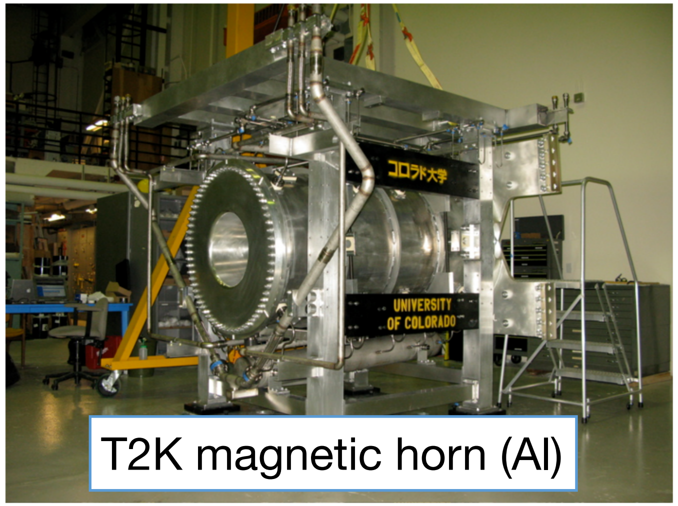
XXXI International Conference on Neutrino Physics and Astrophysics (NEUTRINO 24)
June 16-22, 2024 Milan, Italy

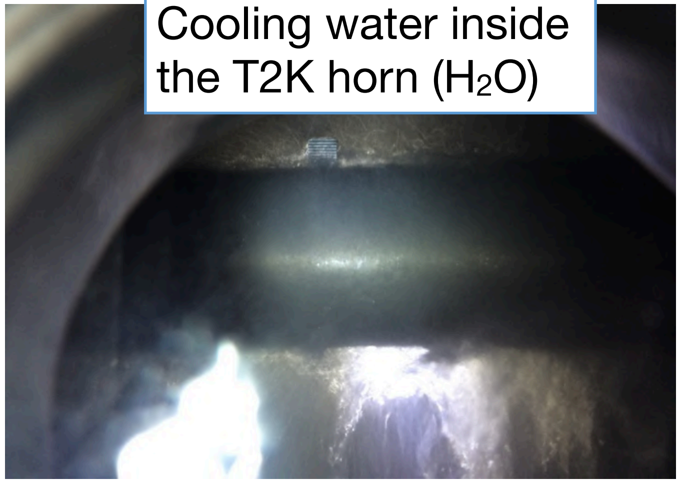
Neutrino Production

Example:
Accelerator-based experiments




T2K target (graphite)


T2K magnetic horn (Al)


Cooling water inside the T2K horn (H_2O)

Hadron production process is complex!!

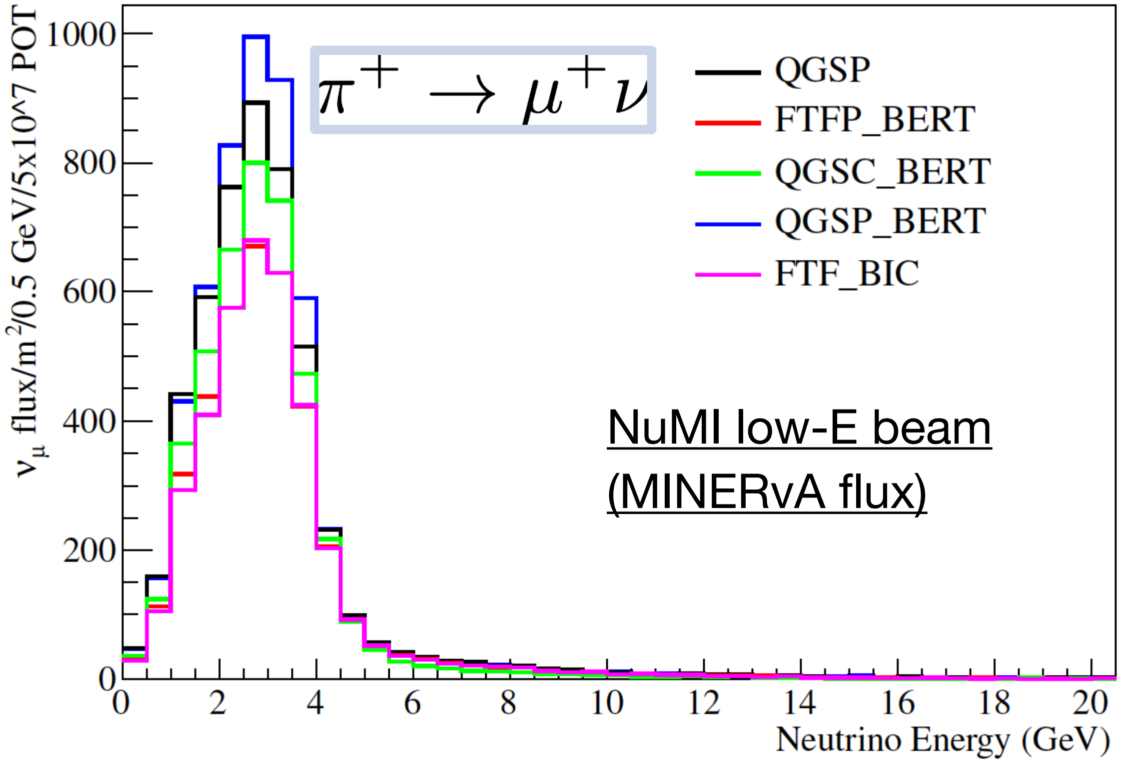
- Primary (p + C/Be -> $\pi^{\pm}$ and $K^{\pm}$) and secondary (Hadrons + C/Ti/Al/Cooling Water ..) interactions
- Neutral hadron decay (p + C —> V^0 + X) ($V^0 = \Lambda, K^0_L$, etc)

Neutrino Flux Prediction

We rely on hadronic interaction models to calculate the neutrino flux

- FLUKA (J-PARC/T2K), Geant 4 FTFP_BERT (Fermilab experiments)

Leo Aliaga (Ph.D Thesis, 2016)



Hadron production modeling is tough..

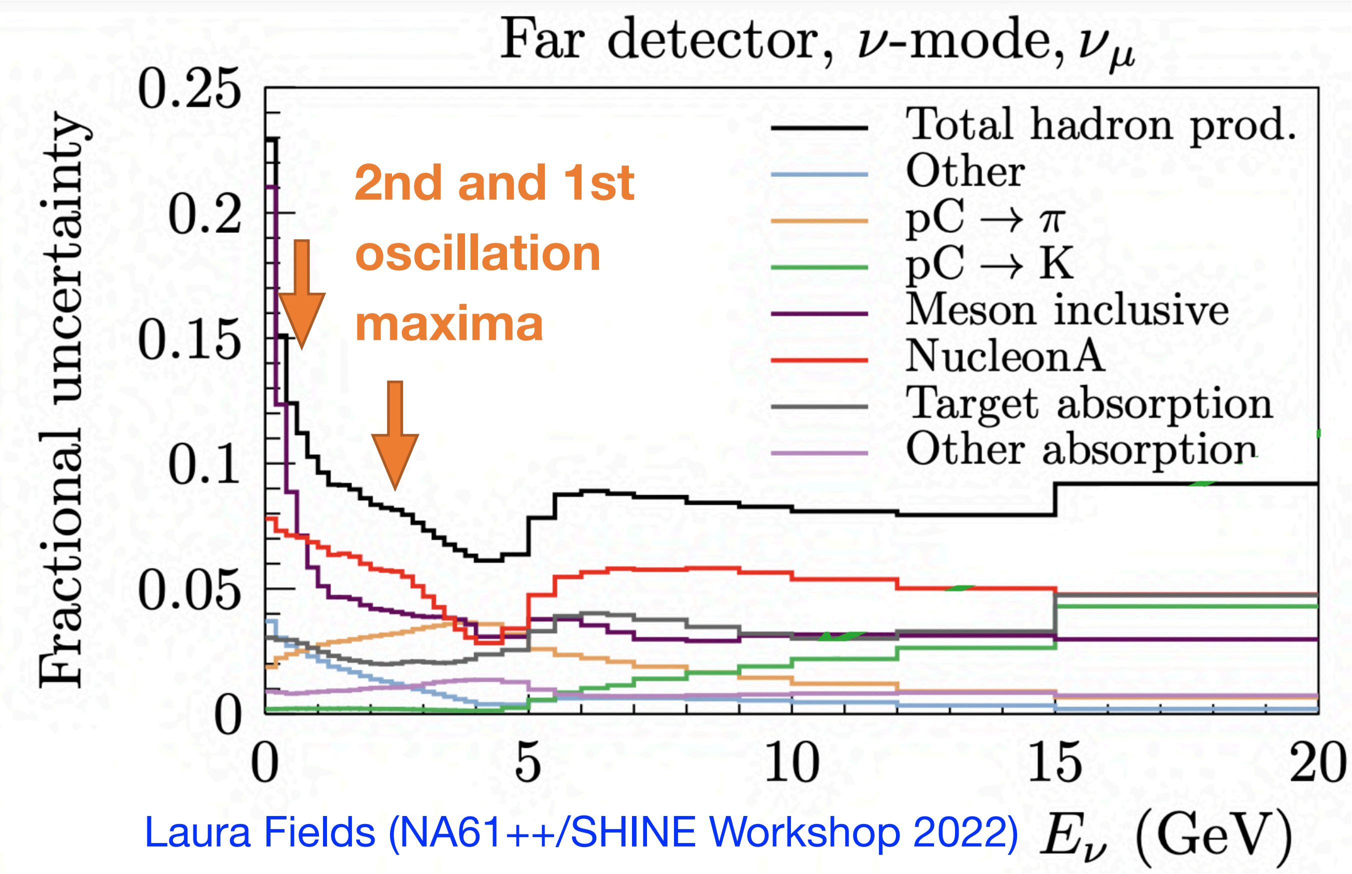
It can reach **> 40%** uncertainty if we do not have any data to constrain hadron production and interactions of neutrino parents

To meet the requirement of next-generation experiments,

External hadron production data are crucial!!

Neutrino Flux Uncertainty

DUNE flux (future LBNF, proton 120 GeV)



Laura Fields (NA61++/SHINE Workshop 2022)

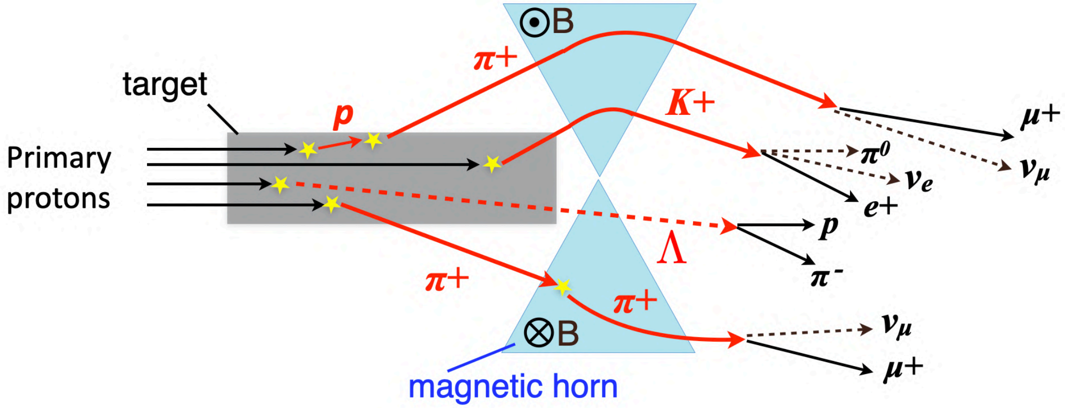
Used data NA49 (CERN SPS) data with x_F-scaling

More reduction is desirable to achieve physics goals for current and future experiments

—> Same demand for other accelerator-based experiments (T2K, NOvA, SBND, etc)

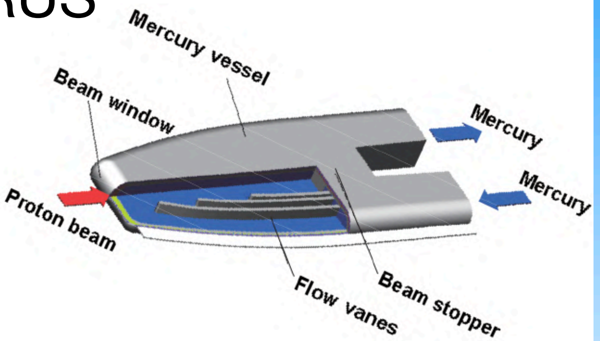
Relevant Neutrino Experiments

Flux calculation of these experiments include **hadron production & interactions**



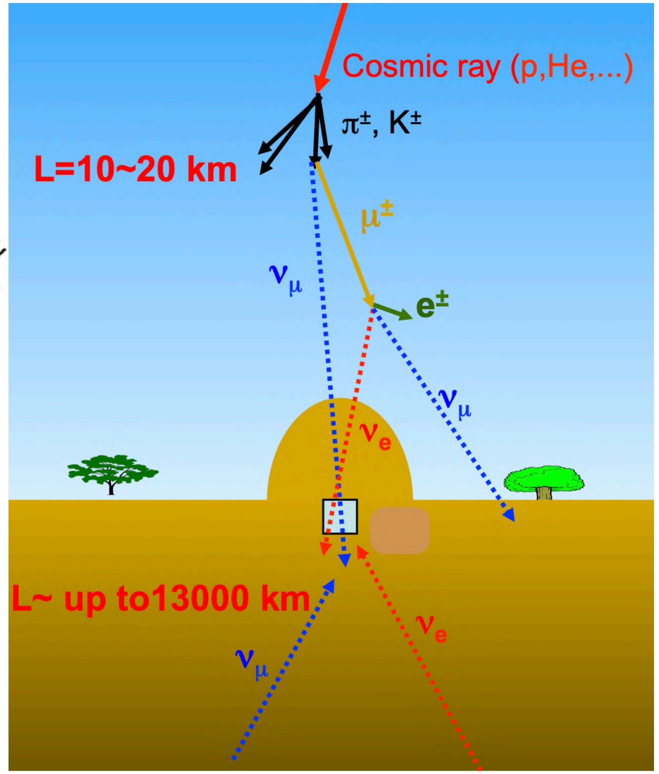
Accelerator-based

- (Long-baseline) NOvA, T2K, DUNE, T2HK
- (Short-baseline) SBND, MicroBooNE, ICARUS



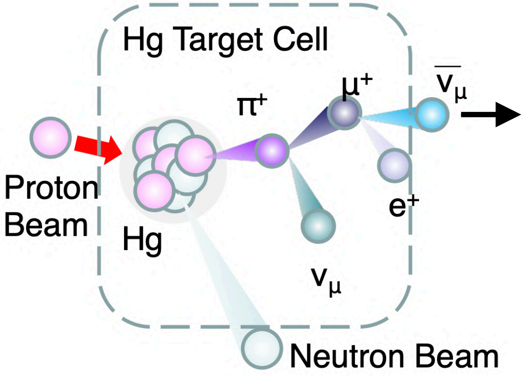
Atmospheric

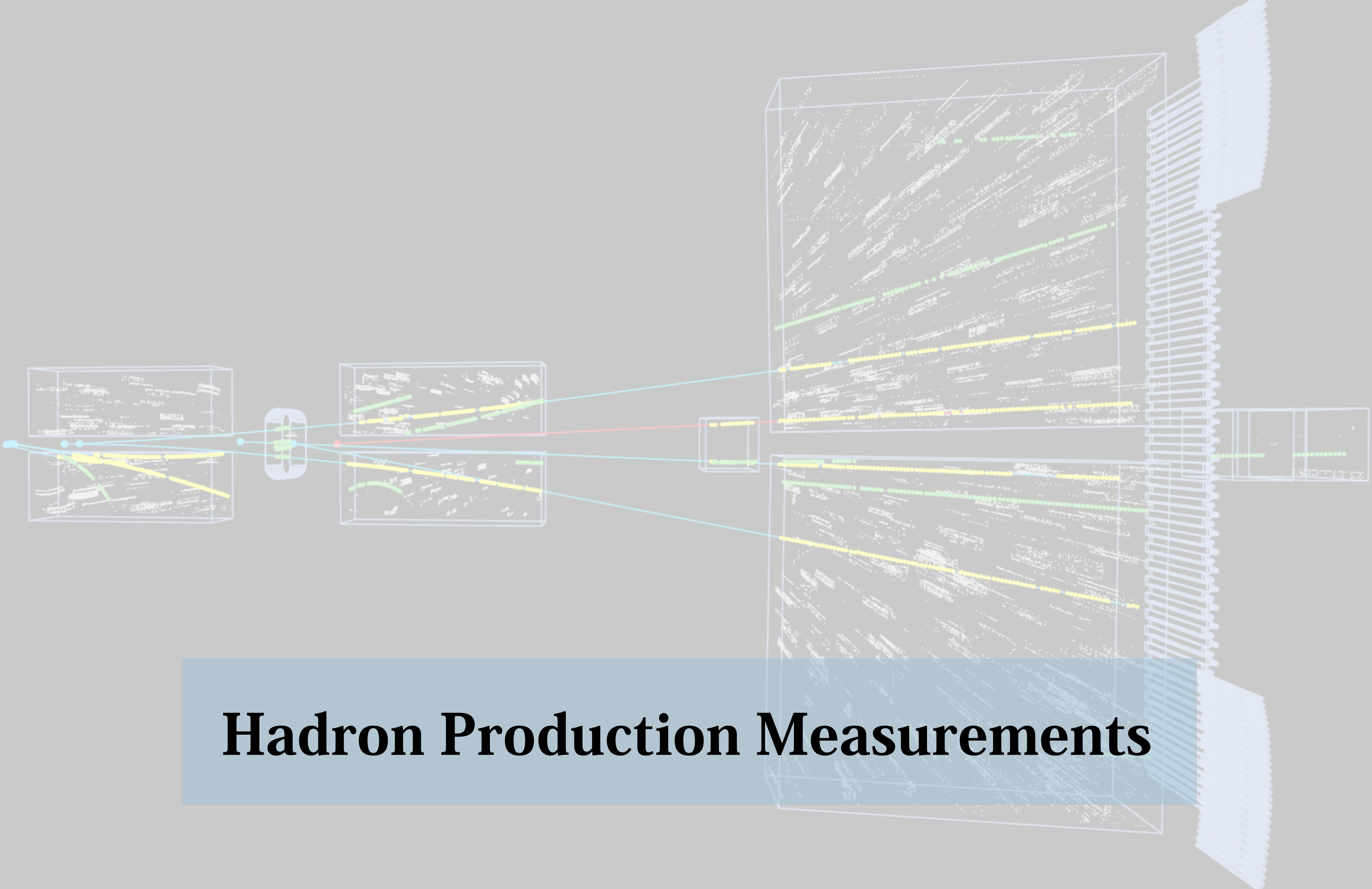
- (Long-baseline FDs) SK, DUNE, HK
- (Primarily for high-E) IceCube, KM3net



Neutron spallation facility

- (Short-baseline) JSNS², COHERENT
- (Long-baseline) ESSnuSB



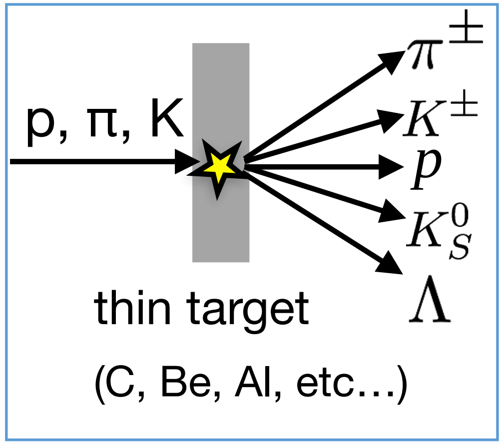


Hadron Production Measurements

Two Types of Measurements

Thin targets

A few % of λ nuclear targets to study single interactions

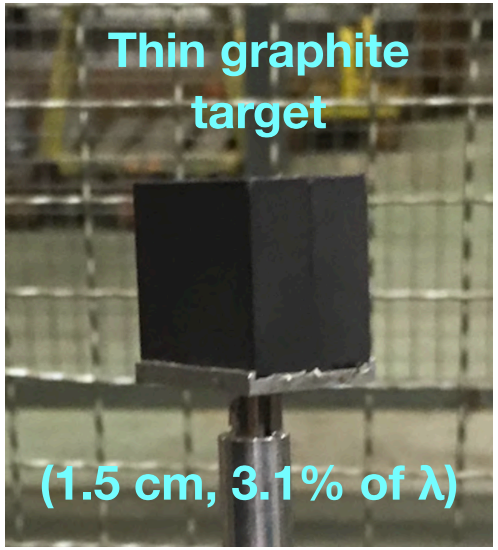


- **Total cross section**

$$\sigma_{\text{inel}} = \sigma_{\text{total}} - \sigma_{\text{el}}$$
$$\sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}}$$

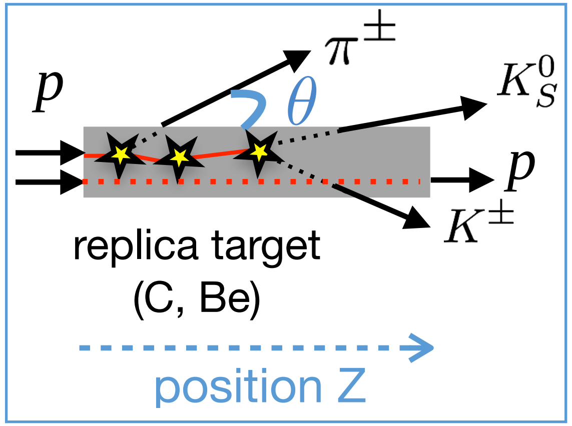
- **Differential hadron yields (Differential cross section)**

$$\frac{d^2 n}{dp\, d\theta} = \frac{1}{\sigma_{\text{prod}}} \frac{d^2\sigma}{dp\, d\theta}$$



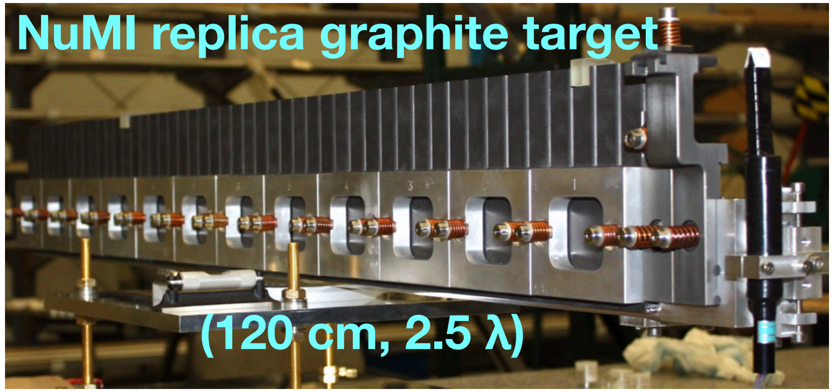
Replica (thick) targets

Exact copy of neutrino production targets



- **Differential hadron yields** $d^3 n / dp\, d\theta\, dz$
- **Beam attenuation (Production cross section)**

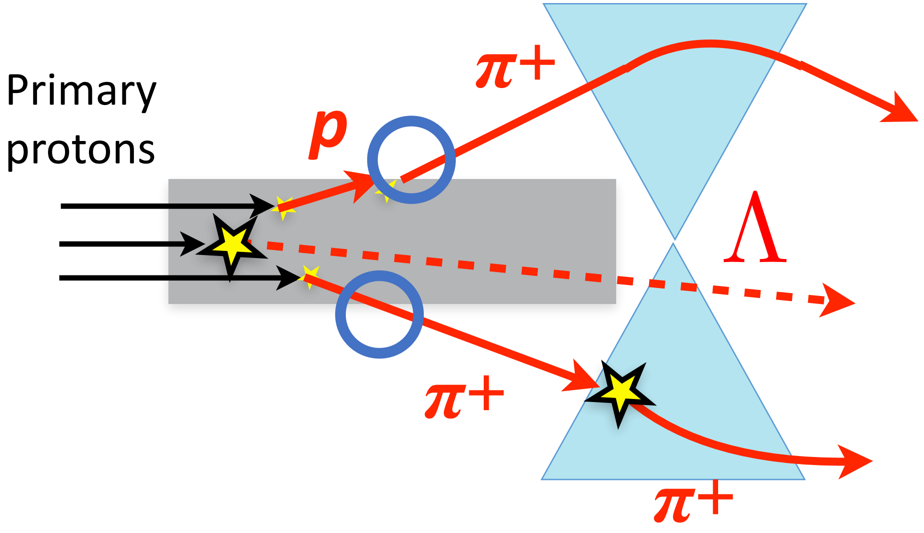
$$P_{\text{survival}} = e^{-Ln\sigma_{\text{prod}}}$$

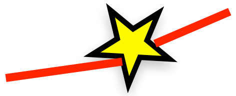
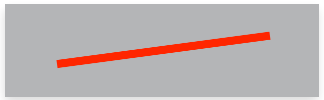


How to Improve Flux Model with External Data

Two corrections to constrain model ambiguity

- Interaction length: Tune production cross section to external measurement.
- Multiplicity: Tune differential hadron multiplicity to external measurement

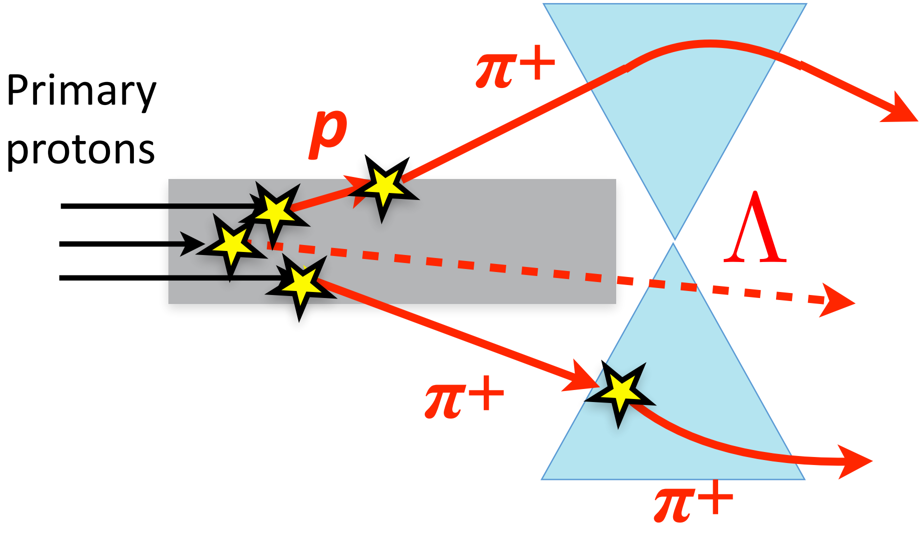


	Interaction length	Multiplicity
(replica target data) At exiting point 	N/A	"replica" weight $\left(\frac{d^3n}{dp\,d\theta\,dz}\right)_{\mathrm{Data}} \Big/ \left(\frac{d^3n}{dp\,d\theta\,dz}\right)_{\mathrm{MC}}$
(thin target data) At interaction 	"vertex" weight $\sigma_{\mathrm{Data}} / \sigma_{\mathrm{MC}}$	"thin" weight $\left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{Data}} \Big/ \left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{MC}}$
For distance L traversed 	"attenuation" weight $e^{-(\sigma_{\mathrm{Data}}-\sigma_{\mathrm{MC}})\rho L}$	N/A

How to Improve Flux Model with External Data

Two corrections to constrain model ambiguity

- Interaction length: Tune production cross section to external measurement
- Multiplicity: Tune differential hadron multiplicity to external measurement

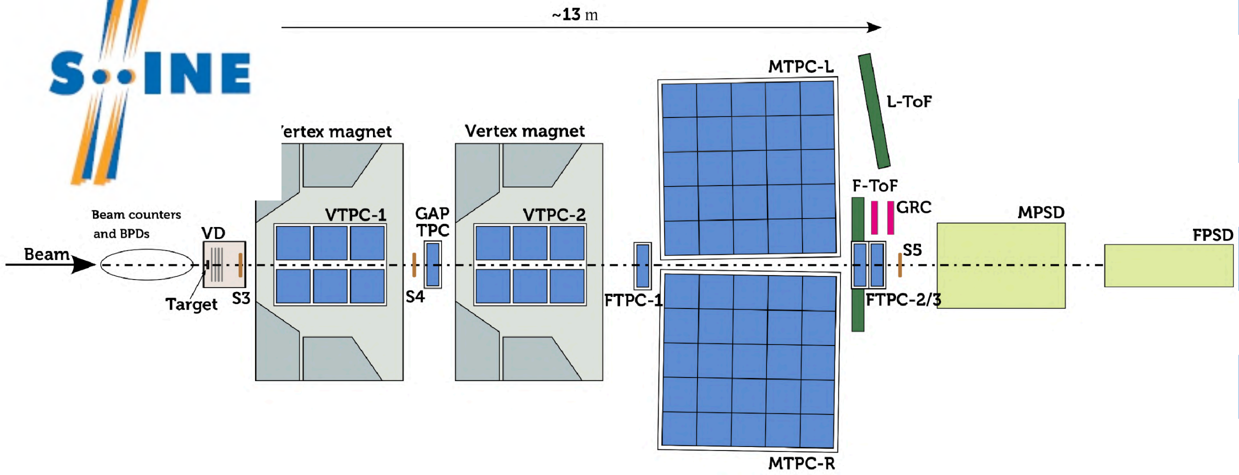


	Interaction length	Multiplicity
(replica target data) At exiting point	N/A	“replica” weight $\left(\frac{d^3n}{dp\,d\theta\,dz}\right)_{\mathrm{Data}} \Big/ \left(\frac{d^3n}{dp\,d\theta\,dz}\right)_{\mathrm{MC}}$
(thin target data) At interaction	“vertex” weight $\sigma_{\mathrm{Data}} / \sigma_{\mathrm{MC}}$	“thin” weight $\left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{Data}} \Big/ \left(\frac{d^2n}{dp\,d\theta}\right)_{\mathrm{MC}}$
For distance L traversed	“attenuation” weight $e^{-(\sigma_{\mathrm{Data}}-\sigma_{\mathrm{MC}})\rho L}$	N/A

Or, rely on “thin” weights if no “replica” weights are available

The Main Players

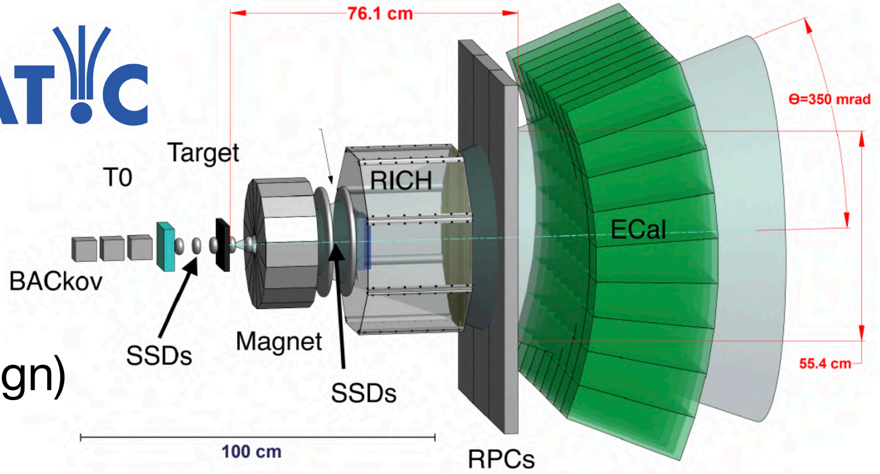
NA61/SHINE @ CERN SPS



The SPS Heavy Ion and Neutrino Experiment

EMPHATIC @ Fermilab Test Beam Facility

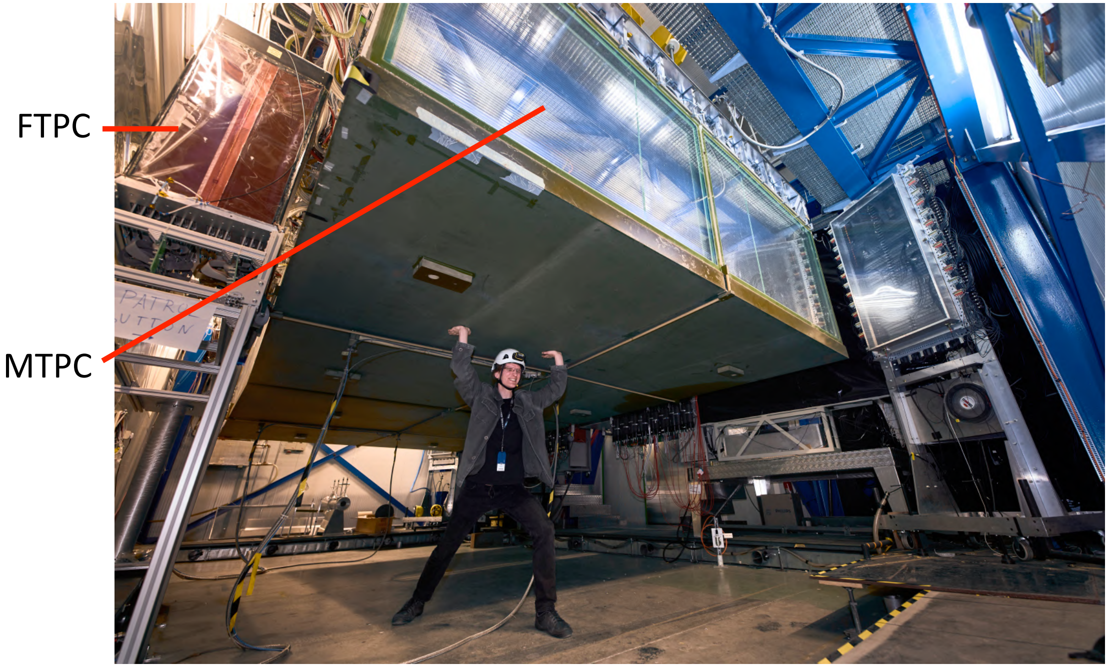
(ultimate design)



Experiment to Measure the Production of Hadrons At Testbeam In Chicagoland

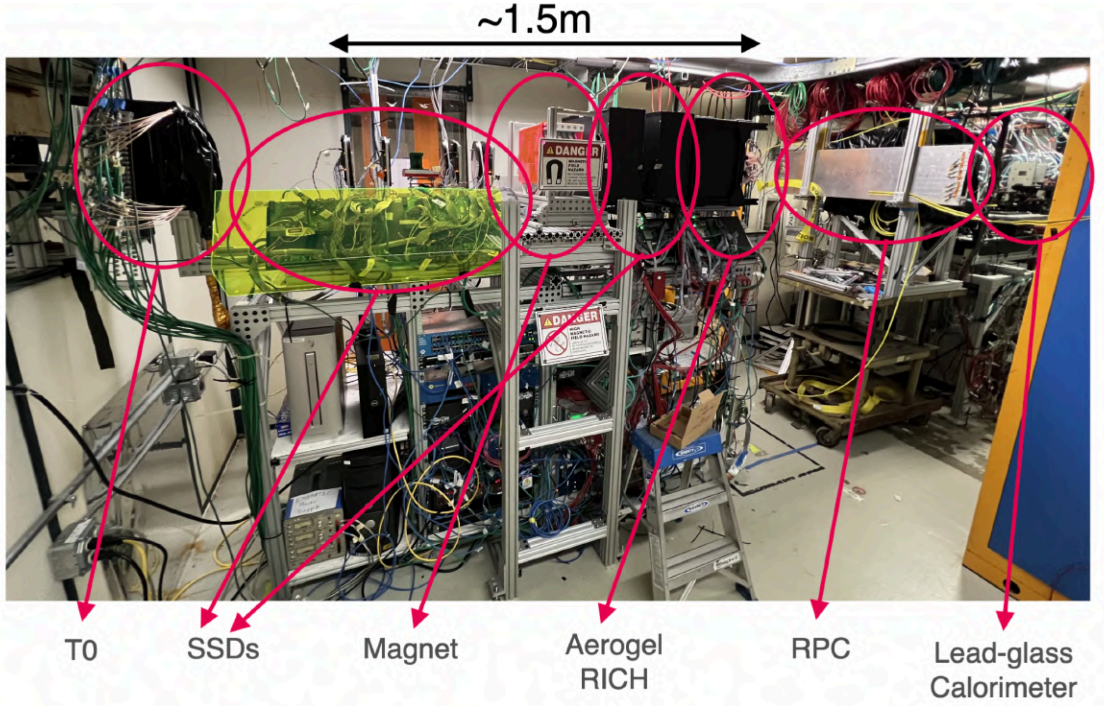
The Main Players

NA61/SHINE @ CERN SPS

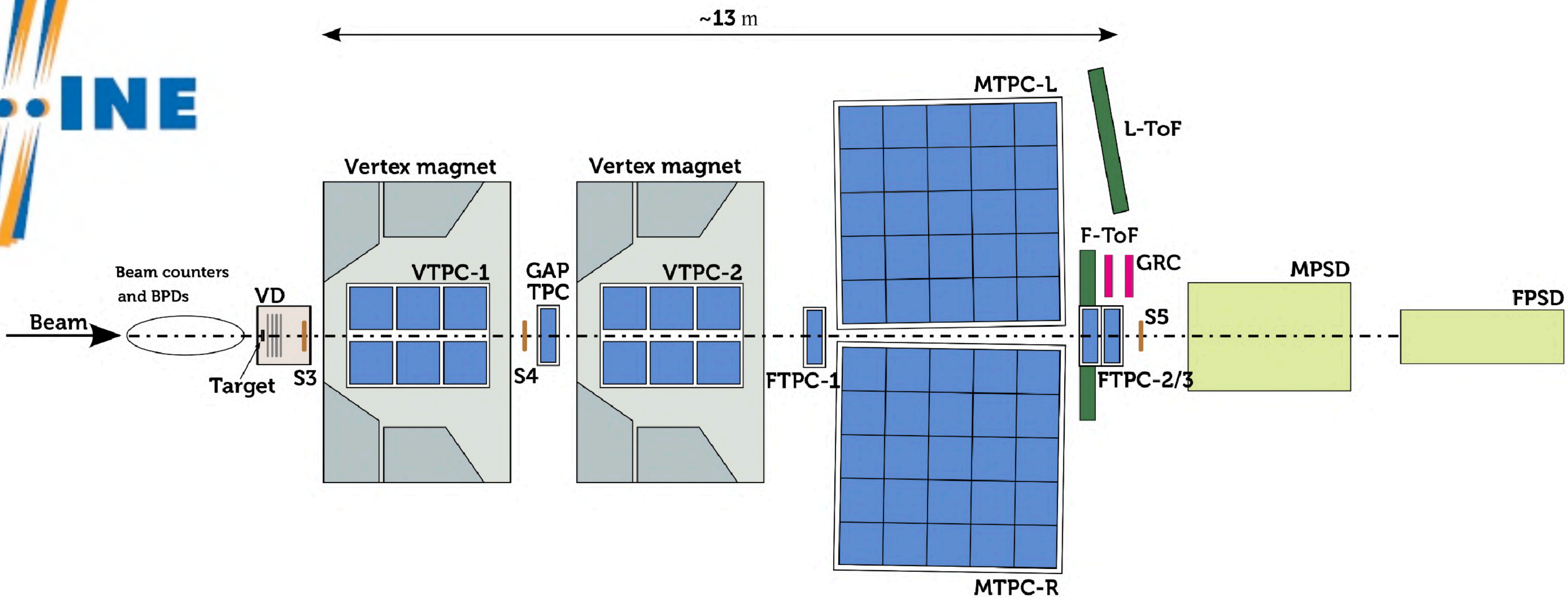


- Hadron beam: 13-350 GeV/c
- Large TPC-based spectrometer
  - 2 superconducting magnets (max 9 Tm)
- PID with TPC (dE/dx) + ToF
- DAQ rate: upgraded to ~1.5 kHz (was ~80 Hz)
- Capable of thin and replica target measurements

EMPHATIC @ Fermilab Test Beam Facility



- Hadron beam: 4-120 GeV/c
- Small-scale silicon strip-based spectrometer
  - a neodymium permanent magnet (1.2 Tm)
- PID with ToF + ARICH + Calorimeter
- DAQ rate: 17 kHz (now), up to 30 kHz (future)
- Capable of thin and target+horn measurements



NA61/SHINE Highlights

NA61/SHINE Data Collection History

2007 - 2010 | Long Shutdown (LS) 1 | 2015 - 2018 | LS2 | 2022 - 2025

Phase 1: T2K
protons at 31 GeV/c
- p + C (2cm graphite)
- p + T2K replica (90 cm graphite)

publications:
- *PRC* 84 034604 (2011)
- *PRC* 85 035210 (2012)
- *NIMA* 701 99-114 (2013)
- *PRC* 89 025205 (2014)
- *EPJC* 76 84 (2016)
- *EPJC* 76 617 (2016)
- *EPJC* 79 no.2 100 (2019)
- *PRD* 103 012006 (2021)

Analysis complete!

Phase 2: NuMI and LBNF
hadrons at 60-120 GeV/c
- various thin targets (C, Be, Al)
- p + NuMI replica (120 cm graphite)

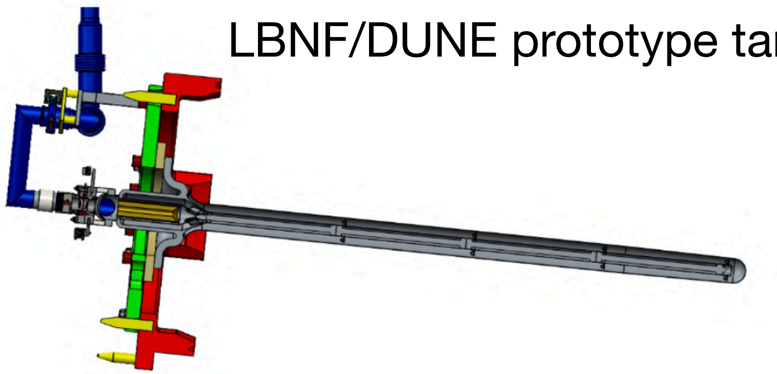
publications:
- *PRD* 98 052001 (2018)
- *PRD* 100 112001 (2019)
- *PRD* 100 112004 (2019)
- *PRD* 107 072004 (2023)
- *PRD* 108 072013 (2023)

Data collection complete.
More results will come!

Phase 3: T2K, NuMI, LBNF
hadrons at 31-120 GeV/c
- p + T2K replica (x15 data stat.)
- various thin targets (C, Ti)
- p+DUNE prototype (150 cm graphite)

Data collection is ongoing!

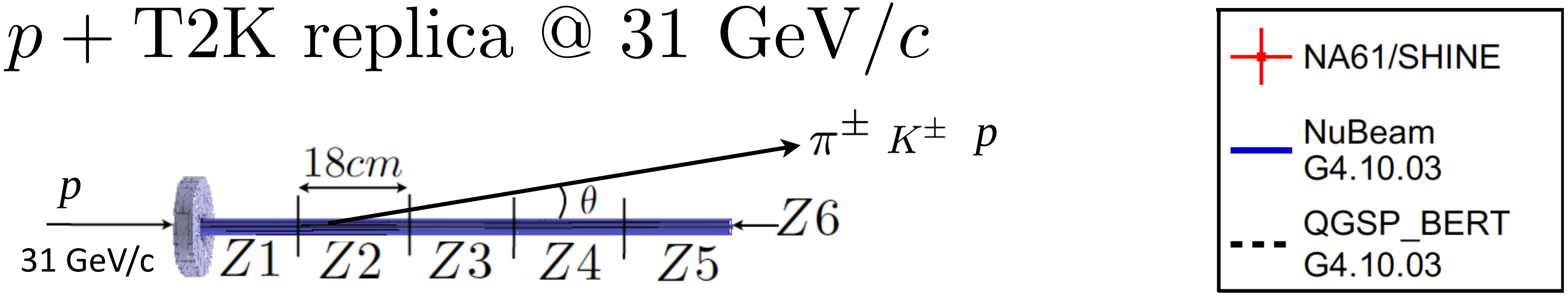
LBNF/DUNE prototype target

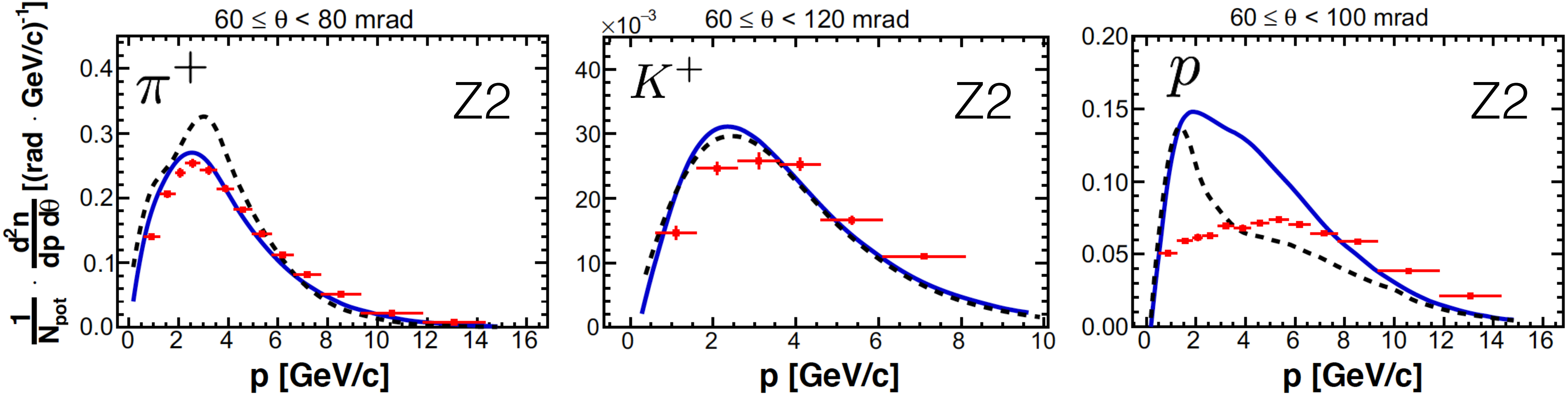


Summer 24 run in two weeks!!

NA61/SHINE Highlights: Phase 1 for T2K

$p + \text{T2K replica @ 31 GeV}/c$





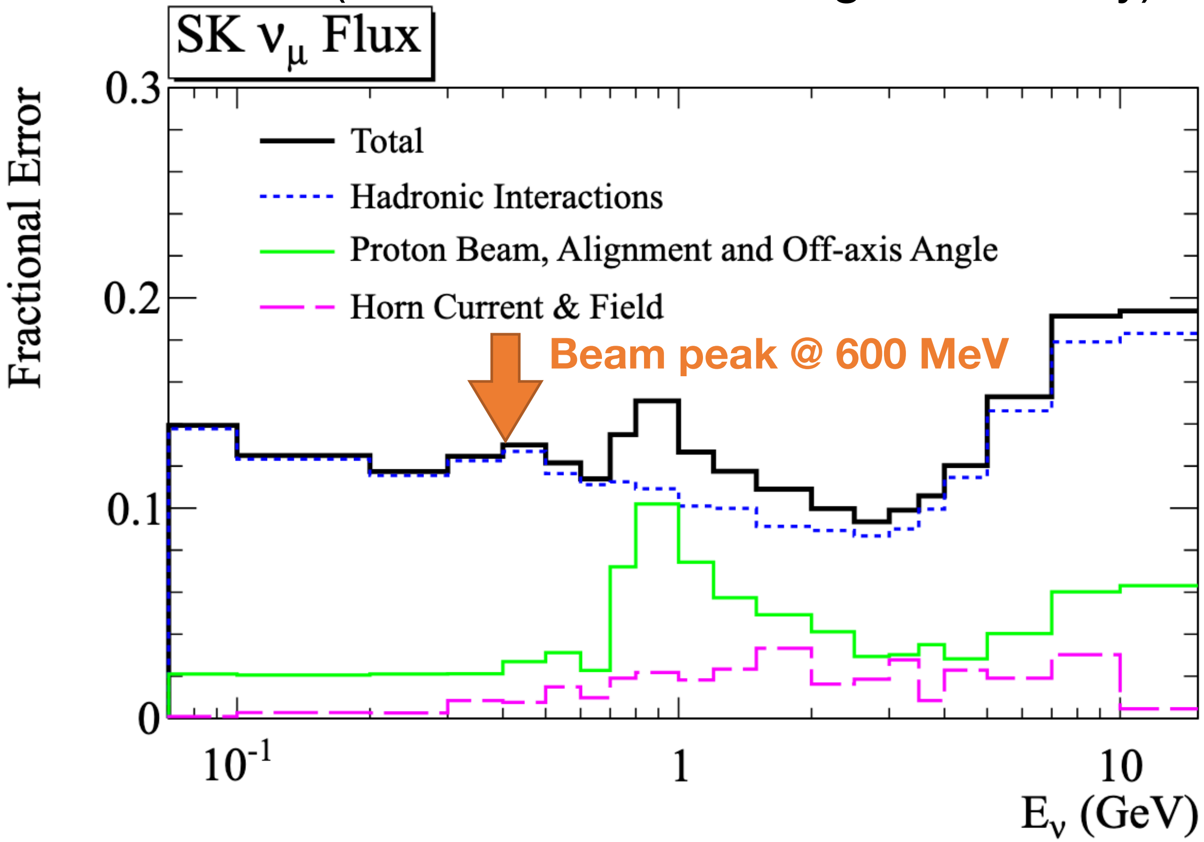
Eur. Phys. J. C79, no.2 100 (2019)

Provide constraints on hadron yields exiting the T2K target

T2K Flux Prediction with NA61/SHINE Data

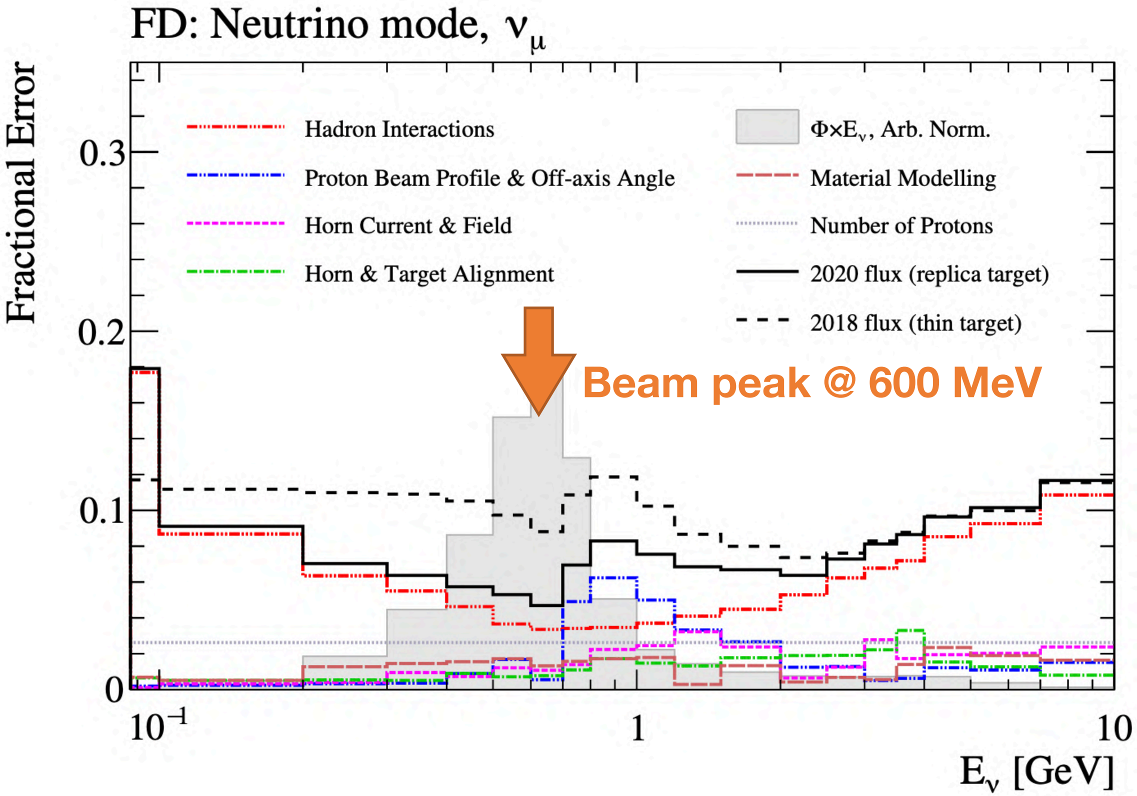
T2K: Phys. Rev. D87, 012001 (2013)

(NA61/SHINE thin target data only)



T2K: Eur. Phys. J.C 83, no.9, 782 (2023)

(NA61/SHINE thin + replica target data)



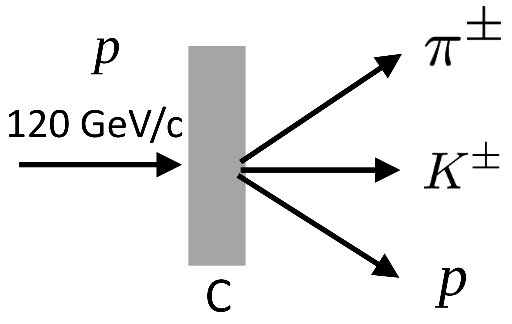
Achieved: T2K flux uncertainty down to 5% (~3% from hadron interactions)

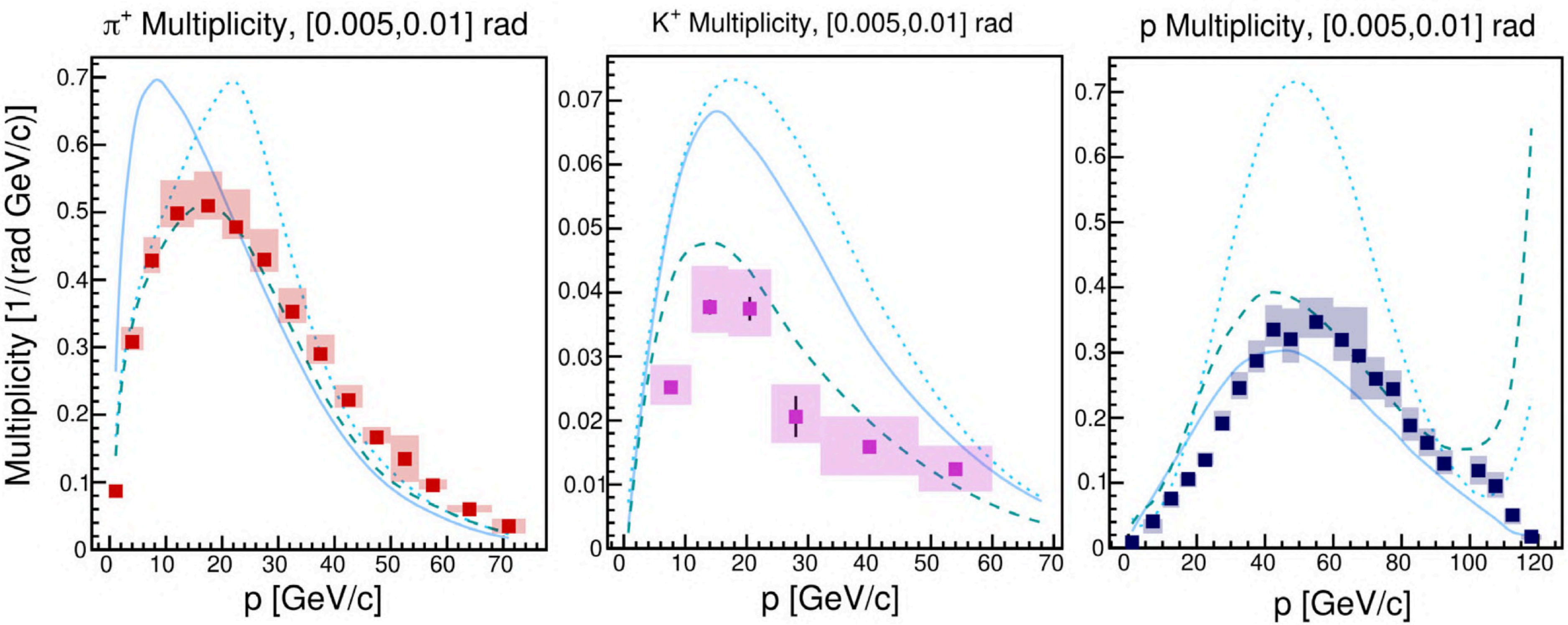
Future improvement: off-peak flux uncertainty, intrinsic beam background (anti-ν, ν_e)

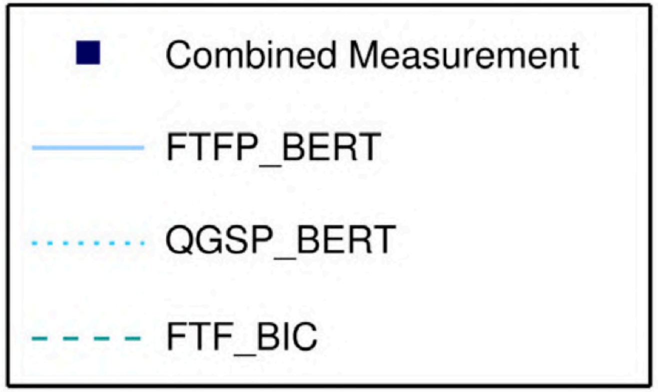
(For intrinsic beam background, current uncertainty is 5-10% at the beam peak)

NA61/SHINE Highlights: Phase 2 for NuMI/LBNF

$p + \mathrm{C}$ @ $120\ \mathrm{GeV}/c$

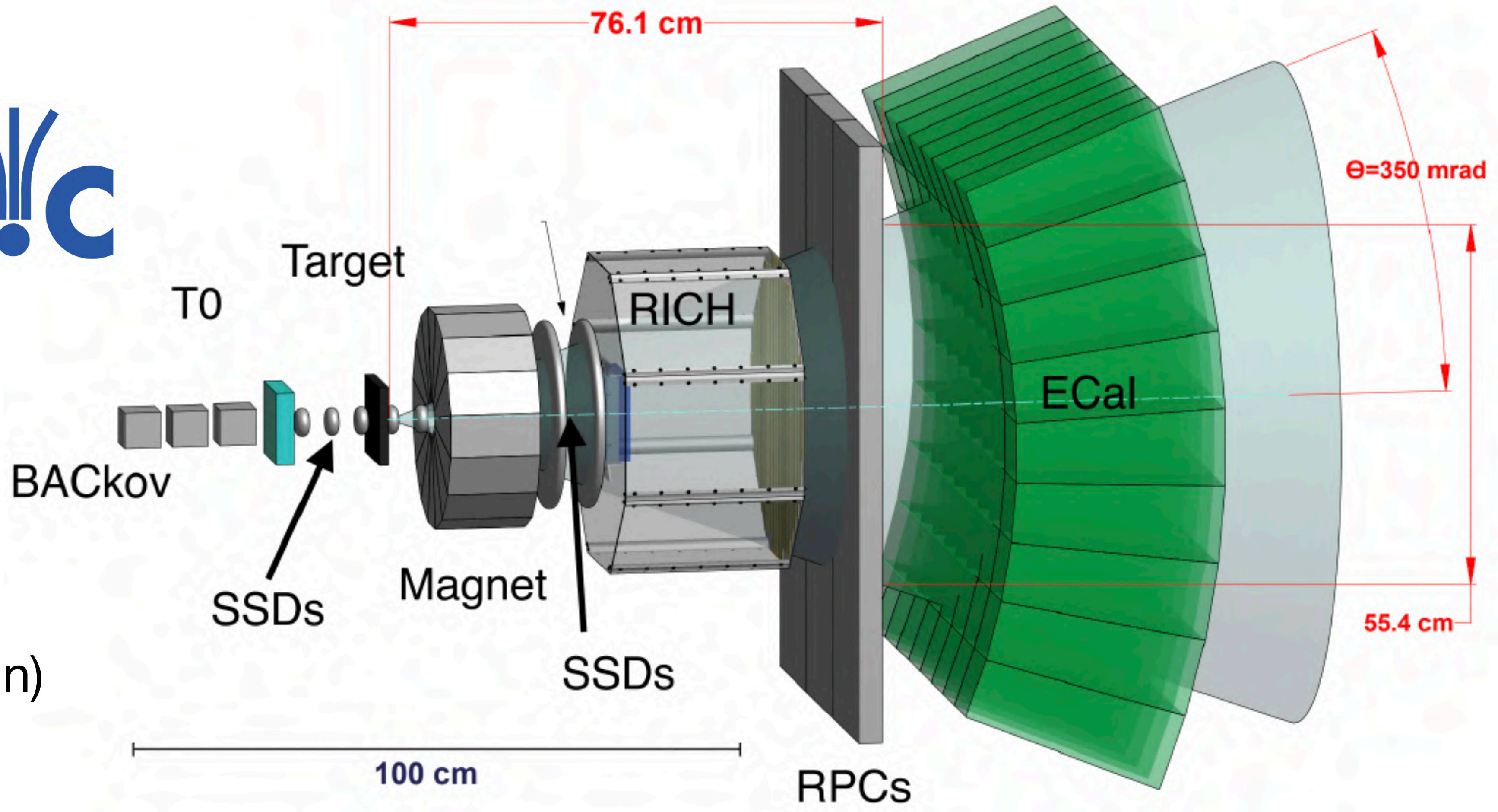






Phys. Rev. D 108, 072013 (2023)

Provide constraints on primary interactions for NuMI/LBNF neutrino fluxes



(ultimate design)

EMPHATIC Highlights

EMPHATIC Data Collection History

Phase 0 (2018)
- Proof-of-principle (0-20 mrad)
  - No spectrometer
- Total cross section measurements in forward scattering

- *PRD* 106 112008 (2022)

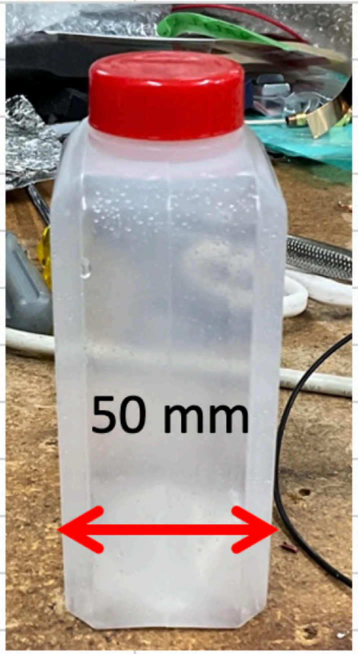
Phase 1 (2022-2023)
- Limited phase-space (0-100 mrad)
- 4-120 GeV/c hadron beams beams
  - proton, pion, kaon

Data collection complete.
More results will come!

Phase 1 datasets

Target	Beam Mom (GeV/c)	# Triggers	Target	Beam Mom (GeV/c)	# Triggers
Graphite	120	2.5M	Berylium	-4	11M
	4	11M		4	11M
	-4	11M		8	13M
	-8	38M	CH2	-20	14M
	-12	18M		-8	8.5M
	20	12M		-4	3M
	-20	14M	H2O	-4	10M
	30	23M		4	10M
				-20	5.6M

Leo Aliaga (NuINT 2024)

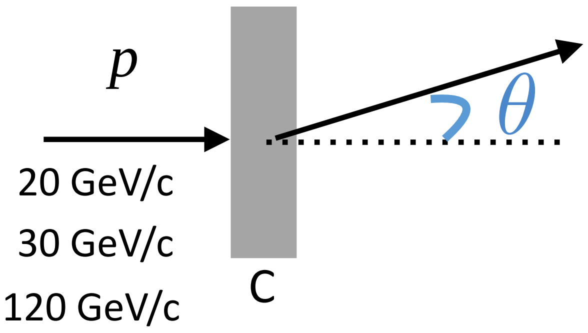


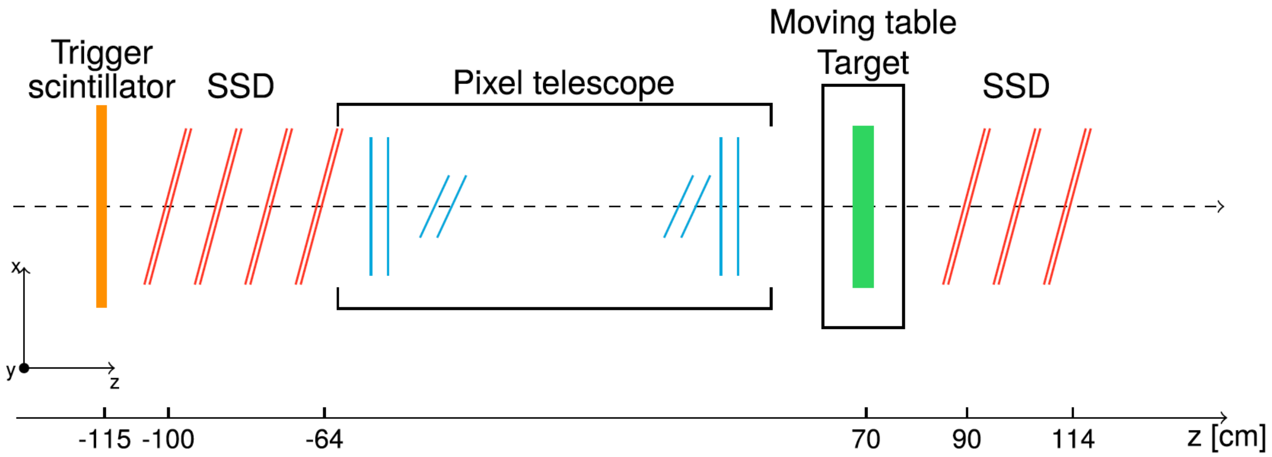
Super-fancy water target

Phase 2 (beginning 2024)
- Similar acceptance as Phase 1
- Install motion table for larger phase-space scan

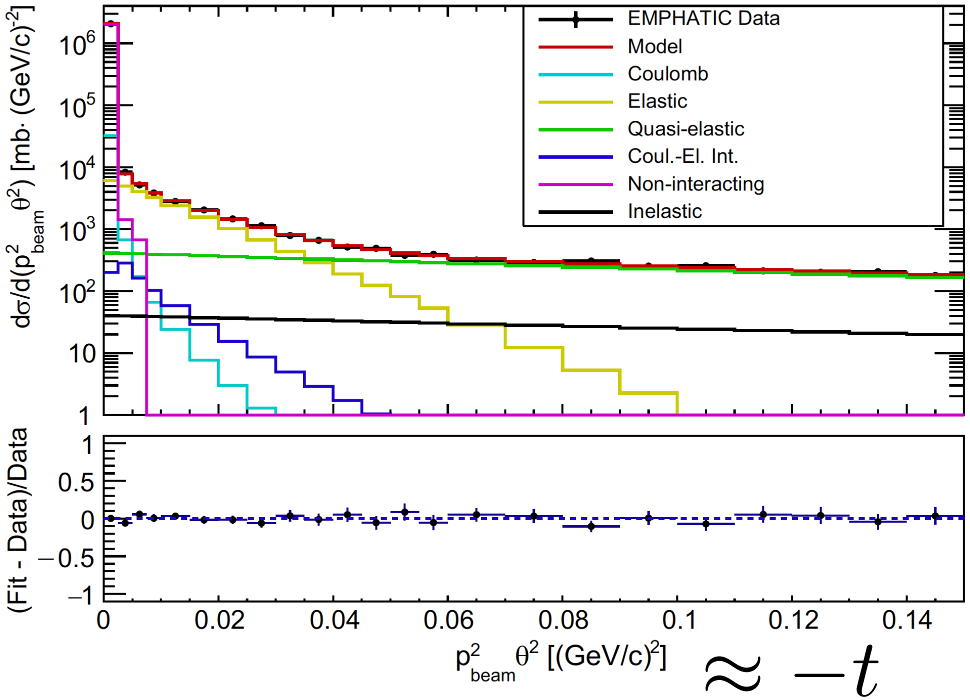
The new approach with the advantage of the small-scale experiment

EMPHATIC Highlights: Phase 0 PoP

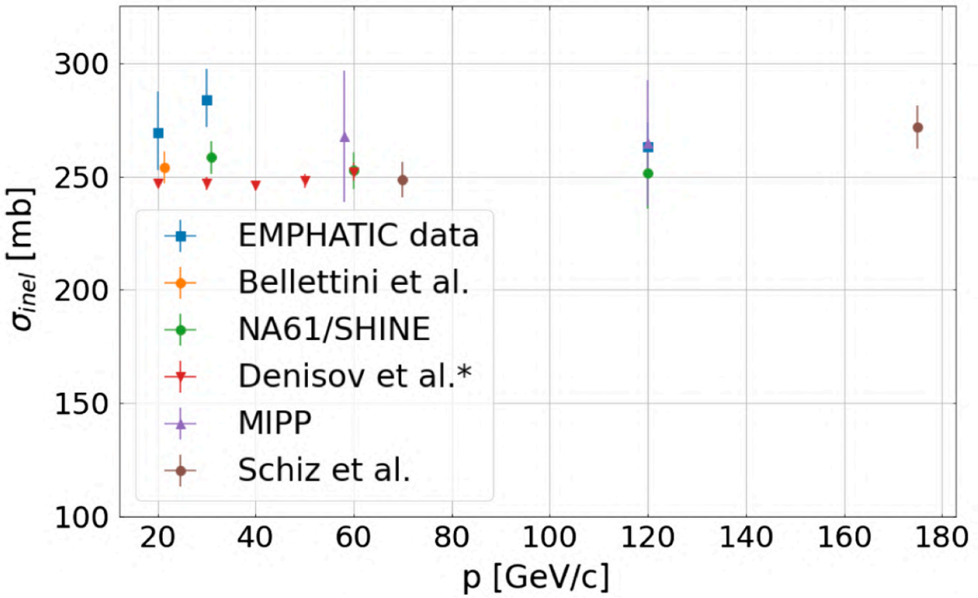




(No spectrometer)



$\approx -t$

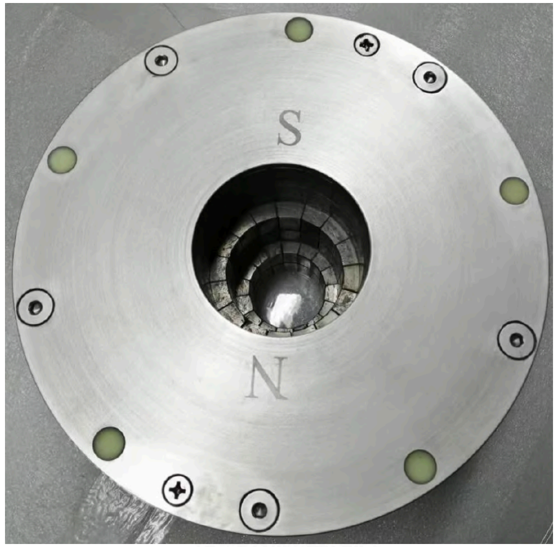


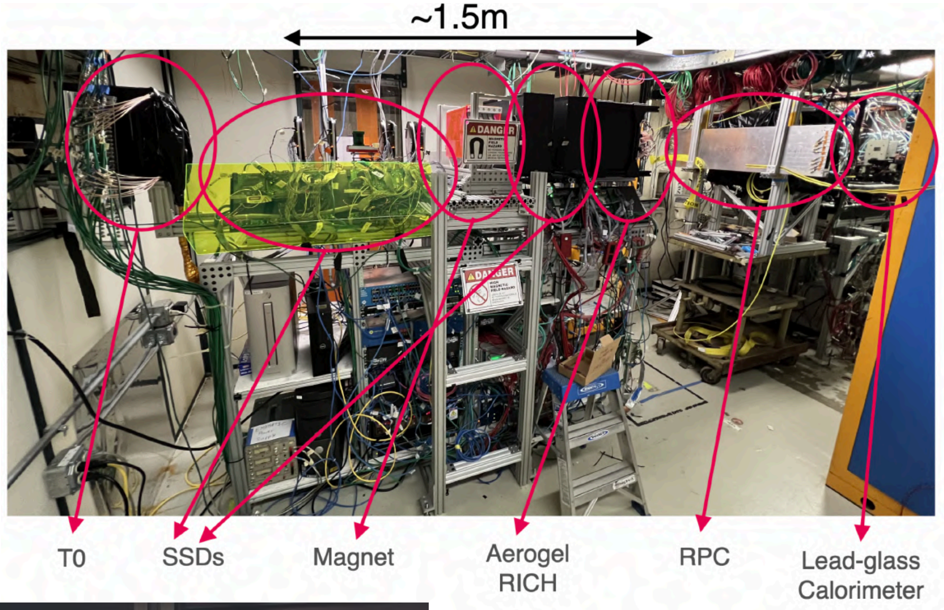
Total, elastic, and inelastic cross sections are measured.

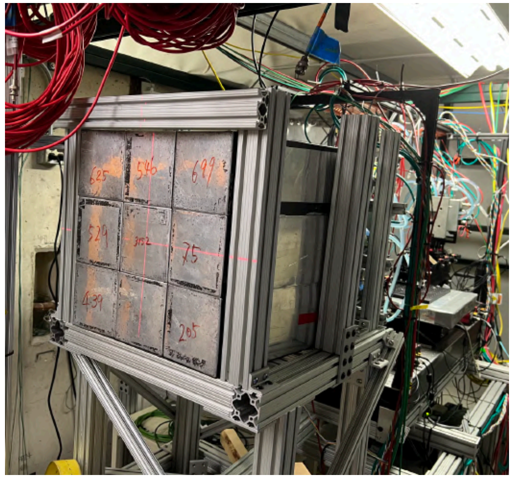
Statistically-limited measurement
—> systematics are at the few % level

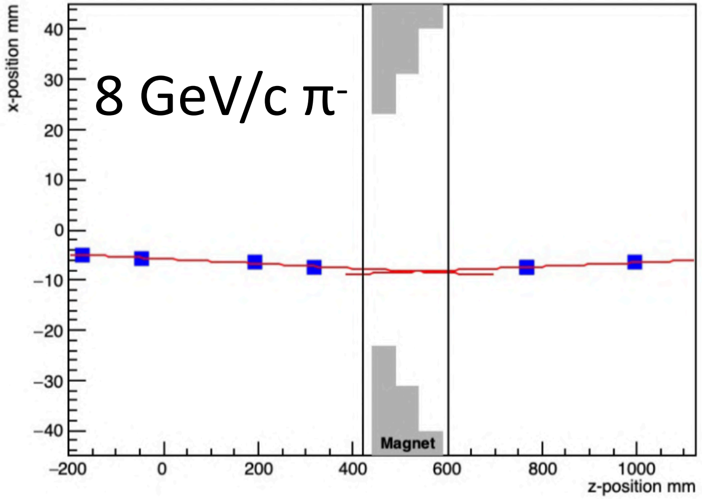
Phys. Rev. D 106, 112008 (2022)

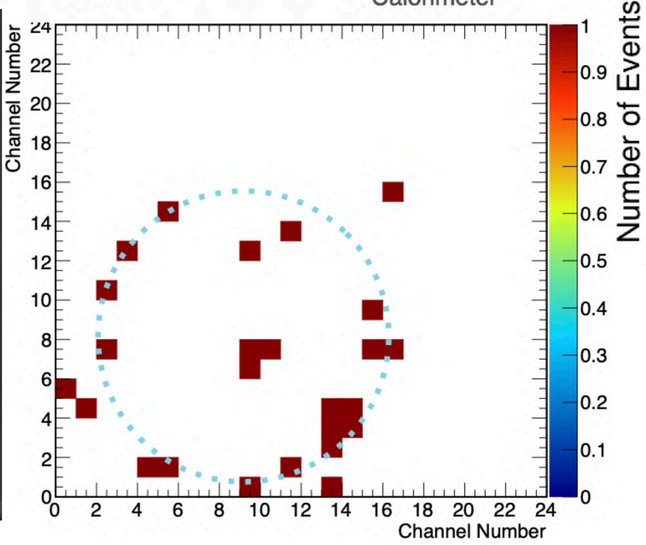
EMPHATIC Highlights: Phase 1 Data

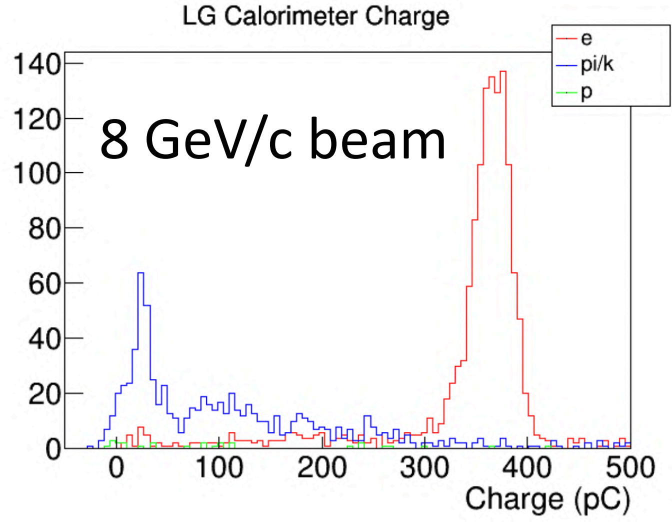




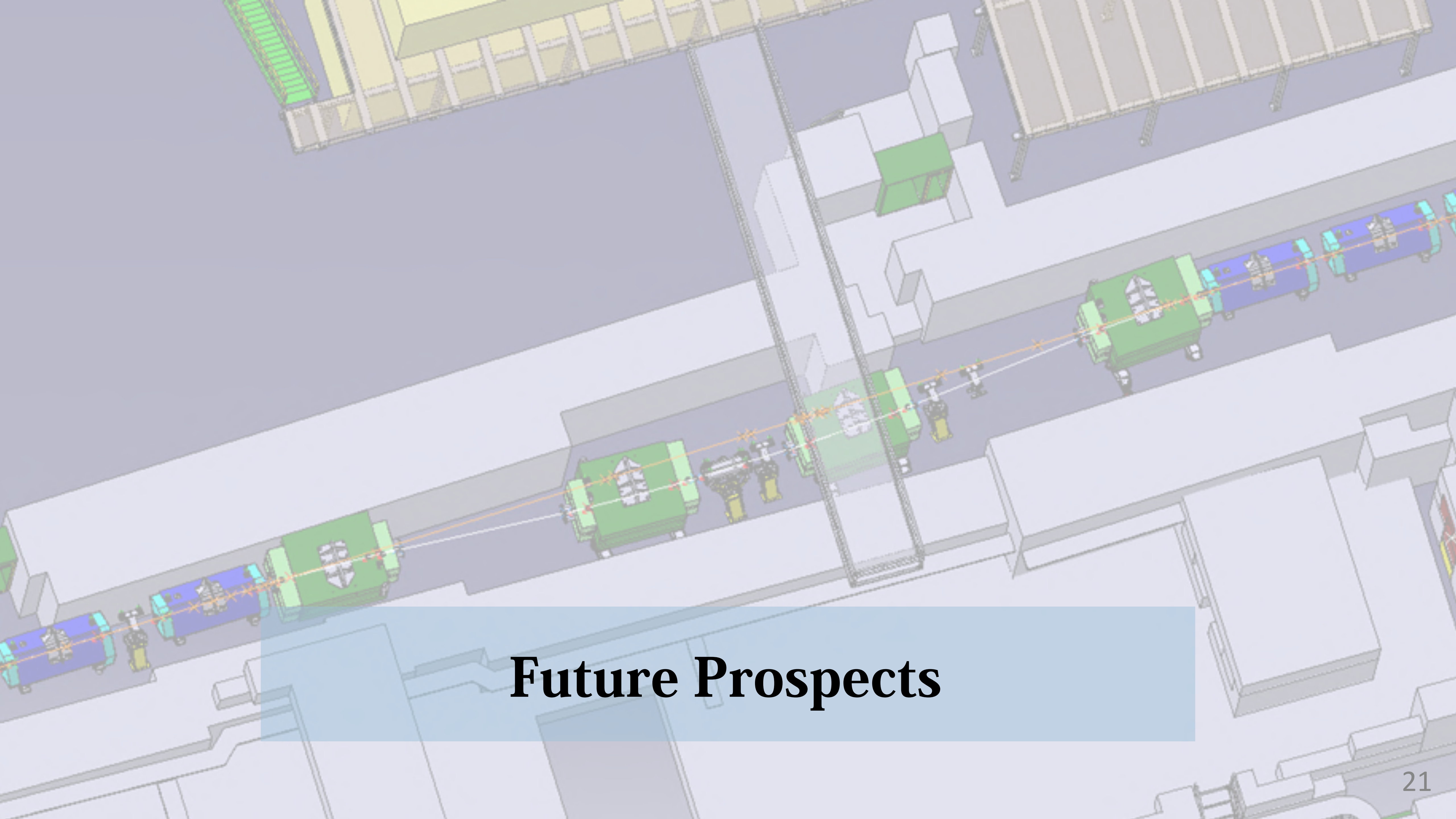








Data with PID and momentum measurement **-> Stay tuned!** (EMPHATIC work in progress)

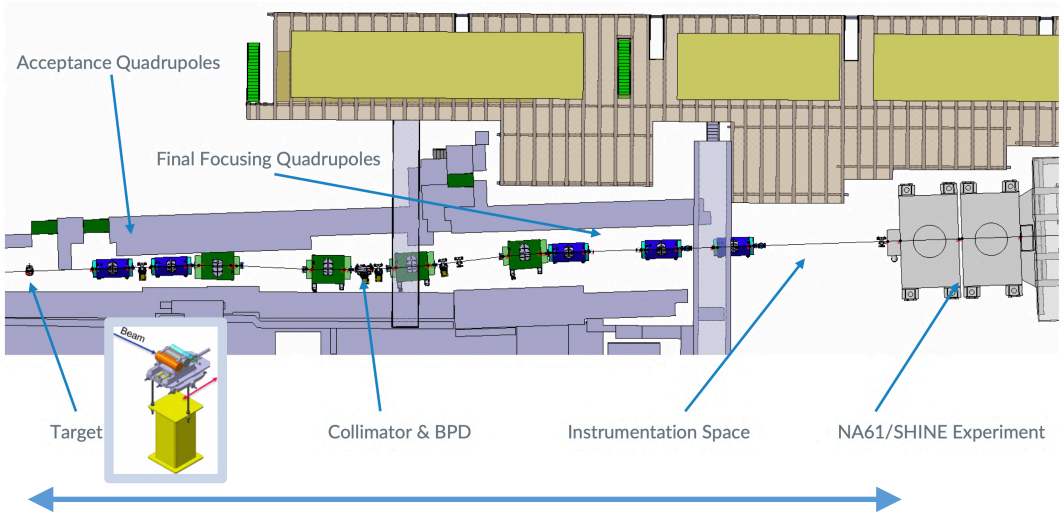


Future Prospects

Beyond Current Program

- Exploring unconstrained phase-space
  - Low-energy hadron interactions that could not be measured with the current setup

Low-Energy beamline @ CERN SPS

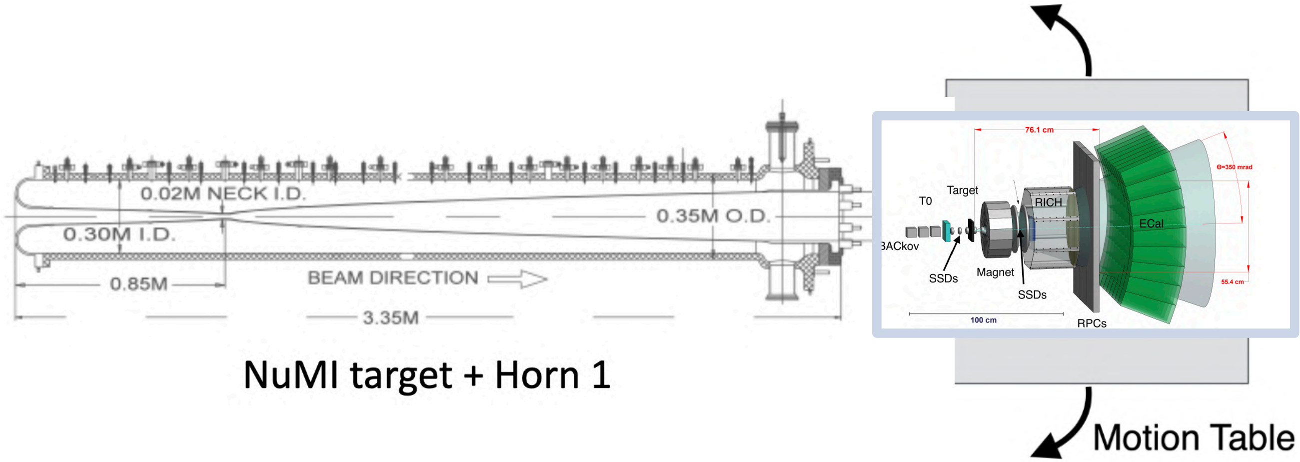


- Deliver low-E (2-30 GeV/c) hadron beams to NA61/SHINE
- Design/feasibility studies complete
  - Propose construction soon! (during CERN shutdown: 2026-2027)

Y. Nagai et al.
SPSC-P-330-ADD-12 (2021)
SPSC-M-793 (2022)
SPSC-M-795 (2023)

- Extension of replica measurements
  - Not only "target" but also surrounding "horn"

EMPHATIC Phase-2 with a motion table

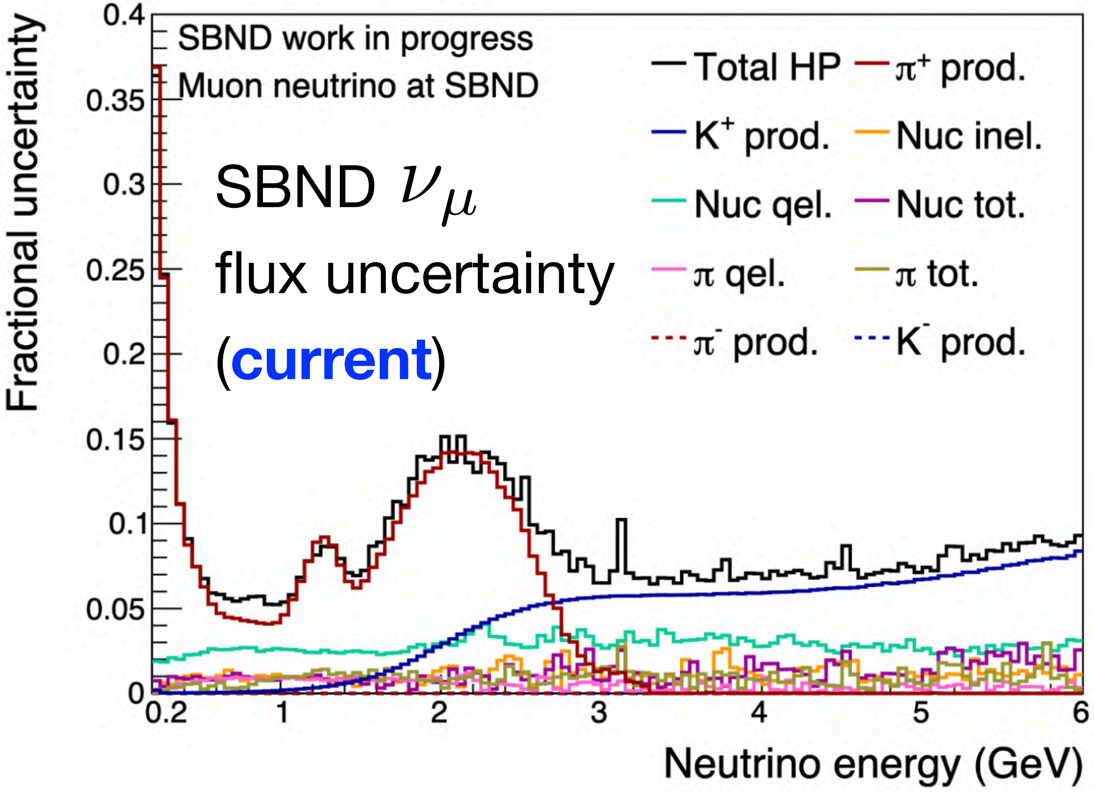


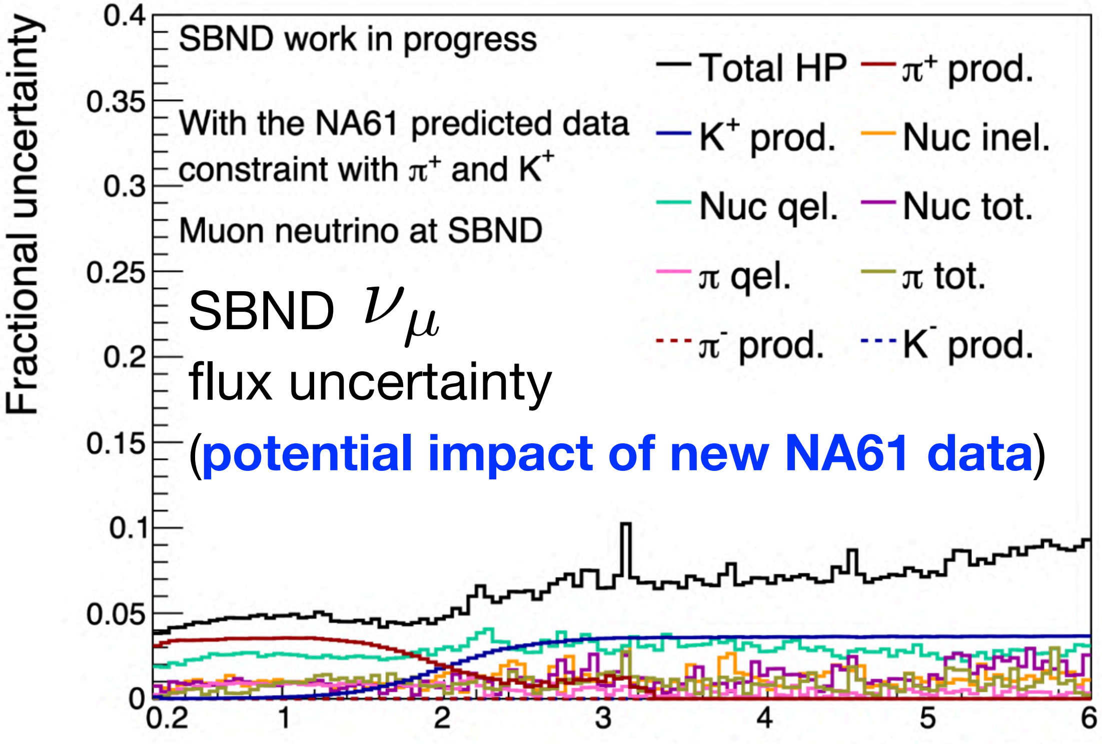
- Scan downstream hadron flux of NuMI Horn 1
  - Aim to run in 2025 without powering it
  - Future possibility with powering a horn!

Leo Aliaga (NuINT 2024)

Promising Impact to the Future Flux Prediction

If we have p+Be @ 8 GeV/c data with NA61/SHINE low-E beams?





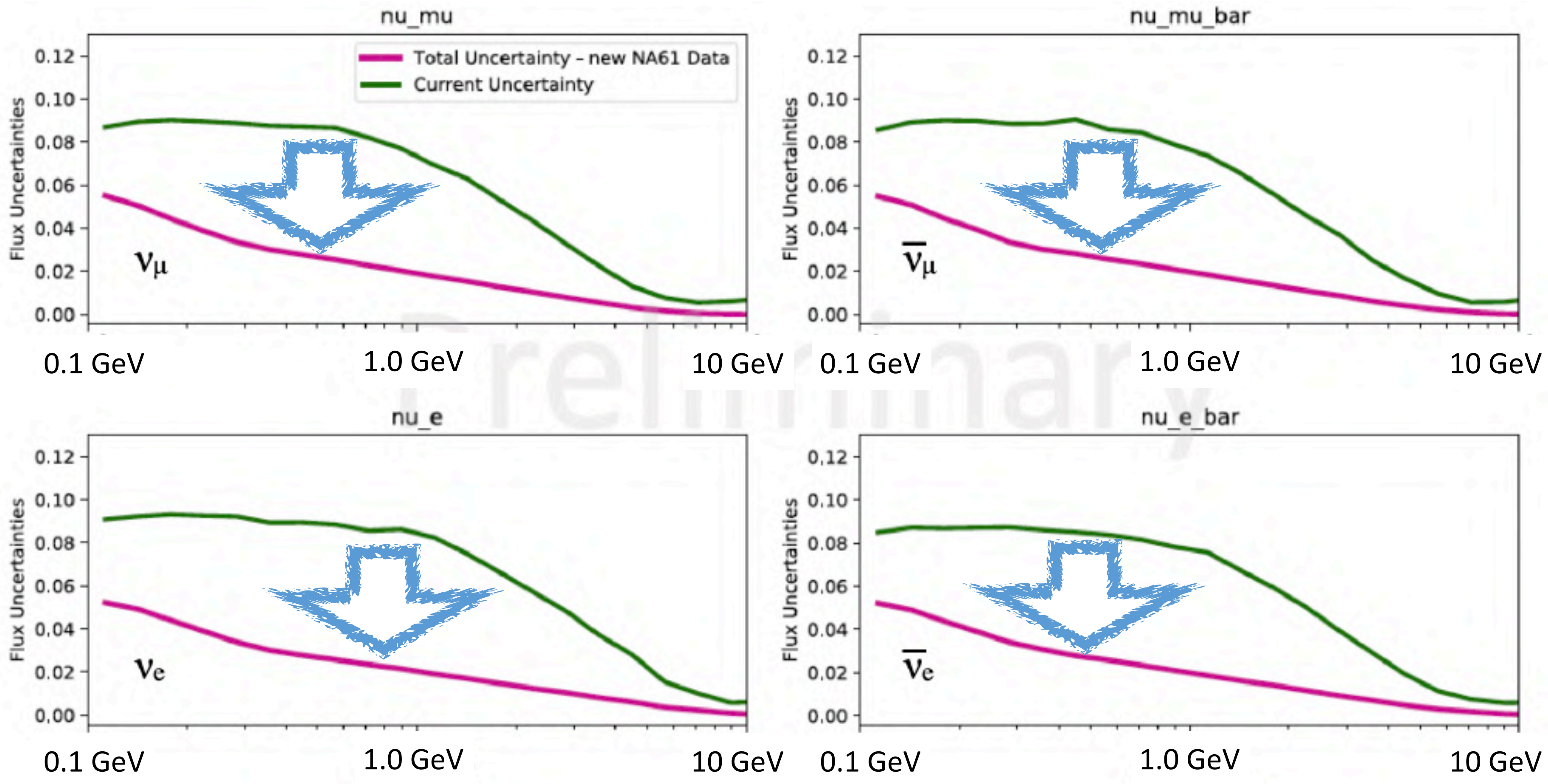
SBND (work in progress)

Drastic improvement on the SBND flux error at the BNB beamline!

(Will have a big impact on SBND cross section measurements, and DUNE!)

Promising Impact to the Future Flux Prediction

If we have p+N (or p+C) @ 2-15 GeV/c data with NA61/SHINE low-E beams?



Plots produced by Bartol group

plots available in
Y. Nagai et al., SPSC-M-793 (2022)

Notable improvement on sub-GeV to multi-GeV atmospheric neutrino flux!

(These are *CP* and mass-hierarchy sensitive regions)

Posters Related to Hadron Production & Flux Prediction

(Tuesday at 5:30 pm)

NA61/SHINE: "NA61/SHINE Hadron Production Measurements for Neutrino Oscillation Analyses" — poster #309, Amelia Camino

Material modeling: "Improved prediction of the T2K neutrino beam flux by estimation of hadronic secondary interactions in the cooling water of magnetic horns using measurement-based material modeling" — poster #338, Sakiko Nishimori

Flux simulation: "Neutrino Beams Simulations for the Hyper-Kamiokande experiment and target alternatives" — poster #233, Lucas Machado

Check them out !!

Summary

- Hadron production experiments provide critical data to reduce the leading systematic uncertainty on neutrino flux predictions
- Running experiments, **NA61/SHINE and EMPHATIC**, are making measurements to improve neutrino flux predictions for
  - accelerator-based experiments (long-baseline & short-baseline)
  - relevant neutrino experiments (atmospheric neutrinos, neutron spallation facility)
- Lots of recent ***complementary*** activities by NA61/SHINE and EMPHATIC
  - A very established experiment with various interaction data collected
  - Exploring new phase-space with low-E hadron beams down to 2 GeV/c
  - A novel experiment with Proof-of-Principle successfully demonstrated
  - Exploring a new approach to gaining accelerator neutrino flux knowledge

Need hadron data? Join our effort!!

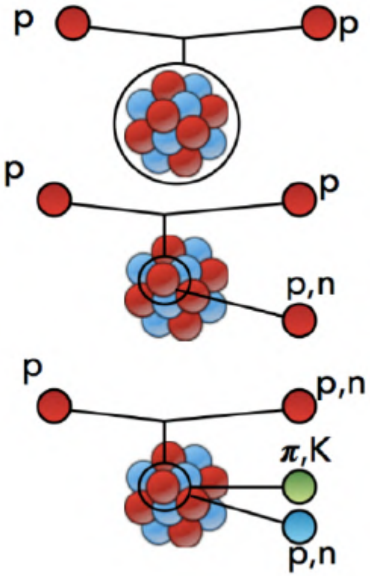
Thank you very much for your attention !!

The speaker is supported by the National Research Development and Innovation Office (NKFIH) in Hungary through the OTKA grant FK 137812 and TKP grant 2021-NKTA-64.

Backup

Note: Notation of Production Cross Section

- Not all experiments use the same definition for the production cross section



Coherent elastic process:
interaction on the nucleus —> $\sigma_{\rm el}$

Quasi-elastic process:
interaction on bound nucleons —> $\sigma_{\rm qe}$

Production process:
interaction with new hadron production
—> $\sigma_{\rm prod}$

—> Inelastic process $\sigma_{\rm inel}$

$$\sigma_{\rm inel} = \sigma_{\rm total} - \sigma_{\rm el}$$
$$\sigma_{\rm prod} = \sigma_{\rm inel} - \sigma_{\rm qe}$$

Use this definition through the talk
(T2K uses this definition)

- NuMI flux tuning definition: $\sigma_{\rm inel} = \sigma_{\rm total} - \sigma_{\rm el} - \sigma_{\rm qe}$ —> $\sigma_{\rm prod}$ in above definition
  $\sigma_{\rm absorption} = \sigma_{\rm total} - \sigma_{\rm el}$ —> $\sigma_{\rm inel}$ in above definition

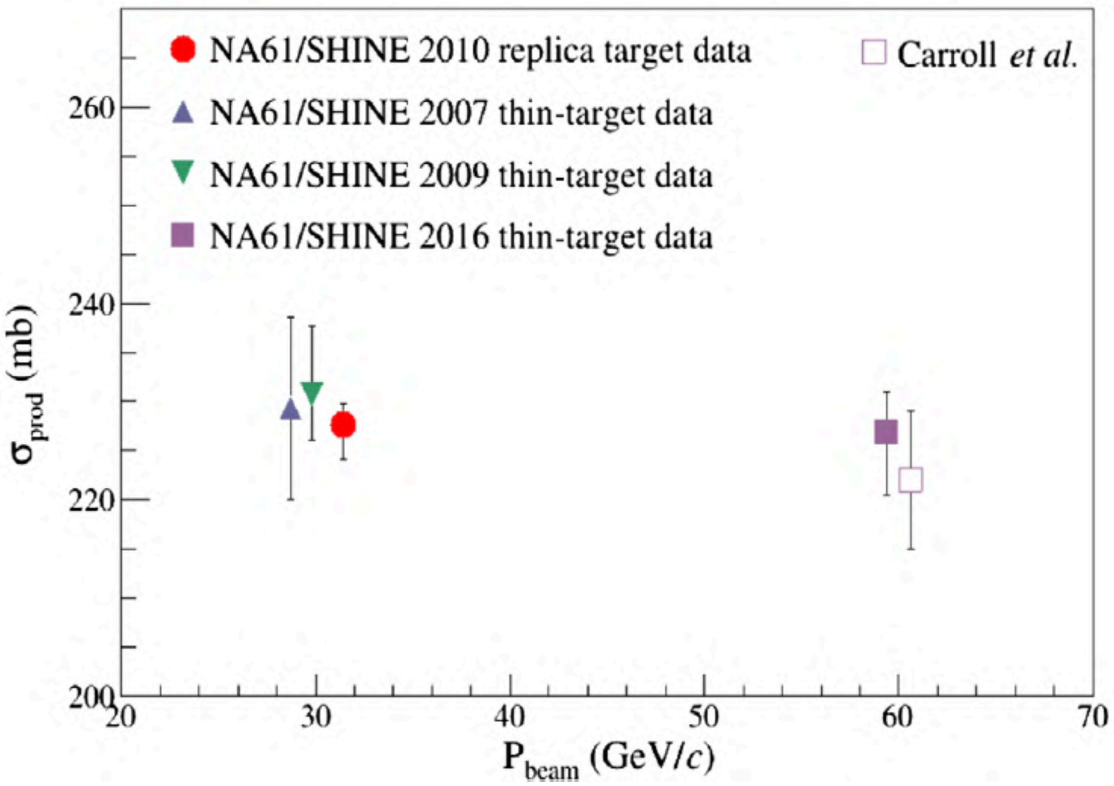
- Earlier experiments: mixed up inelastic and production cross sections

  e.g. Denisov, et. al (1973): $\sigma_{\rm absorption} = \sigma_{\rm total} - \sigma_{\rm el}$ —> $\sigma_{\rm inel}$ in above definition

  e.g. Carroll, et. al (1979): $\sigma_{\rm absorption} = \sigma_{\rm total} - \sigma_{\rm el} - \sigma_{\rm qe}$ —> $\sigma_{\rm prod}$ in above definition

NA61/SHINE: Phase 1 for T2K

$$p + \text{T2K replica @ 31 GeV}/c$$



$$P_{\text{survival}} = e^{-Ln\sigma_{\text{prod}}}$$

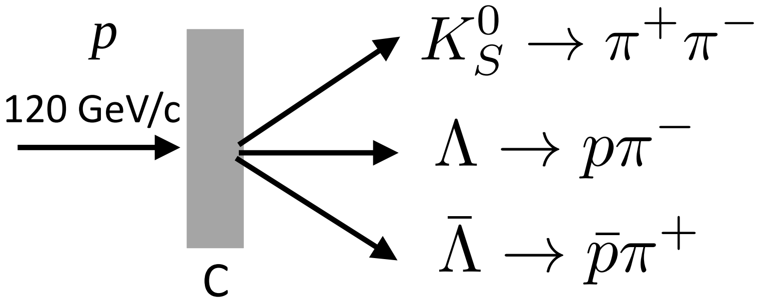
Phys. Rev. D 103, 012006 (2021)

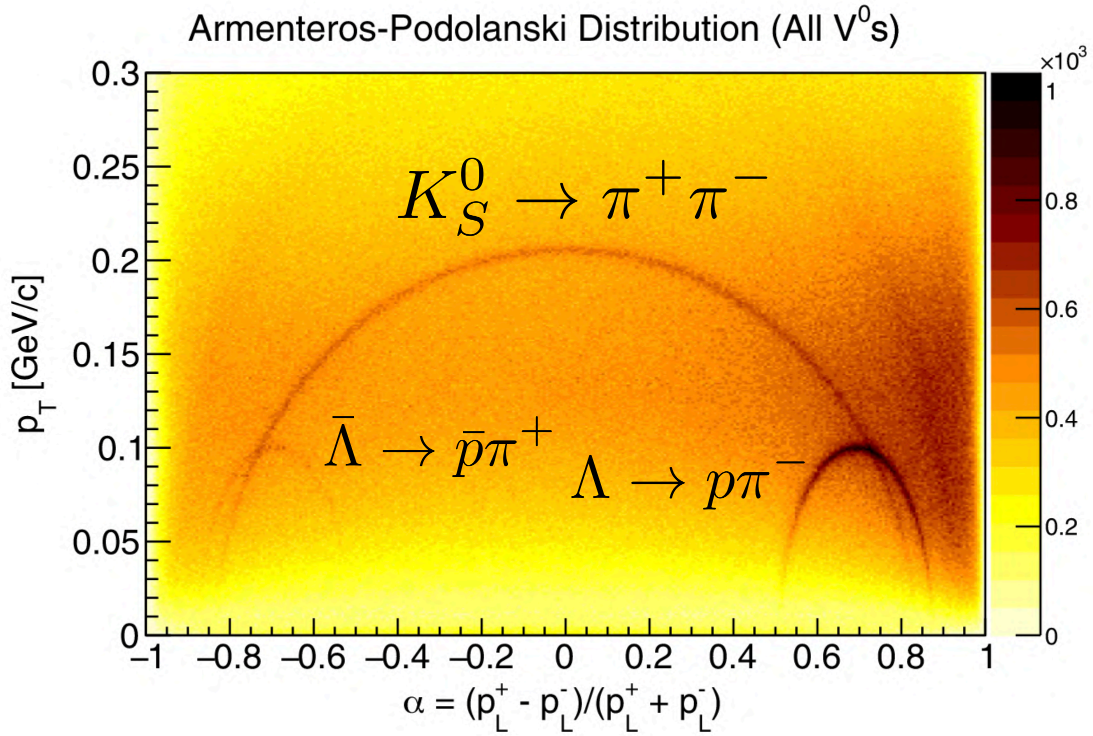
A production cross section measurement using the attenuation of beam particles

—> Achieved 2% total uncertainty in good agreement with past measurements

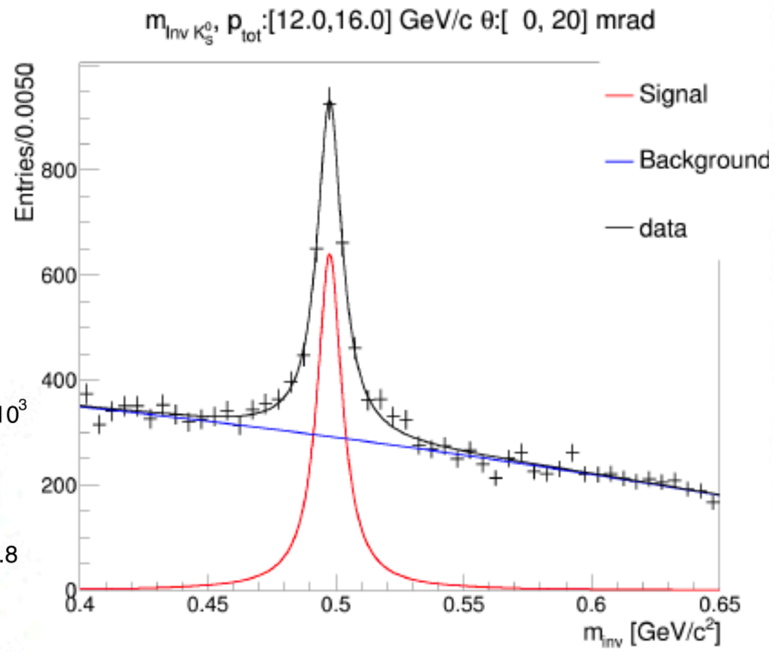
NA61/SHINE Highlights: Phase 2 for NuMI/LBNF

$p + \mathrm{C}$ @ 120 GeV/c

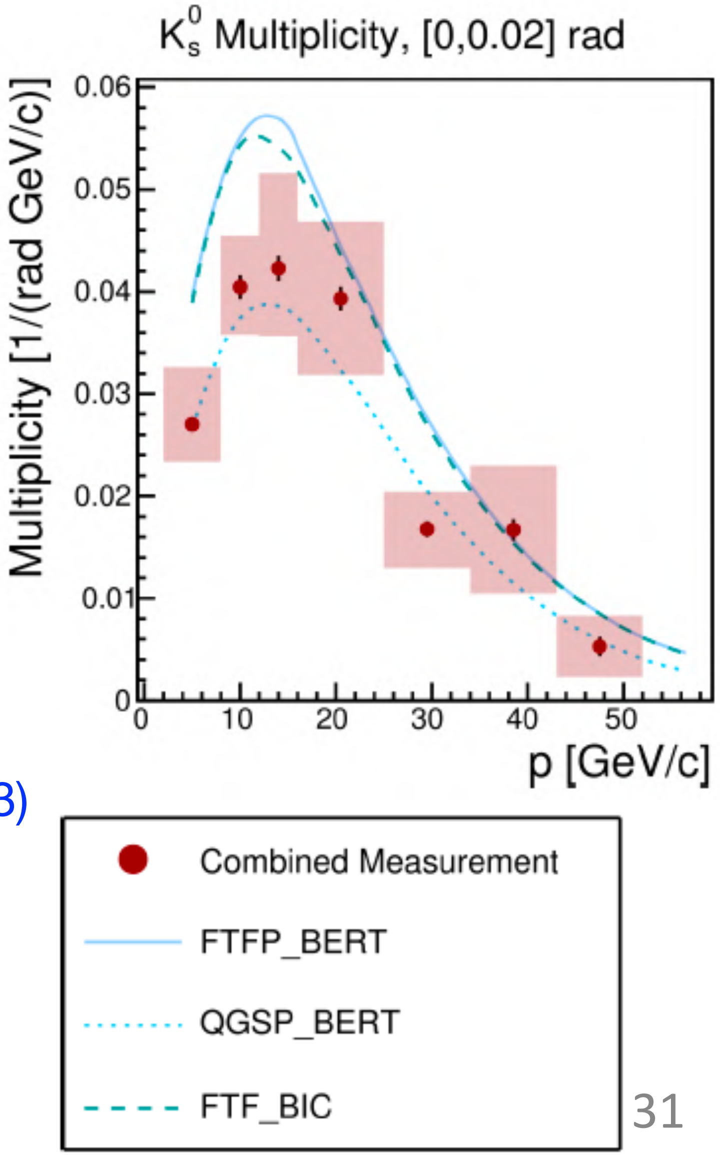




$K^0_S \to \pi^+\pi^-$

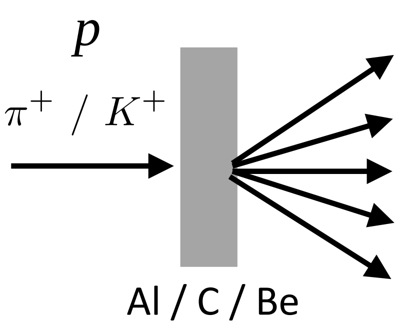


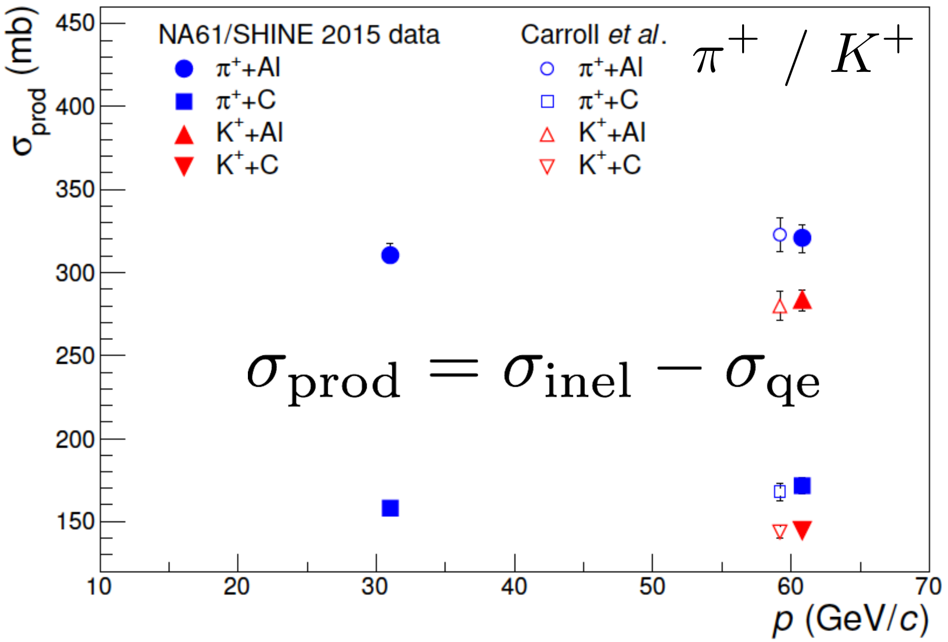
Phys. Rev. D 107, 7, 072004 (2023)



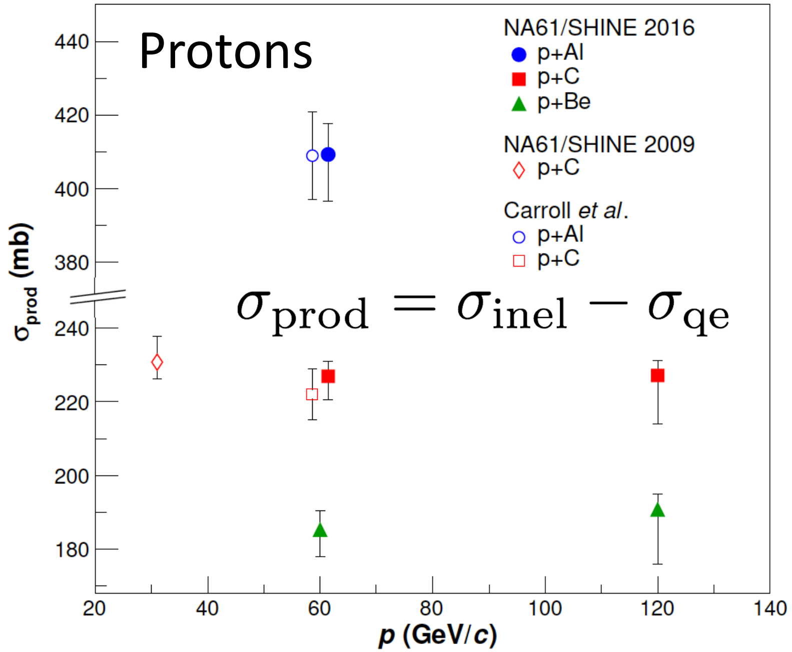
Provide constraints on primary interactions for NuMI/LBNF neutrino fluxes

NA61/SHINE: Phase 2 (Total Cross Section)





Phys. Rev. D98, 052001 (2018)



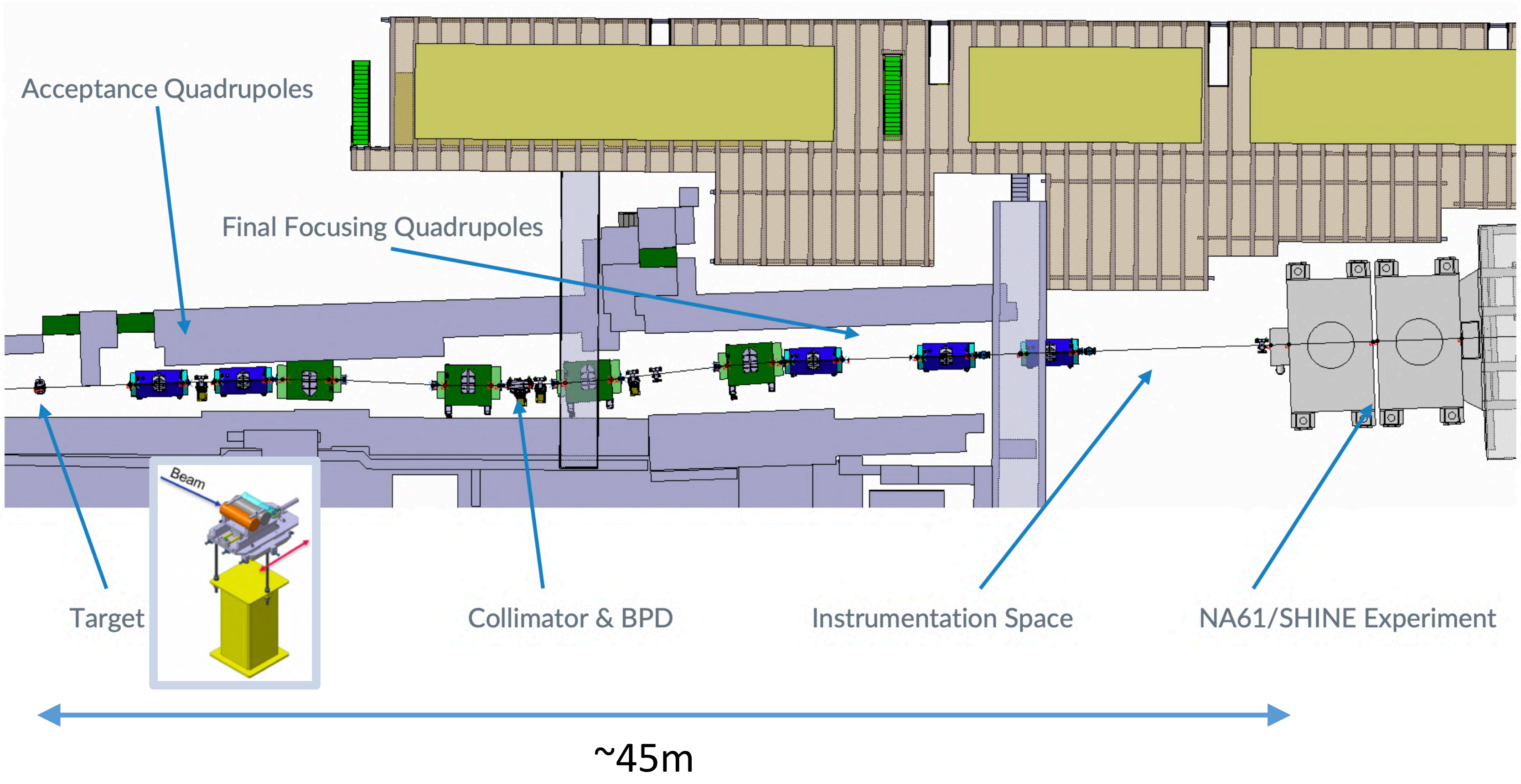
Phys. Rev. D100, 112004 (2019)

- Precision of measurements: 2~4% (30, 60 GeV/c) and 6~8% (120 GeV/c)
  - It was 5% for pions, 15-30% for kaons
  - First measurement on proton at 120 GeV

Upgrade Plan: Extending Hadron Beam Energy

<u>Low-Energy Beamline Project</u>

- A project to build a new branch beamline to deliver low-energy hadron beams
  - Low-Energy = 1-30 GeV (30-350 GeV can be covered by the current beamline configuration)



Project documents

Y. Nagai et al.
SPSC-P-330-ADD-12 (2021)
SPSC-M-793 (2022)
SPSC-M-795 (2023)