Hadron Production Measurements for Neutrino Experiments at NA61/SHINE

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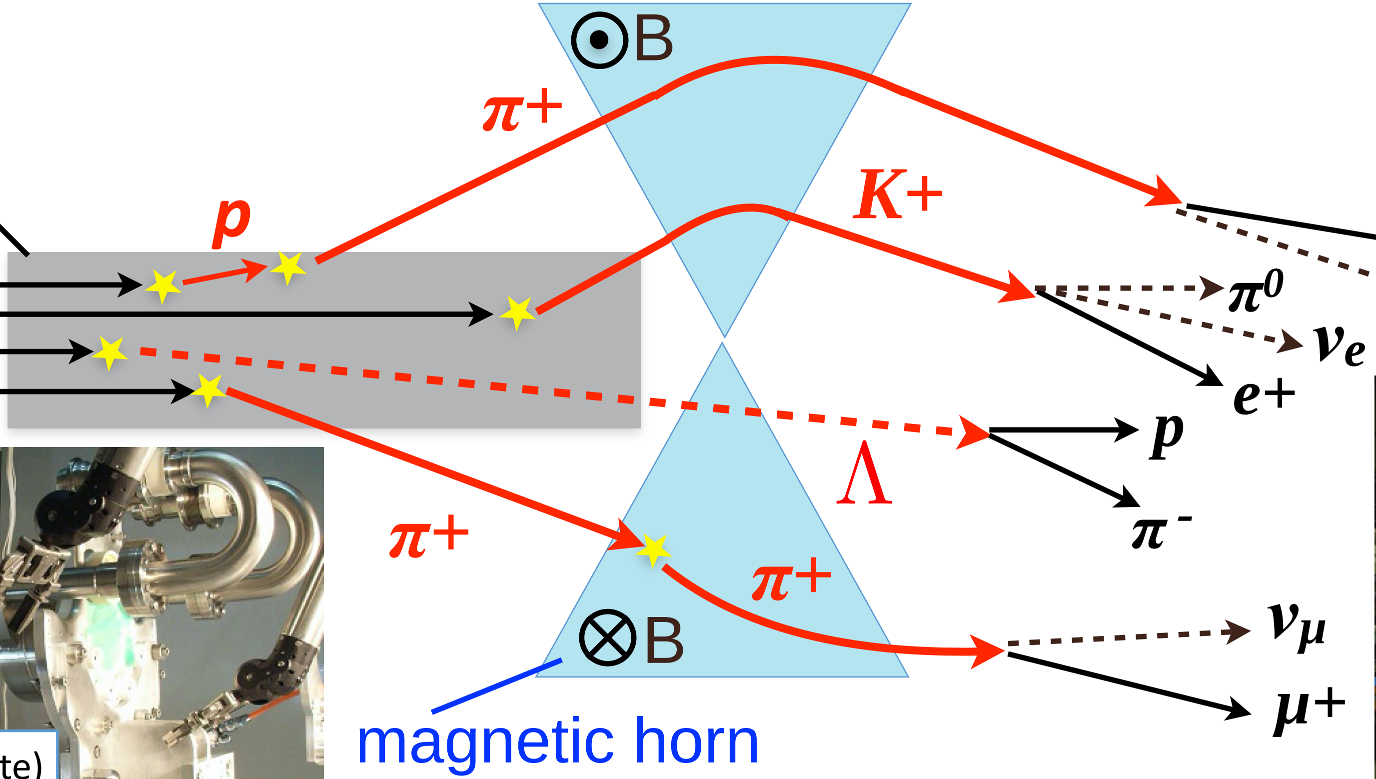
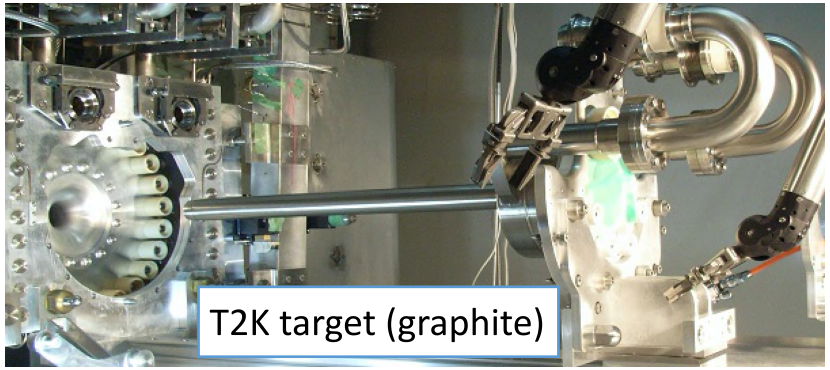
for the NA61/SHINE collaboration

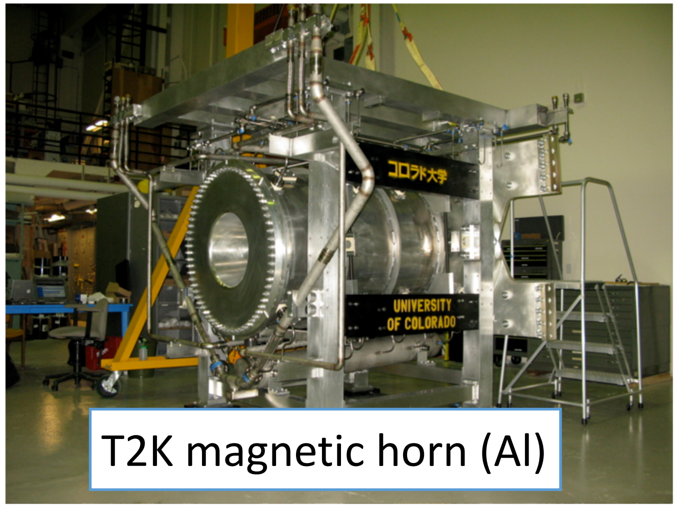
ELTE
Eötvös Loránd University

October 23-27, 2023, XX International Workshop on Neutrino Telescopes@Venice, Italy

Accelerator Neutrino Production




T2K target (graphite)



T2K magnetic horn (Al)

Hadron production process is complex:

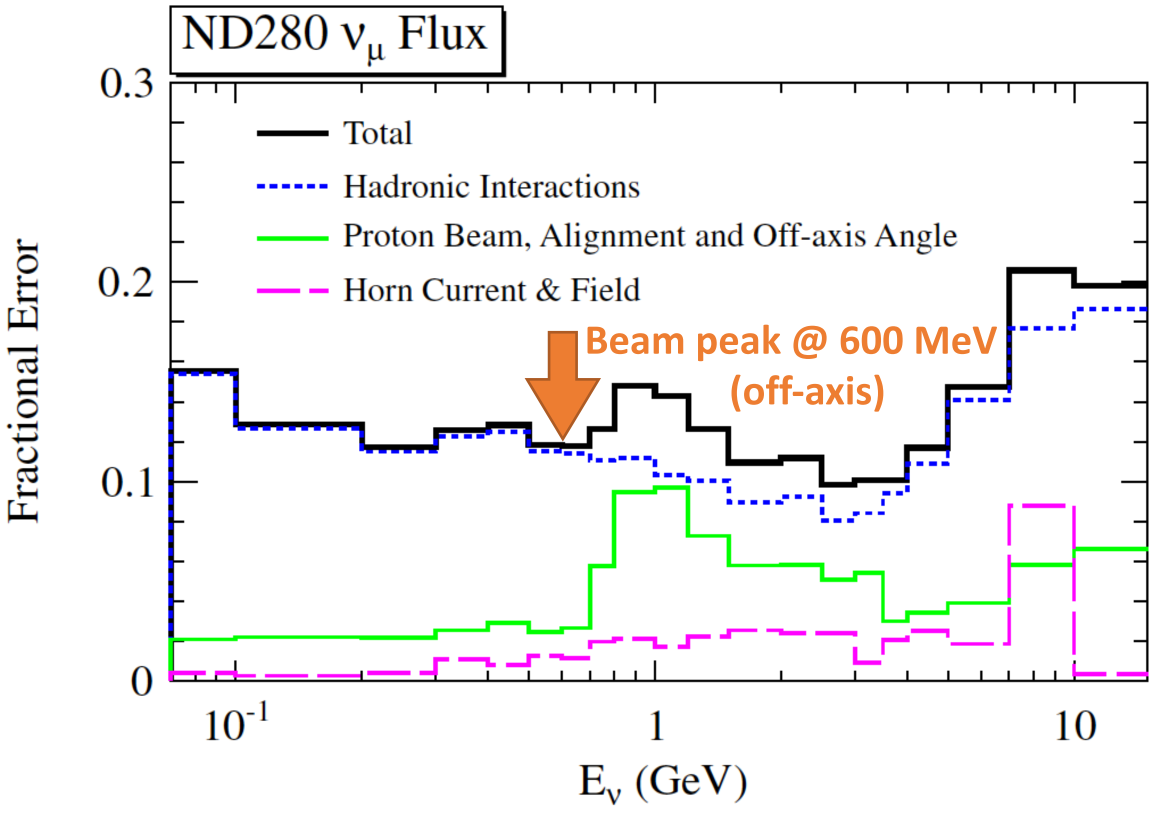
- Primary interactions in the target (p + C -> $\pi^{\pm}$ and $K^{\pm}$) -> Primary contribution to the neutrino flux
- Secondary interactions with beamline materials (hadrons + C/Be/Al/Ti/Fe/H_2O/etc..)
- Neutral hadron decay (p + C —> V^0 + X)

Non-negligible contribution to the neutrino flux

Flux Uncertainties of Accelerator-based Neutrinos

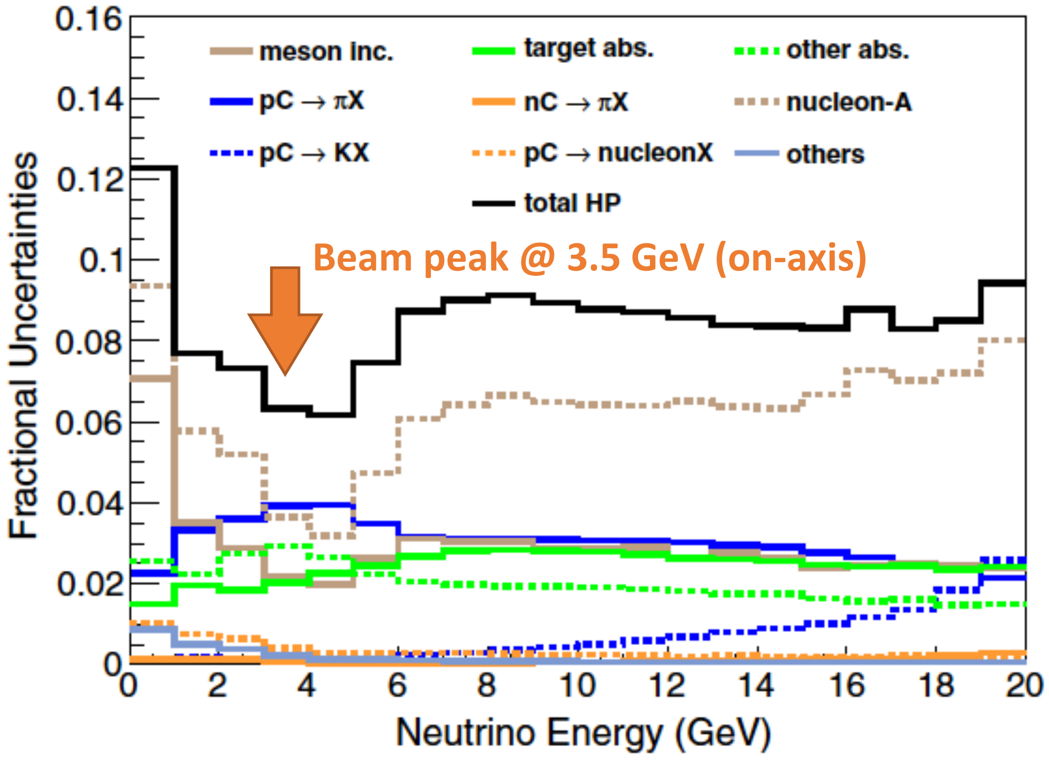
Hadron Production is the leading uncertainty source of flux predictions

J-PARC beamline (T2K flux)



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

NuMI beamline (MINERvA flux)
(low energy configuration)



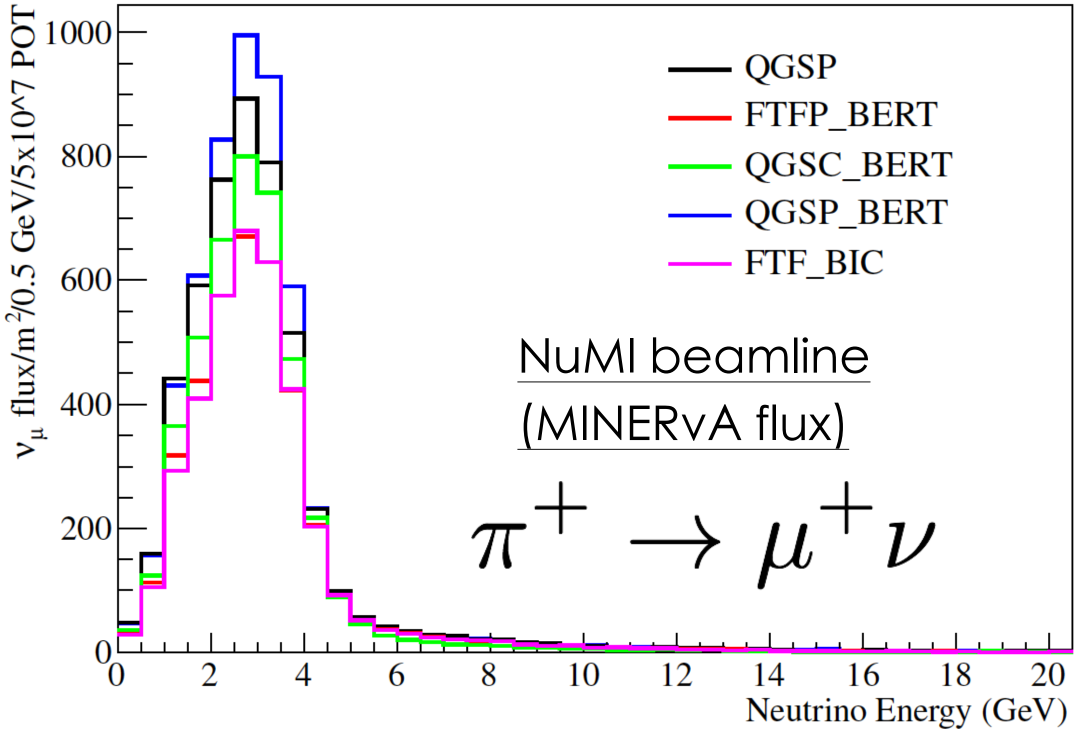
MINERvA: Phys. Rev. D94, 092005 (2016)
(only hadron production-related errors)

Flux Prediction

We rely on hadronic interaction models to calculate the neutrino flux

- FLUKA (J-PARC/T2K)
- Geant 4 FTFP_BERT (Fermilab experiments at NuMI, LBNF, and Booster beamlines)

However, prediction of hadron production is difficult…



Leonidas Aliaga (Ph.D Thesis, 2016)

Need to constrain flux uncertainty coming from hadron production

External Hadron production data is crucial!!

a dedicated experiment: NA61/SHINE

The NA61/SHINE Experiment

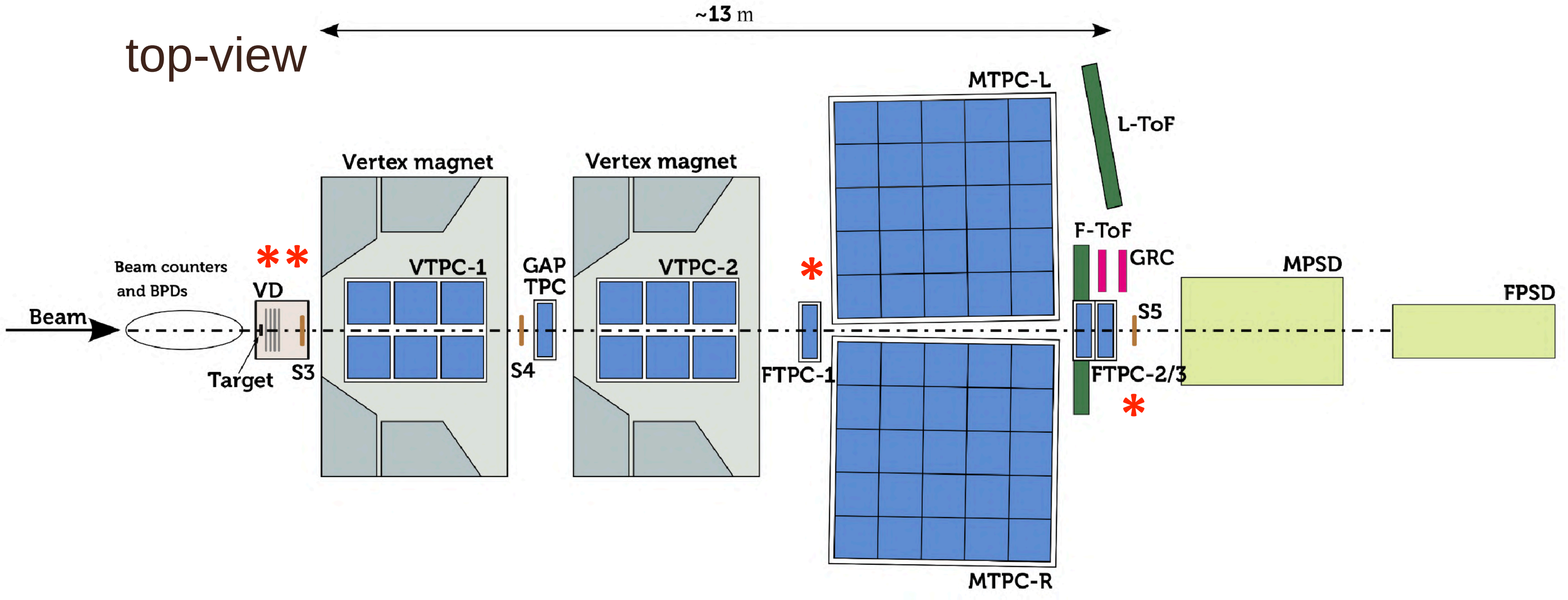
"The SPS Heavy Ion and Neutrino Experiment"

Over 150 physicists from 30 institutions and 15 countries

The NA61/SHINE Experiment

- Hadron beams
  - primary protons at 400 GeV/c
  - secondary hadrons (p, π, K) at 13 - 350 GeV/c
- Ion beams
  - primary (Ar, Xe, Pb) at 13-150 AGeV/c
  - secondary Be at 13 - 150 AGeV/c (from Pb fragmentation)
- Broad physics program
  - Neutrino
    - Hadron production measurements to improve neutrino beam flux predictions
  - Strong interaction / Heavy ion
    - Search for the critical point
    - Study the onset of QCD deconfinement
    - Study open-charm production mechanism
  - Cosmic ray
    - Hadron production measurements to improve air-shower model predictions
    - Study (anti-)deuteron production mechanism for the AMS and GAPS experiments
    - Nuclear fragmentation cross sections to understand cosmic-ray flux

NA61/SHINE Experimental Facility



* FTPC 1-3
installed in 2017

** VD
(pixel vertex detector)
for heavy ion run

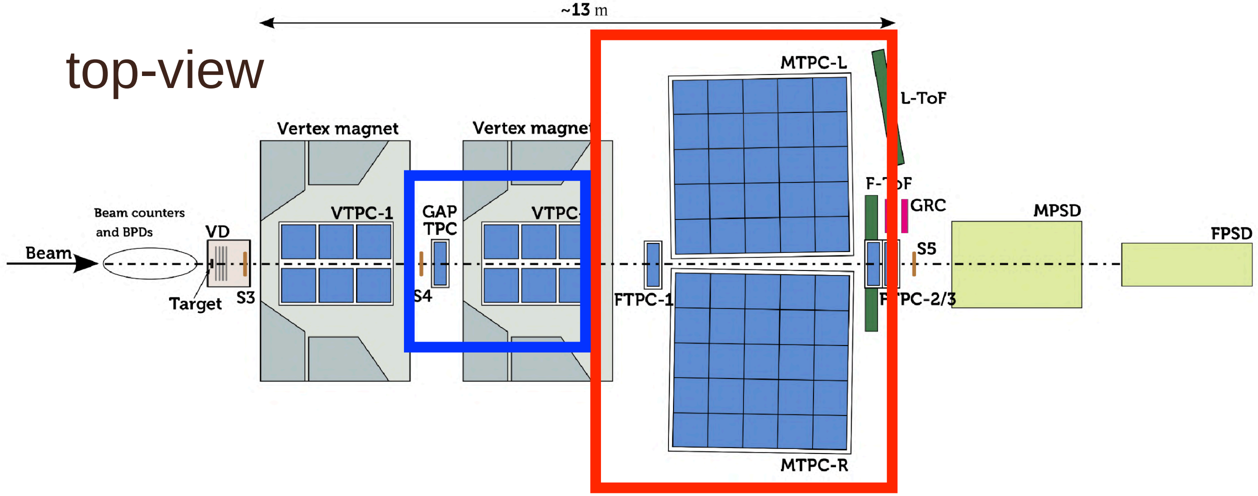
A fixed target experiment at SPS with

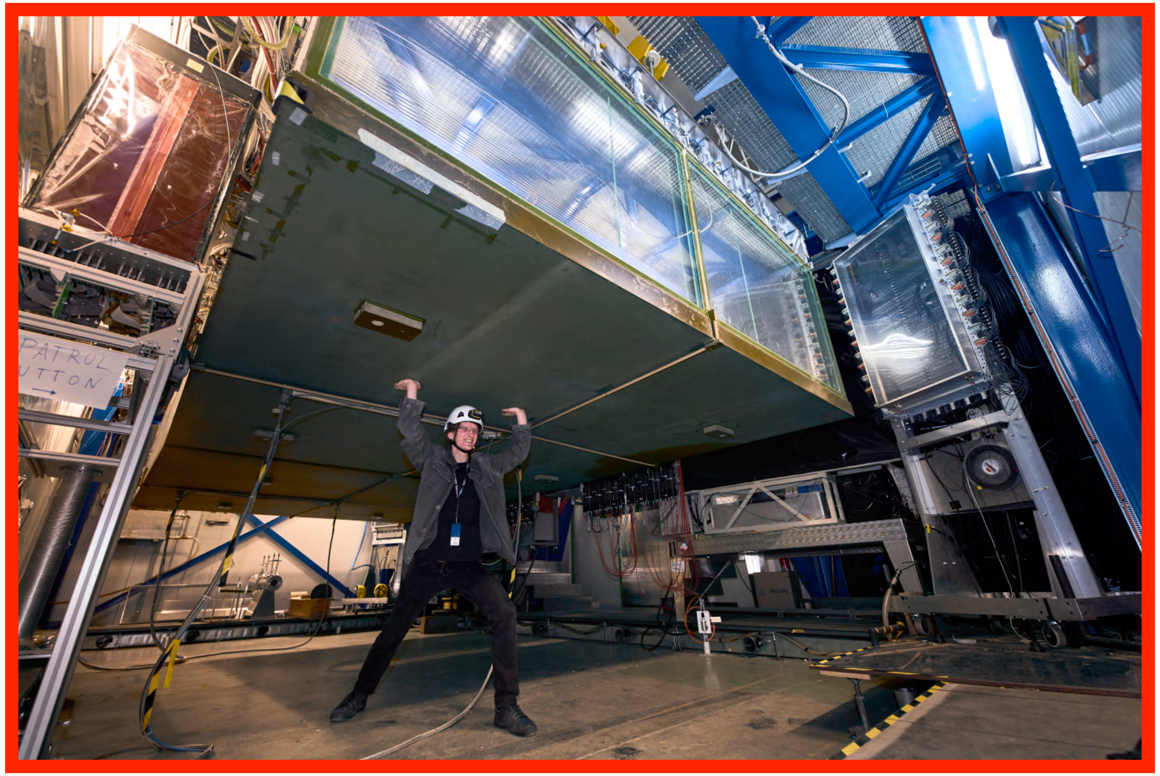
- Good beam particle selection (p, π, K) using beamline Cherenkov detectors
- Large acceptance spectrometer for charged particles
  - Time Projection Chambers (TPCs) for tracking and dE/dx
  - 2 dipole magnets with 1.5 T field
  - Time-of-flight detectors placed downstream

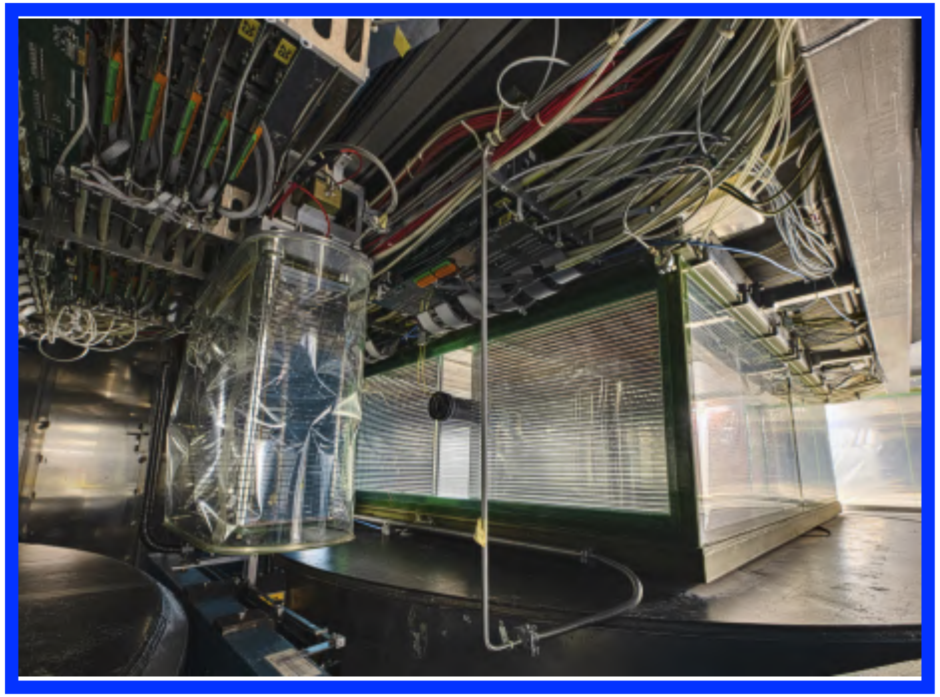
Precise tracking with:
- Particle identification
- Momentum measurement

NA61/SHINE Experimental Facility

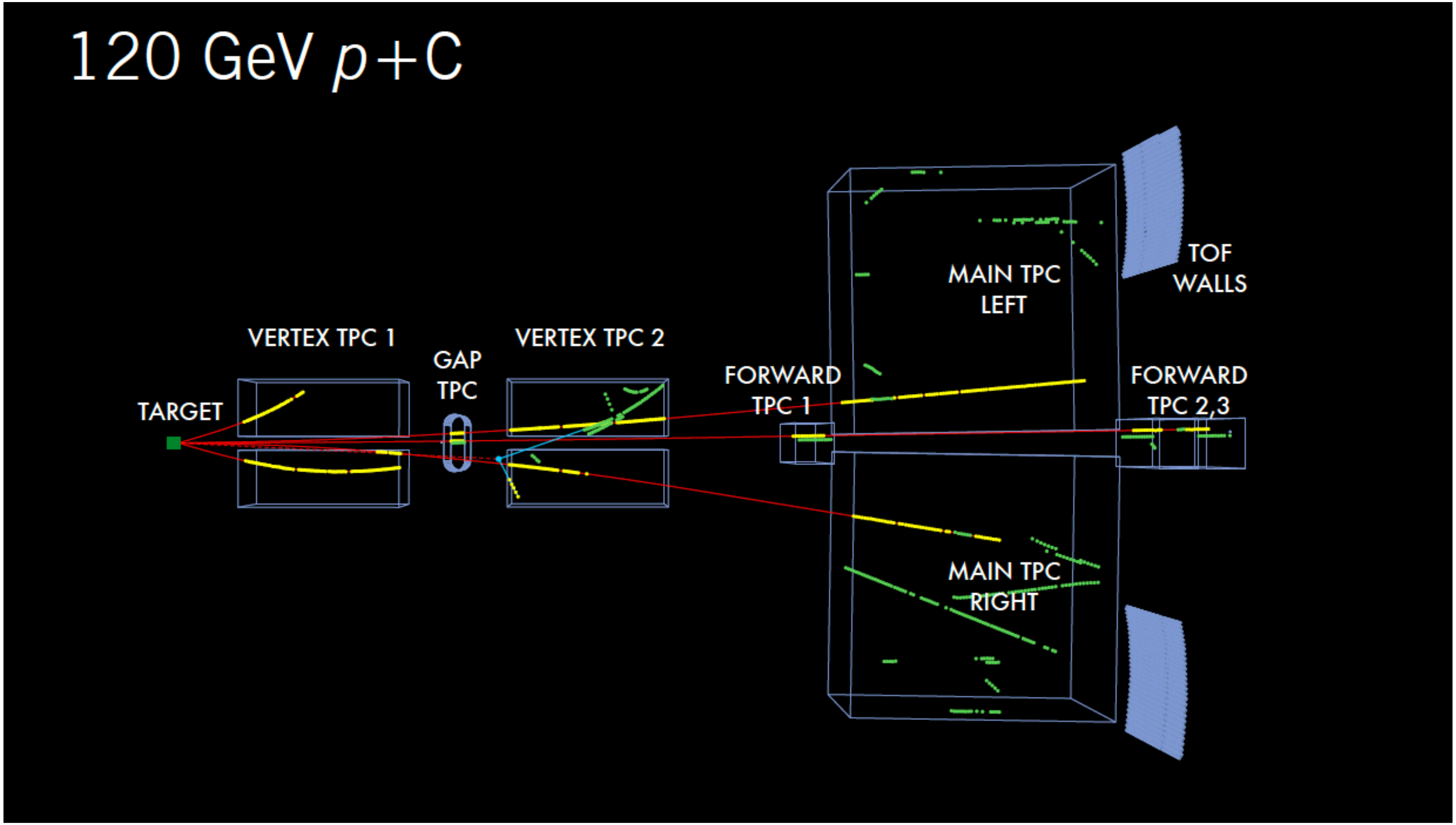
top-view







Event Display



NA61/SHINE Data Collection History

Phase 1 (2006-2010): p+C (2cm graphite or 90-cm-long T2K replica graphite) at 31 GeV/c -> T2K

Data analyses are complete!

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)

Phase 2 (2015-2018): various -> Fermilab beamlines (NuMI, LBNF/DUNE)

Several data analyses are complete!
More data analysis ongoing

publications: *PRD* 98 052001 (2018), *PRD* 100 112001 (2019), *PRD* 100 112004 (2019), *PRD* 107 072004 (2023), arXiv:2306.02961 (accepted by *PRD*)

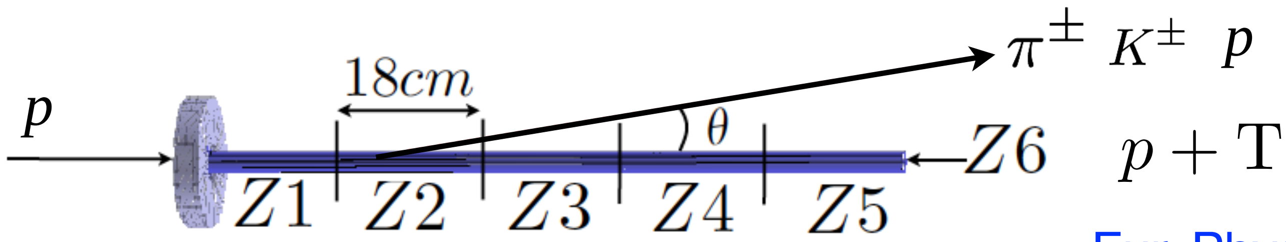
Phase 3 (2022-2025): various -> T2K, Hyper-K, LBNF/DUNE

2022 and 2023 data collections are complete!
Will continue for next years

We are in the middle of Phase 3 data collection campaign!!

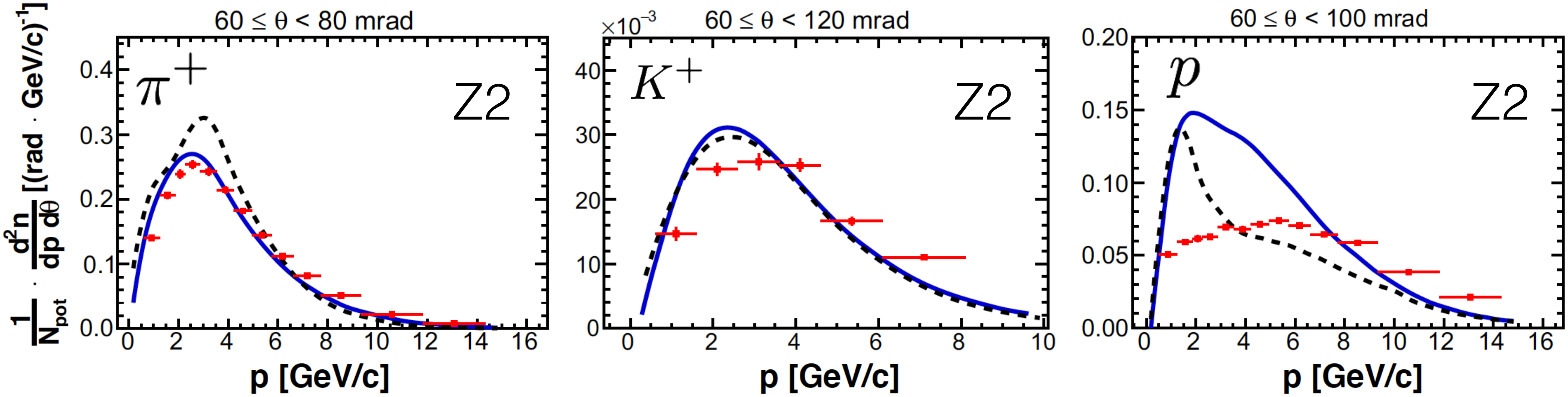
After LS3 (2027-???): various -> Planning phase

Phase 1 Example: a Measurement for T2K

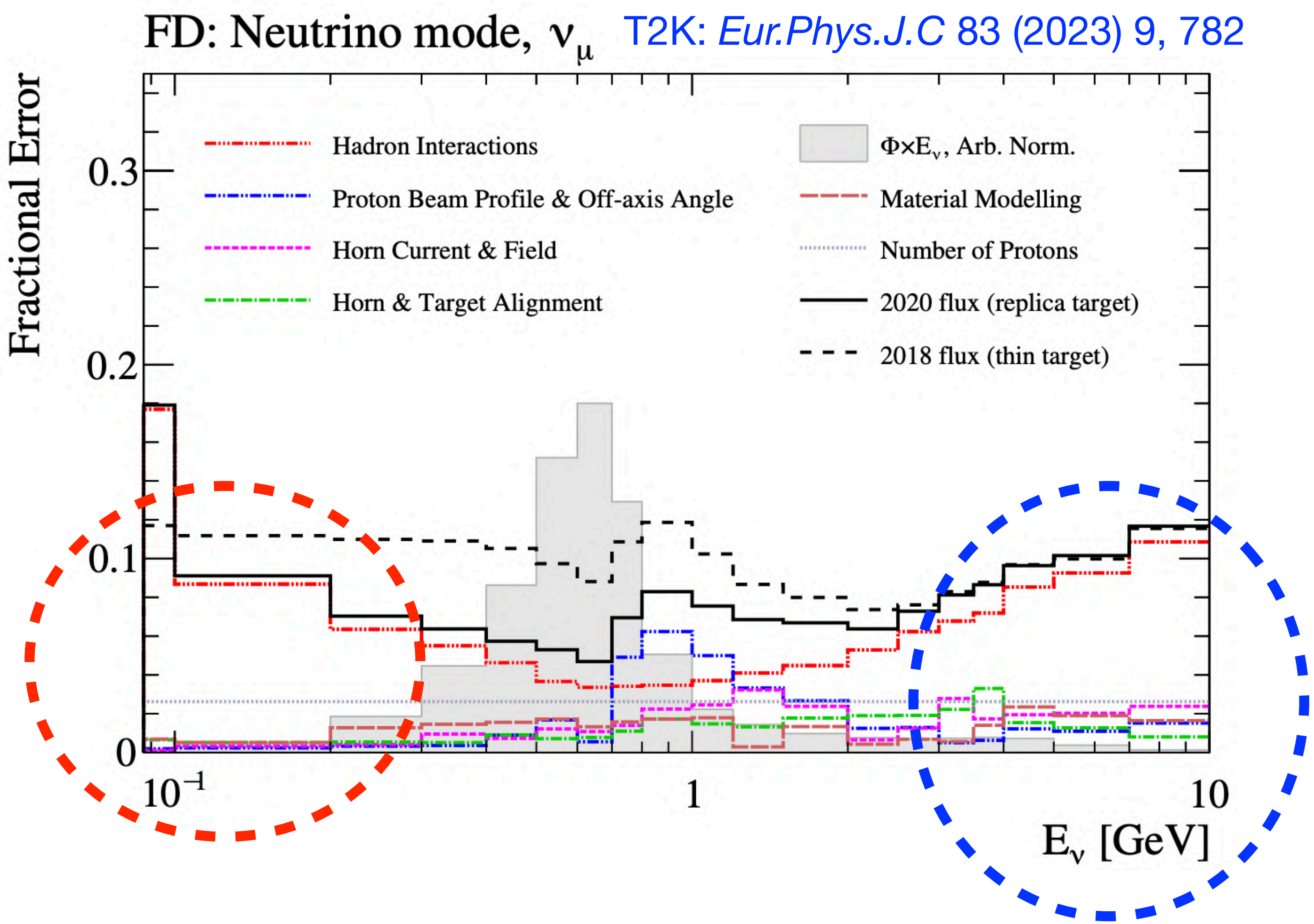


$p + \text{T2K replica} @ 30\ \text{GeV}$

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



T2K Flux Uncertainty with Phase 1 Data



<u>Achieved</u>

- Flux uncertainty < 5% at the flux peak

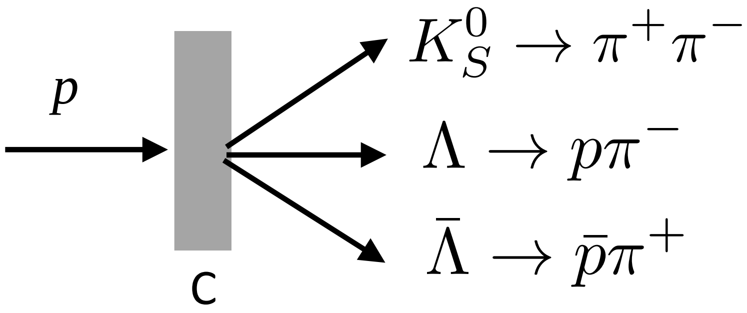
<u>Next step</u>

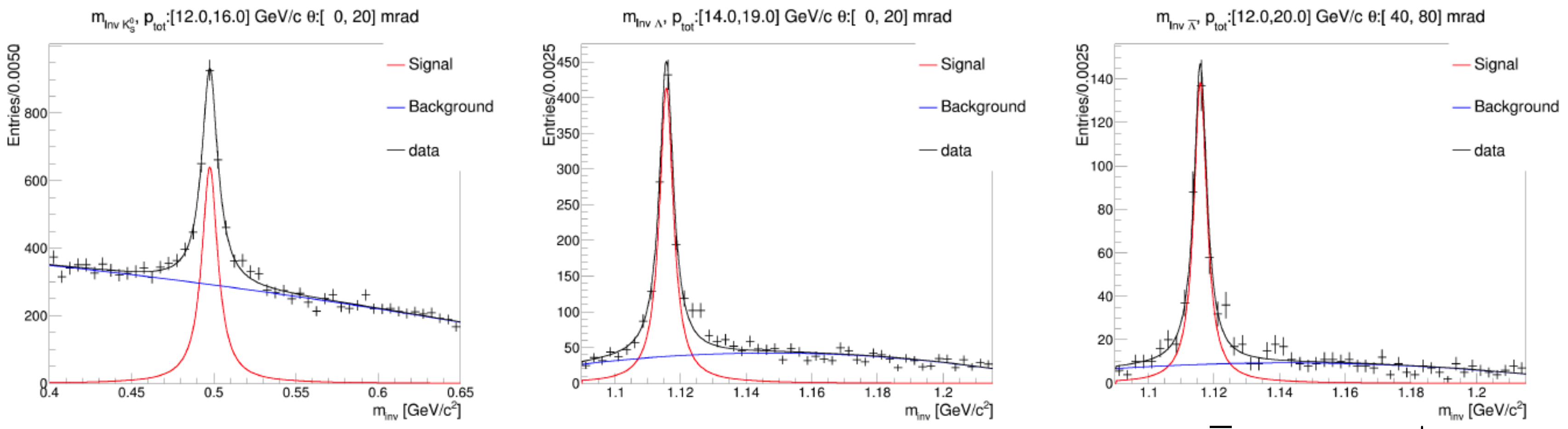
- Flux outside of the peak needs to be further reduced
  - Low energy side: low-momentum hadron rescattering
  - High energy side: kaon production
- Flux of intrinsic beam background
  - anti-ν and electron-ν

For further improvement, continue further data taking at Phase 3 and beyond

Phase 2 Example: A Measurement for Fermilab Beamlines

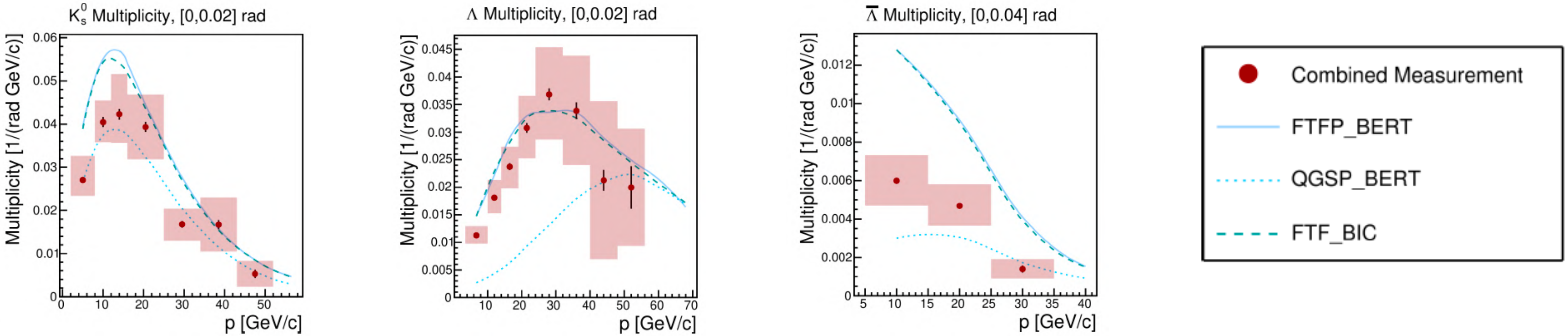
$$\mathrm{p} + \mathrm{C@120\,GeV}$$





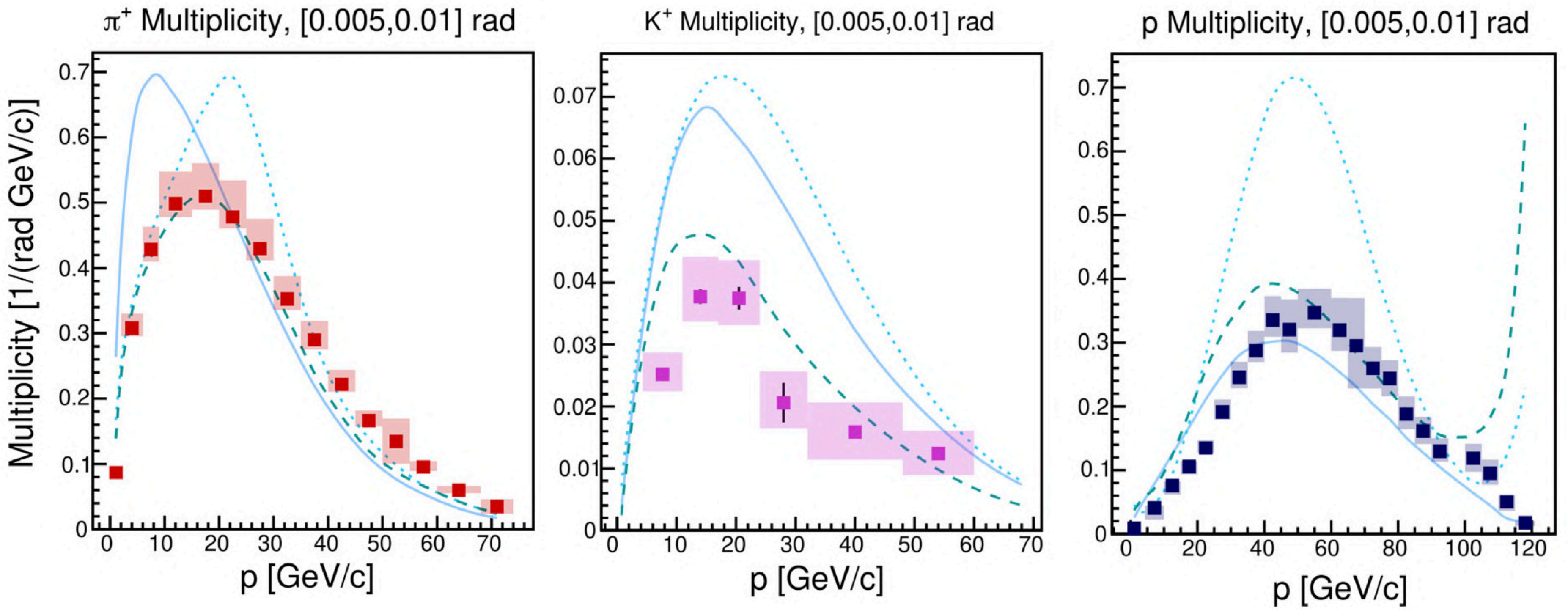
$K_S^0 \to \pi^+\pi^-$ $\Lambda \to p\pi^-$ $\bar{\Lambda} \to \bar{p}\pi^+$

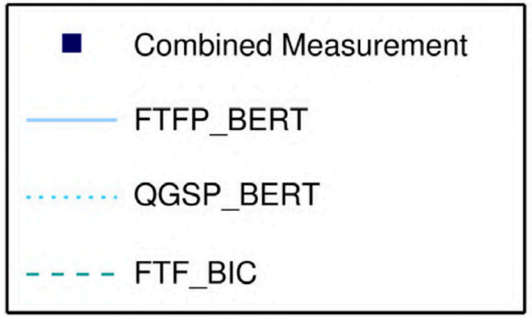
Phys. Rev. D 107, 7, 072004 (2023)

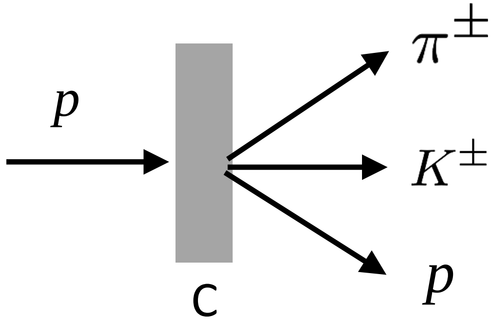


Phase 2 Example: A Measurement for Fermilab Beamlines

$$\mathrm{p + C@120\,GeV}$$





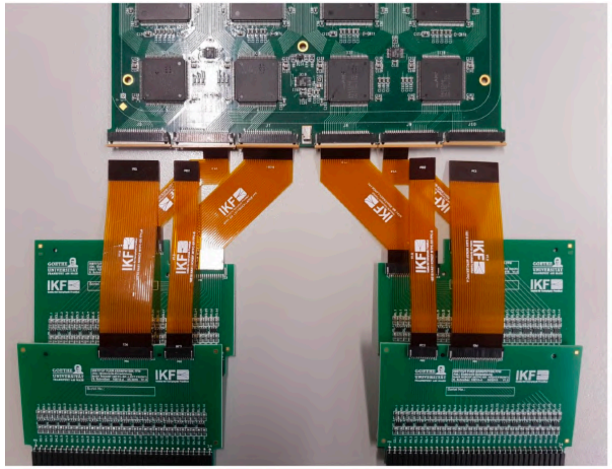


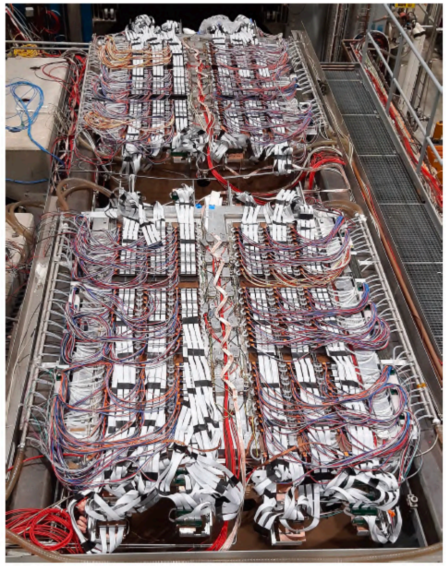
arXiv: 2306.02961
(Accepted by Phys. Rev. D)

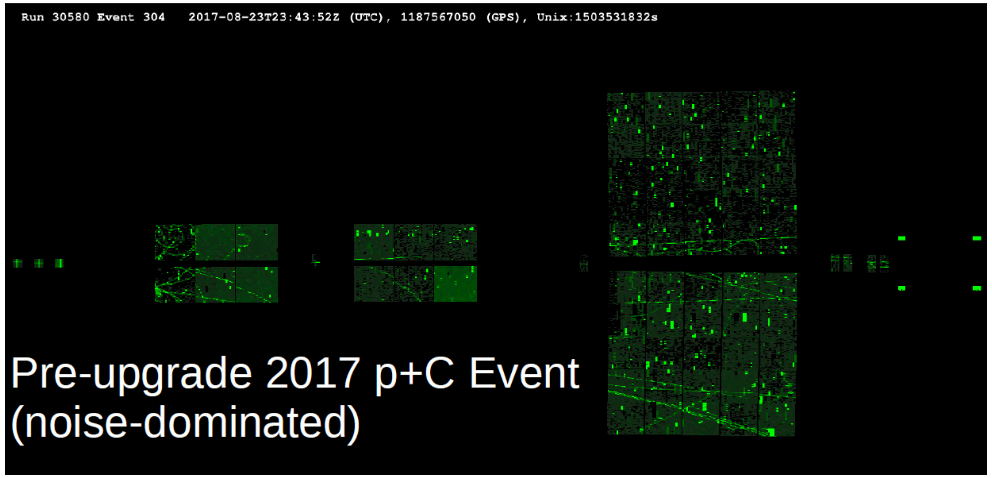
A brand-new result!

Phase 3: NA61/SHINE Detector Upgrade

- Facility Upgrade (2019-2022)
  - Many major upgrades recently completed
    - TPC electronics with ALICE board
      - The DAQ rate: ~100 Hz -> above 1 kHz
      - Improved raw data quality (low noise level)
    - Replacement of ToF readout with DRS4 board

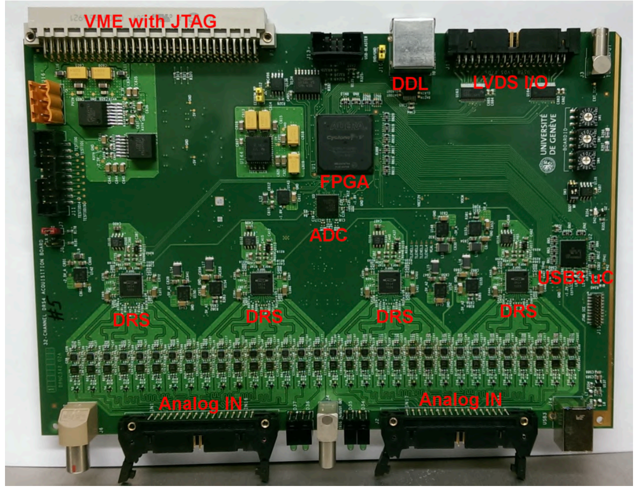






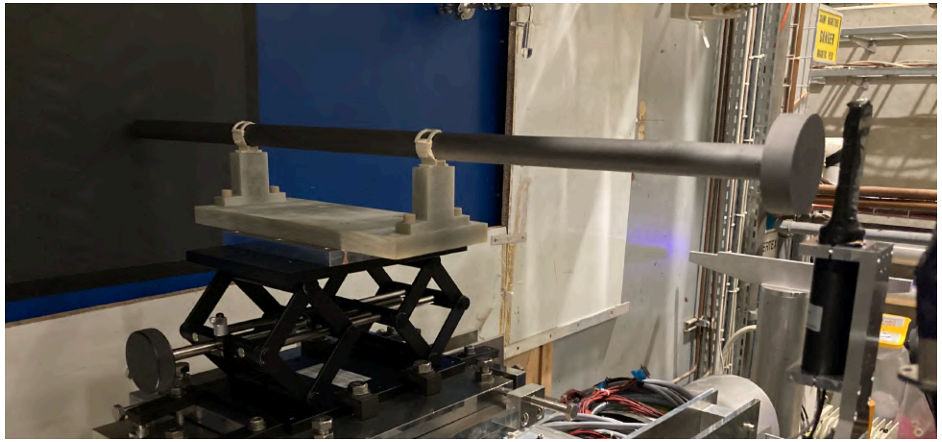
Pre-upgrade 2017 p+C Event
(noise-dominated)

Post-upgrade 2022 p+T2K Event
(track-dominated)

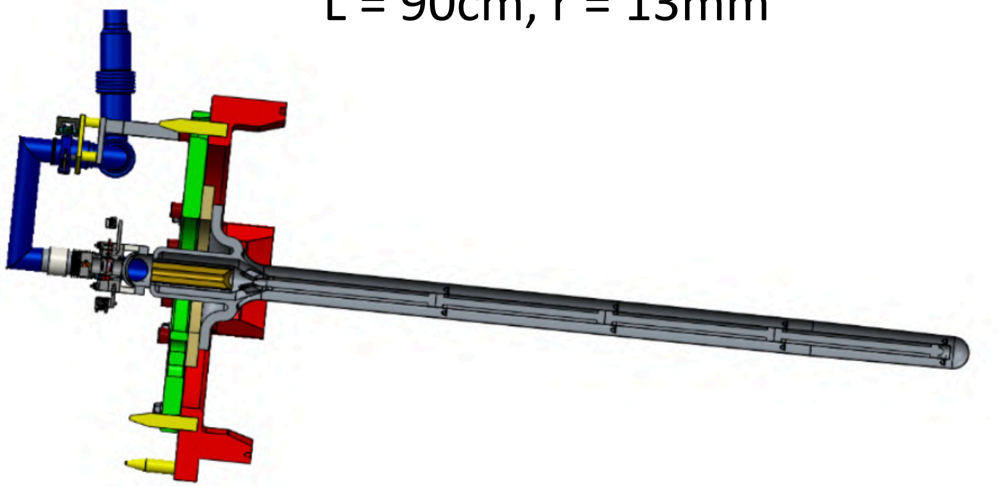


Upgrade detail is available: https://cds.cern.ch/record/2309890

Phase 3 Data Collection



T2K replica target
L = 90cm, r = 13mm



LBNF/DUNE target
L = 1.5m, r = 8mm (possibly extended to 1.8m)

2022 (complete)
- > 150M events dedicated to constraining T2K flux uncertainty
  - Data calibration is ongoing

2023 (complete)
- 380M events with various thin targets
  - Dedicated to constraining DUNE flux uncertainty

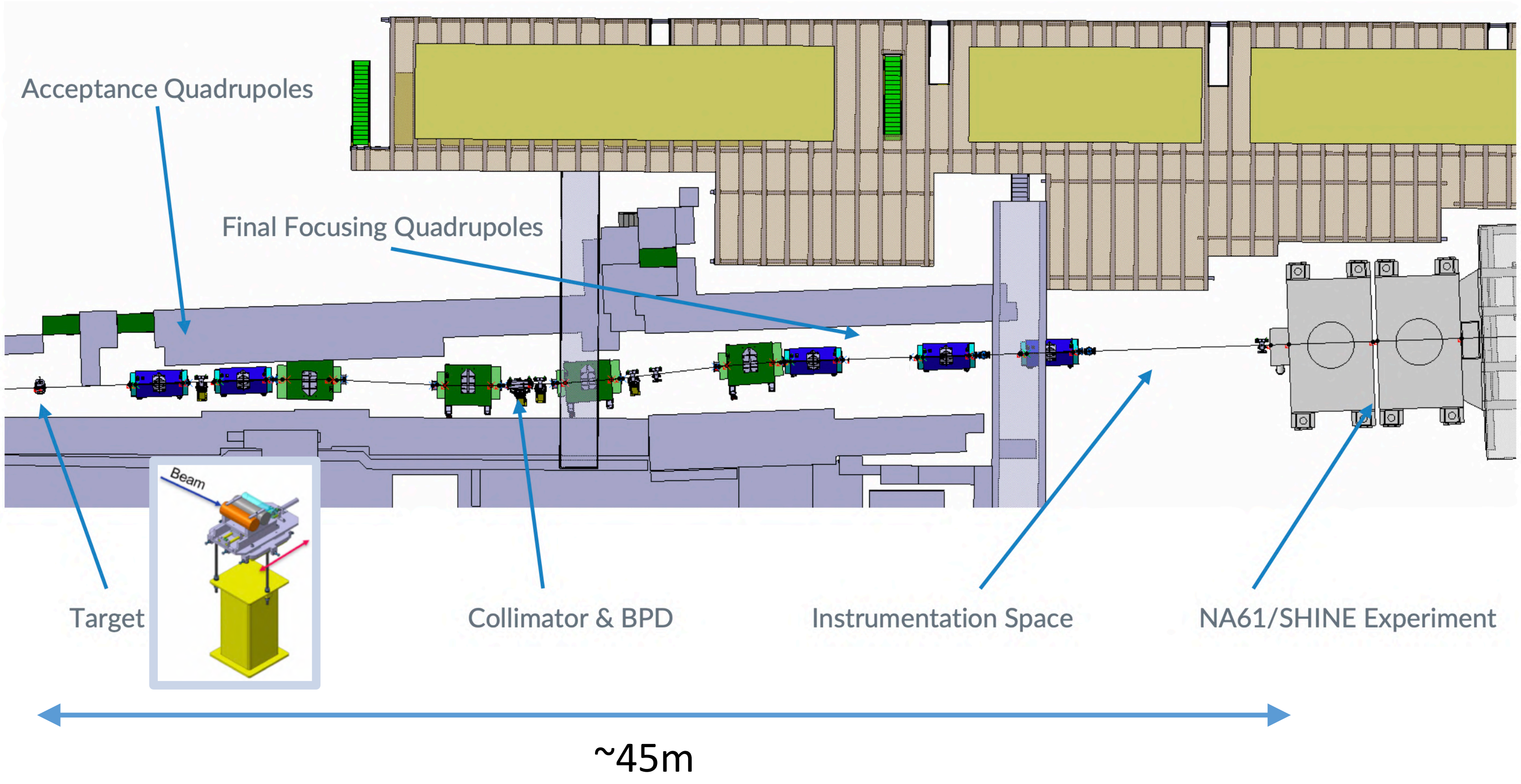
2024 (plan)
- 120 GeV proton interactions on a replica LBNF/DUNE target

2025 (plan)
- Low-E hadron interactions -> next page

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)



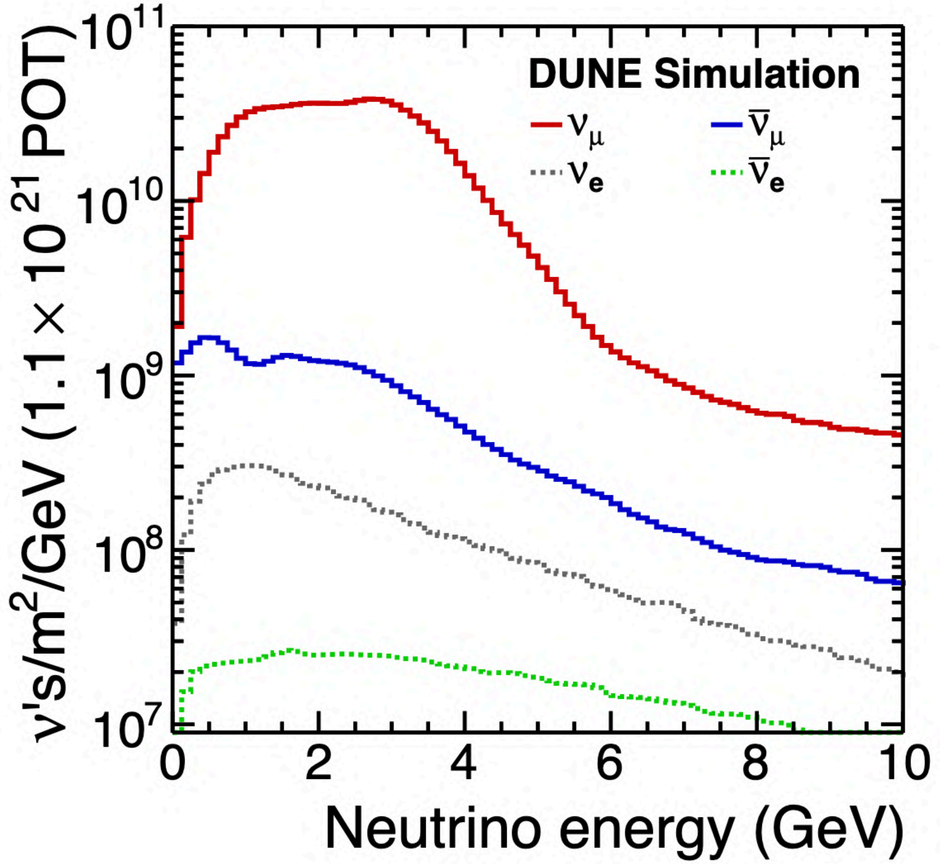
First beam in 2025
(at the earliest)

<u>Project documents</u>

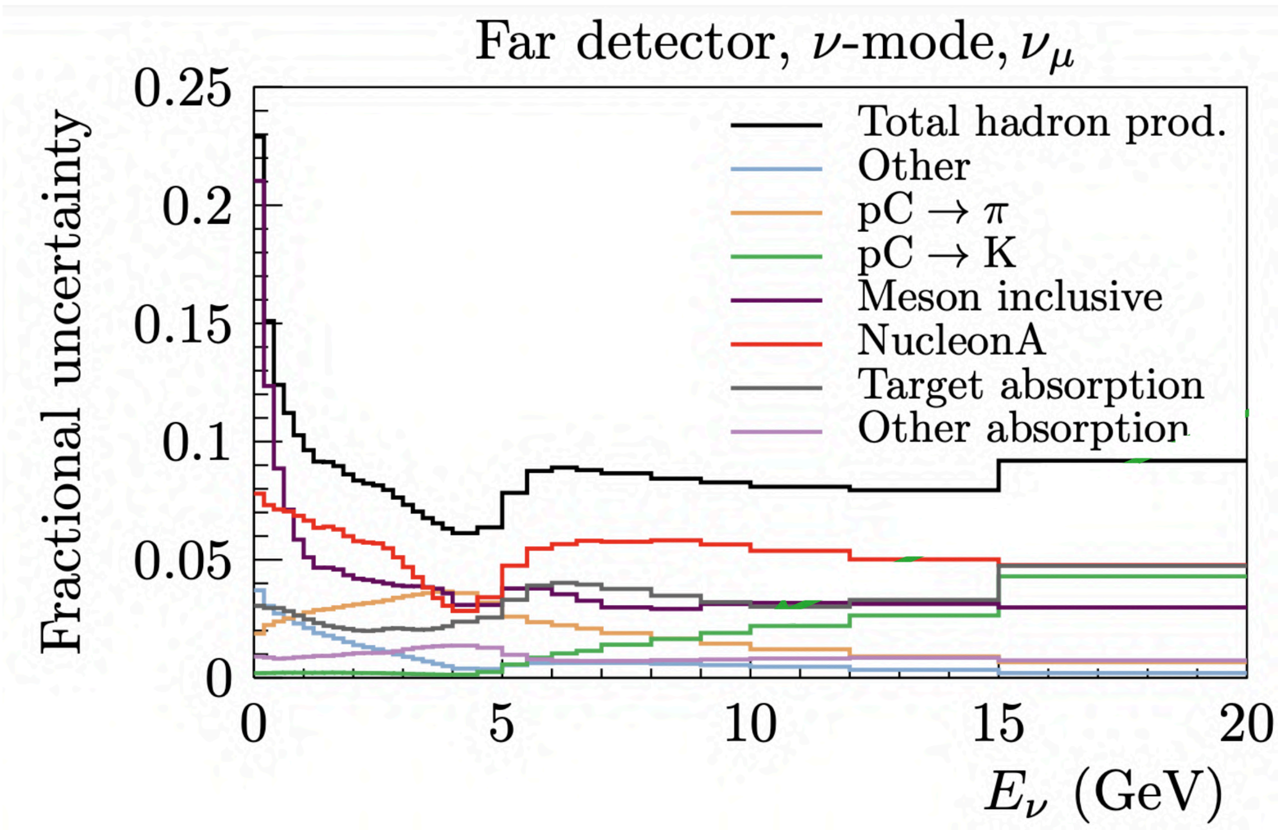
http://cds.cern.ch/record/2783037

https://cds.cern.ch/record/2810696

Prospect for the DUNE experiment



DUNE: Eur. Phys. J. C 80, 978 (2020)



Laura Fields (NA61++/SHINE Workshop, 2022)

We need to understand the broader energy range of neutrino flux compared to T2K.

-> Phase 2, 3, and future data will help for the reduction of the flux uncertainty

-> Aiming at unprecedented precision, below 2~3% uncertainty on flux prediction

NA61++/SHINE Era

Phase 1 (2006-2010): p+C (2cm graphite or 90-cm-long T2K replica graphite) at 31 GeV/c -> T2K

Phase 2 (2015-2018): various -> Fermilab beamlines (NuMI, LBNF/DUNE)

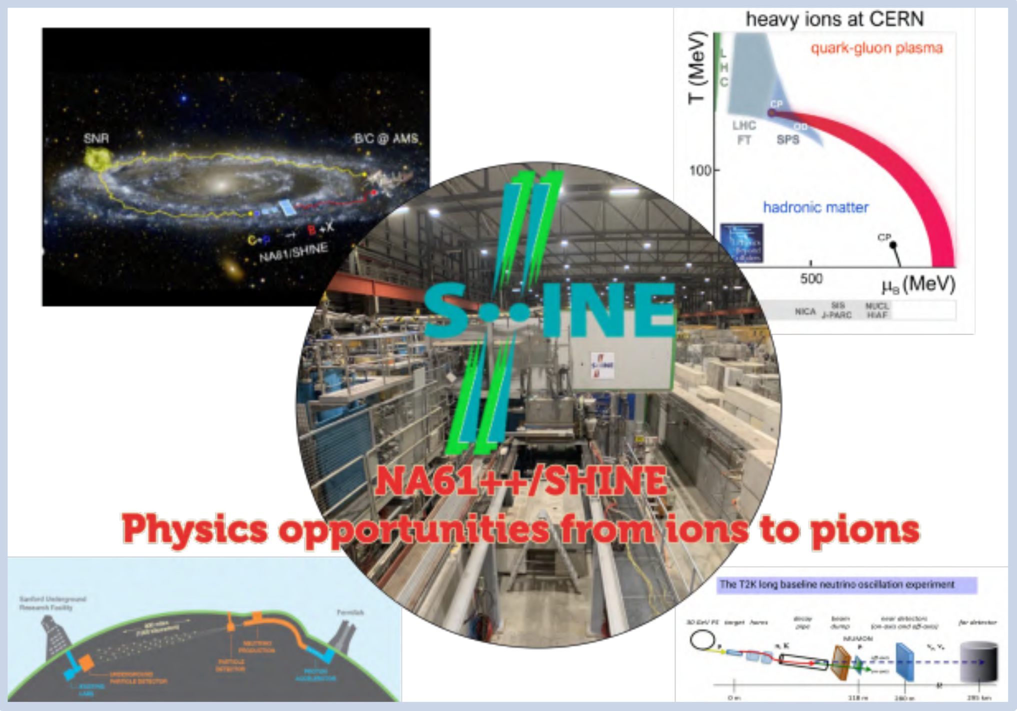
Phase 3 (2022-2025): various -> T2K, LBNF/DUNE

After LS3 (2027-???): various -> Planning phase

note: CERN's Long-Shutdown 3, LS3, is currently planned 2026-2027 or 2026-2028

Physics opportunities

- Conventional SPS beams (hadrons & ions, up to SPS energy)
- Low-energy hadron beams (1-30 GeV)
- Interdisciplinary program
  - **Neutrino Physics**
  - Strong interaction and heavy ion physics
  - Cosmic ray physics
  - and more..?
- We held a dedicated workshop (December 15-17, 2022)
  - Discussion regarding technical issues and physics opportunities



https://indico.cern.ch/event/1174830

Summary

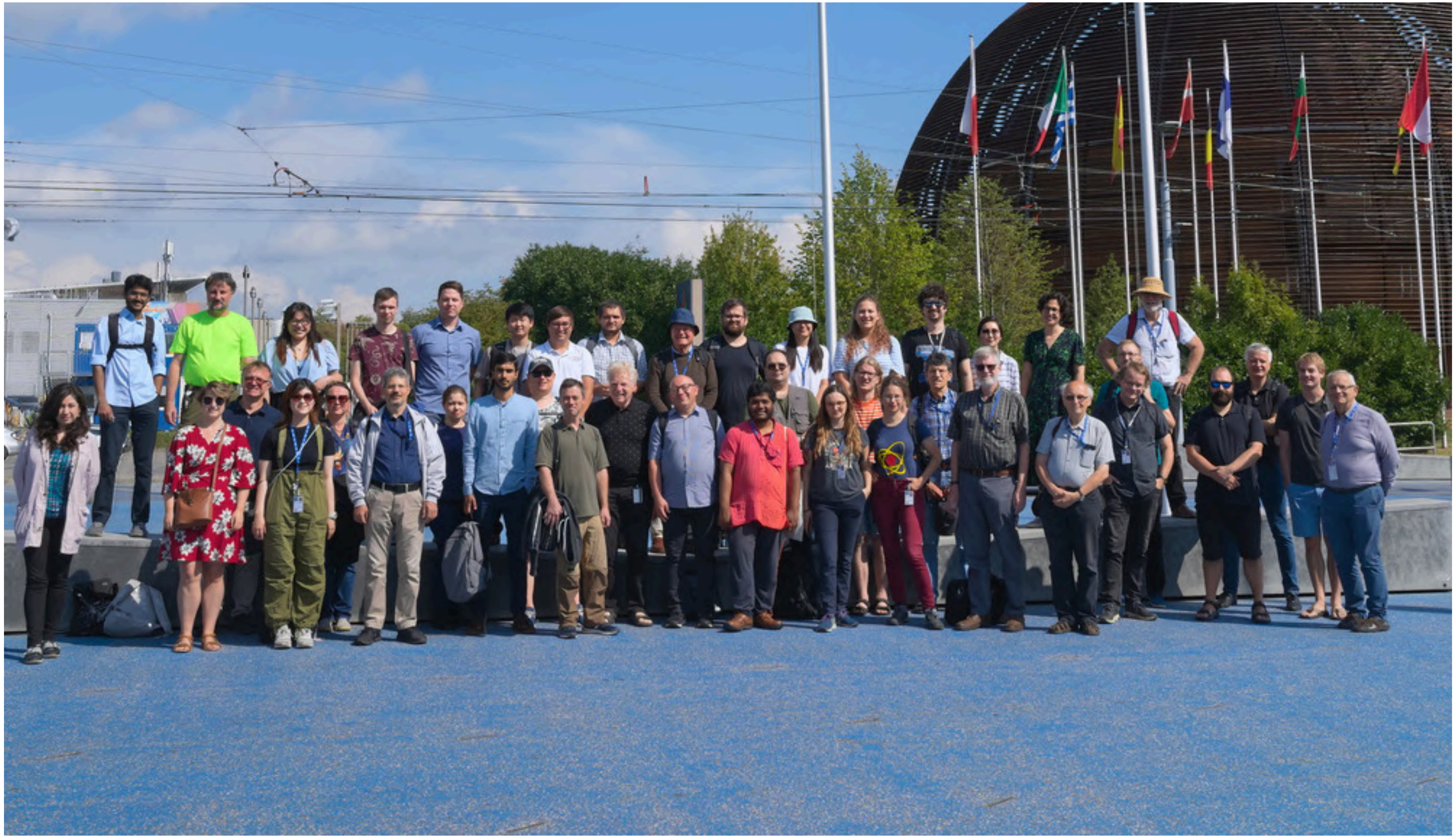
- Precision hadron production measurements are essential to reduce the leading systematic uncertainty on the neutrino flux prediction for accelerator-based neutrino experiments

- Lots of recent activities by NA61/SHINE
  - Recent data helps a lot to improve flux knowledge of T2K, and near future for Fermilab beamlines including DUNE

- Phase is shifting to envision next-generation experiments
  - These experiments require unprecedented knowledge of neutrino fluxes
  - The NA61/SHINE experiment prepares for their needs

We welcome new collaborators!! Stay Tuned!

Thank you for your attention!



http://shine.web.cern.ch

The NA61/SHINE Collaboration

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Backup

NA61/SHINE Data Collection History

Phase 1 (2006-2010): p+C (2cm graphite or 90-cm-long T2K replica graphite) at 31 GeV/c -> T2K

- Thin target:
  - total cross-section and $\pi^{+/-}$ spectra measurements (Phys. Rev. C84 034604 (2011))
  - K^{+} spectra measurement (Phys. Rev. C85 035210 (2012))
  - K^{0}_{S} and Λ spectra measurements (Phys. Rev. C89 (2014) 025205)
  - total cross-section and $\pi^{+/-}$,$K^{+/-}$ p, K^{0}_{S}, and Λ spectra measurements (Eur. Phys. J. C76 84 (2016))
- Replica target:
  - methodology, $\pi^{+/-}$ yield measurement (Nucl. Instrum. Meth. A701 99-114 (2013))
  - $\pi^{+/-}$ yield measurement (Eur. Phys. J. C76 617 (2016))
  - $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79, no.2 100 (2019))
  - Production cross-section via beam attenuation (Phys. Rev. D103, 012006 (2021))

NA61/SHINE Data Collection History

Phase 1 (2006-2010): p+C (2cm graphite or 90-cm-long T2K replica graphite) at 31 GeV/c -> T2K

Phase 2 (2015-2018): various -> Fermilab beamlines (NuMI, LBNF/DUNE)

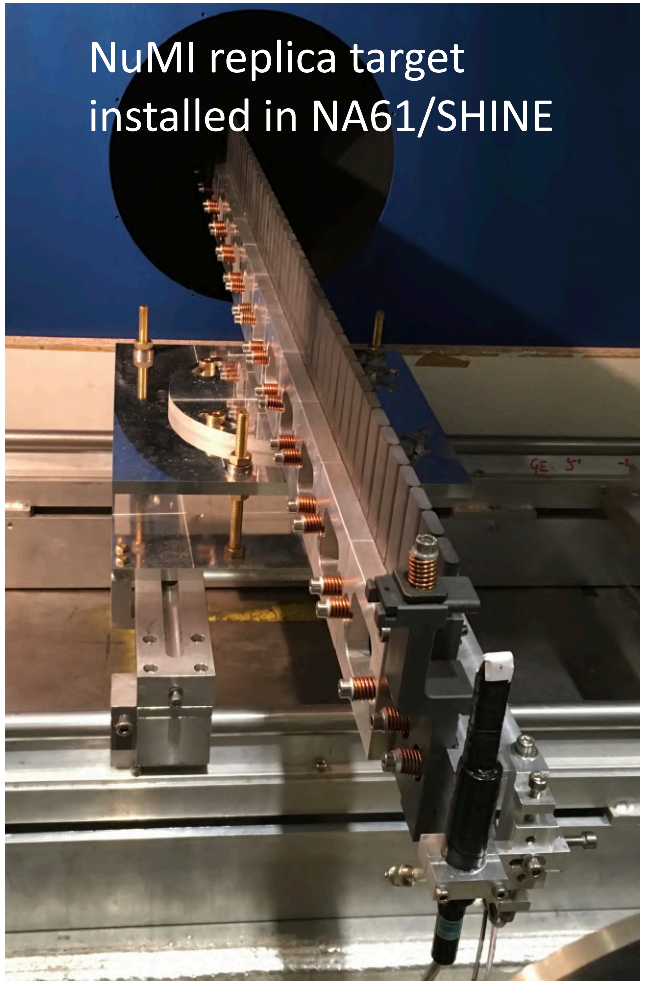
Data sets			
2015	2016	2017	2018
no magnetic field	with magnetic field	with magnetic field	with magnetic field
p+C (31 GeV/c)	p+Al/Be/C (60 GeV/c)	p+C (90 GeV/c)	p+NuMI medium-e target
π^++Al/C (31 GeV/c)	p+Be/C (120 GeV/c)	p+Be/C (120 GeV/c)	(120 GeV/c)
π^++Al/C (60 GeV/c)	π^++Be/C (60 GeV/c)	π^++C (31 GeV/c)	
K^++Al/C (60 GeV/c)		π^++Al (60 GeV/c)	
		π^-+C (60 GeV/c)	

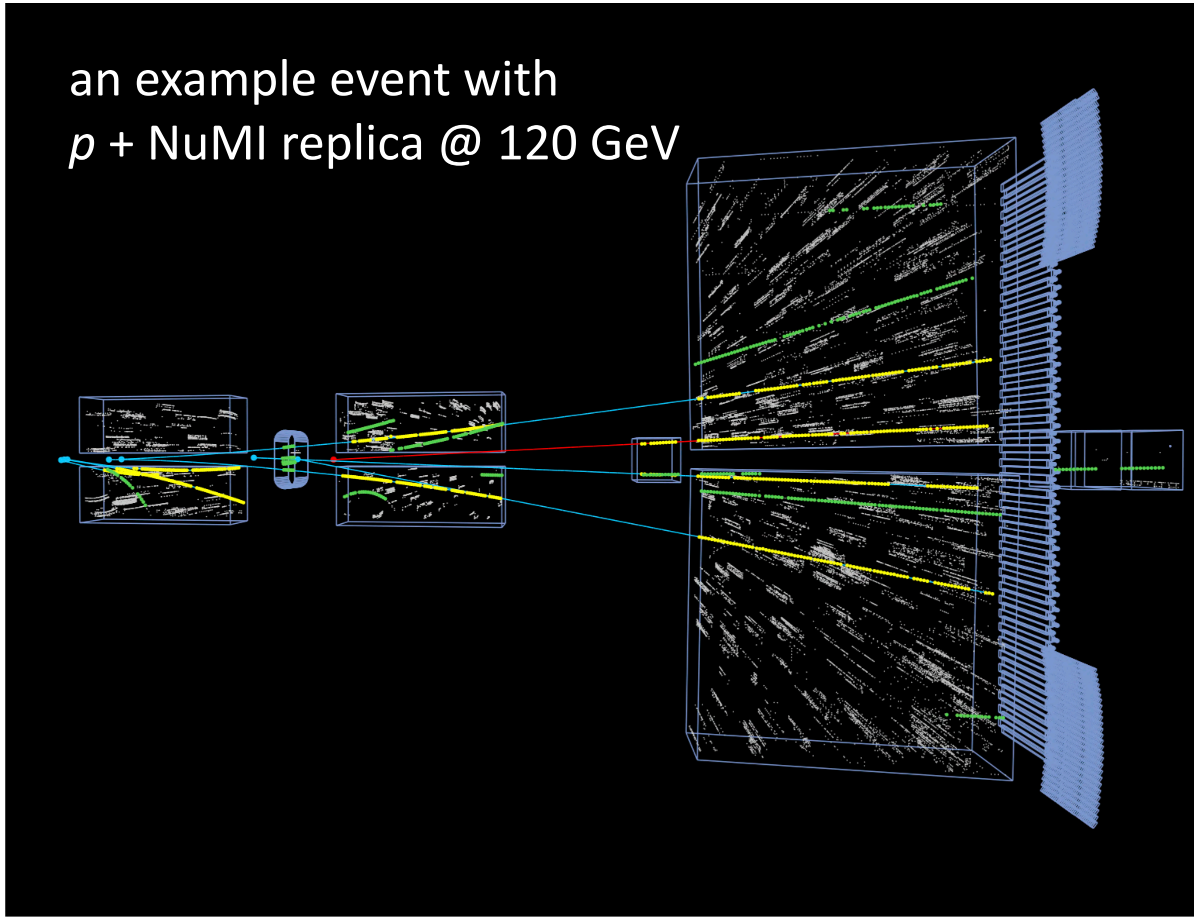
- Total cross-section
  - π^+ and K^+ beams (Phys. Rev. D98, 052001 (2018))
  - proton beams (Phys. Rev. D100, 112001 (2019))
  - π^+ beams (Phys. Rev. D100, 112004 (2019))

- Differential production multiplicity
  - π^+ beams (Phys. Rev. D100, 112004 (2019))
  - proton beams (analyses ongoing)

Phase 2 example: NuMI Replica Target Data

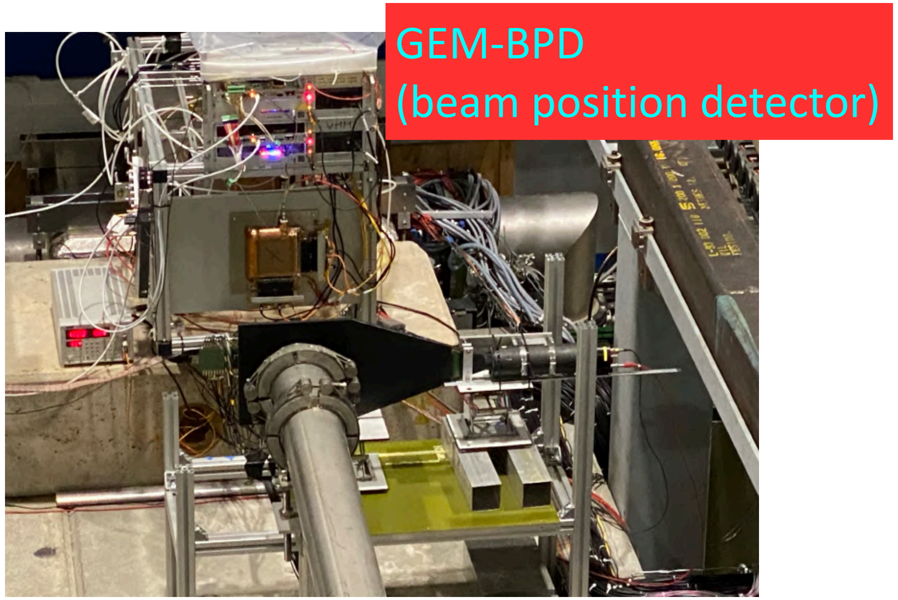
- <u>Replica target</u>: proton beam @ 120 GeV/c on NOvA replica target (2018)

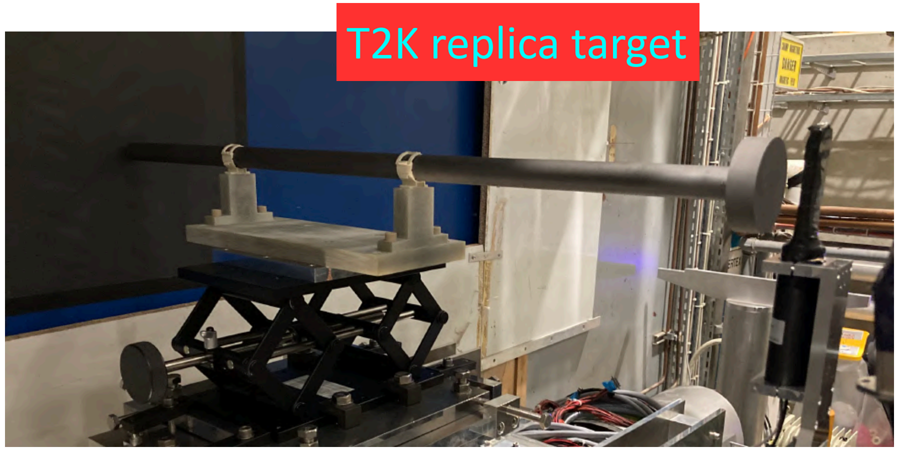




Data analysis is ongoing

Phase 3: T2K Replica Target Data





Dataset	Statistics (in Million)	Data collection period
Full MF, target OUT	6.0	4-5 July, 2022
Half MF, target IN	149.7	7-23 and 25-27 July, 2022
Half MF, target OUT	9.1	
Half MF, empty target holder IN	2.9	
1/8 MF, target IN	14.0	23-25 July, 2022
1/8 MF, target OUT	1.4	
Total	183.1	4-27 July, 2022

Table 1: Summary of collected datasets with the T2K replica target during 2022 run.

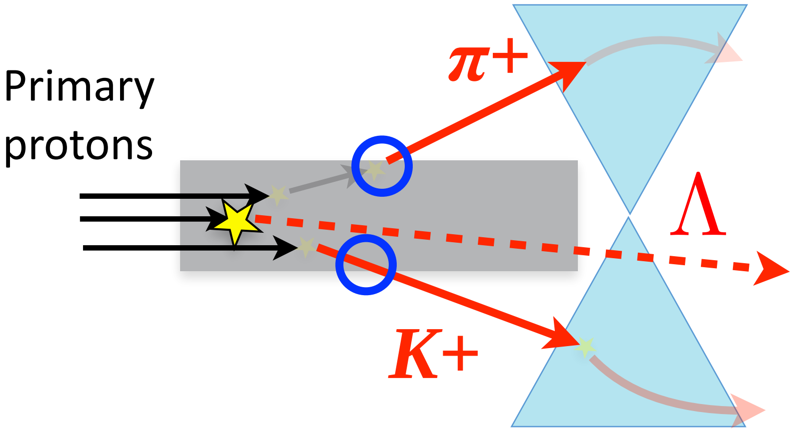
- Two weeks of detector commissioning followed by three weeks of data taking
  - Main physics data: 150 M events
  - Total physics data: over 180 M events

    (c.f. phase 1 T2K replica data stat. was about 10 M events)
- Data calibration and analysis have just started

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 (differential cross section) to external measurement



	Interaction length tune σ_{prod}(p+C) to NA61 measurement	**Multiplicity** Mostly 30 GeV p+C data by NA61
At interaction	"Vertex" weight $\sigma_{\mathrm{DATA}}/\sigma_{\mathrm{MC}}$	$\left(\frac{\mathrm{d}^2 n}{\mathrm{d}p\,\mathrm{d}\theta}\right)_{\mathrm{DATA}} \Big/ \left(\frac{\mathrm{d}^2 n}{\mathrm{d}p\,\mathrm{d}\theta}\right)_{\mathrm{MC}}$ p, θ: outgoing particle kinematics
For distance L traversed in matter	"Attenuation" weight $e^{-(\sigma_{\mathrm{DATA}}-\sigma_{\mathrm{MC}})\,\rho L}$	N.A.

with replica target data… weights applied at the exiting point