# Hadron Production Measurements for Neutrino Experiments at NA61/SHINE

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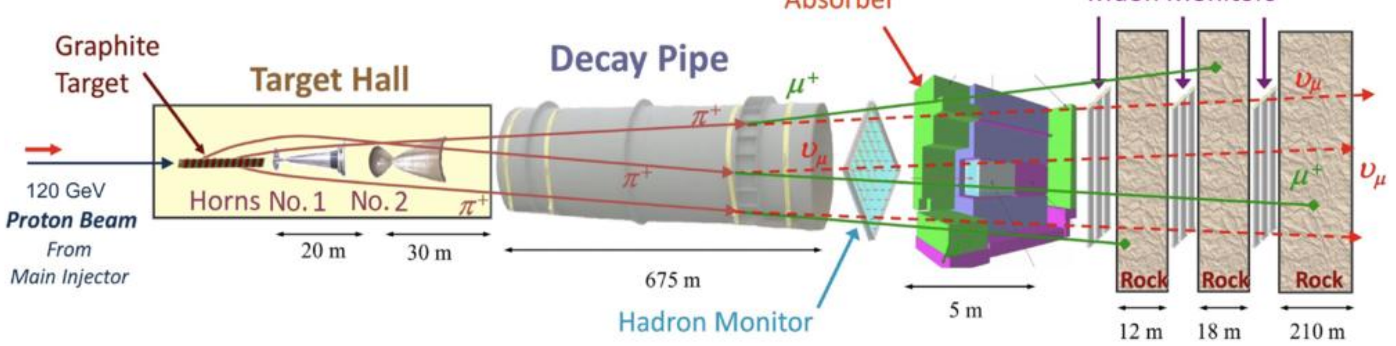
On Behalf of the NA61/SHINE Collaboration

University of Colorado Boulder

# Motivation: Flux Uncertainties

- Neutrino Beam: protons on target → focusing produced hadrons → decay to neutrinos → absorb remaining charged leptons and other particles
- Accelerator-based experiments suffer from large neutrino flux uncertainties
  - Major contribution from hadron production uncertainty
- Limits the precision of measurements
- Can be improved by measuring hadron-nucleus interactions
  - Primary proton-target interactions
  - Secondary interactions
    - Further processes within the target
    - Other beamline materials

NuMI



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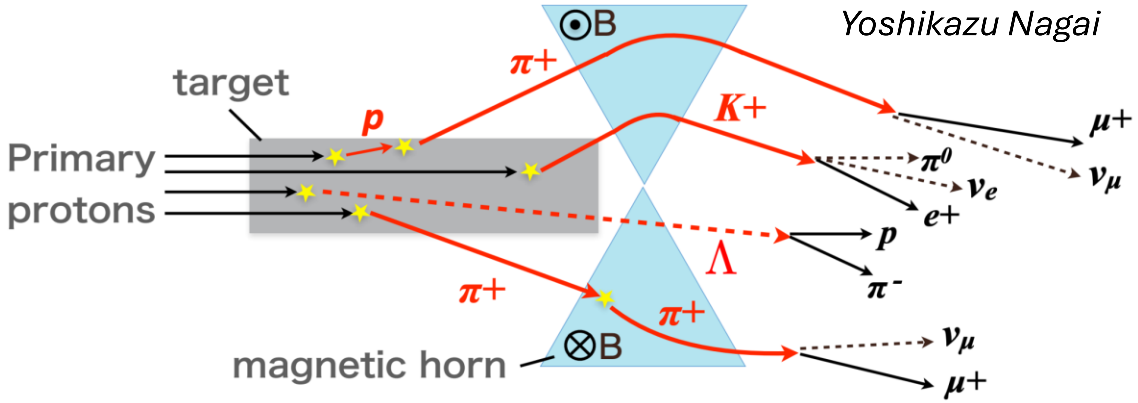
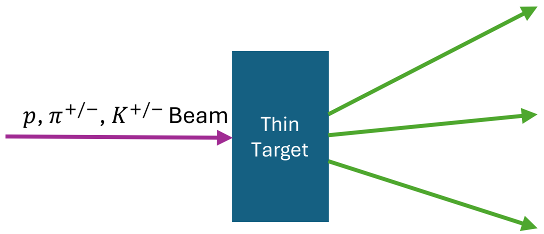
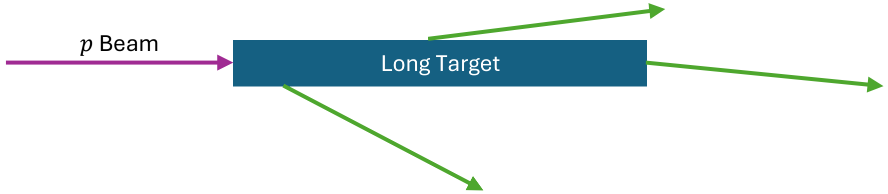


# Thin vs Long Targets

- Thin-target measurements
  - For calculating inelastic and production cross sections
  - Hadron yields for both primary and expected secondary interactions
- Long-target (replica-target) measurements
  - For calculating differential production yields (specifically from the surface) and beam survival probability
  - Helps understand beam attenuation

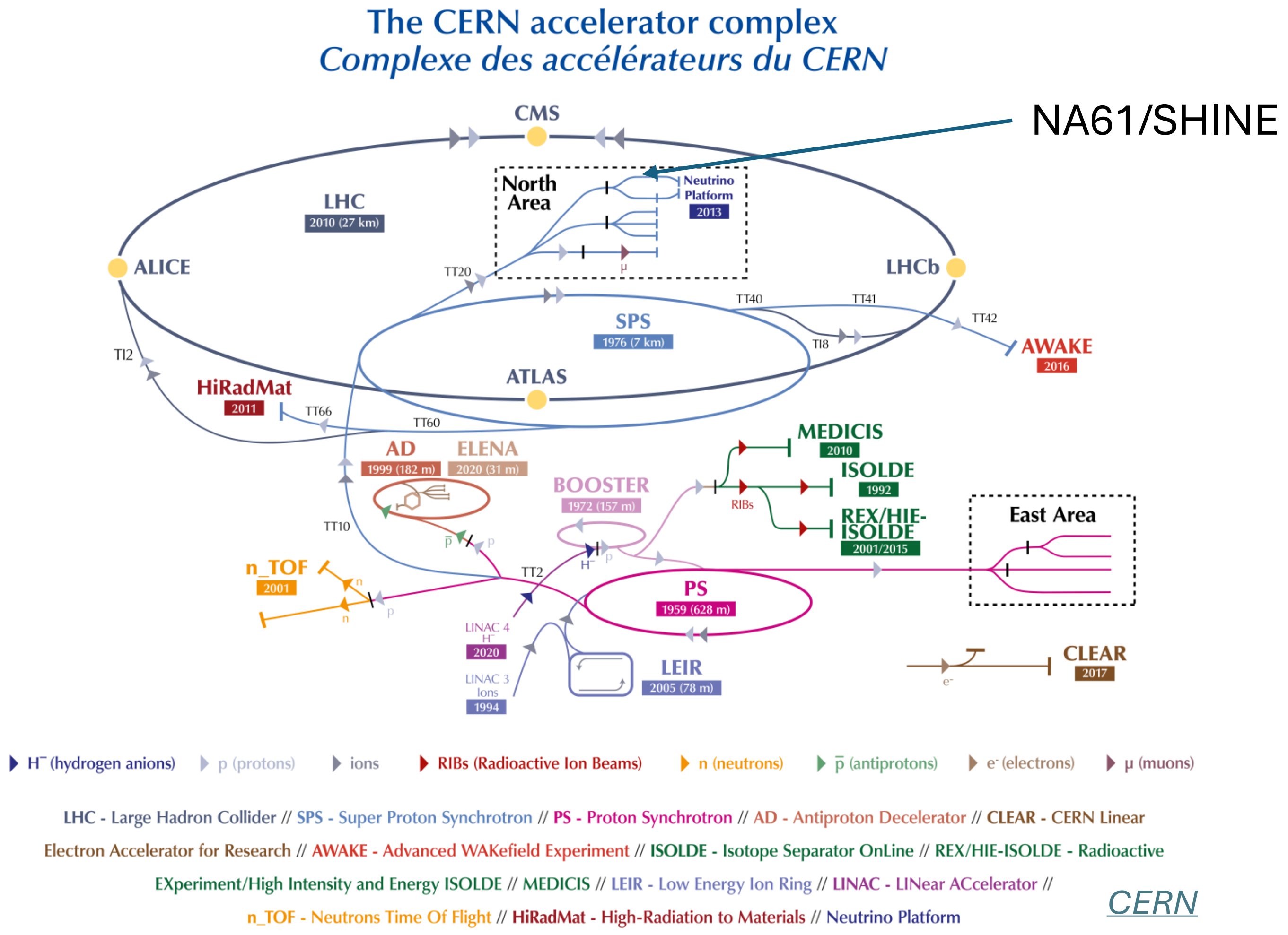



Diagrams not to scale



# NA61/SHINE

- Fixed-target experiment in the **N**orth **A**rea complex at CERN
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Physics Program:
  - Strong Interaction Physics
  - Hadron Production for Neutrino Experiments
  - Cosmic-Ray Physics

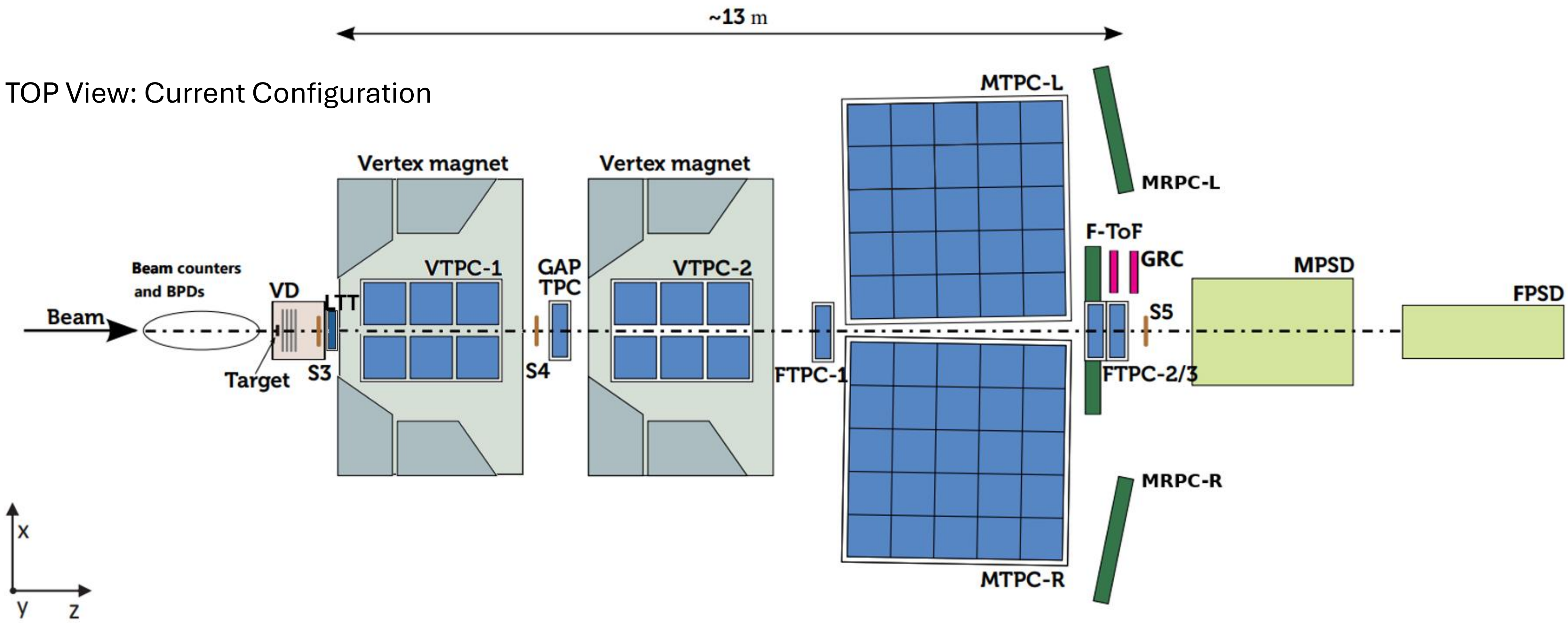



CERN

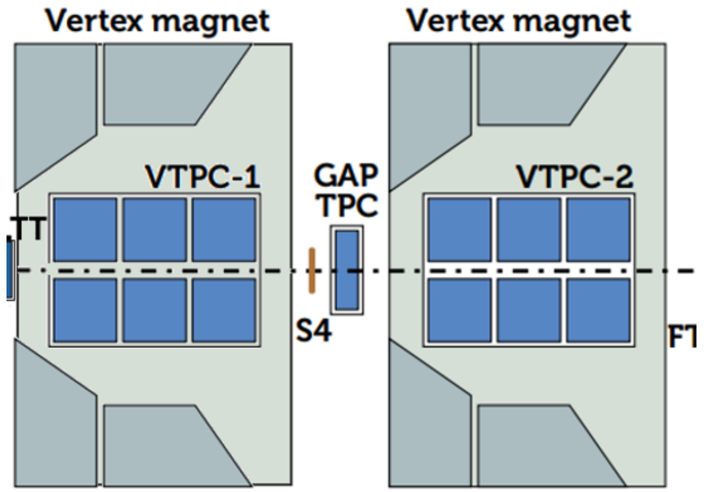
# NA61/SHINE: In the North Area

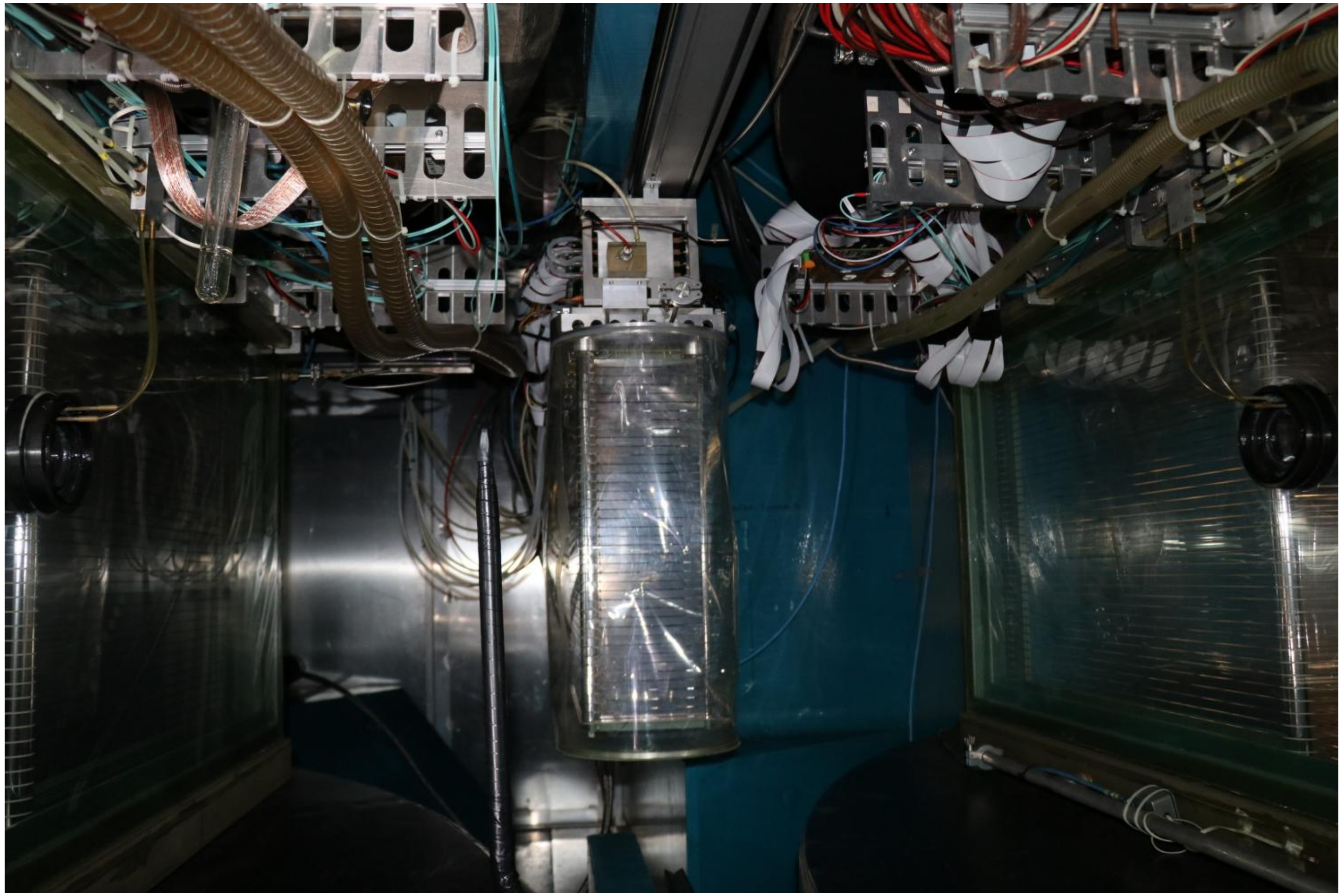
# NA61/SHINE: Detector

TOP View: Current Configuration



# NA61/SHINE: Detector



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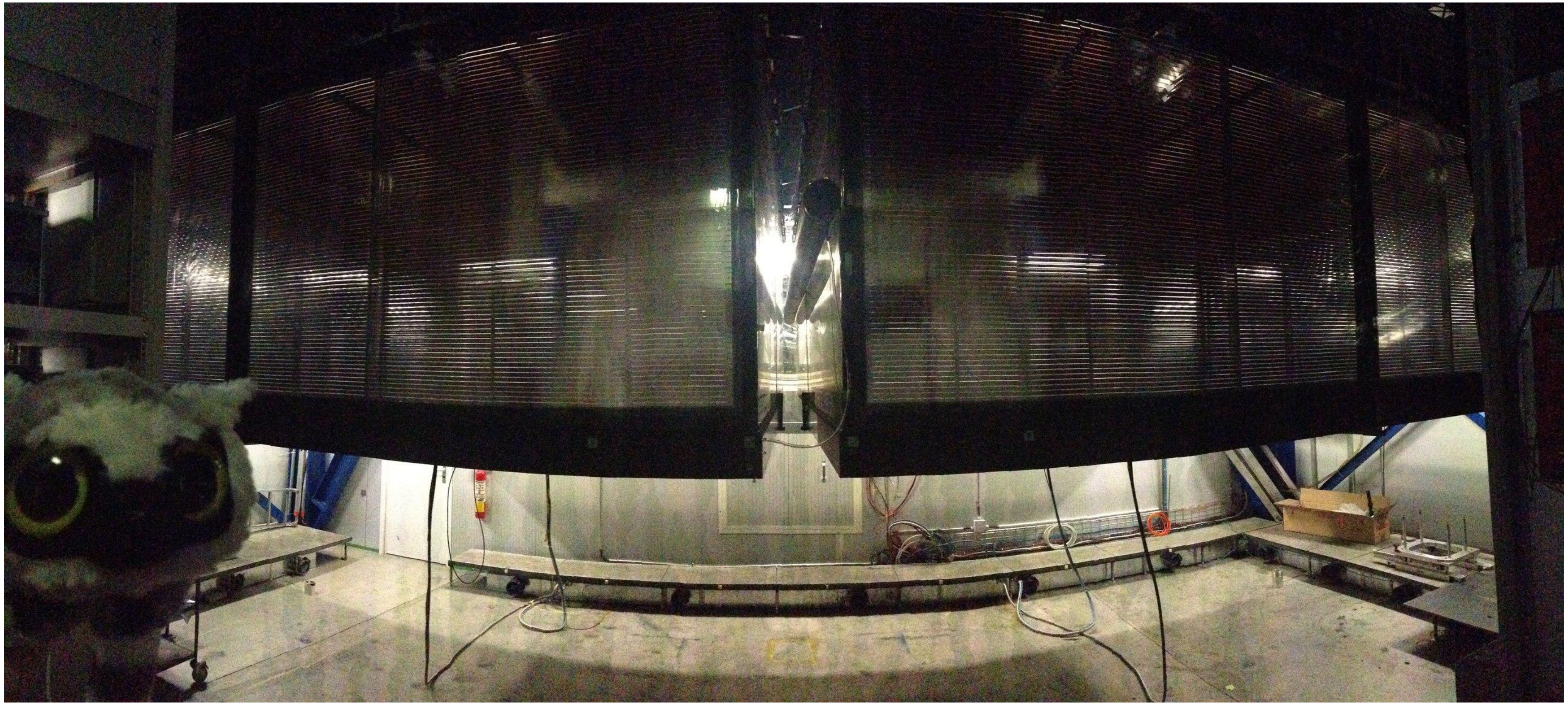

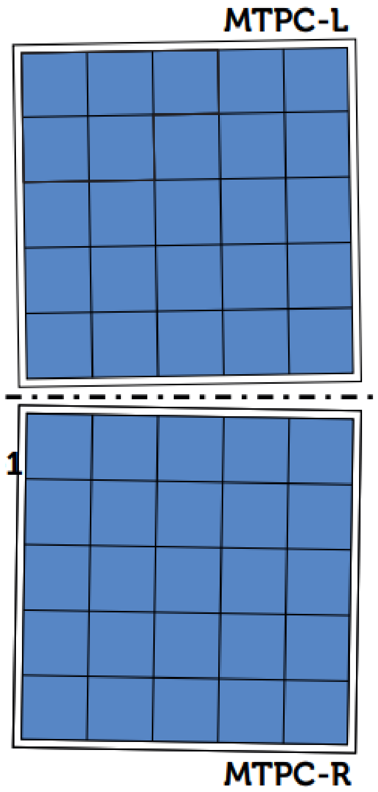

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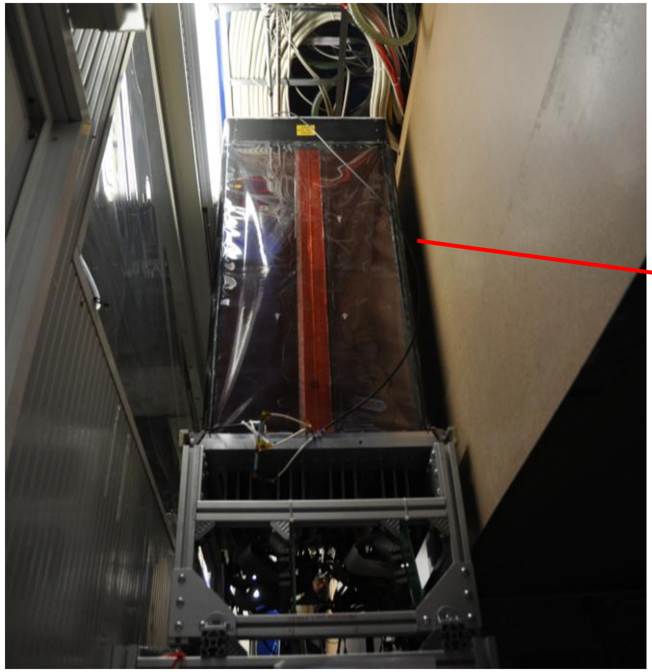
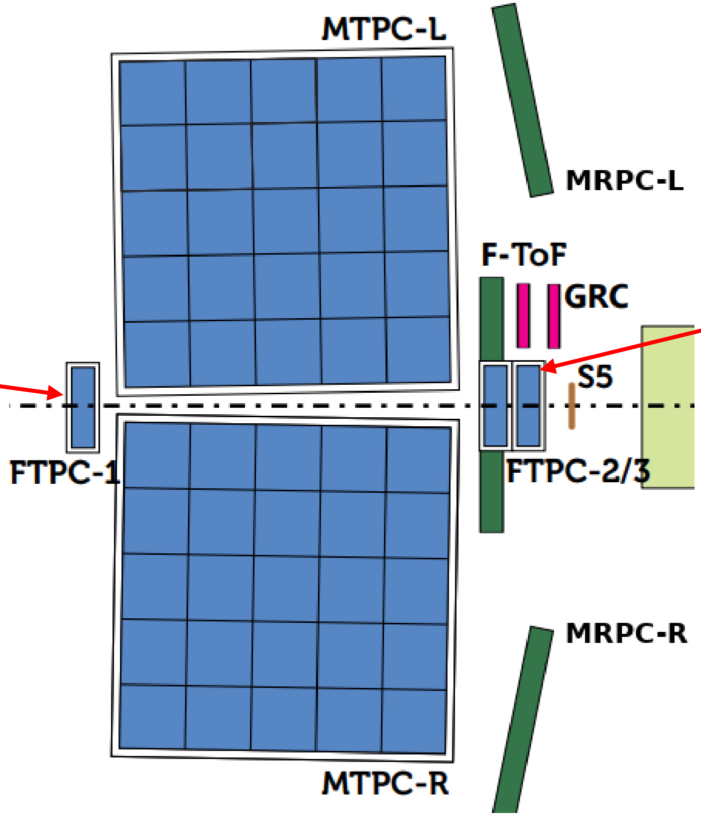
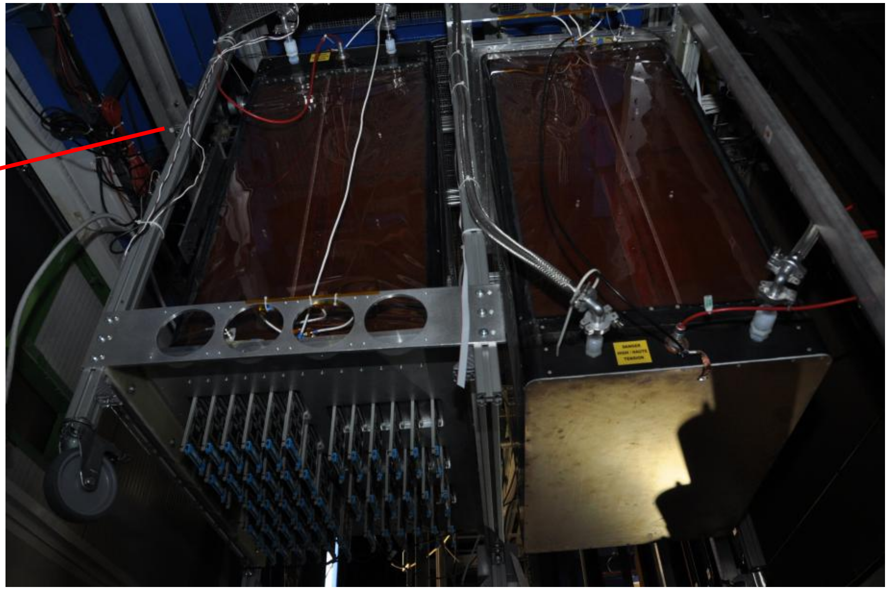
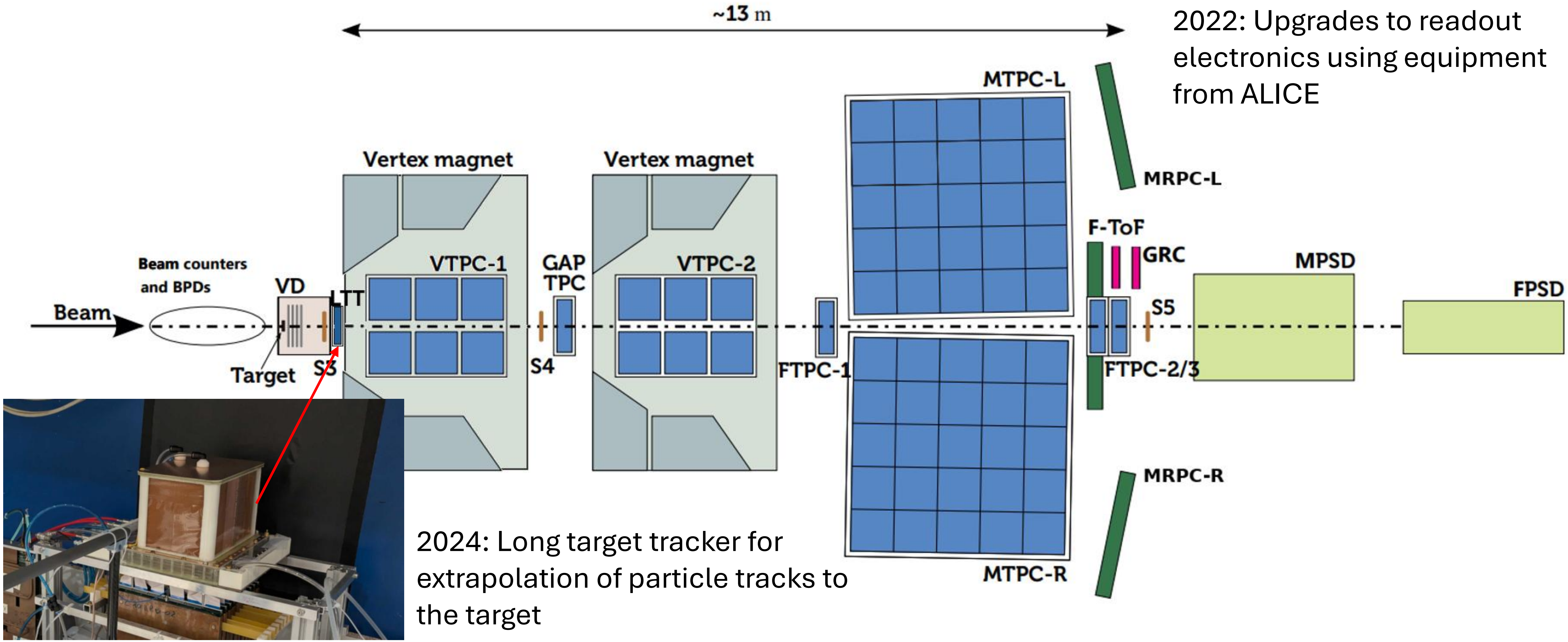




# NA61/SHINE: Detector Upgrades




2022: Upgrades to readout electronics using equipment from ALICE

2024: Long target tracker for extrapolation of particle tracks to the target

# NA61/SHINE: Data Timeline

**Run 1**
2007 – 2010

**T2K**
Proton 31 GeV/*c*

**Long Shutdown**
(LS) 1

**Run 2**
2015 – 2018

**NuMI Experiments and LBNF/DUNE**
Proton 120 GeV/*c*
Proton 60, 90 GeV/*c*
Pion 60 GeV/*c*

**Long Shutdown**
(LS) 2

**Run 3**
2022 – 2026

**T2K**
Proton 31 GeV/*c*

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Proton 120 GeV/*c*
Kaon 60 GeV/*c*

**Atmospheric neutrinos**
Proton 15 GeV/*c*

**BNB**
Proton 15 GeV/*c*

**Long Shutdown**
(LS) 3

**Run 4**
2029 –

**Low-Energy Beamline Program**
(TBC)

# Measurements for T2K

**Run 1**
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(LS) 1

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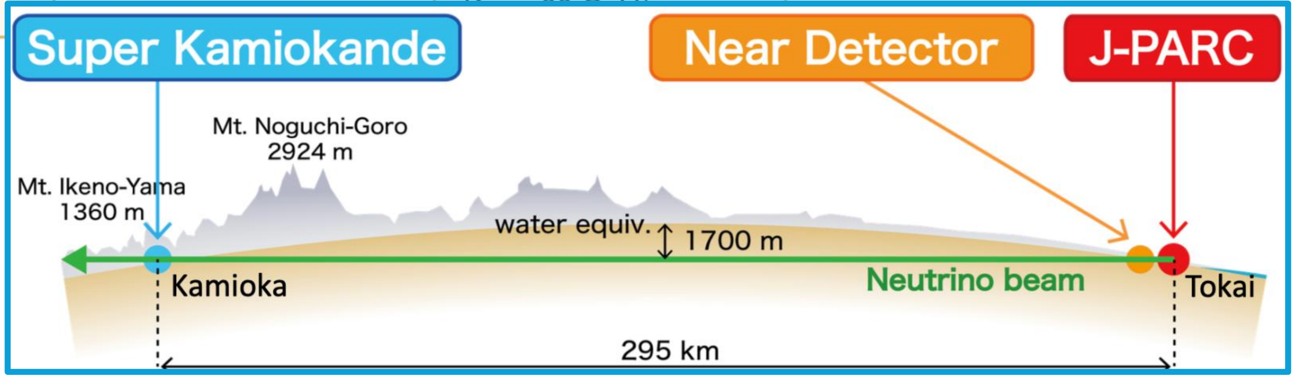
**Run 4**
2029 –

**Low-Energy Beamline Program**
(TBC)

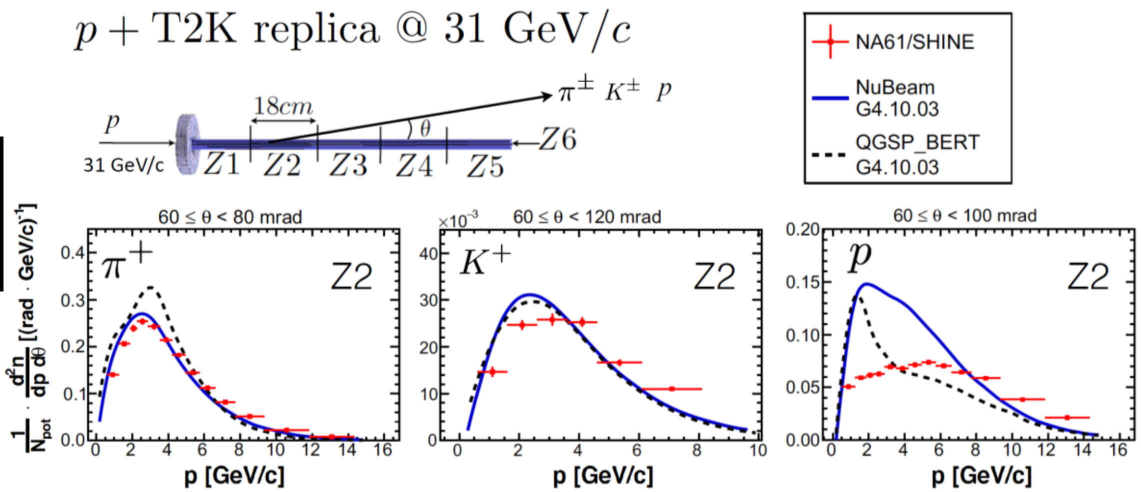
- Targets:
  - Thin: C
  - Replica target




T2K

# Run 1 Measurements for T2K

- Reduced T2K flux uncertainty down to 5% (~3% from hadron interactions)




Eur. Phys. J. C 79, no. 2, 100 (2019)

Phys. Rev. C 84, 034604 (2011)

Phys. Rev. C 85, 035210 (2012)

Phys. Rev. C 89, 025205 (2014)

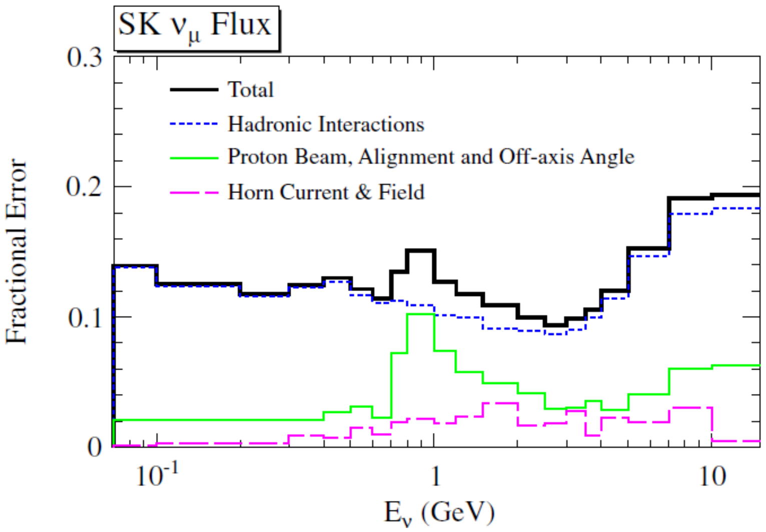
Eur. Phys. J. C 76, 84 (2016)

NIMA 701, 99-114 (2013)

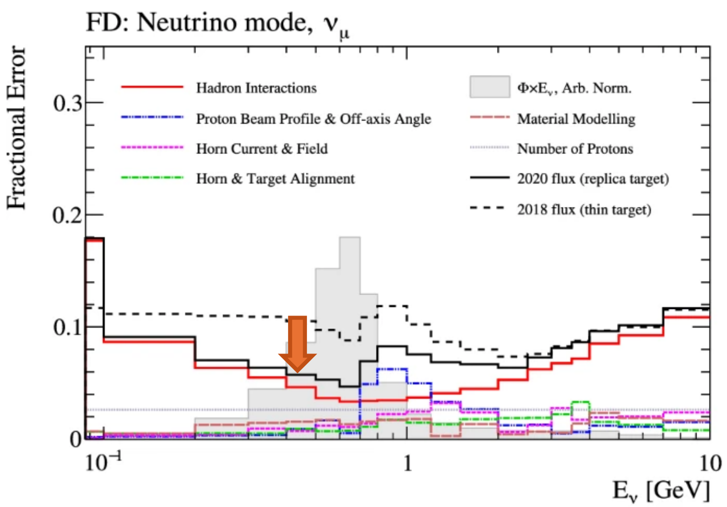
Eur. Phys. J. C 76, 617 (2016)

Eur. Phys. J. C 79, no. 2, 100 (2019)

Phys. Rev. D 103, 012006 (2021)



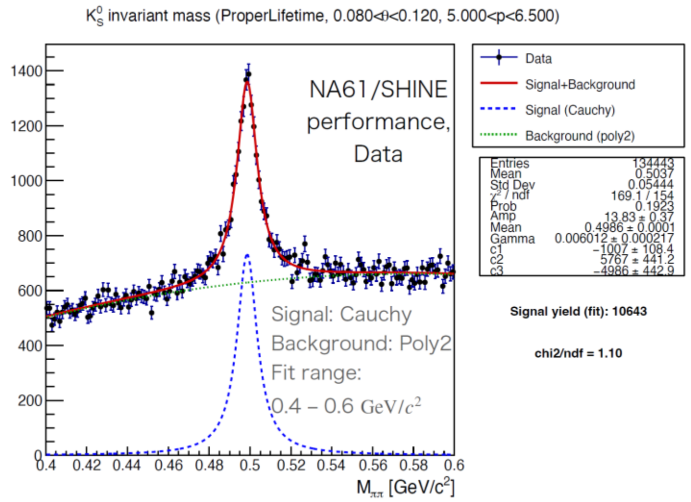

NA61/SHINE thin target data only
Phys. Rev. D 87, 012001 (2013)



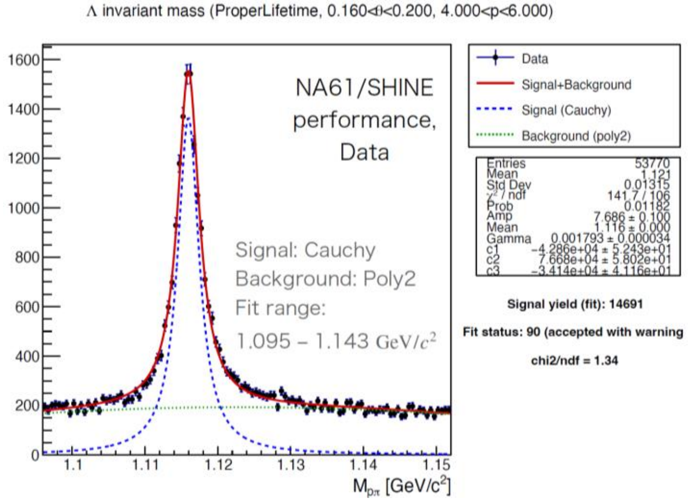

NA61/SHINE thin + replica-target data
Eur. Phys. J. C 83, no. 9, 782 (2023)

# Run 3 Measurements for T2K

- More data taken with the replica target
  - 15 times more statistics than 2010
  - 14M events w/ same magnetic field (MF) as 2010
  - 150M events with double the MF strength
- Higher MF allows measurement of higher momentum charged-kaon production
- 1-z bin neutral-hadron results coming soon

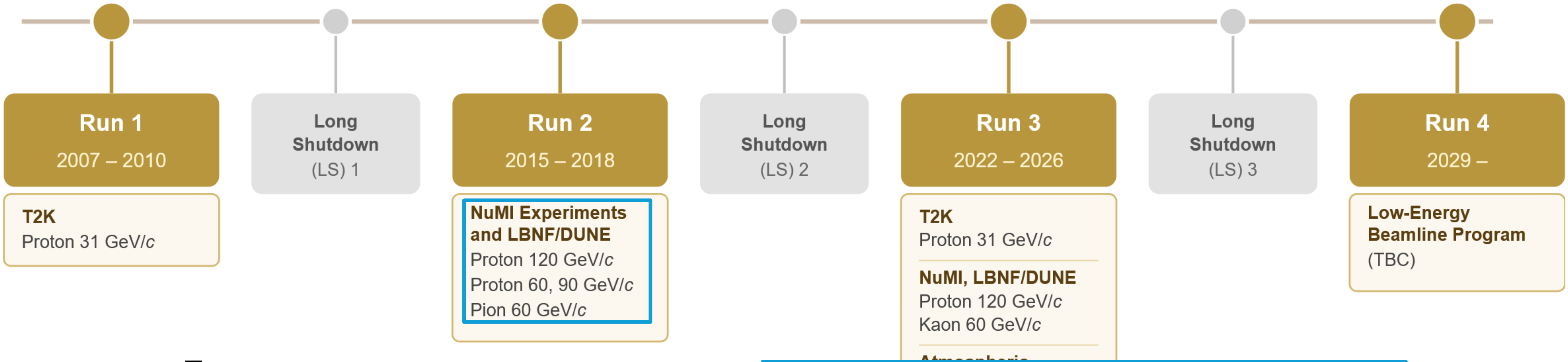



$K^0_S$ invariant mass fit by *Sakiko Nishimori*

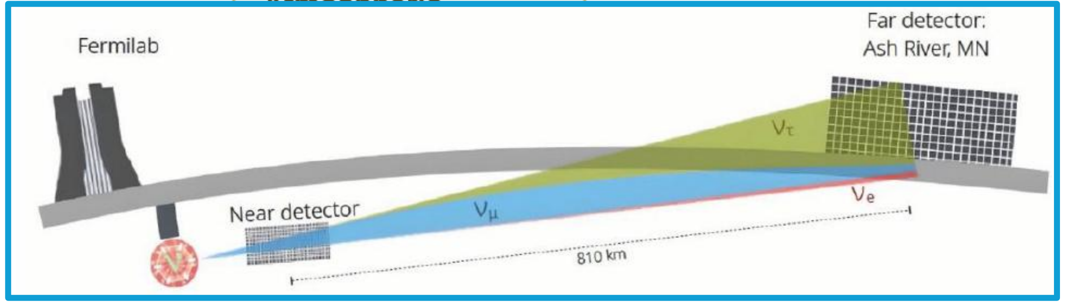



$\Lambda$ invariant mass fit by *Sakiko Nishimori*

# Run 2 Measurements for Neutrinos at the Main Injector (NuMI)



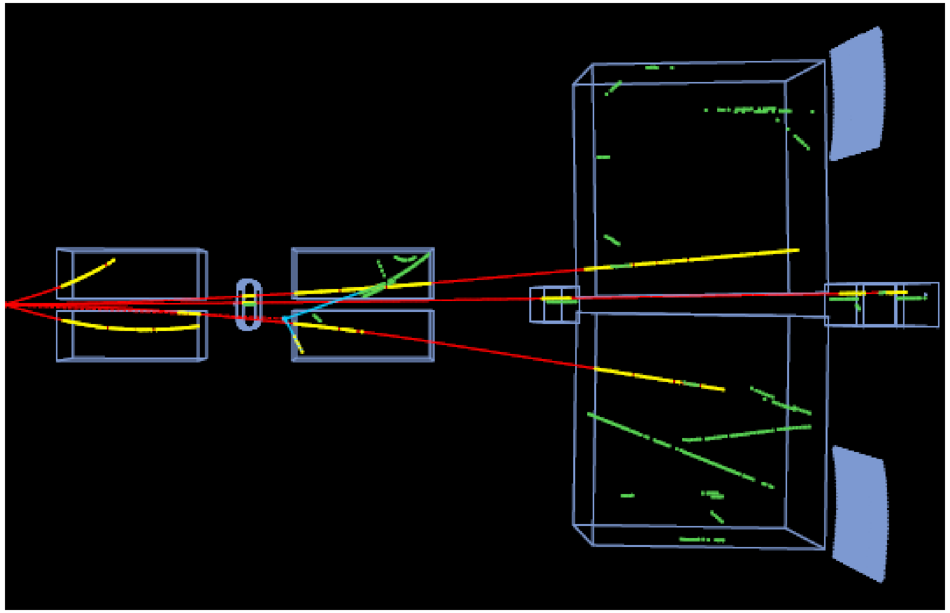

- Targets:
  - Thin: C, Al, Be
  - Replica target




FNAL

# Thin-Target Measurements for NuMI (Graphite)

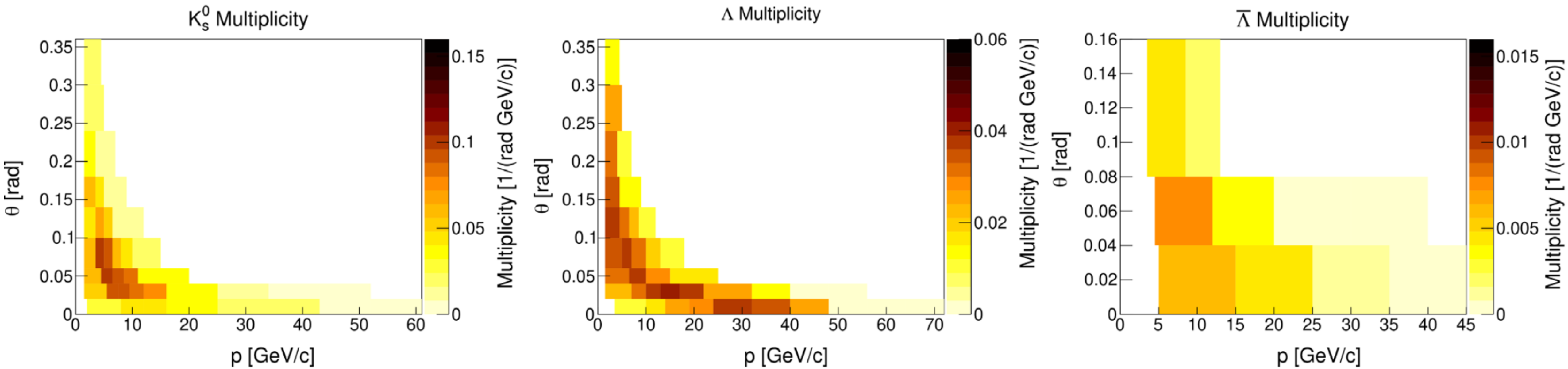
- 120 GeV/*c* proton beam (primary)
  - Neutral ($K_S^0$, $\Lambda$, $\overline{\Lambda}$): Phys. Rev. D 107, 072004 (2023)
  - Charged ($\pi^{\pm}$, $K^{\pm}$, $p$, $\bar{p}$): Phys. Rev. D 108, 072013 (2023)
- 90 GeV/*c* proton beam (secondary)
  - Charged and Neutral: Phys. Rev. D 112, 012011 (2025)
- 60 GeV/*c* proton beam (secondary)
  - Neutral: preliminary
  - Charged: coming soon



Event Browser for $p$+C at 120 GeV/*c*

# Neutral-Hadron Multiplicities for $p$+C at 120 GeV/$c$

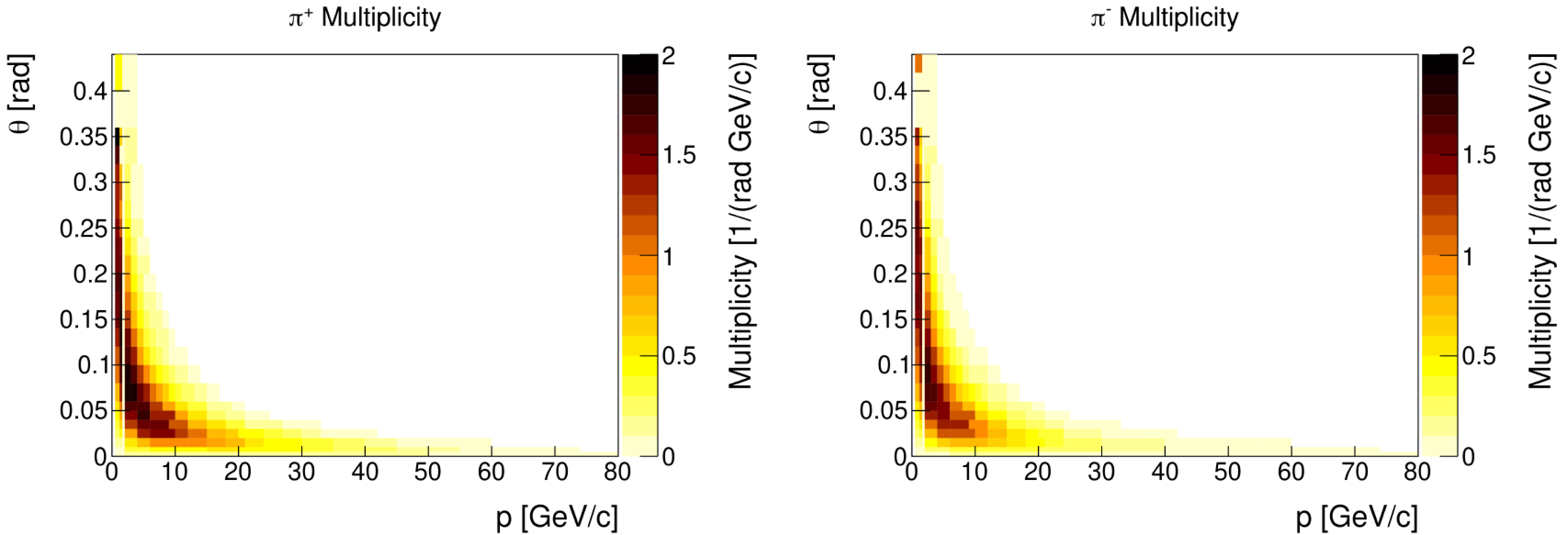
Data from 2016 and 2017 combined




[Phys. Rev. D 107, 072004 (2023)]

# Charged-Hadron Multiplicities for $p$+C at 120 GeV/$c$

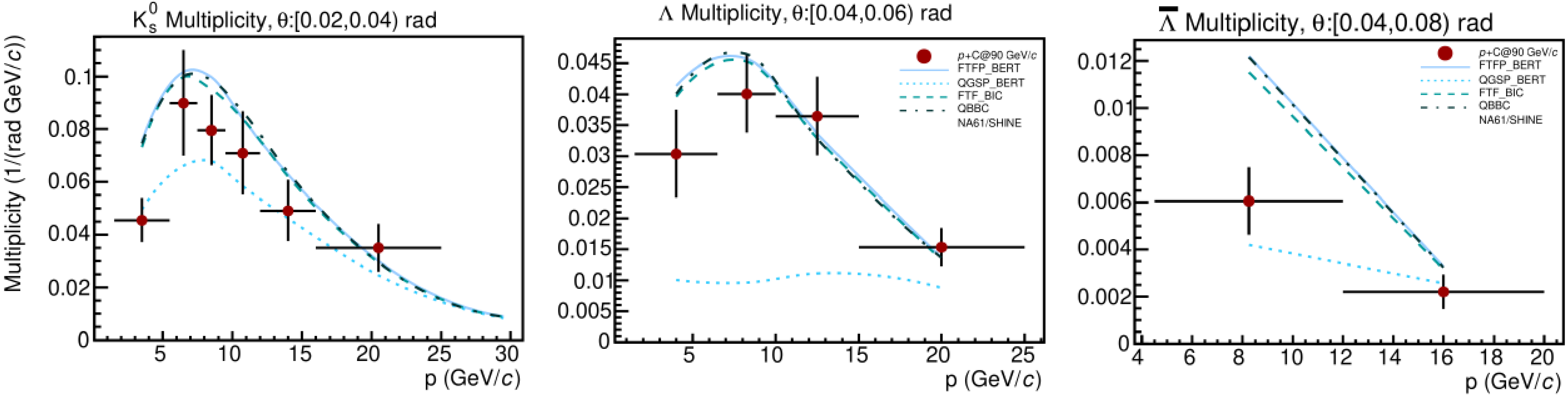
Data from 2016 and 2017 combined




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

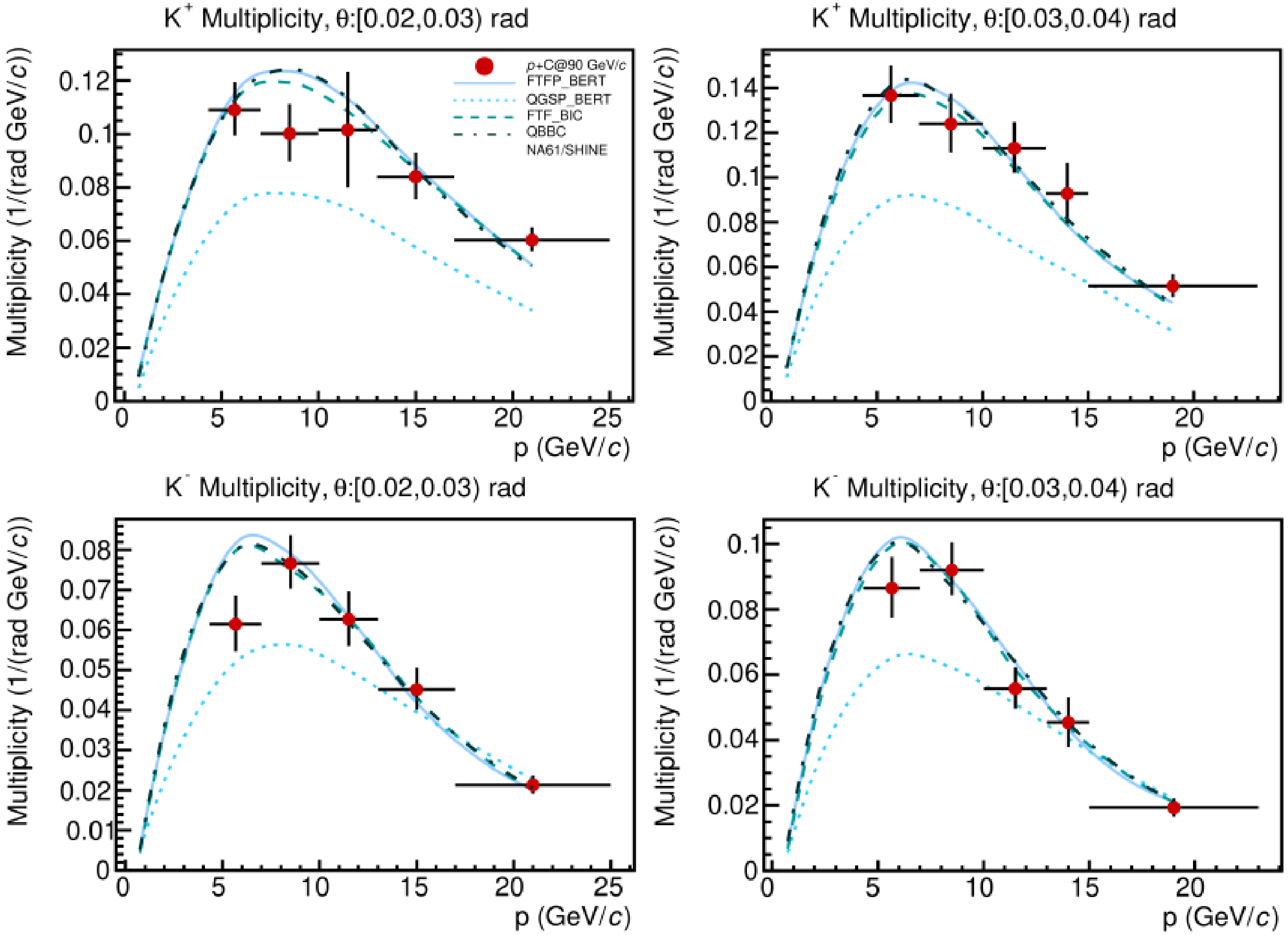
# Neutral-Hadron Multiplicities for $p$+C at 90 GeV/$c$

Data from 2017




Phys. Rev. D 112, 012011 (2025)

# Charged-Hadron Multiplicities for $p$+C at 90 GeV/$c$

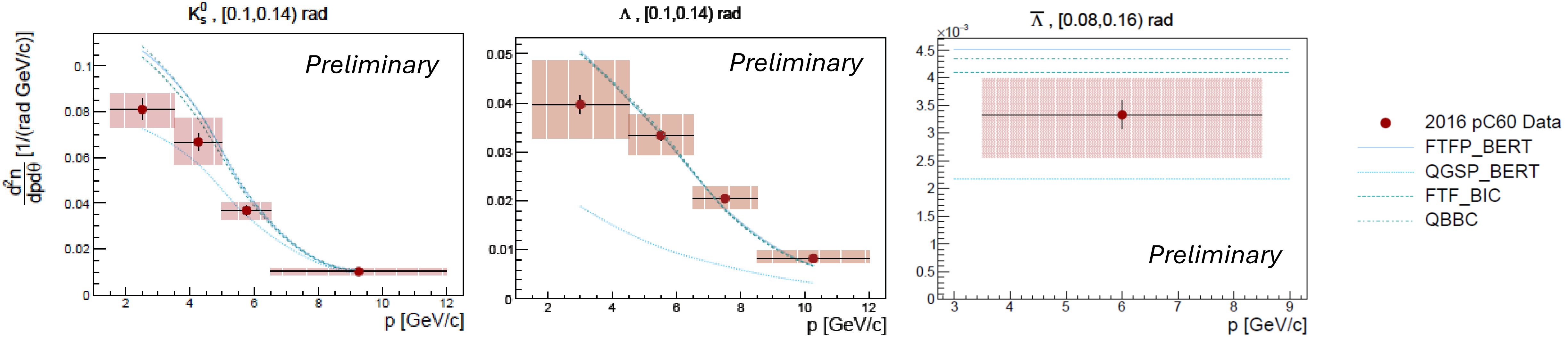



Data from 2017

Phys. Rev. D 112, 012011 (2025)

# Neutral-Hadron Multiplicities for $p$+C at 60 GeV/$c$

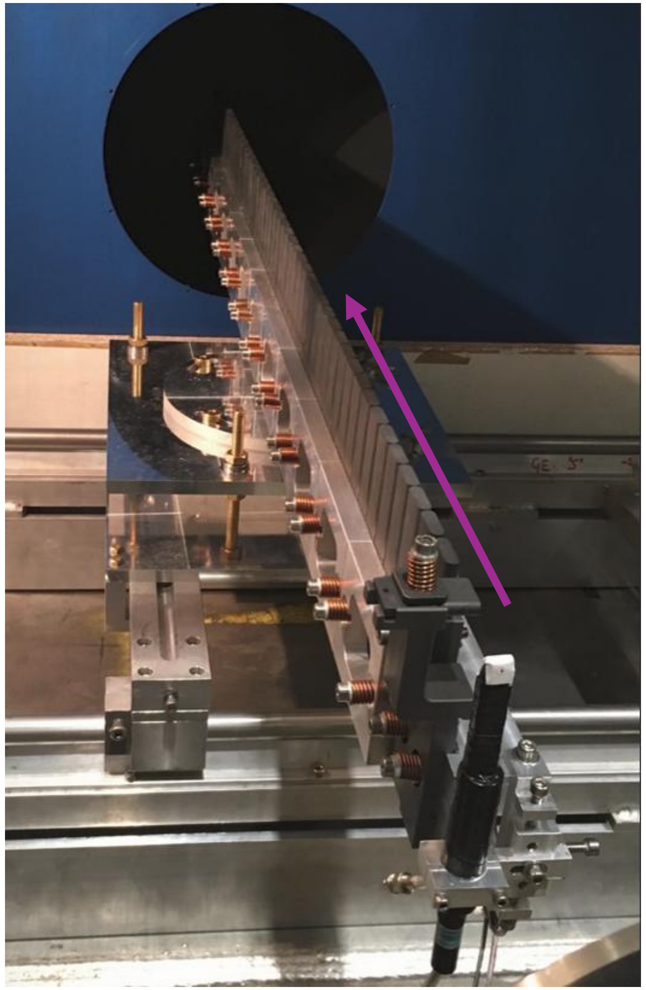
## PRELIMINARY




Data from 2016

# Long-Target Measurements for NuMI

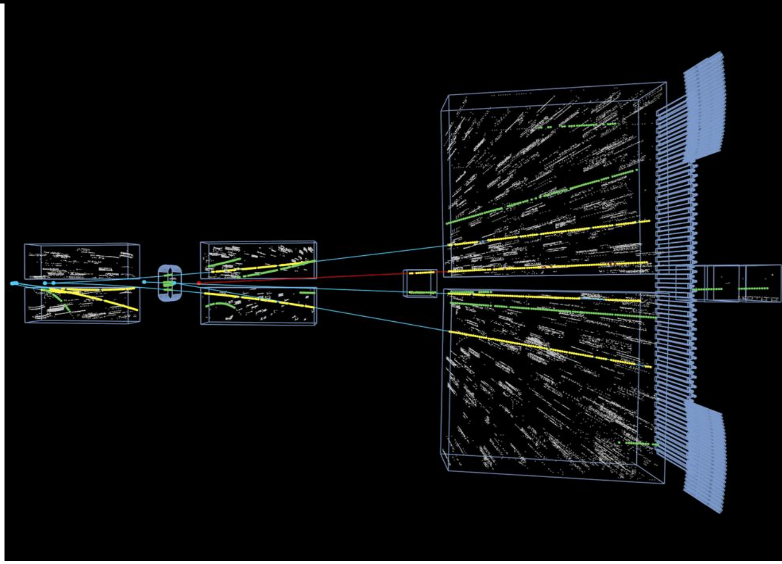
- NuMI replica target:
  - 123 cm long
  - 50 graphite “fins”
  - First used for NOvA and other experiments on the beamline

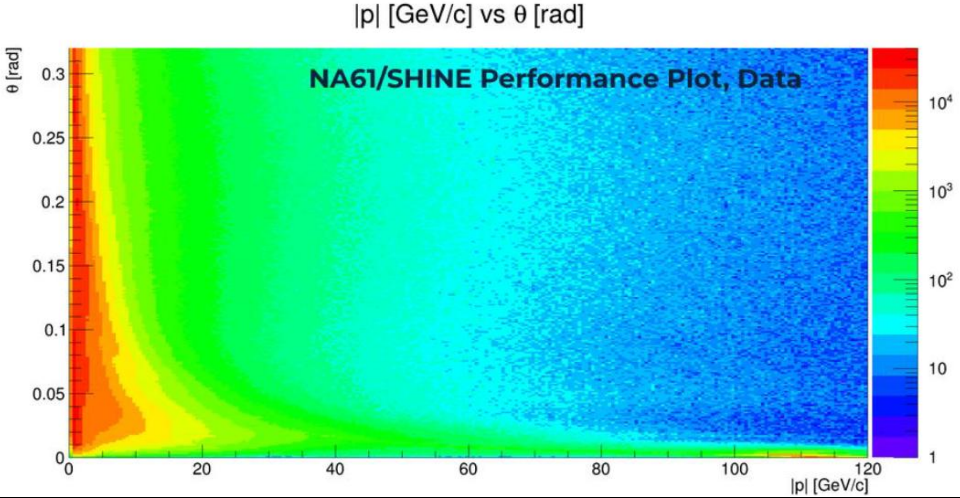



# Long-Target Measurements for NuMI

- Dataset with 18 million events collected in 2018
- NuMI replica target has complicated geometry
- Not axially symmetric
- 1-z bin charged-hadron results coming soon

Sample Event Browser with the NuMI replica target





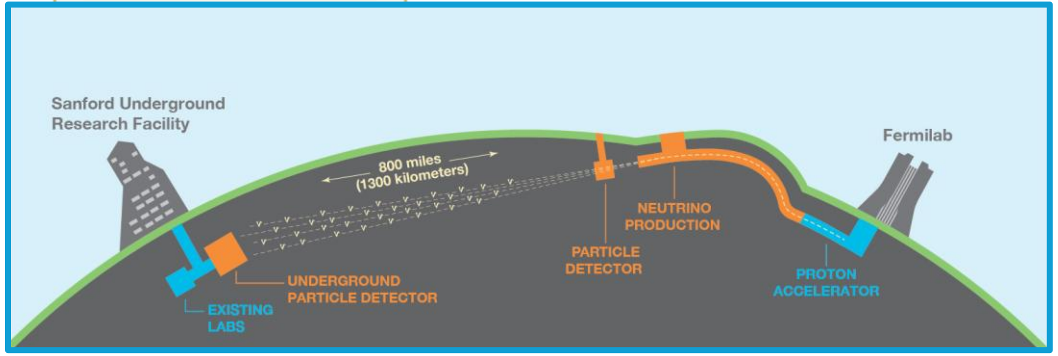

Raw yields plotted as $p$ vs $\theta$ by *Michael Quintieri*

# Run 3 Efforts

| Run 1 | Long Shutdown | Run 2 | Long Shutdown | Run 3 | Long Shutdown | Run 4 |
|---|---|---|---|---|---|---|
| 2007 – 2010 | (LS) 1 | 2015 – 2018 | (LS) 2 | 2022 – 2026 | (LS) 3 | 2029 – |
| **T2K**<br>Proton 31 GeV/*c* | | **NuMI Experiments and LBNF/DUNE**<br>Proton 120 GeV/*c*<br>Proton 60, 90 GeV/*c*<br>Pion 60 GeV/*c* | | **T2K**<br>Proton 31 GeV/*c*<br>**NuMI, LBNF/DUNE**<br>Proton 120 GeV/*c*<br>Kaon 60 GeV/*c* | | **Low-Energy Beamline Program**<br>(TBC) |

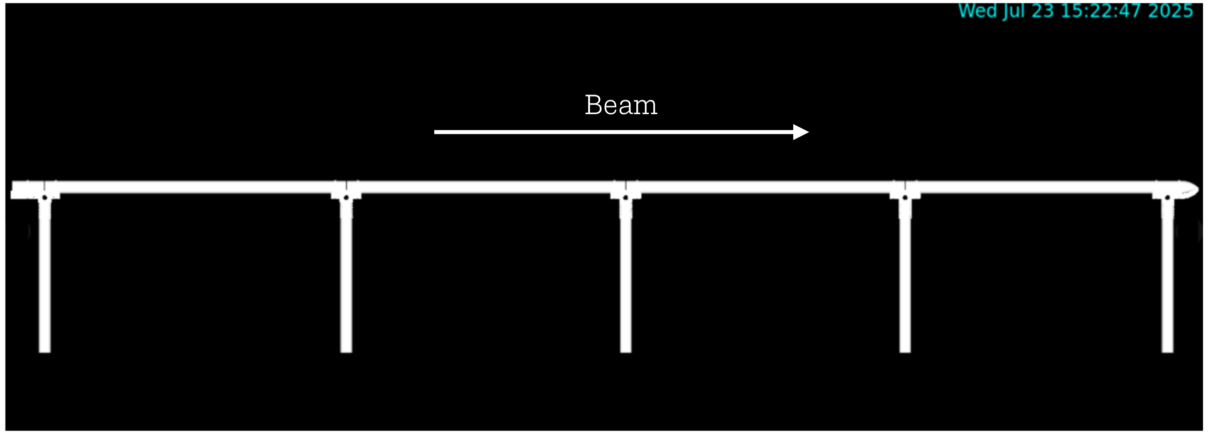
- More thin-target measurements in 2023
  - Dataset ~20 times larger
- LBNF/DUNE replica target (2024-25)

*DUNE*

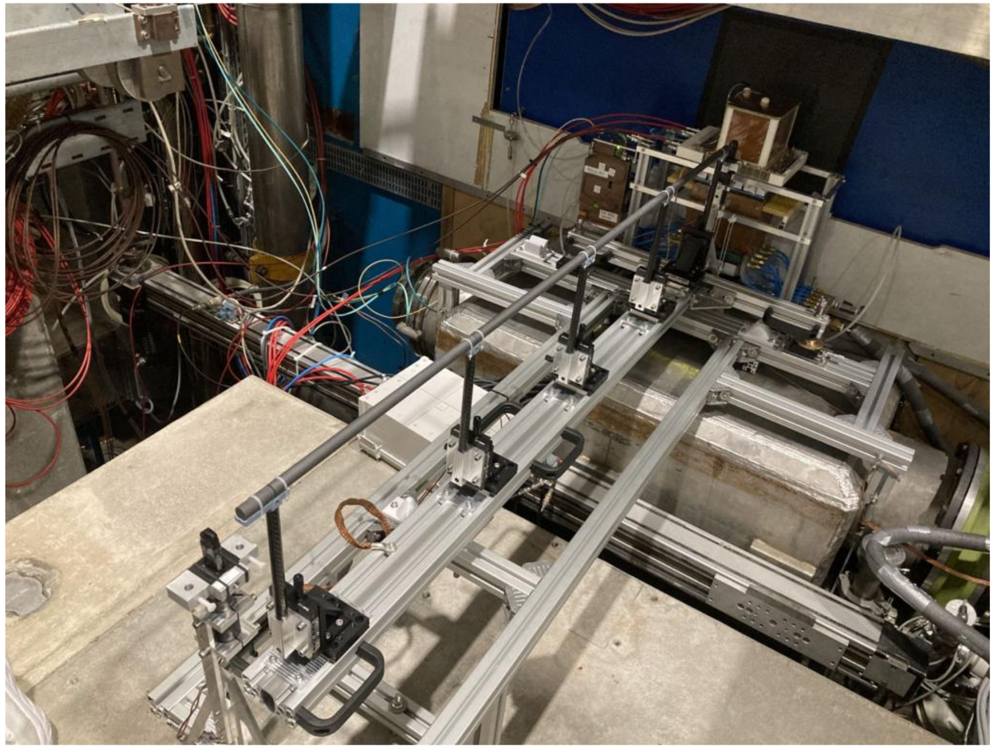


# Run 3 Efforts: DUNE Replica Target

- 150 cm long graphite target with 5 segments
- Targets with 2 different densities measured over 2024 and 2025
- Combined total of 390 million events collected




Simulation of the DUNE Replica Target with the supports



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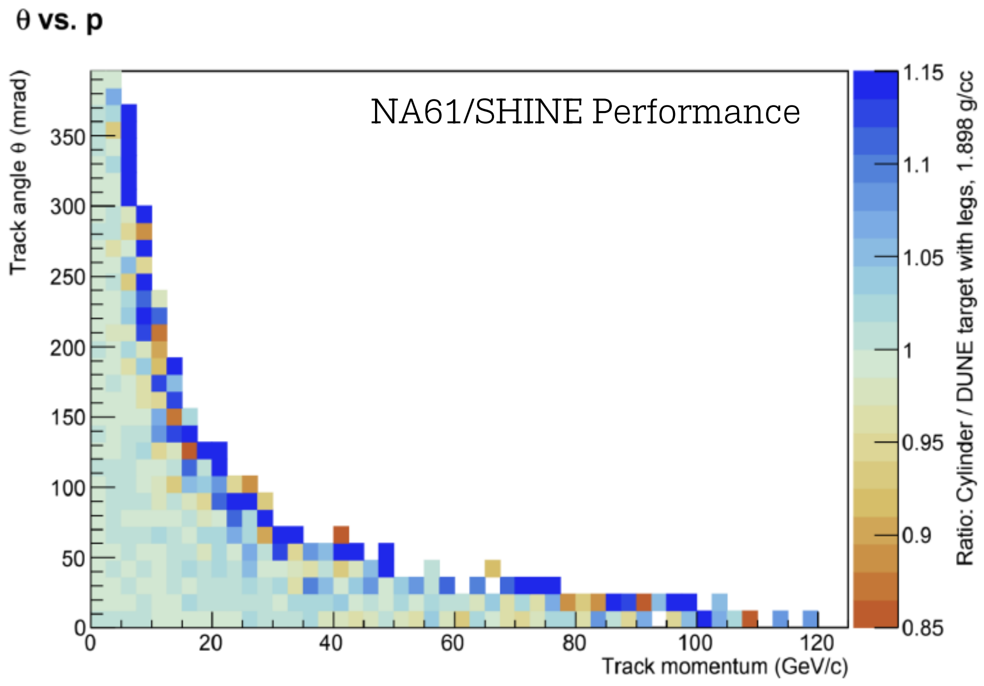
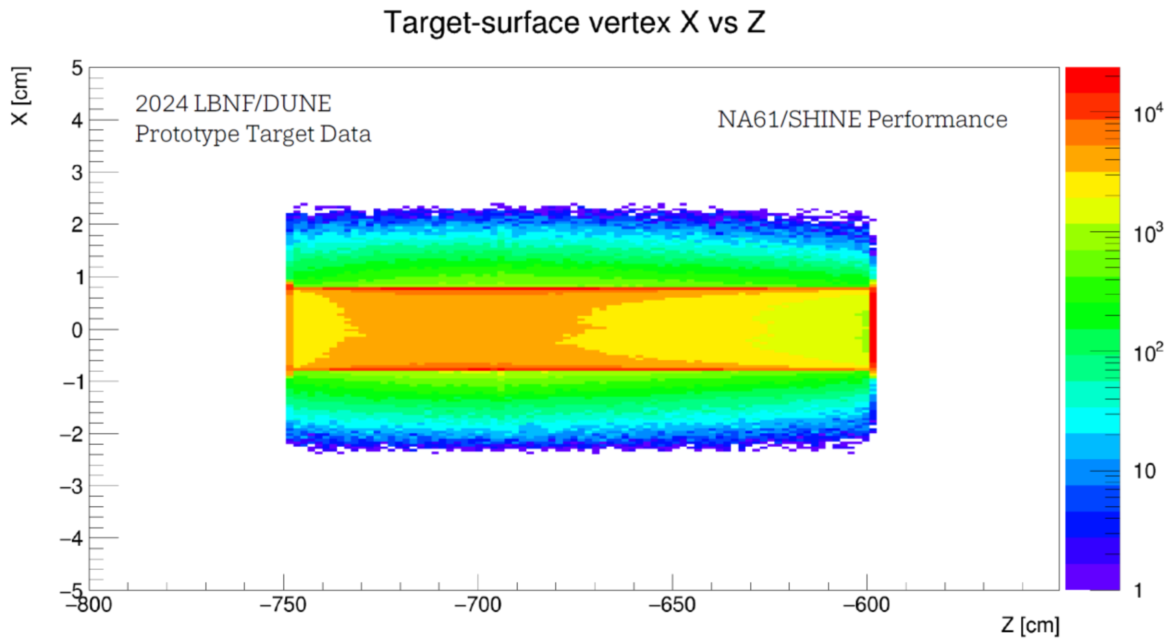



MC Simulation by *Dante Wilson*




Distribution of X vs Z positions of the target-surface vertices after the selection cuts

# Run 3 Efforts

| Run 1 | Long Shutdown | Run 2 | Long Shutdown | Run 3 | Long Shutdown (LS) 3 | Run 4 |
|---|---|---|---|---|---|---|
| | | | | 2022 – 2026 | | 2029 – |


*FNAL*

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**Atmospheric neutrinos**
Proton 15 GeV/*c*

**BNB**
Proton 15 GeV/*c*

- Liquid Nitrogen Target for atmospheric neutrino flux
  - Thin- (16M events) and Long-Target (89M events) configurations
- Beryllium Thin Target (9M events) for Booster Neutrino Beam (BNB) flux

# Run 4 Efforts

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(LS) 1

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2015 – 2018

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**Long Shutdown**
(LS) 3

**Run 4**
2029 –

**Low-Energy Beamline Program**
(TBC)

- Developing a low-energy beamline for 2-13 GeV/*c* momenta

# Run 4 Efforts: Low-Energy Beamline

*Okayama Workshop*

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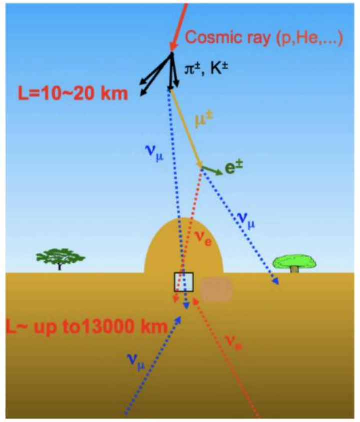
*Okayama Workshop*




Atmospheric neutrino experiments

- sub-GeV neutrinos at Super-K, Hyper-K, DUNE

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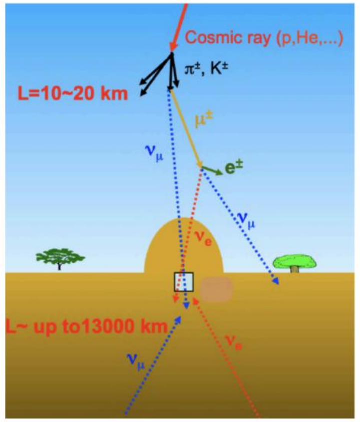
Okayama Workshop

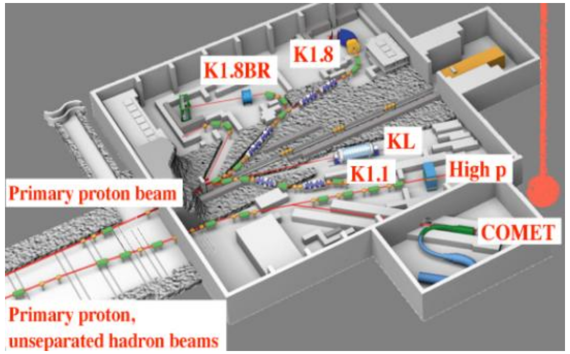


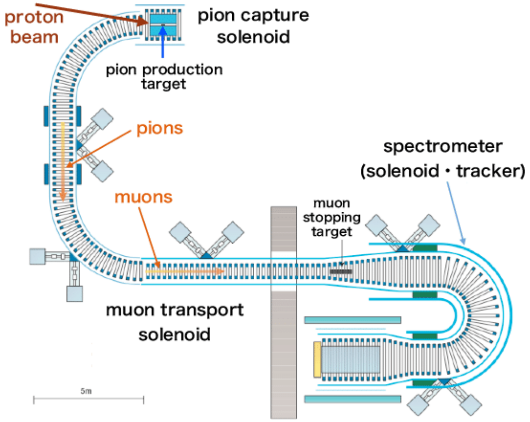

Atmospheric neutrino experiments

- sub-GeV neutrinos at Super-K, Hyper-K, DUNE

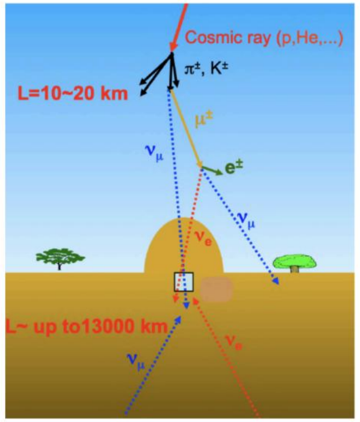
Muon experiments

- COMET (proton at 8 GeV)



# Run 4 Efforts: Low-Energy Beamline



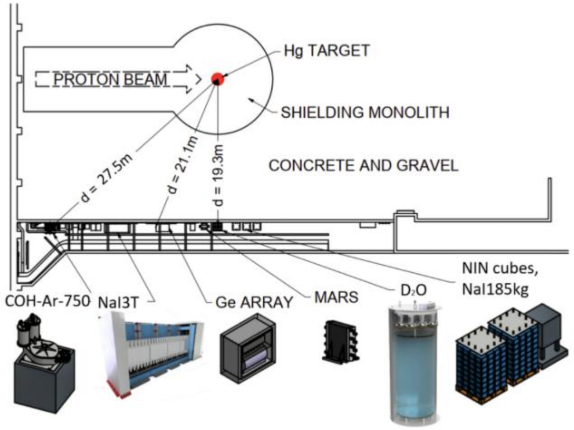

Okayama Workshop

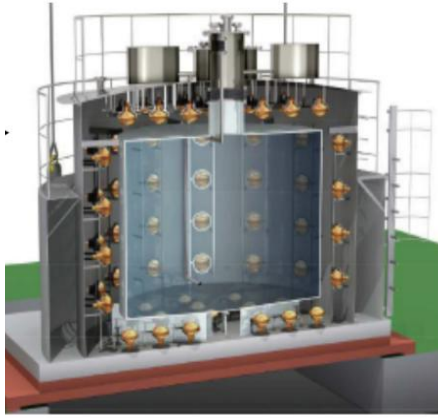
Atmospheric neutrino experiments

- sub-GeV neutrinos at Super-K, Hyper-K, DUNE

Spallation neutron source experiments

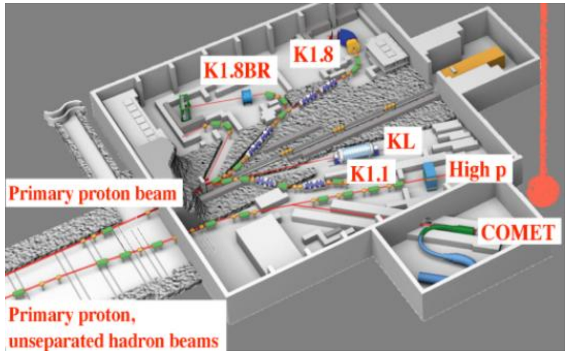
- JSNS$^2$ (proton at 3 GeV)
- COHERENT (proton <2 GeV)

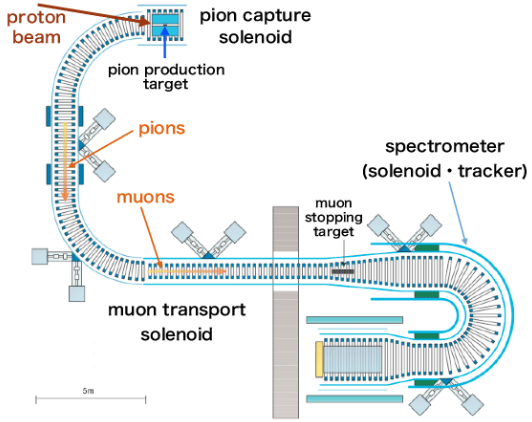


Muon experiments

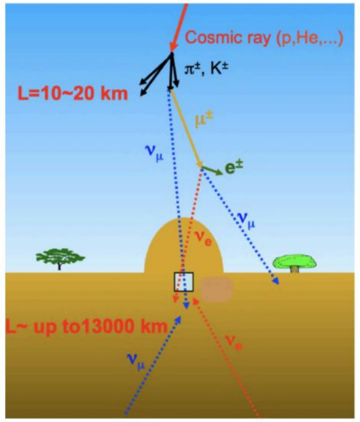
- COMET (proton at 8 GeV)



# Run 4 Efforts: Low-Energy Beamline

Okayama Workshop

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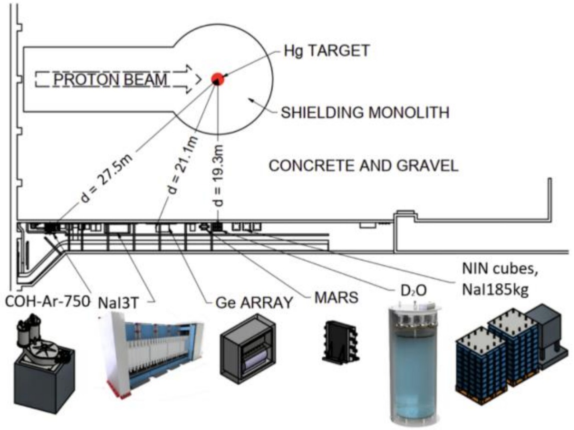
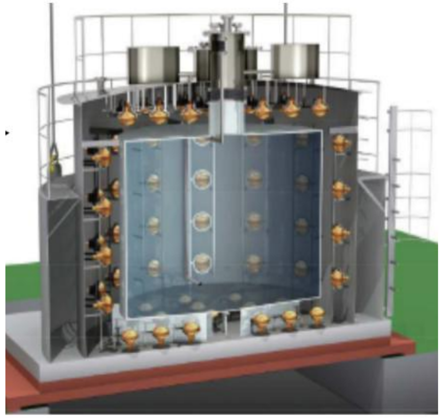
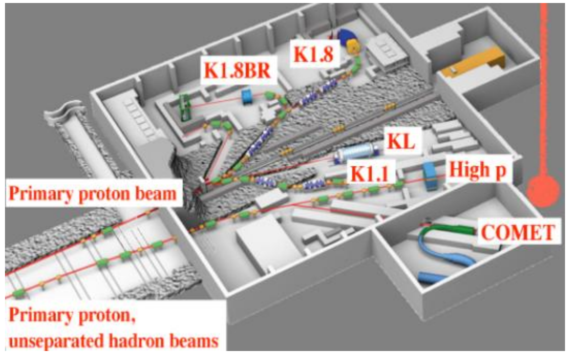
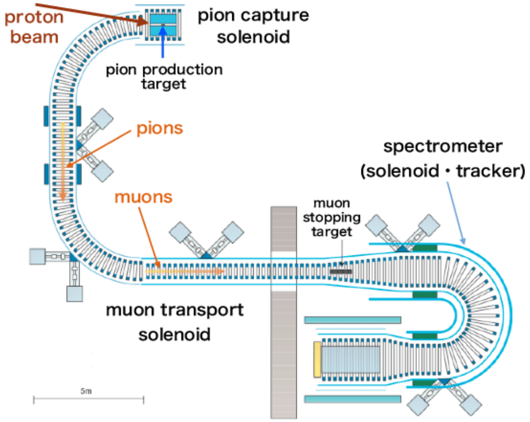


Muon experiments

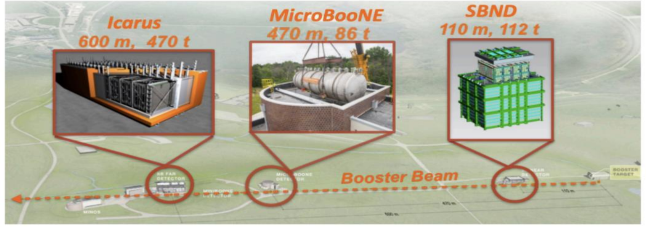
- COMET (proton at 8 GeV)




Accelerator-based neutrino experiments

- T2K, Hyper-K (pion at 2 GeV, 8 GeV)
- Short-Baseline Neutrino Program (proton at 8 Gev)



# Summary

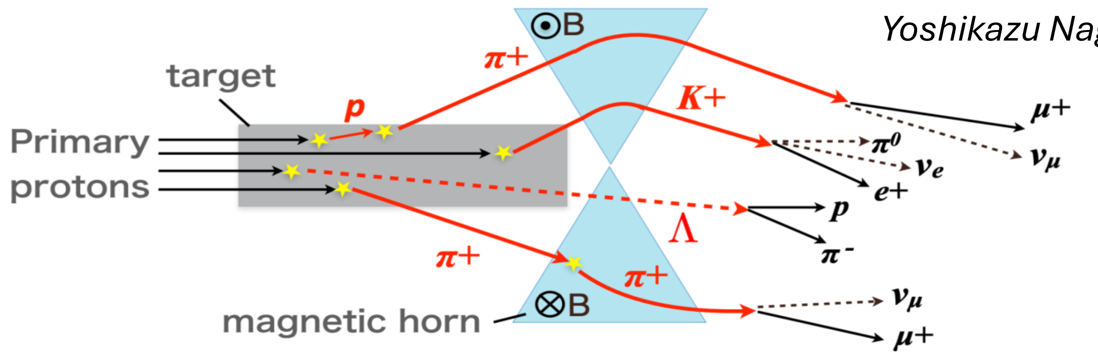
- NA61/SHINE provides hadron production measurements that help constrain neutrino flux uncertainties
- These measurements are also crucial for improving hadron production models (in particular, GEANT 4 physics lists)
- Run 1 and Run 3 data will help with T2K
- Run 2 and Run 3 data will help with NuMI and LBNF/DUNE
- More precision measurements were conducted earlier this year for BNB and atmospheric neutrino flux calculations
- Planned development for a low-energy beamline; many opportunities after Long Shutdown 3

# THANK YOU!


NA61/SHINE Collaboration Meeting, Zakopane (2026)

# BACKUP SLIDES

# Motivation: Flux Uncertainties

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