Hadron Production Measurements for Neutrino Experiments

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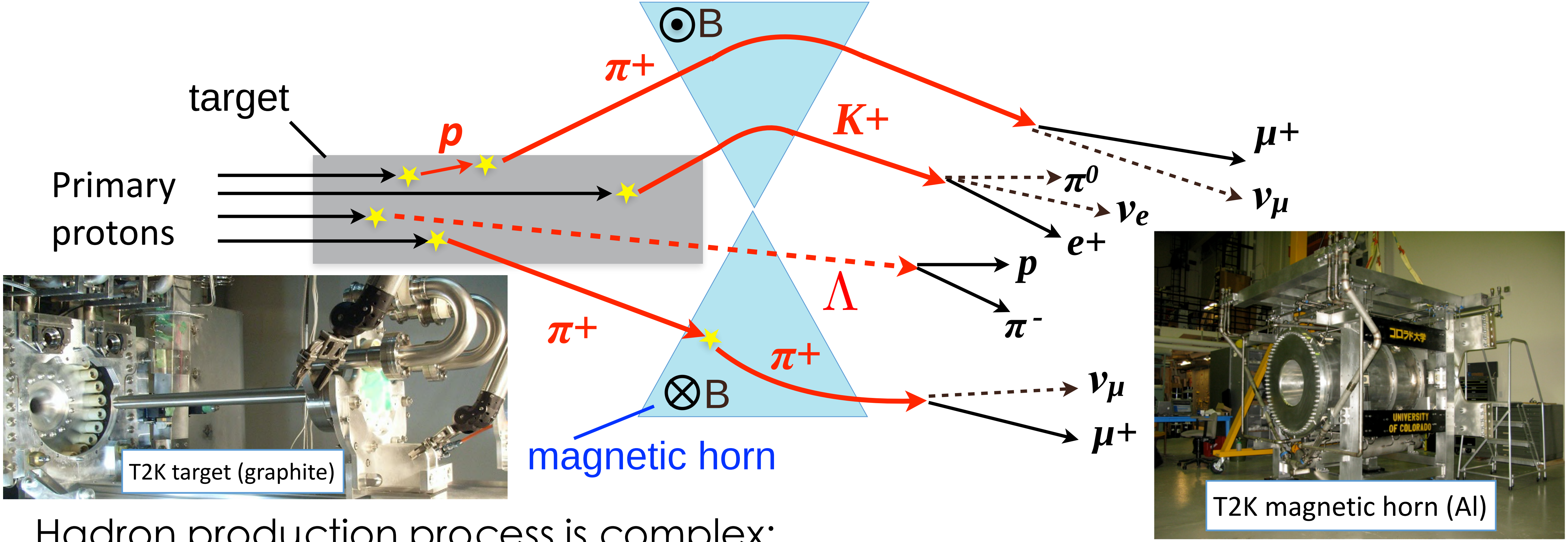
Contents

Introduction

- Why Hadron Production Measurements?

Accelerator Neutrino Production



<u>Hadron production process is complex:</u>

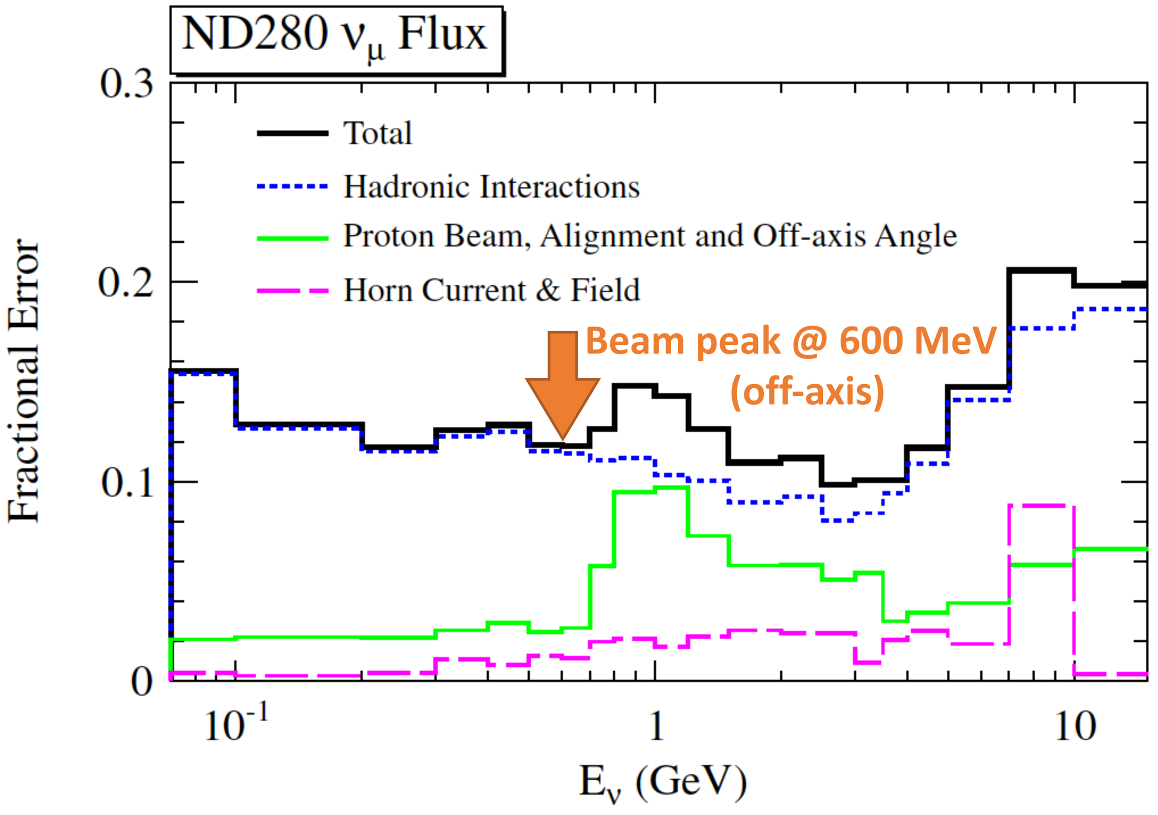
- Primary interactions in the target (p + C -> $\pi^{\pm}$ and $K^{\pm}$) -> Primary contribution to the neutrino flux
- Secondary interactions with beamline materials (hadrons + C/Be/Al/Ti/Fe/H_2O/etc..)
- Neutral hadron decay (p + C —> V^0 + X)

Non-negligible contribution to the neutrino flux

Flux Uncertainties of Accelerator-based Neutrinos

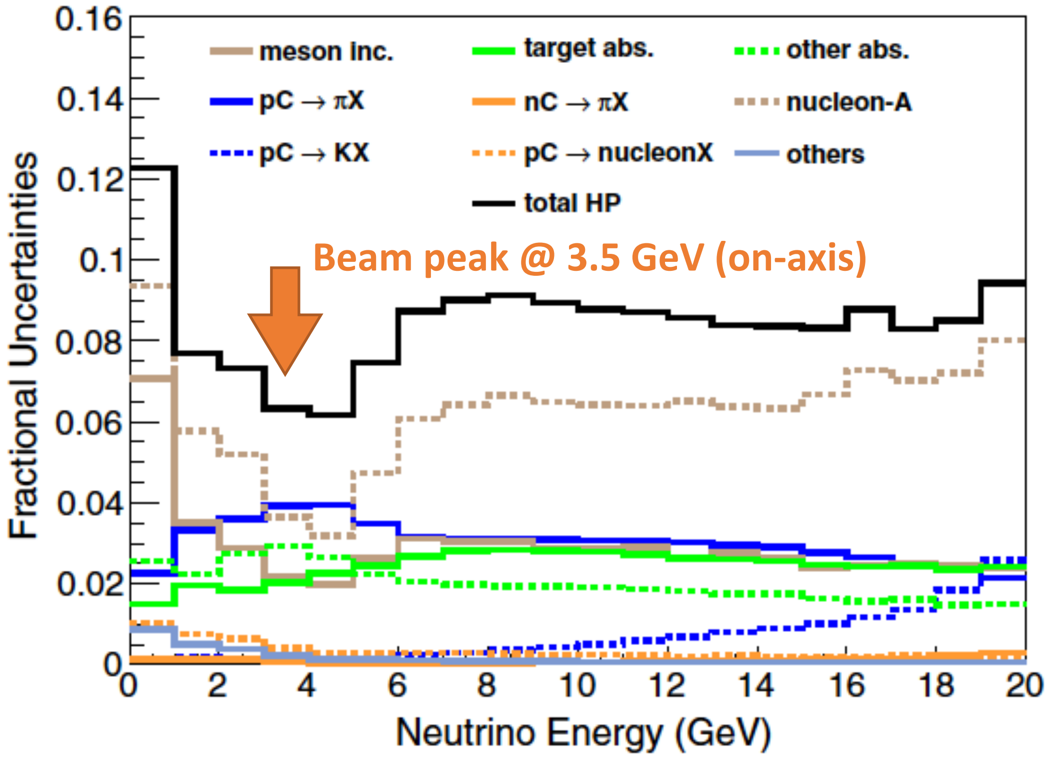
Hadron Production is the leading uncertainty source of flux predictions

J-PARC beamline (T2K flux)



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

NuMI beamline (MINERvA flux)
(low energy configuration)



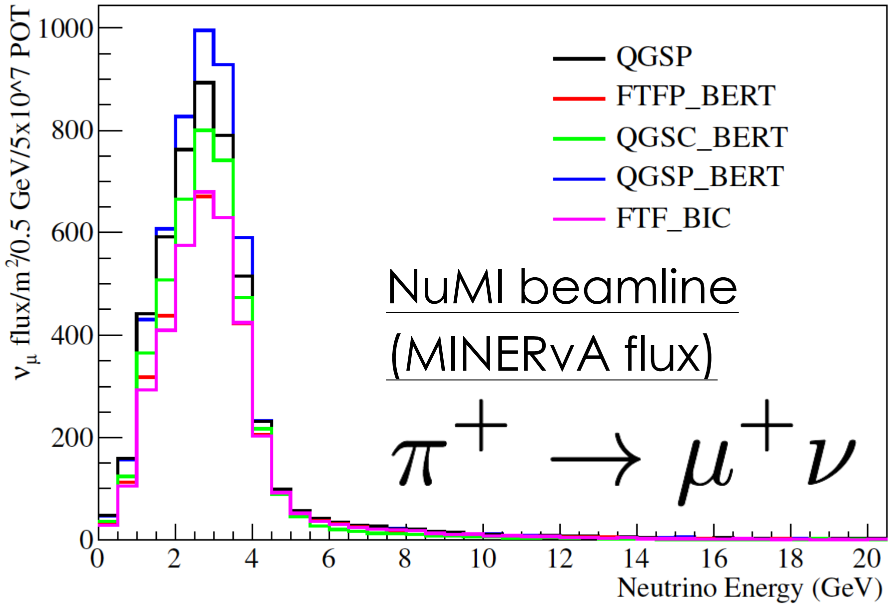
MINERvA: Phys. Rev. D94, 092005 (2016)
(only hadron production-relating errors)

Flux Prediction with MC Simulation

- We rely on hadronic interaction models for the neutrino flux predictions
  - FLUKA (J-PARC/T2K), Geant4 FTFP_BERT (NuMI experiments)

However, prediction of hadron production is difficult…

e.g. Five interaction models in Geant 4
—> neutrino flux predictions differ by
~40% at the focusing peak

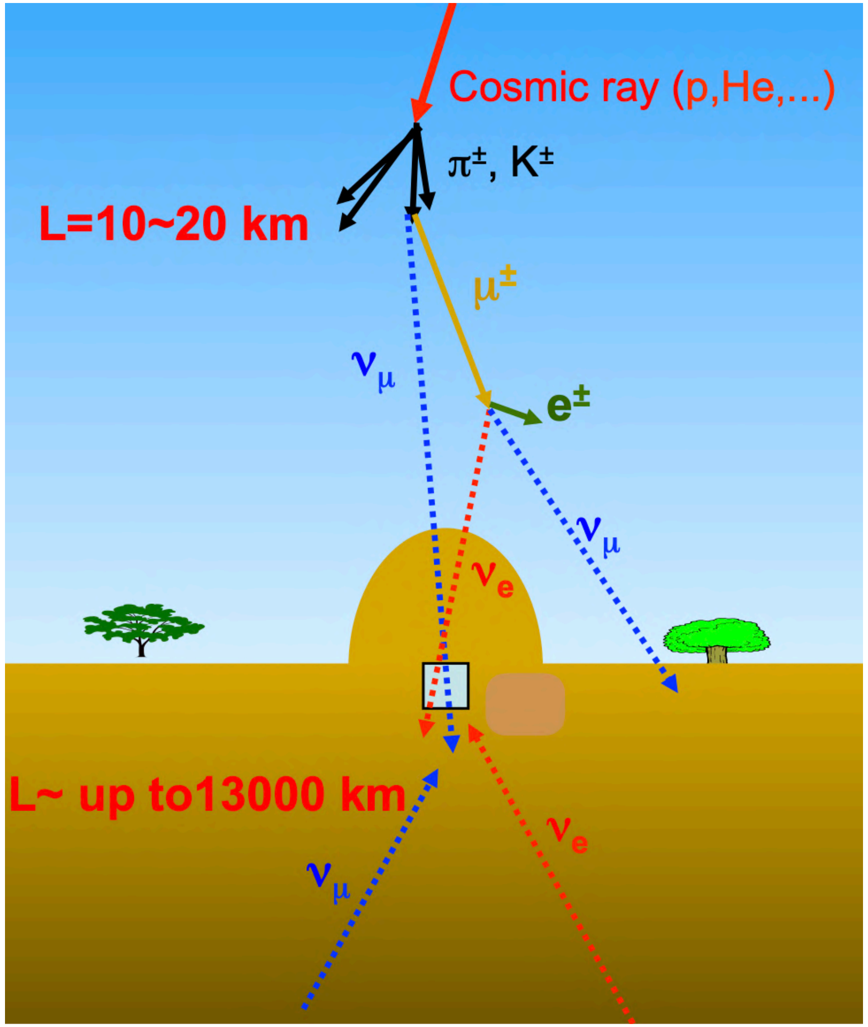


Leonidas Aliaga (Ph.D Thesis, 2016)

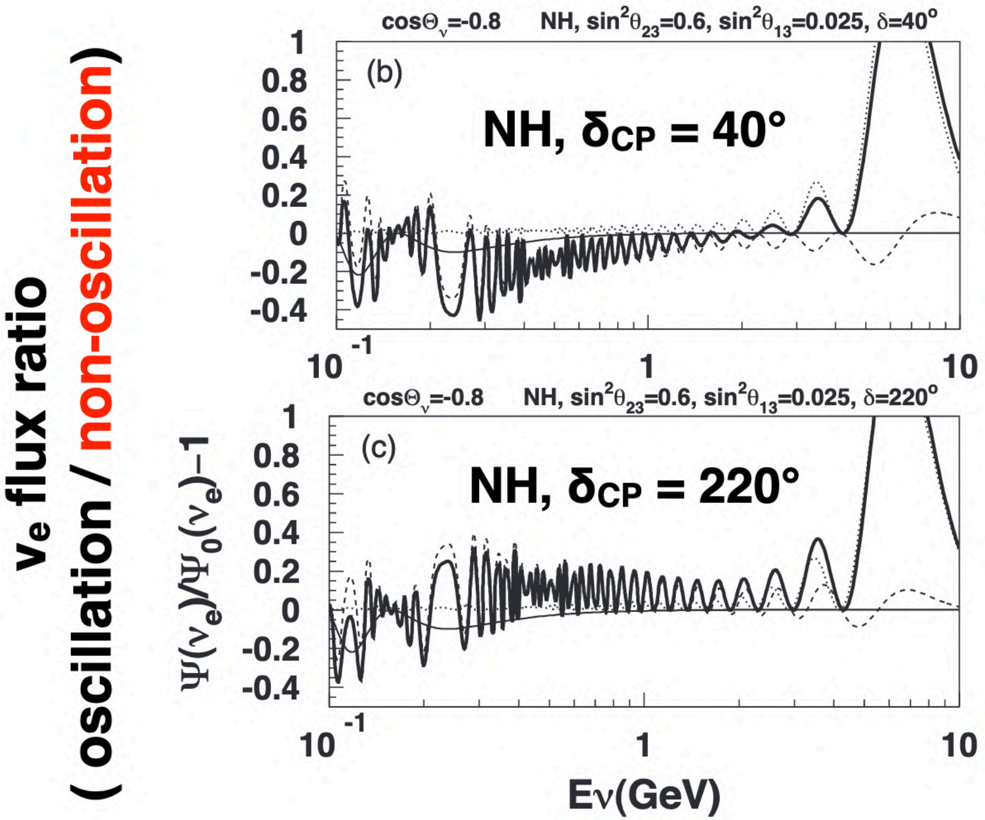
Need to constrain neutrino flux uncertainty coming from hadron production

⇨ External Hadron production data are critical

Atmospheric Neutrino Production



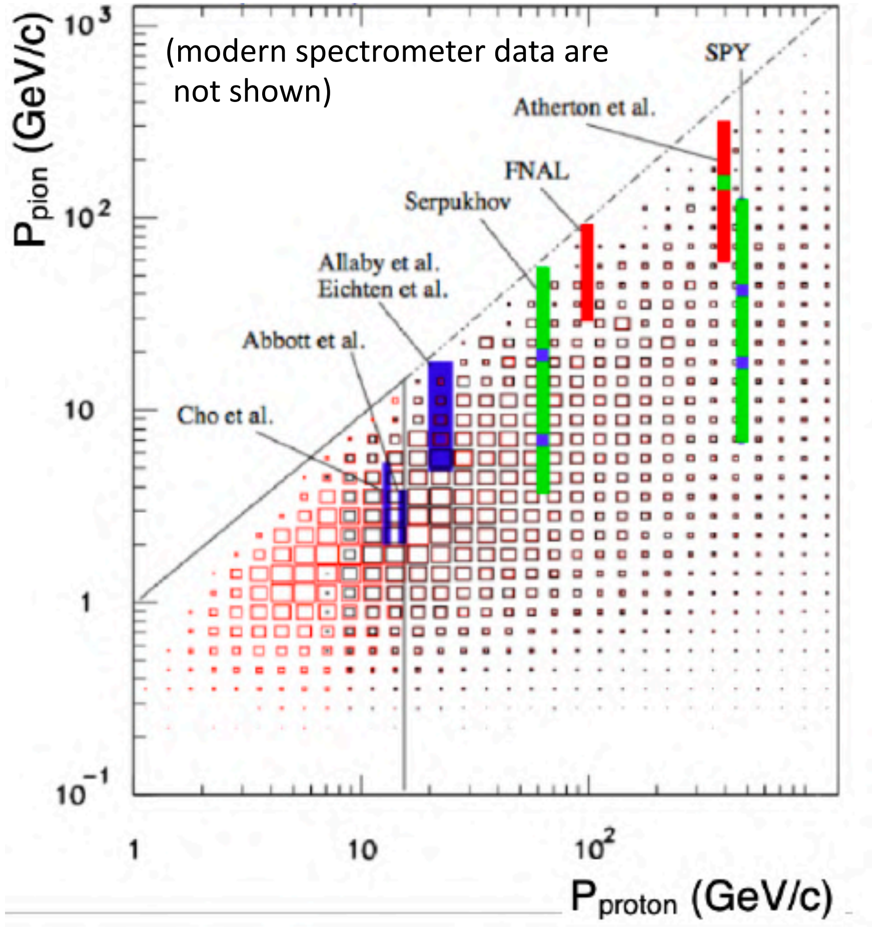
- Primary interactions in atmosphere (p + N -> π)
- Neutrino flux ranges below 100 MeV to above 10 TeV
  - 0.1-1.0 GeV (sub-GeV): sensitive to CP phase
  - 1.0-10 GeV (multi-GeV): sensitive to mass hierarchy



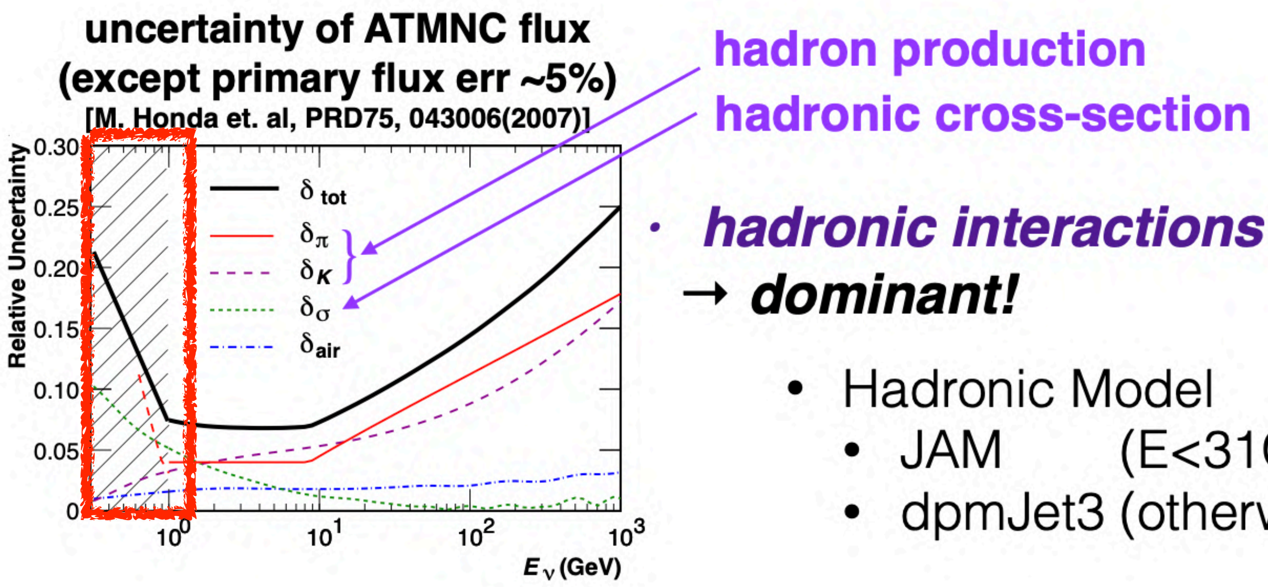
HK design report

Flux Uncertainties of Atmospheric Neutrinos

- Hadron production data is sparse
  - Hadron Production is the leading uncertainty source of flux predictions



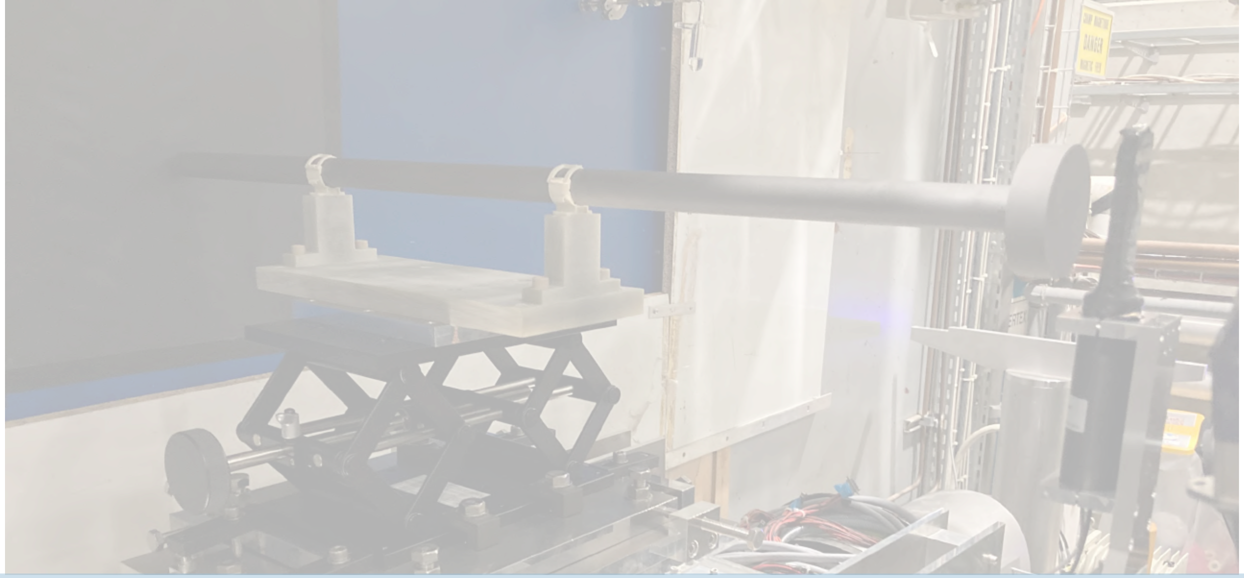
Phys. Rev. D74, 094009 (2006)



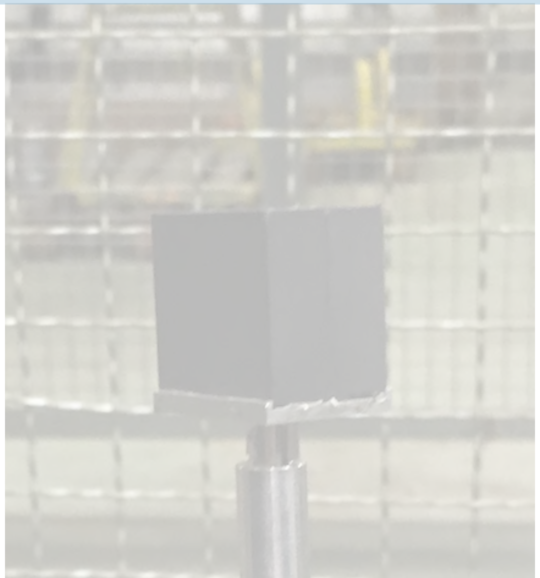
- ***hadronic interactions in air shower***
  → ***dominant!***
  - Hadronic Model
    - JAM (E<31GeV)
    - dpmJet3 (otherwise)

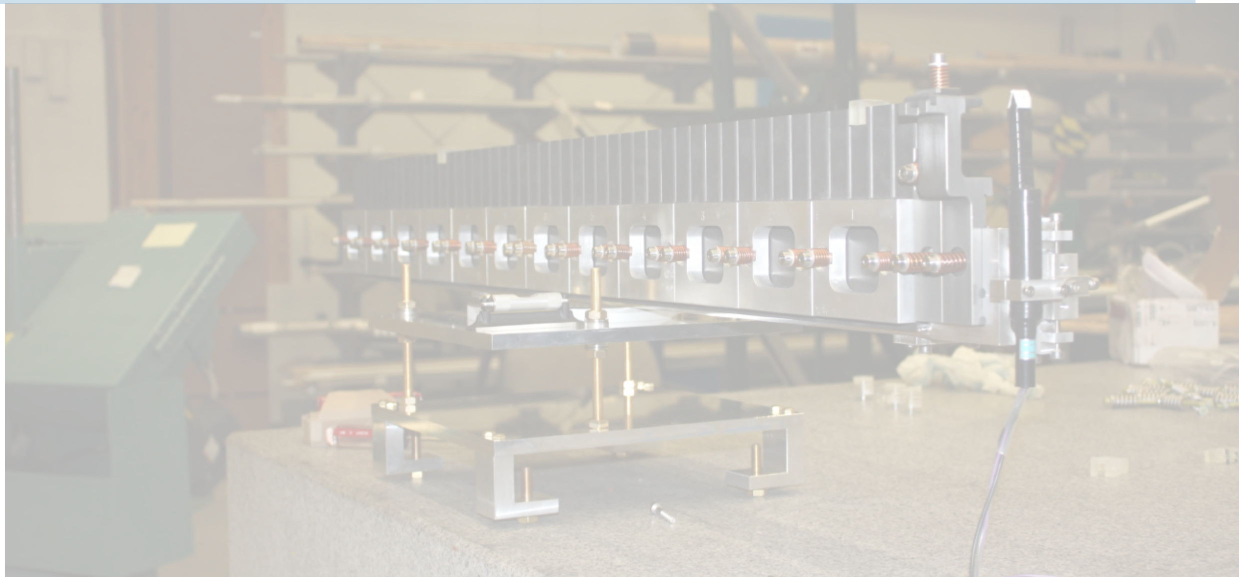
K. Sato, talk at the "NA61/SHINE at Low Energy workshop" (2020)

⇨ More hadron production data are necessary



Strategy of Measurements





Hadron Production Data Needs

- In situ hadron production measurement is too difficult
  - Accelerators: needs to tolerate O(100 kW) beams, or even MW beams near future
  - Atmosphere: hadron production at high altitude
    - In either case, external hadron production data will help to model hadron interactions
- What data are necessary for the precise prediction of neutrino fluxes?
  - Total production cross section: constrain interaction probabilities of hadrons
  - Particle production multiplicity: tune production multiplicity of hadrons
    - Hadron production experiments typically report in bins of hadrons (p, θ) or (x_F, p_T)

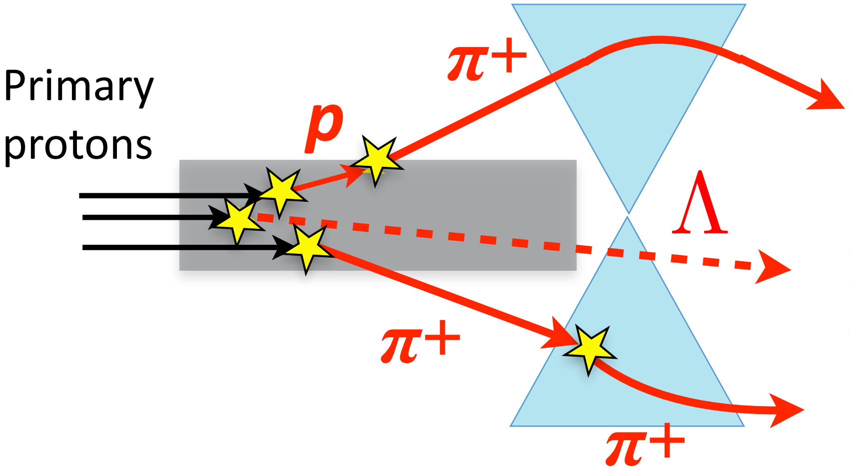
$$x_F = 2p_L^*/\sqrt{s}$$

- Also, the proper format of error report is crucial
  - Stat. and systematic uncertainties separately
  - Correlation of systematic uncertainty sources (covariance matrix)
    - Old data often lack this information

How to Improve Flux Model with External Data

Two corrections to constrain model ambiguity

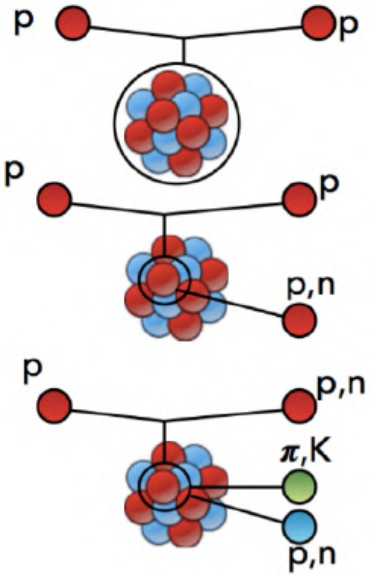
- Interaction length: Tune production cross-section to external measurement
- Multiplicity: Tune differential hadron multiplicity (differential cross section) to external measurement



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

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 —> σ_{el}

Quasi-elastic process:
interaction on bound nucleons —> σ_{qe}

Production process:
interaction with new hadron production
—> σ_{prod}

—> Inelastic process σ_{inel}

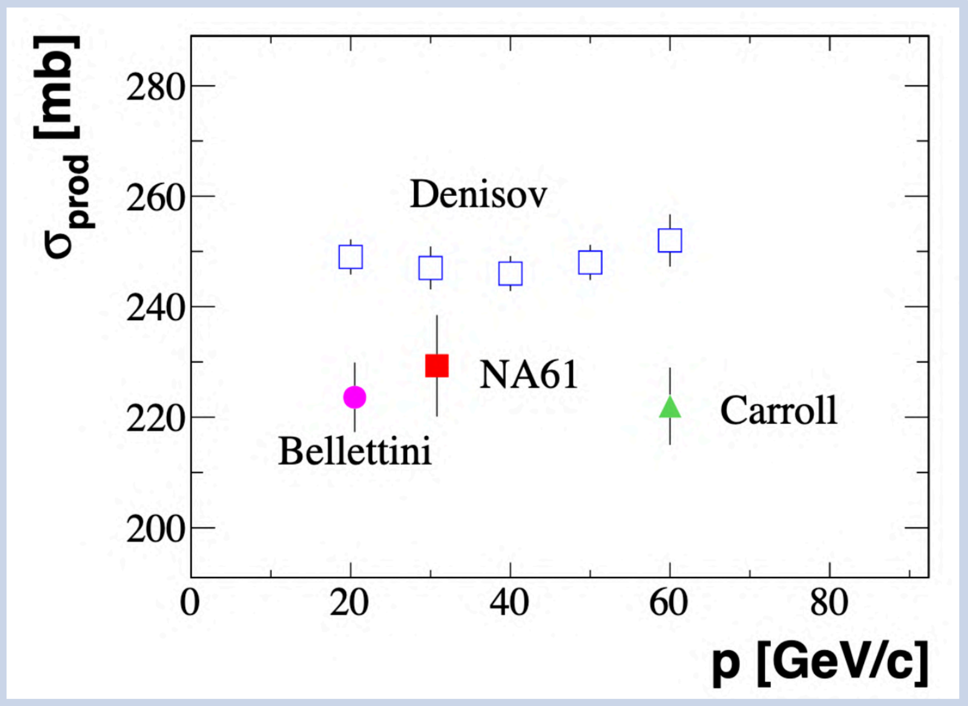
$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$$
$$\sigma_{\mathrm{prod}} = \sigma_{\mathrm{inel}} - \sigma_{\mathrm{qe}}$$

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

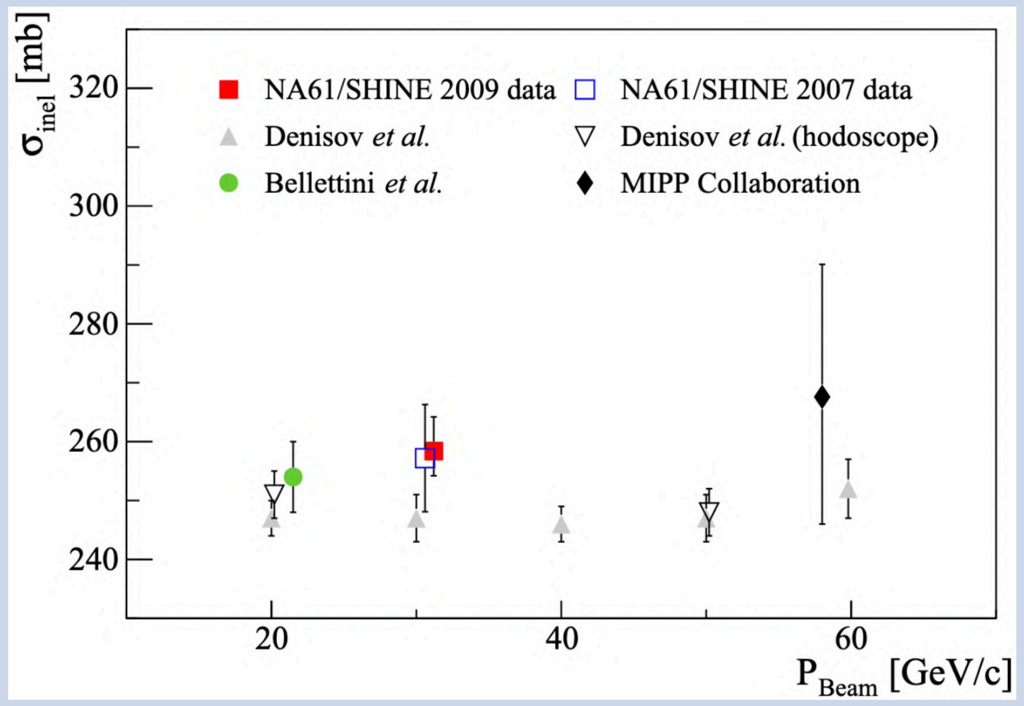
- NuMI flux tuning definition:
  $\sigma_{\mathrm{inel}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{qe}}$ —> σ_{prod} in above definition
  $\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$ —> σ_{inel} in above definition

- Earlier experiments: mixed up inelastic and production cross sections
  e.g. Denisov, et. al (1973): $\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$ —> σ_{inel} in above definition
  e.g. Carroll, et. al (1979): $\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{qe}}$ —> σ_{prod} in above definition

Note: Notation of Production Cross Section



Phys. Rev. C **84**, 034604 (2011)



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

Example comparison between old data and NA61/SHINE

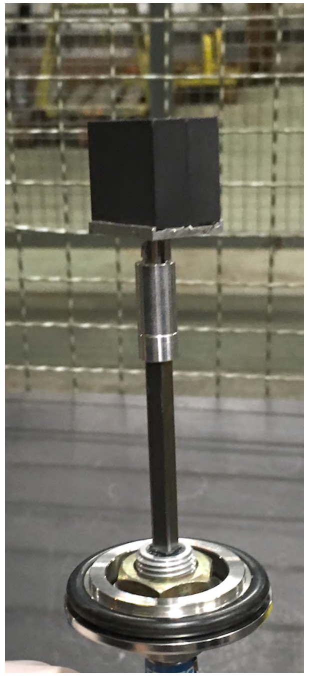
- Denisov and Carroll claim absorption cross section is measured
- NA61 measured production and inelastic cross sections

An important role of modern experiments: make clear what was the measured physics quantity in old data

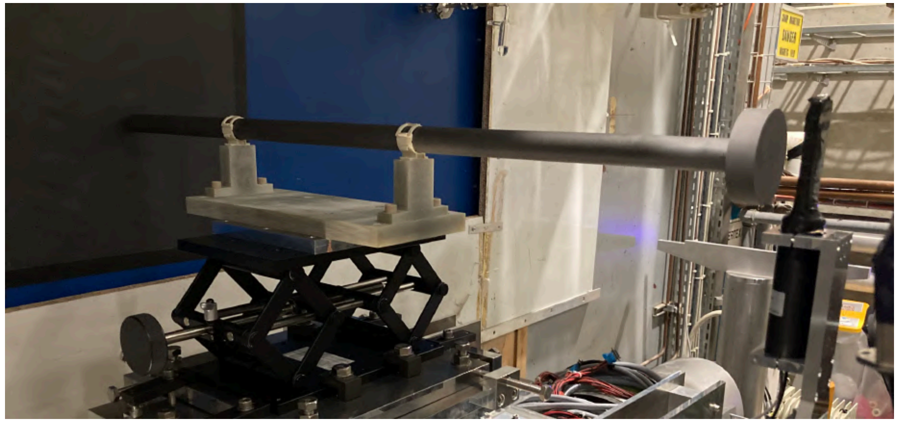
Strategy of Measurements

- <u>Thin target</u>: a few % of nuclear interaction length (λ) to study single interactions
  - Total cross sections (inelastic and production cross sections)
  - Measurement of differential production yields (multiplicity)
- <u>Replica (thick) target</u>: same geometry and material as real neutrino beamline
  - Measurement of differential production yields
  - Production cross section via beam attenuation

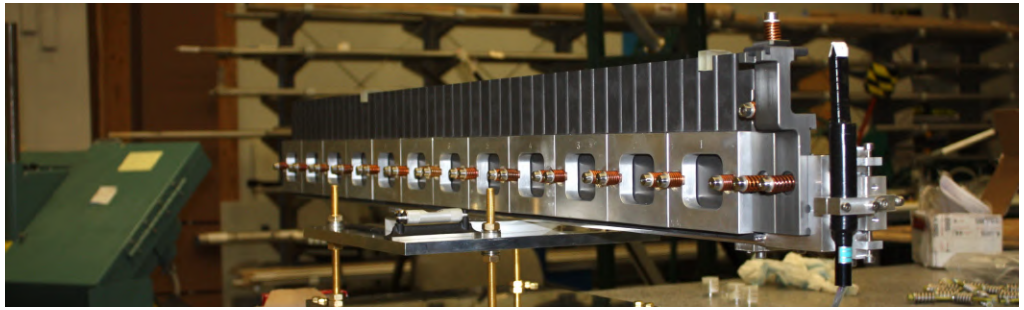
Thin graphite target (1.5 cm, 3.1% of λ)



T2K replica graphite target (90 cm, 1.9 λ)

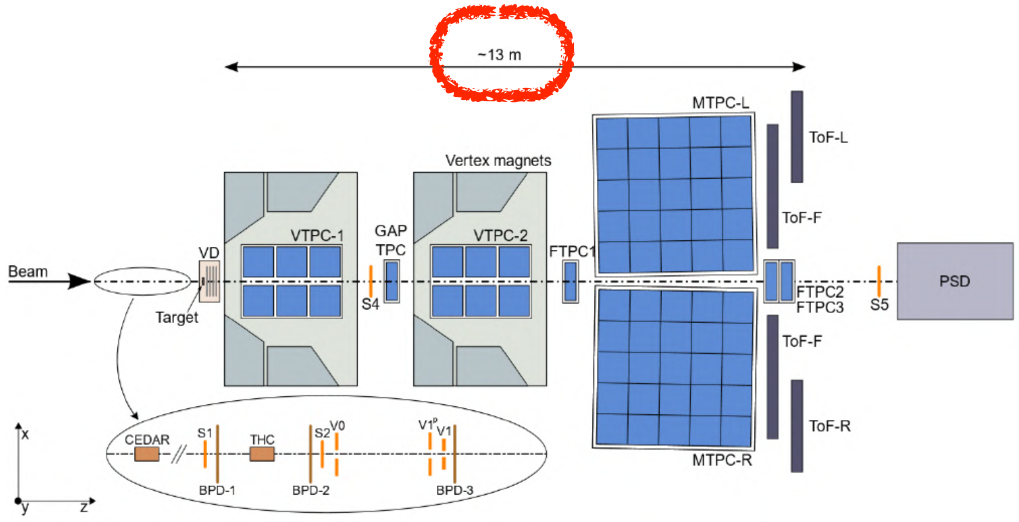


NuMI replica graphite target (120 cm, 2.5 λ)



Running Experiments: Two Main Players

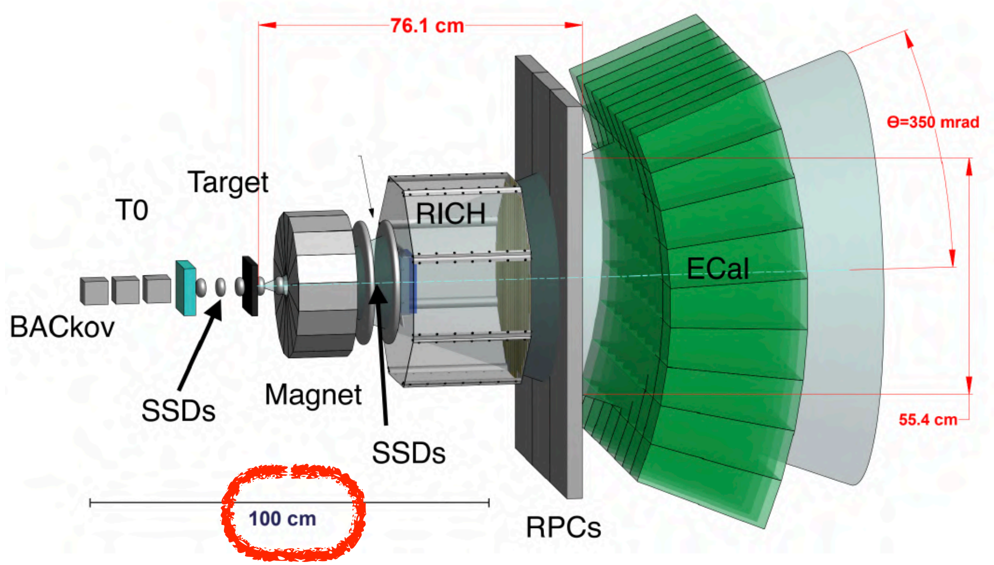
NA61/SHINE (about 150 collaborators)



- At the CERN SPS North Area
  - Hadron beam: 13-350 GeV/c
- Large TPC-based spectrometer
- Thin and Replica target measurements

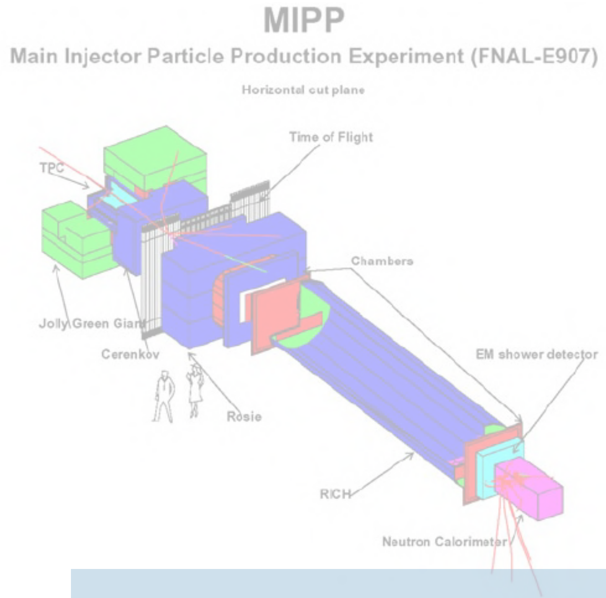
See details in later this talk!

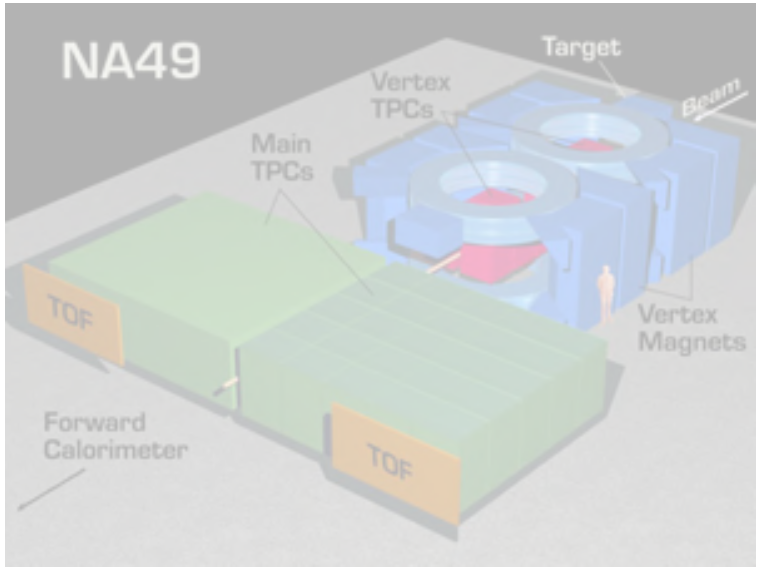
EMPHATIC (about 20 collaborators)



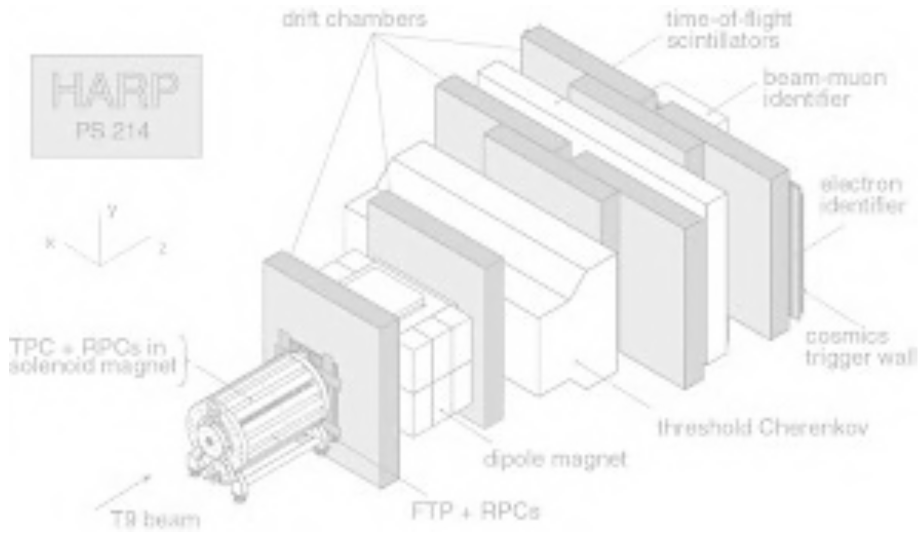
- At the Fermilab Test Beam Facility (FTBF)
  - Hadron beam: 0.2-120 GeV/c
- Table-top size silicon-baed spectrometer
- Thin target measurements

See the next talk for more detail!





Brief Overview of Available Datasets



Key Hadron Production Data

Below 25 GeV/c

- HARP: $\mathrm{p + C}$ or $\pi^+ + \mathrm{C} \to \pi^\pm$ at 3-12.9 GeV/c (Eur. Phys. JC 52 (2007) 29, Nucl. Phys. B 732 (2006) 1, Astr. Phys. 29 (2008) 257, Phys. Rev. C 80 (2009) 035208)
- BNL E910: $\mathrm{p + Be} \to \pi^\pm$ at 6.4, 12.3, and 17.5 GeV/c (Phys. Rev. C 77 (2008) 015209)
- BNL E802: $\mathrm{p + Al/Be} \to \pi^\pm$ at 14.6 GeV/c (Phys. Rev. Lett. 66 (1991) 1567-1570 , Phys. Rev. D 45 (1992) 3906-3920)
- Allaby, et al: $\mathrm{p + Al/Be} \to \pi^\pm, k^\pm, p, \bar{p}$ at 19.2 GeV/c (Tech. Rep. 70-12 (CERN, 1970))
- Eichten, et al: $\mathrm{p + Al/Be} \to \pi^\pm, k^\pm, p, \bar{p}$ at 24 GeV/c (Nucl. Phys. B44, 333 (1972))

Around 100 GeV/c

- MIPP: $\mathrm{p + Be/C} \to n$ at 58, 84, and 120 GeV/c (Phys. Rev. D 83 (2011) 012002),
  $\mathrm{p + NuMI\ (low\ energy\ target)} \to \pi^\pm$ at 120 GeV/c (Phys. Rev. D 90 (2014) 032001)
- NA49: $\mathrm{p + C} \to \pi^\pm$ at 158 GeV/c (Eur. Phys. J. C49 (2007) 897)

Above 400 GeV/c

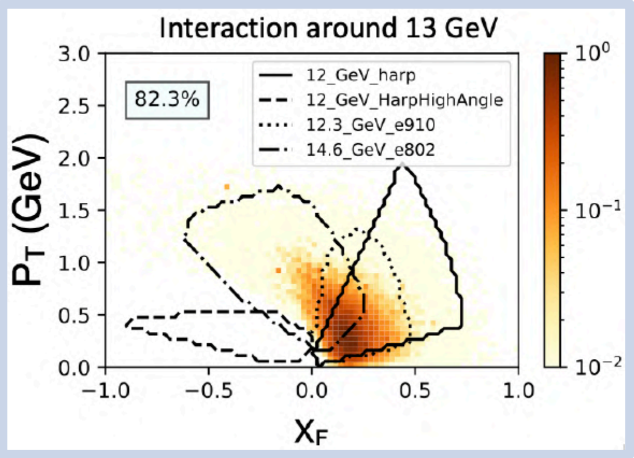
- NA20: $\mathrm{p + Be} \to \pi^\pm, k^\pm, p, \bar{p}$ at 400 GeV/c (CERN Tech. Rept. 80-70 (1980))
- NA56/SPY: $\mathrm{p + Be} \to \pi^\pm, k^\pm, p, \bar{p}$ at 450 GeV/c (Phys. Lett. B420 (1998) 225, Phys. Lett. B425 (1998) 208, Eur. Jour. Phys, C10 (1998) 605)

Recent NA61 data at 31 GeV/c and 60-120 GeV/c are also available (see later in this talk)

Note: Old Hadron Production Data Issues

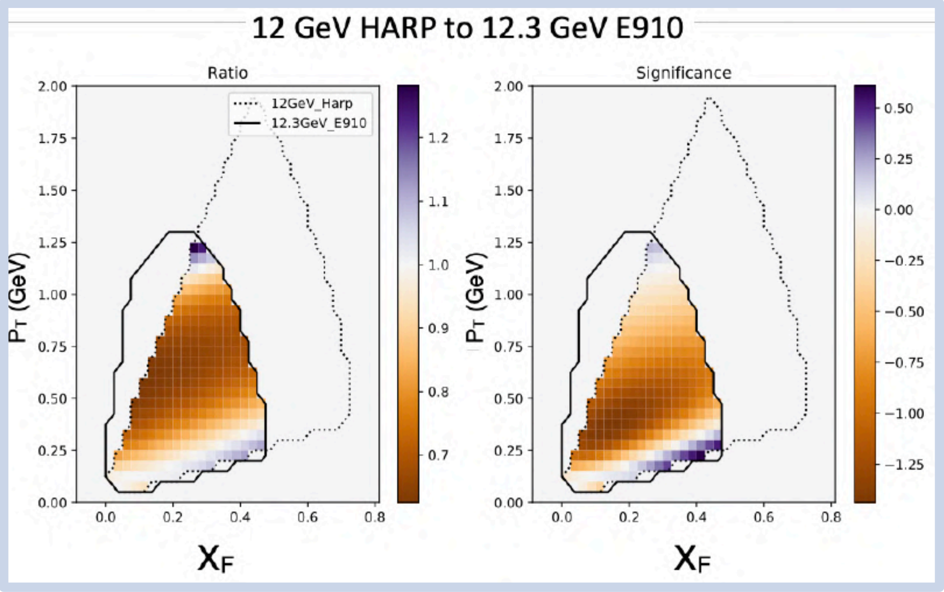
- List of concerns:
  - No detail on error report
  - No covariance matrix
  - Inconsistency between experiments

phase-space coverage of 3 experiments



example: Hadron production data for
< 15 GeV atmospheric neutrino fluxes

(In)consistency b/w HARP and E910

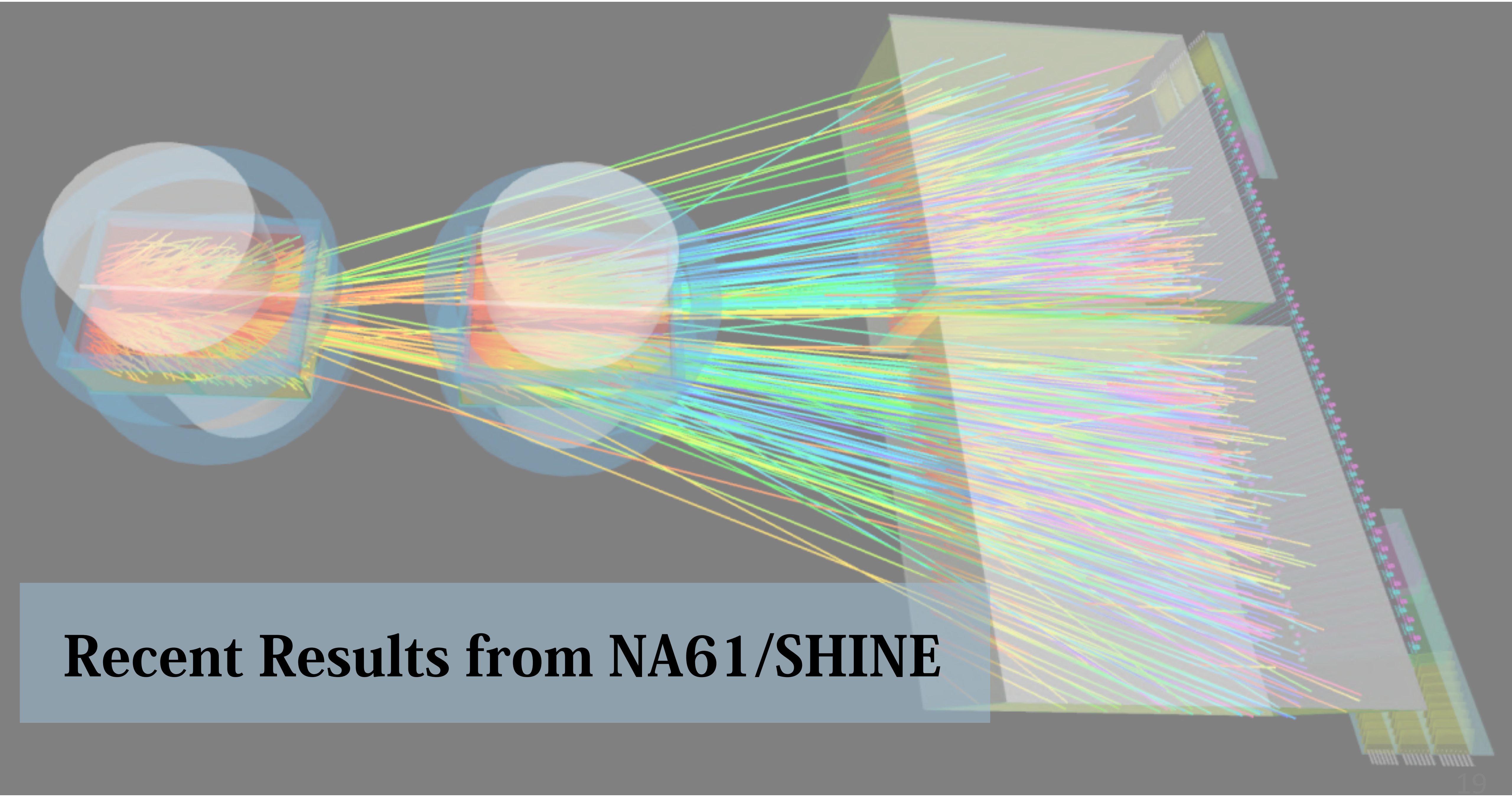


Energy [GeV]	Process	Error report	Covariance Matrix	Experiment (year)
3, 5, 8, 12	p+C $\to \pi^{\pm}, K^{\pm}$	stat. and syst. separately	No	HARP (2009)
6.4, 12.3, 17.5	p+Be $\to \pi^{\pm}$	only total error	No	E910 (2008)
14.6	p+Al $\to \pi^{\pm}, K^{\pm}$	only stat.	No	E802 (1991)

Table 1: Past hadron production datasets relevant to the momentum range of the low-E beamline project.

CERN-SPSC-2022-022

These issues remain as of now -> We want to improve this!!

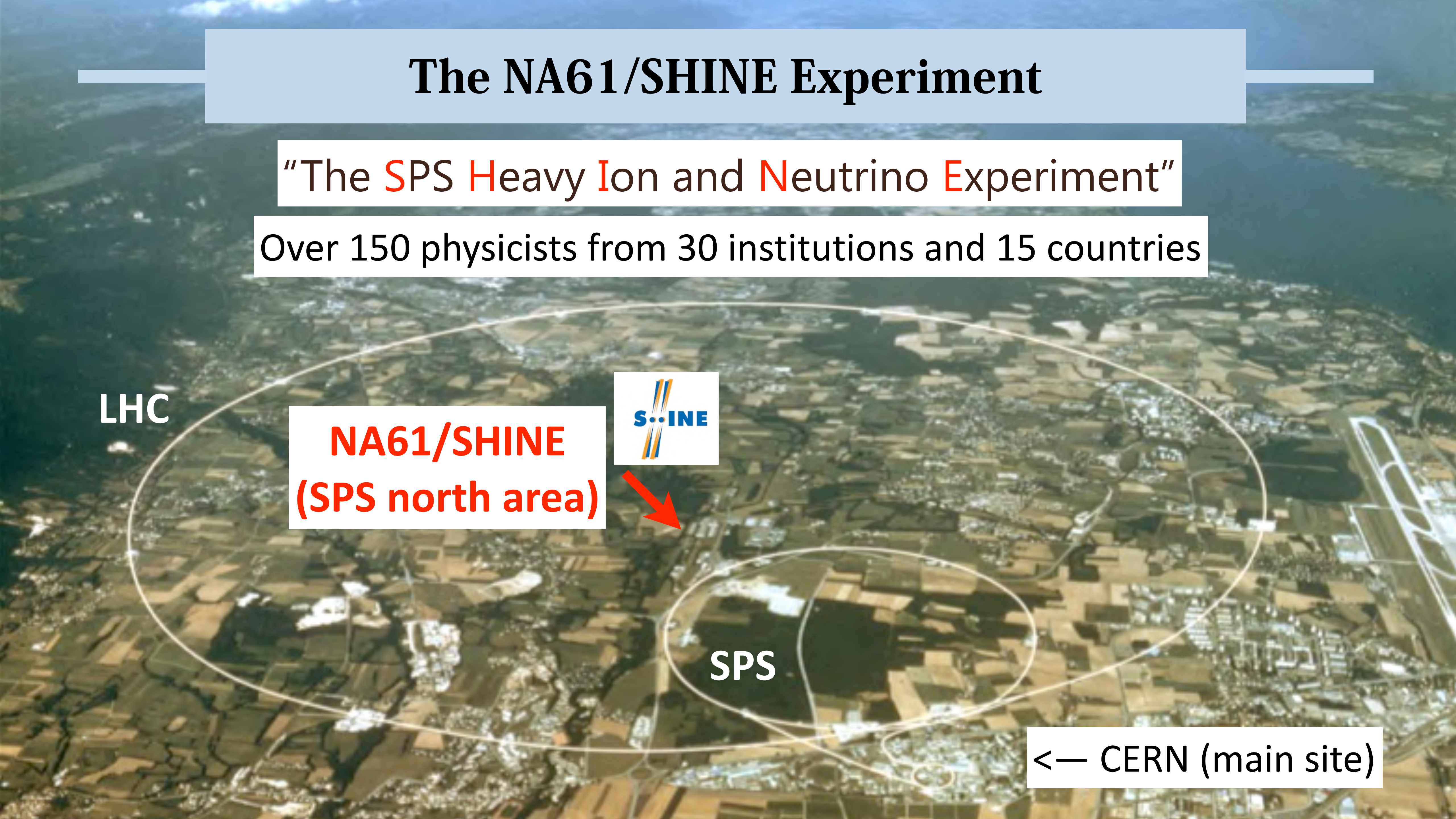


Recent Results from NA61/SHINE

The NA61/SHINE Experiment

"The SPS Heavy Ion and Neutrino Experiment"

Over 150 physicists from 30 institutions and 15 countries



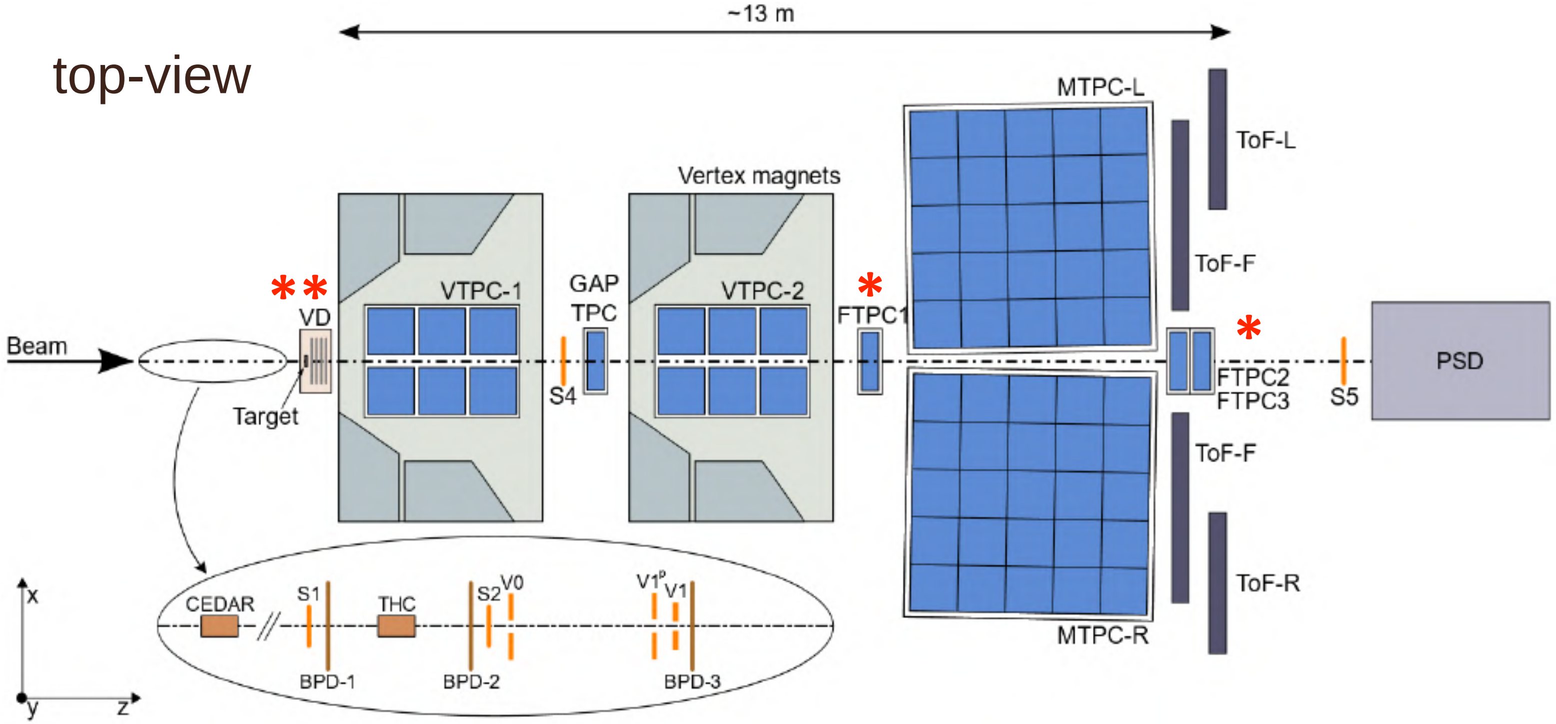
The NA61/SHINE Experiment

- 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

top-view

(as of 2018)



* FTPC 1-3
installed in 2017

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

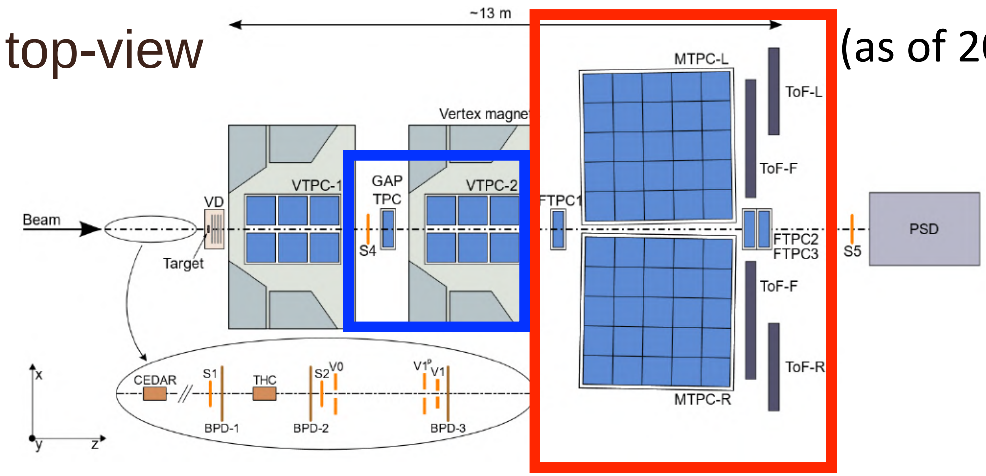
A fixed target experiment at SPS with

- 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

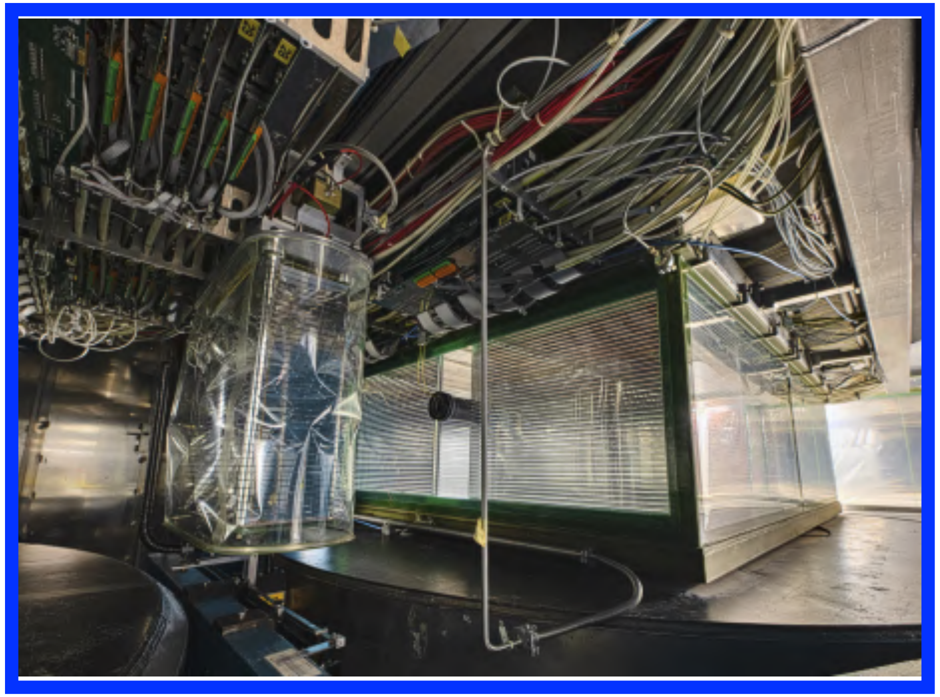
Precise tracking with:
- Particle identification
- Momentum measurement

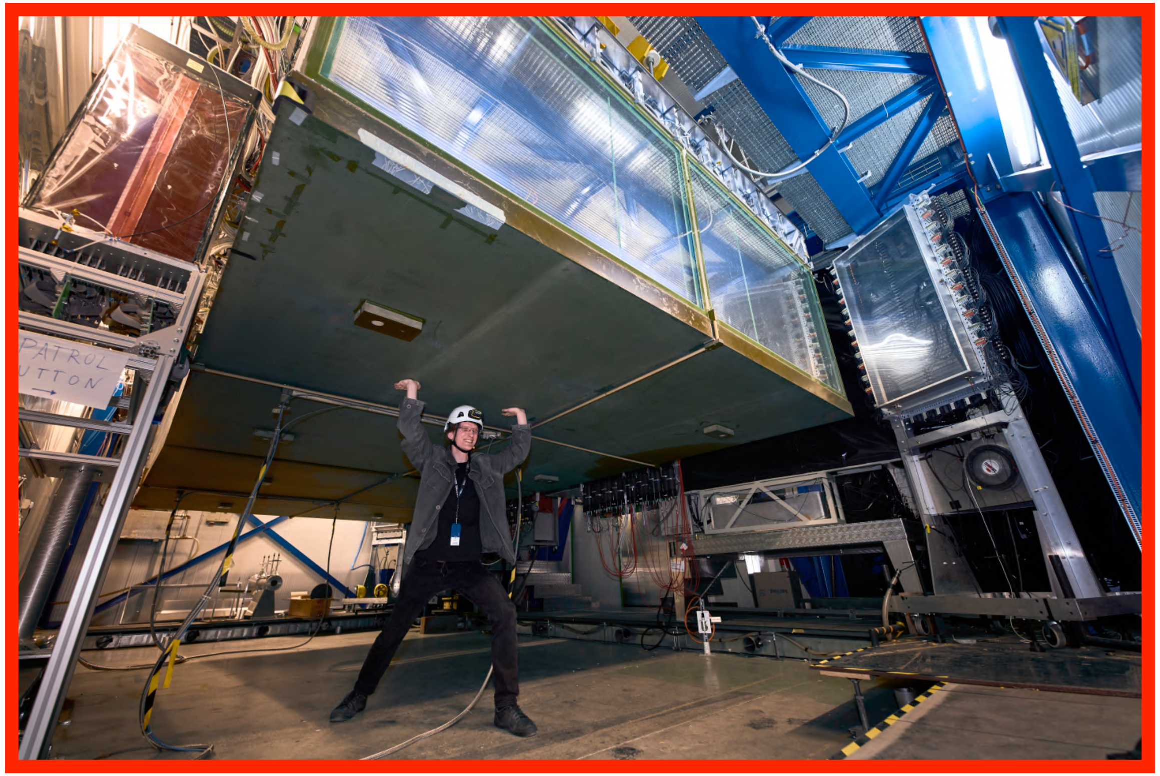
NA61/SHINE Experimental Facility

top-view



(as of 2018)



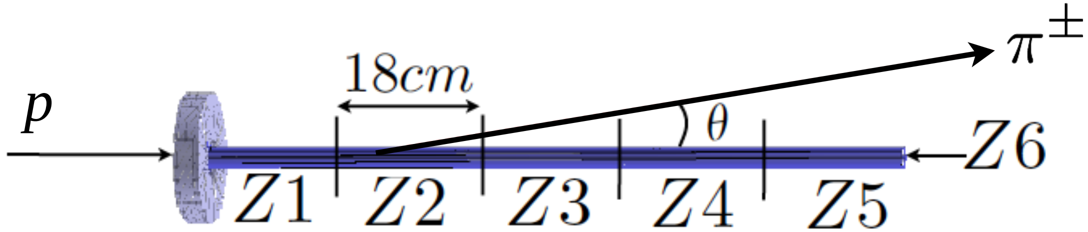


NA61/SHINE Data Collection History

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

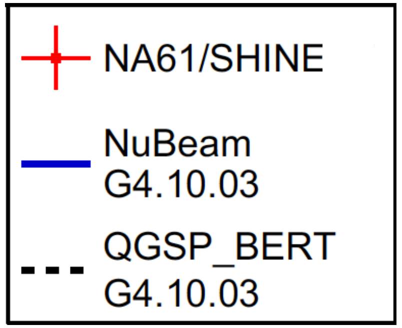
- Thin target:
  - total cross-section and $\pi^{+/-}$ spectra measurements (Phys. Rev. C84 034604 (2011))
  - K^+ spectra measurement (Phys. Rev. C85 035210 (2012))
  - K^0_S and Λ spectra measurements (Phys. Rev. C89 (2014) 025205)
  - total cross-section and $\pi^{+/-}$,$K^{+/-}$ p, K^0_S, and Λ spectra 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))

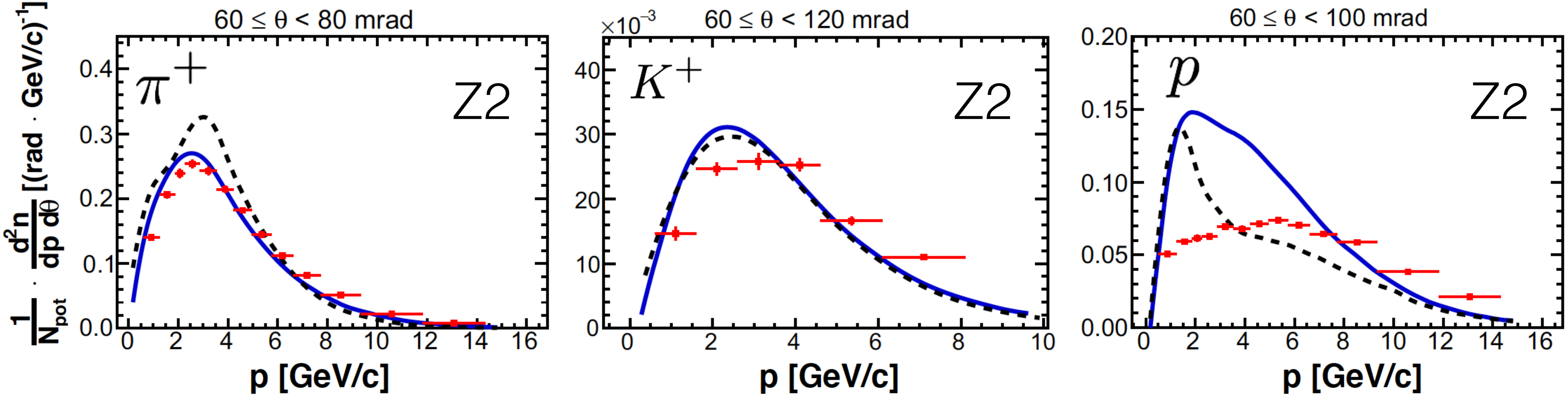
Example: T2K Replica Target Results



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

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





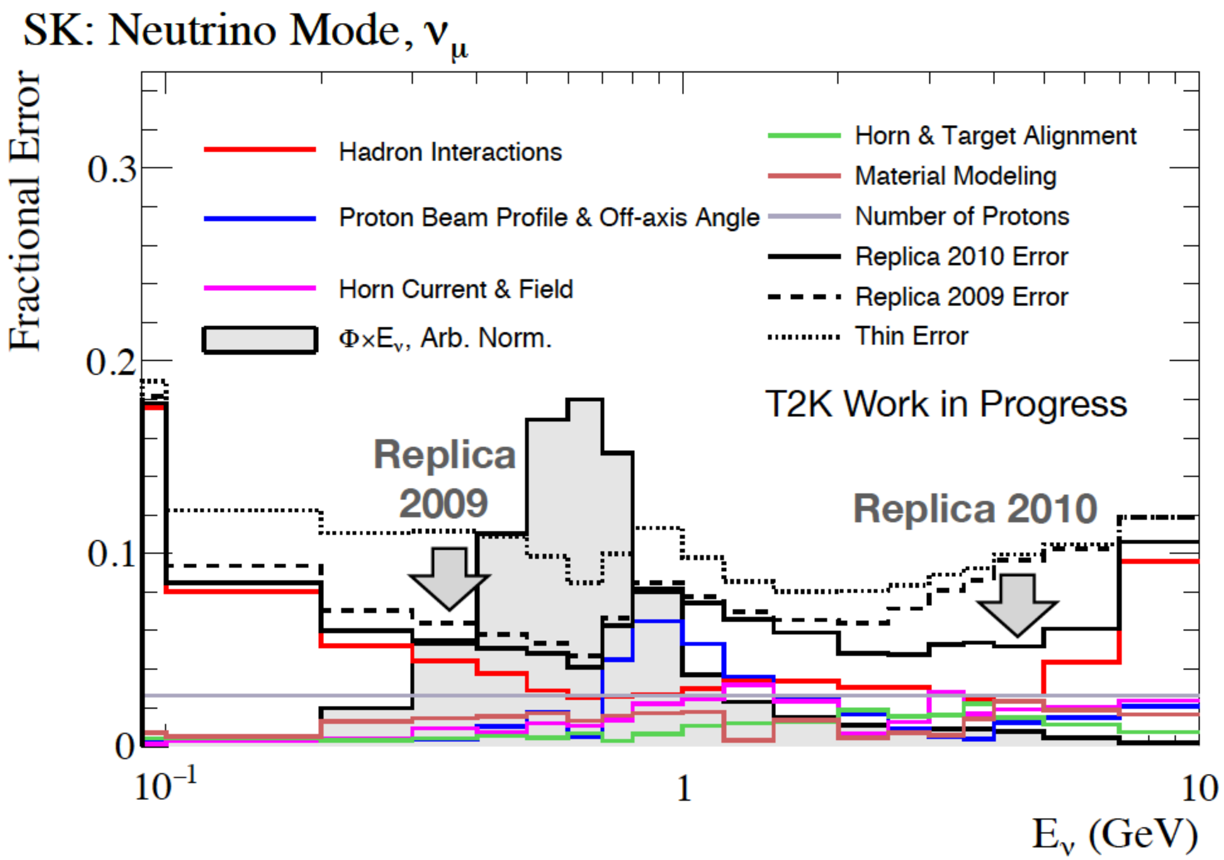
(15 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
10 θ-bins for 0 < θ < 300 mrad (Z6))

(4 θ-bins for 0 < θ < 280 mrad (Z1-Z5)
2 θ-bins for 0 < θ < 120 mrad (Z6))

(10 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
8 θ-bins for 0 < θ < 260 mrad (Z6))

Negative pions and kaons have been measured as well.

T2K Flux Uncertainty with NA61/SHINE Measurements



Lukas Berns (NBI 2019)

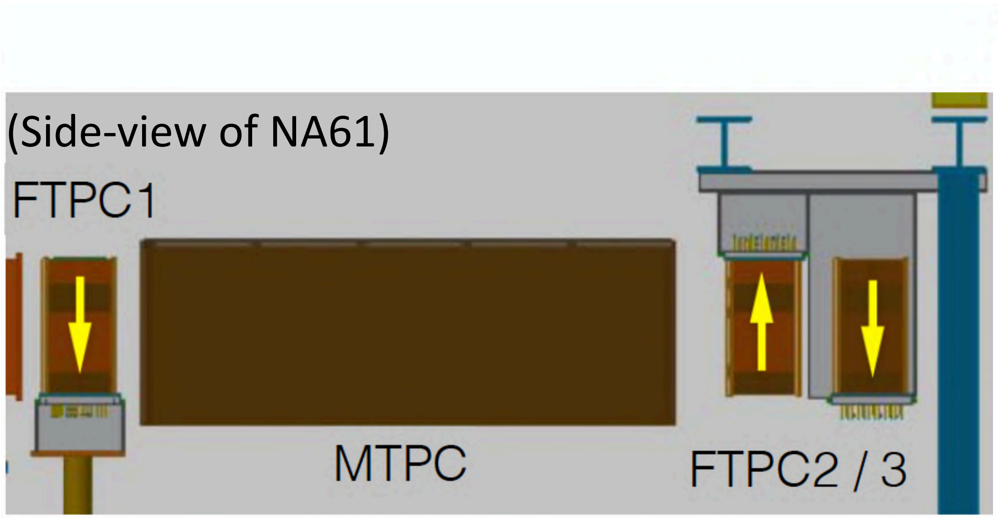
- Replica target measurements will improve uncertainty down to < 5%
  —> For phase space which is not covered by replica target measurements, we still rely on thin target measurements (e.g. re-interactions outside of target)

NA61/SHINE Data Collection History

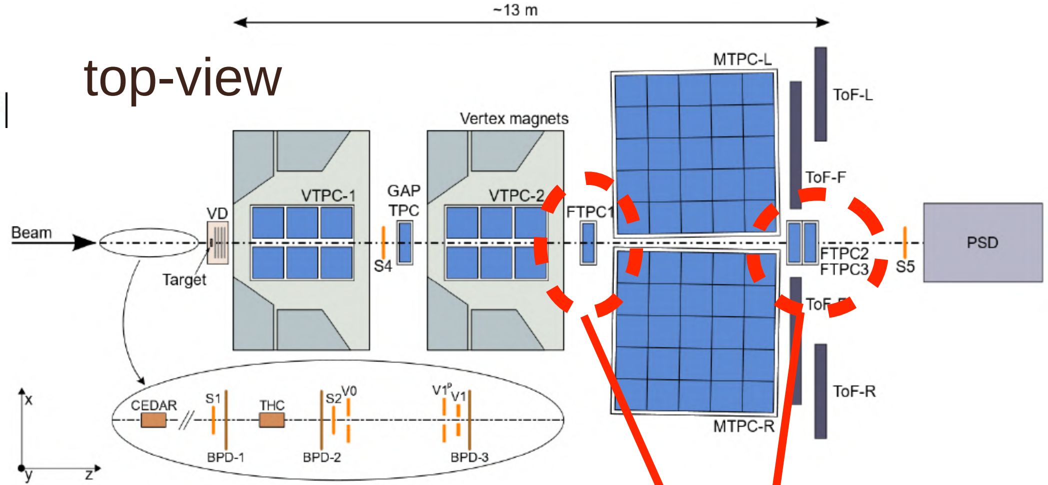
Phase 1 (2006-2010): p+C (2cm graphite or 90-cm-long T2K replica graphite) at 31 GeV/c -> T2K

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

- Facility Upgrade
  - Forward TPCs (after 2017) to measure forward hadron production with higher momentum
    - NuMI: 120 GeV, LBNF: 60-120 GeV



(allow indicates drift direction)



3 TPCs (FTPCs) installed in 2017

Rejection of out-of-time tracks with "Tandem" TPC concept

JINST 15, no.07, P07013 (2020)

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

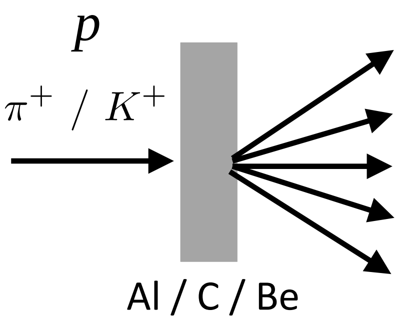
Phase 2 (2015-2018): various -> Fermilab beamlines (NuMI, LBNF/DUNE)

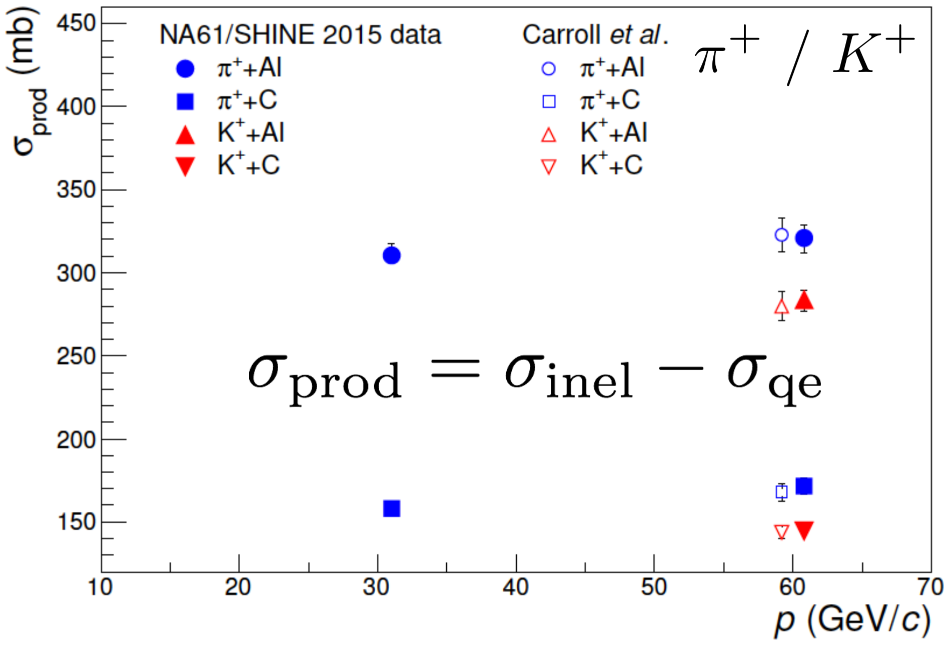
Data sets			
2015	2016	2017	2018
no magnetic field	with magnetic field	with magnetic field	with magnetic field
p+C (31 GeV/c)	p+Al/Be/C (60 GeV/c)	p+C (90 GeV/c)	p+NuMI medium-e target
π^++Al/C (31 GeV/c)	p+Be/C (120 GeV/c)	p+Be/C (120 GeV/c)	(120 GeV/c)
π^++Al/C (60 GeV/c)	π^++Be/C (60 GeV/c)	π^++C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

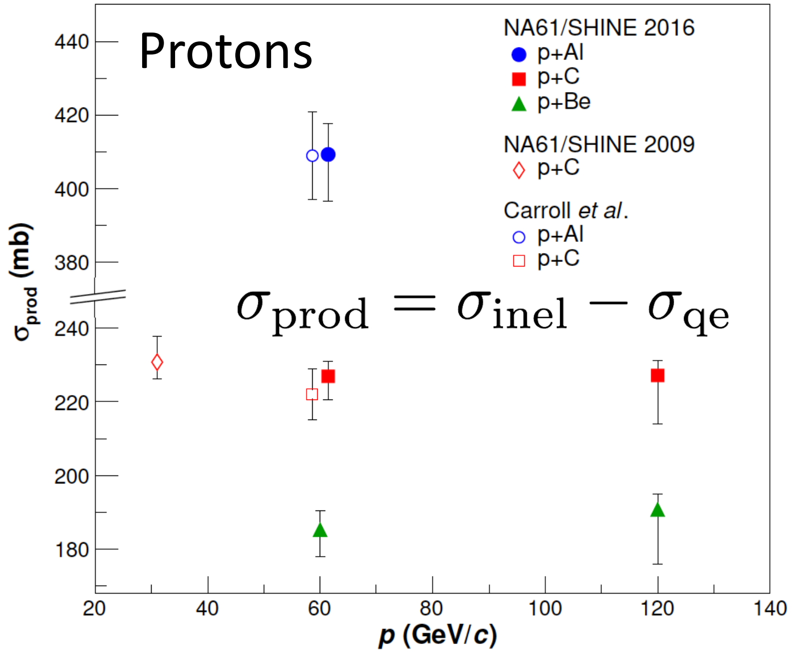
- Differential production multiplicity
  - π^+ beams (Phys. Rev. D100, 112004 (2019))
  - proton beams (analyses ongoing)

Example: Total Cross Section





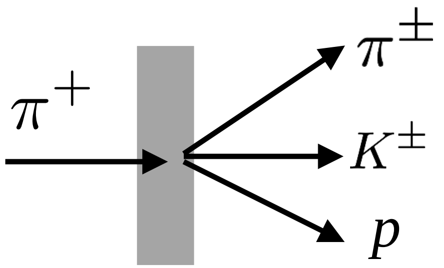
Phys. Rev. D98, 052001 (2018)



Phys. Rev. D100, 112004 (2019)

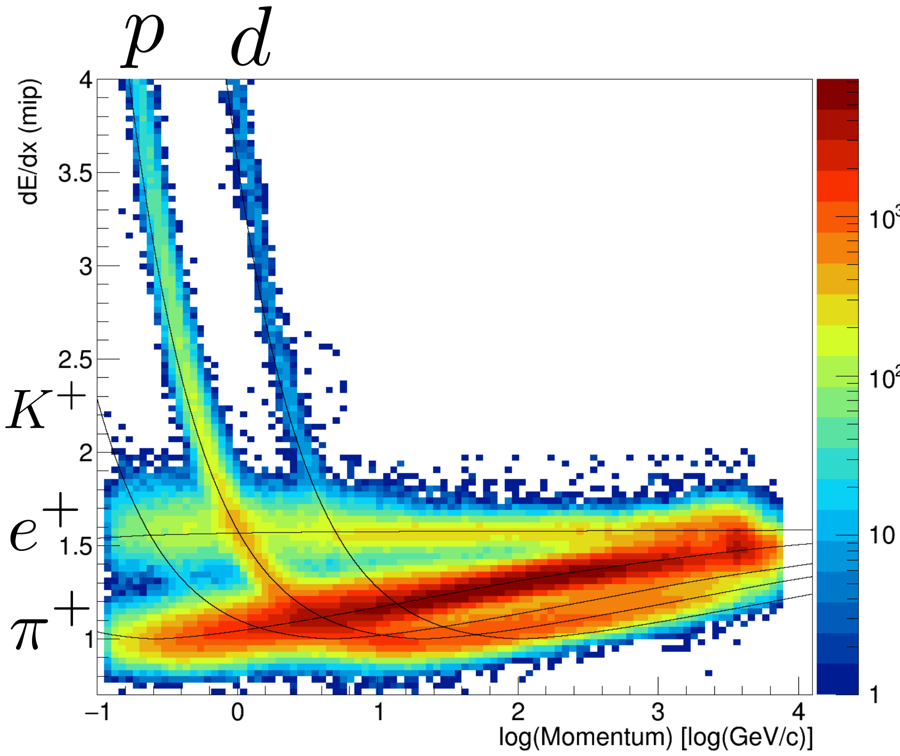
- Precision of measurements: 2~4% (30, 60 GeV/c) and 6~8% (120 GeV/c)
  - It was 5% for pions, 15-30% for kaons
  - First measurement on proton at 120 GeV

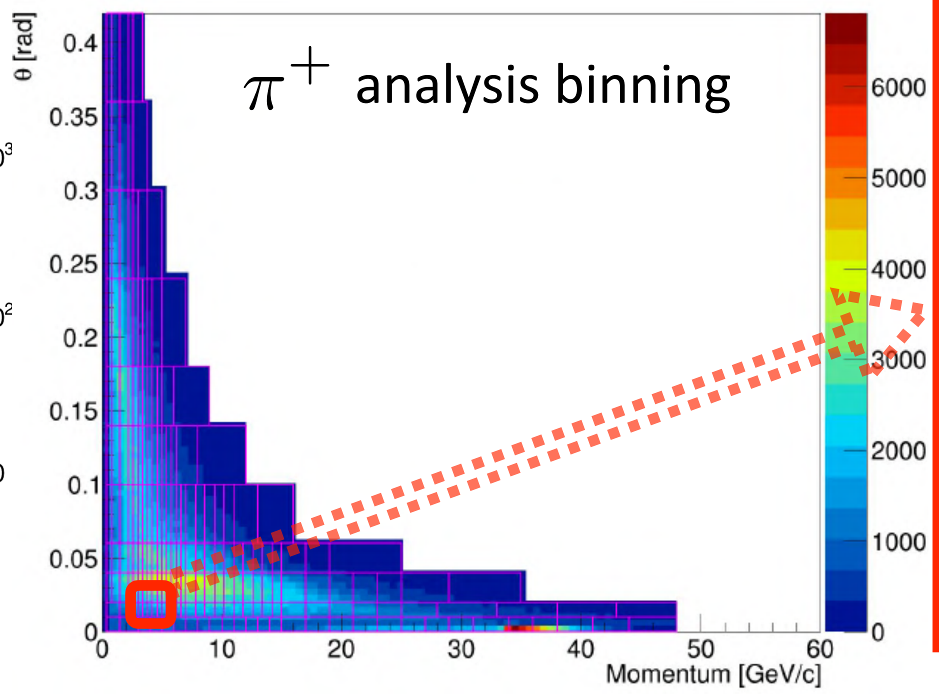
Example: Charged Hadron Production

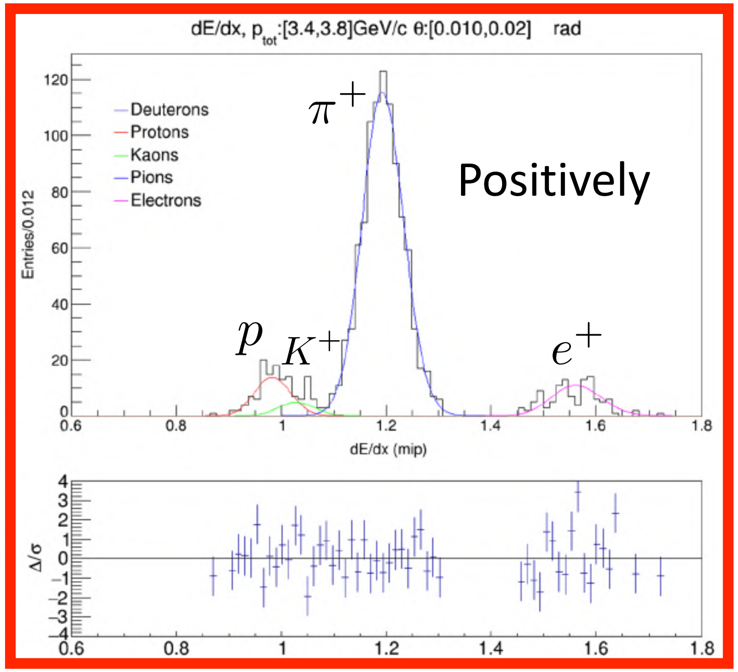


- Example: $\pi^+ + \mathrm{C}\ @\ 60\ \mathrm{GeV}$ Phys. Rev. D100, 112004 (2019)

Binning of pions, kaons, and protons is optimized for each particle species



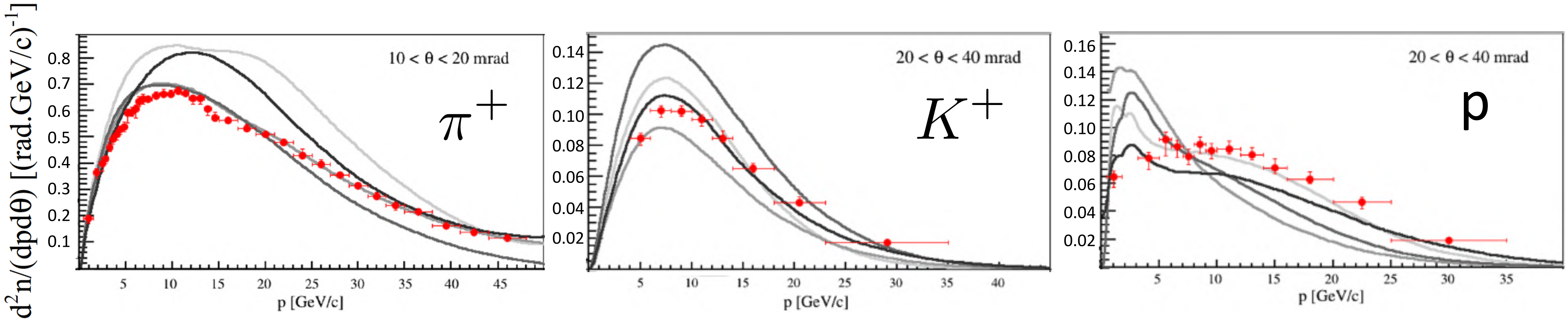


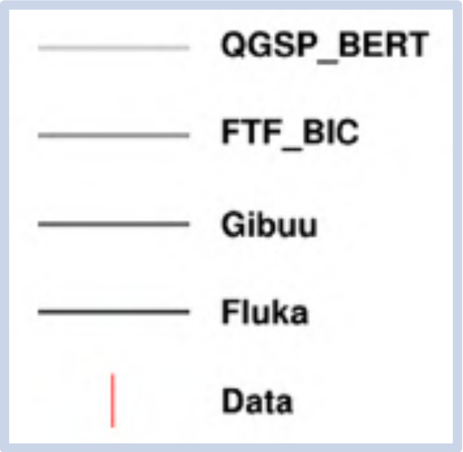


Example: Charged Hadron Production

- Measured differential production yields $(\pi^+ + \mathrm{C}\,@\,60\ \mathrm{GeV})$

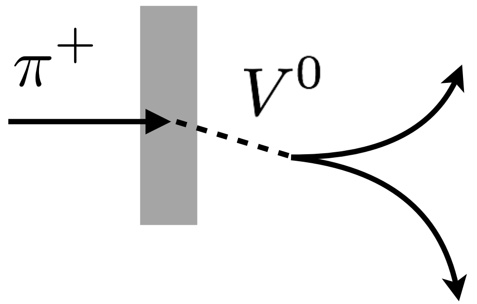
  Phys. Rev. D100, 112004 (2019)





Negative pions and kaons have been measured as well.

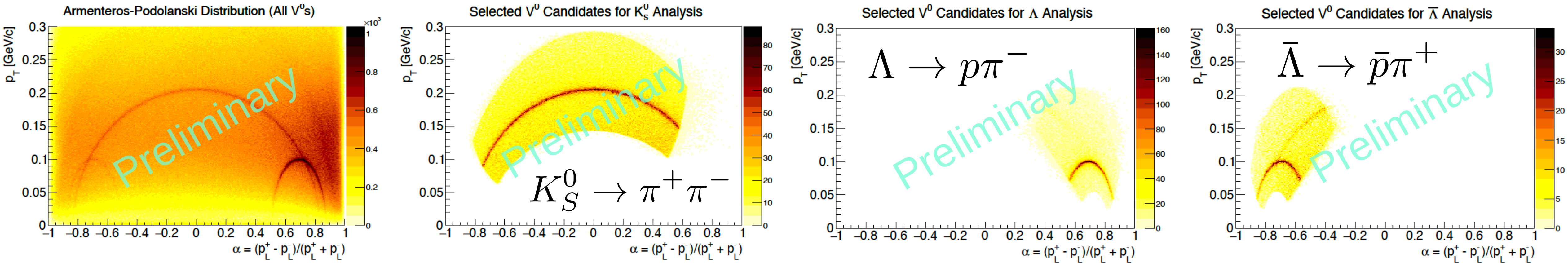
Example: Neutral Hadron Production



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

Preliminary result (paper to be submitted to a journal soon!)

- The Armenteros-Podolansky distribution (visualization of V^0 candidates)



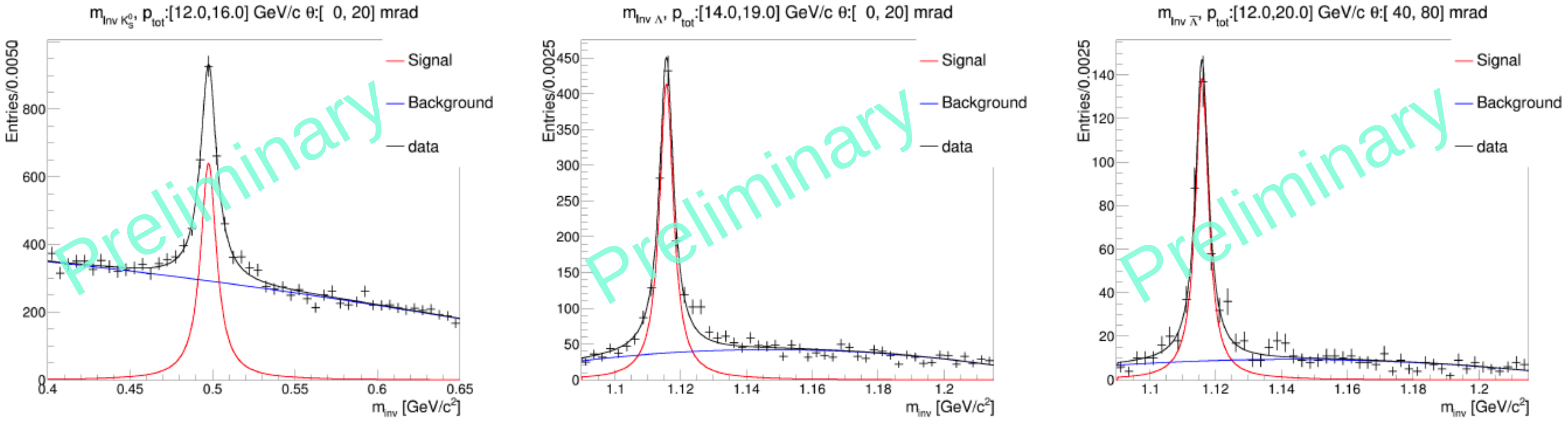
X-axis: $\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$ (Asymmetry in the longitudinal momenta of the child tracks with respect to the V^0 track)

Y-axis: p_T (Transverse momenta of V^0 track)

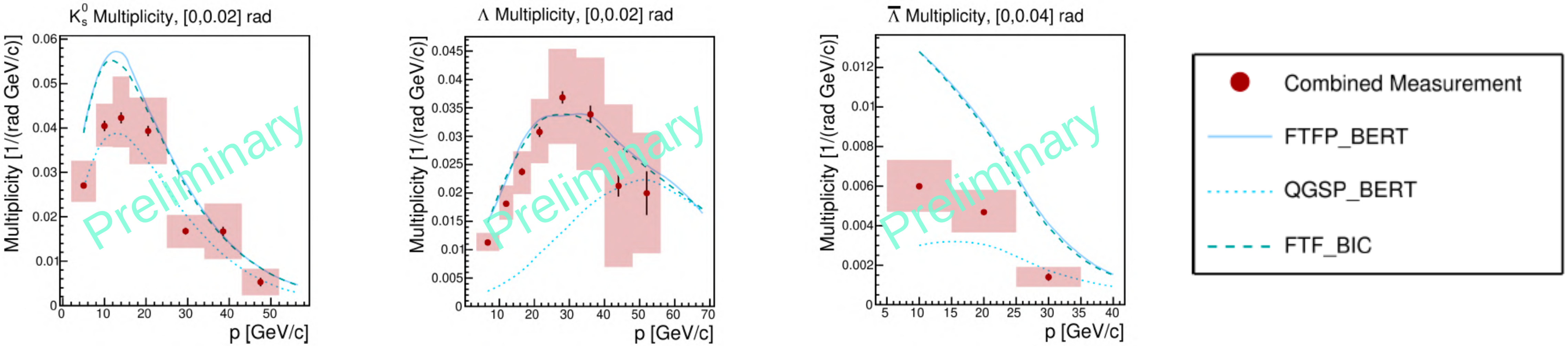
Example: Neutral Hadron Production

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

Preliminary result (paper to be submitted to a journal soon!)

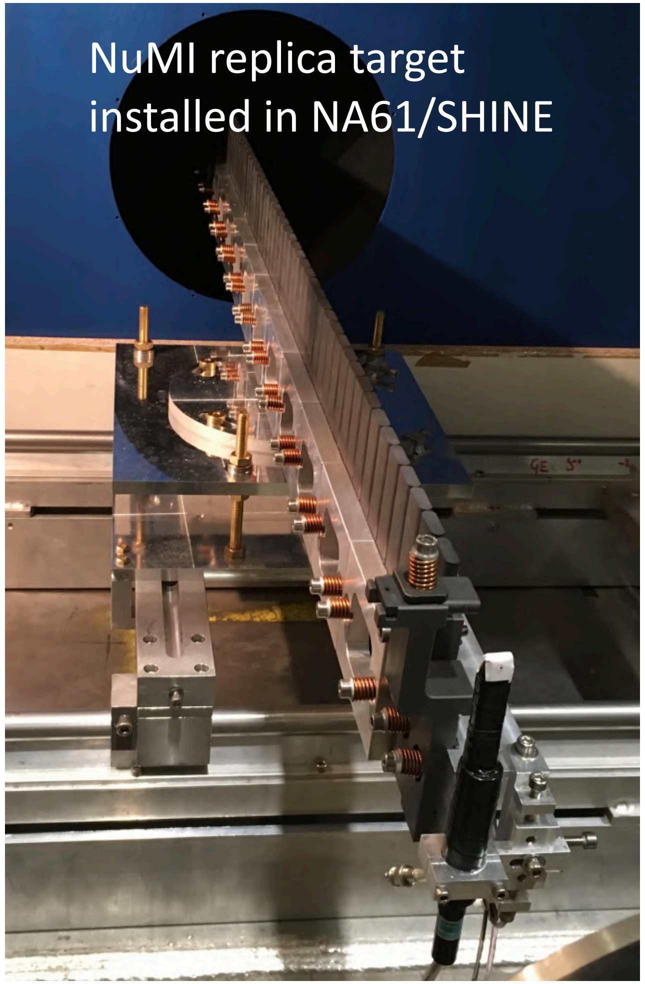


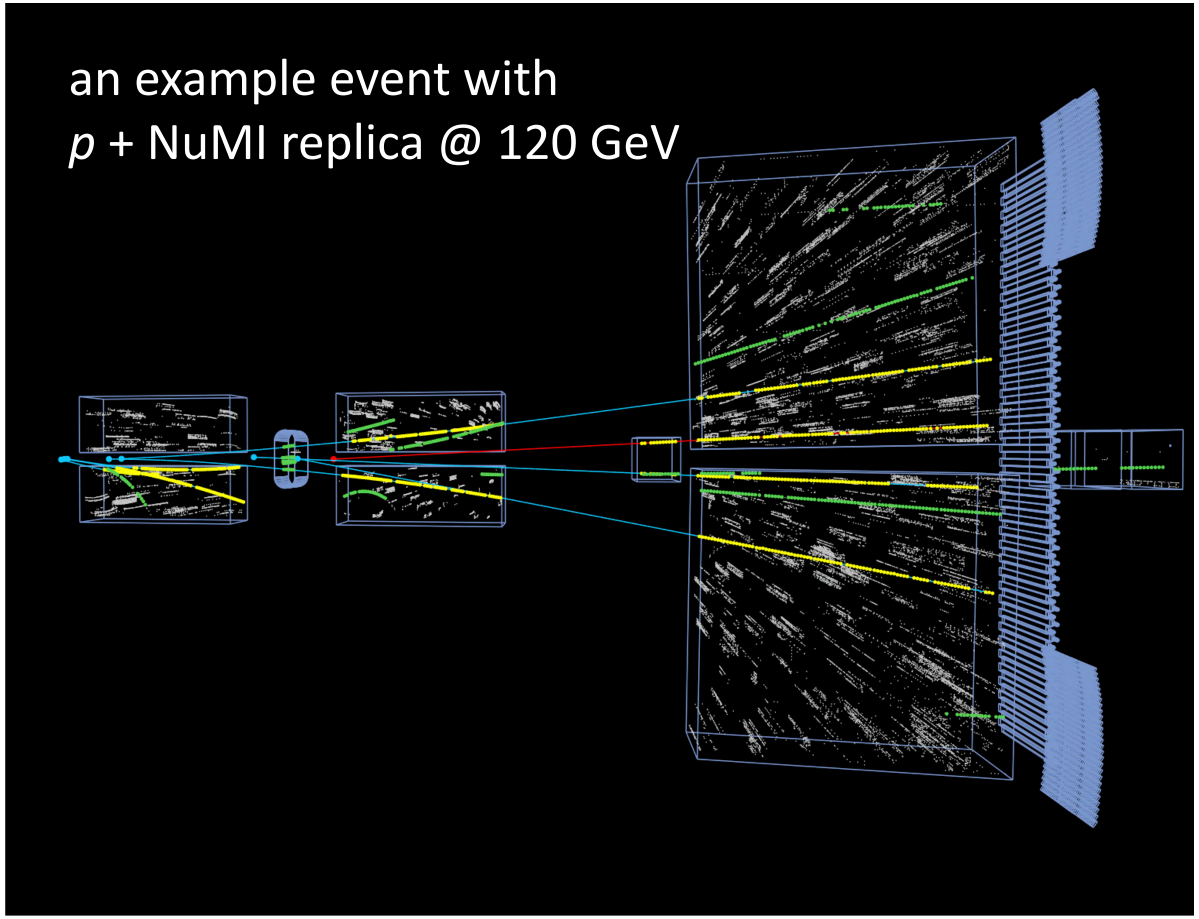
$K_S^0 \to \pi^+\pi^-$ $\Lambda \to p\pi^-$ $\bar{\Lambda} \to \bar{p}\pi^+$



Coming Soon: p+NuMI Replica Target @120 GeV/c

- Replica target: proton beam @ 120 GeV/c in 2018 on NOvA replica target





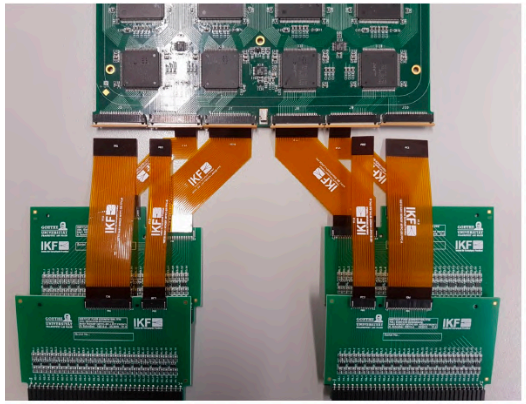
NA61/SHINE Data Collection History

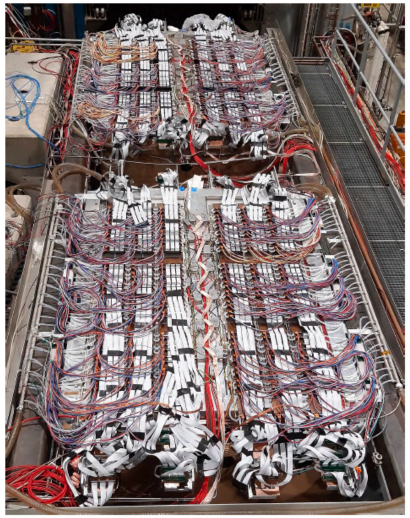
Phase 1 (2006-2010): p+C (2cm graphite or 90-cm-long T2K replica graphite) at 31 GeV/c -> T2K

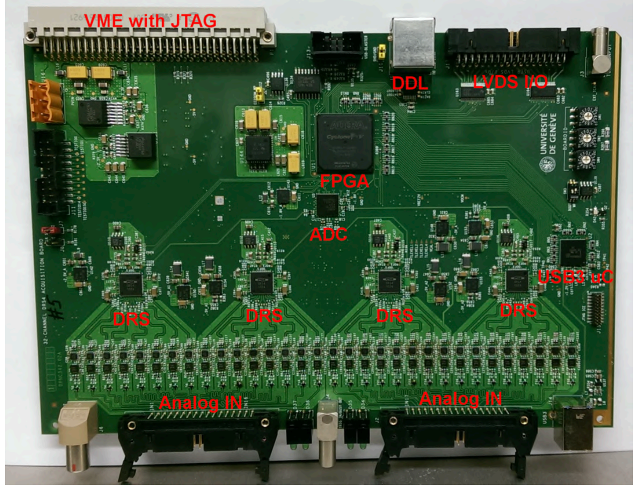
Phase 2 (2015-2018): various -> Fermilab beamlines (NuMI, LBNF/DUNE)

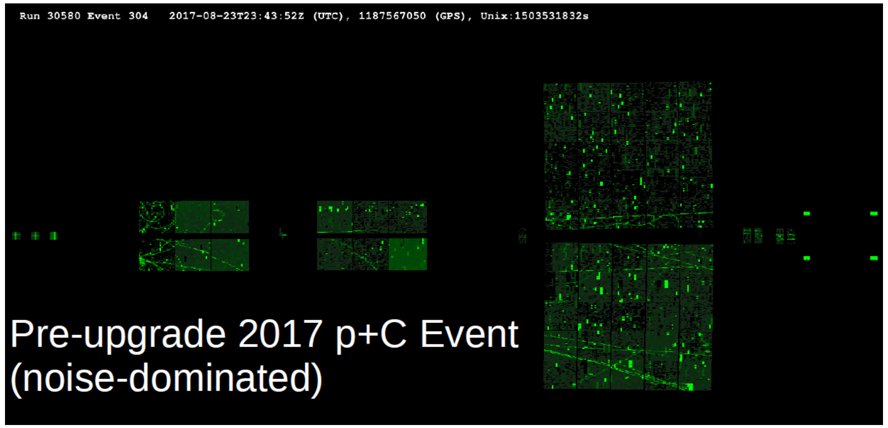
Phase 3 (2022-2025): various -> T2K, LBNF/DUNE

- Facility Upgrade (2019-2022)
  - Many major upgrades recently completed
    - Replacement of 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

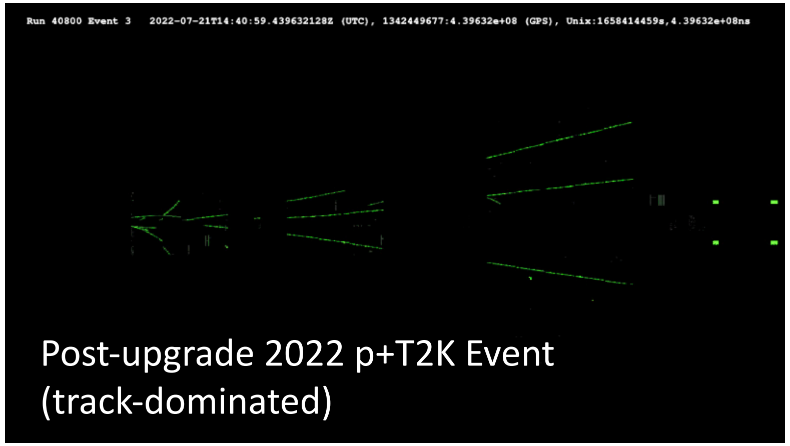








Pre-upgrade 2017 p+C Event (noise-dominated)



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

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

NA61/SHINE Data Collection History

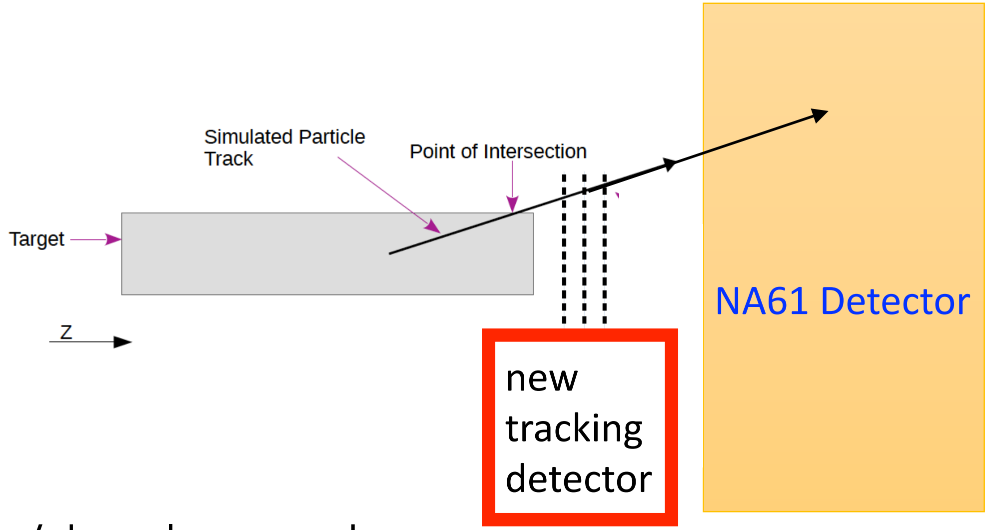
Phase 1 (2006-2010): p+C (2cm graphite or 90-cm-long T2K replica graphite) at 31 GeV/c -> T2K

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

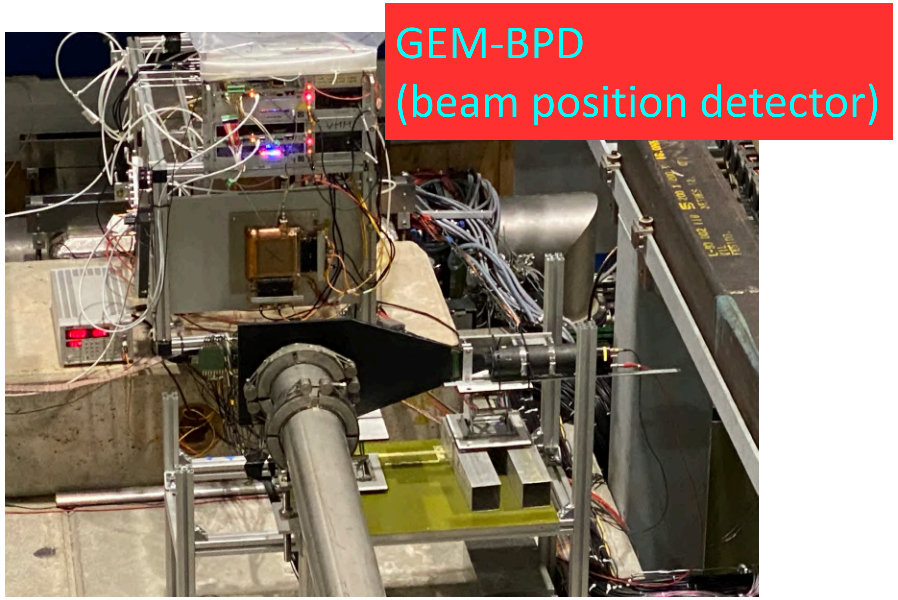
Phase 3 (2022-2025): various -> T2K, LBNF/DUNE (we are here!!)

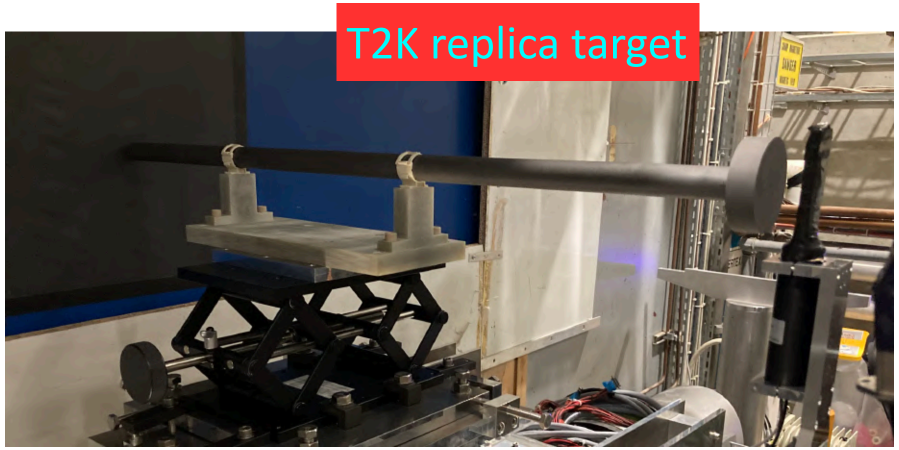
- T2K replica target run (summer 2022) -> T2K
  - A dedicated dataset to further reduce hadron production uncertainty coming from
    - forward charged kaons (primary uncertainty source at high-energy region)
    - K^0_S production (primary uncertainty source of wrong-sign ν_e)

- Future plans (2023-2025) -> LBNF/DUNE
  - Charged kaon scattering with thin targets to constrain secondary interaction uncertainties
  - LBNF/DUNE replica target (after 2024)
    - At least a 1.5 m long target that introduces tracking challenge on track extrapolation
    - An additional tracking detector is under consideration/development



Summer 2022 T2K Replica Run





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

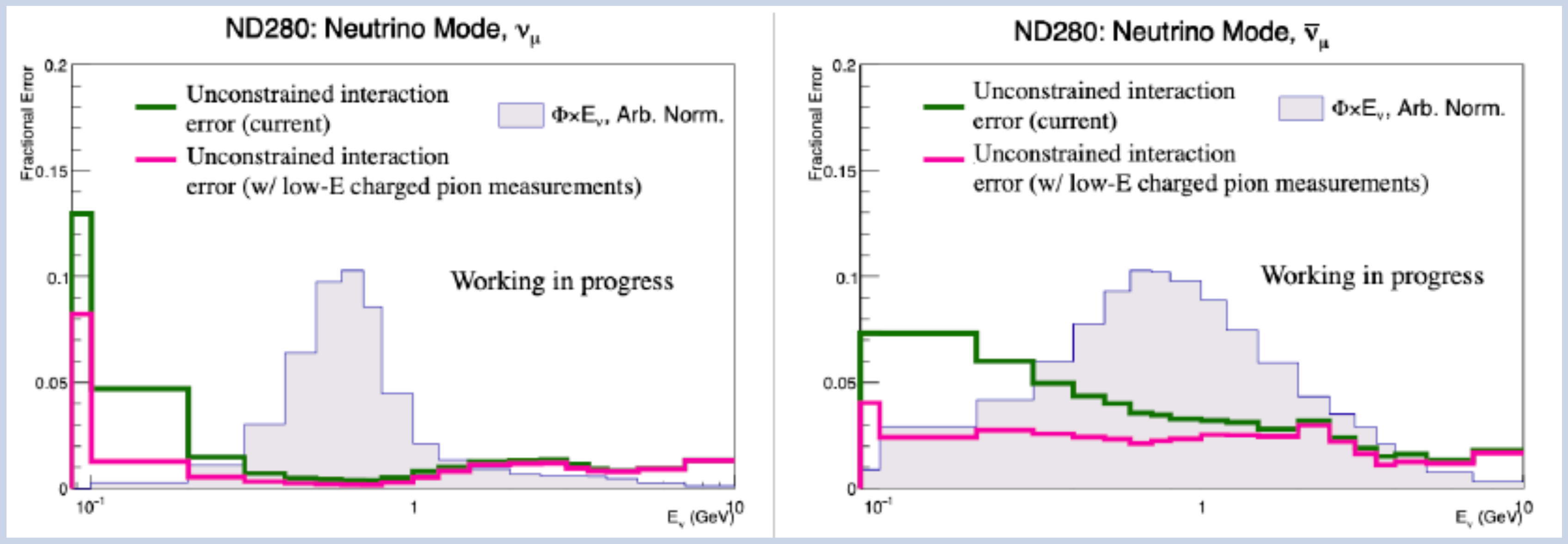
      (c.f. phase 1 T2K replica data stat. was about 10 M events)
- Data calibration and analysis have just started

Future Prospects

The needs (accelerator-neutrinos)

After all available data…

Example from T2K/Hyper-K:



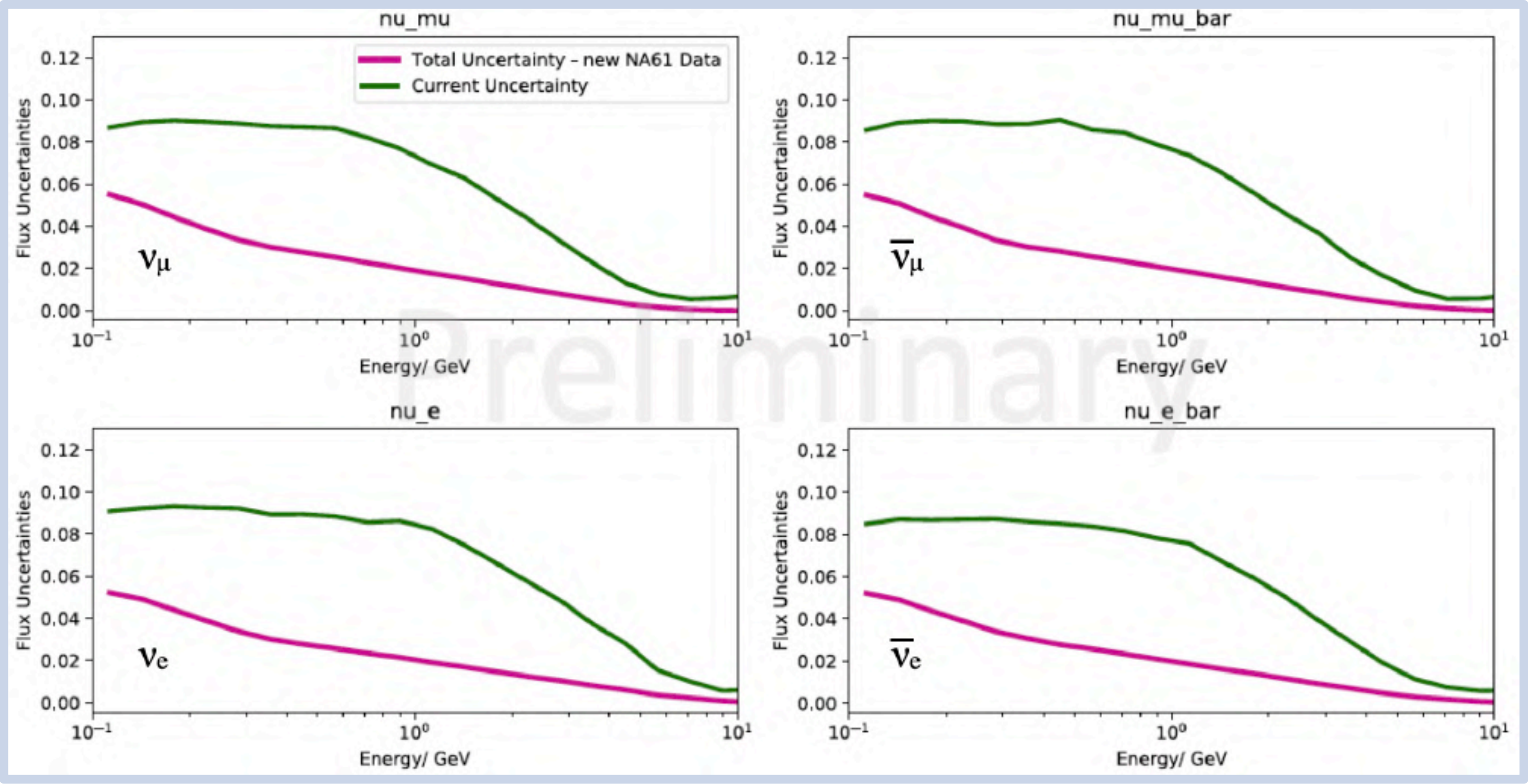
CERN-SPSC-2022-022

For the next generation experiments (DUNE, Hyper-K), flux uncertainty needs to be constrained within 2-3%

There are still unconstrained interactions that limit physics sensitivity.
Improvement is possible if we have additional hadron production data not yet measured by past/present experiments.
(e.g. low energy pion scattering)

The needs (atmospheric neutrinos)

After all available data…



CERN-SPSC-2022-022

Knowledge of atmospheric neutrino flux is even worse, but..

Drastic improvement in the atmospheric neutrino flux is possible

if we have lower energy $\mathrm{p} + \mathrm{N} \rightarrow \pi^{\pm} + X$ for lower energies (down to a few GeV)

NA61++/SHINE Era

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

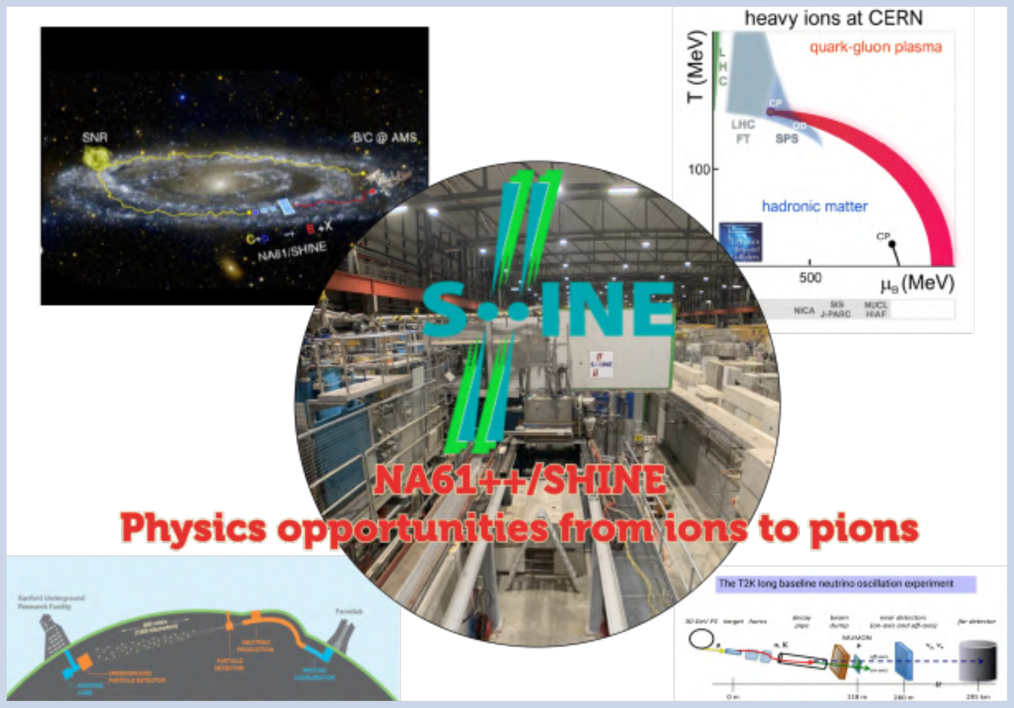
Phase 2 (2015-2018): various -> Fermilab beamlines (NuMI, LBNF/DUNE)

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 (1-20 GeV)
    - New initiative to build a tertiary beamline (next page)
  - Interdisciplinary program
    - Neutrino Physics
    - Strong interaction and heavy ion physics
    - Cosmic ray physics
    - and more..?
  - An open workshop will be held at CERN (December 15-17, 2022)
    - Discussion regarding technical issues and physics opportunities
    - Registration is open: https://indico.cern.ch/event/1174830

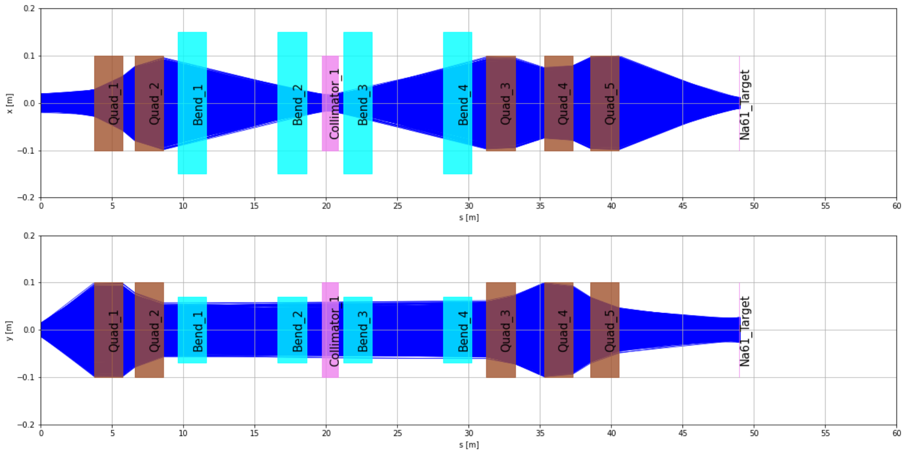


https://indico.cern.ch/event/1174830

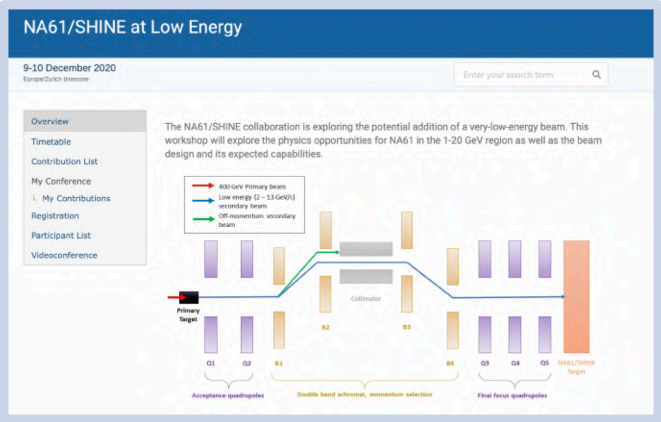
Low-Energy Beamline Project

- A new tertiary low-E hadron beamline at CERN SPS H2 (same beamline as NA61/SHINE)
  - Low-Energy = 1-20 GeV (higher-energy covered by conventional beamline)
- Project is moving forward quickly —> obtained positively evaluation from the SPSC committee
  - First beam in 2024 at the earliest (depending on the funding)

~45m

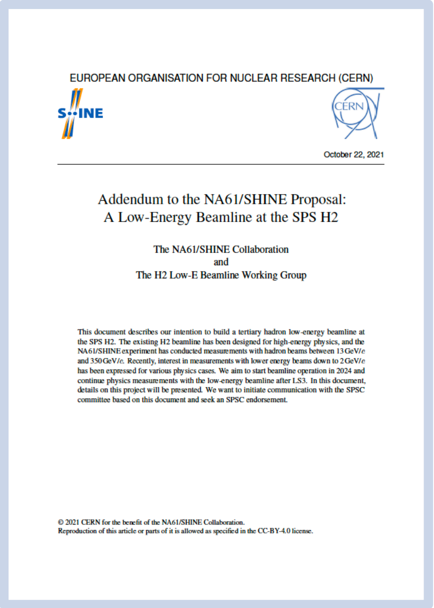


Dedicated workshop in 2020



https://indico.cern.ch/event/973899

Project documents (for SPSC evaluation)



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

October 22, 2021

Addendum to the NA61/SHINE Proposal:
A Low-Energy Beamline at the SPS H2

The NA61/SHINE Collaboration
and
The H2 Low-E Beamline Working Group

This document describes our intention to build a tertiary hadron low-energy beamline at the SPS H2. The existing H2 beamline has been designed for high-energy physics, and the NA61/SHINE experiment has conducted measurements with hadron beams between 13 GeV/c and 350 GeV/c. Recently, interest in measurements with lower energy beams down to 2 GeV/c has been expressed for various physics cases. We aim to start beamline operation in 2024 and continue physics measurements with the low-energy beamline after LS3. In this document, details on this project will be presented. We want to initiate communication with the SPSC committee based on this document and seek an SPSC endorsement.

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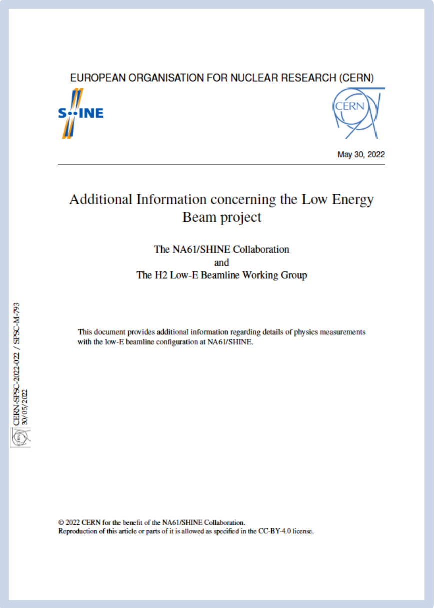
http://cds.cern.ch/record/2783037



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

May 30, 2022

Additional Information concerning the Low Energy Beam project

The NA61/SHINE Collaboration
and
The H2 Low-E Beamline Working Group

CERN-SPSC-2022-022 / SPSC-M-793
30/05/2022

This document provides additional information regarding details of physics measurements with the low-E beamline configuration at NA61/SHINE.

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

Interested in the project? Please contact us!!

New ideas and contributions are welcome!

Summary

- Precision hadron production measurements are essential to reduce the leading systematic uncertainty on the neutrino flux prediction for accelerator-based and atmospheric neutrino experiments
- Lots of recent activities by NA61/SHINE (this talk) and EMPHATIC (next talk)
  - Recent data helps a lot to improve flux knowledge of T2K, and near future for Fermilab beamlines
- Phase is shifting to envision next-generation experiments (DUNE, Hyper-K)
  - These experiments require unprecedented knowledge of neutrino fluxes
  - Hadron production experiments prepares for their needs

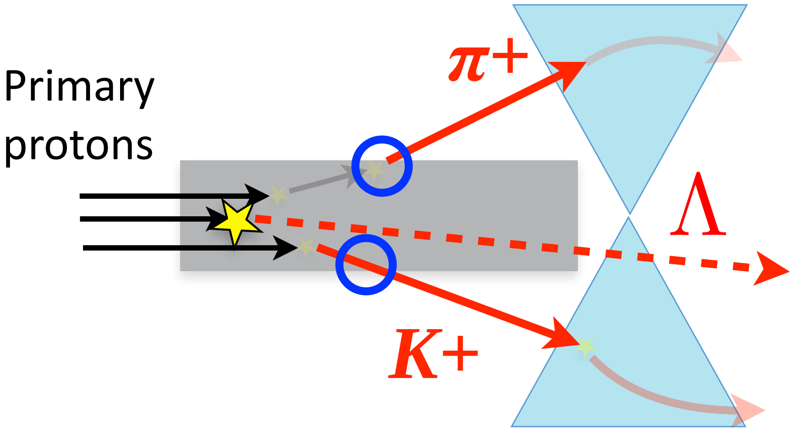
Stay Tuned!

Backup

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 $\sigma_{DATA}/\sigma_{MC}$	$\left(\frac{d^2n}{dp\,d\theta}\right)_{DATA} \Big/ \left(\frac{d^2n}{dp\,d\theta}\right)_{MC}$ p, θ: outgoing particle kinematics
For distance L traversed in matter	"Attenuation" weight $e^{-(\sigma_{DATA}-\sigma_{MC})\rho L}$	N.A.

with replica target data… weights applied at the exiting point