

# New results for neutrino and cosmic-ray physics from NA61/SHINE



Yoshikazu Nagai

for the NA61/SHINE collaboration



**ELTE**

Eötvös Loránd  
University

## Neutrino physics program

- Published: p+C at 120 GeV/c (neutral and charged hadron production)
- Analysis in progress: p+C at 60 GeV/c and 90 GeV/c, p+replica targets (T2K, NOvA)
- Next step: p+DUNE replica at 120 GeV/c, low-energy hadron interactions

## Cosmic-ray physics program

- Published:  $\pi^-$ +C at 158 and 350 GeV/c  
neutral and charged hadron production
- Preliminary result: nuclear fragments from C+p at 13.5A GeV/c
- Analysis in progress: Deuteron production in p+p at 158 GeV/c
- Next step: Nuclear fragmentation measurements for Galactic cosmic-ray physics

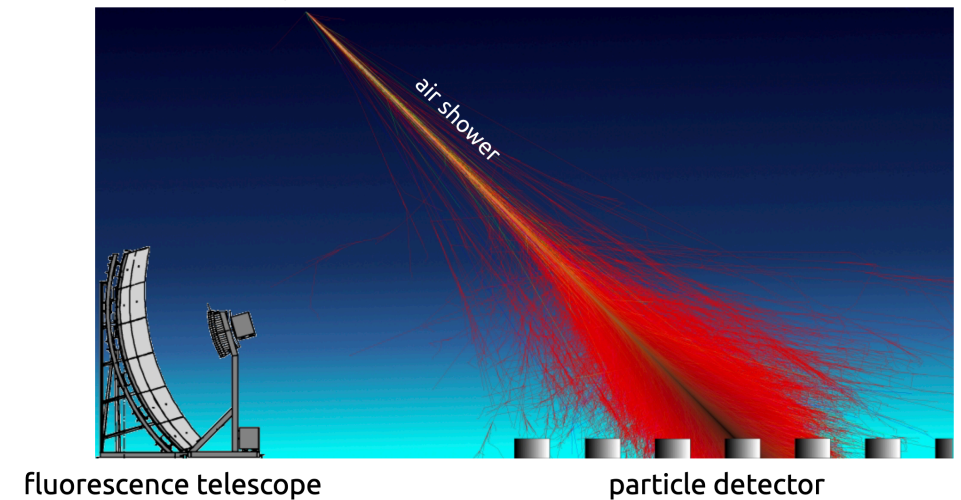
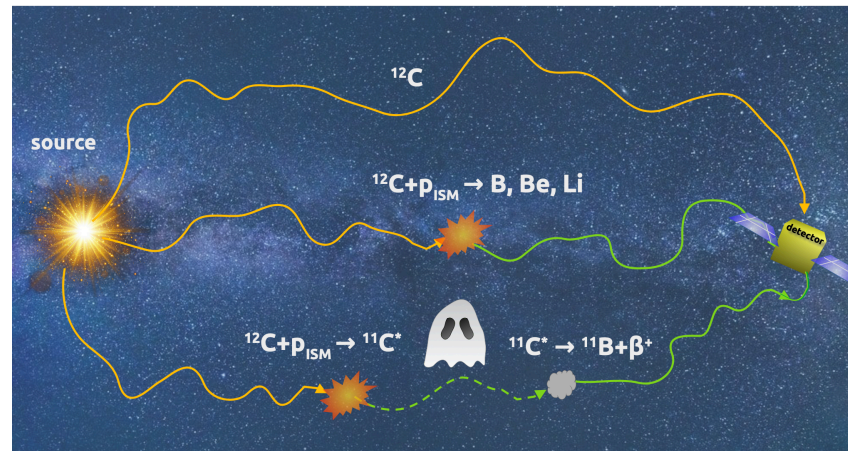
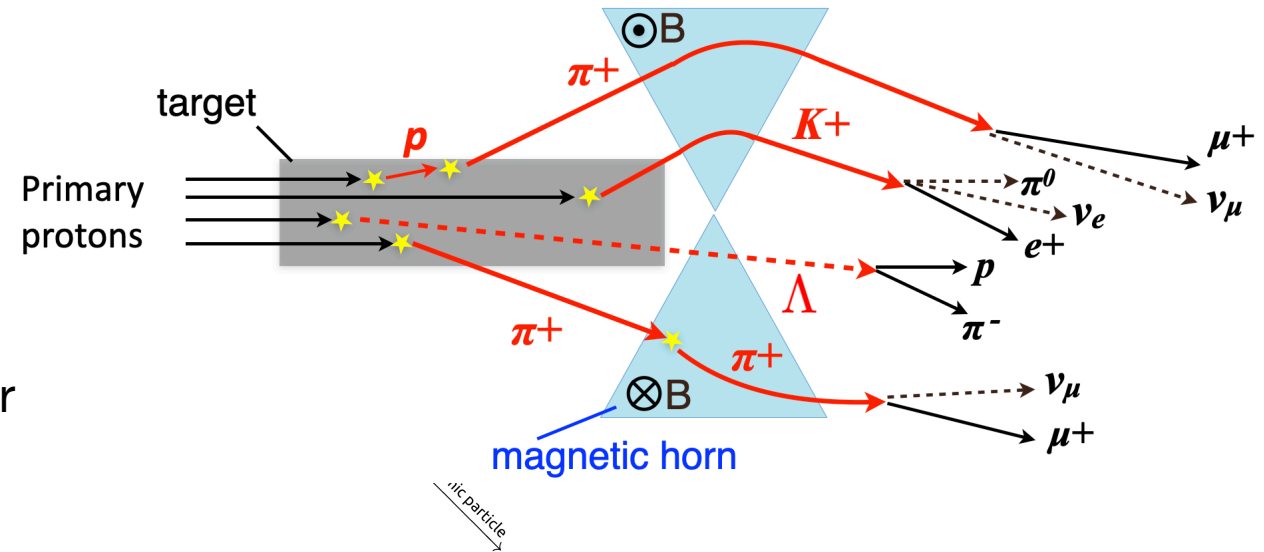
# Neutrino and Cosmic-Ray physics program: Motivation

## Neutrino physics

- Hadron production measurements to reduce the leading uncertainty on neutrino flux predictions

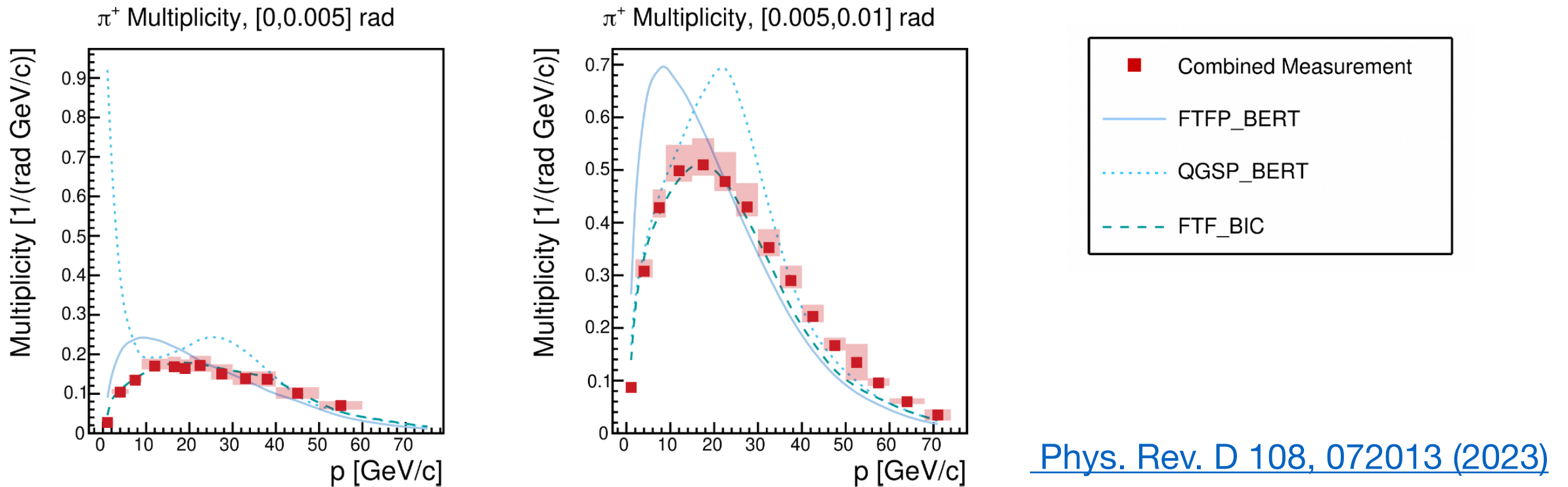
## Cosmic-ray physics

- Air shower data
  - hadron production measurements to improve air shower model
- Galactic cosmic-ray data
  - Nuclear fragmentation cross-section measurement
  - (anti-)deuteron production cross-section measurement



# New Neutrino Results: Charged hadrons from p+C at 120 GeV/c

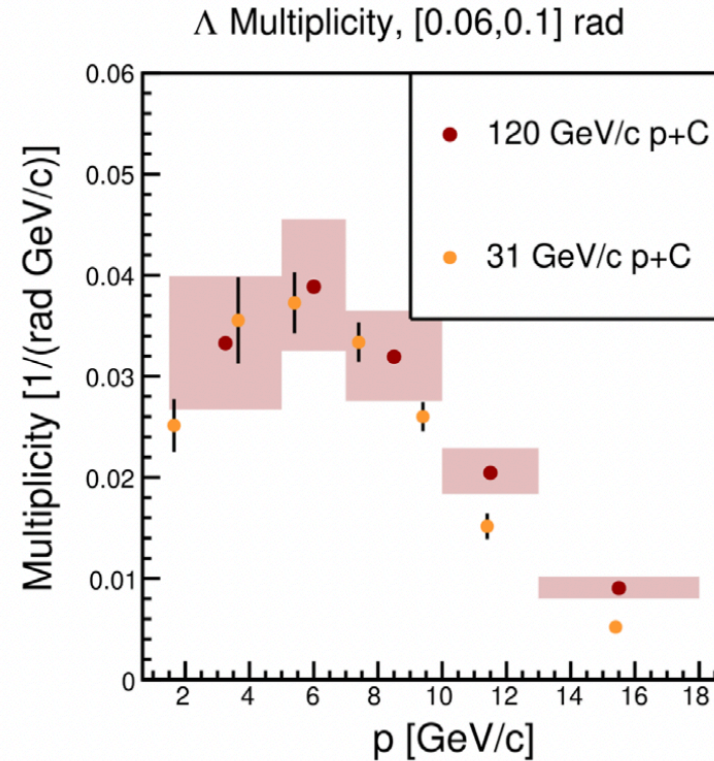
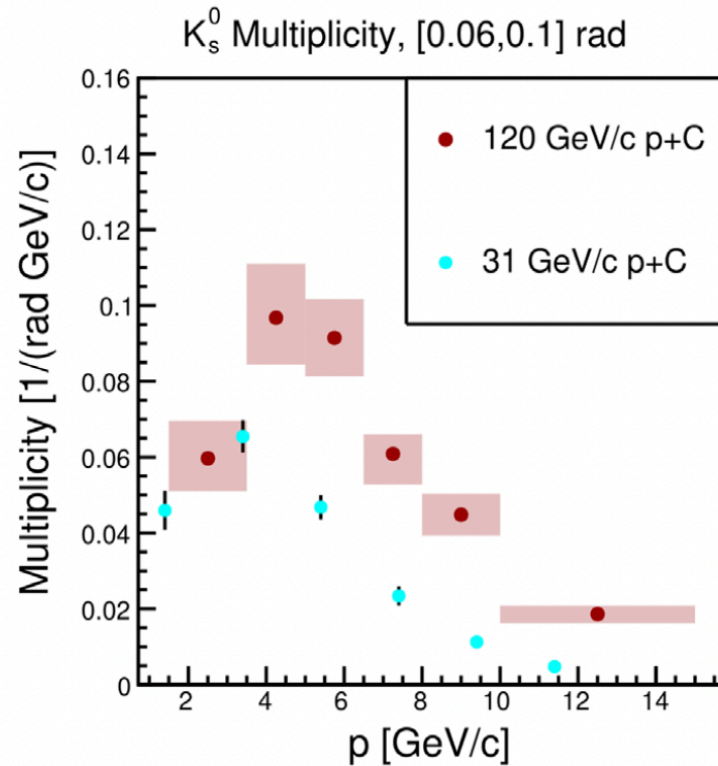
NuMI (LBNF) beamline at Fermilab uses (will likely use) 120 GeV/c protons on a thick graphite target



Measured spectra of  $\pi^\pm$ ,  $K^\pm$ ,  $\rho$ , and  $\bar{p}$  are compared to model predictions including forward acceptance important for neutrino flux prediction.

Results are compared with several model predictions.

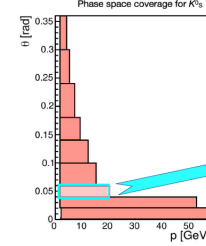
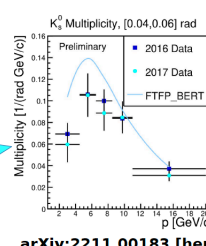
# New Neutrino Results: Neutral hadrons from p+C at 120 GeV/c



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

## 2022 SPSC annual report

**New Neutrino Result: Neutral Hadrons from p+C @ 120 GeV/c**

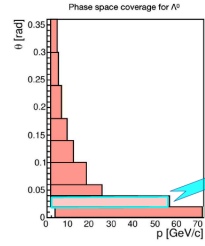
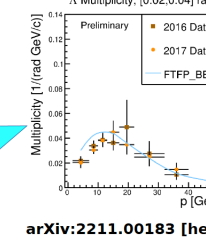
**arXiv:2211.00183 [hep-ex]**

- Neutrino beamlines for current and future long-baseline experiments at Fermilab use (and likely will use) 120 GeV/c protons
- First results on **production of  $K_s^0$ ,  $\Lambda$ ,  $\bar{\Lambda}$**  submitted to PRD
- Results in a single angular bin for  $K_s^0$  shown above

Eric D. Zimmerman      Report from NA61/SHINE      SPSC Open Session 17

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**New Neutrino Result: Neutral Hadrons from p+C @ 120 GeV/c**

**arXiv:2211.00183 [hep-ex]**

- Results in a single angular bin for  $\Lambda^0$  are shown above
- Results for production of charged hadrons ( $\pi^+$ ,  $\pi^-$ ,  $K^+$ ,  $K^-$ ,  $p$ ) should be released soon

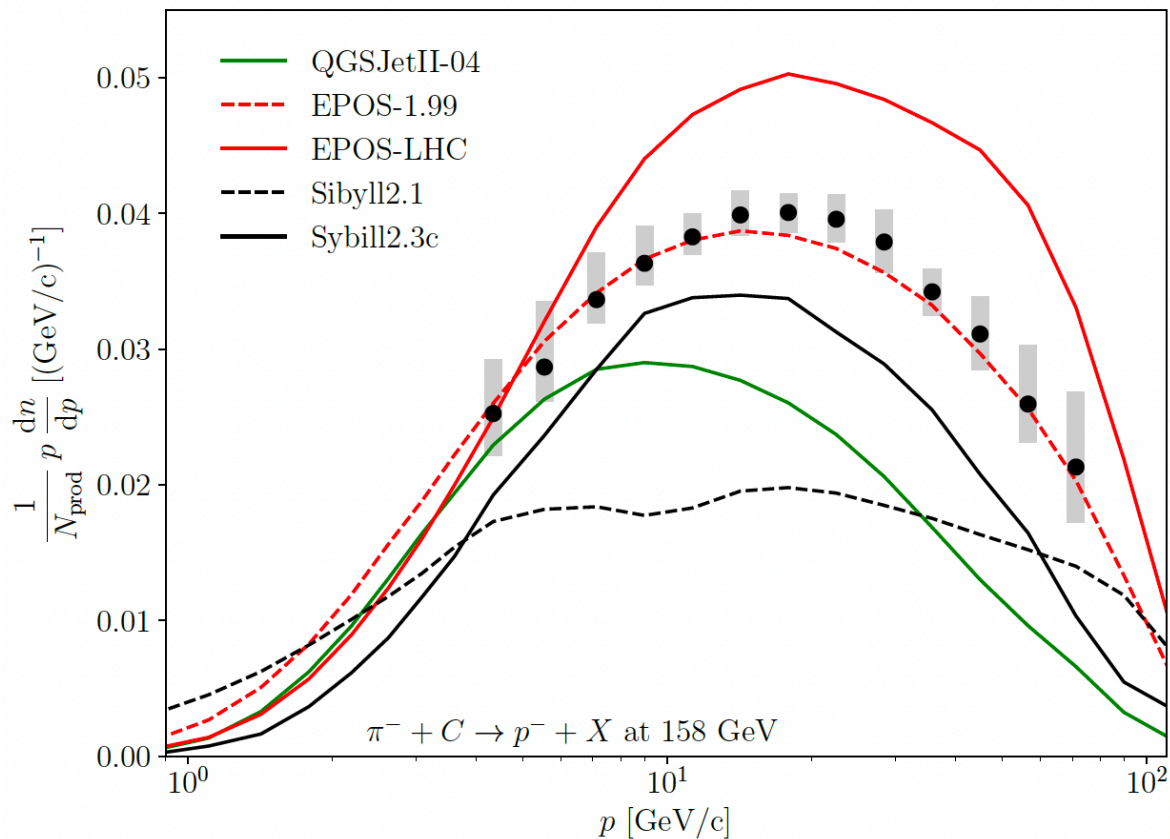
Eric D. Zimmerman      Report from NA61/SHINE      SPSC Open Session 18

The preliminary results were reported in the SPSC open session last year.



# New Cosmic-Ray Results: $\pi^-+C$ interactions at 158 and 350 GeV/c

$\bar{p}$  production in  $\pi^-+C$  interactions at 158 GeV/c



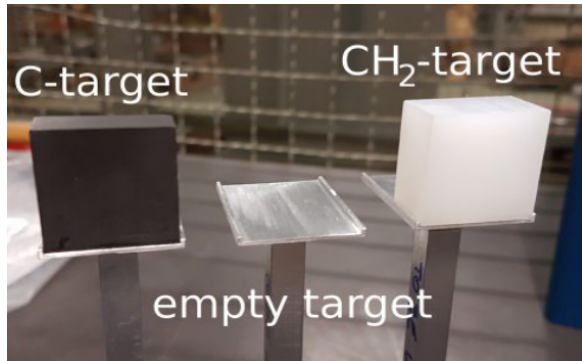
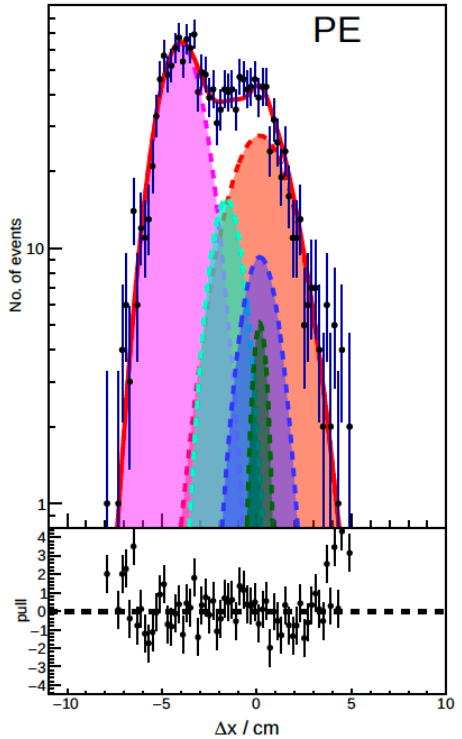
- Finalized hadron production measurements for
  - charged hadrons ( $\pi^\pm, K^\pm, p, \bar{p}$ )
  - neutral hadrons ( $K^0_S, \Lambda, \bar{\Lambda}$ )
- **Completed hadron production studies to understand air showers induced by ultra-high energy cosmic rays**

Reminder:

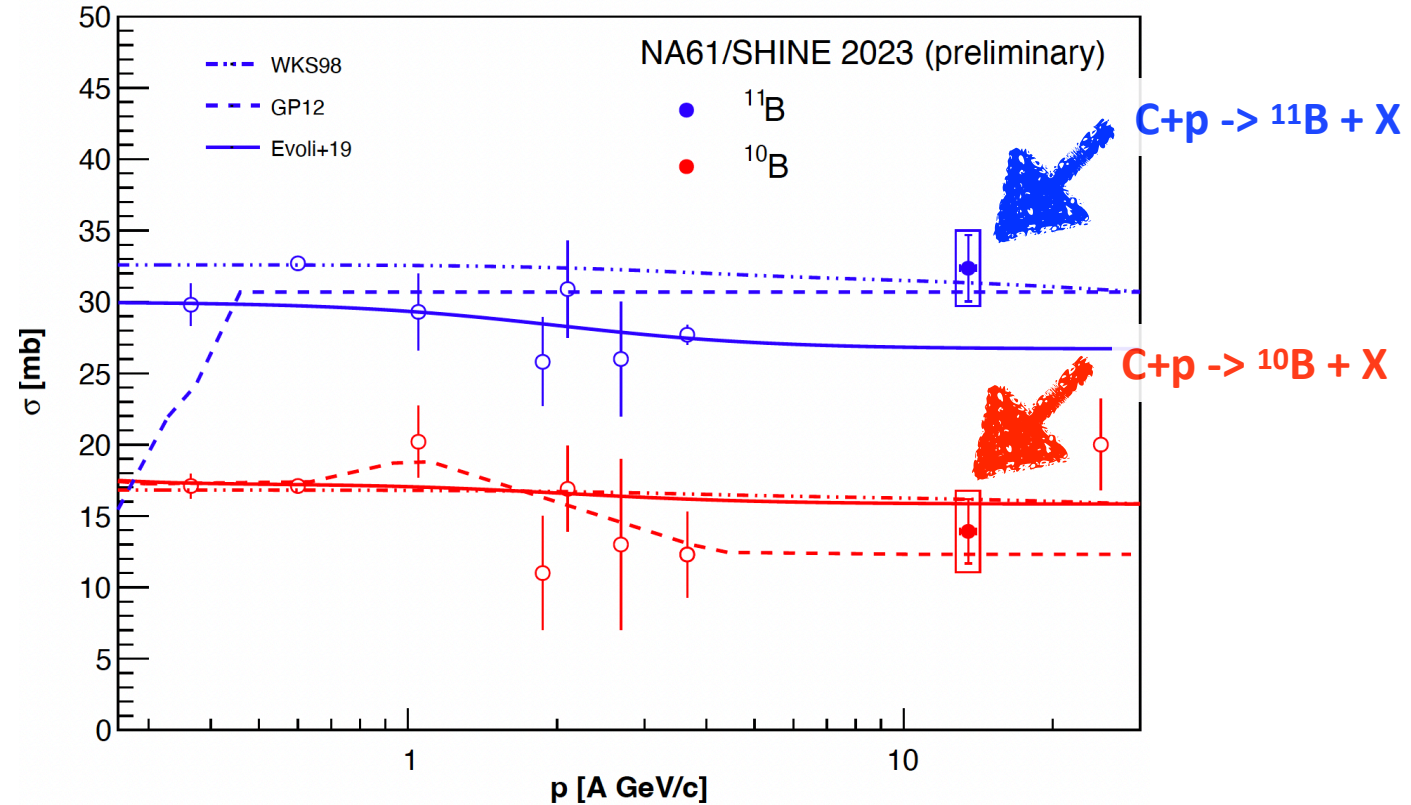
- meson resonance production with the same dataset  
[Eur. Phys. J. C 77, no.9, 626 \(2017\)](#)

[Phys. Rev. D 107, 062004 \(2023\)](#)

# New Cosmic-Ray Results: Nuclear fragments from C+p at 13.5A GeV/c



“p = CH<sub>2</sub> - C - empty”

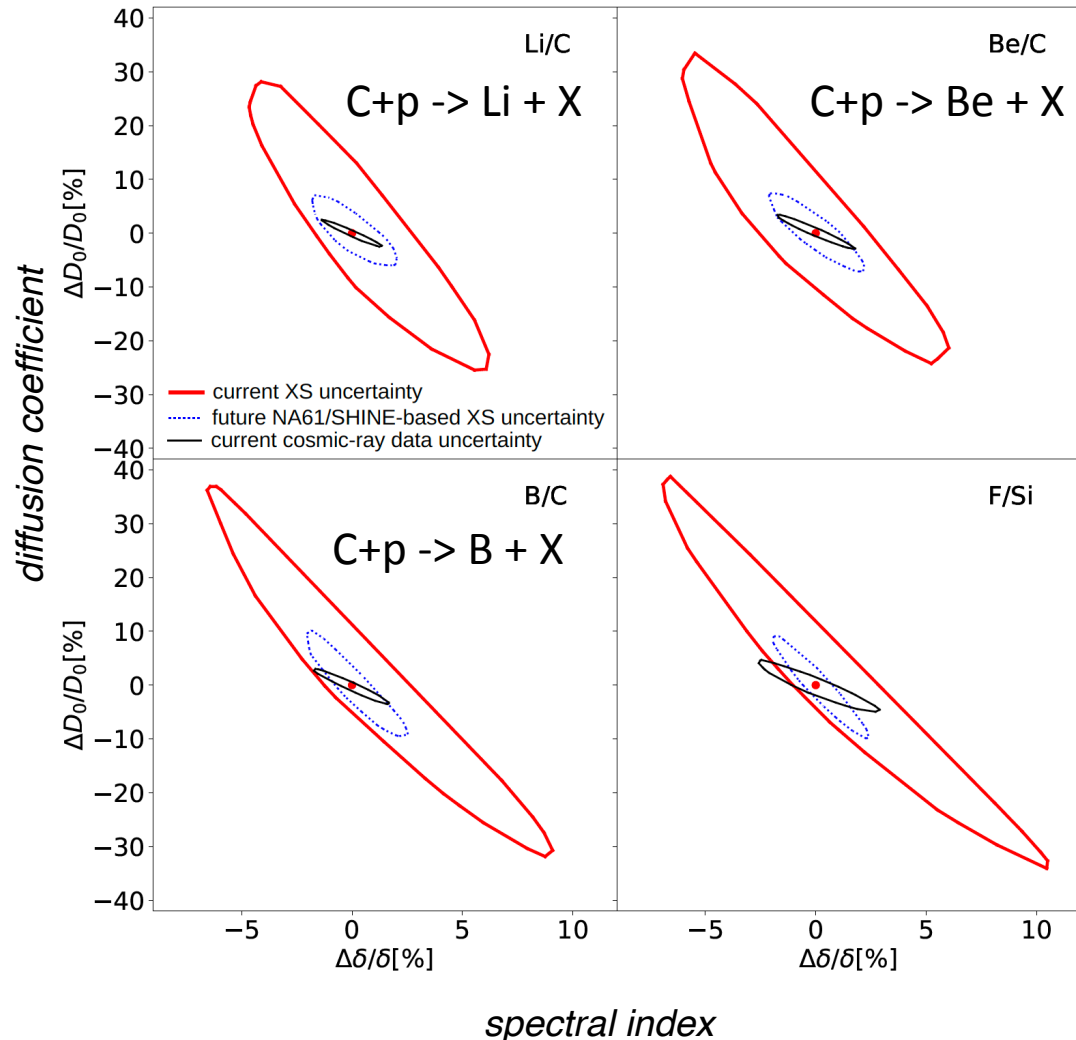


## Preliminary results

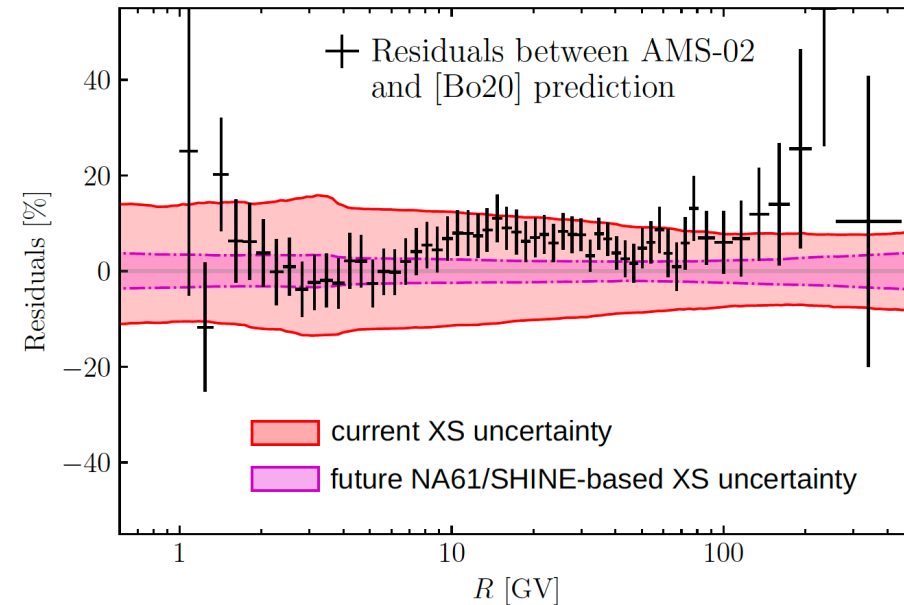
- a small stat. 2018 pilot run on C+p interactions at 13.5A GeV/c (20k interactions on C projectiles)
  - Measurement of <sup>11</sup>B and <sup>10</sup>B production cross-sections: [PoS ICRC2023 \(2023\) 075](#)
    - c.f. Already derived total B production ([PoS ICRC2019 \(2020\) 446](#)) and <sup>11</sup>C production ([PoS ICRC2021 \(2021\)](#))
- The technique to extract interactions on proton from C and PE has been established
- **One week of data (4 x 10<sup>5</sup> total interactions) will give a future big boost**

# Cosmic-Ray Physics: Impact of new NA61/SHINE nuclear fragment data

Reduction of transport parameter uncertainties  
by future measurements



anti-proton flux with the proposed measurements



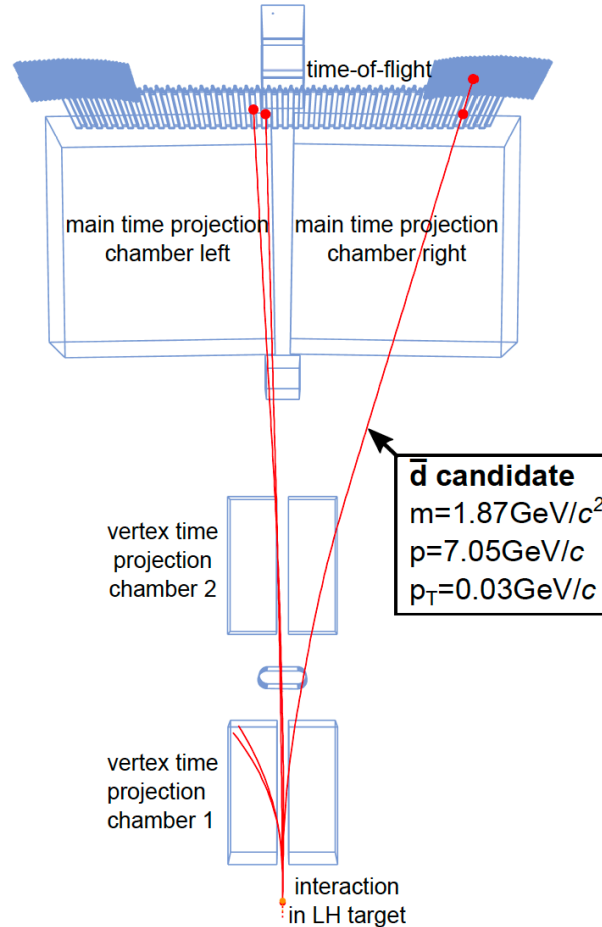
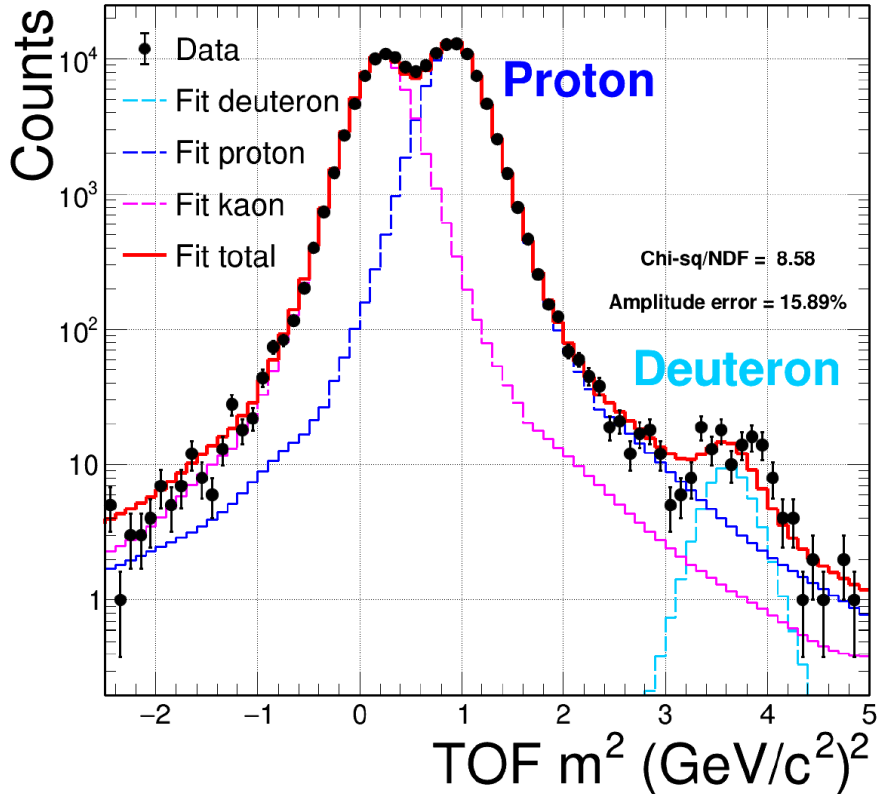
## Prospects with future NA61/SHINE data

- The flux ratios of secondary to primary cosmic-ray are a key observable for Galactic cosmic-ray physics
- Drastic improvement in transportation model and flux prediction uncertainties
  - precise understanding of cosmic-ray propagation
  - understanding of Li-excess and F-anomaly
  - improved prediction of astrophysical anti-proton
  - improved determination of cosmic-ray halo size of Milky Way

# Cosmic-Ray analysis in progress : (anti-)deuteron production in p+p at 158 GeV/c

Data-driven template fit on a  $(p, p_T)$  bin

Vol 4, +ve,  $[p, p_T] = [6.0 - 8.0, 0.0 - 0.5]$  (GeV/c)



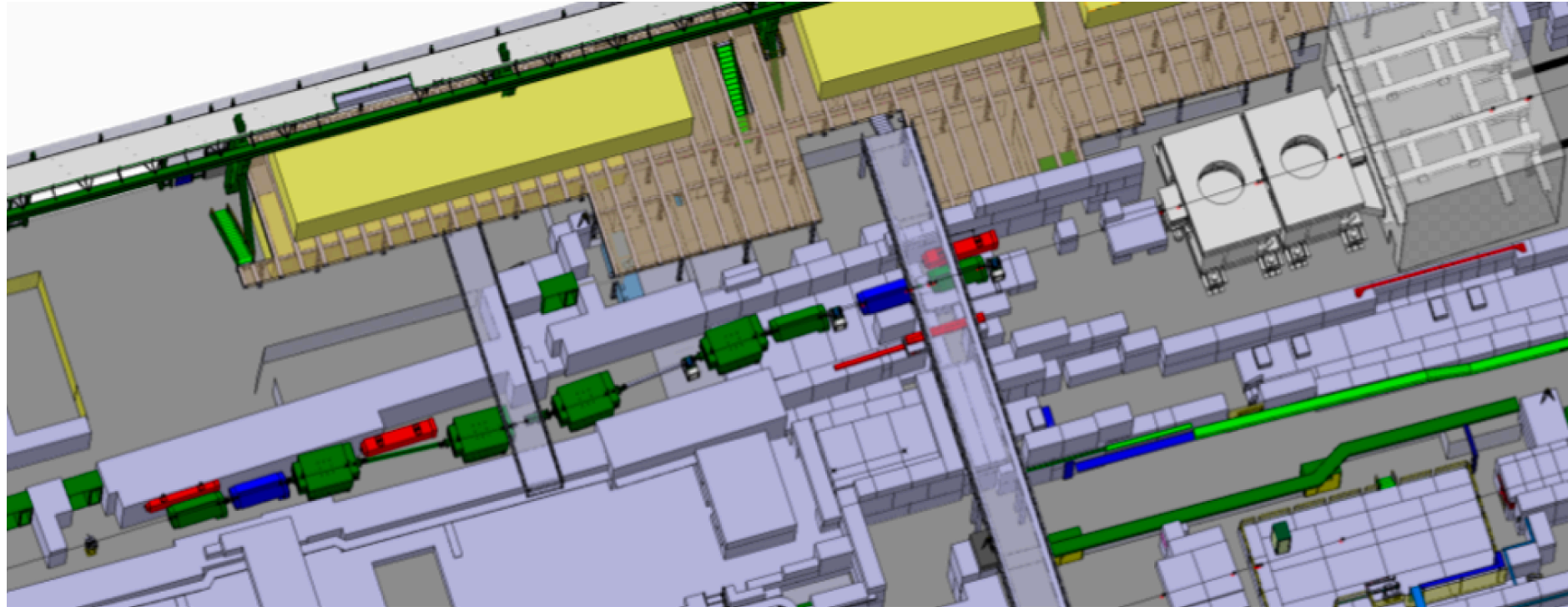
## Promising result

- Study anti-deuteron production for understanding the origin of AMS-02 cosmic anti-deuteron event
- Using recorded 50M events
  - Confirmed deuteron peak in data
    - First step to understanding anti-nuclei production
  - Identified anti-deuteron candidates
    - Stat. was low, future high-statistics data taking is necessary
      - **Plan to record 600M p+p events at 300 GeV/c**



## Charged hadron beams down to 2 GeV/c

- Opens up many new physics opportunities beyond current program
- Design and feasibility studies of the H2 branch beamline completed



# Low-E Beams: Physics Motivation

## Accelerator-based neutrino experiments

- Long-baseline: T2K, Hyper-K, LBNF/DUNE
- Short-baseline: **Booster Neutrinos (SBND, MicroBooNE, ICARUS)**

## Atmospheric neutrino experiments

- Sub-GeV and Multi-GeV neutrinos: Super-K, Hyper-K, DUNE

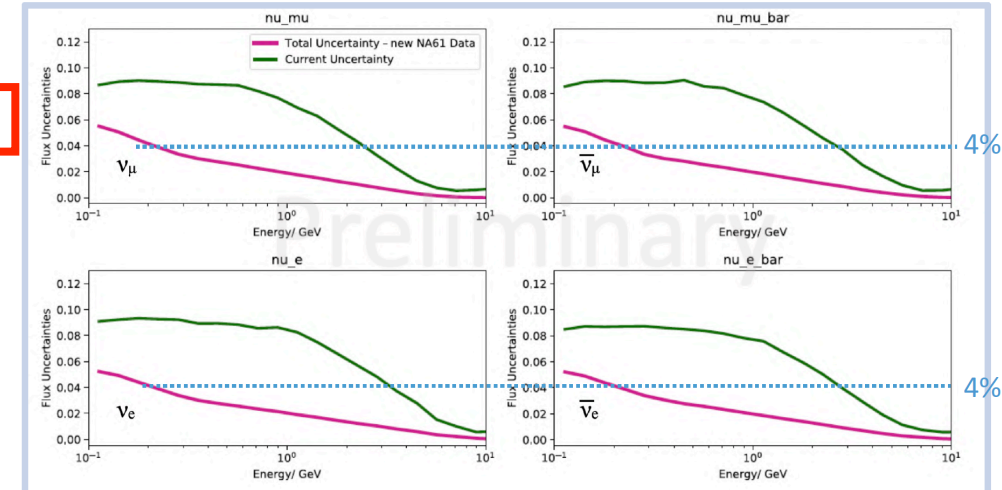
## Spallation neutron source neutrino experiments

- **JSNS<sup>2</sup> at J-PARC MLF (sterile neutrino search)**
- COHERENT at ORNL (coherent elastic neutrino scattering)

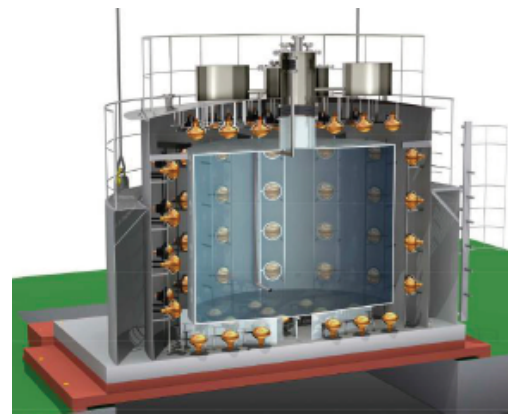
## Muon experiments

- COMET at J-PARC (muon to electron)

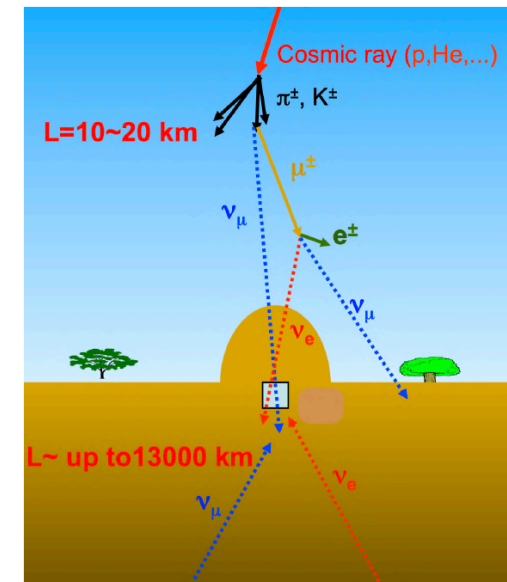
## Reduction on atmospheric neutrino flux uncertainty



Fermilab short-baseline



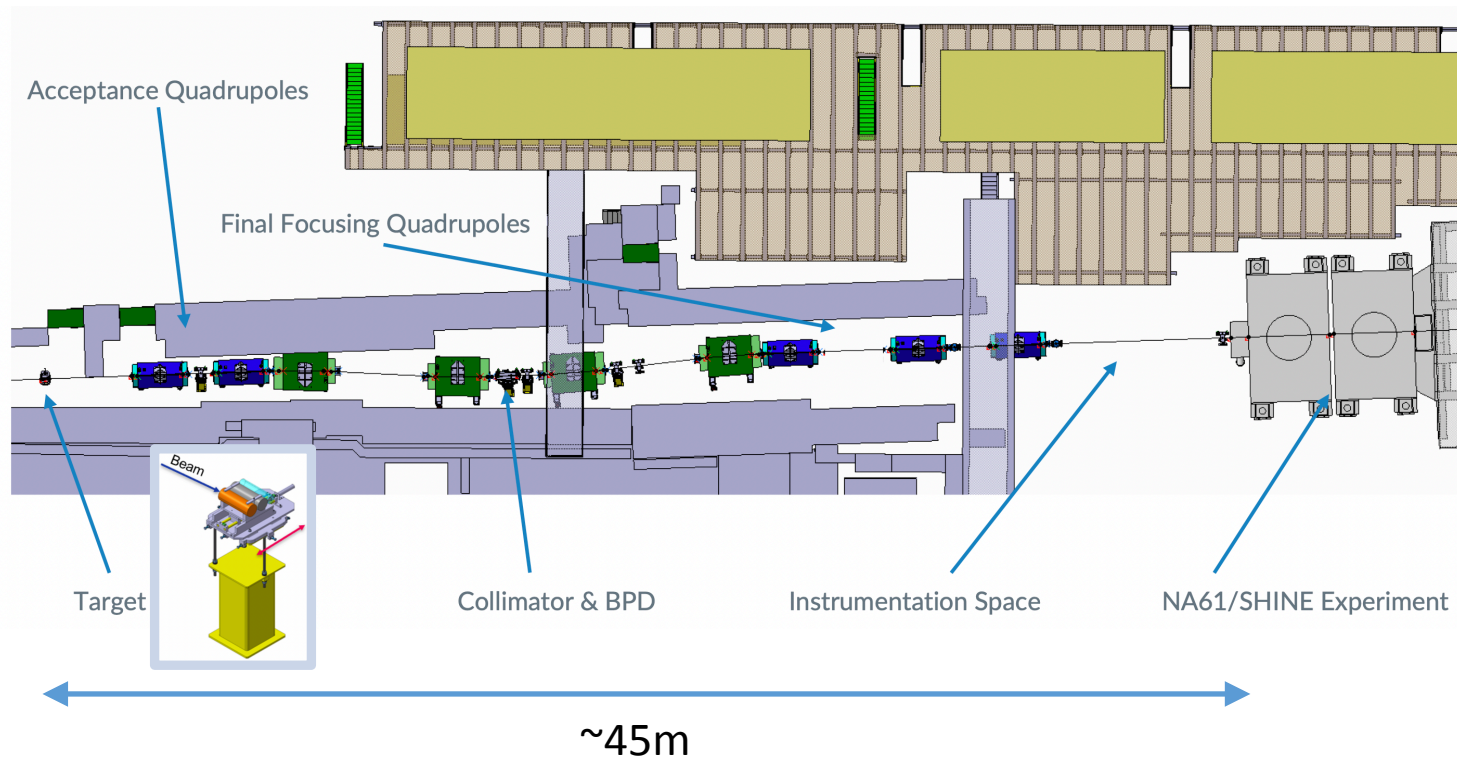
JSNS<sup>2</sup> experiment



**Two high-priority physics cases**

# Low-Energy Beamline Project

- A project to build a new branch of the H2 beamline to deliver low-energy hadron beams
- Low-Energy = 2-13 GeV/c (>13 GeV/c can be covered by the current beamline configuration)



- Several groups (Japan, UK, and US) expressed interest in measurements with low-energy beams
  - Discussion ongoing to join NA61/SHINE as limited member institutes



# Low-Energy Beamline Project

" [the minutes of the 146th meeting of the SPSC](#) (2022)  
7.2 NA61 low energy beam line  
The SPSC recognizes the scientific value of the improvements that the low-energy beamline could bring to the knowledge of the neutrino cross sections and recommends that the corresponding technical feasibility be studied in detail.  
"

## Engineering Change Request (2023)

CERN  
Eplanade des Particules 1  
P.O. Box  
1211 Geneva 23 - Switzerland

EDMS NO. **2803011** REV. **0.3** VALIDITY **DRAFT**

REFERENCE  
**SPSX-L-EC-0009**

Date: 2023-08-24

ENGINEERING CHANGE REQUEST

**H2-LE: NEW TERTIARY BRANCH OF THE H2 BEAM LINE FOR LOW-ENERGY PARTICLE BEAMS**

BRIEF DESCRIPTION OF THE PROPOSED CHANGE(S):

This document describes the necessary changes to install a new tertiary branch of the H2 line (designated H2-LE), to be located in PPE132-142-152 zones in EHN1, in front of the NA61/SHINE TPC hut. New magnets and new beam instrumentation will need to be installed. The existing power supplies powering the H2-VLE line of the neutrino platform, will be used to power the new magnets. Extra shielding needs to be installed, as well as rail systems that will allow the transition between the existing H2 line and this low-energy configuration. In this ECR, the new configuration is described, as well as its necessary cost breakdown.

DOCUMENT PREPARED BY:	DOCUMENT TO BE CHECKED BY:	DOCUMENT TO BE APPROVED BY:
Carlo Musolino Nikolaos Charitonidis	Johannes Bernhard, Philippe Boisseaux-Bourgeois, Miguel Diogo dos Santos, Aboubakr Ebn Rahmoun, Ramon Folch, Sylvain Girod, David Jaillet, Michael Lazzaroni, Bastien Rae, Giulia Romagnoli (BE/EA), Sylvain Fumey (EN/HE), Christelle Gaignant (BE/ASR), Yves Gaillard, Xavier Genillon (SY/EPC), Marek Gazdzicki, Seweryn Kowalski, Yoshikazu Nagai (EP/UFT), Guillaume Gros (EN/EL), Jani Lehtinen (EN/CV), Philip Schwarz (TE/MSC), Jocelyn Tan, Inaki Ortega-Ruiz (SY/BI), D. Vaxelaire (EN/AA), Camille Vendeuvre (BE/GM)	M. Brugger for BE-EA IEFC EATM

DOCUMENT SENT FOR INFORMATION TO:

SUMMARY OF THE ACTIONS TO BE UNDERTAKEN:

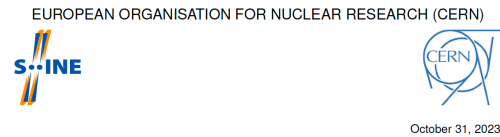
**This ECR is not for immediate implementation, and only the technical aspects are here-in discussed. The planning & resources aspects are subject to approval by the relevant CERN committees.**

Install a new tertiary branch of the H2 line (H2-LE):

- Install new magnets and new beam instrumentation.
- Connect existing power supplies.

Note: When approved, an Engineering Change Request becomes an Engineering Change Order.  
This document is uncontrolled when printed. Check the EDMS to verify that this is the correct version before use.

## Memorandum to SPSC(2023)



Memorandum to the SPSC:  
Answer to the request raised in the minutes of the 146th meeting of the SPSC regarding the Low Energy Beam project

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

In response to the last SPSC minutes, this document provides information regarding the final design of a low-energy beamline, technical details for beamline engineering, and the status of R&D related to the low-E beam instrumentation.

CERN-SPSC-2023-034 / SPSC-M-795  
01/11/2023

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## Technical feasibility studies complete

- In response to the minutes of the SPSC
  - Details on the necessary changes are given in ECR
  - Summarized in the memorandum
- Switching between high-E and low-E operations within at most 2-3 days
- Total cost: **706.5-967.2 kCHF**
  - In-kind contribution
    - Beam instrumentation (Japan, 120 kCHF)
    - Vacuum hardware (USA, under discussion)



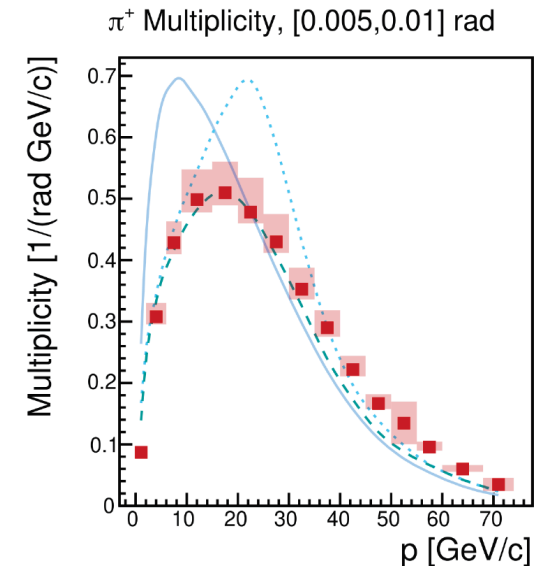
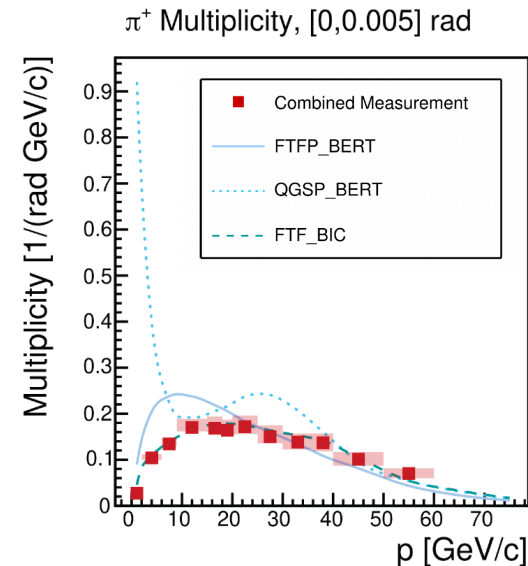
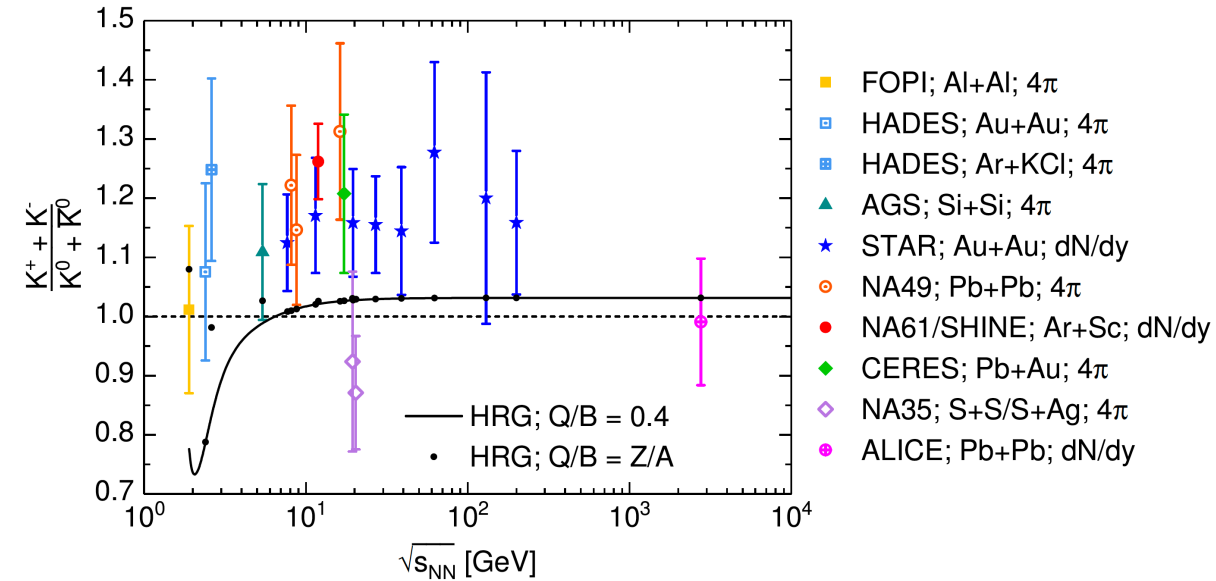
# Summary: Physics Results

## Datasets collected

- Strong interaction physics
  - Pb+Pb: 30M events (2022) + 150M events (2023)
- Neutrino and cosmic-ray physics
  - Fermilab neutrino physics: > 250M events (2023)
    - k+C at 60 GeV/c
    - p+Ti and p+C at 120 GeV/c

## New physics results

- Strong interaction physics results on p+p, Xe+La, and Ar+Sc interactions
- hadron production in p+C interactions
- nuclear fragmentation in C+p interactions



# Summary: Requests to SPSC

## 2024 beam request

- **Primary oxygen beam**
  - **Four days at 150A GeV/c**
    - **Test:** post-LS3 measurements with light ion beams, nuclear fragmentation cross-section
    - [SPSC-P-330-ADD-13](#), [SPSC-P-330-ADD-14](#)
- **Secondary proton and hadron beams**
  - **Four weeks of proton beam at 120 GeV/c**
    - **Physics:** hadron yield measurements with a DUNE replica target
    - [SPSC-P-330-ADD-10](#) (Section 8), [SPSC-SR-336](#) (Section 6.1)
  - **Two weeks of hadron beam at various momenta**
    - **Test:** PSD calibration, liquid hydrogen target operation, commissioning before lead run
    - [SPSC-SR-336](#) (Section 6.1)

## • **Lead beam**

- **One week of fragmented Pb beam at 13A GeV/c**
  - **Physics:** nuclear fragmentation cross-section
  - [SPSC-P-330-ADD-10](#) (Sec.7), [SPSC-SR-336](#) (App.A)
- **Three weeks of Pb beam at 150A GeV/c**
  - **Physics:** charm production in Pb+Pb collisions
  - [SPSC-P-330-ADD-10](#) (Section 4), [SPSC-M-792](#)

## Post-LS3 light ion beams

- **We request an SPSC recommendation for light ion beams**
- [SPSC-P-330-ADD-14](#)

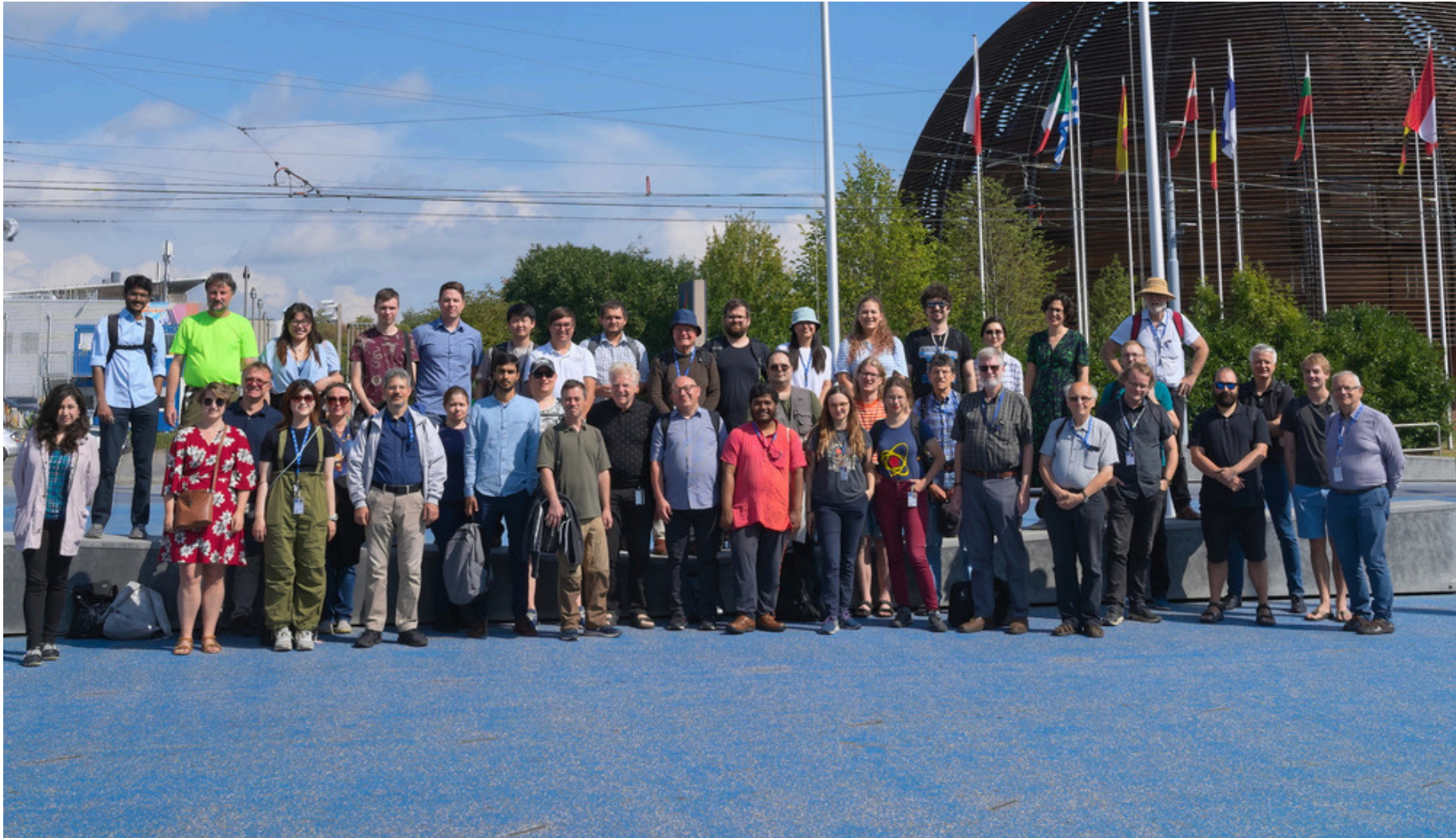
## Low-Energy beamline

- **We request an SPSC recommendation to be proposed for the Research Board approval for YETS 24-25 construction**
- [SPSC-P-330-ADD-12](#), [SPSC-M-793](#), [SPSC-M-795](#)

We also plan measurements with lead and hadron beams in 2025

**We would like to thank the CERN EP, BE, HSE, and EN Departments for their strong support of NA61/SHINE**

# Thank you for your attention!



<http://shine.web.cern.ch>



# The NA61/SHINE Collaboration

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## Germany

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W. Rauch
- **University of Frankfurt**  
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H. Ströbele, A. Toia

## Switzerland

- **University of Geneva**  
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A. Bravar
- **CERN**  
CERN, Geneva, Switzerland  
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# Backup

# Analyses in Progress

## p+C at 60 GeV/c (Fermilab)

- 2016 dataset
  - no FTPCs
- Reported preliminary result in 2021 SPSC report
  - Found a discrepancy in neutral hadron yields compared to other momenta
    - Addressing the problem
- Plans: neutral and charged hadron yields

## p+C at 90 GeV/c (Fermilab)

- 2017 dataset
  - with FTPCs
- Trigger issue prevents extraction of total cross-section
  - a dedicated dataset collected in July 2023
- Plans: neutral and charged hadron yields

## p+NOvA target at 120 GeV/c (Fermilab)

- 2018 dataset
  - with FTPCs
- Data calibration in progress
- Plans: charged hadron yields

## p+T2K target at 31 GeV/c (J-PARC)

- 2022 dataset
  - with FTPCs
  - with upgraded DAQ
- Data calibration in progress
- Plans: neutral and charged hadron yields

## p+C at 90 GeV/c (Fermilab)

- 2023 dataset
  - magnet off
- A dedicated dataset for total cross-section
- Plans: extract total cross-section

# 2025 plans

## Physics with lead beams

- **Open charm measurements:**
  - **Physics:** four weeks of Pb beam at 150A GeV/c

## Physics with hadron beams

- **Low-energy hadron beams for neutrino physics:**
  - **Construction:** beamline deployment during the YETS 24-25
  - **Commissioning:** one-week pilot run
  - **Physics:** several weeks dedicated to SBN at Fermilab and JSNS<sup>2</sup> at J-PARC
- **Proton beam at 300 GeV/c for cosmic-ray physics:**
  - **Construction:** MRPC ToF-R detector before data taking
  - **Commissioning:** one-week pilot run
  - **Physics:** several weeks dedicated for anti-deuteron production