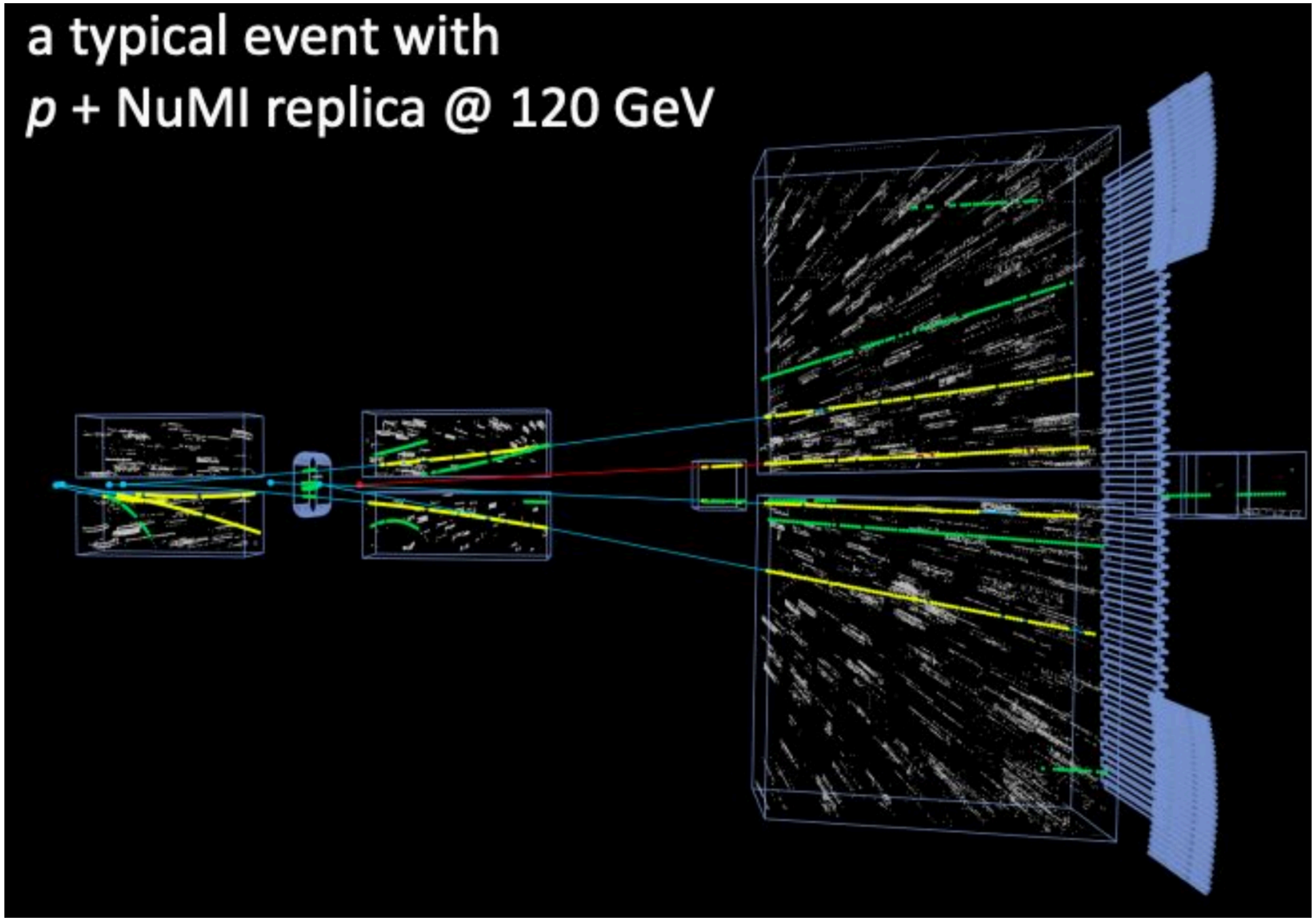


NA61/SHINE Status Update: Neutrino/Cosmic Ray Physics and Requests/Future Plans

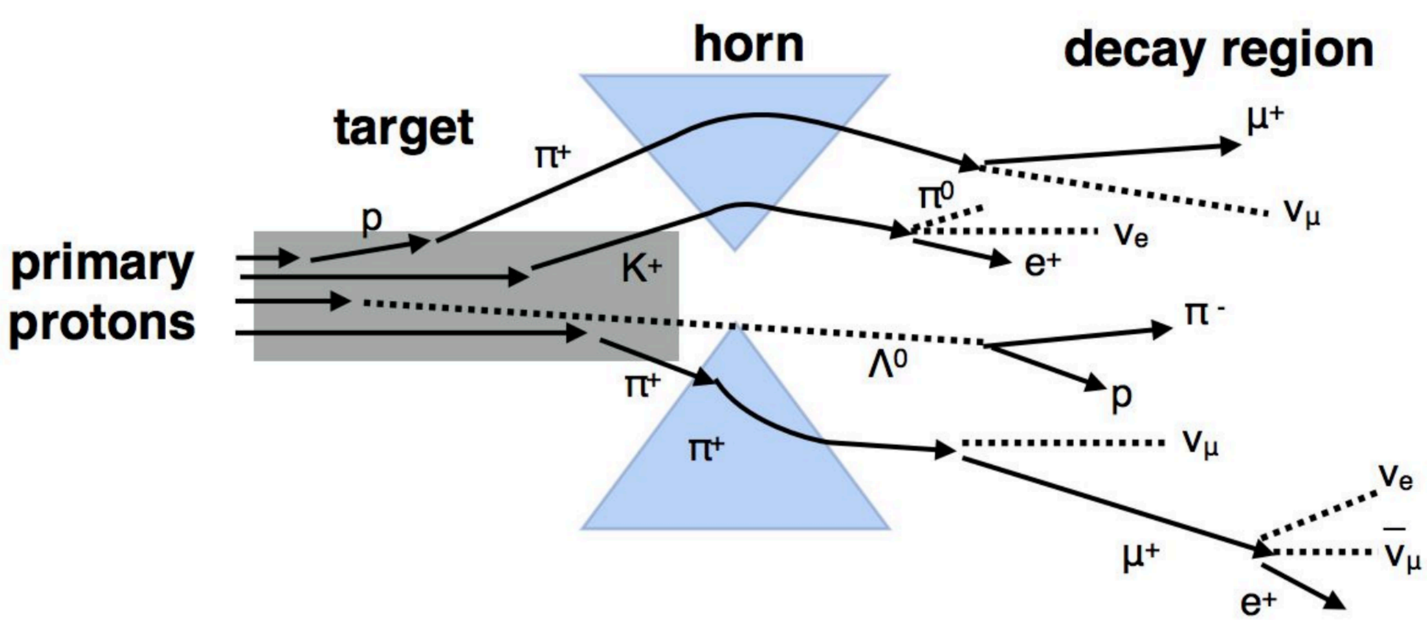
Laura Fields (Fermilab)

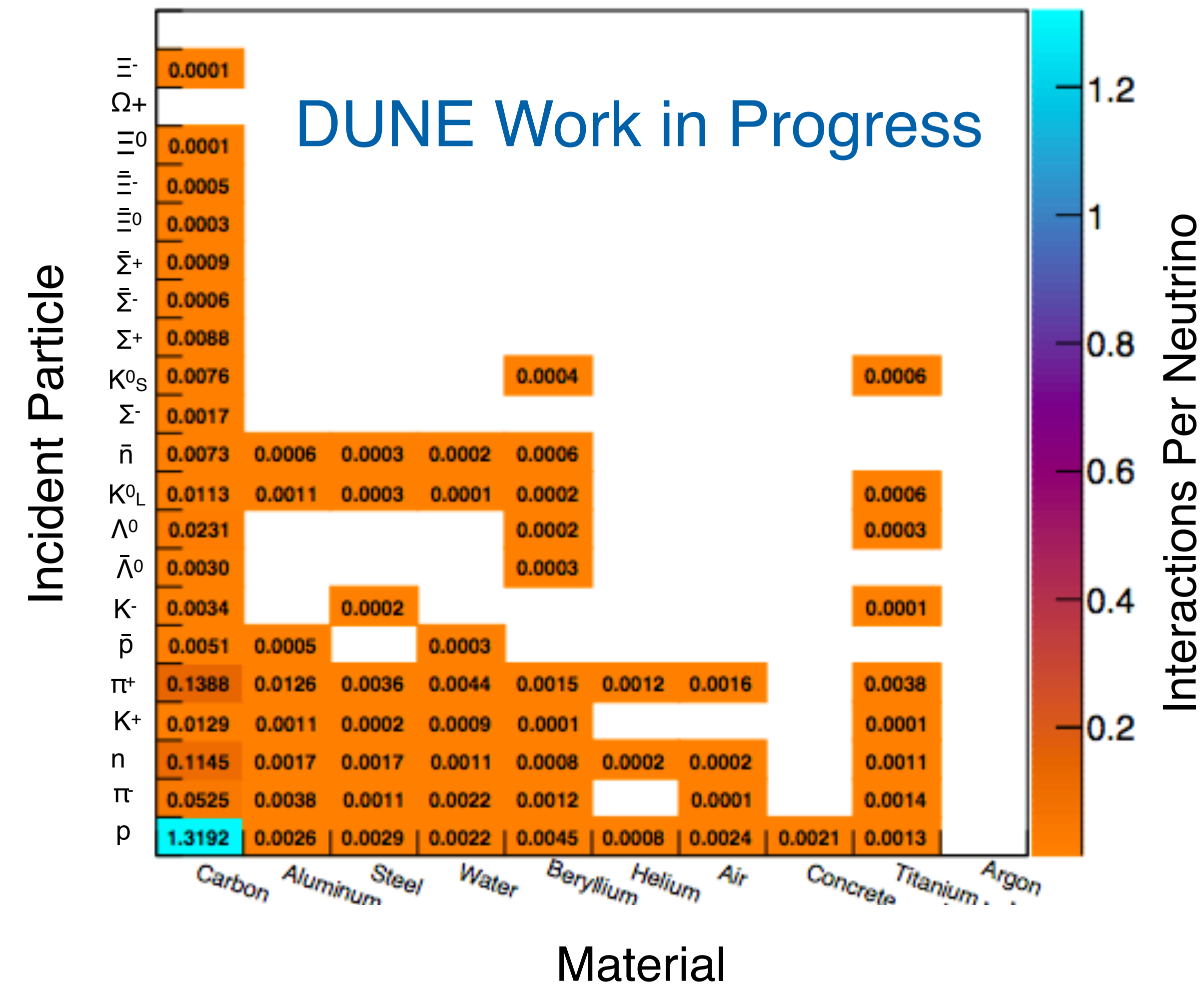
13 October 2020

Recent Results: Neutrino and Cosmic Ray Program

Why Neutrinos Need NA61/SHINE

- Neutrino Experiments (e.g. NOvA, T2K, DUNE, and Hyper-K) need to know the **kinematics of particles from our targets** to predict the neutrino flux through our detectors:

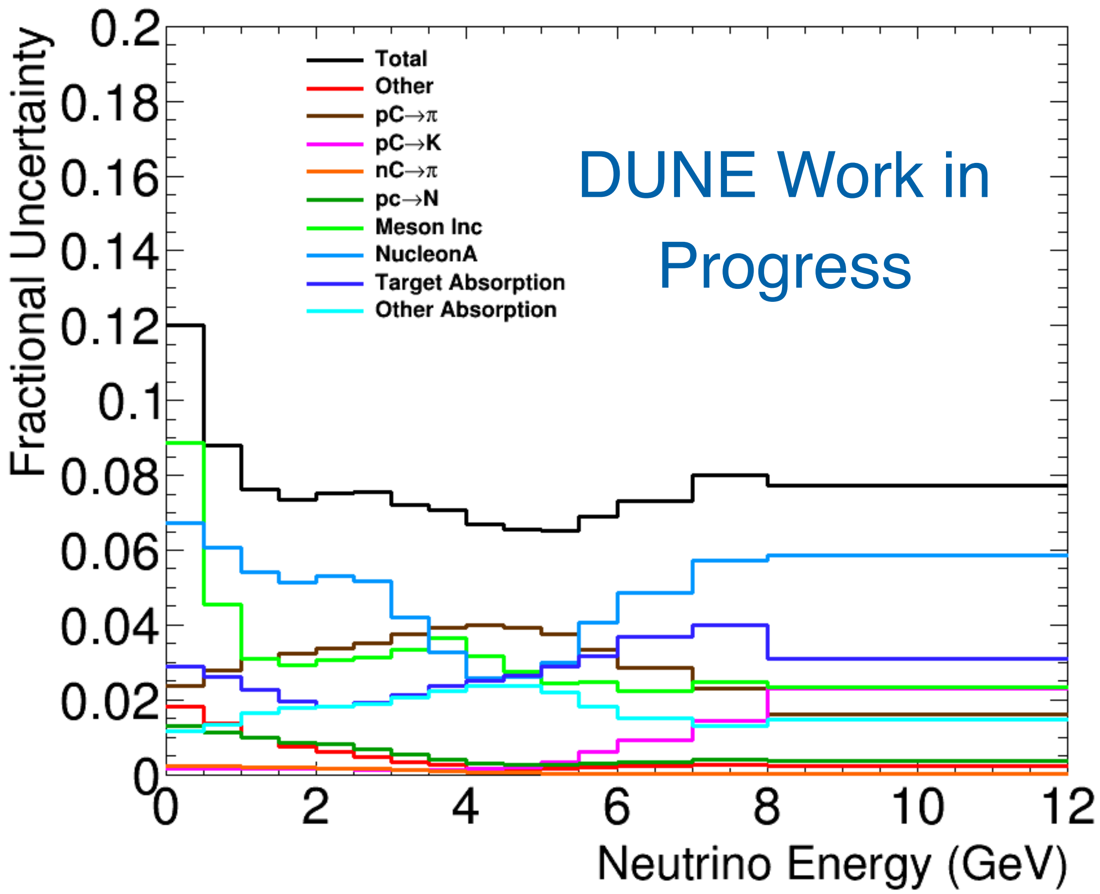


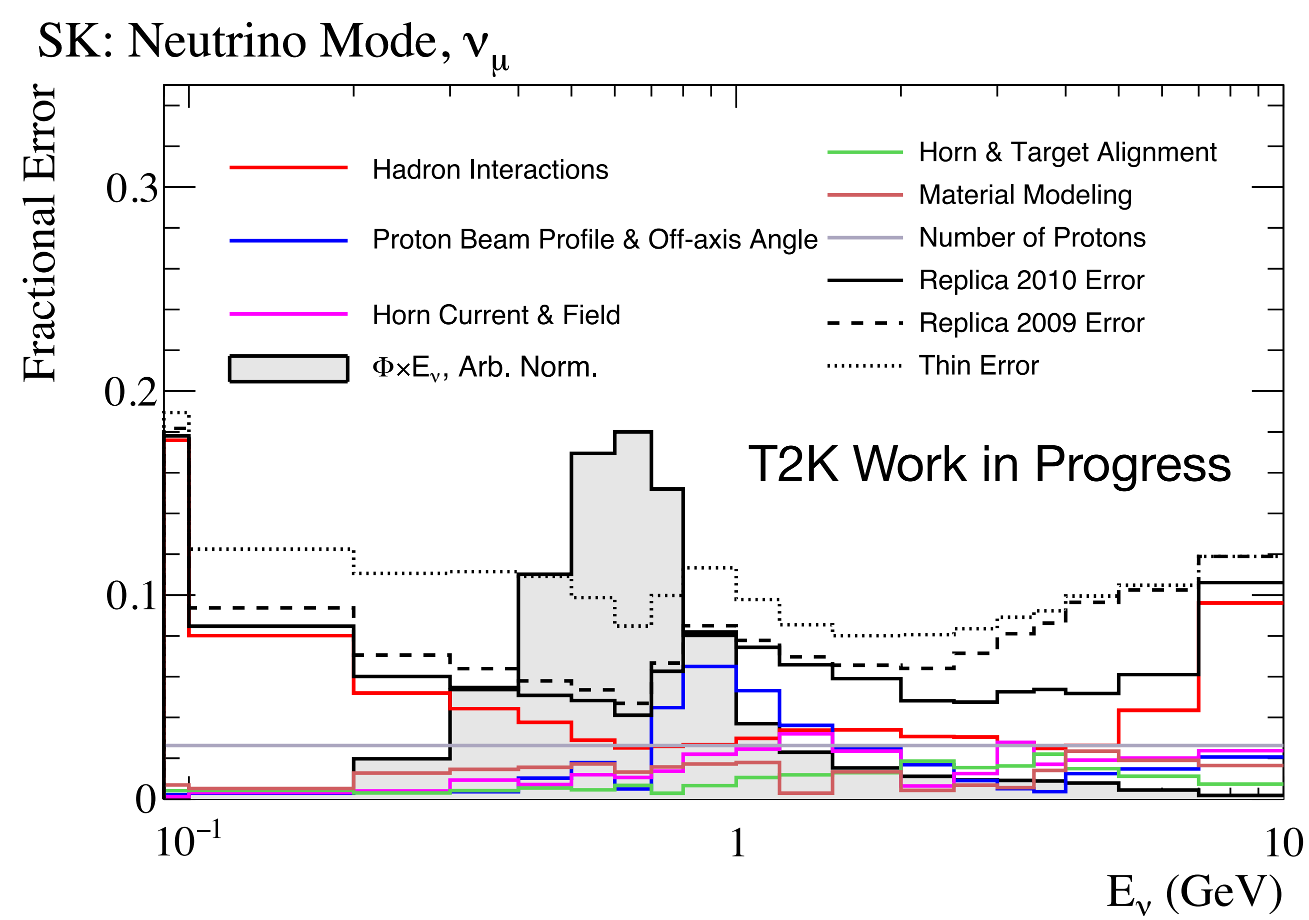


Knowledge of **Hadronic Interactions** in target and other materials is limiting uncertainty.
Cannot be precisely predicted by theory → **Need measurements** of all beamline interactions.

Why Neutrinos Need NA61/SHINE

- As much as we need to know our neutrino flux, we need to know **how accurate our flux predictions** are:



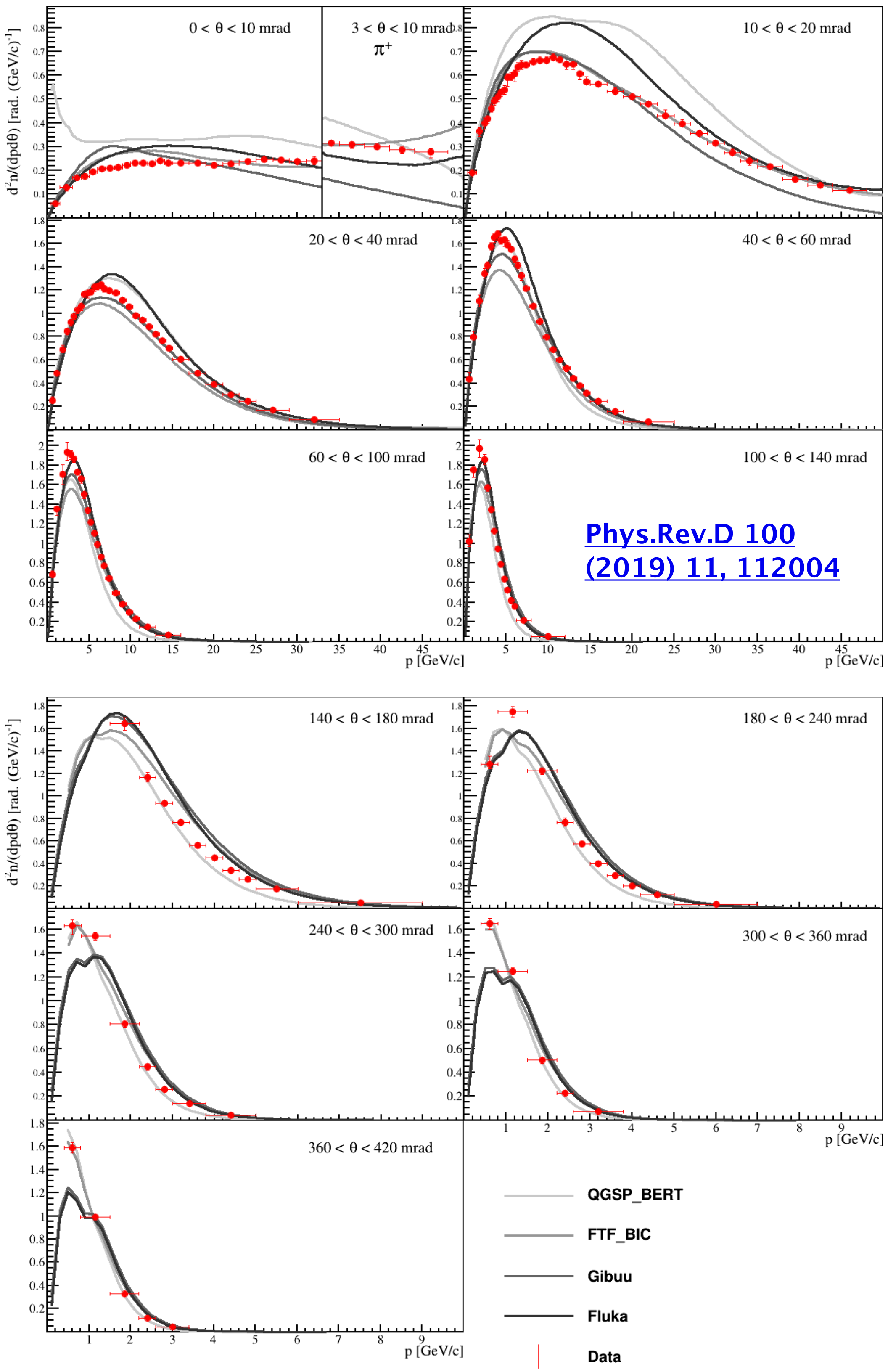


Every hadronic interaction that happens in a neutrino beamline introduces flux uncertainty.

40% of interactions creating neutrinos in DUNE are **unconstrained by data** and yield large uncertainties

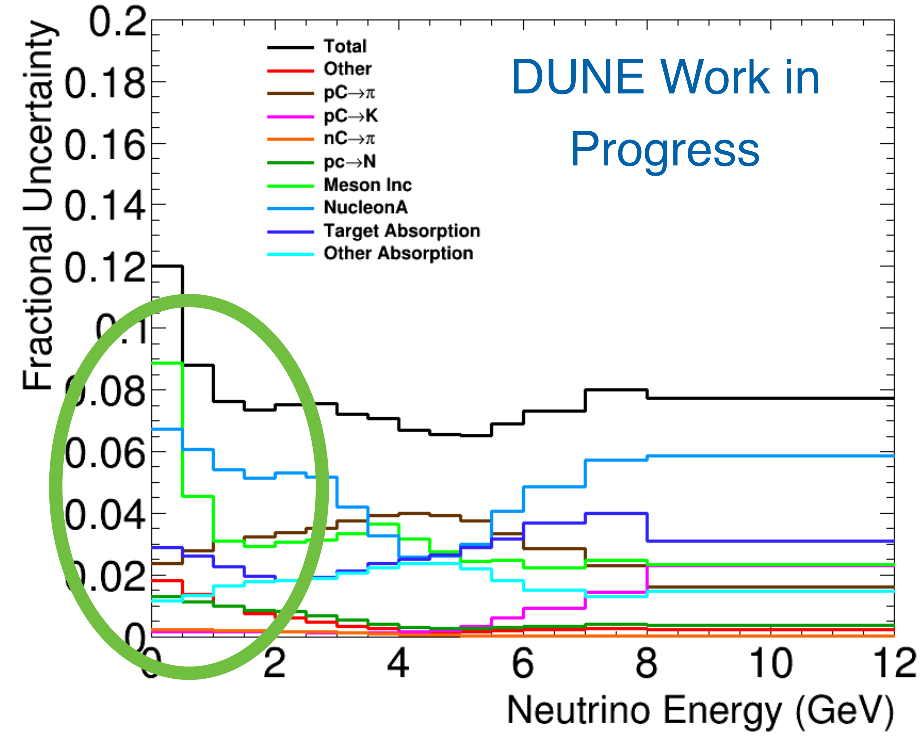
NA61's Neutrino Program is aimed at making these uncertainties both **lower and more reliable**.

Recent Results: Thin Target Measurements for Neutrinos



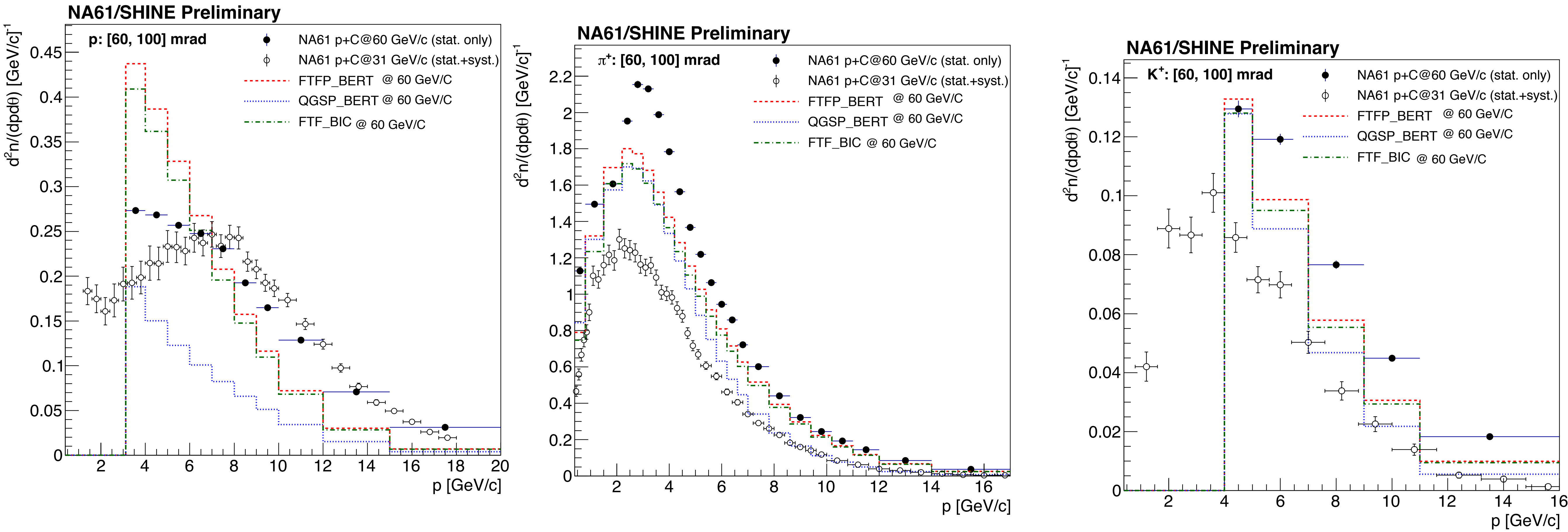
Phys.Rev.D 100 (2019) 11, 112004

Published differential cross sections for π+ on Carbon at 60 GeV/c, compared with two Geant4 physics lists, Gibuu, and Fluka



Will allow **substantial reduction of the 40% uncertainties** currently assumed for these processes by DUNE, NOvA, and MINERvA

Recent Results: Thin Target Measurements for Neutrinos



- New preliminary differential hadron yields for **60 GeV protons on Carbon**
- Will be a critical **test of energy scaling** in Fermilab neutrino beam simulations
- A similar analysis of **120 GeV protons is ongoing**
  - All of these measurements will provide critical covariance matrices absent from older data

Recent Results: Thick Target Measurements for Neutrinos

The **best way** to constrain neutrino flux uncertainties is through measurements with **replica targets**

NA61 data using a replica of the T2K target has produced **world-leading flux uncertainties**.

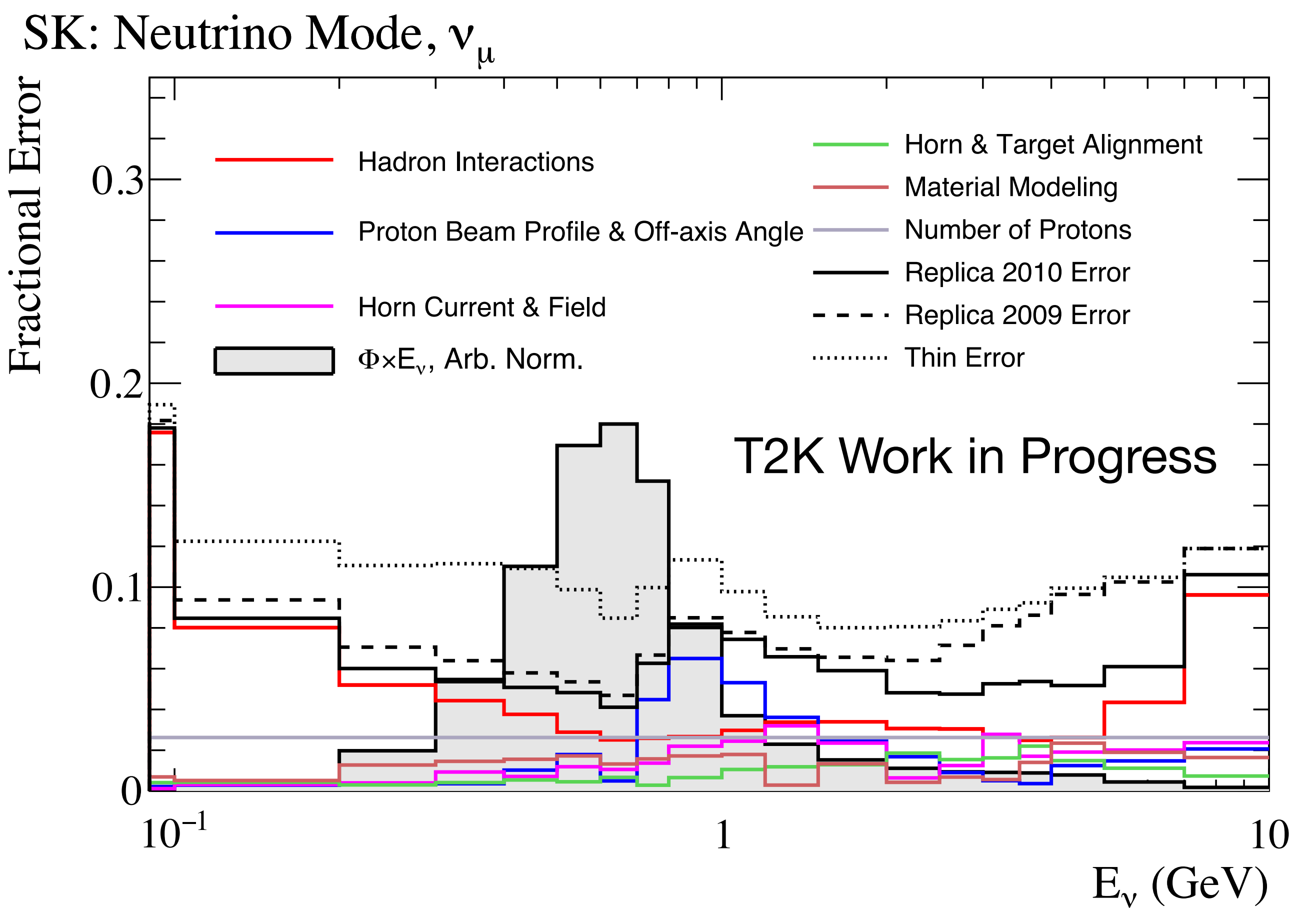
Additional measurements can **further reduce** these uncertainties.

This year, we finalized a measurement of the **total production cross section**:

$$\sigma_{\text{prod}} = 227.6 \pm 0.8(stat)\,^{+1.9}_{-3.2}(sys)\ -0.8(mod)\ mb.$$

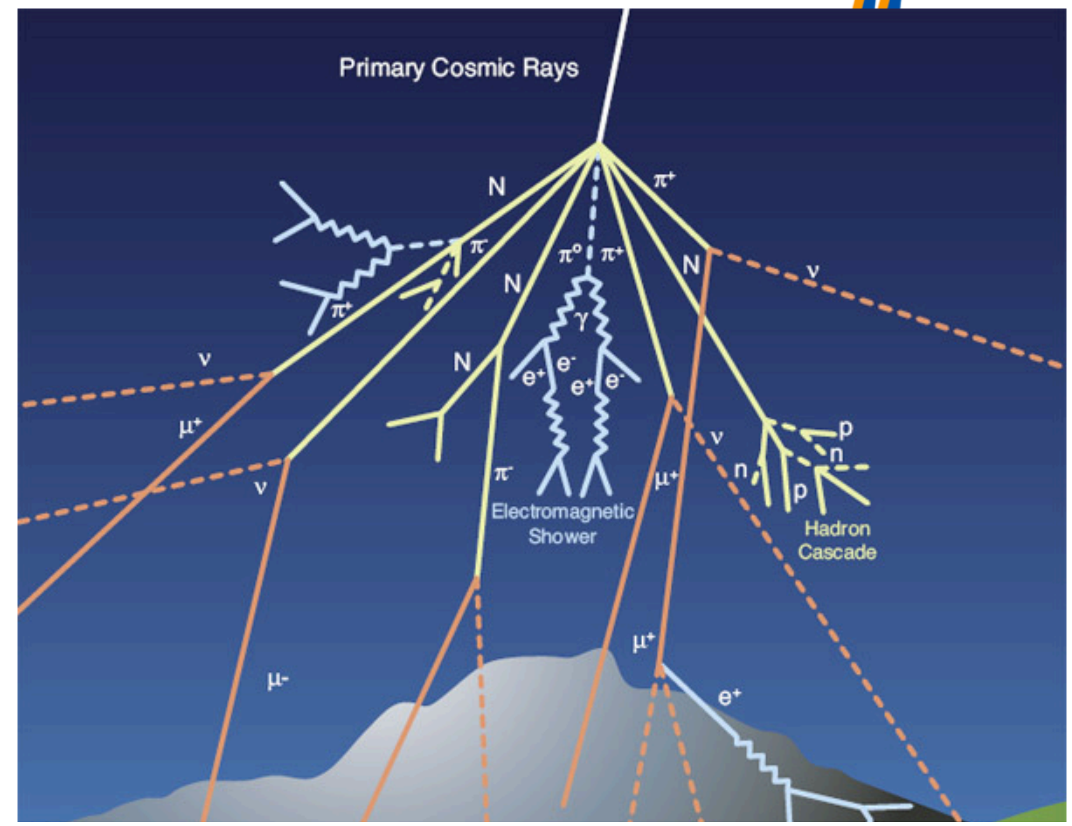
A publication is in preparation.

90 cm T2K Replica Target

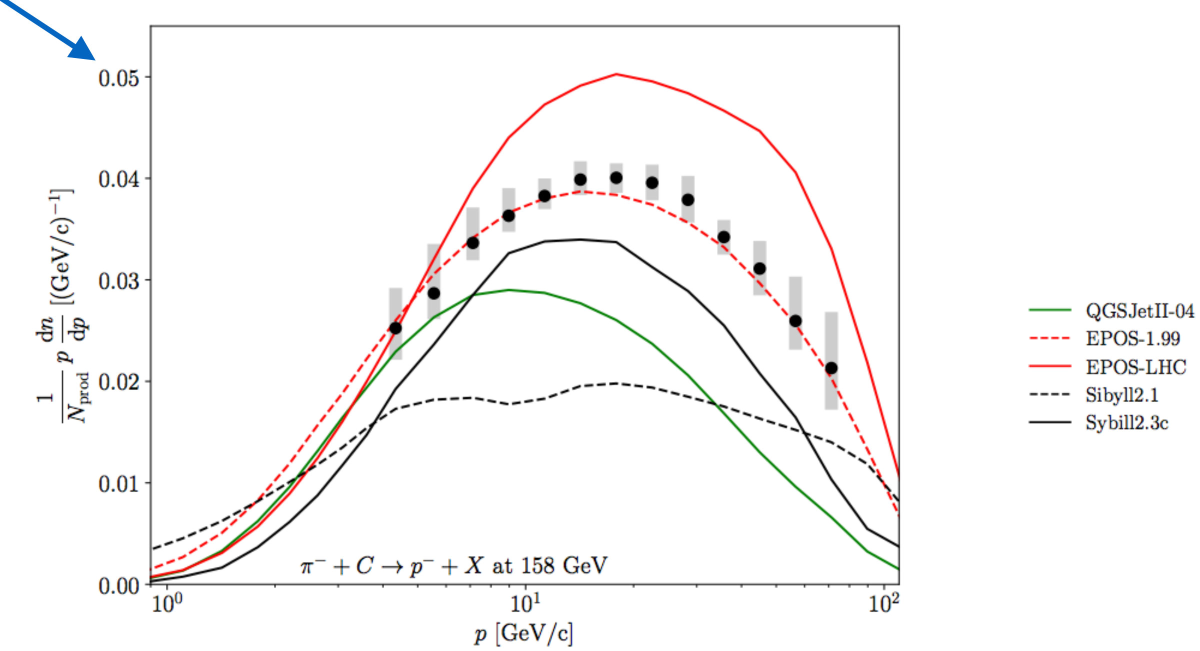


Recent Progress: Measurements for Cosmic Ray Physics

- NA61/SHINE is able to measure processes that occur in **cosmic ray air showers** and during **generation/propagation of galactic cosmic rays**
- Recent Progress:
  - Finalizing paper on cross sections of **158 and 350 GeV pions** on carbon
  - Ongoing analysis of **proton, antiproton, pion, and kaon production** in p+p interactions (important for modeling light anti-nuclei production, a background in dark matter searches)
  - Analysis of a run that studied feasibility of **nuclear fragmentation measurements** relevant for Galactic cosmic rays

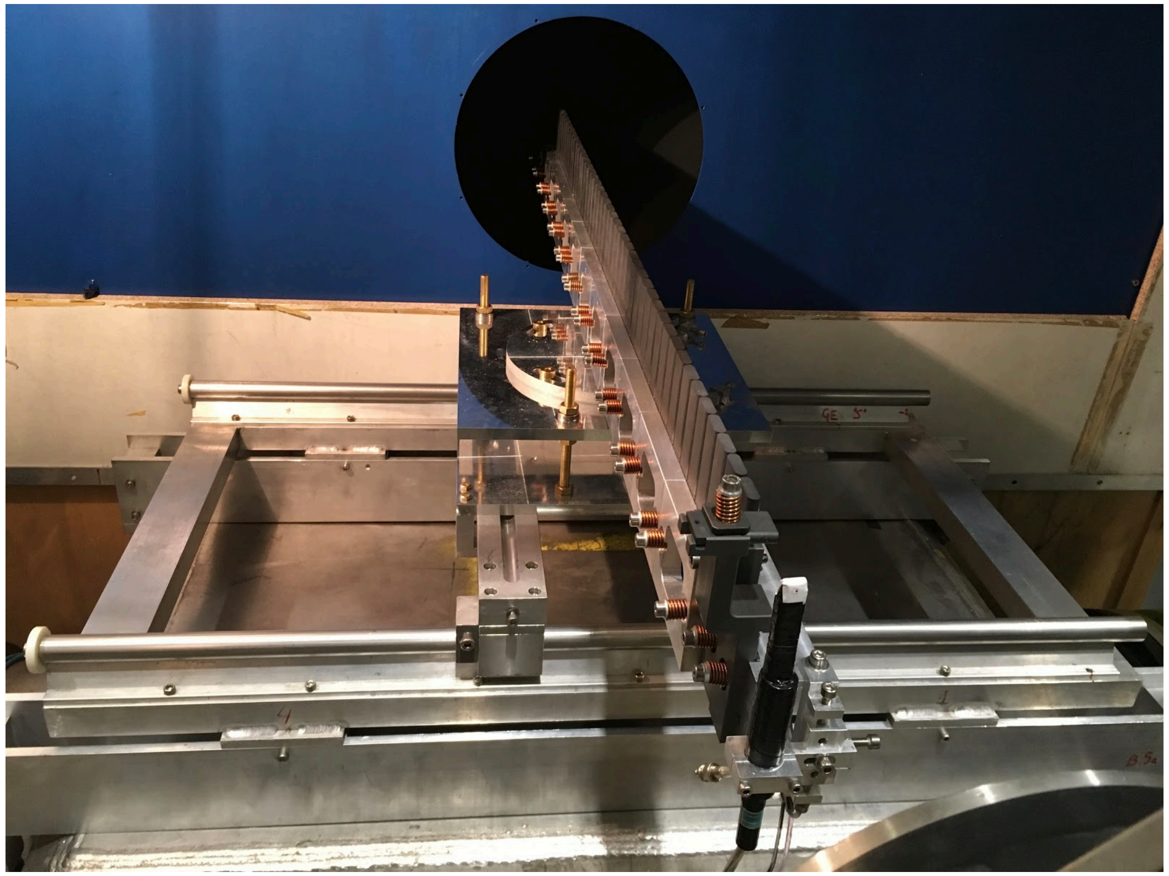


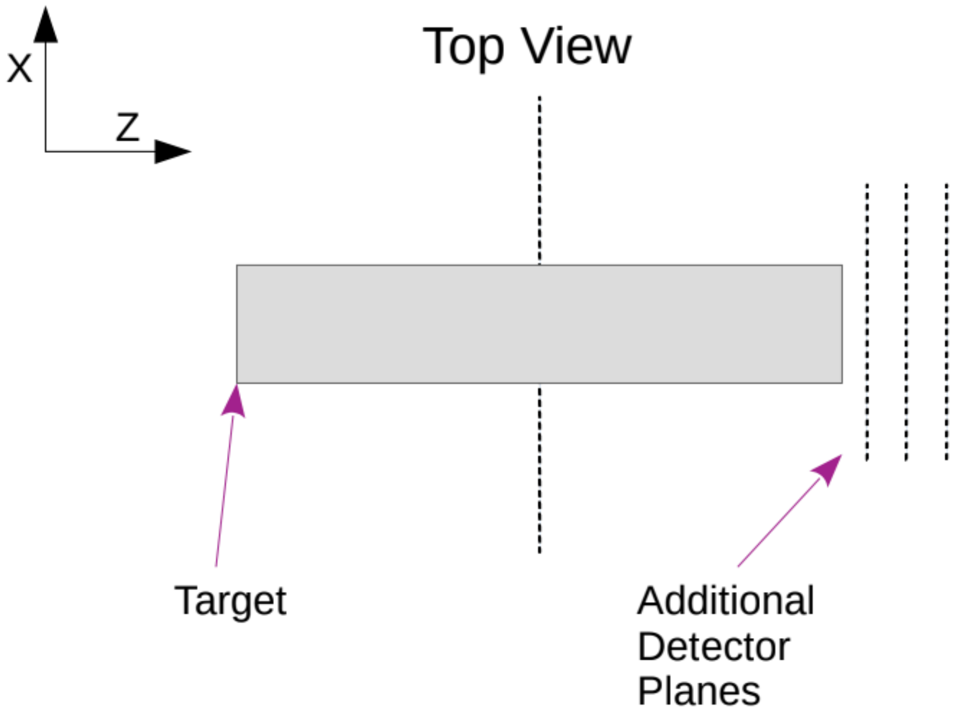
https://arxiv.org/abs/1909.07136



Neutrinos and Cosmic Rays: Ongoing Analyses

- Many **active analyses** in Neutrino and Cosmic Ray group
  - Completion of preliminary results
    - **120 and 60 GeV p+C** for Fermilab neutrino beams
    - Production of p, p̄, π, K in p+p, **nuclear fragmentation data** for cosmic ray physics





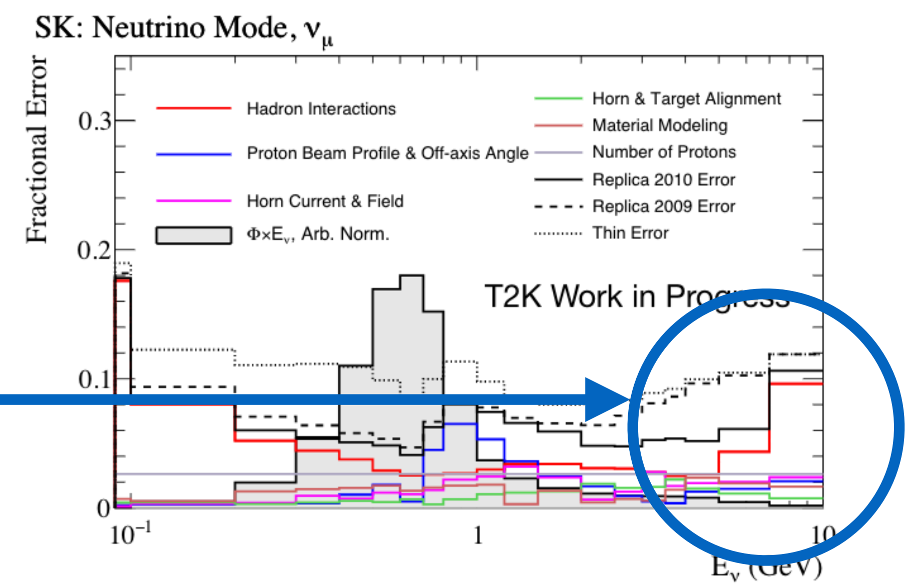
- Also beginning analysis of **NuMI replica target** data
- And studying options for **new tracking detector** for future DUNE (and other) replica target running

Requests and Future Plans for Strong Interaction, Neutrino and Cosmic Ray Measurements

Requests: 2021

- Our previously **requested and SPSC recommended run plan for 2021** has been modified given COVID-19 delays to the beam schedule:
  - Five weeks of **commissioning and calibration runs**:
    - (i) July 2021: two weeks of a hadron beam for the detector commissioning,
    - (ii) August 2021: one week of access for fixing uncovered issues,
    - (iii) September 2021: three weeks of a hadron beam for the detector commissioning and calibration runs.
  - Five weeks of **secondary hadron beams:**
    - (i) October/November 2021: 5 weeks of proton beam at 31 GeV/c for data taking for neutrino physics.

The five weeks of 31 GeV/c proton beam will be used for T2K replica target data, with the aim of increasing statistics for kaon yields, which dominates uncertainties in high energy tail



Requests: 2021

- We are **reiterating our request** for:
  - Four weeks of lead beams:
    - (i) November/December 2021: three weeks of Pb beam at 150 A GeV/c for **charm hadron measurements** in Pb+Pb collisions,
    - (ii) December 2021: one week of a secondary (fragmented) light-ion beam at 13 A GeV/c for **nuclear fragmentation** cross-section measurements.

Requests: 2022-2024

- We are also requesting a recommendation from the SPSC for measurements in **2022-2024, as detailed in Addendum 10**:
  - Physics with lead beams:
    - (i) 2022:
      - four weeks of **Pb beam at 150A GeV/c** for charm hadron measurements in Pb+Pb collisions,
      - two weeks of a **secondary light-ion beam at 13A GeV/c** for nuclear fragmentation cross-section measurements for cosmic-ray physics,
    - (ii) 2023: six weeks of **Pb beam at 150A GeV/c** for charm hadron measurements in Pb+Pb collisions,
    - (iii) 2024: six weeks of **Pb beam at 40A GeV/c** for charm hadron measurements in Pb+Pb collisions.

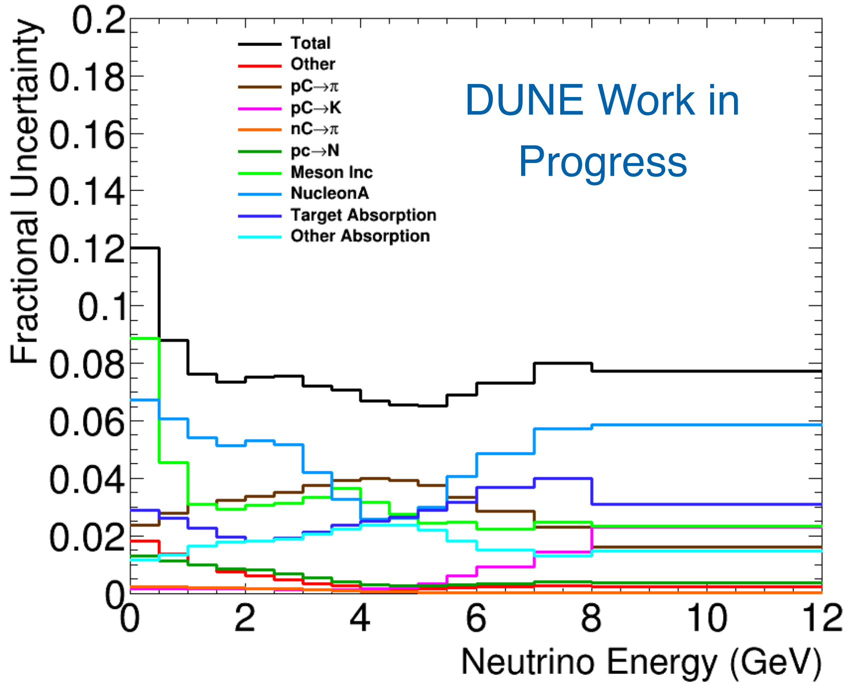
Requests: 2022-2024

- Request for 2022-2024, continued:
  - Physics with secondary hadron beams:
    - (i) 2022:
      - four weeks of **K+ beam at 60 GeV/c** for thin-target graphite cross-section measurements
      - four weeks of 120 GeV/c proton beam for **thin-target titanium** cross-section measurements,
    - (iii) 2023: four weeks of 120 GeV/c proton beam for measurements on a **LBNF/DUNE replica target**.

These will provide data constraints on as many interactions in the LBNF/DUNE beamline as possible.

Kaons dominate the neutrino flux above ~5 GeV

The target containment vessel will be made out of titanium



Future Plans: Low Energy Beam Improvements

- Several possible future NA61/SHINE measurements will require an **improvement of the quality of beams at low momenta** (below 40 GeV/c)
- Several options are being considered:
  - **Improvements to the ion emittance** from the machine
    - This requires studies from the machine side.
    - We are in discussions with EN-EA and BE-OP about this.
  - Implementation of **Gabor lenses** into the existing beam line.
    - Static confined electron column for focusing and manipulating beams
    - Experiments are planned to test to what extent the luminosity can be improved by using this type of lens.
  - NA61/SHINE is developing a design for a **Very Low Energy (VLE)** 1-20 GeV beamline
    - Hosting an **open workshop** on physics opportunities with VLE beam
    - We are **writing an addendum** that includes details of the physics case and beam requests (possibly in 2024)

Future Plans: After LS3

- We are not yet making a formal request for **data after LS3**, but have begun considering possibilities:
  - A **two-dimensional scan of ion beams** versus energy and system size
    - Will further illuminate **unexpected results** in earlier NA61/SHINE ion beam data
  - **$\bar{p}$ + p and $\bar{p}$+A** (A = 9, 12, 40, 208) measurements, and comparative studies with corresponding p + p and p + A reactions
    - Facilitates understanding of baryon stopping processes
  - Continued measurements to **support neutrino and cosmic ray** flux estimation:
    - Replica DUNE and Hyper-K targets
    - Further thin target data with e.g. future target materials

Conclusion

- The NA61/SHINE Collaboration has made **excellent progress in the past year**
  - Many new results have been reported from both the strong interaction and neutrino/cosmic ray physics programs
  - Funding for the ongoing upgrade have been secured and the upgrade tasks are on schedule
- We have modified our approved 2021 run plan given COVID-19 affects on the beam schedule and **are reiterating our request for four weeks of lead beams**
- **We are asking for a recommendation for a series of measurements in 2022-2024**:
  - Six weeks / year of ion beams for strong interaction and cosmic ray physics
  - Twelve weeks (total) of secondary hadron beams for Fermilab neutrino beam flux estimation
- Several options for improved **low energy beams** are being pursued
- We have begun **considering ideas for data-taking** after Long Shutdown 3

On behalf of the NA61/SHINE collaboration:

Thank You!

Backup

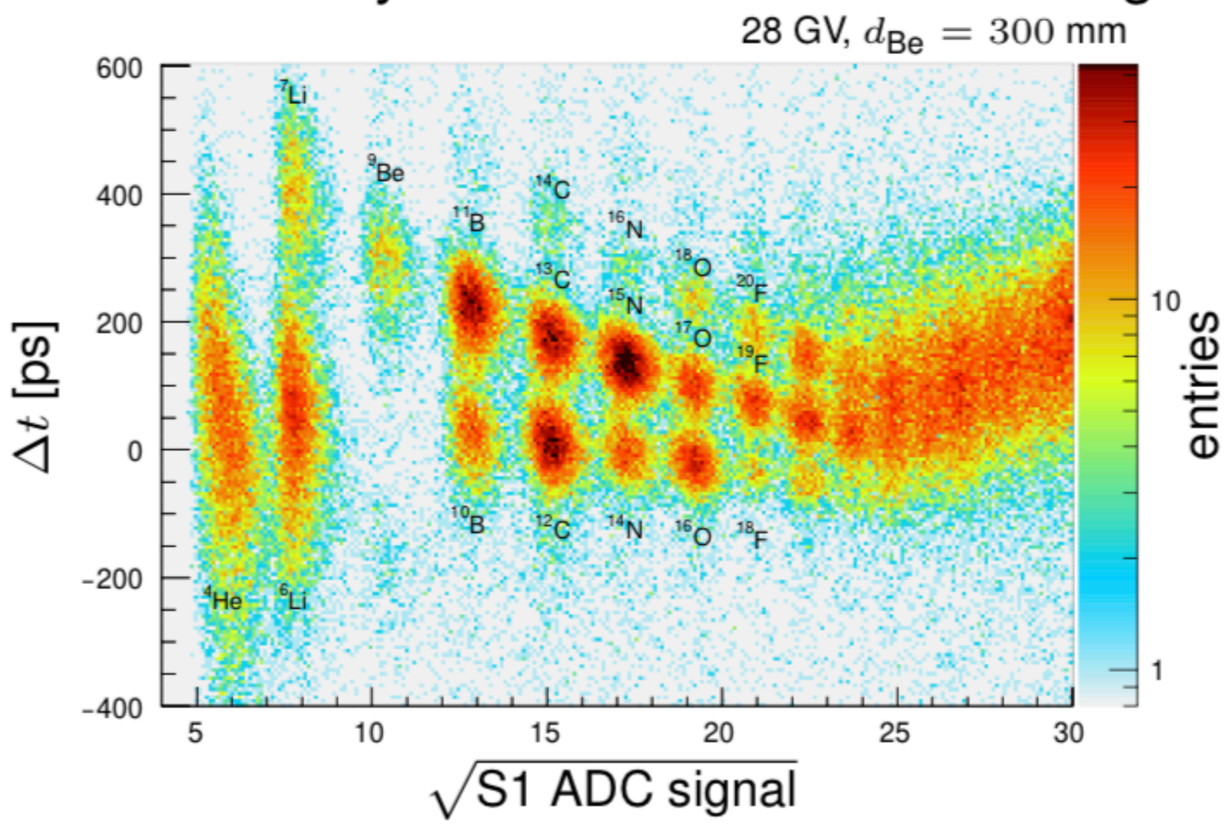
Software and Calibration Status

- We have recently developed a **new software framework** called SHINE
  - Many benefits: ability to incorporate **new detectors**, use **modern particle interaction models**, and support **64-bit builds**
  - Now **using SHINE exclusively**, with some modules from legacy framework inside SHINE wrappers.

- Software development over the past year has focused on **simulation, reconstruction, and calibration**:
  - Full **Geant4 simulation chain** implemented
  - Improvements to **Kalman Filter** tracking algorithm
  - New **ToF reconstruction + simulation** modules added
  - Comprehensive **TPC dE/dx calibration** package developed in SHINE
  - Several recent **datasets calibrated**

2018 Pilot Run on Nuclear Fragmentation

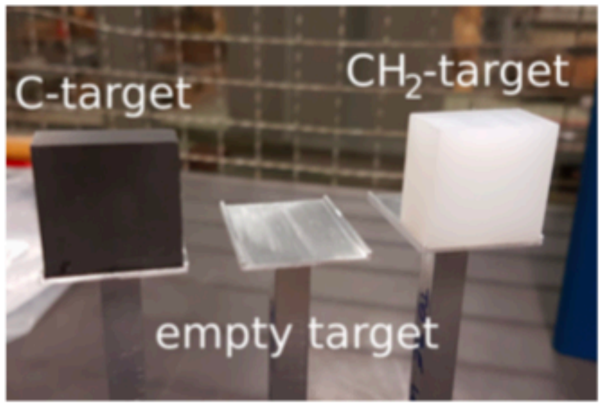
composition of secondary ion beam measured during data taking:

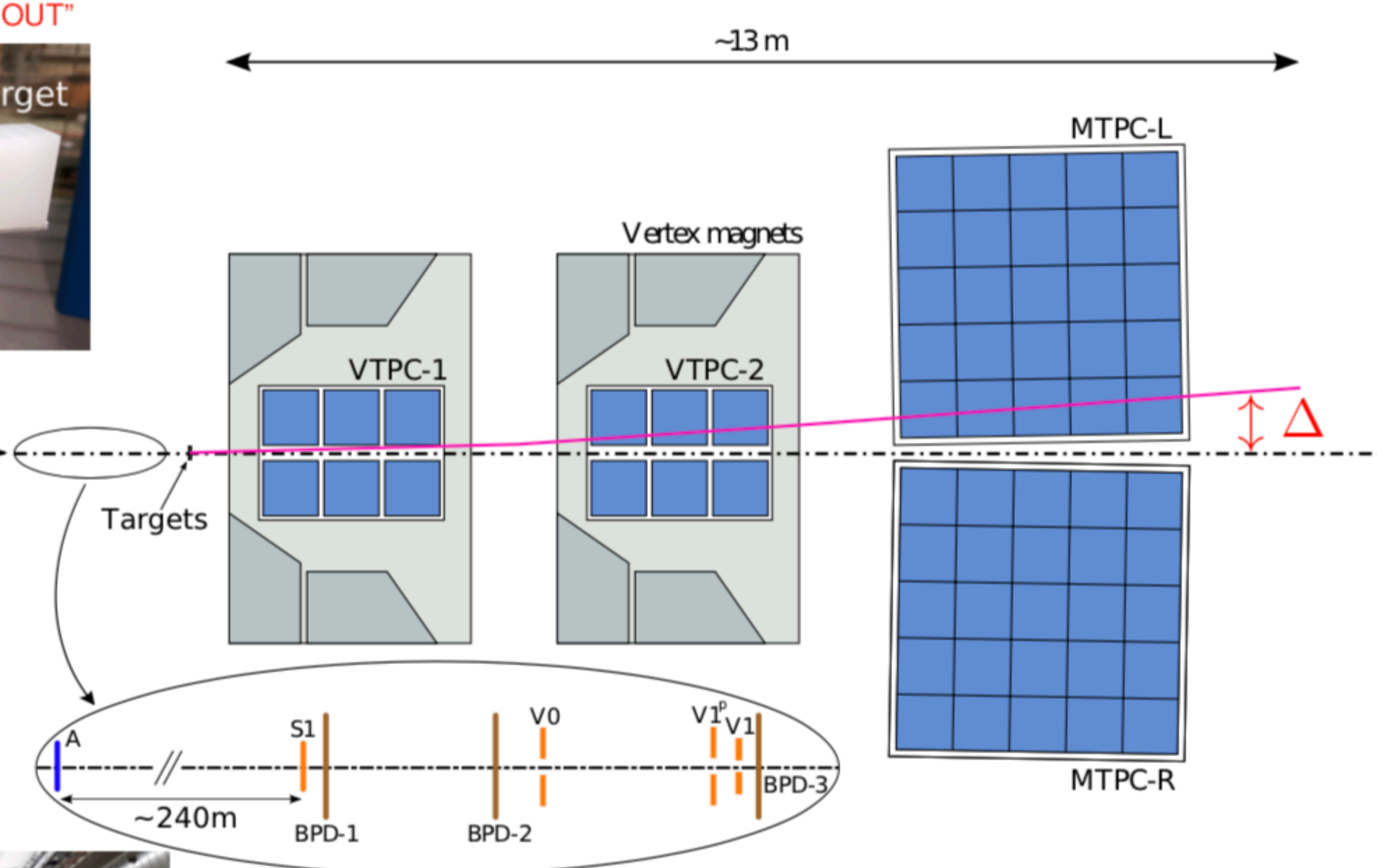


- primary Pb beam on Be target, rigidity selection in H2 beam line
- special H2 beamline optics (simulation and operation by N.Charitonidis)
- three days of data taking at 27 GV
- 1.1 $\times 10^6$ beam trigger on $Z^2 = 36$
- offline selection: 3.6 $\times 10^5$ ^{12}C beam particles
- 20k (^{12}C+CH_2) and 17k (^{12}C+^{12}C) interactions

2018 Pilot Run on Nuclear Fragmentation

"C+p = (C+CH_2) - (C+C) - OUT"





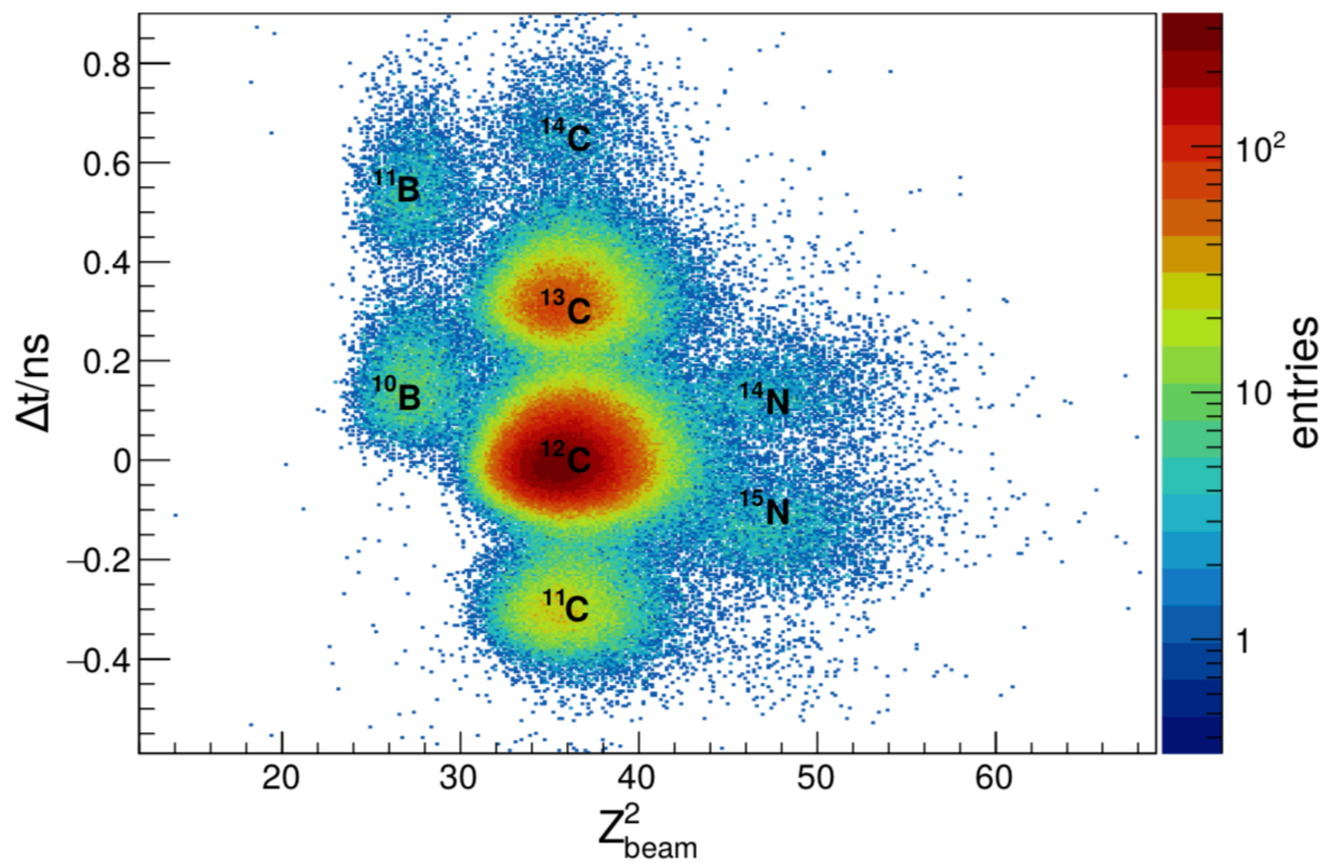
$$\text{ToF(A to S1)} + dE/dx(\text{S1}) \rightarrow (\text{A}, Z^2)_{\text{beam}}$$

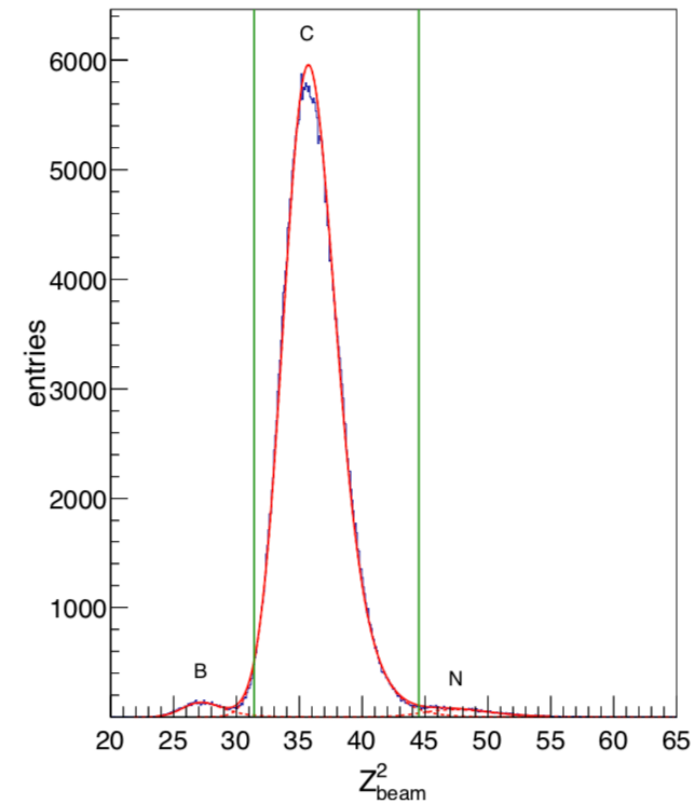
$$\Delta + dE/dx(\text{MTPC}) \rightarrow (\text{A}, Z^2)_{\text{fragment}}$$

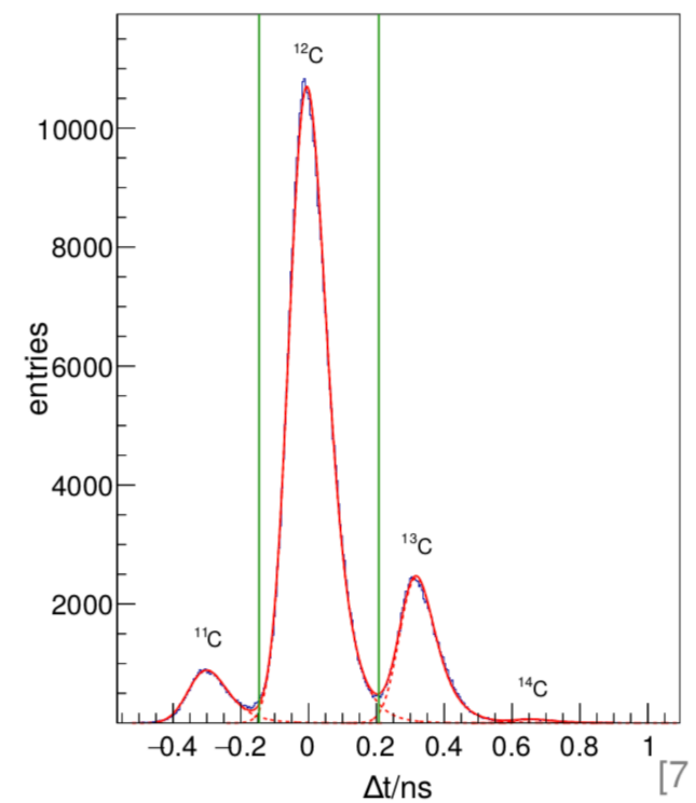
2018 Pilot Run on Nuclear Fragmentation

^{12}C Beam Selection

triggered beam composition:







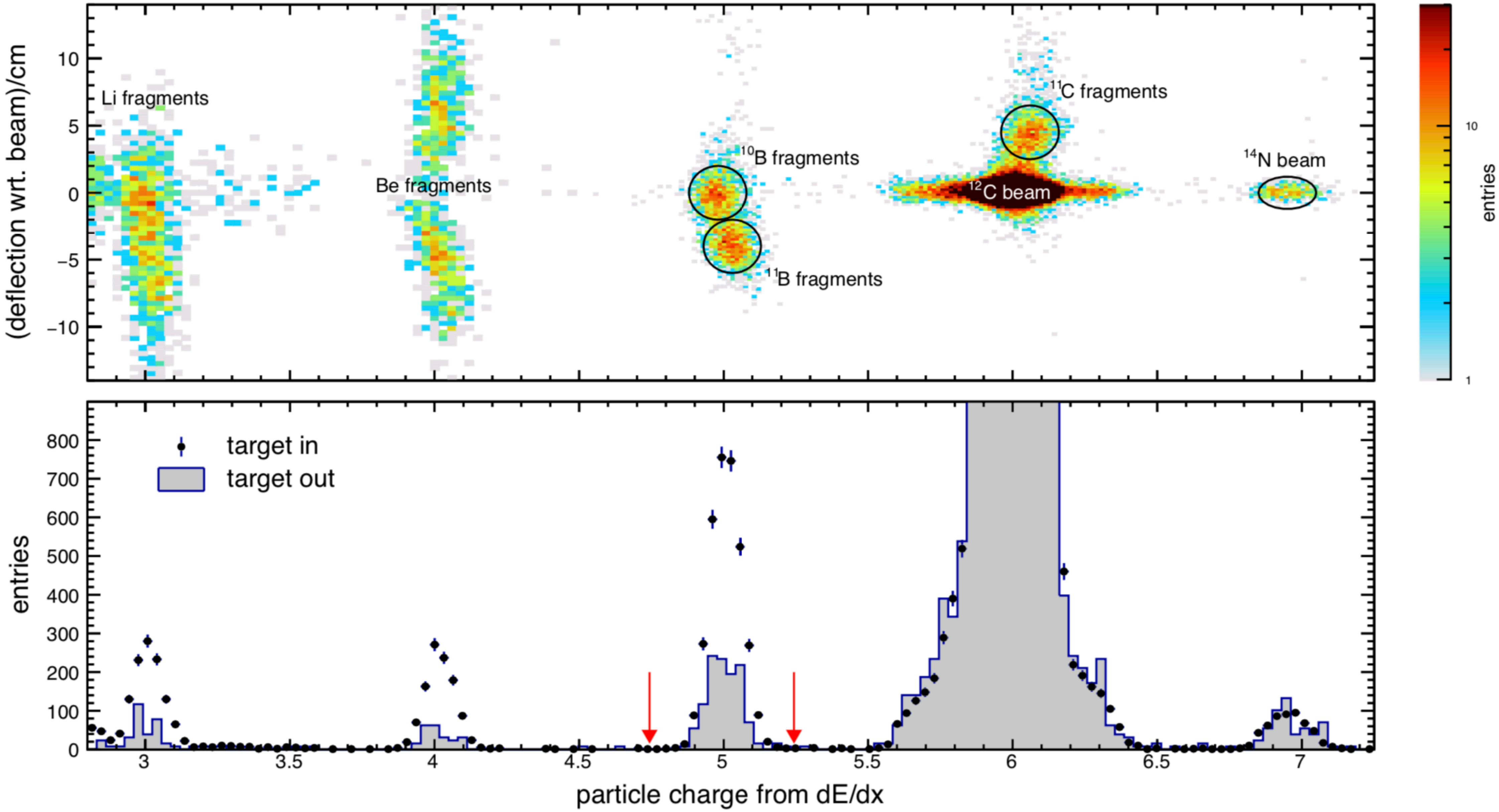
offline beam selection:

- ^{12}C purity: 99.2%
- B contamination: $<$0.1%

[7 of 10]

2018 Pilot Run on Nuclear Fragmentation

Identification of Isotopes Produced in Target (MTPC)

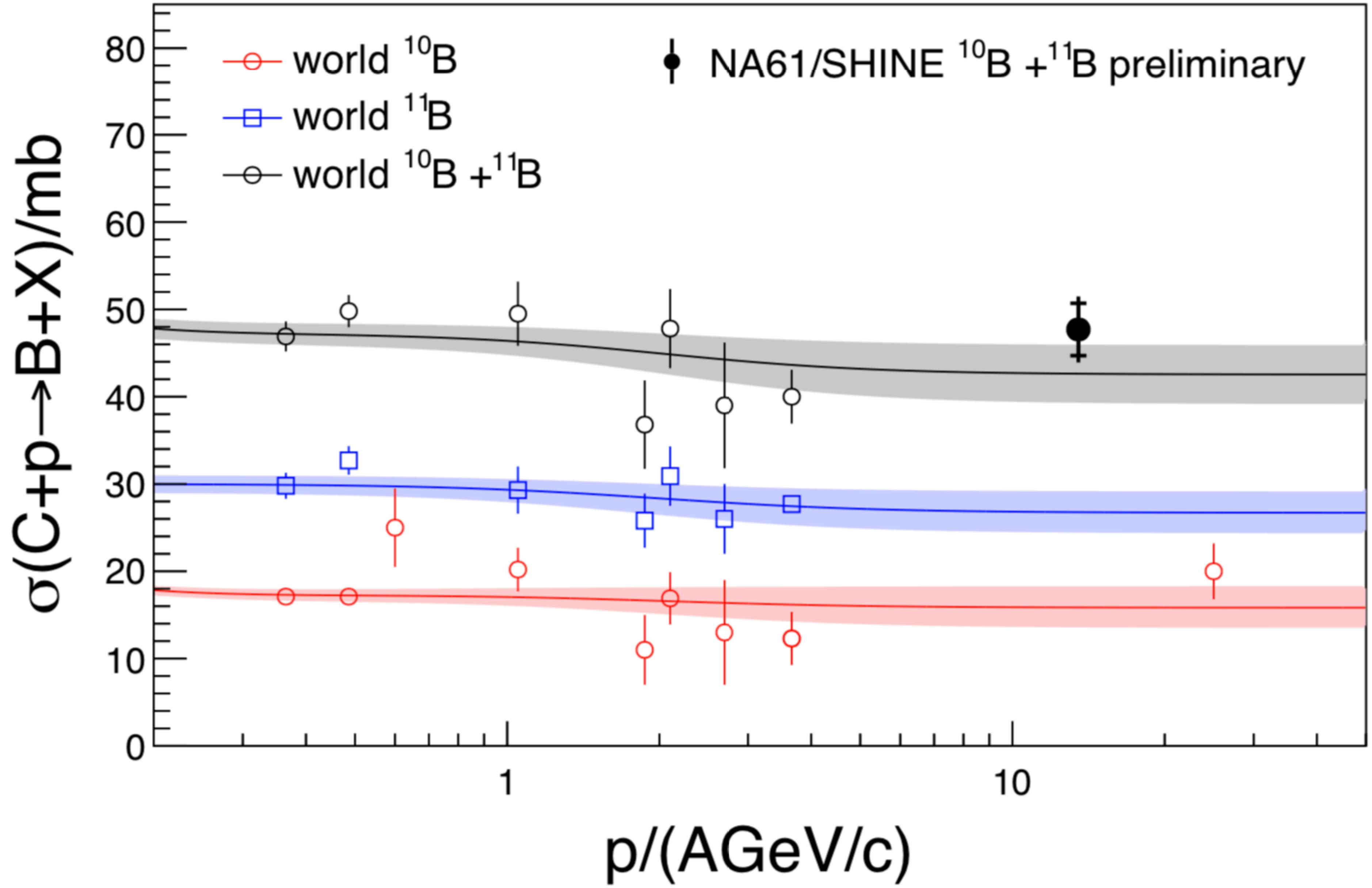


B-selection indicated by red arrows

Direct ^{10}B + ^{11}B Production (NA61/SHINE preliminary at ICRC19)

$$\sigma(^{12}\mathrm{C} + \mathrm{p} \rightarrow ^{10}\mathrm{B} + X) + \sigma(^{12}\mathrm{C} + \mathrm{p} \rightarrow ^{11}\mathrm{B} + X) =$$

$$\underline{47.7 \pm 3.0\ (\mathrm{stat.}) \pm 2.3\ (\mathrm{syst.})\ \mathrm{mb}}$$



F. Sutter, Masters Thesis KIT 2019; NA61/SHINE PoS(ICRC2019)446, arXiv:1909.07136

Fit: Evoli+19, Data: Korejwo+02, Korejwo+99, Webber+98, Webber90, Olson+83, Fontes+77