Hadron Production Measurements at NA61/SHINE for Neutrino Oscillation Experiments

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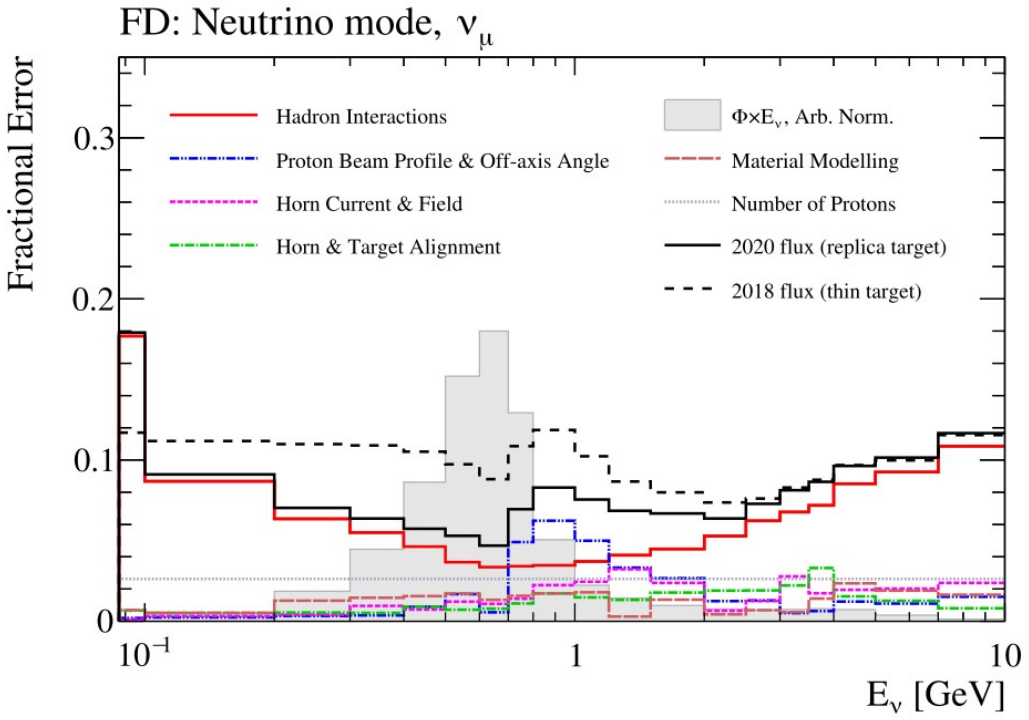
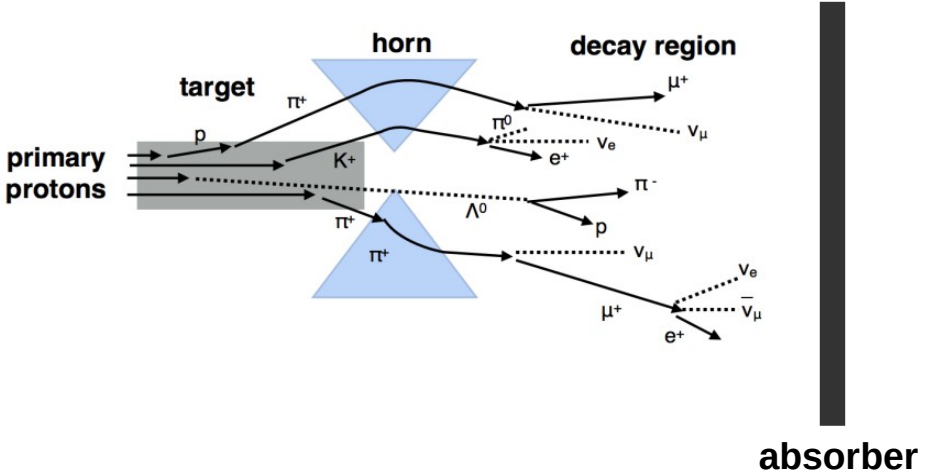
University of Colorado **Boulder**

Uncertainties in Long-Baseline Experiments

- Large uncertainties in predicted neutrino beam properties, if they are not constrained (~20-40%)
  - Inclusion of NA61/SHINE data **significantly constrains hadron interaction uncertainty**



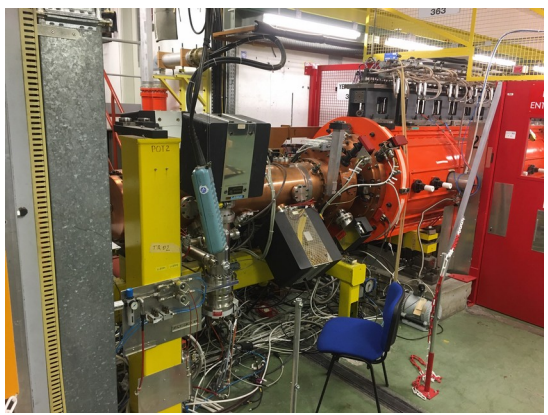
Eur. Phys. J. C (2023) 83:782



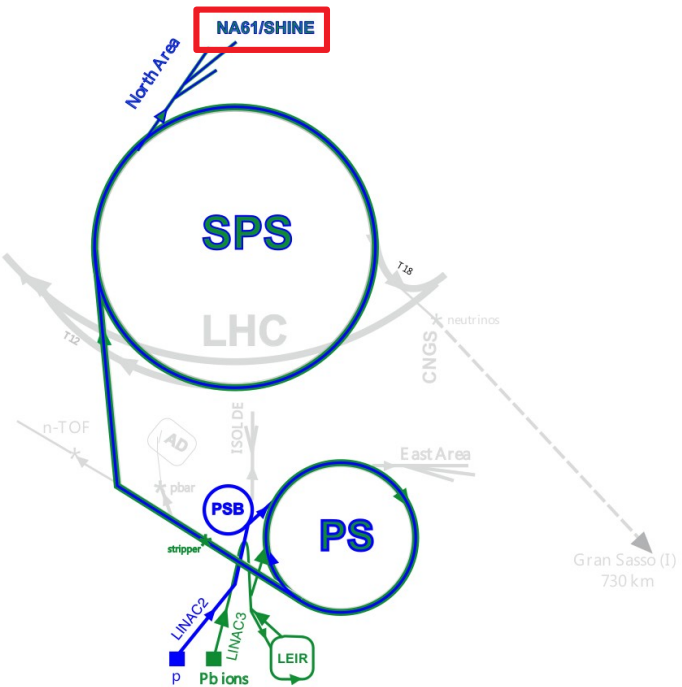
NA61/SHINE

NA61 = North Area experiment 61
SHINE = SPS (super proton synchrotron) Heavy Ion and Neutrino Experiment

- Multi-focus experiment
  - Heavy Ion
    - Deconfinement, quark-gluon plasma
  - Cosmic rays
  - **Neutrino**
    - Measure multiplicity of particles produced in hadronic interactions



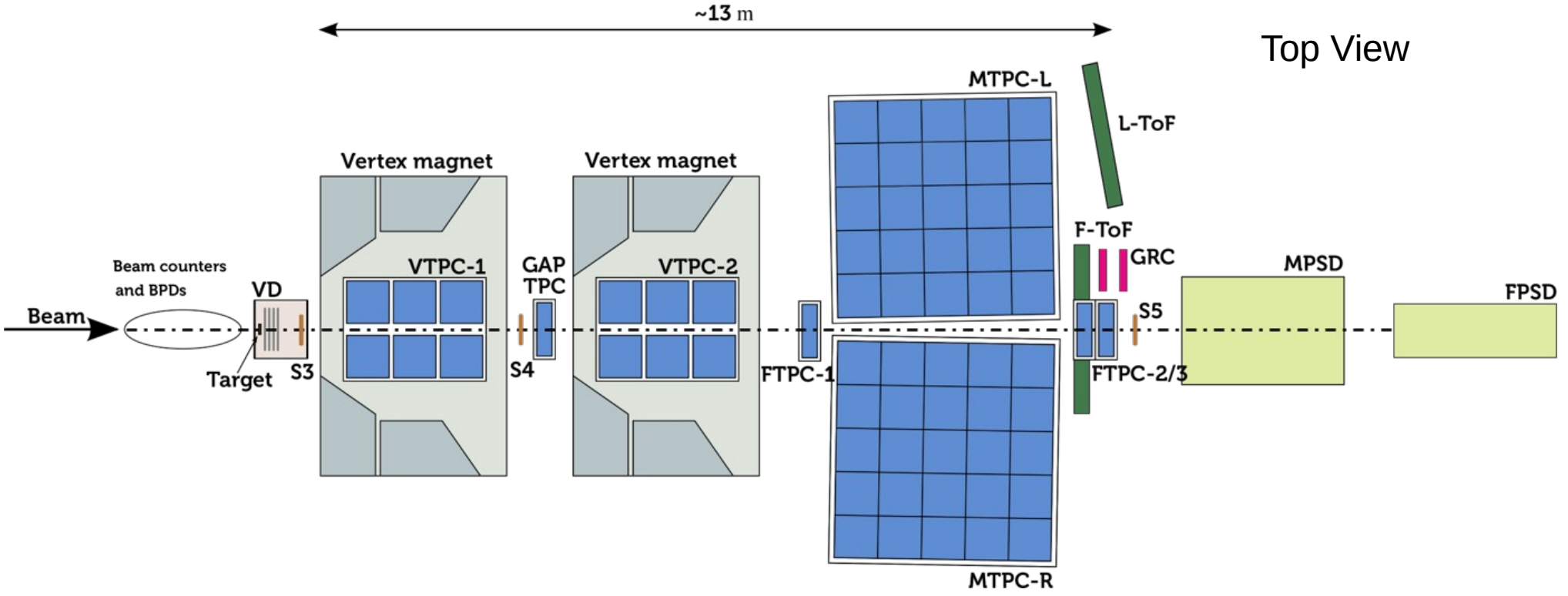
Start of the LINAC2



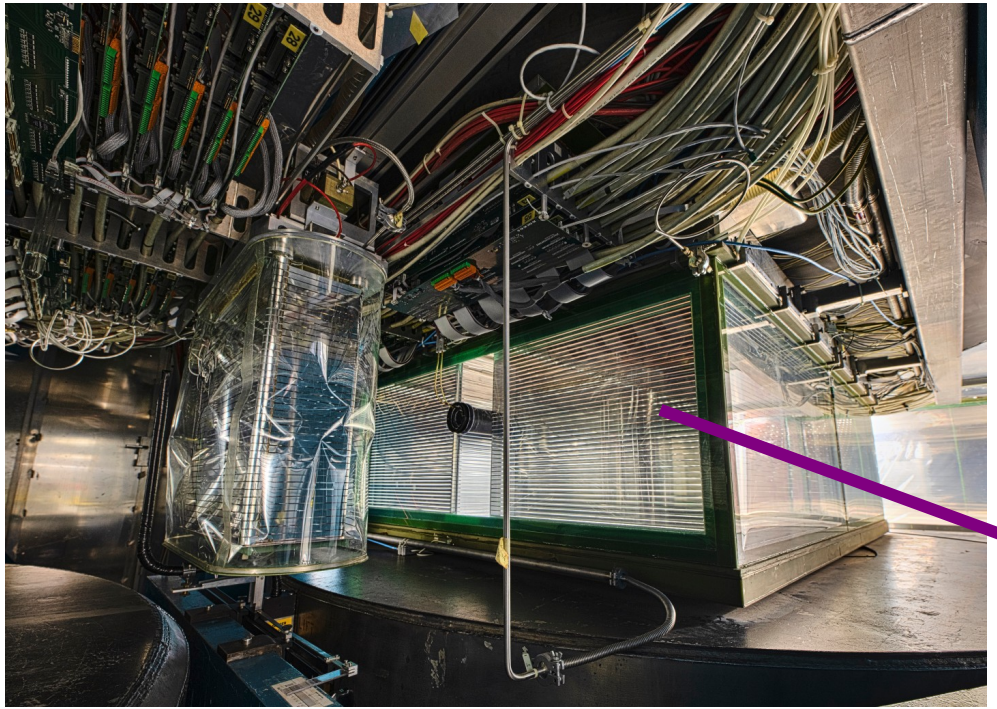
Detailed detector paper:
J. Inst. 9 (2014): P06005

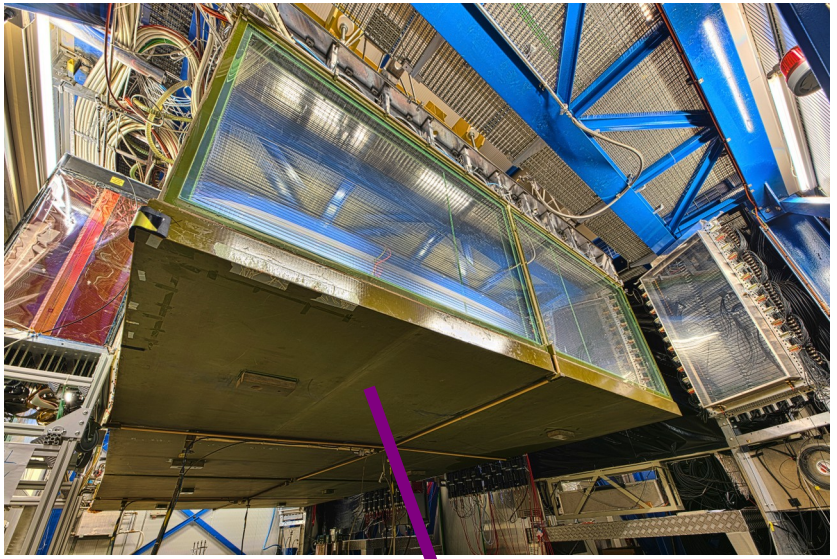
NA61/SHINE Detector

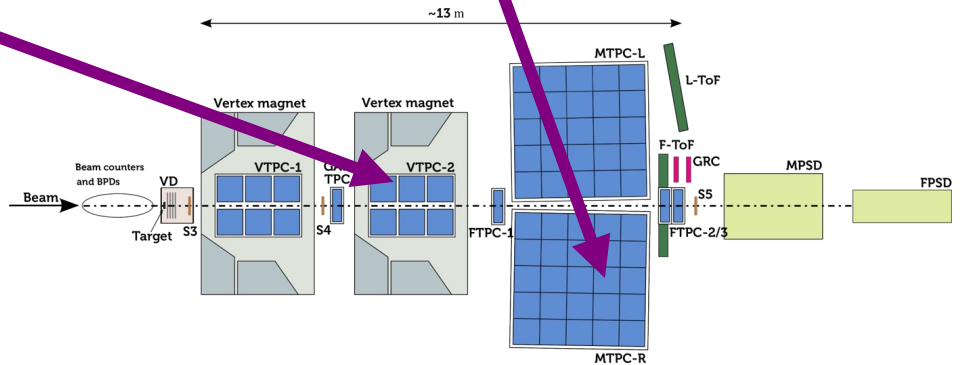
- 8 Time Projection Chambers (TPCs) + 2 magnets
- Time-of-Flight walls (ToF)
- Beam counters and Beam Position Detectors (BPDs)
- Projectile Spectator Detectors (PSDs)



NA61/SHINE Detector





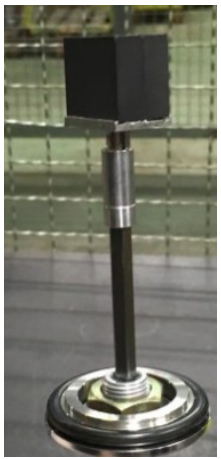


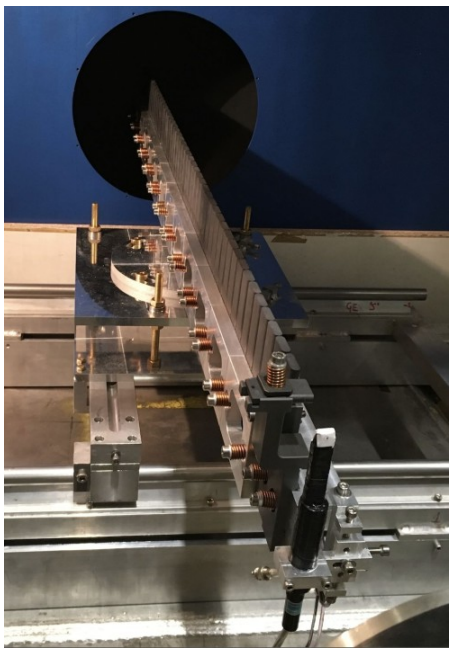
Neutrino Program at NA61/SHINE

- Dedicated hadron production measurements for long-baseline neutrino oscillation experiments
  - DUNE, T2K, NOvA, …

- **Thin target:**
  - Production, inelastic, and total cross sections
  - Differential hadron yields from proton-nucleus interactions
    - Can be incorporated directly into interaction generators
  - Reweight neutrino beam flux simulations

- **Replica Target:**
  - Differential hadron yields from target surface
  - Directly constrain neutrino beam flux simulations
    - No need to simulate secondary + tertiary interactions inside the target
  - Beam attenuation





NuMI replica target.

NA61/SHINE Measurements

- T2K beamline uses 31 GeV/c protons
- NuMI for NOvA uses 120 GeV/c protons
- LBNF for DUNE will use 120 GeV/c protons

2007-2010	Long Shutdown 1 (LS1)	2015-2018	LS2	2022-2025	LS3	2027-?

T2K:
31 GeV/c protons

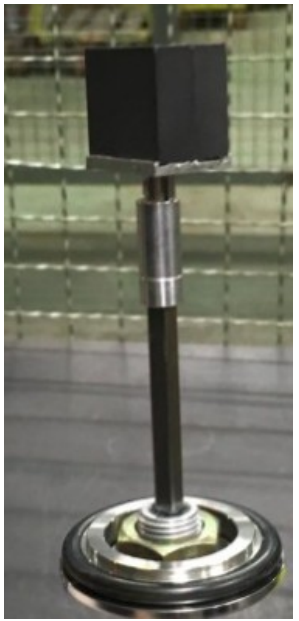
NuMI:
120, 90, 60 GeV/c protons
60 GeV/c pions

T2K:
31 GeV/c protons

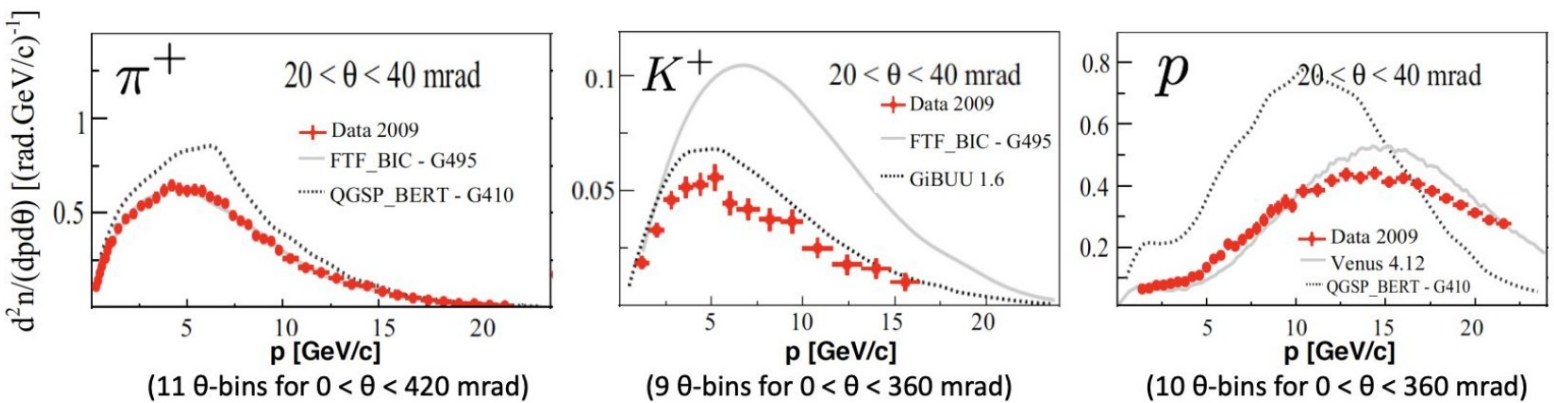
NuMI, LBNF/DUNE
120 GeV/c protons
60 GeV/c kaons

Measurements for T2K

- **31 GeV/c protons on a thin carbon target:**
  - Total cross-section and $\pi^{\pm}$ differential multiplicity measurements
    - Phys. Rev. C84 (2011) 034604
  - K^{+}
    - Phys. Rev. C85 (2012) 035210
  - K^{0}_{S} and Λ
    - Phys. Rev. C89 (2014) 025205
  - Total cross-section and $\pi^{\pm}$, $K^{\pm}$, p, K^{0}_{S}, and Λ
    - Eur. Phys. J. C76 (2016) 84

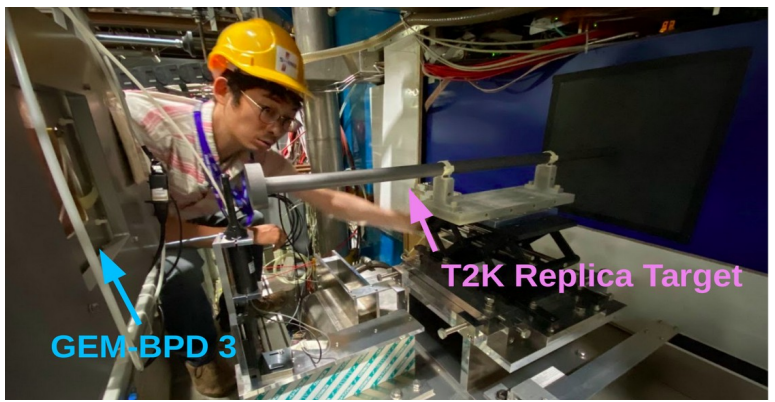


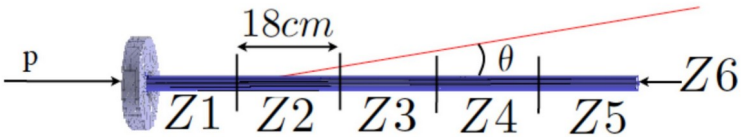
1.5 cm thin carbon target

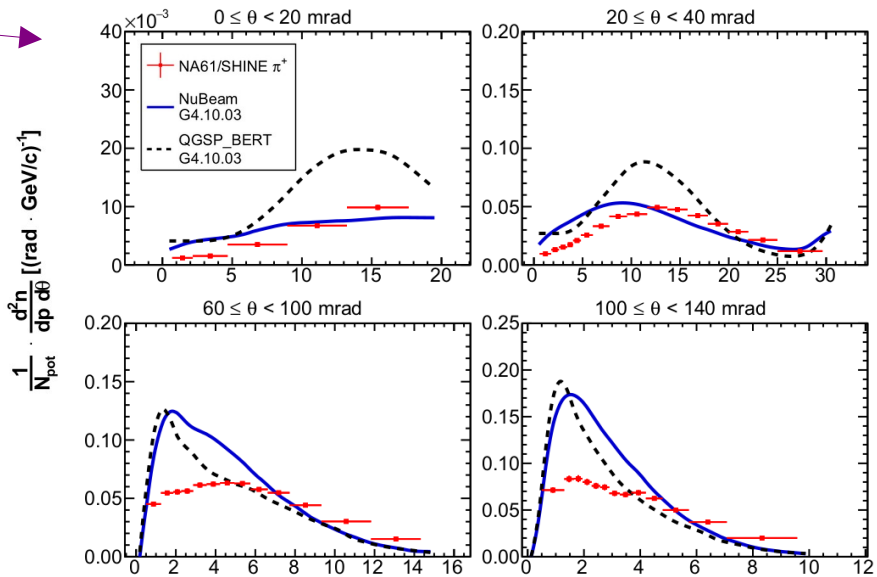


Measurements for T2K

- **31 GeV/c protons on a T2K replica target:**
  - $\pi^{\pm}$, p, and $K^{\pm}$
    - Eur. Phys. J. C79 100 (2019)
  - p beam survival probability
    - Phys. Rev. D103 012006 (2021)
- Application of NA61/SHINE measurements to T2K:
  - Phys. Rev. D87 012001 (2013)
- Ongoing:
  - 18 times higher stats replica target data from 2022

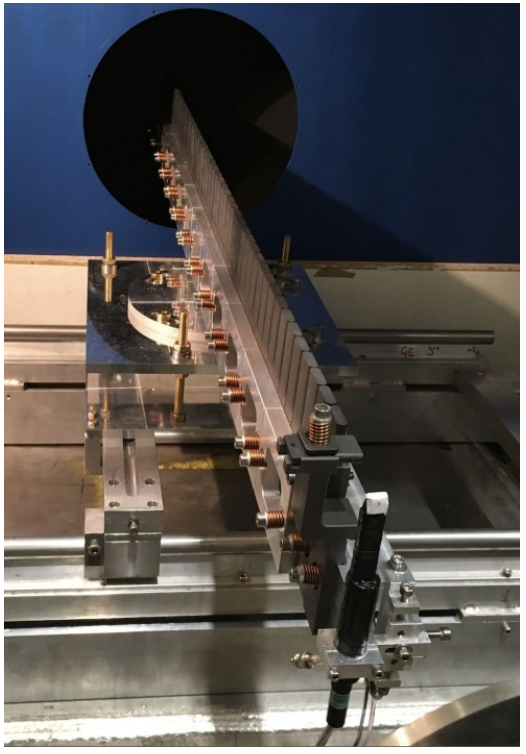






Measurements for Fermilab Experiments

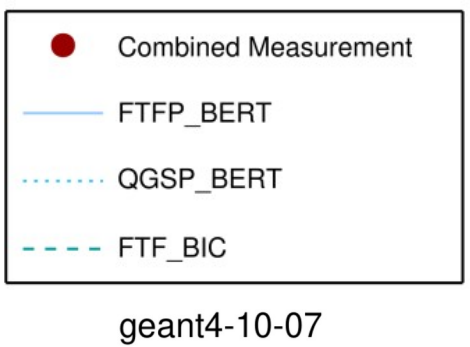
- **Thin target:**
  - **120 GeV/c proton-carbon: $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$, K^0_S, Λ, and $\bar{\Lambda}$**
    - Phys. Rev. D108 072013 (2023)
    - Phys. Rev. D107 072004 (2023)
  - **90 GeV/c proton-carbon: $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$, K^0_S, Λ, and $\bar{\Lambda}$**
    - Preparing paper + data release
  - 60 GeV/c π^+-beryllium and π^+-carbon: $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$, K^0_S, Λ, and $\bar{\Lambda}$
    - Phys. Rev. D100 112004 (2019)
  - 120 GeV/c proton-beryllium cross sections
    - Phys. Rev. D100 112001 (2019)
  - 60 GeV/c proton-aluminum, proton-beryllium, proton-carbon thin target cross sections
    - Phys. Rev. D100 112001 (2019)
- Ongoing:
  - **Replica target:**
    - 120 GeV/c proton-NuMI replica target
  - **Thin target:**
    - 120 GeV/c proton-titanium
    - 60 GeV/c K^+-carbon

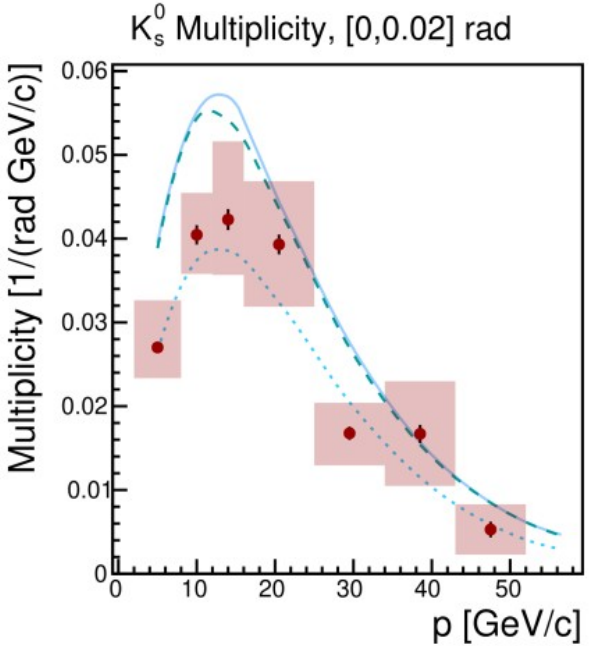


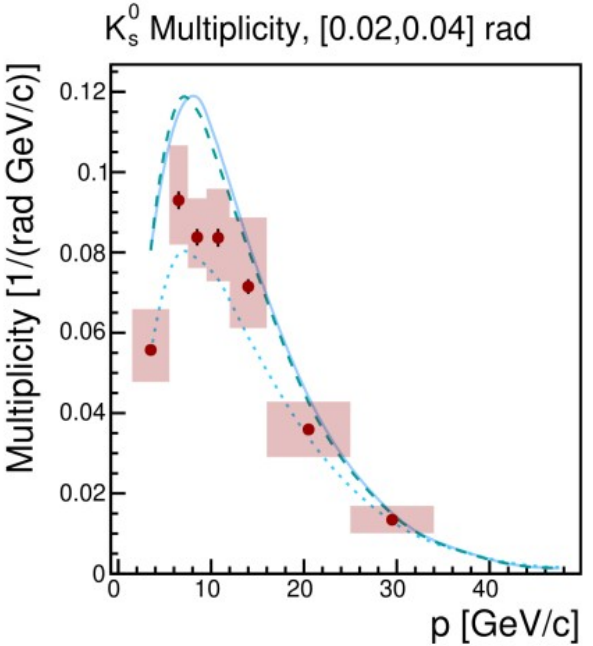
NuMI replica target.

120 GeV/c Proton-Carbon Thin Target

- Combined two datasets for one measurement
  - Neutral hadrons: K^0_S, Λ, $\bar{\Lambda}$



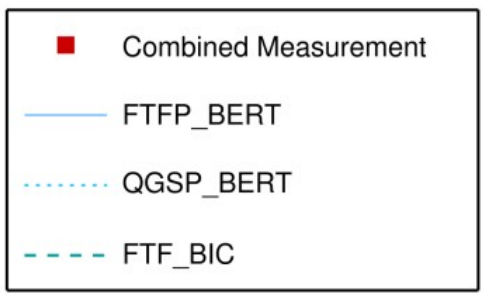




Phys. Rev. D107 072004 (2023)

120 GeV/c Proton-Carbon Thin Target

- Combined two datasets for one measurement
  - Charged hadrons: $\pi^{\pm}$, $p/\bar{p}$, and $K^{\pm}$



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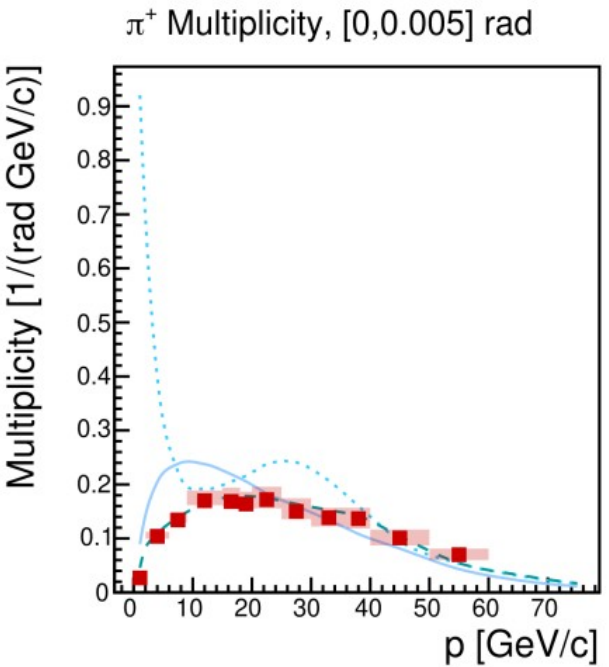
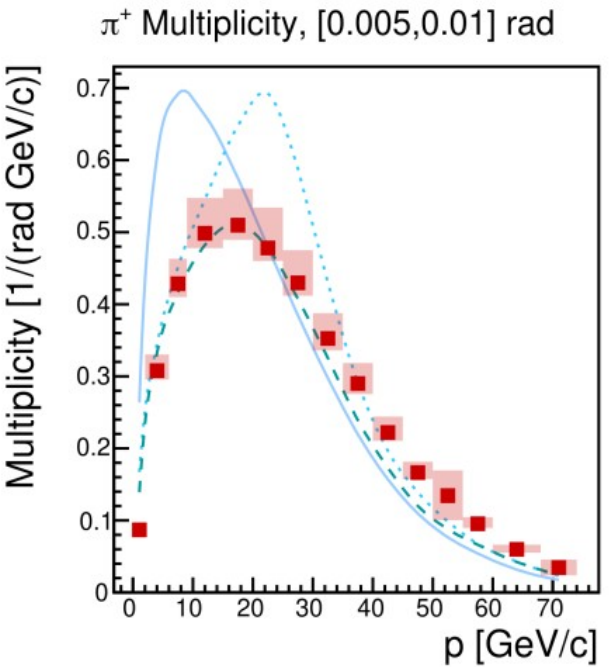
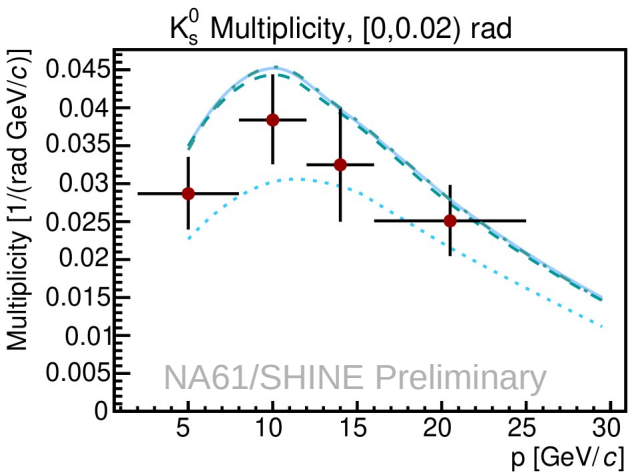


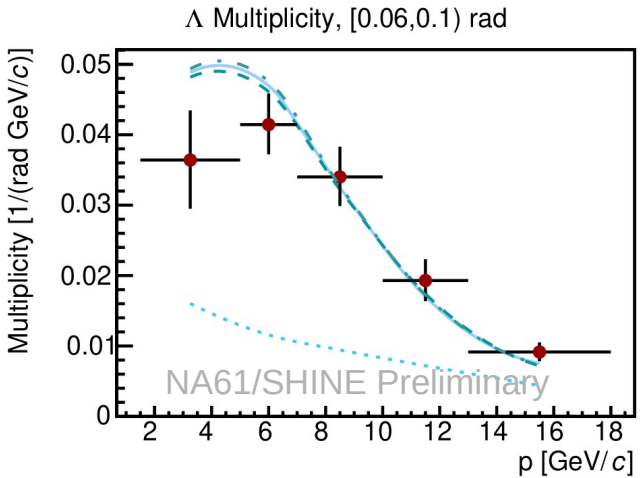


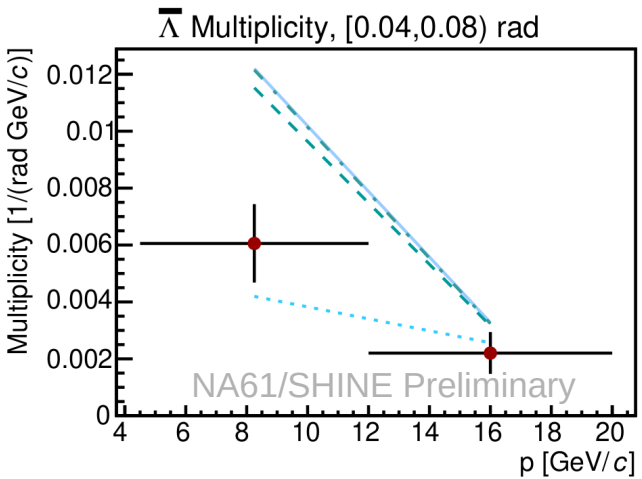
Phys. Rev. D108 072013 (2023)

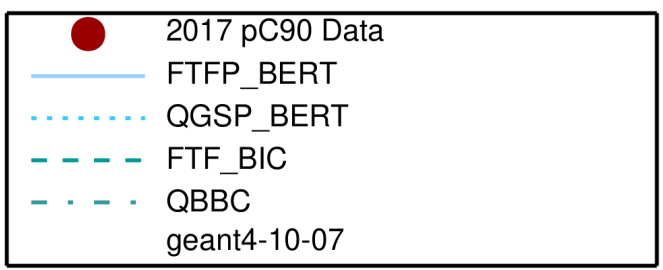
90 GeV/c Proton-Carbon Thin Target

- Neutral hadrons: K^0_S, Λ, $\bar{\Lambda}$
  - New result: Paper in progress
  - Constrain secondary + tertiary interactions









90 GeV/c Proton-Carbon Thin Target

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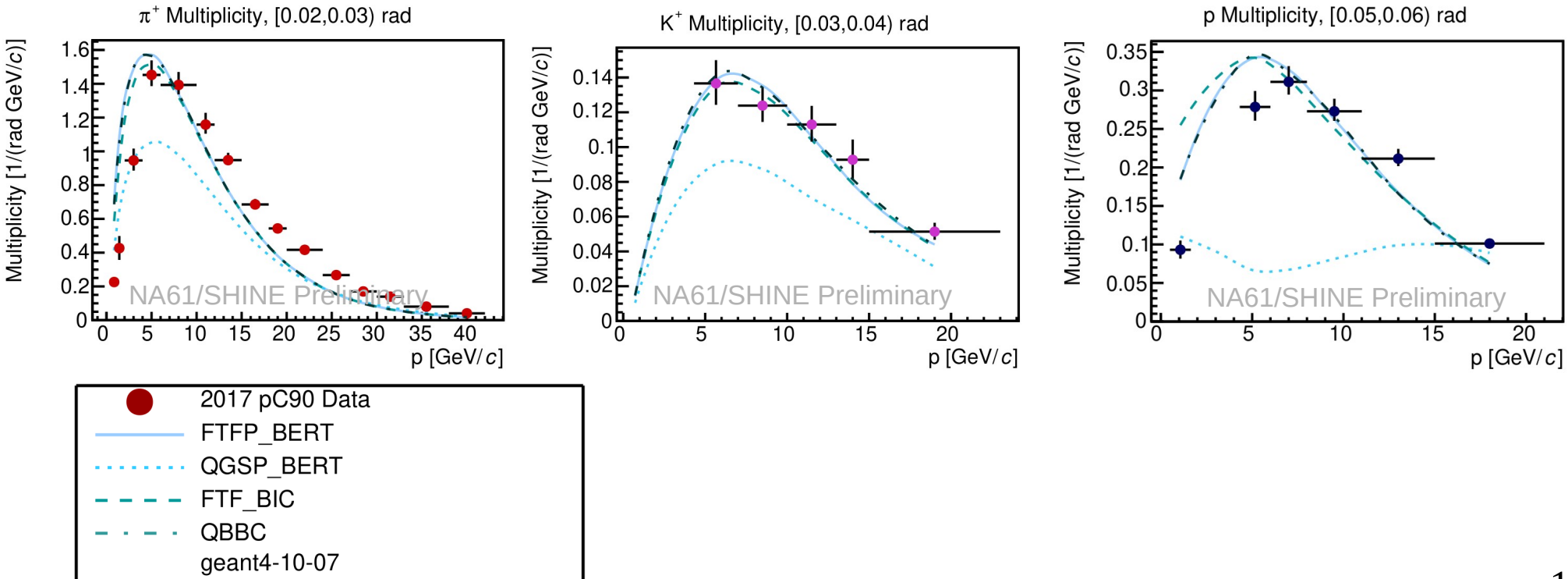


DUNE Prototype Target

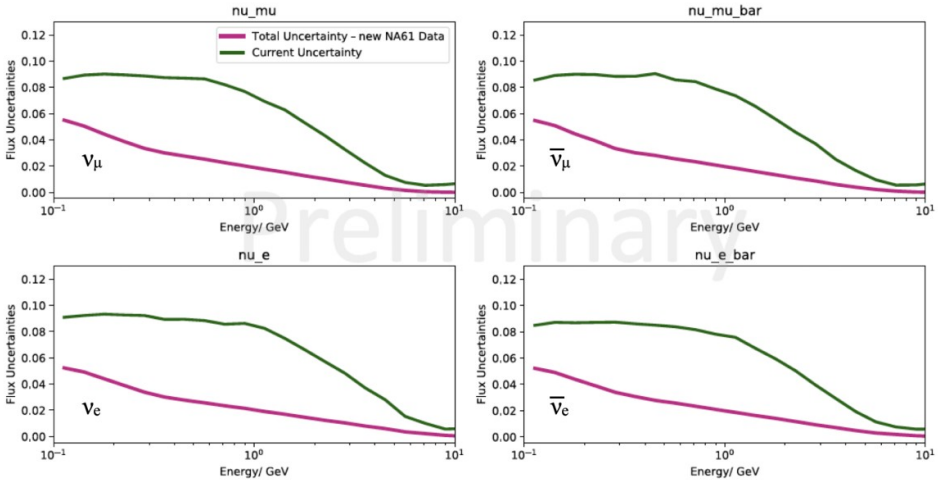
- Data taking by NA61/SHINE summer 2024
- 120 GeV/c proton beam
- DUNE prototype replica target designed by Rutherford Appleton Laboratory
  - 150 cm long, 0.8 cm radius
- Differential multiplicities, beam attenuation

DUNE prototype replica target

DUNE prototype replica target

Post Long Shutdown 3 (2027+)

- Low energy beam line (2-13 GeV/c)
  - Currently limited to a minimum of ~13 GeV/c
  - Accelerator-based neutrino experiments
    - Low-E secondaries for second oscillation maximum
  - Atmospheric neutrino flux
    - Applicable for DUNE
  - Spallation neutron source neutrino experiments
    - COHERENT (proton <2 GeV)
    - JSNS^2 (proton at 3 GeV)
  - Muon experiments
    - COMET (proton at 8 GeV)
- Link to: NA61++/SHINE open workshop



SPSC-M-793 https://cds.cern.ch/record/2810696
G. Barr and L. Cook

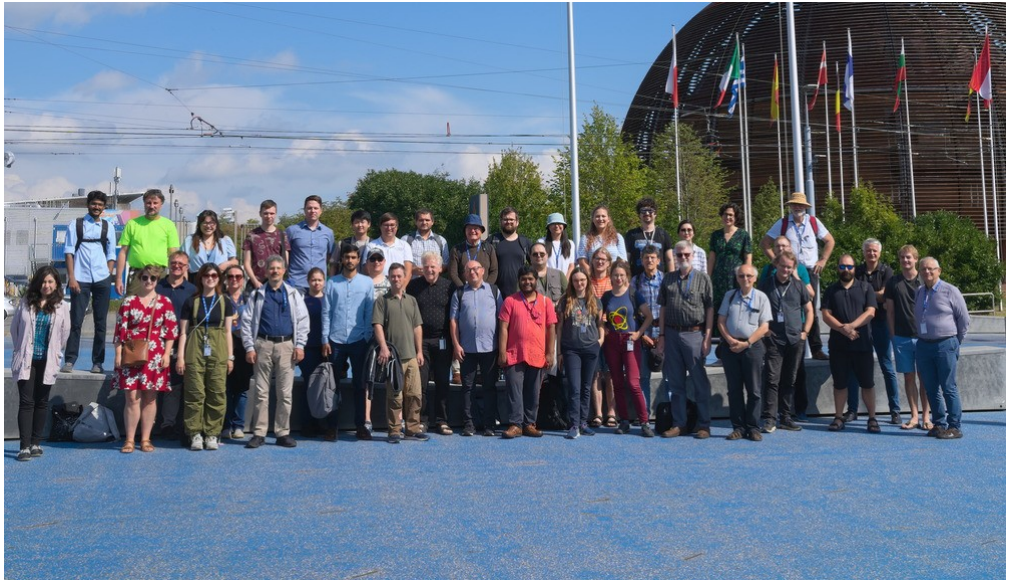
Atmospheric neutrino flux uncertainties from p + N -> $\pi^{\pm}$ + X

Green: Current Uncertainty
Purple: Uncertainty with low-energy data from NA61/SHINE

Summary

- NA61/SHINE provides vital hadron production measurements
  - Significantly constrained T2K neutrino flux uncertainties
- Recent 120 GeV/c proton-carbon multiplicity results
  - Work is being done to add the results to the flux predictions for NuMI and LBNF
- Preliminary 90 GeV/c proton-carbon multiplicity results
  - Paper + release of results coming soon
- DUNE prototype replica target data currently being taken
- **Exciting opportunities post Long Shutdown 3**

Thanks!

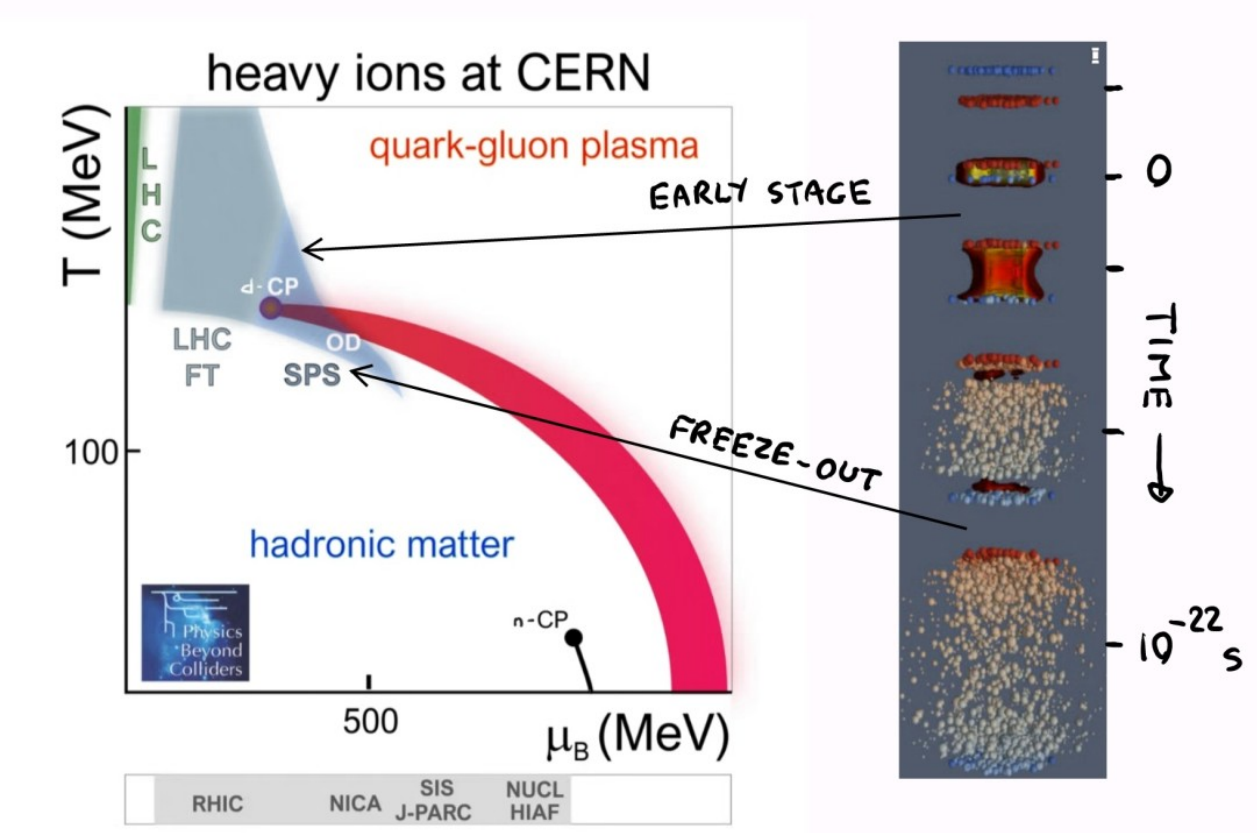


U.S. DEPARTMENT OF ENERGY

Office of Science

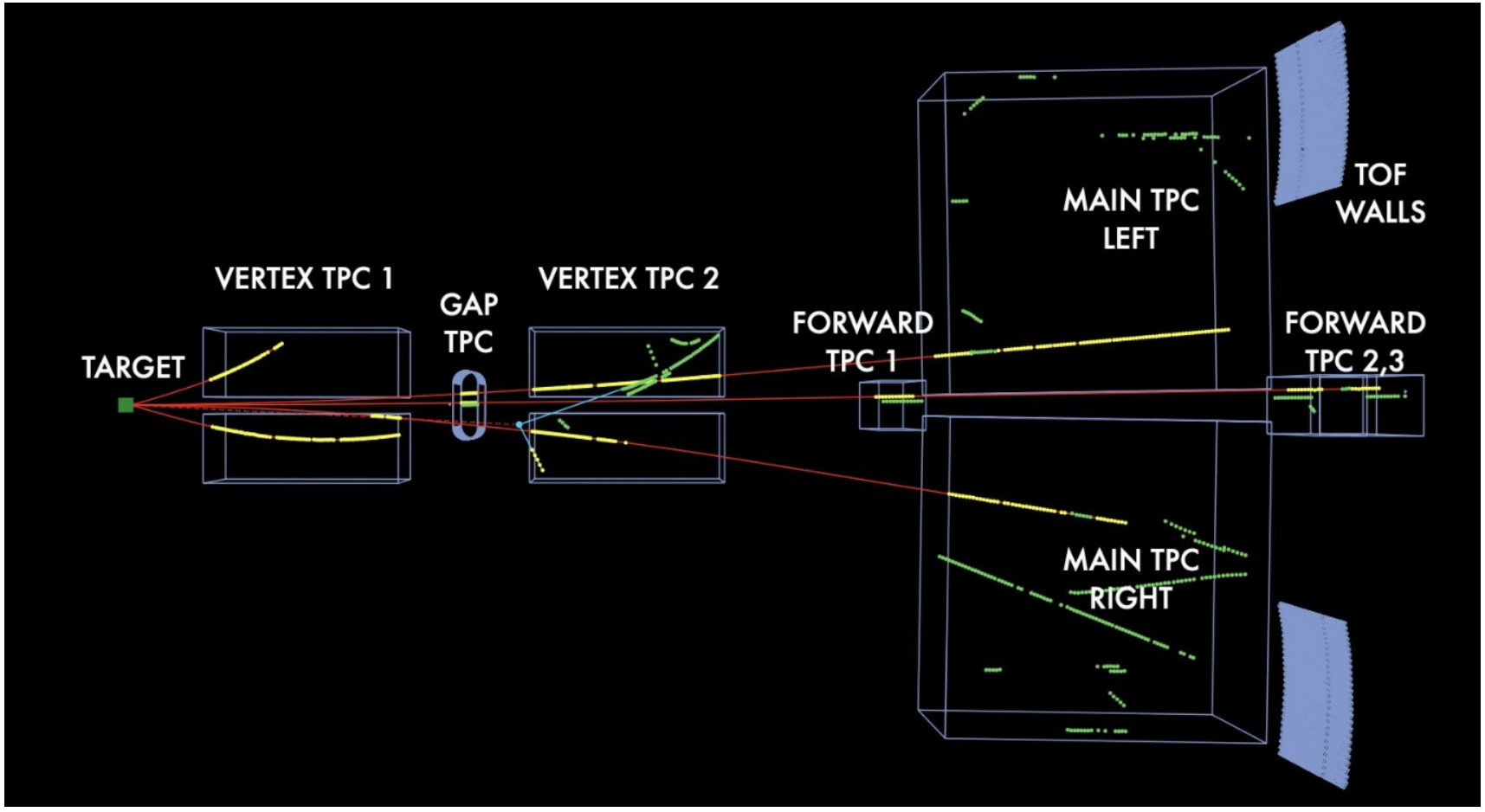
Cosmic Rays and Heavy Ion Physics

- **Heavy Ion Physics:**
  - Onset of deconfinement:
    - Quark-gluon-plasma creation
  - Critical point search
- **Cosmic Rays:**
  - Nuclear fragmentation data to aid cosmic ray simulations
  - Anti-deuteron production



Marek Gazdzicki, 2020 SHINE Autumn School

Sample pC@120 GeV/c Event in NA61/SHINE



90 GeV/c Proton-Carbon Thin Target

- Uncertainties typically on the 5-15% level