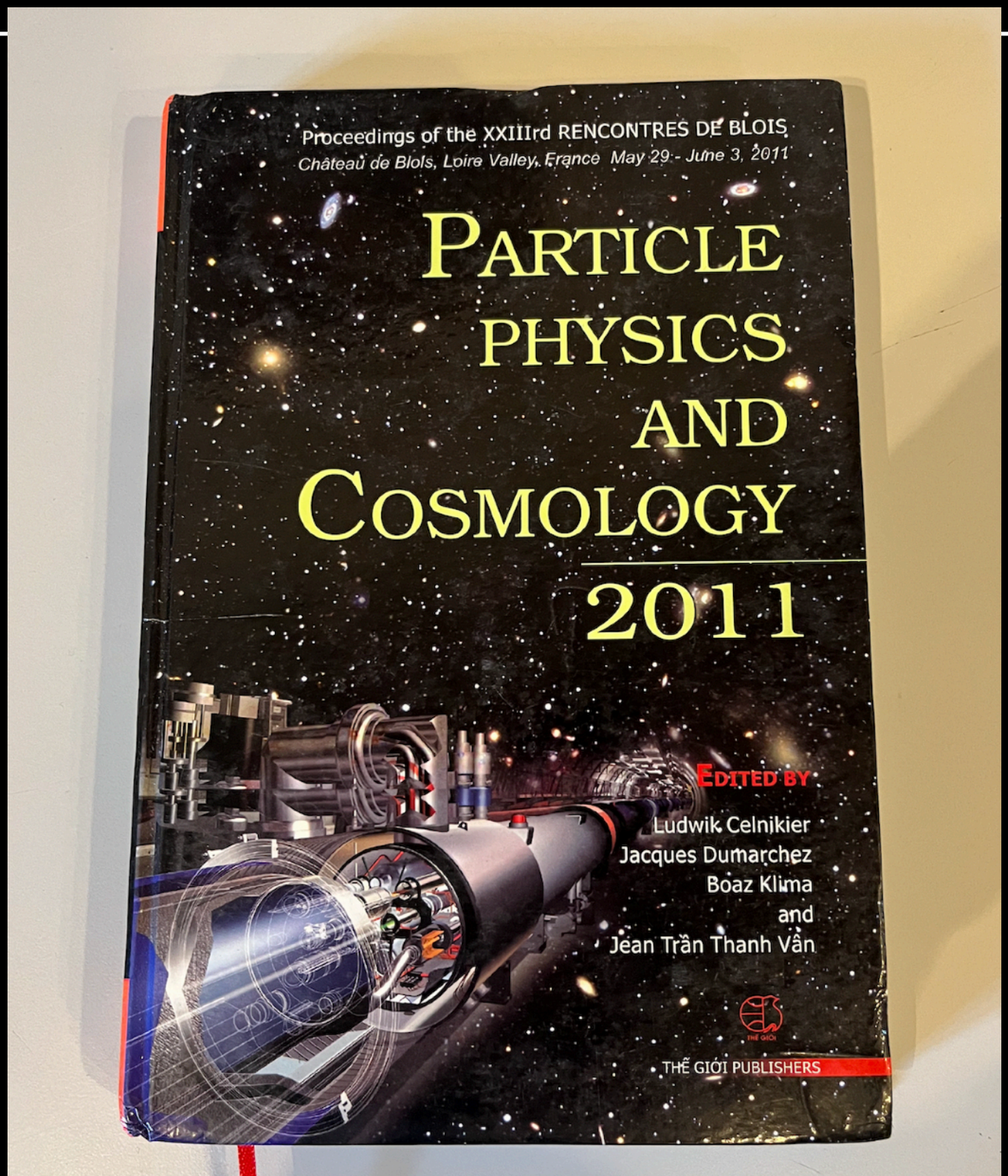
NA61/SHINE: Hadron production for neutrino beams

E. D. Zimmerman
University of Colorado, Boulder

35e Rencontres de Blois
Blois, Val de Loire, France
22 Octobre 2024

In the conference office...

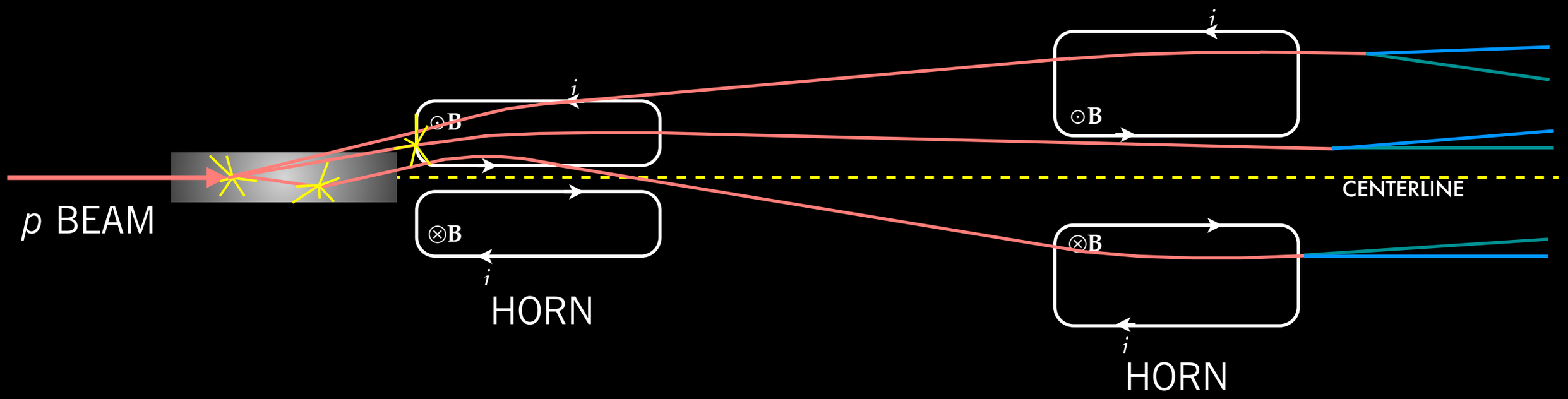


NA61/SHINE Neutrino Program

- Neutrino beam physics: why measure hadron production?
- NA61/SHINE neutrino program
- Current and new results
- New data sets
- New opportunities

Flux from a neutrino beam

- Neutrino flux comes from:
  - Pions, kaons produced directly from primary p+C interactions
  - Also produced from re-interactions of secondary p, π in the target
- Secondary particles from target focused in a series of horns
  - Horns contain substantial amounts of aluminum, which also acts as a secondary target
- **All of these sources of mesons contribute significantly to the neutrino flux.**



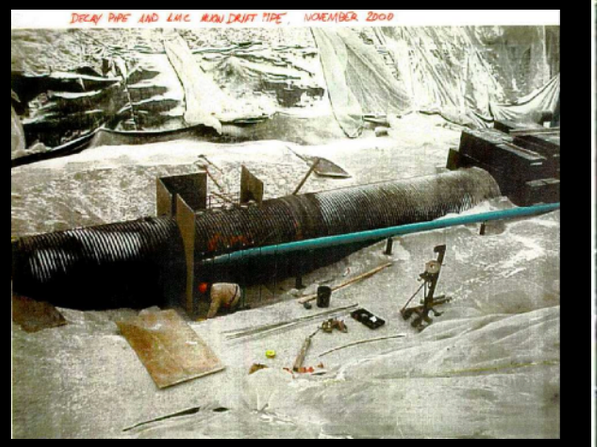
Understanding the flux

- Use Monte Carlo techniques to simulate the beam, but this is generally a very complicated and challenging environment. **Uncertainties can be large: 20-50% with standard simulation tools.**
- Monte Carlo must simulate:
  - Interaction of proton in target
  - Production of pions, kaons in target
  - Propagation of particles through horn (scattering, interactions, field)
  - Propagation through decay volume and loss in beam absorber
  - Meson decays to neutrinos, muons

All of these require knowing hadron interaction physics!

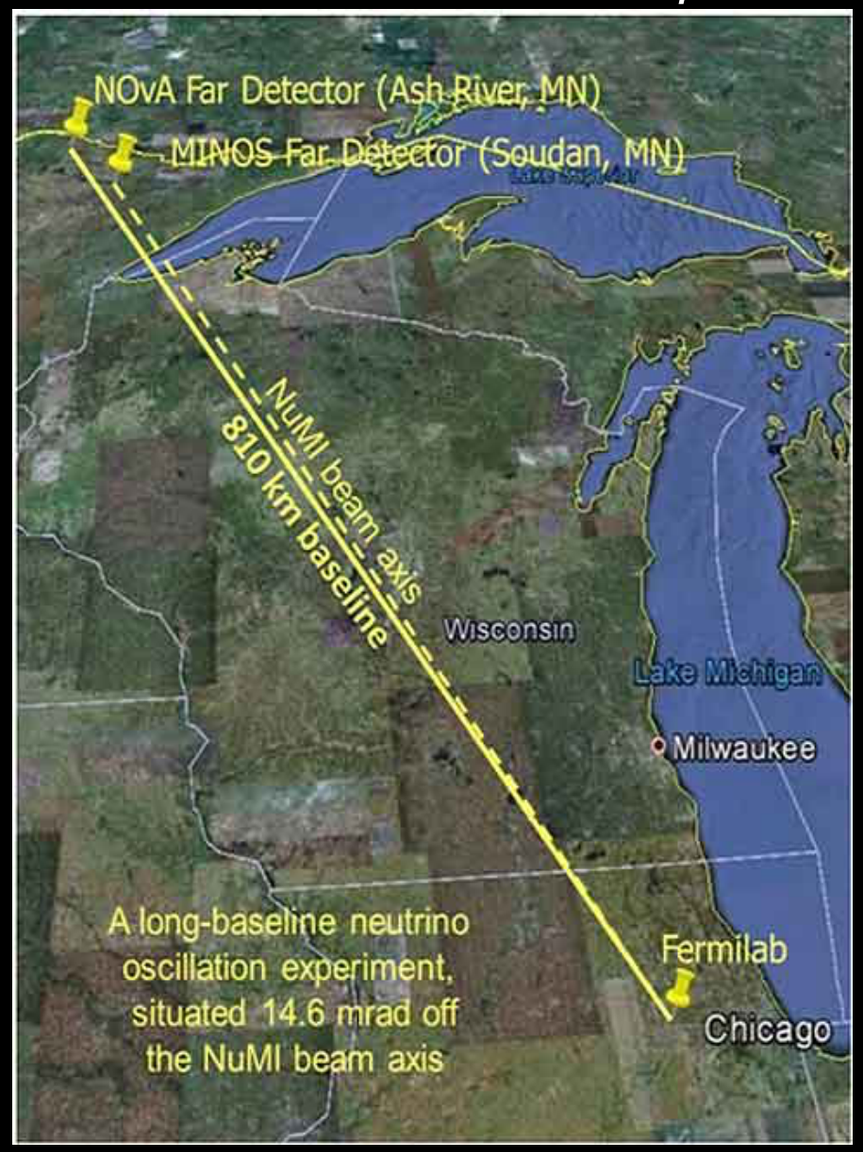
Primary beam energies for current and near future neutrino beams

T2K, T2HK: 31 GeV/*c* *p*

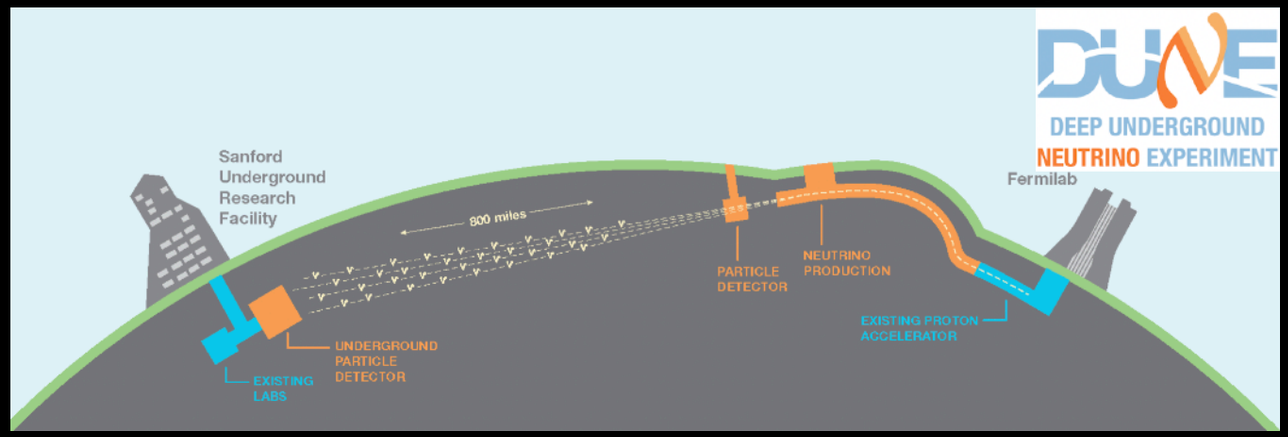


BNB: 8.9 GeV/*c* *p*

NuMI: 120 GeV/*c* *p*



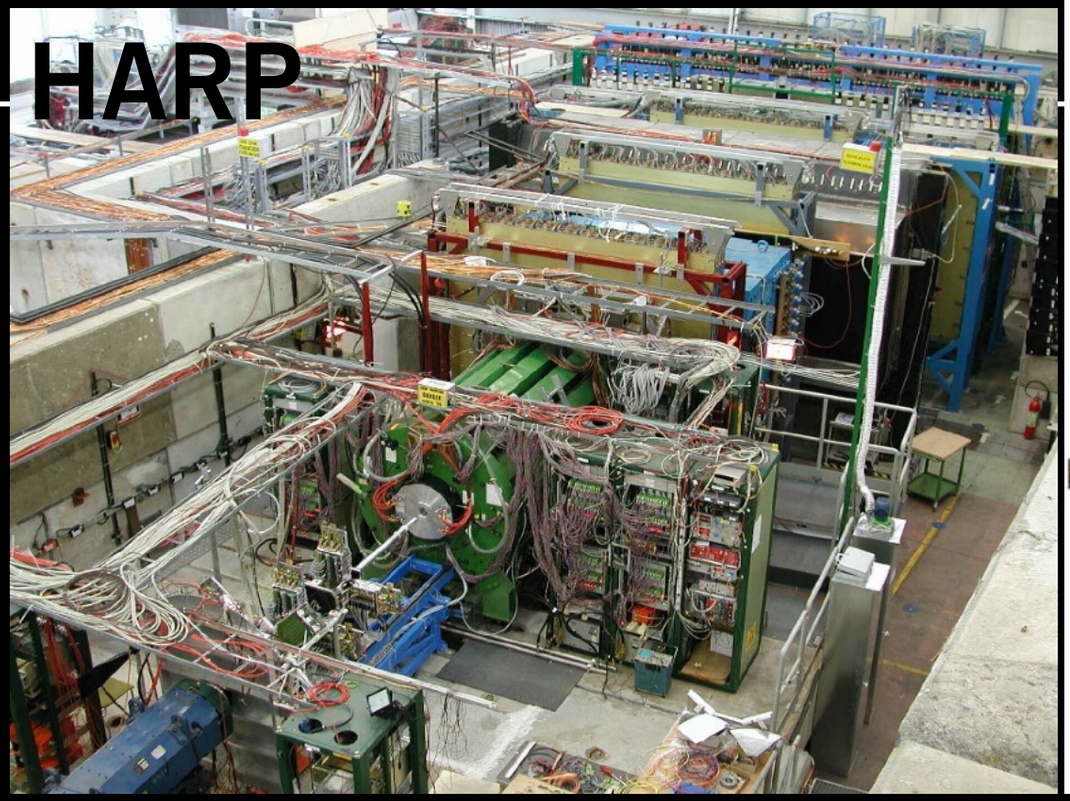
LBNF/DUNE: 60-120 GeV/*c* *p*

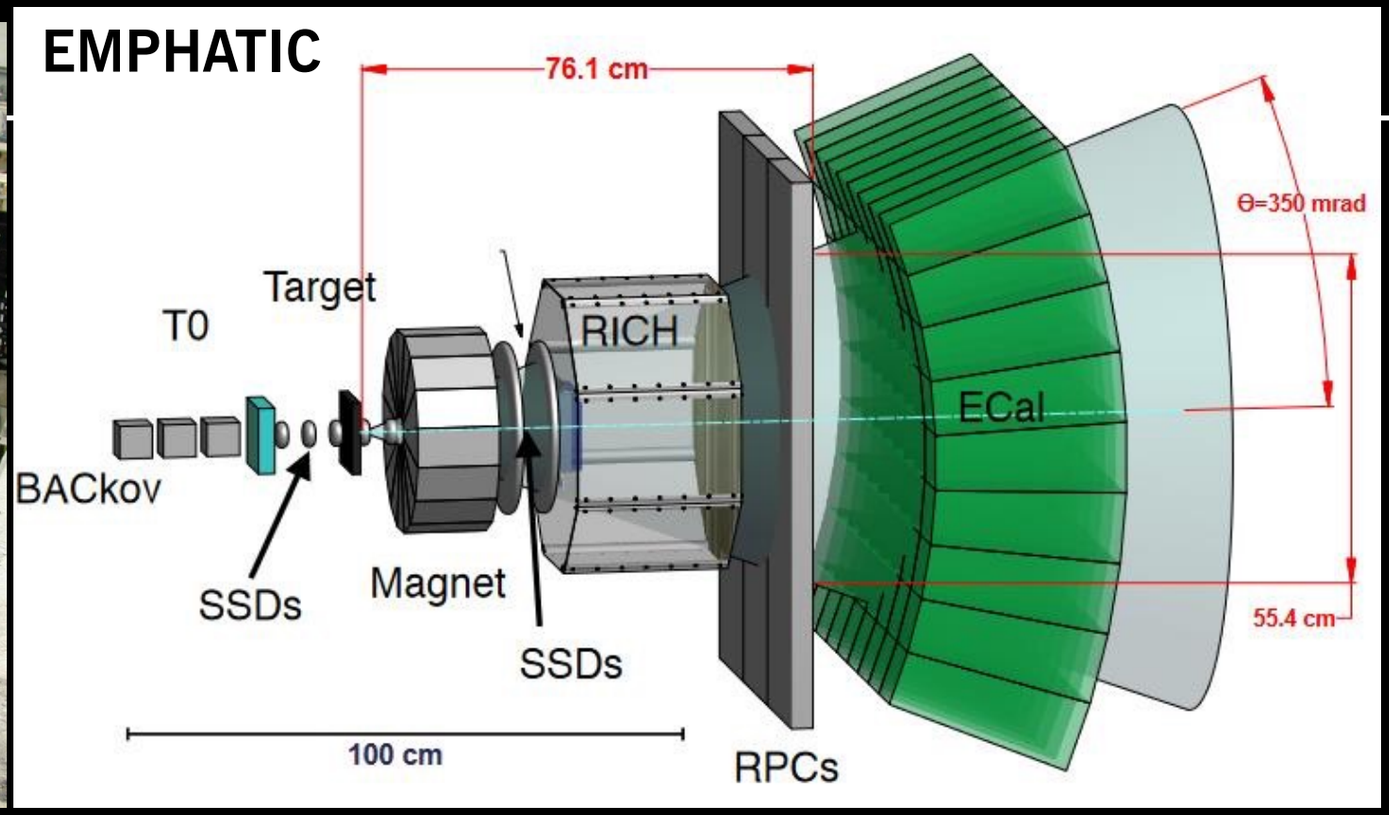


Understanding a neutrino beam

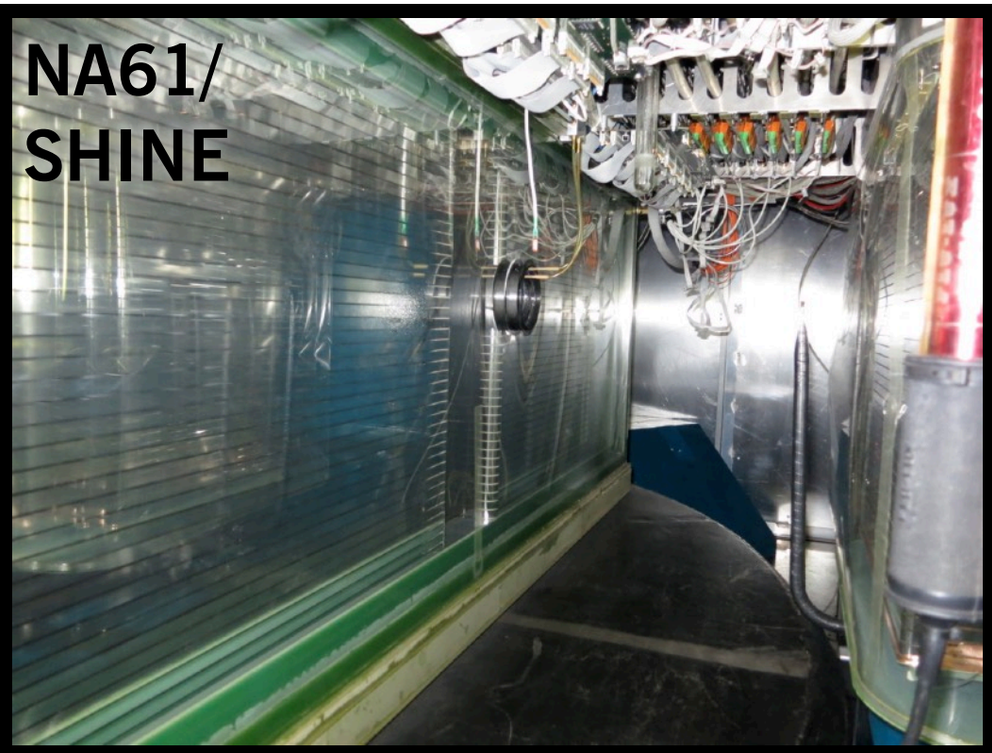
- Two complementary techniques needed to understand the beam well enough to do oscillation measurements
  - Secondary muon monitors for indirect monitoring of pion decays
  - Near neutrino detector
    - Goal is cancellation of flux uncertainties in near/far ratio.
    - Not perfect for constraining flux, due to neutrino cross-section (don't cancel if detectors are different), acceptance/reconstruction differences, and parallax effects due to being near an extended neutrino source
- **Measurement of pion, kaon production and interactions**
  - Essential for measuring neutrino interaction cross-sections
  - Reduces oscillation systematic errors

Dedicated experiments



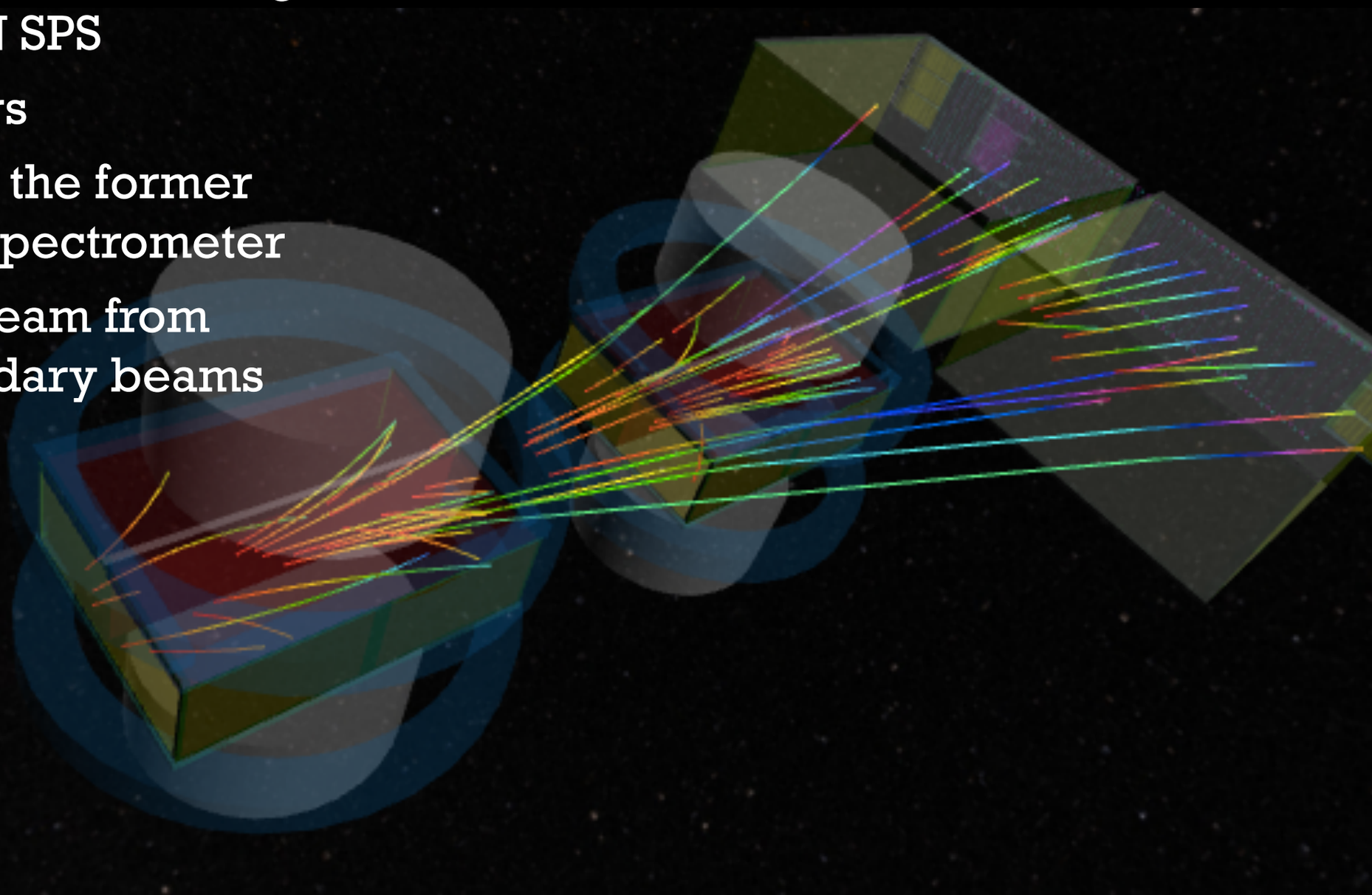


- In recent years, a loose program of hadron production measurements specifically for neutrino experiments has been underway
- HARP (CERN PS)
- EMPHATIC (FNAL MI)
- NA61/SHINE (CERN SPS)



NA61: The SPS Heavy Ion and Neutrino Experiment

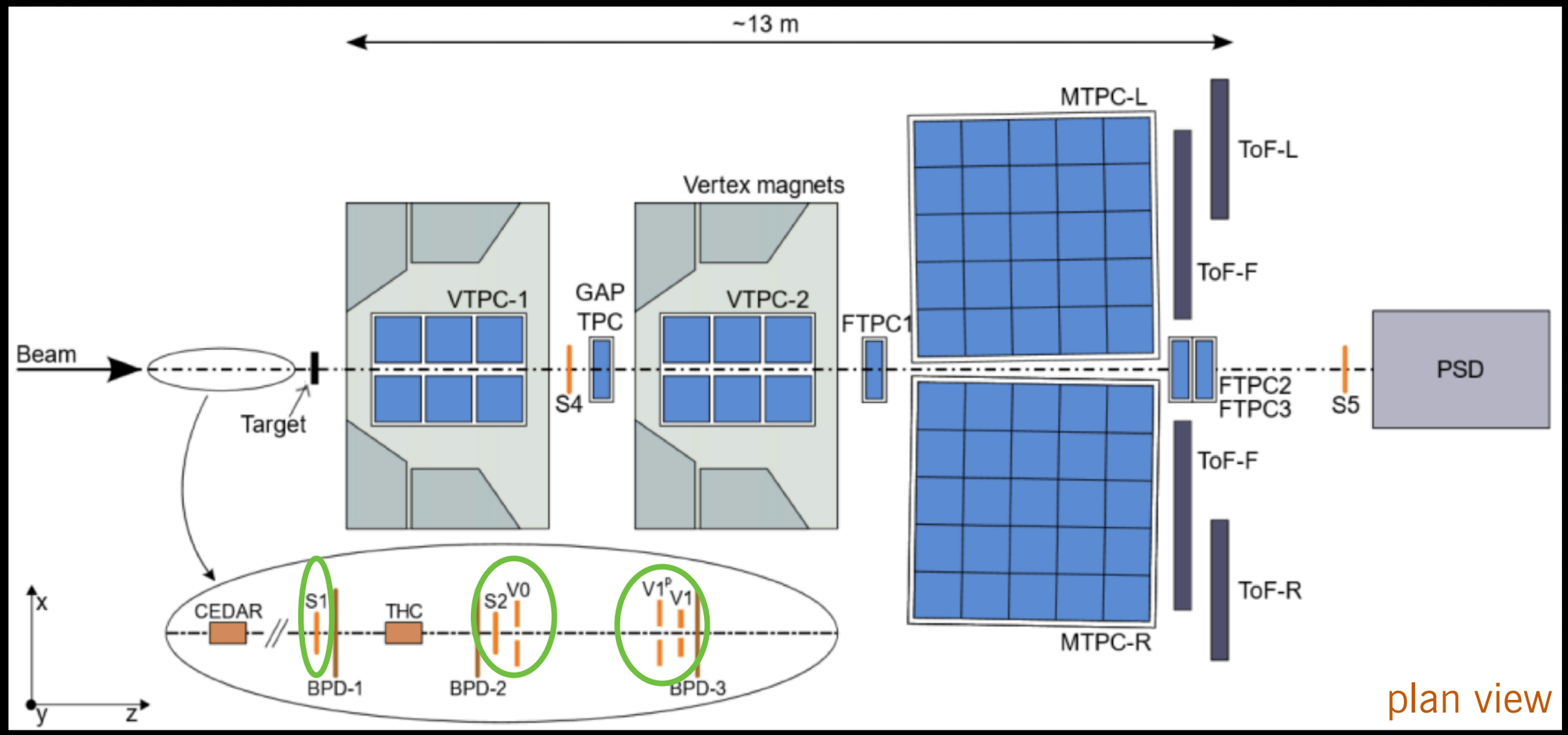
- Fixed-target experiment using H2 beam at CERN SPS
- ~150 collaborators
- Designed around the former NA49 heavy-ion spectrometer
- Primary proton beam from CERN SPS, Secondary beams ~25 to 350 GeV/*c*



NA61: The SPS Heavy Ion and Neutrino Experiment

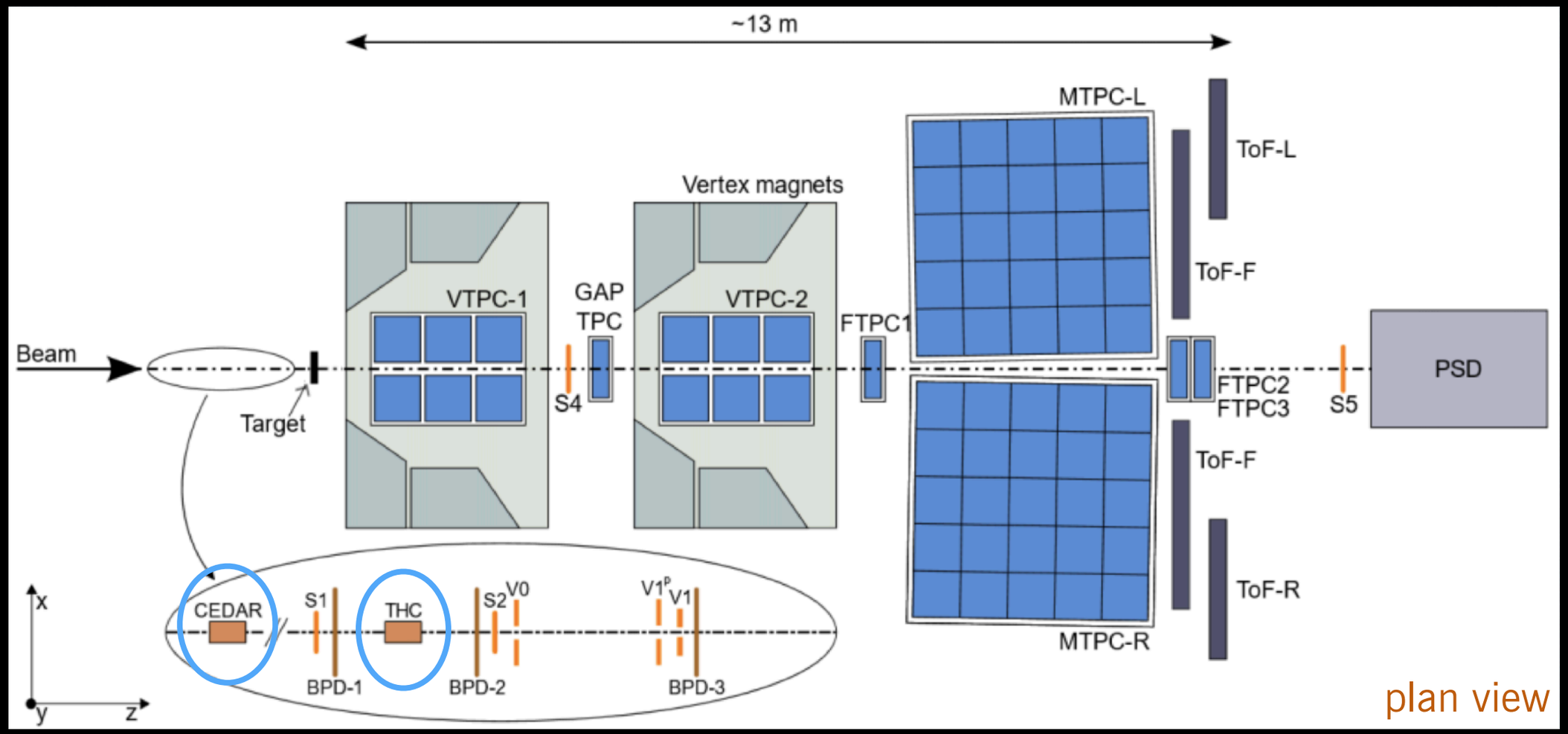
- Diverse physics program includes
  - Strong interactions/heavy ion physics
    - Onset of QCD deconfinement
    - Search for critical point
    - Open-charm production
  - Hadron production for neutrino beams
  - Cosmic ray interaction studies
    - Hadron production for air-shower model predictions
    - $d/\bar{d}$ production for AMS experiment
    - Nuclear fragmentation cross-sections

NA61/SHINE: a large-acceptance multiparticle spectrometer



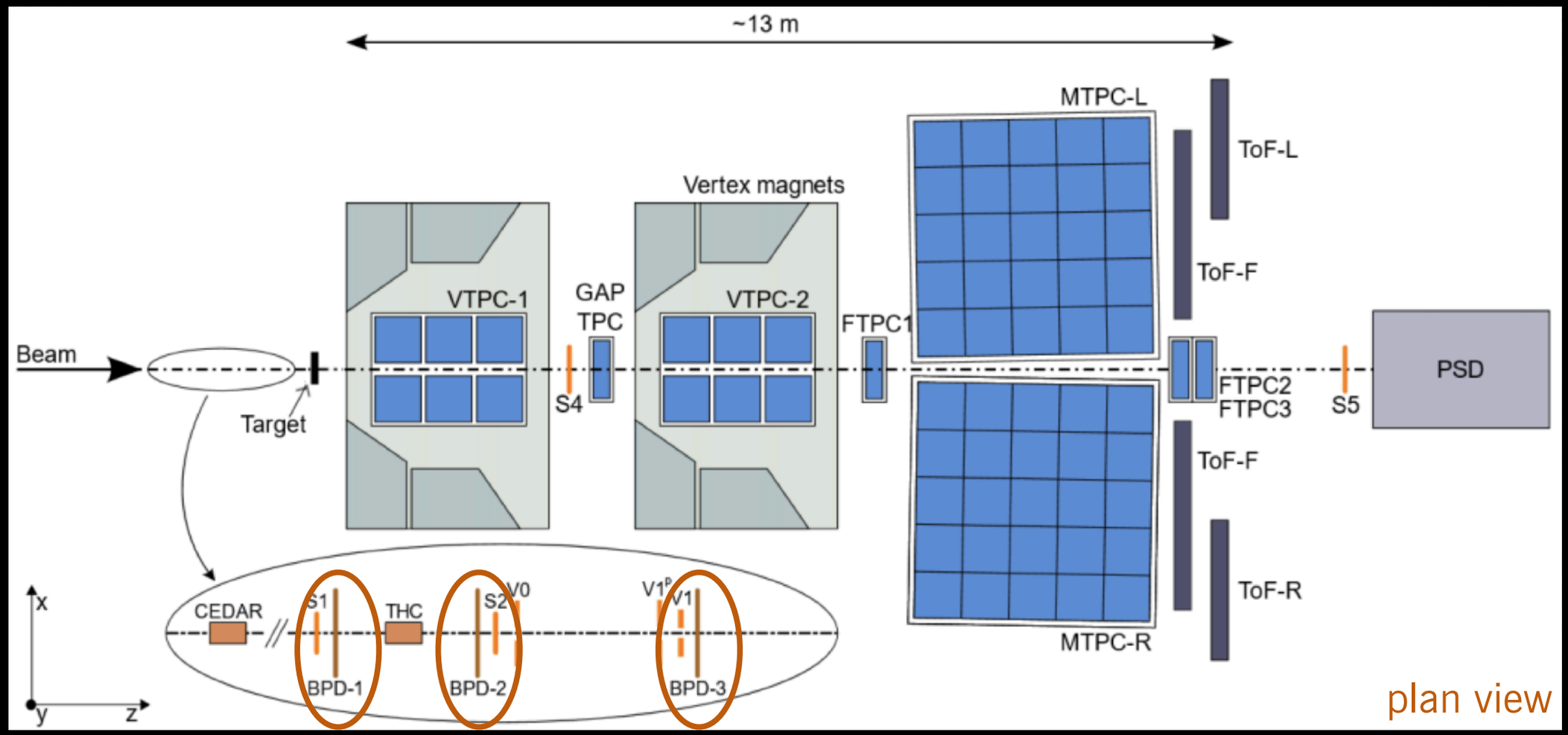
- Beam instrumentation:
  - Scintillators serve as initial trigger and detector timing signal, veto halo particles

NA61/SHINE: a large-acceptance multiparticle spectrometer



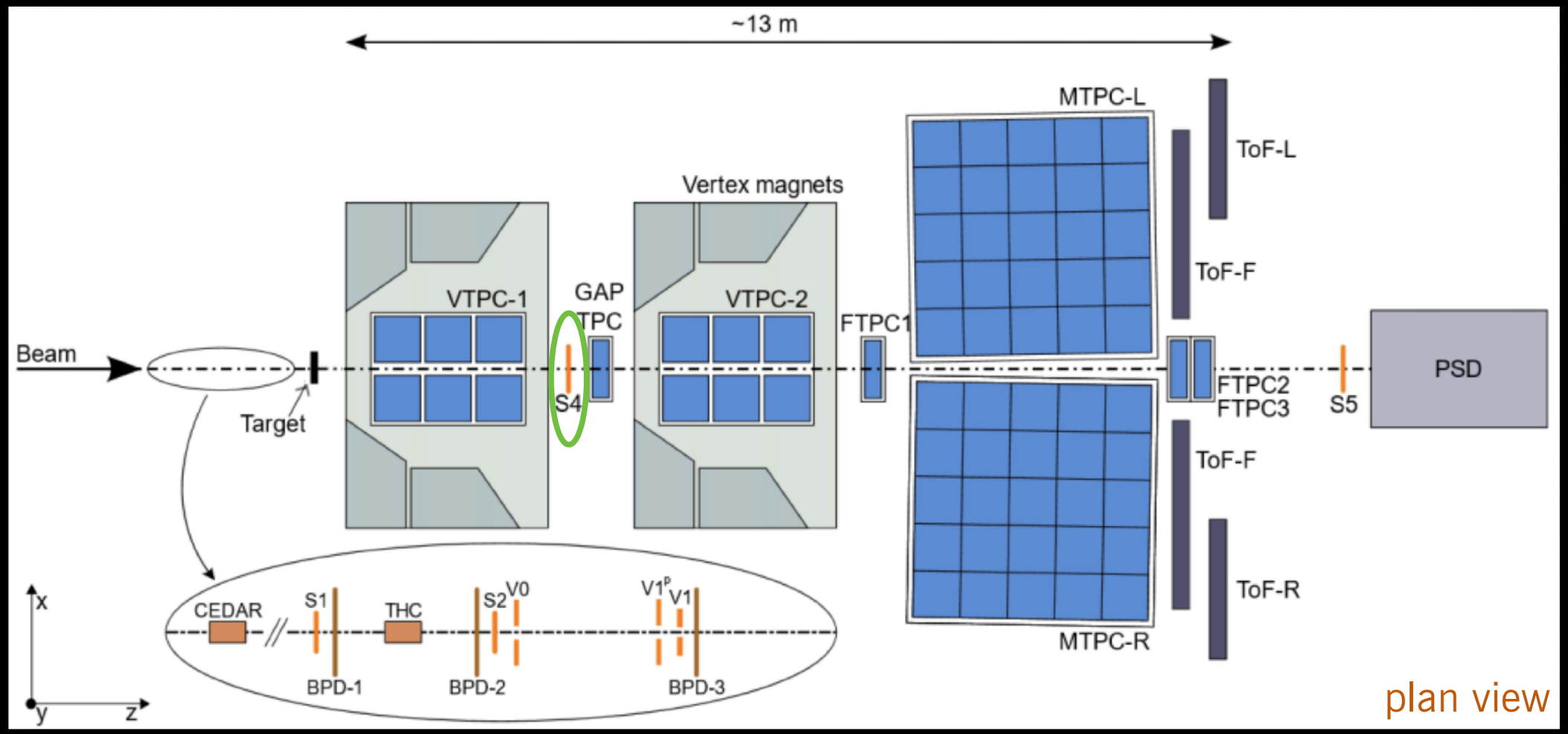
- Beam instrumentation:
  - CEDAR, THC (Threshold Cherenkov) identify beam particles with high accuracy

NA61/SHINE: a large-acceptance multiparticle spectrometer



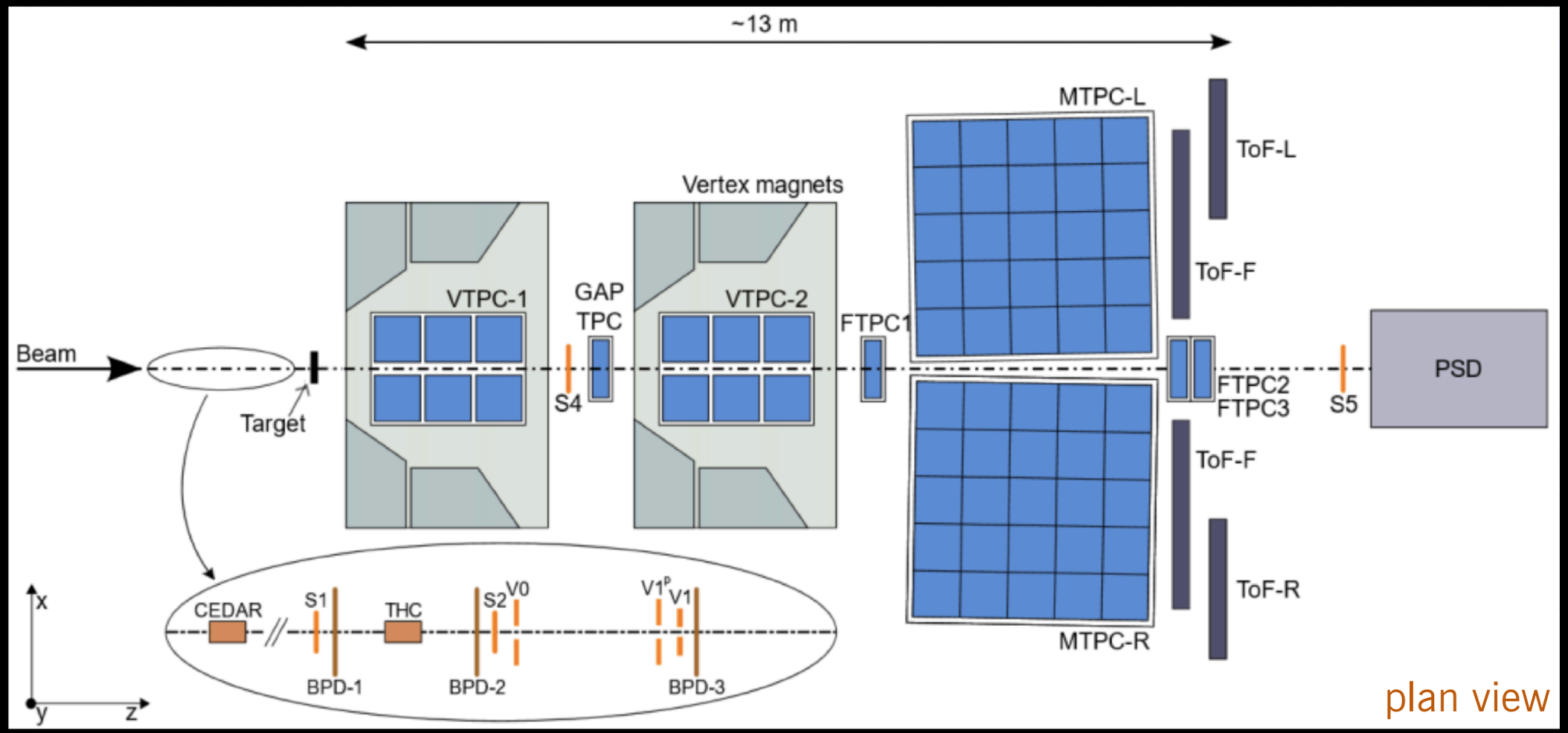
- Beam instrumentation:
  - Beam Position Detectors (BPDs) are MWPC-based tracking detectors that measure transverse position of each beam particle

NA61/SHINE: a large-acceptance multiparticle spectrometer



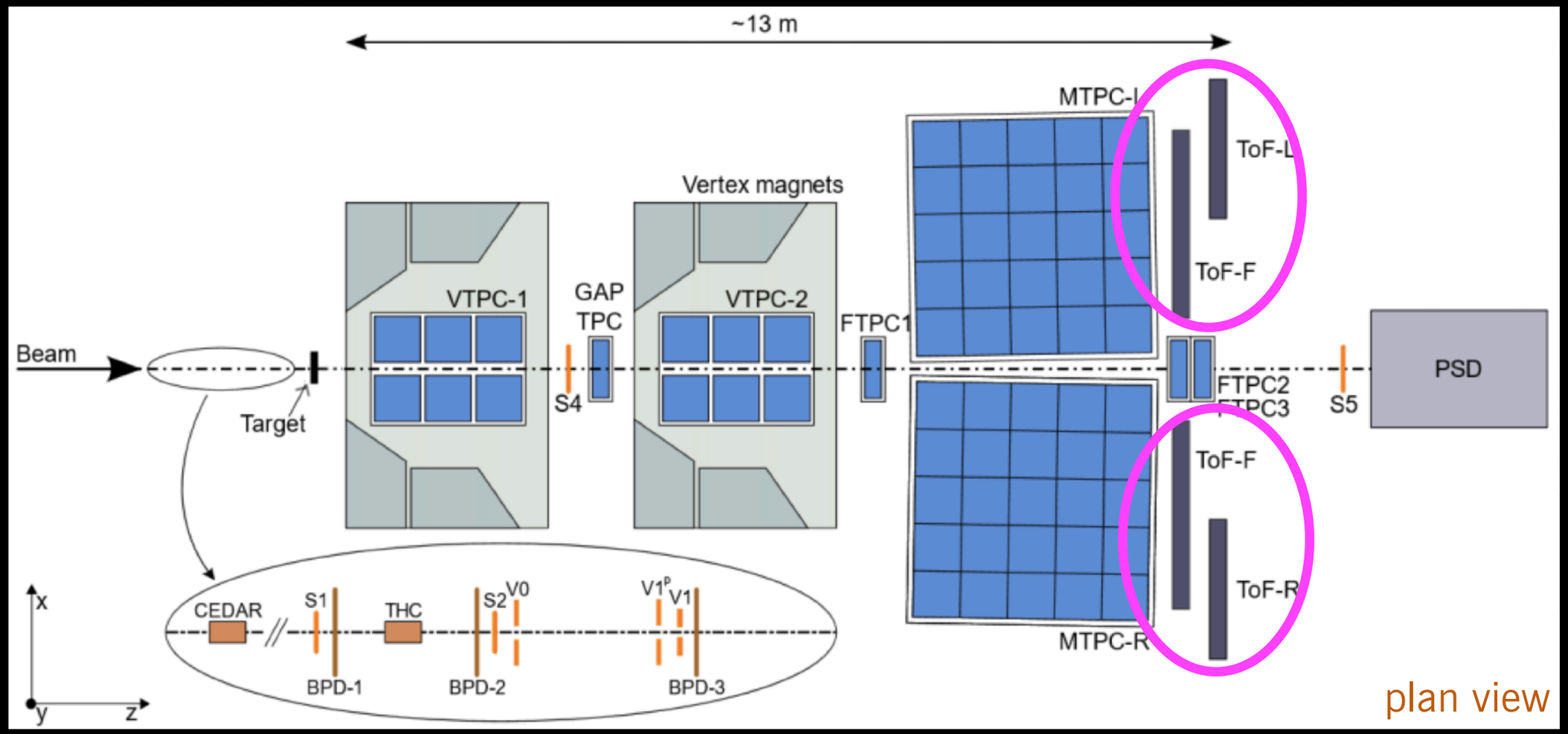
- Beam instrumentation:
  - Additional scintillator S4 in magnetic field can veto beam-momentum forward particles (non-interaction events)

NA61/SHINE: a large-acceptance multiparticle spectrometer



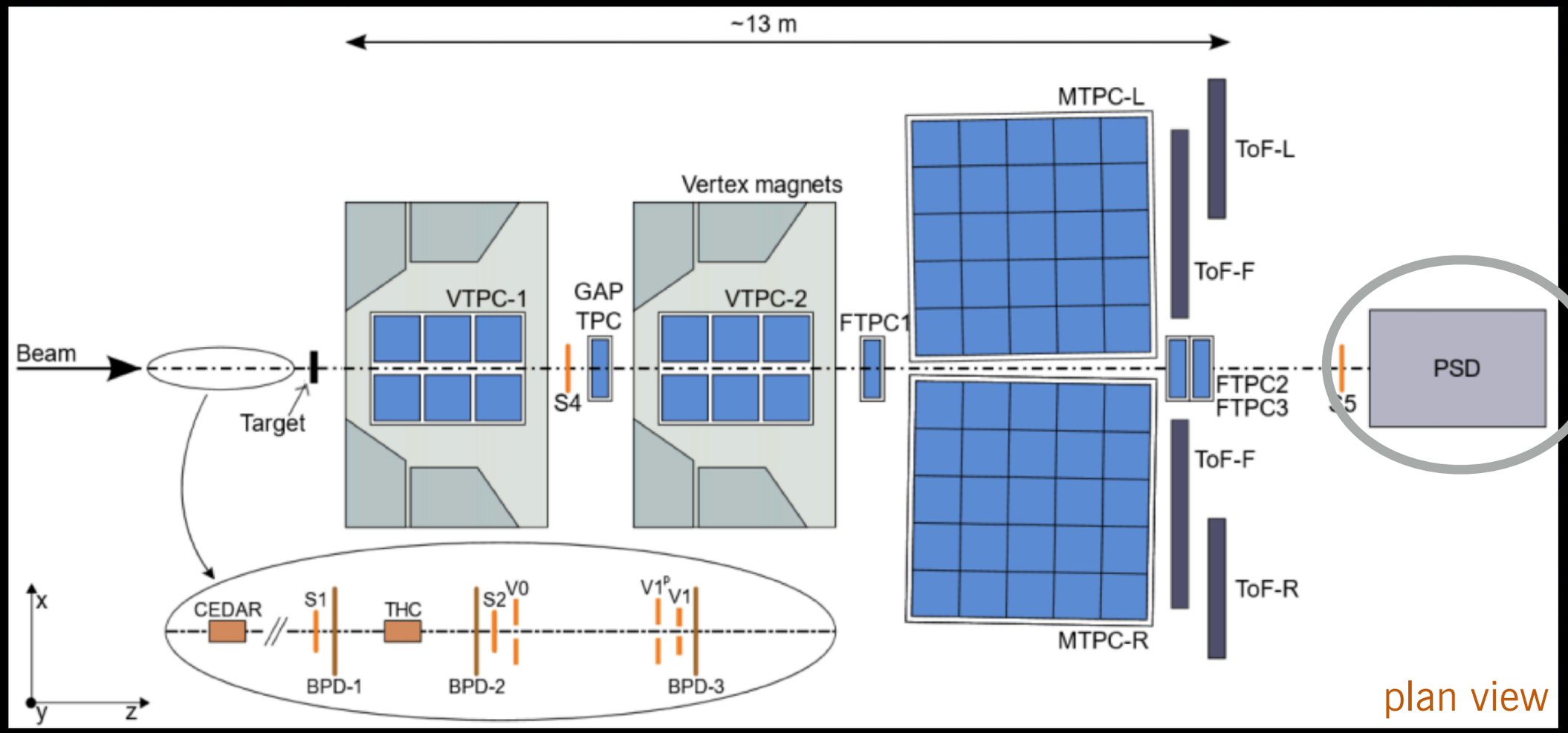
- Several large-acceptance TPCs provide charged-particle tracking and measure dE/dx.
- VTPC-1 and VTPC-2 sit inside superconducting analysis magnets for momentum measurement

NA61/SHINE: a large-acceptance multiparticle spectrometer



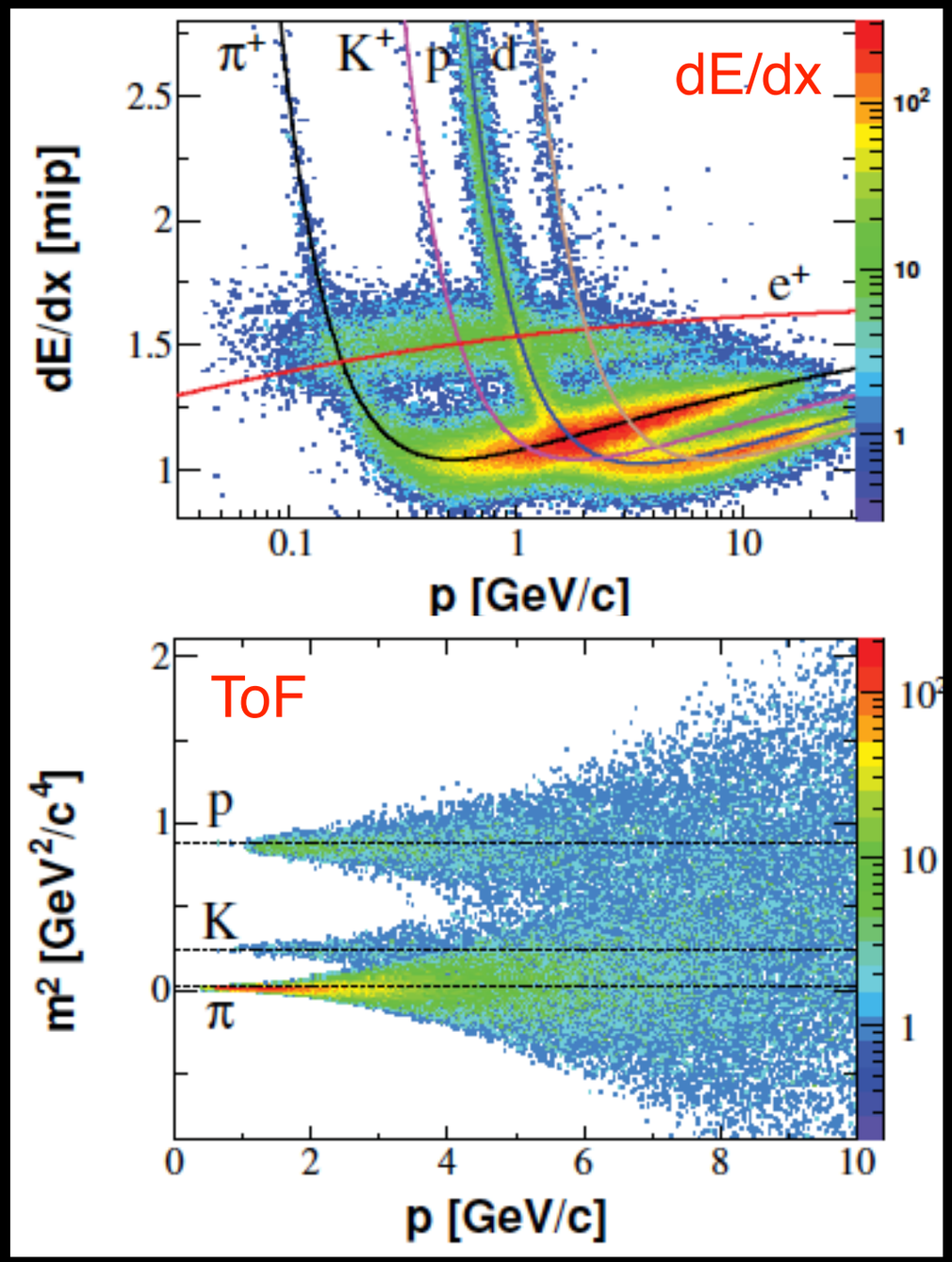
- Scintillator and multilayer resistive plate chamber (MRPC) time-of-flight detectors

NA61/SHINE: a large-acceptance multiparticle spectrometer

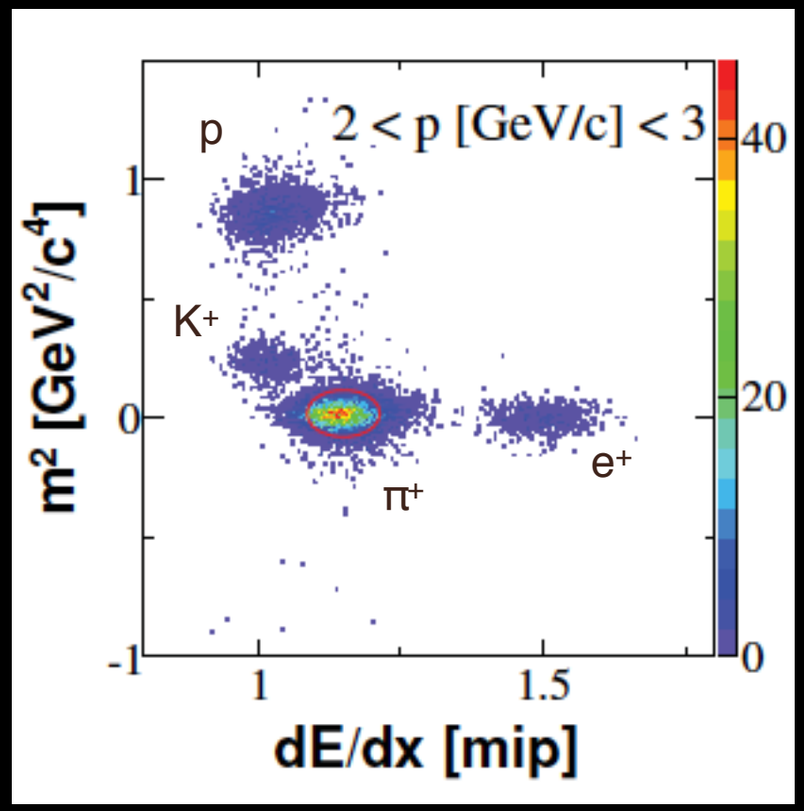


- Projectile Spectator Detector: forward hadron calorimeter (not used much for neutrino measurements)

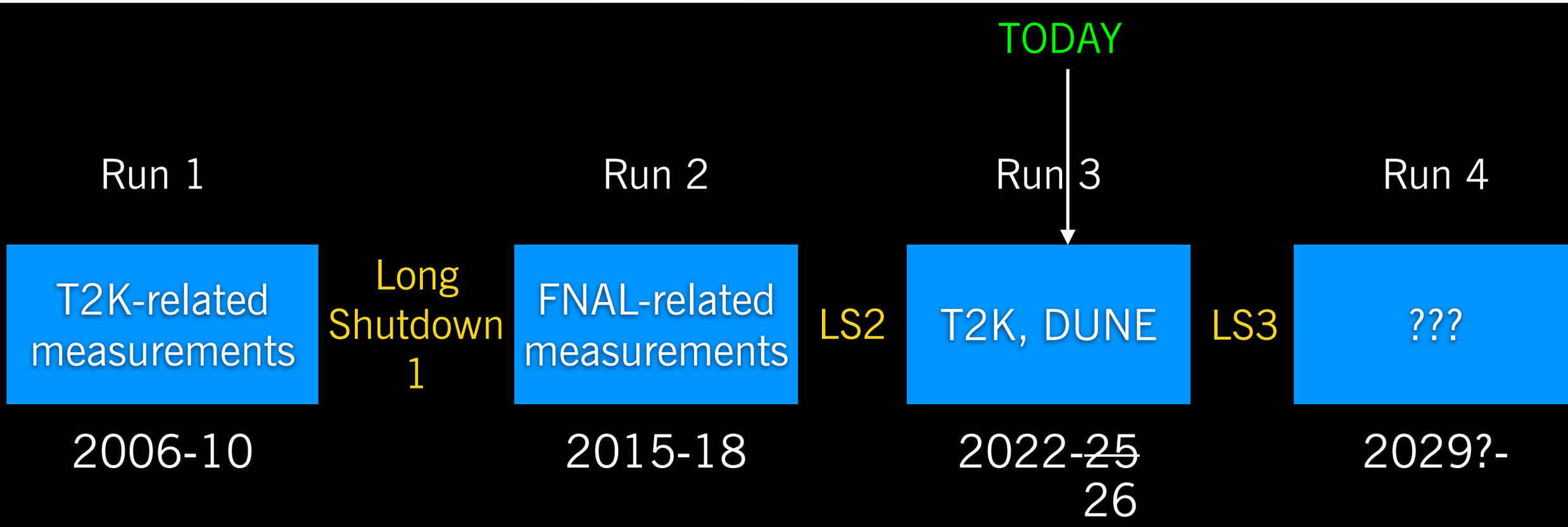
Particle identification



- Uses dE/dx in TPCs at higher momentum
- Transitions to TOF at lower p



NA61/SHINE operational eras

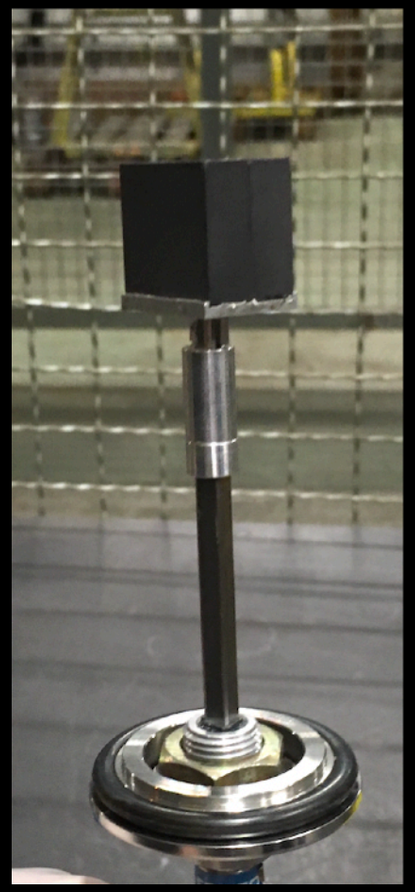


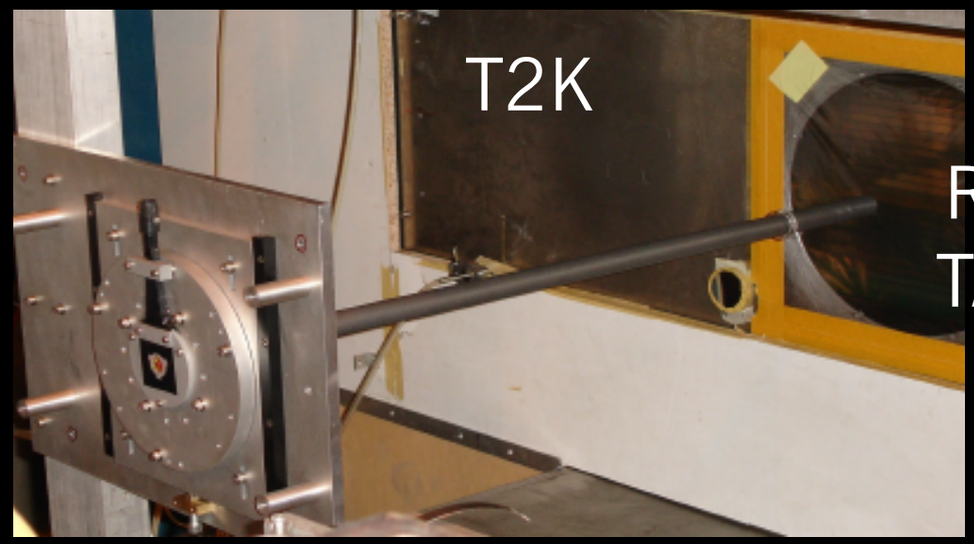
- Multi-phase program of hadron production measurements dedicated for neutrino physics
- Major upgrades during each Long Shutdown
- Plans continue to evolve for future upgrades and operations

Twin approaches: thin- and replica-target measurements

- Need thin-target measurements to measure physics cross-sections (total inelastic and production cross-sections, and differential spectra), for inputs to generators
- Need measurements on replica (~meter-long) targets of same material and geometry as neutrino production targets.
  - Measure both beam survival probability and differential yields.
  - Make measurements specifically for each neutrino beam.
  - Usually use results to re-weight particles in beam MC at surface of target

Graphite thin target
(1.5 cm, 3.1% of λ_I)





REPLICA TARGETS

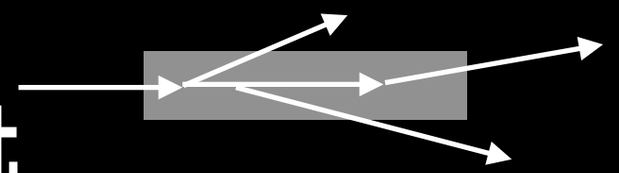
NA61/SHINE measurements for T2K

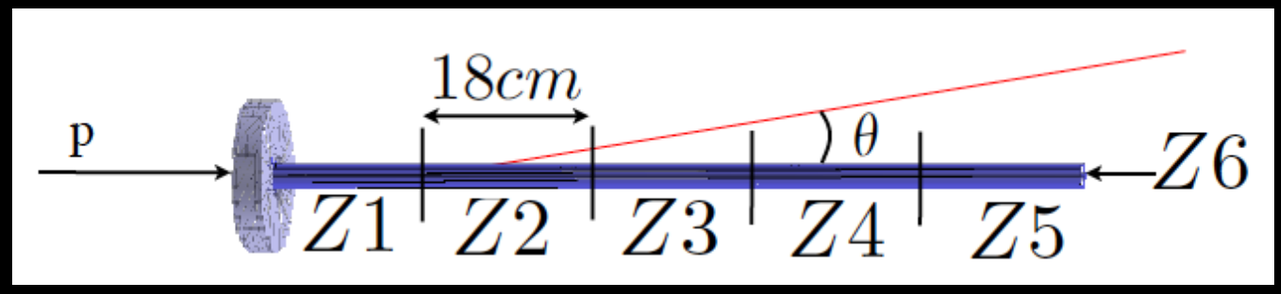
- NA61/SHINE took thin- and thick- target data with 30 GeV/c protons specifically for T2K in **2007 (thin) 2009 (thin and replica)**, and **2010 (replica)**.
- Eight NA61/SHINE publications have come out of these data sets

THIN TARGET	
Total xsec, pion spectra	Phys. Rev. C84 034604 (2011)
K^+ spectra	Phys. Rev. C85 035210 (2012)
K^0_S and Λ^0 spectra	Phys. Rev. C89 025205 (2014)
$\pi^\pm$,$K^\pm$, p, K^0_S, Λ^0 spectra	Eur. Phys. J. C76 84 (2016)

T2K REPLICA TARGET	
methodology, $\pi^\pm$ yield	Nucl. Instrum. Meth. A701 99-114 (2013)
$\pi^\pm$ yield	Eur. Phys. J. C76 617 (2016)
$\pi^\pm$,$K^\pm$, p yield	Eur. Phys. J. C79 100 (2019)
p beam survival probability	Phys. Rev. D103 012006 (2021)

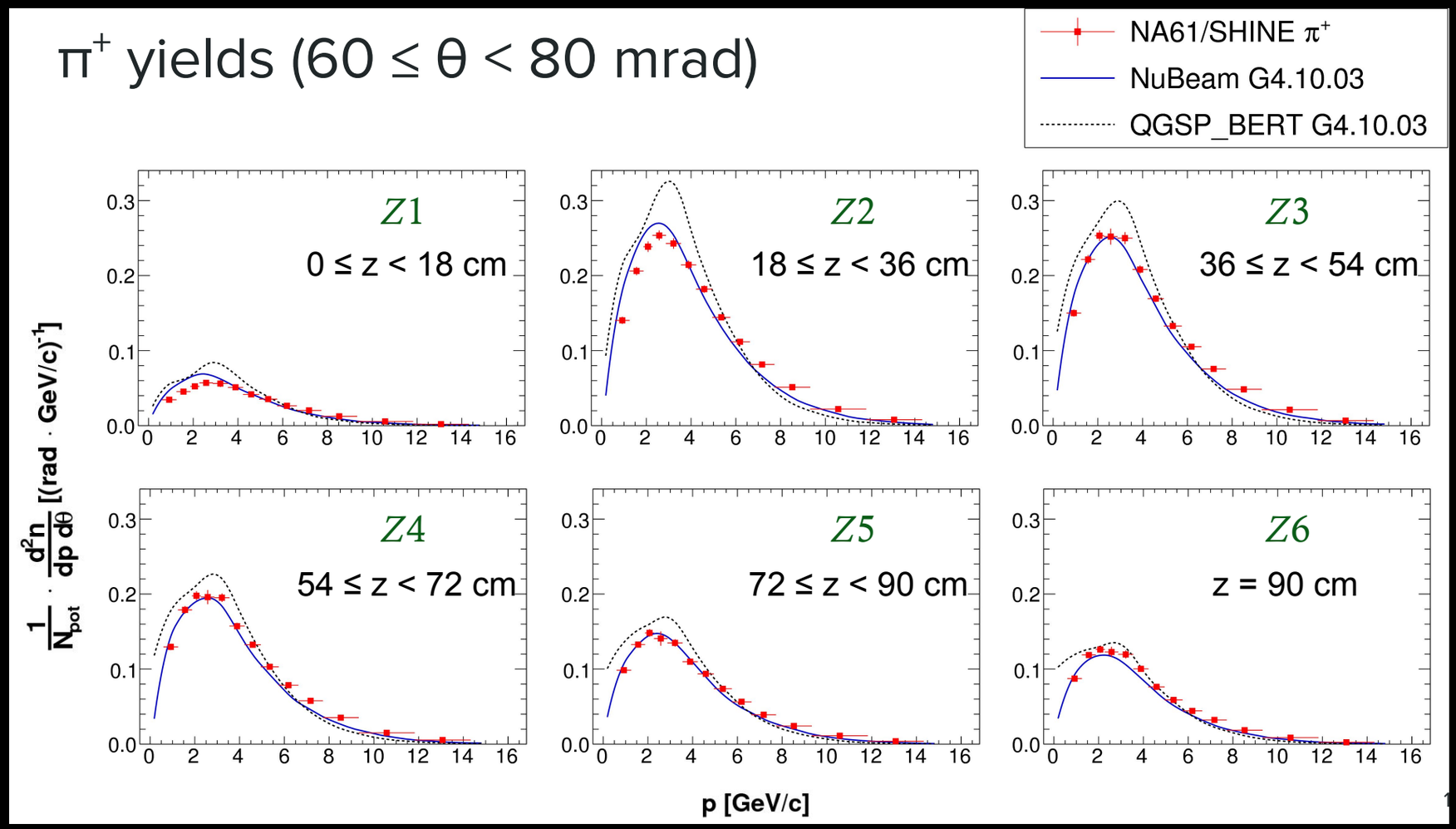
NA61 result: full differential yields from T2K replica target





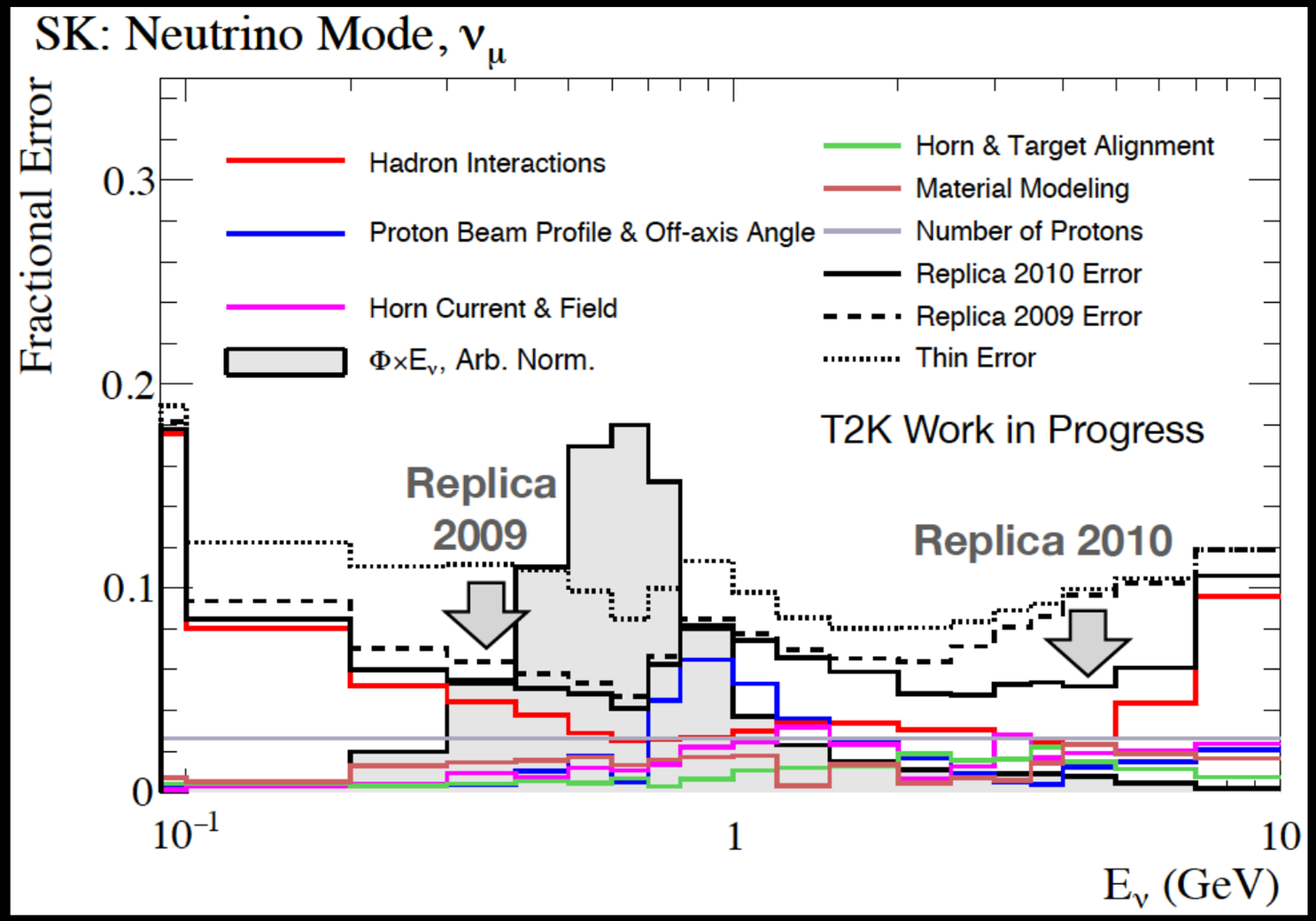
- *Eur.Phys.J.* **C 79** 2, 100 (2019)
- Showing one angle bin of π^+ for illustration.

  Also have π^-, $K^\pm$, p yields



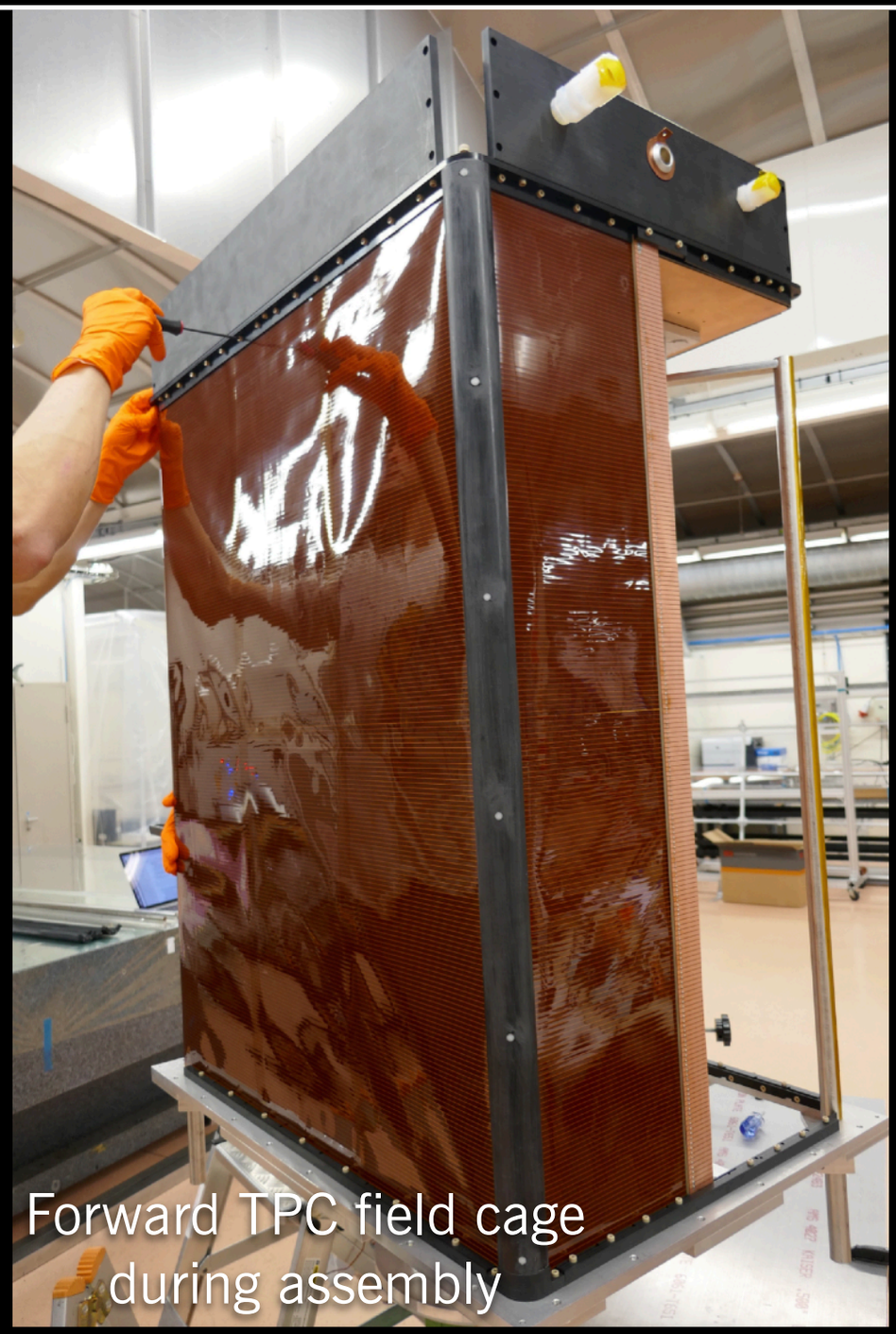
NA61/SHINE measurements for T2K

- Steady improvements to the T2K flux prediction (described in Phys.Rev. D87 (2013) no.1, 012001 and J.Phys.Conf.Ser. 888 (2017) no.1, 012064) as more NA61 data sets have been incorporated:
  - first thin-target
  - 2009 replica
  - 2010 replica data set (which added statistics and included kaon yields)



2015-18: A second phase of NA61 neutrino measurements

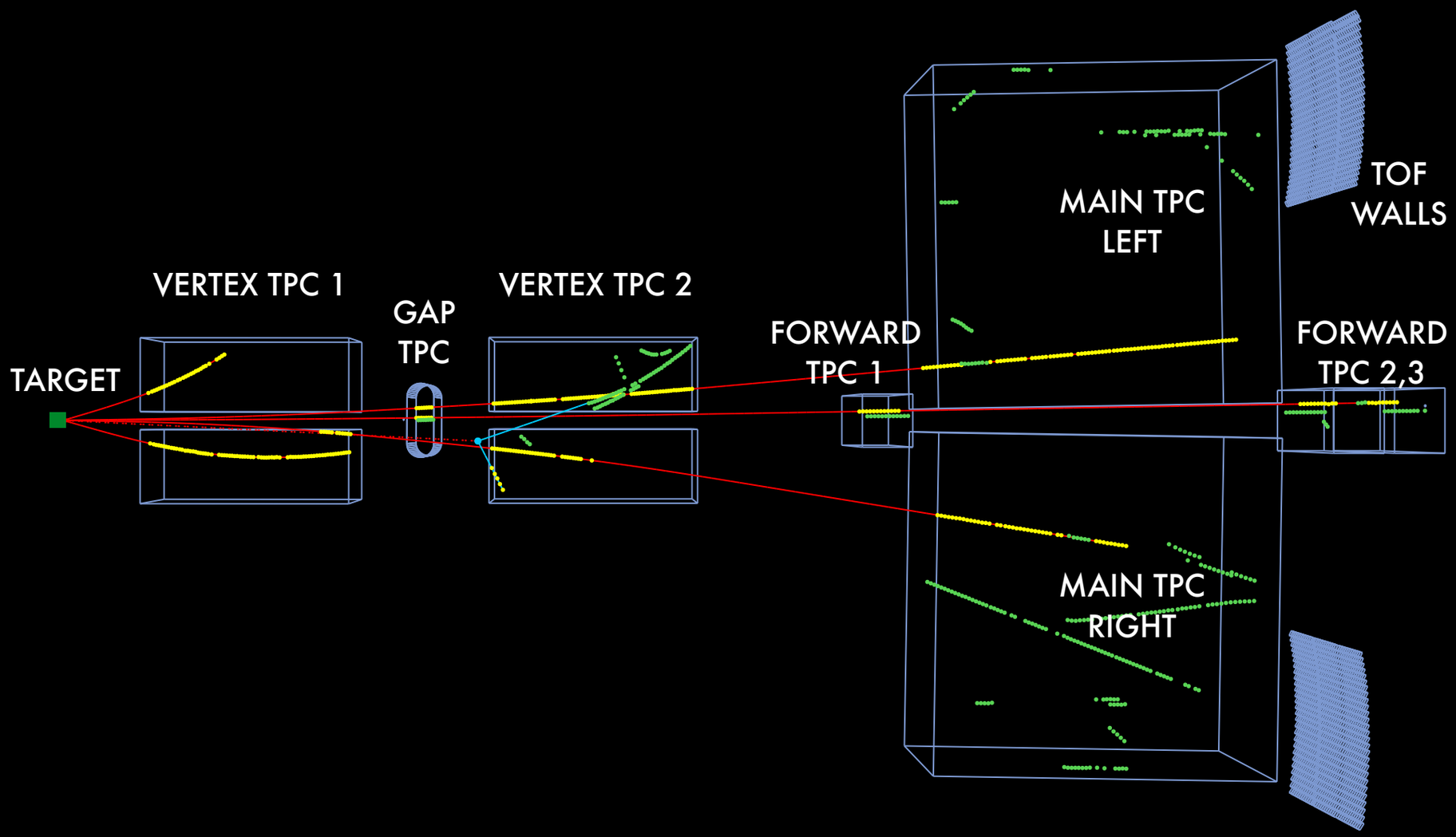
- Motivation: new coverage will be needed for DUNE, can help existing experiments as well in shorter term
- Project made specific upgrades:
  - Forward tracking system filled hole in zero-angle acceptance
    - New tandem TPC concept for rejecting out-of-time tracks: JINST 15 (07), P07013
  - New readout electronics for time-of-flight detector
- Data collected in 2015-18 for this program



Forward TPC field cage during assembly

Event display

120 GeV p+C



NA61 2016-17 neutrino data
Thin targets

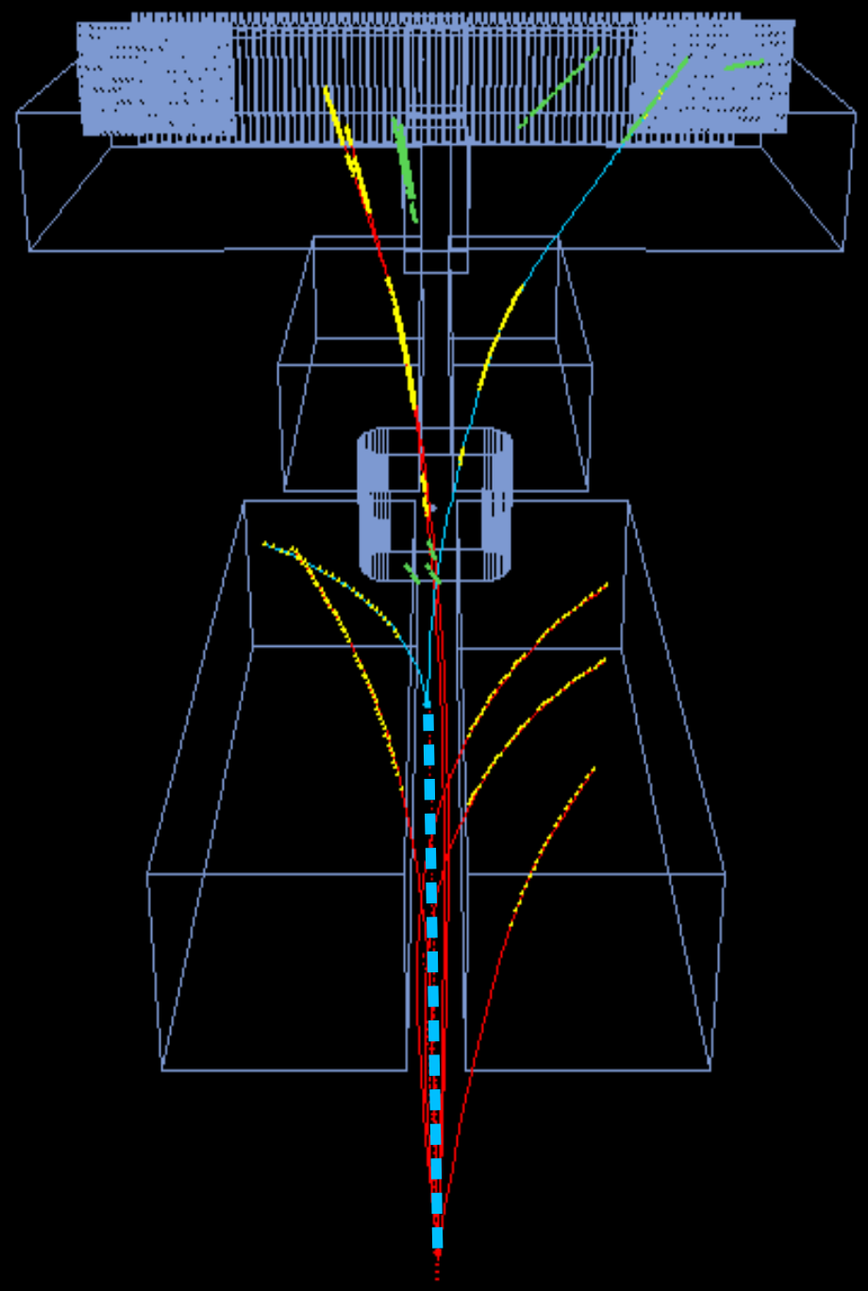
2016	2017
● p + C @ 120 GeV/c	π^+ + Al @ 60GeV/c
▲ p + Be @ 120 GeV/c	π^+ + C @ 30 GeV/c
■▲ p + C @ 60 GeV/c	π^- + C @ 60 GeV/c ■
● p + Al @ 60 GeV/c	p + C @ 120 GeV/c (w FTPCs) ●
● p + Be @ 60 GeV/c	p + Be @ 120 GeV/c (w FTPCs)
● π^+ + C @ 60GeV/c	p + C @ 90 GeV/c (w FTPCs) ■
● π^+ + Be @ 60 GeV/c	

● Published (▲no spectra) ■ Publication in progress ■ Advanced analysis

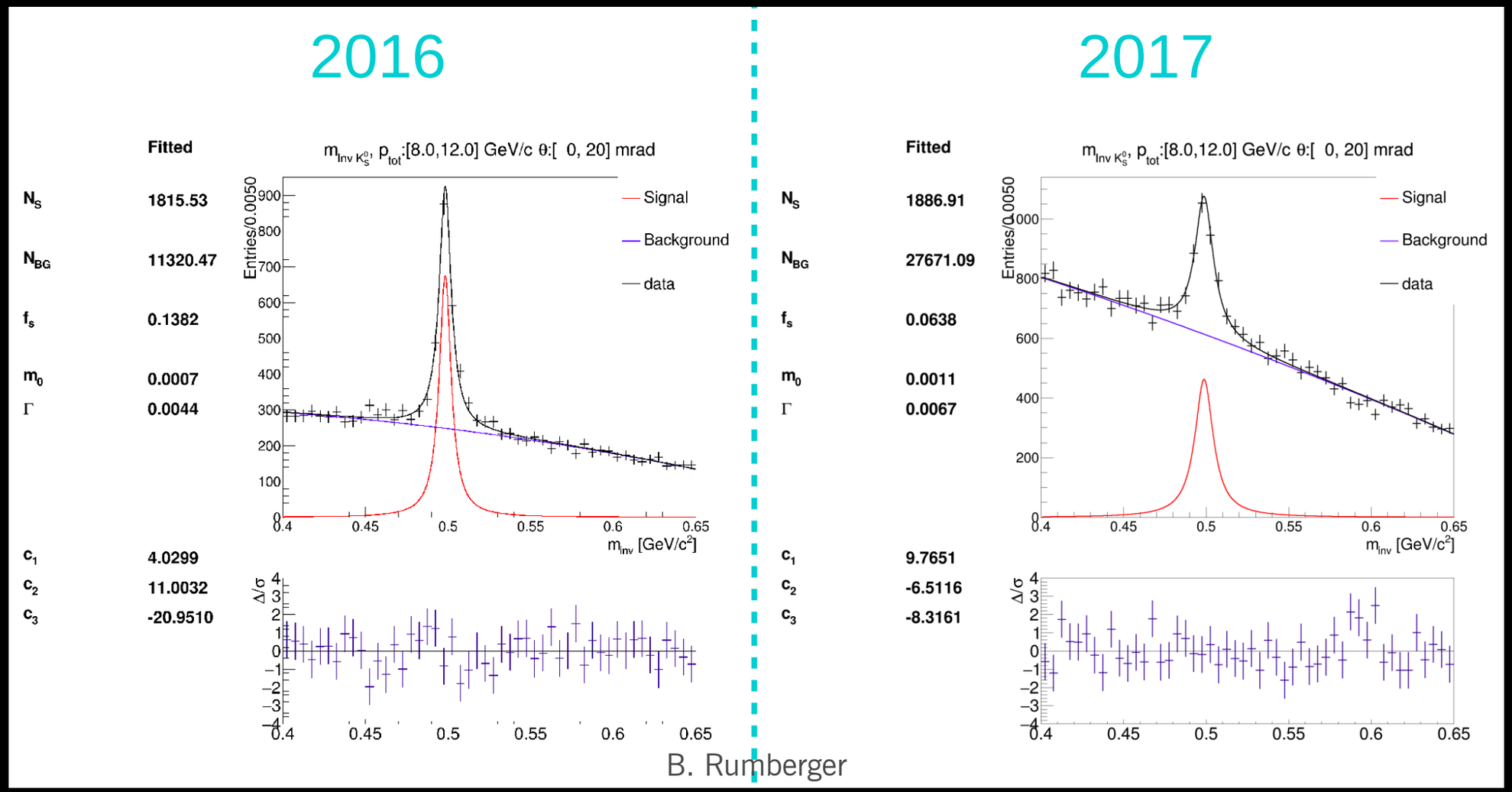
- Full particle yields and spectra from these data sets
- Goal with these measurements is to span the phase space of primary and secondary interactions in neutrino targets and surrounding materials
- Each measurement becomes a point for interpolation in MC generators

Results on spectra from thin-target p+C @ 120 GeV

- This data set is high priority: represents the primary proton interaction in NuMI/NOvA/MINERvA.
- Relies on new Forward TPCs to see elastic, quasi-elastic events
- New tracking algorithm is used for integrating the FTPCs into the analysis:
  - Cellular automaton-based local tracking with Kalman filter for global track fit
- Charged and neutral particle yields from ~3 million interactions



p+C @ 120 GeV
K^0_S invariant mass fits

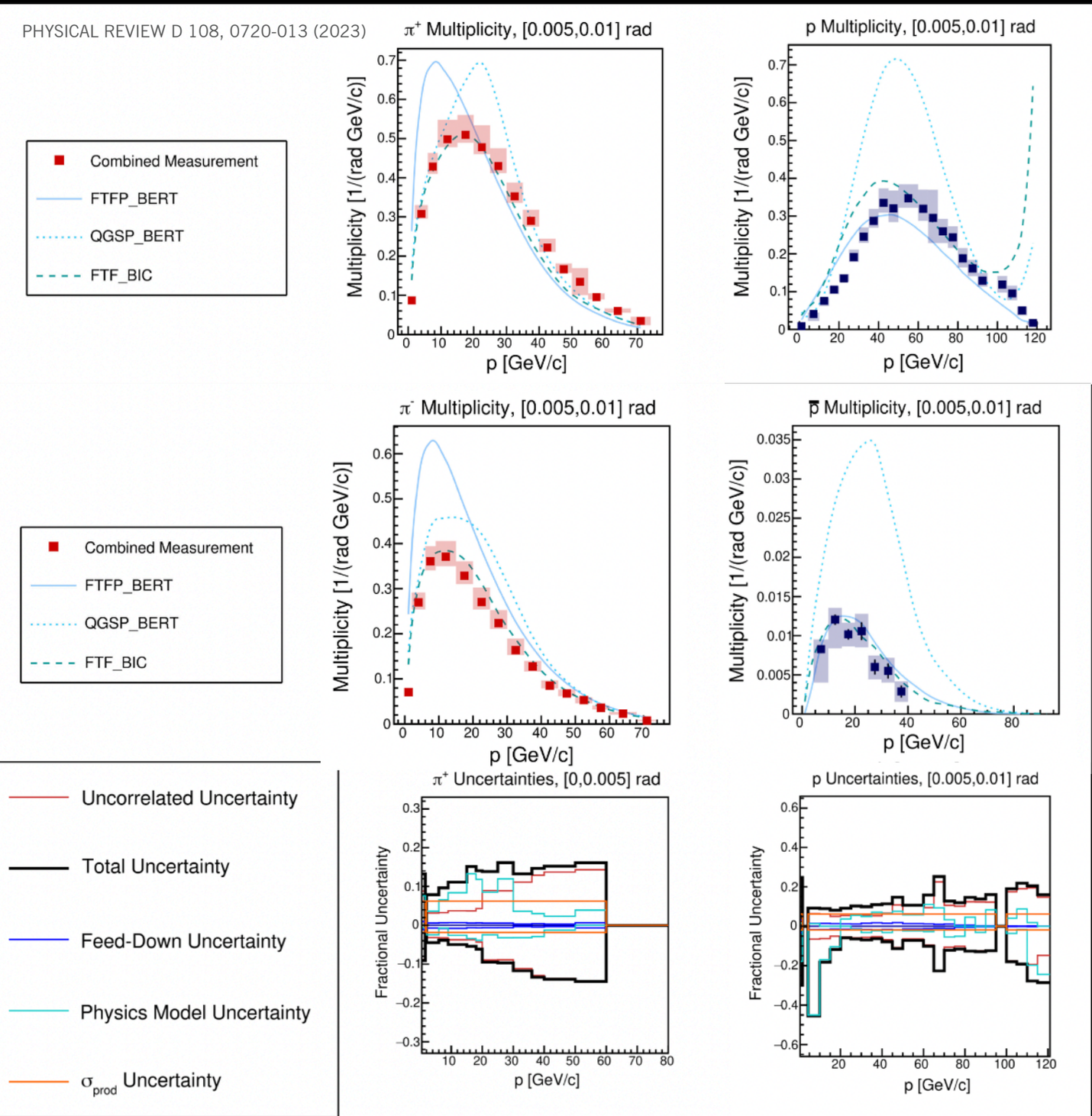


B. Rumberger

- 2016: Higher magnetic field, no forward TPCs
- 2017: Lower magnetic field, full forward TPC system

p+C @ 120 GeV Charged hadron multiplicities: published last year

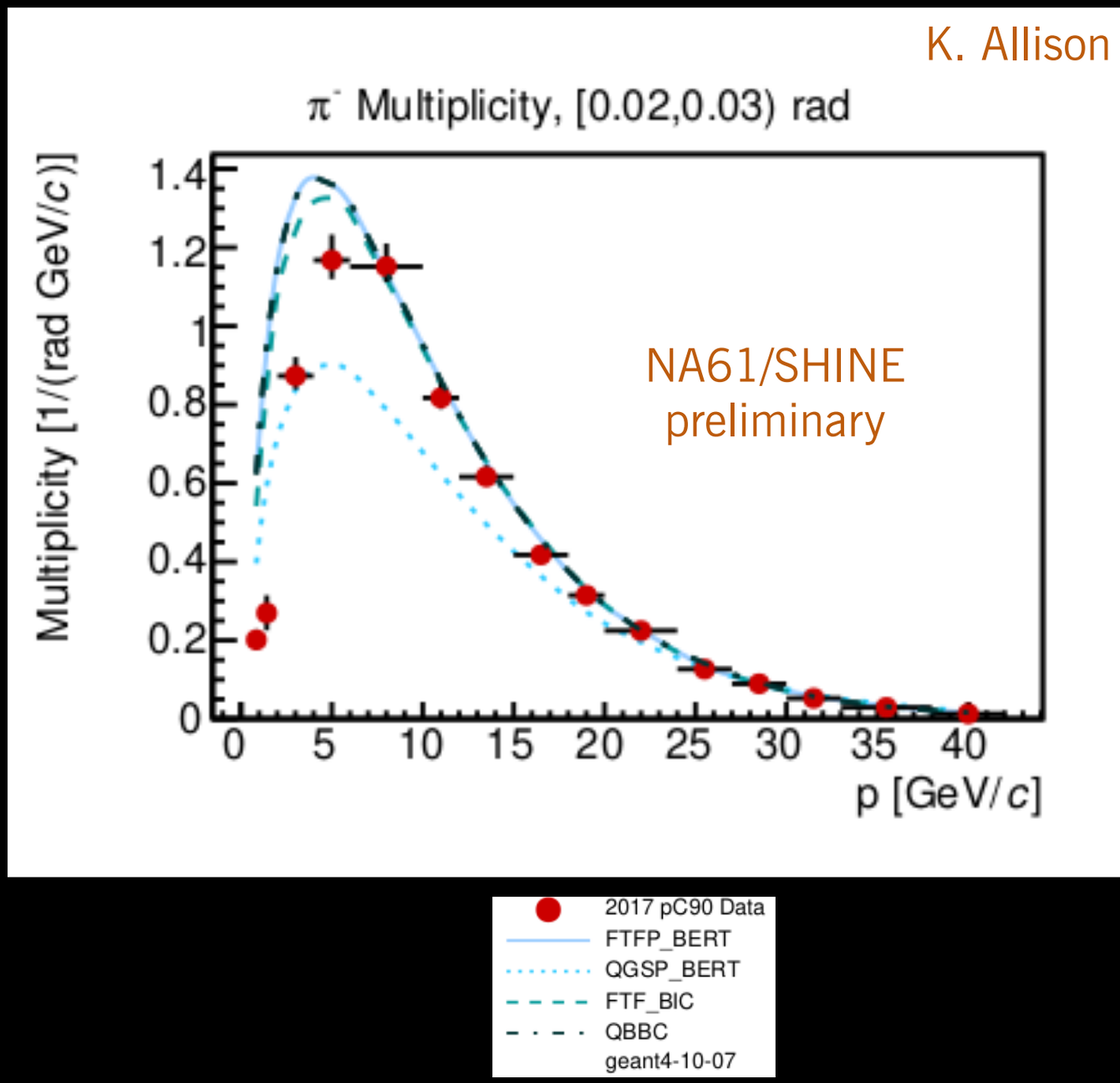
- Measured multiplicities: π^+, π^-, p, $\bar{p}$, K^+, K^-
- Neutral hadron multiplicities used to estimate backgrounds from with weak neutral decay products
- Two complementary data sets again combined for final multiplicity result
- Results will soon be used to reduce DUNE beam flux uncertainties
- 2016, 2017 data sets combined



p+C 90 GeV/c

- Differential multiplicities for the charged and neutral analysis of the p+C 90 GeV/c dataset
- Newest NA61 result - publication in progress
- One angular bin for selected samples shown
- Have results on $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, K^0_S, Λ, $\bar{\Lambda}$

K. Allison



PPFX: Package to Predict FluX

L. Ren

- Developed by the MINERvA collaboration for the NuMI beam
- Experiment-independent neutrino flux determination package for the Neutrinos at the Main Injector (NuMI) beam
  - MINERvA Collaboration, Phys. Rev. D 94, 092005, Leonidas Aliaga Soplin, PhD thesis
- Provides hadron production corrections and propagate uncertainties
- Uses external hadron production data

PPFX: Package to Predict FluX

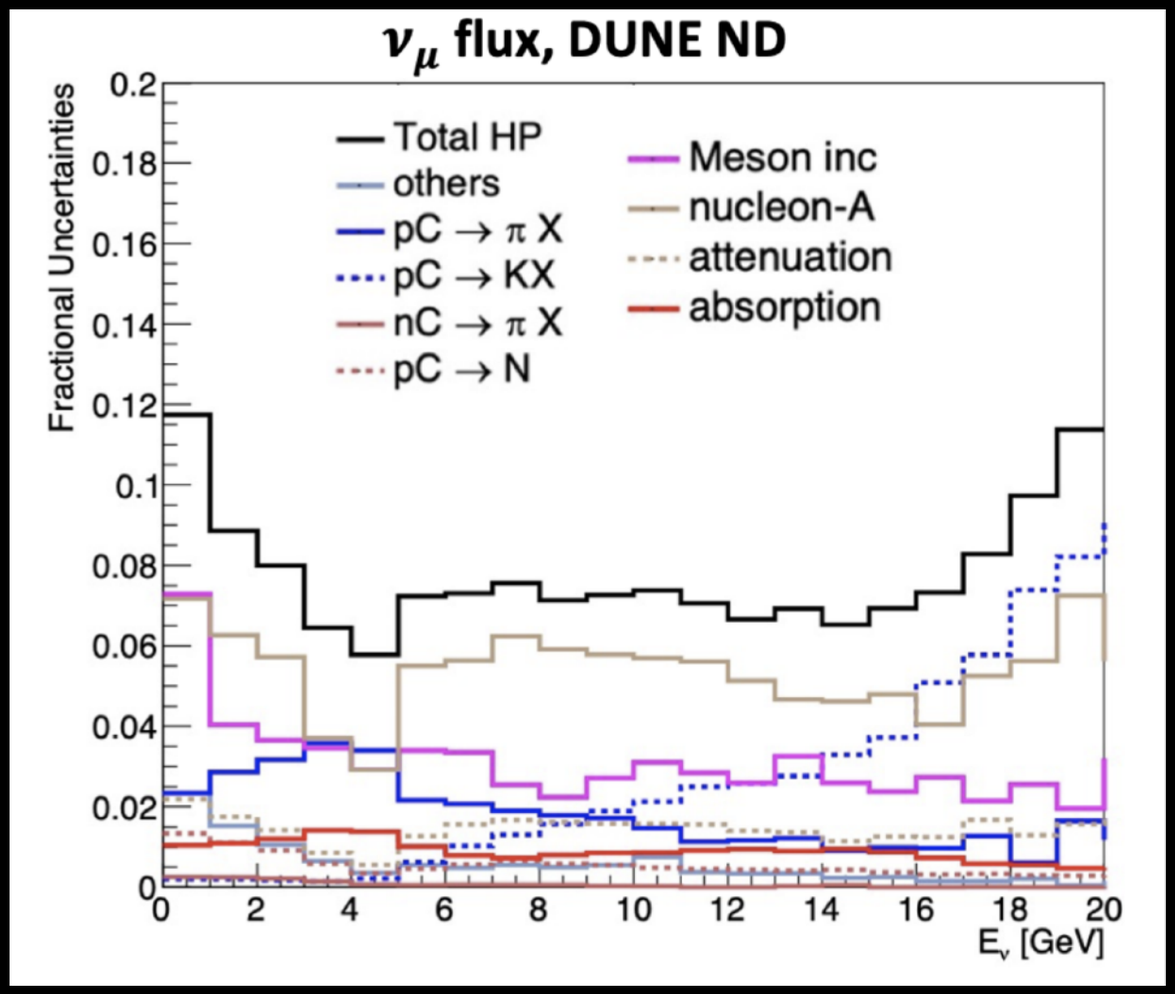
L. Ren

Total hadron production uncertainty includes:

- Pion production (proton + carbon)
- Kaon production (proton + carbon)
- Pion production (neutron + carbon)
- Nucleon production (proton + carbon)
- Meson incident interactions
- Nucleon incident interactions
- Absorption outside the target
- Absorption inside the target
- Others not covered by below categories

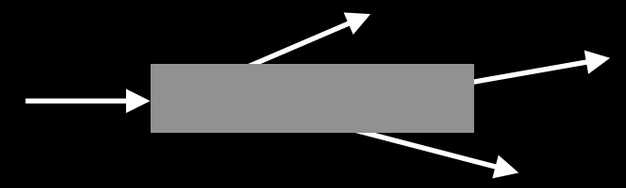
NA61 p+C 120 GeV/c results can address the red items

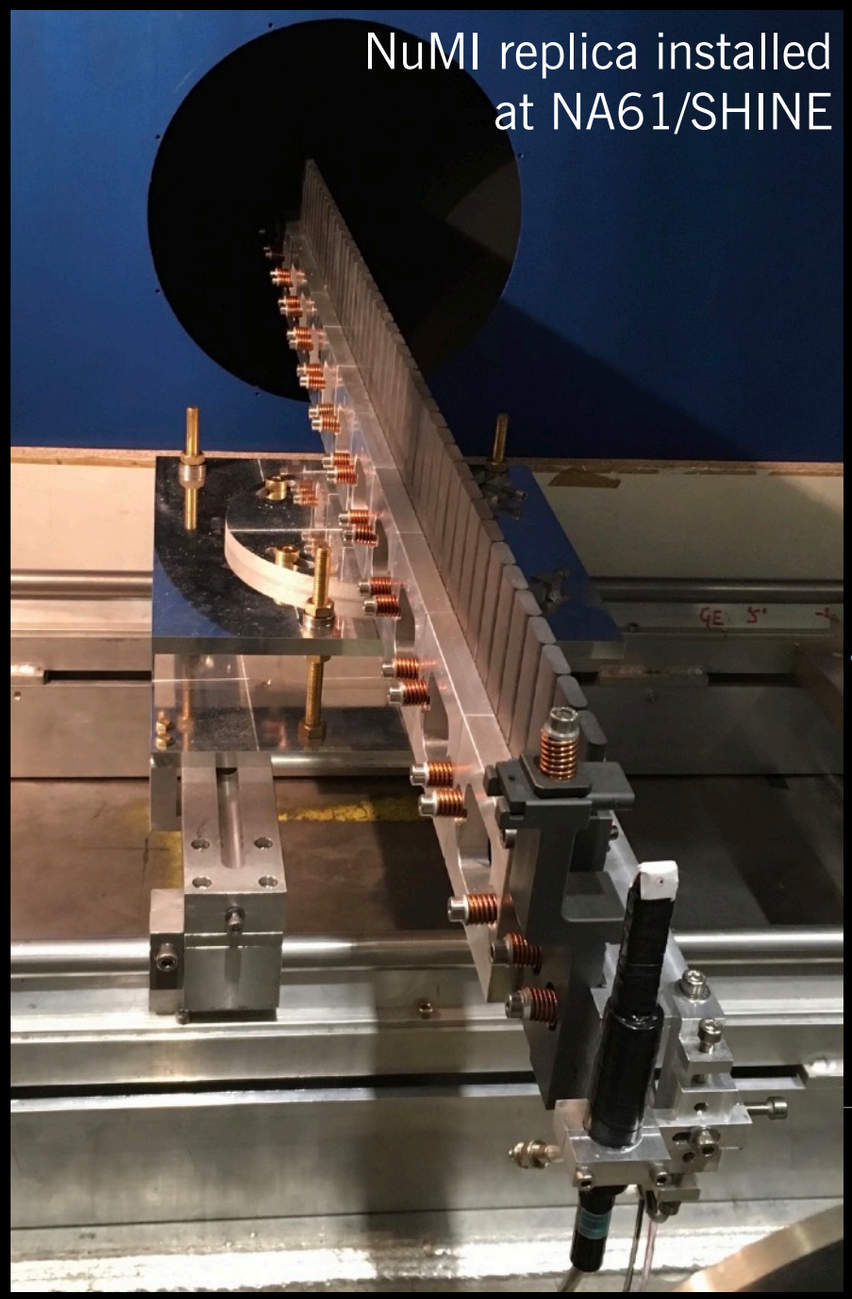
Current PPFX uncertainty using data sets scaled to NuMI parameters



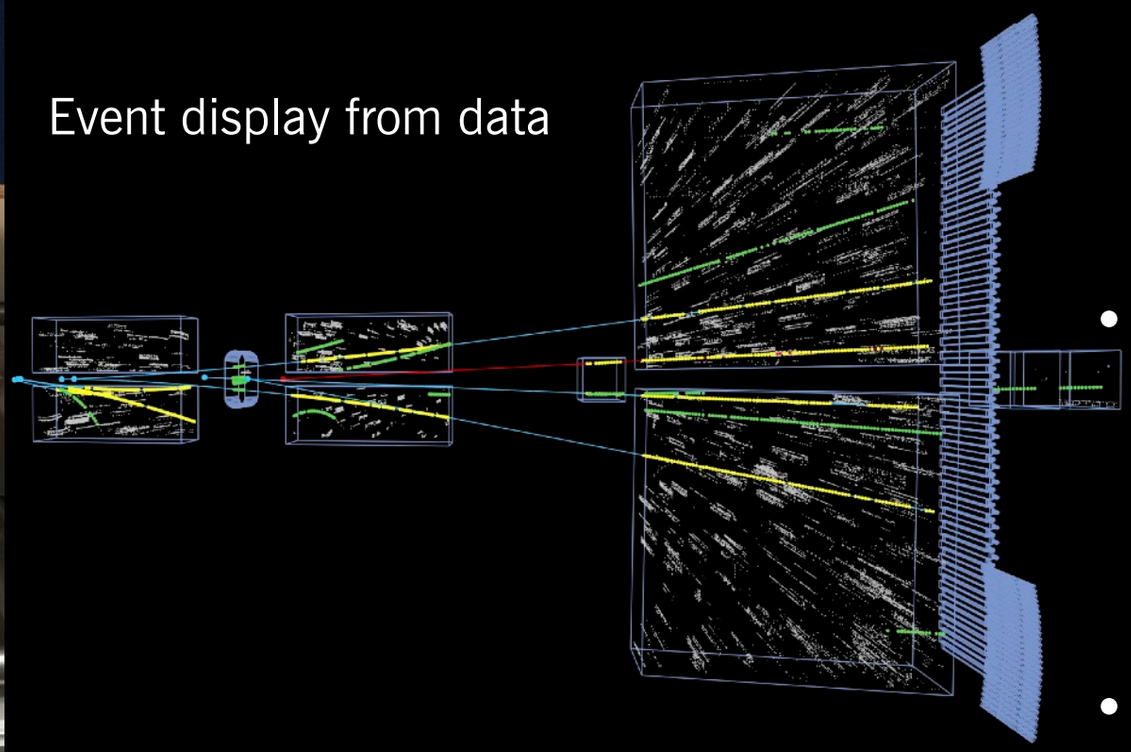
Expect updated PPFX predictions in a few months!

Coming soon: measurements with NuMI replica target





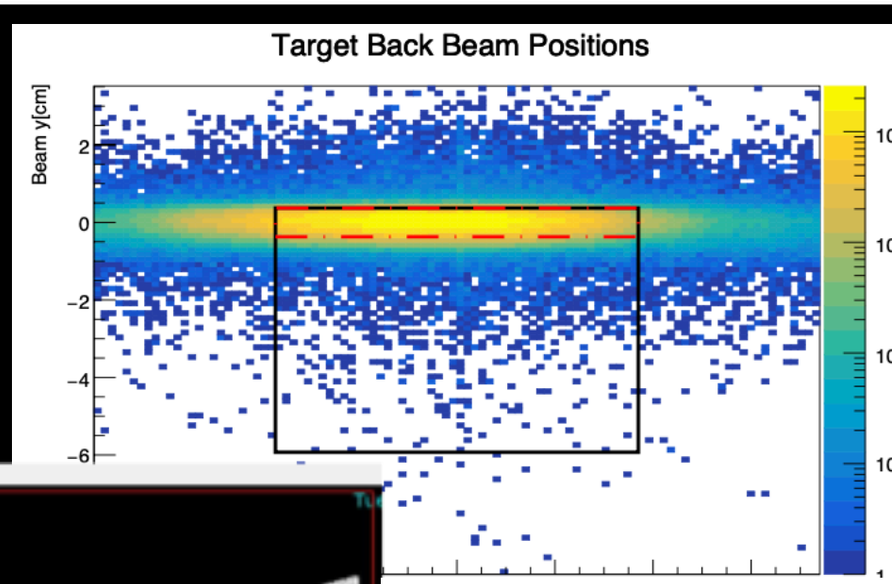
Event display from data



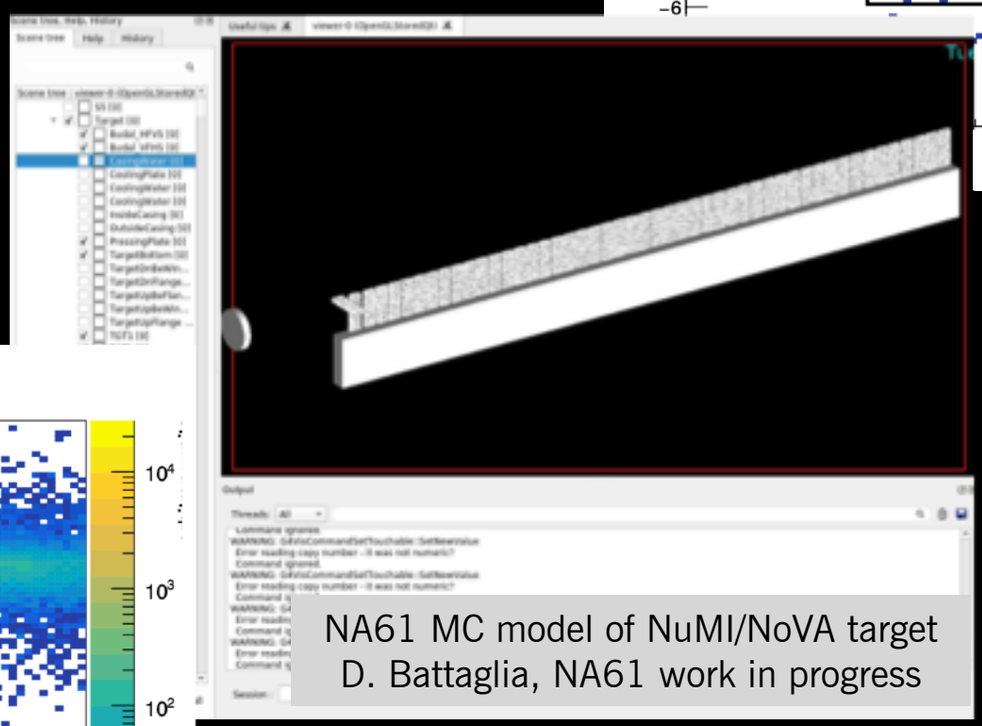
- Took high statistics (18M events) in 2018 with 120 GeV/c protons
- Analysis underway on hadron yields from this target
- Calibration in progress for this data set

NuMI target analysis

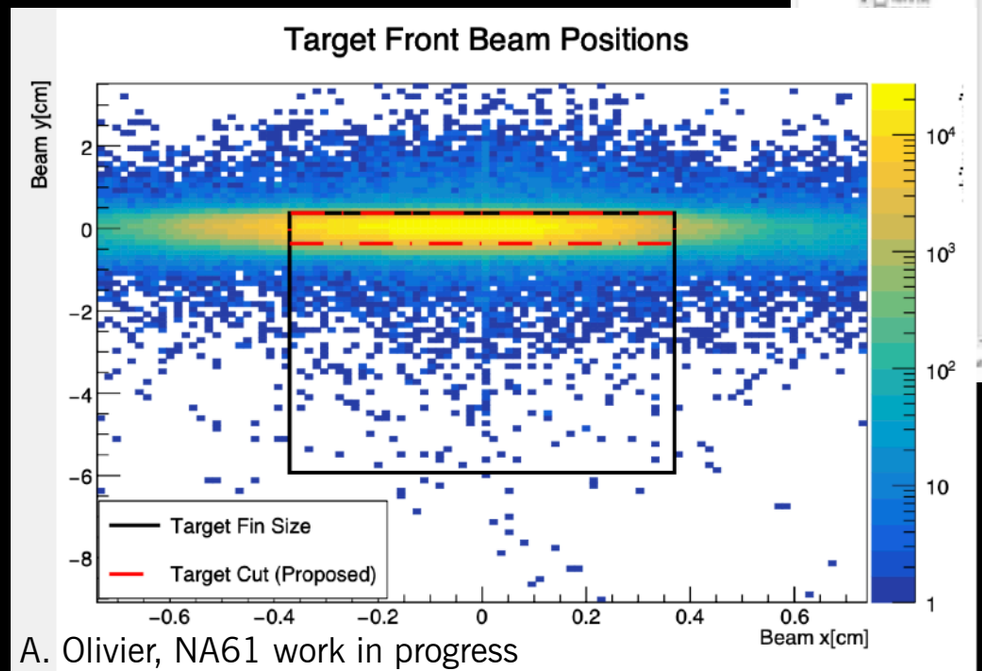
- Calibration of detectors underway
- Complicated geometry of the target, with azimuthal dependence
- NA61 acceptance is not uniform due to dipole analysis magnet!



A. Olivier, NA61 work in progress

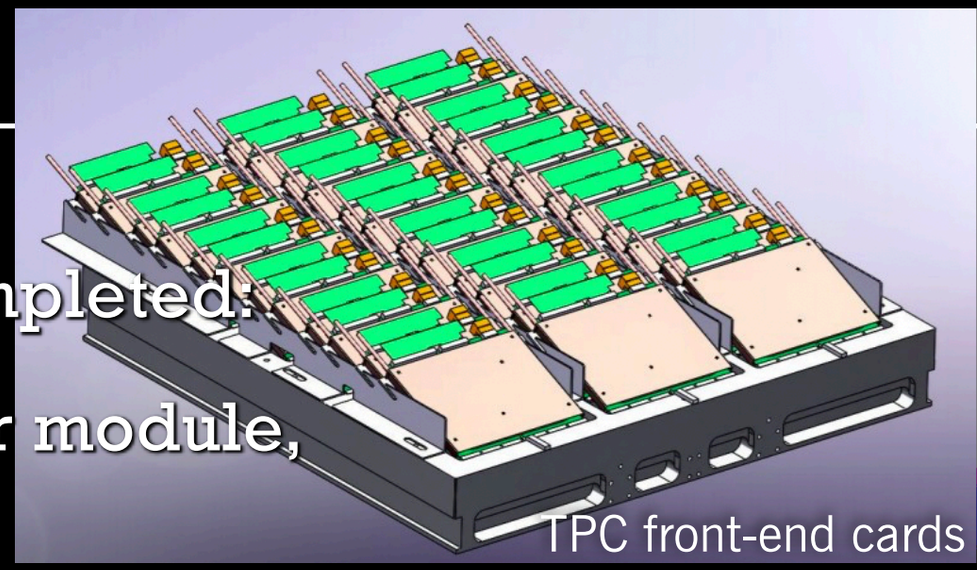


NA61 MC model of NuMI/NoVA target
D. Battaglia, NA61 work in progress



A. Olivier, NA61 work in progress

Third phase: upgraded detector



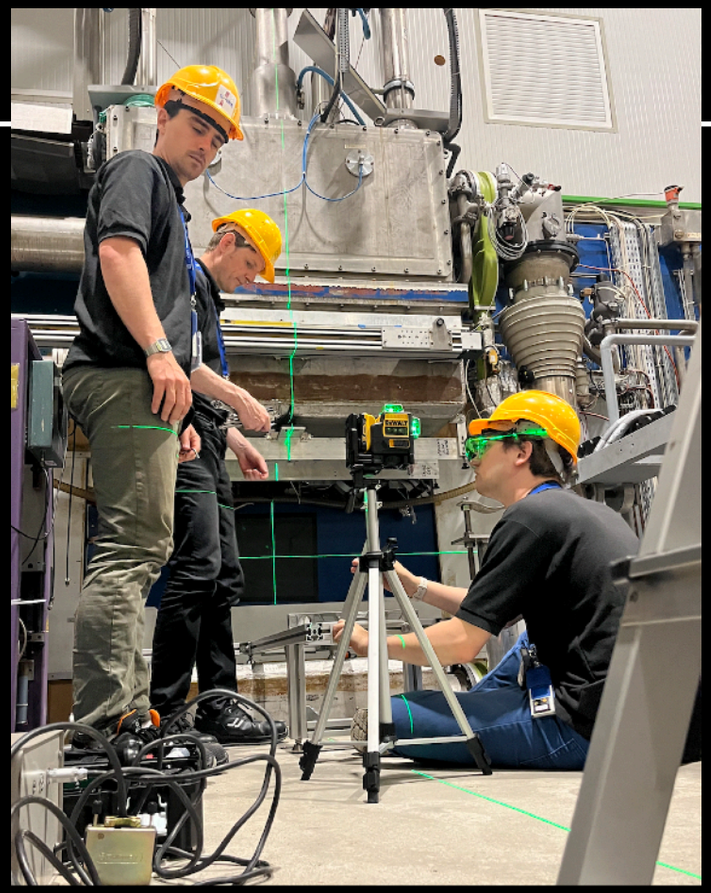
- Many major detector upgrades recently completed:
  - New forward Projectile Spectator Detector module, reconfiguration of existing detector
  - Replacement of old TPC electronics with system from ALICE
  - New silicon vertex detector for open charm studies
  - RPC-based replacement for TOF-L/R walls
  - New beam position detectors
  - New trigger/DAQ, combined with new electronics, will give a major upgrade in data collection rate (~100 Hz → ~1 kHz)

Data collection: now and near future

- **Data collection is underway for the Run 3 program!**
  - 31 GeV/c protons on T2K replica-target: collected 180M events in 2022 (nearly 20x 2010 statistics) to measure high-momentum kaon yields
  - Kaon scattering with thin targets for secondary interaction modeling. In 2023, took:
    - K+C @ 60GeV: 137.7 M
  - Higher statistics at 120 GeV/c:
    - p + Ti @ 120 GeV: 111.7 M
    - p + C @ 120 GeV: 82.4 M

>20x just-published paper!

Data collection: now and near future

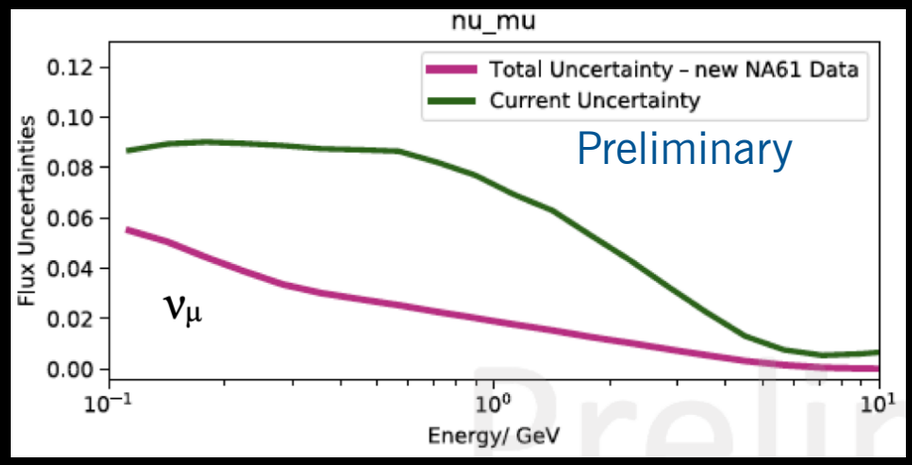


- LBNF/DUNE prototype target (2024)
- Target designed and built by RAL targetry group to expected dimensions of LBNF/DUNE target: 1.5 m long
- New TPC added to track particles exiting target
- Took 250M events summer 2024
- 2025 data: planning to run with lower-density graphite target

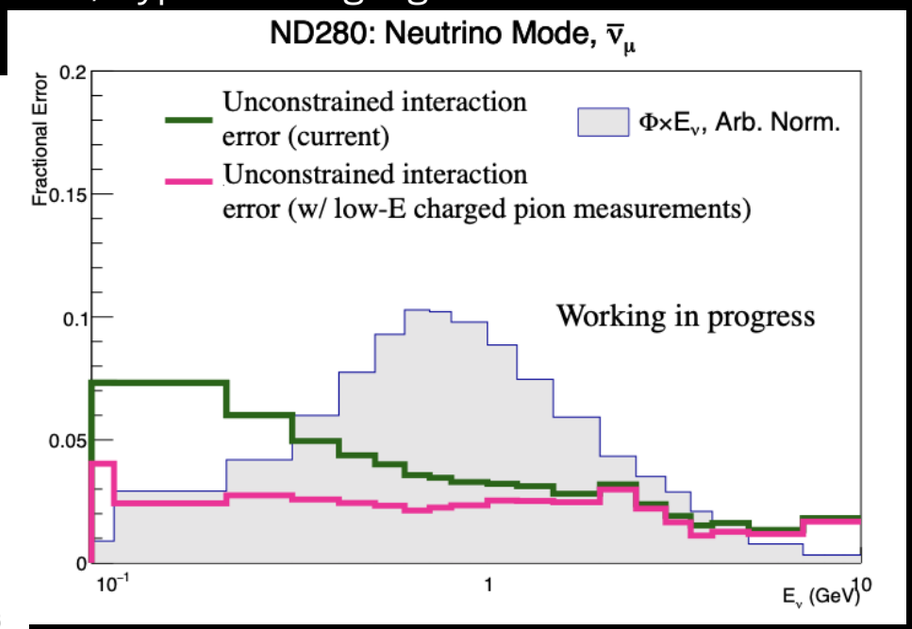
Future after 2025: low-energy beam?

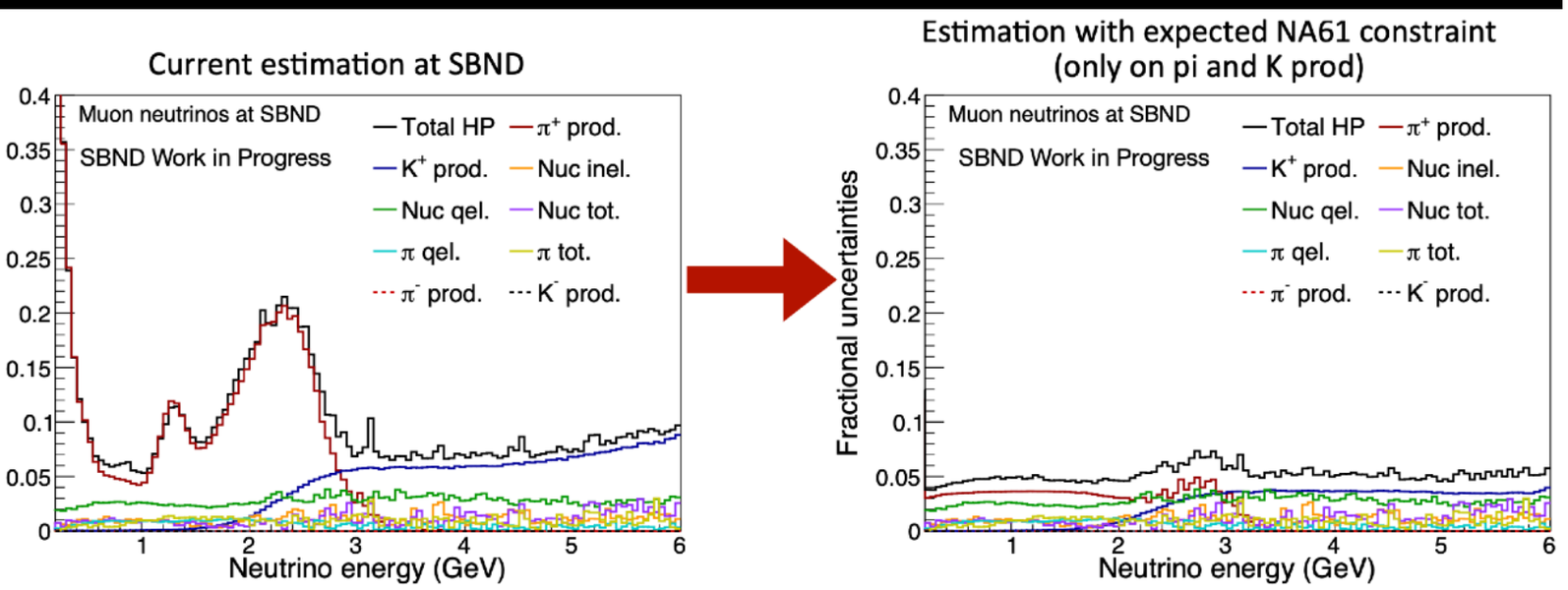
- Many groups are interested in hadron production with beams in the 1-20 GeV region, below the range the current H2 beam is capable of providing
  - Potential significant improvement in atmospheric neutrino flux prediction
  - FNAL Booster Neutrino Beam
  - T2K/HyperK secondary interactions
  - Spallation sources, cosmic rays, others…

L. Cook (Bartol Group) atmospheric neutrino flux

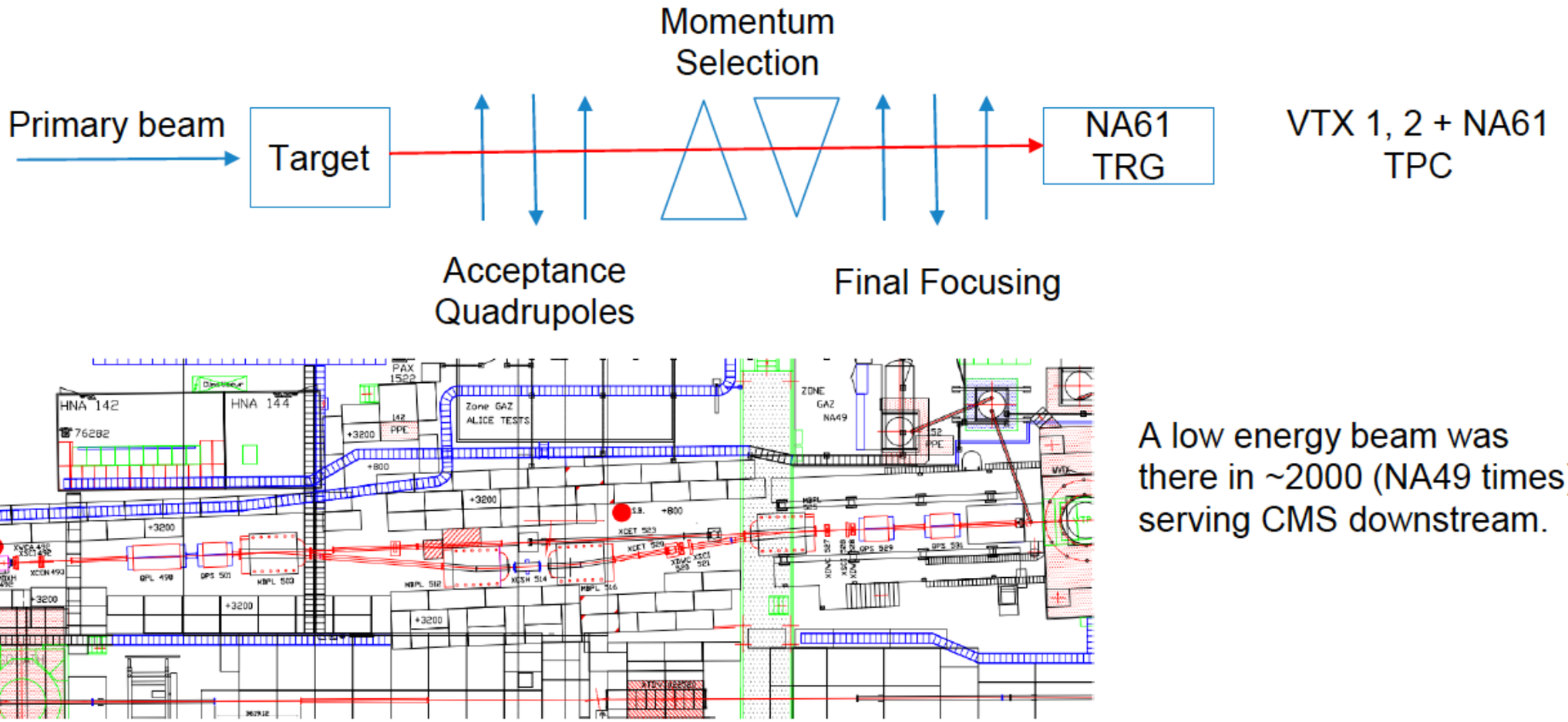


T2K/HyperK wrong-sign flux uncertainties





Principle of a low-energy beam for NA61/SHINE



- New beam design by CERN beam group in collaboration with NA61/SHINE.
- Goal is to have beam available after (or even before) the next Long Shutdown
- Preparing a new organizational structure to seek funding for this project

NA61/SHINE++ Opportunities beyond 2025

- Interested in **low-energy data** at NA61/SHINE?
  - Or in other possible new beam/target combinations? Current beam will still be available.
  - Open workshop "NA61++/SHINE: Physics Opportunities from Ions to Pions" was held in December 2022 at CERN - and we are still looking for new ideas and new people
  - *INDICO: https://indico.cern.ch/event/1174830/*

- Atmospheric neutrino flux
- T2K/HK beam-related physics
- DUNE beam-related physics
- Booster Neutrino Beam
- New target materials
- COMET
- JSNS2

and much more!

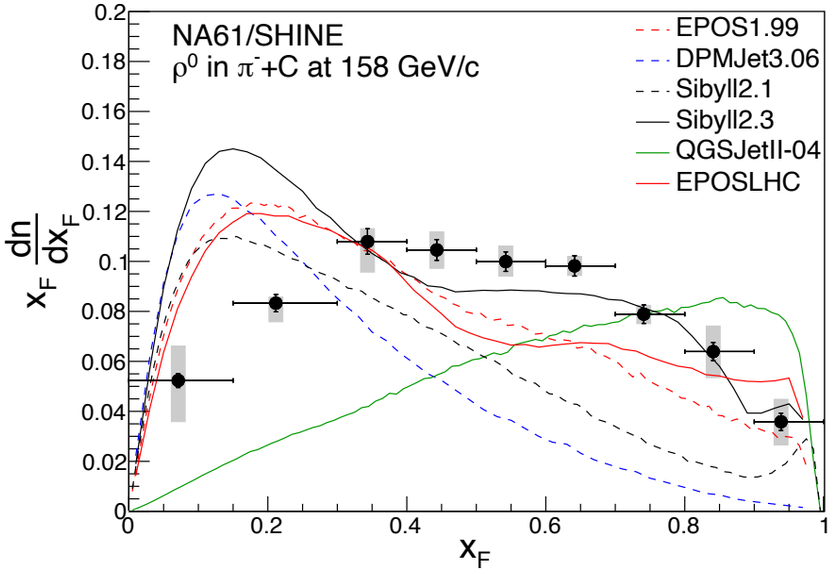
Cosmic-ray physics in NA61/ SHINE

- Long-standing program within NA61/SHINE to make measurements of physics processes important to cosmic ray studies
  - Hadroproduction in ultrahigh-energy air showers
  - $\bar{p}$ production in the galaxy
  - Antinuclei in the galaxy
  - Cosmic-ray propagation in the galaxy

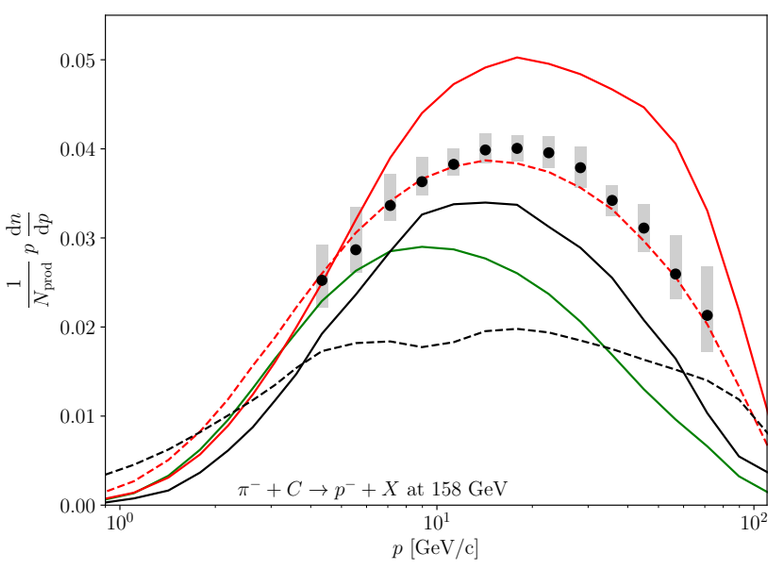
New data coming!

→ Large $p+p$ data set in 2025-26

→ Nuclear fragmentation data to be collected late 2024



NA61/SHINE EPJ **C77** (2017) 626



NA61/SHINE PRD **107** (2023) 062004

Conclusions

- NA61/SHINE has provided unique and critical data to support the global neutrino and cosmic ray programs
- Efforts have reduced T2K's flux errors by factors of 4+
- A new set of analyses is coming out, geared toward the current Fermilab program
- Took data summer 2024 with LBNF/DUNE prototype target
- Low-energy beam and other future options under study

Speaker supported by US Department of Energy