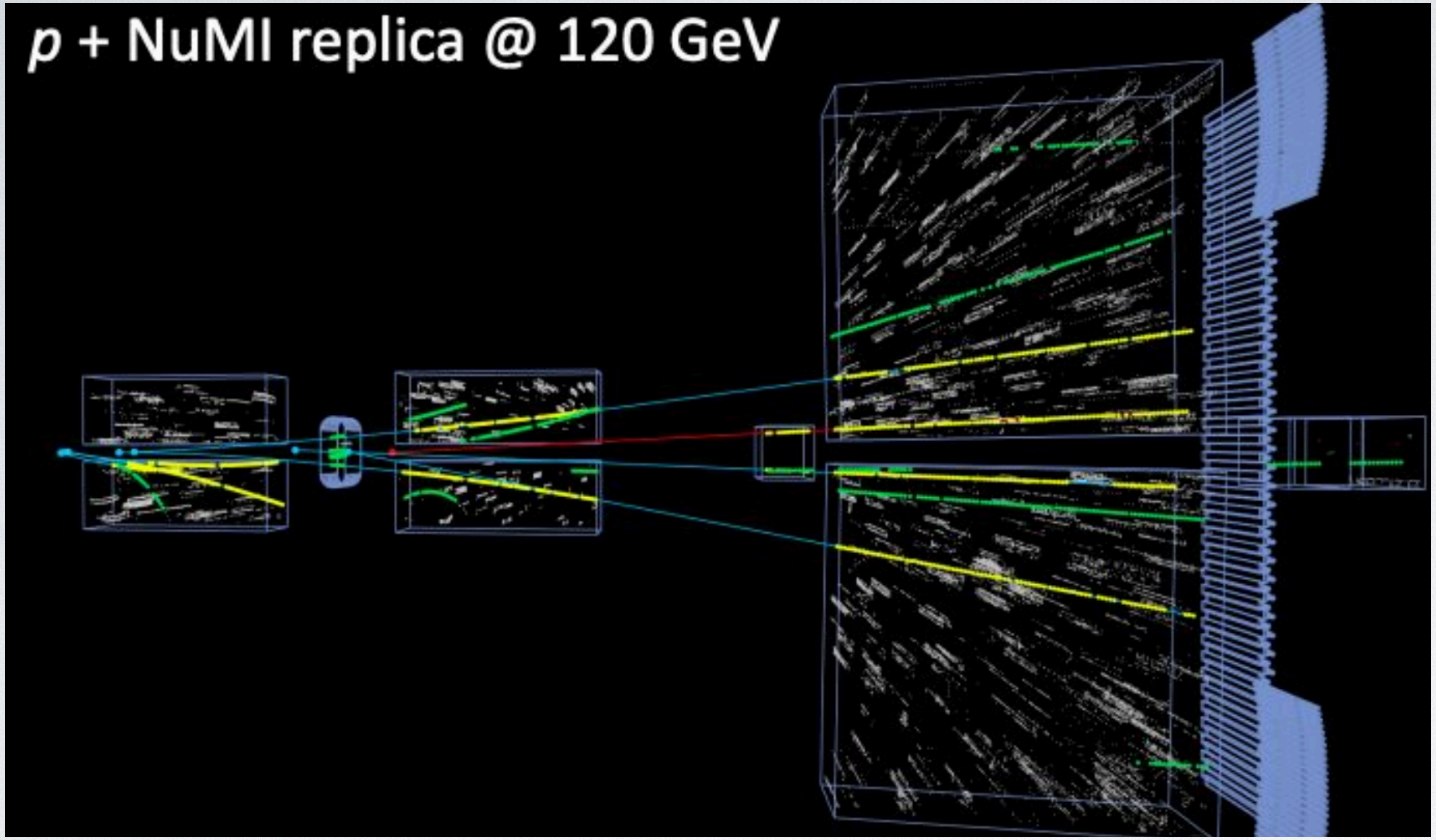
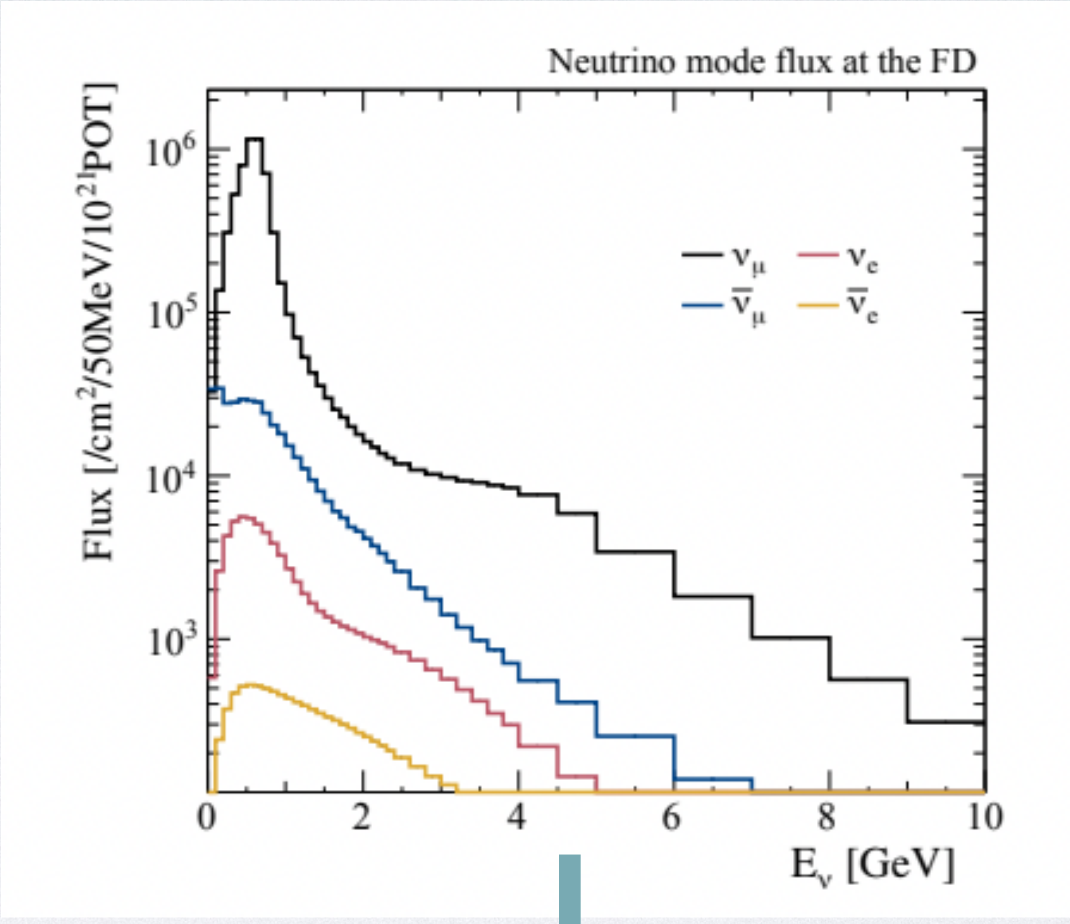


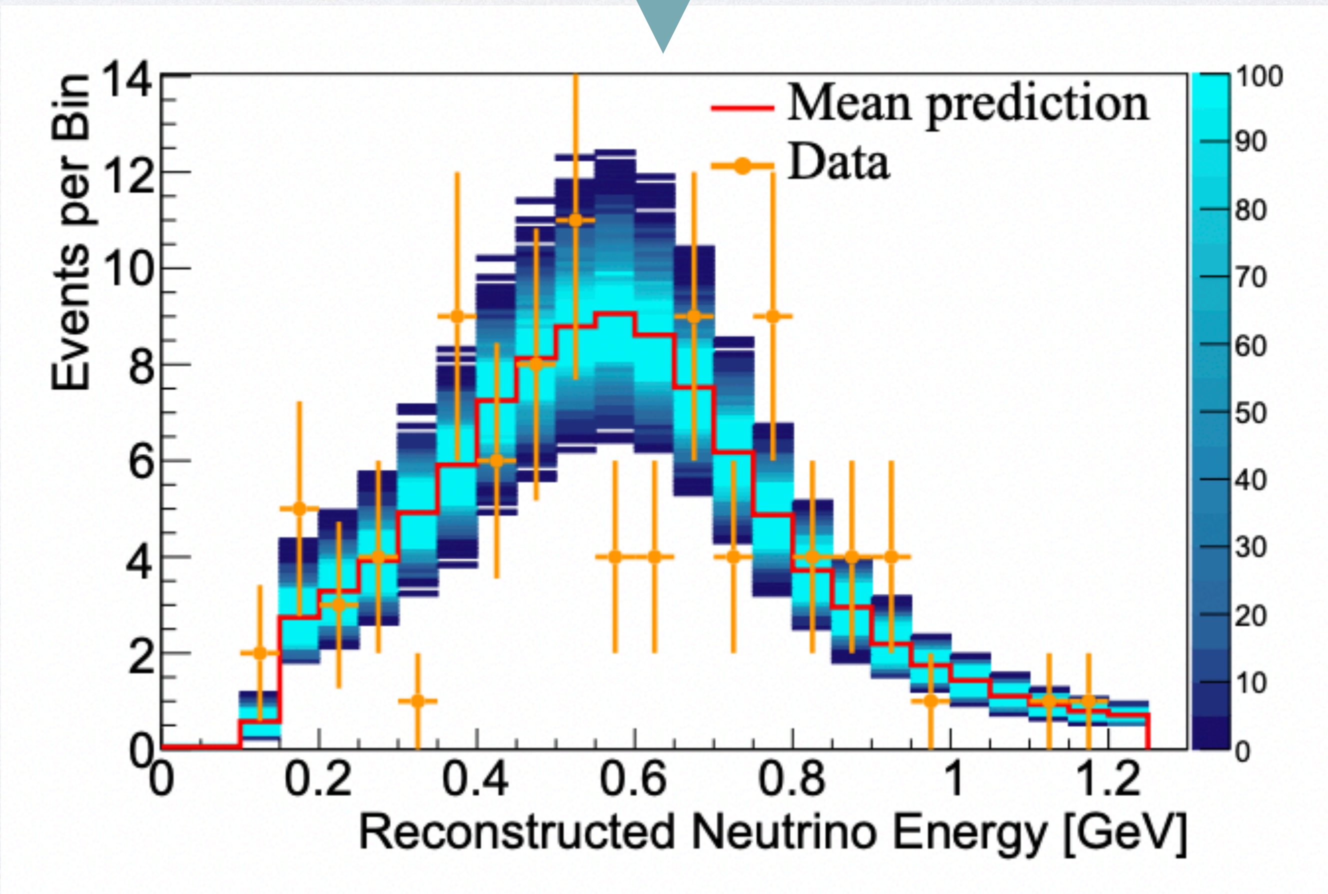
NA61/SHINE MEASUREMENTS FOR NEUTRINOS

Laura Fields, University of Notre Dame
NuFact 2024 WG1x3
19 Sept 2024

NEED FOR NEUTRINO FLUX PREDICTIONS

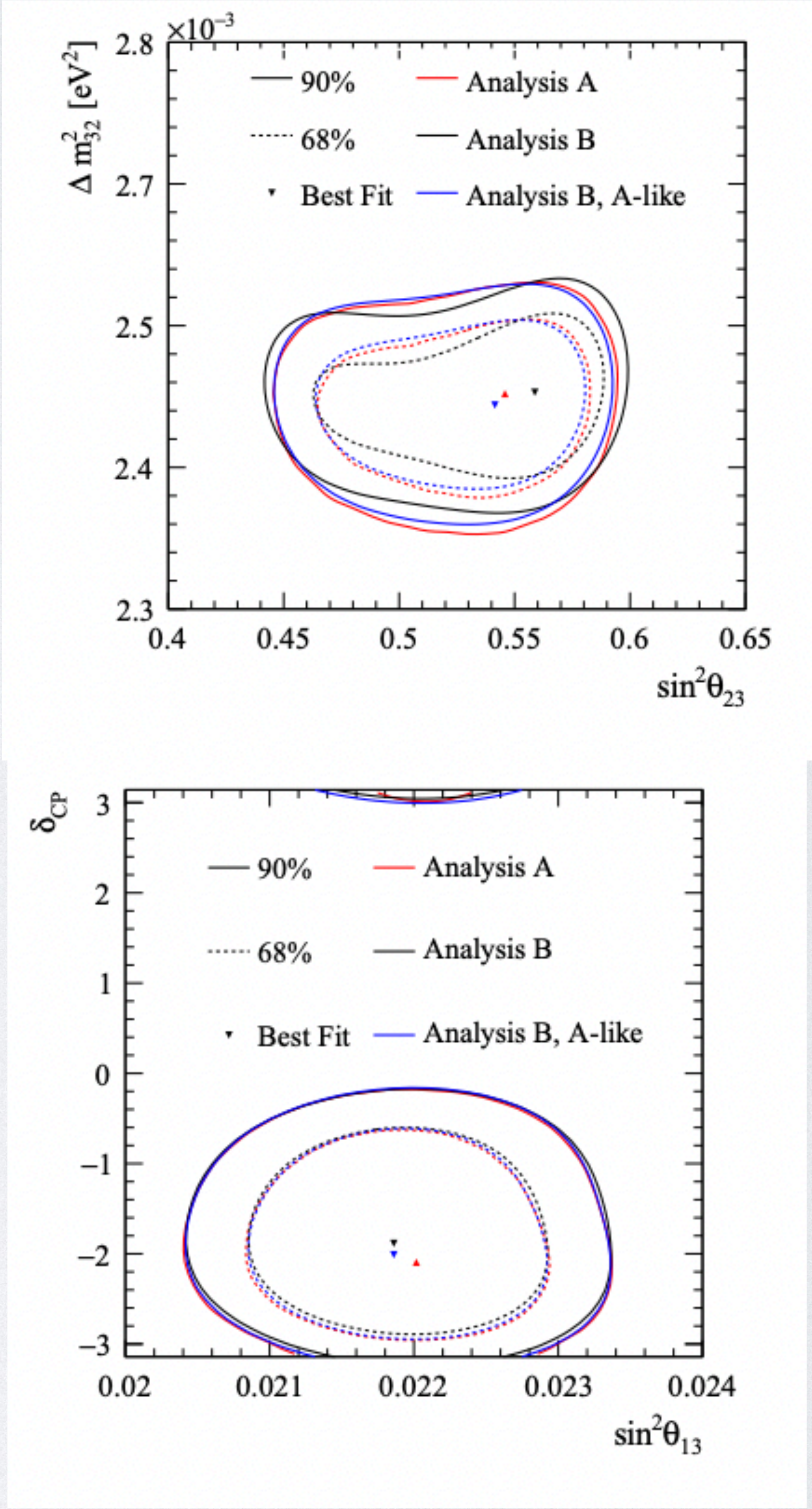
- Accelerator-based neutrino experiments **rely heavily on neutrino flux predictions**
- **Extracting oscillation parameters** from data requires comparisons to predictions.
- Neutrino **flux predictions underpin** all accelerator-based neutrino simulations.



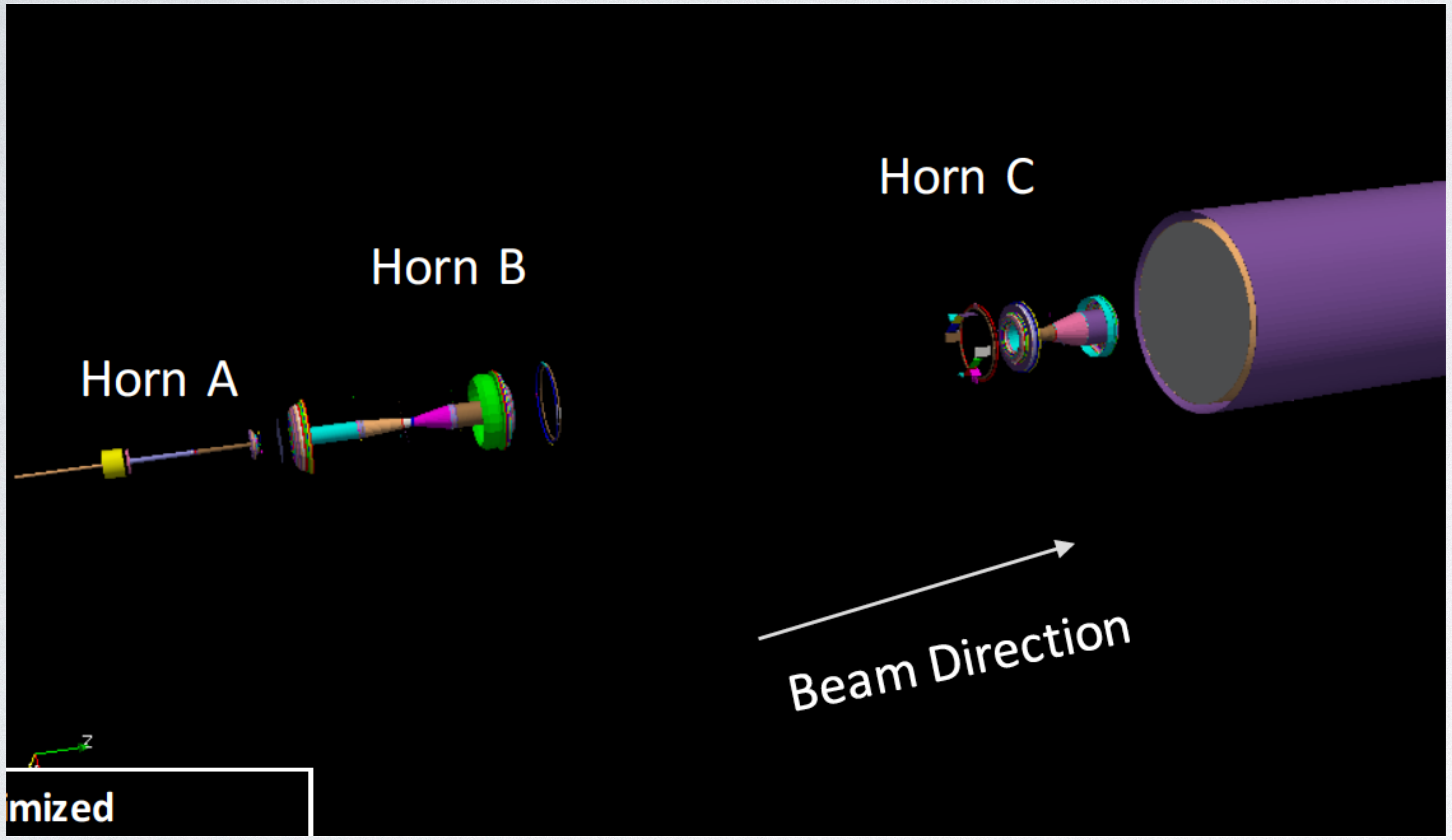


(b) ν-mode 1Re

T2K, Eur.Phys.J.C 83 (2023) 9, 782

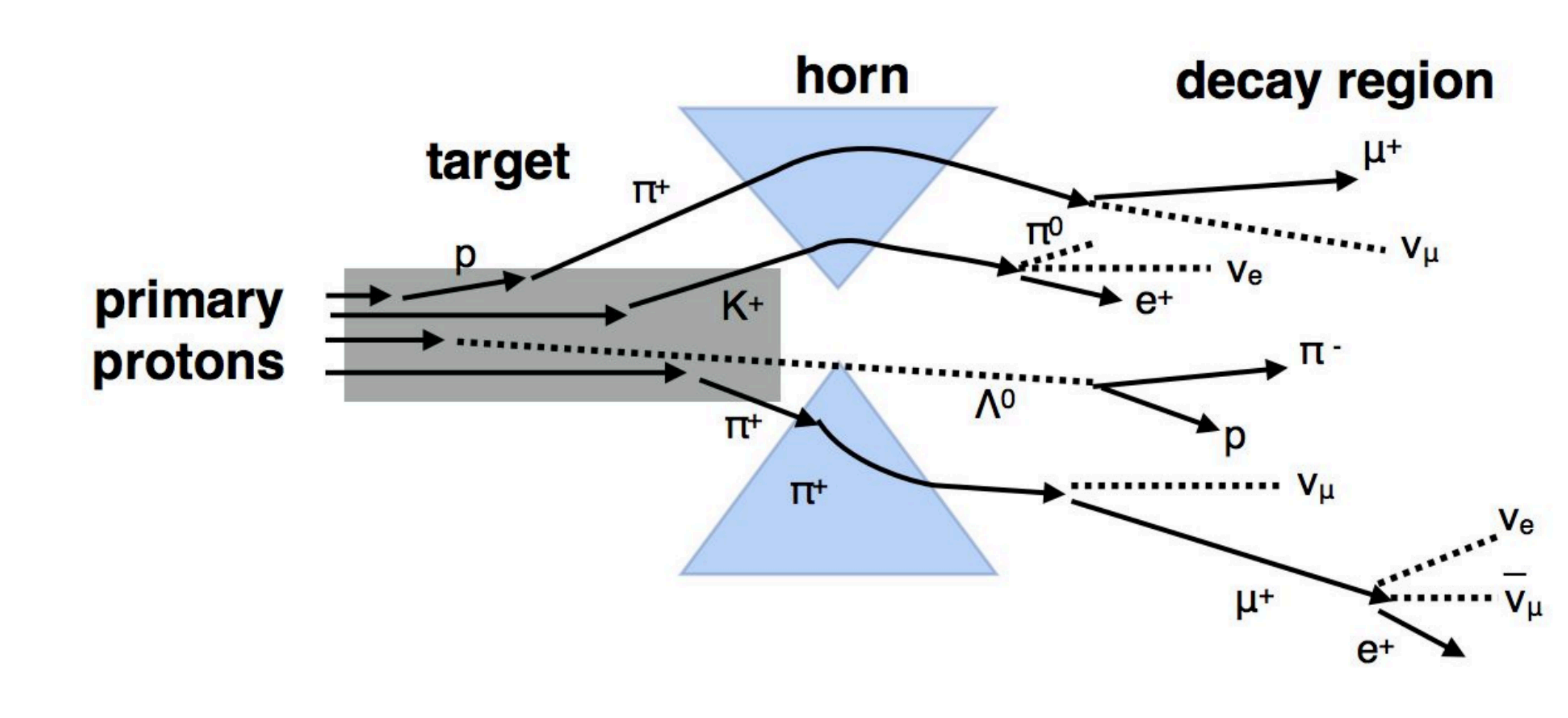


NEUTRINO FLUX SIMULATIONS



Neutrino flux predictions start with **detailed simulations** of the neutrino beam line.

Geant4 or Fluka are typically used to predict hadrons produced in the beam line that decay to neutrino.

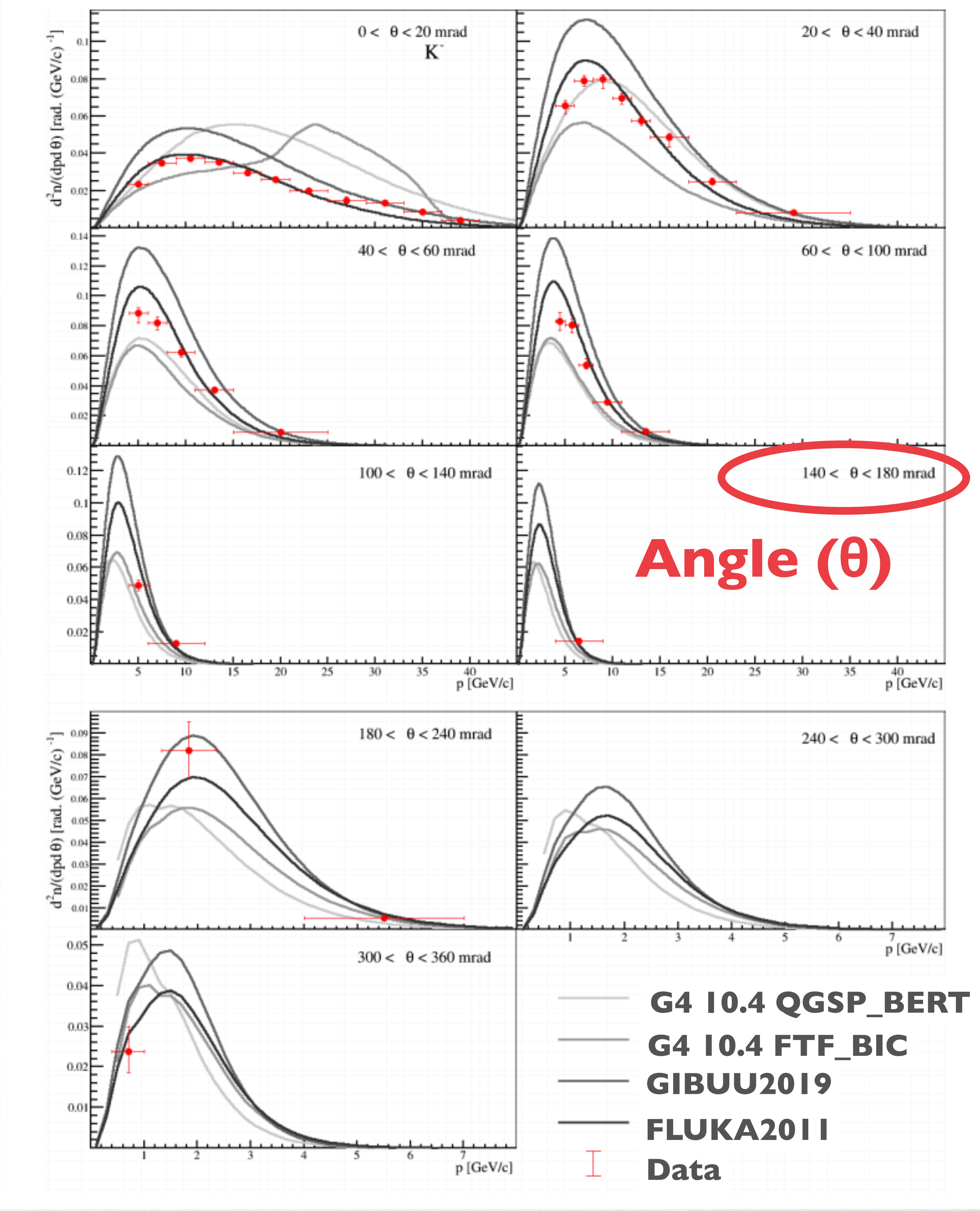


SIMULATION CHALLENGES

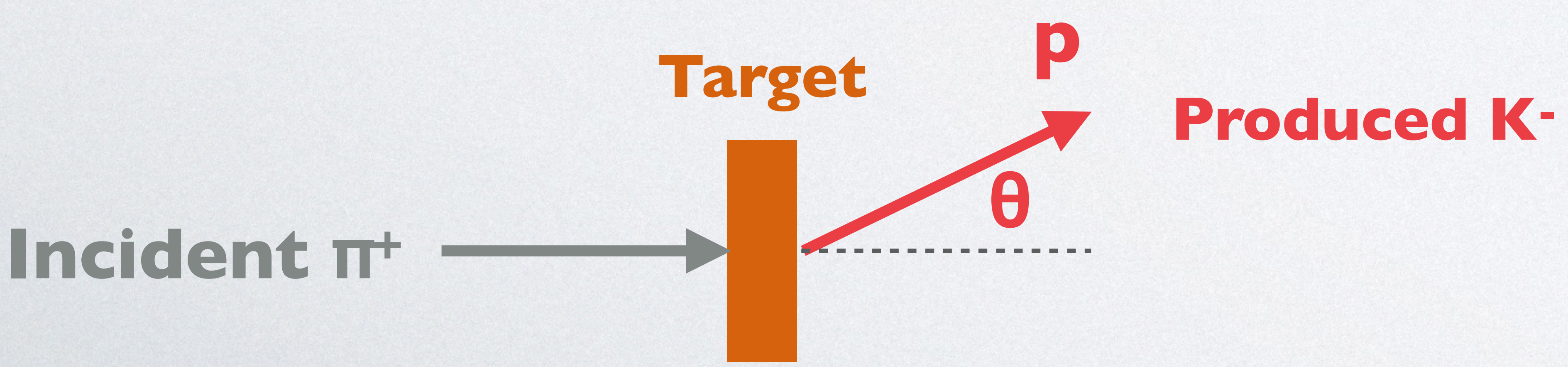
- But we know **simulations are imperfect**
- Many models **differ significantly from data**; model developers are always trying to improve, but it is not realistic to expect perfect predictions of all processes that matter to flux predictions.

Kaon momenta in 60 GeV/c $\pi^+ + C \rightarrow K^- + X$ interactions, measured at NA61/SHINE and compared to two Geant4 models, as well as Gibuu and Fluka.

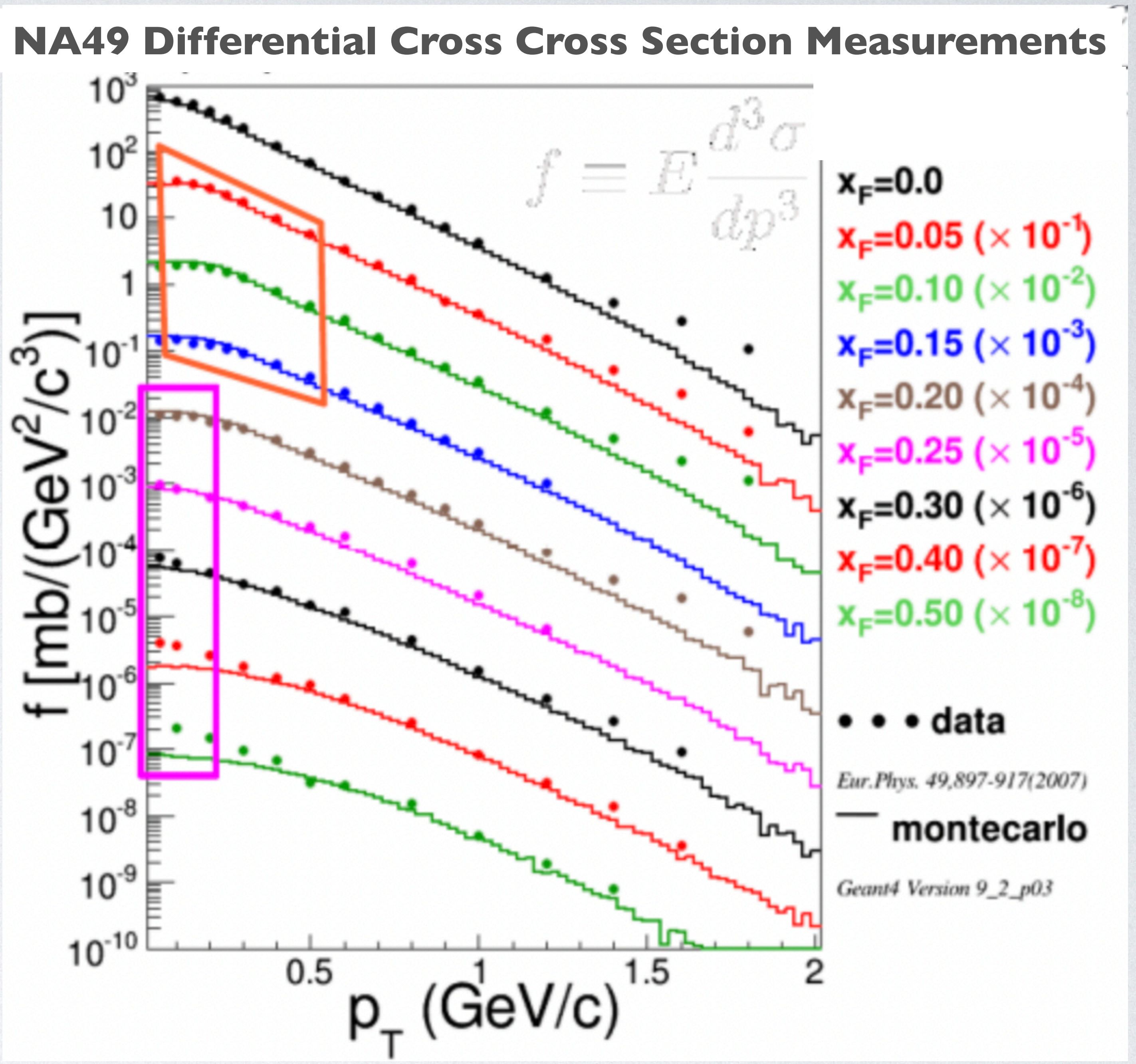
NA61/SHINE *Phys.Rev.D* 100 (2019) 11, 112004



x axis = Particle Momentum (p)



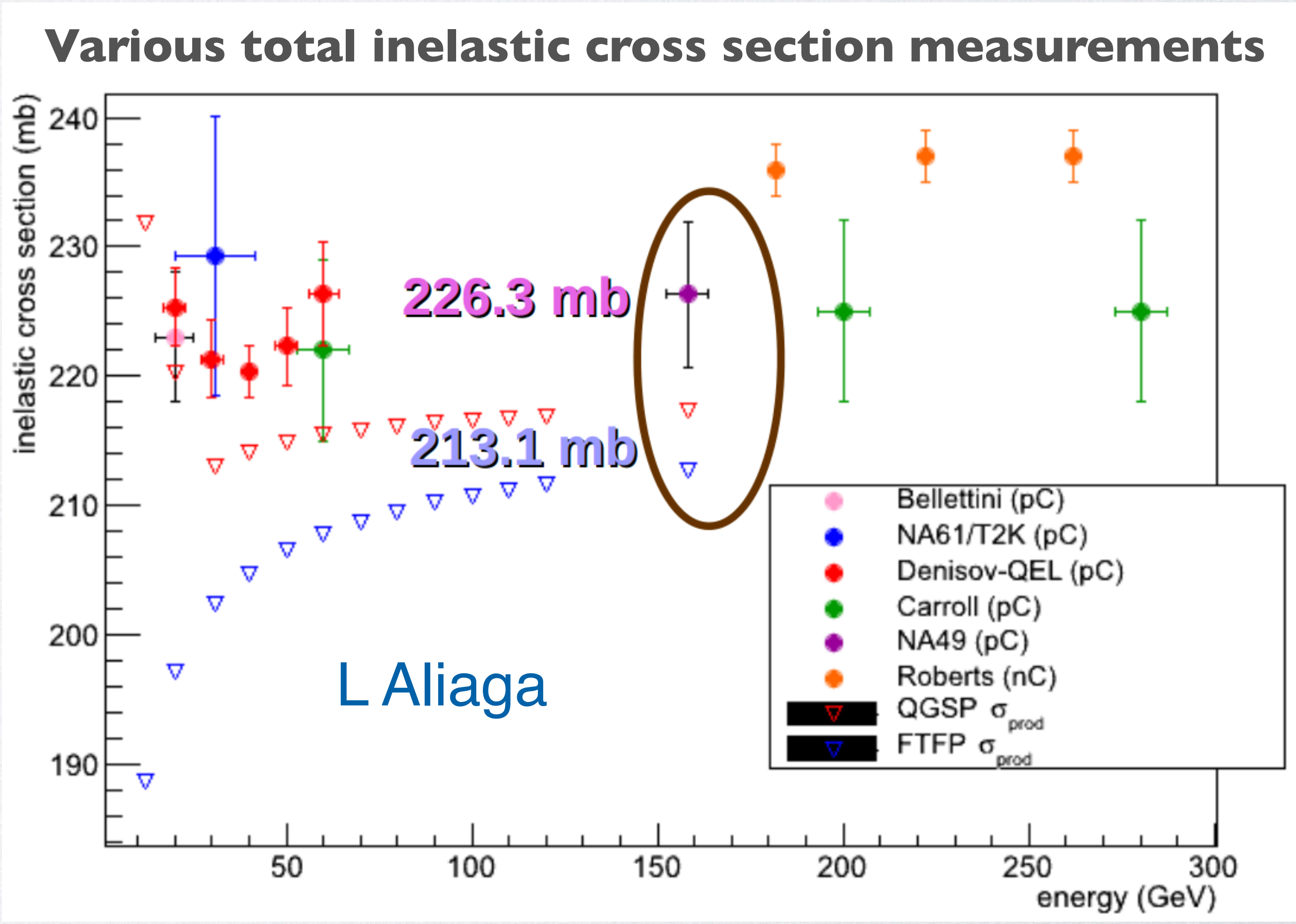
CORRECTING SIMULATIONS



- So we have to **fix our predictions**
  - The only practical way to do this is **through reweighting**
  - **An example** of how thin target data is used, from NuMI/DUNE:
    - **Complete information about cascades** leading to a neutrino is recorded for each proton on target and stored in the flux tuples
    - In MINERvA/NOvA/LBNF analyses, neutrino **events are weighted** by:

$$w_{\rm HP} = \frac{f_{\rm Data}\,(x_F, p_T, E)}{f_{\rm MC}\,(x_f, p_T, E)}$$

Uses differential cross sections

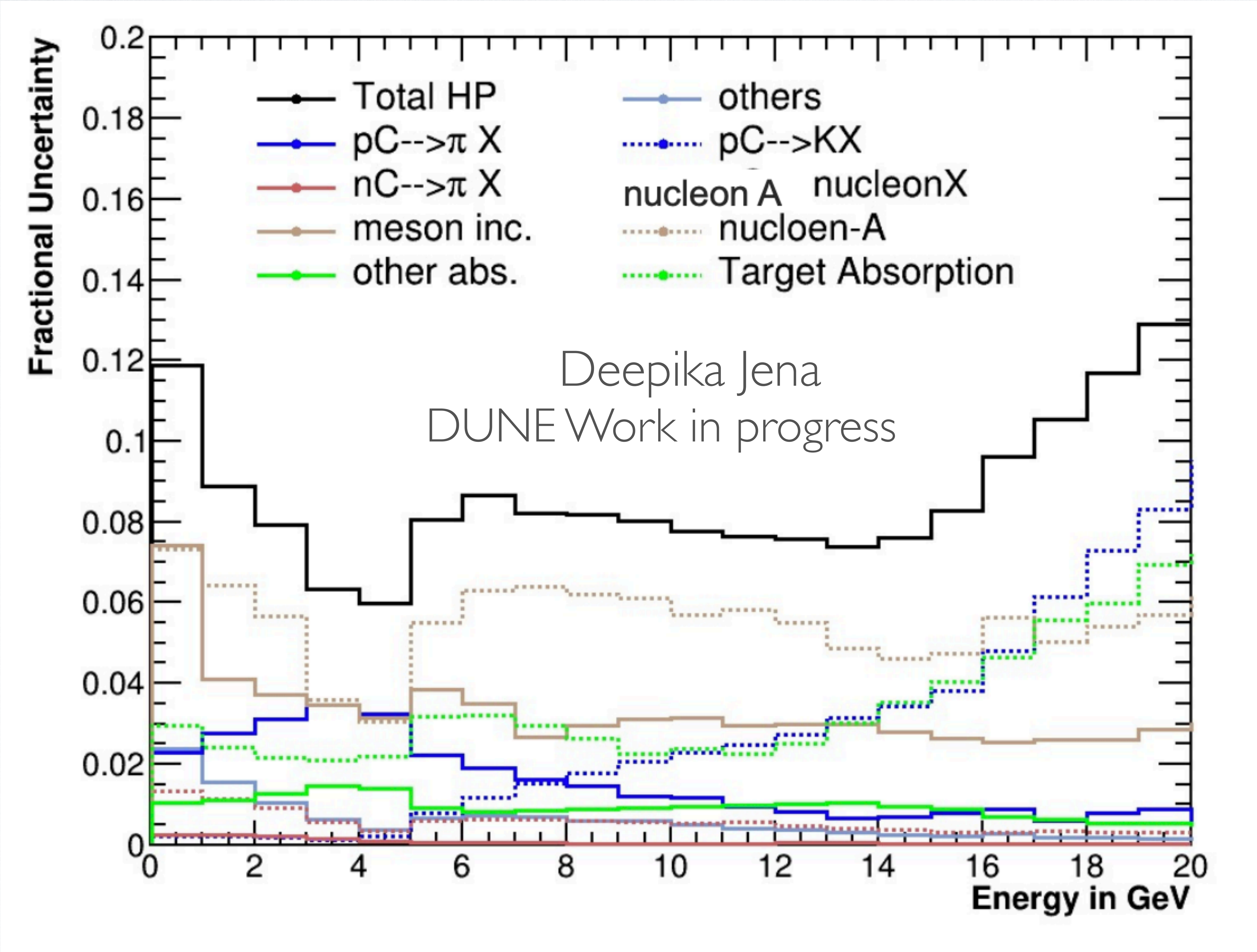


- Weights for events with multiple interactions in the ancestor chain are the product of the weight for each interaction
- A second weight is applied to account for assuming exponential exponential **attenuation of beam**:

$$w_{\rm att} = e^{-L\rho(\sigma_{\rm data} - \sigma_{\rm MC})}$$

Total Inlastic Cross sections

FLUX UNCERTAINTIES

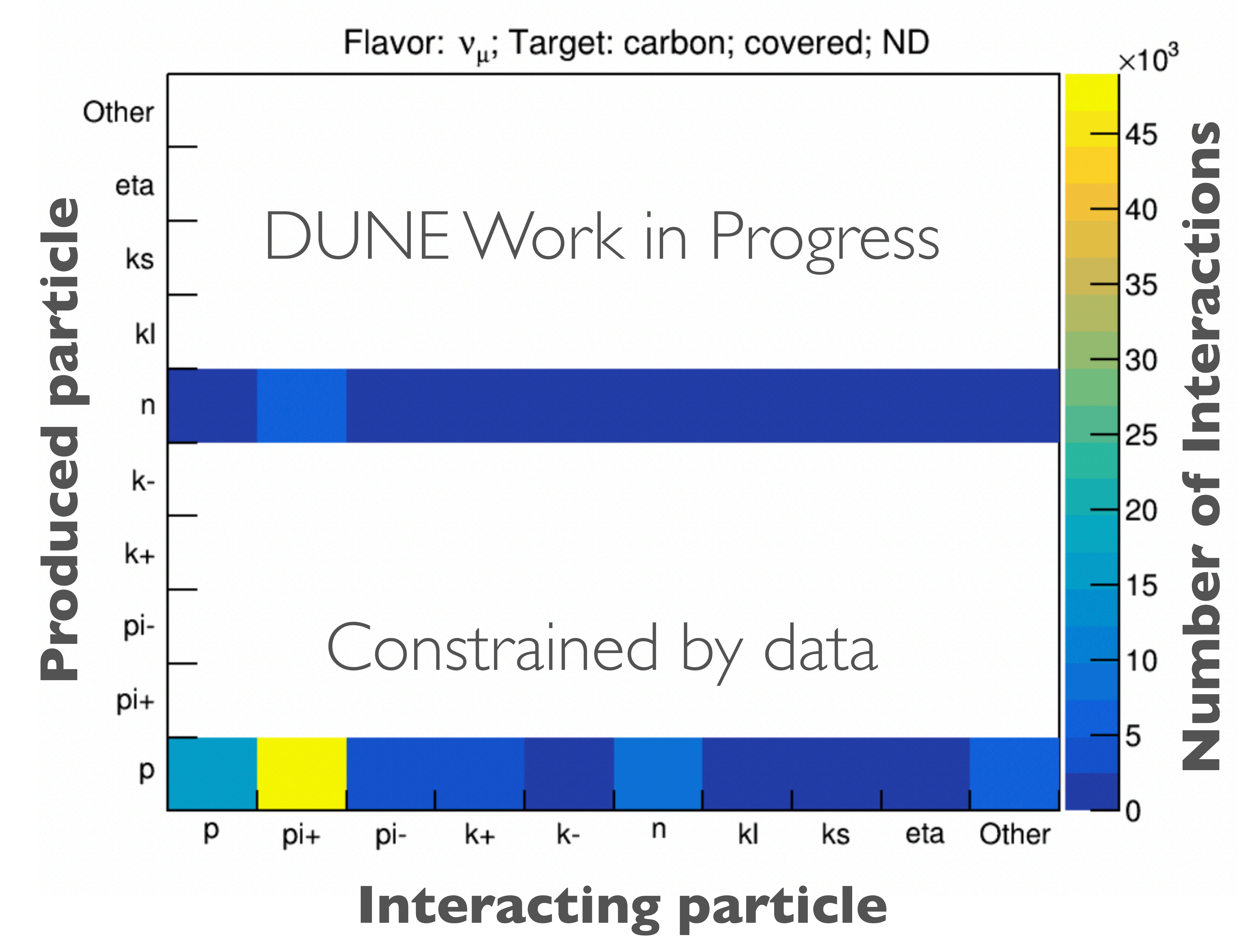


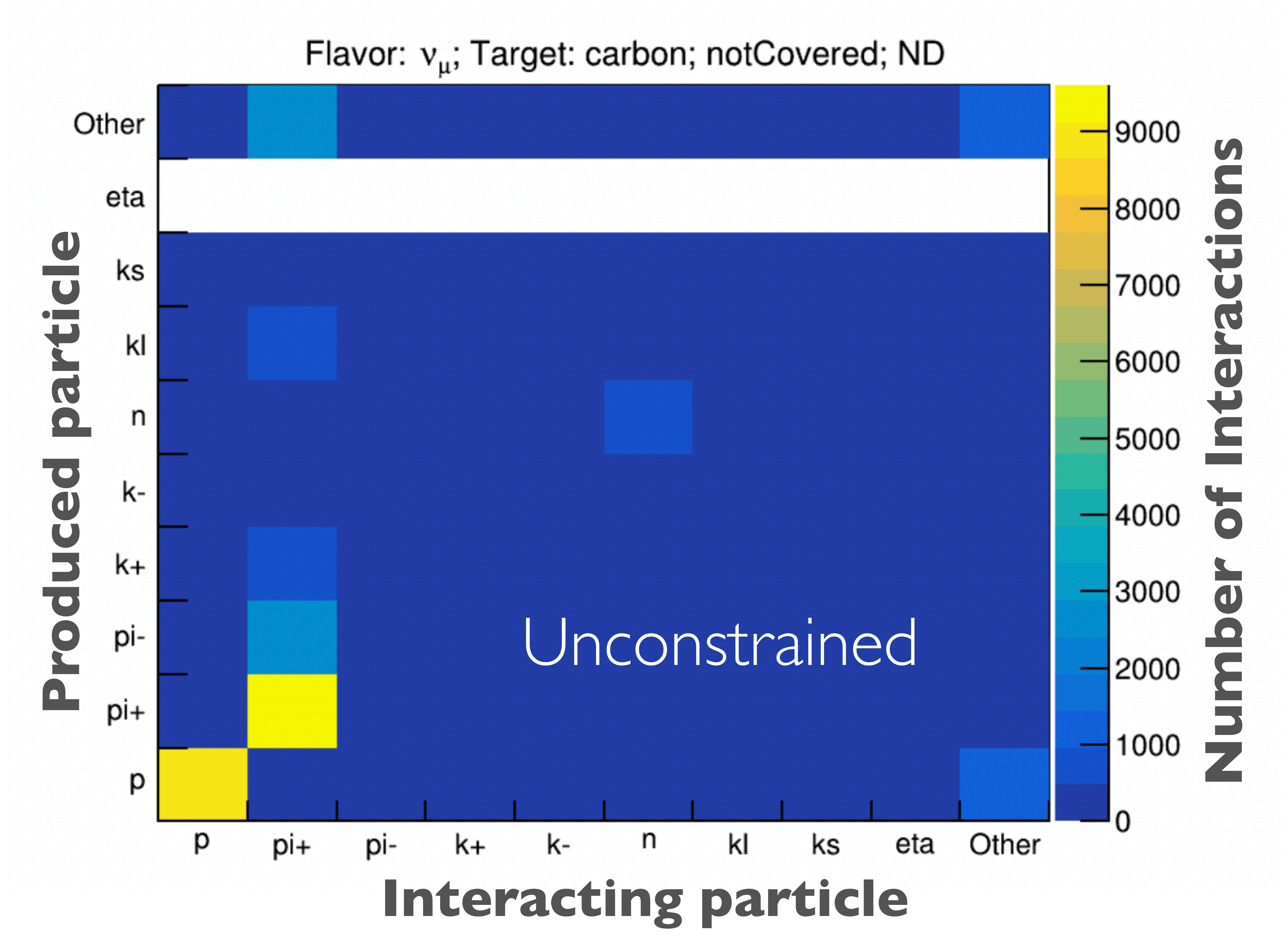
- To construct flux uncertainties, we **assign uncertainties to every interaction** in the simulation, using the PPFX package developed by MINERvA
- In cases where the interaction has been measured, we **take the uncertainty from data**
- In cases where there is **no data, we assign large (~40%) uncertainties** based on data/MC disagreements where we do have data

- Those interactions with **no data dominate our uncertainties** almost everywhere

CORRECTING SIMULATIONS

- We need lots of data!





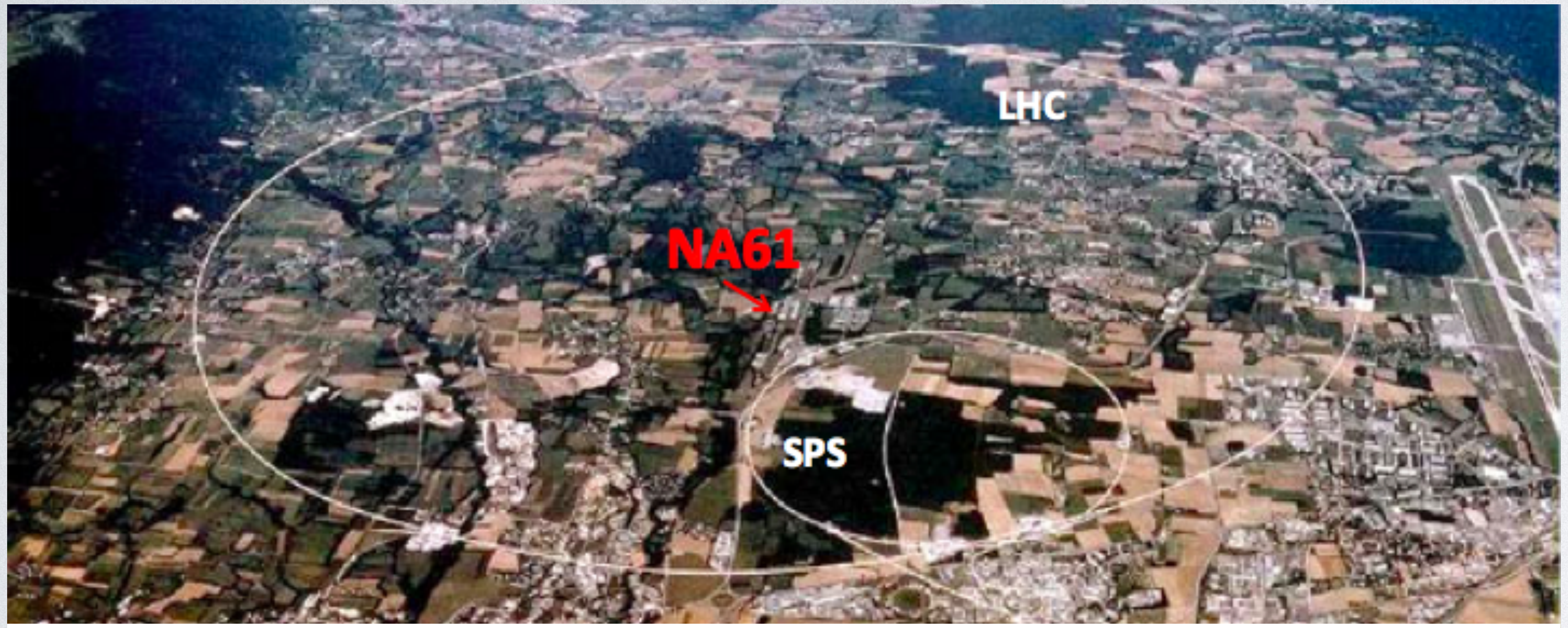
HADRON PRODUCTION EXPERIMENTS

This talk

The next talk
(Robert Chirco)

Then Leo Aliaga will talk about what we're going to do with all this data!

NA61/SHINE:OVERVIEW

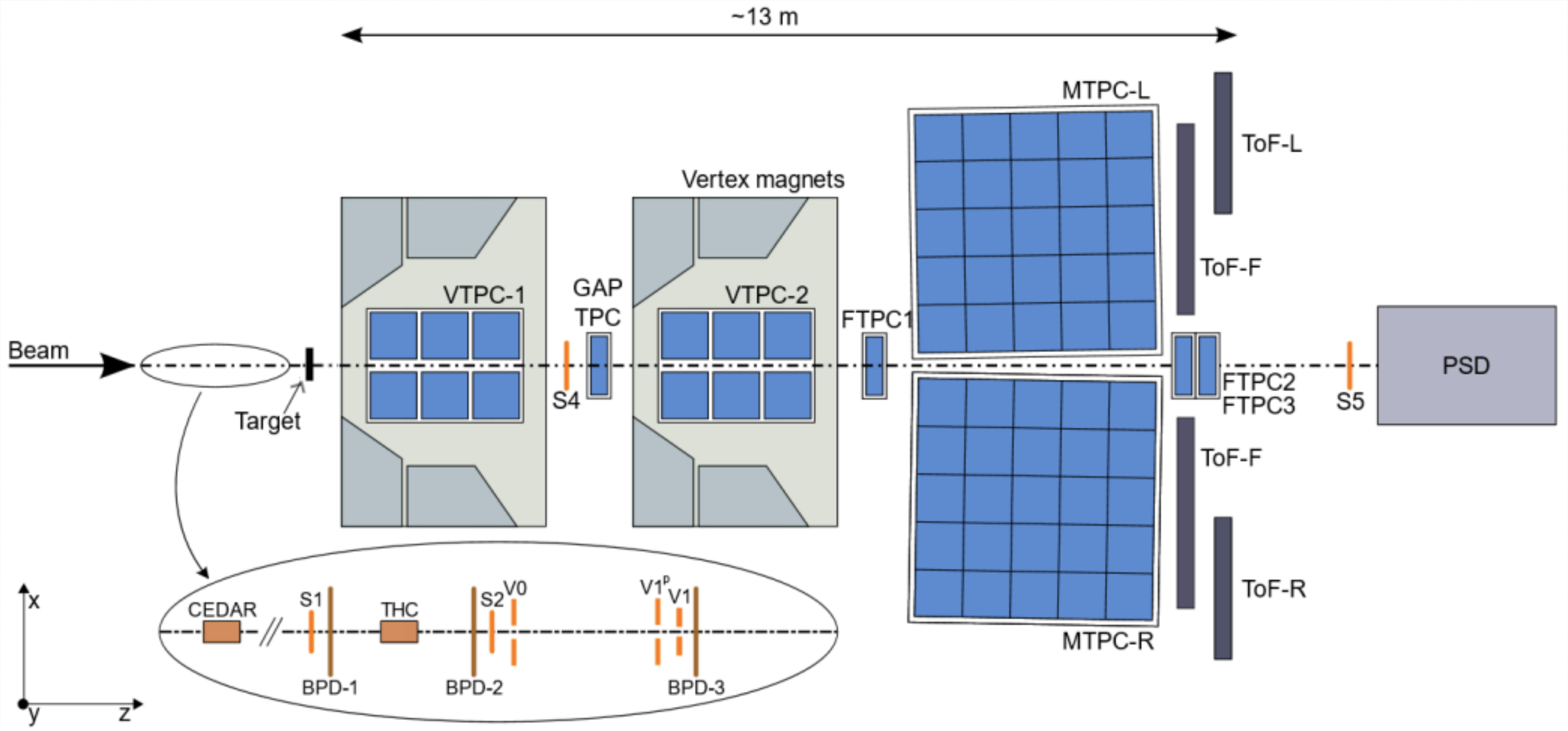


- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - Rudjer Boskovic Institute, Zagreb
- France
  - LPNHE, Paris
- Germany
  - University of Frankfurt, Frankfurt
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - Institute of Advanced Studies, Frankfurt
- Greece
  - University of Athens, Athens
- Great Britain
  - University of Warwick, Warwick
- Hungary
  - Eötvös Loránd University, Budapest
  - Wigner Research Centre for Physics, Budapest
- Japan
  - KEK, Tsukuba
  - University of Okayama, Okayama
- Norway
  - University of Bergen, Bergen
  - University of Oslo, Oslo
- Poland
  - AGH University of Science and Technology, Cracow
  - Institute of Nuclear Physics, PAS, Cracow
  - Jagiellonian University, Cracow
  - University of Silesia, Katowice
  - Jan Kochanowski University, Kielce
  - Warsaw University of Technology, Warsaw
  - University of Warsaw, Warsaw
  - National Centre for Nuclear Research, Warsaw
  - Wroclaw University, Wroclaw
- Russia
  - Joint Institute for Nuclear Research, Dubna
  - Institute for Nuclear Research, Moscow
  - National Nuclear Research Institute MEPhI, Moscow
  - St. Petersburg State University, St. Petersburg
- Serbia
  - University of Belgrade, Belgrade
- Switzerland
  - University of Geneva, Geneva
  - CERN, Geneva
- United States
  - Fermilab, Batavia
  - University of Colorado, Boulder
  - University of Hawaii, Manoa
  - University of Notre Dame, Notre Dame
  - University of Pittsburgh, Pittsburgh

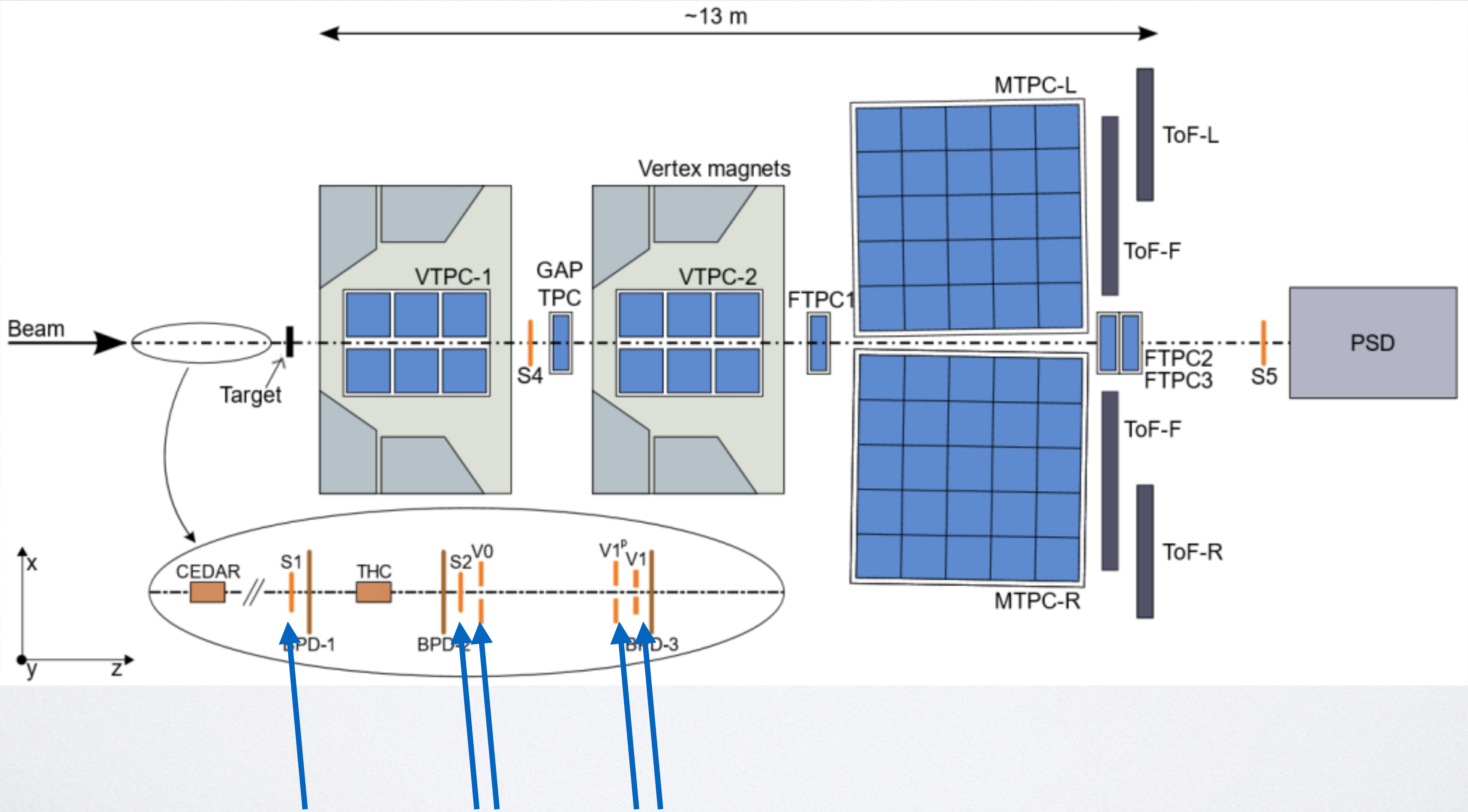
~150 Collaborators from 35 Institutions in 15 Countries

- **Fixed target experiment** located at CERN's SPS (Super Proton Synchrotron)
- Receives secondary beam initiated by 400 GeV/c SPS protons
- Series of magnets selects desired **momentum from 13-350 GeV/c** range
- NA61's physics program covers three main topics:
  - **Nuclear physics** - Study the phase transition between hadron gas and QGP and search for a critical point
  - **Cosmic ray physics** - Hadron production measurements relevant to space and ground-based cosmic ray experiments
  - **Neutrino physics** - Hadron production measurements used to constrain neutrino flux uncertainties for accelerator-based neutrino experiments

NA61/SHINE EXPERIMENT

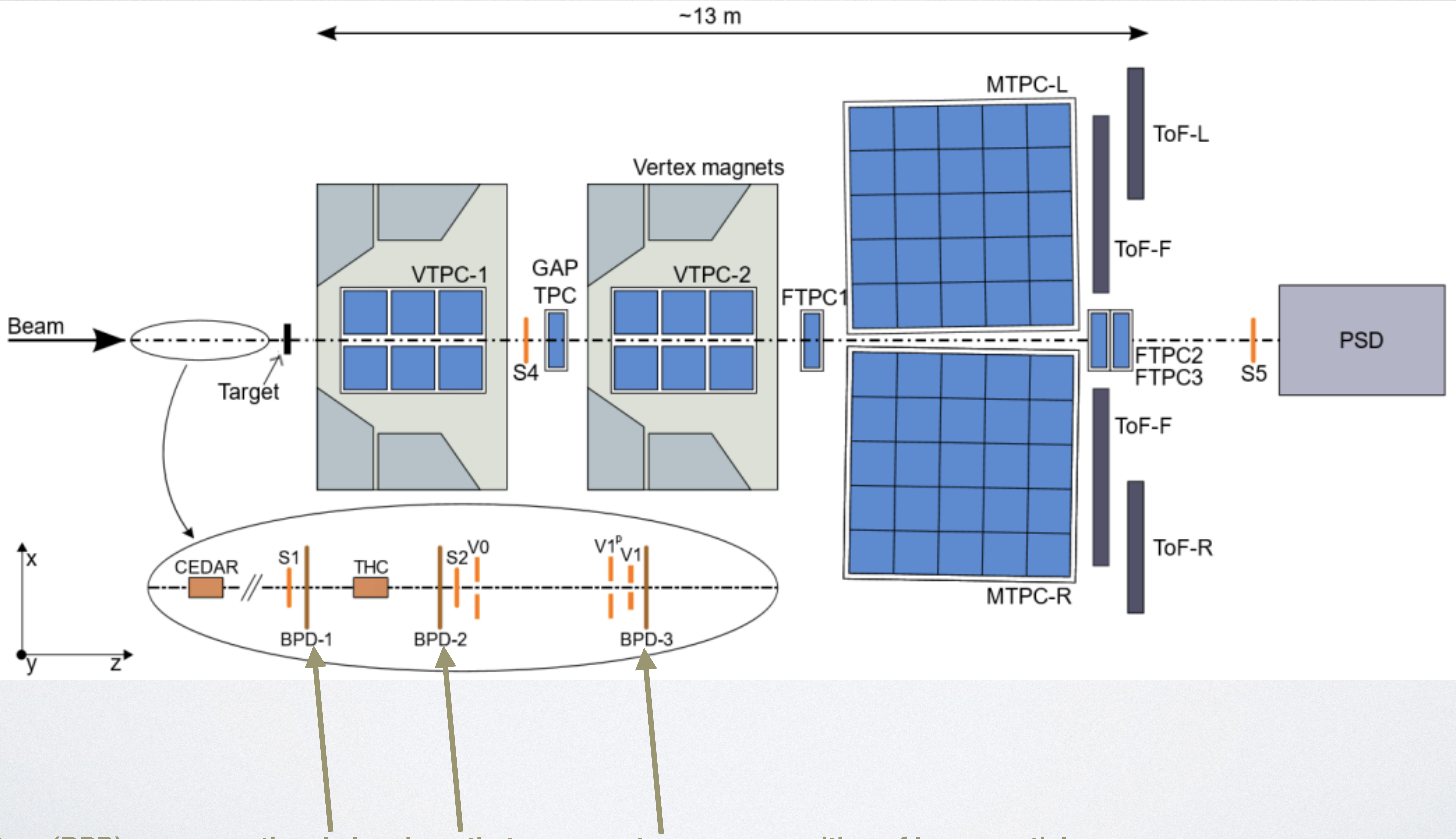


NA61/SHINE EXPERIMENT



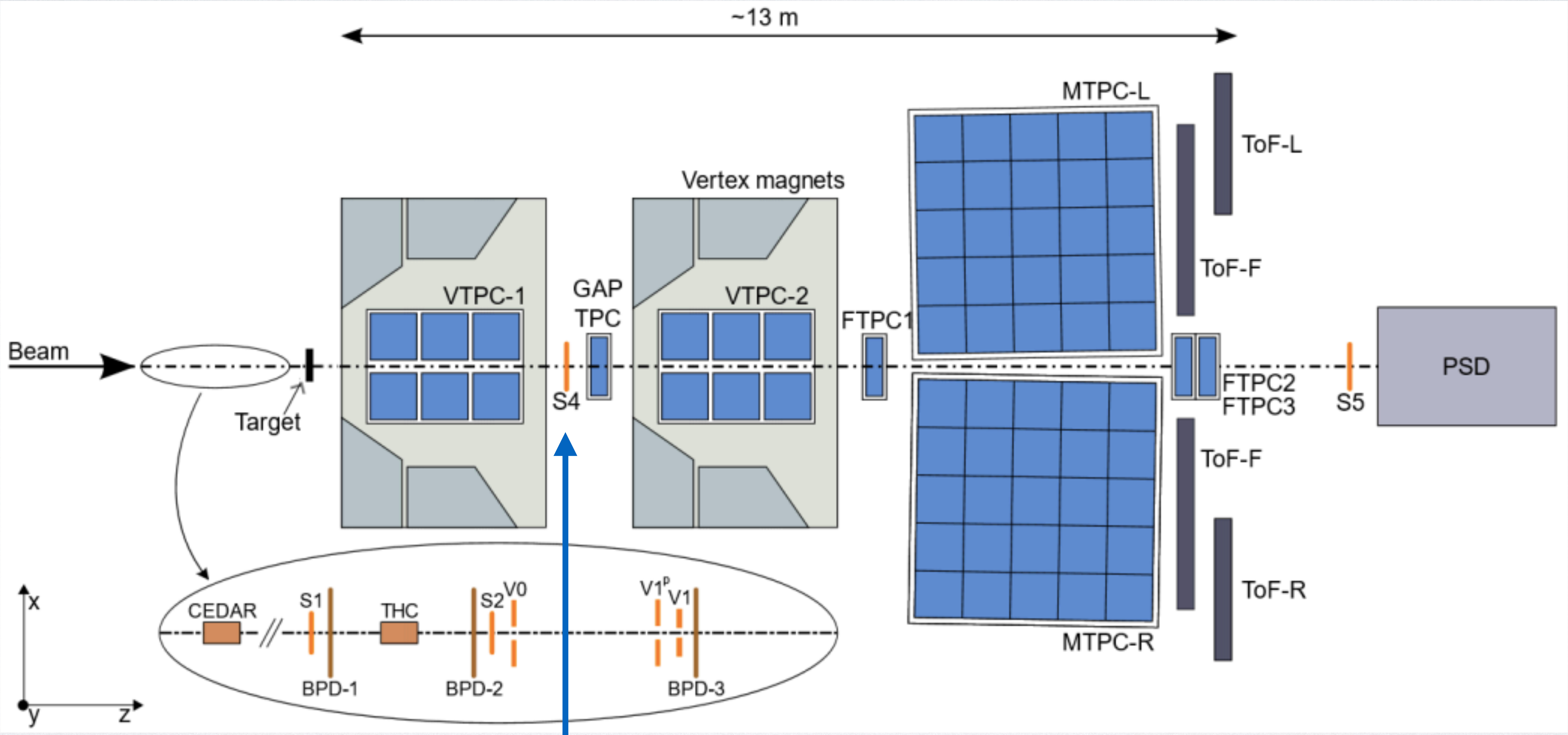
Series of scintillator counters serve as triggers, identifying good beam particles.

NA61/SHINE EXPERIMENT



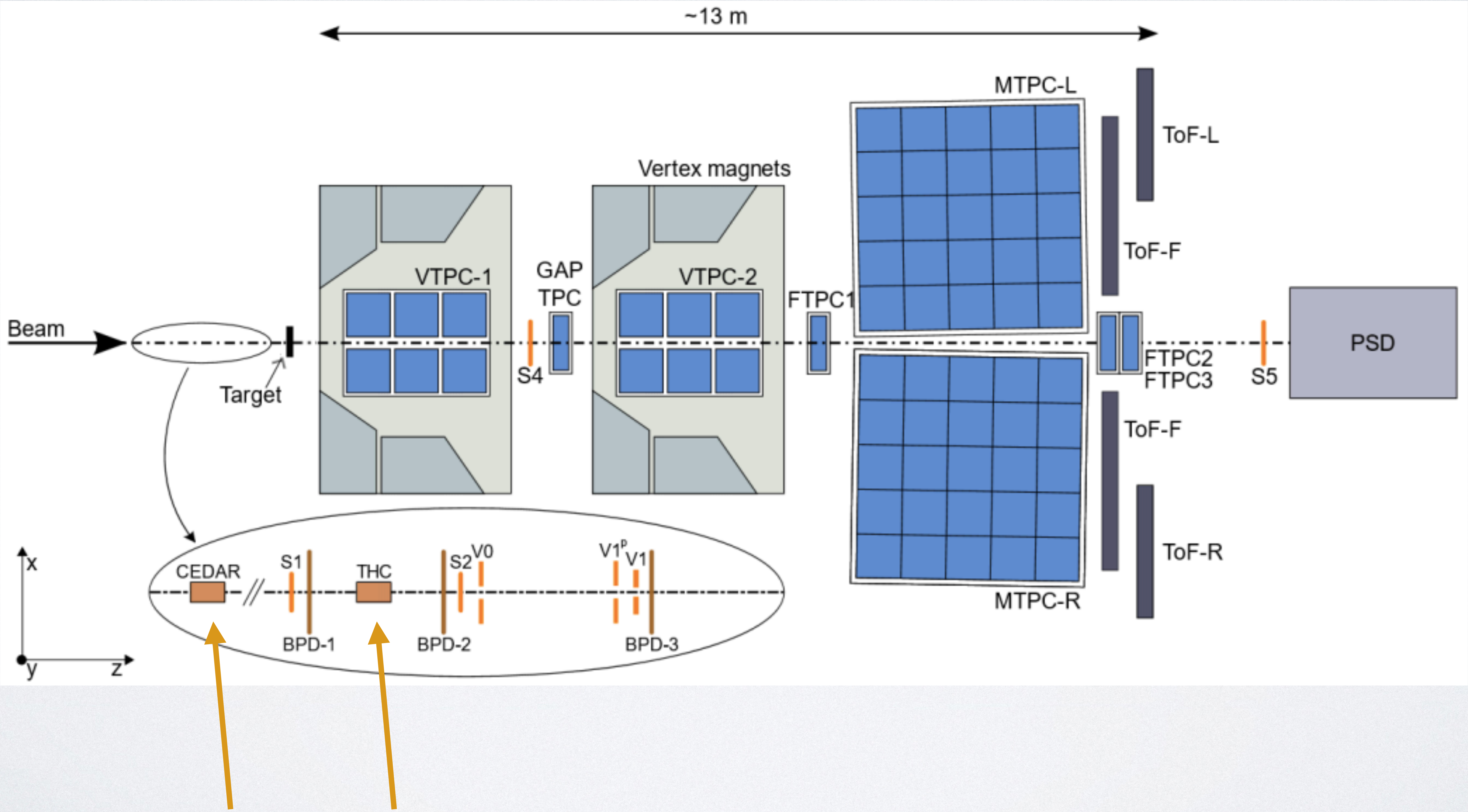
Beam Position Detectors (BPD) are proportional chambers that measure transverse position of beam particles

NA61/SHINE EXPERIMENT



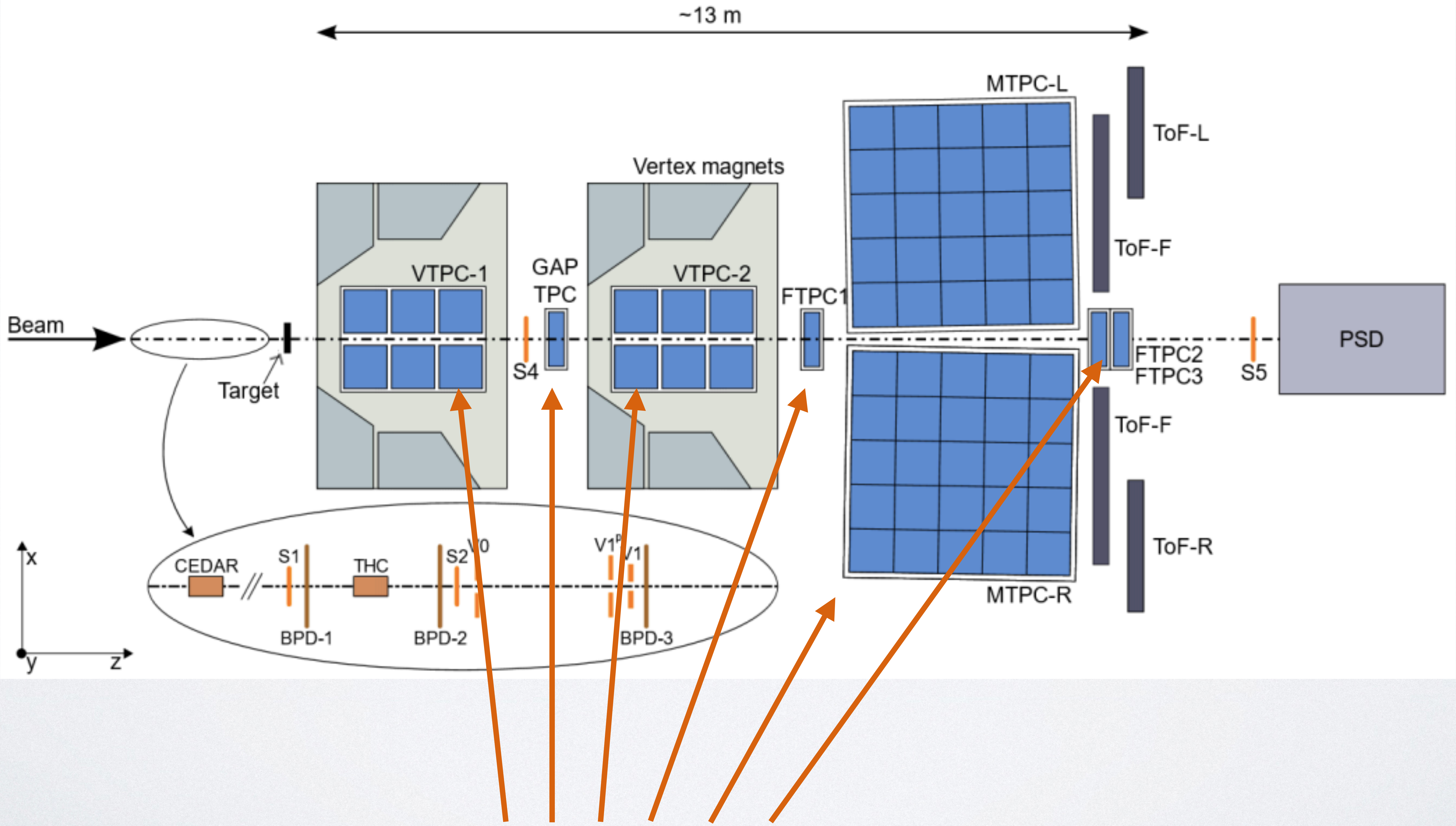
An additional scintillator counter downstream of target vetoes beam particles that do not interact

NA61/SHINE EXPERIMENT



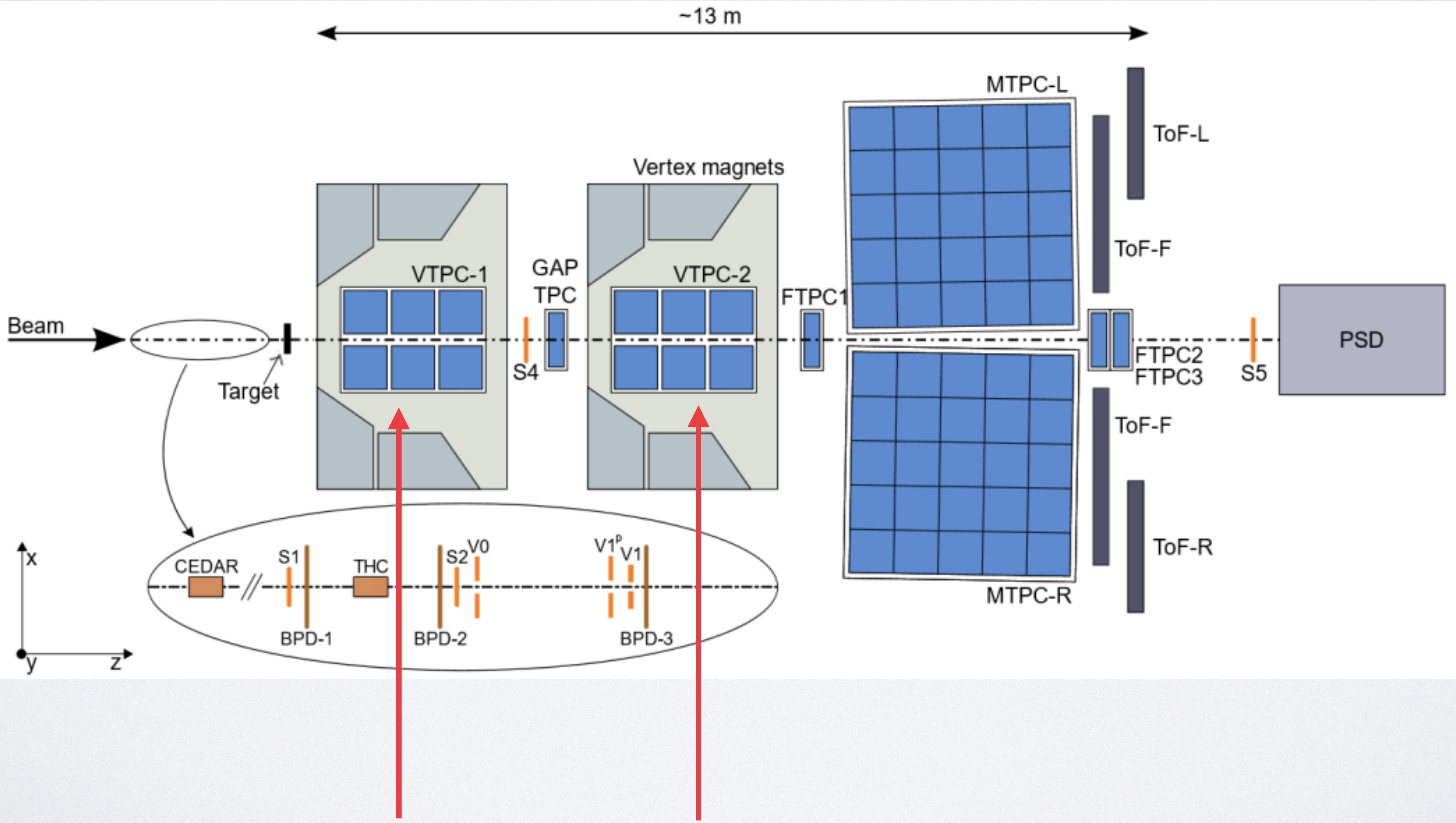
CEDAR and THC (Cerenkov Detectors) provide particle ID of beam particles.

NA61/SHINE EXPERIMENT



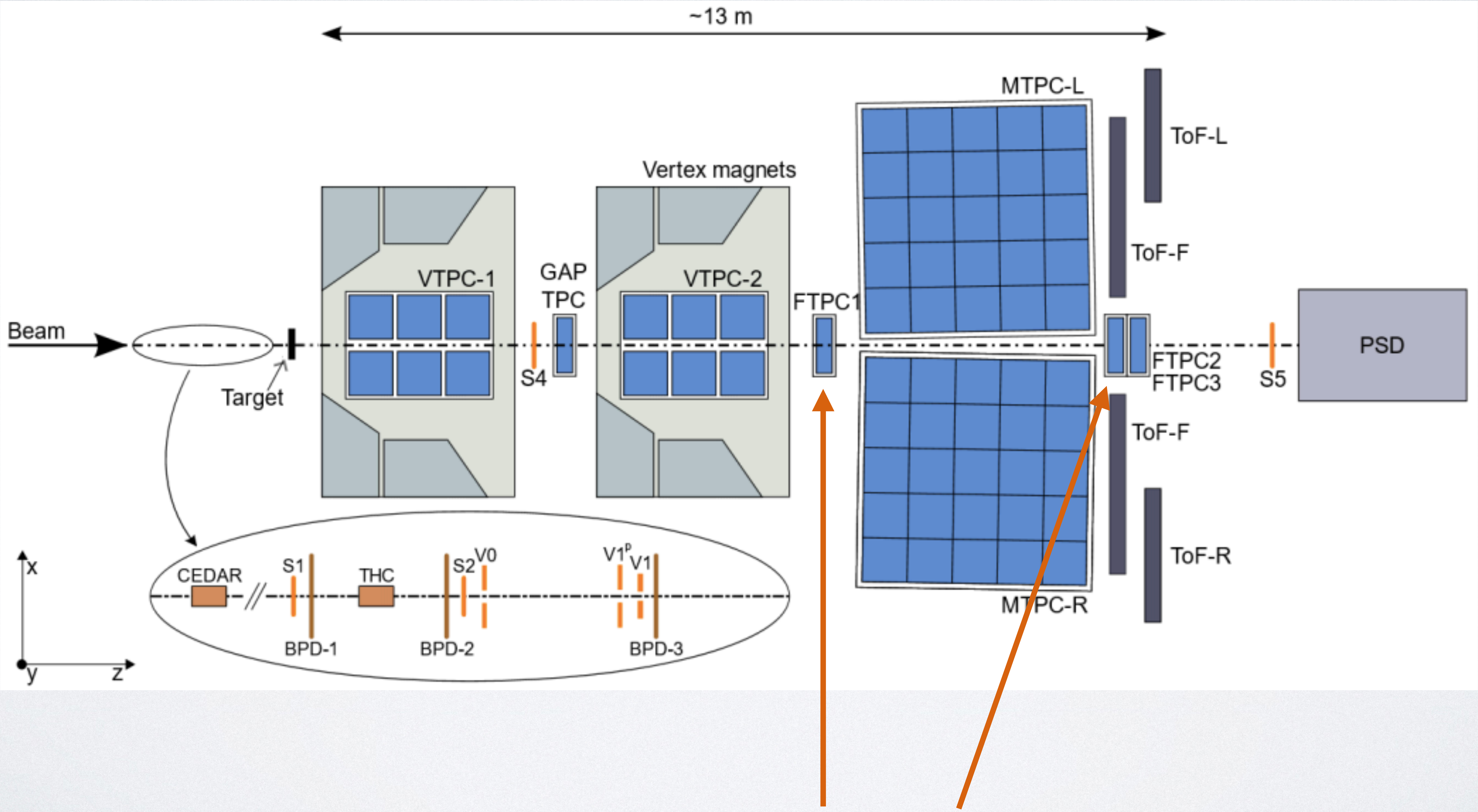
TPC system tracks charged particles and measures dE/dx with typical resolution of $\sigma_{dE/dx}/\langle dE/dx \rangle \approx .04$

NA61/SHINE EXPERIMENT



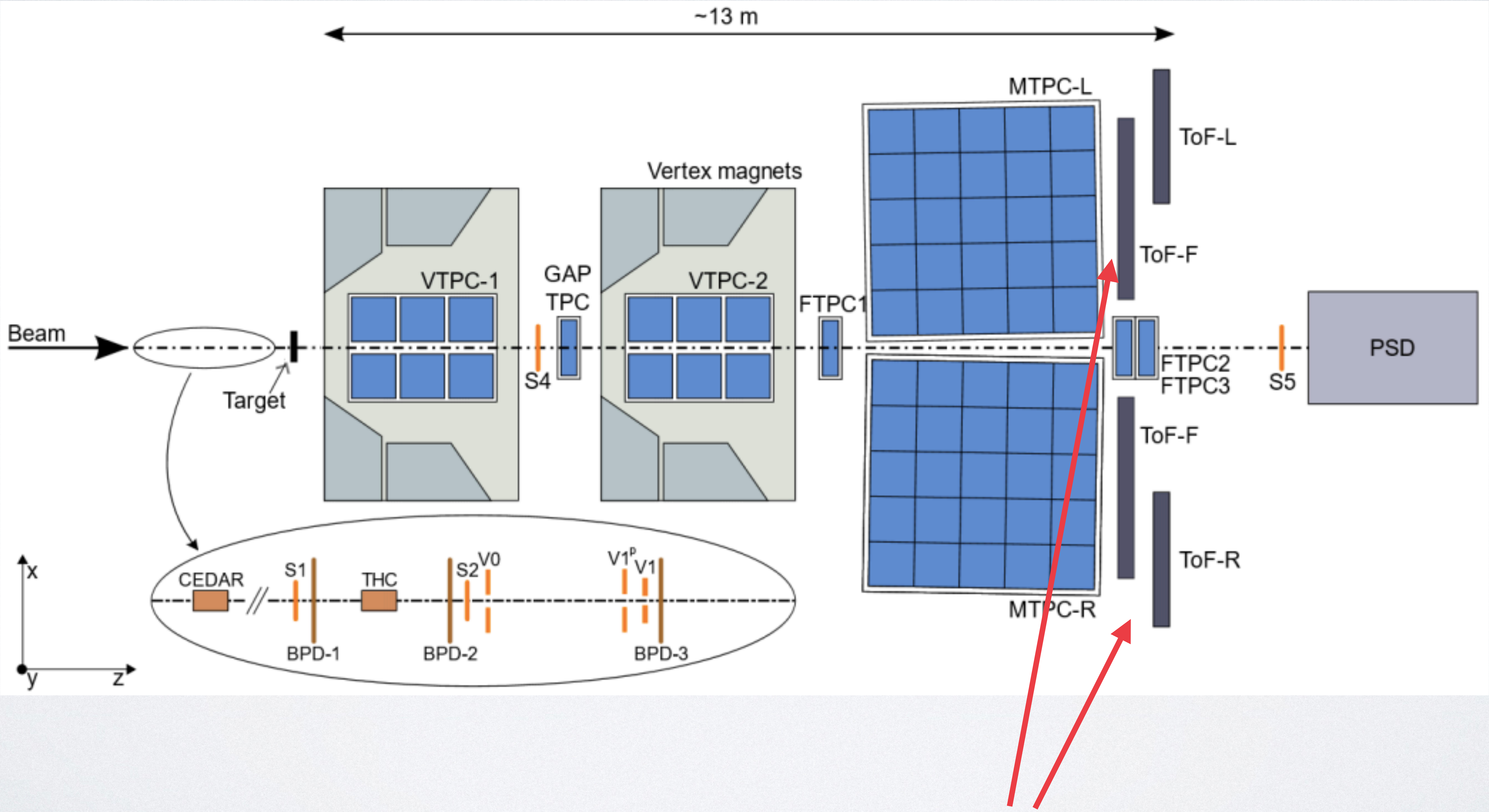
Analysis magnets facilitate charge and momentum reconstruction

NA61/SHINE EXPERIMENT



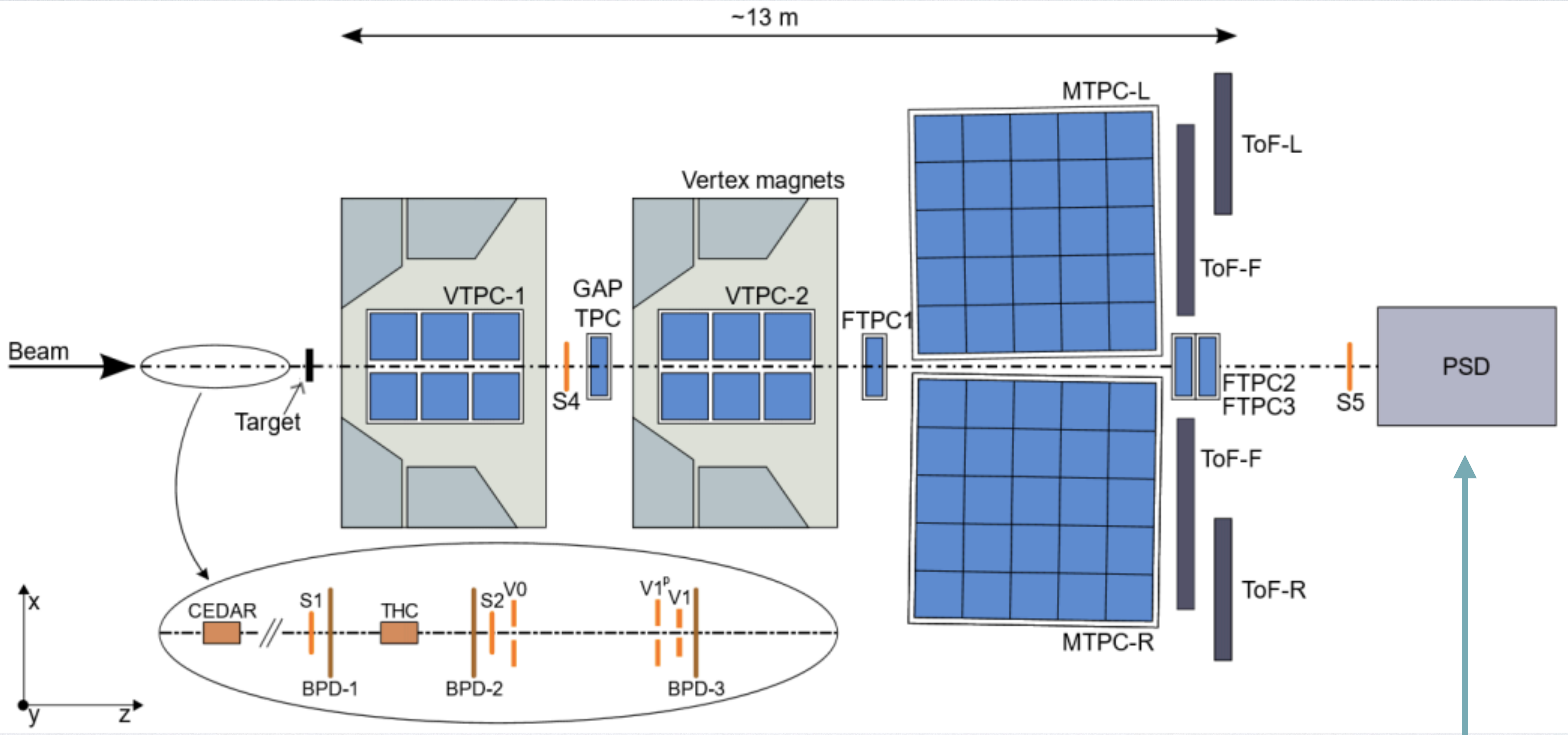
New Forward TPCs improve forward acceptance installed in 2016

NA61/SHINE EXPERIMENT



Time of Flight System provides particle ID (along with dE/dx in TPCs)

NA61/SHINE EXPERIMENT



"Projectile Spectator Detector"
Hadron Calorimeter not used for neutrino program

NA61/SHINE OPERATIONAL ERAS

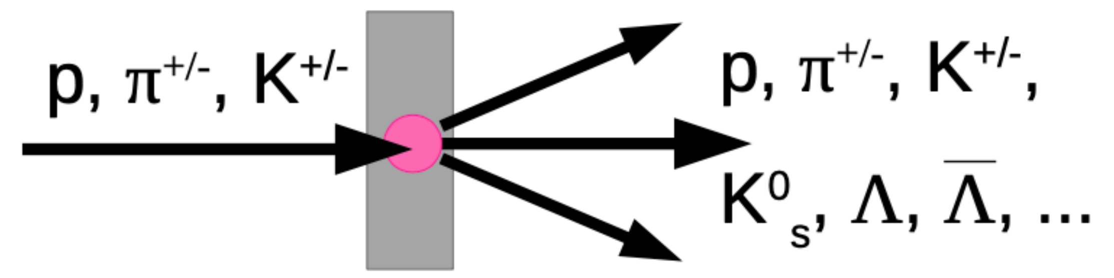
- **Multi-phase** program of hadron production measurements dedicated for neutrino physics
- Major **upgrades** during each Long Shutdown; e.g. improving forward TPCs to improve forward acceptance and new electronics for ~factor of 10 increase in DAQ rate (to 1 kHZ)
- Plans **continue to evolve** for future upgrades and operations

PHASE 1&2 DATA AND RESULTS

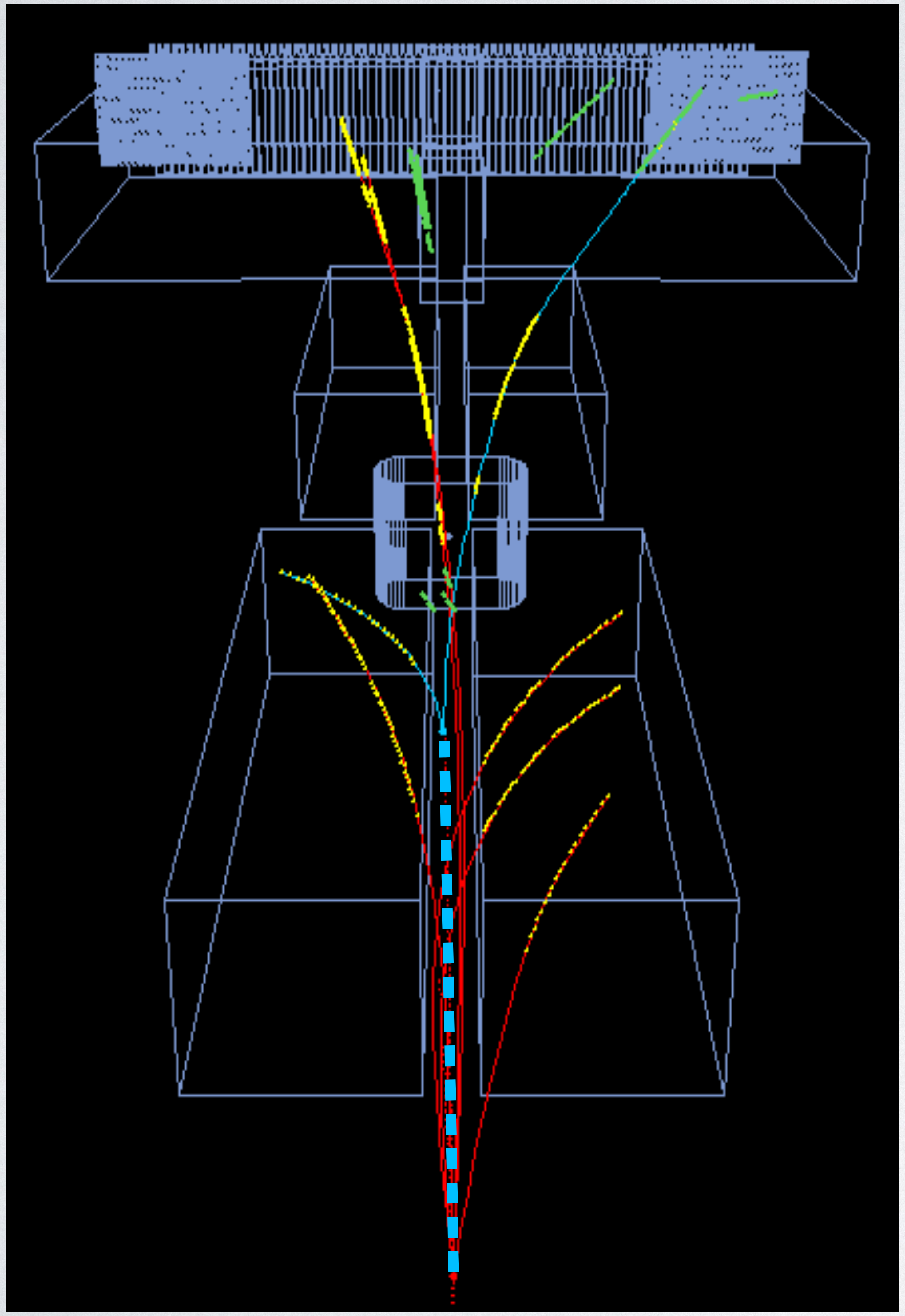
Beam	Target	Year	Measurements
p@31 GeV/c	C	2007	$\pi^{\pm}$ [1], K^{+} [2], K^0_S, Λ^0 [3]
p@31 GeV/c	C	2009	$\pi^{\pm}$, $K^{\pm}$, p, K^0_S, Λ^0 [4]
π^+@31 GeV/c	C,Be	2015	Total Cross Section[5] (Magnet Off)
π^+@60 GeV/c	C,Be	2015	Total Cross Section[5] (Magnet Off)
K^+@60 GeV/c	C,Be	2015	Total Cross Section[5] (Magnet Off)
π^+@60 GeV/c	C,Be	2016	p, $\pi^{\pm}$, K^+, K^0_S, Λ [6]
p@60 GeV/c	C, Al, Be	2016	Total Cross Sections[7]; Spectra Analysis
p@120 GeV/c	C, Be	2016	Total Cross Sections[7]; Spectra Analysis[8,9]
π^+@60 GeV/c	C, AL	2017	In Progress
π^+@30 GeV/c	C	2017	In Progress
p@120 GeV/c	C, Be	2017	Spectra Analysis[9]
p@90 GeV/c	C	2017	In Progress

1 Phys. Rev. C84, 034604 (2011).
2 Phys. Rev. C85, 035210 (2012).
3 Phys. Rev C89, 025205 (2014).
4 Eur. Phys. J. C (2016) 76: 84
5 Phys. Rev. D98, No.5 052001 (2018)
6 Phys. Rev. D100, 112004 (2019)
7 Phys. Rev. D100, 112001 (2019)
8 Phys. Rev. D107, 072004 (2023)
9 Phys. Rev. D108, 072013 (2023)

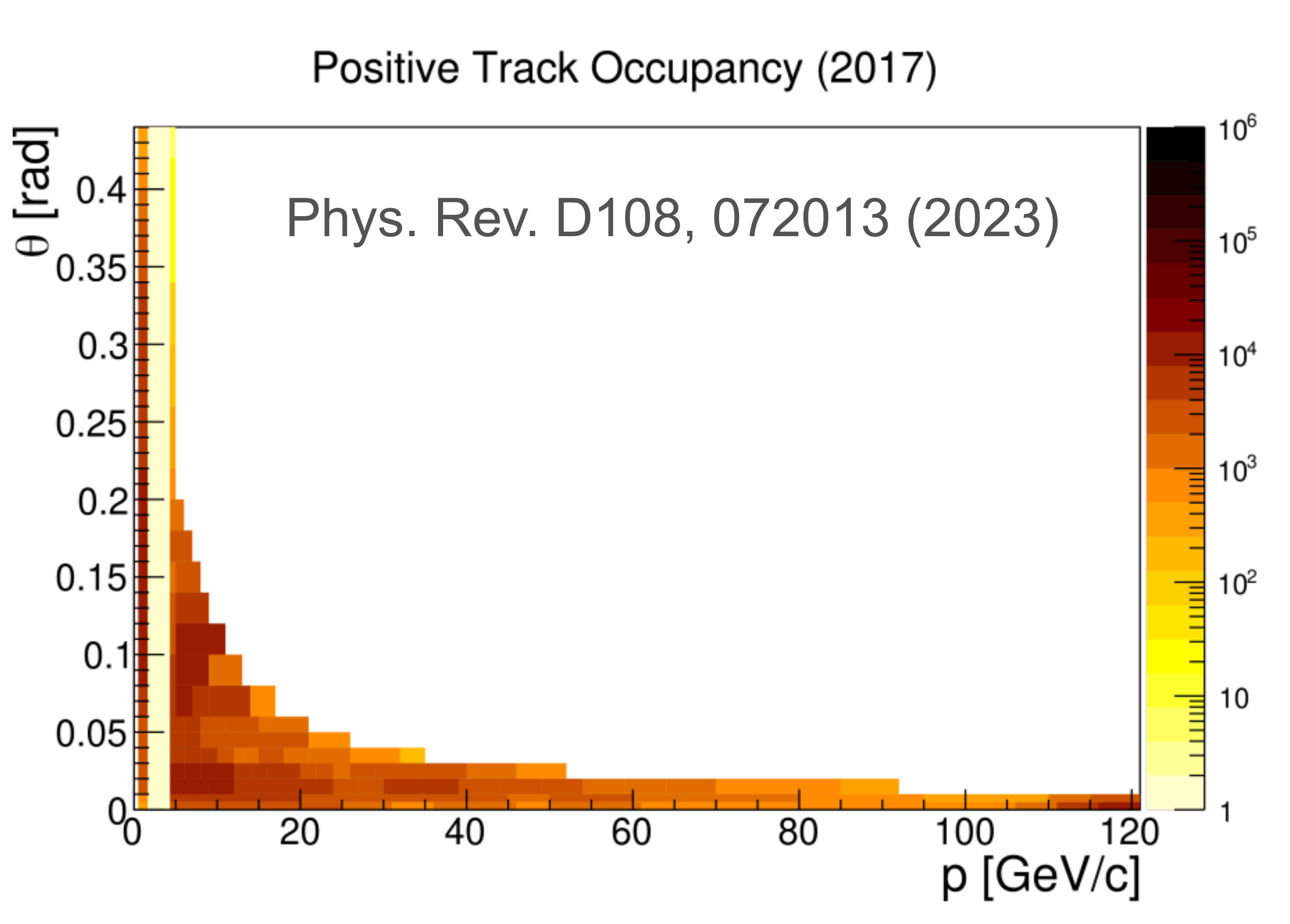
Thin-Target Measurements

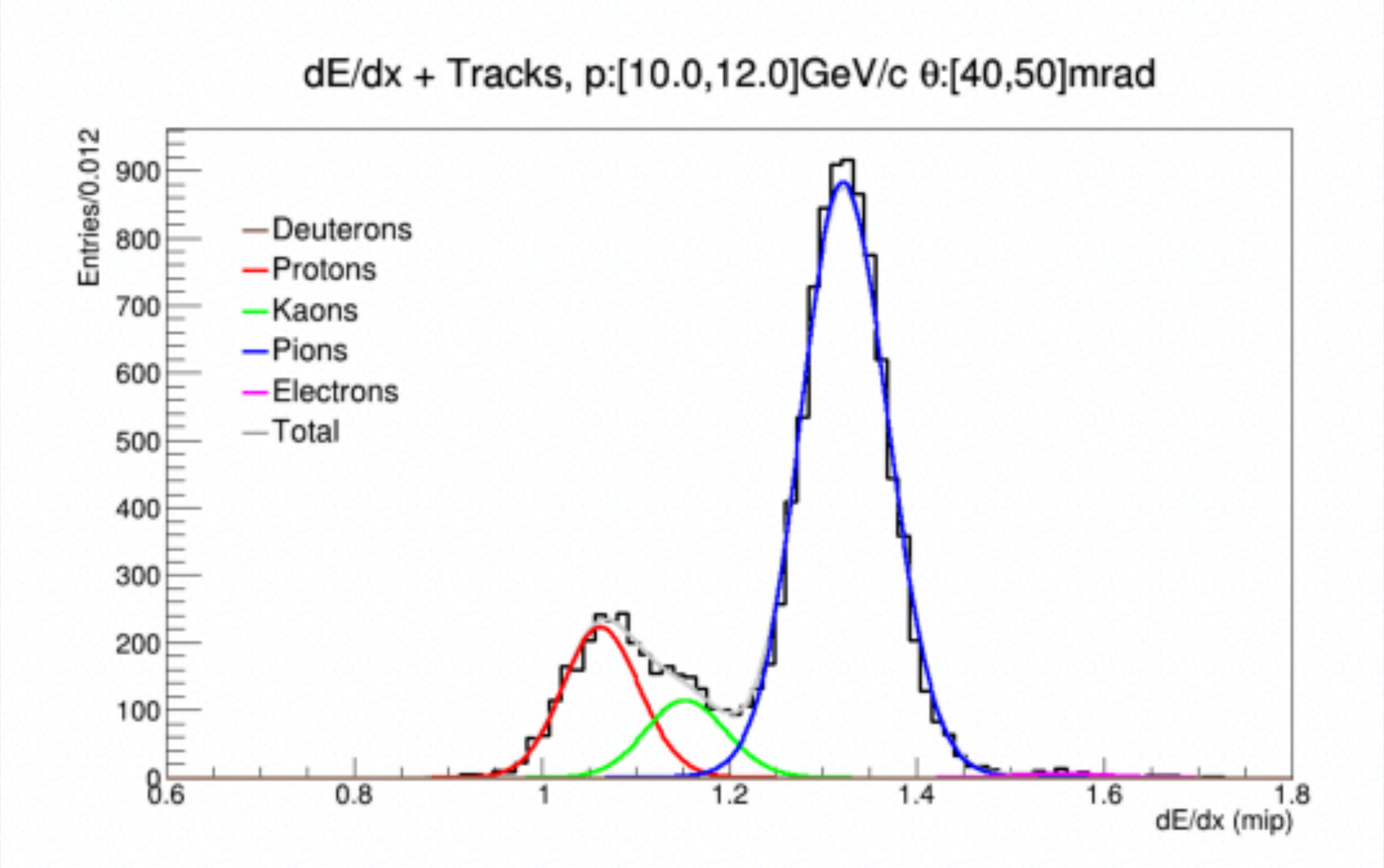


RECENT RESULT: 120 GEV/C P+C



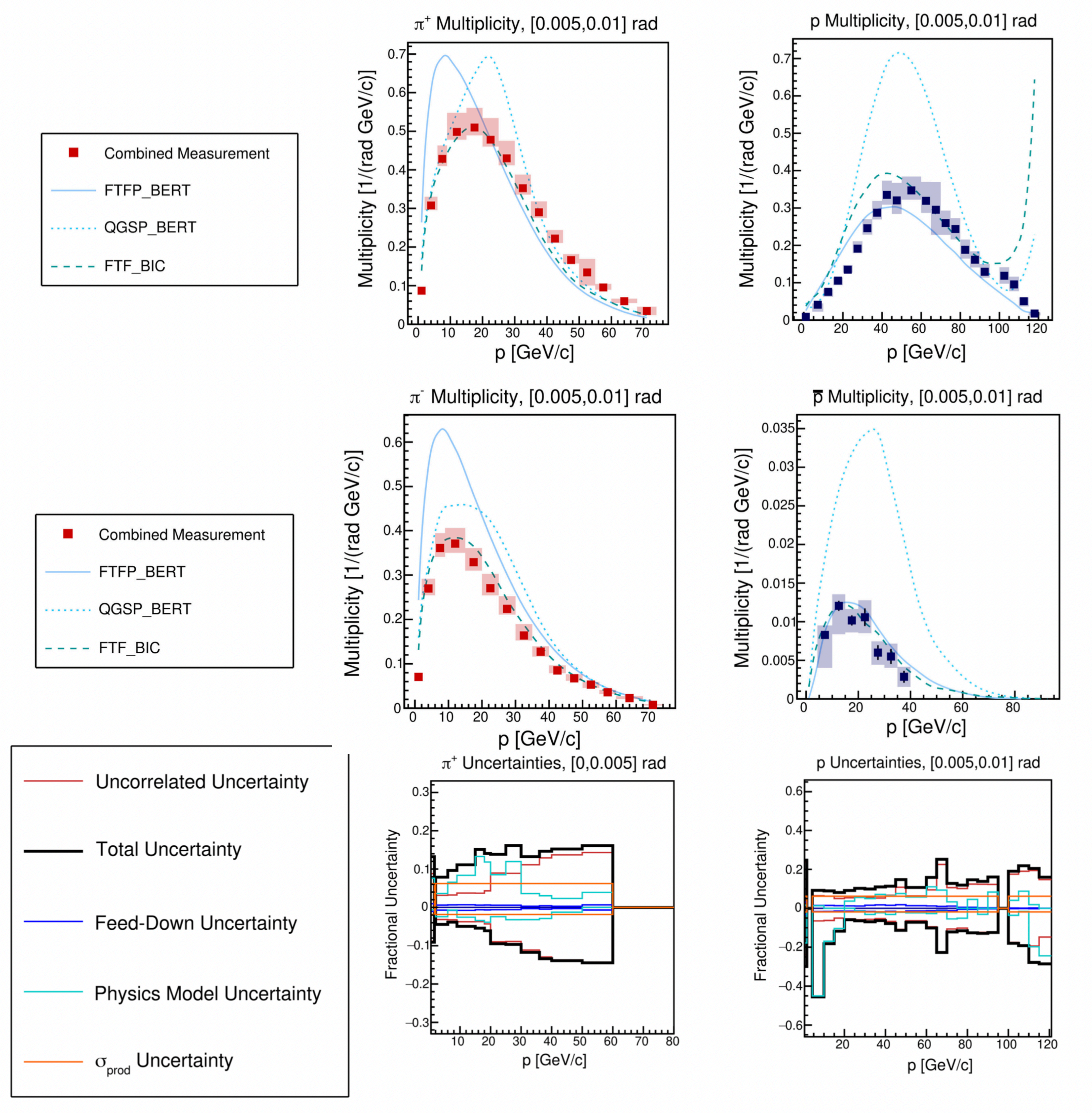
- **Interacting events** are binned in p/theta of final state particle
- **Dedx distributions** are fit to extract number of protons, kaons and pions
- Those numbers are corrected for **detector acceptance and backgrounds**
- Normalized using **total production cross section** (also measured by NA61/SHINE) to produce multiplicities per p/theta bin





RECENT RESULT: 120 GEV P+C

- **Measured multiplicities**: π^+, π^-, p, $\bar{p}$, K^+, K^-
- Comparison with Geant4 physics lists shows **big discrepancies**
- **Uncertainties** dominated by statistics, G4 model uncertainties
- Will be used for **DUNE and NuMI** flux prediction, replacing older NA49 data
- Full **covariance matrices** provided
  - Necessary for evaluating flux uncertainties and bin-to-bin correlations

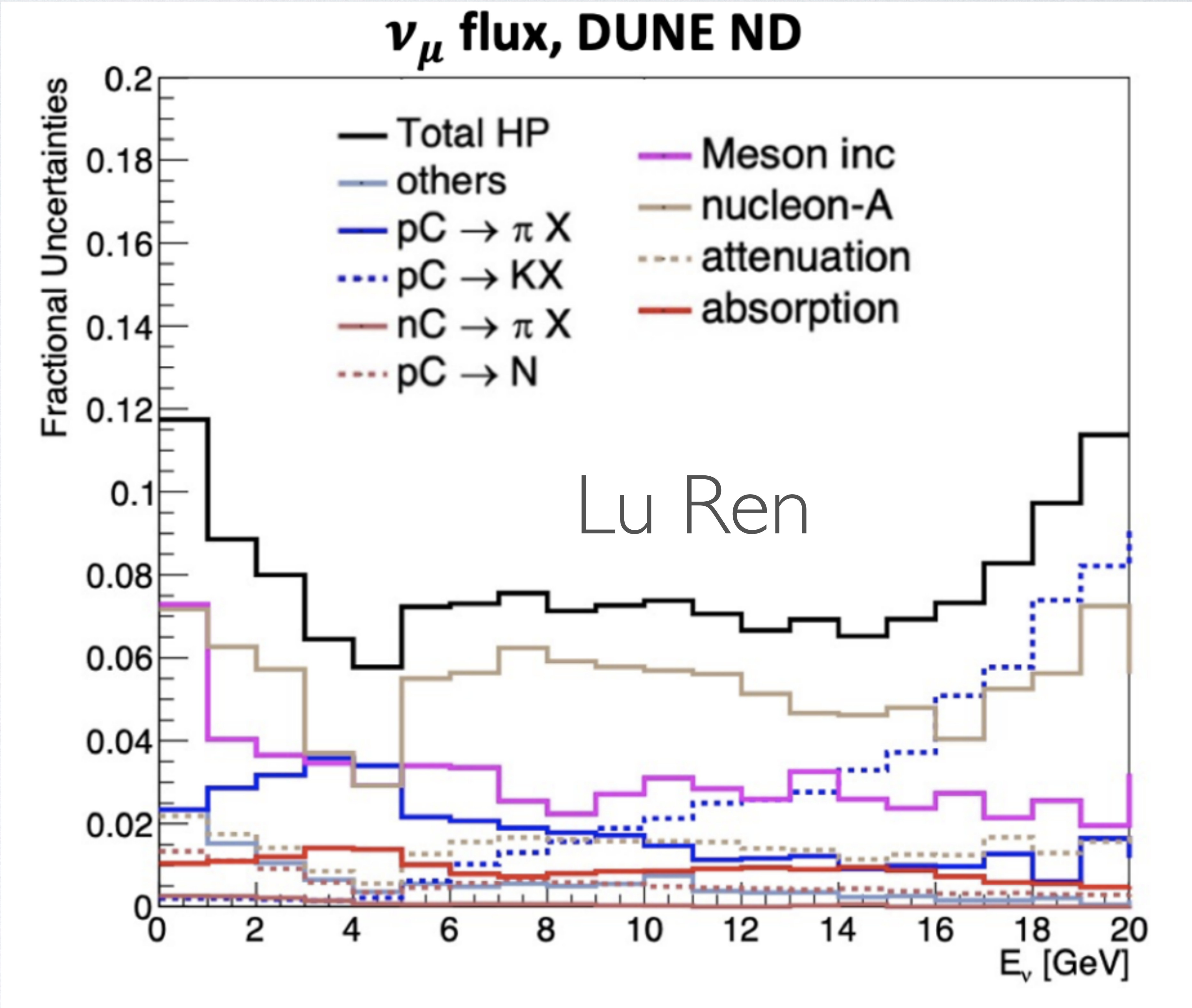


THIN TARGET DATA IN PPFX

- 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

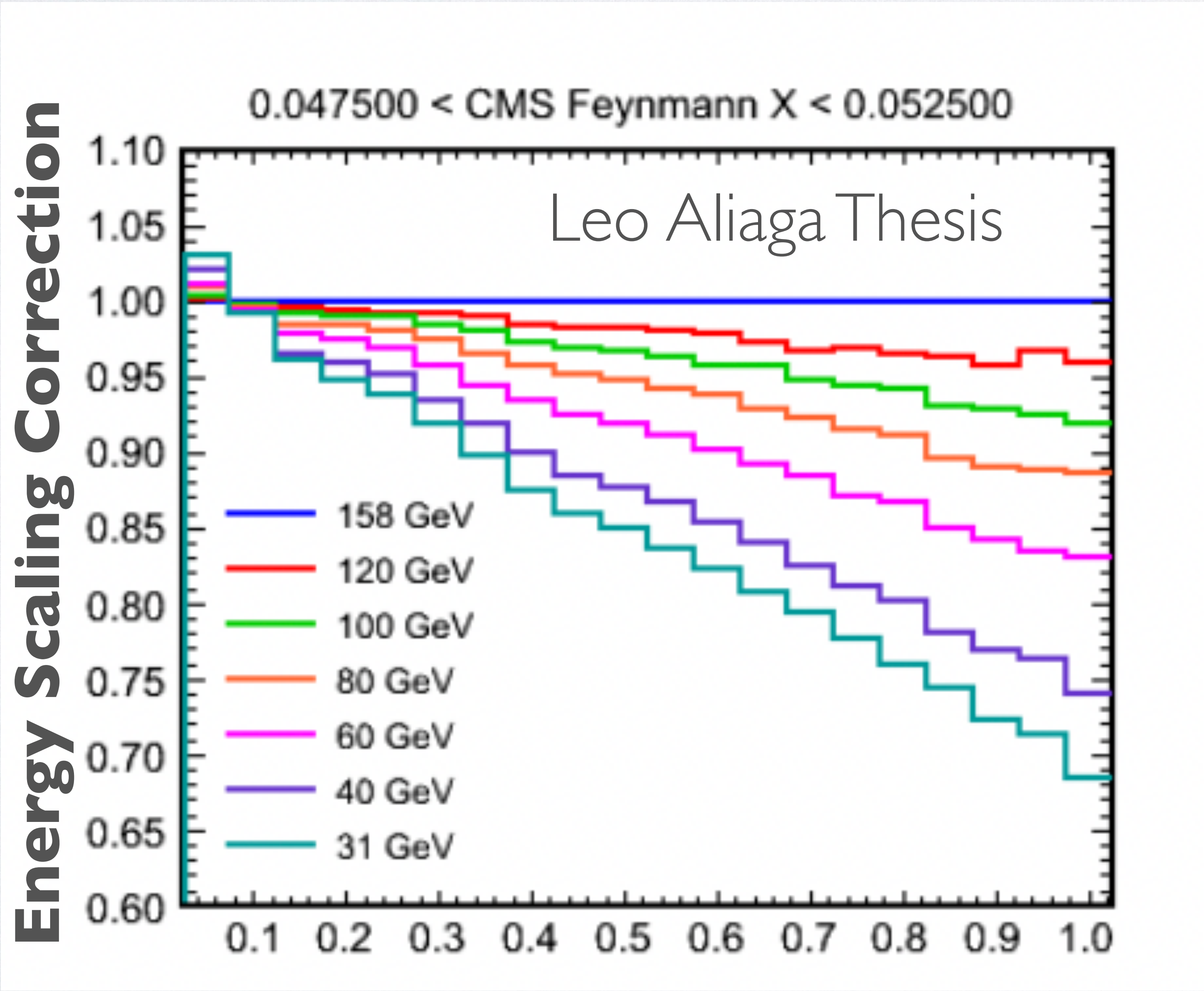
Current PPFX uncertainty

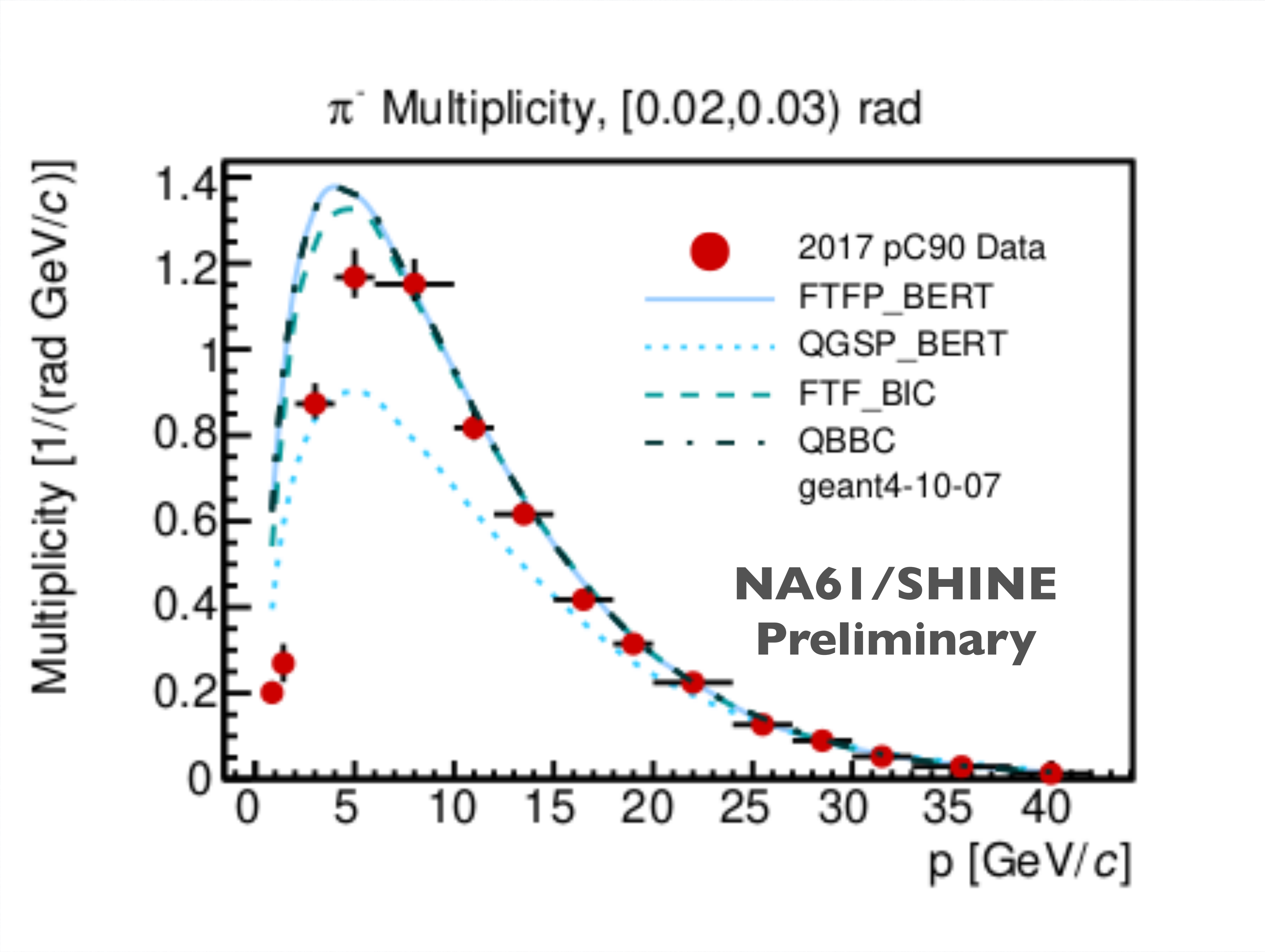


Stay tuned for more detail on updating PPFX from Leo Aliaga, later in this session

UPCOMING RESULT: 90 GEV P+C

- Also have mature analysis of **90 GeV/c proton+C** data
- Combined with 60 GeV, 120 GeV/c will provide important data for **validation of energy scaling** in flux predictions

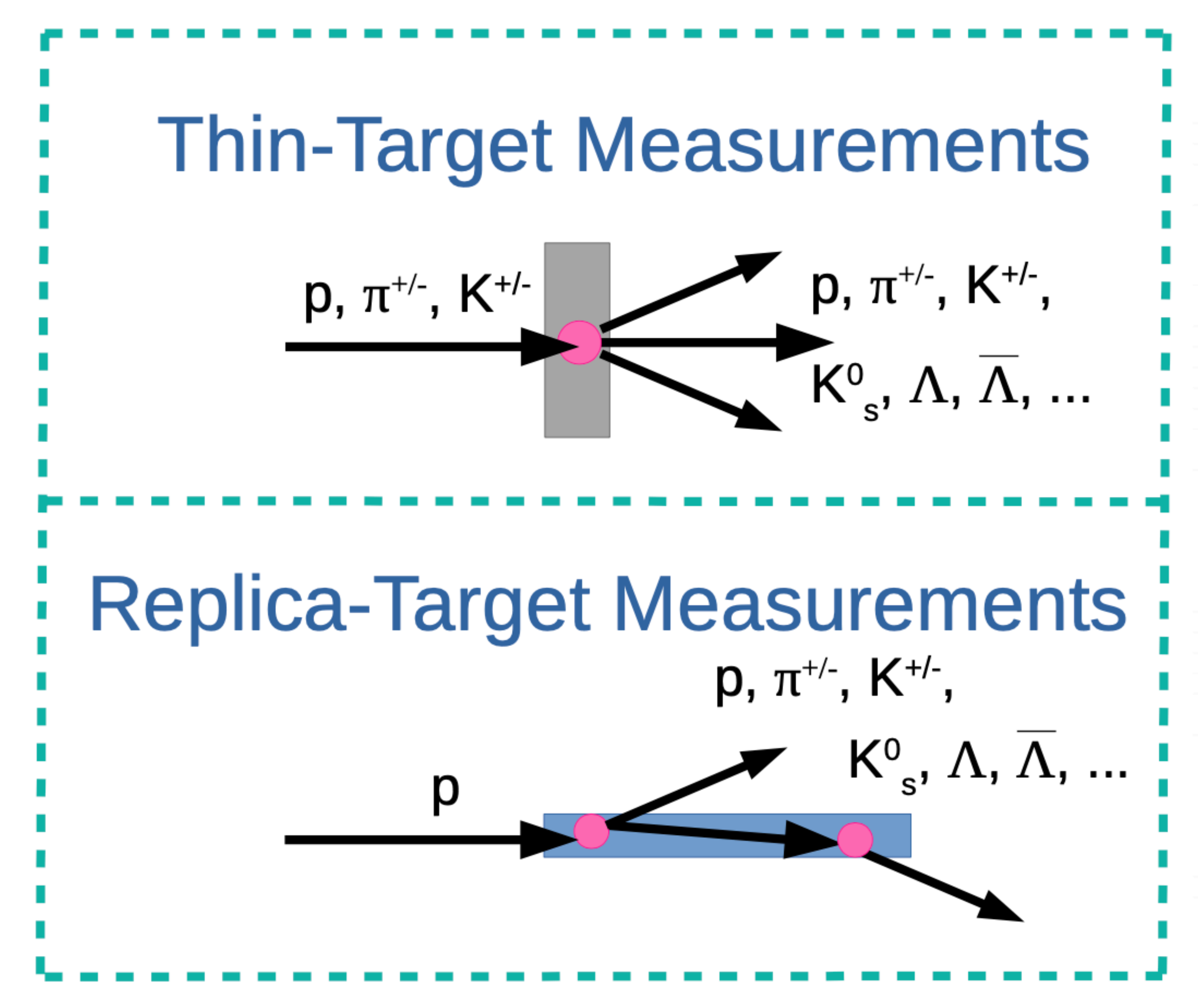




REPLICA TARGET MEASUREMENTS

Measure differential multiplicities, normalized by production cross section

Measure differential yields normalized by number of protons

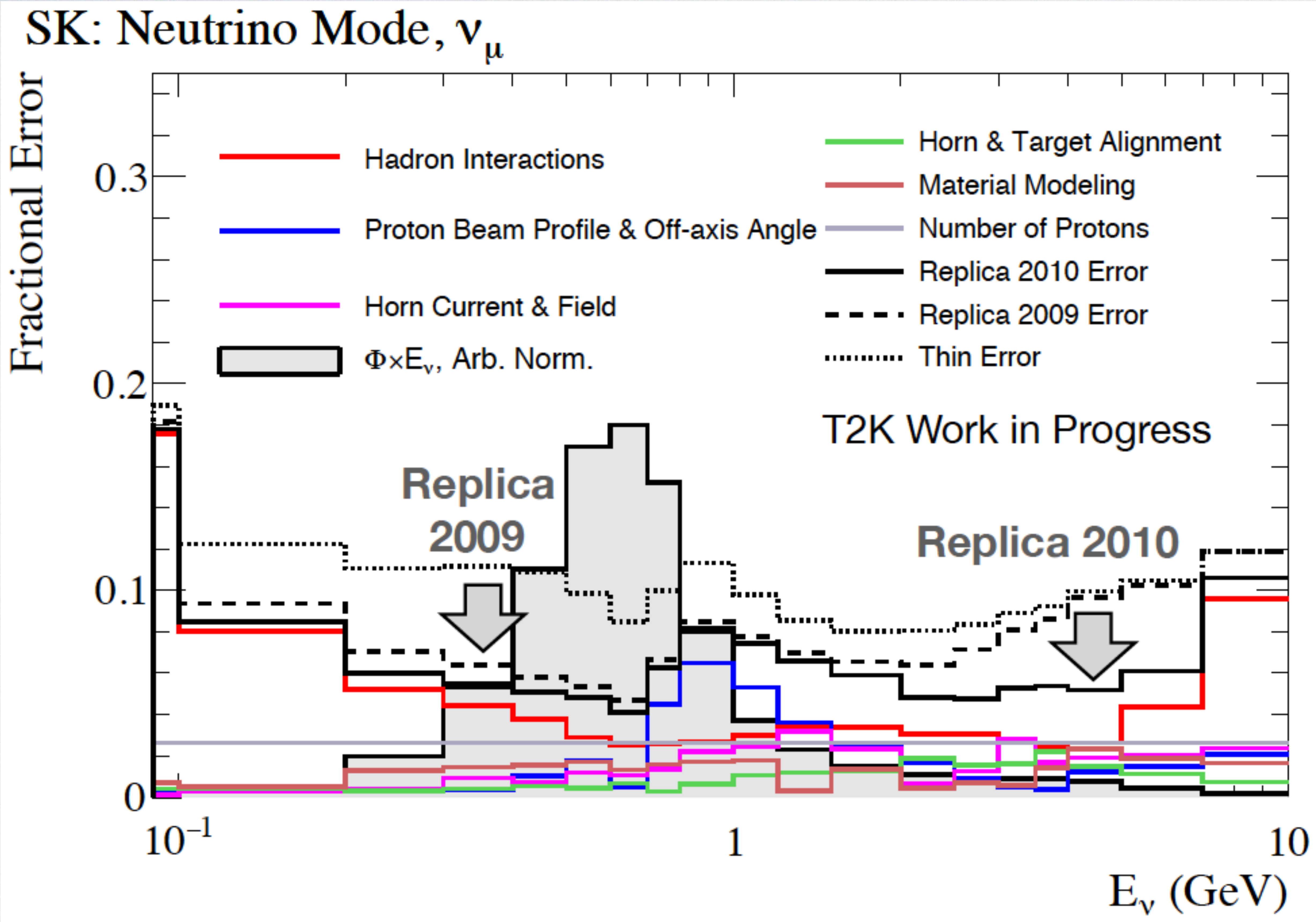


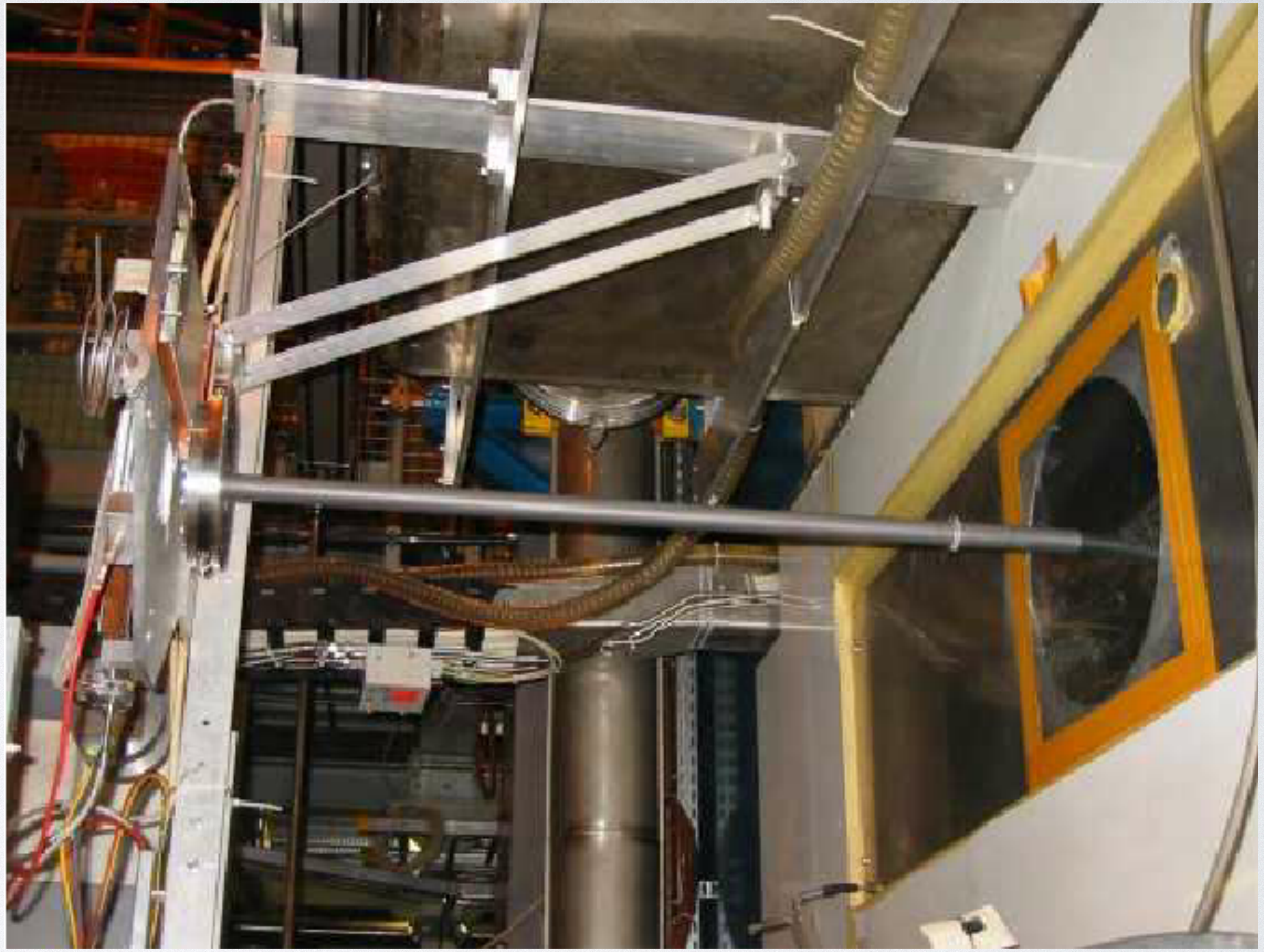
Beam	Target	Year	Measurements
p@31 GeV/c	T2K	2007	$\pi^\pm$ yields[1,2,3], $K^\pm$,p yields[3], production cross
p@120GeV/c	NuMI	2018	In Progress
p@120 GeV/c	LBNF	2024	In Progress

[1] Nucl. Instrum. Meth. A701 99-114 (2013).
[2] Eur. Phys. J. C76 617 (2016).
[3] Eur. Phys. J. C79, no.2 100 (2019).
[4] Phys. Rev. D103, 012006 (2021))

- Replica target measurements are the **gold standard of hadron production** measurements

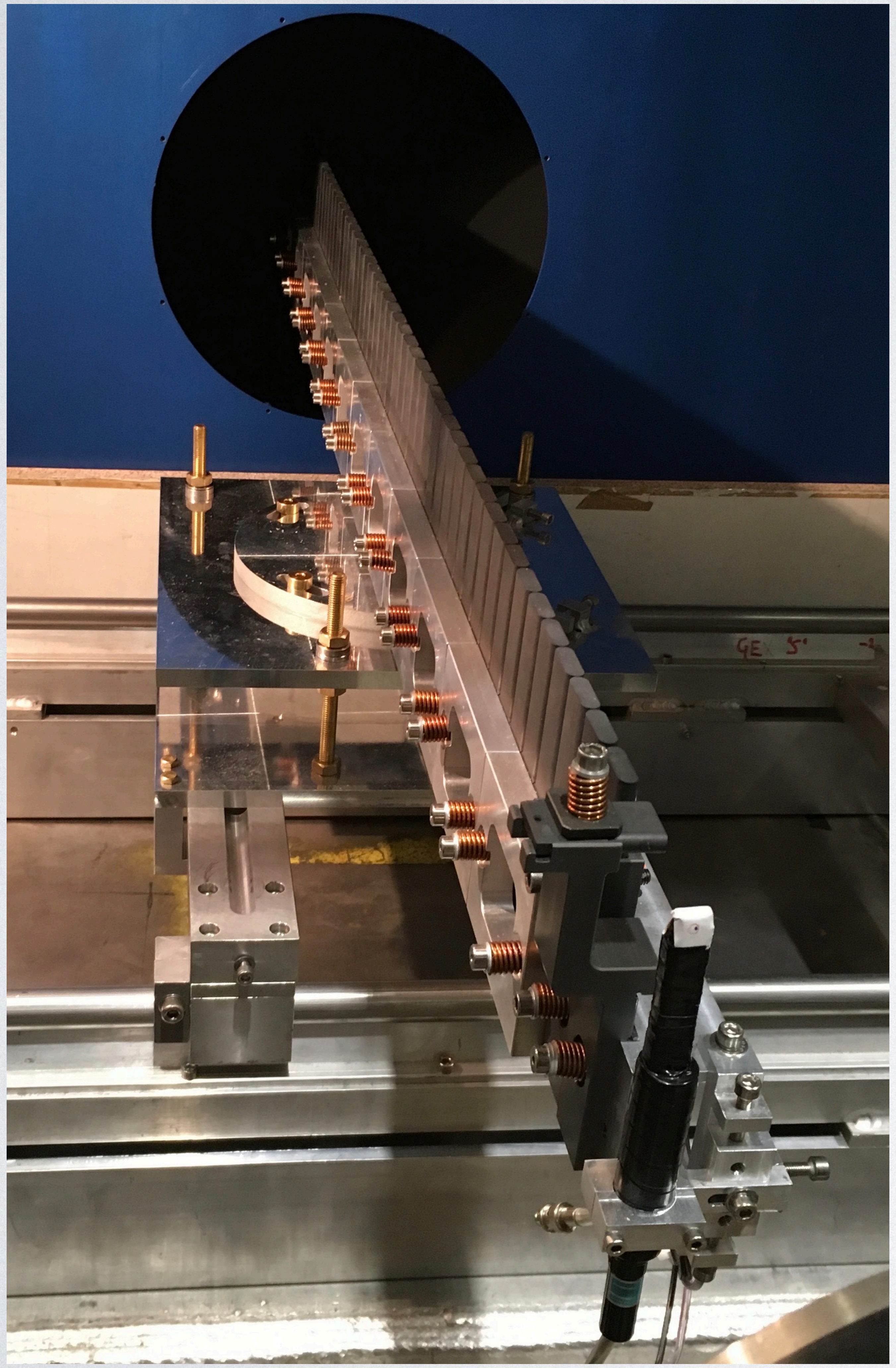
REPLICA TARGET MEASUREMENTS:T2K

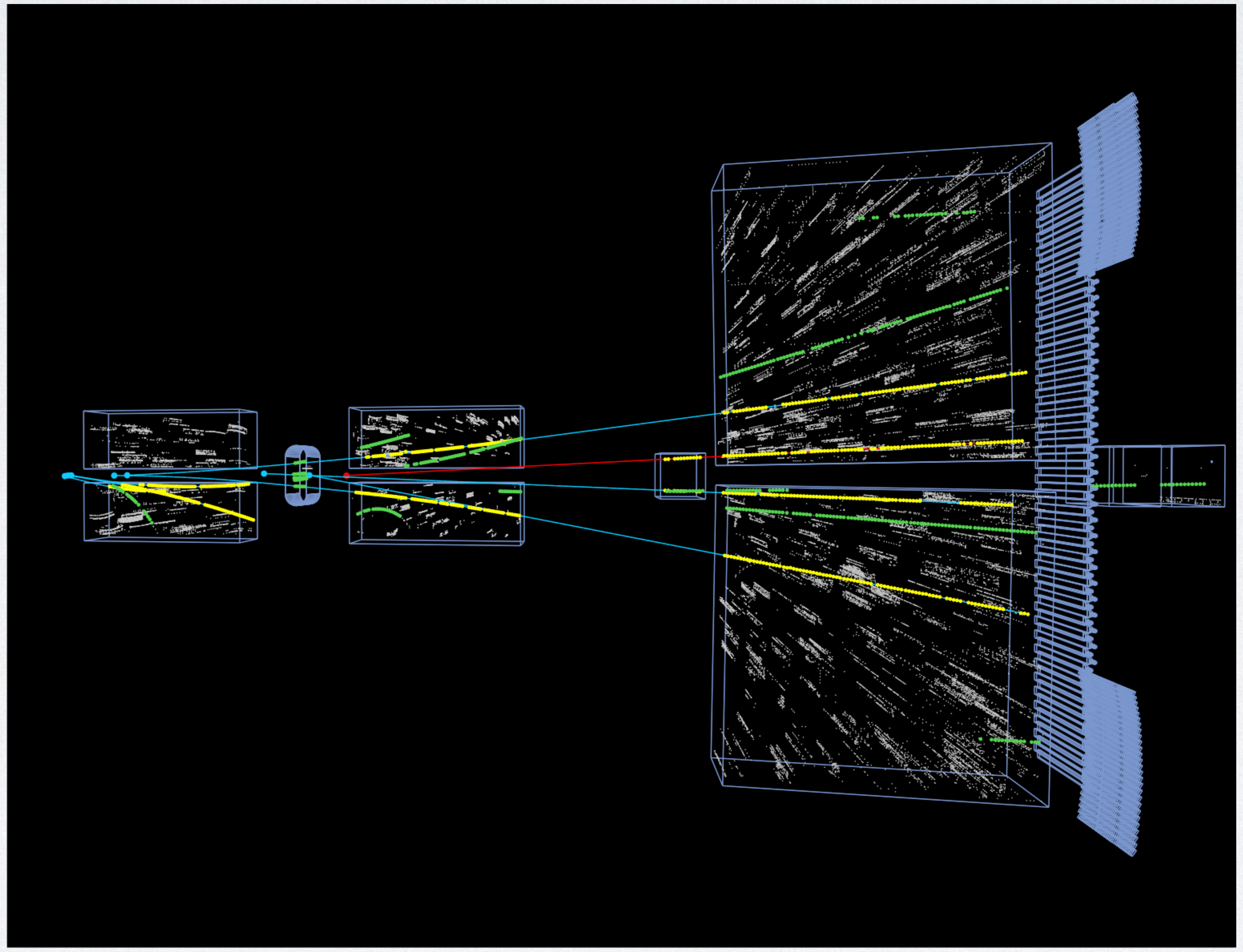




- Have ~**halved T2K flux** uncertainties at focusing peak

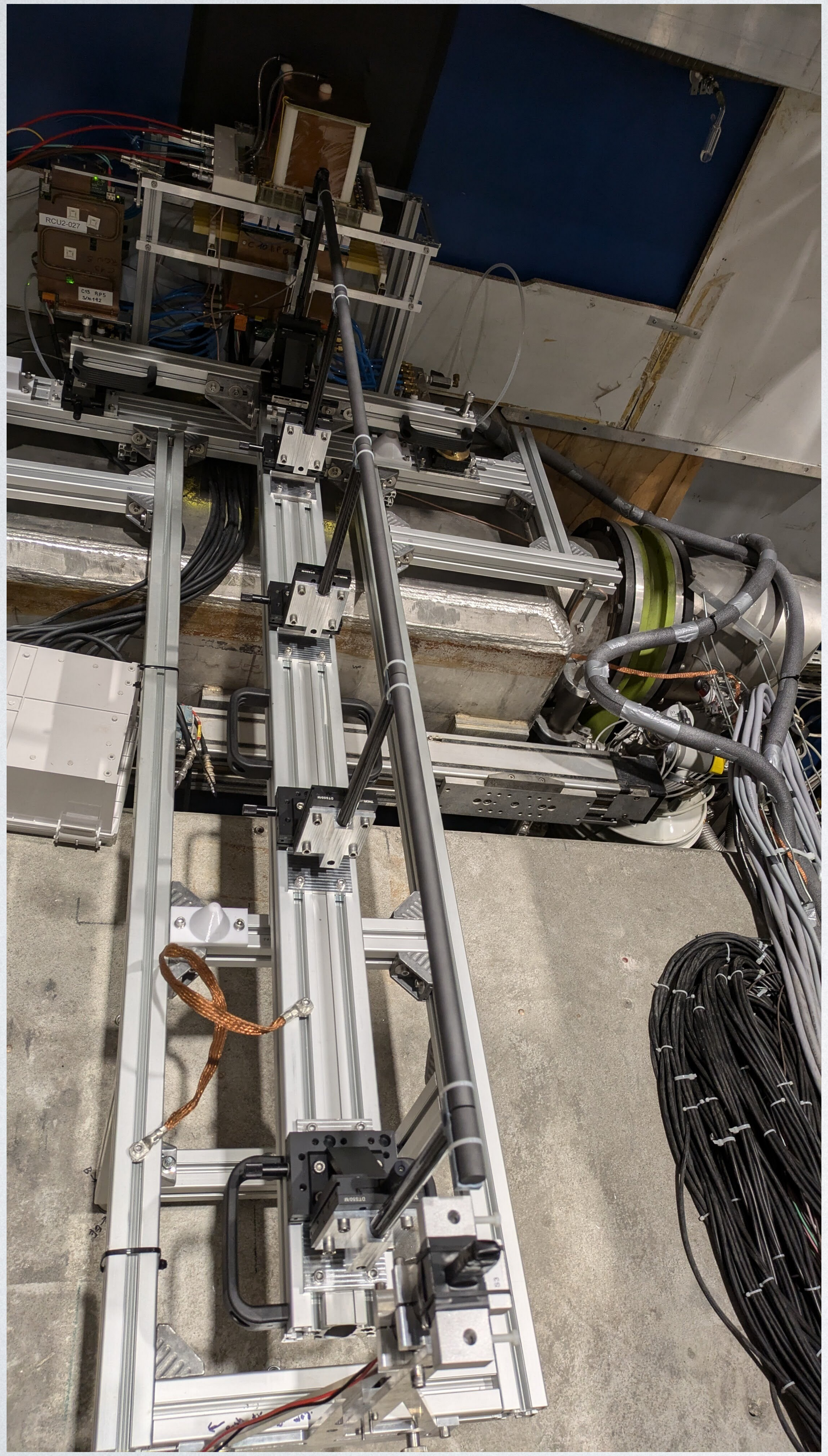
REPLICA TARGET MEASUREMENTS: NUMI

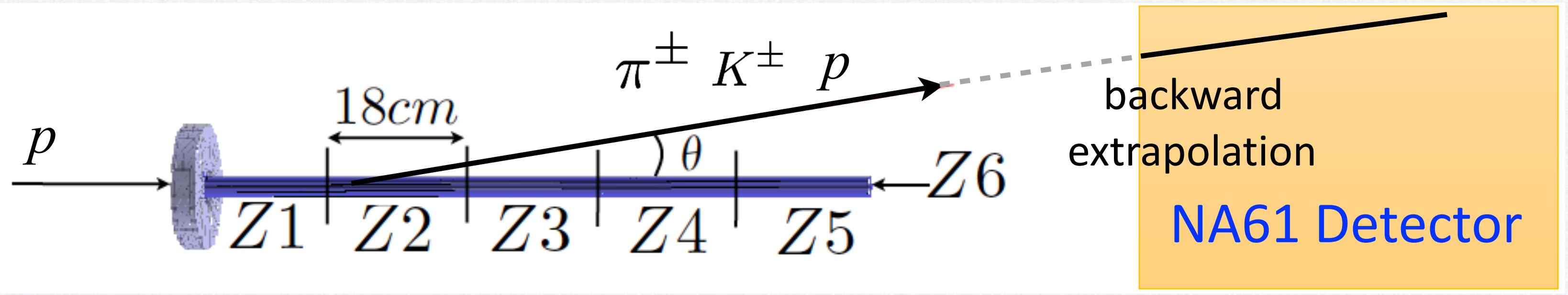




- Took high statistics **(18M events)** in 2018 with 120 GeV/c protons
- **Calibration** in progress for this data set
- **Analysis** underway on hadron yields from this target
- Complicated **geometry of the target**, with azimuthal dependence

REPLICA TARGET MEASUREMENTS: DUNE



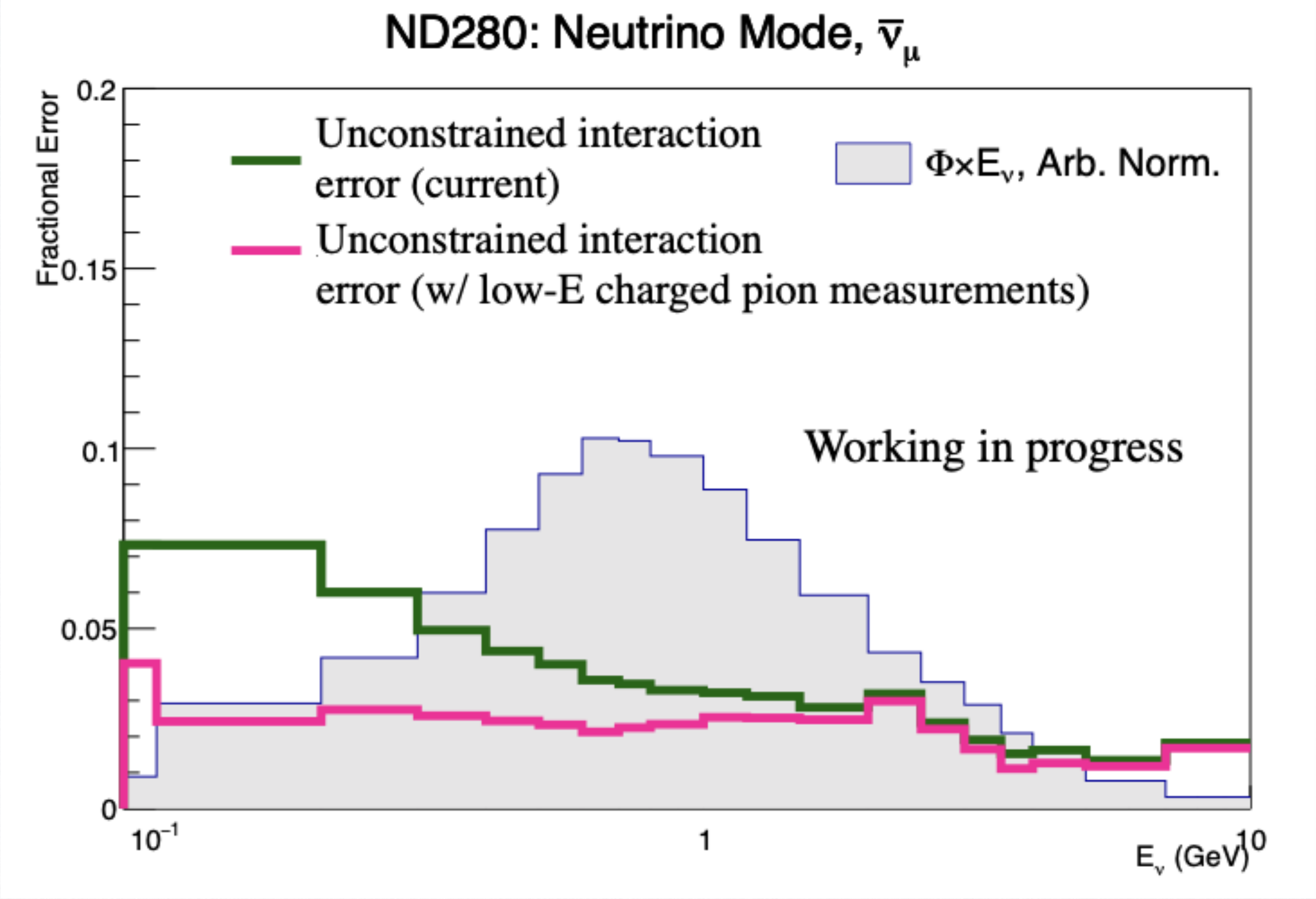


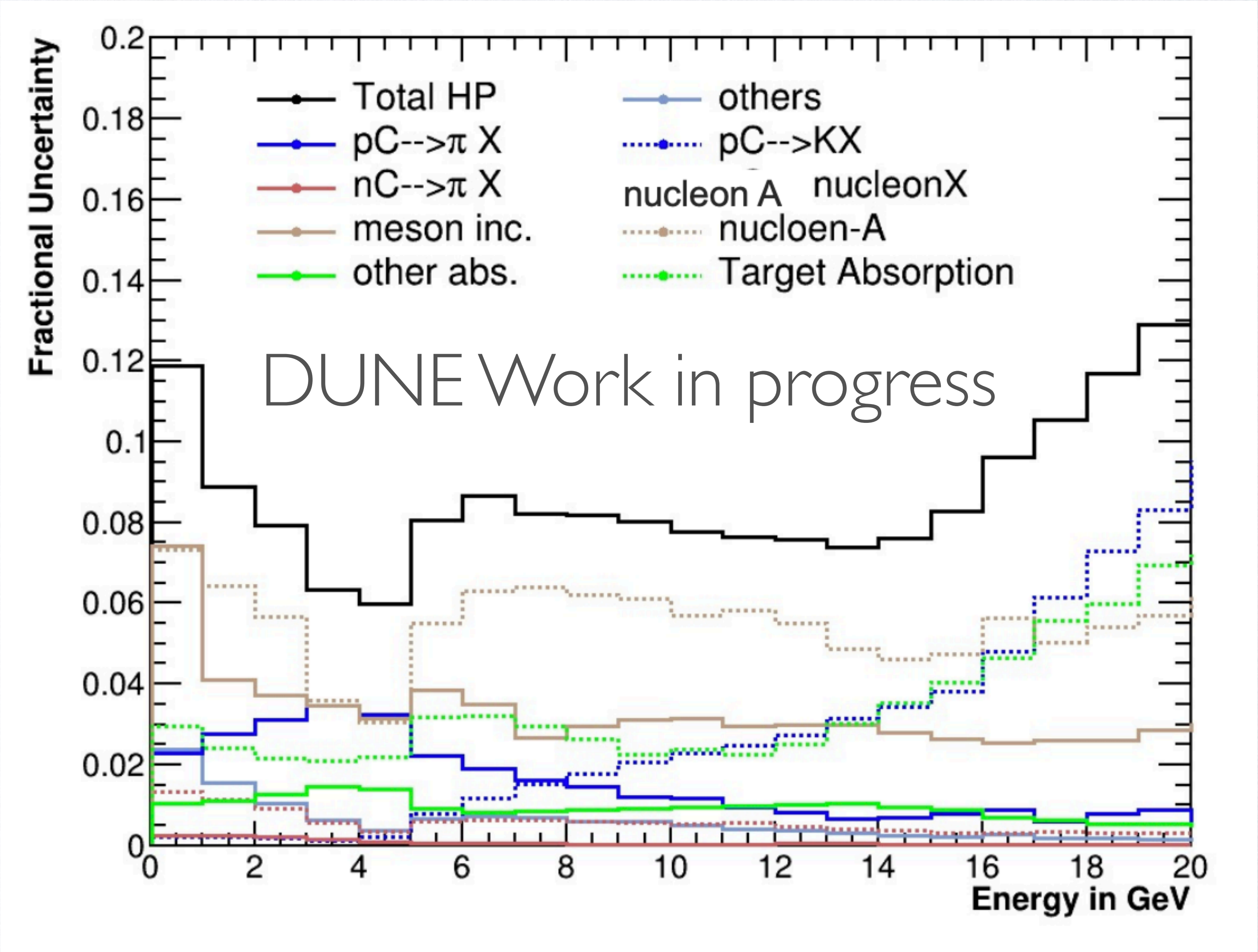
- Data with a **LBNF/DUNE prototype target** was collected this summer
- Designed and built by RAL target group with **expected dimensions of LBNF target**
- Includes **new long-target tracker** designed to mitigate a significant uncertainty in long target analyses
  - Identification of **track vertices** along length of target

FUTURE: 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**
  - DUNE **2nd Oscillation Maximum**
  - T2K/HyperK **secondary** interactions
  - **Spallation** sources, **cosmic rays**, muons…

T2K/HyperK wrong-sign flux uncertainties





CONCLUSION

- **Accelerator-based flux predictions** currently uses models to predict strong interactions that have never been measured
- NA61/SHINE is working to make our beam simulations **grounded in data**
- We **welcome new collaborators** and can offer young researchers experience in hardware, data collection and data analysis in the coming decade

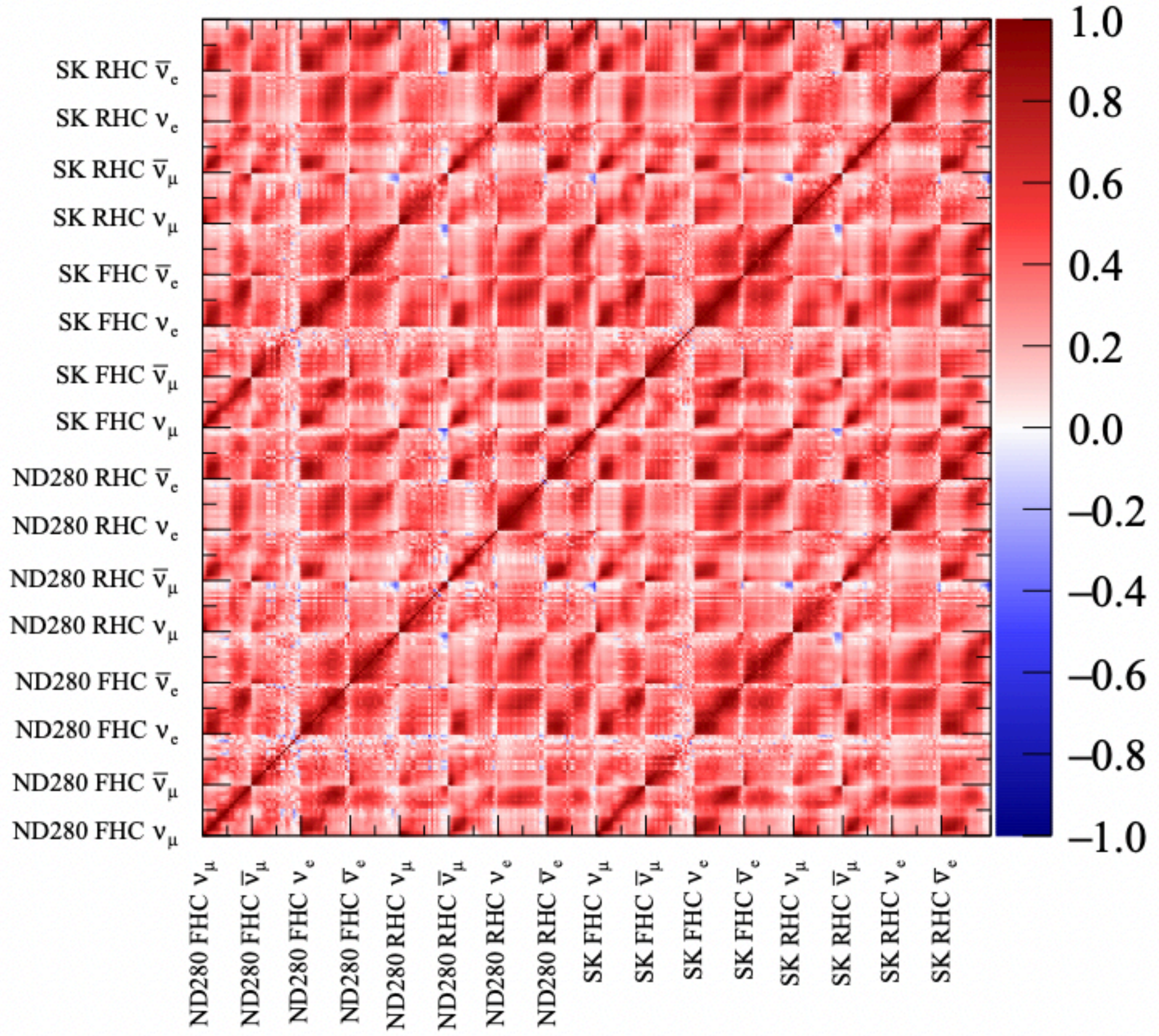
THANK YOU FOR LISTENING!

Speaker supported by US Department of Energy Office of Science

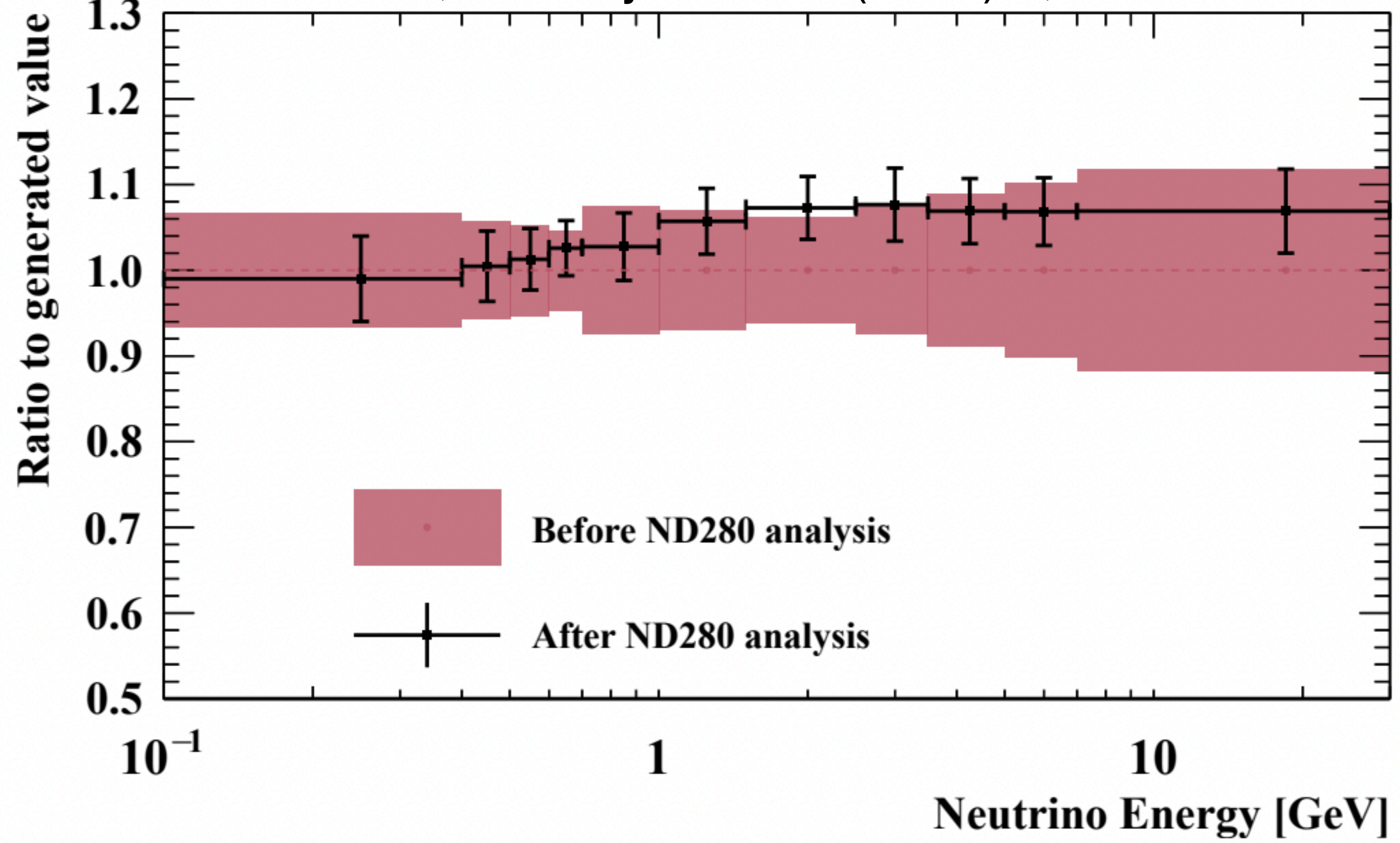
NEED FOR NEUTRINO FLUX PREDICTIONS

- **Near detectors** are powerful
- Modern oscillation experiments execute complex fits that **rely heavily on a priori flux uncertainties** and correlations

Tomislav Vladisavljevic, Thesis



T2K, Eur.Phys.J.C 83 (2023) 9, 782



NA61/SHINE PARTICLE ID

- **The TPC system** provides high-efficiency, high resolution charged-particle tracking
- **Particle ID** provided by a combination of ToF and TPC dE/dx