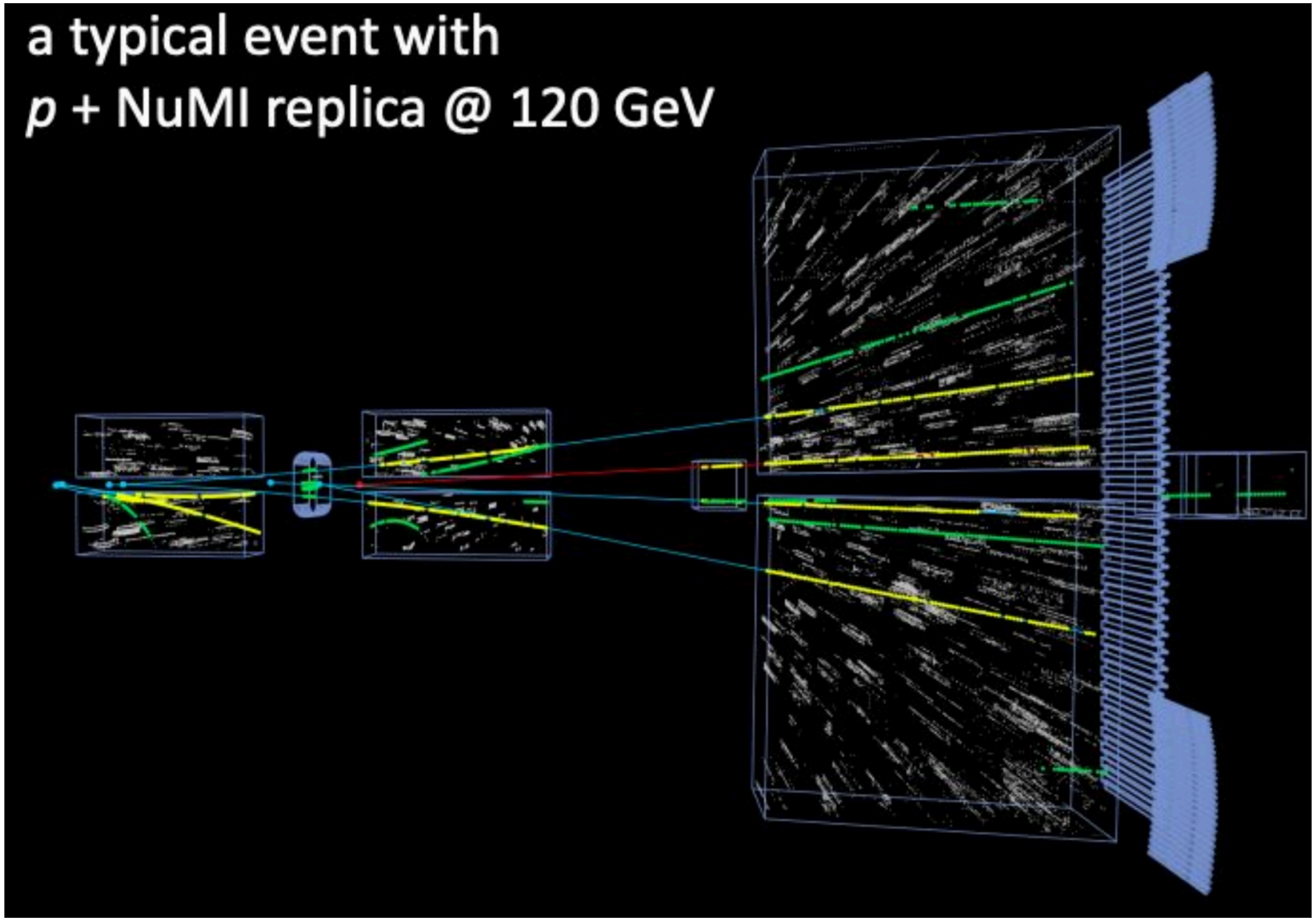


NA61/SHINE Measurements for Neutrinos

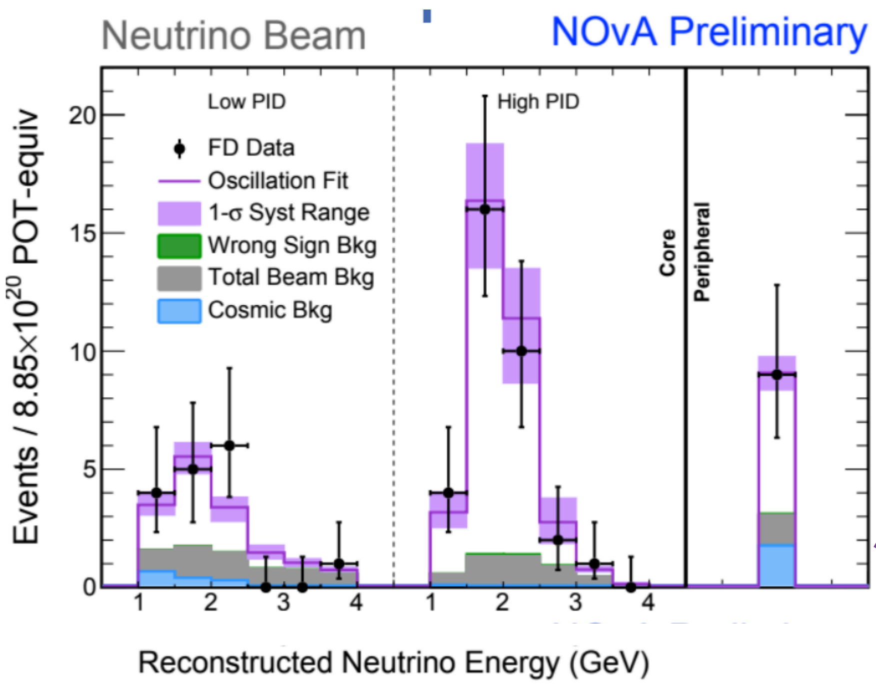
Laura Fields

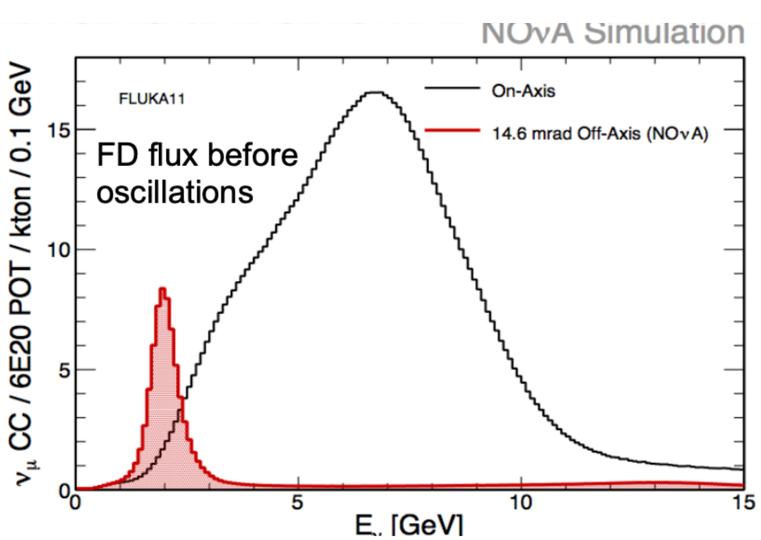
Neutrino Beams and Instrumentation Workshop

October 22, 2019

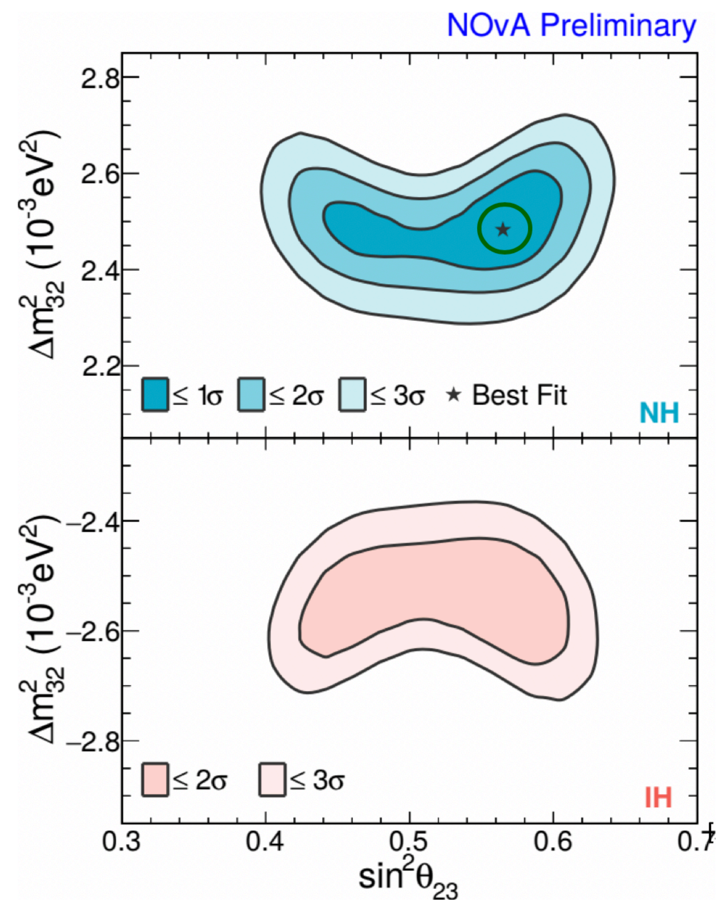
Importance of Neutrino Flux Predictions

- Neutrino experiments rely heavily on neutrino flux predictions





J Wolcott, NuFact 2019



Extracting oscillation parameters from data **requires comparisons to predictions**.

Neutrino flux predictions **underpin all accelerator-based neutrino simulations**.

Importance of Neutrino Flux Predictions

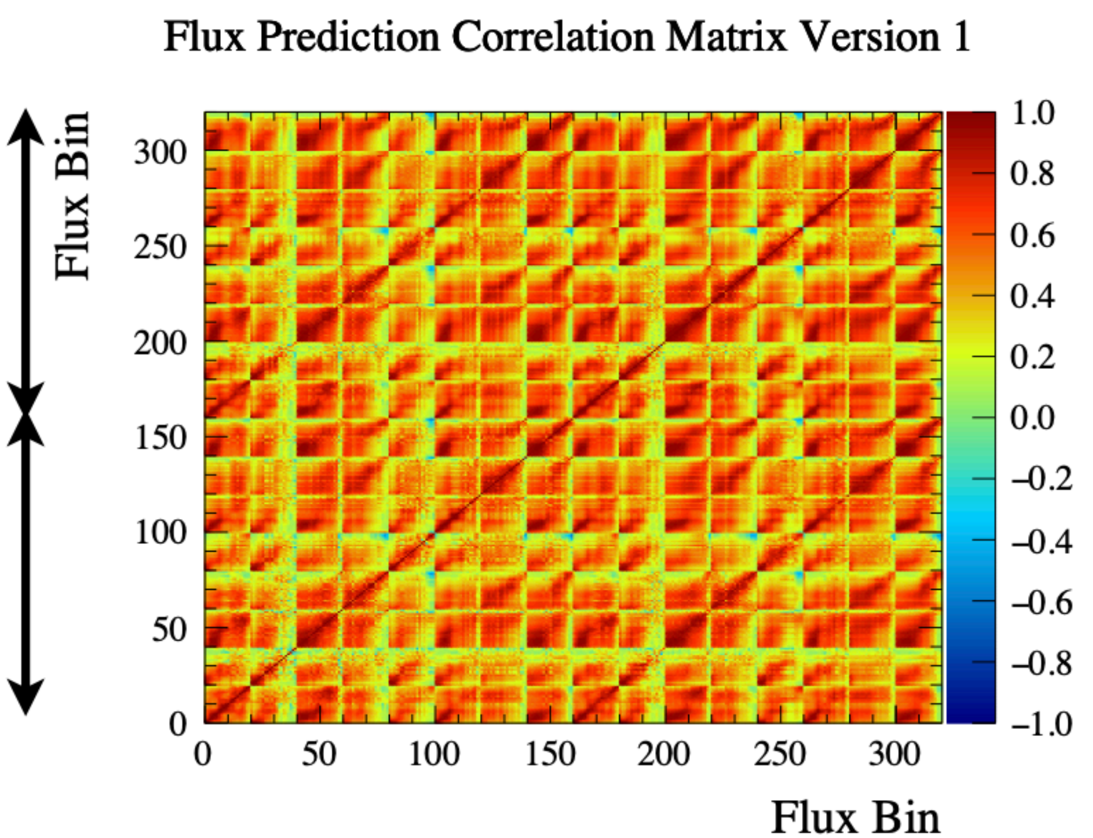
- We rely even more heavily on estimates of flux uncertainties

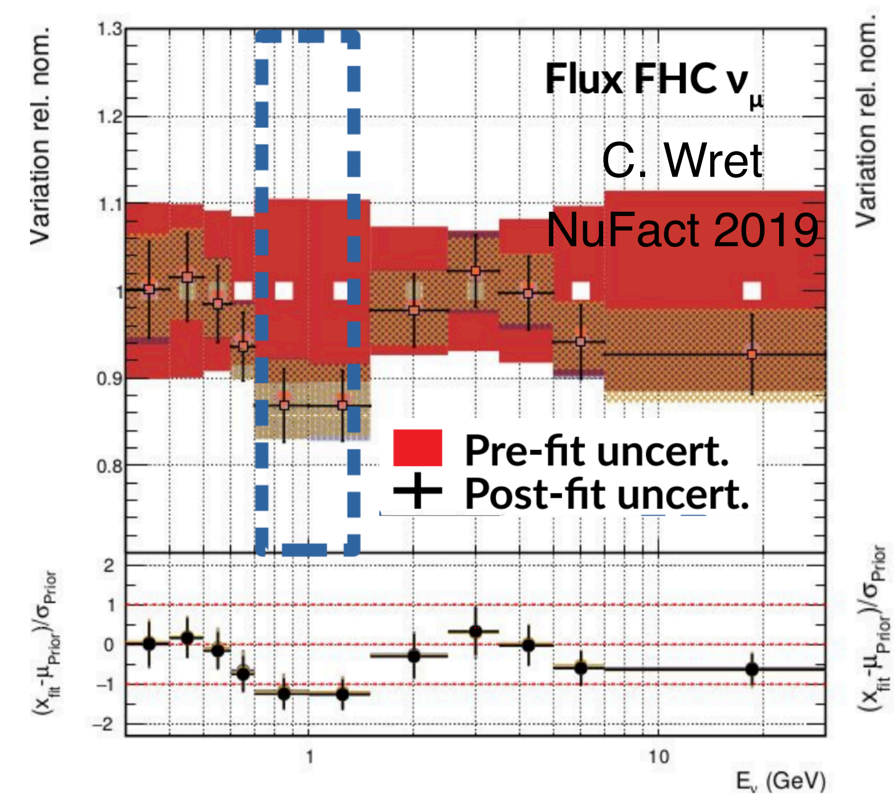
The era of "everything cancels in the near detector" is long past

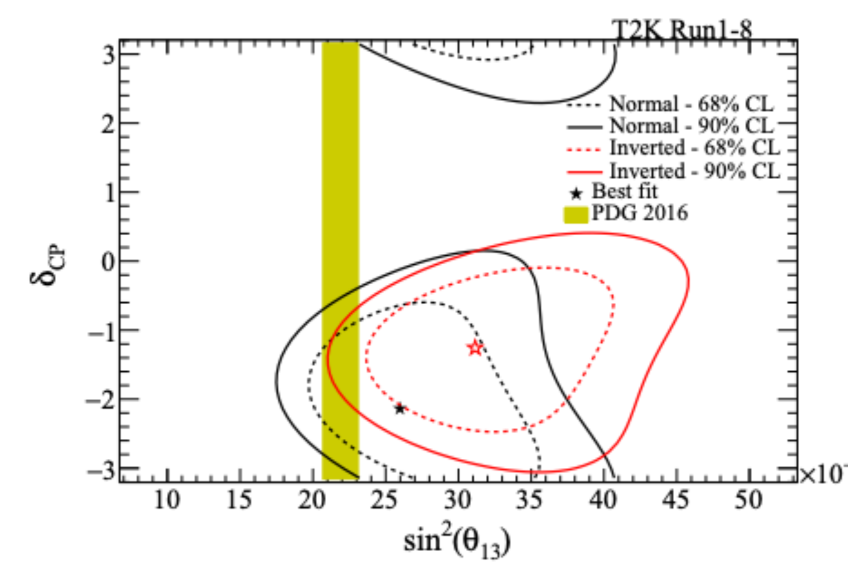
Far Detector

D. Sgalaberna
NuFact 2019

Near Detector



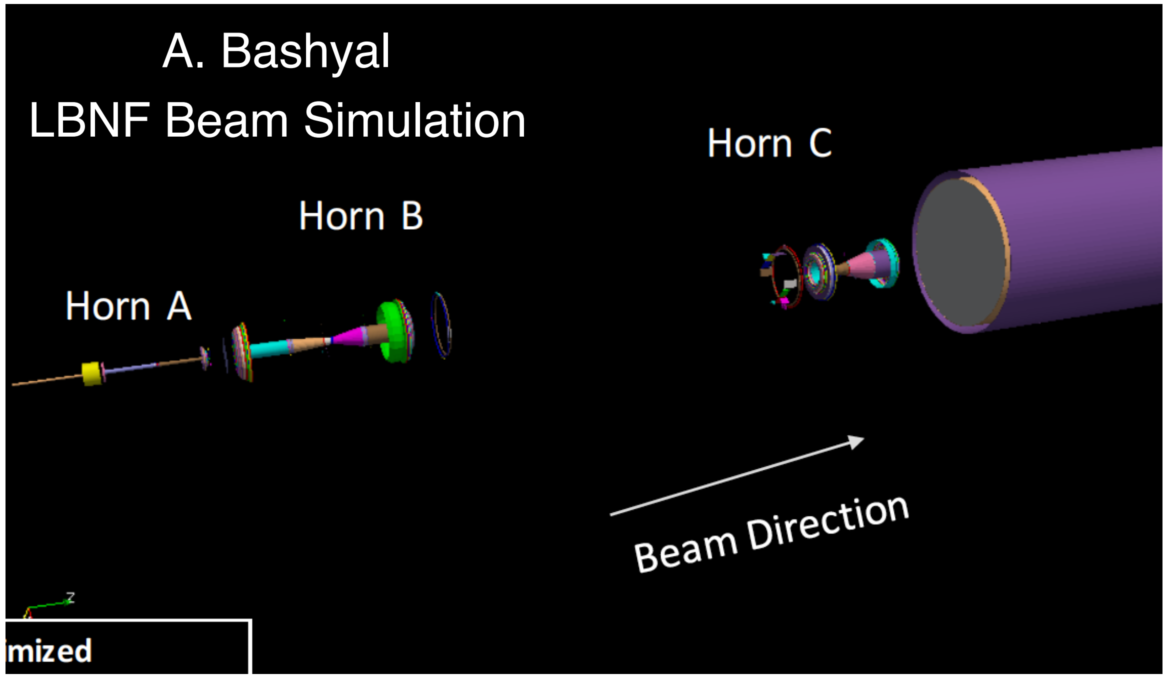




Modern oscillation experiments execute complex fits that **rely heavily on a priori flux uncertainties** and correlations

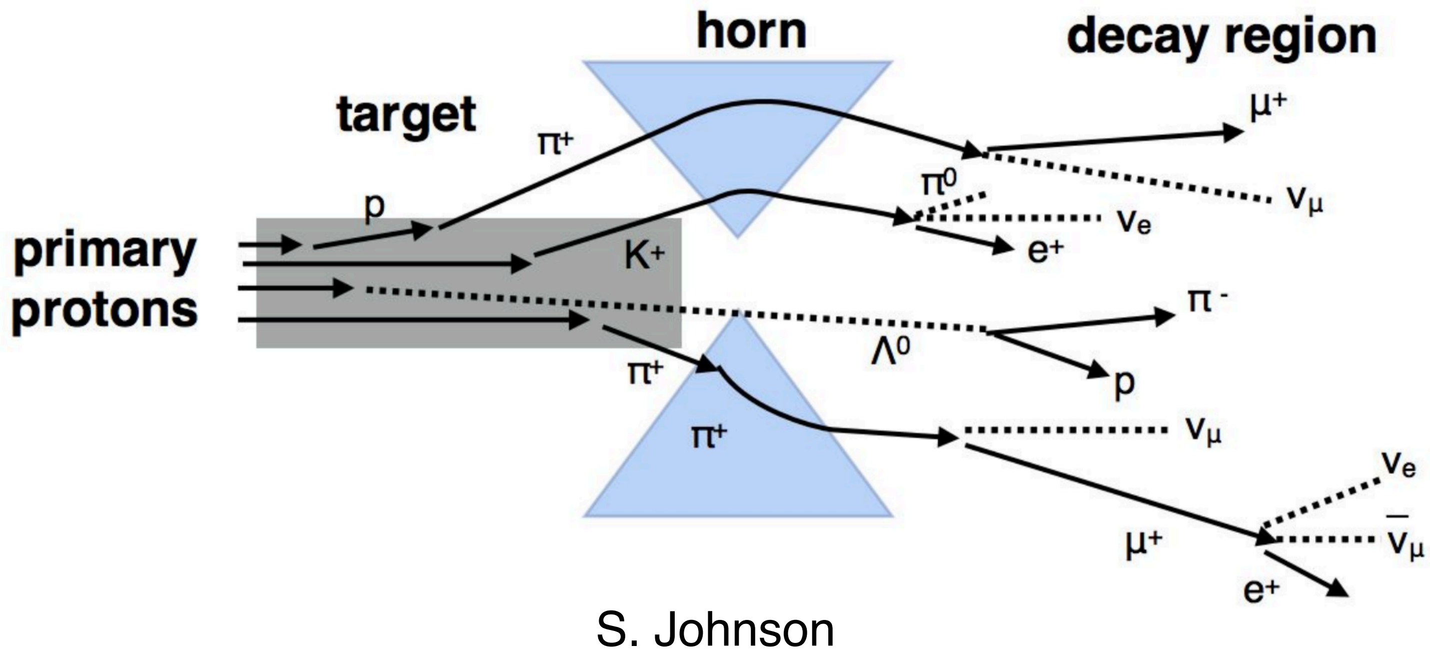
Neutrino Flux Simulations

- How we produce flux predictions:



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

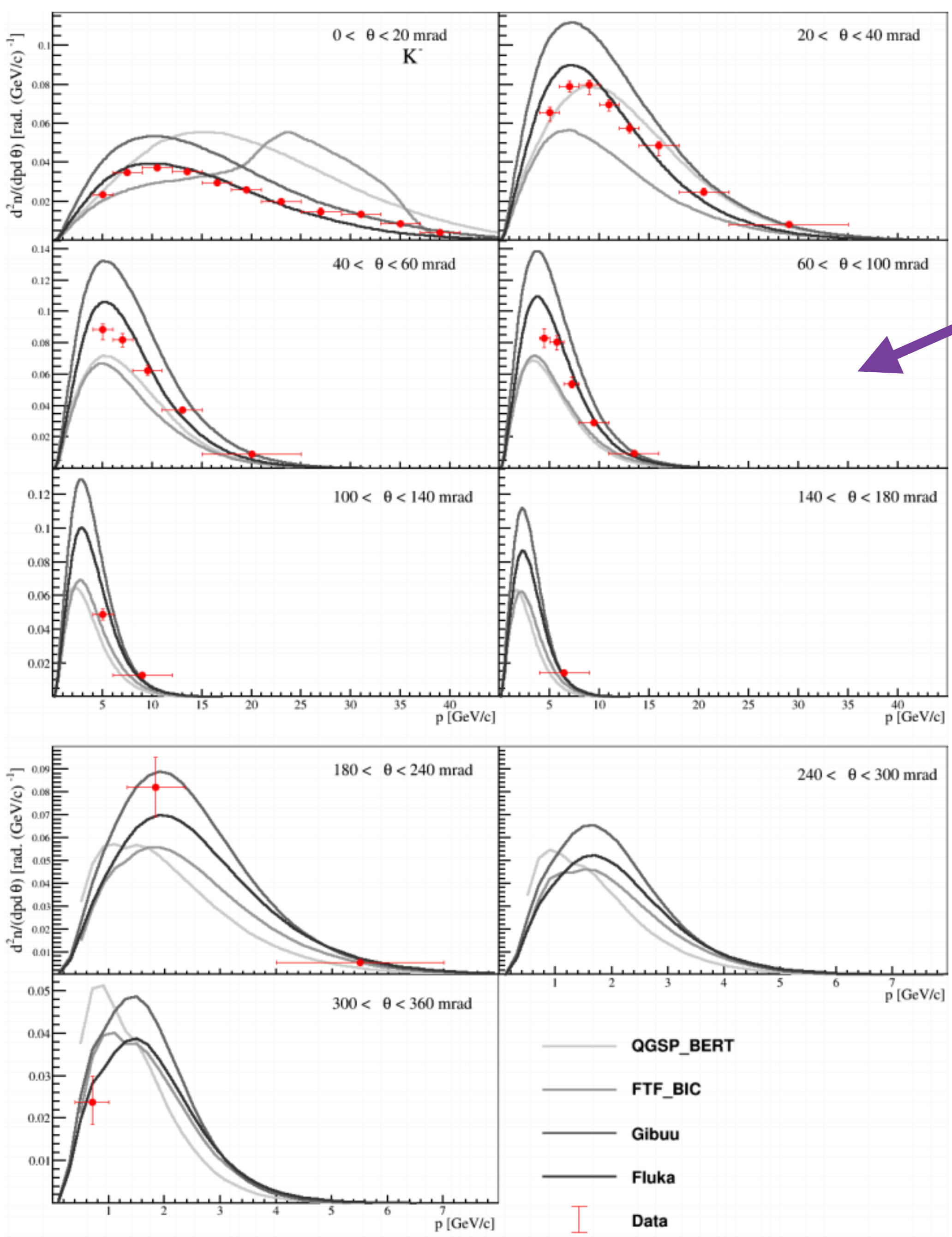
Geant4 or Fluka are typically used to predict hadrons produced in the beam line that decay to neutrino.



Problems with Neutrino Flux Simulations

- But we know Geant4 and Fluka models to be imperfect:

arXiv:1909.06294



Kaon momenta in 60 GeV π^++C → K+X interactions, measured at NA61/SHINE and compared to two Geant4 models, as well as Gibuu and Fluka.

More on this measurement in a bit!

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.

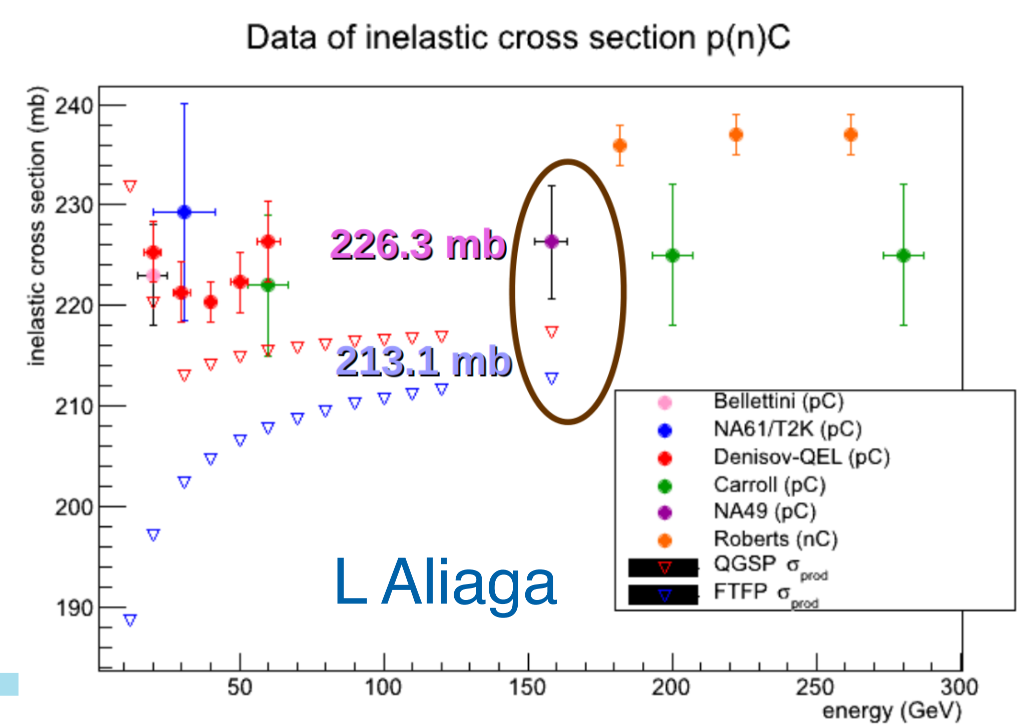
Correcting Neutrino Flux Simulations

- 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:
    - **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:

$$w_{\mathrm{HP}} = \frac{f_{\mathrm{Data}}\left(x_F, p_T, E\right)}{f_{\mathrm{MC}}\left(x_f, p_T, E\right)} \qquad f = E\frac{d^3\sigma}{dp^3}$$

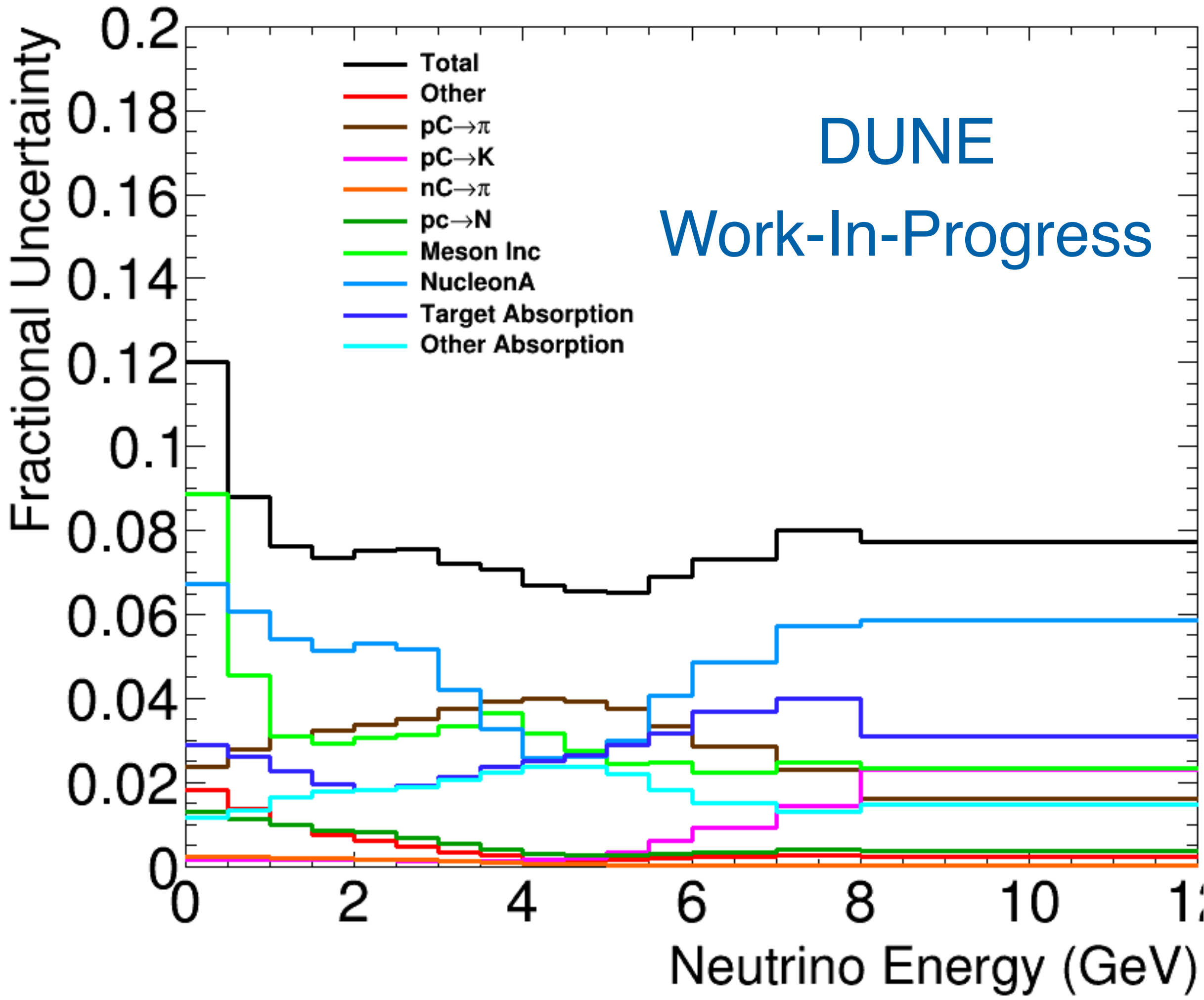
    - Weights for events with multiple interactions in the ancestor chain are the product of the weight for each interaction
    - A second weight is applied to account for exponential **decay of beam**:

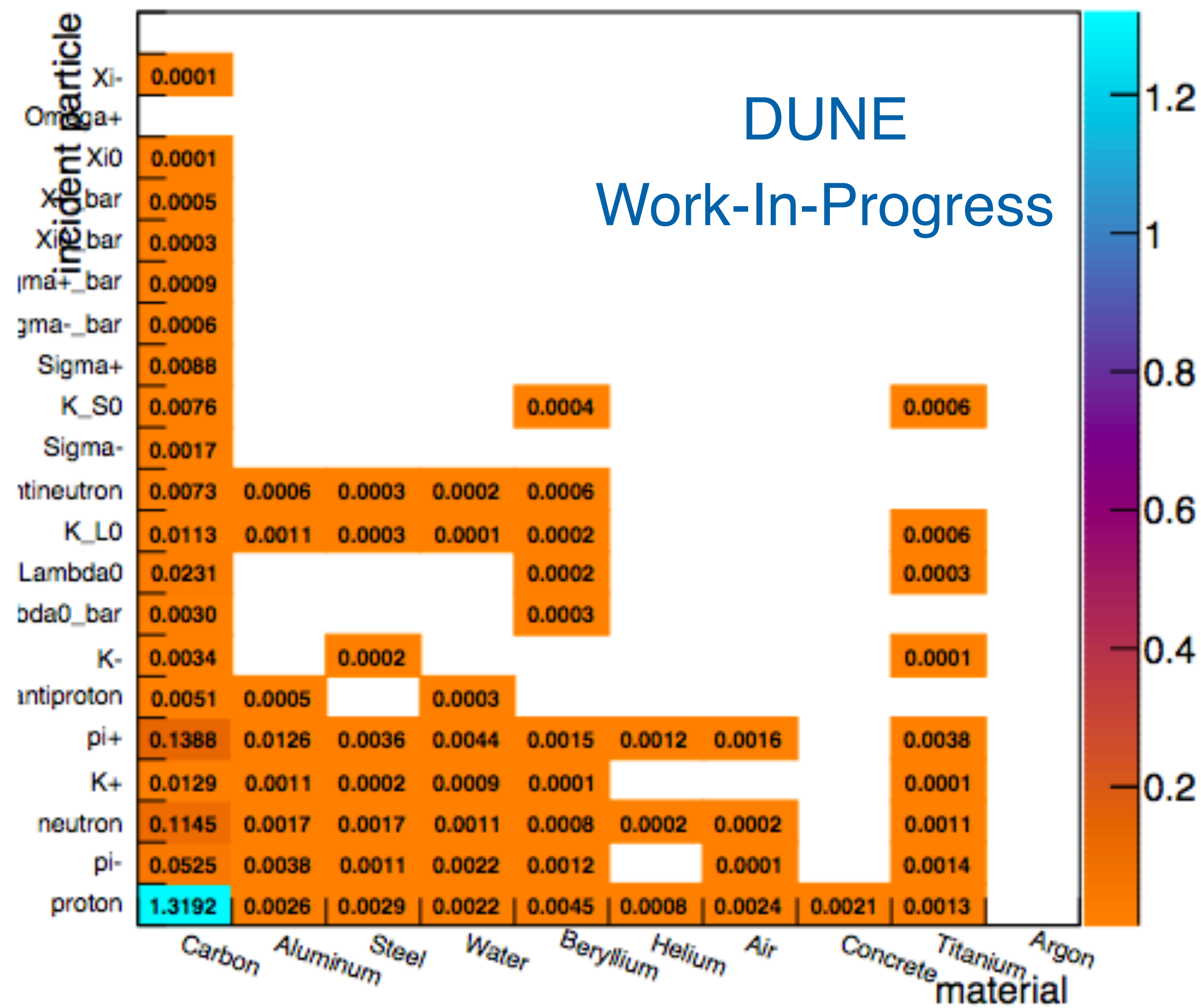
$$w_{\mathrm{att}} = e^{-L\rho(\sigma_{\mathrm{data}} - \sigma_{\mathrm{MC}})}$$



Correcting Neutrino Flux Simulations

- What interactions are important?





Proton interactions are by far the most prevalent and dominate systematic budgets.

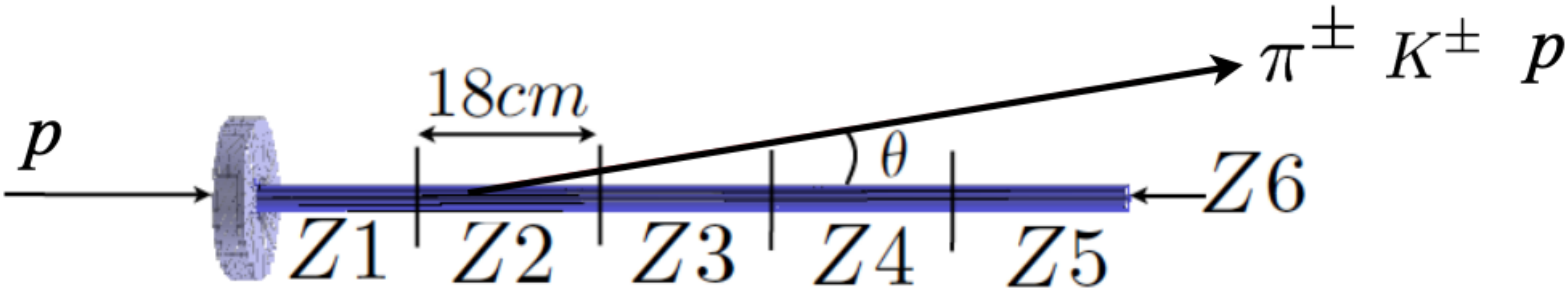
Pion incident interactions the next-most prevalent, followed by a slew of **small contributions**.

40% of interactions creating neutrinos in DUNE are completely unmeasured!

Correcting Neutrino Flux Simulations

- A way to measure the 'slew':
  - **Long target measurements** measure hadrons produced on replicas of actual targets

(replica)

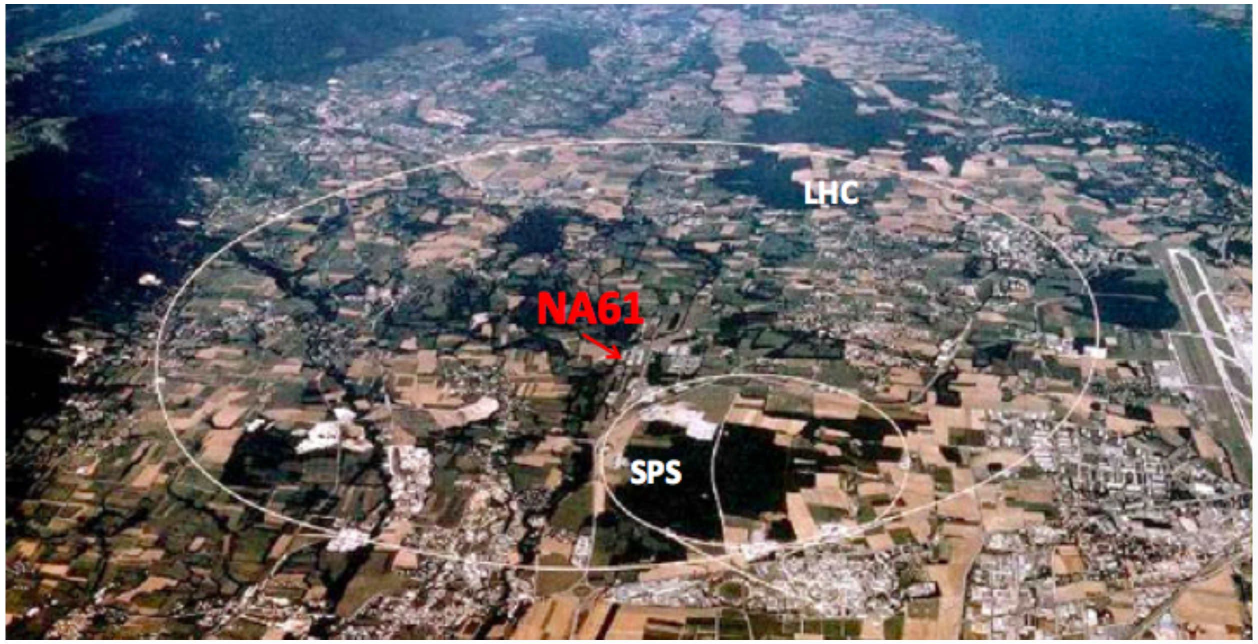


  - Results also **applied via reweighting**:

$$w_s = \frac{m_s(p,\theta,z)^{\mathrm{data}}}{m_s(p,\theta,z)^{\mathrm{MC}}}$$

m_s = multiplicity of a produced hadron species s

NA61/SHINE Experiment



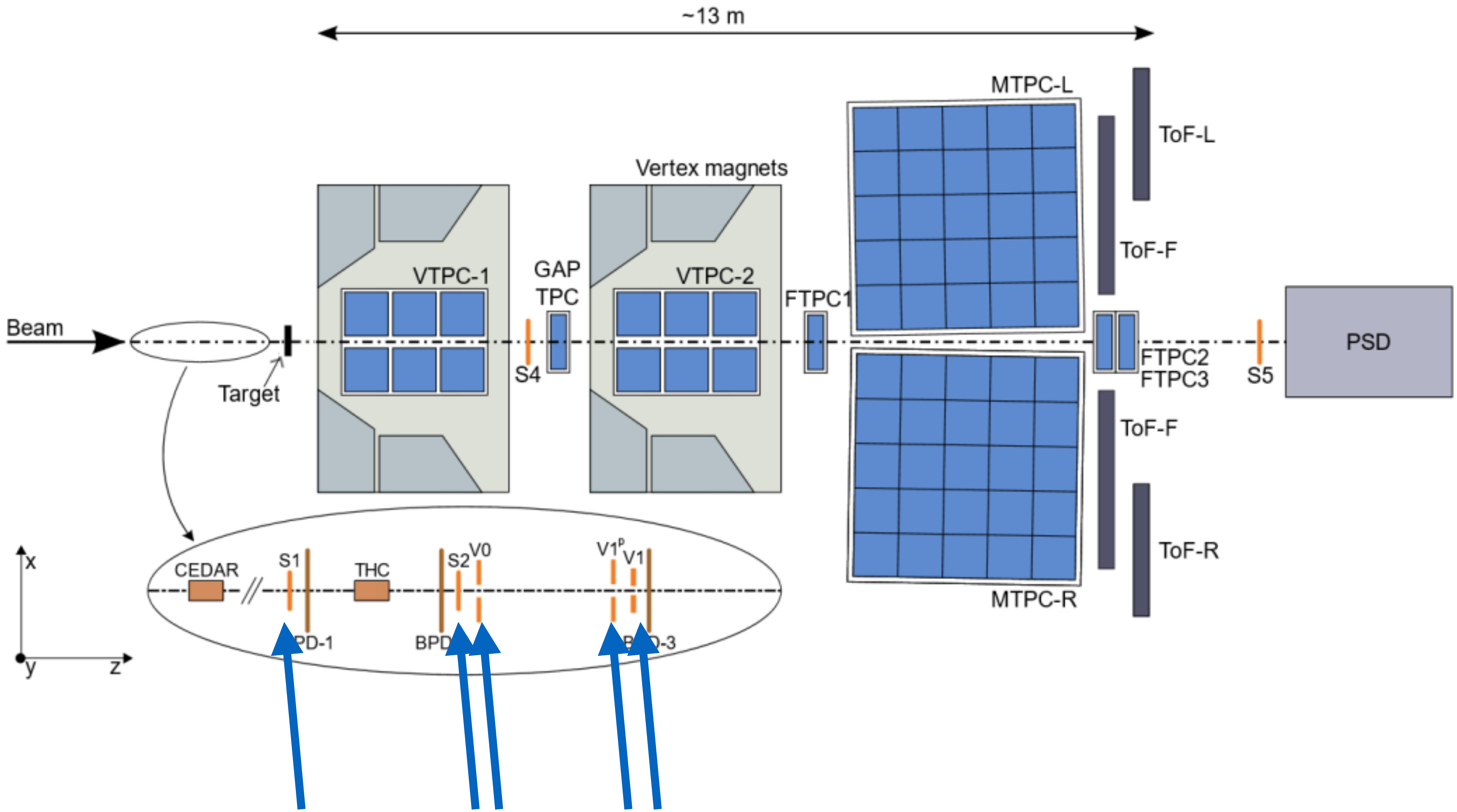
- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
- Hungary
  - Wigner RCP, Budapest
- Japan
  - KEK Tsukuba, Tsukuba
- Norway
  - University of Bergen, Bergen
- Poland
  - UJK, Kielce
  - NCBJ, Warsaw
  - University of Warsaw, Warsaw
  - WUT, Warsaw
  - Jagiellonian University, Kraków
  - IFJ PAN, Kraków
  - AGH, Kraków
  - University of Silesia, Katowice
  - University of Wrocław, Wrocław
- Russia
  - INR Moscow, Moscow
  - JINR Dubna, Dubna
  - SPBU, St.Petersburg
  - MEPhI, Moscow
- Serbia
  - University of Belgrade, Belgrade
- Switzerland
  - ETH Zürich, Zürich
  - University of Bern, Bern
  - University of Geneva, Geneva
- USA
  - University of Colorado Boulder, Boulder
  - LANL, Los Alamos
  - University of Pittsburgh, Pittsburgh
  - FNAL, Batavia
  - University of Hawaii, Manoa

$\sim$150 physicists from $\sim$30 institutes

- **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

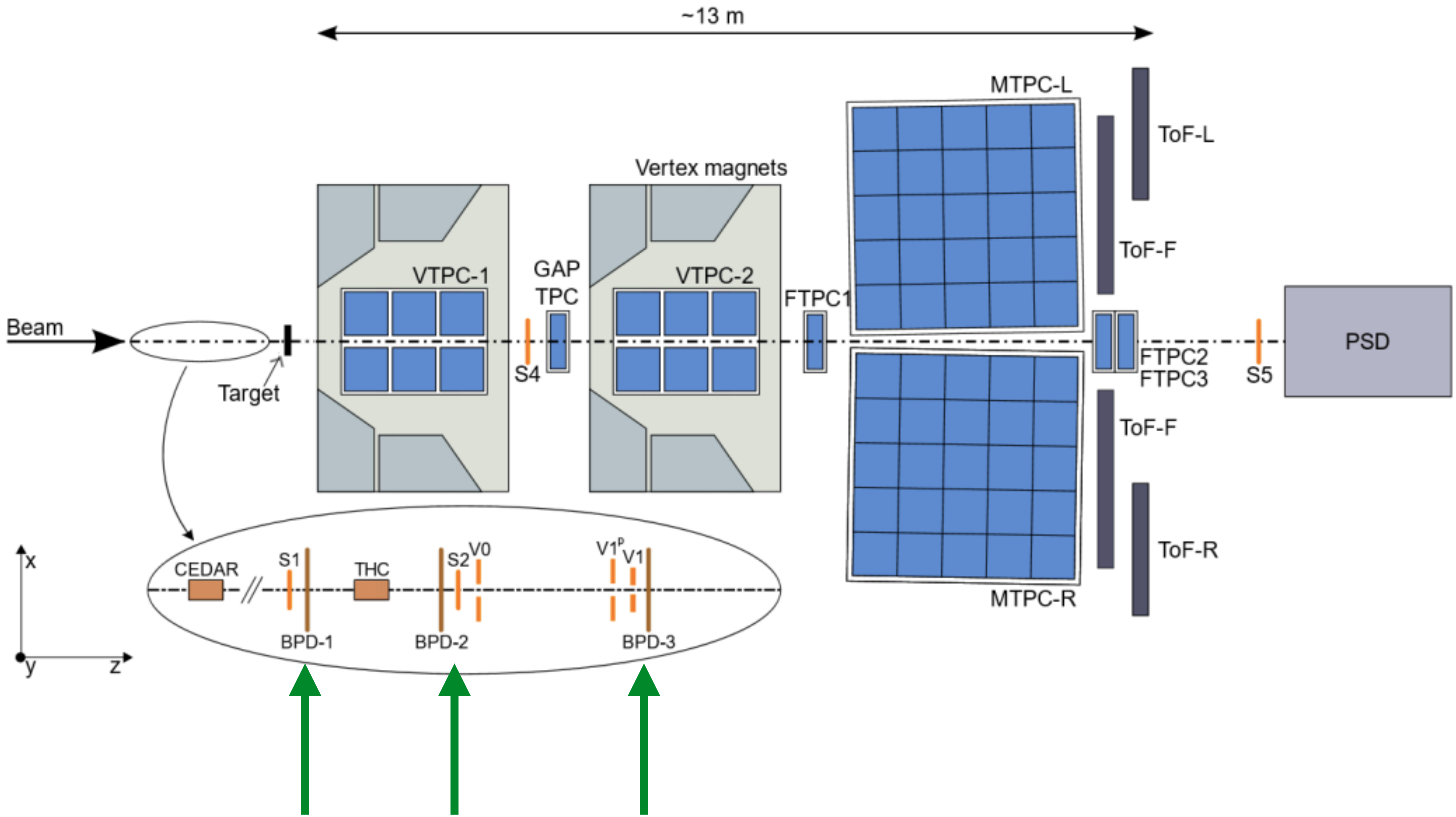
- NA61's physics program covers **three main topics**:
  - Nuclear physics - Study the phase transition between hadron gas and QGP and search for a critical point
  - Cosmic ray physics - Hadron production measurements relevant to space and ground-based cosmic ray experimen
  - **Neutrino physics - Hadron production measurements used to constrain neutrino flux uncertainties for accelerator-based neutrino experiments**

NA61/SHINE Experiment



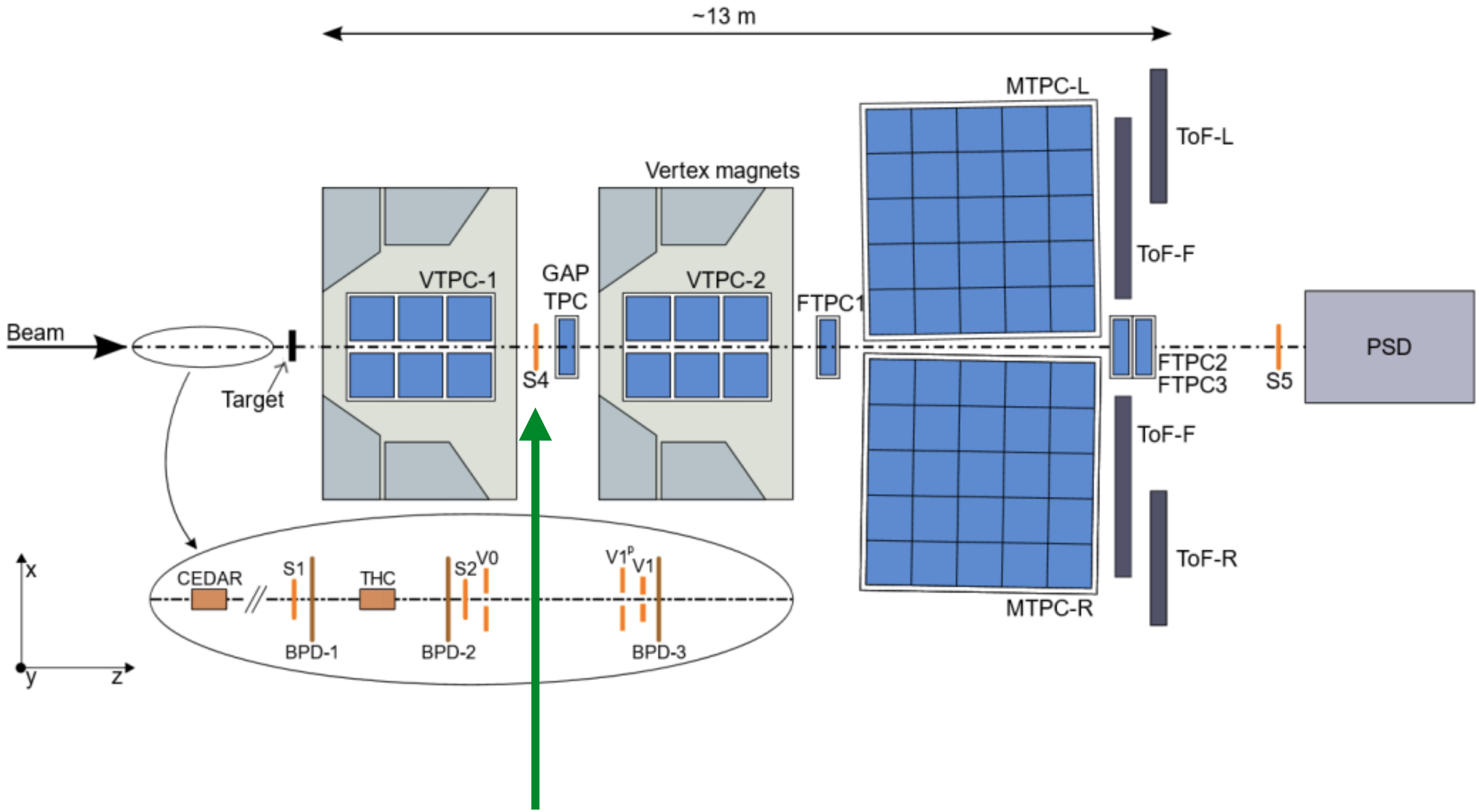
Series of scintillator counters serve as triggers, identifying good beam particles.

NA61/SHINE Experiment



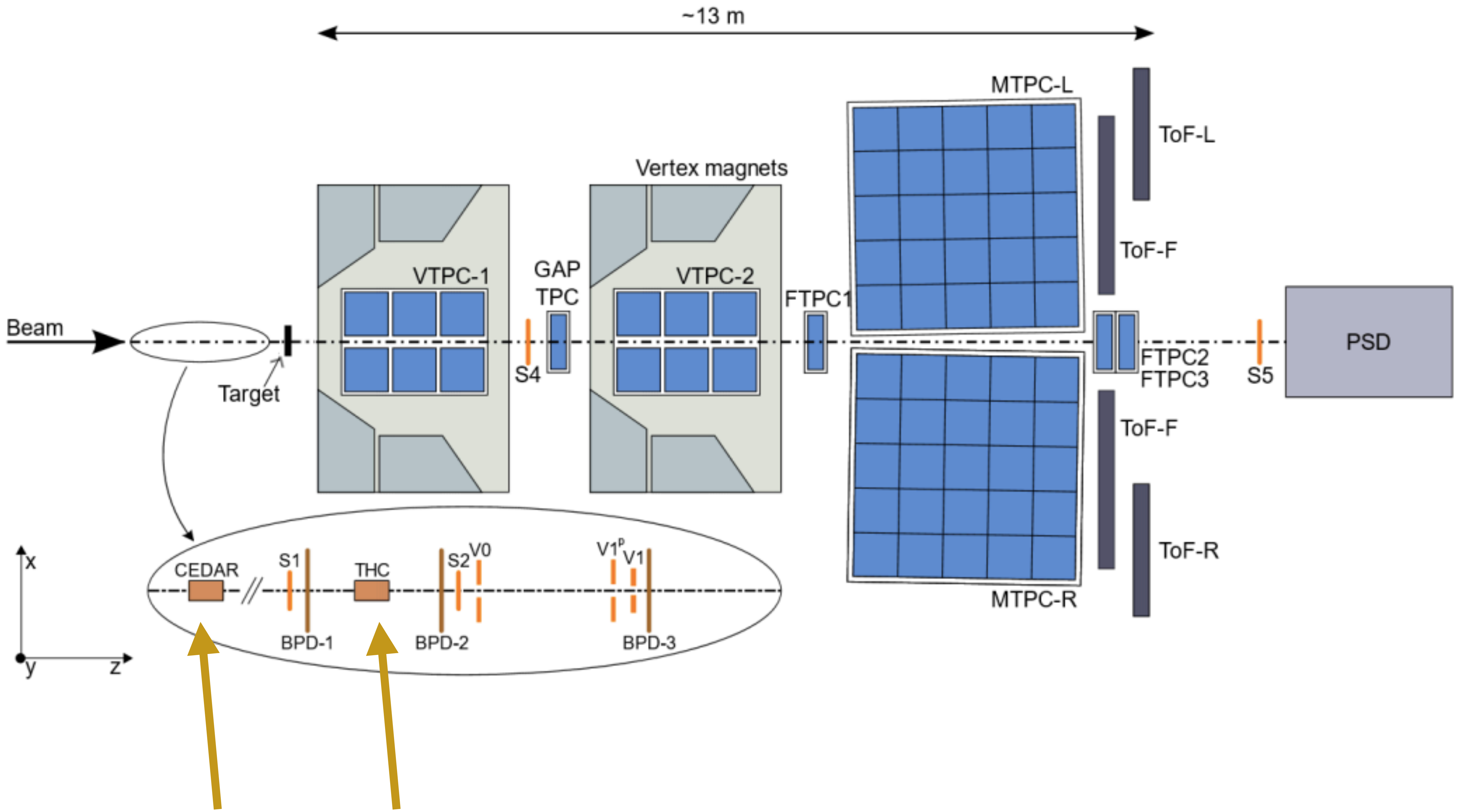
Beam Position Detectors (BPD) are proportional chambers that measure transverse position of beam particles

NA61/SHINE Experiment



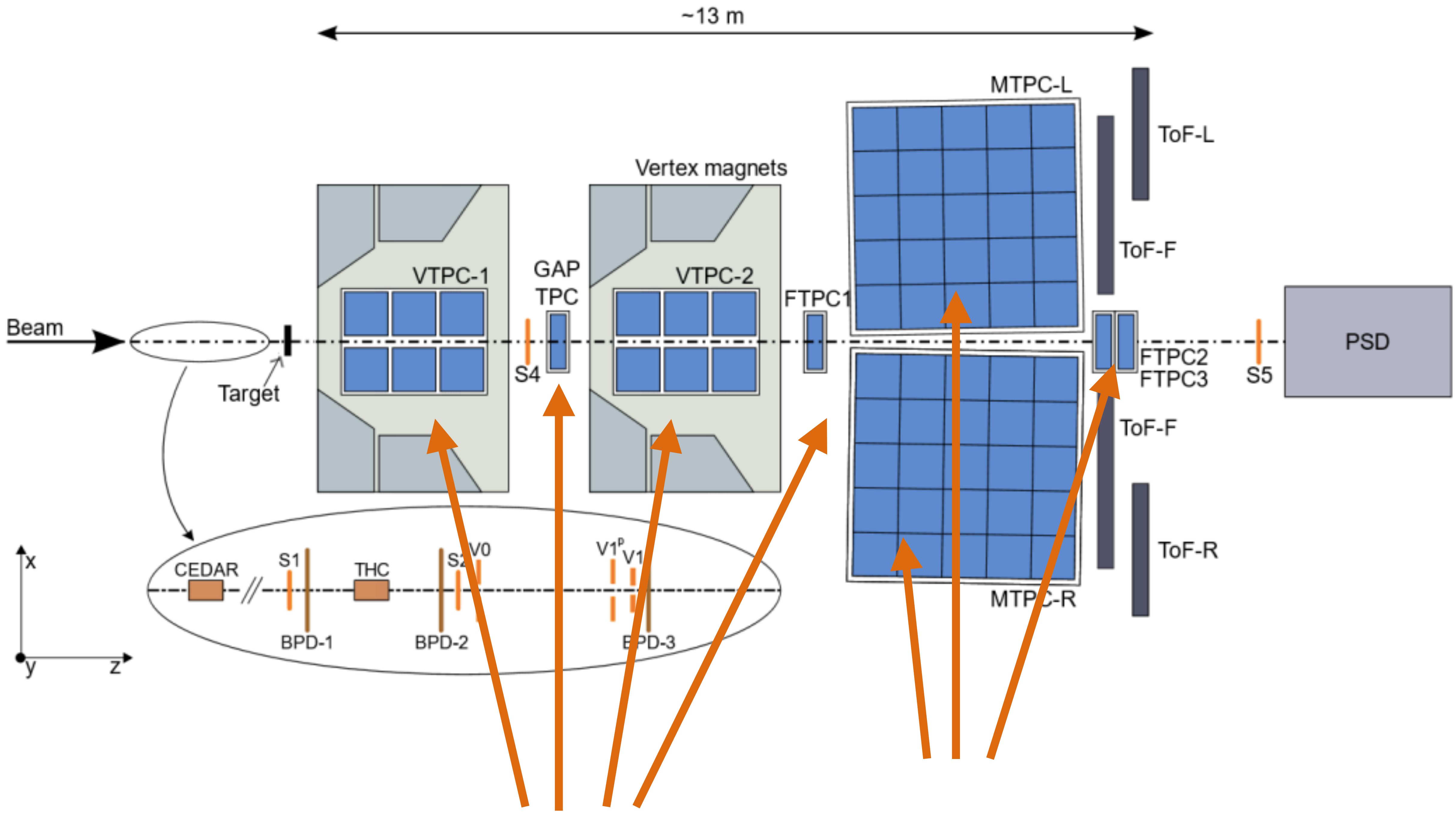
An additional scintillator counter downstream of target vetoes beam particles that do not interact

NA61/SHINE Experiment



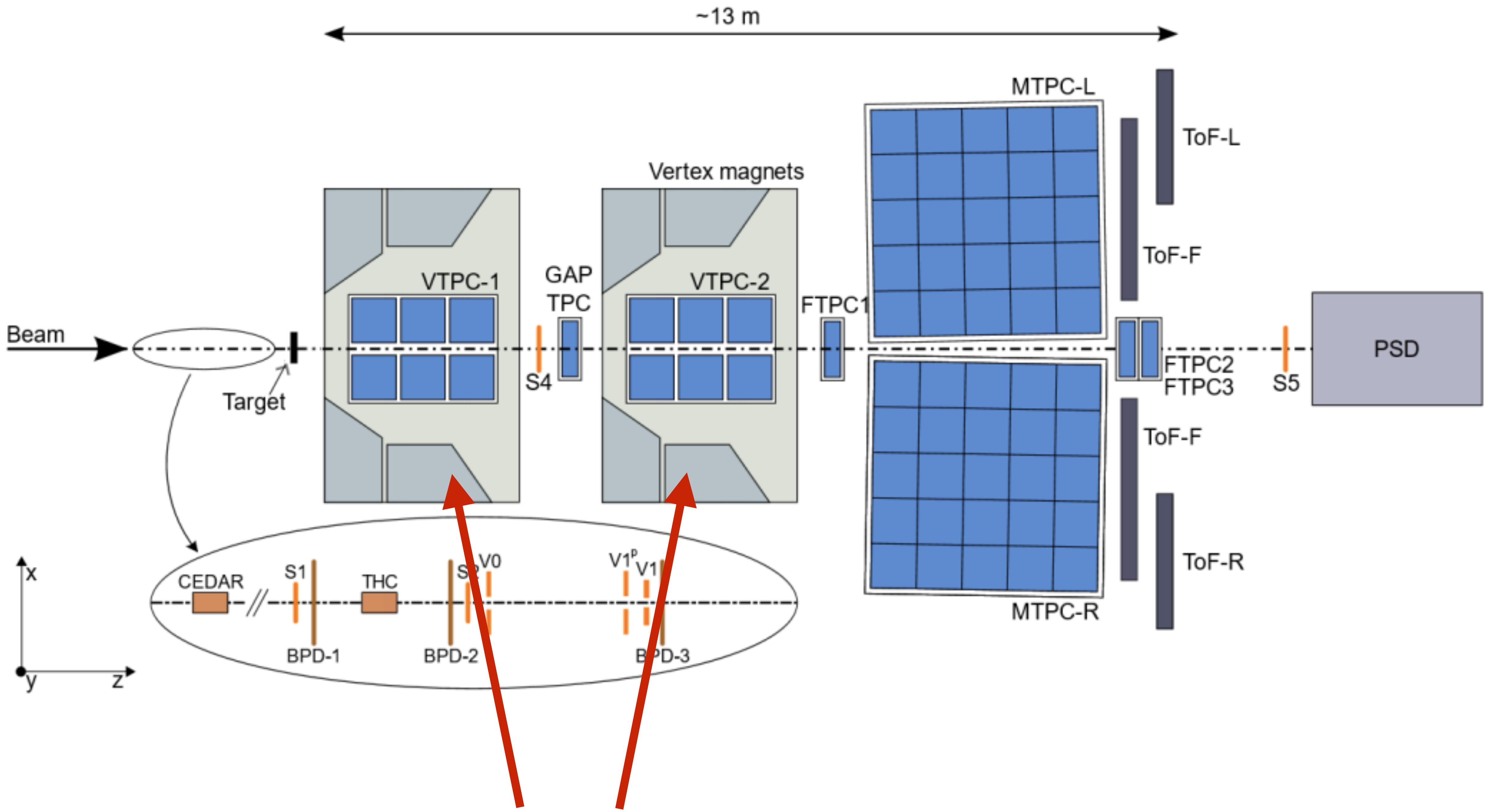
CEDAR and THC (Cerenkov Detectors) provide particle ID of beam particles.

NA61/SHINE Experiment



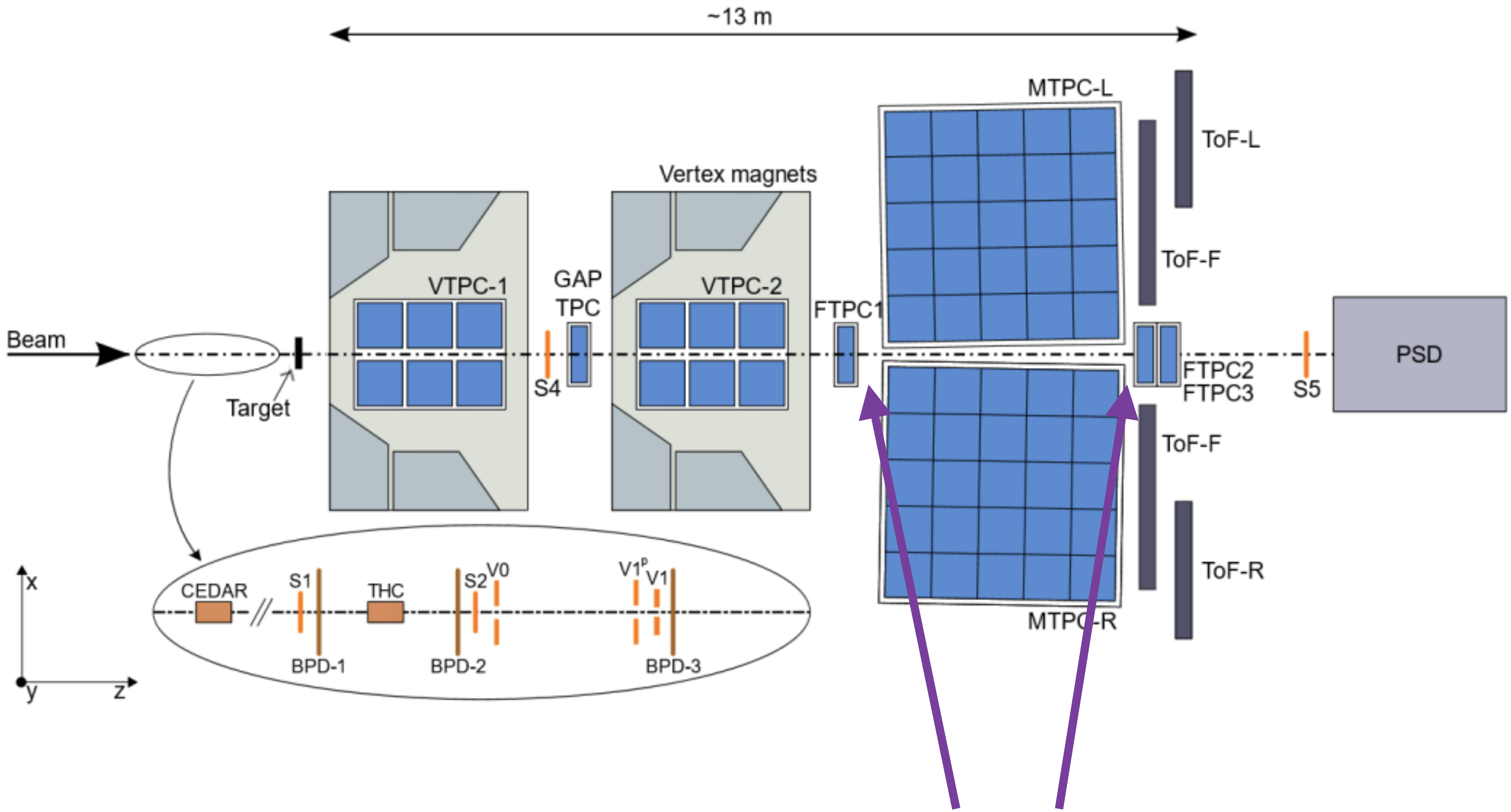
TPC system tracks charged particles and measures dE/dx ($\sigma_{dE/dx}$/<dE/dx> ≈ .04)

NA61/SHINE Experiment



Two Vertex TPCs are contained inside superconducting vertex magnets (with 9 Tm of bending power)

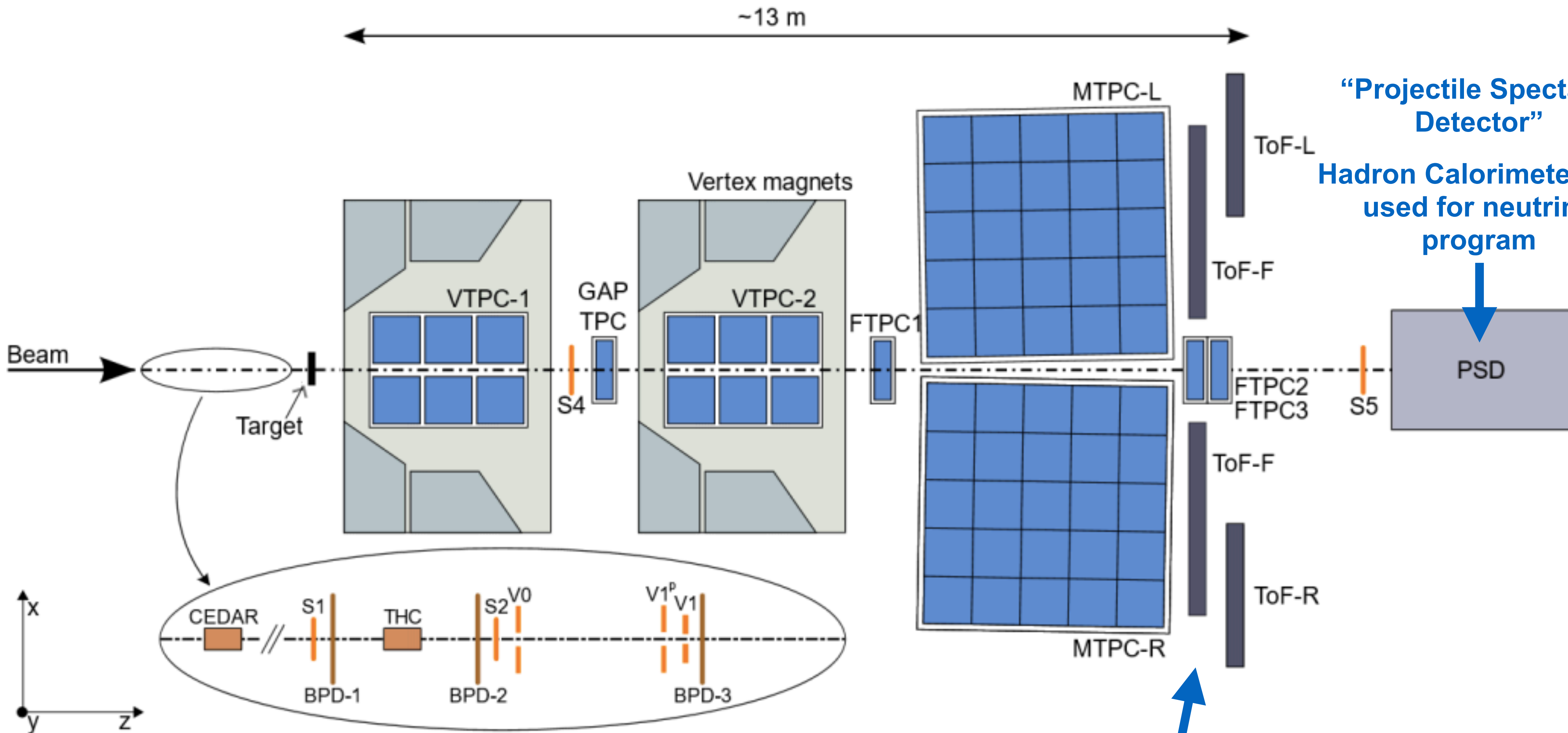
NA61/SHINE Experiment



New Forward TPCs improve forward acceptance.

Were installed for 2017 data run, so not available in 2016 data discussed today.

NA61/SHINE Experiment



"Projectile Spectator Detector"

Hadron Calorimeter not used for neutrino program

Time of Flight System measures m² with 100 ps resolution.

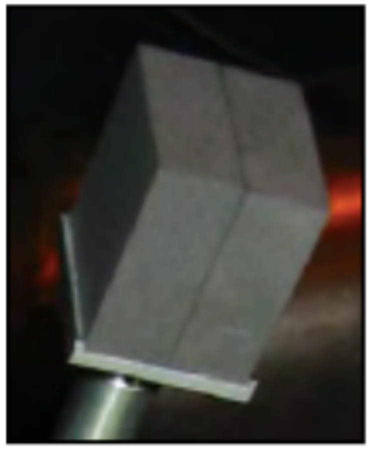
Forward TOF (ToF-F) not yet installed for 2016 data discussed today

NA61/SHINE Thin Target Measurements

- NA61/SHINE has banked a large suite of thin-target measurements aimed at T2K and Fermilab flux predictions:

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,Be	2015	Total Cross Section[5] (Magnet Off)
π^{+}@60 GeV	C,Be	2015	Total Cross Section[5] (Magnet Off)
K^{+}@60 GeV	C,Be	2015	Total Cross Section[5] (Magnet Off)
π^{+}@60 GeV	C,Be	2016	p, $\pi^{\pm}$, K^{+}, K^{0}_{S}, Λ [6]
p@60 GeV	C, Al, Be	2016	Total Cross Sections; Spectra Analysis in Progress
p@120 GeV	C, Be	2016	Total Cross Sections; Spectra Analysis in Progress

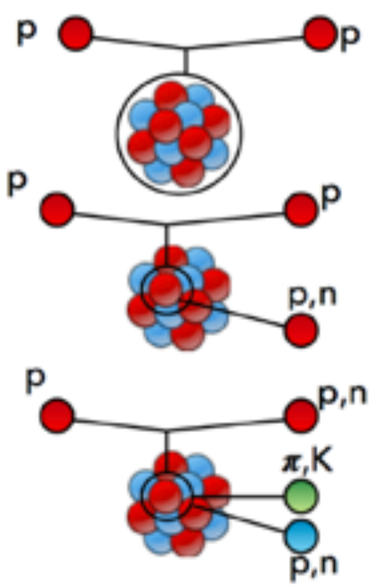
[1] Phys. Rev. C84, 034604 (2011).
[2] Phys. Rev. C85, 035210 (2012).
[3] Phys. Rev C89, 025205 (2014).
[4] Eur. Phys. J. C (2016) 76: 84
[5] Phys. Rev. D98, No.5 052001 (2018)
[6] arXiv:1909.06294
[7] arXiv:1909.03351



2 cm carbon target

NA61/SHINE Thin Target Measurements

- An Example in Detail: Total and Inelastic Cross Section Measurements



Coherent **elastic** scattering of a hadron with the nucleus as a whole

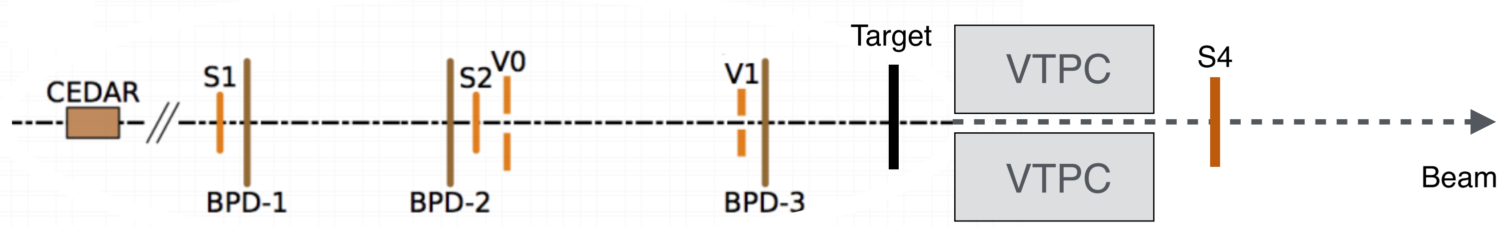
$$\sigma_{tot} = \sigma_{inel} + \sigma_{el}$$

Quasi-elastic scattering of a hadron with a proton or neutron, which can cause fragmentation of the nucleus but produces no new hadrons

$$\sigma_{inel} = \sigma_{prod} + \sigma_{qe}$$

Production processes occur when new hadrons are formed

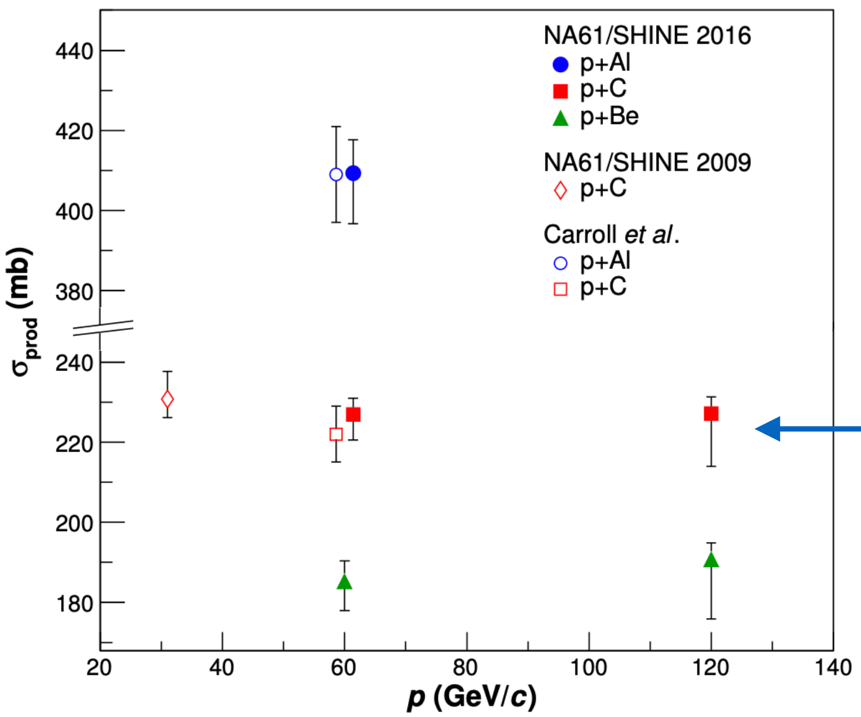
- **Beam detectors are critical** for these measurements
  - Uncertainties dominated by **model-dependent scattering angle corrections** for various processes



NA61/SHINE Thin Target Measurements

- An Example in Detail: Total and Inelastic Cross Section Measurements

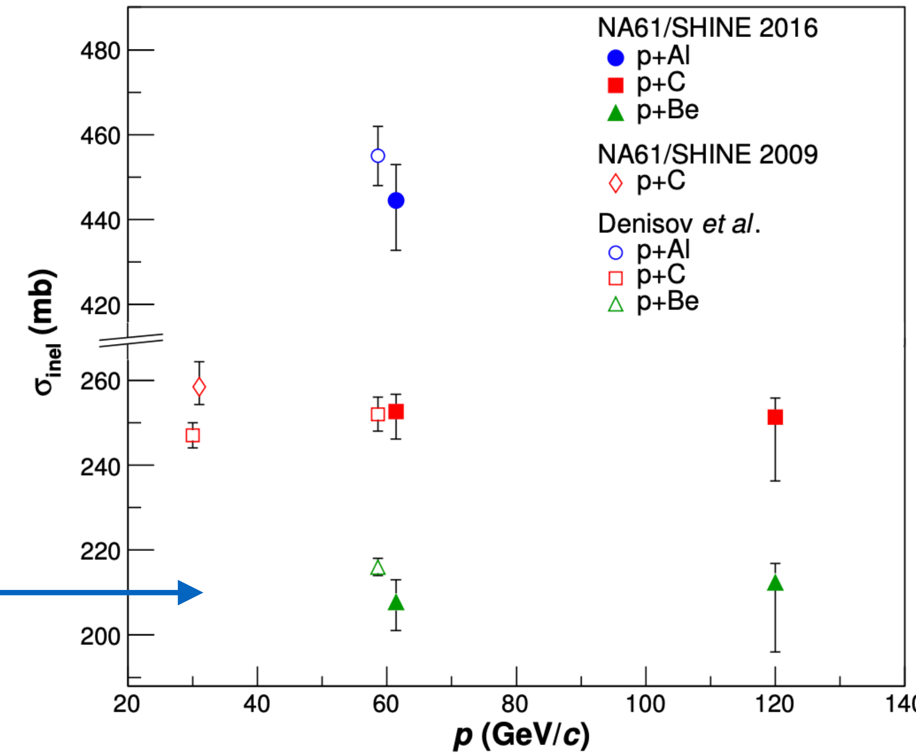
arXiv:1909.03351



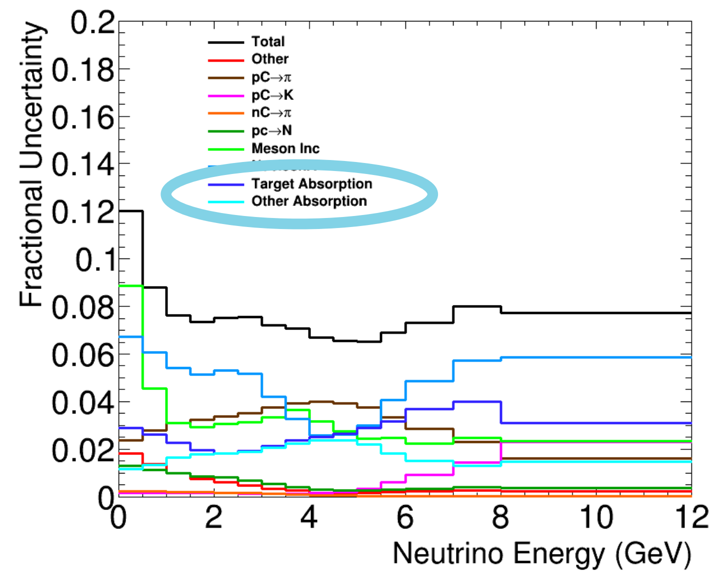
Proton Beams

Production Cross Section

Inelastic Cross Section



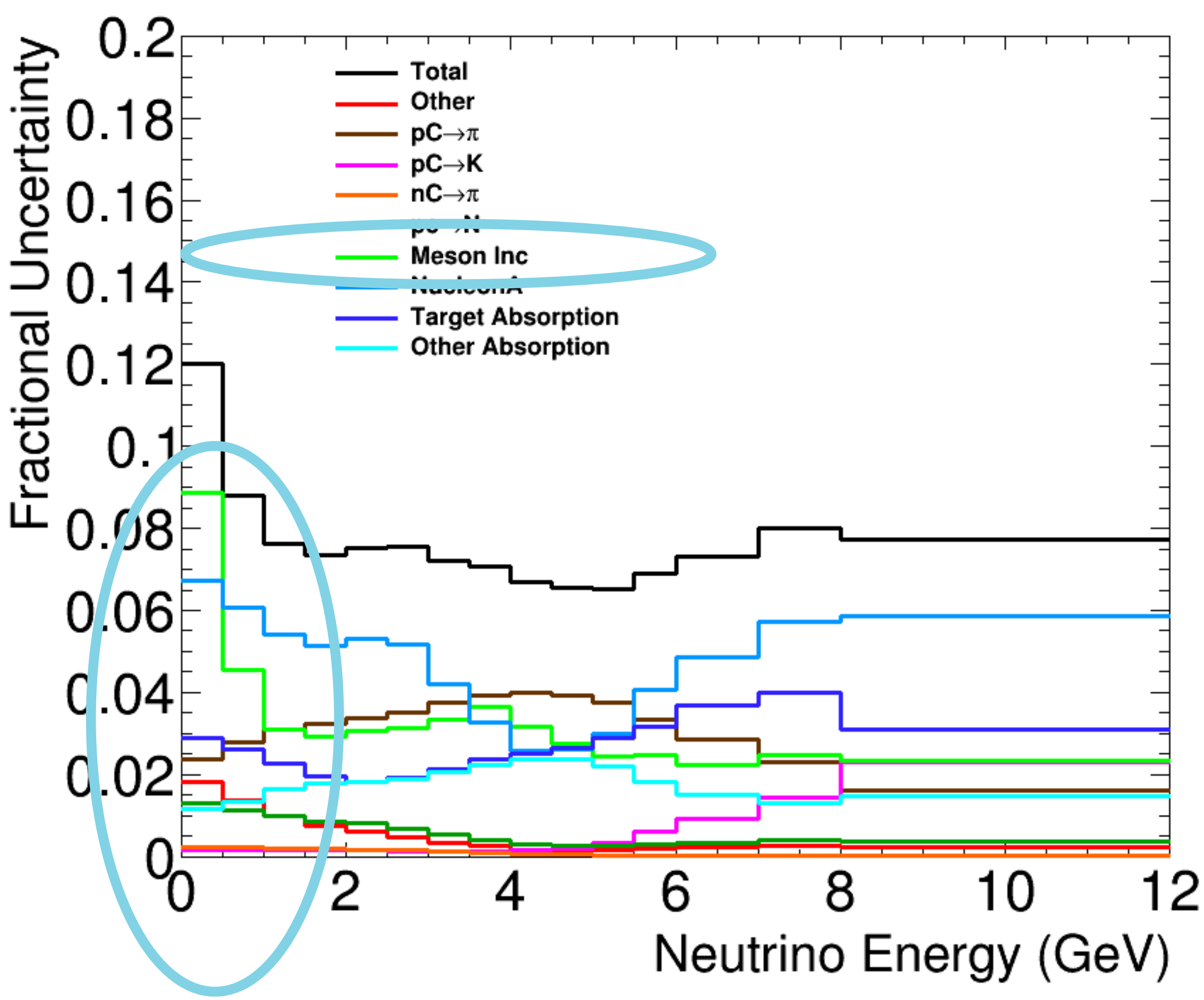
Validates **"Absorption" uncertainties** assumed for NuMI flux uncertainties



Also necessary to **normalize differential spectra** measurements

NA61/SHINE Thin Target Measurements

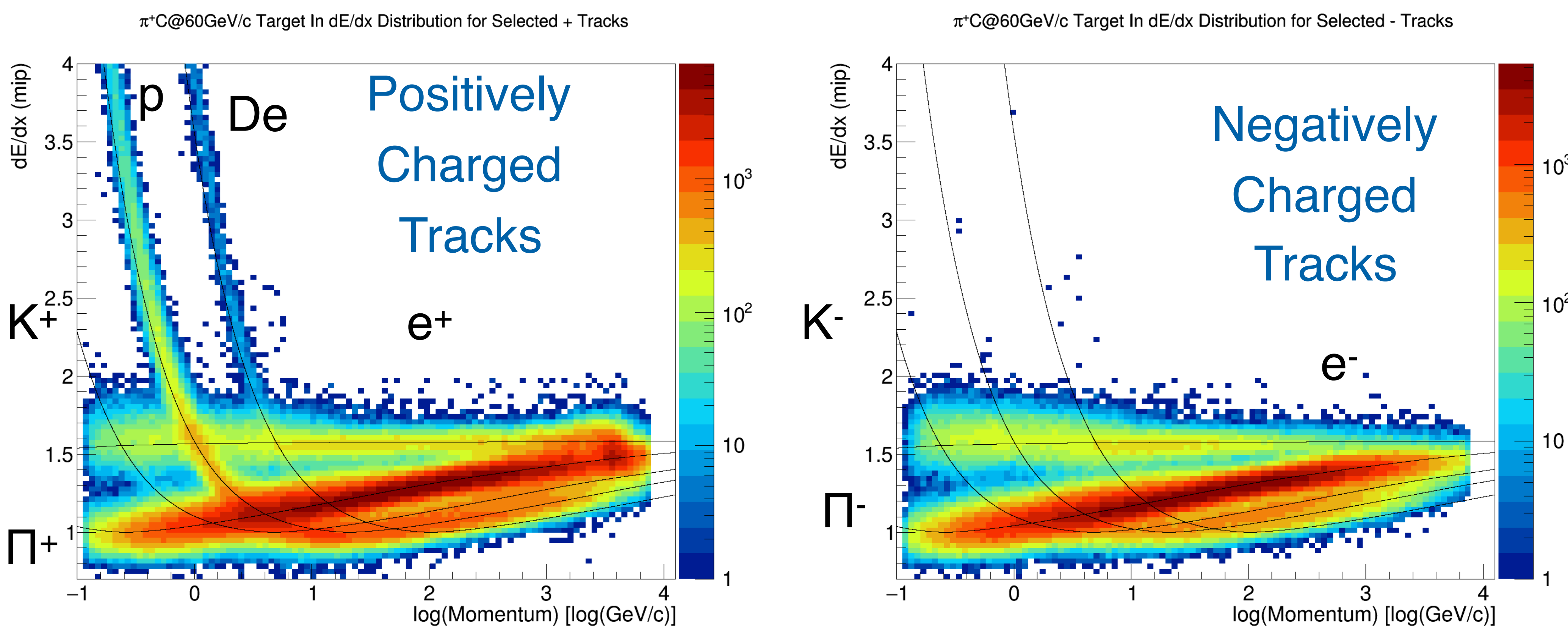
- Another Example in Detail: Pion Rescattering Differential Cross Section



- Fermilab experiments are currently making a major leap of faith on the **validity of pion and kaon interaction models** in our flux predictions
- These data are **completely unconstrained** in our flux predictions
- Apply a **40% uncertainty** on each of these interactions
- NA61/SHINE recently produced the **first relevant measurements** of these processes

NA61/SHINE Thin Target Measurements

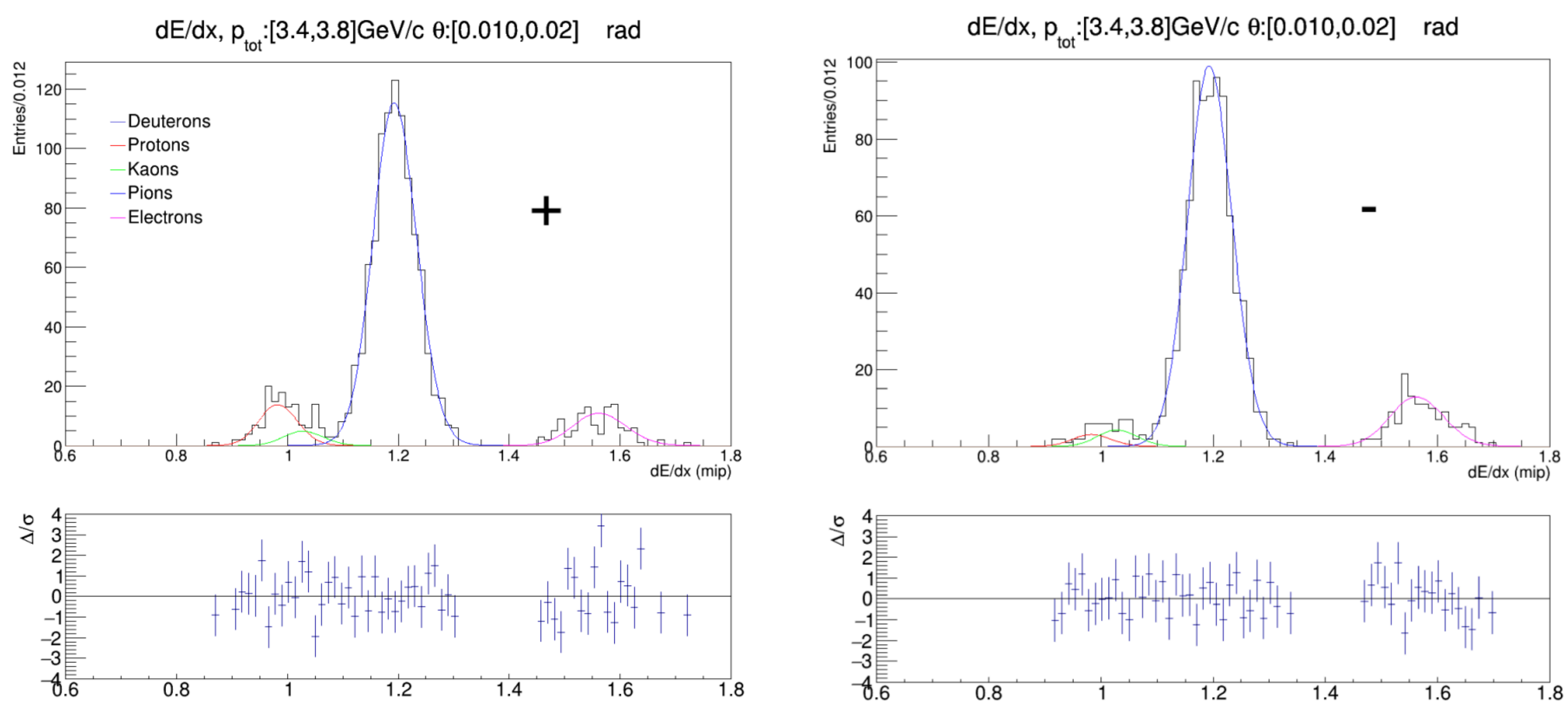
- Charged Hadron Spectra **Analysis Technique**
  - Charged **tracks are reconstructed** to a main event vertex
  - **Reconstructed momenta** are extracted from vertex fits
  - **Energy loss** is calculated from charge collected in the TPCs
  - e±, π±, K±, protons and deuterons **fall along their Bethe-Bloch curves** (dE/dx from π+ +C@60GeV/c interactions shown)



arXiv:1909.06294

NA61/SHINE Thin Target Measurements

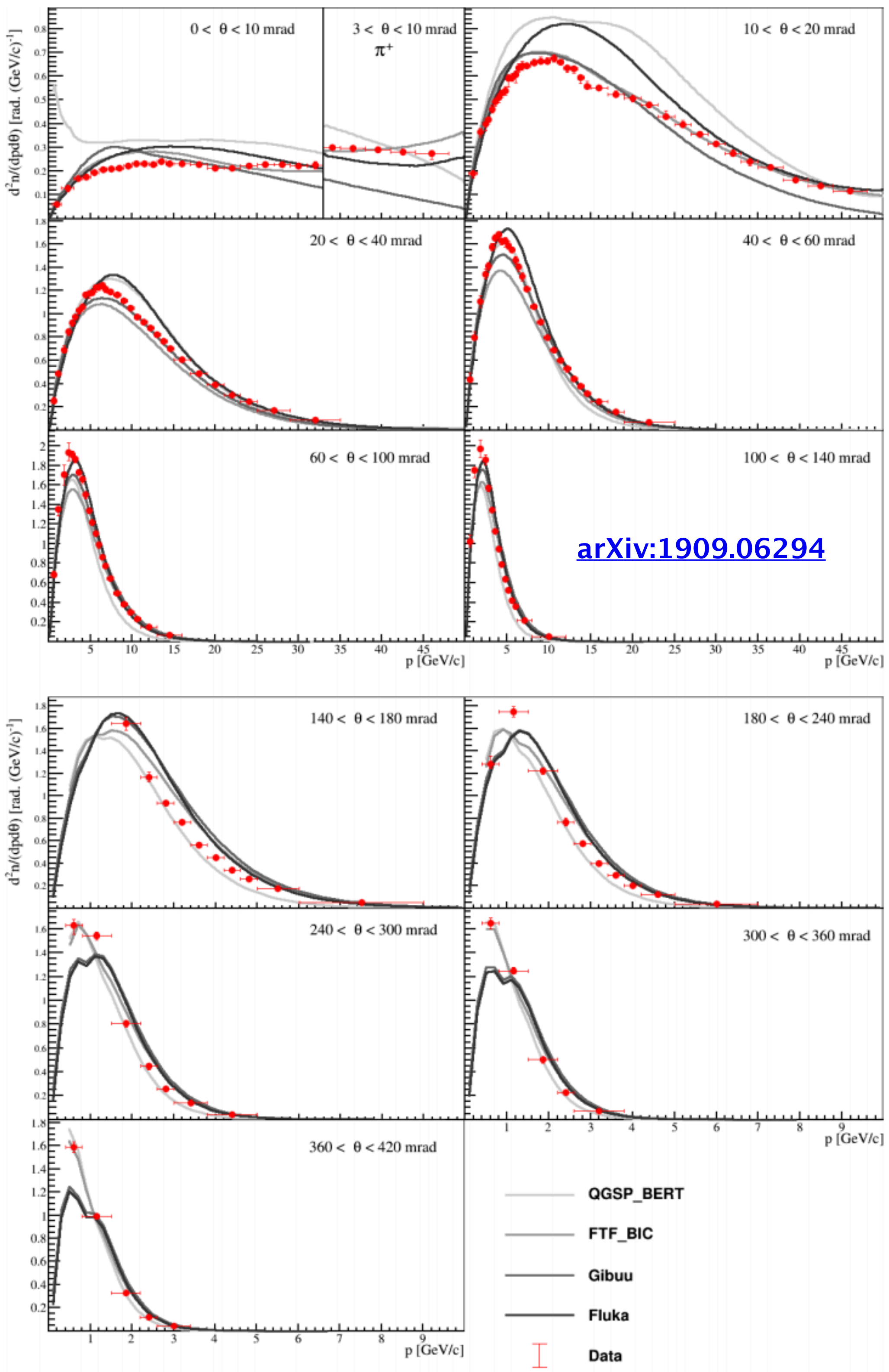
- Charged Hadron Spectra **Analysis Technique**
  - For each kinematic bin, **fits to dE/dx distributions extract yield** of each charged particle type in that bin



arXiv:1909.06294

  - **Simulation-based corrections are made** for fit biases, detector acceptance, reconstruction and selection efficiency, feed-down, and muon contamination

NA61/SHINE Thin Target Measurements



Differential π+ multiplicity spectra from π+ on Carbon at 60 GeV/c, compared with two Geant4 physics lists, Gibuu, and Fluka

- These can be transformed into **differential cross sections** by normalizing by total cross sections (also measured by NA61/SHINE)
- Will allow **substantial reduction of the 40% uncertainties** currently assumed for these processes by DUNE, NOvA, and MINERvA

NA61/SHINE Thin Target Measurements

- What's next for the thin target program?

Datasets collected in 2017:

Beam Particle	Target	
60 GeV/c π^+	Al	
30 GeV/c π^+	C	
60 GeV/c π^-	C	w/ FTPCs and F-ToF
120 GeV/c p	C	w/ FTPCs and F-ToF
120 GeV/c p	Be	w/ FTPCs and F-ToF
90 GeV/c p	C	w/ FTPCs and F-ToF

- Analysis of **recent datasets ongoing**
- Addition of **forward TPC and time-of-flight detectors** will increase phase space of measurements and decrease systematic uncertainties
- Additional data (including kaon beams) to be collected **after CERN long-shutdown**

NA61 Thick Target Measurements

- NA61 has also measured yields off of a T2K replica target:

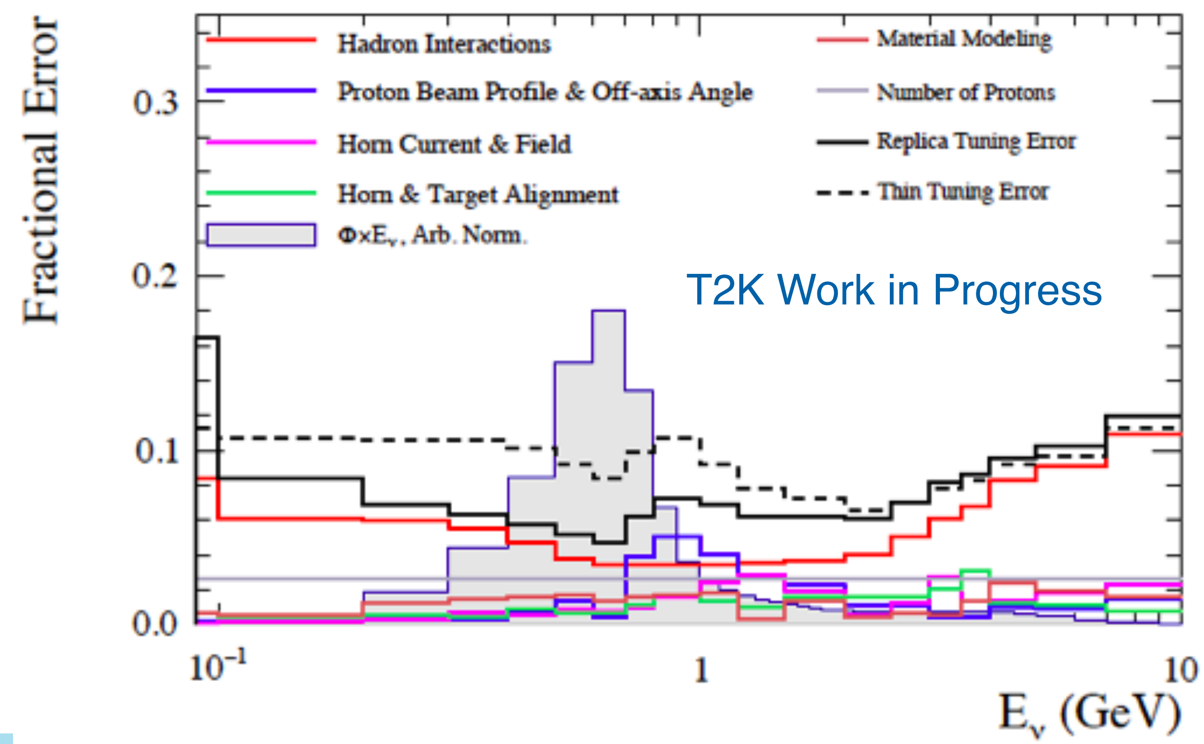
[1] Nucl. Instrum. Meth. A701, 99 (2013)
[2] Eur.Phys.J. C76 (2016) no.11, 617
[3] Eur. Phys. J. C79, no.2 100 (2019)

Beam	Year	Measurements
p@31 GeV/c	2007	$\pi^{\pm}$ [1]
p@31 GeV/c	2009	$\pi^{\pm}$ [2]
p@31 GeV/c	2010	$\pi^{\pm}$, $K^{\pm}$, p [3]
p@31 GeV/c High Field	2010	Production cross section analysis in progress

90 cm T2K Replica Target

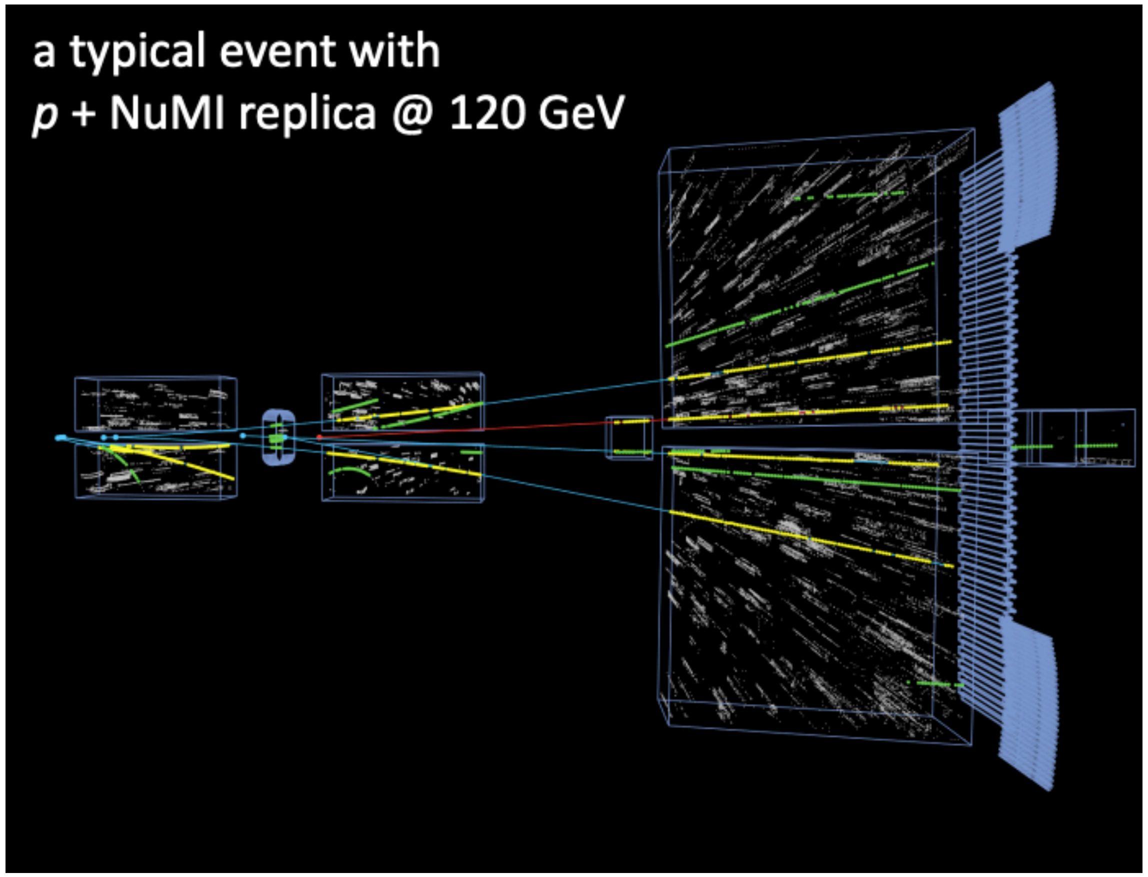
Uncertainties at focusing peak reduced from ~10% to ~5%

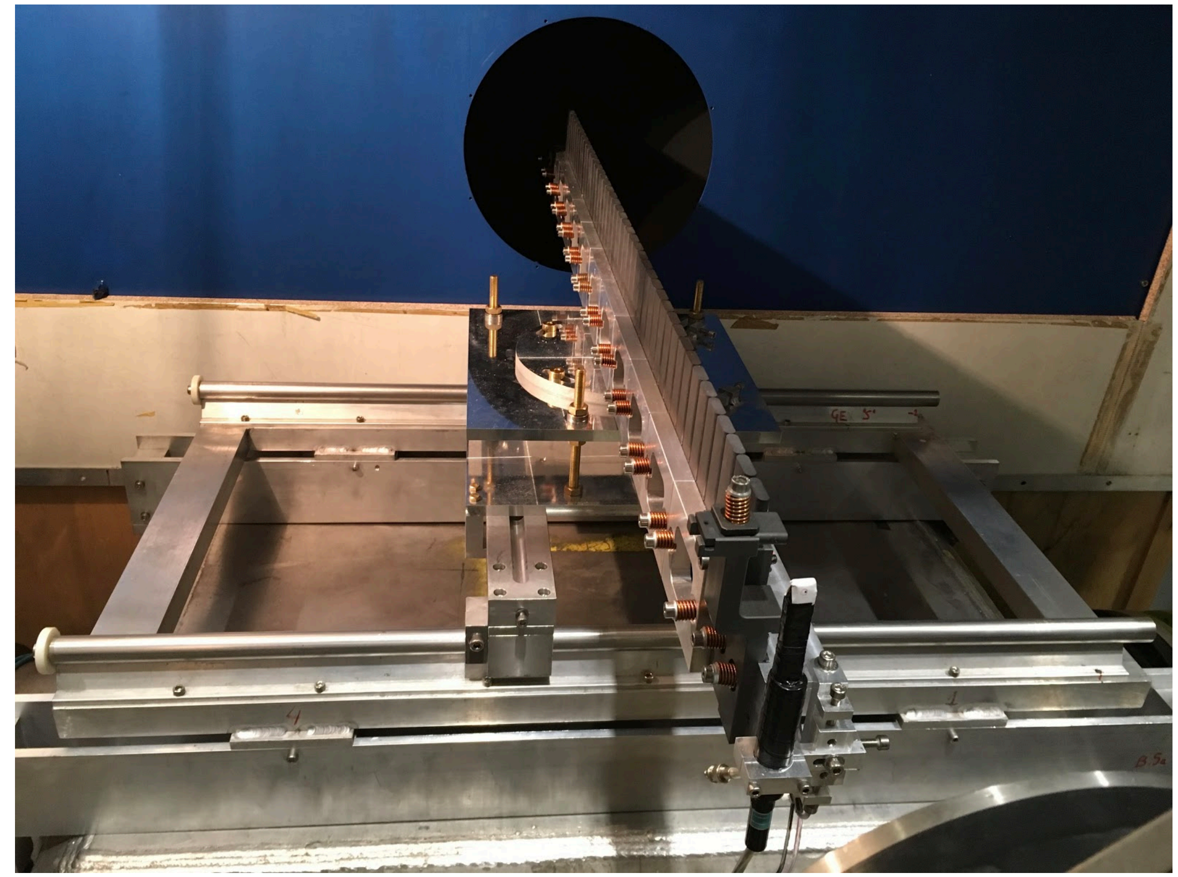
Further reduction possible with ongoing analysis of 2010 data



NA61 Thick Target Measurements

- Data on a **NuMI (NOvA-era) target** was collected in 2018:



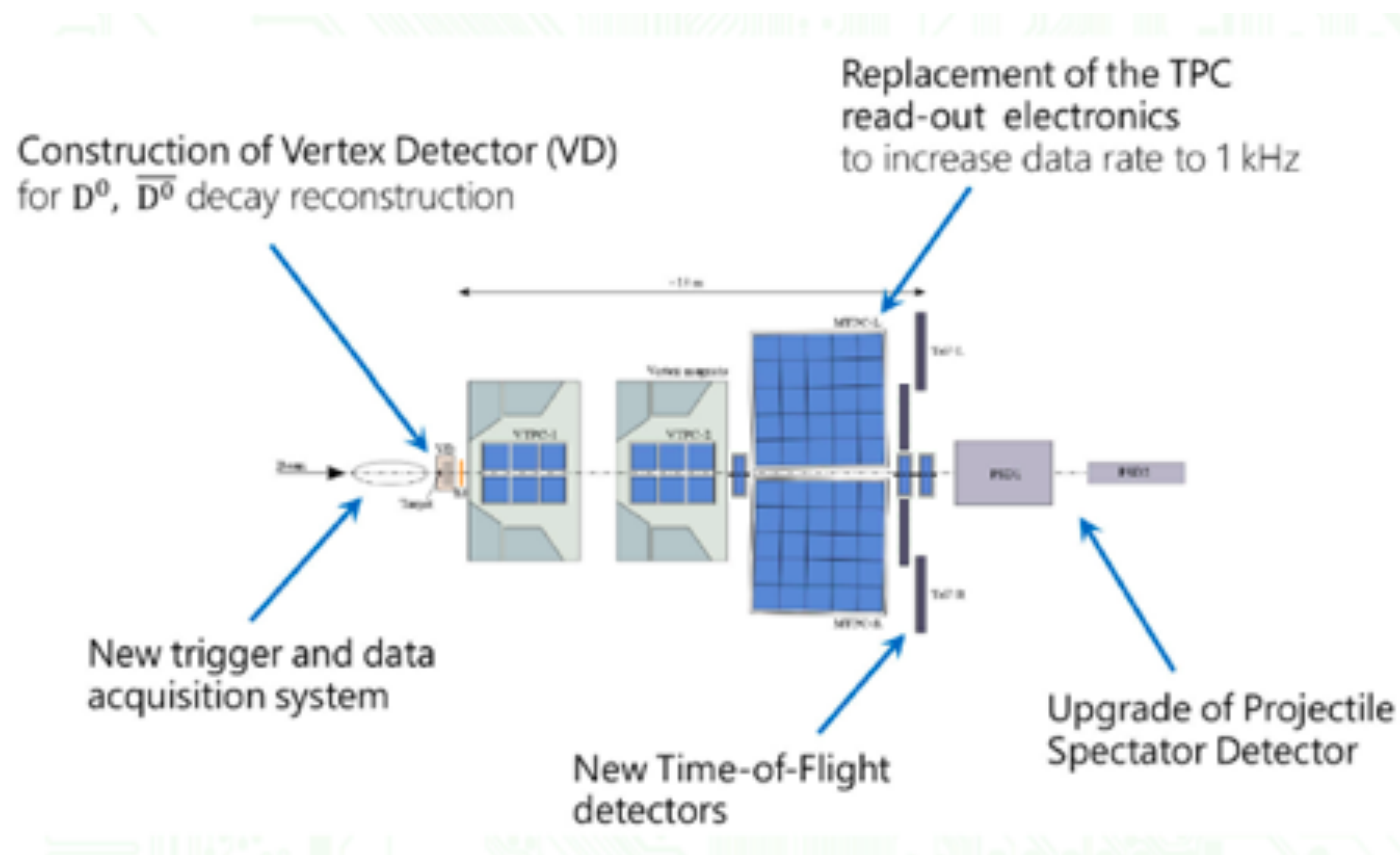


- Big effort underway to **improve replica target reconstruction software** to more precisely determine locations of particles exiting the target

- **Calibration** underway; **analysis** will be begin soon.

NA61 Beyond 2020

- NA61 **Upgrade in progress**:
  - Upgrades to **TPC readout and DAQ** system allowing 1 kHz readout rate
  - New **ToF walls** based on mRPC
  - New DRS4 **readout electronics**
  - New **Beam Positions Detectors** based on scintillating fibers
  - Large Acceptance **Vertex Detector** based on ALPIDE sensors



- Other **upgrades being considered**
  - Possible tertiary beam allowing for **lower energy hadron beams**
  - **Target tracking detector** for replica target data taking

Conclusion

- Neutrino **flux uncertainties have improved significantly in recent years due to NA61** hadron production measurements
- We are still making some **major leaps of faith in our flux uncertainty budgets**, for interactions that have not been measured
- NA61 is building **a bank of data to rectify this**, and is rolling out publications of this data
  - Recent highlights include **first measurements of 120 GeV proton** inelastic and total cross sections and differential multiplicity spectra for 60 GeV pions
  - Considerable additional data is being analyzed, including NuMI **NOvA-era replica target data**
- An **upgrade is underway now** that will increase data rate and expand acceptance of the detector
- Upgrades to **prepare for the DUNE era**, including (very) long target measurements are being considered

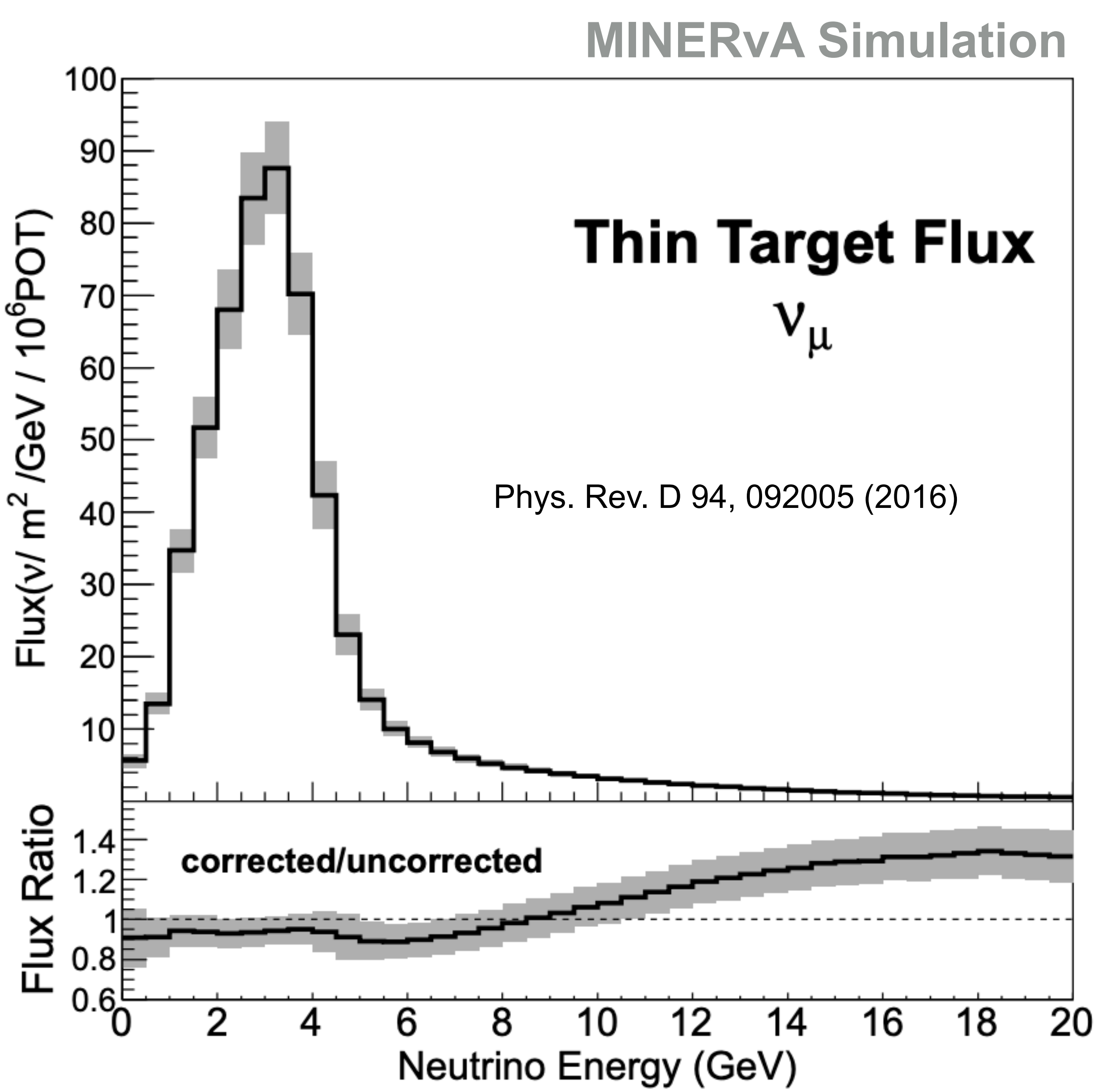
On Behalf of the NA61 Collaboration

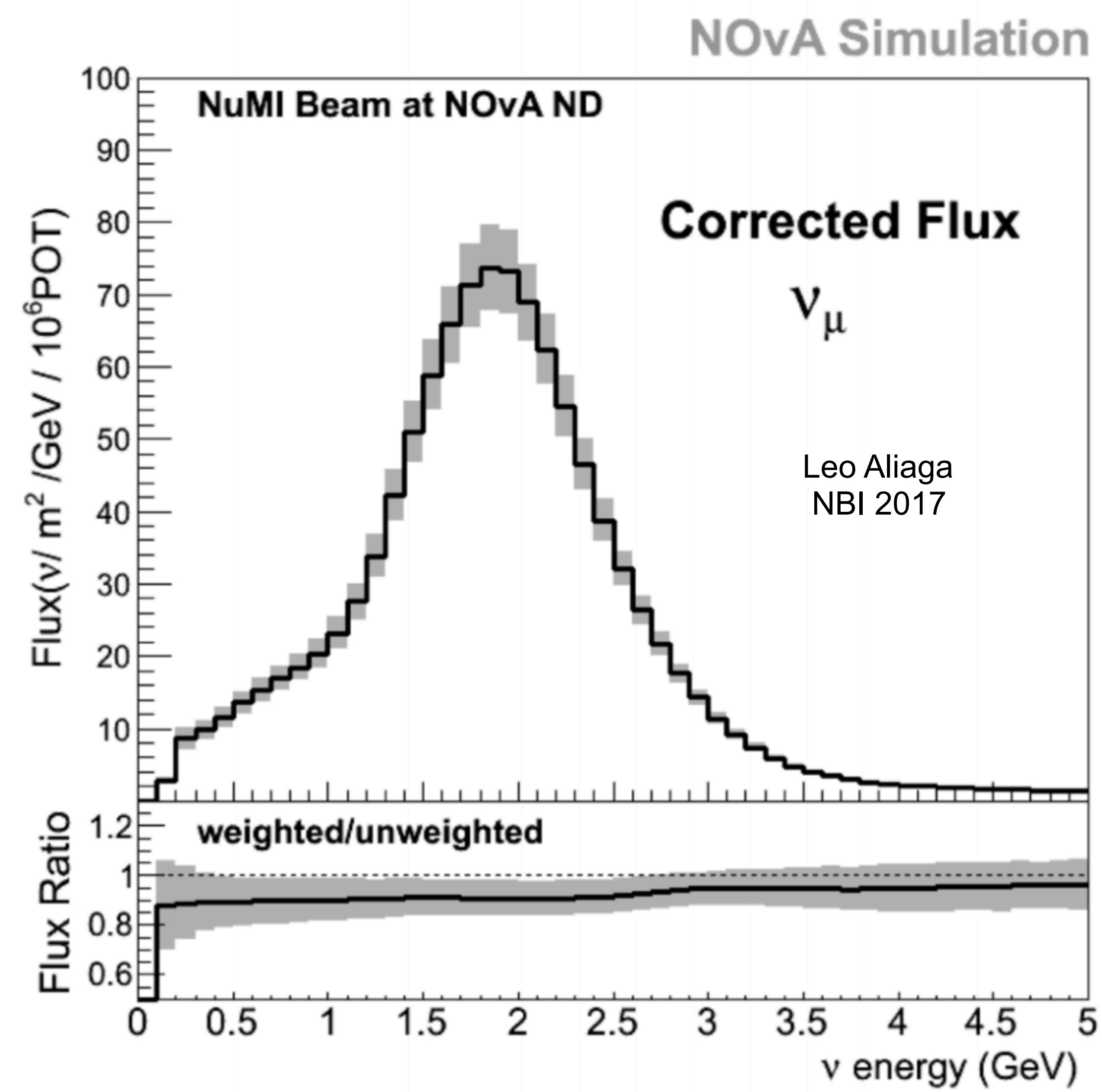
Thank You!

Backup

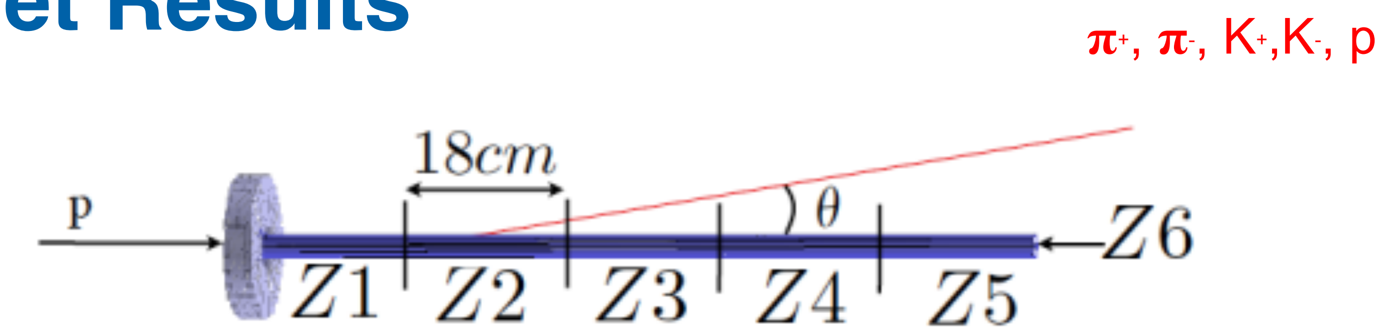
Correcting Neutrino Flux Simulations

- Results of correcting Flux predictions:

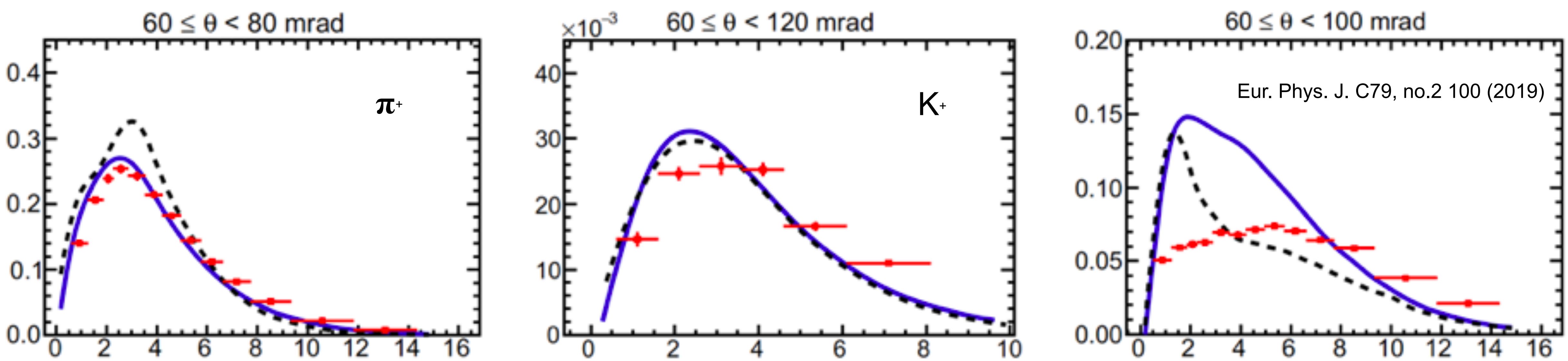




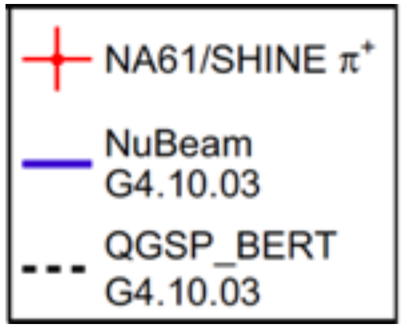
T2K Replica Target Results



- High statistics data set of 31 GeV/c protons interacting with a T2K replica target recorded in 2010
- Triple differential multiplicity measurements of charged pions, charged kaons and protons emanating from a T2K repli
target



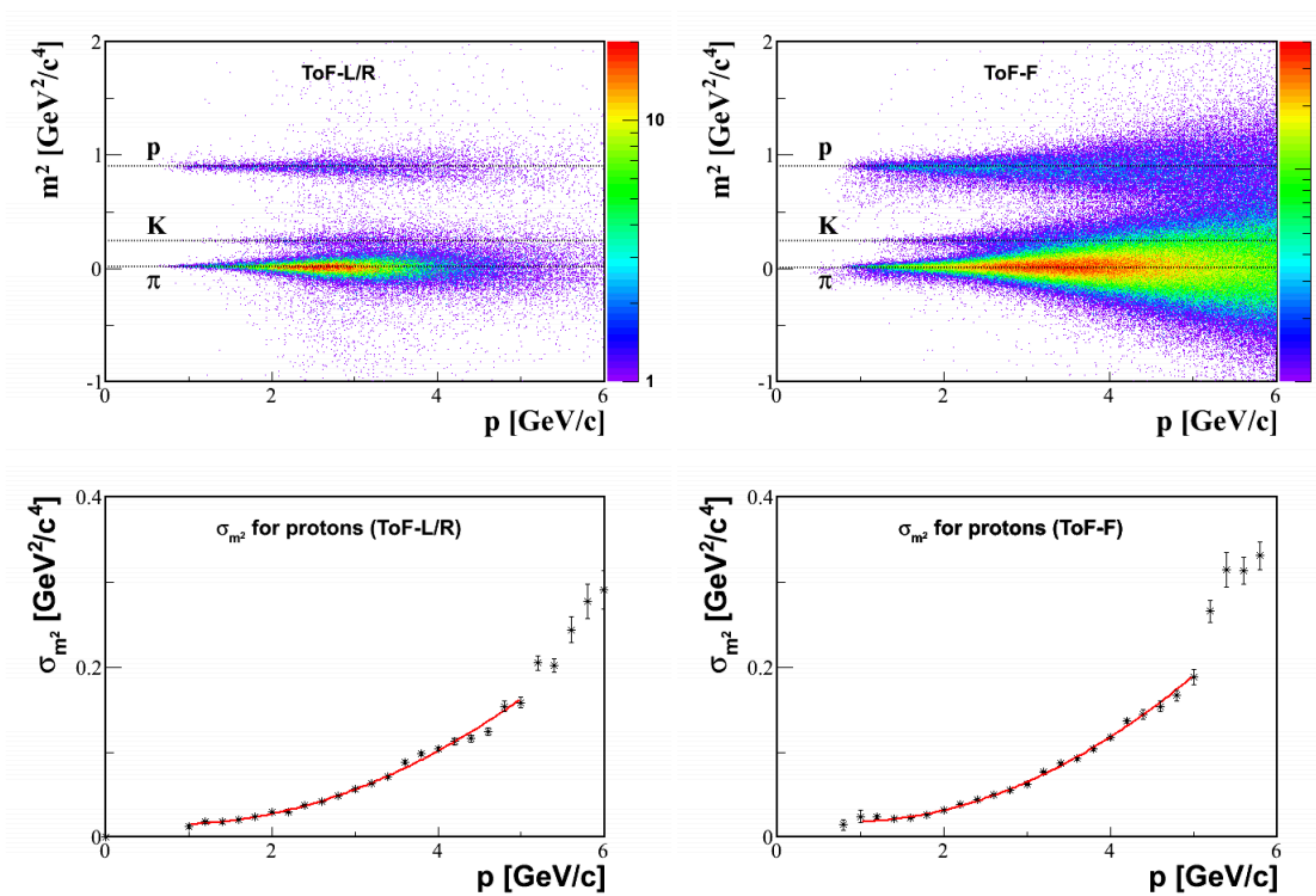
Another analysis is underway to more precisely measure the production cross section by measuring the survival rate of beam protons through the T2K replica target data



TOF Detectors

$$m^2 = p^2\left(\frac{c^2\,tof^2}{l^2} - 1\right)$$

arXiv:
1401.4699



NA61/SHINE Thin Target Measurements

- Systematic uncertainties on thin target spectra measurements
  - dE/dx fits:
    - Standard deviations on particle yields from fits are propagated to multiplicity measurements
  - Physics model
    - Corrections are evaluated using different G4 physics list
  - Feed-down (backgrounds from decays of higher mass hadrons)
    - 50% uncertainty on MC prediction
  - Selection uncertainties
    - Data tracks were found to be 5% shorter than simulation tracks; MC track length was artificially decreased by 5%
  - Reconstruction
    - Positions of various detectors were varied by conservative amounts
  - Momentum measurement
    - 0.3%, based on comparison of track multiplicity

NA61/SHINE Thin Target Measurements

60 GeV pi+C beam