The physics of neutrino flux:

The NA61/SHINE neutrino program

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Neutrino Oscillation Workshop
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NA61/SHINE Neutrino Program

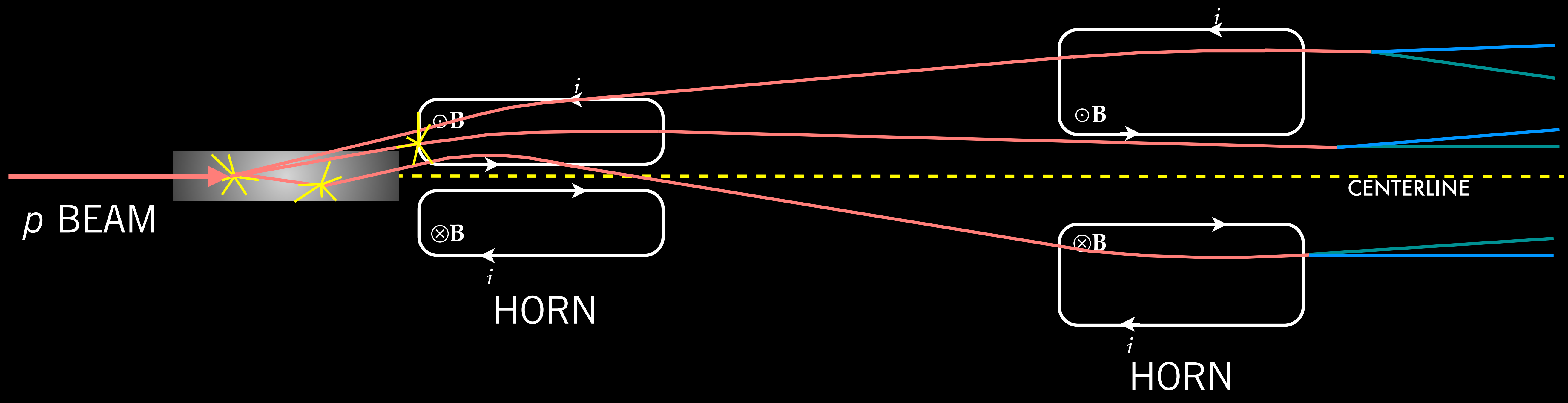
- Neutrino beam physics
- NA61/SHINE neutrino program
- Current and new results
- Upcoming data sets
- New opportunities

Neutrino beam physics

- Modern accelerator-based oscillation experiments use "conventional" beams: primary protons strike a target, secondary mesons enter a decay region, and they decay in flight to neutrinos upstream of a beam stop
- All have common properties:
  - Predominantly ν_μ, with ν_e contamination at the ~1% level from muon, kaon decays.
  - Even "narrow-band" beams tend to have tails to high energy
  - Fluxes have significant systematic errors

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.**

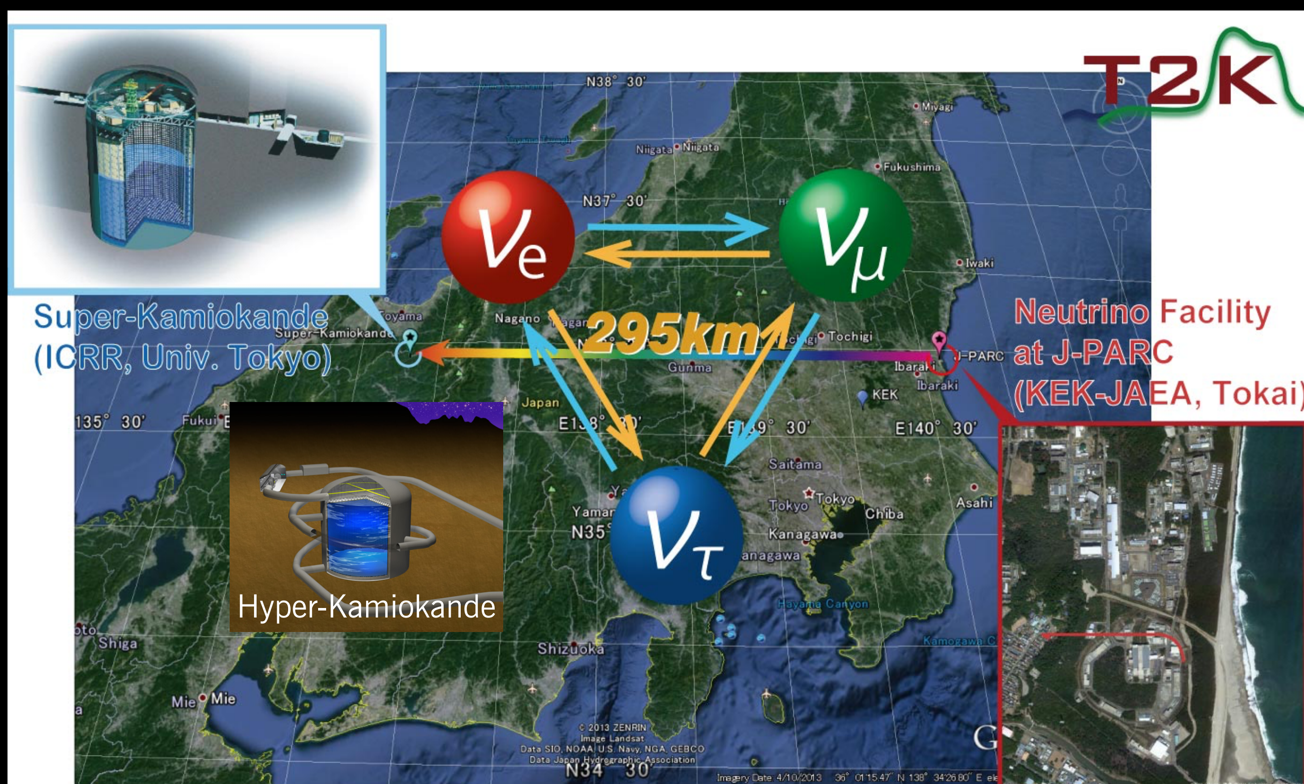


Understanding the flux

- 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!

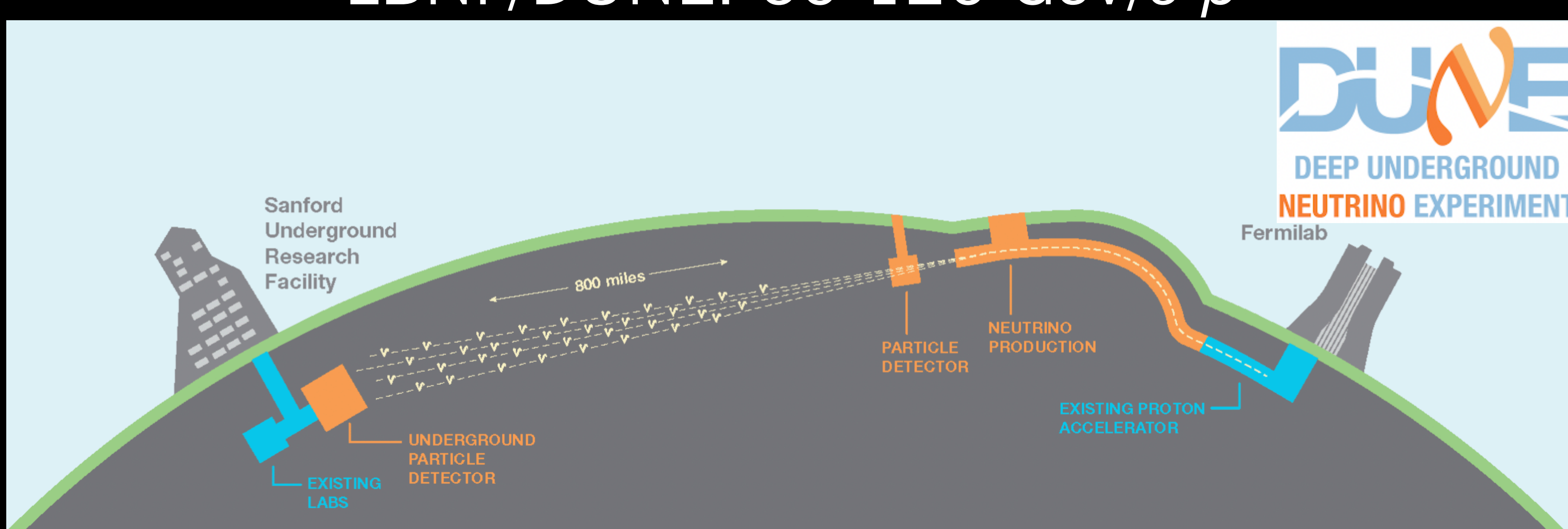
Primary beam energies for current and near future LB neutrino beams



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

NuMI: 120 GeV/*c* *p*

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

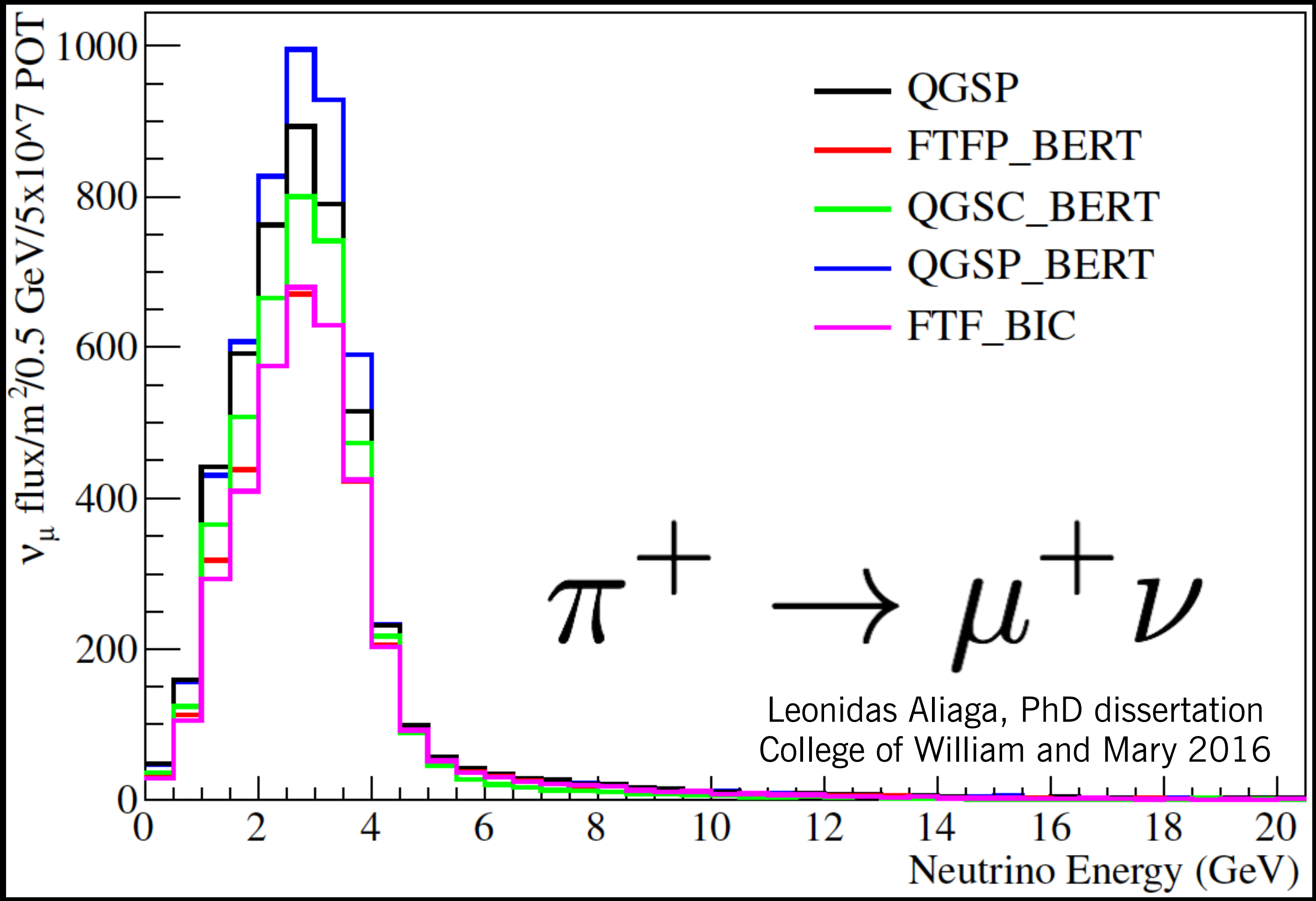


Understanding a neutrino beam

- 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

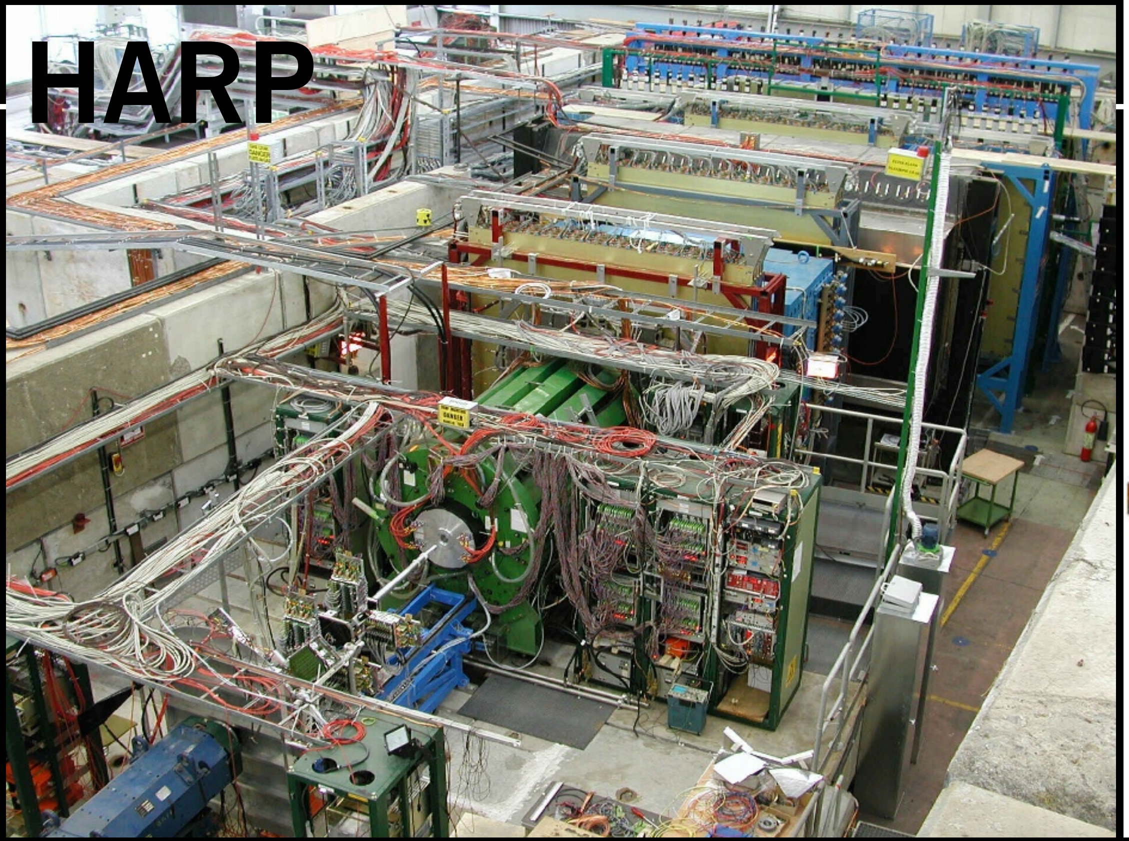
Monte Carlo generators

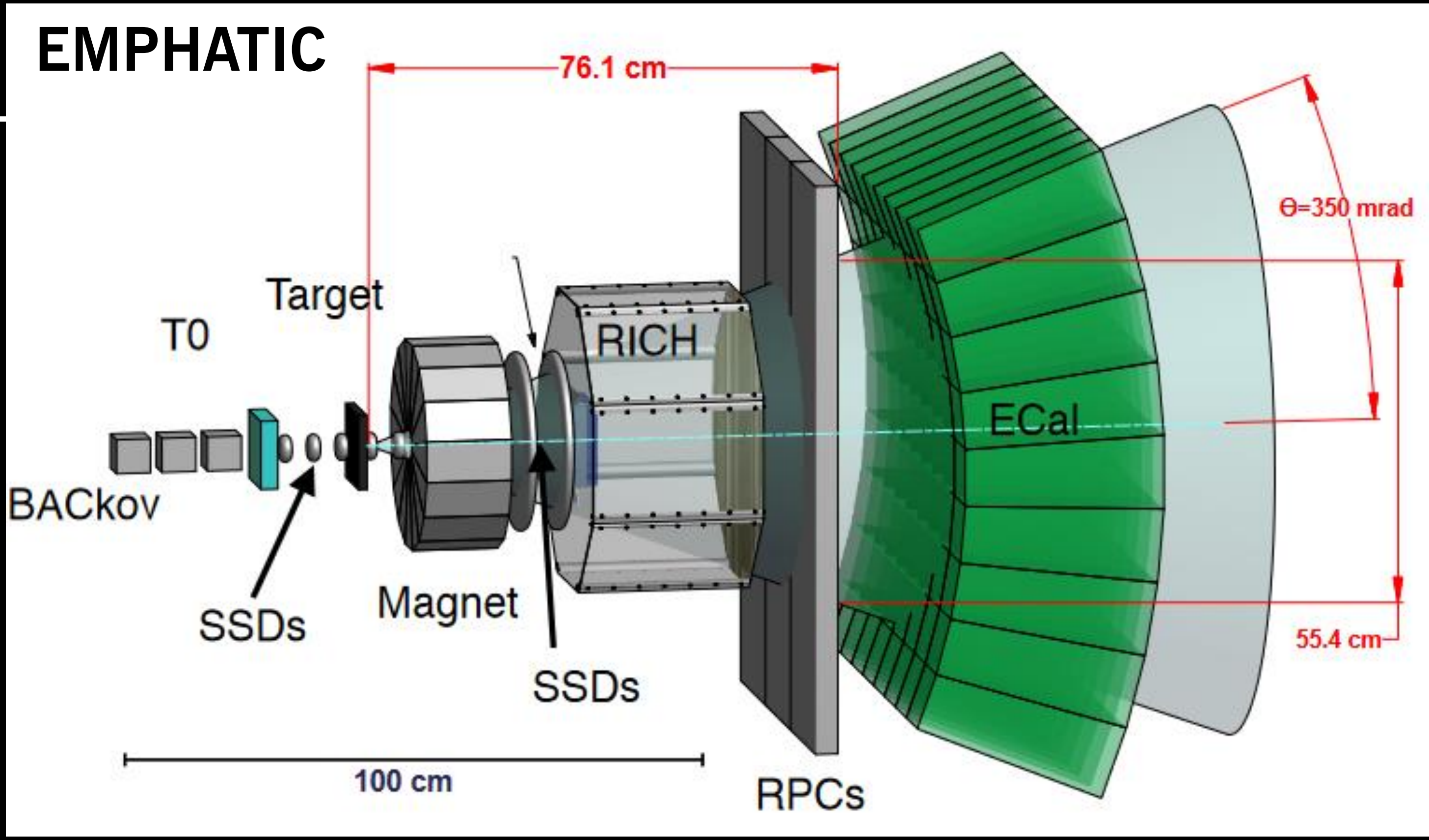
- Neutrino experiments use hadronic interaction generators including FLUKA, GEANT4 with various physics lists
- But these generators have **very large** disagreements with one another: 20%+ is common, or even factors of two for kaon production!
- Very important to have constraints on the hadronic processes

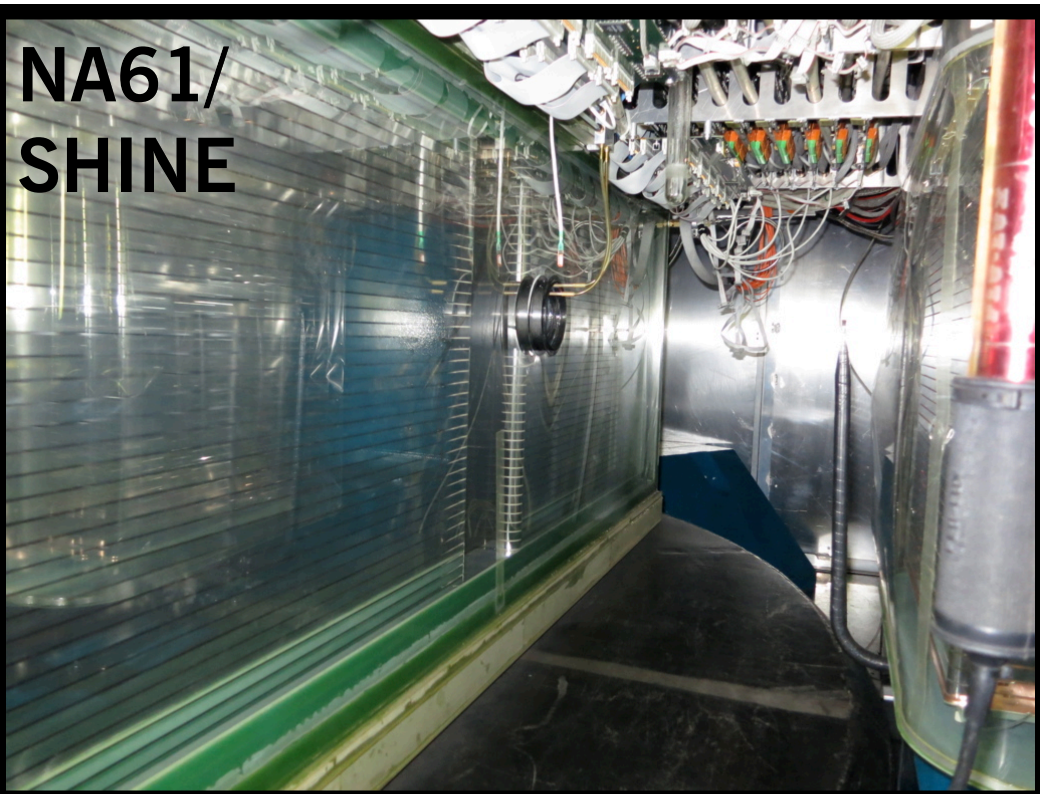


Flux of FNAL's NuMI neutrino beam with different physics generators

Dedicated experiments



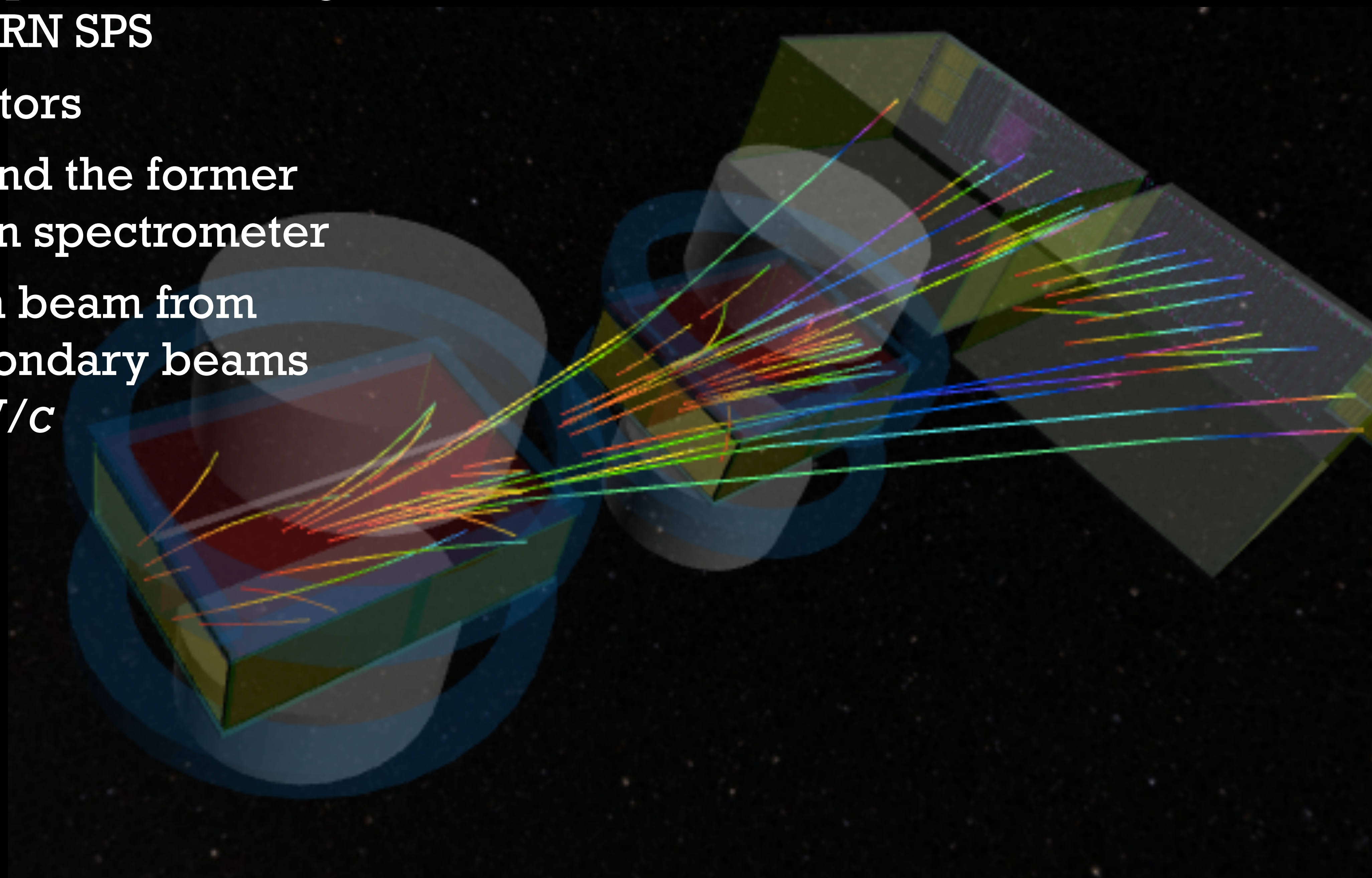




- In recent years, a loose program of hadron production measurements specifically for neutrino experiments has been underway
- HARP (CERN PS)
- EMPHATIC (FNAL MI)
- NA61/SHINE (CERN SPS)

NA61: The SPS Heavy Ion and Neutrino Experiment

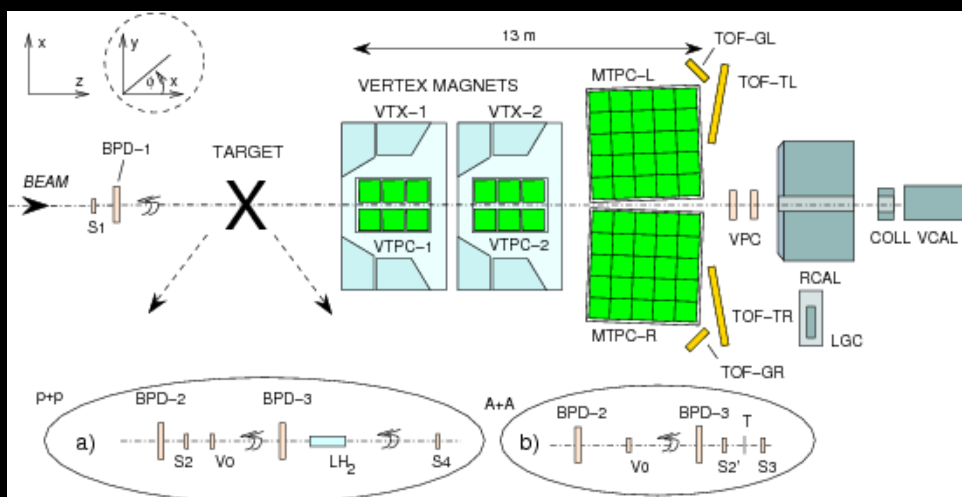
- Fixed-target experiment using H2 beam at CERN SPS
- ~150 collaborators
- Designed around the former NA49 heavy-ion spectrometer
- Primary proton beam from CERN SPS, Secondary beams ~25 to 350 GeV/*c*



NA61: The SPS Heavy Ion and Neutrino Experiment

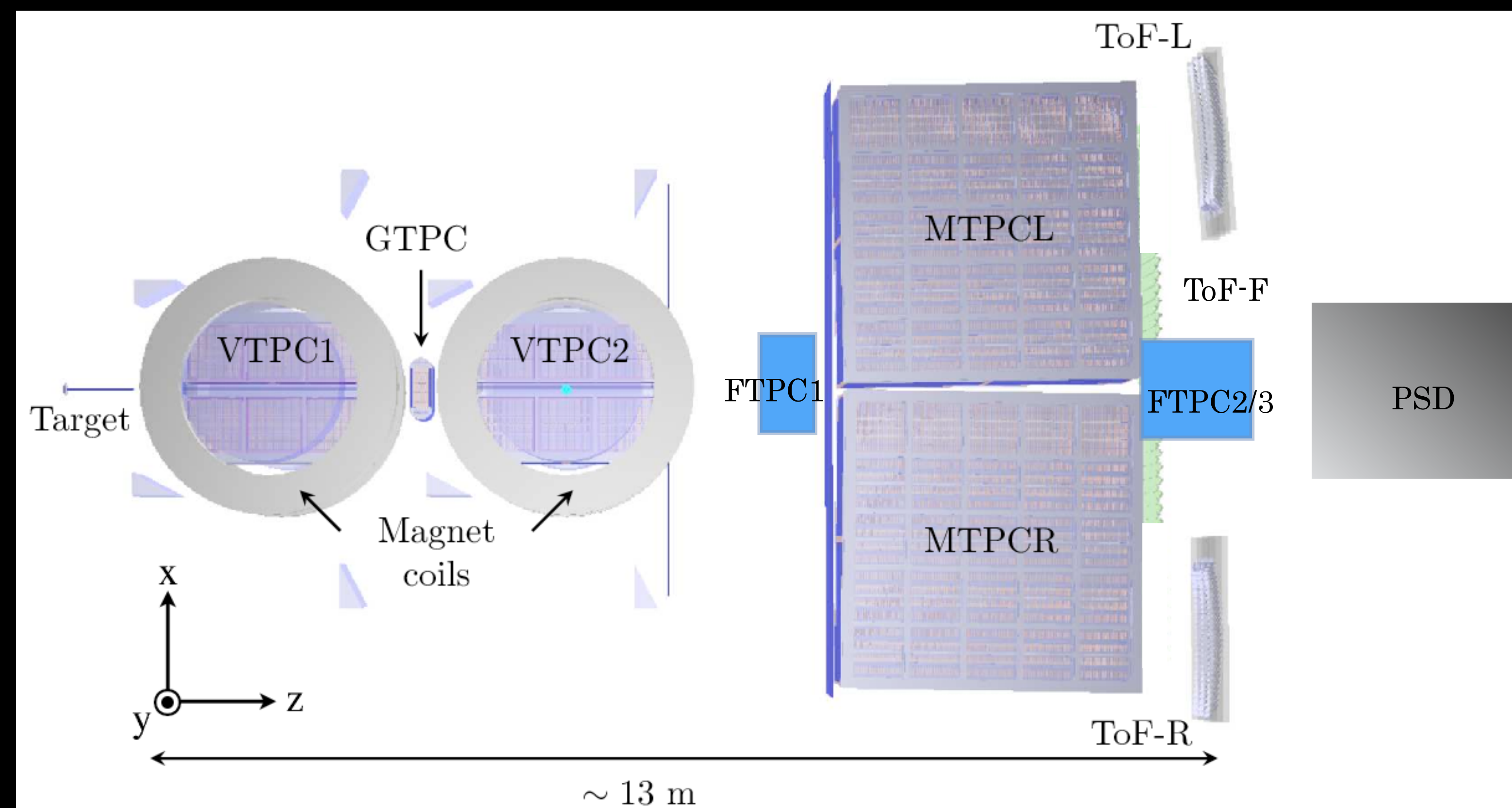
- Diverse physics program includes
  - Strong interactions/heavy ion physics
    - Onset of QCD deconfinement
    - Search for critical point
    - Open-charm production
  - Cosmic ray production
    - Hadron production for air-shower model predictions
    - $d/\bar{d}$ production for AMS experiment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

NA61/SHINE: a large-acceptance multiparticle spectrometer



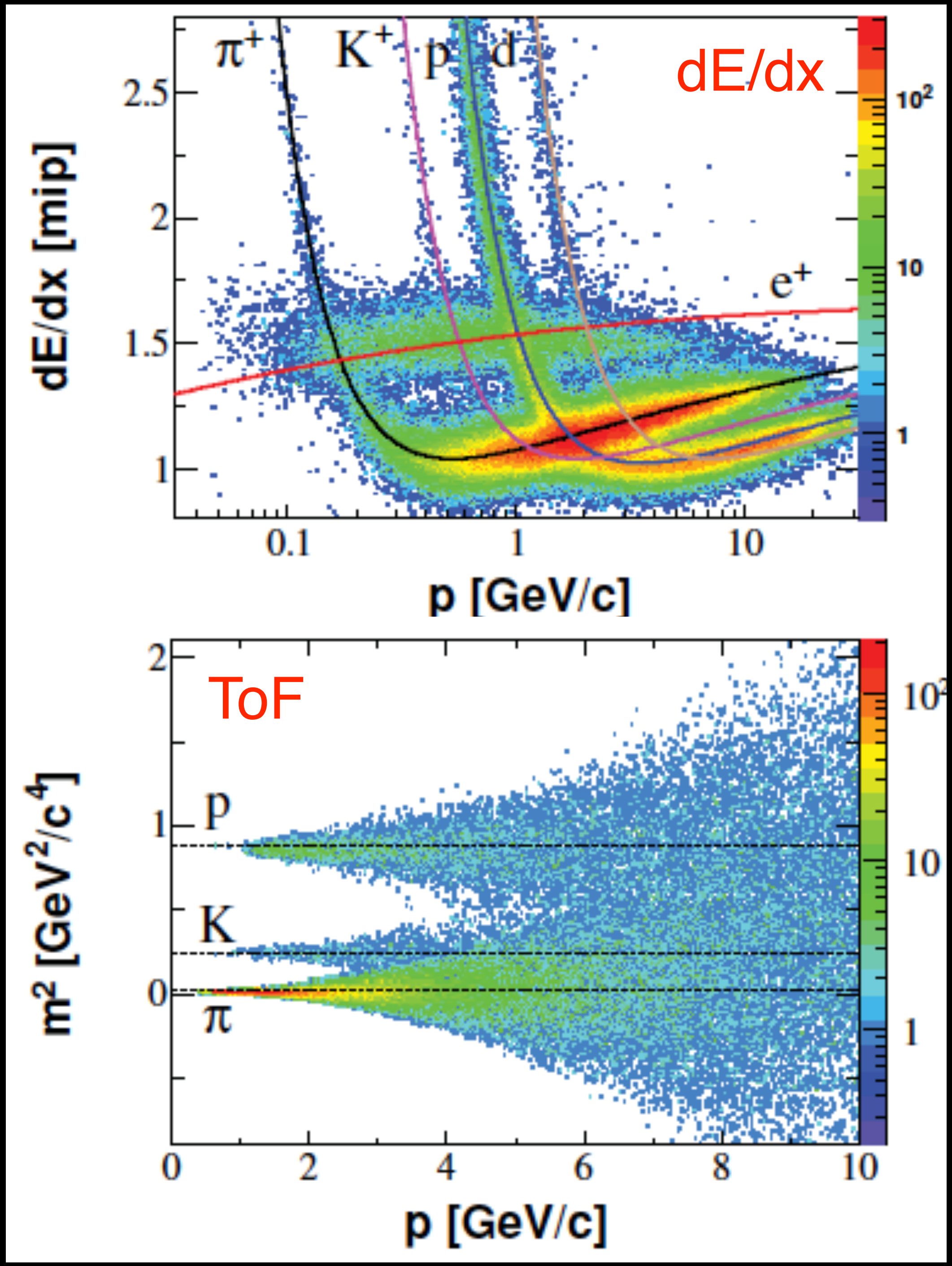
NA49

NA61

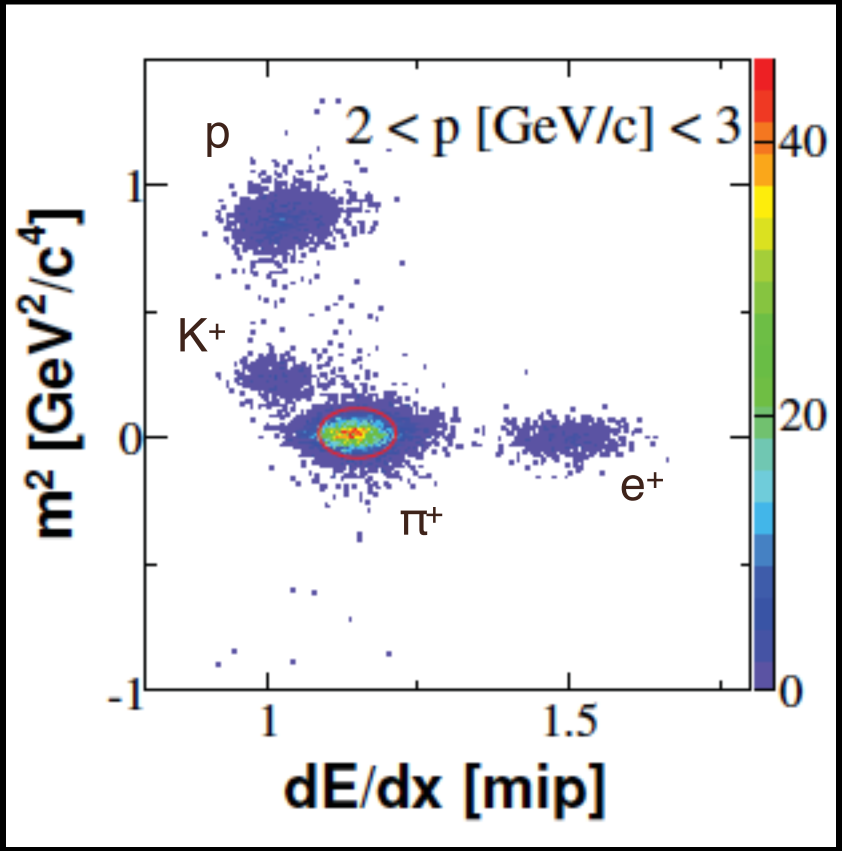


- Detailed beam instrumentation including PID and tracking before the target
- Several large-acceptance TPCs, two superconducting analysis magnets
- Scintillator- and MRPC-based time-of-flight detectors
- Projectile Spectator Detector: forward hadron calorimeter

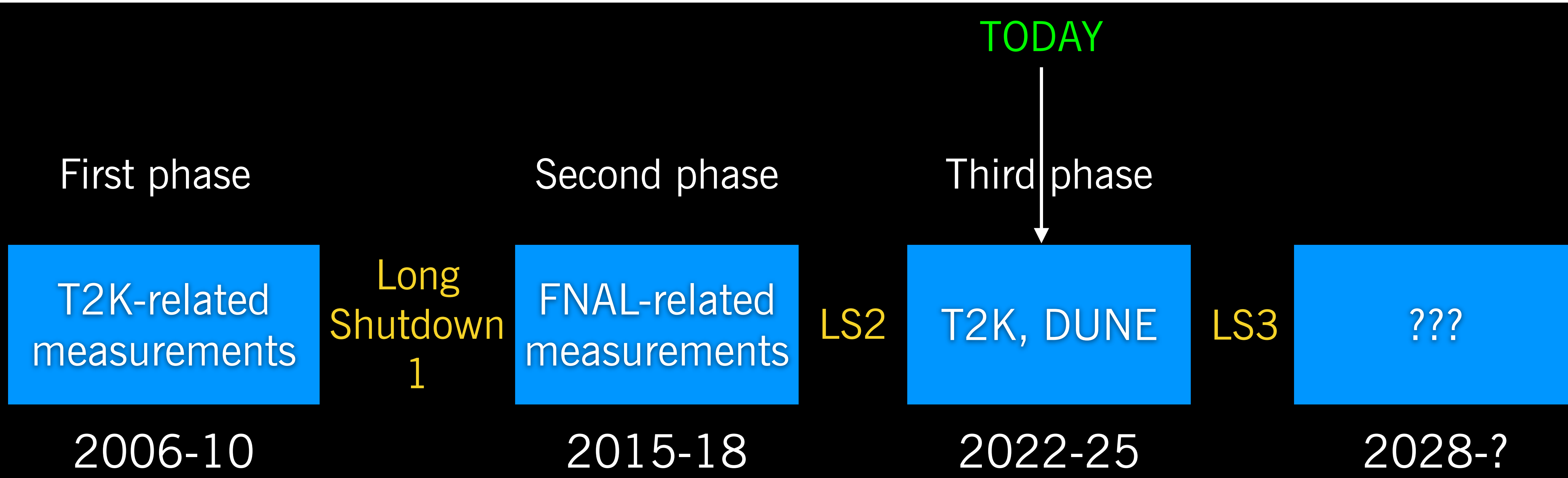
Particle identification



- 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

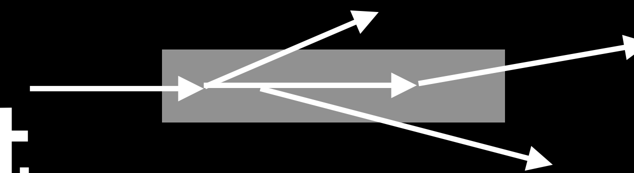
NA61/SHINE measurements for T2K

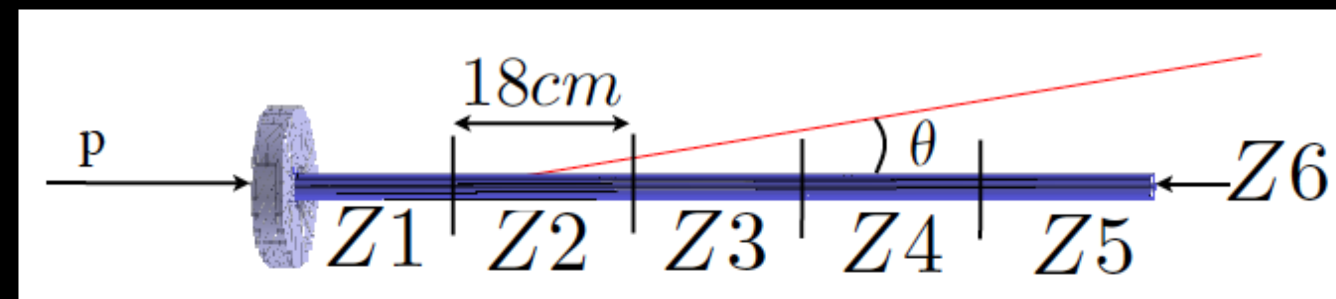
- NA61/SHINE took thin- and thick- target data with 30 GeV/*c* protons specifically for T2K in **2007 (thin) 2009 (thin and replica)**, and **2010 (replica)**.
- Eight NA61/SHINE publications have come out of these data sets

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)

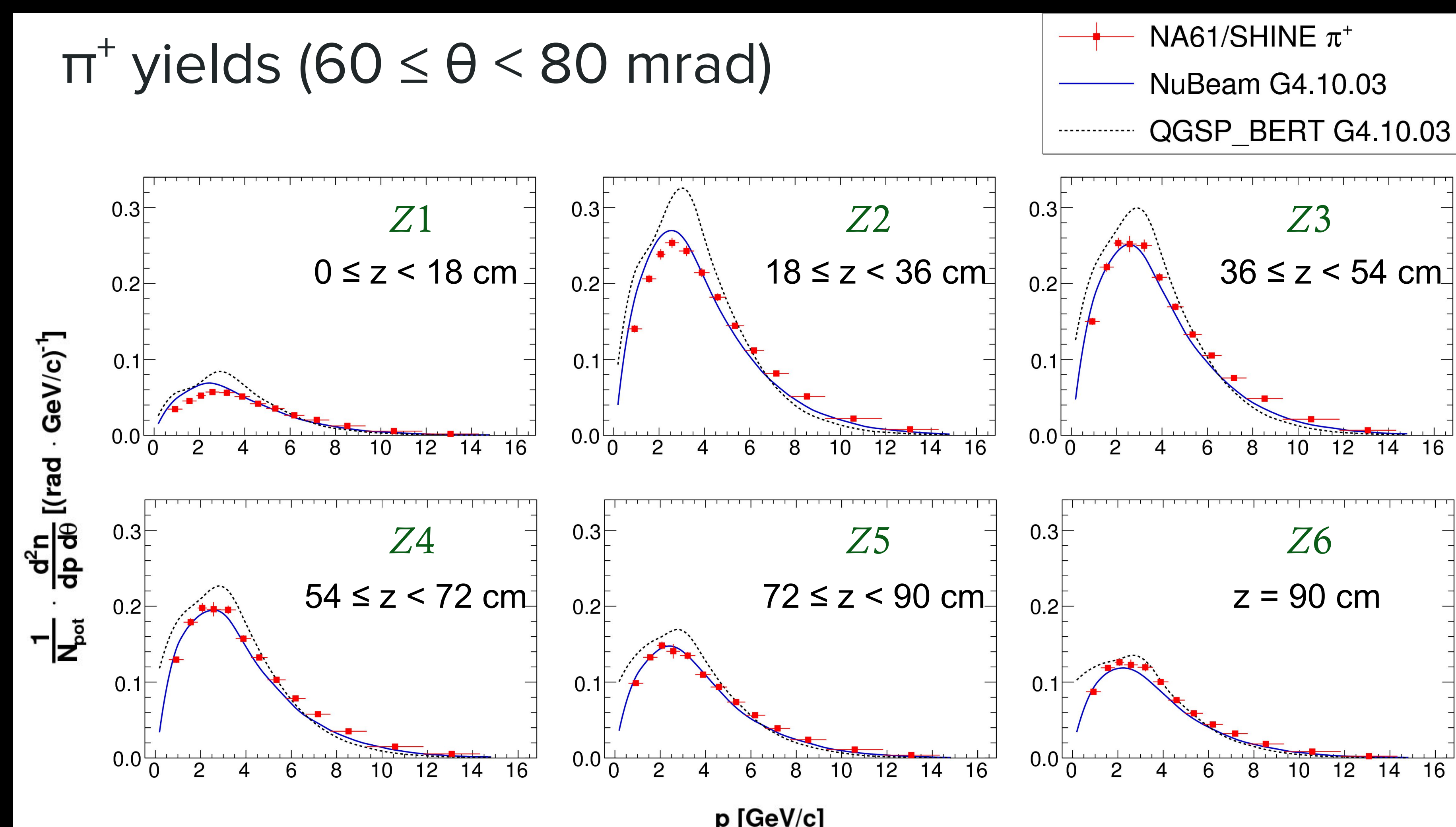
NA61 result: full differential yields from T2K replica target





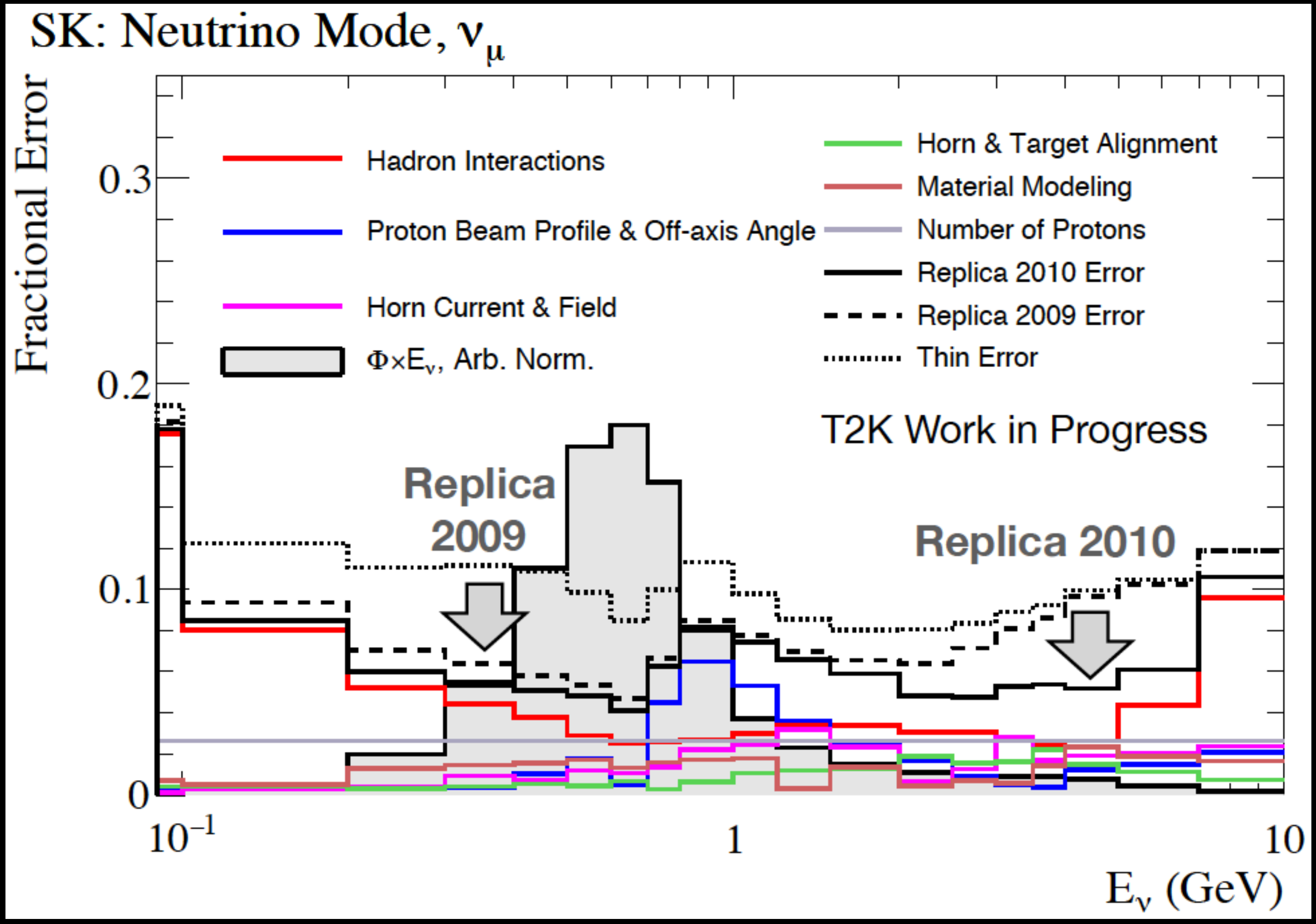
- *Eur.Phys.J.* **C 79** 2, 100 (2019)
- Showing one angle bin of π^+ for illustration.

  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)



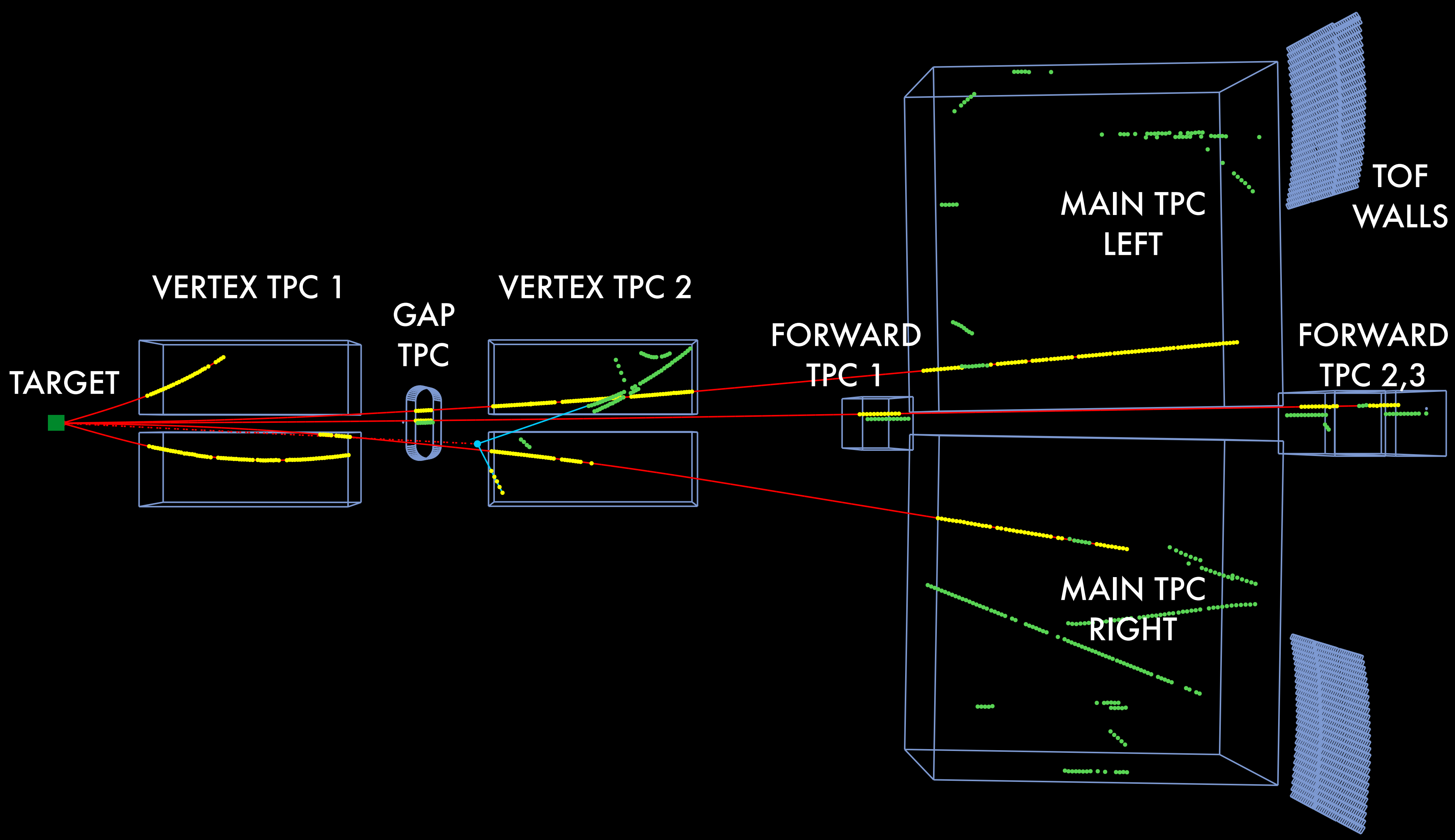
2015-18: A second phase of NA61 neutrino measurements

- 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

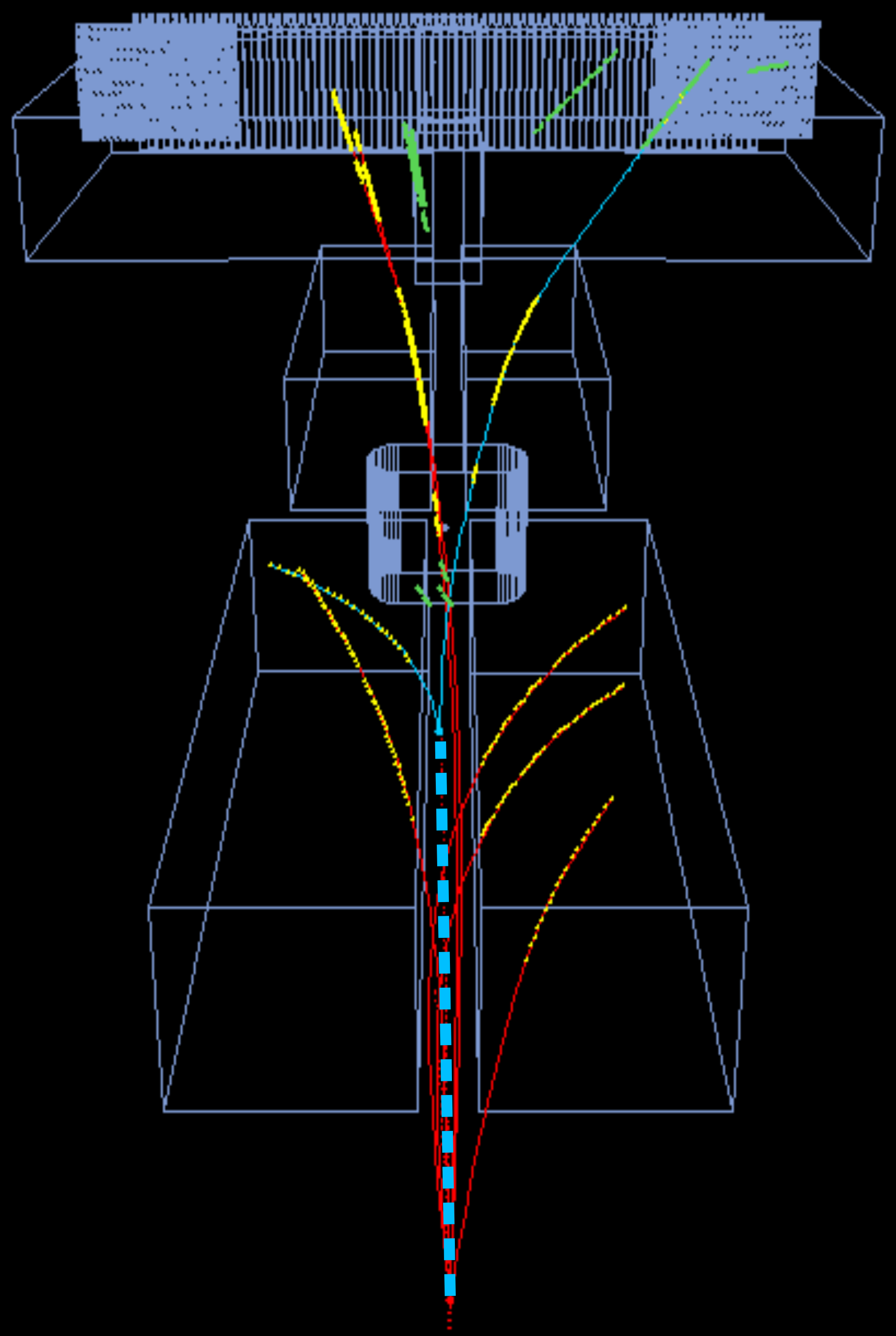
2016	2017
● p + C @ 120 GeV/c	π^+ + Al @ 60GeV/c
▲ p + Be @ 120 GeV/c	π^+ + C @ 30 GeV/c
■▲ p + C @ 60 GeV/c	π^- + C @ 60 GeV/c ■
● p + Al @ 60 GeV/c	p + C @ 120 GeV/c (w FTPCs) ●
● p + Be @ 60 GeV/c	p + Be @ 120 GeV/c (w FTPCs)
● π^+ + C @ 60GeV/c	p + C @ 90 GeV/c (w FTPCs) ◧
● π^+ + Be @ 60 GeV/c	

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

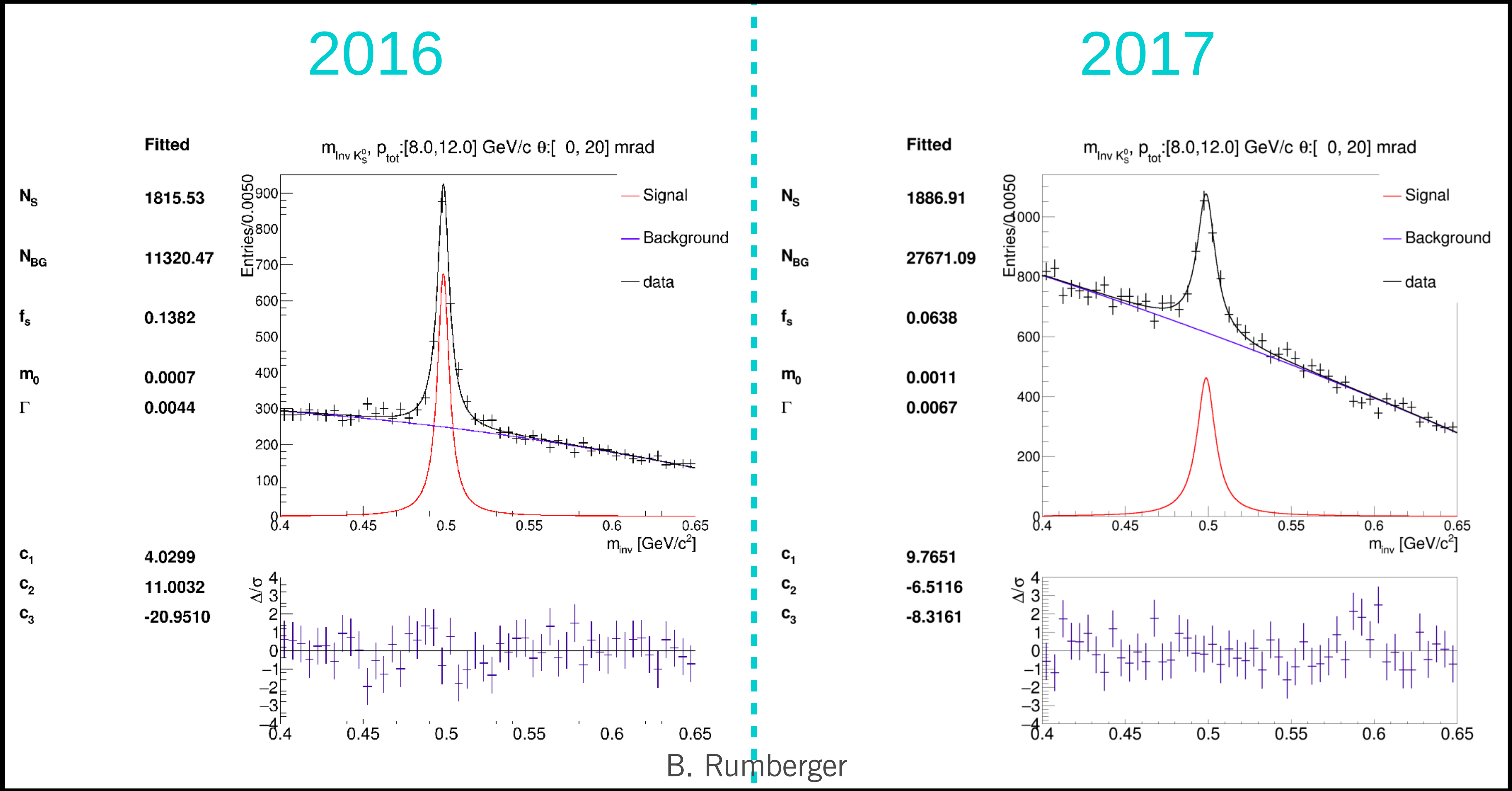
- Full particle yields and spectra from these data sets
- Goal with these measurements is to span the phase space of primary and secondary interactions in neutrino targets and surrounding materials
- Each measurement becomes a point for interpolation in MC generators

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

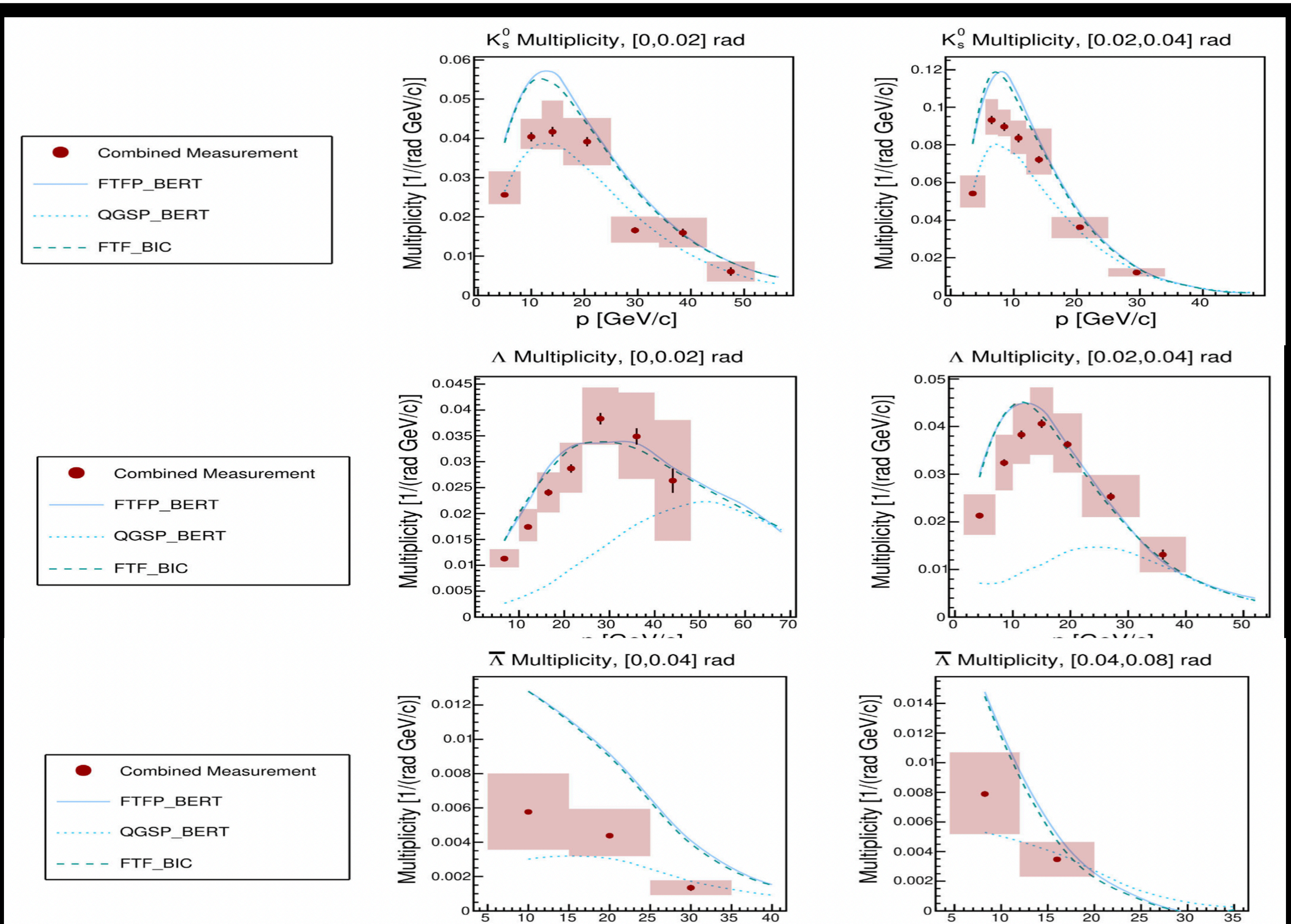


K^0_S invariant mass fits



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

Neutral hadron multiplicity measurements published last year



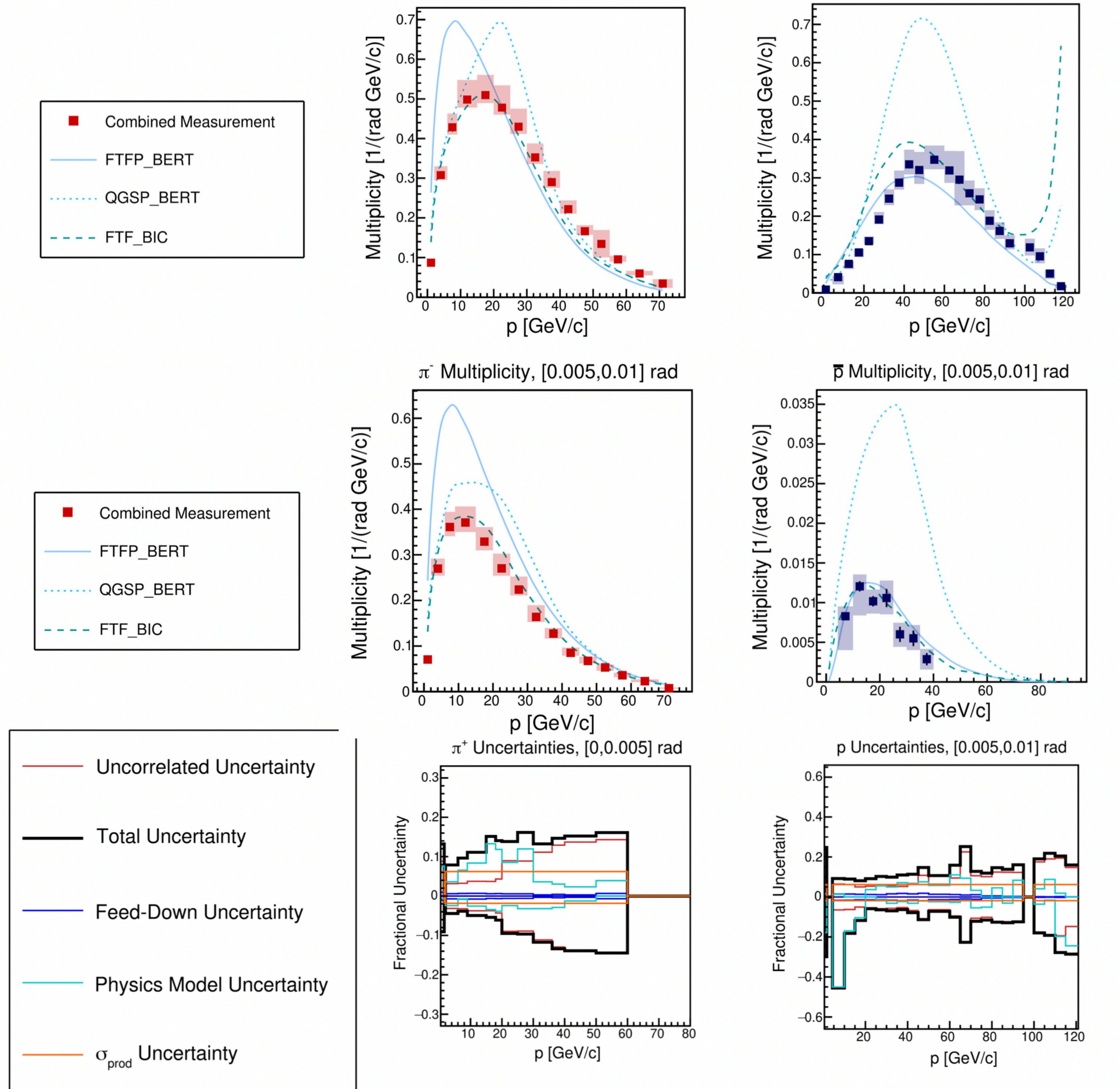
PHYSICAL REVIEW D 107, 072004 (2023)

- 2016 and 2017 combined to optimize resolution while increasing phase space coverage

Charged hadron multiplicities: published last year

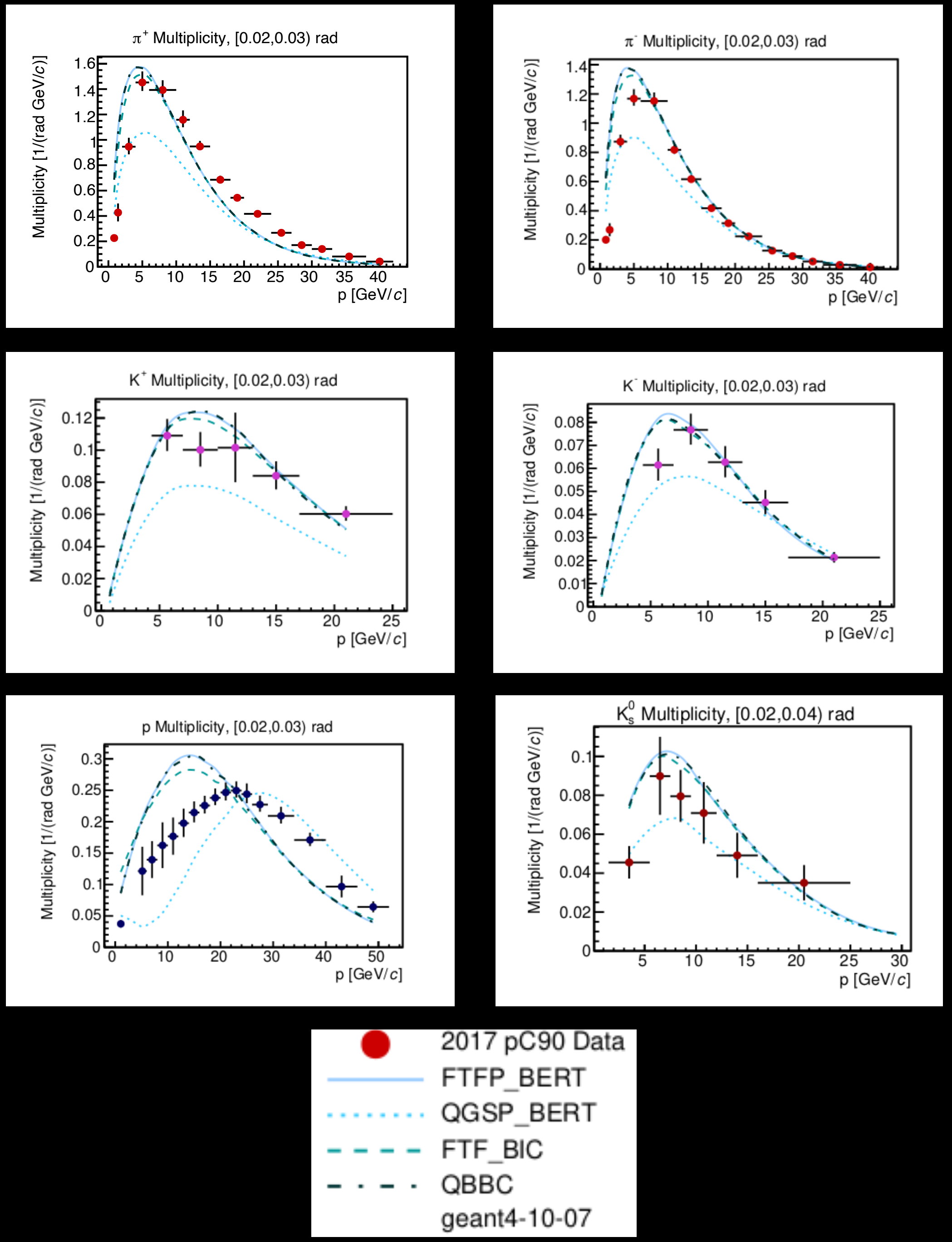
- Measured multiplicities: π⁺, π⁻, p, p̄, K⁺, K⁻
- Neutral hadron multiplicities used to estimate backgrounds from with weak neutral decay products
- Two complementary data sets again combined for final multiplicity result
- Results will soon be used to reduce DUNE beam flux uncertainties
- 2016, 2017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

PHYSICAL REVIEW D 108, 0720-013 (2023)



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, $\bar{\Lambda}$



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

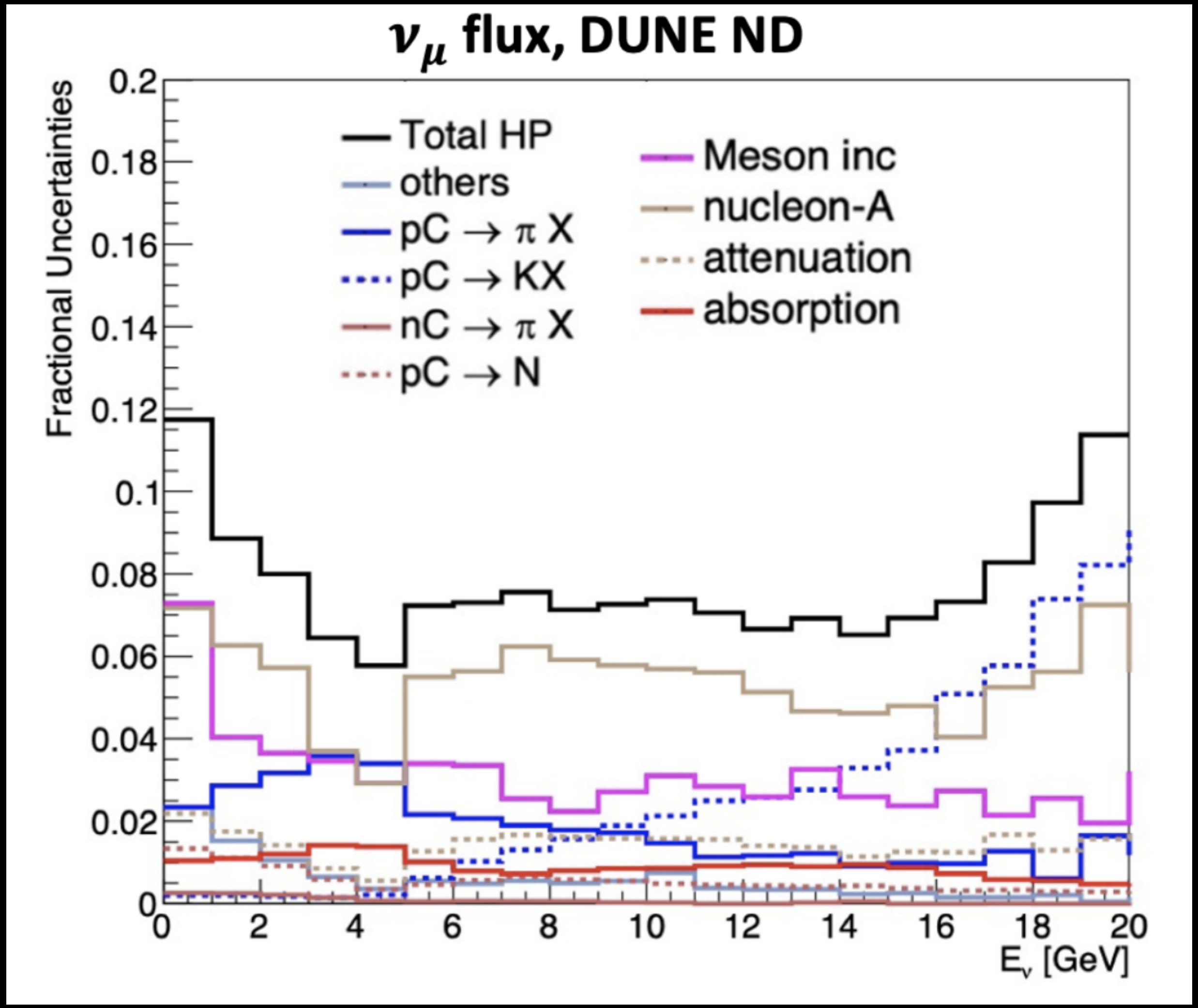
L. Ren

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

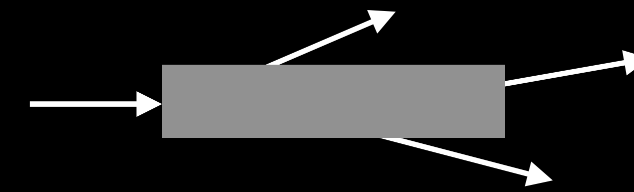
NA61 p+C 120 GeV/c results can address the red items

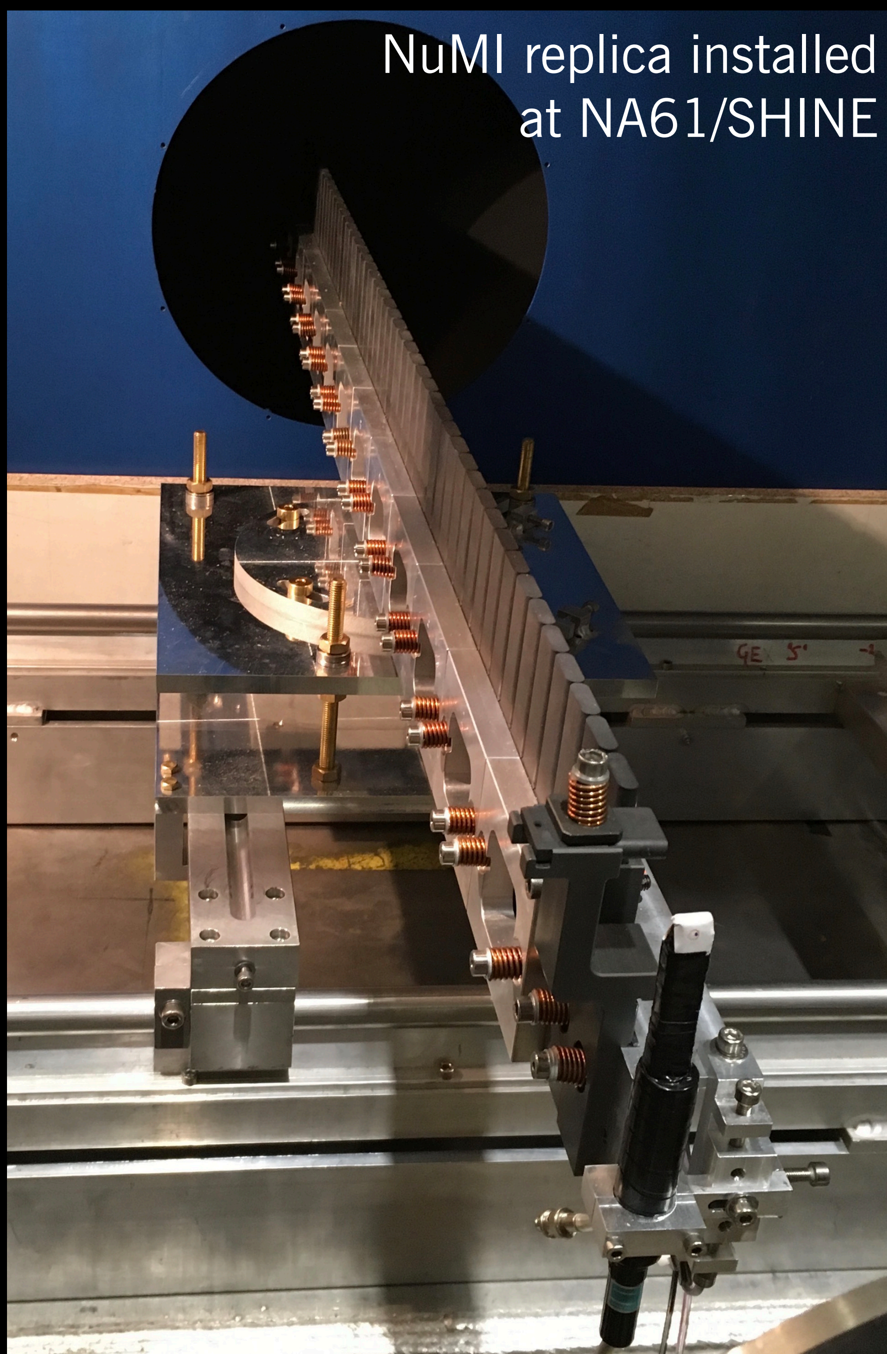
Current PPFX uncertainty using data sets scaled to NuMI parameters



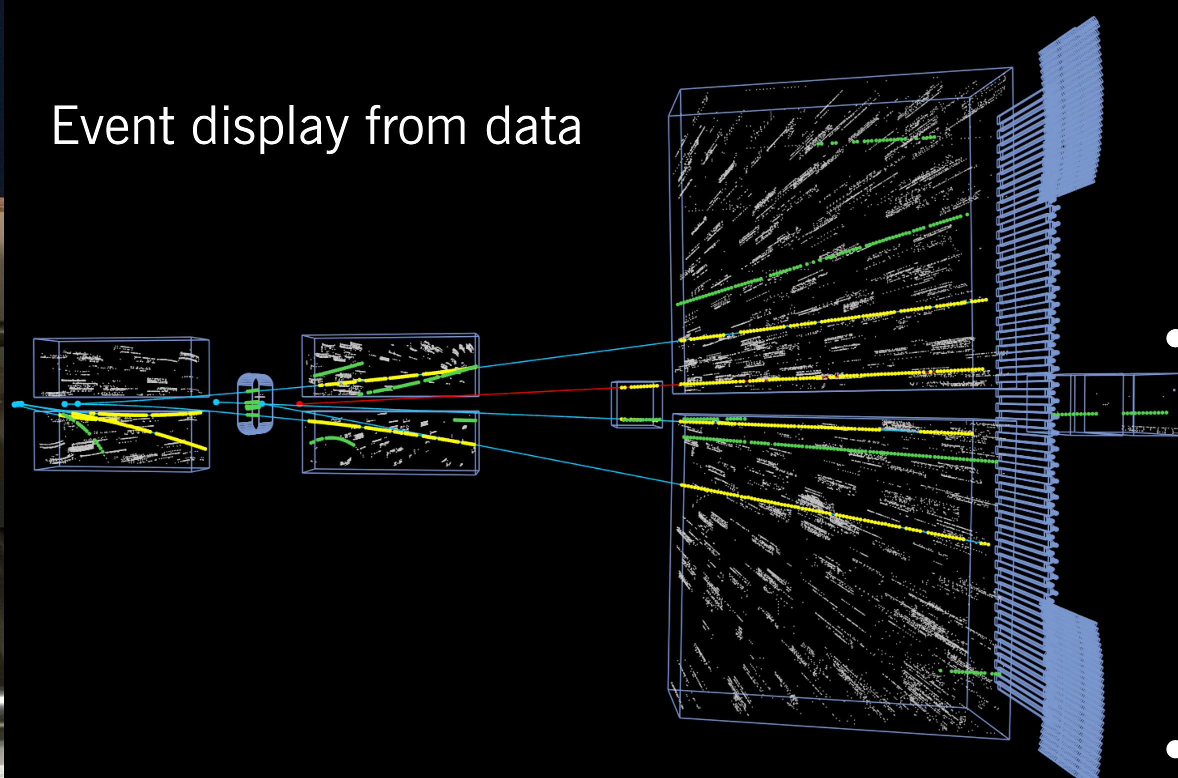
Expect updated PPFX predictions in a few months!

Coming soon: measurements with NuMI replica target





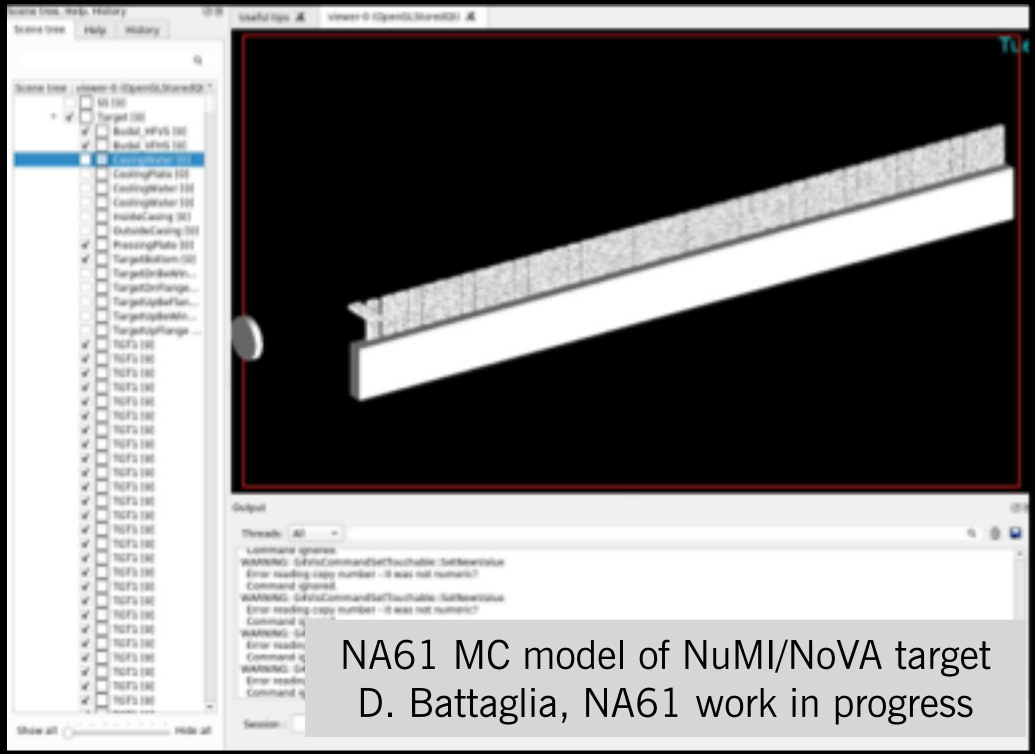
Event display from data



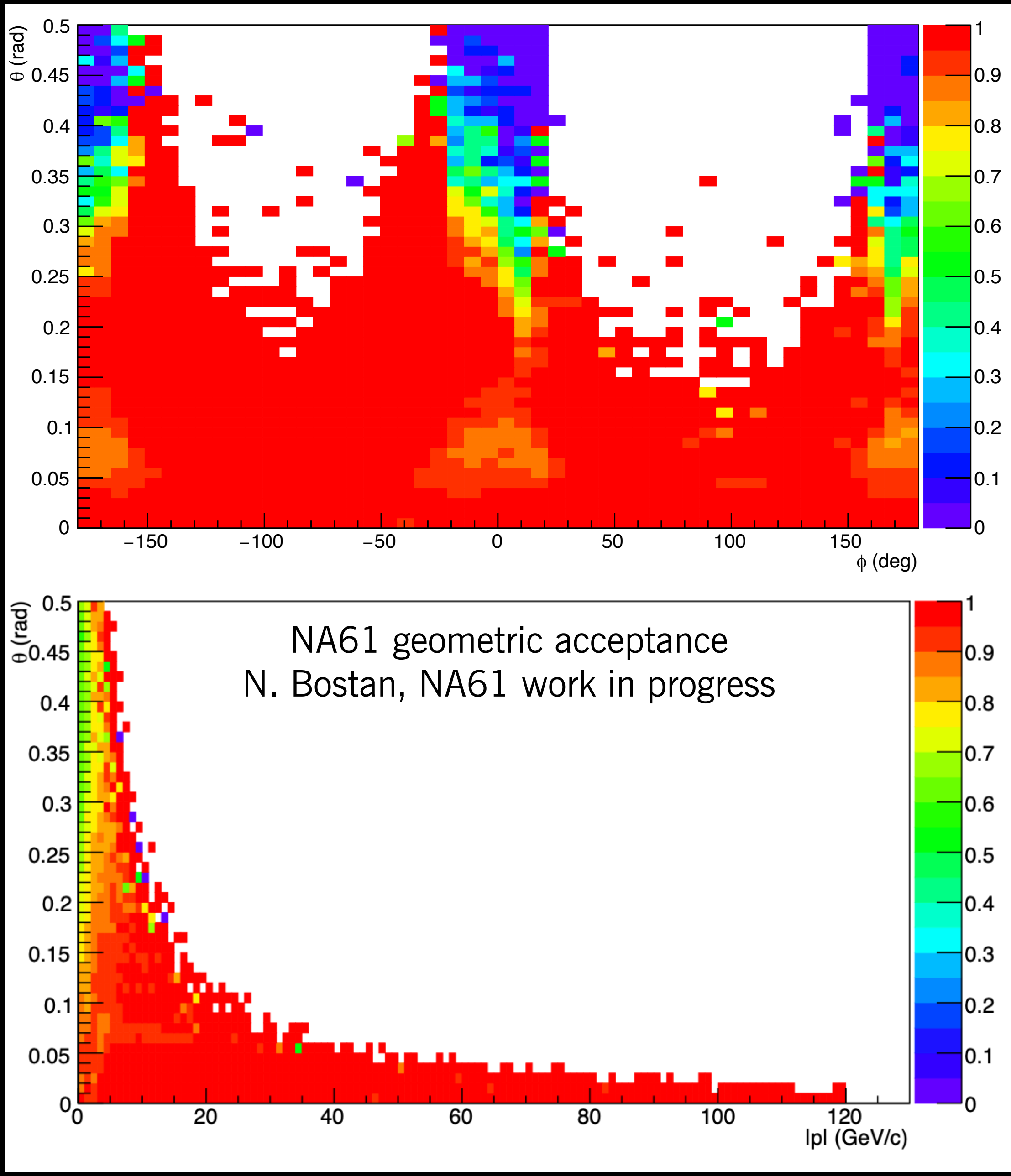
- Took high statistics (18M events) in 2018 with 120 GeV protons
- Analysis underway on hadron yields from this target
- Calibration in progress for this data set

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!

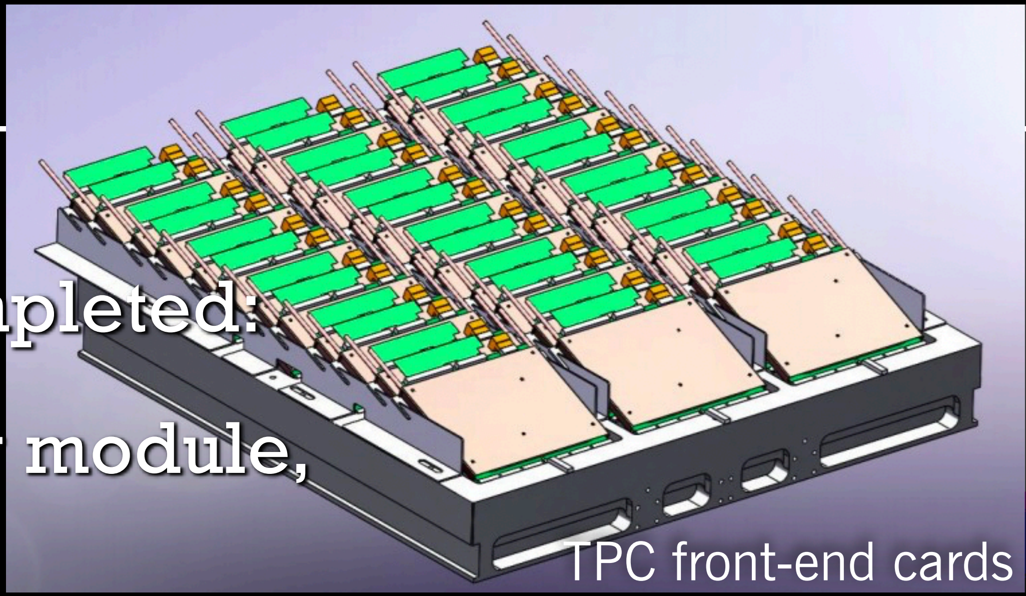


NA61 MC model of NuMI/NoVA target
D. Battaglia, NA61 work in progress



NA61 geometric acceptance
N. Bostan, 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

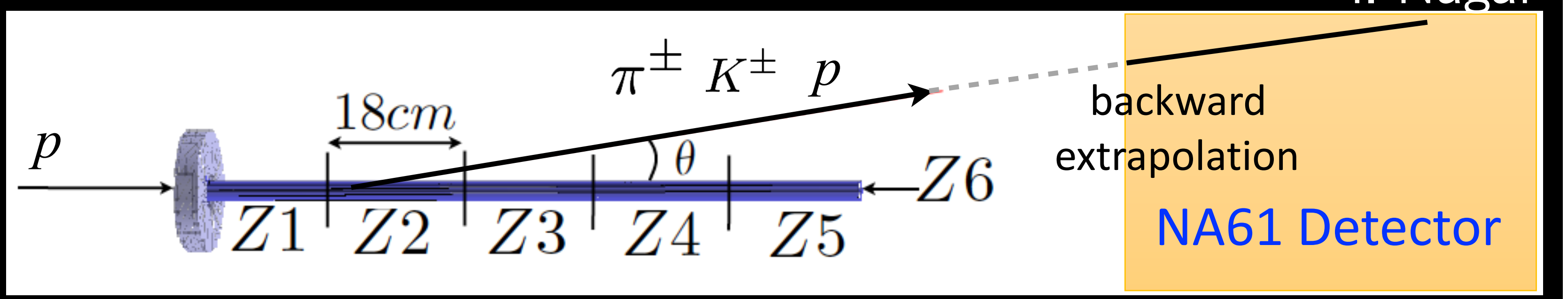
- **Data collection is underway!**
  - 31 GeV/c protons on T2K replica-target: collected 180M events (nearly 20x 2010 statistics) to measure high-momentum kaon yields
  - Kaon scattering with thin targets for secondary interaction modeling. In 2023, took:
    - K+C @ 60GeV: 137.7 M
  - Higher statistics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

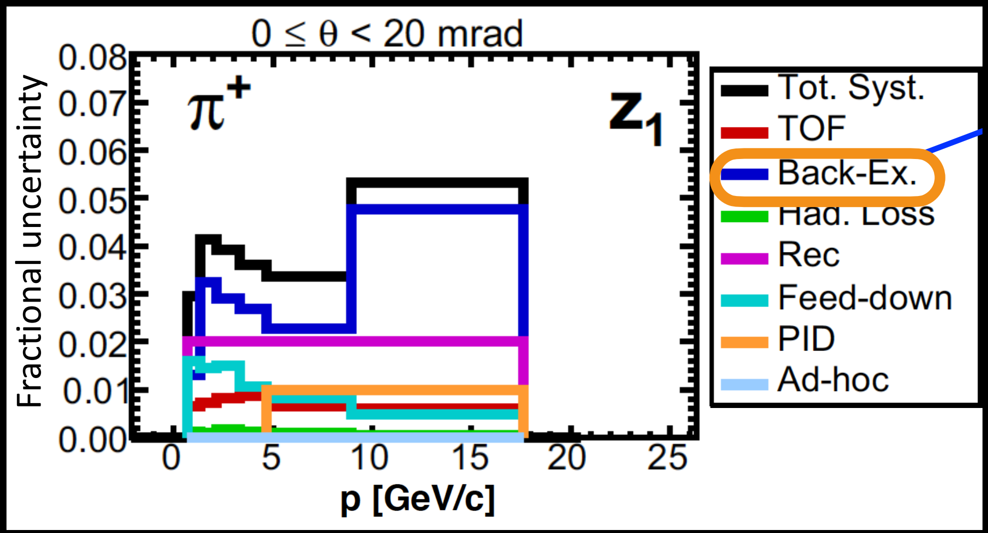
Data collection: now and near future

- LBNF/DUNE prototype target (2024)
- Target designed and built by RAL targetry group to expected dimensions of LBNF/DUNE target: 1.5 m long
  - Took 250M events summer 2024
  - 2025 data: exploring most useful configuration; may run with partial target

Long-target tracker

Y. Nagai

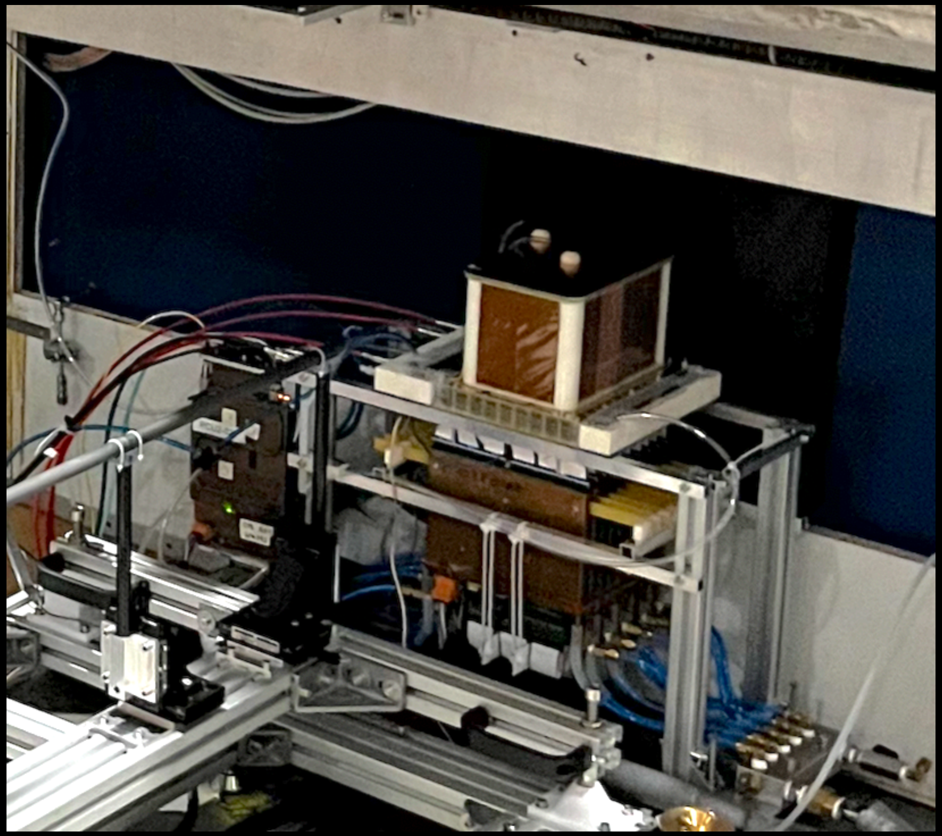




- A leading systematic error with the T2K replica target has been extrapolation of shallow-angle tracks backward to the target surface

- Additional small TPC built at KFKI/Wigner in Budapest

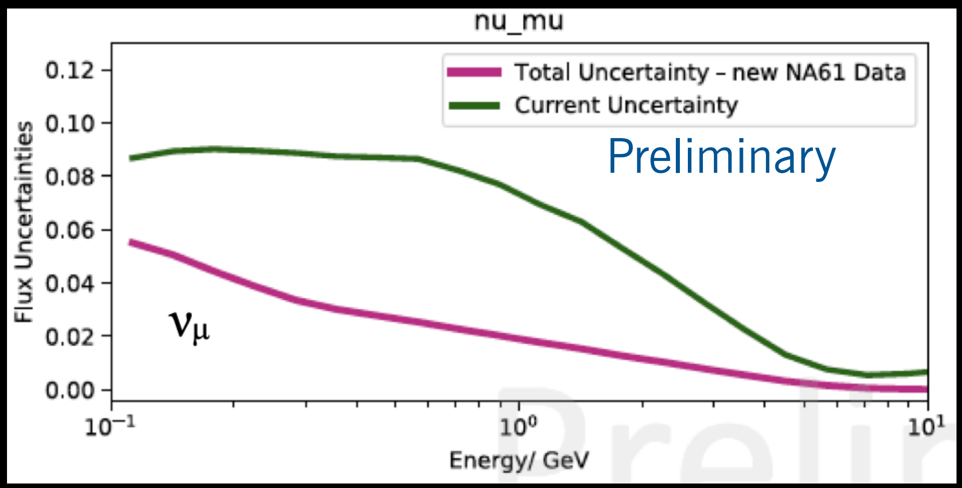
  - Sits at the end of the target to measure exit point of tracks more precisely



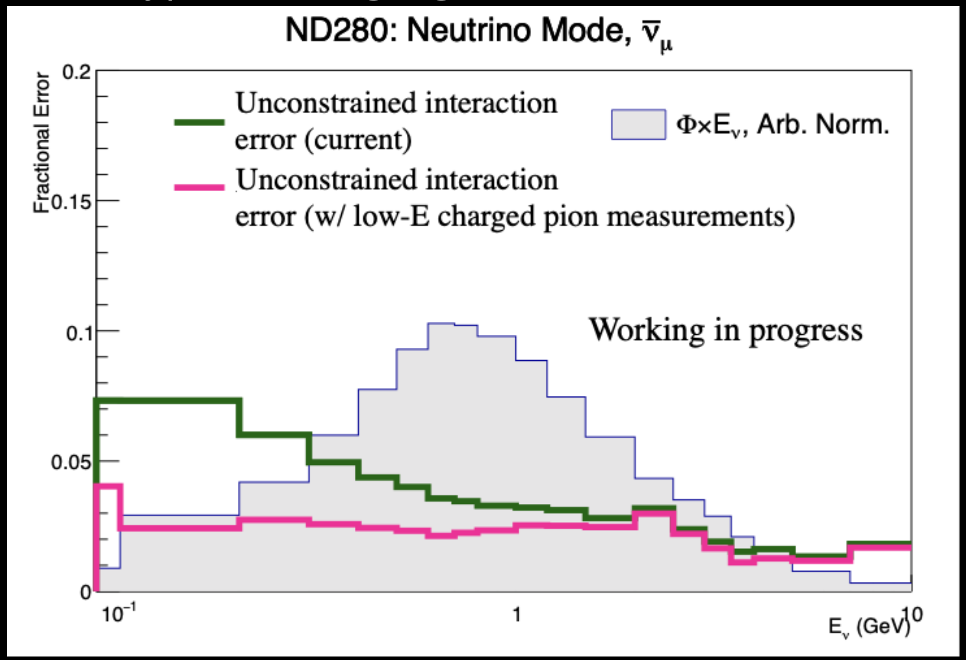
Future after 2025: low-energy beam?

- 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…

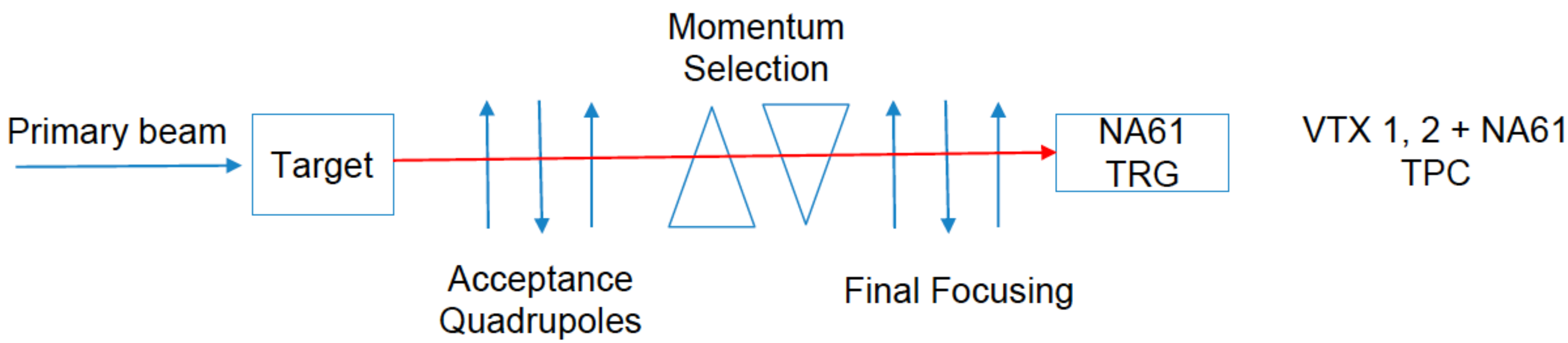
L. Cook (Bartol Group) atmospheric neutrino flux

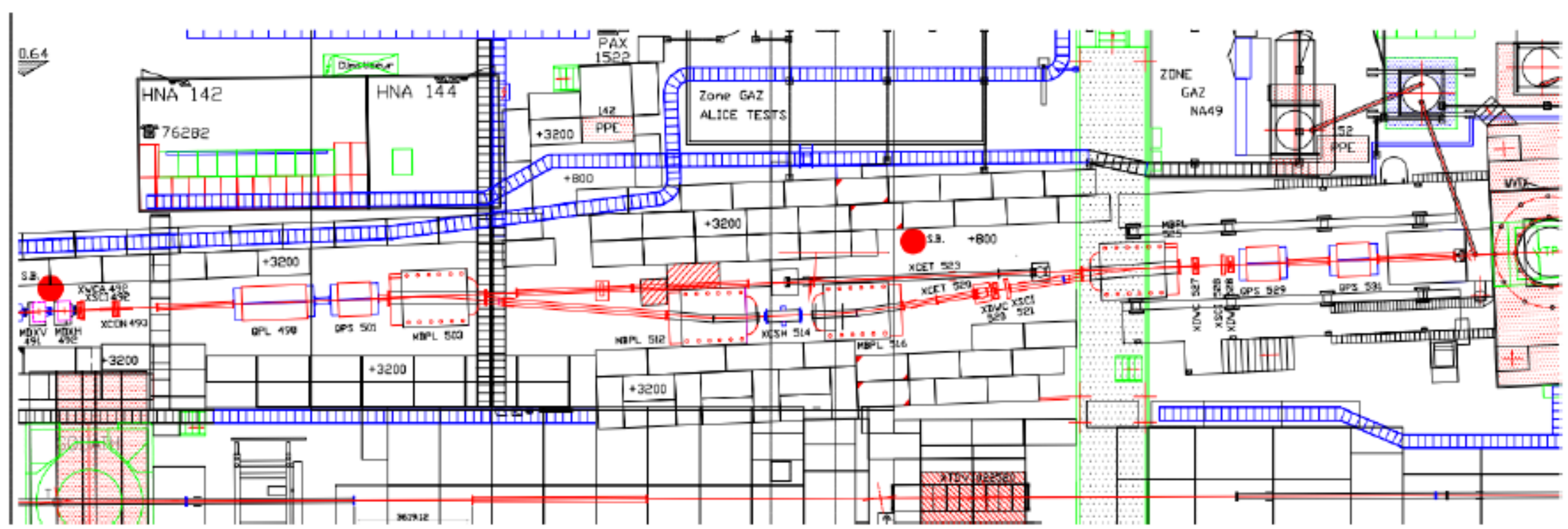


T2K/HyperK wrong-sign flux uncertainties



Principle of a low-energy beam for NA61/SHINE





A low energy beam was there in ~2000 (NA49 times) serving CMS downstream.

C. A. Mussolini, N. Charitonidis

- 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!

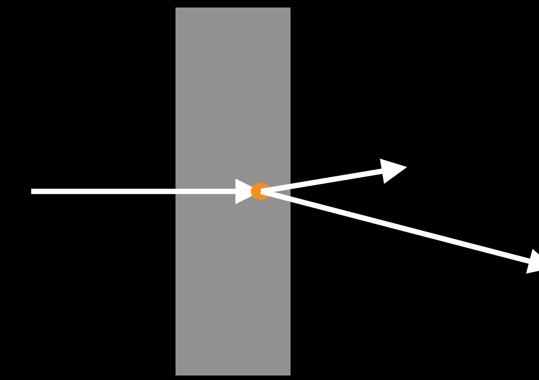
Conclusions

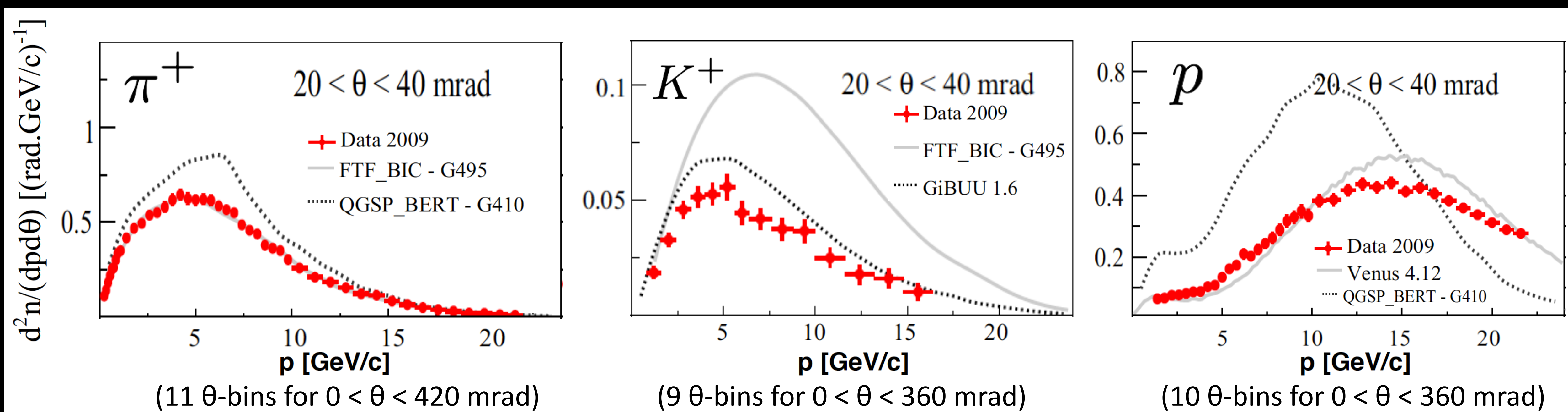
- NA61/SHINE has provided unique and critical data to support the global neutrino program
- Efforts have reduced T2K's flux errors by factors of 4+
- A new set of analyses is coming out, geared toward the current Fermilab program
- Took data summer 2024 with LBNF/DUNE prototype target
- Low-energy beam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

Speaker supported by US Department of Energy

BACKUP

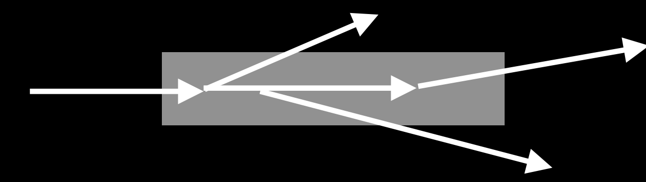
Thin-target results:
p+C @ 30 GeV





- One angle bin shown here for illustration
- MC generators fail badly for kaons and protons
- Published in Eur. Phys. J. **C76** 84 (2016): also contains yields of negative particles and neutral strange particles (V^0).

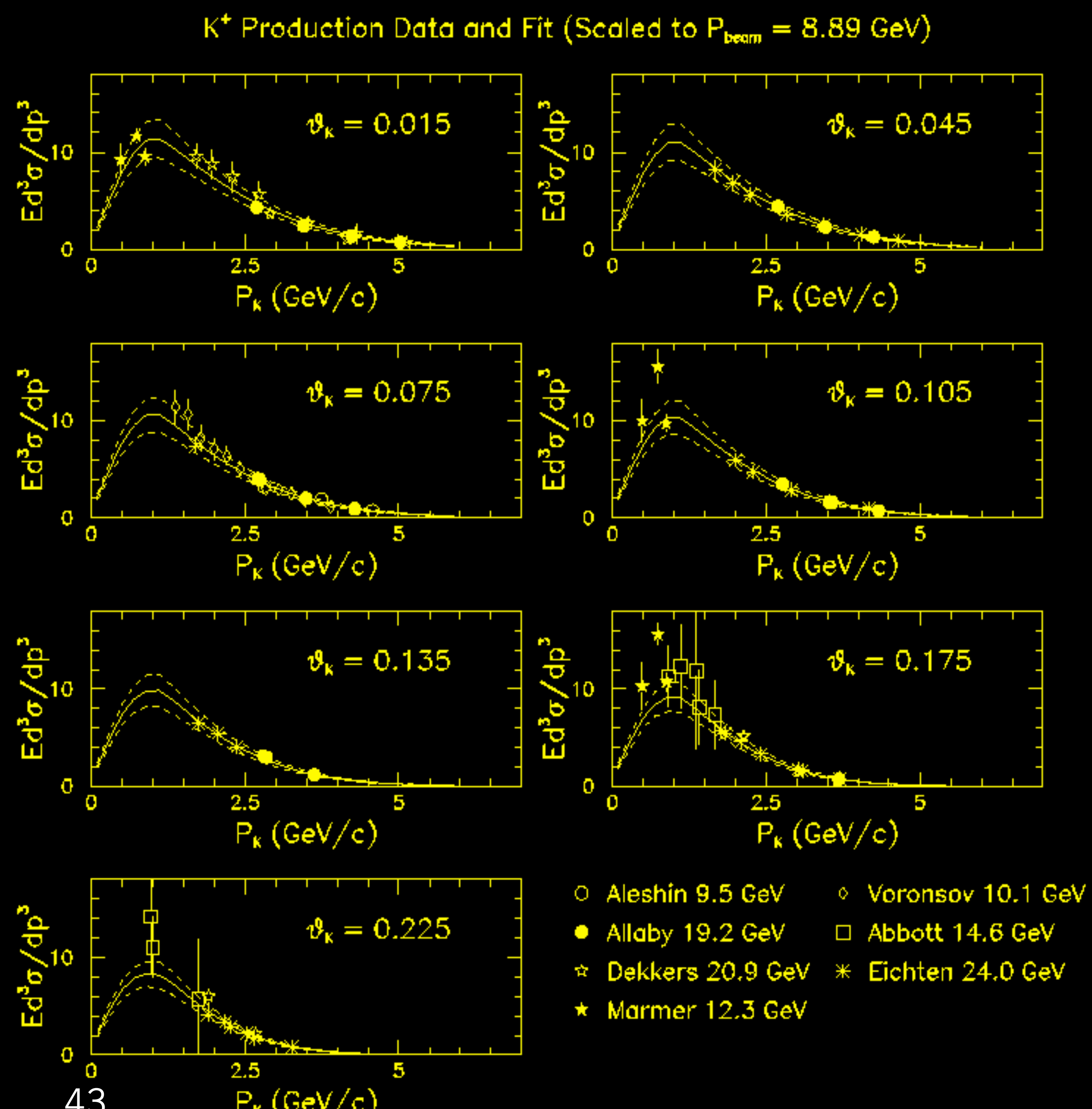
Replica-target measurements



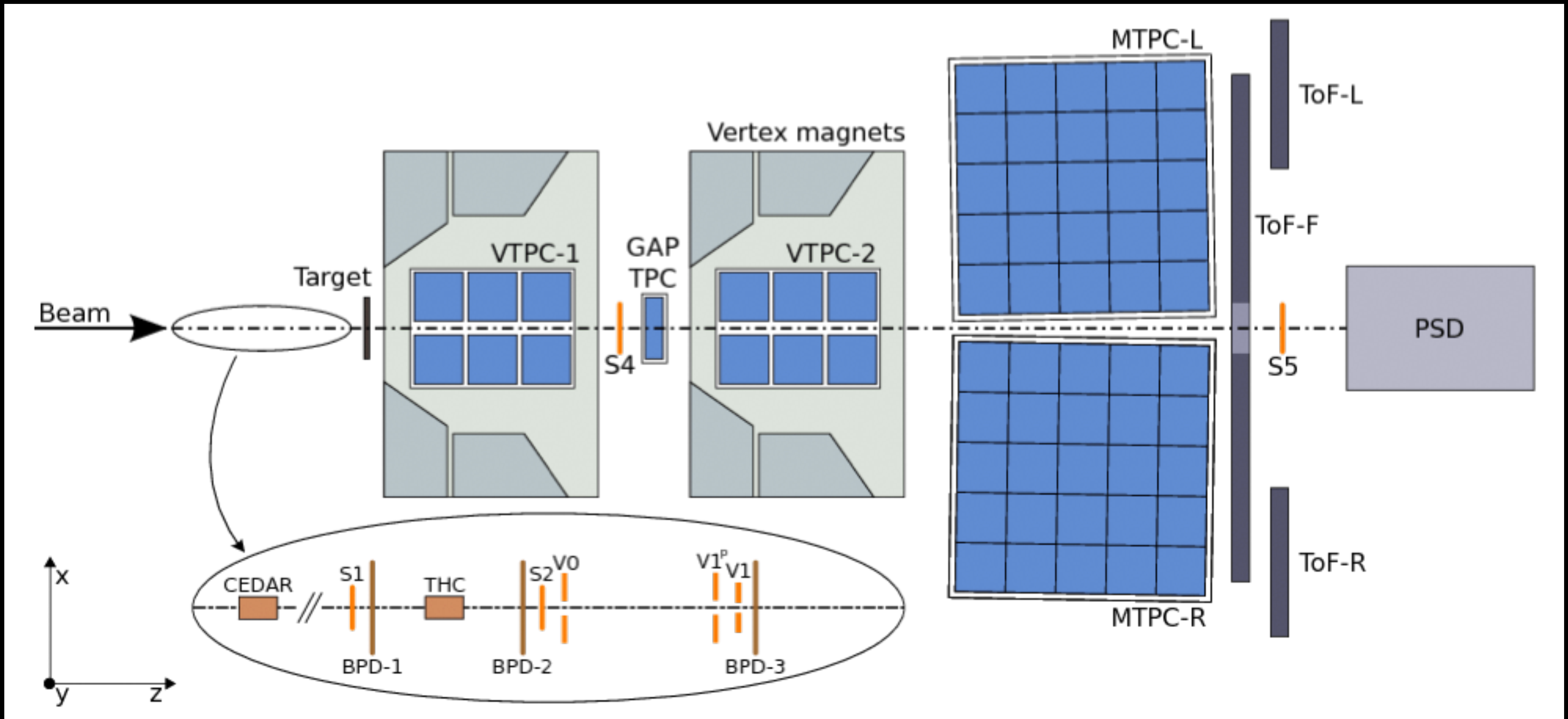
- Exact target geometry of a particular neutrino beam (T2K: 90cm cylinder, NuMI/NOvA: 120cm of graphite fins)
- Most events have primary and secondary interactions in the target
- Measure particle yields vs not only p and θ, but also exit z along target (and possibly ϕ for targets like NuMI's that aren't cylindrically symmetric)
- Also measure beam particle survival as additional constraint on σ_{prod}
- In neutrino beam MC, apply weights to particles at surface of target in the simulation

External measurements of meson production

- Until recently, depended on fits to multiple measurements at different labs with different beam energies
- These measurements were made many years ago for other purposes, and had varying applicability to neutrino beams
- Significant issues with combining systematic errors across very different experiments
- Model dependence in extrapolating from different energies, target nuclei



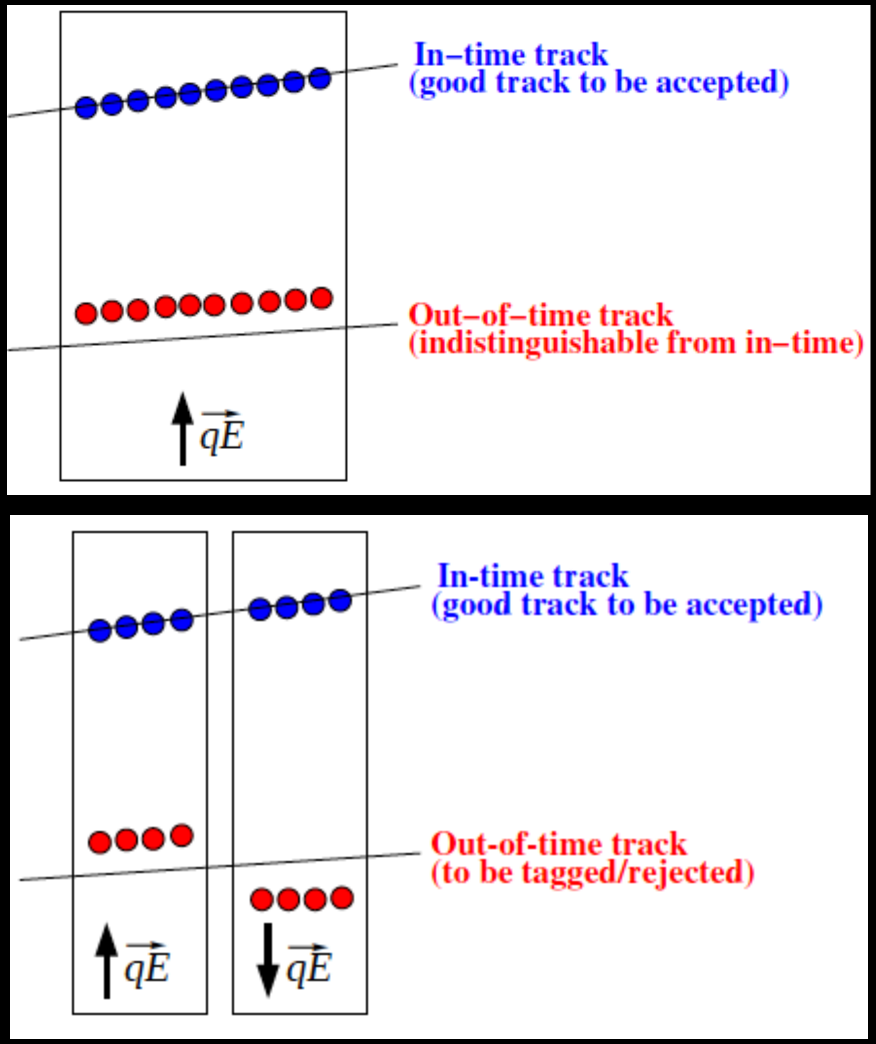
NA61 acceptance



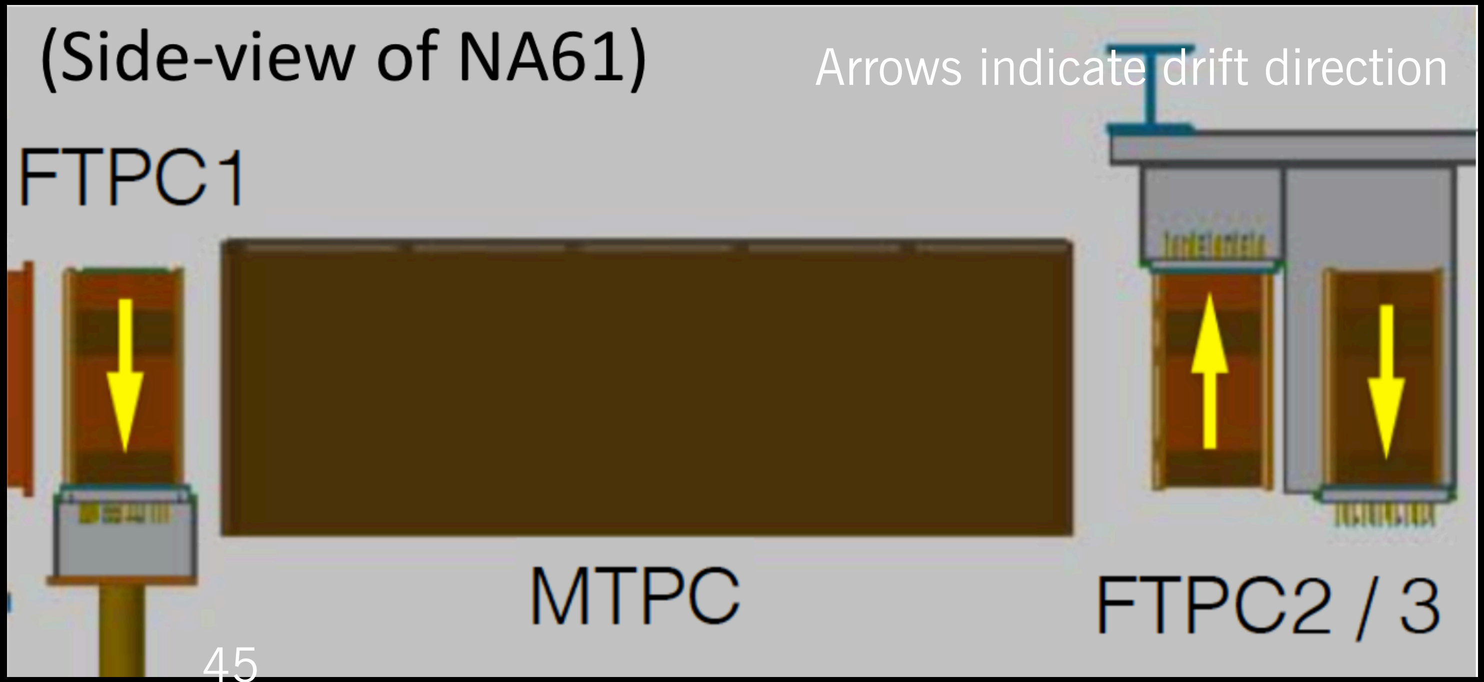
- NA61 setup before 2017 had a hole in the acceptance where the beam passes through
- Hole due to heavy ion needs: intense beam can't go through chambers

Forward TPCs

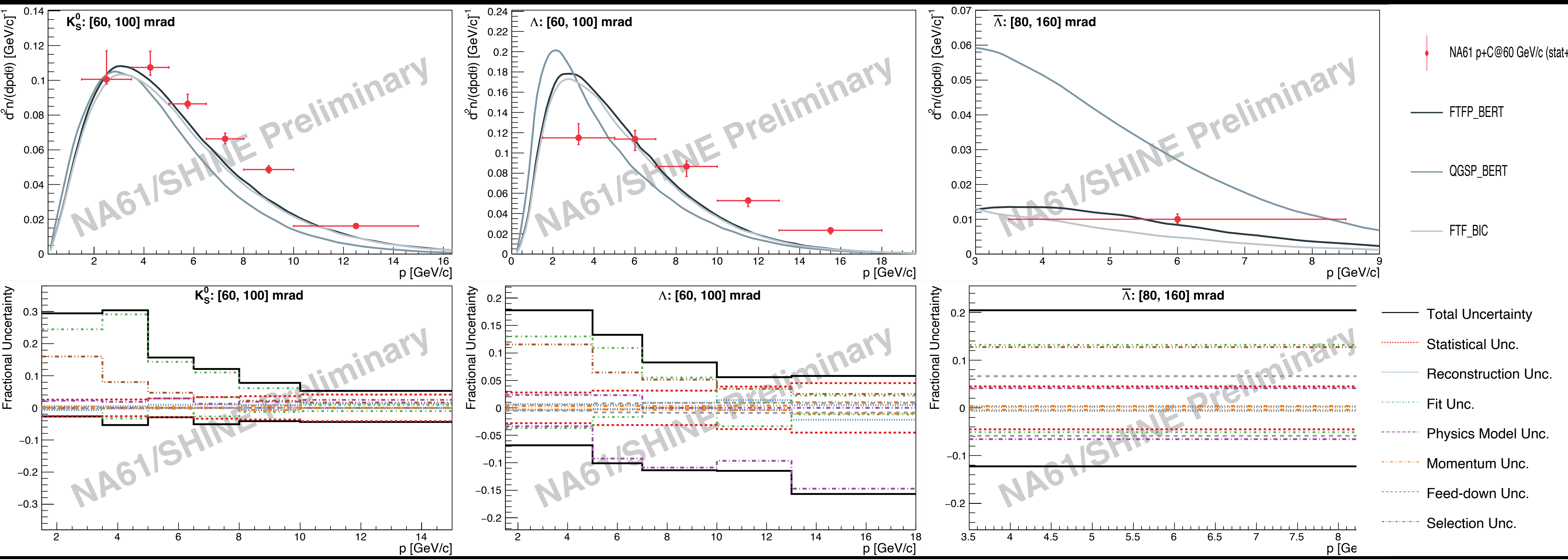
- New TPCs have been built for the neutrino program to fill the hole and complete the acceptance in the forward region
- Low-mass design with light plastic frame and thin printed Kapton field cage; FTPC1 removable for heavy-ion running
- Uses same electronics as other TPCs
- High rates in beam region drove development of new "Tandem TPC" concept. Paper published JINST 15 (07), P07013



- Out-of-time tracks in a TPC are reconstructed as shifted in drift direction
- Successive field volumes have opposite drift direction: out-of-time tracks appear discontinuous and can be easily rejected

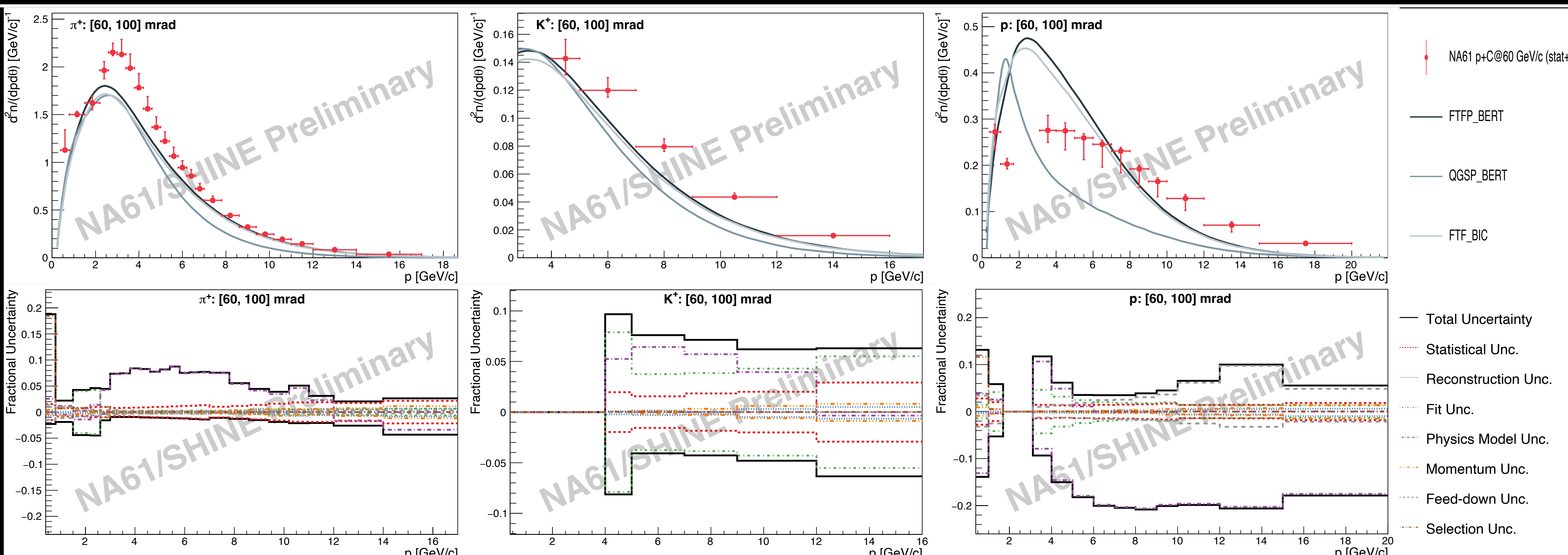


New! p+C and p+Al @ 60 GeV/c



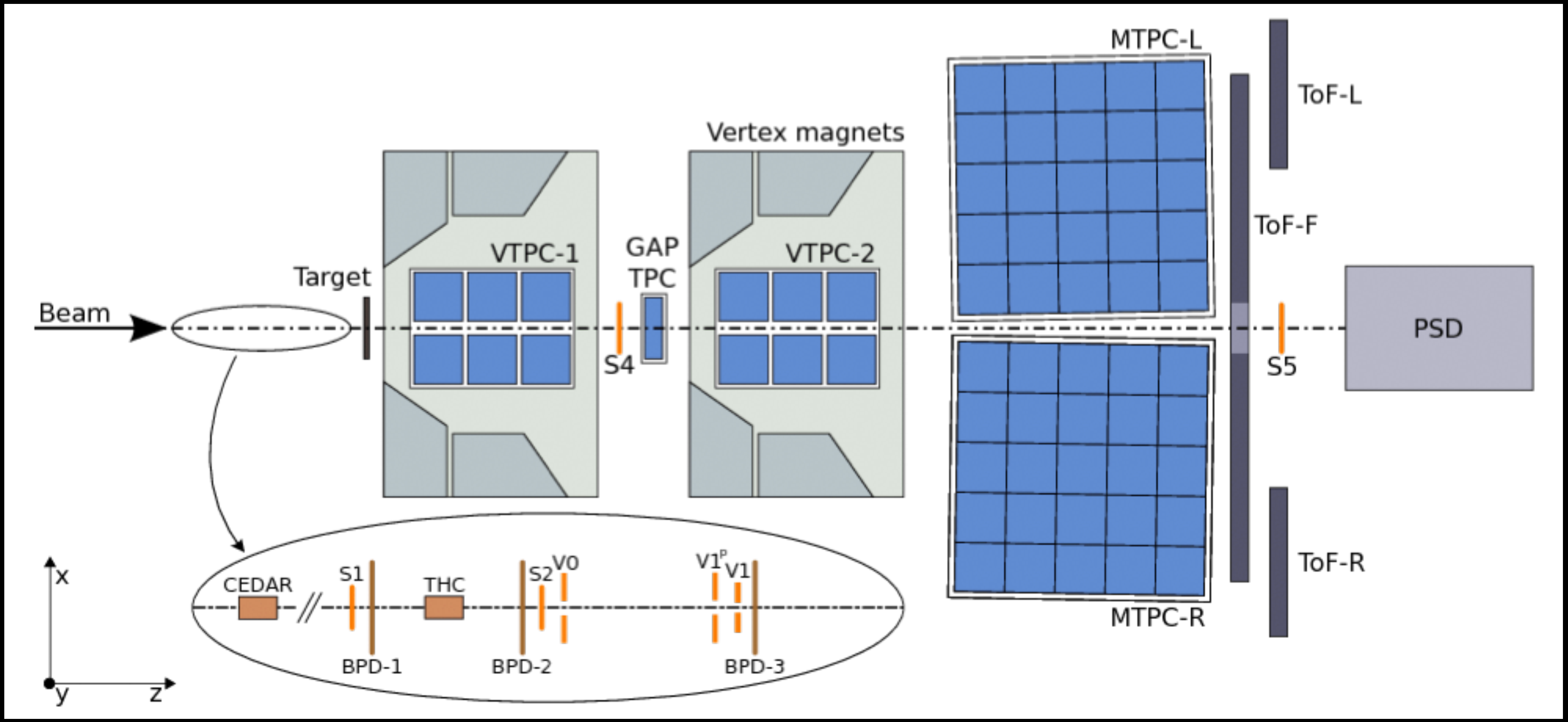
- K^0_S, Λ, $\bar{\Lambda}$ spectra from p+C @ 60 GeV/c
- Showing one angle bin

New! p+C and p+Al @ 60 GeV/c



- π+, K^+, p spectra from p+C @ 60 GeV/c
- Showing one angle bin

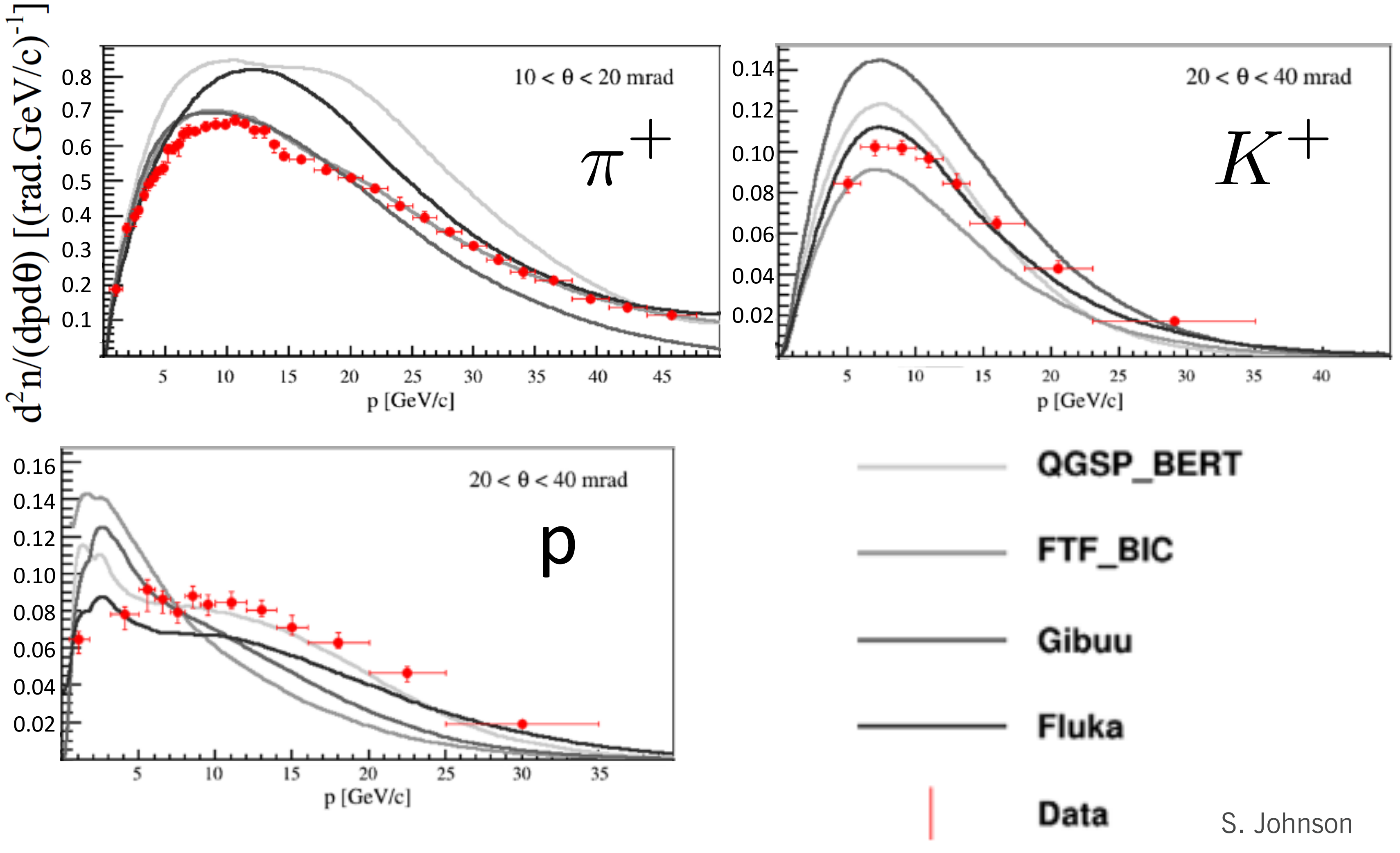
NA61 acceptance



- NA61 setup before 2017 had a hole in the acceptance where the beam passes through
- Hole due to heavy ion needs: intense beam can't go through chambers

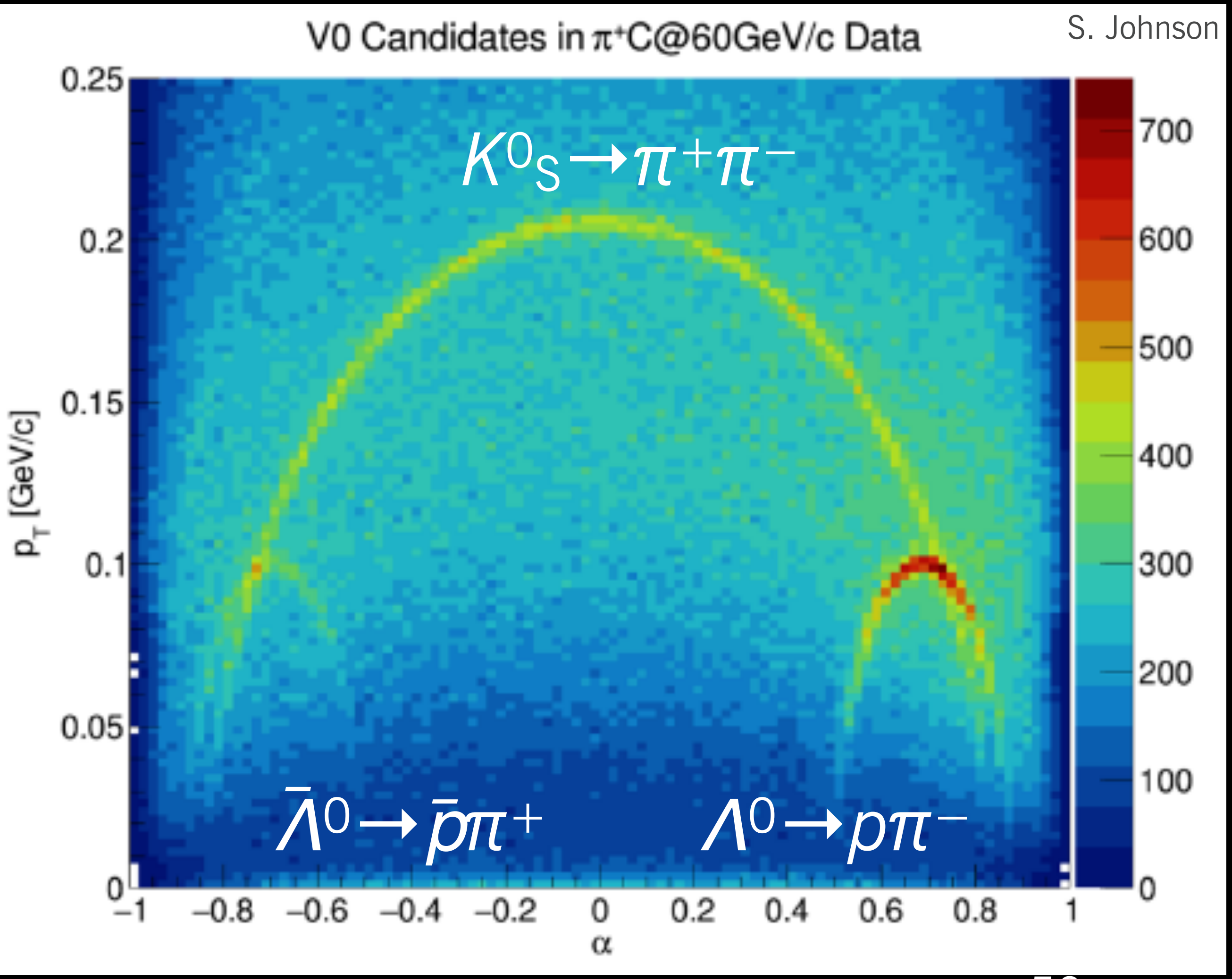
Thin-target charged hadron spectra

- Example: π^++C @ 60 GeV (Phys.Rev. **D100** 112004 (2019))
- Measured differential production yields (positively-charged shown, also measured negatives)



Thin-target neutral hadron spectra

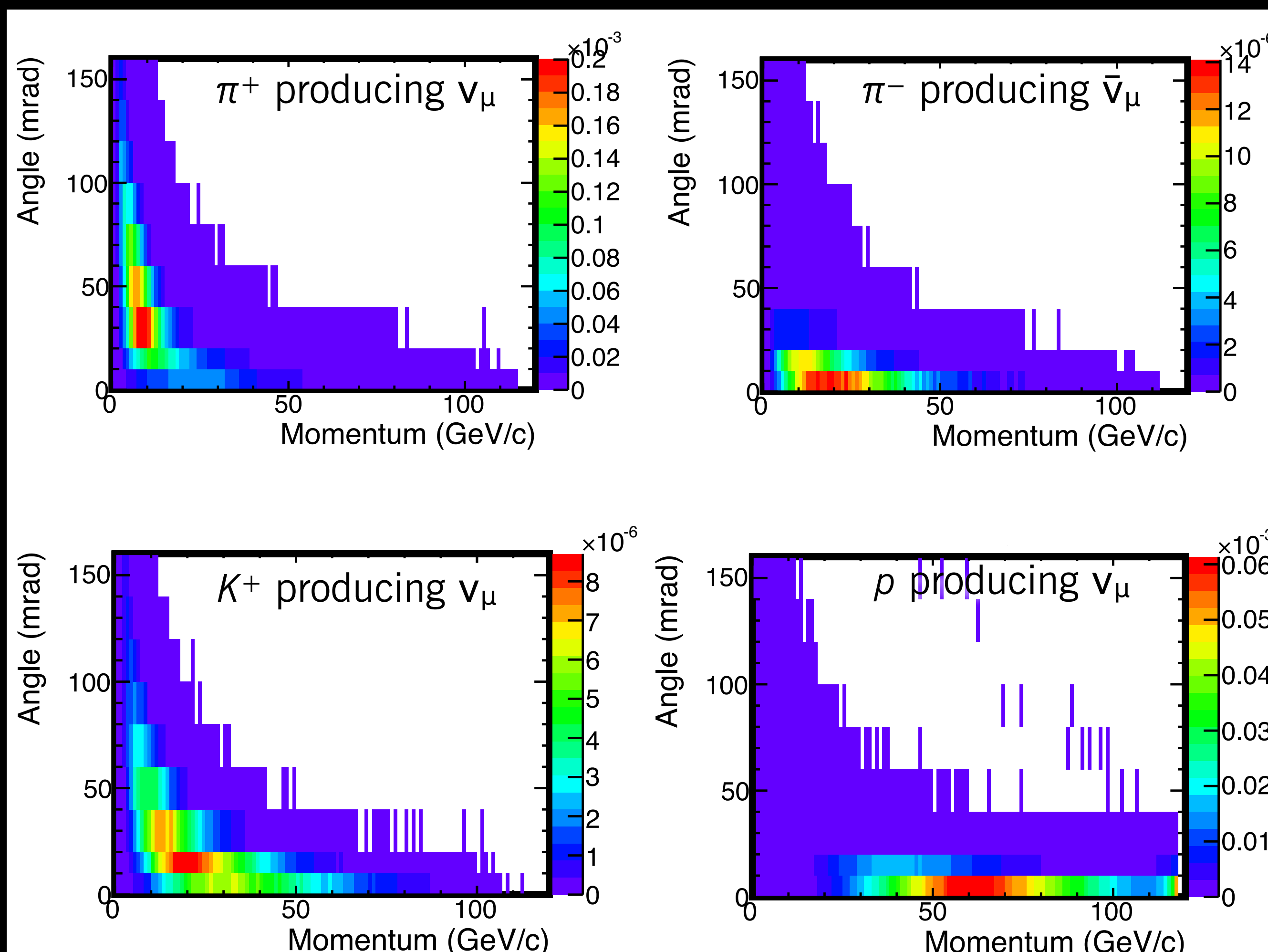
- Analysis of decays in flight using "V^0" events: displaced vertex of two oppositely-charged particles.
- Visualize the events using Armenteros-Podolansky plots

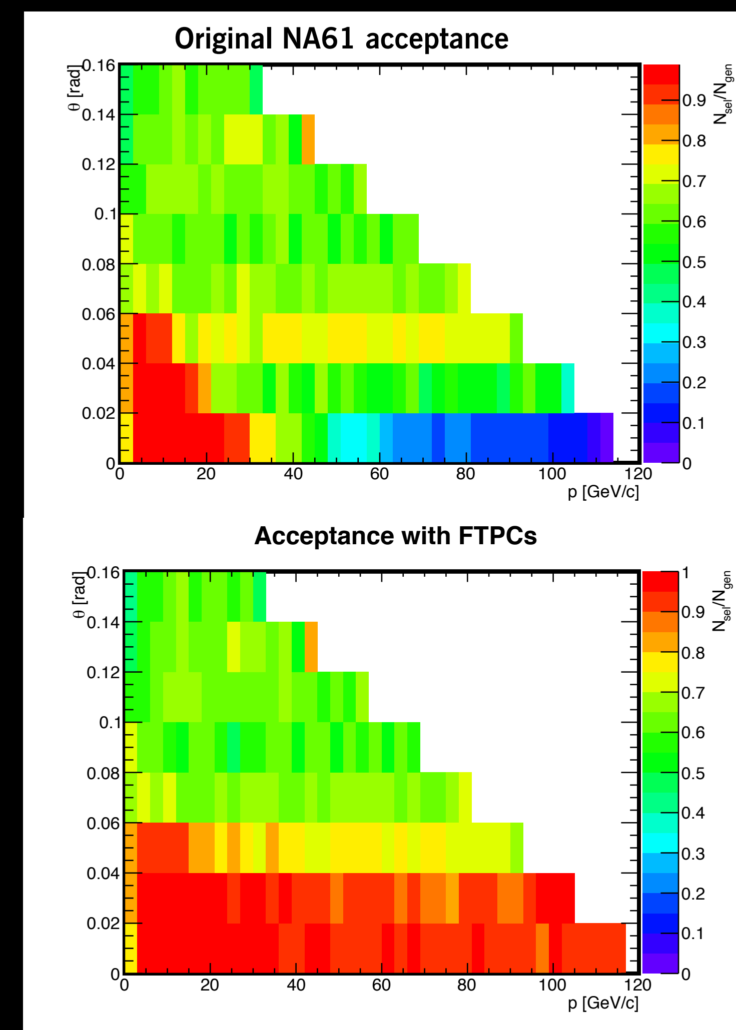


- Plot track p_T vs V trajectory against longitudinal momentum asymmetry of the tracks

$$\alpha \equiv \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$$

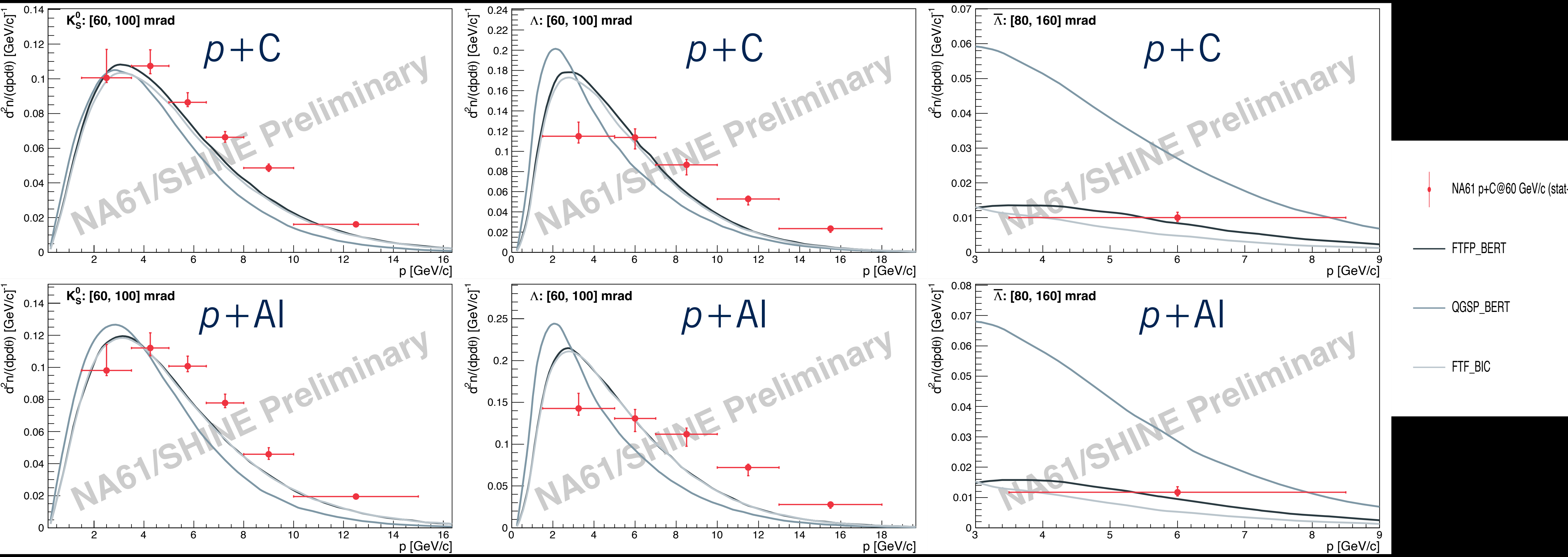
Measurements for LBNF/DUNE flux: acceptance with new FTPCs





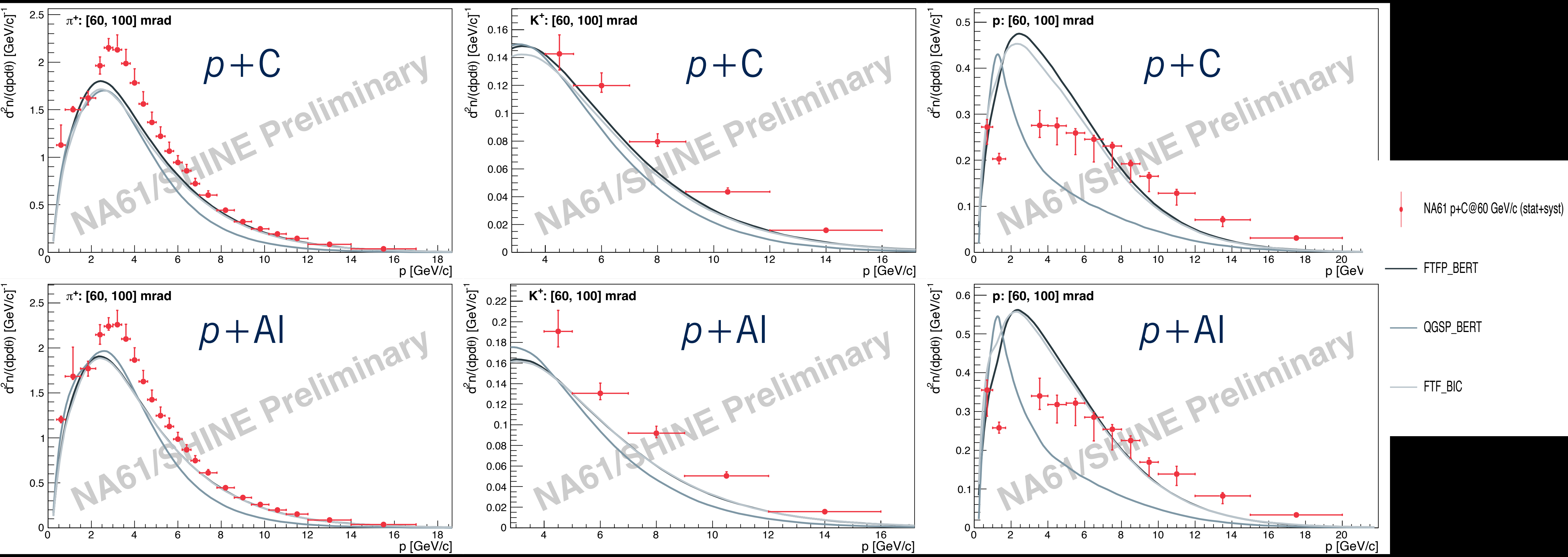
- New forward TPCs make measurements of important secondary protons possible
- Acceptance is now well-matched to secondaries that generate neutrinos in DUNE (and NuMI too!)
- First analysis with new Forward TPCs (120 GeV/c protons on thin graphite target) is expected in the next couple of months

New! p+C and p+Al @ 60 GeV/c



- Left to right: $K^0{}_S$, Λ, $\bar{\Lambda}$ spectra
- Showing one angle bin

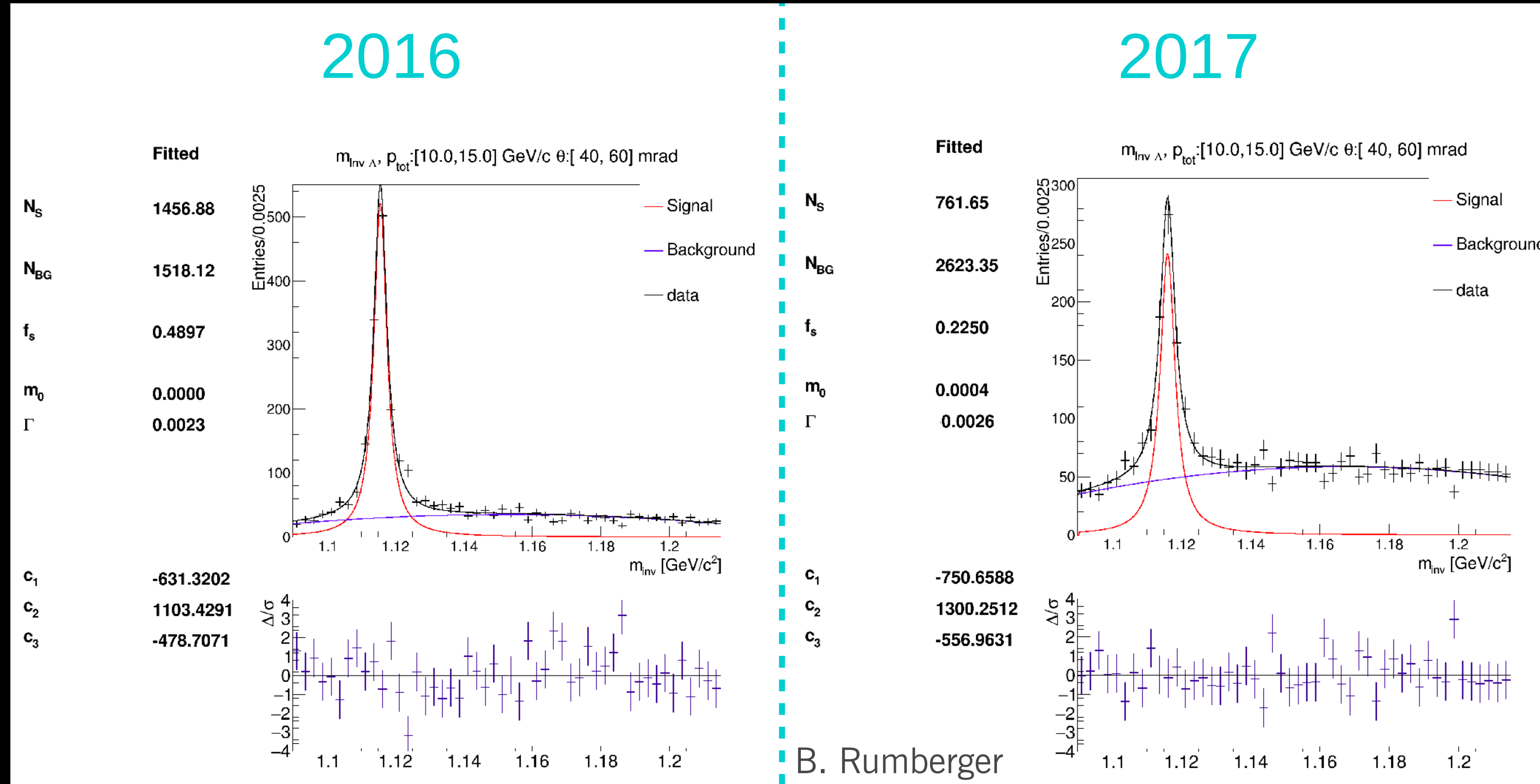
New! p+C and p+Al @ 60 GeV/c



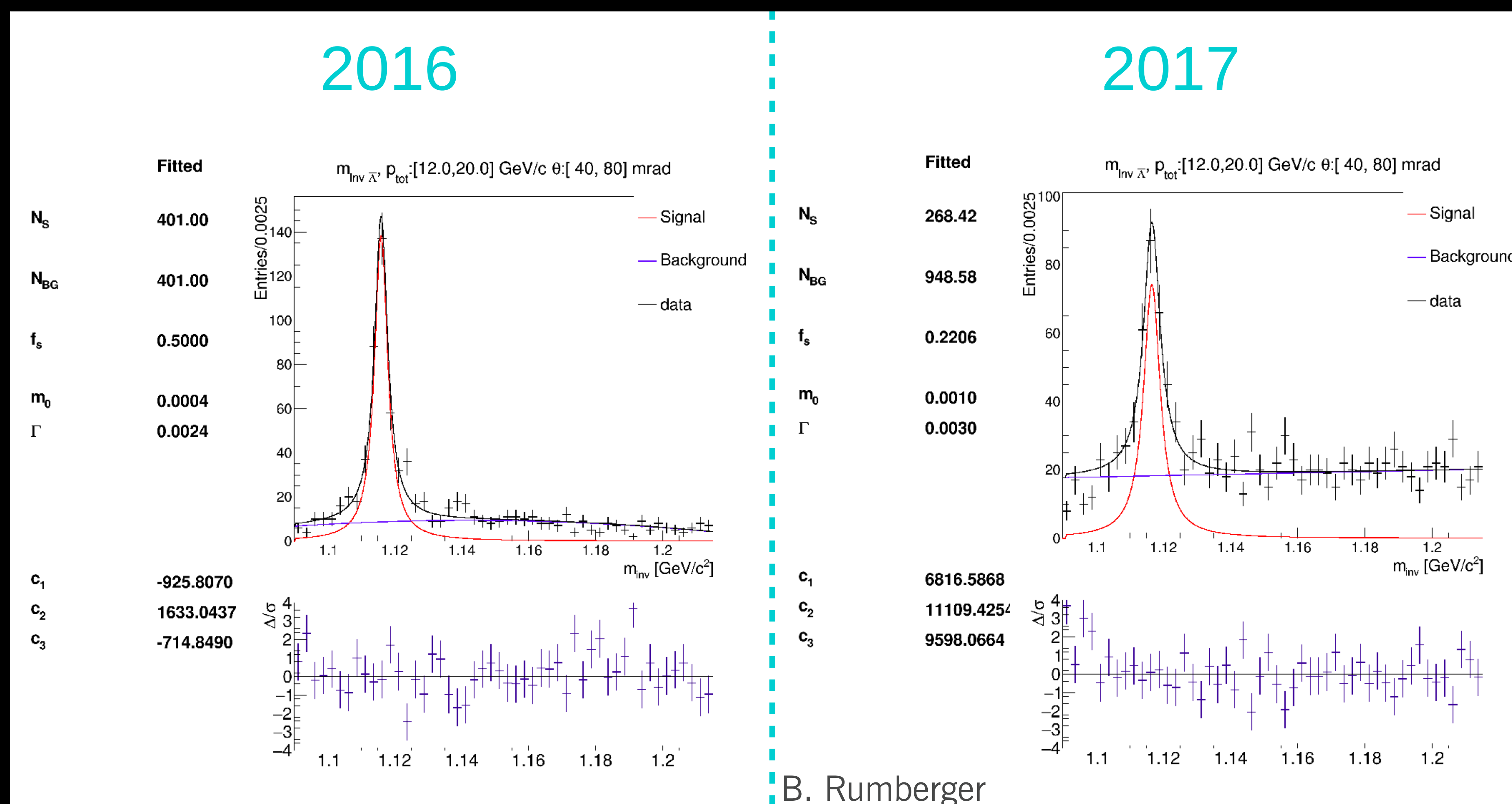
- Left to right: π^+, K^+, p spectra
- Showing one angle bin

120 GeV p+C

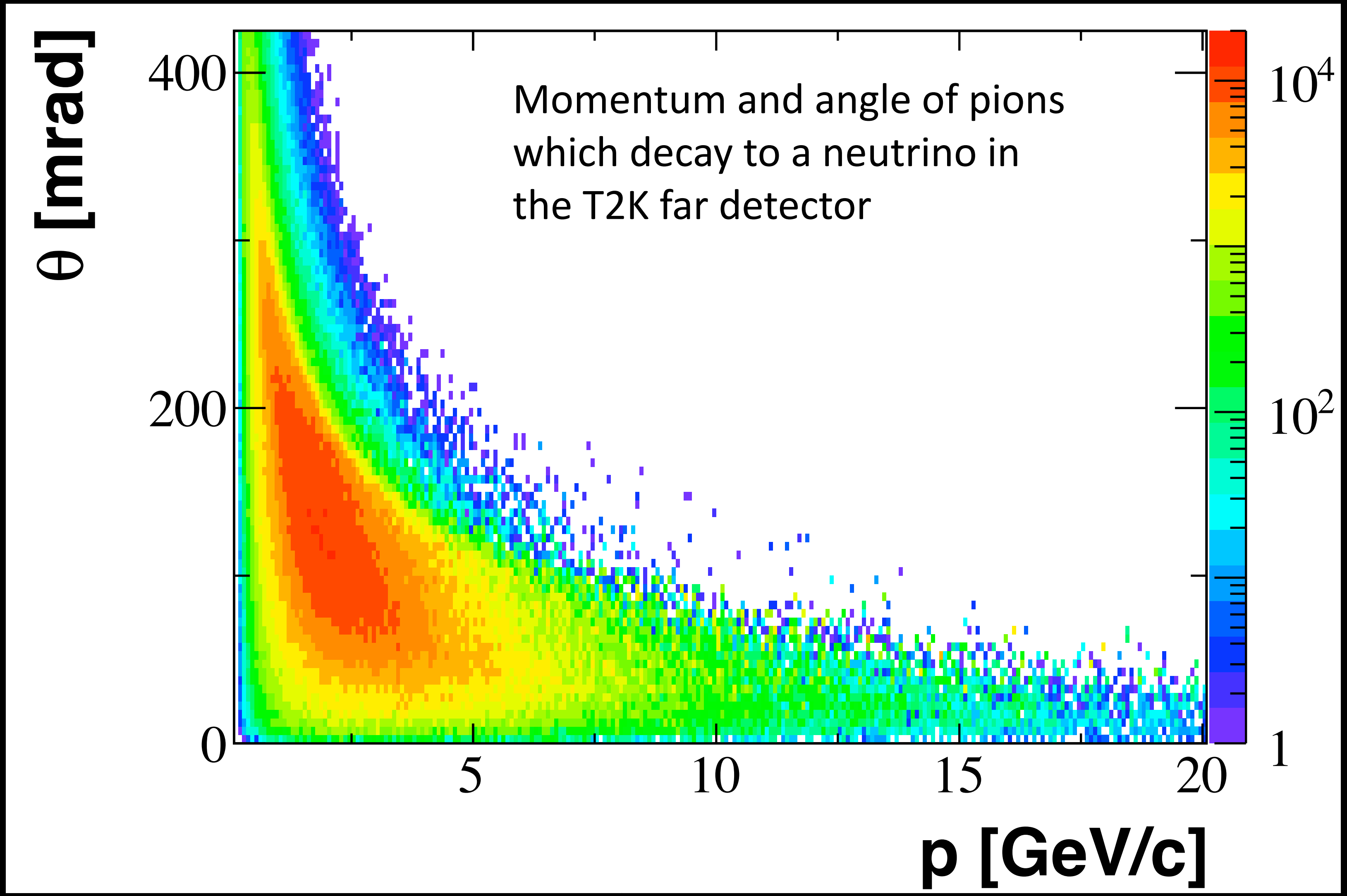
Λ^0



$\bar{\Lambda}^0$



Meson production

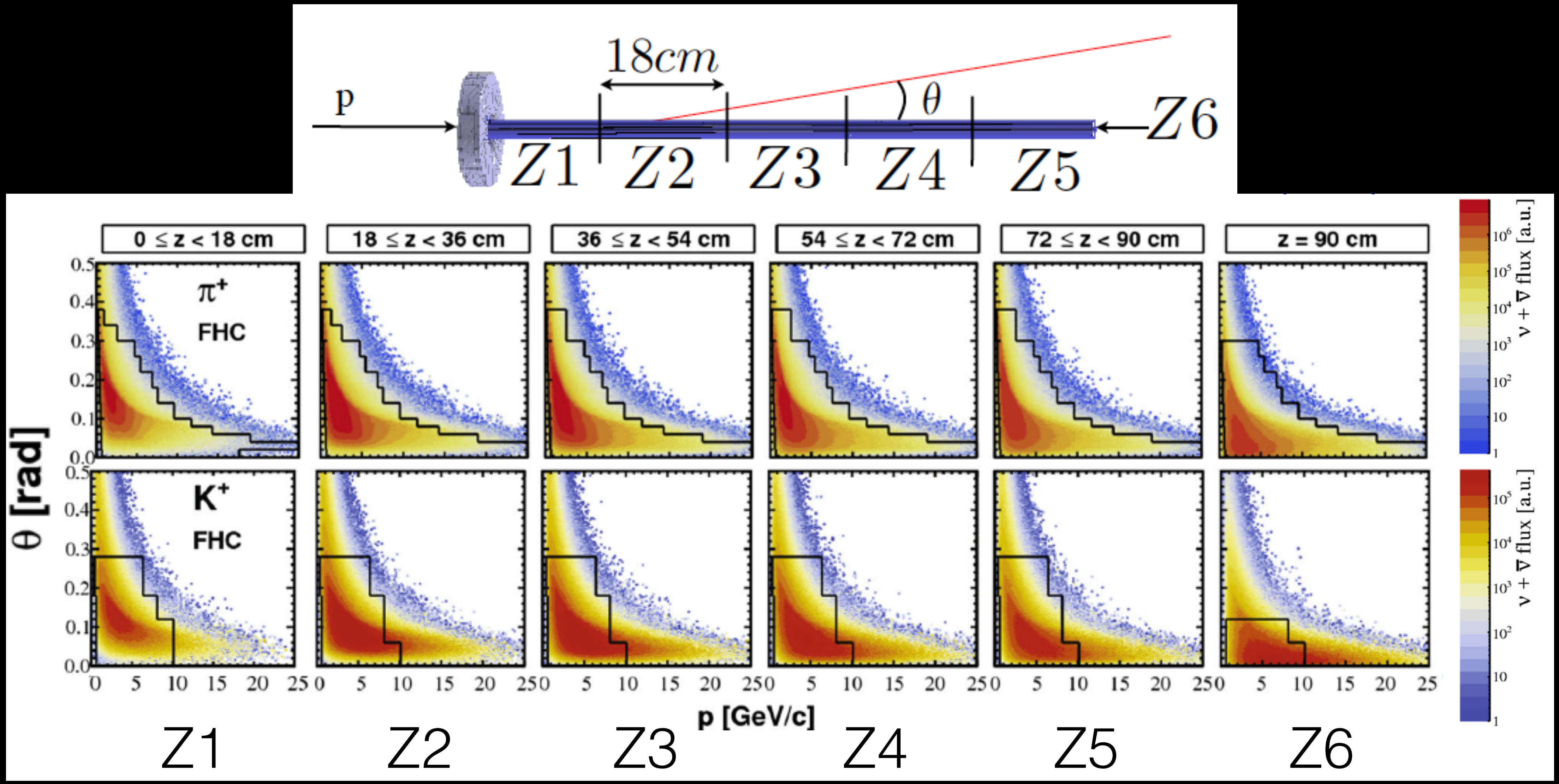


- T2K example: pion production phase space relevant for neutrino production
- *p* and θ are the momentum and angle in the lab frame

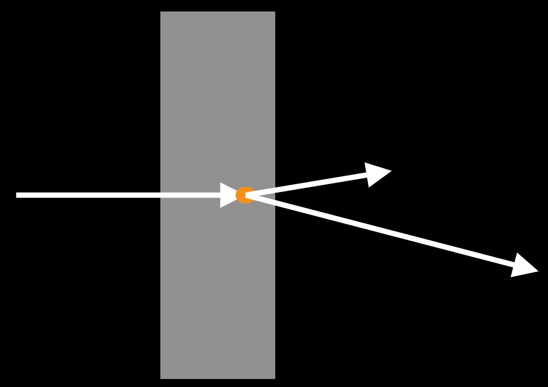
Equivalent result in T2K neutrino flux

MAKE BACKUP

- T2K beam simulation based on replica-target results

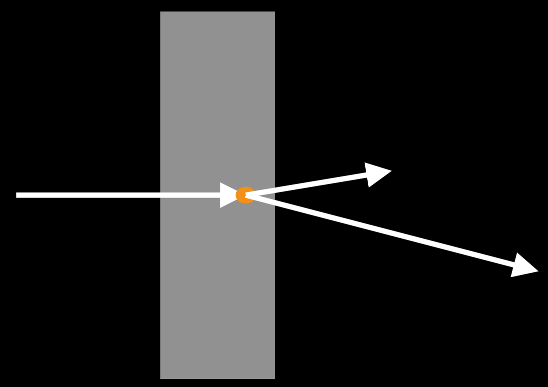


Thin-target measurements



- We study single interactions with a thin target
- Target is a few percent of an interaction length
- Total cross-section definition:
  - $\sigma_{total} = \sigma_{el} + \sigma_{inel}$
    $\sigma_{inel} = \sigma_{qe} + \sigma_{prod}$
  - quasi-elastic: target nucleus breaks up
  - production: new hadrons produced
  - (Careful: some collaborations use subtly different definitions!)

Thin-target measurements

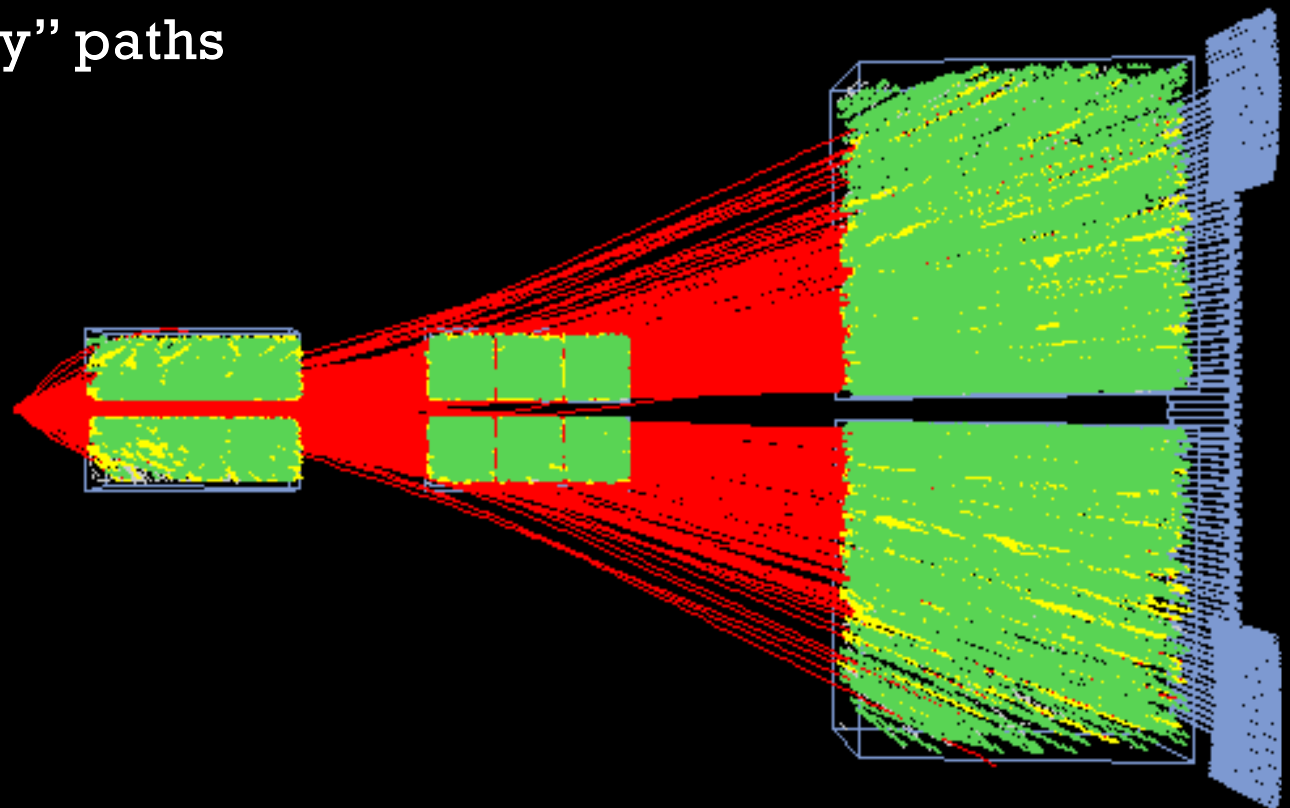


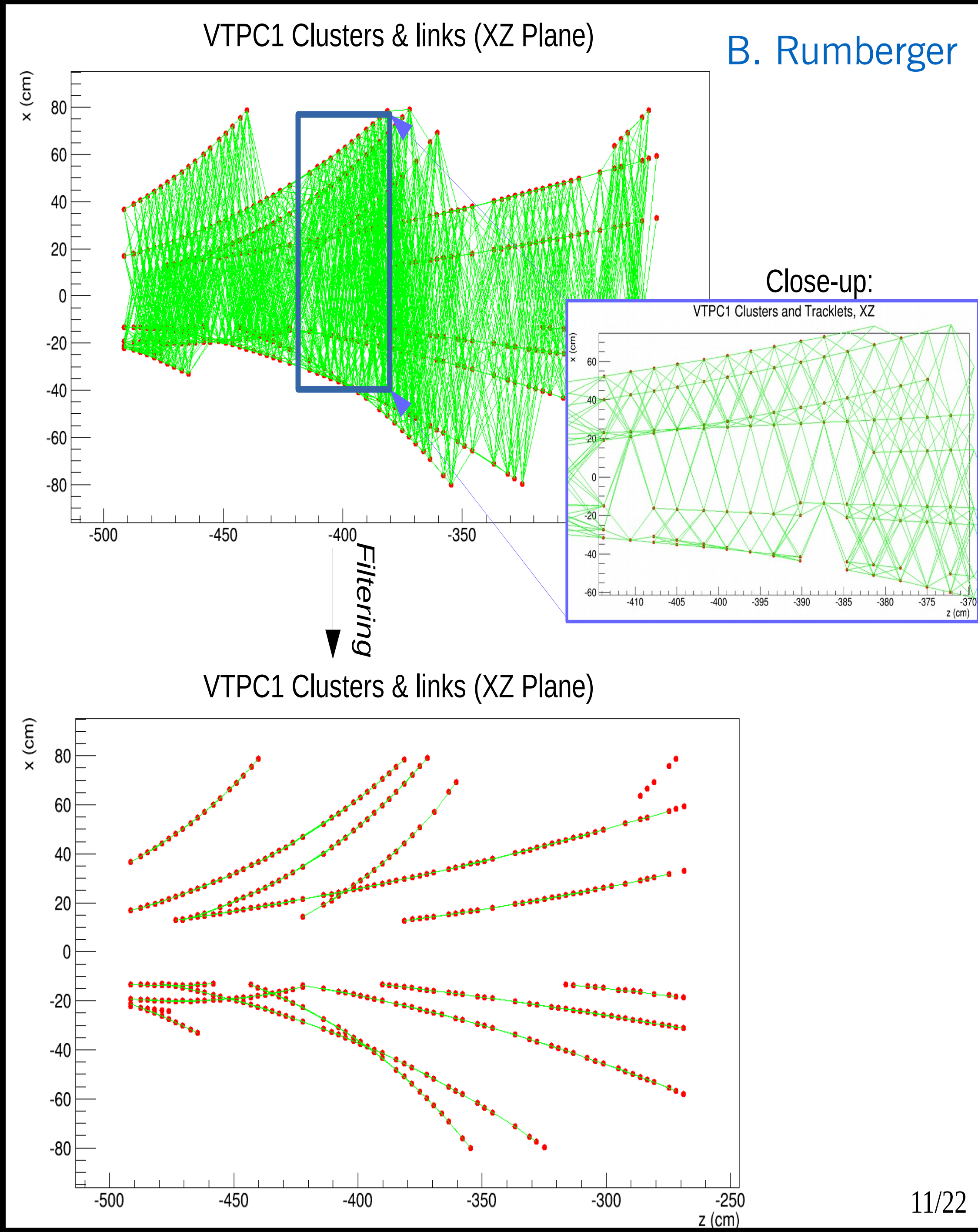
- Also measure differential yields (spectrum): $d^2n/dpd\theta$ for each measurable daughter particle ($\pi^{\pm}$, $K^{\pm}$, p, K^0, Λ^0)
- Use measured σ_{prod} to relate the yields to the differential cross-section $d^2\sigma/dpd\theta = \sigma_{\text{prod}} \cdot d^2n/dpd\theta$
- We can then use these to calculate weights for each interaction in a neutrino beam Monte Carlo:

$$W(p,\theta) = \frac{N(p,\theta)_{\text{Data}}}{N(p,\theta)_{\text{MC}}}$$

New tracking development

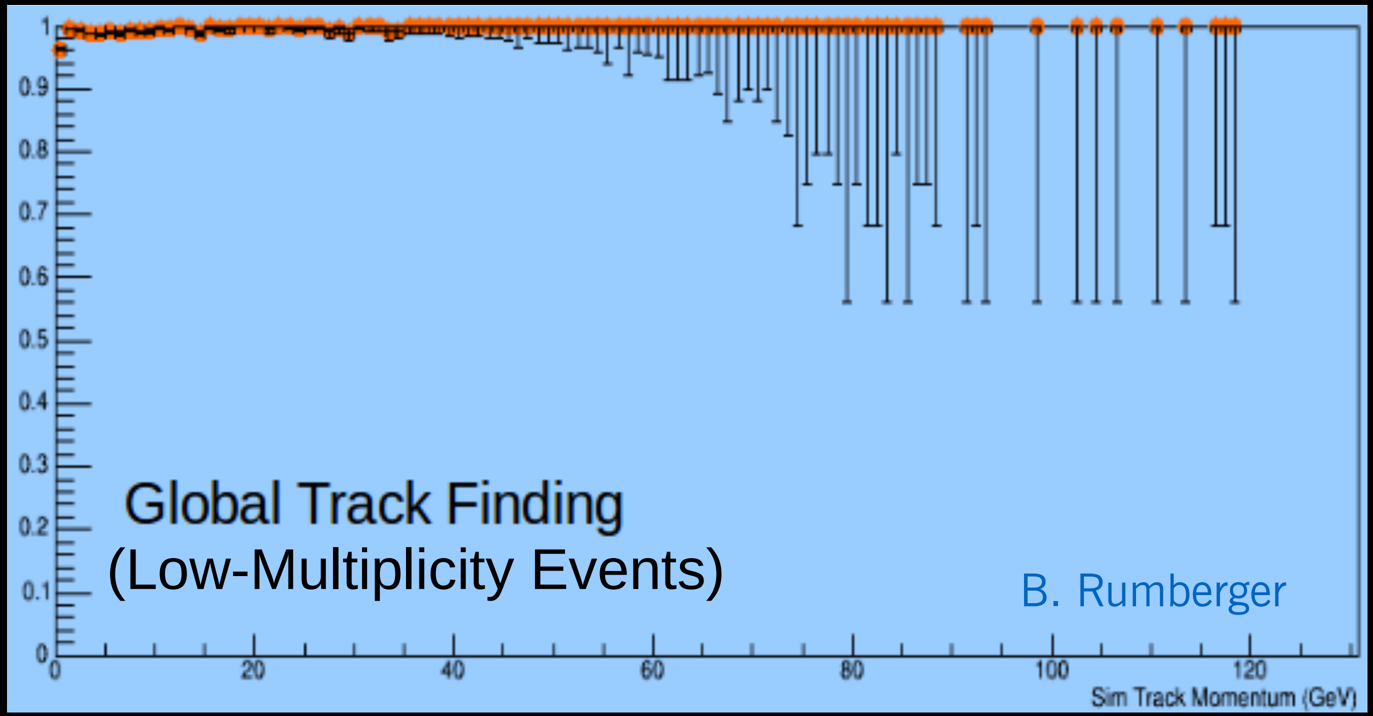
- Tracking has to work not only in low-multiplicity environment but also for NA61's heavy-ion data
- High speed needed for online reconstruction in post-LS2 running
- Local tracks within a chamber are formed by a cellular automaton algorithm that links all possible track-hit combinations and then filters for least-“jumpy” paths

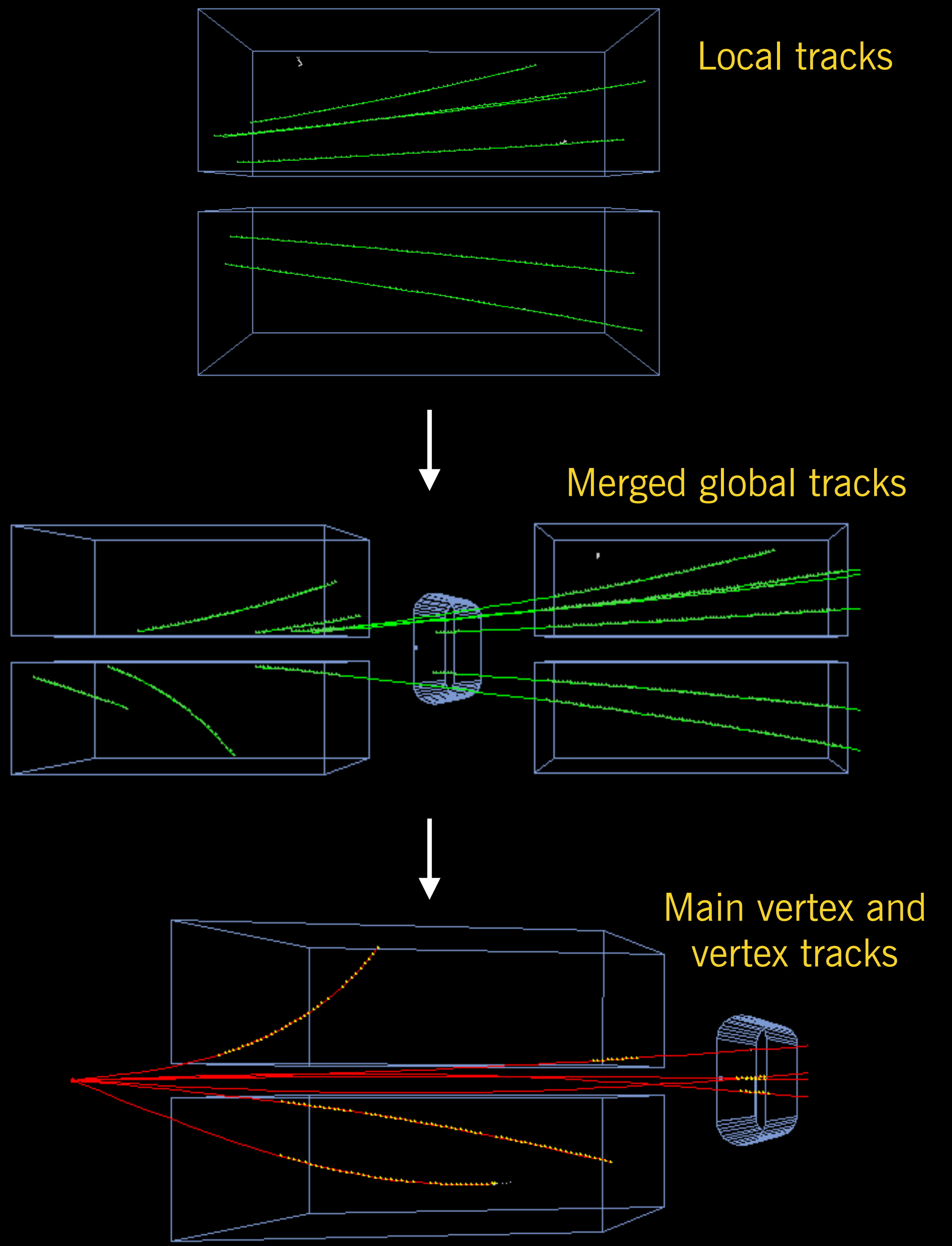




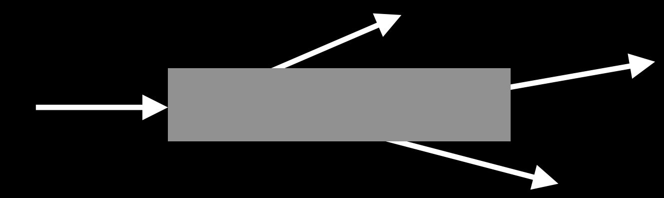
New tracking development

- Local track segments are merged into global tracks
- Overall track finding efficiency >99% for low-multiplicity events
- Track parameters are fitted using Kalman filter

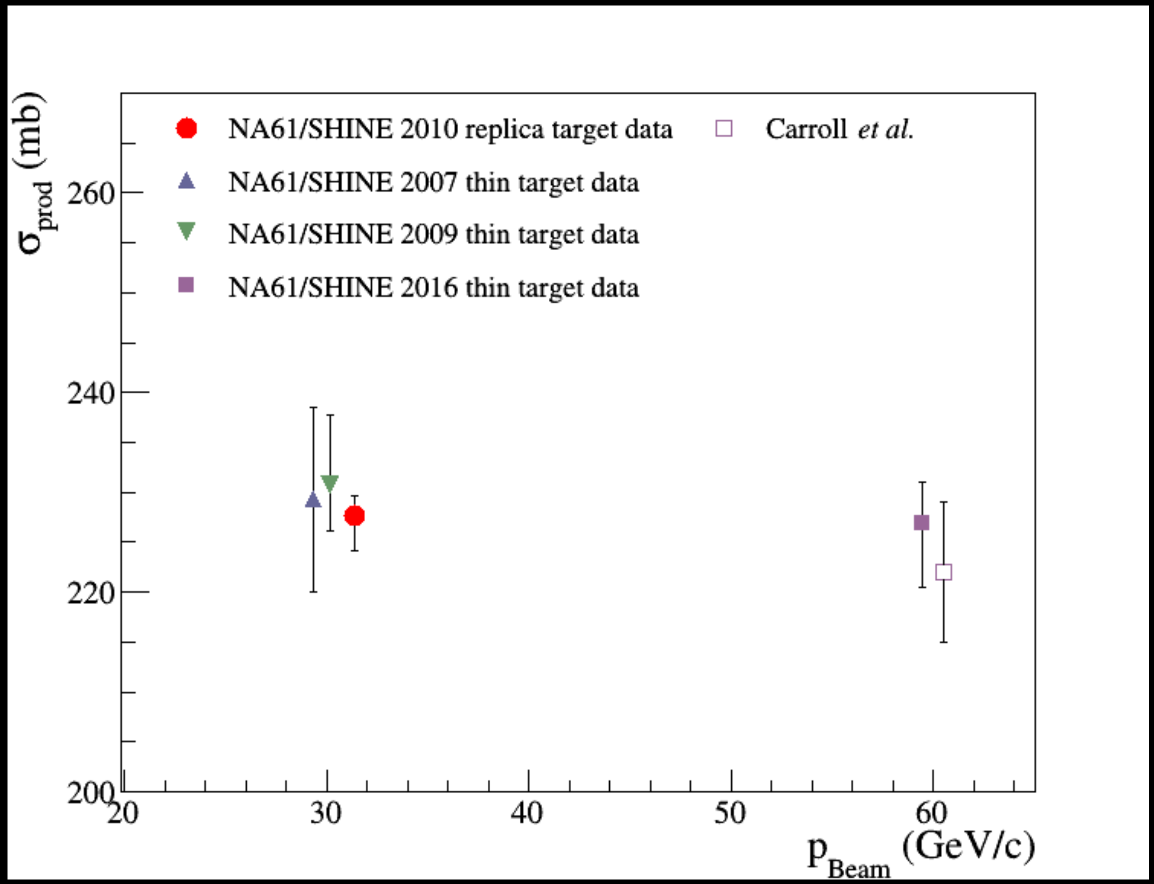




Latest results for T2K replica target

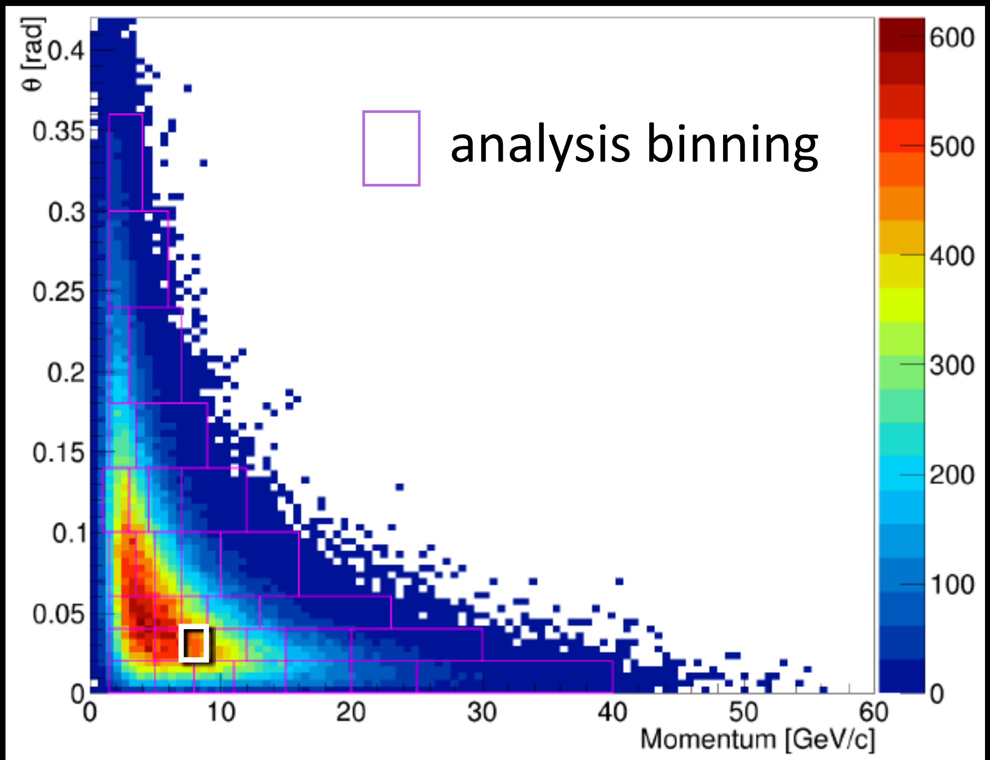


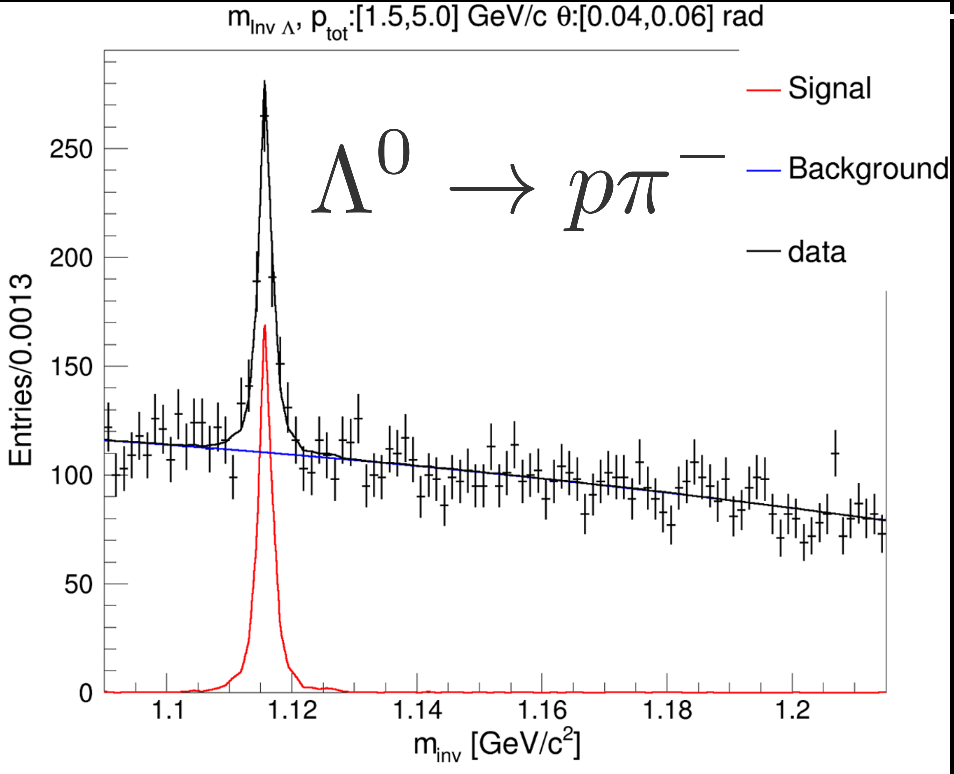
- Direct measurement of the production cross-section by measuring beam proton survival probability in the 90cm T2K replica target
- Used a special run with high vertex magnet field (Forward TPCs were not built yet) to bend beam protons into the main TPC
- A. Acharya *et al.*, *Phys. Rev. D*103 (2021) 1, 012006

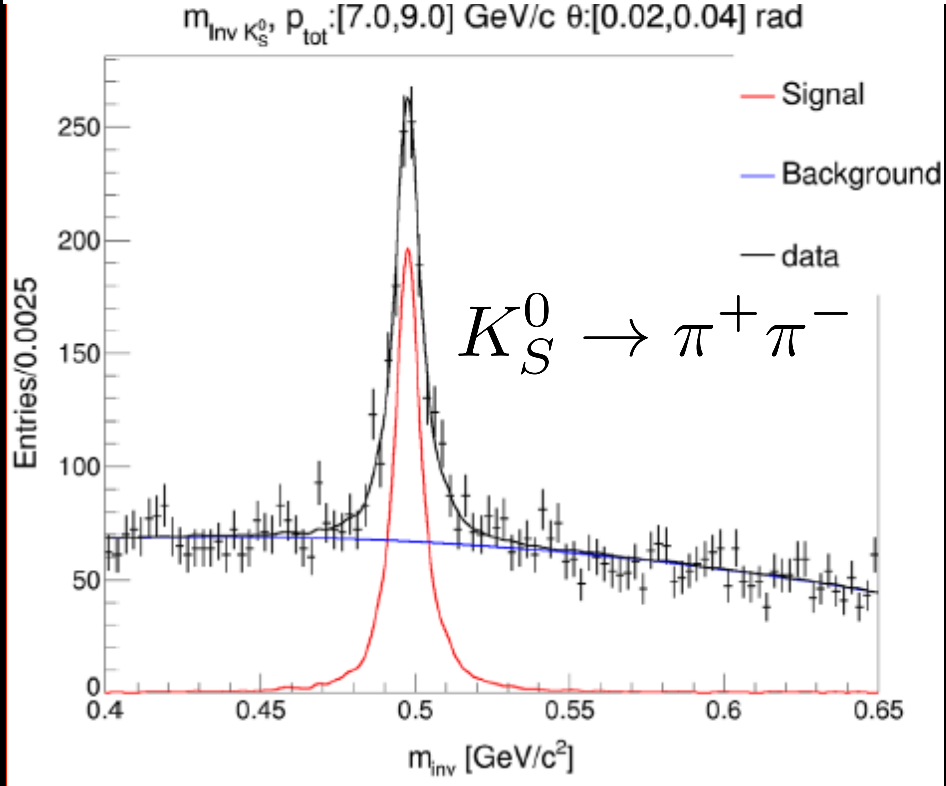


Thin-target neutral hadron spectra

- Yields of neutral kaons, Λ from specific kinematic bins



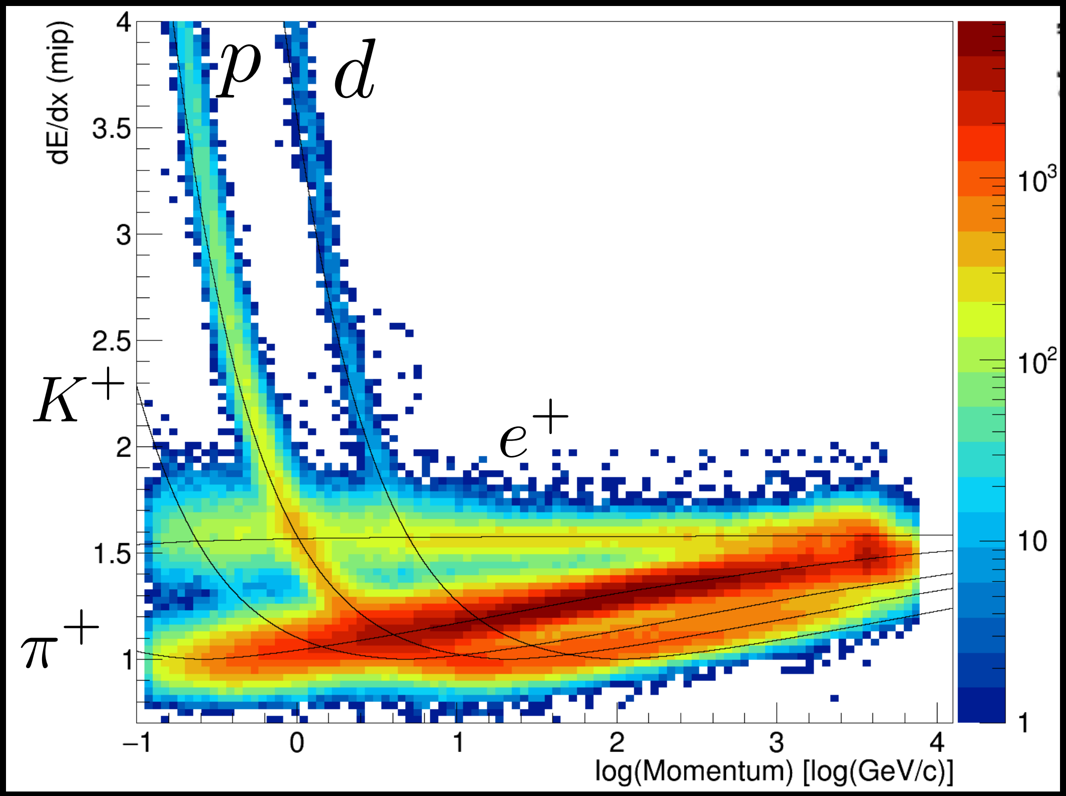


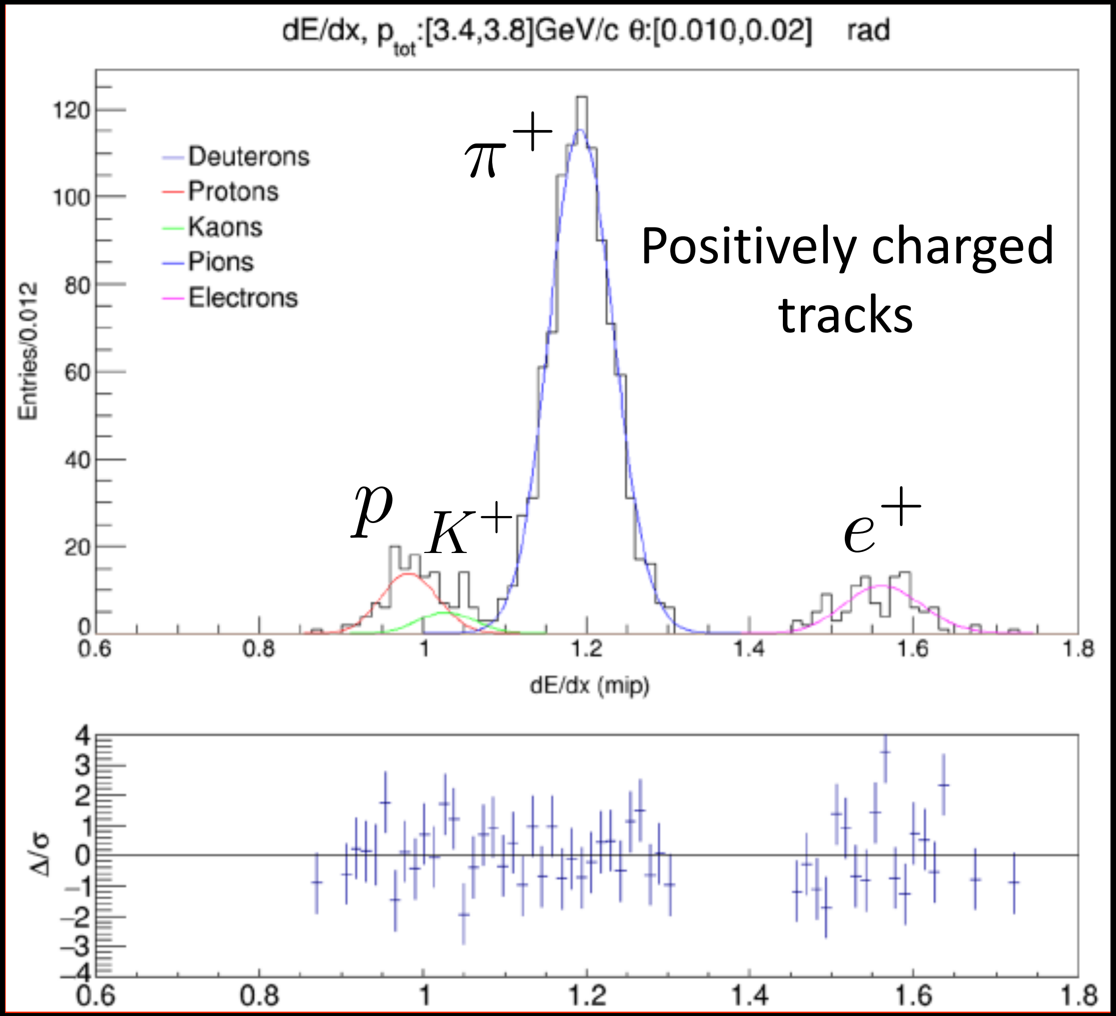


- Phys.Rev. **D100** 112004 (2019)

Thin-target charged hadron spectra

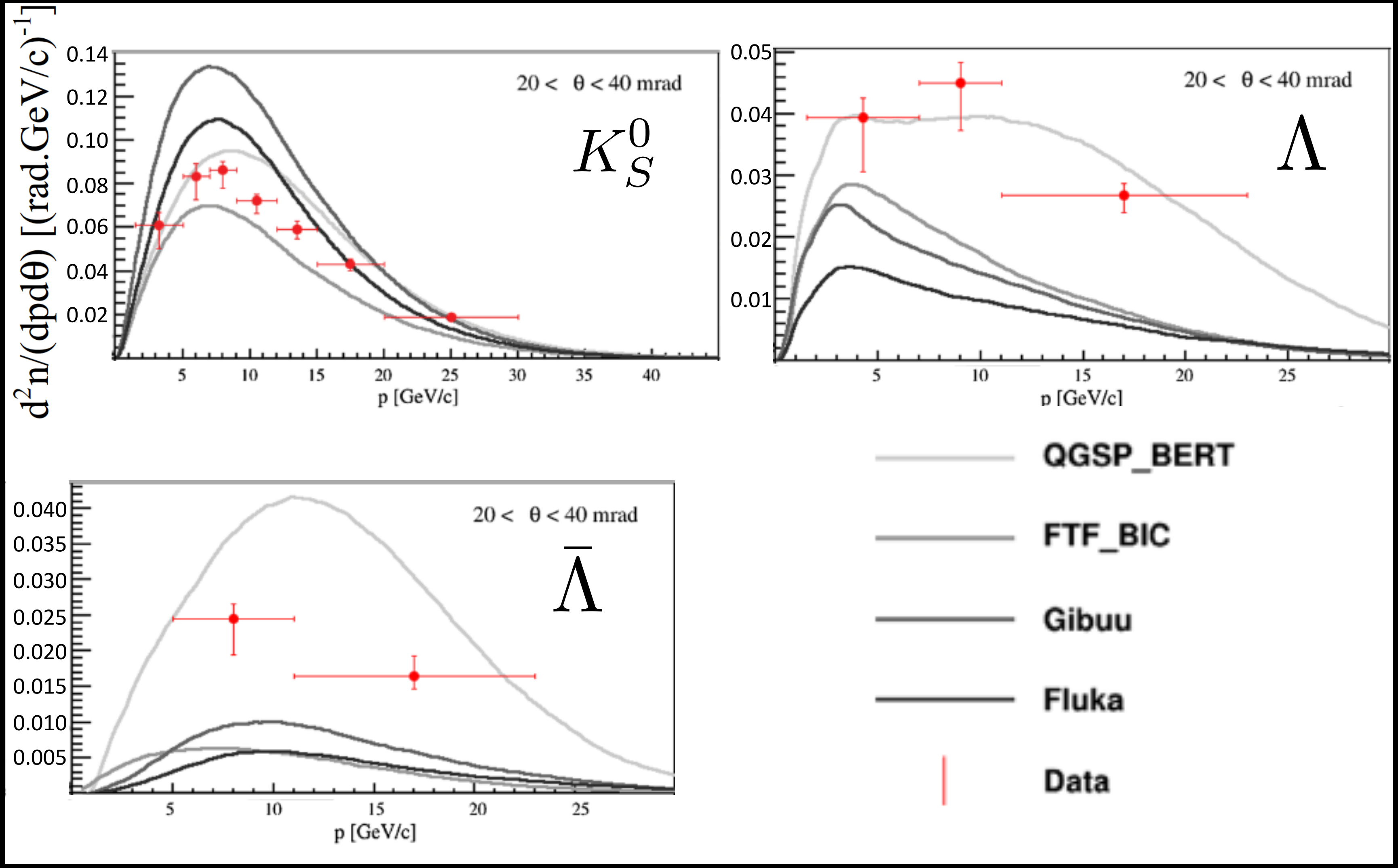
- Example: π^++C @ 60 GeV (Phys.Rev. **D100** 112004 (2019))
- *dE/dx* yields from TPC tracks and PIT fit for one p,θ bin





Thin-target neutral hadron spectra

- Yields of neutral kaons, Λ, $\bar{\Lambda}$ from specific angle bin



- Phys.Rev. **D100** 112004 (2019)

Data available now to PPFX

- Thin target experiments
  - Inelastic cross section
    - Belletini, Denisov, etc. cross sections of pC, πC, πAl etc
    - NA49: pC @ 158 GeV
    - NA61 pC @ 31 GeV
  - Hadron Production
    - Barton: pC → π ±X @ 100 GeV xF > 0.3
    - NA49: pC → π ±X @ 158 GeV xF < 0.5
    - NA49: pC → n(p)X @ 158 GeV for xF < 0.95
    - NA49: pC → K ±X @ 158 GeV for xF < 0.2
    - NA61: pC → π ±X @ 31 GeV
    - MIPP: π/K from pC at 120 GeV for pZ > 20GeV/c
- Thick targets experiments (off by default)
  - MIPP: proton on a spare NuMI target at 120 GeV
    - π ± up to 80 GeV/c.
    - K/π for > 20 GeV/c.

Detailed descriptions in Section 4.3.-4.5 of Leo's thesis)