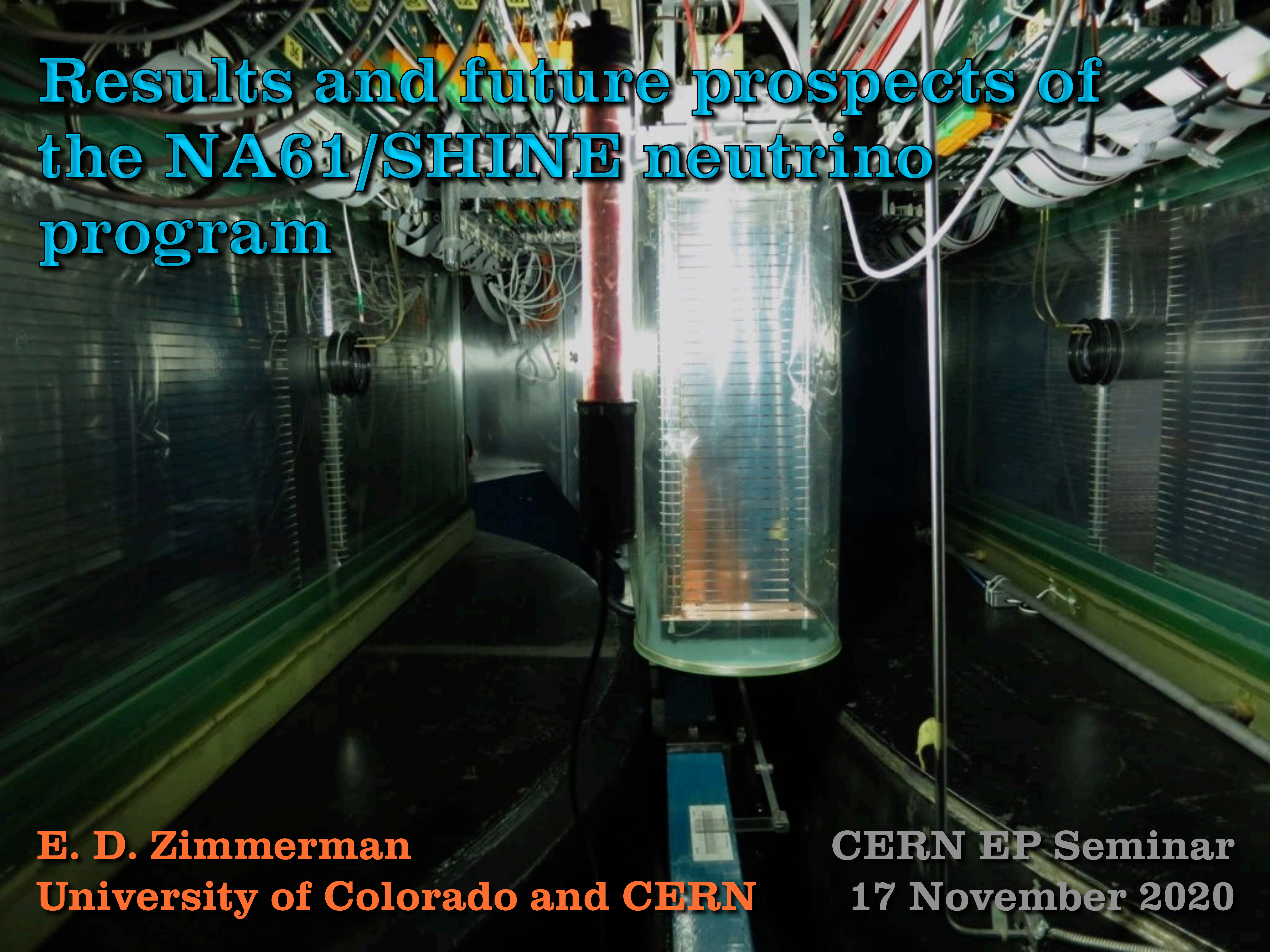

Results and future prospects of the NA61/SHINE neutrino program

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CERN EP Seminar
17 November 2020

NA61/SHINE Neutrino Program

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

Neutrino Oscillations

- ASSUME:
  - Two neutrinos (simpler than three)
  - Massive, but masses are non-degenerate
  - Mass eigenstates are NOT the same as flavor eigenstates
- This is a **quantum-mechanical two-state system**:

Flavor basis → $$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$ ← Mass basis

- ν_1 and ν_2 phases rotate at different rates:

$$|\nu_1\rangle \rightarrow e^{-im_1 t}|\nu_1\rangle \qquad (\hbar = c = 1)$$

- So, starting at t=0 with one flavor:

$$|\psi(0)\rangle = |\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

- The state evolves a component of the other flavor:

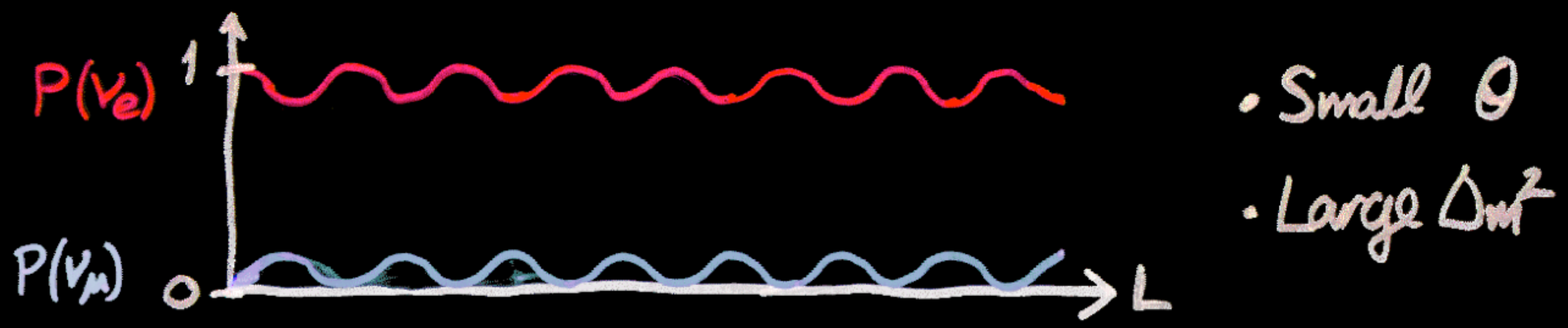
$$|\psi(t)\rangle = \cos\theta e^{-im_1 t}|\nu_1\rangle + \sin\theta e^{-im_2 t}|\nu_2\rangle$$

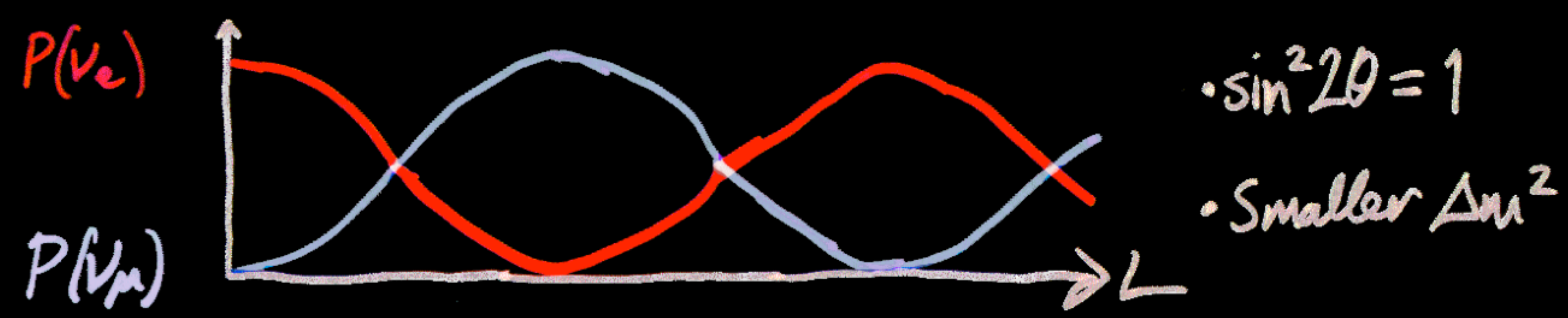
Neutrino Oscillations

- Solving and plugging in sensible units, probability of measuring ν_μ if state was created as ν_e:

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$

  - L = flight distance (km); E = neutrino energy (GeV); m = mass (eV/c^2)

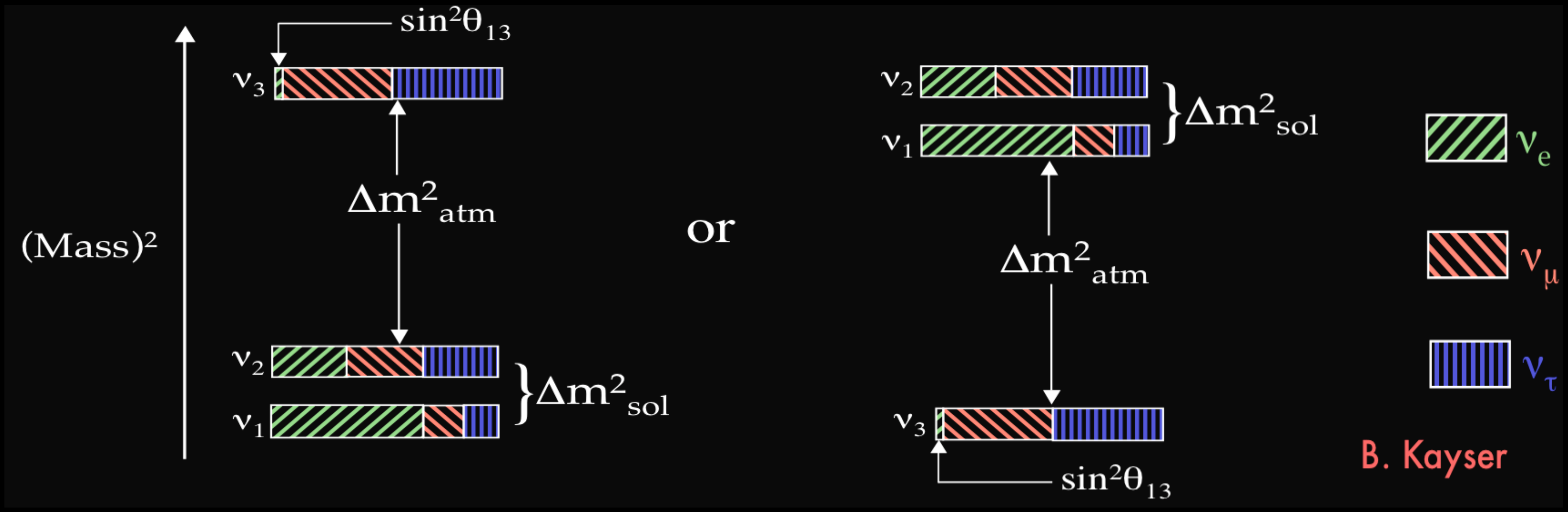




Mass splittings are such that at accessible energies, oscillation phenomena generally occur at terrestrial or astronomical distance scales.

Character of the parameters

- Matrix is characterized by large mixing angles (unlike the quark sector)
- Hierarchy of masses: one mass splitting is about 30 times the other. We do not know, however, what the order is or whether there's a significant offset from zero.



"NORMAL" ORDERING "INVERTED" ORDERING

Neutrino oscillation experiments

- Experiments using accelerator beams start with muon neutrinos, and the relevant Δm^2 is Δm^2_{32} (the "atmospheric" scale), which puts the first oscillation maximum at ~500 km for 1 GeV neutrinos
- Compare event rates at far sites to expectations: Appearance of electron neutrinos and disappearance of muon neutrinos are the main experimental signatures. Ignoring matter effects:

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \overset{(-)}{+} O(\delta_{CP})$$

- Long-baseline neutrino experiments are now studying the mass hierarchy and searching for *CP* violation in neutrino oscillations

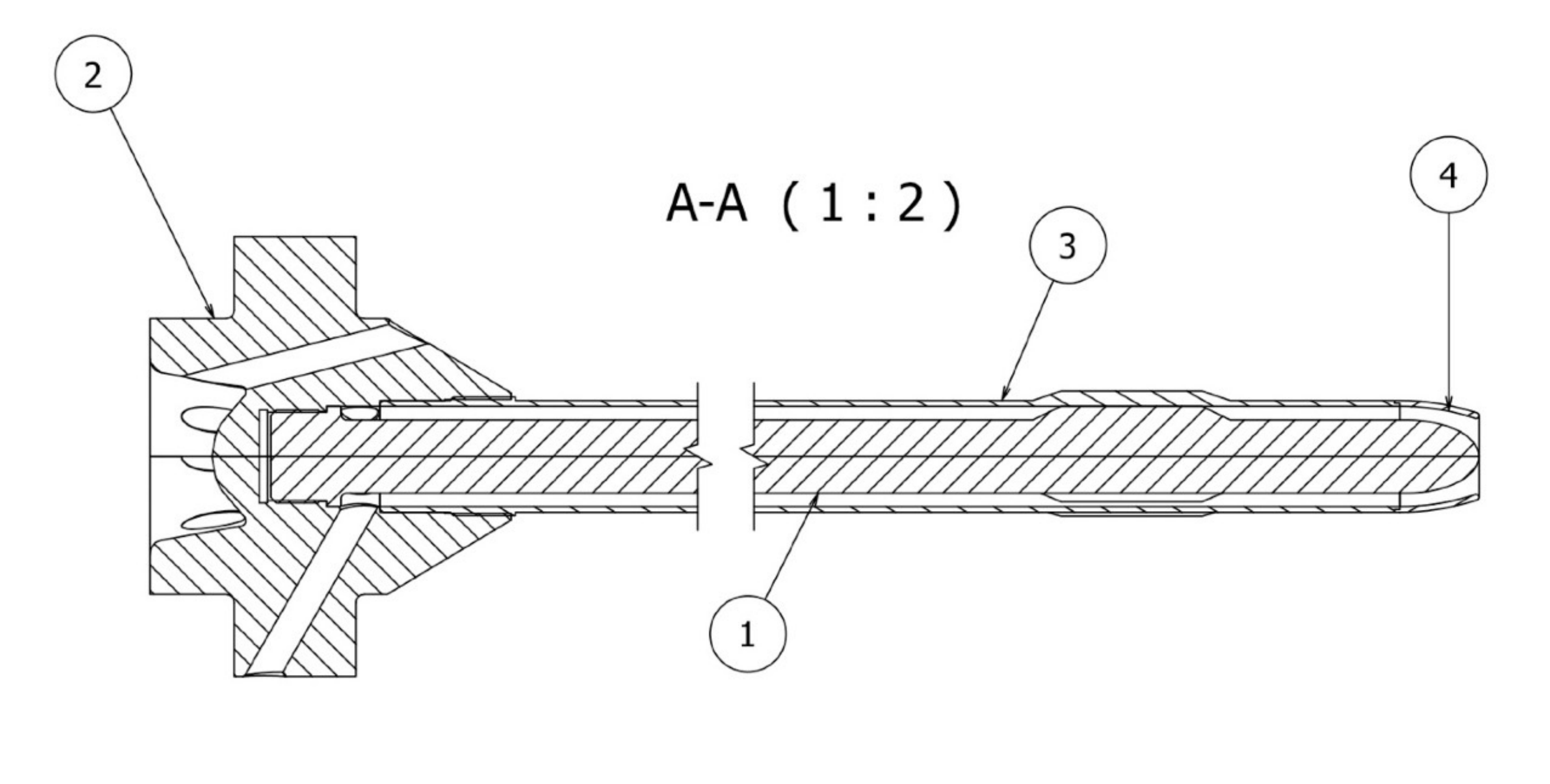
How to make a neutrino beam

- Modern long-baseline 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
- Fifty-plus-year history of these beams!
- Numerous variants on the conventional beam: narrow-band, broad-band, off-axis…
- 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

Targets

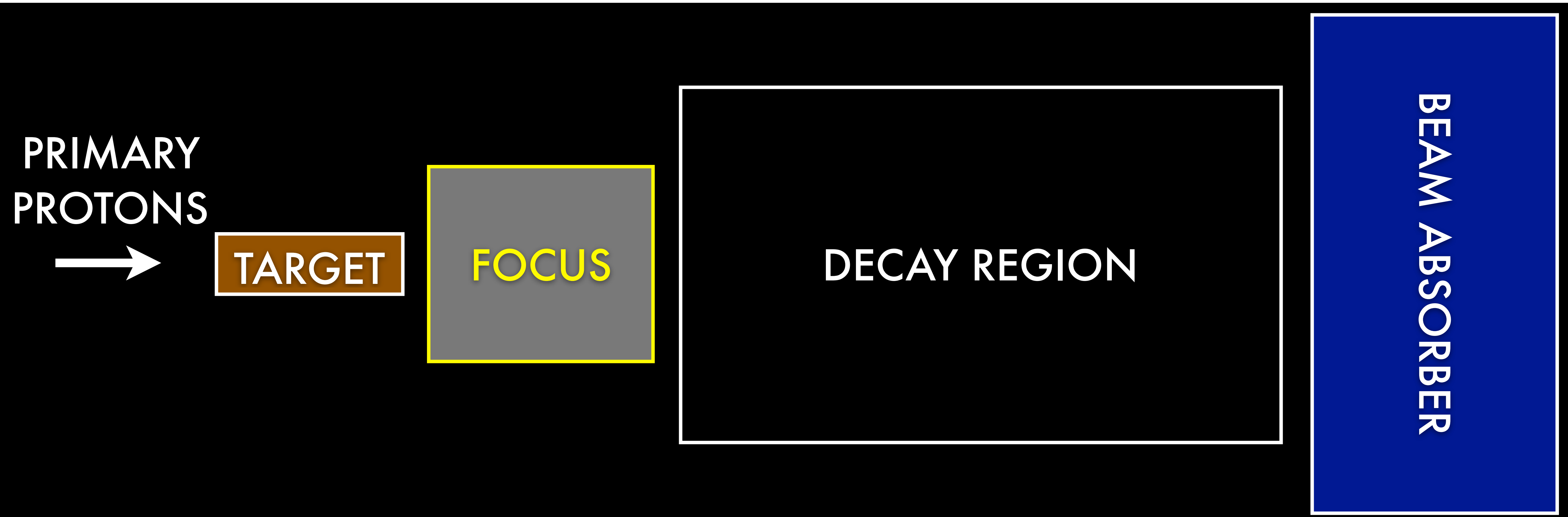
- Target must be ~2 λ_0 in beam direction, to maximize interactions
- Should be wide enough to contain the primary beam, but narrow enough to allow interaction products with average p_T to escape the side
- Target material is generally selected to be low-A, since lighter nuclides tend to produce shorter-lived radioactive isotopes with lower gamma energies. Also, want to maximize interactions while minimizing multiple scattering: low λ_0/X_0 ratio preferred.
- Targets must handle very high beam power deposition! Modern targets need dedicated cooling; future targets may need to be liquid or powder-jet as solids may not be able to survive thermal shock.

T2K target



- Graphite target, like most modern beams
- 90 cm long, 2.5cm diameter. Beam radius is large (6mm) to reduce local intensity and thermal shock
- Target cooled by very high velocity helium gas in closed loop

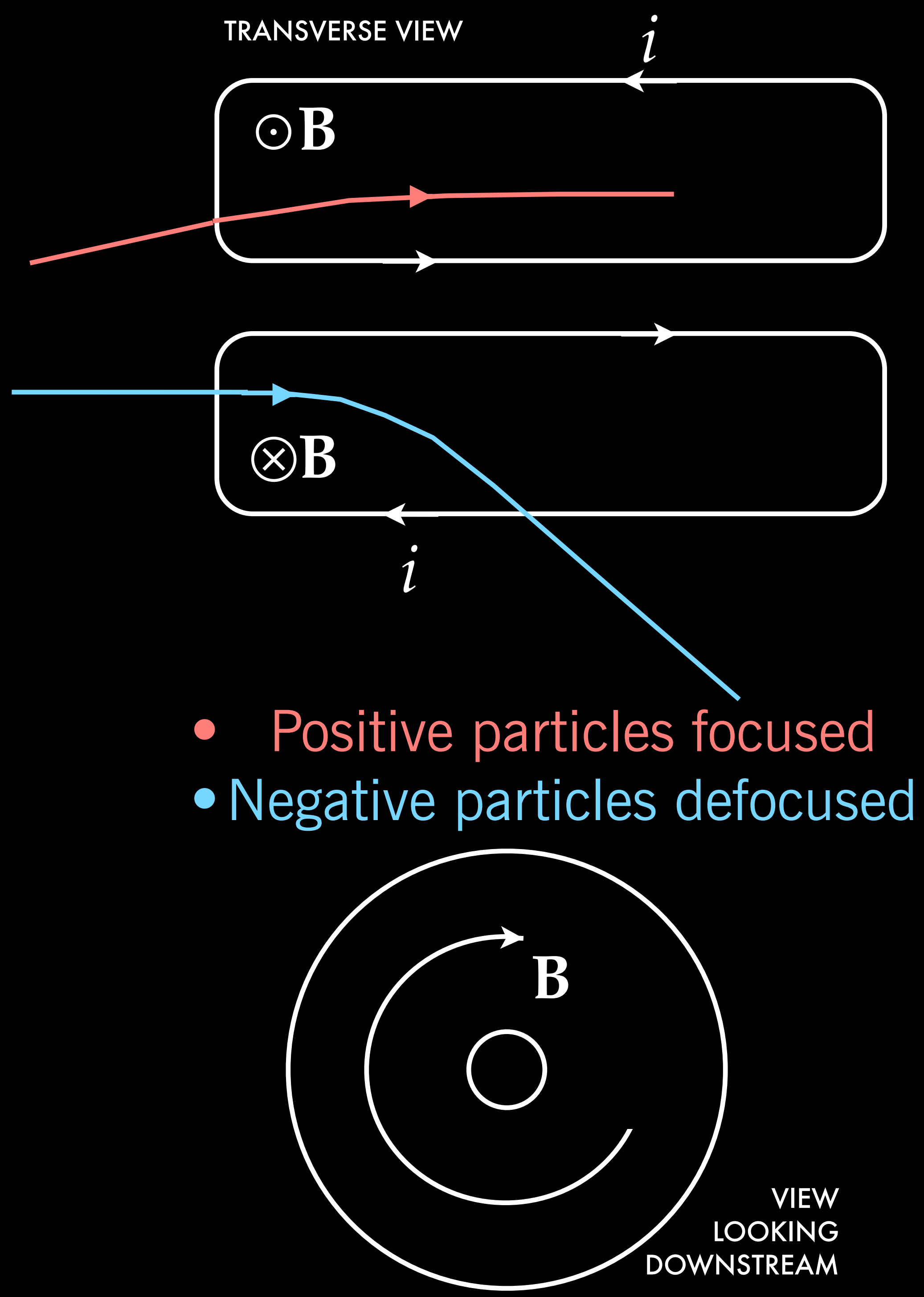
CONVENTIONAL BEAMS: Basic components



- After leaving target, charged particles may be focused before entering decay volume
  - Several focusing schemes possible
  - Focusing not strictly necessary: 1962 two-flavor neutrino discovery experiment used unfocused mesons.

Horns

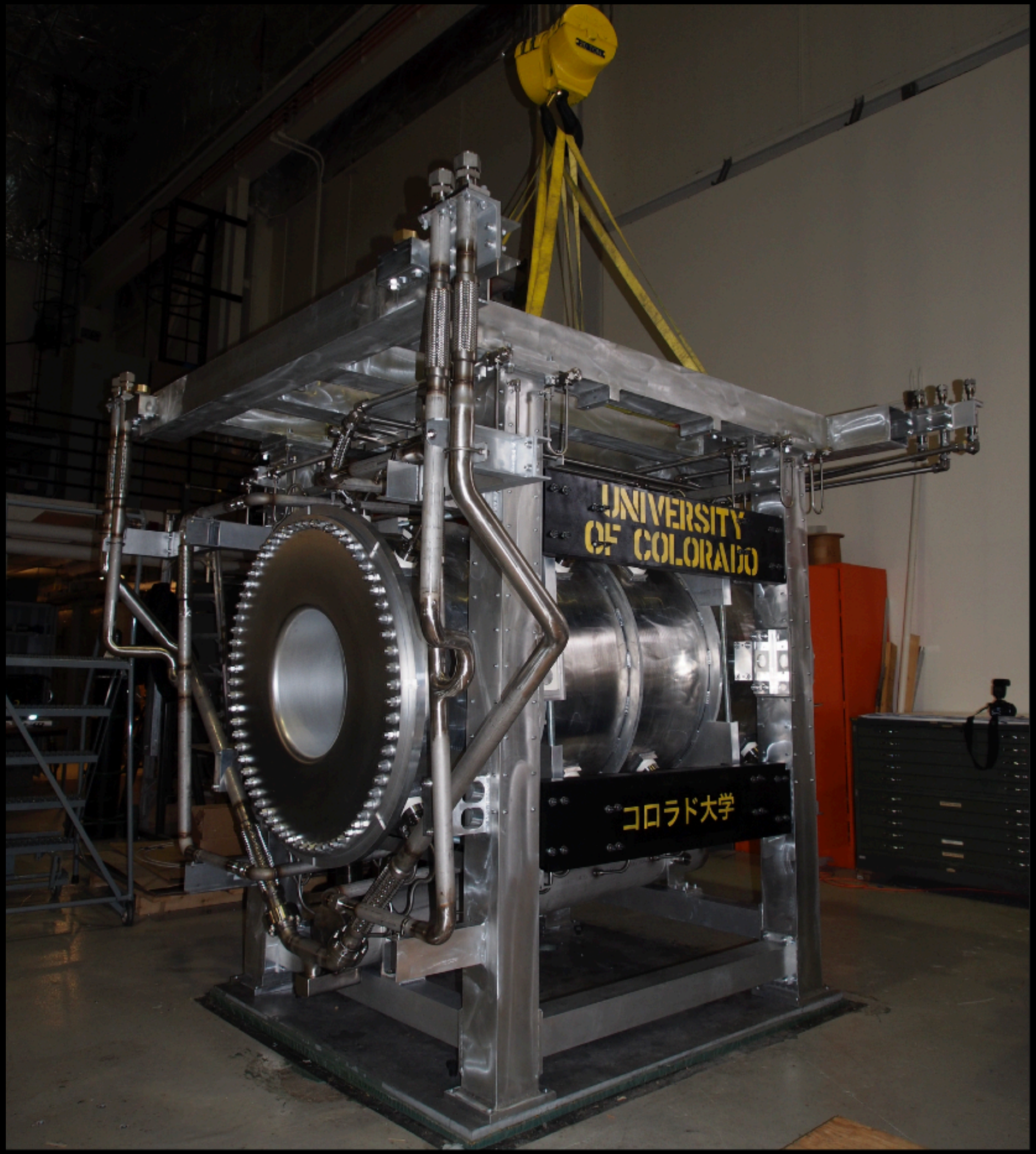
- Horns first proposed by Van der Meer (1961)
- At the most basic level:
  - Two coaxial conductors: a toroidal field exists in the region radially between inner and outer conductors
  - Inner conductor is thin enough (2-3 mm) for most pions to pass through
  - Conductor currents are 100-300 kA so water cooling, pulsed operation necessary to prevent melting
  - Generally made of aluminum alloy



Horns

1960s

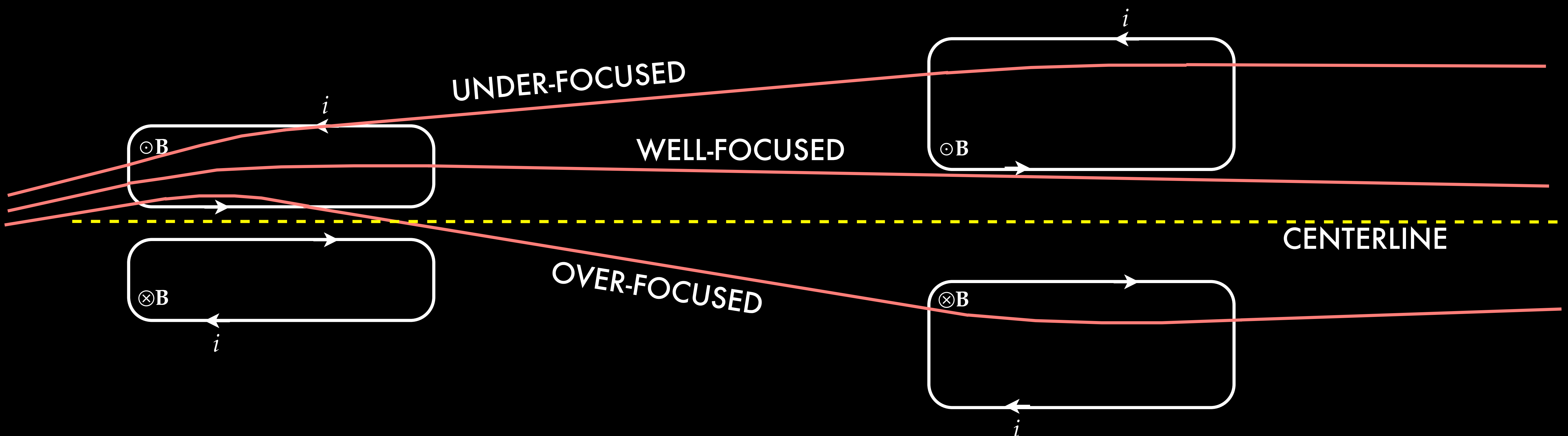
2010s



Multi-horn systems

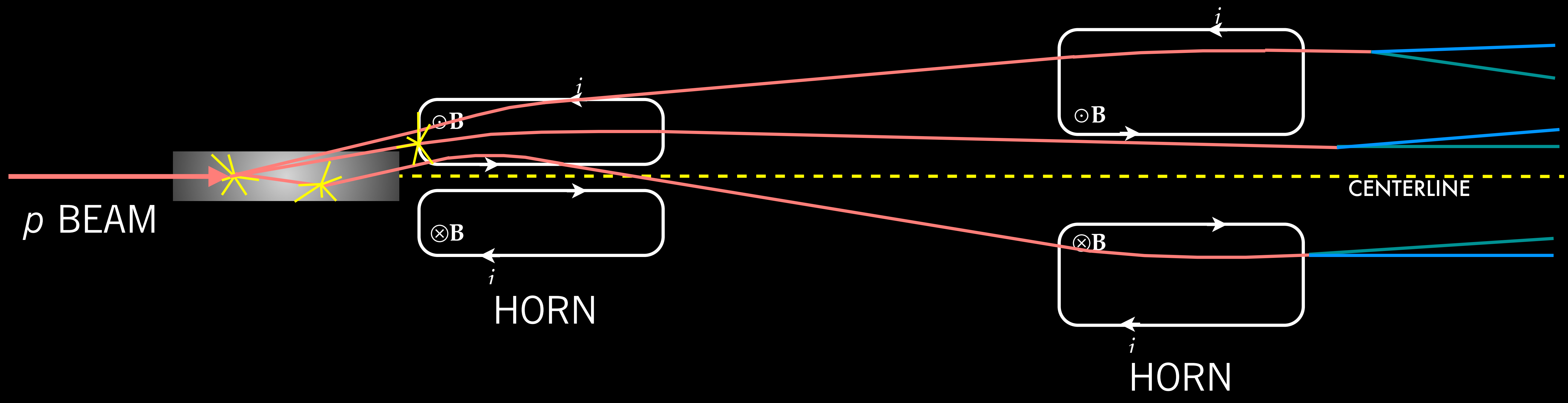
- A single horn generally reduces the angular spread of the beam by a factor of ~2. The resulting beam, observed from far enough downstream, looks again like a point source of pions with an angular spread ⇒ it can be focused further by adding another horn.

- Common for beams to be designed with two (or even three) horns in series. The downstream horns allow correction of both under- and over-focused particles:



Understanding 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 like a secondary target
- **All of these sources of mesons contribute significantly to the neutrino flux.**



Understanding the flux

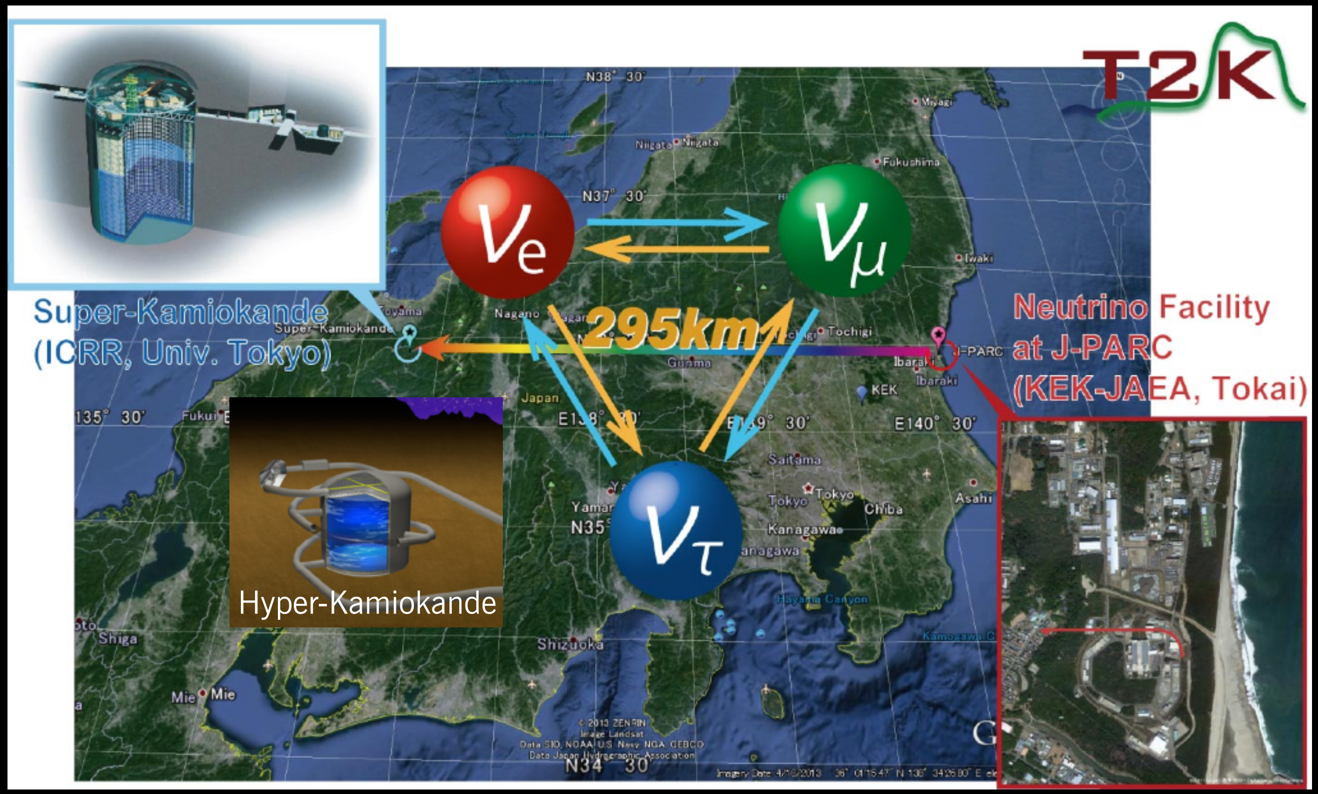
- Use Monte Carlo techniques to simulate the beam, but this is generally a very complicated and challenging environment. Uncertainties can be large: 20-50% with standard simulation tools.
- Monte Carlo must simulate:
  - Interaction of proton in target
  - Production of pions, kaons in target
  - Propagation 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!

Understanding a neutrino beam

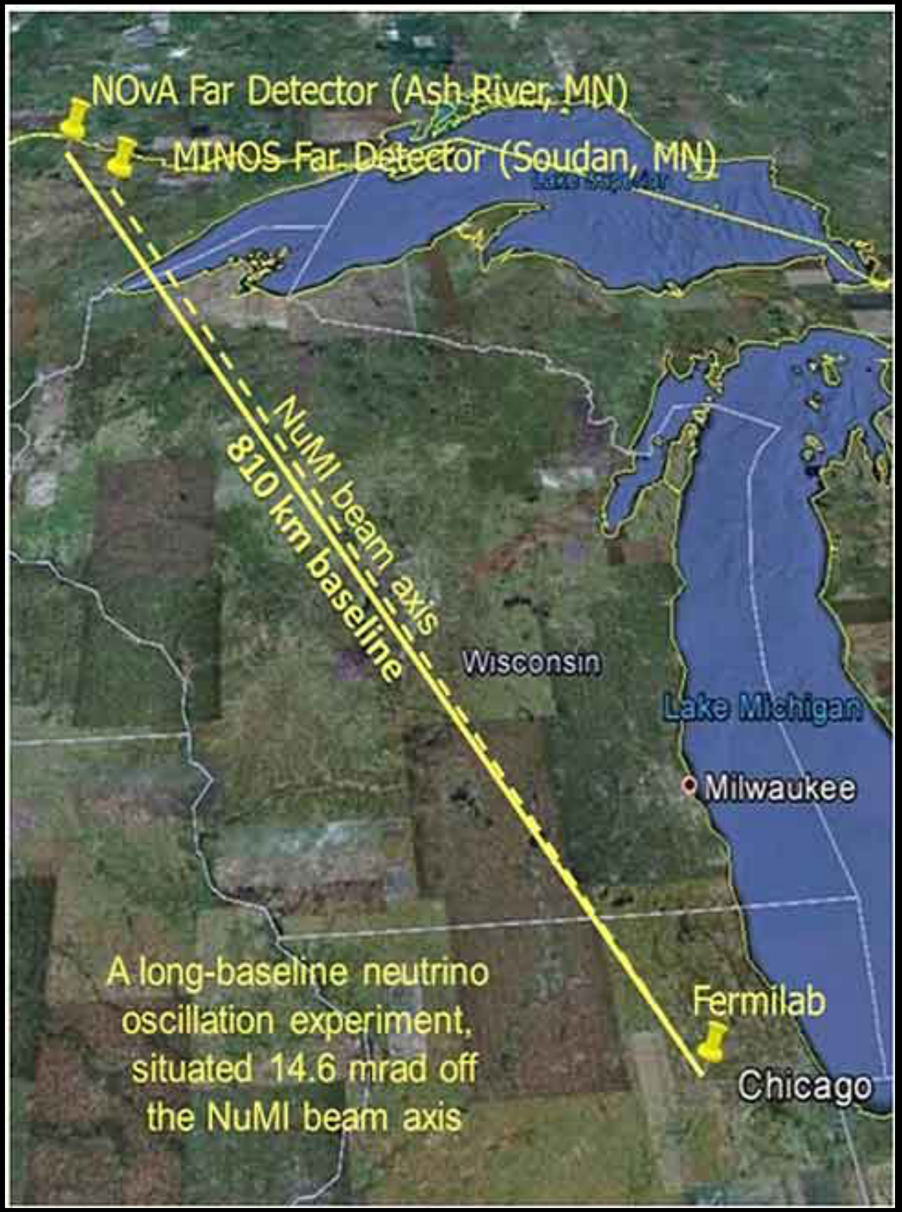
- Two complementary techniques needed to understand the beam well enough to do oscillation measurements
  - Near neutrino detector
    - Standard for modern oscillation experiments. Place a small neutrino detector near the source to measure neutrinos before oscillation.
    - Goal is cancellation of flux uncertainties in near/far ratio.
    - These are not perfect for constraining flux, due to neutrino cross-section (don’t cancel if detectors are different) and reconstruction uncertainties, 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
    - Needed for reducing oscillation systematic errors

Primary beam energies for current and near future neutrino beams

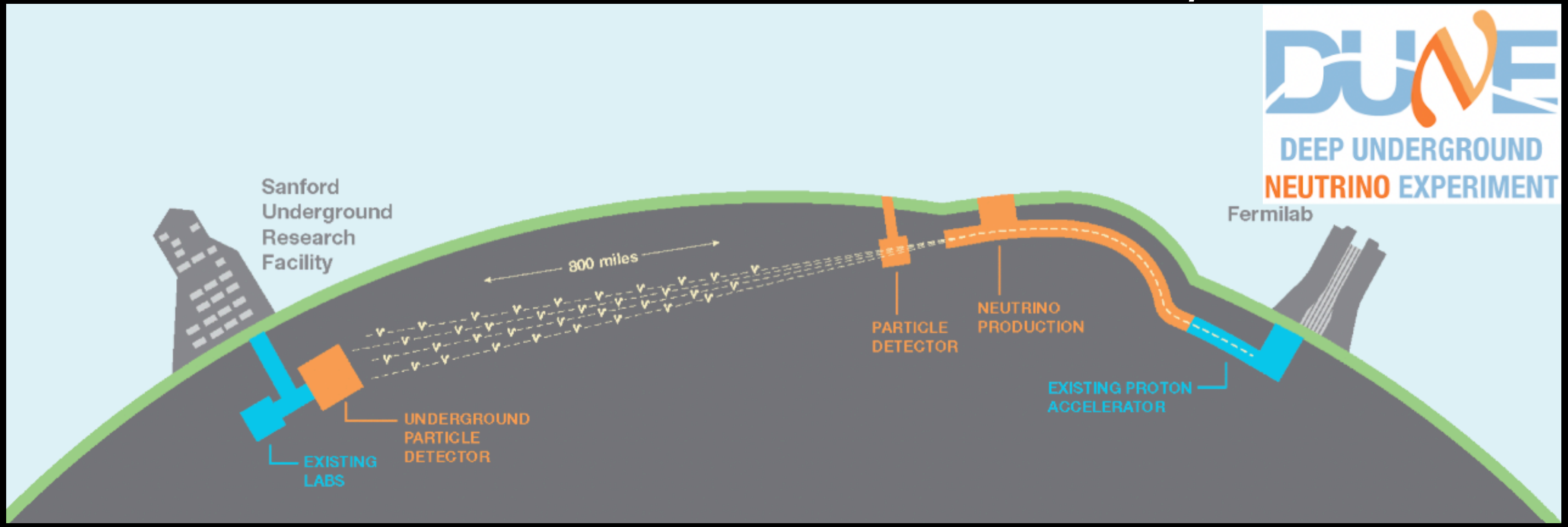


T2K, T2HK: 30 GeV/*c* *p*

NuMI: 120 GeV/*c* *p*

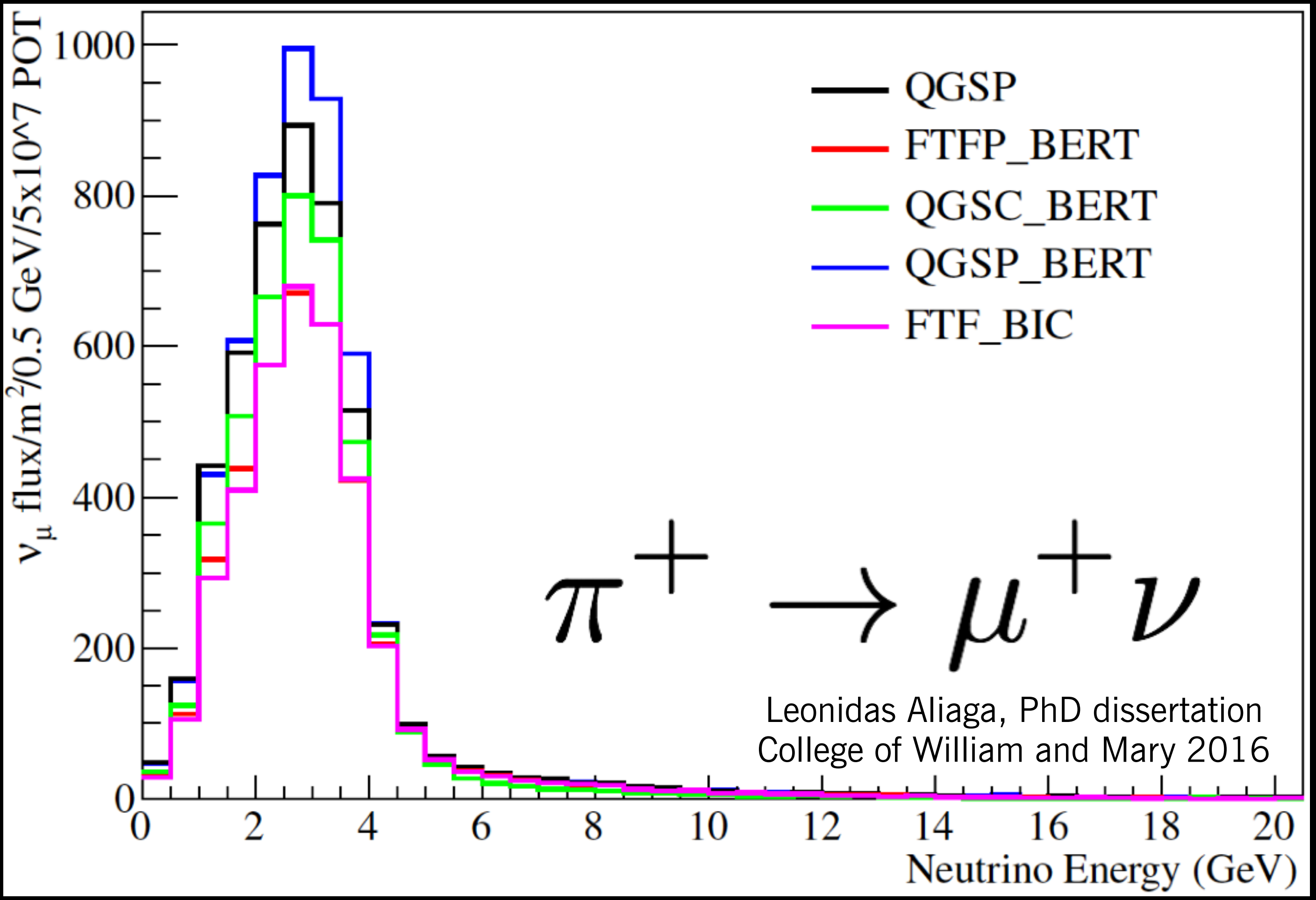


LBNF/DUNE: 60-120 GeV/*c* *p*



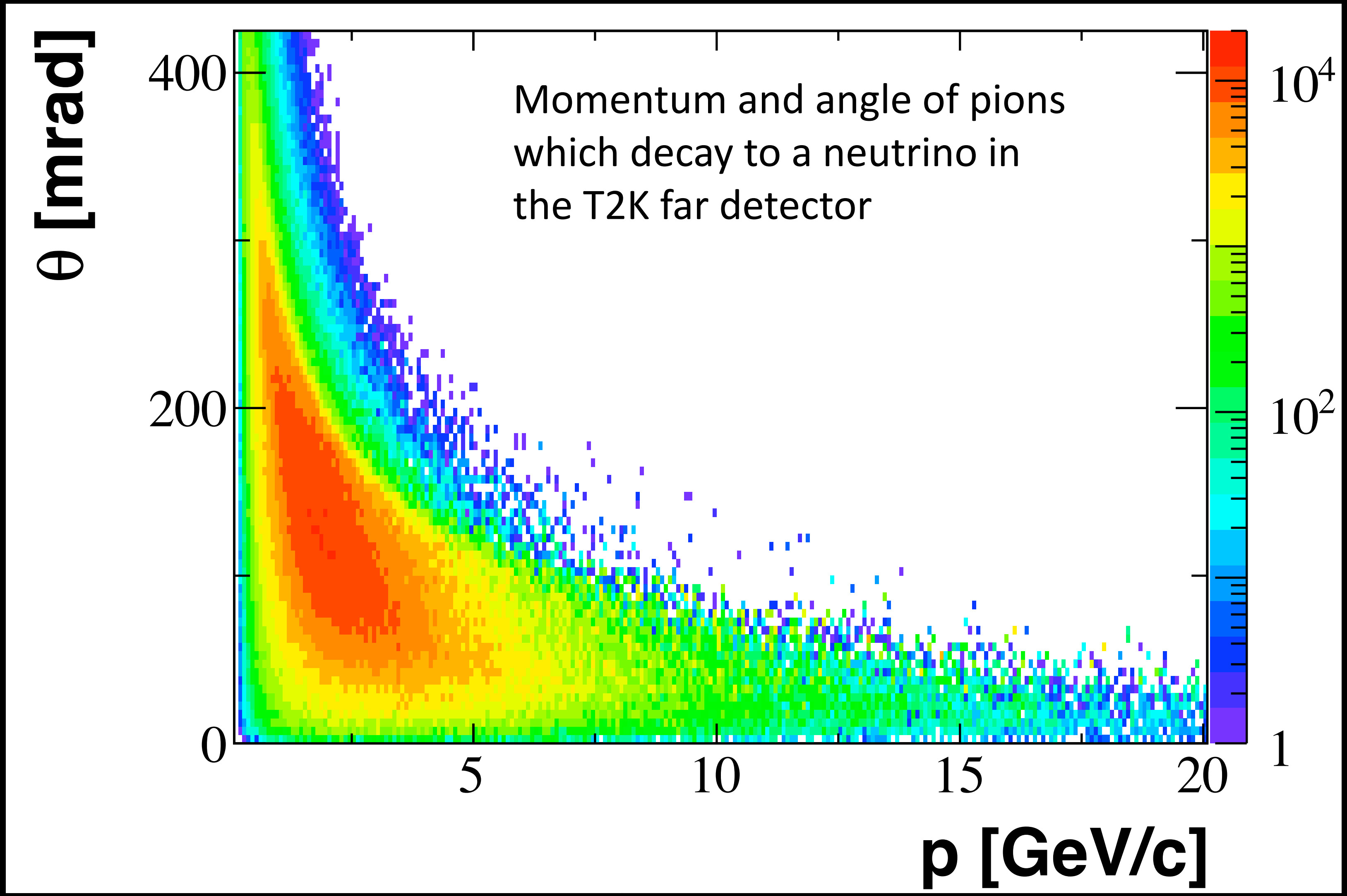
Monte Carlo generators

- 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 Fermilab'sNuMI neutrino beam with different physics generators

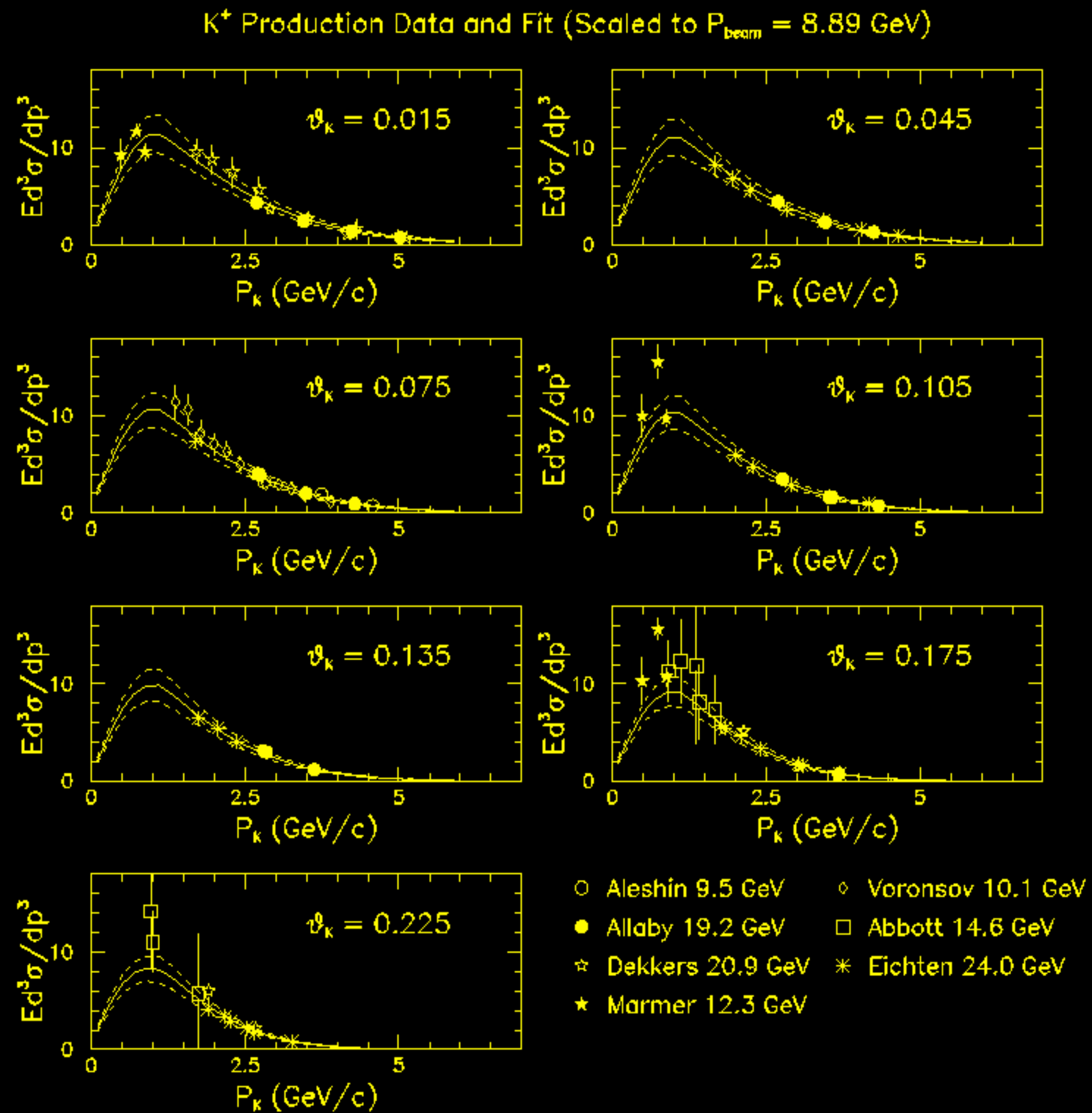
Meson production



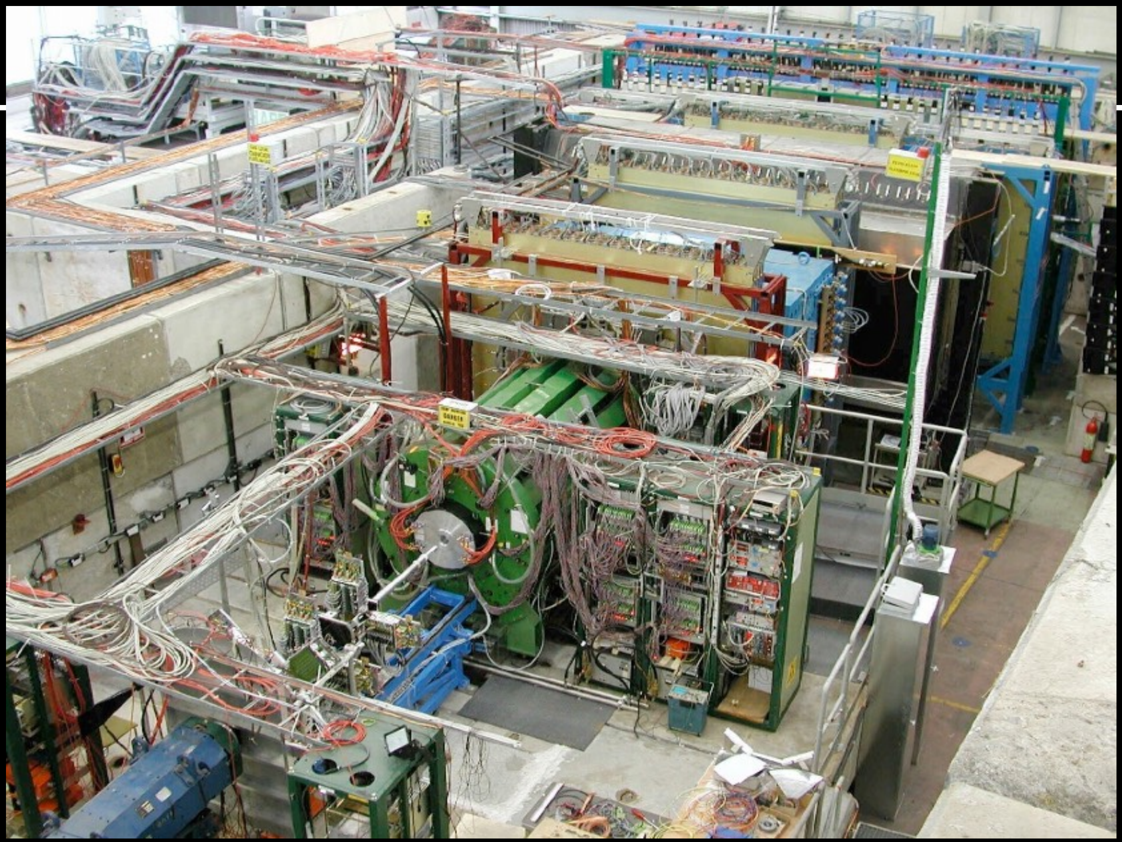
- T2K example: pion production phase space relevant for neutrino production
- *p* and θ are the momentum and angle in the lab frame

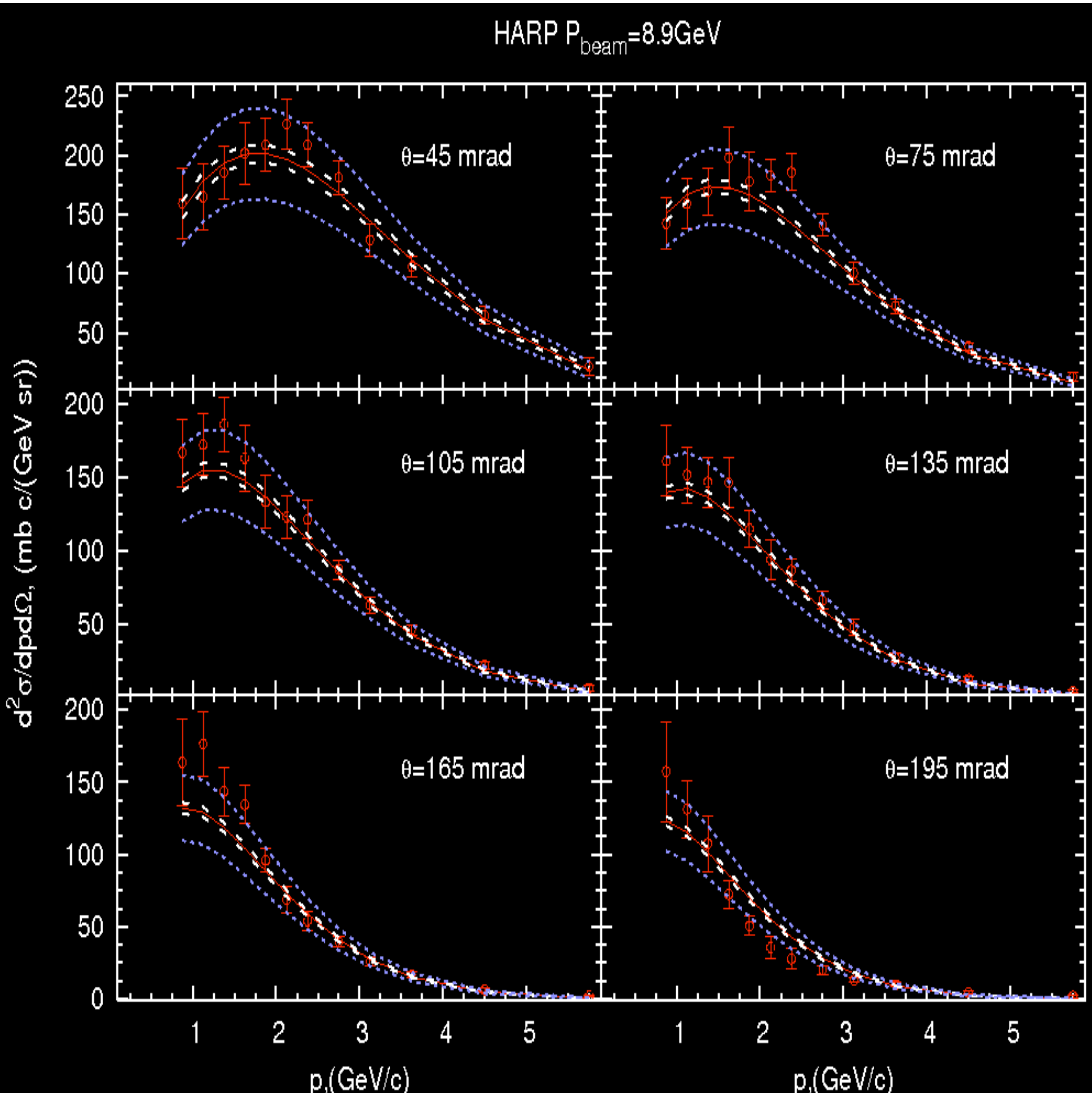
External measurements of meson production

- 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



Dedicated experiments

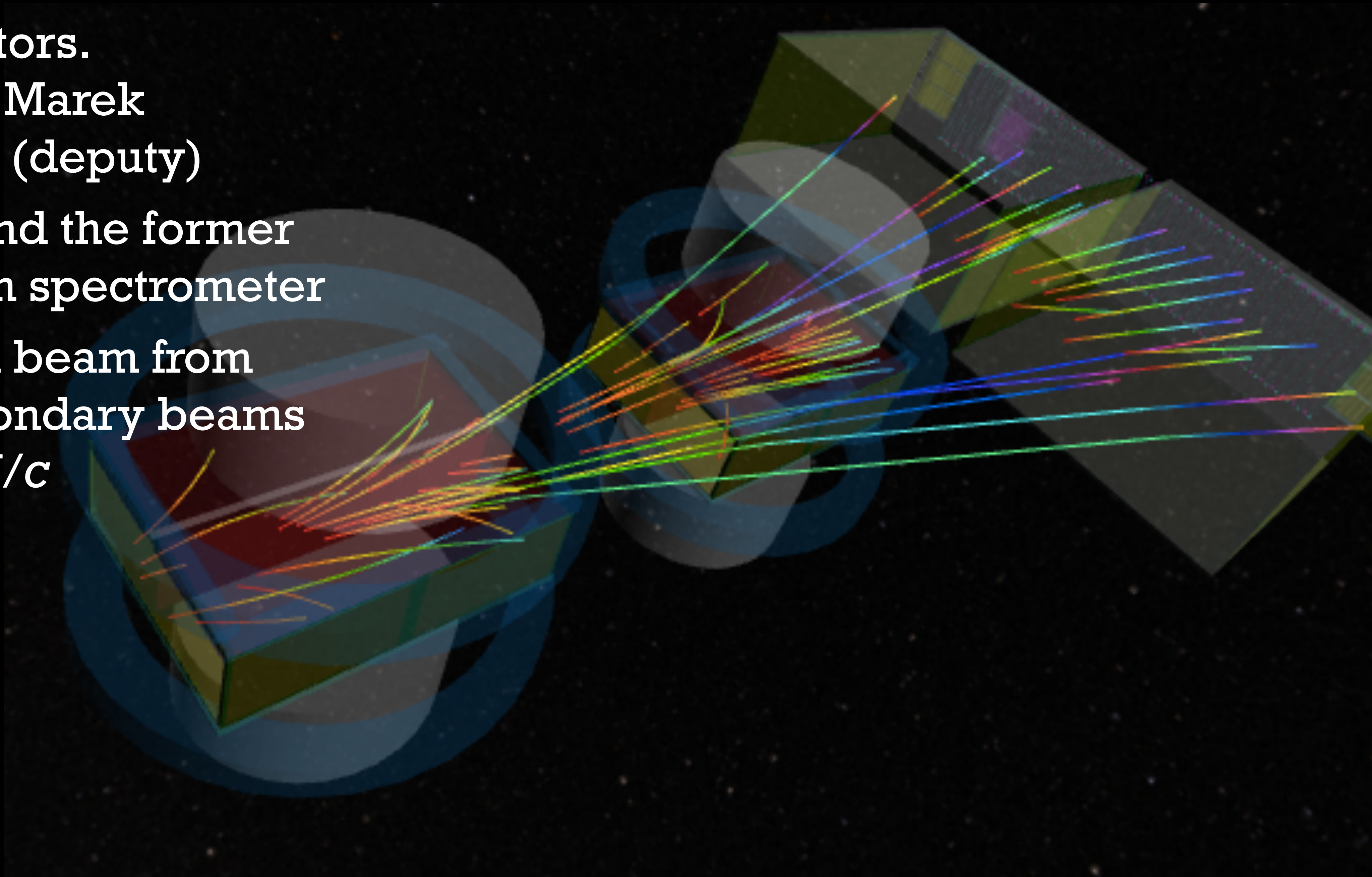




- In recent years, a loose program of hadron production measurements specifically for neutrino experiments has been underway
- Started with HARP experiment at CERN, which measured production from 8 GeV protons (for studying Booster Neutrino Beam) and from 12 GeV protons (for studying K2K beam).
- NA61 has been measuring since 2007

NA61: The SPS Heavy Ion and Neutrino Experiment

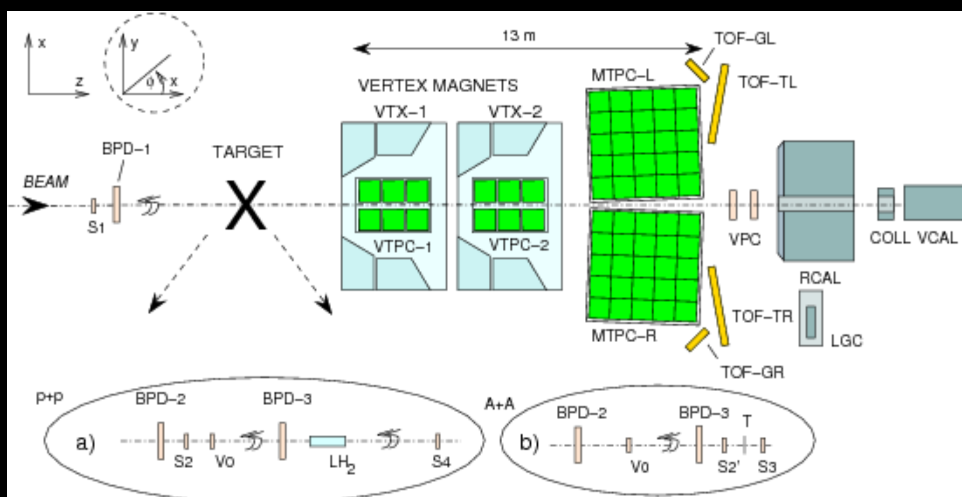
- Fixed-target experiment using H2 beam at CERN SPS
- ~150 collaborators. Spokespeople: Marek Gazdzicki, EDZ (deputy)
- Designed around the former NA49 heavy-ion spectrometer
- Primary proton beam from CERN SPS, Secondary beams ~25 to 350 GeV/*c*



NA61: The SPS Heavy Ion and Neutrino Experiment

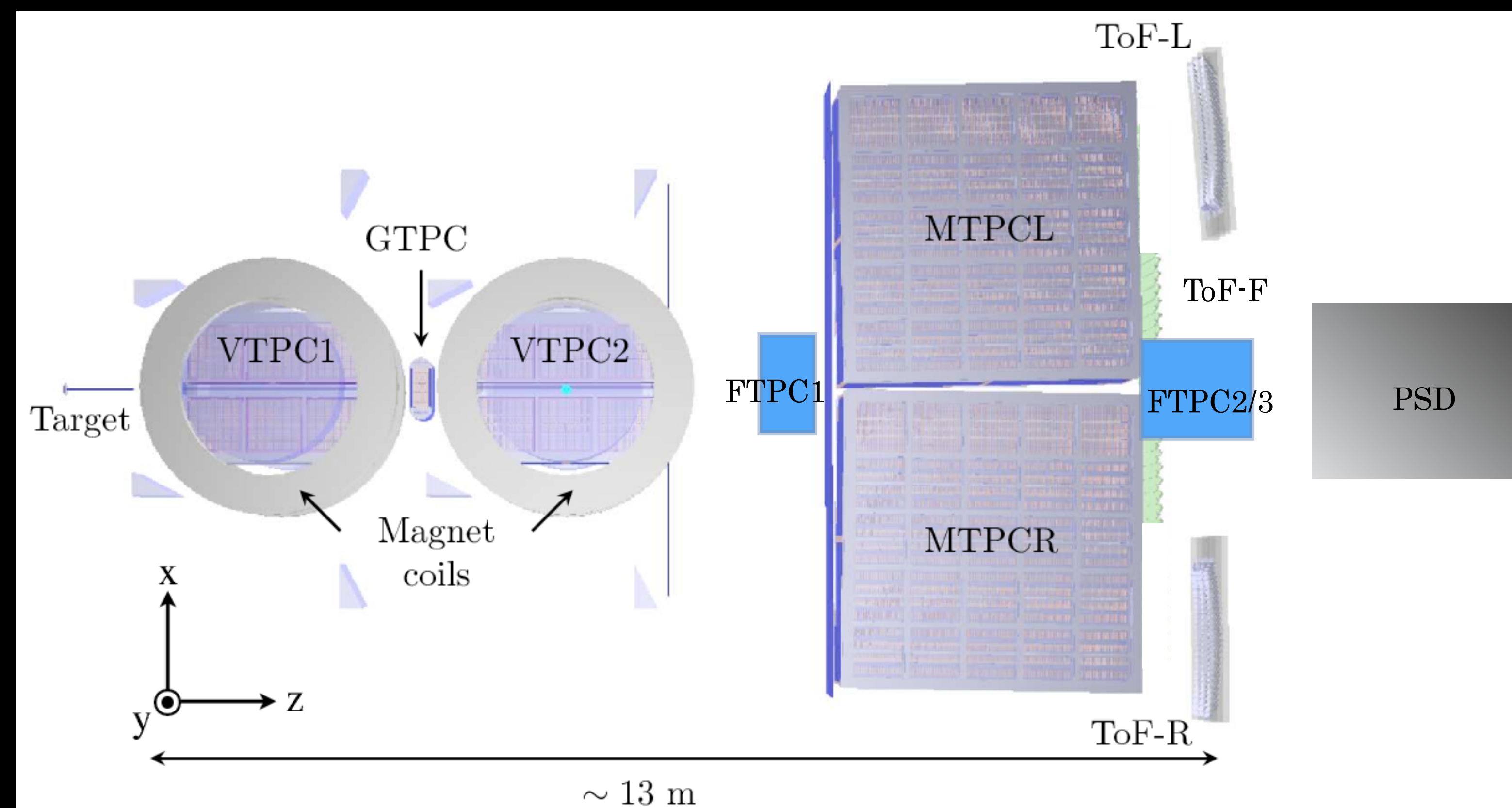
- Diverse physics program includes
  - Strong interactions/heavy ion physics
    - Onset of QCD deconfinement
    - Search for critical point
    - Open-charm production
  - Hadron production for neutrino beams
  - Cosmic ray production
    - Hadron production for air-shower model predictions
    - d/$\bar{d}$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

NA61 detector system



NA49

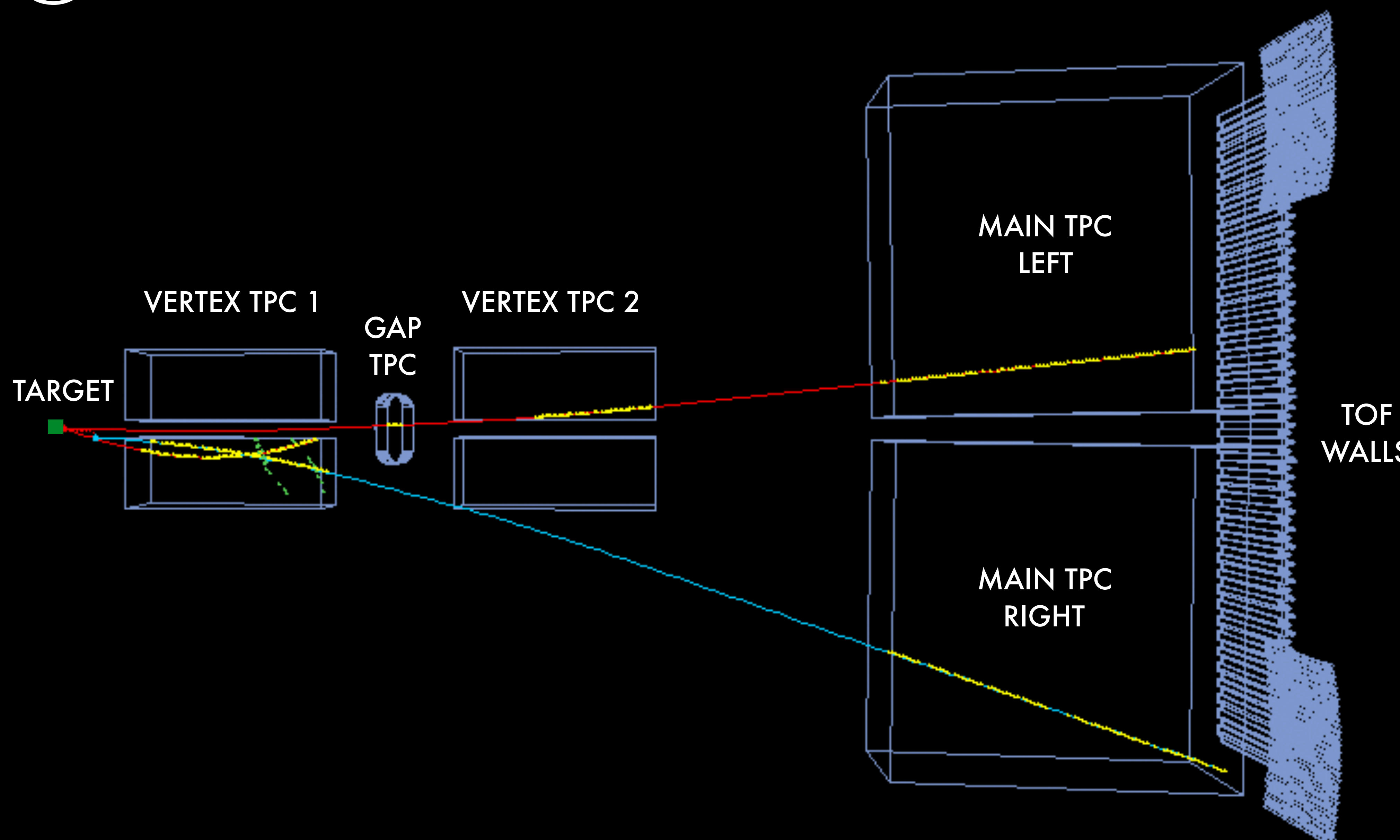
NA61



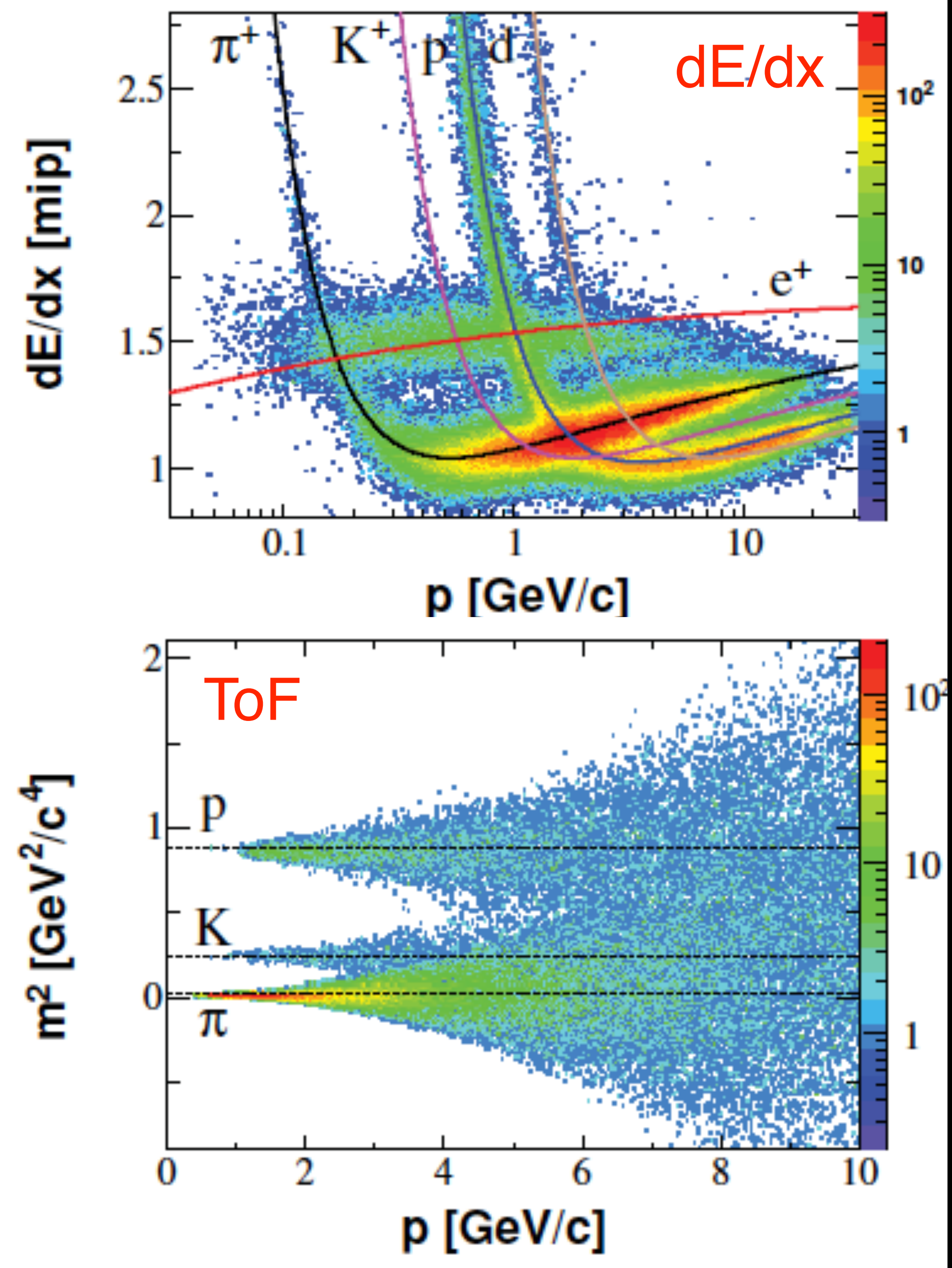
- Detailed beam instrumentation including PID and tracking before the target
- Several large-acceptance TPCs, two superconducting analysis magnets
- Scintillator-based time-of-flight detectors
- Projectile Spectator Detector: forward hadron calorimeter

Event display

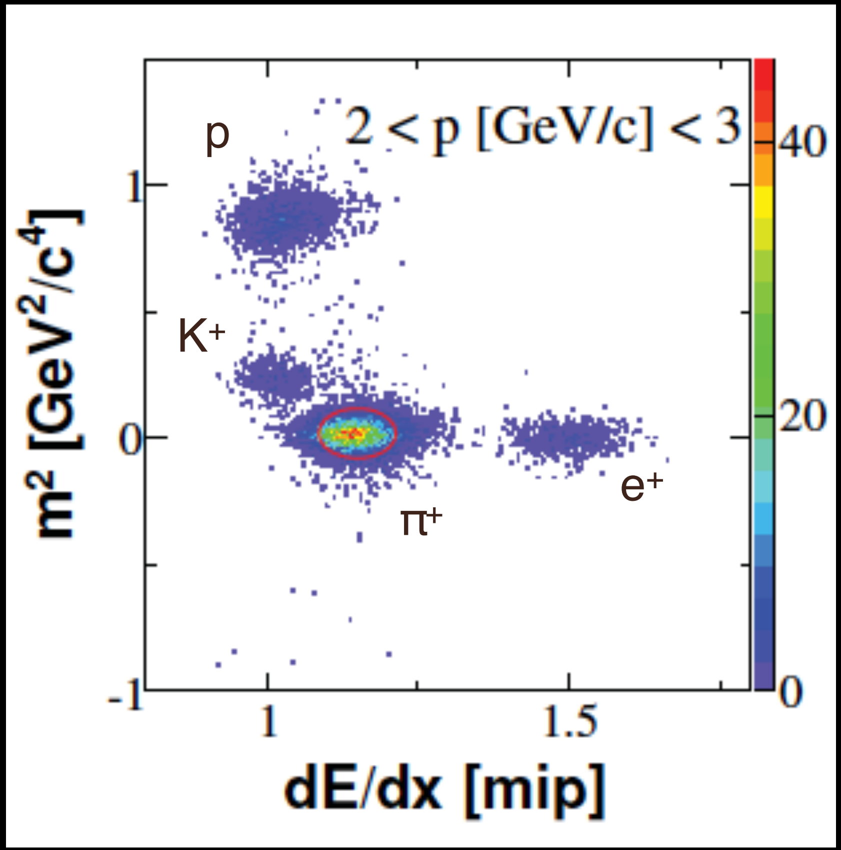
p+C @ 60 GeV



Particle identification



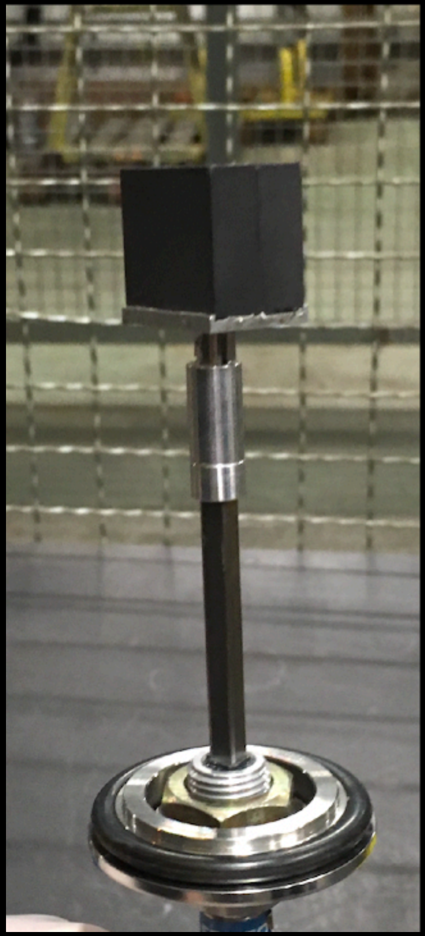
- Uses dE/dx in TPCs at higher momentum
- Transitions to TOF at lower p

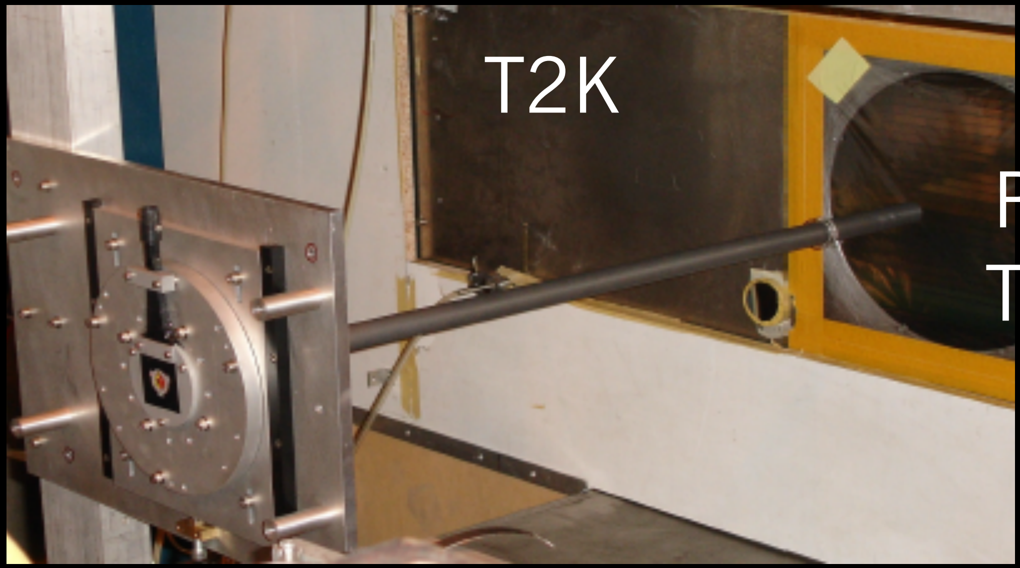


Twin approaches: thin- and replica-target measurements

- 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.
  - Have to make measurements specifically for each neutrino beam.
  - Usually use results to re-weight neutrino beam MC at surface of target

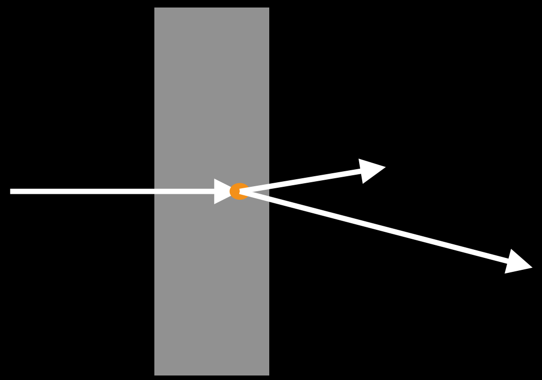
Graphite thin target (1.5 cm, 3.1% of λ_I)





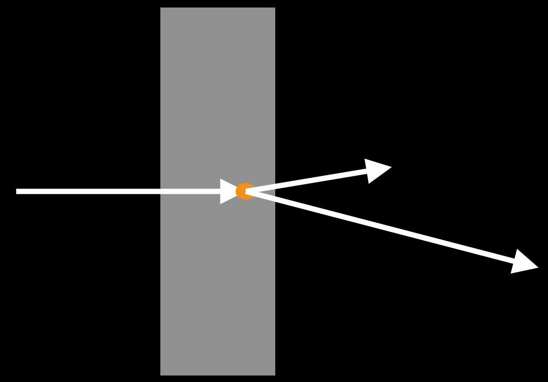
REPLICA TARGETS

Thin-target measurements



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

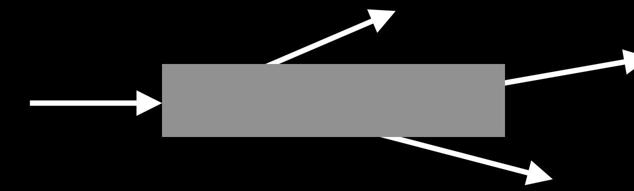
Thin-target measurements



- 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 $d^2\sigma/dpd\theta = \sigma_{prod} \cdot d^2n/dpd\theta$
- We can then use these to calculate weights for each interaction in a neutrino beam Monte Carlo:

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

Replica-target measurements

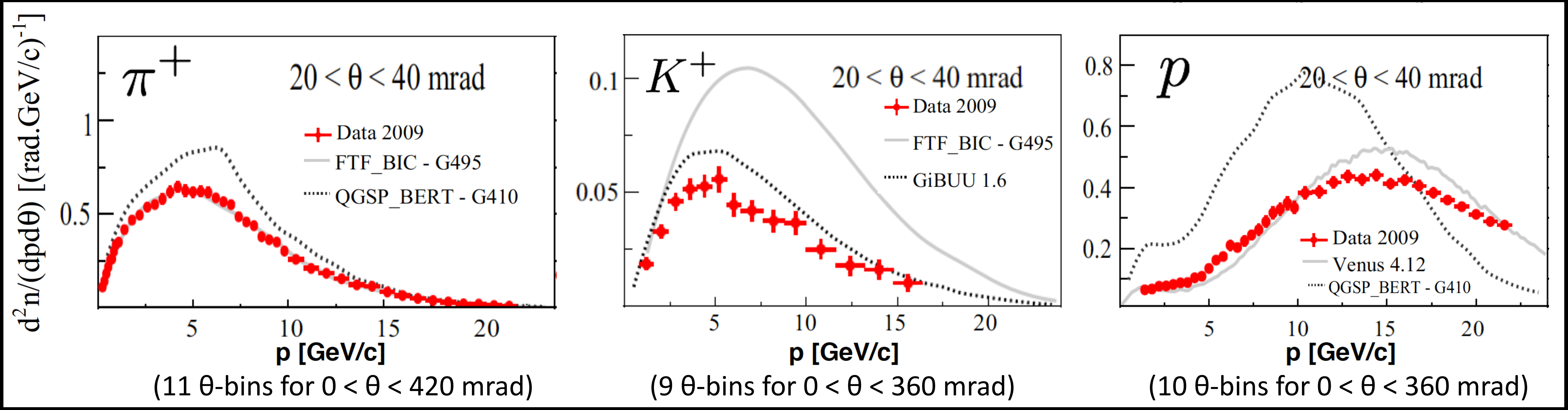


- Exact target geometry of a particular neutrino beam (T2K: 90cm cylinder, NuMI/NOvA: 120cm of graphite fins)
- Most events have primary and secondary interactions in the target
- Measure particle yields vs not only p and θ, but also exit z along target (and possibly ϕ for targets like NuMI's that aren't 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

NA61/SHINE measurements for T2K

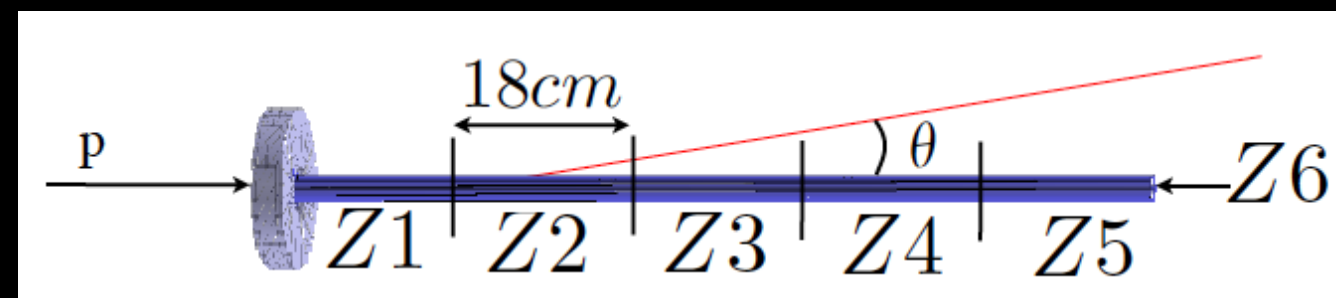
- NA61/SHINE took thin- and thick- target data with 30 GeV/*c* protons specifically for T2K in **2007 (thin) 2009 (thin and replica)**, and **2010 (replica)**.
- Eight NA61/SHINE publications have come out of these data sets — final one just submitted!
- Thin target:
  - total cross-section and $\pi^{\pm}$ spectra measurements (Phys. Rev. C84 034604 (2011))
  - K+ spectra measurement (Phys. Rev. C85 035210 (2012))
  - K^0_S and Λ spectra measurements (Phys. Rev. C89 (2014) 025205)
  - total cross-section and $\pi^{\pm}$,$K^{\pm}$, p, K^0_S, and Λ spectra measurements (Eur. Phys. J. C76 84 (2016))
- Replica target:
  - methodology, π+/- yield measurement (Nucl. Instrum. Meth. A701 99-114 (2013))
  - π+/- yield measurement (Eur. Phys. J. C76 617 (2016))
  - π+/-, p, and K+/- yield measurements (Eur. Phys. J. C79, no.2 100 (2019))
  - proton beam survival probability (arXiv:2010.11819, under review at PRD)

Thin-target results: p+C @ 30 GeV



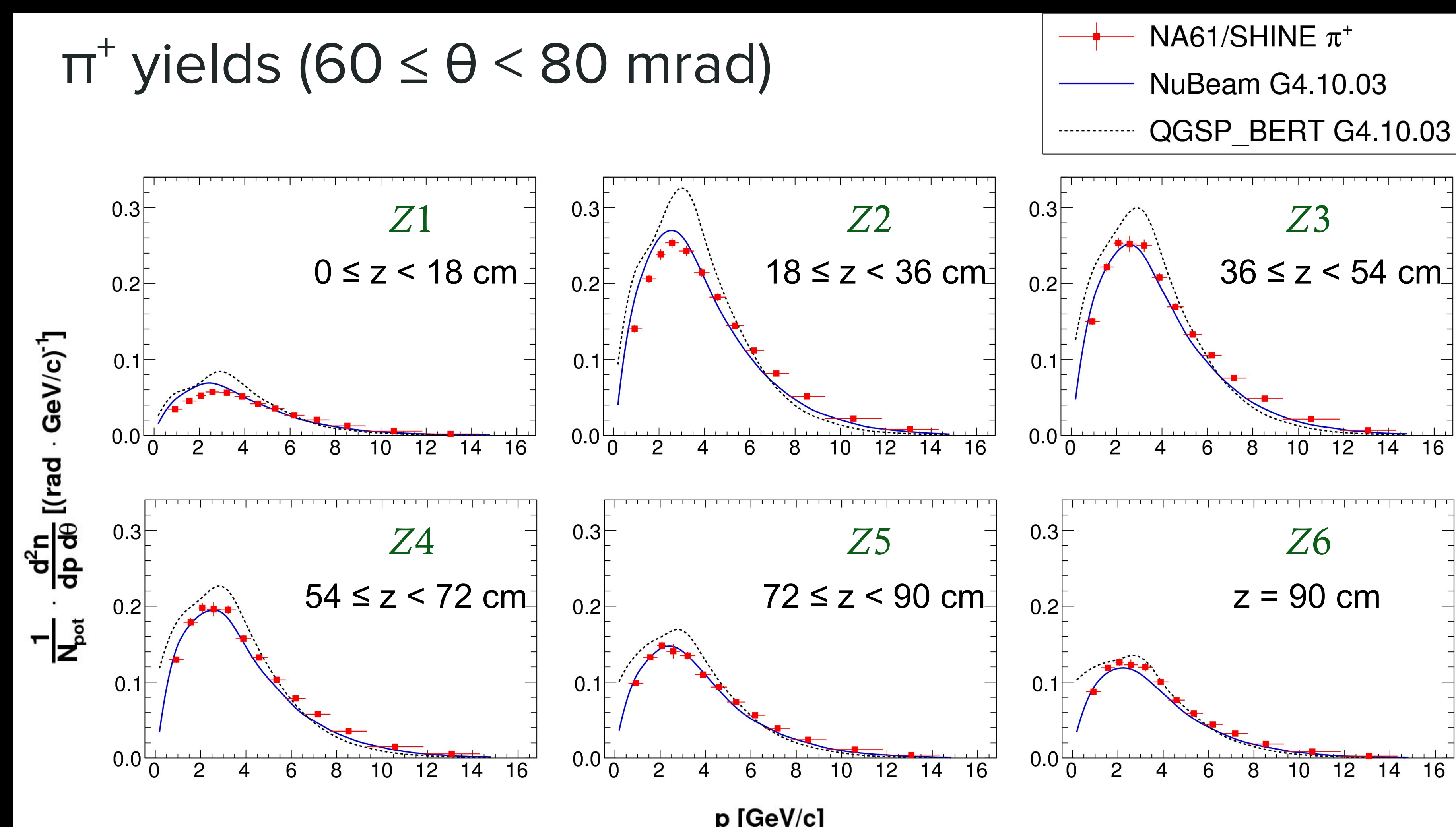
- One angle bin shown here for illustration
- MC generators fail badly for kaons and protons
- Published in Eur. Phys. J. **C76** 84 (2016): also contains yields of negative particles and neutral strange particles (V^0).

Recent result: full differential yields from T2K replica target



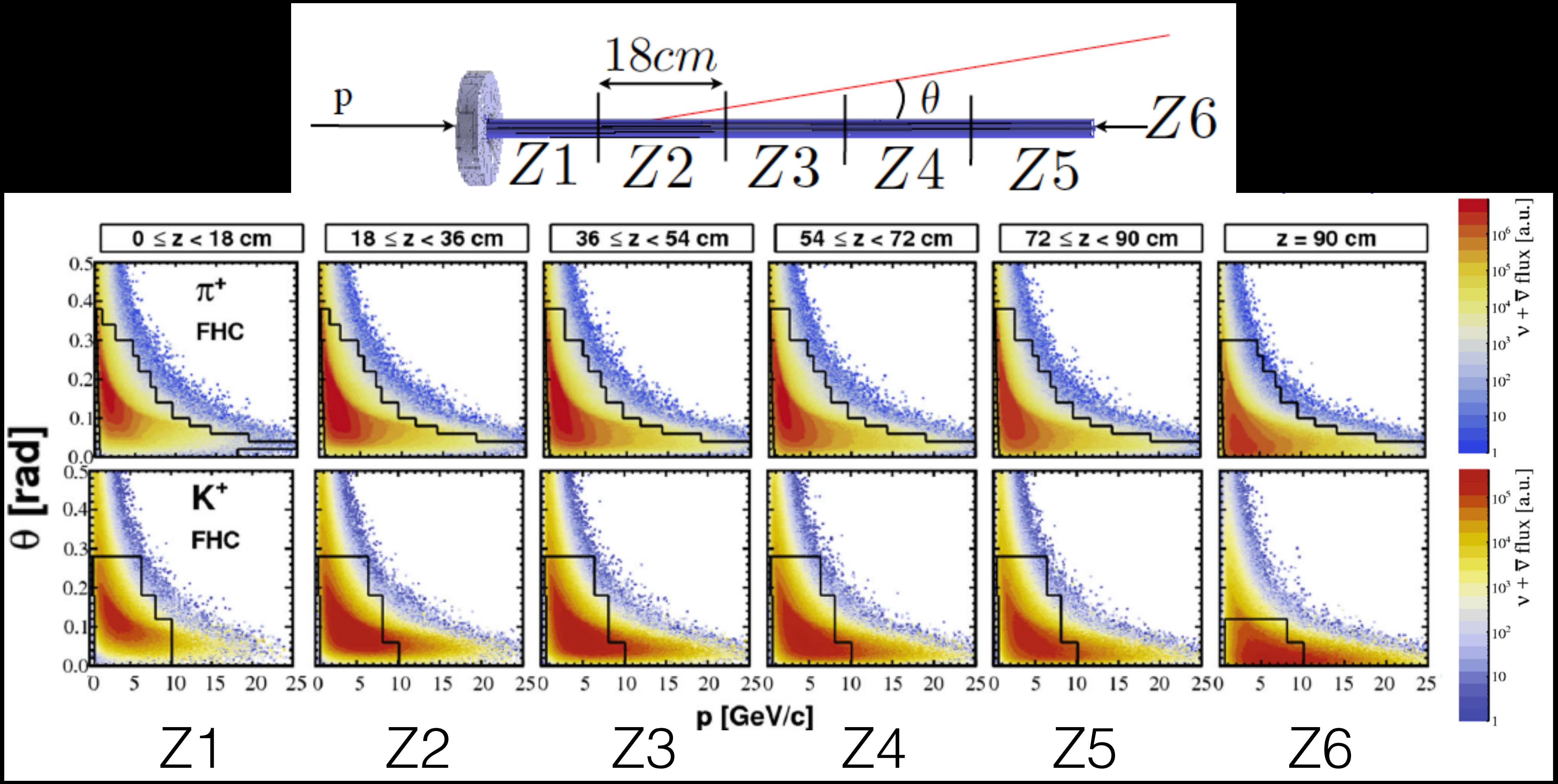
- *Eur.Phys.J.* **C 79** 2, 100 (2019)
- Showing one angle bin of π^+ for illustration.

  Also have π^-, $K^\pm$, p yields



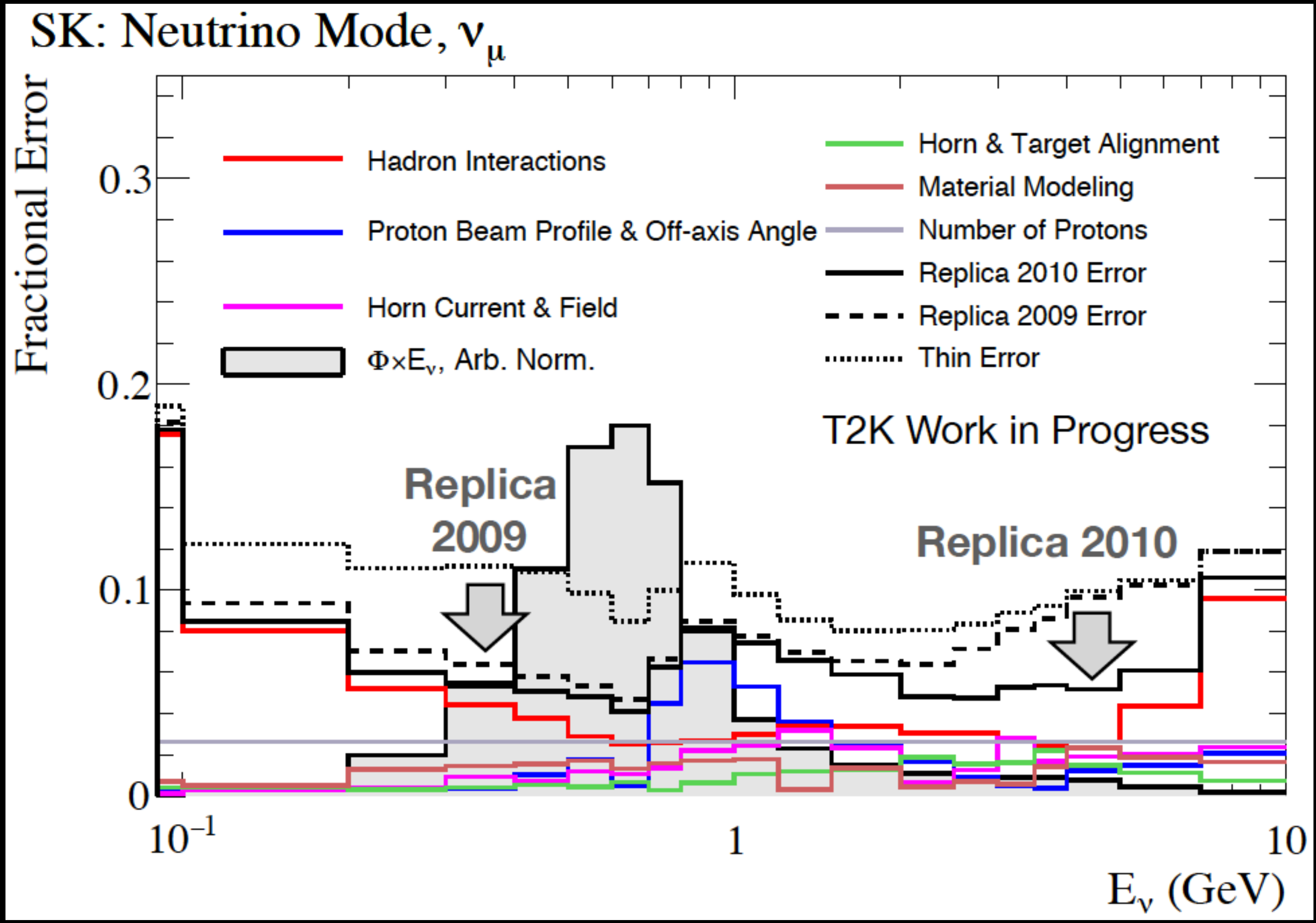
Equivalent result in T2K neutrino flux

- T2K beam simulation based on replica-target results



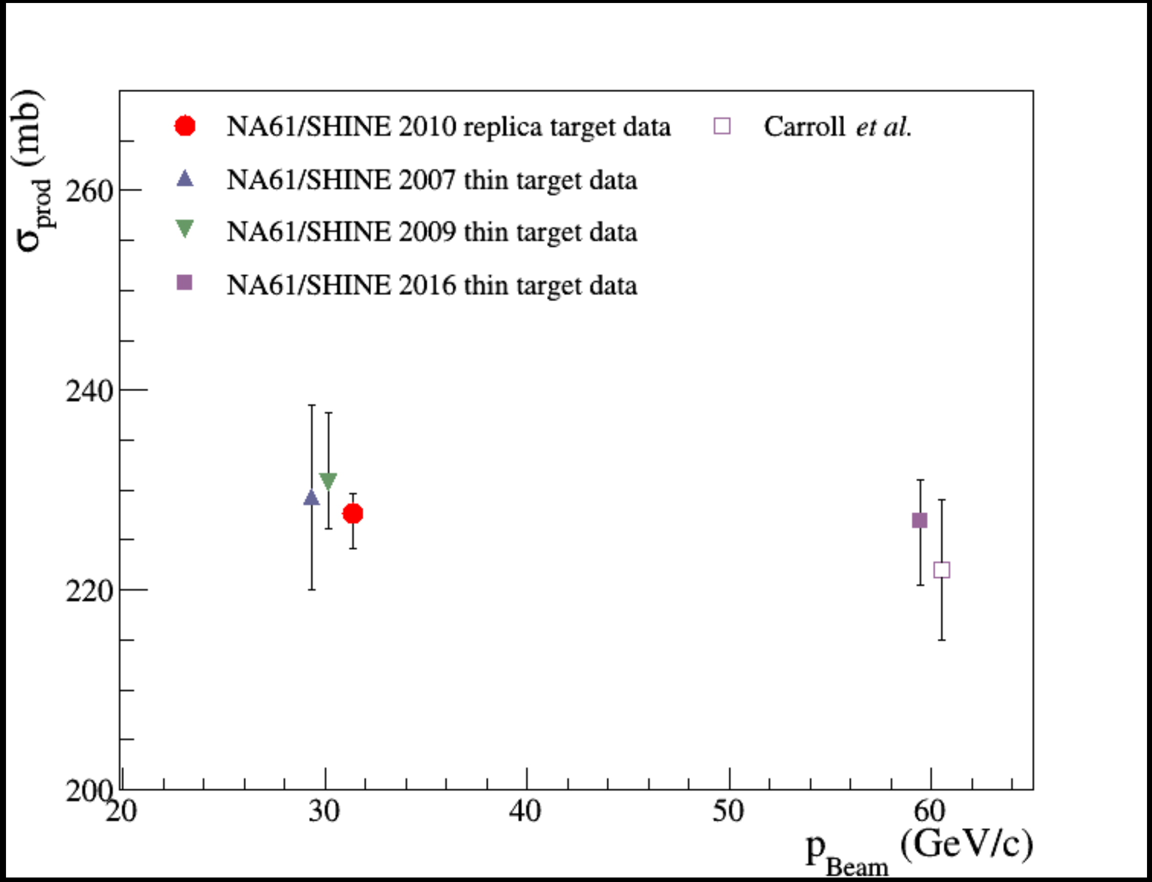
NA61/SHINE measurements for T2K

- 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)



New results for T2K replica target

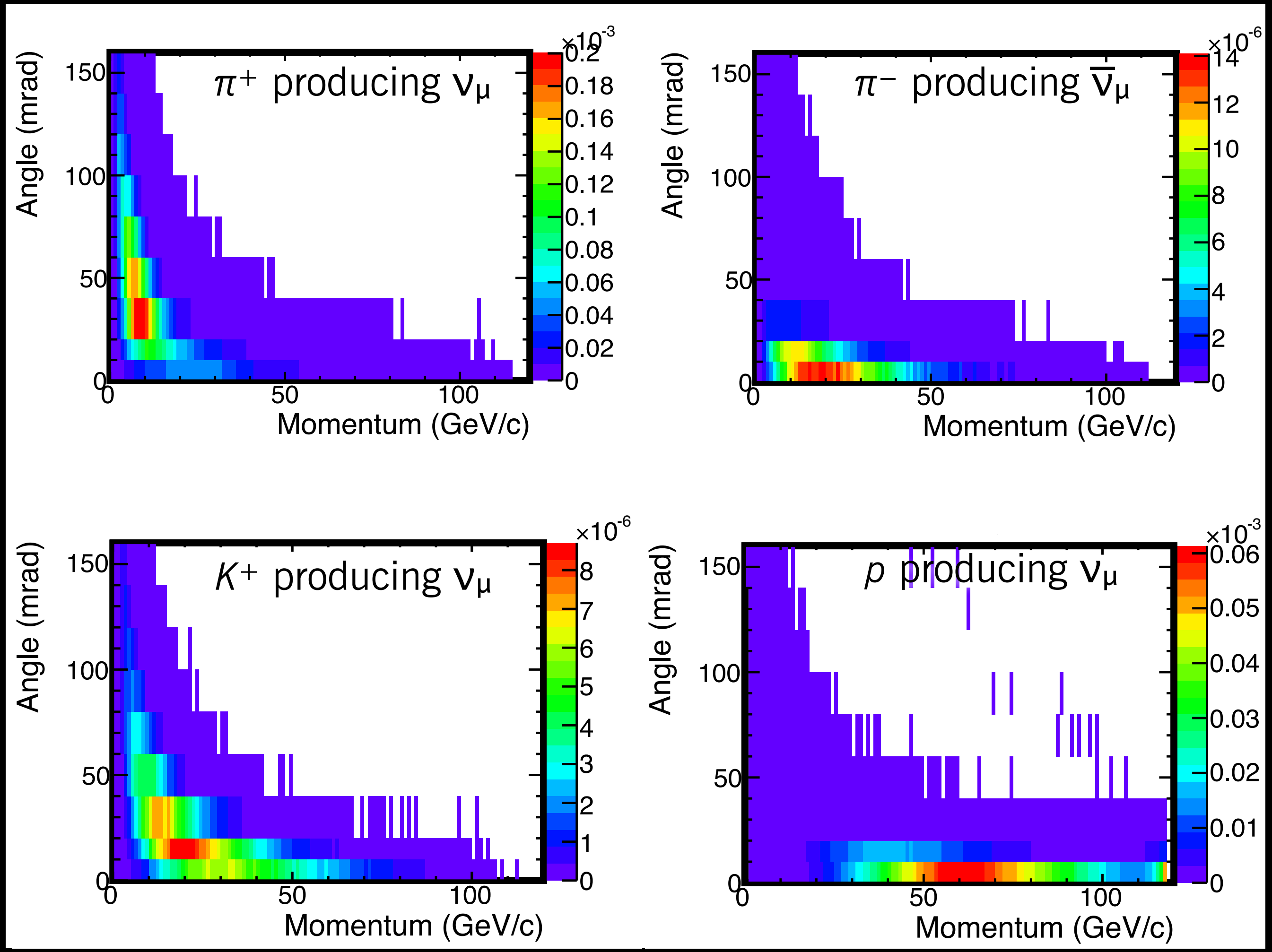
- Direct measurement of the production cross-section by measuring beam proton survival probability in the 90cm T2K replica target
- Used a special run with high vertex magnet field (Forward TPCs were not built yet) to bend beam protons into the main TPC
- Released last month:
  A. Acharya *et al.*,
  arXiv:2010.11819

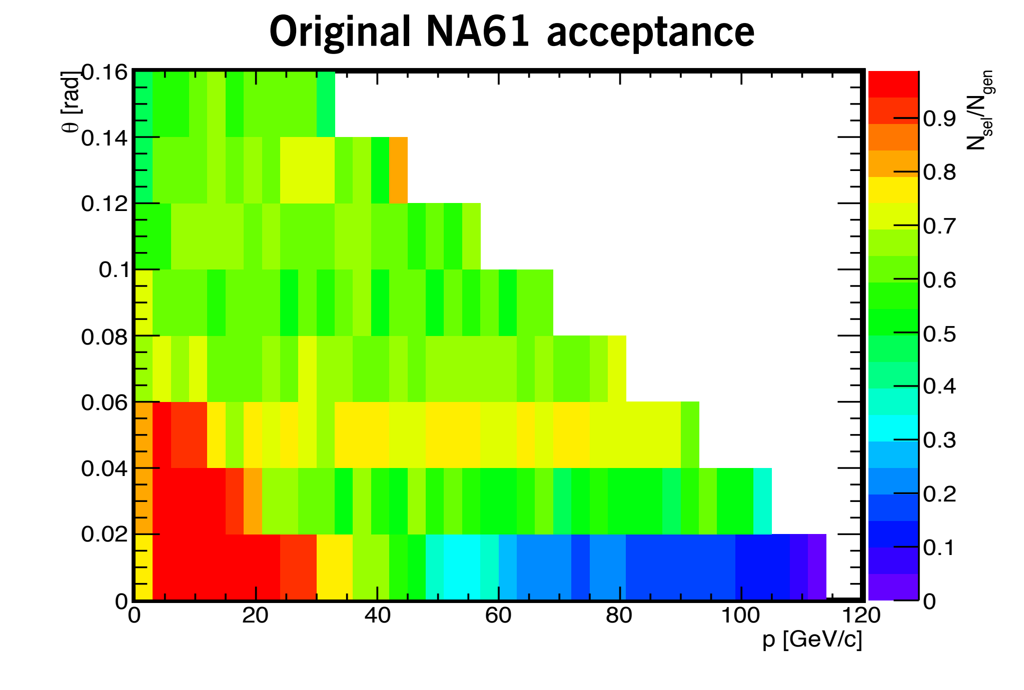


A second phase of NA61 neutrino measurements

- Four US-based groups joined NA61 in 2014 to make measurements specifically for the Fermilab-based neutrino program.
- Motivation: new coverage will be needed for future experiment DUNE, can help existing experiments as well in shorter term
- US-funded project made specific upgrades:
  - Forward tracking system
  - New readout electronics for time-of-flight detector
- Data collected in 2015-18 for this program

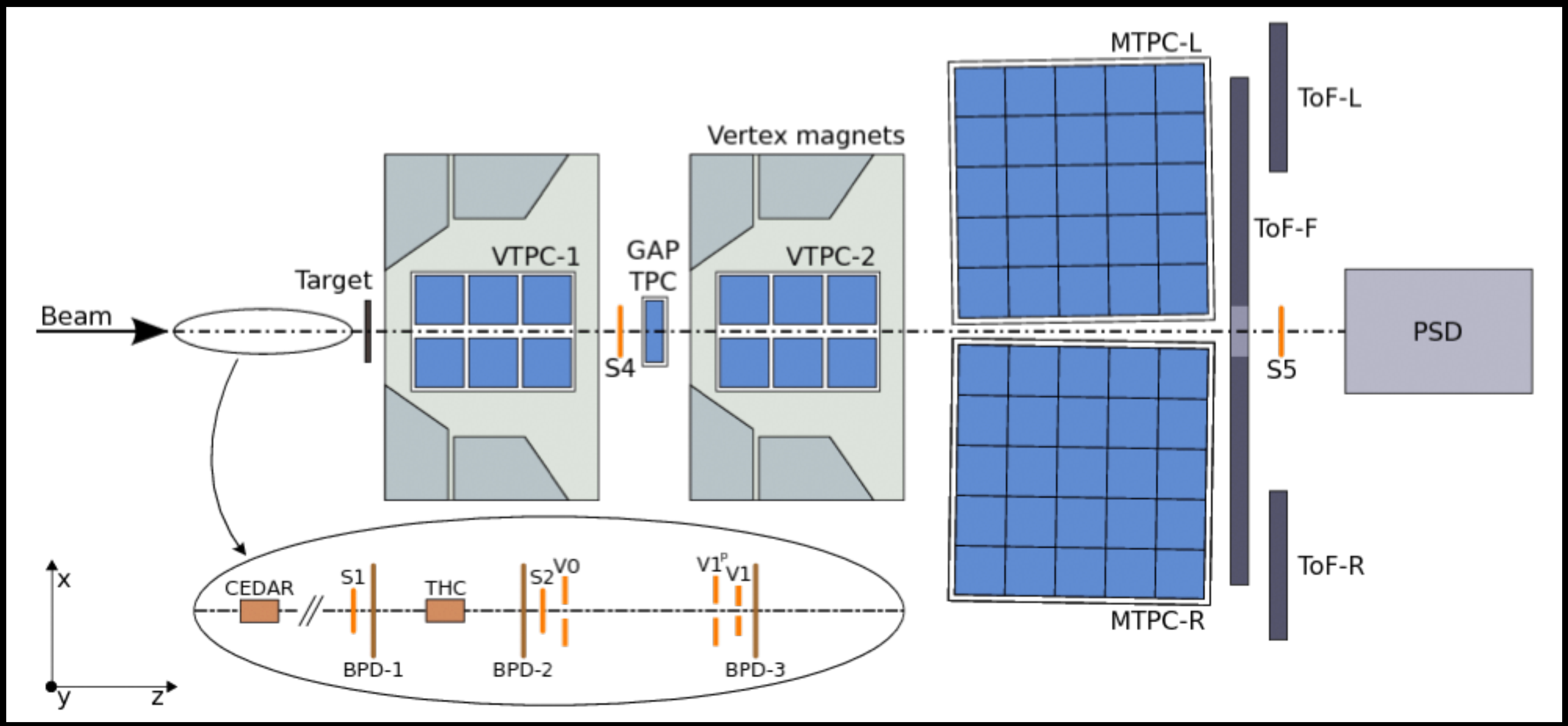
Measurements for LBNF/DUNE flux: need to expand acceptance





- Contribution to DUNE far detector neutrino flux, for Nov 2017 DUNE Optimized and Engineered Beam design (120 GeV/*c* protons)
- NA61 acceptance had a hole in forward region: particularly important for proton production
- New forward TPCs built to add coverage here

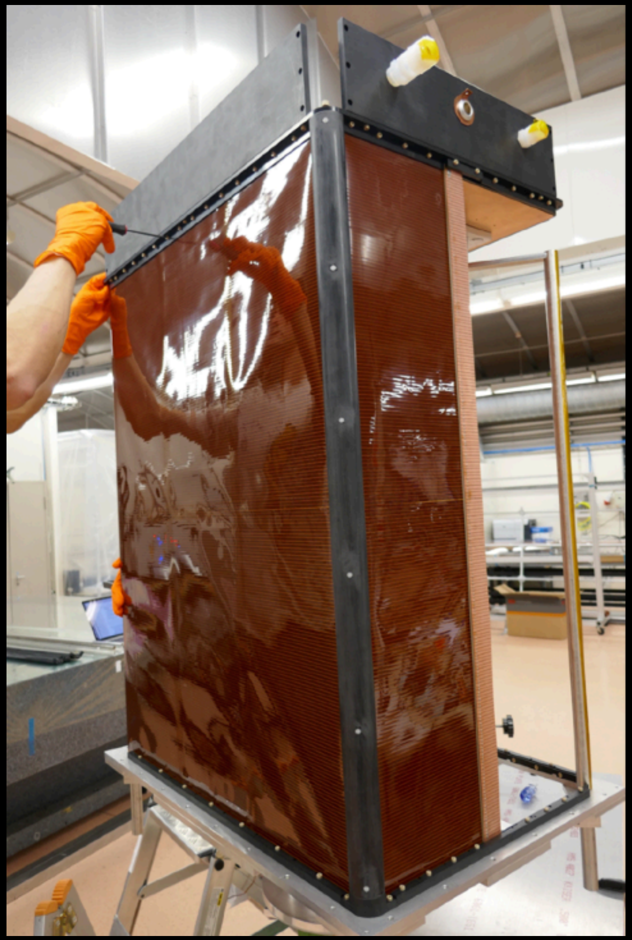
NA61 acceptance

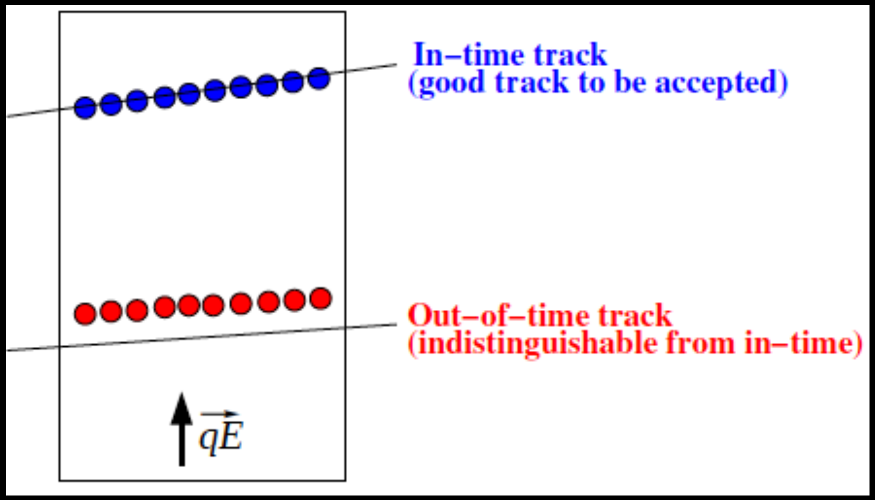


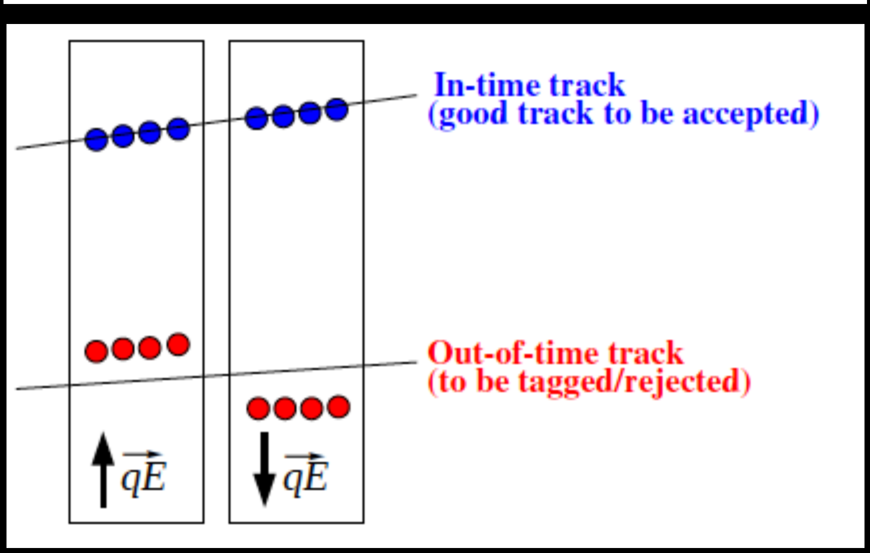
- NA61 setup before 2017 had a hole in the acceptance where the beam passes through
- Hole due to heavy ion needs: intense beam can't go through chambers

Forward TPCs

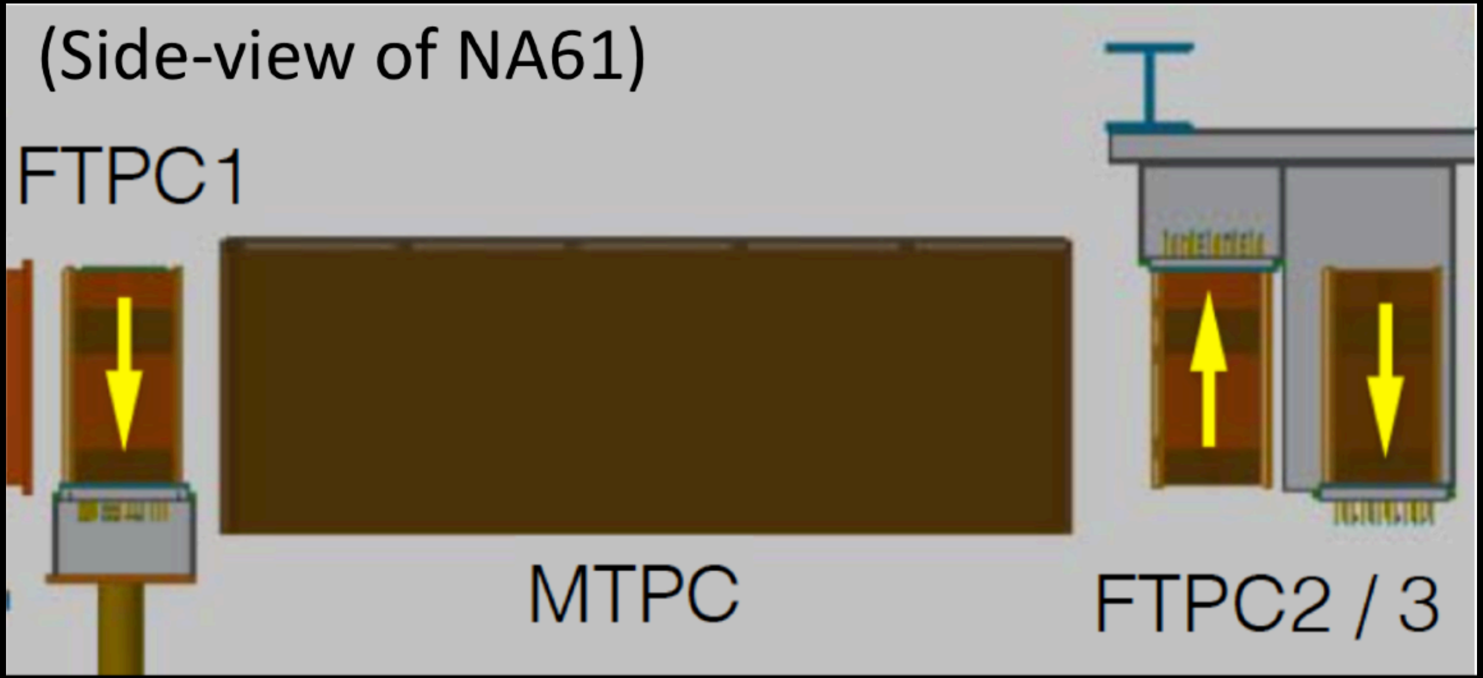
- New TPCs have been built for the neutrino program to fill the hole and complete the acceptance in the forward region
- Low-mass design with light plastic frame and thin printed Kapton field cage; FTPC1 removable for heavy-ion running
- Uses same electronics as other TPCs
- High rates in beam region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



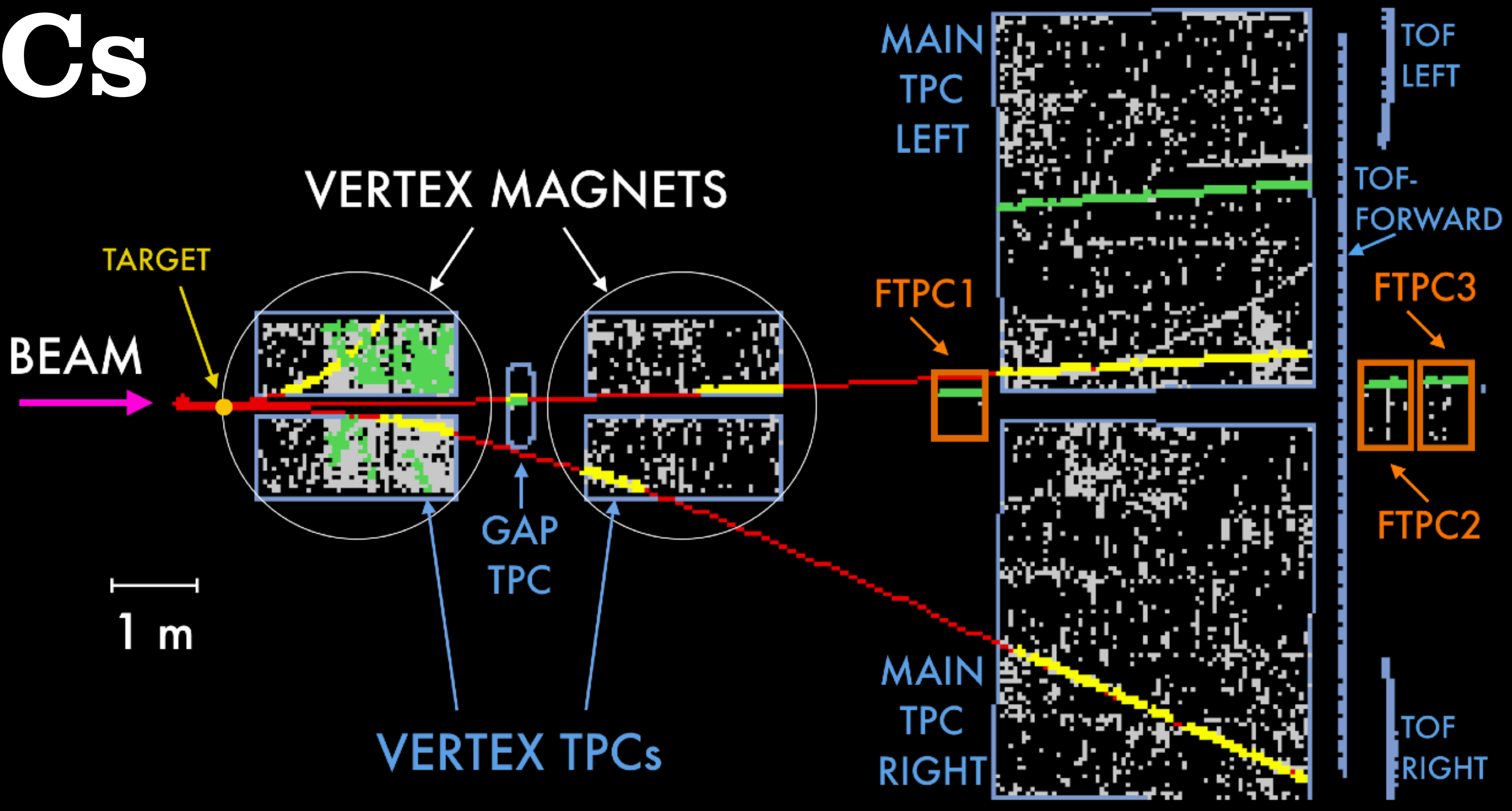




- Out-of-time tracks in a TPC are reconstructed as shifted in drift direction
- Successive field volumes have opposite drift direction: out-of-time tracks appear discontinuous and can be easily rejected



Forward TPCs

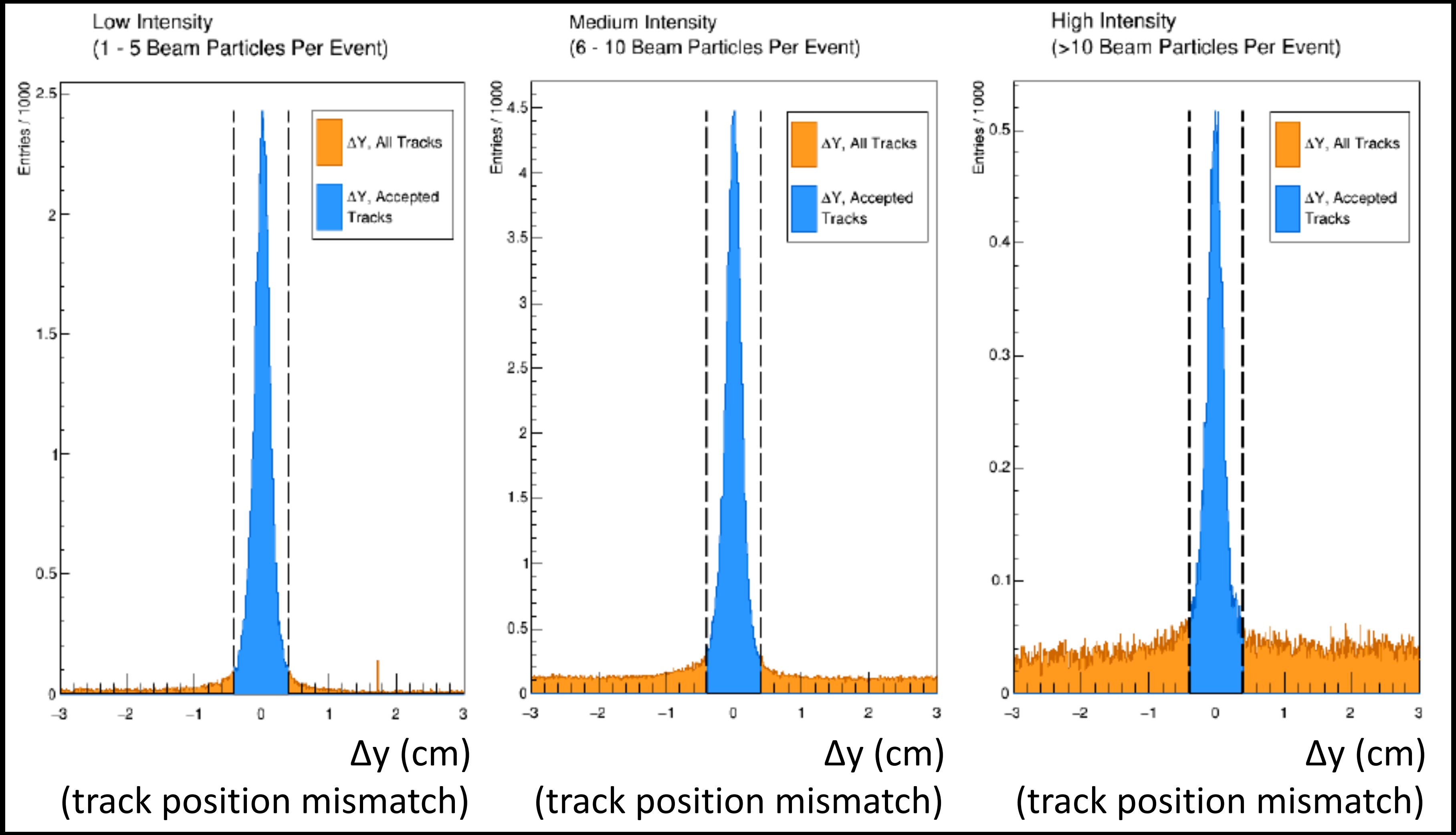


- FTPCs installed 2016-17, used in 2017 and 2018 data run
- Chambers work well
- Event display above from 2017 data with local (green) tracks reconstructed
- New global tracking algorithm in final development stage

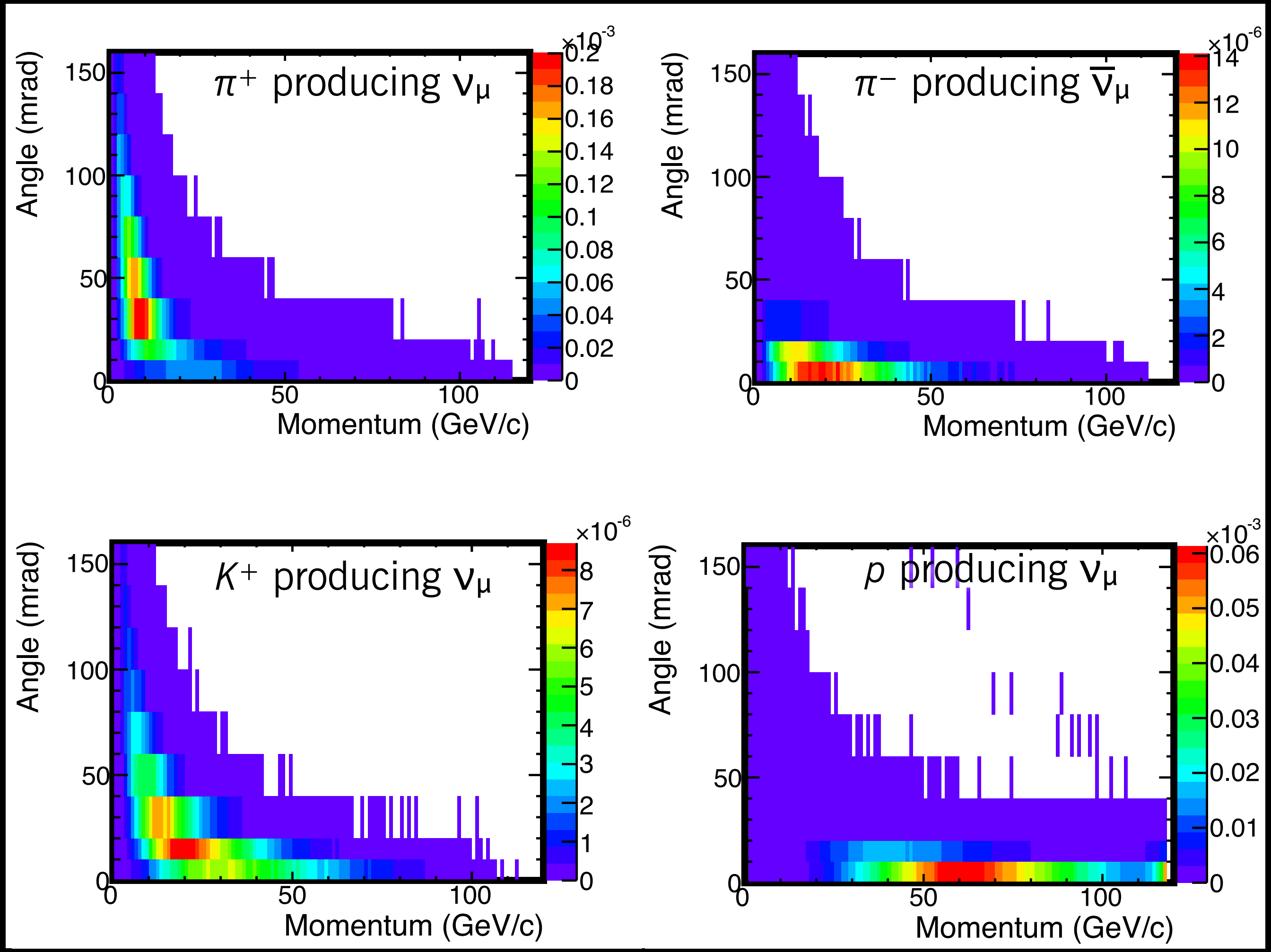
Tandem TPC data

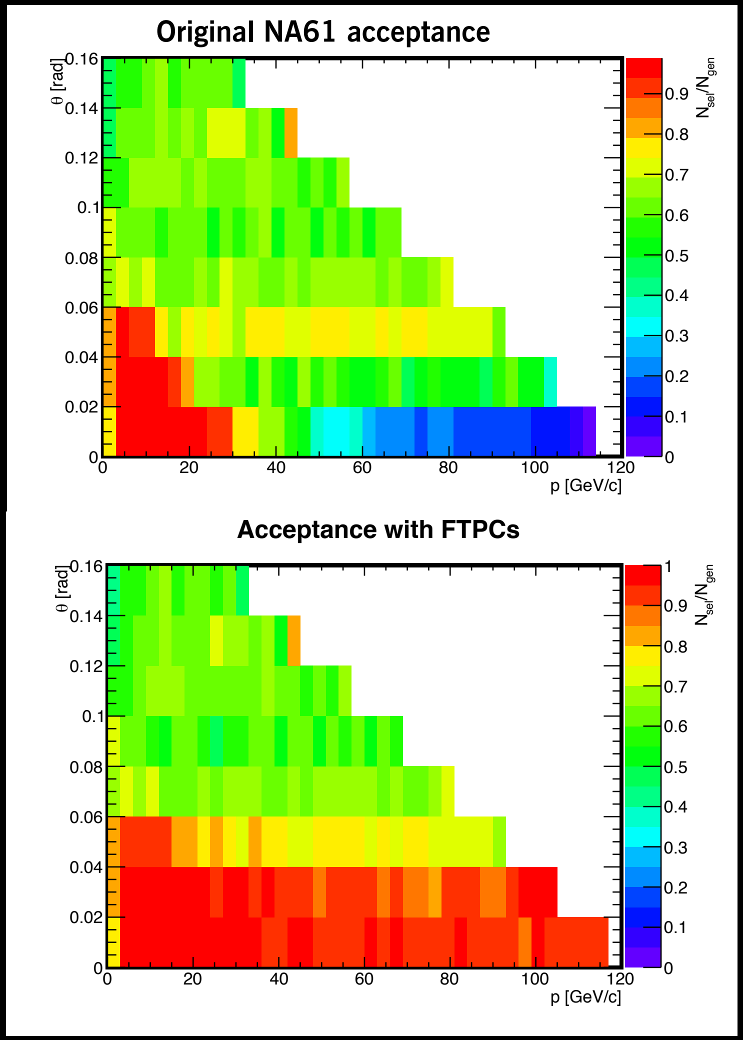
- Out-of-time track rejection: fraction of these tracks scales with intensity; can be rejected by cutting out tracks that don't match up between chambers

B. Rumberger *et al.*, *JINST* 15 (2020) P07013



Measurements for LBNF/DUNE flux: acceptance with new FTPCs

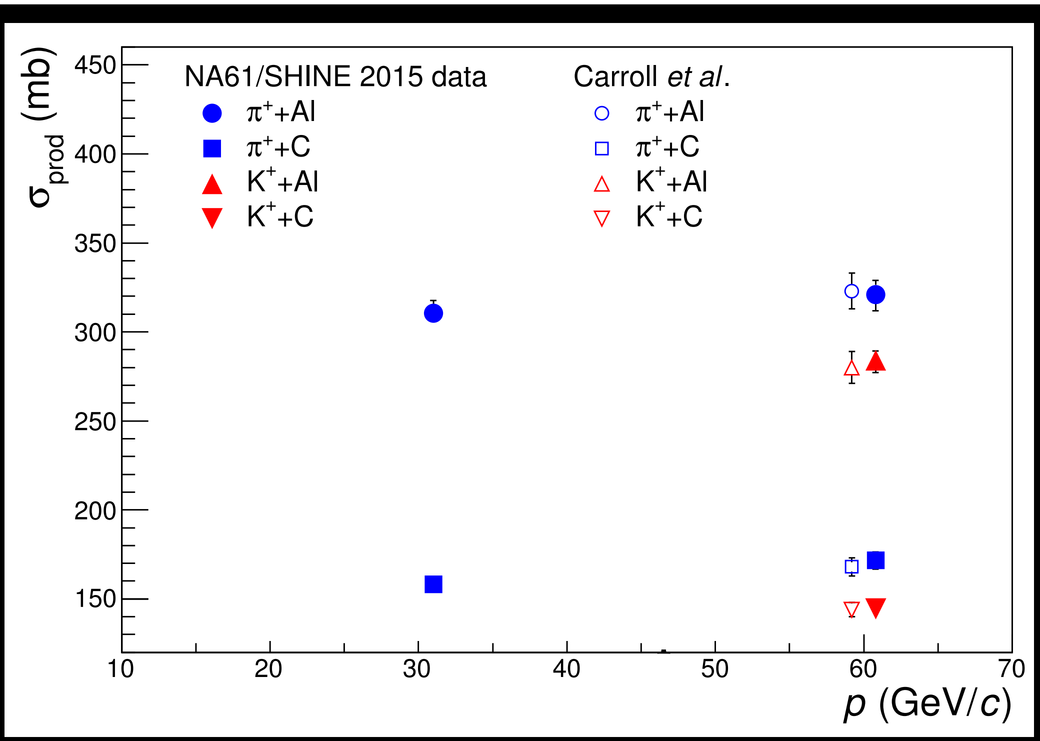


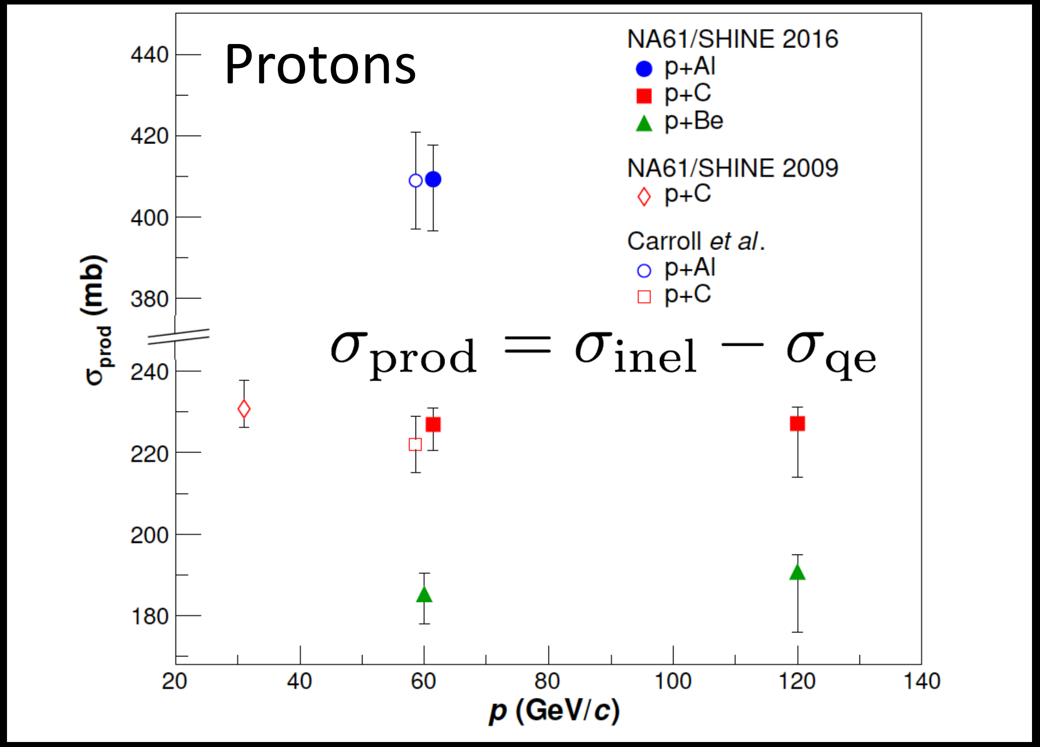


- New forward TPCs make measurements of important secondary protons possible
- Acceptance is now well-matched to secondaries that generate neutrinos in DUNE (and NuMI too!)
- First analysis with new Forward TPCs (120 GeV/c protons on thin graphite target) is expected in the next couple of months

First results: total production cross-sections on nuclear targets

- 2015 data set collected with no magnetic field due to failure of old superconducting magnets: no momentum measurements
- Pion and kaon scattering on carbon and aluminum
- Published total production and total inelastic cross section measurements for data without magnetic field
- pion/kaon scattering: Phys.Rev. **D98** 052001 (2018); proton scattering: Phys.Rev. **D100** 112004 (2019)
- Note: here $\sigma_{prod} = \sigma_{total} - \sigma_{el} - \sigma_{qe}$, requires new hadrons to be produced. Also $\sigma_{inel} = \sigma_{total} - \sigma_{el}$. This terminology not always used consistently in community or in hadronic event generators.
- Before, NuMI had 5% error on pion interactions, 10-30% for kaons, and had to extrapolate from other energies for protons





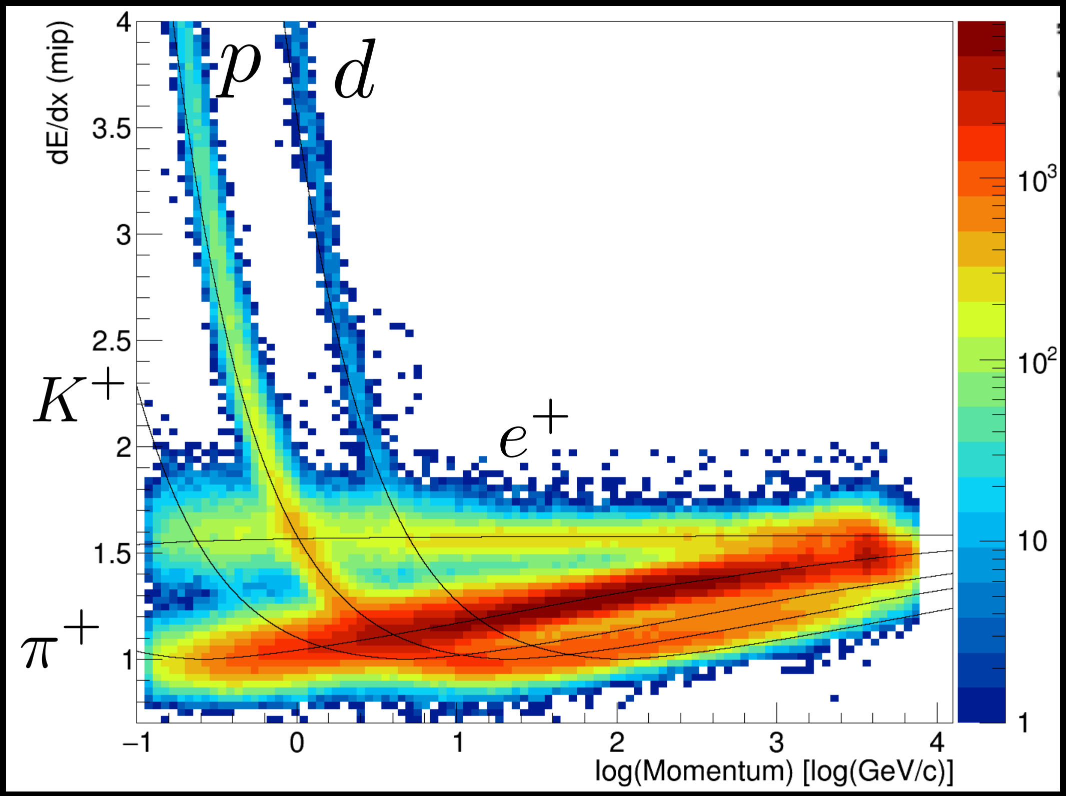
NA61 2016-17 neutrino data
Thin targets

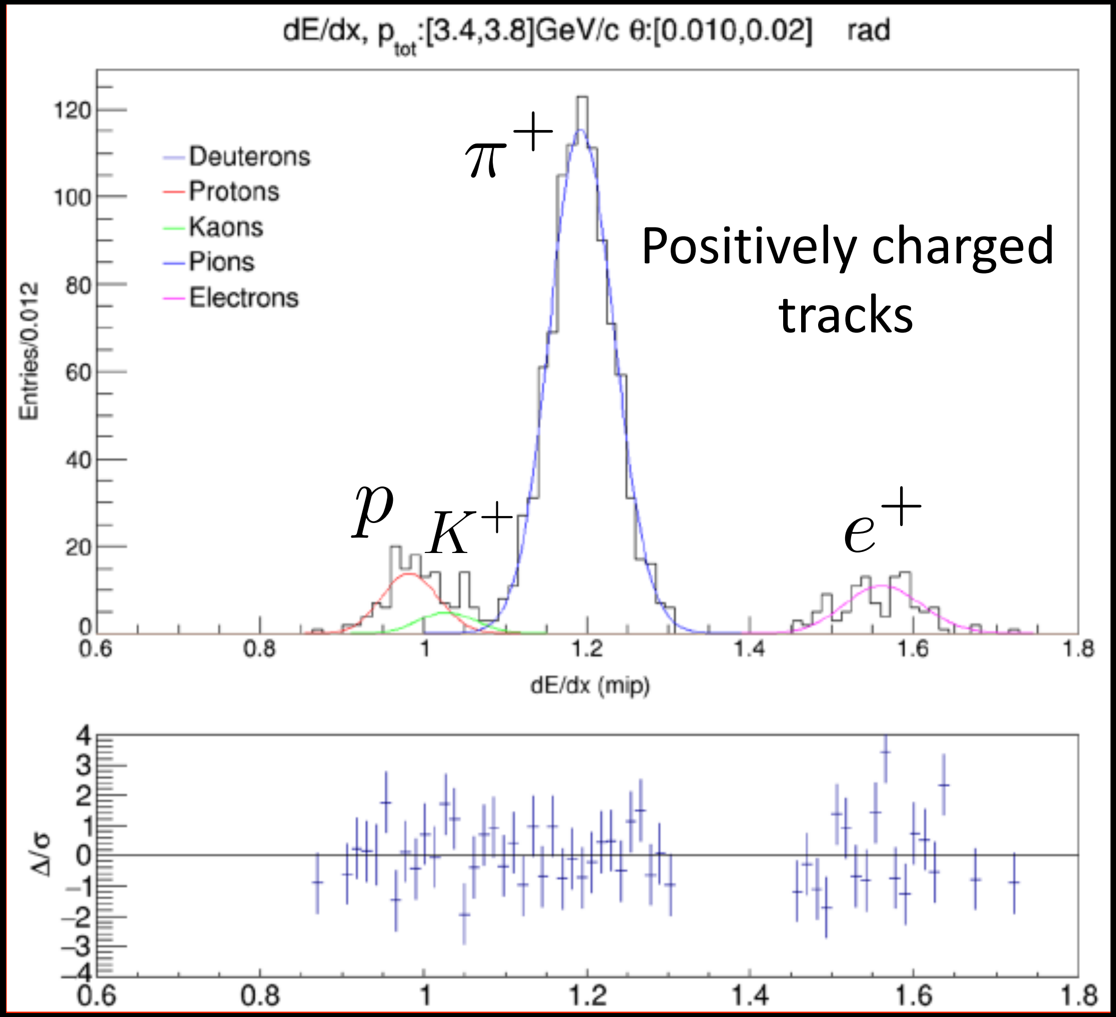
2016	2017
p + C @ 120 GeV/c	π^+ + Al @ 60GeV/c
p + Be @ 120 GeV/c	π^+ + C @ 30 GeV/c
p + C @ 60 GeV/c	π^- + C @ 60 GeV/c
p + Al @ 60 GeV/c	p + C @ 120 GeV/c (w FTPCs)
p + Be @ 60 GeV/c	p + Be @ 120 GeV/c (w FTPCs)
π^+ + C @ 60GeV/c	p + C @ 90 GeV/c (w FTPCs)
π^+ + Be @ 60 GeV/c	

- 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
- Analysis is progressing on some, completed on others
- Each measurement will be a point for interpolation in MC generators

Thin-target charged hadron spectra

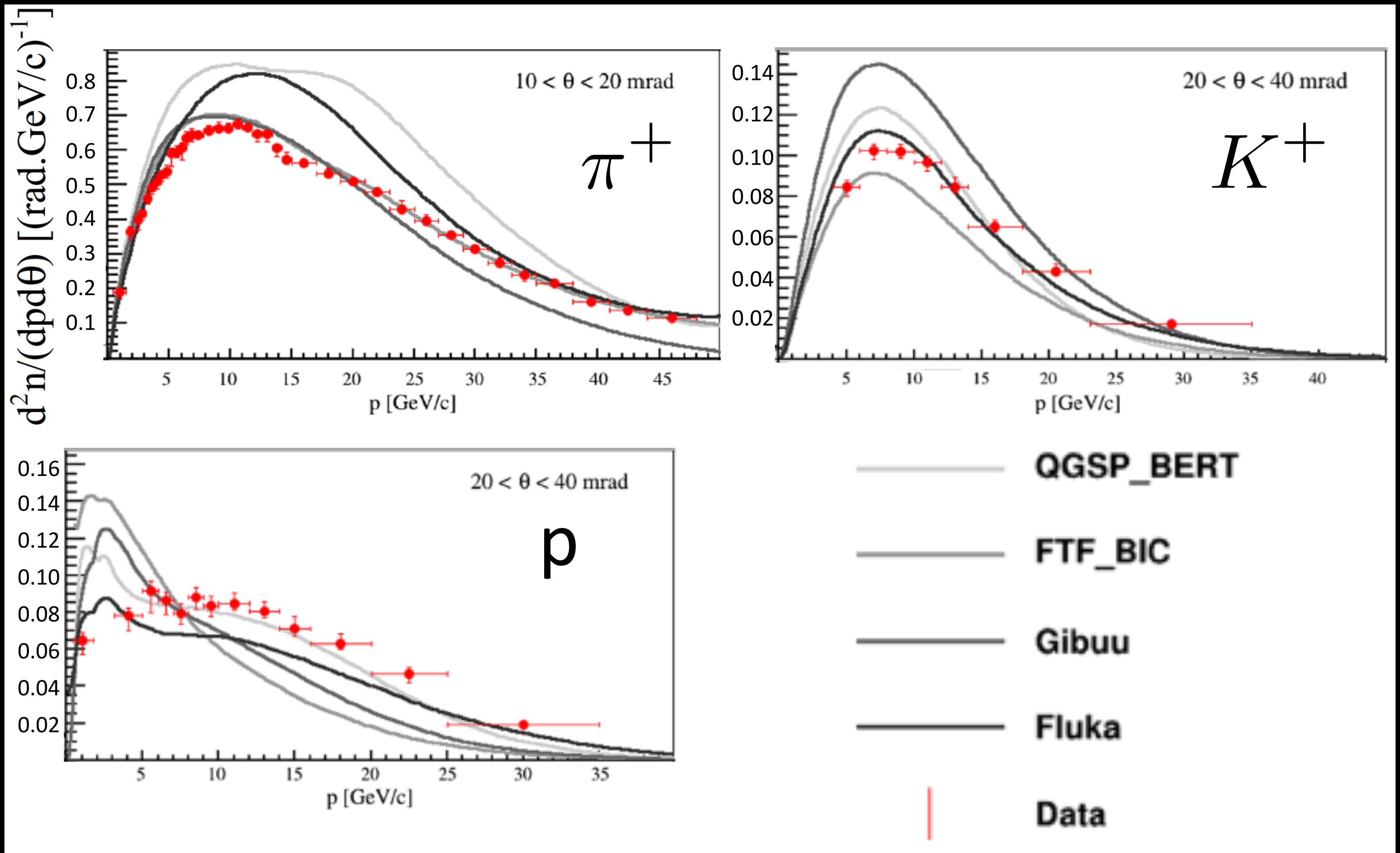
- Example: π^++C @ 60 GeV (Phys.Rev. **D100** 112004 (2019))
- *dE/dx* yields from TPC tracks and PIT fit for one *p*, θ bin





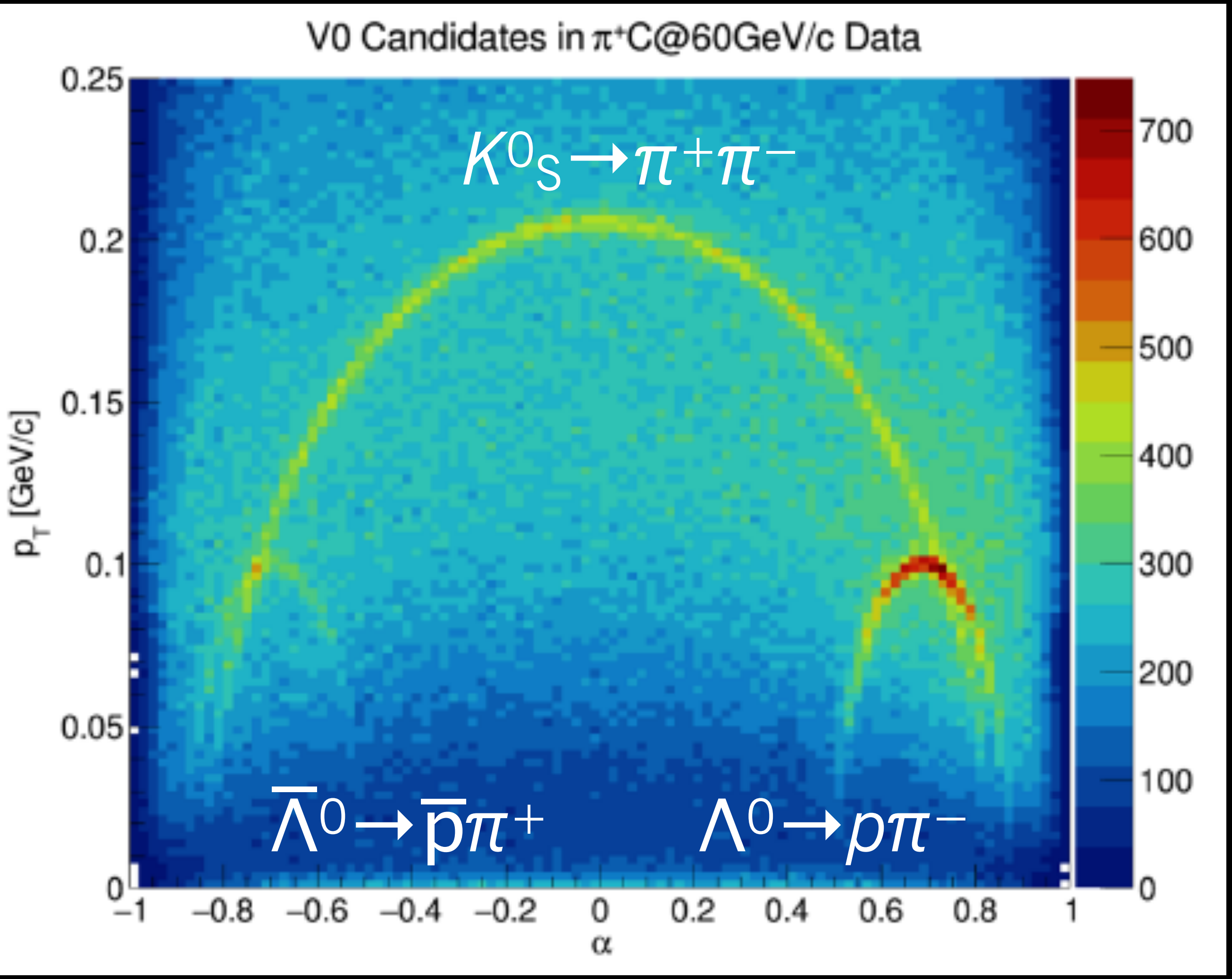
Thin-target charged hadron spectra

- 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

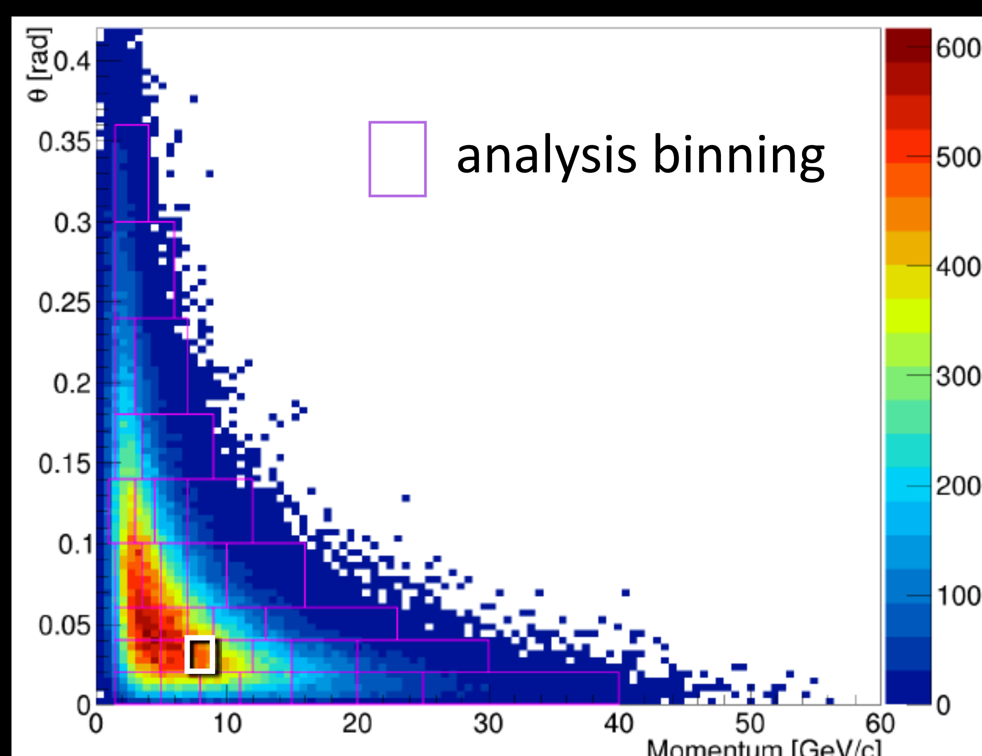


- Plot track p_T vs V trajectory against longitudinal momentum asymmetry of the tracks

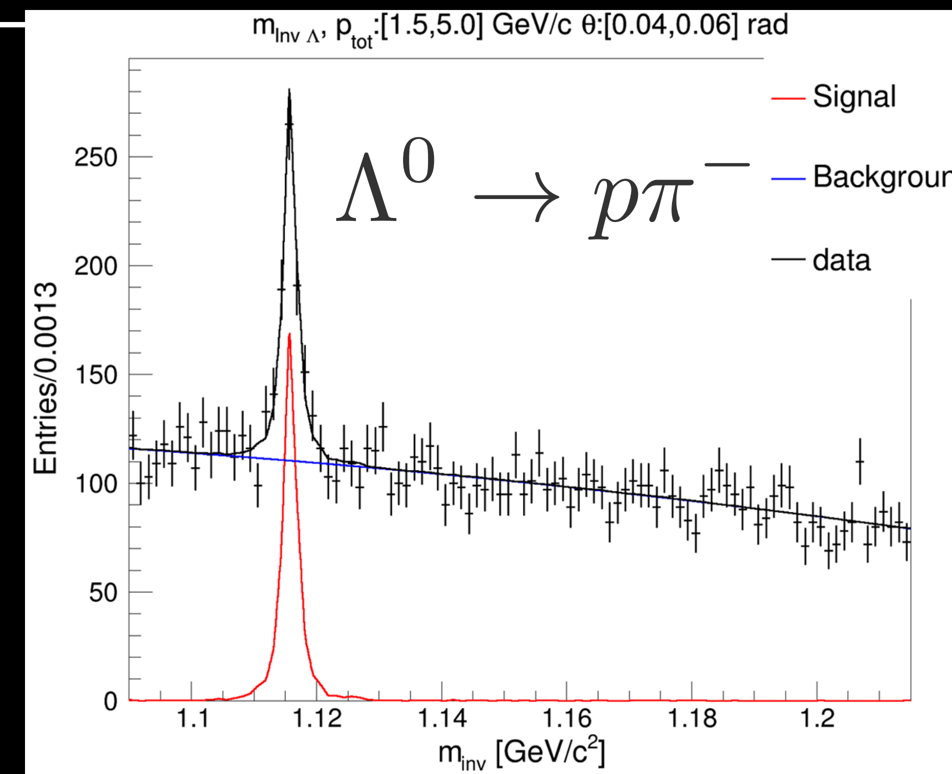
$$\alpha \equiv \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$$

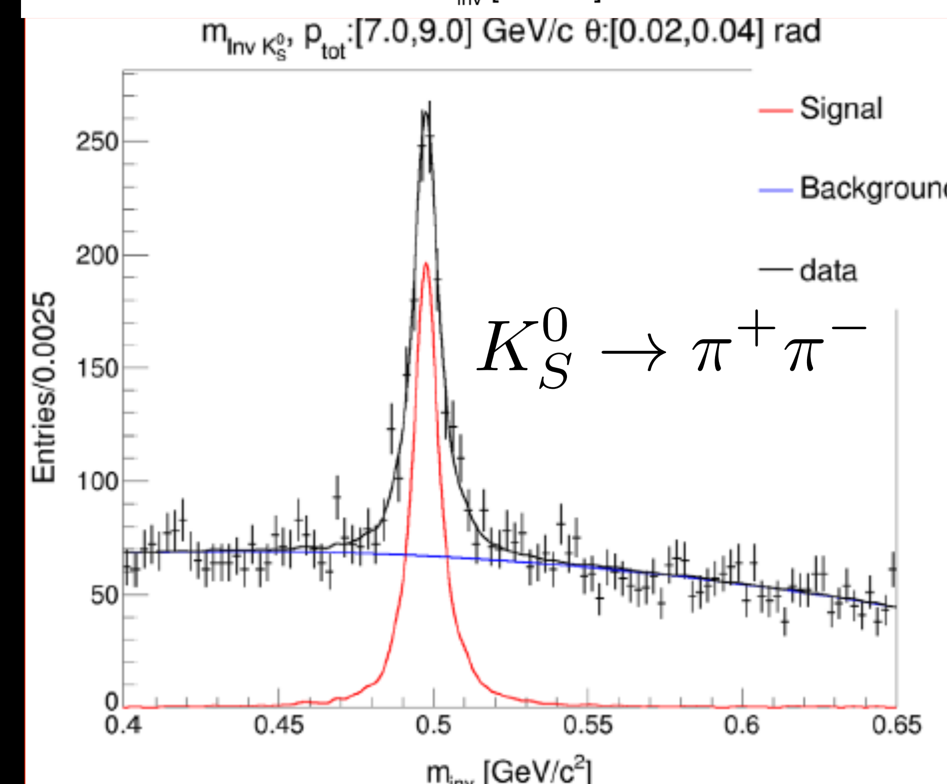
Thin-target neutral hadron spectra

- Yields of neutral kaons, Λ from specific kinematic bins



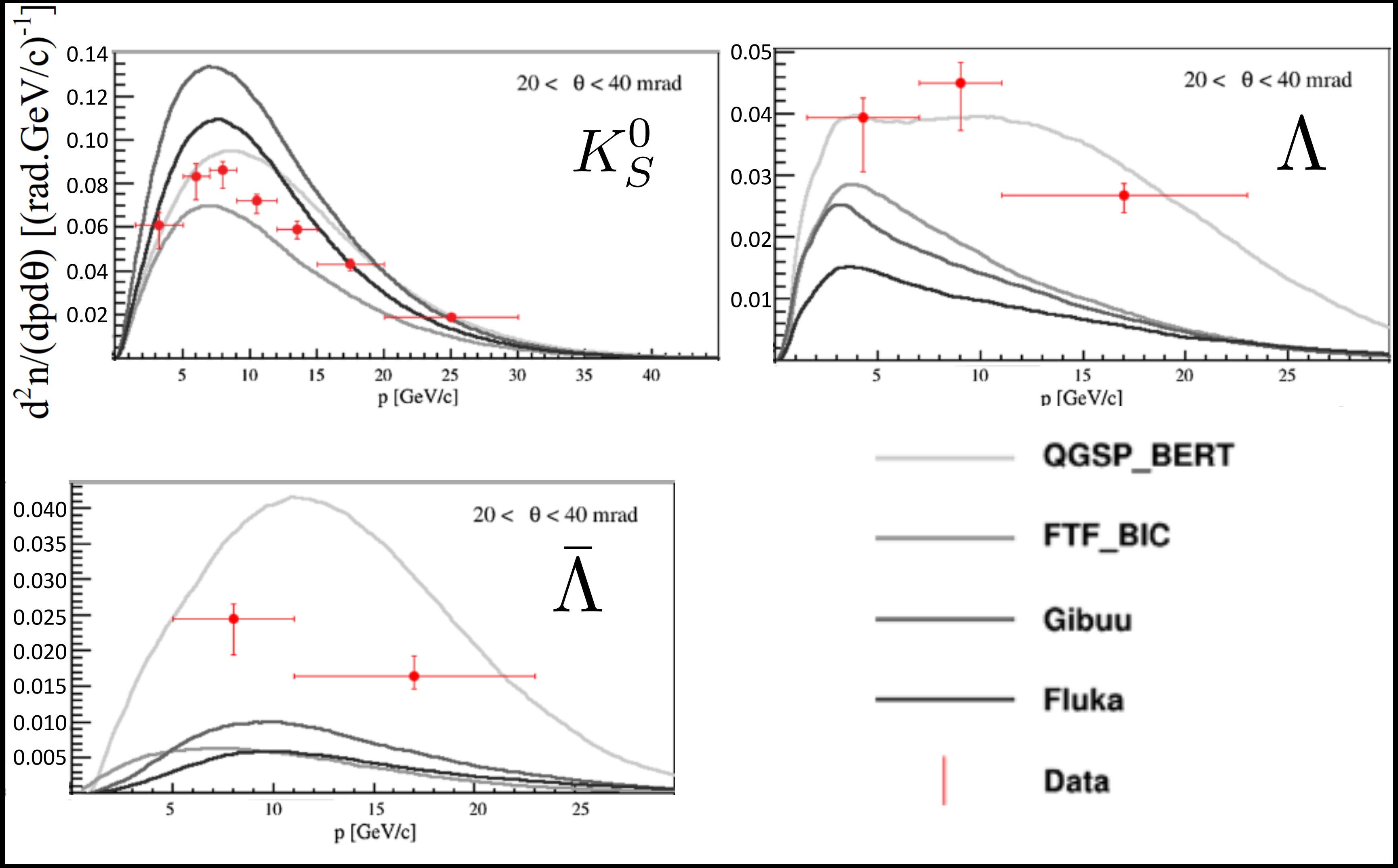
- Phys.Rev. **D100** 112004 (2019)





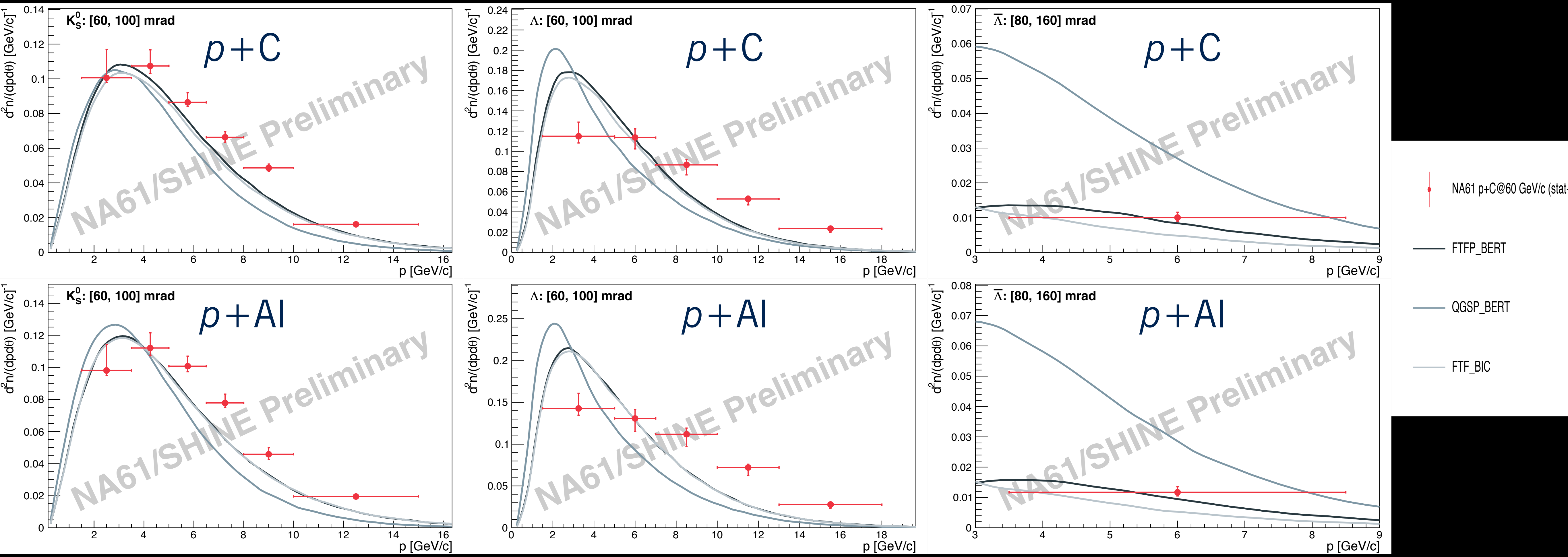
Thin-target neutral hadron spectra

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



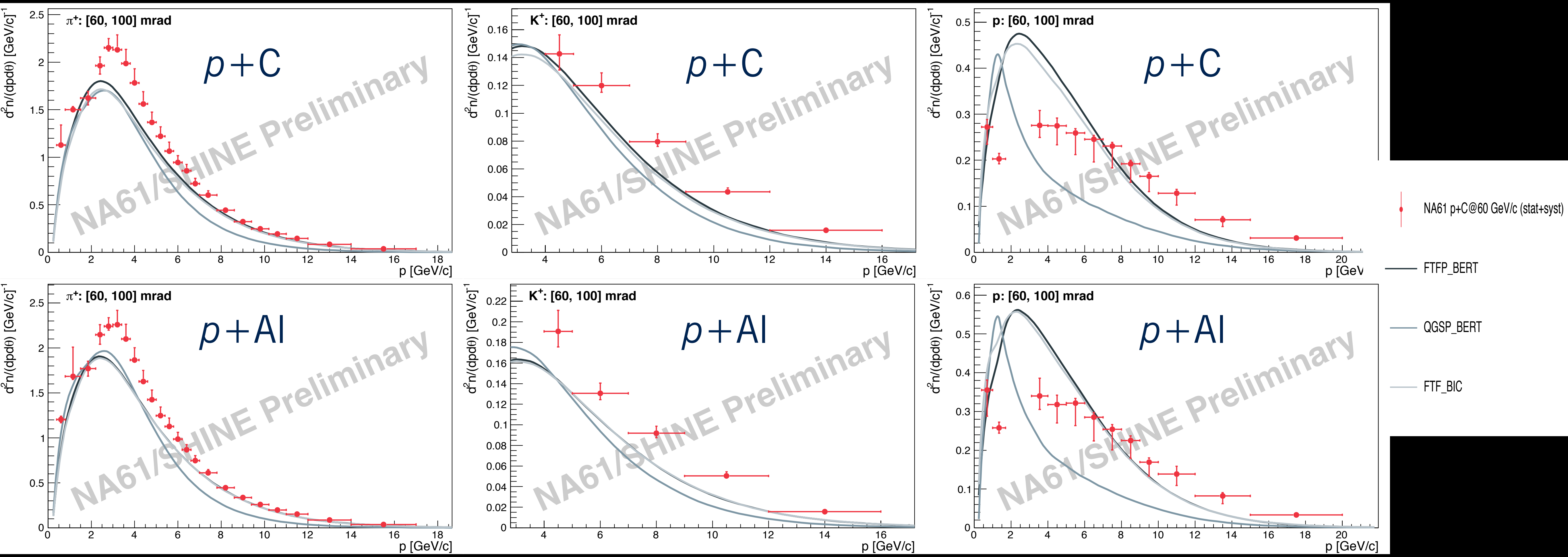
- Phys.Rev. **D100** 112004 (2019)

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



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

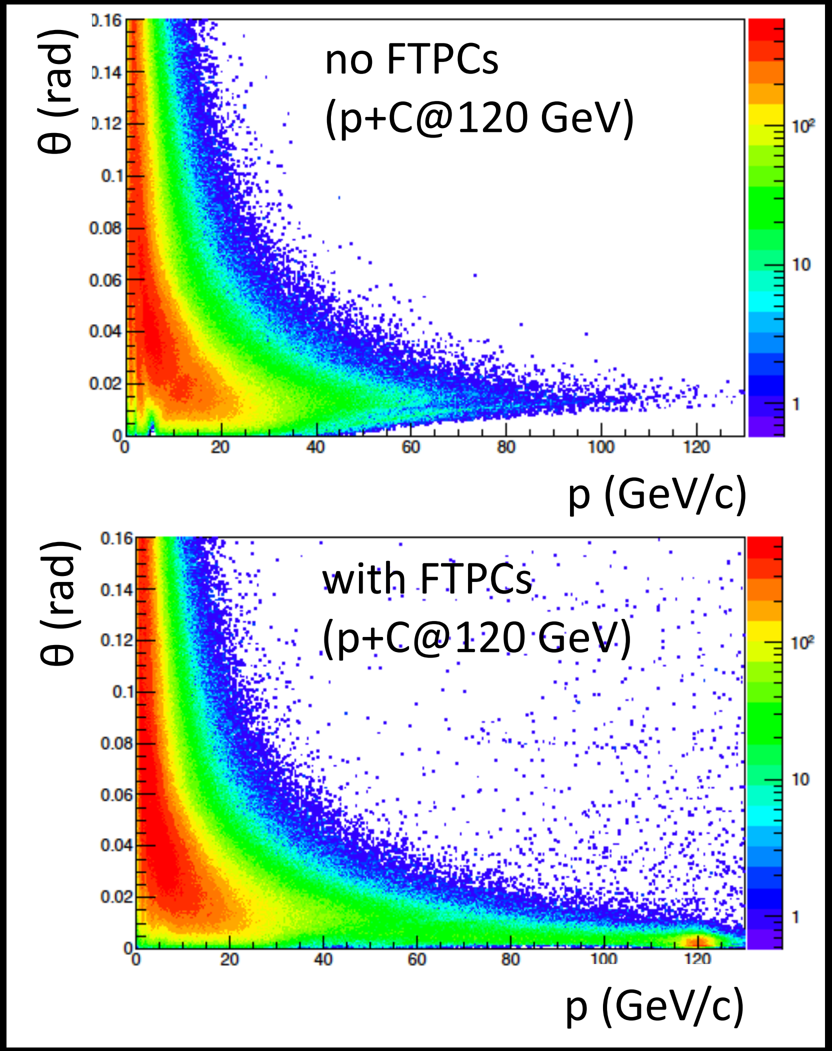
New! p+C and p+Al @ 60 GeV/c



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

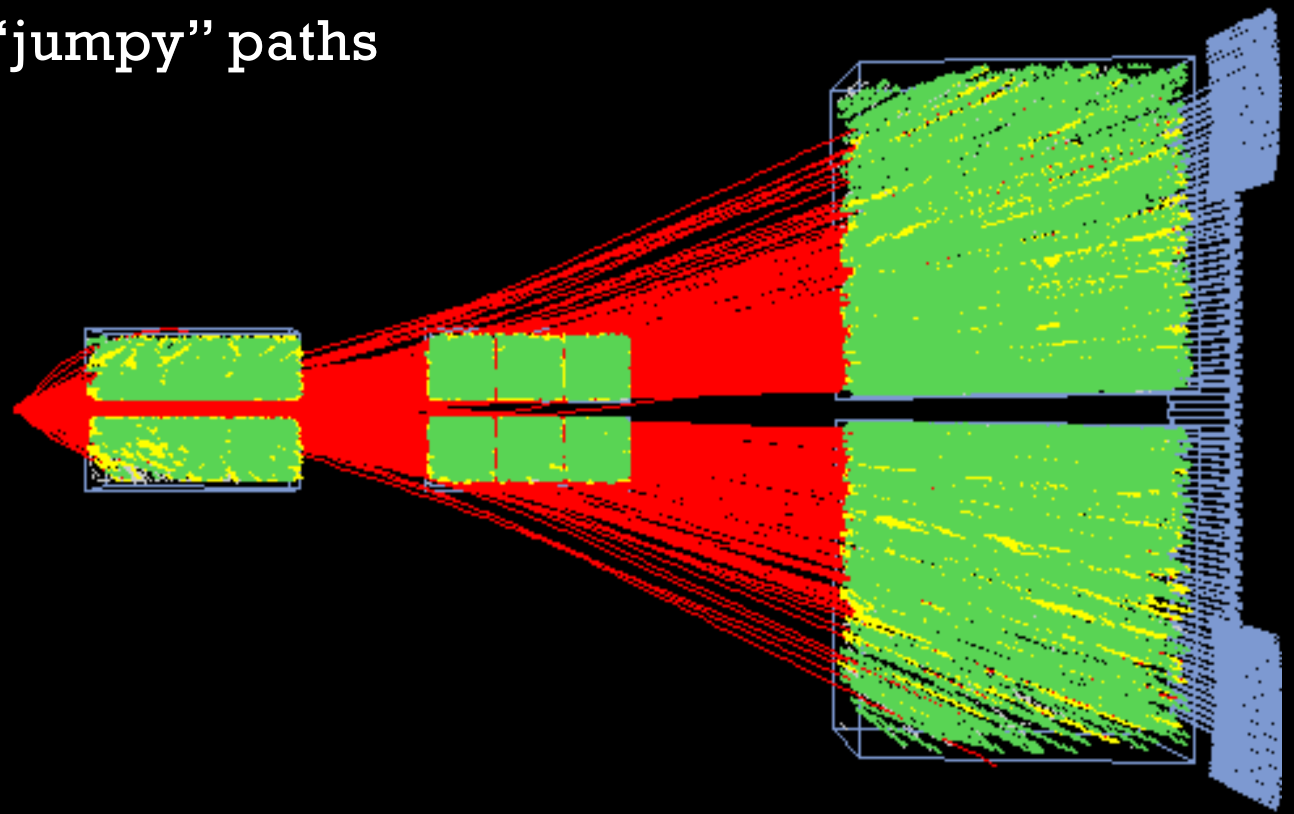
Coming soon: spectra from thin-target p+C @ 120 GeV

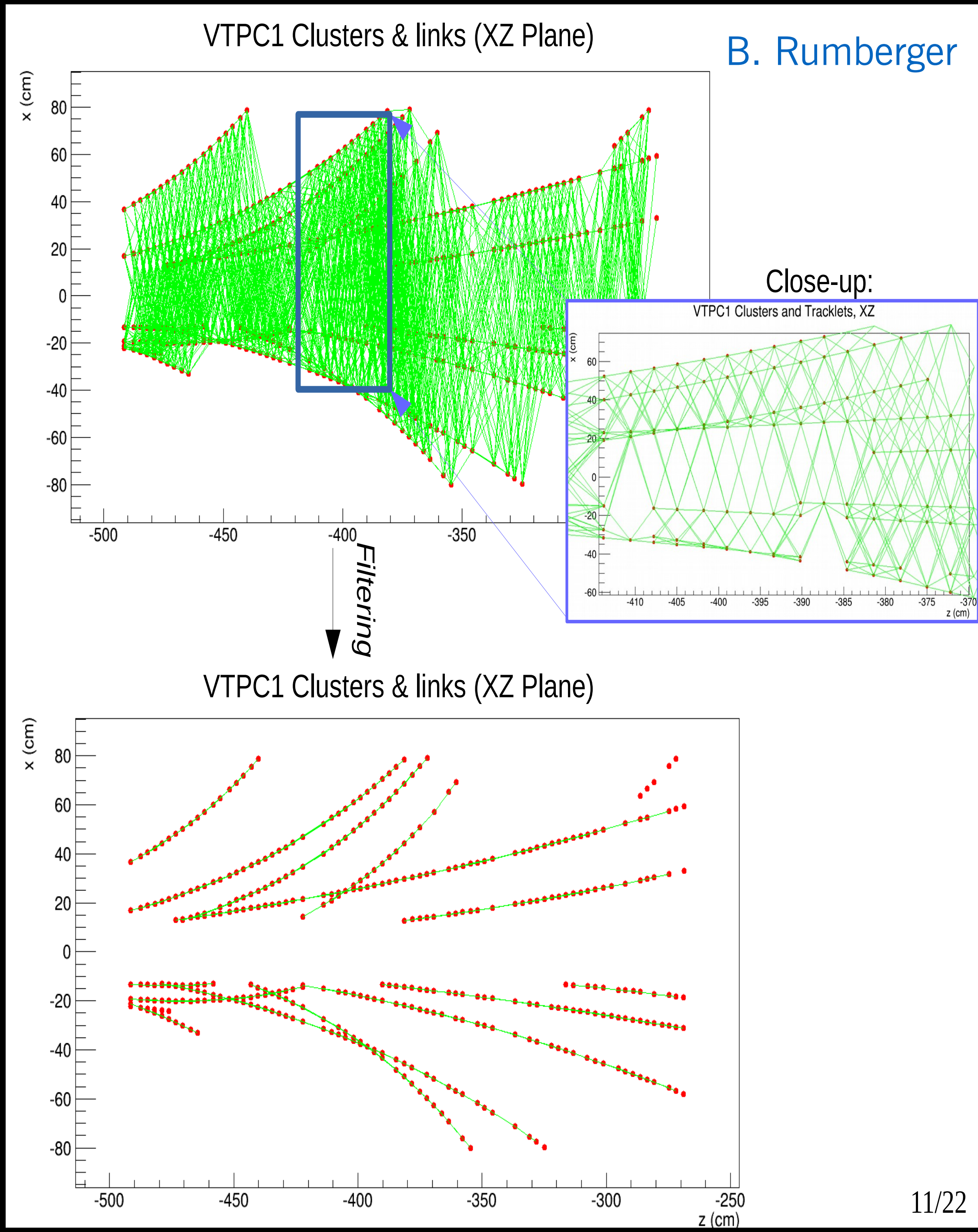
- This data set is high priority: represents the primary proton interaction in NuMI/NOvA/MINERvA.
- Relies on new Forward TPCs to provide forward acceptance (magnet doesn't bend beam-energy protons into the older TPCs) to see elastic, quasi-elastic events
- New tracking algorithm is needed for integrating the FTPCs into the analysis:
    - Cellular automaton-based local tracking with Kalman filter for global track fit is in final development
    - Calibration of new detectors is almost ready too
- Expect results on ~3 million interactions in a very few months!
- See B. Rumberger, ICHEP2020: https://indico.cern.ch/event/868940/contributions/3817070/



New tracking development

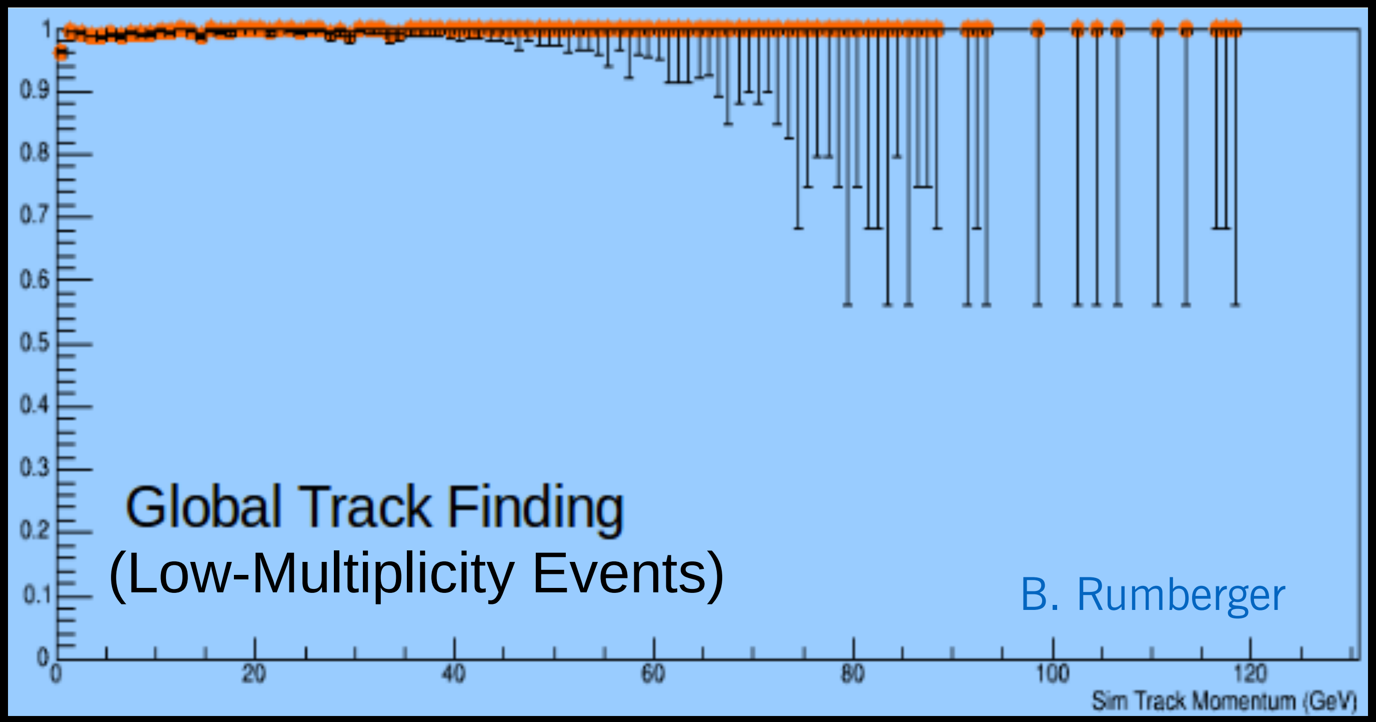
- Tracking has to work not only in low-multiplicity environment but also for NA61's heavy-ion data
- High speed needed for online reconstruction in post-LS2 running
- Local tracks within a chamber are formed by a cellular automaton algorithm that links all possible track-hit combinations and then filters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

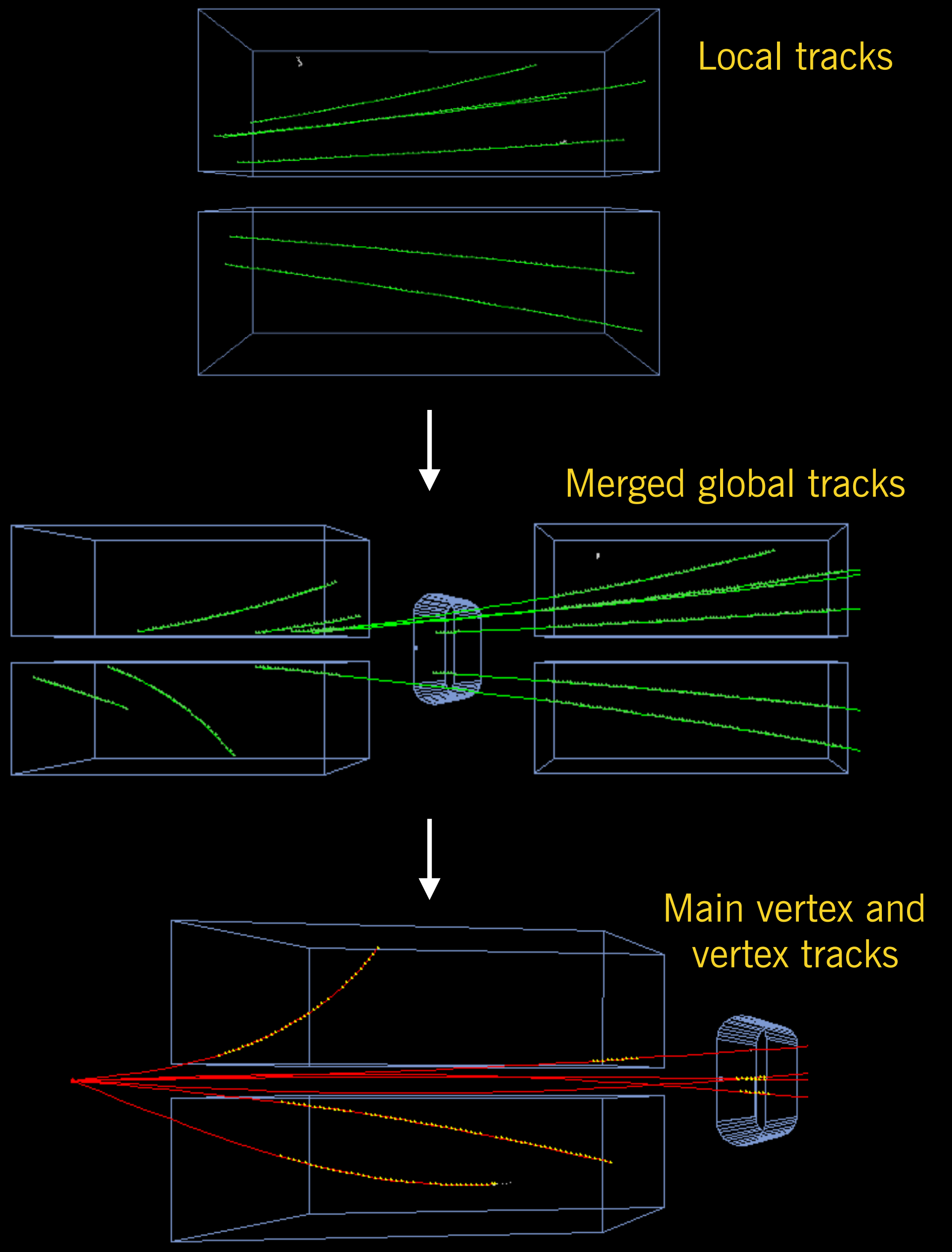




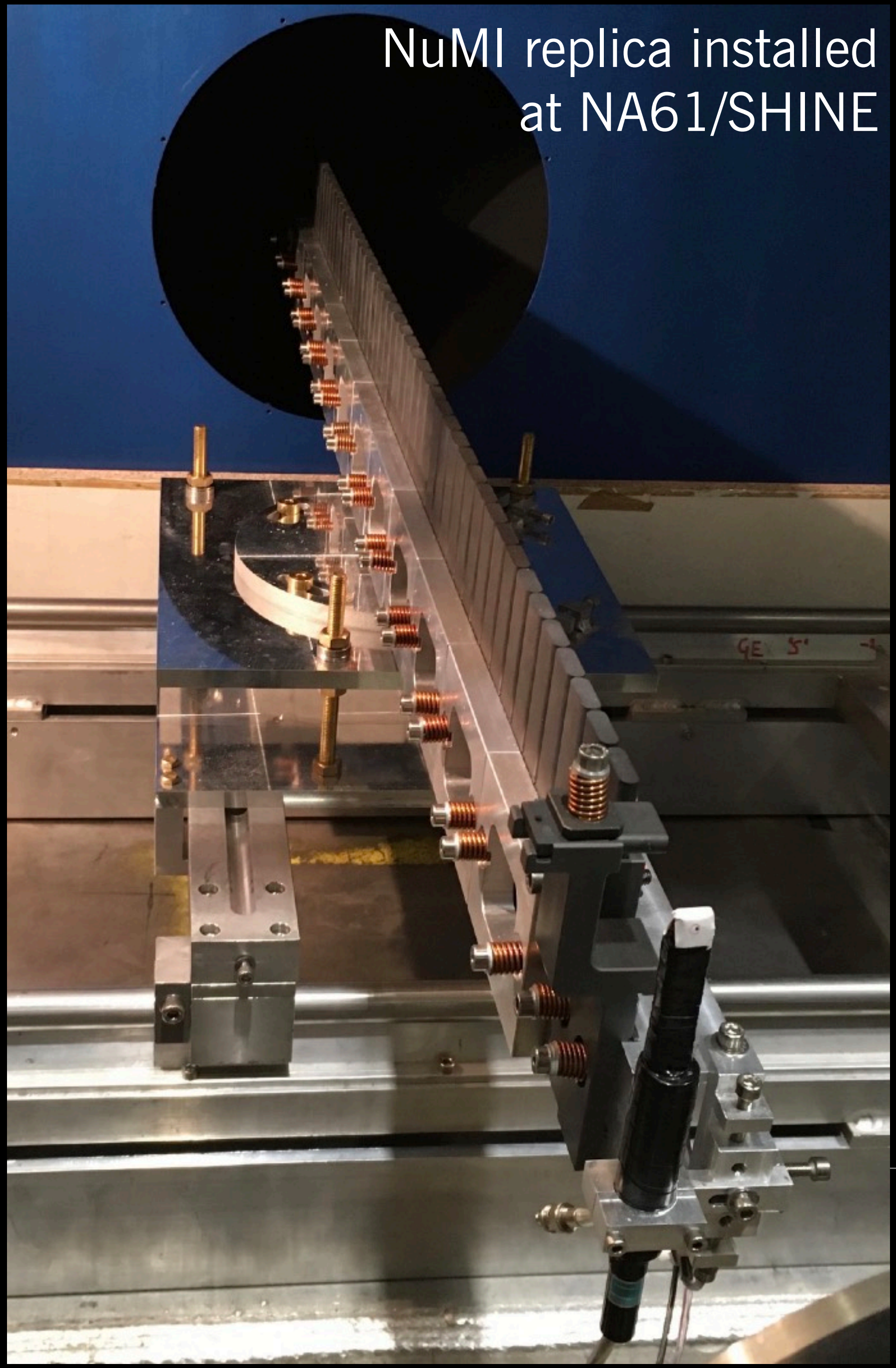
New tracking development

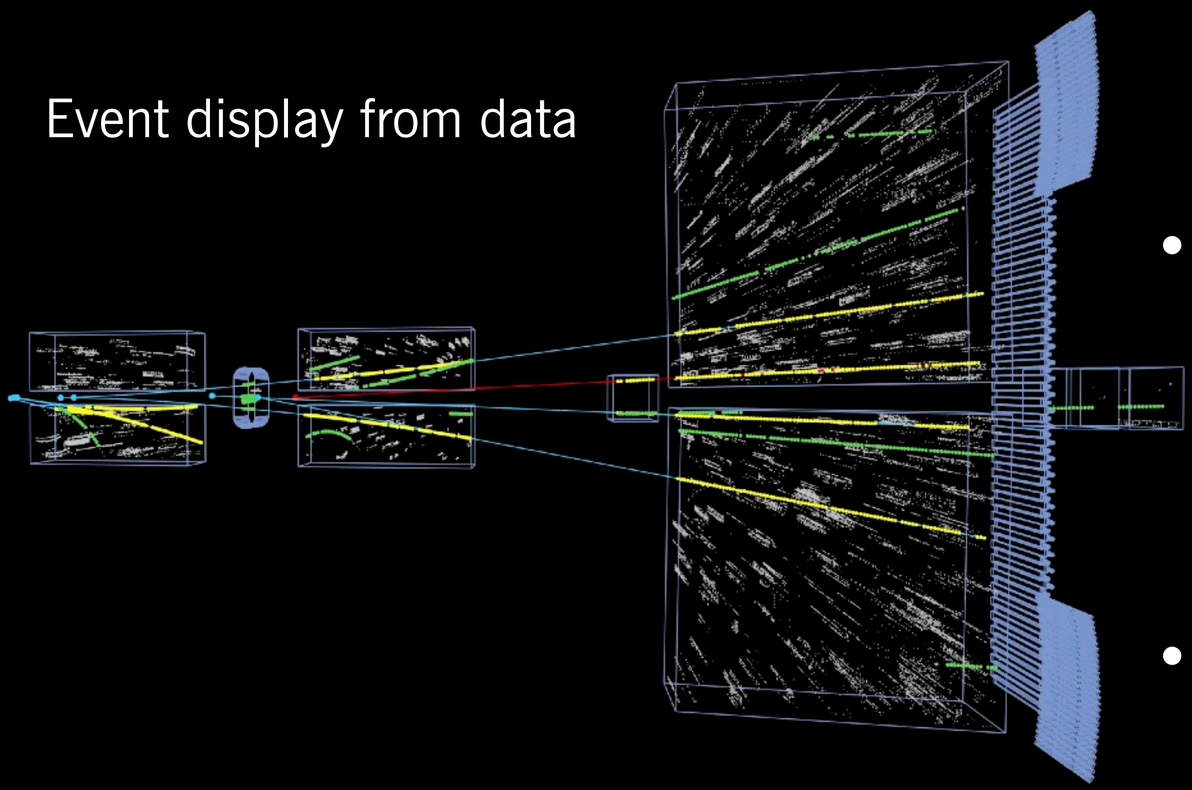
- Local track segments are merged into global tracks
- Overall track finding efficiency >99% for low-multiplicity events
- Track parameters are fitted using Kalman filter





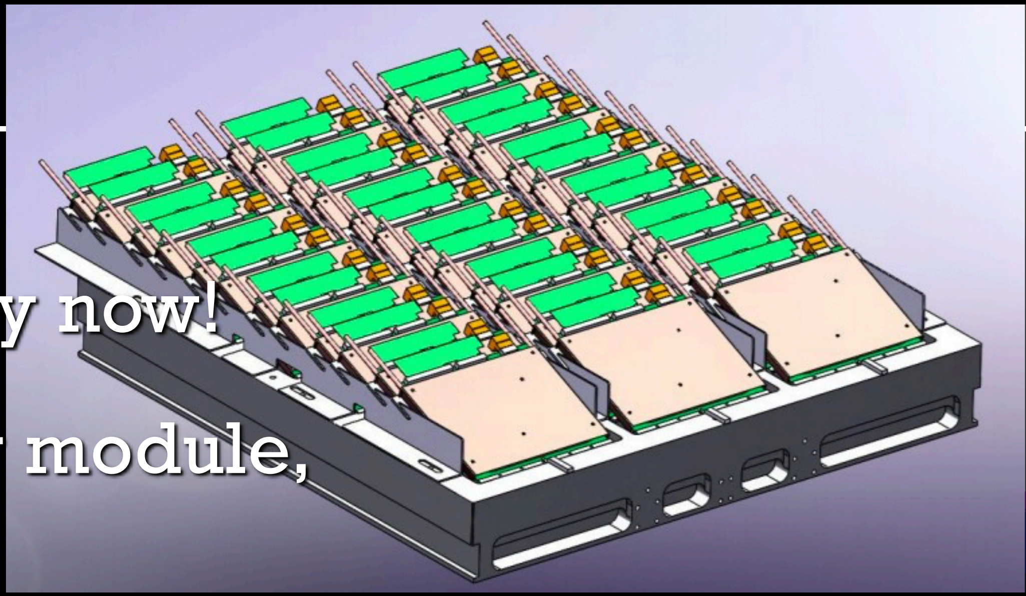
Coming soon: measurements with NuMI replica target





- Took high statistics (18M events) in 2018 with 120 GeV protons
- Analysis underway on hadron yields from this target
- Asymmetric design means binning in ϕ becomes important

Post-LS2 plans



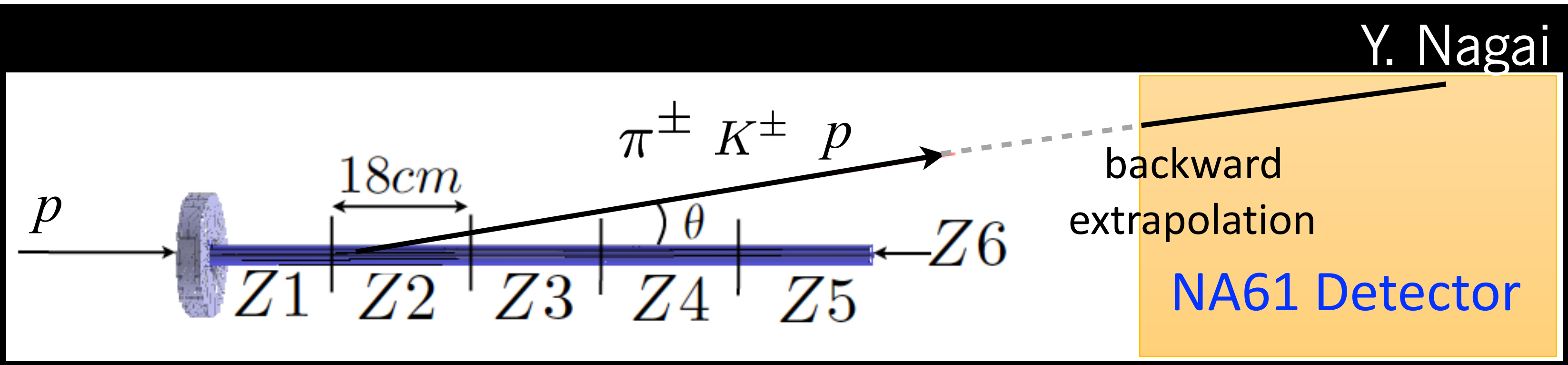
- Many major detector upgrades are underway now!
  - New forward Projectile Spectator Detector module, reconfiguration of existing detector
  - Replacement of old TPC electronics with system from ALICE
  - New silicon vertex detector for open charm studies
  - RPC-based replacement for TOF-L/R walls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

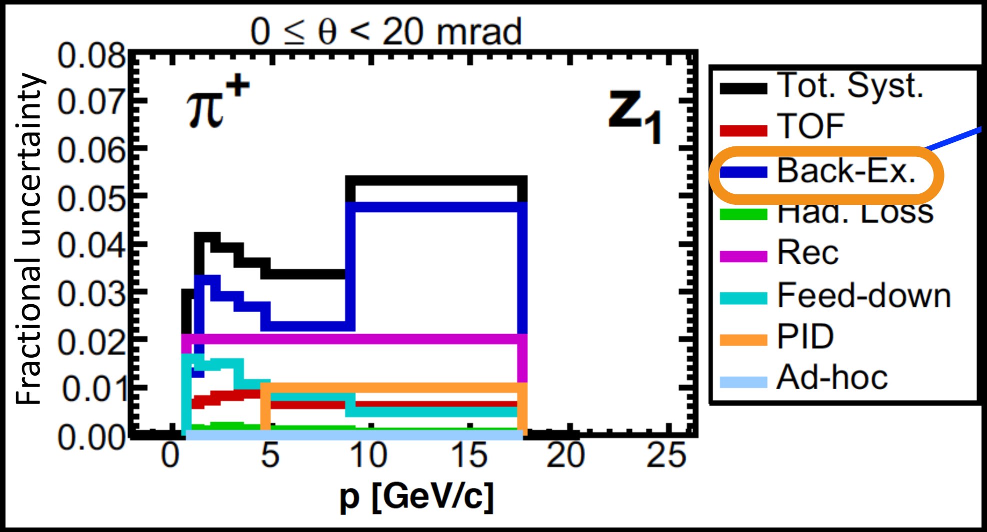
Relevant for neutrino running

Future after LS2: Planned data collection

- Commissioning and possible short physics runs in 2021 expected
- After that, priorities will be:
  - Additional T2K long-target running
  - LBNF/DUNE replica target when available (2023 likely). This target will be at least 1.5 m long and may create some challenges for reconstruction…
  - Kaon scattering with thin targets for secondary interaction modeling
  - Improved statistics on multiple measurements

Future after LS2: long-target tracker?

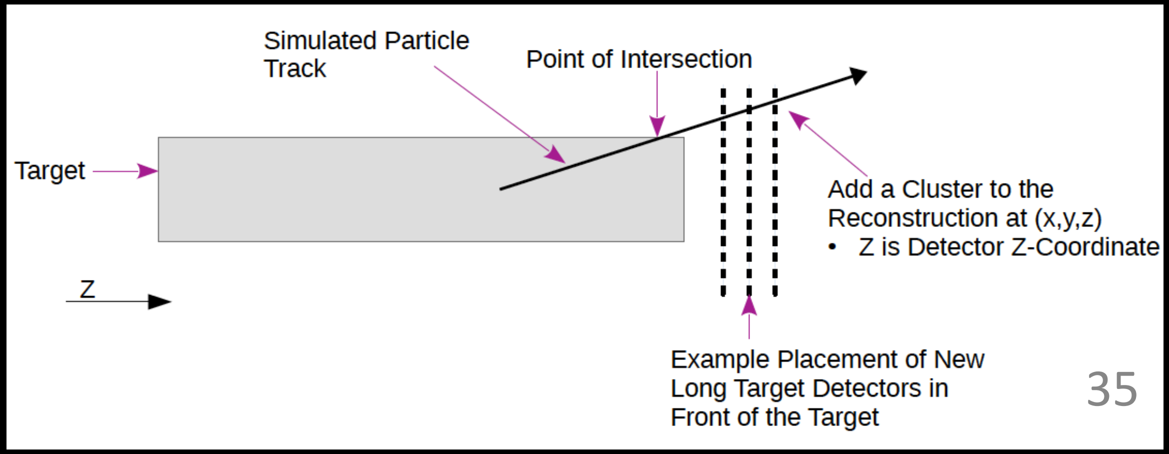




- A leading systematic error with the T2K replica target has been extrapolation of shallow-angle tracks backward to the target surface

- Additional tracking detectors at the end of the target will probably be needed for the longer LBNF/DUNE target as well as a more precise measurement for T2K

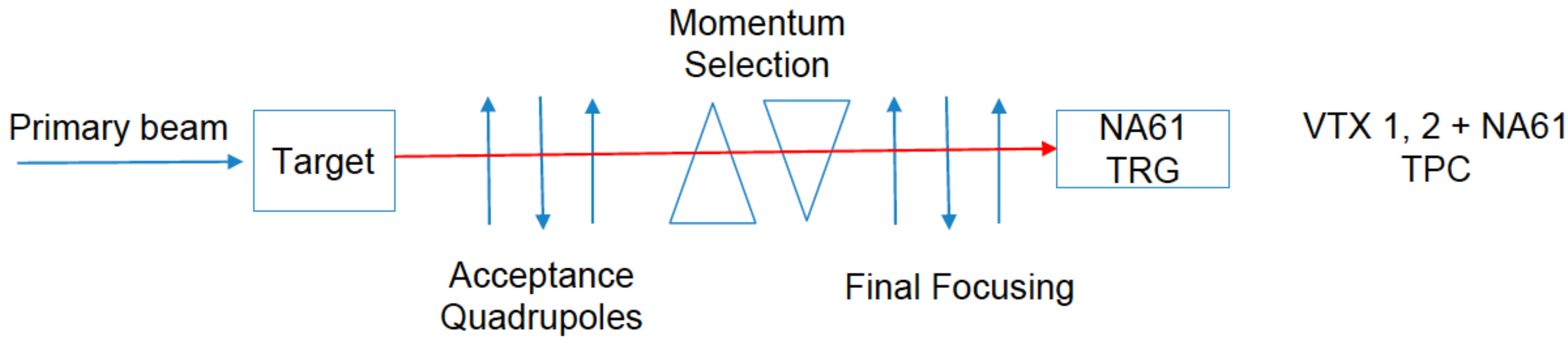
- Considering options such as silicon planes or a small TPC

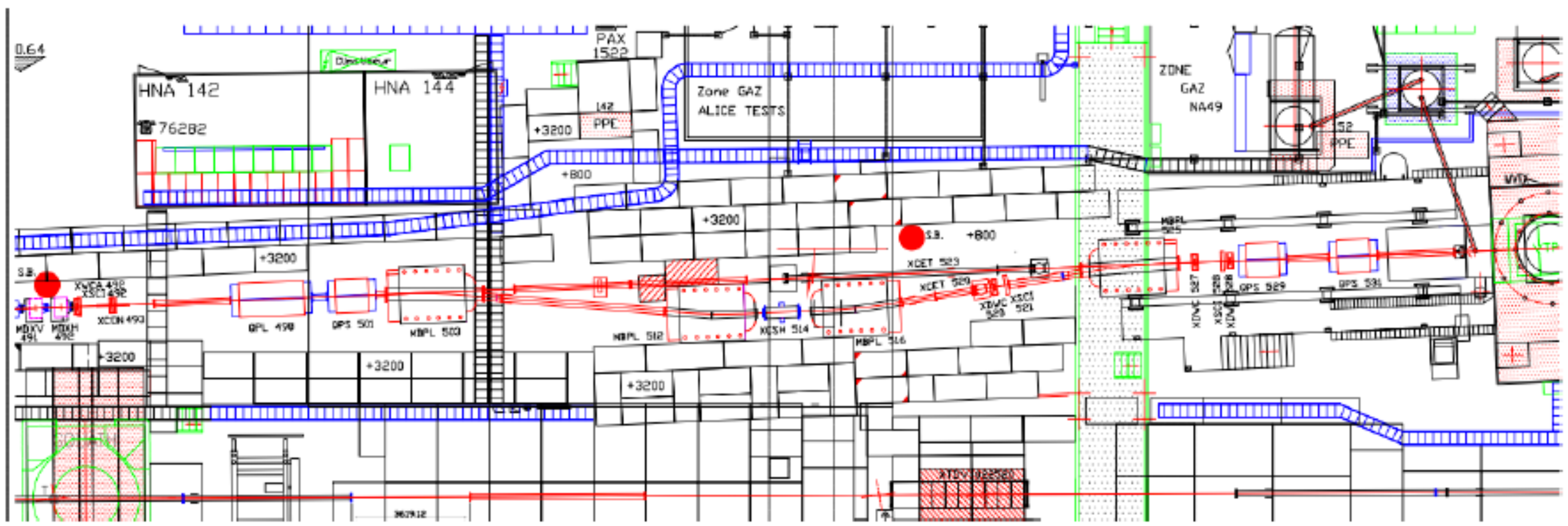


Future after LS2/3: low-energy beam?

- 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
- Interest from spallation sources, T2K/Hyper-K for secondary interactions and atmospheric neutrino flux, even DUNE for secondary re-interactions

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 ongoing by CERN beam group in collaboration with NA61/SHINE. Aiming to begin construction fairly soon (resources permitting)

NA61/SHINE at Low Energy Workshop

- Interested in low-energy data at NA61/SHINE?
- Open workshop to be held December 9-10 online
- Technical issues and physics opportunities (let me know if you wish to present one)
- https://indico.cern.ch/event/973899/

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
- New opportunities abound for data sets after LS2!
- Low-energy workshop:

https://indico.cern.ch/event/973899/

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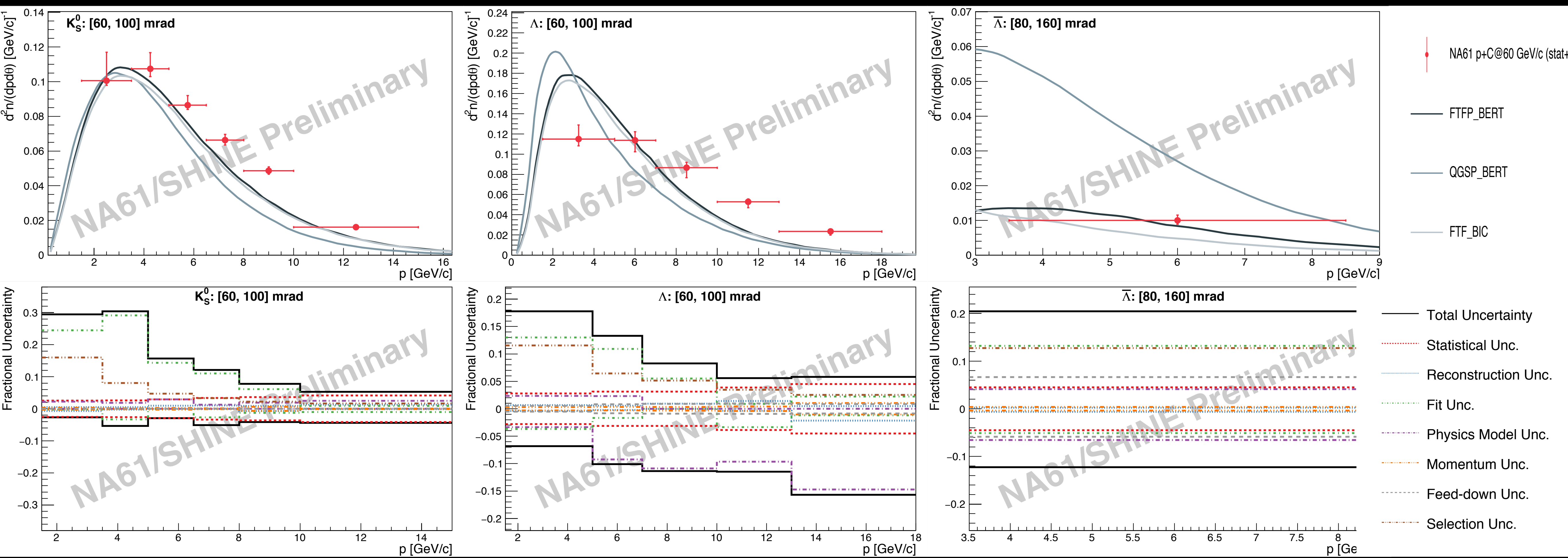
New! p+C and p+Al @ 60 GeV/c



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

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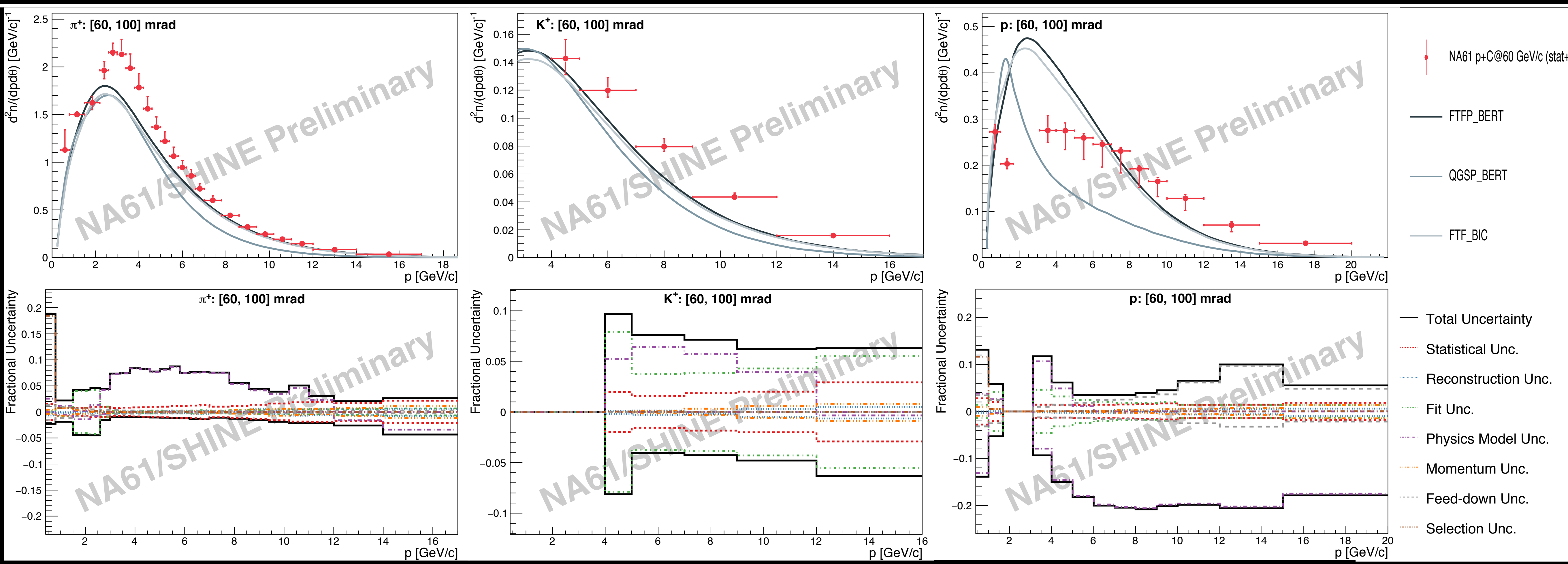

- π^+, K^+, p spectra from p+C @ 60 GeV/c
- Showing one angle bin