Measuring Neutrino Beam Flux with NA61/SHINE

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NA61/SHINE Neutrino Program

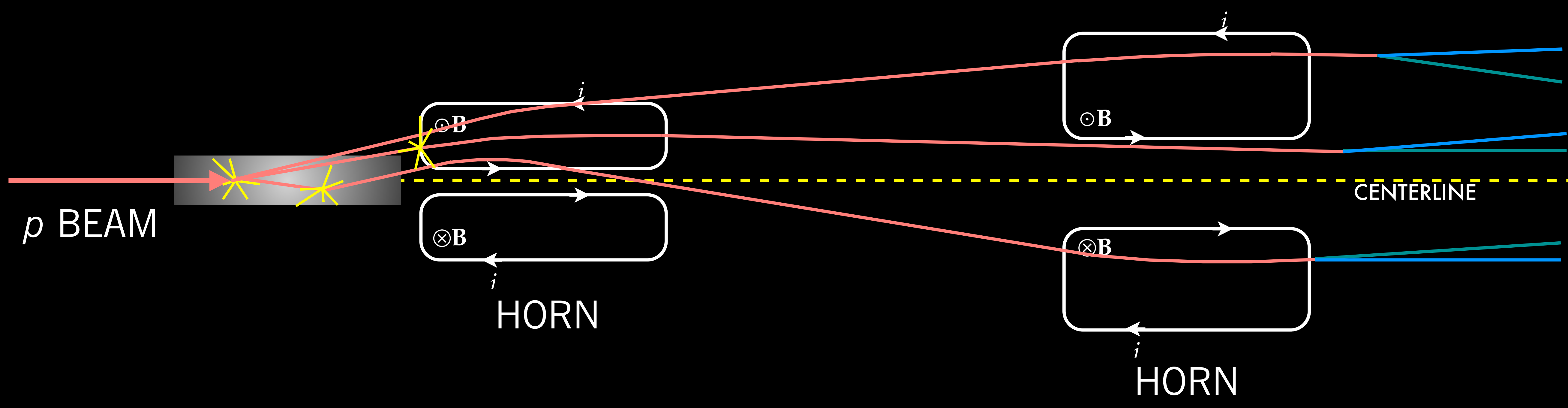
- Neutrino beam physics
- NA61/SHINE neutrino program
- Current and new results
- Upcoming data sets
- New opportunities

Neutrino beam physics

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

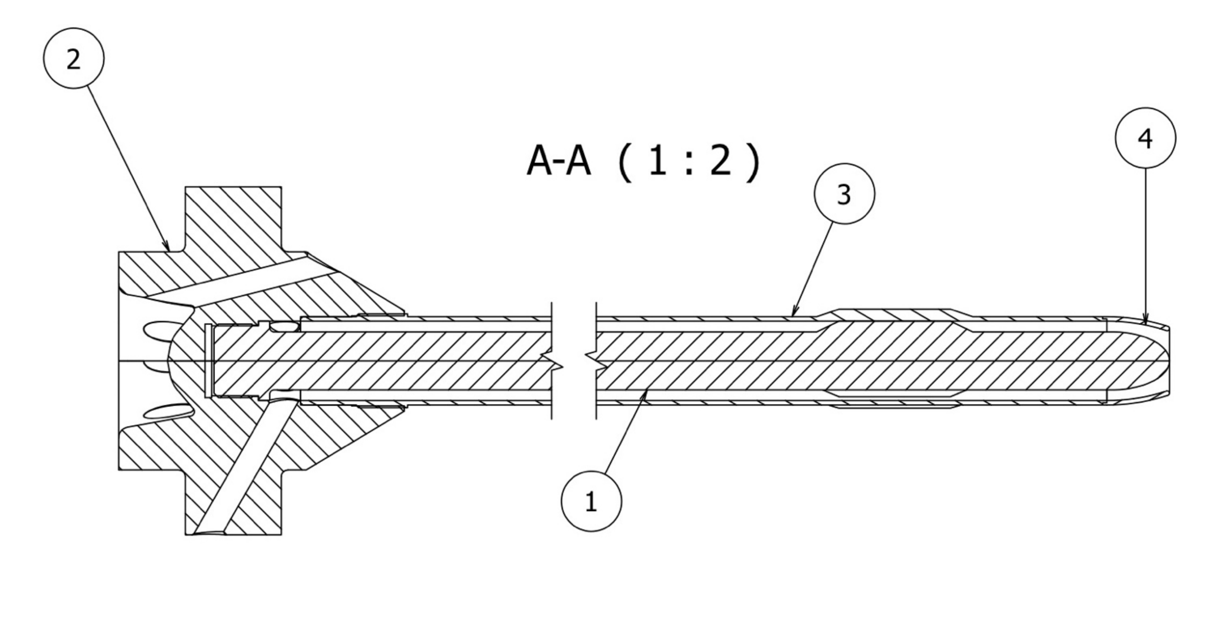


Understanding the flux

- 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!

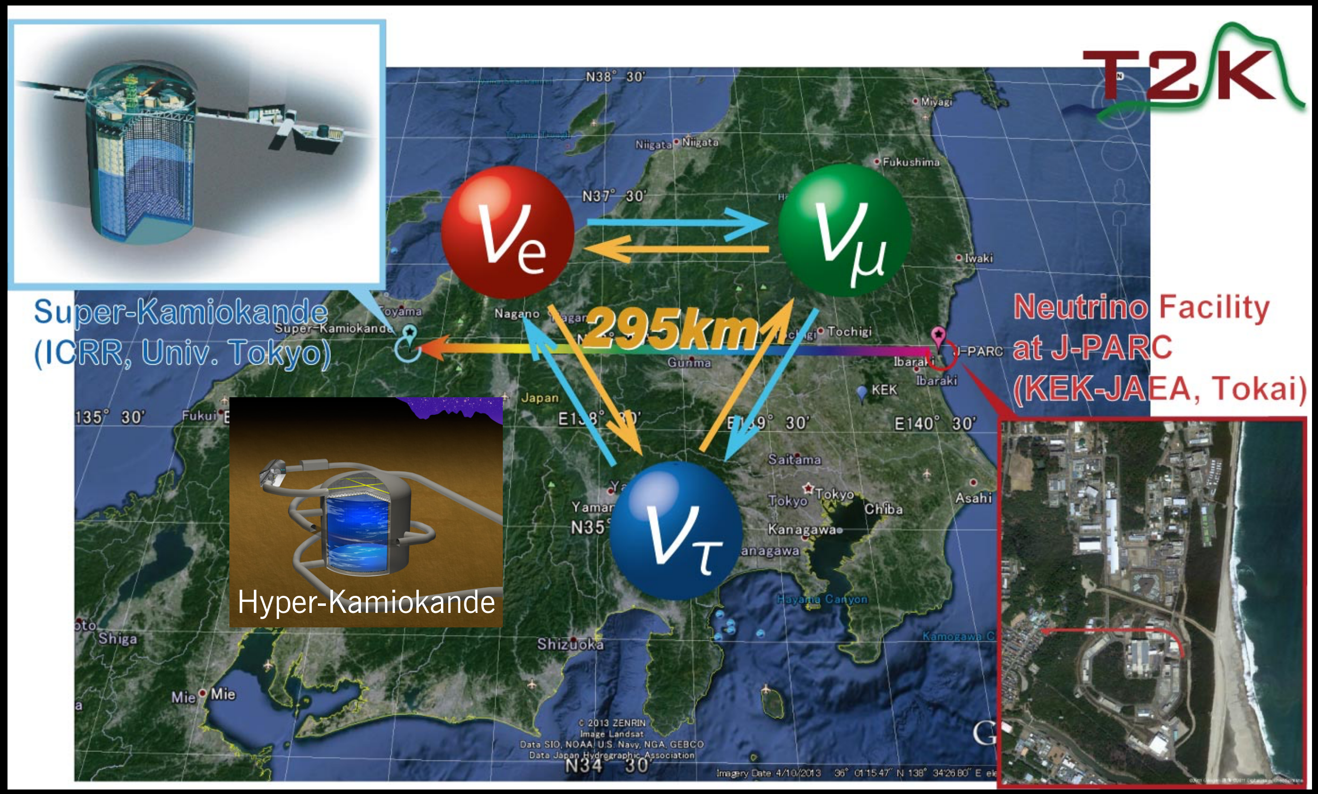
Targets



T2K target
(for illustration)

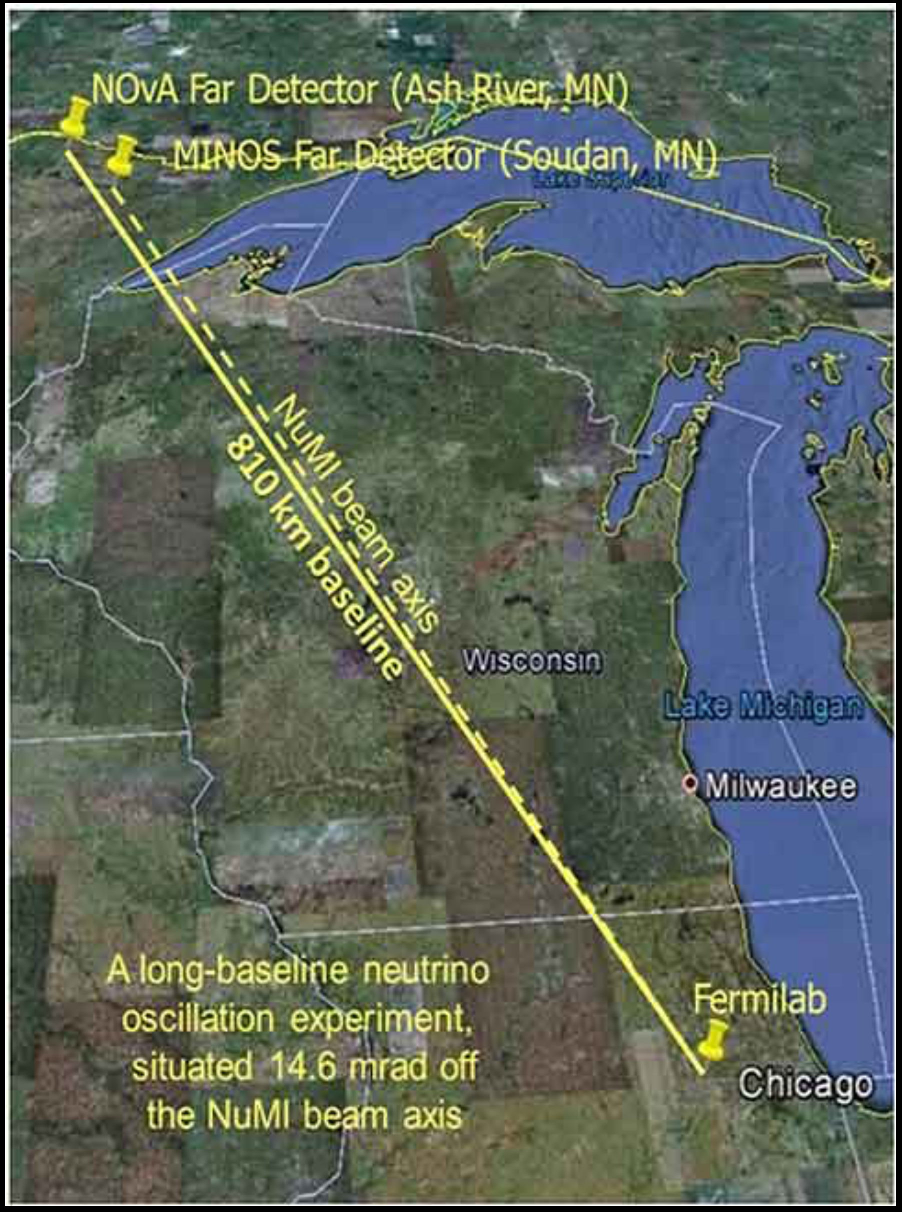
- Graphite target, like most modern beams
- 90 cm long: ~2 $\lambda 0$ in beam direction, to maximize interactions
- 2.5 cm diameter: Should be wide enough to contain the primary beam, but narrow enough to allow interaction products with average pT to escape the side
- Primary beam radius is large (6mm) to reduce local intensity and thermal shock
- Target cooled by very high velocity helium gas in closed loop

Primary beam energies for current and near future neutrino beams

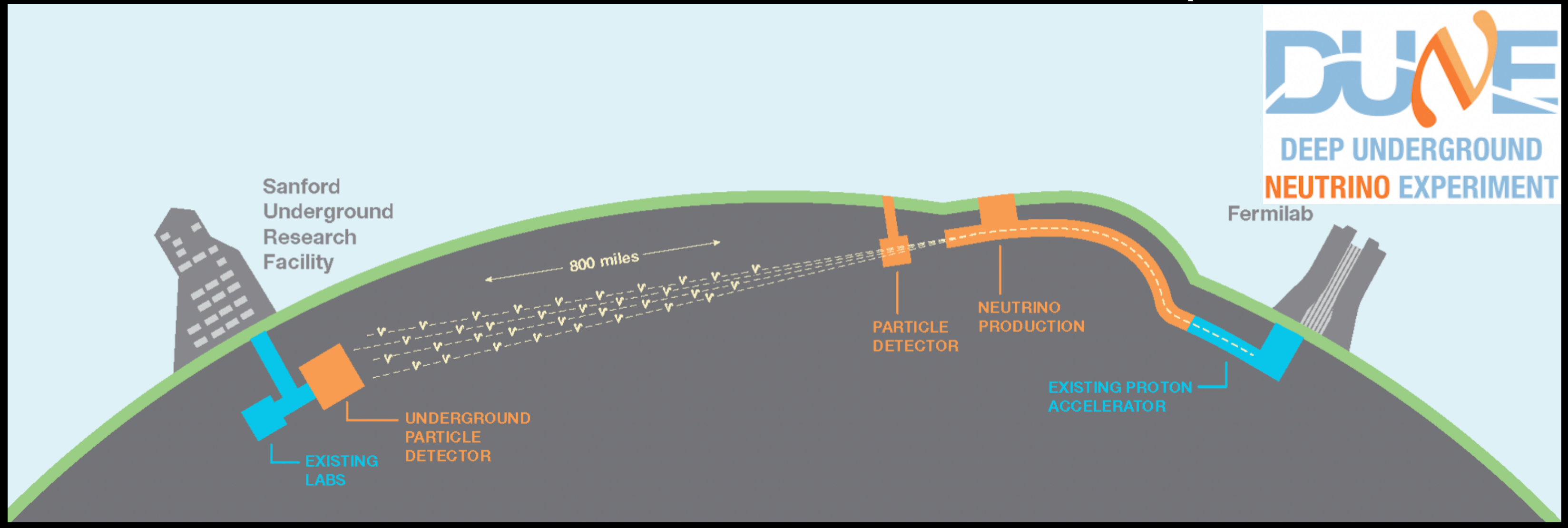


T2K, T2HK: 30 GeV/*c* *p*

NuMI: 120 GeV/*c* *p*



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

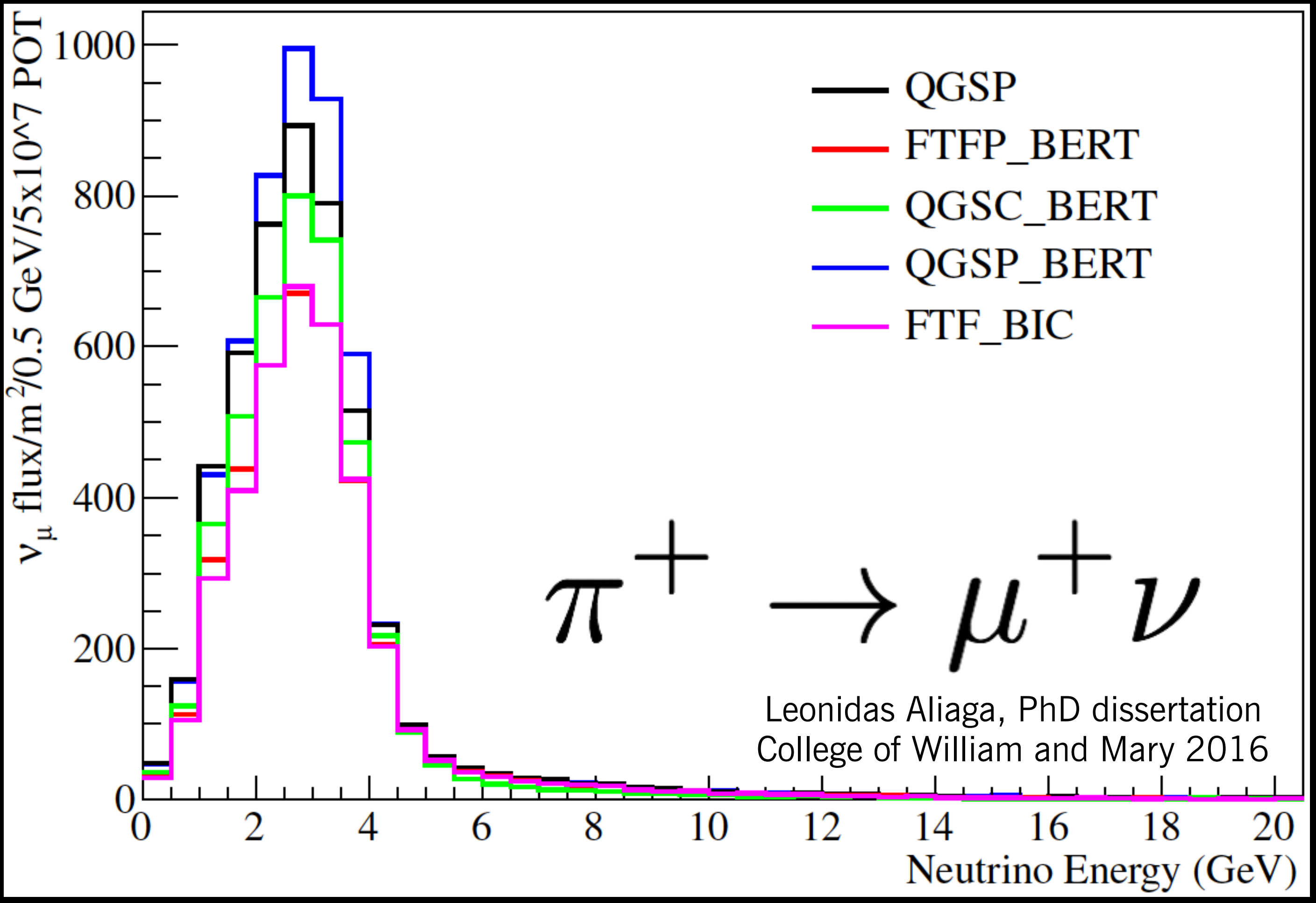


Understanding a neutrino beam

- Two complementary techniques needed to understand the beam well enough to do oscillation measurements
  - 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) 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
    - Reduces oscillation systematic errors

Monte Carlo generators

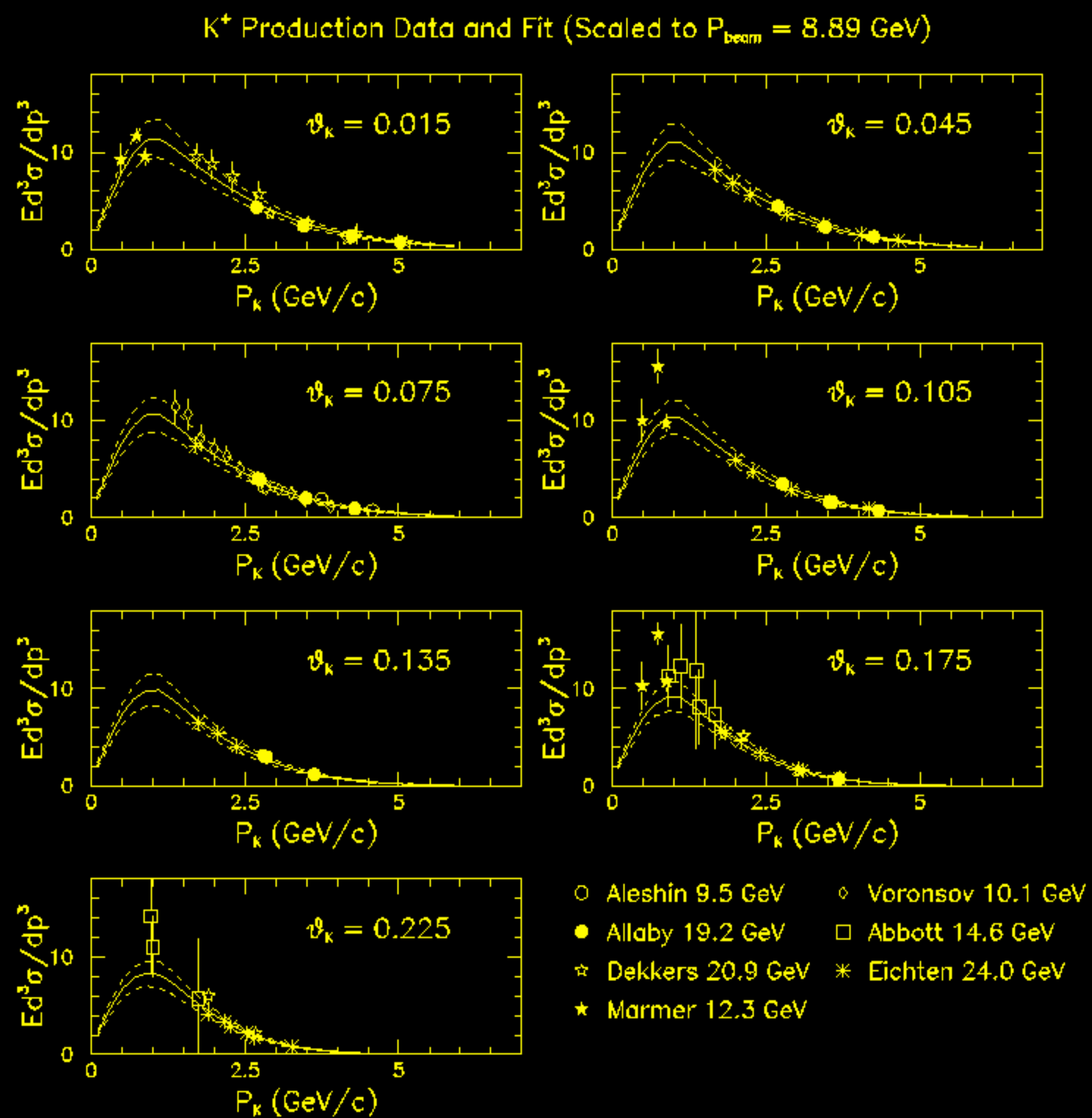
- Neutrino experiments use hadronic interaction generators including FLUKA, GEANT4 with various physics lists
- But these generators have **very large** disagreements with one another: 20%+ is common, or even factors of two for kaon production!
- Very important to have constraints on the hadronic processes



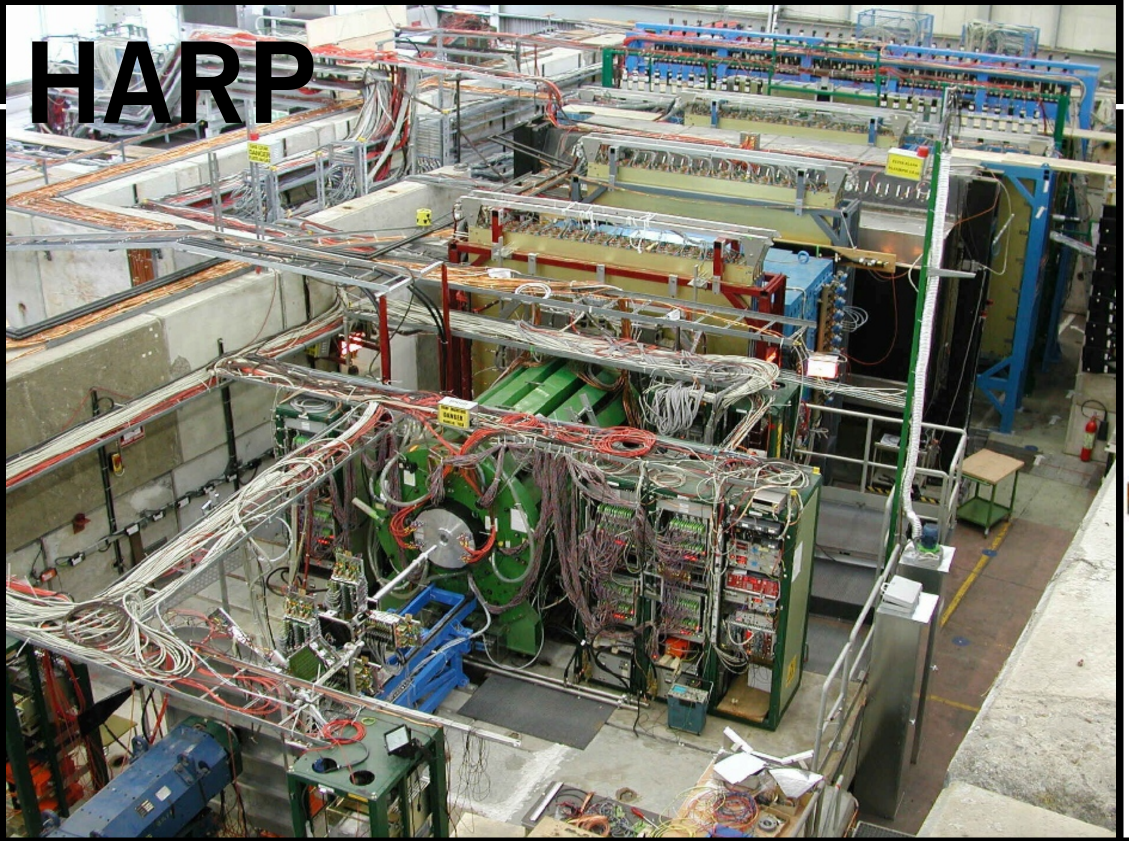
Flux of FNAL's NuMI neutrino beam with different physics generators

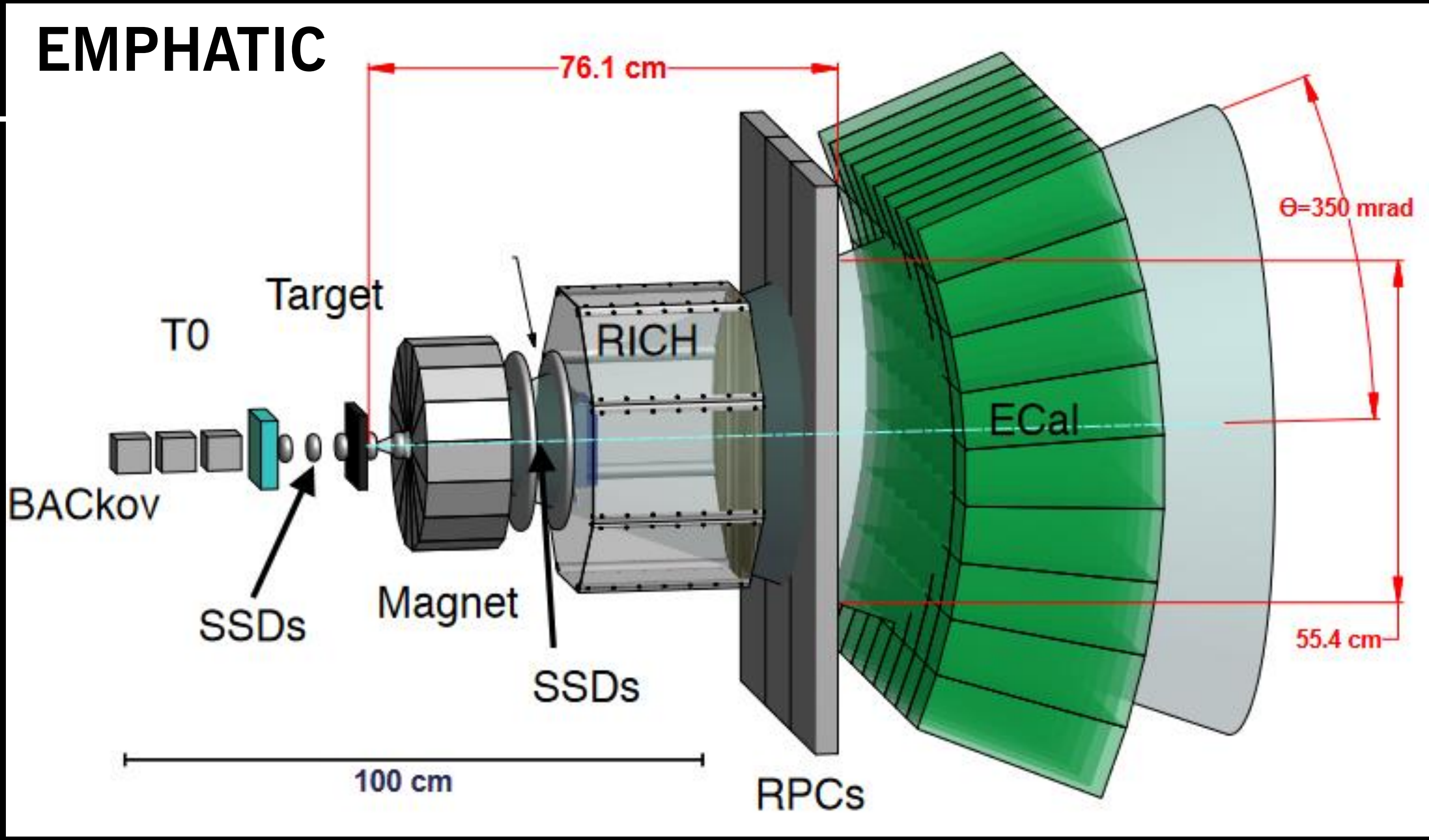
External measurements of meson production

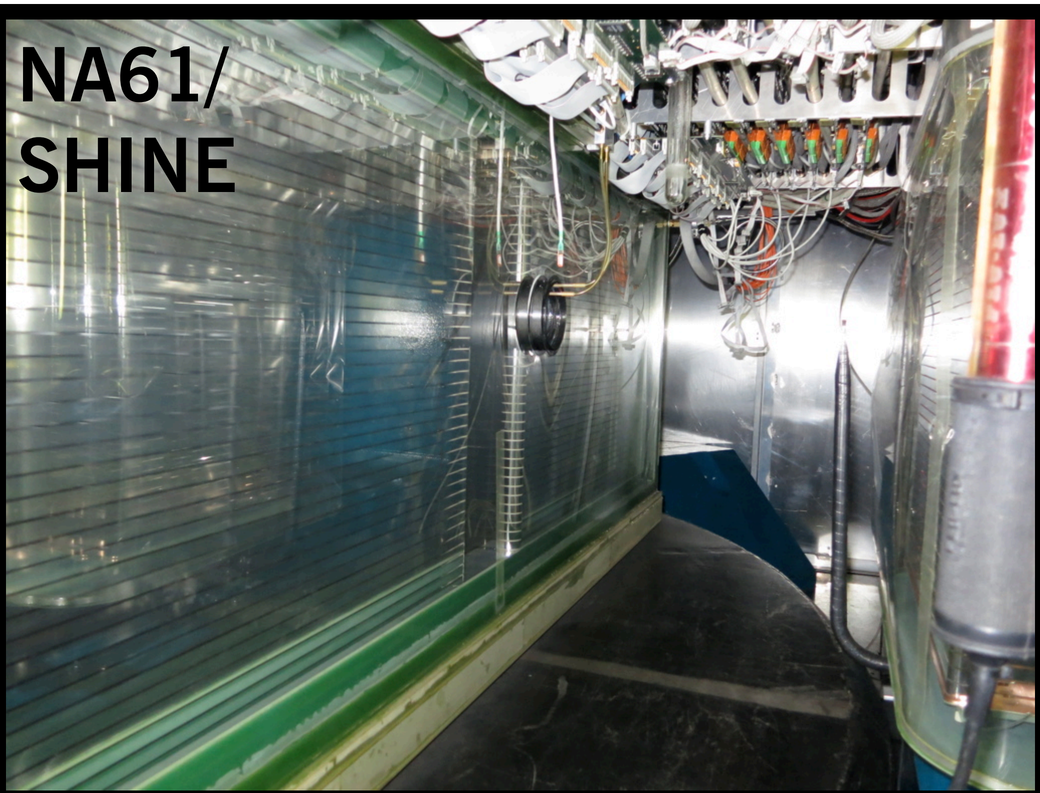
- Until recently, depended on fits to multiple measurements at different labs with different beam energies
- These measurements were made many years ago for other purposes, and had varying applicability to neutrino beams
- Significant issues with combining systematic errors across very different experiments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



Dedicated experiments



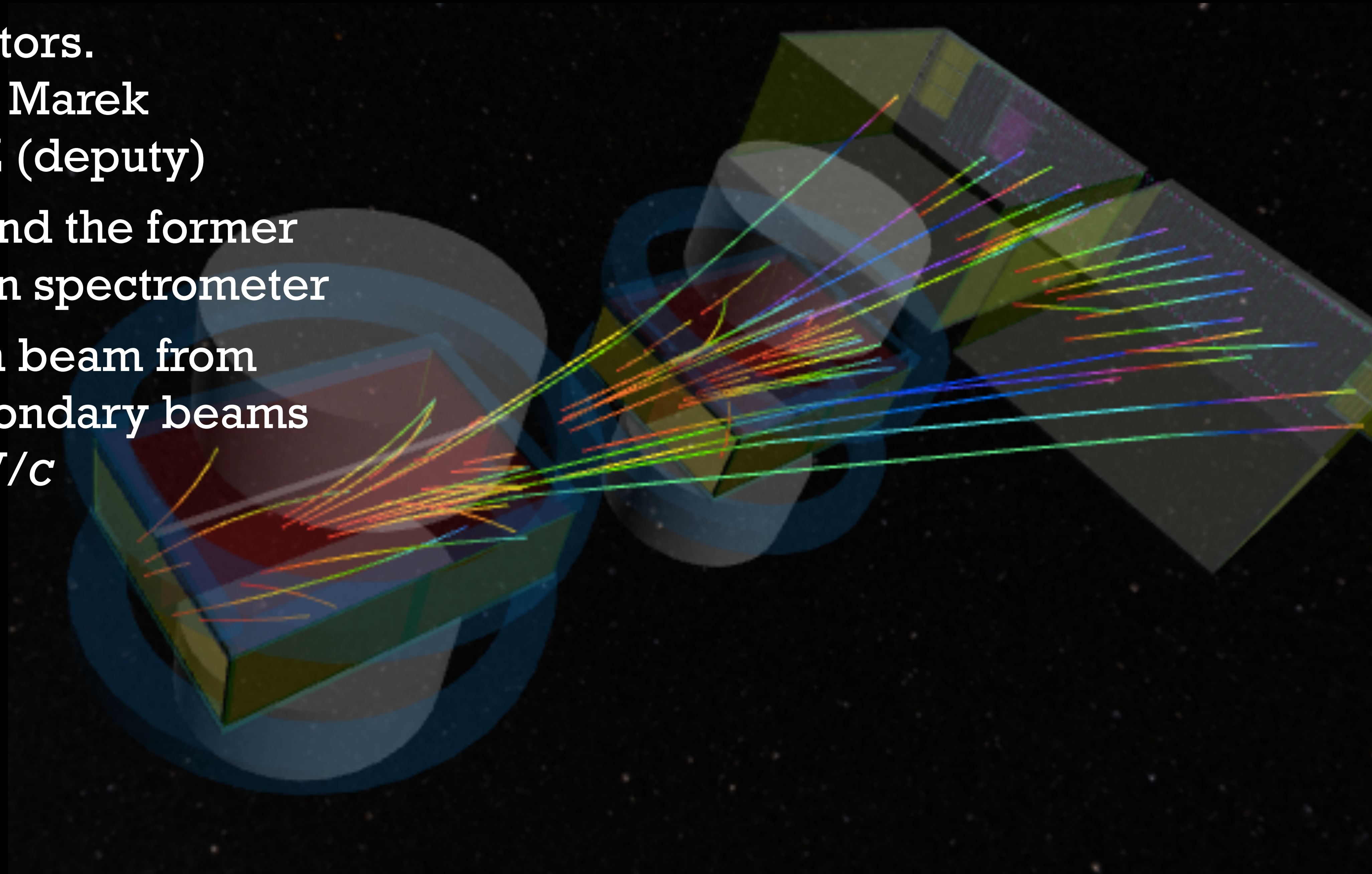




- In recent years, a loose program of hadron production measurements specifically for neutrino experiments has been underway
- HARP (CERN PS)
- EMPHATIC (FNAL MI)
- NA61/SHINE (CERN SPS)

NA61: The SPS Heavy Ion and Neutrino Experiment

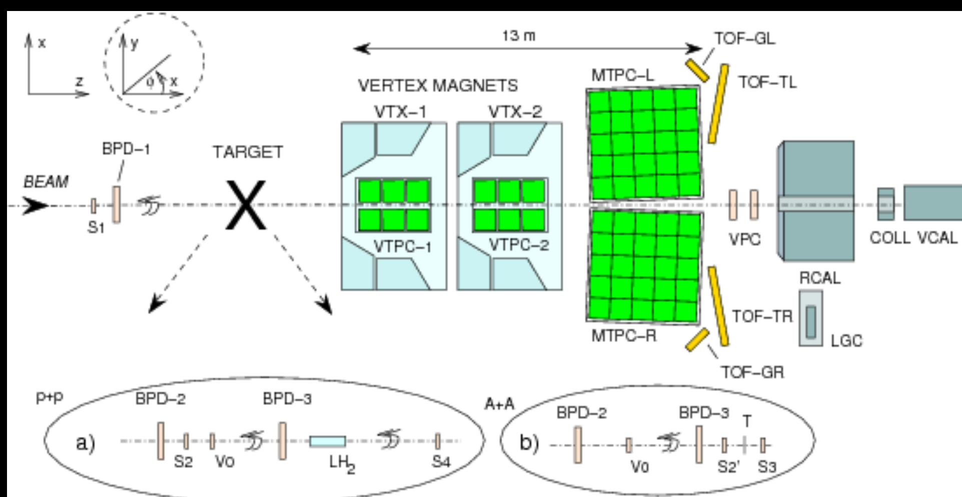
- Fixed-target experiment using H2 beam at CERN SPS
- ~150 collaborators. Spokespeople: Marek Gazdzicki, EDZ (deputy)
- Designed around the former NA49 heavy-ion spectrometer
- Primary proton beam from CERN SPS, Secondary beams ~25 to 350 GeV/*c*



NA61: The SPS Heavy Ion and Neutrino Experiment

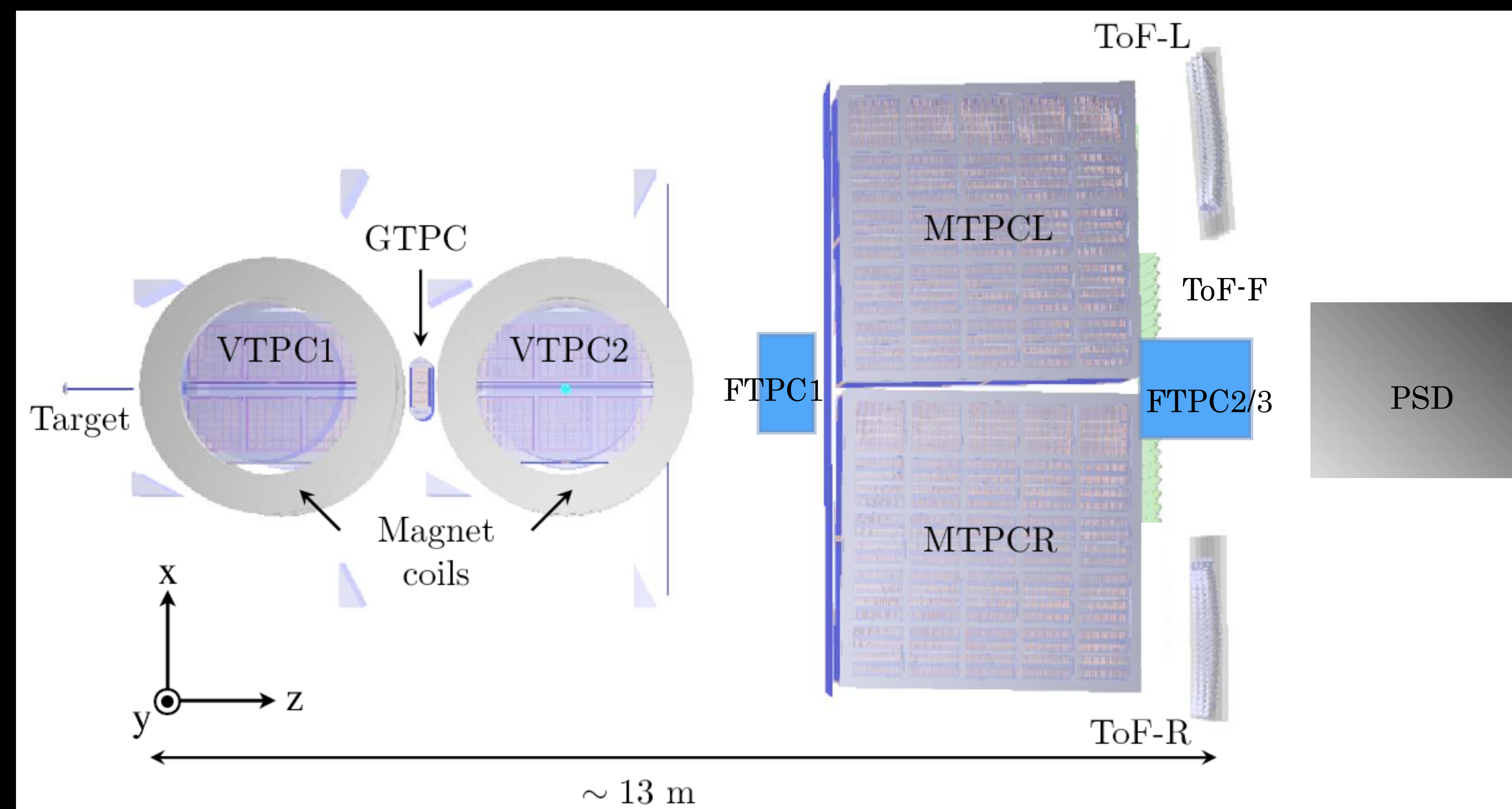
- Diverse physics program includes
  - Strong interactions/heavy ion physics
    - Onset of QCD deconfinement
    - Search for critical point
    - Open-charm production
  - Hadron production for neutrino beams
  - Cosmic ray production
    - Hadron production for air-shower model predictions
    - $d/\bar{d}$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

NA61 detector system



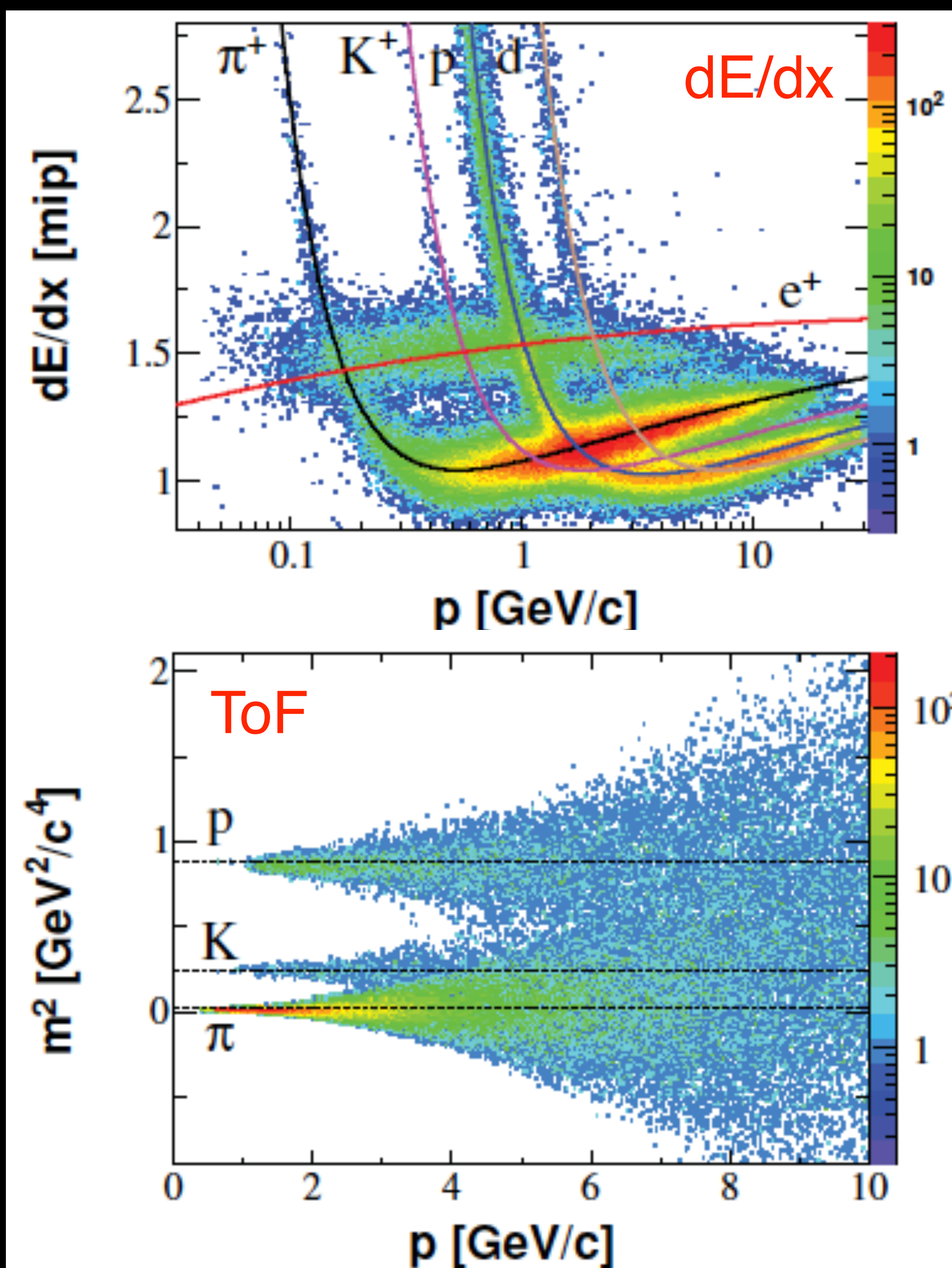
NA49

NA61

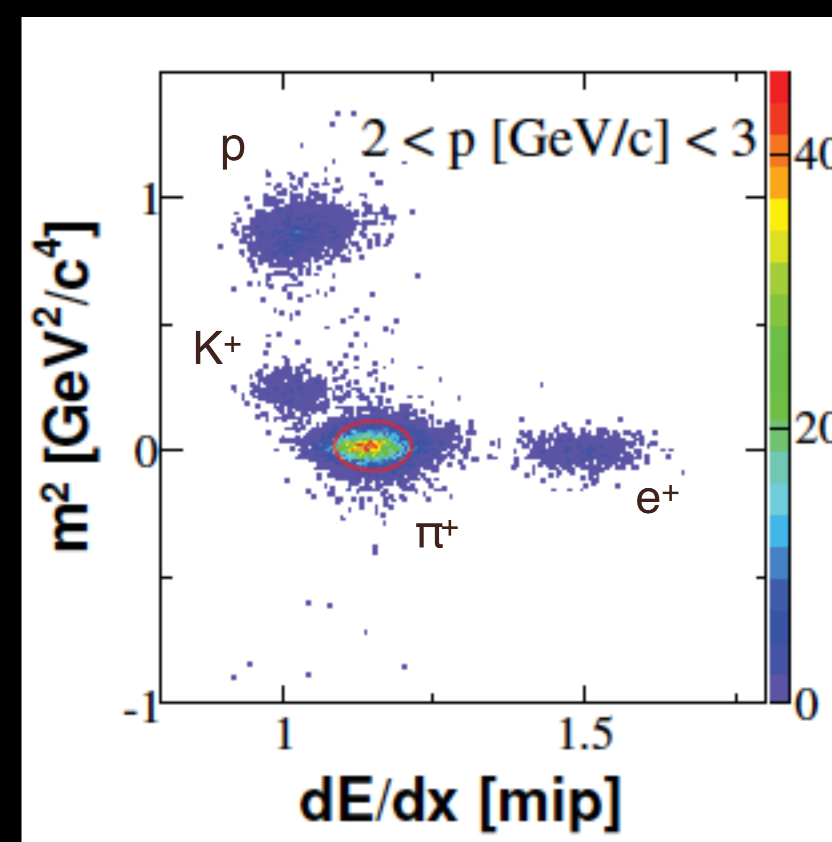


- Detailed beam instrumentation including PID and tracking before the target
- Several large-acceptance TPCs, two superconducting analysis magnets
- Scintillator-based time-of-flight detectors
- Projectile Spectator Detector: forward hadron calorimeter

Particle identification

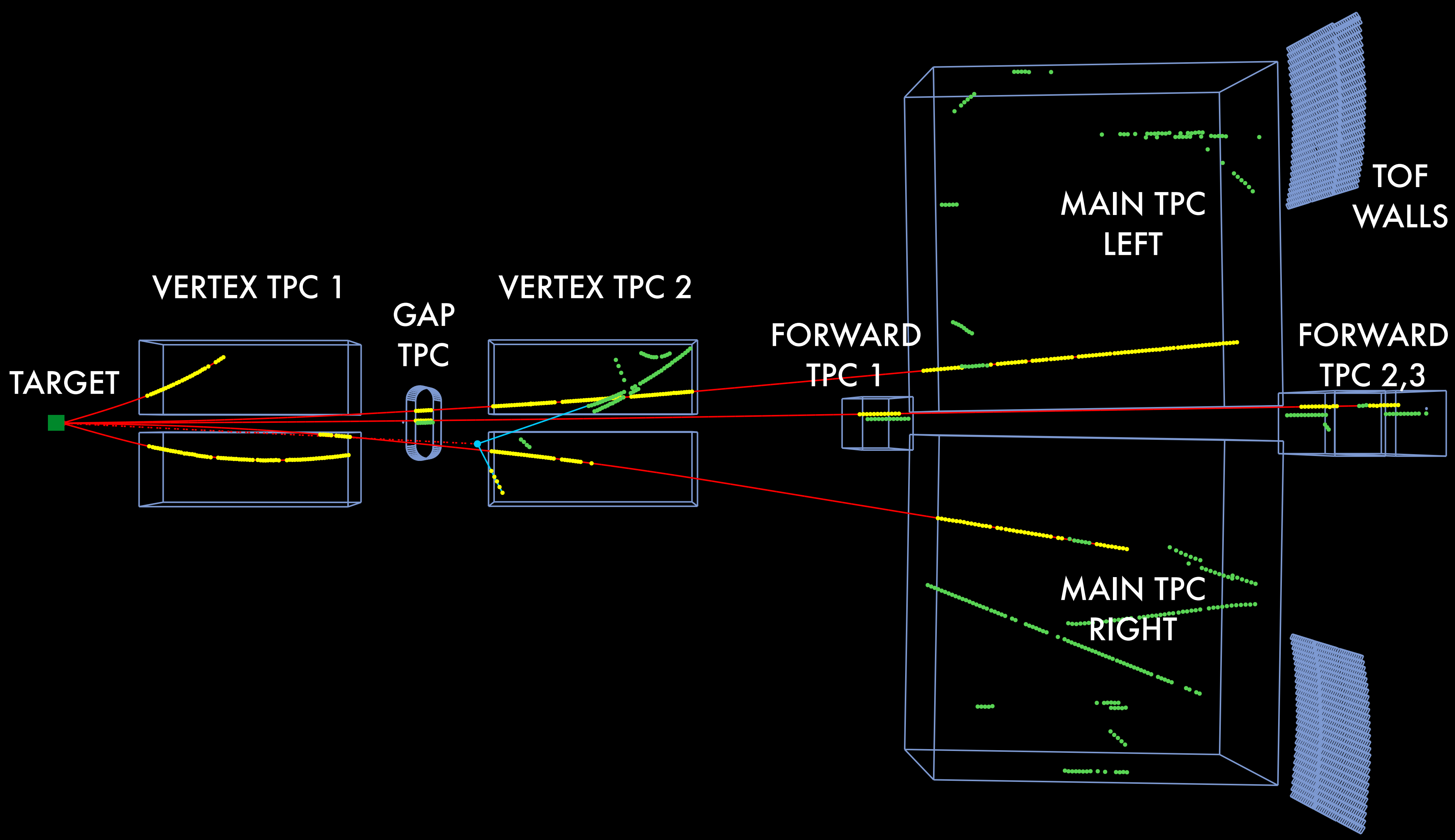


- Uses dE/dx in TPCs at higher momentum
- Transitions to TOF at lower p

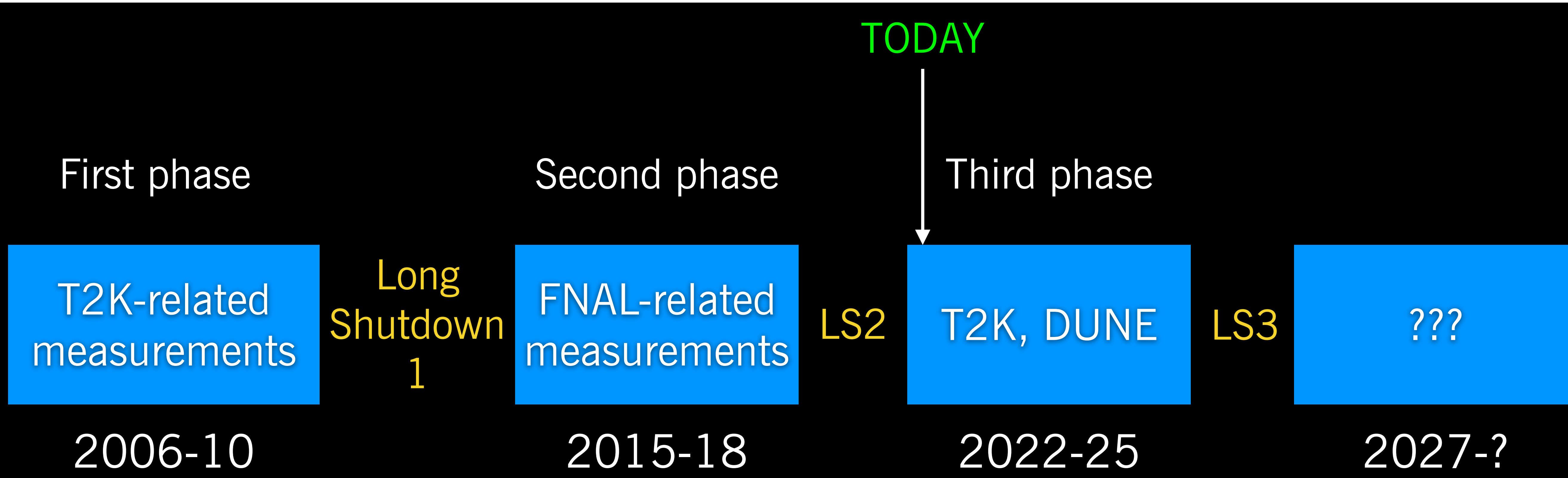


Event display

120 GeV p+C



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

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

- 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 particles in beam MC at surface of target

REPLICA TARGETS

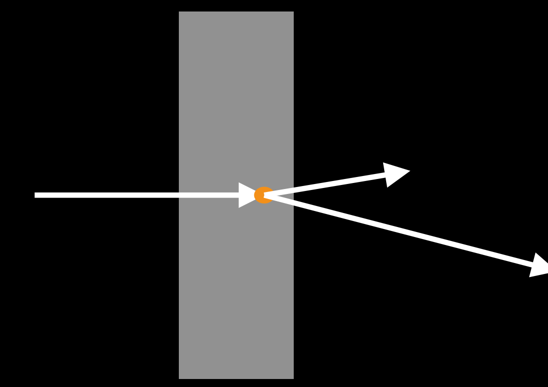
NA61/SHINE measurements for T2K

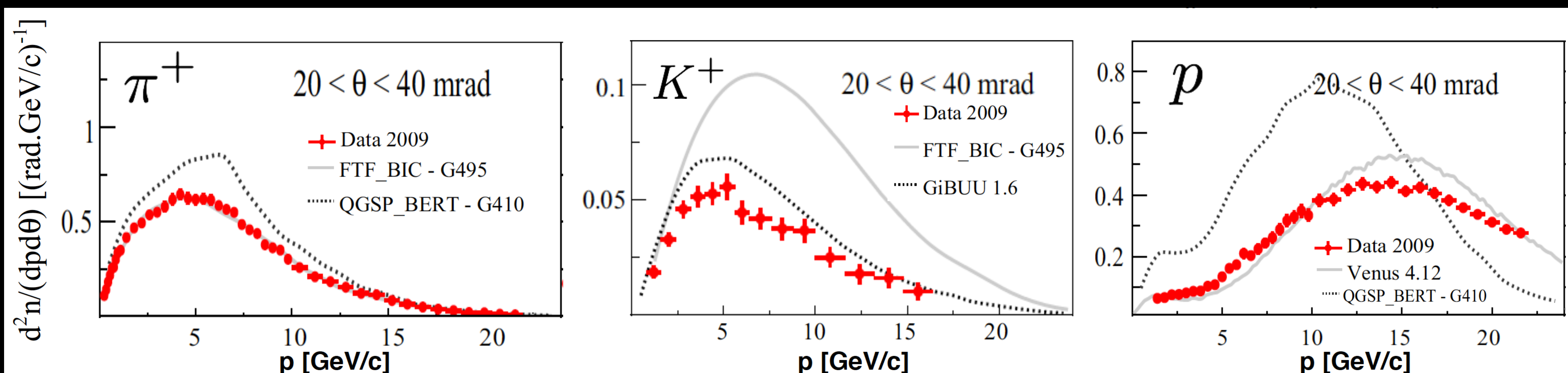
- NA61/SHINE took thin- and thick- target data with 30 GeV/*c* protons specifically for T2K in **2007 (thin) 2009 (thin and replica)**, and **2010 (replica)**.
- Eight NA61/SHINE publications have come out of these data sets

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)

Thin-target results:
p+C @ 30 GeV

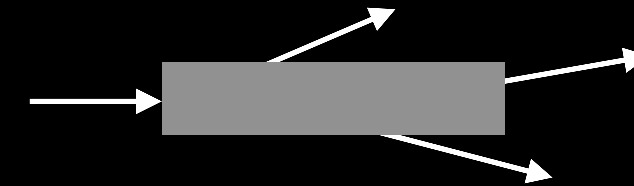




(11 θ-bins for 0 < θ < 420 mrad) (9 θ-bins for 0 < θ < 360 mrad) (10 θ-bins for 0 < θ < 360 mrad)

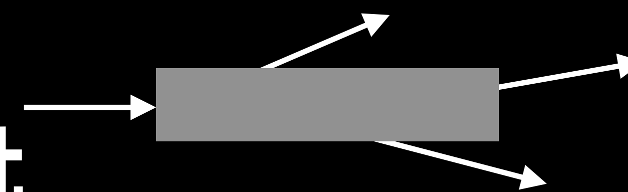
- One angle bin shown here for illustration
- MC generators fail badly for kaons and protons
- Published in Eur. Phys. J. **C76** 84 (2016): also contains yields of negative particles and neutral strange particles (V^0).

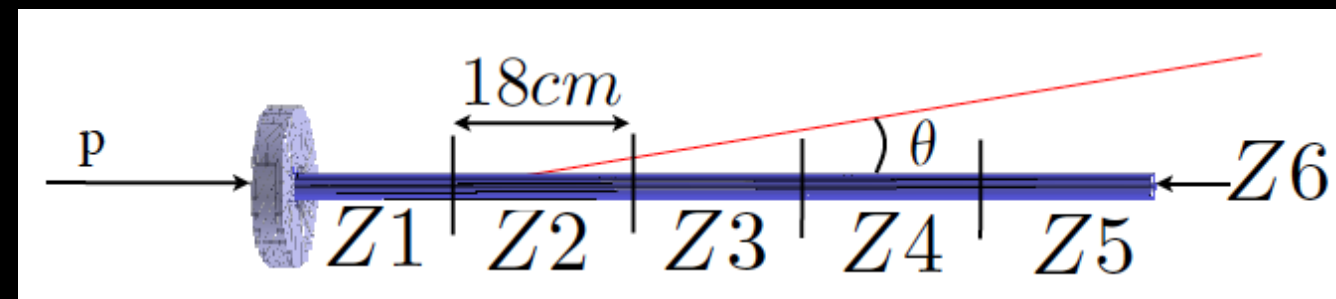
Replica-target measurements



- 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

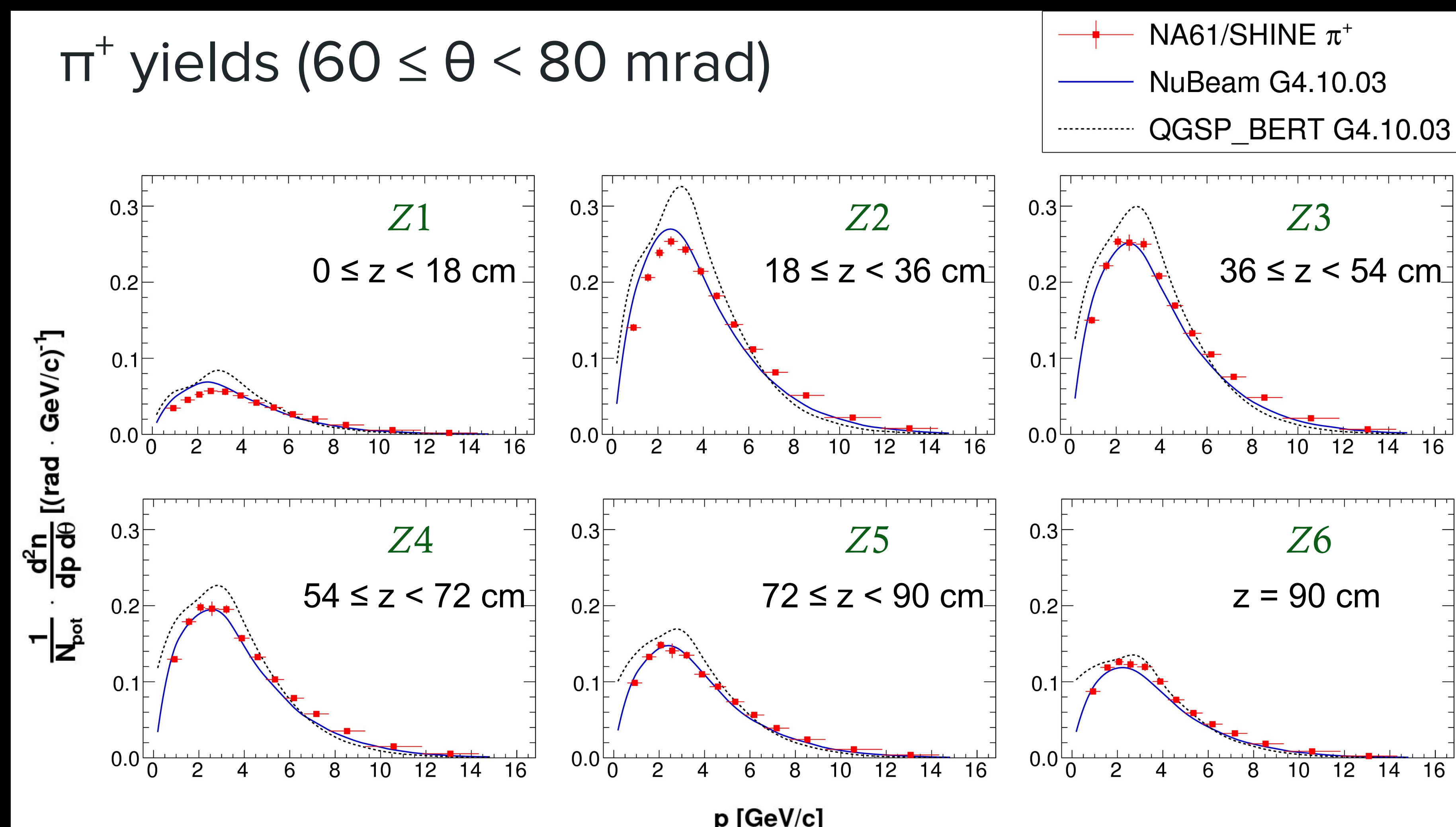
NA61 result: full differential yields from T2K replica target





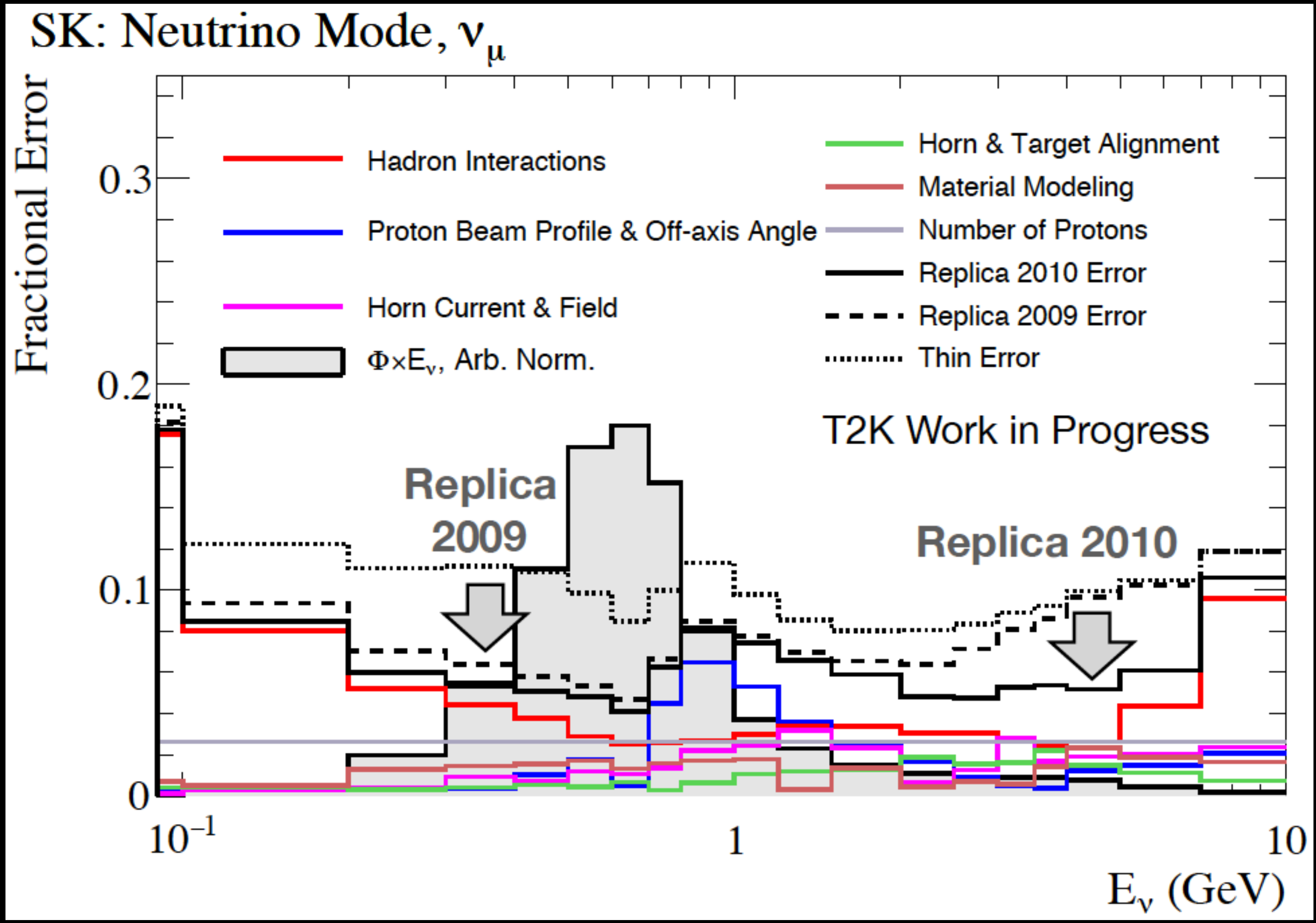
- *Eur.Phys.J.* **C 79** 2, 100 (2019)
- Showing one angle bin of π^+ for illustration.

  Also have π^-, $K^\pm$, p yields



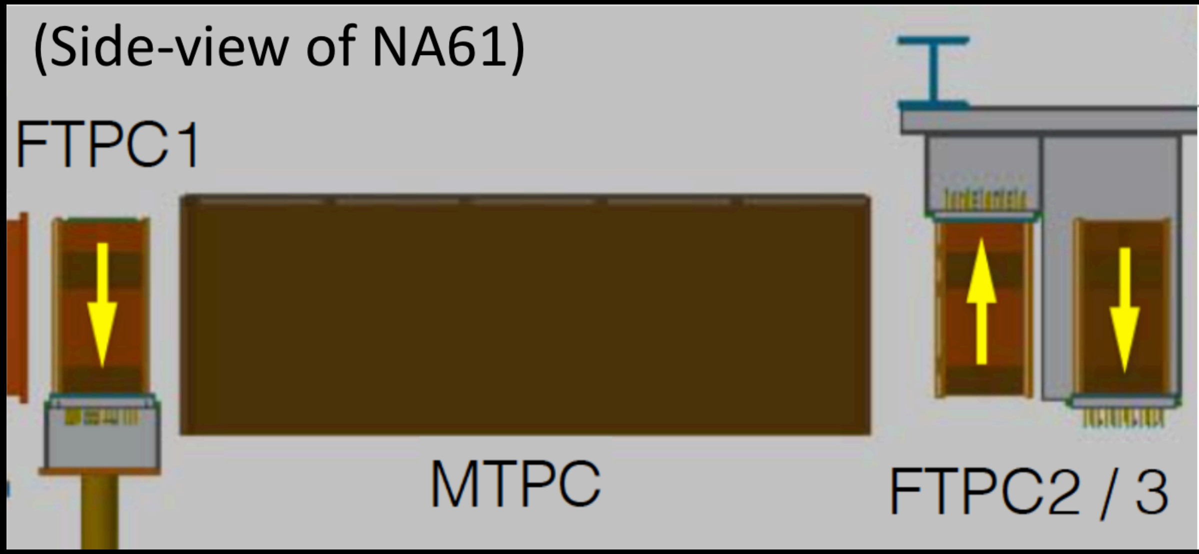
NA61/SHINE measurements for T2K

- 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

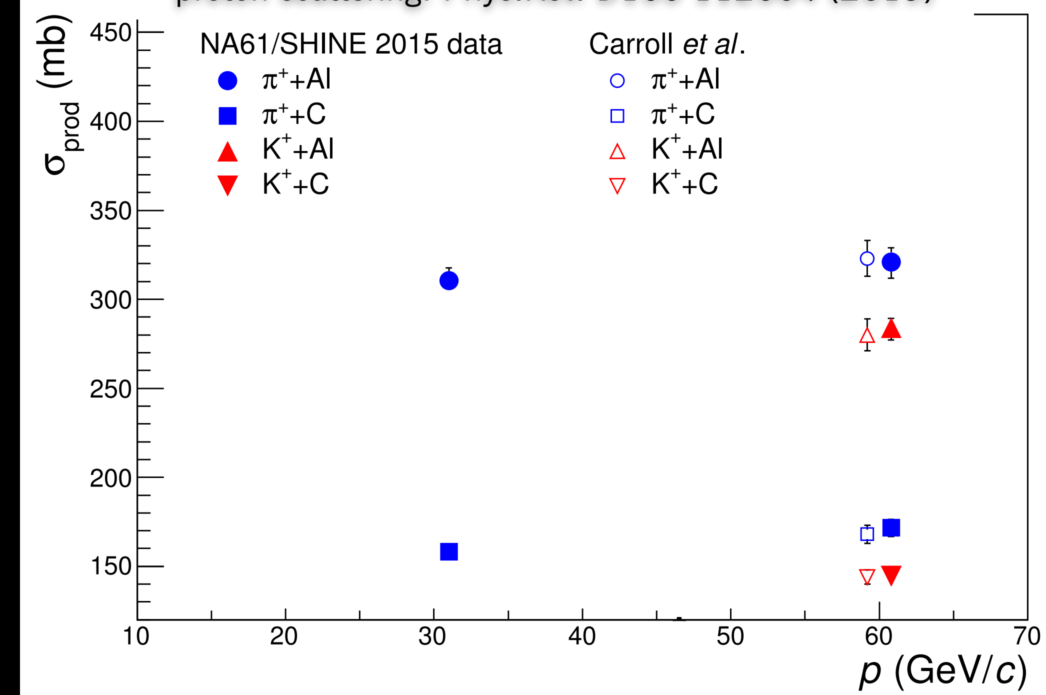
- Motivation: new coverage will be needed for future experiment DUNE, can help existing experiments as well in shorter term
- Project made specific upgrades:
  - Forward tracking system
  - New readout electronics for time-of-flight detector
- Data collected in 2015-18 for this program

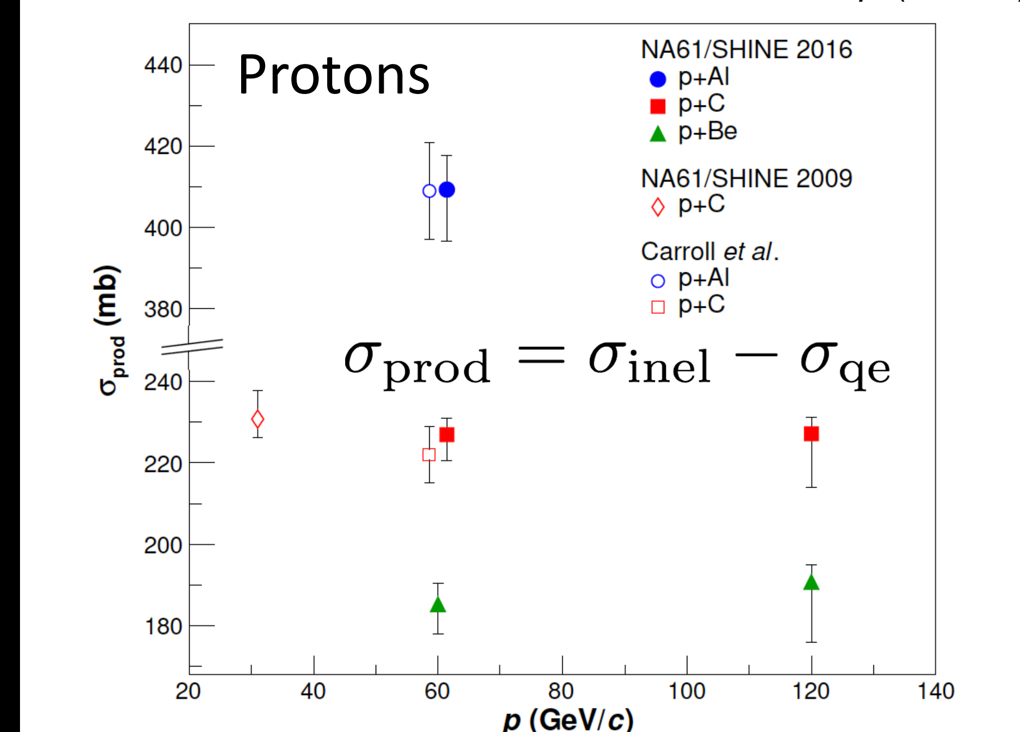


NA61/SHINE results: total production cross-sections on nuclear targets

- Pion and kaon scattering on carbon and aluminum
- Published total production and total inelastic cross section measurements for data without magnetic field
- Definitions: (terminology not always used consistently in community or in hadronic event generators.)
  - $\sigma_{prod} = \sigma_{total} - \sigma_{el} - \sigma_{qe}$, requires new hadrons to be produced.
  - $\sigma_{inel} = \sigma_{total} - \sigma_{el}$.
- Before, NuMI had 5% error on pion interactions, 10-30% for kaons, and had to extrapolate from other energies for protons

pion/kaon scattering: Phys.Rev. D98 052001 (2018);
proton scattering: Phys.Rev. D100 112004 (2019)





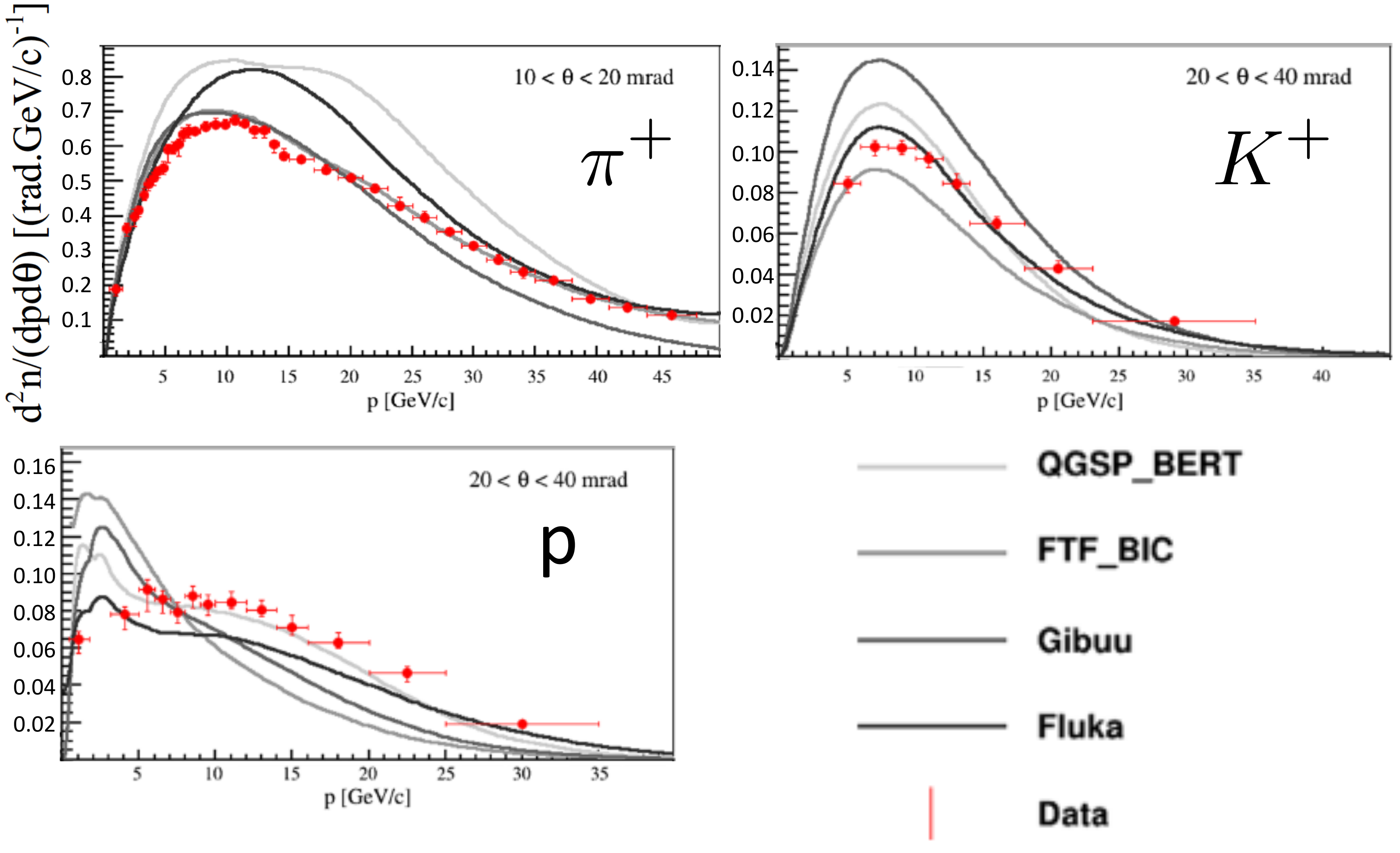
NA61 2016-17 neutrino data
Thin targets

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

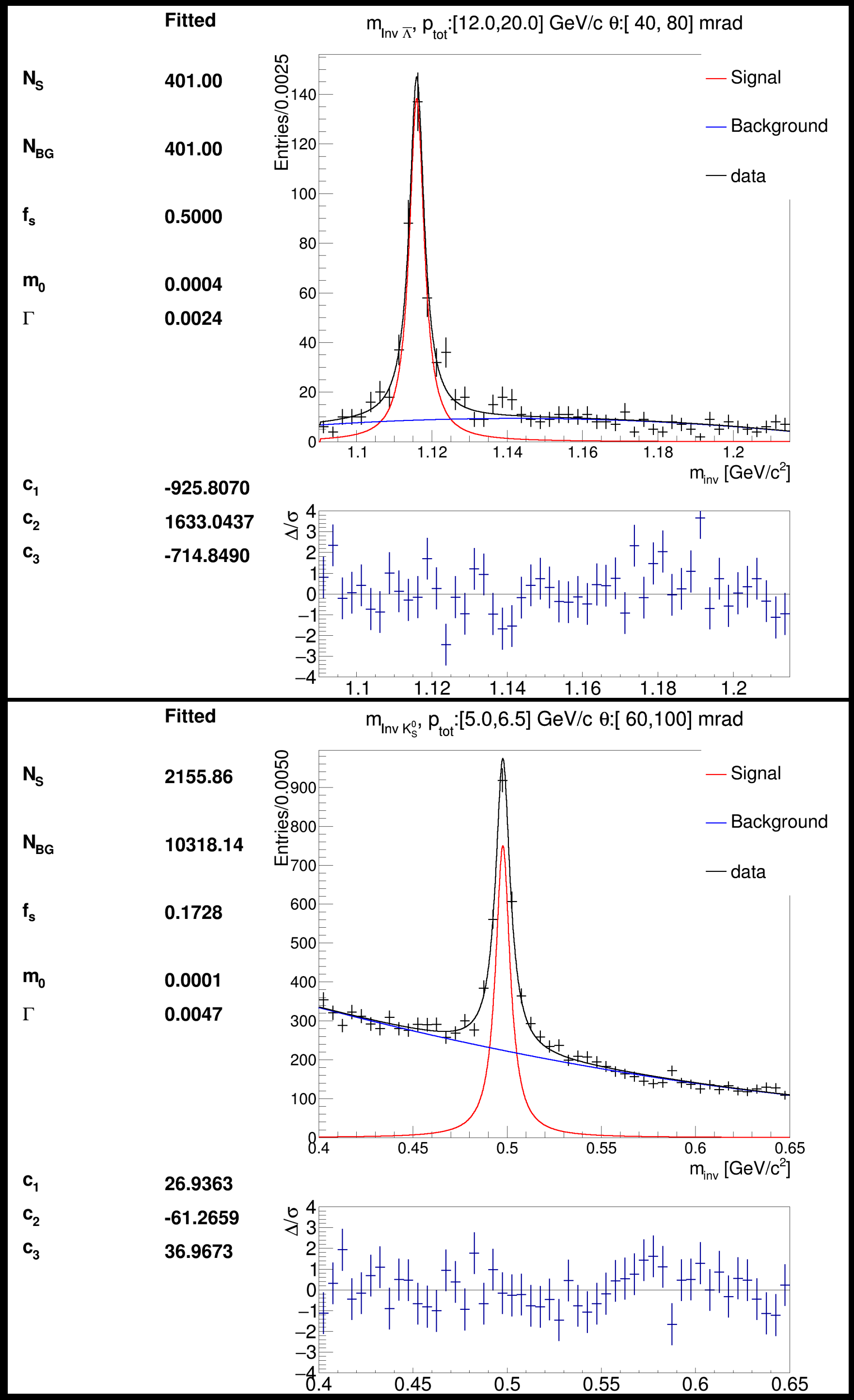
- Example: π^{+}+C @ 60 GeV (Phys.Rev. **D100** 112004 (2019))
- Measured differential production yields (positively-charged shown, also measured negatives)



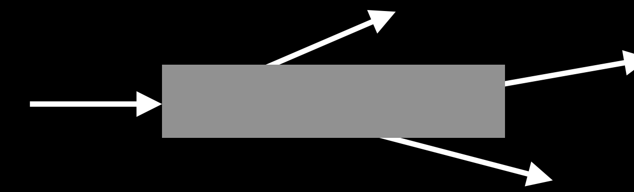
Coming soon: results on spectra from thin-target p+C @ 120 GeV

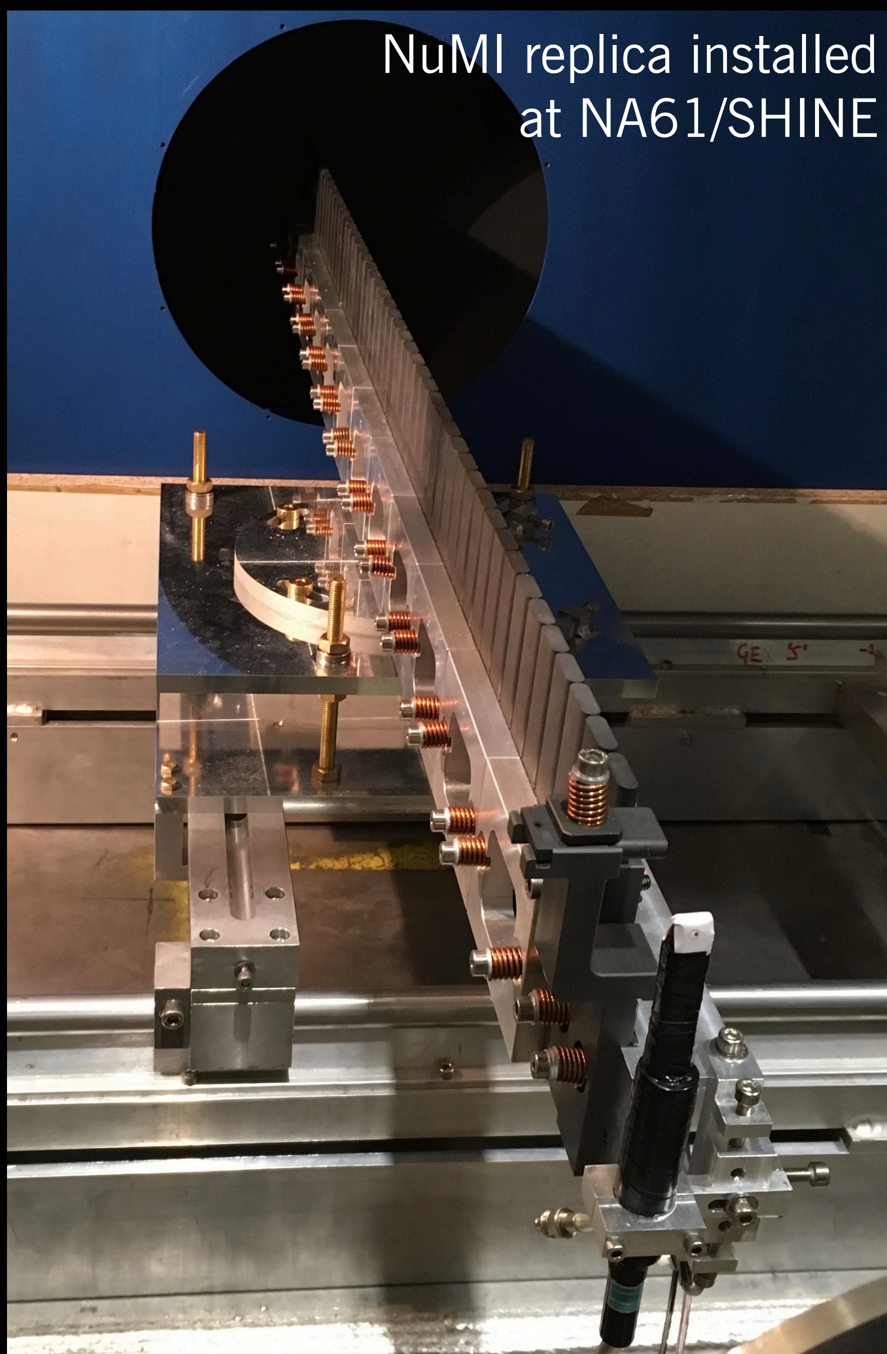
- This data set is high priority: represents the primary proton interaction in NuMI/NOvA/MINERvA.
- Relies on new Forward TPCs to provide forward acceptance (magnet doesn't bend beam-energy protons into the older TPCs) to see elastic, quasi-elastic events
- New tracking algorithm is used for integrating the FTPCs into the analysis:
    - Cellular automaton-based local tracking with Kalman filter for global track fit is in final development
- Superior identification of V^0 events
- Expect results on charged and neutral particle yields from ~3 million interactions in a few weeks!

B. Rumberger, NA61 work in progress

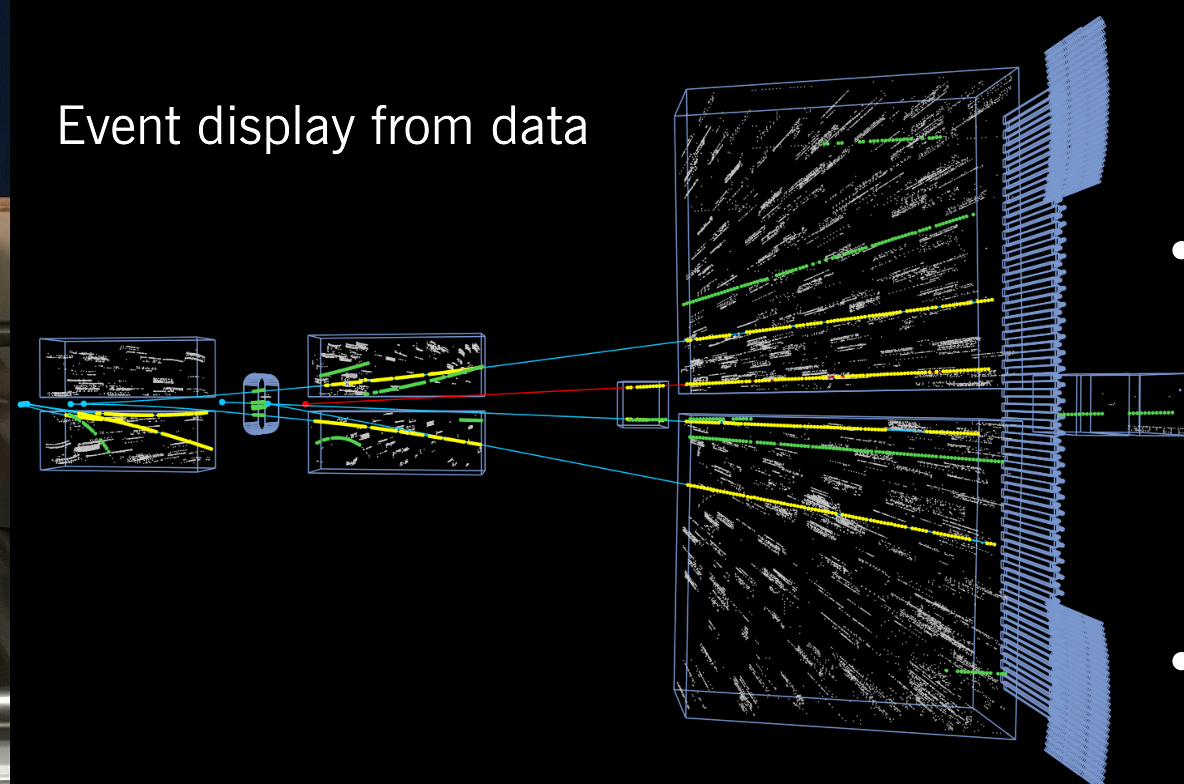


Coming soon: measurements with NuMI replica target





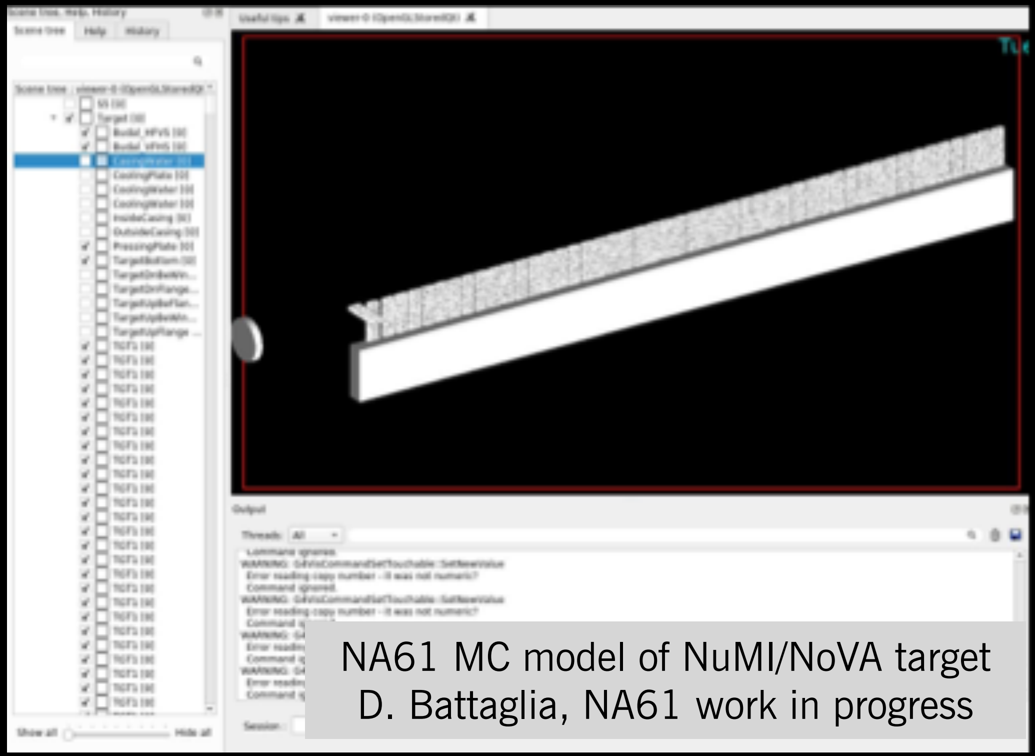
Event display from data



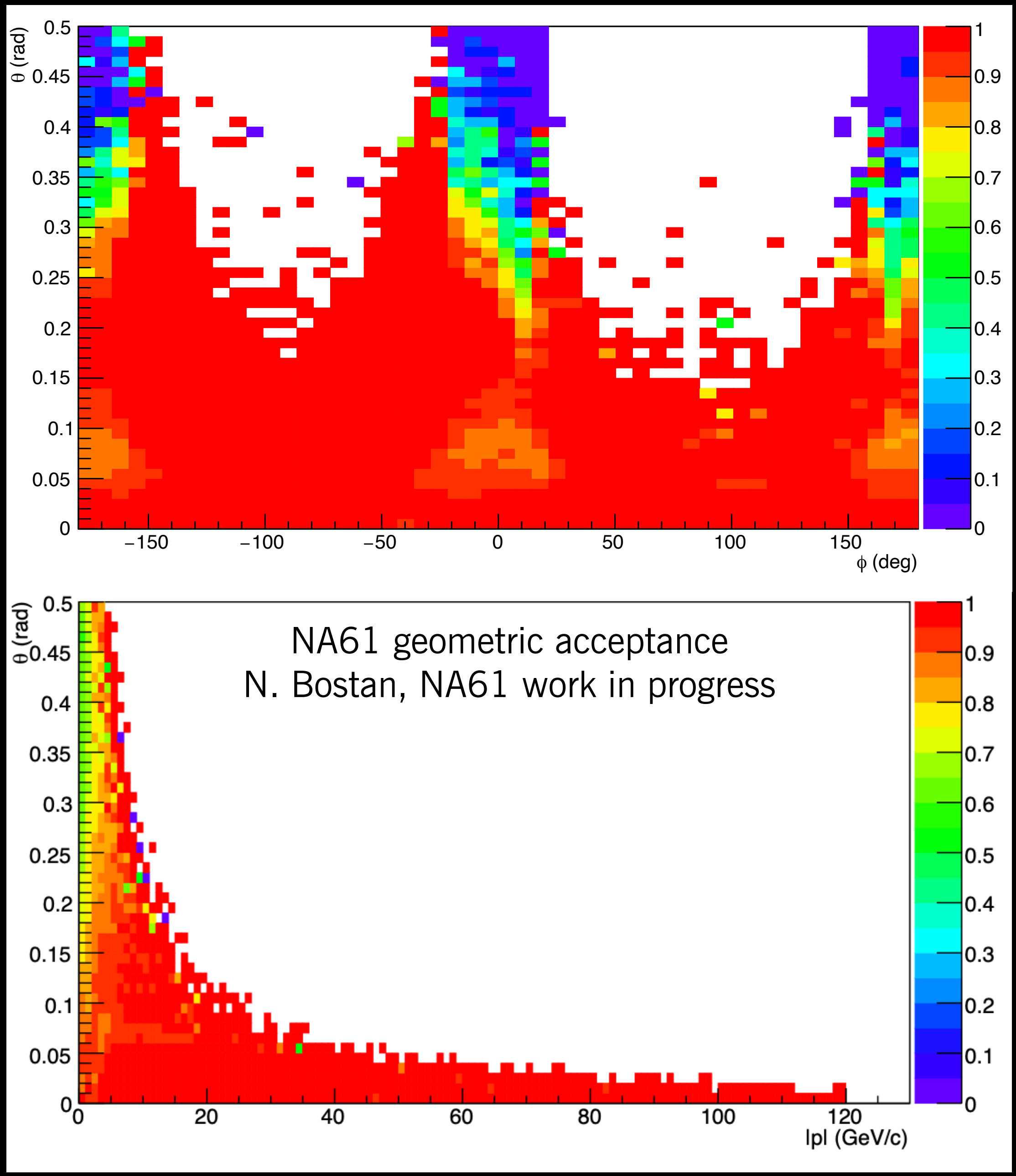
- Took high statistics (18M events) in 2018 with 120 GeV protons
- Analysis underway on hadron yields from this target
- Asymmetric design means binning in ϕ becomes important

NuMI target analysis

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

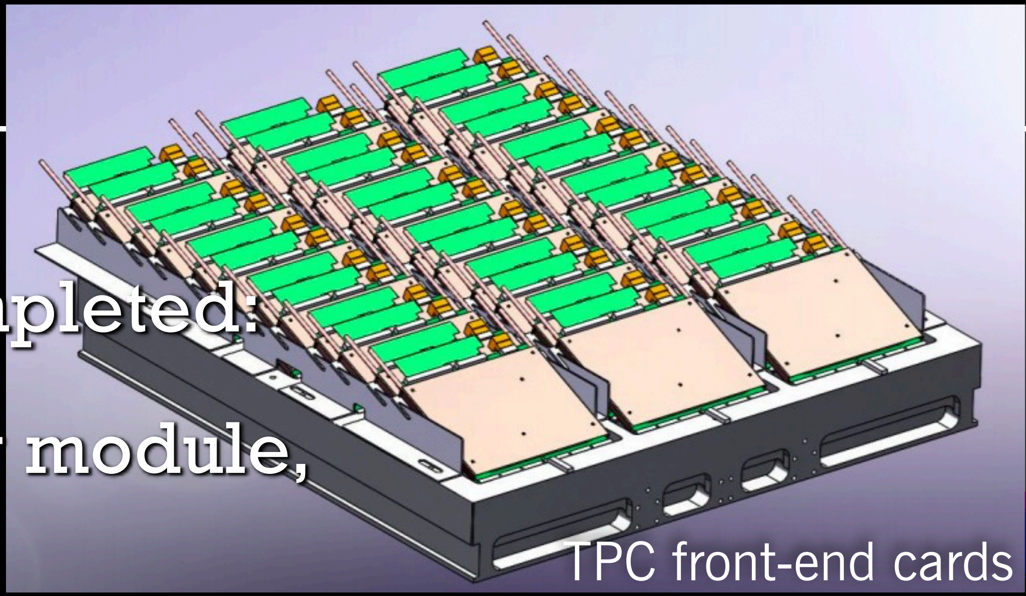


NA61 MC model of NuMI/NoVA target
D. Battaglia, NA61 work in progress



NA61 geometric acceptance
N. Bostan, NA61 work in progress

Third phase: upgraded detector



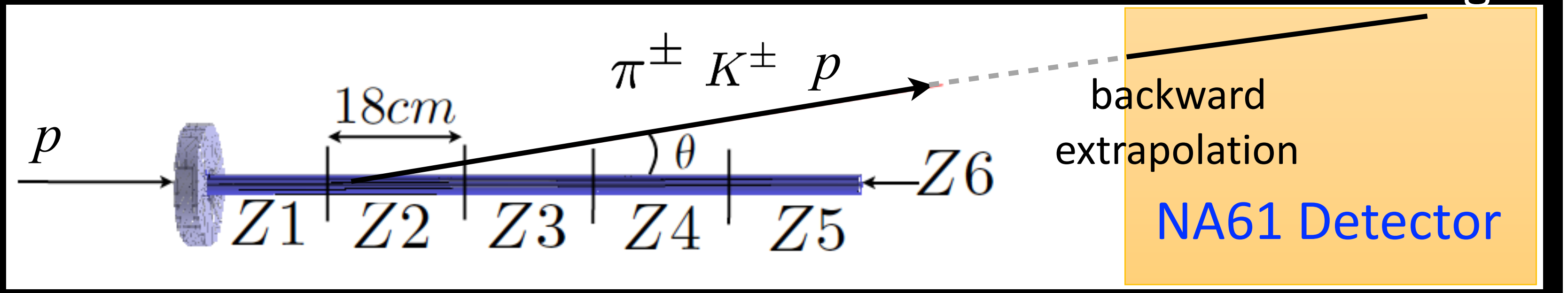
- Many major detector upgrades recently completed:
  - New forward Projectile Spectator Detector module, reconfiguration of existing detector
  - Replacement of old TPC electronics with system from ALICE
  - New silicon vertex detector for open charm studies
  - RPC-based replacement for TOF-L/R walls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

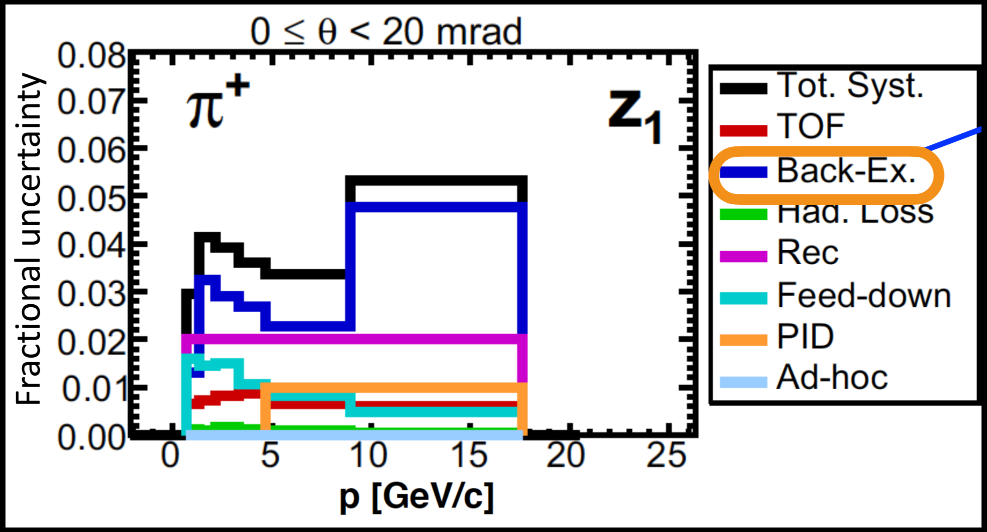
Data collection: now and near future

- **Data collection has begun!** Expect 3-4 years of operation.
- Priorities will be:
  - Additional T2K replica-target running (underway) to increase statistics 20x from 2010 and measure high-momentum kaon yields
  - Kaon scattering with thin targets for secondary interaction modeling
  - LBNF/DUNE replica target (2024). This target will be at least 1.5 m long and may create some challenges for reconstruction.
  - Improved statistics as needed on multiple measurements

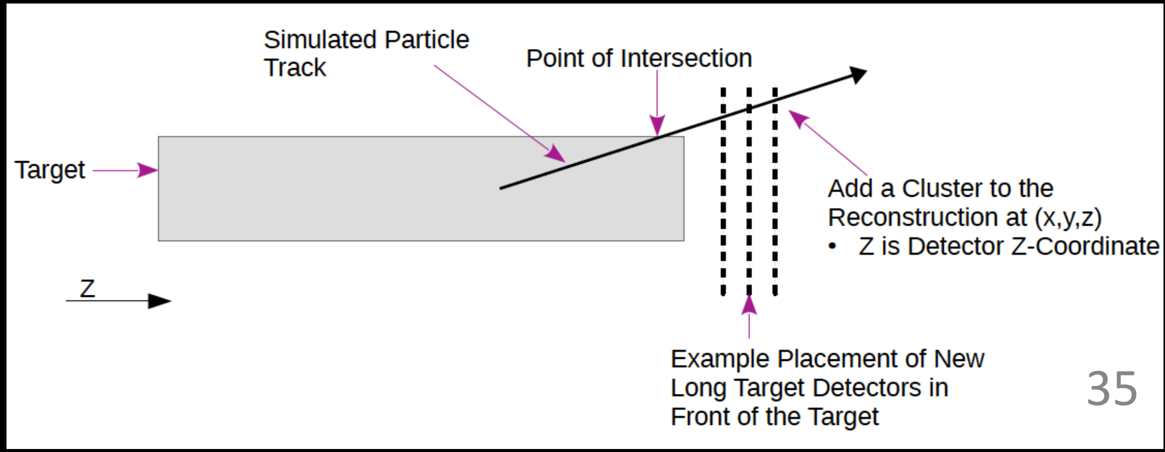
Long-target tracker

Y. Nagai





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



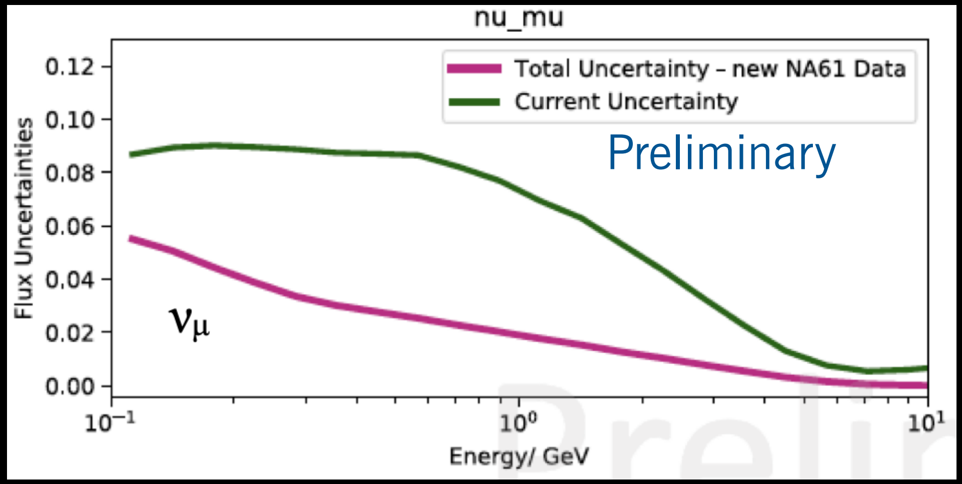
- Additional tracking detectors at the end of the target will probably be needed for the longer LBNF/DUNE target as well as a more precise measurement for T2K

- Considering options such as silicon planes or a (more likely) a small TPC

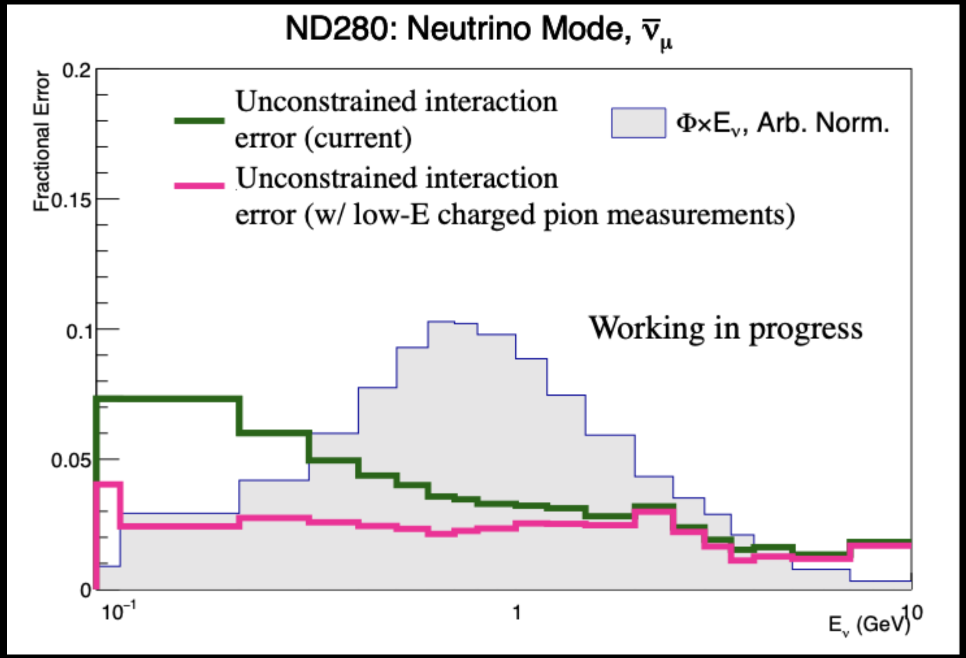
Future after LS2/3: low-energy beam?

- 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
  - Atmospheric neutrino flux
  - T2K/HyperK secondary interactions
  - Spallation sources, cosmic rays, others…
- Beam modifications under design at CERN, project being formed now after positive response from SPSC

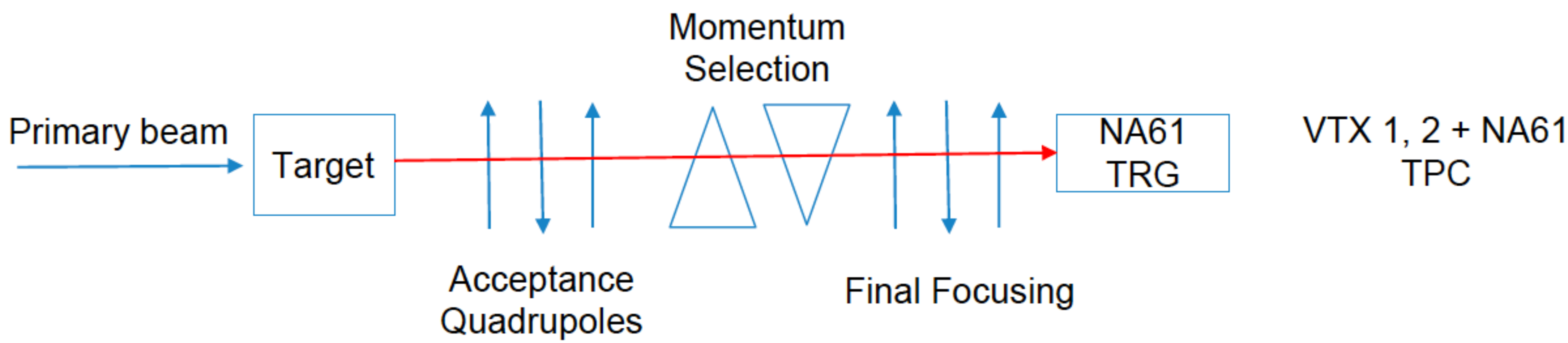
L. Cook (Bartol Group) atmospheric neutrino flux

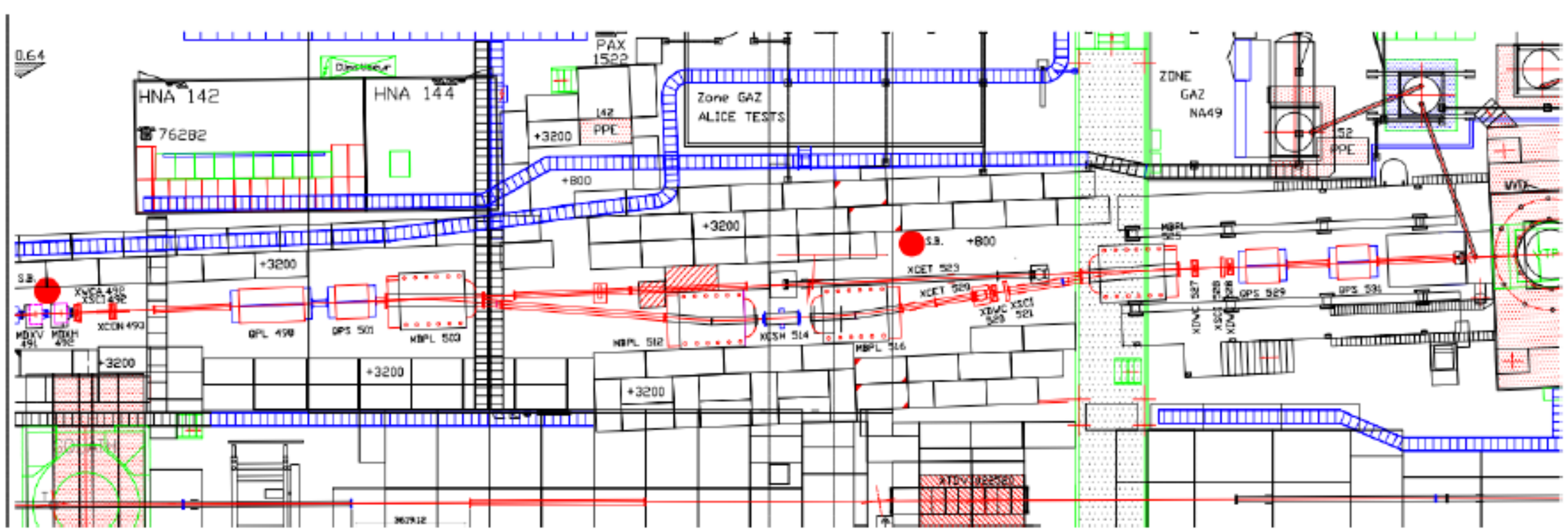


T2K/HyperK wrong-sign flux uncertainties



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 ongoing by CERN beam group in collaboration with NA61/SHINE.
- Goal is to have beam available in 2025, and again after the next Long Shutdown

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 on opportunities after the next Long Shutdown
- December 15-17 at CERN
- Technical issues and physics opportunities (let me know if you wish to present one)
- *Look for posting on INSPIRE and Indico soon*

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
- More data sets coming in the next three years, with T2K and LBNF/DUNE targets
- Low-energy beam and other future options under study