NA61/SHINE Experiment

- Results from the Neutrino Program and Future Prospects

Yoshikazu Nagai

University of Colorado Boulder

May 14, 2020, Fermilab Neutrino Seminar

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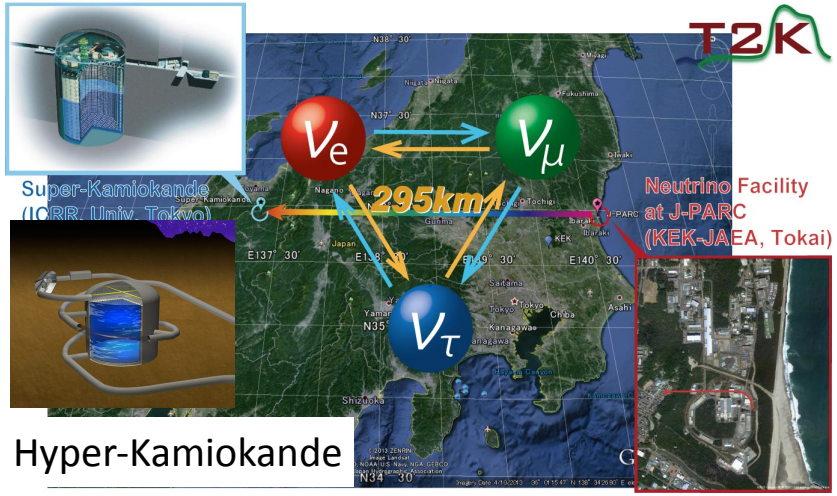
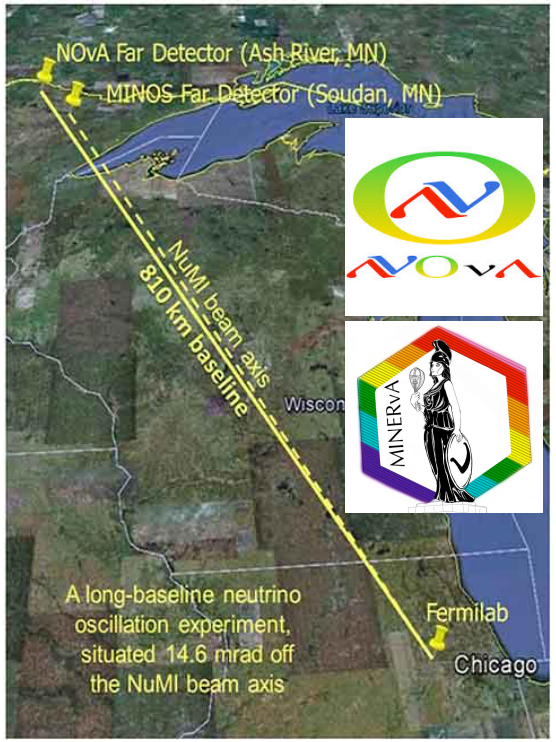
- Summary

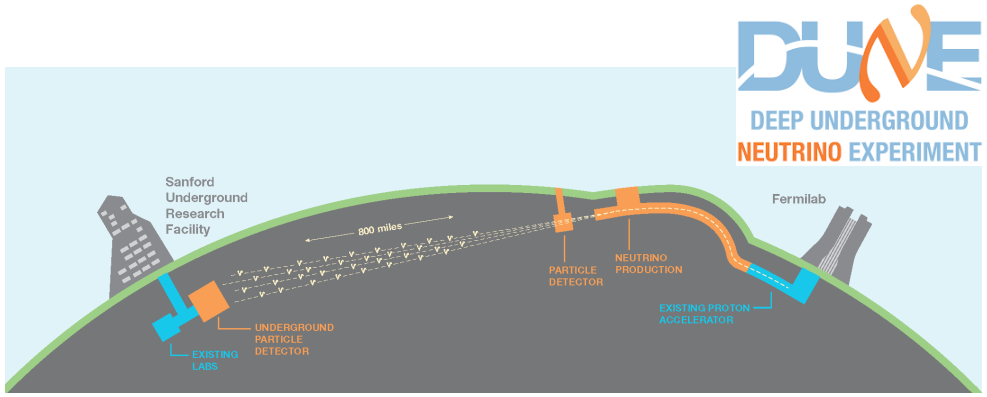
Focus of This Talk: LBN Beamlines

- Current and future accelerator-based neutrino experiments
  - Understanding neutrino flux produced in neutrino beamlines: J-PARC, NuMI, LBNF



J-PARC beamline (30 GeV proton beam)
experiments: T2K, T2HK



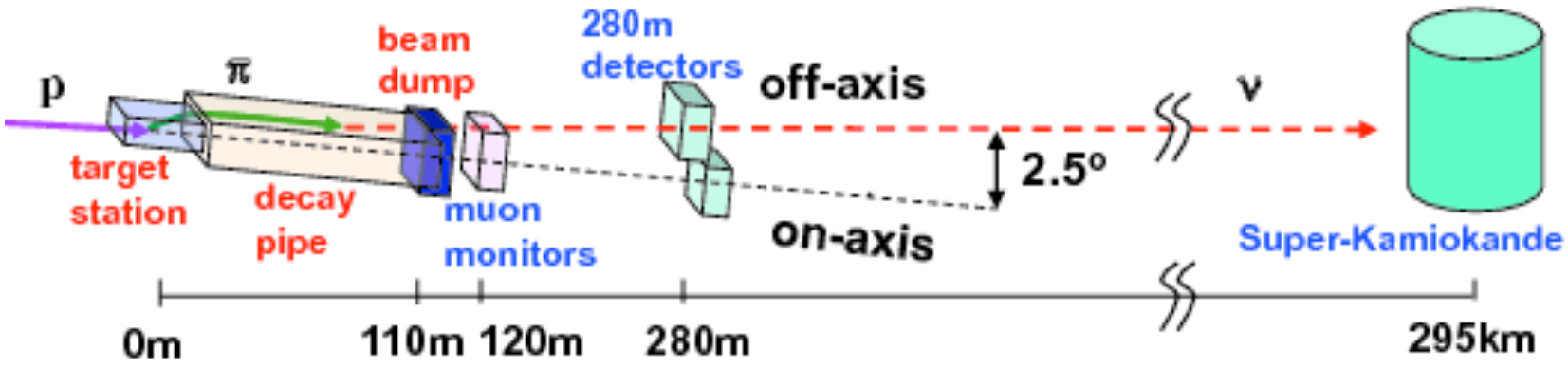


LBNF beamline (60 - 120 GeV proton beam not yet determined)
experiment: DUNE

NuMI beamline (120 GeV proton beam)
experiments: NOvA (and MINERvA)

Introduction

Long-baseline Neutrino Experiments



Beamline

- Create intense ν_μ and $\bar{\nu}_\mu$ beams by shooting proton beams on target, focusing hadrons, and letting them decay to neutrinos

$$\Phi_{\text{initial}}$$

Near detector

- Flux and cross section constraint for far detector prediction
- Near detector physics measurements (e.g. neutrino-nucleus cross sections)

$$N_{ND} \propto \int \Phi_{ND} \cdot \sigma \; dE_\nu$$

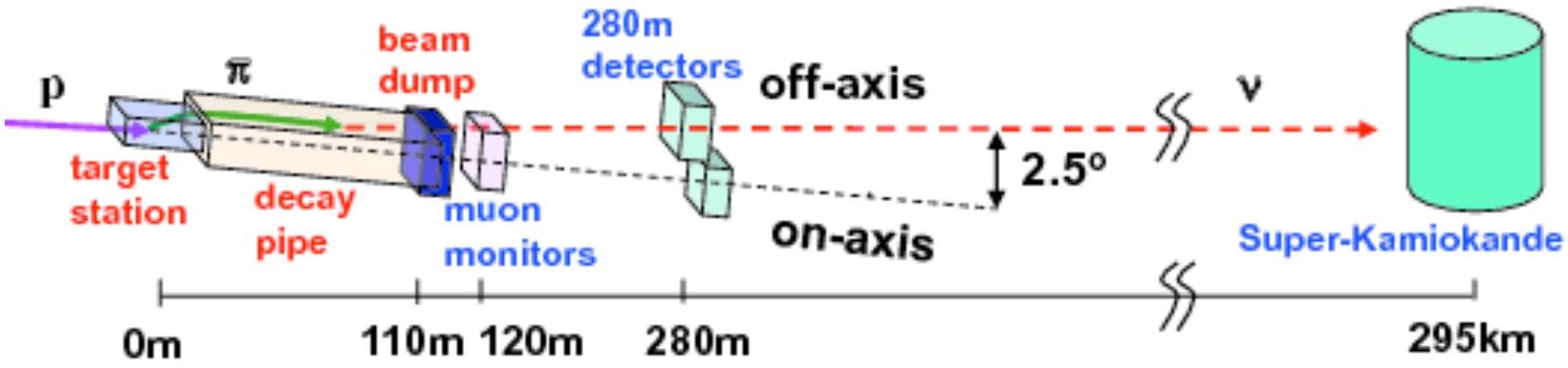
Far detector

- Count ν_e and $\bar{\nu}_e$ appearance signals (measure the size of CP violation)
- Measure ν_μ and $\bar{\nu}_\mu$ disappearance

$$N_{FD} \propto \int \Phi_{FD} \cdot \sigma \cdot P_{osc} \; dE_\nu$$

$$\propto \int R_{\frac{FD}{ND}} \cdot \Phi_{ND} \cdot \sigma \cdot P_{osc} \; dE_\nu$$

Long-baseline Neutrino Experiments



Beamline

- Create intense ν_μ and $\bar{\nu}_\mu$ beams by shooting proton beams on target, focusing hadrons, and letting them decay to neutrinos

Φ_{initial}

Near detector

- Flux and cross section constraint for far detector prediction
- Near detector physics measurements (e.g. neutrino-nucleus cross sections)

$$N_{ND} \propto \int \Phi_{ND} \cdot \sigma \; dE_\nu$$

My talk focuses on this part
to precisely know *a priori* neutrino flux

Far detector

- Count ν_e and $\bar{\nu}_e$ appearance signals (measure the size of CP violation)
- Measure ν_μ and $\bar{\nu}_\mu$ disappearance

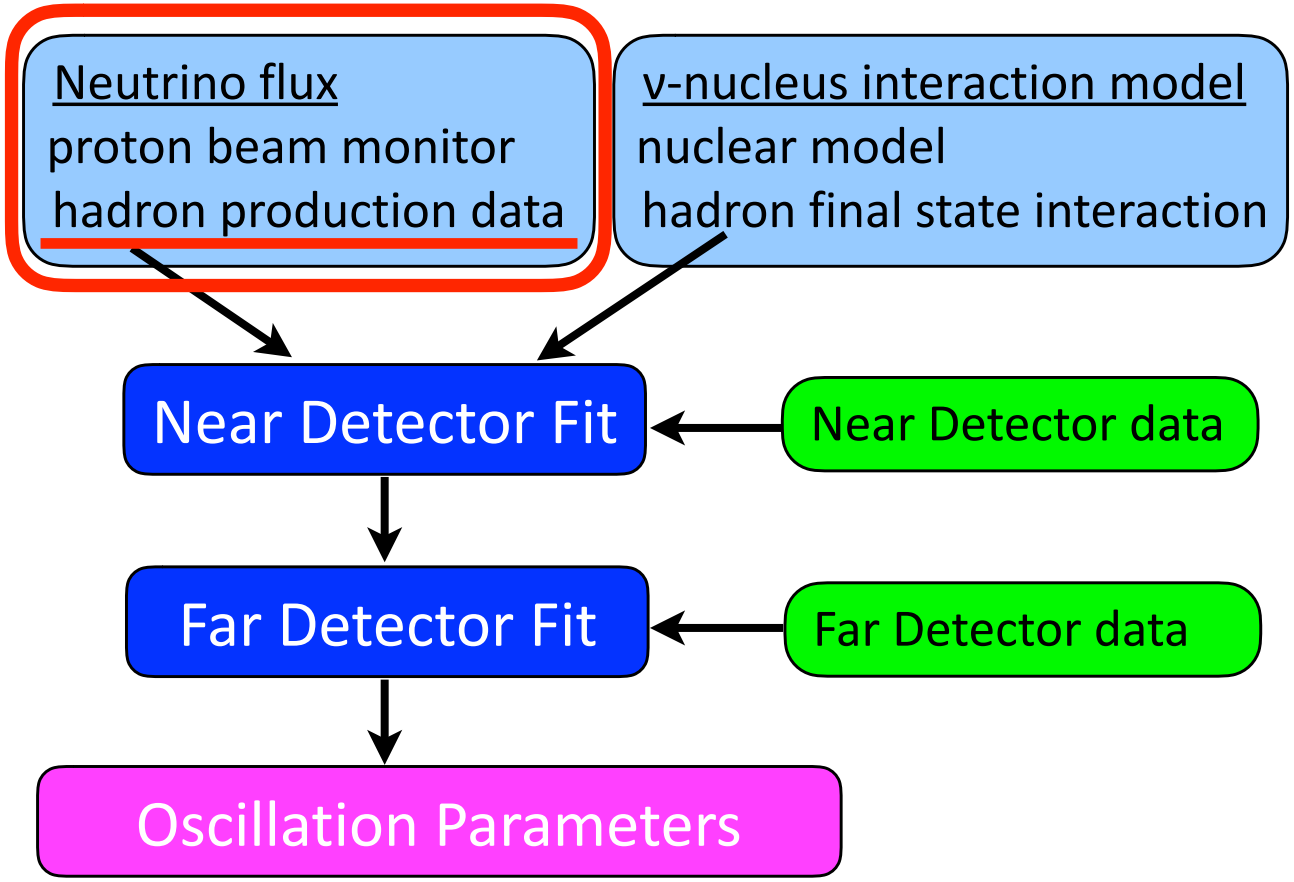
$$N_{FD} \propto \int \Phi_{FD} \cdot \sigma \cdot P_{osc} \; dE_\nu$$

$$\propto \int R_{\frac{FD}{ND}} \cdot \Phi_{ND}^{*} \cdot \sigma \cdot P_{osc} \; dE_\nu$$

* ND and FD do not see same flux

LBN Physics Program

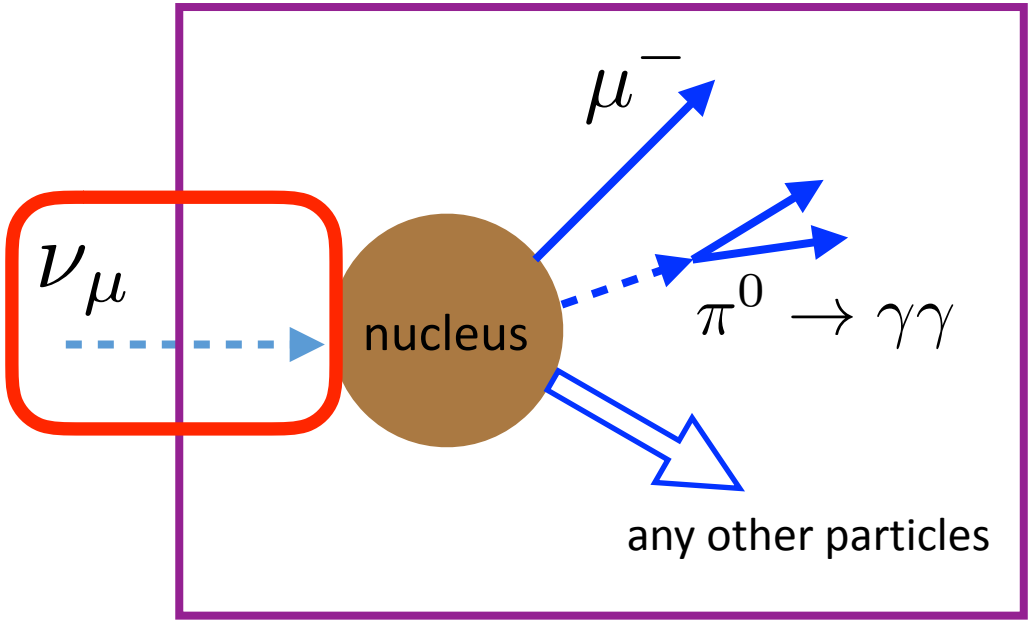
- Neutrino oscillation



θ_{23}, θ_{13}, δ_{CP}, Δm^2_{32} or Δm^2_{13}

(Normal) (Inverted)

- Neutrino-nucleus interaction

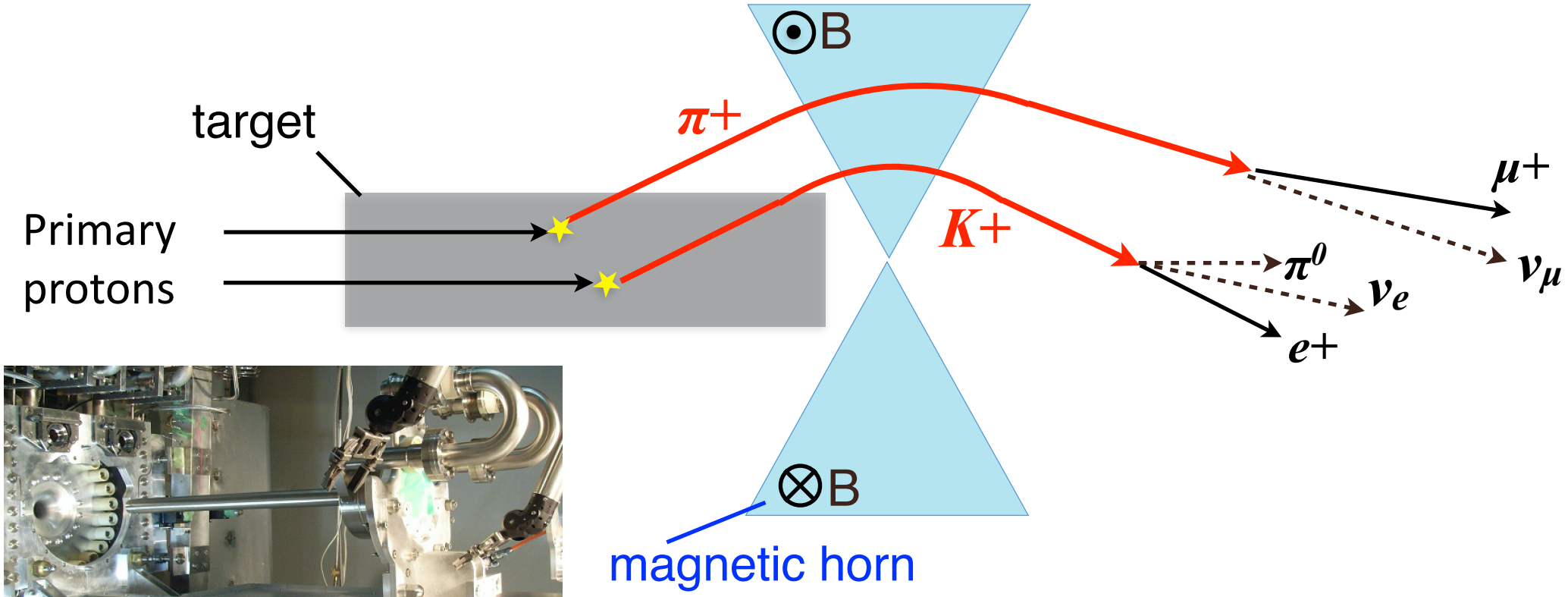


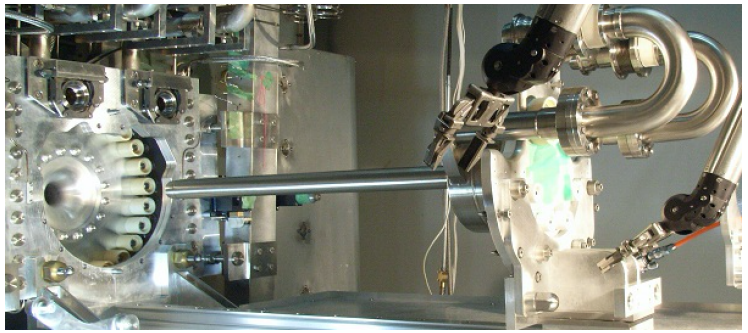
Near Detector

Flux uncertainty directly impacts precision of measurement in case of near detector physics

Flux knowledge is crucial !!

How to Make a Neutrino Beam



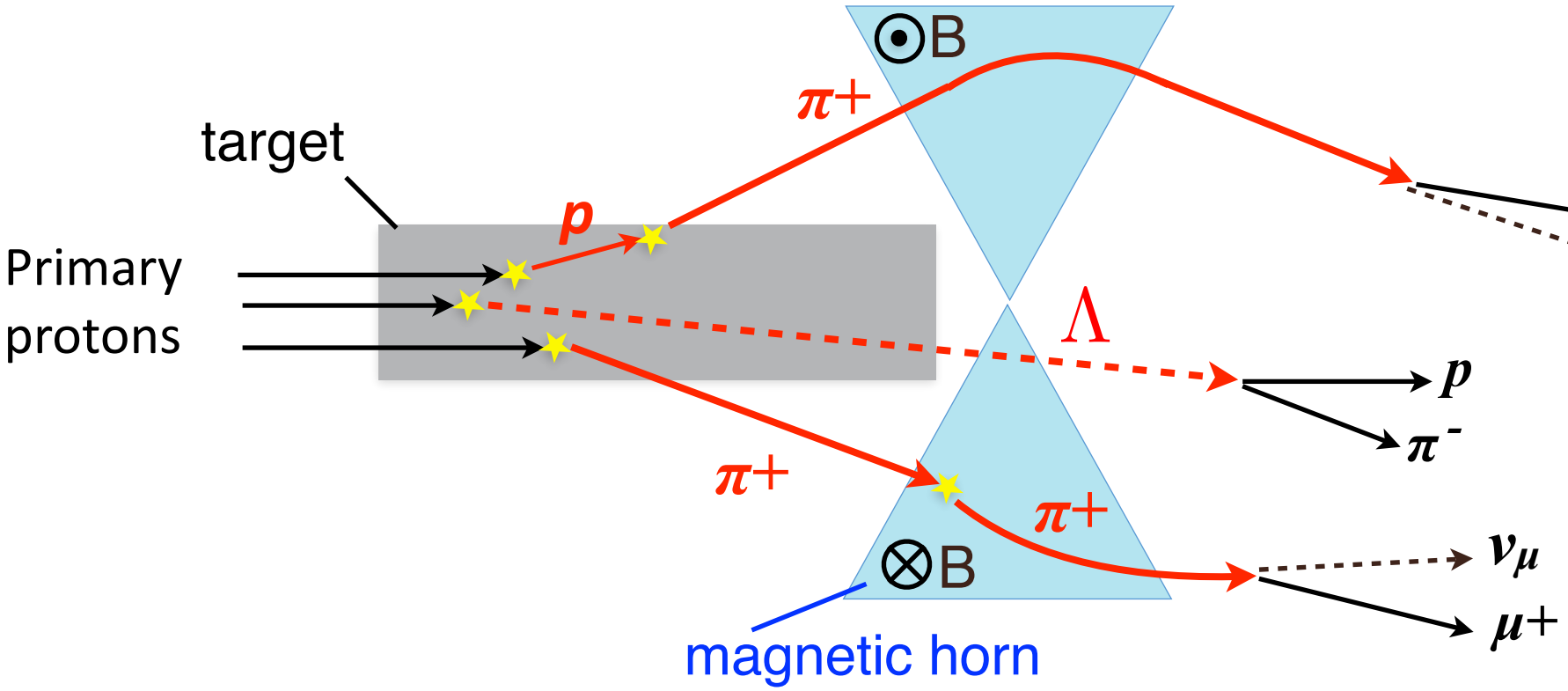


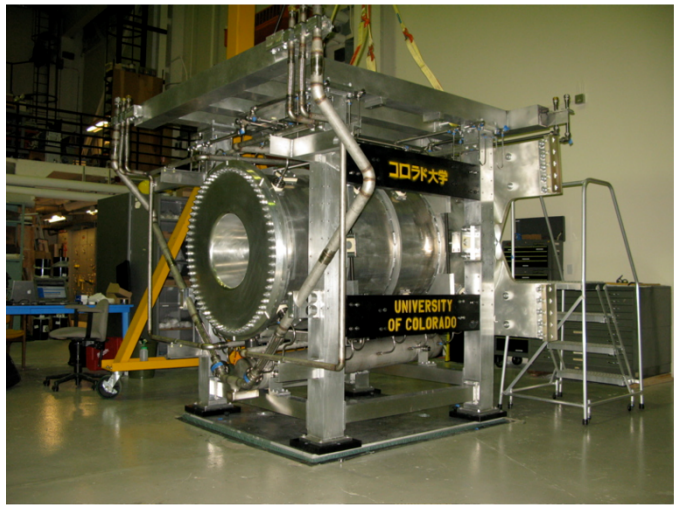
T2K target

Hadron productions of $\pi^{\pm}$ and $K^{\pm}$ through primary interactions in the target (p + C, p + Be)

—> Primary contribution to the neutrino flux

How to Make a Neutrino Beam





T2K magnetic horn

Hadron production process can be more complex:

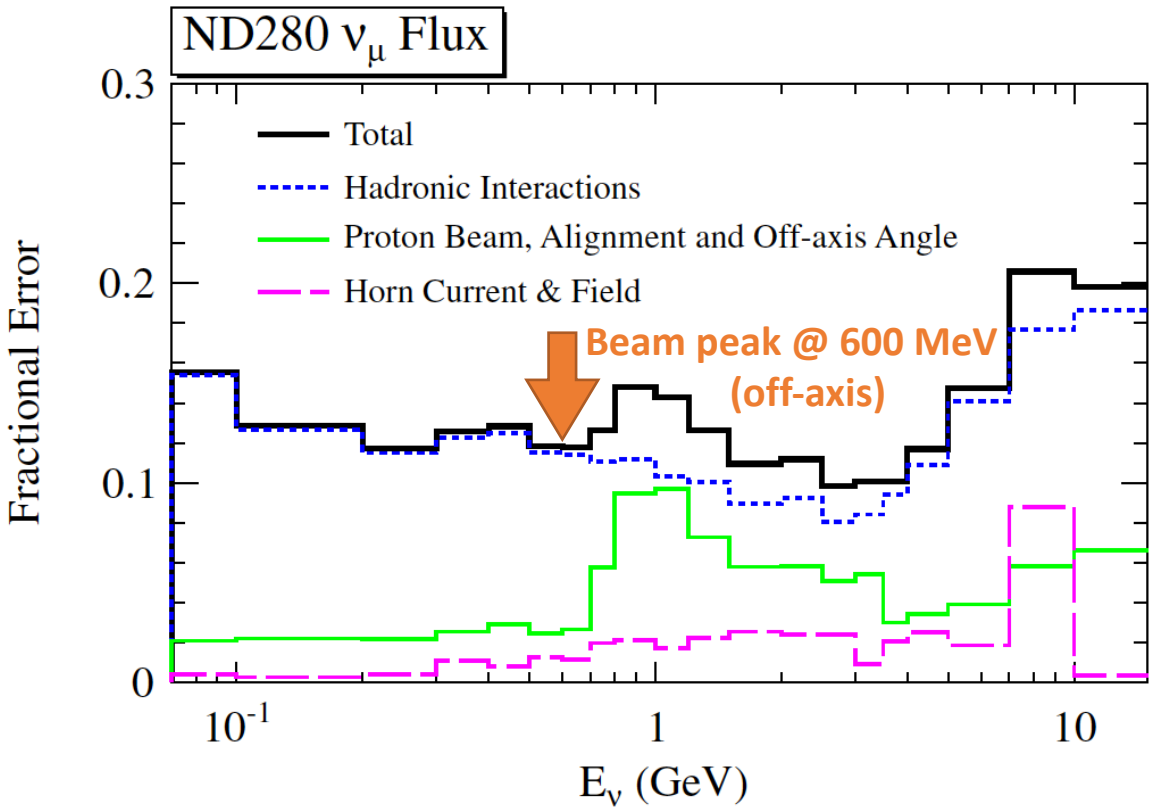
- Secondary interactions in the target (hadrons + C/Be)
- Secondary interactions with horn or beamline materials (hadrons + X)
- Neutral hadron decay (p + C / Be —> V^0 + X)

—>Non-negligible contribution to the neutrino flux

Why Hadron Production Measurements?

Hadron Production is the leading uncertainty source of flux predictions

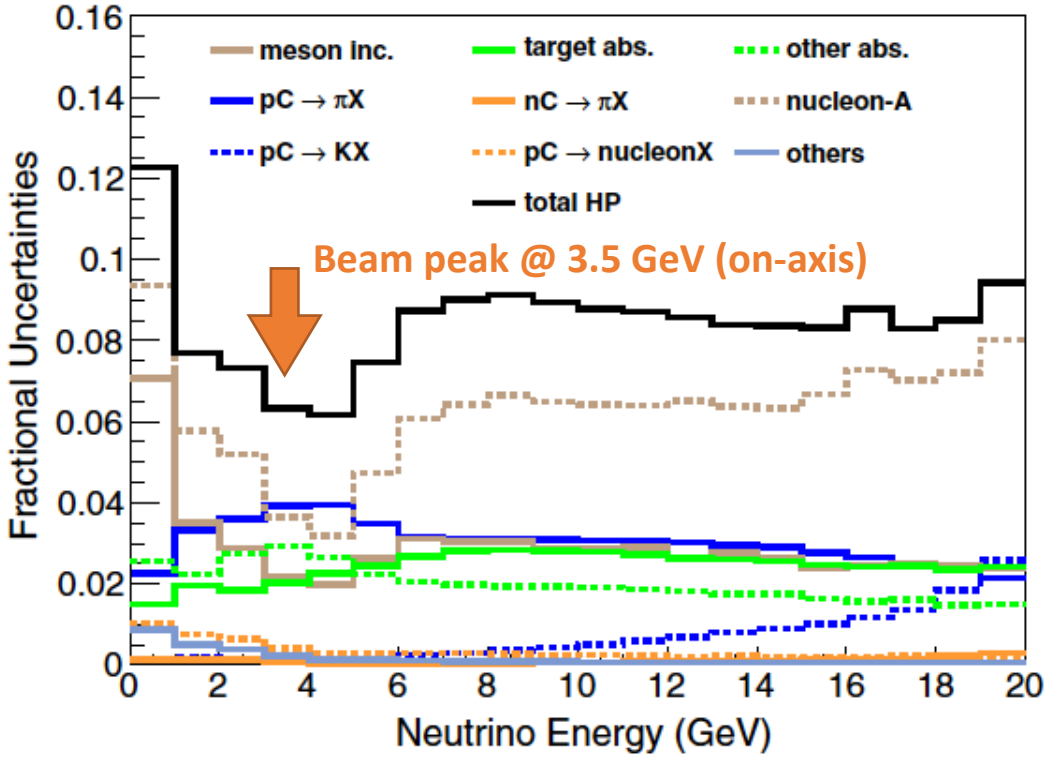
J-PARC beamline (T2K flux)



T2K: Phys. Rev. D87, 012001 (2013)

NuMI beamline (MINERvA flux)

(low energy configuration)



MINERvA: Phys. Rev. D94, 092005 (2016)

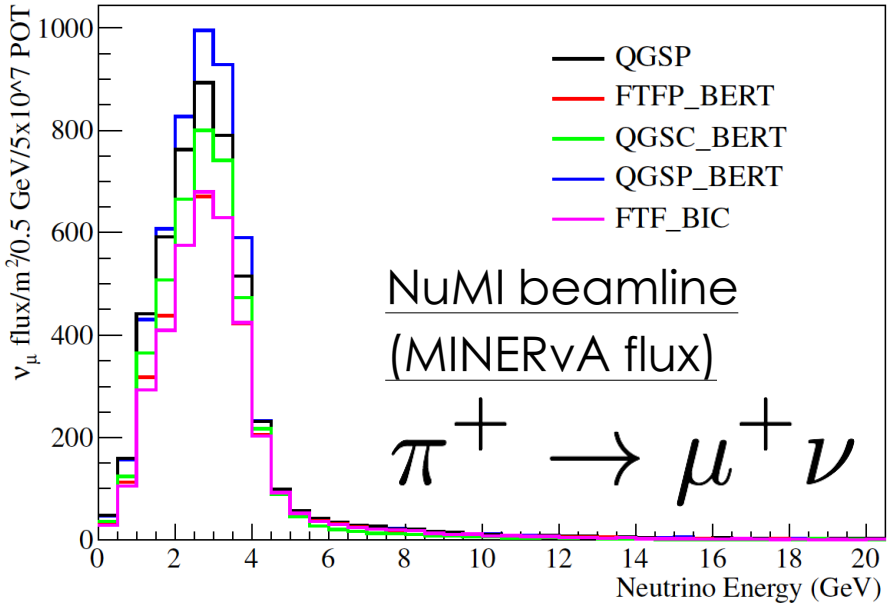
(only hadron production-relating errors)

Why Hadron Production Measurements?

- We rely on hadronic interaction models for the neutrino flux predictions
  - FLUKA (J-PARC/T2K), Geant4 FTFP_BERT (NuMI experiments)

However, hadron production prediction is difficult…

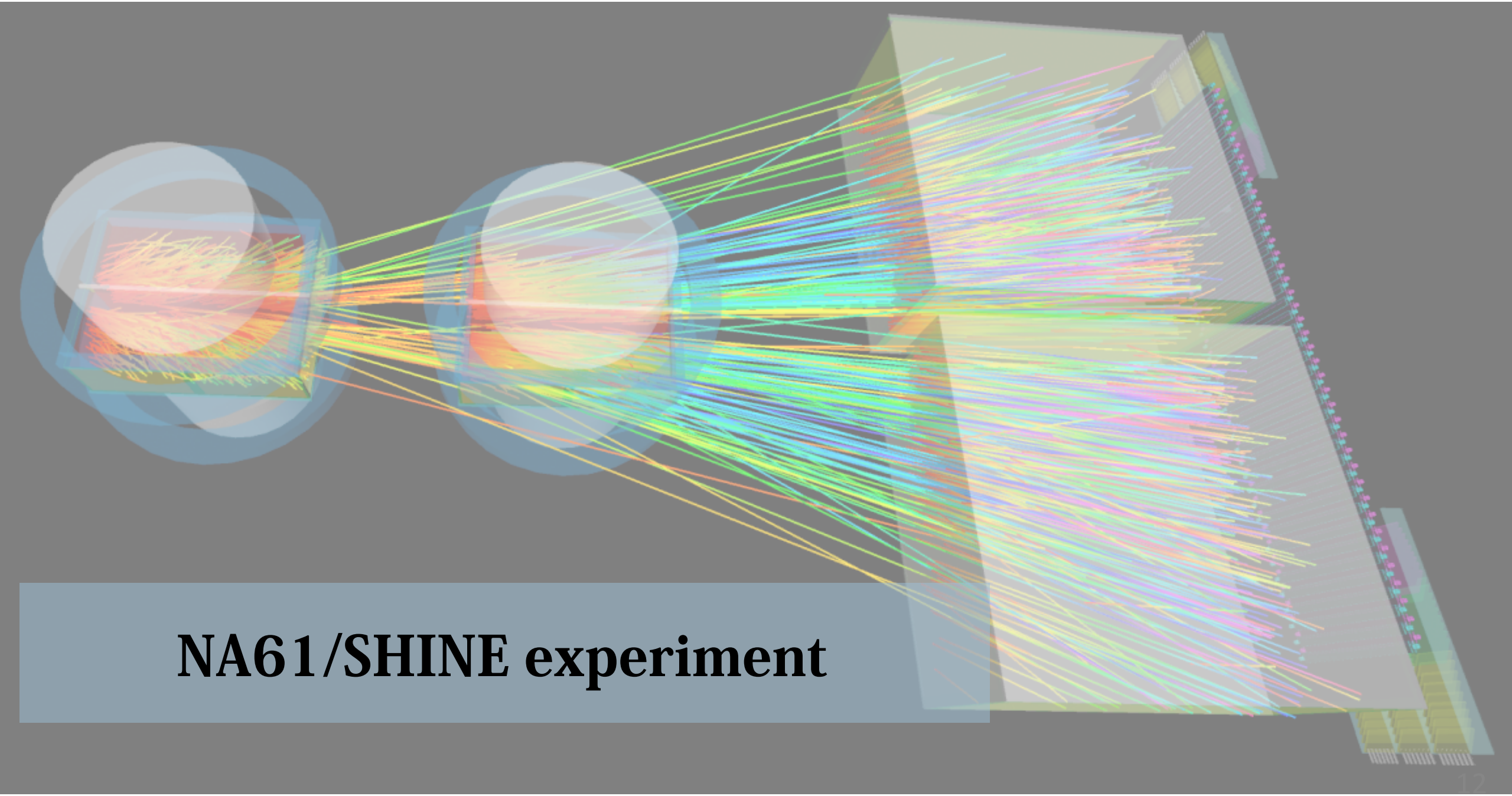
e.g. Five interaction models in Geant 4
—> variations neutrino flux prediction
~40% at the focusing peak



Leonidas Aliaga (Ph.D Thesis, 2016)

Need to constrain neutrino flux uncertainty coming from hadron production

⇨ Hadron production measurements with NA61/SHINE

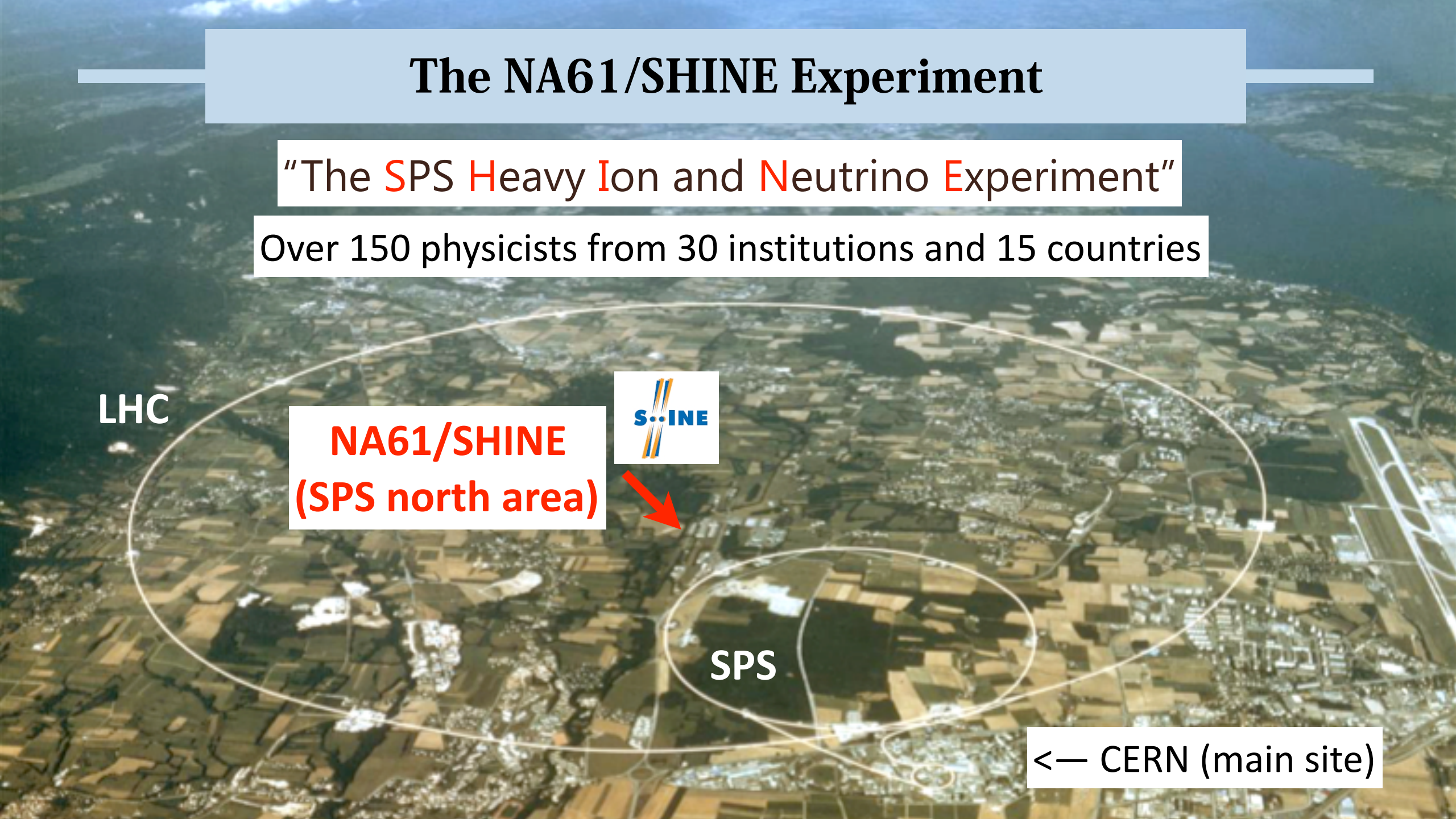


NA61/SHINE experiment

The NA61/SHINE Experiment

"The SPS Heavy Ion and Neutrino Experiment"

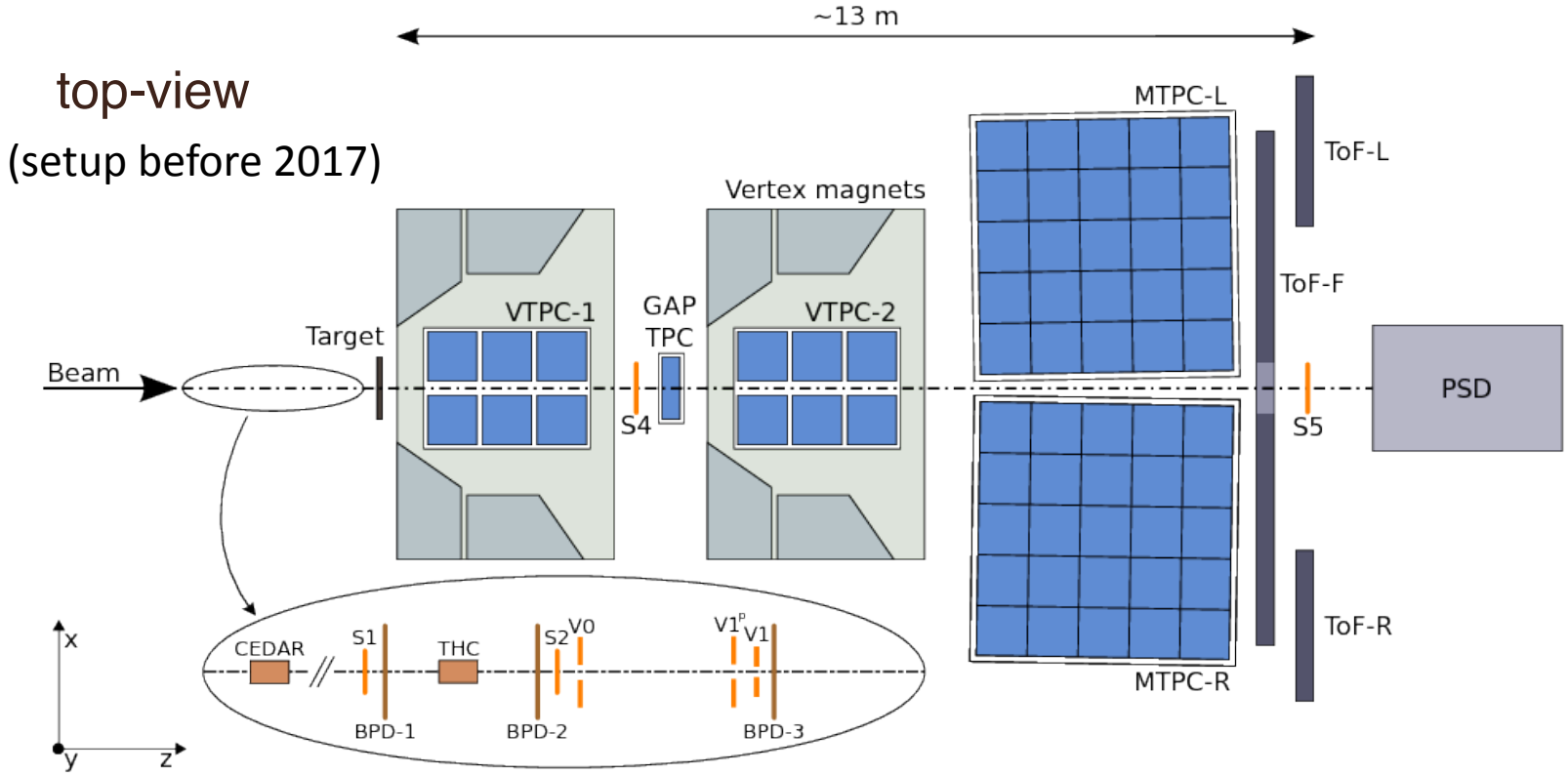
Over 150 physicists from 30 institutions and 15 countries



The NA61/SHINE Experiment

- Hadron beams
  - primary protons at 400 GeV/c
  - secondary hadrons (p, π, K) at 13 - 350 GeV/c
- Ion beams
  - primary (Ar, Xe, Pb) at 13-150 AGeV/c
  - secondary Be at 13 - 150 AGeV/c (from Pb fragmentation)
- Broad physics program
  - Neutrino
    - Hadron production measurements to improve neutrino beam flux predictions
  - Strong interaction / Heavy ion
    - Search for the critical point
    - Study the onset of QCD deconfinement
    - Study open-charm production mechanism
  - Cosmic ray
    - Hadron production measurements to improve air-shower model predictions
    - Study (anti-)deuteron production mechanism for the AMS and GAPS experiments
    - Nuclear fragmentation cross sections to understand cosmic-ray flux

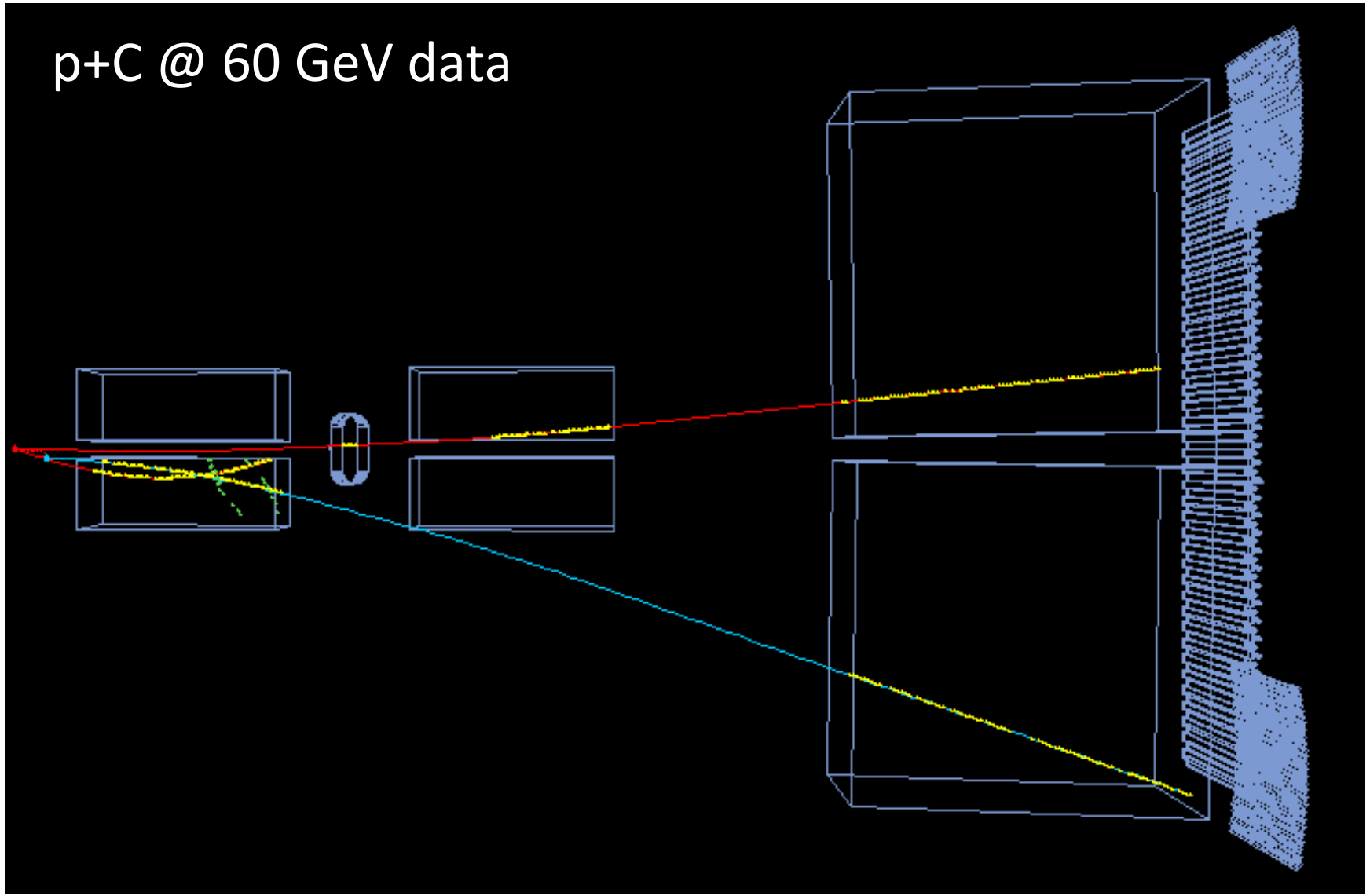
NA61/SHINE Experimental Facility



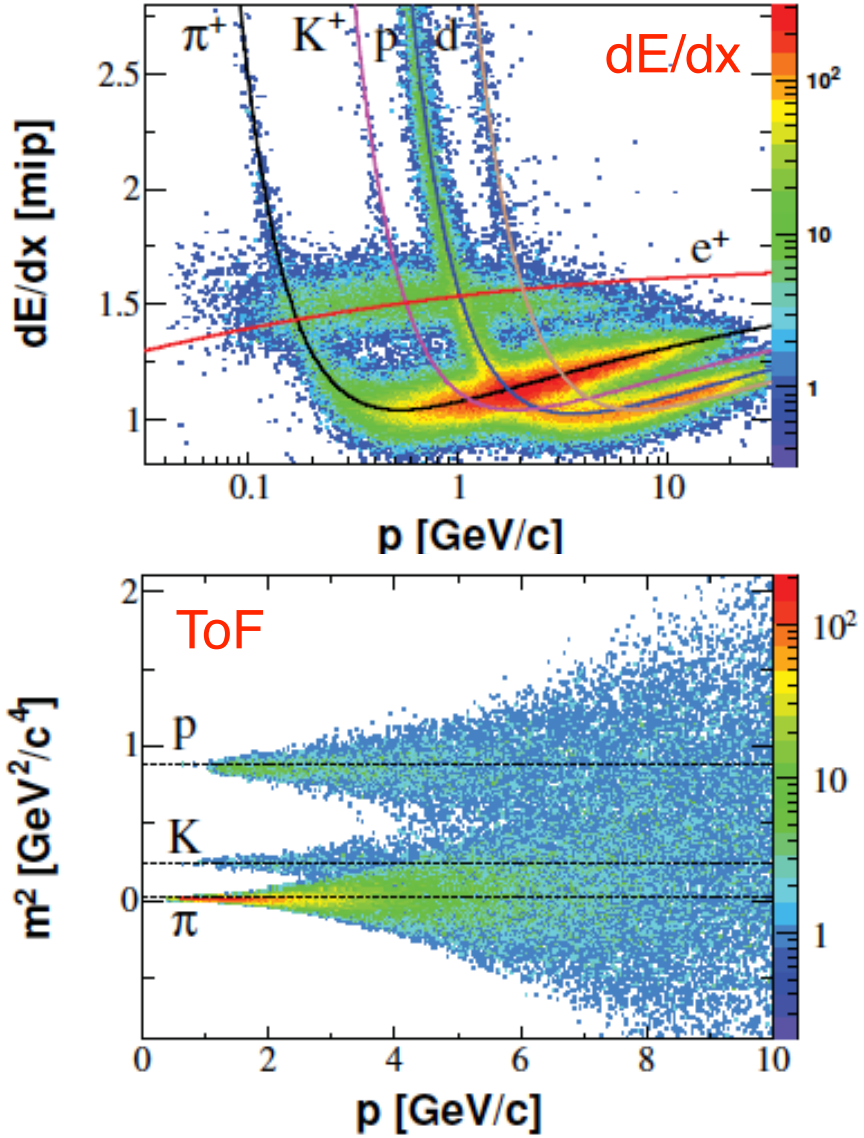
- Good beam particle selection (p, π, K) using beamline Cherenkov detectors
- Large acceptance spectrometer for charged particles
  - Time Projection Chambers (TPCs) for tracking and dE/dx
  - 2 dipole magnets with 1.5 T maximum field
  - Time-of-flight detectors placed downstream

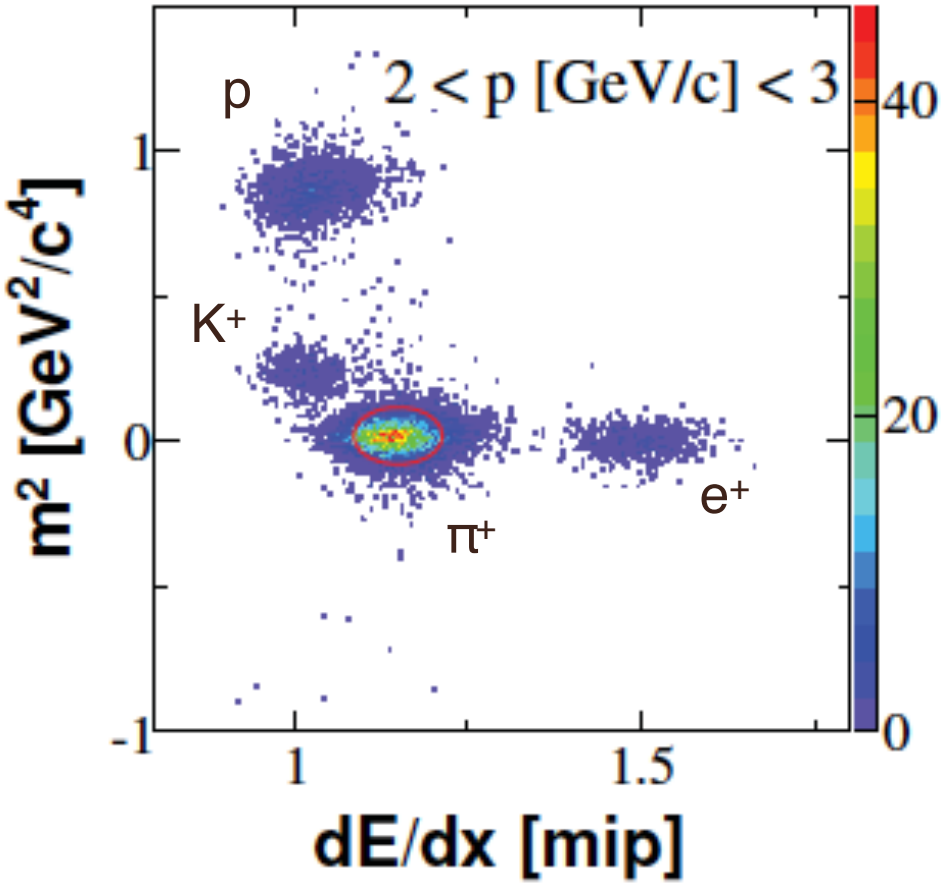
Precise tracking with:
- Particle identification
- Momentum measurement

Event Display



Particle Identification Performance



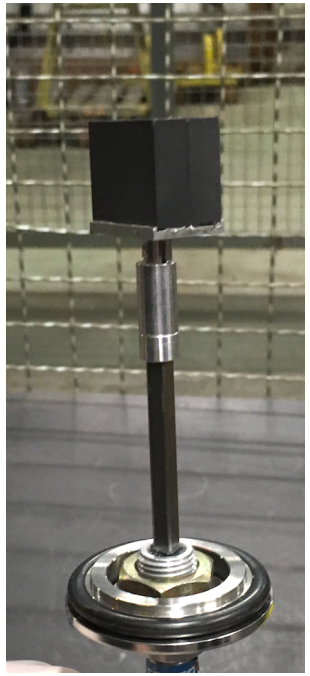


Good particle identification including Bethe-Bloch overlap region

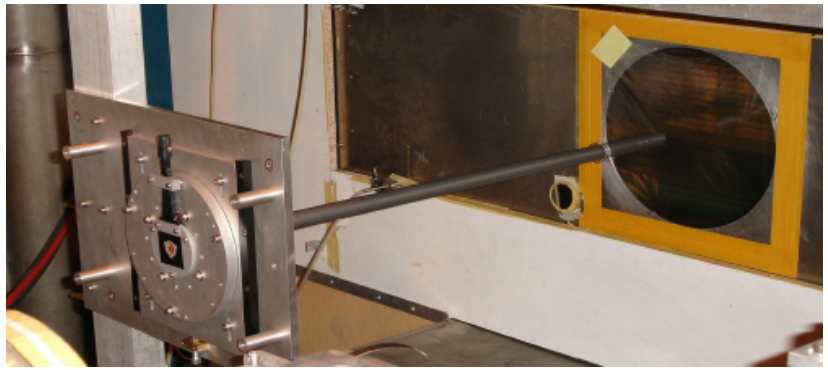
Strategy of Measurements in NA61/SHINE

- Thin target: a few % of nuclear interaction length (λ) to study single interactions
  - Total cross sections (inelastic and production cross sections)
  - Measurement of differential cross section
- Replica (thick) target: same geometry and material as real neutrino beamline
  - Measurement of differential production yields
  - Measurement of beam survival probability

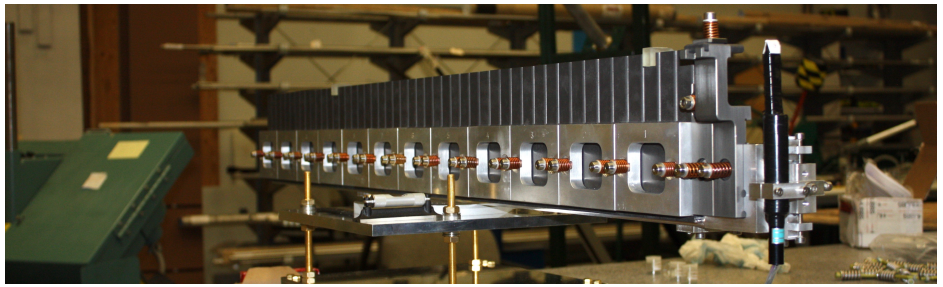
Thin graphite target (1.5 cm, 3.1% of λ)



T2K replica graphite target (90 cm, 1.9 λ)



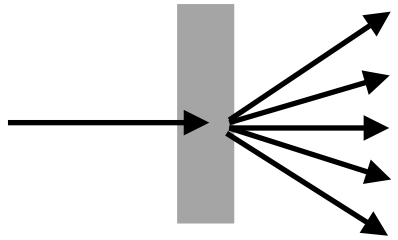
NuMI replica graphite target (120 cm, 2.5 λ)

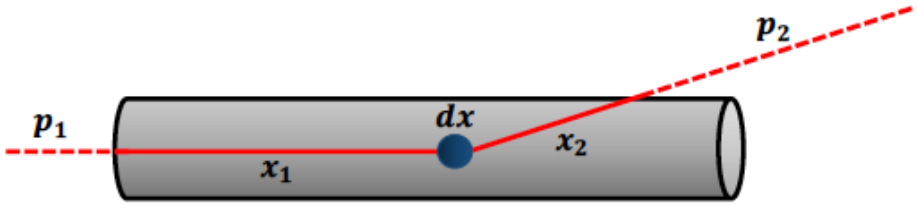


Thin Target Measurement

- Thin target: a few % of nuclear interaction length (λ) to study single interactions
  - Total cross sections (inelastic and production cross sections)

$$\sigma_{\text{inel}} = \sigma_{\text{total}} - \sigma_{\text{el}}, \quad \sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}}$$





—> Results are used to correct hadron interaction length (probability of interaction)

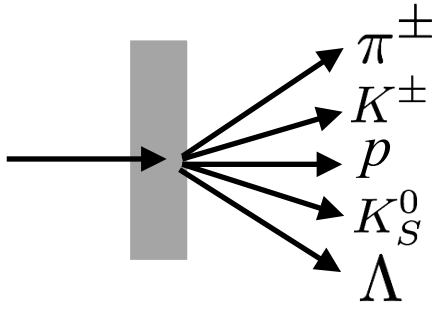
$$\mathrm{W}(p_1, p_2, x_1, x_2) = \frac{[P_{\text{interaction}} \cdot P_{\text{escape}}]_{\text{data}}}{[P_{\text{interaction}} \cdot P_{\text{escape}}]_{\text{MC}}}$$

$$= \frac{\sigma_{\text{data}}(p_1)}{\sigma_{\text{MC}}(p_1)} \cdot e^{-x_1[\sigma_{\text{data}}(p_1) - \sigma_{\text{MC}}(p_1)]\rho} \cdot e^{-x_2[\sigma_{\text{data}}(p_2) - \sigma_{\text{MC}}(p_2)]\rho}$$

—> Results are also important to obtain proper normalization for the differential cross section yields

Thin Target Measurement

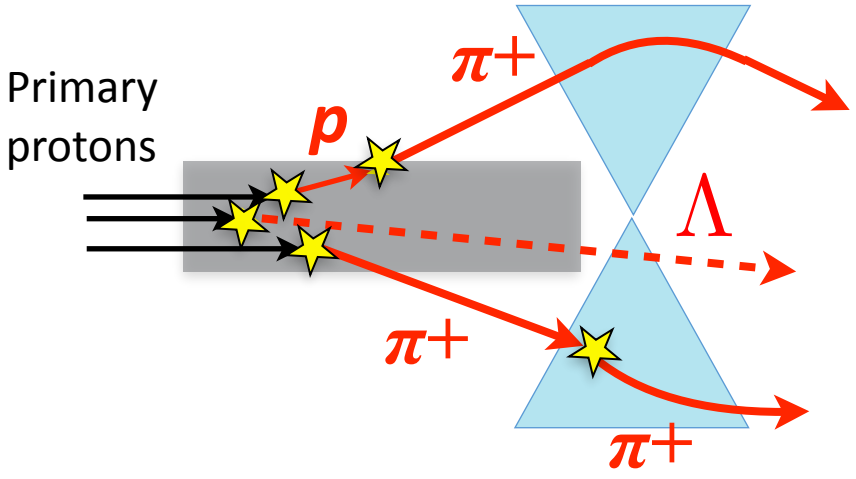
- Thin target: a few % of nuclear interaction length (λ) to study single interactions
  - Measurement of differential cross sections ($\frac{d^2\sigma}{dpd\theta}$)



We measure differential production yields ($\frac{d^2n}{dpd\theta} = N(p,\theta)$)

(yield of particles per interaction, momentum, radian)

then, relate to differential cross section via σ_{prod} : $\frac{d^2\sigma}{dpd\theta} = \sigma_{\text{prod}} \frac{d^2n}{dpd\theta}$

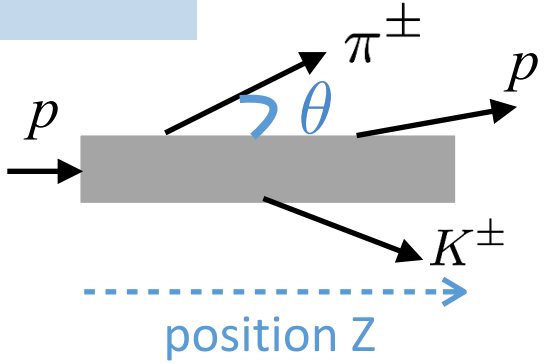


—> Results are used to calculate weights for each interactions (✯) to correct neutrino flux predictions

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

Replica Target Measurements

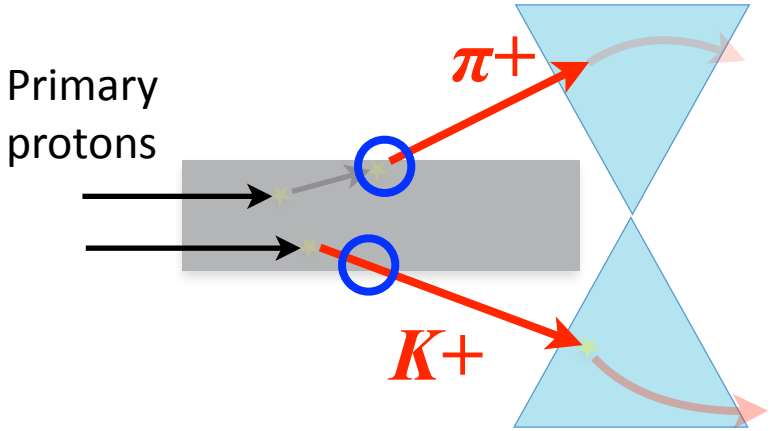
- Replica (thick) target: T2K (90 cm graphite), NuMI (120 cm graphite)



  - Measurement of differential production yields ($\frac{d^3n}{dpd\theta dz} = N(p,\theta,z)$)

    (yield of particles per interaction, momentum, radian, z)

    —> maybe also φ if target cross-section is not circular, like NuMI target

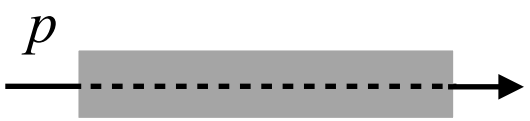


Weights for each exiting point (○) to apply correction to neutrino flux prediction

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

  - Measurement of beam survival probability ($P_{\mathrm{survival}} = e^{-Ln\sigma_{\mathrm{prod}}}$)

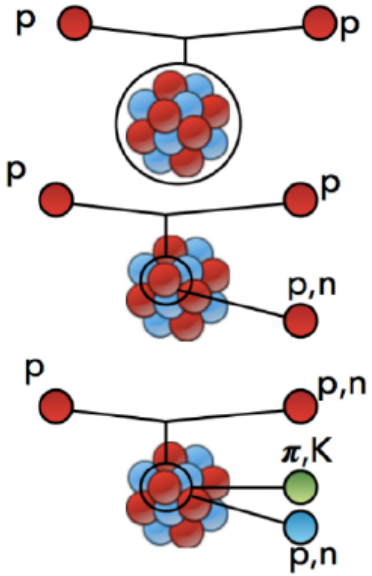
    (L: length of target, n: number of atoms per unit volume)



—> Results are useful to understand beam attenuation inside the target via σ_{prod} measurement

Note: Notation of Production Cross Section

- Not all experiments use the same definition for the production cross section



Coherent elastic process:
interaction on the nucleus —> σ_{el}

Quasi-elastic process:
interaction on bound nucleons —> σ_{qe}

Production process:
interaction with new hadron production
—> σ_{prod}

—> σ_{inel}

$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$$
$$\sigma_{\mathrm{prod}} = \sigma_{\mathrm{inel}} - \sigma_{\mathrm{qe}}$$

<u>Use this definition through the talk</u>
(T2K uses this definition)

- NuMI flux tuning definition:

$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{qe}}$$ —> σ_{prod} in our definition

$$\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$$ —> σ_{inel} in our definition

- Earlier experiments: mixed up inelastic and production cross sections

e.g. Denisov, et. al (1973): $\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$ —> σ_{inel} in our definition

e.g. Carroll, et. al (1979): $\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{qe}}$ —> σ_{prod} in our definition

Series of Data Taking for Neutrino Program

- Measurements for T2K (2007-2010): with proton beam at 30 GeV
  - Thin graphite target measurements to study primary interactions
  - T2K replica graphite target measurements

  —> Almost complete data analysis

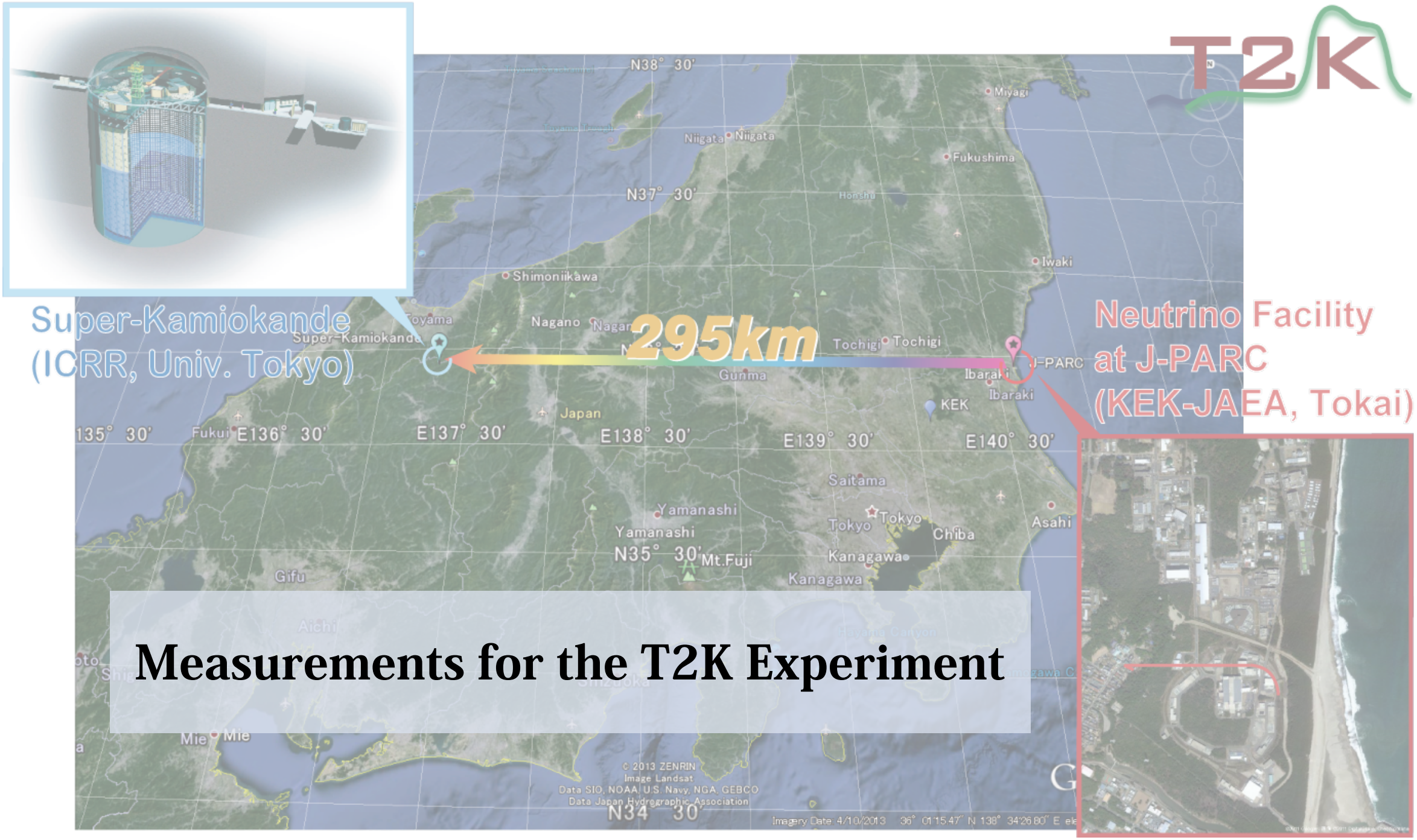
  —> Further data taking after 2021 is under discussion

- Measurements for Fermilab (2015-2018): with various beam types and energies
  - Thin target (C, Be, Al) measurements to study primary and secondary interactions
  - NOvA replica graphite target measurements

  —> Complete first data taking between 2015 and 2018

  —> Analysis ongoing

  —> Further data taking after 2021 is under discussion



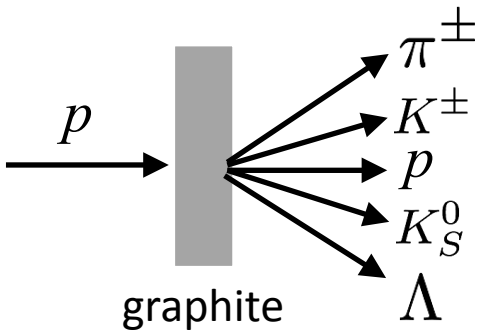
Measurements for the T2K Experiment

Thin Target Measurements for T2K

- Thin target: p@30 GeVon 2cm graphite target
  - total cross-section and $\pi^{+/-}$ 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 $\pi^{+/-}$,$K^{+/-}$ p, K^{0}_{S}, and Λ spectra measurements (Eur. Phys. J. C76 84 (2016))

Review these results

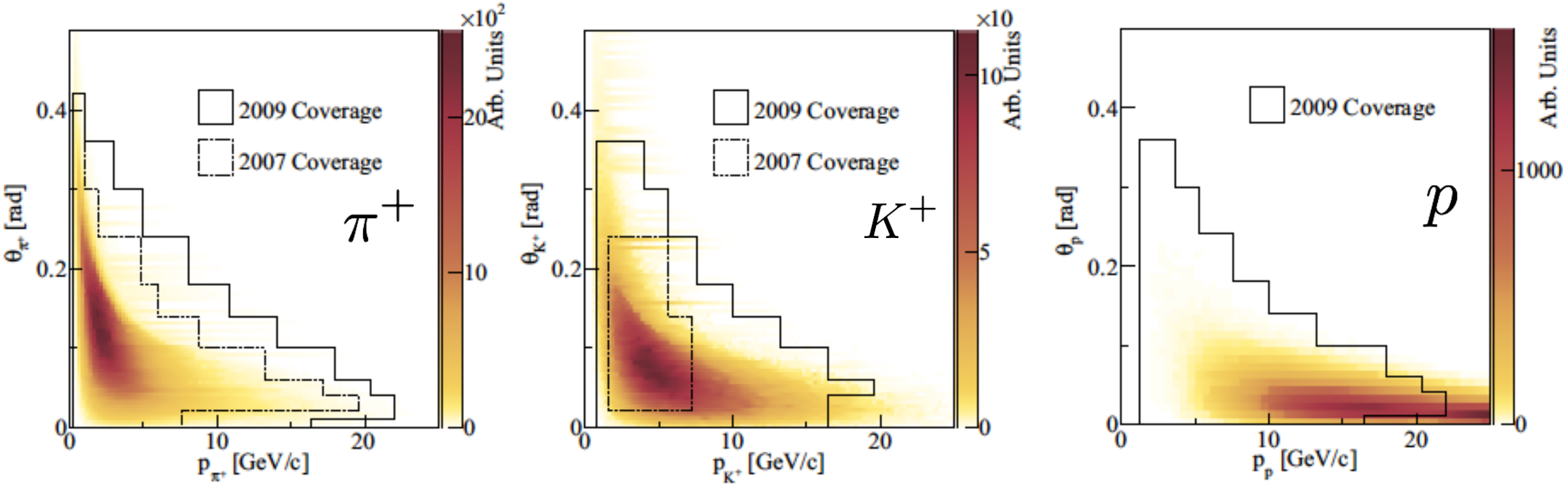
Thin Target Results



$p + \mathrm{C} \,@\, 30\ \mathrm{GeV}$

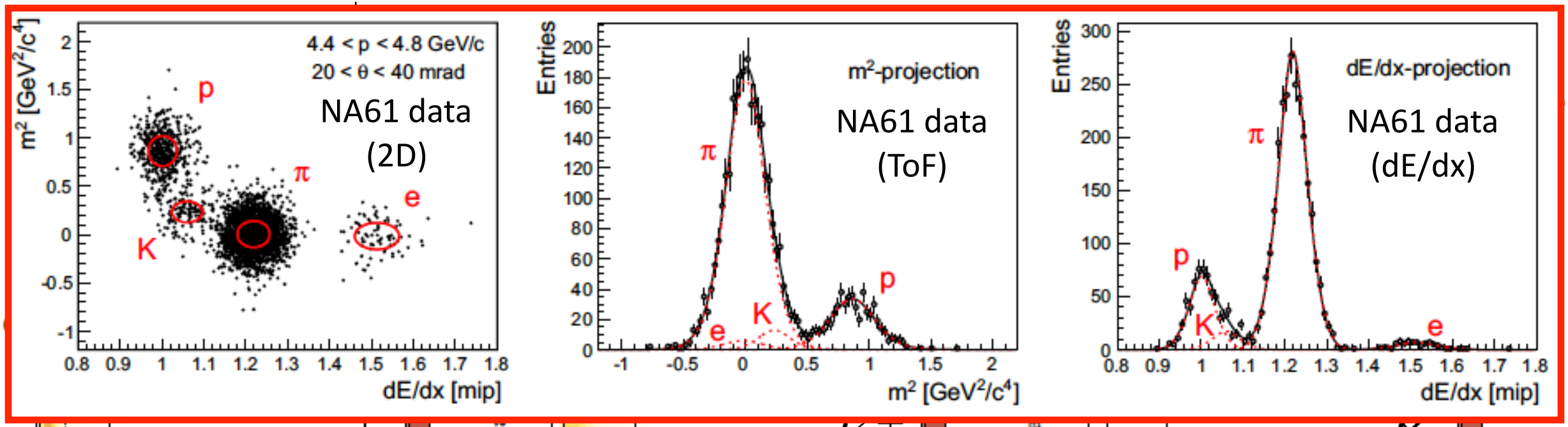
Eur. Phys. J. C76 (2016) 84

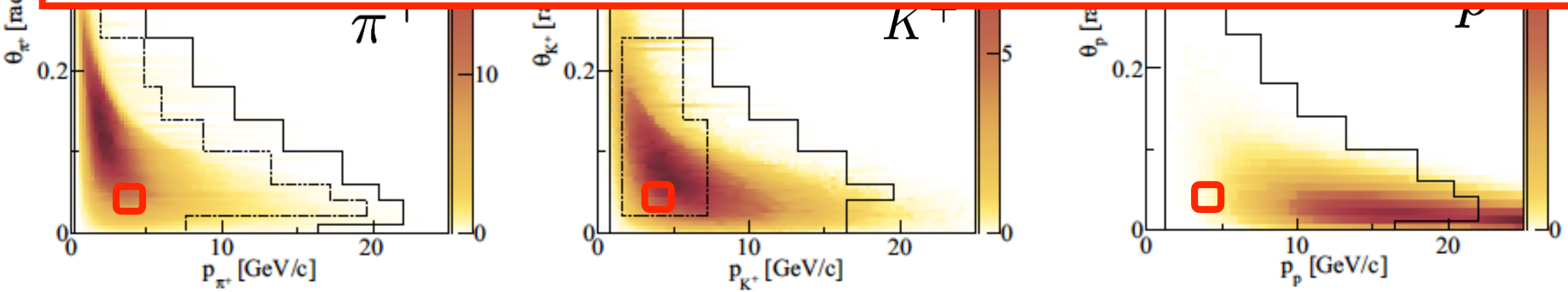
NA61 acceptance largely covers phase-space where T2K is interested in



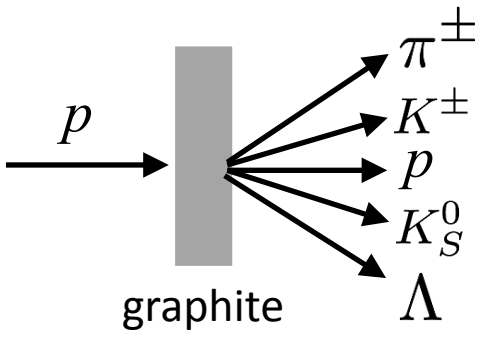
(This shows hadron distribution contributing to the T2K flux, not NA61 data)

Thin Target Results



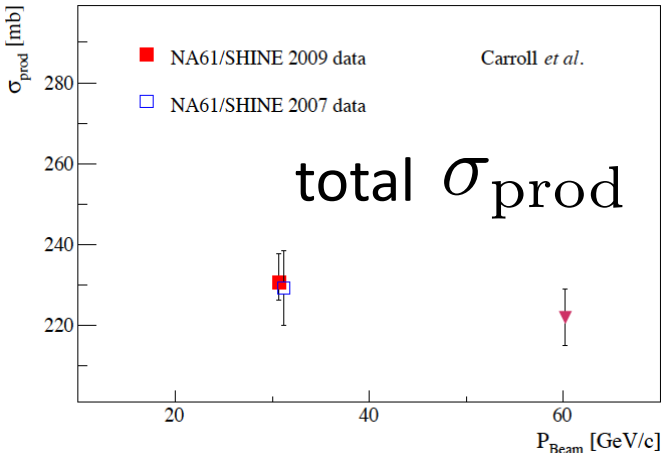


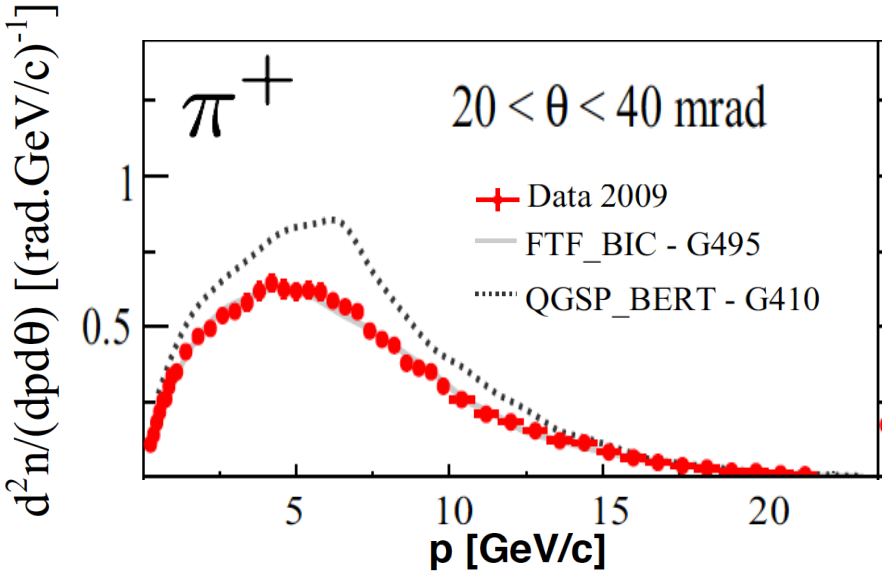
Thin Target Results



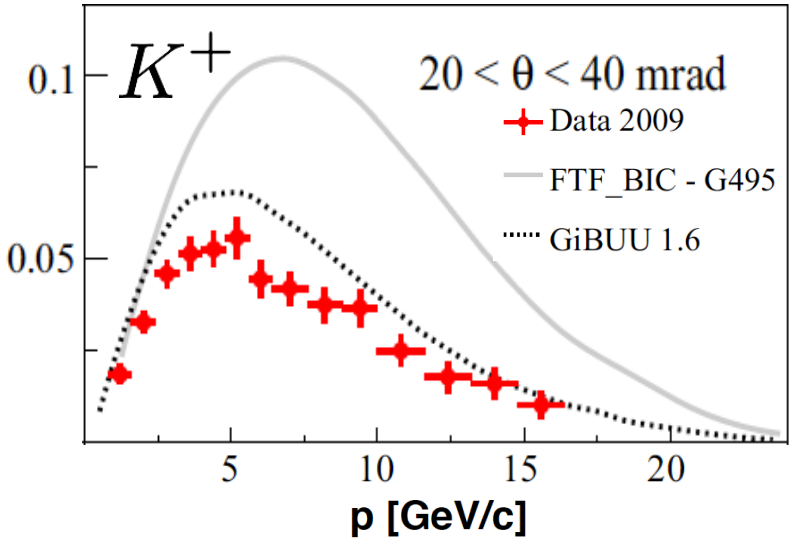
$p + \mathrm{C} \,@\, 30\ \mathrm{GeV}$

Eur. Phys. J. C76 (2016) 84

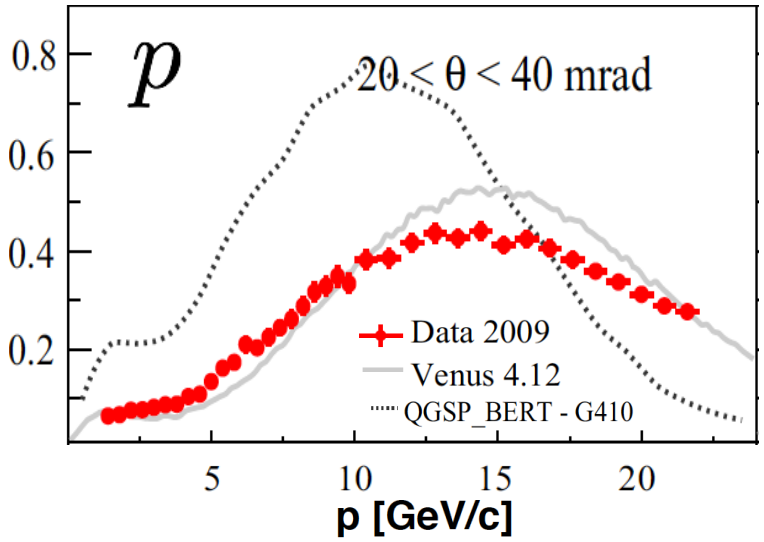




(11 θ-bins for 0 < θ < 420 mrad)



(9 θ-bins for 0 < θ < 360 mrad)

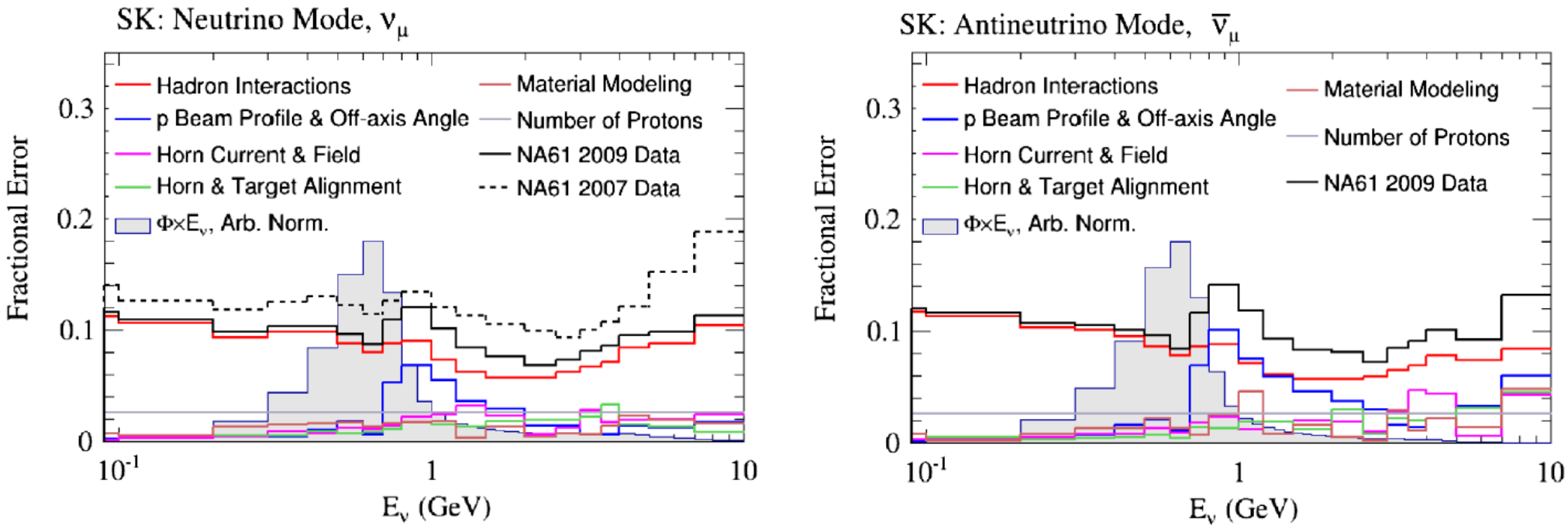


(10 θ-bins for 0 < θ < 360 mrad)

Negative pions and kaons, and V⁰ particles(K_S^0, Λ) productions have been measured as well.

Flux Uncertainty with Thin Target Measurements

- Thin target measurements reduced hadron production uncertainty down to ~10%



T2K: Phys. Rev. D96 092006 (2017)

- NA61/SHINE thin target measurements have been used for various T2K results including the recent Nature result

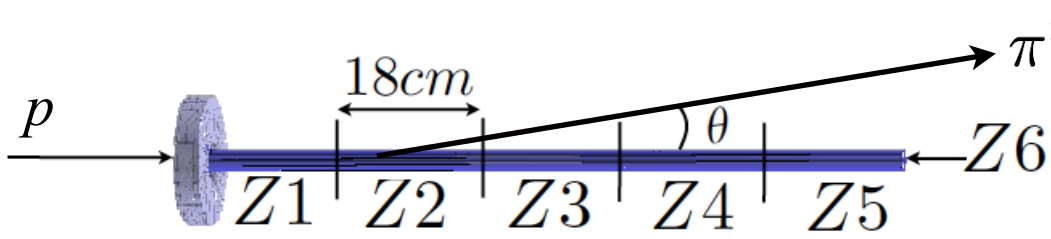
T2K: Nature 580, 339-344 (2020)

Replica Target Measurements for T2K

- Replica target: p@30 GeV on 90cm replica graphite target
  - methodology, $\pi^{+/-}$ yield measurement (Nucl. Instrum. Meth. A701 99-114 (2013))
  - $\pi^{+/-}$ yield measurement (Eur. Phys. J. C76 617 (2016))
  - $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79, no.2 100 (2019))
  - proton beam survival probability measurement (Analysis ongoing)

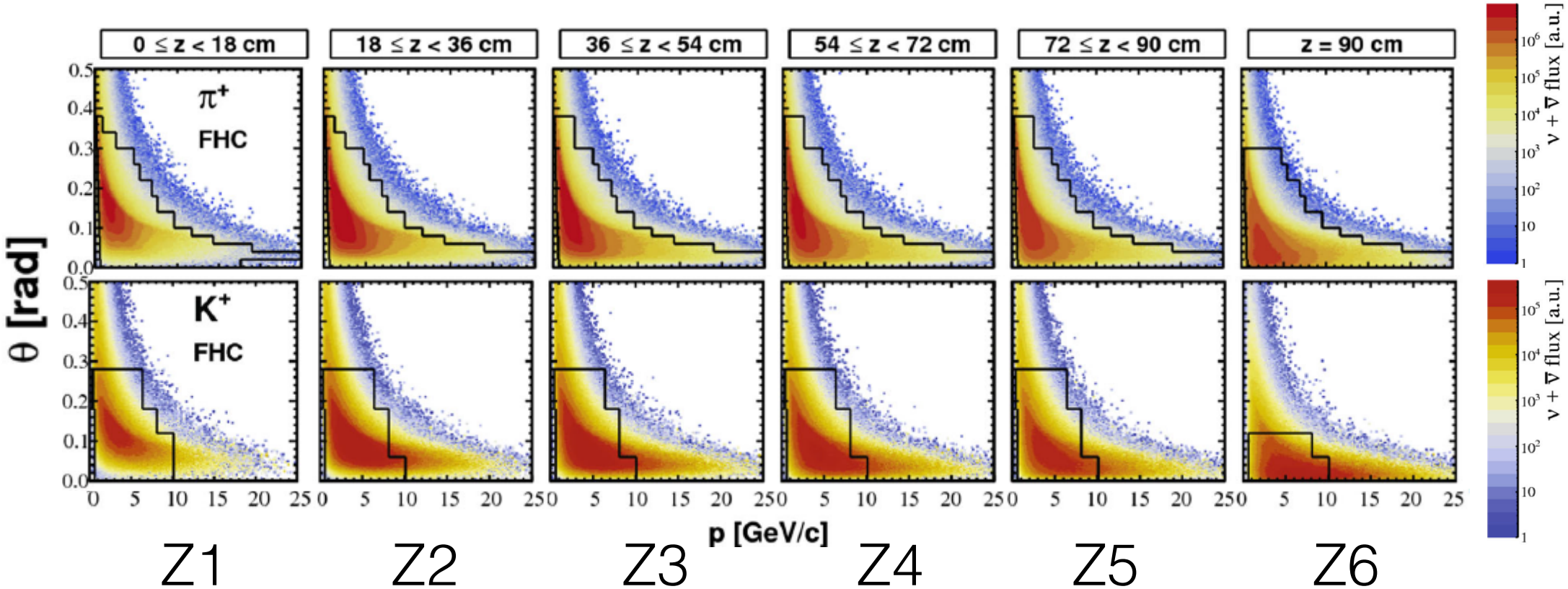
Review these results

T2K Replica Target Results



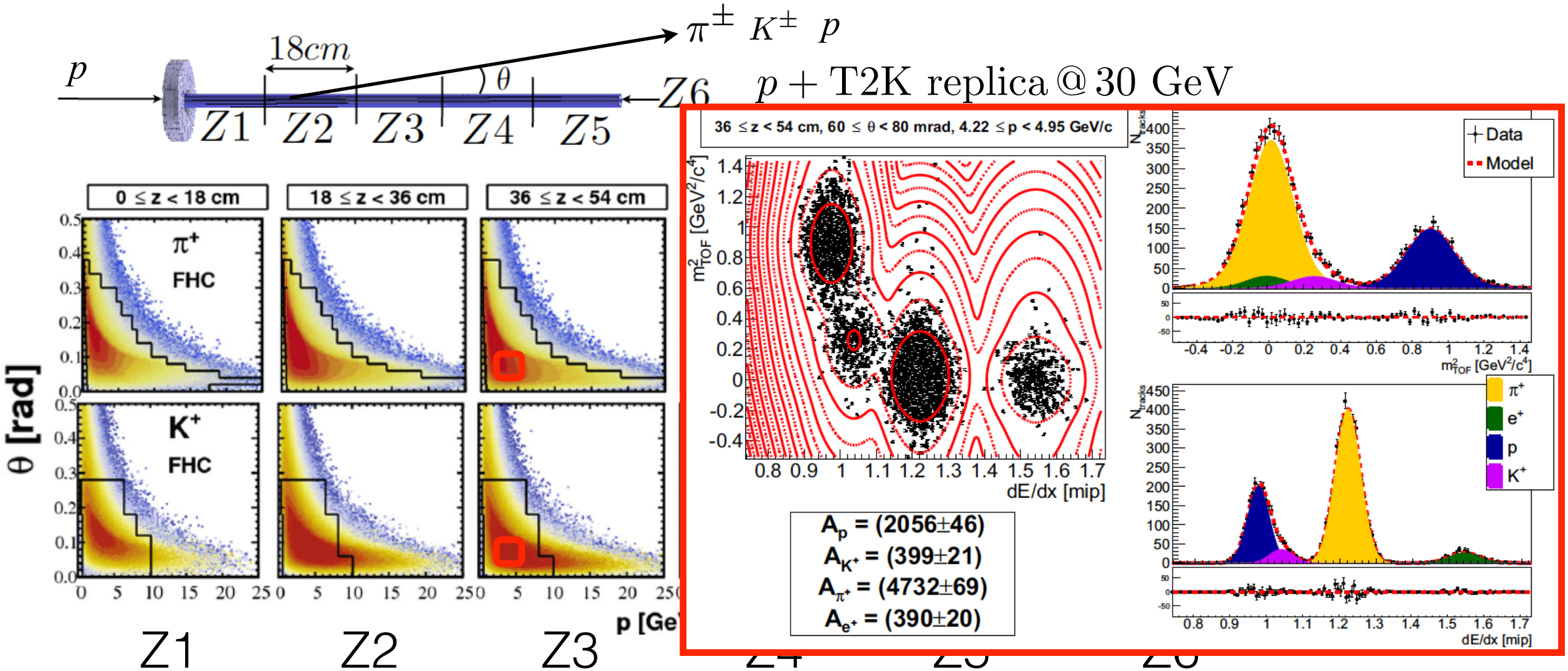
$p + \text{T2K replica} @ 30\ \text{GeV}$

Eur. Phys. J. C79, no.2 100 (2019)



(This shows hadron distribution contributing to the T2K flux, not NA61 data)

T2K Replica Target Results

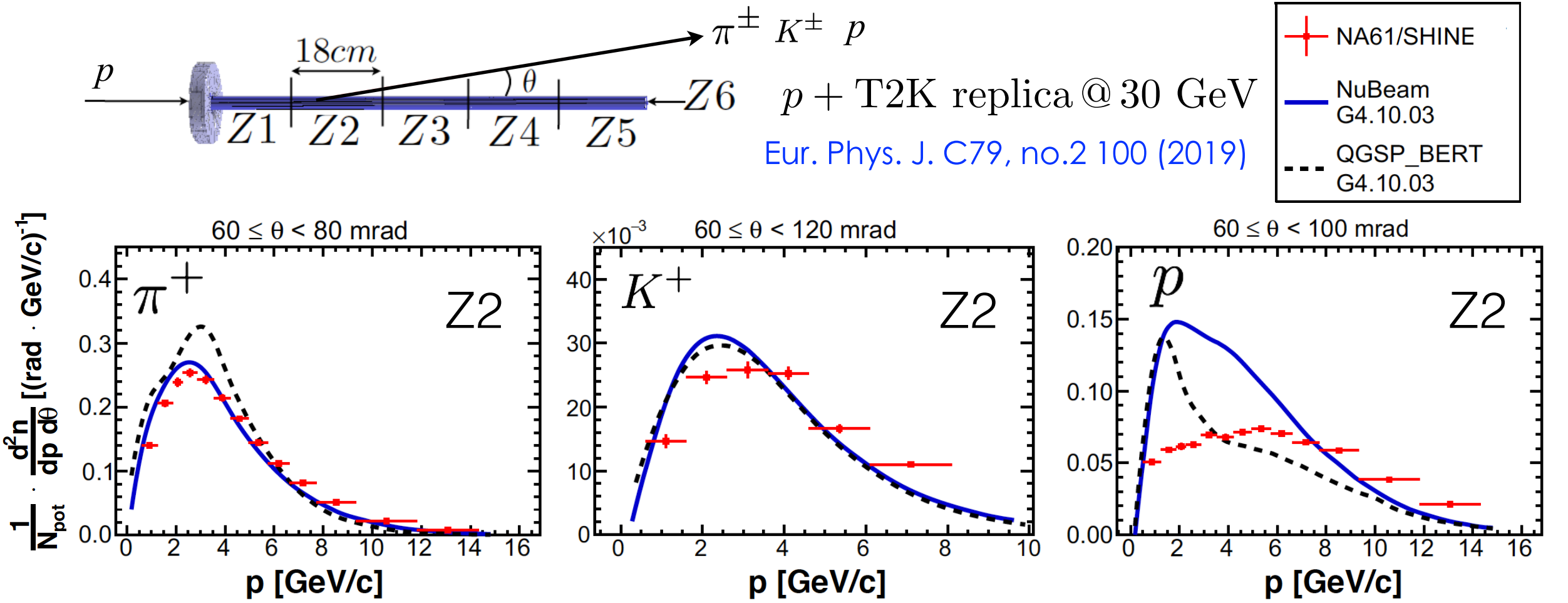


(This shows hadron distribution contributing to the T2K flux, not NA61 data)

T2K Replica Target Results

$p + \text{T2K replica} @ 30\ \text{GeV}$

Eur. Phys. J. C79, no.2 100 (2019)



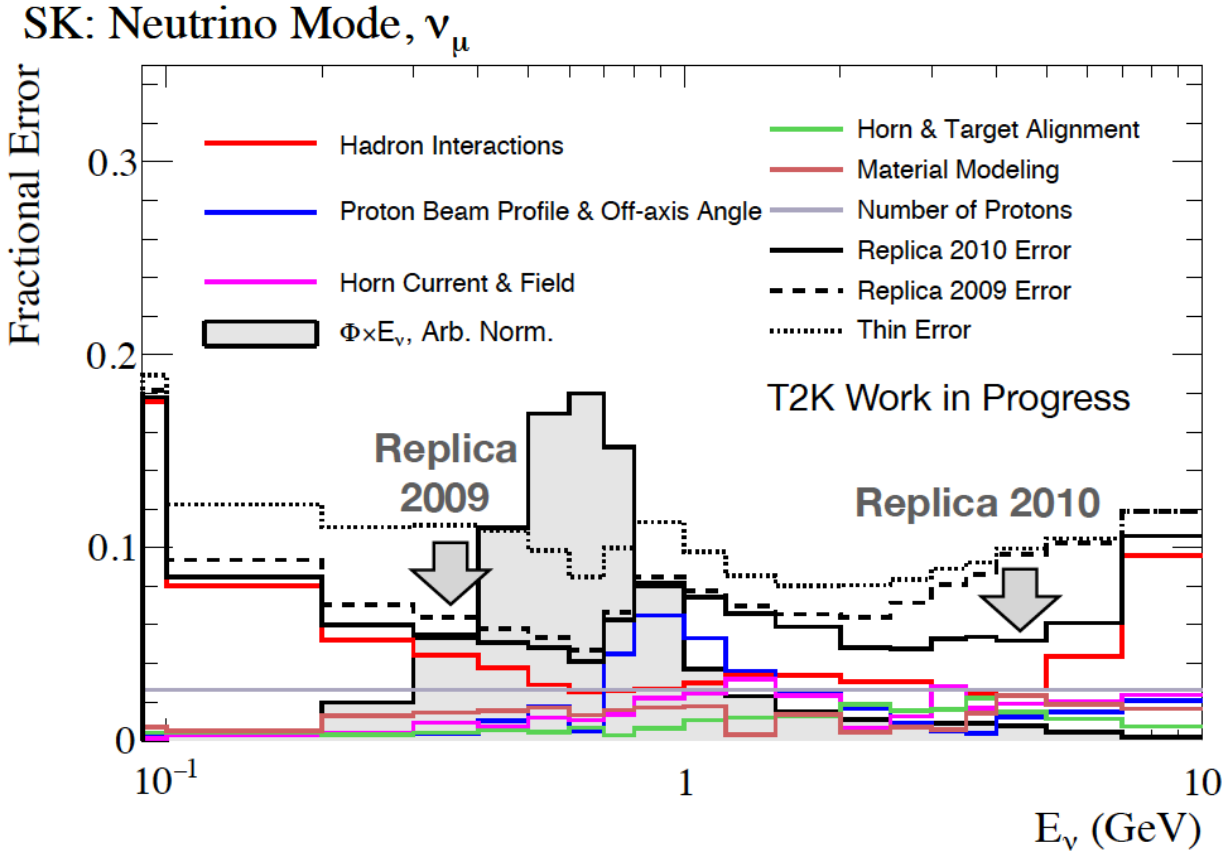
(15 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
10 θ-bins for 0 < θ < 300 mrad (Z6))

(4 θ-bins for 0 < θ < 280 mrad (Z1-Z5)
2 θ-bins for 0 < θ < 120 mrad (Z6))

(10 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
8 θ-bins for 0 < θ < 260 mrad (Z6))

Negative pions and kaons have been measured as well.

Flux Uncertainty with Replica Target Measurements

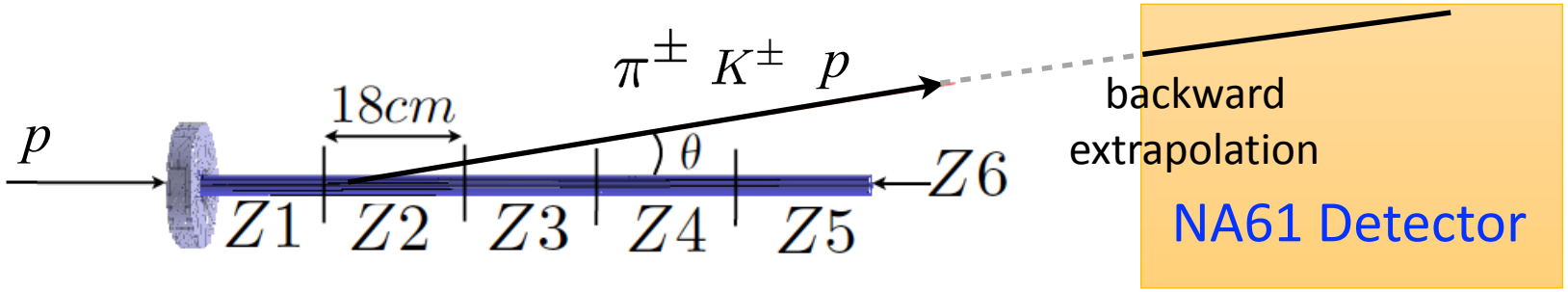


Lukas Berns (NBI 2019)

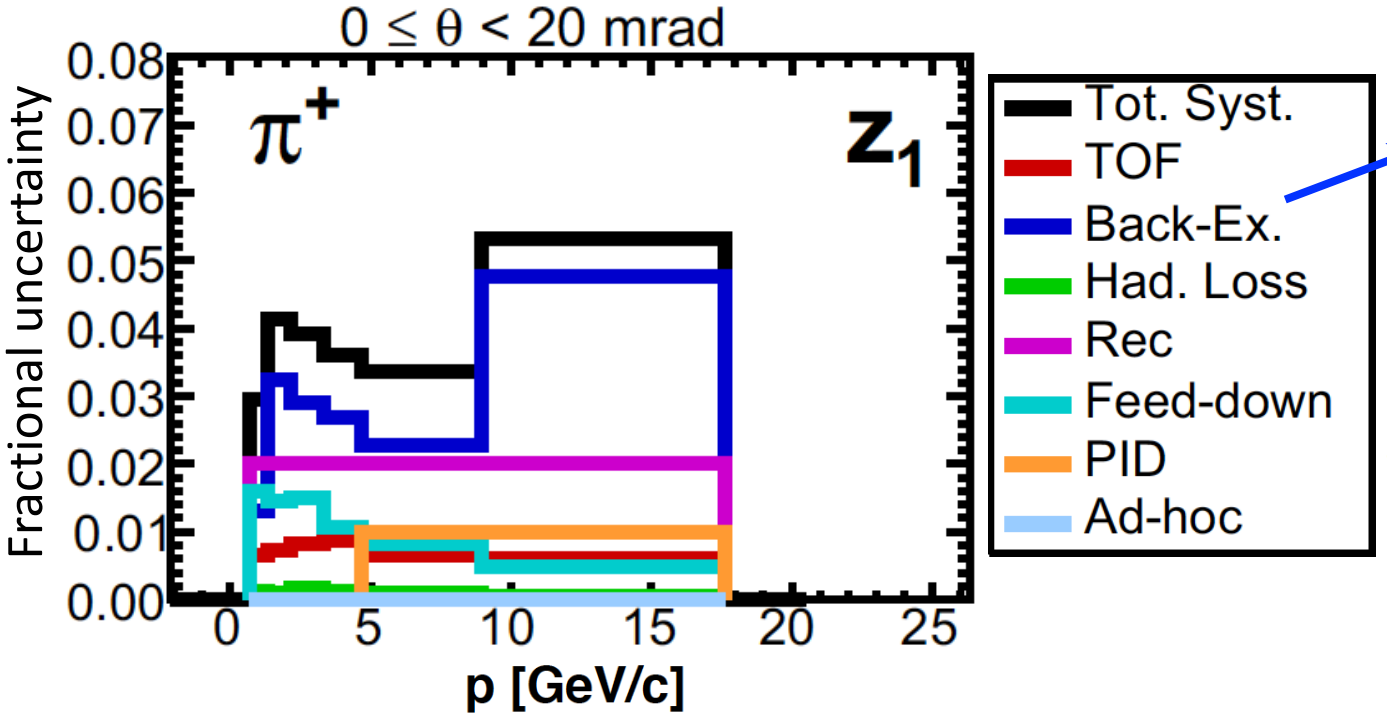
- Replica target measurements will improve uncertainty down to < 5%
  —> For phase space which is not covered by replica target measurements, we still rely on thin target measurements
  (e.g. re-interactions outside of target)

T2K Replica Target Results (Systematic Uncertainties)

- What was limitation of replica target measurements and how can we do better?

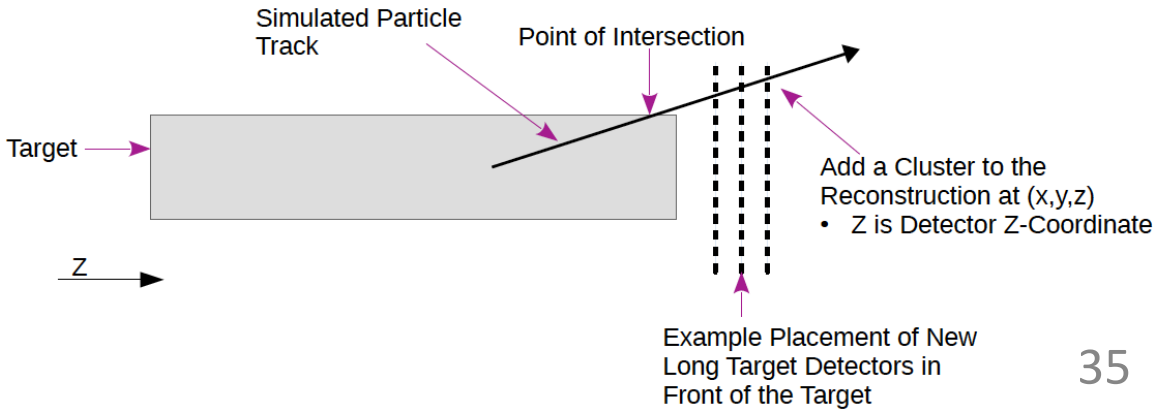


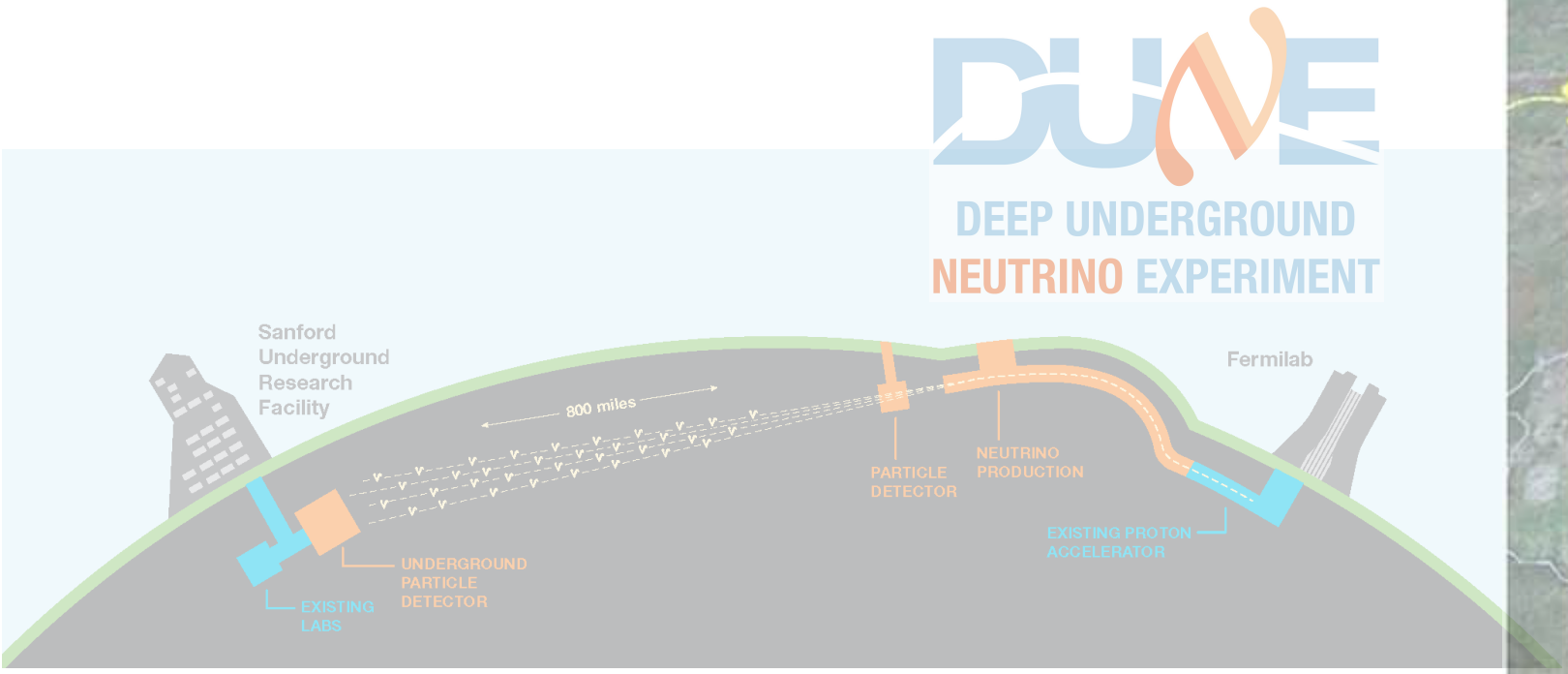
Eur. Phys. J. C79, no.2 100 (2019)

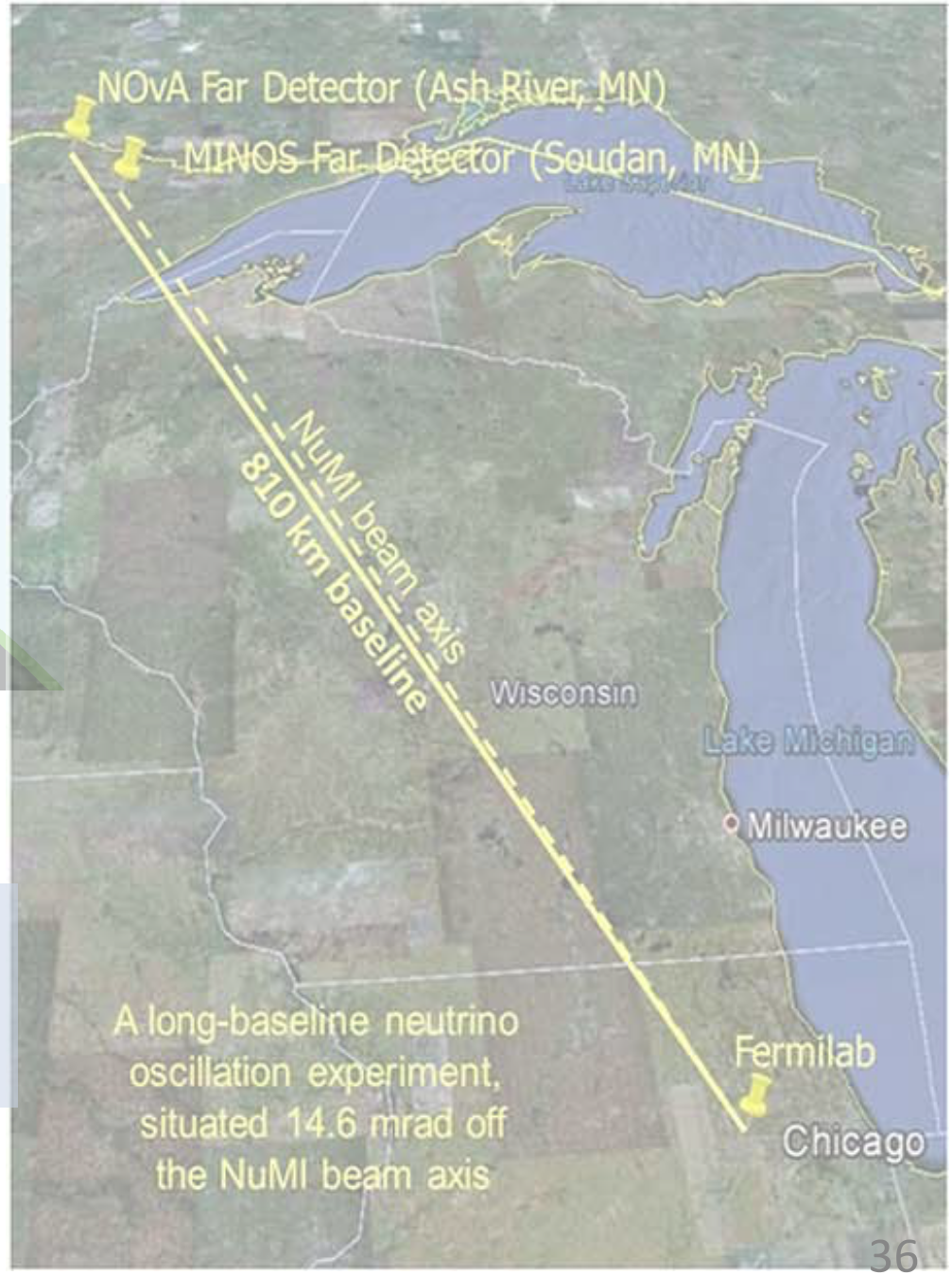


Track position uncertainty on the target surface.

—> Having additional tracker surrounding the target to help track extrapolation







Measurements for the Fermilab Experiments

Facility Upgrade for Fermilab Measurements

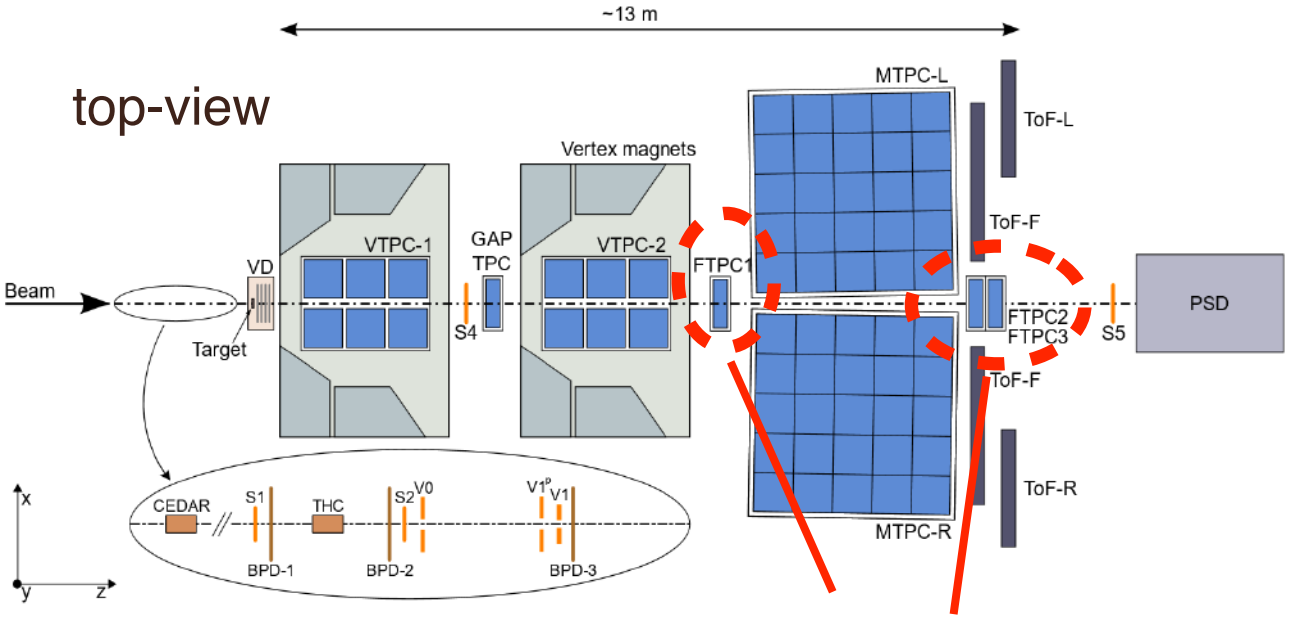
- Fermilab long-baseline neutrino experiments have proton beam energy:
  - NuMI: 120 GeV, LBNF: 60 - 120 GeV

—> Large chance to have forward hadron production with higher momentum

—> Need to improve NA61/SHINE detector acceptance for the forward region

- Requirements
  - Low mass to minimize multiple scattering and beam interactions
  - Beam off-time background rejection "Tandem-TPC" concept
  - Momentum resolution (< 10% @ 100 GeV)
  - Proton / Pion particle identification

—> Our Solution: gaseous ($Ar+CO_2$) TPCs



3 TPCs (FTPCs) built in 2015-2017

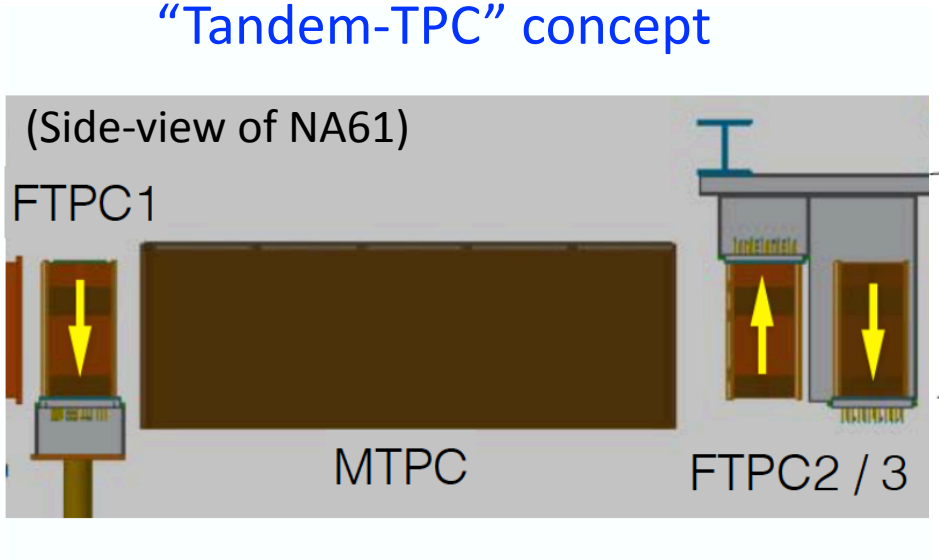
Forward Time Projection Chambers (FTPCs)

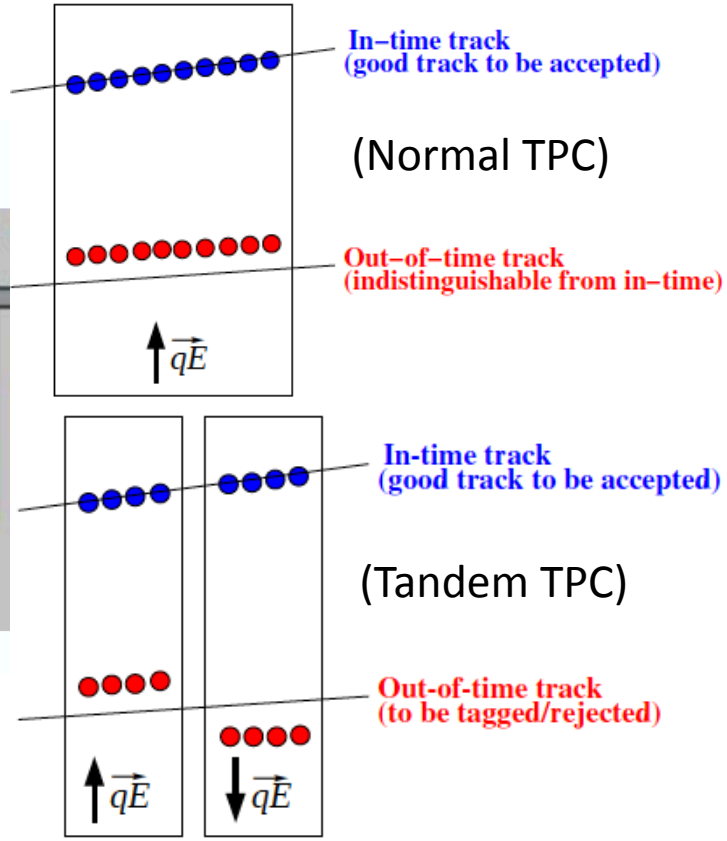
- Construction complete by 2017 and included in data taking since 2017
  - A major contribution from the US-NA61 group

Low mass TPC design

- light plastic frame
- thin copper-etched kapton film field cage

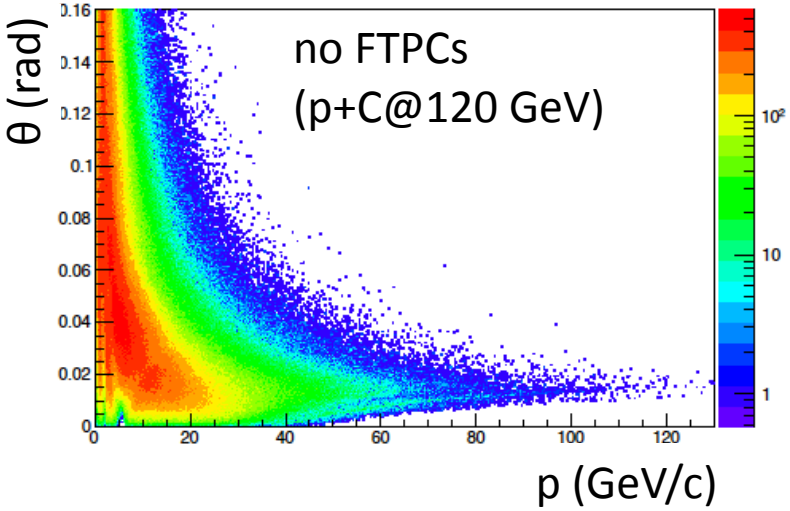
Beam off-time background rejection

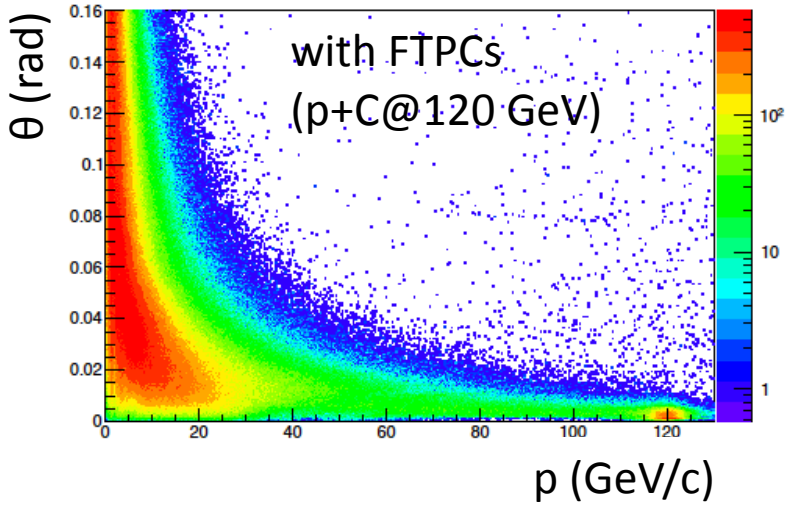




FTPC Performance

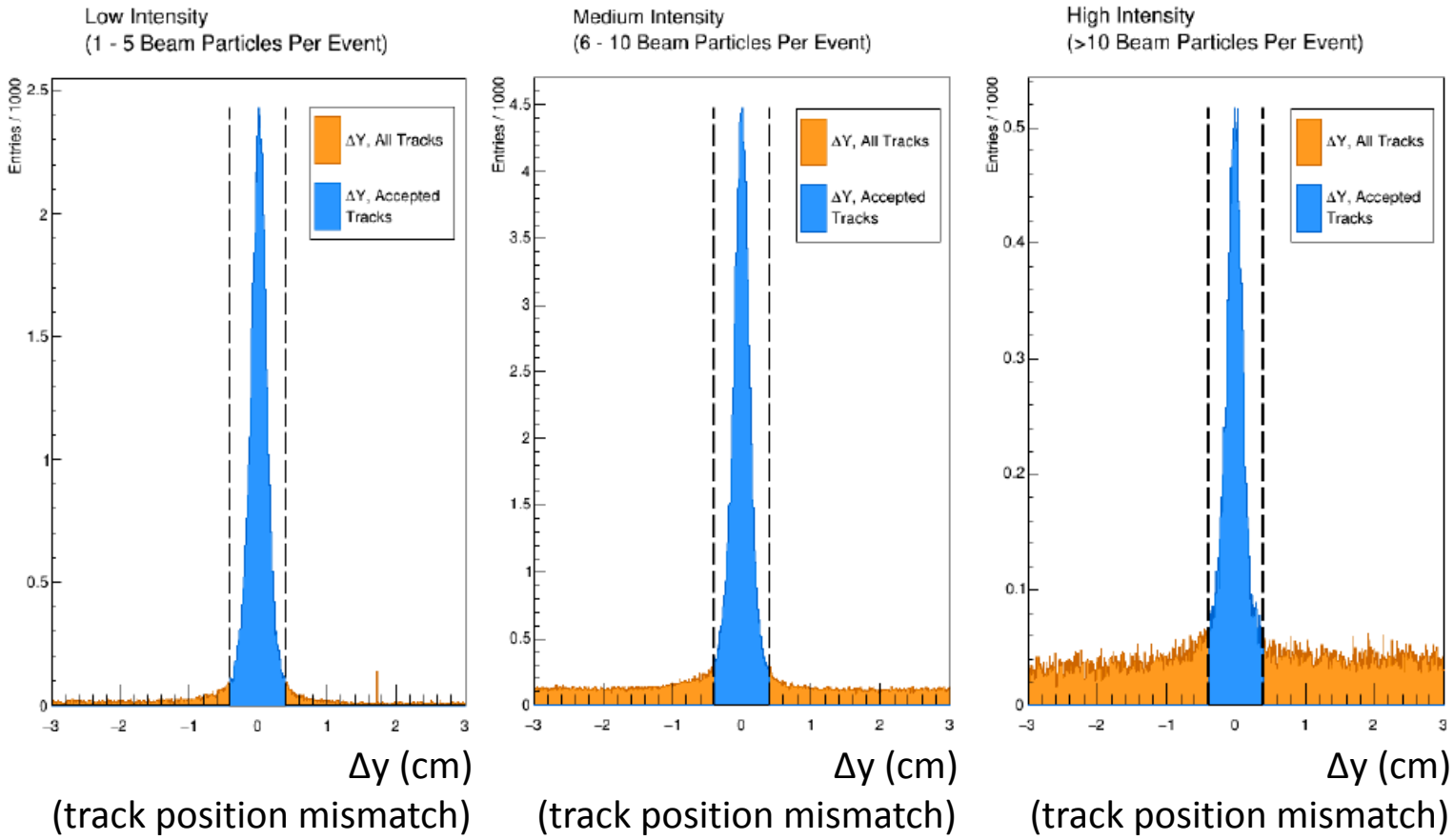
- Particle acceptance





Greatly improves the forward acceptance

- Beam off-time background rejection



Can select particles that arrive in-time (= trigger timing)

FTPC performance paper has been submitted to *JINST*
(Preprint —> arXiv:2004.11358)

Measurements for Fermilab Neutrino Program

- Thin target: various interactions in 2015 - 2017

Data sets		
no magnetic field (2015)	with magnetic field (2016)	with magnetic field (2017)
p+C (31 GeV/c)	p+Al/Be/C (60 GeV/c)	p+C (90 GeV/c) **(with FTPCs)**
π^++Al/C (31 GeV/c)	p+Be/C (120 GeV/c)	p+Be/C (120 GeV/c) **(with FTPCs)**
π^++Al/C (60 GeV/c)	π^++Be/C (60 GeV/c)	π^++C (31 GeV/c) **(no FTPCs)**
K^++Al/C (60 GeV/c)		π^++Al (60 GeV/c) **(no FTPCs)**
(no FTPCs)	**(no FTPCs)**	π^-+C (60 GeV/c) **(with FTPCs)**

- Total cross-section
  - 2015 π^+ and K^+ beams (Phys. Rev. D98, 052001 (2018))
  - 2016 proton beams (Phys. Rev. D100, 112001 (2019))
  - 2016 π^+ beams (Phys. Rev. D100, 112004 (2019)) (with differential multiplicity analysis)

Measurements for Fermilab Neutrino Program

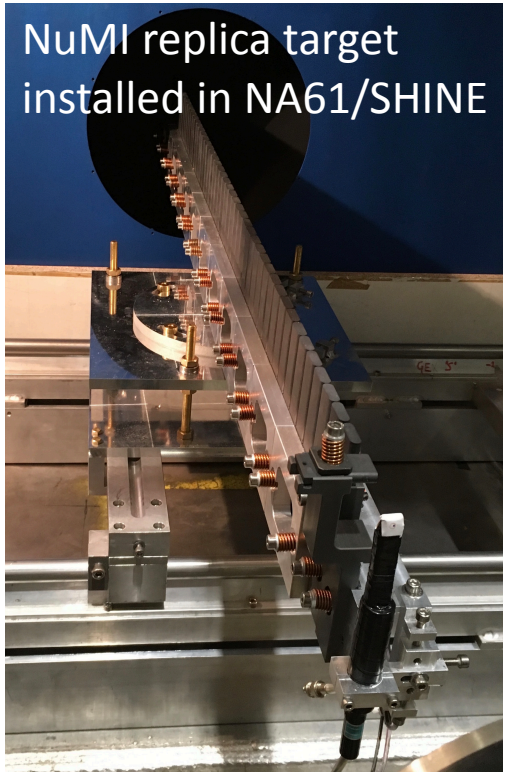
- Thin target: various interactions in 2015 - 2017

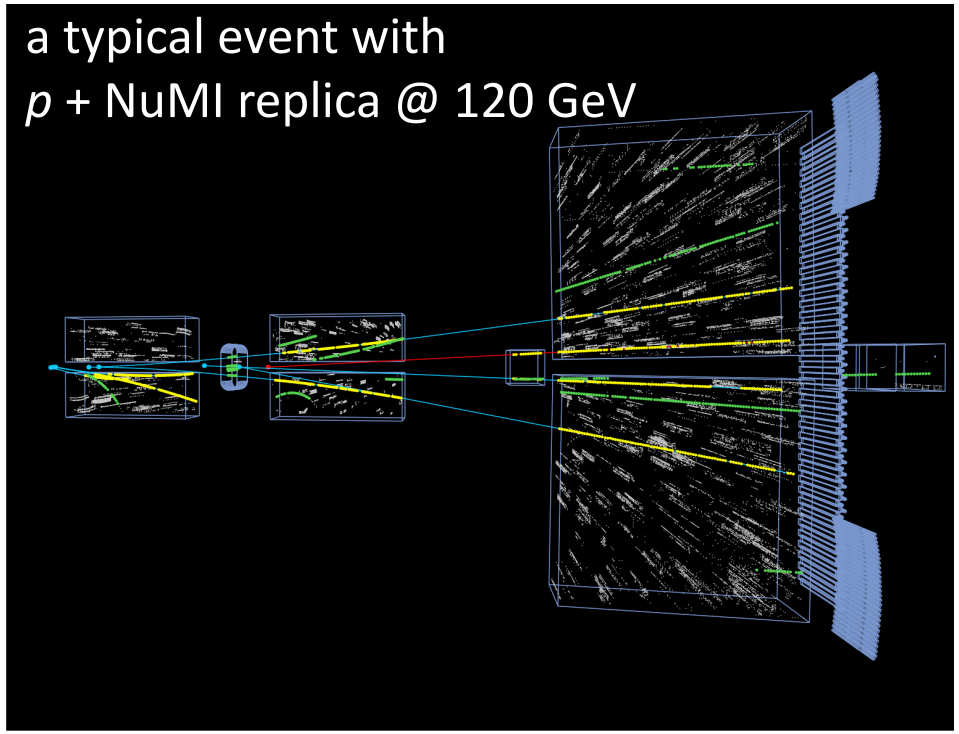
Data sets		
no magnetic field (2015)	with magnetic field (2016)	with magnetic field (2017)
p+C (31 GeV/c)	p+Al/Be/C (60 GeV/c)	p+C (90 GeV/c) **(with FTPCs)**
π^++Al/C (31 GeV/c)	p+Be/C (120 GeV/c)	p+Be/C (120 GeV/c) **(with FTPCs)**
π^++Al/C (60 GeV/c)	π^++Be/C (60 GeV/c)	π^++C (31 GeV/c) **(no FTPCs)**
K^++Al/C (60 GeV/c)		π^++Al (60 GeV/c) **(no FTPCs)**
(no FTPCs)	**(no FTPCs)**	π^-+C (60 GeV/c) **(with FTPCs)**

- Differential production multiplicity
  - 2016 π^+ beams (Phys. Rev. D100, 112004 (2019)) (with total cross-section analysis)
  - 2016 and 2017 proton beams (analysis ongoing)

Measurements for Fermilab Neutrino Program

- Replica target: proton beam @ 120 GeV/c in 2018 on NOvA replica target
  - Large statistics (~18M events) for measurement of differential hadron yields

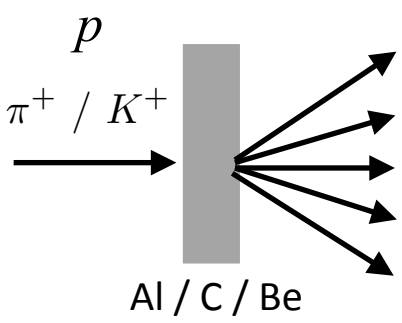


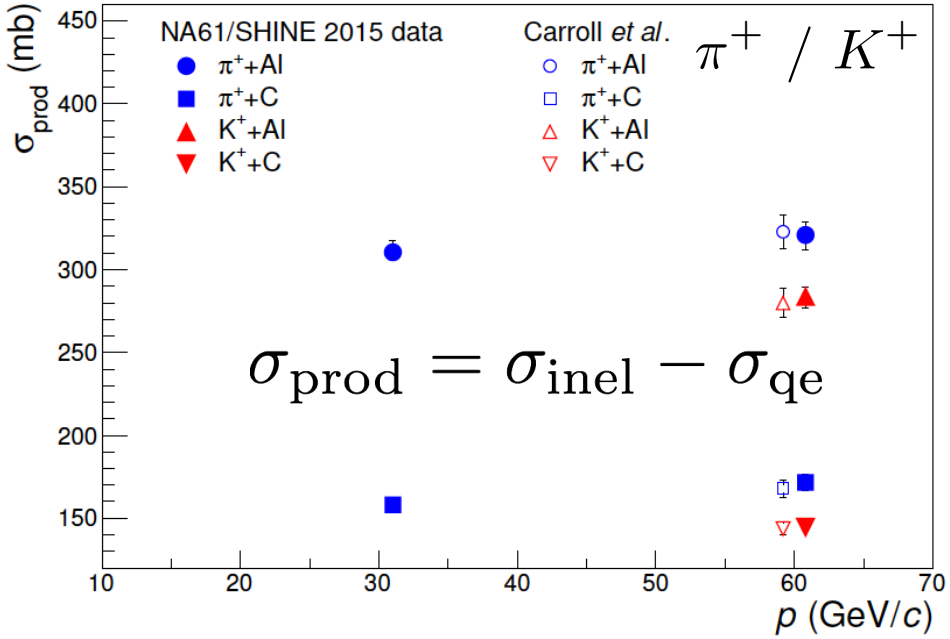


- Measurement of differential hadron production yields
  - Measurement will be conducted in similar way as T2K replica target measurement

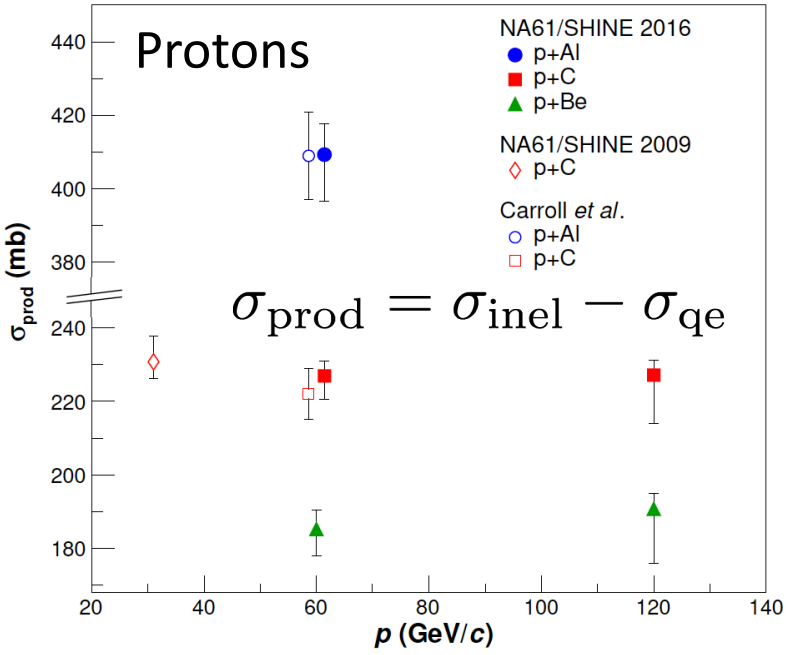
—> Possibly additional binning because of asymmetric geometry in ϕ

Thin Target: Total Cross Section





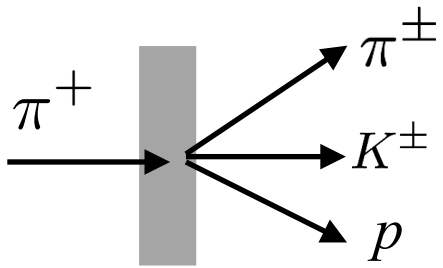
Phys. Rev. D98, 052001 (2018)



Phys. Rev. D100, 112004 (2019)

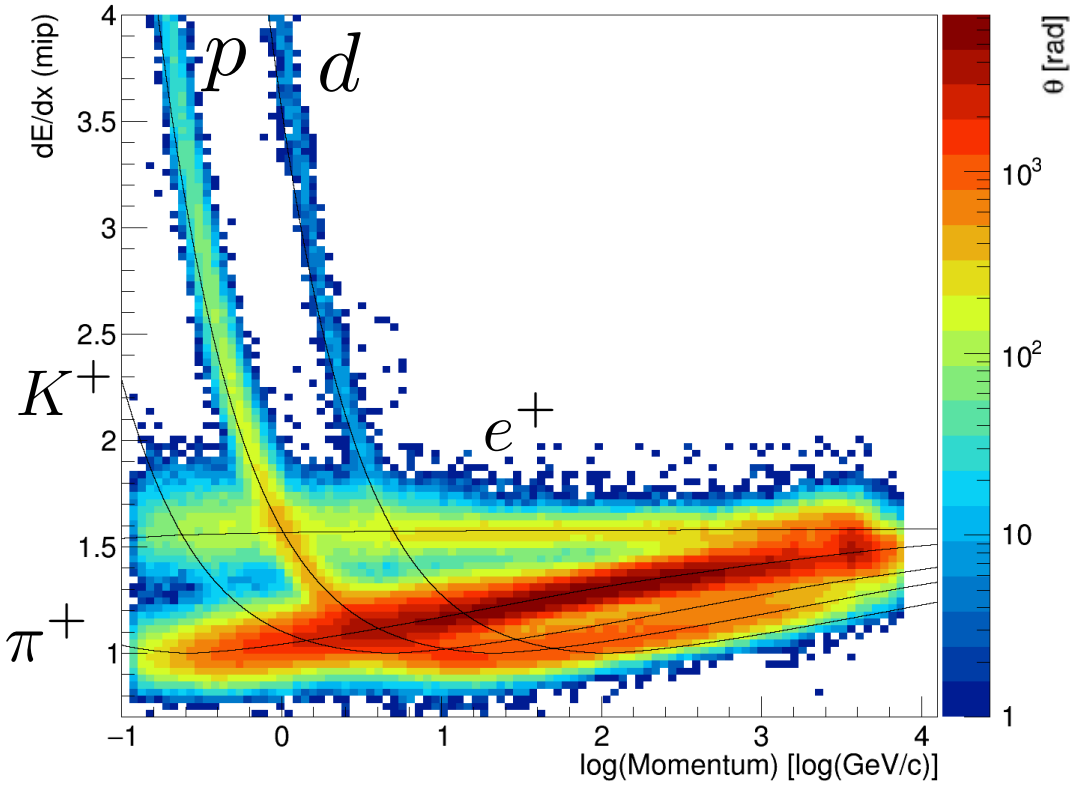
- Precision of measurements: 2~4% (30, 60 GeV/c) and 6~8% (120 GeV/c)
  —> NuMI simulation assumes an uncertainty of 5% for pion interactions, 10-30% for kaon interactions, and extrapolates data at lower or higher energy for protons
  —> Can improve NuMI flux predictions
  —> Also relevant for LBNF beamline

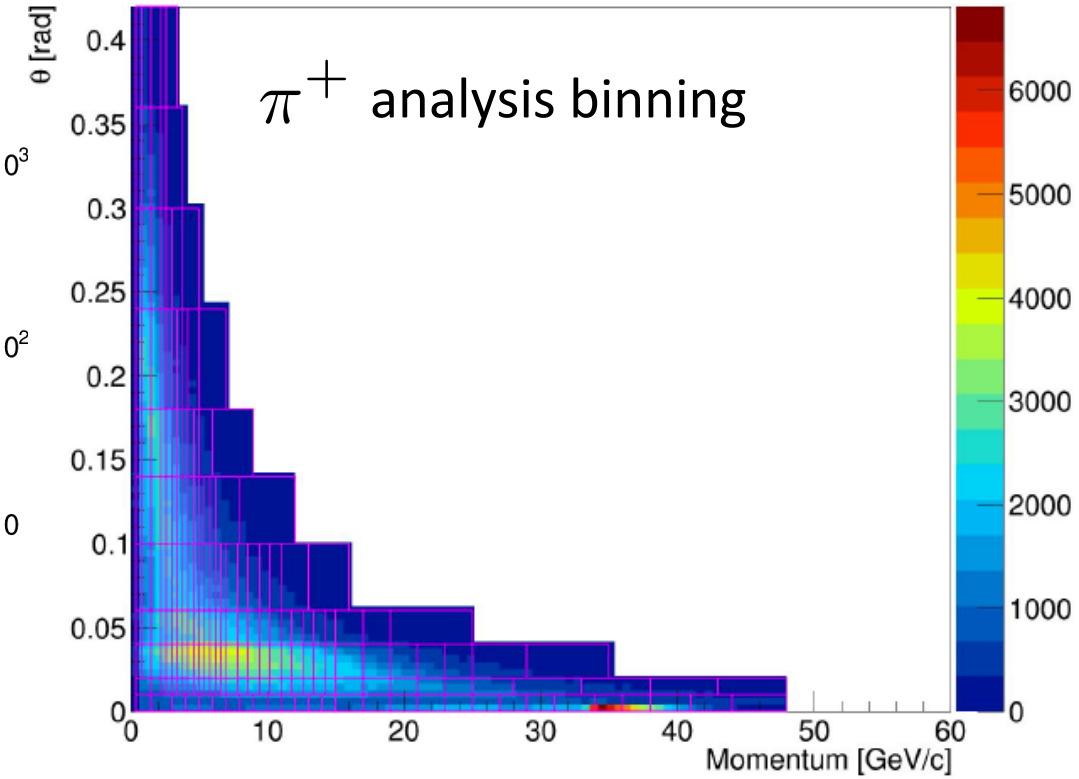
Thin Target: Charged Hadron Production



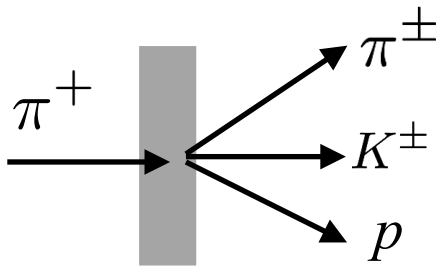
- Example: $\pi^+ + \mathrm{C} \,@\, 60\ \mathrm{GeV}$ Phys. Rev. D100, 112004 (2019)

Binning of pions, kaons, and protons is optimized for each particle species

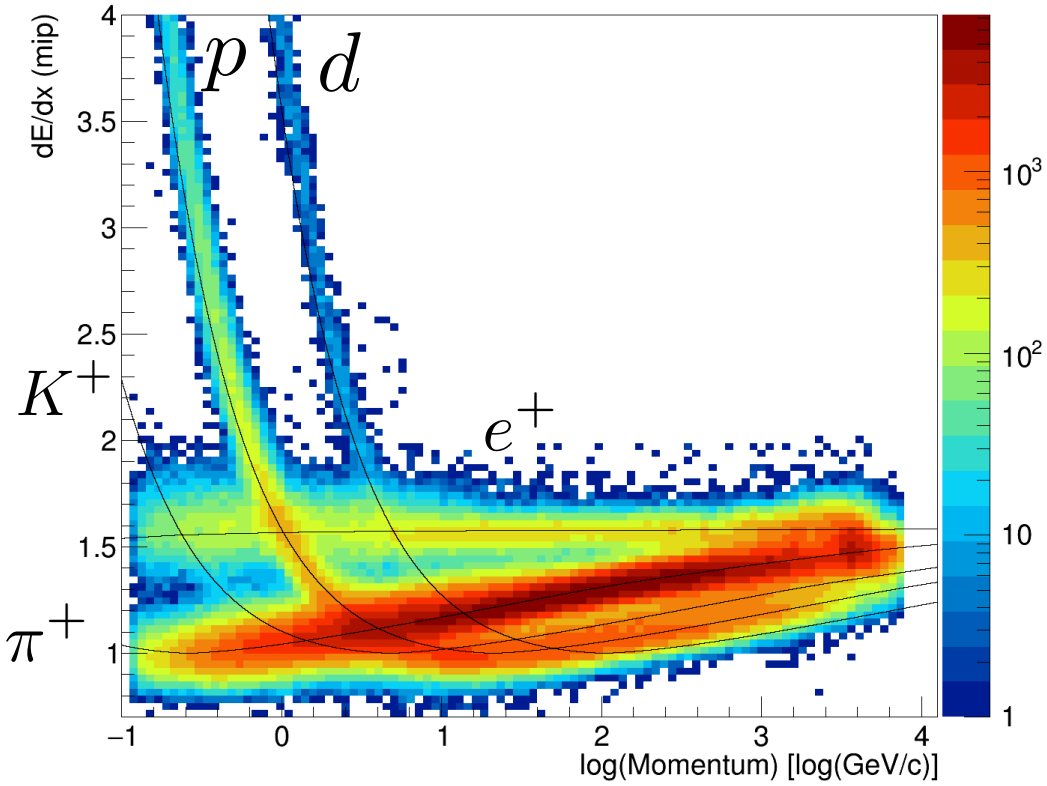


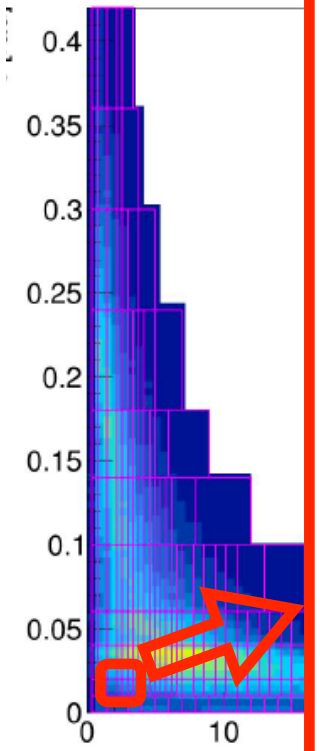


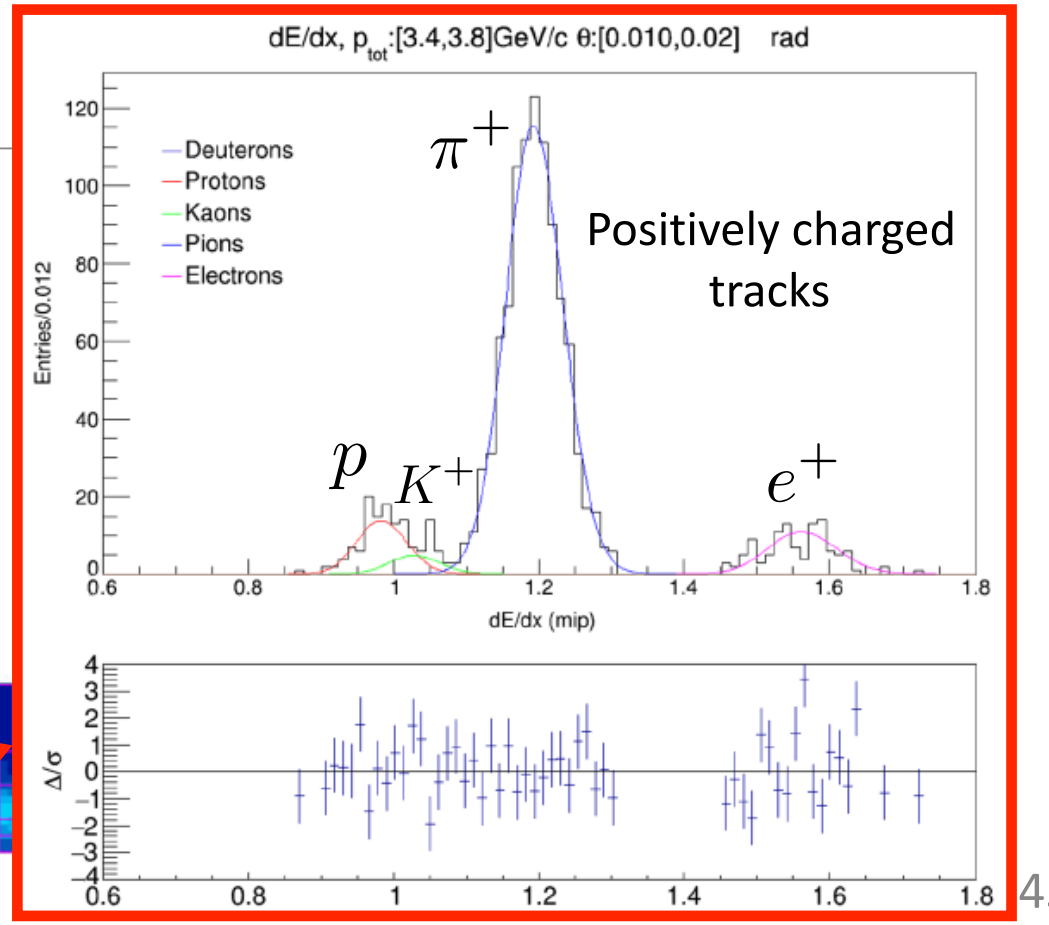
Thin Target: Charged Hadron Production



- Example: $\pi^+ + \mathrm{C} \,@\, 60\ \mathrm{GeV}$ Phys. Rev. D100, 112004 (2019)



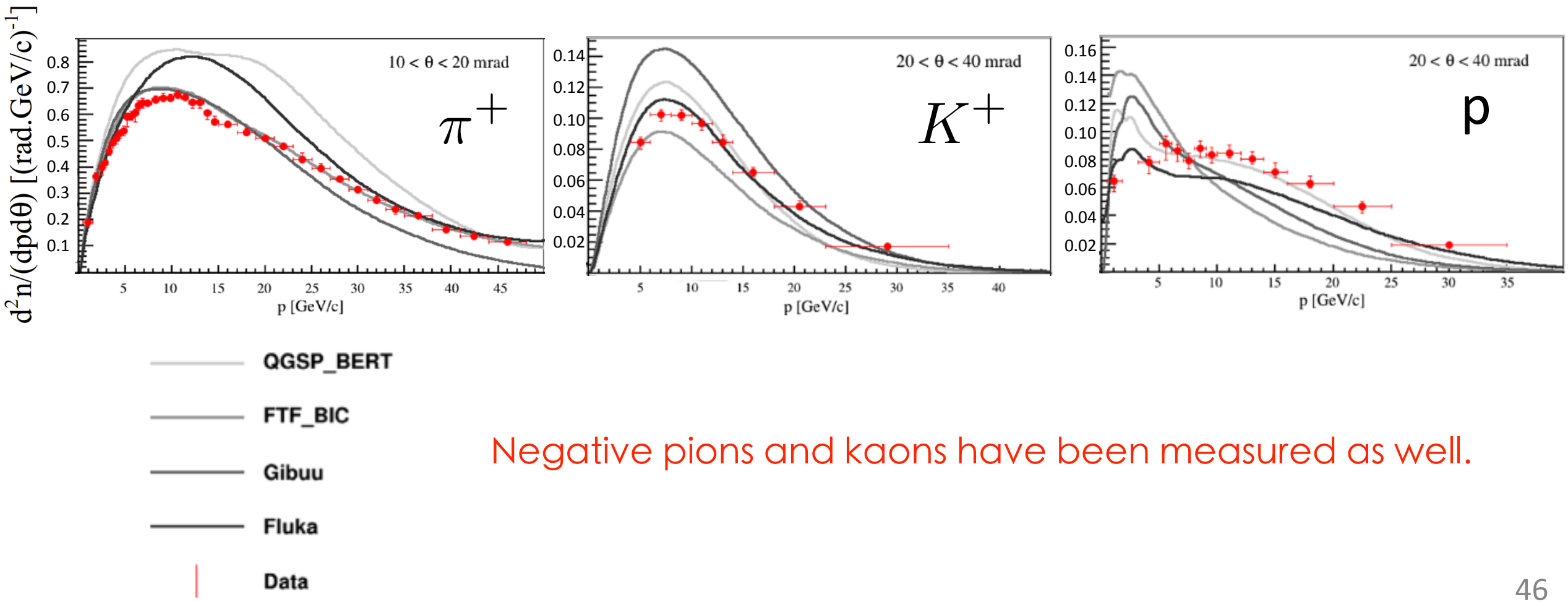




Thin Target: Charged Hadron Production

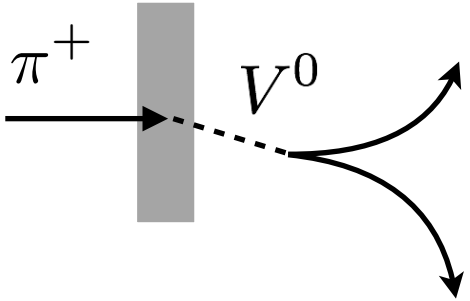
- Measured differential production yields $(\pi^+ + \mathrm{C} \,@\, 60\ \mathrm{GeV})$

  Phys. Rev. D100, 112004 (2019)



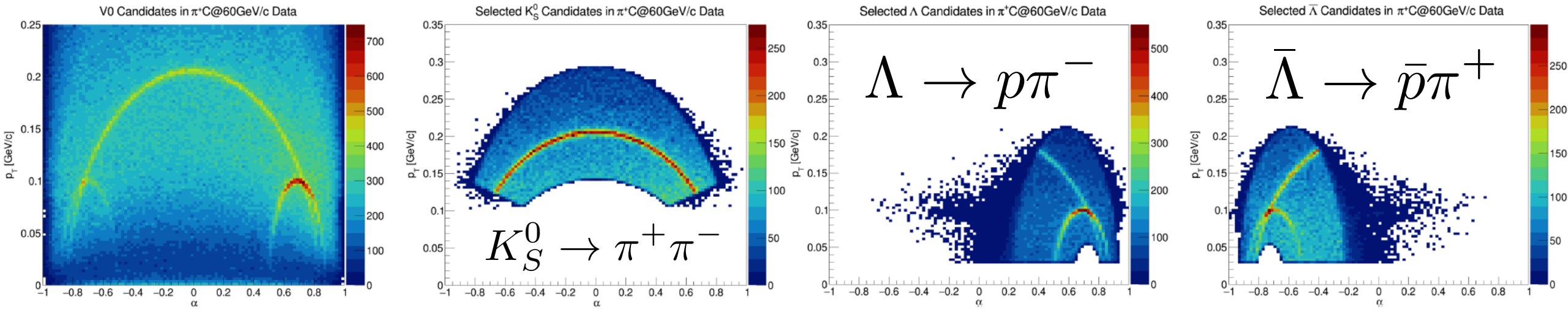
Negative pions and kaons have been measured as well.

Thin Target: Neutral Hadron Production



- Example: $\pi^+ + \mathrm{C} \,@\, 60\ \mathrm{GeV}$ Phys. Rev. D100, 112004 (2019)

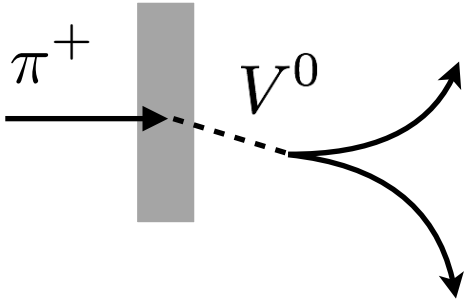
- The Armenteros-Podolansky distribution (visualization of V^0 candidates)



X-axis: $\alpha = \dfrac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$ (Asymmetry in the longitudinal momenta of the child tracks with respect to the V^0 track)

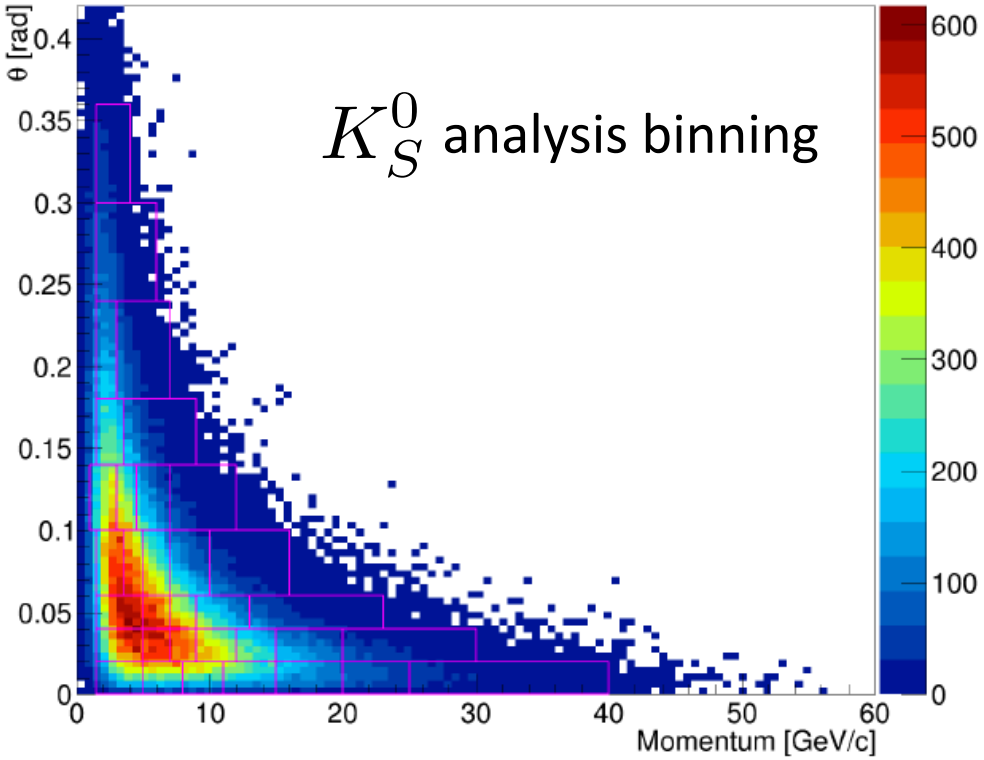
Y-axis: p_T (Transverse momenta of V^0 track)

Thin Target: Neutral Hadron Production

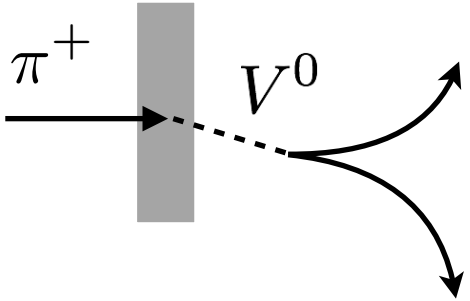


- Example: $\pi^+ + \mathrm{C} \,@\, 60\ \mathrm{GeV}$ Phys. Rev. D100, 112004 (2019)

Binning of K_S^0, Λ, and $\bar{\Lambda}$ is optimized for each particle species

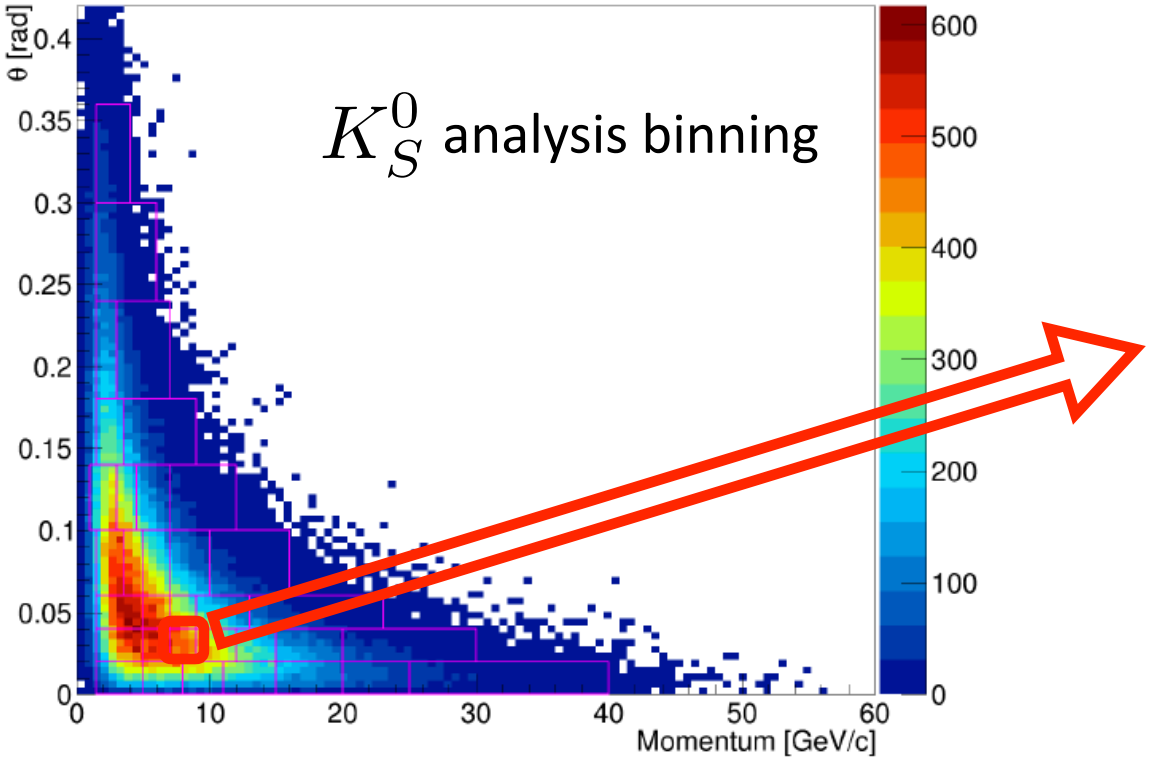


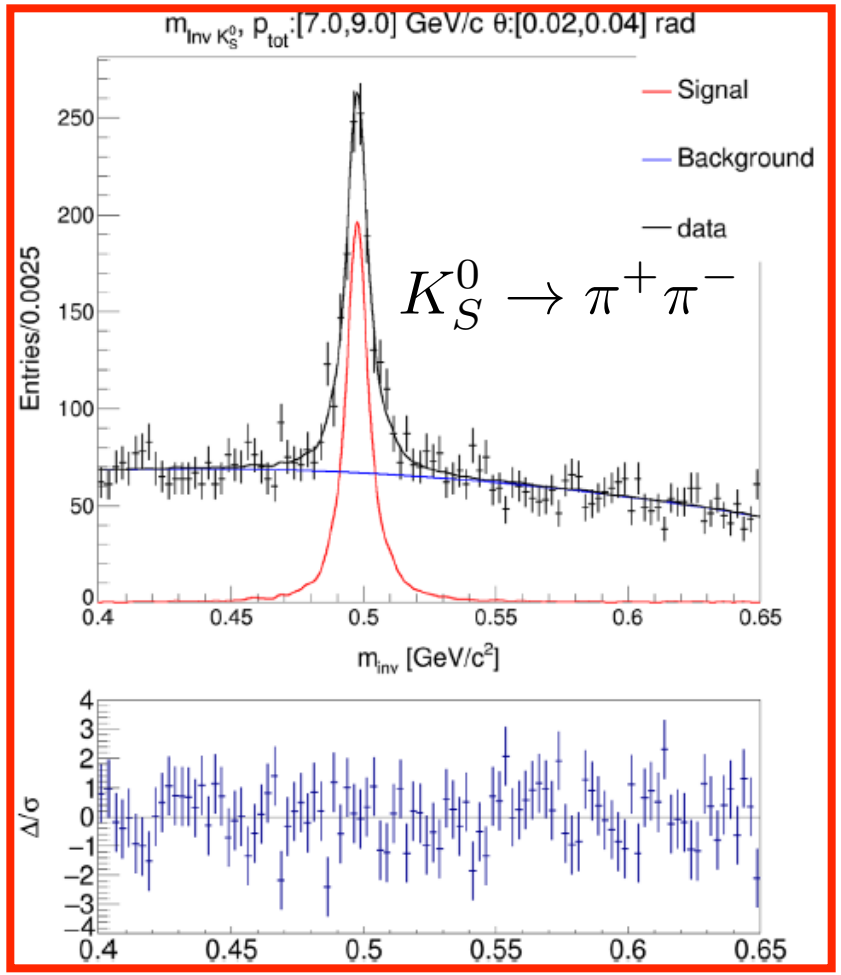
Thin Target: Neutral Hadron Production



- Example: $\pi^+ + \mathrm{C} \,@\, 60\ \mathrm{GeV}$ Phys. Rev. D100, 112004 (2019)

Binning of K_S^0, Λ, and $\bar{\Lambda}$ is optimized for each particle species



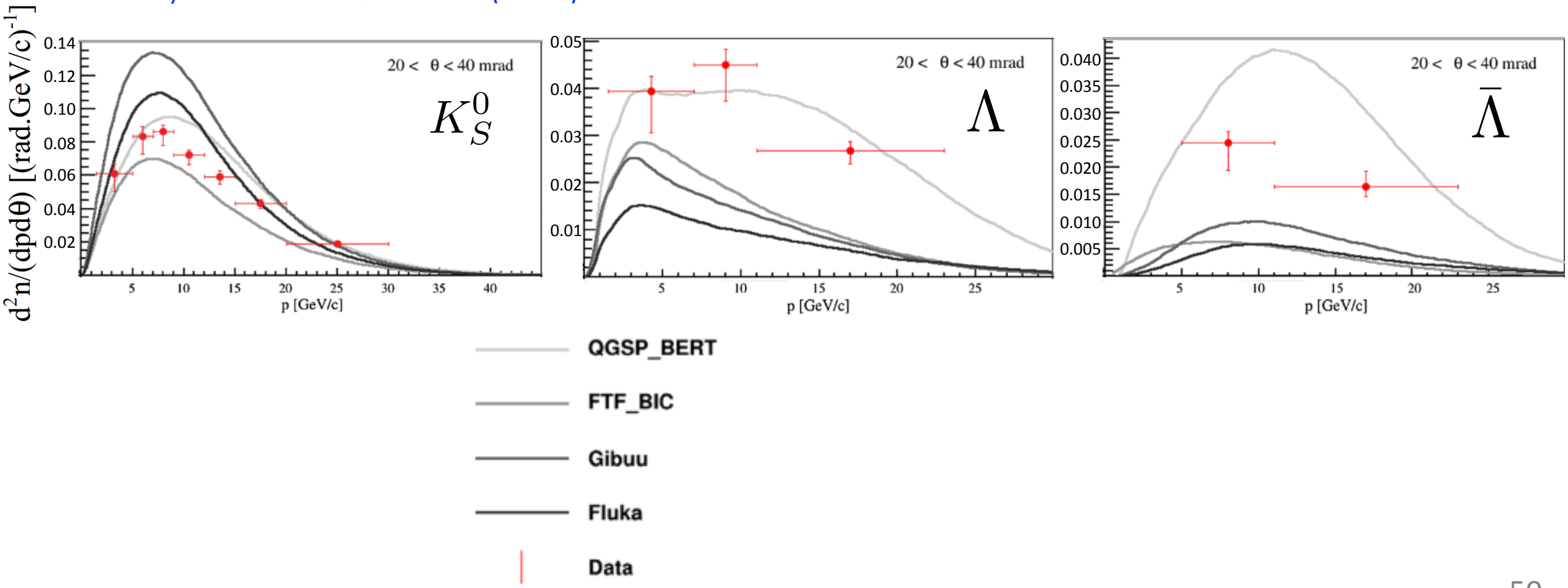


$$m(K^0)_{\mathrm{PDG}} = 497.611 \pm 0.013\,(\mathrm{MeV})$$

Thin Target: Neutral Hadron Production

- Measured differential production yields $(\pi^+ + \mathrm{C} \,@\, 60\ \mathrm{GeV})$

  Phys. Rev. D100, 112004 (2019)



Hadron Production Model Improvement

- NA61/SHINE thin target data are also useful to improve model prediction
  - Measurements for T2K (p+C@31 GeV/c) are used to improve hadronic interaction models
  - Measurements for Fermilab (various interactions) will be used

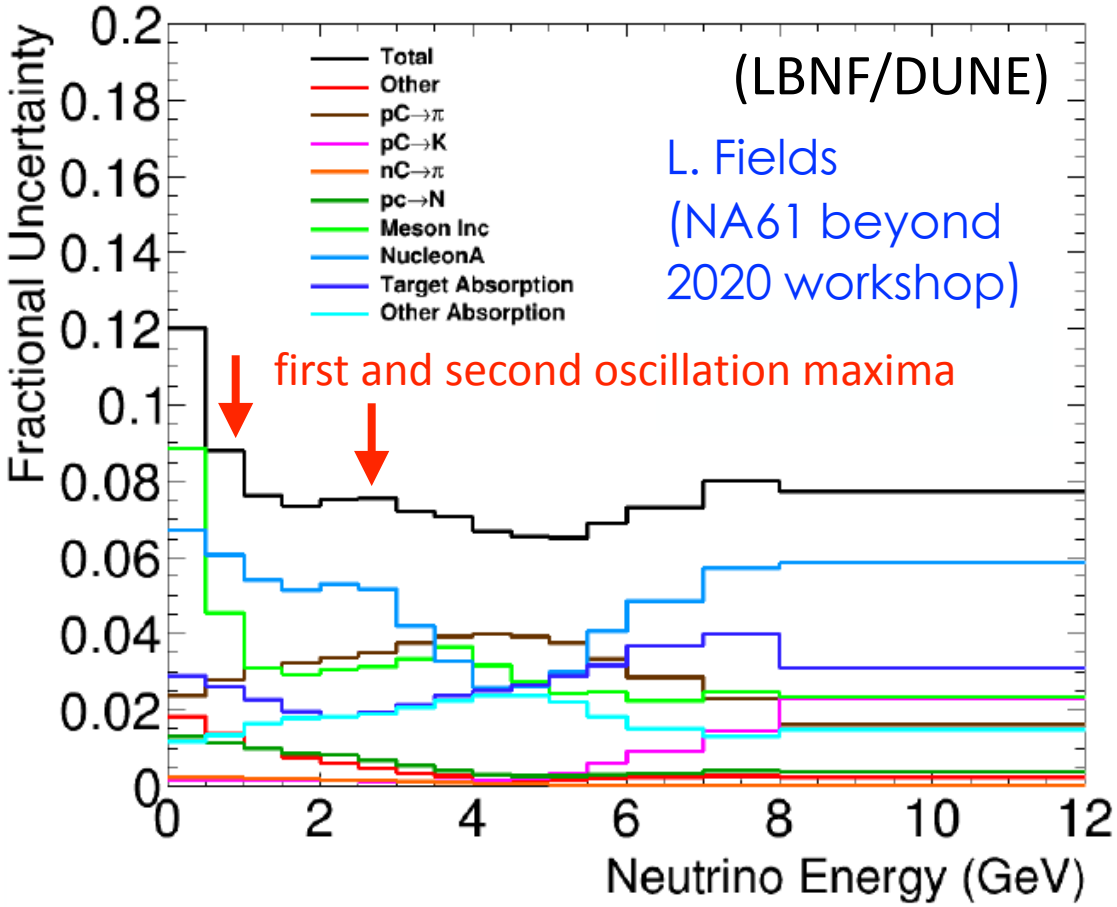
- Examples of references:
  - https://arxiv.org/abs/1910.06417, https://arxiv.org/abs/1109.6768 (Geant4 FTF model)
  - https://arxiv.org/abs/1810.09973 (Production of strange particles)
  - https://arxiv.org/abs/1107.0374 (UrQMD model)
  - https://arxiv.org/abs/1806.01534 (Geant4 QGS model)*
  - https://arxiv.org/abs/1404.2026, https://arxiv.org/abs/1308.0736 (pp and pC for higher energy)*

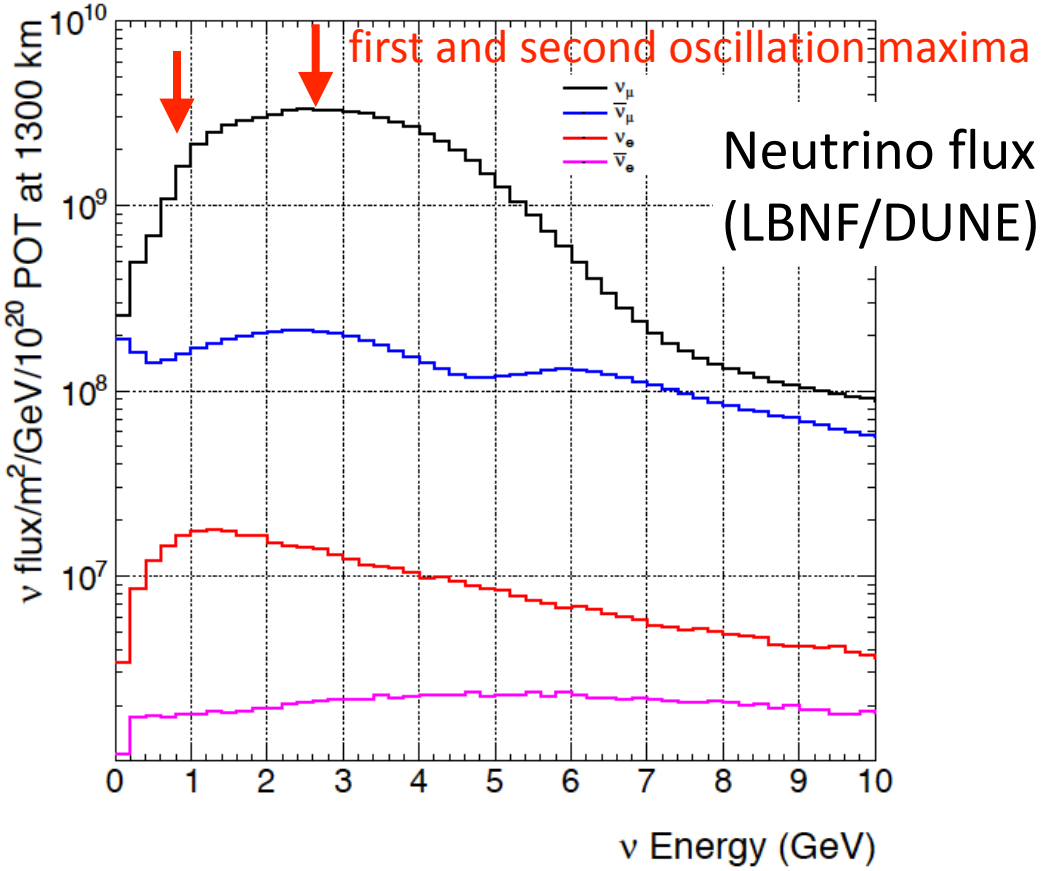
* with NA61 data not presented in this talk

Measurements for Future Neutrino Experiments

Requirements for Future LBN Experiments

- Towards J-PARC/Hyper-K (off-axis) and LBNF/DUNE (on-axis)
  - "Total" systematic uncertainty: below 5% for neutrino oscillation measurements
    —> goal for flux: 2-3% on flux uncertainty for broad range of energies!!





Future Hadron Production Measurements

- What do we need before the start of next generation LBN experiments?

Thin Target

- Uncovered materials

—> With various nuclear targets (Al, Fe, Ti, Water, etc…)

- Uncovered phase-space

—> T2K/Hyper-K: low momentum (1-5 GeV/c) hadron interactions

—> DUNE: $\pi^{\pm}$ and $K^{\pm}$ re-interactions (30-60 GeV/c)

- Improved precision

—> More statistics to reduce statistical uncertainty

Replica Target

- New replica target

—> Hyper-K and DUNE targets are under development

- Improved precision

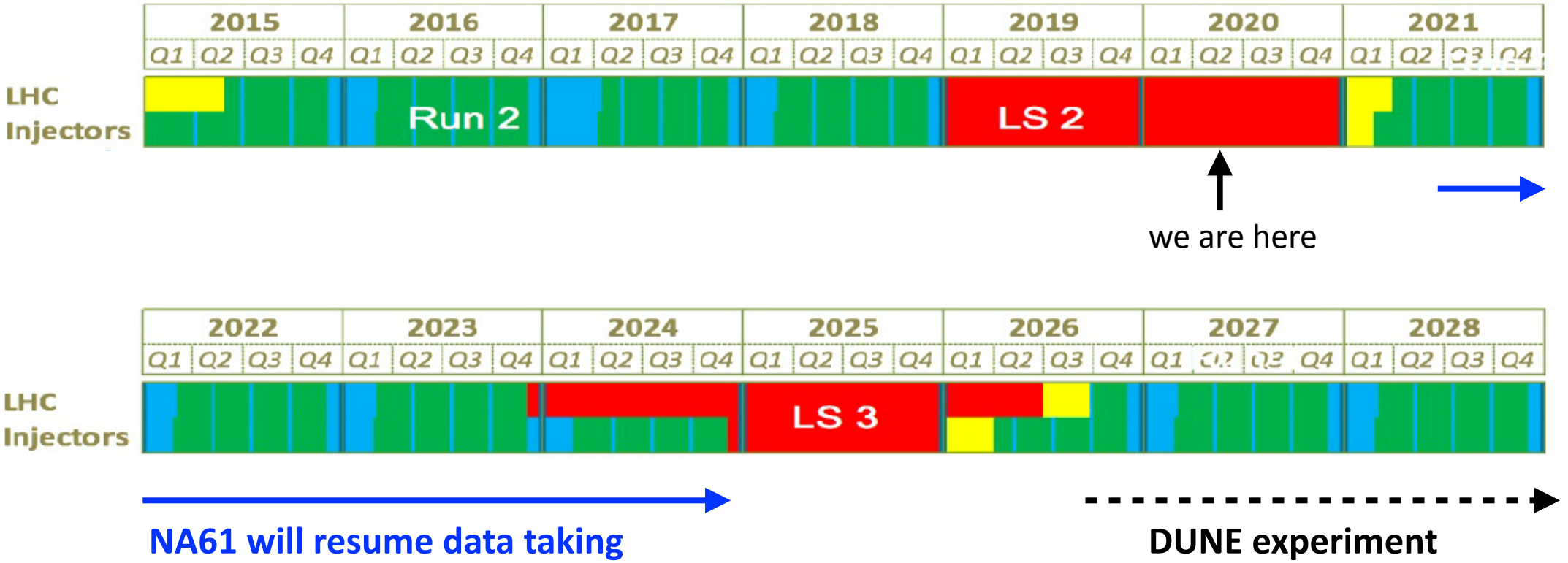
—> More statistics for T2K and NuMI replica target data

—> Target tracking detector will be necessary

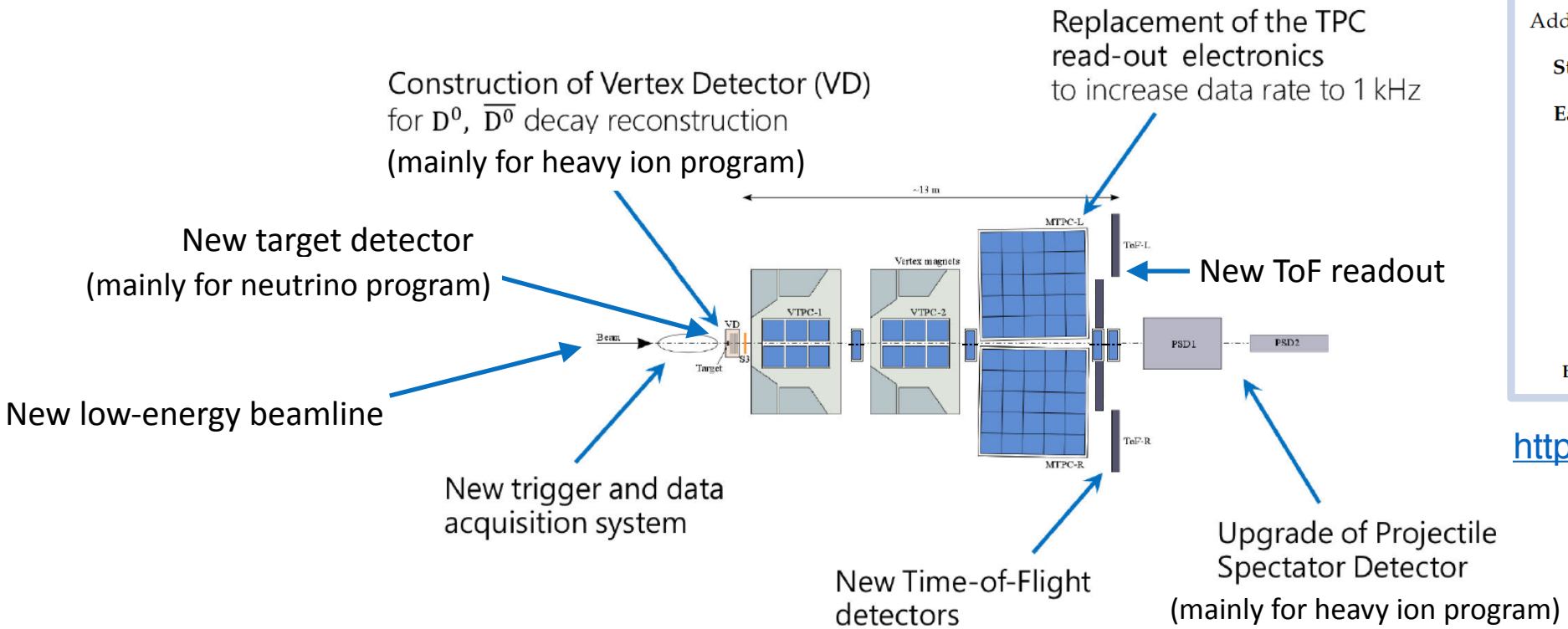
all measurements are possible with NA61/SHINE after upgrade

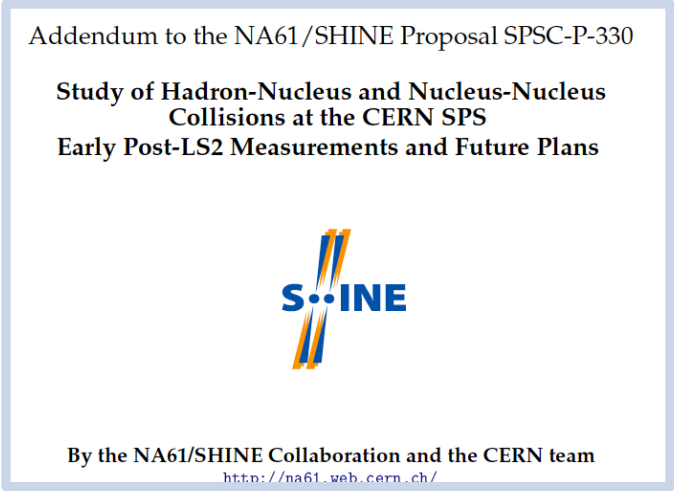
Future Measurement with NA61/SHINE

- NA61/SHINE will resume data taking after LS 2



NA61/SHINE Upgrade Detector




Addendum to the NA61/SHINE Proposal SPSC-P-330

Study of Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS
Early Post-LS2 Measurements and Future Plans

By the NA61/SHINE Collaboration and the CERN team
http://na61.web.cern.ch/

https://cds.cern.ch/record/2309890

- Facility upgrades in progress
  - DAQ upgrade: ~1kHz TPC readout
  - New ToF walls with mRPC
- Various ideas under consideration
  - Construction of low-energy beamline
  - New target tracking detector

- So far no major delays
  - covid-19 pandemic may affect upgrade schedule, but we still expect upgrade to be completed by mid-2021

NA61/SHINE Upgrade Detector

Construction of Vertex Detector (VD)
for D^0, $\overline{D^0}$ decay reconstruction
(mainly for heavy ion program)

Replacement of the TPC
read-out electronics
to increase data rate to 1 kHz

New target detector
(mainly for neutrino program)

New ToF readout

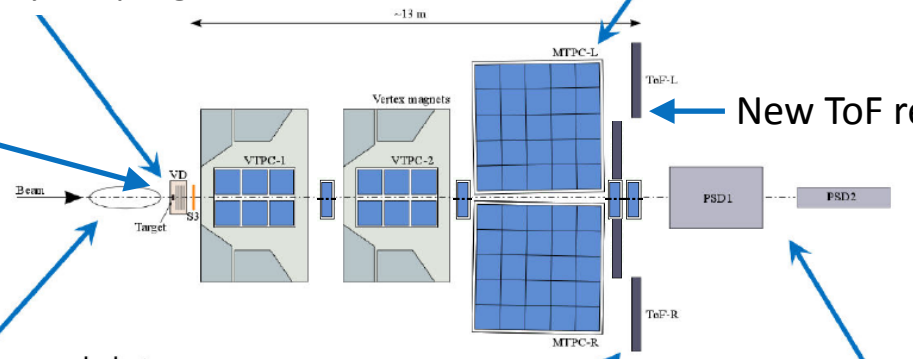
New low-energy beamline

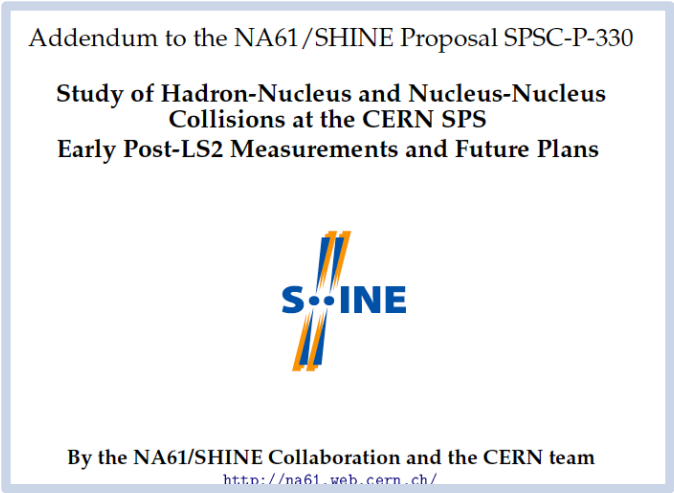
I'll talk a bit about this

New trigger and data
acquisition system

New Time-of-Flight
detectors

Upgrade of Projectile
Spectator Detector
(mainly for heavy ion program)

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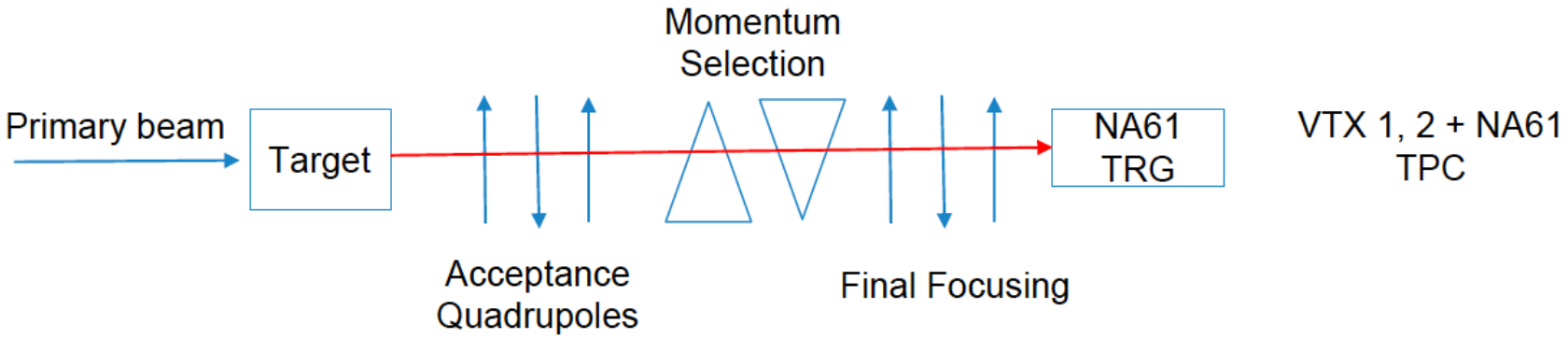
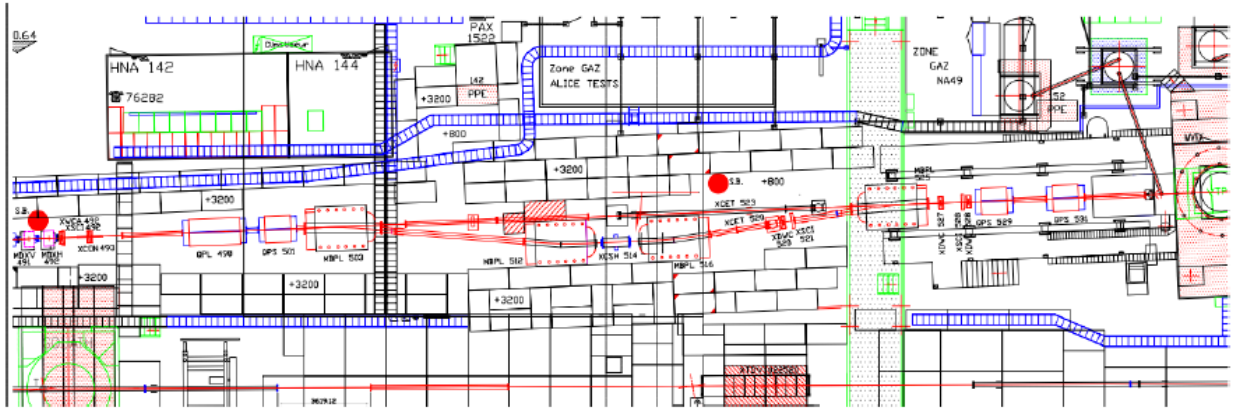
Low-Energy Beamline at NA61/SHINE

- We have started design works for new low-E beamline at CERN SPS H2-bemeline
  - Low-Energy = 1-13 GeV —> the lowest energy NA61 achieved was 13 GeV

Principle of a Low Energy Beam for SHINE





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

C. A. Mussolini, N. Charitonidis

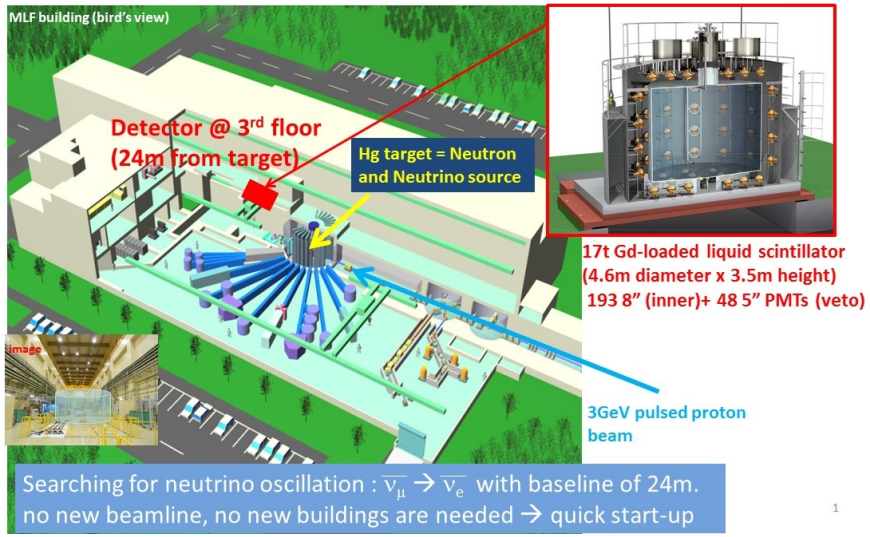
Low-Energy Beamline at NA61/SHINE

T2K / Hyper-K

- Measurements of unconstrained interactions
  - pion beam: 1-6 GeV
  - proton beam: > 4 GeV
  - kaon beam: 1-10 GeV

JSNS2 (J-PARC E56) experiment (sterile neutrino)

- proton (3 GeV) on mercury target
  - No data exist —> Hard to predict BG



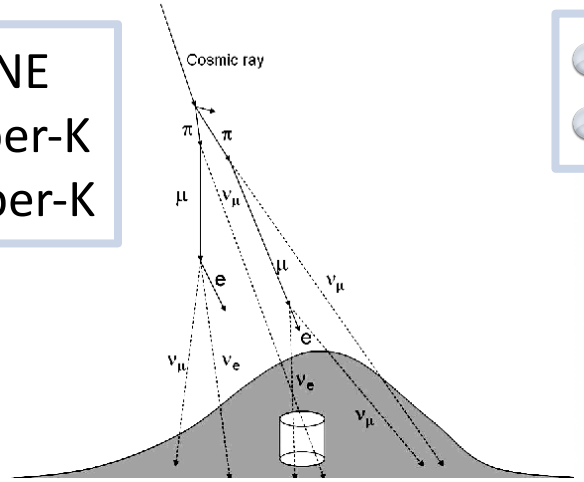
(At MLF building in J-PARC)

- Other possible physics cases

Atmospheric neutrinos

- Measurements to improve flux predictions

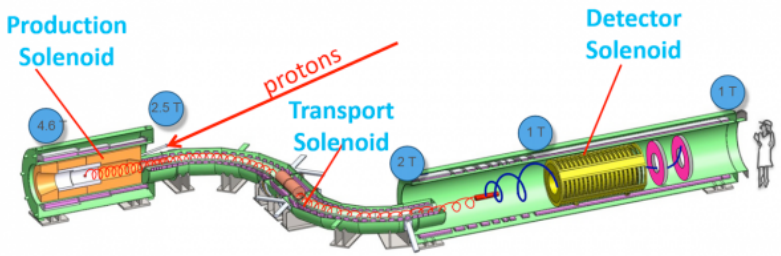
- DUNE
- Super-K
- Hyper-K



Muon to electron

- Measurements to understand hadron production on target

- Mu2e (FNAL)
- COMET (J-PARC)



We welcome new ideas and collaborators !!

Summary

- Precision hadron production measurements are essential to reduce the leading systematic uncertainty on the neutrino flux prediction
  - NA61/SHINE thin and replica target measurements have improved and will further improve the flux prediction in T2K
  - NA61/SHINE measurements for the Fermilab neutrino programs are ongoing
- NA61/SHINE is proposing a program extension after LS2
  - Significant facility upgrades allow us to pursue necessary measurements

There are many opportunities in NA61/SHINE.
We welcome new collaborators !!

Thank you for your attention!

NA61/SHINE Collaboration

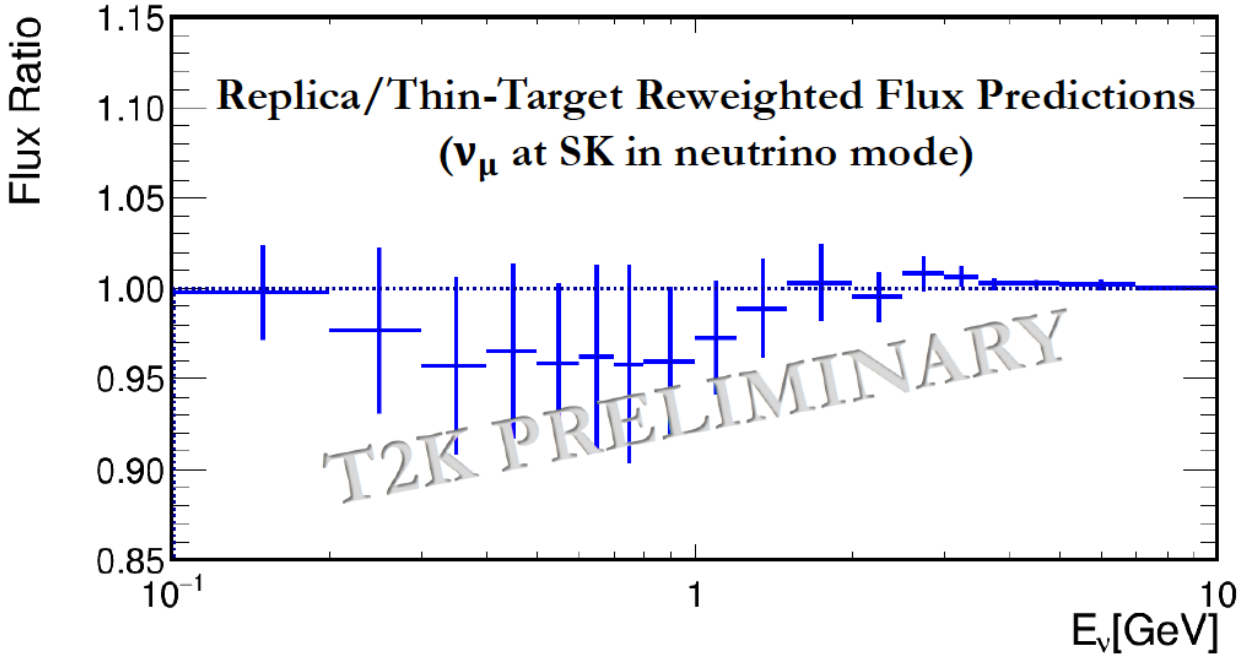
- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
-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

~150 physicists from ~30 institutes

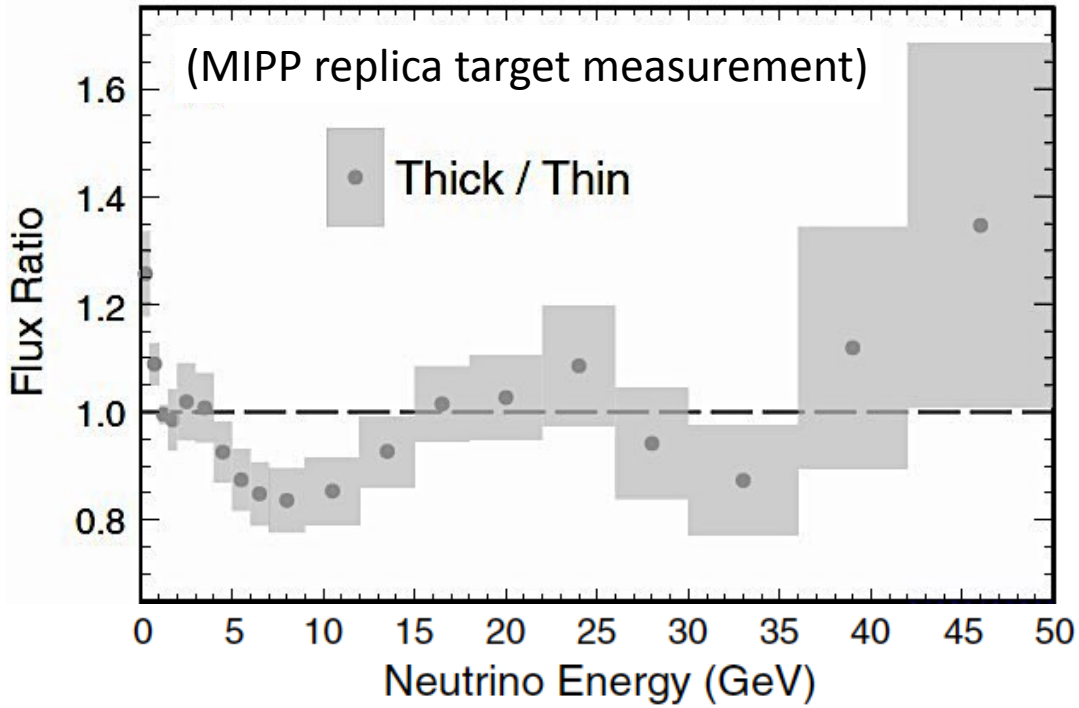
http://shine.web.cern.ch

Backup

Thin vs Replica Data Flux Tuning



T2K (T. Vladisavljevic): arXiv:1804.00272



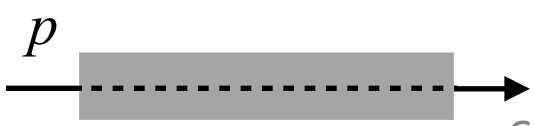
MINERvA: Phys. Rev. D94, 092005 (2016)

- Difference observed for both T2K and NuMI beamlines —> Due to beam interaction rate?
- This issue needs to be understood

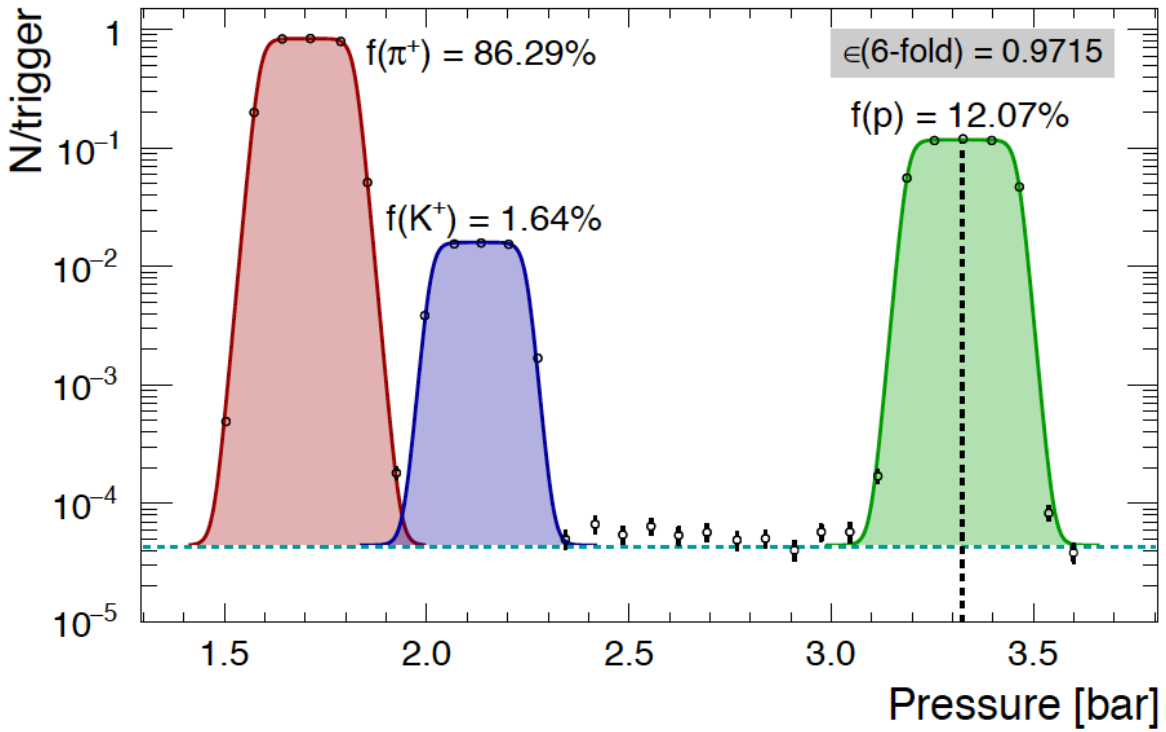
  —> Measurements of beam attenuation, further precision total cross section

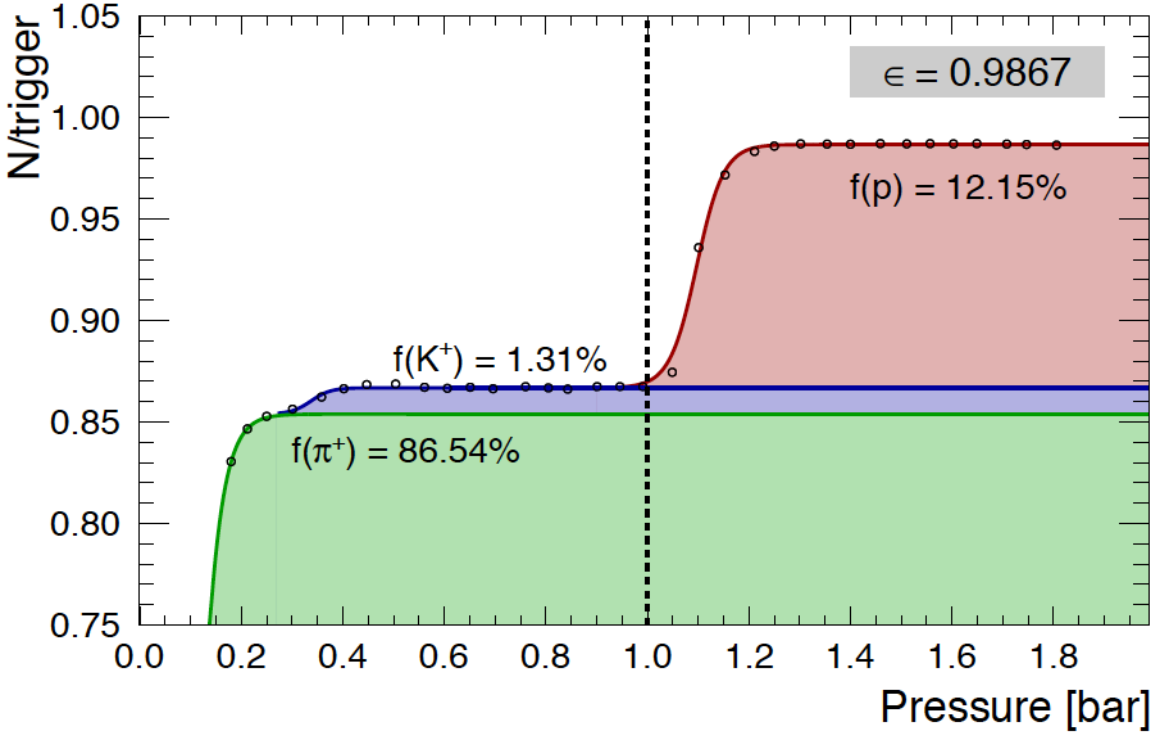
- Measurement of beam survival probability ($P_{\text{survival}} = e^{-Ln\sigma_{\text{prod}}}$)

  (*L*: length of target, *n*: number of atoms per unit volume)



Beam Particle Selection





NA61/SHINE Detector Performance

typical momentum resolution

$$\frac{\sigma(p)}{p^2} \approx 10^{-4}\ (\mathrm{GeV}/c)^{-1}$$

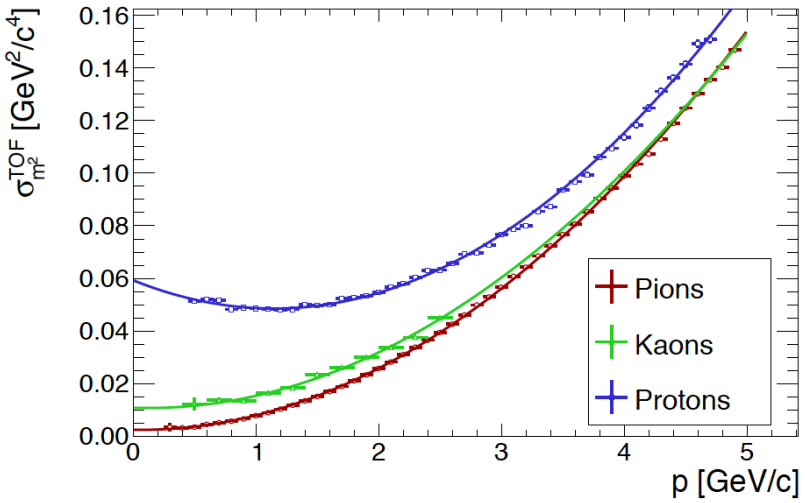
typical dE/dx resolution

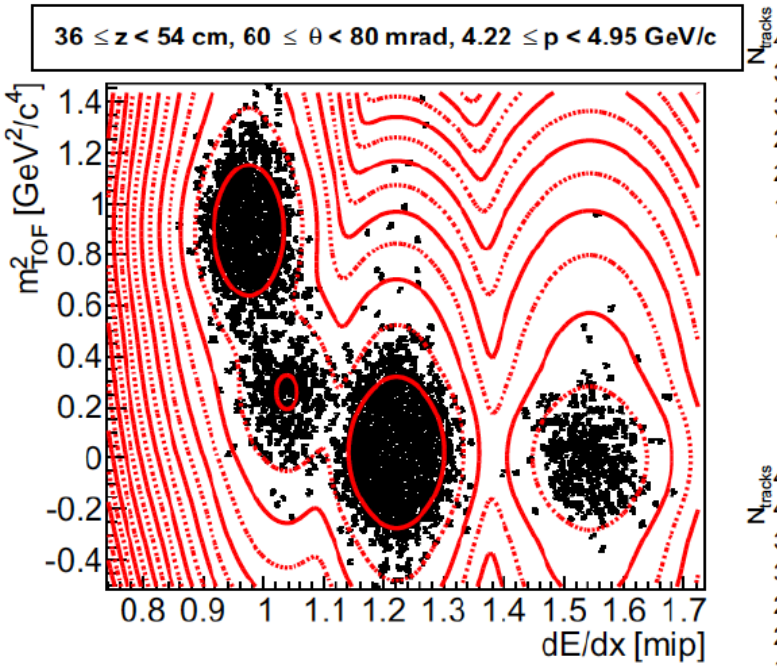
$$\frac{\sigma(dE/dx)}{dE/dx} \approx 0.04$$

ToF resolution

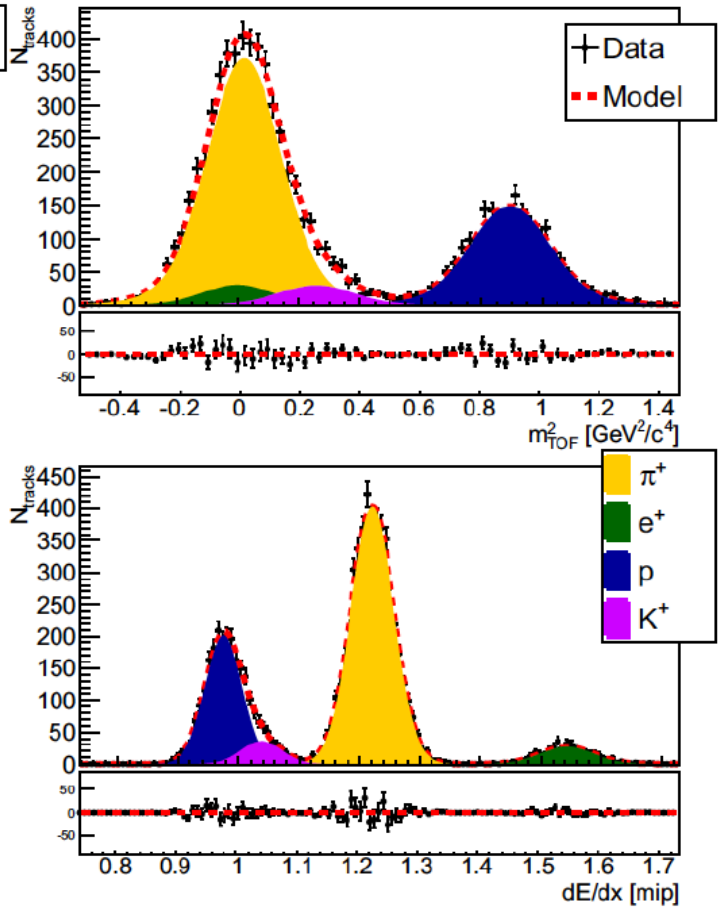
$$\sigma(\text{ToF-L/R}) < 90\ \text{ps}$$

$$\sigma(\text{ToF-F}) \approx 120\ \text{ps}$$

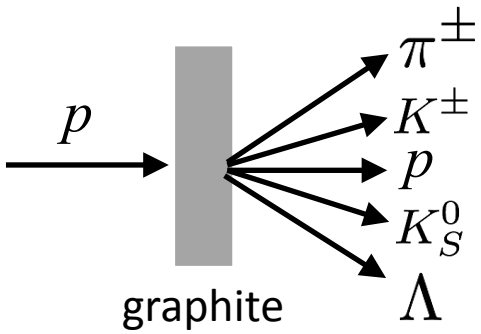




A_p = (2056±46)
A_{K^+} = (399±21)
A_{π^+} = (4732±69)
A_{e^+} = (390±20)



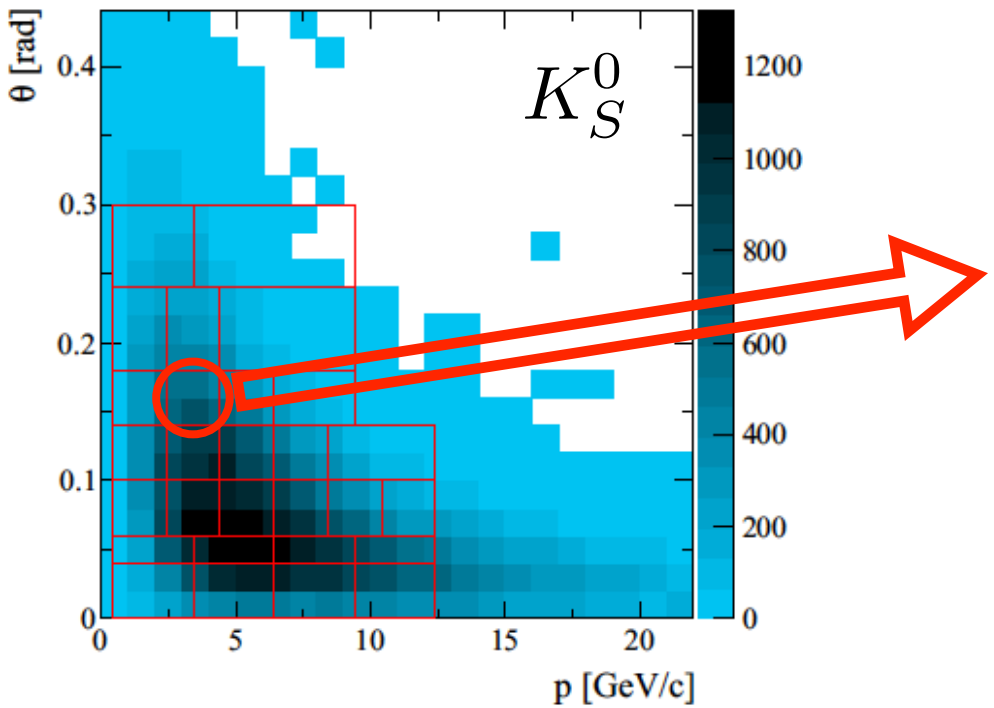
Thin Target Results

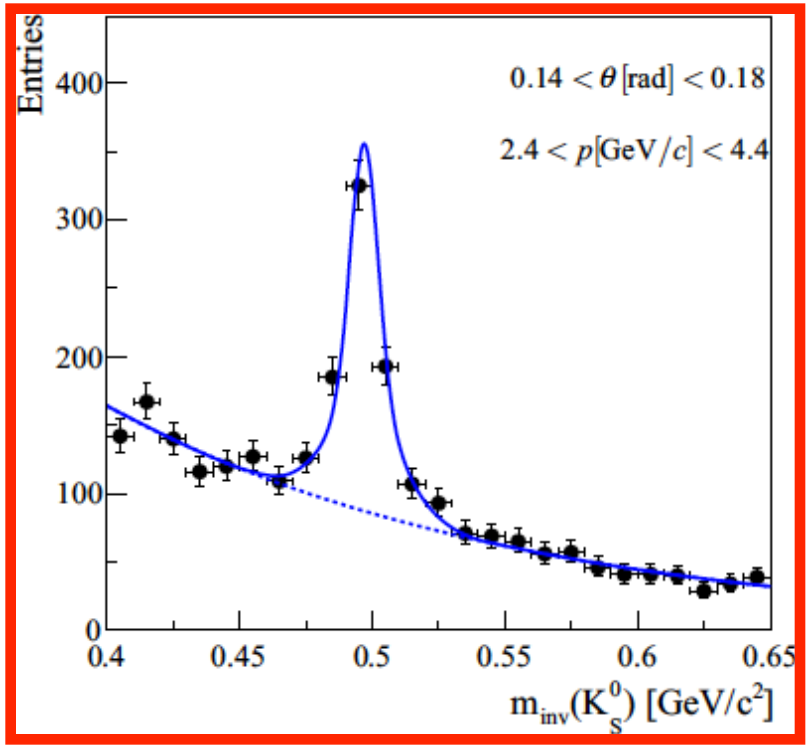


$p + \mathrm{C} \,@\, 30\ \mathrm{GeV}$

Eur. Phys. J. C76 (2016) 84

NA61 acceptance largely covers phase-space where T2K flux is interested in



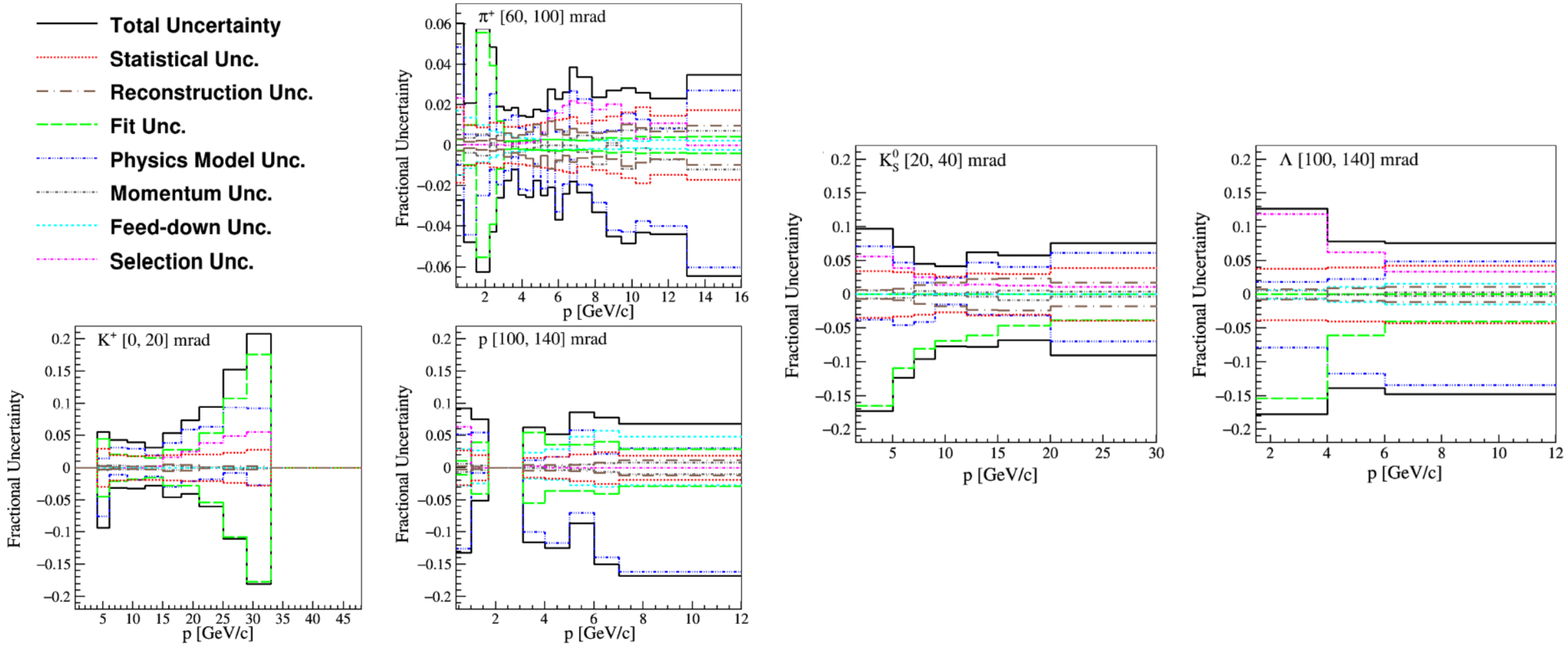


(This shows hadron distribution contributing to the T2K flux, not NA61 data)

Thin Target: Systematics of Spectra Measurements

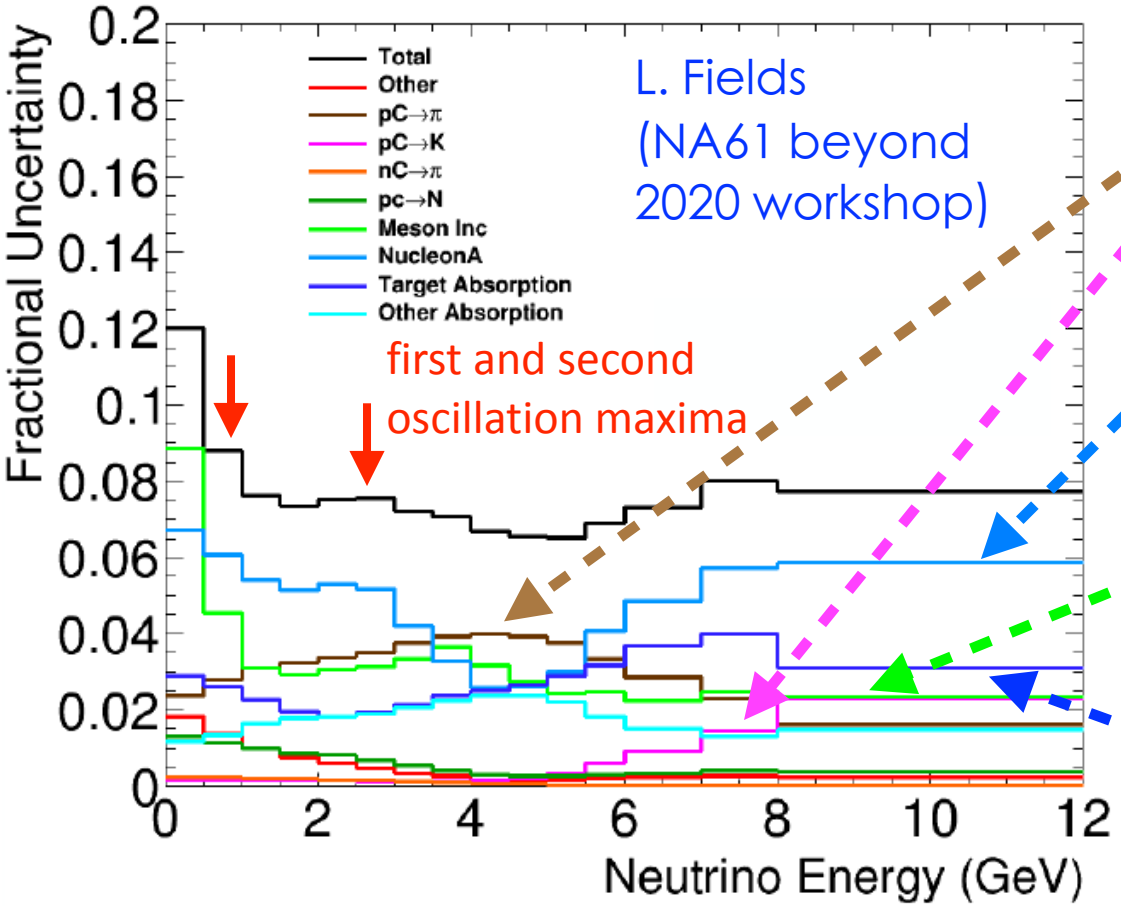
- Measured differential production yields $(\pi^+ + \mathrm{C} \,@\, 60\ \mathrm{GeV})$

  Phys. Rev. D100, 112004 (2019)



Importance of Hadron Production Measurements

- Requirements for the DUNE experiment
  - "Total" systematic uncertainty: below 5% for neutrino oscillation measurements
    —> goal for flux: 2-3% on flux uncertainty for broad range of energies!!



Source of uncertainty

Errors on existing pion and kaon productions on *p*+C data

Nucleon interactions not covered by existing data

Pion and Kaon re-interactions

Total probability of interaction in target

What we need !!

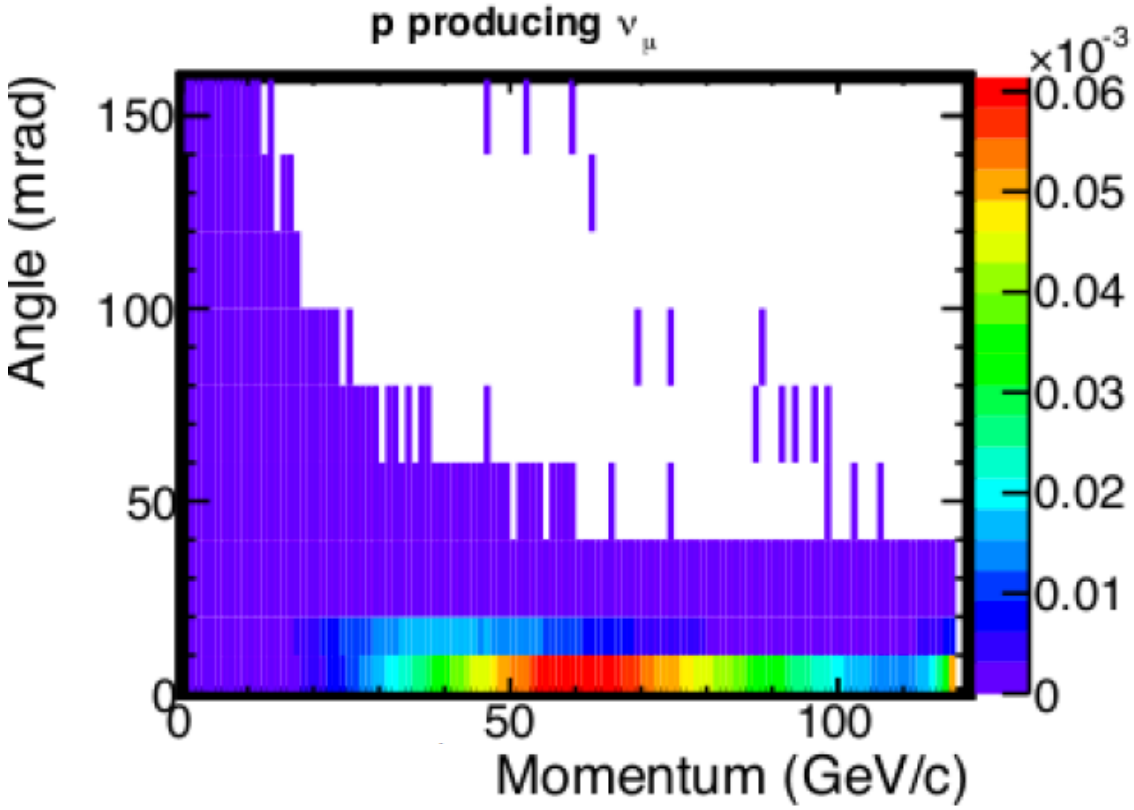
Measurements with larger statistics

New measurements with sufficient large acceptance

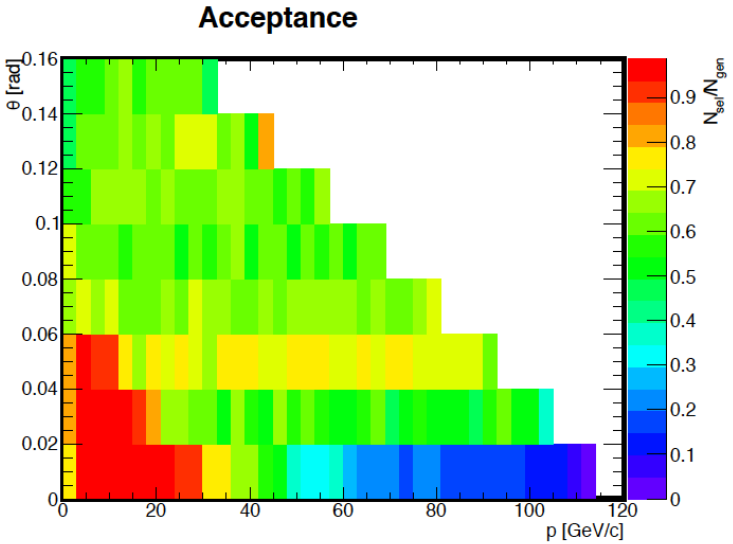
Measurements with π and K beams

Measurements with DUNE replica target

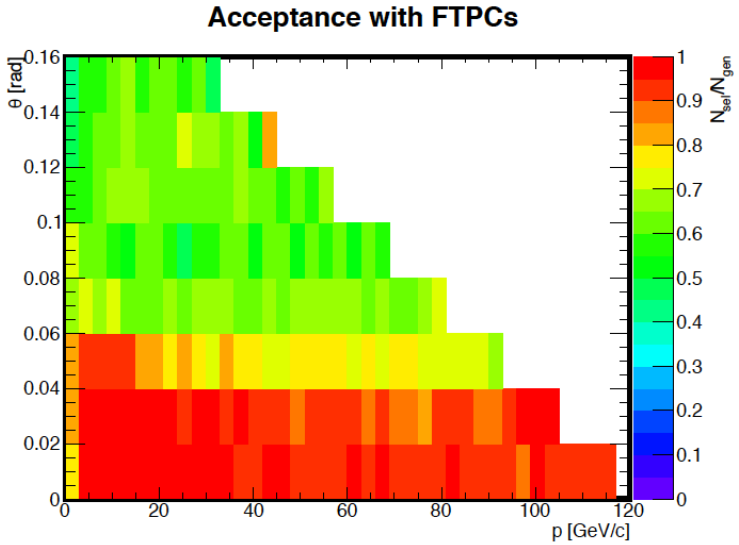
Hardware: Forward TPCs



DUNE with 120 GeV beam
(proton contribution to the neutrino flux)



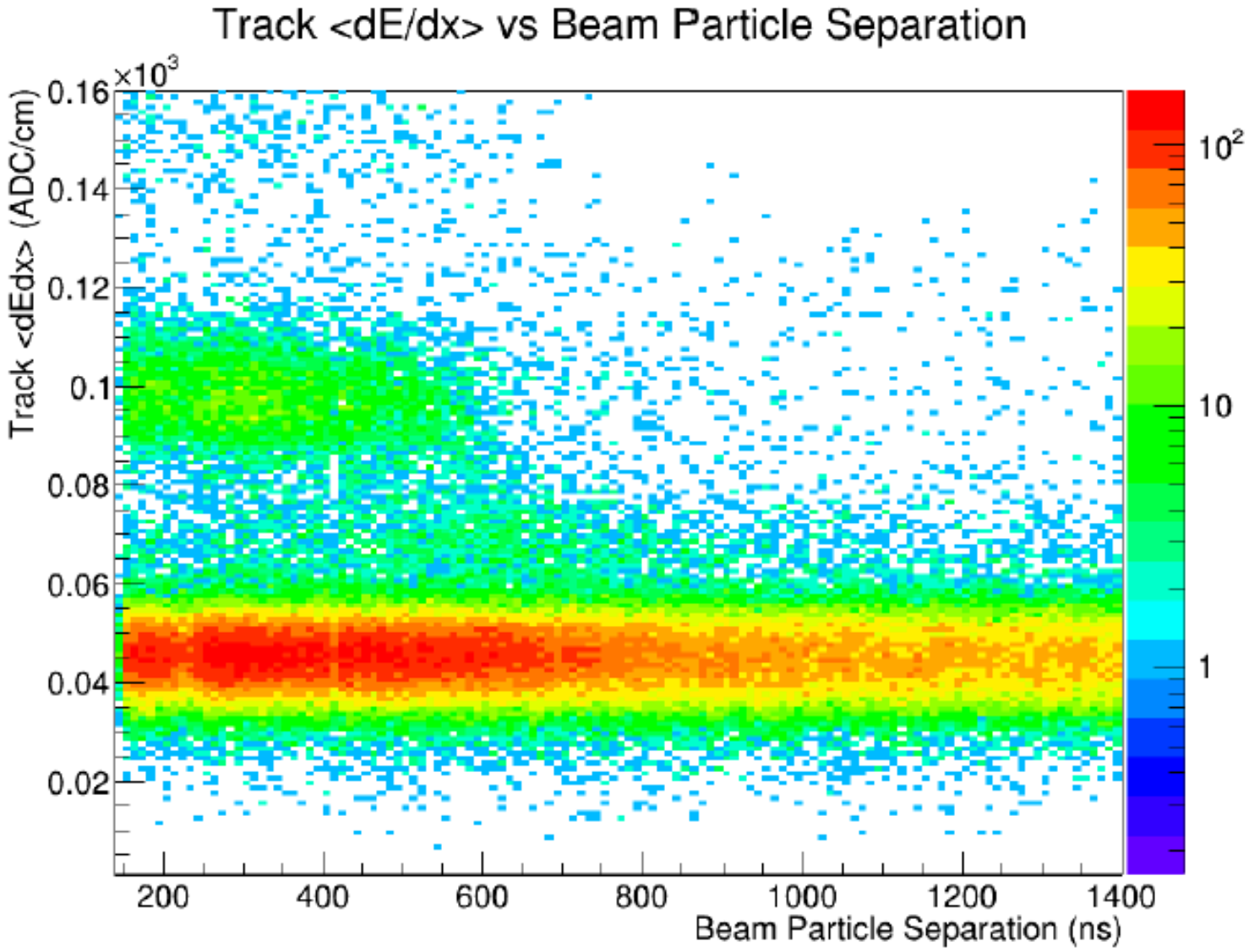
NA61/SHINE acceptance (original)



(with FTPCs)

- Fully cover important phase-space for the LBNF beamline

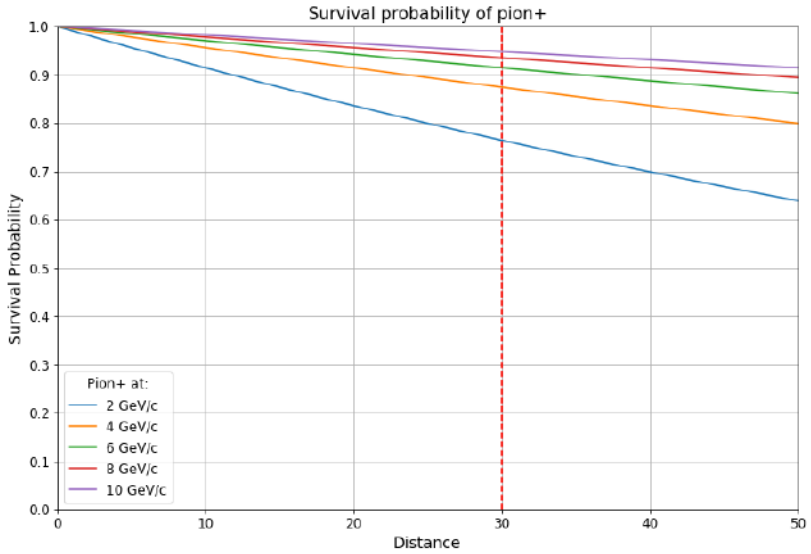
Hardware: Forward TPCs

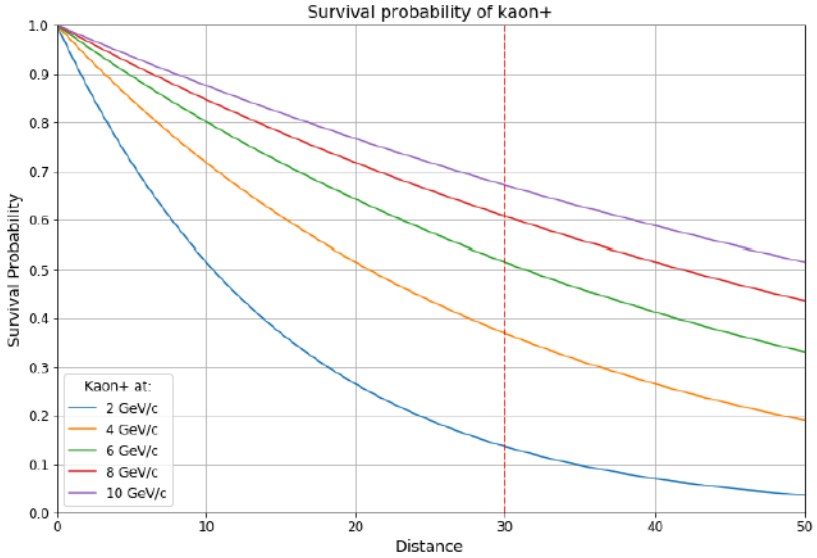


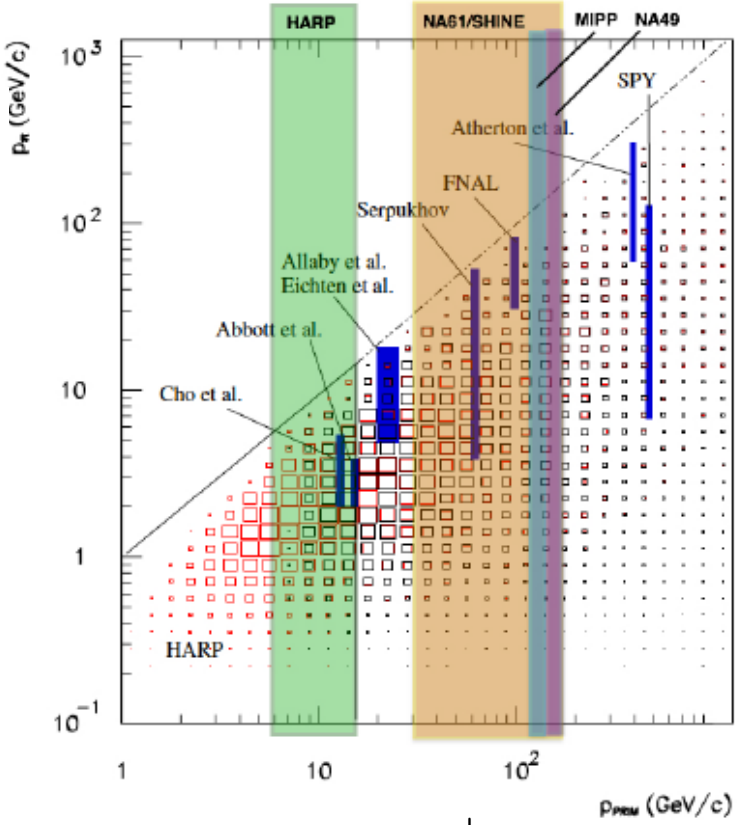
Low Momentum Beamline

- There is a possibility to have a low momentum (< 13 GeV/c) beamline after 2020
- This can be useful for:
  - Low momentum hadron data set which does not exist to constrain neutrino flux
  - Atmospheric neutrino flux studies

G. Barr
(NA61 beyond 2020 workshop)

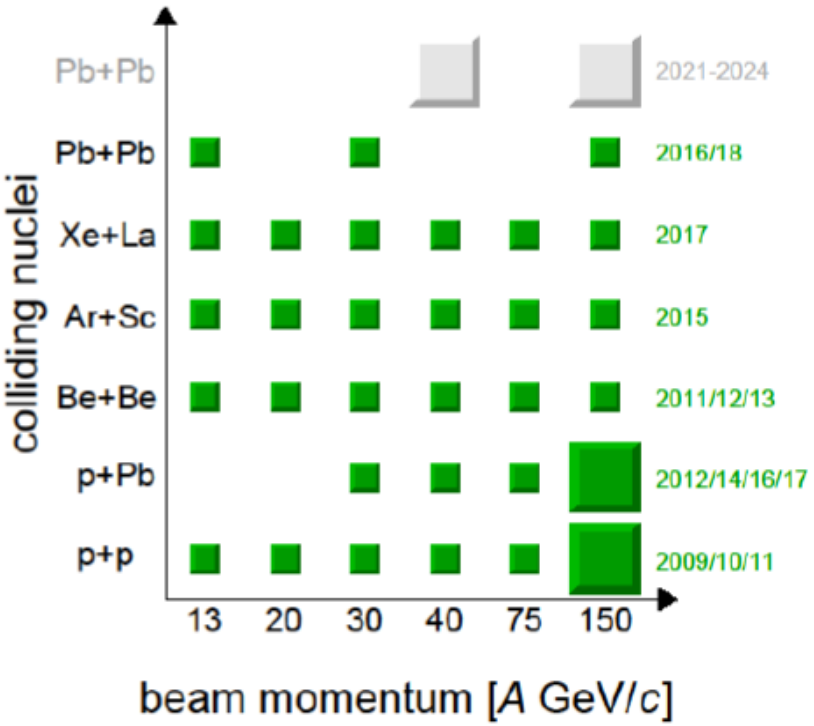


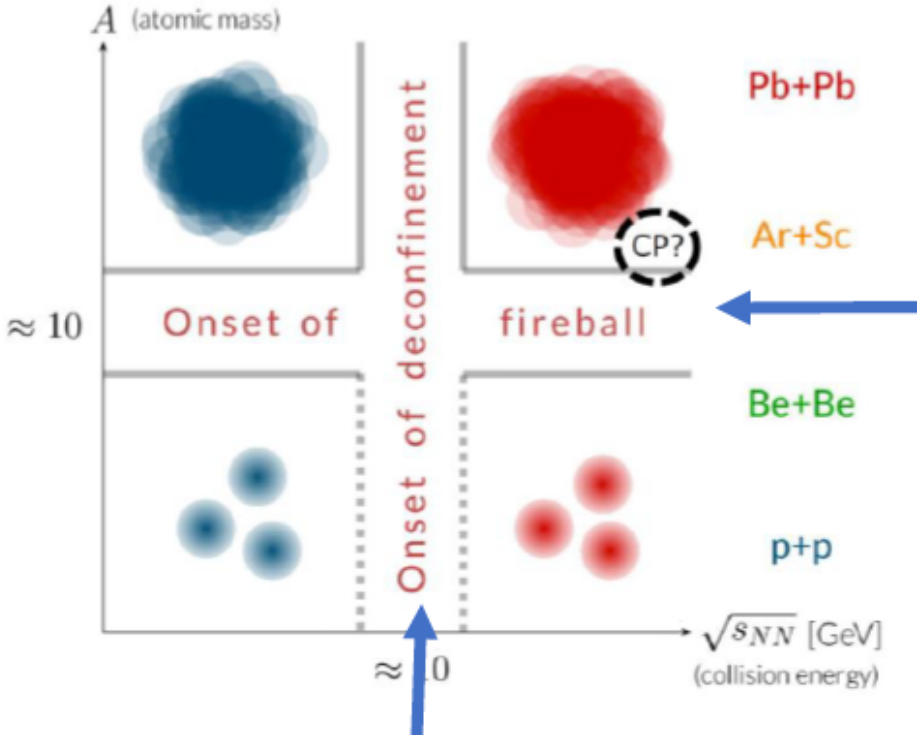


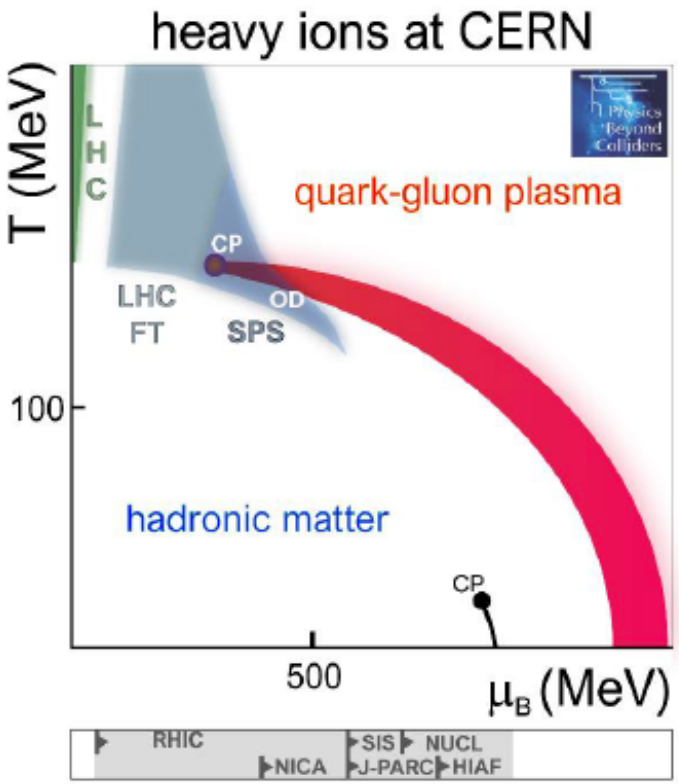


$$p + \mathrm{N} \rightarrow \pi^{\pm} + X$$

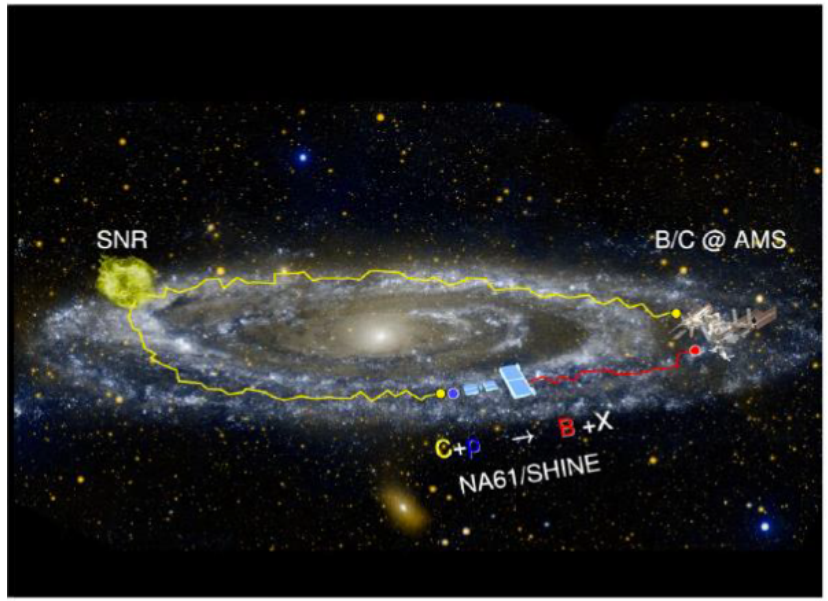
Heavy Ion Physics in NA61/SHINE



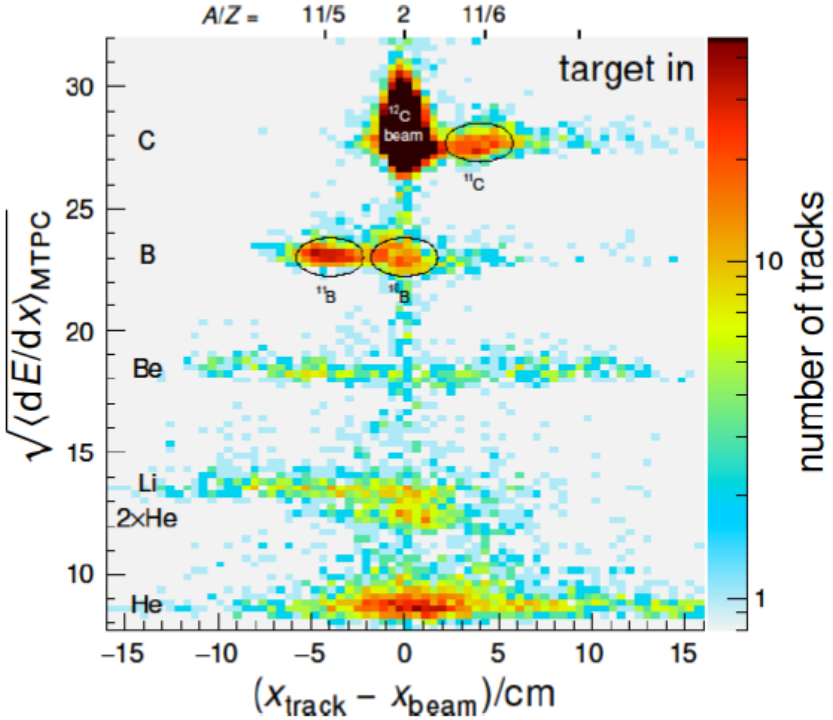




Cosmic Ray Physics in NA61/SHINE



- Primary cosmic rays from supernova remnants
- Secondary cosmic rays from interactions with interstellar matter during propagation e.g.
  $^{12}C + p \xrightarrow{frag.} B + X$
  $^{12}C + p \xrightarrow{frag.} {}^{11}C + p \xrightarrow{decay} B + Y$
- Primary-to-secondary ratios (e.g. B/C) → traversed mass density
- Unstable-to-stable ratios (e.g. $^{10}Be/^{9}Be$) → traversed distance
- Important for the understanding of origin of Galactic cosmic rays and backgrounds for DM searches



Understanding of cosmic ray propagation limited by uncertainties of fragmentation cross sections

NA61/SHINE will significantly reduce the uncertainties (from 20% to 0.5%)