Precise Determination of Neutrino Flux with Hadron Production Measurements

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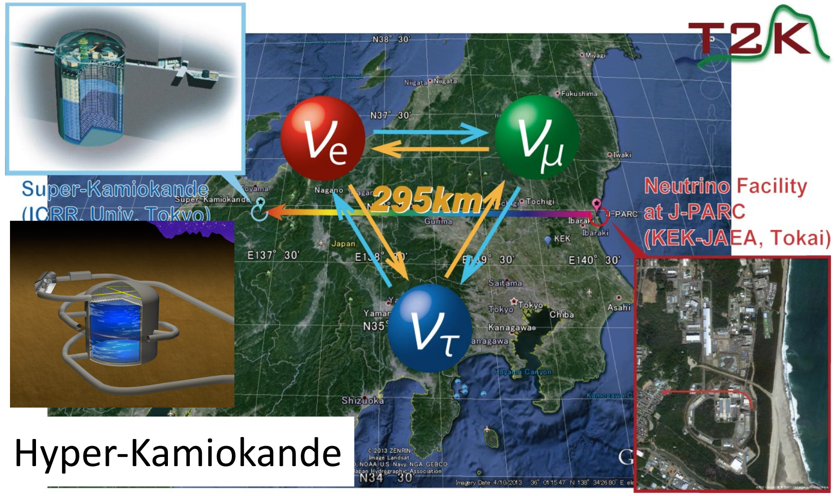
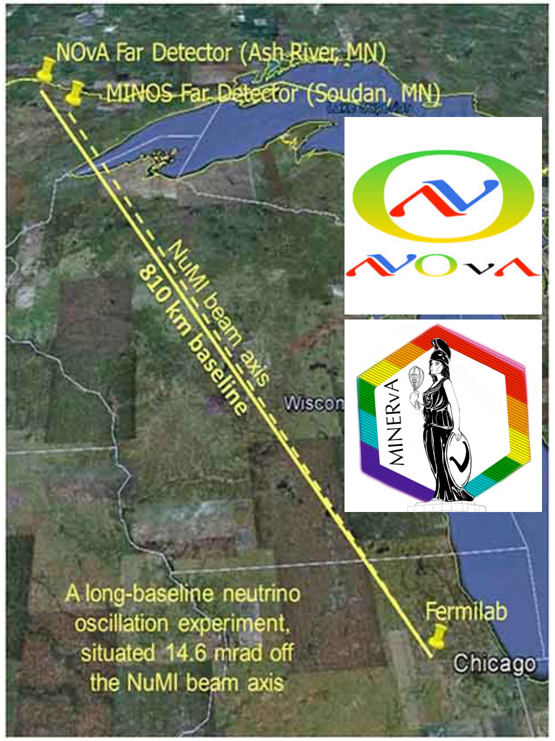
Contents

Focus of This Talk: LBN Beamlines

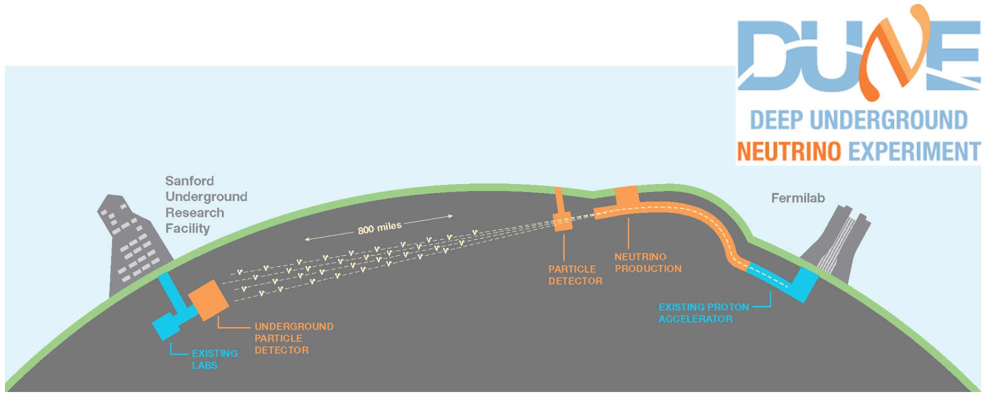
- Current and future long-baseline neutrino beamlines



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

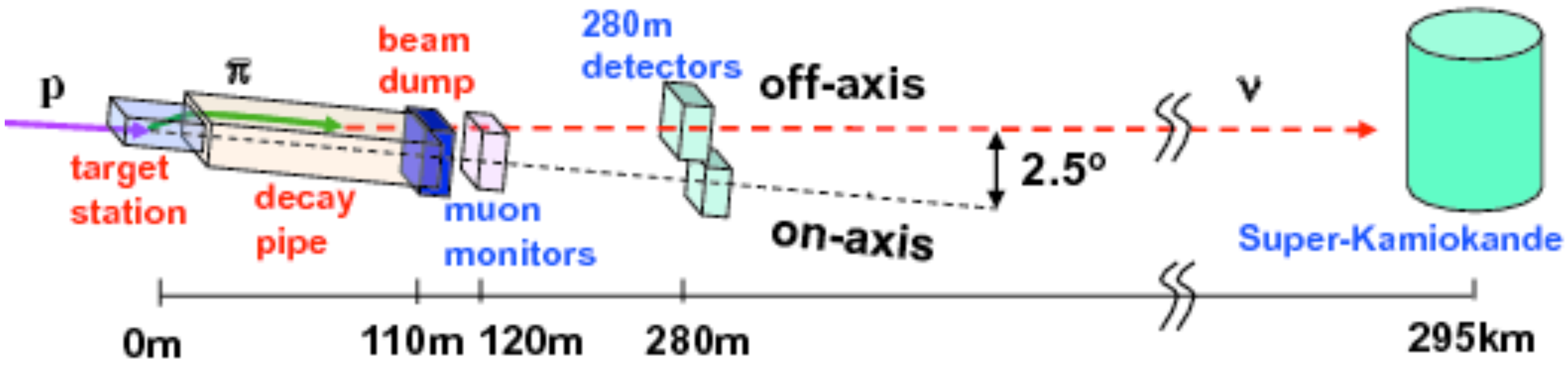


NuMI beamline (120 GeV proton beam)
experiments: NOvA (and MINERvA)



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

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)

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

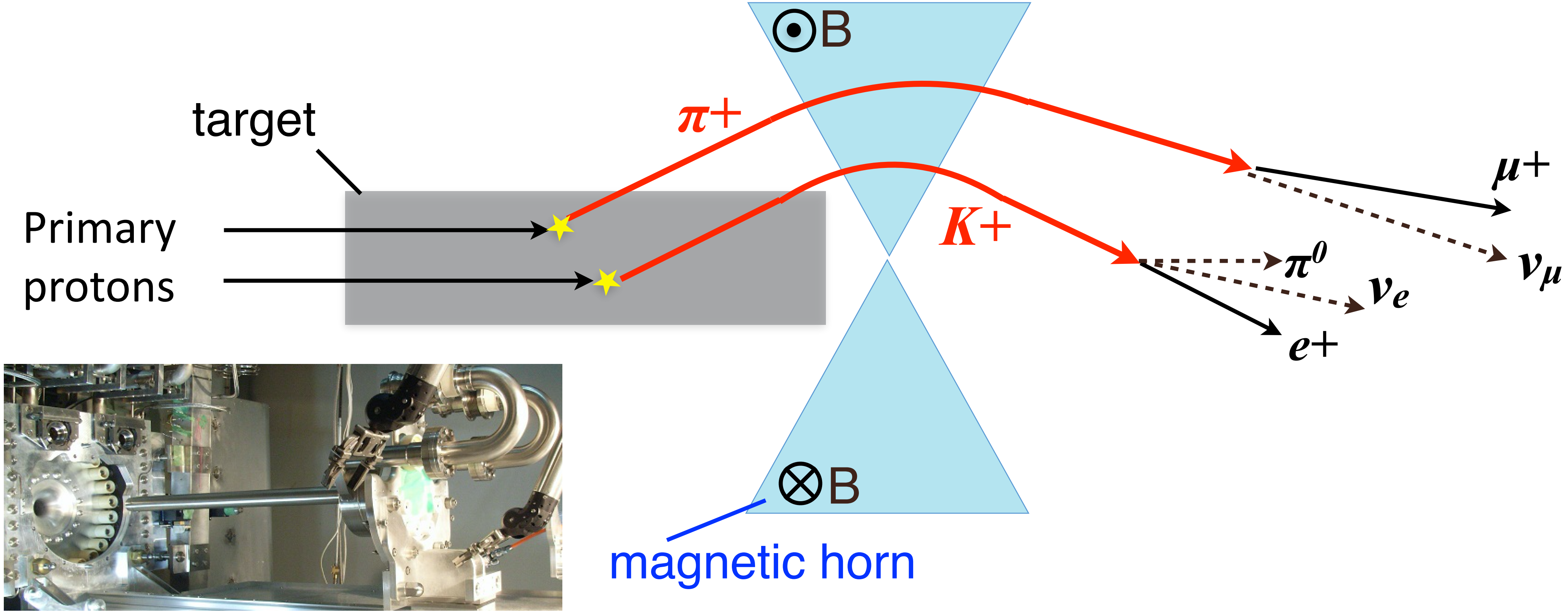
My talk focuses on this part
to precisely know *a priori* neutrino flux

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

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

How to Make a Neutrino Beam

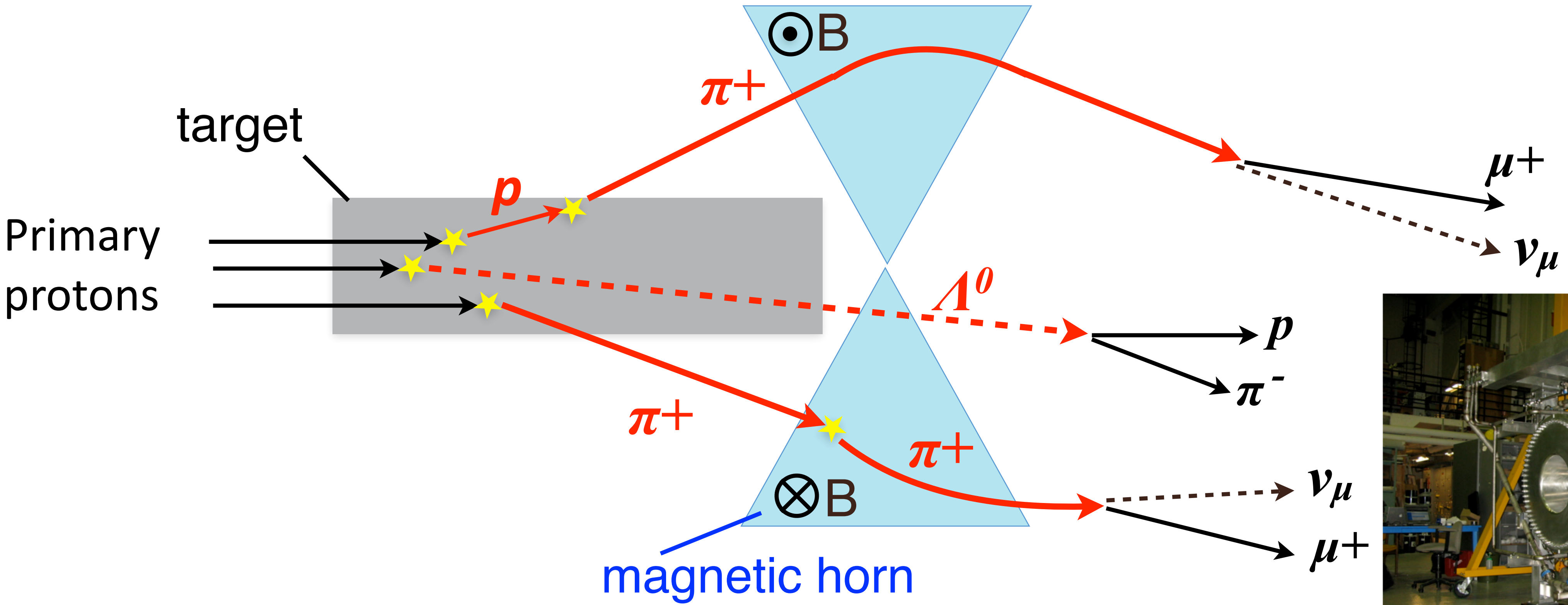


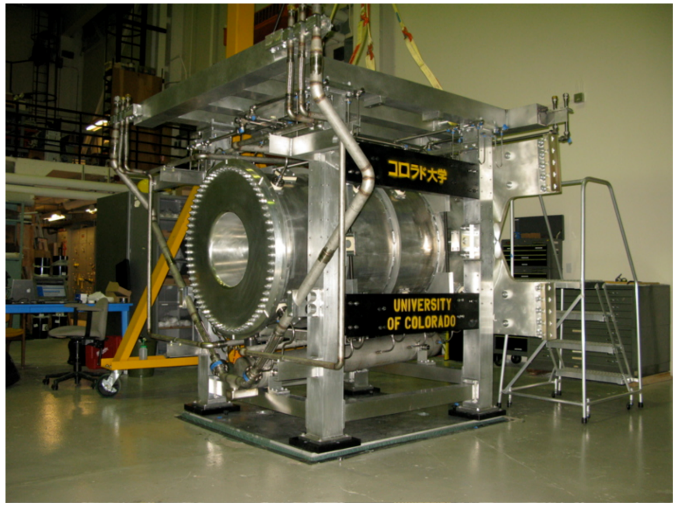
T2K target

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 horn

Hadron production process can be more complex:

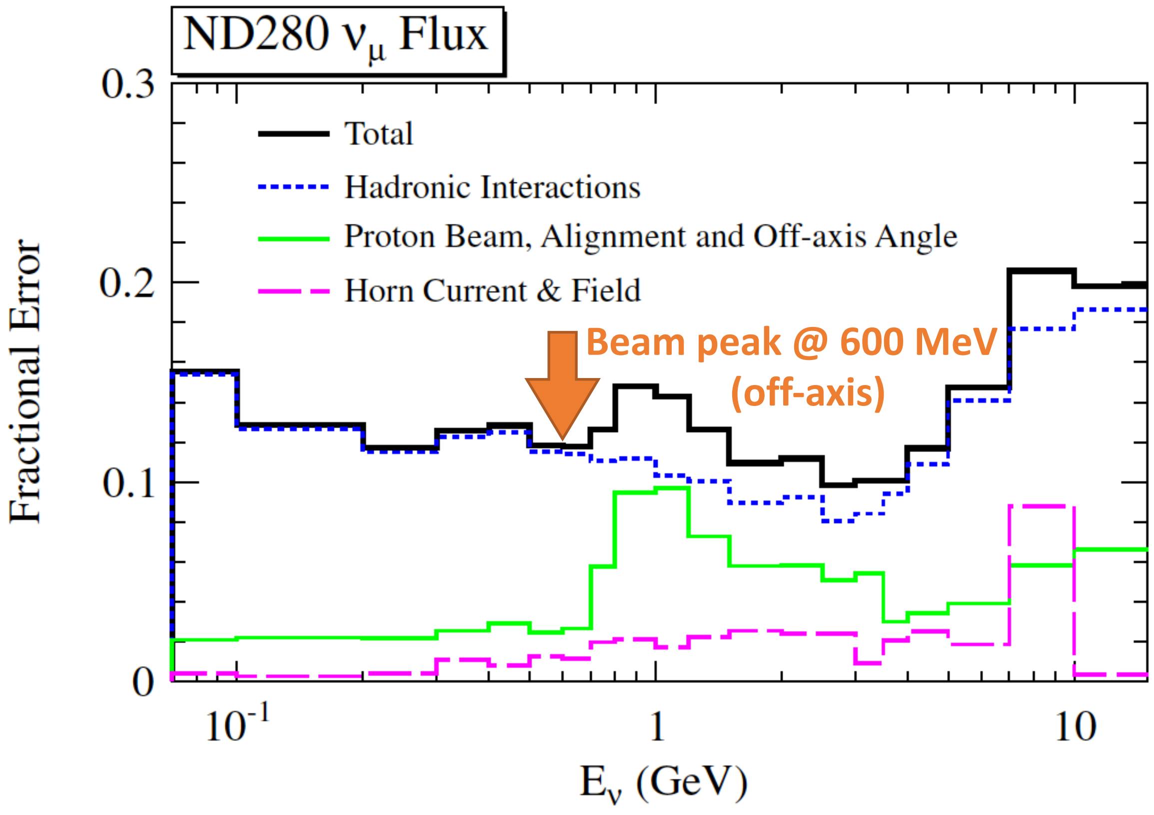
- Secondary interactions in the target (hadrons + C/Be)
- Secondary interactions with horn or beamline materials (hadrons + X)
- Neutral hadron decay (p + C / Be —> V^0 + X)

—>Non-negligible contribution to the neutrino flux

Why Hadron Production Measurements?

Hadron Production is the leading uncertainty source of the flux prediction

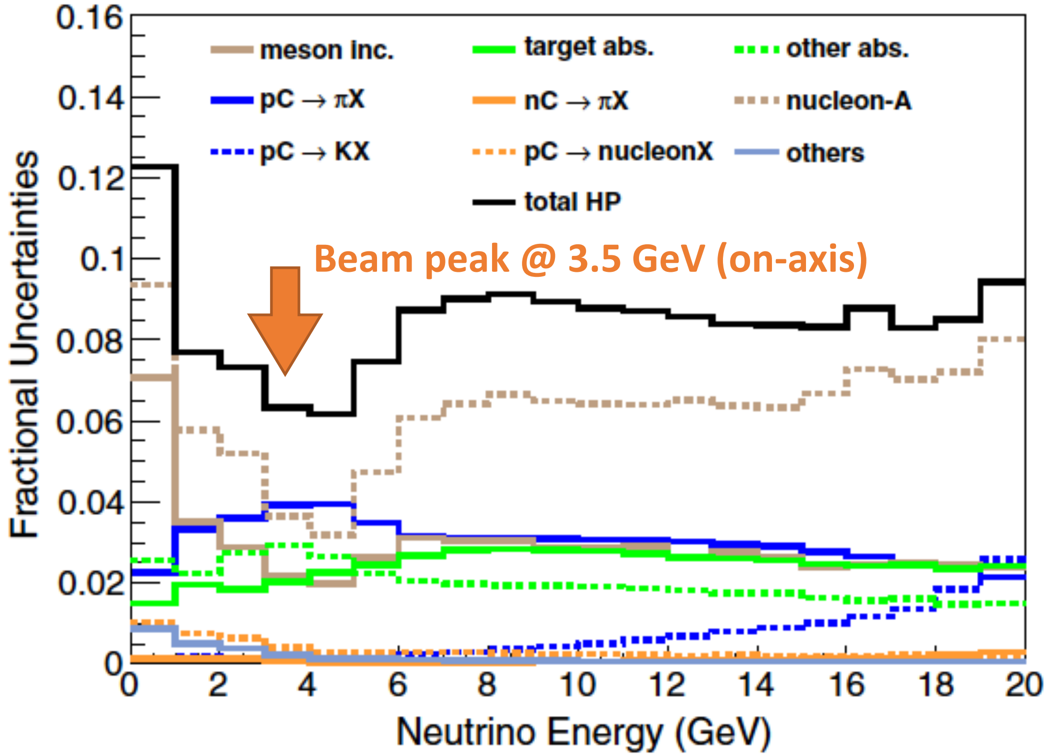
J-PARC beamline (T2K flux)



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)
- Precision neutrino flux prediction is a key for:
  - neutrino oscillation measurements ($\Phi_{ND} \cdot \sigma$, $\Phi_{FD} \cdot \sigma$)
  - various near detector measurements (direct Φ_{ND})

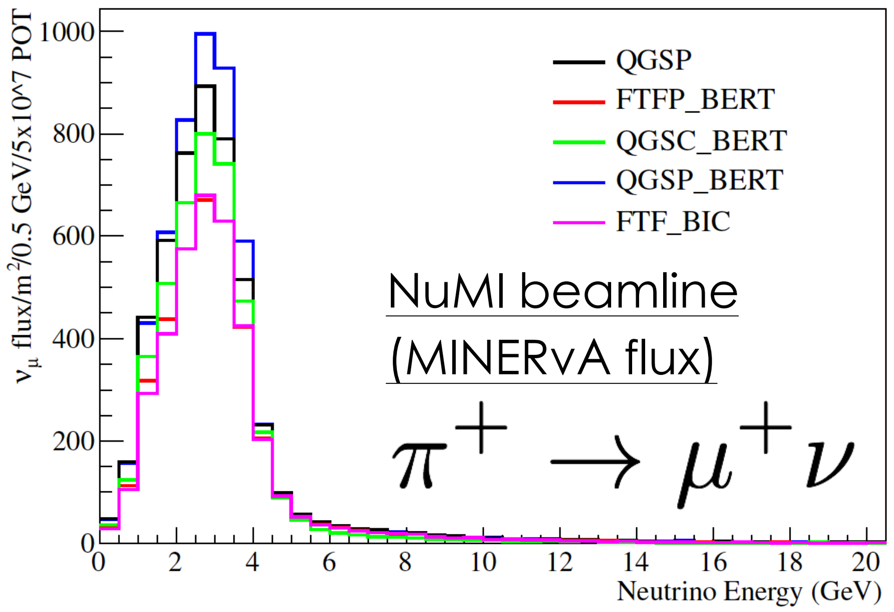
However, hadron production prediction is difficult

e.g. Five interaction models in Geant 4

—> variations neutrino flux prediction

~40% at the focusing peak

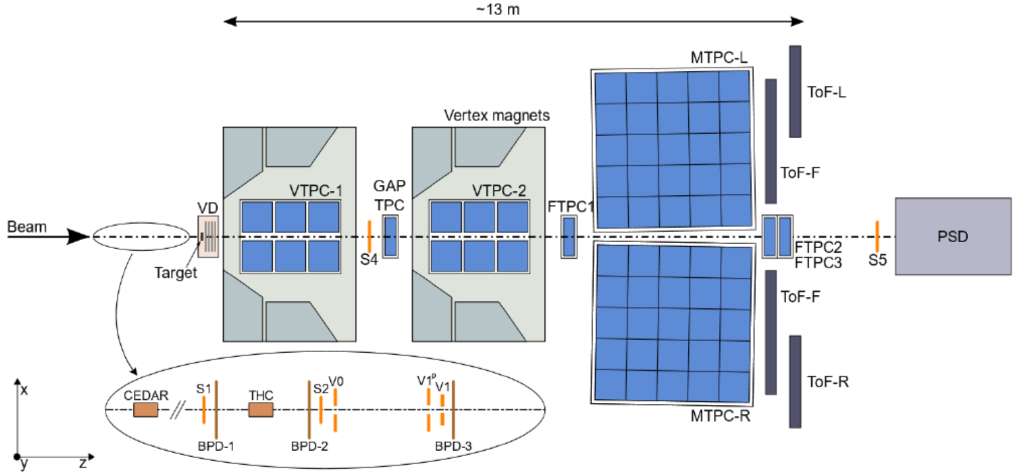
Need to constrain neutrino flux uncertainty coming from hadron production



Leonidas Aliaga (Ph.D Thesis, 2016)

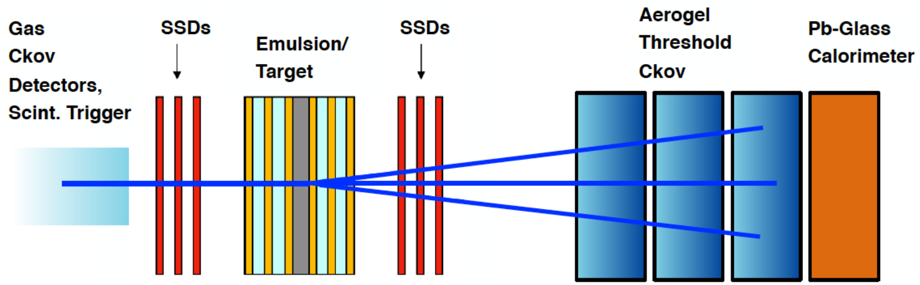
Hadron Production Experiments

NA61/SHINE (about 150 collaborators)



- CERN SPS North Area
  - Hadron beam: 13-350 GeV/c
- Large acceptance
  - TPCs as the main tracking detector
  - Momentum measurement
  - Particle ID with TPC and ToF
- Thin and Replica target measurements
- Completed approved data taking
  - Program extension for 2021-2024

EMPHATIC (about 20 collaborators)



- Fermilab Test Beam Facility (FTBF)
  - Hadron beam: 0.2-120 GeV/c
- Forward precision measurement
  - Silicon and emulsion detectors as the tracking detectors
  - No momentum measurement yet
- Thin target measurements
- Completed test data taking in 2018
  - Upgrade is under consideration

Former Experiments

- MIPP
  - Fermilab
- HARP
  - CERN PS
- NA56/SPY
  - CERN SPS

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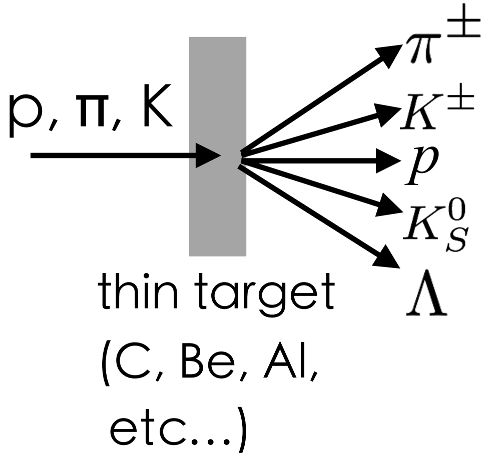
Thin Target Measurements

1.5 cm thin graphite target

Strategy of Thin Target Measurements

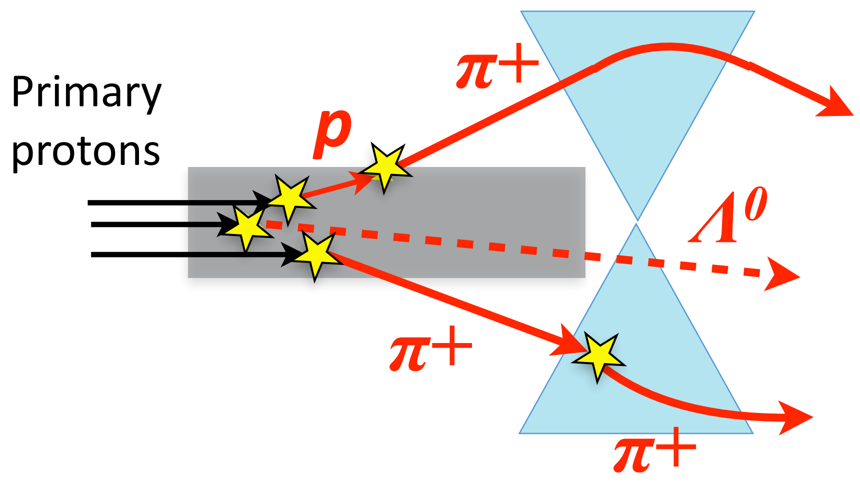


- Thin target: a few % of λ nuclear targets to study single interactions
  - Measurement of total cross sections

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

  - Measurement of differential cross sections $d^2\sigma/dp\,d\theta$

Thin target measurements are used to re-weight hadron interaction model predictions



Correction is applied for each interaction (★)

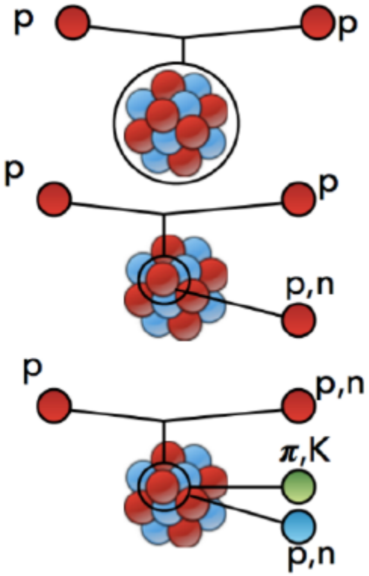
- Interaction rate tuning: $W = \frac{\sigma_{\mathrm{data}}}{\sigma_{\mathrm{MC}}} e^{-x(\sigma_{\mathrm{data}} - \sigma_{\mathrm{MC}})\rho}$

(x: travel distance, ρ: target material density)

- Differential production tuning: $W(p,\theta) = \frac{N(p,\theta)_{\mathrm{Data}}}{N(p,\theta)_{\mathrm{MC}}}$

Thin Target: Total Cross section

- Not all experiments use same definition for total 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}

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

Use this definition through the talk
(T2K uses this definition)

- NuMI flux tuning definition: $\sigma_{\text{inel}} = \sigma_{\text{total}} - \sigma_{\text{el}} - \sigma_{\text{qe}}$ —> σ_{prod} in our definition

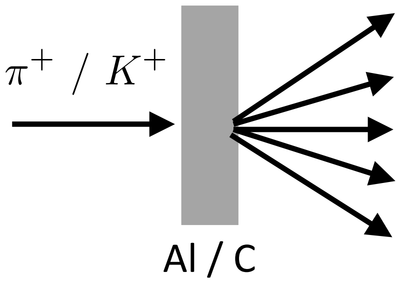
  $\sigma_{\text{absorption}} = \sigma_{\text{total}} - \sigma_{\text{el}}$ —> σ_{inel} in our definition

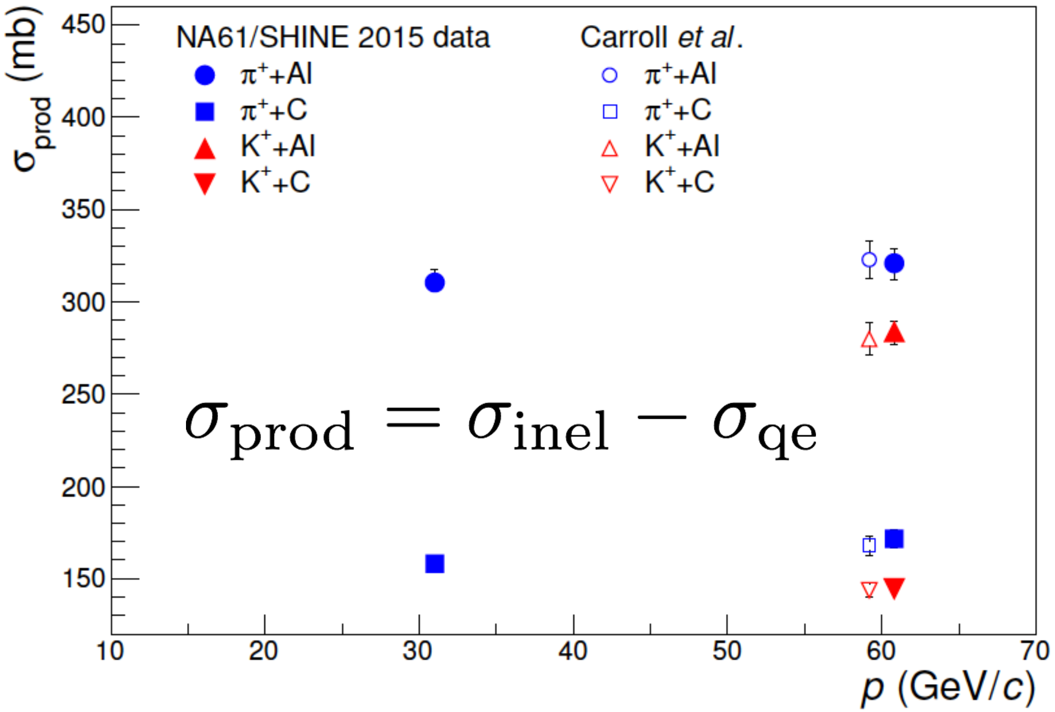
- Earlier experiments: mixed up inelastic and production cross sections

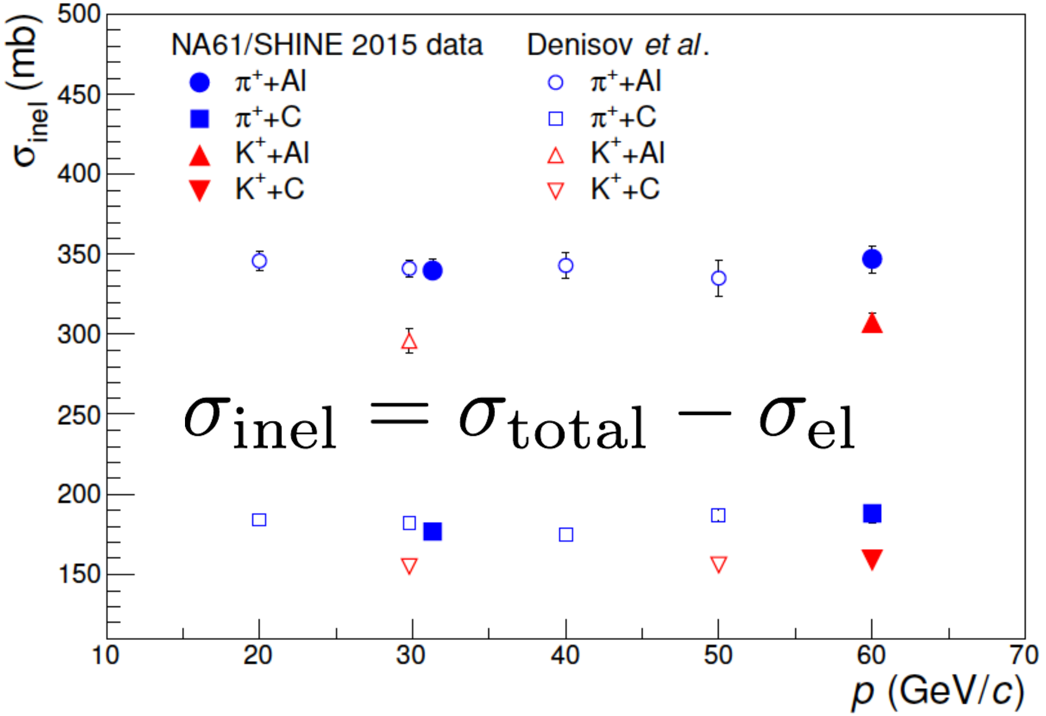
  e.g. Denisov, et. al (1973): $\sigma_{\text{absorption}} = \sigma_{\text{total}} - \sigma_{\text{el}}$ —> σ_{inel} in our definition

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

NA61/SHINE: Total Cross section (π^+, K^+)







Main objective:
Fermilab beamlines

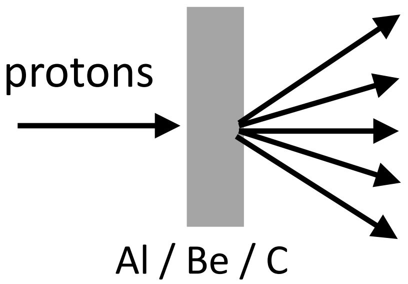
NA61/SHINE: Phys. Rev. D98, No.5 052001 (2018)

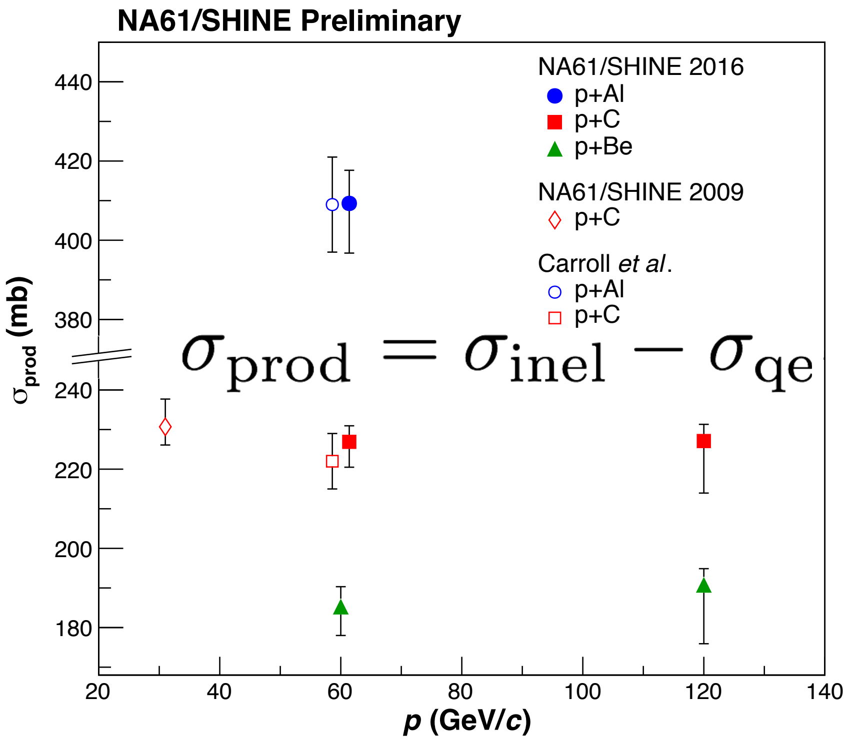
- Precision of new measurements: 2~3%

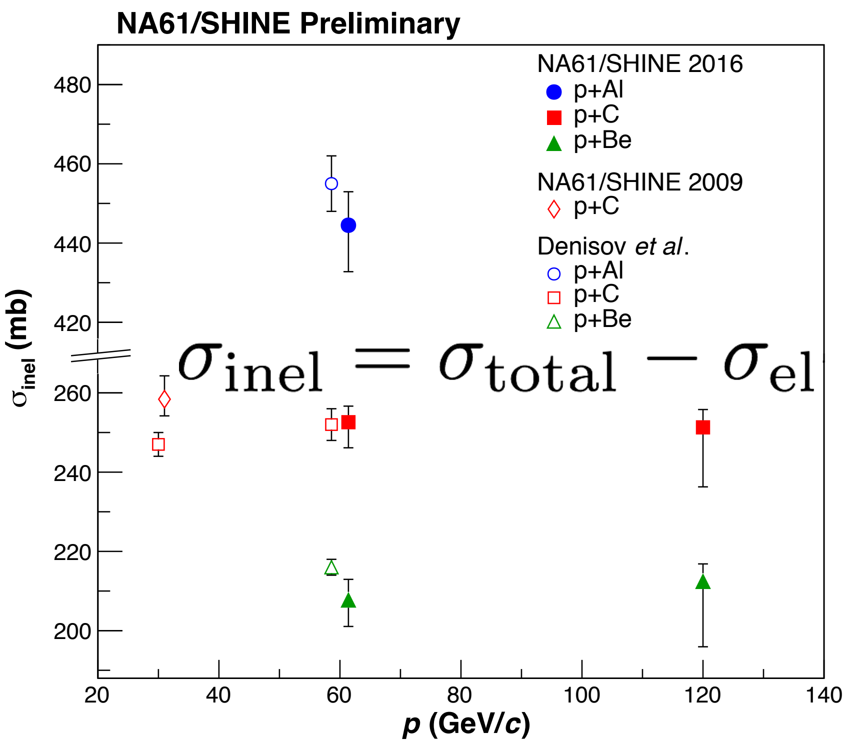
—> NuMI simulation assumes an uncertainty of 5% for pion reinteractions and 10-30% for kaon reinteractions

—> Greatly reduce the uncertainty, especially for kaon interactions

NA61/SHINE: Total Cross section (*protons*)







Main objective:
J-PARC beamline (30 GeV)
Fermilab beamlines (all)

NA61/SHINE: Paper under preparation

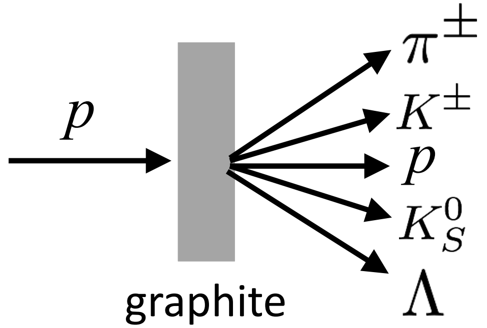
Brand new results!!

- Precision of measurements: 2-3% (stat. + syst.), ~1% (el model), 2-8% (qe, inel model)

—> Improved precision for 60 GeV protons, first measurement for 120 GeV protons

—> Future measurement to reduce model uncertainty is desirable
(one of the EMPHATIC's physics goal)

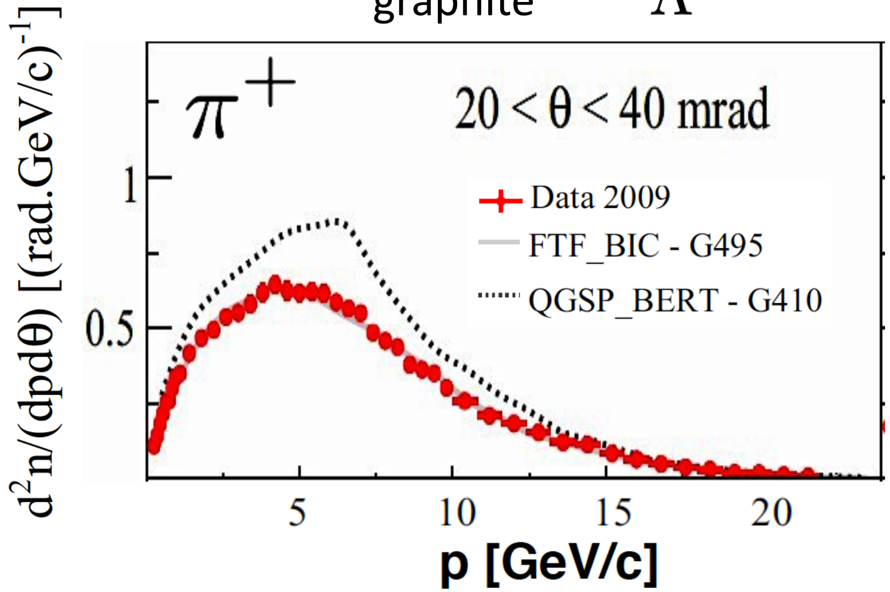
NA61/SHINE: Differential Cross section (*protons*)



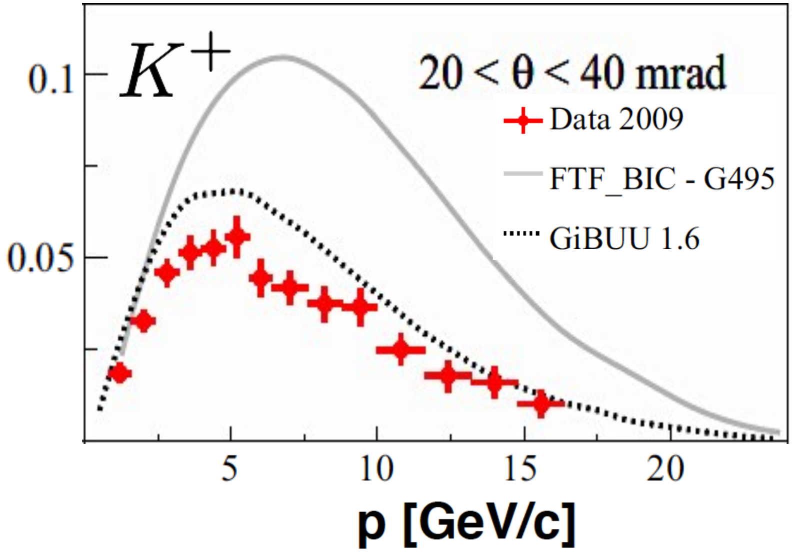
$p + \mathrm{C}\ @\ 30\ \mathrm{GeV}$

Main objective:
J-PARC beamline (30 GeV)

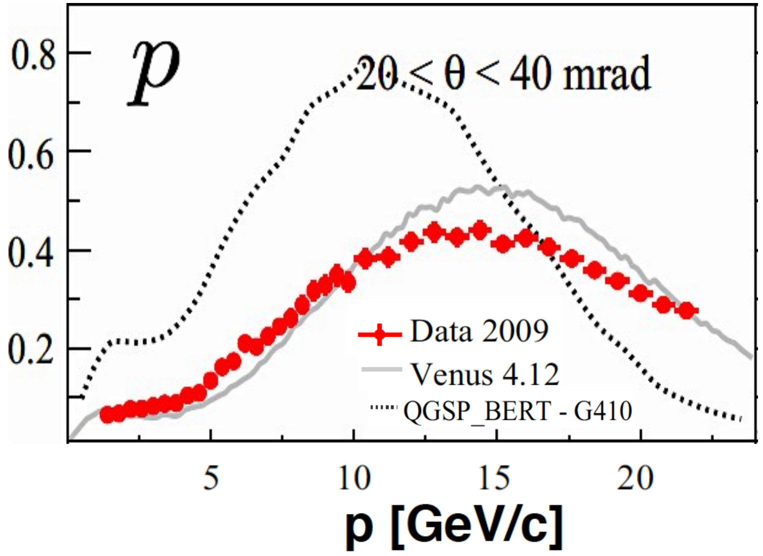
NA61/SHINE: Eur. Phys. J. C76 (2016) 84



(11 θ-bins for 0 < θ < 420 mrad)



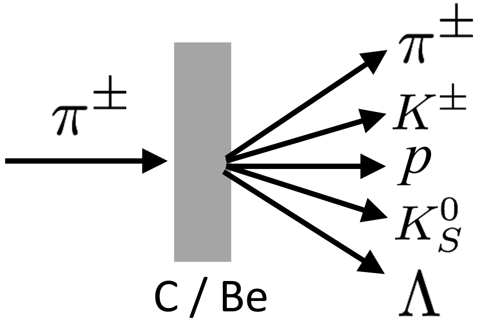
(9 θ-bins for 0 < θ < 360 mrad)



(10 θ-bins for 0 < θ < 360 mrad)

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

NA61/SHINE: Differential Cross section (π^+)

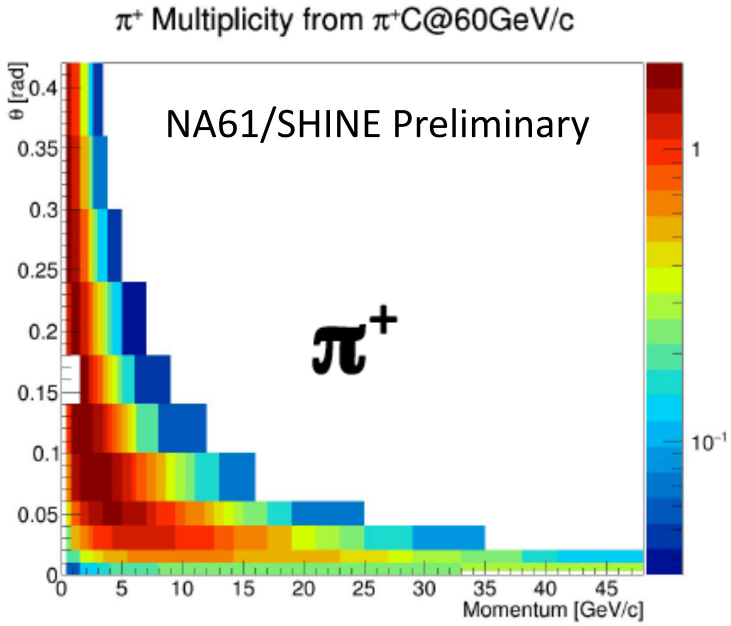


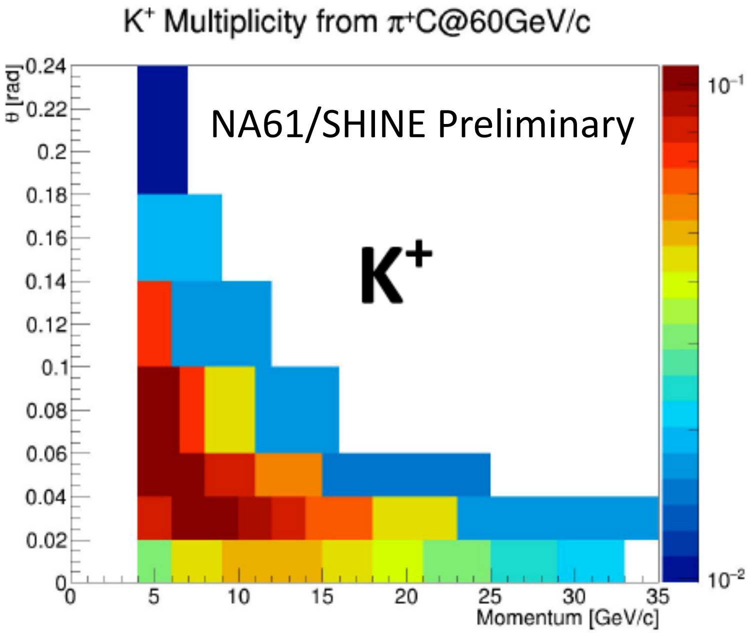
$$\pi^+ + \mathrm{C/Be} @ 60\,\mathrm{GeV}$$

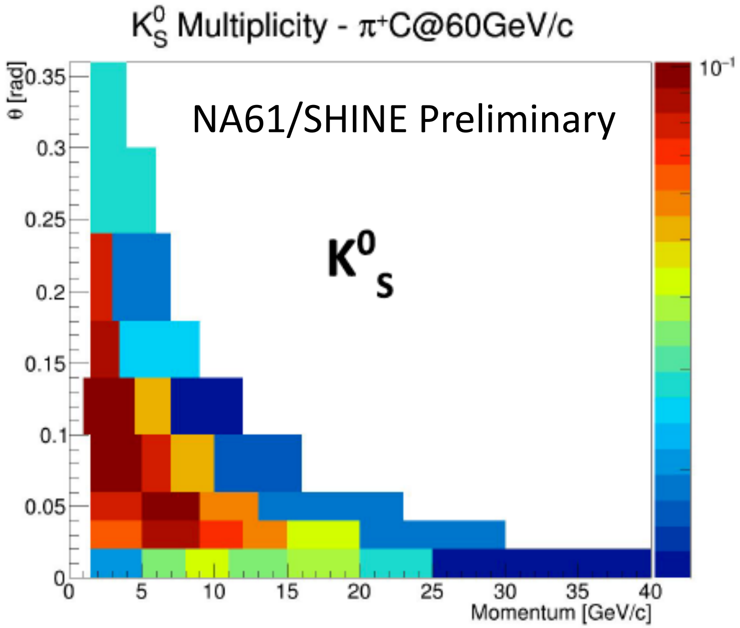
Main objective:
Fermilab beamlines

NA61/SHINE: paper in preparation

- Multiplicity (particles produced per production interaction) is shown

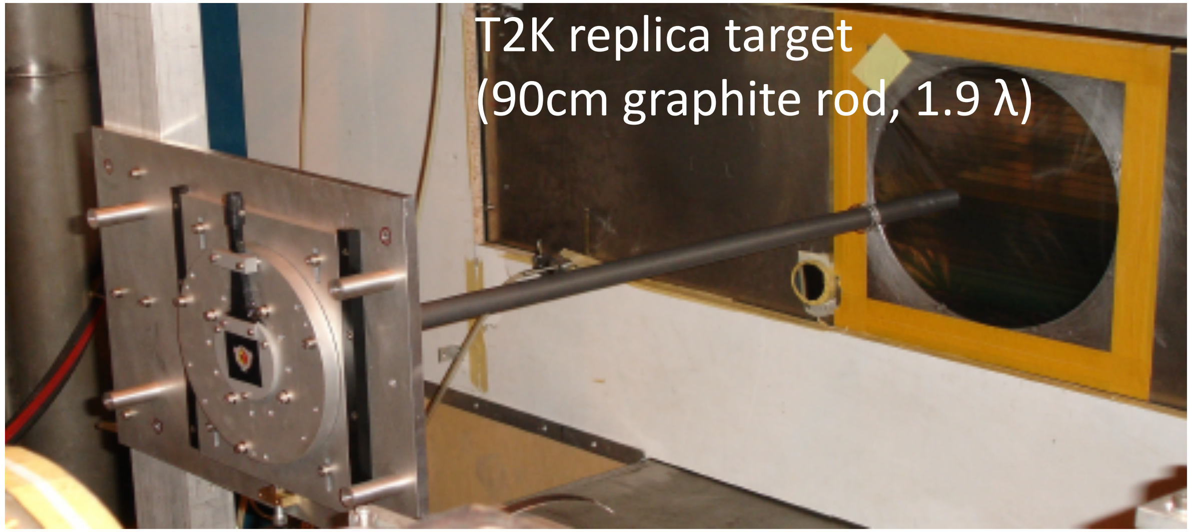


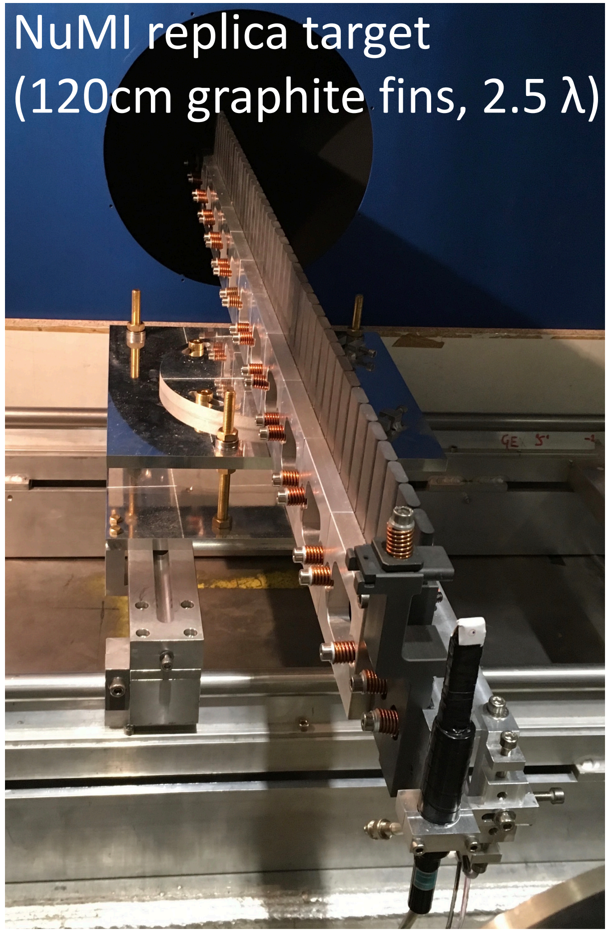




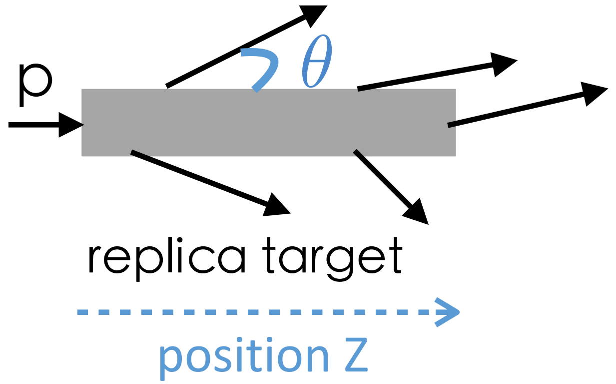
Measured negative pions and kaons, protons, and V^0 particles (Λ , $\bar{\Lambda}$) as well

Replica (Thick) Target Measurements





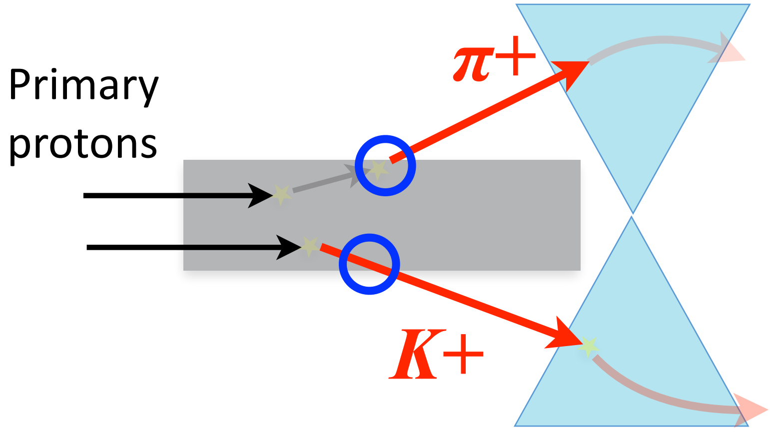
Strategy of Replica Target Measurements



- Replica (thick) target: T2K (90 cm graphite), NuMI (120 cm graphite)
  - Measurement of hadron production yields $d^3n/dp\,d\theta\,dz$
  - Measurement of beam survival probability $P_{\mathrm{survival}} = e^{-Ln\sigma_{\mathrm{prod}}}$

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

Replica target measurements are used to re-weight hadron yield predictions

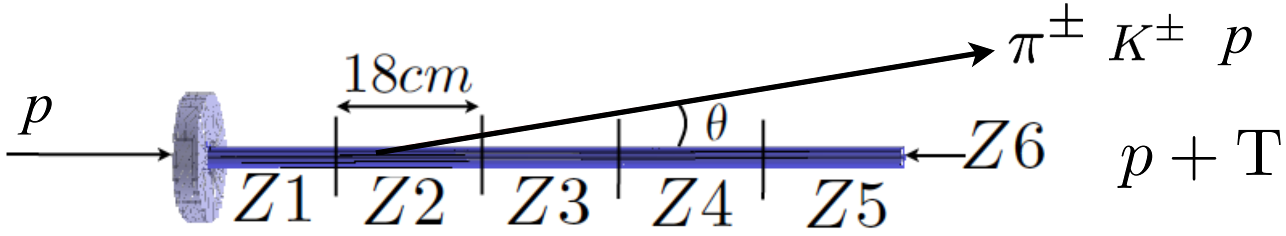


Correction is applied to each exiting point (○)

- Differential production tuning: $W(p,\theta,z) = \dfrac{N(p,\theta,z)_{\mathrm{Data}}}{N(p,\theta,z)_{\mathrm{MC}}}$

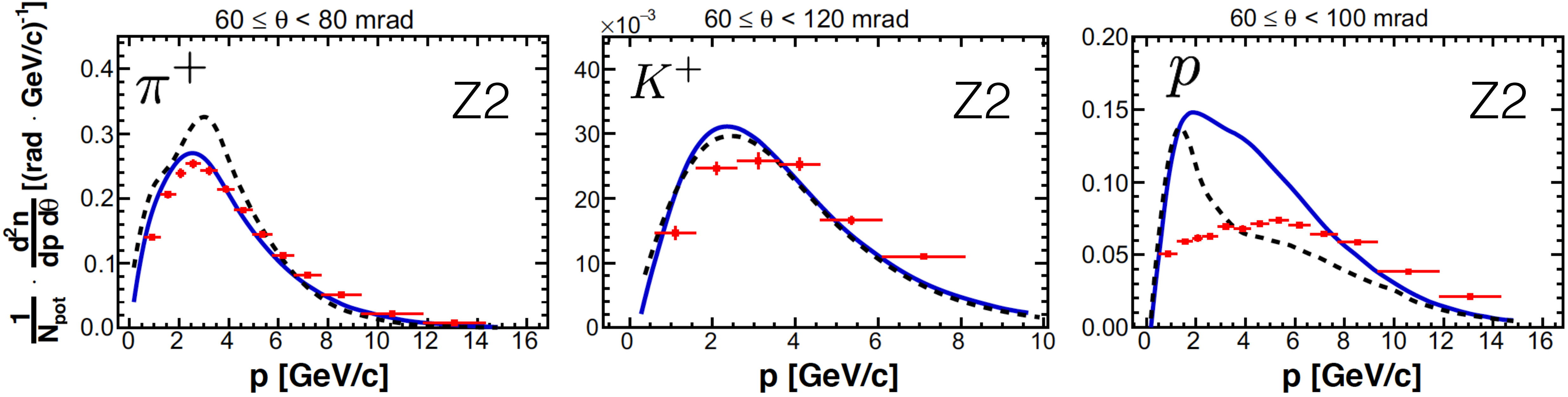
In addition, measurement of beam survival probability will be used to study beam interaction rate in target
—> This will be important to understand thin vs replica based tuning discrepancy (discussed later)

NA61/SHINE: T2K Replica Target



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

NA61/SHINE: Eur. Phys. J. C79, no.2 100 (2019)



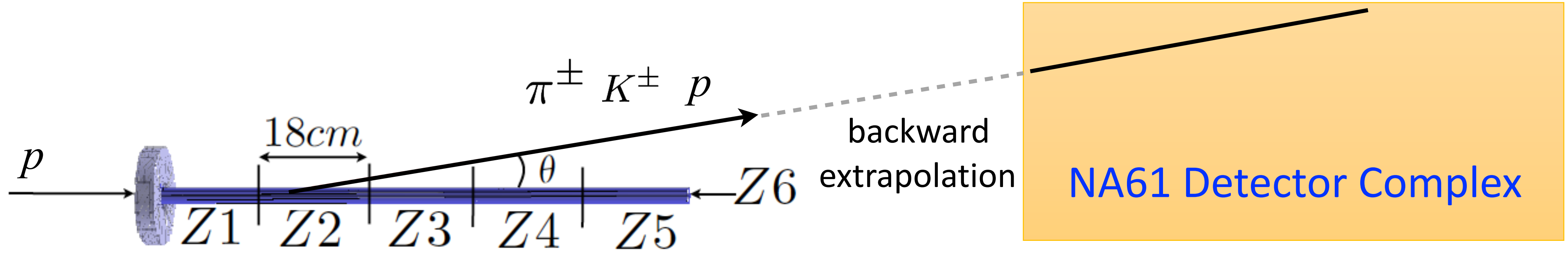
(15 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
10 θ-bins for 0 < θ < 300 mrad (Z6))

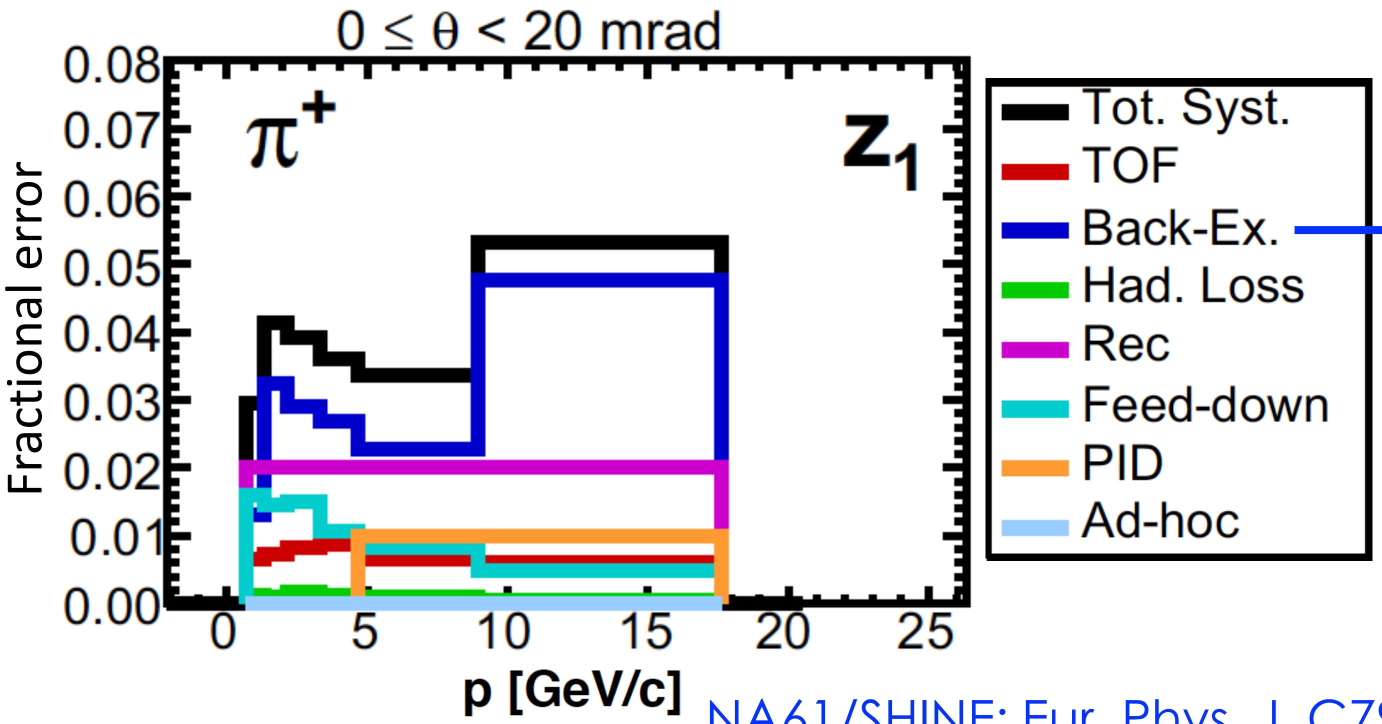
(4 θ-bins for 0 < θ < 280 mrad (Z1-Z5)
2 θ-bins for 0 < θ < 120 mrad (Z6))

(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

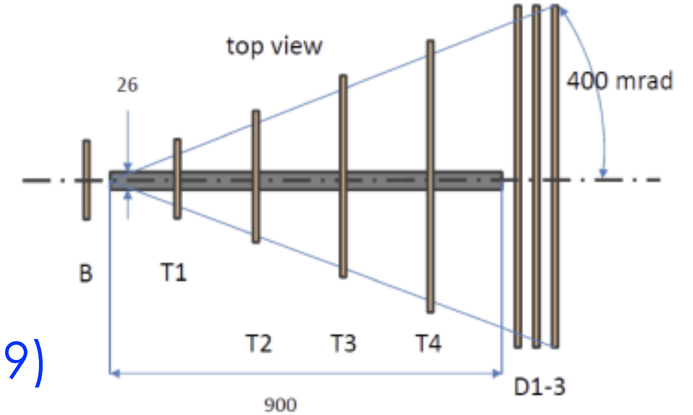
NA61/SHINE: T2K Replica Target (Systematic)





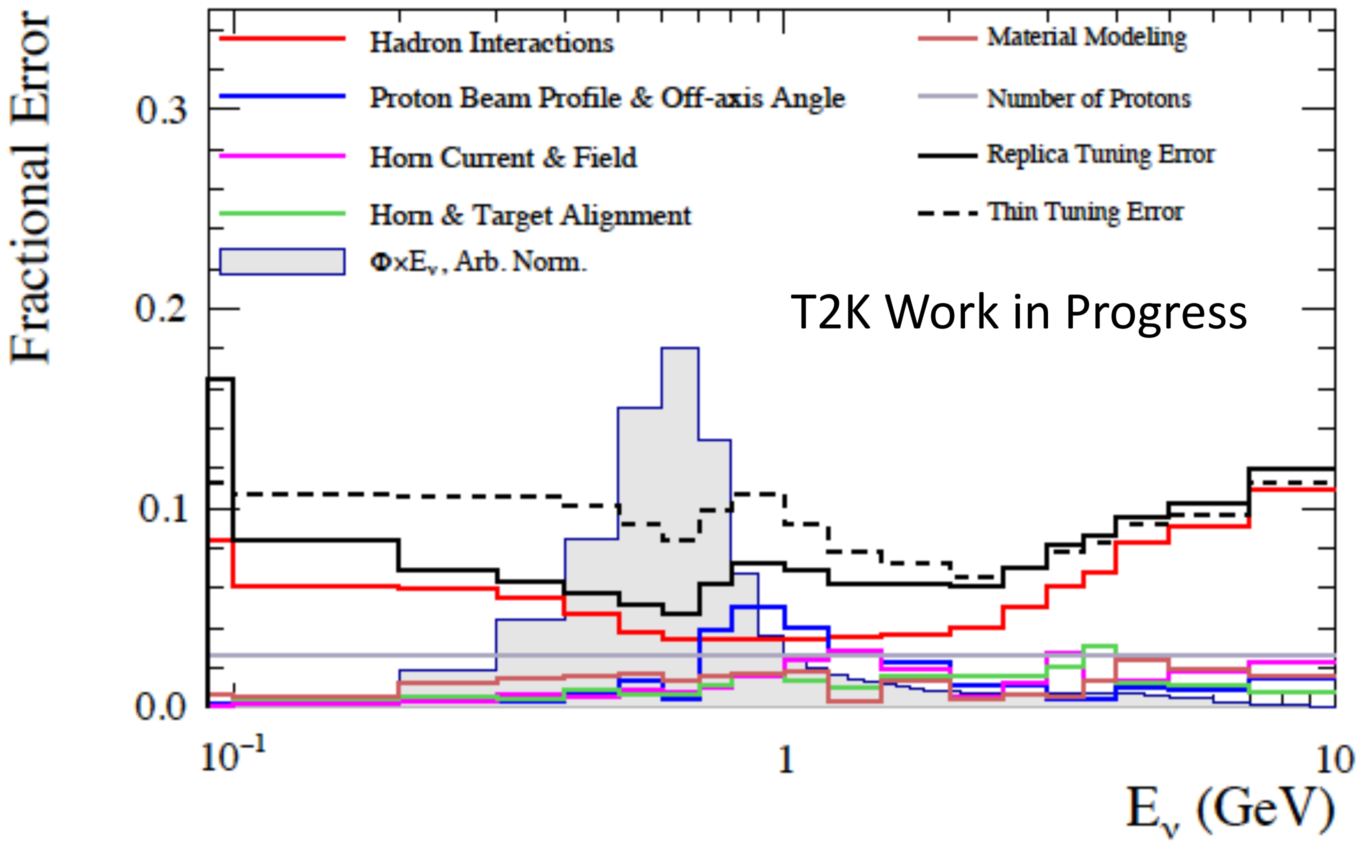
- What was limitation of measurements?

Track position uncertainty on the target surface.
—> Having additional tracker surrounding the target to help track extrapolation
—> Future detector upgrade is necessary



NA61/SHINE: Eur. Phys. J. C79, no.2 100 (2019)

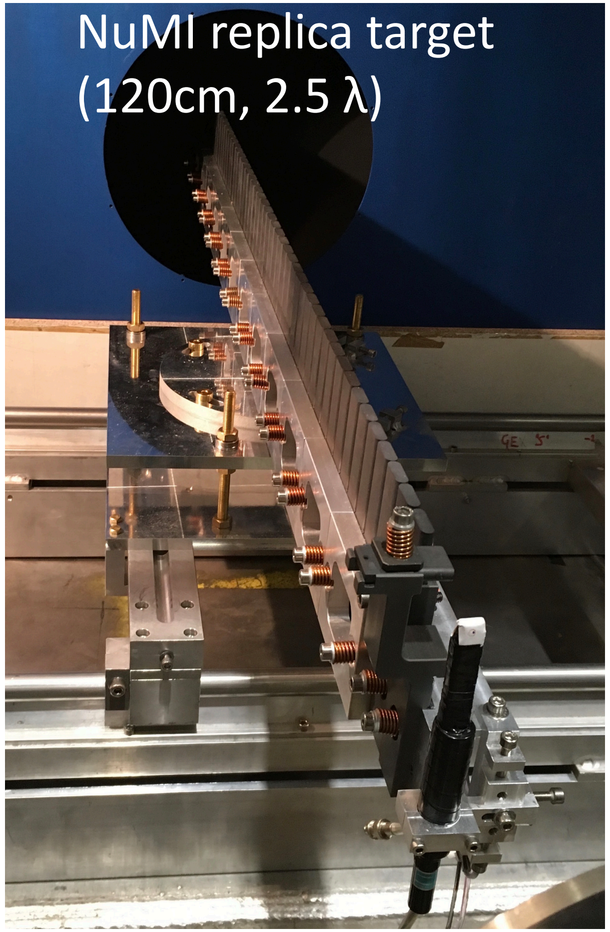
T2K Flux Uncertainty with Hadron Production Data Set

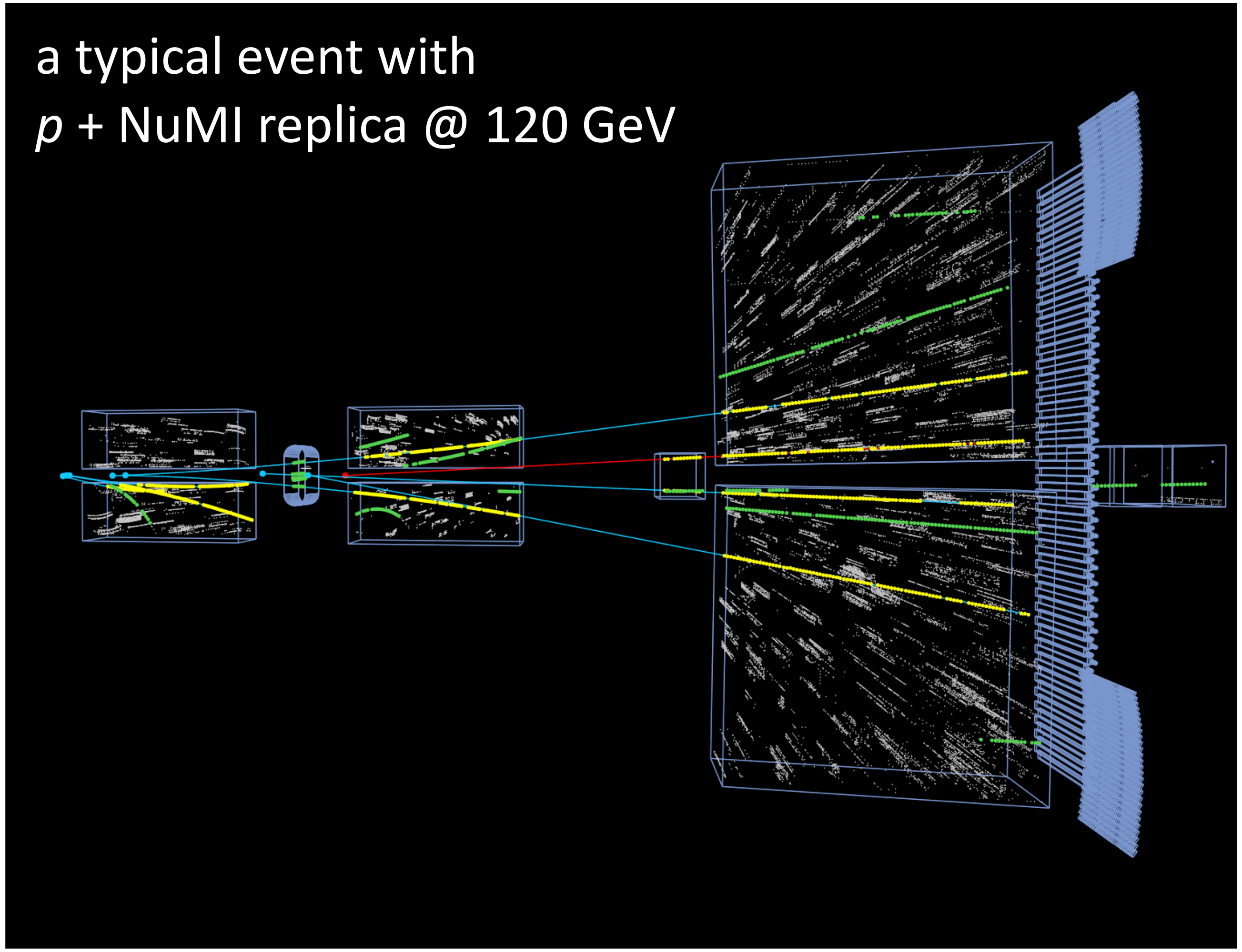


- Thin target measurements improved T2K flux uncertainty down to 10%
- Replica target measurements will improve uncertainty down to ~5%
  (Replica tuning in figure only considers pions.
  Result will further improve with kaons and protons taken into account !!)

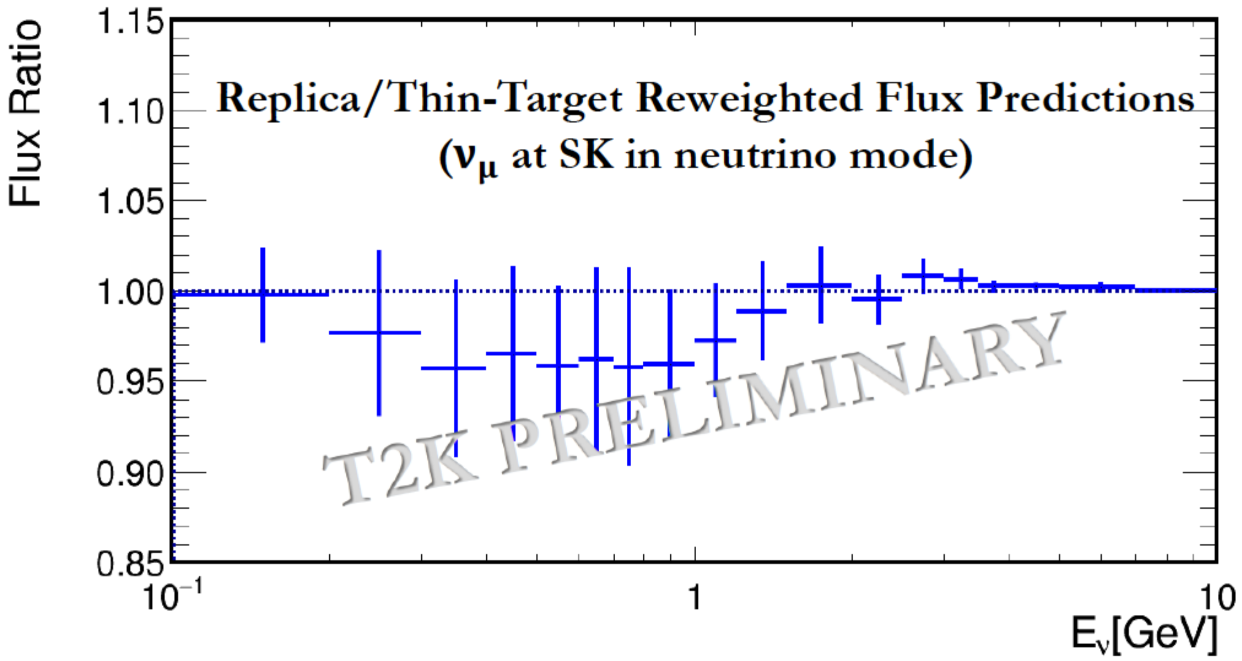
NA61/SHINE: NuMI Replica Target

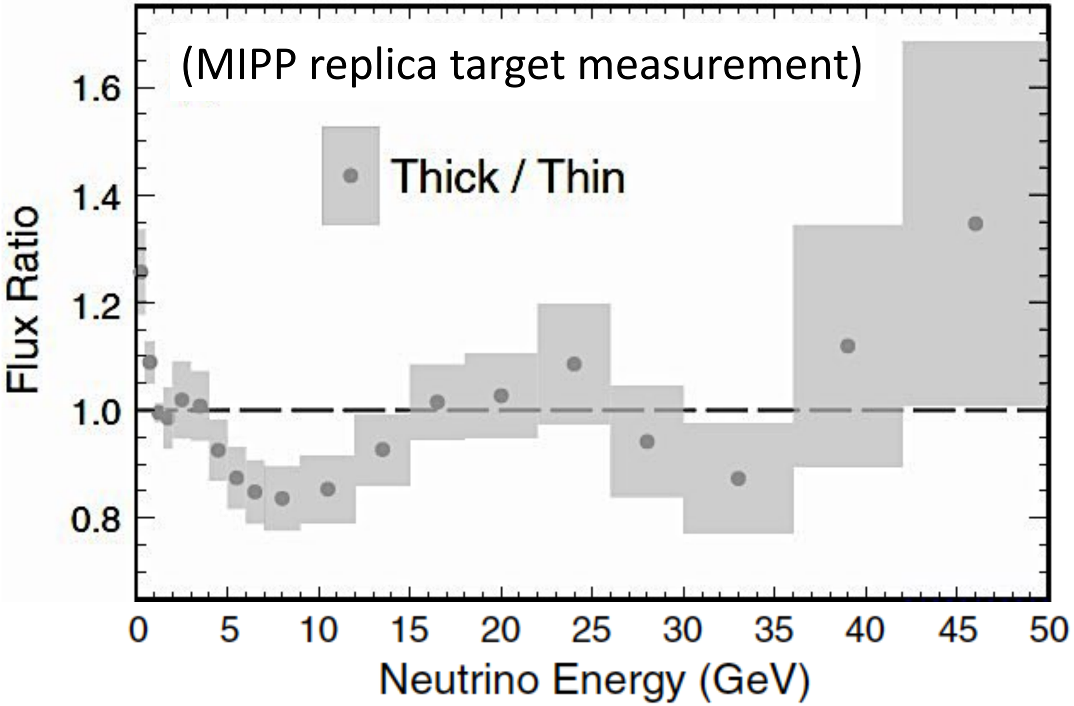
- Complete data taking in 2018 with NuMI Replica Target (NOvA configuration)
- Data analysis will start soon





Thin vs Replica Data Flux Tuning



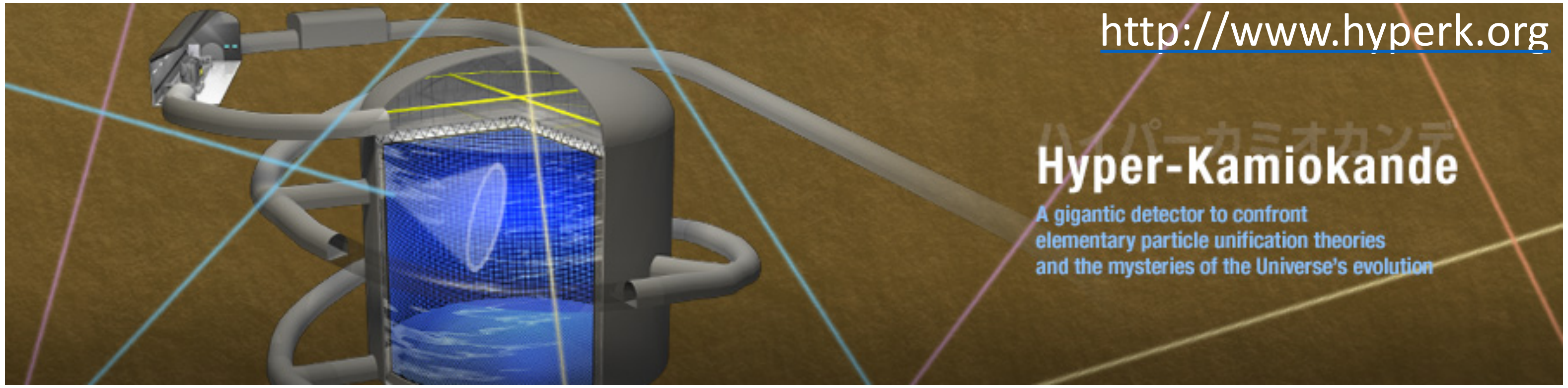


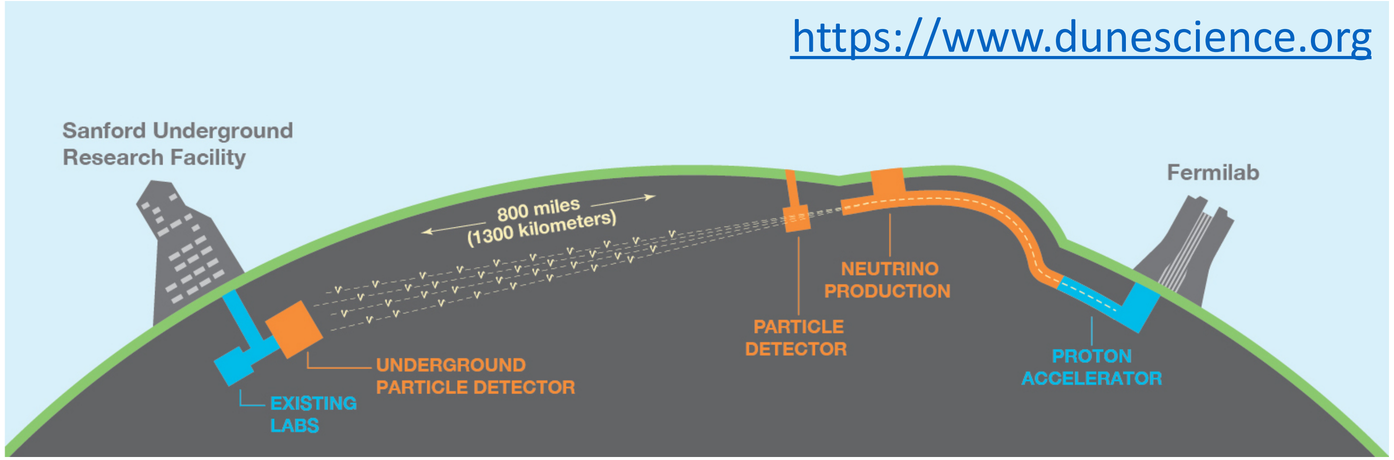
T2K (T. Vladisavljevic): arXiv:1804.00272

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

Future Prospect

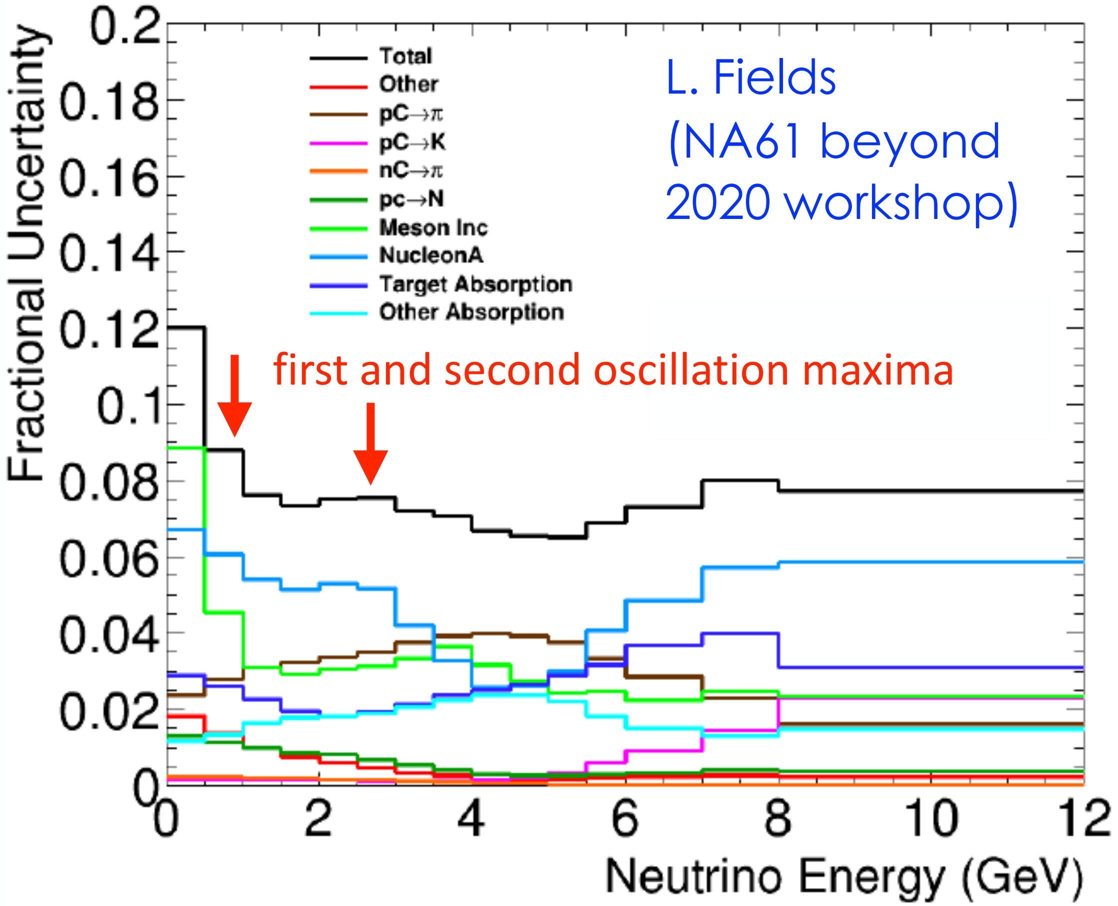


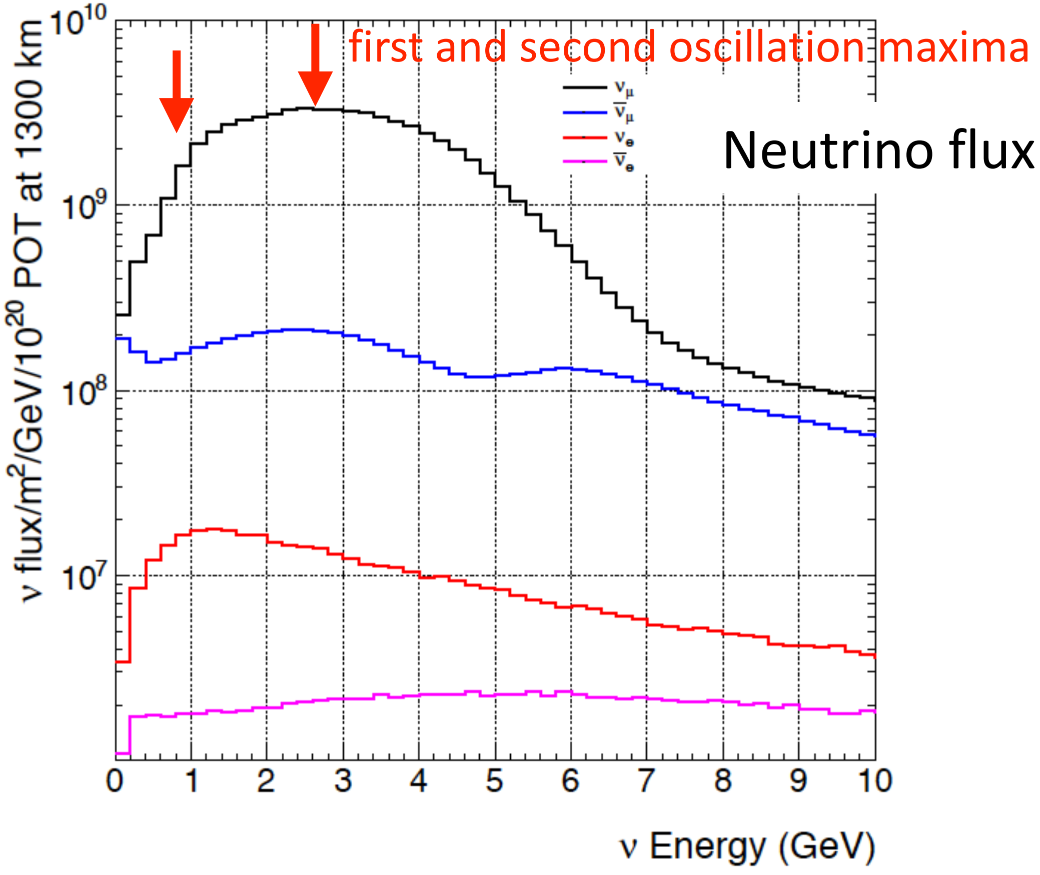


Requirements for Future LBN Experiments

- 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?

<u>Thin Target</u>

- Uncovered materials
  —> With various nuclear targets (Al, Fe, Ti, Water, etc…)
  —> With new target material (SiC, Super-Sialon)
- Uncovered phase-space
  —> T2K: 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
  —> Direct measurement of $\sigma_{\rm el}$, $\sigma_{\rm qe}$, $\sigma_{\rm inel}$

<u>Replica Target</u>

- New replica target
  —> Hyper-K and DUNE targets are under development
- Improved precision
  —> Tracking detector upgrade is necessary

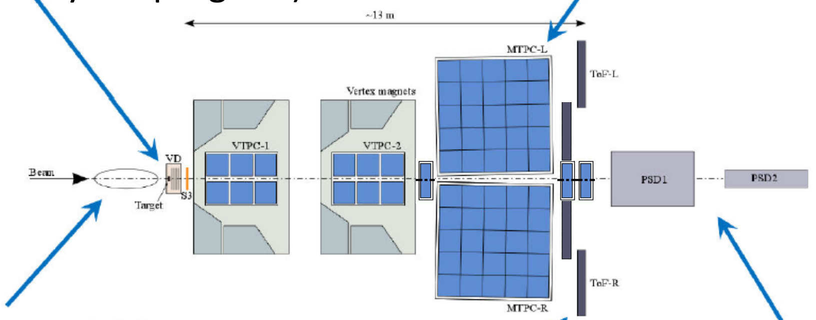
<u>Main players</u>

Thin Target:
- NA61/SHINE in 2021-2024
- EMPHATIC upgrade

Replica Target:
- NA61/SHINE in 2021-2024

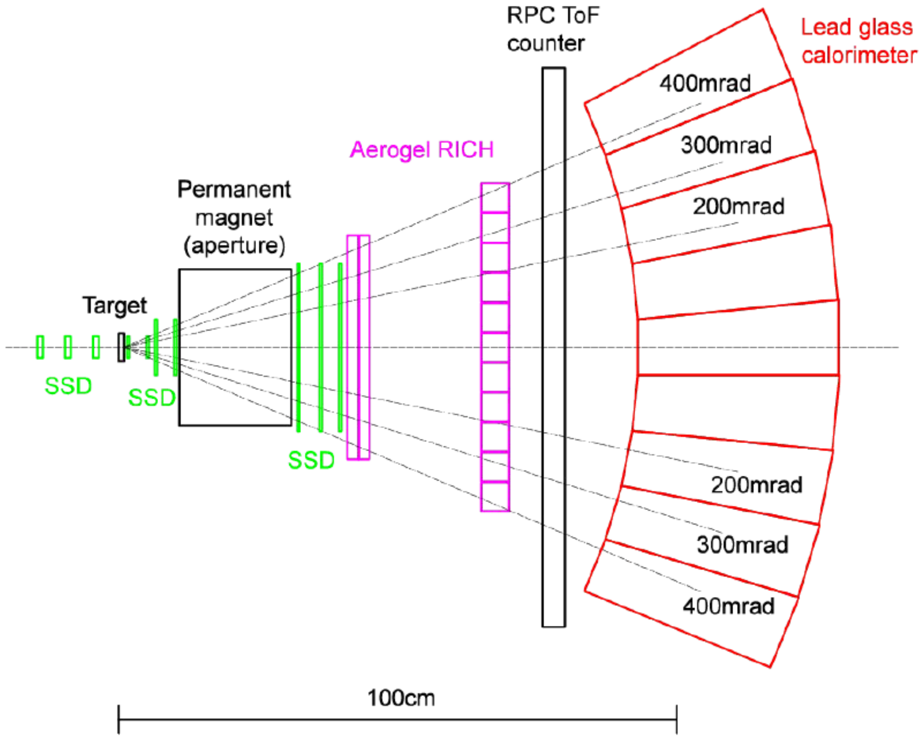
Future Hadron Production Experiments

NA61/SHINE



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

EMPHATIC



- Facility upgrades under consideration
  - Beam particle ID below 15 GeV/c
  - Large acceptance
  - Momentum measurement with magnet

Summary

- Precise hadron production measurements are essential to reduce the leading systematic uncertainty on the neutrino flux prediction
  - Thin and replica measurements reduce flux uncertainty down to < 5% (T2K)
  - Rich hadron production data has been collected and being analyzed (NA61/SHINE)
  - Dedicated forward measurement has started to understand total cross sections more precisely (EMPHATIC)
- More precise hadron production measurement is necessary for future LBN
  - Significant facility upgrades are planned and ongoing (NA61/SHINE, EMPHATIC), which allows new measurements with thin target (NA61/SHINE, EMPHATIC) and replica target (NA61/SHINE)