The T2K Flux Predictions

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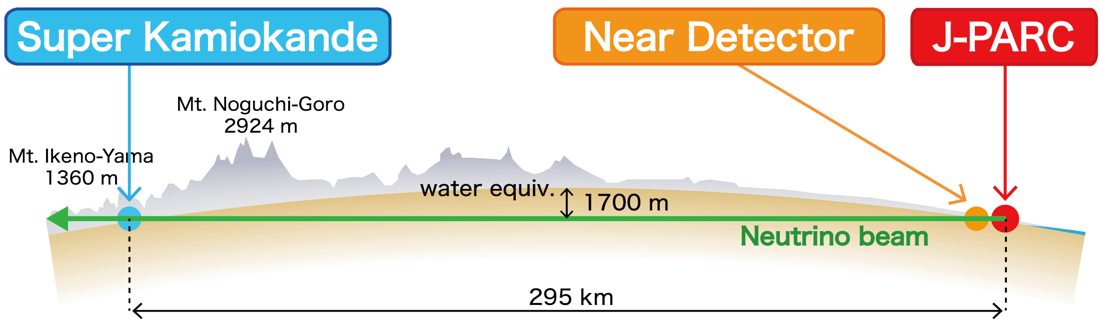
On behalf of the T2K Collaboration

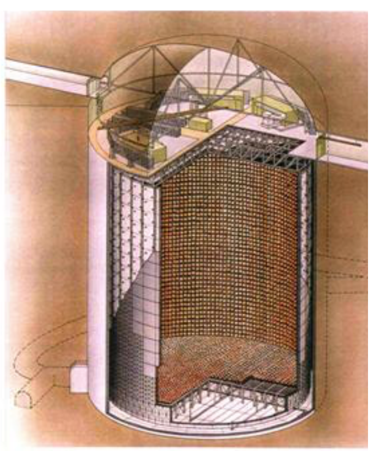
T2K Experiment

Tokai-to-Kamioka – long-baseline neutrino experiment in Japan

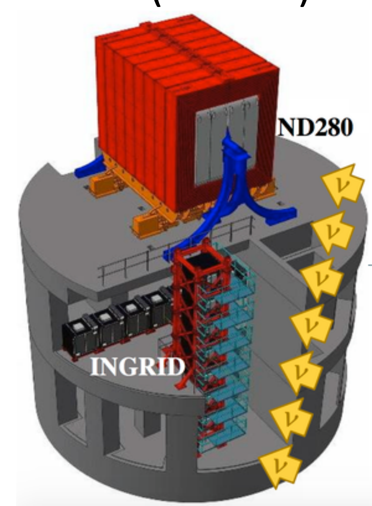
- Measure θ_{13} $\nu_\mu \rightarrow \nu_e$ appearance
- Measure θ_{23} $\nu_\mu \rightarrow \nu_\mu$ disappearance
- Resolving octant of θ_{23}
- Various cross-section measurements
- Search for CP violation



Far Detector in Kamioka



Neutrino Source and Near Detectors in Tokai (J-PARC)

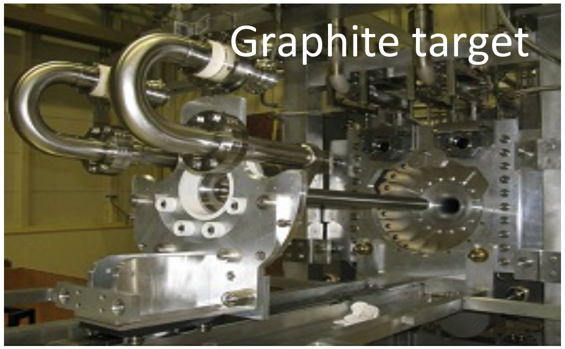


Flux predictions are important for the far-to-near ratio and cross section measurements

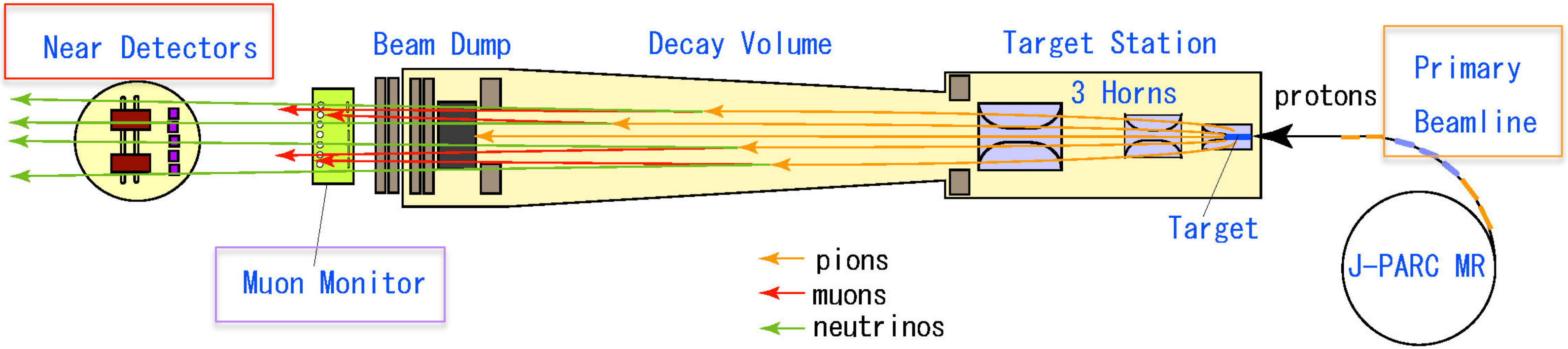
T2K Neutrino Production Beamline

- 30 GeV protons extracted from J-PARC MR
- secondary π, K focused by 3 magnetic horns
- reverse polarity for anti-neutrino beam

+250 kA (-250 kA) for ν (anti-ν) enhanced mode



90 cm long and 2.6 cm diameter



INGRID
monitors the stability of ν flux and direction

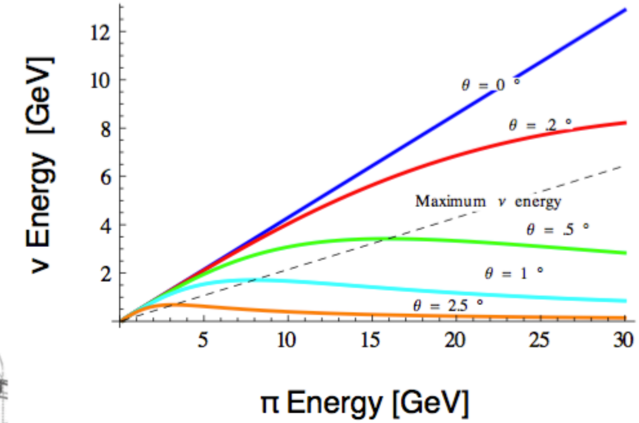
Muon Monitor
measures the muon profile after beam dump

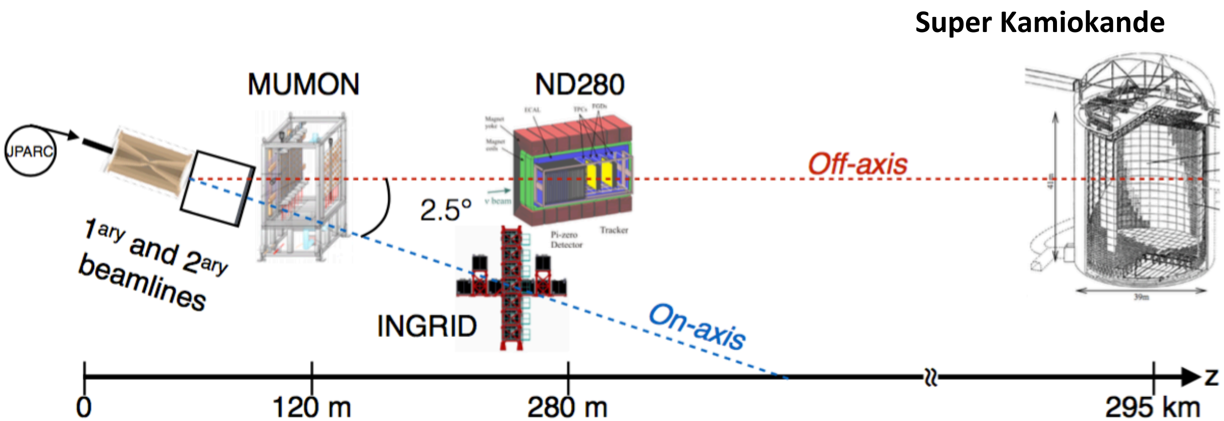
Proton Beam Monitors
measure the proton beam intensity, direction

- Beam direction is stable to within 1 mrd → 2% shift of the E_ν peak at far detector SK
- Stable beam operation achieved at the maximum beam power 470 kW

The Off-Axis T2K Beam

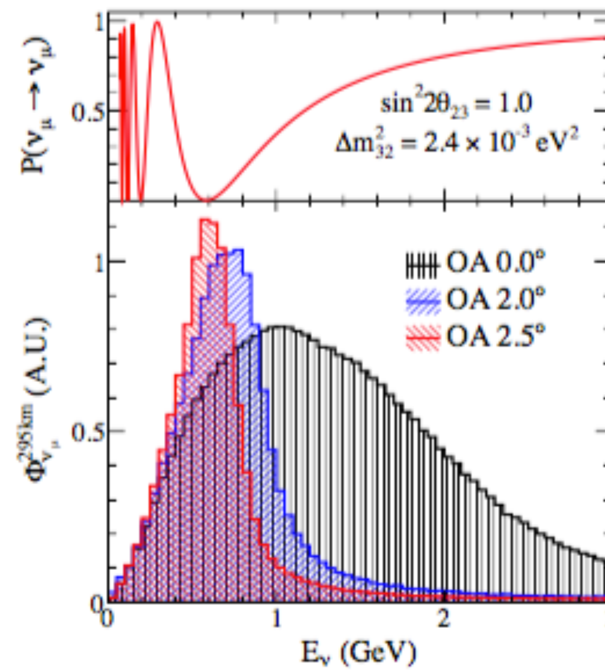
The off-axis technique uses the fact that the energy of neutrino emitted in the 2-body pion (kaon) decay depends only weakly on neutrino parent momentum



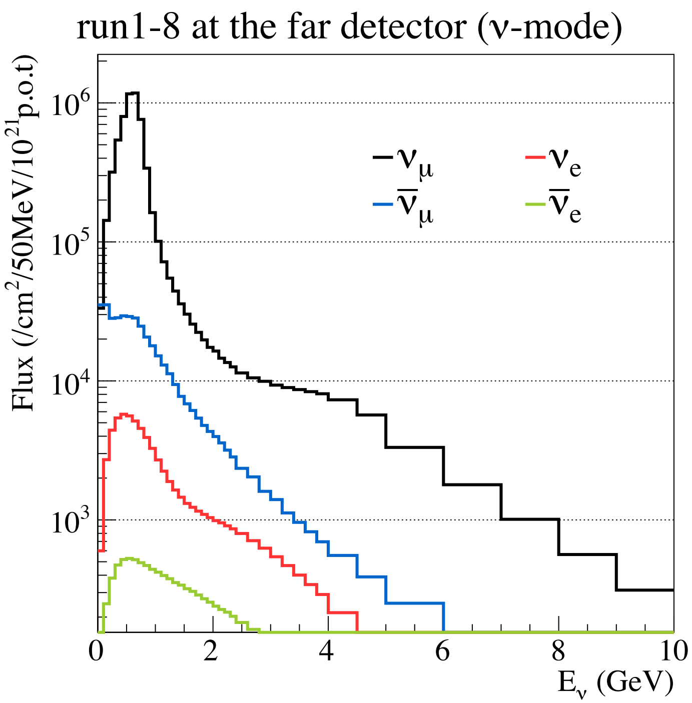


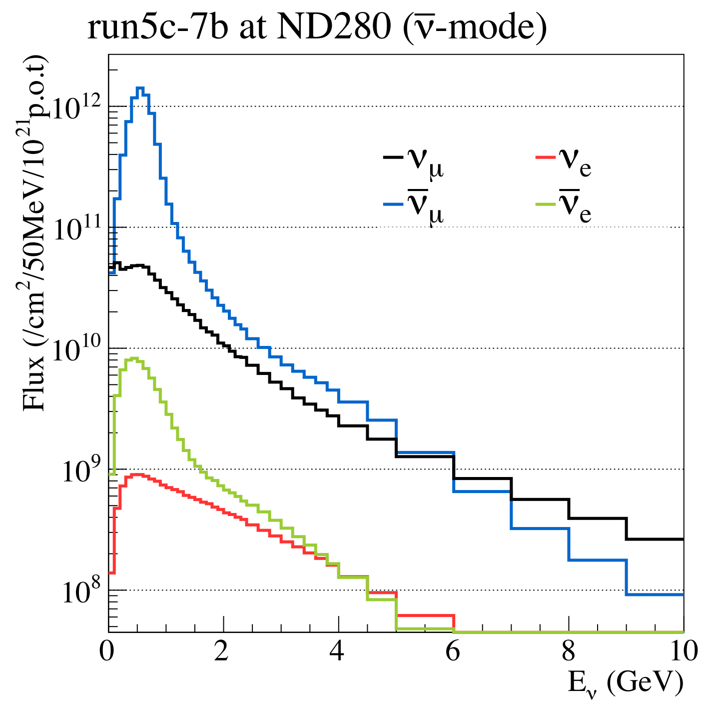
ND280 and SK are placed at the angle 2.5^0 off the target

- Narrow spectrum of beam with peak ~0.6 GeV
- Energy peaks close to the expected first oscillation maximum at L = 295 km
- Reduces the higher-energy background



Neutrino and Anti-Neutrino Flux Predictions



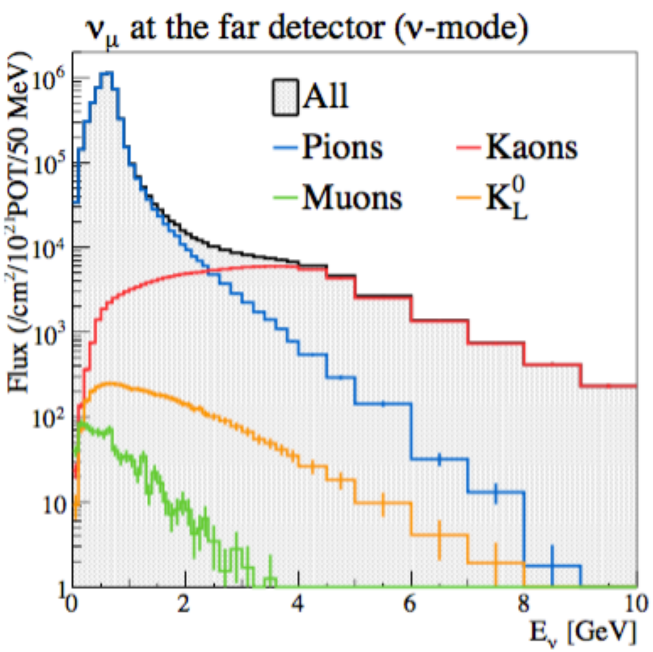


- Mostly but not only pions are produced in the target
- Other ν parents – kaons as well as muons produce a background flux coming from:
  - ν_e flux (< 1% at the peak energy) - it is an important background for the appearance analysis
  - "Wrong sign neutrinos" - a bigger contribution for the anti-neutrino mode

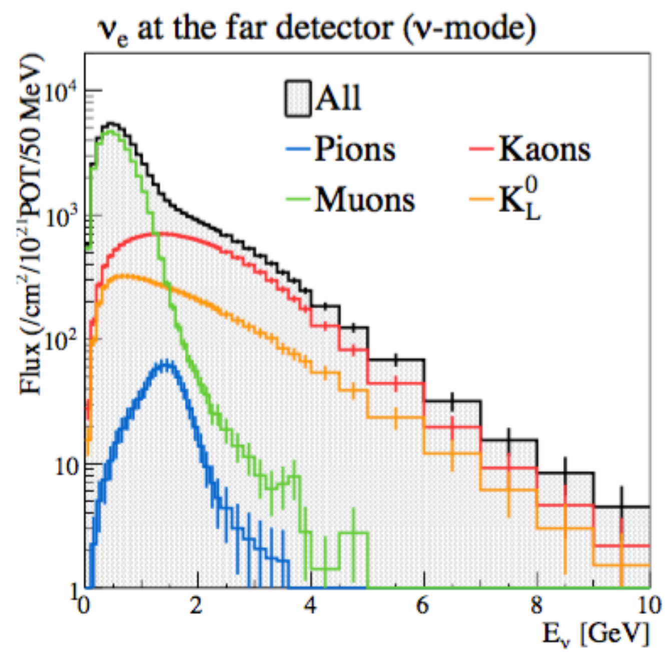
		channel	BR [%]
π	$\rightarrow$	$\mu\ \nu_\mu$	99.9
	$\rightarrow$	$e\ \nu_e$	10^{-4}
K	$\rightarrow$	$\mu\ \nu_\mu$	63.5
	$\rightarrow$	$\pi^0\ e\ \nu_e$	5.1
	$\rightarrow$	$\pi^0\ \mu\ \nu_\mu$	3.3
K^0_L	$\rightarrow$	$\pi\ e\ \nu_e$	40.5
	$\rightarrow$	$\pi\ \mu\ \nu_\mu$	27.0
μ	$\rightarrow$	$e\ \nu_e\ \nu_\mu$	100

Motivation for Hadron Production Measurements

- The flux predictions in accelerator-based neutrino experiments depend on hadron production models of ν parents
- Hadron production at present is still one of the dominant uncertainties in flux estimates



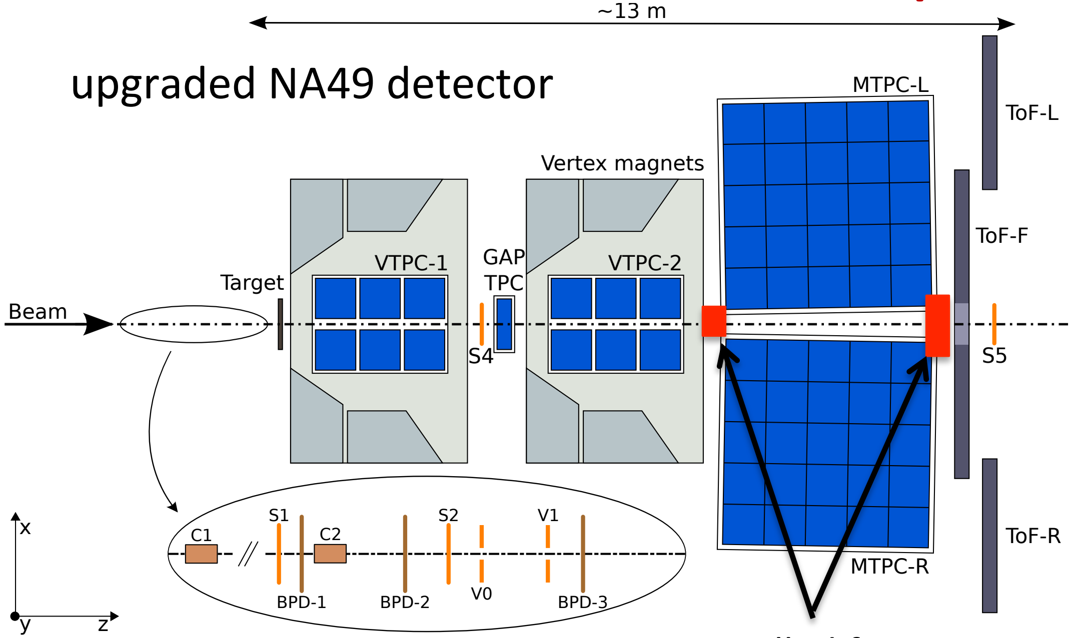
ν_μ (anti-ν_μ) : pions at low E_ν, kaons at large E_ν

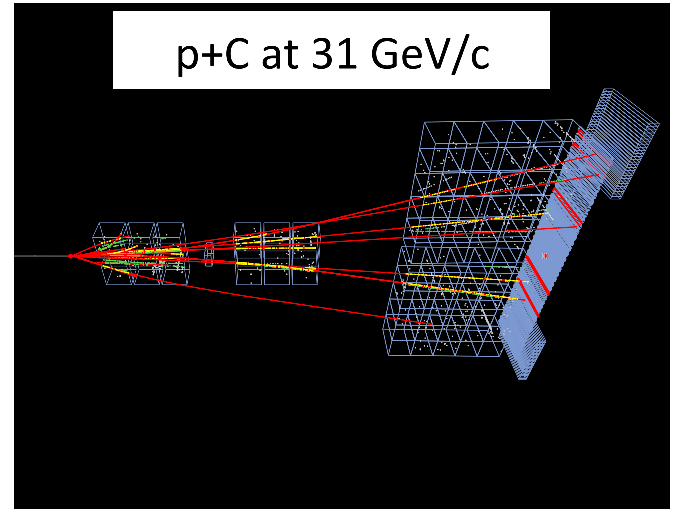


ν_e : muons at at low $E_{\nu,}$ kaons at high E_ν
anti-ν_e : kaons for all E_ν

NA61 measurements replace model-based calculations for hadron production in ν flux estimates thus reduce one of the largest sources of uncertainty

NA61/SHINE Experimental Setup

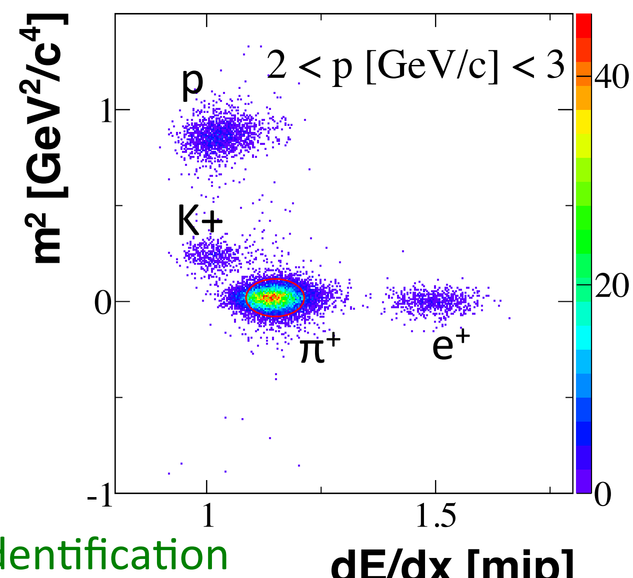




Fixed target experiment at CERN SPS with the large acceptance spectrometer

- **Time Projection Chambers** : tracking and particle identification
  - Momentum resolution $\sigma(p)/p^2 \approx 10^{-4}$ $(GeV/c)^{-1}$
  - Particle identification : σ(dE/dx)/ <dE/dx> ≈ 4%
- **Time of Flight :** particle identification
  - ToF-F array installed to fully cover T2K acceptance
  - Time resolution σ(t)ToF-F ≈ 120ps, σ(t)ToF-L/R ≈ 80ps

Combined dE/dx + ToF

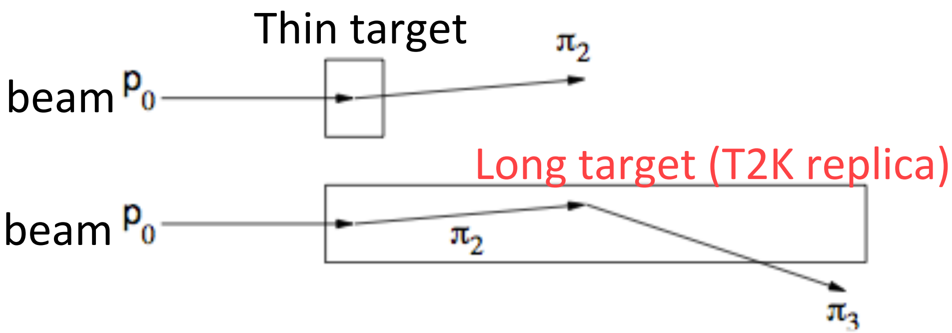


TPC and ToF detectors provide very good particle identification

NA61/SHINE Hadron Production Data

Two different targets were used:

- **thin carbon** (2 cm, 0.04 λ_I): hadrons from primary interactions (sensitive to 60% of the flux)
- **T2K replica** (90 cm,1.9 λ_I): hadrons from primary and secondary interactions (constrains 90% of the flux)



Data to constrain T2K flux:

Beam+Target	p[GeV/c]	Year	$N_{triggers}$ [10^6]
p+C	31	2007	0.7
p+T2K Replica	31	2007	0.2
p+C	31	2009	5.4
p+T2K Replica	31	2009	2.8
p+T2K Replica	31	2010	10.0

Thin target spectra $\pi^{\pm}$, $K^{\pm}$, K^0_S, Λ, protons:

2007 : Phys.Rev. C84 (2011), 034604

Phys.Rev. C85 (2012) 035210

2009 : Eur.Phys.J. C76 (2016) no.2, 84

Replica target spectra $\pi^{\pm}$

2007 : NIM A701 (2013) 99-114

2009 : Eur.Phys.J. C76 (2016) no.11, 617

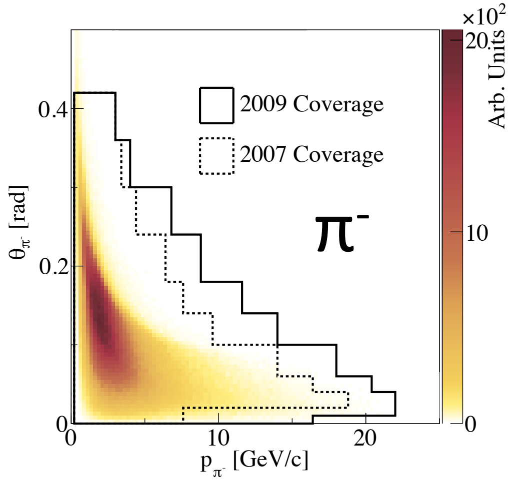
Status of the analysis:

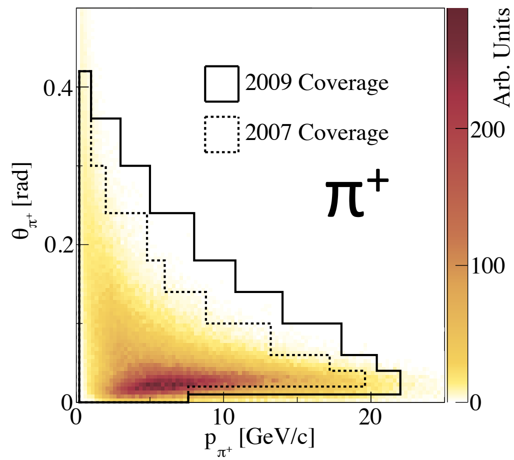
- 2007 published, small stat. pilot runs
- 2009 published, large stat. for thin target and first results for T2K replica
- 2010 new T2K replica results for $\pi^{\pm}$ ongoing analysis for $K^{\pm}$, proton

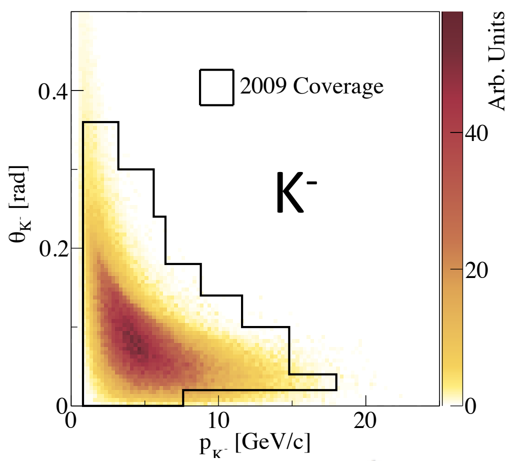
Measurements with both targets are important to understand hadron-production
2009 thin target data used for recent tuning of T2K flux

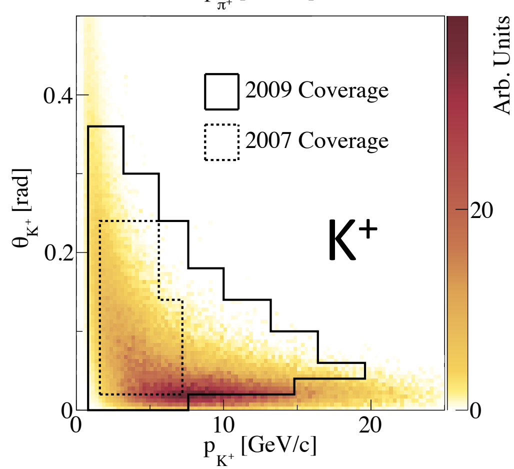
Hadron Measurements on Thin Target

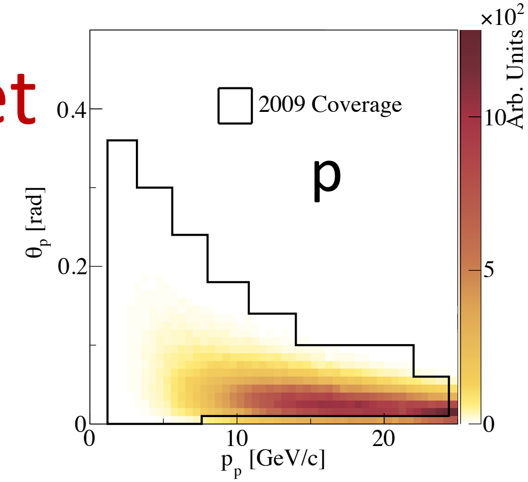
The phase space contributing to the predicted neutrino flux at SK and the NA61 data coverage.

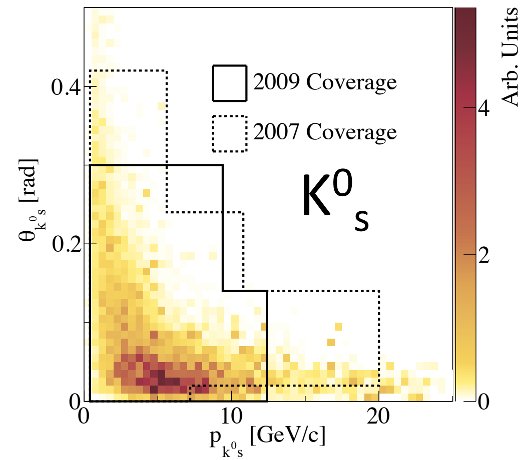


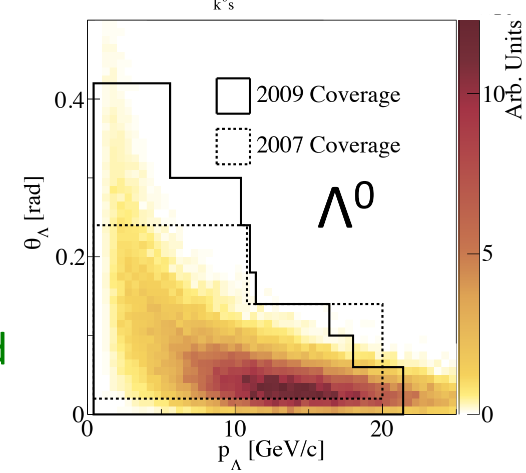


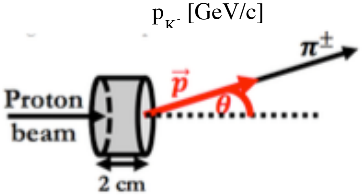








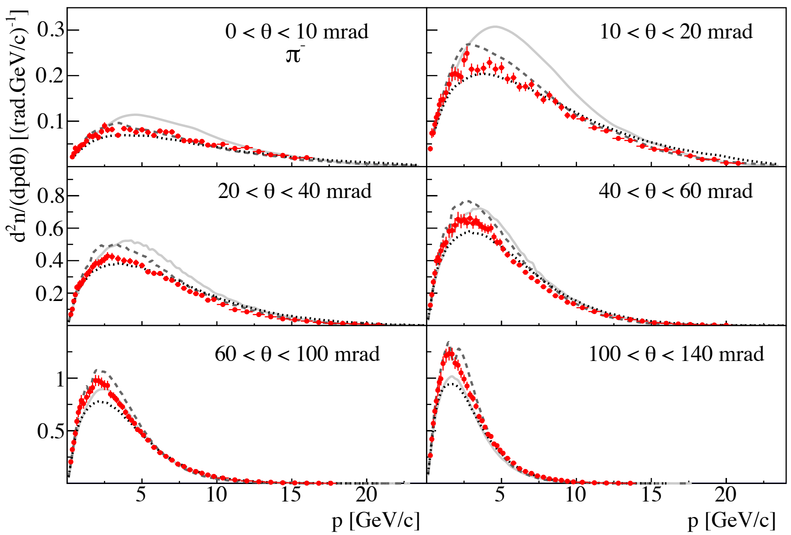


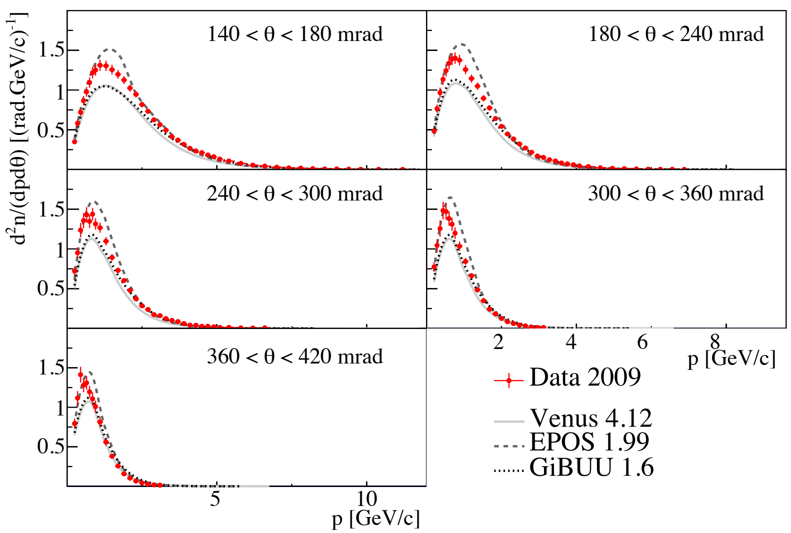


NA61 provides good coverage of required phase-space

Measurements with Thin Target Data

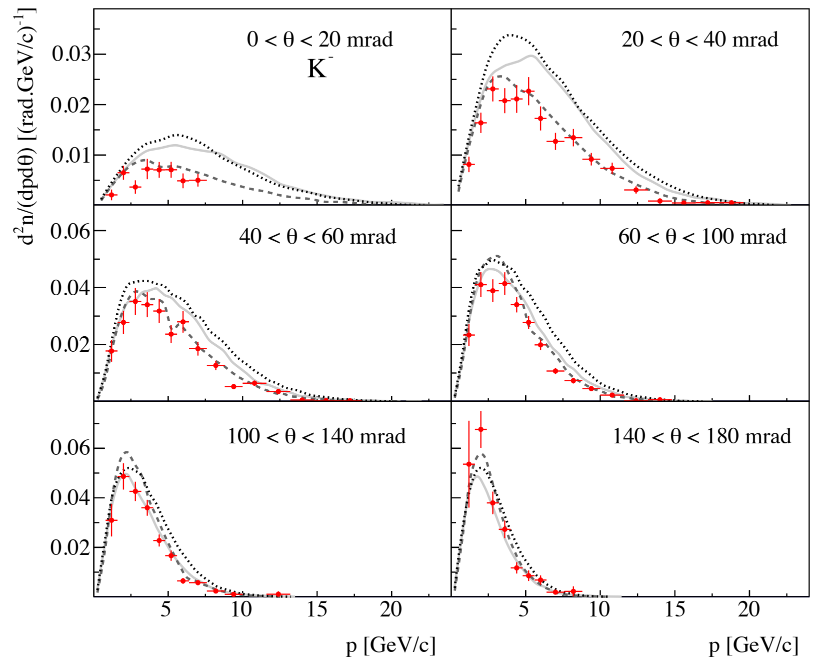
π^- Multiplicities

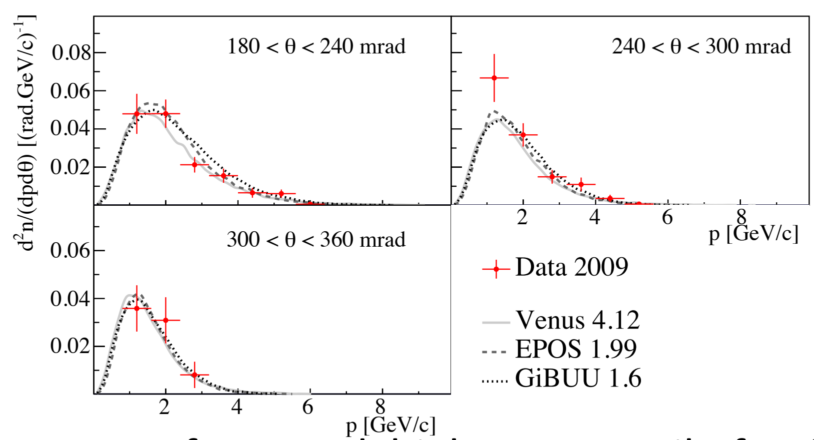




Relative errors ~4%

K^- Multiplicities





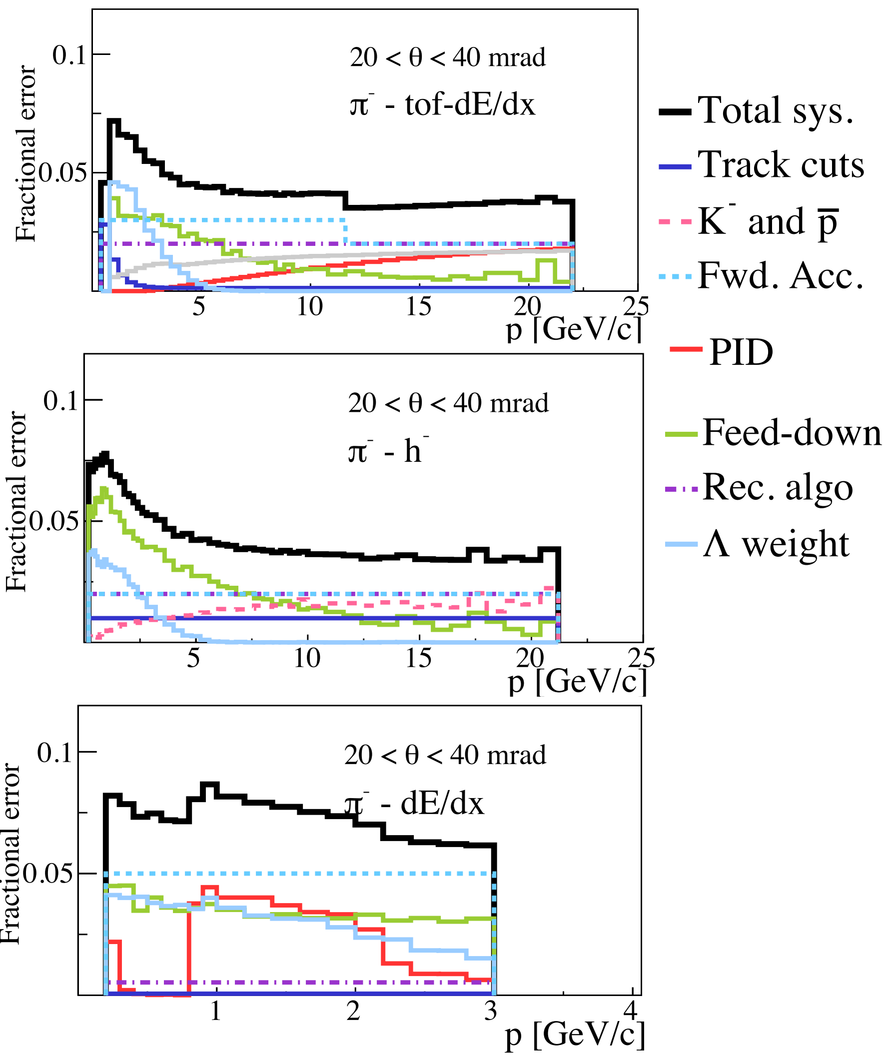
Important for ν_e and high-energy tail of ν_μ flux

Relative errors ~15%

Published: Eur.Phys.J.C76 (2016) no.2, 84

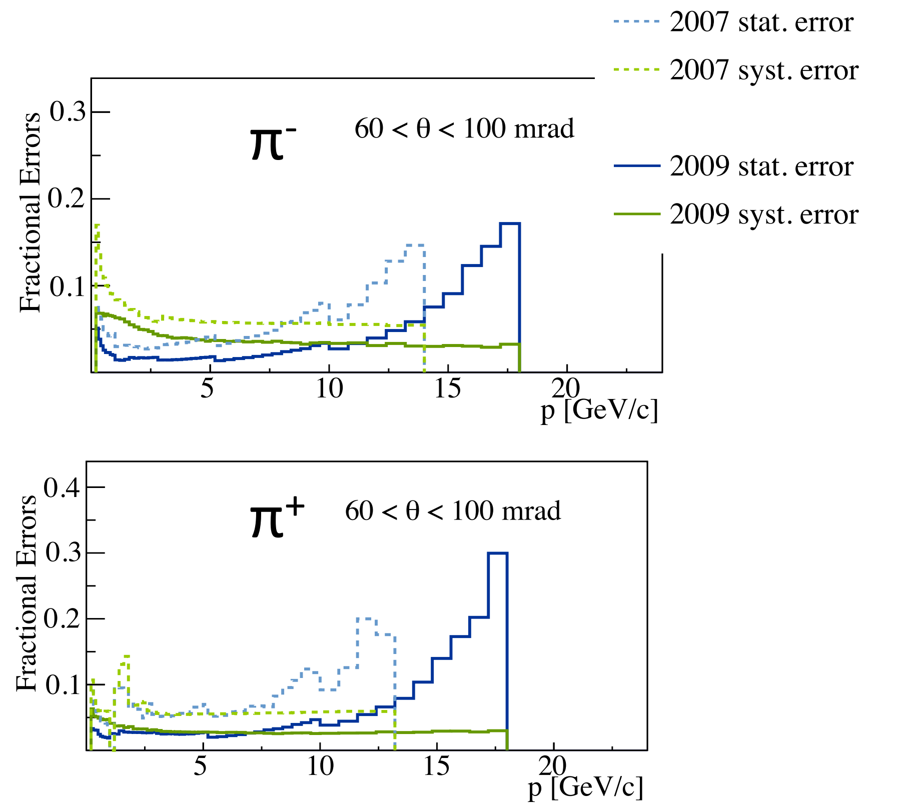
Pion Spectra Uncertainties

The largest contributions to sys. error: **feed-down** improved with studies of decay of strange particles (K^0_s and Λ), particle identification (PID) and forward acceptance



Improvements in 2009 compared to pilot run:

- Statistical precision improved by factor 2-3
- Systematic error reduced by factor 2



Systematic errors are dominant at low p while at high p statistical errors still are the largest

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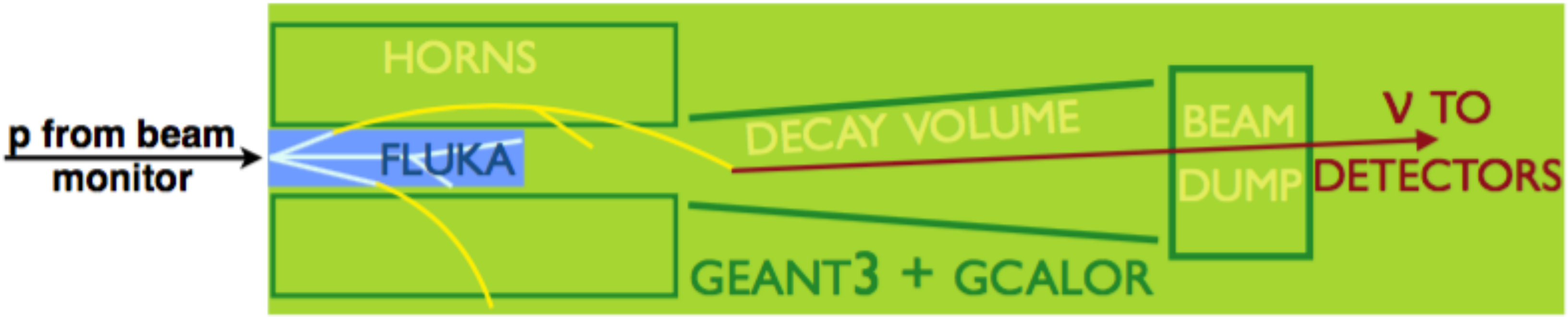
Modeling of T2K Flux



FLUKA
Primary p+C interaction in the target

Beamline monitors data are parameterized to obtain the proton beam profile

GEANT3+GCALOR
tracking particles exiting the target through horns, magnetic field and decay volume.

Accurate description of secondary beamline in simulation is required

RE-WEIGHTING
pion, kaon multiplicity and interaction rate are used to re-weight simulations

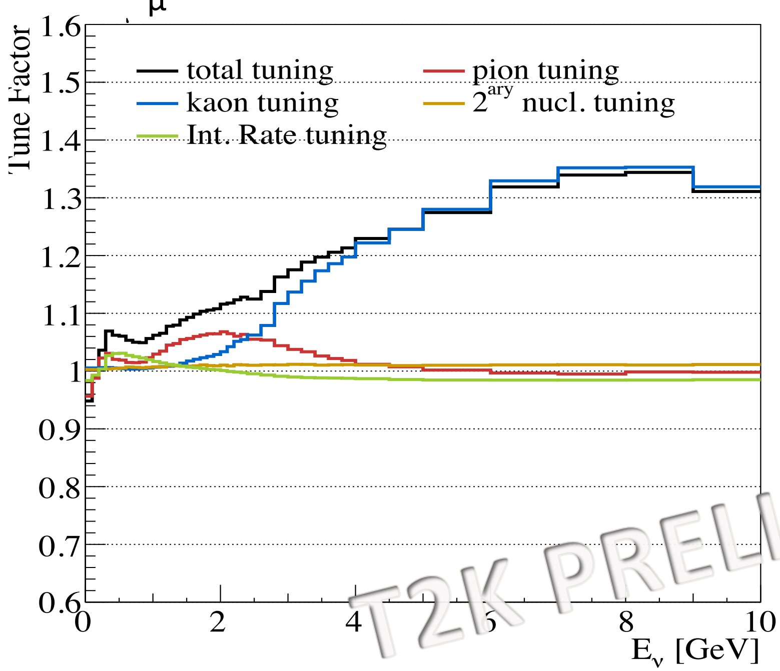
External hadron production measurements are used - mostly NA61/SHINE

T2K Flux Tuning with Thin Target NA61 Data

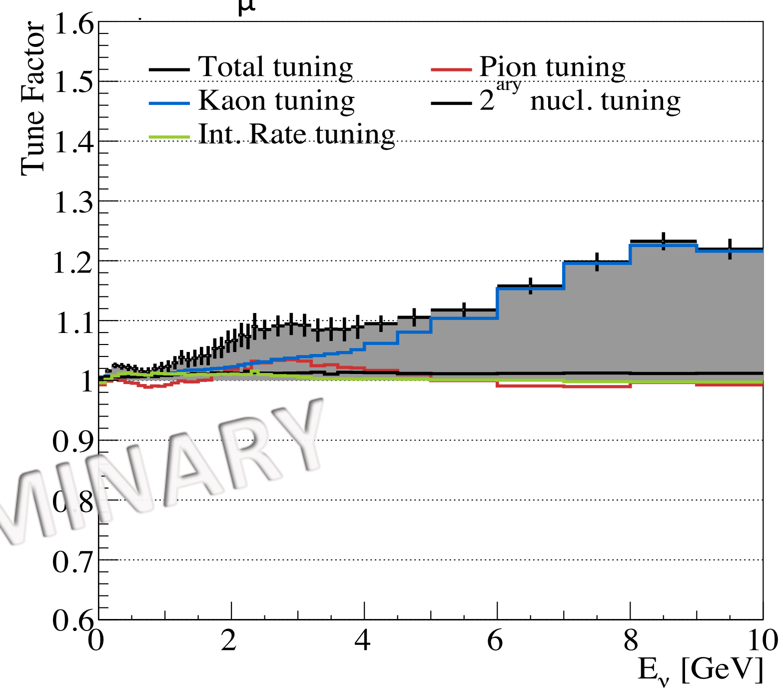
To tune T2K flux, for each simulated neutrino interaction, a weight is calculated for simulated event to adjust MC to data

- Primary interactions can be directly re-weighted with NA61 thin target data for $\pi^{\pm}$, $K^{\pm}$
- The kinematic coverage is extended by using parameterization obtained from fit to data
- Scaling is used for secondary interactions and interactions on material other than carbon such as iron (decay volume walls) or aluminum (horns)

ν_{μ} at SK



anti-ν_{μ} at SK

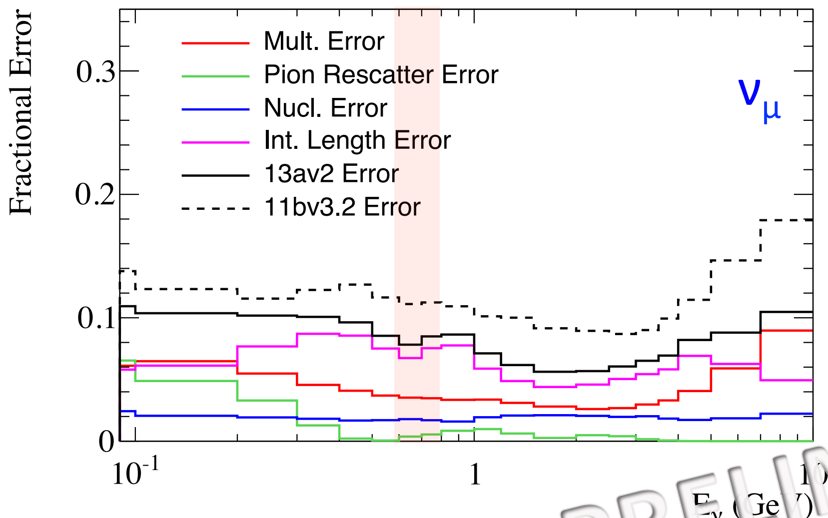


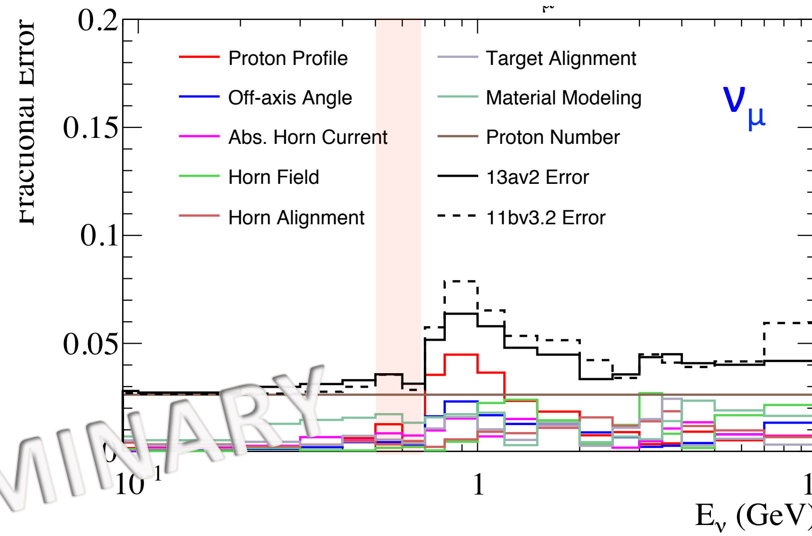
Flux Uncertainties at SK

Hadron Modeling Part

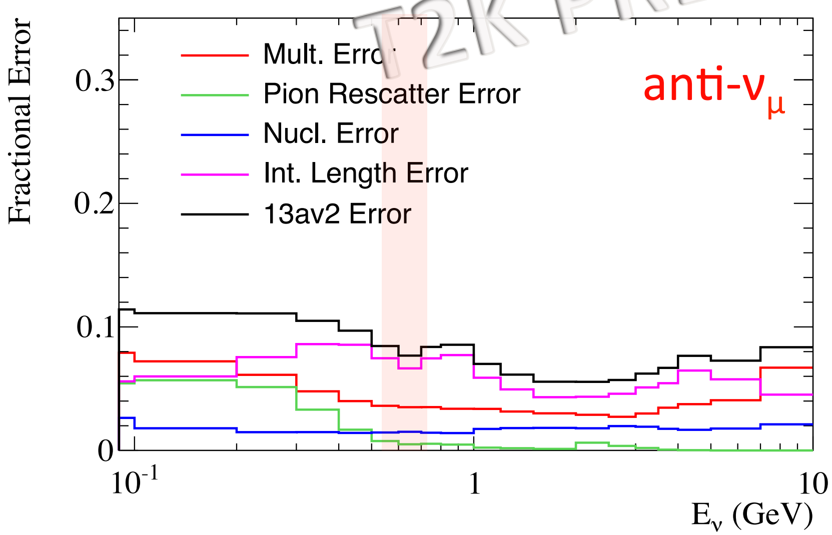
Non-Hadronic Part

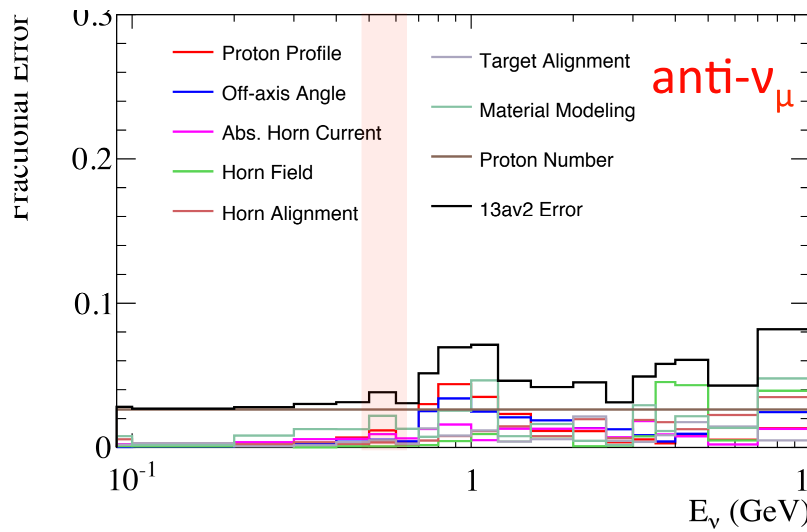
ν_μ at SK





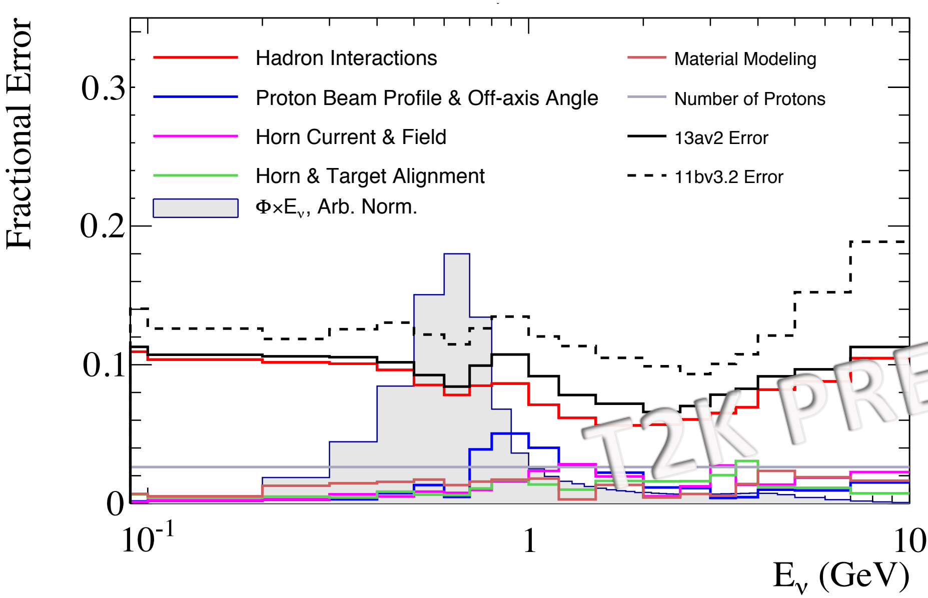
anti-ν_μ at SK





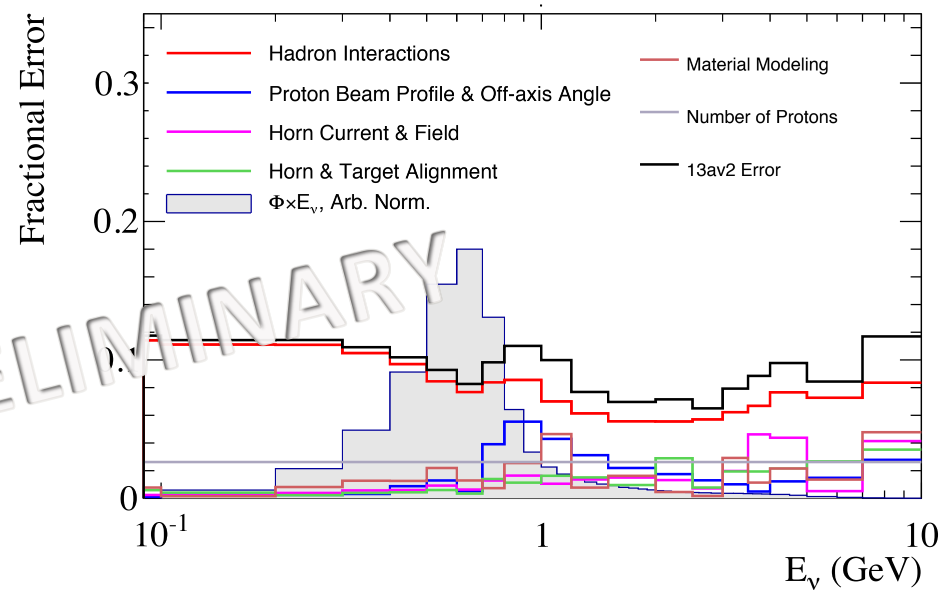
Total Flux Uncertainty

ν_μ at SK



New tuning including 2009 NA61 data reduced the neutrino flux uncertainty to ~9% at E_ν peak as compared to 11% obtained with the previous tuning

anti-ν_μ at SK



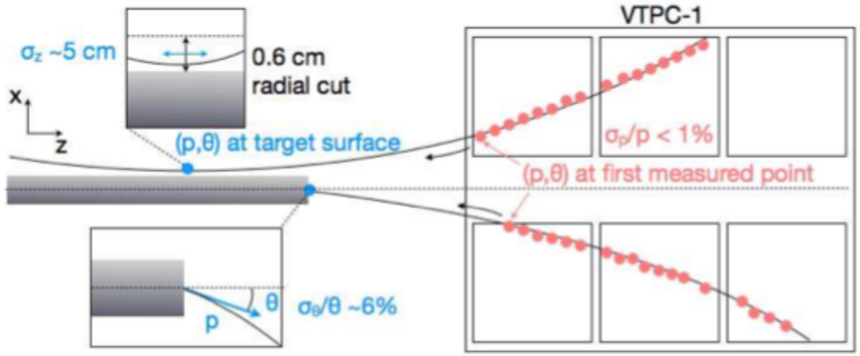
First flux tuning for anti-neutrino gives uncertainty ~9% at E_ν peak based on 2009 NA61 data

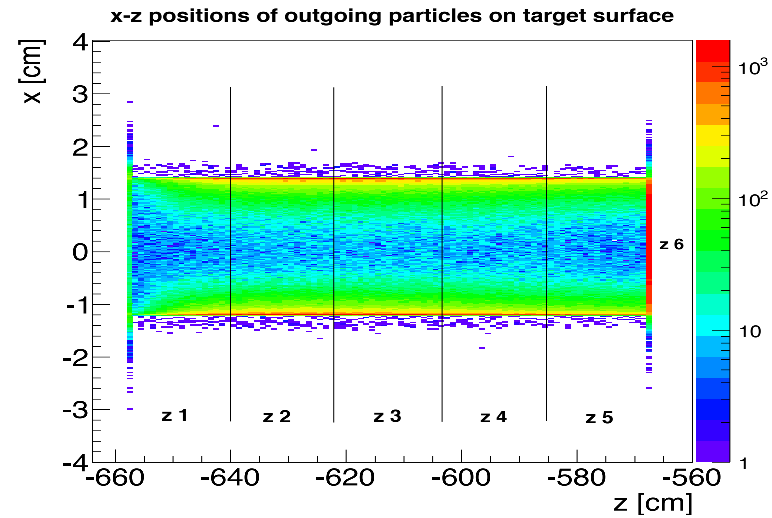
Hadron Production remains the largest contribution to the flux uncertainty
→ Uncertainties can be further reduced with the replica target

Long Target (T2K Replica) Analysis

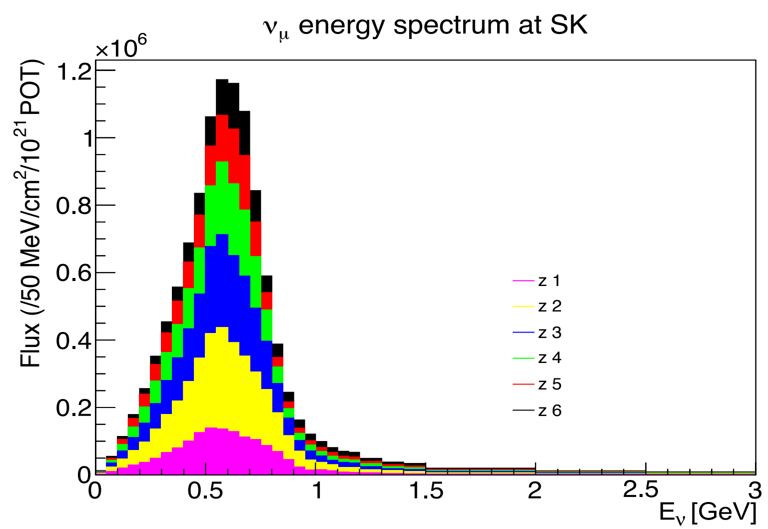
Neutrinos are coming from hadrons produced in **primary p+C interactions** (~60%) and in **interactions of secondary particles** either in the target (~30%) or outside the target (~10%)

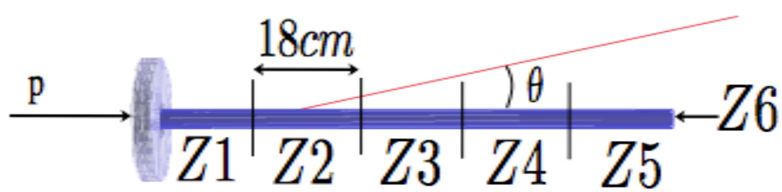
- Multiplicities measured at the surface of the T2K replica target (tracks extrapolated backwards)





- Measurements in bins of {p,θ,Z}
- 5 bins along beam Z-direction + 1 bin target downstream face
- Shape of E_ν depends on the additional Z-binning

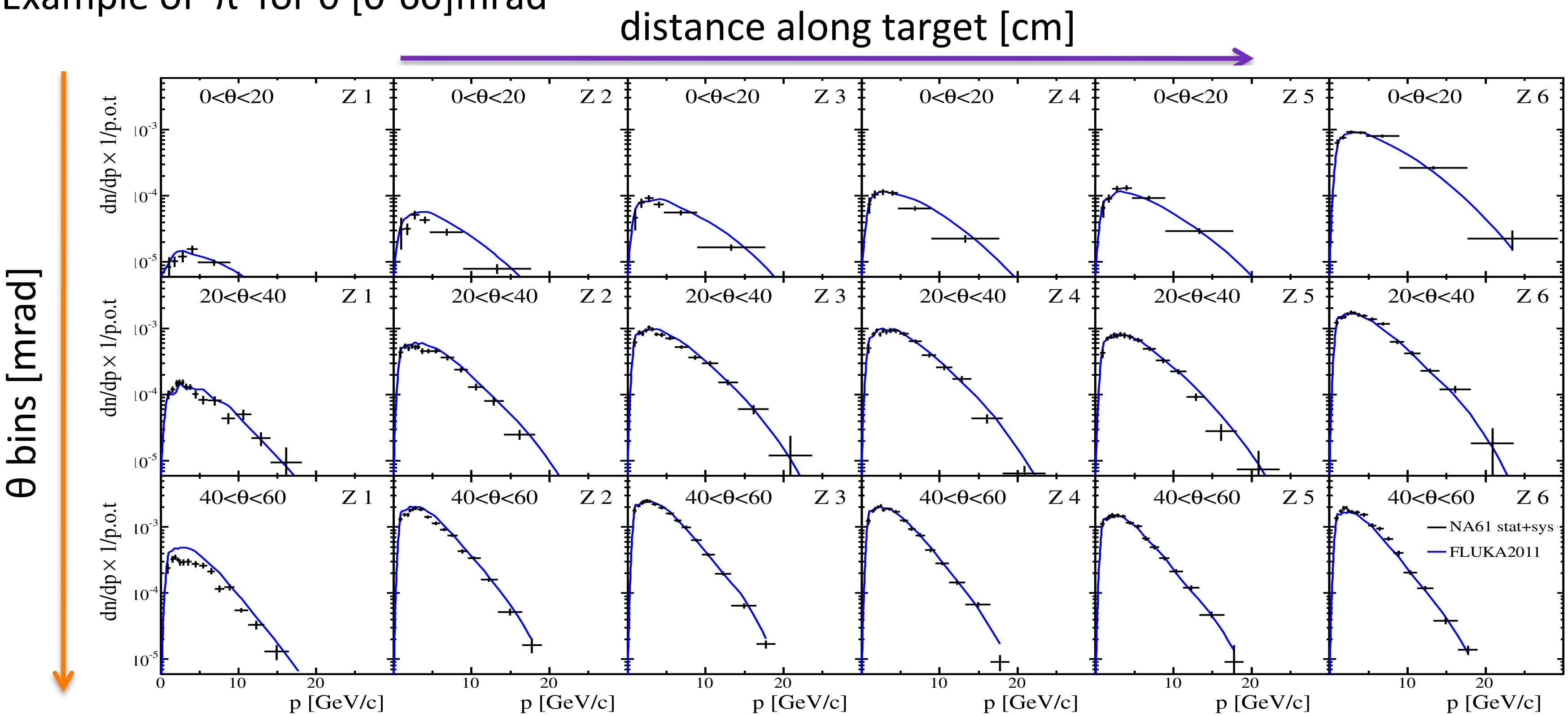




First π⁻ Measurements with T2K Replica Target

The spectra of $\pi^{\pm}$ were measured (dE/dx+ToF analysis method was used) for the 2009 data

Example of π^- for θ [0-60]mrad

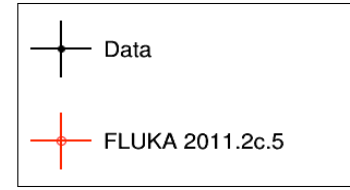


- Statistical precision ~5% in most of the bins
- Systematic errors vary from ~5% in the center of target to ~10% in the most upstream and downstream bins (large contribution from track extrapolation)
- Ongoing work to tune T2K flux simulation using pion spectra → Poster by Tomislav Vladisavljevic: Estimating the T2K Neutrino Flux with NA61 2009 Replica-Target Data

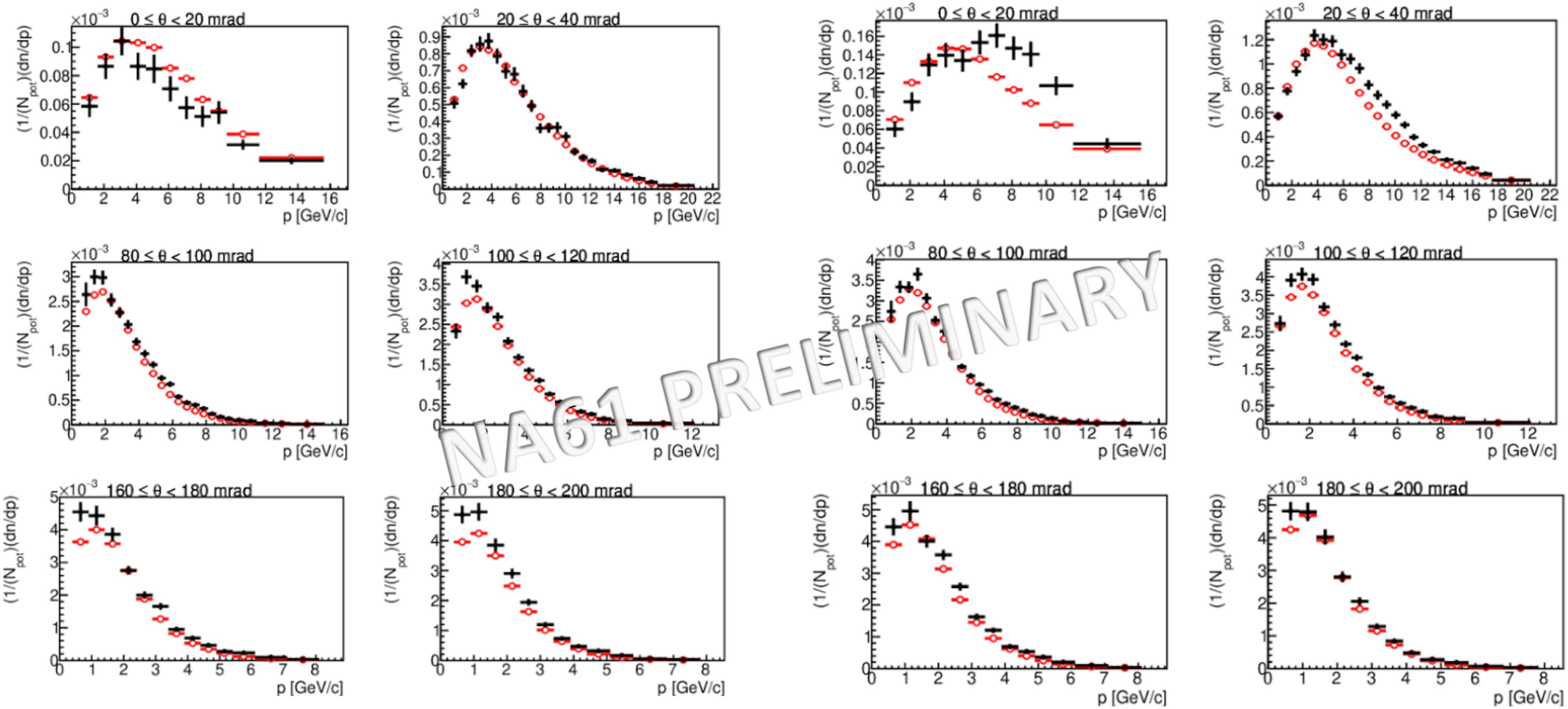
Published : Eur.Phys.J. C76 (2016) no.11, 617; A.Hasler PhD (2015) Geneva U.

$\pi^{\pm}$ for T2K Replica Target for Largest Dataset

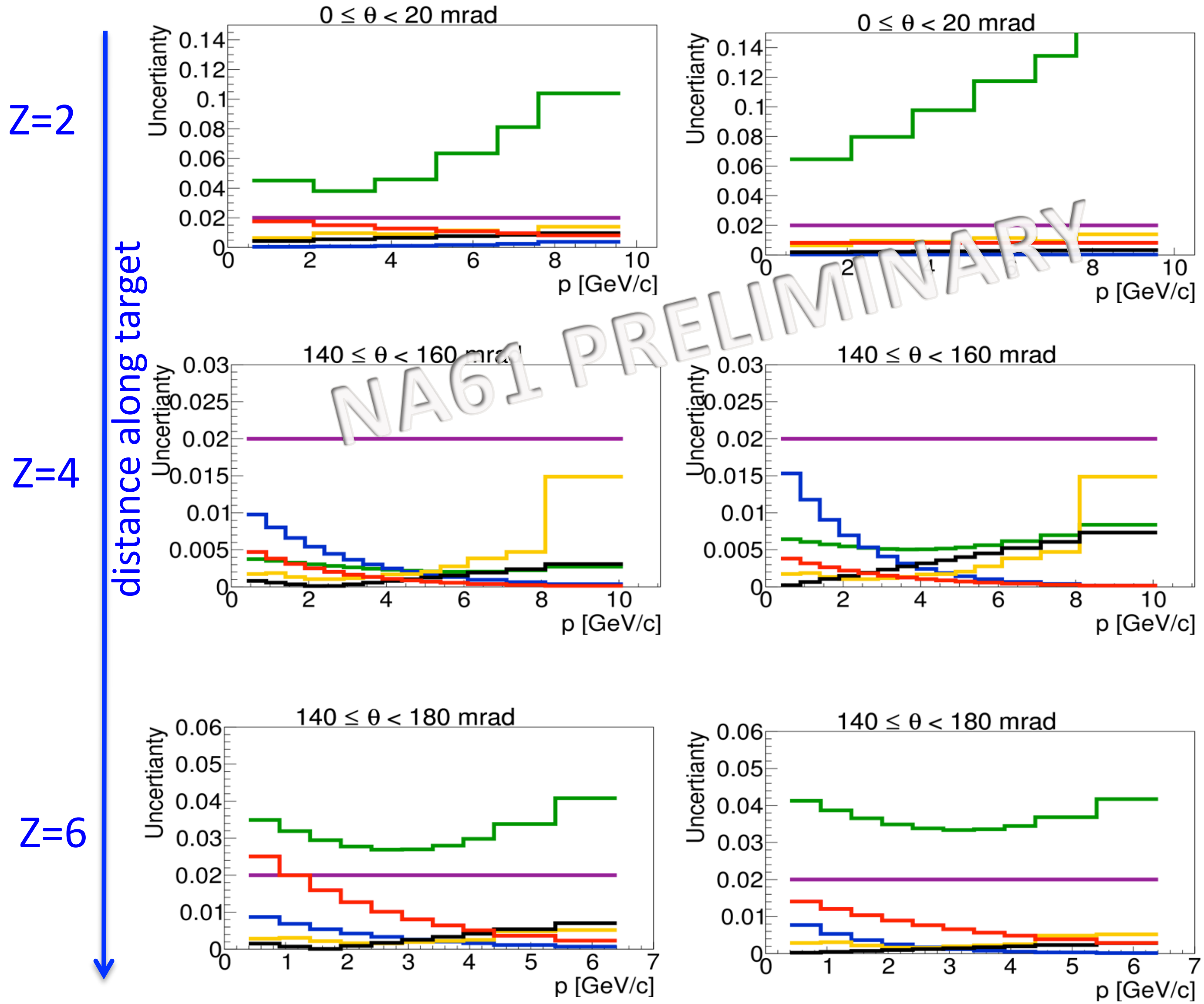
- Analysis of 3x bigger statistics (2010 dataset) than previously is ongoing
- Preliminary results (examples) for $\pi^{\pm}$ presented here
- Extraction of $K^{\pm}$ as well as proton spectra is possible



π^- Multiplicity for Z=5 | π^+ Multiplicity for Z=5



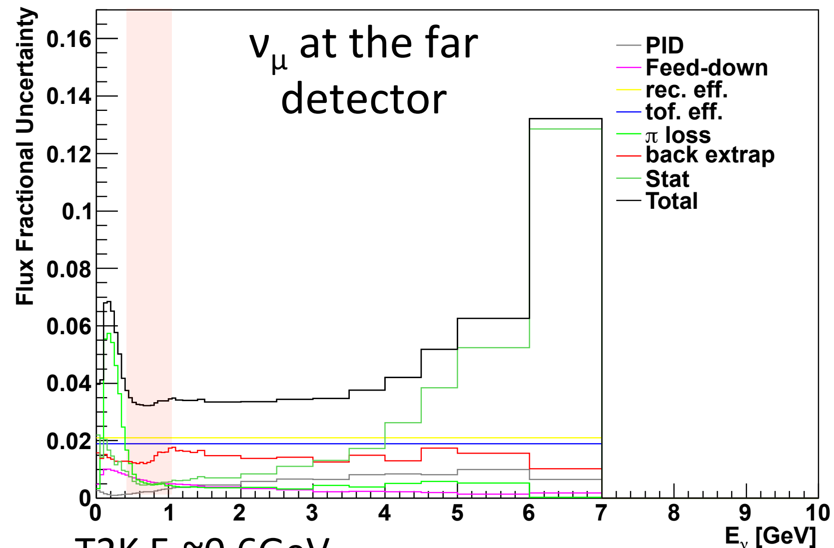
$\pi^{\pm}$ Systematic Uncertainties



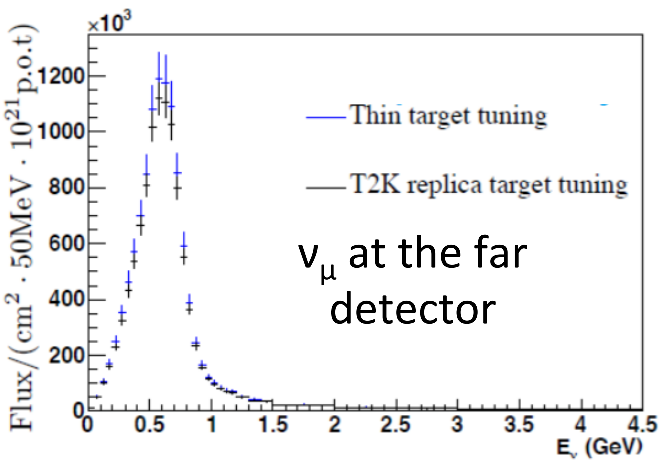
- Position of target is dominant systematic error for most up- and downstream Z-bins
- Sys. errors are similar to the ones obtained for the previous long target analysis

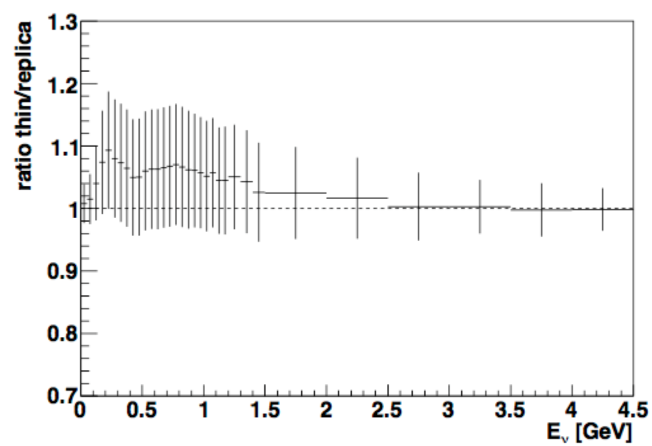
Flux Predictions for T2K Replica Target

- NA61-only specific errors only propagated
- Precision of about 4% at T2K E_ν peak as compared to ~9% for thin target
- Only using $\pi^\pm$ measurements – improvement of flux uncertainty at low E_ν
- $K^\pm$ measurement for long target will be important to constrain flux at higher E_ν



T2K E_ν~0.6GeV





- Up to 5-10% difference between thin (+ secondary interactions modeled with MC) and long target flux predictions; however they are consistent within errors

Published : Eur.Phys.J. C76 (2016) no.11, 617; A.Hasler PhD (2015) Geneva U.

Summary

- T2K flux is predicted with the use of the NA61/SHINE data
- The flux uncertainty is about 9% at T2K E_ν peak when using the thin target data
- T2K flux tuning with the T2K replica target data is ongoing → See poster by Tomislav Vladisavljevic
- Measurements for $\pi^\pm$ with replica target are expected to further reduces the error on flux to about 4% at T2K E_ν peak
- First-time spectra for $K^\pm$ are expected from ongoing analysis of the largest dataset with T2K replica → reduction of uncertainties for ν_e and high-energy tail of ν_μ flux

Other T2K Talks and Posters

Talks:

- Steve Dennis: T2K: Impact of Cross Section uncertainties on the oscillation anlaysis
- Alfonso Garcia: Muon neutrino inclusive CC cross section measurement on carbon and carbon/oxygen ratio at T2K
- Sophie King: Measurement of electron neutrino and antineutrino cross sections in the off-axis near detector at T2K
- Marcela Bartkiewicz: Pion production measurements at T2K
- Stephen Dolan: Neutrino charged current pionless cross section measurements from T2K
- Blair Jamieson: J-PARC Intermediate Water Cherenkov Detector

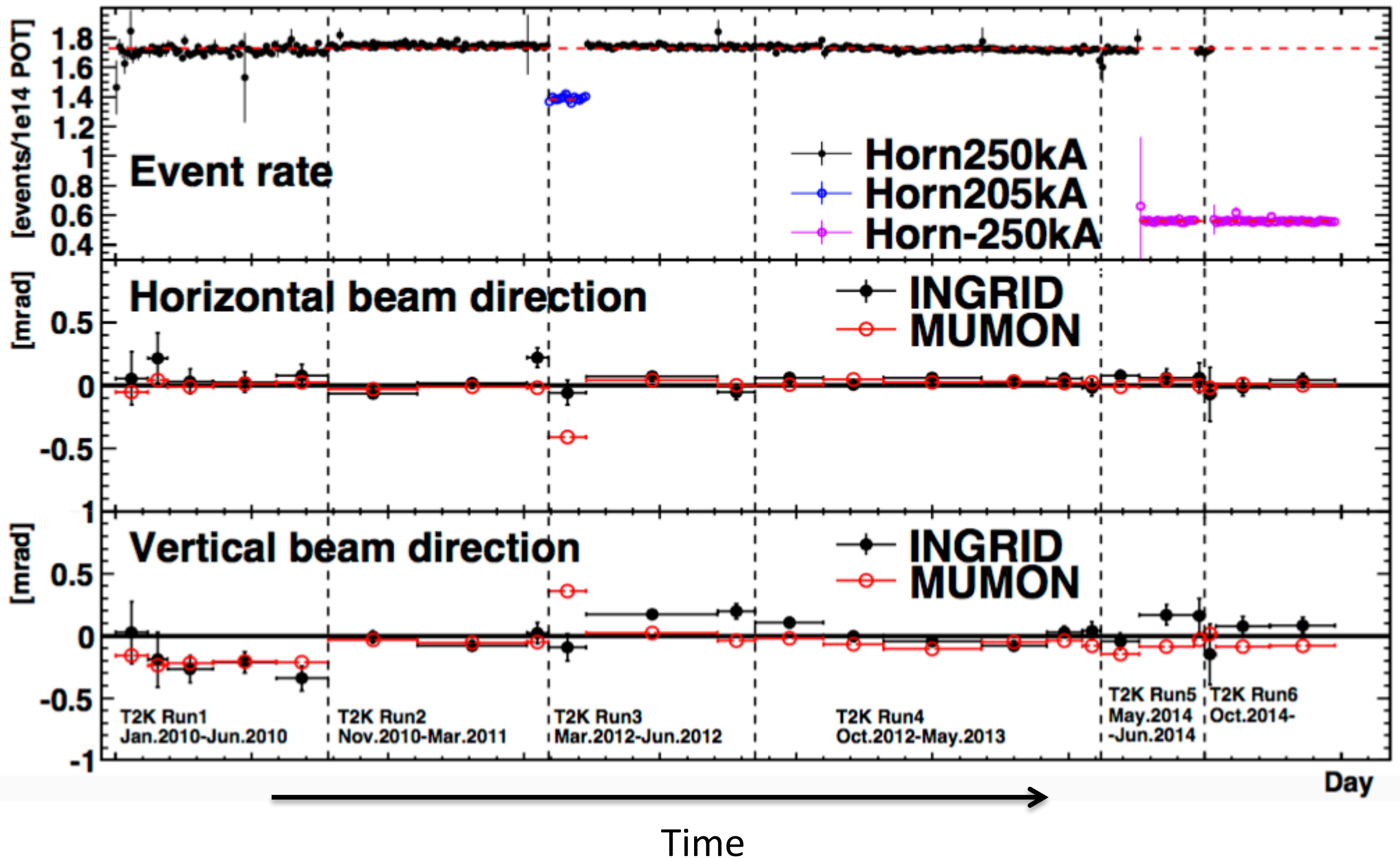
Posters:

- Stephen Dolan: Probing Nuclear Effects at the T2K Near Detector Using Transverse Kinematic Imbalance
- Fady Shaker: A New Framework To Extract The AntiNuE Cross Section At The T2K Off-Axis Near Detector
- Tomislav Vladisavljevic: Estimating the T2K Neutrino Flux with NA61/SHINE 2009 Replica-Target Data
- Andrew Cudd: Multinucleon Extication (2p2h) Model Comparison
- Lucas Koch: Muon neutrino interaction cross sections on argon gas in the T2K near detector
- Tomasz Wąchała: ν_μ CC-0π Interactions on Led in the Near Detector of the T2K Experiment
- Zoya Vallari: Neutral Current Single π^0 event rate on Water in Pi0 detector at T2K
- Teppei Katori: Search for NC1gamma production in ND280
- Mitchell Yu : Constraining the pion secondary interaction systematic uncertainties using ND280 data

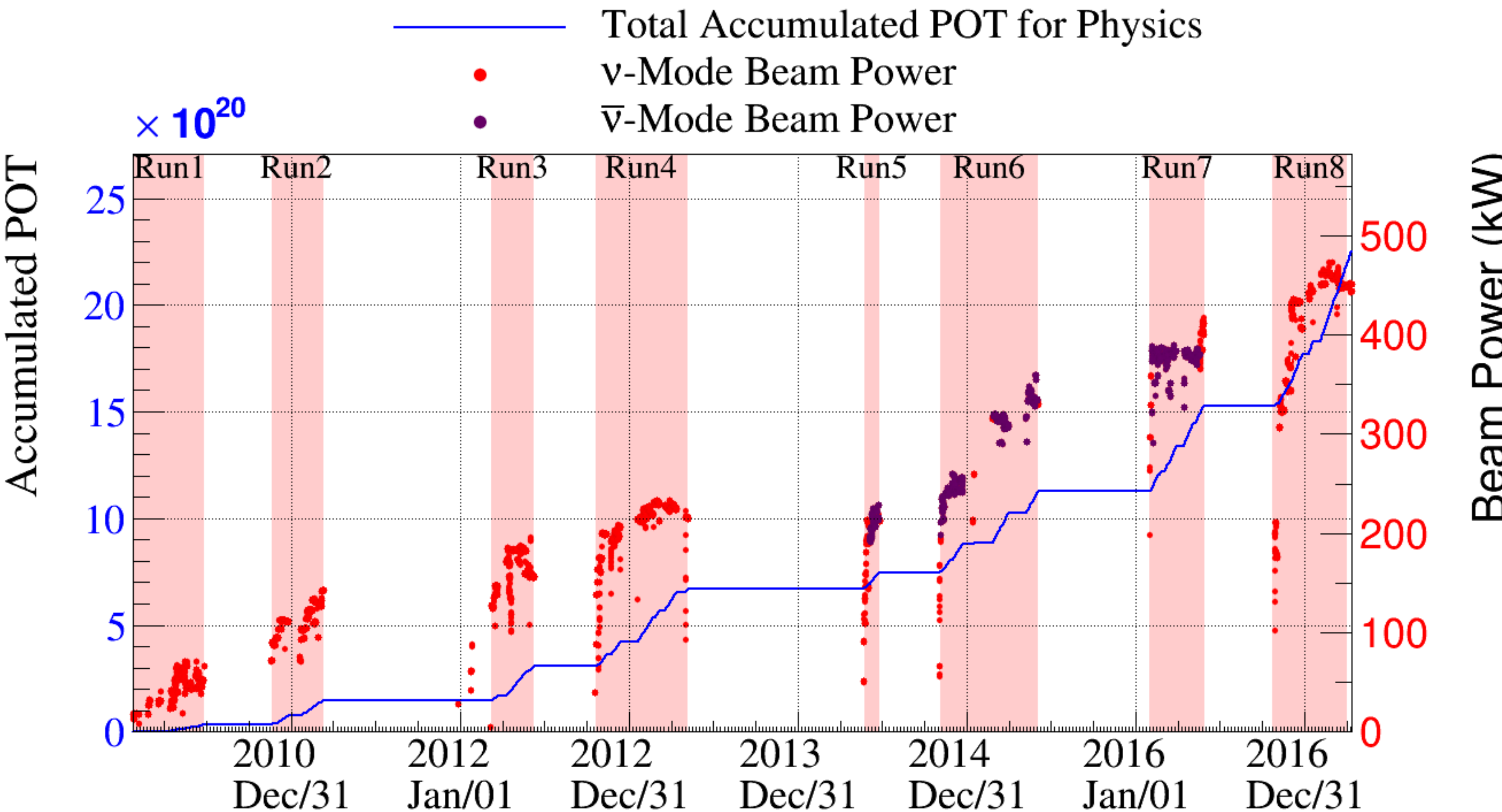
Backup Slides

Beam Stability Measurements

- INGRID is scintillator/iron tracking detectors on the beam axis
- Event rate normalized to POT is stable within 1%
- Beam direction is stable to within 1mrd → corresponds to 2% shift of the E_ν peak



Accumulated Data and Beam Power

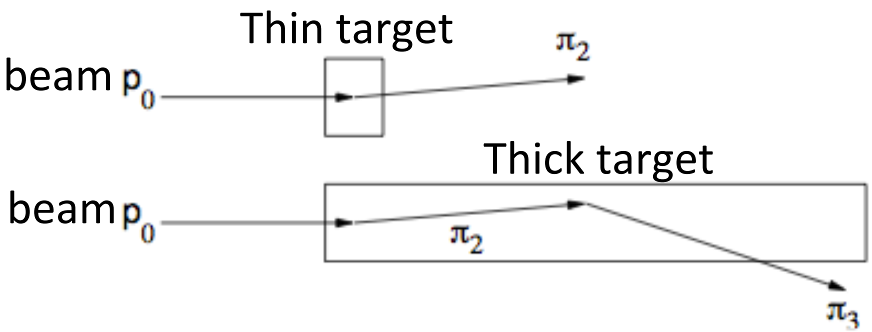


Total collected data : 2.25 x 10^{21} **P**roton **O**n **T**arget (POT)

- ν mode: 1.49 x 10^{21} POT
- anti-ν mode: 0.76 x 10^{21} POT

Stable beam operation achieved at 470 kW during Run 8

Importance of Pion Reinteractions in Target



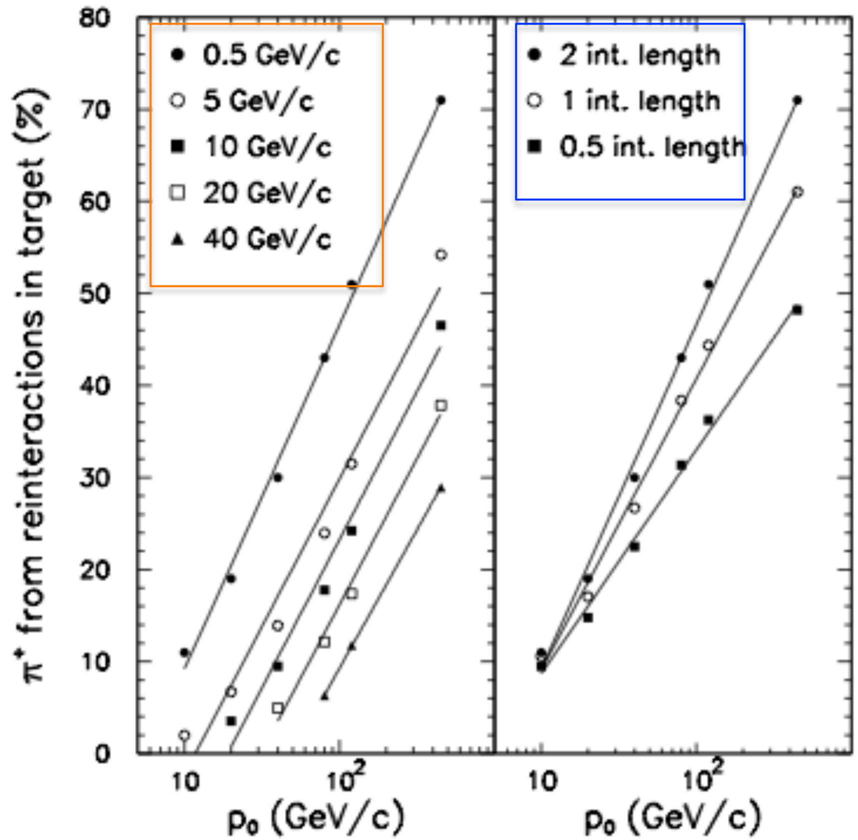
NuMI proton beam of 80-120GeV/c scatters off graphite target

About 20-40% of pions which yield ν_μ in MINERvA and MINOS were are not created directly in pC collisions

The fraction of pions from reinteractions grows:

- As the traget thinkness increases
- As the beam momentum increases (p_0)
- Pion momentum decreases

Fluka, the graphite target



Beam momentum

A good understanding of reinteractions is important for the precise flux determination

Derivation of Spectra

The corrected number of particles α in (p,θ) intervals with target inserted Δn_α^I and target removed Δn_α^R are used to calculate double differential cross section:

$$\frac{d^2\sigma_\alpha}{dpd\theta} = \frac{\sigma_{trig}}{1-\varepsilon}\left(\underbrace{\frac{1}{N^I}\frac{\Delta n_\alpha^I}{\Delta p \Delta\theta}}_{\text{Target-in}} - \underbrace{\frac{\varepsilon}{N^R}\frac{\Delta n_\alpha^R}{\Delta p \Delta\theta}}_{\text{Out-of target correction}}\right)$$

σ_{trig} – trigger cross section gives the probability to have an interaction in the target

σ_{trig} = 305.7±2.7(stat)±1.0(det)mb

ε – the ratio of interaction probabilities for removed and inserted target

ε=0.123±0.004

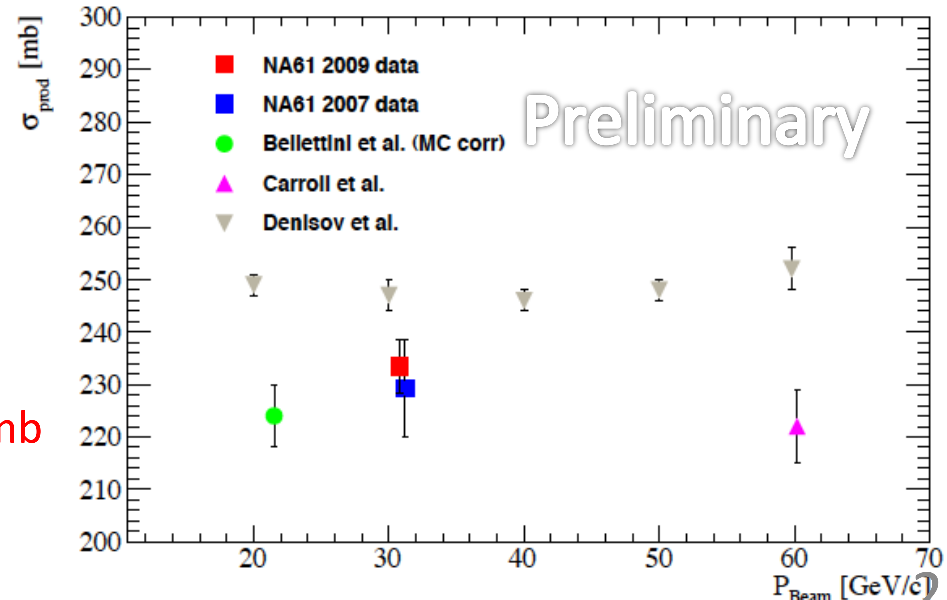
N_I, N_R – the number of events with target inserted and removed

The pion spectra normalized to the mean pion multiplicity in production interactions:

$$\frac{d^2\sigma_\alpha}{dpd\theta} = \frac{1}{\sigma_{prod}} \cdot \frac{d^2\sigma_\alpha}{dpd\theta}$$

σ_{prod} = 233.5±2.8(stat)±2.4(det) ± 3.5(mod)mb

σ_{prod} is one of contributions to systematic flux uncertainty



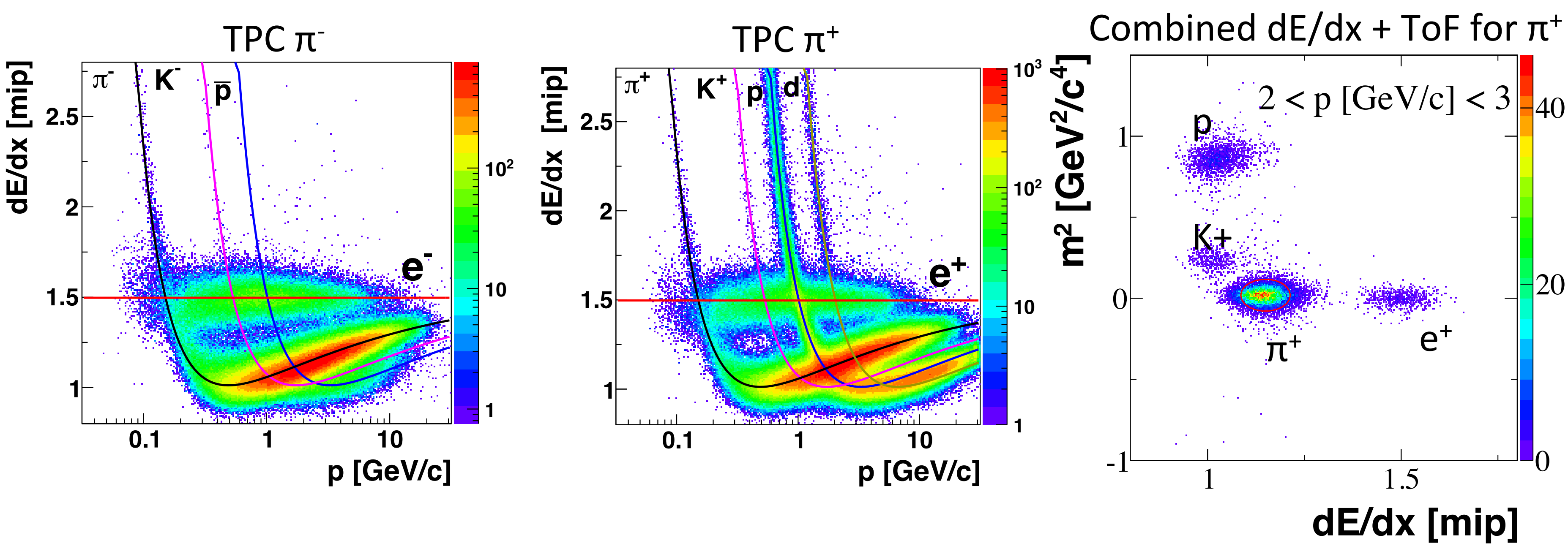
Analysis Methods for Charged Hadrons

There are 3 different analysis :

• h- analysis : no PID required, small non-pion contribution is subtracted using MC
Corrected spectra of π^- in a broad kinematic range

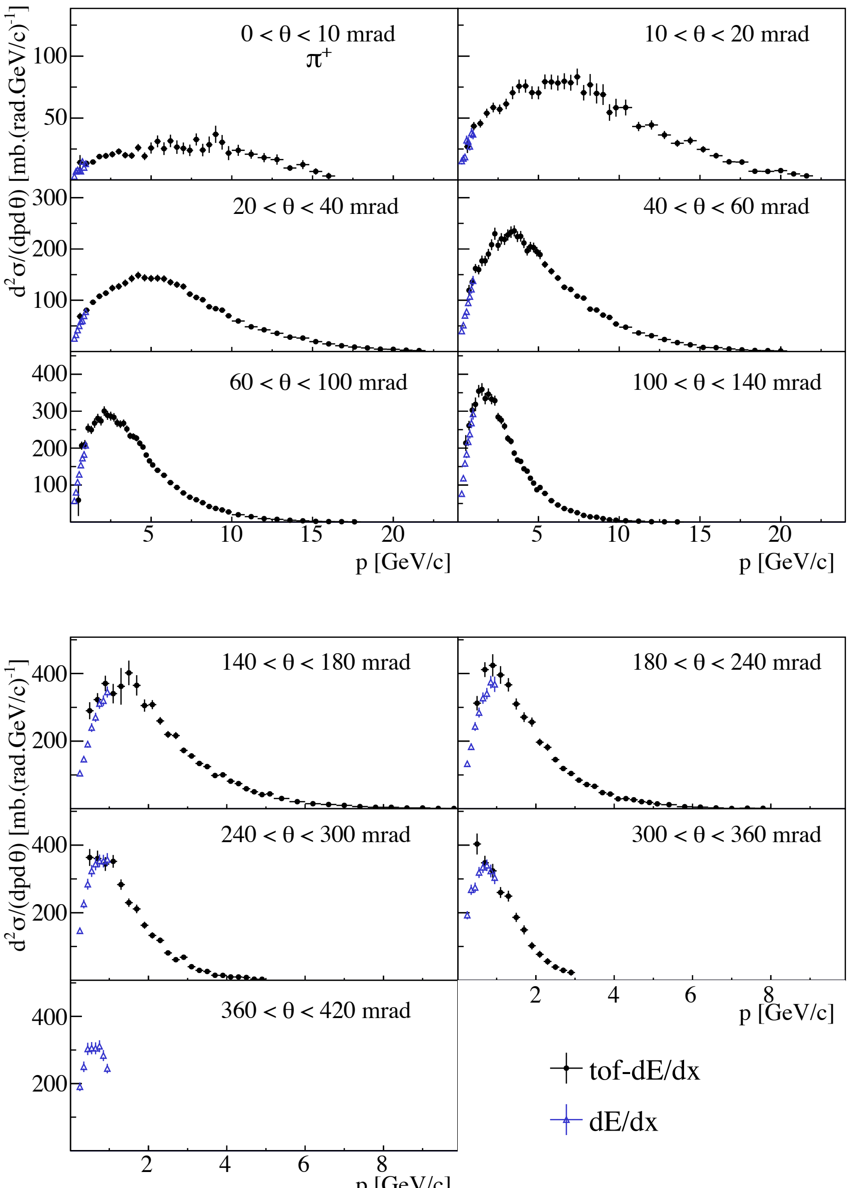
• dE/dx analysis at low p : yields fitted to dE/dx distributions at low momentum region
Corrected spectra of $\pi^{\pm}$,p up to 3GeV/C

• Combined dE/dx +ToF analysis: yield fitted to 2-dimentional m^2 versus dE/dx distributions
Corrected spectra of $\pi^{\pm}$,$K^{\pm}$,p above 1GeV/C

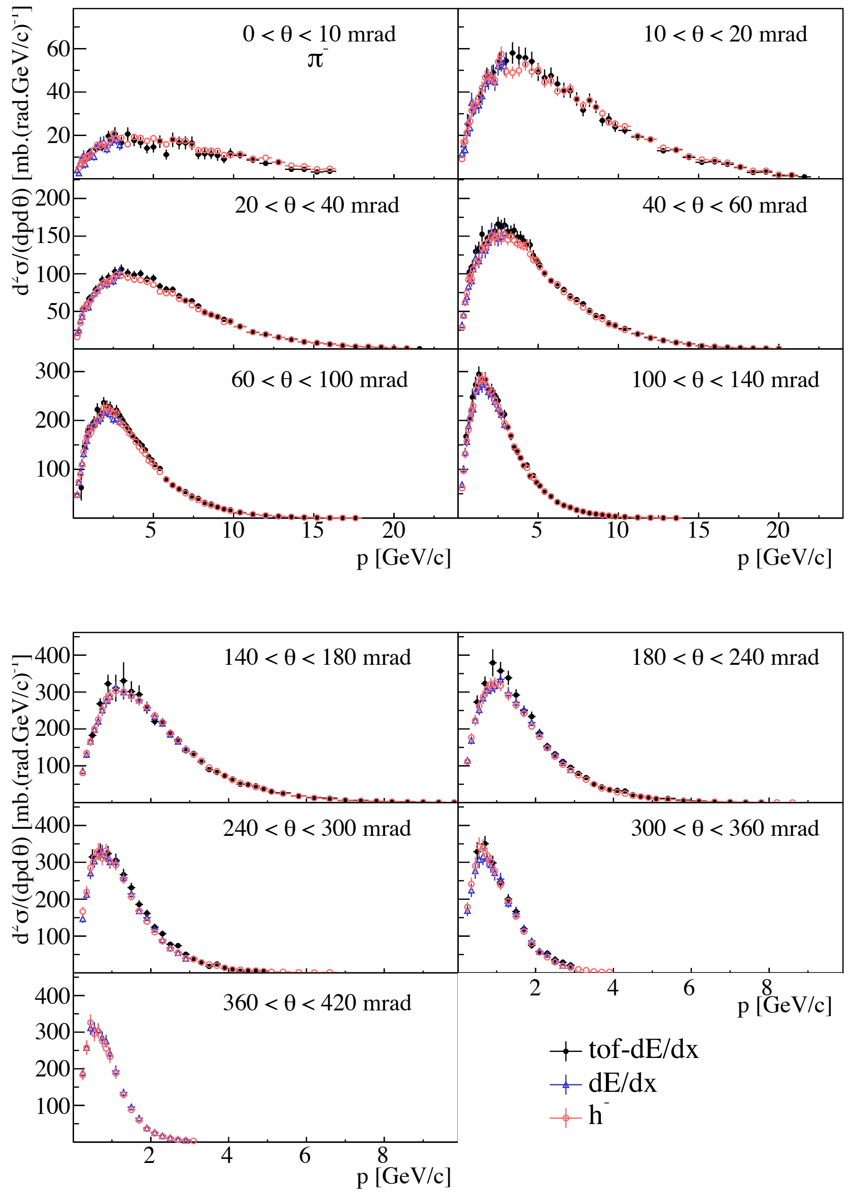


π± Measurements with Thin Target Data

π^+ Multiplicities



π^- Multiplicities

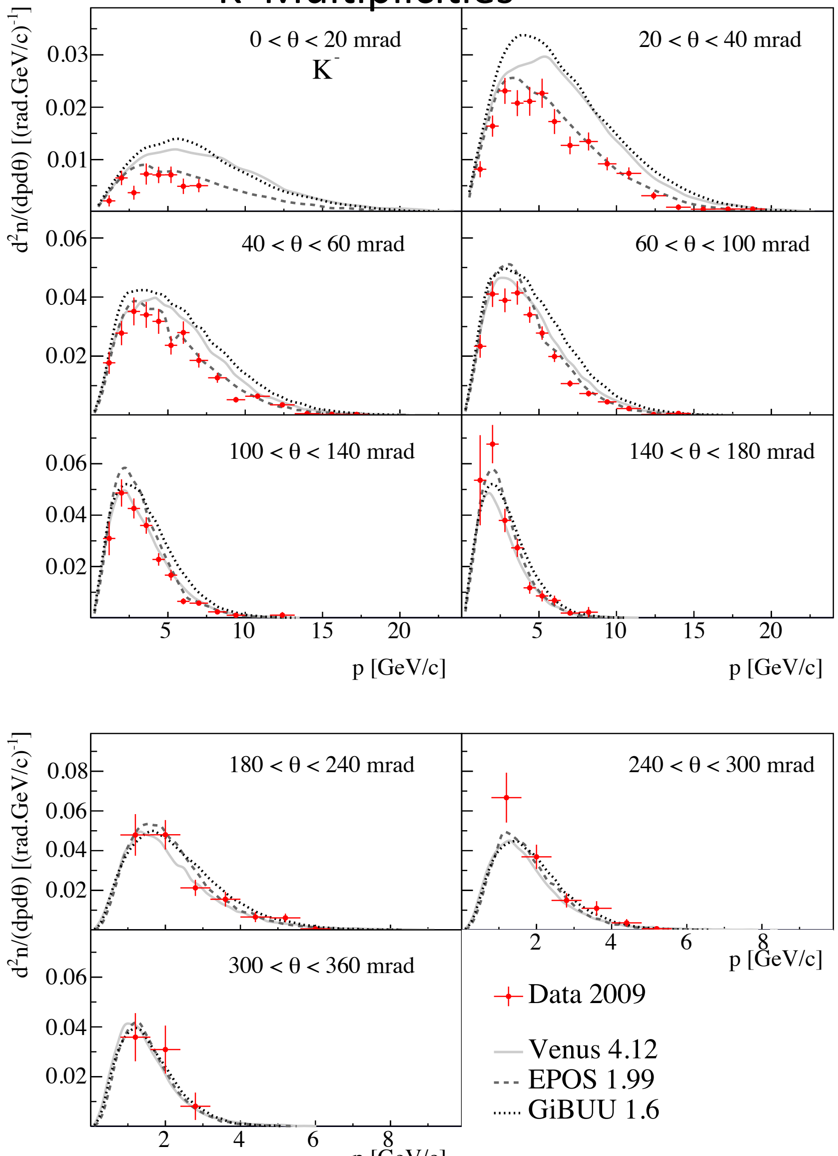


Relative errors in the region of the T2K interest ~4%

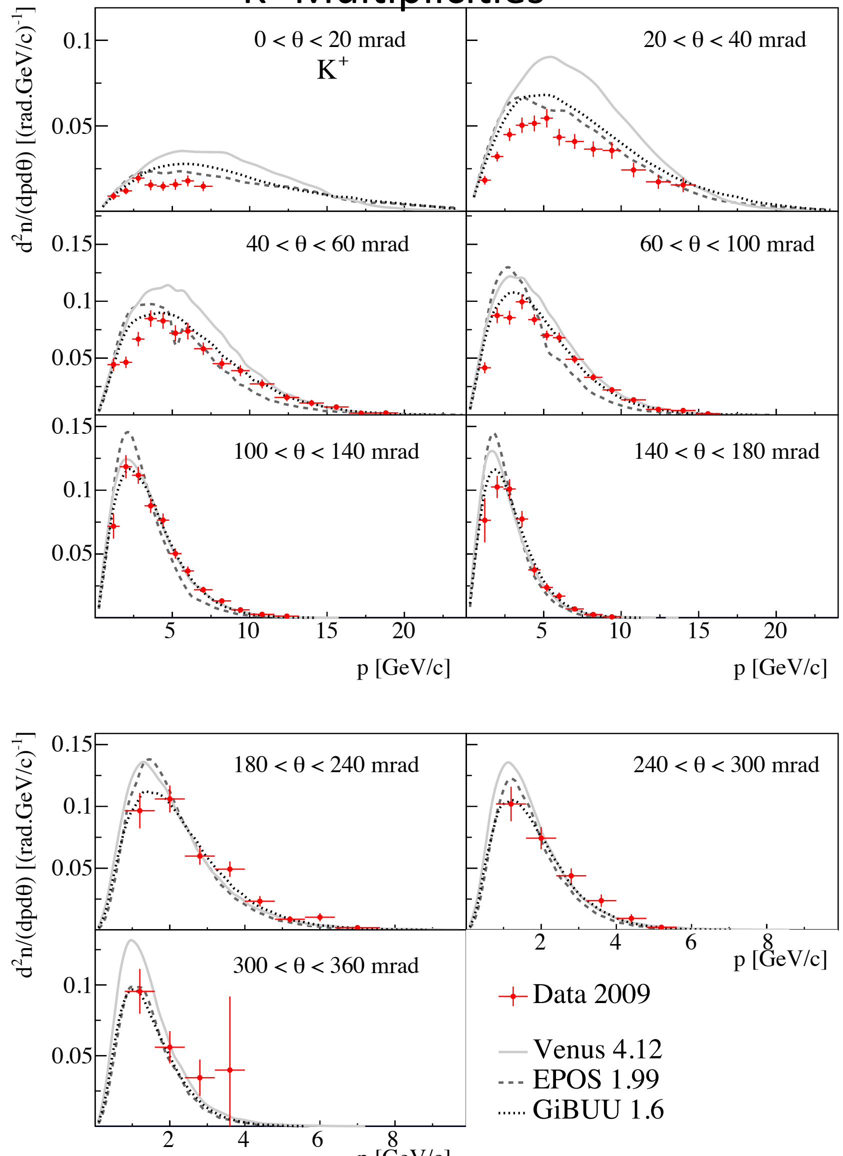
$K^{\pm}$ Measurements with Thin Target Data

Important for ν_e and high energy tail of ν_μ flux in T2K

K^- Multiplicities



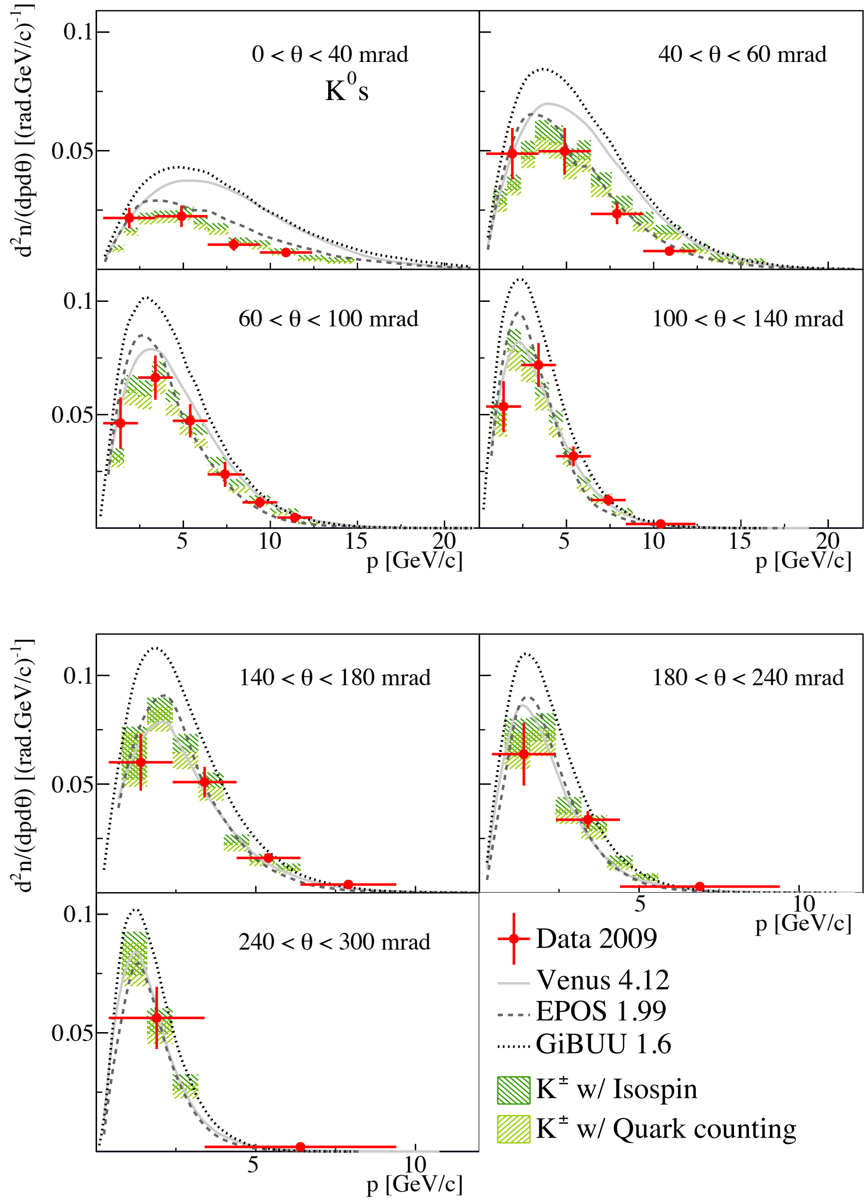
K^+ Multiplicities

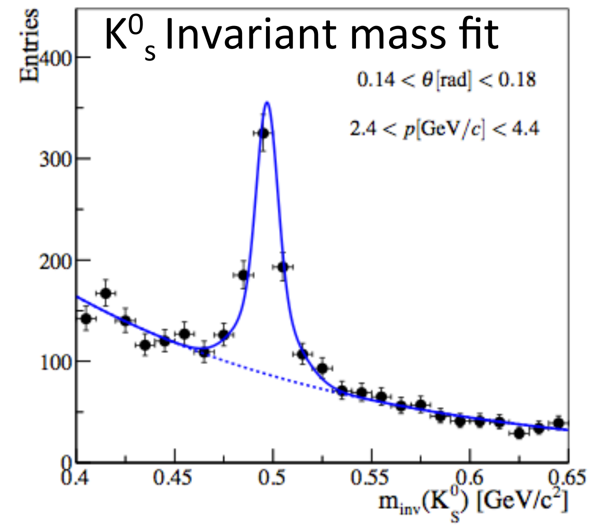


Relative errors in the T2K region of interest ~15%

K^0_S Analysis

$K^0_L \to \pi^- e^+ \nu_e$ is the main source of high energy ν_e at T2K





K^0_S yields can be predicted from $K^\pm$ measurements using:

- the isospin symmetry assumption:

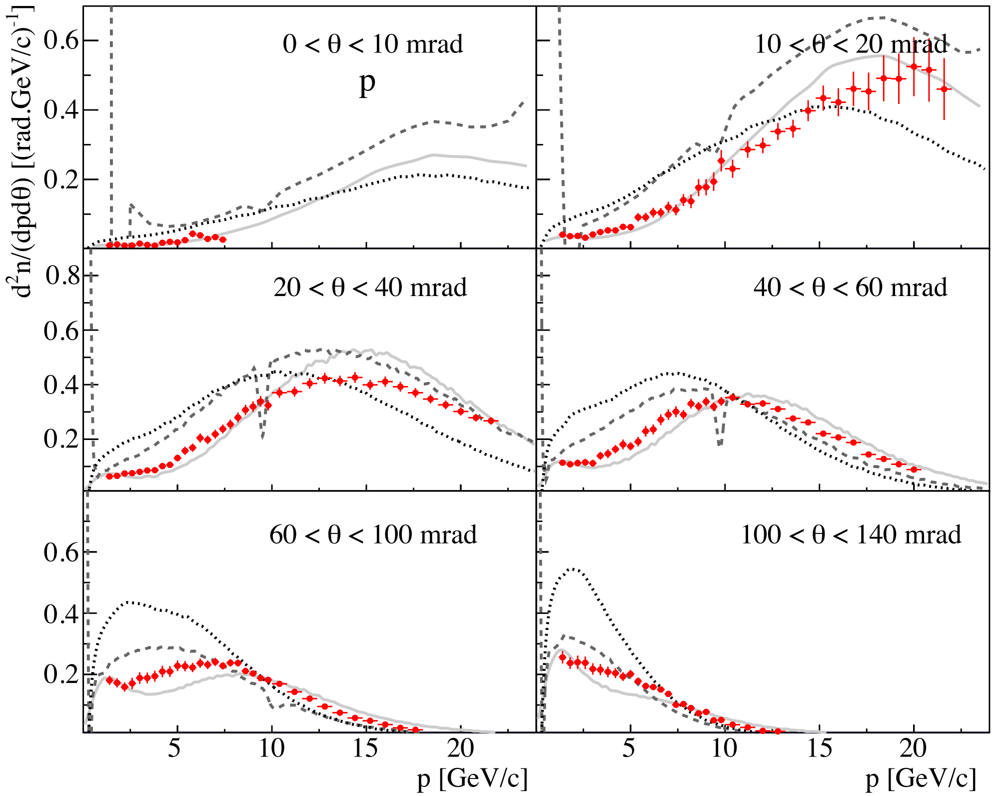
$$N(K^0_S) = \frac{1}{2}(N(K^+) + N(K^-))$$

- the quark-counting argument:

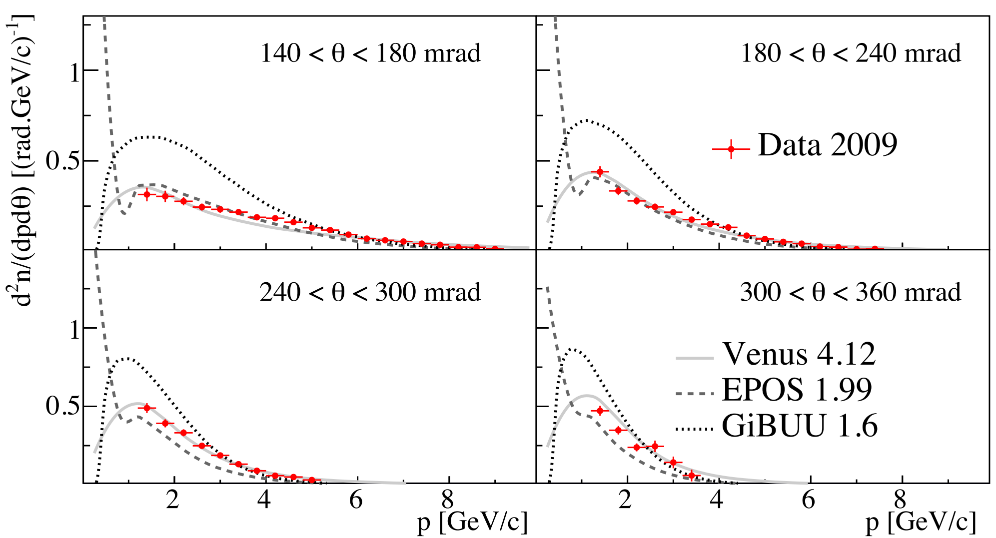
$$N(K^0_S) = \frac{1}{8}(3N(K^+) + 5N(K^-))$$

Good agreement of K^0_S yields predicted from $K^\pm$ measurements

Protons

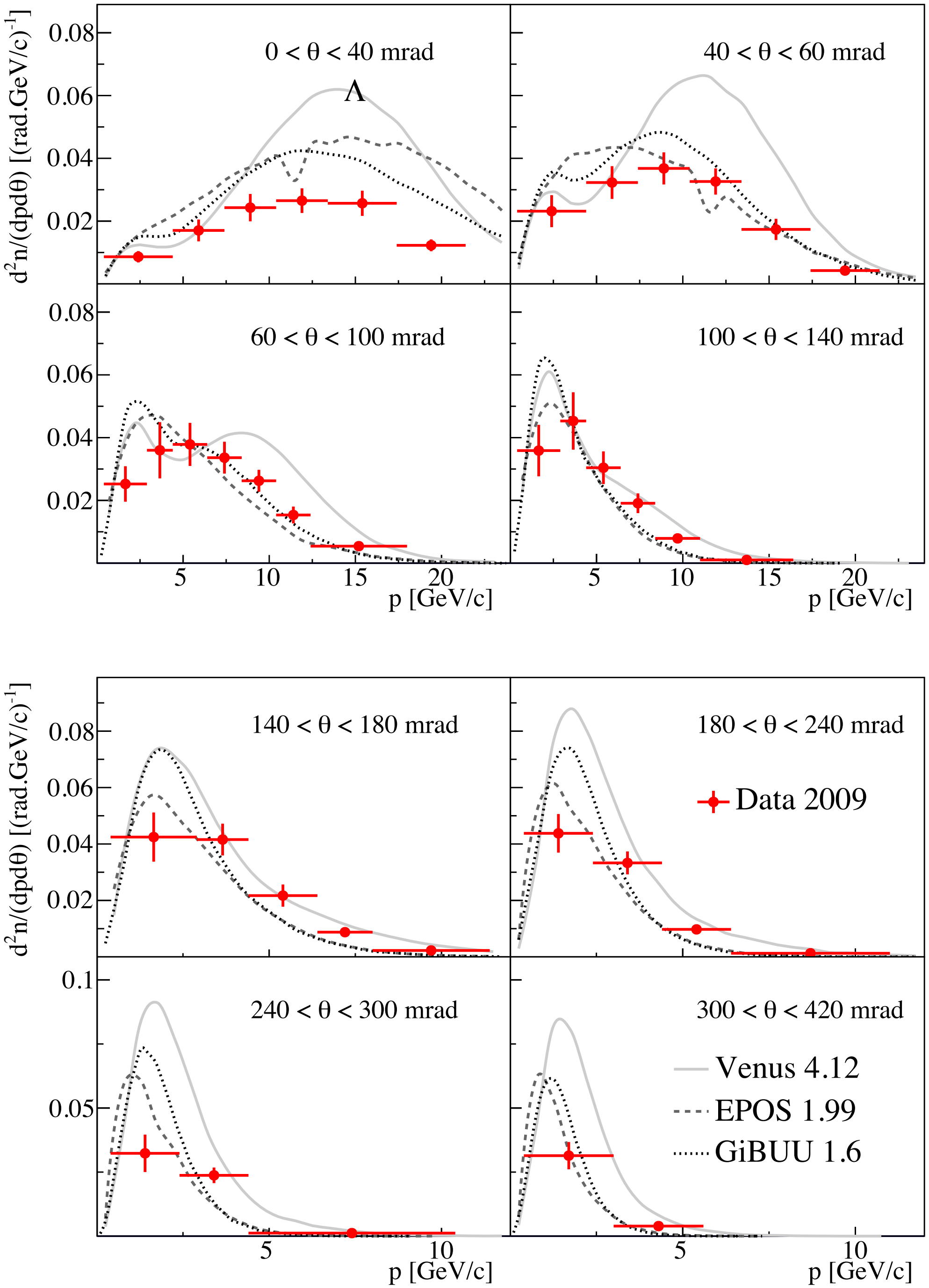


0 < θ < 10 mrad
p
10 < θ < 20 mrad
20 < θ < 40 mrad
40 < θ < 60 mrad
60 < θ < 100 mrad
100 < θ < 140 mrad
d²n/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]



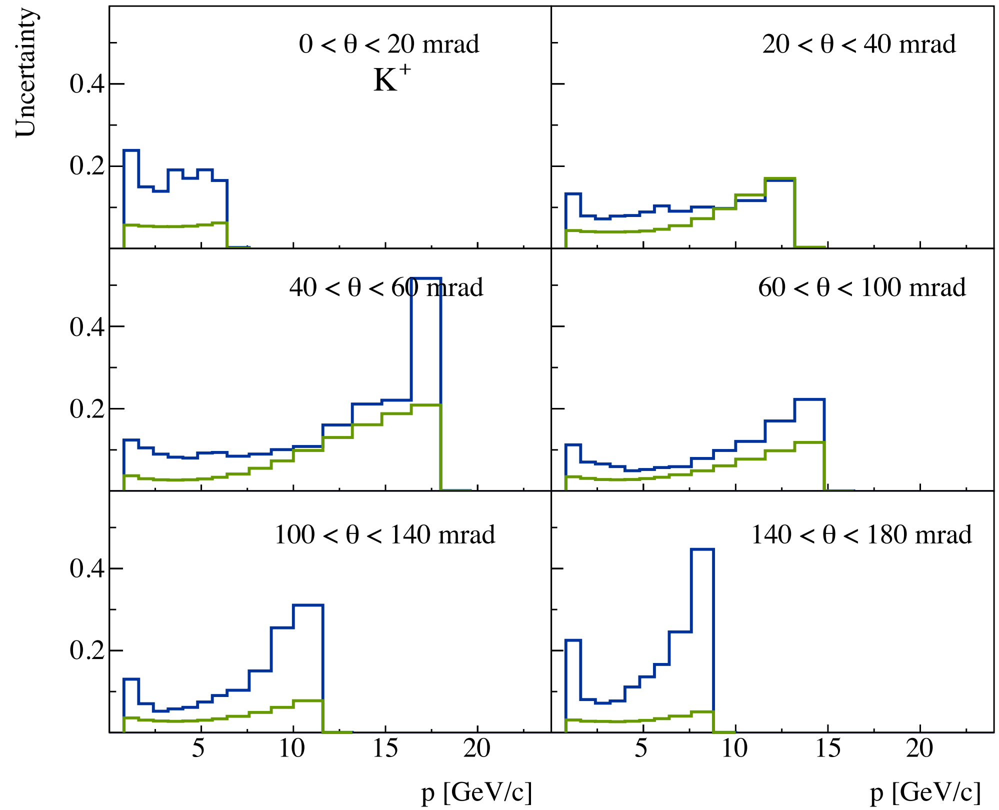
140 < θ < 180 mrad
180 < θ < 240 mrad
Data 2009
240 < θ < 300 mrad
300 < θ < 360 mrad
Venus 4.12
EPOS 1.99
GiBUU 1.6
d²n/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]

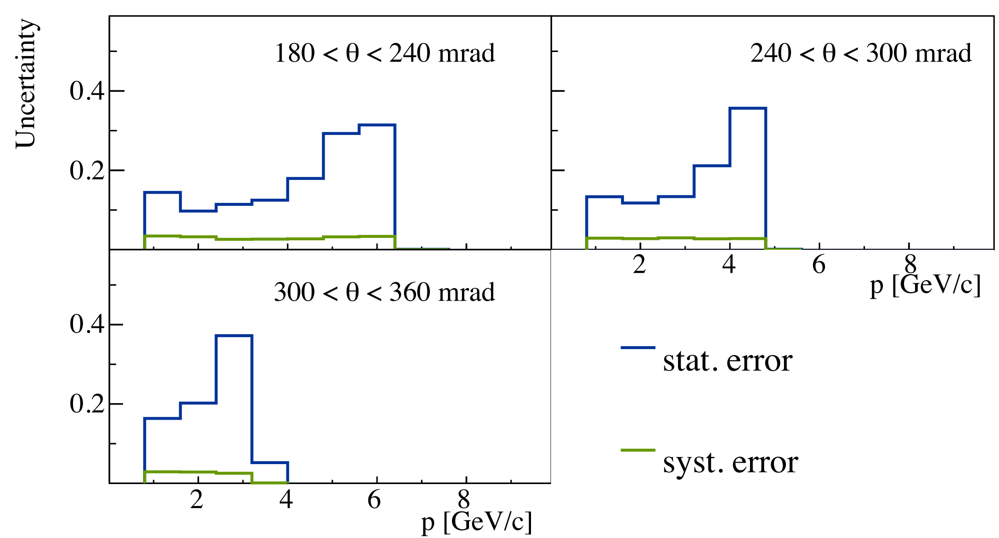
Λ^0



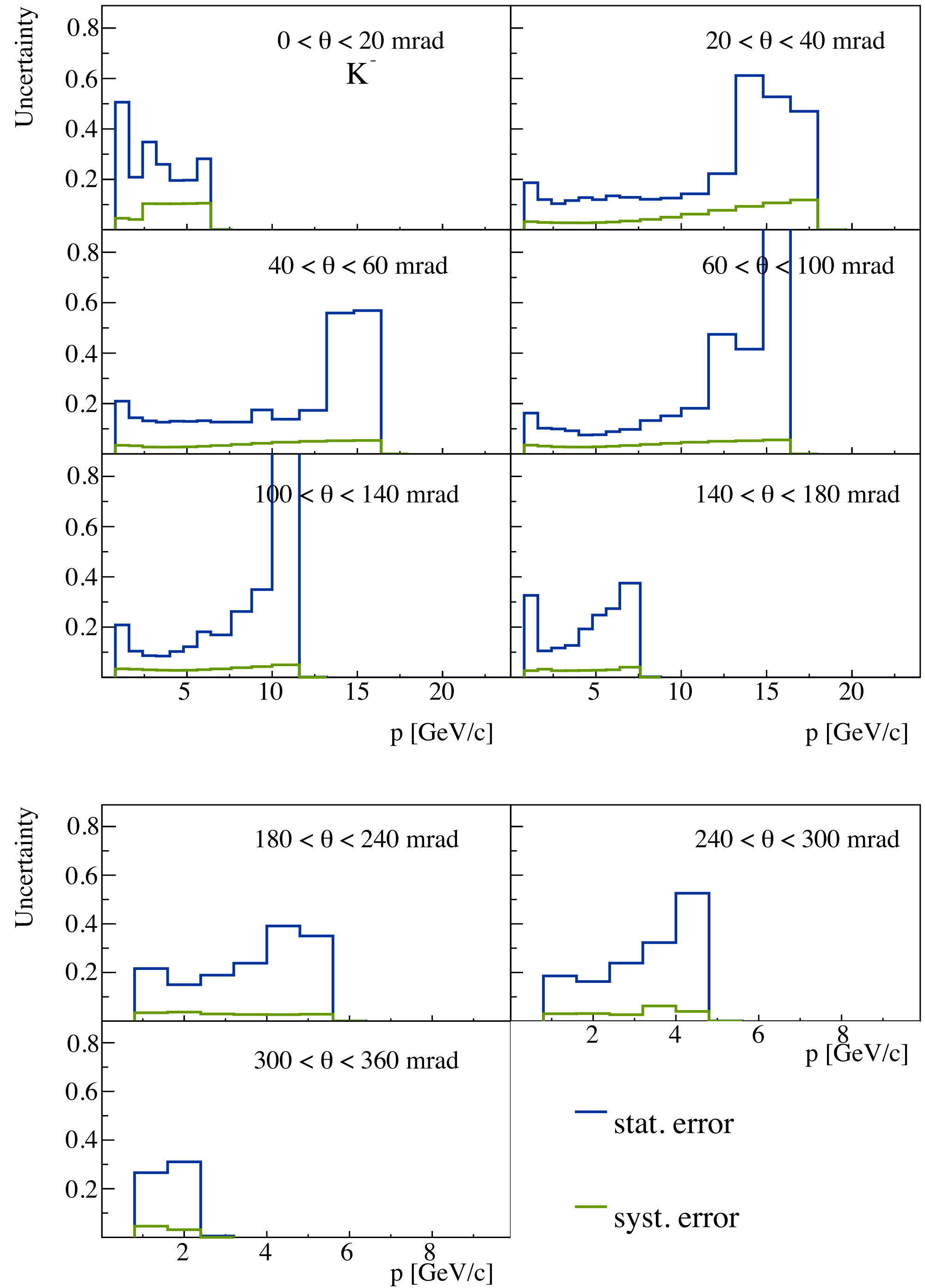
0 < θ < 40 mrad
Λ
40 < θ < 60 mrad
60 < θ < 100 mrad
100 < θ < 140 mrad
140 < θ < 180 mrad
180 < θ < 240 mrad
240 < θ < 300 mrad
300 < θ < 420 mrad
d²n/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]
Data 2009
Venus 4.12
EPOS 1.99
GiBUU 1.6

K+ Uncertainties





K- Uncertainties

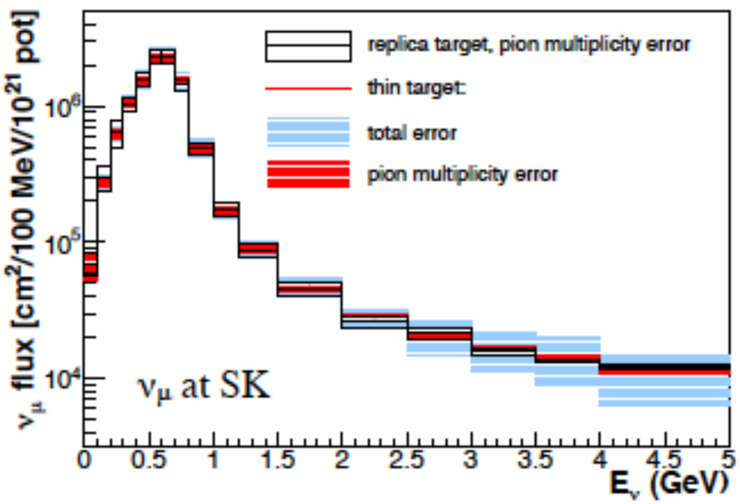


Long Target Analysis

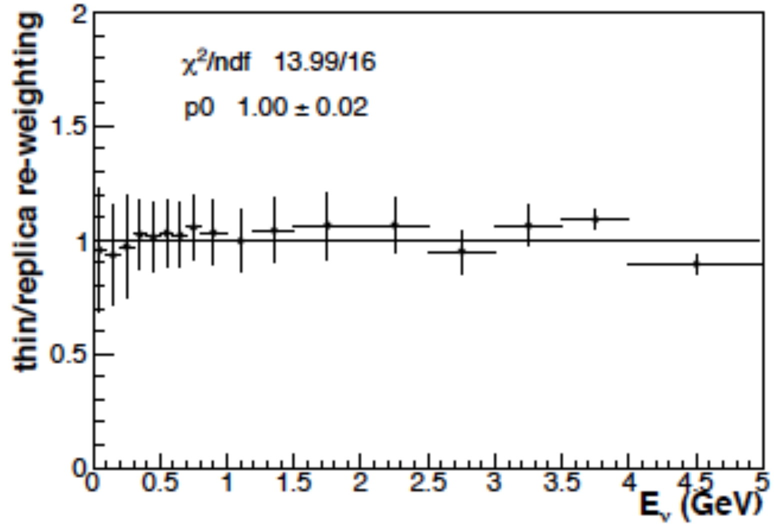
Neutrinos are coming from hadrons produced in the **primary interactions** of the proton beam (~60%) and in **interactions of secondary particles**, either in the target (~30%) or outside the target (~10%)

90% of the flux is constrained with the replica target

The 2007 pilot run

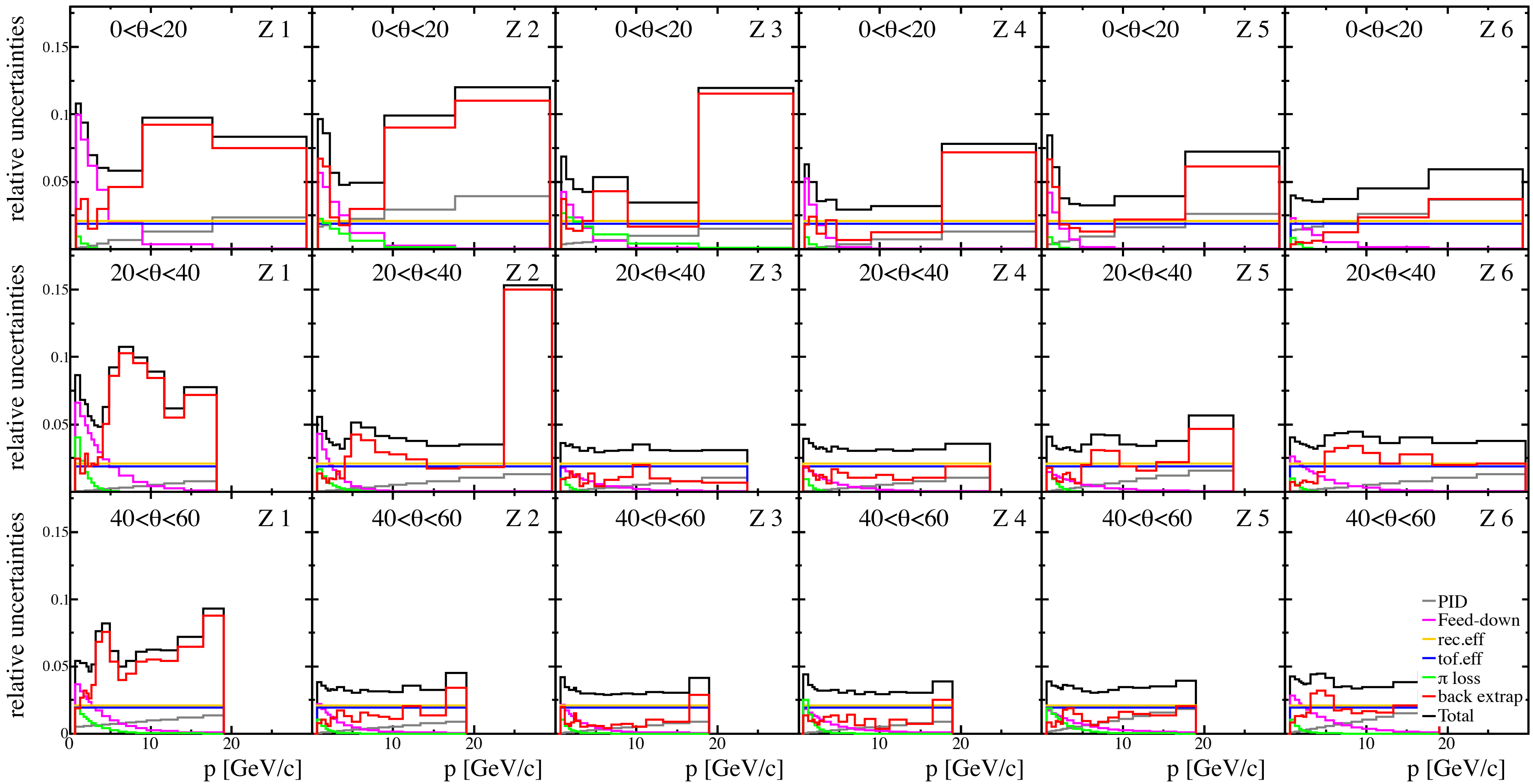


Thin to replica ratio for π (the 2007 pilot run)



The flux tuning method was tested with small 2007 pilot data. The method was applied to 14x larger sample (the 2009 dataset).

Systematics for 2009 π- Measurements with Long Target



Ongoing Analysis of Long Target Largest Dataset

- Analysis of 3x bigger statistics that previously is ongoing
- Extraction of $K^{\pm}$ as well as proton spectra possible

Moriond 2016, M.Pavin

Uncorrected spectra