Hadron Production Measurements from NA61/SHINE for Neutrino Flux Predictions

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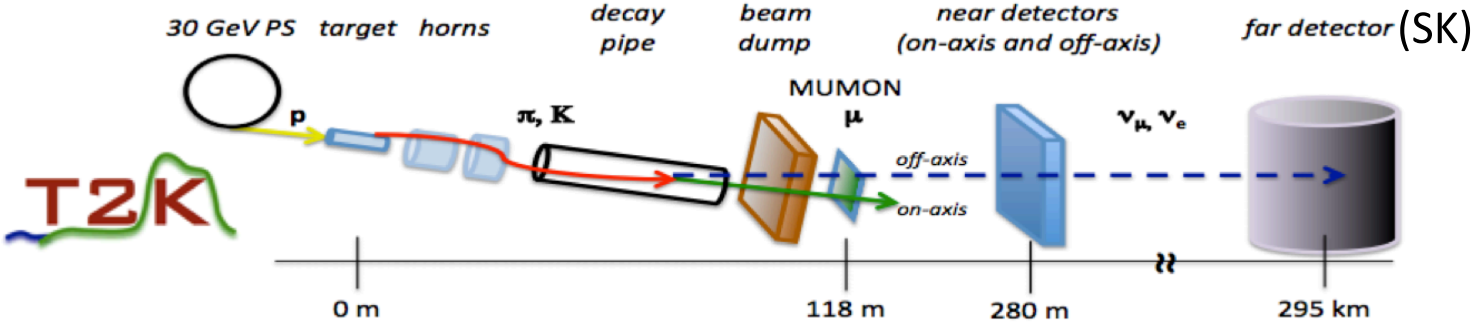
On behalf of the NA61/SHINE Collaboration

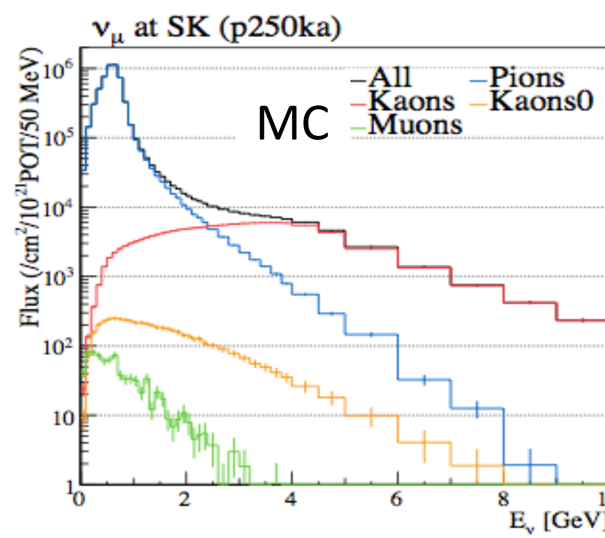
27th Rencontres de Blois, 31 May - 5 June 2015

Motivation for Hadron Production Measurements

Hadron production at present is one of the dominant uncertainties in the neutrino flux predictions at accelerator based neutrino experiments.

Example T2K : secondary π and K are focused to obtain neutrino beams



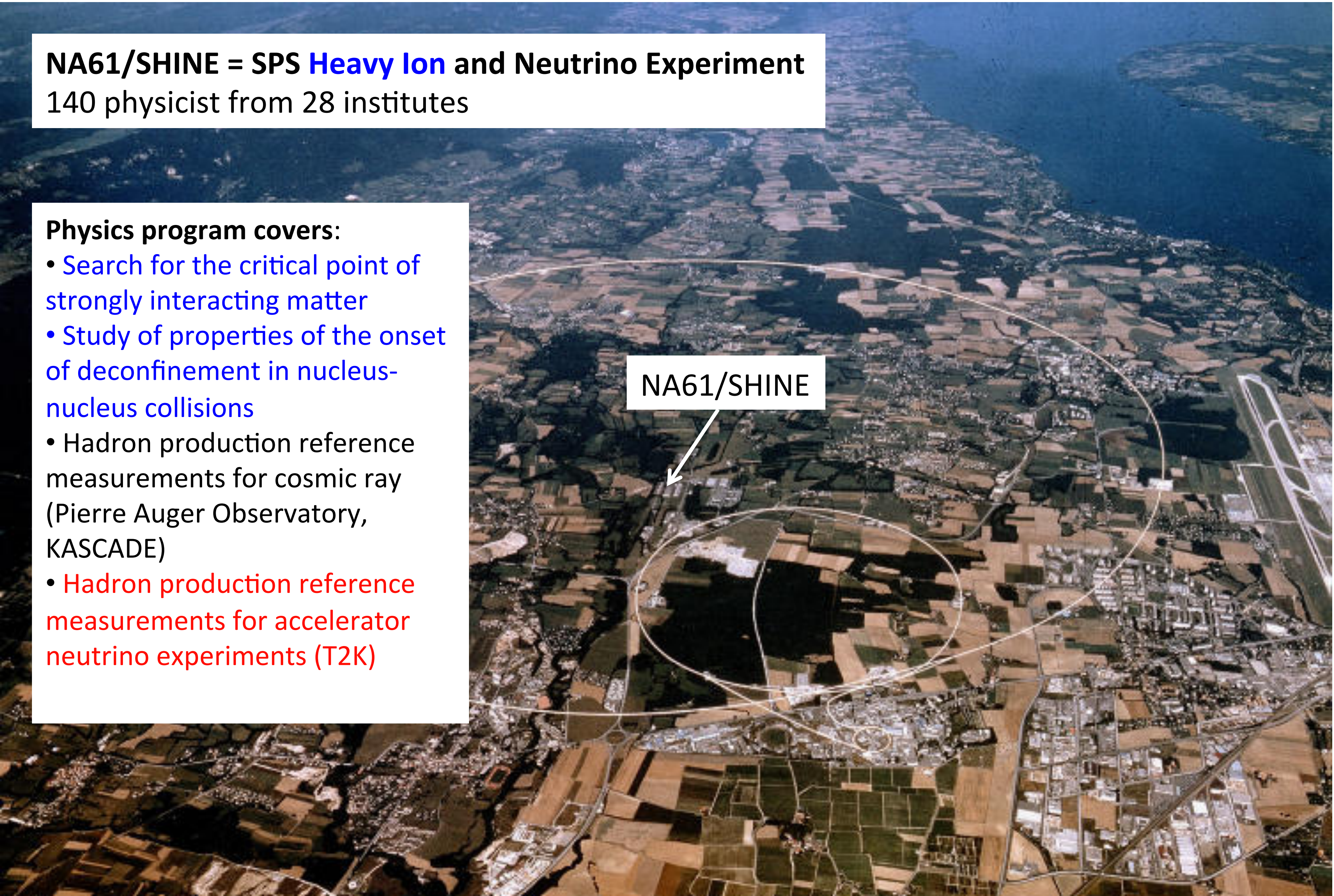


By measuring hadron spectra in experiments such as NA61/SHINE one can replace model predicted hadron interactions rates with data to determine the neutrino flux.

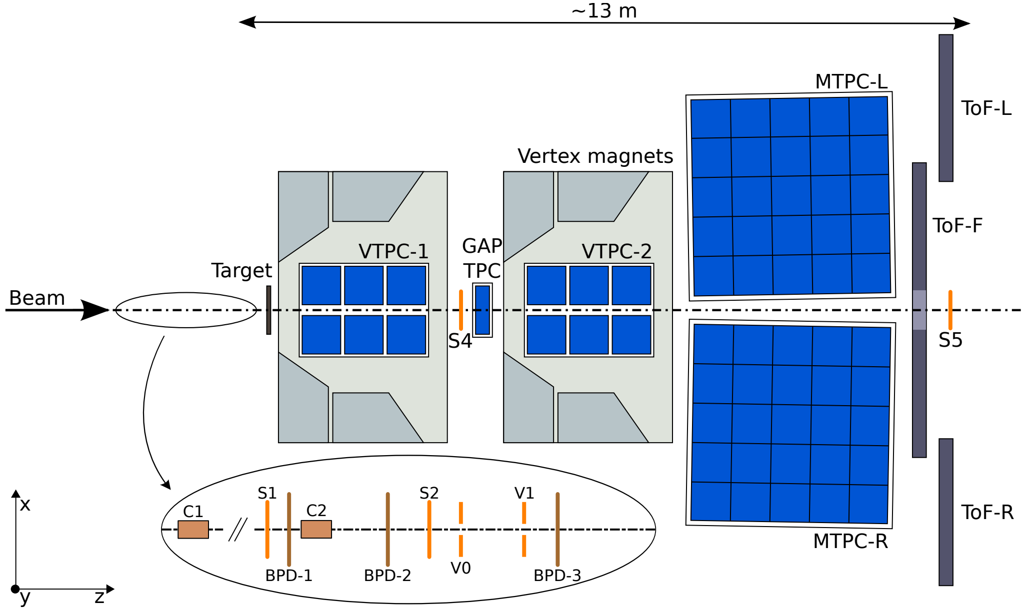
The NA61/SHINE Experiment at CERN SPS

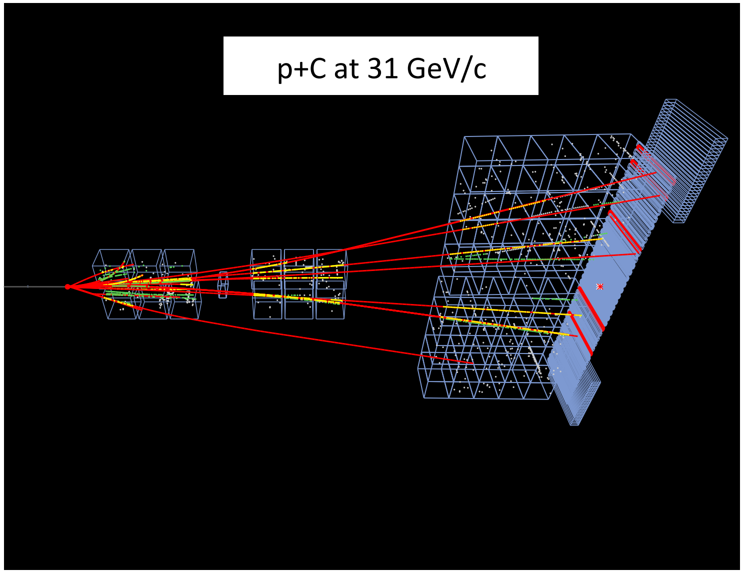
NA61/SHINE = SPS Heavy Ion and Neutrino Experiment
140 physicist from 28 institutes

Physics program covers:
- Search for the critical point of strongly interacting matter
- Study of properties of the onset of deconfinement in nucleus-nucleus collisions
- Hadron production reference measurements for cosmic ray (Pierre Auger Observatory, KASCADE)
- Hadron production reference measurements for accelerator neutrino experiments (T2K)



NA61/SHINE Experimental Setup





Fixed target experiment at CERN SPS with the large acceptance spectrometer.

- **Time Projection Chambers** : tracking and particle identification
  - Two vertex TPCs located between coils of superconducting magnets (1.14Tm)
  - Momentum resolution $\sigma(p)/p^2 \approx 10^{-4}\,(GeV/c)^{-1}$
  - Particle identification : $\sigma(dE/dx)/ \langle dE/dx \rangle \approx 4\%$

- **Time of Flight:** particle identification
  - New ToF-F array installed to fully cover T2K acceptance
  - Time resolution $\sigma(t)$ToF-F ≈ 120ps, $\sigma(t)$ToF-L/R ≈ 80ps

TPC and ToF detectors provide very good particle identification

NA61/SHINE Hadron Production Data

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
π^-+C	158	2009	5.5
π^-+C	350	2009	4.6
p+p	13	2010	0.7
p+p	13	2011	1.4
p+p	20	2009	2.2
p+p	31	2009	3.1
p+p	40	2009	5.2
p+p	80	2009	4.5
p+p	158	2009	3.5
p+p	158	2010	44.0
p+p	158	2011	15.0
p+Pb	158	2012	4.5
p+Pb	158	2014	18

Data taken to constrain T2K flux predictions:
- 2007 published, pilot run
- **2009 new preliminary results**, large statistics for thin target and first results for replica
- 2010 calibrated, to be analyzed

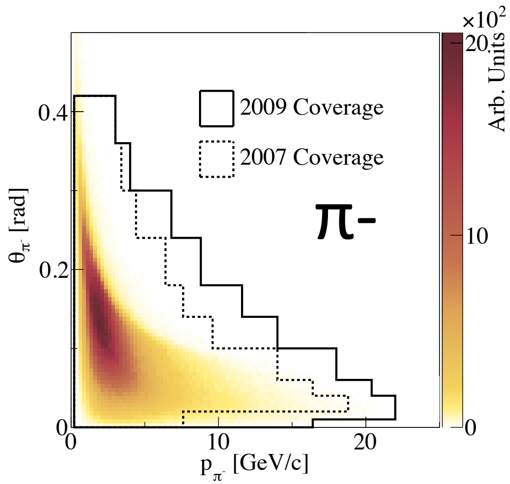
Targets used:
- **thin carbon** (2cm, $0.04\lambda_I$): hadrons from primary interactions
- **T2K replica** (90cm,$1.9\lambda_I$): hadrons from primary and secondary interactions

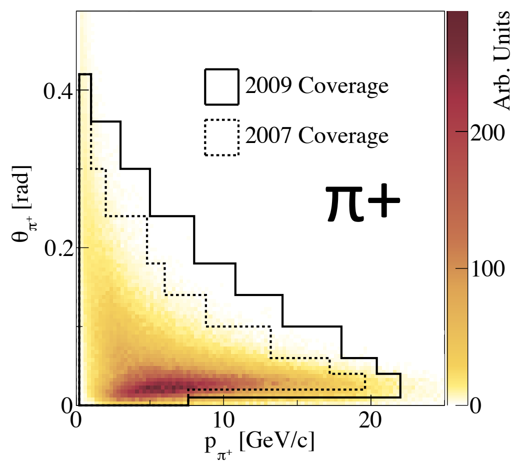
Measured spectra :
Thin target: $\pi\pm$, $K\pm$, K^0_S, Λ, protons
Replica target: $\pi\pm$

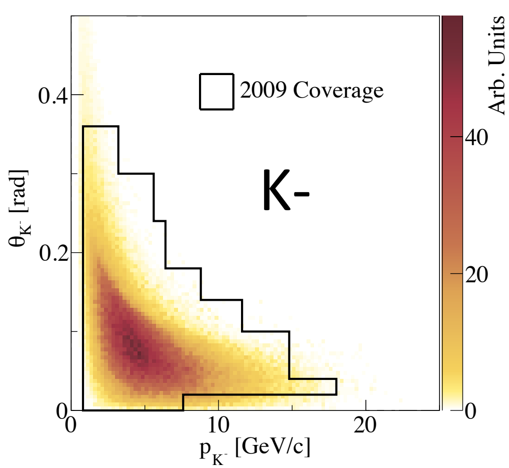
2015: Ar+Sc: 13-150GeV, in the fall of 2015 Pb+Pb and neutrino program for Fermilab

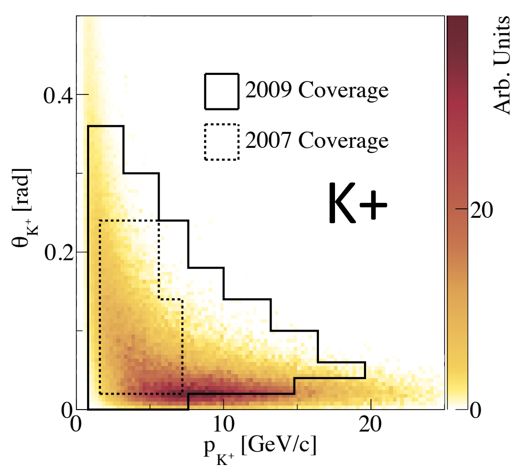
Hadron Measurements on Thin Target

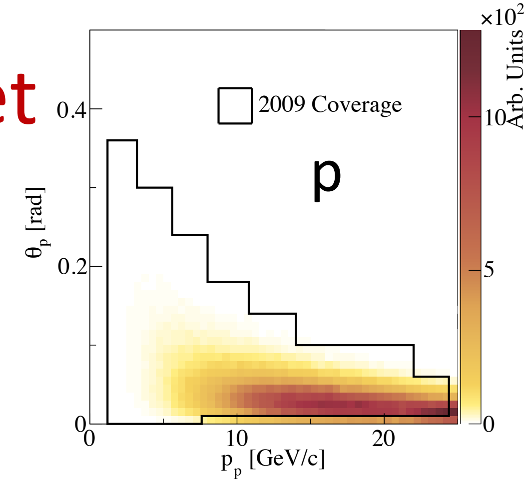
The phase space contributing to the predicted neutrino flux at SK and the NA61 data coverage.

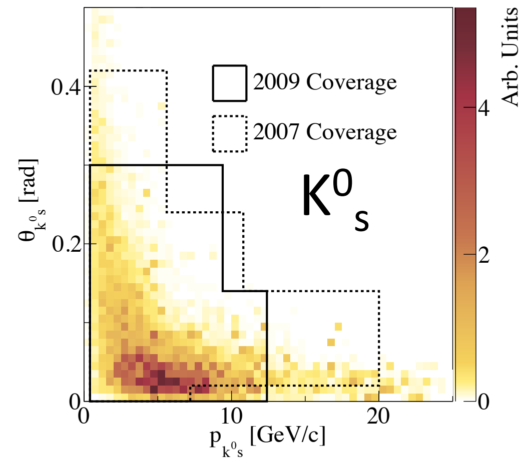


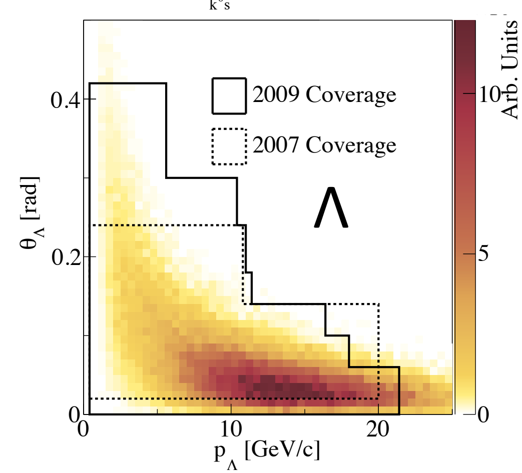












Analysis Methods for Charged Hadrons

There are 3 different analysis :

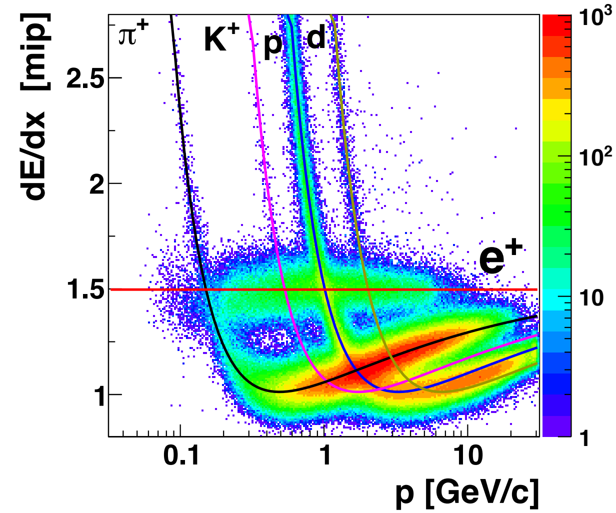
• h- analysis : no PID required, small non-pion contribution is subtracted using Monte Carlo simulations
Corrected spectra of π^- in a broad kinematic range

• dE/dx analysis at low p : yields fitted to dE/dx distributions at low momentum region
Corrected spectra of π±,p up to 3GeV/C

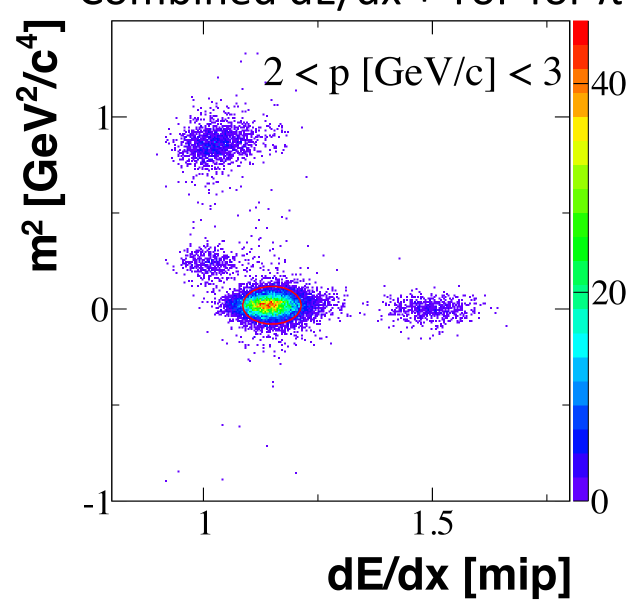
• Combined dE/dx +ToF analysis: yield fitted to 2-dimentional m^2 versus dE/dx distributions
Corrected spectra of π±,K±,p above 1GeV/C

The raw spectra are corrected for :
• geometrical acceptance,
• reconstruction efficiency,
• non-pion contribution (h-analysis),
• secondary interactions and weak decays (feed-down)

TPC π+



Combined dE/dx + ToF for π+



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

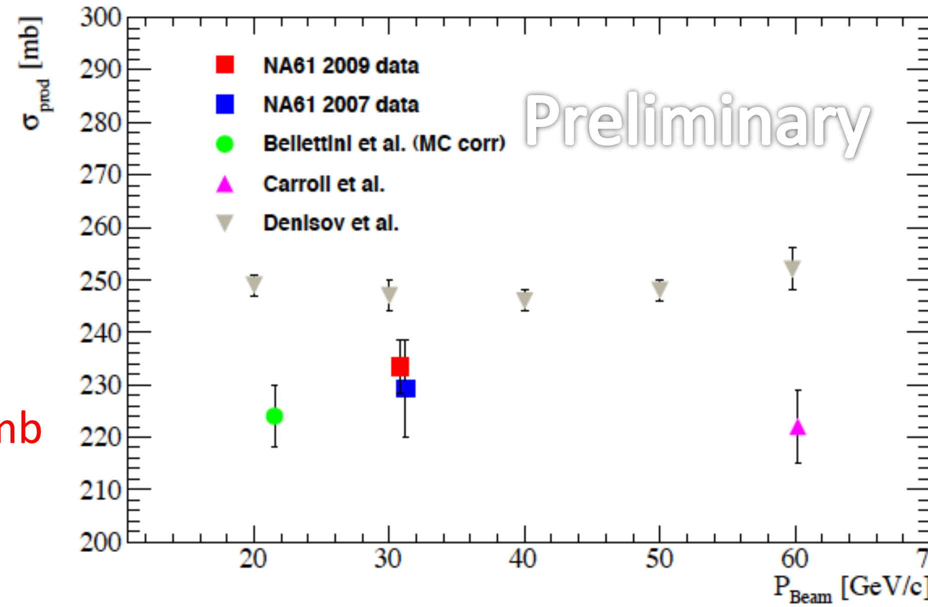
N_I, N_R – the number of events with target inserted and removed

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

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

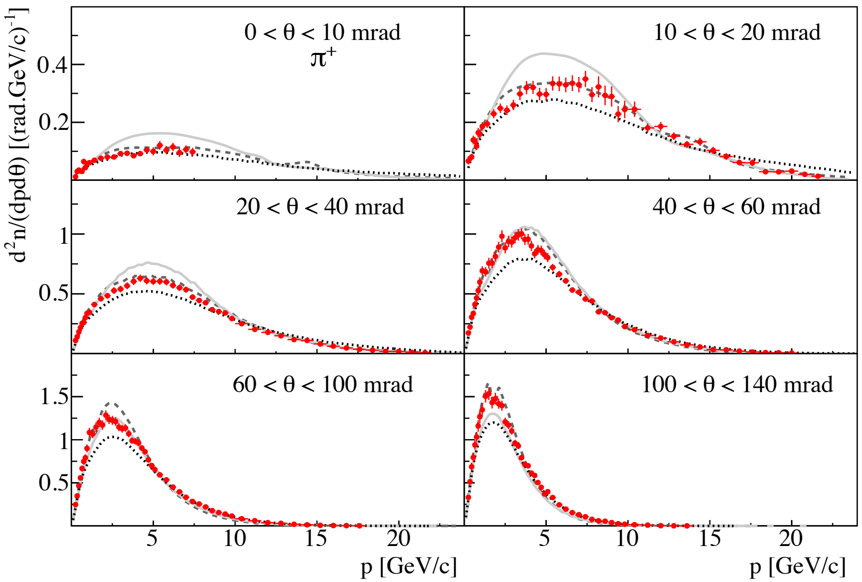
σ_{prod} = 233.5±2.8(stat)±2.4(det) ± 3.5(mod)mb

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

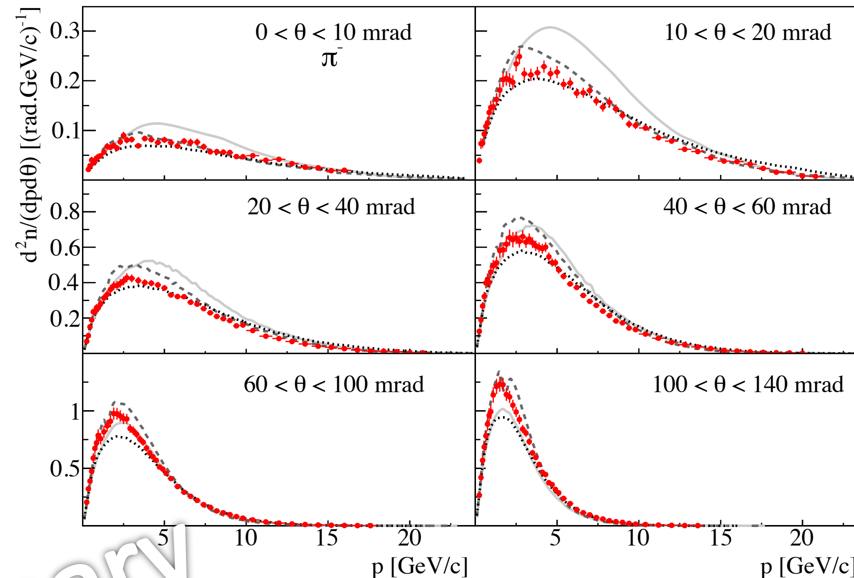


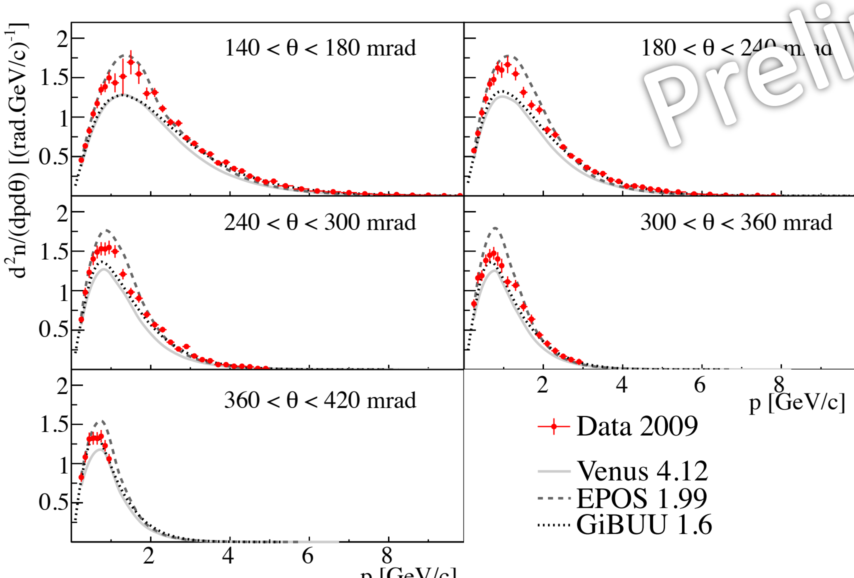
π± Measurements with Thin Target Data

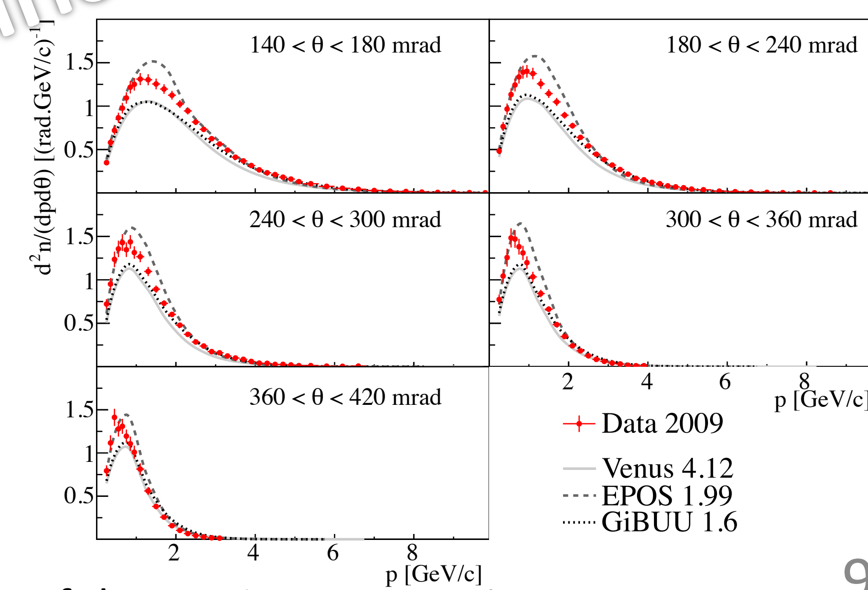
π^+ Multiplicities



π^- Multiplicities



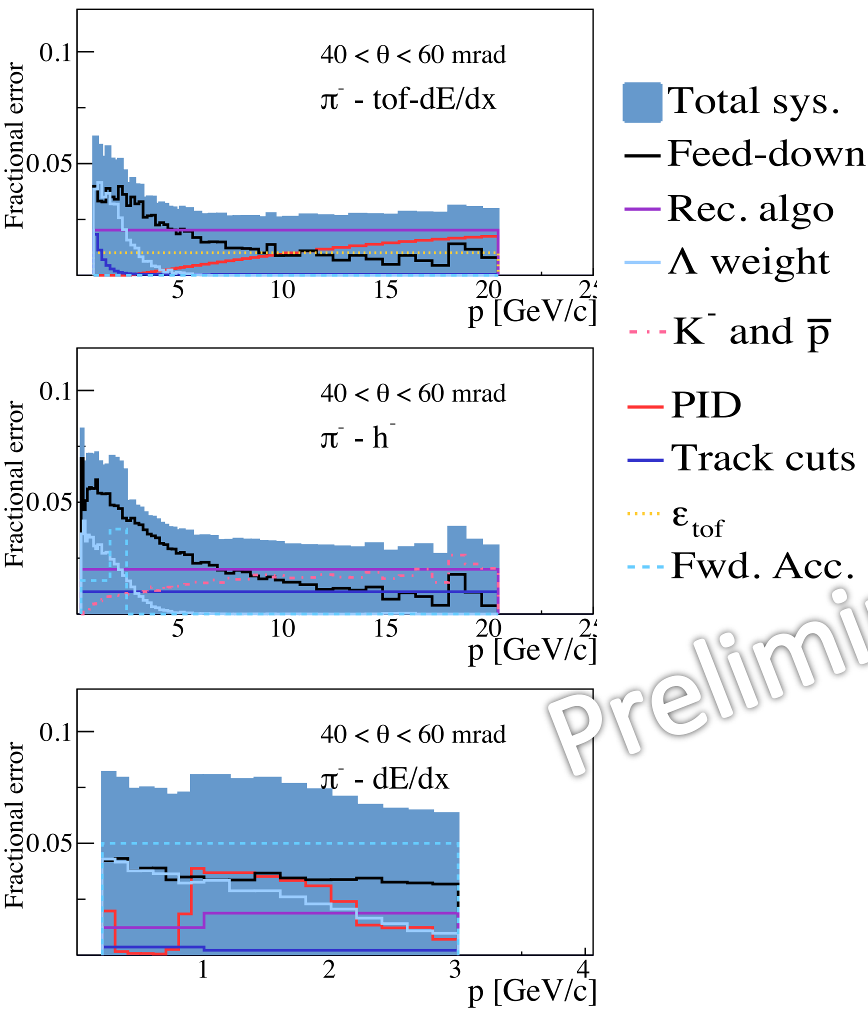




Relative errors in the region of the T2K interest ~4%

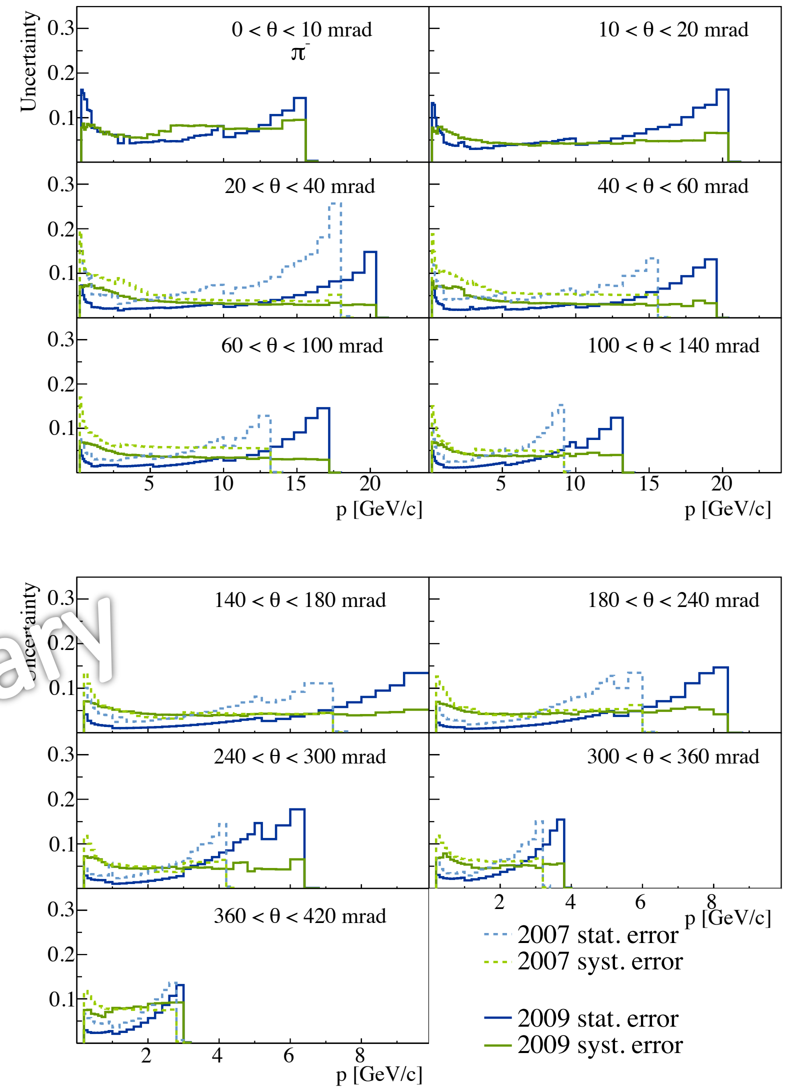
Spectra Uncertainties : π- example

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



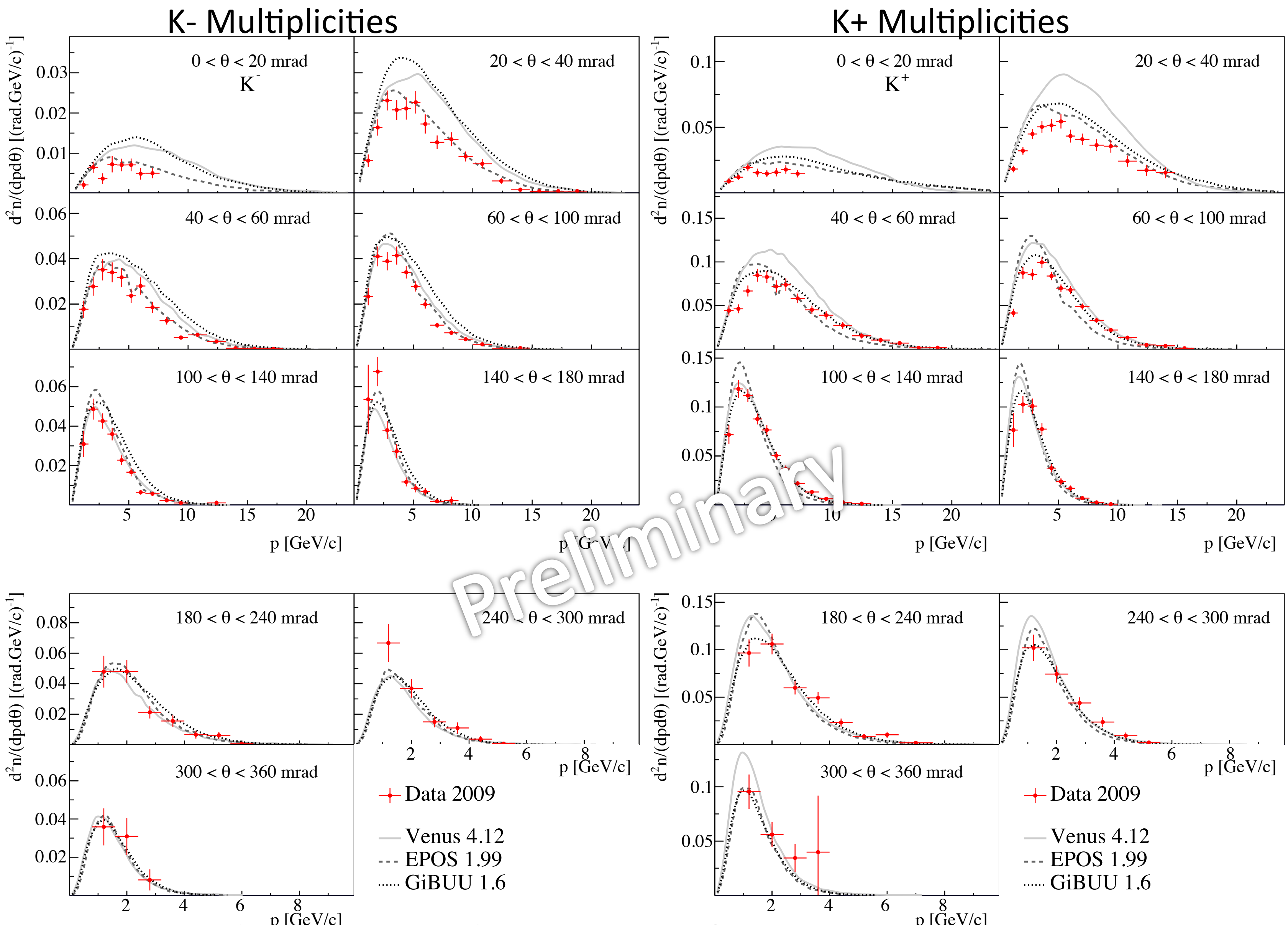
Improvements in 2009 compared to pilot run :

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



K± Measurements with Thin Target Data

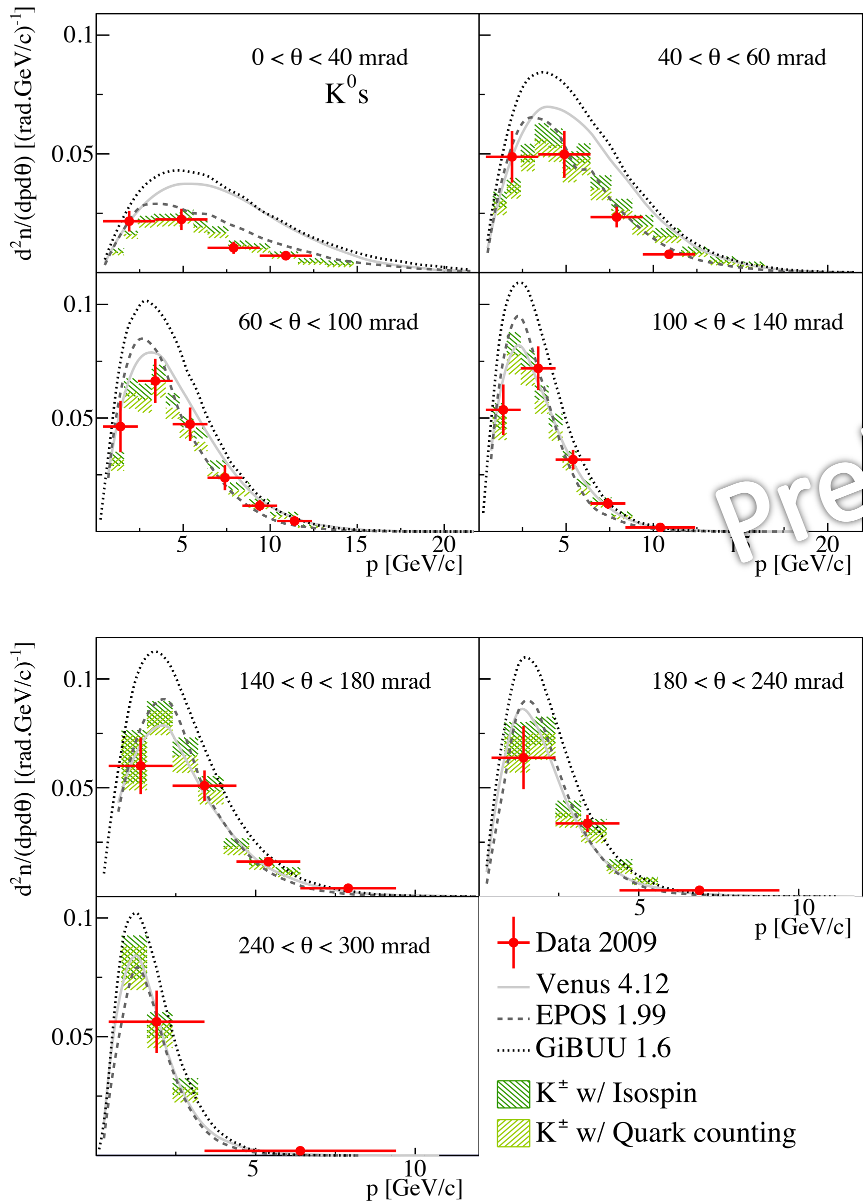
Important for high energy tail of ν_μ and ν_e flux in T2K

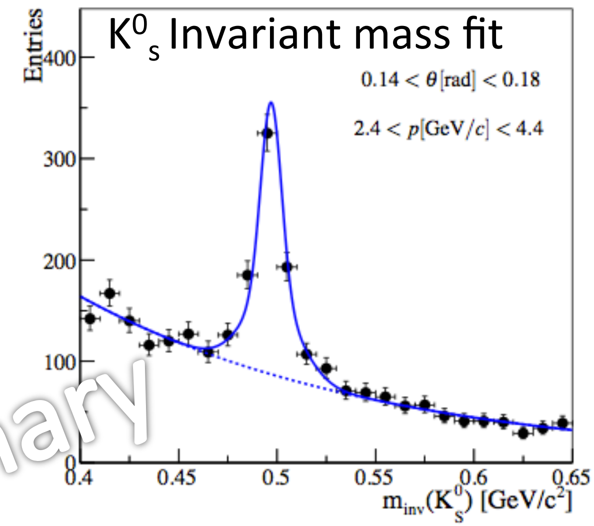


Relative errors in the T2K region of interest ~15%

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:

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

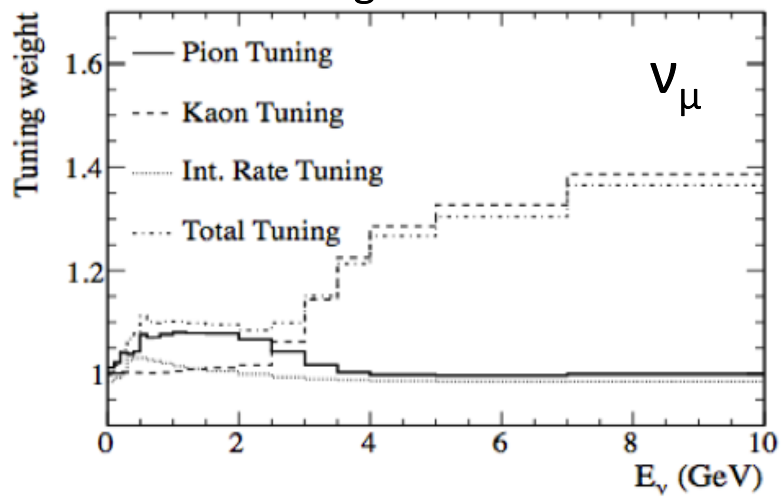
Good agreement of K^0_S yields predicted from $K^\pm$ measurements

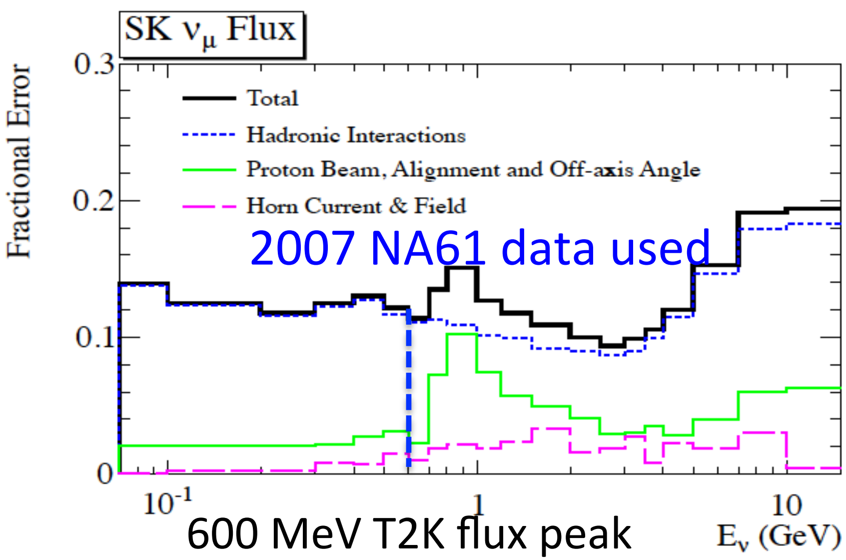
Impact of Hadron Production on Flux Predictions

Modeling of T2K flux :
- Primary p+C interactions simulated with FLUKA
- GEANT3+GCALOR used for propagation in the beam line

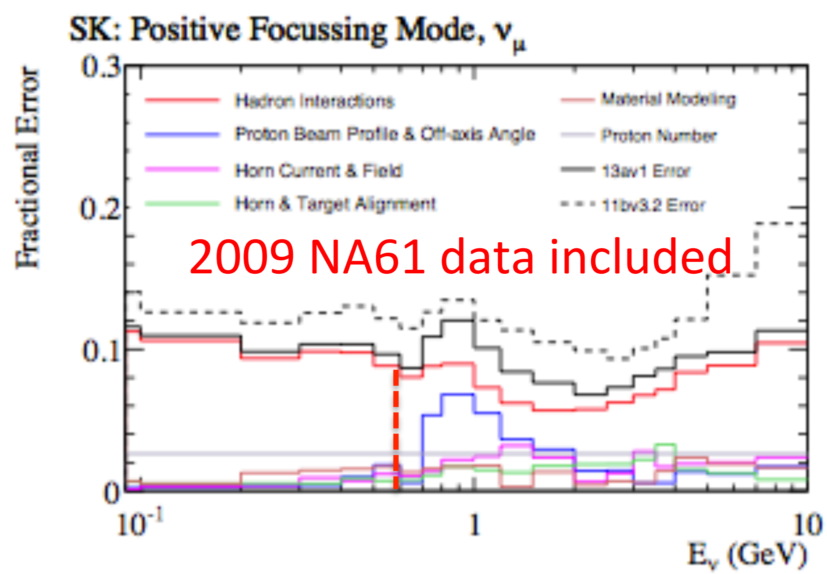
To tune the T2K flux, weights are calculated and applied to the simulated flux.
Primary pC interactions can be reweighted directly with the NA61/SHINE data.

Ratio of reweighted flux to the nominal





600 MeV T2K flux peak

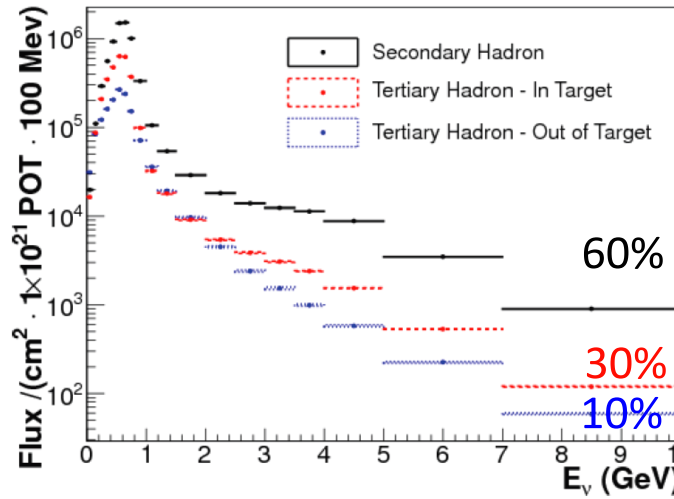


The neutrino flux uncertainty reduced to < 10% with new tuning including 2009 the NA61 data

Long Target Analysis

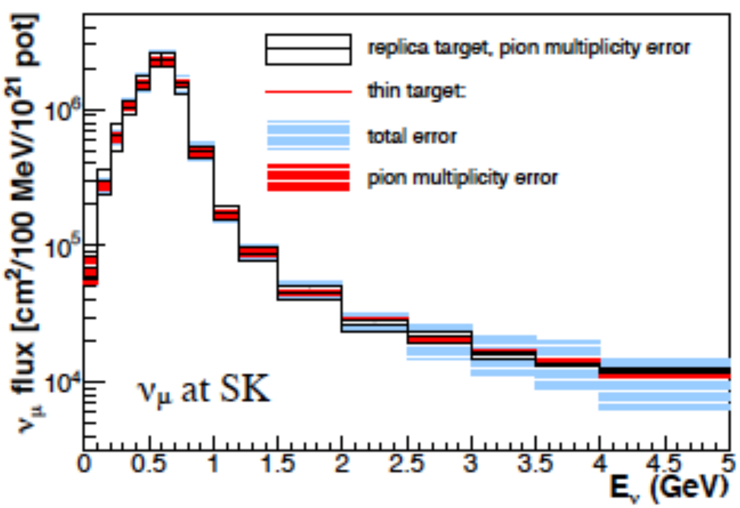
Neutrinos are coming from hadrons produced in the **primary interactions** of the proton beam (~60%) and in **interactions of secondary particles**, either in the target (~30%) or outside the target (~10%)

90% of the flux is constrained with the replica target

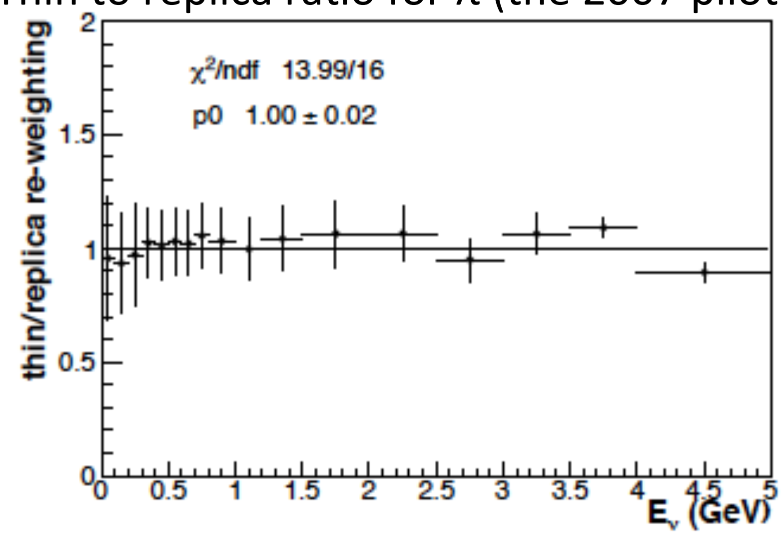


N.Abgrall et.al., NIM A701, 99-114 (2013)

The 2007 pilot run



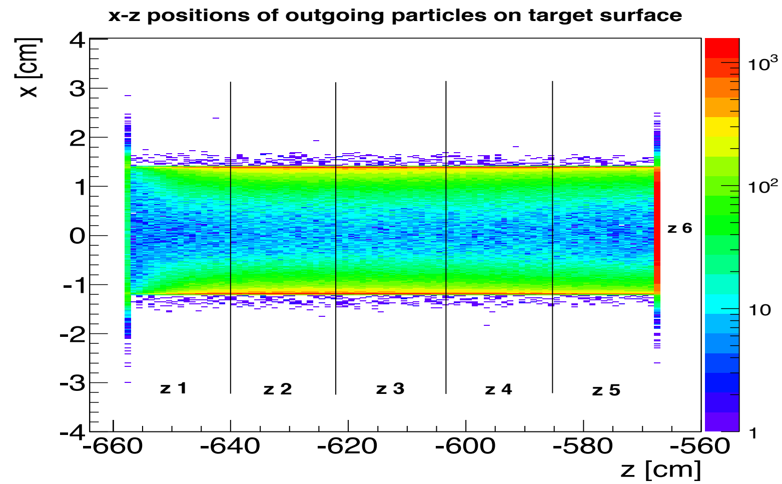
Thin to replica ratio for π (the 2007 pilot run)



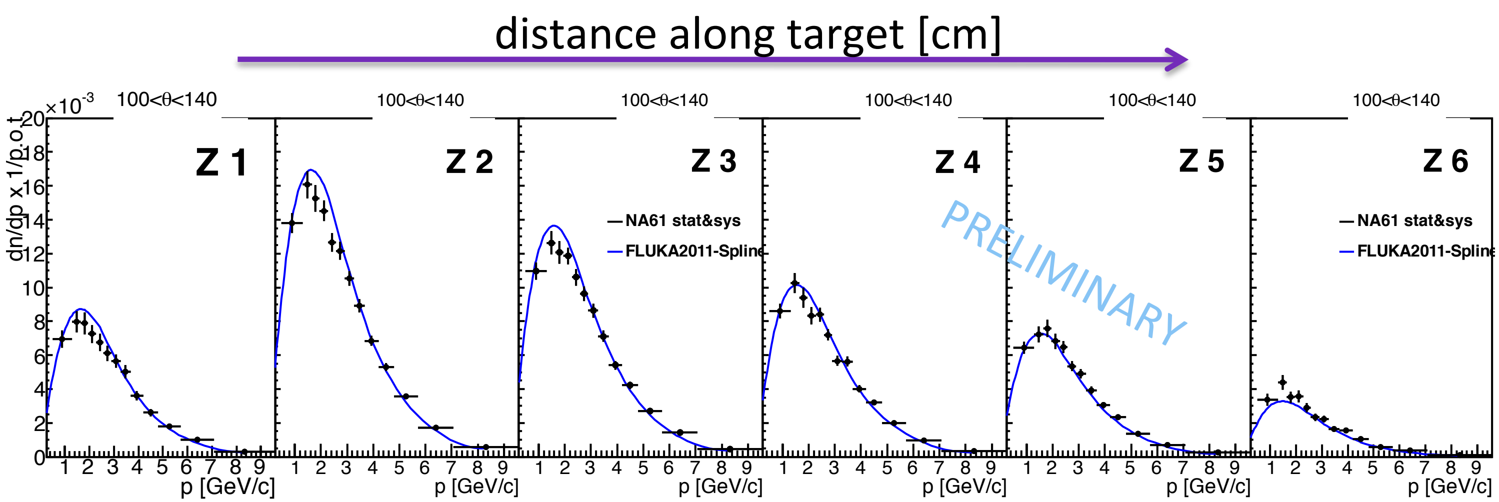
The flux tuning method tested with 2007 pilot data. New preliminary results for 2009 dataset

π^+ Measurements with Long Target

- Measurements of hadron multiplicities at the surface of the T2K replica target (tracks extrapolated backwards)
- 5 bins along beam direction + target downstream face

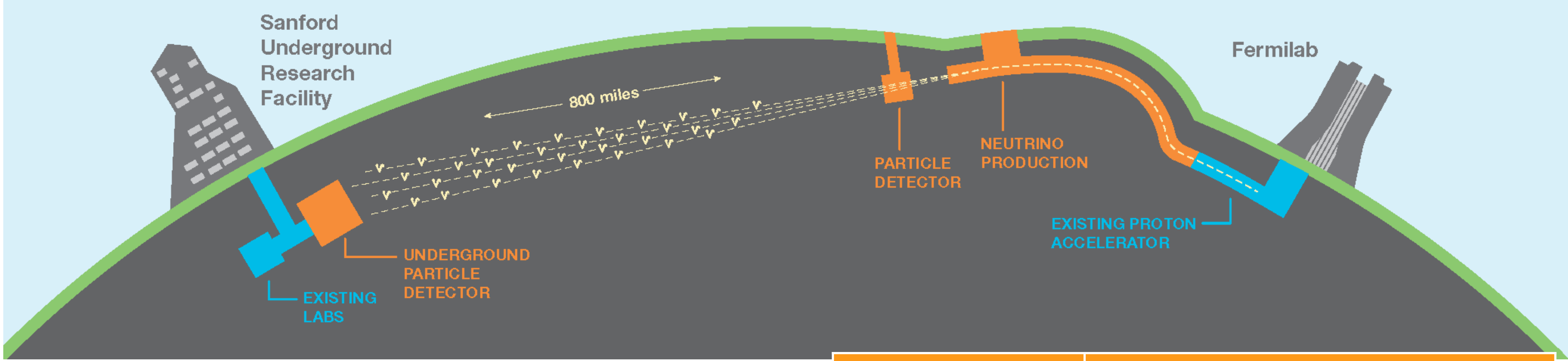


Example: Preliminary 2009 π+ measurements



- Statistical precision ~5%, systematic error ~5% (in the center of target) and ~14% (upstream and downstream part)
- Ongoing work to tune T2K flux simulation using pion spectra

Data for Fermilab Neutrino Program



- Data will be taken on thin target ($< 0.05\ \lambda_I$) as well as NUMI and DUNE replica targets
- Pions and protons beams
- Beam momentum: 120,60,30 GeV/c

- Data collection is planned in the fall of 2015
- Full program is expected to take about 4 years to complete
- A set of runs in 2015 has lower energies to take later the advantage of upgrade for the far-forward region (FTPCs)

Target	Incident proton/pion beam momentum		
	120 GeV/c	60 GeV/c	30 GeV/c
Replica NUMI	future		
Replica DUNE	future		
Thin graphite	future	2015	(T2K)
Thin aluminum		2015	2015
Thin iron	future	future	future
Thin beryllium	future	2015	2015

CERN-SPSC-2014-032/SPSC-P-330-Add-714/10/2014

Summary

• Results for $\pi^{\pm}$, $K^{\pm}$, p, K^0_S, Λ spectra were measured with **full thin target dataset** (2009+2007)
- Wider kinematic coverage in (p,θ) phase space compared to pilot run
- Statistical and systematic error reduced by factor ~2-3 for charged hadron spectra
- Results used for T2K flux tuning – the total flux precision is below 10% as compared to 12% obtained with the pilot 2007 data
- The publication including all spectra is being finalized

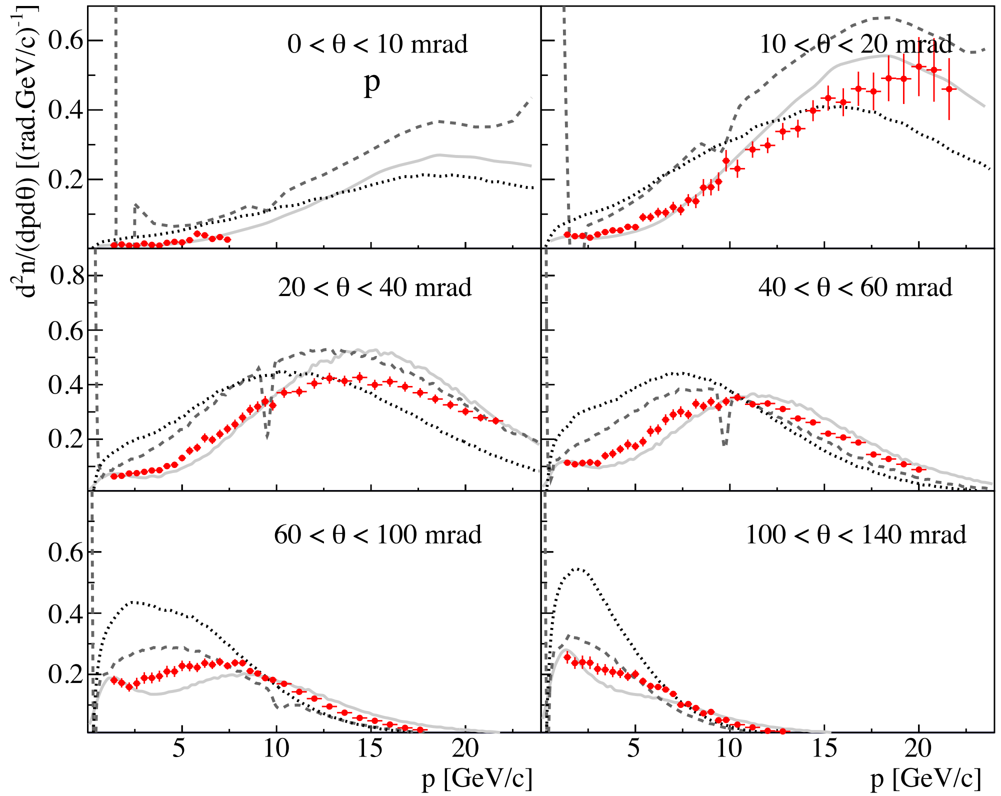
• First results for charged hadron spectra with **the T2K replica target** were released for the 2009 dataset with large statistics
- Up to 90% of flux can be constrained as compared to 60% with only the thin target
- Ongoing work to implement new results to tune the T2K flux

• The collection of data for **Fermilab neutrino program** is planned to start in the fall of 2015

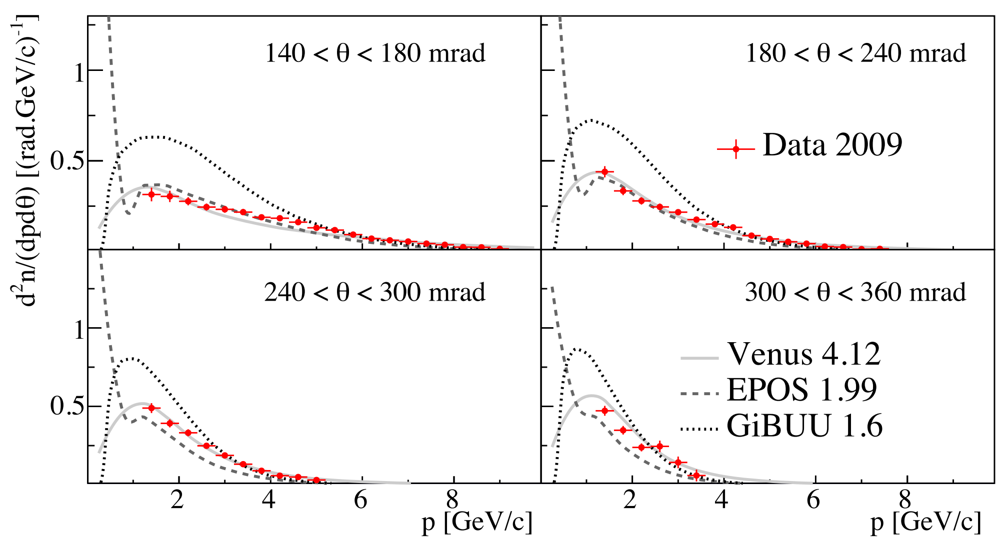
• A good knowledge of flux is important for T2K goals but became mandatory for future neutrino experiments

Backup Slides

Protons

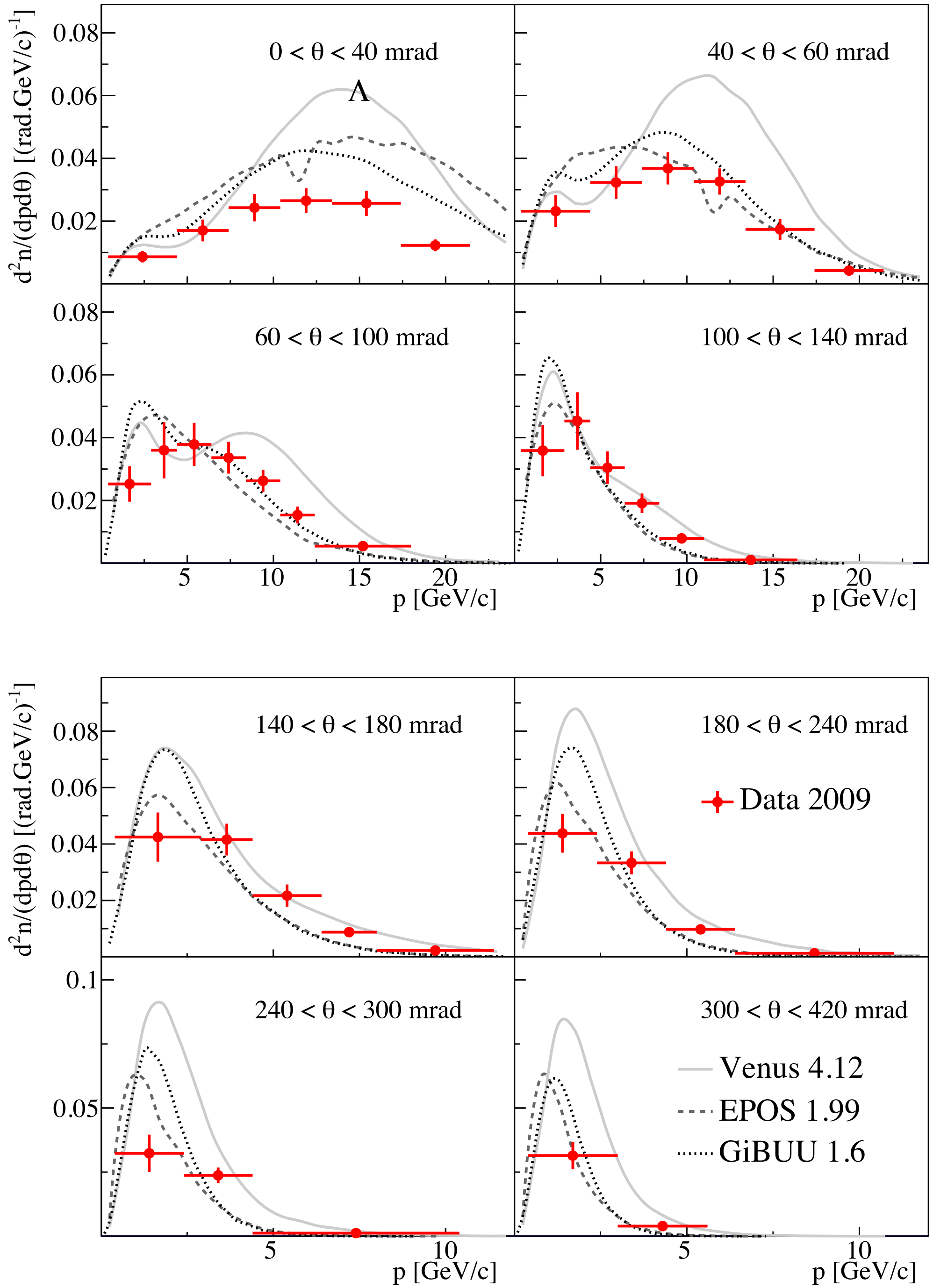


0 < θ < 10 mrad
p
10 < θ < 20 mrad
20 < θ < 40 mrad
40 < θ < 60 mrad
60 < θ < 100 mrad
100 < θ < 140 mrad
d²n/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]
p [GeV/c]

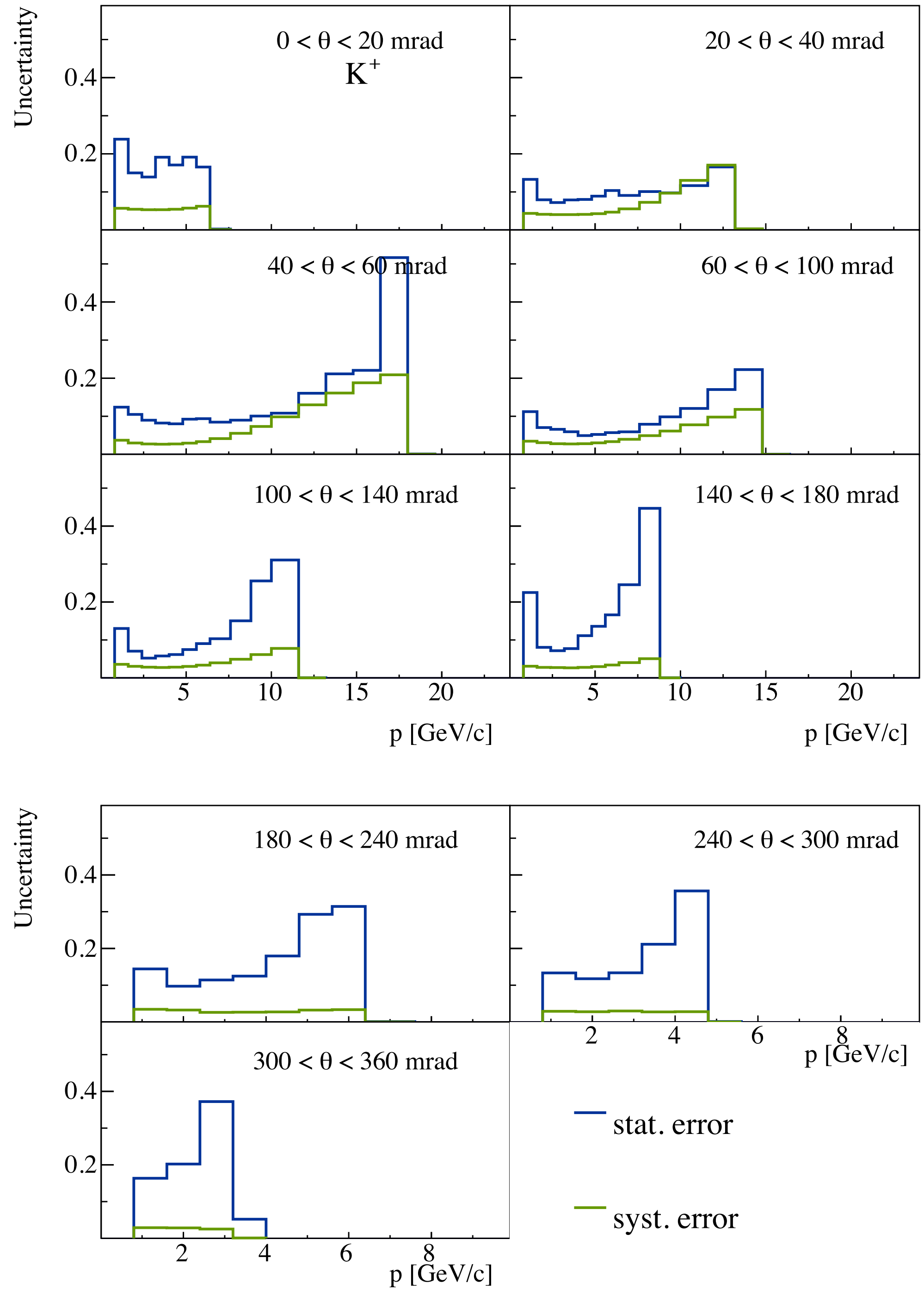


140 < θ < 180 mrad
180 < θ < 240 mrad
Data 2009
240 < θ < 300 mrad
300 < θ < 360 mrad
Venus 4.12
EPOS 1.99
GiBUU 1.6
d²n/(dpdθ) [(rad.GeV/c)⁻¹]
p [GeV/c]
p [GeV/c]

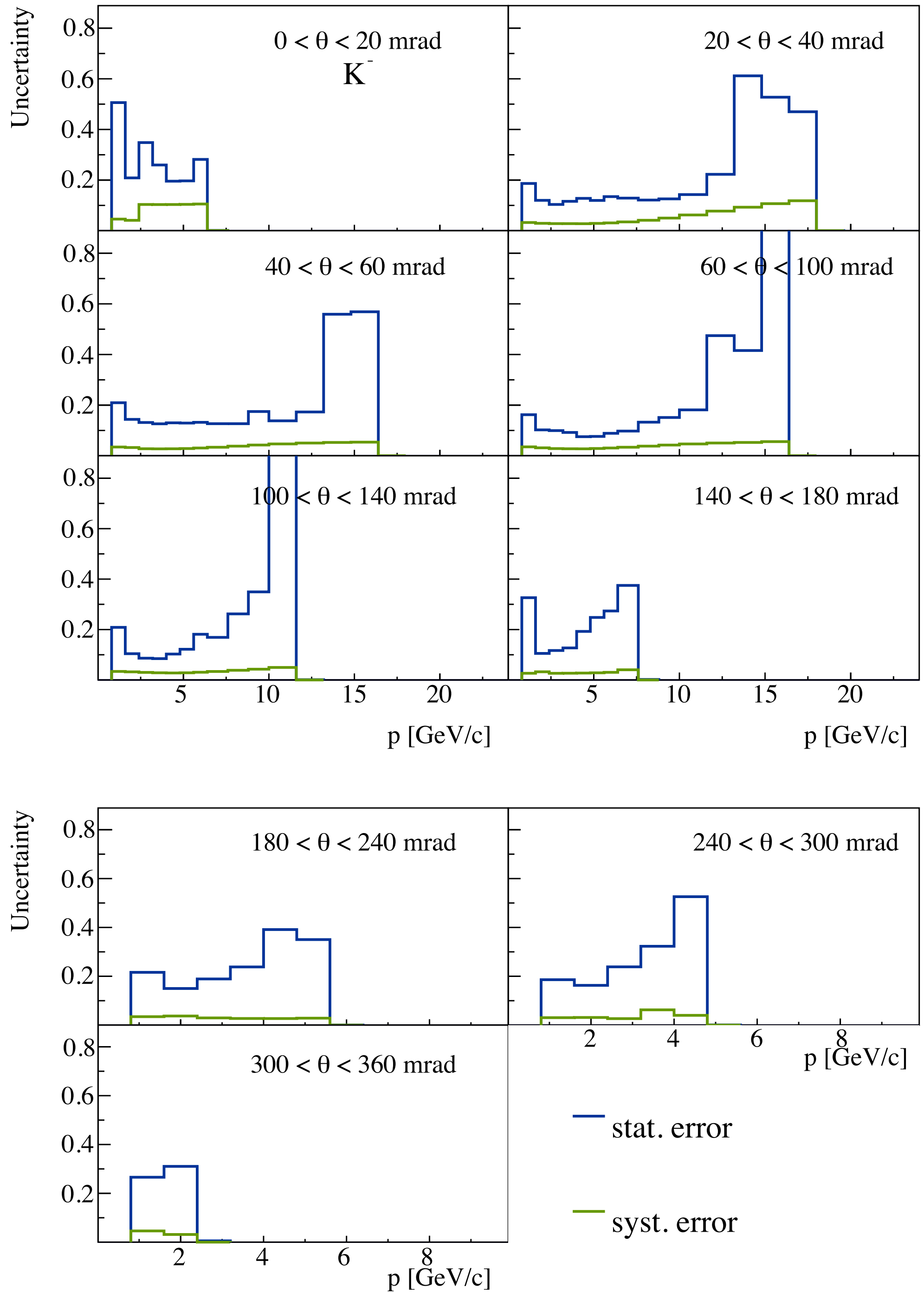
Λ


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

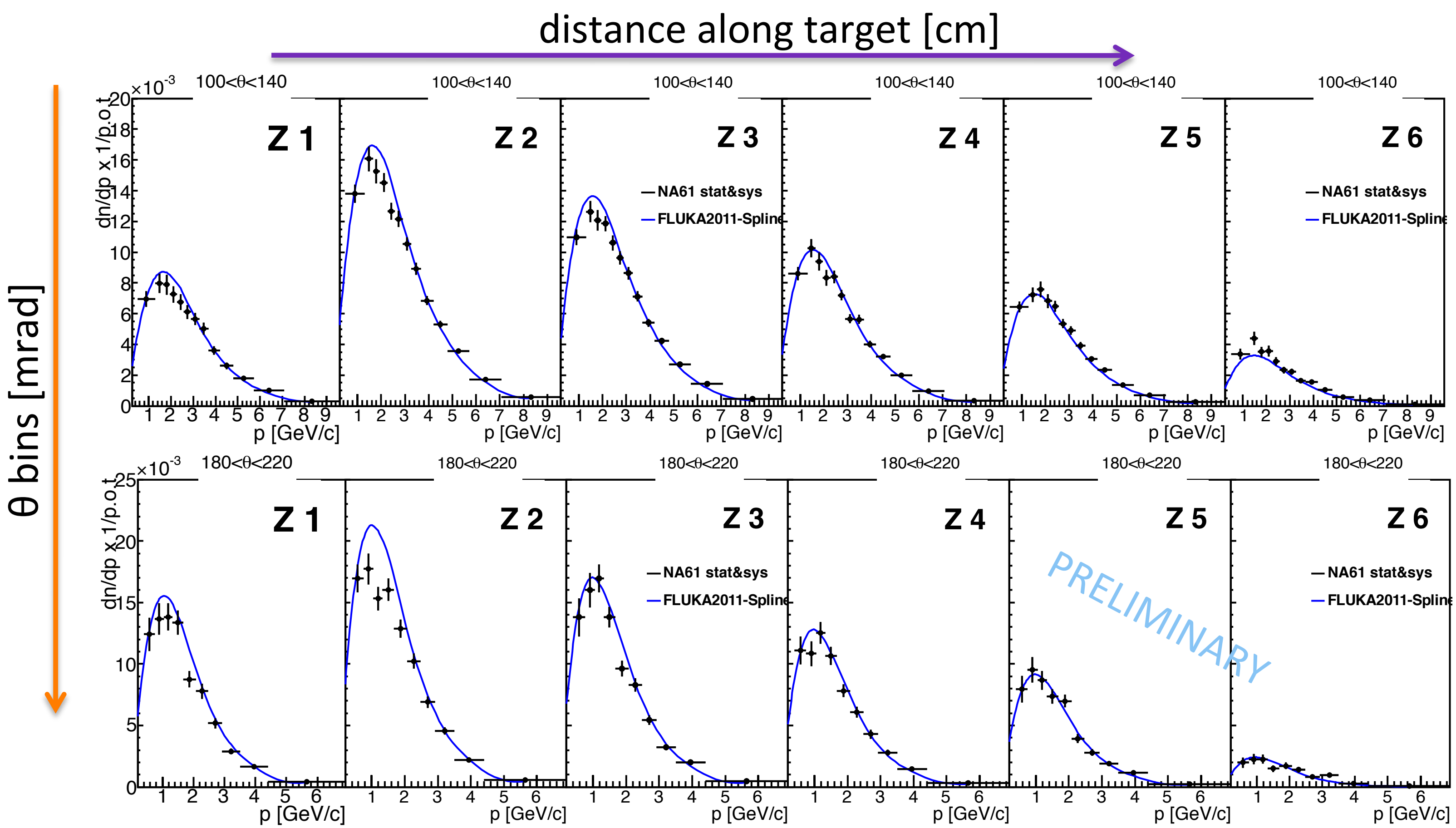


K- Uncertainties



π⁺ Measurements with The Long Target

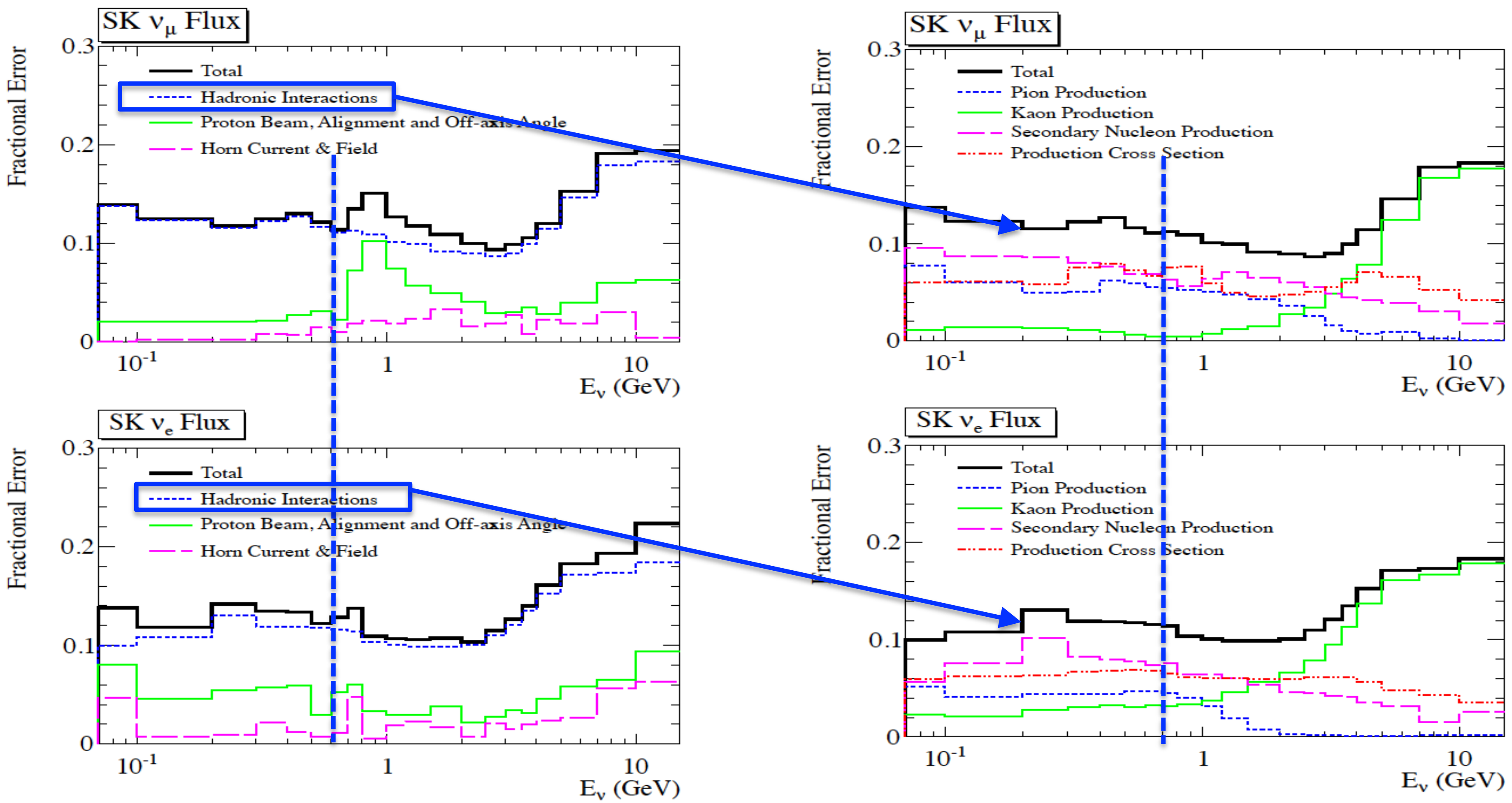
Example: Preliminary 2009 π+ measurements



Fractional flux error

The fractional flux errors are calculated with use of $\pi^{\pm}$, K^{+} measurements from 2007 pilot run

Different sources of flux error | Breakdown of Hadron Production Error



E_V~0.6GeV

(Phys.Rev. D87, 012001, 2013)