NA61/SHINE HADRON PRODUCTION MEASUREMENTS

For the long-baseline neutrino experiments

Journées de Rencontre des Jeunes Chercheurs
16. 11. 2015.

Matej Pavin
on behalf of the NA61/SHINE collaboration

LPNHE PARIS

SHINE

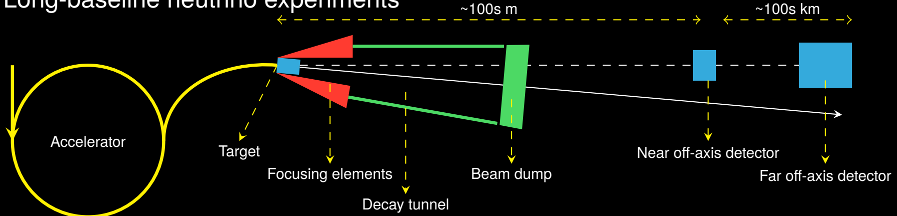
T2K

Outline

- Motivation: Long-baseline neutrino experiments
- T2K Experiment
  - Basic information
  - Neutrino beam
  - Neutrino flux re-weighting
- NA61/SHINE experiment
  - Hadron production measurements for T2K
  - Recent results
  - Future of NA61/SHINE hadron production measurements
- Conclusions

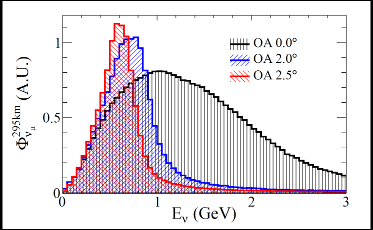
Motivation

Long-baseline neutrino experiments



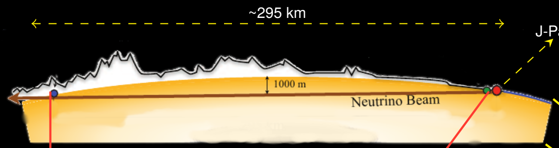
- Neutrino flux is produced by weak decays of hadrons coming from the interaction and re-interaction in the target and beam elements
- Neutrino flux is calculated with MC models → huge uncertainties of the hadron production models → huge uncertainties in neutrino oscillation measurements

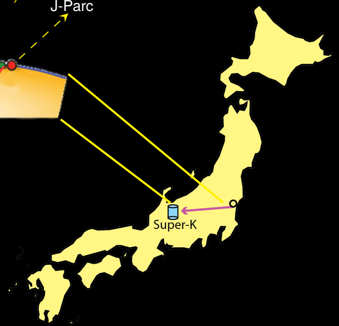
Off-axis method

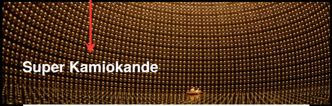


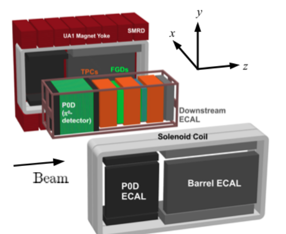
Hadron production measurements are needed for reducing flux uncertainties!!!

T2K (Tokai to Kamioka) Experiment





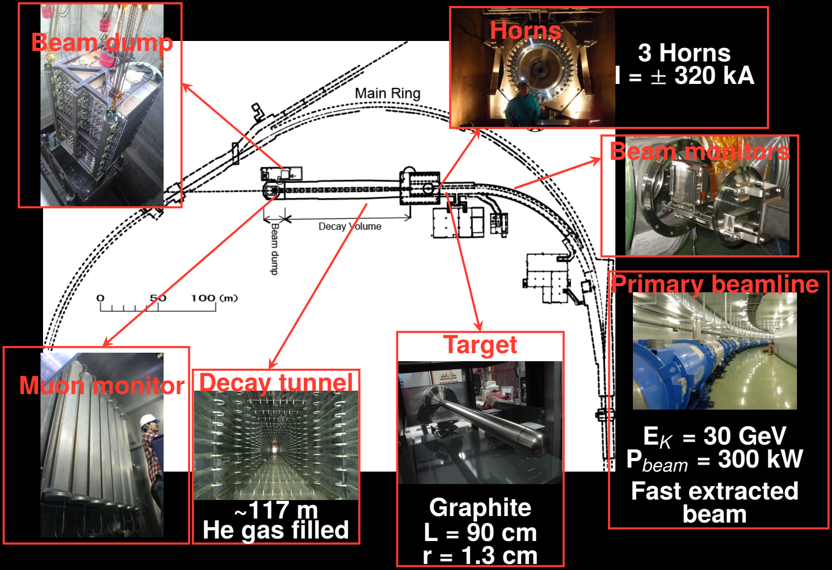




ND280 - near detector (280 m away)

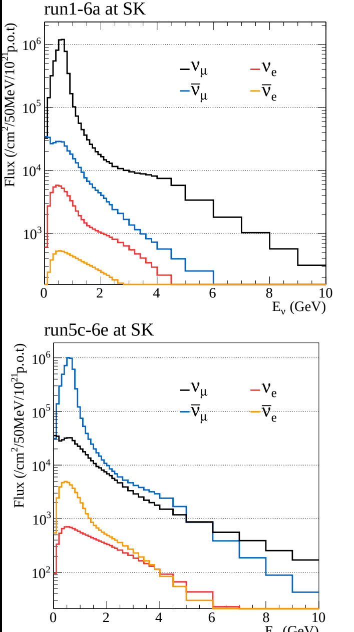
- Neutrino beam produced at J-Parc
- Length of the baseline: 295 km
- Near detector: 280 m from the target
- Off-axis method (2.5°)
- For more details about SK and ND280 look at Francesco's talk

J-PARC Neutrino beam facility



Nucl. Instrum. Meth. A 659, 106 (2011)

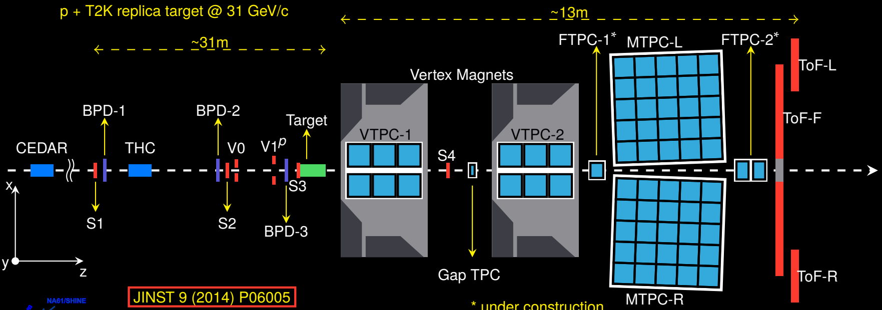
T2K Neutrino flux



- Changing horn polarity $\rightarrow \nu_\mu$ or $\overline{\nu}_\mu$ enhanced neutrino beam
- Peak energy: 0.6 GeV
- Neutrino flux simulation: FLUKA 2011 (primary interactions) + GEANT3
- Neutrino parents are re-weighted with the data (mainly with NA61/SHINE data)
- For lower energies majority of $\mu_\nu(\overline{\mu}_\nu)$ are coming from $\pi^\pm$ decays
- For higher energies majority of $\mu_\nu(\overline{\mu}_\nu)$ are coming from $K^\pm$ decays

NA61/SHINE Experiment

- SPS Heavy Ion and Neutrino Experiment



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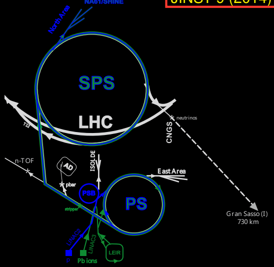
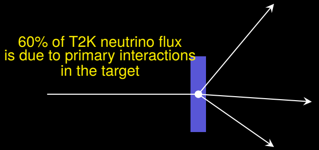


- Search for the critical point of strongly interacting matter (p+p, p+A, A+A)
- Precise hadron production measurements for neutrino flux re-weighting in T2K and Fermilab neutrino experiments
- More reliable simulations of cosmic-ray air showers

Hadron Production Measurements for T2K

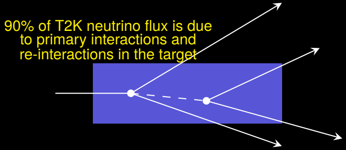
Thin carbon target

- 2.5×2.5 cm^2 , L = 2 cm = 0.04 λ_{int}
- Measurements of production cross section and spectra of $\pi^{\pm}$, $K^{\pm}$, K^0_s, p, Λ



T2K replica target

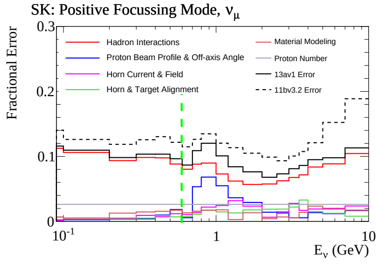
- L = 90 cm = 1.9 λ_{int}, r = 1.3 cm
- Measurement of charged pion spectra exiting the target

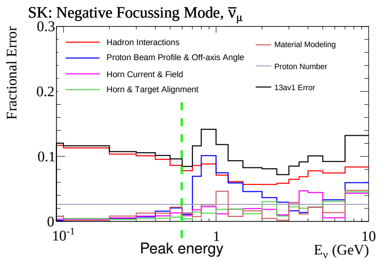


Beam	Target	Year	Triggers [10^6]	Status	Comment
	thin	2007	0.7	published ($\pi^{\pm}$, K^{+}, K^s_0, Λ)[1,2]	has been used for T2K
protons	replica	2007	0.2	published ($\pi^{\pm}$)[3,4]	proof of principle
at	thin	2009	5.4	paper submitted ($\pi^{\pm}$, $K^{\pm}$, p, K^s_0, Λ)[5,6]	being used in T2K
31 GeV/c	replica	2009	2.8	paper is being finalized ($\pi^{\pm}$)[7]	-
	replica	2010	10.2	analysis in progress	-

[1] Phys. Rev. C84, 034604 (2011).
[2] Phys. Rev. C85, 035210 (2012).
[3] Nucl. Instrum. Meth. A701, 99 (2013).
[4] CERN-THESIS-2011-165
[5] CERN-THESIS-2013-290
[6] arXiv:1510.02703
[7] CERN-THESIS-2015-103

T2K Neutrino Flux Re-weighting





Interaction probability tuning

- Probability of interaction and survival for each particle is calculated
- Weight: ratio of probability calculated from the data and probability from the MC model

Differential multiplicity tuning

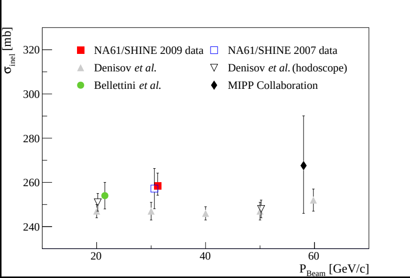
- Weight: ratio of double differential multiplicity calculated from the data and one obtained from the MC model

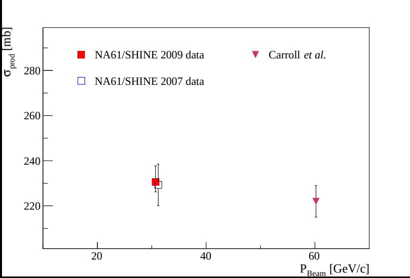
- Hadron interaction uncertainty is reduced from ~30% to ~9% → tuning based on the T2K replica target data is needed reach T2K goal of 5%

1. Phys. Rev. D 87, 012001 (2013)
2. Flux Tuning and Uncertainty Updates for the 13a Flux (http://www.t2k.org/docs/technotes/217)

Inelastic and Production Cross Section (p + C @ 31 GeV/c)

- Trigger cross section: $\sigma_{trig} = 305.7 \pm 2.7(stat) \pm 1.0(det)$ mb
- Inelastic cross section: $\sigma_{inel} = (\sigma_{trig} - f_{el}\sigma_{el})\frac{1}{f_{inel}}$
- Production cross section: $\sigma_{prod} = (\sigma_{trig} - f_{el}\sigma_{el} - f_{qe}\sigma_{qe})\frac{1}{f_{prod}}$
- Trigger efficiencies (f_i), σ_{el} and σ_{qe} were calculated from MC





$$\sigma_{inel} = 258.4 \pm 2.8(\text{stat}) \pm 1.2(\text{det}) {}^{+5.0}_{-2.9}(\text{mod})\ \text{mb}$$

$$\sigma_{prod} = 230.7 \pm 2.7(\text{stat}) \pm 1.2(\text{det}) {}^{+6.3}_{-3.4}(\text{mod})\ \text{mb}$$

Charged Hadron Production in p + C @ 31 GeV/c

dE/dx – tof analysis

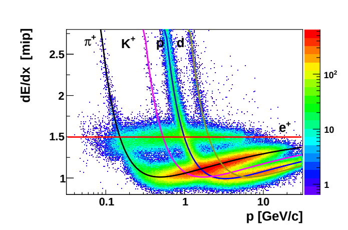
- $\pi^{\pm}$, $K^{\pm}$, p
- PID: energy deposition in TPCs and time of flight information
- Usage of TOF $<$ 10 GeV/c

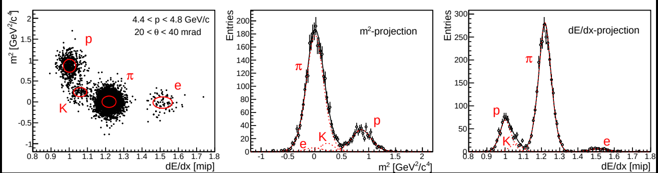
dE/dx analysis

- $\pi^{\pm}$
- PID: energy deposition in TPCs
- Up to 1 GeV/c for π^{+} and to 4 GeV/c for π^{-}

h^{-} analysis

- Majority of negative particles are π^{-} $\rightarrow$ negative particles are assumed to be π^{-}
- Number of pions is corrected with MC simulation



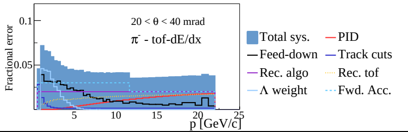


Charged Hadron Production in p + C @ 31 GeV/c (2009)

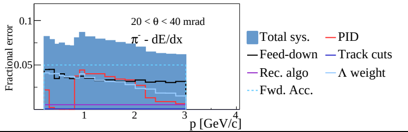
Systematic uncertainties

- PID (*dE*/*dx* – *tof*, *dE*/*dx*, 2% for $\pi^{\pm}$ and up to 20% for $K^{\pm}$)
- Feed-down and Λ weighting (data based feed-down correction for π^{-}), 30% of correction factor
- Track cuts (1%)
- Reconstruction efficiency (2%)
- Forward acceptance (4%)
- Analysis specific errors (TOF efficiency, hadron loss, K^{-} and $\overline{p}$ contamination, etc.), 1-5%

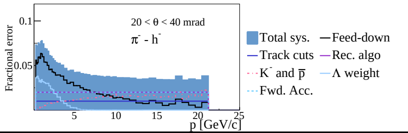
dE/*dx* – *tof* analysis



dE/*dx* analysis



h^{-} analysis

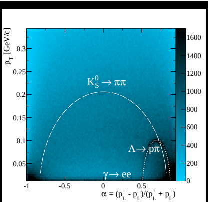


V0 Analysis in p + C @ 31 GeV/c

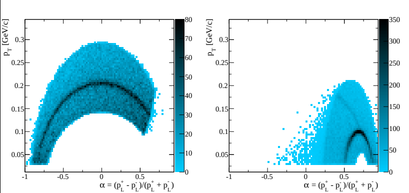
$$K_s^0 \rightarrow \pi^+ + \pi^- \quad \Gamma = (69.20 \pm 0.05)\%$$

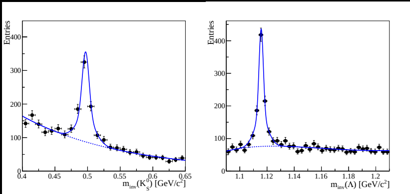
$$\Lambda \rightarrow p + \pi^- \quad \Gamma = (63.9 \pm 0.5)\%$$

- Important for reducing systematics of pion and proton multiplicities
- Improvement of the ν_e and $\overline{\nu}_e$ fluxes because of 3 body K_L^0 decay
- Analysis procedure - search for decay vertexes of neutral strange particles
- Number of particles obtained from fit of invariant mass spectra

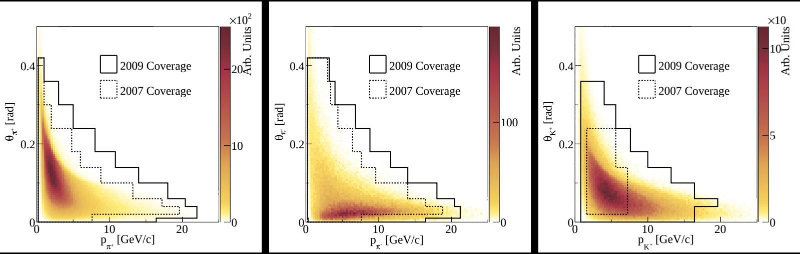


K_s^0 Λ

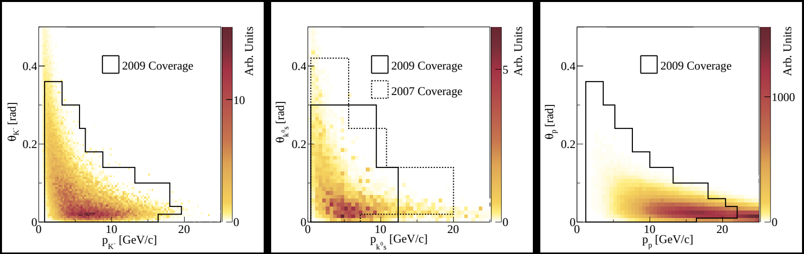




NA61/SHINE coverage of T2K phase space (neutrino mode)

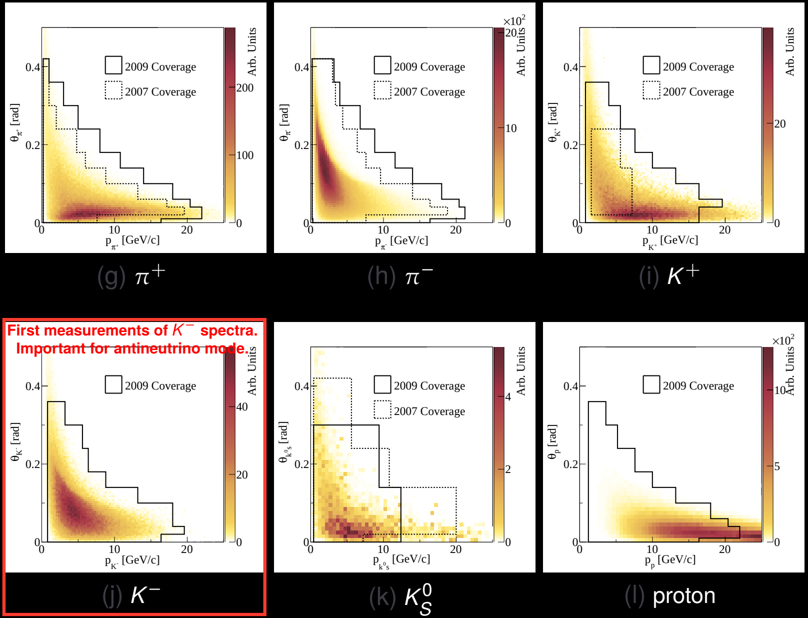


(a) π^+ (b) π^- (c) K^+



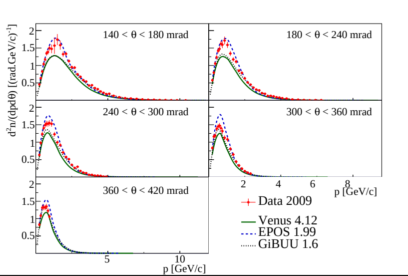
(d) K^- (e) K_S^0 (f) proton

NA61/SHINE coverage of T2K phase space (antineutrino mode)



Results

- RESULTS: Double differential multiplicities v.s. momentum in polar angle bins



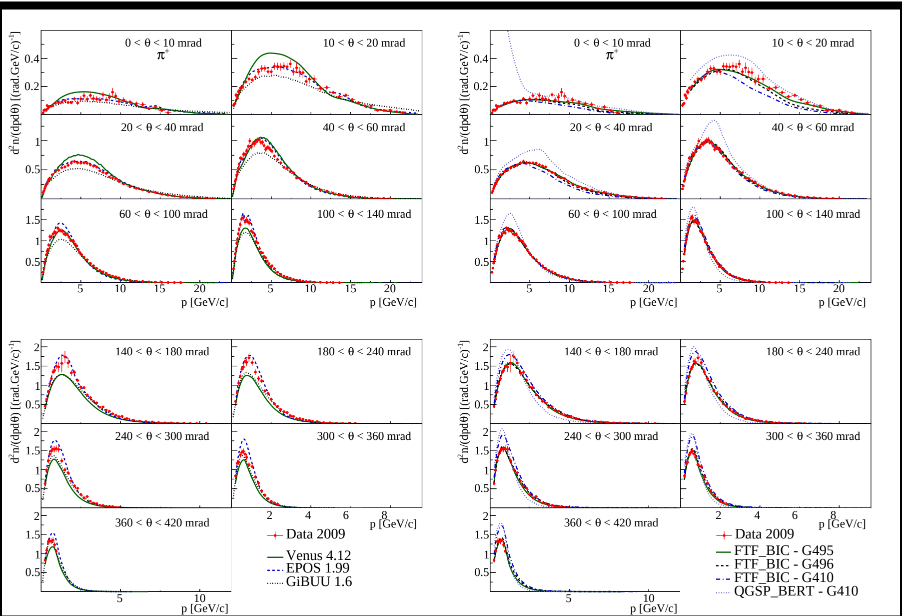
Comparison with models

- Venus 4.12, EPOS 1.99, GiBUU 1.6
- GEANT4: FTF_BIC-G495, FTF_BIC-G496, FTF_BIC-G410, QGSP_BERT-G410

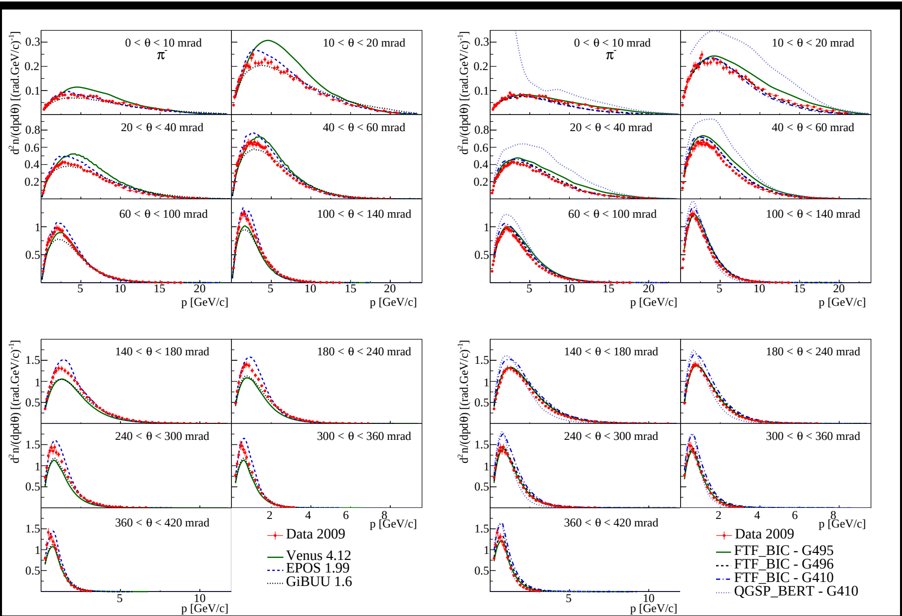
Two additional comparisons for K_s^0

- Hypotheses based on the $K^{\pm}$ results
- Isospin symmetry in kaon production: $N(K_s^0) = \frac{1}{2}(N(K^+) + N(K^-))$
- Quark counting: $u_s = \overline{u}_s = d_s = \overline{d}_s = s_s = \overline{s}_s$, $n = u_v/d_v$
  - $N(K_s^0) = \frac{1}{8}(3N(K^+) + 5N(K^-))$

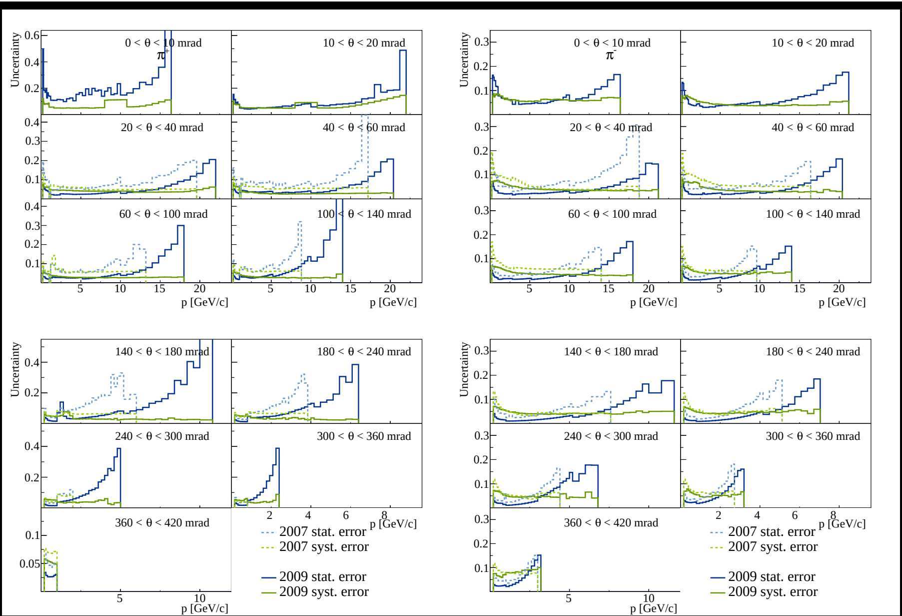
Comparison of π^+ spectra with models



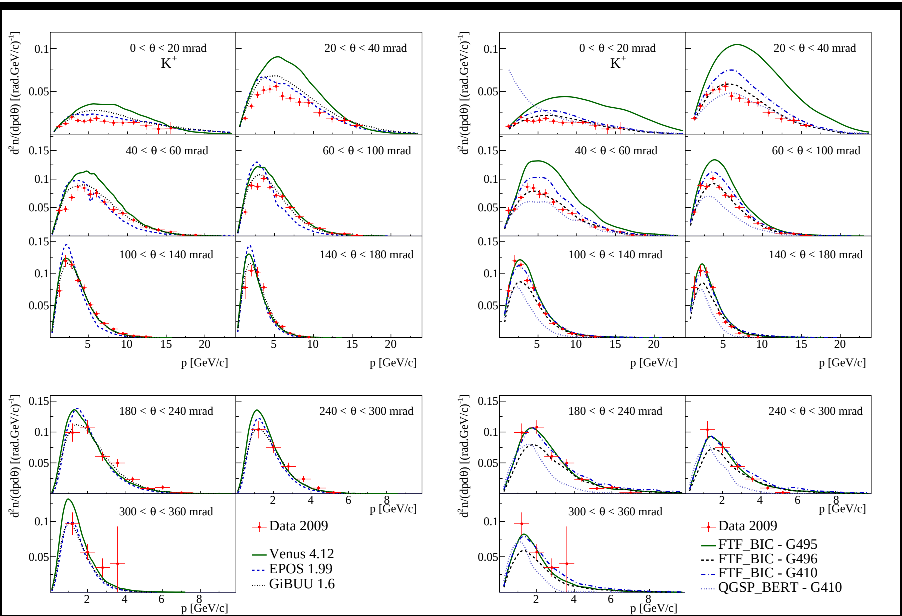
Comparison of π^- spectra with models



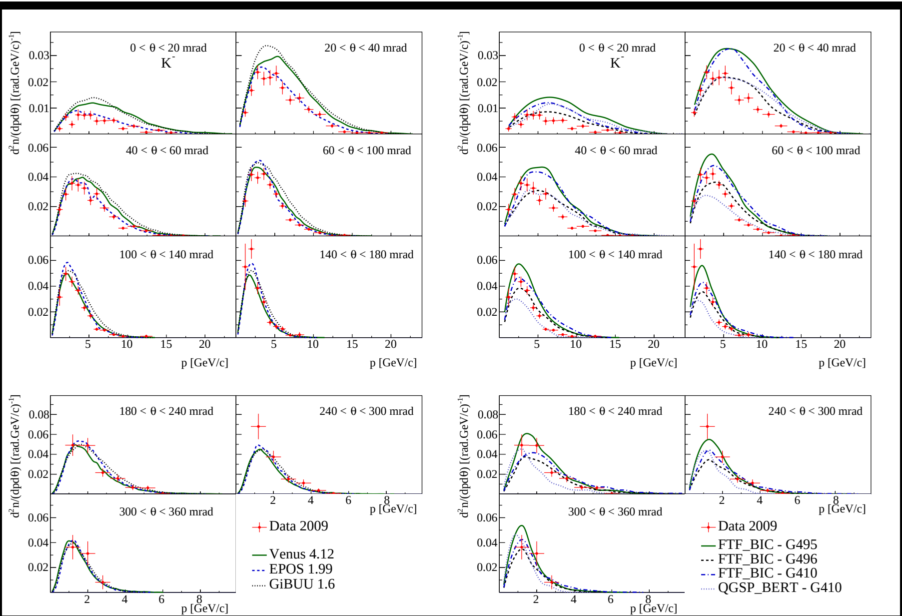
Uncertainties of π^+ spectra (left) and π^- spectra (right)



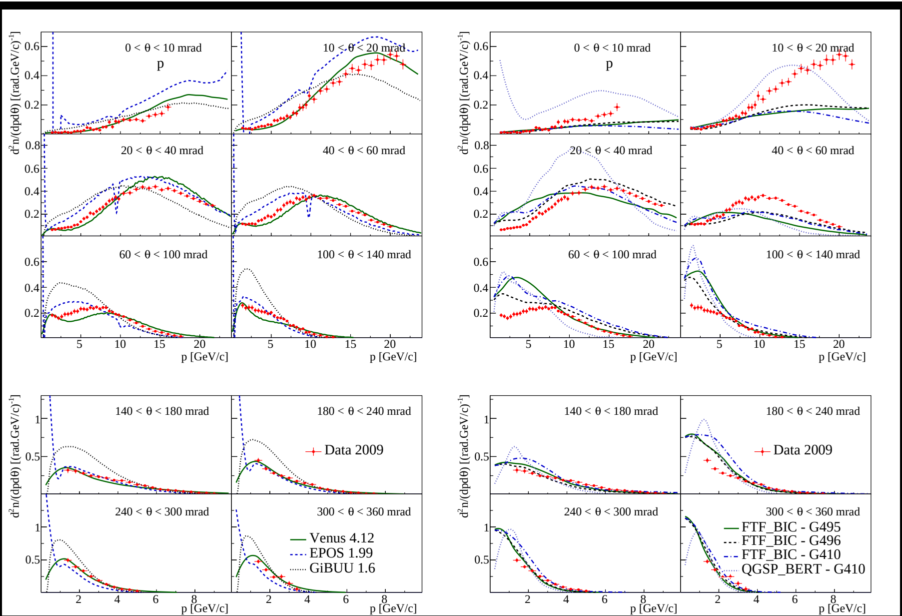
Comparison of K^+ spectra with models



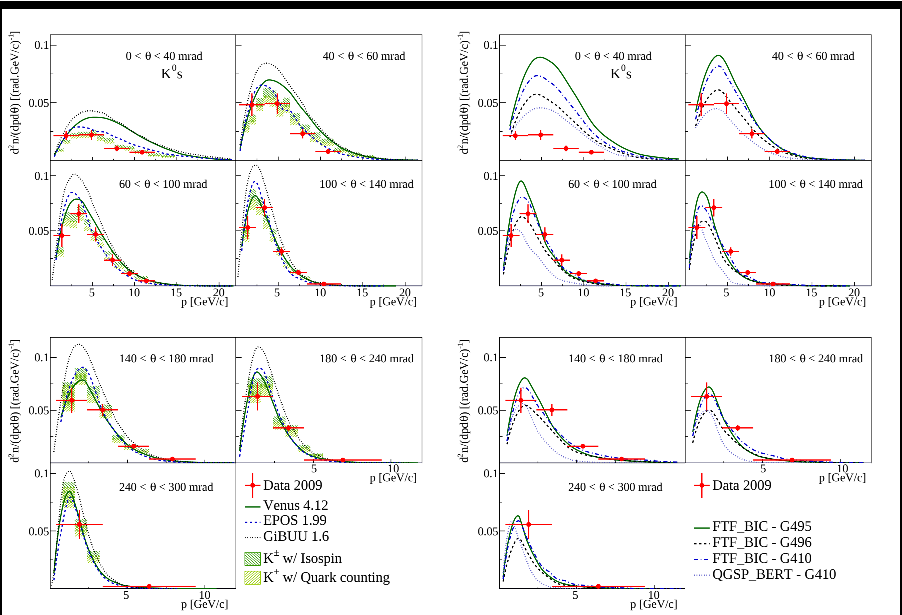
Comparison of K^- spectra with models



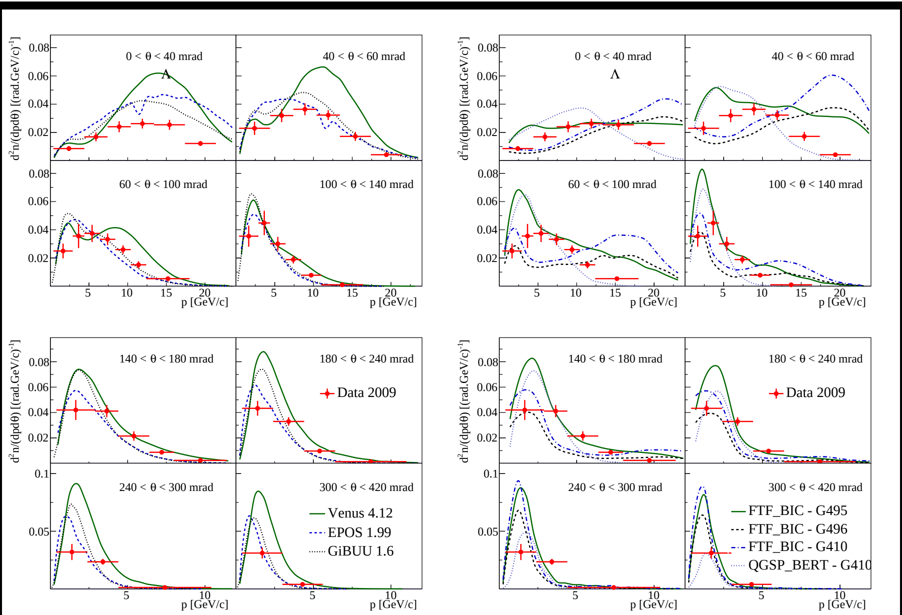
Comparison of proton spectra with models



Comparison of K_s^0 spectra with models

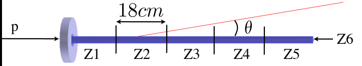


Comparison of Λ spectra with models

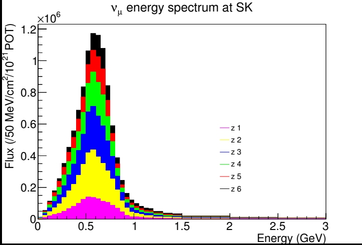


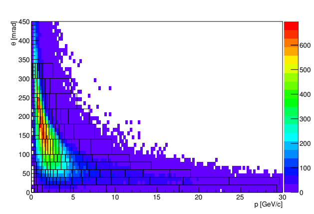
p + T2K Replica Target @ 31 GeV/c (2009)

- *dE/dx* – *tof* and h^- analysis
- Vertex position is not required → TPC tracks are extrapolated towards the target surface
- Phase space: momentum *p*, polar angle θ and position along the target surface *z*
- Shape of the spectra depends on the track position → 5 longitudinal bins + downstream target face



- z bin contribution to the ν_μ flux at SK

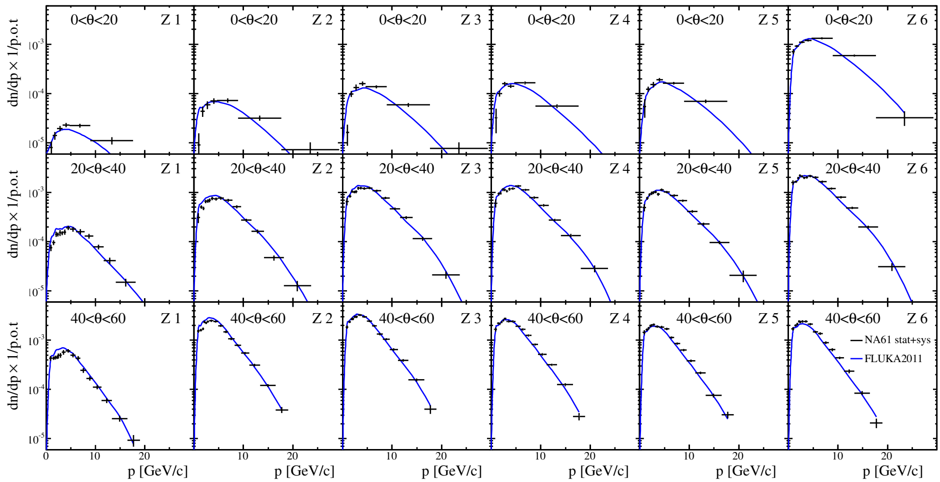




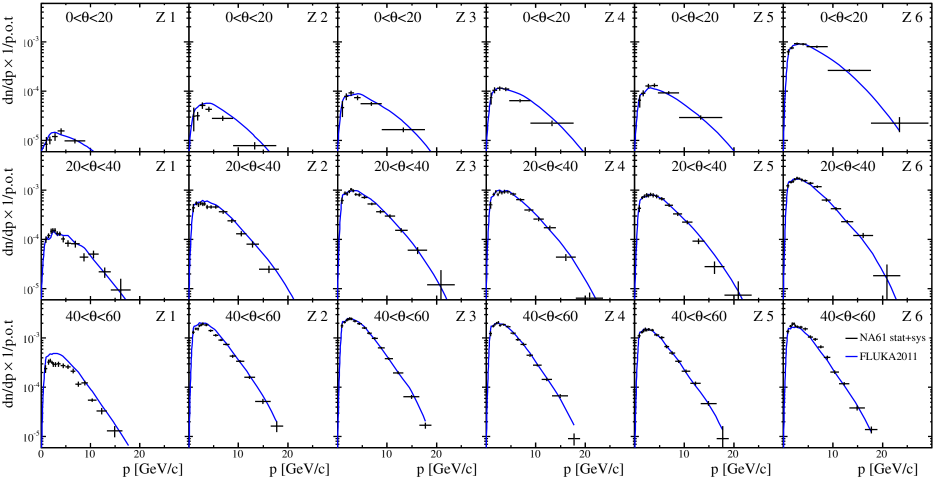
Systematic uncertainties

- Backward track extrapolation (up to 10% for small θ)
- Other contributions: less than 5%

Comparison of π^+ spectra with FLUKA 2011 (0 – 60 mrad)

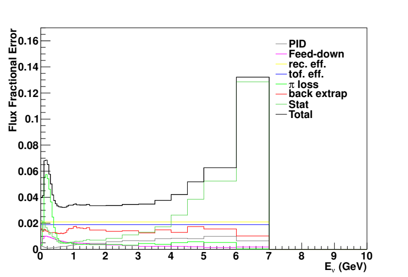


Comparison of π^- spectra with FLUKA 2011 (0 − 60 mrad)



Re-weighting with replica target data

Fractional error of the ν_μ flux at SK

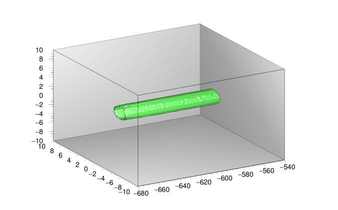


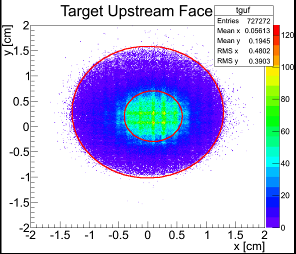
IMPORTANT: Only component of the ν_μ flux coming from the pions exiting the target

- At peak energy (0.6 GeV) 90% of the flux is coming from the pions exiting the target
- At 4 GeV only 10% of ν_μ flux is coming from the pions exiting the target
- At peak energy 90% of the flux has hadron production uncertainty of 4%, but at 4 GeV only 10% of the flux has hadron production uncertainty of 4%
- $K^\pm$ multiplicities are needed to further constrain neutrino flux

p + T2K Replica Target @ 31 GeV/c (2010)

- High-statistics dataset (3.5× 2009 statistics)
  - 9 million events with standard magnetic field
  - 1.2 million events with high magnetic field
- *dE/dx – tof* analysis in progress
- Because of high statistics, extraction of the $K^{\pm}$ and proton multiplicities is possible
- Backward track extrapolation systematic uncertainty is reduced because of better knowledge of the target position





2009 target position

$$(x, y, z) = (0.16, 0.21, -657.62) \text{ cm}$$
$$(\delta x, \delta y, \delta z) = (0.04, 0.04, 0.36) \text{ cm}$$

2010 target position

$$(x, y, z) = (-0.096, 0.233, -657.400) \text{ cm}$$
$$(\delta x, \delta y, \delta z) = (0.011, 0.005, 0.050) \text{ cm}$$

Future NA61/SHINE Neutrino Program

- Measurements for the Fermilab neutrino beams

Beam Prim.	Beam Sec.	Target	Momentum (AGeV/c) prim. (sec.) beam	Year	Days	Physics
p	h^+	A	400(40-400)	2016	4x7 days	tests
p	p	p	400 (400)	2016	28 days	SI
p	**h^+**	**A**	400 (30–120)	2016	42 days	ν
Pb		Pb	13, 19, 30, 40	2016	40 days	SI
Pb		Pb	150	2016	5 days	tests
p	p	p/Pb	400 (13, 19, 30, 40, 75)	2017	35 days	SI
p	**h^+**	**A**	400 (30–120)	2017	42 days	ν
Xe		La	13, 19, 30, 40, 75, 150	2017	60 days	SI
p	p	p/Pb	400 (13, 19, 30, 40, 75)	2018	35 days	SI
p	**h^+**	**A**	400 (30–120)	2018	42 days	ν
Pb		Pb	75, 150	2018	40 days	SI

- Targets: C, Al, thin, replica
- Beams: p, π^+
- Beam momentum 30-120 GeV/c
- New hardware: 2 additional forward TPCs + vertex detector

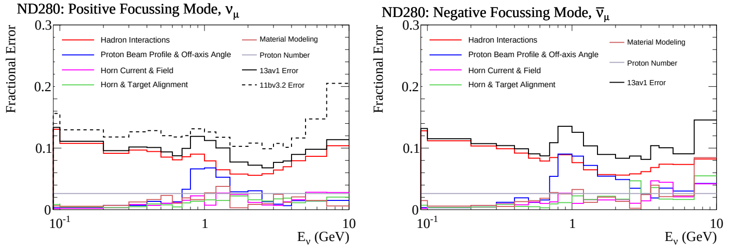
Report from the NA61/SHINE experiment, http://cds.cern.ch/record/2059310

Conclusions

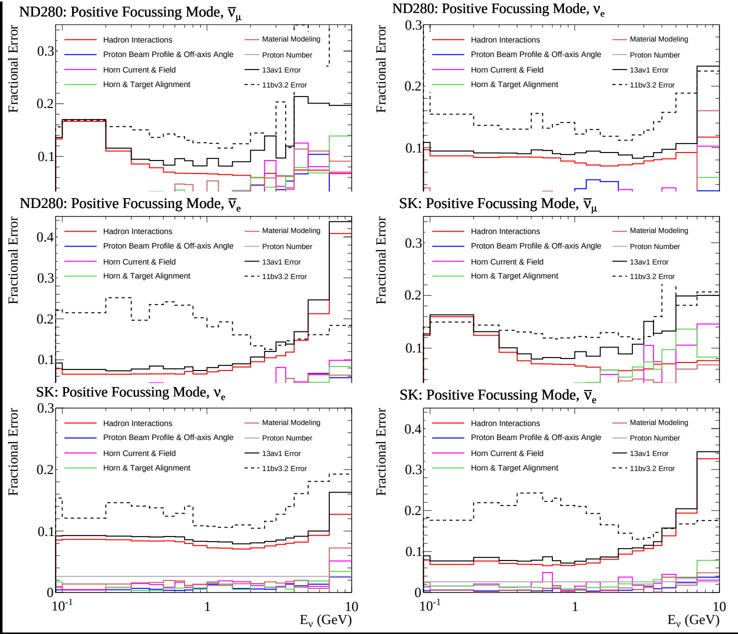
- Hadron production measurements are important for reducing neutrino flux uncertainties in accelerator neutrino experiments
- Measurements for T2K are performed at NA61/SHINE experiment
- Thin target measurements
  - Extracted spectra of $\pi^{\pm}$, $K^{\pm}$, p, K^0_s, Λ
  - Measurements of production cross section
  - Whole T2K phase space has been covered
  - Results are being used for the T2K neutrino beam simulation
  - Uncertainty of the flux is 10% at peak energy $\rightarrow$ hadron production is still dominant contribution
- T2K replica target measurements
  - $\pi^{\pm}$ spectra so far ...
  - 2010 T2K replica target analysis in progress
  - New results are being implemented to the T2K beam simulation
- Extensive measurements for the Fermilab neutrino experiments will be performed

Backup

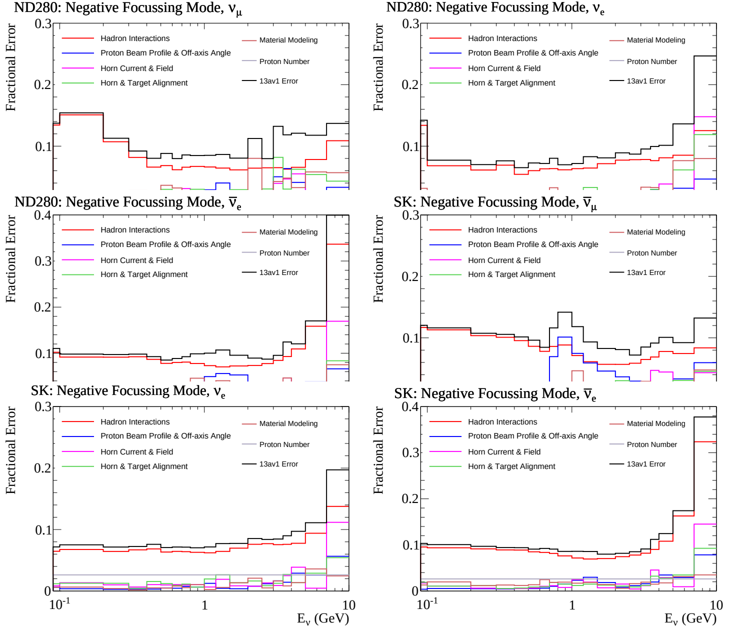
Neutrino flux uncertainties at T2K



Neutrino flux uncertainties at T2K (positive focusing)



Neutrino flux uncertainties at T2K (negative focusing)



Inelastic and Production Cross Section (p + C @ 31 GeV/c)

- Elastic cross section σ_{el} - i.e. exication of a nucleus
- Inelastic cross section $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$
- Quasi-elastic cross section σ_{qe} - i.e. nucleon is ejected from the nucleus
- Production cross section - production of a new particle (i.e. pion), $\sigma_{prod} = \sigma_{inel} - \sigma_{qe}$

Interaction probability — Number of beam $\wedge$ interaction triggers

$$P = \frac{n}{N}$$

→ Number of beam triggers

- Nonzero probability of interaction outside the target → 2 datasets: target inserted and target removed

$$P_{int} = \frac{P_{TI} - P_{TR}}{1 - P_{TR}}$$

- P_{int} - interaction probability inside the target
- P_{TI} - interaction probability in target inserted sample
- P_{TR} - interaction probability in target removed sample

$$\sigma_{trig} = \frac{1}{\rho L_{eff} N_A / A} P_{int}$$

- σ_{trig} - trigger cross section
- ρ - target density
- N_A - Avogadro's number
- A - atomic number
- $L_{eff} = \lambda_{abs}\left(1 - e^{(-L/\lambda_{abs})}\right)$ - effective target length
- $\lambda_{abs} = \frac{A}{\rho N_A \sigma_{trig}}$ - absorption length

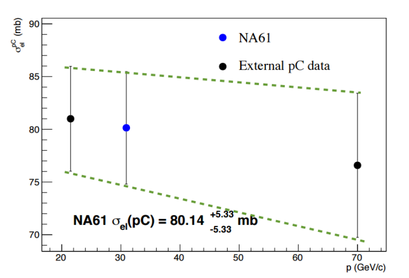
$$\sigma_{trig} = \frac{A}{\rho L N_A} \ln\left(\frac{1}{1 - P_{int}}\right)$$

$$\sigma_{inel} = (\sigma_{trig} - f_{el}\sigma_{el})\frac{1}{f_{inel}}$$

$$\sigma_{prod} = (\sigma_{trig} - f_{el}\sigma_{el} - f_{qe}\sigma_{qe})\frac{1}{f_{prod}}$$

- $f_{el}, f_{qe}, f_{inel}, f_{prod}$ - trigger efficiencies , obtained from MC

Inelastic and Production Cross Section (p + C @ 31 GeV/c)



$$f_{prod} = 0.993 \pm 0.000(det)^{+0.001}_{-0.012}(mod)$$

$$f_{inel} = 0.998^{+0.001}_{-0.008}(det)^{+0.000}_{-0.008}(mod)$$

$$f_{el}\sigma_{el} = 50.4^{+0.6}_{-0.5}(det)^{+4.9}_{-2.0}(mod)$$

$$f_{qe}\sigma_{qe} = 26.2^{+0.4}_{-0.3}(det)^{+3.9}_{-0.0}(mod)$$

Charged Hadron Production in p + C @ 31 GeV/c (2009)

Differential multiplicities

$$\frac{dn_h}{d\theta dp} = \frac{1}{\sigma_{prod}} \frac{\sigma_{trig}}{1-\epsilon} \left(\frac{1}{N^I} \frac{\Delta n_h^I}{\Delta\theta\Delta p} - \frac{\epsilon}{N^R} \frac{\Delta n_h^R}{\Delta\theta\Delta p} \right)$$

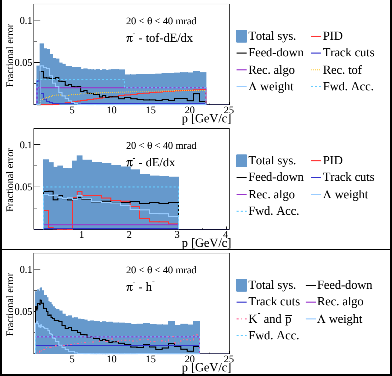
- h - particle species
- $\epsilon = (12.03 \pm 0.04)\%$ - fraction of the out-of-target interactions in the target inserted sample
- N^I, N^R - number of selected events for target inserted and target removed sample
- Δn_h^I, Δn_h^R - corrected number of particles for target inserted and target removed sample for a given bin
- $\Delta\theta$, Δp - polar angle and momentum bin size

Corrections

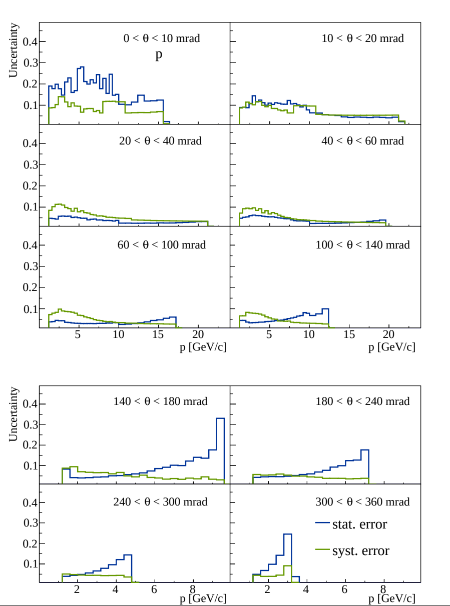
- Geometrical acceptance
- Reconstruction efficiency
- Off-target interaction
- Feed-down from decays of neutral strange particles
- Analysis specific corrections (e.g. ToF-F efficiency, PID, K^-, $\bar{p}$ contamination, etc.)

Systematic uncertainties

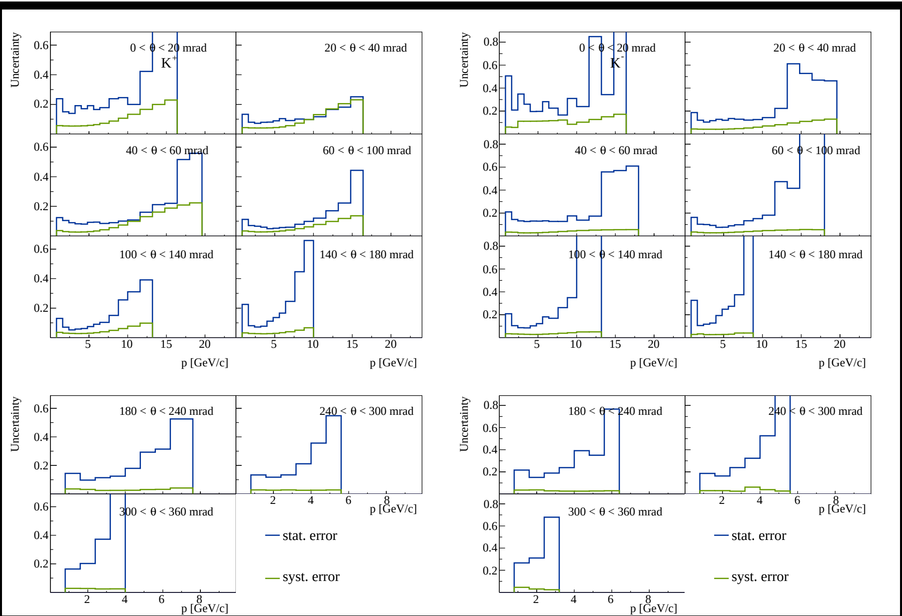
- Feed-down and Λ weighting (data based feed-down correction for π^-), 30% of correction factor
- Track cuts (1%)
- Reconstruction efficiency (2%)
- Forward acceptance (4%)
- Analysis specific errors (PID, p and $\bar{p}$ contamination, etc.), 1-5%



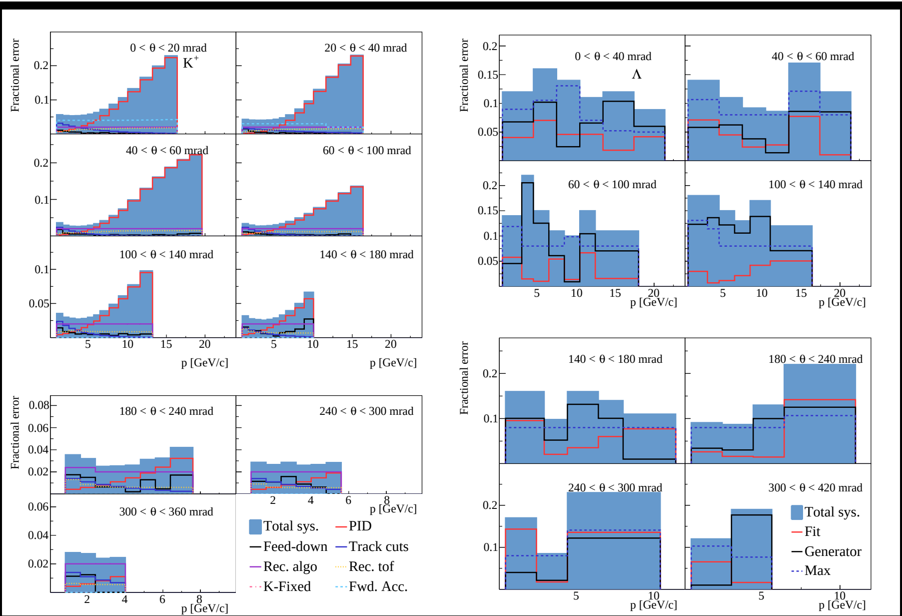
Uncertainties of proton spectra



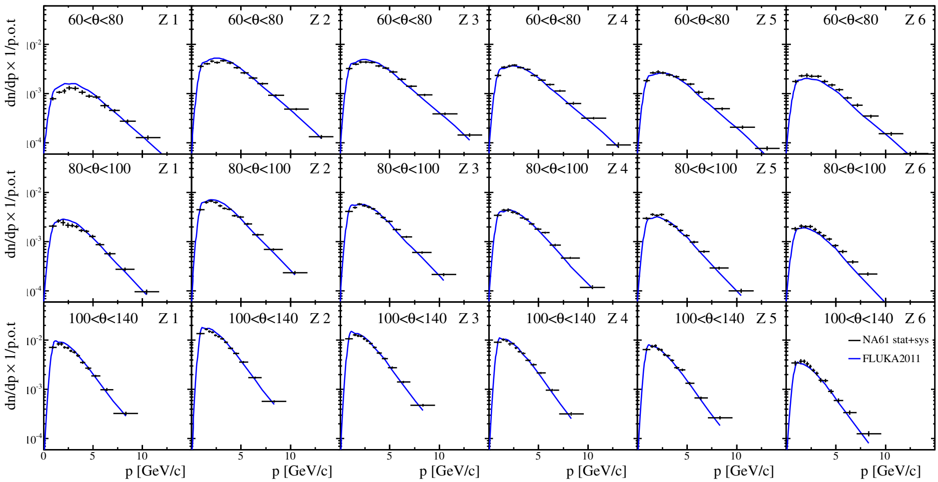
Uncertainties of K^+ spectra (left) and K^- spectra (right)



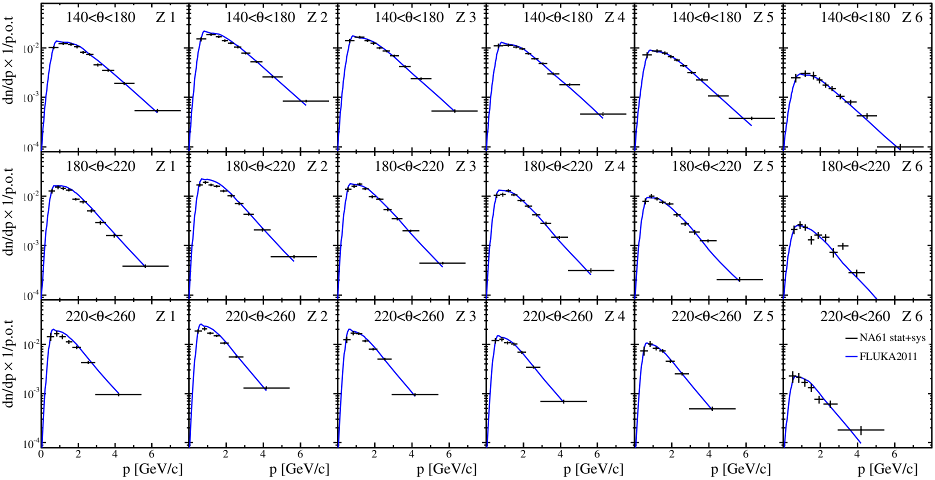
Uncertainties of K_s^0 spectra (left) and Λ spectra (right)



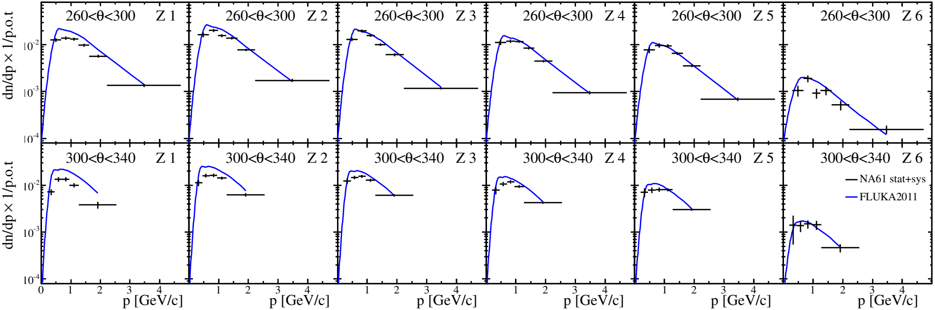
Comparison of π^+ spectra with FLUKA 2011 $(60 - 140$ mrad)



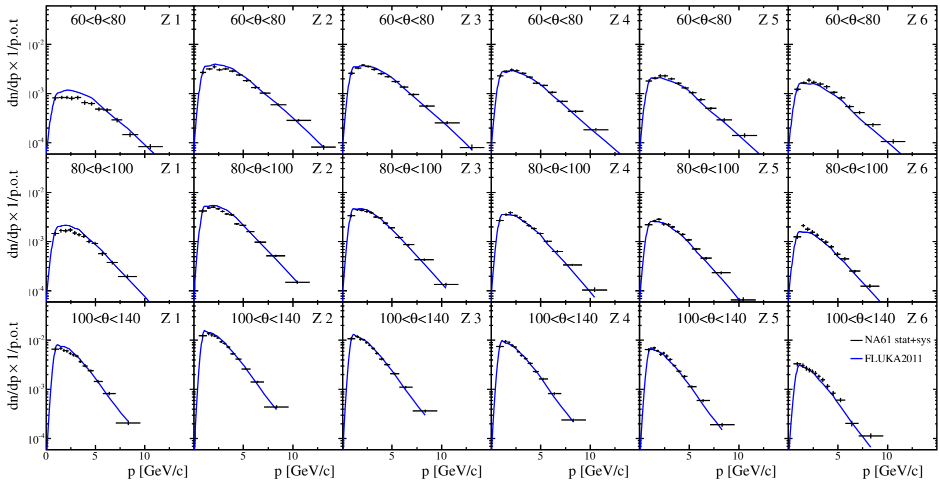
Comparison of π^+ spectra with FLUKA 2011 (140 – 260 mrad)



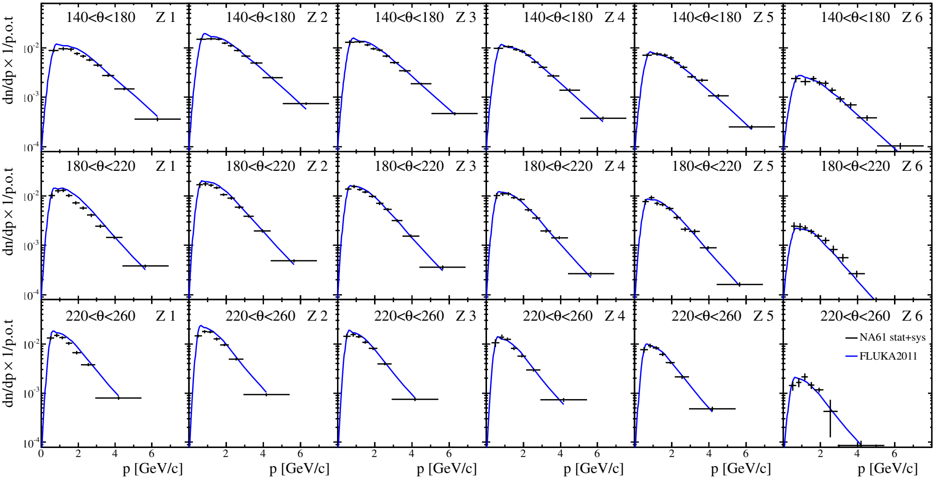
Comparison of π^+ spectra with FLUKA 2011 (260 – 340 mrad)



Comparison of π^- spectra with FLUKA 2011 (60 – 140 mrad)



Comparison of π^- spectra with FLUKA 2011 ($140 - 260$ mrad)



Comparison of π^- spectra with FLUKA 2011 (260 – 340 mrad)