Constraining the J-PARC neutrino beam

1. The T2K experiment.
   - The T2K neutrino beamline
   - The off-axis method
   - The T2K neutrino simulation
2. The NA61/SHINE experiment
   - Charged and neutral hadron analysis on thin target (4% λ_{int})
   - Impact of T2K replica data (1.9 λ_{int})
3. From NA61/SHINE measurements to T2K flux tuning
4. Summary and conclusions

Magdalena Posiadała, University of Warsaw
on behalf of the T2K Collaboration,

The T2K experiment

Primary goals:

*measurement of θ_{13} **by** ν_{μ}**->**ν_{e} appearance:

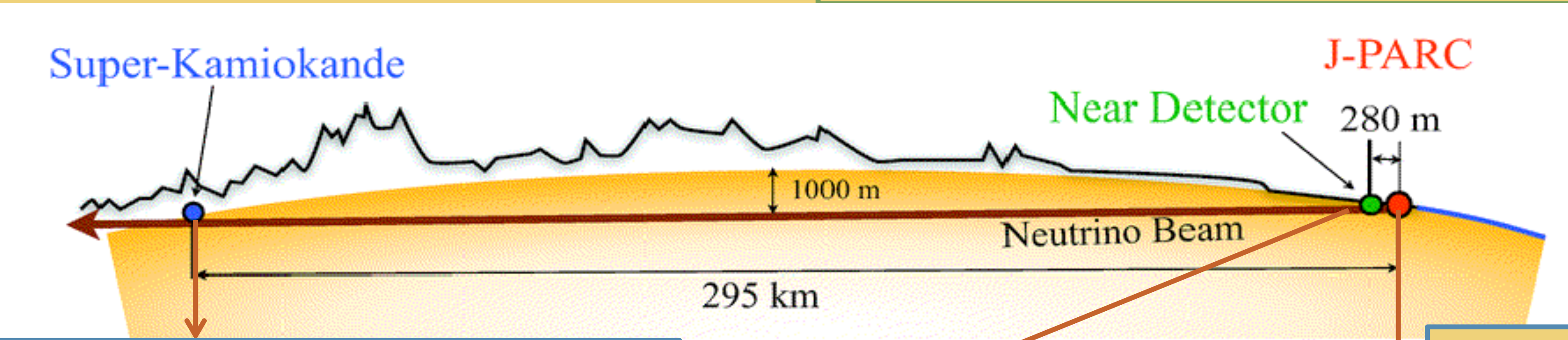
K. Abe et al.,Phys.Rev.Lett.107,041801 (2011)
K. Abe et al.,Phys.Rev. D88, 032002 (2013)
K. Abe et al.,Phys.Rev.Lett.112,061802(2014)

$\sin^2 2\theta_{13} = 0.140 \pm^{0.038}_{0.032}$ (N.H.)at 68% C.L.

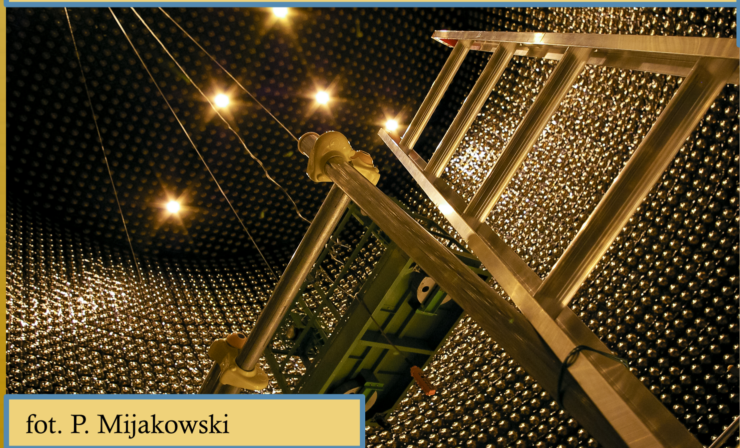
*measurement of θ_{23} **by** ν_{μ}**->**ν_{μ} disappearance:

K. Abe et al., Phys.Rev.D85,031101 (2012)
K. Abe et al., Phys.Rev.Lett. 111, 211803 (2013)
K. Abe et al., Submitted to Phys.Rev.Lett., arXiV:1403.1532

$\sin^2\theta_{23}$=0.514±0.082 (N.H.) at 90% C.L.

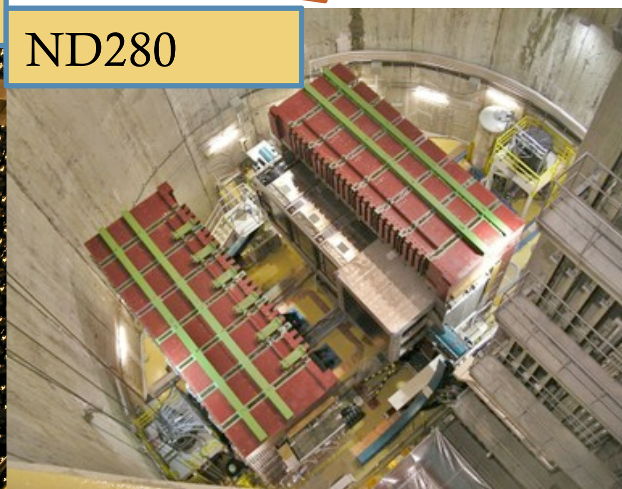


Super-Kamiokande

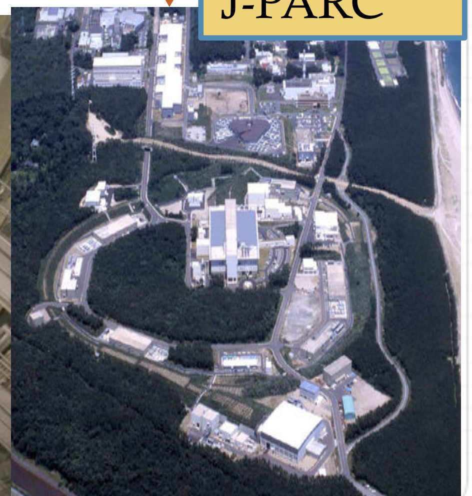


fot. P. Mijakowski

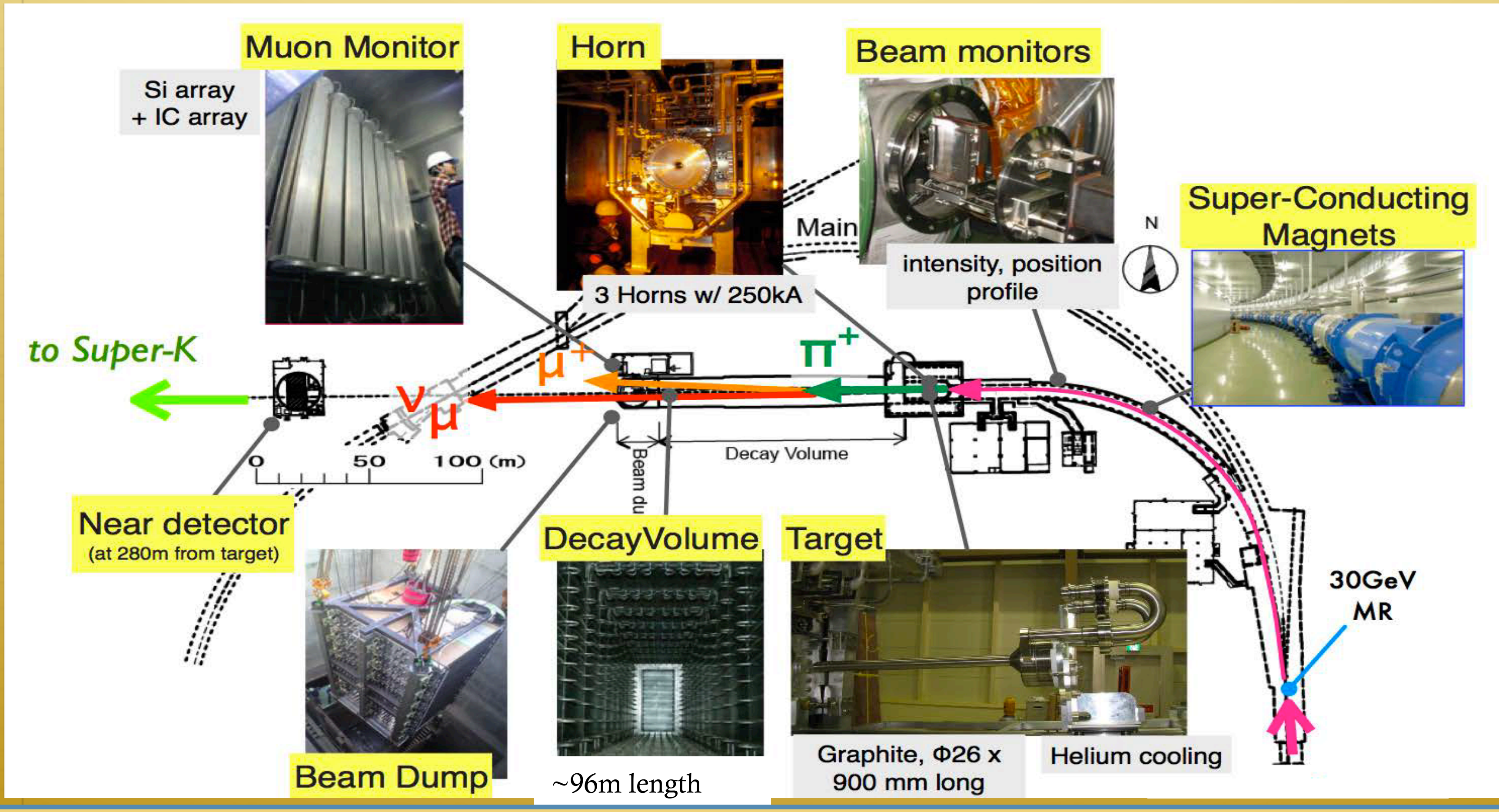
ND280



J-PARC



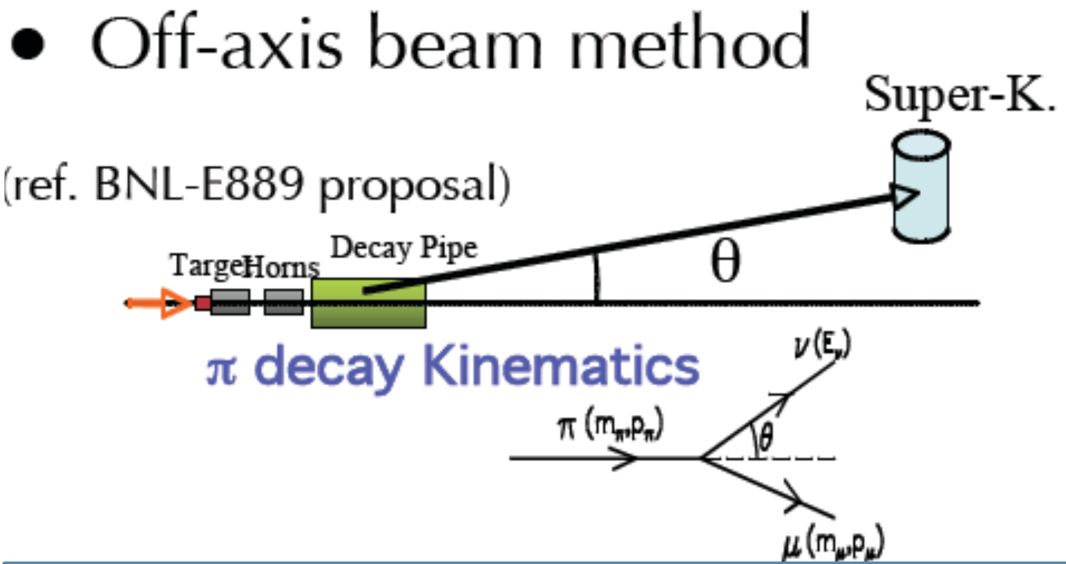
T2K neutrino beamline

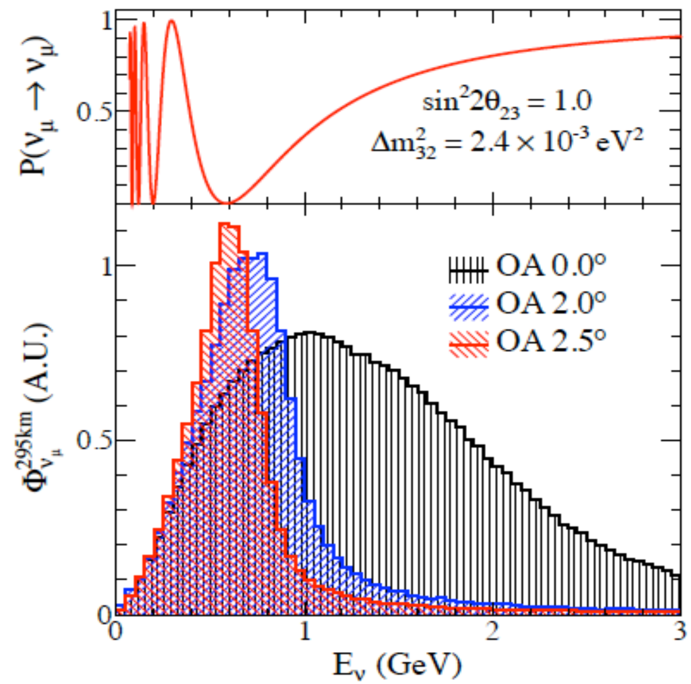


The J-PARC Main Ring (MR) extracts a 30 GeV proton beam every 2-3 seconds.
For each acceleration cycle a beam is extracted to T2K neutrino beamline as a spill.
One spill contains 8 bunches in about 5 μ s.

The off-axis method

The T2K experiment employs the off-axis method, which for the first time has been used in search for neutrino oscillations (BNL-E889 proposal).

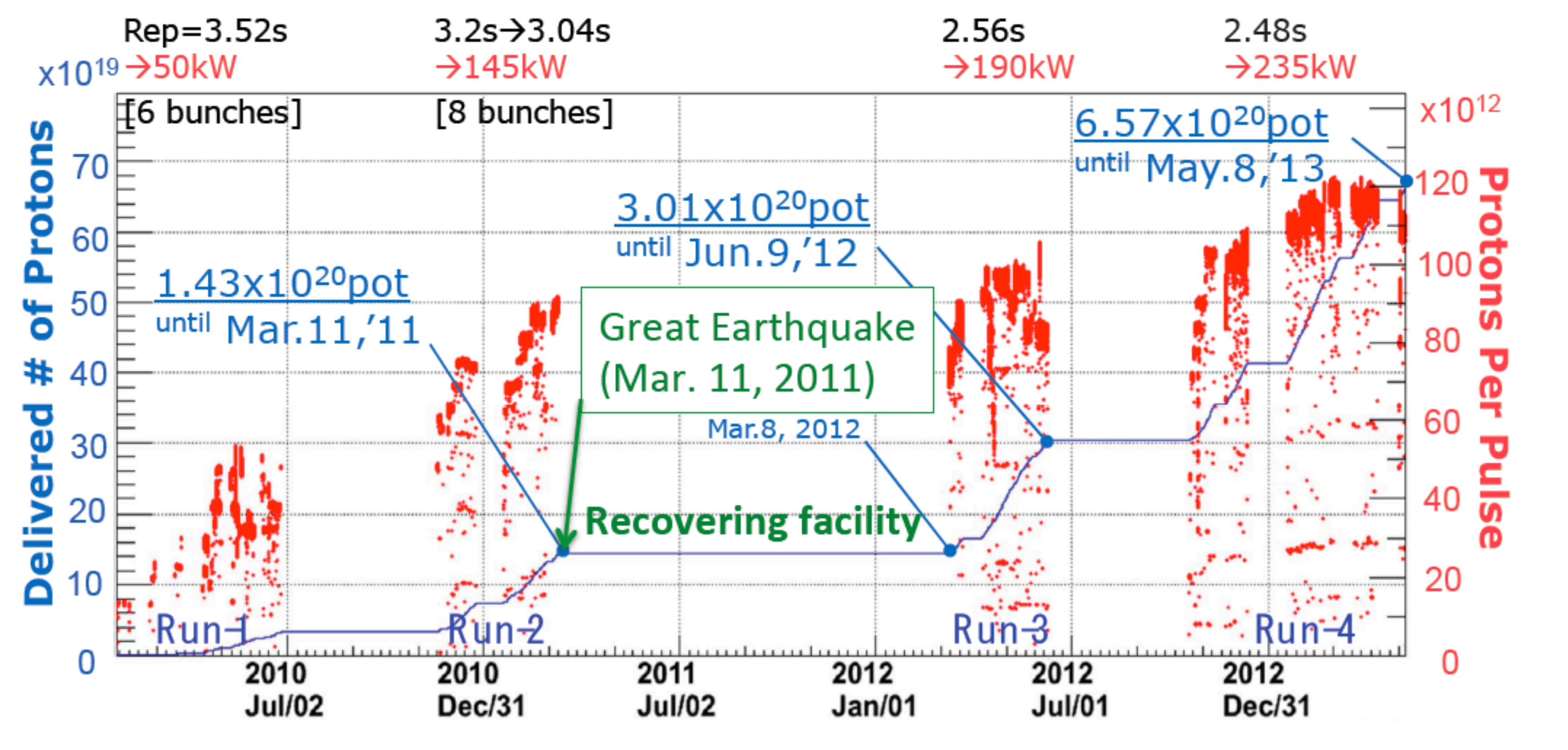




The off-axis method uses the fact that neutrino energy $\mathbf{E}_\nu$ emitted in two-body pion (kaon) decay at angle relative to the π,K direction **is only weakly dependent on the momentum** of the parent meson.

In the T2K the **off-axis angle** is set to **2.5^0** and the **neutrino beam at SK** has peak energy at **~0.6GeV**, near the expected first oscillation maximum (Phys.Rev. D87, 012001, 2013).

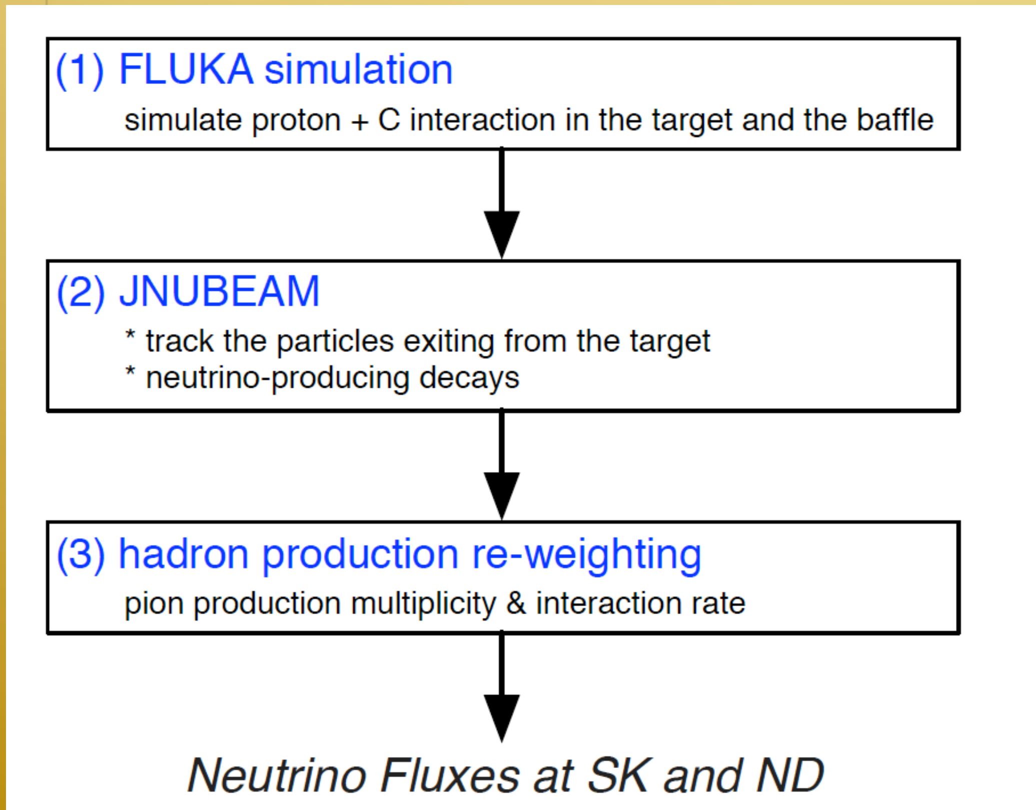
Beam operation history



History of total accumulated protons and protons per pulse for good quality beam data. The solid line shows the accumulated POT. The dot points show the number of protons per pulse.

The neutrino flux simulation

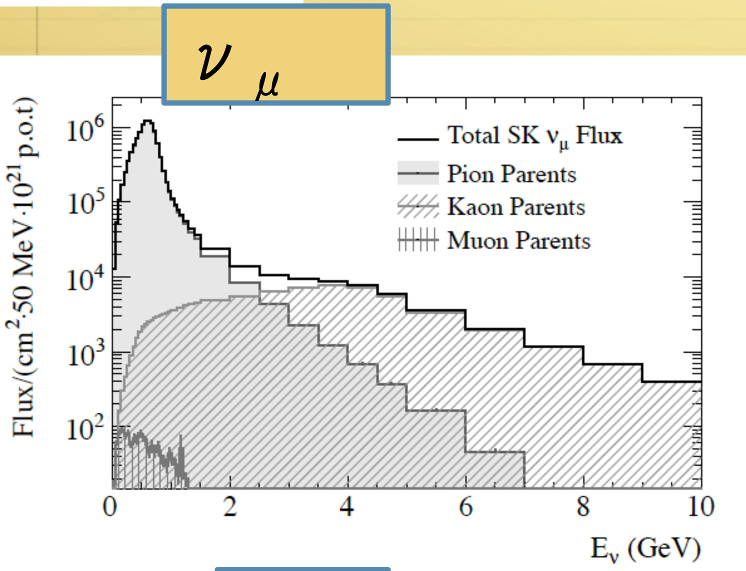
The prediction of the flux and spectrum of neutrinos at the T2K detectors (INGRID, ND280 and SK) is based on a simulation that begins with the primary proton beam upstream of the baffle and ends with the decay of hadrons and muons that produce neutrinos (Phys.Rev. D87, 012001, 2013).

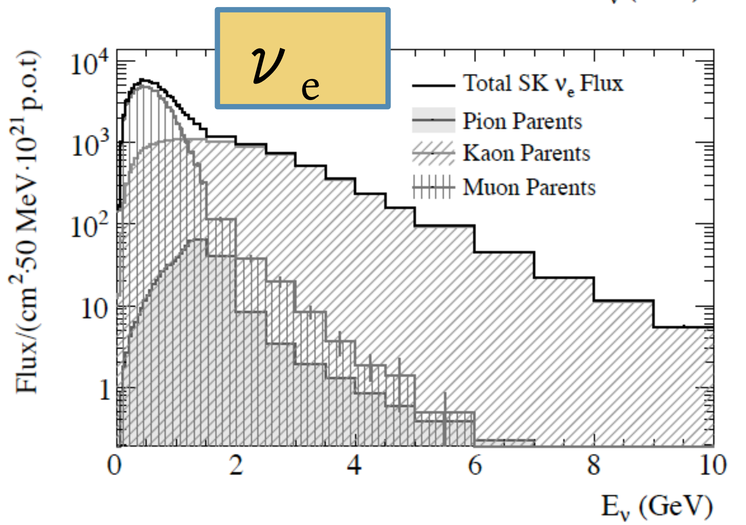


The *JNUBEAM* is GEANT3 Monte Carlo simulation of the baffle, target, horn magnets, helium vessel, decay volume, beam dump and muon monitor.

The *JNUBEAM* simulation and its associated uncertainties are driven by primary beam profile measurements, measurements of the horns magnetic fields, hadron production data, including **NA61/SHINE measurements** (Phys.Rev. C85, 035210, 2012, Phys.Rev. C84, 034604, 2011).

The flux predictions





Major neutrino-producing decay modes:

1) $\pi^+ \rightarrow \mu^+ + \nu_\mu$ BR (99.97%)

2) $K^+ \rightarrow \mu^+ + \nu_\mu$ BR (63.55%)

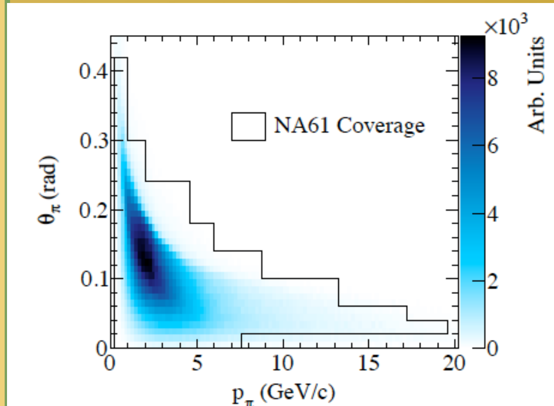
$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$ BR (3.35%)

$K^+ \rightarrow \pi^0 + e^+ + \nu_e$ BR (5.07%)

3) $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$ BR (100%)

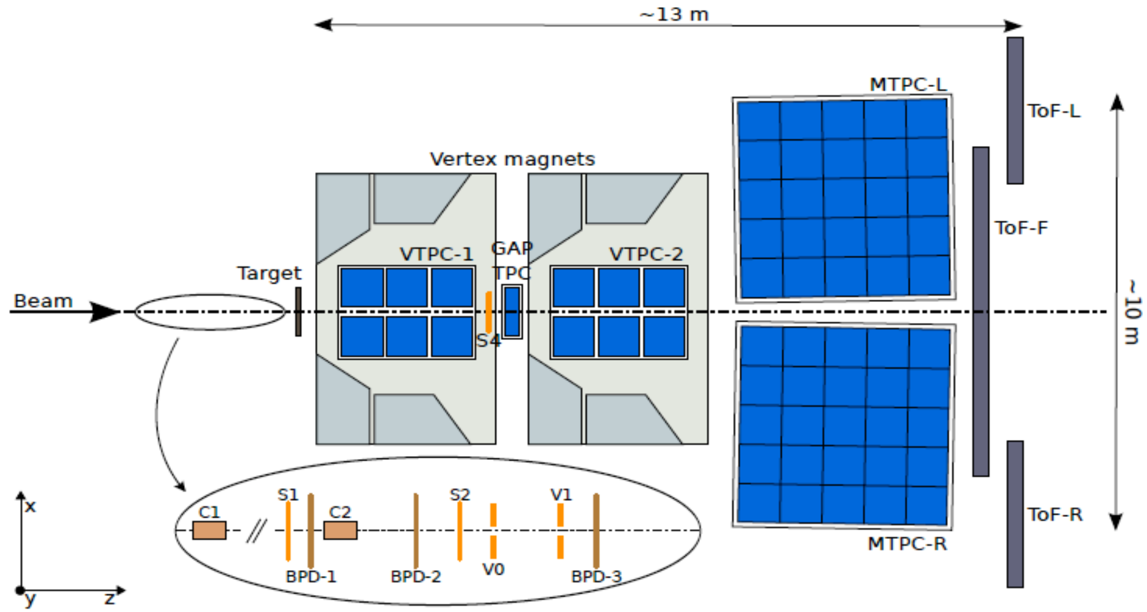
Parent	Flux percentage of each(all) flavor(s) ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0(55.6)%	41.8(2.5)%	31.9(0.4)%	2.8(0.0)%
$K^\pm$	4.0(3.7)%	4.3(0.3)%	26.9(0.3)%	11.3(0.0)%

To predict the neutrino flux T2K relies primarily on the measurements of pion and kaon yields by the NA61/SHINE experiment at CERN SPS.



NA61/SHINE at CERN SPS

➢**Large-acceptance hadron spectrometer**. Its main components were used by NA49 Collaboration.
➢**The main tracking and particle identification devices** are large-volume TPCs and ToF.
➢Two TPCs are located between coils of the two superconducting magnets (1.14 Tm)



Two types of **measurements were done for T2K**: 31GeV/c protons on:
1). **Thin target (4% λ_{int})**- studies of primary interactions
2). **Replica of the T2K target (1.9 λ_{int})**- production of all hadrons along the target

Year	Thin target	Replica target	Status
2007	630 $*10^3$	$230*10^3$	Published
2009	$4.4*10^6$	$2.4*10^6$	Being analyzed
2010	-	$10*10^6$	Under Calibration

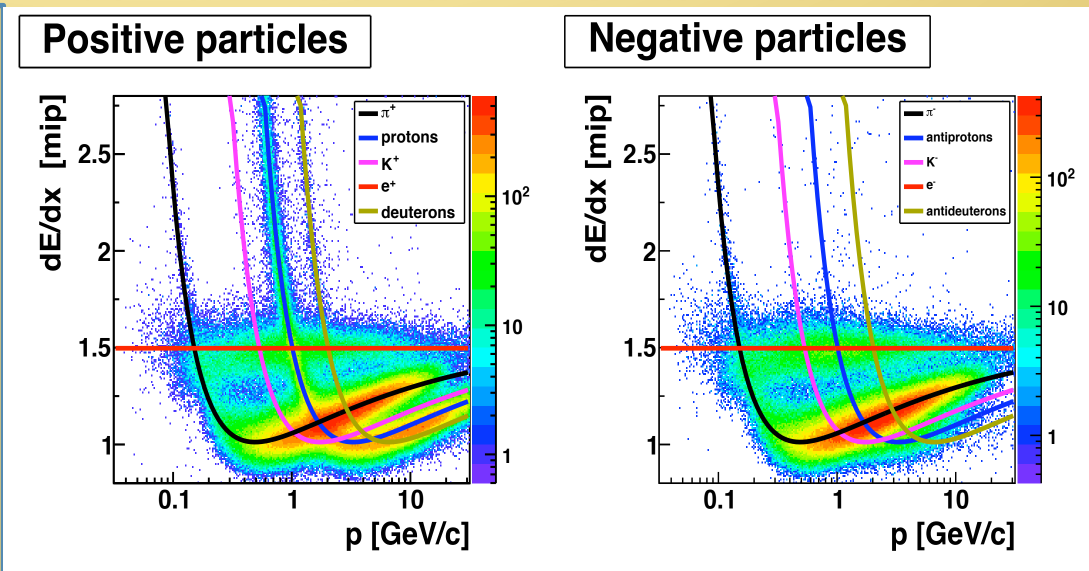
Charge hadron measurements from thin target data

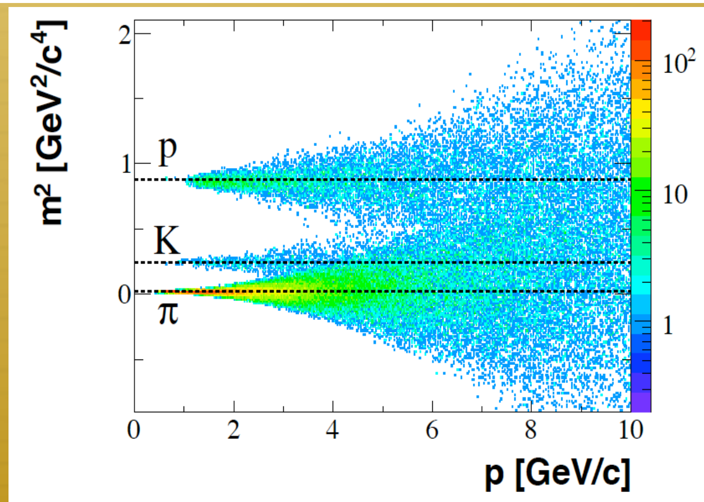
We developed three analyses techniques:

1). **dE/dx+ToF** –particles identified via time-of-flight and dE/dx measurements in the ToF and TPCs. $\pi^{\pm}$, K^{+},p with p≥1GeV/c- 2007 data and in addition K^{-} with 2009 data- **status of 2009 : finished with total error values.**

2). **dE/dx analysis at low momentum,** π^{+} (π^{-}) with p≤1 (3)GeV/c- **status of 2009: released central values up to 1 GeV/c, systematic in progress.**

3). **h^{-} analysis** via measurements of negatively charged particles; spectra of π^{-} in broad momentum range- **status of 2009: work in progress**.

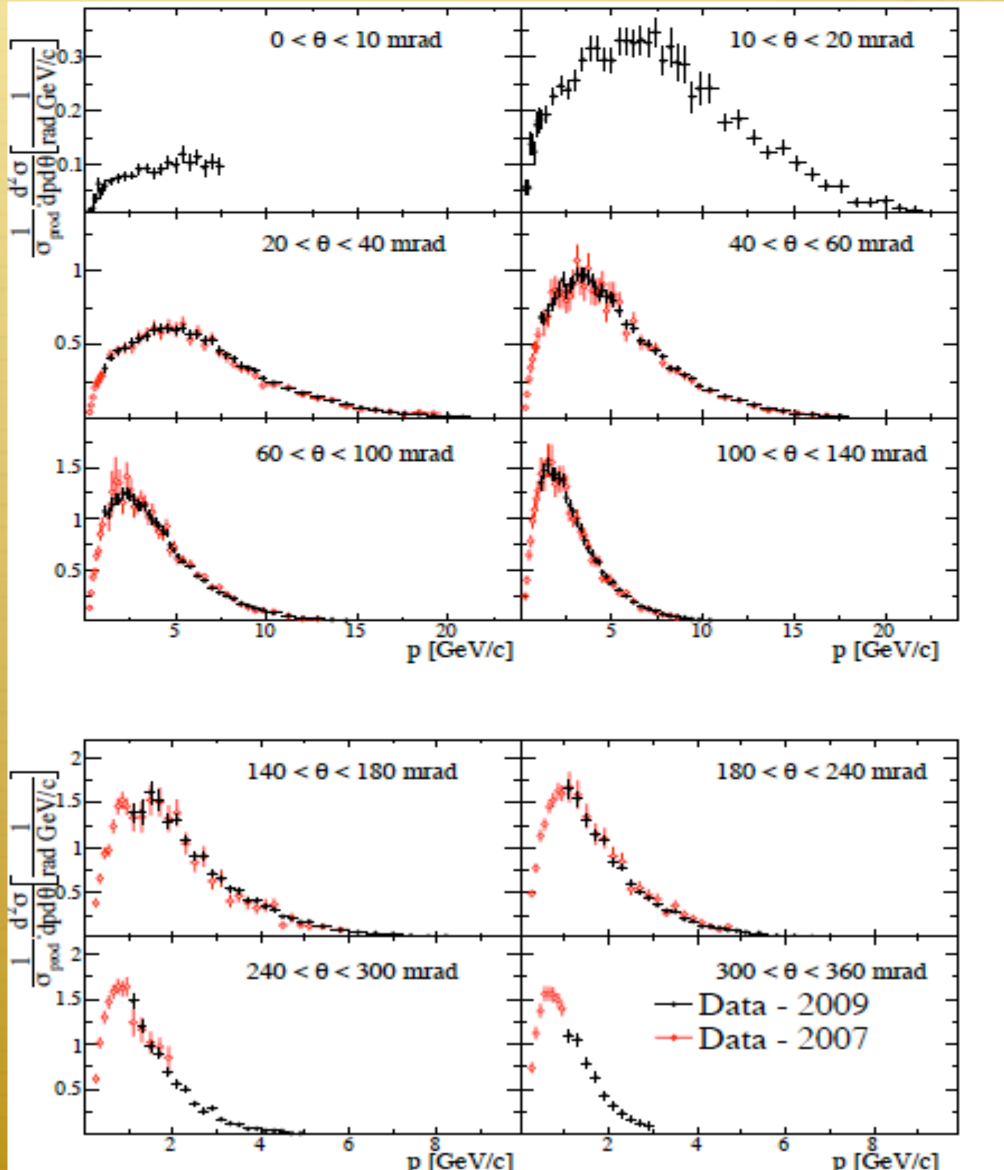




Charge hadron measurements from thin target data

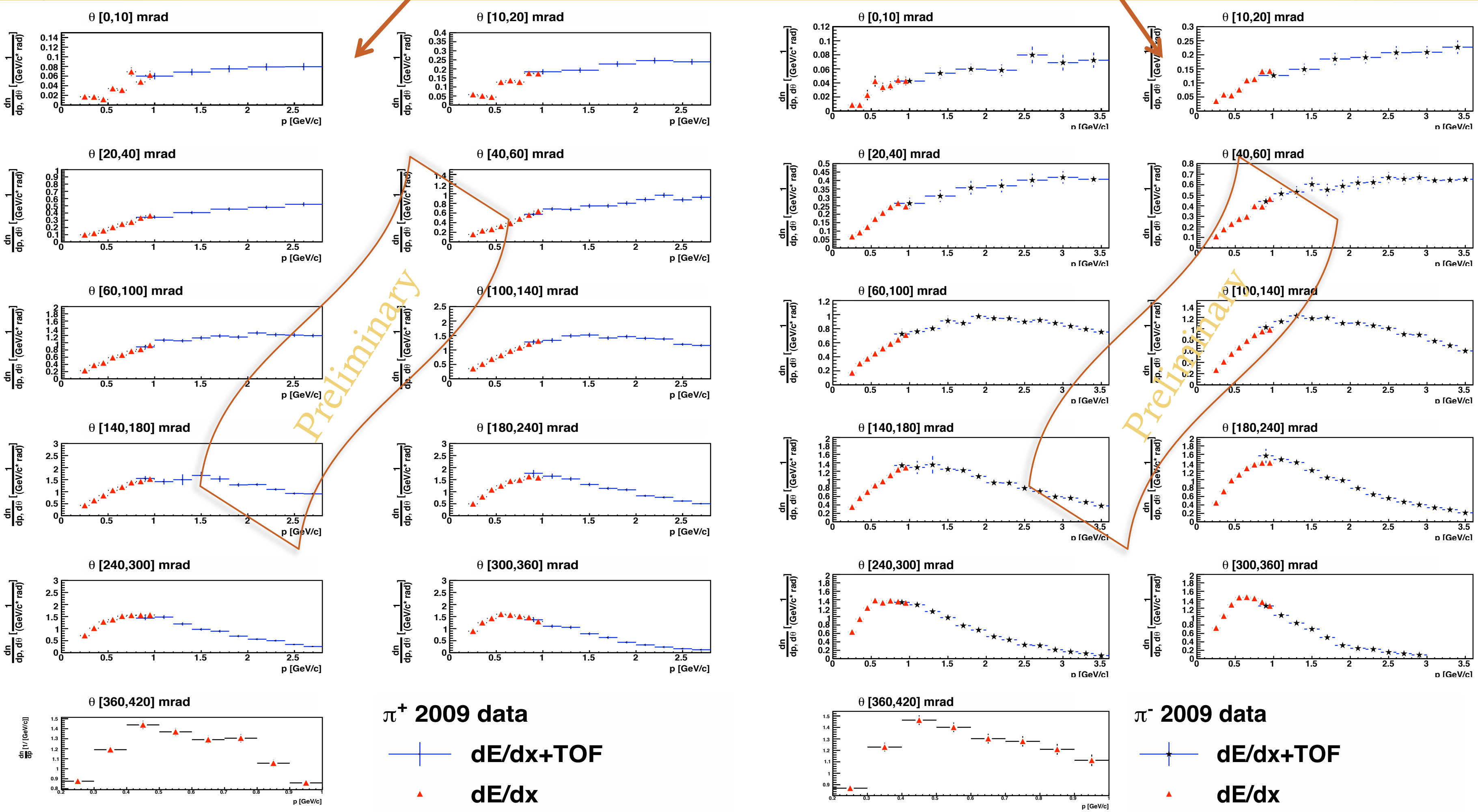
- π^+ **multiplicities** in p+C at 31 GeV/c from **dE/dx +ToF analysis from 2009** data compared to 2007 results.
- Total error plotted.
- Improved statistical precision with 2009 data.

Results for $K^{\pm}$,p, π^- in the appendix



Comparison of 2009 multiplicities for π^+ (left) and π^- (right) - dEdx vs dEdx+ToF

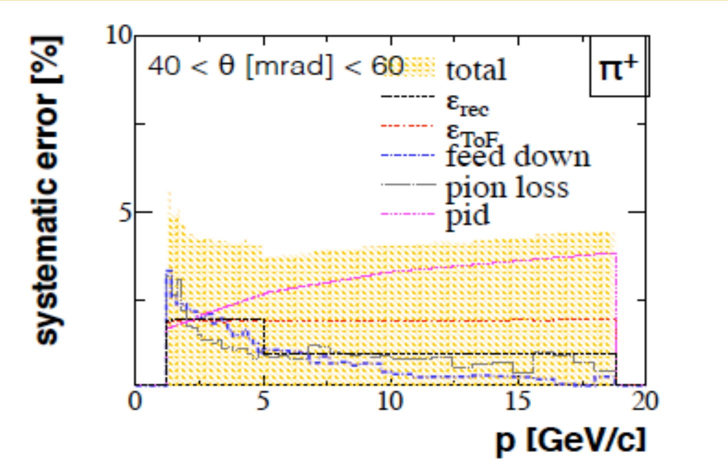
dE/dx – statistical error, dE/dx+ToF total error

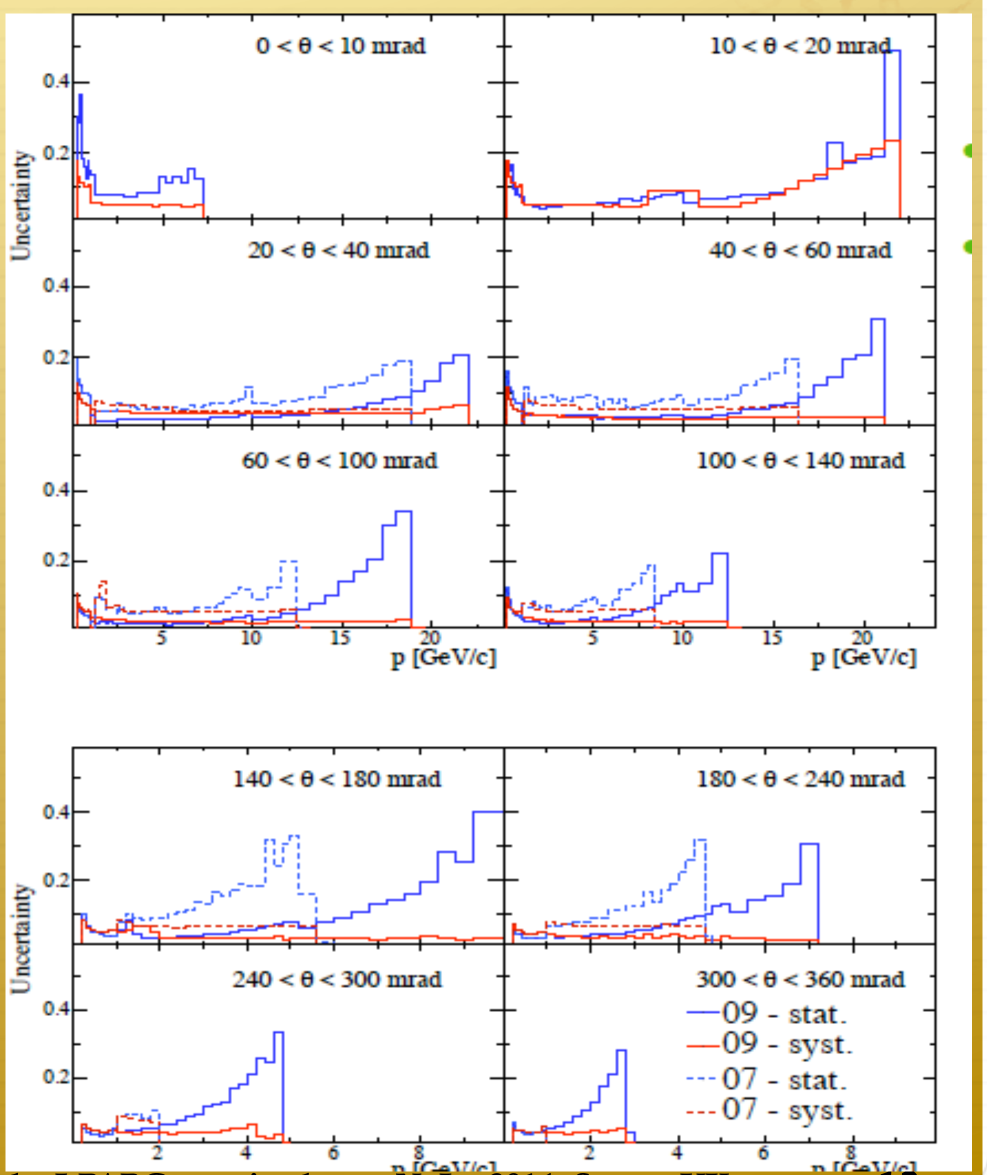


π^+ and π^- spectra determined at low momenta merge smoothly with results from dE/dx+ToF

Charge hadron measurements from thin target data

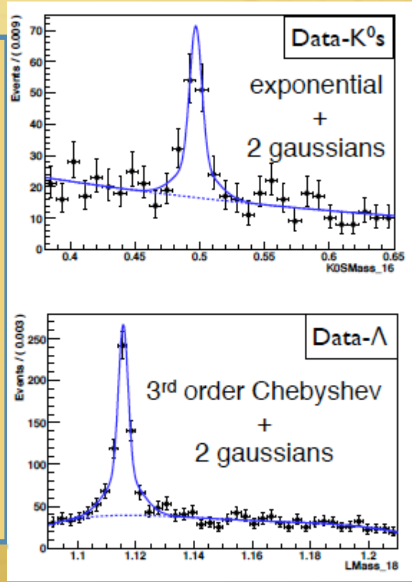
- π^+ **uncertainties** in p+C at 31 GeV/c from dE/dx +ToF analysis from 2009 data compared to 2007 results.
- Statistical uncertainty lowered by a factor of 2-3
- Systematic uncertainty lowered by a factor of ~2.
- Main contributors to systematic error in dE/dx+ToF analysis is:
  - PID
  - feed down: improved with studies of decay of strange particles (K^0_s and Λ).



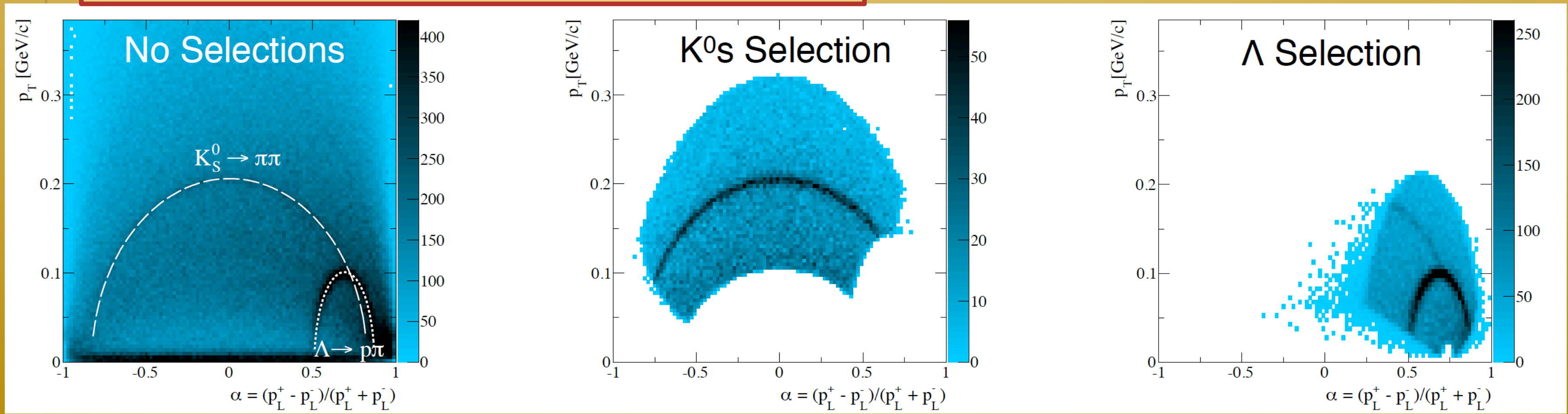


K^0_s and Λ measurements from thin target data

- Main source of systematic uncertainty in $\pi^{\pm}$ and p measurements comes from decays: $K^0_s \to \pi^+ + \pi^-$, $\Lambda \to p + \pi^-$
- Moreover main source of ν_e at high energy in T2K comes from $K^0_L \to \pi^- + e^+ + \nu_e$
- Yields of K^0_s and Λ candidates are extracted from invariant mass fits.
- 2007 results recently published (Phys. Rev. C89, 025205, 2014).
- 2009 data are released, work on new publication in progress.



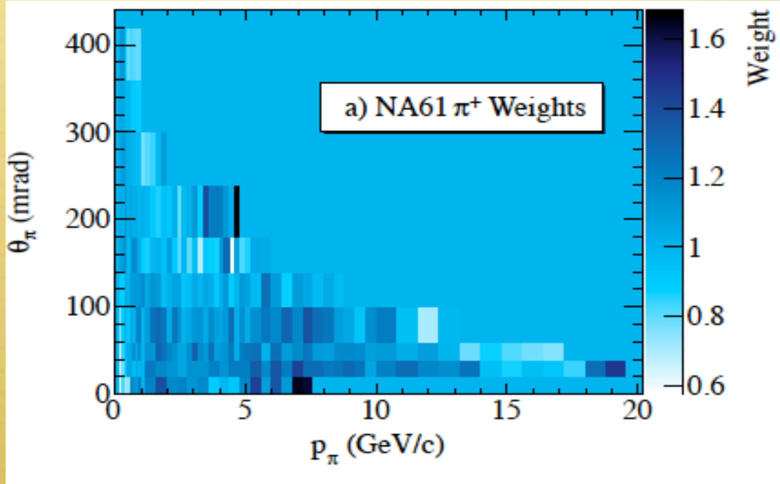
Podolanski-Armenteros plots

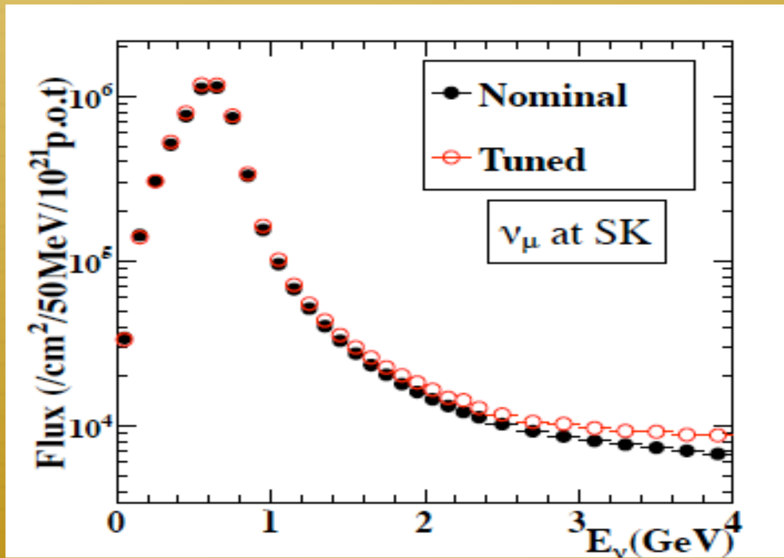


From NA61 measurements to T2K flux tuning

1. **The simulation of hadronic interactions** in the *JNUBEAM:*
   -*inside the target* are modeled with FLUKA
   -*outside the target* are modeled with GCALOR used in GEANT3.
2. **Hadron differential production re-weighting** is evaluated using the differential multiplicity in the momentum p of the produced particle and its angle ϑ. Mainly NA61 results are used.
3. Obtain tuned flux
4. Calculate flux uncertainties

(Phys.Rev. D87, 012001, 2013)

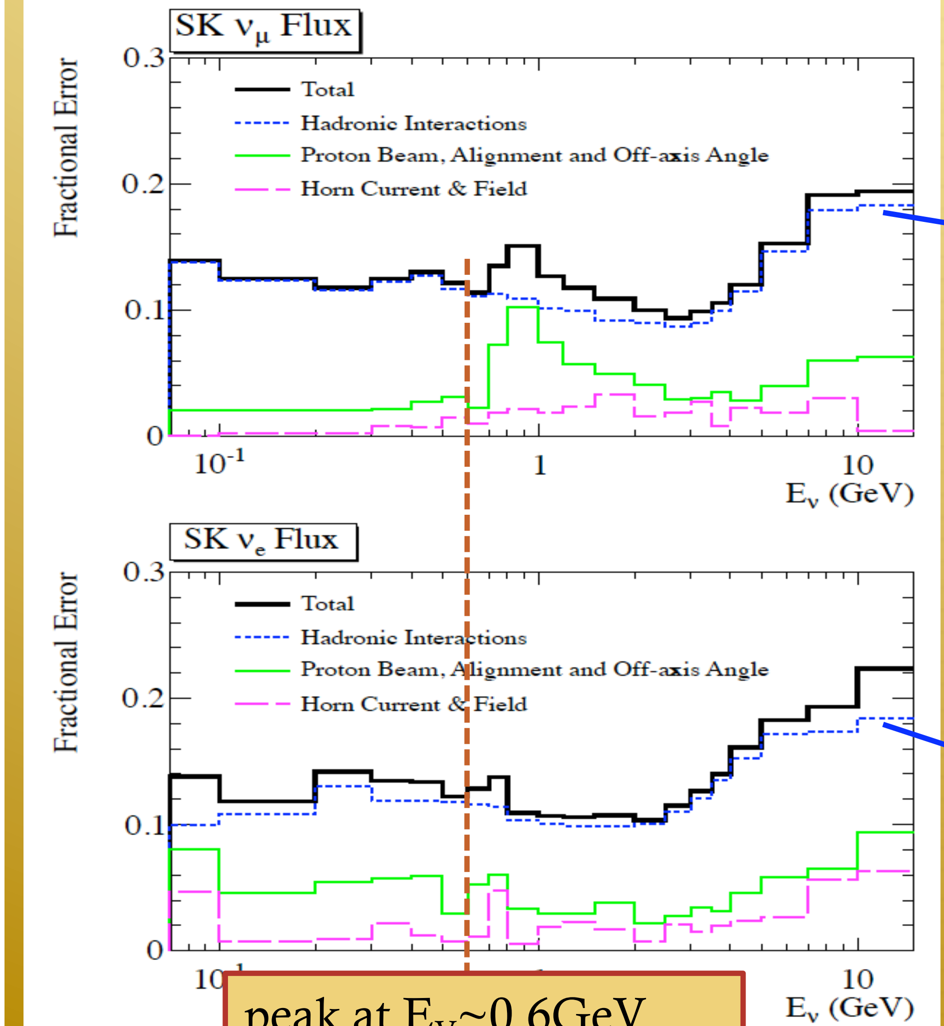




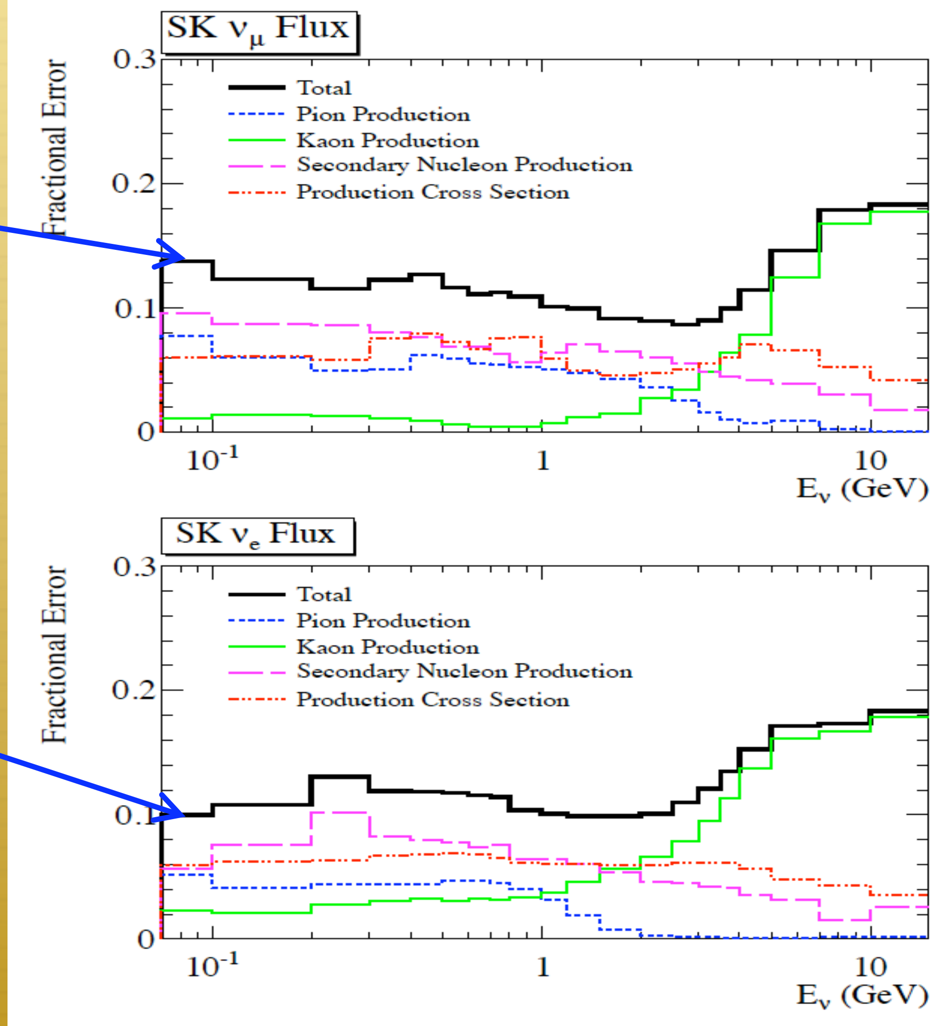
Fractional flux error

(Phys.Rev. D87, 012001, 2013)

Used $\pi^{\pm}$, K^{+} measurements from 2007 run of NA61

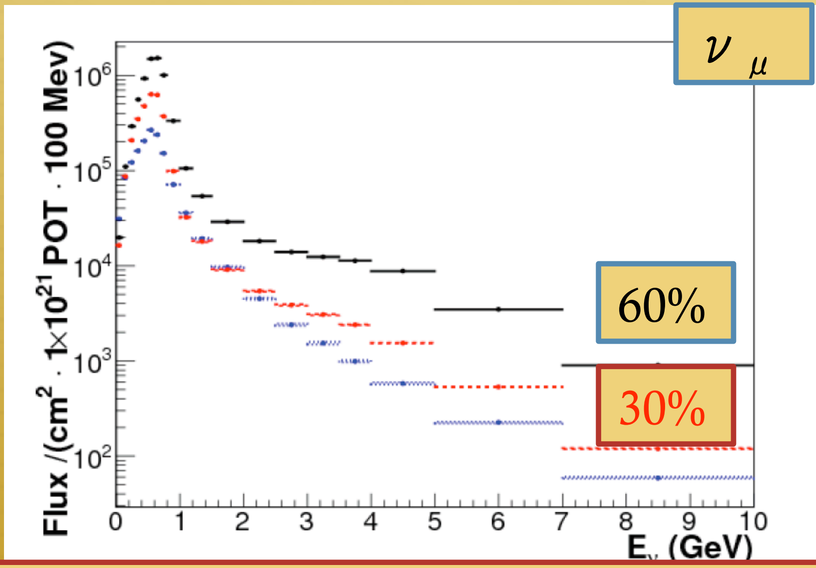


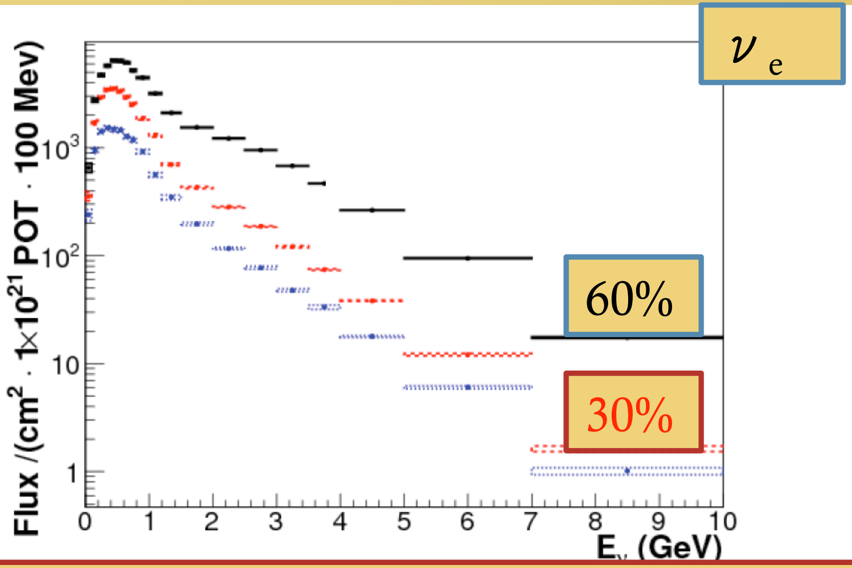
peak at E_ν~0.6GeV



Importance of the T2K replica target analysis

Neutrinos are coming from hadrons produced by **primary interaction** and from other various interactions which can occur **in the long target (~90 cm length)** as well as in the **surrounding target material present in the beamline** (Nucl. Instrum. Meth. A701, 99-114, 2013).

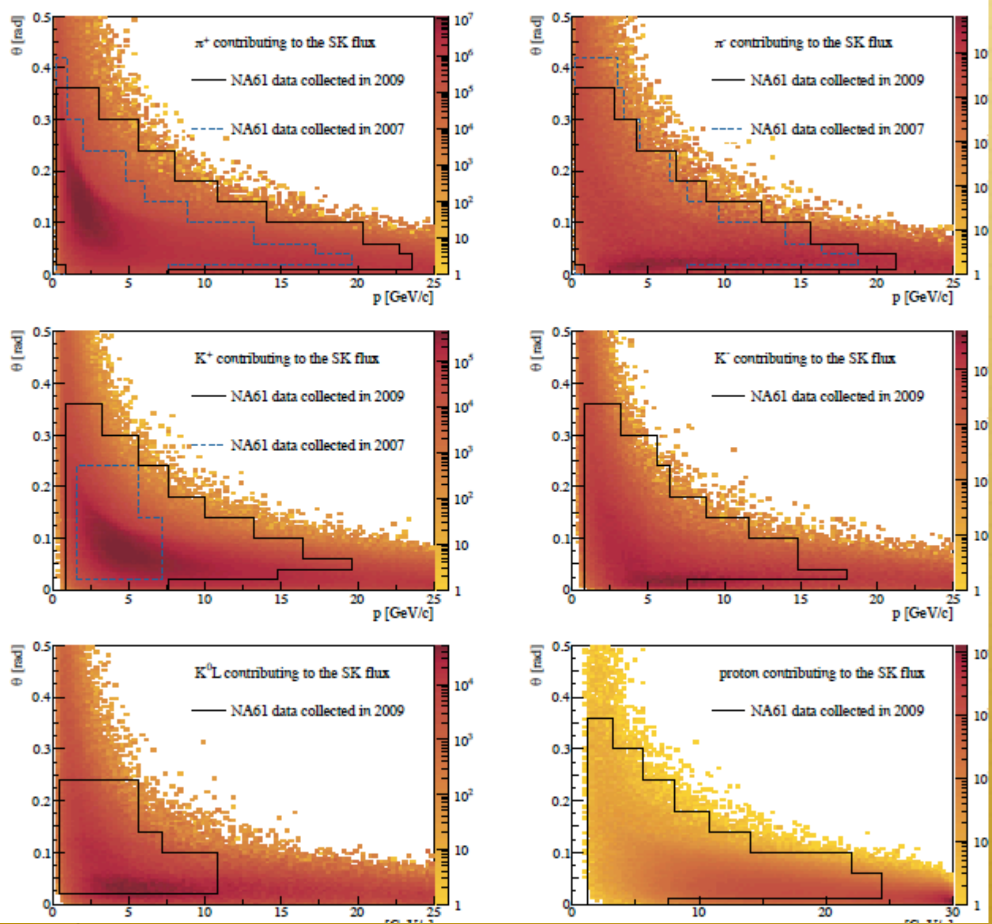




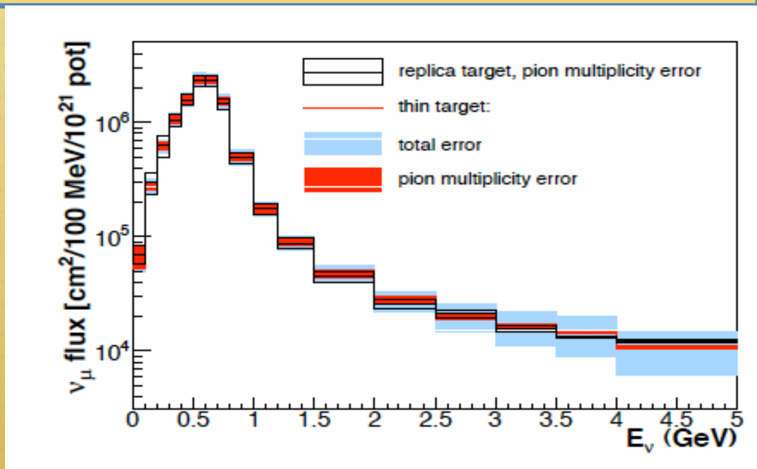
- The contribution of parents originating from the target sums up to 90 %, among which 60% are due to primary interactions, and 30% are due to re-interactions in the target. The remaining 10% are interactions outside the target.
- We used limited in statistics 2007 T2K replica target data to test the method of tuning T2K flux.
- 2009 T2K replica target analysis is almost finished, pion spectra will be used to tune T2K simulation.

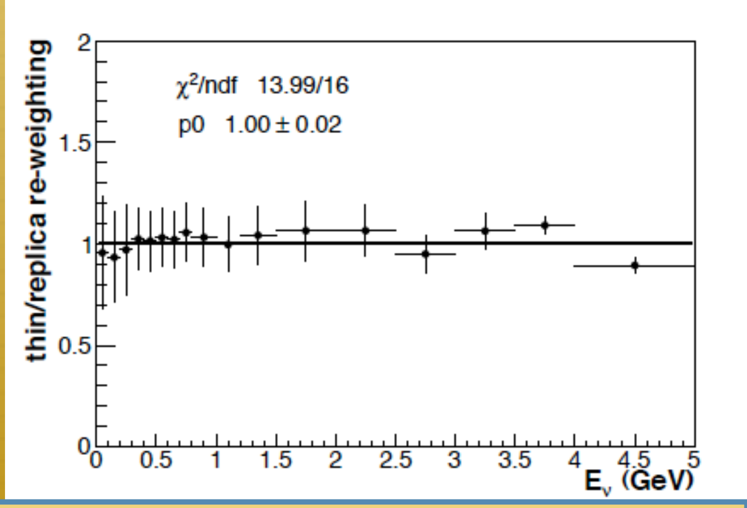
Possible improvements with 2009 NA61 data

with thin target data:
better coverage, new hadronic measurements



with T2K replica target data,
tested on 2007 data





Nucl.Instrum.Meth.A701, 2013

Summary and conclusions

➢**For the first T2K** analyses the uncertainties on the **flux predictions** are evaluated to **be below 15% near the flux peak.**

➢There is still place for improvement with **new 2009 NA61** measurements for:

- ➢**Thin target data:**
  - ➢The $\pi^{\pm}$, $K^{\pm}$, p, Λ, K0s spectra were released from 2009 and will be used to tune once again T2K flux.
  - ➢Those spectra have wider p-θ coverage, lower statistical and systematic uncertainties.
- ➢**The T2K replica target data** – analysis very advanced.

➢The 5% precision on the T2K flux predictions may be reachable, with all mentioned NA61 data included in the re-weighting chain.

➢Similar procedure with flux tuning may be used for other neutrino experiments (Hyper-Kamiokande, Laguna-LBNO, LBNE).

Other T2K talks at NuInt 2014

1). T. Dealtry, *Controlling neutrino interaction systematics: The T2K experiment*
2). T. Kikawa, *T2K CC numu inclusive*
3). B. Smith, *T2K CC nue inclusive*
4). M. Tzanov, *T2K tracker CCQE xsec result*
5). T. Kikawa, *INGRID CCQE xsec results*
6). P.Sinclar, *np-nh in T2K*
7). M. Wilking, *T2K-ND280 upgrade for neutrino-nucleus cross section studies and NuPRISM*
8). T Kikawa, *T2K on-axis CC coherent pion production*

appendix

Hadron differential production re-weighting

Data set	Particle	Secondary interaction	Tertiary interactions
NA61/SHINE (2007 4% λ_{int})	$\pi^{\pm}$, K^{+}	straightforward tuning, data used to tune interactions also in horns (Al)	yes, extrapolation to lower momentum and targets (horns-Al)
Eichten et al. Allaby et al. data on Be used, no data for C	K^{+} and K^{-} not covered by NA61/SHINE	yes	yes
no re-weighting applied to regions not covered by any data	-	-	-

The T2K replica target re-weighting

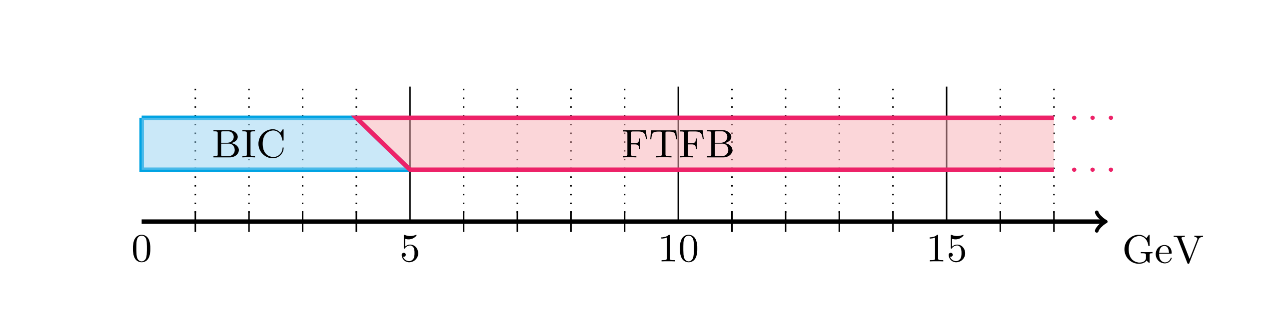
At least two different approaches based on the NA61 replica target data can be used to in T2K simulation:

- ***absolute yields***, we use the NA61 measured yields at the surface of the target corrected for various efficiencies like detector geometrical acceptance, particle losses. In this case weights are defined the same way as for thin target data, and **re-weighting is done within T2K simulation**
- ***raw yields***, we use NA61 measured yields at the surface of the target without any corrections. We need also the reconstructed yields obtained from the NA61 simulation based on the model used in T2K. **Re-weighting is done within NA61 simulation- model dependent.**

NA61 thin target results are compared to Geant4

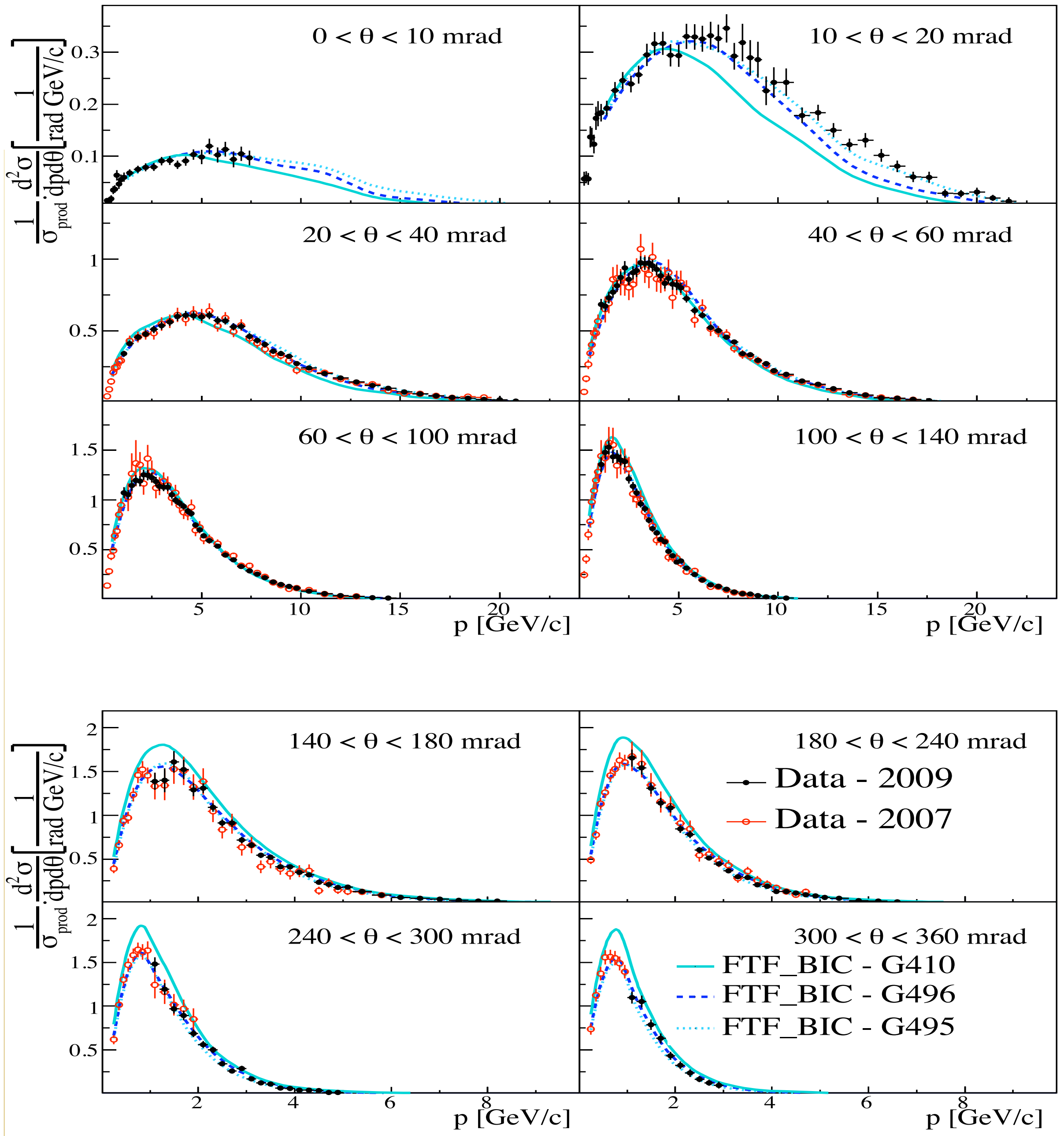
Among all available physics list, we will focus on the most promising one: FTF_BIC

- For interactions < ~5GeV/c Binary Cascade model is used
- For interactions at higher energies Fritiof model is used



Our measurements are very useful for Geant4 developpers in order to improve their models.
In order to see the evolution, FTF_BIC predictions will be shown for three Geant4 releases:

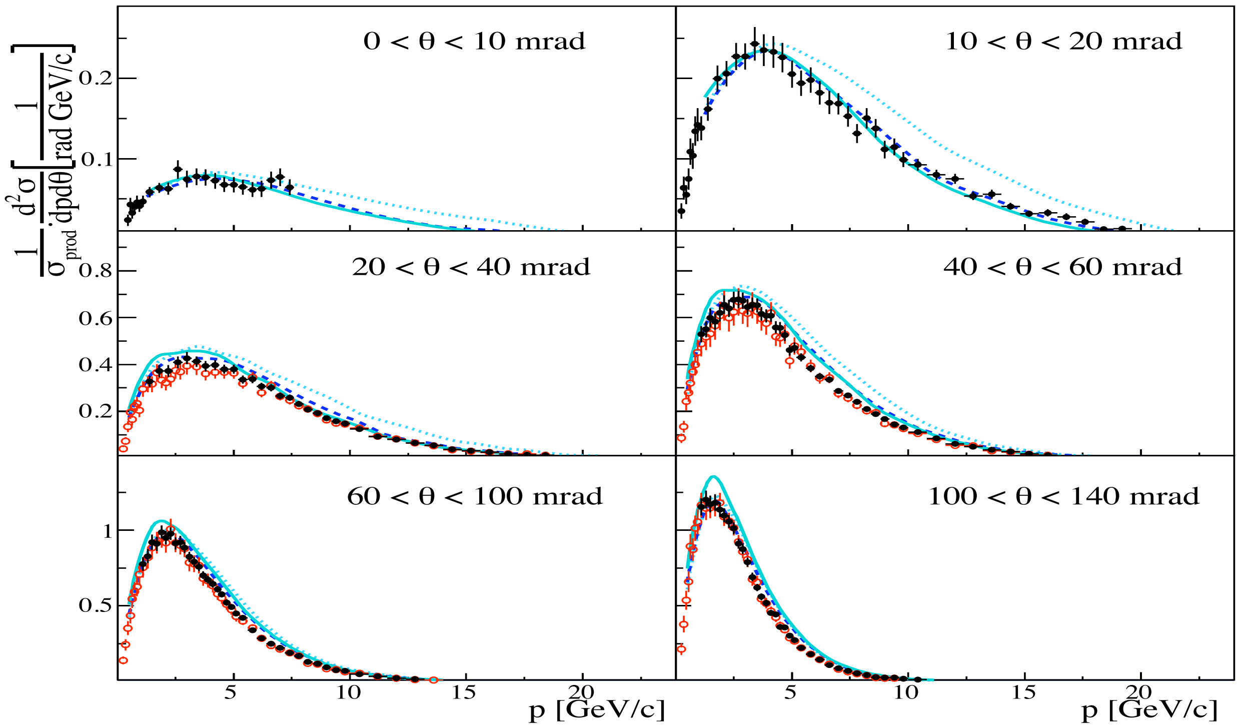
- Geant4.9.5 [October 2012]
- Geant4.9.6 [May 2013]
- Geant4.10 [December 2013] LATEST RELEASE

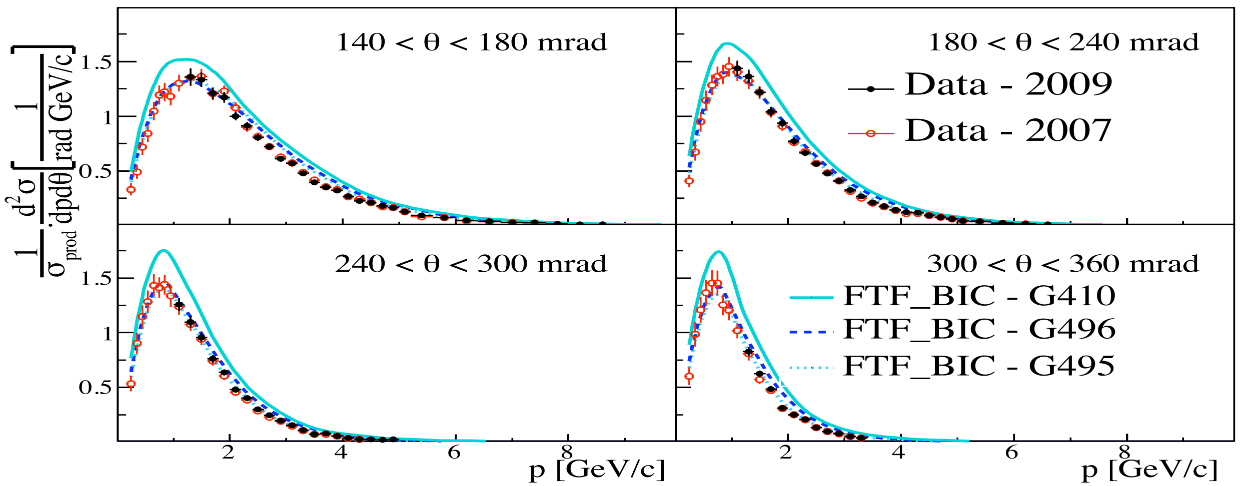


π^+ multiplicities

For forward going pions and large angle pions, there are strong modifications wrt different releases.

Latest release predictions are worst than the previous one.



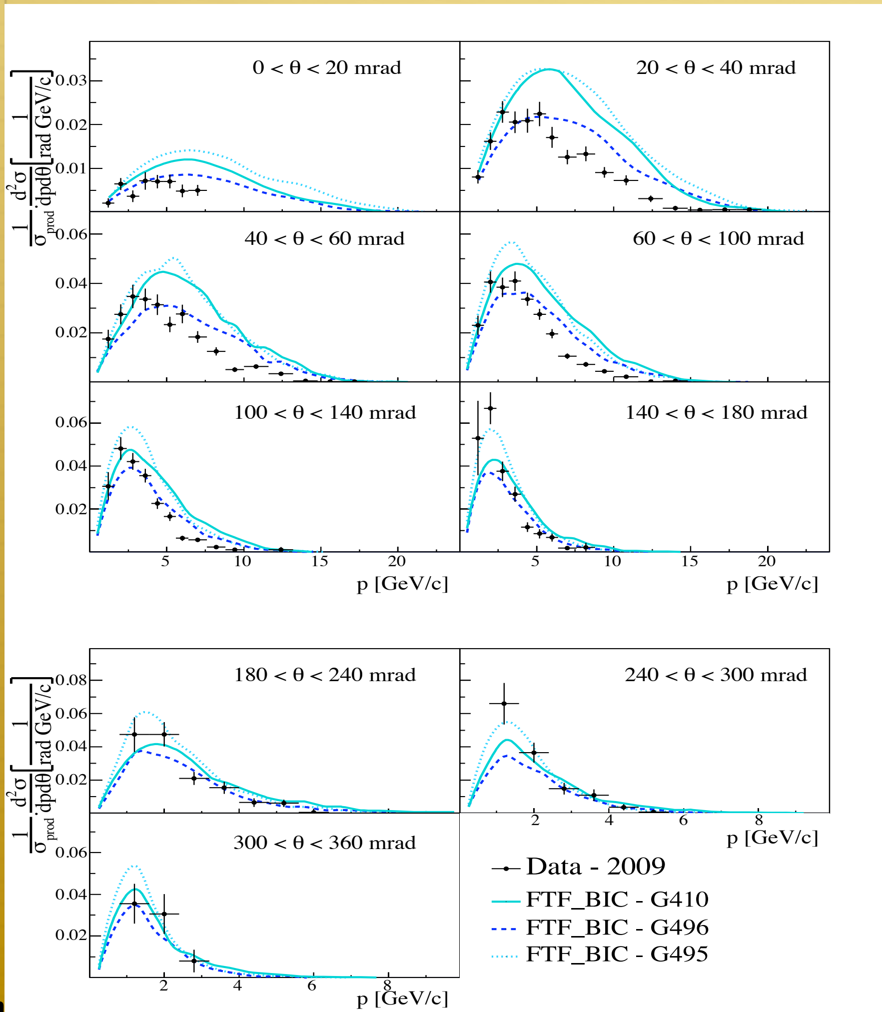


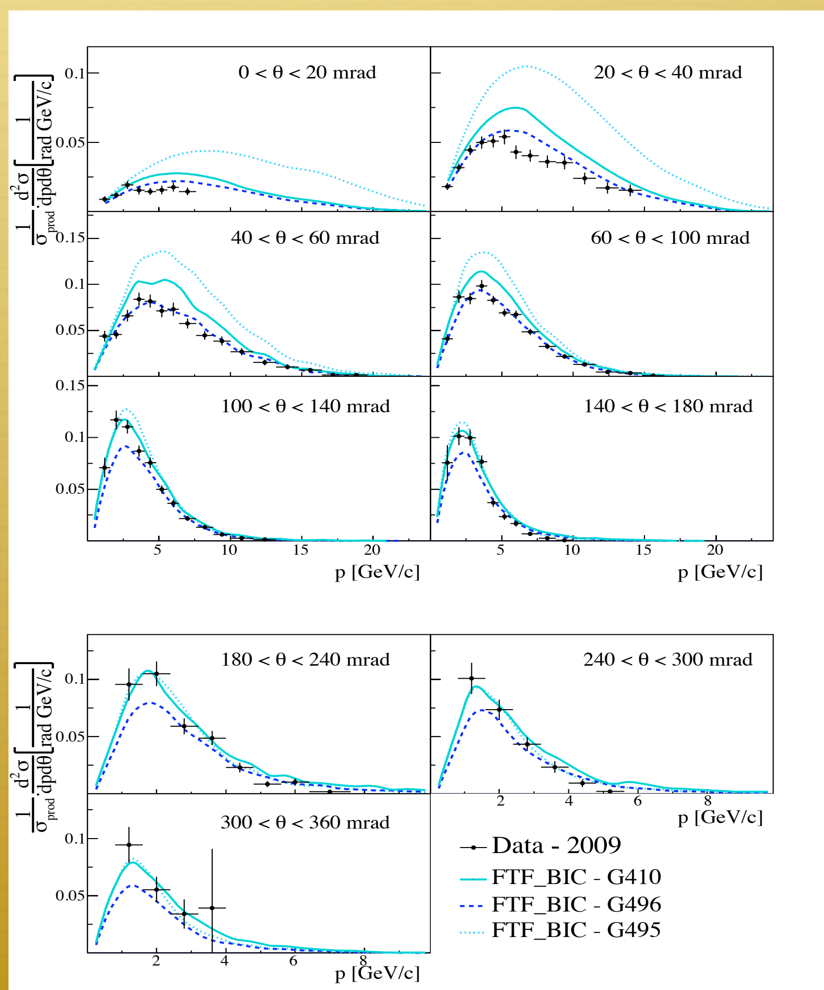
π^- multiplicities

Similar behaviour as for pi+.

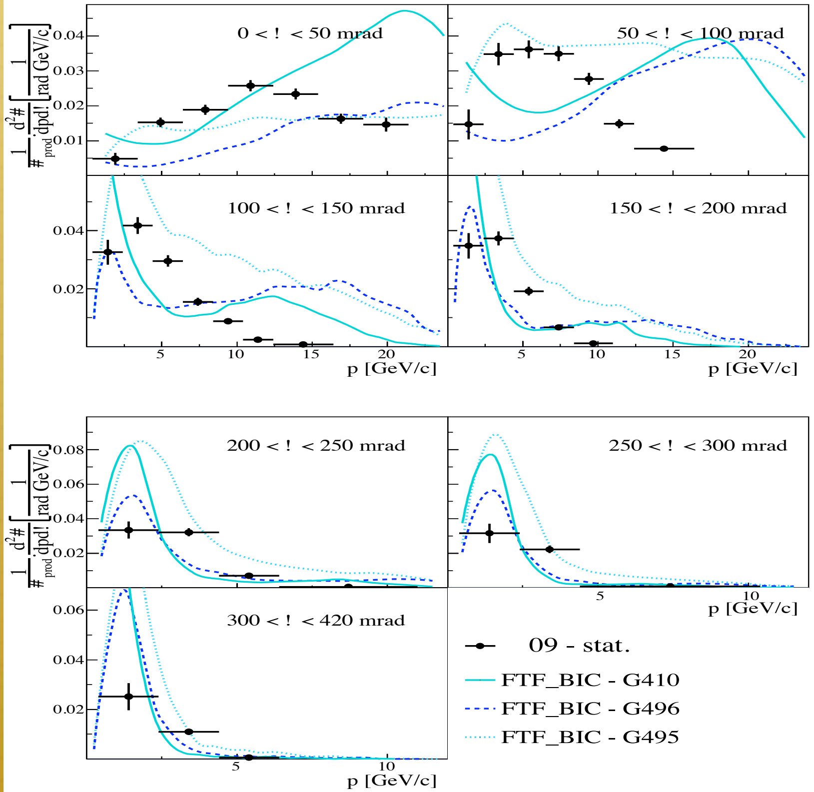
It goes the same way for charged kaons, K^0_s , Λ particles and protons.

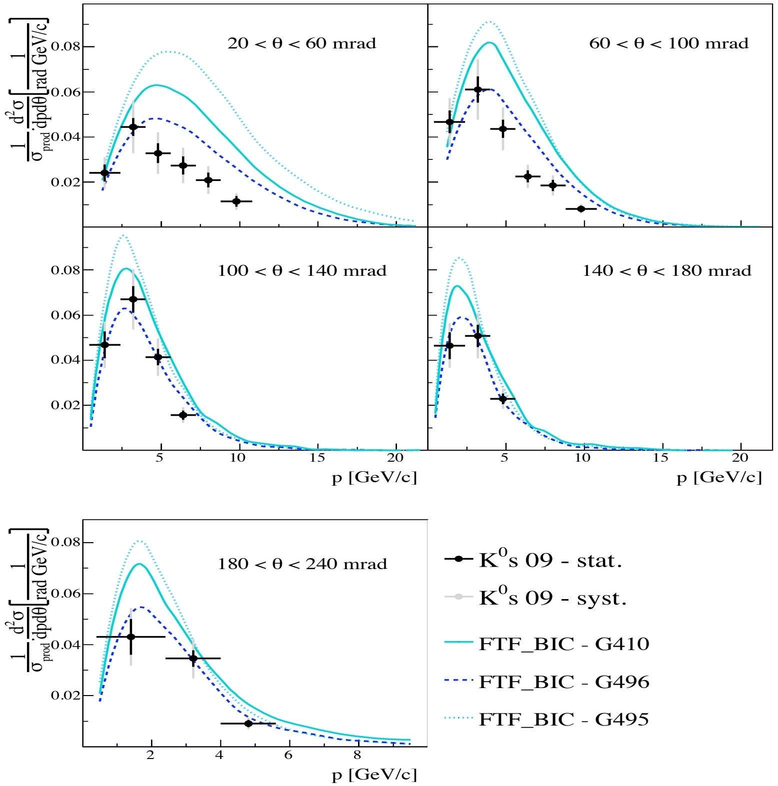
K⁻ (left) and K⁺ (right) multiplicities, compared to GEANT 4 predictions



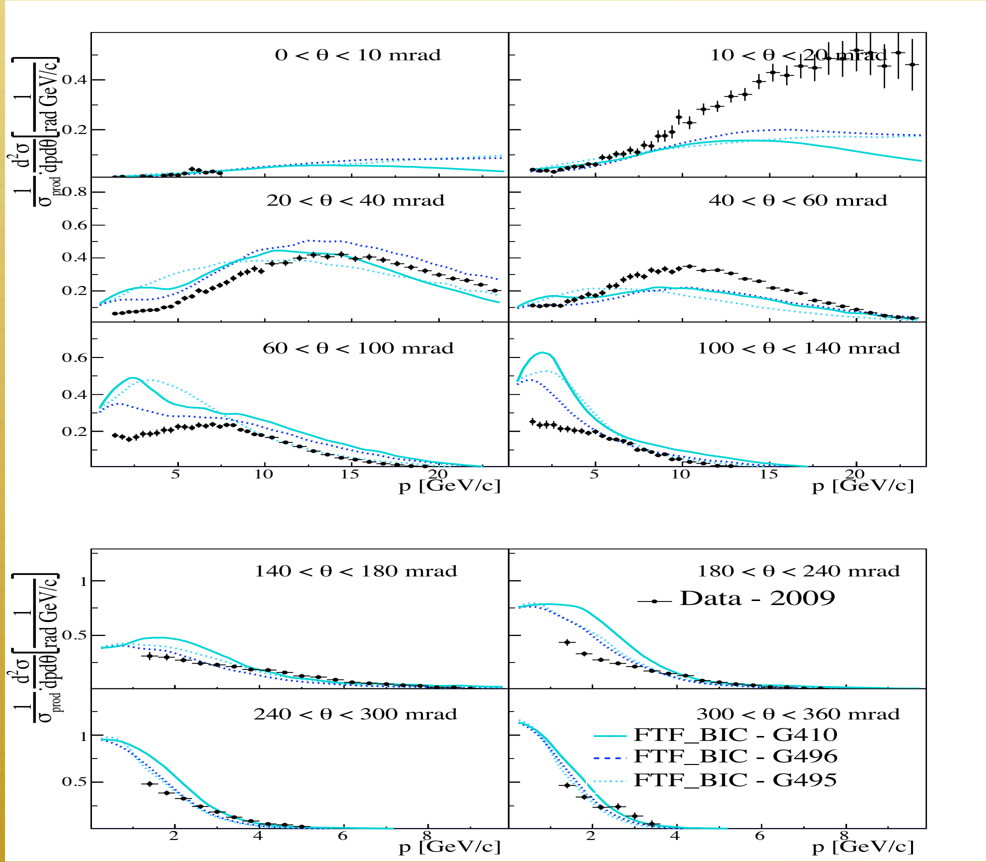


Λ (left) and K^0 (right) multiplicities, compared to GEANT 4 predictions



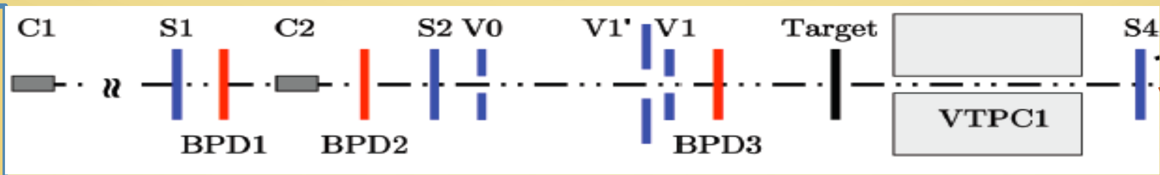


Proton multiplicities, compared to GEANT 4 predictions



Production cross section measurements

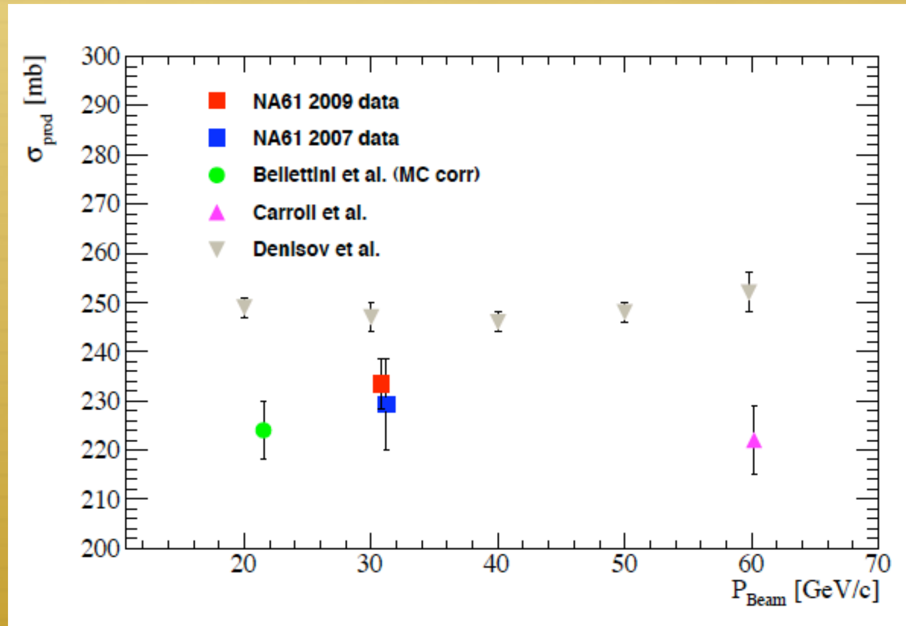
Trigger system in NA61/SHINE



scintillator, ϕ =1cm

σ_{inel} measured with $C_1 {*} \overline{C_2} {*} S_1 {*} S_2 {*} \overline{V} {*} \overline{S_4}$,
S_4 requires correction- GEANT4 used with Fritof physics list.

The production cross section
$\sigma_{prod} = \sigma_{inel} - \sigma_{QE}$,
where σ_{QE} is also estimated with MC models with GEANT4.
σ_{QE} =27.8±0.2±3.6 mb



$$\sigma_{prod}^{2007} = 229.3 \pm 1.9(stat.) \pm 9.0(syst.) mb$$

$$\sigma_{prod}^{2009} = 233.5 \pm 2.8(stat.) \pm 4.2(\mathrm{model}) mb \pm 1.0(trigger) mb$$

Normalization- the NA61 trigger based approach.

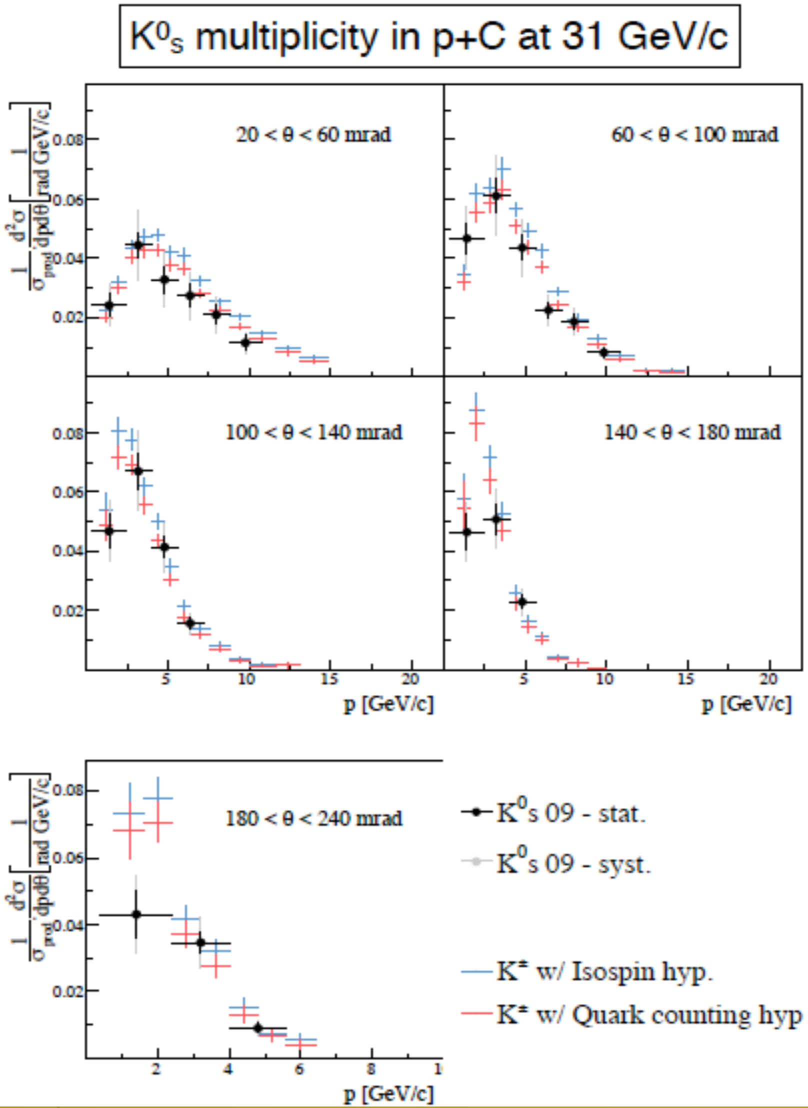
- The mean multiplicity in p+C interactions for pions is calculated as follows:

$$\frac{dn}{dp} = \frac{1}{1-\varepsilon}\frac{\sigma_{trig}}{\sigma_{prod}}\left(\frac{1}{N^{in}}\frac{\Delta n_{\pi}^{\ in}}{\Delta p} - \frac{\varepsilon}{N^{rem}}\frac{\Delta n_{\pi}^{\ rem}}{\Delta p}\right)$$

impact of target removed data

data	ε	σ_{trig} [mb]	σ_{prod} [mb]
2009	0.123	305.7	233.5
2007	0.118	298.1	229.2

K^0_s measurements from thin target data



- Large statistical error due to electronic noise in the dataset.
- Major source of systematic uncertainties:
  - fitting procedure
  - cuts
- K^0s yields can be predicted from $K^\pm$ measurement:
  - using the isospin symmetry assumption:

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

  - using a quark-counting argument:

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

where pp and pn interactions in the Carbon nucleus have been taken into account.