Hadron Production Experiments

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ICFA ν panel

Paris, Jan 08 '14

Why hadro-production measurements

Understand the neutrino source

solar neutrinos

ν flux predictions based on the solar model

reactor based neutrino sources

ν flux predictions based on fission models and reactor power

accelerator based neutrino sources

ν flux predictions based on π, K ($\rightarrow \nu$ + X) hadro-production models
(+ modeling of the target complex, focusing and decay channel, …)

ν flux at far detector predicted on the base of ν flux measured in near detector

neutrino cross sections $\rightarrow$ absolute neutrino flux

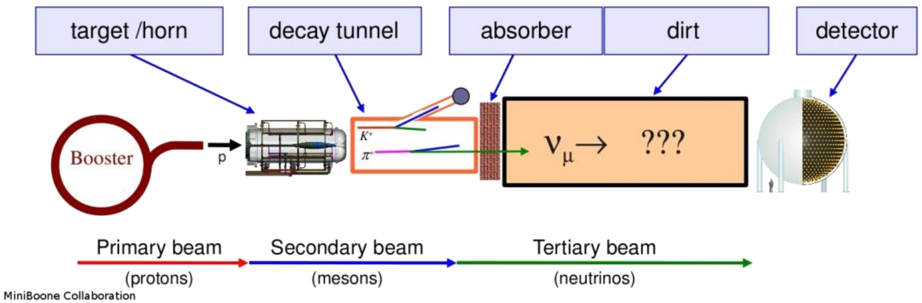
neutrino interaction physics

neutrino oscillations $\rightarrow$ compare measured neutrino spectrum "far" from the source with the predicted one (flux shape and Far / Near flux ratio)

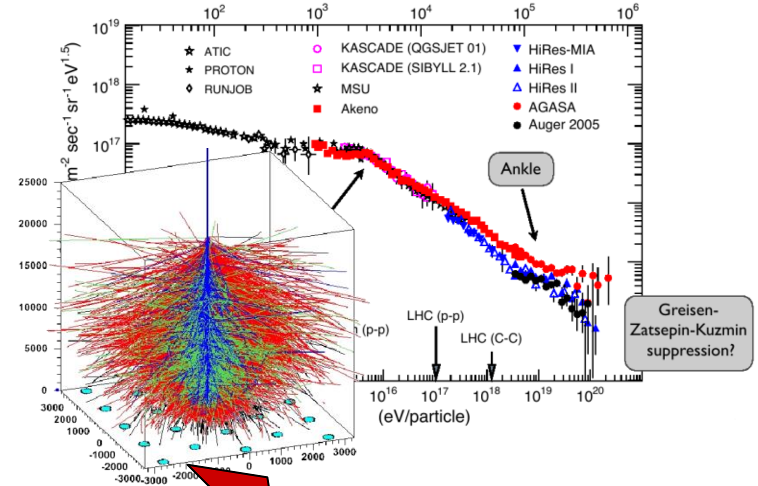
deviations from "predictions" $\Rightarrow$ evidence for neutrino oscillations

$\Rightarrow$ oscillation parameters

conventional accelerator based ν beam

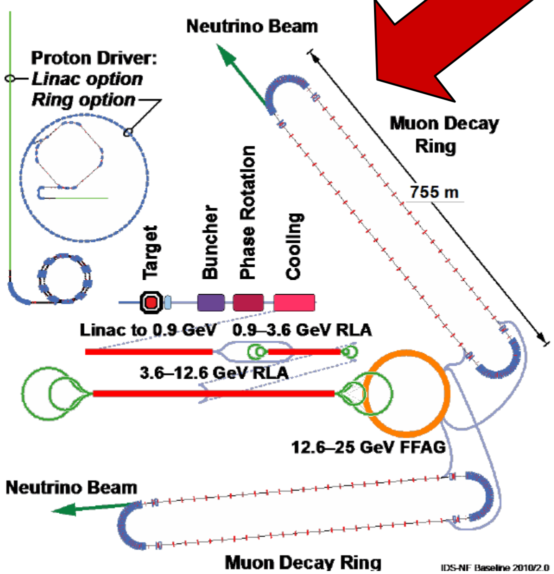


atmospheric showers

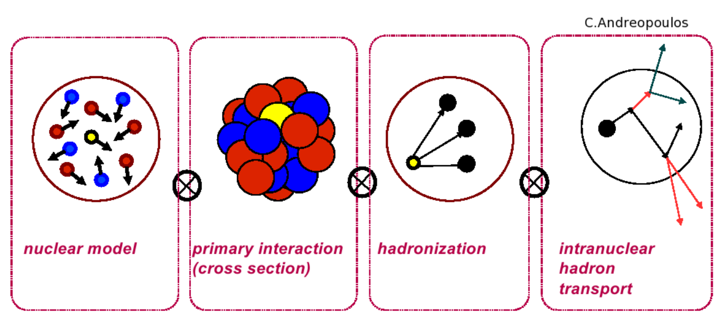


Hadroproduction measurements
$p(\pi) + A \rightarrow h + X$

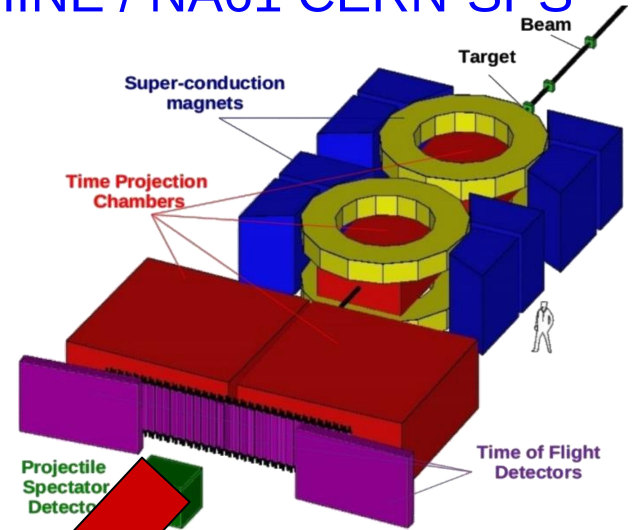
neutrino factory



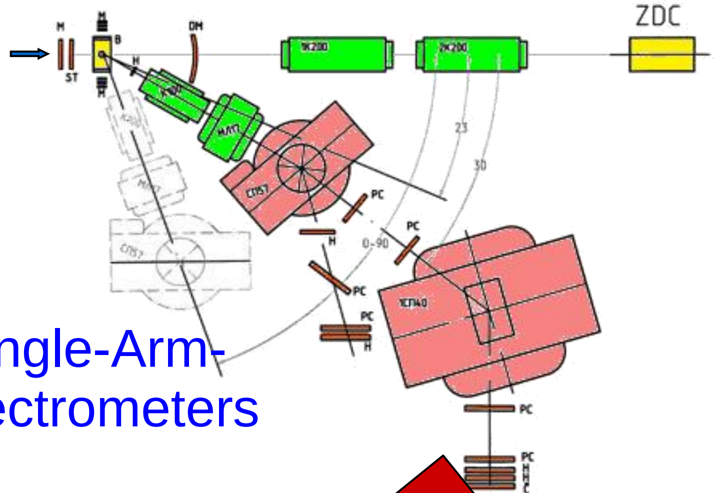
MC generators



SHINE / NA61 CERN-SPS

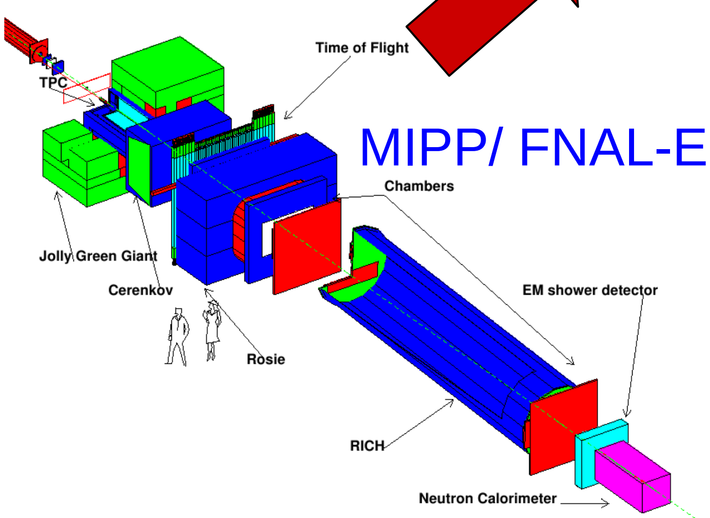


Single-Arm-Spectrometers

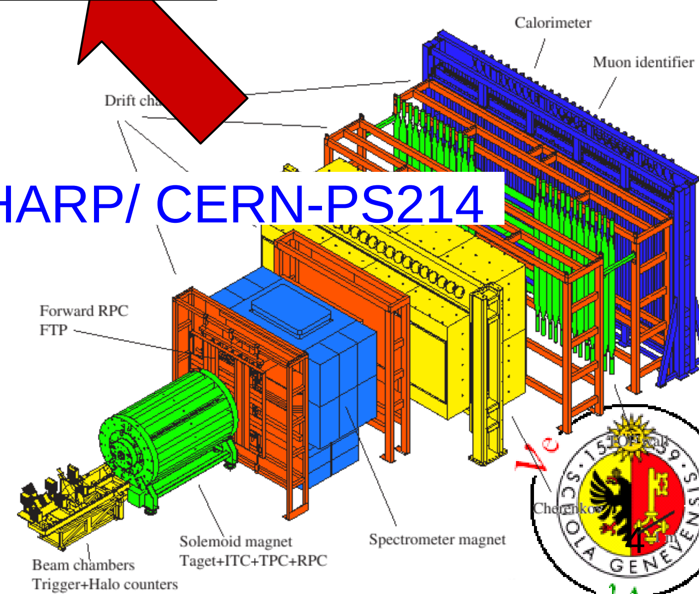


Hadroproduction measurements
$p(\pi) + A \rightarrow h + X$

MIPP/ FNAL-E907



HARP/ CERN-PS214



hadron production experiment	neutrino experiment
NA20 & SPY/NA56 400-450 GeV beam	WANF (NOMAD, CHORUS) CNGS (OPERA, ICARUS)
NA49 / CERN-SPS 160 GeV beam	MINOS (Fermilab to Soudan) MINERvA
HARP / CERN-PS214 1.5-15 GeV beam	(Mini-, Sci-, Micro-)BooNE at Fermilab K2K (KEK to Super-Kamiokande)
SHINE / CERN-SPS-NA61 30-160 GeV beam	T2K (JPARC to Super-Kamiokande) NuMI (MINERvA, NOvA)

+ many many other experiments that measured cross sections …

$\Rightarrow$ critical survey of all existing cross section measurements !

How Well Do We Know ν Fluxes Today

AGS ν experiments (~1960) knew their fluxes to 30%

Ingredients to flux prediction from upstream to downstream

proton dynamics (protons on target, spot size, …)

hadron production off target

(~60% from primary interactions, ~30% from reinteractions in target, ~10% from around target)

need measurements on both thin and thick targets, same materials, same energies

horn current → **B** (focusing), alignment, etc.

HADRON PRODUCTION most important of these ingredients

need dedicated hadron production experiments

Two detector experiments (near and far), flux uncertainties partially cancel !

In situ measurements

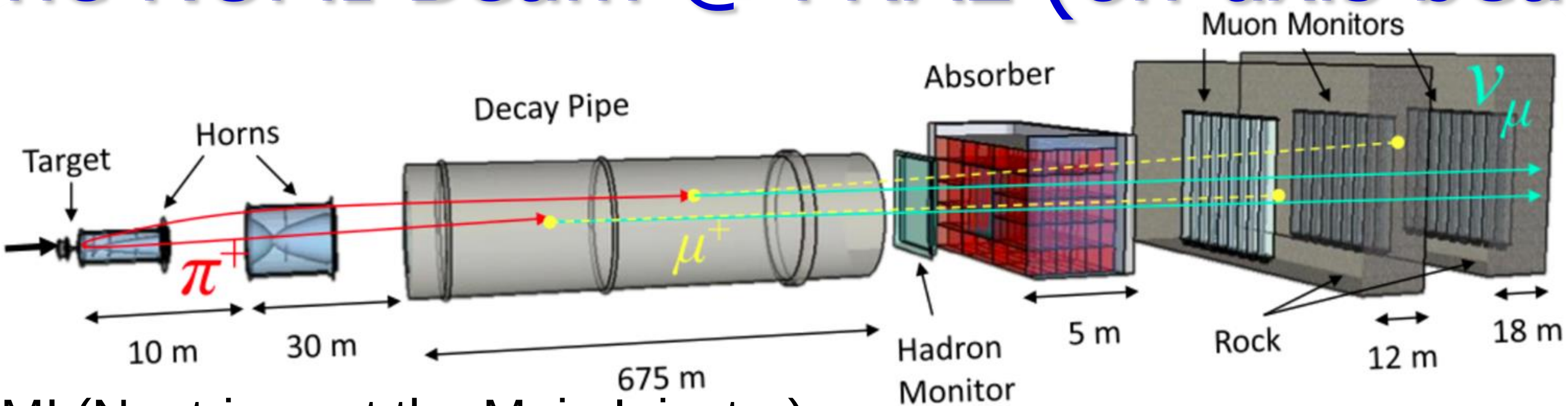
constraints from special in situ runs in modified beam optics

constraints from muon monitor data with scans of horn currents

"low ν" events to constrain flux from high energy measurements (A. Bodek et al.)

In 50 years we have gone from 30% uncertainties to 10% uncertainties while increasing proton fluxes on target by ~10^3 – 10^4 .

The NUMI Beam @ FNAL (on-axis beam)



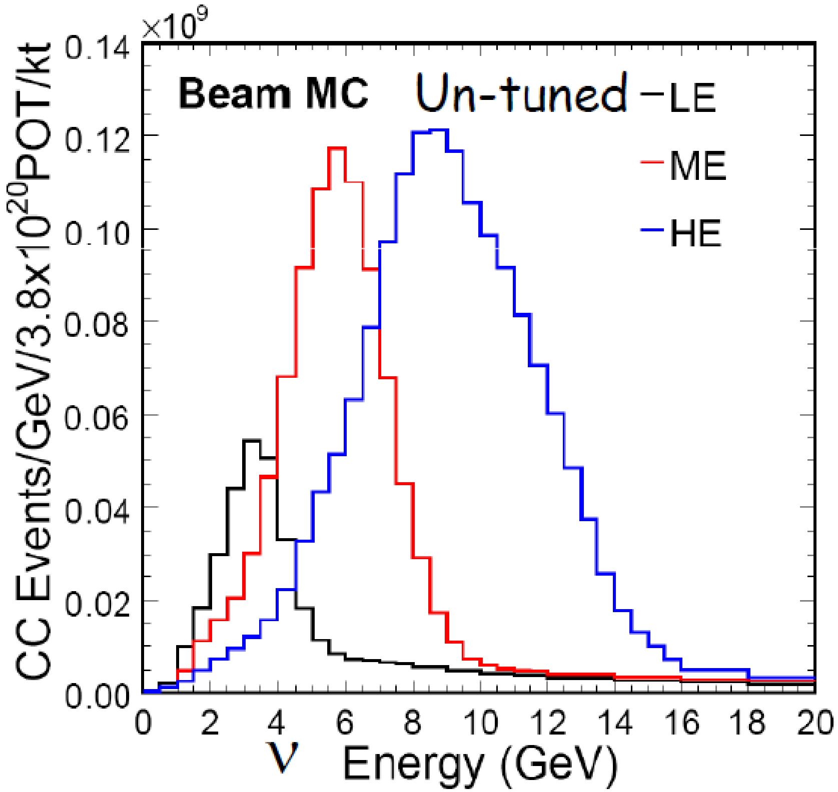
NuMI (Neutrinos at the Main Injector)

120 GeV protons from Main Injector, ~ 300 - 350 kW

90 cm graphite target

675 m decay tunnel

By moving the production target w.r.t. 1st horn and the distance between horn 1 and horn 2 one can modify the ν spectrum:
LE (peak ~3 GeV) $\rightarrow$ ME (peak ~6 GeV)



Flux determination

muon monitor data

special runs (vary beam parameters)

ν_μ – electron scattering

low–ν method

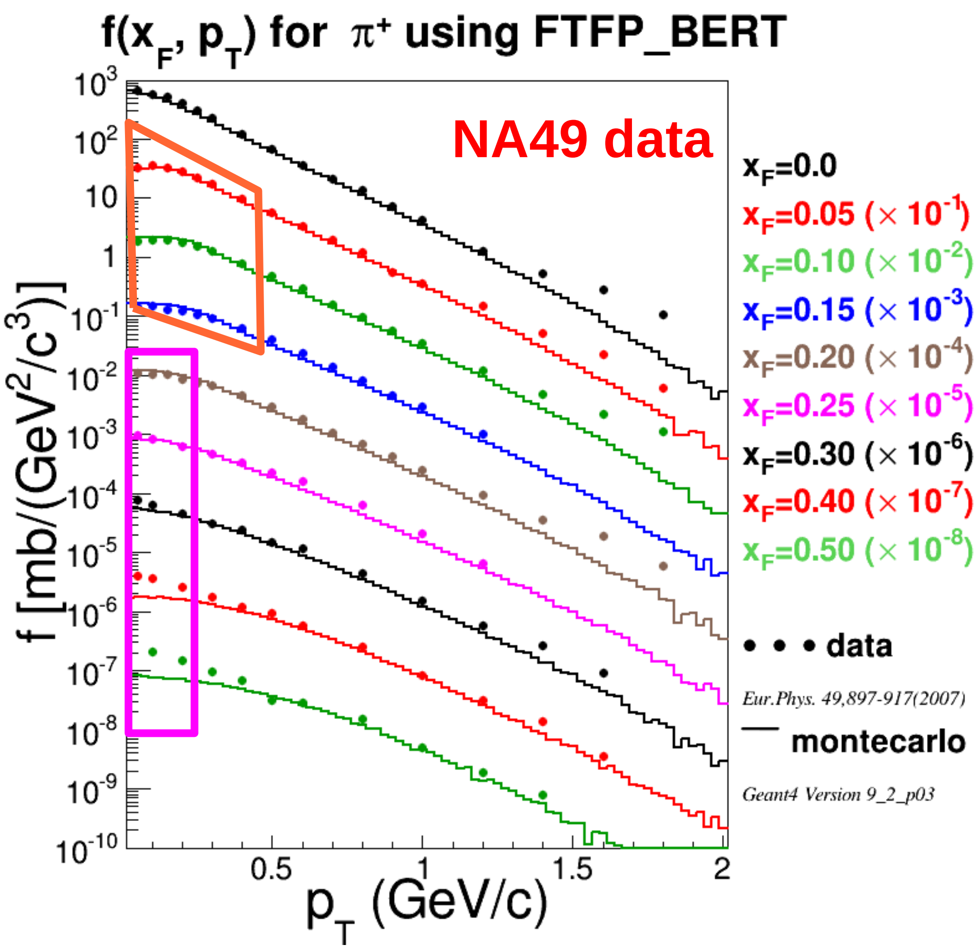
external hadron production data

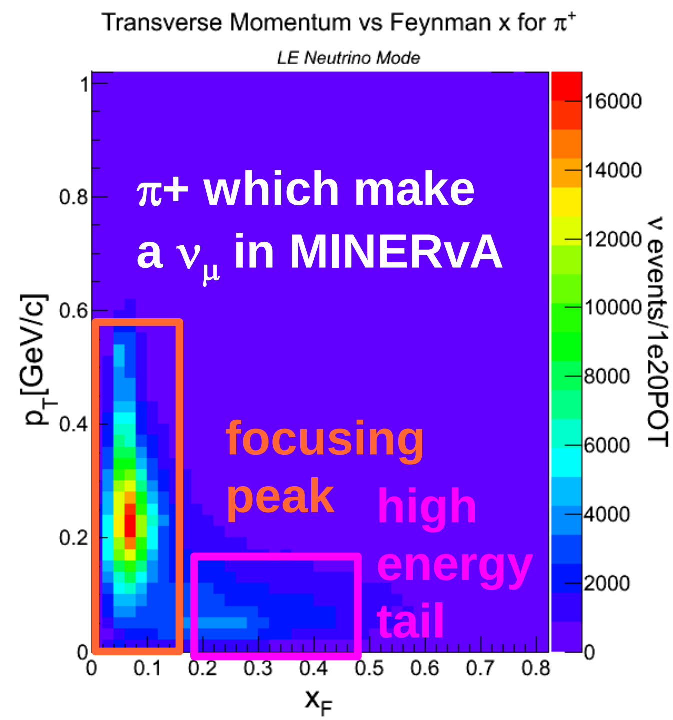
NuMI ν Flux

NuMI beam : hadron production simulated with Geant4 to predict flux.

Flux is reweighted based mainly on NA49 hadron production data compared to a Geant4 model and rescaled down to 120 GeV

$f(x_F,p_T) = E\, d^3\sigma/dp^3$



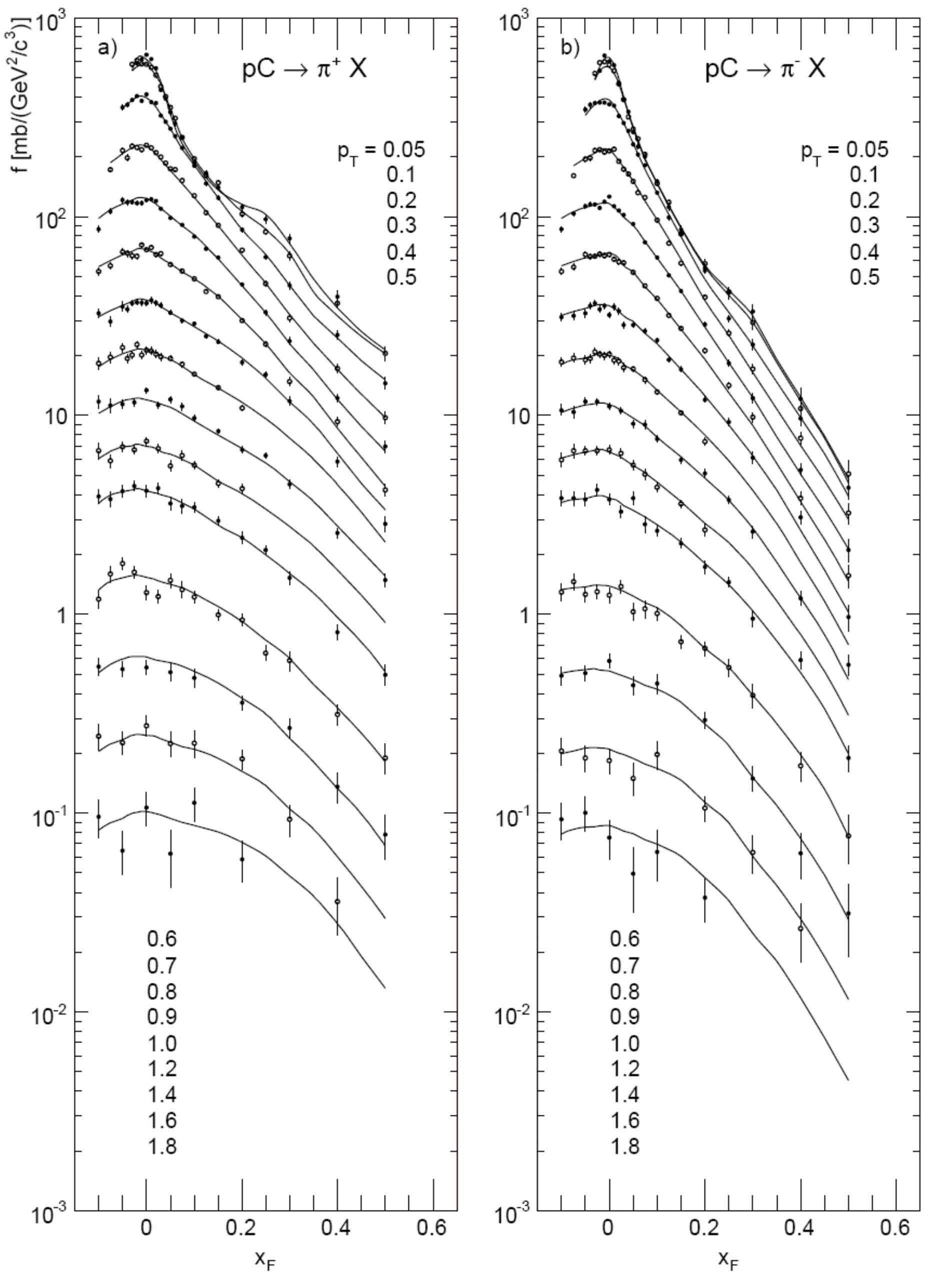


<u>NA49 Uncertainties</u>

7.5% systematic

2-10% statistical

NA49 Charged Pion Spectra



charged pion spectra in
pC interactions at 158 GeV/c
measured by NA49
over broad kinematical range

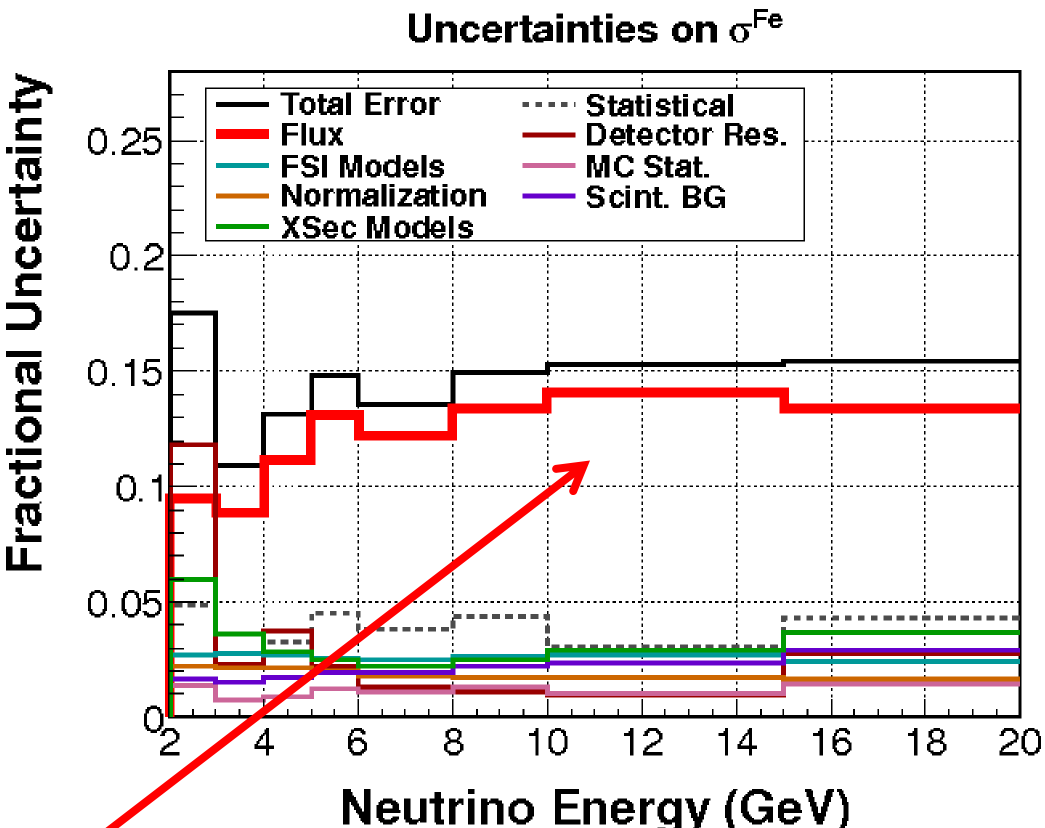
NA49 with empirical fits to the data

systematic error

Normalisation	2.5%
Tracking efficiency	0.5%
Trigger bias	1%
Feed-down	1–2.5%
Detector absorption	
Pion decay $\pi \to \mu + \nu_\mu$	0.5%
Re-interaction in the target	
Binning	0.5%
Total (upper limit)	7.5%
Total (quadratic sum)	3.8%

NA49, C. Alt *et al*., EPJ C49 (2007) 897

MINERνA Inclusive Cross Section Uncertainties



flux : NA49 data
tertiary interactions
beam focus

Beam Focus – Magnetic horns focusing the charged mesons that decay to neutrino beam

NA49 – A CERN hadron production experiment that constrains flux simulation (pC $\rightarrow$ X)

Tertiary – Neutrinos produced by decay of products other than pC in the NuMI target

Normalization – Uncertainty on flat normalization corrections applied to Monte Carlo

Hadronic Energy – Uncertainty on calorimetric recoil energy reconstruction

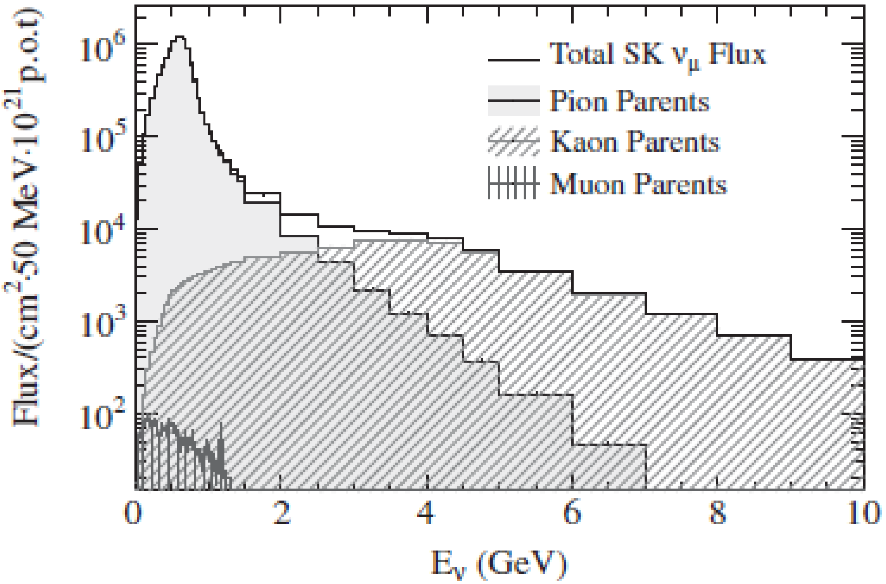
Muon Energy – Uncertainty on MINOS's momentum reconstruction + energy loss in MINERνA

GENIE– Neutrino event generator Uncertainties for cross section, final state interaction models.

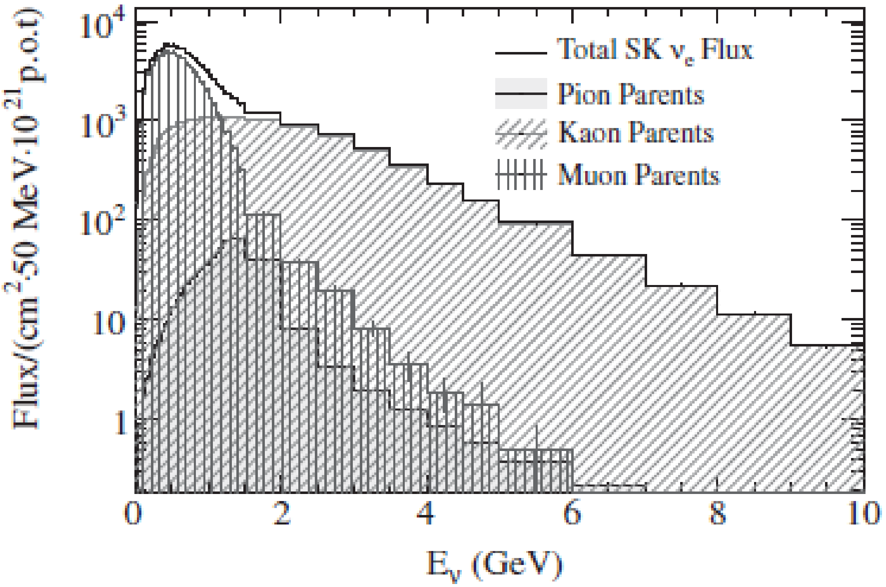
Which Hadron Cross-Sections Measurements

what is the composition of the ν_μ and ν_e flux (at SK) in terms of the ν parents ?

T2K, PRD 87 (2013) 012001



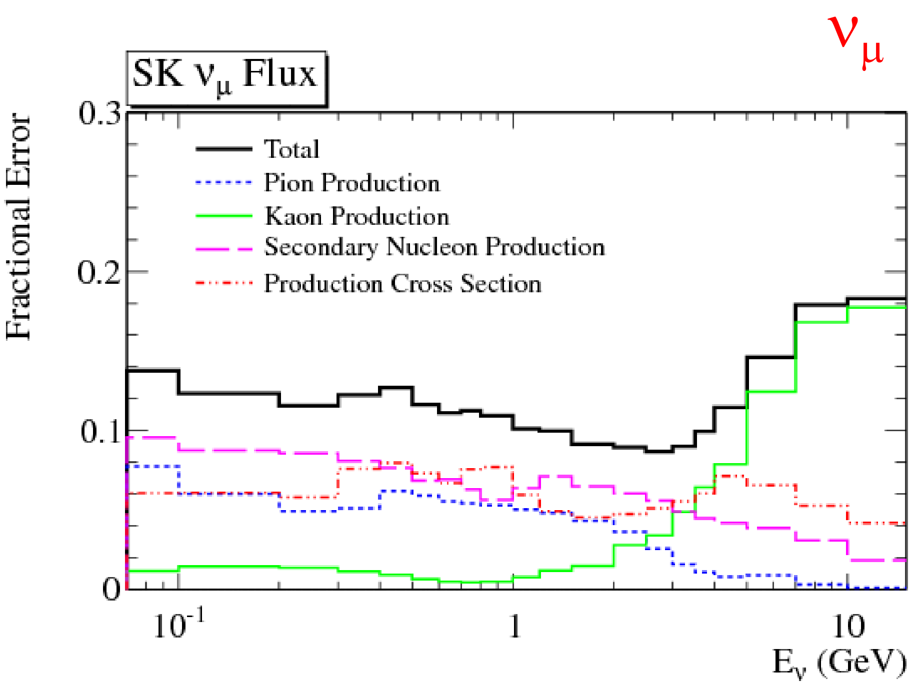
ν_μ predominantly from π^+ decay at peak energy,
higher energy ν_μ (tail) from kaons

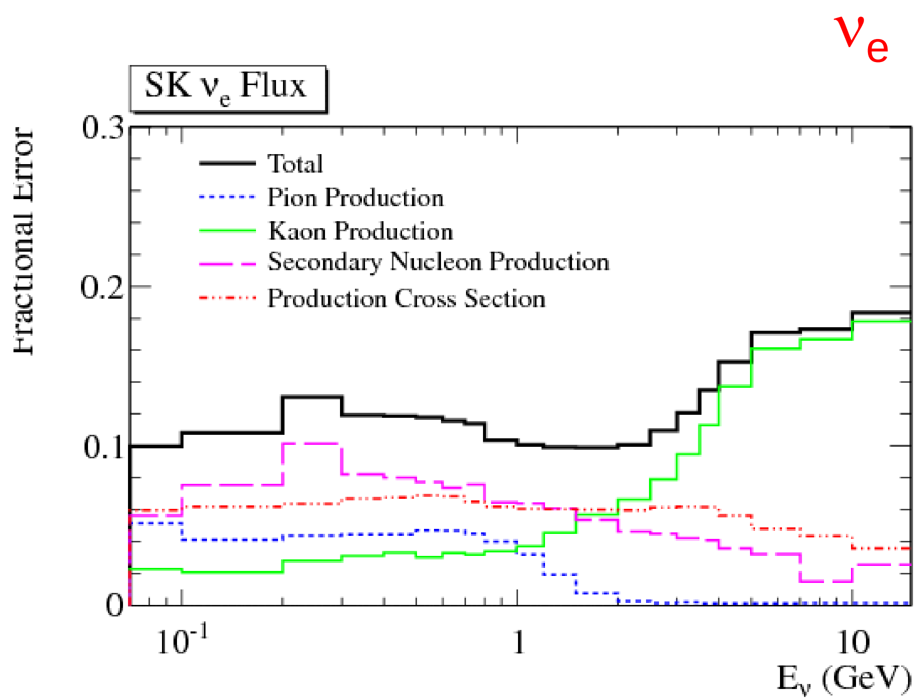


ν_e predominantly from μ^+ and K^+ decays at peak energy,
higher energy ν_e (tail) from kaons

How Well Do We Know ν Fluxes

fractional uncertainties on the ν_μ and ν_e fluxes at the T2K far detector
T2K, PRD 87 (2013) 012001





the errors are around 10 – 15%
in the oscillation region (< 1 GeV)

uncertainty on secondary (tertiary)
hadron production dominates

HARP : Hardon Production Exp. at PS

- Measurement of secondary π, K, p production cross section for various nuclear targets with p / π beams in 1.5-15 GeV/*c* momentum range

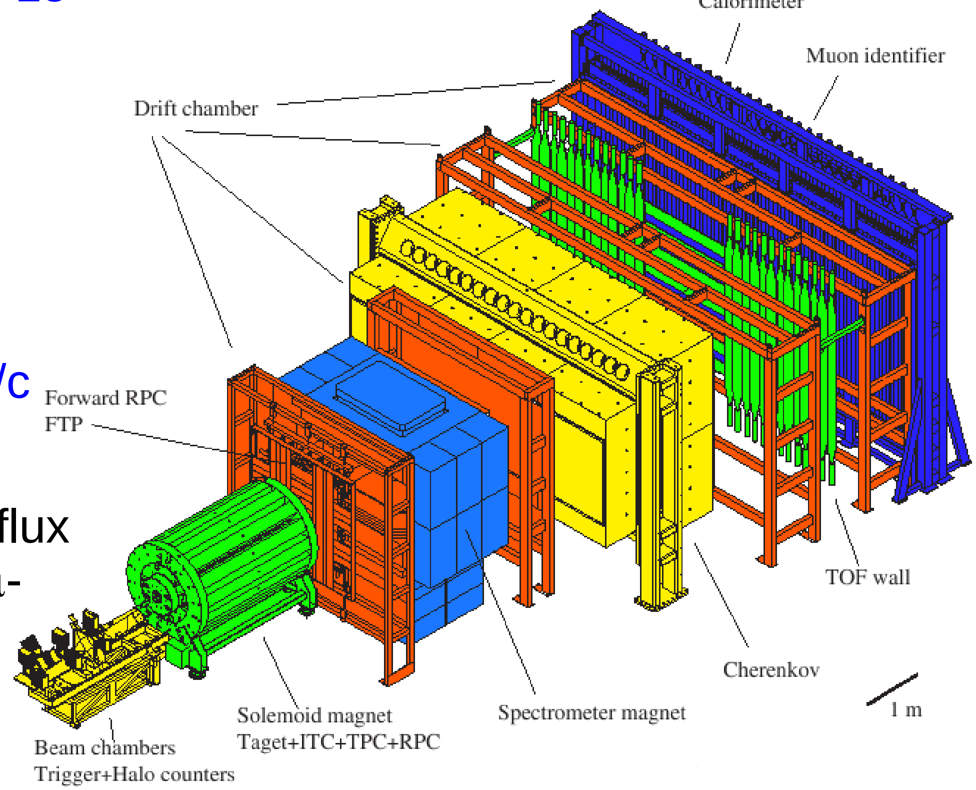
- Results of measurements have been used for ν flux prediction in
  - K2K: Al target, 12.9 GeV/c
  - Mini(Sci)BooNE: Be targ, 8.9 GeV/c

- Also to be used for the atmospheric ν flux calculations and for the high intensit μ-stopped source

- Kinematic acceptance
  - Forward spectrometer

  $0.5 < p < 8$ GeV/*c*, $0.025 < \theta < 0.25$ rad
  - Large angles (TPC + RPD)

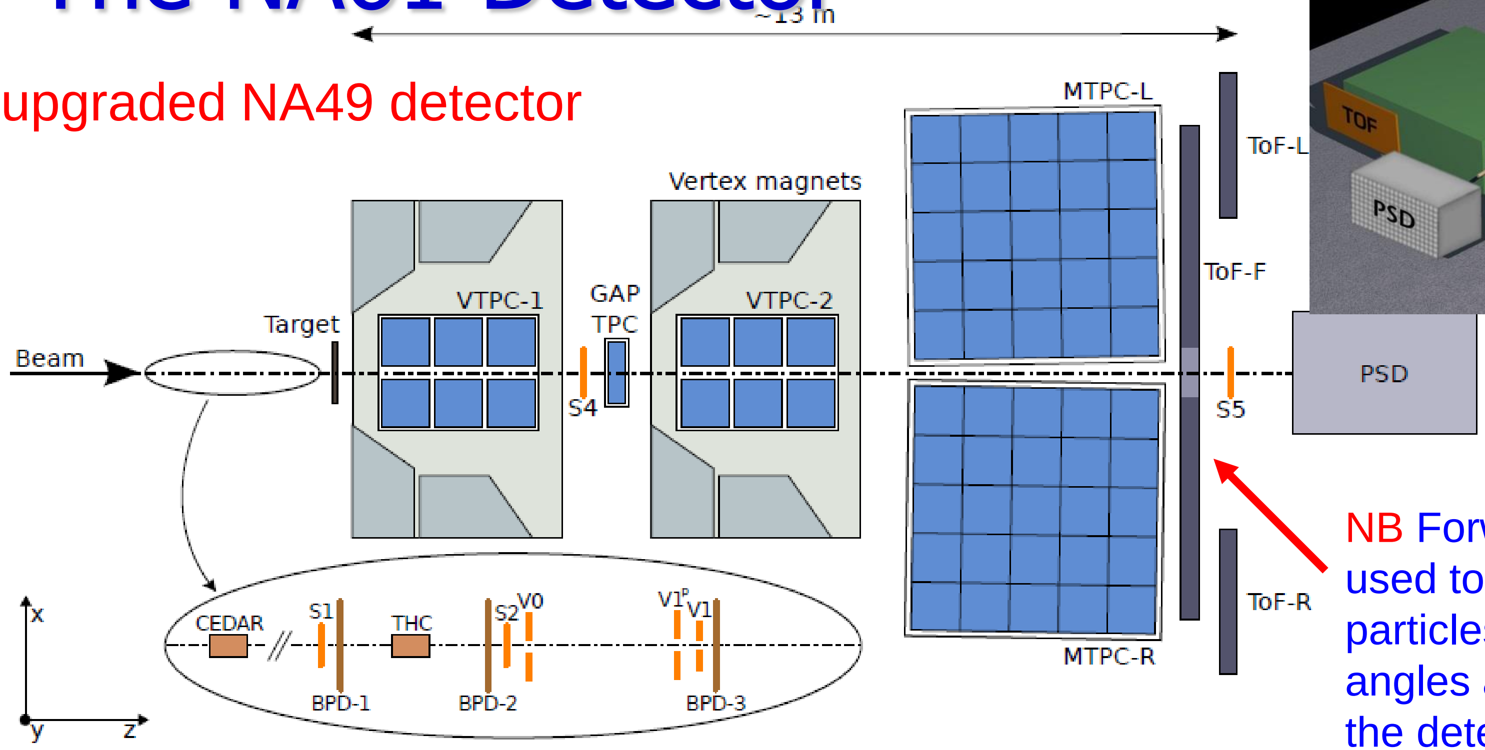
  $0.1 < p < 0.8$ GeV/*c*, $0.35 < \theta < 2.15$ rad

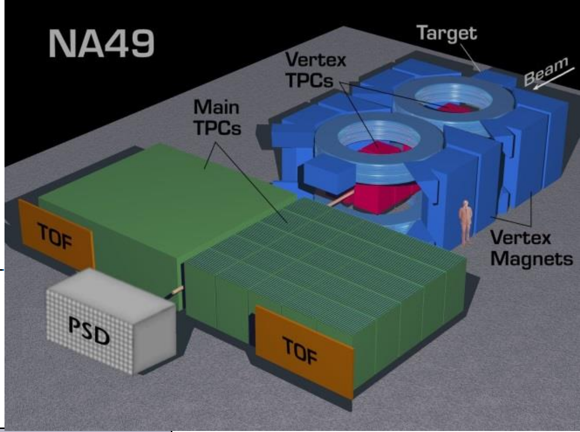


HARP, NIM A571 (2007) 527

The NA61 Detector

upgraded NA49 detector





NB Forward-ToF wall used to identify low mom. particles produced at large angles and bent back into the detector acceptance by the vertex magnets

large acceptance spectrometer for charged particles

4 large volume TPCs as main tracking devices

2 dipole magnets with bending power of max 9 Tm over 7 m length (T2K runs: $\int Bdl \sim 1.14$ Tm)

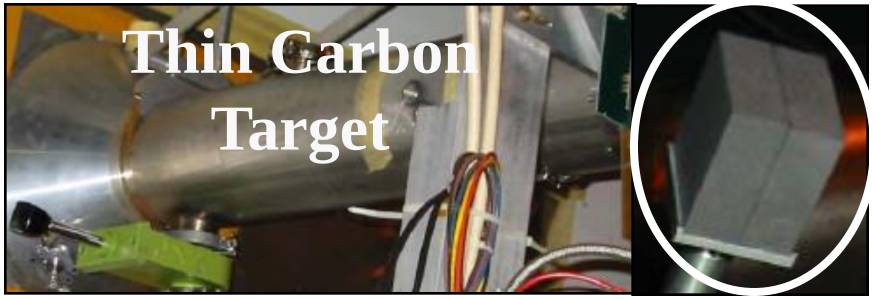
high momentum resolution

good particle identification: σ(ToF-L/R) ≈ 110 ps, σ(dE/dx)/<dE/dx> ≈ 0.04, $\sigma(m_{inv}) \approx 5$ MeV

new ToF-F to entirely cover T2K acceptance (σ(ToF-F) ≈ 110 ps, $1 < p < 4$ GeV/c, $\theta < 250$ mrad)

several additional upgrades are under way

The NA61 Targets



2 different graphite (carbon) targets

Thin Carbon Target
- **length=2 cm, cross section 2.5x 2.5 cm^2**
- **ρ = 1.84 g/cm^3**
- **~0.04 λ_{int}**

T2K replica Target
- **length = 90 cm, Ø=2.6 cm**
- **ρ = 1.83 g/cm^3**
- **~1.9 λ_{int}**

Important to study hadro-production with replica targets since ~ 30 % of π, K from secondary interactions, which in general are very difficult to model. Both targets required to model reliably the ν flux.

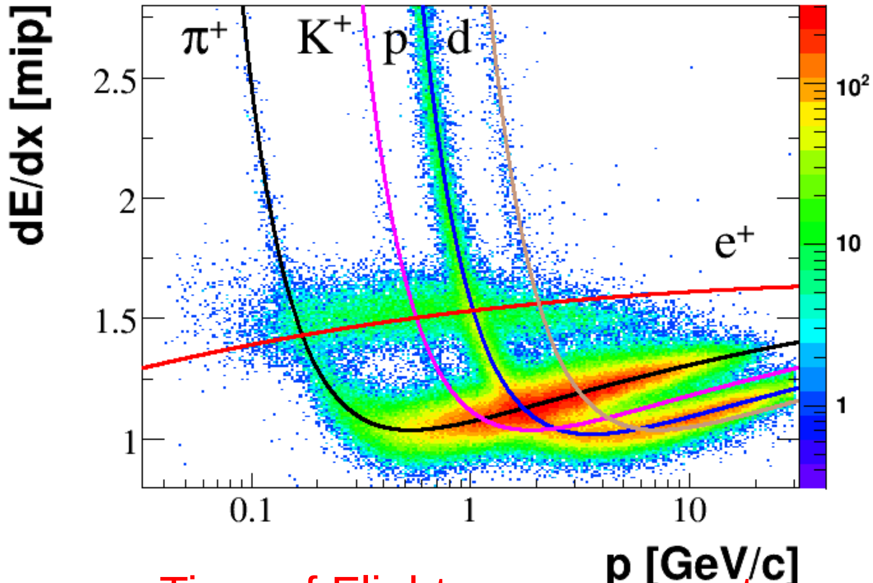
2007 pilot run
Thin target: ~ 660k triggers
Replica target: ~ 230k triggers

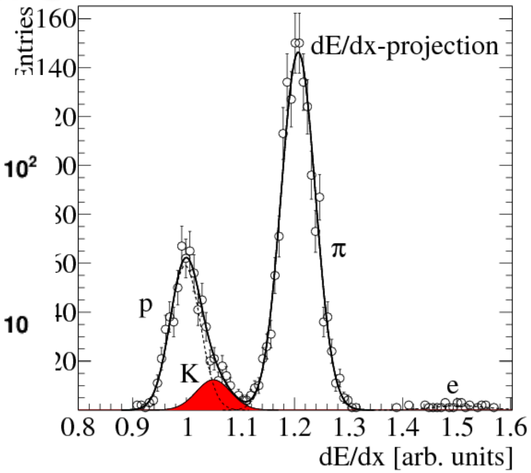
2009 run
~ 6 M triggers
~ 2 M triggers
$\Rightarrow$ 200 k π^+ tracks in T2K *phase space*

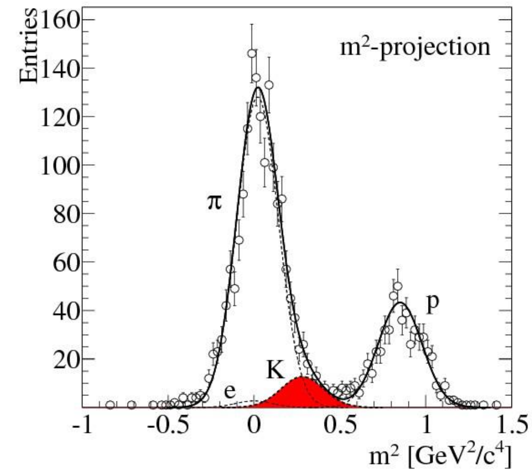
2010 run
Replica target: ~ 10 M triggers

Particle Identification

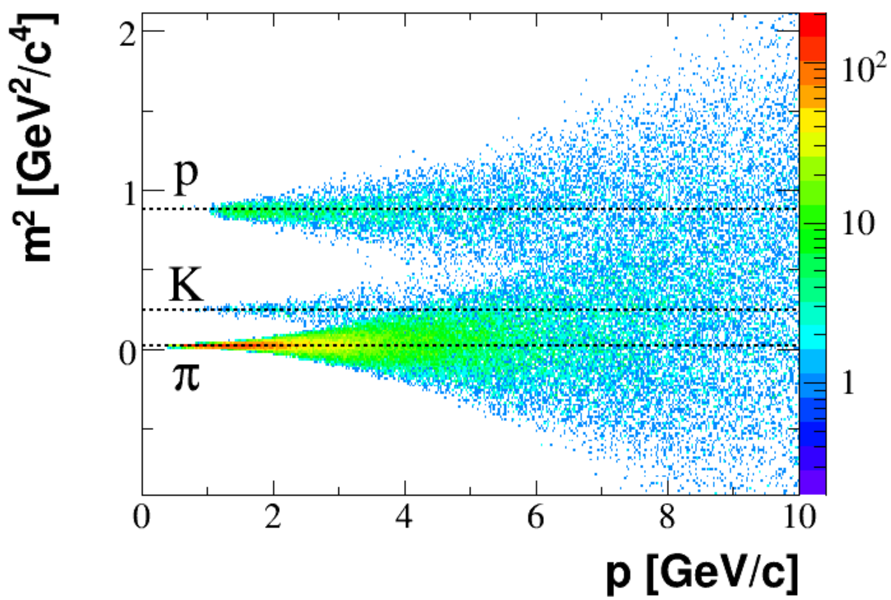
Energy loss in TPCs



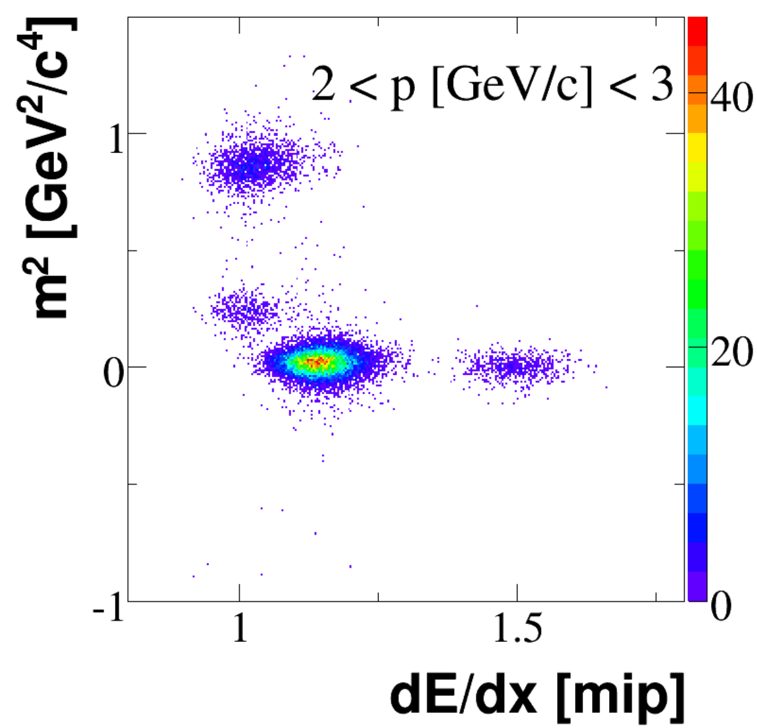




Time of Flight measurements



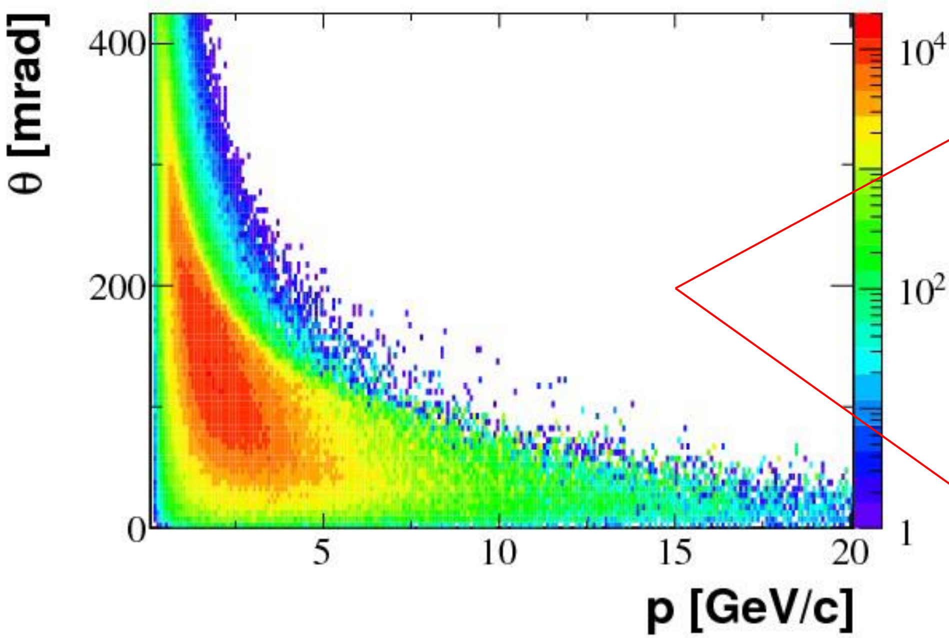
combined ToF + dE/dx

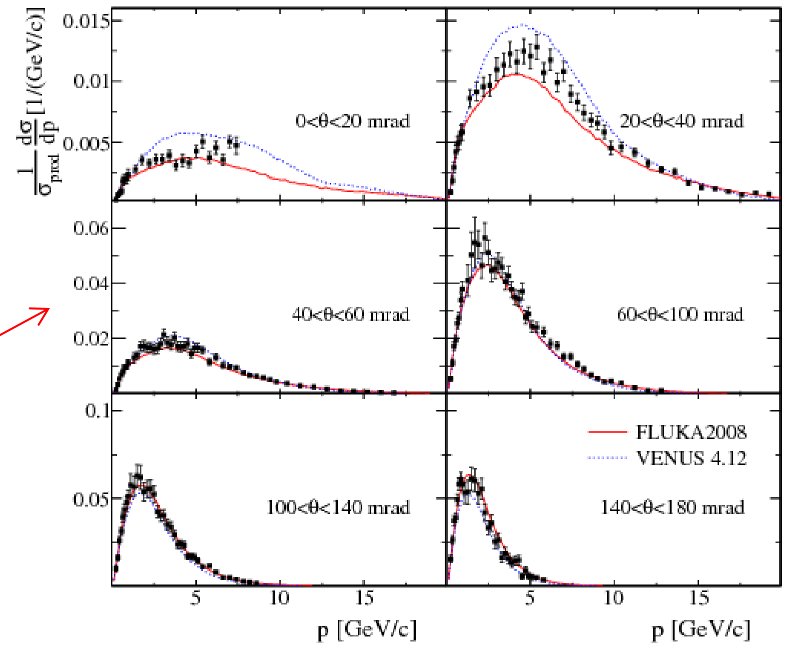


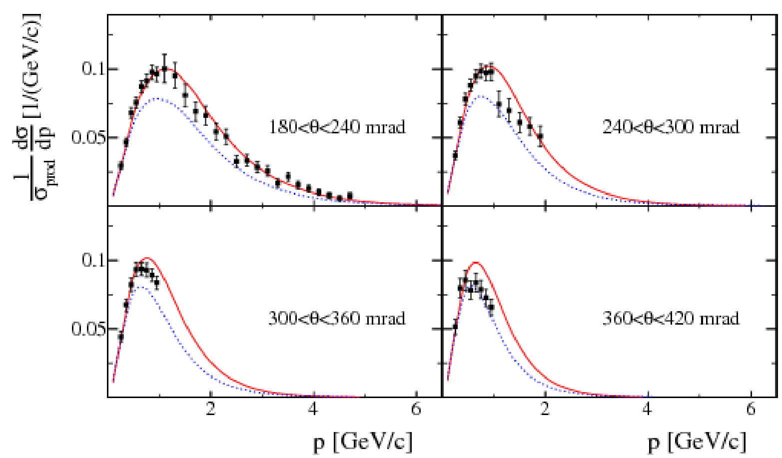
NA61 p + C → π^+ + X @ 30 GeV

NA61, PRC 85 (2011) 035604

T2K beam simulation :
{p, θ} distribution of π^+
yielding ν_μ in SK “acceptance”





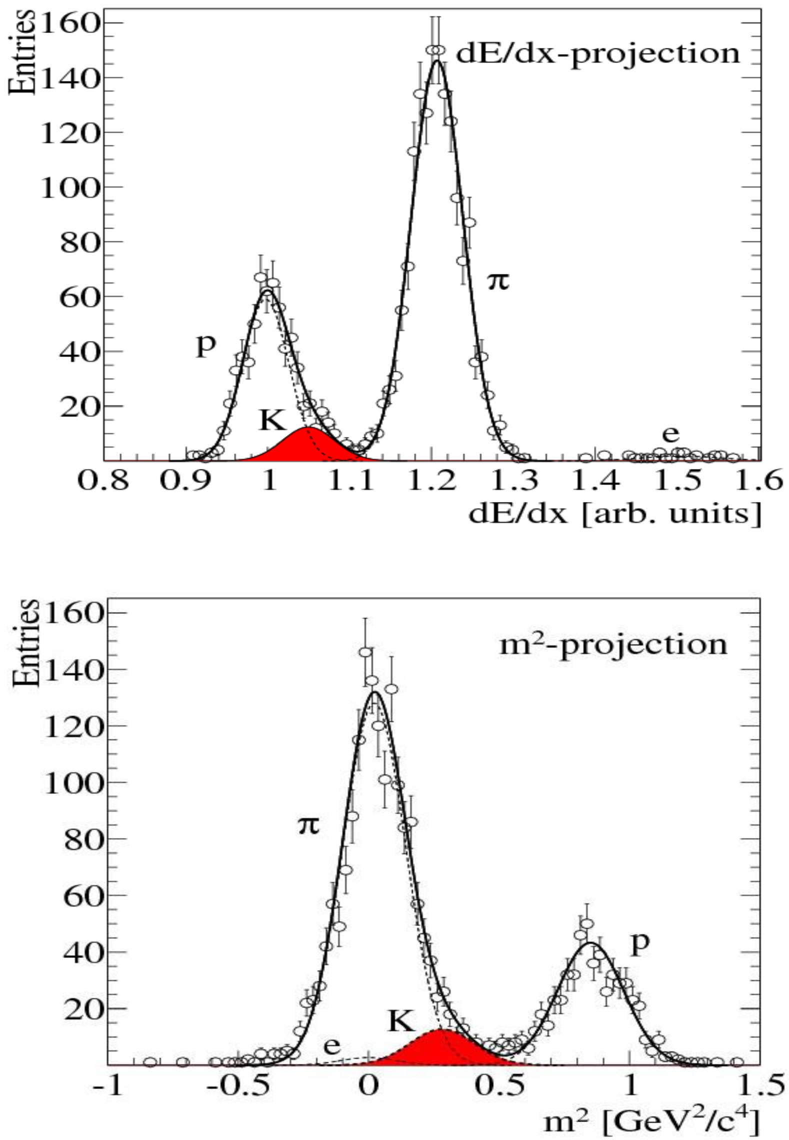


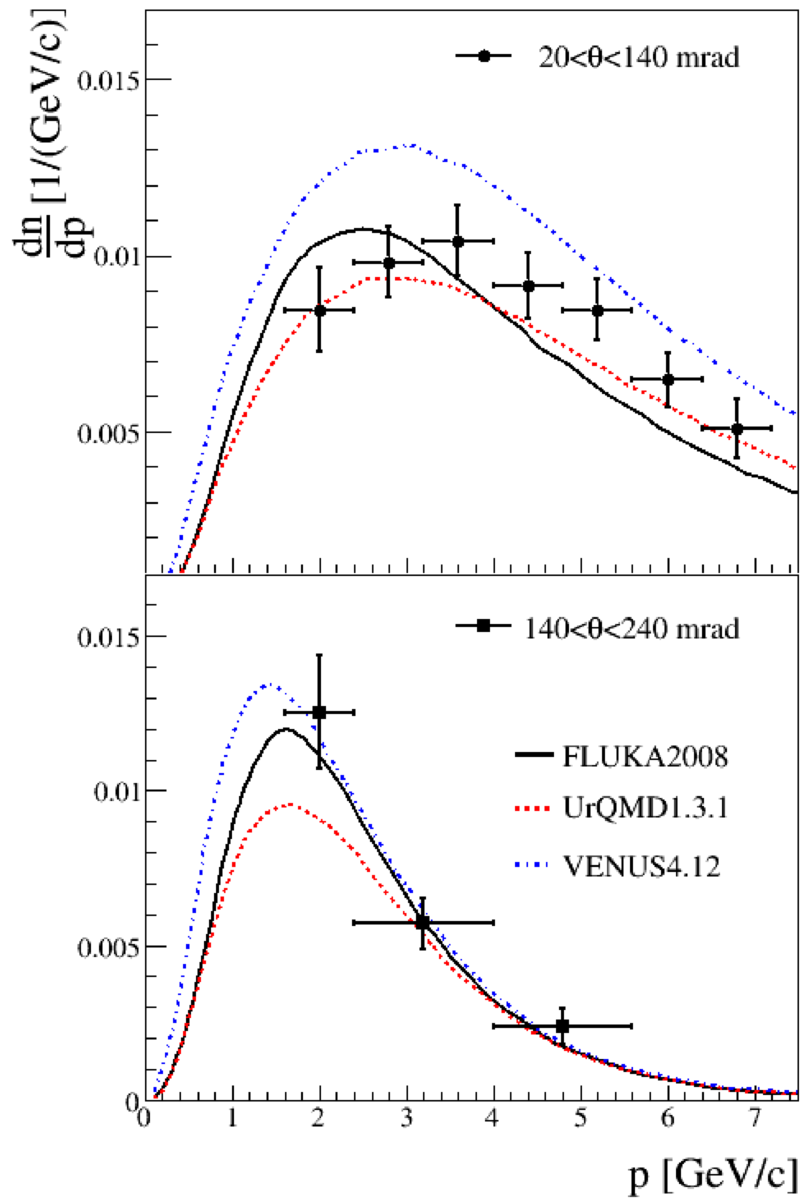
T2K beam “phase space”
very well covered in NA61

NA61 p + C → K$^+$ + X @ 30 GeV

Kaon identification

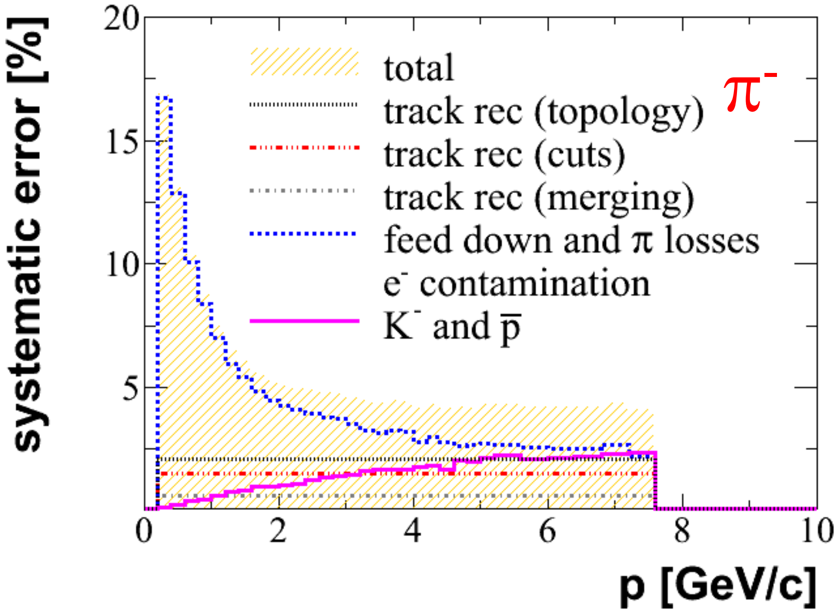
NA61, PRC 84 (2012) 035210



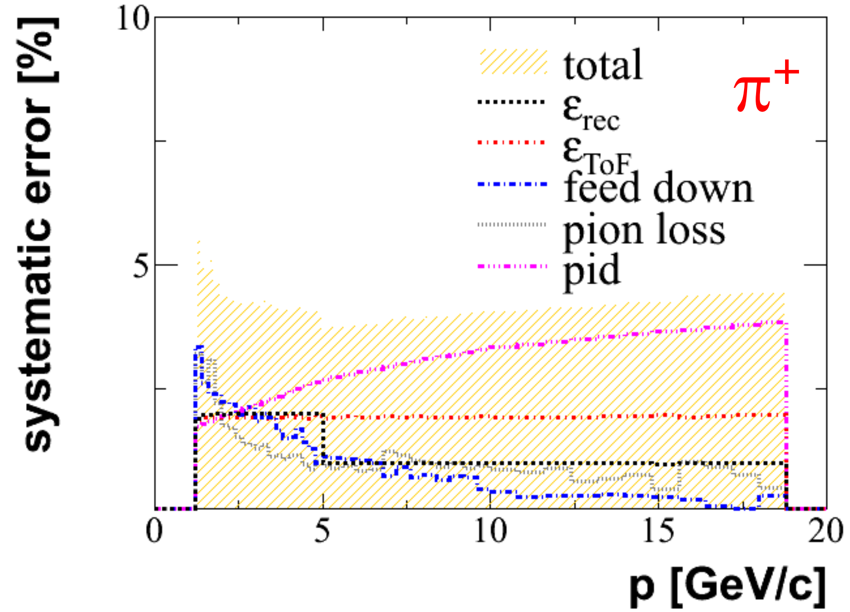


NA61 Systematical Errors – 2007 Data

h^- analysis ($h^- \sim \pi^-$)



full PID analysis



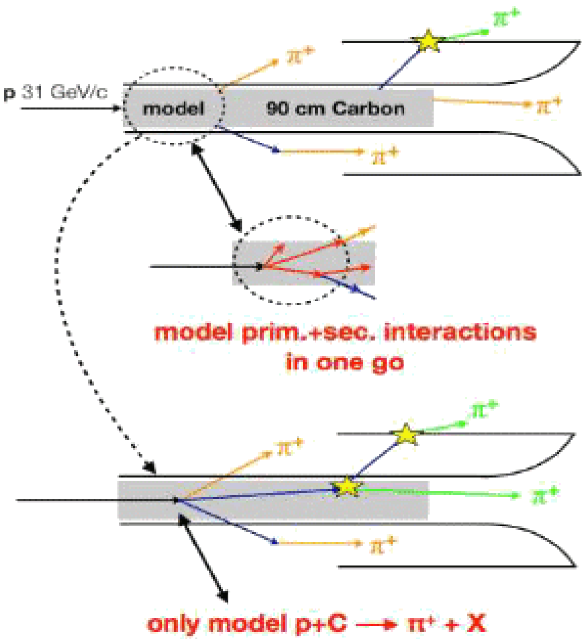
typical value 6% for 2007 data sample

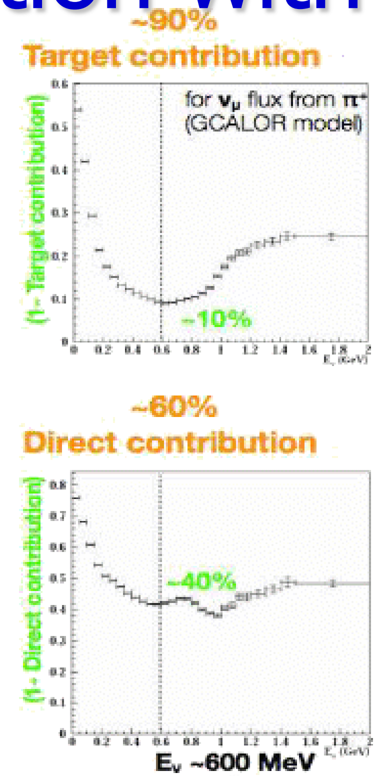
work in progress to reduce this error for the 2009 data sample

- significant improvements in PID
- "feed down" corrections from measured K^0 and Λ yields
- improved normalization (trigger)

$10 \times$ higher statistics in 2009 $\rightarrow$ $3 \times$ smaller statistical error

ν Flux Prediction with T2K Replica Target

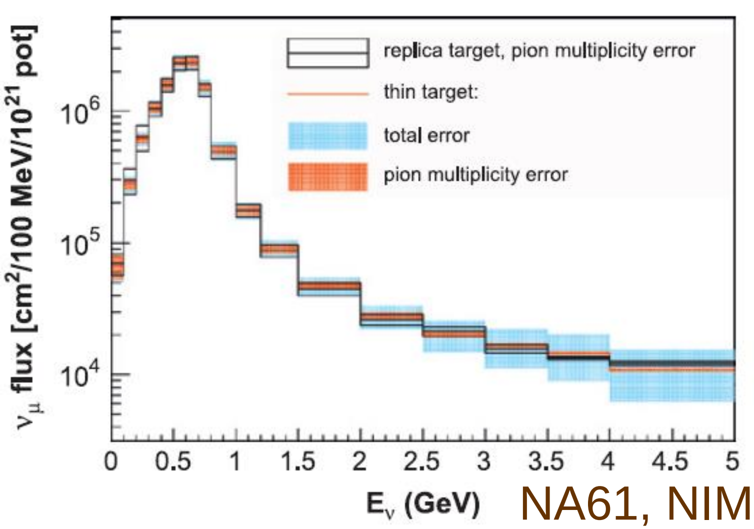




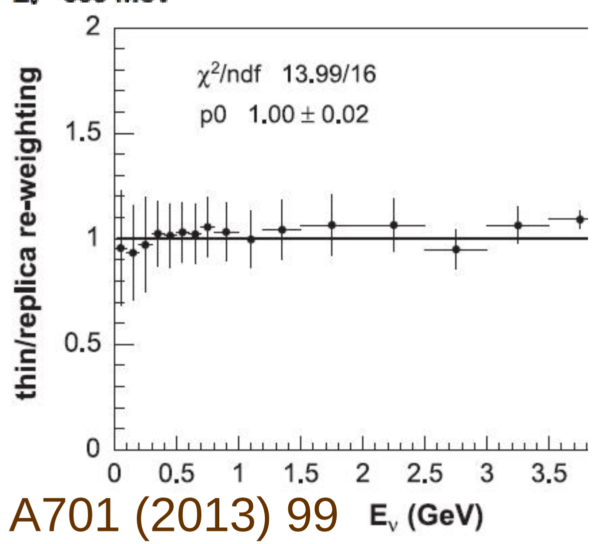
we see only particles coming
out of the target
we do not see what happens
inside the target

hadron multiplicities are measured
at the target surface in bins of {p, θ, z}
(no vertex reconstruction)

model dependence is reduced down
to 10% as compared to 40%



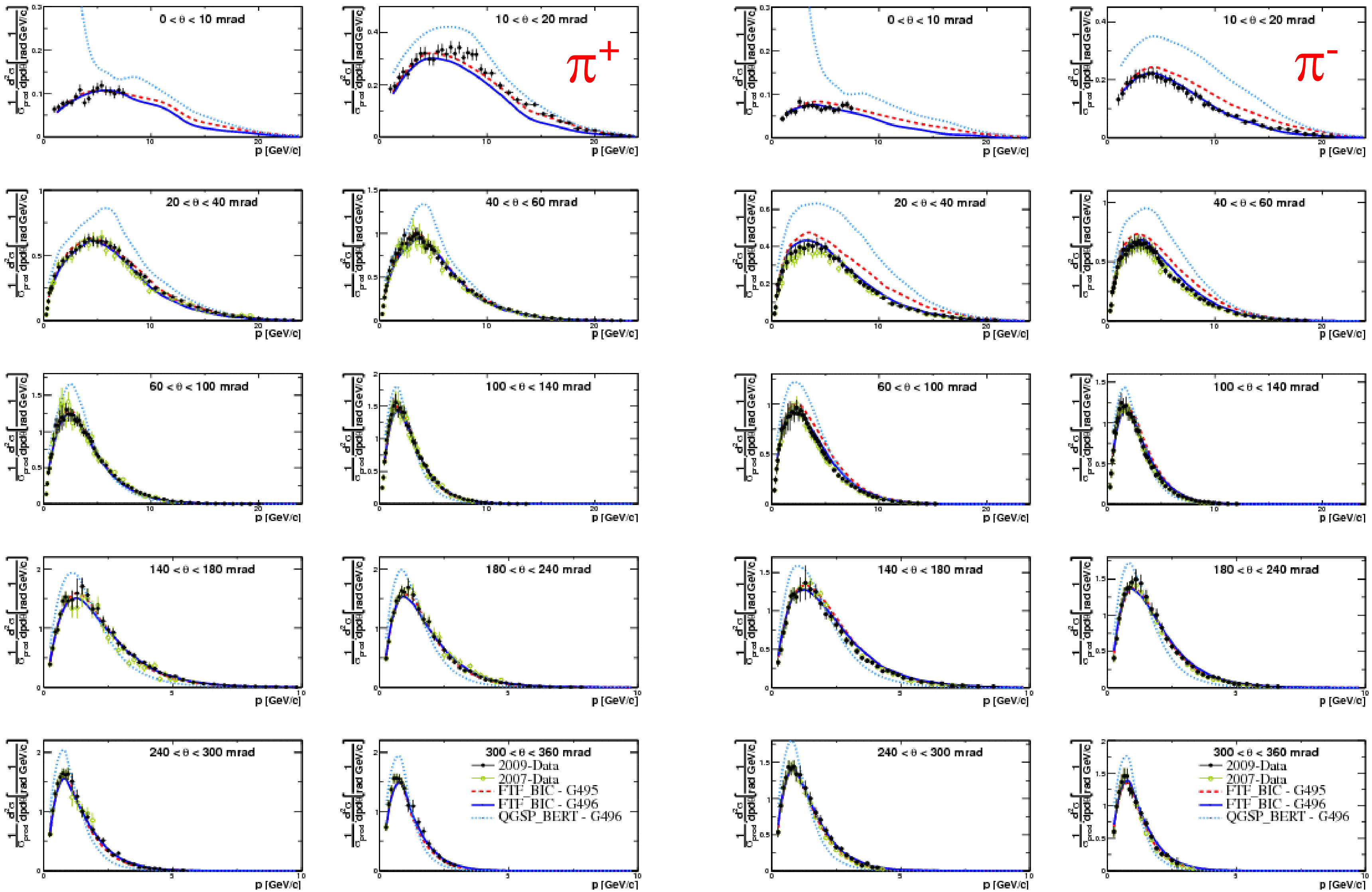
NA61, NIM A701 (2013) 99



comparison of ν flux
predictions
thin target vs.
replica target

in very good agreement
just an accident or real ?

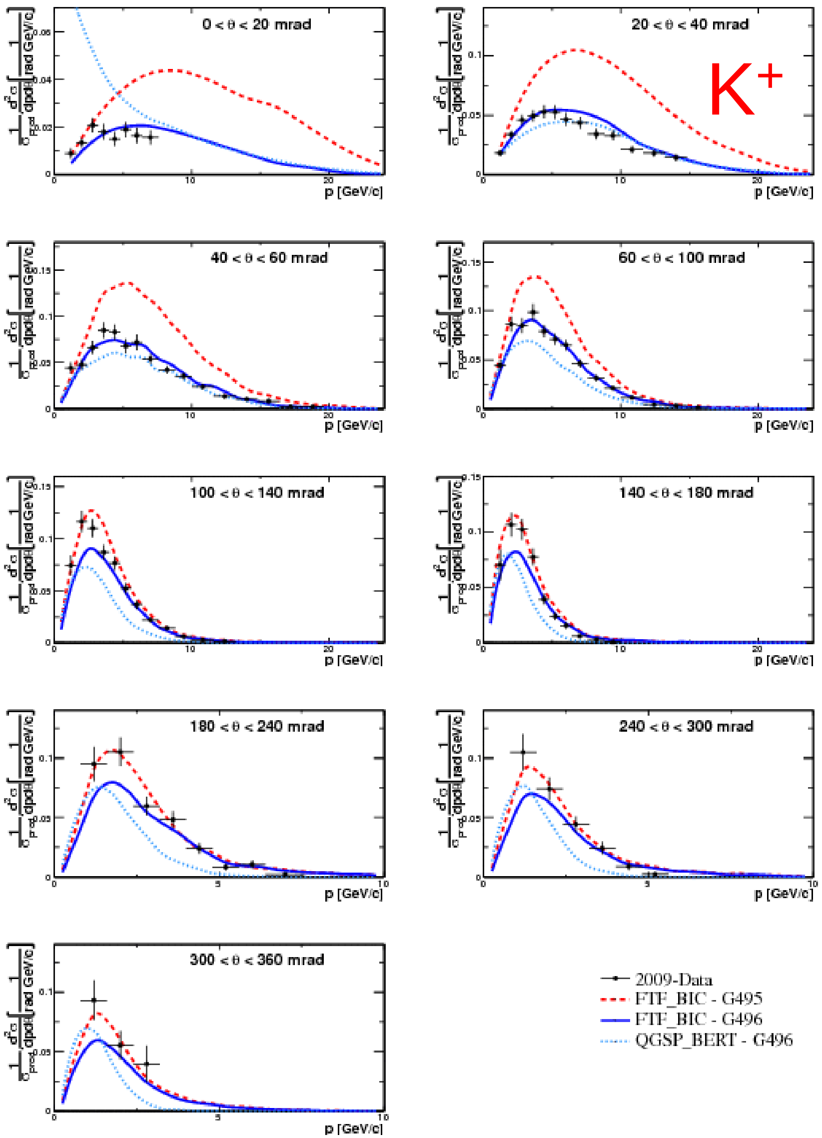
NA61 p + C → $\pi^{+/-}$ + X @ 30 GeV (2009)

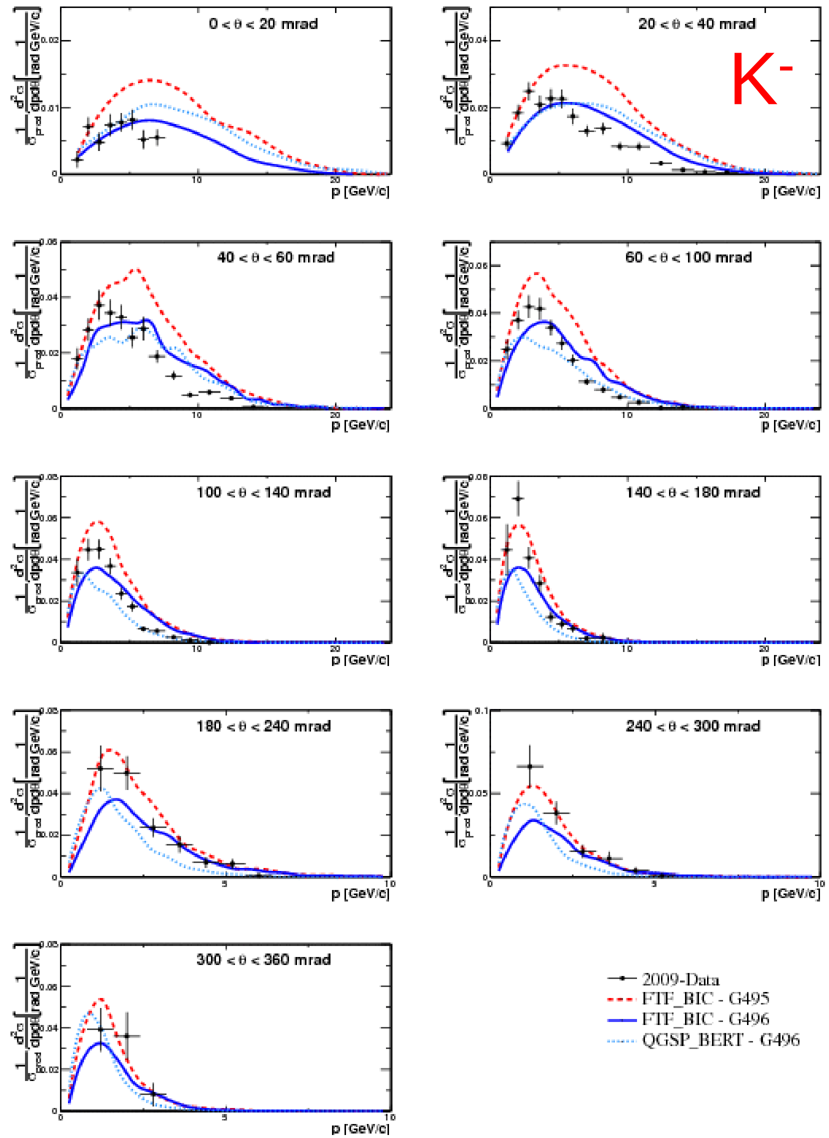


systematical errors as for 2007 data : work in progress to reduce these errors

NA61, A. Korzenev et al., arXiV:1311.5719 [nucl-ex]

NA61 p + C → $K^{+/-}$ + X @ 30 GeV (2009)

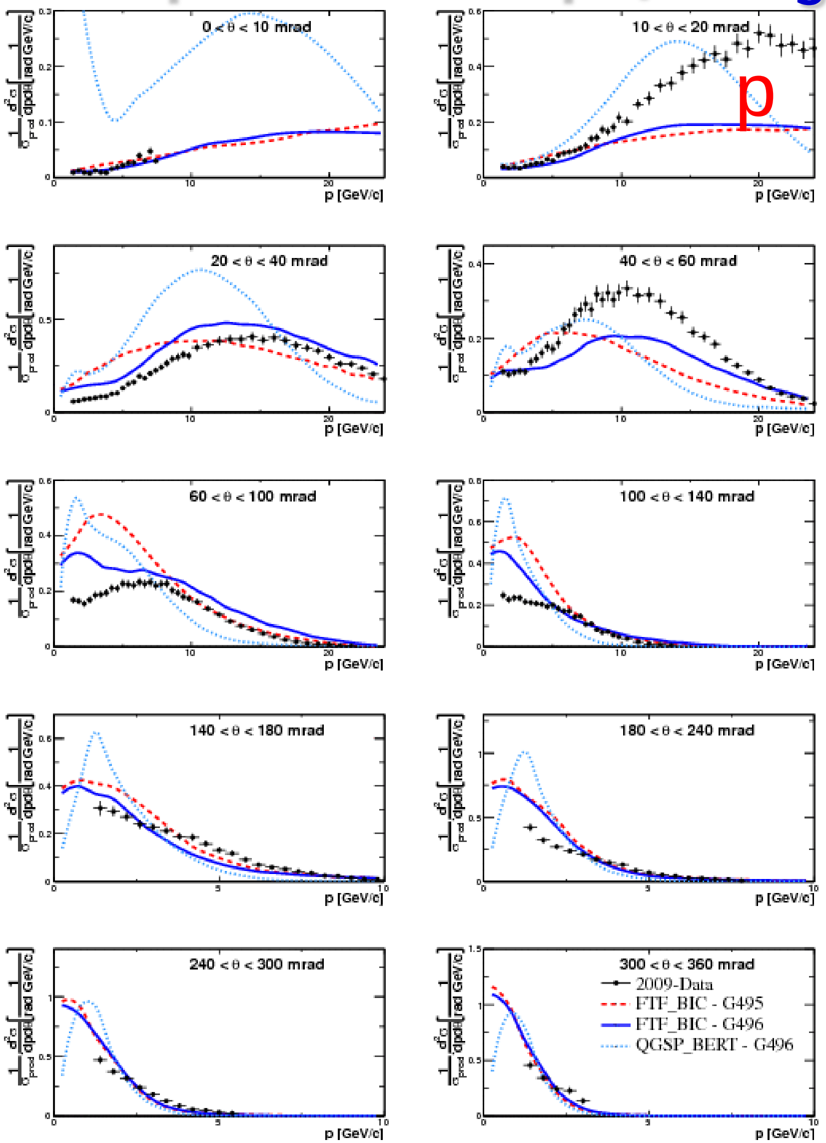


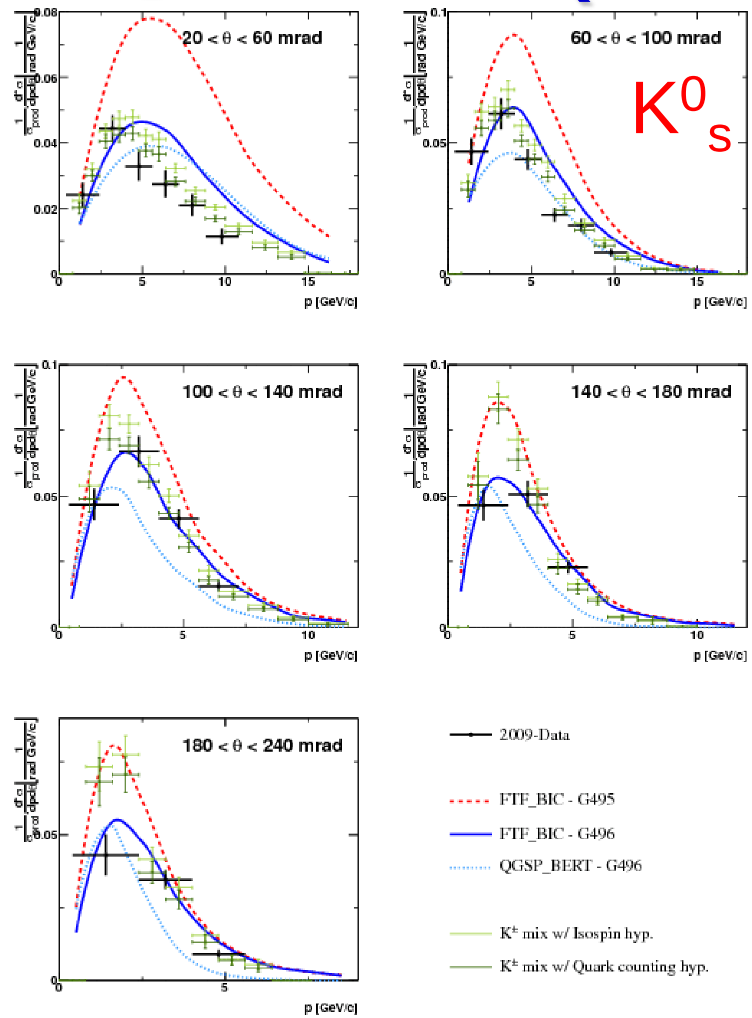


systematical errors as for 2007 data : work in progress to reduce these errors

NA61, A. Korzenev et al., arXiV:1311.5719 [nucl-ex]

NA61 p + C → p / K^0_s + X @ 30 GeV (2009)





Λ also available

systematical errors as for 2007 data : work in progress to reduce these errors

NA61, A. Korzenev et al., arXiV:1311.5719 [nucl-ex]

Conclusions

In 50 years we have gone from 30% uncertainties on ν fluxes to 15% (10%), while increasing proton fluxes on target by ~ $10^3 - 10^4$.

We have still to learn more about understanding neutrino fluxes to get to precision cross section measurements and next steps in oscillation physics

Hadro production measurements are essential to make further progress :

- flux prediction for conventional accelerator ν beams
- improved calculations for atmospheric ν flux
- MC generator tuning

Hadro production measurements require :

- large acceptance detectors with PID over whole kinematical range
- large statistics
- different targets to study various particle production effects

NA61 initial goals for T2K : 5% error on absolute neutrino fluxes

3% error on the far-to-near ratio

NA61 very likely to continue with measurements for NuMI at FNAL (2015 +)