Status of NA61 hadro-production measurements to characterize the T2K neutrino beam flux

- The T2K experiment
- Need for hadro-production measurements
- NA61 data taking for T2K
- Status of the NA61 data analysis

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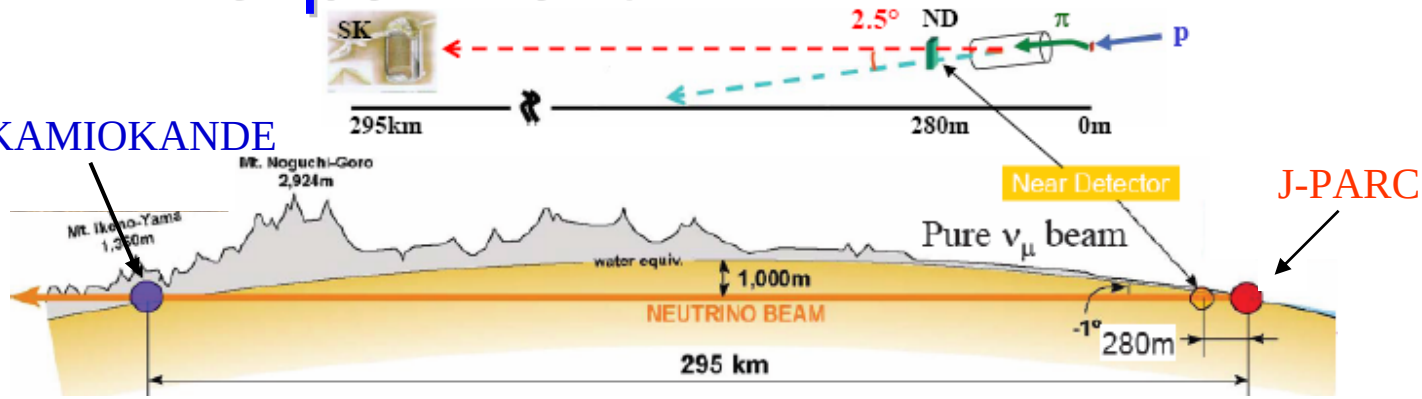
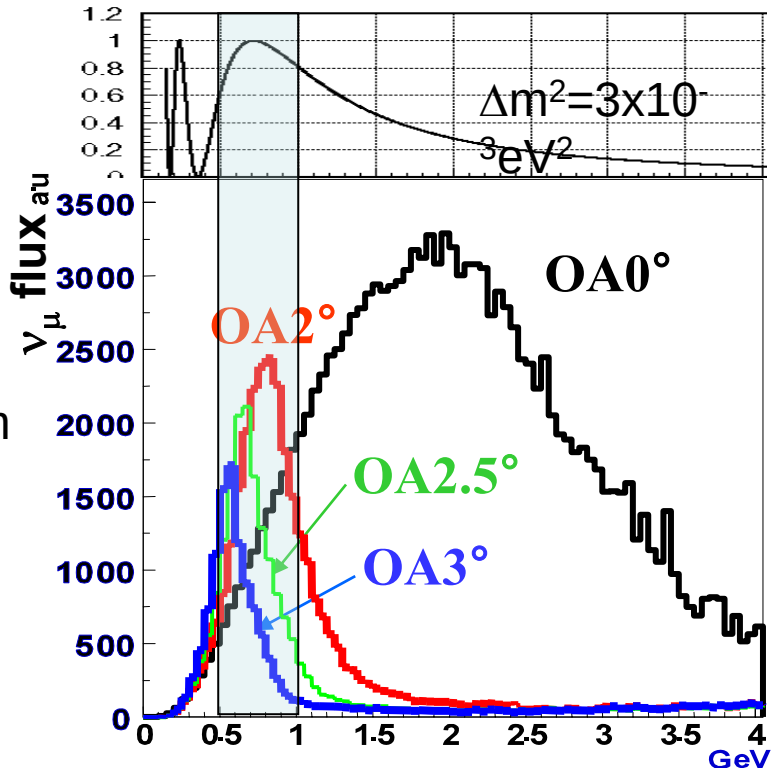
SPSC meeting
28 September 2011

The T2K experiment



- next generation long-baseline (295 km) neutrino oscillation experiment
- intense ν_μ beam generated by new J-PARC facility (~MW facility)
- first off axis neutrino beam:
  - Super-Kamiokande is at a 2.5^0 off-axis angle
  - neutrino flux at interesting energy region higher than for on-axis setting
- very narrow energy spectrum with small high energy tail:
  - ν beam energy "tuned" to oscillation maximum
  - suppression of neutral current π^0 background from higher energy tail (ideal for ν_e searches)

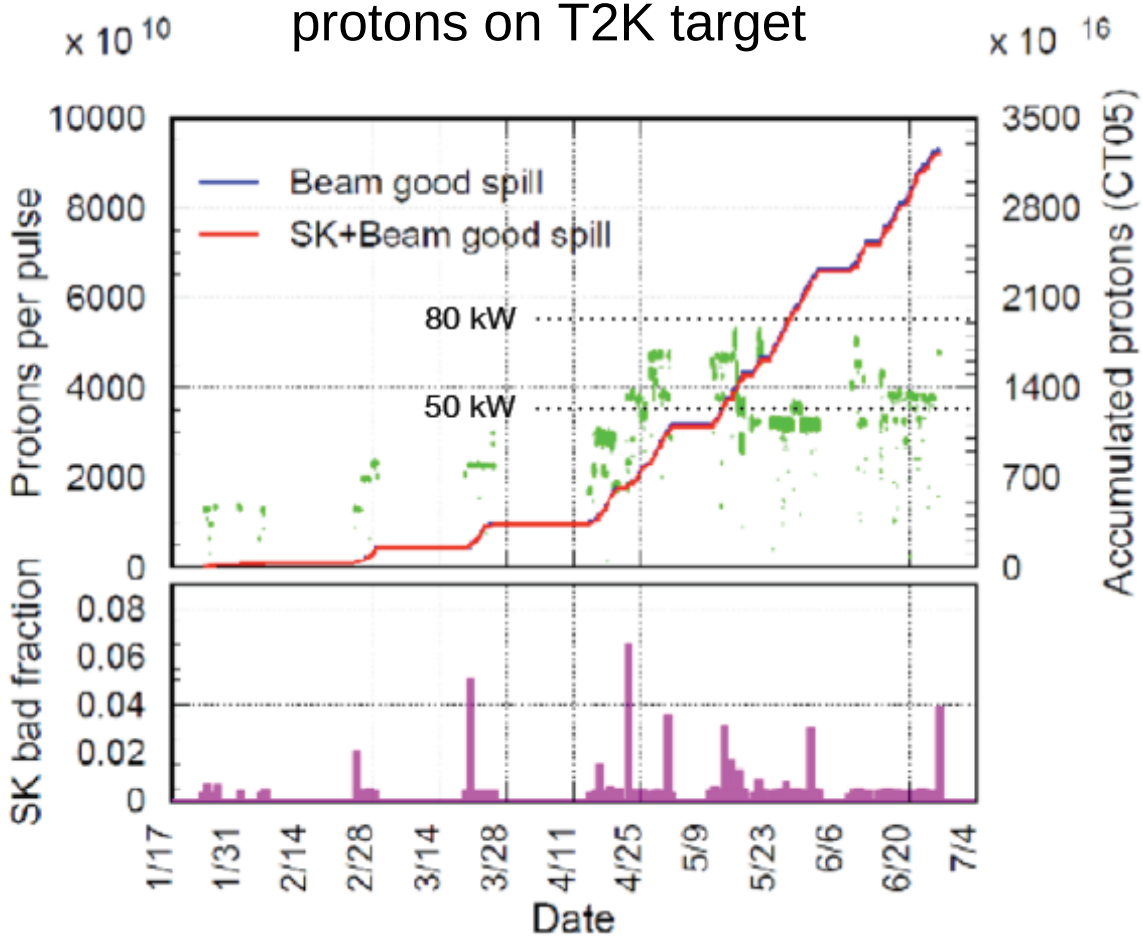


Neutrino beam depends upon secondary beam geometry and hadron distributions off target

T2K beam performance

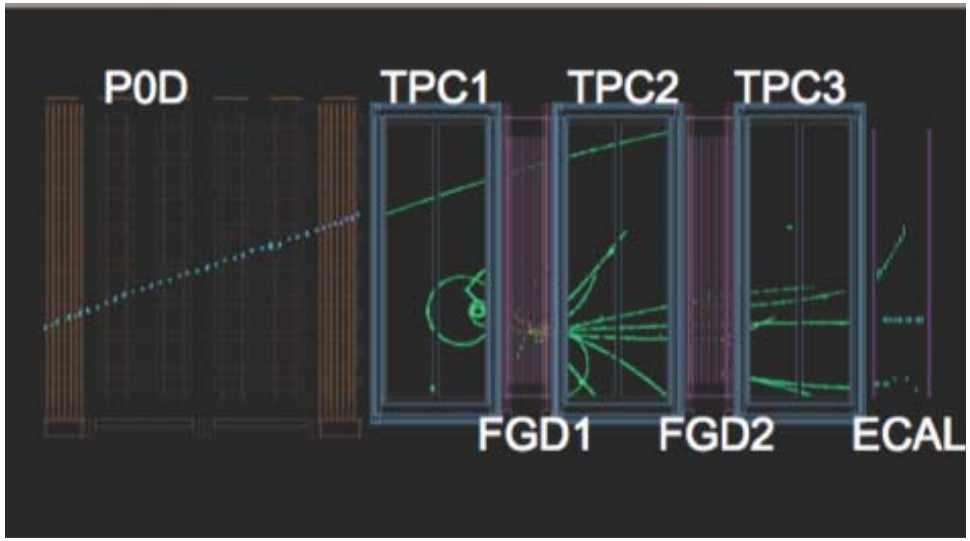
First T2K run completed (January to June 2010)

- 3.3 × 10^{19} protons accumulated for T2K analysis
- 50 kW stable operation with trials at 100 kW
- Super-K live fraction in excess of 99%
- 2011 goal: accumulate 150 kW × 10^{7} sec

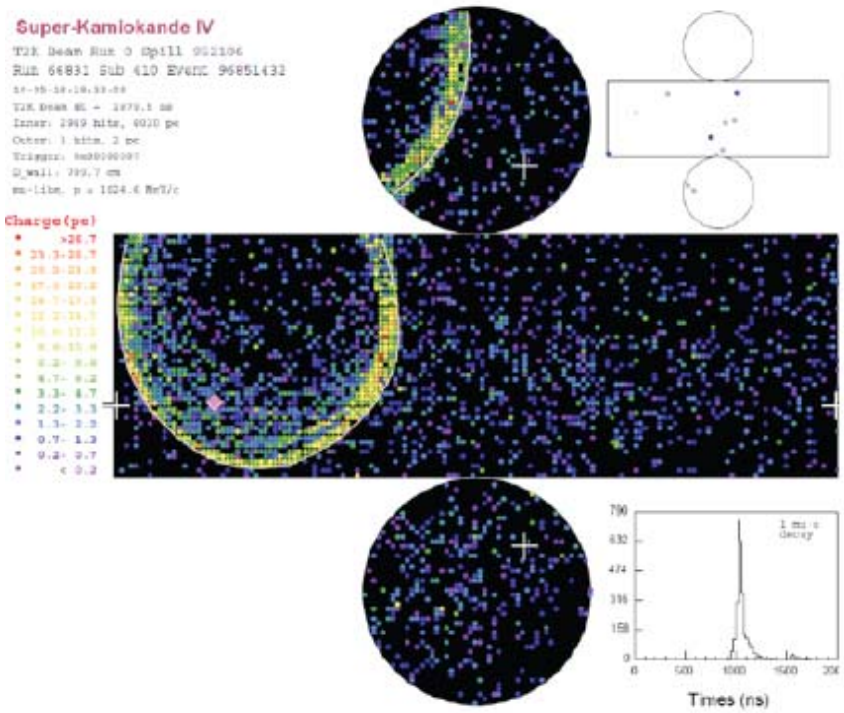


ν interactions in T2K detectors

ND280 off-axis neutrino events

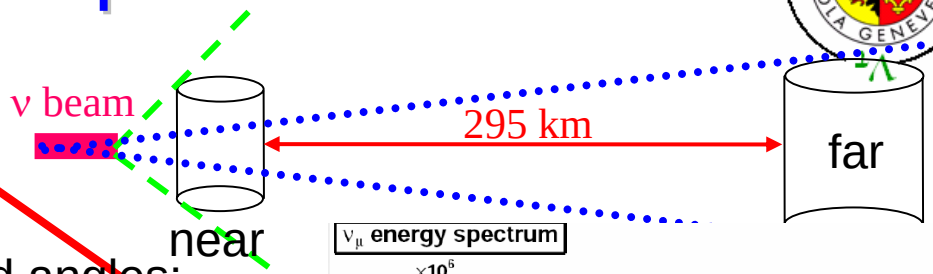


T2K ν event in Super-K



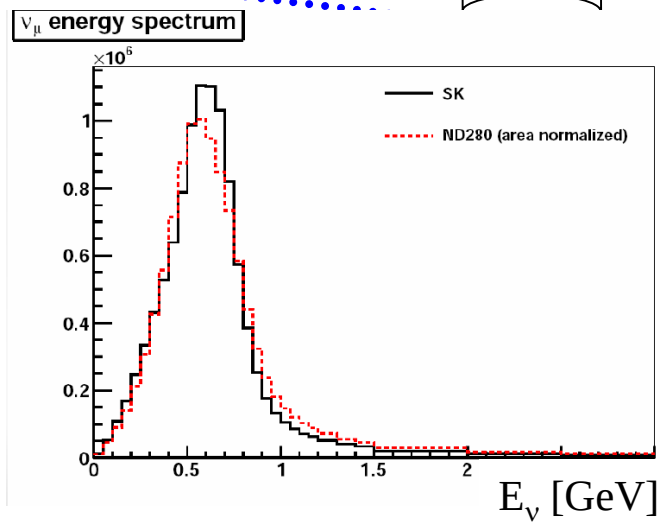
Far / Near flux ratio extrapolation

ν spectrum at far site is different from near site even w/o oscillations
effect of non-point-like source



Near and Far detectors see different solid angles:
- far detector: point-like source at 2.5^0
- near detector: extended source 1^0 to 3^0

⇒ complicated far to near flux ratio



expected flux at SK

$$\Phi_{SK}^{\exp} = R_{F/N} \cdot \Phi_{ND}^{obs}$$

σ, ε

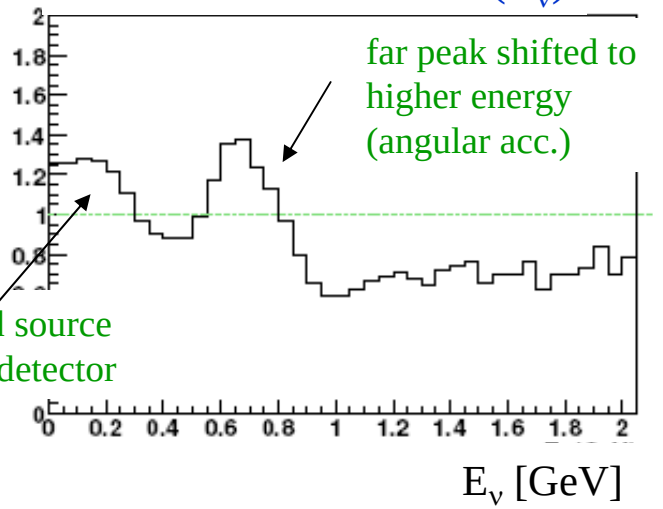
SK expected

SK observed

Far / Near ratio

$$R_{F/N} = \Phi_{SK} / \Phi_{ND}$$

Far-to-Near flux ratio (E_ν)



To predict the ν flux ratio correctly need to know the details of the ν parent hadro-production kinematics

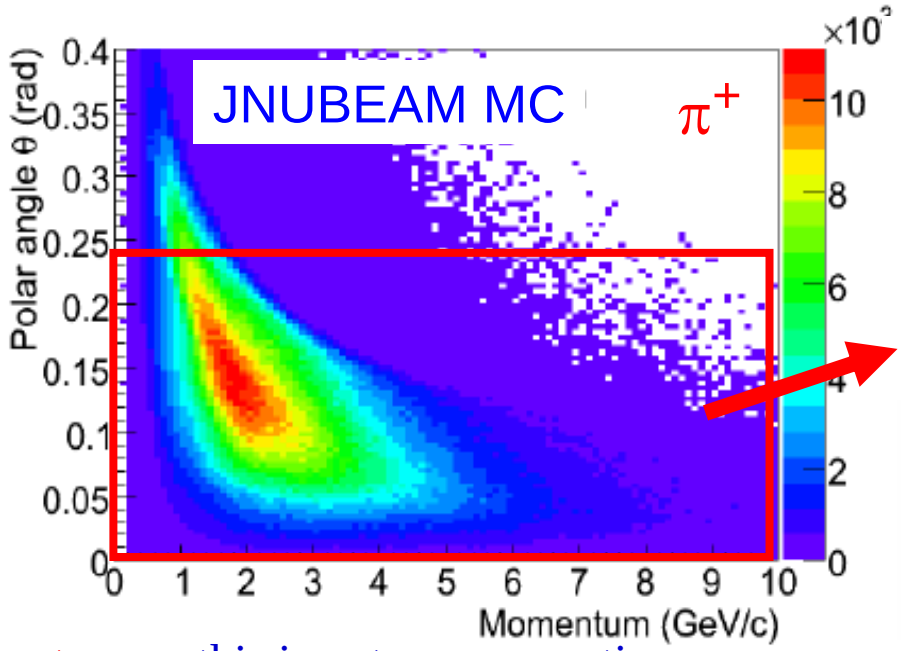
No measurement of particle production off carbon with 30 GeV protons over required phase space
Difficult to evaluate the validity of existing models

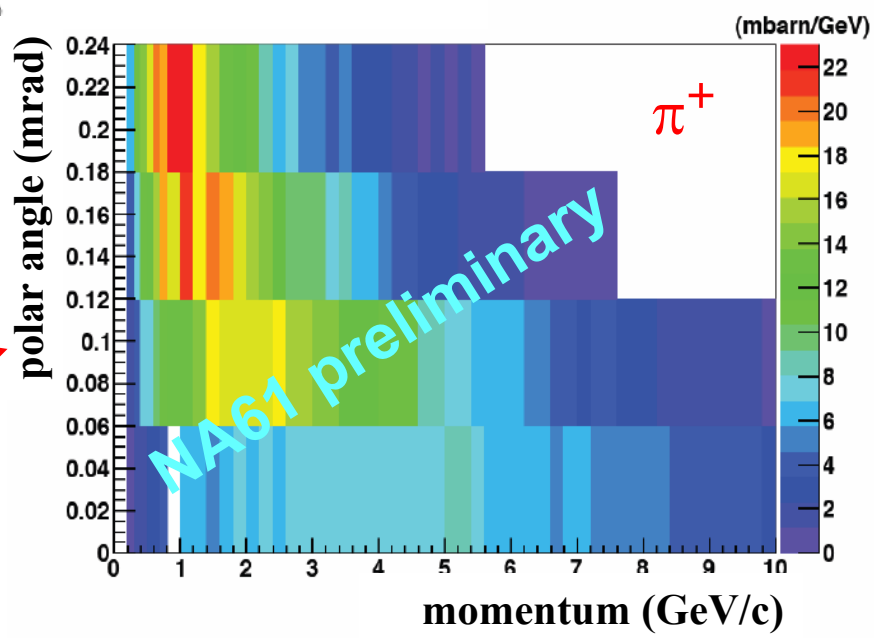
➔ NA61 (SHINE) @ CERN

T2K ν parent hadron phase space

30 GeV proton beam on the 90 cm long T2K graphite target

no hadro-production data available at this energy and kinematical region





note: this is not a cross section
it shows the distributions of π
contributing to the ν flux at SK

the NA61 detector covers nicely
required kinematical region
with very good PID capabilities

To achieve the T2K physics goals need to

Predict Far / Near neutrino flux ratio to 3%
Predict the neutrino flux to 5%

That implies that in NA61
we have to
measure π hadro-production cross sections to 5 % and K / π ratio to 10 %

The NA61/SHINE Collaboration

University of Athens, Athens, Greece
University of Bergen, Bergen, Norway
University of Bern, Bern, Switzerland
KFKI IPNP, Budapest, Hungary
Cape Town University, Cape Town, South Africa
Jagiellonian University, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
Fachhochschule Frankfurt, Frankfurt, Germany
University of Frankfurt, Frankfurt, Germany
University of Geneva, Geneva, Switzerland
Forschungszentrum Karlsruhe, Karlsruhe, Germany
University of Silesia, Katowice, Poland
Swietokrzyska Academy, Kielce, Poland
Institute for Nuclear Research, Moscow, Russia
LPNHE, Université de Paris VI et VII, Paris, France
Pusan National University, Pusan, Republic of Korea
Faculty of Physics, University of Sofia, Sofia, Bulgaria
St. Petersburg State University, St. Petersburg, Russia
State University of New York, Stony Brook, USA
KEK, Tsukuba, Japan
Soltan Institute for Nuclear Studies, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
University of Warsaw, Warsaw, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
ETH Zurich, Zurich, Switzerland

~ 130 physicists from
24 institutes and 13 countries

in green T2K groups

SHINE
NA61

NA61 data taking for T2K

2 different graphite (carbon) targets

2007 pilot run
- thin target ~ 660 k triggers
- replica target ~ 230 k triggers

2009 run
- thin target ~ 6 M triggers
  - $\Rightarrow$ 200 k π^+ in T2K phase space
- replica target ~ 2 M triggers

2010 run

complete measurements with
- replica target ~ 10 M triggers

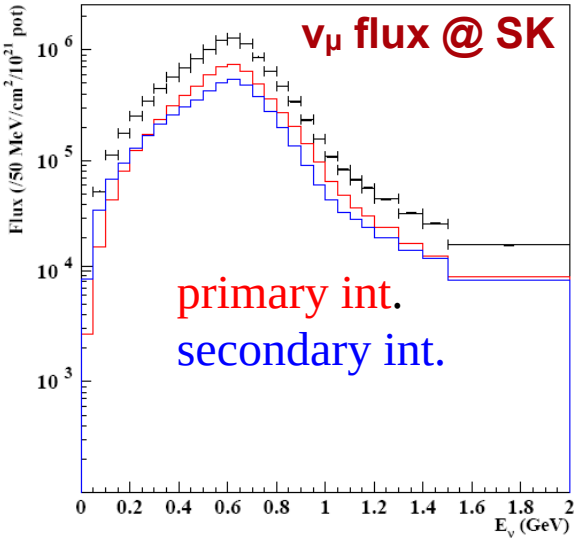
(~ 1 M additional triggers taken with max B in the forward region to predict μ flux in on-axis μ monitors)

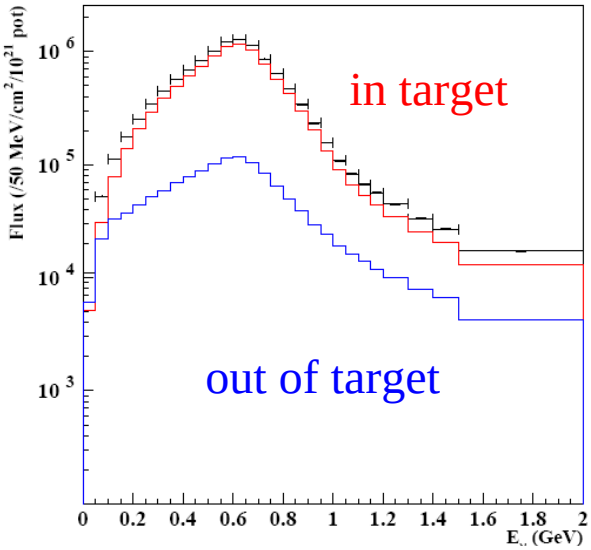
Both targets required to understand pC interactions and model reliably the neutrino flux.

Thin Carbon Target
- **length = 2 cm, 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}**

Role of secondary interactions





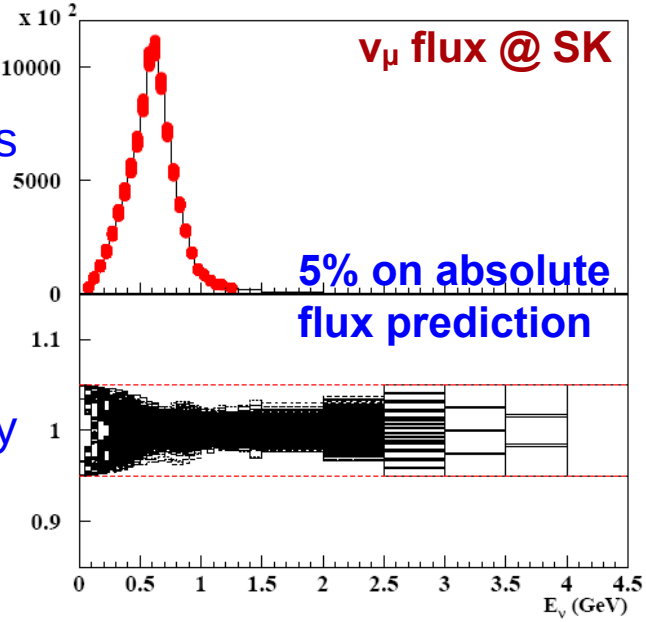
~40% of ν flux is coming from secondary interactions (thin target alone not enough)

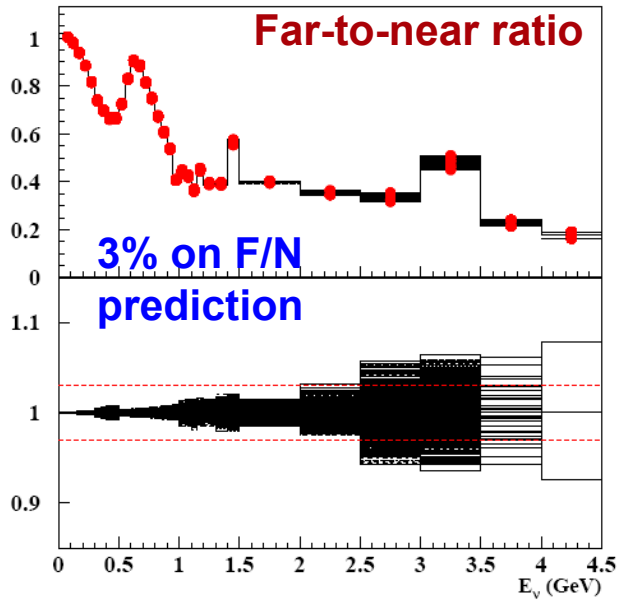
~90 % of ν_μ and ν_e fluxes at peak energy are coming from parents produced in the target: measure production from replica target directly !

NA61 statistics required to fulfill T2K physics goals

10 M triggers off replica target

(assuming 5% uncertainty on hadro-production measurements)





π spectra analysis

Three independent analyses procedures adopted depending on the kinematical region (→ acceptance) covered:

1) negative hadrons

pure tracking with no PID, large acceptance, model corrected

2) dE/dx at low momentum (p < 1 GeV/c)

relativistic rise region in preparation

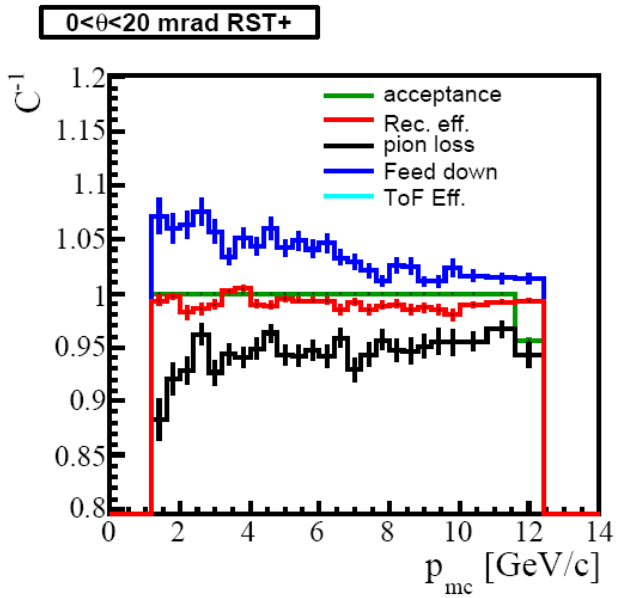
3) combined ToF – dE/dx at intermediate p

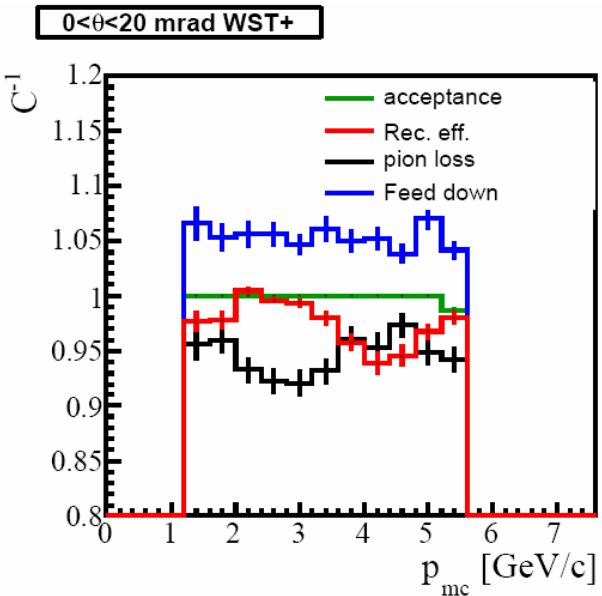
high purity π / K / p separation, but reduced acc.

Size of corrections to pion spectra:

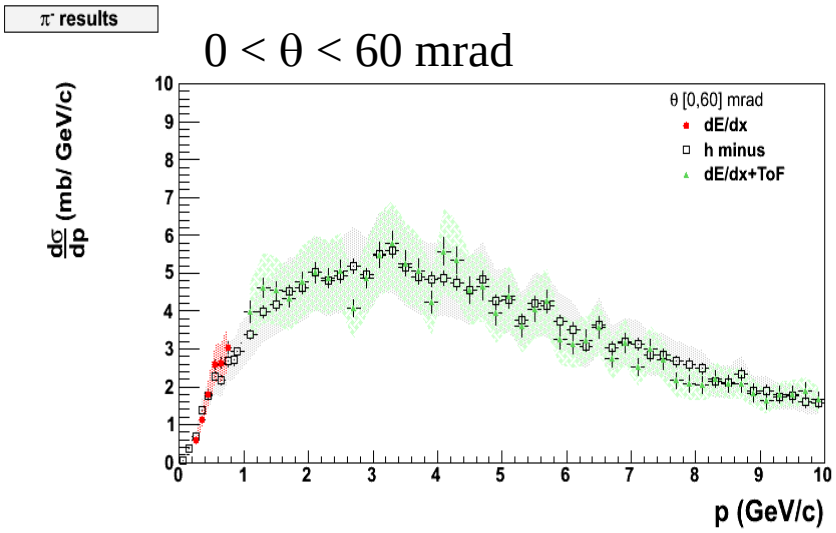
- acceptance < 1%
- reconstruction eff. < 4%
- pion decay < 10 %
- feed down < 10%

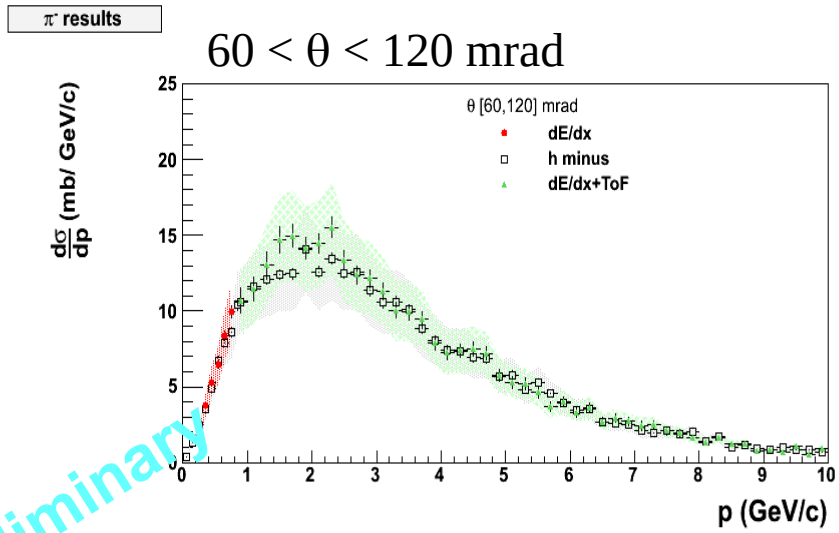
current overall systematic uncertainty < 20%

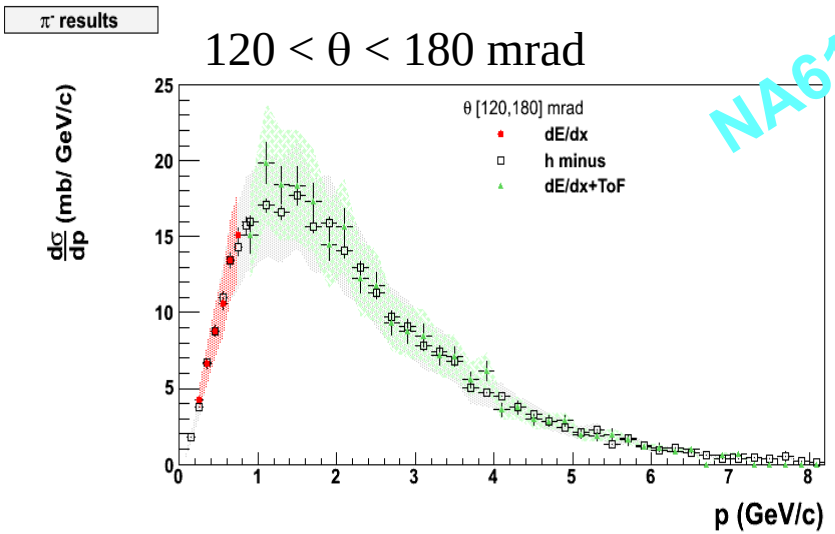


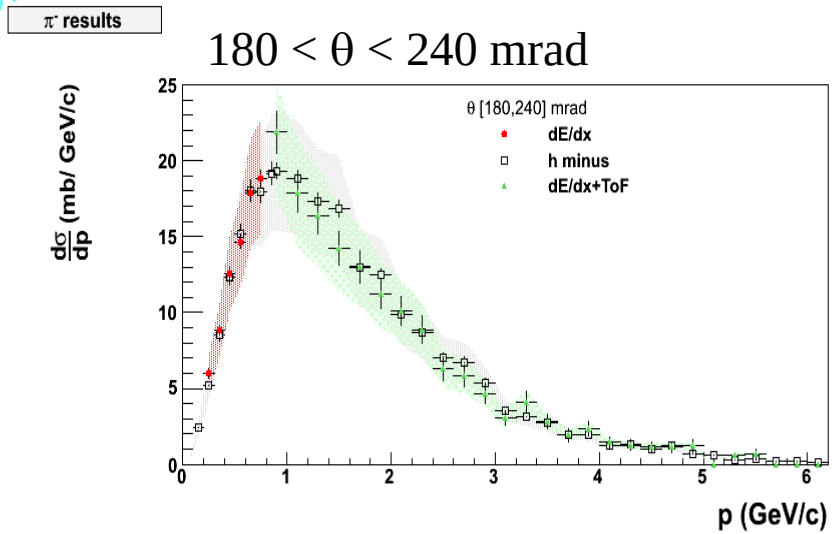


Preliminary π^- spectra





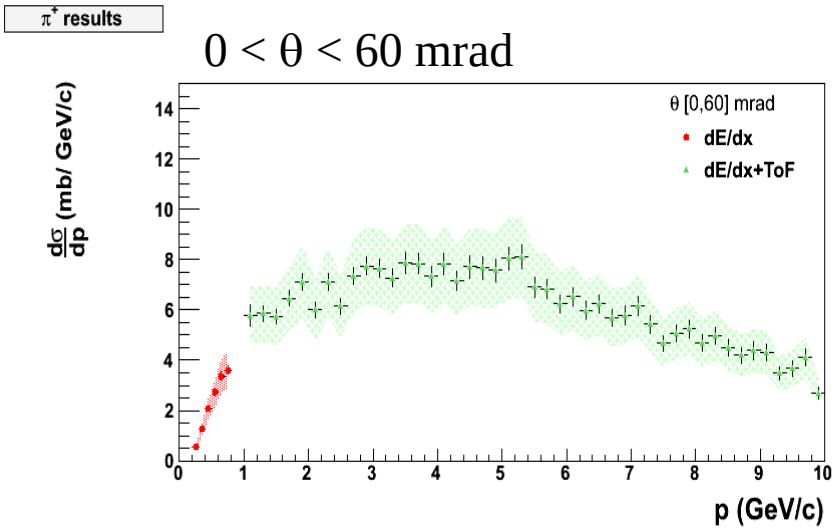


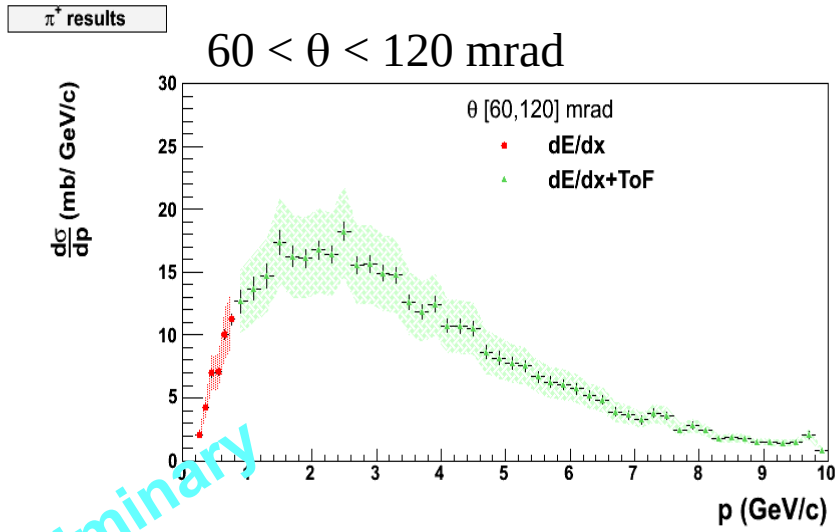


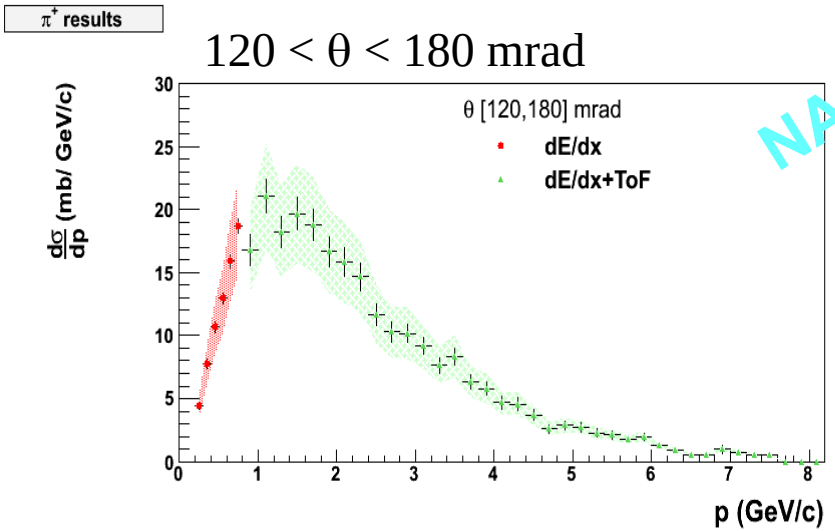
NA61 preliminary

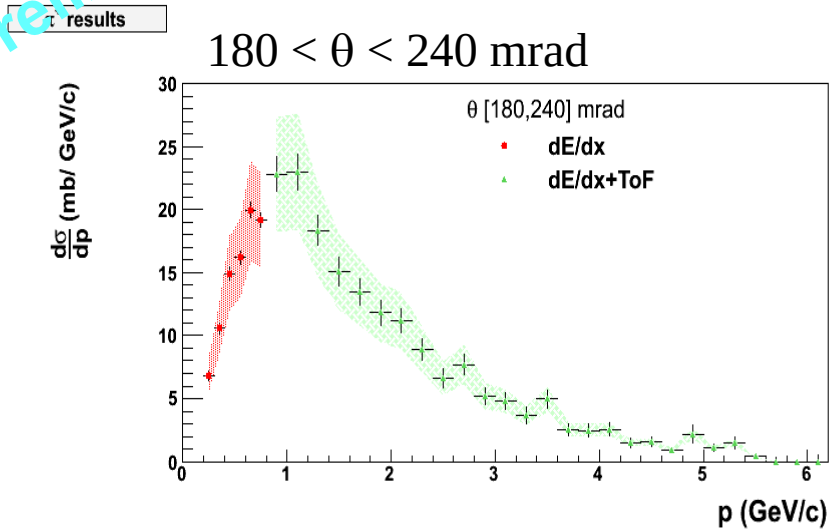
different approaches yield consistent results within **20% systematic errors**
work is in progress to reduce the current systematical uncertainties

Preliminary π^+ spectra





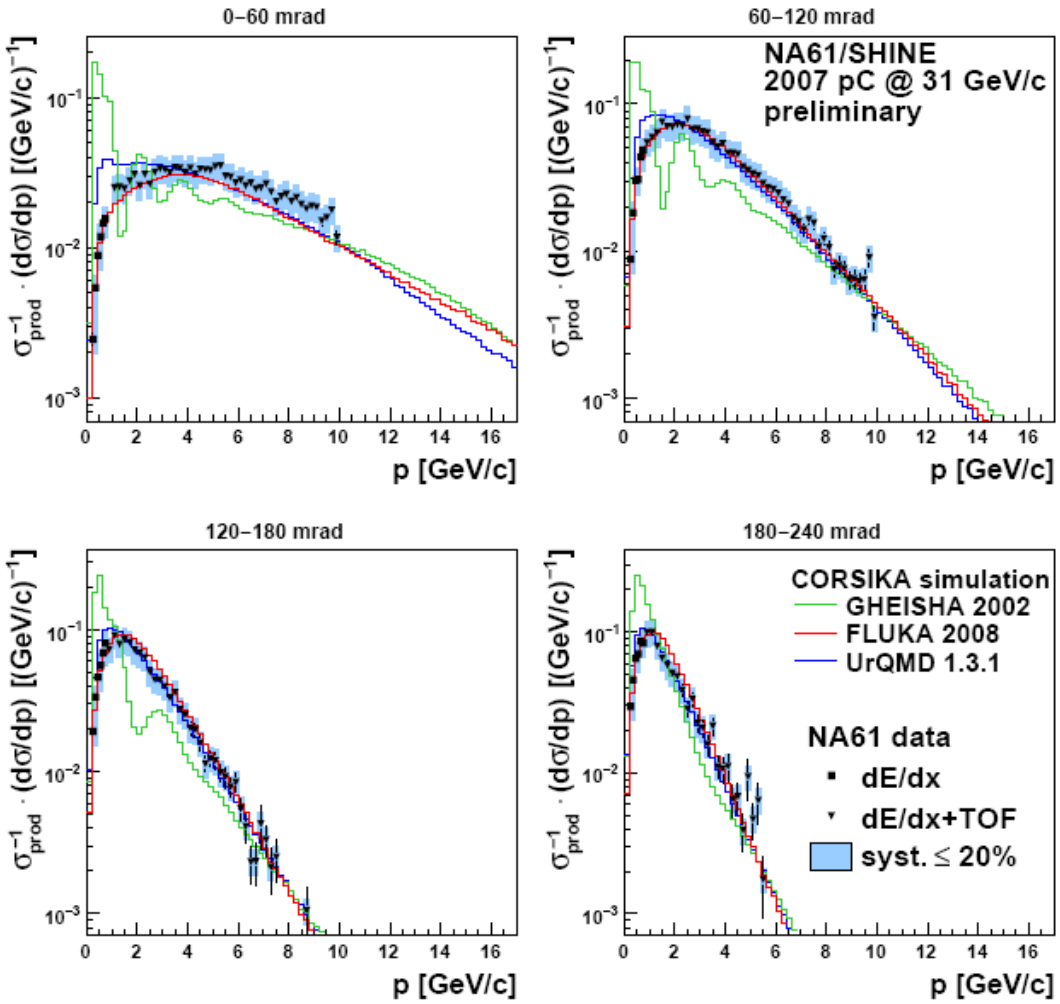




NA61 preliminary

continuity observed in the distributions (different analyses)
same **20% systematic errors** as for π^- spectra

Model comparisons for π^+



pion production: $\frac{1}{\sigma_{\text{prod}}}\frac{d\sigma}{dp}$, where $\sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qel}}$

FLUKA 2008 and UrQMD 1.3.1 follow the trend of the data,
whereas qualitative disagreement is observed for GHEISHA 2002 (to be further investigated).

Analysis progress

Preliminary spectra of charged pions (π^+ and π^-) from the 2007 data have been released up to p ~ 10 (15) GeV/*c* :

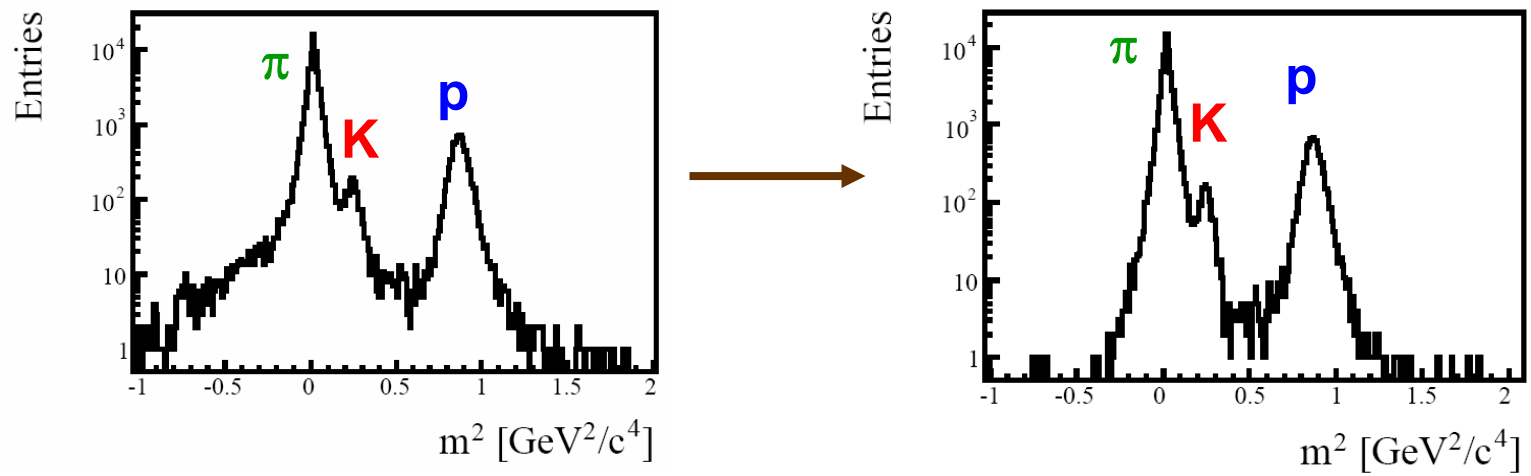
Work is in progress to extend the pion spectra to $x_F \rightarrow 1$

dE/dx analysis at low p has been extended up to 1 GeV/c for π^+ and up to 3 GeV/c for π^-

dE/dx analysis in relativistic rise region in preparation

Revisiting 2007 calibrations:

based on improvements introduced on 2009 data and improved tracking recalibration of ToF → improved resolution and PID discrimination



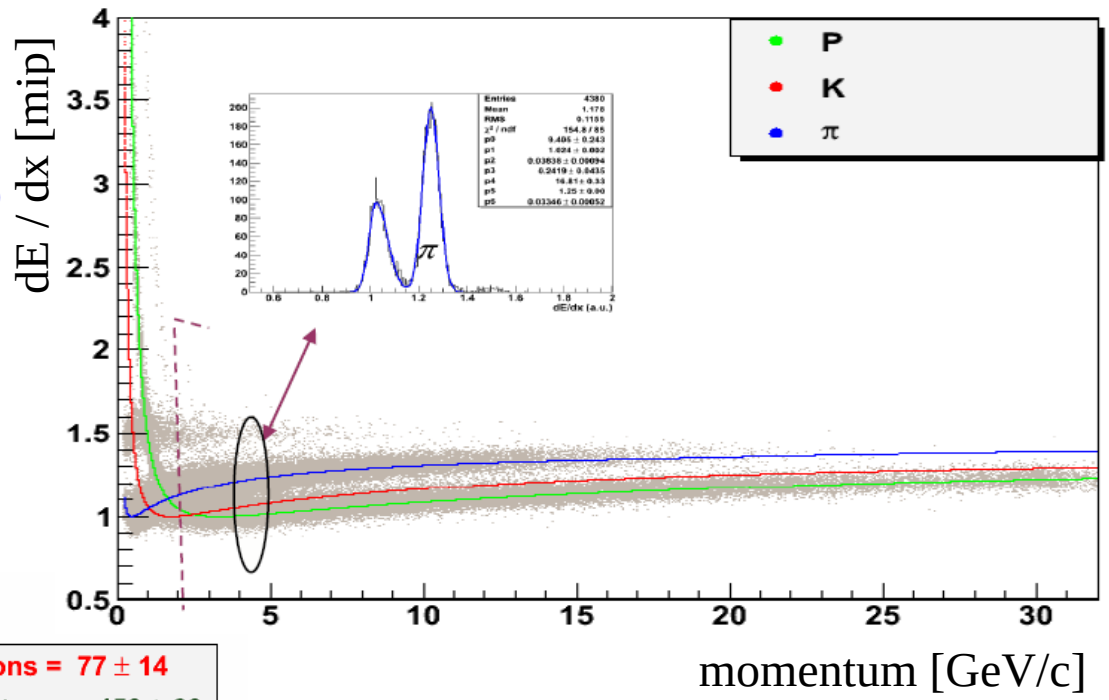
Methods to analyze and use data on the T2K replica target are advancing

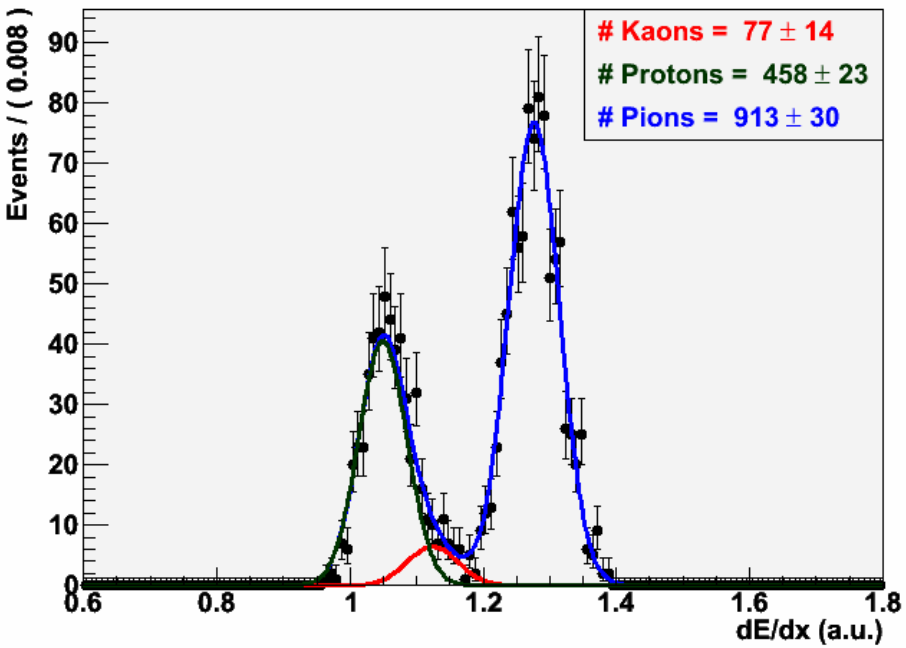
→ new estimate of statistics required and additional data taking in 2010

dE/dx in relativistic rise region

Energy loss in TPCs
Bethe-Bloch curves (dE/dx)
for different particles

σ (dE/dx) / $\langle$dE/dx$\rangle$ < 4 %





fitting procedure:

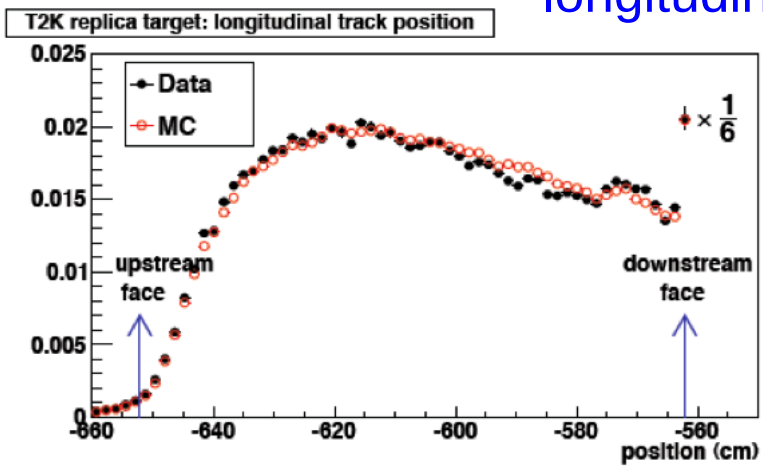
superposition of 3 gaussians
maximum likelihood fit

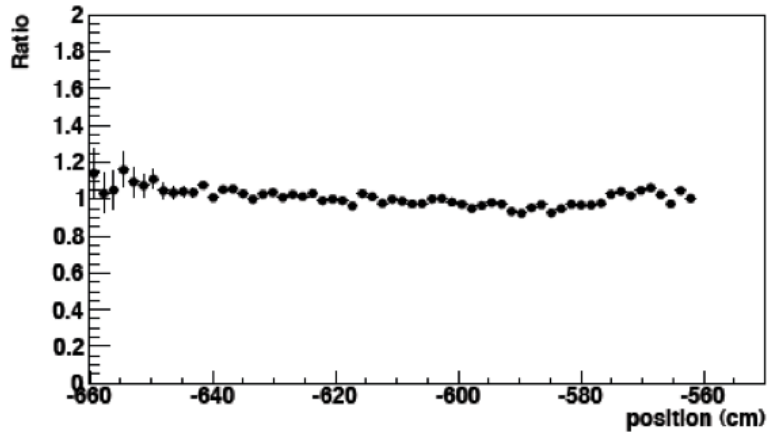
- relative peak positions constrained by the expected Bethe-Block values
- assume same width for π, K, and p (5 free parameters instead of 9)

Replica target analysis

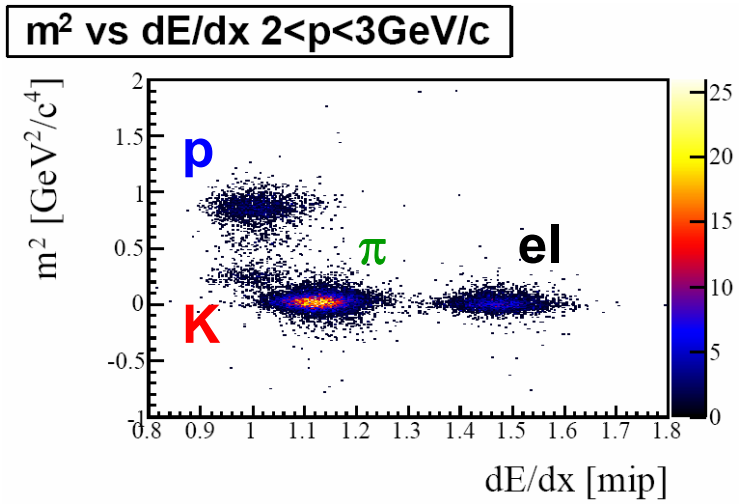
Tracks reconstructed in the TPCs are extrapolated upstream to the target skin (at this stage no vertex constrain)

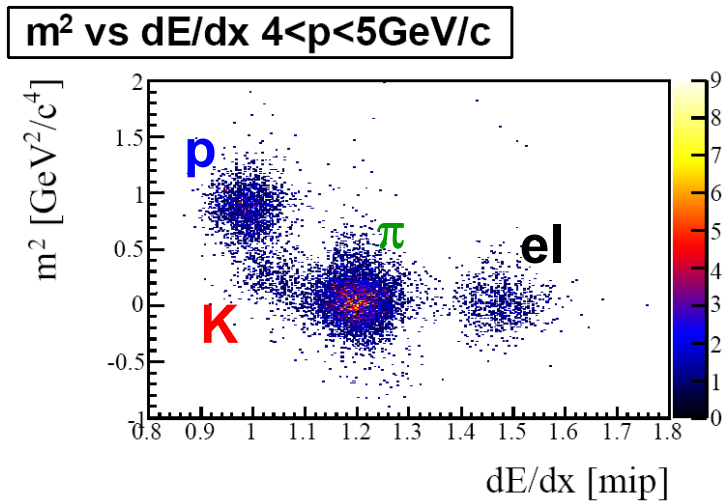
longitudinal distribution of exit position on target skin





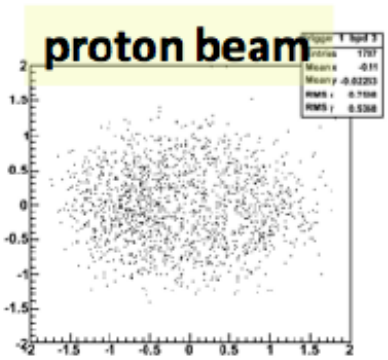
Particle IDentification performance with replica target very similar to thin target

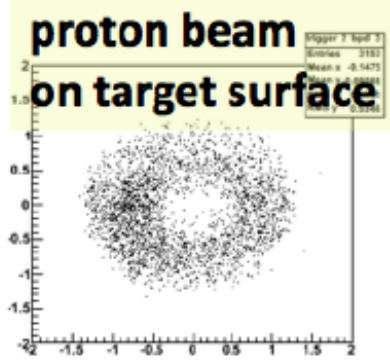


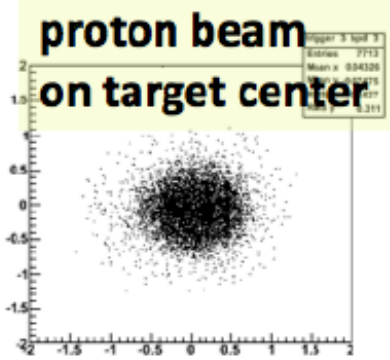


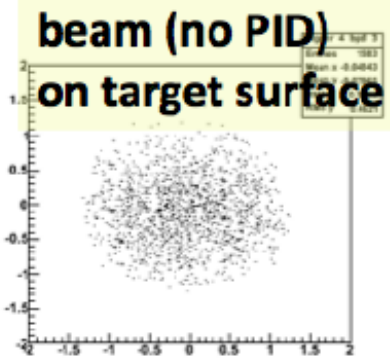
T2K replica target alignment

(using 4 different triggers running in parallel)

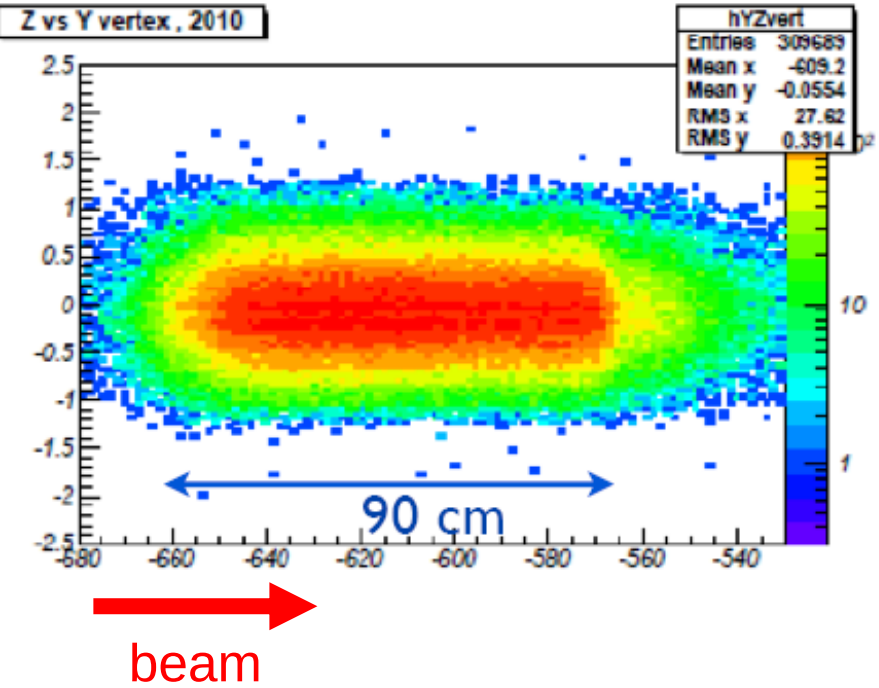




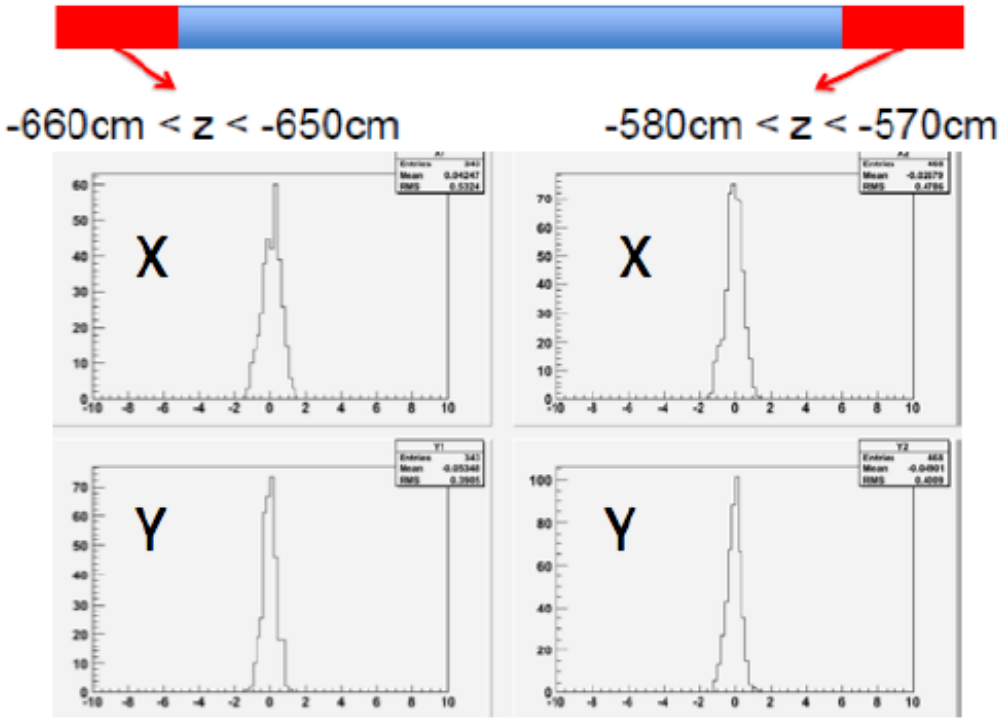




reconstructed vertex

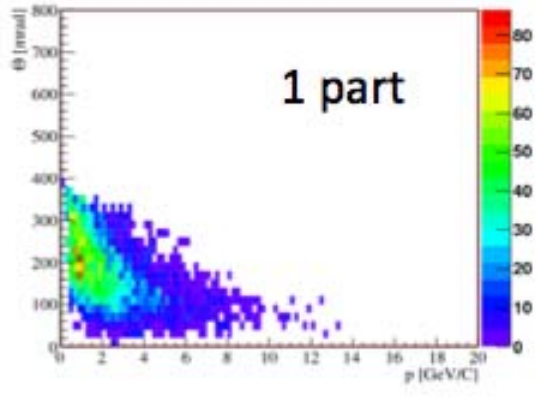


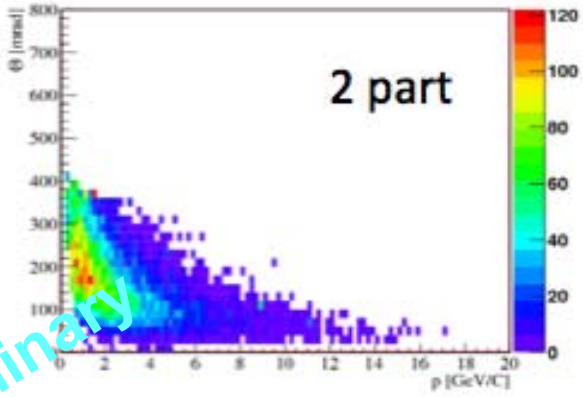
target aligned to better than 1 mrad

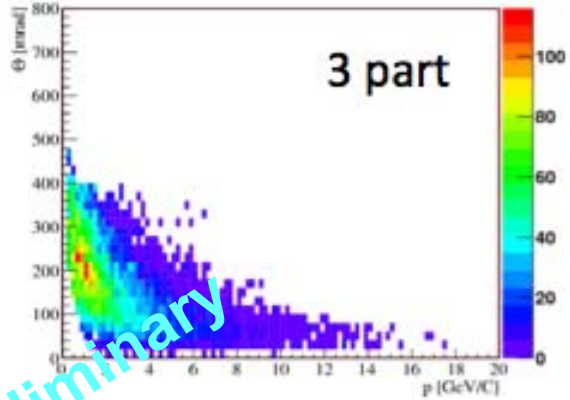


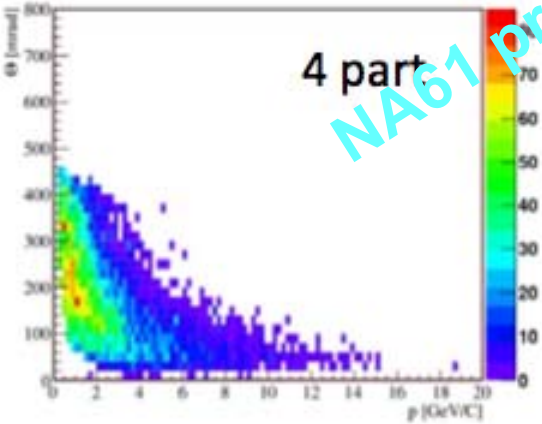
h^- spectra off T2K replica target

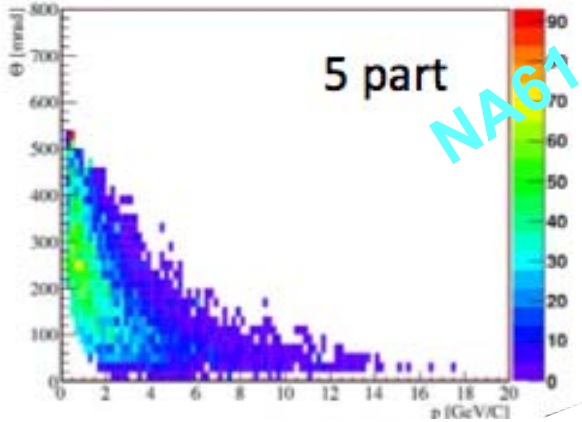
h^- p / θ distributions for 5 longitudinal bins & target downstream face measured at target skin with correction procedures similar to the thin target h^- analysis

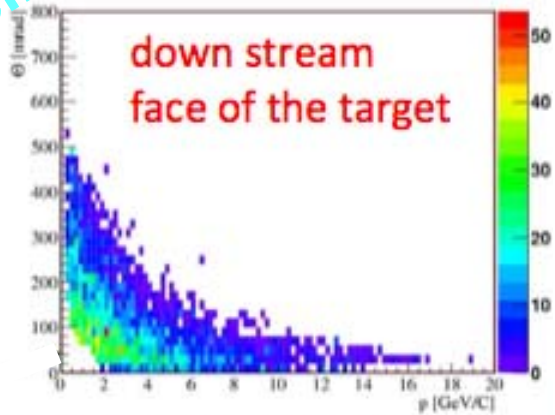












The p / θ distributions change along the target

Longitudinal distribution sensitive to:
- target geometry
- re-interactions
- target interaction length

Summary and Conclusions

T2K data taking started:
- first physics run completed in June 2010;
- will soon release results.

NA61 data taking for T2K (hadro-production measurements) has been completed in summer 2010.

Preliminary pion spectra (π^+ and π^-) from 2007 data have been released and shown at conferences.
These data are being used by T2K in the simulations of ν beam.

Work is in progress to finalize the 2007 thin target data analysis:
- final results expected by the end of 2010;
- goal: systematic error < 10% (for 2007 data sample).

Big effort has been placed in data taking and methods to analyze and use the data taken with the T2K replica target.

According to the current T2K plans and NA61 progress, NA61 results will be in time for T2K analysis.

T2K physics goals

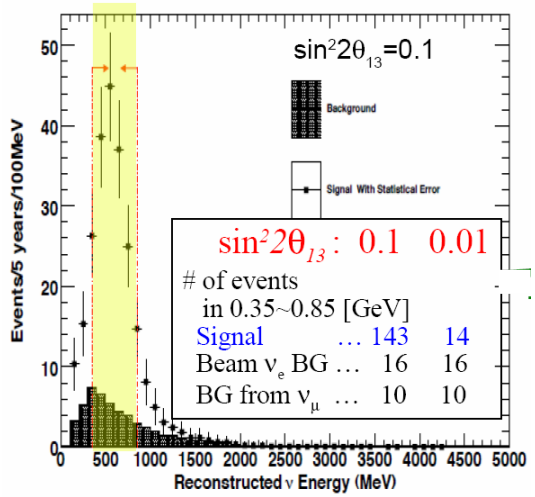
measure θ_{13}, $|\Delta m^2_{13}|$ by searching for ν_e appearance: $\nu_\mu \rightarrow \nu_e$

$\sin^2(2\theta_{13}) < 0.008$ (@ 90% CL) (depends also on δ_{CP})

is $\theta_{13} \neq 0$?

→ first step toward CP violation searches in lepton sector

$$P_{\mu\rightarrow e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(1.27\ \Delta m^2_{13}\ L/E_\nu\right)$$



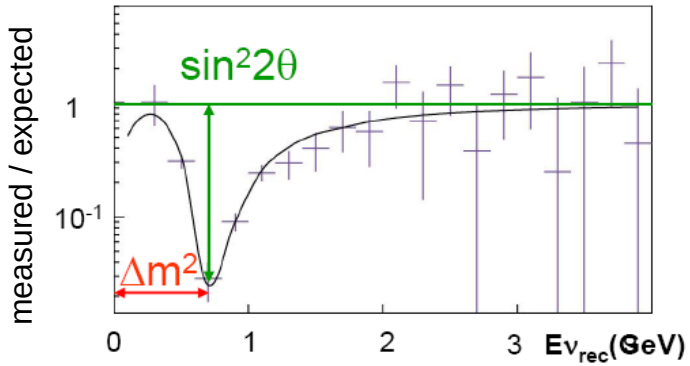
common for normal hierarchy

better measurement of θ_{23}, Δm^2_{23} by studying ν_μ disappearance: $\nu_\mu \rightarrow \nu_x$

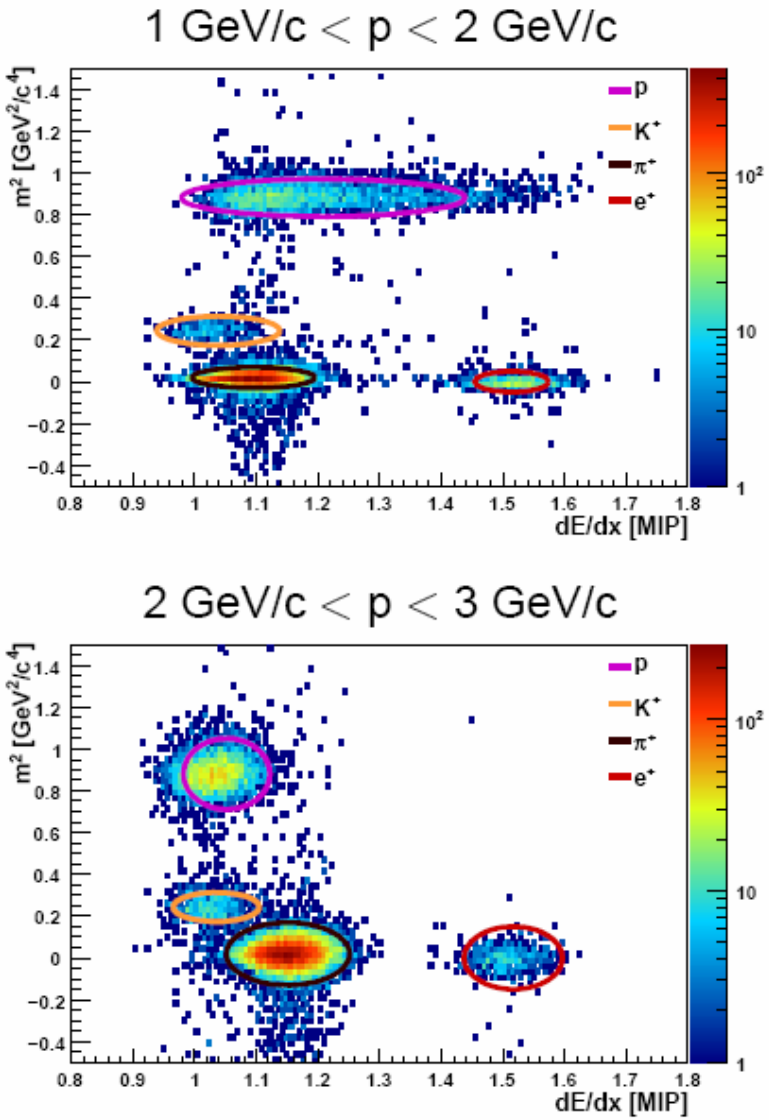
$\delta(\sin^2(2\theta_{23})) \sim 0.01$ $\delta(\Delta m^2_{23}) < 1\times10^{-4}$ ev^2 (@ 90% CL)

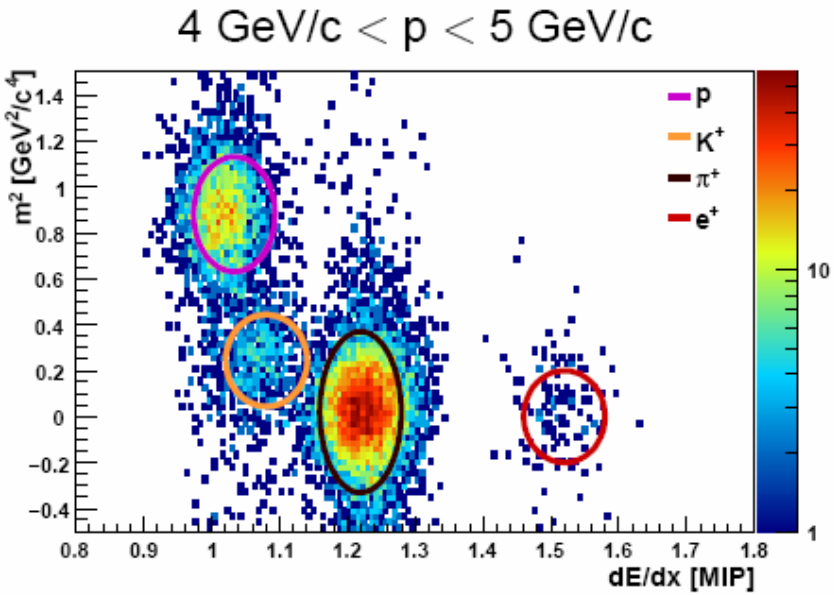
is θ_{23} maximal ?

$$P_{\mu\rightarrow x} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\ \Delta m^2_{23}\ L/E_\nu\right)$$



Particle Identification





by combining the dE/dx and the ToF information we can select high purity π / K / p samples

2-dim gaussian fits to the m^2 vs dE/dx distributions using up to 3 (m^2) + 4 (dE/dx) gaussians