NA61/SHINE : A Hadron-Production Experiment for the T2K Beam Flux Prediction

Alexis Hasler

NA61/SHINE Collaboration

December 9, 2012

The NA61/SHINE experiment

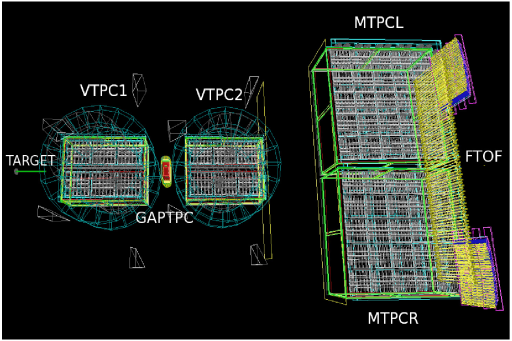
NA61/SHINE : hadron-production experiment at SPS CERN

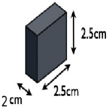
Rich physics programme covering:

- heavy ion physics
- hadron-production measurements for cosmic ray experiments
- hadron-production measurements for neutrino experiments

Large acceptance spectrometer:

- 5 TPCs
- 2 dipole magnets
- $\sigma(p)/p^2 \sim 10^{-4}(GeV/c)^{-1}$
- $\sigma(dE/dx)/ < dE/dx > \sim 0.04$
- 3 ToF
- $\sigma(FTOF) \sim 120ps$
- $\sigma(TOF\ L/R) \sim 60ps$





Two targets used for hadron-production measurements for the T2K neutrino experiment
Three data sets with different statistics:

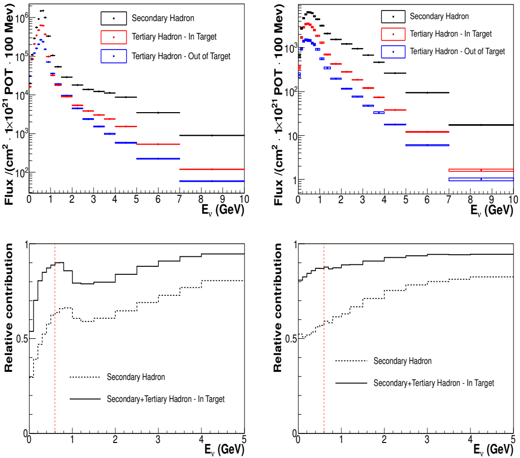
	2007	2009	2010
Thin Target	0.7 M	5.4M	-
Replica Target	0.2 M	3M	10M

Hadron-Production measurements for the T2K Neutrino Flux Prediction

Differentiate hadrons produced through 3 different processes:

- Secondary Hadrons
  directly produced from incident proton beam
  can be constrained via cross-section measurement
  account for $\sim 60\%$ of the total ν flux
- Tertiary Hadrons - In Target
  produced via re-interaction of secondary hadrons within the target
  can be constrained via "replica" target measurements
  sum of secondary and tertiary hadrons accounts for $\sim 90\%$ of the total ν flux
- Tertiary Hadrons - Out of Target
  produced via re-interaction of hadrons off the target within the target surrounding material
  most difficult to constrained, only via scaling of cross-section measurements
  account for $\sim 10\%$ of the total ν flux

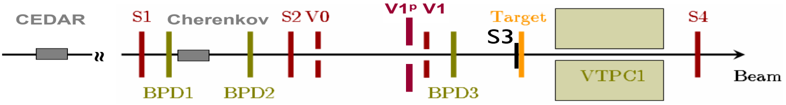
Flux compositions from Secondary and Tertiary Hadrons at far detector in T2K for ν_μ (left) and ν_e (right)



Two different hadro-production measurements are of interest:
"Thin Target" measurements → cross-section and production rate
"Replica Target" measurements → total hadron production along the target surface

The NA61 Beam Line

Schematic position of the counters:



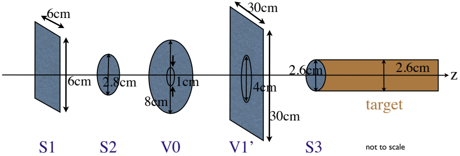
thin target

Beam	Interaction
$S1S2\bar{V}1\bar{V}0\bar{C}CED$	$S1S2\bar{V}1\bar{V}0\bar{C}CED\bar{S}4$

T2K replica target

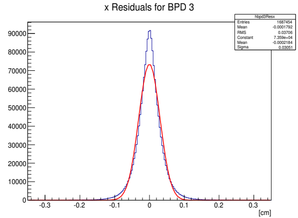
Beam	"T2" Interaction	"T3" Interaction
$S1S2\bar{V}1'\bar{C}CED$	$S1S2S3\bar{V}1'\bar{C}CED$	$S1S2S3\bar{V}0\bar{V}1'\bar{C}CED$

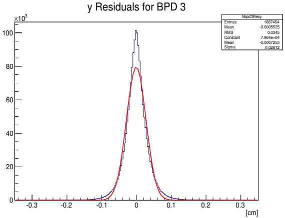
- 30.9 GeV/c secondary proton beam from the SPS
- beam composition given by CEDAR and Cherenkov detector: $\sim 83\%\pi$, $\sim 15\% protons$, $\sim 2\% K$
- different combination of counters for different triggers
- 3 Beam Position Detectors (BPD; 2D proportional chambers) allowing to reconstruct beam tracks

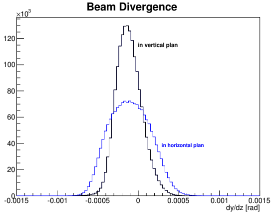


Beam Profile on Target - I

- Thin Target analysis ⇒ cross section measurements ⇒ independent from the beam profile
- T2K replica target ⇒ allow a comparison between all generated hadrons (primary and secondary) ⇒ depends on the beam profile
  ⇒ measure beam position and beam divergence:
  Residuals are computed as the difference between the fitted track and the measured point in BPD's.
  Selection criteria for beam tracks:
  - interaction trigger
  - beam track having a hit in all 6 planes of the BPD's
  - χ^2 cut on the result of the fit of the beam track





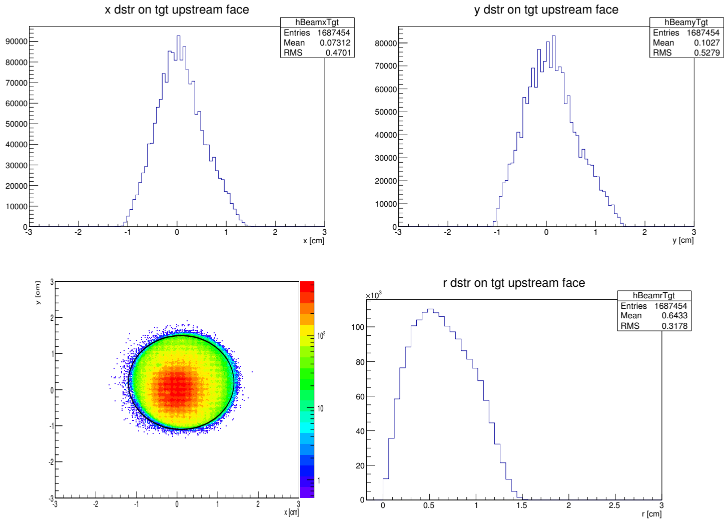


Multiple scattering for a 31 GeV/c proton on the 90cm long target: $\theta \sim \frac{14MeV}{\beta p}\sqrt{\frac{L}{X_0}} \sim 1mrad$, X_0=19.32 for graphite

Beam Profile on the target upstream face reconstructed through extrapolation of the fitted beam track
Resolution on the position of impact of the proton on the target upstream face $\sim 300\mu m$

Beam Profile on Target - II

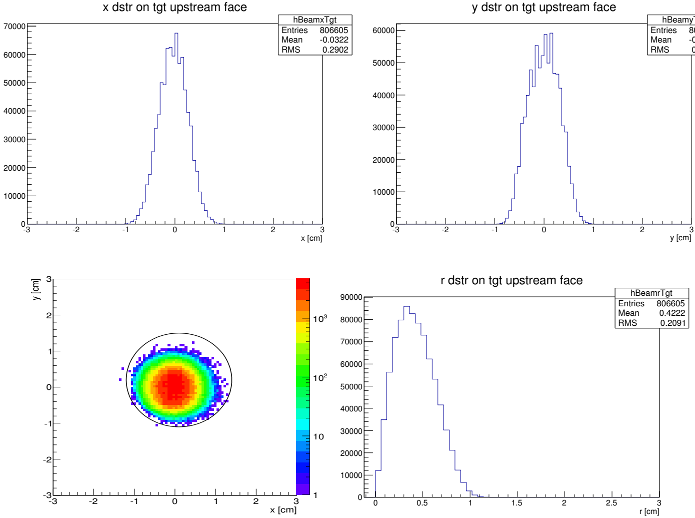
Beam profile for the T2K replica target data under the T2 trigger condition:



$\sim$ 1.5% of the protons extrapolated out of Target

Beam Profile on Target - III

Beam profile for the T2K replica target data under the T3 trigger condition:



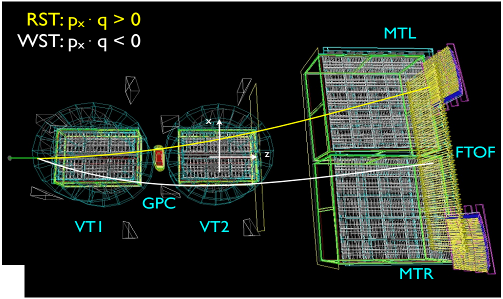
Reconstructed Tracks in the Spectrometer

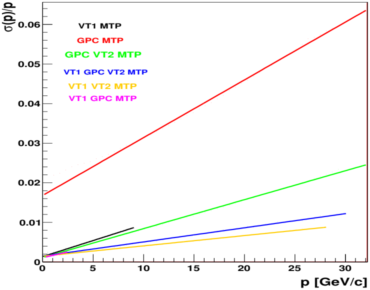
Two kind of reconstructed tracks are used:

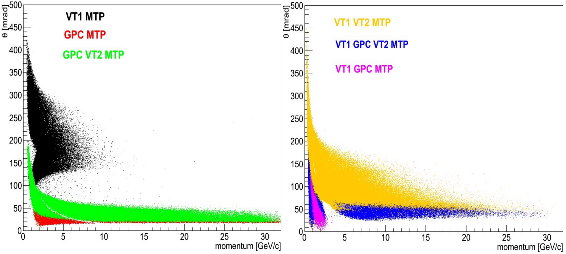
- for the thin target analysis: global tracks with main vertex constrain corresponding to the target position
- for the T2K replica target analysis: global tracks without any vertex constrain but extrapolated to the target surface

Two kind of track topologies:

- Right Side Tracks: where $p_x \cdot q > 0$
- Wrong Side Tracks: where $p_x \cdot q < 0$

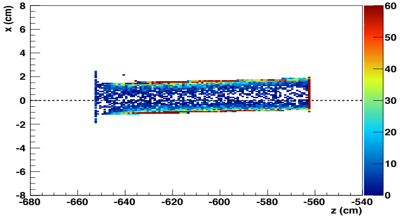


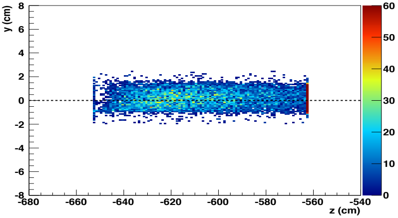




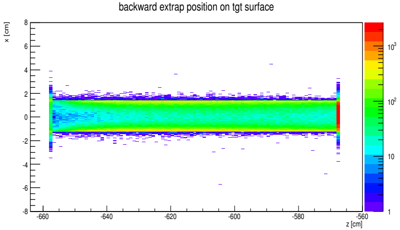
T2K Replica Target Alignment

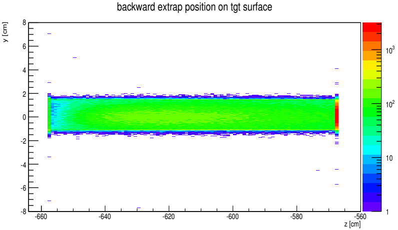
The relative position of the target with respect to the beam line is also important.
In 2007, the T2K replica target was tilted and shifted with respect to the beam





In 2009, no tilt but a small shift of 2mm in vertical plan and 1mm in the horizontal plan

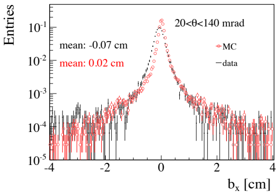


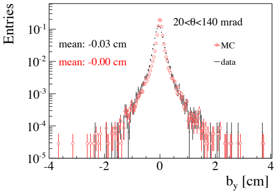


Impact Parameter and Point of Closest Approach

Thin Target

Reconstructed global tracks are further constrained by the main vertex at a fixed z position of the target

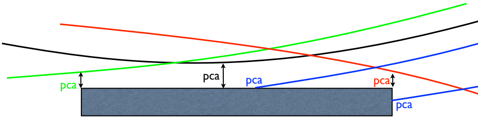


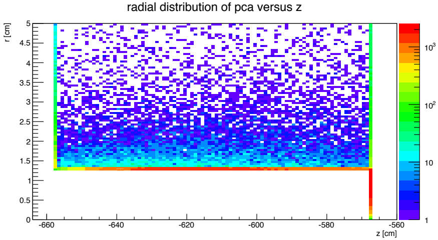


Impact parameter has to be $< 4cm$

Long Target

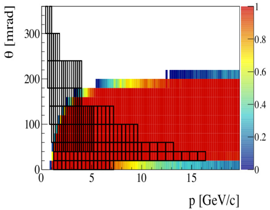
No constraint on the main vertex.
Tracks are extrapolated backwards to the target surface



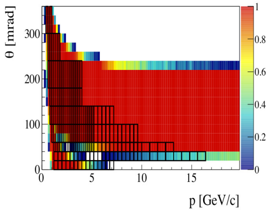


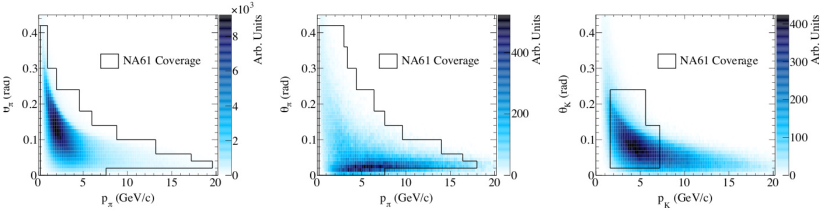
PCA within its uncertainty has to touch the target surface

Right Side Track π^+



Wrong Side Track π^+





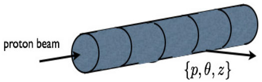
(a) π^+ (b) π^- (c) K^+

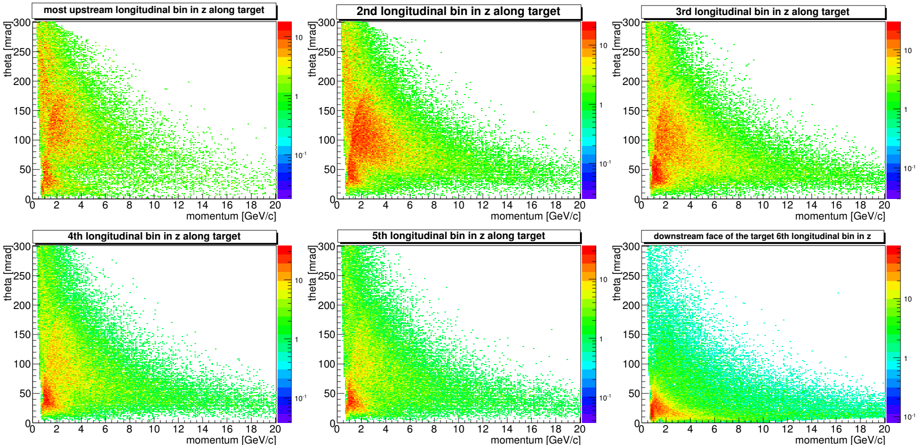
FIG. 15: The phase space of pions and kaons contributing to the predicted neutrino flux at SK, and the regions covered by NA61/SHINE measurements.

From: The T2K neutrino Flux Prediction (arXiv:1211.0469)

(p, θ, z) Phase-Space for the T2K Replica Target Data

90cm long target $\Rightarrow$ cannot be considered to be a point-like source
Divide the target into 6 longitudinal bins:
5 along the target surface + 6th bin for the downstream face



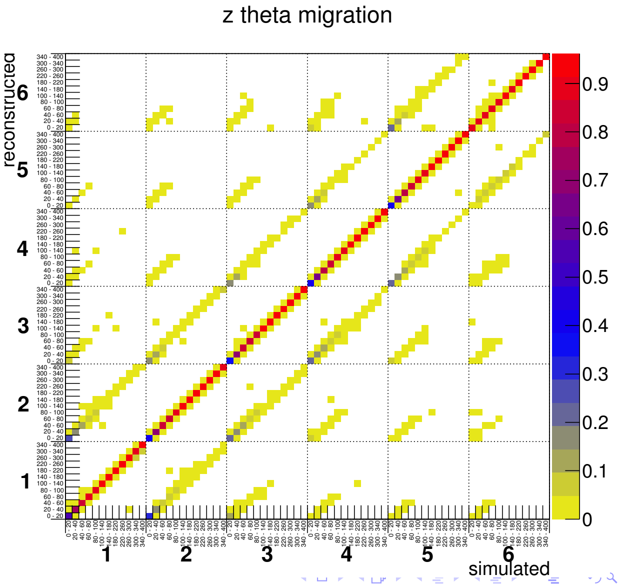


z Binning and Longitudinal Bin Migration

The migration is shown between simulated and reconstructed (θ, z) bins

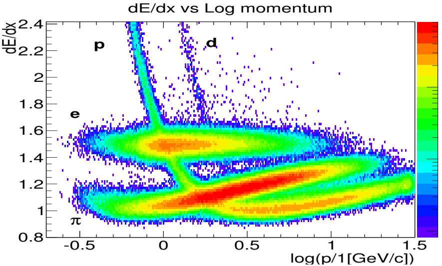
- longitudinal (z) bins 1 - 6
- subdivision of eight θ bins 0 - 400 mrad

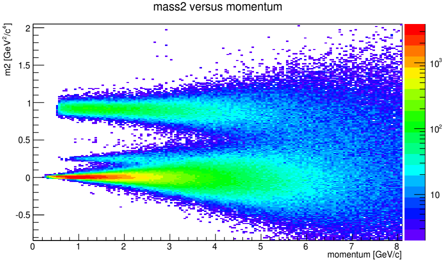
Histogram normalized to simulated tracks
Large bin migration only for small polar angle ranges.
Below $10 - 15\%$ for larger angles.



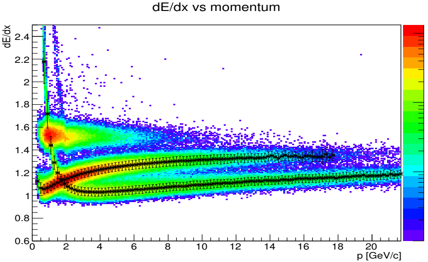
PID Capabilities

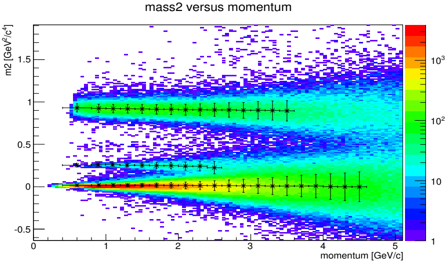
Usual m2 and dE/dx distribution as function of the momentum:



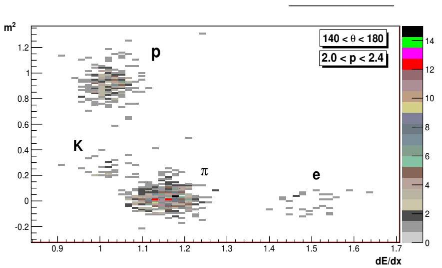


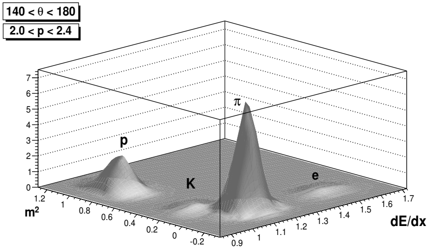
Parametrization of the above distribution allow to get the following curves (later used for the initialization of the 2D pid fits):

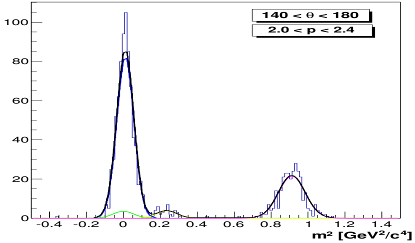


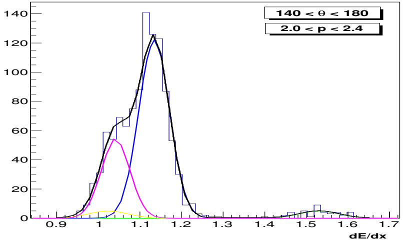


Combined TOF-dE/dx Analysis



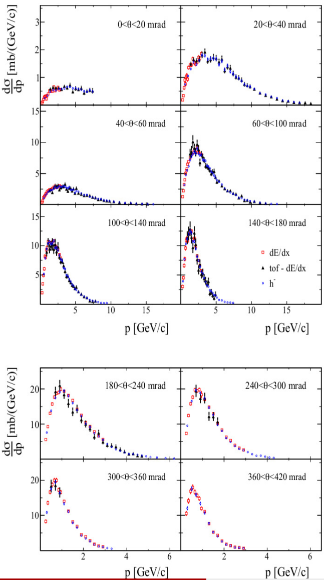






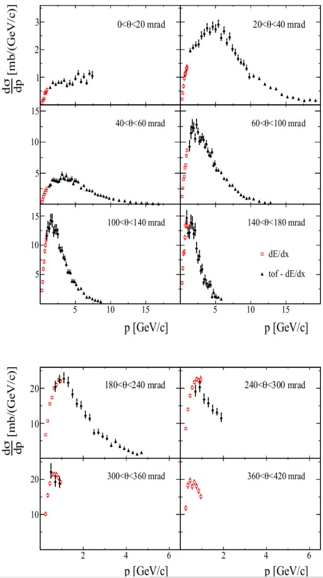
2007 Thin Target Results: pions

π^- differential cross-section



Differential cross-section for π^-. The three different analysis techniques are labelled. dE/dx is used at low momenta, combined TOF-dE/dx at middle and large momenta. h^- over the full momentum range

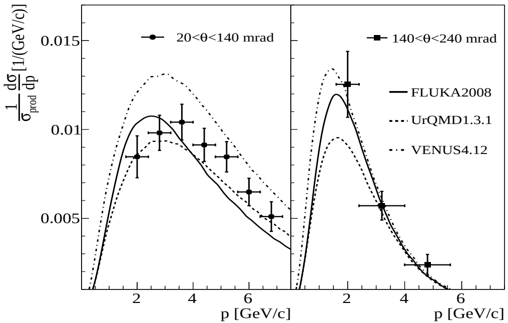
π^+ differential cross-section



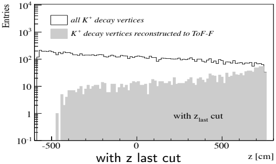
Differential cross-section for π^+. The two different analysis techniques are labelled. dE/dx is used at low momenta, combined TOF-dE/dx at middle and large momenta. The two analysis techniques overlap at low momenta and show very good agreement.

2007 Thin Target Results: Kaons

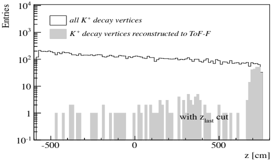
Low statistics in 2007 data set $\Rightarrow$ large binning.
Two bin in polar angles: $20 < \theta < 140$; $140 < \theta < 240$
One important difference with the pion analysis: consider a "z last" cut in order to reduce systematic uncertainty due to K decay



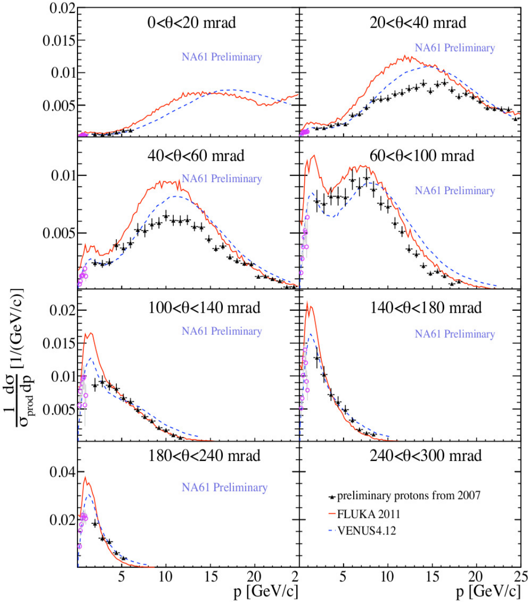
without z last cut



with z last cut



2007 Thin Target Results: Preliminary Proton Results



Uncertainties on Results for Thin Target Data

Example of typical systematic uncertainties for two different polar angle intervals for pions and kaons

π

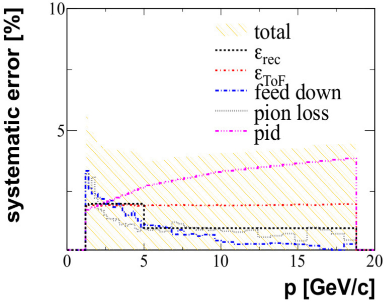


Figure: contributions to systematic errors for **pions** in the angular interval [40,60] mrad

K

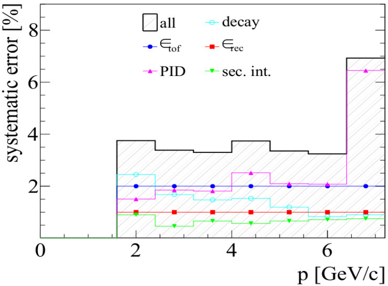


Figure: contributions to systematic errors for **kaons** in the angular interval [140,180] mrad

Published papers:

Measurement of Production Properties of Positively Charged Kaons in Proton-Carbon Interactions at 31 GeV/c, Phys.Rev. C85 (2012)
Measurements of Cross Sections and Charged Pion Spectra in Proton-Carbon Interactions at 31 GeV/c. Phys.Rev. C84 (2011)

Two re-weighting schemes are applied:

- differential production of $\pi^{\pm}$, $K^{\pm}$ and K_L^0 in the interactions of protons on the target material

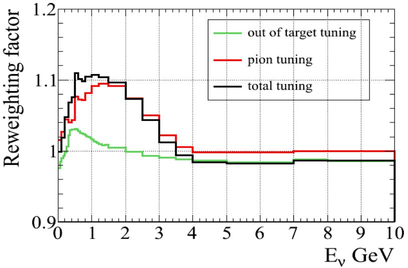
$$\frac{dn}{dpd\theta}(p_{in}, A) = \frac{1}{\sigma_{prod}(p_{in}, A)} \frac{d\sigma(p_{in}, A)}{dpd\theta} \Rightarrow W(p_{in}, A) = \frac{\left[\frac{dn}{dpd\theta}(p_{in}, A)\right]_{data}}{\left[\frac{dn}{dpd\theta}(p_{in}, A)\right]_{MC}}$$

- interaction rates for $\pi^{\pm}$ and $K^{\pm}$
  Probability of interaction after path x in Δx:

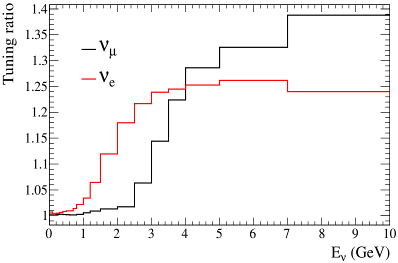
$$P(x; \sigma_{prod}) = \int_x^{x+\Delta x} \sigma_{prod}\rho e^{-x'\sigma_{prod}\rho} dx' = \Delta x \sigma_{prod}\rho e^{-x\sigma_{prod}\rho}$$

$$\sigma_{prod}^{MC} \neq \sigma_{prod}^{data} \Rightarrow \text{the weights } W = \frac{P(x; \sigma_{prod}^{MC})}{P(x; \sigma_{prod}^{data})} = \frac{\sigma_{prod}^{MC}}{\sigma_{prod}^{data}} e^{-x(\sigma_{prod}^{MC} - \sigma_{prod}^{data})\rho}$$

Pion tuning effect for SK ν_μ flux



Kaon tuning effect for SK ν flux



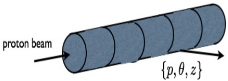
See : The T2K neutrino Flux Prediction (arXiv:1211.0469)

NA61 Results for T2K Replica Target

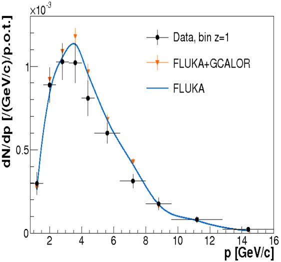
First test of flux re-weighting with the 2007 replica target data within the T2K beam simulation: compute ratio of produced particles (e.g. π) for data and Monte-Carlo simulation

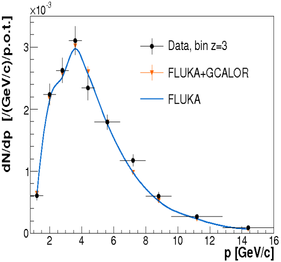
- use the same PID procedure
- normalize to number of protons on target (p.o.t)

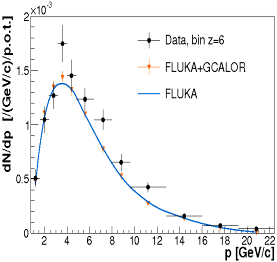
$$\omega_\pi^{NA61}(p,\theta,z) = \frac{N_{\pi\, data}^{NA61}(p,\theta,z)}{N_{\pi\, MC}^{NA61}(p,\theta,z)} \cdot \frac{p.o.t_{data}}{p.o.t_{MC}}$$



And use these weights to tune the T2K simulation: $N_{\pi\, MC\ tuned}^{T2K} = N_{\pi\, MC}^{T2K} \times \omega_\pi^{NA61}$

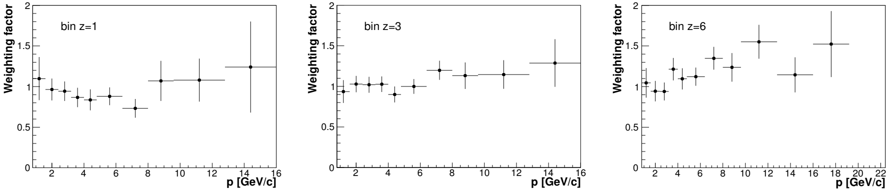






NA61 Results for T2K Replica Target

Computing the ratios $\omega_{\pi}^{NA61}(p, \theta, z) = N_{\pi\, data}^{NA61} / N_{\pi\, MC}^{NA61}$



Propagating these results in the T2K beam simulation:

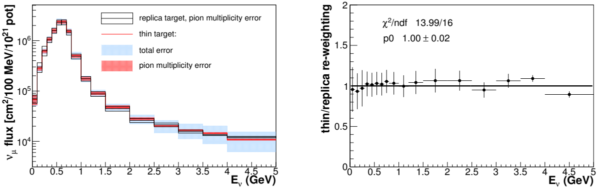


Figure: For the replica-target re-weighted prediction, errors are shown and correspond to a fully correlated 1-sigma shift of the pion re-weighting factors only

Published paper: "Pion emission from the T2K replica target: method, results and application" Nuclear Inst. and Methods in Physics Research, A (2013) pp. 99-114 (available online)

Status of 2009 data analysis for T2K

Thin Target

- statistics increased by one order of magnitude with respect to 2007 published results
- GPC was included in the analysis $\Rightarrow$ lower polar angles are covered
- larger forward time of flight wall $\Rightarrow$ higher acceptance at large polar angles
- high enough statistics to extract simultaneously all six particles species ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$)
- preliminary results expected for the beginning of 2013

T2K Replica Target

- statistics increased by one order of magnitude with respect to 2007 published results
- better target alignment compared to 2007
- new analysis approach with corrected particles' spectra normalized to the number of protons on target
- preliminary $\pi^{\pm}$ spectra expected for the beginning of 2013
- 2010 data are being calibrated; two different magnetic field configurations were used; the highest configuration will allow us to cover the very forward region ($0 < \theta < 20$) with high statistics

Conclusions

- NA61/SHINE has demonstrated its ability to improve the T2K Neutrino Flux predictions through hadron-production measurements
- the T2K experiment is already extensively using the NA61/SHINE data
- the T2K neutrino flux prediction will be further improved with the NA61/SHINE 2009 and 2010 data sets
- US institutions have joined NA61 this year and have taken a first data set this summer (pC@120GeV/c); further data taking is planned in order to get hadron-production measurements for the NuMI neutrino beam at Fermilab
- The LAGUNA-LBNO Letter Of Intent considers using the NA61/SHINE set-up for its neutrino flux predictions
- NA61 published three papers covering hadron-production measurements for T2K; T2K published one detailed paper in which the extensive use and importance of NA61 measurements for a precise neutrino flux prediction are stressed and used NA61/SHINE data for neutrino oscillation analyses/publications:
    - Measurement of Production Properties of Positively Charged Kaons in Proton-Carbon Interactions at 31 GeV/c, Phys.Rev. C85 (2012)
    - Measurements of Cross Sections and Charged Pion Spectra in Proton-Carbon Interactions at 31 GeV/c, Phys.Rev. C84 (2011)
    - Pion emission from the T2K replica target: method, results and application, Nuclear Inst. and Methods in Physics Research, A (2013) pp. 99-114 (available online)
    - The T2K neutrino Flux Prediction (arXiv:1211.0469)