Hadron Production Measurements with the T2K Replica Target in NA61/SHINE for the T2K Neutrino Flux Prediction

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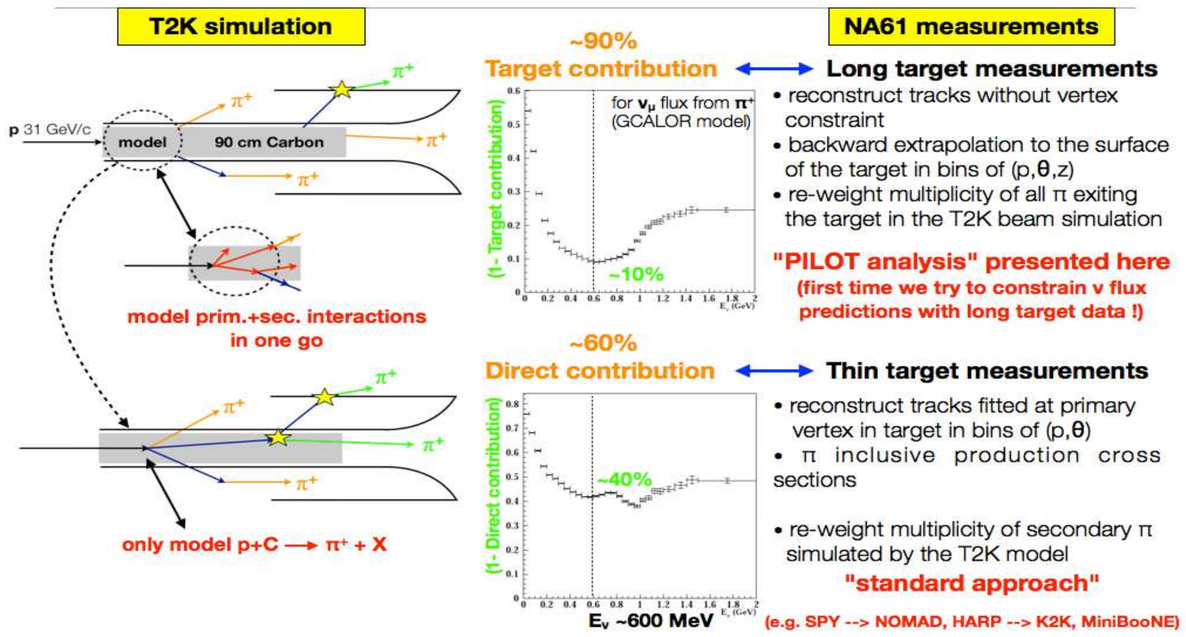
Neutrino 2014; Boston 2 - 7 June 2014

Motivation for the T2K Replica Target Analysis

In the T2K long baseline neutrino oscillation experiment [1], a high intensity neutrino beam is created by a 30 GeV proton beam impinging on the 90 cm long T2K graphite target. The neutrino flux can be decomposed in 2 categories:

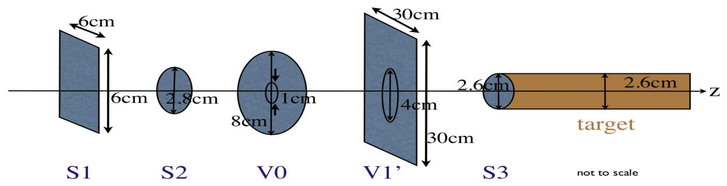
- the secondary component relates to neutrinos coming from decays of pions produced in primary interactions of the protons in the target $p + C \rightarrow \pi^+ + X$; represents $\sim 60\%$ of pions produced in the 90 cm long T2K target; this component can be contained by measurements of pion and kaon cross-sections with a thin graphite target [2, 3].
- the tertiary component relates to neutrinos coming from decays of hadrons produced in interactions of secondary particles either in the target or out of the target (elements in the beam line). This component represent $\sim 40\%$ of the neutrino flux and can only be constrained through measurements of hadron production with a replica of the T2K target.

Three set of measurements with a replica of the T2K target have been taken in NA61/SHINE. 0.2 M triggers for the 2007 period, 4M trigger for the 2009 period and 10M triggers for the 2010 period.

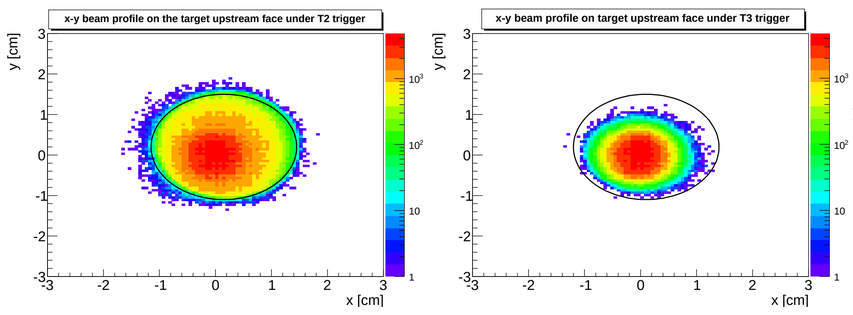


NA61/SHINE Set Up

The NA61/SHINE experiment at CERN is a fixed target experiment based on large acceptance spectrometer [4]. Upstream of the target, the beam line contains 3 Beam Position Detectors (BPD's) and a set of counters. The BPD's allow to reconstruct the proton beam trajectories. Different sets of counters define different triggers for the data taking. For the 2009 data taking period, two triggers (namely T2 and T3) were based on a scintillation counter (S3) glued on the upstream face of the target in order to assure that selected beam protons hit the target. Definition of the triggers and distributions of the beam under the two different triggers T2 and T3 are given bellow.



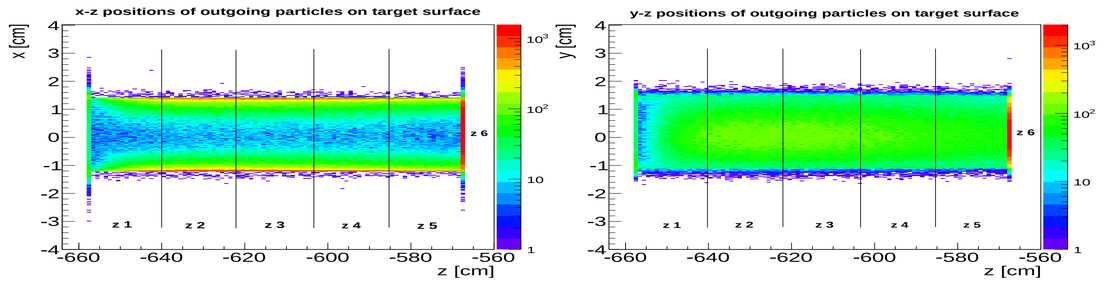
2009 Triggers :	counters in trigger
T2	S1 S2 S3 $\bar{V1'}$
T3	S1 S2 S3 $\bar{V1'}$ $\bar{V0}$



Beam profile on the target upstream face under T2 and T3 triggers for the 2009 data set period. The black circle shows the position of the target upstream face. The resolution of the position of the beam protons given by the BPD is $\sim 300\mu m$ in both x and y directions.

Downstream of the target the NA61 spectrometer consists of five large Time Projection Chambers (TPC's), two of them being embedded in superconducting dipole magnets, and a Time Of Flight (TOF) detector. For each particle going trough the TPC's and hitting the TOF detector, a track can be reconstructed with associated energy loss and mass squared information.

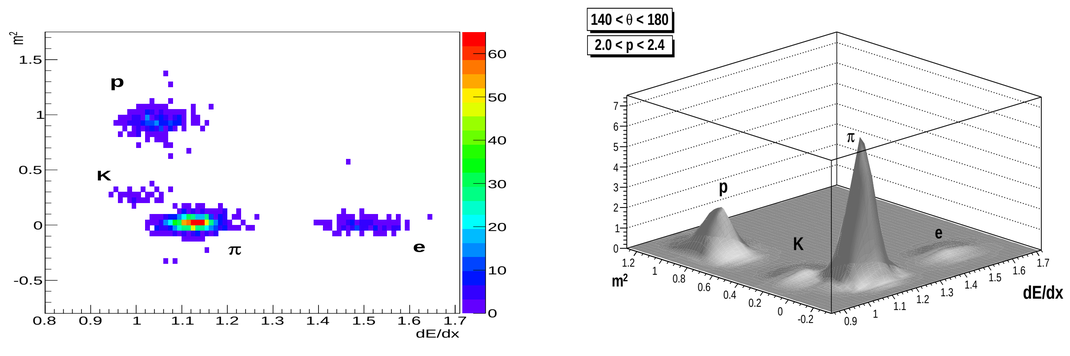
A backward extrapolation of the tracks through the magnetic field up to the target surface allow to reconstruct the position of the outgoing particles created by the interaction of the beam in the target. Bellow, 2D distributions in the x-z plan and y-z plan of outgoing particles off the target are shown.



A new target support system for the 2009 and 2010 data set periods allowed to get a precise alignment of the target in the beam as shown here for the 2009 data. A total of 6 longitudinal bins are considered for the analysis: 5 bins of 18 cm each along the target surface plus the target downstream face as the 6th bin.

NA61/SHINE PID Capabilities for the 2009 Data Set

The Particle Identification in NA61/SHINE is done through a combined TOF-dE/dx analysis [3]. A precise knowledge of the m^2 and dE/dx distributions and parametrizations is important to initialize 2d-likelihood fits used to extract particle yields in the $(m^2,\ dE/dx)$ plan.



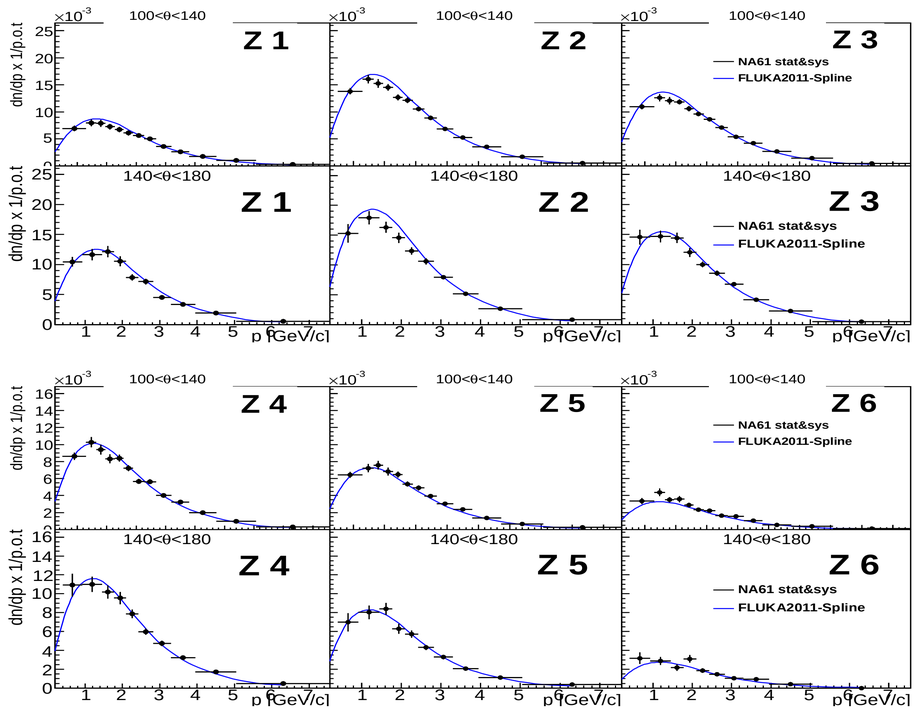
Analysis binning in (p, θ, z)

Detailed studies of the T2K beam line have shown that the neutrino energy spectrum is sensitive to exit position of neutrino parent particles on the target surface. The analysis of the replica target is divided in 6 longitudinal bins: 5 bins of 18 cm each along the target surface and the downstream face of the target considered as the 6th bin (forward production of particles).

The analysis binning in the (p, θ) phase space (polar angle and momentum of exiting particles off the target) is chosen so that most of the phase space of interest for T2K can be covered after all the track quality cuts needed for the combined TOF-dE/dx analysis. A first pilot analysis was performed on the 2007 data set [5] using the (p, θ, z) binning. Raw pion spectra were extracted but no corrections were computed. The results of the 2007 pilot analysis were given as ratio of uncorrected pion spectra over reconstructed Monte-Carlo simulation. For the 2009 analysis, Monte-Carlo based correction factors have been computed and allow to present corrected pion spectra in (p, θ, z) bins at the surface of the target.

Preliminary Results for the 2009 Data Set

Raw number of pions are extracted from the two dimensional (m^2 - dE/dx) fits in each (p, θ, z) bin. Monte-Carlo based corrections account for geometrical acceptance, particles decaying in flight, interaction within the detector materials, ... The final corrected π^+ spectra are given in (θ, z) bins as a function of particle momentum. The total uncertainties are calculated as the sum in quadrature of the statistical and systematic uncertainties. They are normalized to momentum bin size and number of incident protons on target. The simulation using FLUKA 2011 is overlaid on top of the data for comparisons.

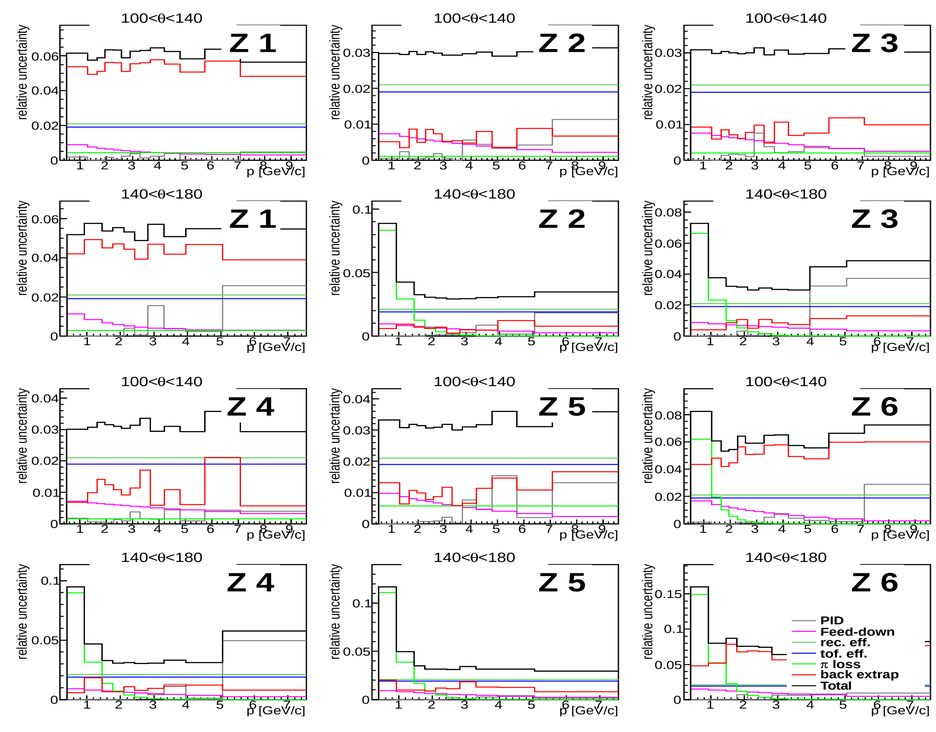


Systematic uncertainties

Six different sources of systematic uncertainties are estimated:

1. PID: dE/dx distrubutions are not exactly gaussians; consider fit functions using a single gaussians or the sum of two gaussians to describe the dE/dx distributions
2. Feed down: particles exiting the target and decaying into a π before entering the TPC's might be wrongly identified as π exiting the target surface
3. Reconstruction efficiency: capability of the reconstruction algorithm to identify TPC clusters and match segments of tracks between the difference TPCs
4. TOF efficiency: capability to match a recontructed tracks from the TPCs to a hit in the TOF wall and compute a proper value for m^2
5. π loss: pion decaying in flight before reaching the TOF wall
6. Backward extrapolation: capability to extrapolate backward the reconstucted tracks from the measured points in the TPC to the target surface with high accuray on the position and polar angle of the exiting particle

As expected, component of the systematics coming from the backward extrapolation dominates for the first z bin (most upstream part of the target) while the feed-down components and π loss are getting large at low momenta. The total systematic uncertainty for this analysis varies between 4 and 14% (here shown for π^+), depending of the region of the phase space.



References

[1] T2K Collaboration K. Abe et al. The T2K experiment. *NIM A*, 659(1):106 – 135, 2011.

[2] N. Abgrall et al. (NA61/SHINE collabration). Measurement of production properties of positively charged kaons in proton-carbon interactions at 31 GeV/c. *Phys. Rev. C*, 85:035210, Mar 2012.

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[4] N. Abgrall et al. NA61/SHINE facility at the CERN SPS: beams and detector system. 2014.

[5] N. Abgrall et al. Pion emission from the T2K replica target: method, results and application. *Nuclear Instruments and Methods in Physics Research*, A:99–114, 2013.