T2K replica target measurements in NA61/SHINE and T2K neutrino flux predictions

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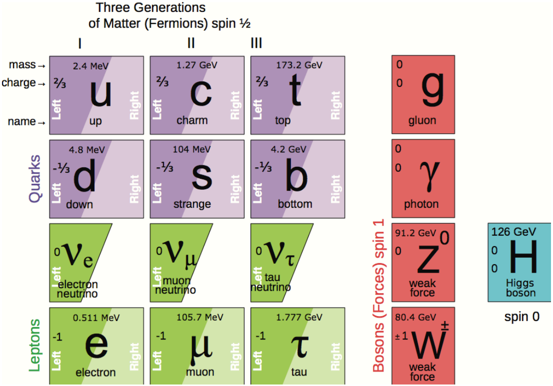
The Standard Model

- With the discovery of the Higgs Boson, all particles of the Standard Model have been found.
- Is the standard model complete and correct?
- In the SM neutrinos are massless !
- In the SM only left handed neutrinos (and right handed anti-neutrinos) !
- No unique way to give mass to neutrinos.

$\Rightarrow$ Very probably new degrees of freedom



Neutrino Physics

Observed phenomenon that cannot be explained by the present Standard Model:

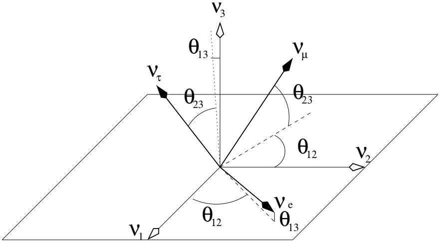
- neutrino oscillations: observed in solar, reactor, atmospheric and accelerator neutrino experiments
- oscillation probability (in a first approximation) is given by:

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta) \sin^2 \left(\frac{(m_2^2 - m_1^2)L}{4E} \right)$$

$\Rightarrow$ neutrinos have non-zero masses

$\Rightarrow$ neutrinos mix and all neutrino experiments can be explained (with some tensions) in the PMNS framework that relates weak states to mass states:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{+i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{pmatrix}$$

Extension of the Standard Model is mandatory for our understanding of the neutrino physics

Extension of the Standard Model

Which extension of the Standard Model can generate neutrino masses ?
What are the values of the mixing parameters in the PMNS matrix?

Answering these questions might shed light on fundamental features of the universe

- Baryon asymmetry of the universe:
  leptongenesis based on Majorana neutrinos is one potential model to explain the matter-antimatter asymmetry of the present universe.
- Dark matter:
  right handed neutrinos could be interesting candidates.
  what are their masses ?

Neutrino Masses

Standard Model	Dirac mass term only	Majorana mass term only	Dirac+Majorana mass terms
no mass ν_L $\overline{\nu_R}$ $I_w = \frac{1}{2}$ $\frac{1}{2}$	m_3 m_2 m_1 ν_L ν_R $\overline{\nu_R}$ $\overline{\nu_L}$ $I_w = \frac{1}{2}$ 0 $\frac{1}{2}$ 0	m_3 m_2 m_1 ν_L $\overline{\nu_R}$ $I_w = \frac{1}{2}$ $\frac{1}{2}$	M_3 M_2 M_1 m_3 m_2 m_1 ν_L N_R $\overline{\nu_R}$ $\overline{N_L}$ $I_w = \frac{1}{2}$ 0 $\frac{1}{2}$ 0
• 6 massless states	• 3 masses • 12 states • 3 active ν • 3 active $\overline{\nu}$ • 6 sterile ν • 3 mixing angles • 1 CP violating phase • $0\nu\beta\beta = 0$	• 3 masses • 6 active states • No sterile ν • 3 mixing angles • 3 CP violating phases • $0\nu\beta\beta \neq 0$	• 6 masses • 12 states • 6 active states • 6 sterile ν • More mixing angles and CP phases • $0\nu\beta\beta \neq 0$ • See-Saw mechanism $\Rightarrow$ Baryon asymmetry of the universe and dark matter candidates

Dirac+Majorana mass terms seems to be the preferred and most convincing scenario

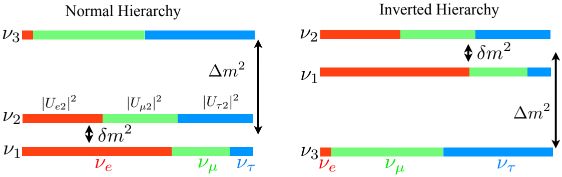
Neutrino Physics

Current knowledge:

- 3 neutrino flavors have been observed (ν_e, ν_μ, ν_τ)
- All mixing angles have been measured (with different accuracies) ($\theta_{23} \simeq 45^\circ, \theta_{13} \simeq 9^\circ, \theta_{12} \simeq 34^\circ$)
- Two mass splittings are known ($\Delta m^2_{23} \simeq 2.4 \times 10^{-3} eV^2, \Delta m^2_{12} \simeq 8 \times 10^{-5} eV^2$)

Open questions:

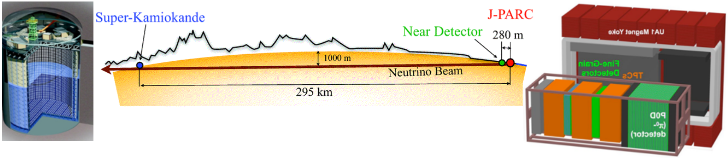
- Nature of the neutrino masses (Dirac or/and Majorana)?
- Do neutrino transformation violate CP ?
- Absolute mass scale of neutrinos?
- Mass hierarchy ?
- More than 3 mass eigenstates (Are there non-weakly-interacting "sterile" neutrinos)?



The T2K experiment addresses some of these questions through its physics goals:

- study electron neutrino appearance in a muon neutrino beam ($\nu_\mu \rightarrow \nu_e$) $\Rightarrow$ measure θ_{13} and explore CP violating phase δ_{CP}
- precise measurements of muon neutrino disappearance $\Rightarrow$ precise determination of θ_{23} and Δm^2_{23}
- a search for sterile components in muon neutrino disappearance by observation of neutral-current events
- world-leading contributions to neutrino-nucleus cross-section measurements

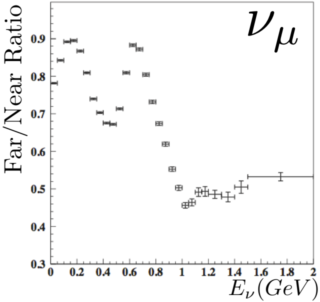
The T2K Experiment



- Neutrino beam created at J-PARC crosses a Near Detector (ND280) and the Super-Kamiokande (SK) far detector
- Extrapolate and compare the information from the Near Detector (ND280) before oscillation to the far detector (SK) to study appearance and disappearance probabilities

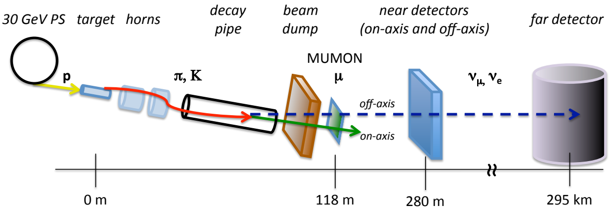
- ND280: composite complex detector
  SK: water cherenkov detector
- ND280 sees a line source of neutrinos
  SK sees a (almost) point source
- Extrapolation from near to far detector does not follow a simple $1/L^2$ behavior
- Far to Near Flux ratio depends on the Neutrino Energy

$\Rightarrow$ **Precise understanding of Neutrino Source mandatory**

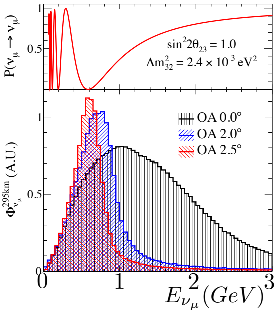


Abgrall,CERN-THESIS-2011-165

The T2K Beam Line

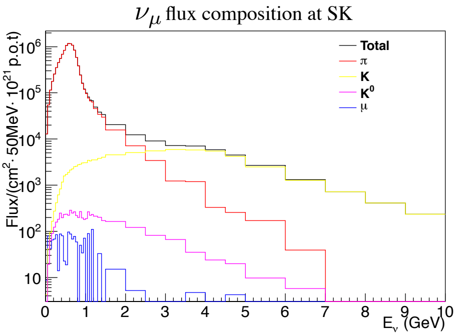


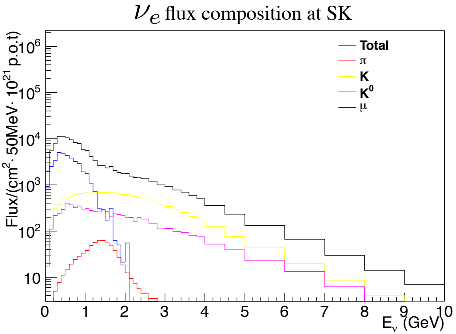
- 2.5° off-axis neutrino beam
- Low energy narrow band beam
- Energy peak around oscillation maximum ($\sim$ 0.65 GeV)
- Neutrino Source created by interactions of 30 GeV protons on a 90cm long fixed graphite target
- Neutrino beam predictions rely on modeling the proton interactions and hadron production in the target
- Precise hadron production measurements allow to reduce uncertainties on neutrino flux prediction

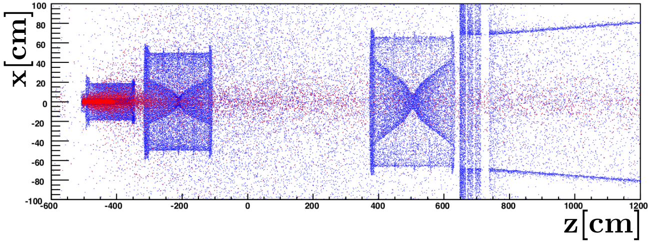


(T2K) K.Abe et al., Phys.Rev.D87 (2013)012001

Neutrino Source Composition







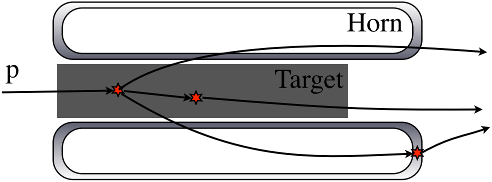
Production point of neutrino parent particles
red: parents produced in the target or along decay chains
Abgrall,CERN-THESIS-2011-165

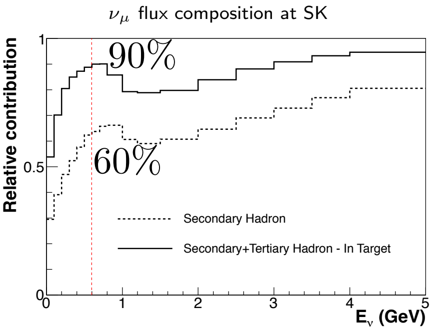
- π at low energies
- K at higher energies
- K and μ: sources for ν_e background

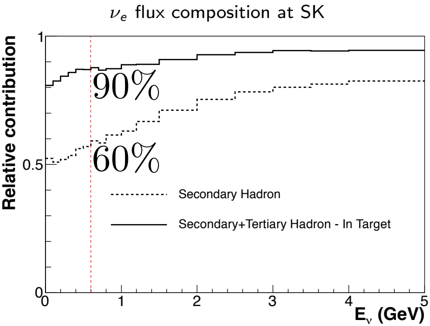
Neutrino Source Production

Different production schemes:

- direct contribution:
  secondary hadrons exit the target and decay into ν
- target contribution:
  secondary and tertiary hadrons exiting the target and decaying into ν
- non-target contribution:
  re-interaction in the target surrounding material







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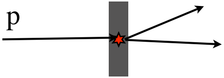
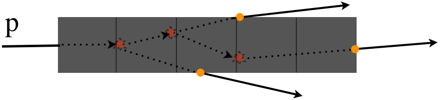
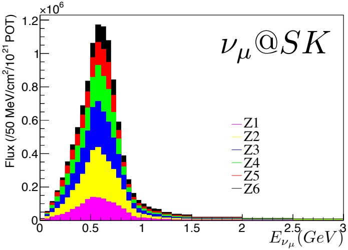
Relevant Hadron Production Measurements

- p+C cross-sections at the interaction:
  - different particle species can be extracted and used to constrain the neutrino flux prediction
  - allow to constrain up to 60% of the ν_μ (ν_e) flux at beam pick energy
- Hadron production at the surface of the T2K target:
  - different particle species can be extracted and used to constrain the neutrino flux prediction
  - measurements of all charged hadrons exiting the target allow to constrain up to 90% of the ν_μ (ν_e) flux
  - the longitudinal distribution of the particles exiting the target surface is important for the neutrino flux predictions







The NA61/SHINE experiment at the CERN SPS is able to deliver such high quality measurements.

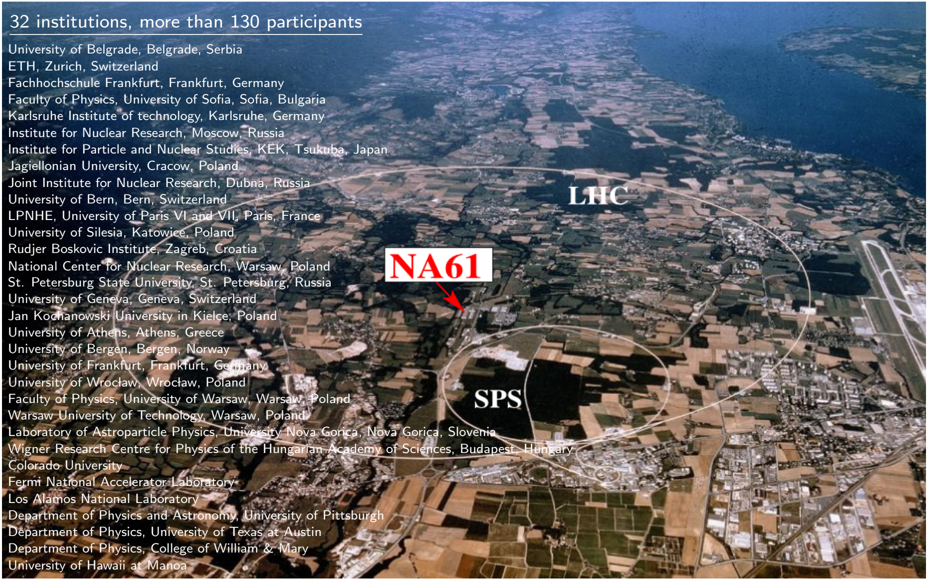
Work of this thesis:

extract hadron production measurements in NA61/SHINE at the surface of a T2K replica target and implement these measurements in the T2K neutrino beam simulation to constrain the T2K neutrino flux predictions

The NA61/SHINE fixed target experiment at SPS CERN

32 institutions, more than 130 participants

University of Belgrade, Belgrade, Serbia
ETH, Zurich, Switzerland
Fachhochschule Frankfurt, Frankfurt, Germany
Faculty of Physics, University of Sofia, Sofia, Bulgaria
Karlsruhe Institute of technology, Karlsruhe, Germany
Institute for Nuclear Research, Moscow, Russia
Institute for Particle and Nuclear Studies, KEK, Tsukuba, Japan
Jagiellonian University, Cracow, Poland
Joint Institute for Nuclear Research, Dubna, Russia
University of Bern, Bern, Switzerland
LPNHE, University of Paris VI and VII, Paris, France
University of Silesia, Katowice, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
National Center for Nuclear Research, Warsaw, Poland
St. Petersburg State University, St. Petersburg, Russia
University of Geneva, Geneva, Switzerland
Jan Kochanowski University in Kielce, Poland
University of Athens, Athens, Greece
University of Bergen, Bergen, Norway
University of Frankfurt, Frankfurt, Germany
University of Wrocław, Wrocław, Poland
Faculty of Physics, University of Warsaw, Warsaw, Poland
Warsaw University of Technology, Warsaw, Poland
Laboratory of Astroparticle Physics, University Nova Gorica, Nova Gorica, Slovenia
Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Budapest, Hungary
Colorado University
Fermi National Accelerator Laboratory
Los Alamos National Laboratory
Department of Physics and Astronomy, University of Pittsburgh
Department of Physics, University of Texas at Austin
Department of Physics, College of William & Mary
University of Hawaii at Manoa



The NA61/SHINE experiment

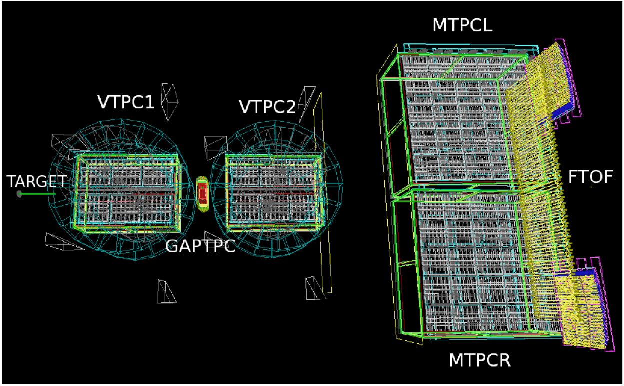
NA61/SHINE : SPS Heavy Ion and Neutrino Experiment

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
- $\sigma(FTOF) \sim 120ps$
- $\sigma(TOF\ L/R) \sim 60ps$

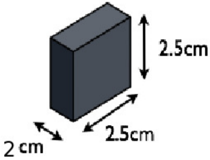


Let's look at:

- Targets and Beamline
- TPC's
- FTOF
- Combined TOF-dE/dx analysis

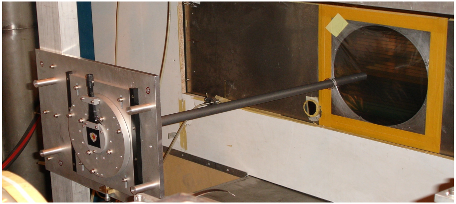
Targets and Datasets

Thin Carbon Target (2cm$\equiv$ 4%λ_I)



- length: 2cm; x-section: $2.5 \times 2.5cm^2$
- $\rho = 1.84g/cm^3$
- $0.04\lambda_I$

T2K Replica Target (90cm$\equiv$ 1.9λ_I)



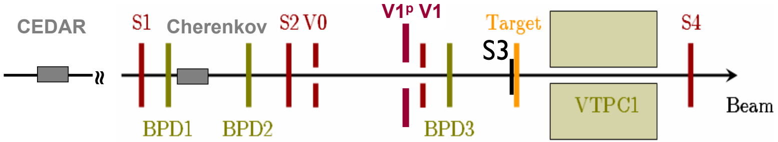
- length: 90cm; diameter: 2.6cm
- $\rho = 1.83g/cm^3$ (1.804 for the T2K target)
- $1.9\lambda_I$

Data taken for the Neutrino Physics Program:

Beam	(GeV/c)	graphite target	year	Nx10^6
p	31	2cm	2007	0.7
p	31	2cm	2009	5.4
p	31	90cm "T2K replica"	2007	0.2
p	**31**	**90cm "T2K replica"**	**2009**	**4**
p	31	90cm "T2K replica"	2010	10

The NA61/SHINE Beam Detectors and Trigger System

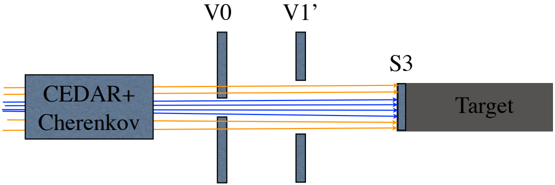
Schematic position of the counters:



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

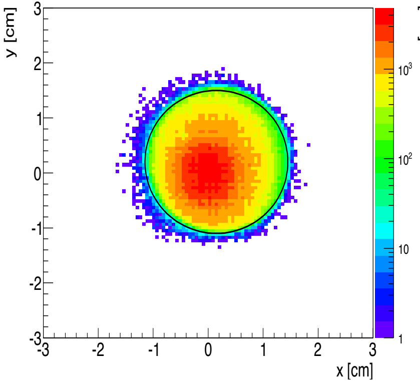
Triggers:

- thin target: include S4 ⇒ interaction trigger
- T2K replica target:
  T2 trigger ⇒ large beam profile covering entire target surface
  T3 trigger ⇒ narrow beam profile

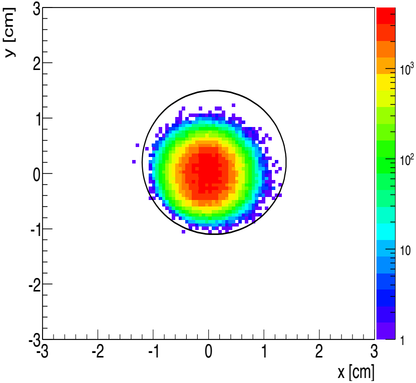


Beam Profile on Target upstream face

T2 trigger



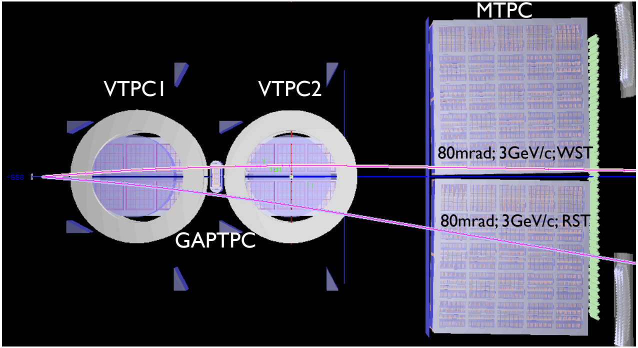
T3 trigger

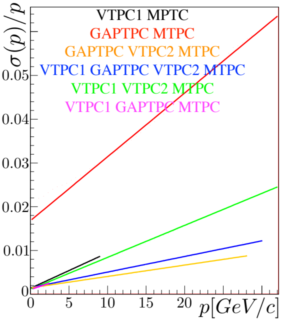


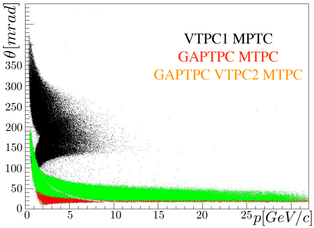
- Beam Profile on the target upstream face reconstructed through extrapolation of the fitted beam track from the BPDs
- Resolution on the position of impact of the proton on the target upstream face $\sim 300\mu m$

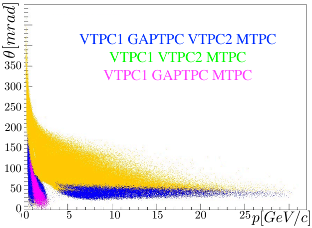
Reconstructed Tracks in the TPC's

- 2 categories of tracks with different acceptance:
  - **Right Side Tracks (RST)**: $p_x \cdot q > 0$
  - **Wrong Side Tracks (WST)**: $p_x \cdot q < 0$
- Very forward going particles cannot be reconstructed $\Rightarrow$ hole in the acceptance
- Large angle tracks (>340mrad) not considered; hit in TOF requested for the analysis









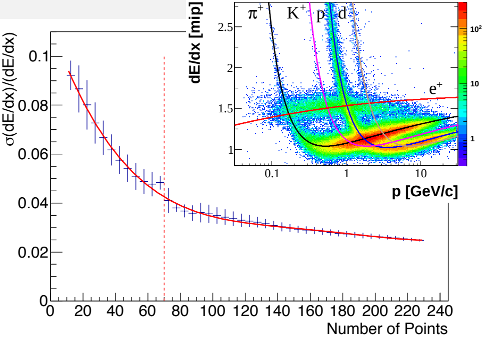
Energy Loss in the TPCs

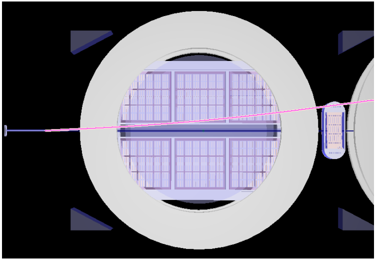
Number of pad rows in TPC's:

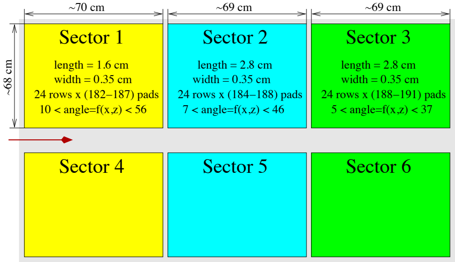
- VTPCs : 3x24 = 72
- GAP TPC: 7
- MTPCs : 18x5 = 90

Reconstructed points:

- more than one pad (row) can be hit
  ⇒ reconstruct points
- apply cuts on the number of points in TPC's to get high resolution on dE/dx





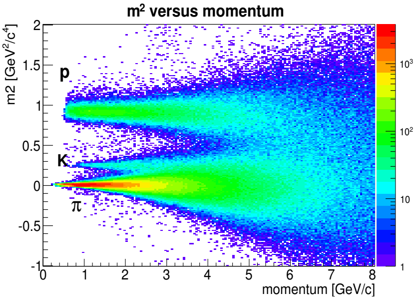


The Forward Time-of-Flight Wall

- built at the University of Geneva (A.Bravar et al.)
- 80 scintillator bars ($120 \times 10 \times 2.5 cm^3$)
- Read out on both sides by PMT's
- Overlap between the bars insure good coverage
- m^2 of the particles can be computed from the recorded time of flight

$$m^2 = p^2 \left(\frac{c^2 \times tof^2}{L^2} - 1 \right)$$

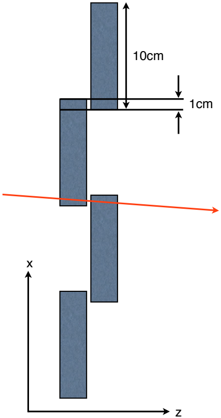
the momentum p and track length L are determined by the track reconstruction

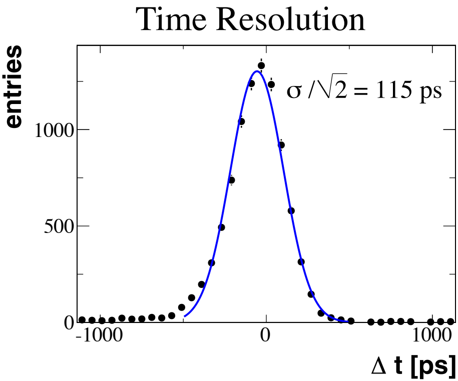


The Forward Time-of-Flight Resolution

FTOF Resolution

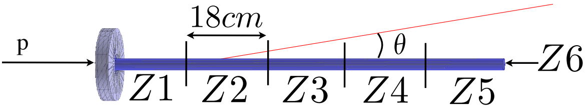
- Use simultaneous hits in 2 slabs
  - ↪ consider events with hits in the overlap regions on scintillators
  - ↪ plot the difference between two measurements in two independent slabs

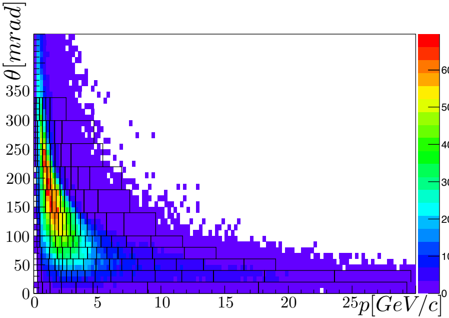




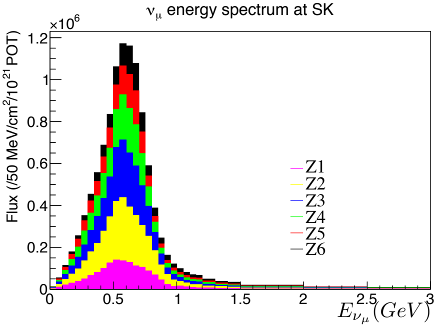
The T2K Replica Target Analysis

- Extract particle production **at the surface of the target**
- Introduce (p, θ, z) binning





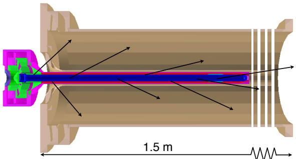
Analysis binning overlaid on the (p, θ) distributions of the pion parent particles exiting the target surface and producing ν_μ at SK.



Contribution of each Z bin to the neutrino ν_μ flux at SK

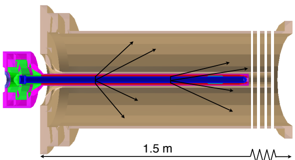
(p, θ, z) Analysis Binning for the T2K Replica Target Analysis

Nominal Beam



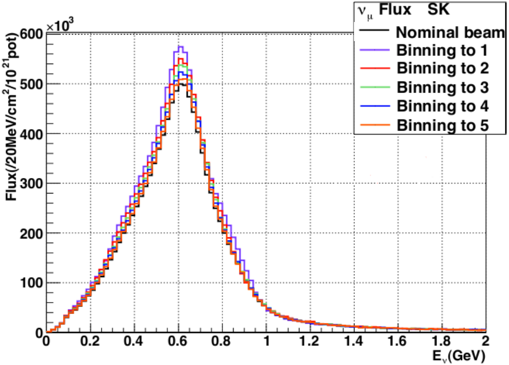
Input the nominal simulation variables into the neutrino flux simulation

Binning to 2



Input modified simulation variables to simulate two longitudinal bins in Z

- position of the peak energy not influenced by number of z bins
- absolute flux at beam peak energy is affected by number of z bins

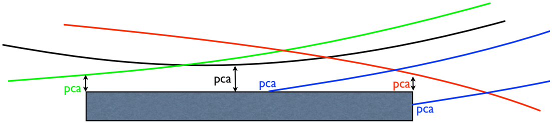


Murakami,T2K beam group

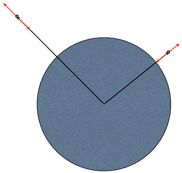
- **important to reconstruct the exit position of the particles on the target surface**

Backward Extrapolation to the Target Surface

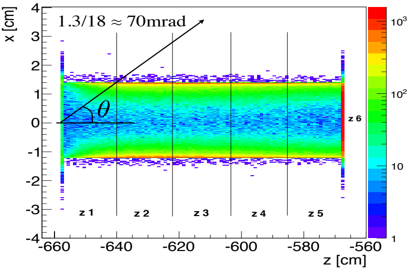
Extrapolate the tracks from the TPCs back to the target surface.

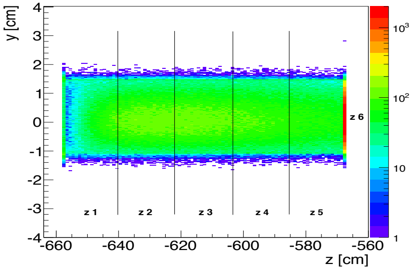


PCA within its uncertainty has to touch the target surface



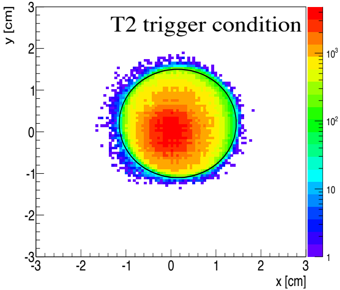
Reconstructed position of particles exiting the target surface



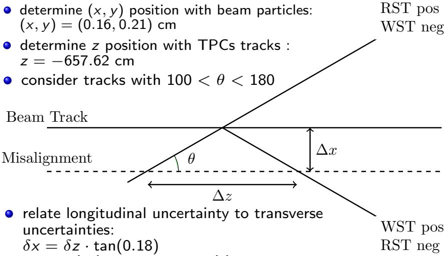


!! Very important to precisely know the target position with respect to the TPCs !!

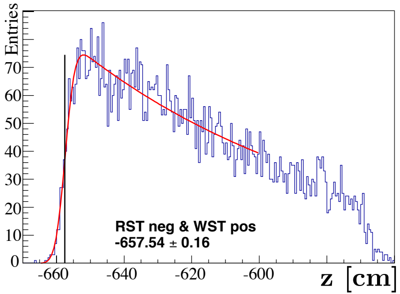
Determination of the Target Position

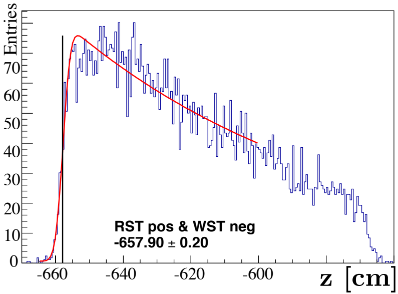


- determine (x, y) position with beam particles: $(x, y) = (0.16, 0.21)$ cm
- determine z position with TPCs tracks : $z = -657.62$ cm
- consider tracks with $100 < \theta < 180$



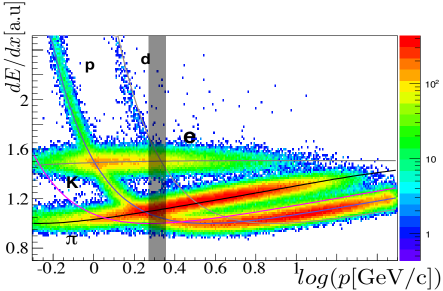
- relate longitudinal uncertainty to transverse uncertainties: $\delta x = \delta z \cdot \tan(0.18)$
- uncertainties on target position : $(\delta x, \delta y, \delta z) = (0.04, 0.04, 0.36)$ cm

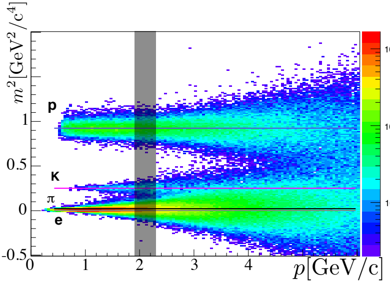


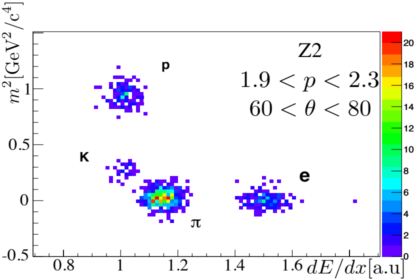


Particle Identification

- *ToF − dE/dx* **analysis: combine information from dE/dx and ToF ⇒identify $\pi^{\pm}$, $K^{\pm}$ and protons in each (p, θ, z) bin**
- here: $(1.9 < p < 2.3,\ 60 < \theta < 80,\ z2)$

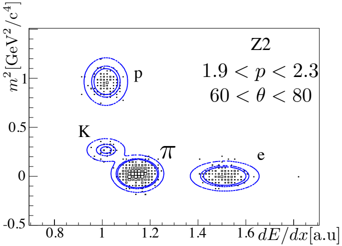






Combined TOF-dE/dx Analysis for the T2K Replica Target

- for each (p, θ, z), bin construct a 2D distribution in $m^2 - dE/dx$ for positively and negatively charged particles
- fit each distribution with four 2D Gaussians ($\pi^{\pm}, K^{\pm}, (anti) - protons, e^{\pm}$) using a binned maximum likelihood method; the fits are initialized with the m^2 and dE/dx parametrizations

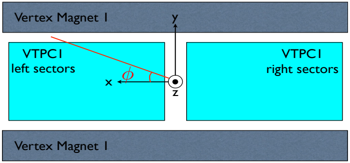


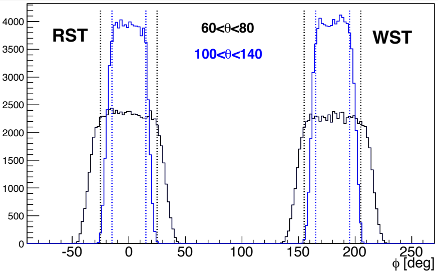
- the returned amplitude of the gaussians gives the number of particles in each (p, θ, z) bin
- correct the spectra using bin-by-bin MC corrections
- normalize the spectra to the number of protons on target (allow comparisons between different analysis or between data and simulations)
- plot the results in different (θ, z) intervals as a function of momentum

π^+ and π^- spectra are extracted following this procedure.

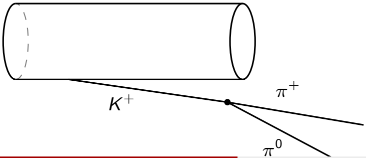
Breakdown of the Corrections

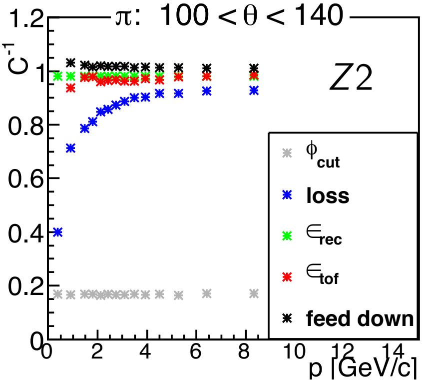
- ϕ cut:



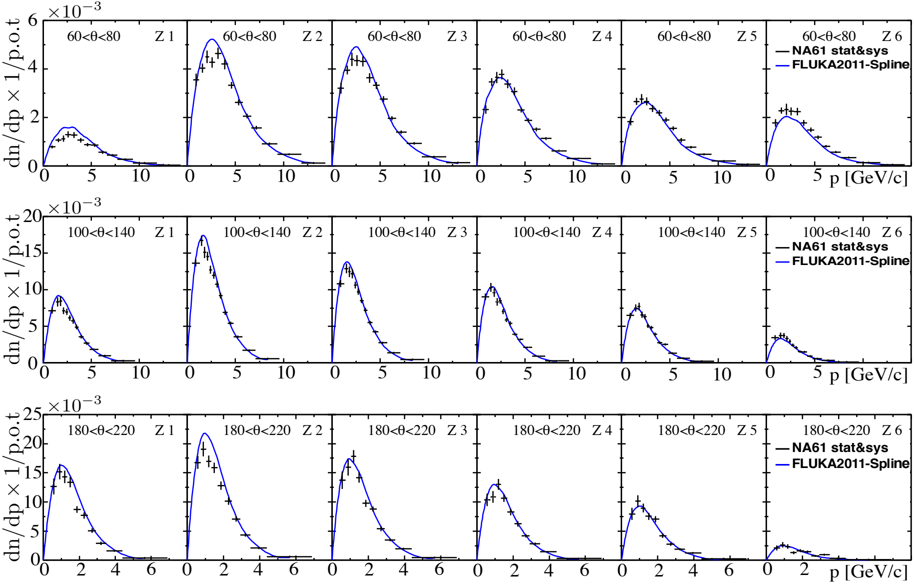


- π loss:
  pions decaying before reaching the forward TOF
- reconstruction efficiency:
  > 0.98 reconstruction efficiency
- forward TOF efficiency:
  ~ 0.98 efficiency, mainly due to double hits in a same slab (more important for the forward region)
- feed-down:
  particles decaying into pion before entering the spectrometer





π^+ Spectra on Target Surface

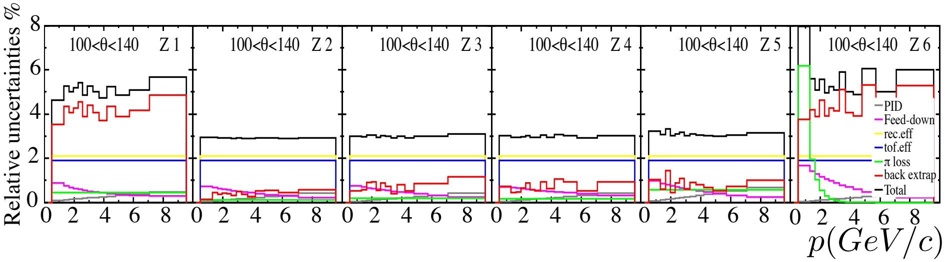


Systematic Uncertainties

Six Components of systematic uncertainties:

- PID: 1 Gaussian versus 2 Gaussians
  to describe dE/dx
- Feed-down: 30% on model dependent corrections
- Reconstruction efficiency: evaluated to 2%
- FTOF efficiency: evaluated to 2%
- π loss: effect on last point measured in TPCs
- Backward extrapolation:
  precision on reconstructed target position

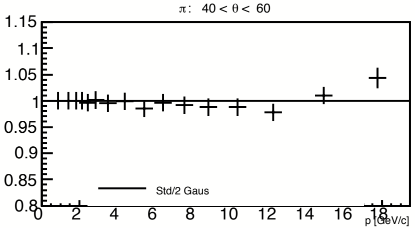
PID
Feed-down
rec. eff.
tof. eff.
π loss
back extrap
Total



Systematic Uncertainties

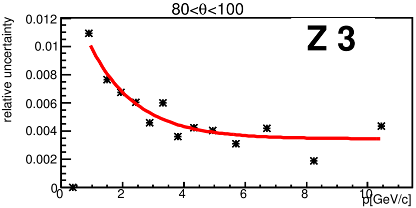
PID: 1Gaussian versus 2 Gaussians to describe dE/dx

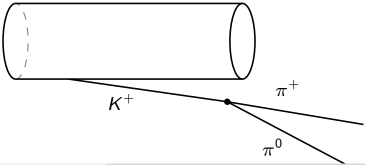
- 1 Gaussian versus 2 Gaussians to describe dE/dx distributions
- $f(x) = 0.7 \cdot G(x, m, w) + 0.3 \cdot G(x, m, 2w)$
- small effect (less than 5%) for π as they are well separated from other species
- visible only for larger momentum where TOF is not used



Feed-down: 30% on model dependent corrections

- particle exiting the target, decaying before the TPC's and being reconstructed as a pion exiting the target
- corrections are up to $\sim$ 15% for low momenta and upstream part of the target
- assign 30% of the correction as the systematic uncertainty
- fit with an exponential in order to remove statistical fluctuations due to limited MC sample





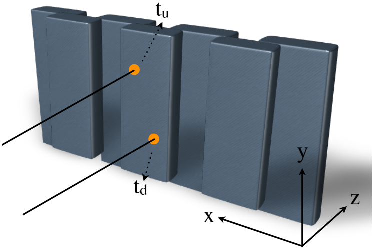
Systematic Uncertainties

Reconstruction efficiency: evaluated to 2%

- systematics related to reconstruction efficiency : 2% (as for 2007 published data and 2009 thin target analysis)
- estimated by studying reconstruction capabilities for Monte-Carlo samples (same reconstruction algorithm is used in data and Monte-Carlo)
- confirmed by eye scans of data in the event browser, performed with the 2007 data set

FTOF efficiency: evaluated to 2%

- consider only hits in the FTOF if the up and down PMTs time measurements are consistent
- correct for this "inefficiency"
- corrections are position "x" dependent (more double hits in the central region with higher track multiplicities)
- corrections are based on the limited data set statistics ⇒ estimated to 2%

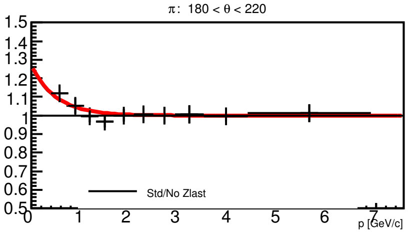


Systematic Uncertainties

π loss: effect on last point measured in TPCs

- for the T2K replica target analysis at least 35 measured points are required in MTPCs
- vary the number of requested measured points in MTPCs
- check the differnces and assign them as systematics
- fit with an exponential function in order to remove fluctuations

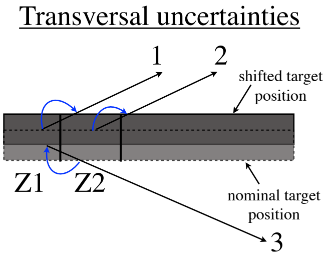
Z3

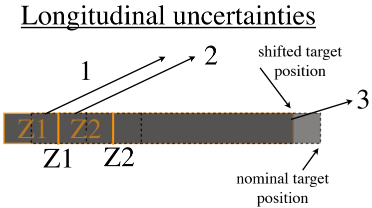


Backward extrapolation:

precision on reconstructed target position

- $(x, y, z) = (0.16, 0.21, -657.62)$ cm $(\delta x, \delta y, \delta z) = (0.04, 0.04, 0.36)$ cm





Comparing Thin Target and Replica Target Results

T2K uses thin target measurements to re-weight the neutrino flux predictions.
Before implementing T2K replica target results in the T2K neutrion flux predictions:
compare the pion spectra predictions re-weighted with thin target measurements and the T2K replica target results.

- Each simulated interaction is stored at the simulation level to be tuned later with measurements (priority to NA61/SHINE)
- Tuning of hadron multiplicities:

$$W(p_{in}, A) = \frac{\left[\frac{dn}{dpd\theta}(p_{in}, A)\right]_{data}}{\left[\frac{dn}{dpd\theta}(p_{in}, A)\right]_{MC}}$$

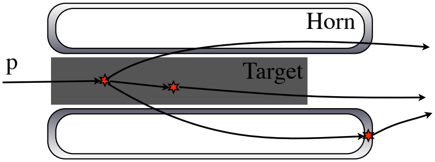
- Tuning of production cross-section:

$$W = \frac{P(x; \sigma'_{prod})}{P(x; \sigma_{prod})} = \frac{\sigma'_{prod}}{\sigma_{prod}} e^{-x(\sigma'_{prod} - \sigma_{prod})\rho}$$

$\frac{\sigma'_{prod}}{\sigma_{prod}} = 1$ if particle decay or exit the target before interacting

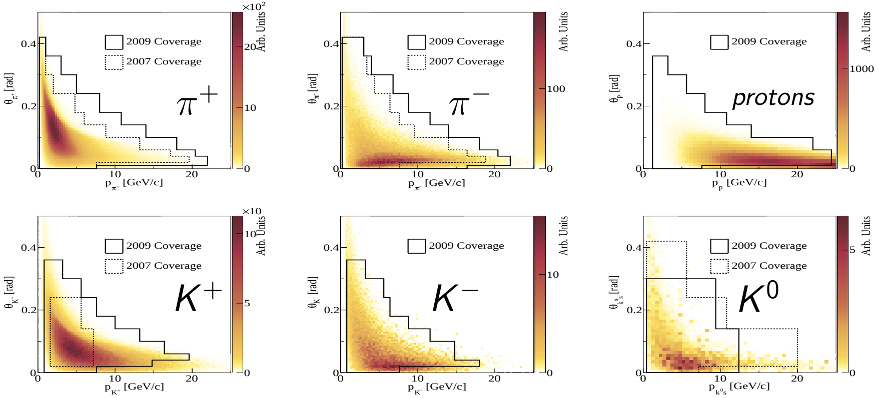
- Compare pion spectra **at the surface of the target**

- FLUKA generator is used to model all interactions inside the 90cm long carbon target
- $\Rightarrow$ all weights are computed with respect to FLUKA



- Double differential cross section $\frac{d\sigma}{dpd\theta}$ in (p, θ) bins extracted for 7 particle species: $\pi^{\pm}$, $K^{\pm}$, K^0, Λ, protons
- Hadron multiplicity:

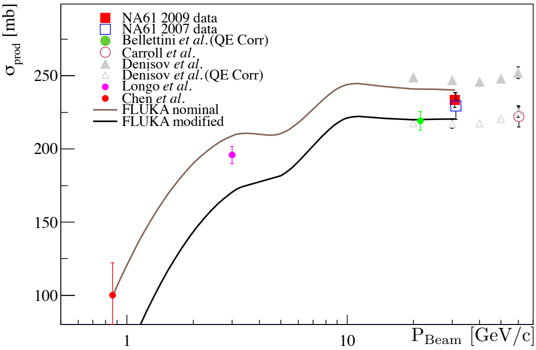
$$\frac{dn_{\alpha}}{dpd\theta} = \frac{1}{\sigma_{prod}} \frac{d\sigma_{\alpha}}{dpd\theta} \quad \text{where} \quad \sigma_{prod} = \sigma_{total} - \sigma_{elastic} - \sigma_{quasi-el}.$$



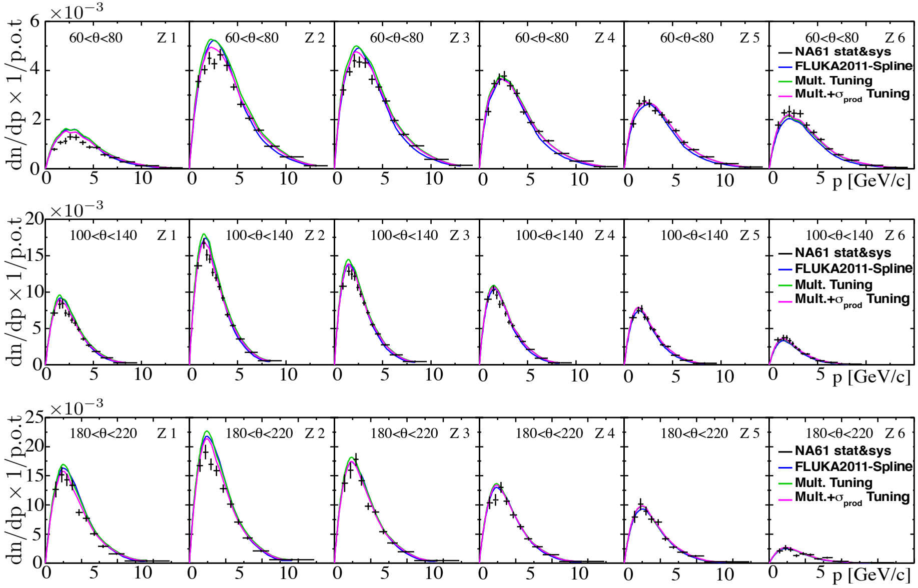
Thin Target Measurements

- Production cross-section:
  $\sigma_{prod} = \sigma_{total} - \sigma_{elastic} - \sigma_{quasi-el.}$
- Definition of $\sigma_{quasi-el.}$ is ambiguous:
  photon emission or knock out of proton included in $\sigma_{quasi-el.}$?
- $\sigma_{quasi-el.}$ can be estimated based on models (Glauber, Bellettini):
  for p+C@31GeV/c: $\sigma_{quasi-el.} \approx 30$ mbarn
- $\sigma^{FLUKA}_{"prod"} = 241 mb$ for p+C@31GeV/c
  vary it by $2/3 \times \sigma_{quasi-el.} \approx 18$ mbarn @ 31 GeV/c

- current thin target measurements give few information on the different cross-sections
- longitudinal distribution of particles exiting the T2K replica target surface is determined by the different cross-sections



Comparing Thin Target and Replica Target Analysis



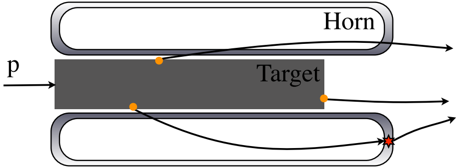
T2K neutrino flux predictions with T2K replica target measurements

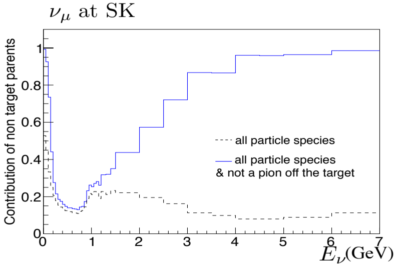
Implementation of T2K replica target measurement in the T2K neutrino beam simulation to produce neutrino flux predictions constrained by the T2K replica target measurement.

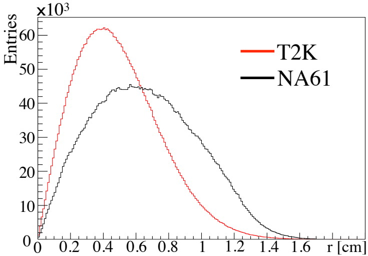
- re-weight pions at the surface of the target

$$W(p_{in}, A) = \frac{\left[\frac{dn}{dp}(\theta, z)\right]_{data}}{\left[\frac{dn}{dp}(\theta, z)\right]_{MC}}$$

- apply thin target procedure for any other particles than pions exiting the target surface and re-interactions in the beam material
- NA61 and T2K have different beam profiles
- T2K replica target results are given with respect to NA61/SHINE beam profile







- it has been shown that it is possible to go from one beam profile to the second one by re-weighting the pion spectra at the surface of the target with respect to the different beam profiles.

Propagation of uncertainties

Propagating the T2K replica target uncertainties means propagating the uncertainties on the weights ω_j
Each (p, θ, z) bin contribute differently to each E_ν bin $\Rightarrow$ linear combination:

$$E^{\omega}_{\nu_i} = \sum_{j=1}^{N} a_{ij} \cdot \omega_j \qquad \text{where} \qquad \omega_j = \frac{n_j^{NA61}}{n_j^{FLUKA}}$$

Two methods:

1. propagation via an "overall 1σ shift" $\Delta\omega$ of the T2K replica target results

$$\Delta E^{\omega}_{\nu} = E^{\omega \pm \Delta\omega}_{\nu} - E^{\omega}_{\nu}$$

2. propagation via "covariance matrices": for each error source

$$C_E = F_\omega \cdot C_\omega \cdot F_\omega^T$$

with

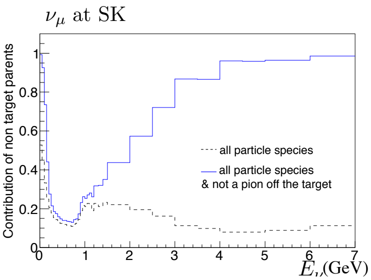
$$F_\omega = \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{p1} & \dots & a_{pn} \end{pmatrix} \qquad \text{and} \qquad C_\omega = \begin{pmatrix} \sigma^2_{\omega_1} & \dots & \sigma_{\omega_1,\omega_n} \\ \sigma_{\omega_2,\omega_1} & \dots & \sigma_{\omega_2,\omega_n} \\ \vdots & \ddots & \vdots \\ \sigma_{\omega_n,\omega_1} & \dots & \sigma^2_{\omega_n} \end{pmatrix}$$

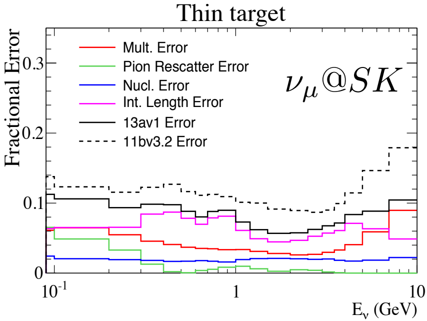
"overall 1σ shift" $\equiv$ "covariance matrices" with $\sigma_{\omega_i,\omega_j} = 1$

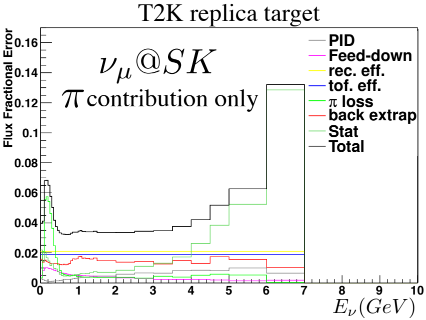
For this special case, both method should give the same results $\Rightarrow$ nice way to cross check algorithm and code

T2K flux uncertainties

- propagate the uncertainties of T2K replica target measurements only to the fraction of the neutrino flux at SK that can be re-weighted
- very small contribution from statistical error of the T2K replica target measurements; they are considered as uncorrelated
- consistent comparison with the official T2K predictions using the thin target measurement is complexe
- larger contribution comes from the interaction length; not present with the T2K replica target re-weighting

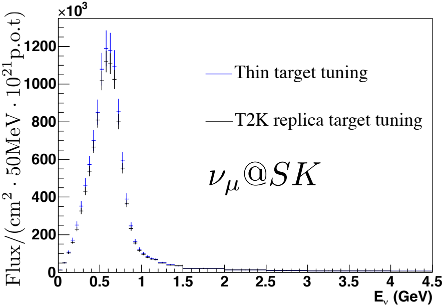




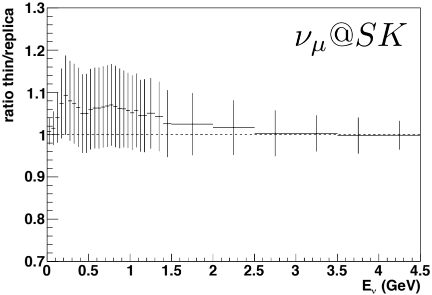


T2K neutrino flux prediction with T2K replica target measurements

- compare T2K neutrino flux predictions with both, thin target and T2K replica target re-weightings
- consider systematic uncertainties
- for the thin target re-weighting:
  apply multiplicity weights **and** vary σ_{prod} by 18 mbarn



ν_μ flux predictions at SK with the thin target and replica target re-weightings



ratio of thin target over T2K replica target re-weightings for the ν_μ flux predictions at SK

Requests of future long base line neutrino experiments
Possible improvements in NA61/SHINE measurements

Future Requests

- future long base line neutrino programmes will use a combination of near and far detectors (as T2K)

$$N_{FD}^{exp.}(\nu_e) = N_{ND}^{data}(\nu_\mu) \times \frac{\Phi_{FD}(\nu_\mu)}{\Phi_{ND}(\nu_\mu)} \times P(\nu_\mu \to \nu_e) \times \frac{\epsilon_{FD}(\nu_e)}{\epsilon_{ND}(\nu_\mu)} \times \frac{\sigma_{FD}(\nu_e)}{\sigma_{ND}(\nu_\mu)}$$

- far-to-near flux ratio has to be constrained to typically $< 2\%$ to reach the physics goals
- Hyper-Kamiokande, LBNO and DUNE (LBNE) mention the importance of NA61/SHINE hadron production measurements to reduce the systematic uncertainties related to the neutrino beam predictions
- typically, a 5% uncertainty on the flux prediction is required.

Possible improvement in NA61/SHINE to reach the desired precision on hadron production measurements:

- For T2K replica target measurements, backward extrapolation to the target surface is the larger uncertainty on current analysis
  1) mount the target closer to or within VTPC1
  2) use a vertex detector surrounding the target
- acceptance gap in the very forward region
  1) take data with different magnetic field settings to bend forward going particles
  2) cover forward region with new TPCs
- production cross section and quasi-elastic cross section entangled
  1) new TPCs in forward region with PID capabilities could allow to better disentangle $\sigma_{elastic}$, $\sigma_{inelastic}$, σ_{qe}
  2) model independent measurement of production cross section

Summary

- Long baseline neutrino experiments need precise neutrino flux predictions to reach their physics goals.
- The NA61/SHINE experiment has proved its ability to deliver high quality data used for Neutrino Physics programs and further improvements are possible.
- Replica Target measurements are of importance as they allow to constrain the major part of the neutrino flux.
- Comparisons of thin target and replica target measurements allow to constrain the issue of production cross sections.
- NA61/SHINE plans to continue taking hadron production measurements for future neutrino program at Fermilab in the U.S. and discussion has started for the Hyper-Kamiokande experiment in Japan.

- The work accomplished in this thesis covers:
  - extraction of π^+ and π^- spectra at the surface of the T2K replica target
  - estimations of systematic uncertainties of these spectra
  - comparisons of thin target and T2K replica target results, based on a framework developed by the T2K beam group
  - predictions of the T2K neutrino beam at the near and far detectors using the T2K replica target measurements
  - estimations of the T2K neutrino beam uncertainties when using the T2K replica target measurements to constrain the neutrino fluxes
  - estimations of the effect of different proton beam profiles on the pion spectra off the surface of the T2K replica target
- The NA61/SHINE collaboration plans to publish the results of this thesis in an article
- The T2K collaboration is currently working on implementing the work of this thesis in the T2K neutrino beam prediction framework

T2K replica target measurements in NA61/SHINE and T2K neutrino flux predictions

Alexis Häsler

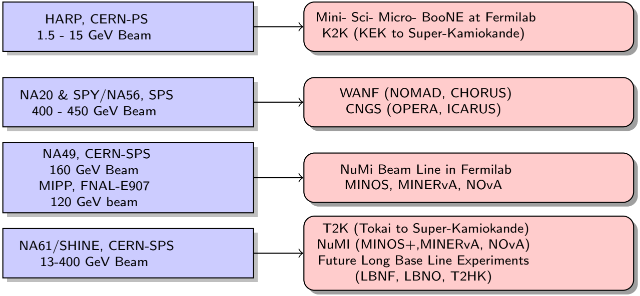
Thank you for your attention

Thank you to the members of the jury and my colleagues for the interesting discussions and guidance

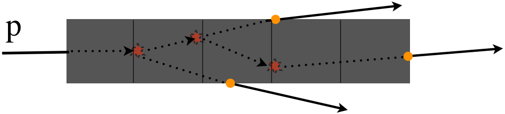
BACKUP SLIDES

Hadron production experiments for neutrino physics

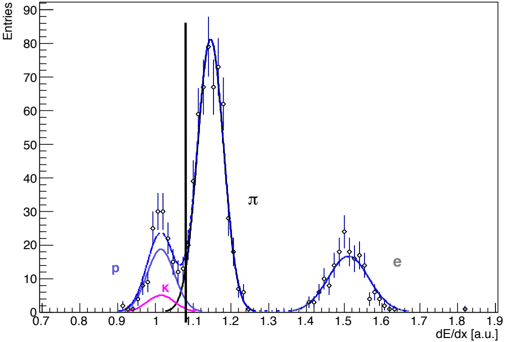
Few examples of hadron production experiments for neutrino experiments:



NA61 and T2K Beam Profiles

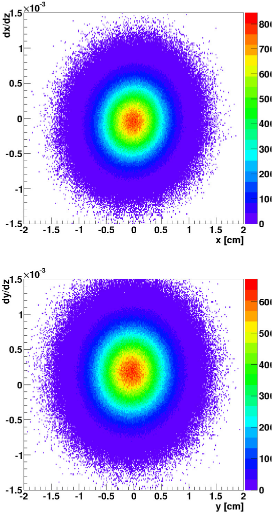


$$t = (r, \phi, x, y, z, P(\pi), P(K), P(e), P(p))$$

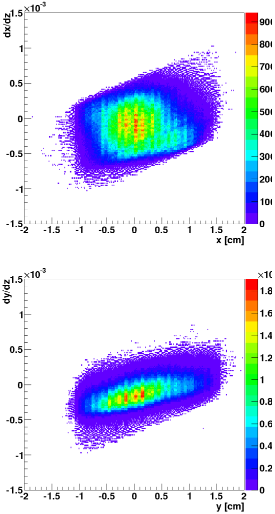


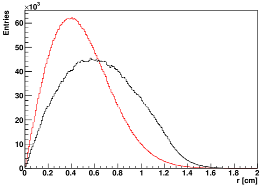
NA61 and T2K Beam Profiles

T2K Beam



NA61 Beam





radial distributions for NA61 (black) and T2K (red)

Beam Profile Re-weighting

- NA61 and T2K have different beam profiles
- T2K replica target results are given with respect to NA61/SHINE beam profile
- weights should be applied to T2K beam profile

⇒ show that it is possible to go from one beam profile to the second one by re-weighting the pion spectra at the surface of the target with respect to the different beam profiles.

Start with NA61 beam: number of pions at the surface of the target

$$\pi_i^N = \sum_j c_{ij} b_j^N \tag{1}$$

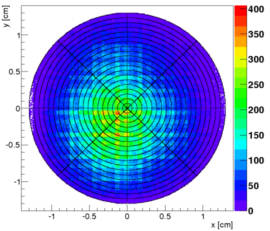
with $i \equiv (p, \theta, z)$ analysis bin; c_{ij} contribution for the beam bin j with number of entries b_j
if the contributions c_{ij} are identical for the NA61 and T2K beam settings then

$$\pi_i^T = \sum_j c_{ij} b_j^T = \sum_j c_{ij} d_j^N b_j^N \tag{2}$$

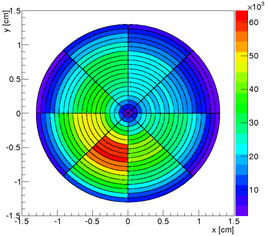
where d_J is the ratio for each beam bin j between the NA61 and T2K beam profile.
⇒ compare the reweighted spectra with a T2K simulation for each (p, θ, z) bins; see if they are consistent

Beam profiles

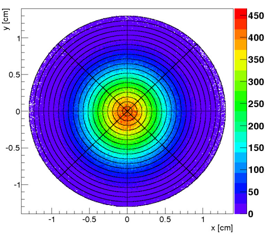
NA61/SHINE



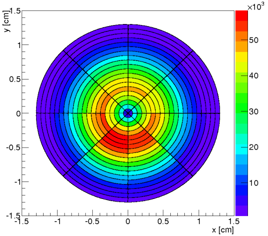
NA61/SHINE

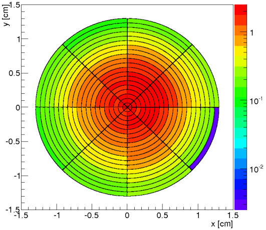


T2K



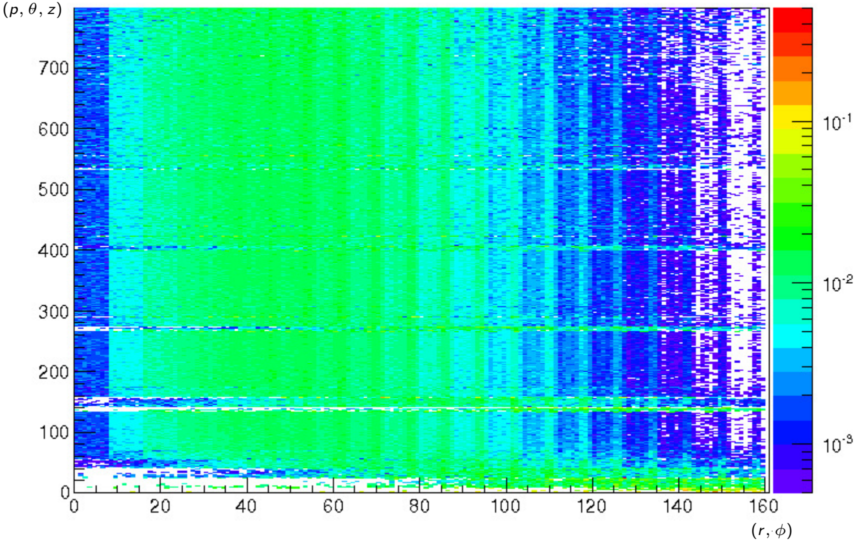
T2K





ratio of T2K/NA61 taken for each beam bin

Contribution of the beam bins to the (p, θ, z) bins



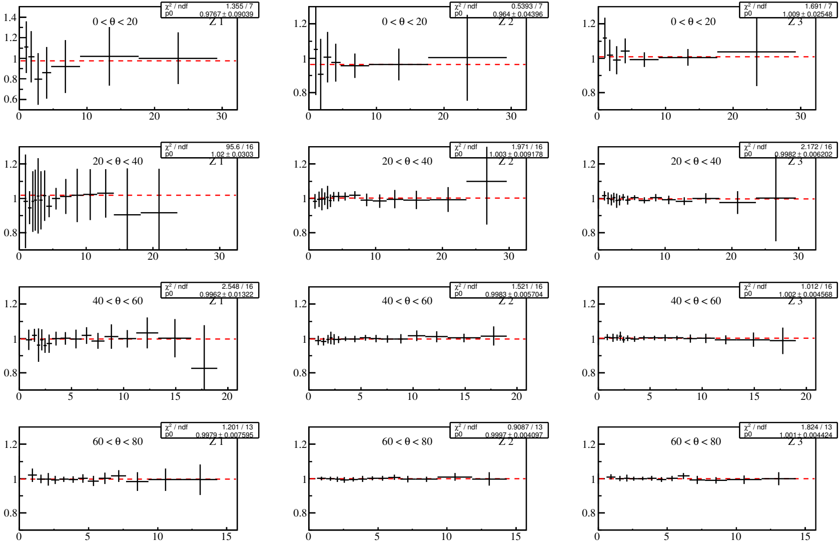
Ratio of reweighted NA61 spectra over T2K spectra

- 4 million protons on target for T2K and NA61 simulations
- Start with NA61 spectra, use the above matrix and multiply it by the column vector containing the T2K beam profile:

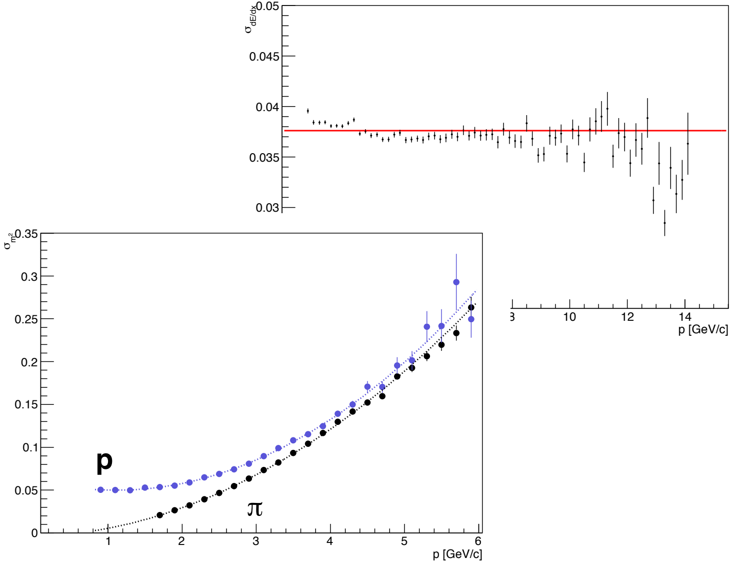
$$\begin{pmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,n} \\ c_{2,1} & c_{2,2} & \cdots & c_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m,1} & c_{m,2} & \cdots & c_{m,n} \end{pmatrix} \cdot \begin{pmatrix} b_1^T \\ b_2^T \\ \vdots \\ b_m^T \end{pmatrix} = \begin{pmatrix} \pi_1^{N_{rw}} \\ \pi_2^{N_{rw}} \\ \vdots \\ \pi_m^{N_{rw}} \end{pmatrix} \quad (3)$$

- compute ratios of $\frac{\pi_i^{N_{rw}}}{\pi_i^T}$ and related uncertainties

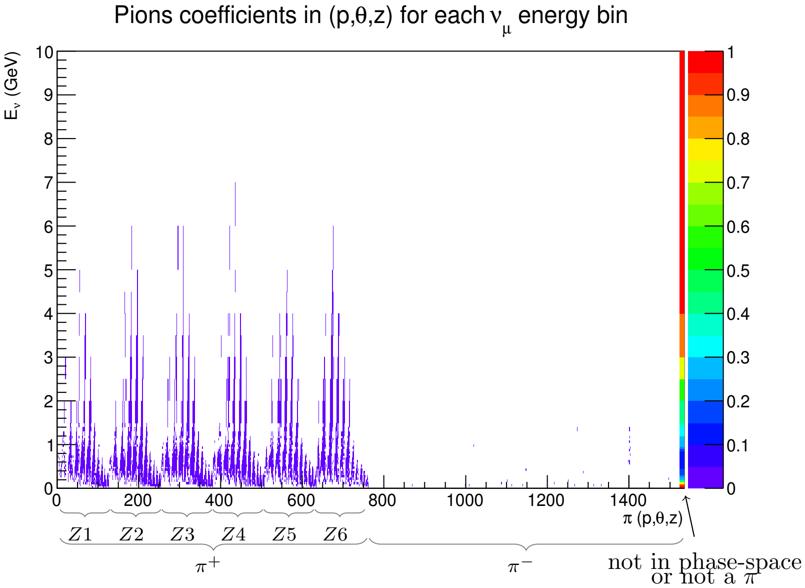
Ratio of reweighted NA61 spectra over T2K spectra



dE/dx and m^2 resolutions



Coefficients of Pions for each Neutrino Energy Bin



Thin Target Measurements

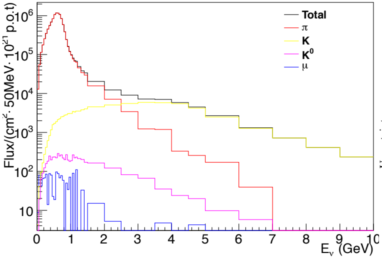
- Double differential cross section $\frac{d\sigma}{dpd\theta}$ in (p, θ) bins extracting for 7 particle species: $\pi^{\pm}$, $K^{\pm}$, K^0, Λ, protons
- Derivation of spectra:

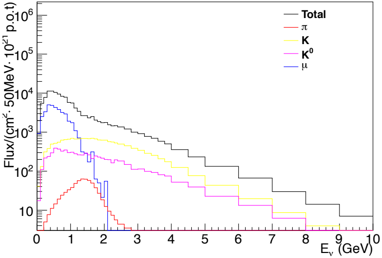
$$\frac{d\sigma_\alpha}{dpd\theta} = \frac{\sigma_{trig}}{1-\epsilon}\left(\frac{1}{N^{in}}\frac{\Delta n_\alpha^{in}}{\Delta p \Delta\theta} - \frac{\epsilon}{N^{out}}\frac{\Delta n_\alpha^{out}}{\Delta p \Delta\theta}\right)$$

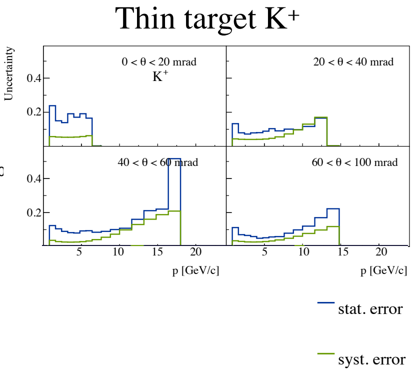
- Hadron multiplicity:

$$\frac{dn_\alpha}{dpd\theta} = \frac{1}{\sigma_{prod}}\frac{d\sigma_\alpha}{dpd\theta} \quad \text{where} \quad \sigma_{prod} = \sigma_{total} - \sigma_{elastic} - \sigma_{quasi-el}.$$

ν_e $\nu\mu$: thin target kaon production

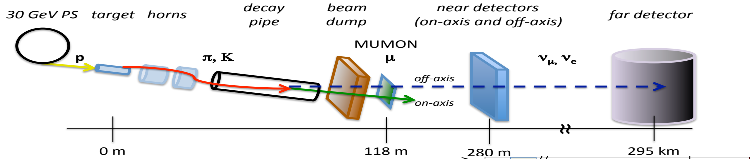






Off Axis beam technique

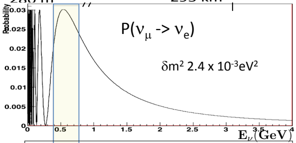
Off-axis neutrino beam



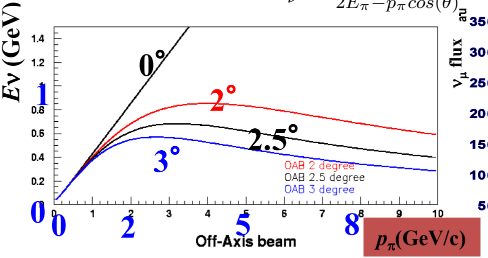
$P(\nu_\mu \to \nu_e) \sim \sin^2(\theta_{23})\sin^2(\theta_{13})\sin^2(1.27\Delta m^2_{32}L/E)$

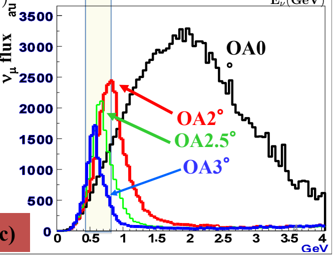
L is set to 290 km (distance between Tokai and Kamioka)

E is the free parameter we can tune



Pion decay kinematics $E_\nu = \frac{m_\pi - m_\mu}{2E_\pi - p_\pi cos(\theta)}$





Breakdown of Neutrino Flux Uncertainties

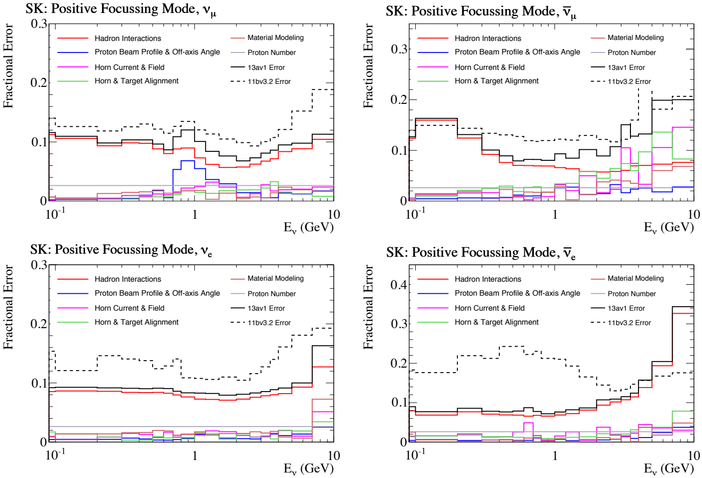
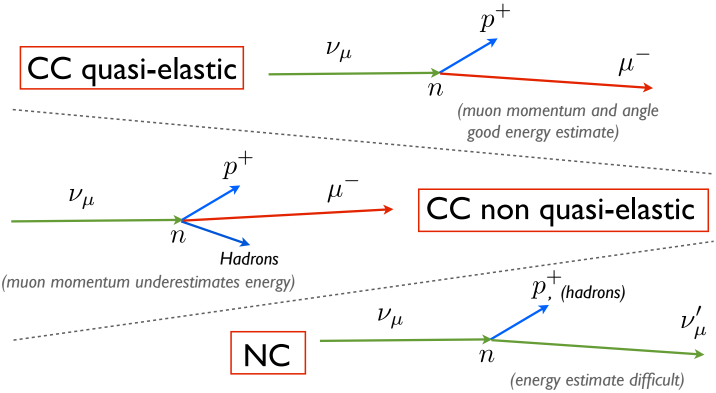


Figure 104: The total uncertainties evaluated on the SK flux prediction. The 13av1 uncertainty is the current version. The 11bv3.2 is the previous version.

Neutrino Nucleon Interactions

Neutrino-Nucleon interactions

Determine precisely the neutrino beam energy spectrum

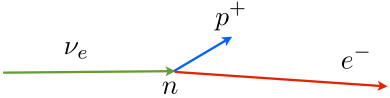


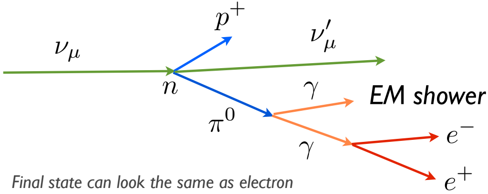
Precise measurements of each of these intercations in ND280 through TPCs and FGDs

Neutrino-Nucleon interactions

Beam flavour content is important for ν_e appearance, reduce the ν_e background in the high ν_μ flux

electron
CC quasi-elastic

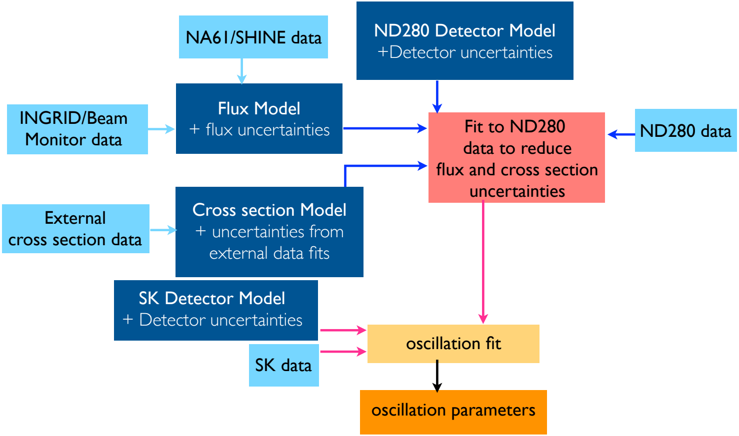




muon
NC pi-zero

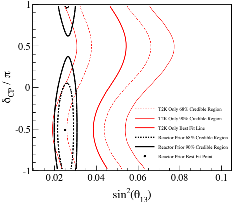
Final state can look the same as electron CCqe if some particles are missed

Precise pi-zero measurements in the P0D

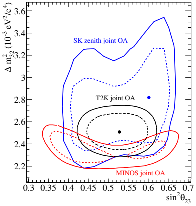


Melody Ravonel Salzgeber

T2K Measurements

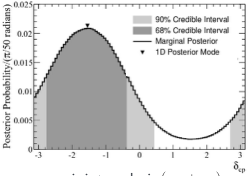


First measurement of flavor appearance with 28 ν_e candidates
Independent measurement of θ_{13}



World-leading measurement of θ_{23}
Significant measurement of Δm^2_{32}

Abe, K., et al. *Physical Review D* 91.7 (2015): 072010.



joint analysis $(\nu_\mu + \nu_e)$
First constraint of δ_{CP}

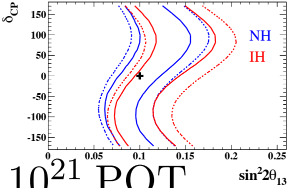
$$\theta_{12} = 33.4 \pm 0.85^o$$
$$\theta_{13} = 8.88 \pm 0.39^o$$
$$\theta_{23} = 45.8 \pm 3.2^o$$

$$\Delta m^2_{21} = (7.53 \pm 0.18) \cdot 10^{-5} eV^2$$
$$|\Delta m^2_{32}| = (2.44 \pm 0.06) \cdot 10^{-3} eV^2$$
$$\delta_{CP} = [-\pi, 0.14\pi] \text{ and } [0.87\pi, \pi] \text{ 90\% interval}$$

parameters measured by T2K

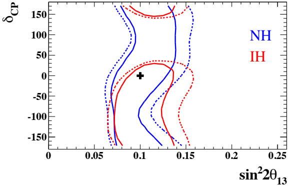
Mass hierarchy, CP phase (and Majorana phases) still not known
↓
only possible with long base line experiments

Melody Ravonel Salzgeber, University of Geneva

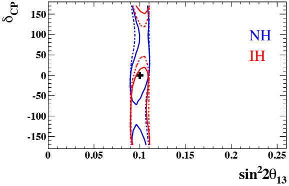


7.8×10^{21} POT

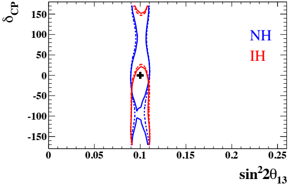
(a) 100% ν-running, true NH.



(b) 50% ν-, 50% $\bar{\nu}$-running, true NH.



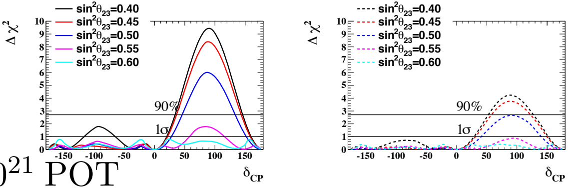
(c) 100% ν-running, with ultimate reactor constraint, true NH.



(d) 50% ν-, 50% $\bar{\nu}$-running, with ultimate reactor constraint, true NH.

Figure 8: δ_{CP} vs. $\sin^2 2\theta_{13}$ 90% C.L. allowed regions for 7.8×10^{21} POT. Contours are plotted assuming true $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0°$, $\sin^2\theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4\times10^{-3}$ eV^2. The blue curves are fit assuming the correct MH, while the red are fit assuming the incorrect MH. The solid contours are with statistical error only, while the dashed contours include current systematic errors fully correlated between ν and $\bar{\nu}$.

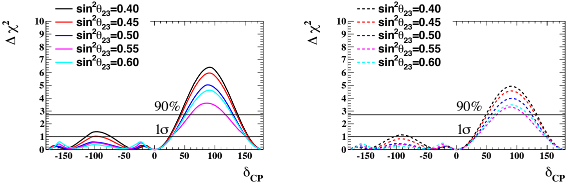
T2K Future Sensitivity



7.8×10^{21} POT

(a) 100% ν-running, statistical error only.

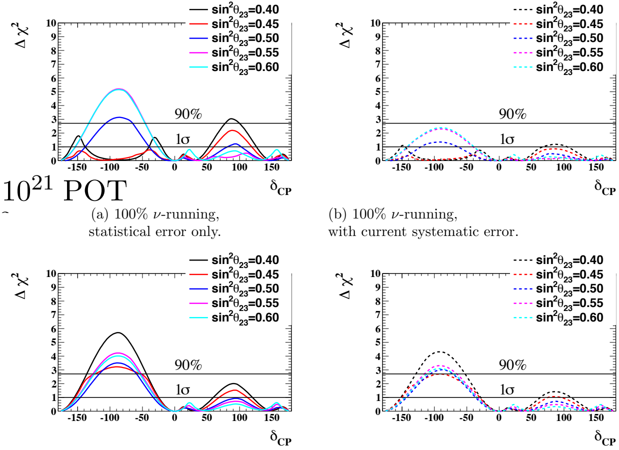
(b) 100% ν-running, with current systematic error.



(c) 50% ν, 50% $\bar{\nu}$-running, statistical error only.

(d) 50% ν-, 50% $\bar{\nu}$-running, with current systematic error.

Figure 13: The expected $\Delta\chi^2$ significance to resolve $\sin\delta_{CP} \neq 0$ as a function of δ_{CP} for various values of $\sin^2\theta_{23}$ (given in the legend) in case of the **inverted mass hierarchy**. The MH and $\sin^2\theta_{23}$ octant are considered unknown (unless it can be constrained by the T2K data) and a constraint based on the ultimate reactor error is used.



7.8×10^{21} POT

(a) 100% ν-running, statistical error only.

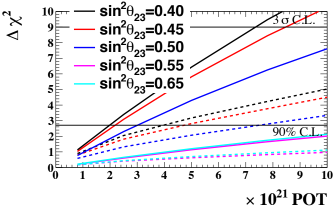
(b) 100% ν-running, with current systematic error.

(c) 50% ν, 50% $\bar{\nu}$-running, statistical error only.

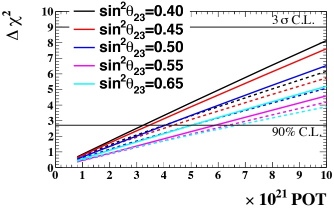
(d) 50% ν-, 50% $\bar{\nu}$-running, with current systematic error.

Figure 12: The expected $\Delta\chi^2$ significance to resolve $\sin\delta_{CP} \neq 0$ as a function of δ_{CP} for various values of $\sin^2\theta_{23}$ (given in the legend) in case of the **normal mass hierarchy**. The MH and $\sin^2\theta_{23}$ octant are considered unknown (unless it can be constrained by the T2K data) and a constraint based on the ultimate reactor error is used.

T2K future sensitivity



(a) 100% ν-running.



(b) 50% ν-, 50% $\bar{\nu}$ running.

Figure 19: The expected $\Delta\chi^2$ significance for $\sin\delta_{CP} \neq 0$ plotted as a function of POT. Plots assume true $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = +90°$, inverted MH, and various true values of $\sin^2\theta_{23}$ (as given in the plot legends). The solid lines assume statistical error only, while the dashed lines include current systematic errors fully correlated between ν and $\bar{\nu}$. Note that the sensitivity heavily depends on the assumed conditions, and that the conditions applied for these figures ($\delta_{CP} = +90°$, inverted MH) correspond to the case where the sensitivity for $\sin\delta_{CP} \neq 0$ is maximal.

	Appearance	Disappearance
BANFF(flux&cross section)	5.0%	4.2%
cross section not-constrained by ND	7.4 %	6.2%
SK detector and FSI	3.9 %	11.0%
total	9.7 %	13.3 %

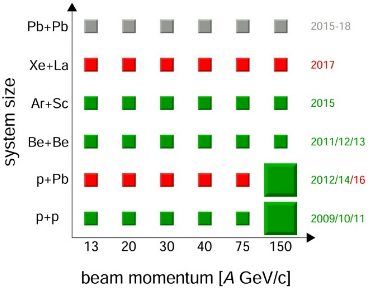
Table 4: The systematic error on the expected number of events in the 2012 oscillation analysis.

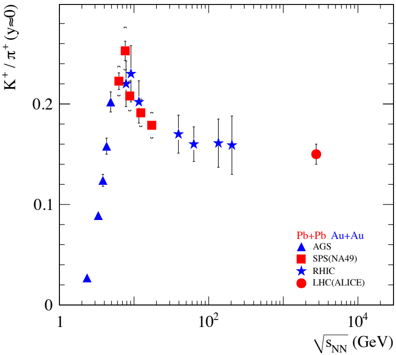
3.5 Effect of the systematic error size reduction

TN-151 also reports an extensive study of the effect of systematic error sizes. Even though actual effect depends on details of errors (see TN-151 for details), here, we generally summarize the results of the study. As shown in Tab.4, the systematic error on N_{SK} in the 2012 oscillation analysis is 9.7% for the ν_e apearance sample and 13% for the ν_μ disappearance sample. For the measurement of δ_{CP}, it is desired to reduce this to

- 5∼8% for ν_e sample
- ∼10% for $\bar{\nu_e}$ sample

to maximally achieve the T2K sensitivity. Results are rather independent from the size of error on ν_μ and $\bar{\nu_\mu}$ samples if we can achieve error size on $\bar{\nu_\mu}$ similar to the current ν_μ's error. For the measurement of θ_{23} and Δm^2_{32}, the systematic error sizes are already visible compared to the statistical error and there would be benefit of systematic error reduction even if the error size is reduced as little as 5%.

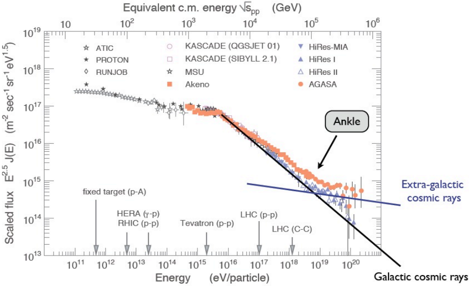




Rapidly changing ratio K/pi : Evidence for the onset of the transition to a system of deconfined quarks and gluons

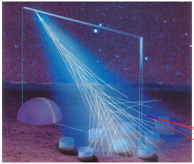
Search for critical point of strongly interacting matter through scans of system size A and Energy E

NA61 Cosmic Ray Physics Programme



- Cosmic Ray composition of central importance for understanding sources, knee, ankle, ...
- Indirect measurements for Ultra High Energy Cosmic Rays: extensive air showers seen by a surface array detector
- Strong model dependence of the reconstructed primary energy from surface detector signals
- Muon production related to hadronic interaction at fixed target energies

UHECR
air shower



NA61/SHINE