Recent Results from NA61 (Flux Related Systematic Uncertainties) and Recent Results from T2K (Overall Systematic Uncertainties)

NNN15
Stony Brook
Oct. 28 – 31 '15

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Recent Results from NA61
Hadro-Production Measurements at CERN

Why Hadro-Production Measurements

Understand the neutrino source

solar neutrinos

- ν flux predictions based on the solar model

reactor based neutrino sources

- ν flux predictions based on fission models and reactor power

accelerator based neutrino sources

- ν flux predictions based on π, K, … (→ ν + X) hadro-production models
  (+ modeling of the target complex, focusing and decay channel, …)
- ν flux at far detector predicted on the basis of ν flux measured in near detector

Make measurements with neutrinos

neutrino cross sections → absolute neutrino flux

- neutrino interaction physics

neutrino oscillations → flux shape and Far / Near flux ratio

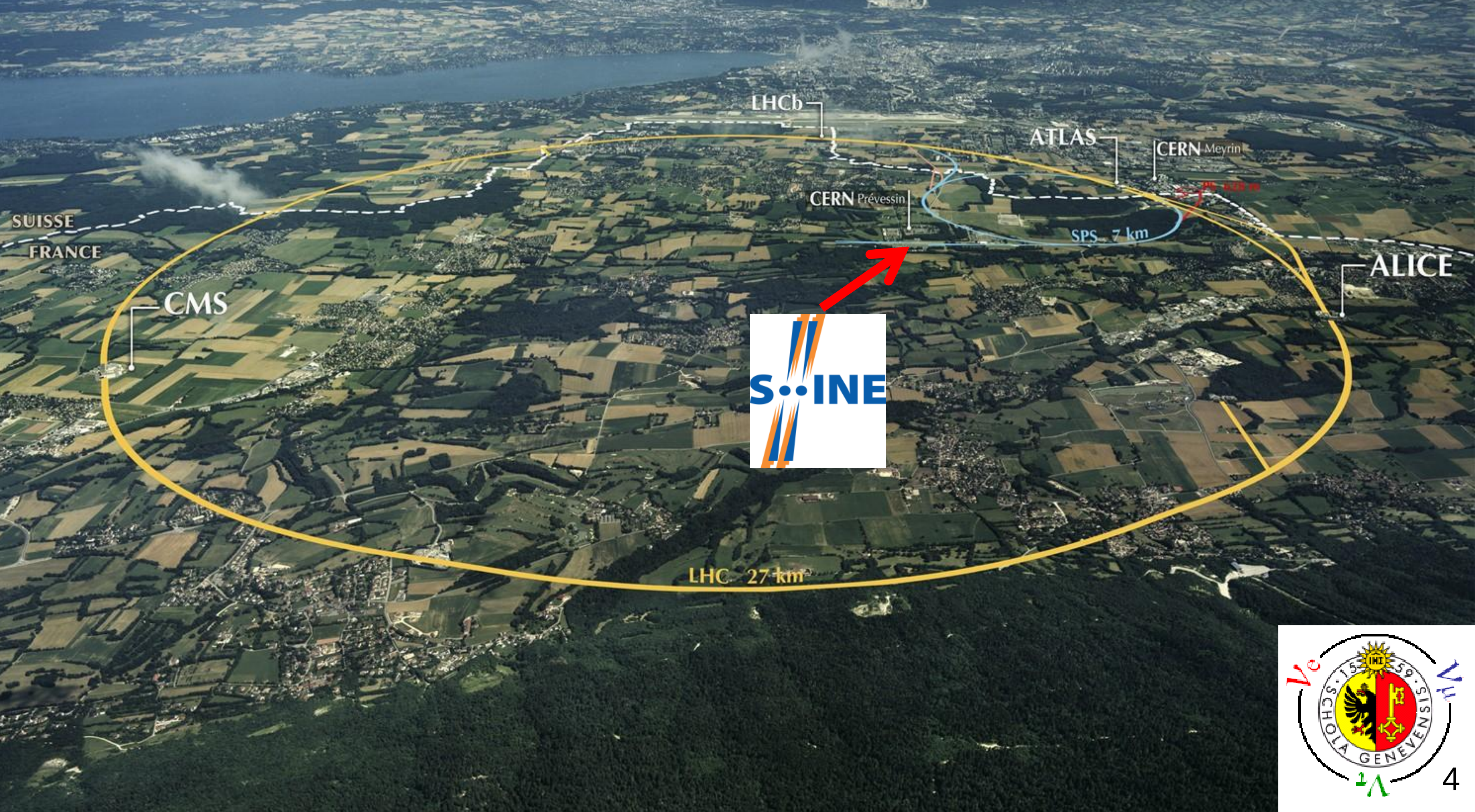
- compare measured neutrino spectrum "far" from the source
  with the predicted one

NA61/SHINE – unique multipurpose facility:

hadron production in h + p (20 – 350 GeV/c) [h = p, π^+, π^-]

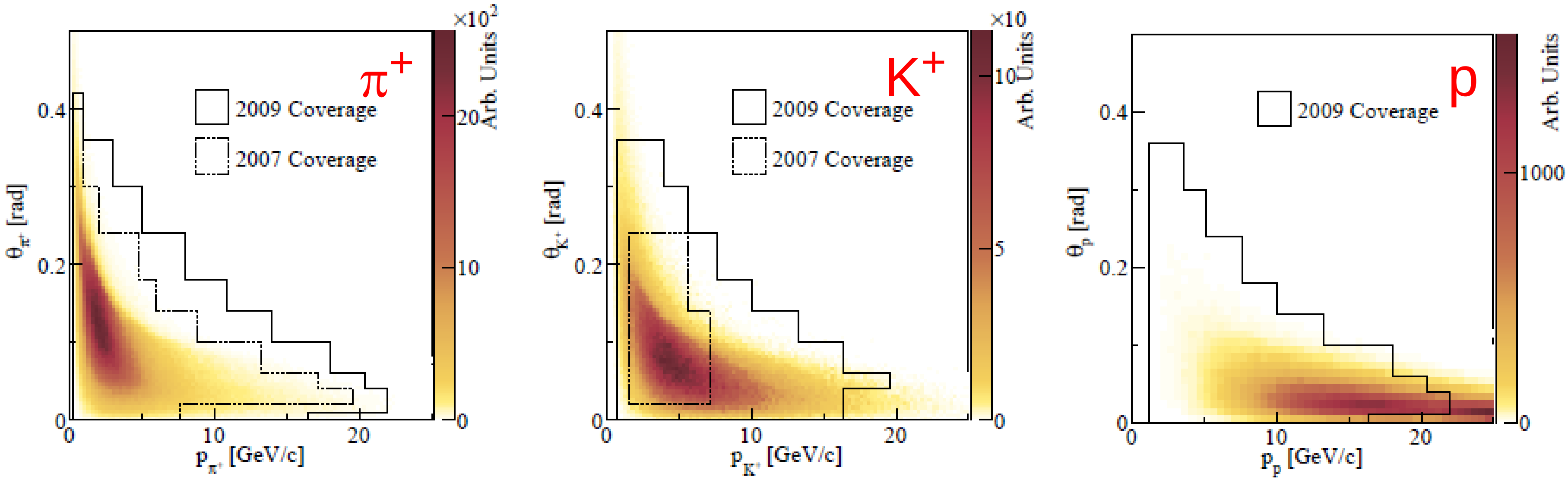
h + A (20 – 350 GeV/c) [A = Be, C, Al, Fe, Pb]

A + A (13*A* - 150*A* GeV/c)



Which Hadron Production Measurements

T2K ν parent hadron phase space
30 GeV proton beam on the 90 cm long T2K graphite target



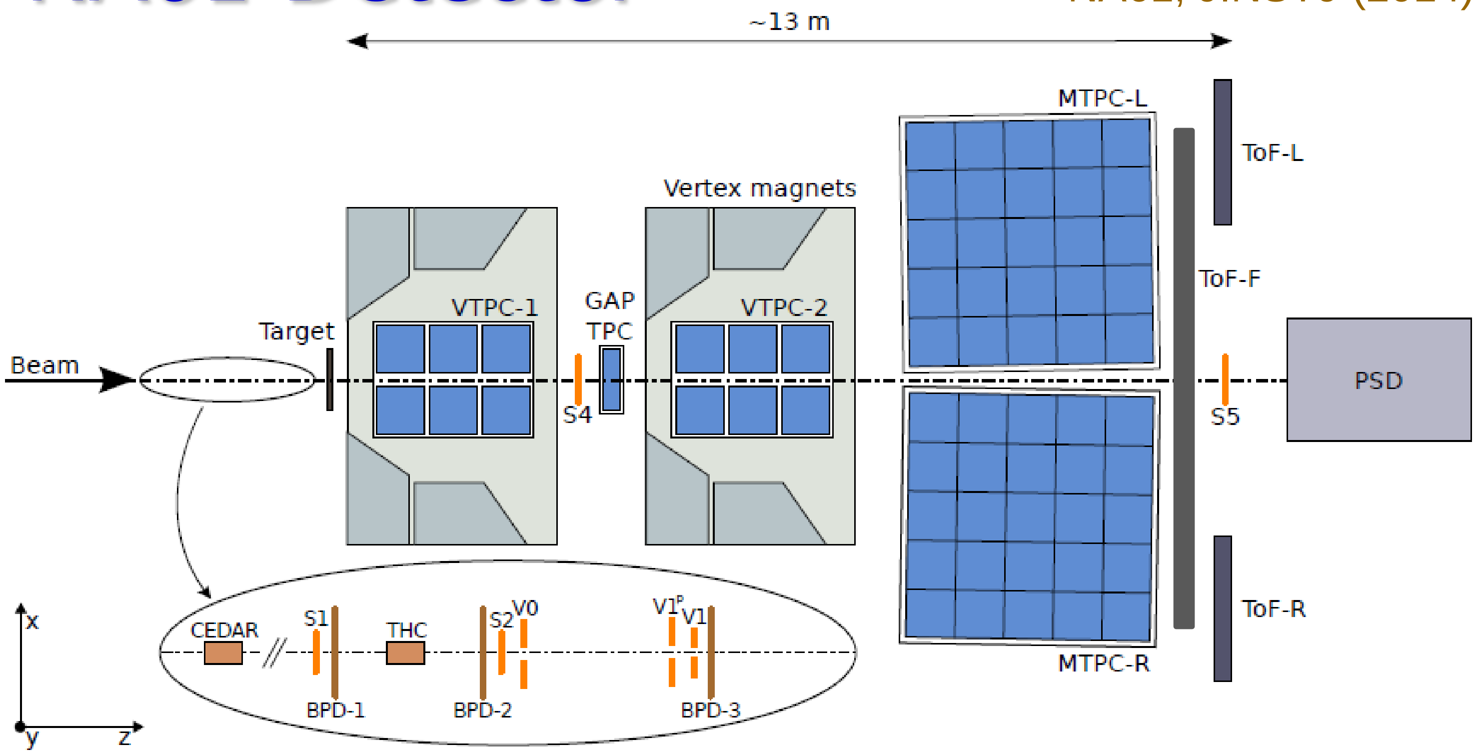
note: this is not a cross section
it shows the distributions of π, K, … contributing to the ν flux at SK

need to cover this kinematical region and identify the outgoing hadrons
K component important for ν_e appearance signal

requires detector with large acceptance
with excellent particle ID capabilities
with high rate capabilities to accumulate sufficient statistics

The NA61 Detector

NA61, JINST9 (2014) P06005



large acceptance spectrometer for charged particles

4 large volume TPCs as main tracking devices

2 dipole magnets with bending power of max 9 Tm over 7 m length (T2K runs: ∫Bdl ~ 1.14 Tm)

high momentum resolution

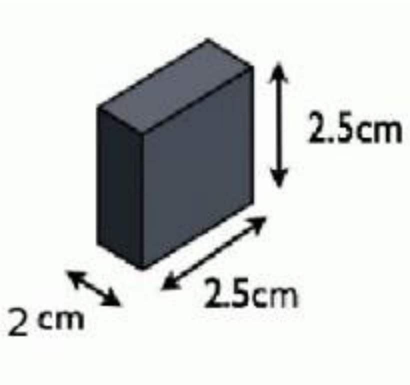
good particle identification: σ(ToF-L/R) ≈ 100 ps, σ(dE/dx)/<dE/dx> ≈ 0.04, $\sigma(m_{inv}) \approx 5$ MeV

new ToF-F to entirely cover T2K acceptance (σ(ToF-F) ≈ 100 ps, $1 < p < 5$ GeV/c, $\theta < 250$ mrad)

several additional upgrades are under way (DAQ/DRS, forward tracking, BPDs, …)

The NA61 Targets

2 different graphite (carbon) targets



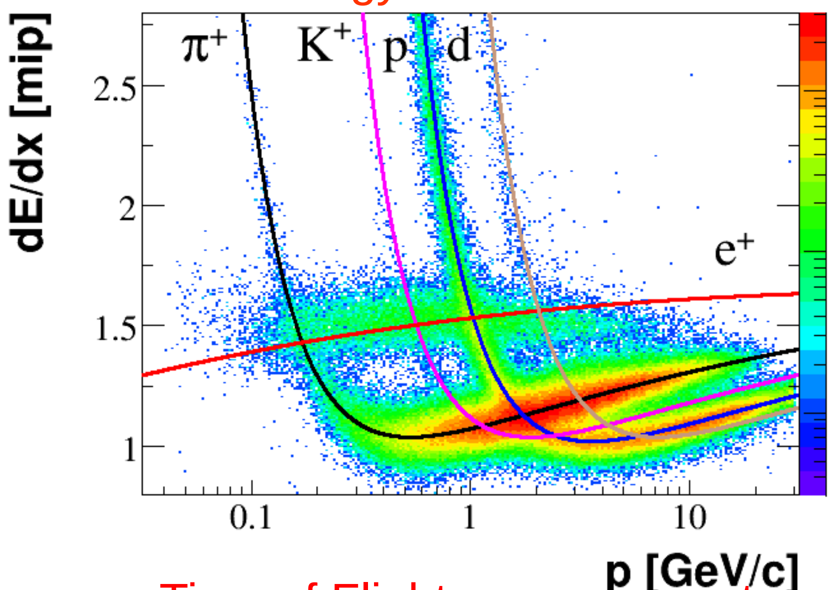
Thin Carbon Target
- length=2 cm, cross section 2.5 x 2.5 cm^2
- ρ = 1.84 g/cm^3
- ~0.04 λ_{int}

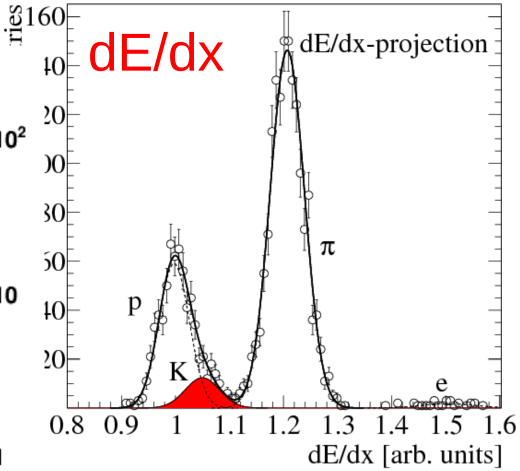
T2K replica Target
- length = 90 cm, Ø=2.6 cm
- ρ = 1.83 g/cm^3
- ~1.9 λ_{int}

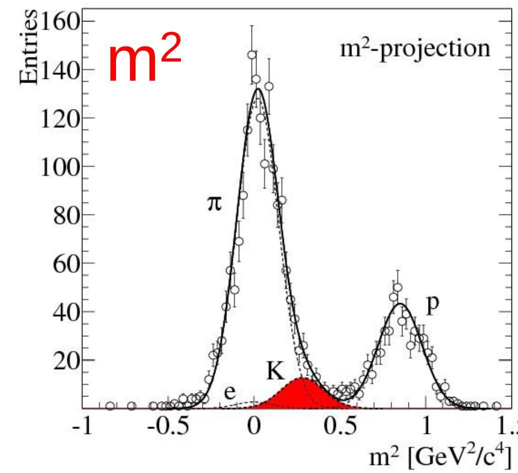
	2007 pilot run	2009 run	2010 run
Thin target:	~660k triggers	~6 M triggers ($\Rightarrow$ ~2×10^5 π^+ tracks in T2K acceptance)	
Replica target:	~230k triggers	~2 M triggers	~10 M triggers

Particle Identification in NA61

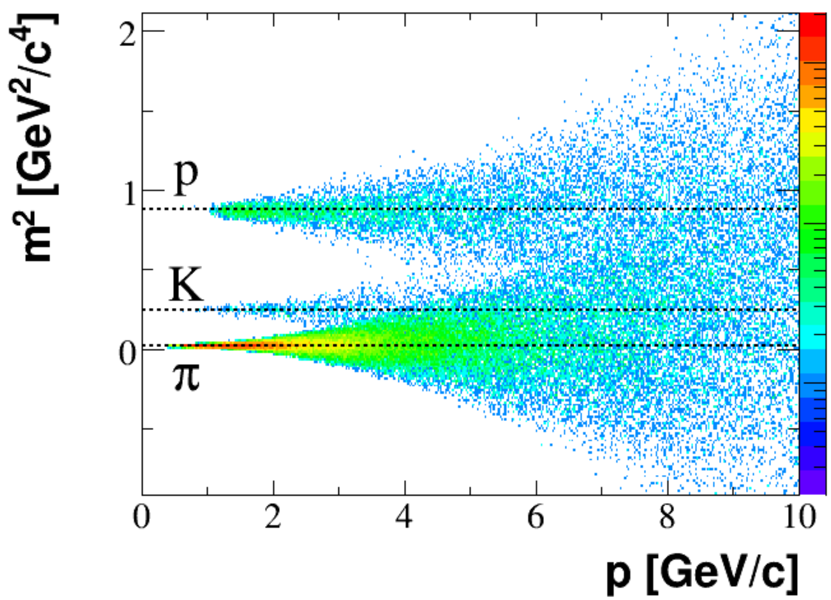
Energy loss in TPCs



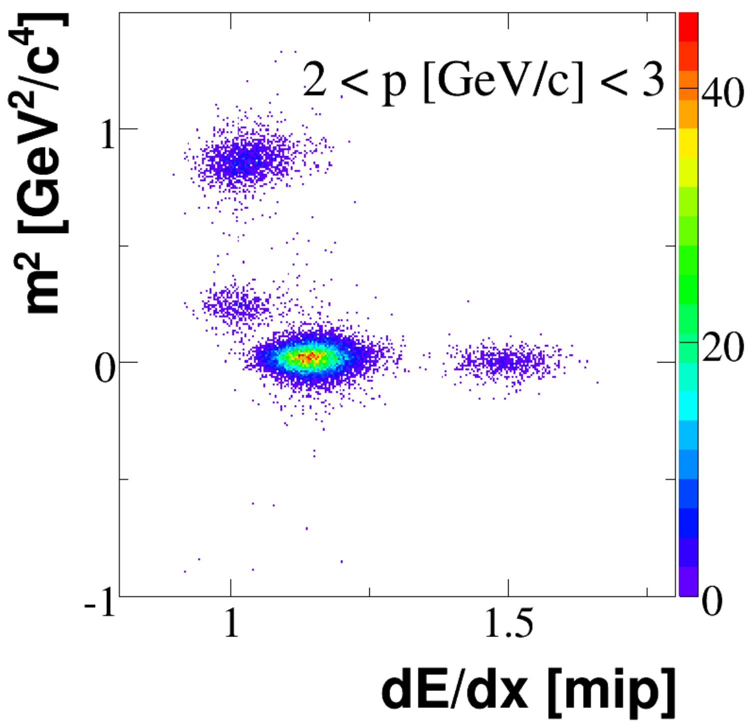




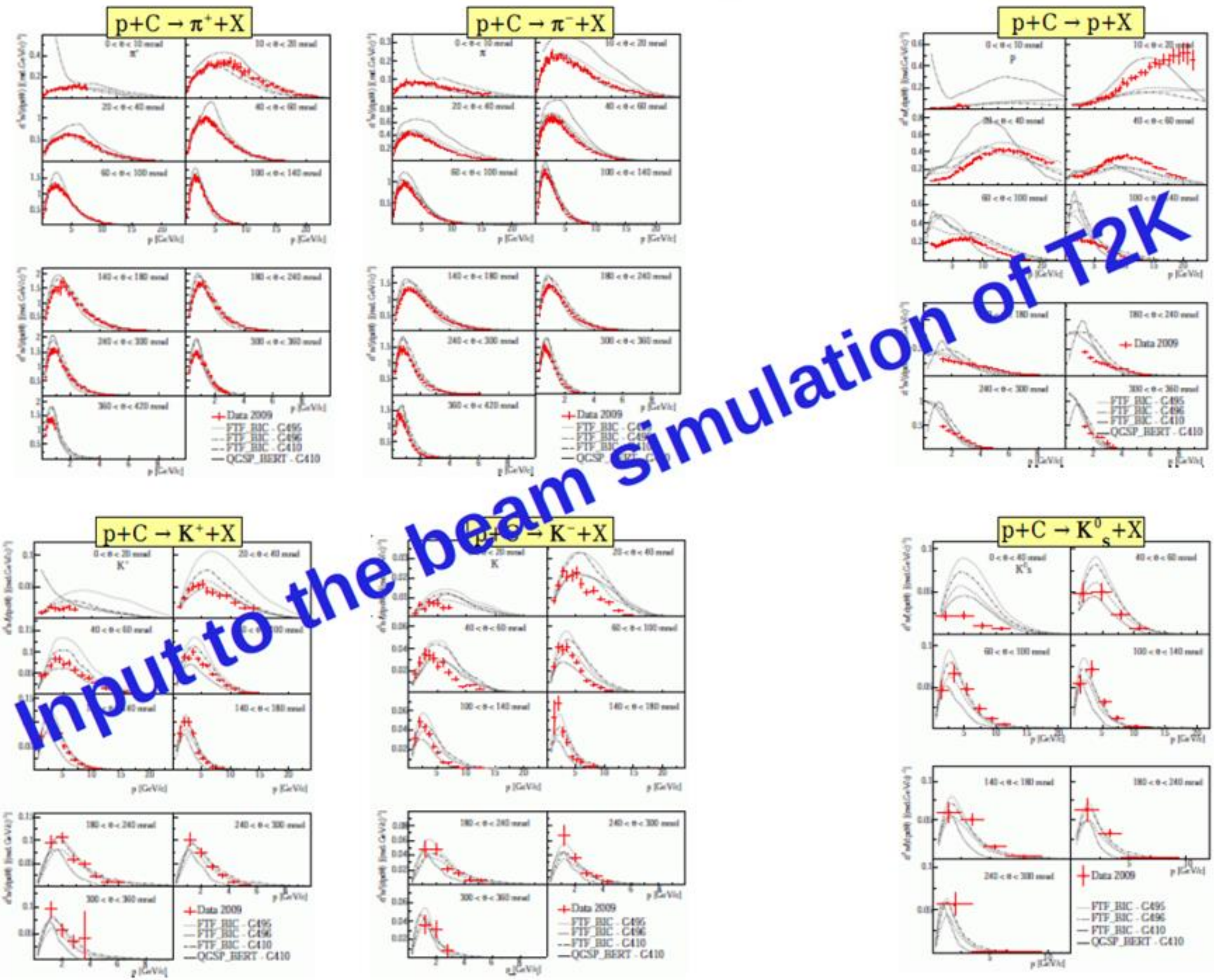
Time of Flight measurements



combined ToF + dE/dx



Input to the beam simulation of T2K



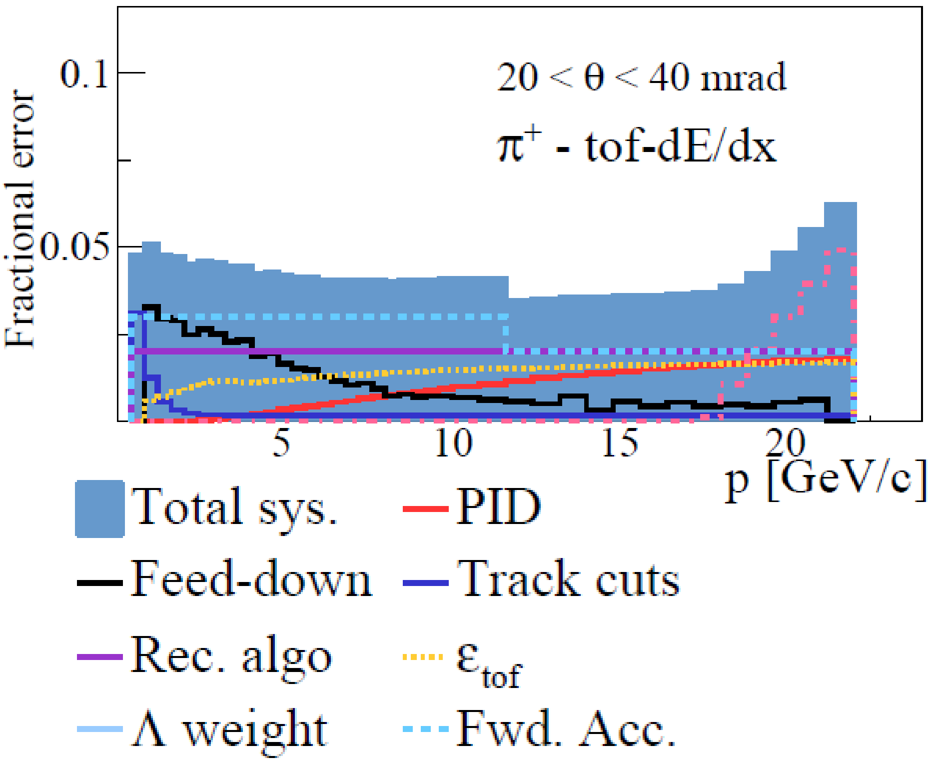
NA61 p + C → π^+ + X Uncertainties (dN/dp)

Compared to 2007 data:

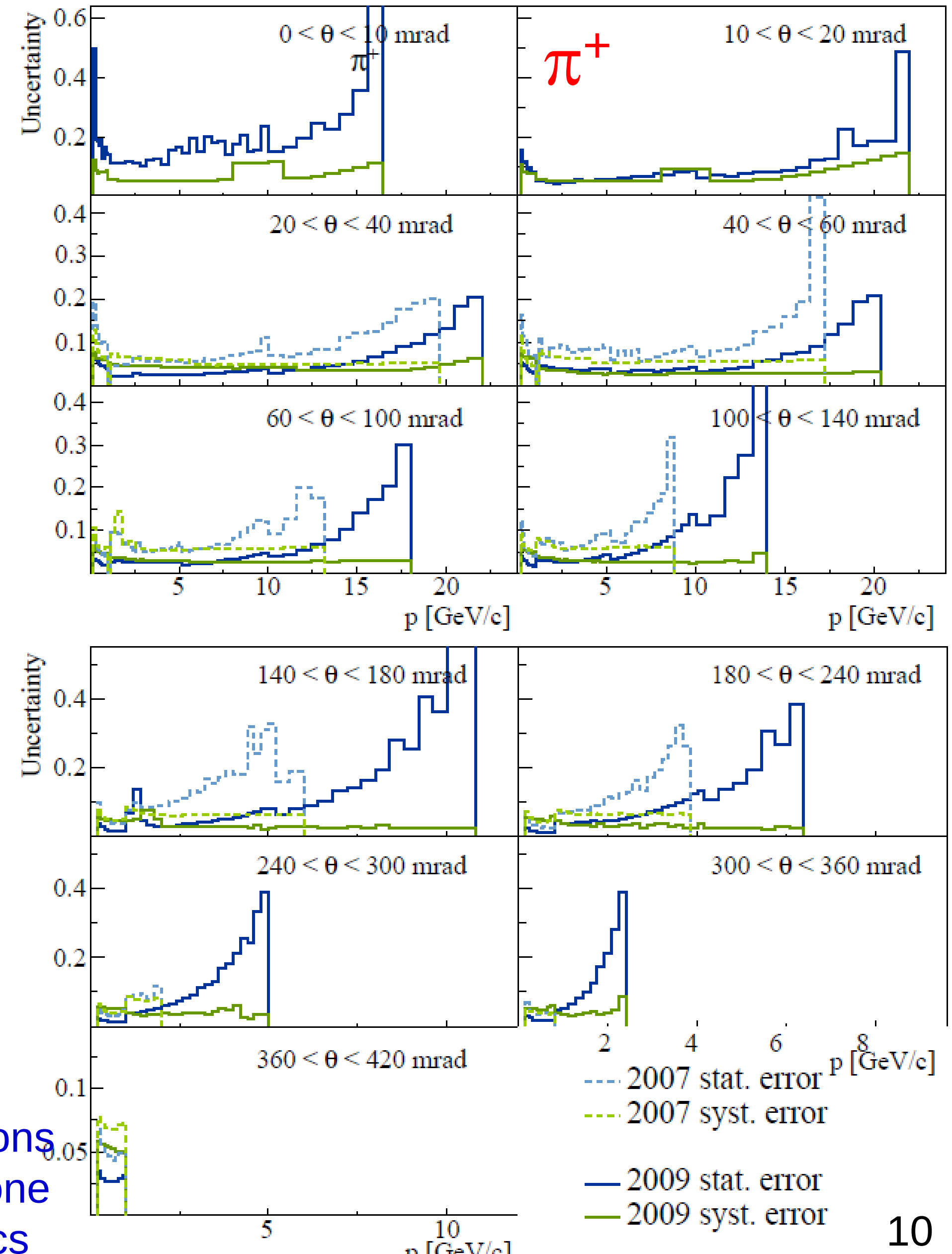
statistical uncertainty improved ~3×

systematical uncertainty reduced ~2×

NA61, arXiv:1510.02703



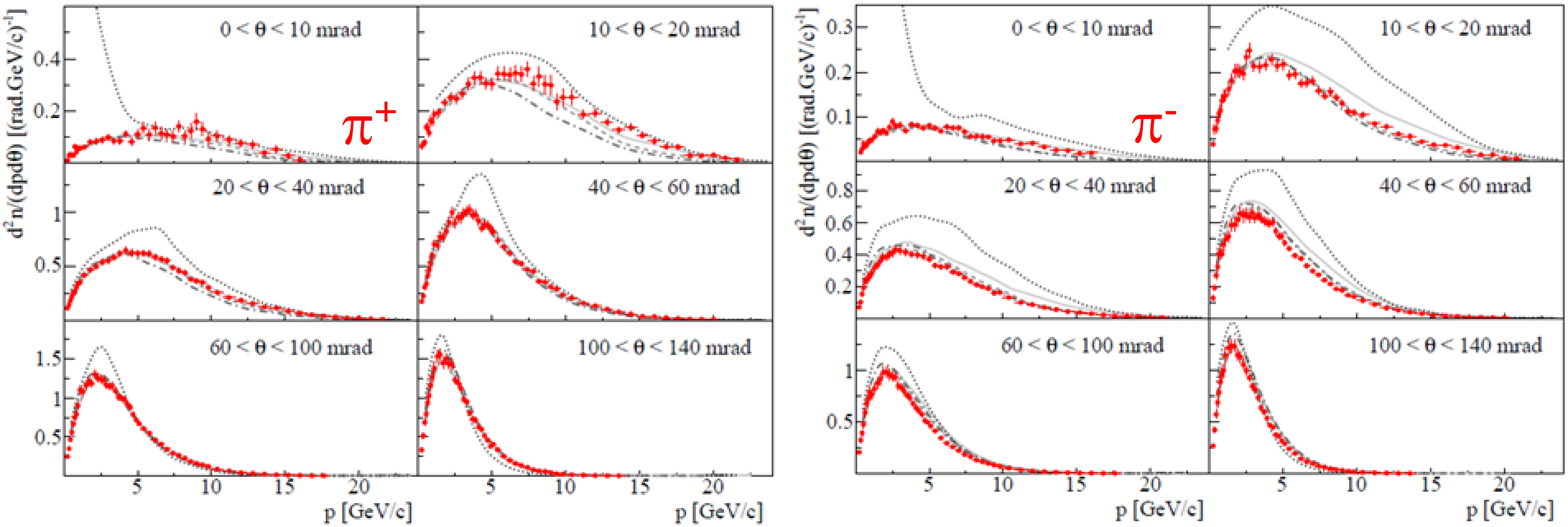
normalization error ~2%

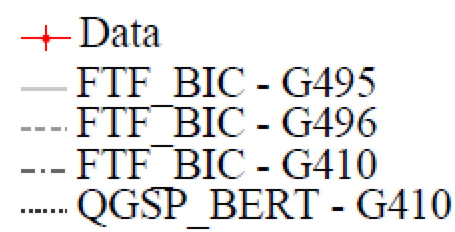


1. systematic uncertainties due to small contributions from various sources not a particular dominating one
2. some kinematical regions dominated by statistics

Comparison with Hadroproduction Models

NA61, arXiv:1510.02703





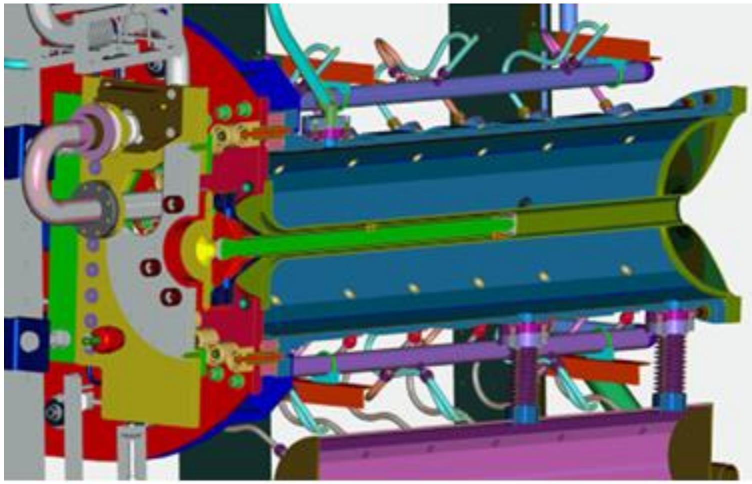
Comparison of NA61 data to some GEANT4 models

None of the existing hadroproduction model describes satisfactorily the ensemble of NA61 measurements (π+, π-, K+, K-, K^0, p, Λ)

New generation of hadroproduction models tuned to NA61 data ?

Which Hadron Production Measurements (2)

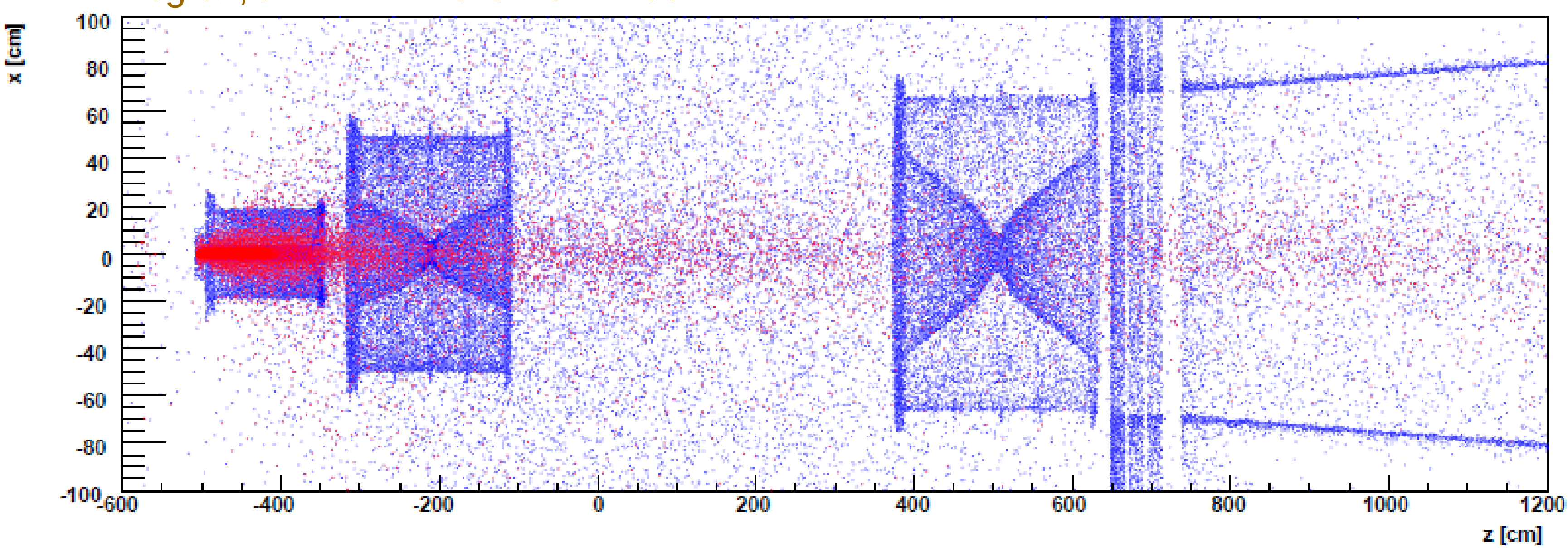
T2K target including 1st horn



blue: production point of neutrino parent particles

red: parents produced in the target or along decay chains

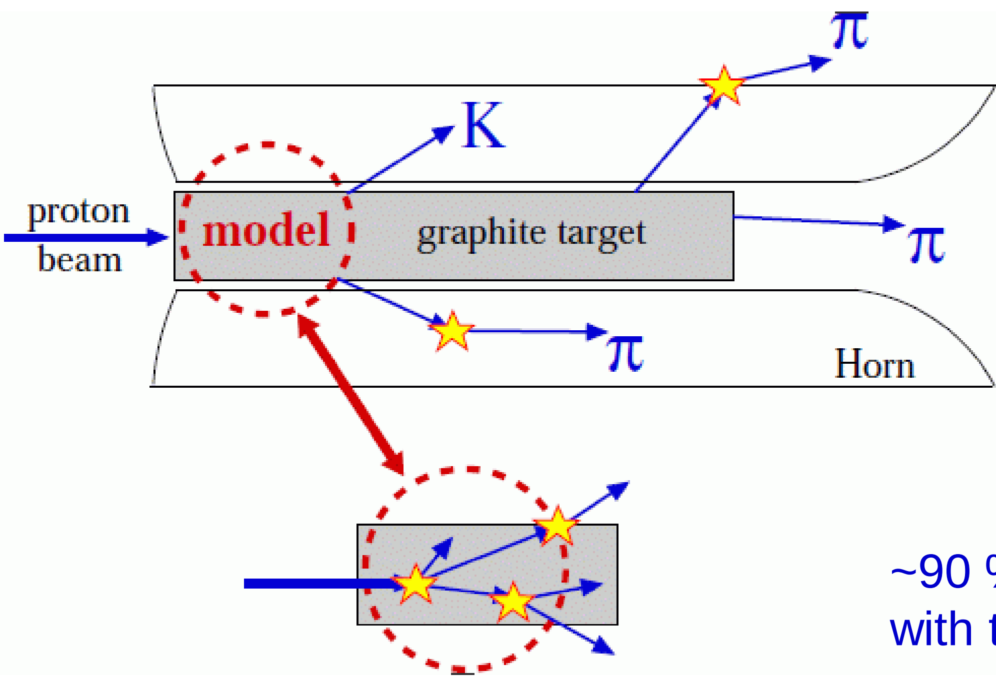
Abgrall,CERN-THESIS-2011-165



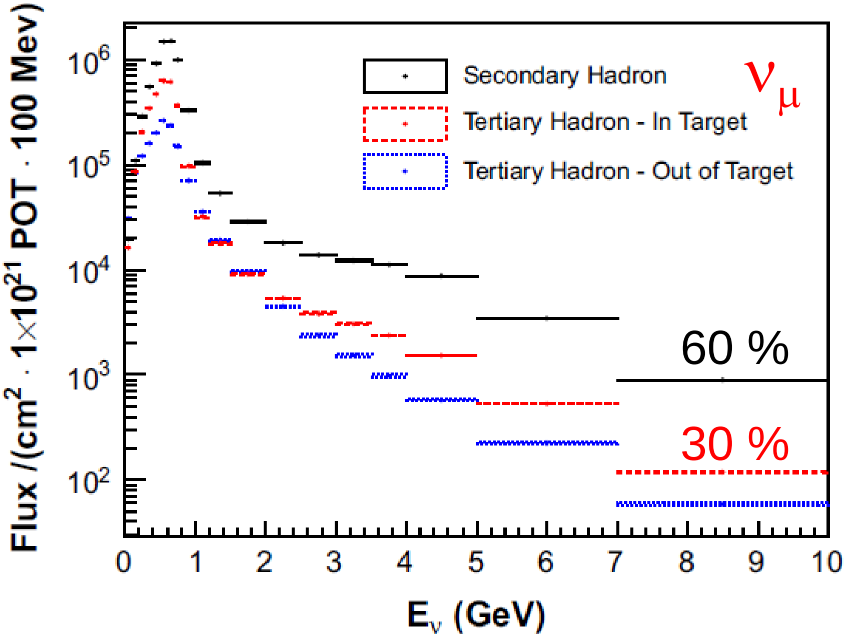
ν Flux Prediction with T2K Replica Target

Neutrinos originate from hadrons produced in **primary interactions** (~60%) and from hadrons produced in (re)interactions **in the production target** (~30%) and in the **surrounding materials in the beamline** (~10%).

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



NA61, NIM A701 (2013) 99



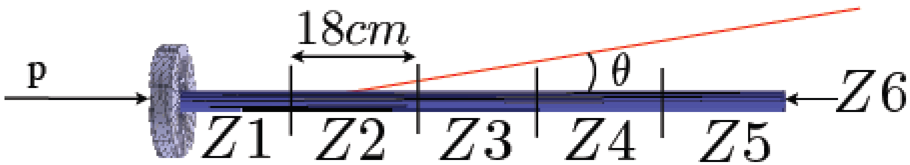
Replica target measurements account for the reinteractions in the target

~90 % of the neutrino flux can be constrained with the T2K replica target measurements

model dependencies are reduced down to 10 % as compared to 40 %

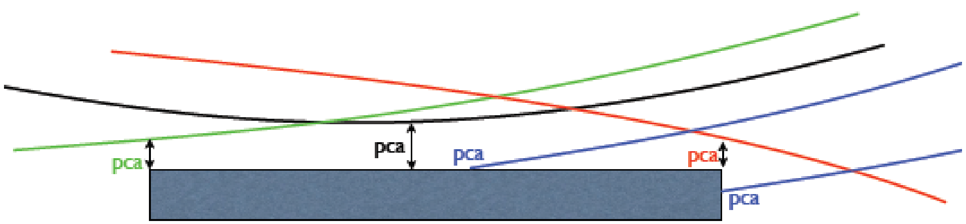
π^+ Hadroproduction on T2K Replica Target

Hadron multiplicities are measured at the target surface in bins of {p, θ, z}

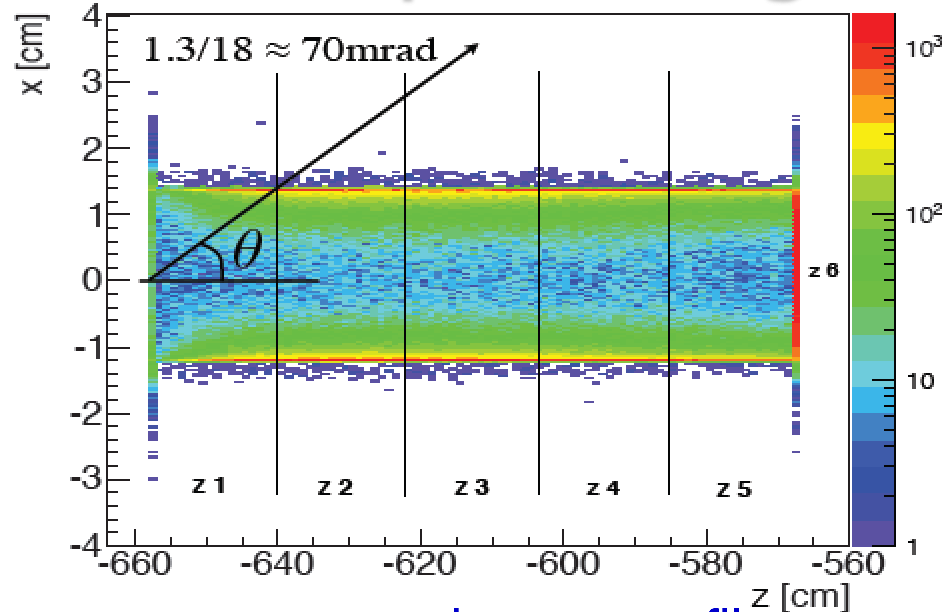


Tracks are extrapolated backwards to the target surface (point of closest approach)

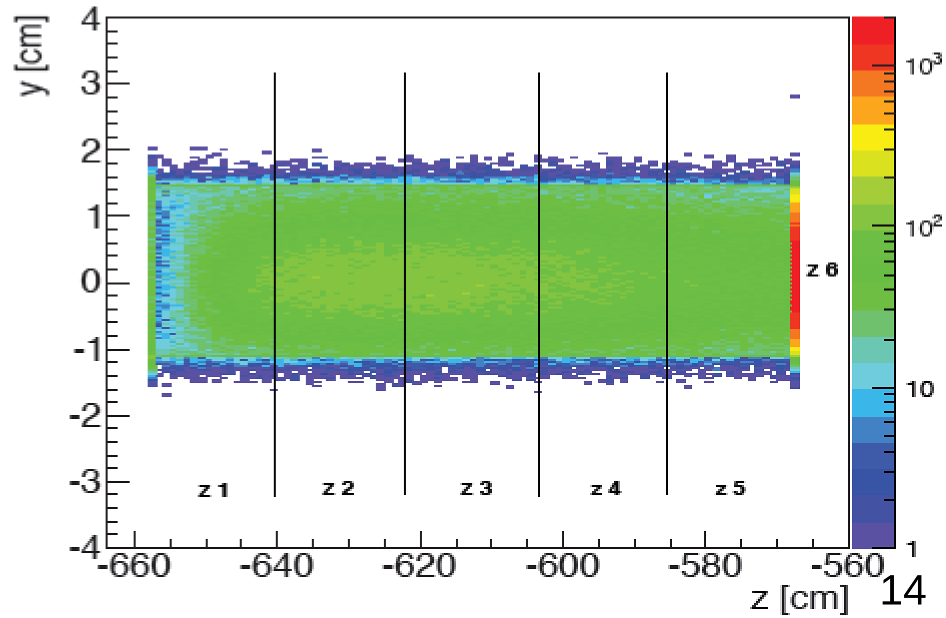
the target is sliced in 5 bins in z
+ downstream exit face



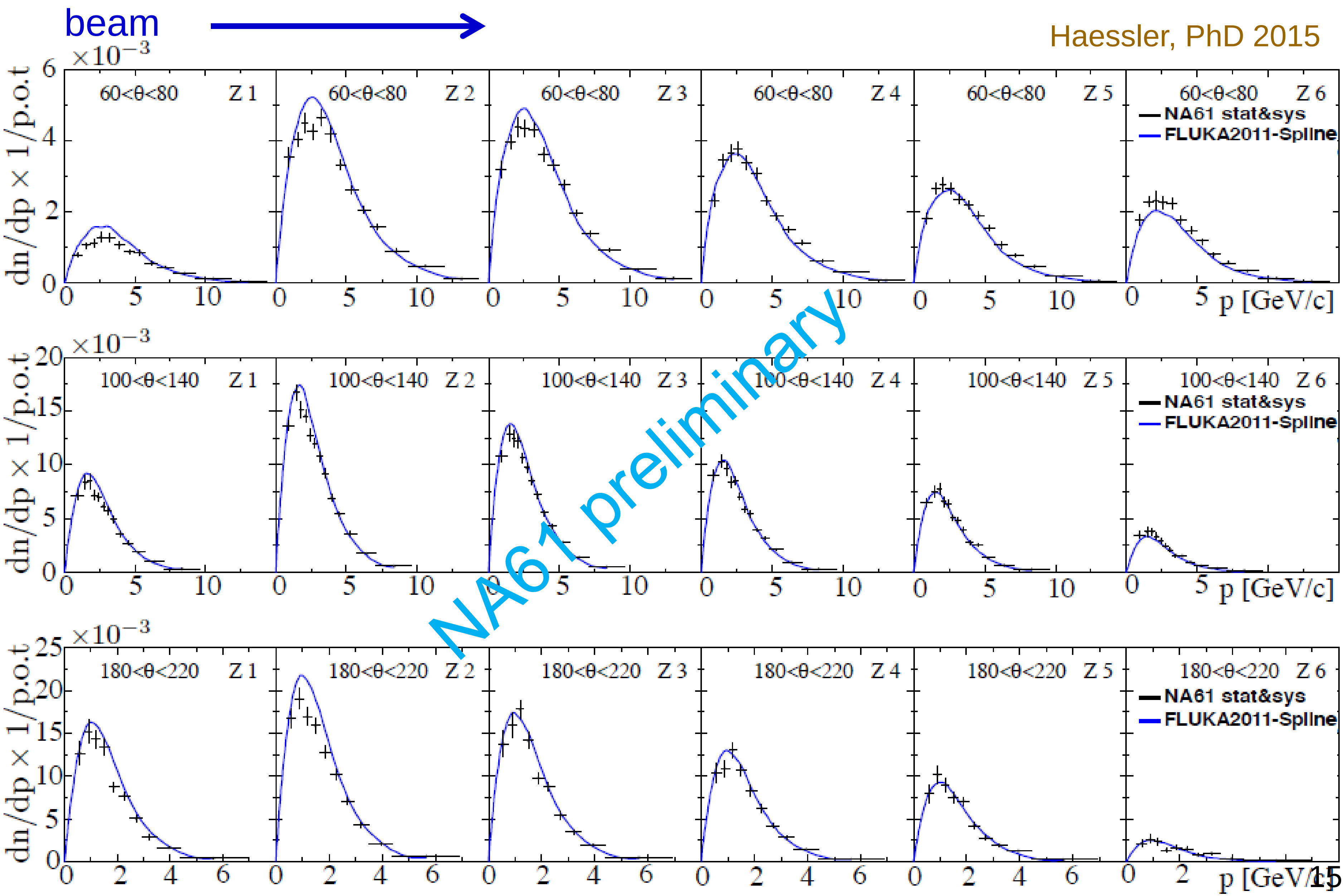
No interaction vertex reconstruction
Will be studied also as a function of r



reconstructed target profile



π^+ Spectra on Target Surface



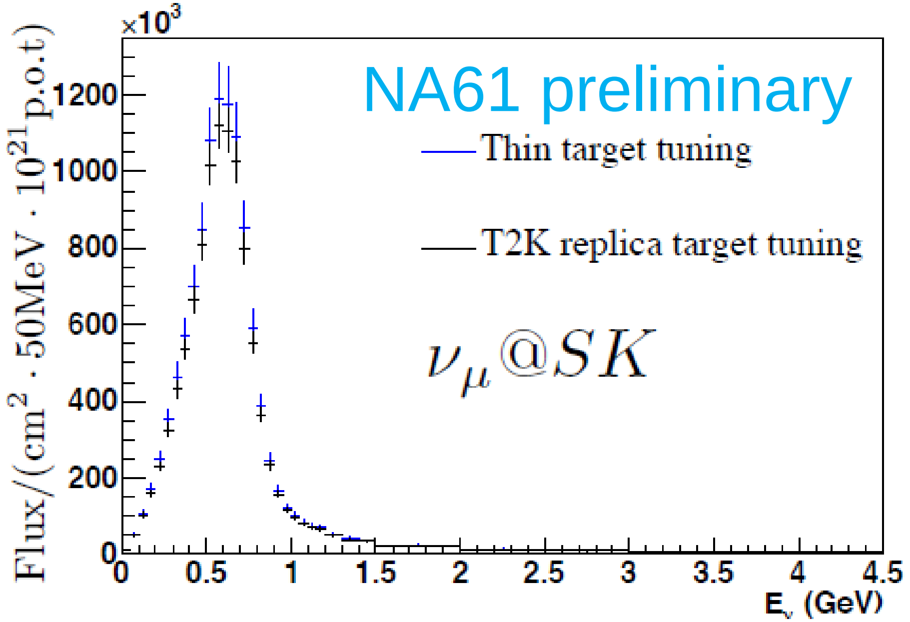
ν Flux Prediction with T2K Replica Target (2)

2009 data

comparison of ν flux predictions

thin target vs. replica target

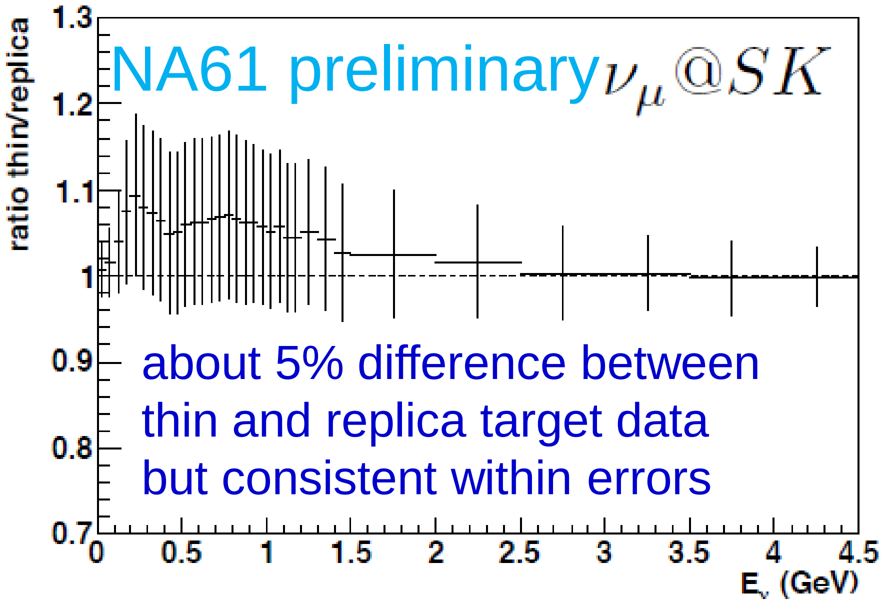
Haessler, PhD 2015, not T2K official result



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

thin to replica target ν flux prediction

secondary interactions modeled with MC model of thin target



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

For the ν_μ flux described by these data (outside target interactions excluded) the uncertainty is below 5% for the oscillation peak region (E_ν ~ 600 MeV)

Conclusions – NA61

NA61 is providing valuable data to constrain the T2K neutrino flux

Over the last 5 years significant progress in understanding neutrino fluxes

$\rightarrow$ ~10 % uncertainty

Hadro production measurements require

- large acceptance detectors with excellent PID over whole kinematical range
- large statistics
- different targets and materials to study various particle production effects
- good vertexing for replica targets

Hadroproduction of $\pi^{+/-}$, $K^{+/-}$, p, K^0_s, Λ in p+C (and p+p) interactions at different energies

Soon also on Be, Al, and Pb targets

High precision NA61/SHINE data presents a challenge for hadroproduction models

None of existing models describes satisfactorily the ensemble of $p + C \rightarrow h + X$ data

Input to new hadroproduction models $\rightarrow$ improvements?

At present, NA61 only experiment capable of making hadroproduction measurements

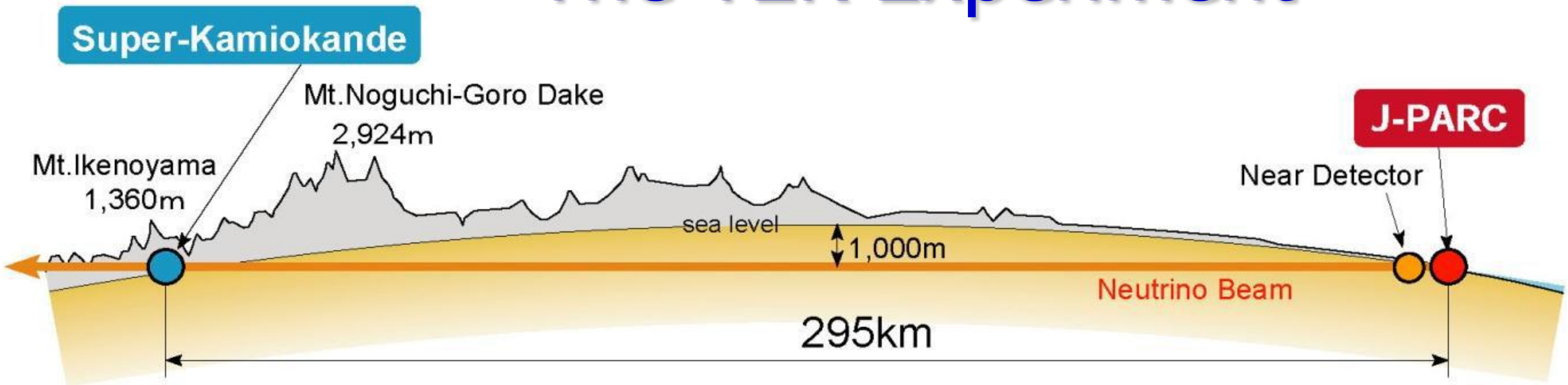
NA61 very likely to continue taking data for the next 5+ years

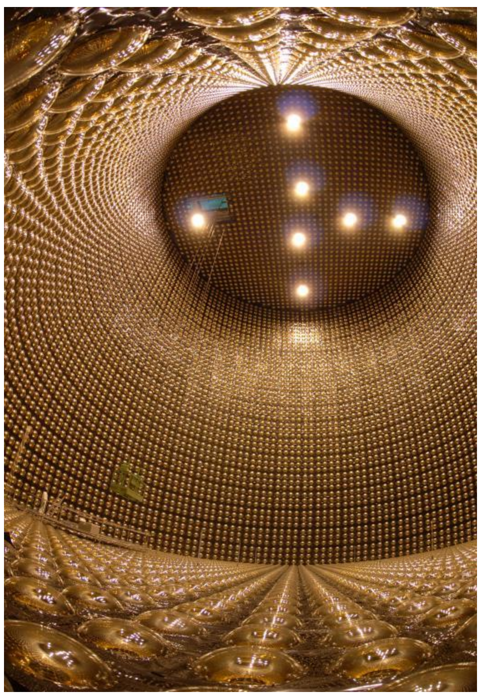
- complete the analysis of the T2K data
- start measurements for NuMI and LBNF
- plan for Hyper-K?
- detector being constantly upgraded and analysis tools being improved

Recent Results from T2K
Overall Systematic Uncertainties

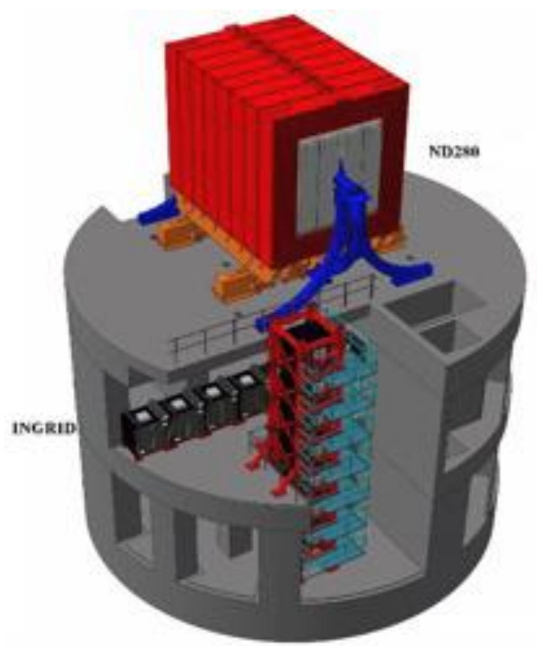
see also talk by Takahiro Hiraki (Friday morning)
Recent Neutrino Oscillation Results from T2K

The T2K Experiment

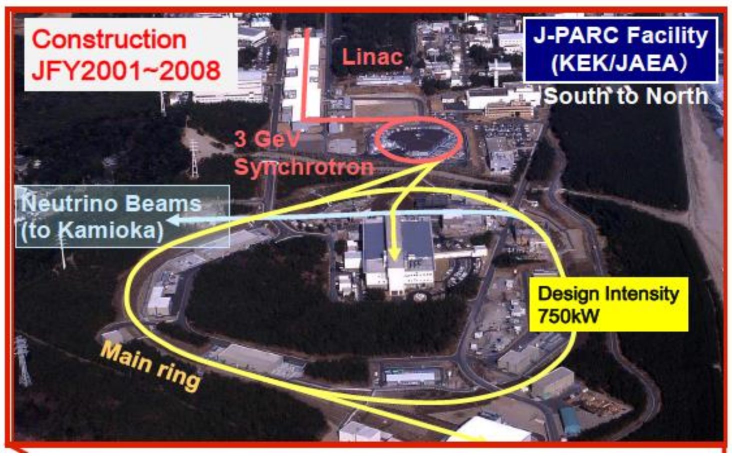




Super–Kamiokande
far detector

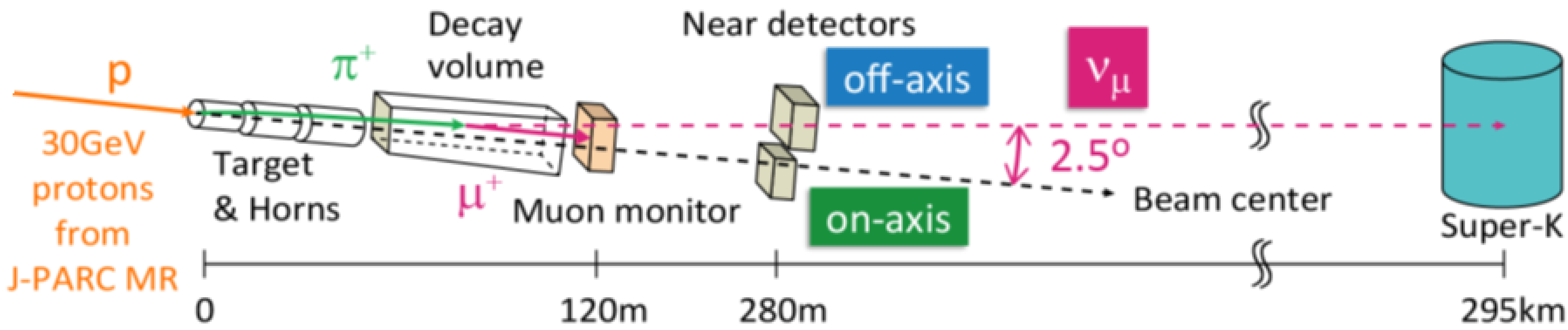


Near detectors
Off-axis: ND280
On-axis: INGRID



Neutrino source
mainly ν_μ

Neutrino Source at J-PARC



Neutrinos (mainly ν_μ) produced by interactions of 30 GeV protons on a 90 cm long graphite rod

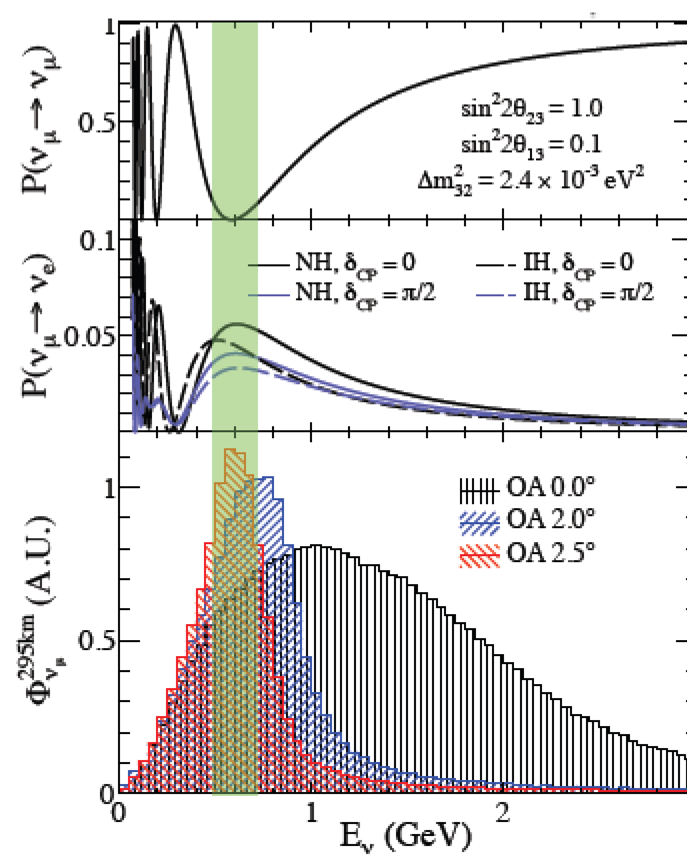
(anti-)ν beam is created in the decay in flight of π / K / μ

2.5^0 off-axis neutrino beam

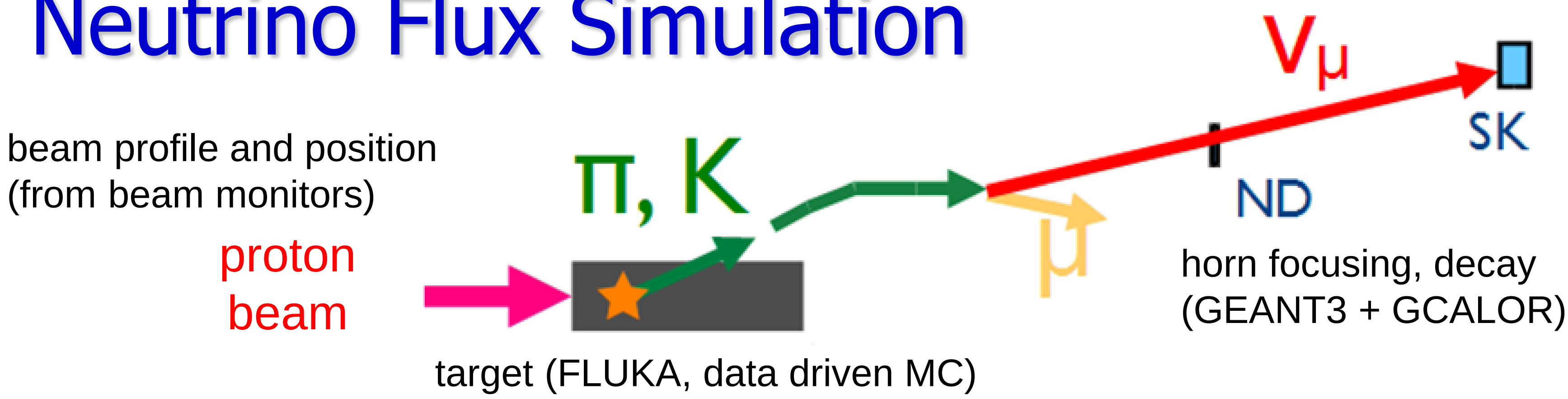
- Very narrow energy spectrum
- Neutrino beam energy "tuned" to oscillation maximum
- Reduced high energy tails
- E_ν almost independent of parent pion energy

Neutrino beam predictions rely on modeling the proton interactions and hadron production in the target

Horn focusing partially cancels the p_T dependence of the parent meson



Neutrino Flux Simulation



Flux prediction from data-driven simulation

Proton beam monitor measurements

Horn field measurements

Beamline components alignment

External hadro-production data used to constrain predictions from generators

- π / K - use CERN NA61/SHINE hadroproduction measurements
- re-interactions in target of primary hadrons and π / K outside NA61 acceptance based on FLUKA
- secondary interactions outside the target (i.e. horns) based on experimentally-measured cross sections

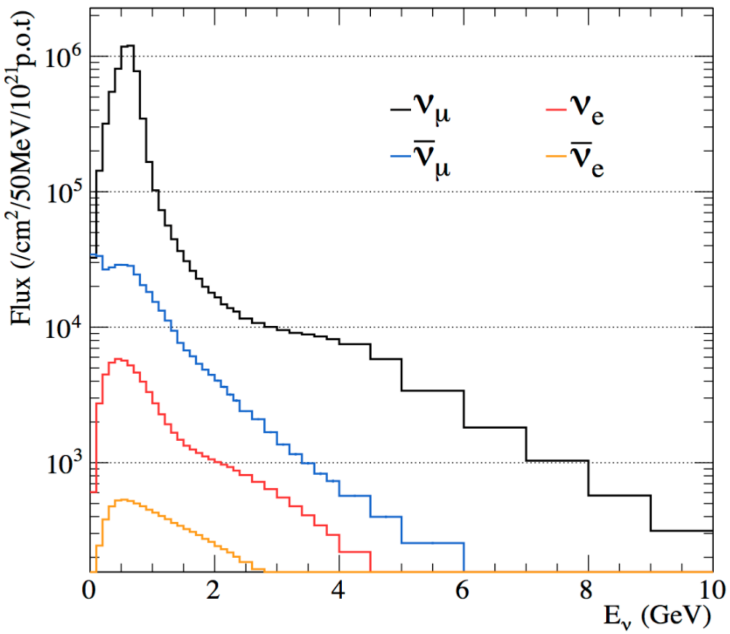
GEANT3 + GCALOR transport simulation used downstream of target

Dominant source of systematic error

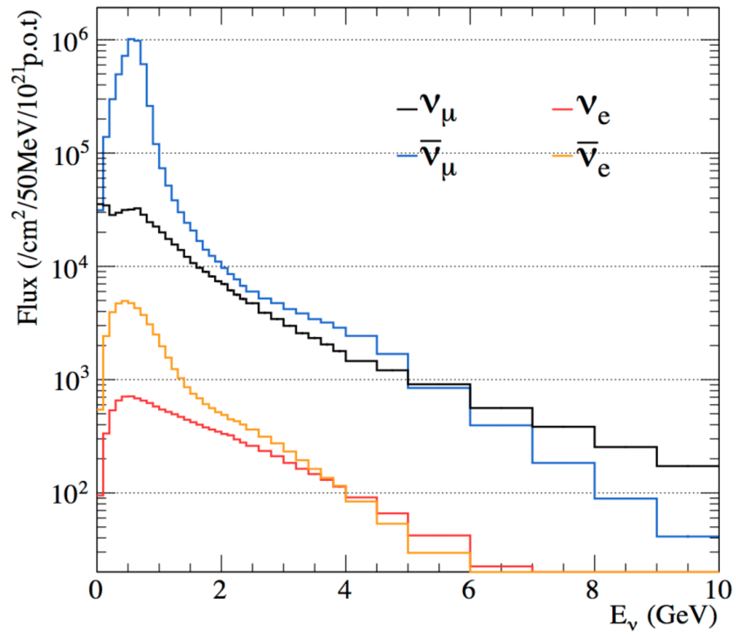
Neutrino Flux Predictions

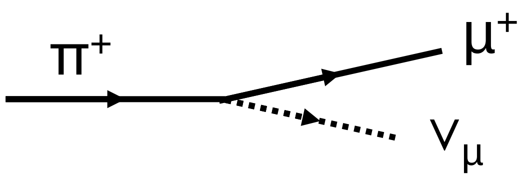
T2K, PRD87 (2013) 012001

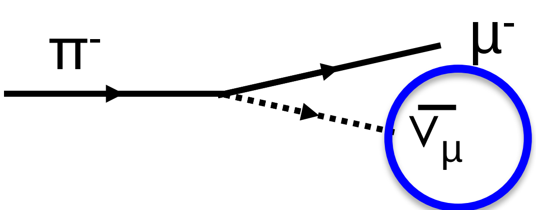
Neutrino mode operation



Antineutrino mode operation







FLUKA/Geant3 based neutrino beam simulation

Significant wrong sign component in antineutrino mode
increases in event rate due to lower antineutrino cross section

Intrinsic electron neutrino component ~0.5% near the peak

Neutrino Flux Uncertainties

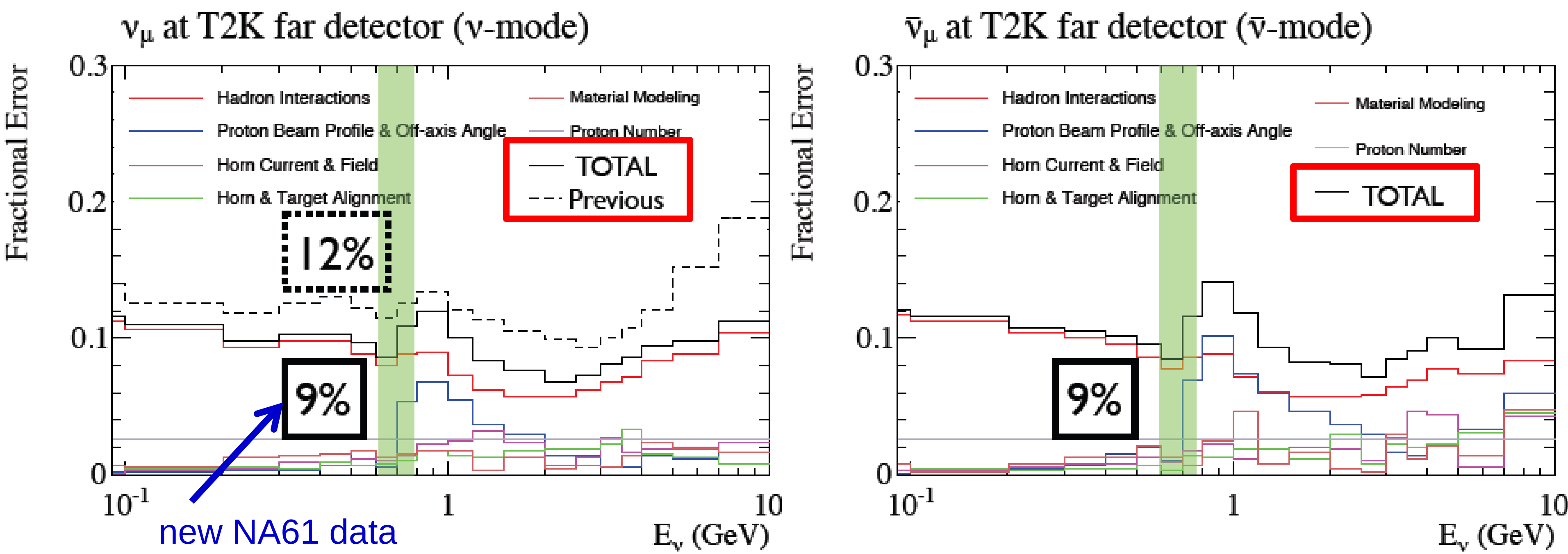
Beamline related uncertainties

- proton beam profile
- off-axis angle
- horn current and field

Hadron interaction model uncertainties

- NA61 uncertainties
- re-interactions
- secondary hadron production

At T2K peak energy, flux uncertainty has decreased to ~10%



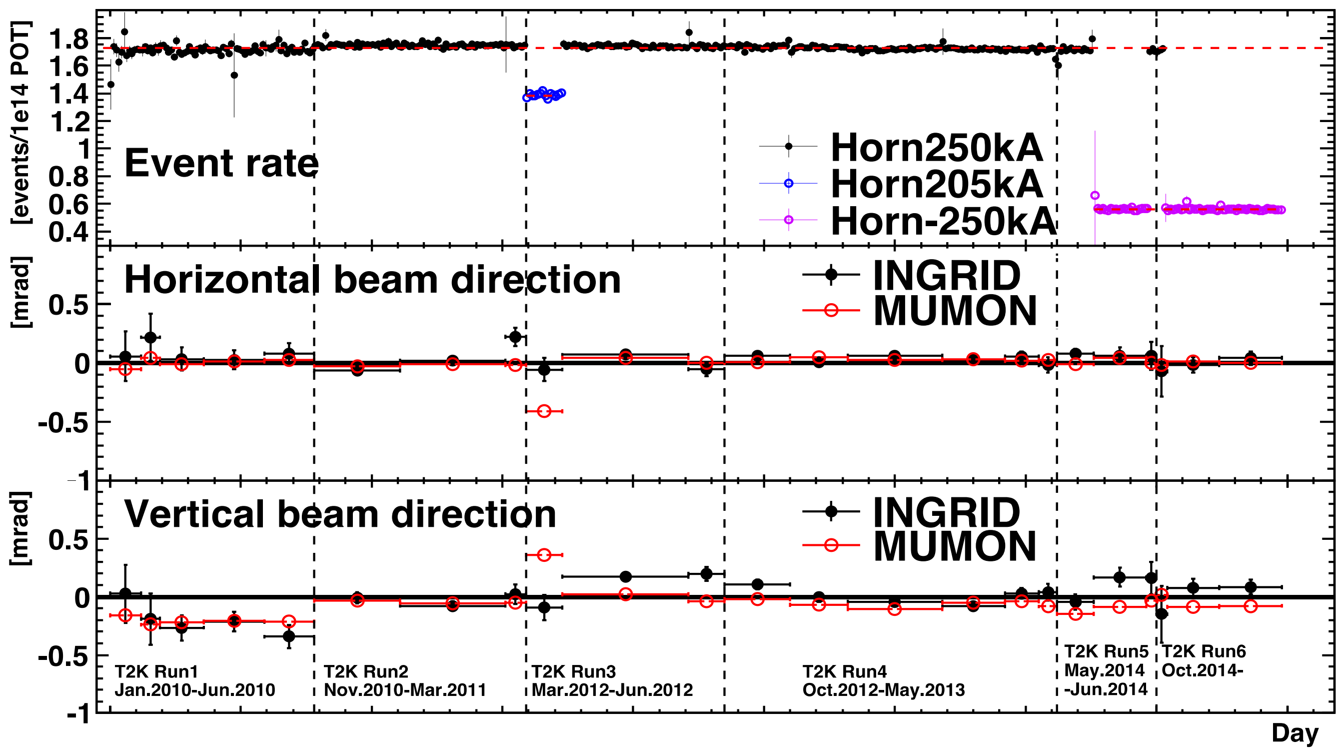
Dominant flux uncertainties stem from hadron interactions

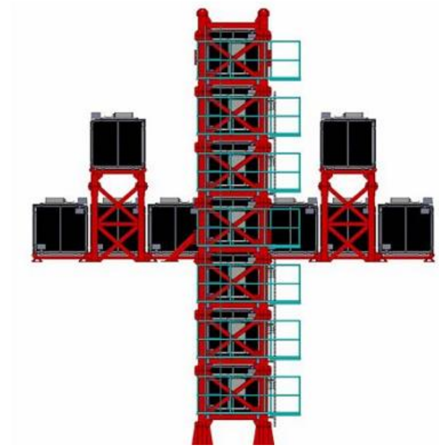
Uncertainties are comparable for neutrino mode and antineutrino mode operation

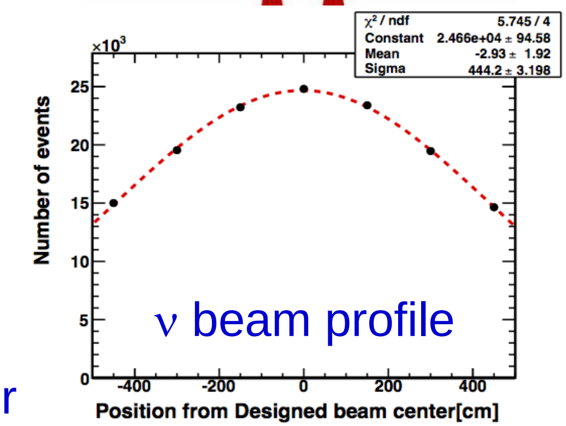
Replica target data from NA61/SHINE is being incorporated in the T2K flux prediction
→ further reduce systematics

Beam Stability

INGRID – on-axis







Neutrino beam profile measured with on-axis INGRID detector

scintillator / iron detectors (0 - 0.9 degrees off-axis)

POT normalized event rate stable to better than 1%

beam direction is stable to within 1 mrad
(1 mrad corresponds to a 2% shift in the peak of the off-axis neutrino energy)

Oscillation Analysis Overview

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \to \nu_e)$$

Fit observed rate of ν_μ and ν_e to determine the oscillation probability P. Depends on:

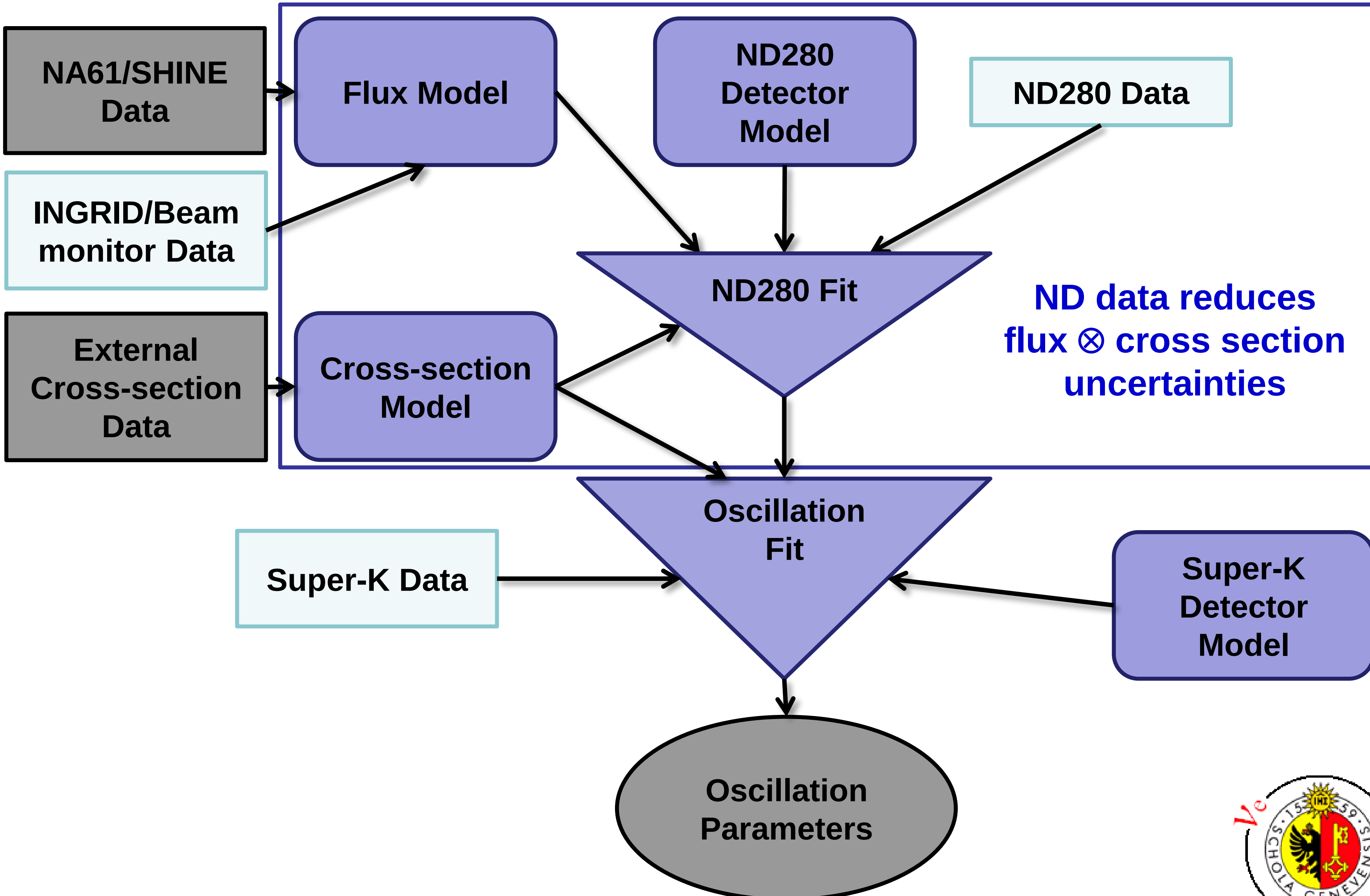
Neutrino flux prediction	Neutrino cross section model	Far Detector selection, efficiency

Reduce the error on the rate of ν_μ with the near detector.

$$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

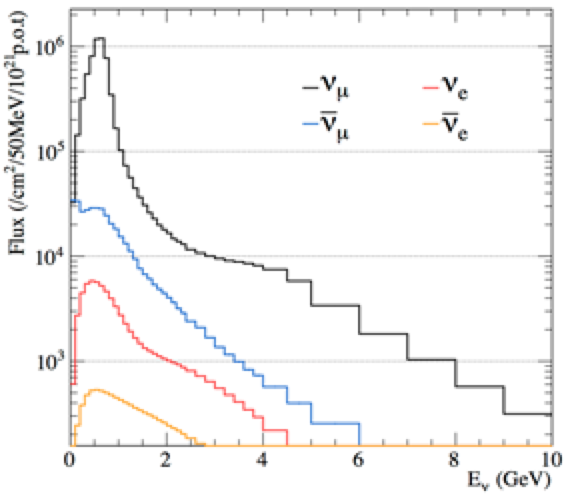
Neutrino flux prediction	Neutrino cross section model	Near Detector selection, efficiency

Oscillation Analysis Strategy

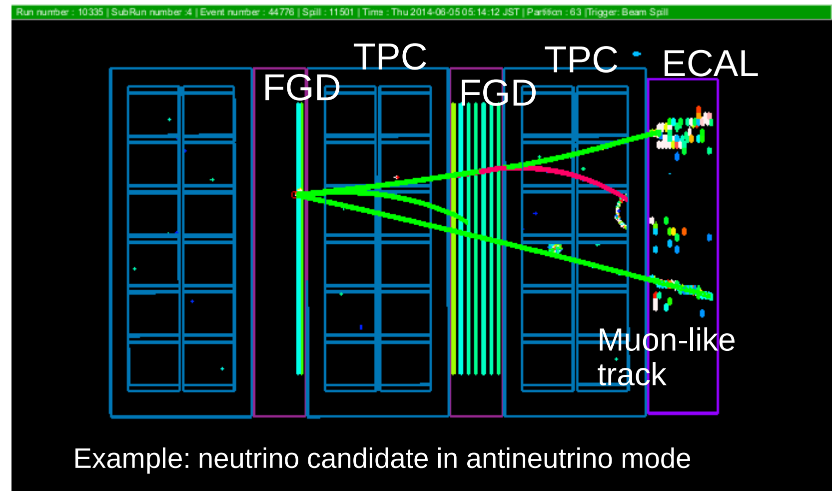


Sources of Systematic Uncertainties

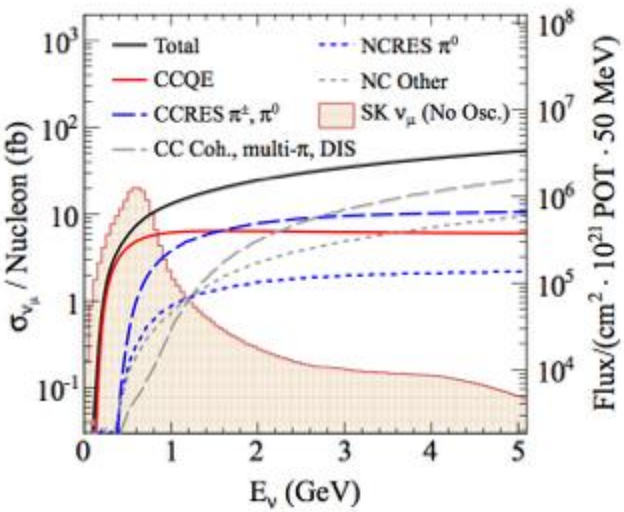
Neutrino flux



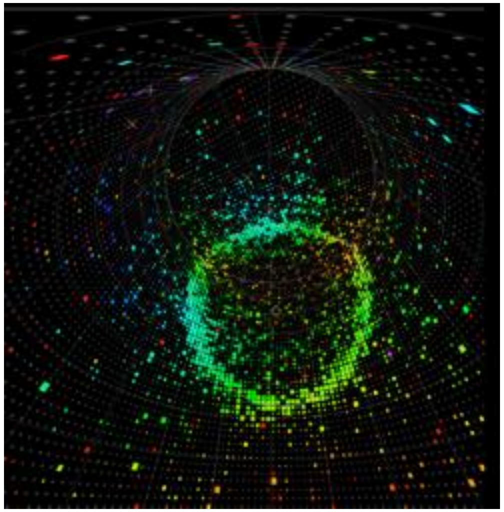
Near detector response



Neutrino interactions



Far detector response

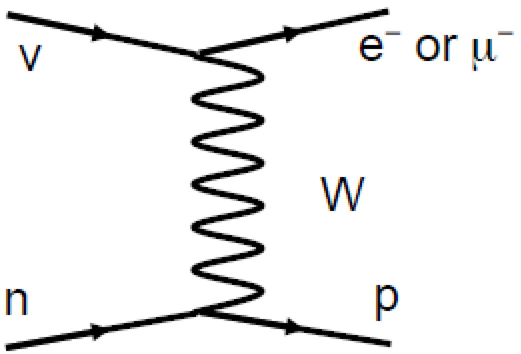


Neutrino Interactions

Oscillation probability depends on neutrino energy.

In T2K energy range, dominant process is Charged-Current Quasi-Elastic

CCQE



Neutrino energy from measured lepton momentum and angle

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest

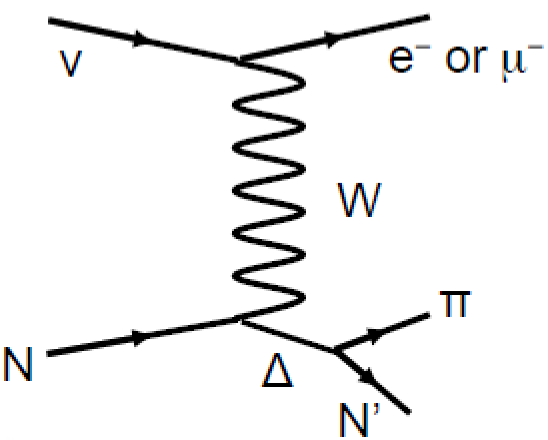
Additional significant processes:

CCQE-like multi-nucleon interaction

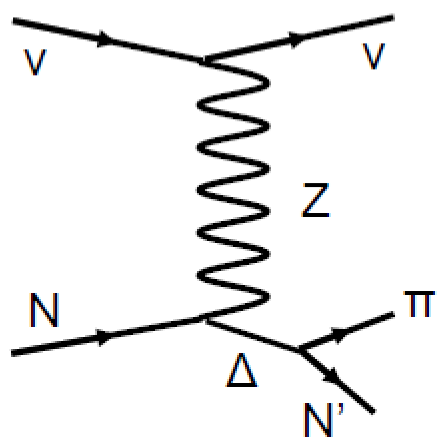
Charged current single pion production (CCπ)

Neutral current single pion production (NCπ)

CCπ



NCπ



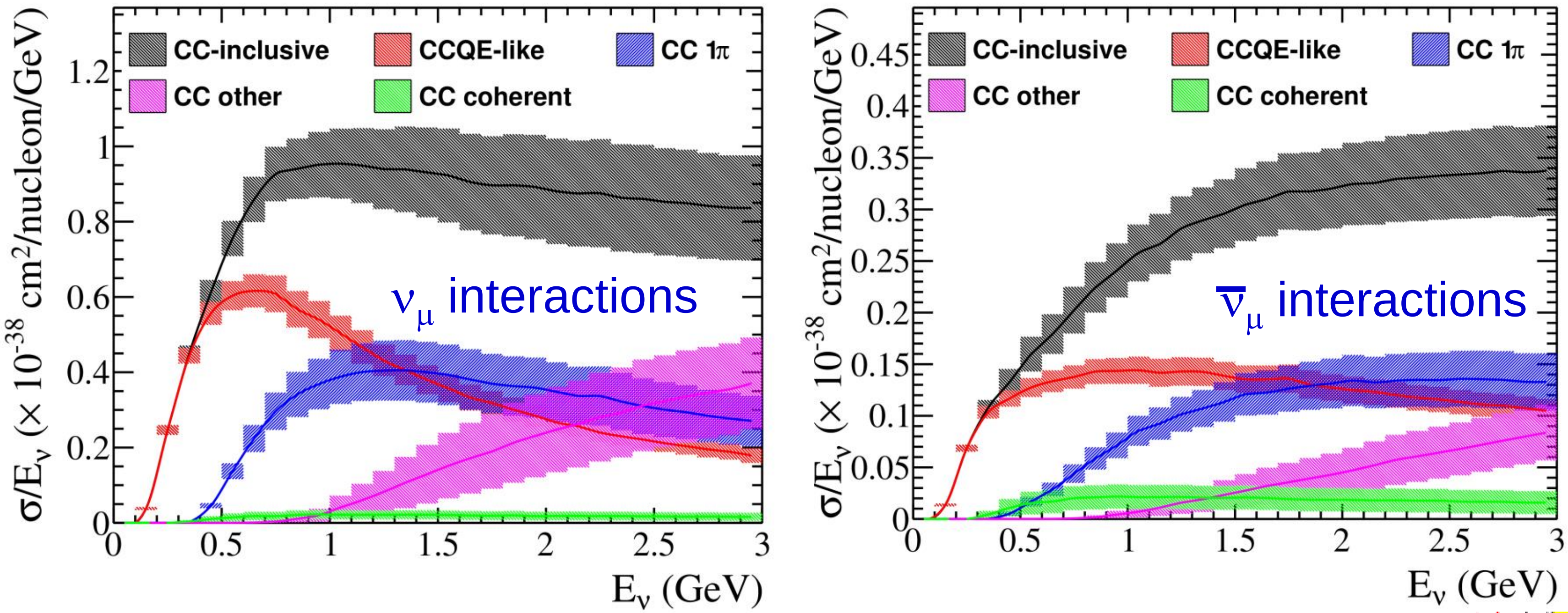
Improved Neutrino Interaction Model

Most recent NEUT generator tuned to external data (MiniBooNE and MINERνA)

Improved CCQE description:

- Relativistic Fermi Gas (RFG) + Random Phase Approximation (RPA)
- Spectral function model (implemented but not used for this analysis)
- Meson Exchange Current (MEC) CCQE-like scattering [Nieves et al.]

Resonant π production [Rein-Sehgal] retuned with modified form factors for Δ's



Cross-section model uncertainties come from underlying model parameters and normalization.

There are tensions with some data sets.

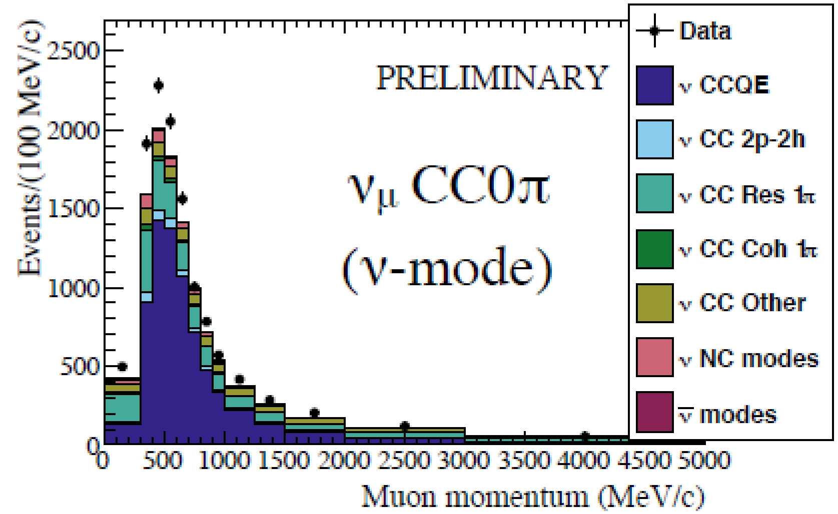
Near Detector Constraints

Expected number of events at the far detector is tuned using a binned likelihood fit to the ND280 data (in bins of p_μ and θ_μ) taking into account

- variations in the flux model parameters
- cross section model parameters
- ND detector uncertainties

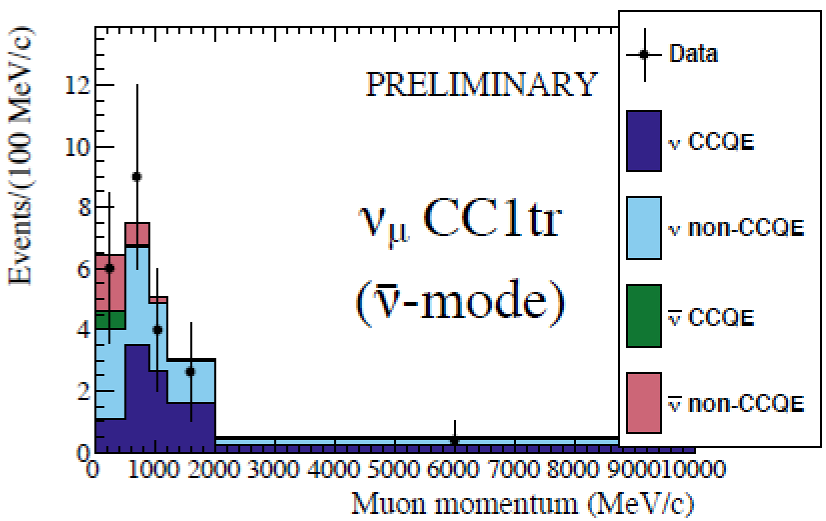
ν – mode data

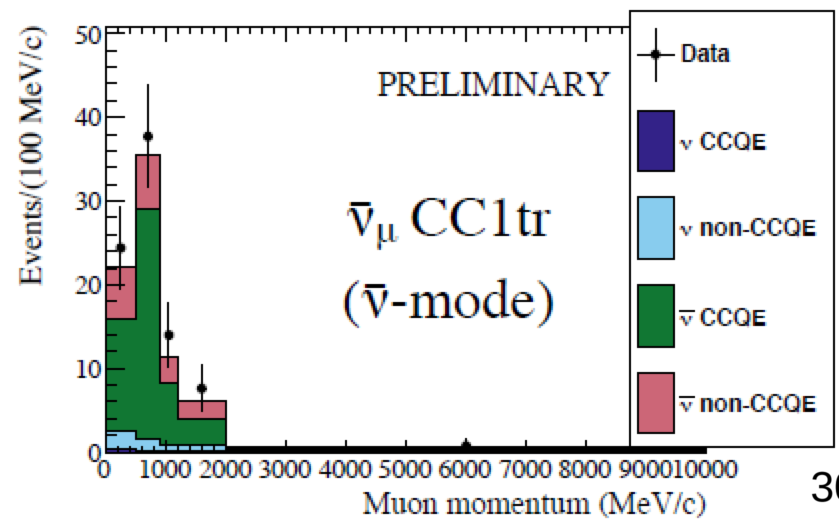
- ν_μ interactions divided into $CC0\pi$, $CC1\pi$, CCother



$\bar{\nu}$ – mode data

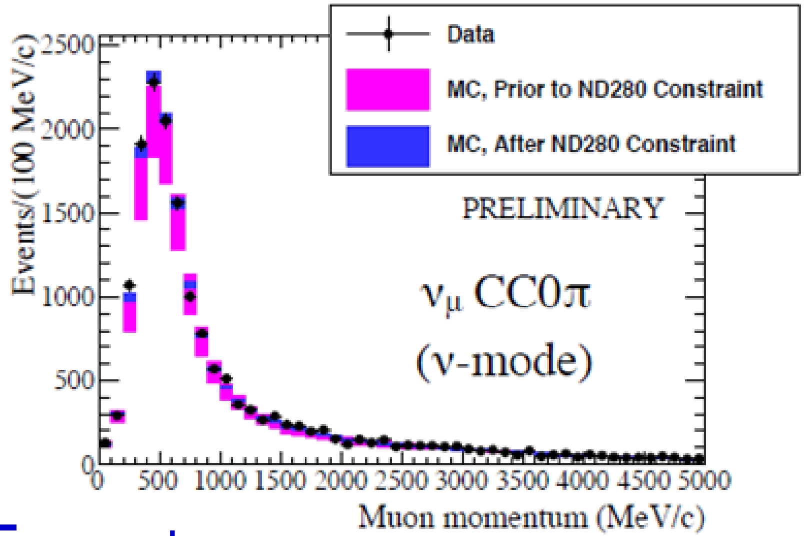
- ν_μ and $\bar{\nu}_\mu$ interactions separated into 1 track (CC1tr) and >1 track (CCNtr)

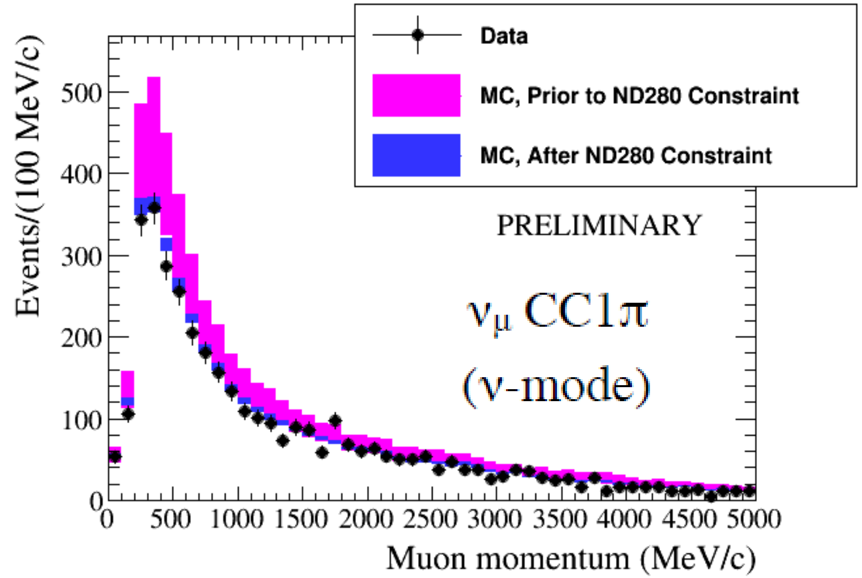




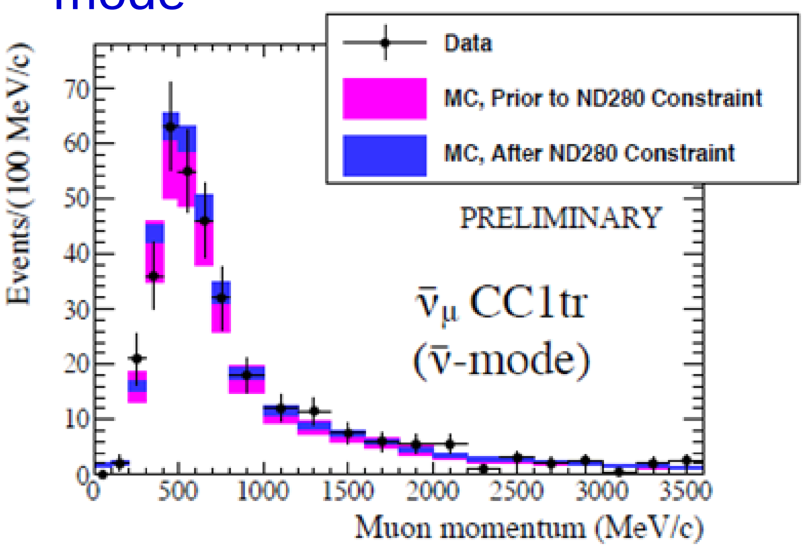
Near Detector Fit

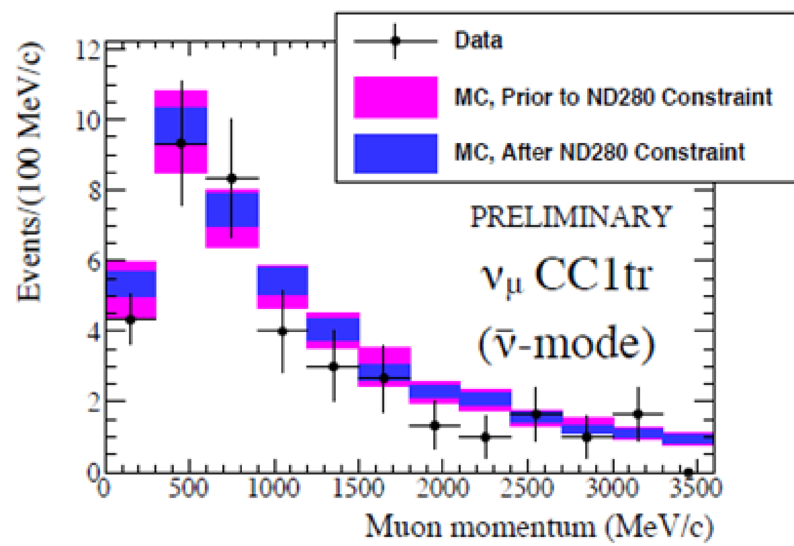
ν – mode





$\bar{\nu}$ – mode

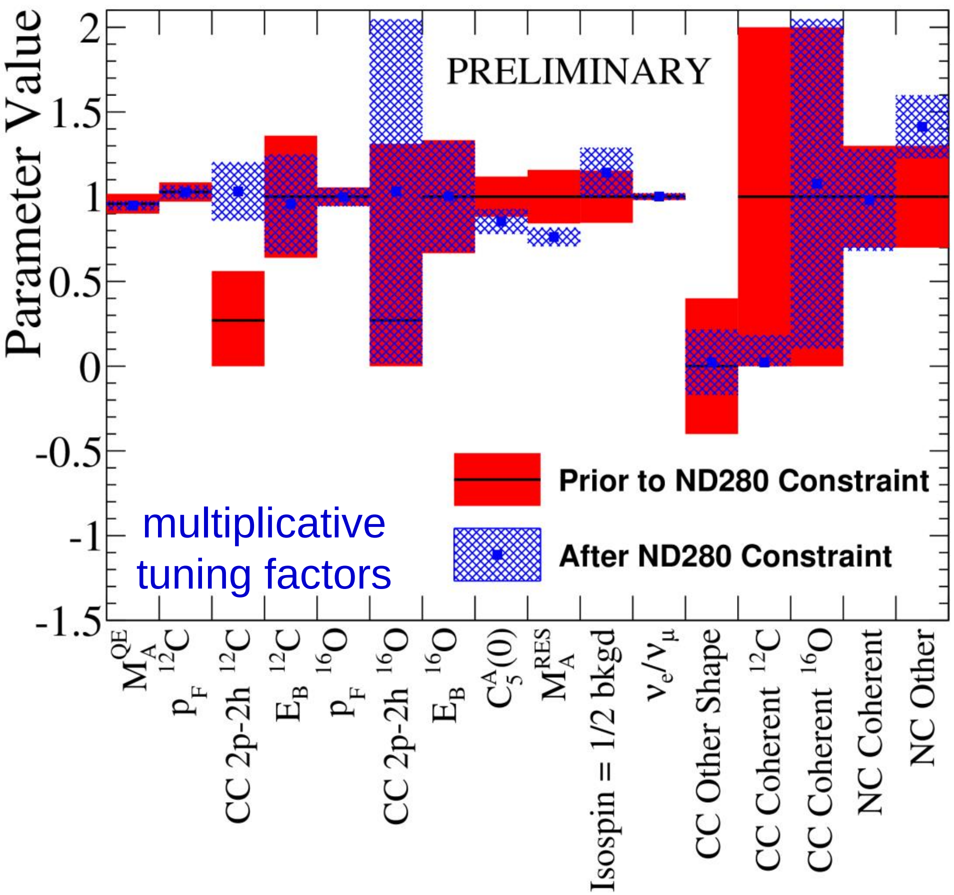




The data is in better agreement after the flux and ND constraints

Cross Section Tuning

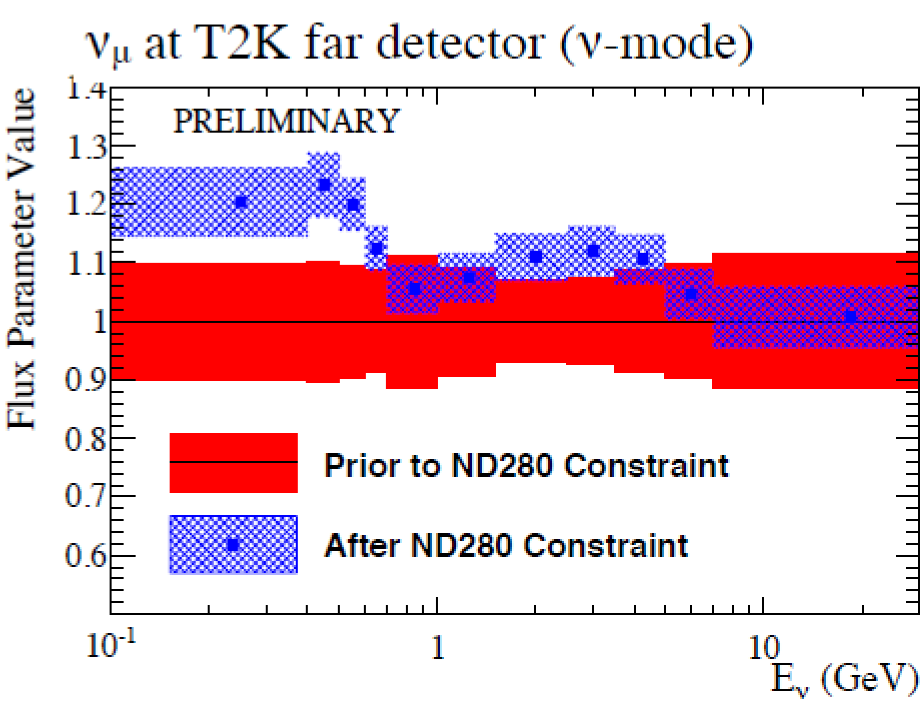
Cross-section model is propagated to far detector rate

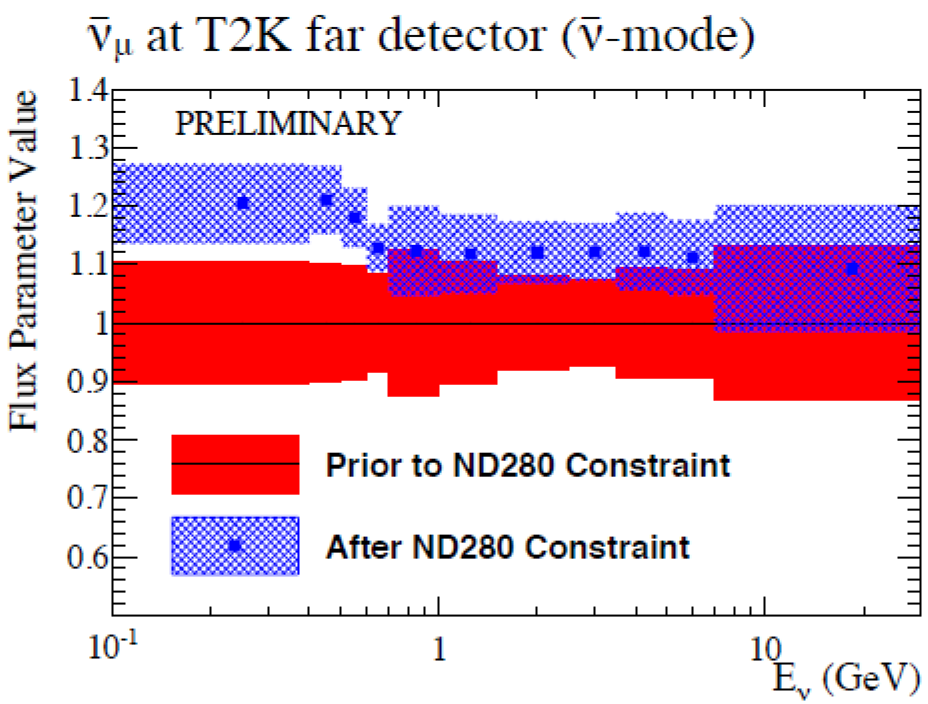


Cross-section Model Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV/c^2)	1.150 ± 0.070	1.137 ± 0.034
CC 2p-2h ^{12}C	0.27 ± 0.29	1.03 ± 0.17
CC 2p-2h ^{16}O	0.27 ± 1.04	1.03 ± 1.01
p_F ^{12}C (MeV/c)	223.0 ± 12.3	222.7 ± 8.8
E_B ^{12}C (MeV)	25.0 ± 9.0	23.9 ± 7.3
$C^A_5(0)$	1.01 ± 0.12	0.862 ± 0.074
M_A^{RES} (GeV/c^2)	0.95 ± 0.15	0.724 ± 0.052
I=1/2 Background	1.3 ± 0.2	1.49 ± 0.19
CC Coherent ^{12}C	1.0 ± 1.0	0.02 ± 0.16
CC Other Shape	0.0 ± 0.4	0.02 ± 0.19

Parameters control CCQE model, multi-nucleon and resonance model
Some cross-section parameters (2p2h on C and O, M_A^{RES}) changed significantly compared to external prior values
In general error on parameters is decreased

Flux Tuning





Muon neutrino / antineutrino flux correlates to electron neutrino / antineutrino flux

Increased flux preferred with new cross section model
$\rightarrow$ predicted flux at far detector is generally increased

Current T2K Oscillation Systematics Errors

2014 errors → 2015 errors

		ν_μ sample	ν_e sample	$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
ν flux		16%	11%	7.1%	8%
ν flux and cross section	w/o ND measurement	21.7%	26.0%	9.2%	9.4%
	w/ ND measurement	2.7%	3.2%	3.4%	3.0%
independent cross sections (different nuclear targets)		5.0%	4.7%	10% *	9.8% *
Final State Interaction / Secondary Interaction at SK		3.0%	2.5%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
Total	w/o ND measurement	23.5%	26.8%	14.4%	13.5%
	w/ ND measurement	7.7%	6.8%	11.6%	11.0%

* 2015 errors include the effect of multi-nucleon bound states in neutrino interactions

The fit to ND280 data constrains the flux and interaction models to the 3% level (excluding separate systemic parameters for the nuclear model / FSI)

Include uncertainties in the FSI and nuclear model assigned due to different target in the near and far detector (CH vs. H_2O)
Expect to be reduced with measurements on H_2O in near detector

Systematics w/o and w/ ND

The near detector significantly reduces the systematic uncertainty in the predicted event rate at the far detector

<table>
<tr><th colspan="3">$\bar{\nu}_\mu$ disappearance analysis</th><th>Without ND</th><th>With ND</th></tr>
<tr><td rowspan="6">ν flux
and
cross section</td><td colspan="2">flux</td><td>7.1%</td><td>3.5%</td></tr>
<tr><td colspan="2">cross section common to ND280</td><td>5.8%</td><td>1.4%</td></tr>
<tr><td colspan="2">common to ND280 and SK</td><td>9.2%</td><td>3.4%</td></tr>
<tr><td rowspan="2">Super-K only</td><td>multi-nucleon effects on oxygen</td><td colspan="2">9.5%</td></tr>
<tr><td>all Super-K</td><td colspan="2">10.0%</td></tr>
<tr><td colspan="2">All</td><td>13.0%</td><td>10.1%</td></tr>
<tr><td colspan="3">Final State / Secondary Hadronic Interactions at Super-K</td><td colspan="2">2.1%</td></tr>
<tr><td colspan="3">Super-K detector</td><td colspan="2">3.8%</td></tr>
<tr><td colspan="3">Total</td><td>14.4%</td><td>11.6%</td></tr>
</table>

(fractional error on number of events prediction)

Anti-neutrino oscillation analyses are statistically limited $\rightarrow$ more data

There are ongoing efforts to reduce uncertainties on multi-nucleon effects on oxygen with water target measurements in ND280

Conclusions – T2K

The near detector significantly reduces the systematic uncertainty in the predicted event rate at the far detector

The use of all available ND measurements in neutrino and anti-neutrino modes constrains the flux ⊗ cross section to a ~3 % uncertainty

Ongoing efforts to include new data sets from water target in near detector

T2K oscillation sensitivities are statistics limited
(~14% of T2K design POT delivered)

With the inclusion of recent NA61 results, the uncertainties on the (anti-)neutrino flux decreased below ~10%
(taking into account also correlations, the error on the number of events is 7%)

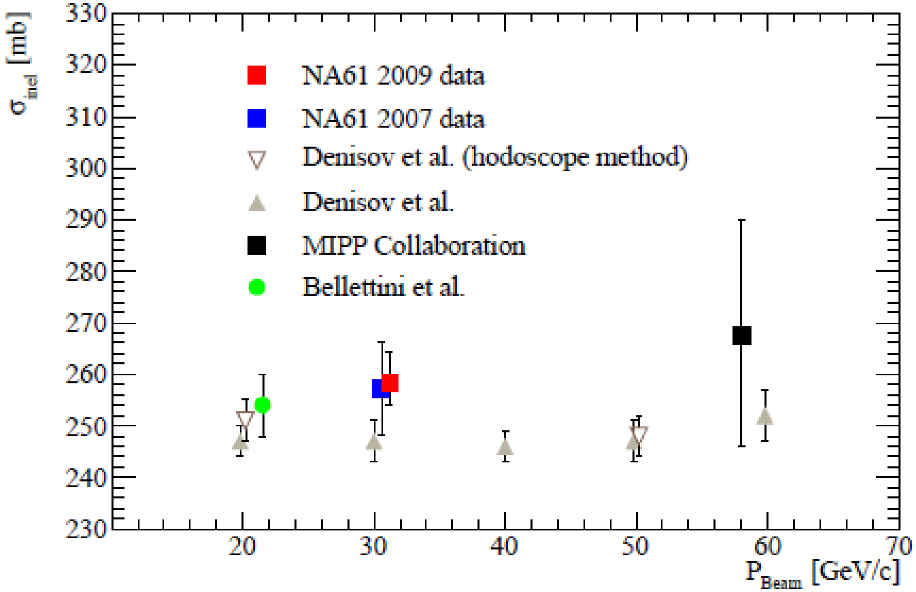
Replica target data from NA61 is being incorporated in the T2K flux predictions and will further reduce the flux uncertainties

Additional material

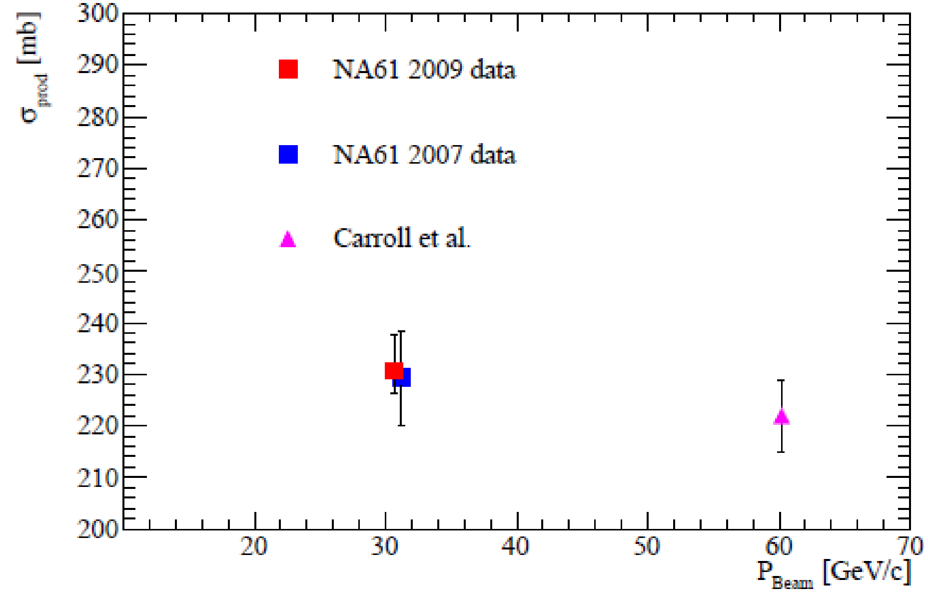
p – C Total Cross Sections @ 31 GeV/c

NA61, arXiv:1510.02703

inelastic cross section



production cross section



$$\sigma_{\mathrm{inel}} = 258.4 \pm 2.8(\mathrm{stat}) \pm 1.2(\mathrm{det})\,^{+5.0}_{-2.9}(\mathrm{mod})\,\mathrm{mb}$$

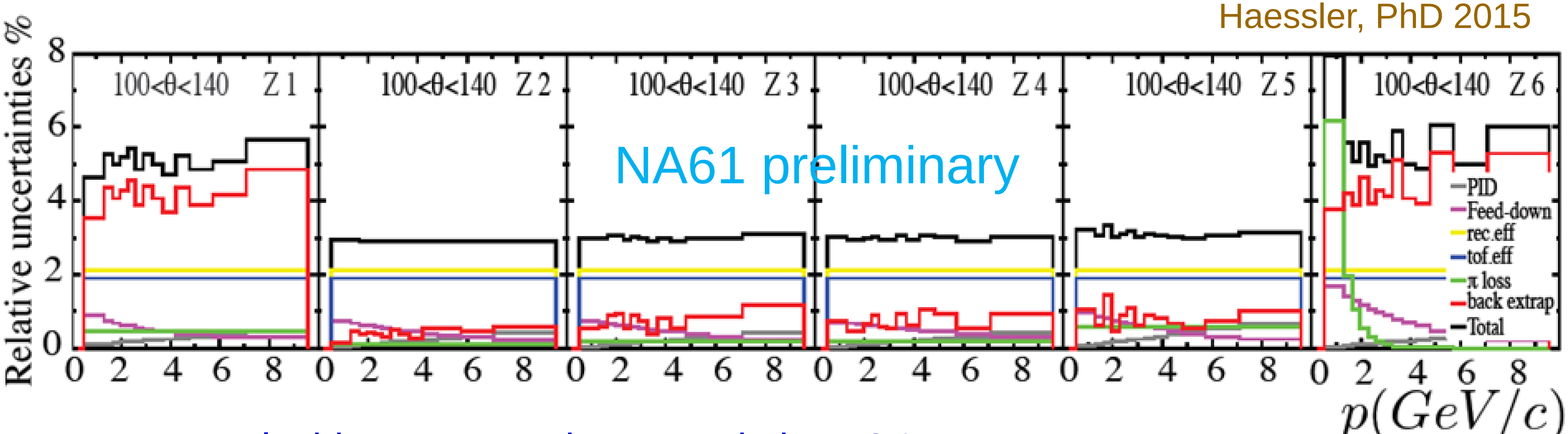
$\sigma_{prod} = \sigma_{inel} - \sigma_{qe}$

$$\sigma_{\mathrm{prod}} = 230.7 \pm 2.7(\mathrm{stat}) \pm 1.2(\mathrm{det})\,^{+6.3}_{-3.4}(\mathrm{mod})\,\mathrm{mb}$$

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

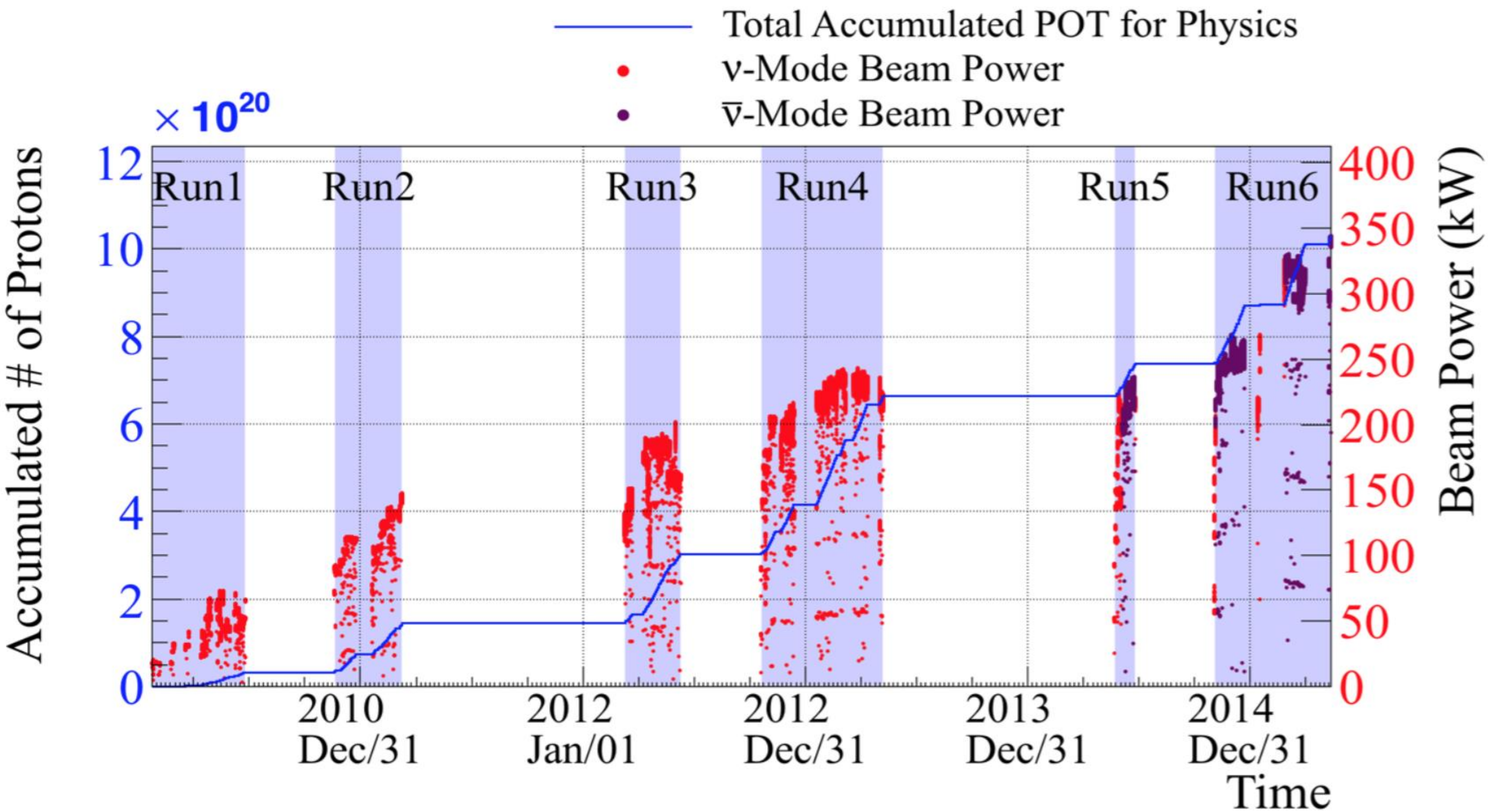
Haessler, PhD 2015



For central z bins, systematic uncertainties ~3 %

Work to implement these data in T2K flux simulations ongoing

Data Collected



Reached a beam power of 371 kW

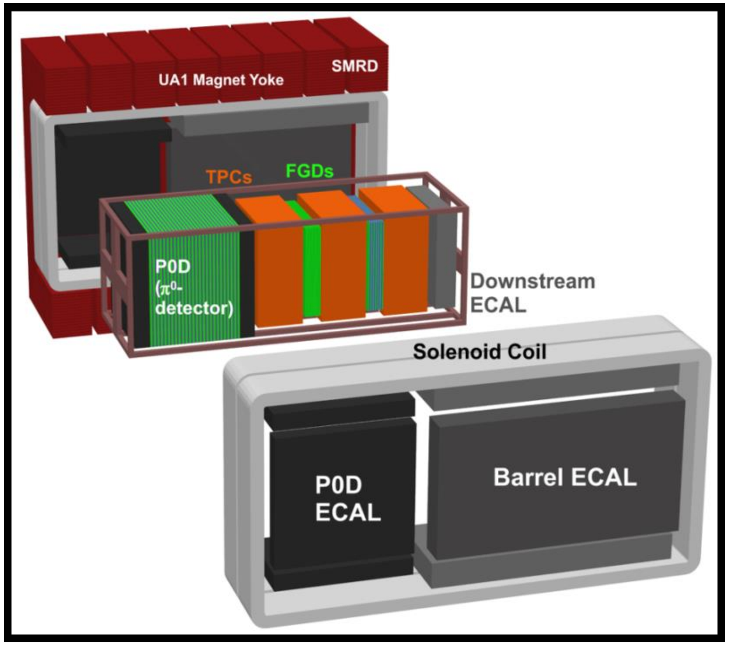
Accumulated protons on target:

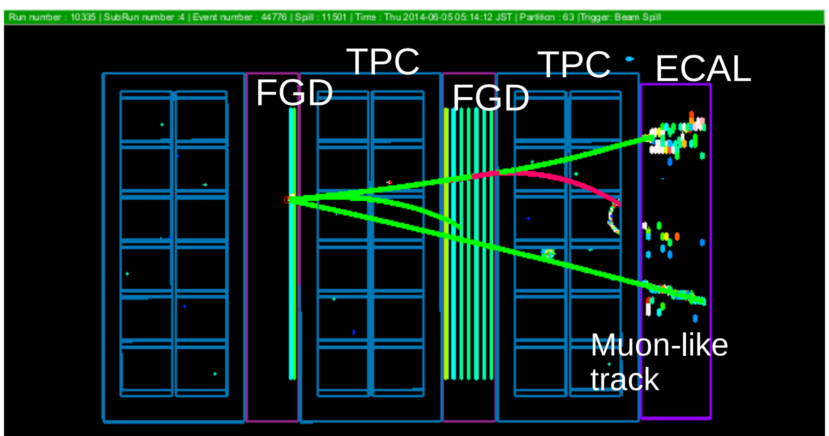
11.04×10^{20} in total

7.00×10^{20} in ν mode

4.04×10^{20} in ν̄ mode

The ND280 Detector





Example: neutrino candidate in antineutrino mode

Constrains neutrino flux before oscillations
(CC ν_μ and $\bar{\nu}_\mu$ data)

Measures neutrino interactions
on scintillator (CH) and water targets

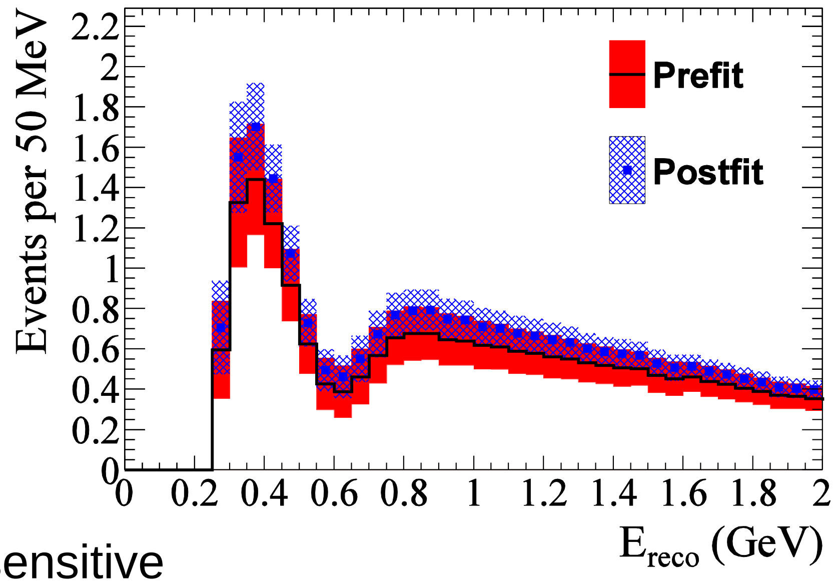
0.2 T magnetic field

Plastic scintillator detectors
(FGD, POD, ECALs, SMRD)

Time Projection Chambers
better than 10% dE/dx resolution

Muon momentum, sign from curvature
in magnetic field
10% p resolution at 1 GeV/c

Super-K Systematics



1. Flux ⊗ cross section common to ND280 and SK

The ND280 significantly reduces the systematic uncertainty in the predicted event rate at SK

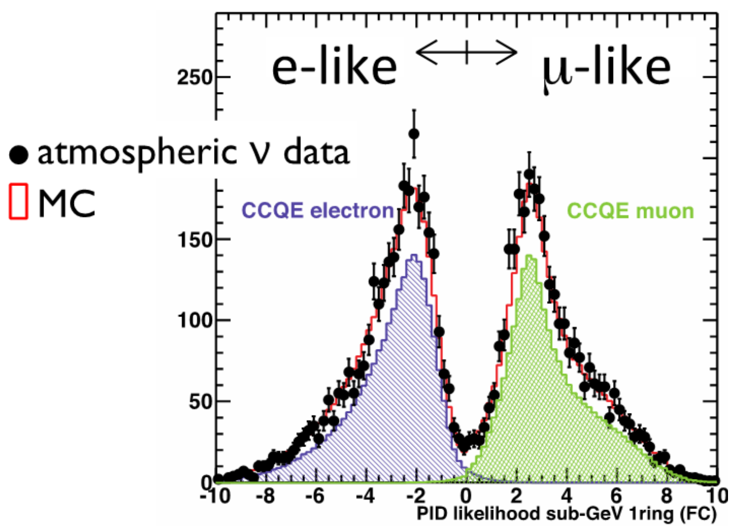
2. Cross section not constrained by ND280

Different target materials (CH vs H_20), multi-nucleon effects on oxygen, and cross-section parameters for which ND280 is insensitive

Multi-nucleon effects introduced for the first time in event simulations.

At present, largest source of systematic uncertainty.

Expect to be reduced with measurements on H_20 in ND.



Probability to reconstruct μ as e ~1%

3. Uncertainties on final state

Final state interactions, secondary interactions and photo-nuclear interactions

4. SK reconstructed energy scale

5. SK efficiencies and background rejection