Prospects for Reducing Beam Flux Uncertainties with Hadron Production Experiments Over the Next 10 Years

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NUFACT 15 RIO DE JANEIRO BRAZIL
AUGUST 10-15

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, … ($\rightarrow \nu$ + X) hadro-production models
(+ modeling of the target complex, focusing and decay channel, …)

ν flux at far detector predicted on the base of ν flux measured in near detector

Make measurements with neutrinos

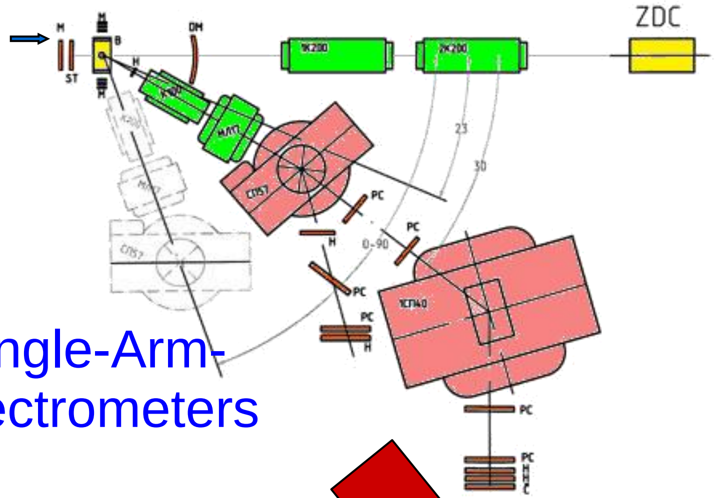
neutrino cross sections $\rightarrow$ absolute neutrino flux

neutrino interaction physics

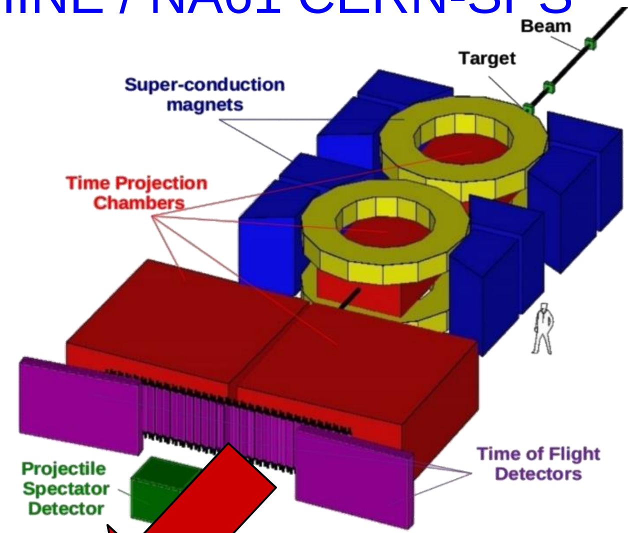
neutrino oscillations $\rightarrow$ flux shape and Far / Near flux ratio

compare measured neutrino spectrum “far” from the source with the predicted one

Single-Arm-Spectrometers

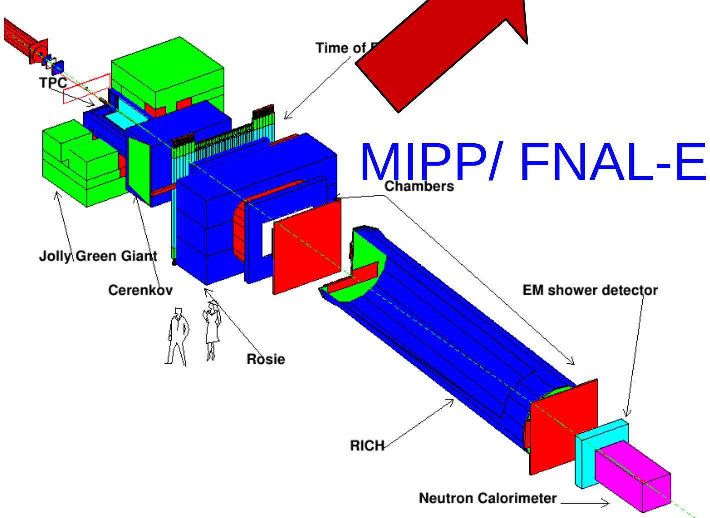


SHINE / NA61 CERN-SPS

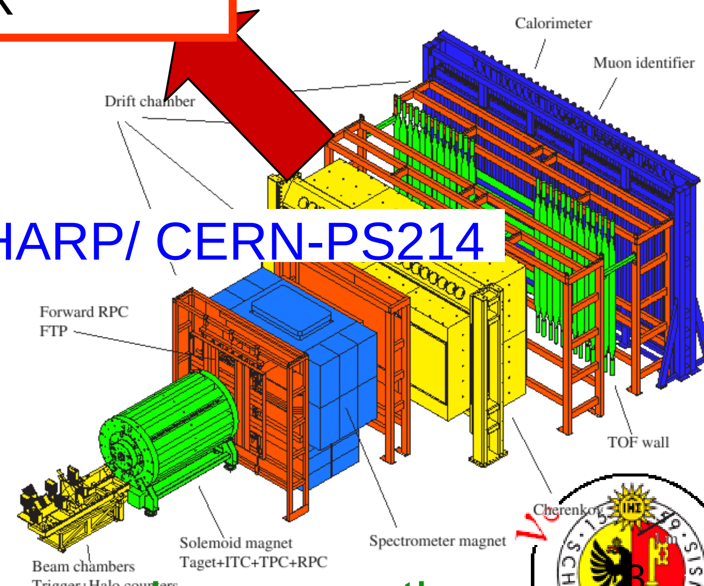


hadro-production measurements
$p(\pi) + A \rightarrow h + X$

MIPP/ FNAL-E907



HARP/ CERN-PS214



+ many many other experiments that measured cross sections ...
$\Rightarrow$ critical survey of all existing cross section measurements !

How Well Do We Know ν Fluxes Today (1)

AGS ν experiments (~1960) knew their fluxes to 30%

Ingredients to flux prediction from upstream to downstream

proton dynamics (protons on target, spot size, …)

hadron production off target

(~60% from primary interactions, ~30% from reinteractions in target, ~10% from around target)

need measurements on both thin and replica targets, same materials, same energies

horn current → **B** (focusing), alignment, etc.

HADRON PRODUCTION most important of these ingredients

need dedicated hadron production experiments

(tuned to a particular ν beam: primary p energy, different target materials, geometry, …)

Two detector experiments (near and far), flux uncertainties partially cancel !

In situ measurements

neutrino – electron elastic scattering (only “standard candle” in neutrino scattering)

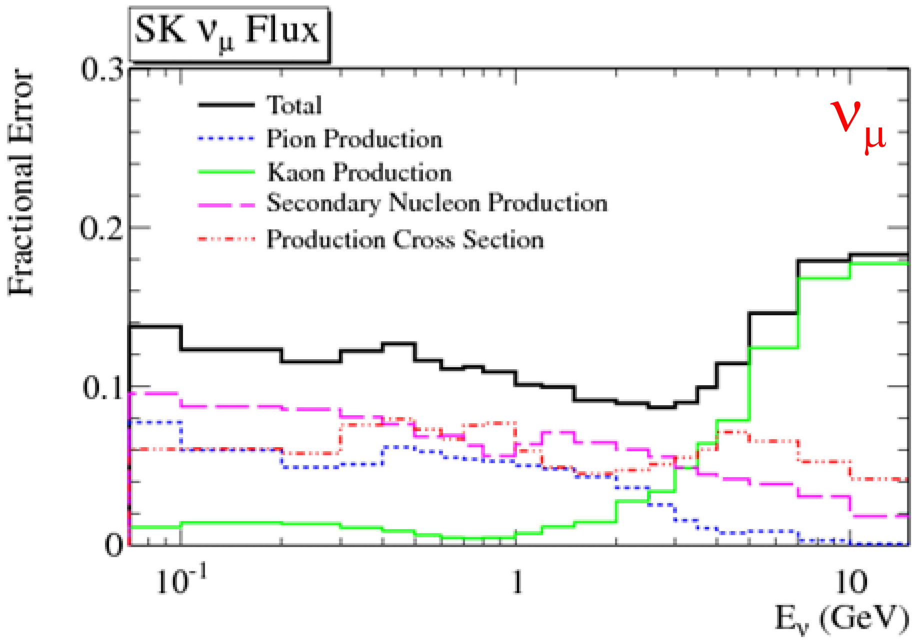
muon monitors

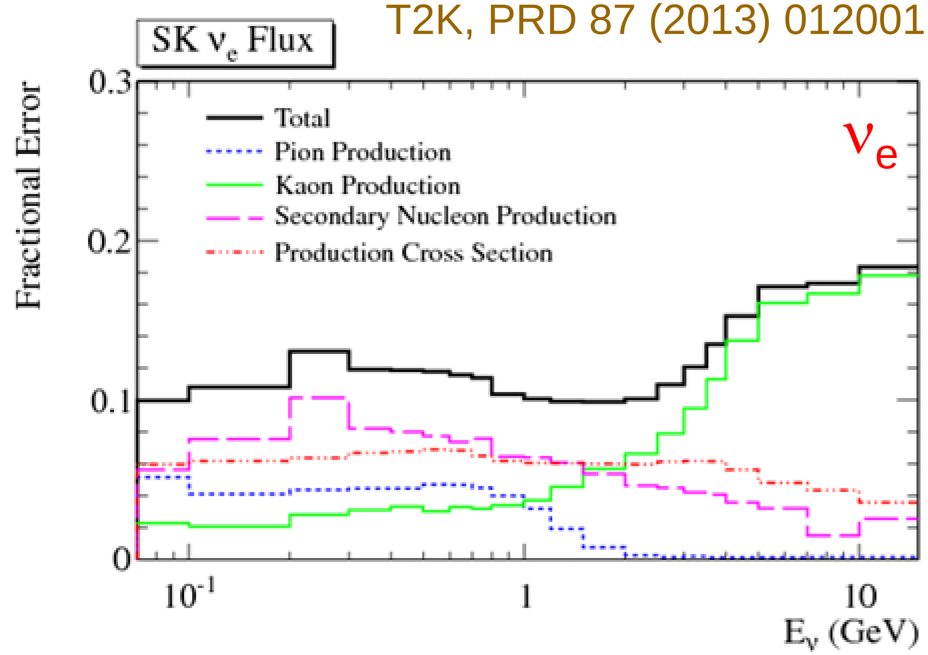
In 50 years we have gone from 30% uncertainties to 10% uncertainties while increasing proton fluxes on target by $\sim 10^3 - 10^4$.

How Well Do We Know ν Fluxes Today (2)

Fractional uncertainties on the ν_μ and ν_e fluxes at the T2K far detector (SK) using NA61 2007 thin target carbon data

T2K, PRD 87 (2013) 012001



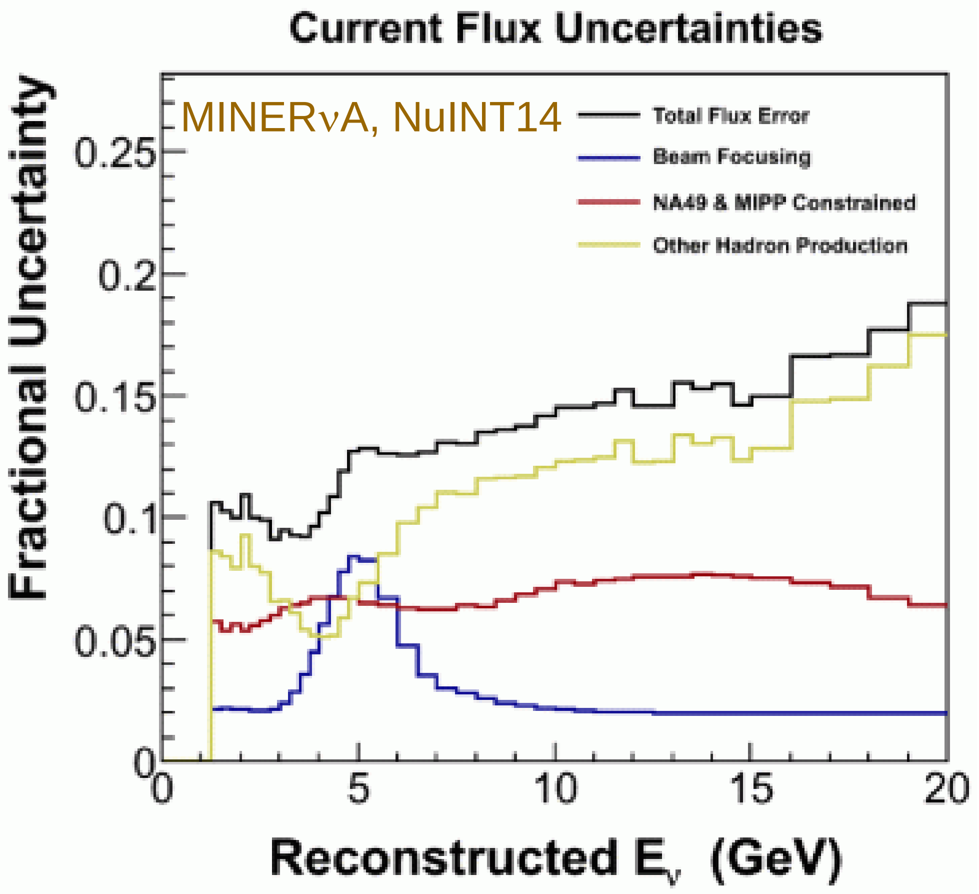


The errors are around 15% in the oscillation region (< 1 GeV)

Uncertainty on secondary (tertiary) hadron production dominates
Improvements expected using T2K replica target data (released very recently

How Well Do We Know ν Fluxes Today (3)

MINERνA (NuMI) flux uncertainties



Beam Focusing – Magnetic horns focusing the charged mesons that decay to neutrino beam

NA49 – A CERN hadron production experiment that constrains flux simulation ($pC \rightarrow X$)

MIPP – A Fnal hadron production experiment that constrains flux simulation ($pC \rightarrow X$)

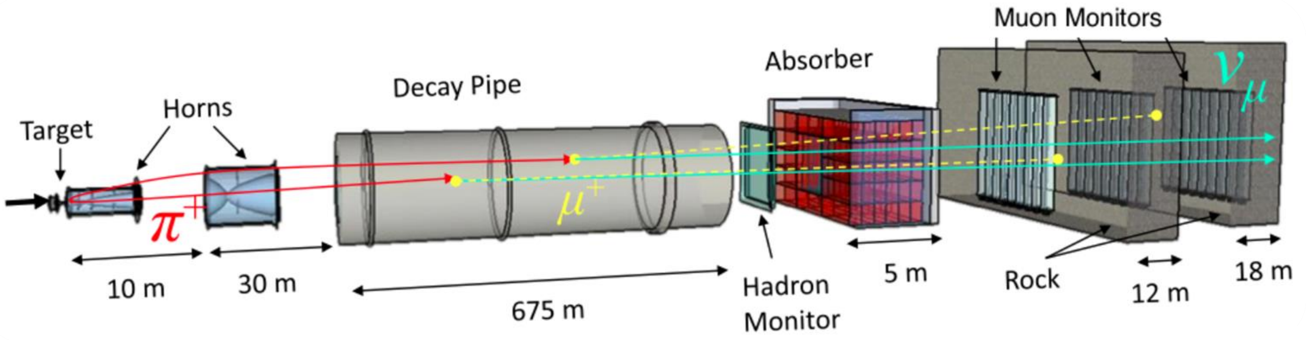
Tertiary – Neutrinos produced by decay of products other than pC in the NuMI target

The errors are around 15%

Uncertainty on secondary (tertiary) hadron production dominates

Important improvements expected with upcoming USNA61 measurements and "in situ" elastic neutrino – electron scattering

The NUMI Beam (Fermilab)



NuMI (Neutrinos at the Main Injector)

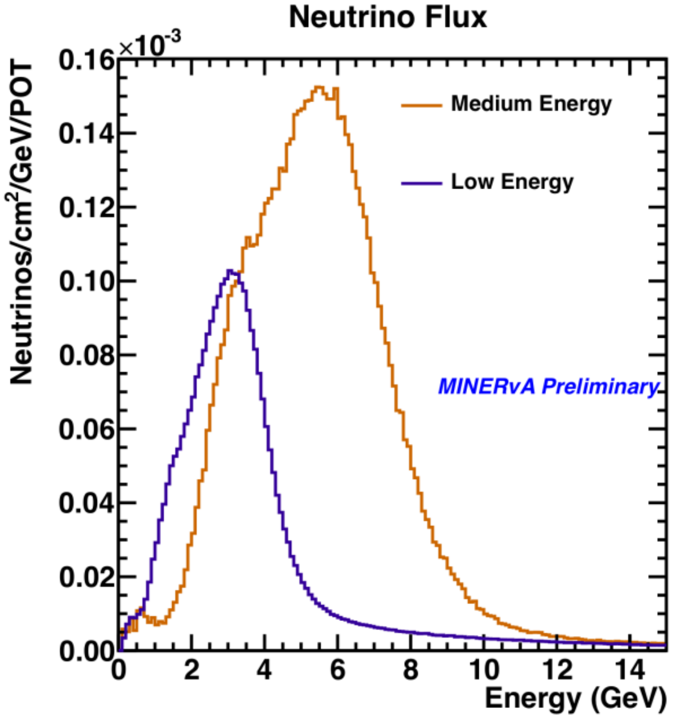
- 120 GeV protons from Main Injector, ~350 kW (→ 700 kW)
- 90 cm graphite target
- 675 m decay tunnel

By moving the production target w.r.t. 1st horn and changing the distance between the horns one can modify the ν spectrum:

- LE (peak ~3 GeV) → ME (peak ~6 GeV)

Flux determination

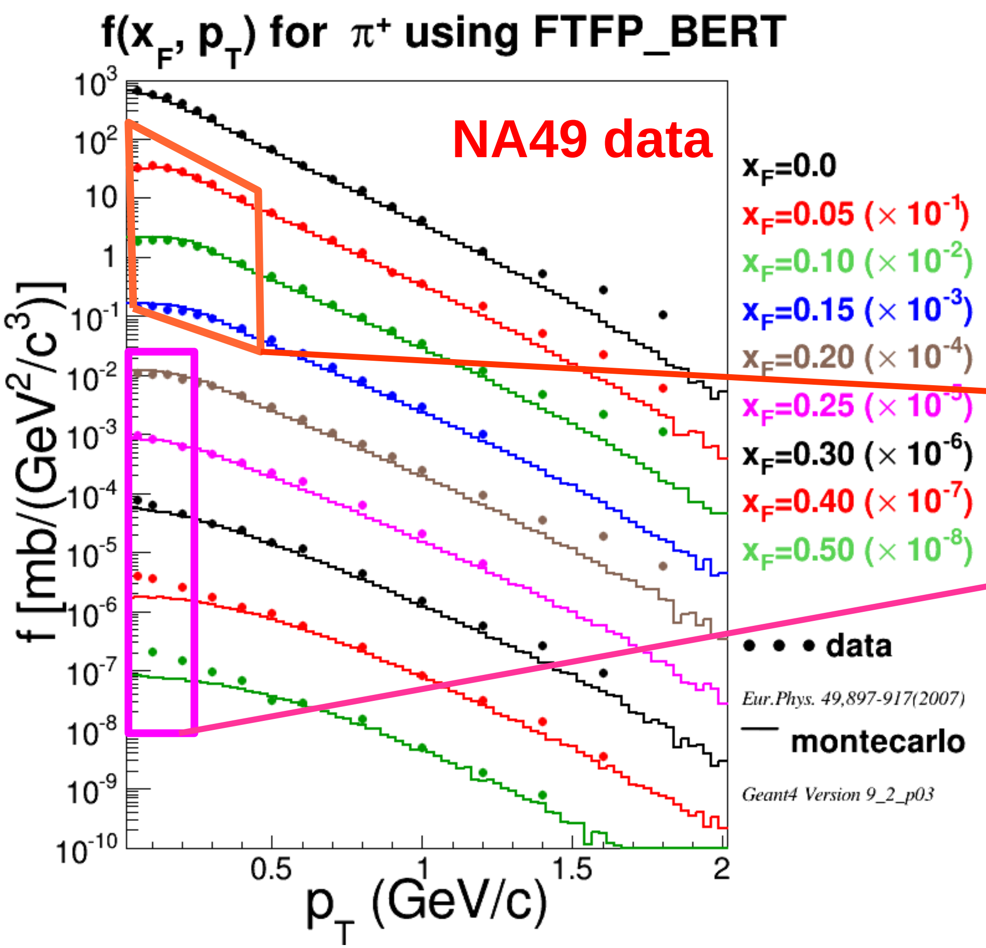
- external hadron production data
- ν – e elastic scattering (in situ measurement!)
- low – ν extrapolation
- muon monitor data
- special runs (vary beam parameters)

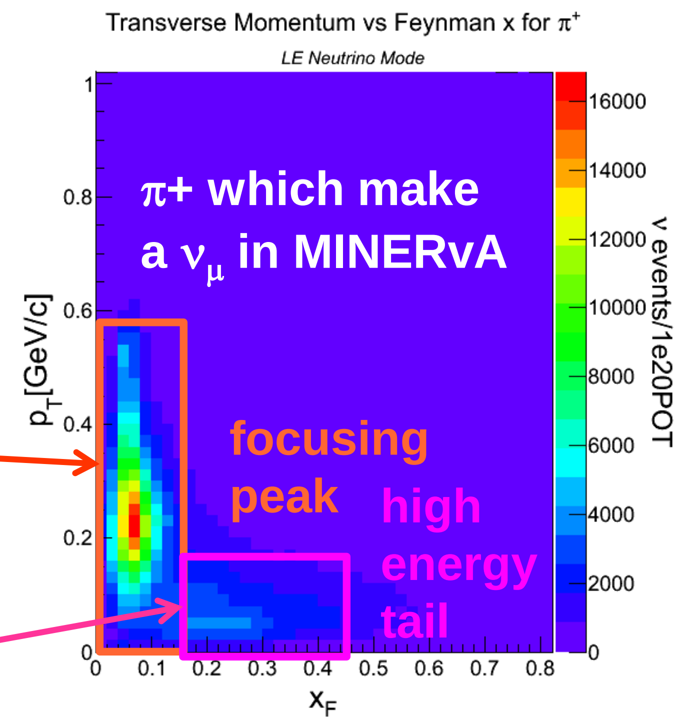


NuMI ν Flux

NuMI beam : hadron production simulated with Geant4 to predict flux.
Flux is reweighted based mainly on NA49 hadron production data compared to a Geant4 model and rescaled down to 120 GeV (MIPP data also used)

$f(x_F,p_T) = E\, d^3\sigma/dp^3$

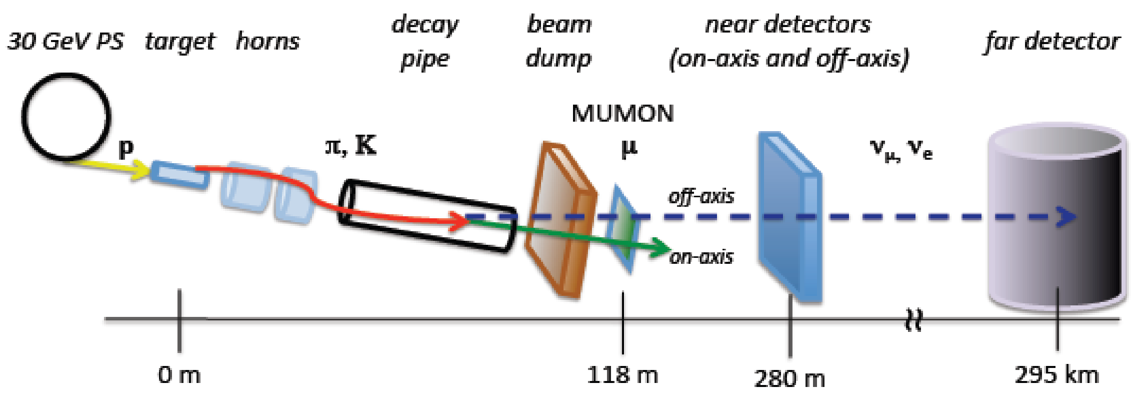


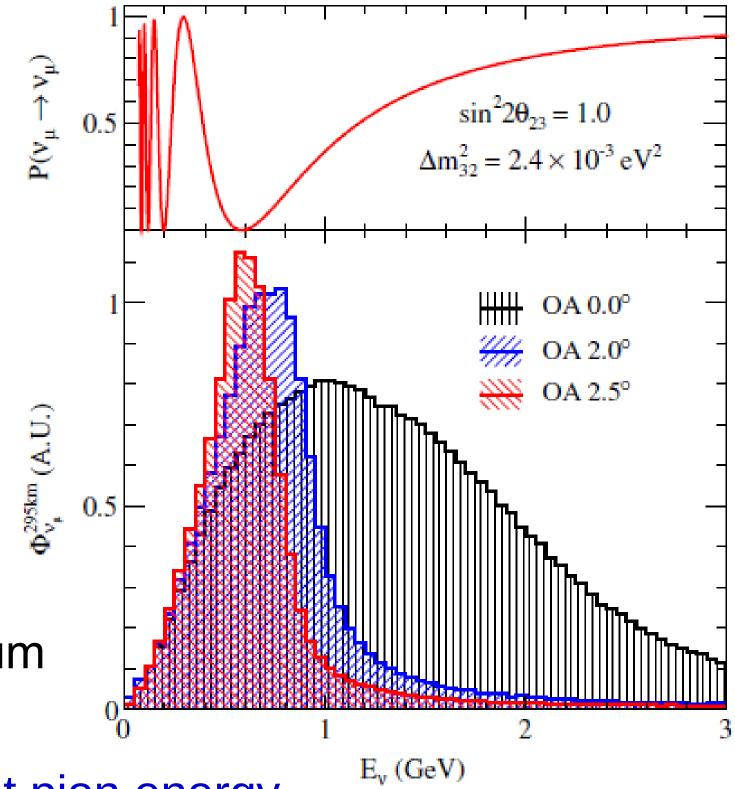


<u>NA49 Uncertainties</u>
7.5% systematic
(when linearly added !)
2-10% statistical

The Off-Axis T2K ν Beam

T2K, PRD87 (2013) 012001





2.5^0 off-axis neutrino beam

- Neutrino beam energy "tuned" to oscillation maximum
- Very narrow energy spectrum (narrow band)
- Neutrino beam energy almost independent of parent pion energy

Neutrino source created by interactions of 30 GeV protons on a 90 cm long graphite rod

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

Horn focusing cancels partially the p_T dependence of the parent pion

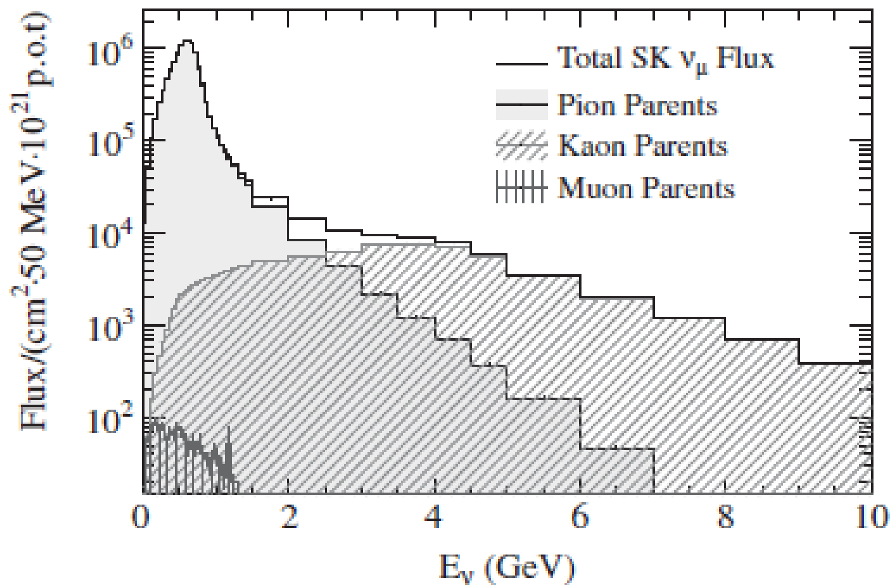
Precise hadron production measurements allow to reduce uncertainties on neutrino flux prediction

Which Hadron Production Measurements (1)

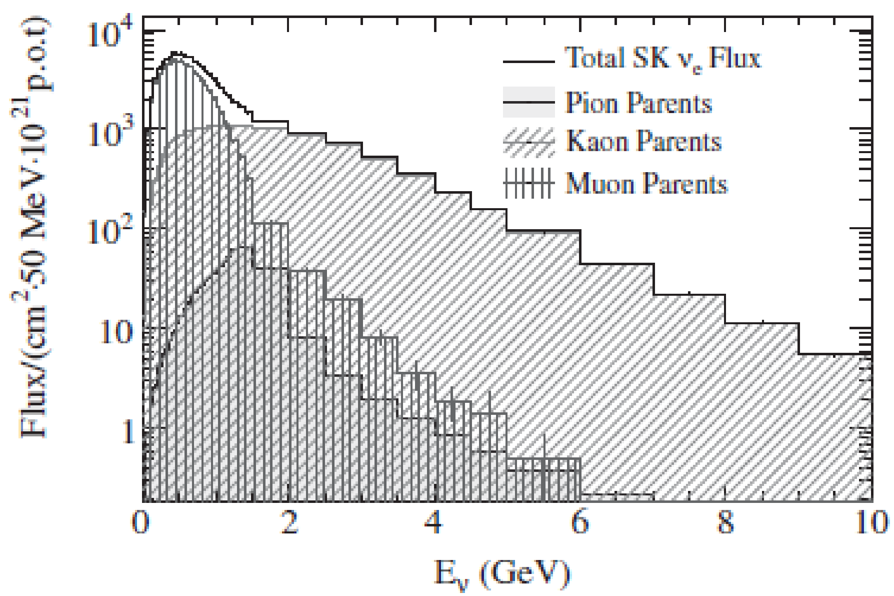
what is the composition of the ν_μ and ν_e flux at SK in terms of the ν parents ?

T2K, PRD 87 (2013) 012001

ν_μ predominantly from π^+ decay at peak energy,
higher energy ν_μ (tail) from kaons

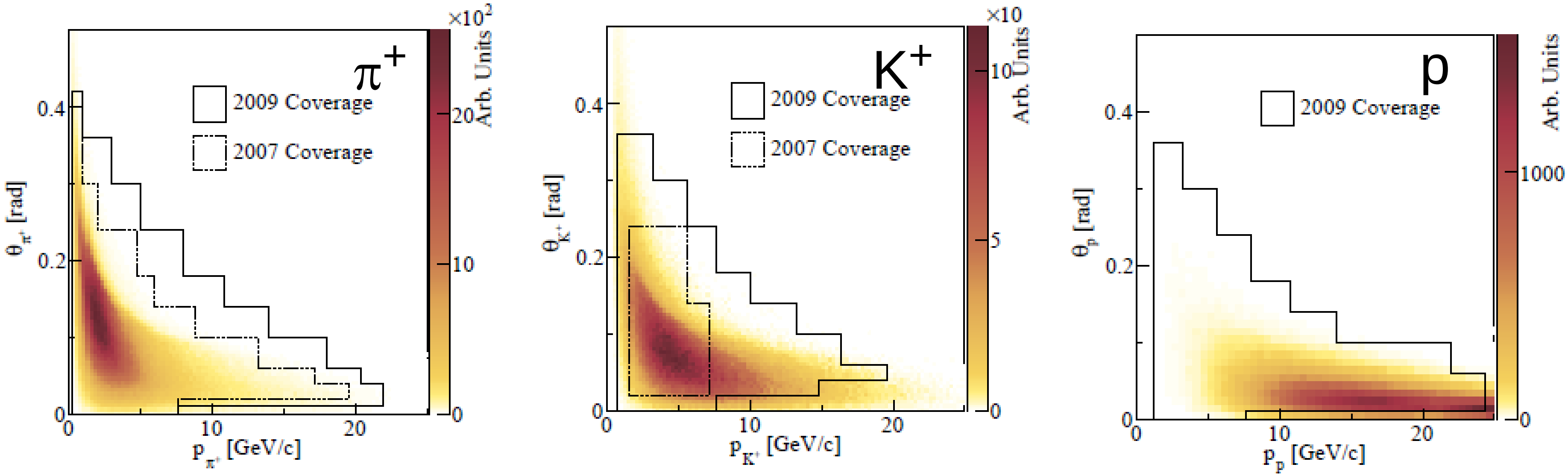


ν_e predominantly from μ^+ and K^+ decays at peak energy,
higher energy ν_e (tail) from kaons



Which Hadron Production Measurements (2)

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

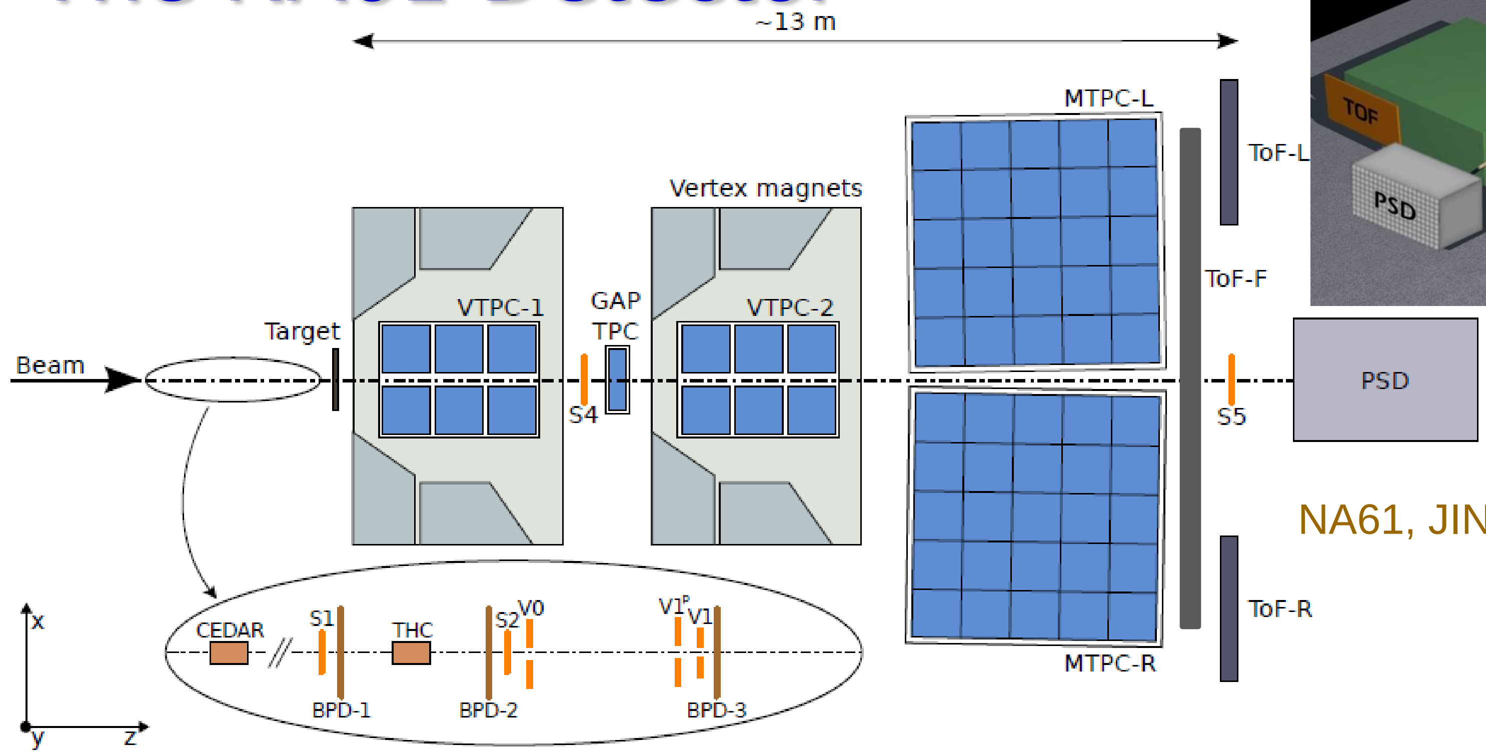


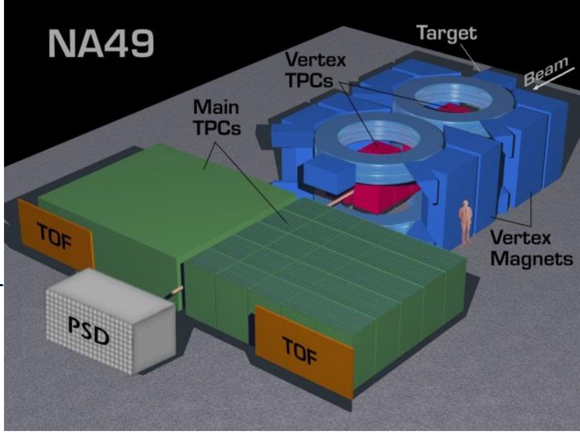
note: this is not a cross section
it shows the distributions of π, K, … contributing to the ν flux at SK

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)

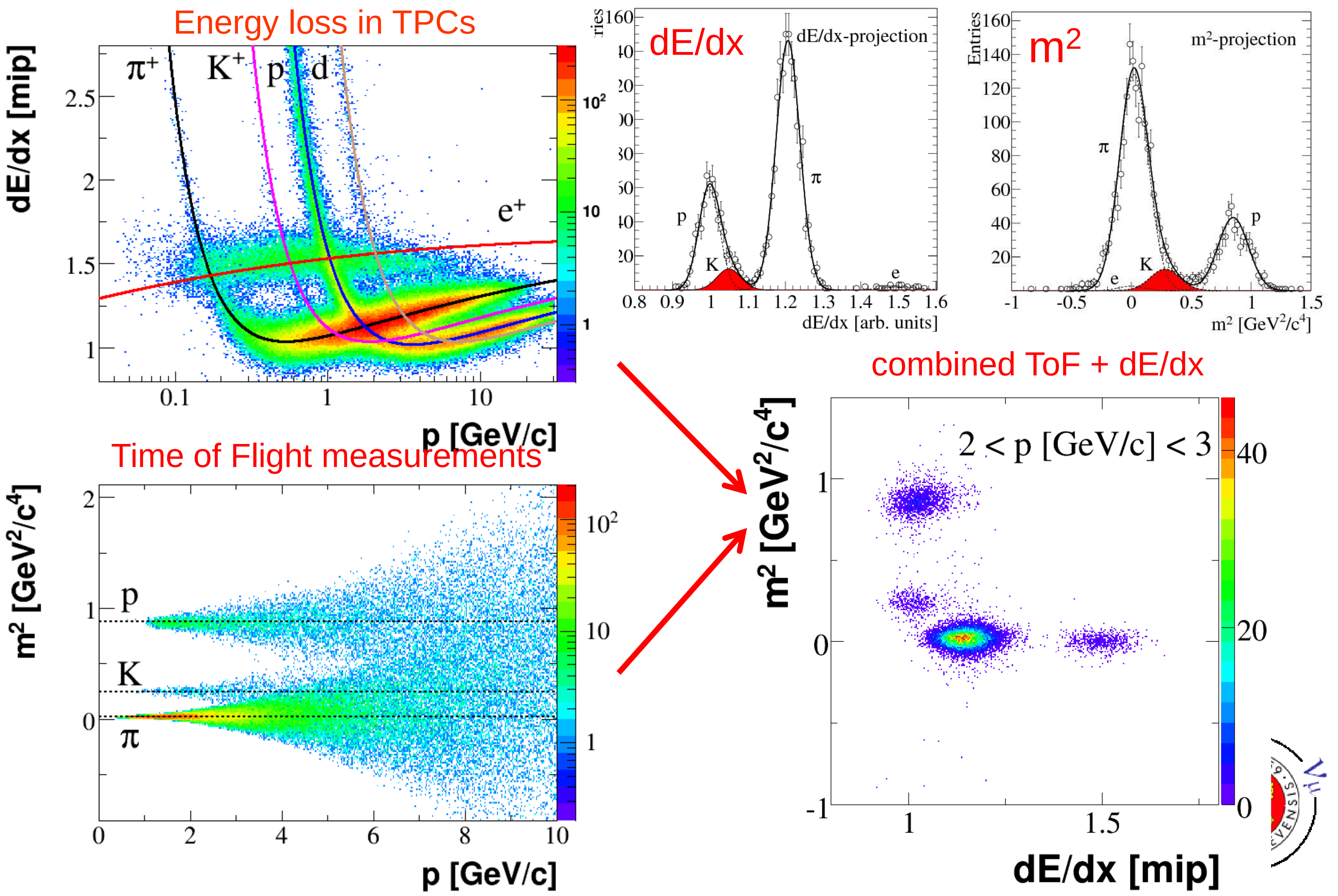
high momentum resolution

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

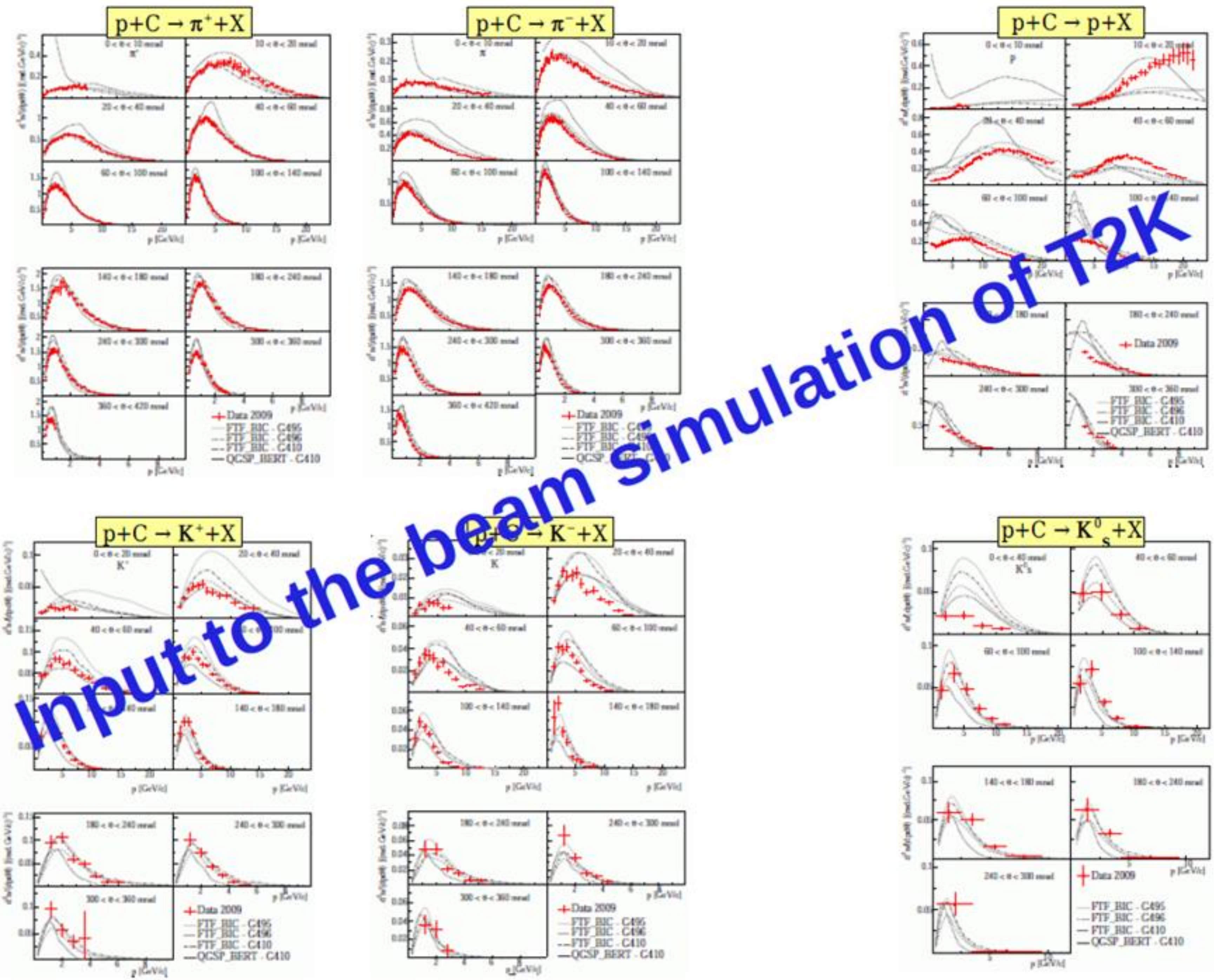
new ToF-F to entirely cover T2K acceptance (σ(ToF-F) ≈ 100 ps, $1 < p < 5$ GeV/c, $\theta < 250$ mrad)

several upgrades are under way

Particle Identification in NA61



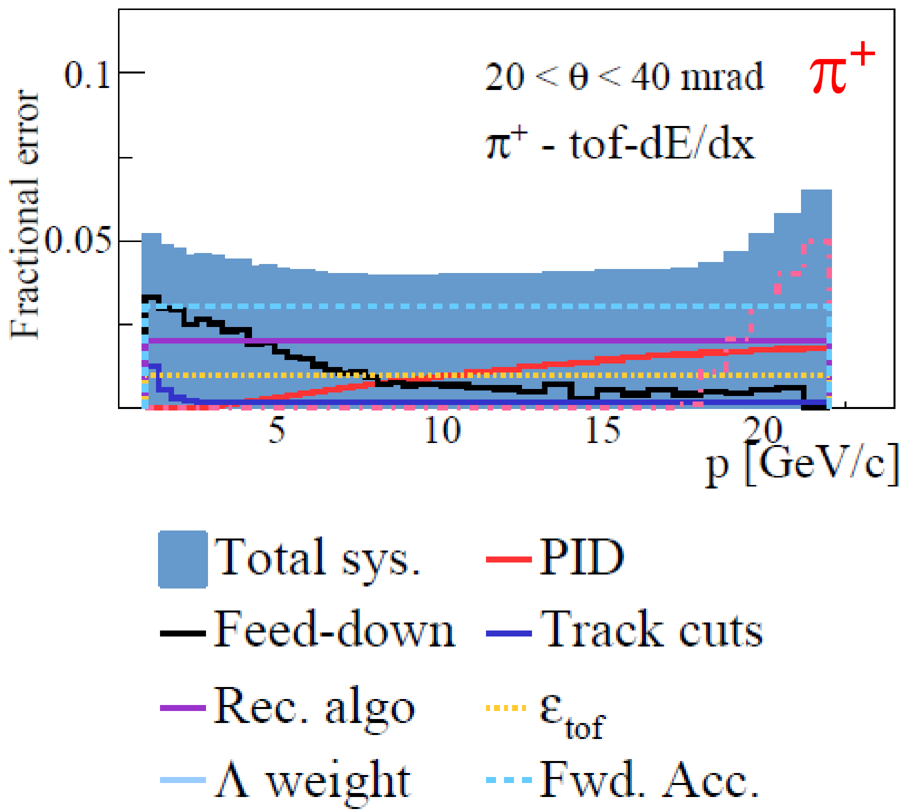
Input to the beam simulation of T2K

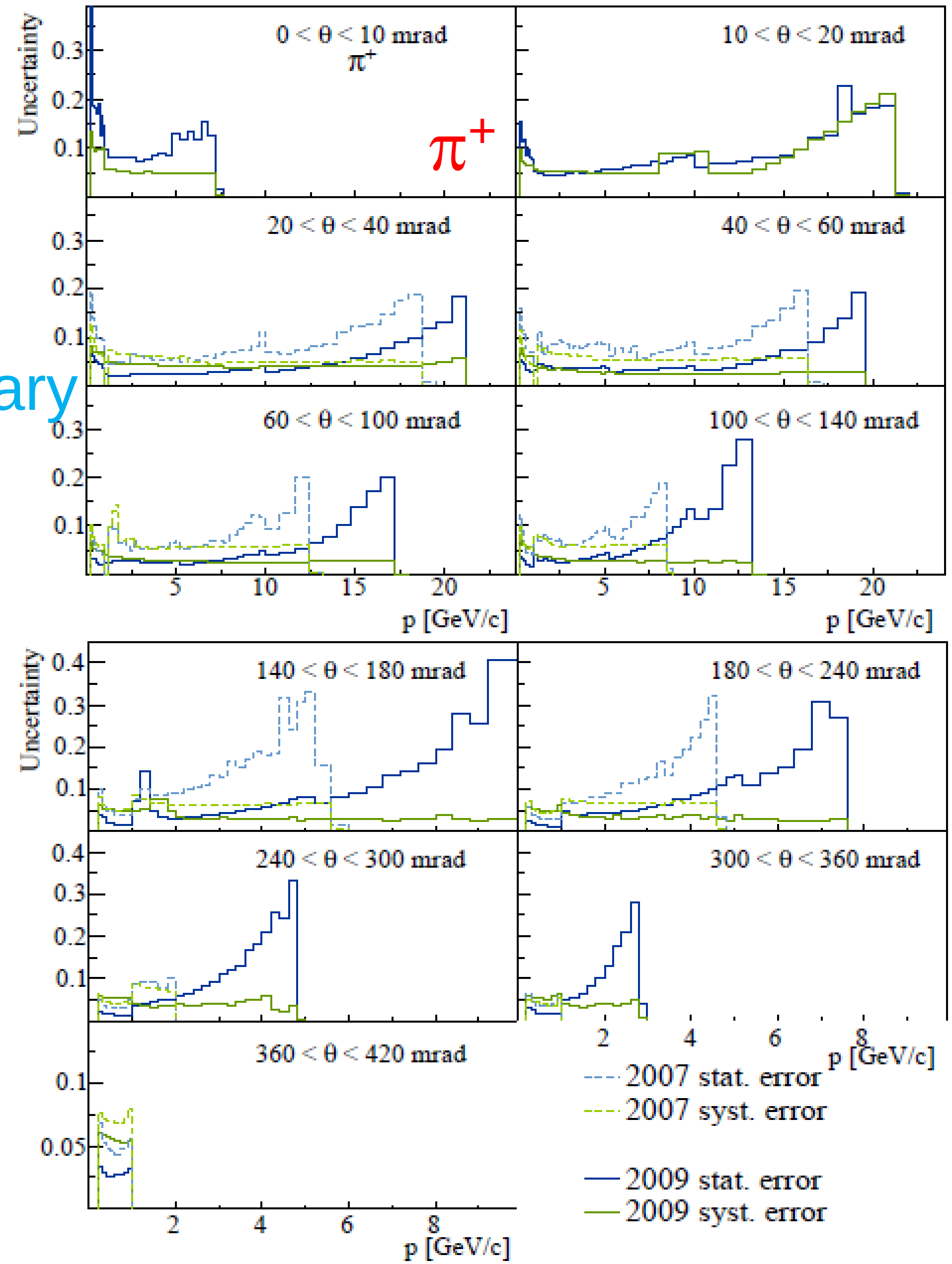


NA61 p + C → π^+ + X Uncertainties (dN/dp)

Compared to 2007 data:
statistical uncertainty
improved by ~3
systematical uncertainty
reduced by ~ 2

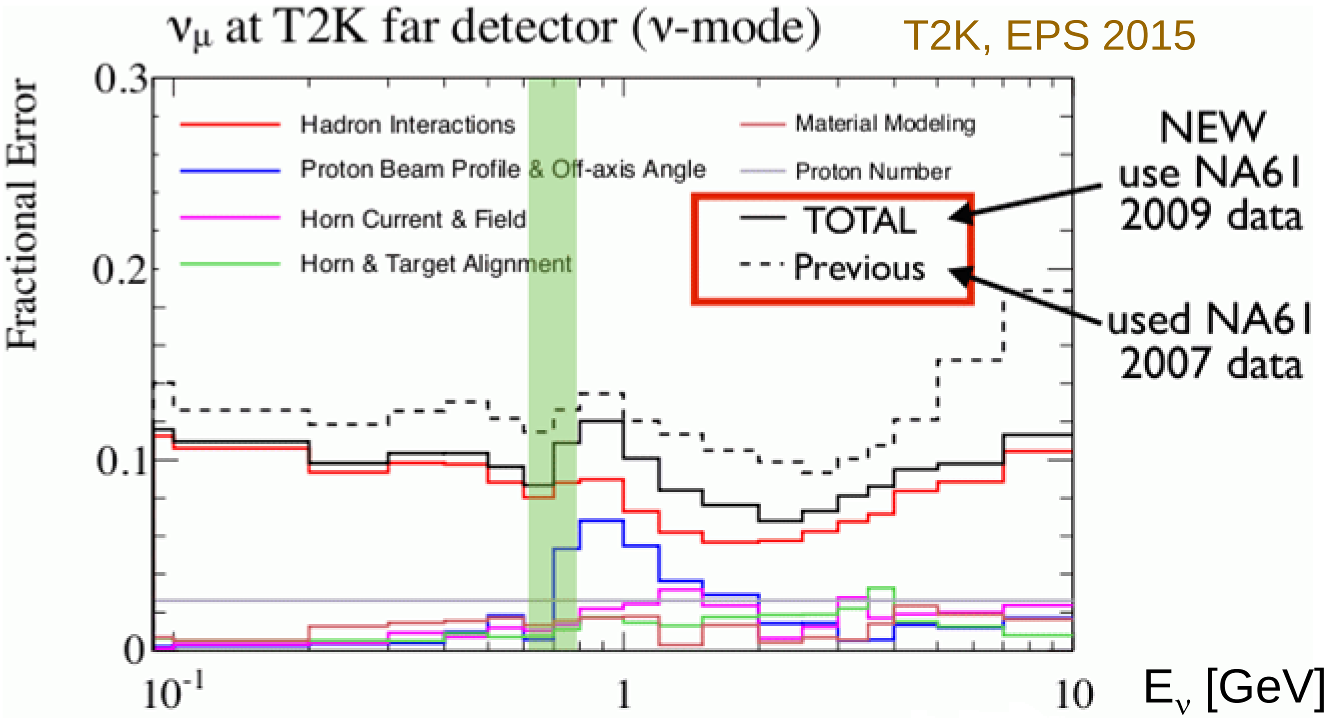
NA61 preliminary





How Well Do We Know ν Fluxes Today (4)

What is the impact of the improved NA61 hadroproduction data?



Uncertainty on the neutrino flux is a dominant contribution to systematics of measurements: ~10 %

Uncertainty on secondary (tertiary) hadronic interactions is dominant contribution to the flux uncertainty

Improvements expected using T2K replica target data (released very recently)
NA61 T2K replica target 2010 still to be analyzed (5 times more statistics)

Some Observations

Hadroproduction measurements require

large acceptance detectors
excellent PID over whole kinematical range
good vertexing (replica targets!)
large statistics
different nuclear targets to study various particle production effects

None of the existing hadroproduction models
describes satisfactorily the ensemble of NA61 data (same for MIPP)!

Systematic uncertainties due to small contributions from various sources
there is not a particular error dominating over others

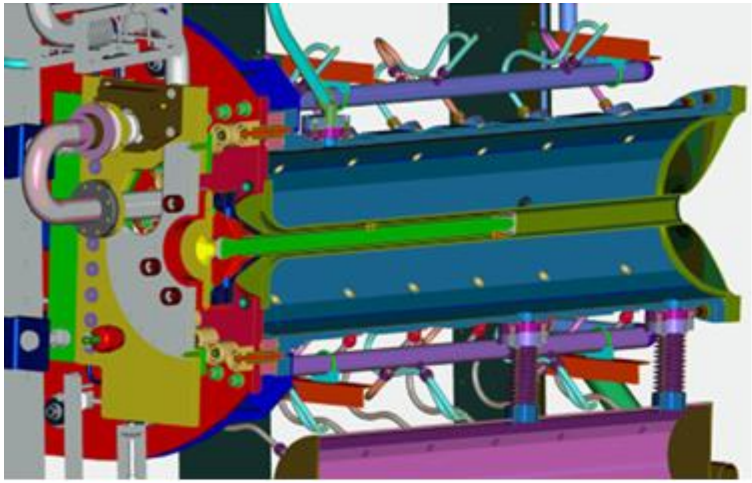
Some kinematical regions still dominated by statistical uncertainties

To improve on NA61 results:

increase statistics by a factor of 10
better understanding of interaction and production cross sections
forward acceptance (upgrades under way)
vertexing (replica targets)

Which Hadron Production Measurements (3)

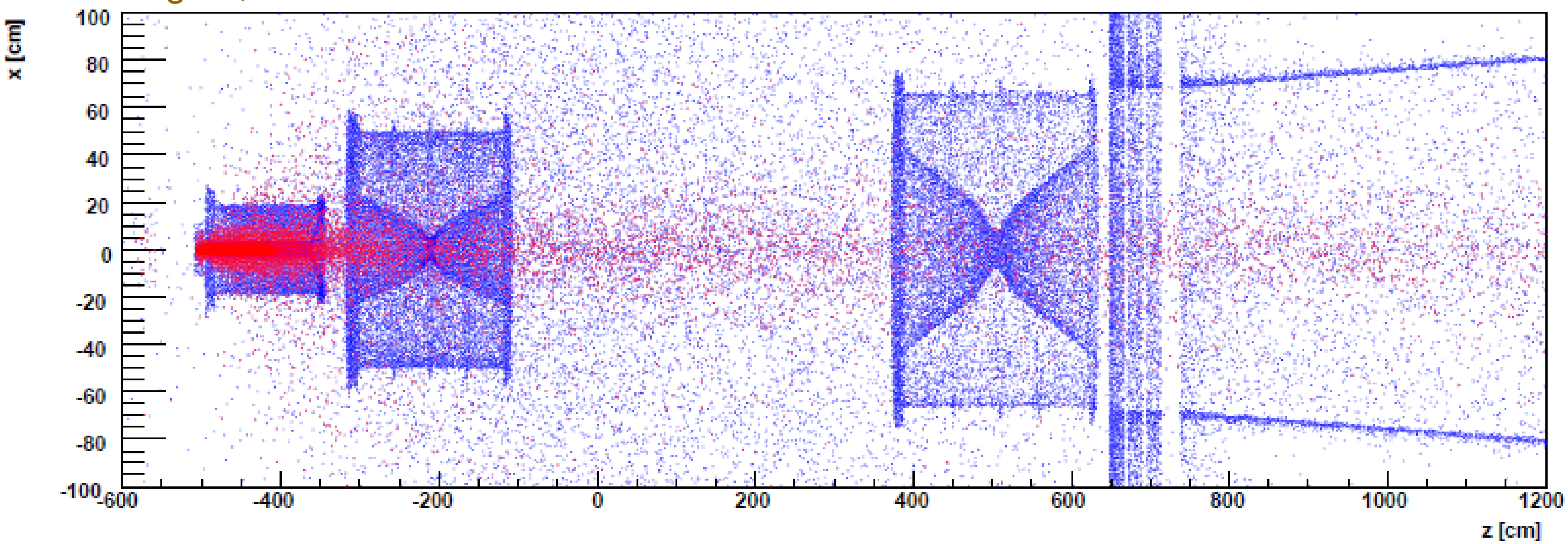
T2K target including 1st horn



blue: production point of neutrino parent particles

red: parents produced in the target or along decay chains

Abgrall,CERN-THESIS-2011-165

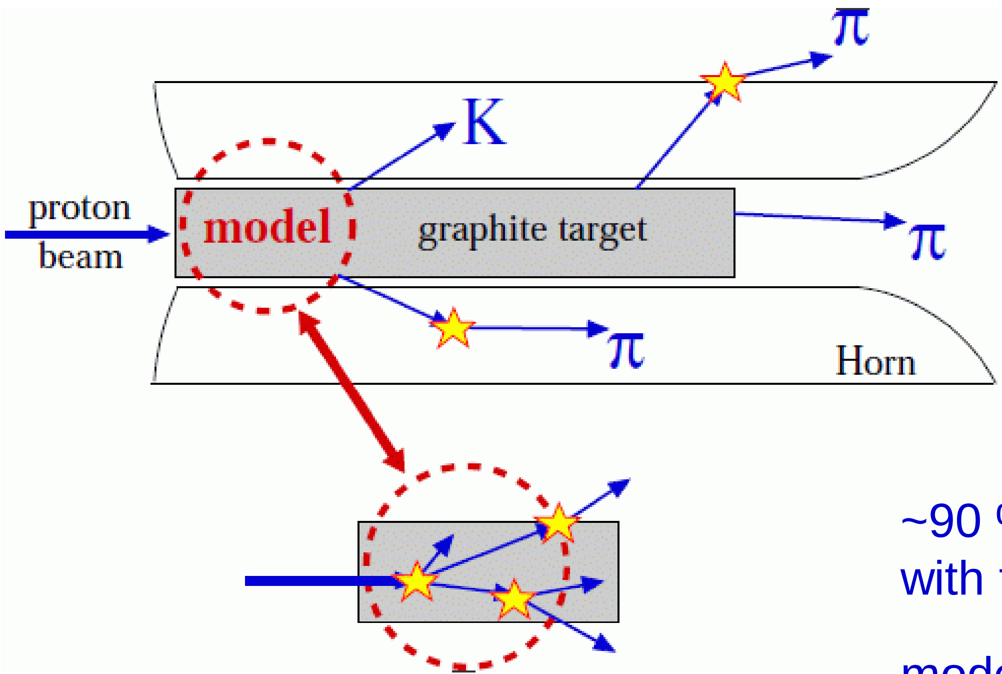


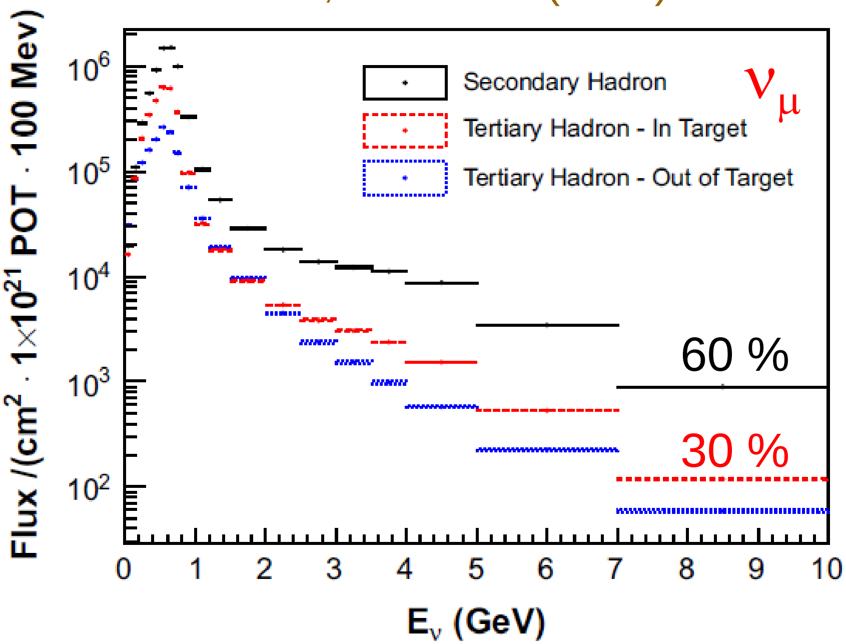
ν Flux Prediction with T2K Replica Target

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%).

NA61, NIM A701 (2013) 99

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



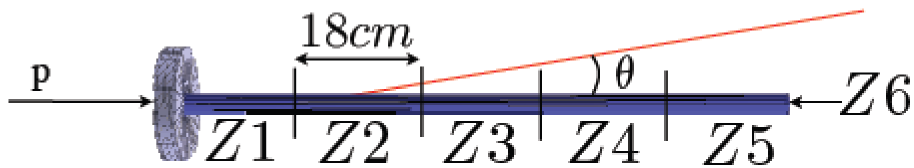


~90 % of the neutrino flux can be constrained with the T2K replica target measurements

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

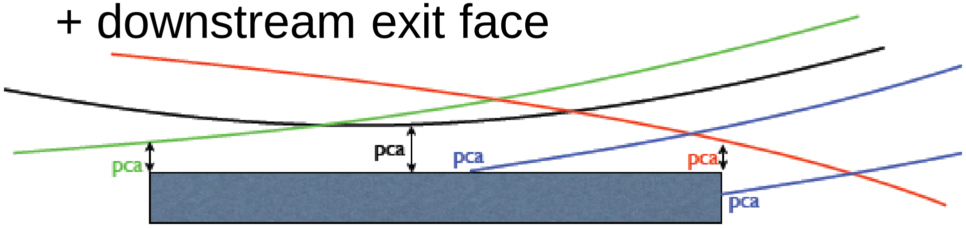
π^+ Hadroproduction on T2K Replica Target

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)

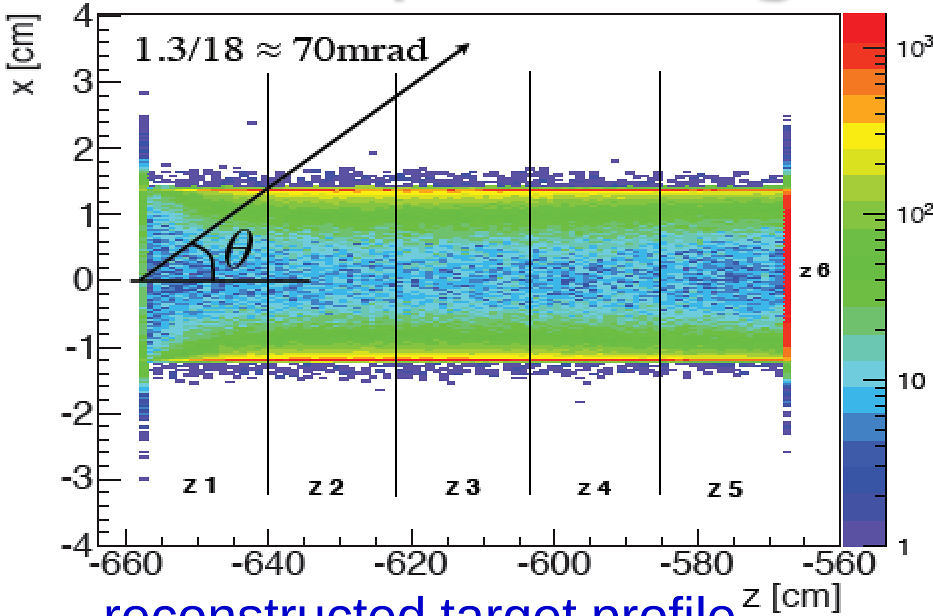
the target is sliced in 5 bins in z
+ downstream exit face



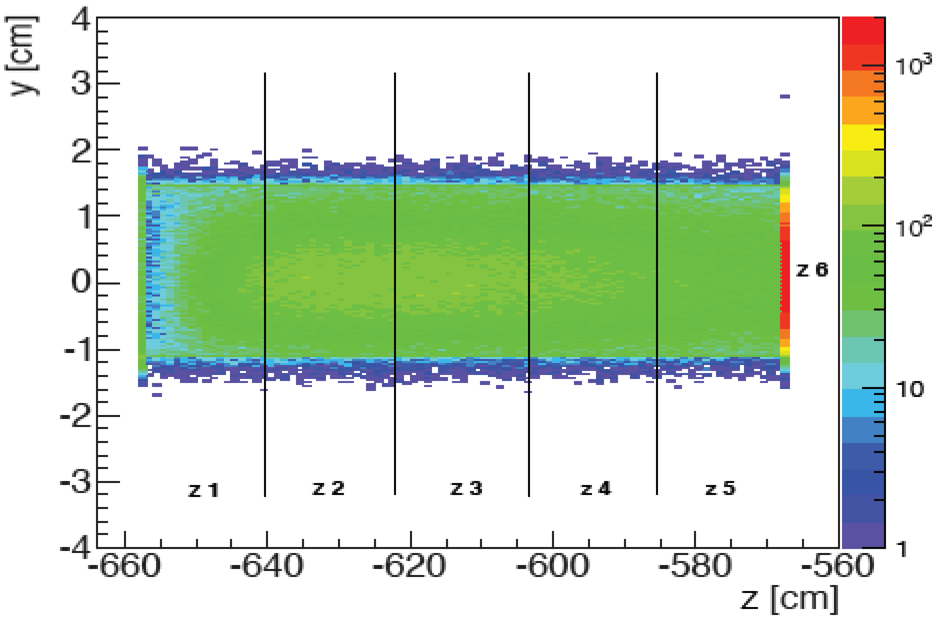
No interaction vertex reconstruction
Will study also as a function of r

Statistical precision ~5%

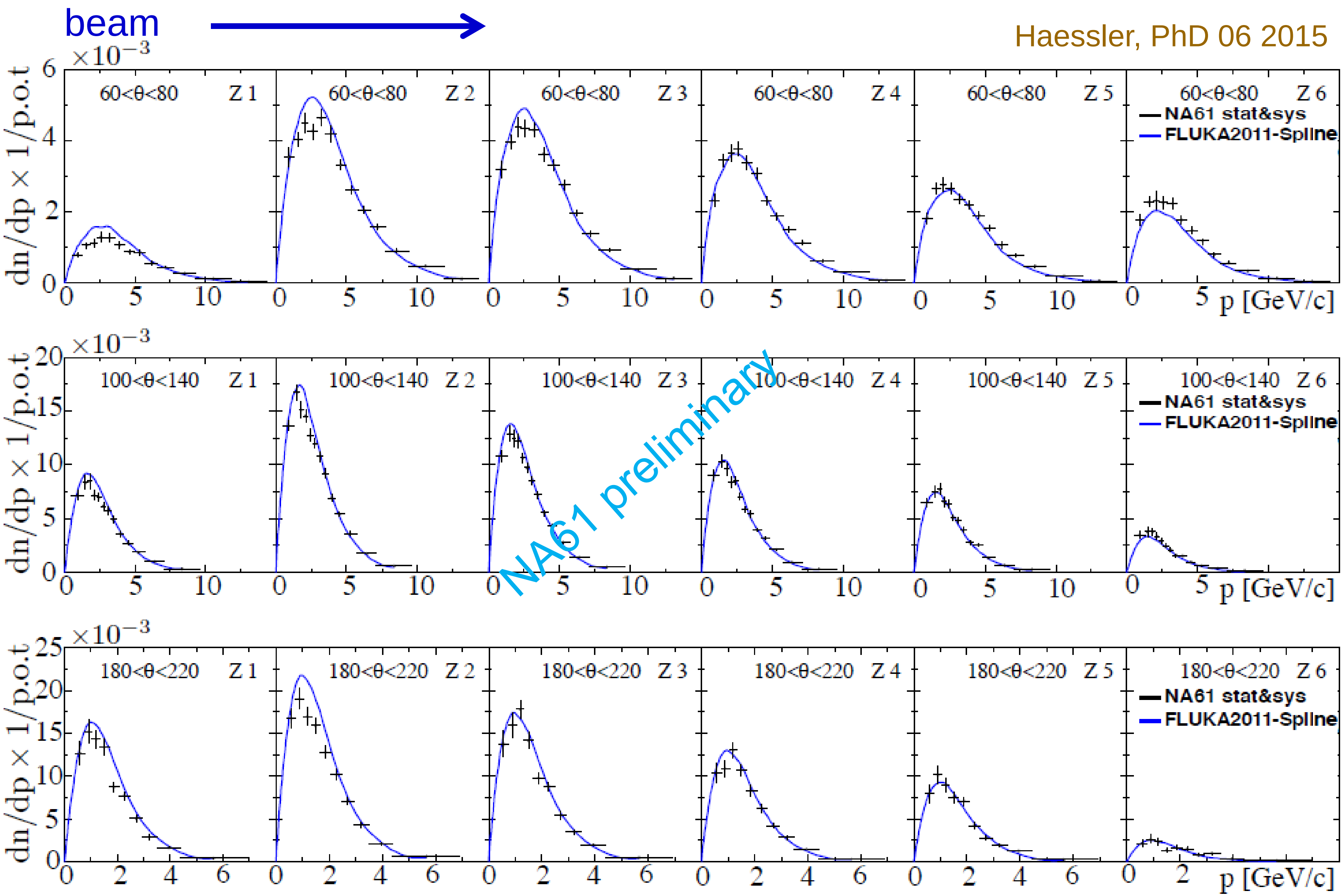
Systematic error ~5%



reconstructed target profile



π⁺ Spectra on Target Surface



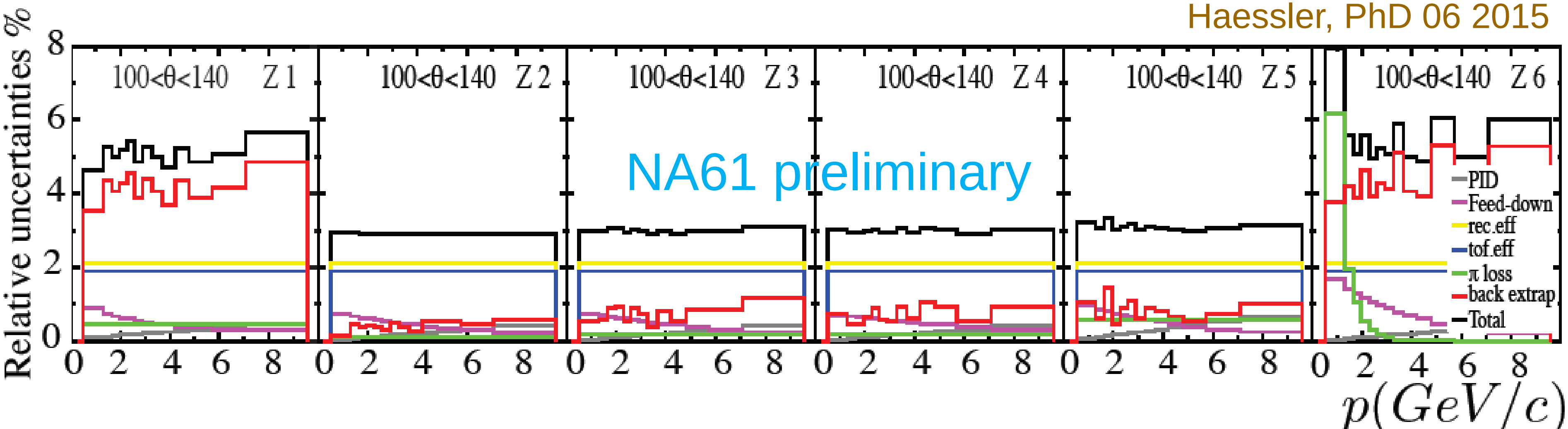
Systematic Uncertainties

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

Haessler, PhD 06 2015



For central z bins, systematic uncertainties ~3 %
Work to implement these data in T2K flux simulations ongoing

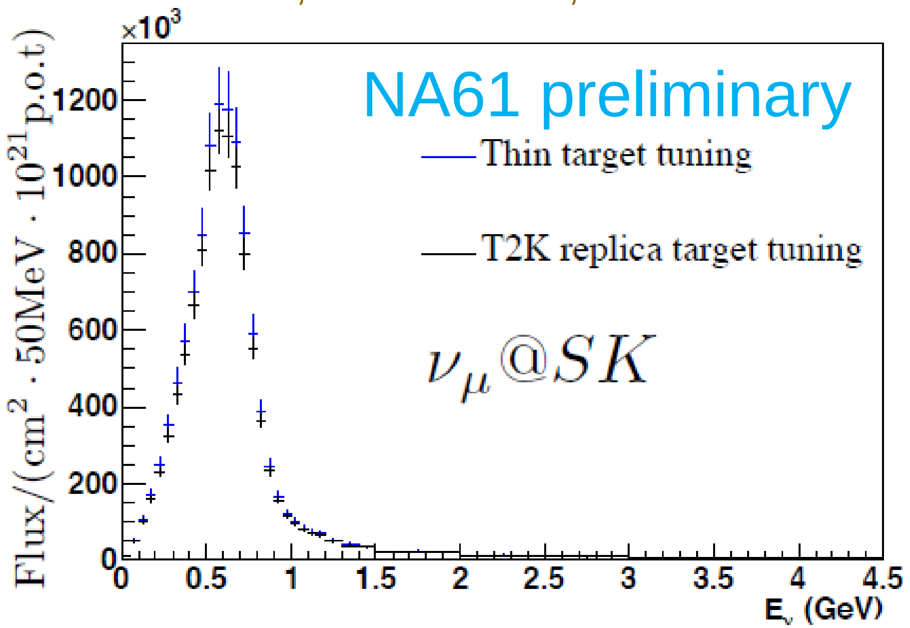
ν Flux Prediction with T2K Replica Target (3)

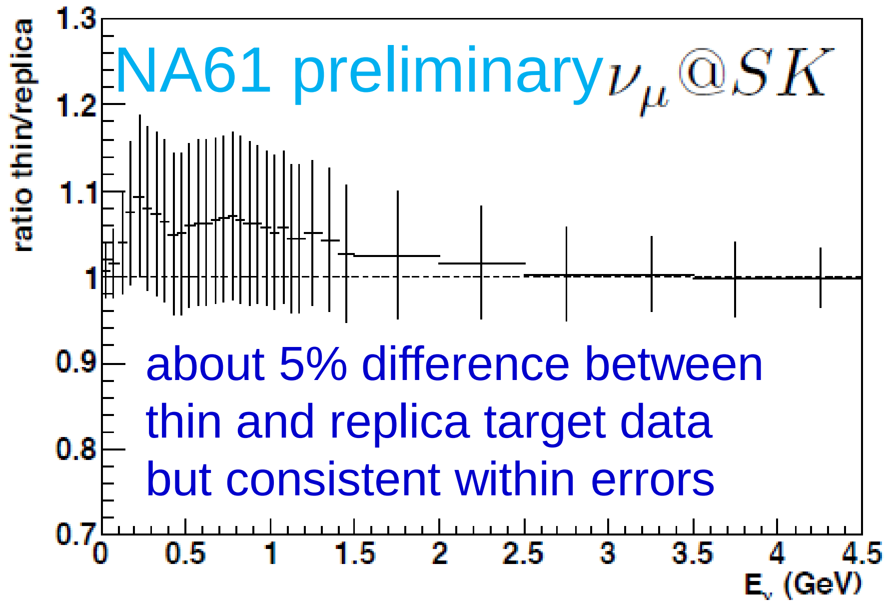
2009 data

comparison of ν flux predictions
thin target vs. replica target

thin to replica target ν flux prediction
secondary interactions modeled
with MC for thin target data

Haessler, PhD 06 2015, not T2K official result





ν_μ 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 predictions at SK

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

"In Situ" Measurements

Hadroproduction measurements can constraint about 90 % of neutrino flux

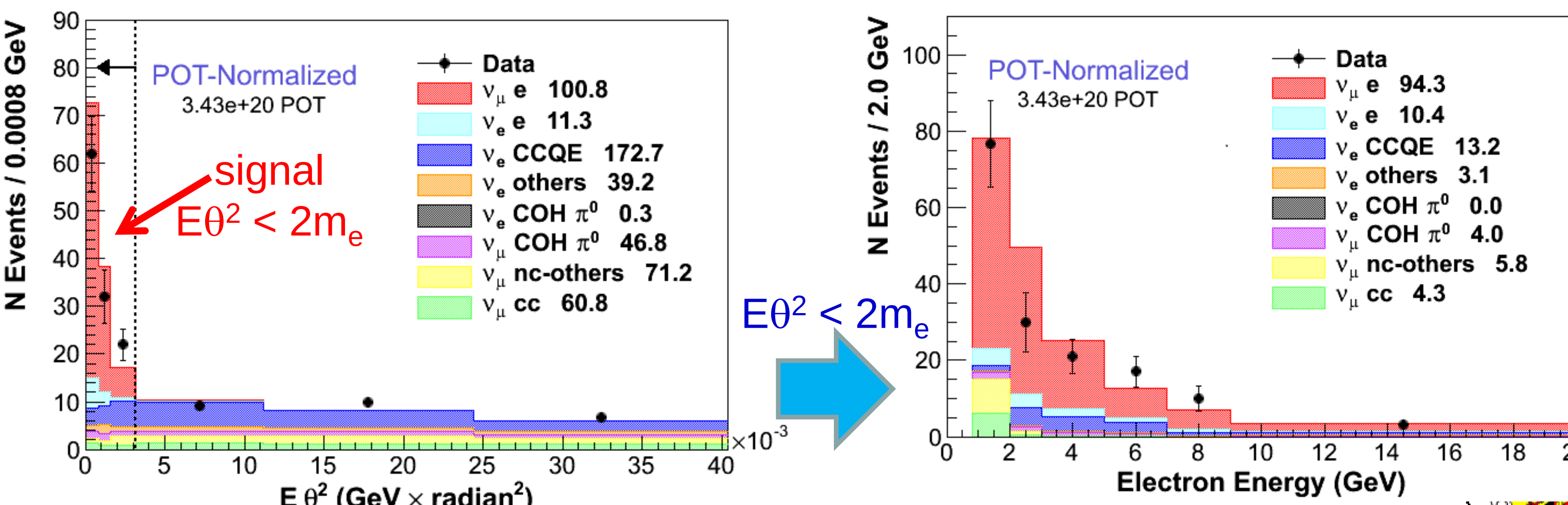
Hadroproduction measurements cannot tell what is actually happening in the beamline

Use "in situ" measurements to further constraint the flux

- neutrino – electron elastic scattering (only "standard candle" in neutrino scattering)
- muon monitors

The combination of both is the best approach to reach the ultimate precision on neutrino fluxes

neutrino – electron elastic scattering in MINERνA

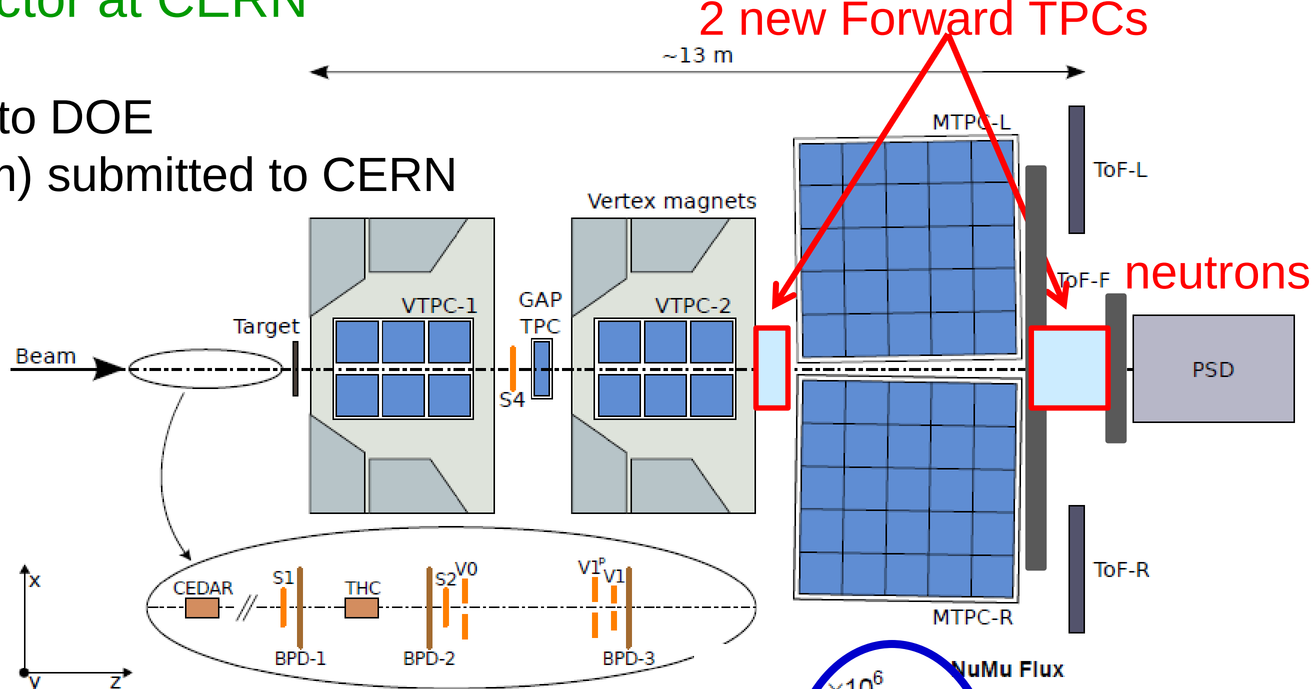


~100 events in LE sample → 10% flux constraint (expect 5% precision in ME)

NA61 4 NuMI (USNA61)

Perform hadroproduction measurements to characterize the NuMI ν beam using the NA61 detector at CERN

- mainly US groups
- proposal submitted to DOE
- proposal (addendum) submitted to CERN



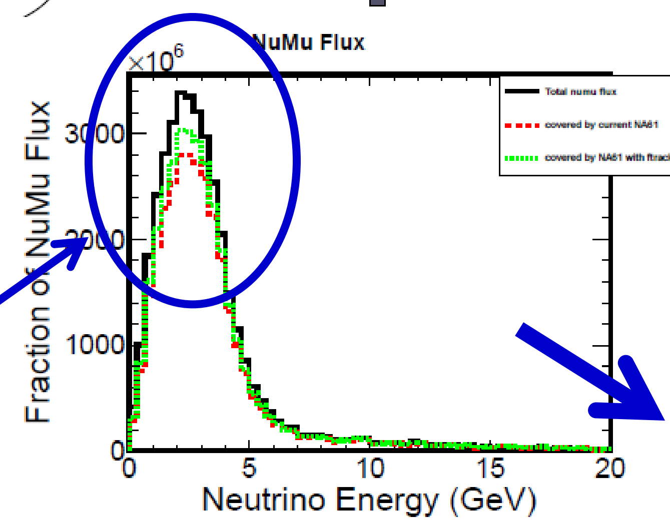
data taking to start this fall

~ 5 year program

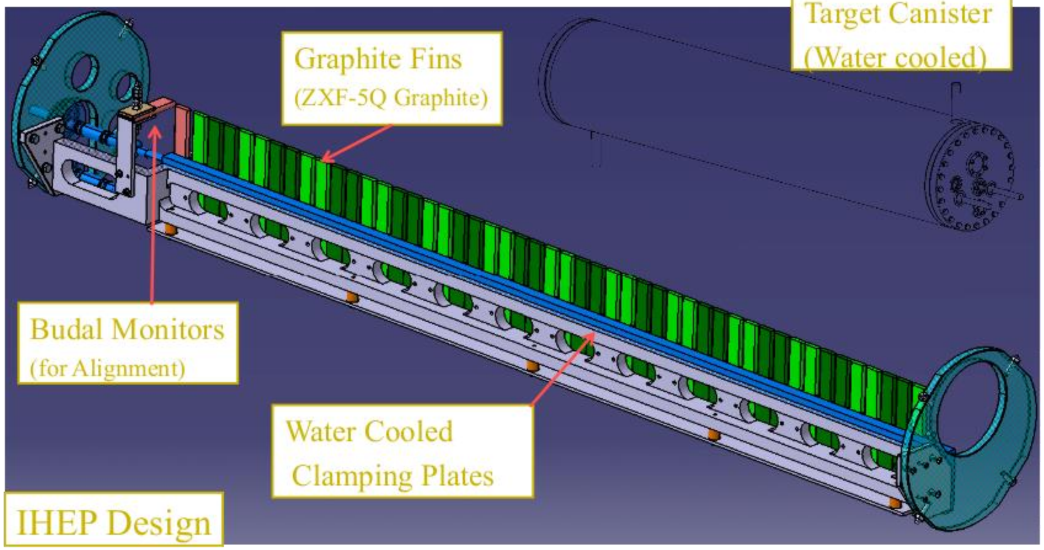
Upgrades:

- add forward tracking
- forward calorimetry (neutrons)
- new DAQ based on the DRS
- improved trigger
- new beam tracking-SciFi detectors

improved coverage

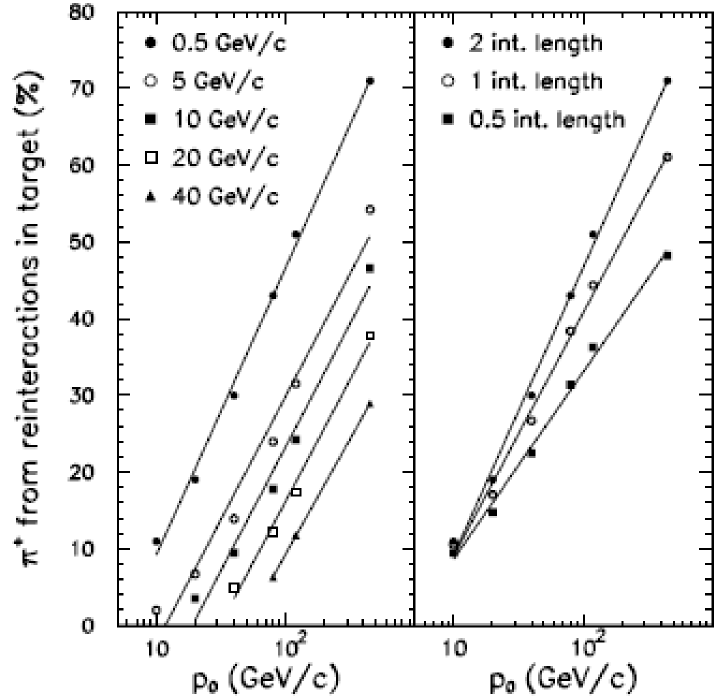


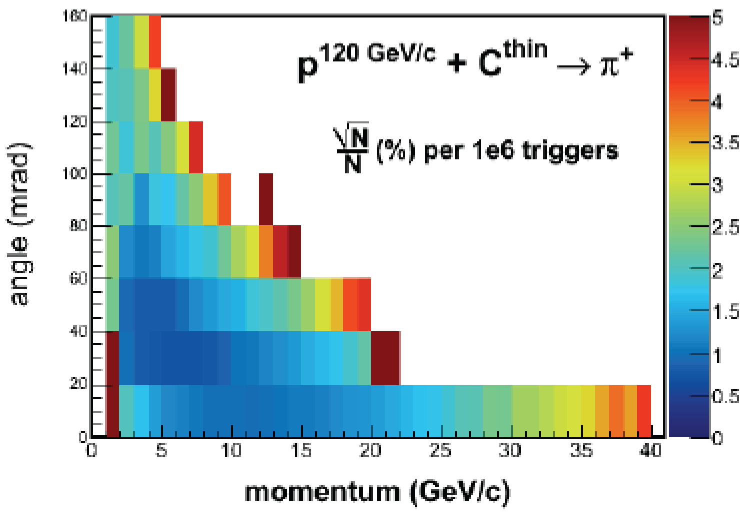
NuMI Target



With good vertexing should be able to tell from Which target the tracks originated

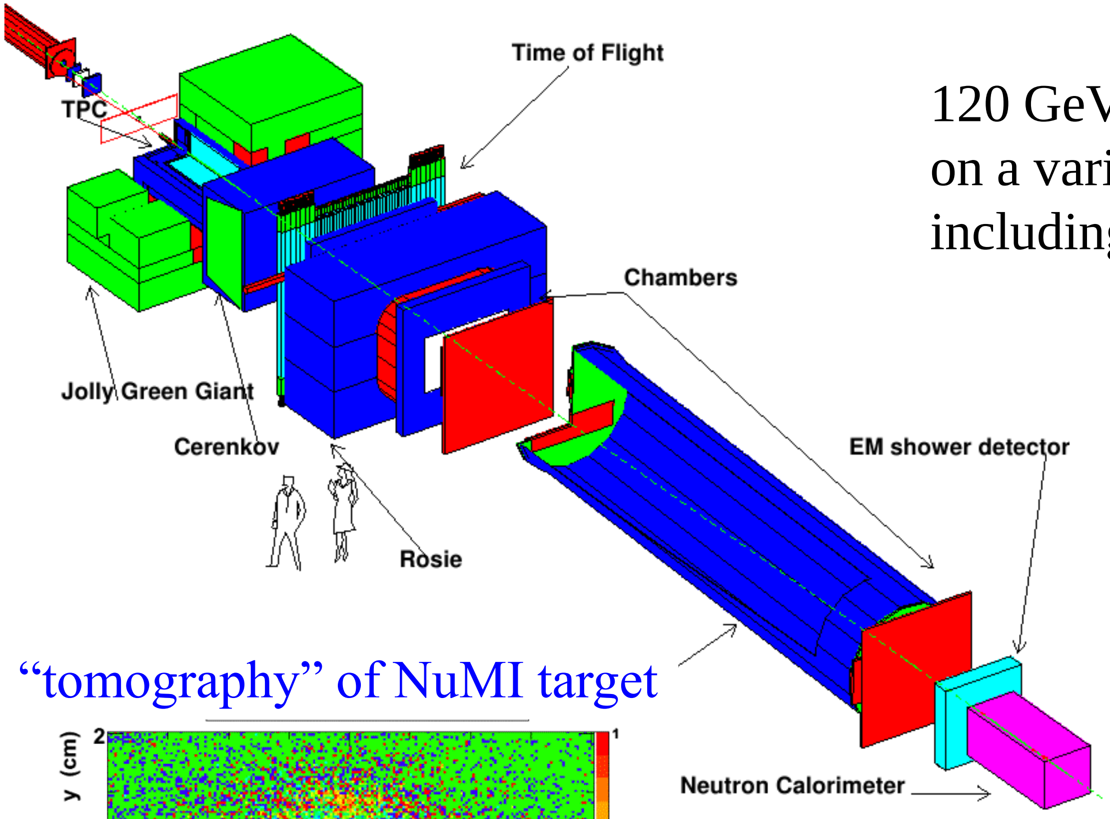
pions from reinteractions





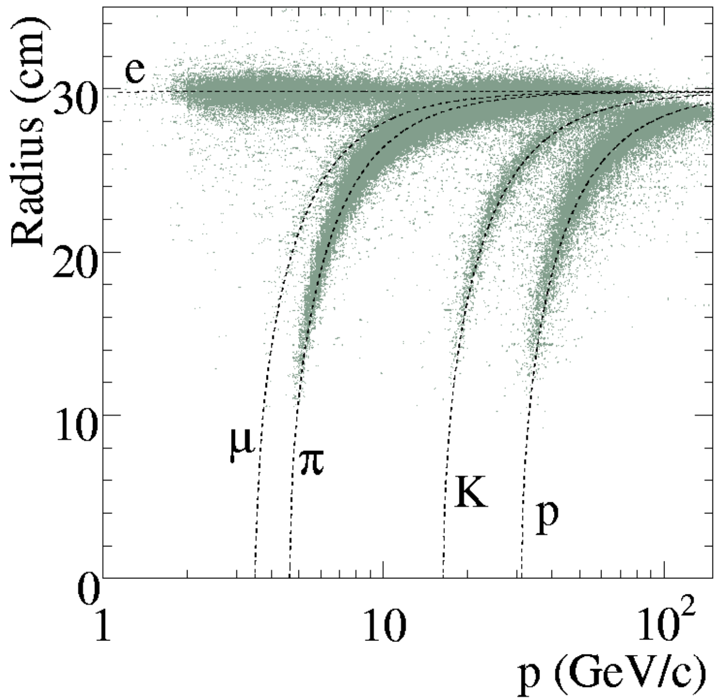
proton+pion event totals	Incident proton/pion beam momentum		
Target	120 GeV/c	60 GeV/c	30 GeV/c
NuMI (spare) replica	*(future)*		
LBNE replica	*(future)*		
thin graphite ($< 0.05\lambda_I$)	3M	3M	(T2K data)
thin aluminum ($< 0.05\lambda_I$)		3M	*(future)*
thin steel ($< 0.05\lambda_I$)	*(future)*	*(future)*	*(future)*
thin beryllium ($< 0.05\lambda_I$)	3M	3M	*(future)*

MIPP : Main Injector Particle Production Exp.

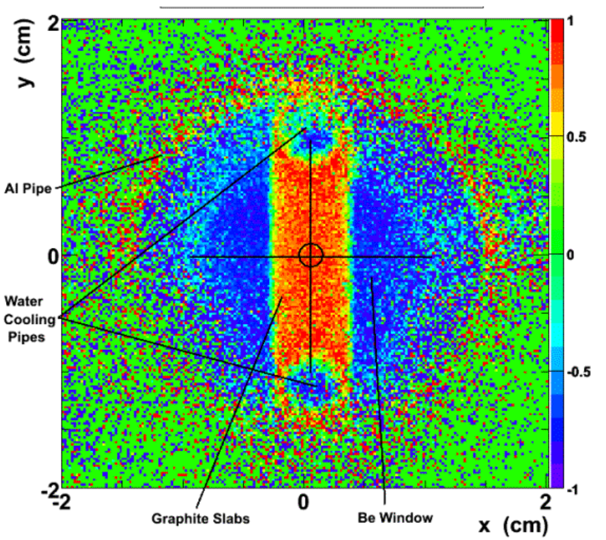


120 GeV proton beam from Main Injector
on a variety of targets
including NuMI replica target

PID with RHIC detector

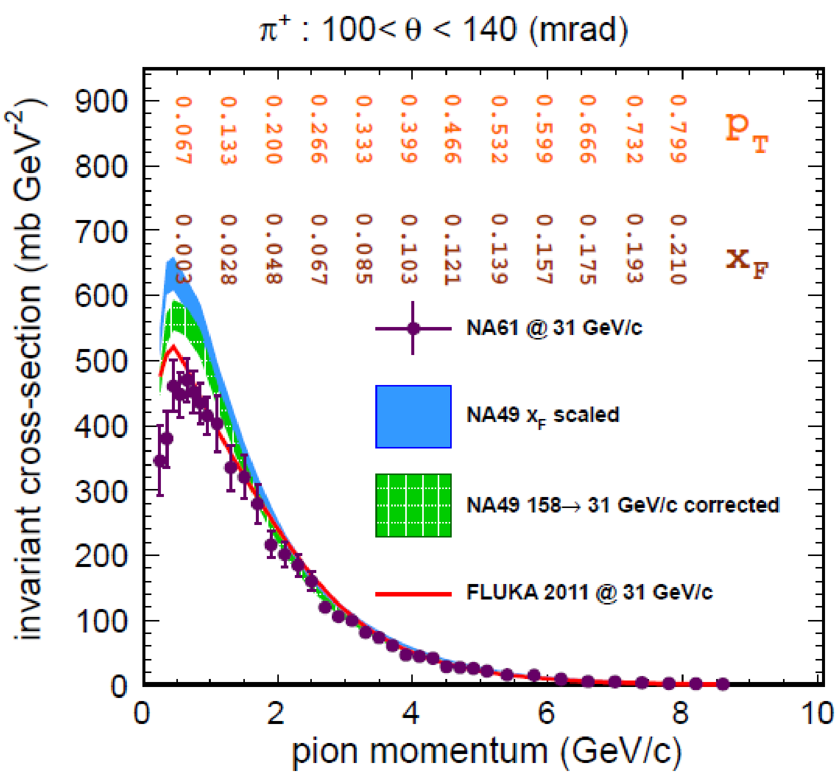


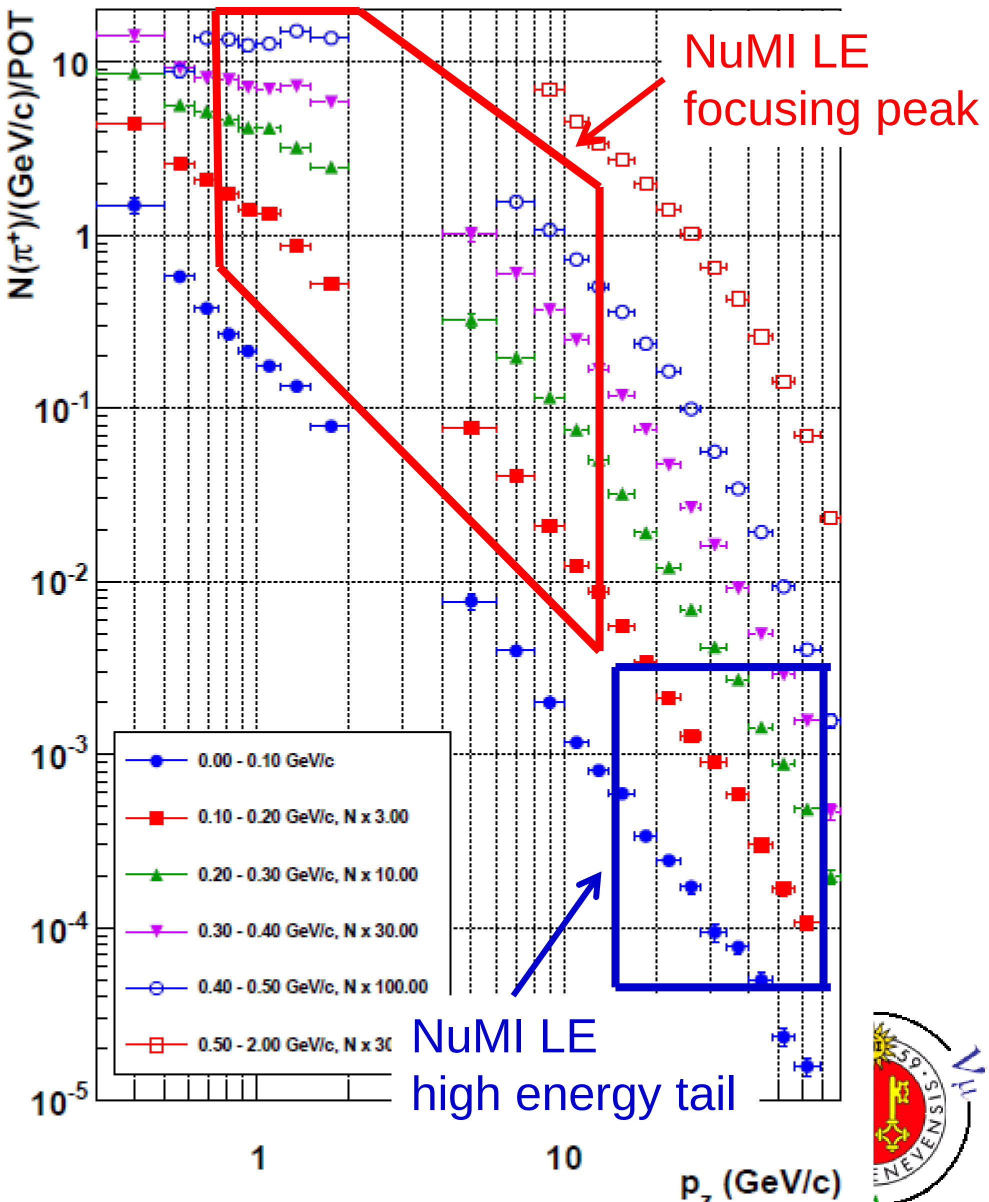
"tomography" of NuMI target



H.Meyer, Nuclear Physics B 142 (2005) 453

NuMI Neutrino Flux





Comparison of hadron production data measured on a thin carbon target at 158 GeV/c (NA49) and 31 GeV/c (NA61)

NA49 data scaled to NA61

Difference → additional systematic error
Good agreement for p_π > 1.5 GeV/c

The Future

Expect that uncertainties on neutrino fluxes will decrease down to 5% from the current ~10 % over the next 5+ years

We are still learning how to fully exploit the replica target measurements
Develop also alternative methods to the 5+1 bins currently considered

The next round of NA61 hadroproduction measurements will focus on constraining the NuMI (and LBNF) fluxes

More hadroproduction data on different nuclear targets and energies from the broad NA61 physics program are underway

- $\rightarrow$ A dependence of cross sections
- $\rightarrow$ energy dependence of cross sections
- $\rightarrow$ improve existing hadroproduction models

"In situ" measurements can complement hadroproduction measurements
The combination of both is probably the best approach to reach the ultimate precision on neutrino fluxes
But we have still to learn how to do this

Conclusions

Over the last 5 years significant progress in understanding neutrino fluxes $\rightarrow$ ~10 %
However still a long way to go to precision cross section measurements and next steps in oscillation physics

Hadro production measurements require

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

At present, NA61 the 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 constantly upgraded and analysis tools being improved

The combination of hadroproduction measurements and “in situ” measurements is probably the best approach to reach the ultimate precision on neutrino fluxes

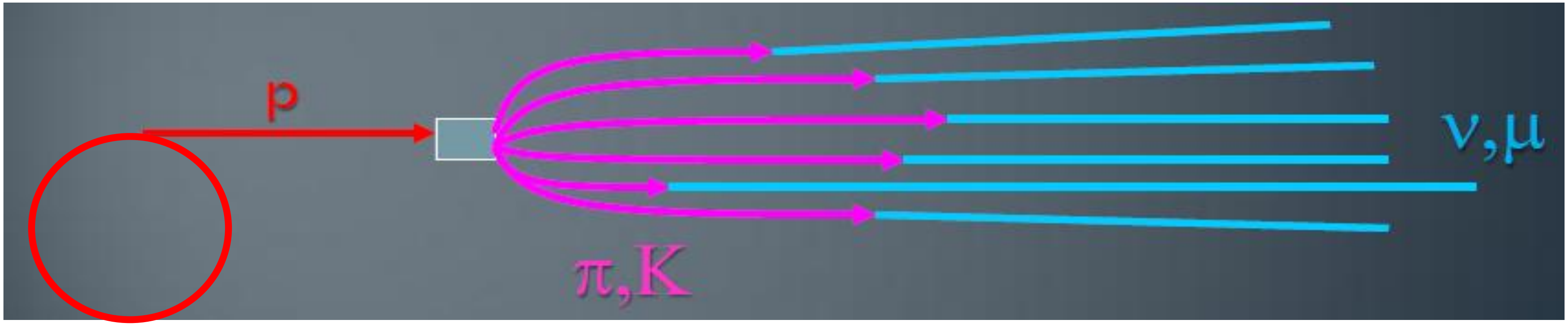
Additional material

Conventional ν Accelerator Beams

high intensity proton beam from accelerator strikes primary production target

protons produce pions and kaons and …

pions and kaons are focused with magnetic horns toward a long decay region (by selecting the polarity of **B** one focuses positive or negative hadrons)

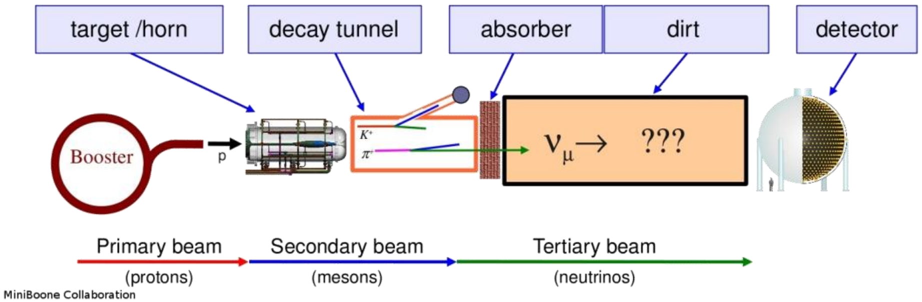


“shieldings” stop all particles but neutrinos

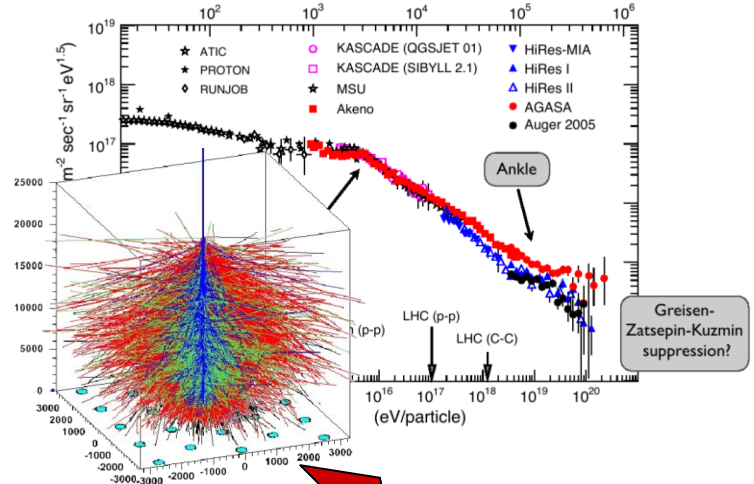
resulting beam composed mainly of ν_μ, with small ν_e (~1 %) component

want to maximize π, K → μ + ν_μ decays for highest ν_μ fluxes
want to know the π, K, … production details to minimize ν flux errors

conventional accelerator based ν beam



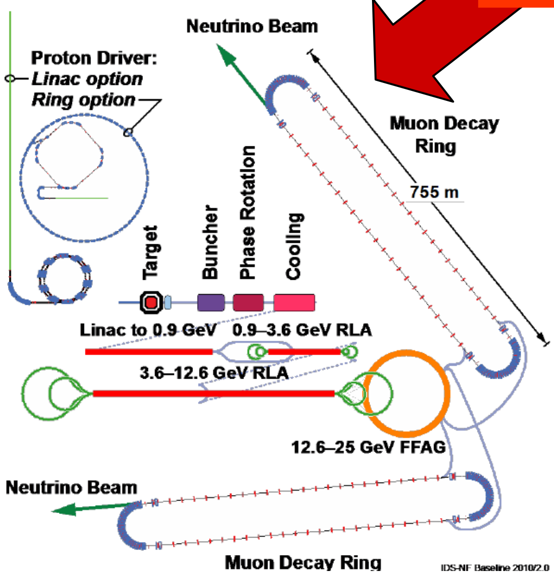
atmospheric showers



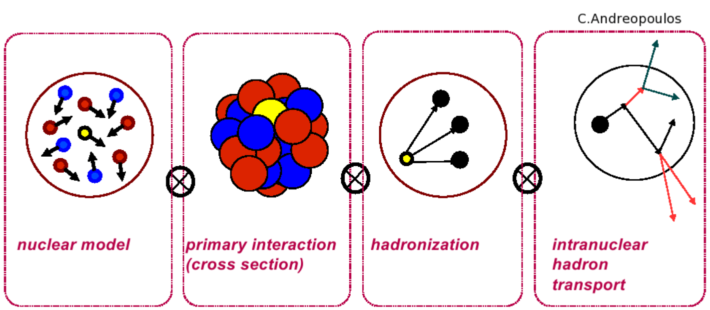
hadro-production measurements

$$p(\pi) + A \to h + X$$

neutrino factory



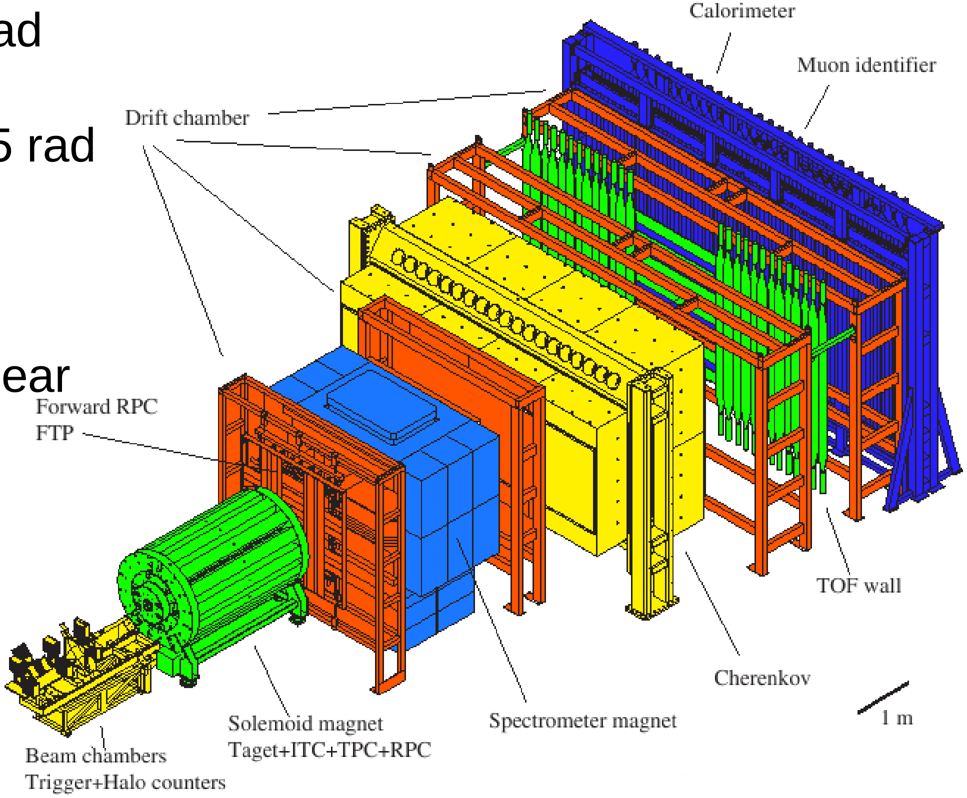
MC generators



HARP : Hardon Production Exp. at PS

Kinematical acceptance of HARP detector
- Forward spectrometer
  - $0.5 < p < 8$ GeV/c, $25 < \theta < 250$ mrad
- Large angles (TPC + RPC)
  - $0.1 < p < 0.8$ GeV/c, $0.35 < \theta < 2.15$ rad

Measurement of secondary π, K, and p Production cross sections for various nuclear targets with p / π beams in 1.5 – 15 GeV/c momentum range



HARP, NIM A571 (2007) 527

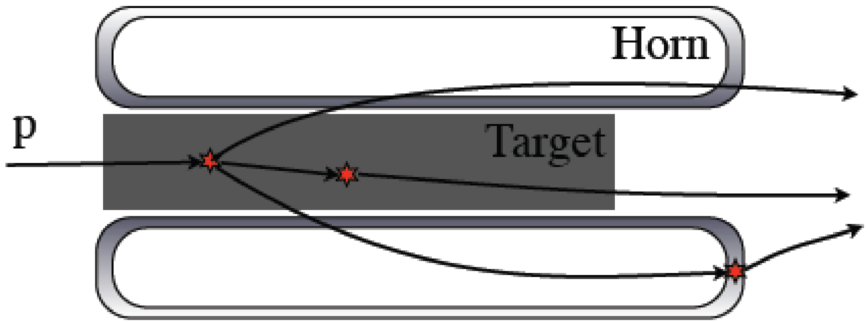
Results of HARP measurements have been used for ν flux predictions in
- K2K: Al target, 12.9 GeV/c p beam
- Mini(Sci)BooNE: Be target, 8.9 GeV/c p beam

Also to be used for atmospheric ν flux calculations and high intensity μ-stopped source

Neutrino Source Production

direct contribution:

secondary hadrons exit the target and decay into ν



target contribution:

tertiary hadrons exit the target and decay into ν

non-target contribution:

re-interactions in the target surrounding material

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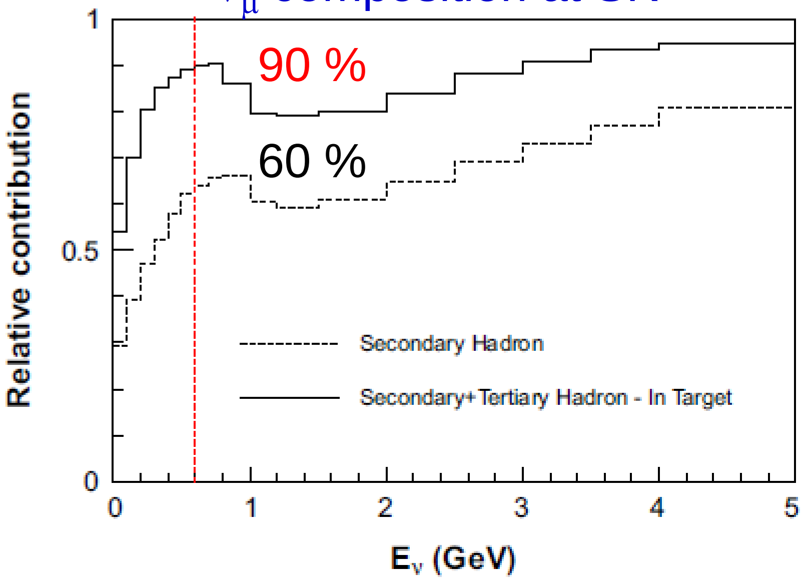
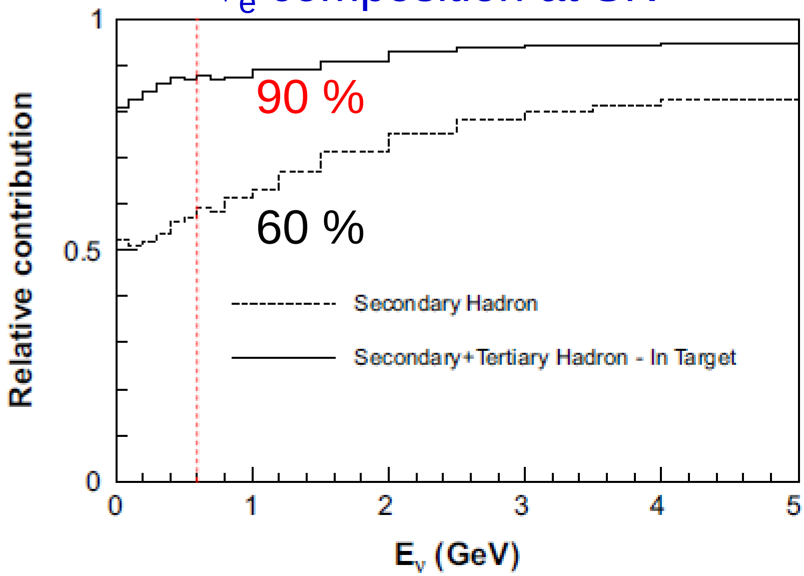
ν_μ composition at SK



ν_e composition at SK



ν Flux Prediction with T2K Replica Target (2)

2007 data

comparison of ν flux predictions
thin target vs. replica target

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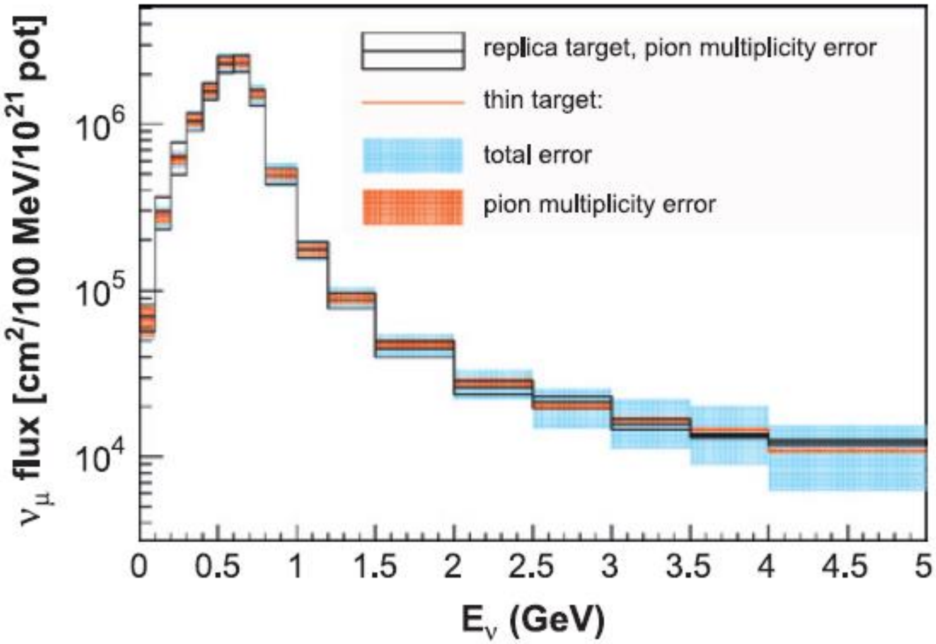
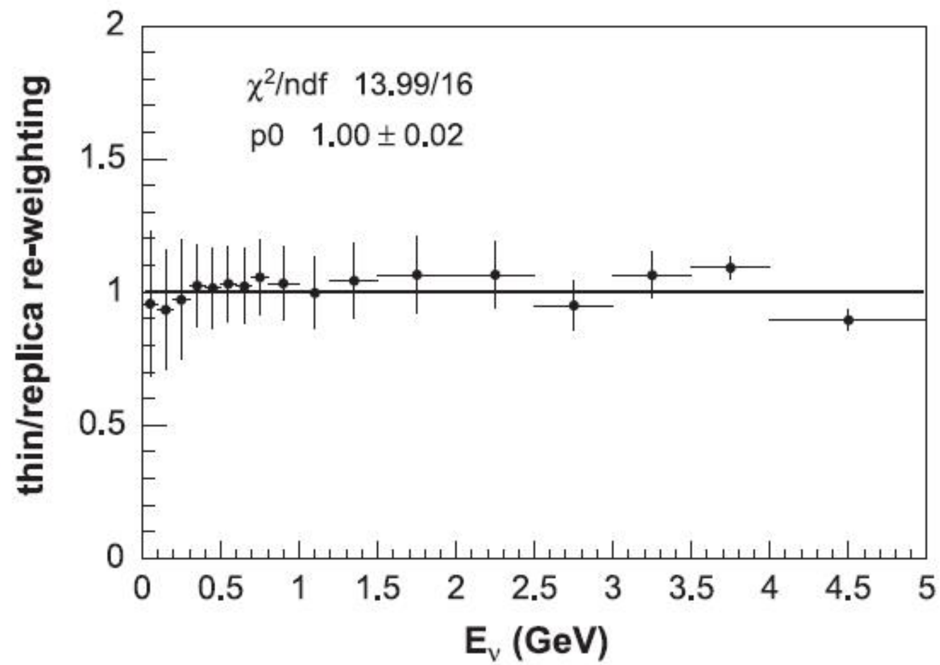


thin to replica target ν flux prediction
secondary interactions modeled
with MC for thin carbon target data



The two fluxes are in very good agreement:
just a coincidence or real ?
are the hadronic models so good ?