Hadron Production Experiments

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NuInt15
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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

Conventional ν Accelerator Beams

high intensity proton beam from accelerator strikes the 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)

"primary" particles do reinteract in the target and/or in the materials surrounding the target generating additional particles

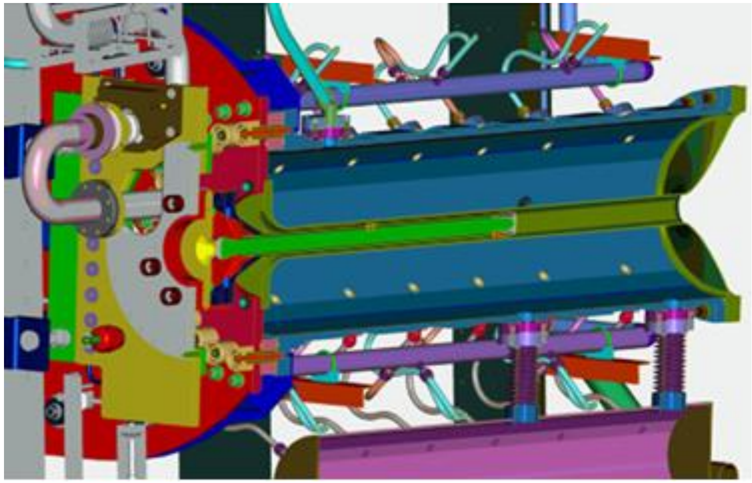
"shieldings" stop all particles but neutrinos

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

want to maximize π, K $\rightarrow \mu + \nu_\mu$ decays for highest ν_μ fluxes
want to know the π, K, … production details to minimize ν flux errors

Outside Target Interactions

T2K target including 1st horn

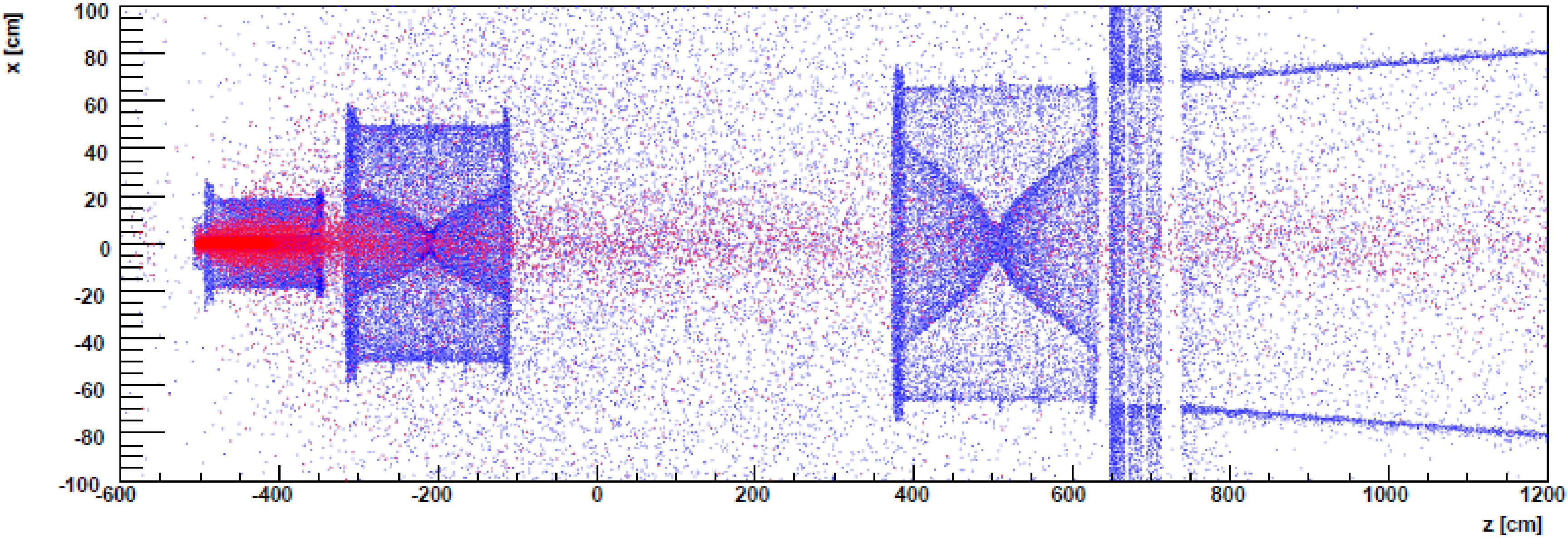


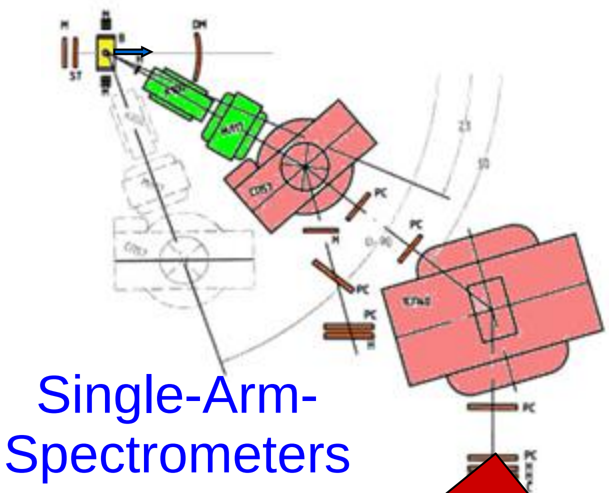
blue: production point of neutrino parent particles

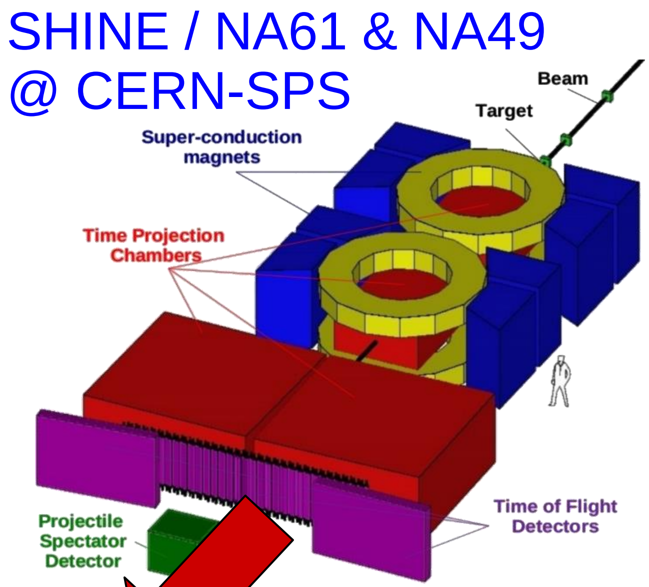
red: parents produced in the target or along decay chains

blue / red ~ 0.1

Abgrall,CERN-THESIS-2011-165

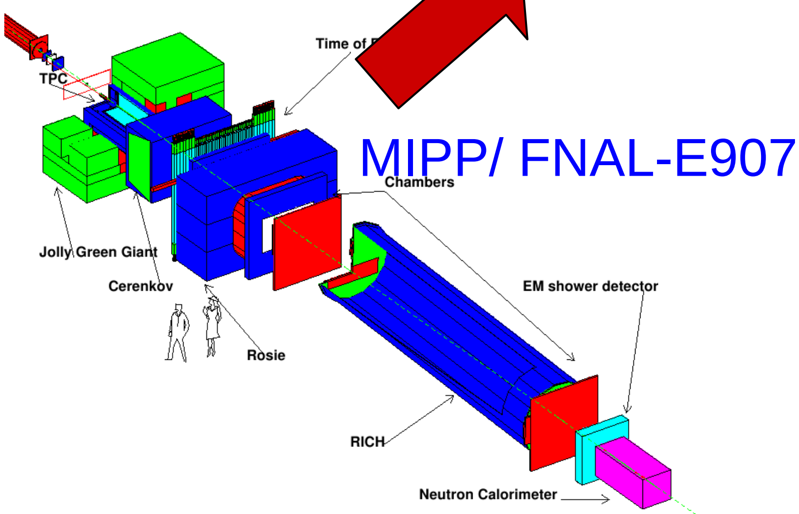


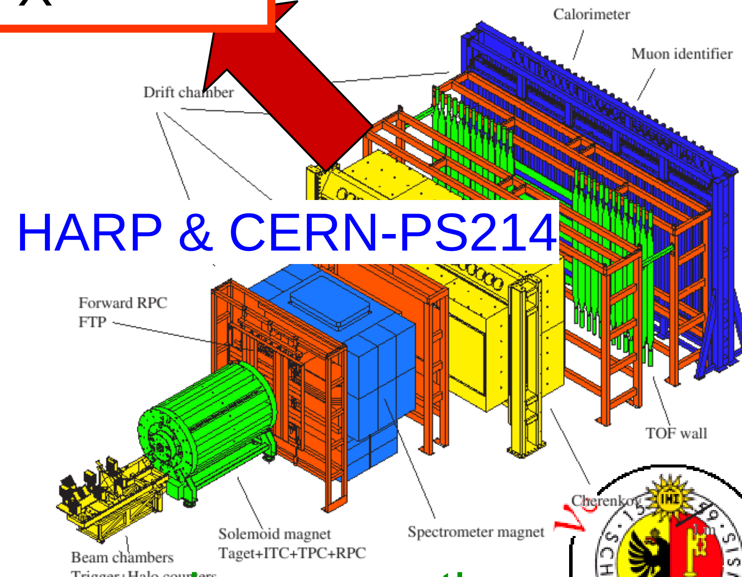




hadro-production measurements

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

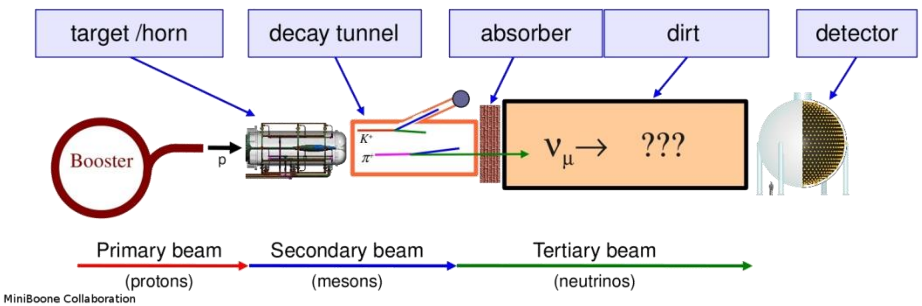




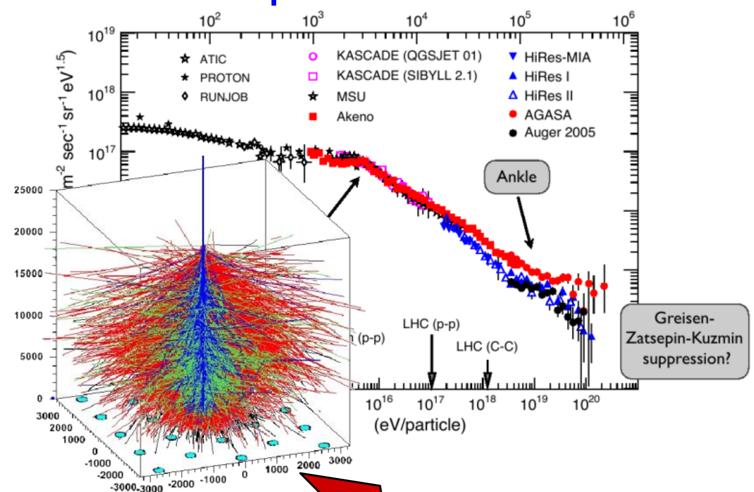
+ many many other experiments that measured cross sections ...

$\Rightarrow$ critical survey of all existing cross section measurements !

conventional accelerator based ν beam



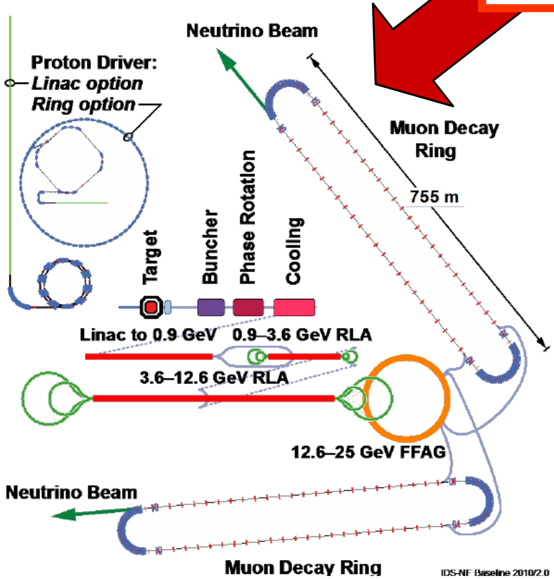
atmospheric showers



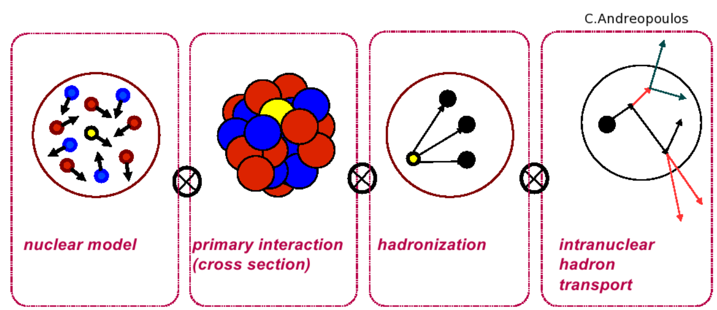
hadro-production measurements

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

neutrino factory



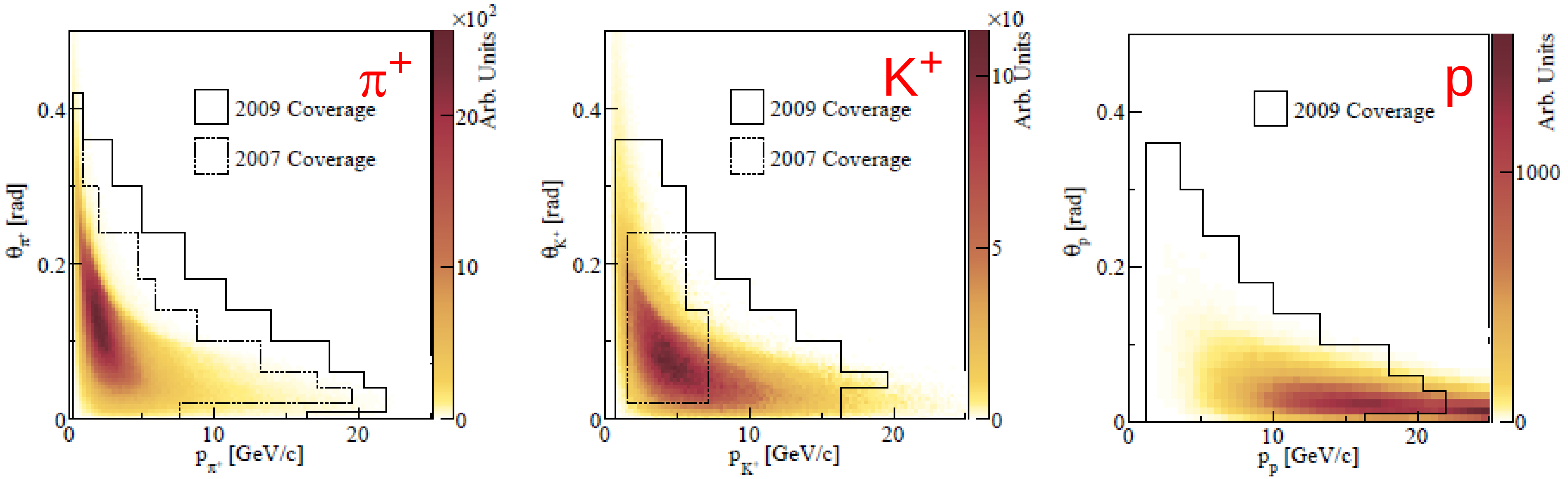
MC generators



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

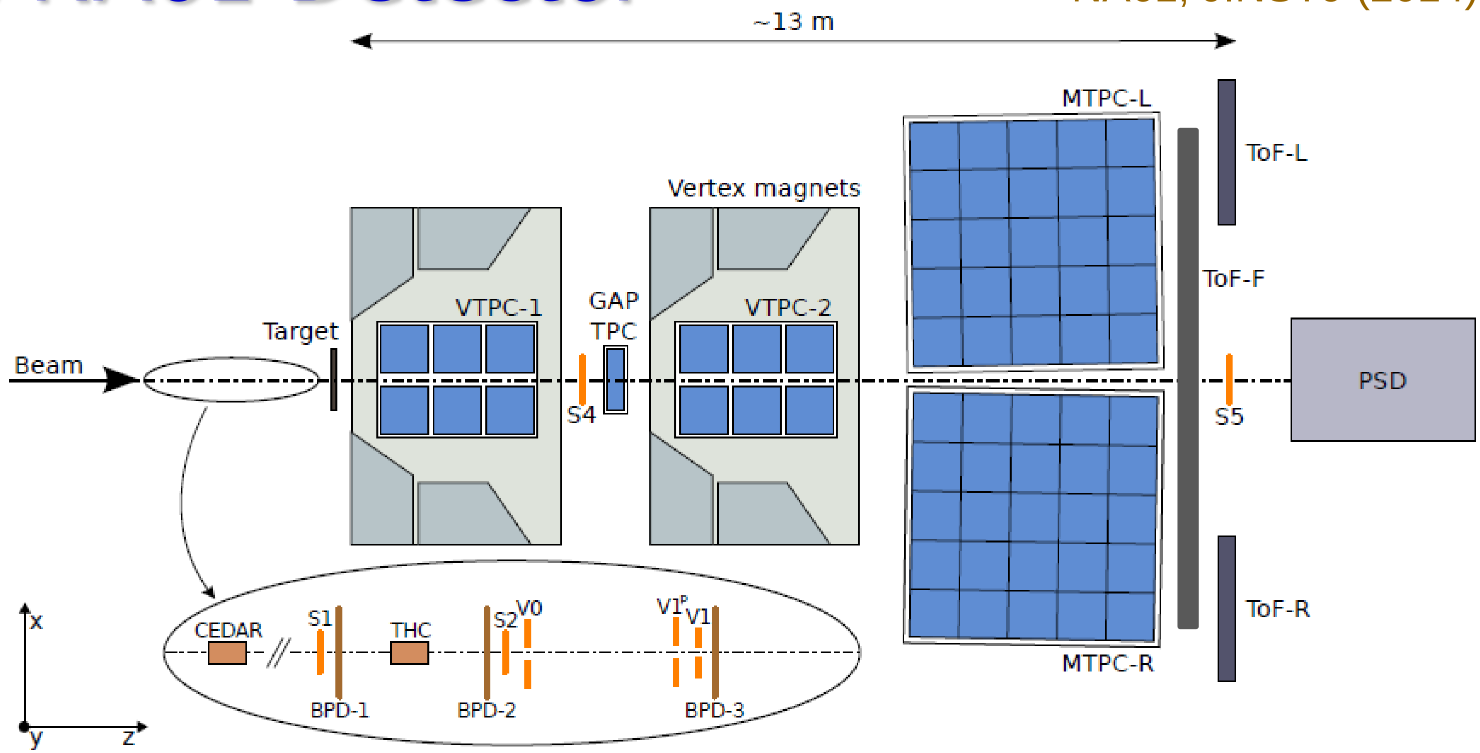
requires detector with large acceptance

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

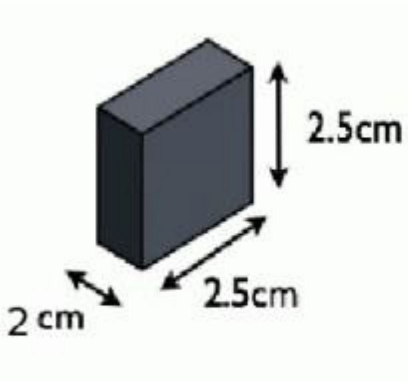
good particle identification: σ(ToF-L/R) ≈ 100 ps, σ(dE/dx)/<dE/dx> ≈ 0.04, $\sigma(m_{inv}) \approx 5$ MeV

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



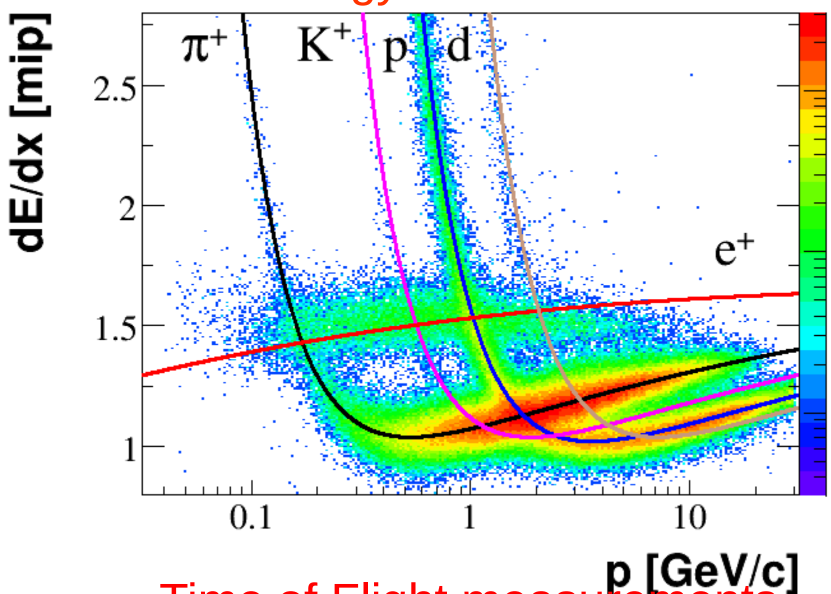
Thin Carbon Target
- length=2 cm, cross section 2.5 x 2.5 cm^2
- ρ = 1.84 g/cm^3
- ~0.04 λ_{int}

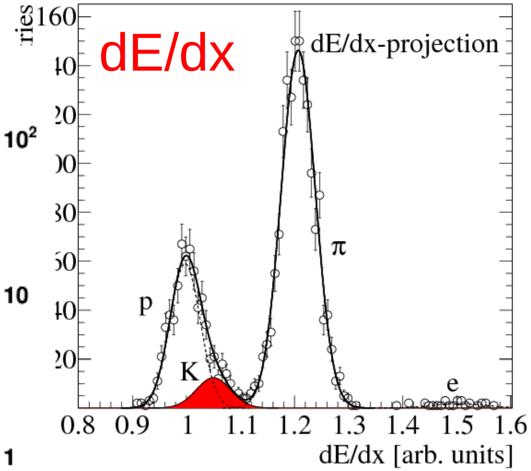
T2K replica Target
- length = 90 cm, Ø=2.6 cm
- ρ = 1.83 g/cm^3
- ~1.9 λ_{int}

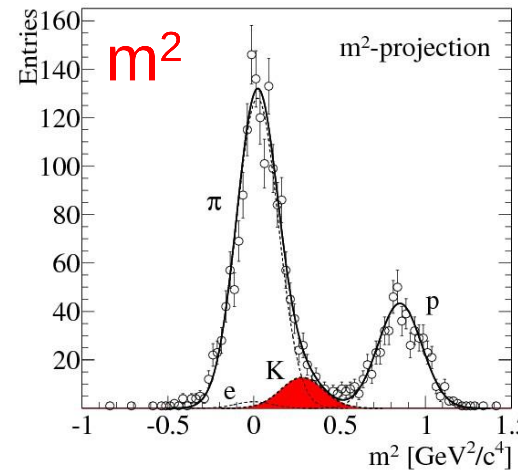
	2007 pilot run	2009 run	2010 run
Thin target:	~660k triggers	~6 M triggers	
		(⇒ ~2×10^5 π^+ tracks in T2K acceptance)	
Replica target:	~230k triggers	~2 M triggers	~10 M triggers

Particle Identification in NA61

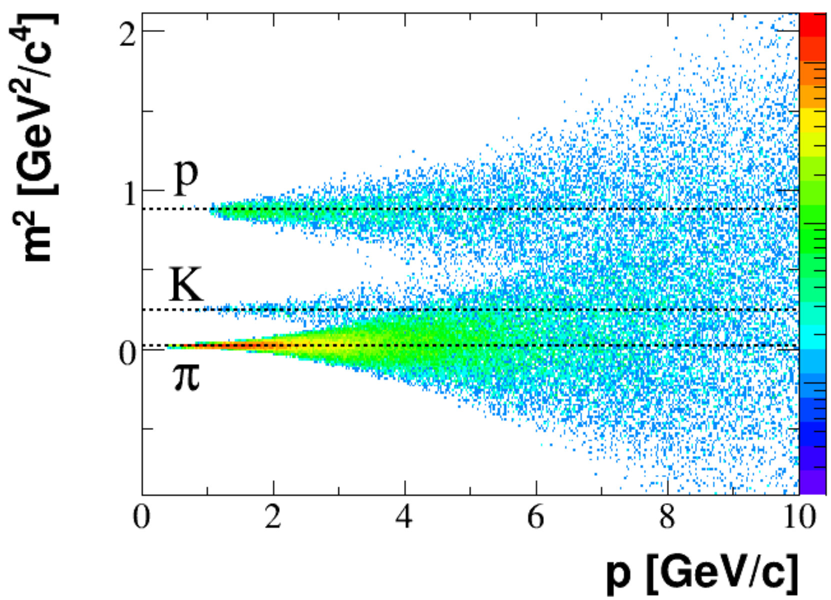
Energy loss in TPCs



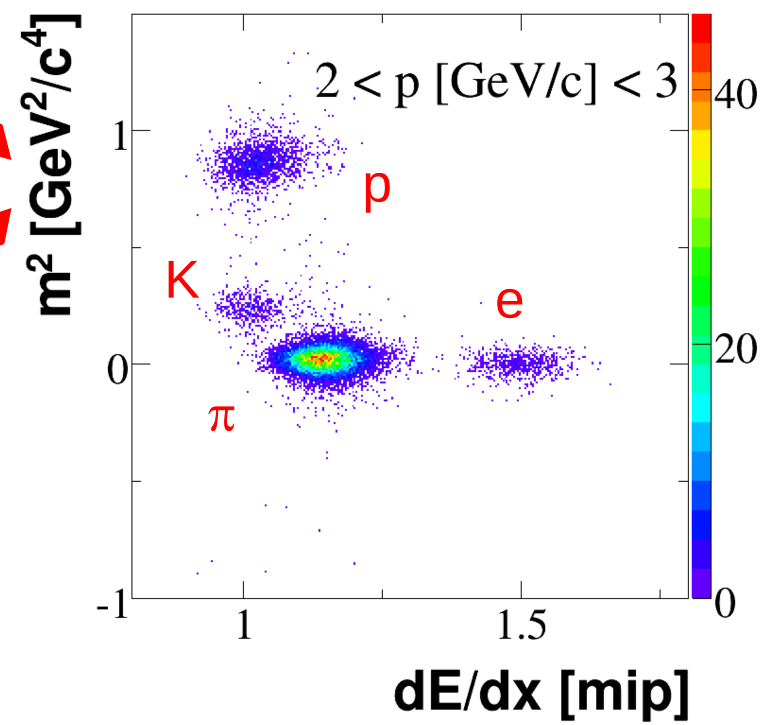


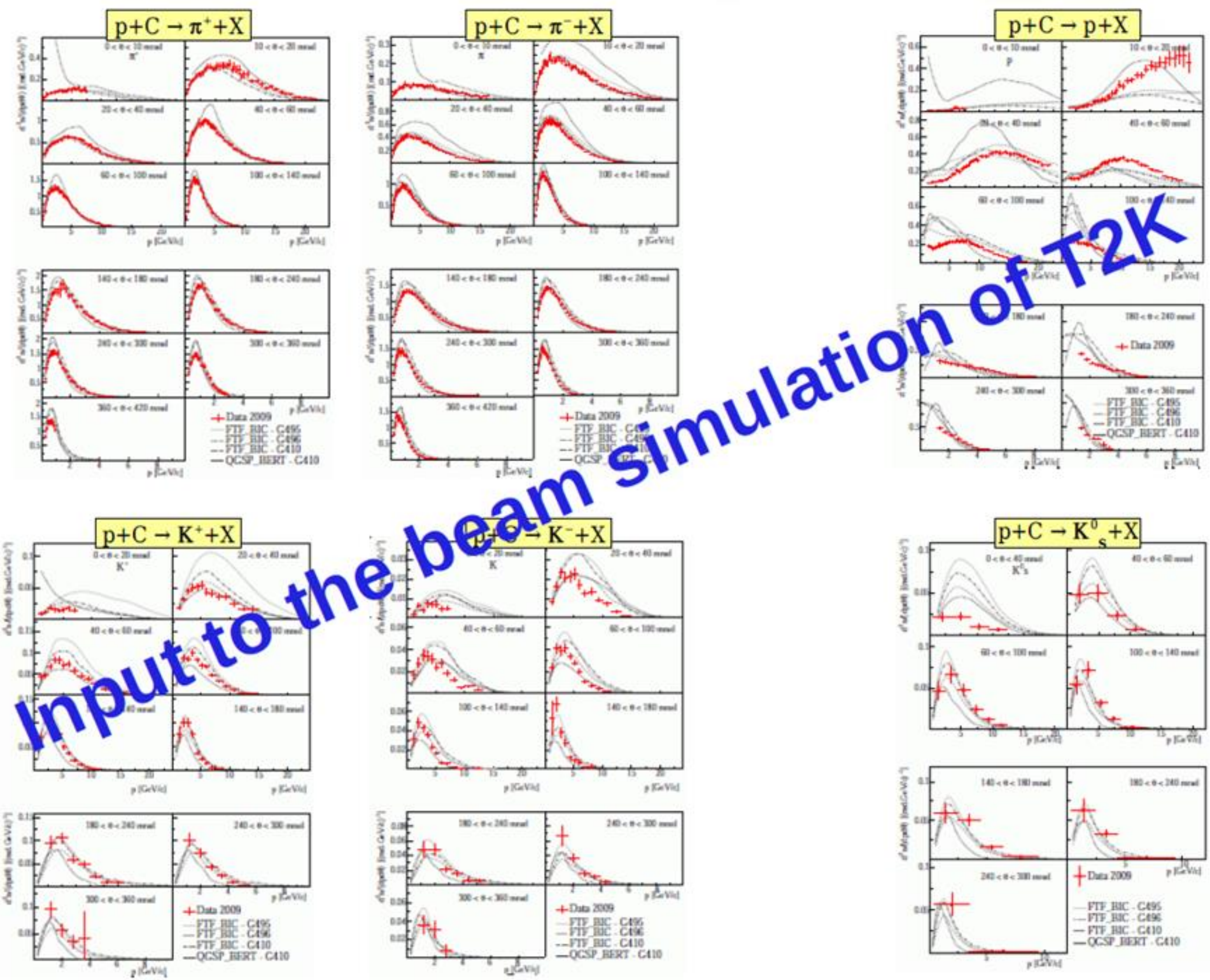


Time of Flight measurements



combined ToF + dE/dx



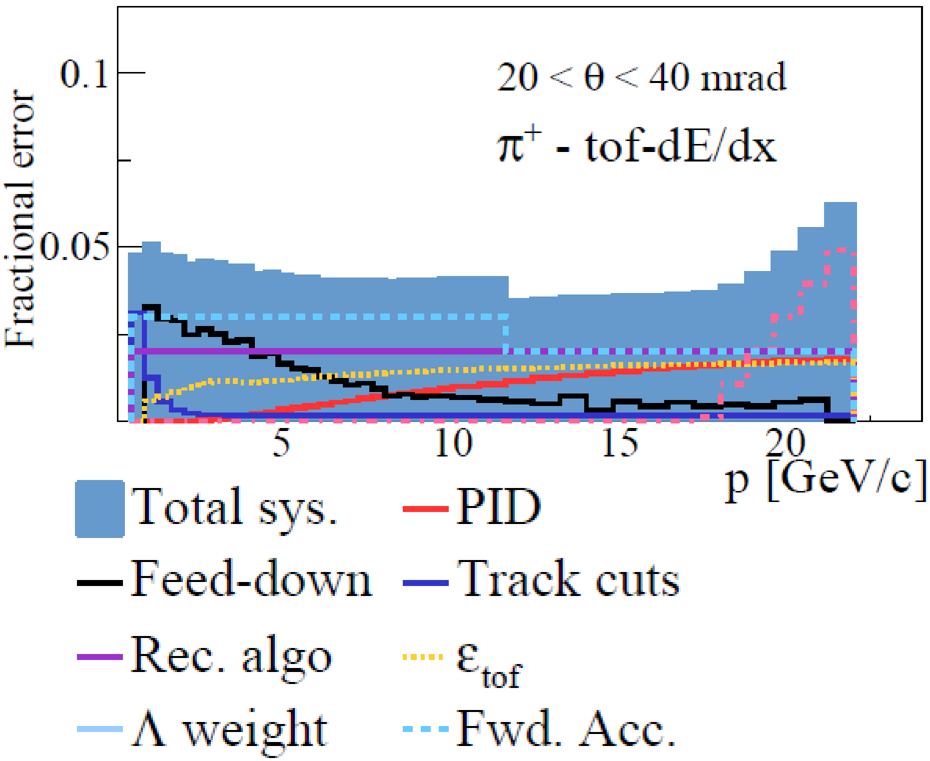

p+C → π⁺+X
p+C → π⁻+X
p+C → p+X
p+C → K⁺+X
p+C → K⁻+X
p+C → K⁰s+X
Data 2009
FTF_BIC - C495
FTF_BIC - C496
FTF_BIC - C410
QCSP_BERT - C410
Input to the beam simulation of T2K

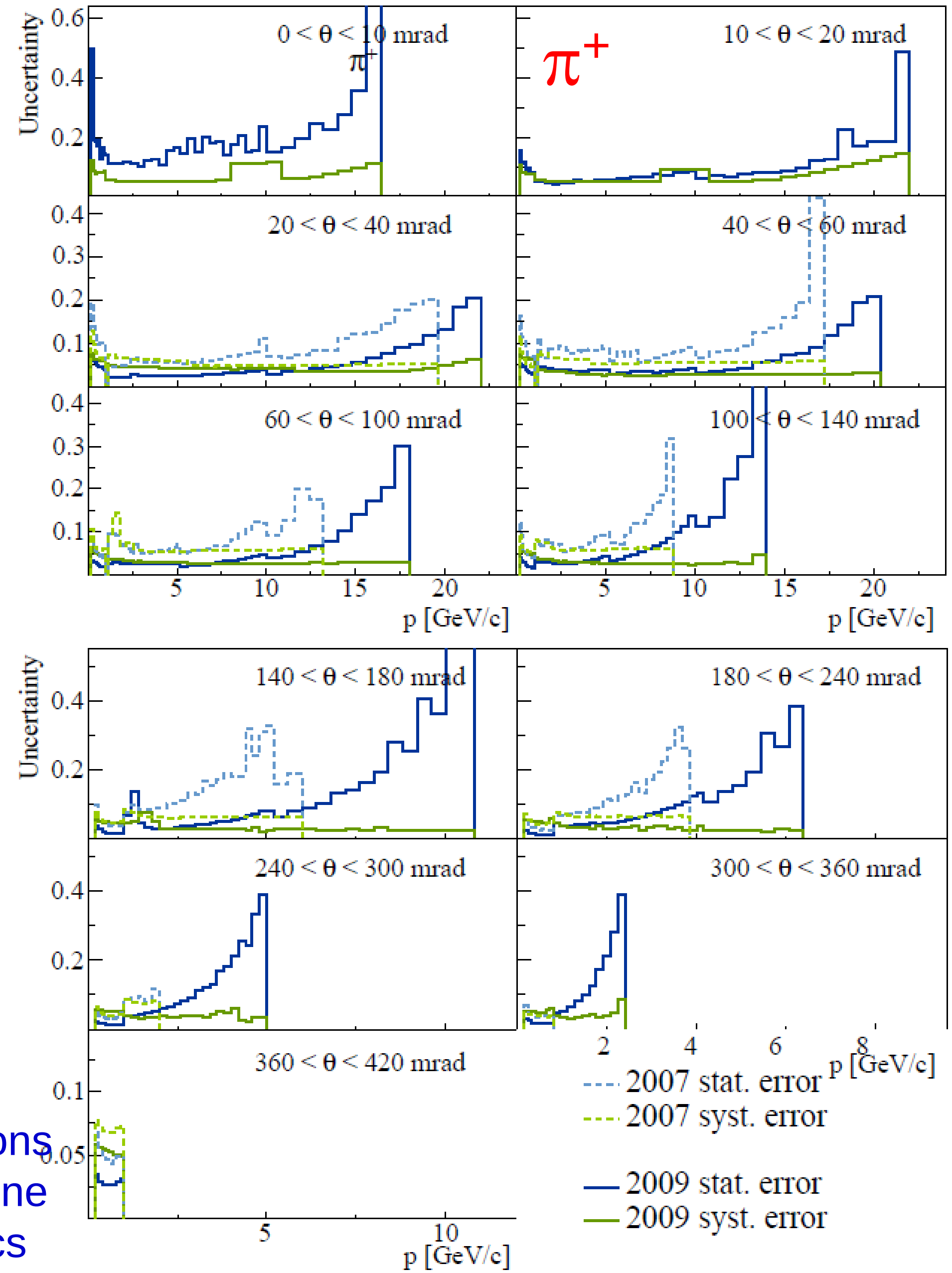
NA61 p + C → π^+ + X Uncertainties (dN/dp)

Compared to 2007 data:

- statistical uncertainty improved ~3×
- systematical uncertainty reduced ~2×

NA61, arXiv:1510.02703



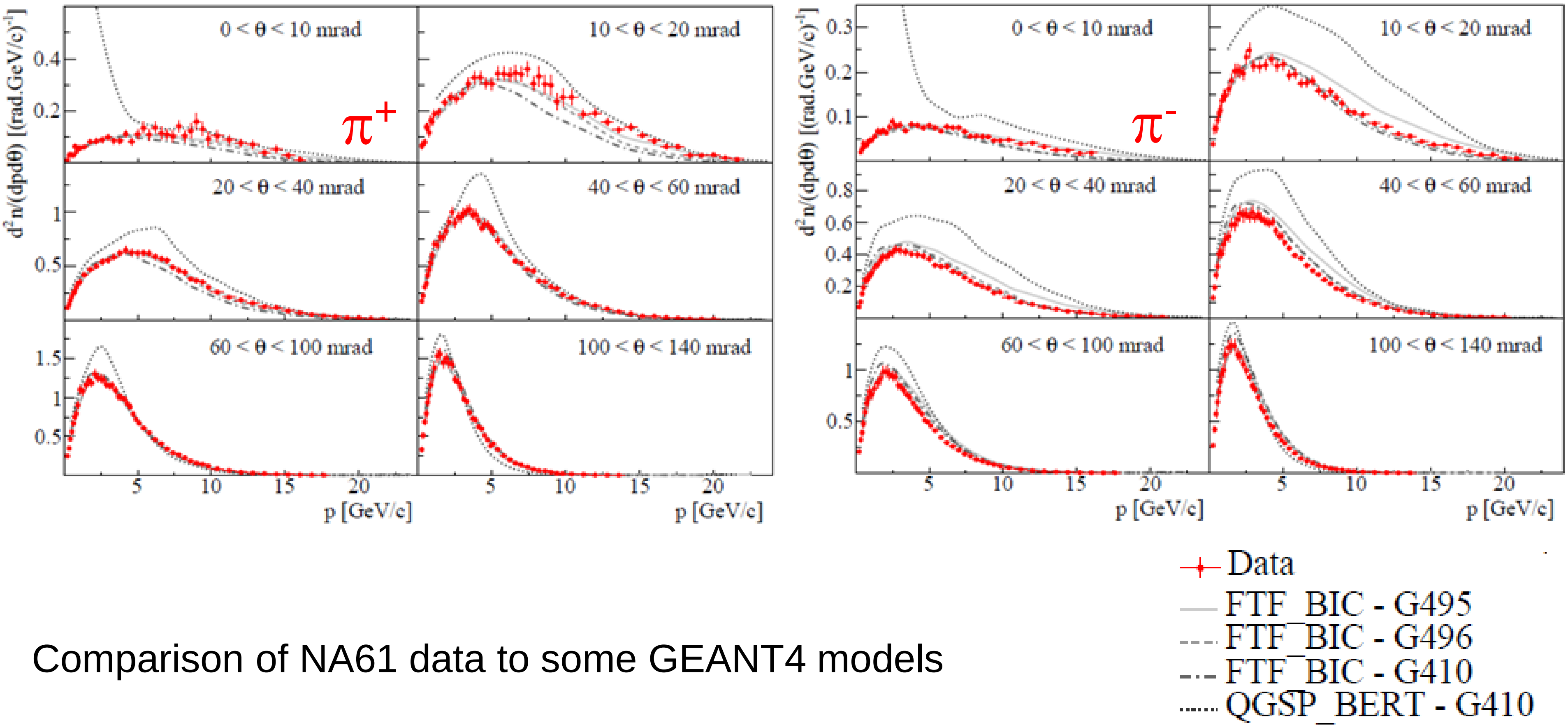


+ normalization error ~2.5%

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

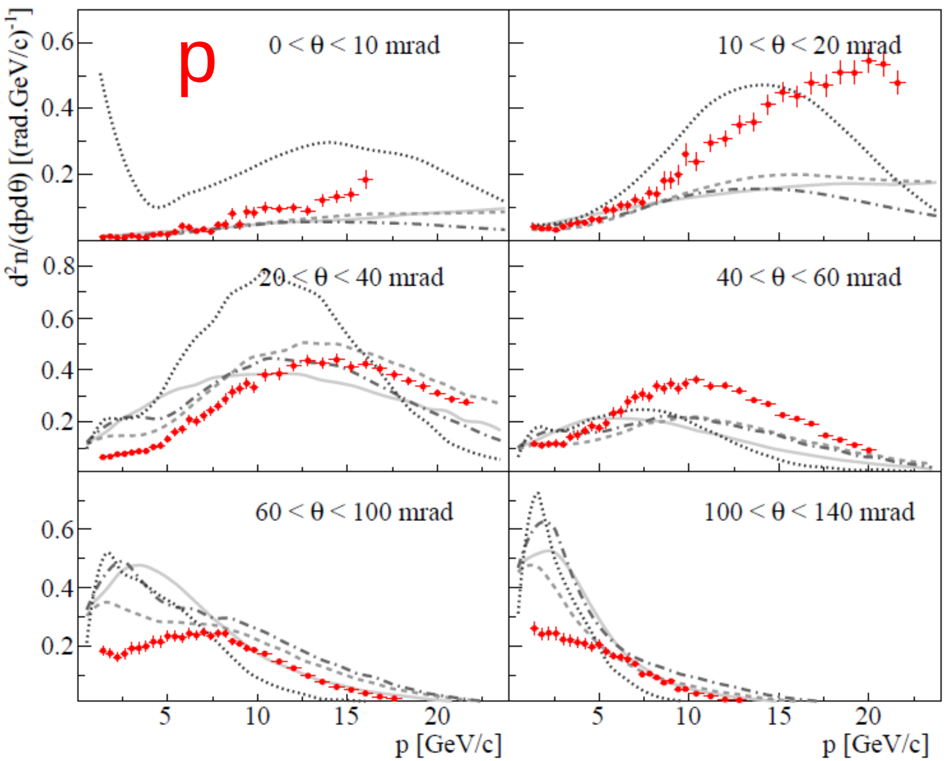


Comparison of NA61 data to some GEANT4 models

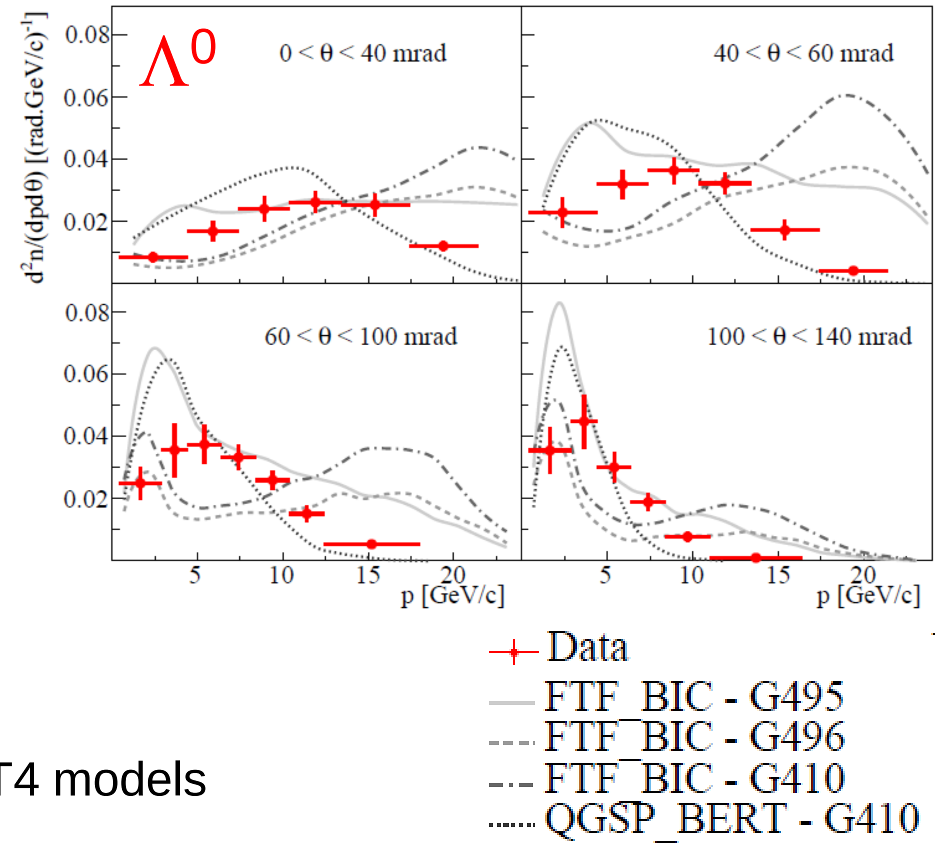
None of the existing hadroproduction models describes satisfactorily the ensemble of NA61 measurements (π+, π-, K+, K-, K^0, p, Λ) !

New generation of hadroproduction models tuned to NA61 data ?

NA61 p + C → p / Λ + X @ 31 GeV/c



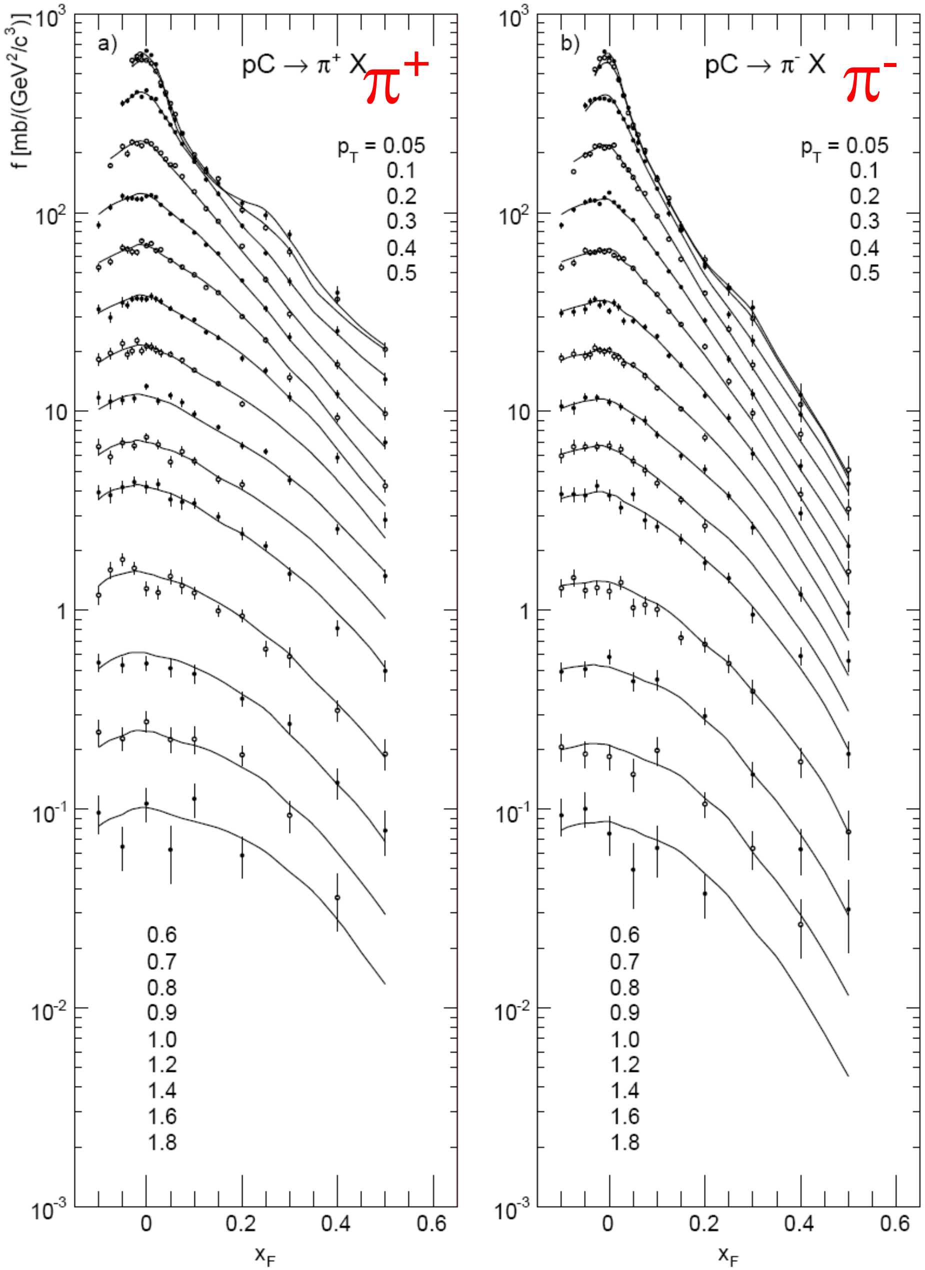
NA61, arXiv:1510.02703



Comparison of NA61 data to some GEANT4 models

For baryons (p, Λ) the comparison is even less satisfactory than for mesons !

NA49 Charged Pion Spectra @ 158 GeV/*c*



charged pion spectra in
pC interactions at 158 GeV/c
measured by NA49
over broad kinematical range

NA49 with empirical fits to the data

systematic error

Normalisation	2.5%
Tracking efficiency	0.5%
Trigger bias	1%
Feed-down	1–2.5%
Detector absorption	
Pion decay $\pi \to \mu + \nu_\mu$	0.5%
Re-interaction in the target	
Binning	0.5%
Total (upper limit)	7.5%
Total (quadratic sum)	3.8%

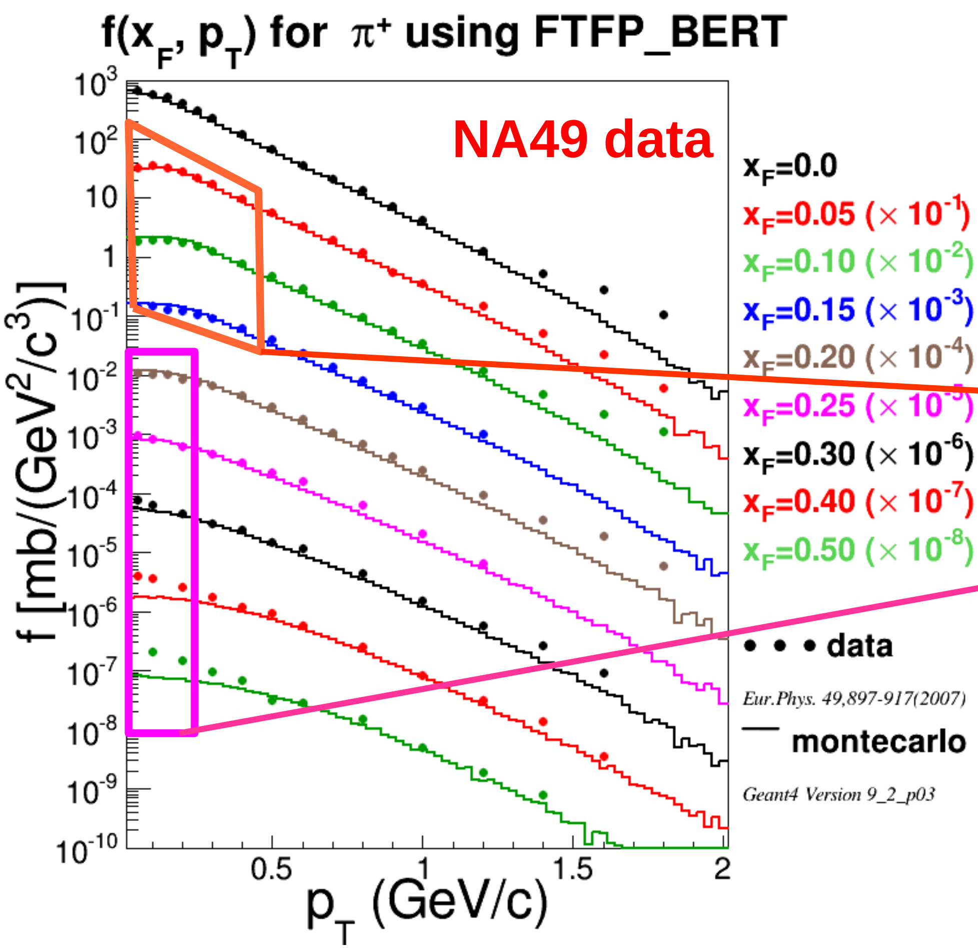
C. Alt *et al.*, EPJ C49 (2007) 897

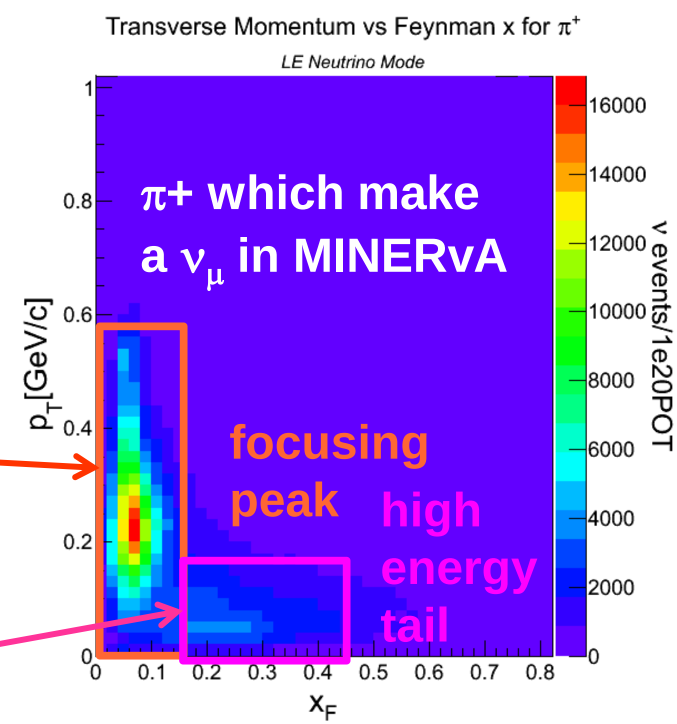
NuMI ν Flux

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)

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





NA49 Uncertainties

7.5% systematic

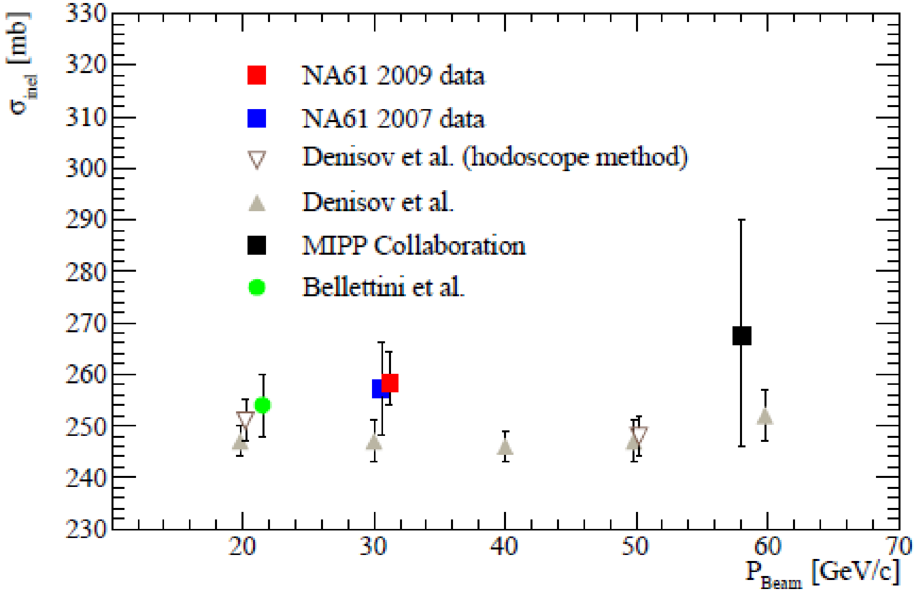
(when linearly added !)

2-10% statistical

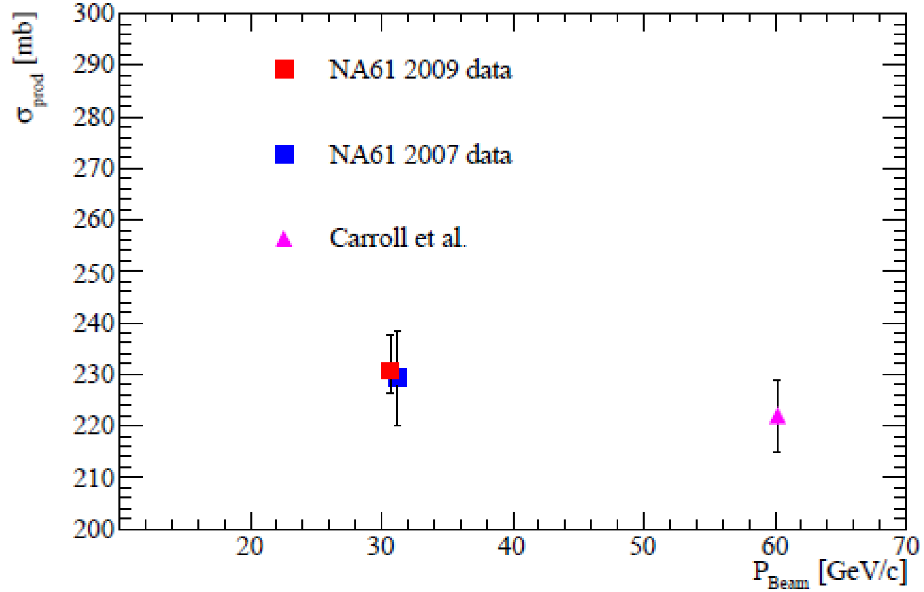
p – C Total Cross Sections @ 31 GeV/c

NA61, arXiv:1510.02703

inelastic cross section



production cross section



$\sigma_{inel} = \sigma_{tot} - \sigma_{el}$

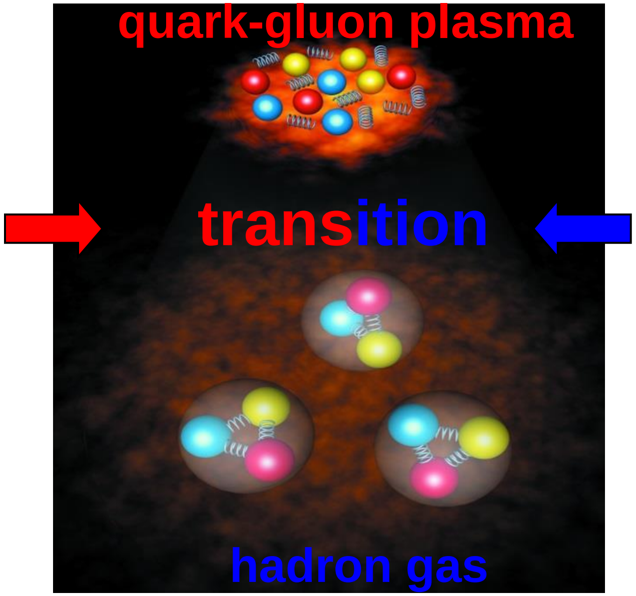
$$\boxed{\sigma_{\text{inel}} = 258.4 \pm 2.8(\text{stat}) \pm 1.2(\text{det})\,^{+5.0}_{-2.9}(\text{mod})\,\text{mb}}$$

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

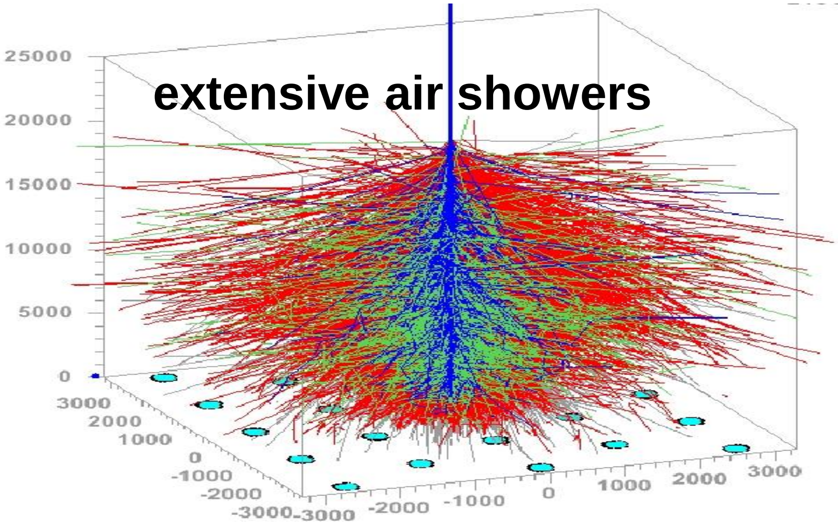
$$\boxed{\sigma_{\text{prod}} = 230.7 \pm 2.7(\text{stat}) \pm 1.2(\text{det})\,^{+6.3}_{-3.4}(\text{mod})\,\text{mb}}$$

NA61 Physics Program

Physics of strongly interacting matter
in heavy ion collisions
Search of the QCD critical point
(AA and pA collisions)



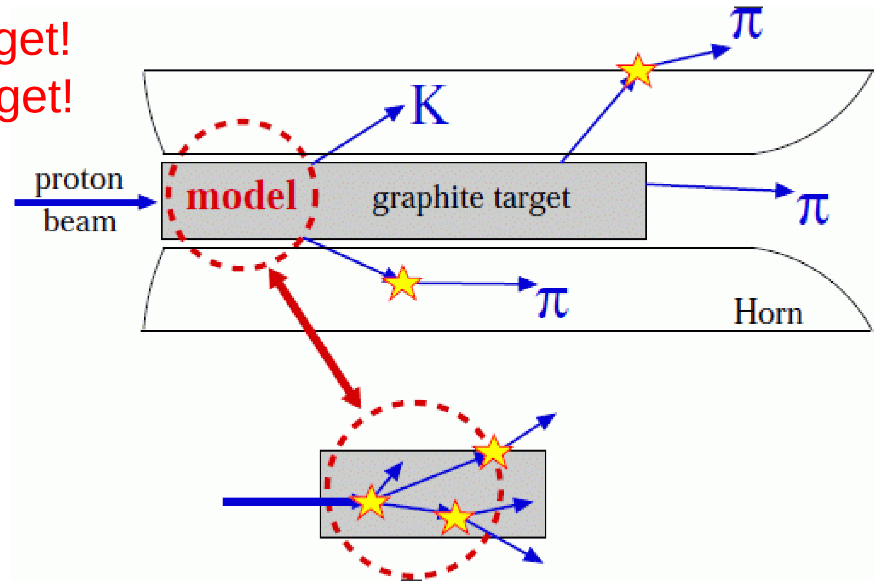
Hadron production measurements
on the T2K target (p+C) to
characterize the T2K neutrino beam
soon also measurements for NuMI



Measurement of hadron production
in p+C interactions needed for the
description of cosmic-ray air showers
(Pierre Auger Observatory
and KASCADE experiments)

Neutrino Source Production

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



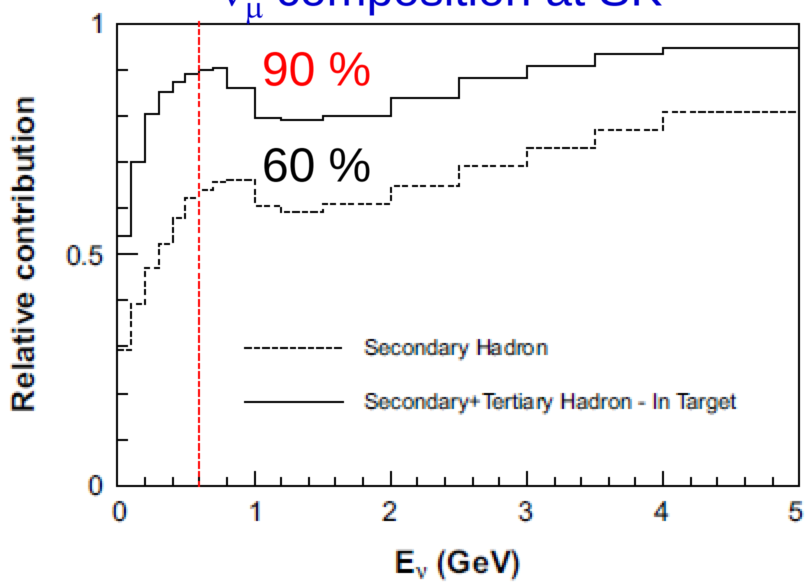
direct contribution:
secondary hadrons exit the target and decay into ν

target contribution:
tertiary hadrons exit the target and decay into ν

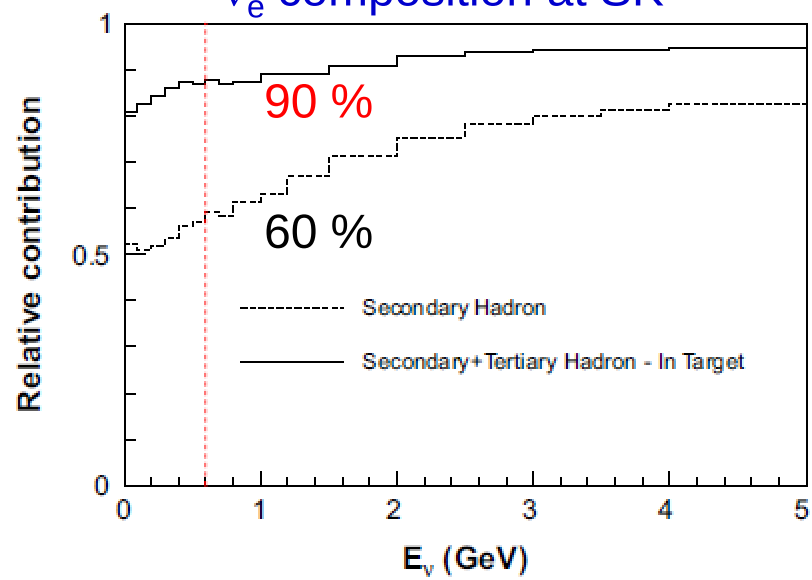
non-target contribution:
re-interactions in the target surrounding material

NA61, NIM A701 (2013) 99

ν_μ composition at SK

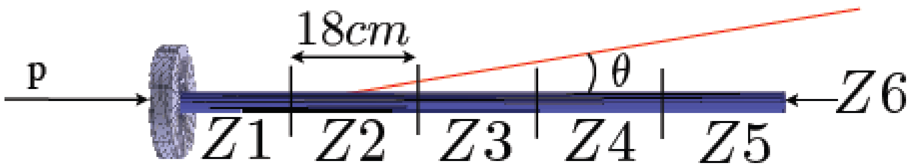


ν_e composition at SK



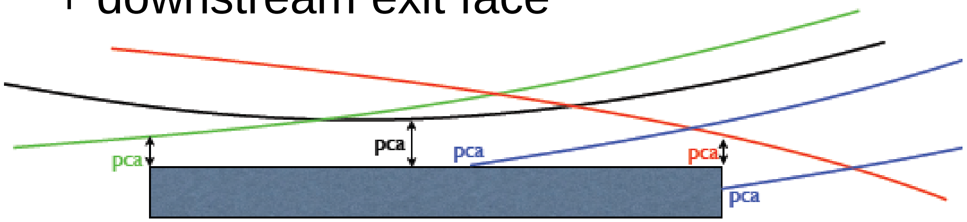
π^+ Hadroproduction on T2K Replica Target

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)

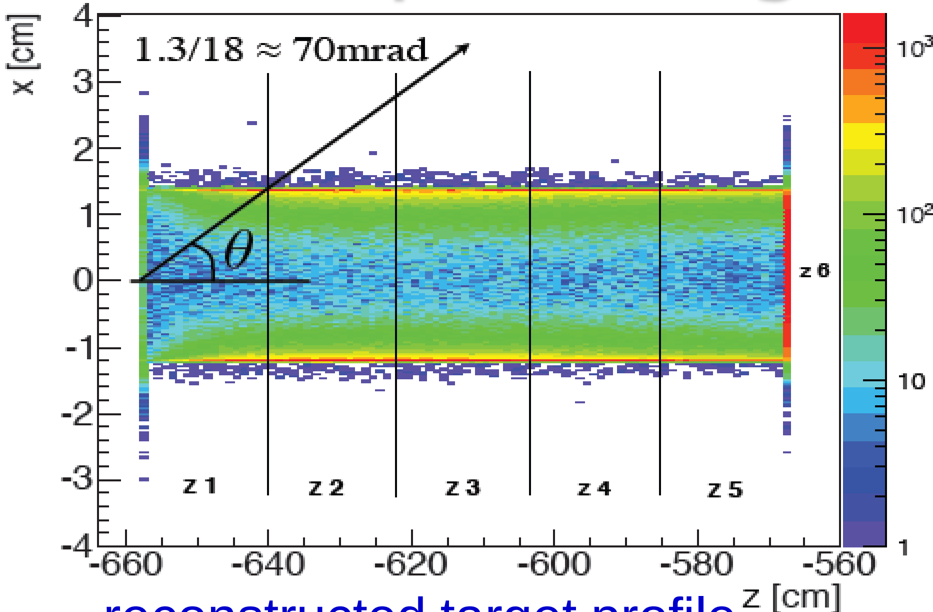
the target is sliced in 5 bins in z
+ downstream exit face



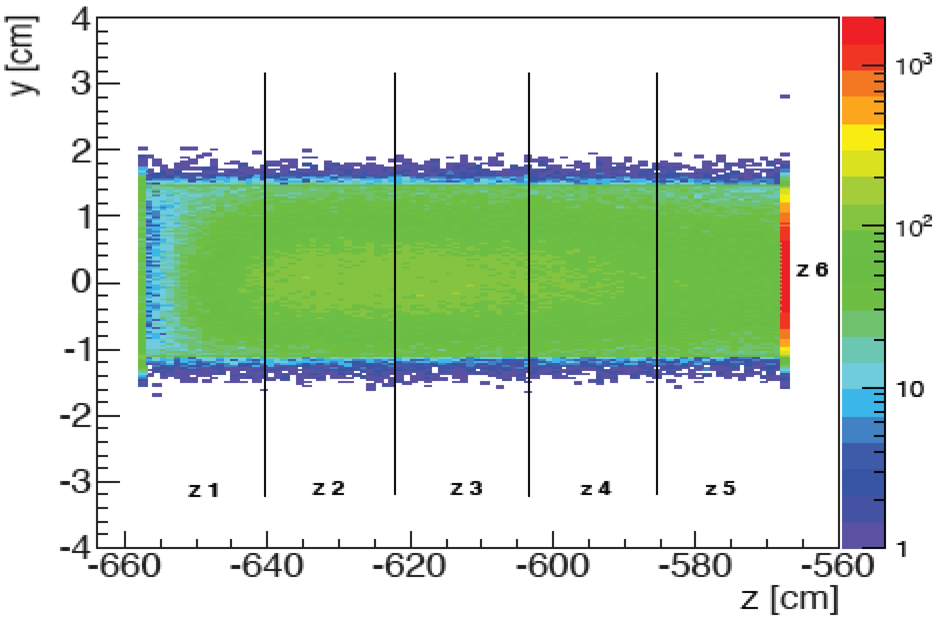
No interaction vertex reconstruction
Will study also as a function of r

Statistical precision ~5%
Systematic error ~5%

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



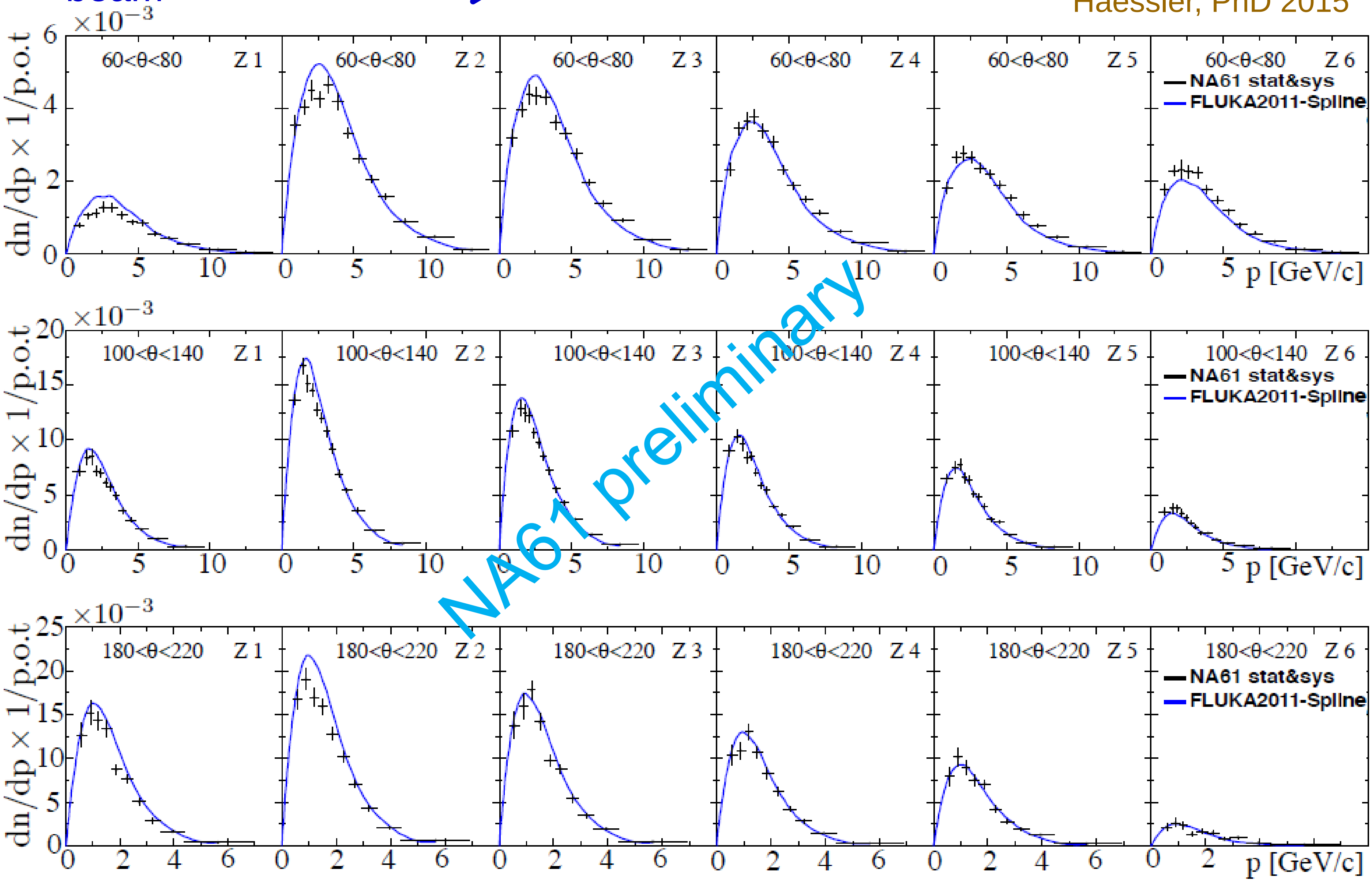
reconstructed target profile



π^+ Spectra on Target Surface

beam →

Haessler, PhD 2015

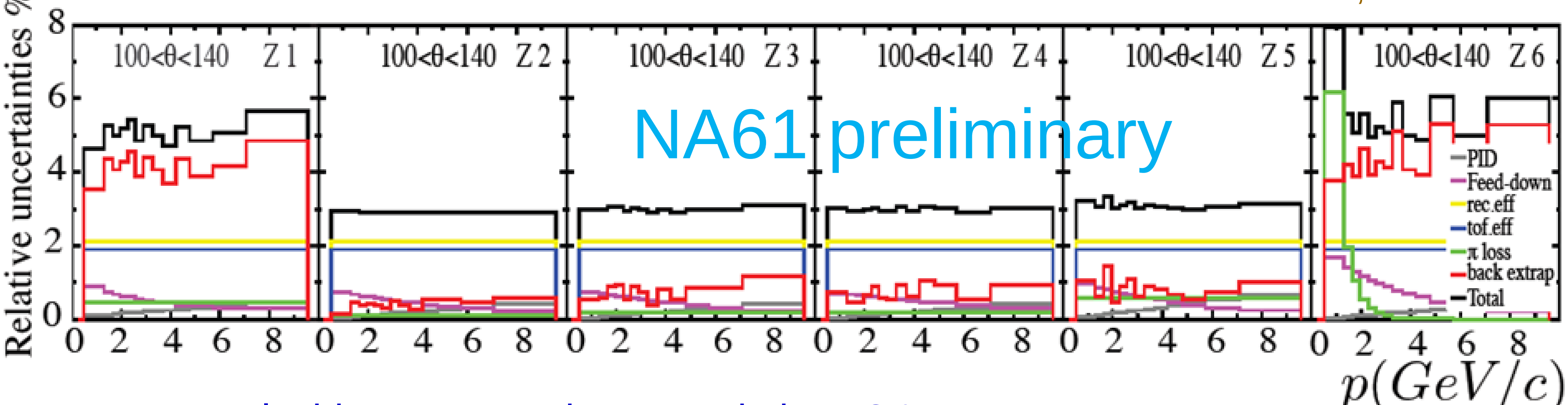


Long Target Systematic Uncertainties

- 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 2015



For central z bins, systematic uncertainties ~3 %

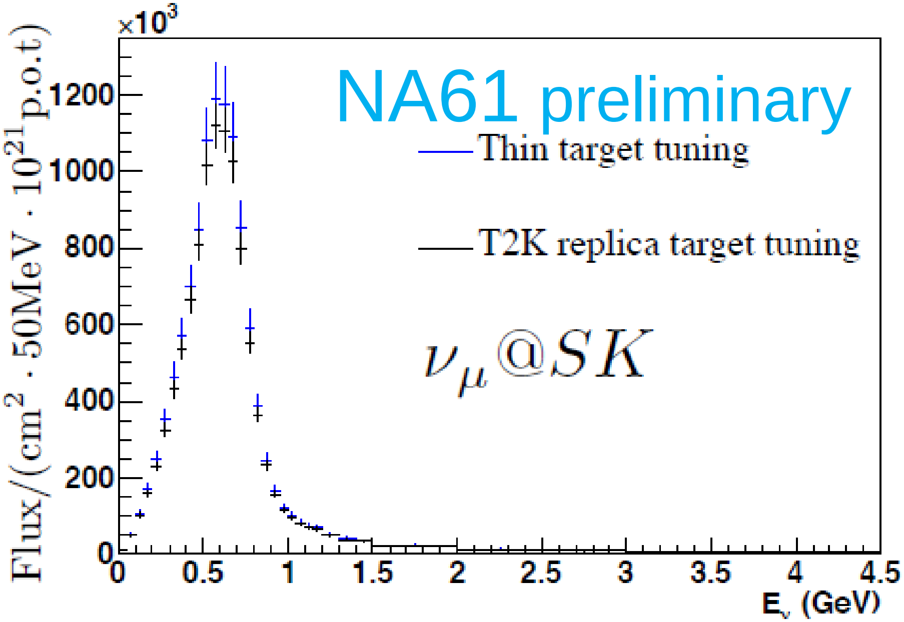
Work to implement these data in T2K flux simulations ongoing

ν Flux Prediction with T2K Replica Target

2009 data

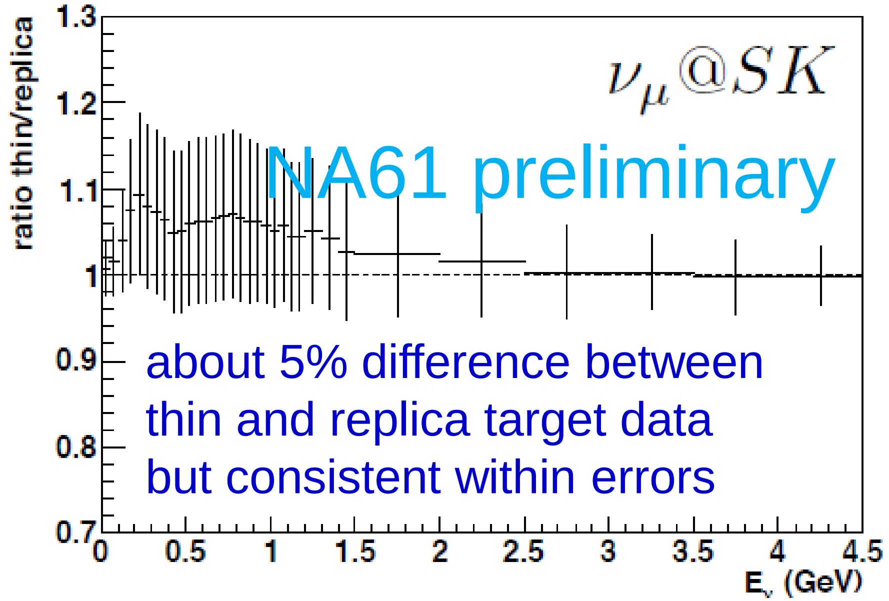
comparison of ν flux predictions
thin target vs. replica target

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 for thin target data



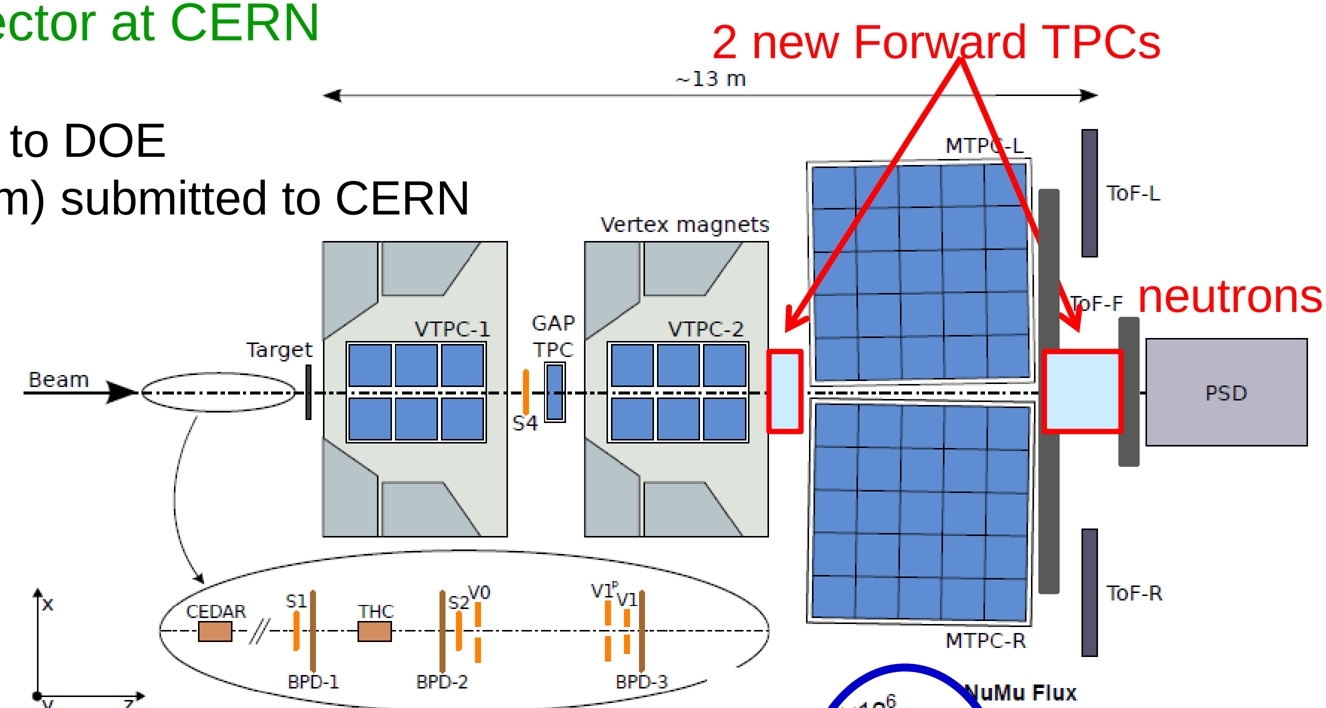
ratio of thin target over T2K replica target re-weightings for the ν_μ predictions at SK

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

NA61 for FNAL ν beams (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



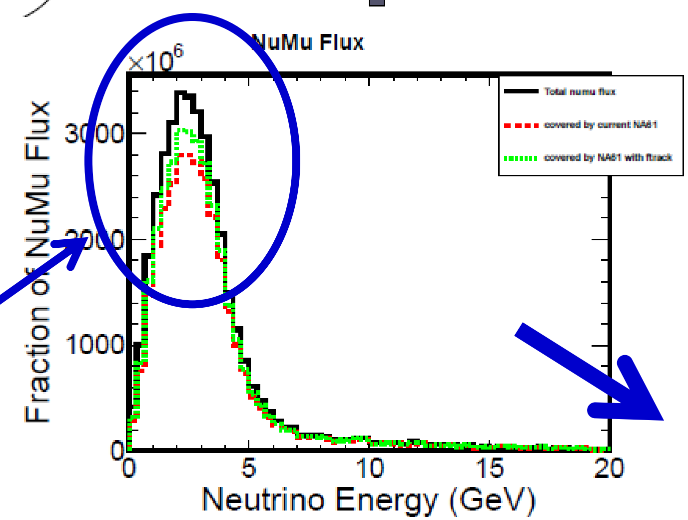
data taking to start this fall

~ 5 year program

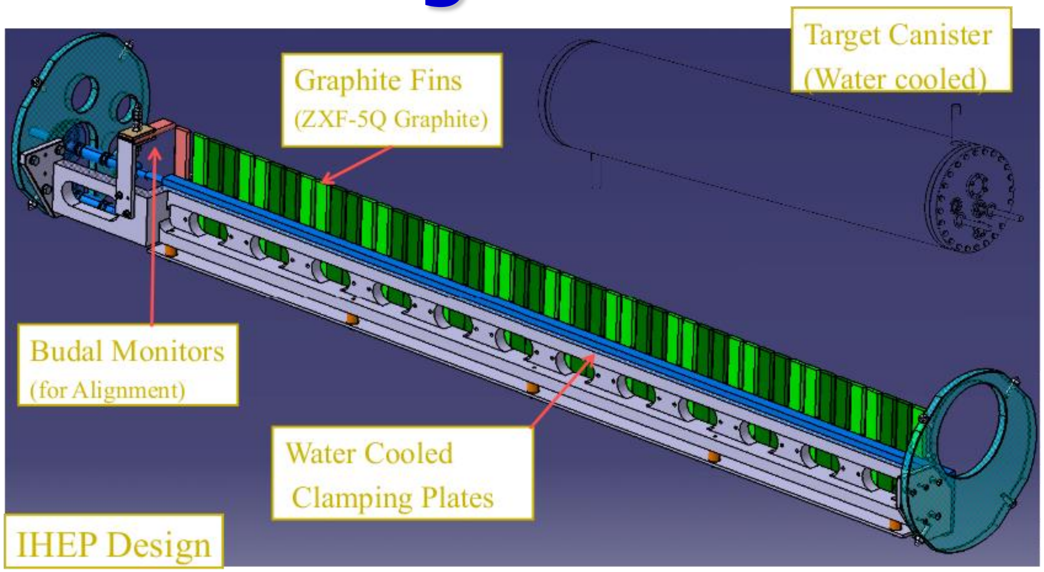
Upgrades:

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

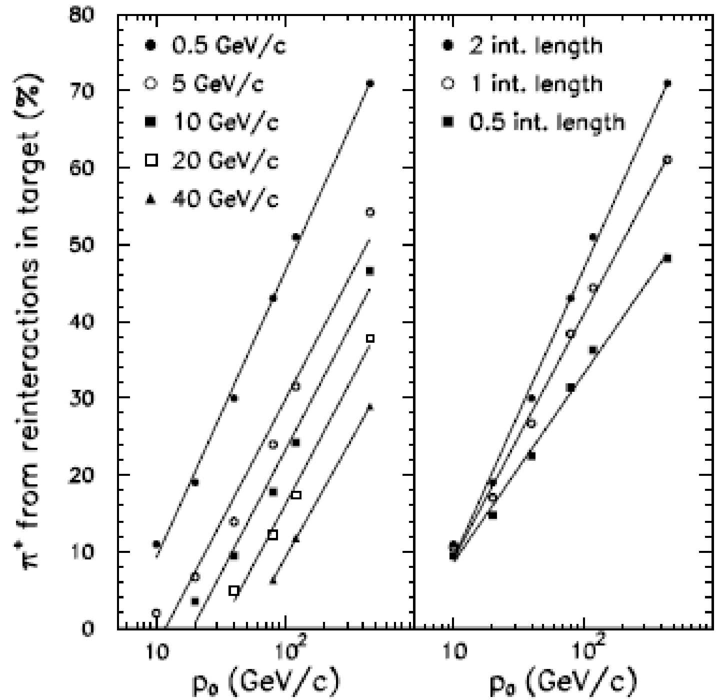
improved coverage



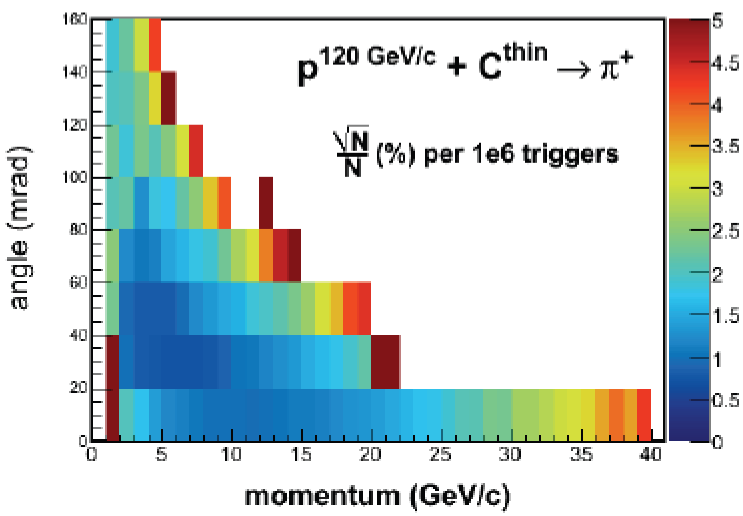
NuMI Target



pions from reinteractions

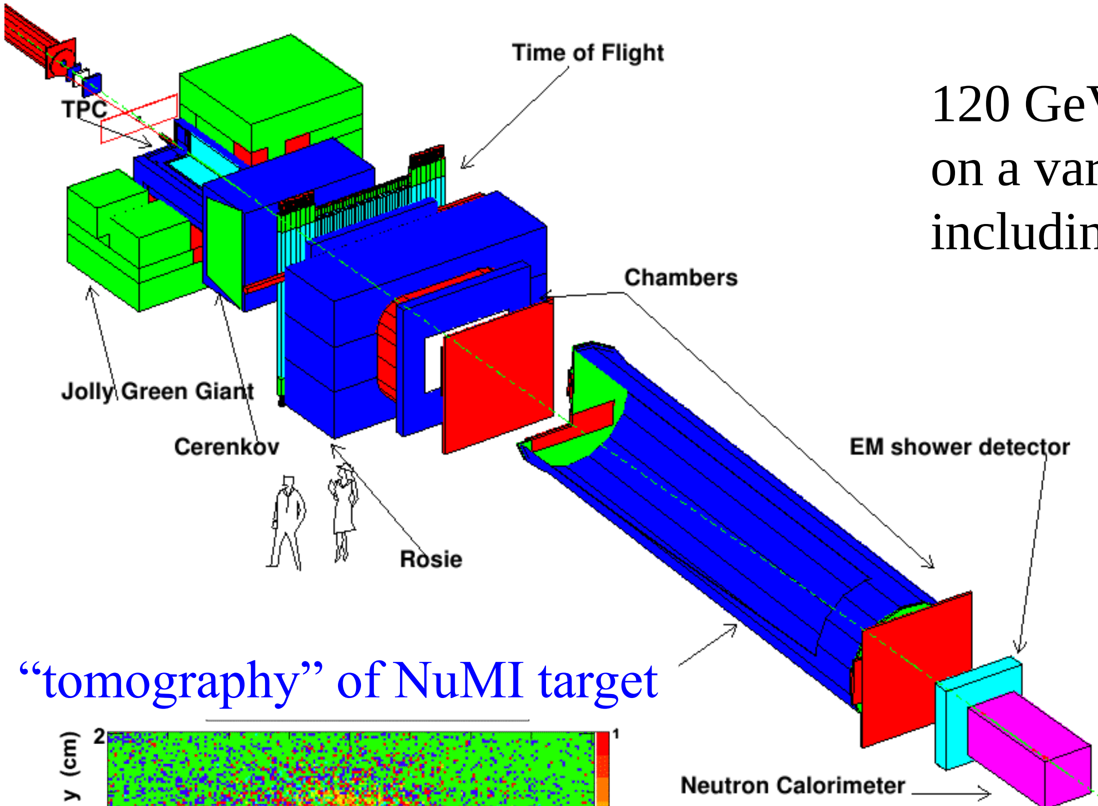


With good vertexing should be able to tell from
Which target the tracks originated



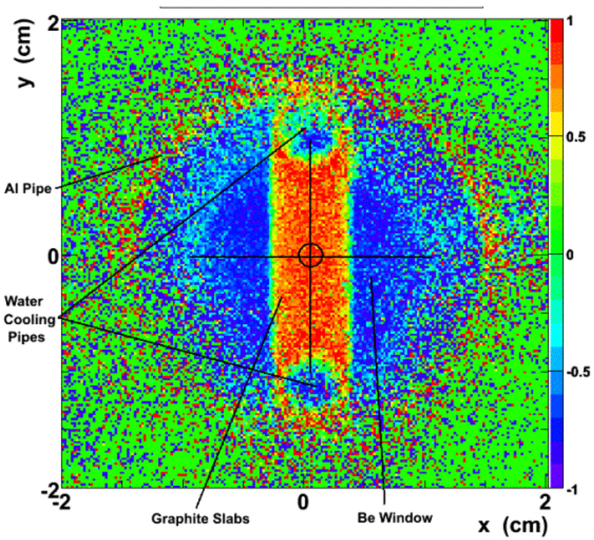
proton+pion event totals	Incident proton/pion beam momentum		
Target	120 GeV/c	60 GeV/c	30 GeV/c
NuMI (spare) replica	*(future)*		
LBNE replica	*(future)*		
thin graphite ($< 0.05\lambda_I$)	3M	3M	(T2K data)
thin aluminum ($< 0.05\lambda_I$)		3M	*(future)*
thin steel ($< 0.05\lambda_I$)	*(future)*	*(future)*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

MIPP : Main Injector Particle Production Exp.

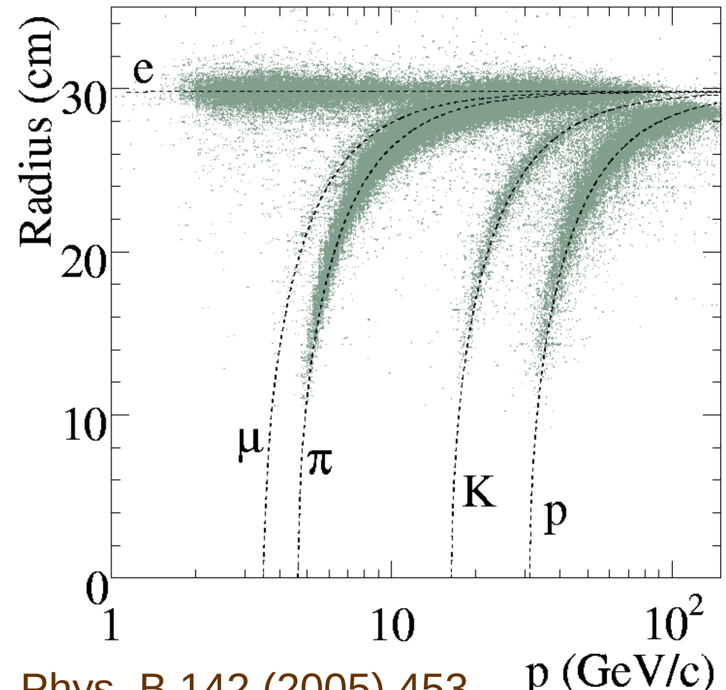


120 GeV proton beam from Main Injector
on a variety of targets
including NuMI replica target

“tomography” of NuMI target



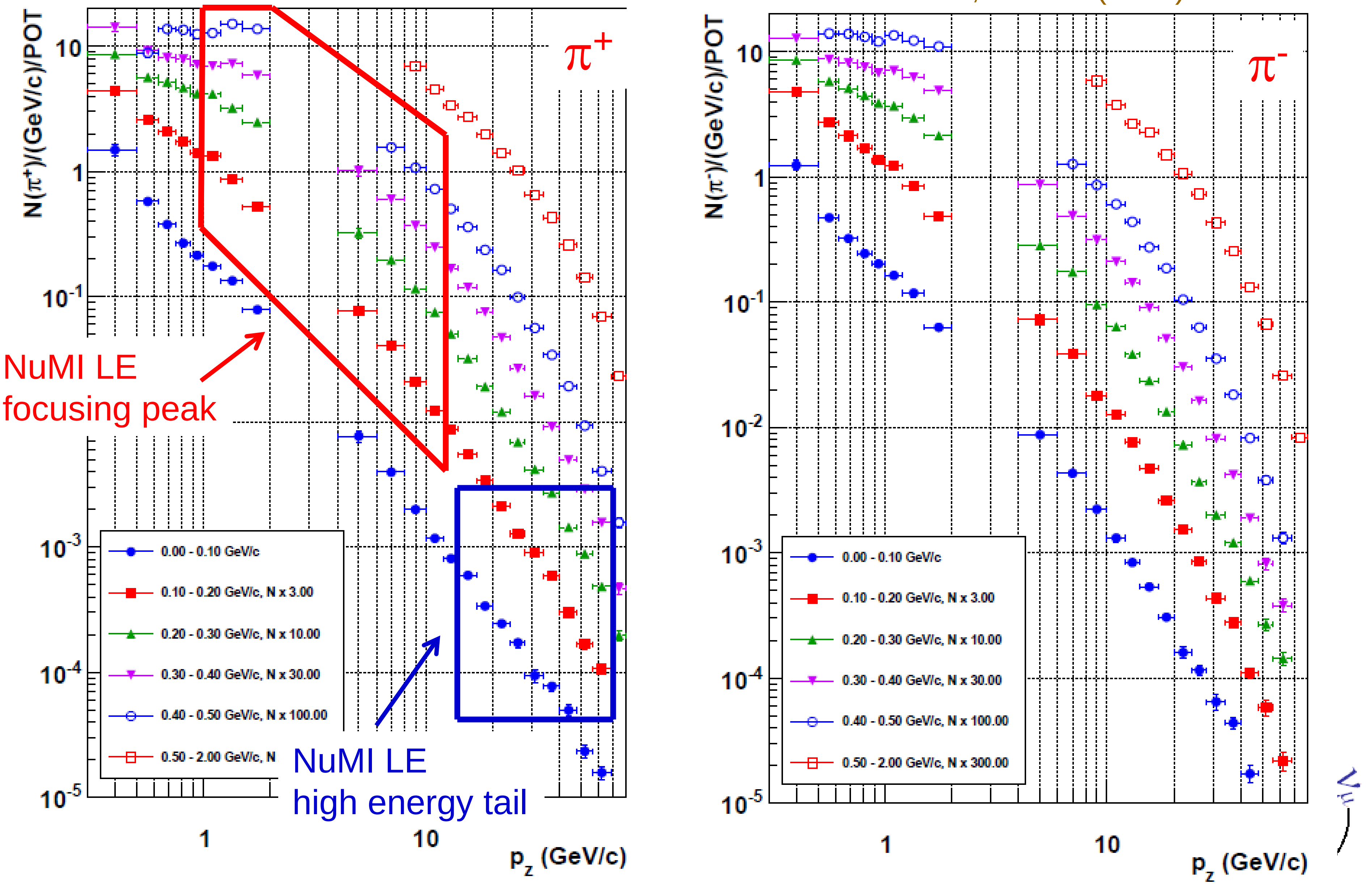
PID with RHIC detector



MIPP, Nucl. Phys. B 142 (2005) 453

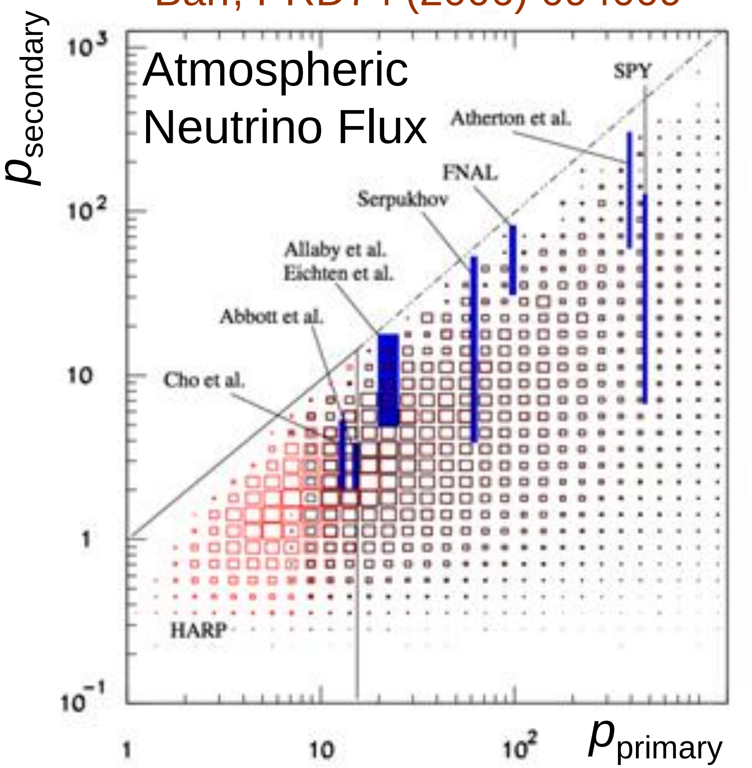
MIPP π^+ / π^- Production

MIPP, PRD90 (2014) 032001



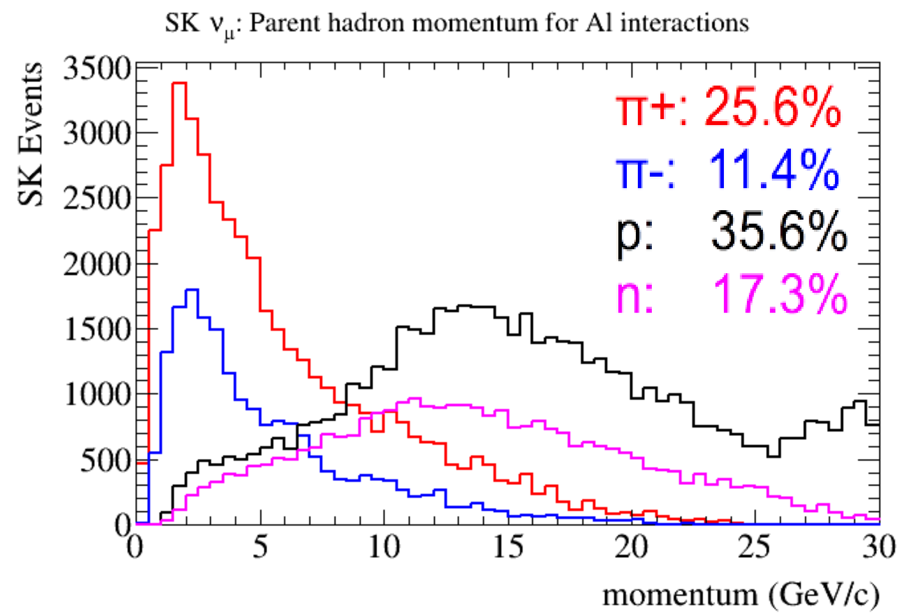
New Hadron Production Measurements

Barr, PRD74 (2006) 094009



Boxes = atmospheric neutrino contribution

T2K Wrong Sign Flux (Out-of-Target)



New measurements with beam energy less than 30 GeV are needed for:

Precision low energy atmospheric flux calculation to improve CP violation sensitivity

Better modeling of the out-of-target interactions in the T2K flux simulation

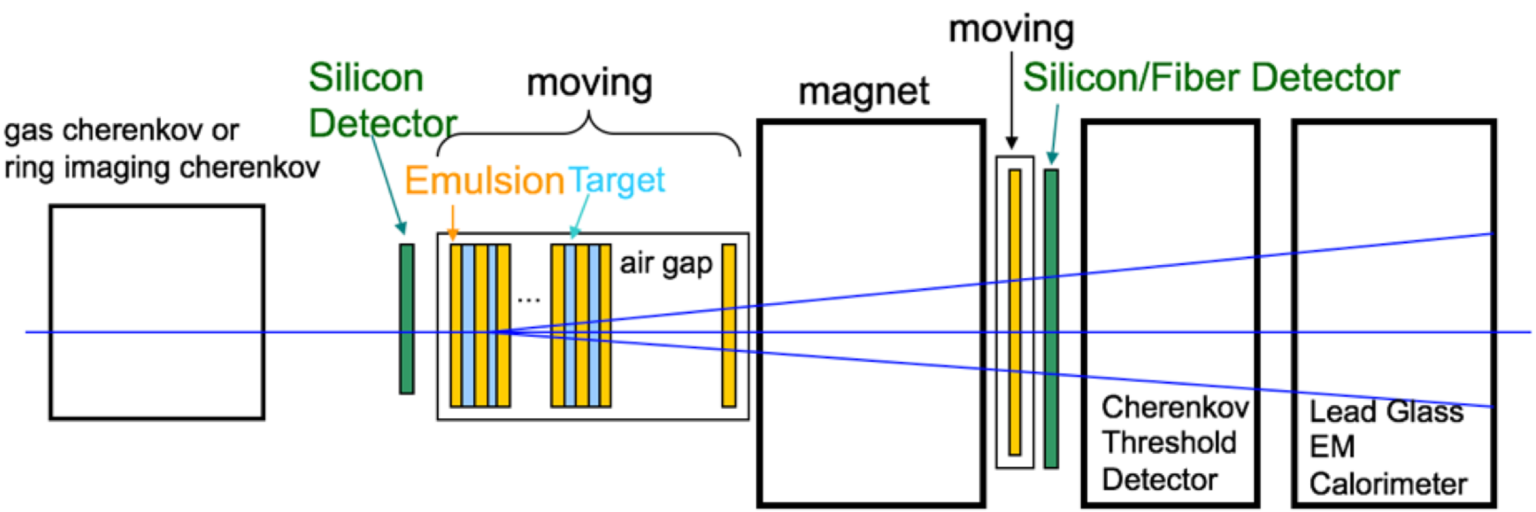
Goal: New hadron production measurements that address systematic issues in previous measurements

Hybrid Emulsion Detector

Detector that uses emulsion film tracking is being developed by ICRR, Kavli IPMU, Kyoto U., Toho U.

- Minimize material between tracker and target (large systematic effect for HARP)
- Compact size detector can be moved between different beam lines
- Detailed measurements of interaction topologies

Emulsion detector tracks connected to upstream and downstream particle ID detectors by silicon strip or pixel detectors



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 NA49, 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 existing results:

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

Conclusions

Over the last 5 years significant progress in understanding neutrino fluxes
$\rightarrow \sim 5$ – 10 % uncertainty

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
- plans for hyper-K?
- detector constantly upgraded and analysis tools being improved

New ideas for new hadroproduction measurements under way (hybrid – emulsion exp.)

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