The NA61 Hadron Production Experiment

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NBI @ FNAL
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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

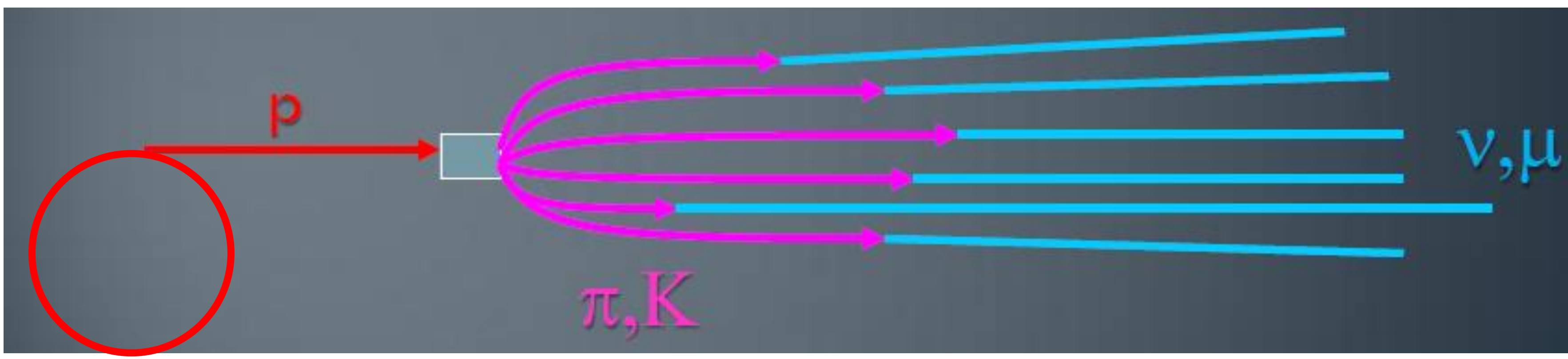
neutrino oscillations $\rightarrow$ compare measured neutrino spectrum “far” from the source with the predicted one (flux shape and Far / Near flux ratio)

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 long decay region (by selecting the polarity of **B** one selects positive or negative hadrons)

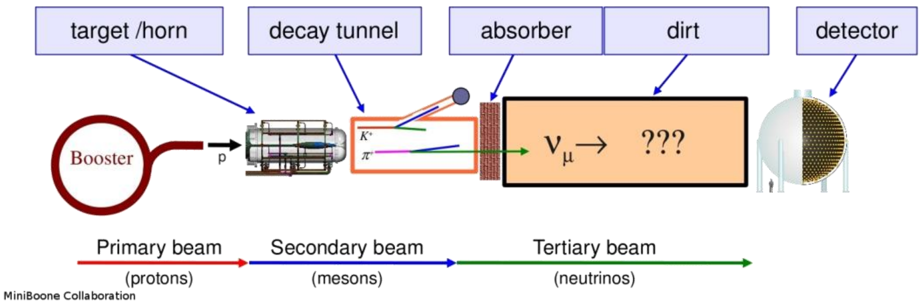


"shieldings" stops all particles but neutrinos

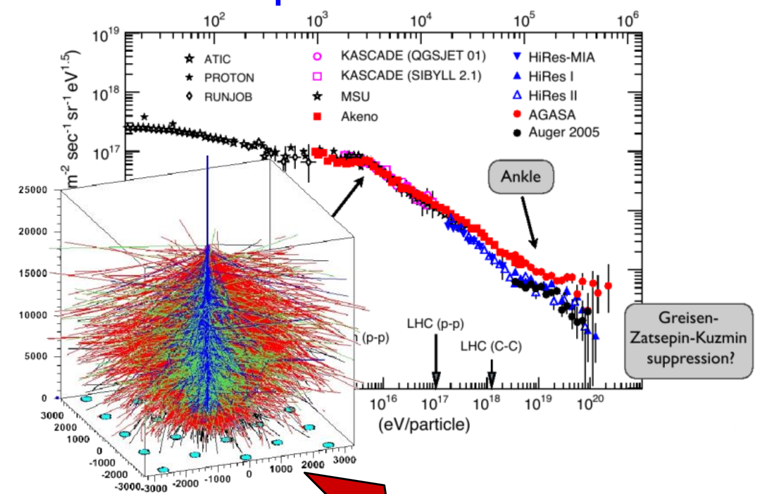
resulting beam composed mainly of ν_μ, with small ν_e (~ 1 %) component

want to maximize π, K $\rightarrow \mu + \nu_\mu$ decays for highest ν_μ fluxes

conventional accelerator based ν beam



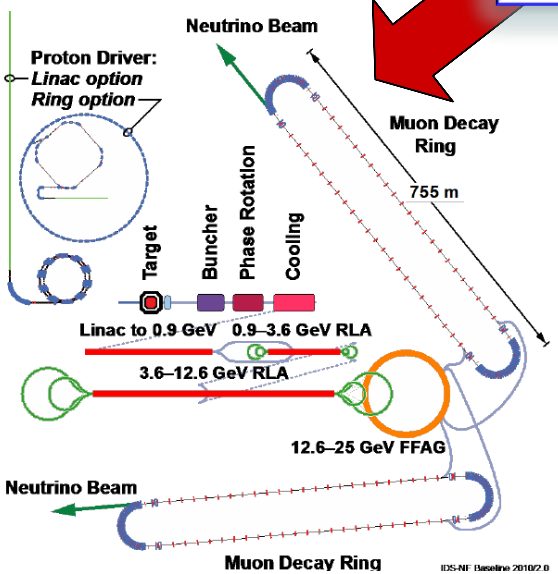
atmospheric showers



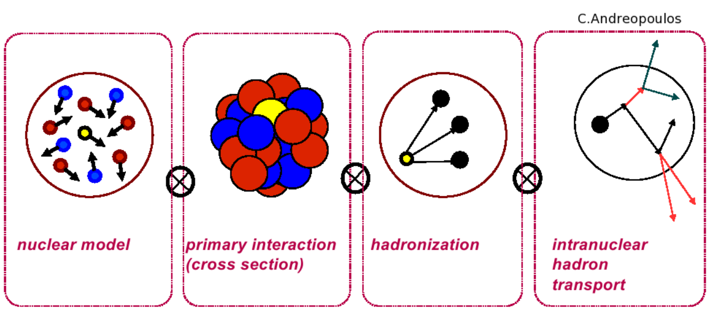
hadroproduction measurements

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

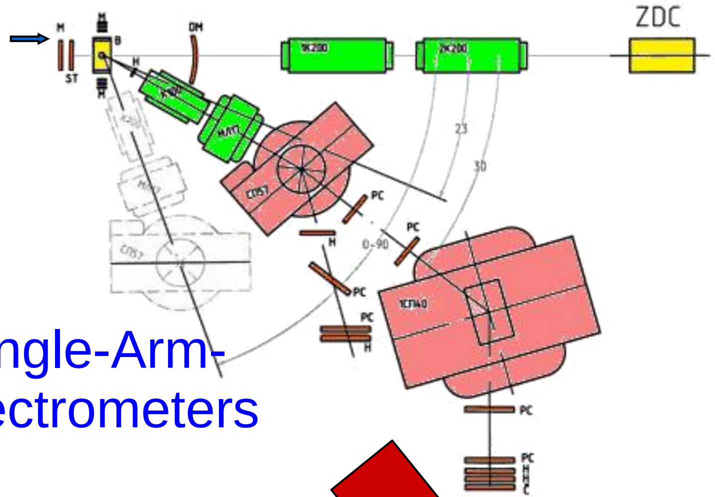
neutrino factory



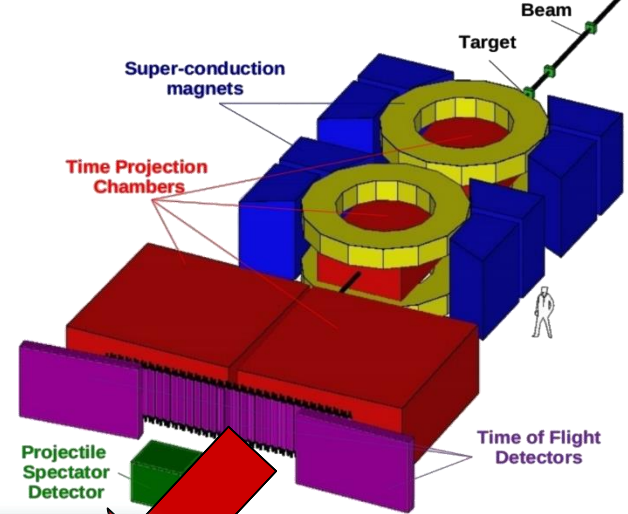
MC generators



Single-Arm-Spectrometers



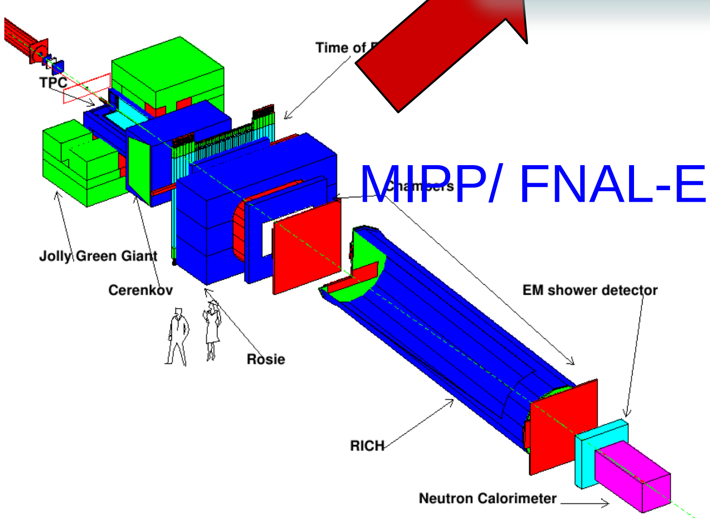
SHINE / NA61 CERN-SPS



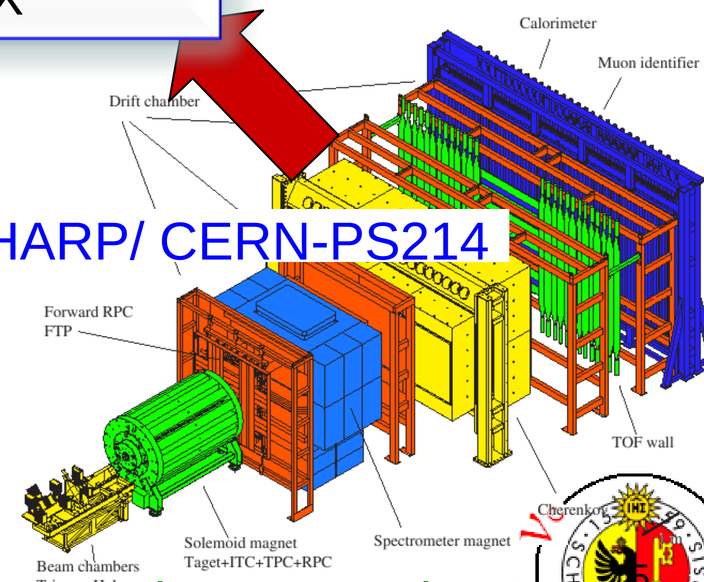
hadroproduction measurements

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

MIPP/ FNAL-E907



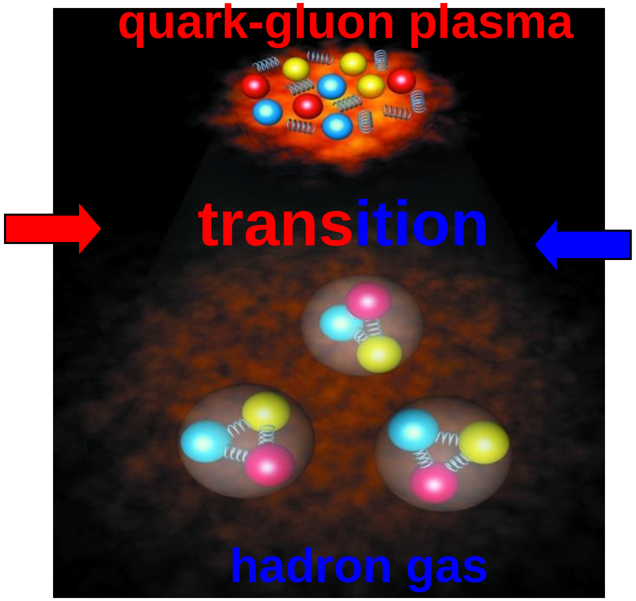
HARP/ CERN-PS214



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

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

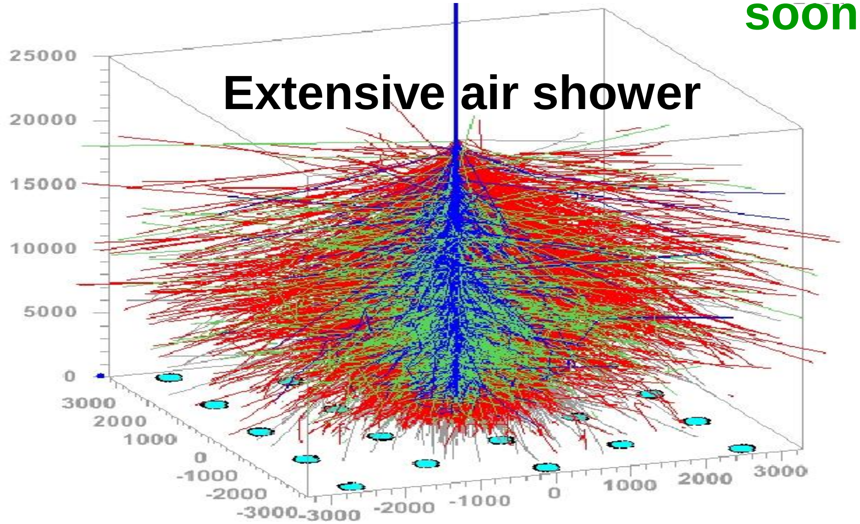
NA61 Physics Program



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

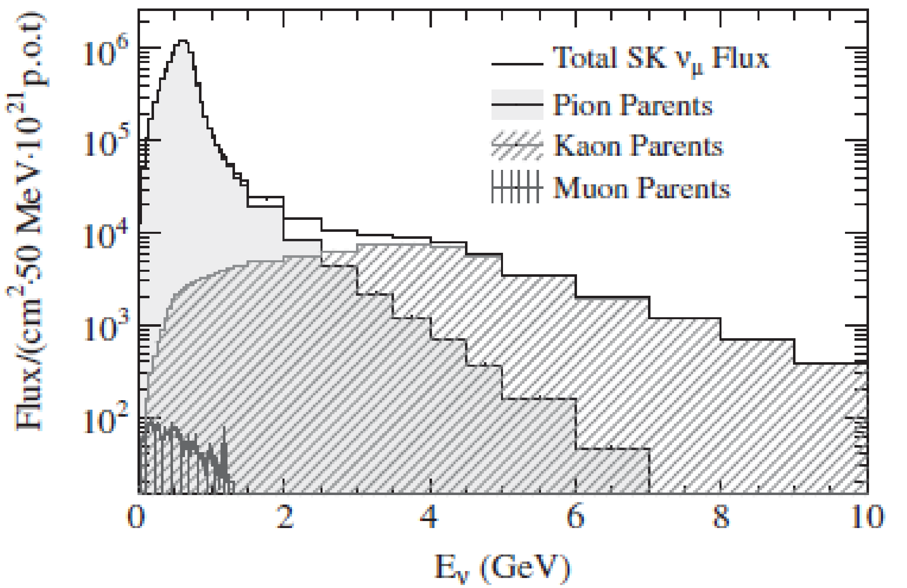
soon also measurements for NuMI



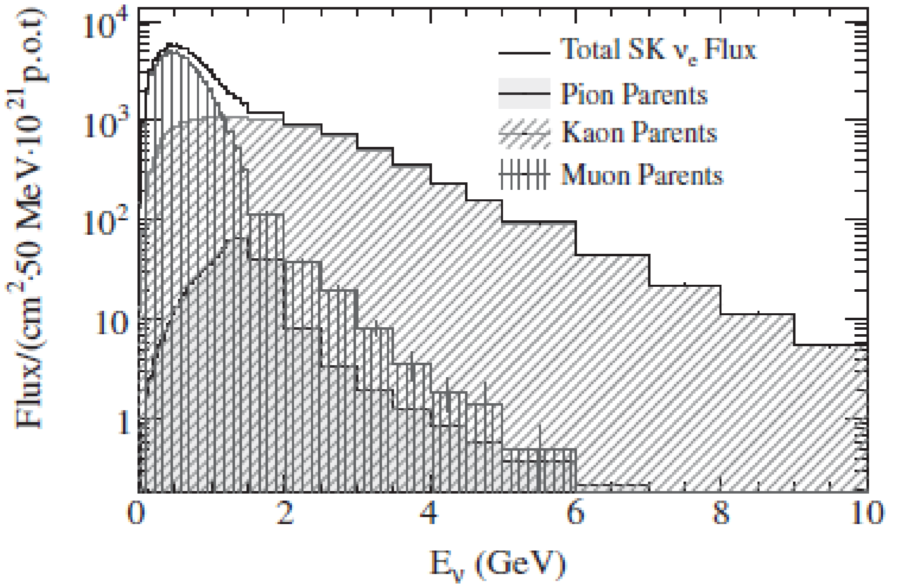
Measurement of hadron production in p+C interactions needed for the description of cosmic-ray air showers (Pierre Auger Observatory and KASCADE experiments)

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

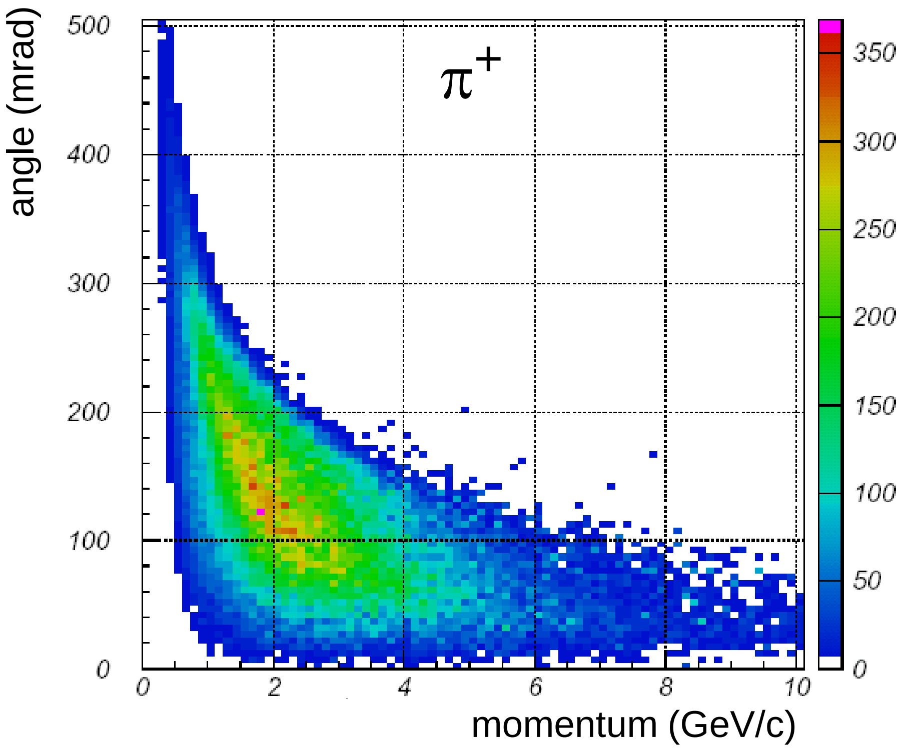


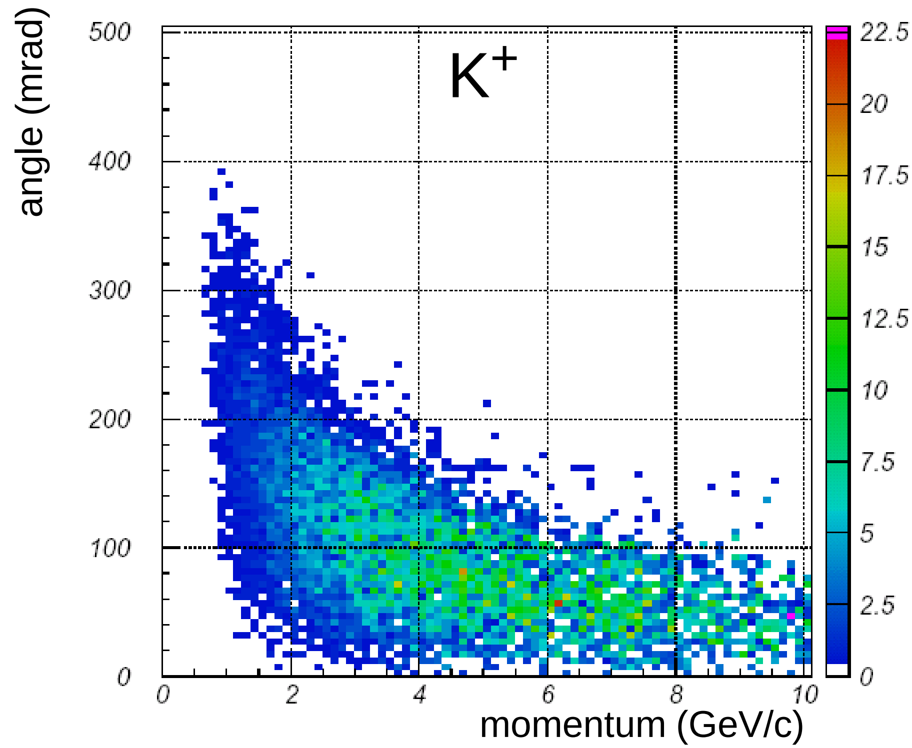
ν_e predominantly from μ^+ and K^+
decays at peak energy,
higher energy ν_e (tail) from kaons

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 and K contribution 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

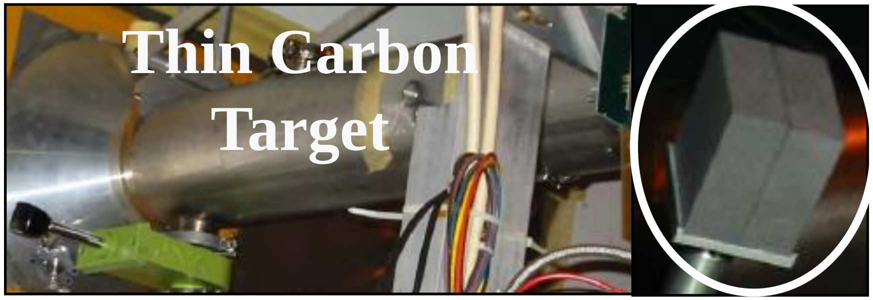
requires detector with large acceptance and excellent particle ID capabilities

Which Hadron Production Measurements (3)

Thin target vs Replica target measurements

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

Thin target: ~ 660k triggers
Replica target: ~ 230k triggers

2009 run

~ 6 M triggers
~ 2 M triggers

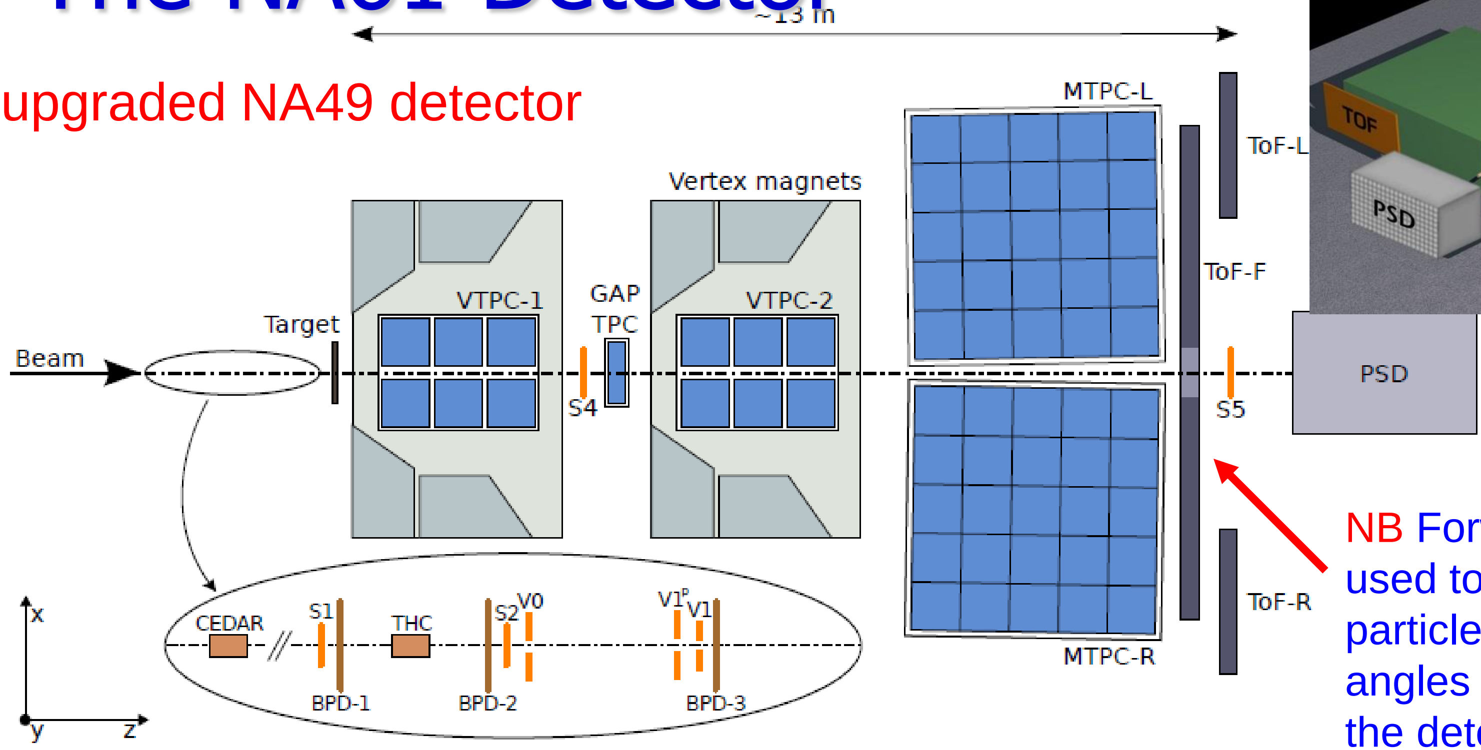
$\Rightarrow$ 200 k π^+ tracks in T2K *phase space*

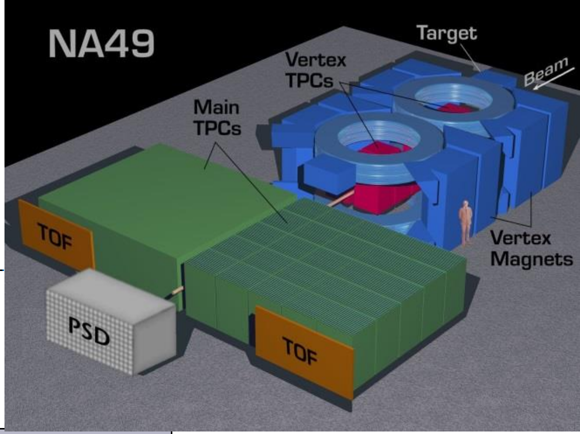
2010 run

Replica target: ~ 10 M triggers

The NA61 Detector

upgraded NA49 detector





NB Forward-ToF wall used to identify low mom. particles produced at large angles and bent back into the detector acceptance by the vertex magnets

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: $\int Bdl \sim 1.14$ Tm)

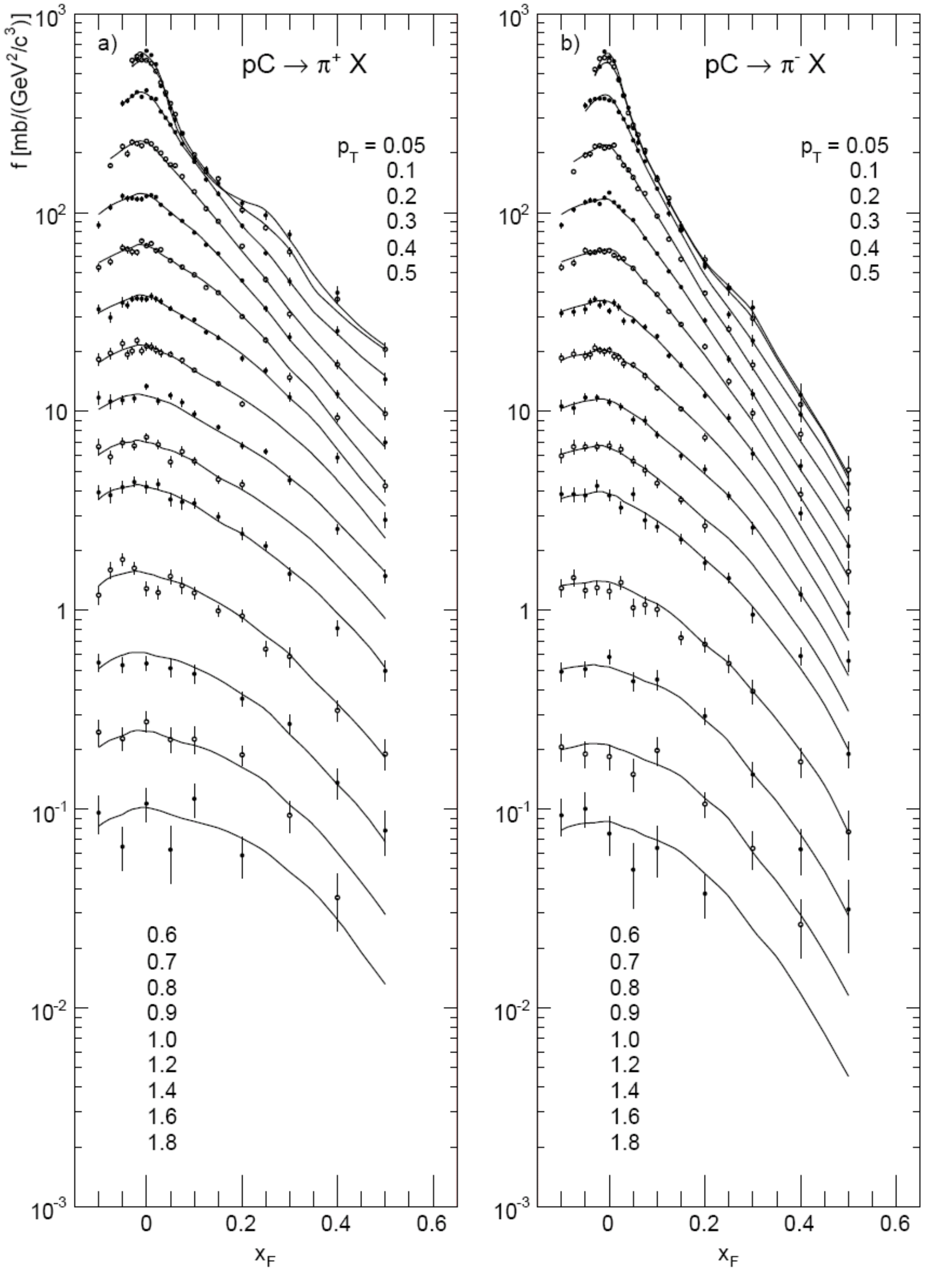
high momentum resolution

good particle identification: σ(ToF-L/R) ≈ 110 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) ≈ 110 ps, $1 < p < 4$ GeV/c, $\theta < 250$ mrad)

several additional upgrades are under way

NA49 Charged Pion Spectra



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

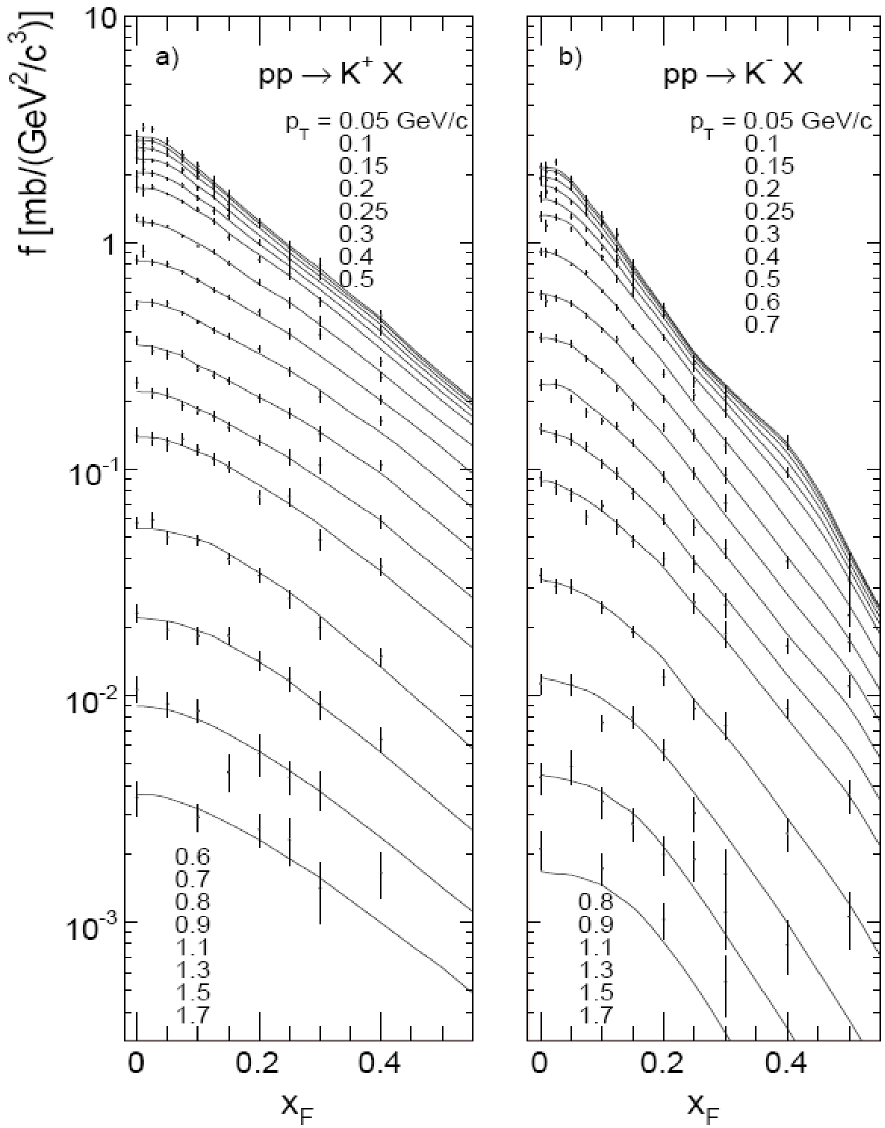
NA49 with empirical fits to the data

statistical error: 2 – 10 %
systematic error (incl. norm.): 3.8 %

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

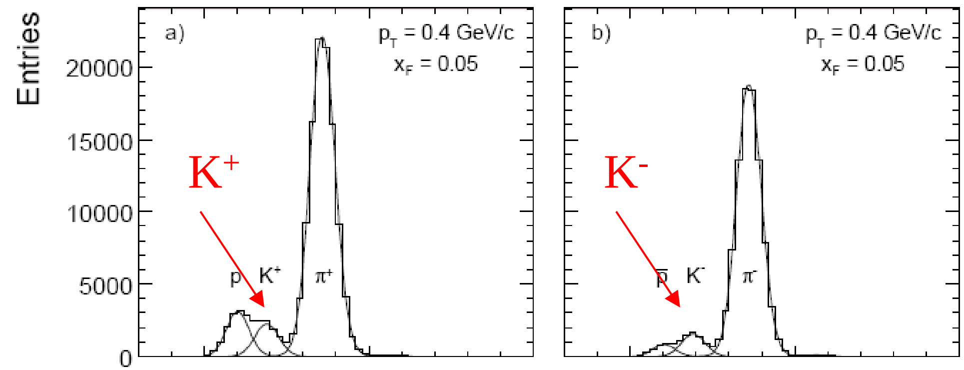
NA49, C. Alt *et al.*, EPJ C49 (2007) 897

NA49 Charged Kaon Spectra



NA49, T. Anticic *et al.*, EPJ C68 (2010) 1

K identified using dE/dx in the TPCs

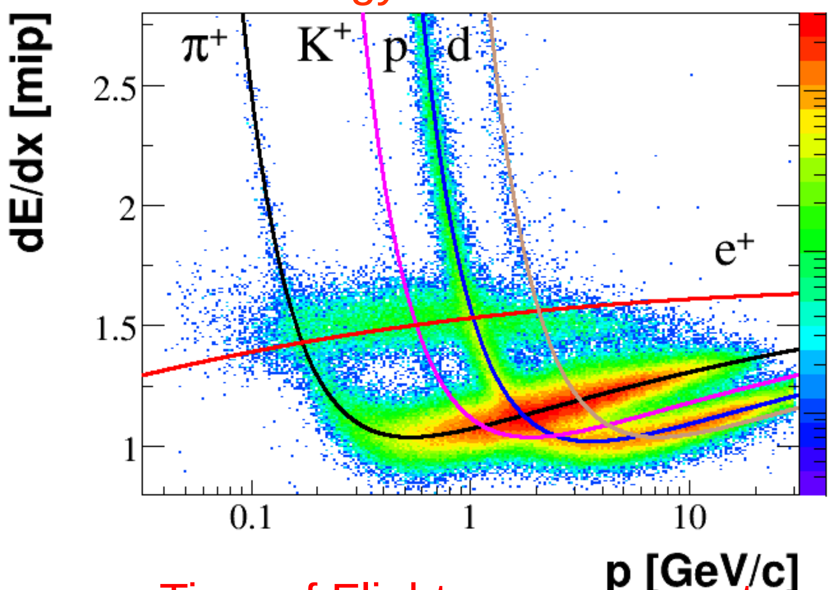


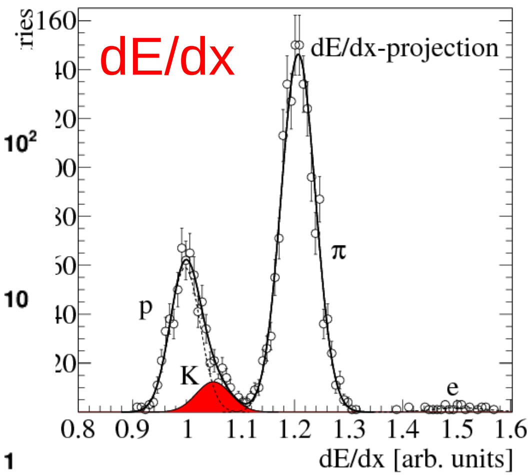
systematic error

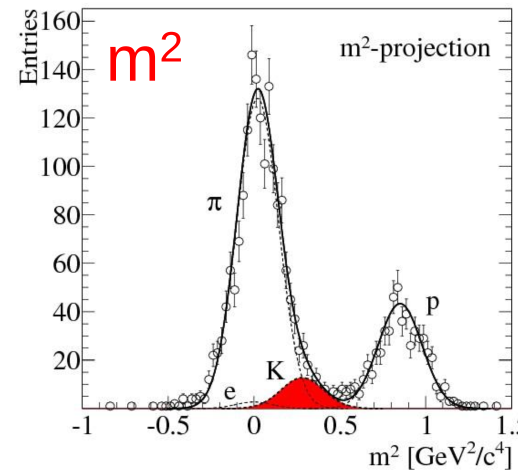
	$x_F \leq 0.2$	$x_F \geq 0.25$	
	K^+,K^-	K^+	K^-
Normalization	1.5%	1.5%	1.5%
Tracking efficiency	0.5%	0.5%	0.5%
Particle identification	0.0%	4–12%	0–6%
Trigger bias	1.0%	1.0%	1.0%
Detector absorption, Kaon decay, Target re-interaction }	1.0%	1.0%	1.0%
Binning	0.5%	0.5%	0.5%
Total(upper limit)	4.5%	8.5–16.5%	4.5–10.5%
Total(quadratic sum)	2.2%	4.6–12.2%	2.2–6.4%

Particle Identification in NA61

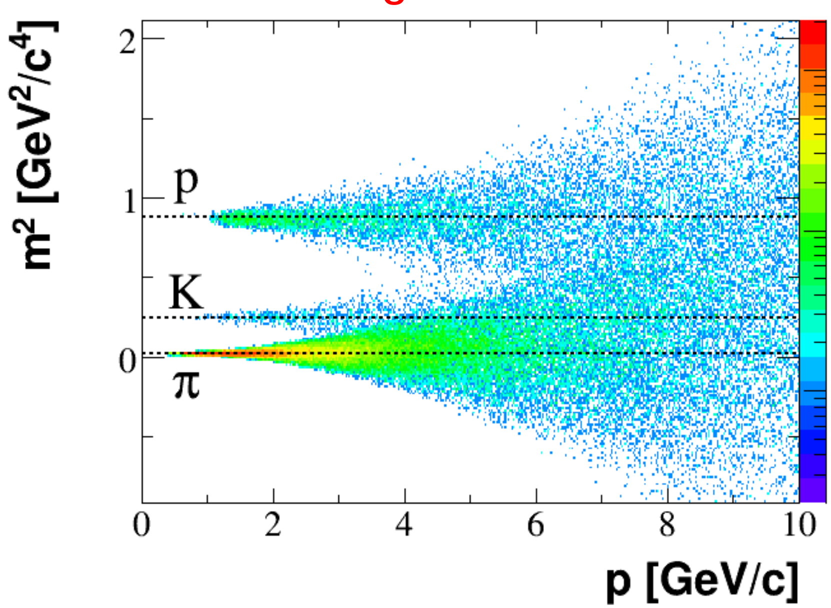
Energy loss in TPCs



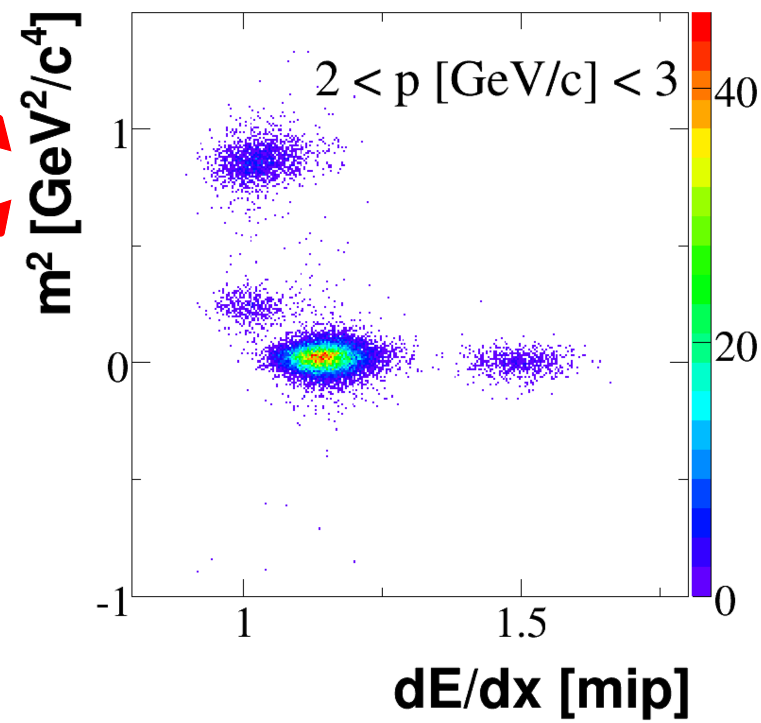




Time of Flight measurements



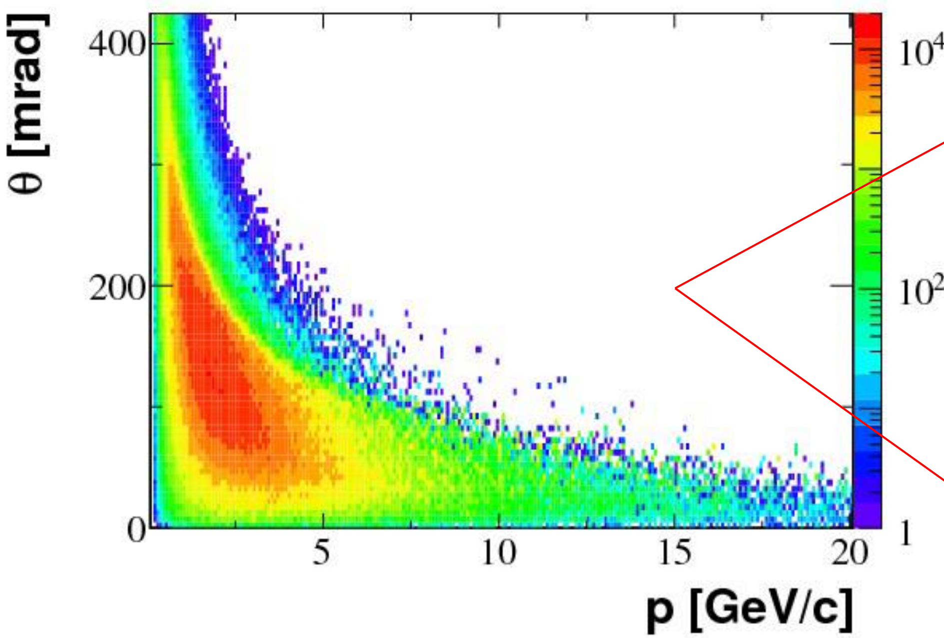
combined ToF + dE/dx

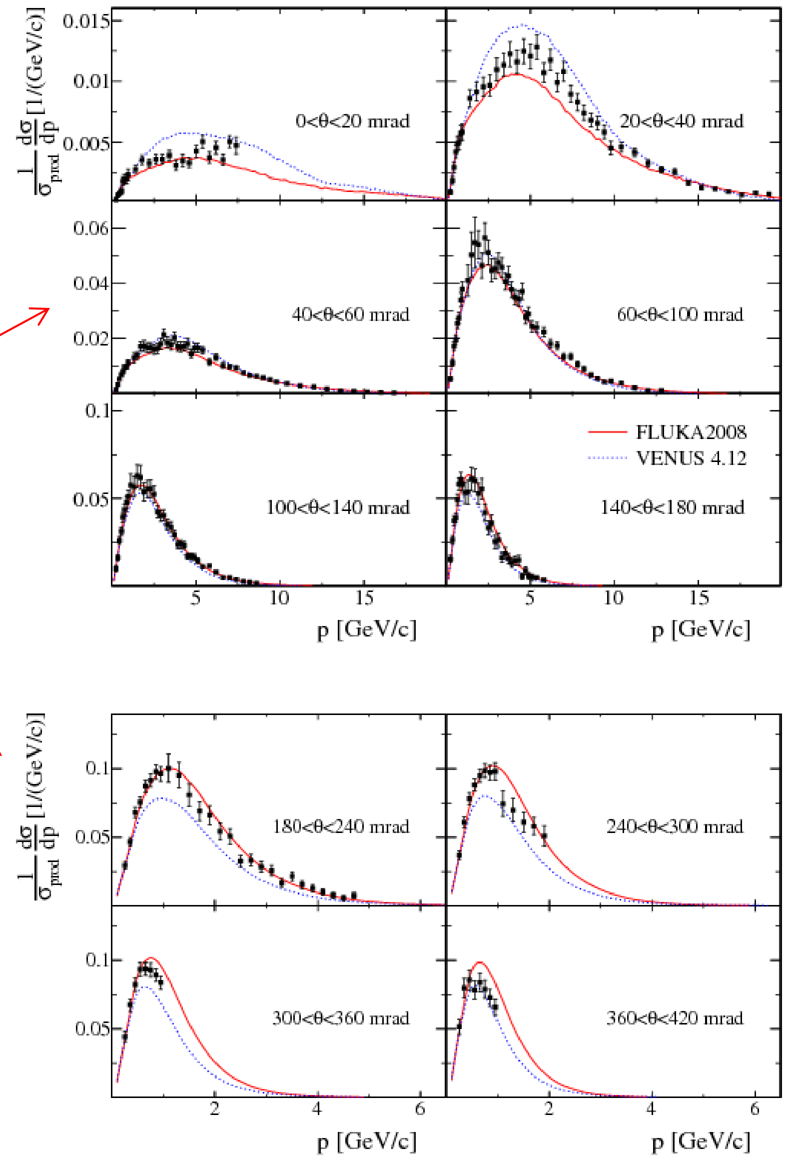


NA61 p + C → π^+ + X @ 30 GeV (2007)

NA61, PRC 85 (2011) 035604

T2K beam simulation :
{p, θ} distribution of π^+
giving ν_μ in SK “acceptance”





T2K beam “phase space”
very well covered in NA61

Analysis Methods

Different analysis procedures adopted depending on the kinematical region covered:

1) negative hadrons: at this beam energy (31 GeV/c) most (> 90%) negative hadrons are π^- with small K^- contamination (< 5%)
pure tracking with no PID, large acceptance, global MC correction

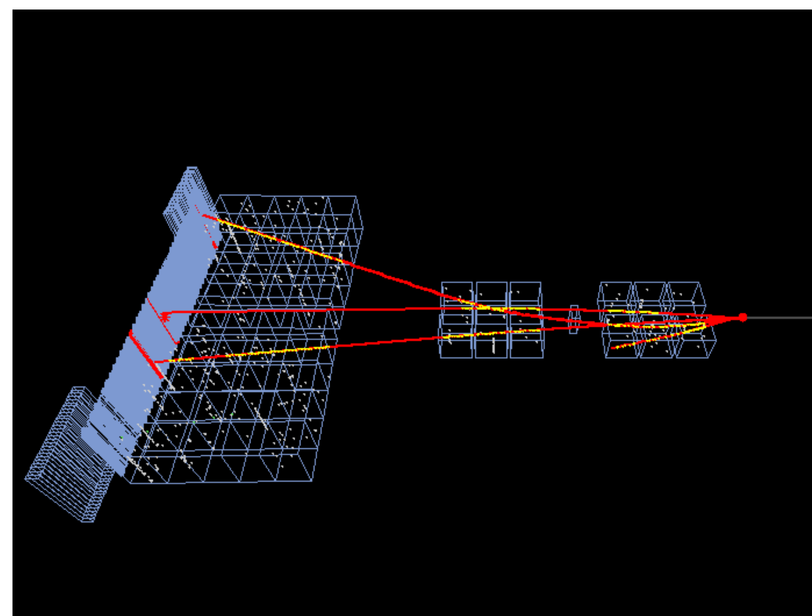
2) p < 1 GeV/c PID based on dE/dx only (below cross-over region in dE/dx)

3) p > 0.8 GeV/c PID combined ToF – dE/dx analysis (π / K / p separation)
particles must reach the ToF, reduced acc.;
factorize all corrections (i.e. acc., recon. eff., decays, etc.), some corrections estimated directly from data, rely less on MC

raw measured particle spectra corrected for:

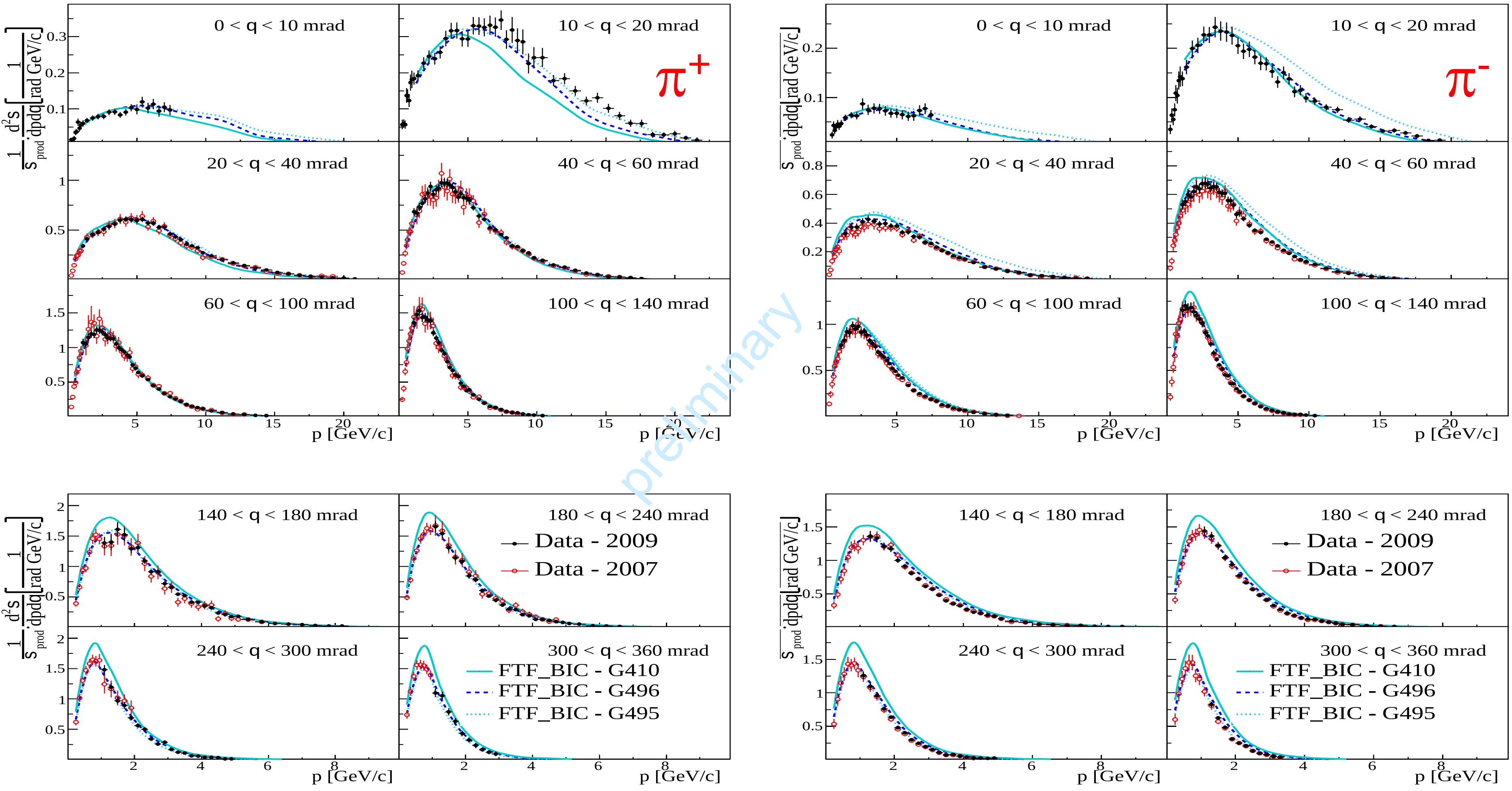
- geometrical acceptance
- reconstruction efficiency
- non-pion contributions
- weak decays (feed-down)

Typical p+C event at 31 GeV/c



NA61 p + C → $\pi^{+/-}$ + X @ 30 GeV

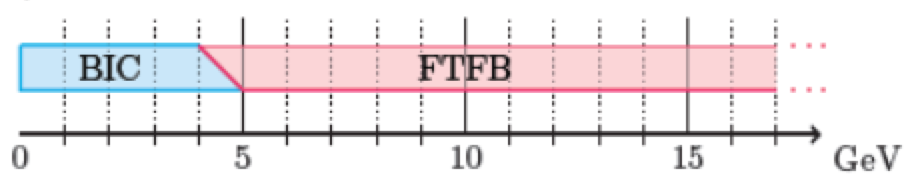
NA61, A. Korzenev et al., arXiV:1311.5719 [nucl-ex]



Relative uncertainty in the T2K region ~ 4%

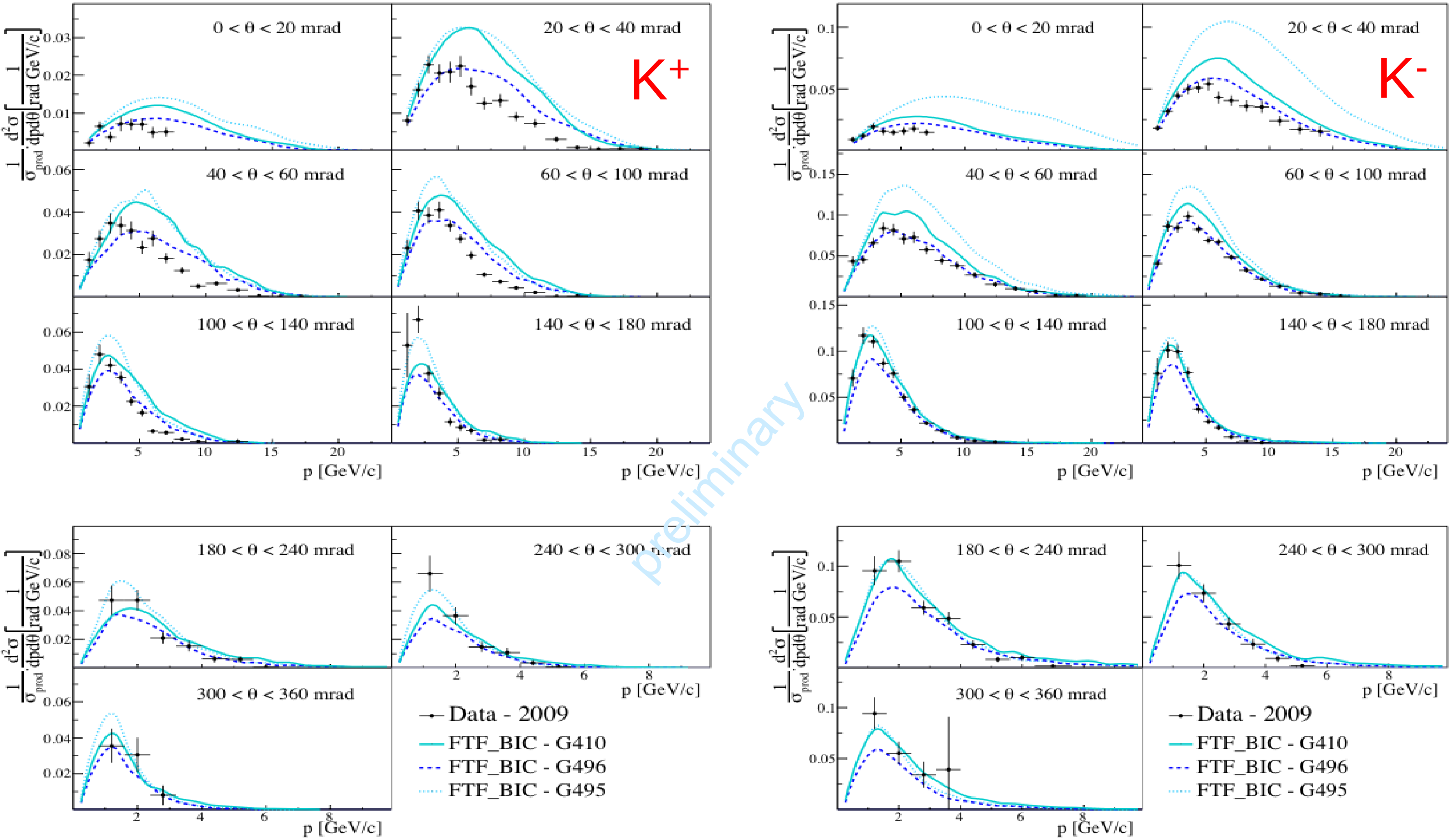
Geant4 FTF_BIC physics list, with 3 different releases of Geant4:

Geant4.9.5 [Oct. 12]
Geant4.9.6 [May 13]
Geant4.10 [Dec 13]



NA61 p + C → $K^{+/-}$ + X @ 30 GeV

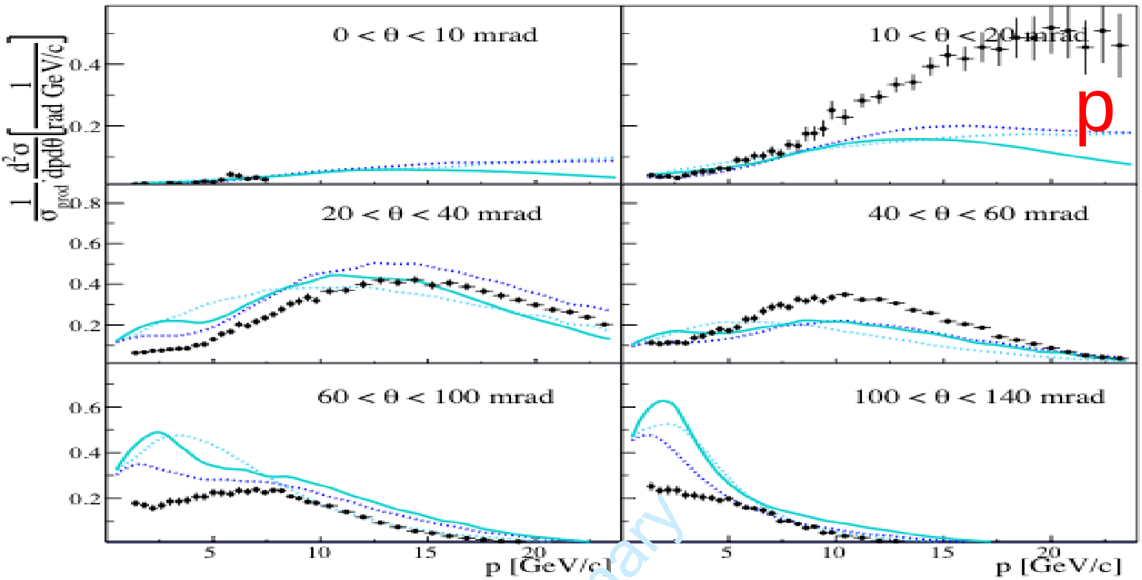
NA61, A. Korzenev et al., arXiV:1311.5719 [nucl-ex]

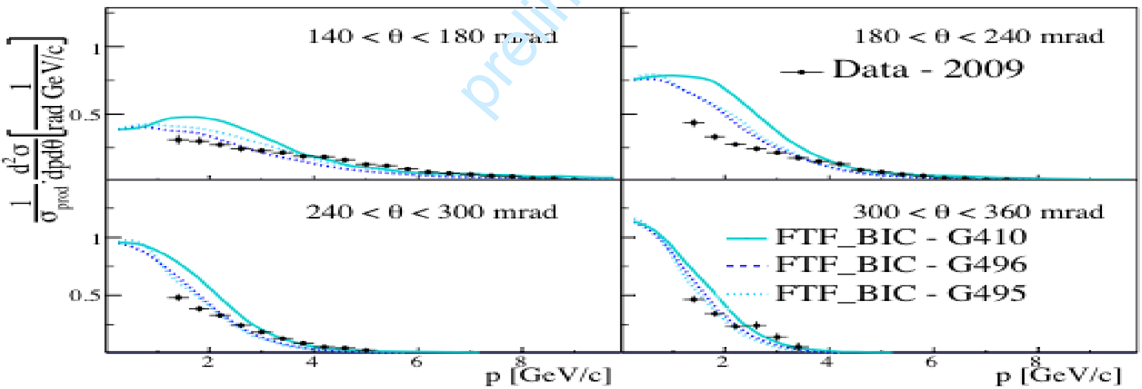


Relative uncertainty in the T2K region ~ 15%

NA61 p + C → p + X @ 30 GeV

NA61, A. Korzenev et al., arXiV:1311.5719 [nucl-ex]

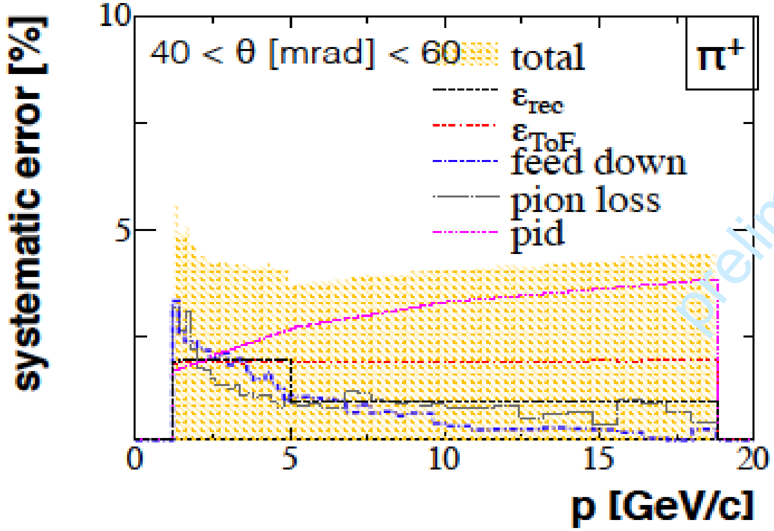


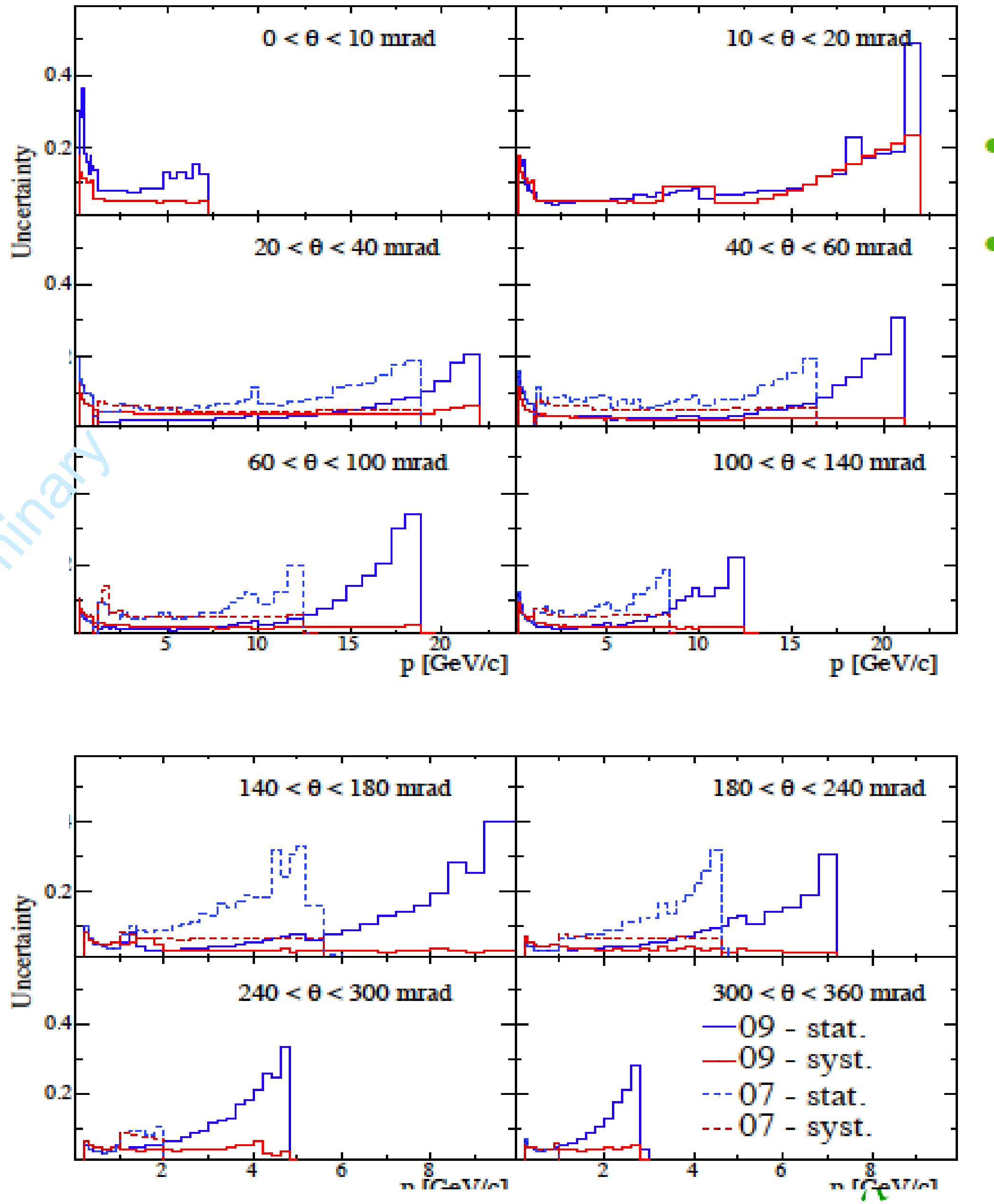


K^0_s and Λ also available

NA61 Systematical Uncertainties (dN/dp)

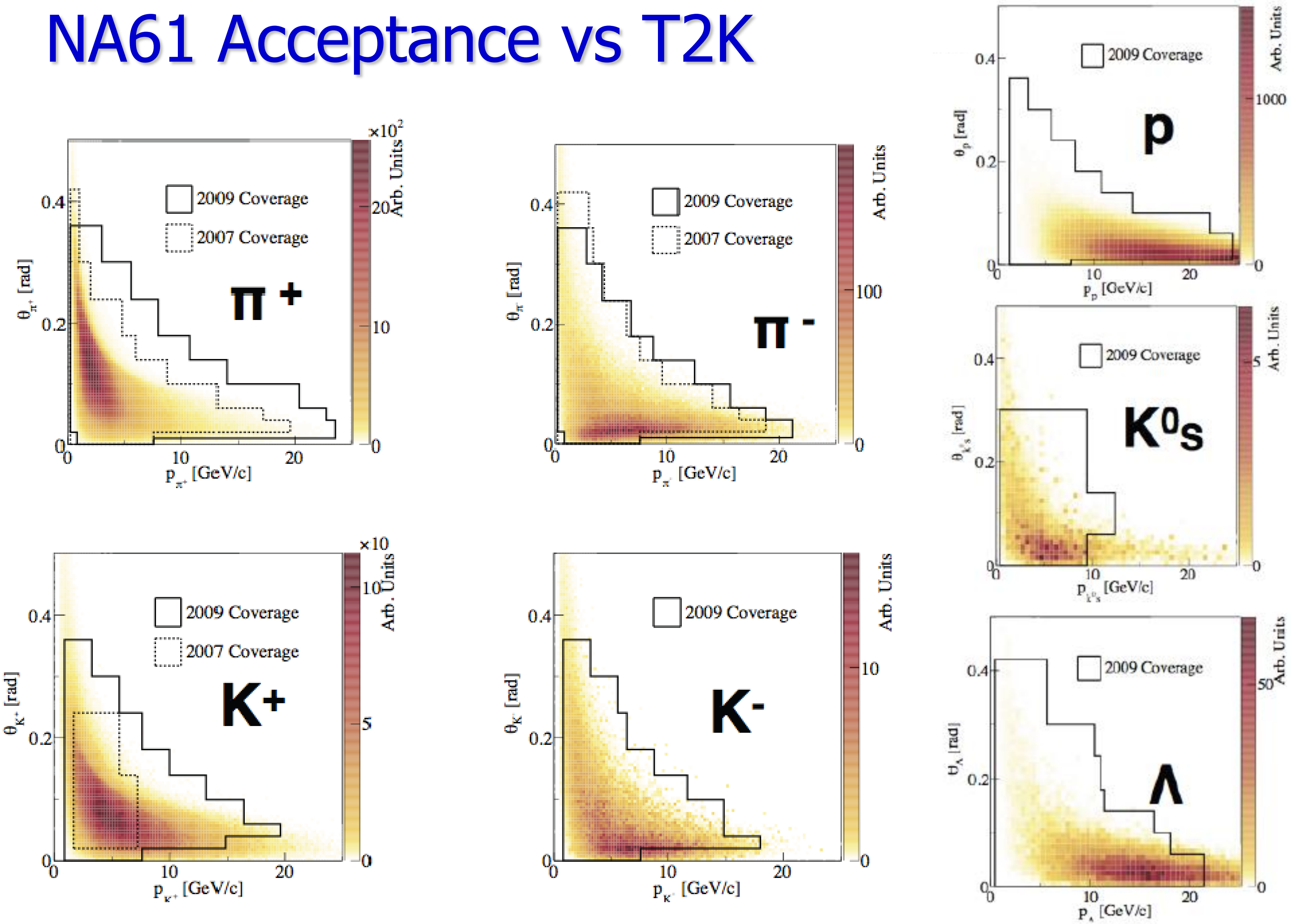
Compared to 2007 data:
- statistical uncertainty improved by ~3
- systematical uncertainty reduced by ~ 2





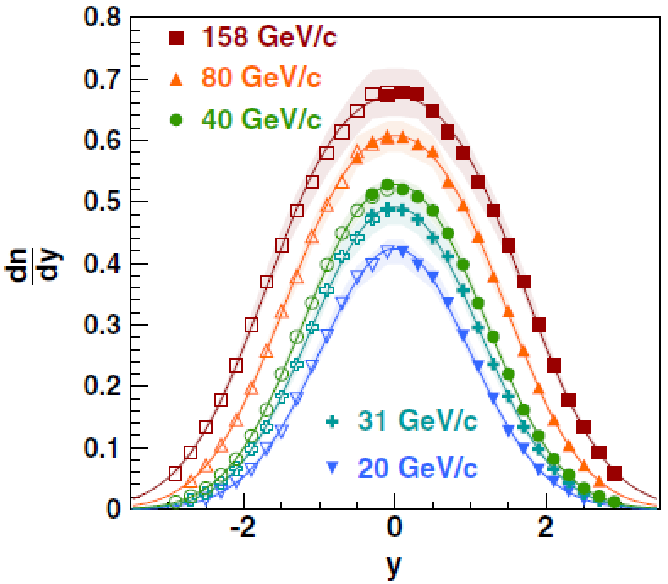
Main contributions to systematical uncertainties from:
- PID
- feed down (improved with studies of strange particles K^0_s and Λ decays)

NA61 Acceptance vs T2K



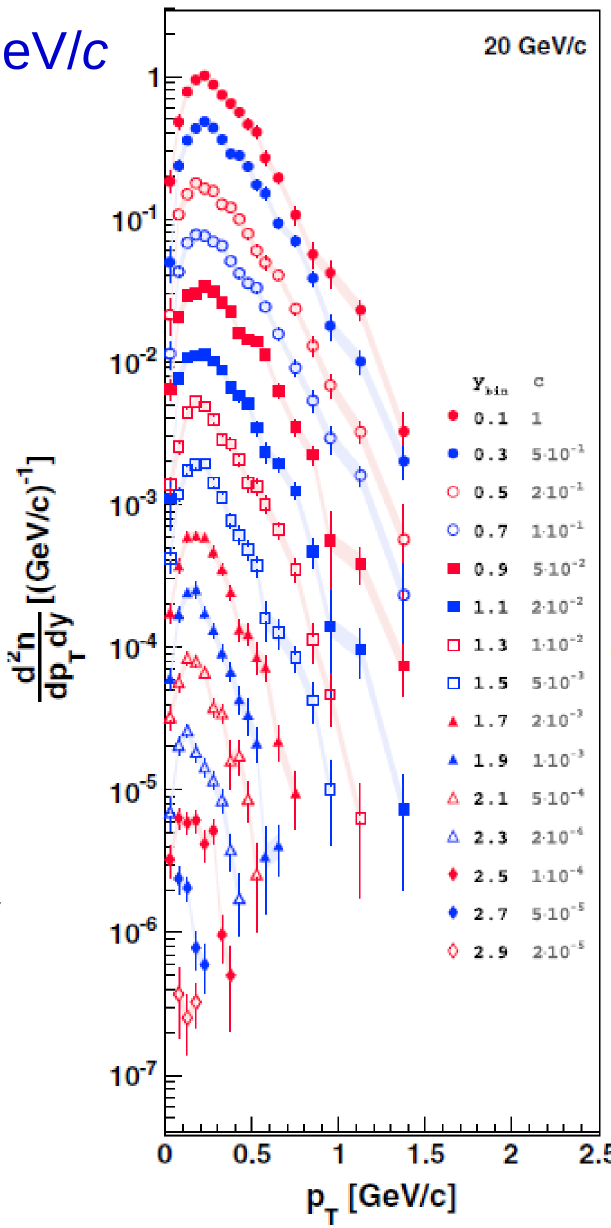
π^- Spectra in p + p $\rightarrow$ π^- + X Energy Scan

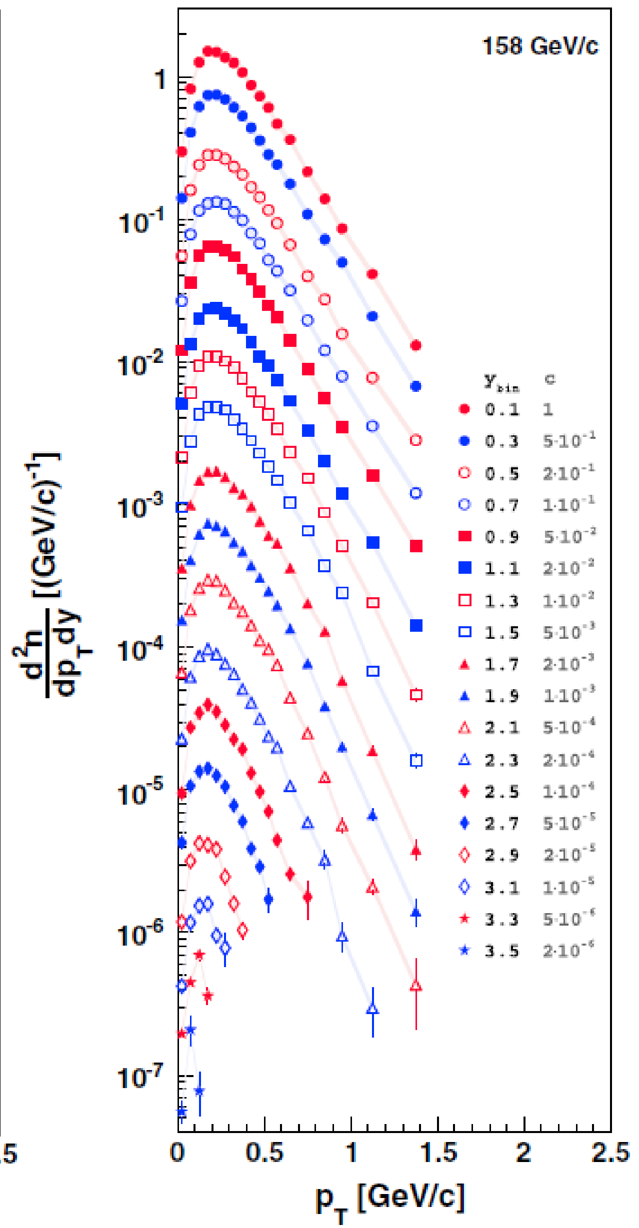
p_{lab} = 20, 30, 40, 80, 158 GeV/*c*



p + p symmetric in rapidity
negative *y* by reflection

NA61, EPJC 74 (2014) 2794

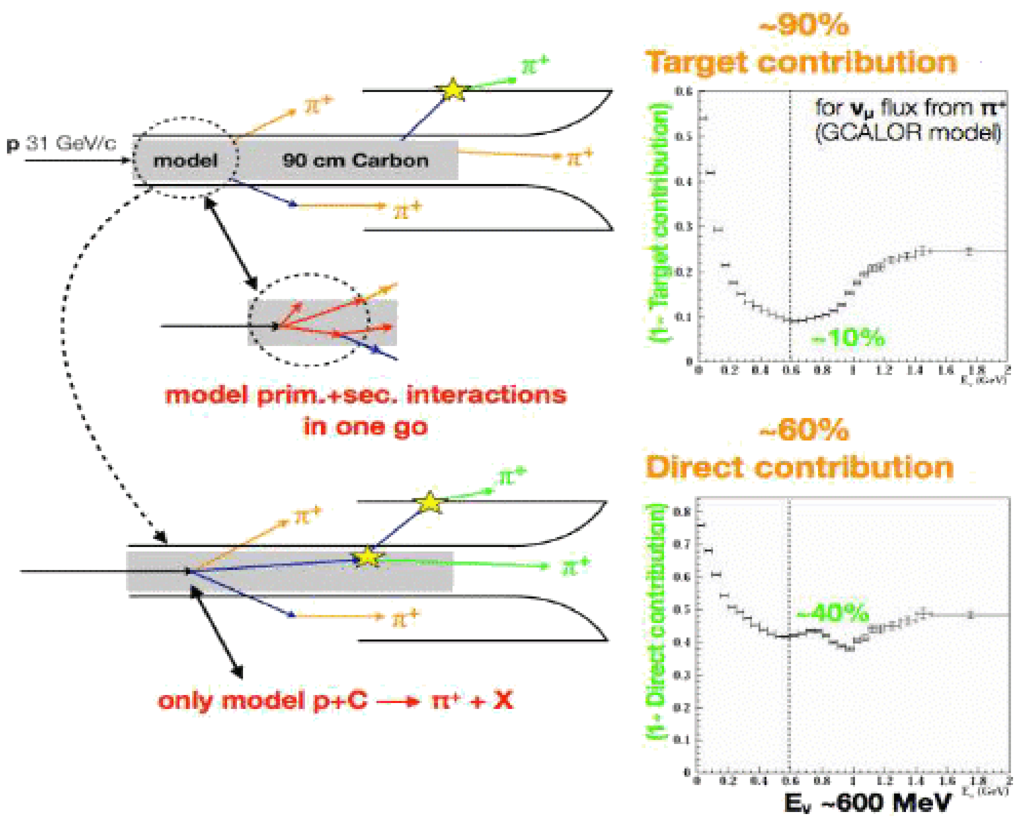


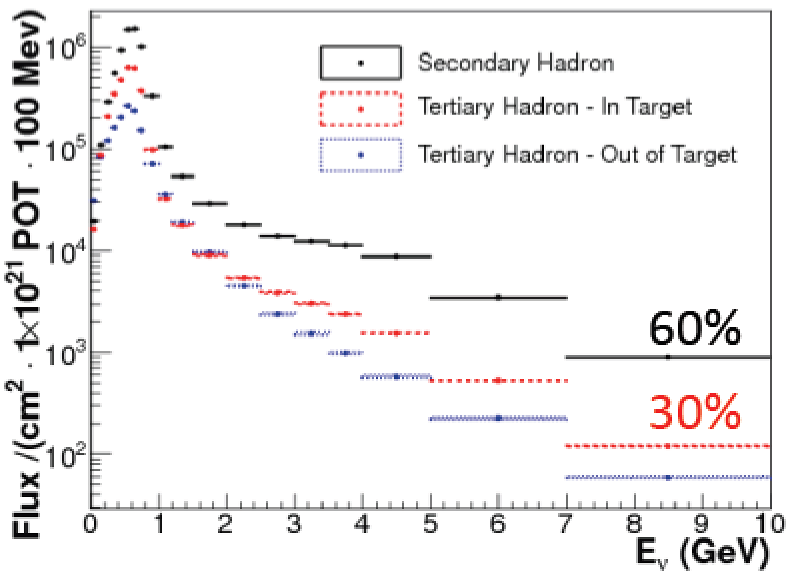


ν Flux Prediction with T2K Replica Target (1)

Neutrinos are coming from hadrons produced in **primary interaction** (~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





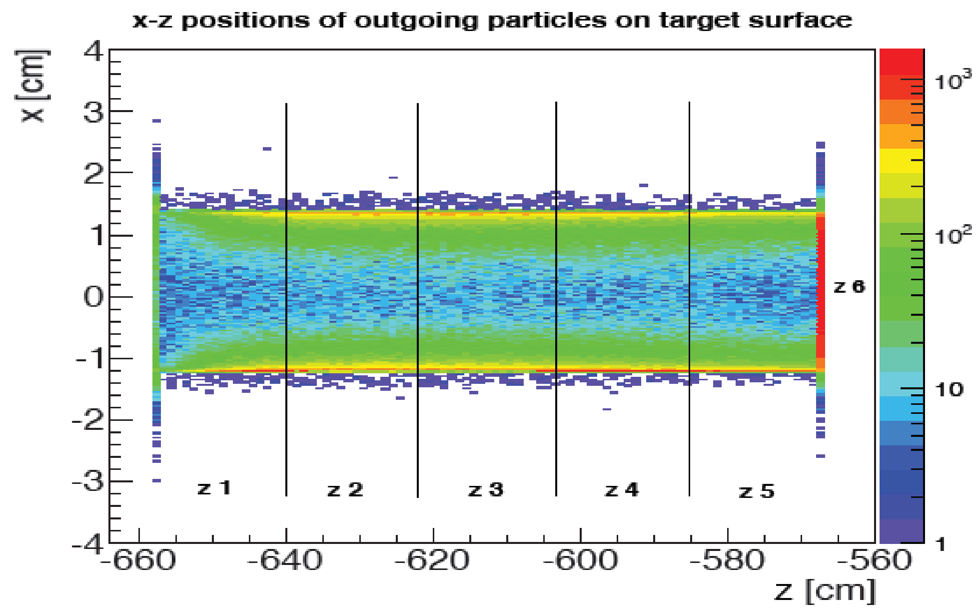
~90% of the neutrino flux can be constrained with the replica target and model dependence is reduced down to 10% as compared to 40%

NA61, NIM A701 (2013) 99

π^+ Hadroproduction on the Replica Target

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

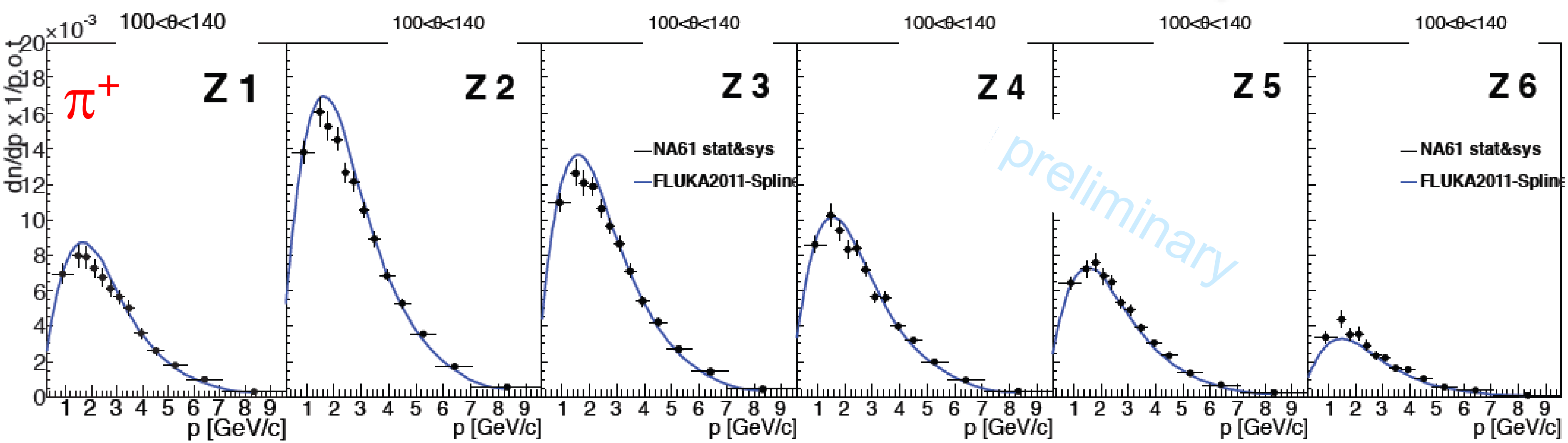
- tracks extrapolated backwards
- no interaction vertex reconstruction
- the target is sliced in five bins in z
    - + downstream exit face
- can study also as a function of r



statistical precision ~5%

systematic error ~5% (center) – 14%

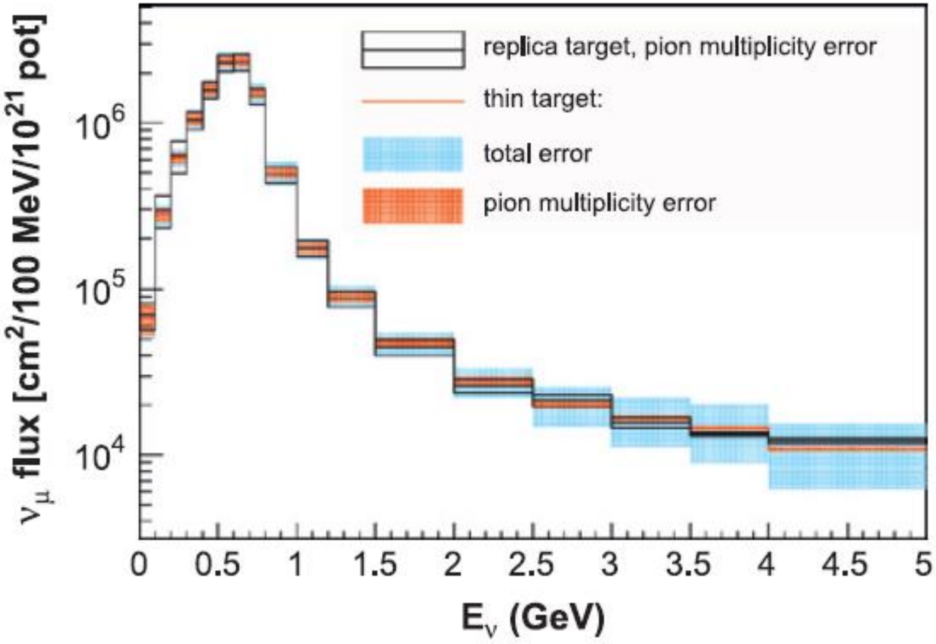
beam



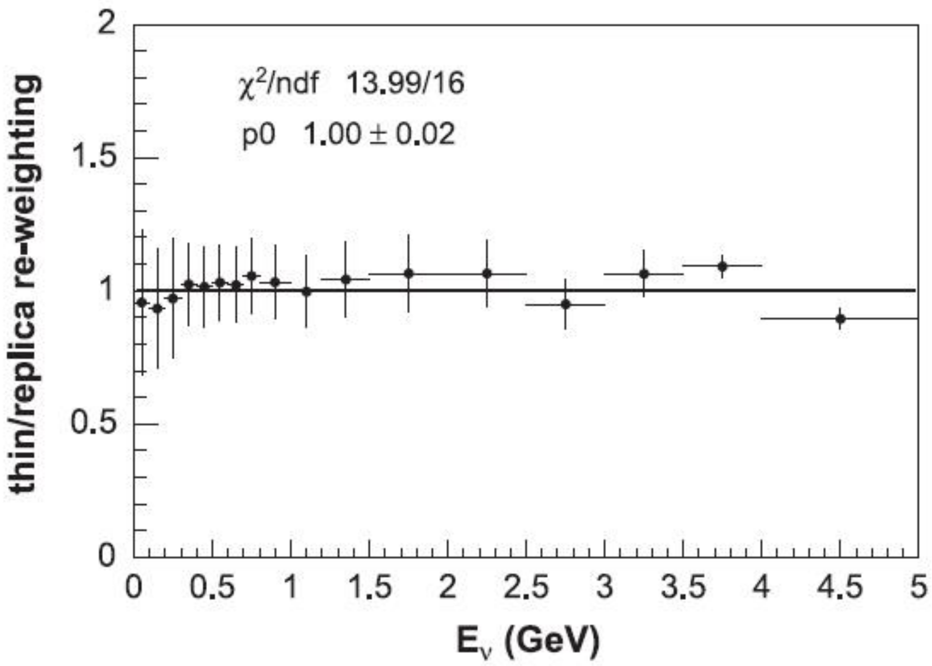
ν Flux Prediction with T2K Replica Target (2)

2007 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



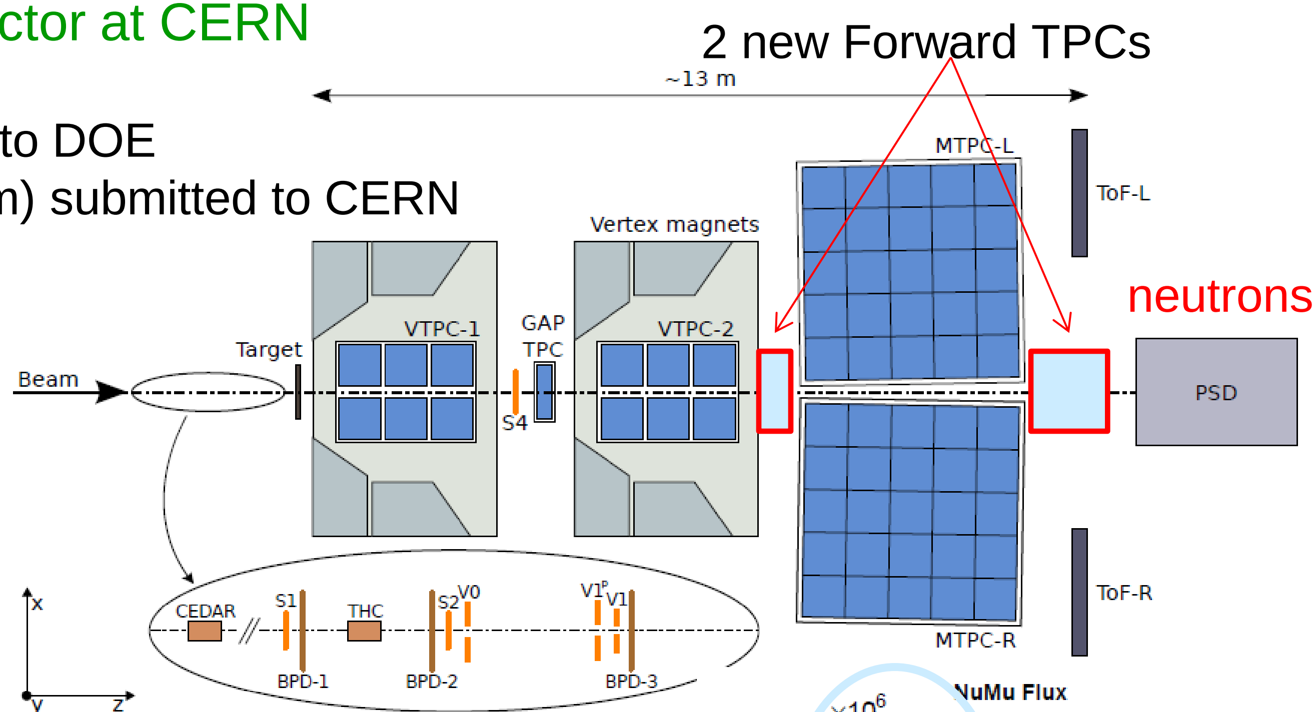
NA61, NIM A701 (2013) 99

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

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

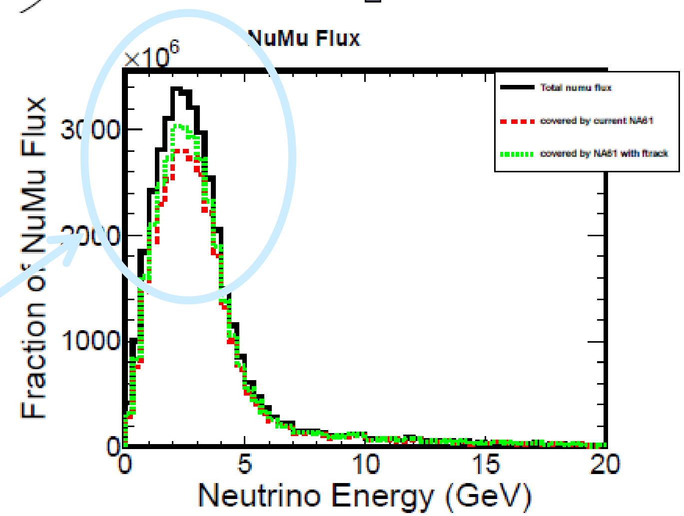


data taking might start already in 2015

Upgrades:

- add forward tracking
- forward calorimetry (neutrons)
- new DAQ based on the DRS

improved coverage

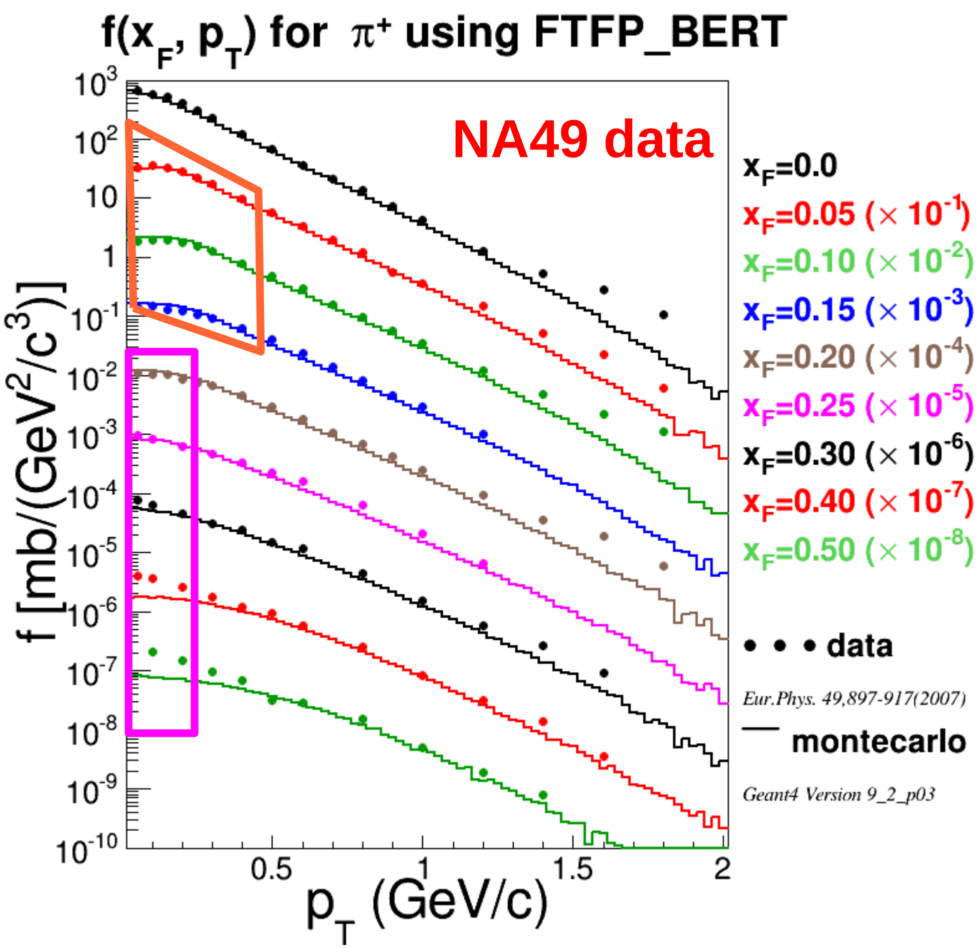


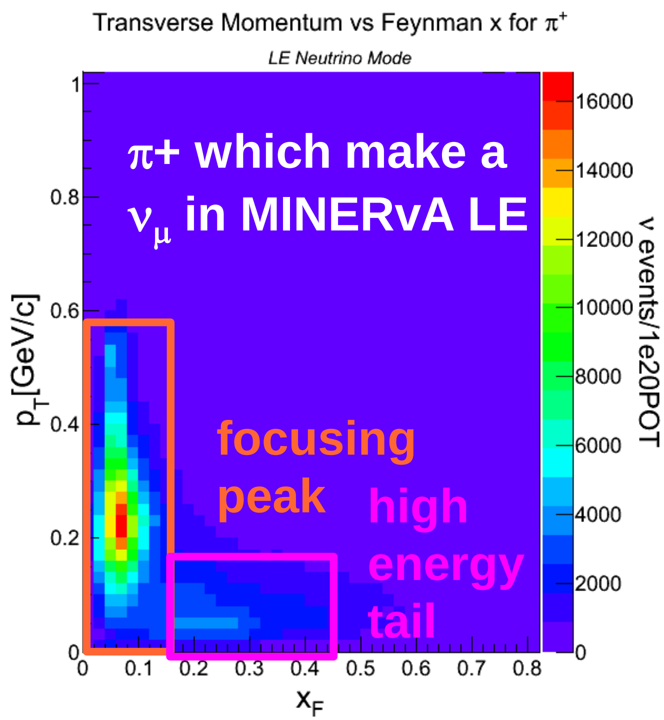
NuMI ν Flux

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

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



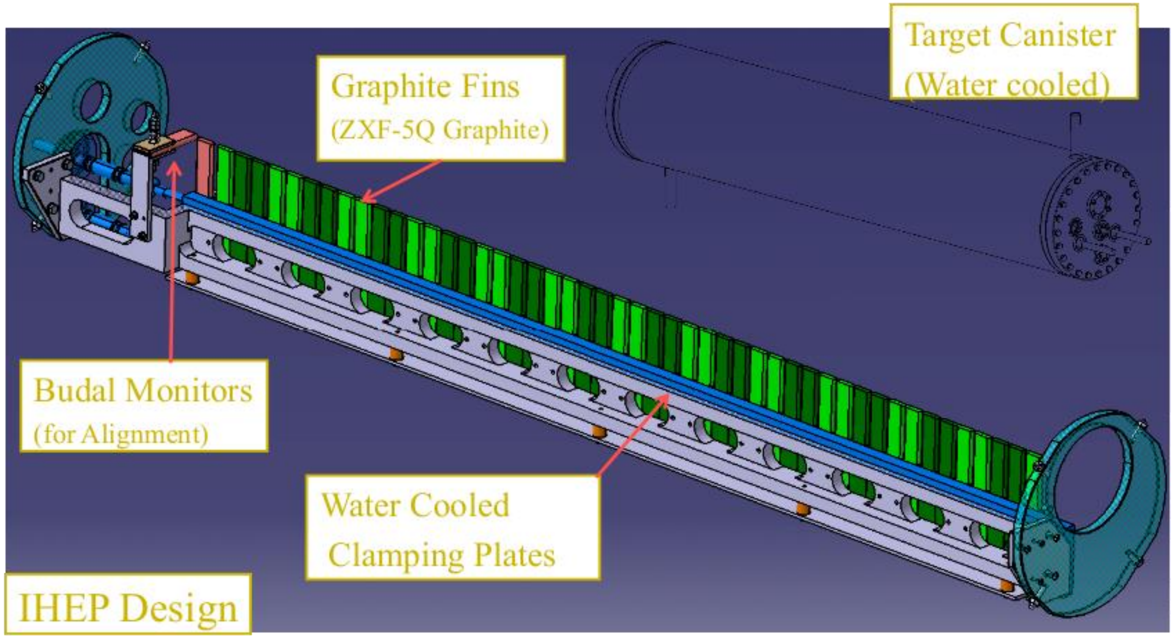


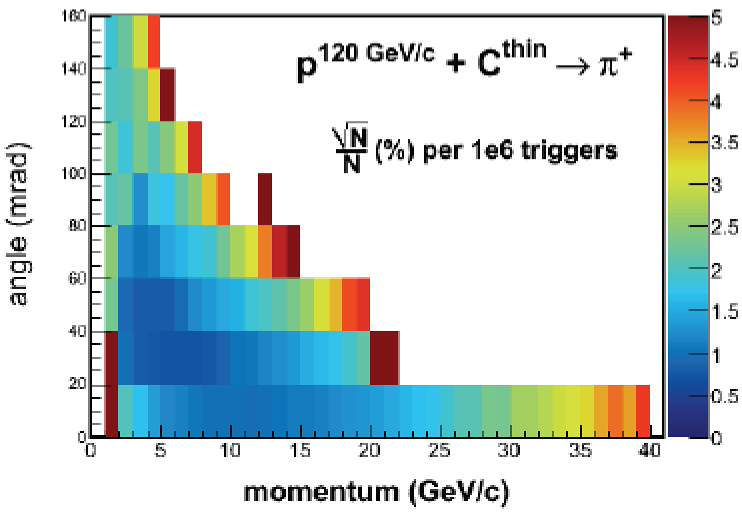
<u>NA49 Uncertainties</u>

7.5% systematic

2-10% statistical

NuMI Target





tentative run plan

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)*

Summary

NA61 initial goals for T2K : 5% error on absolute neutrino fluxes
3% error on the far-to-near ratio

Hadroproduction measurements of charged π and K, p, K^0_s, Λ on thin target
already released publication(s) in preparation (2009 data)

Work in progress on the replica target (2009 data), expect to be finalized soon

Hadro production measurements require :

- large acceptance detectors with PID over whole kinematical range
- large statistics
- different targets to study various particle production effects

Also availabe or soon available:

- pp energy scan from 20 GeV to 158 GeV
- high statistics pp @ 158 GeV
- high statistics pPb @ 158 GeV

NA61 very likely to continue with measurements for NuMI (2015 +)