Hadron Production Experiments

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NuFact2012
July 24th '12

Why hadro-production measurements

neutrino cross sections → absolute neutrino flux
neutrino interaction physics

neutrino oscillations → compare measured neutrino spectrum "far" from the source
with the predicted one (flux shape and Far / Near flux ratio)
background ν_e flux in ν_μ beam

deviations from expectations ⇒ evidence for neutrino oscillations

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

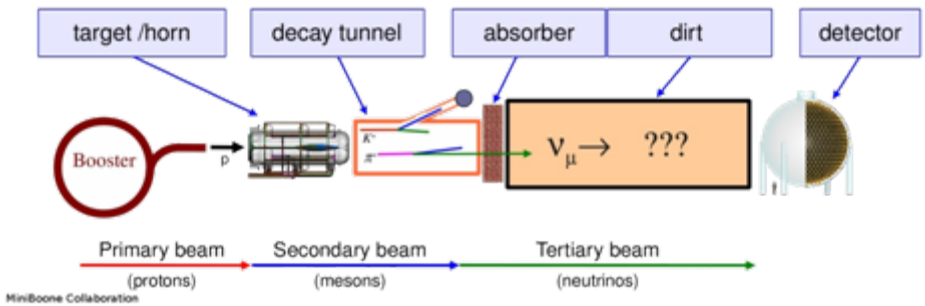
ν flux predictions based on π, K ($\rightarrow \nu + X$) hadro-production models

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

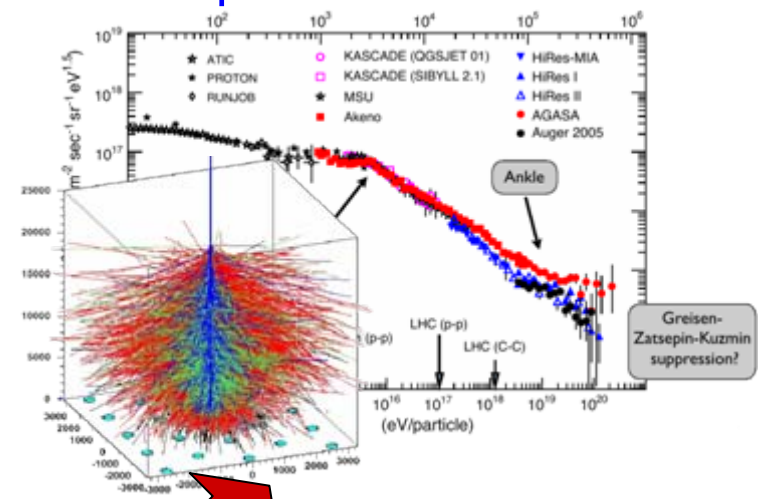
Goals of NA61-T2K

Predict Far / Near neutrino flux ratio to 3%
Predict the neutrino flux to 5%

conventional accelerator ν-beam

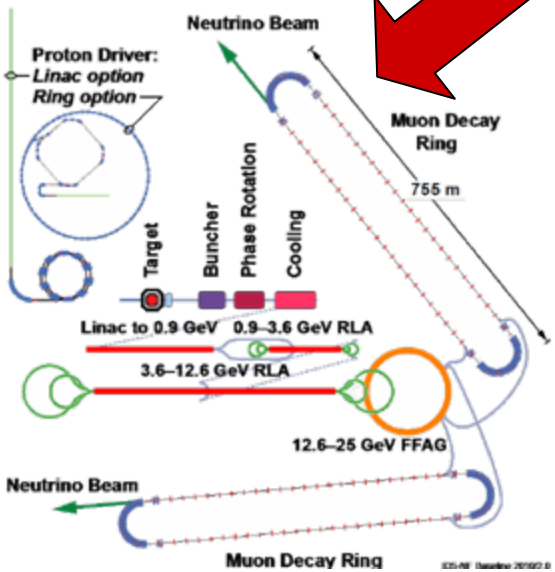


atmospheric showers

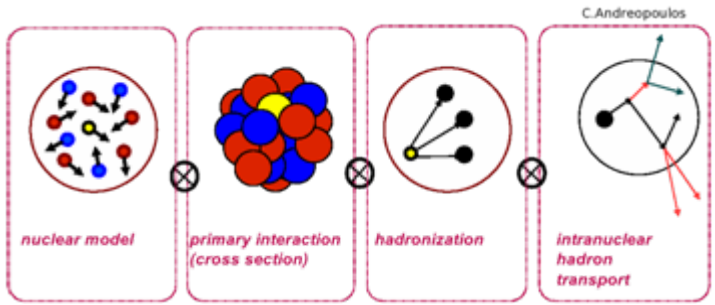


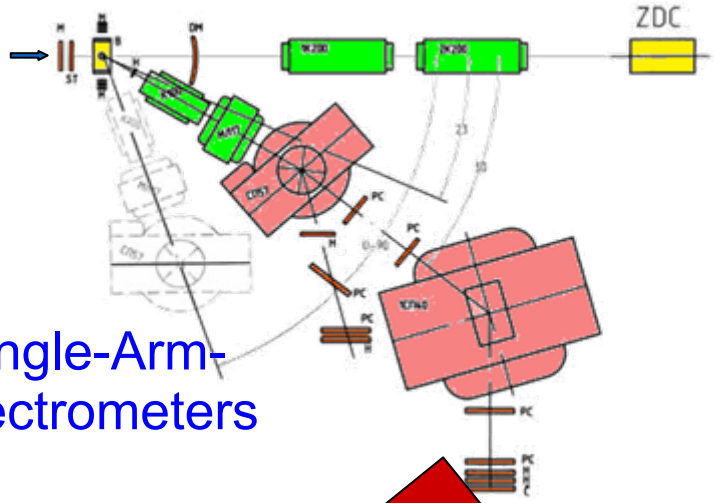
Hadroproduction measurements
$p(\pi) + A \rightarrow h + X$

Neutrino Factory



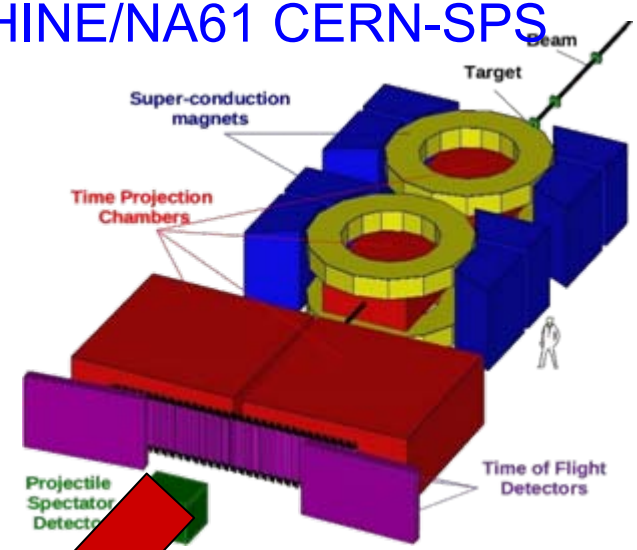
MC generators



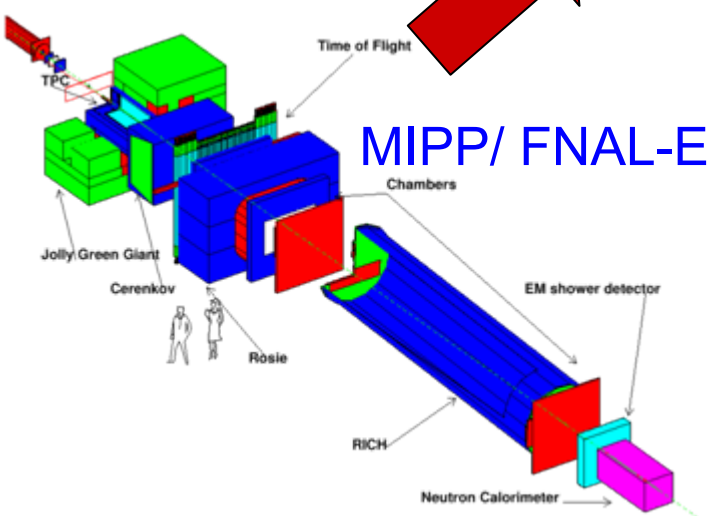


Single-Arm-Spectrometers

SHINE/NA61 CERN-SPS

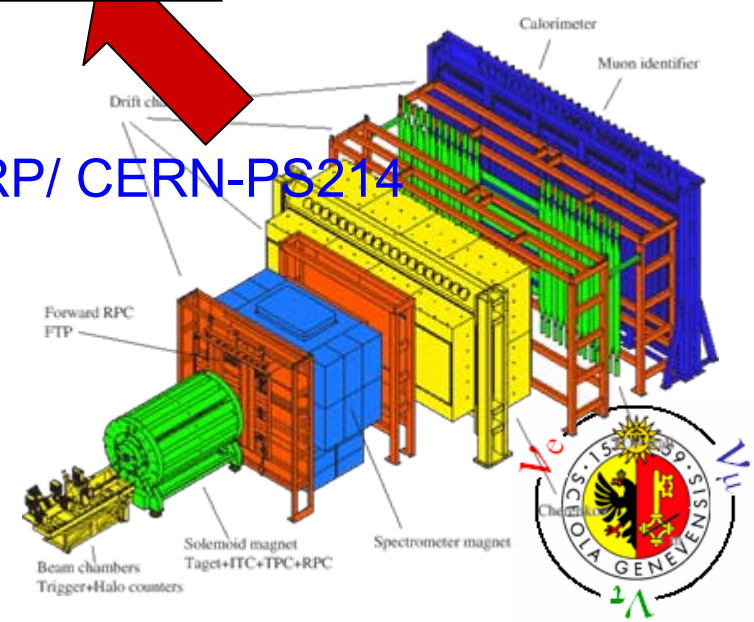


Hadroproduction measurements
$p(\pi) + A \rightarrow h + X$



MIPP/ FNAL-E907

HARP/ CERN-PS214



hadron production experiment	neutrino experiment
HARP / CERN-PS214 1.5-15 GeV beam	(Mini-, Sci-, Micro-)BooNE at Fermilab K2K (KEK to Super-Kamiokande)
NA20 & SPY/NA56 400-450 GeV beam	WANF (NOMAD, CHORUS) CNGS (OPERA, ICARUS)
NA49 / CERN-SPS 160 GeV beam	MINOS (Fermilab to Soudan)
SHINE / CERN-SPS-NA61 30-160 GeV beam	T2K (JPARC to Super-Kamiokande) NuMI (MINERvA, NOvA)

+ many many other experiments that measured cross sections …

HARP : Hardon Production Exp. at PS

- Measurement of secondary π, K, p production cross section for various nuclear targets with p / π beams in 1.5-15 GeV/*c* momentum range

- Approved in 2000
- Data taking 2001-2002
- T9 beam line of CERN PS

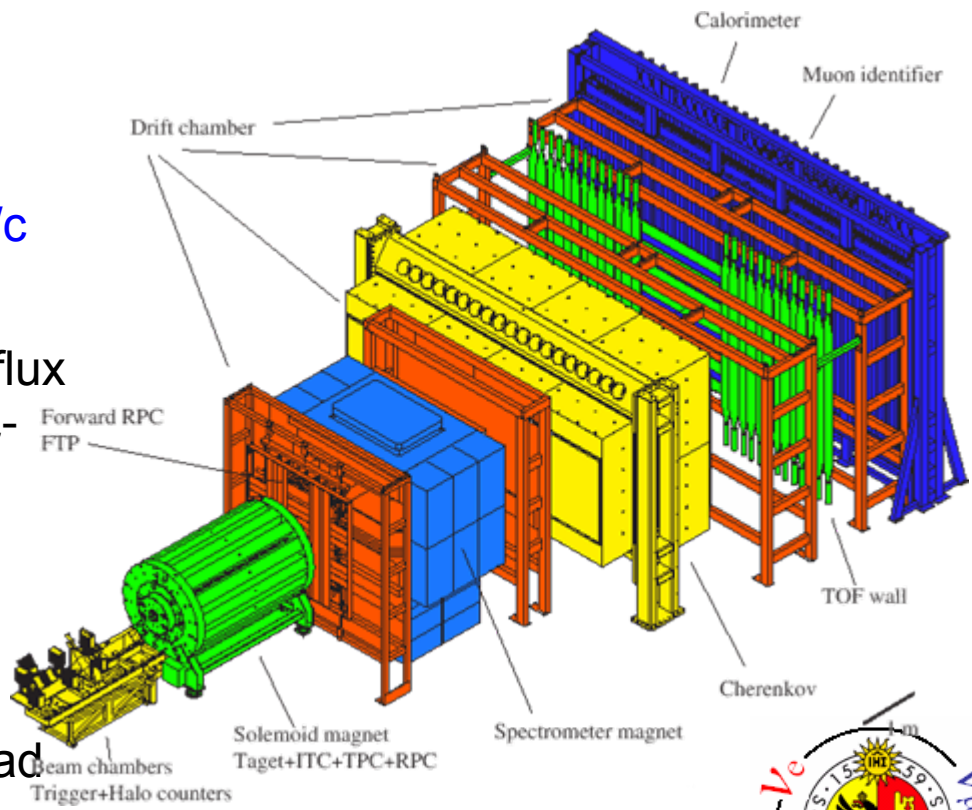
- Results of measurements have been used for ν flux prediction in
  - K2K: Al target, 12.9 GeV/c
  - Mini(Sci)BooNE: Be targ, 8.9 GeV/c

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

- Kinematic acceptance
  - Forward spectrometer

  $0.5 < p < 8$ GeV/*c*, $0.025 < \theta < 0.25$ rad
  - Large angles (TPC + RPD)

  $0.1 < p < 0.8$ GeV/*c*, $0.35 < \theta < 2.15$ rad

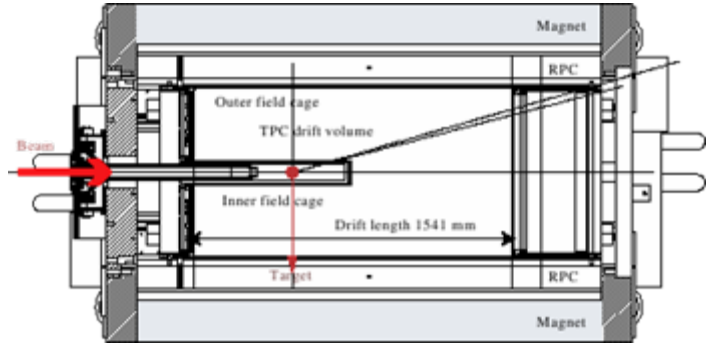


M.G. Catanesi et al., NIM A571(2007) 527

HARP Datasets 2001 - 2002

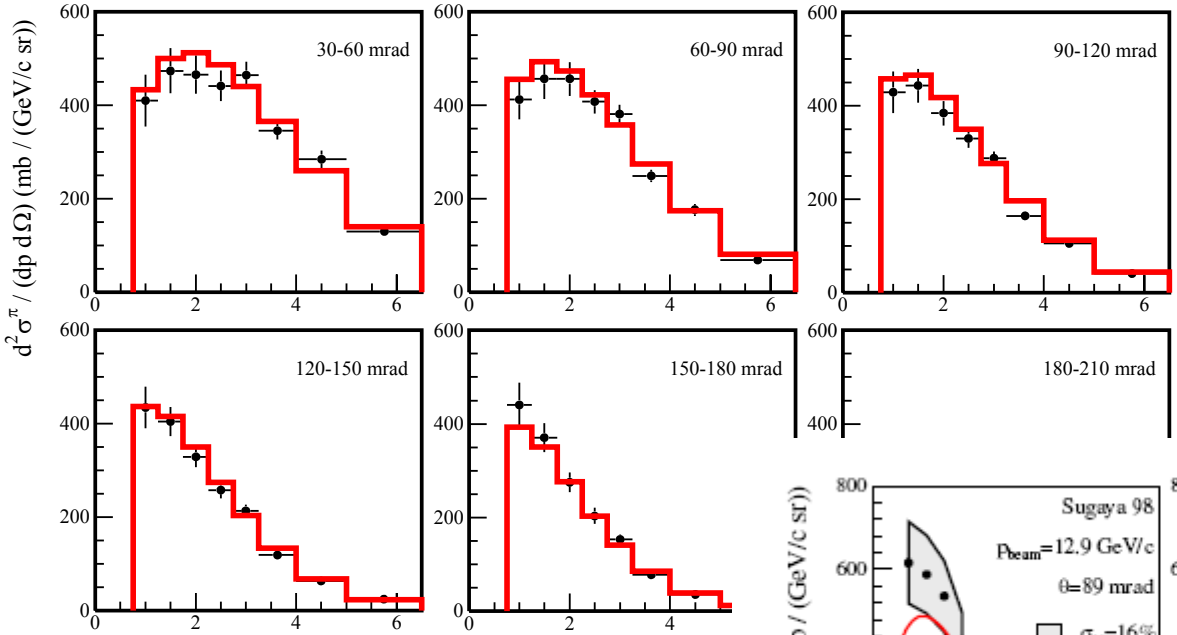
Target	Momentum (GeV/c)	Length (λ_{int})	Event (10^6)
Be	(±) 3, 5, 8, 12, 15	2%, 5%, 100%	37.4
C	(±) 3, 5, 8, 12, 15	2%, 5%, 100%	30.7
Al	(±) 3, 5, 8, 12, 15	2%, 5%, 100%	34.5
Cu	(±) 3, 5, 8, 12, 15	2%, 5%, 100%	36.6
Sn	(±) 3, 5, 8, 12, 15	2%, 5%	23.7
Ta	(±) 3, 5, 8, 12, 15	2%, 5%, 100%	38.2
Pb	(±) 3, 5, 8, 12, 15	2%, 5%, 100%	44.9
N	(±) 3, 5, 8, 12, 15	6 cm	13.0
O	(±) 3, 5, 8, 12, 15	6 cm	15.5
H	(±) 3, 5, 8, 12, 15	6, 18 cm	32.0
D	(±) 3, 5, 8, 12, 15	6 cm	21.0
MiniBooNE	+8.9	5%, 50%, 100% replica target	22.6
K2K	+12.9	5%, 50%, 100% replica target	15.3
H2O	+1.5	10%, 100%	6.4
Pb, Ta, Cu	+1.5	5%	3.2

Large angle spectrometer



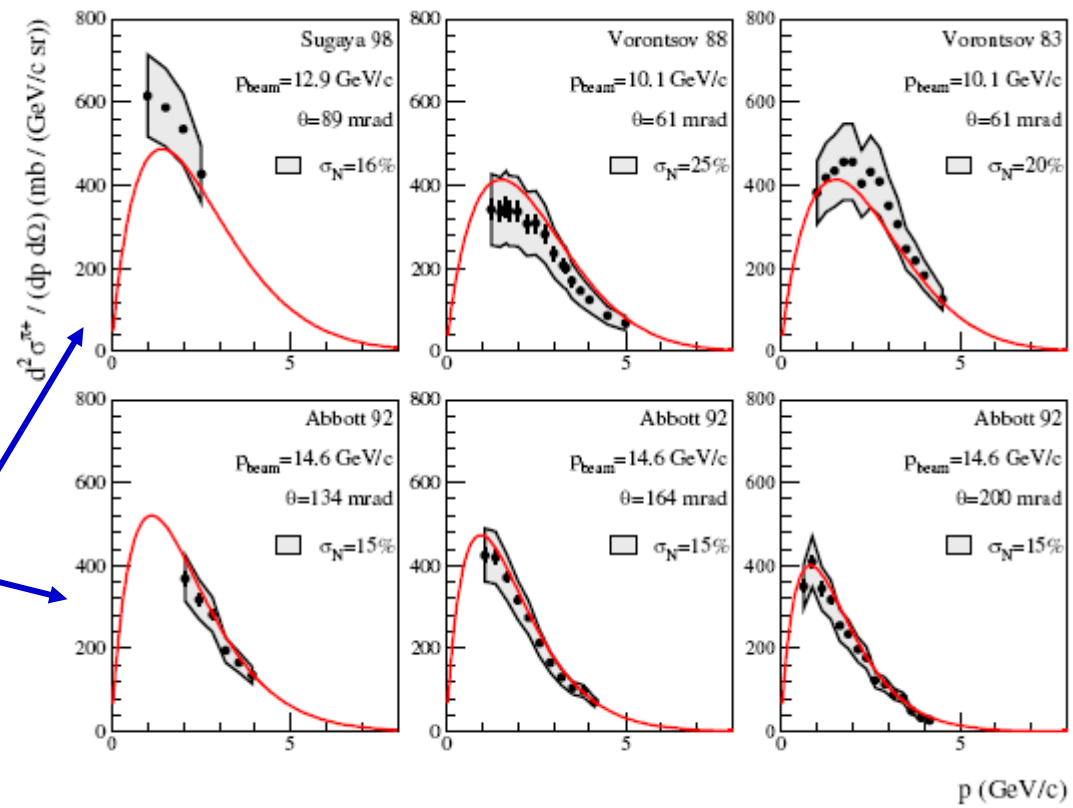
- Targets are mounted 50 cm inside the TPC in order to cover larger solid angle
- Different target width to ensure the corrections for the secondary interaction
- Analysis is basically independent for forward and large-angle spectrometers
  - Large angles: proton driver for Neutrino Factory
  - Forward region: neutrino beams (conventional & superbeam), K2K, MiniBooNE, atmospheric neutrinos

HARP Result (p-Al at 12.9 GeV)



HARP data points

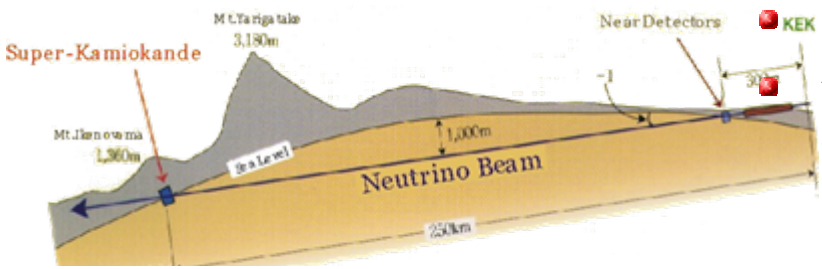
HARP Sanford-Wang parametrization



results based on ~200 k reconstructed tracks

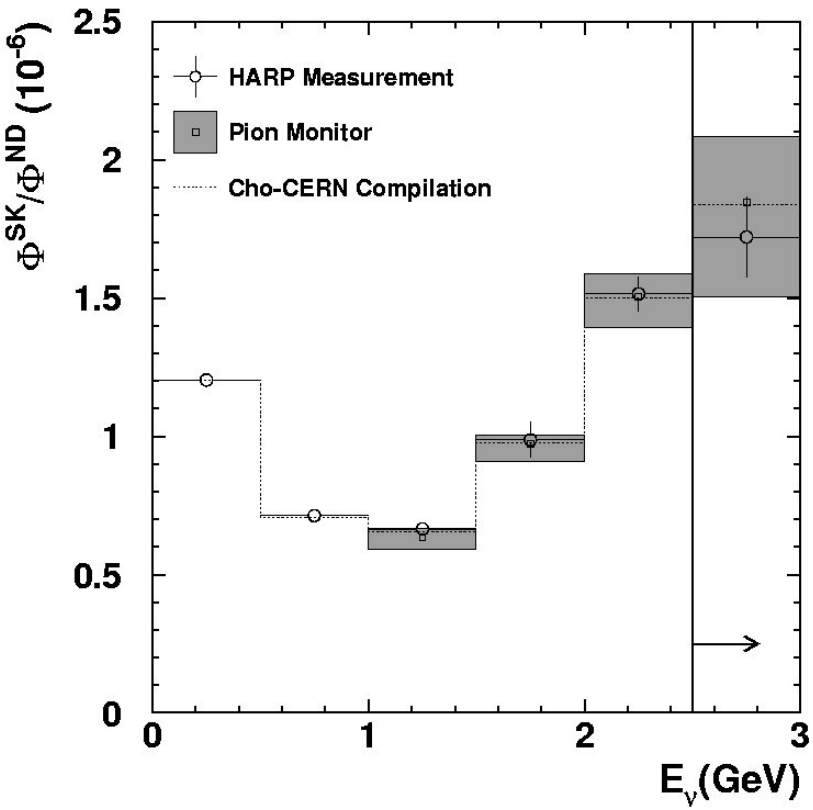
doubly differential cross-section comparison to previous data: large normalization uncertainty

HARP Impact on K2K



K2K measured ν_μ disappearance for θ_{23}, Δm_{23}^2

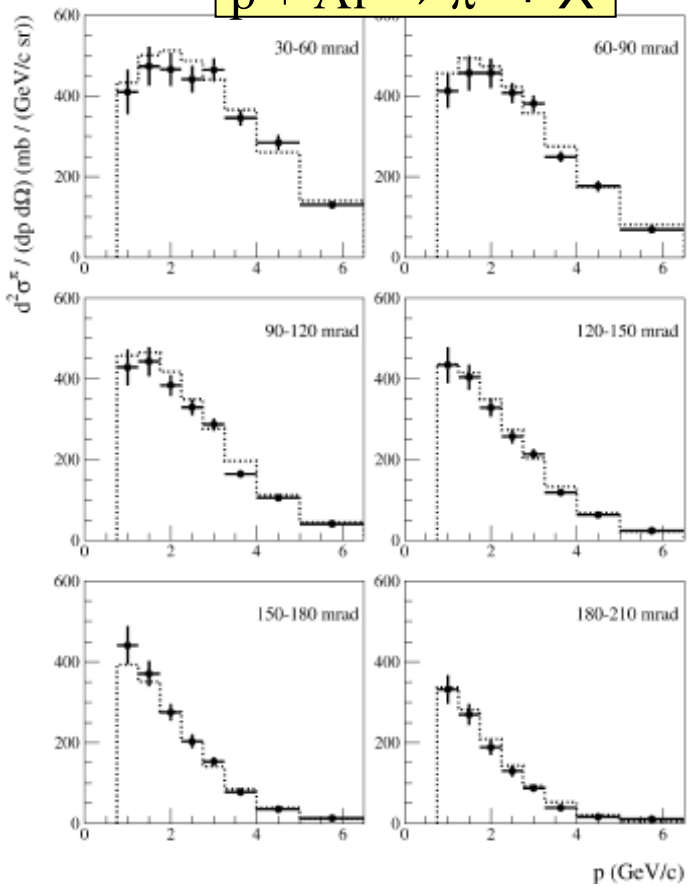
ν_μ beam was produced by 12.9 GeV/c protons scattered off 5% Aluminum target



almost factor of 2 error reduction

(K2K coll.) M.H.Ahn et al., Phys.Rev.D74(2006)072003

$p + Al \rightarrow \pi^+ + X$



M.G. Catanesi et al., Nucl.Phys.B732(2006)1

MIPP : Main Injector Particle Production Exp.

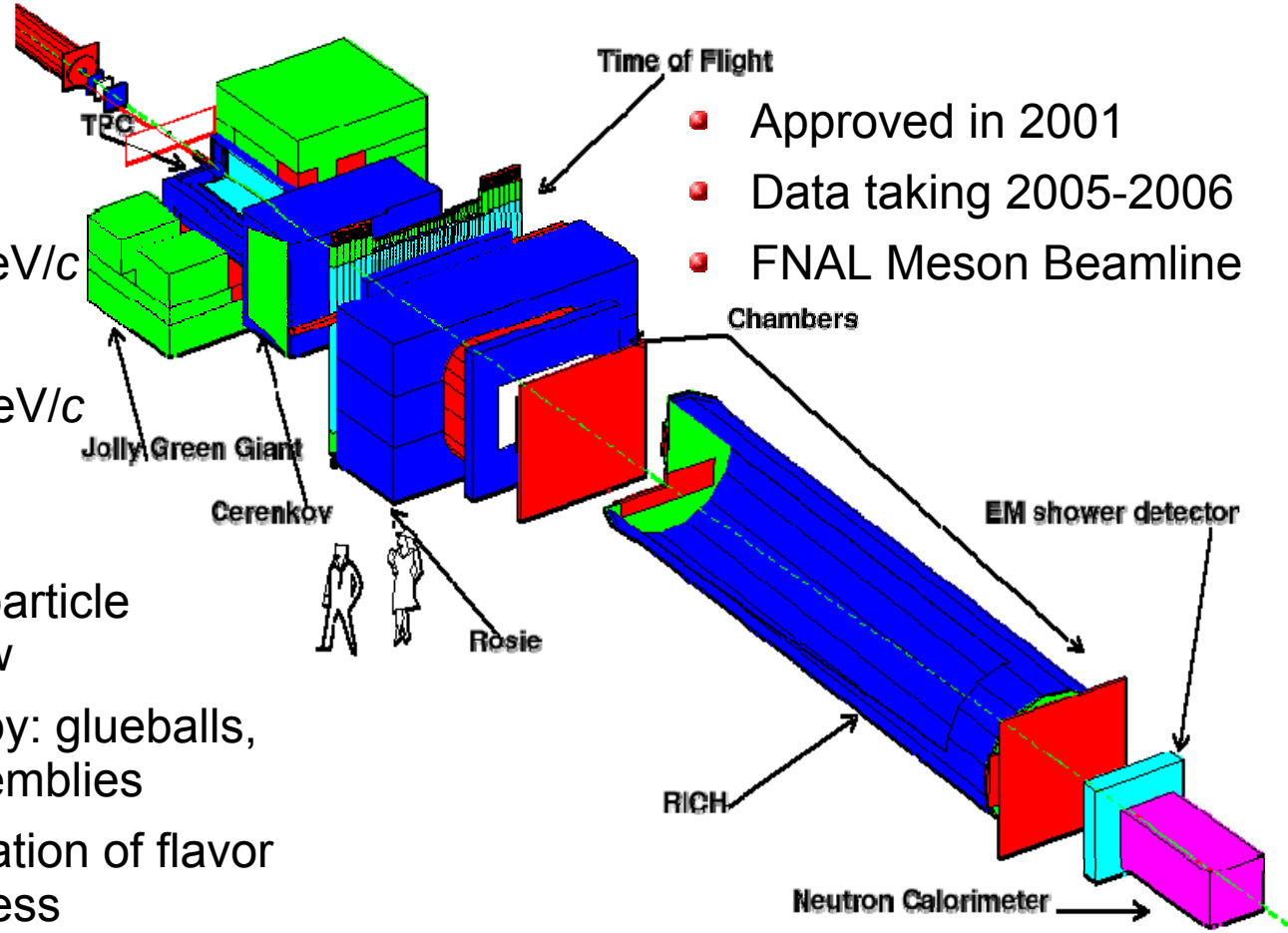
Kinematic acceptance

- RICH: p>17 GeV/c
- Cherenkov: 2.5<p<17 GeV/c
- ToF: 0.5<p<2.5 GeV/c
- TPC *(dE/dx)*: 0.1<p<1 GeV/c

Physics goals

- Non-perturbative QCD: particle fragmentation scaling law
- Light meson spectroscopy: glueballs, hybrids, multi-quark assemblies
- Nuclear physics: propagation of flavor through nuclei, strangeness production
- Measurements for ν physics: hadron cross-sections for MINOS at 120 GeV/c

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



- Approved in 2001
- Data taking 2005-2006
- FNAL Meson Beamline

- Proposal to upgrade (2006): hep-ex/0609057

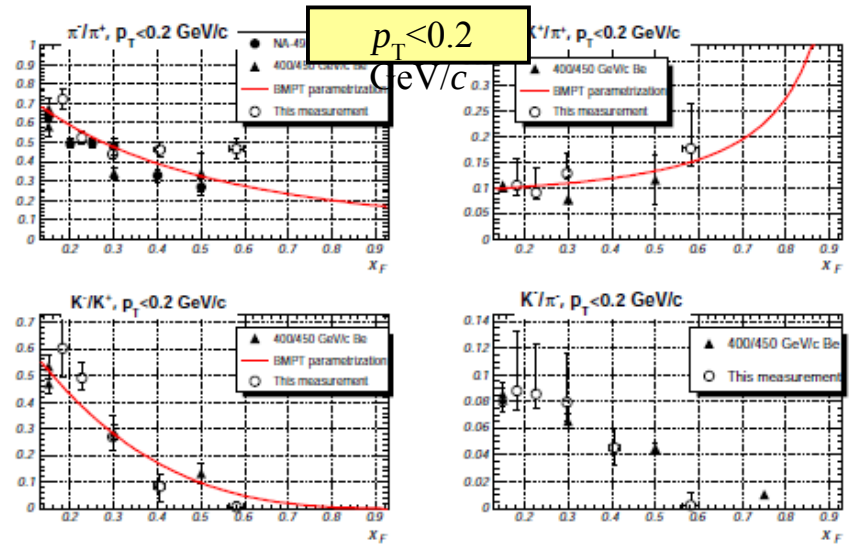
Ratios of Charged Hadron Yields

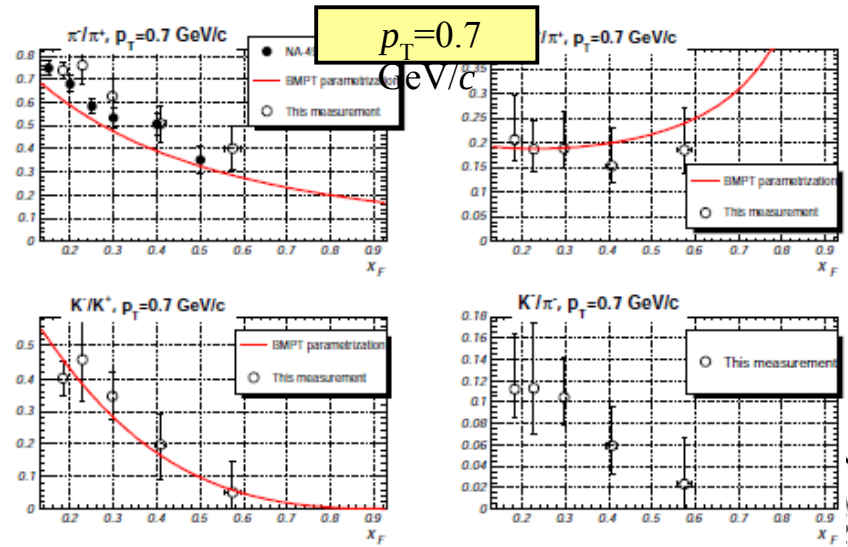
- Measurements for MINOS/ 120 GeV/*c*
  - Thin carbon target
  - NuMI replica target
- Preliminary results for ratios:

  π^-/π^+, K^+/π^+, K^-/K^+ and K^-/π^-

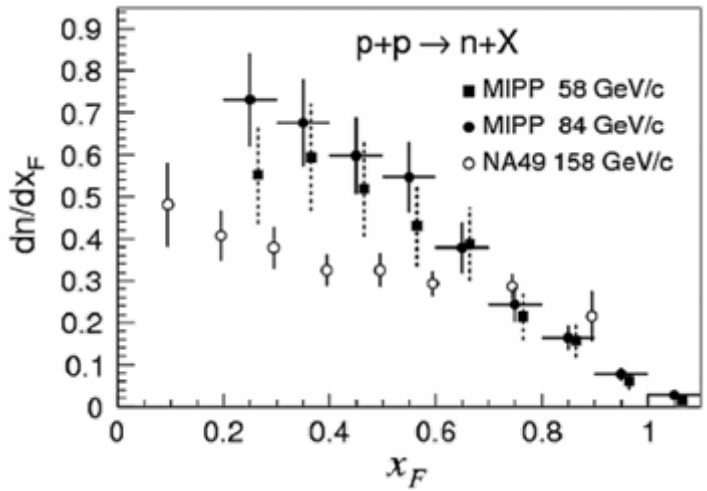
H.Meyer, Nucl.Phys.B187(2009)197

- The only experiment nearby in phase space is NA49 (thin target, 158 GeV/*c* beam)
- Reasonable agreement of MIPP with NA49 and the MINOS spectrum fit has been found for p_{sec}<40 GeV/*c*
- BMPT parametrization (400 GeV/*c* protons on Be target) fits well the data



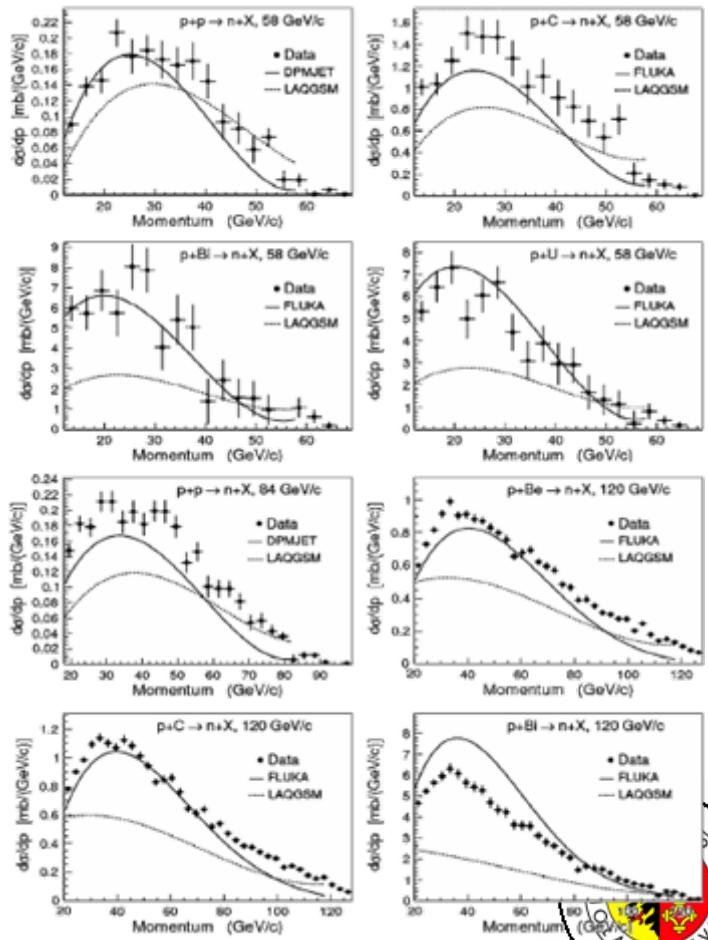


More Results from MIPP



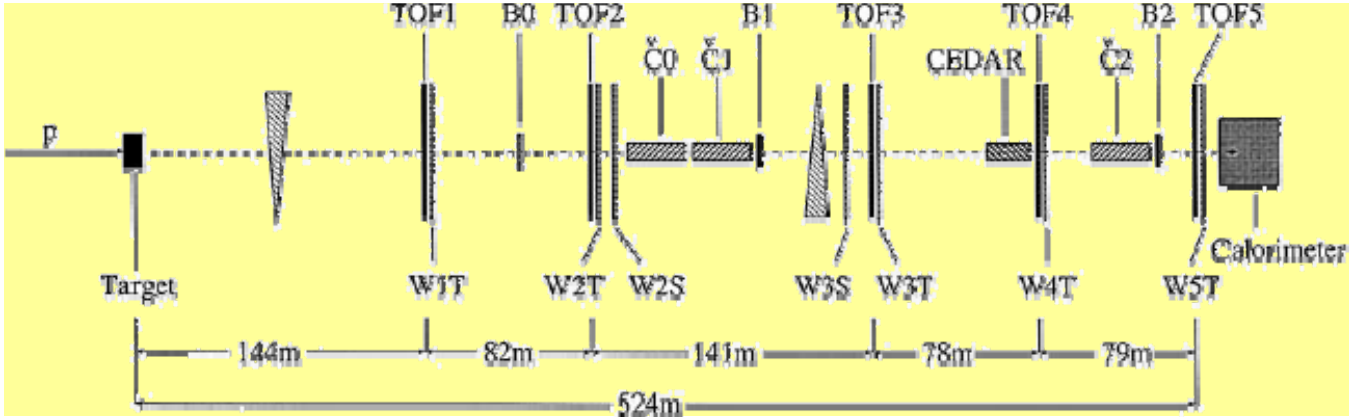
- Forward neutron production in MIPP

Phys.Rev.D83(2011)012002



- Inclusive cross-sections as a function of x_F are presented
- Proton beam momentum 58, 84, 120 GeV/*c*
- Target material: H, C, Bi, U, Be
- Reasonable agreement with FLUKA and DPMJET Monte Carlos (not corrected for acceptance at figure)
- Comparison to NA49 shows agreement at x_F>0.6 and a factor ~2 difference at low x_F

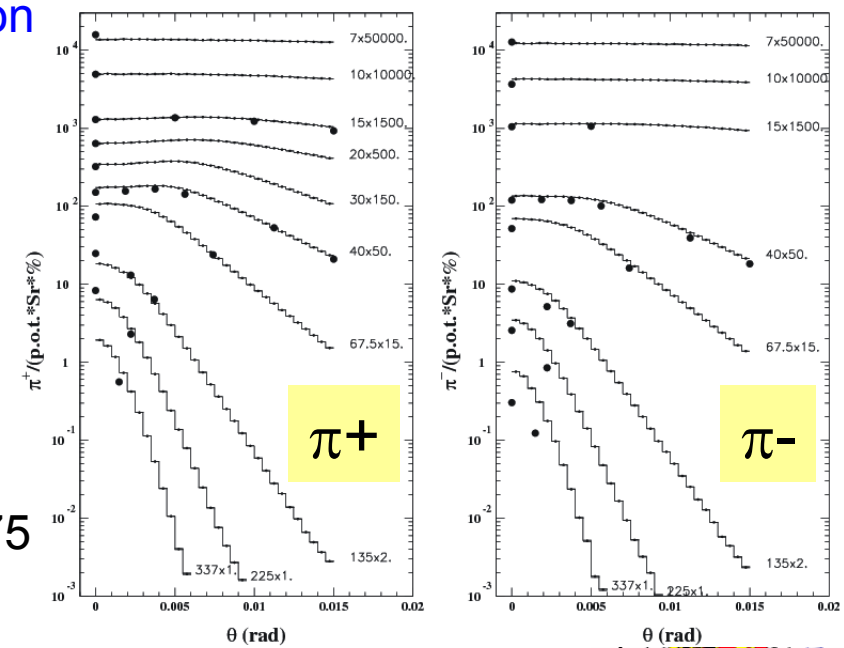
NA58 / SPY : Secondary Particle Yields



- Goal: understanding and planing of ν oscillation experiments
- 450 GeV/*c* protons interact with Be target
- production angle up to 30 mrad
- yields of $\pi^{\pm}$, $K^{\pm}$, p and p̄ have been studied
- secondary momentum range 7-135 GeV/*c* ($0.02<x_F<0.3$) and $p_T<600$ MeV/*c*
- complementary to NA20 (Atherton et al.) measurements at 400 GeV/*c* and $0.15<x_F<0.75$
- NOMAD ν flux

  -> reweighting functions FLUKA / data

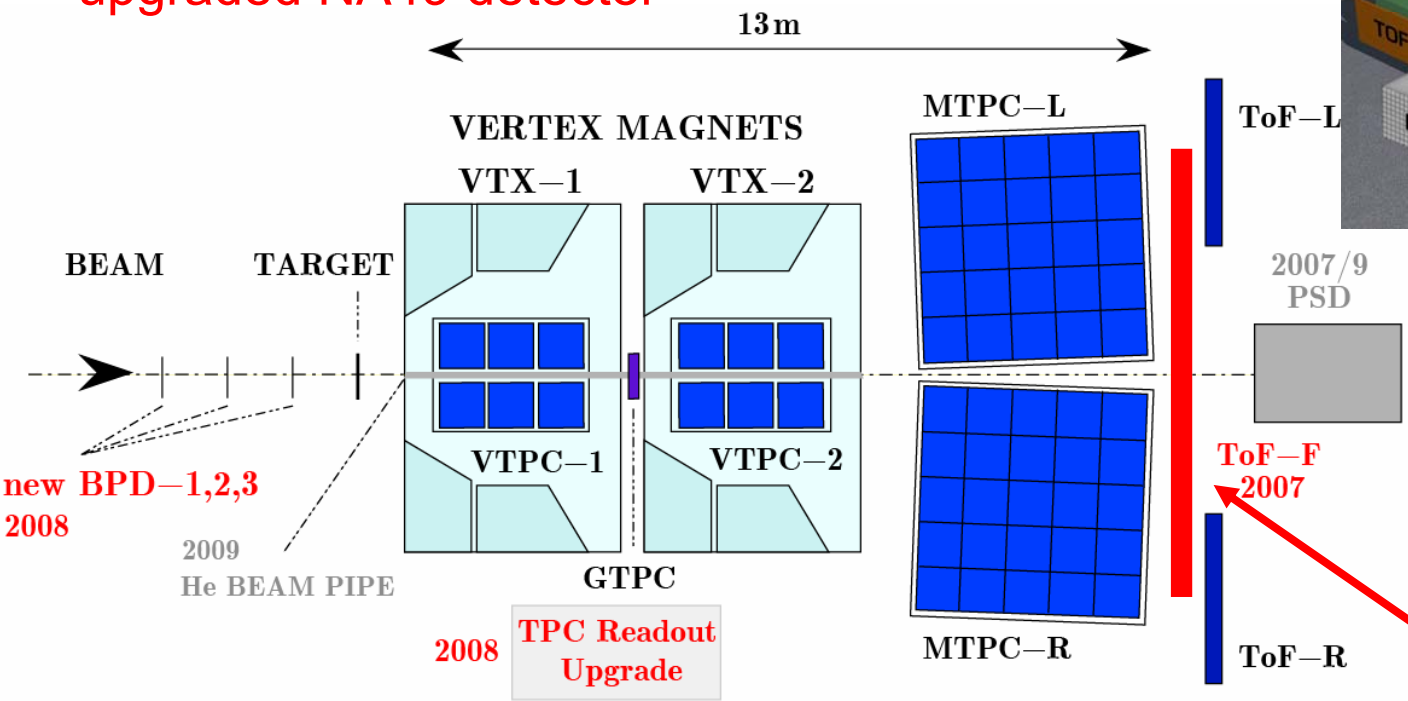
8% ν_μ and ν_e, 10% $\nu_\mu$bar and 12% for $\nu_e$bar

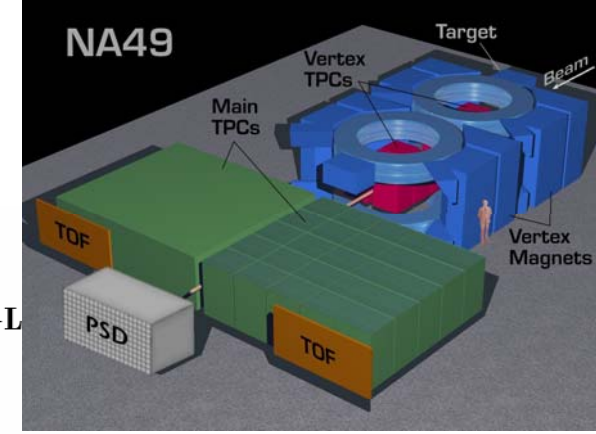


G.Ambrosini et al., Eur.Phys.J.C10(1999)605

The NA61 detector

upgraded NA49 detector



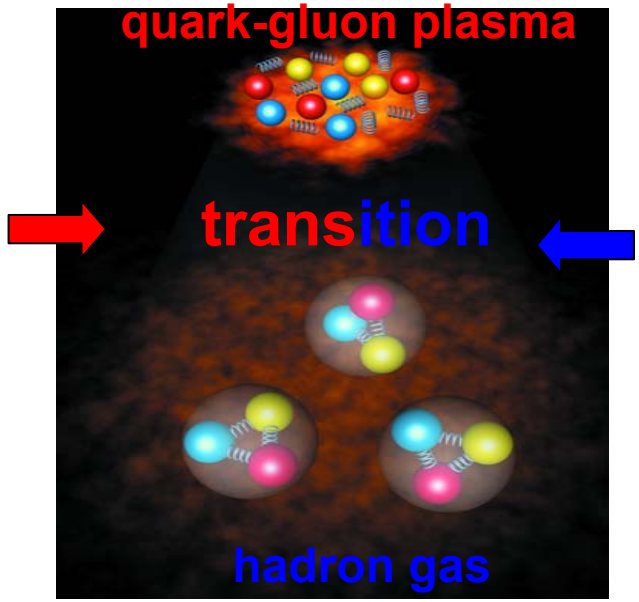


NB Forward-ToF wall used to identify low mom. particles produced at large angles and bent back into the detector acceptance by the vertex magnets

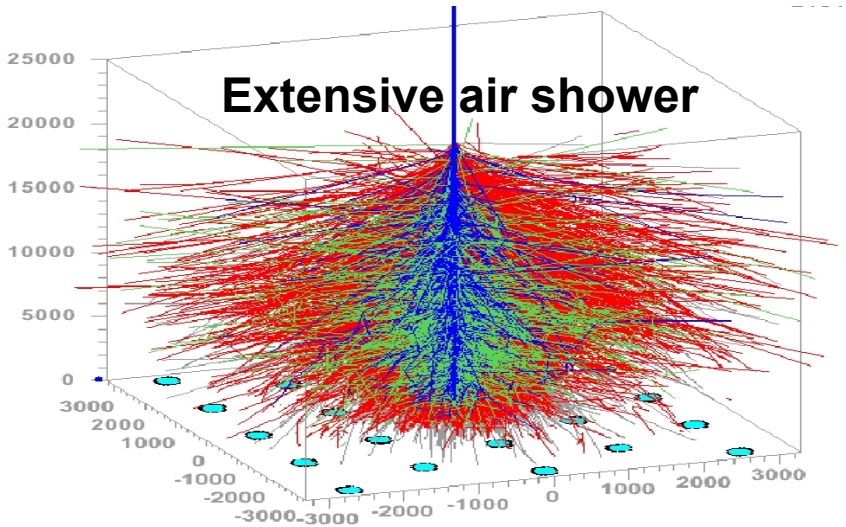
- **Large Acceptance Spectrometer for charged particles**
- **4 large volume TPCs as main tracking devices**
- **2 dipole magnets with bending power of max 9 Tm over 7 m length** (T2K runs: $\int Bdl \sim 1.14$ Tm)
- **High momentum resolution**
- **Good particle identification:** σ(ToF-L/R) ≈ 100 ps, $\sigma(dE/dx)/\langle dE/dx\rangle \approx 0.04$, $\sigma(m_{inv}) \approx 5$ MeV
- **New ToF-F to entirely cover T2K acceptance** (σ(ToF-F) ≈ 120 ps, $1<p<4$ GeV/c, $\theta < 250$ mrad)

NA61 physics program

Physics of strongly interacting matter in heavy ion collisions
Search of the QCD critical point

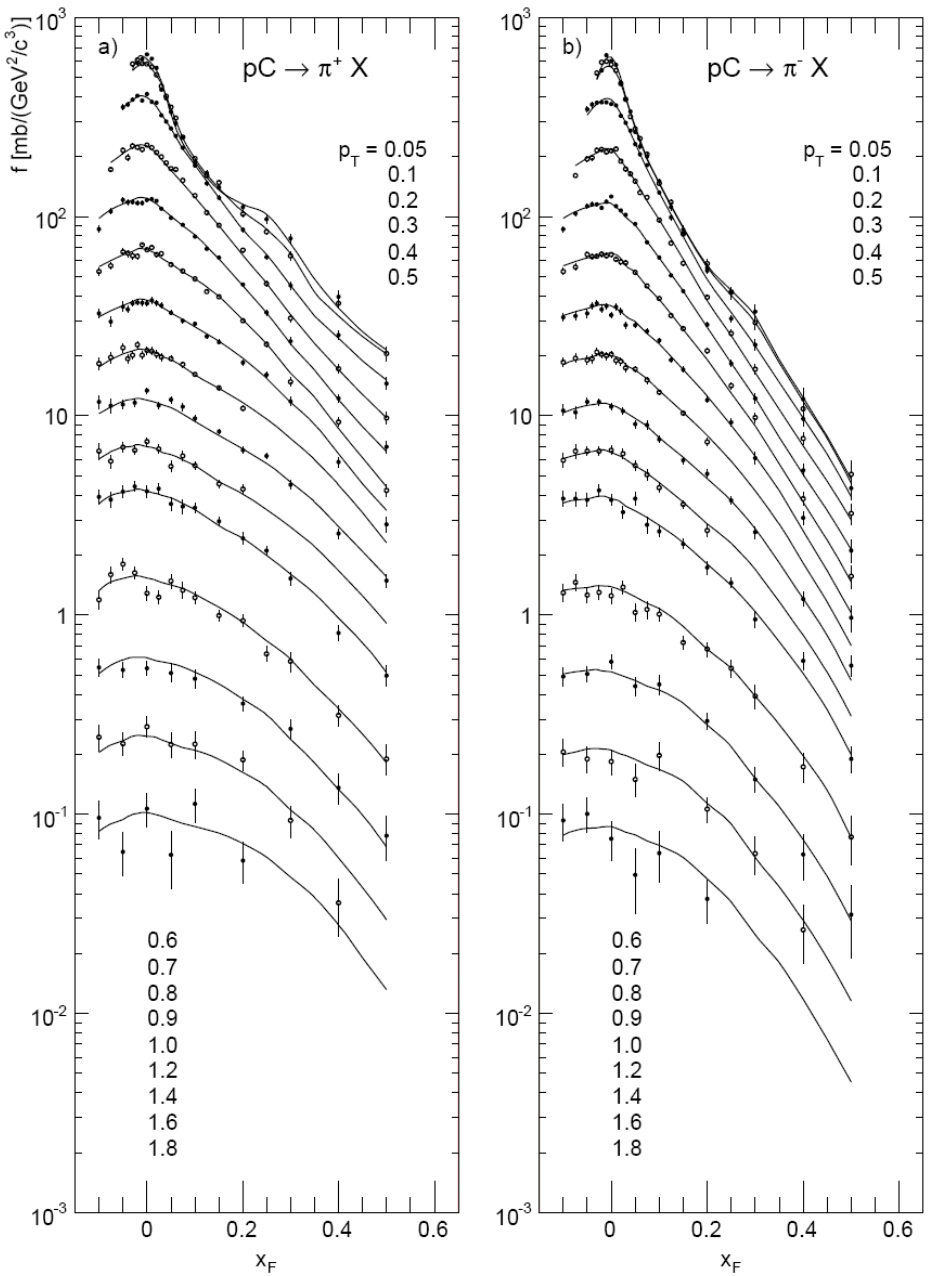


Measurement of hadron production off the T2K target (p+C) needed to characterize the T2K neutrino beam



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

NA49 charged pion spectra



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

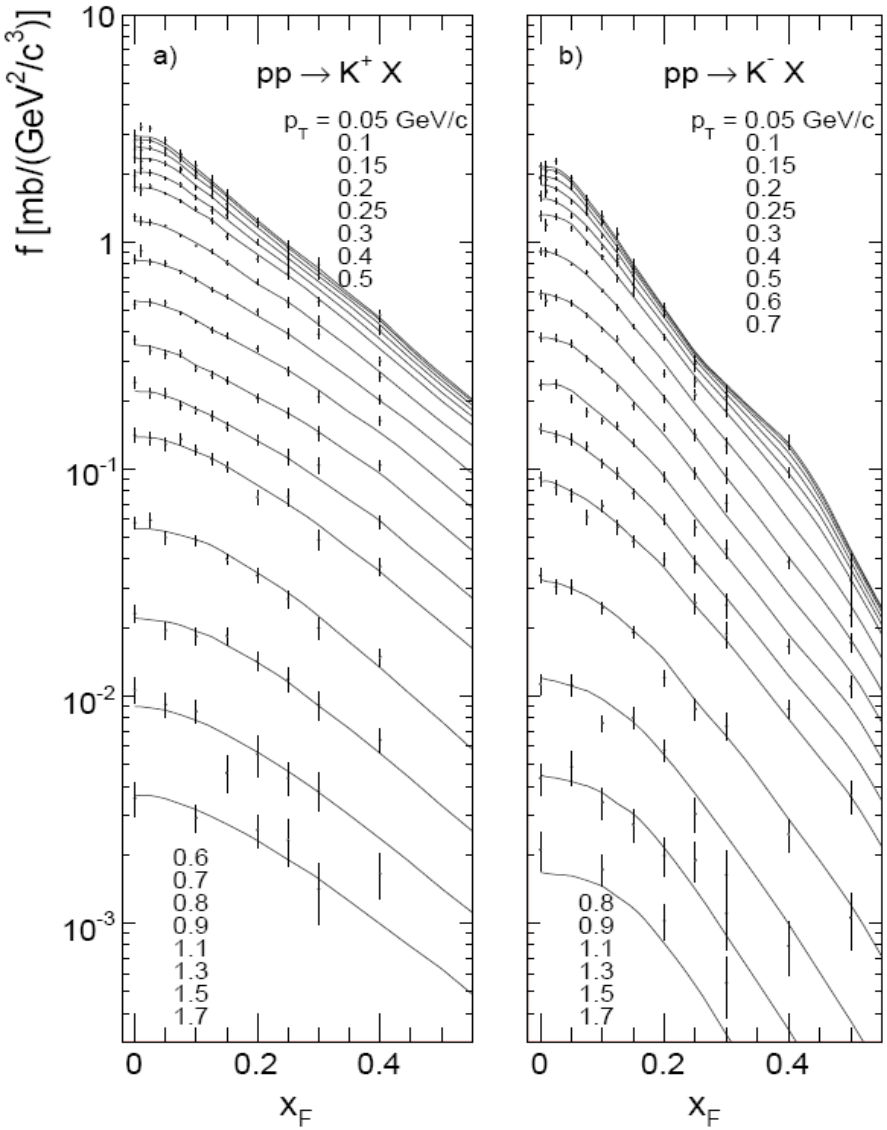
NA49 with empirical fits to the data

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%

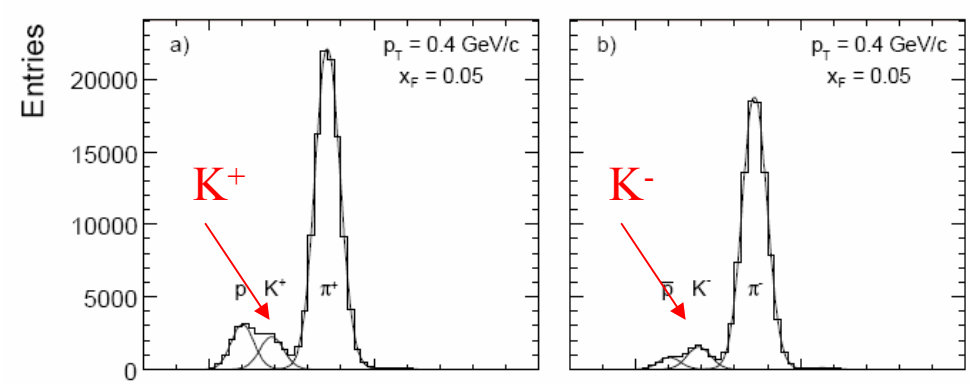
C. Al *et al.*, EPJ C49 (2007) 897

NA49 charged kaon spectra



T. Anticic *et al.*, arXiv:1004.1889

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%

The NA61 targets

2 different graphite (carbon) targets

Thin Carbon Target
- **length=2 cm, cross section 2.5x 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}**

Important to study hadro-production with replica targets since ~ 30 % of π, K from secondary interactions, which in general are very difficult to model. Both targets required to model reliably the ν flux.

2007 pilot run
- Thin target: ~ 660k triggers
- Replica target: ~ 230k triggers

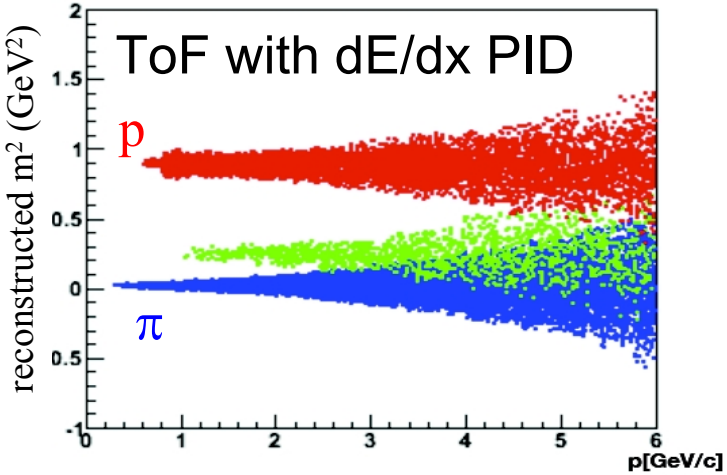
2009 run
- ~ 6 M triggers
- ~ 2 M triggers

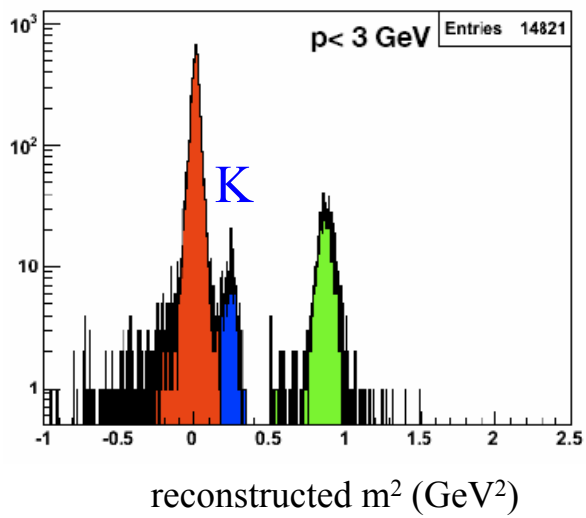
$\Rightarrow$ 200 k π^+ tracks in T2K *phase space*

2010 run
- Replica target: ~ 10 M triggers

Particle identification

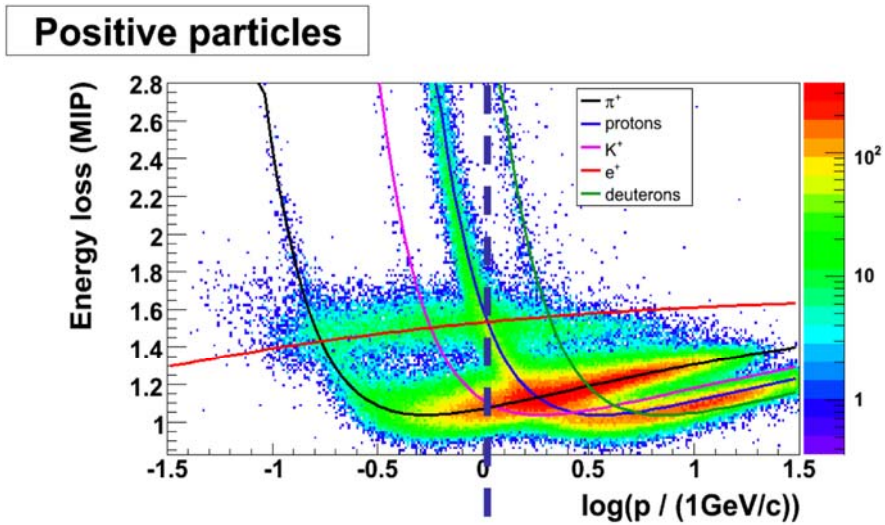
Time of Flight measurements

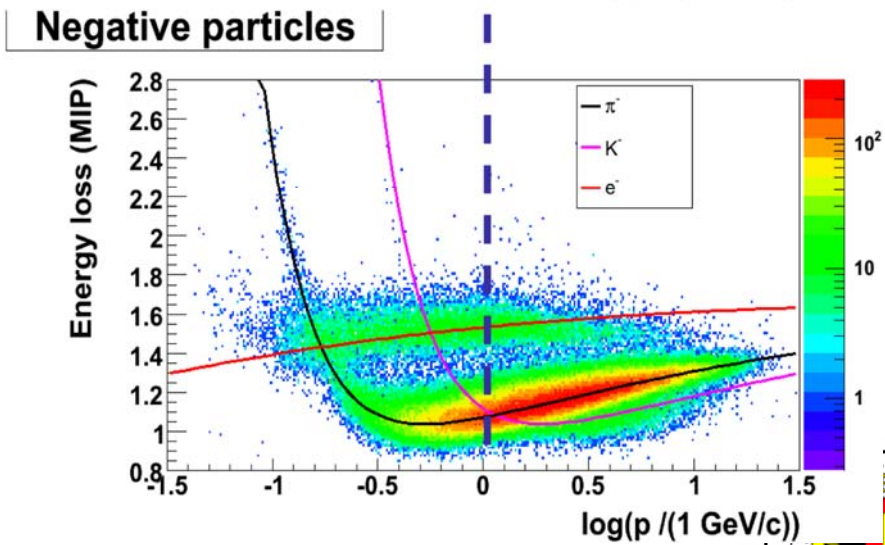




5 σ π/K separation up to 4 GeV/c

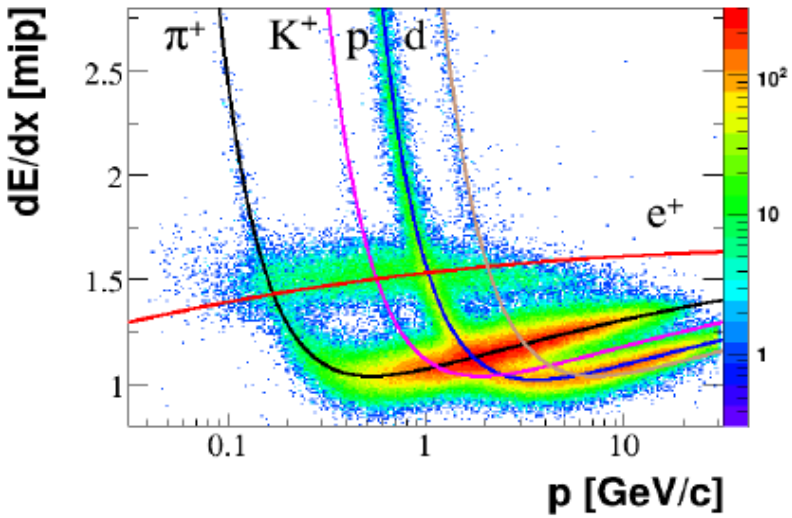
Energy loss in TPCs
Bethe-Bloch curves (dE/dx) for different particles

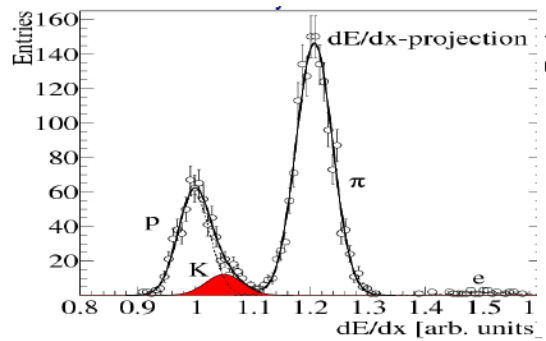


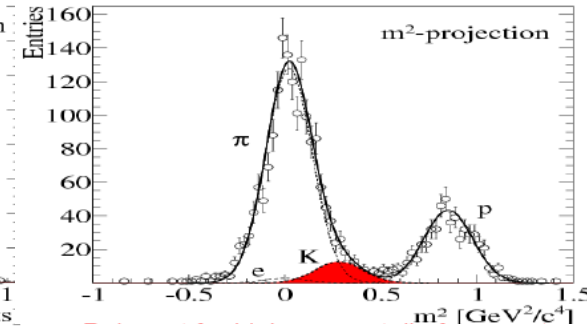


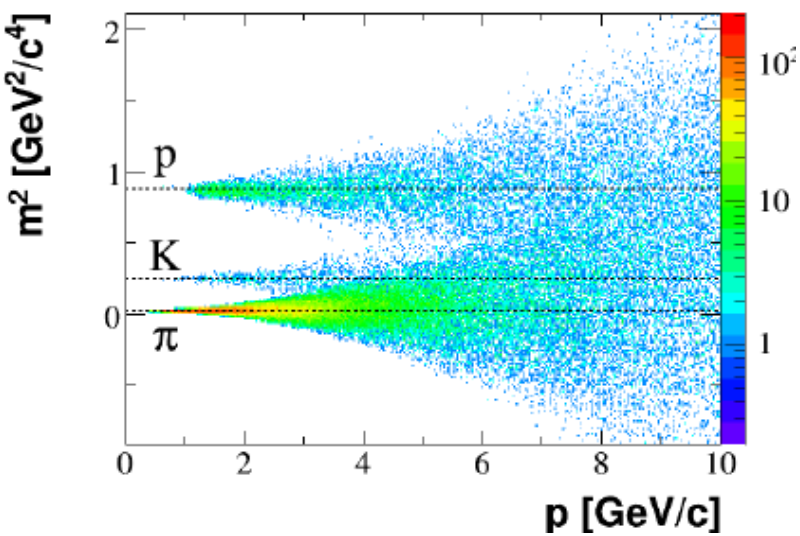
σ(dE/dx)/<dE/dx> < 5 %

Particle Identification (2)

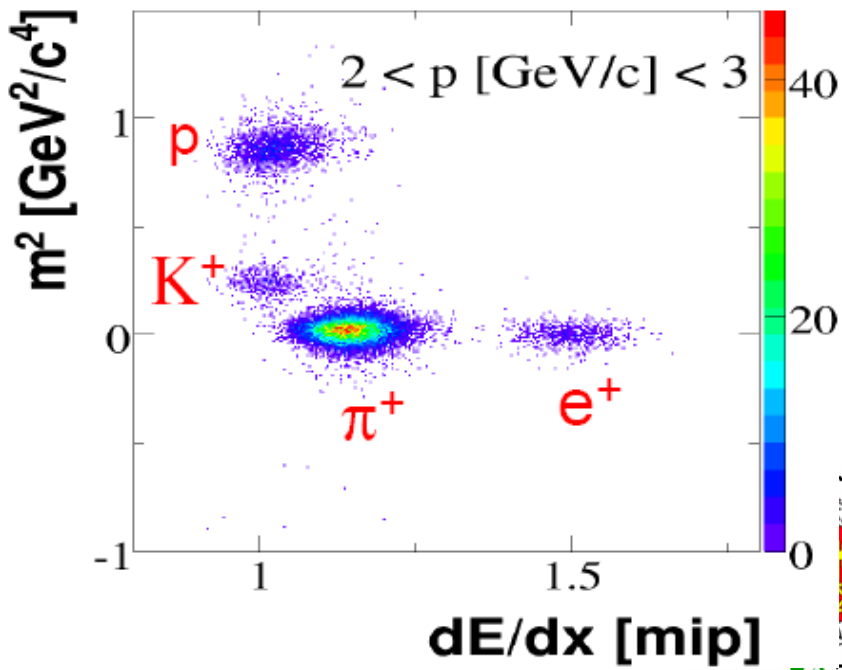




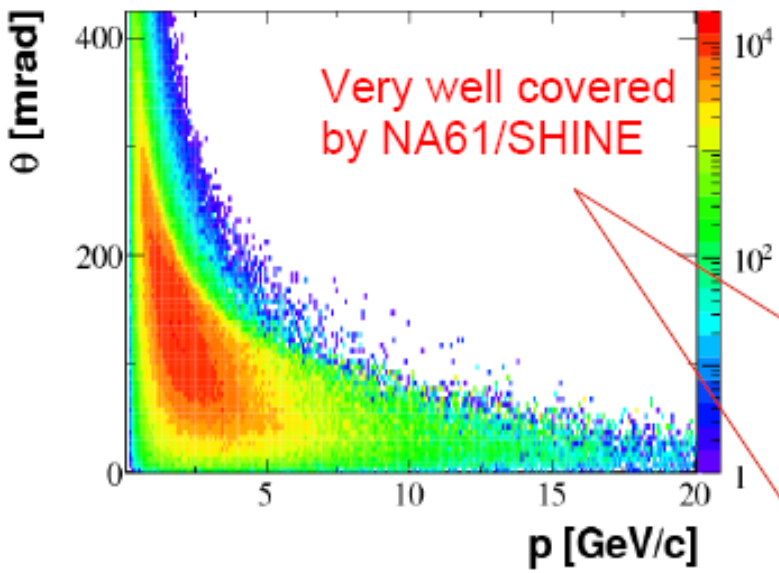




combined ToF + dE/dx
(positively charged particles)

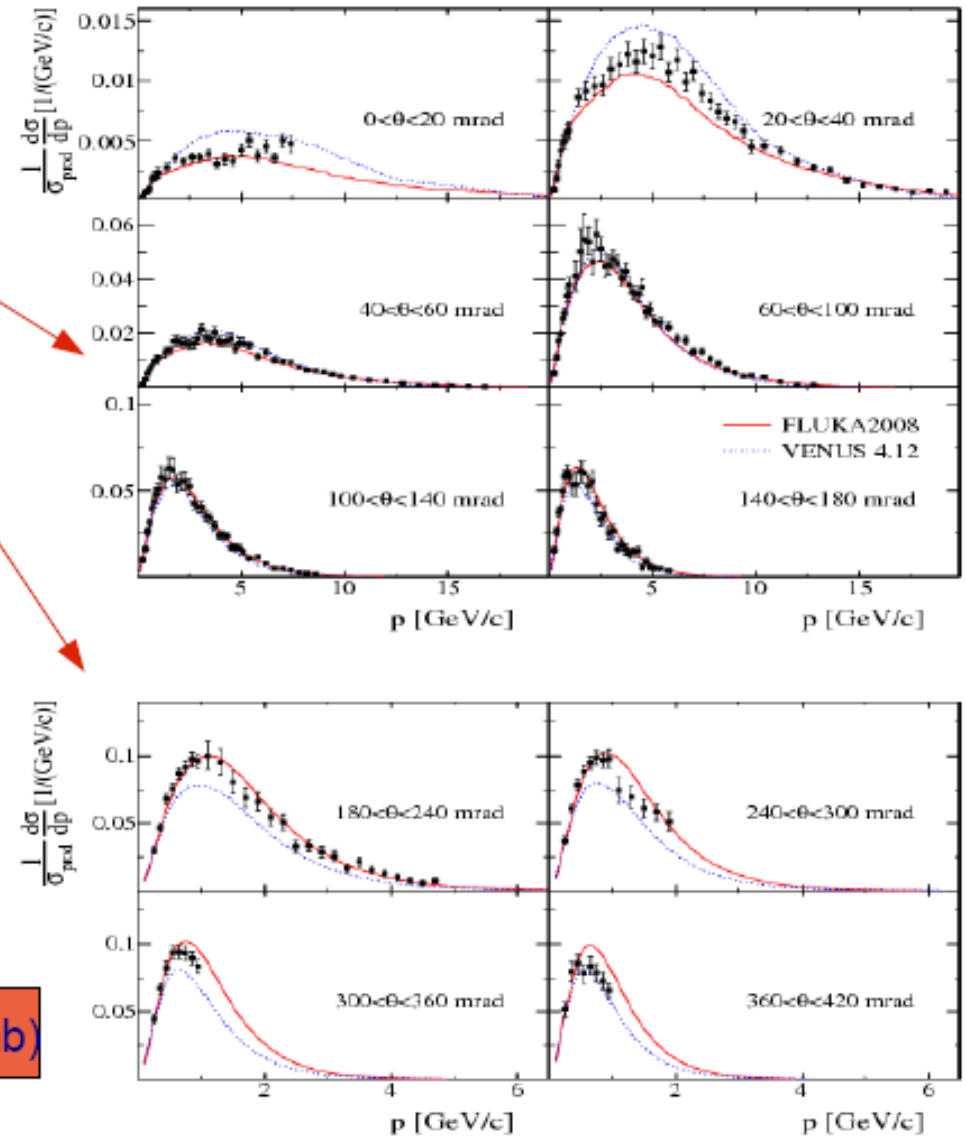


NA61 p + C -> π^+ + X @ 30 GeV



T2K beam simulation: the {p,θ} distribution for π^+ weighted by the probability that their decay produces a ν_μ passing through SK

Published in PRC 84 (2011) 034604



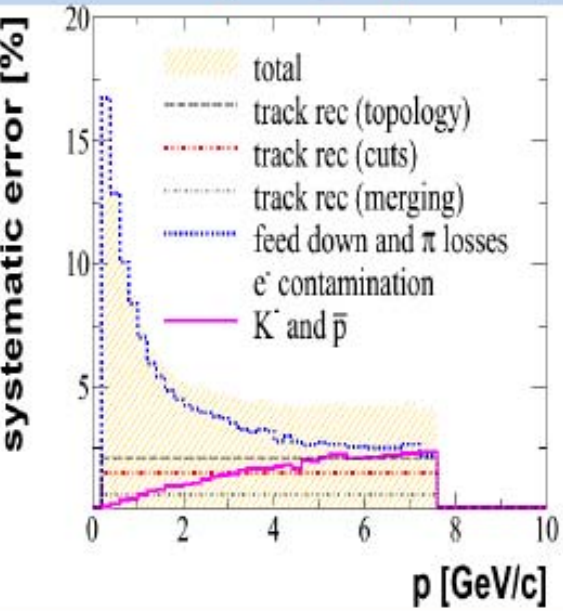
NA61/SHINE measurements

σ_{prod} (pC@31GeV/c)= 229.3 ± 1.9 ± 9.0 (mb)

Systematical Errors

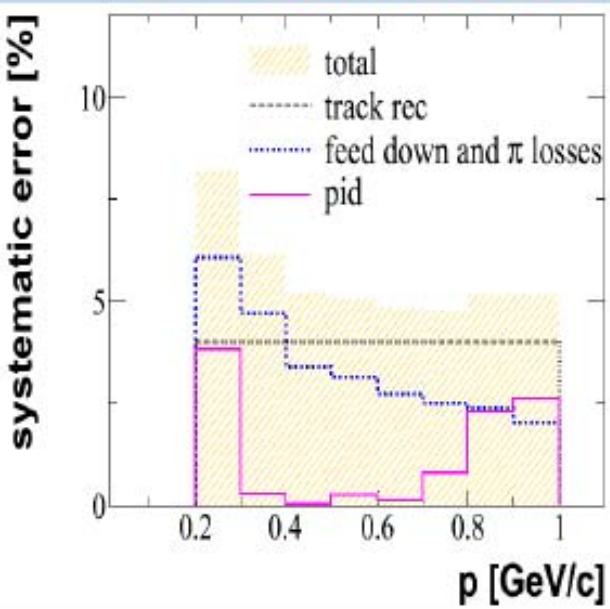
h- analysis

π^- θ=[140,180] mrad



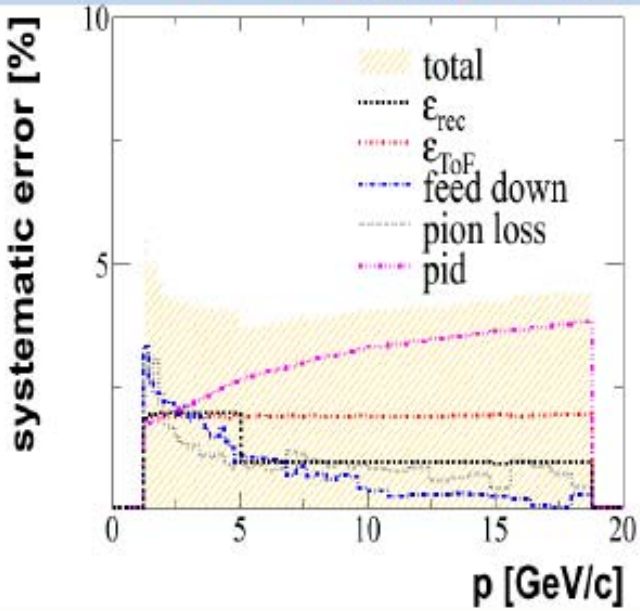
dE/dx analysis

π^+ θ=[140,180] mrad



dE/dx+ToF analysis

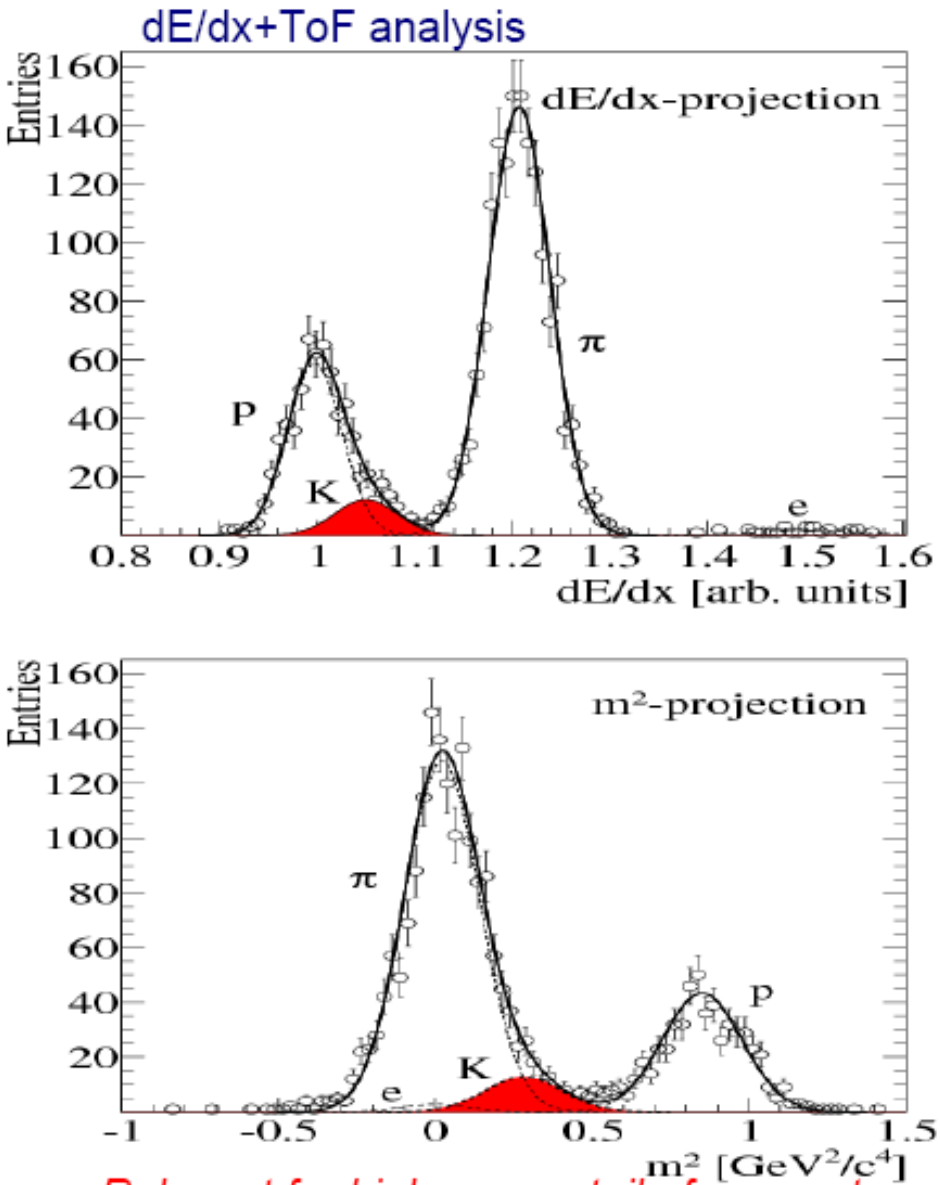
π^+ θ=[40,60] mrad

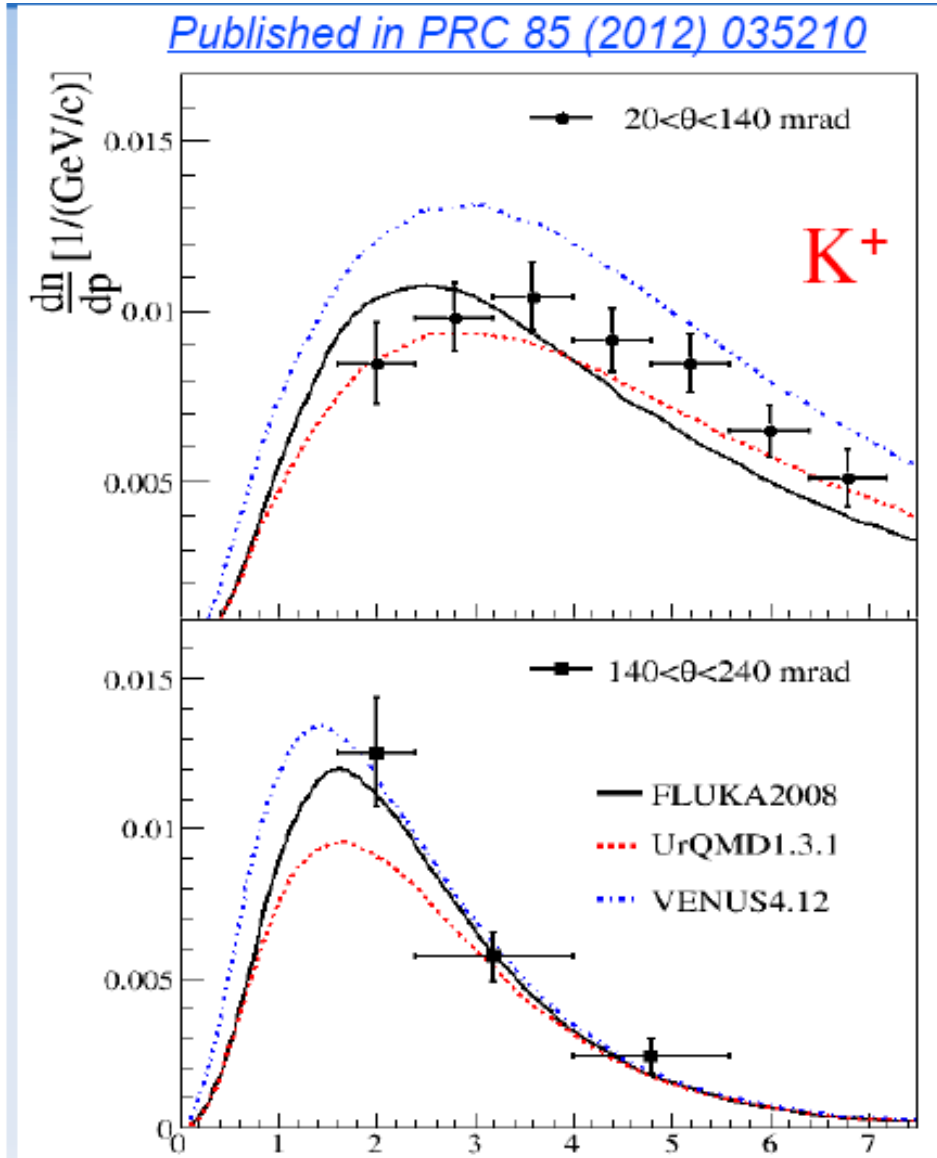


Typical value 6%
Hope to reduce down to 3-4%

Systematic error due to uncertainty of the feeddown correction is larger for π^- than for π^+ due to contribution from Λ hyperon decays.
NA61/SHINE measurements of neutral strange particle production will allow to reduce this systematic error.

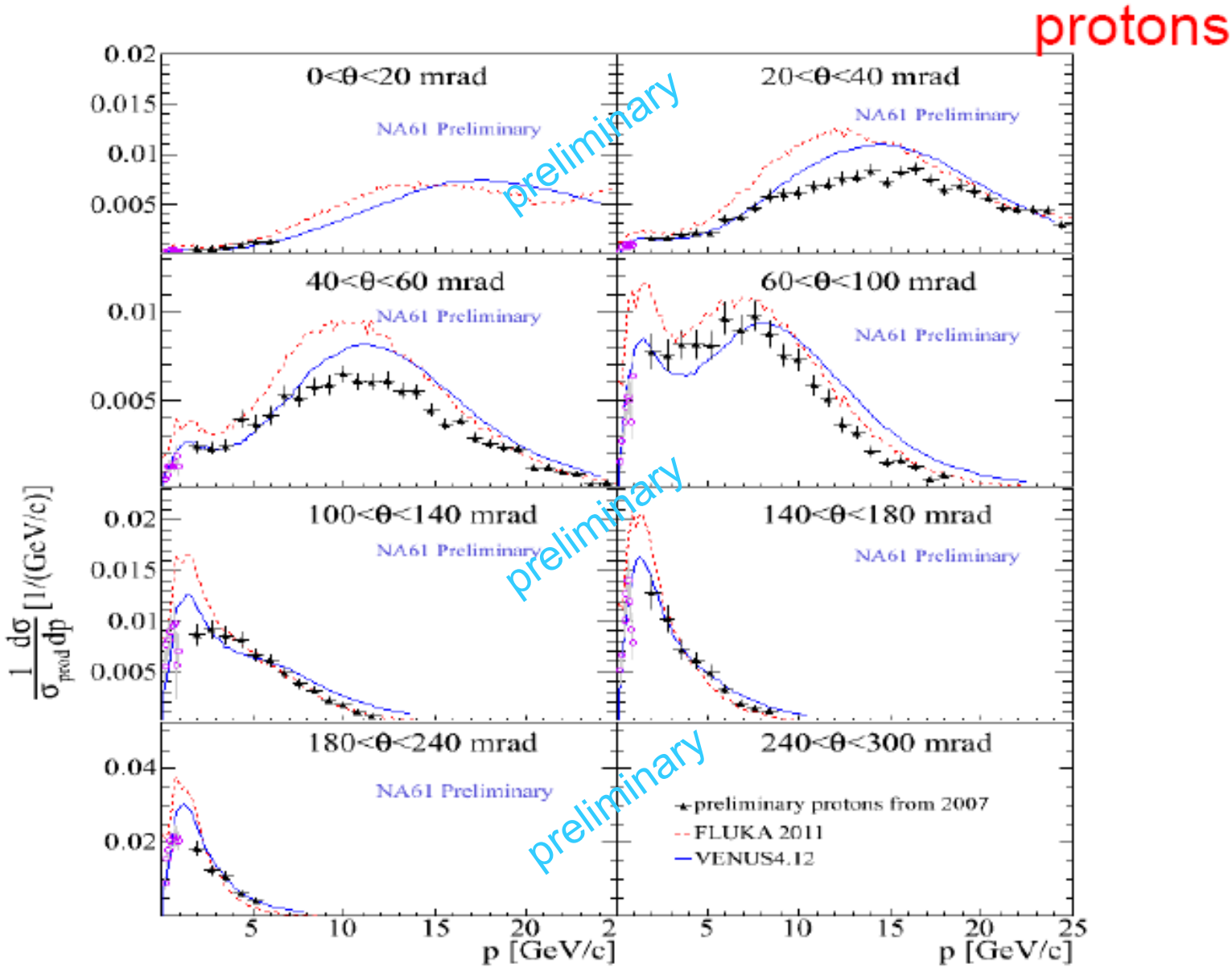
NA61 p + C -> K^+ + X @ 30 GeV





Relevant for high energy tail of ν_μ spectrum and intrinsic ν_e component in T2K

NA61 p + C -> p + X @ 30 GeV



NA61 Impact on T2K

In MC of T2K the pion production yield at the primary interaction vertex (from FLUKA) was reweighed using NA61 data

$$N_{SK}^{exp} = R_{ND}^{\square,data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\square,MC}}$$

Summary of ν flux uncertainty on N_{SK}^{exp} ($\sin^2 2\theta_{13}=0$ assumed)

Error source	$N_{SK}^{MC}/R_{ND}^{\mu,MC}$
Pion production	2.5%
Kaon production	7.6%
Nucleon production	1.4%
Production x-section	0.7%
Proton beam geom.	2.2%
Beam direction measur.	0.7%
Target alignment	0.2%
Horn alignment	0.7%
Horn abs. current	0.2%
Total	8.5%

Contribution of pions is 2.5% when one uses the NA61 data

Phys.Rev. C84 (2011) 034604

The dominant error (7.6%) is due to the uncertainty on the K^+ flux

Total relative uncertainty

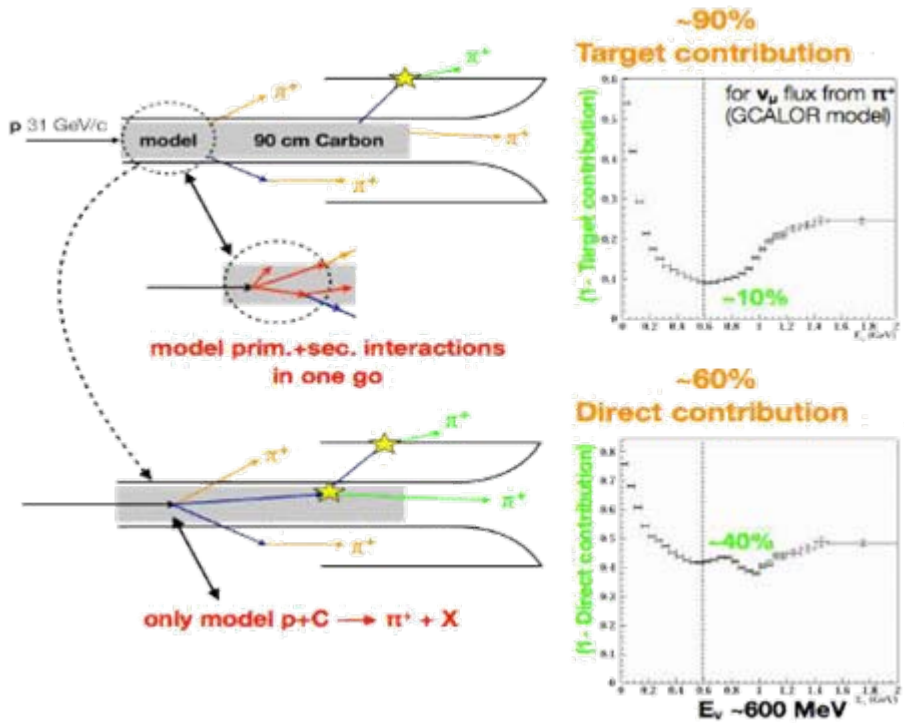
source	error
Neutrino flux	8.5%
Near detector	+5.6/-5.2 %
Near detector stat.	2.7%
Cross-section	10.5%
Far detector	9.4%
Total	+17.6/-17.5%

Contribution from the beam flux to the systematic error is significant (8.5 vs. 17.6 %)

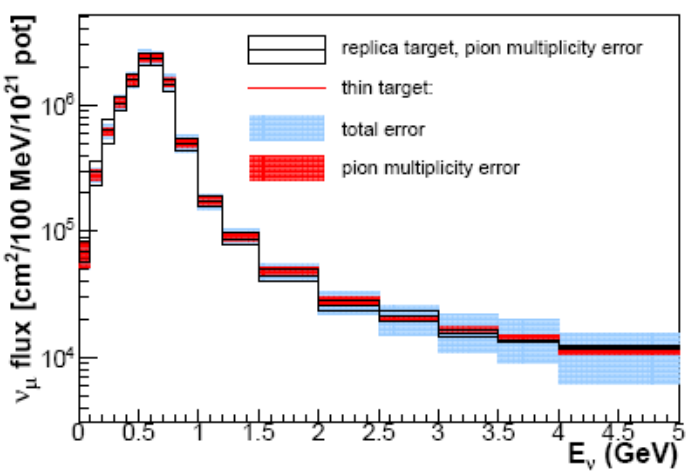
(T2K) Phys.Rev.Lett.107(2011)041801

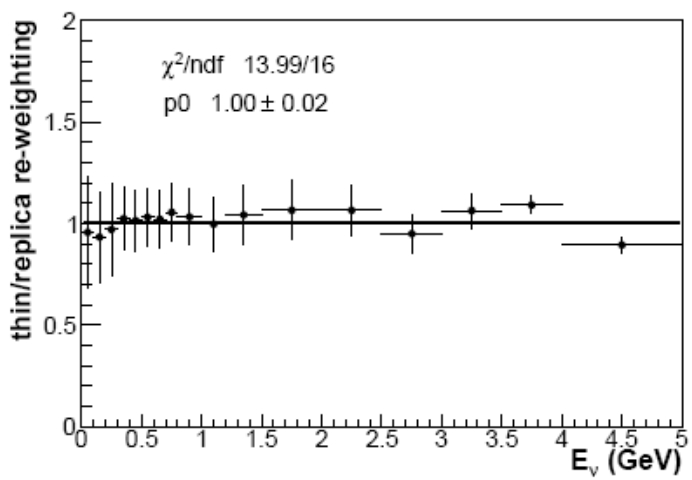
NB 2011 result !

ν Flux Prediction with T2K Replica Target



- Hadron multiplicities are parametrized at the target surface (no vertex reconstruction)
- Analysis in bins of (p, θ, z)
- Re-weighting multiplicities of hadrons exiting the target in the T2K beam simulation
- Model dependence is reduced down to 10% as compared to 40% in the standard approach





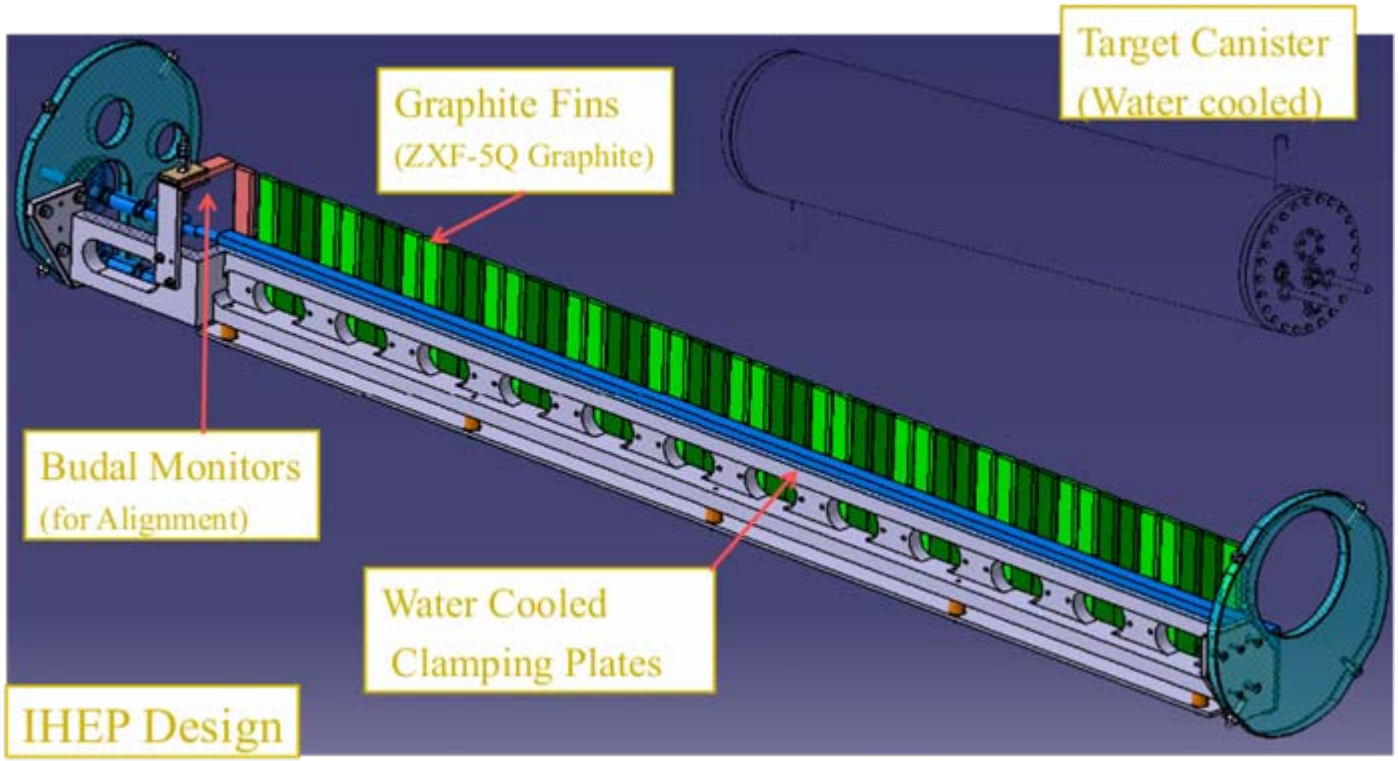
comparison ν flux predictions
thin target
replica target

in very good agreement
just an accident or real ?

Neutrino Beams at FNAL (NuMI)

- NuMI (Neutrinos at the Main Injector)
  - 120 GeV protons from MI
  - 90 cm graphite target
  - 675 m decay tunnel
- BNB (Booster Neutrino Beam)
  - 8 GeV protons from Booster
  - 71 cm beryllium target
  - 50 m decay tunnel
- NuMI / NA61 collaboration being formed
- Primary goal is measurement of hadron multiplicities with a NuMI replica target

NuMI Target



Target	120 GeV/c p	90 GeV/c p	60 GeV/c p	π at ~10-60 GeV/c	8.9 GeV/c
Thin graphite	2012	2014-5?	2014-5?	2014-5?	2014-??
NuMI replica target	2014-5?				
Thin aluminum	2014-5?	2014-5?	2014-??	2014-??	
MiniBooNE target					2014-??

Summary

Hadron Production measurements require

1. large acceptance detectors
   kinematical coverage ≥ ν beam "phase space"
   ~ uniform acceptance

2. particle identification over whole kinematical range

3. large statistics

4. thin targets (cross sections) and replica targets (secondary interactions)

. . .

Precisions achieved on cross section measurements < 5%

Critical survey of all existing cross section measurements !
(not only ν dedicated measurements)

MC generators: still a long way to go … (after tuning can reproduce existing data)