Hadron Production Experiments and Neutrino Beams

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LIONeutrino2012

Oct 22nd '12

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 focusing and decay channel)

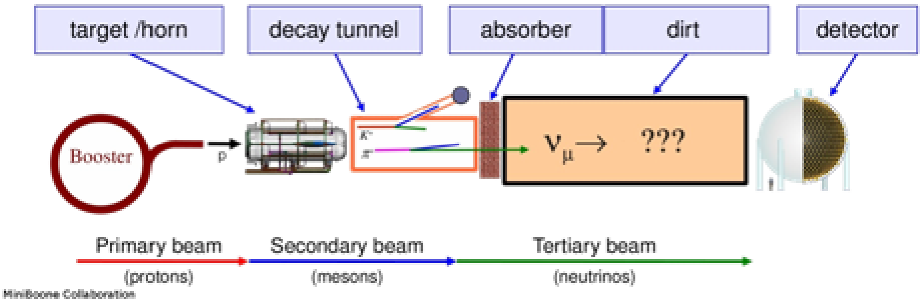
ν flux at far detector predicted on the base of ν flux measured in near detector

neutrino cross sections ® absolute neutrino flux
neutrino interaction physics

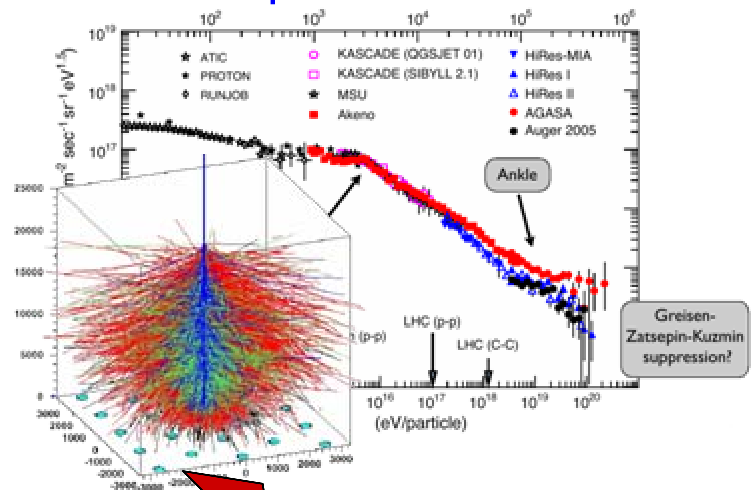
neutrino oscillations ® compare measured neutrino spectrum “far” from the source with the predicted one (flux shape and Far / Near flux ratio)

deviations from expectations $\Rightarrow$ evidence for neutrino oscillations

conventional accelerator based ν beam



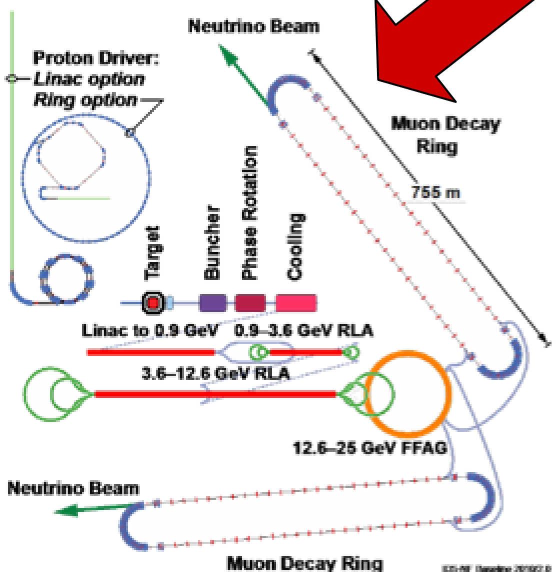
atmospheric showers



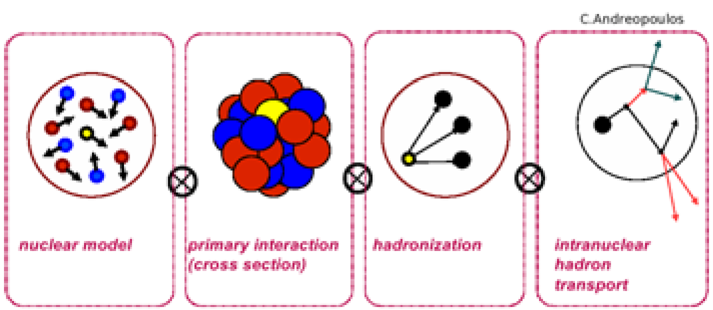
Hadroproduction measurements

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

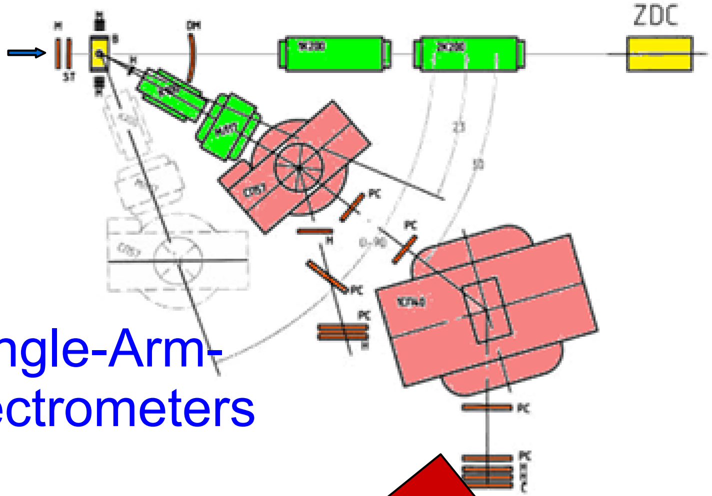
neutrino factory



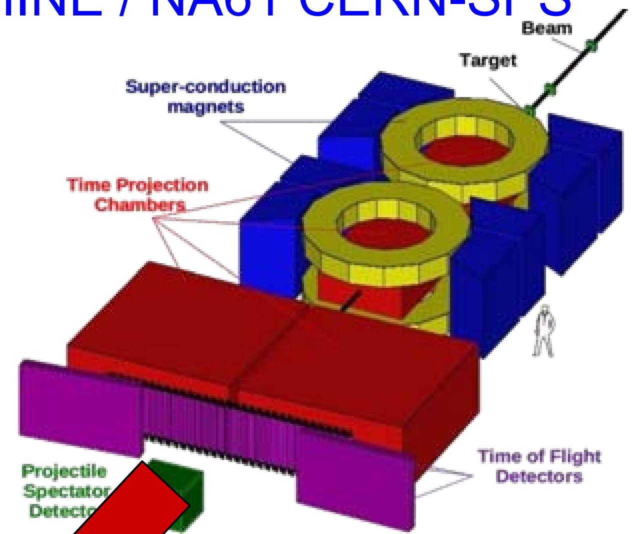
MC generators



Single-Arm-Spectrometers



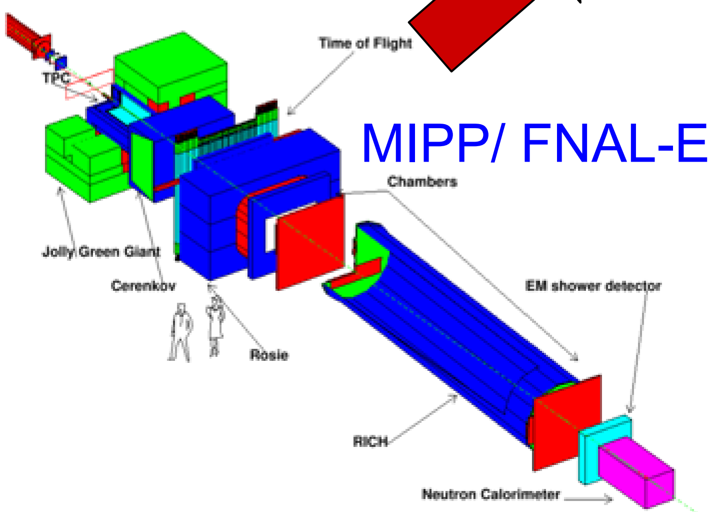
SHINE / NA61 CERN-SPS



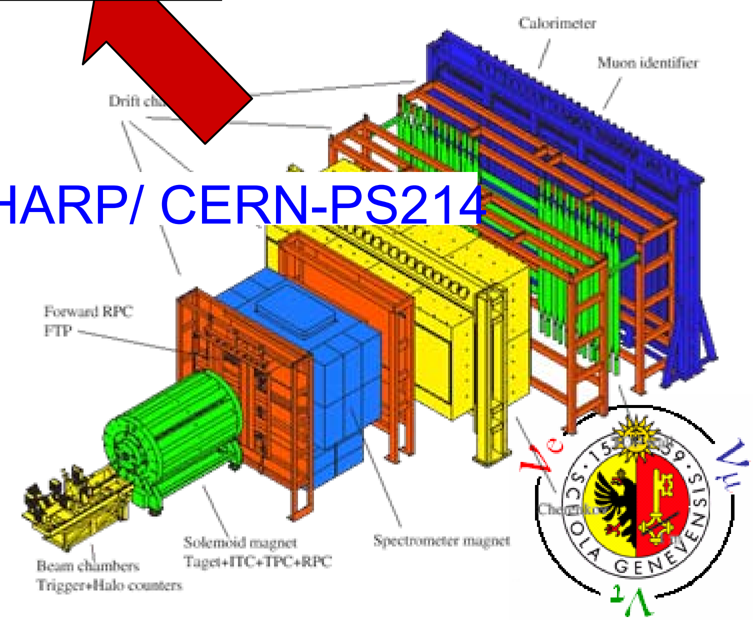
Hadroproduction measurements

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

MIPP/ FNAL-E907



HARP/ CERN-PS214

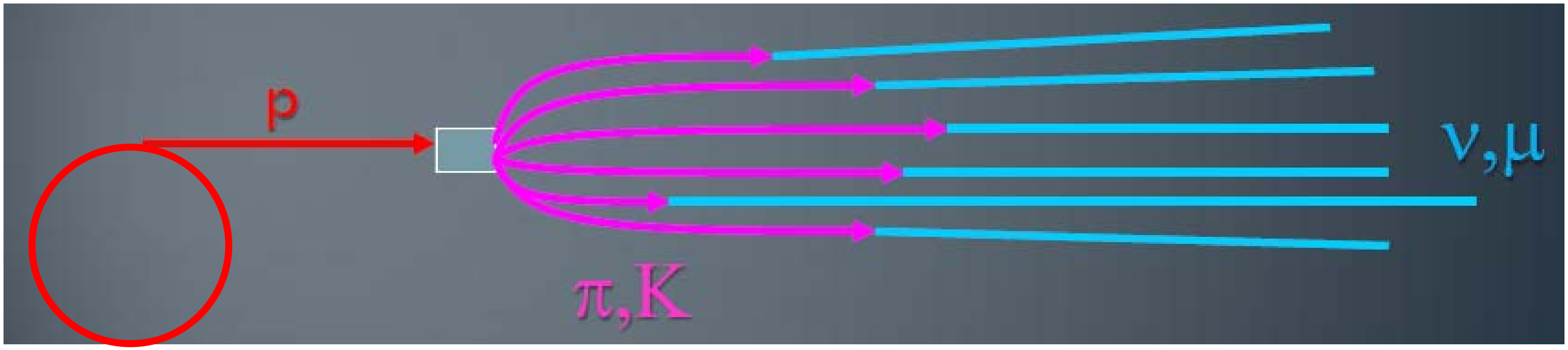


Conventional ν Accelerator Beams

high intensity proton beam from accelerator strike primary production target

protons produce pions and kaons + …

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

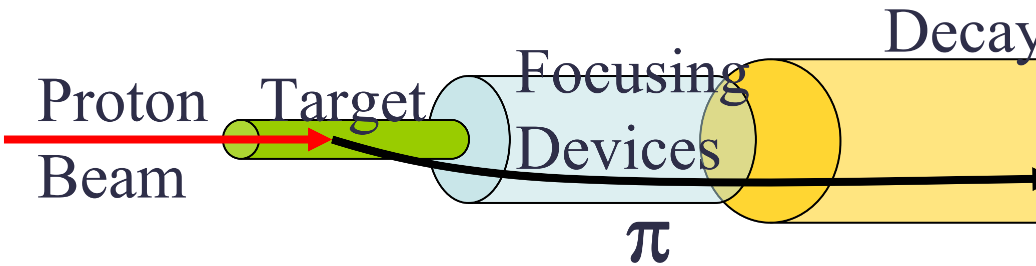


"shieldings" stops all particles but neutrinos

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

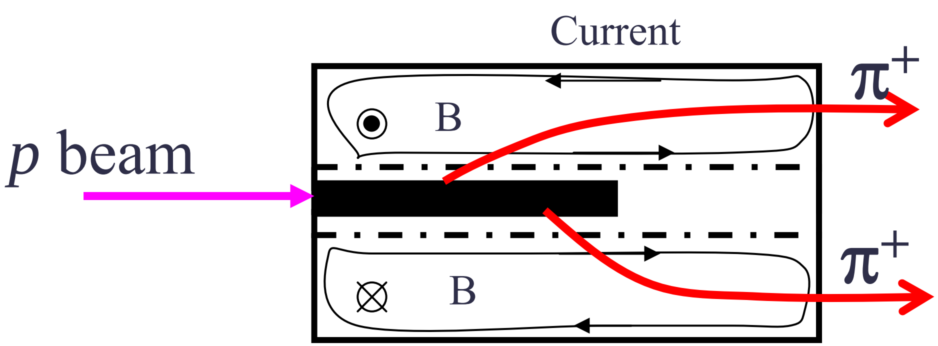
want to maximize π, K $\rightarrow \mu + \nu_\mu$ decays for highest ν_μ fluxes

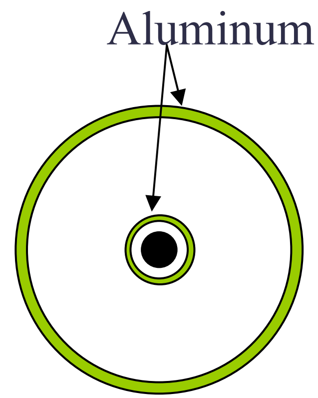
How To Make ν_μ Beams




Simon van der Meer
(1925~2011)

Focusing device: **Electromagnetic Horn**





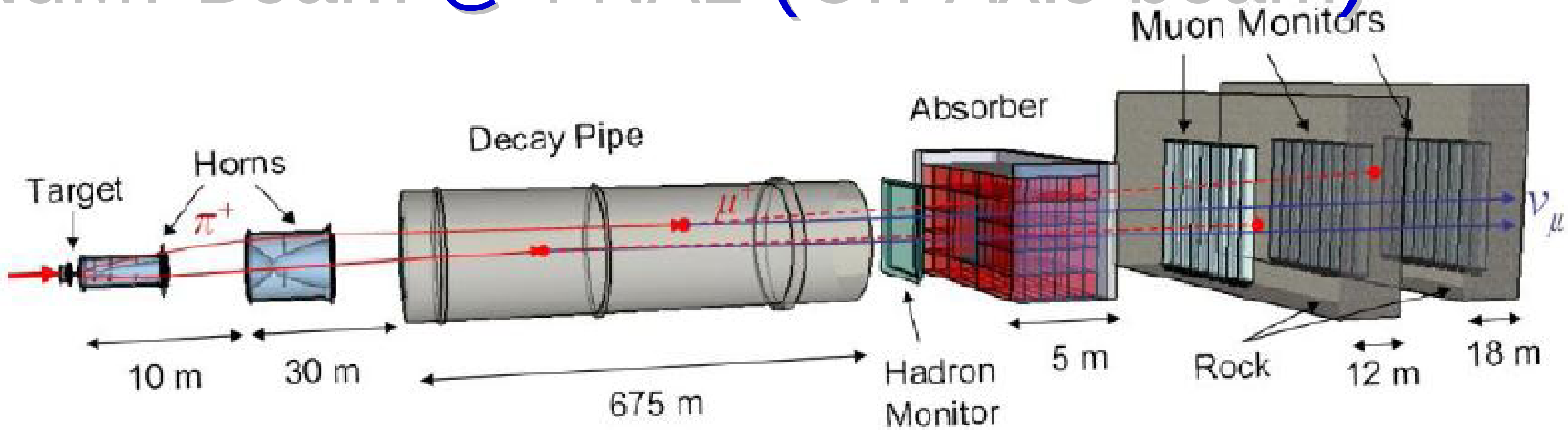
$B = 4.3\,T\ ,\ r = 15\ mm,\ I = 320 kA$

pure ν_μ beam (≳99%)

ν_e (≲1%) from $\pi \to \mu \to e$ chain and K decays (K_{e3})

$\nu_\mu / \overline{\nu_\mu}$ can be switched by flipping polarity of horns

NuMI Beam @ FNAL (On-Axis beam)

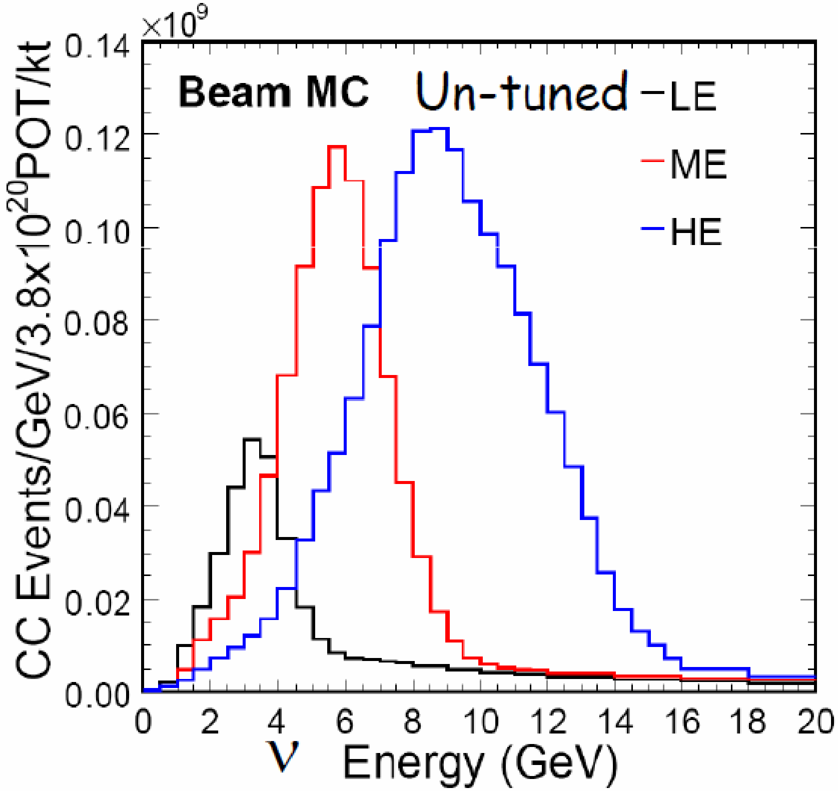


on - axis beam :
ν detected in same direction as p beam

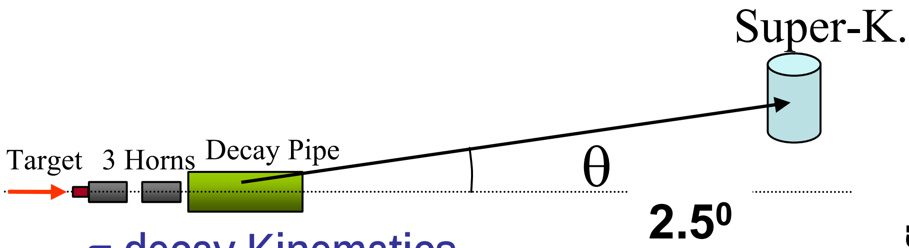
120 GeV protons (graphite target)

operating since 2005
1.5 x 10^{21} POT, beam power 300 kW

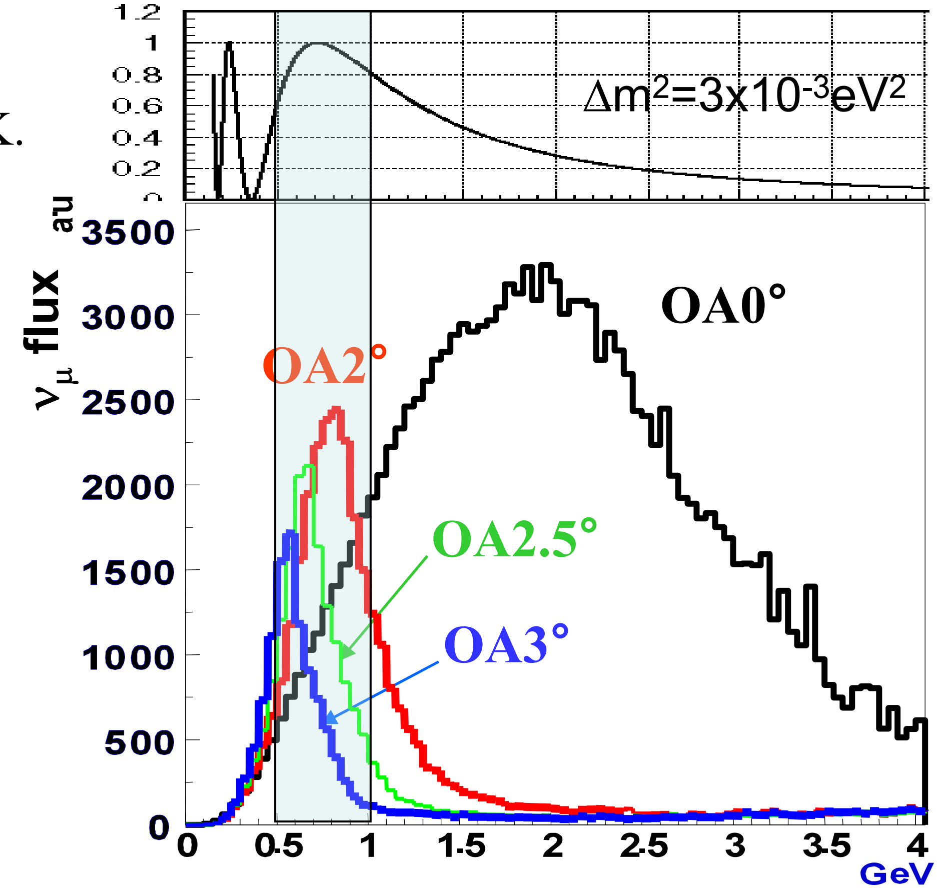
wide ν energy spectrum,
ν peak energies between 3.5 and 10 GeV
(target position w.r.t first horn)



T2K Off-Axis ν Beam



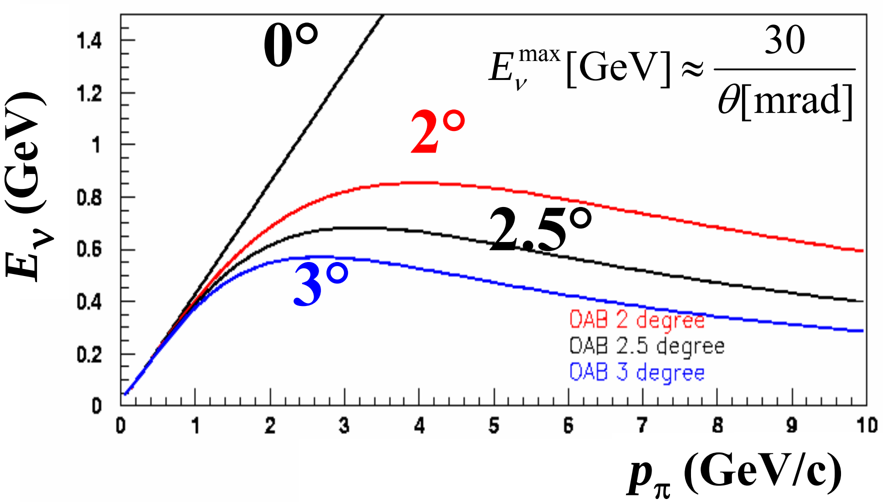
π decay Kinematics



very narrow energy spectrum

neutrino beam energy “tuned” to oscillation maximum

minimizes background y reducing high energy tail

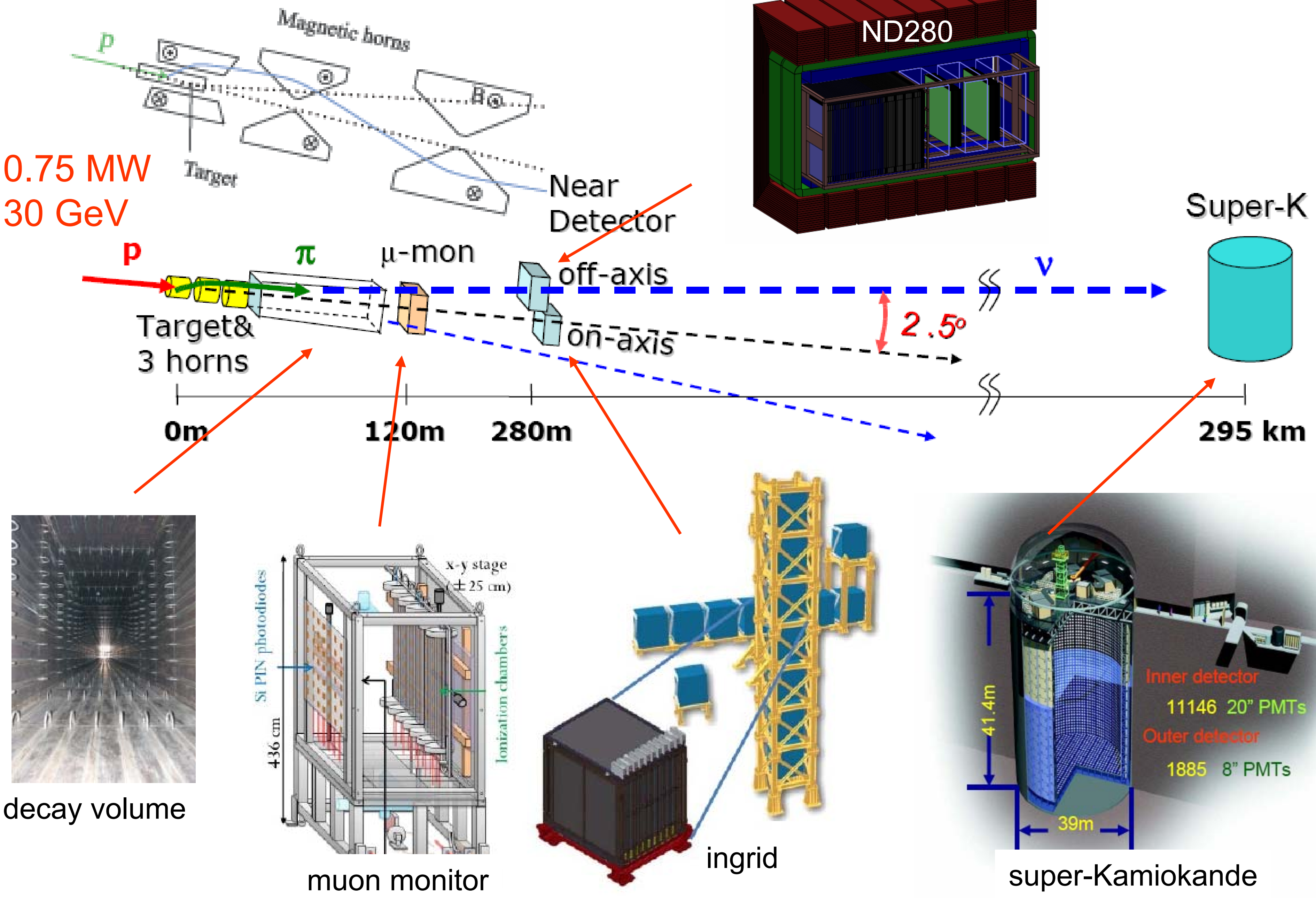


neutrino energy E_ν almost independent of parent pion energy

horn focusing cancels partially the p_T dependence of the parent pion

NOvA will also use an off axis beam

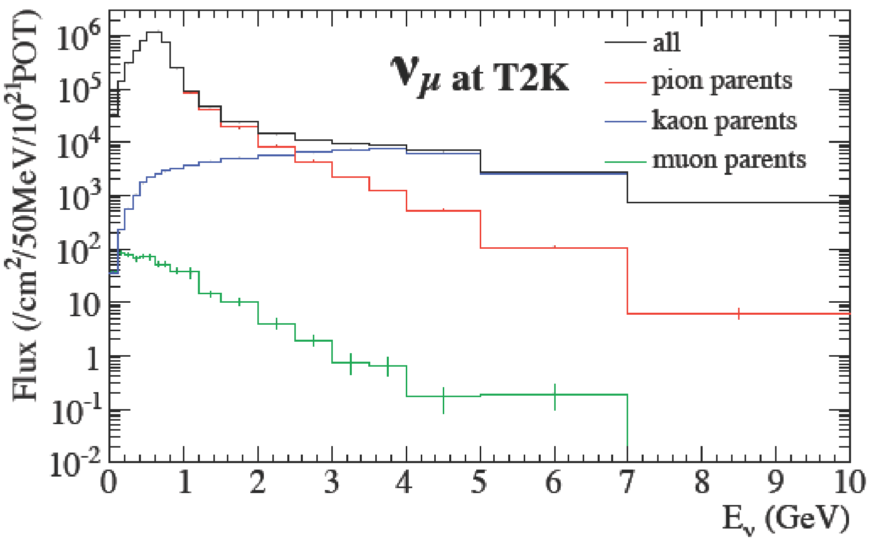
Overview of T2K Beam

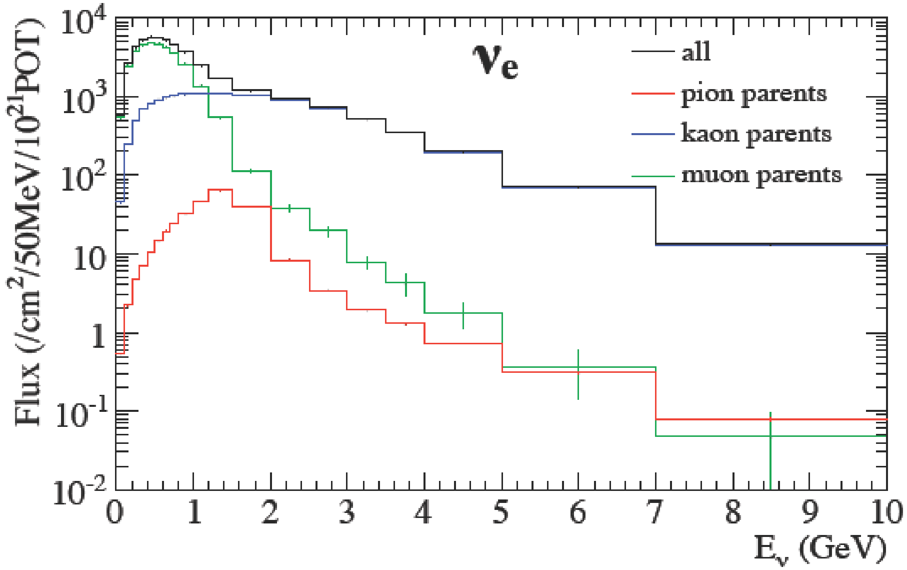


Which Hadron Cross-Sections Measurements

what is the composition of the ν_μ and ν_e flux
in terms of the hadrons exiting the target ?

T2K, S. Murphy, NuFACT12



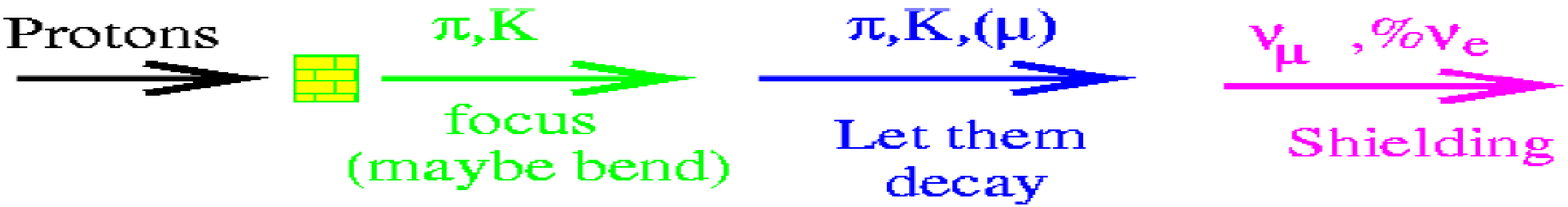


ν_μ predominantly from π^+ decay at peak energy,
higher energy tail from kaon decays

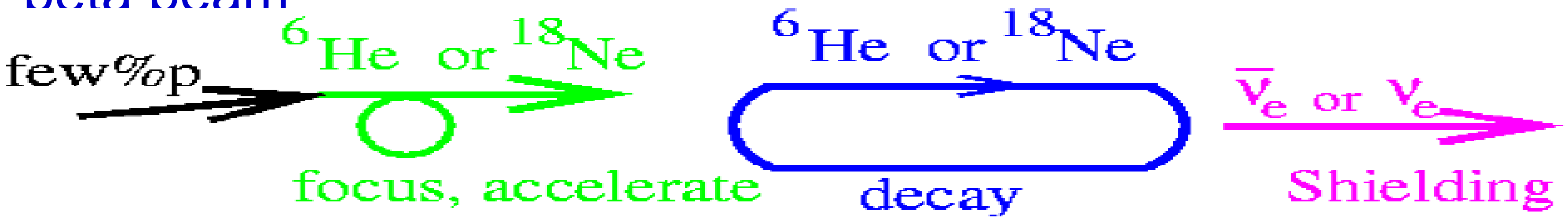
ν_e predominantly from μ^+ and K^+ decay at peak energy,
higher energy tail from kaon decays

Different Ways of Making ν Beams

conventional ν beam



beta beam



muon stored beam

for each of these beams,
ν flux (Φ) is related to boost of parent particles (γ)

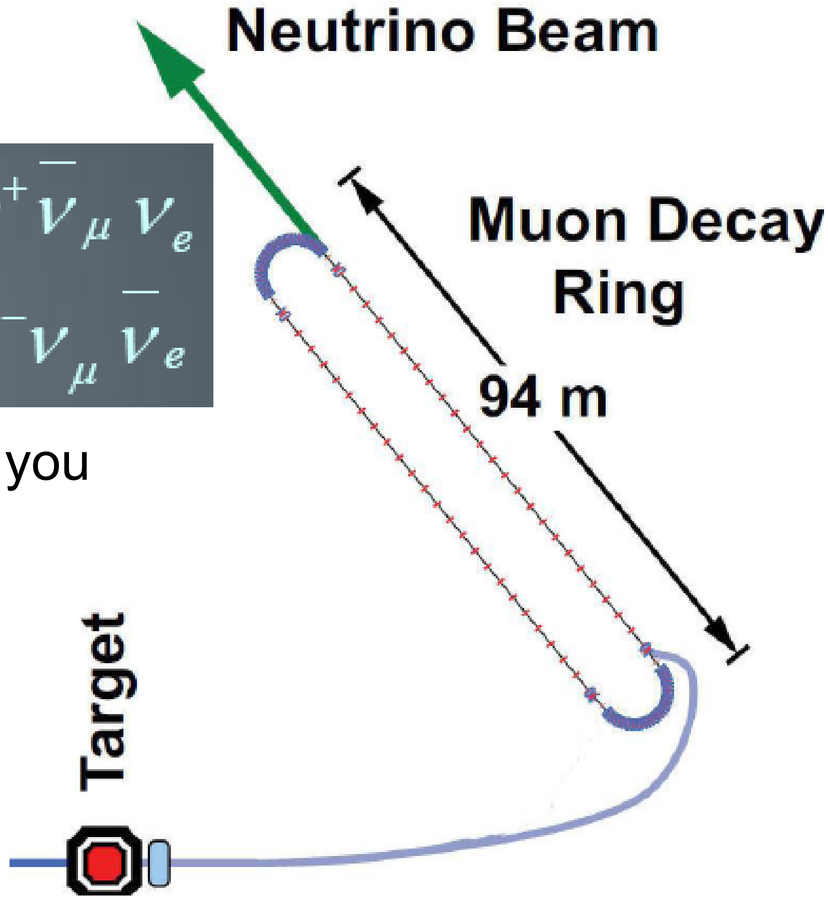
$$\Phi(\nu) \propto \gamma^2$$
$$\sigma \propto \gamma$$

ν-STORM

short baseline oscillation physics
ν cross sections

ν fluxes and spectra
known with very high accuracy
(μ current in ring)

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$
$$\mu^- \to e^- \nu_\mu \bar{\nu}_e$$



final state lepton charge identification tells you flavor of interacting neutrino

100 kW target station

horn collection after target

collection / transport channel
with no muon cooling

decay ring
large aperture FODO
3.8 ± 10% momentum acceptance circumference ~ 350 m

detectors similar to MINOS
magnetized iron + extruded scintillators with Si-PM readout

How Well Do We Know ν Fluxes Now

AGS ν experiment (~1960) knew its flux 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 thick targets, same materials, same energies

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

HADRON PRODUCTION most important of these ingredients

Need to do dedicated hadron production experiments

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

In situ measurements

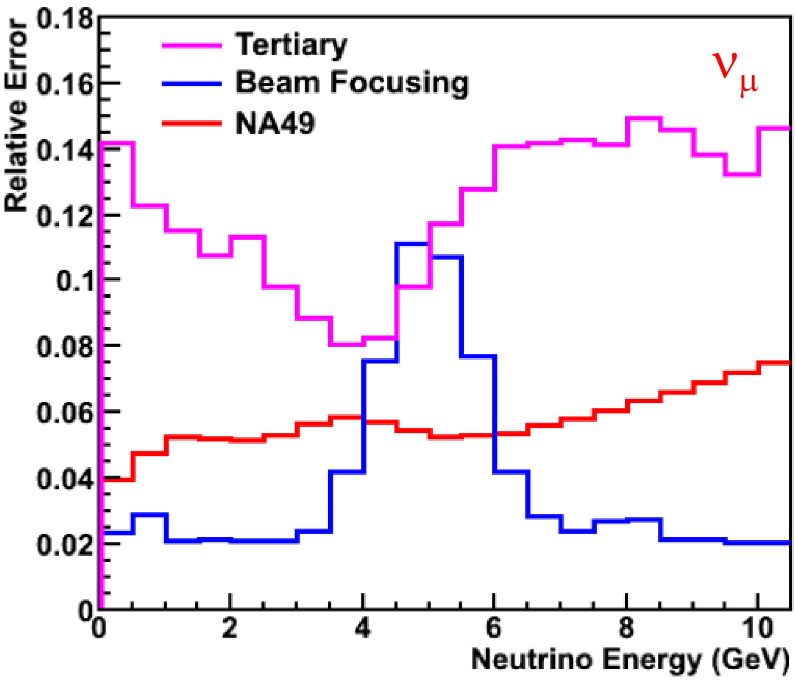
constraints from special in situ runs in modified beam optics

constraints from muon monitor data with scans of horn current

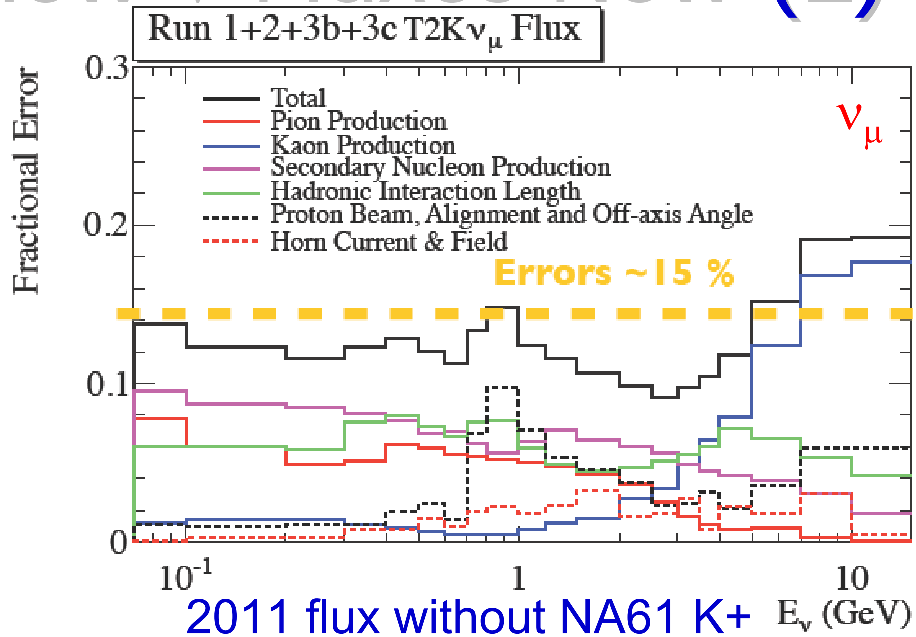
"low ν" events to constrain flux from high energy measurements (A. Bodek et al.)

In 50 years we have gone from 30% uncertainties to 15% uncertainties while increasing proton fluxes on target by ~10^3 – 10^4 .

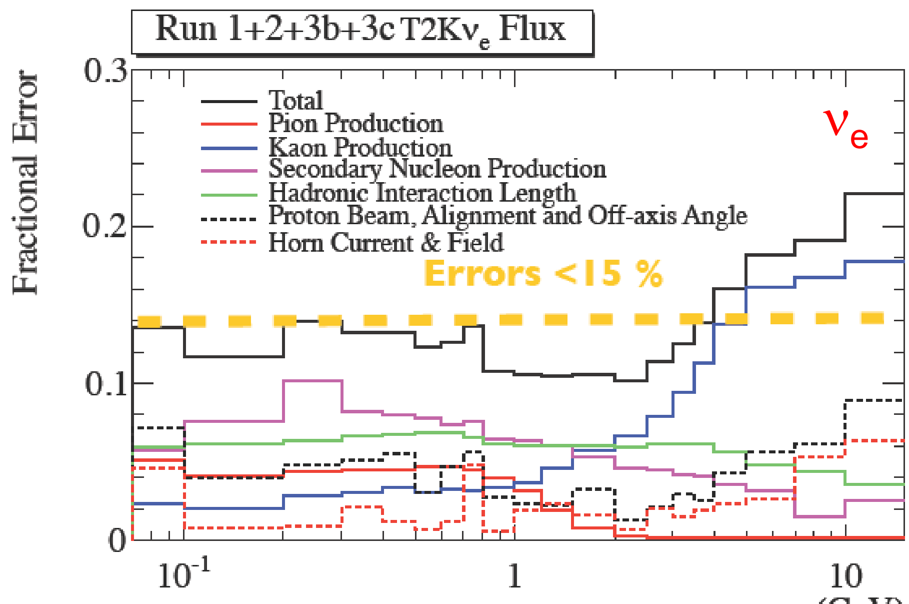
How Well Do We Know ν Fluxes Now (2)



MINERνA, D. Harris, NuFACT2012



2011 flux without NA61 K+



T2K, S. Murphy, NuFACT2012

the errors are of the order ~15%
in the oscillation region (< 1 GeV)

uncertainty on secondary (tertiary)
hadron production dominates

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

+ many many other experiments that measured cross sections …
⇒ critical survey of all existing cross section measurements !,

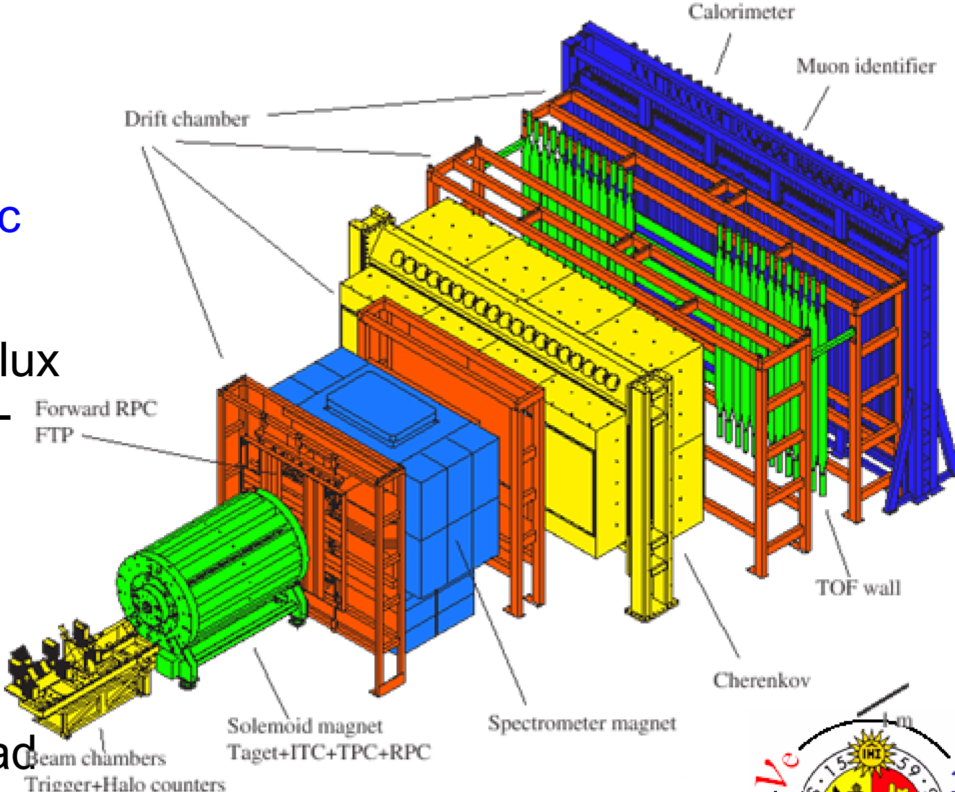
HARP : Hardon Production Exp. at PS

- 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
- 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)

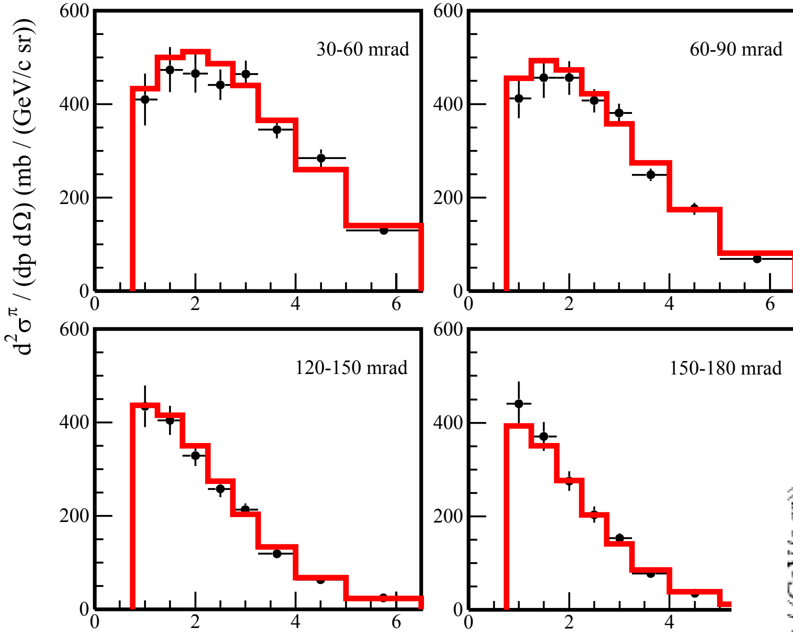
  $0.1< p < 0.8$ GeV/c, $0.35 < \theta < 2.15$ rad

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



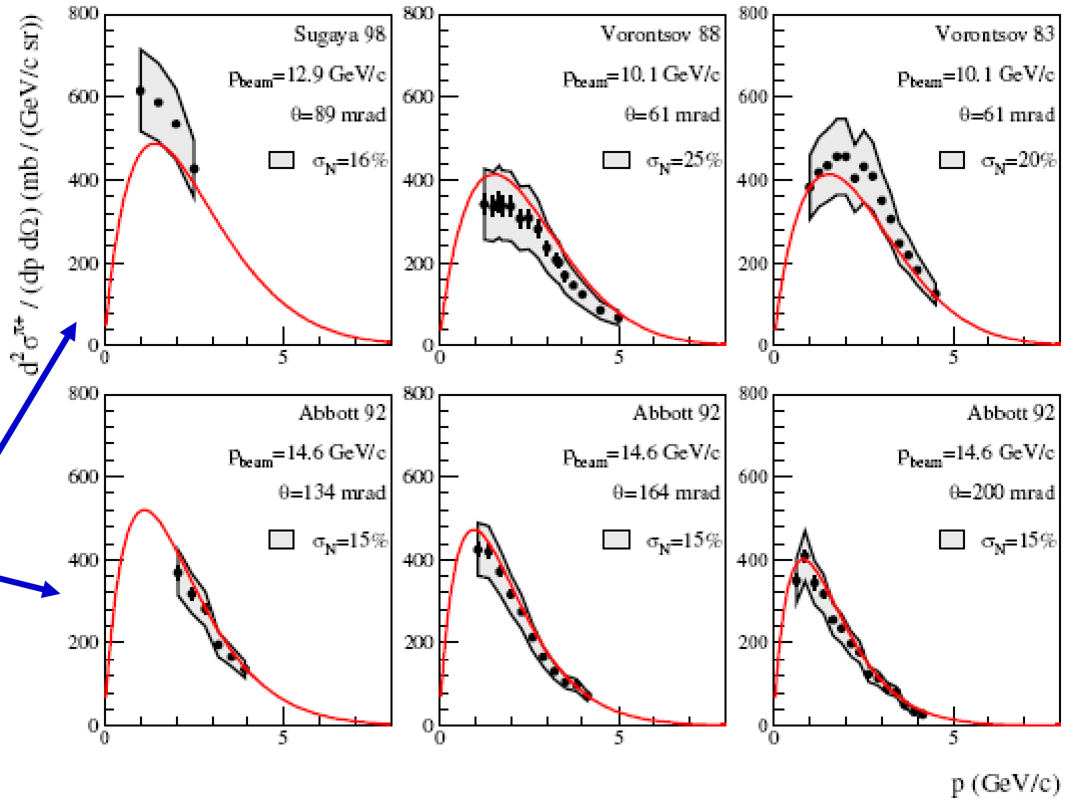
M.G. Catanesi et al., NIM A571(2007)527

HARP Result (p-Al at 12.9 GeV)



HARP data points

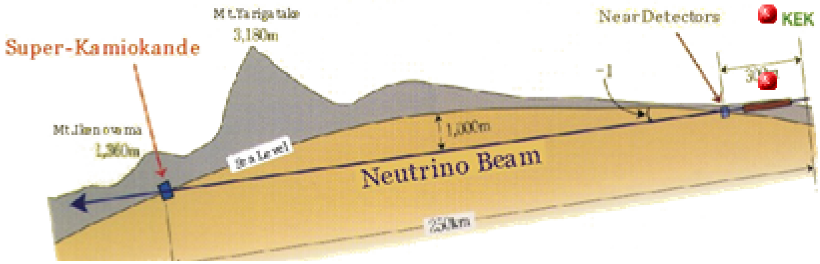
HARP Sanford-Wang parametrization



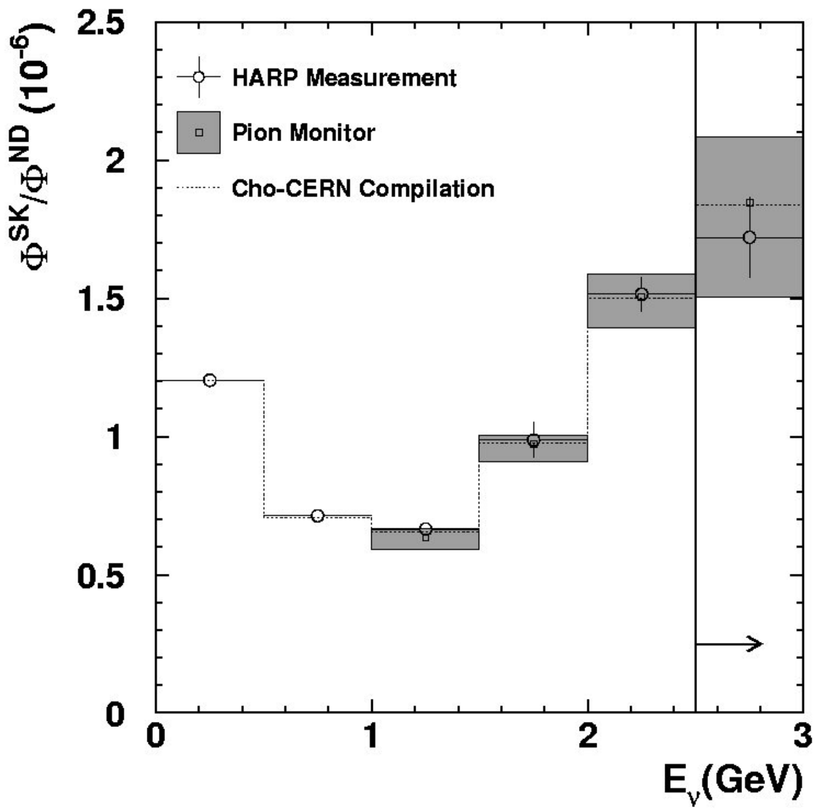
results based on ~200 k reconstructed tracks

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

HARP Impact on K2K

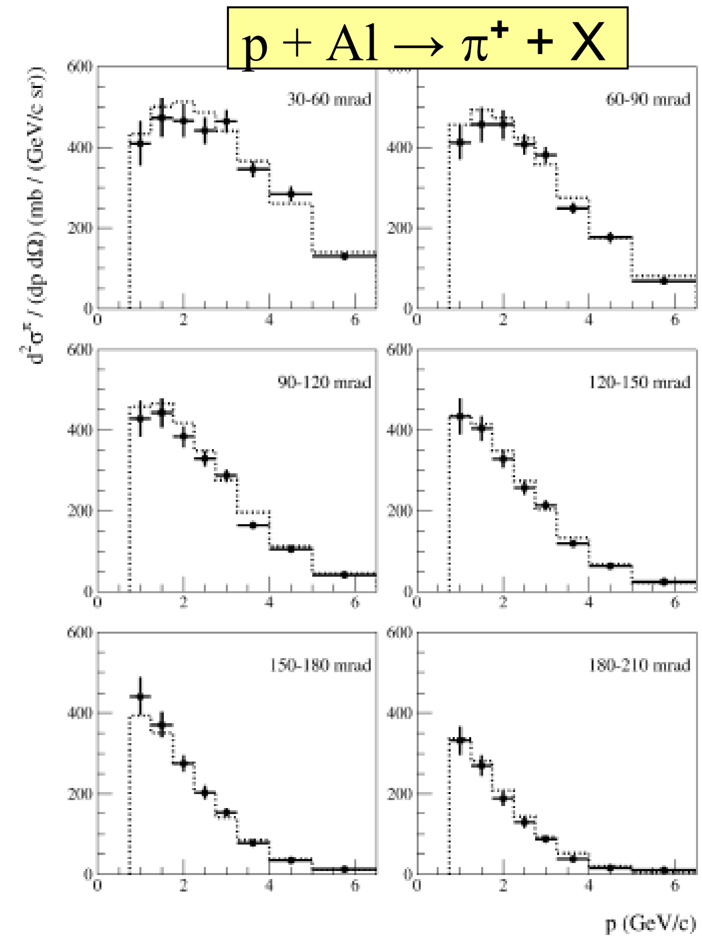


- K2K measured ν_μ disappearance for θ_{23}, Δm_{23}^2
- ν_μ beam was produced by 12.9 GeV/c protons scattered off 5% Aluminum target



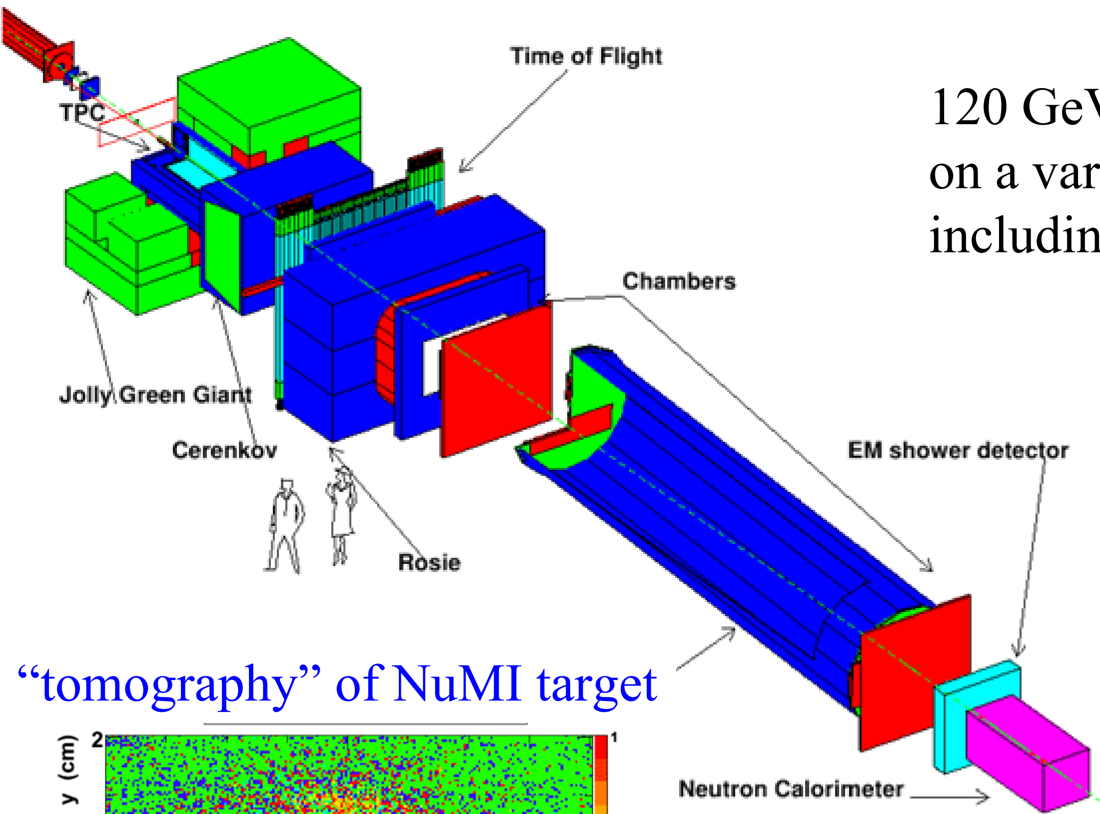
almost factor of 2 error reduction

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



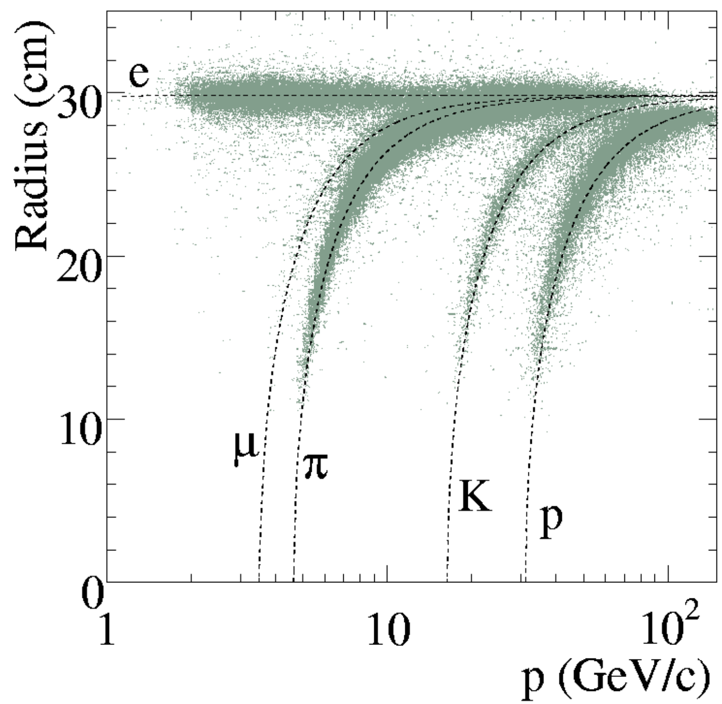
M.G. Catanesi et al., Nucl.Phys.B732(2006)1

MIPP : Main Injector Particle Production Exp.

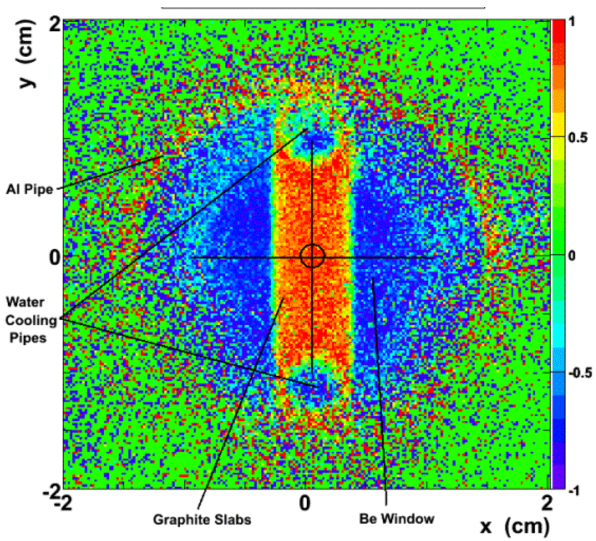


120 GeV proton beam from Main Injector
on a variety of targets
including NuMI replica target

PID with RHIC detector



“tomography” of NuMI target



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

Ratios of Charged Hadron Yields

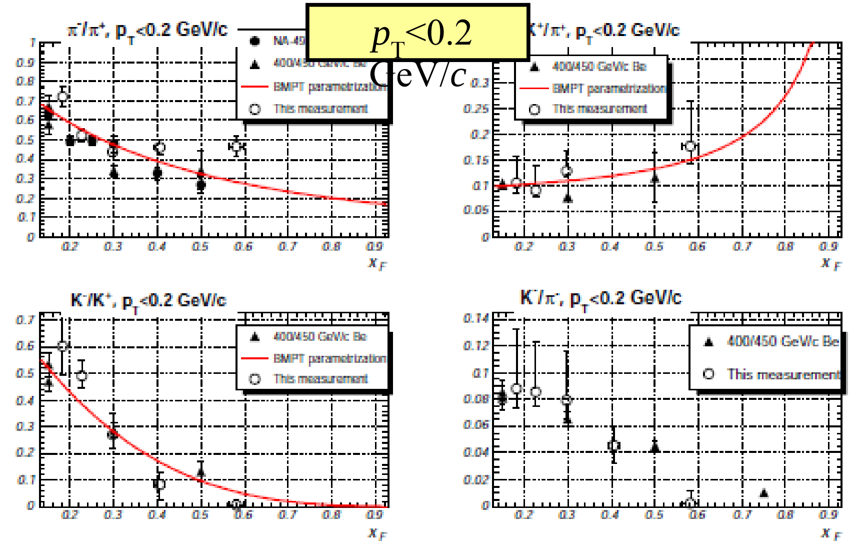
Measurements for MINOS/ 120 GeV/*c*

- Thin carbon target
- NuMI replica target

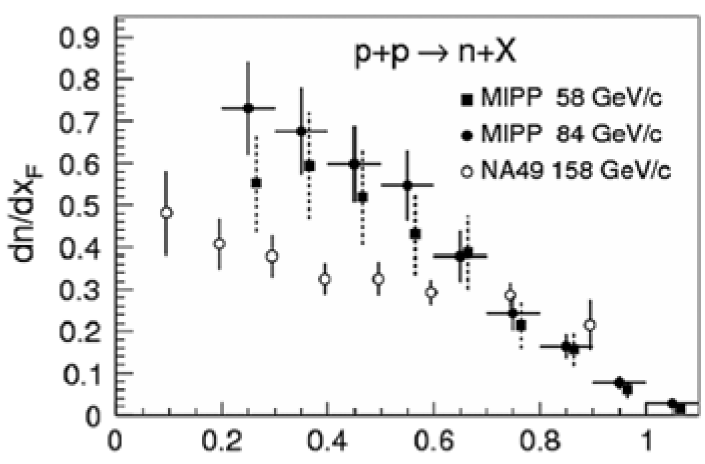
Preliminary results for ratios:

π^-/π^+, K^+/π^+, K^-/K^+ and K^-/π^-

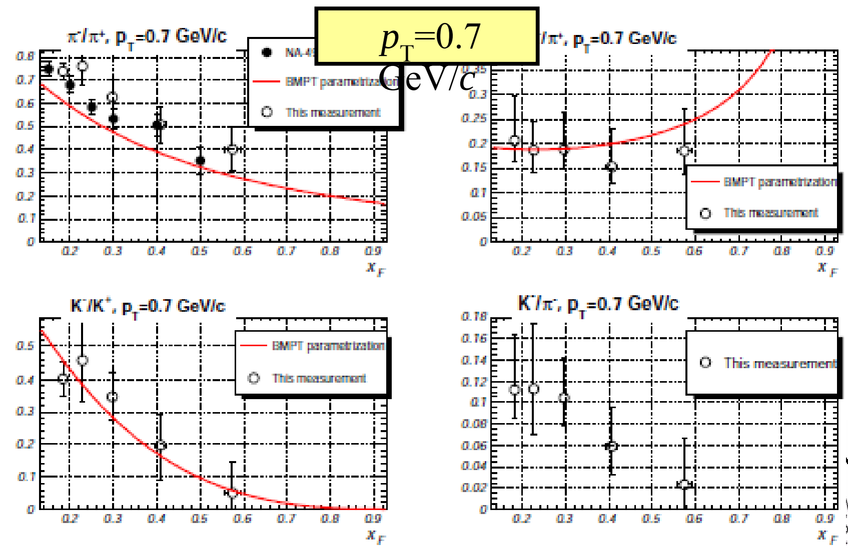
The only experiment nearby in phase space is NA49 (thin target, 158 GeV/*c* beam)



Forward neutron production in MIPP

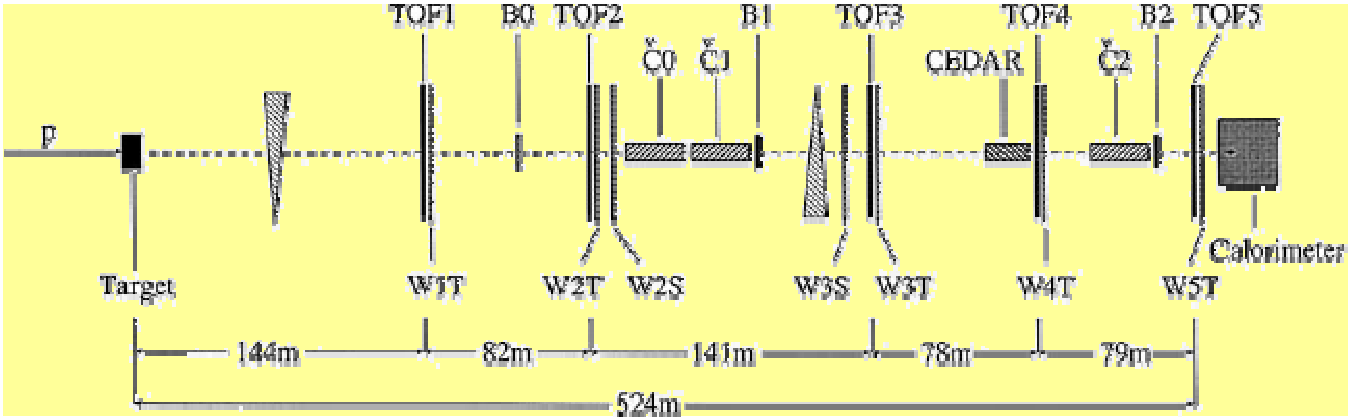


Phys. Rev. D83 (2011) 012002



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

NA58 / SPY : Secondary Particle Yields



understanding and planning of ν oscillation experiments

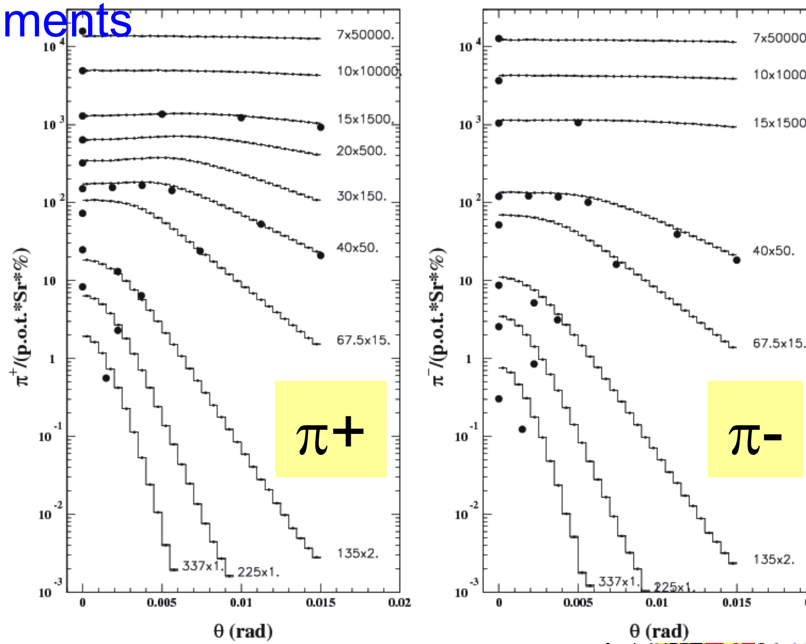
450 GeV/*c* protons interact with Be target

production angle up to 30 mrad

yields of $\pi^{\pm}$, $K^{\pm}$, p and p have been studied

secondary momentum range 7-135 GeV/*c* (0.02<x_F<0.3) and p_T<600 MeV/*c*

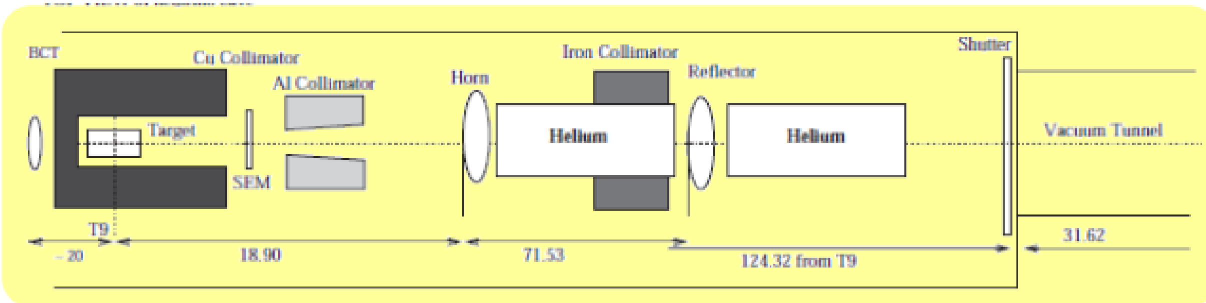
complementary to NA20 (Atherton et al.) measurements at 400 GeV/*c* and 0.15<x_F<0.75



G.Ambrosini et al., EPJ. C10 (1999) 605

SPY Data in NOMAD / WANF

450 GeV/c protons from SPS



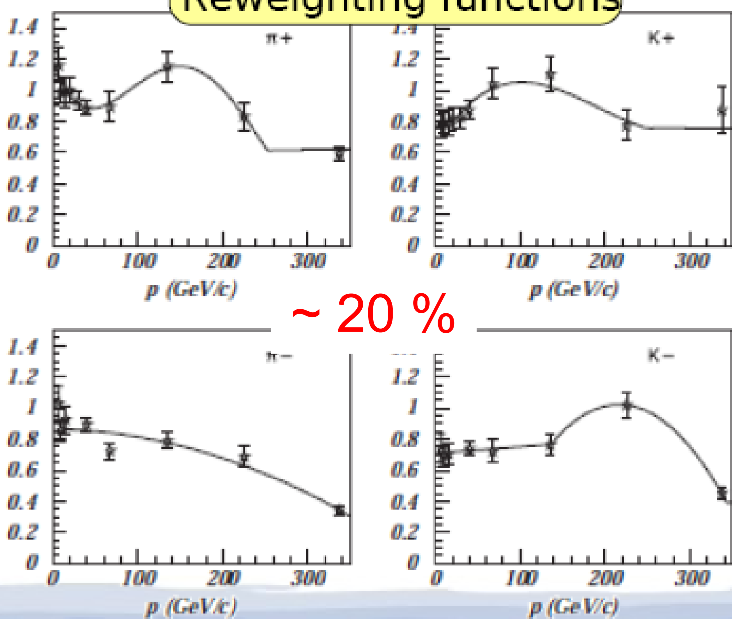
Towards CHORUS & NOMAD

FLUKA 2000 used to calculate rates

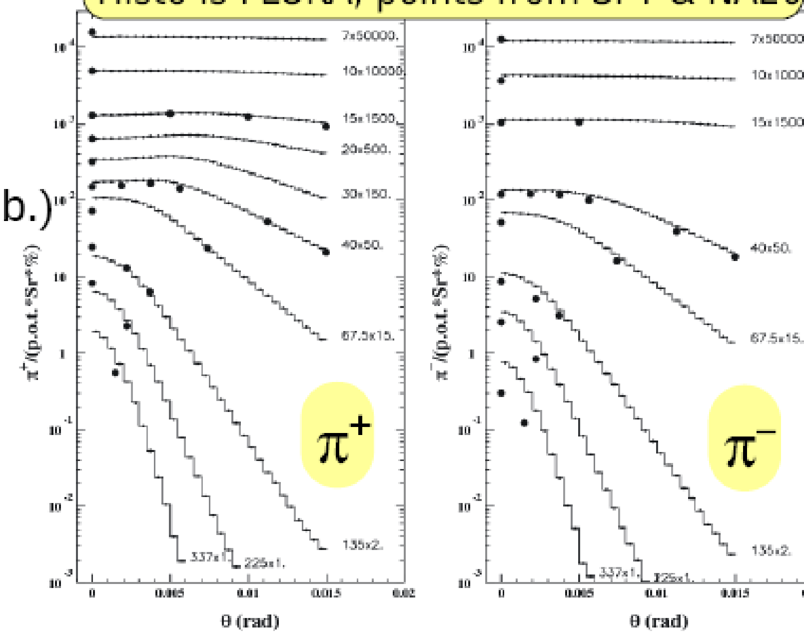
rates modified to account for cross-sections measured by SPY and NA20

weight = data / FLUKA

Reweighting functions



Histo is FLUKA, points from SPY & NA20



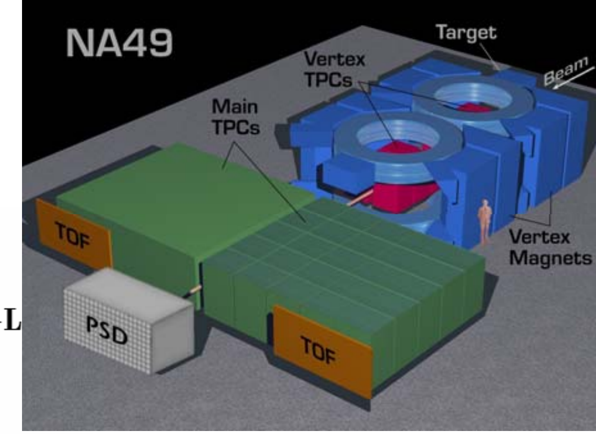
NOMAD ν flux

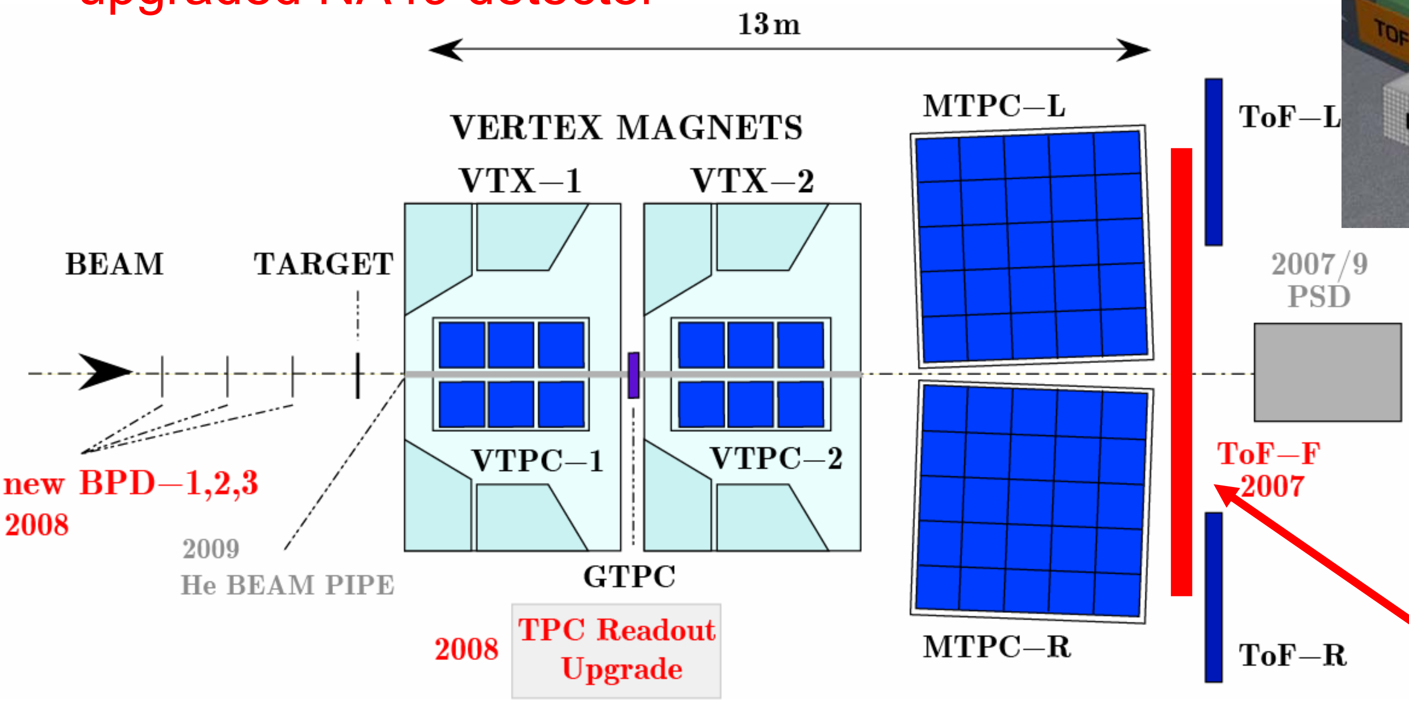
→ reweighting functions FLUKA / data

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

The NA61 Detector

upgraded NA49 detector



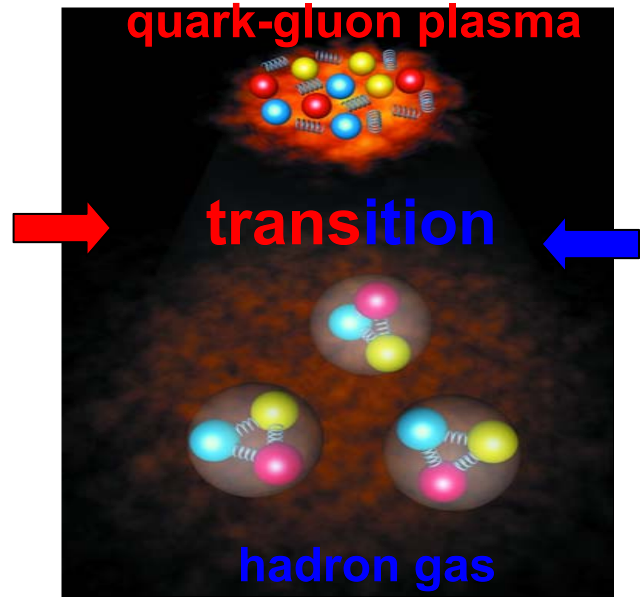


NB Forward-ToF wall used to identify low mom. particles produced at large angles and bent back into the detector acceptance by the vertex magnets

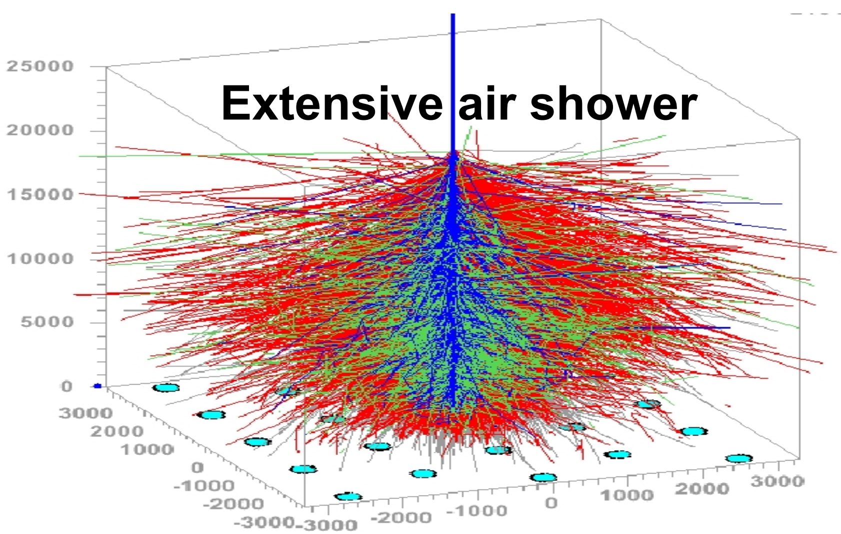
- **Large Acceptance Spectrometer for charged particles**
- **4 large volume TPCs as main tracking devices**
- **2 dipole magnets with bending power of max 9 Tm over 7 m length** (T2K runs: $\int Bdl \sim 1.14$ Tm)
- **High momentum resolution**
- **Good particle identification:** σ(ToF-L/R) ≈ 100 ps, σ(dE/dx)/<dE/dx> ≈ 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

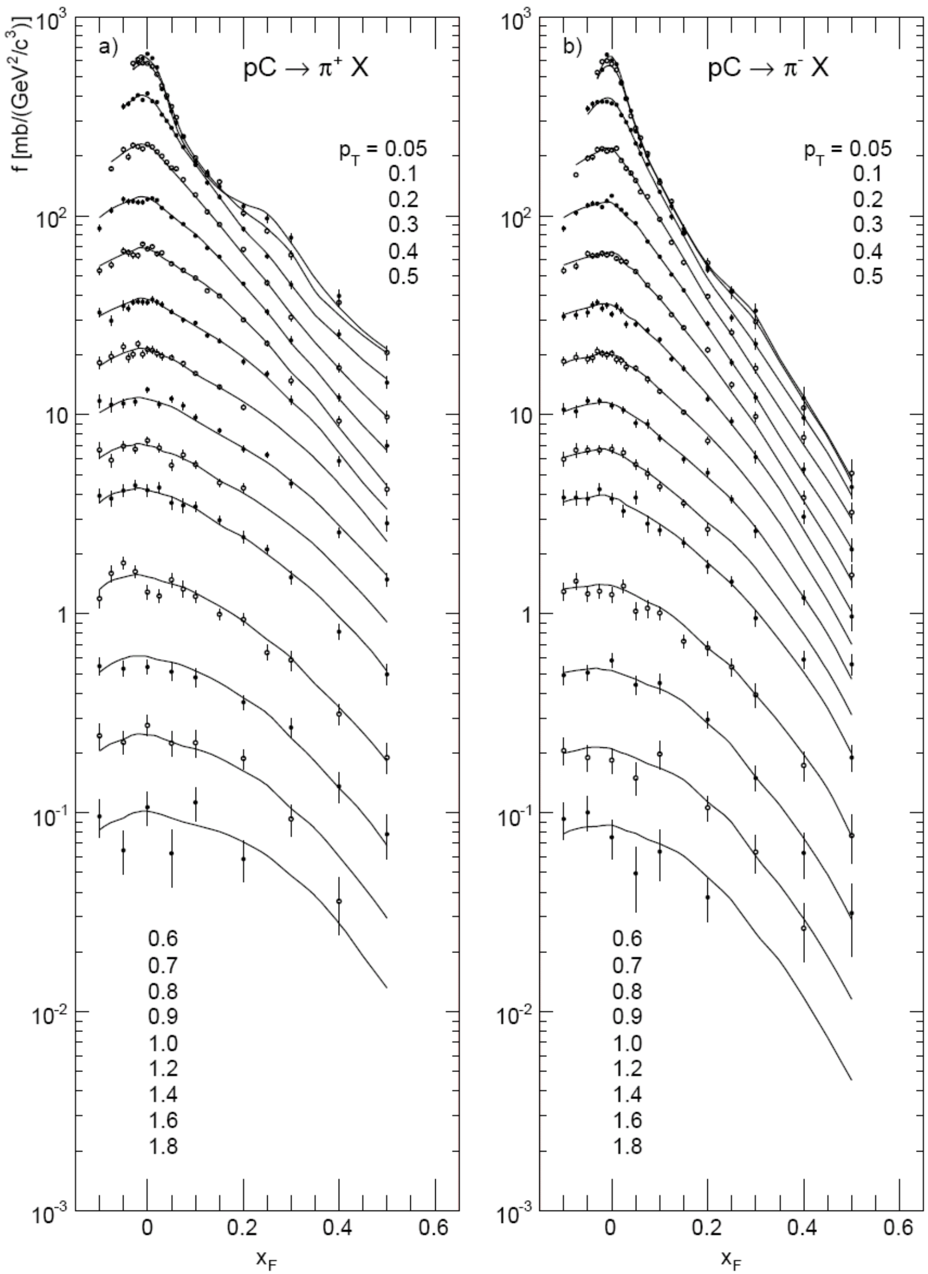


Measurement of hadron production
off the T2K target (p+C) needed to
characterize the T2K neutrino beam



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

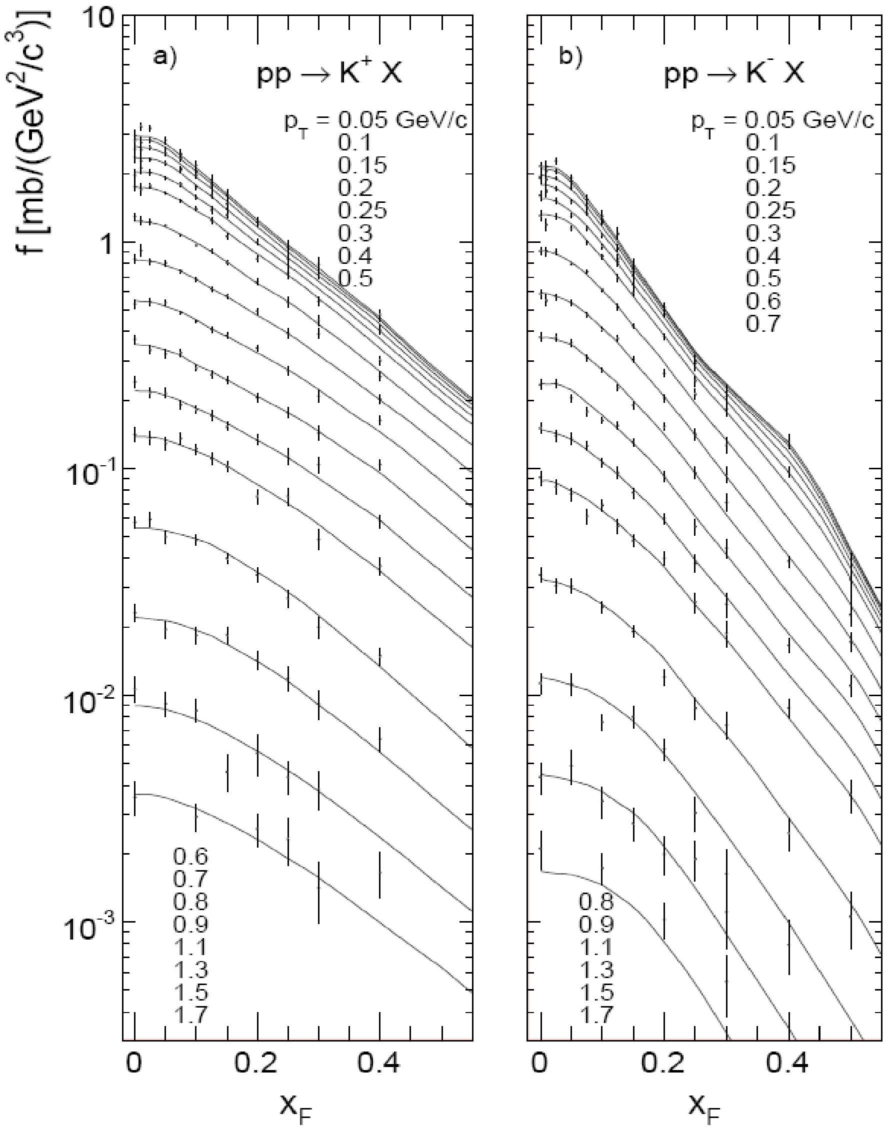
NA49 with empirical fits to the data

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%

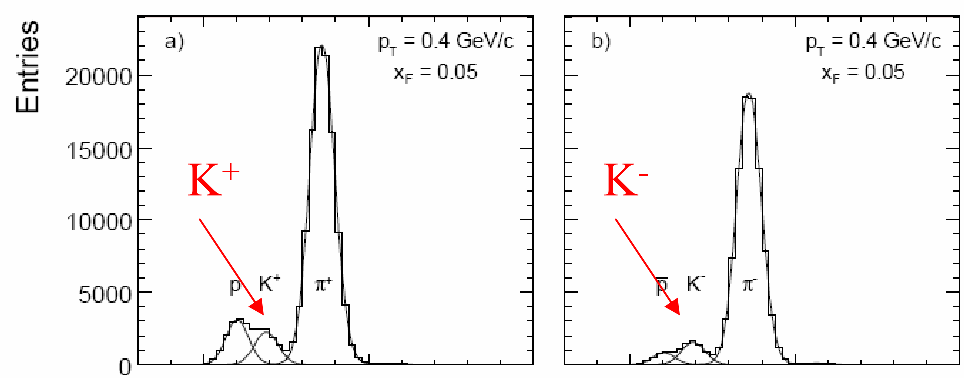
C. Alt *et al.*, EPJ C49 (2007) 897

NA49 Charged Kaon Spectra



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

K identified using dE/dx in the TPCs

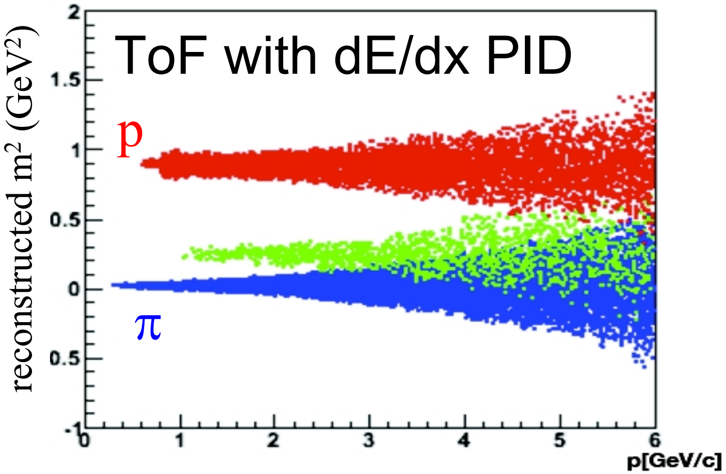


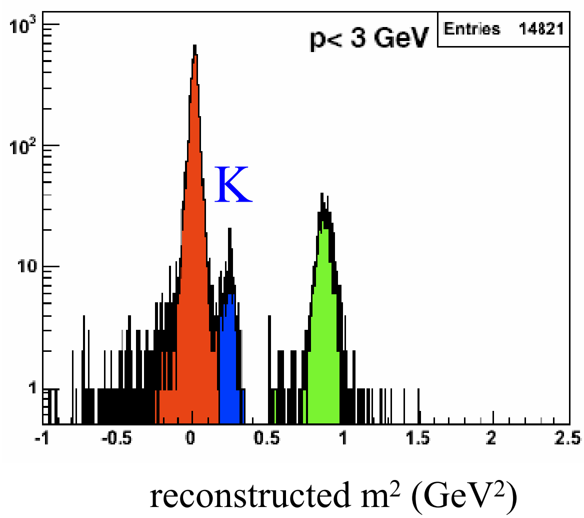
systematic error

	$x_F \leq 0.2$	$x_F \geq 0.25$	
	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%

Particle Identification

Time of Flight measurements

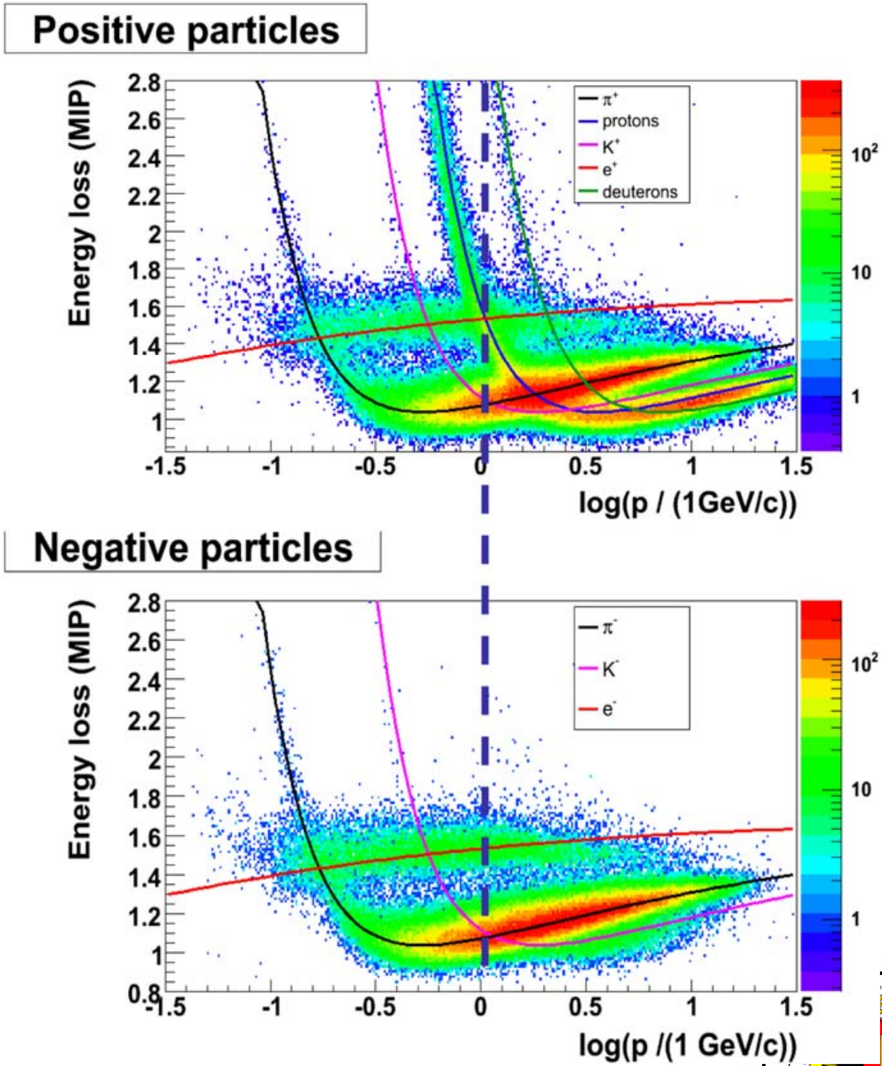




5 σ π/K separation up to 4 GeV/c

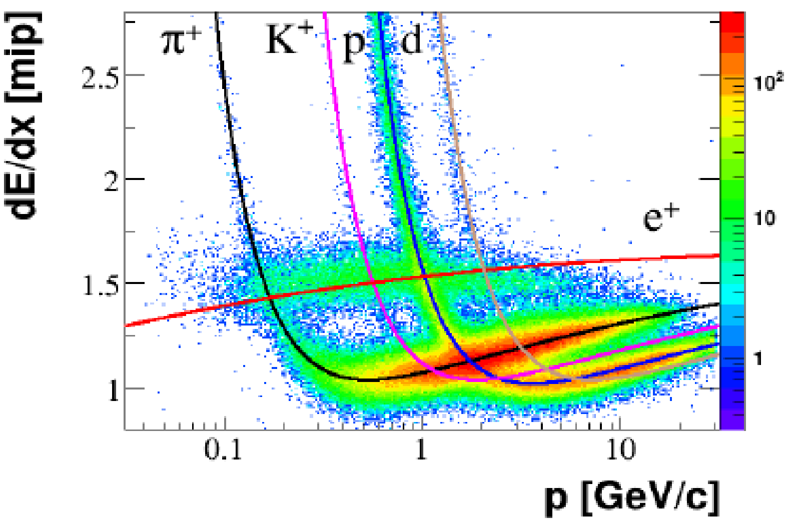
Energy loss in TPCs

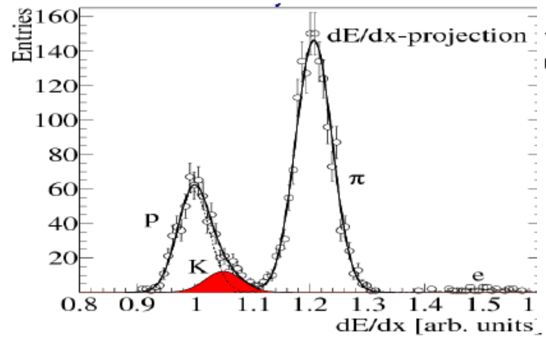
Bethe-Bloch curves (dE/dx) for different particles

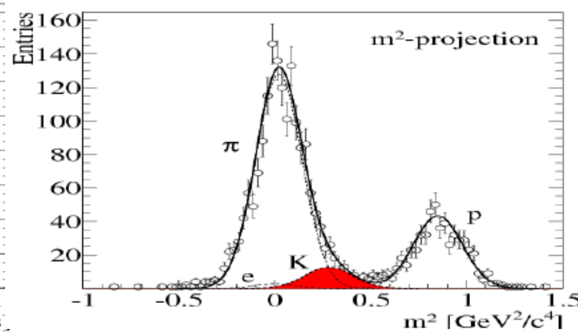


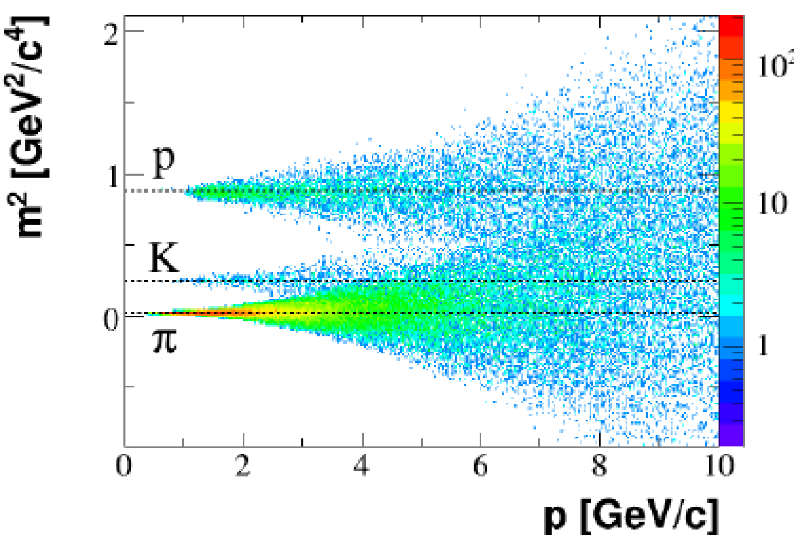
σ(dE/dx)/<dE/dx> < 5 %

Particle Identification (2)

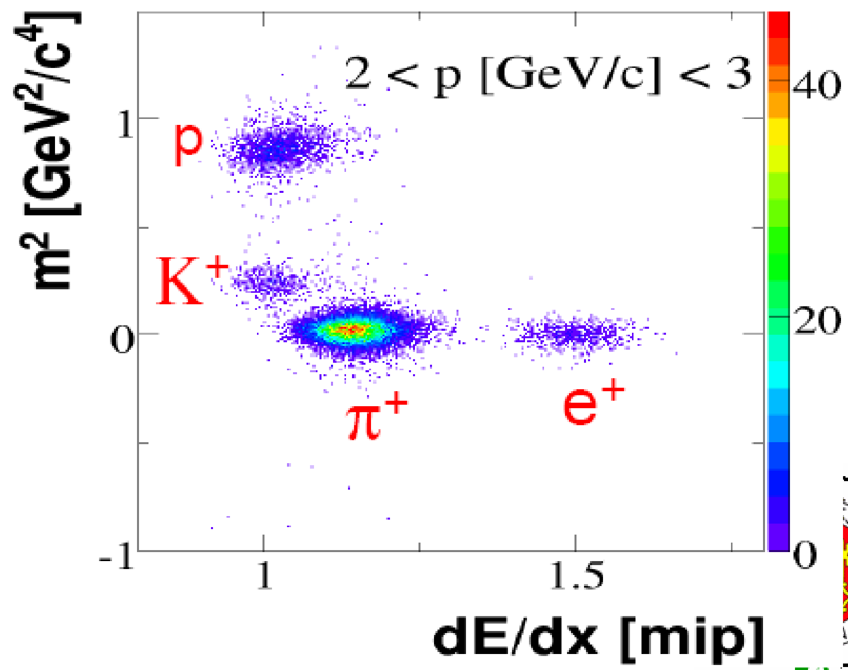




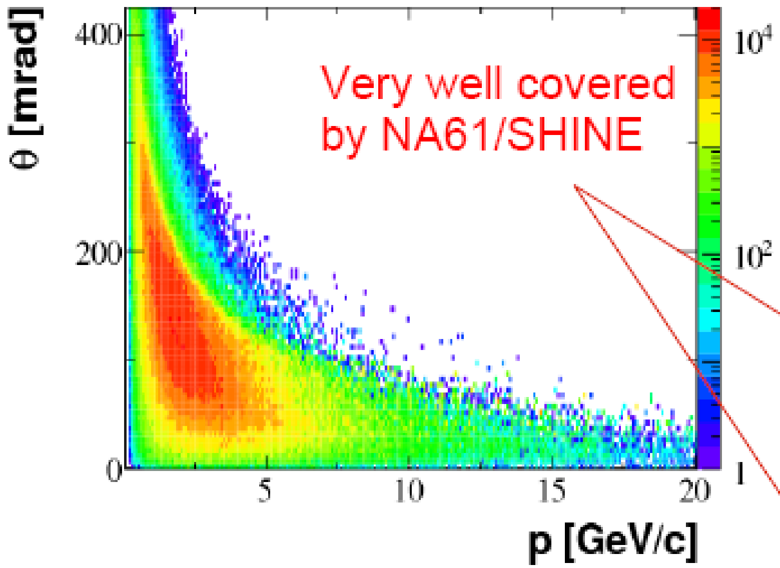




combined ToF + dE/dx
(positively charged particles)

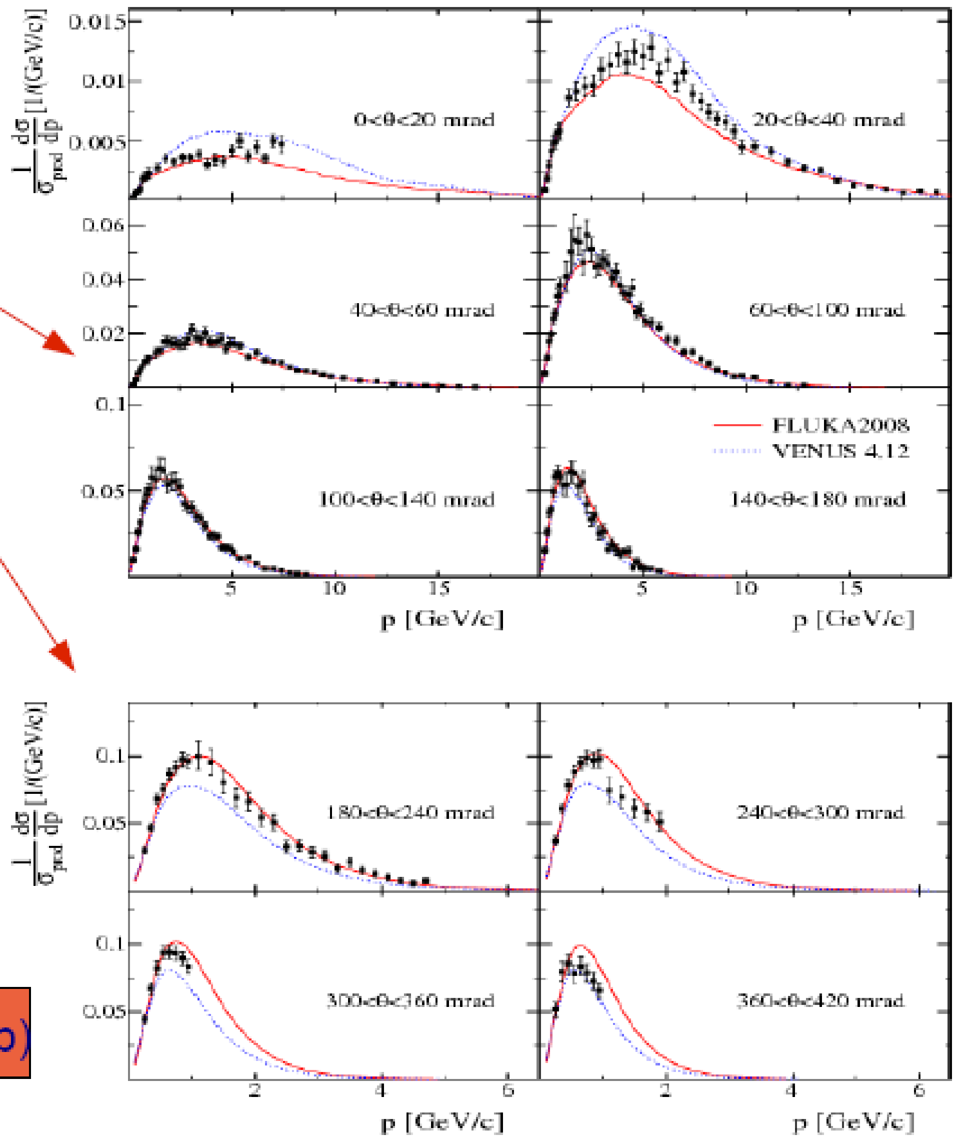


NA61 p + C → π^+ + X @ 30 GeV



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



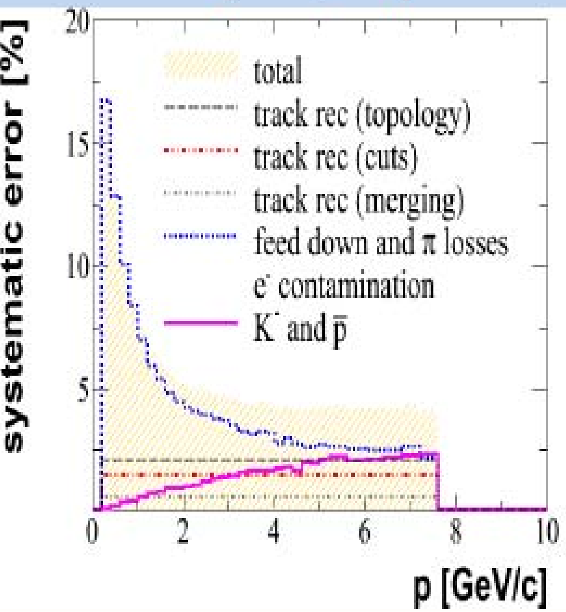
NA61/SHINE measurements

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

Systematical Errors

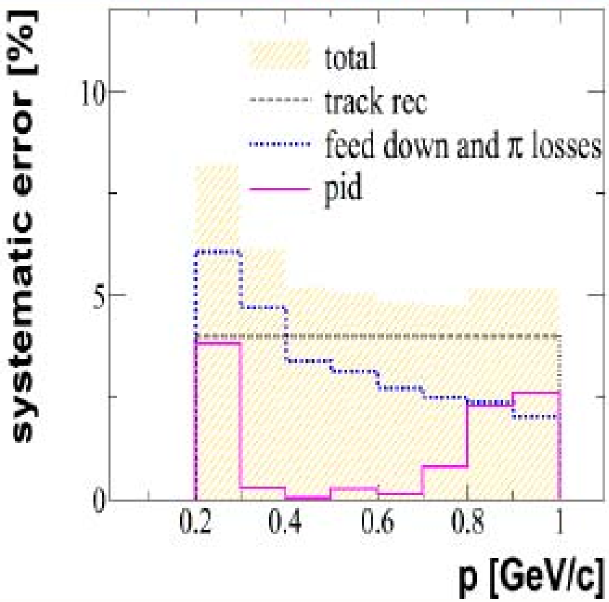
h- analysis

π^- θ=[140,180] mrad



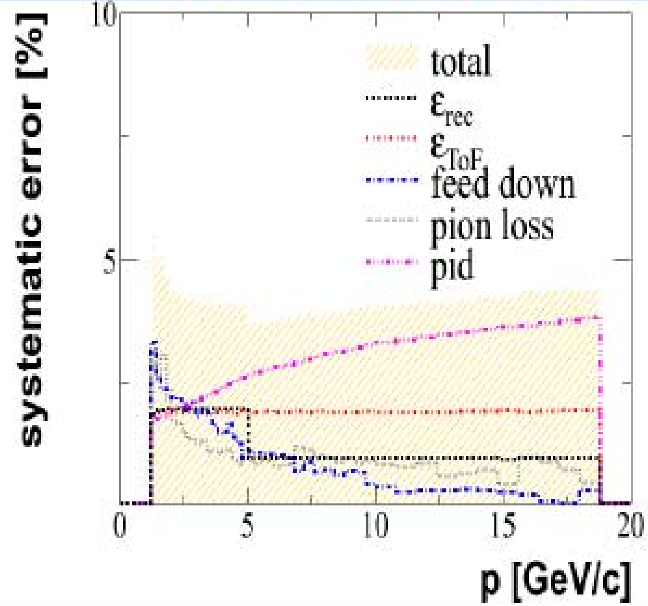
dE/dx analysis

π^+ θ=[140,180] mrad



dE/dx+ToF analysis

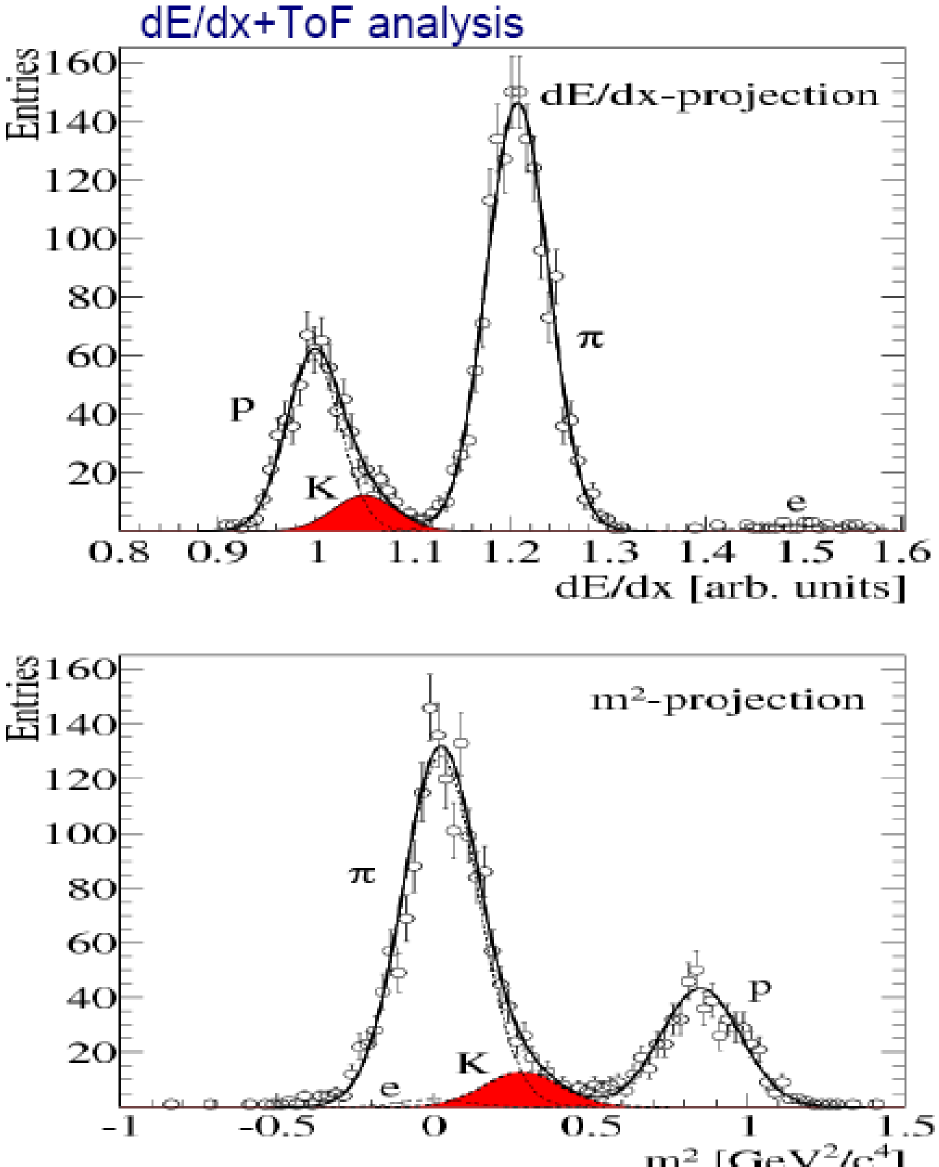
π^+ θ=[40,60] mrad



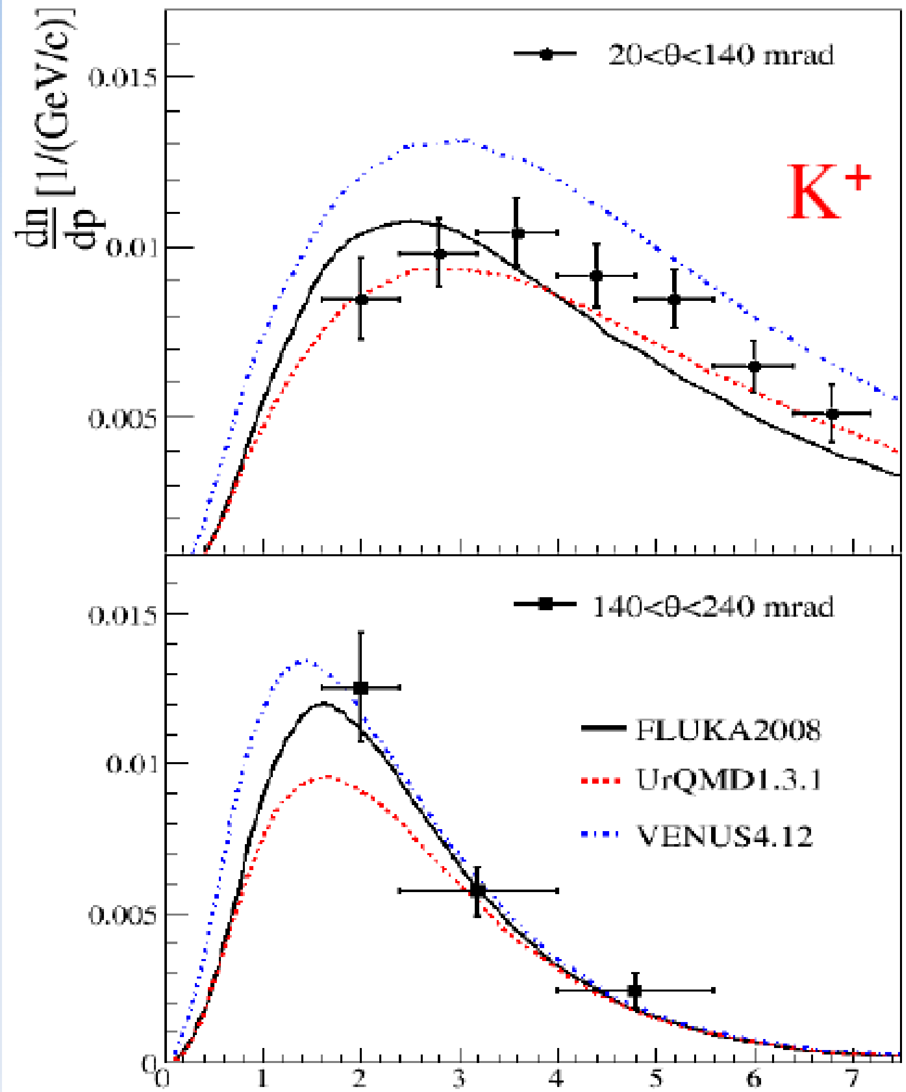
Typical value 6%
Hope to reduce down to 3-4%

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

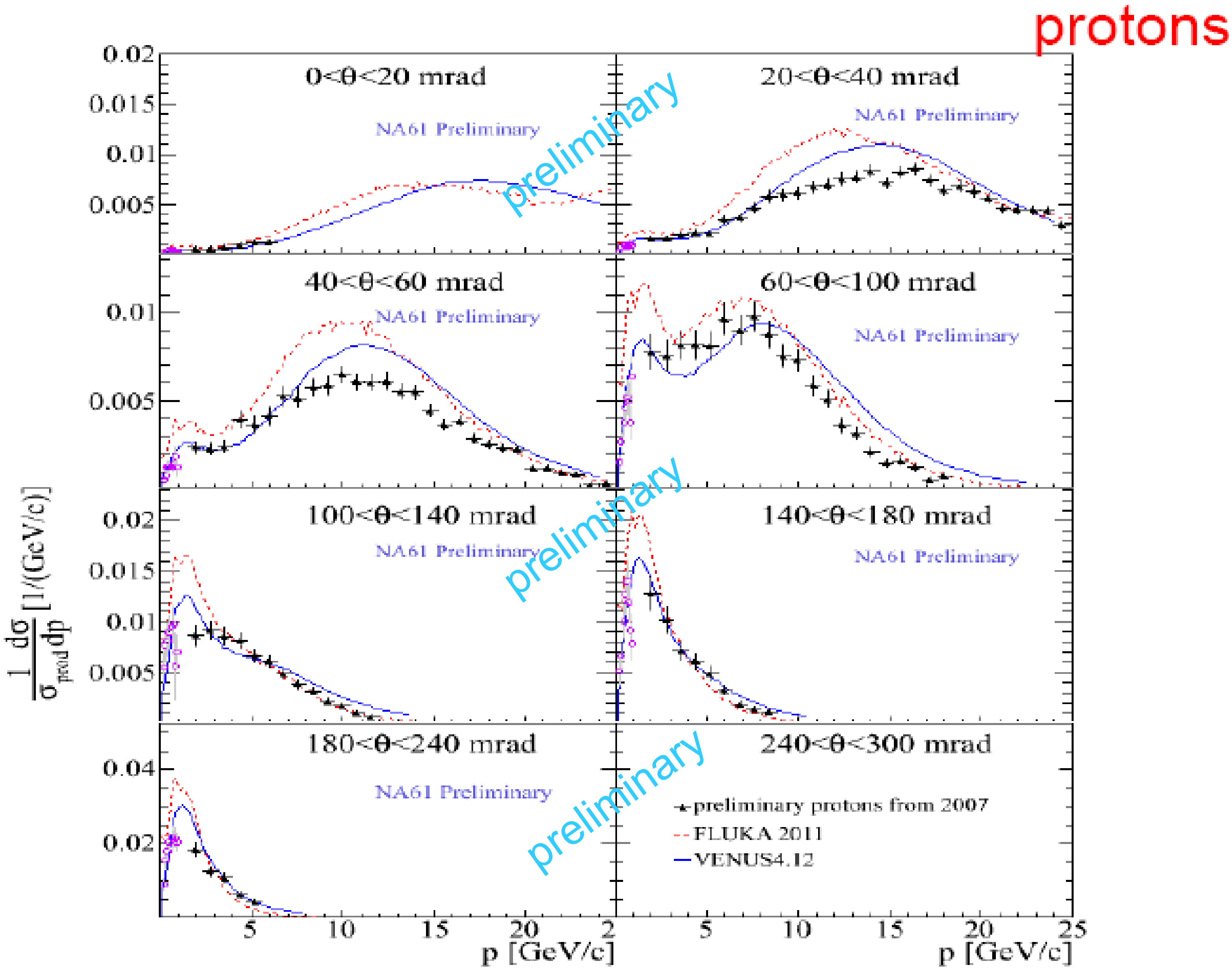


Published in PRC 85 (2012) 035210



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

NA61 p + C → p + X @ 30 GeV



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.

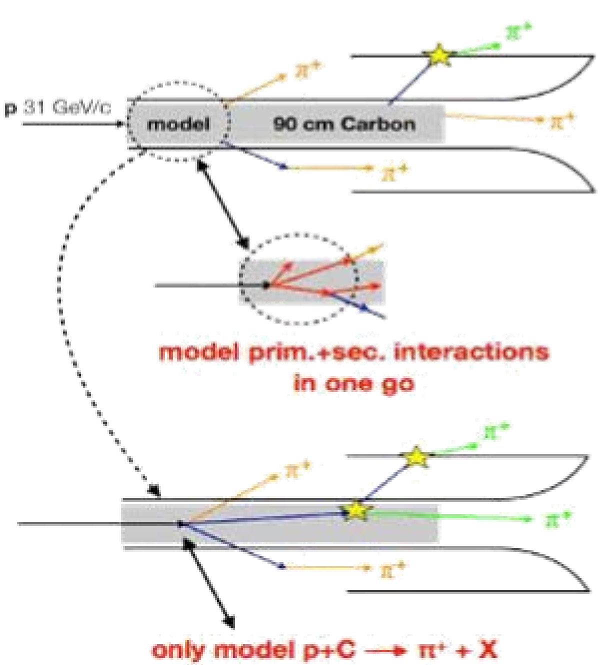
2007 pilot run
- Thin target: ~ 660k triggers
- Replica target: ~ 230k triggers

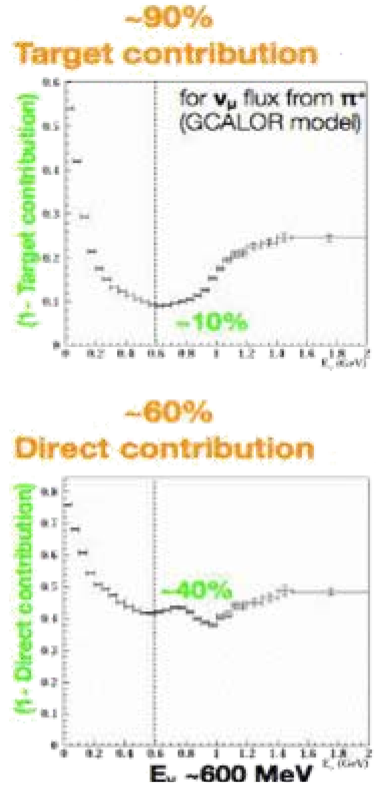
2009 run
- ~ 6 M triggers
- ~ 2 M triggers

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

2010 run
- Replica target: ~ 10 M triggers

ν Flux Prediction with T2K Replica Target



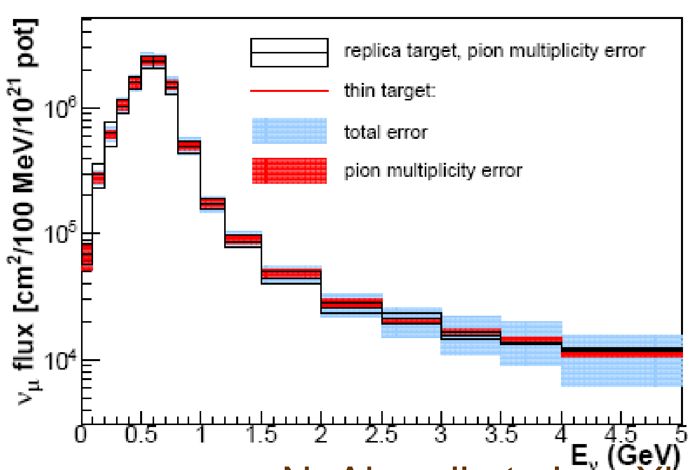


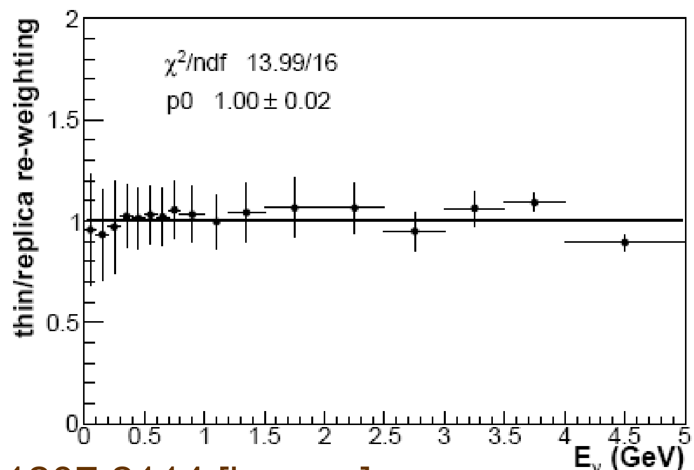
we see only particles coming out of the target

we do not see what happens inside the target

hadron multiplicities are parametrized at the target surface (no vertex reconstruction)

model dependence is reduced down to 10% as compared to 40%





N. Abgrall et al., arXiv:1207.2114 [hep-ex]

comparison ν flux predictions

thin target vs. replica target

in very good agreement

just an accident or real ?

Conclusions

50 years of accelerator based neutrino beams have taught us a lot about particle physics in general and ν in particular

We have more to learn about understanding neutrino fluxes to get to precision cross section measurements and next steps in oscillation physics

Promising ideas for new beam techniques are developing

In 50 years we have gone from 30% uncertainties to 15% (10%) uncertainties, while increasing proton fluxes on target by ~ $10^3 - 10^4$.

Hadro production measurements are essential to make further progress :

- flux prediction for conventional accelerator ν beams
- improved calculations for atmospheric ν flux
- MC generator tuning

Hadro production measurements require :

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