PREDICTING THE NEUTRINO FLUX WITH HADRO-PRODUCTION MEASUREMENTS

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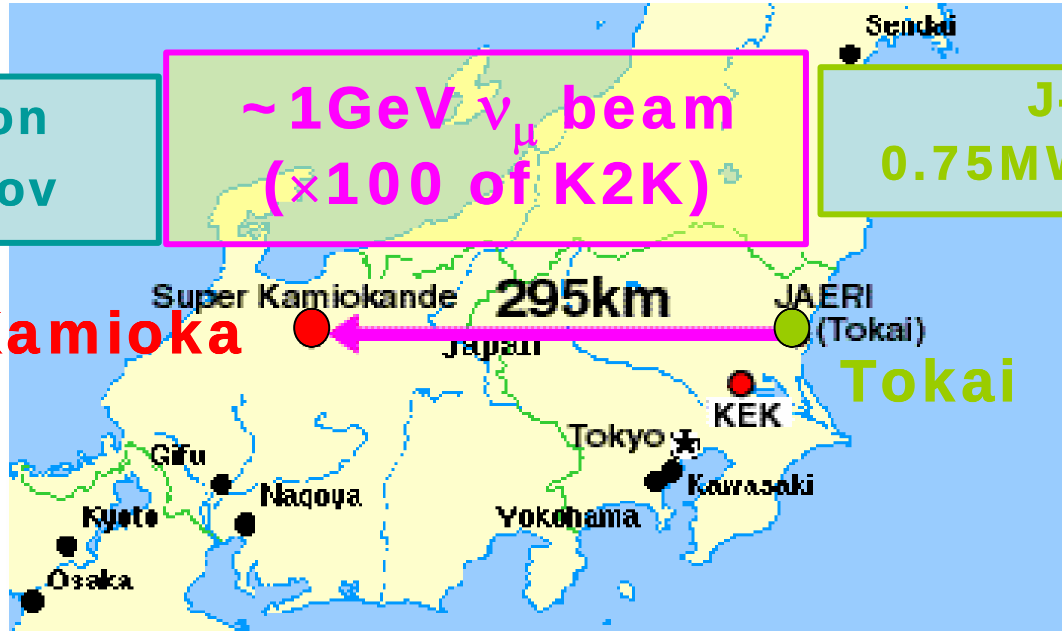
Neutrino Physics at Accelerators
Dubna, January 25 ‘08

T2K (Tokai to Kamioka)

Super-K: 50 kton Water Cherenkov

~1GeV ν_μ beam (×100 of K2K)

J-PARC 0.75MW 50GeV PS



Kamioka

Tokai

Phase2: Hyper-K

Phase2: 4 MW

Physics goals

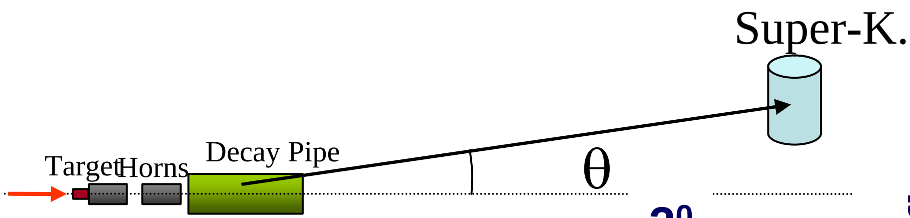
- Discovery of $\nu_\mu \rightarrow \nu_e$ appearance $\Rightarrow$ $\sin^2 2\theta_{13}$
- Precise meas. of disappearance $\nu_\mu \rightarrow \nu_x$

$$\Rightarrow \sin^2 2\theta_{23} \text{ and } \Delta m^2_{23}$$

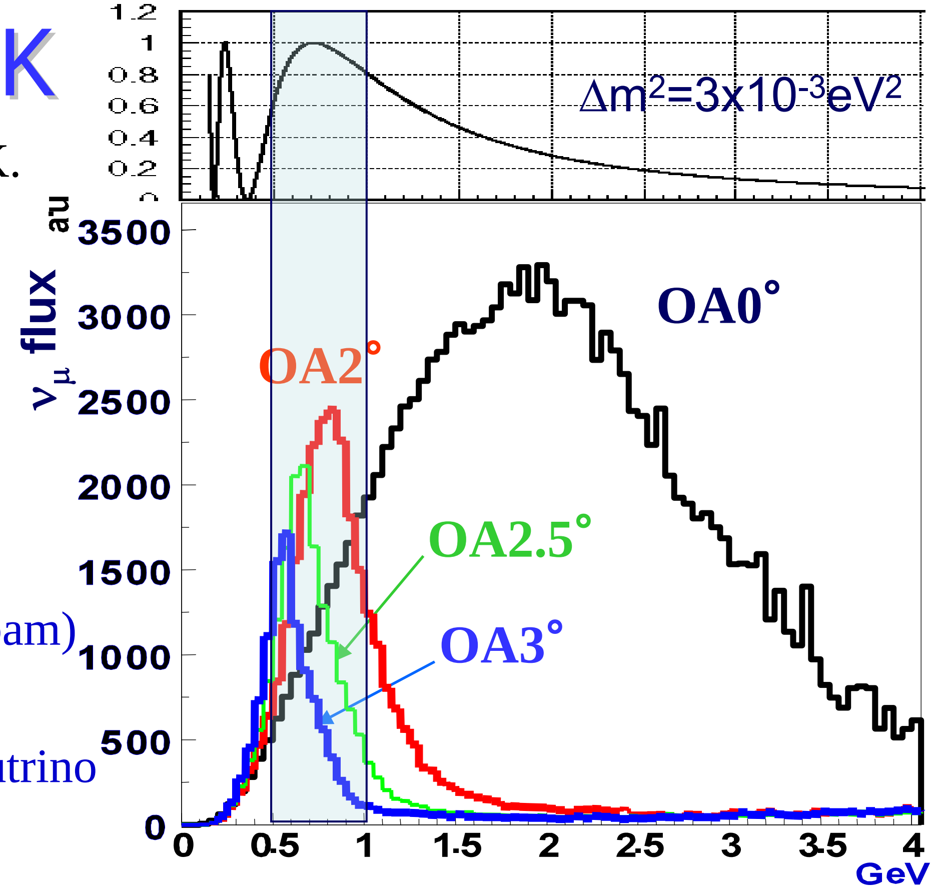
- Neutral current events
- Discovery of CP violation (Phase2)

12 countries
~60 institutions
~180 collaborators

Off-Axis-Beam for T2K



π decay Kinematics

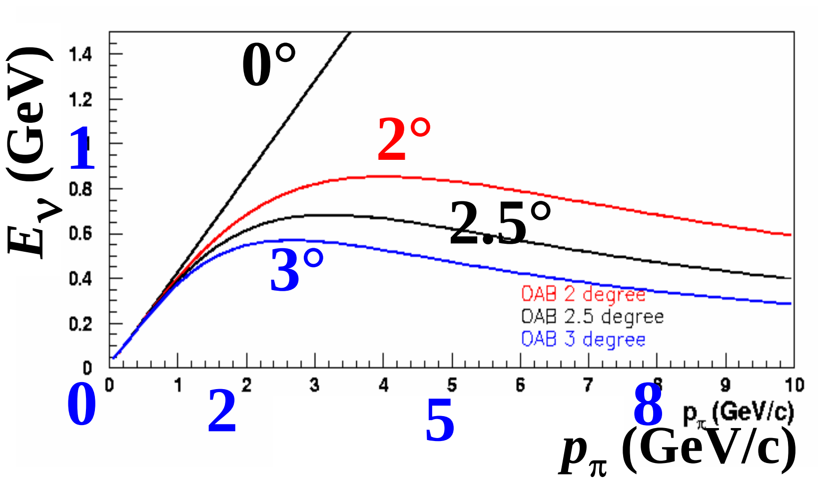


More flux and less background

Very narrow energy spectrum with small high energy tail (almost mono-energetic bam)

Energy "tuned" to oscillation maximum

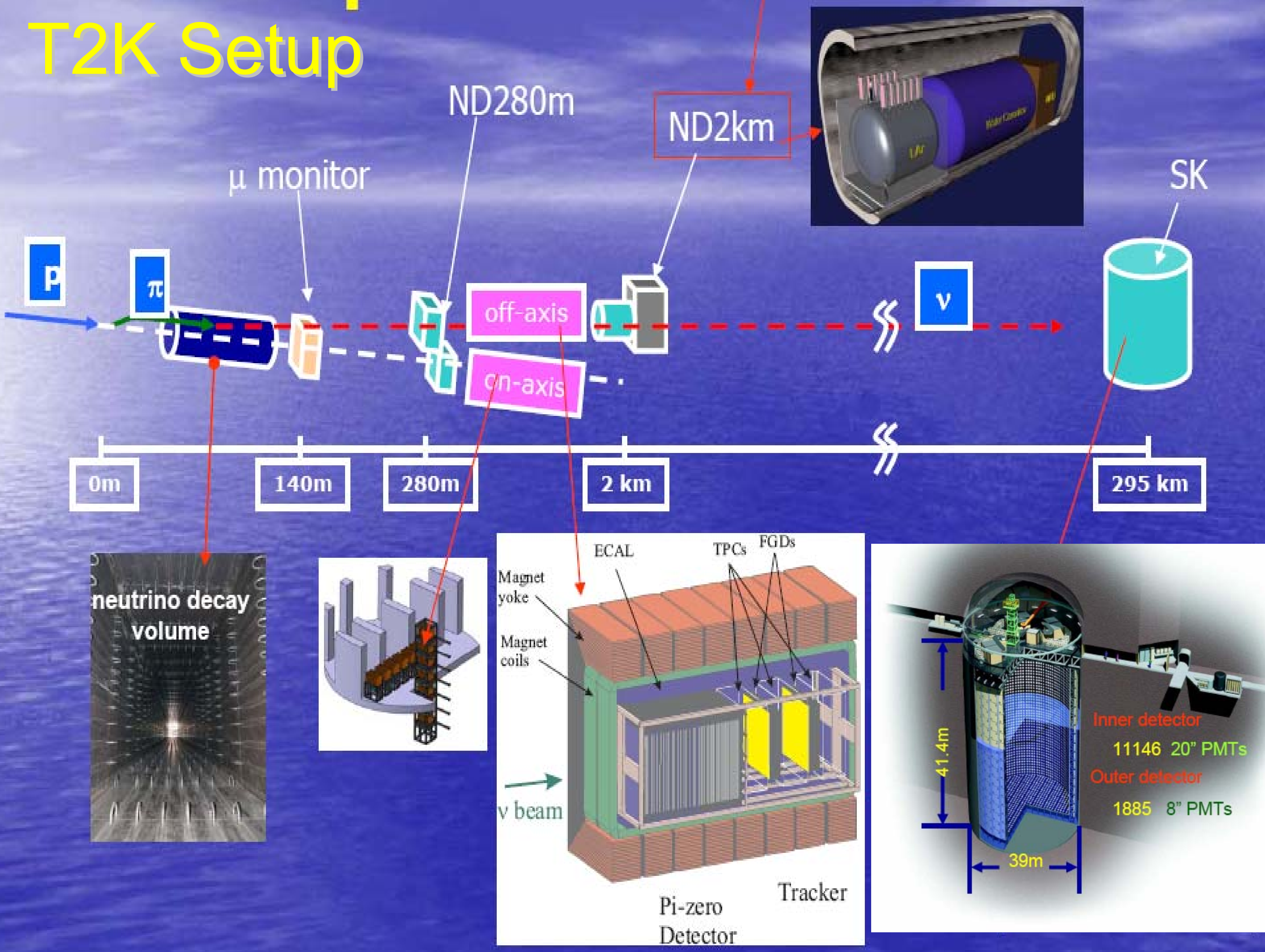
Reduces the backgrounds in the electron neutrino measurement



1. neutrino energy E_ν almost independent of parent pion energy
2. horn focusing cancels partially the p_T dependence of the parent pion

In reality things are more complicated and the predicted n spectrum depends on the hadro-production data / models used

T2K Setup


ND280m
ND2km
μ monitor
SK
p
π
ν
off-axis
on-axis
0m
140m
280m
2 km
295 km
neutrino decay volume
ECAL
TPCs
FGDs
Magnet yoke
Magnet coils
ν beam
Pi-zero Detector
Tracker
41.4m
39m
Inner detector
11146 20" PMTs
Outer detector
1885 8" PMTs

$\nu_\mu \rightarrow \nu_X$ disappearance

Basic analysis strategy

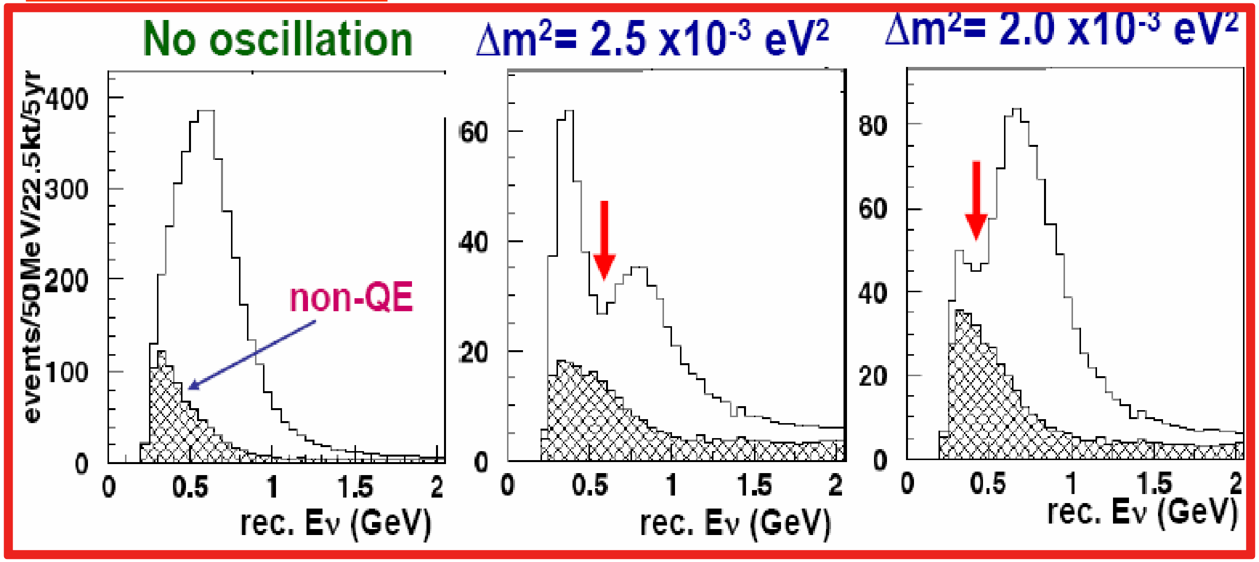
Measure ν_μ flux and energy spectrum with near detectors

Make a ν_μ flux prediction at the far detector by extrapolating the near detector measurements to the far detector using a (energy-dependent) far-to-near ratio prediction from the beam MC assuming no oscillations

Compare the measured ν_μ flux (rate and energy spectrum) at the far detector with the no-oscillation predictions

5 years running

assume $\theta_{23} = \pi/4$

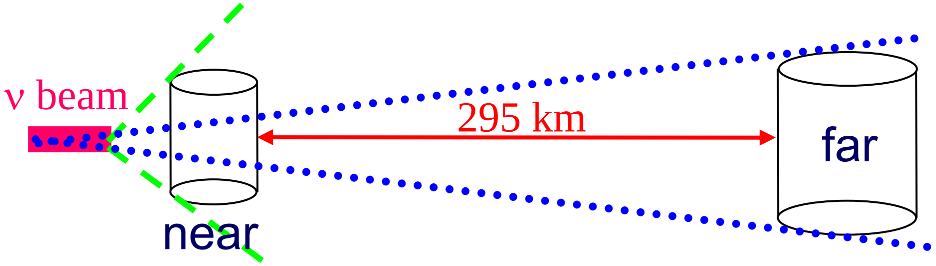


Goal
$\delta(\sin^2 2\theta_{23}) \sim 0.01$
$\delta(\Delta m_{23}^2) \sim < 3\times10^{-5}$

T2K ν beam

1. predict ν_μ flux at far detector
2. estimate ν_e background

$$\Phi_{SK}^{exp} = R_{F/N} \cdot \Phi_{ND}^{obs}$$



Near and far detectors see different solid angles:

1. far detector: point-like source at 2.5°
2. near detector: extended source 1° to 3° (wide off axis angular range)

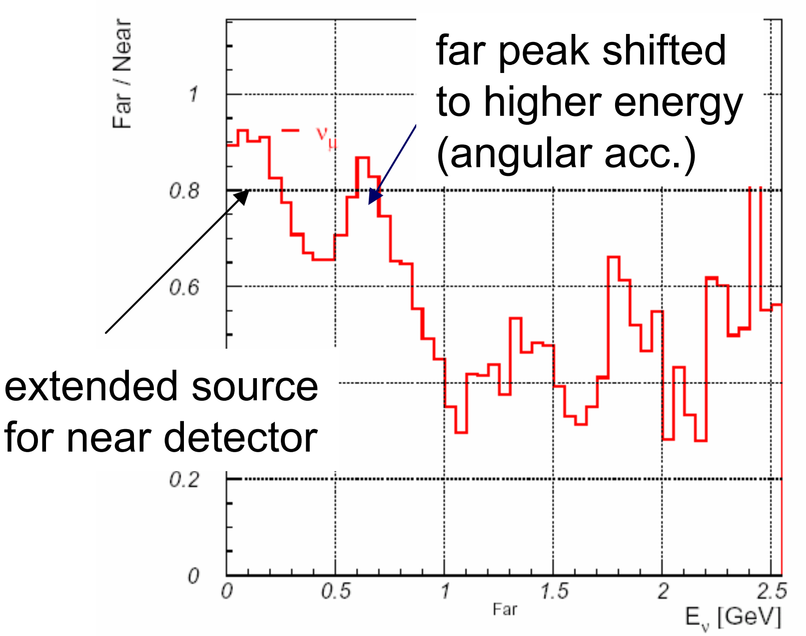
⇒ complicated far to near flux ratio

to predict the ν flux ratio correctly need to know the details of the ν parent hadro-production kinematics

instead of hadronization models (Fluka et al.) use measured pion and kaon x-sections

note: no measurements at these beam energies (30 – 50 GeV) and phase space (very large angles)

far-to-near flux ratio
(T2K beam MC prediction)



F/N Extrapolation & NA61

- Spectrum at far site is different from near site even w/o oscillation
  - Effect of non-point-like source
- T2K analysis

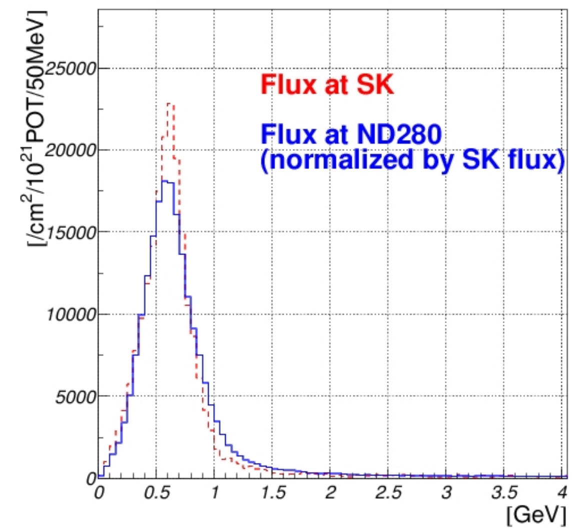
Expected flux at SK

$$\Phi_{SK}^{\exp} = R_{F/N} \cdot \Phi_{ND}^{obs}$$

σ, ε → SK exp'ed obs.

⇕ Osc?

SK observation

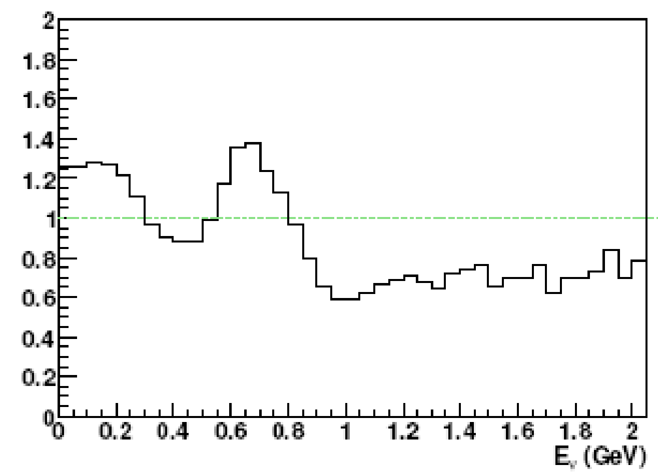


Far/Near ratio

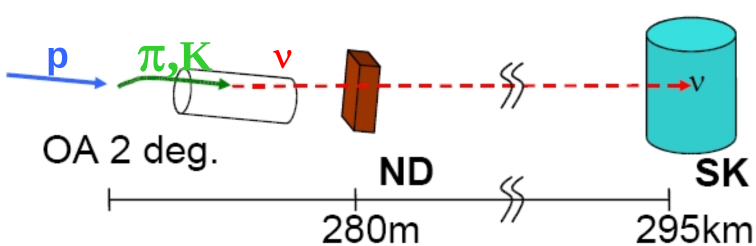
$$R_{F/N} = \Phi_{SK} / \Phi_{ND}$$

Determined by Hadron prod. (&geometry)

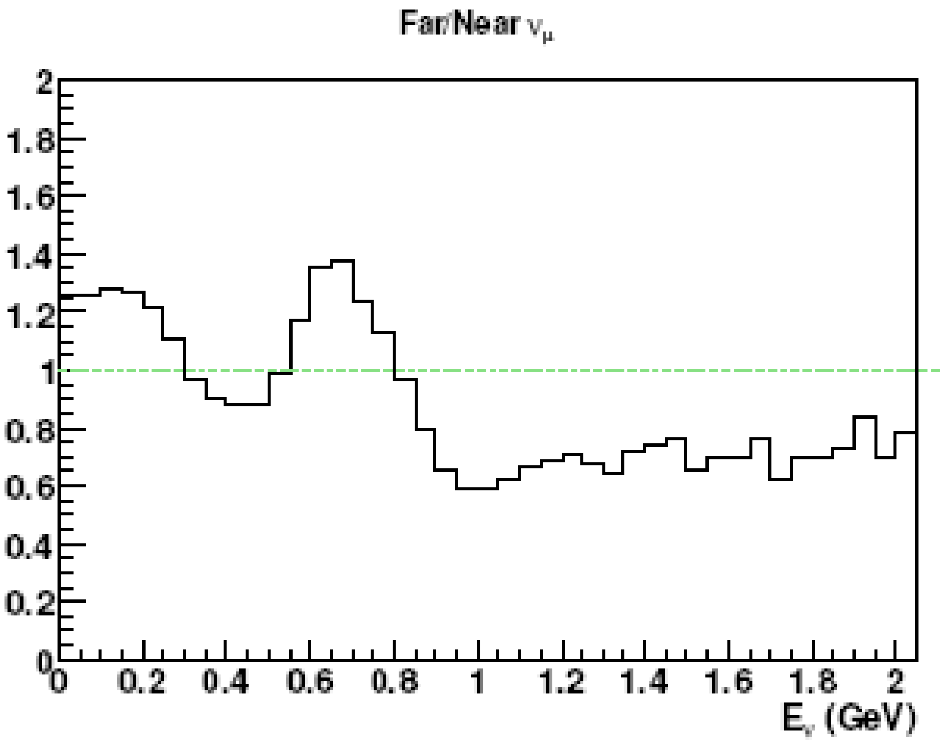
Far/Near ratio



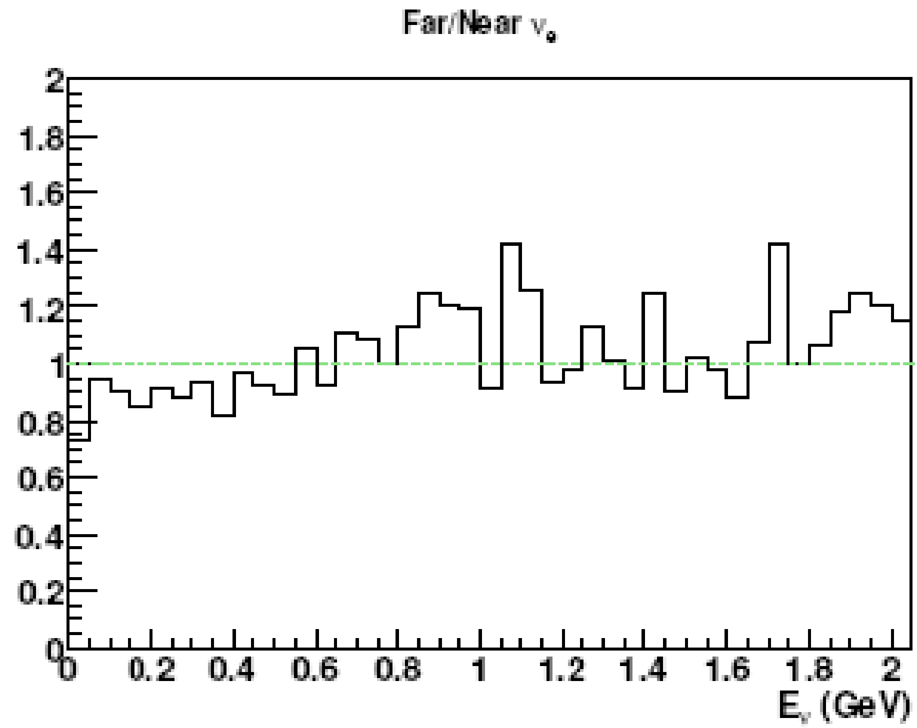
no measurement of particle production off carbon with 30 (,40,50) GeV protons ➔ NA61



Far / Near Flux ratio



near/far ratio
for disappearance ν_μ
is *not* flat



near/far ratio for backgrounds
is quite flat (here ν_e)

Beam studies issues

impact of NA61 measurement

far to near flux ratio

studies based on current beam MonteCarlo

no ND included (yet)

- Effects of
  - K^+/π^+, K^0/π^+ ratio
  - angular distribution (p_T)
  - longitudinal distribution
  - target and horns misalignement

ν + N n.c. π^0 prod.

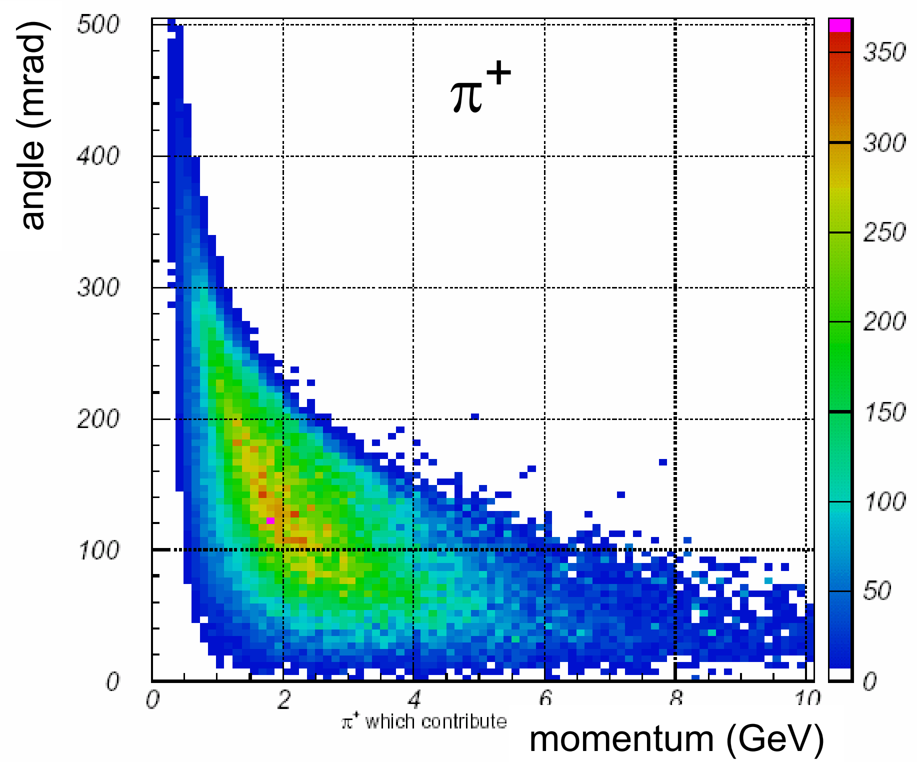
near / far ratio for ν_μ, ν_e, π^0

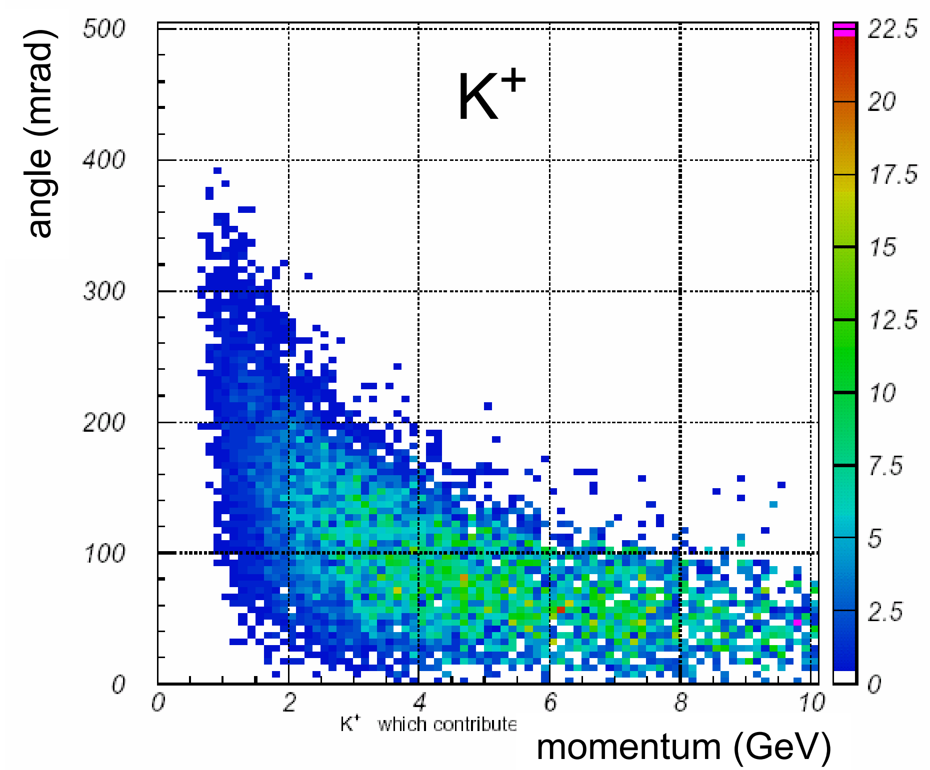
- statistics required

  T2K not statistics limited (ν_μ disappearence)

  200k π events -> ~ 2-3 % error on the flux ratio

T2K ν parent hadron phase space (30 GeV)





note: this is not a cross section

it shows the distributions of π and K giving the ν of the T2K beam

need to cover this kinematical region and identify the outgoing hadrons

K component important for ν_e appearance signal (it represents a *background*)

need to measure K production with similar precision as π production

requires: large acceptance and particle ID

Statistics / precision required

a 2 – 3 % error on the far/near flux ratio is required for ν_μ and ν_e

~ 200k π^+ tracks are needed (crude estimate)

~ 200k K^+ tracks are needed (crude estimate)

in phase space of T2K beam

with a simple interaction trigger (no charge / flavor selection)

for 10^6 interactions will also have (NB ~ 10% acceptance !)

~ 100k π^- tracks

~ 10k K^+ tracks

Why ?

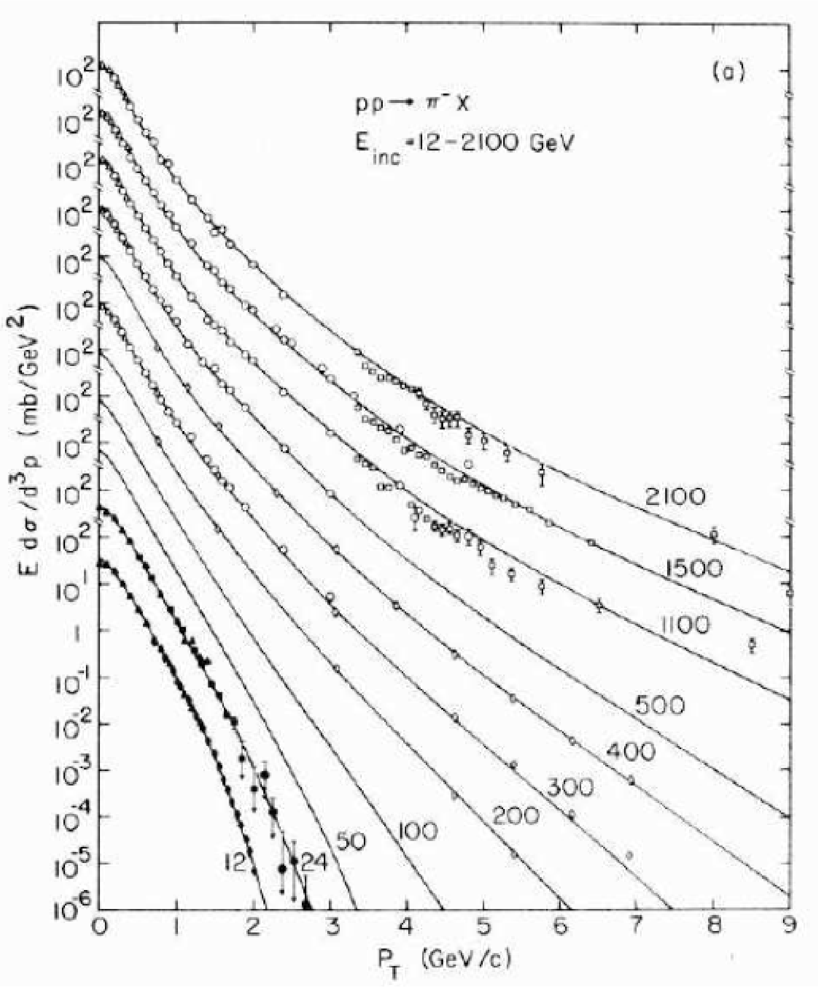
- measure $\pi^{+/-}$, $K^{+/-}$, K^o production
in phase-space of T2K ν beam

- no data at these energies 30 – 50 GeV,
in particular for large production angles
(θ > 100 mrad)
extrapolations possible but not too reliable

- reinteractions / absorbtion of few GeV
pions poorly described
(up to factors of ~ 2)

- Large uncertainties on K production

- prefer to base ν beam description on actual measurements
rather than more or less reliable hadron interaction models

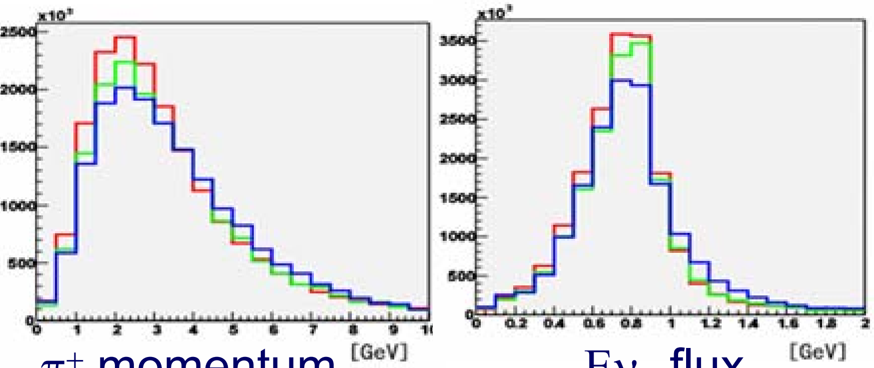


Systematic uncertainties due to "models"

It is difficult to evaluate the validity of the hadron production model !!

→ The uncertainty is probably not less than the difference among several models inspired by similar data sets

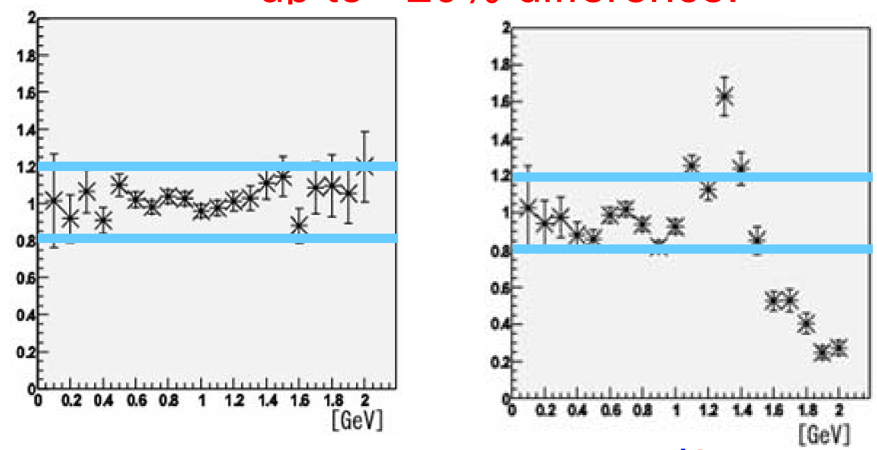
G-FLUKA vs. MARS vs. FLUKA



π^+ momentum $E\nu_\mu$ flux

Ratios of F/N ratios

up to ~20% difference!



MARS/G-FLUKA **FLUKA/G-FLUKA**

F/N ratio difference among hadron production models:
~ 20% @$E\nu \le$1GeV

➡

Syst. error due to F/N

ν_e *appearance*

$\delta(N_{bg}) \sim 15\%$

ν_μ *disappearance*

$\delta(\sin^2 2\theta_{23}) \sim \pm 0.015$ -0.03,
$\delta(\Delta m_{23}^2) <\sim \pm$ 5-10 10^{-5}eV^2

>>

Goal of T2K

ν_e *appearance*

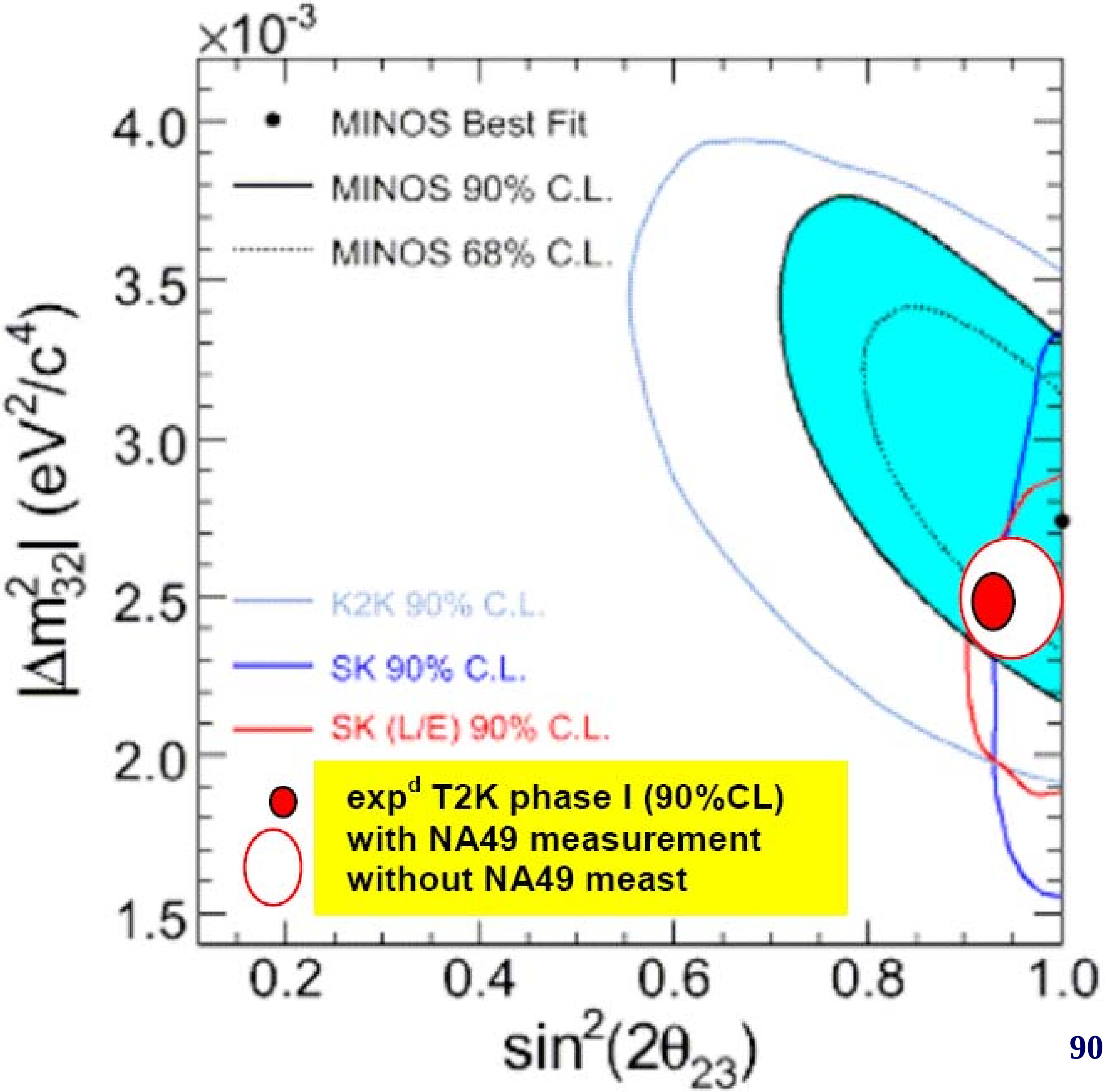
$\delta(N_{bg}) \le 10\%$

ν_μ *disappearance*

$\delta(\sin^2 2\theta_{23}) \sim \pm 0.01$,
$\delta(\Delta m_{23}^2) <\sim \pm 3\ 10^{-5}$eV^2

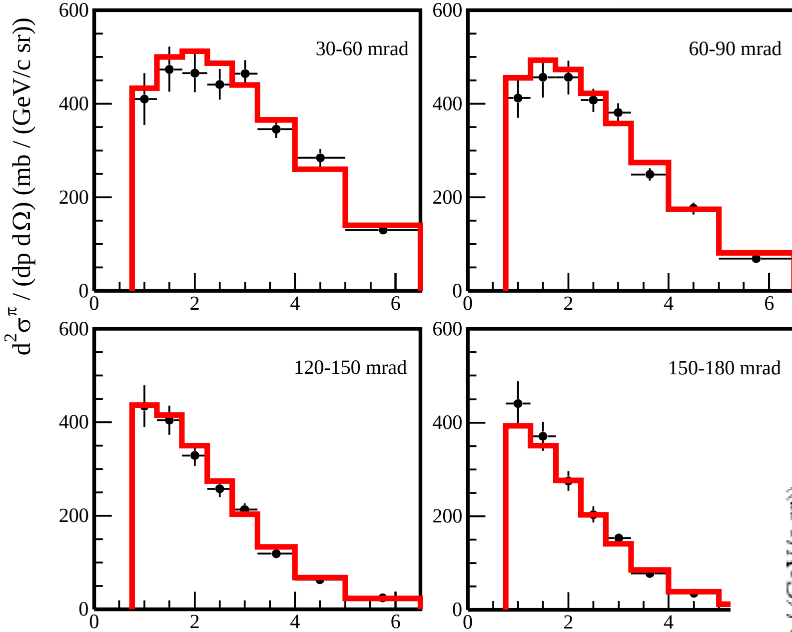
Impossible to achieve T2K GOAL!

Improvement that the NA49 data could bring to the T2K results on atmospheric oscillation parameters:



90%CL ⇔ $\Delta\chi^2 = 4.7$

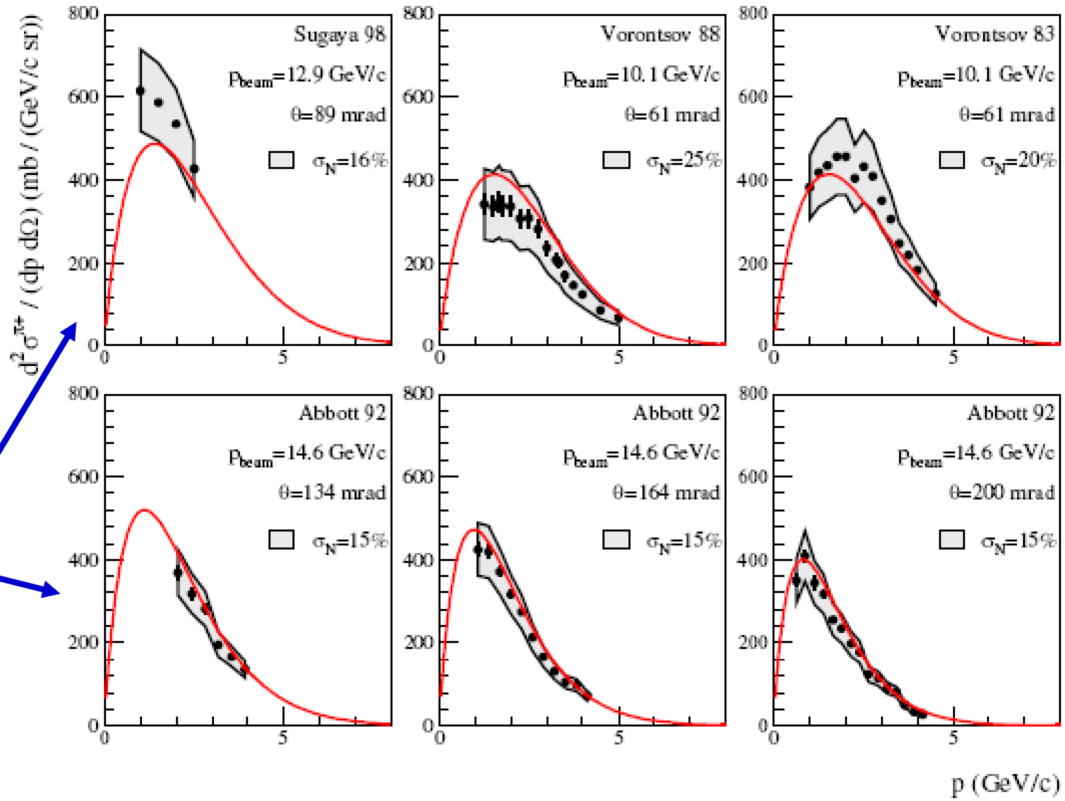
HARP Result (p-Al at 12.9 GeV)



HARP data points

HARP Sanford-Wang parametrization

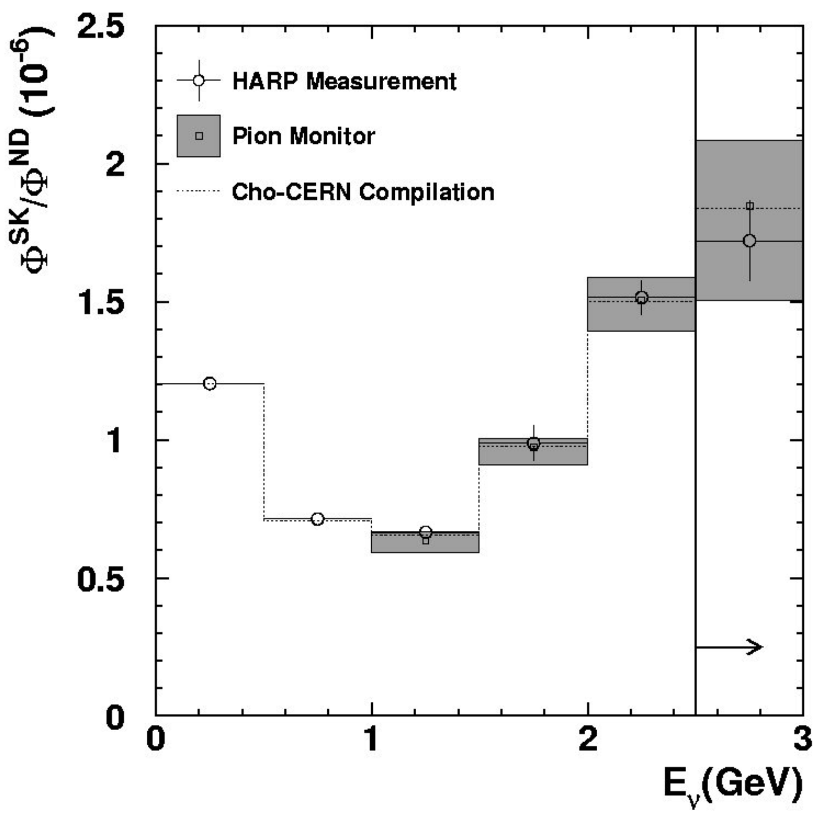
results based on ~200 k reconstructed tracks



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

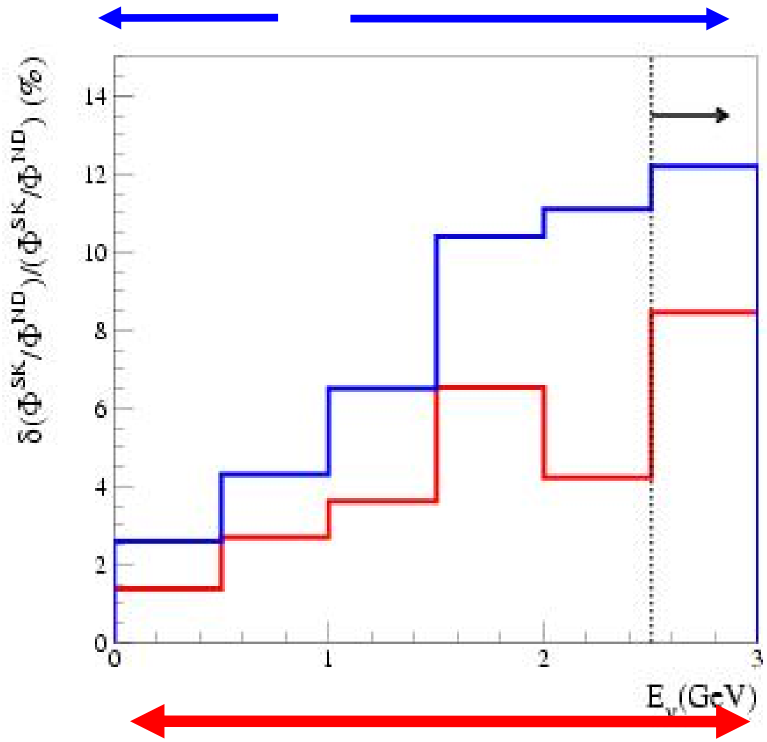
K2K F/N flux ratio prediction

K2K / HARP final result



<1 GeV: Cho/CERN errors

>1 GeV: PIMON errors

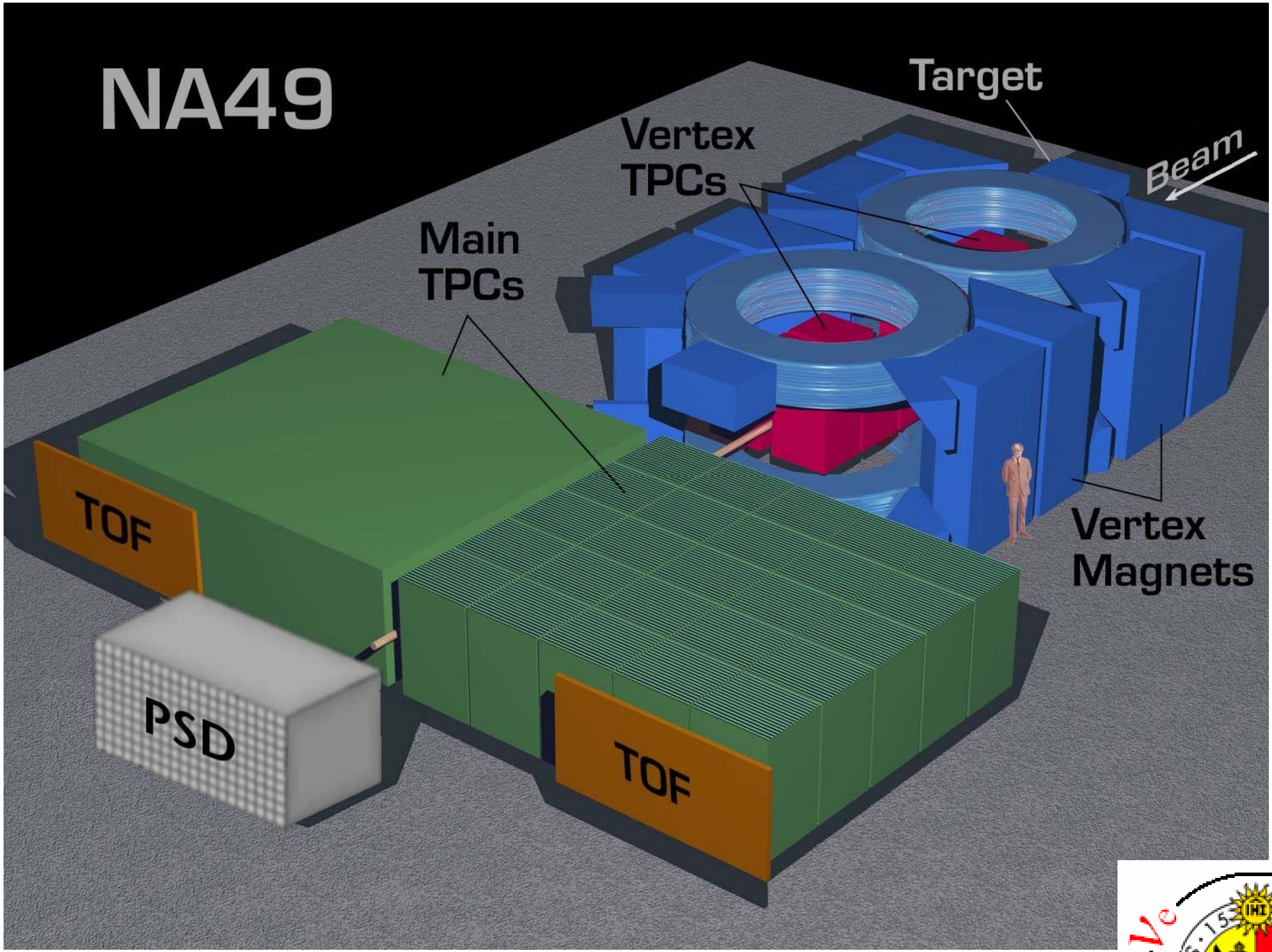


All energies: HARP (plus others) errors

three different predictions,
within errors,
are consistent with each other

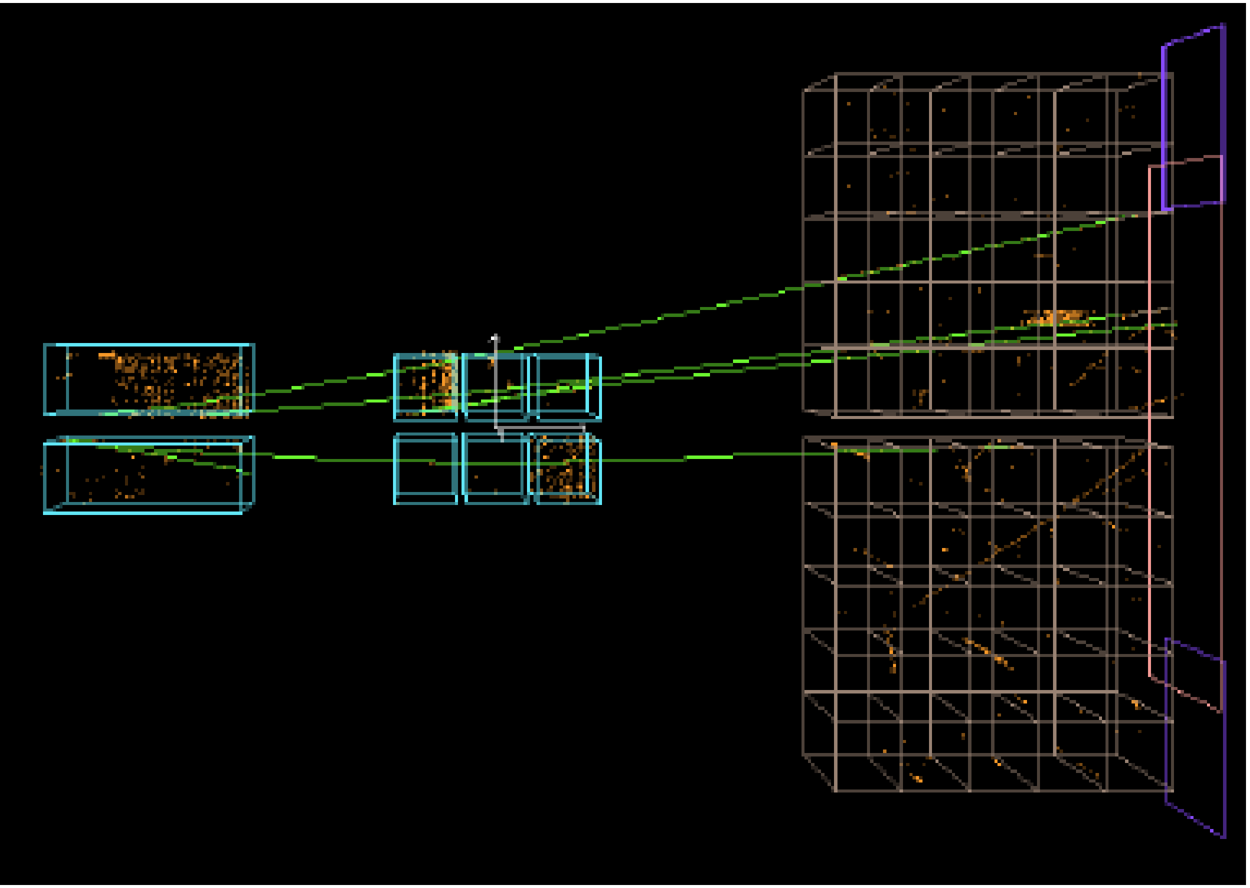
HARP: almost **factor of 2 error reduction**
for all energies compared to previous assumptions
Systematic error on n flux from ~7% down to ~4%

NA61 setup

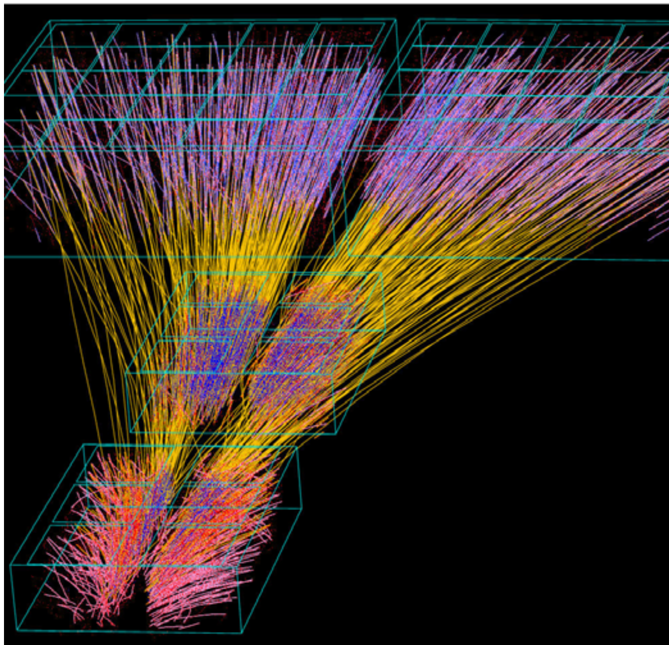


Detector as used by NA49 collaboration:
some upgrades required for NA61 physics (incl. T2K)

Typical Proton Event



Heavy Ion Event



NA49 Cross Sections (158 GeV p beam)

total cross sections
(with simple interaction trigger)

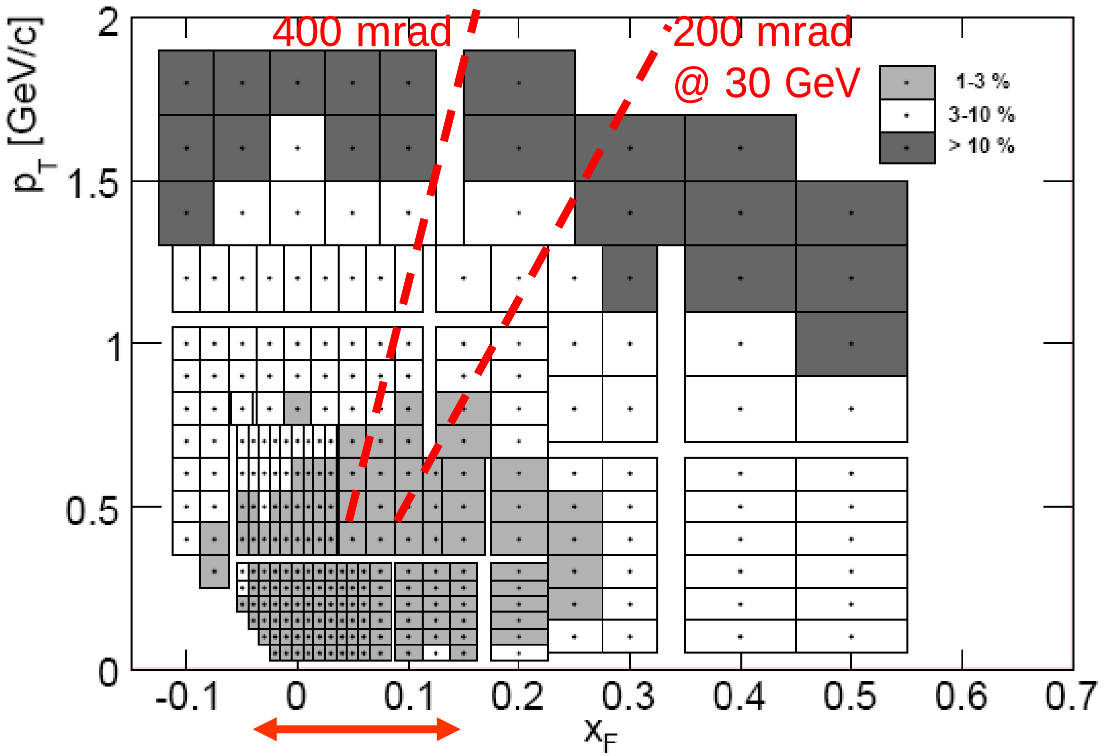
σ_{trig}	28.23 mb
loss from p	3.98 mb
loss from π, K	0.33 mb
contribution from σ_{el}	-1.08 mb
predicted σ_{inel}	31.46 mb
literature value	31.78 mb

p – p collisions
hep-ex/0510009

σ_{trig}	210.1 mb
loss from p	17.1 mb
loss from π and K	2.4 mb
contribution from σ_{el}	-3.3 mb
predicted σ_{inel}	226.3 mb
literature value	225.8 mb

p – C collisions
hep-ex/0606028

π^+ statistical errors



total statistics (p – C)

Events taken		Events after selection	
Full target	Empty target	Full target	Empty target
535.7 k	31.2 k	377.6 k	11.8 k

π^+ production

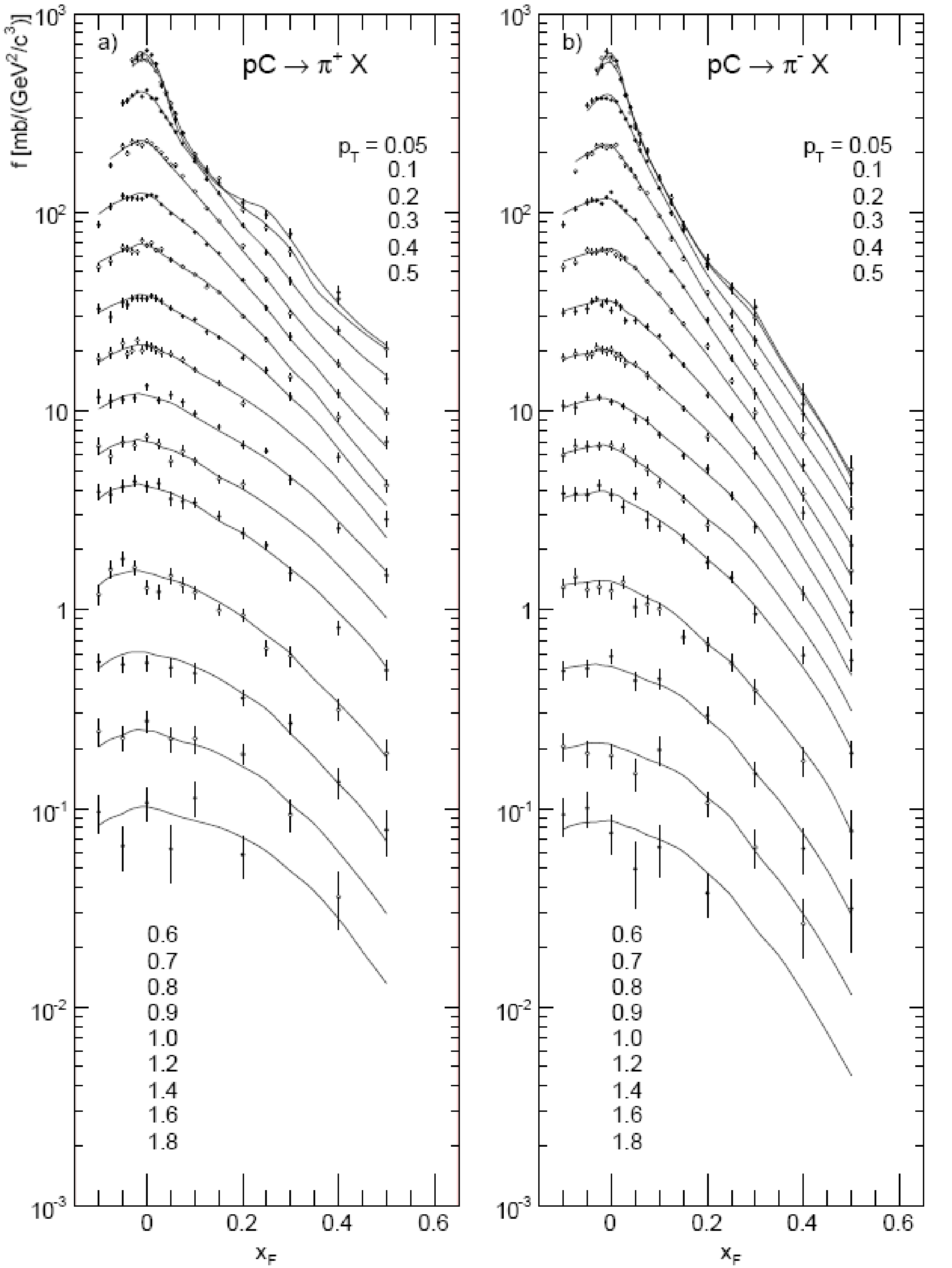
π production Cross Sections (P_{beam} = 158 GeV)

total systematical error
(π+ and π- production)

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

statistical error ~ few %

~ 400 k reconstructed tracks



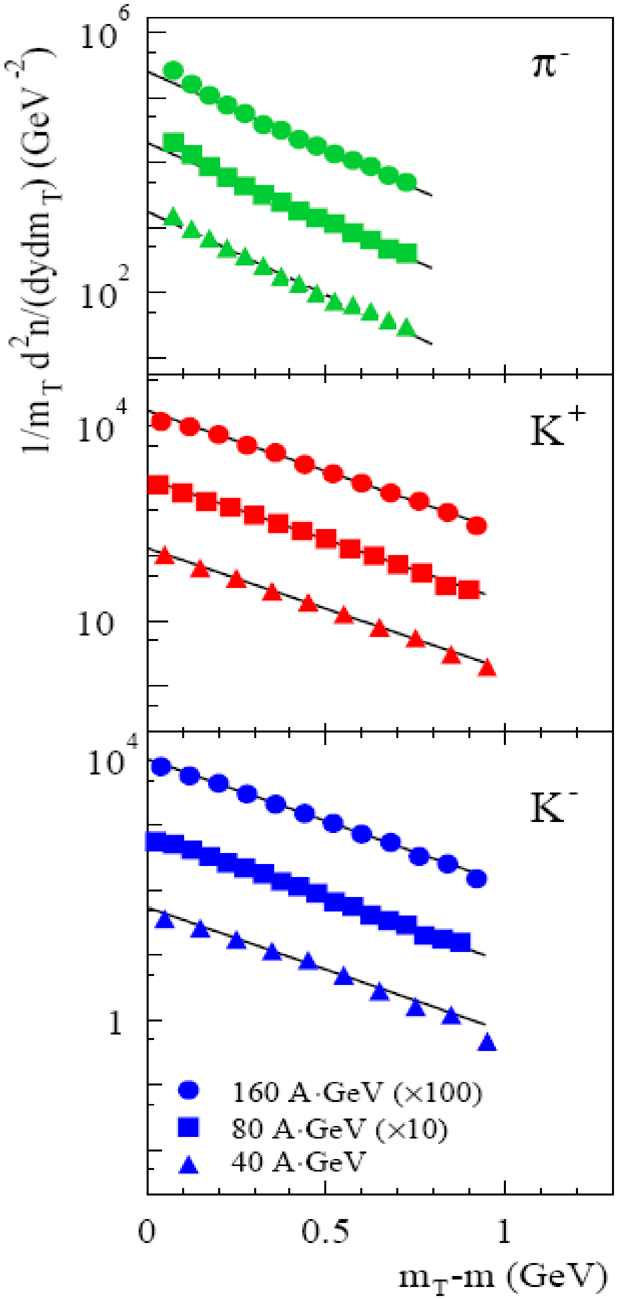
Kaon production

~ 5 to 10 x smaller σ compared to π

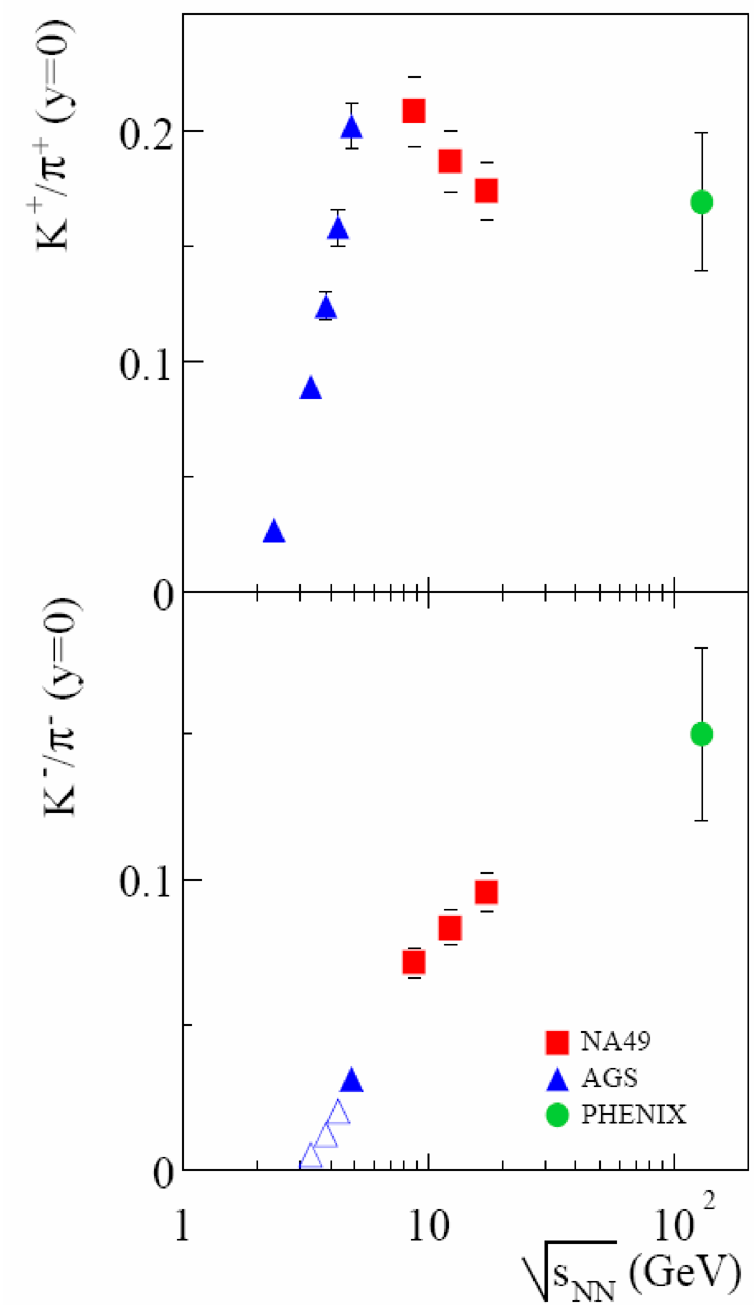
systematical error:

~ 5%
(~10 % acc. edges)

transverse mass



ratios



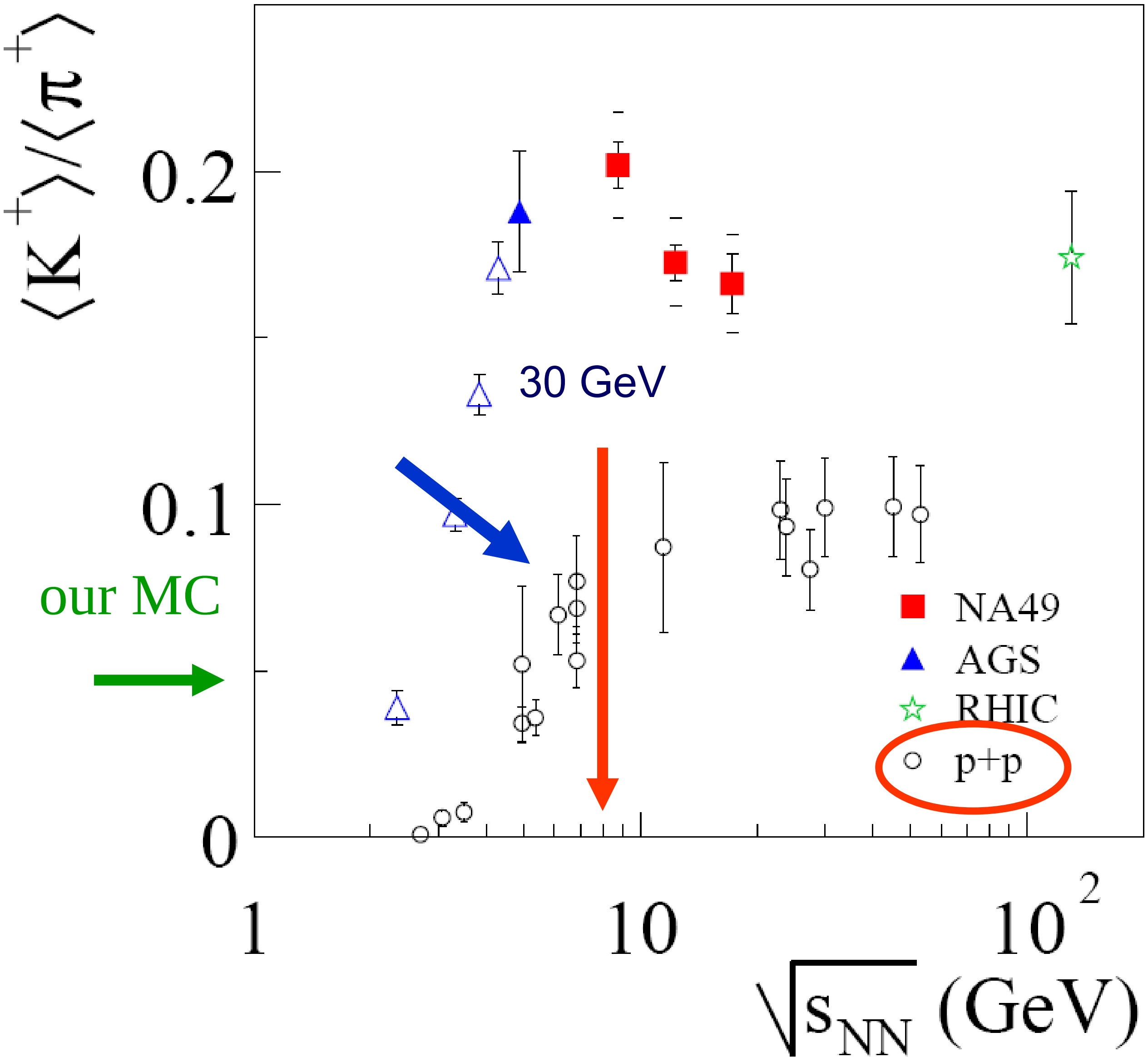
Some data on K production

from NA49 publication
nucl-ex/0205002
Heavy Ion data and
pp data (for comparison)

pp data compiled by
M. Gazdizcki
hep-ex/9607004

from this plot
<K+> / <π+> ~ 0.06 – 0.08
at 30 GeV

clearly the situation is not
satisfactory at all



The 2007 NA61 run

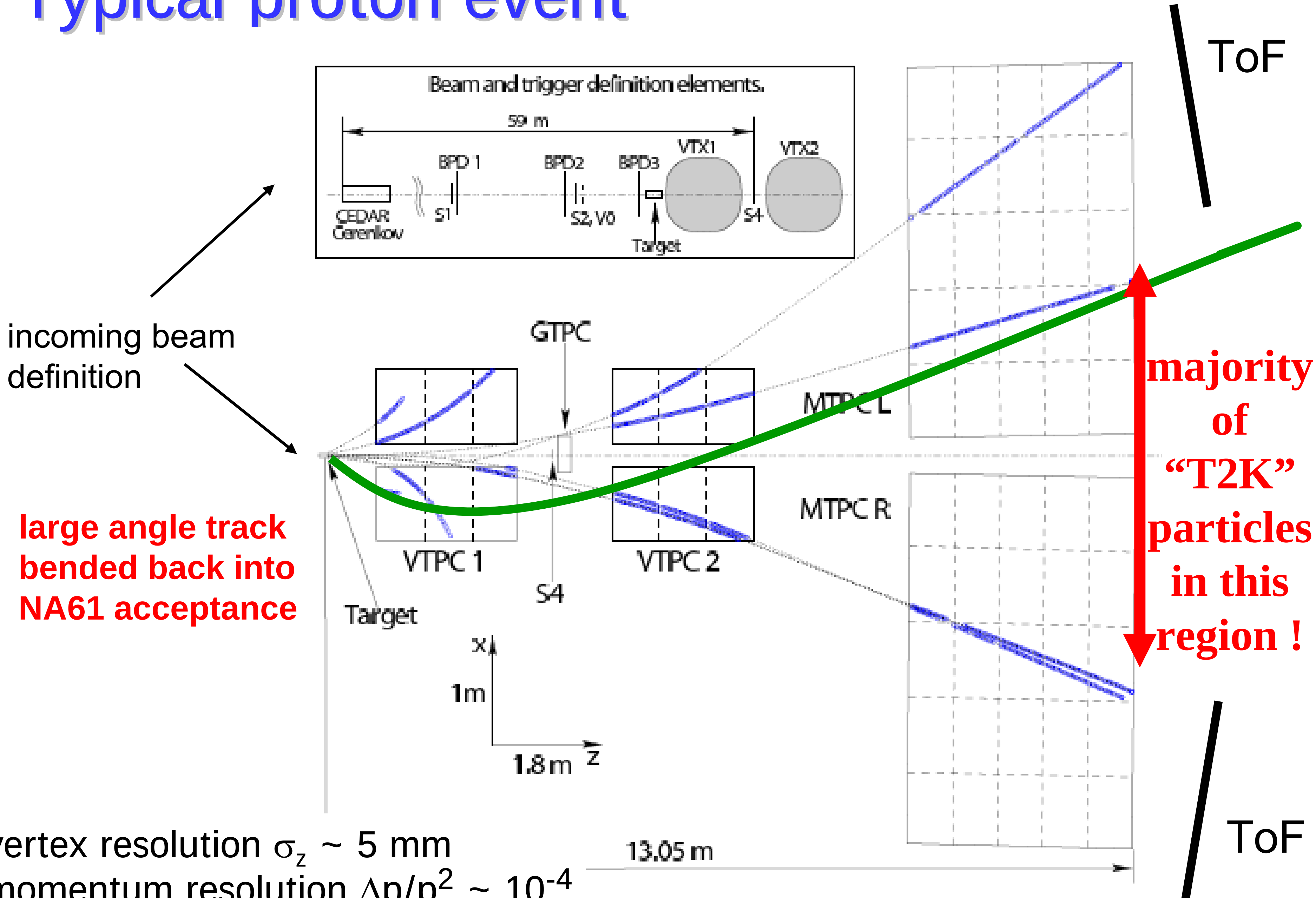
first NA61 run in October 2007 (~30 days)

~ 2 weeks for set up
~ 2 weeks of data taking
 12 days using a thin C target (4% λ_I)
 3 days with the T2K replica target

data collected:

- 660 k triggers with thin target
- 220 k triggers with replica target
- 100 k calibration events

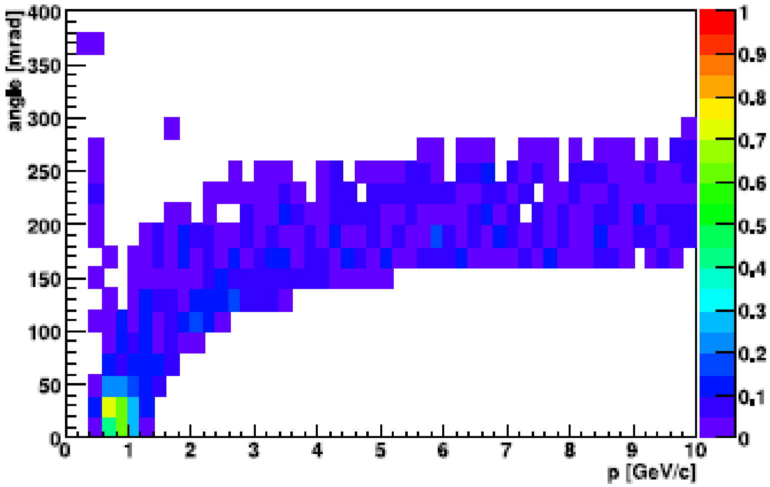
Typical proton event

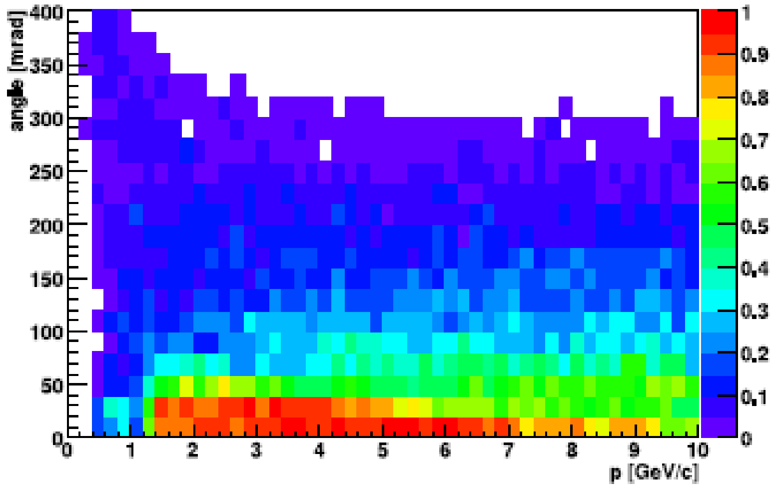


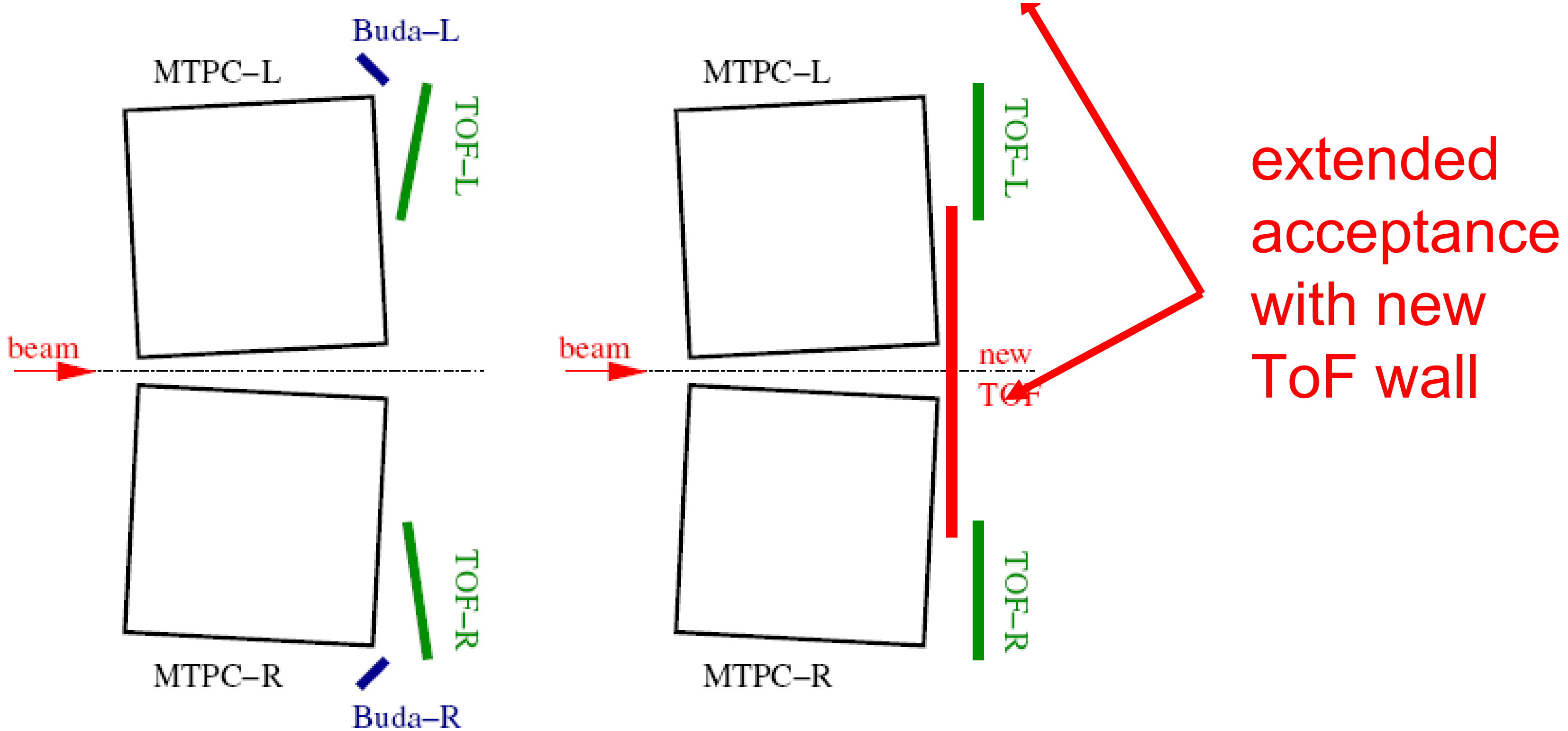
vertex resolution $\sigma_z \sim 5$ mm

momentum resolution $\Delta p/p^2 \sim 10^{-4}$

ToF Acceptance

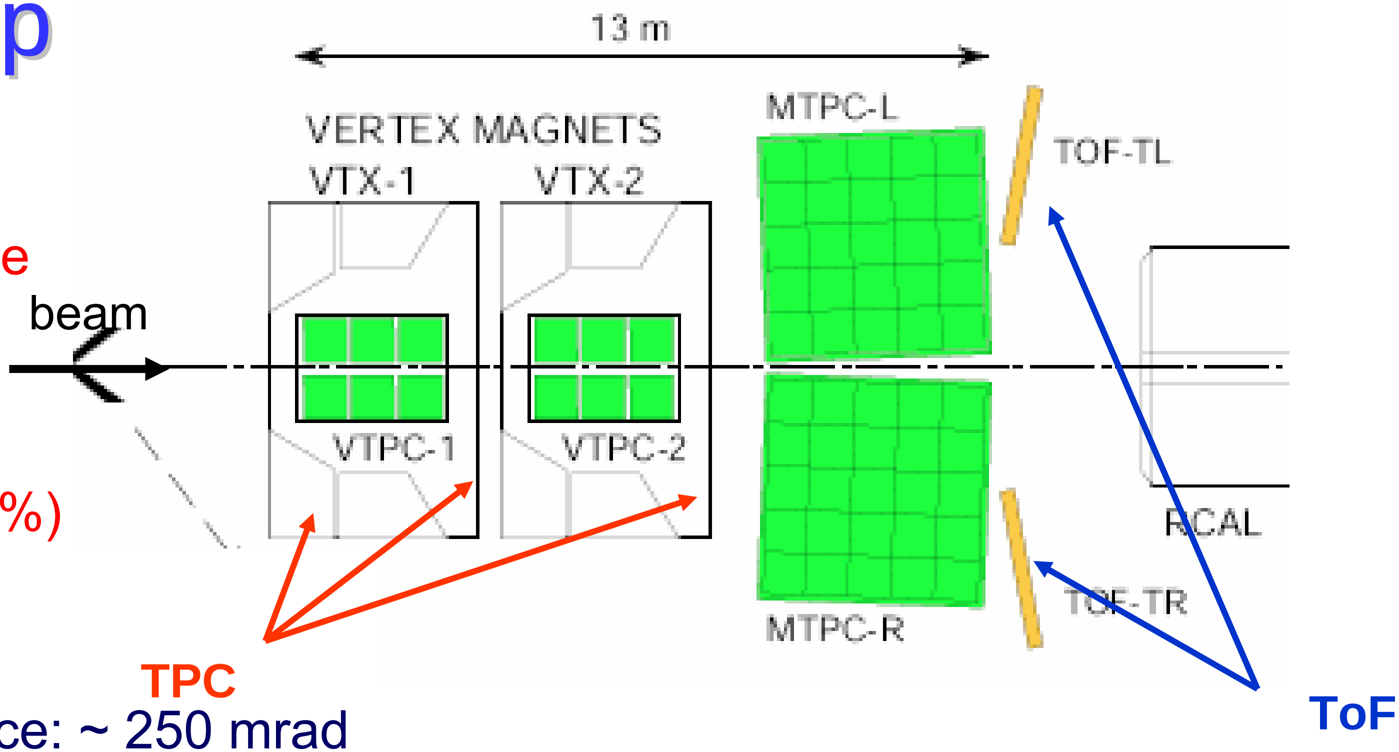






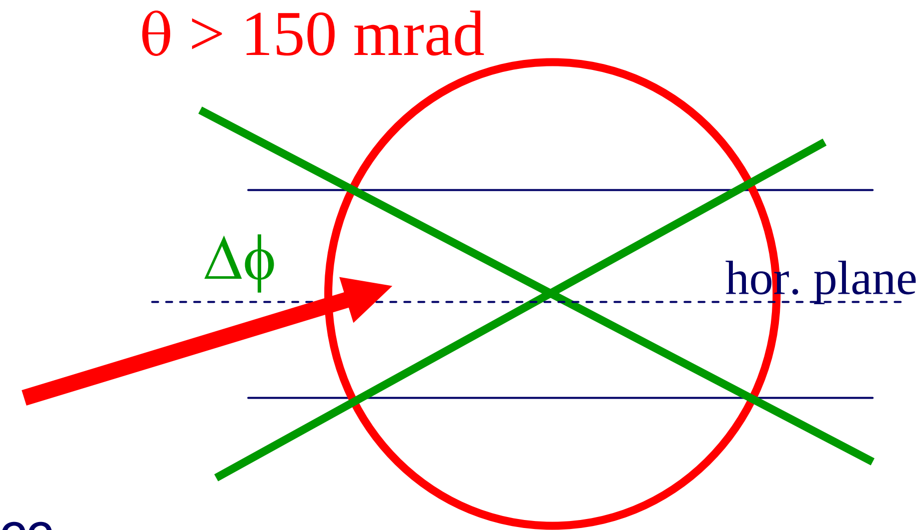
NA61 setup

Why the acceptance
is so small in
the phase space of
the T2K beam ?
(i.e. around 10 - 15%)



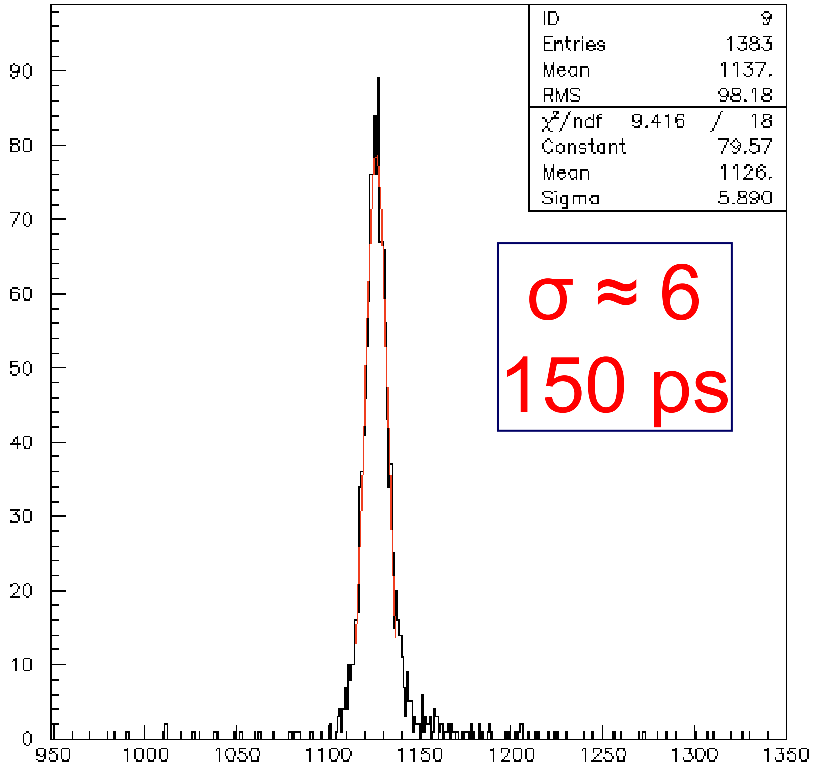
horizontal acceptance: ~ 250 mrad
not an issue

vertical acceptance: ~ 45 mrad !
limited by vertical size of TPCs and ToF



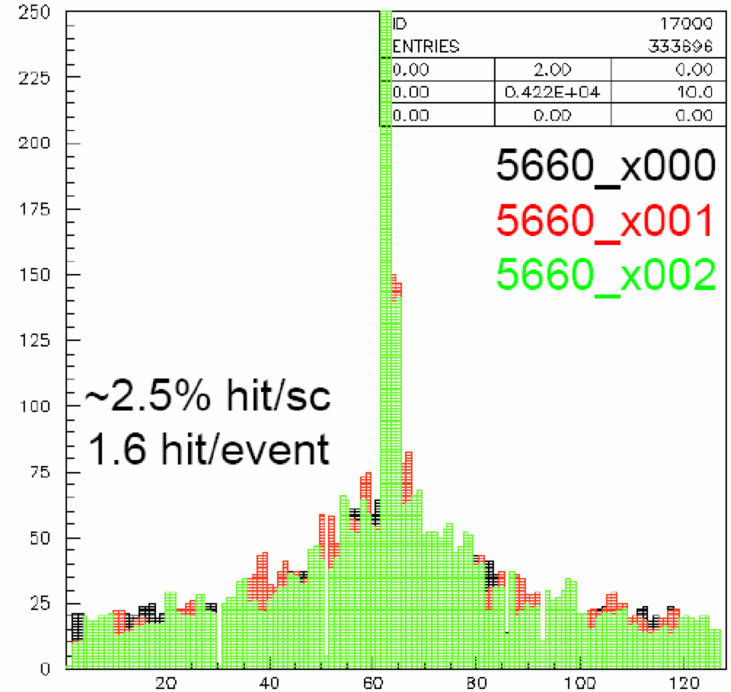
large angle tracks produced close to the horizontal plane and bend back by **B** will be detected:
e.g. for $\theta > 150$ mrad, $\Delta\phi \sim 30^0$ -> 1/12 acc.

ToF Performance (online)

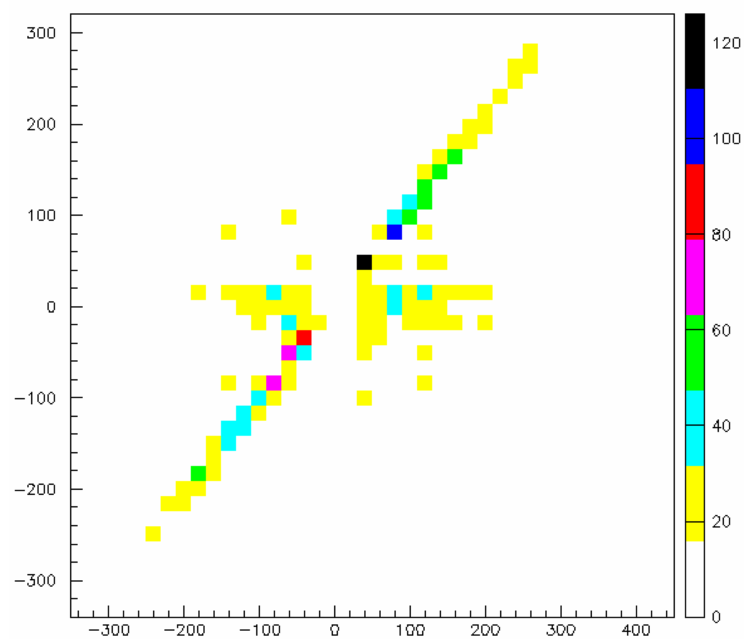


time resolution before calibration

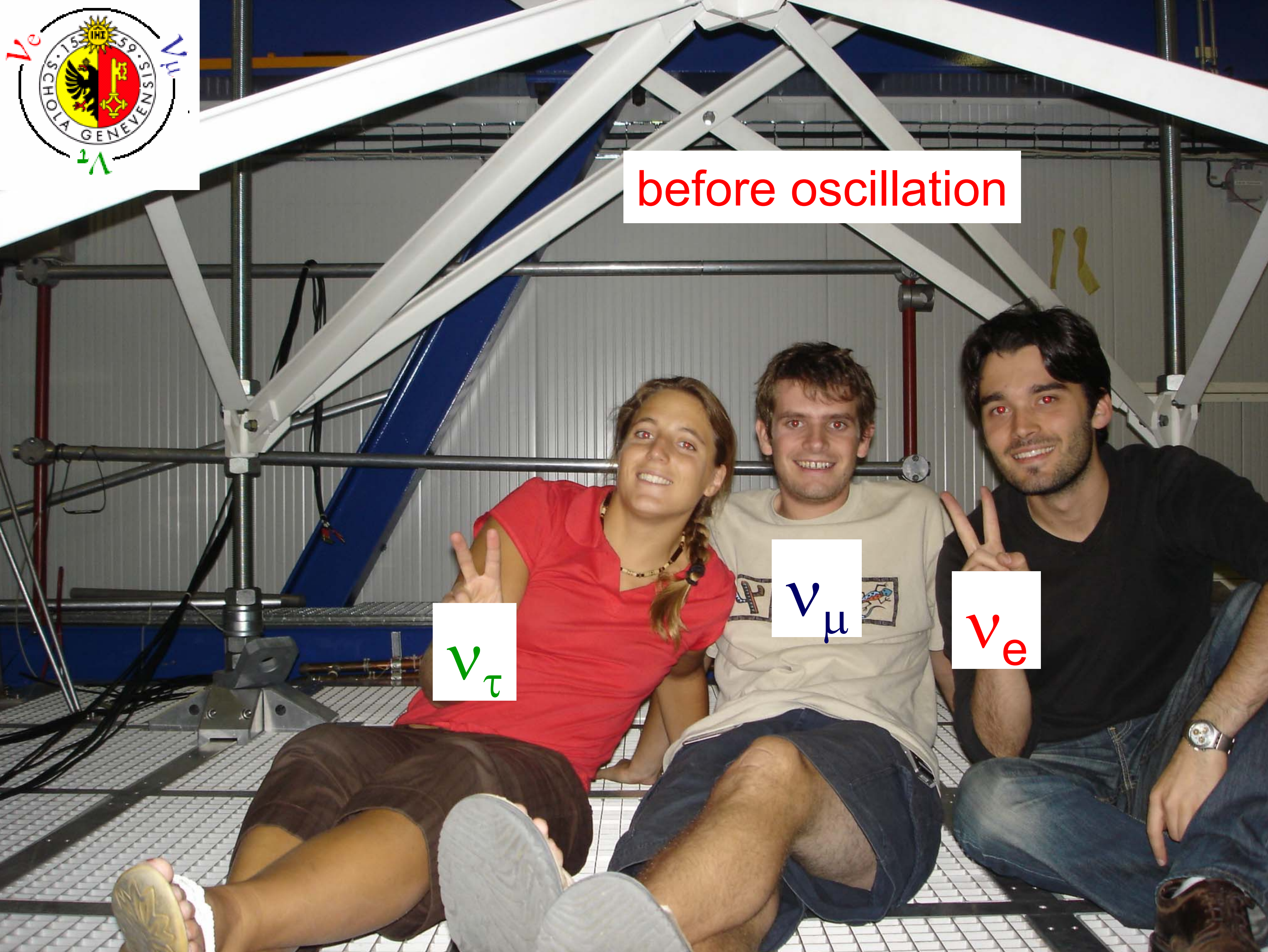
hit distribution / scintillator

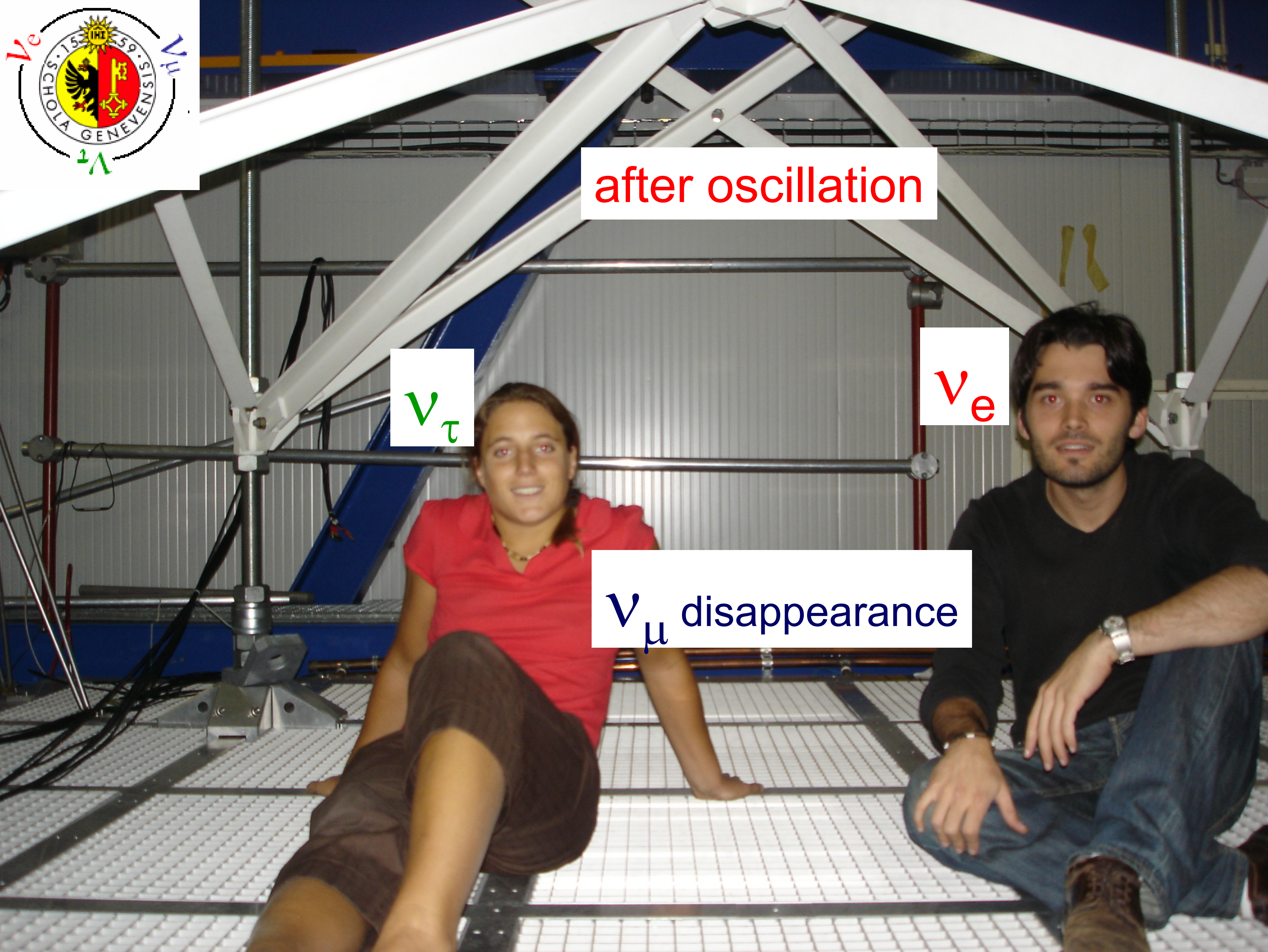


Correlation
ToF – TPC tracks

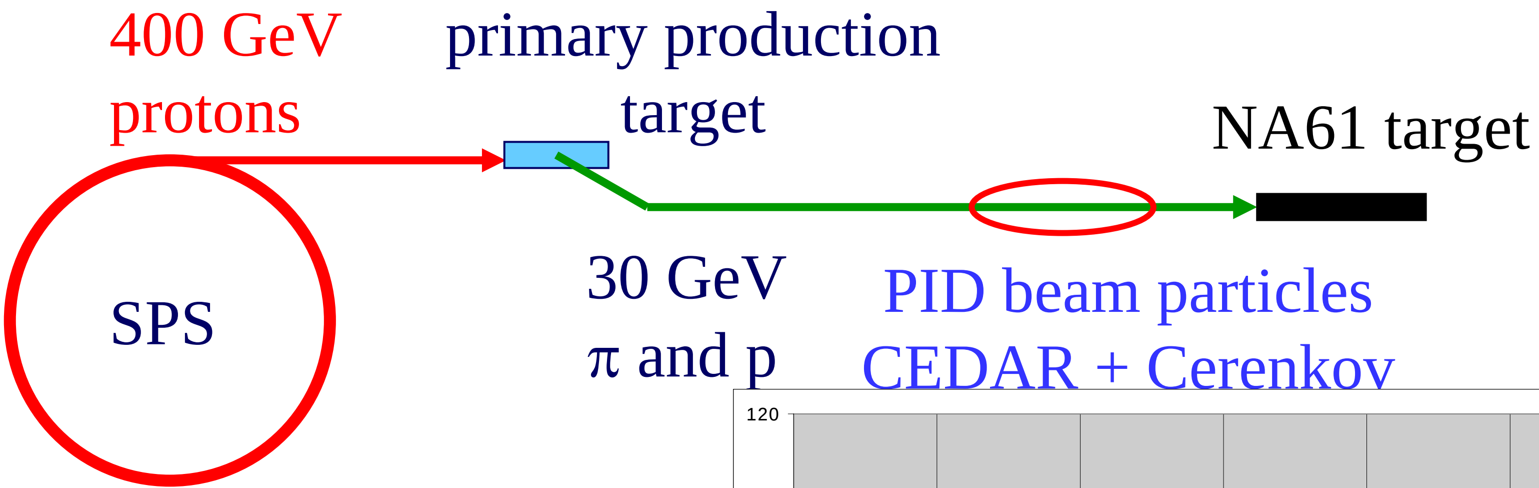


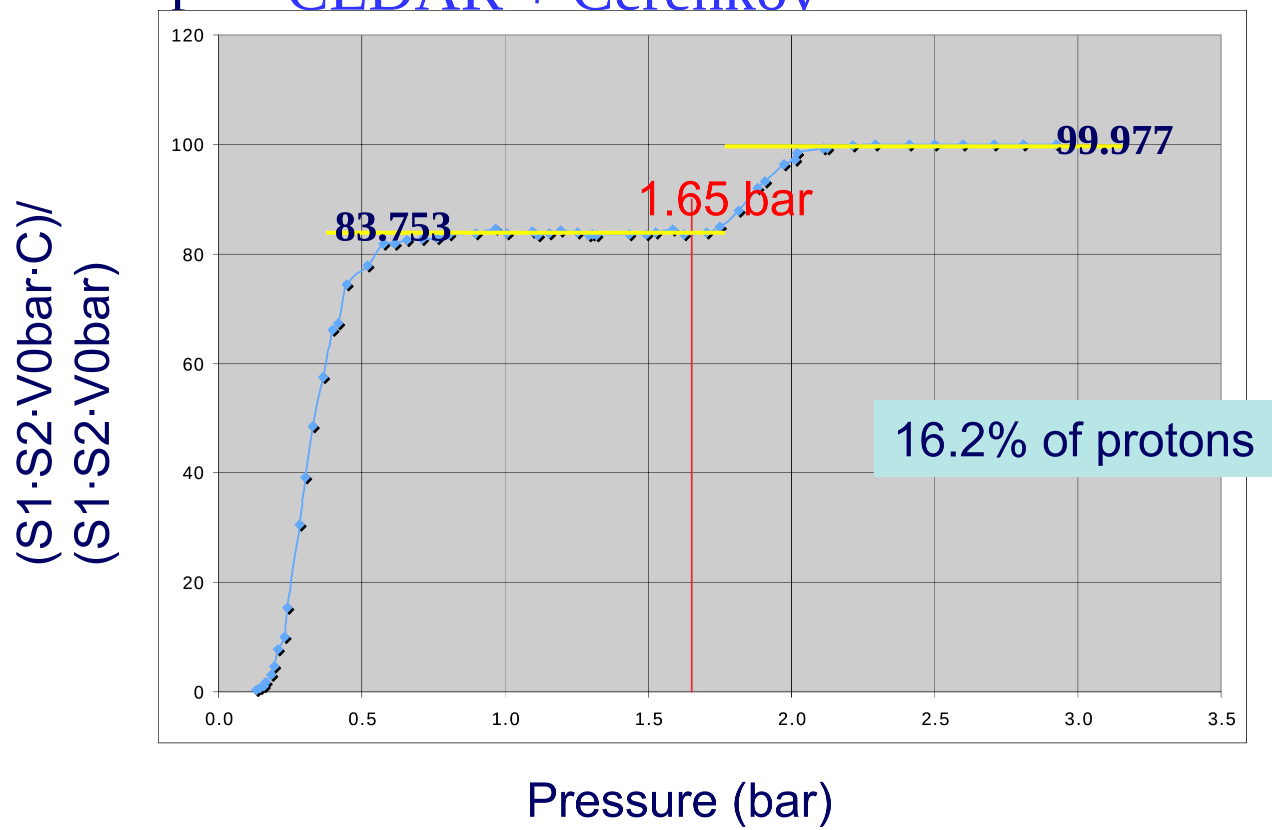
before oscillation




after oscillation
ν_τ
ν_e
ν_μ disappearance

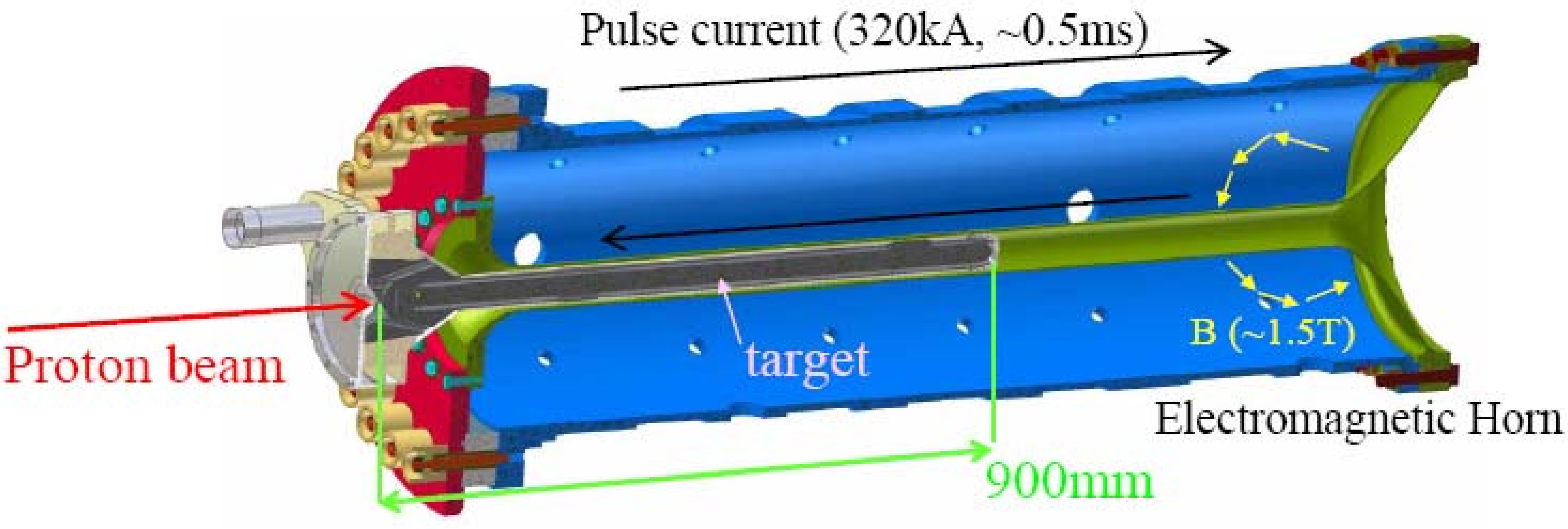
The Beam


400 GeV protons
primary production target
NA61 target
SPS
30 GeV
π and p
PID beam particles
CEDAR + Cerenkov


(S1·S2·V0bar·C)/
(S1·S2·V0bar)
Pressure (bar)
83.753
99.977
1.65 bar
16.2% of protons
0
20
40
60
80
100
120
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

The T2K Target

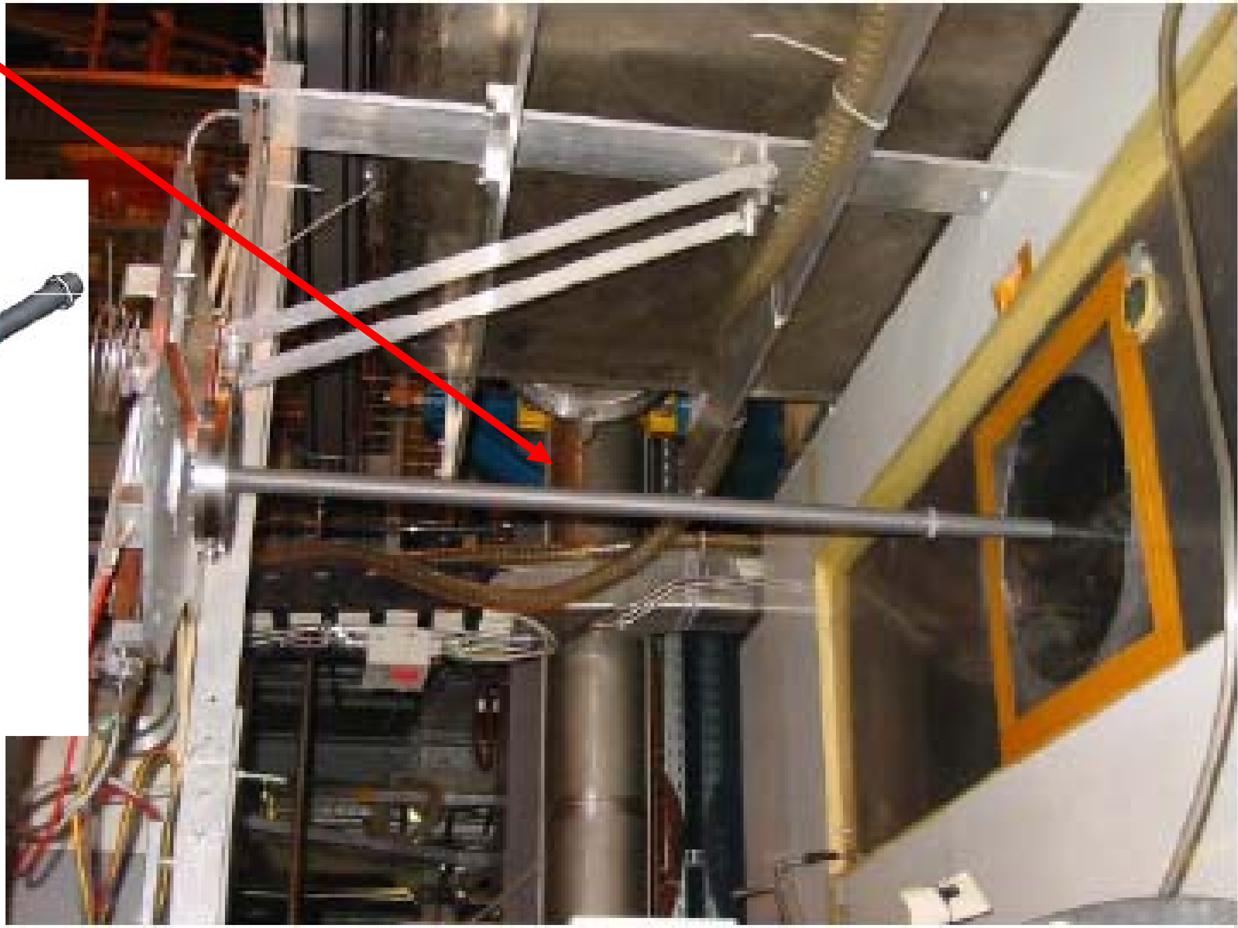
- Material: Isotropic graphite (C) : ρ=1.82g/cm^3
- Length: 900mm = 1.9 $\times$ λ_{int} (85%)
- Diameter: ϕ26mm
  ←→ Beam size: σ_x=σ_y=4.2mm
- Target is installed inside the Electromagnetic horn
  - EM horn generate the toroidal magnetic field to correct pions.
  - Materials between target and the magnetic field:
    - Cooling tube: t=2mm graphite (C) + 0.3mm Ti-Alloy + 0.5mm ceramic



T2K Target replica

KEK

90 cm
graphite
26 mm dia.



not easy installation and alignment

2008 run: important to improve on the alignment of the target !

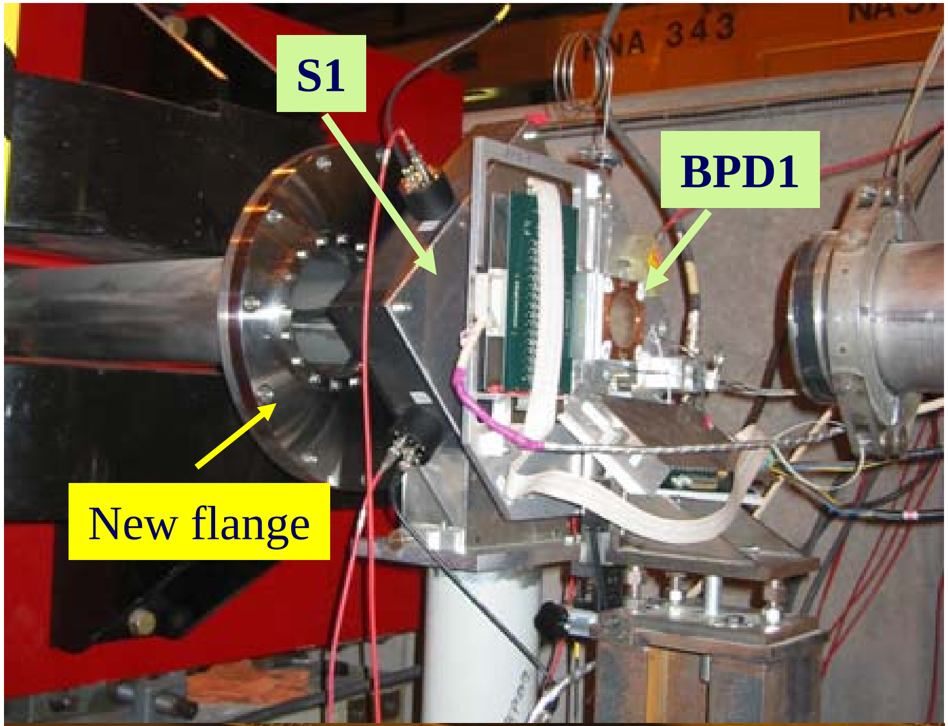
Trigger setup

Trigger definition: $S1 \,\&\, S2 \,\&\, \overline{V0} \,\&\, \overline{V1} \,\&\, \overline{S4}$

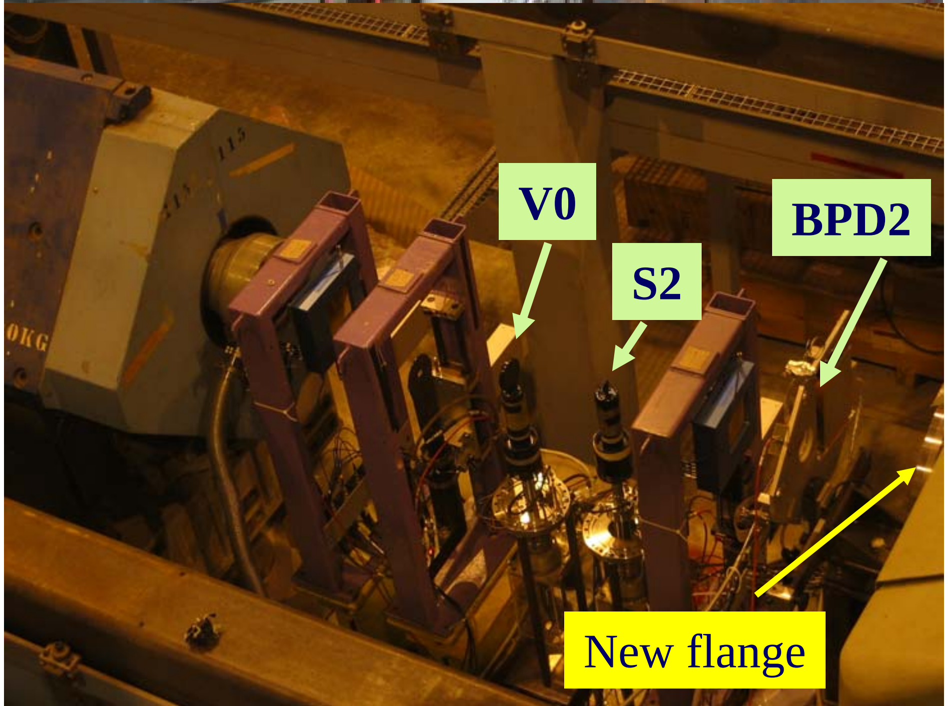
Beam definition: $S1 \,\&\, S2 \,\&\, \overline{V0} \,\&\, \overline{V1}$

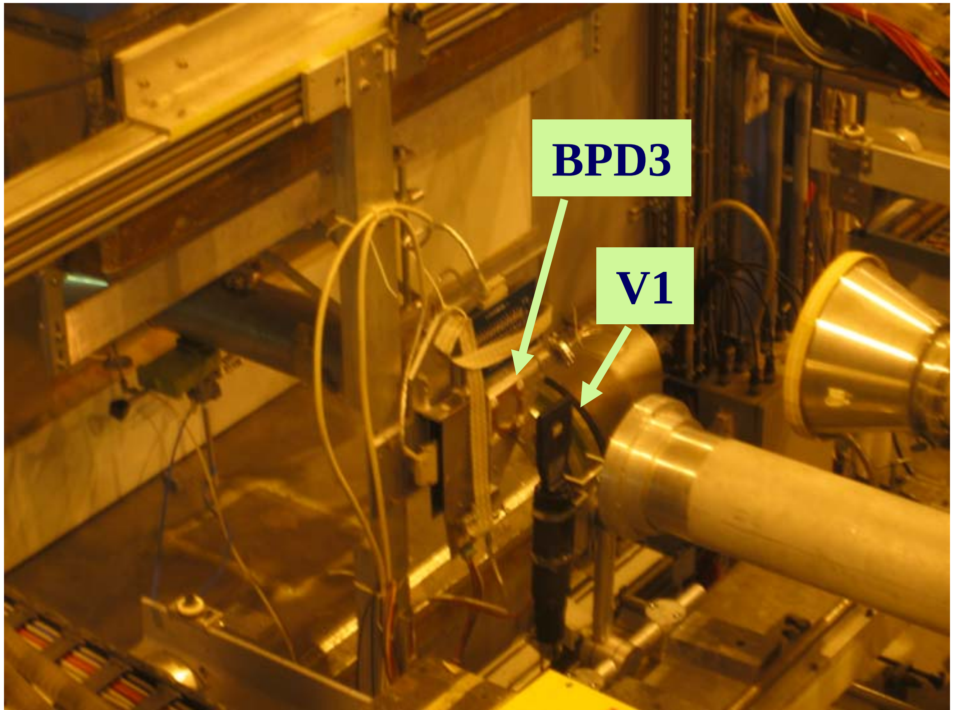
Distances are not exact and do not include survey measurements taken at the end of the run. For more detailed information on beam and trigger see A.Marchionni's talk.

Trigger counters installations

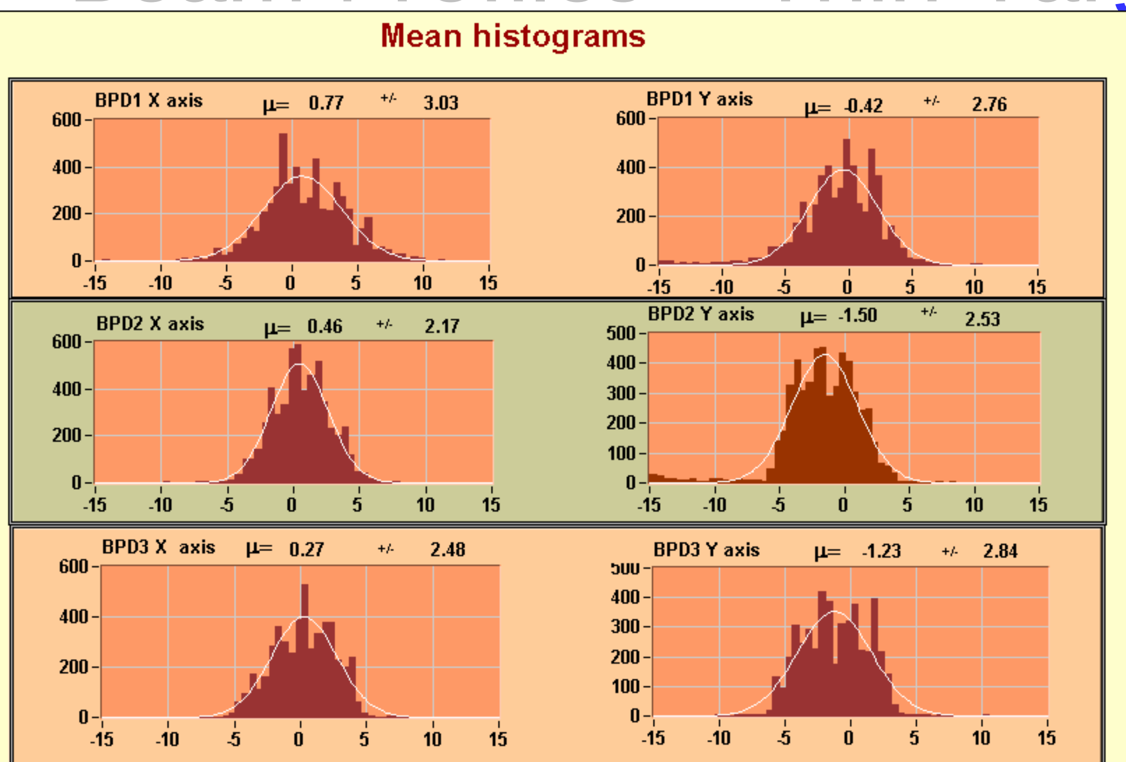


… and S4 between Vertex1 and Vertex2 magnets



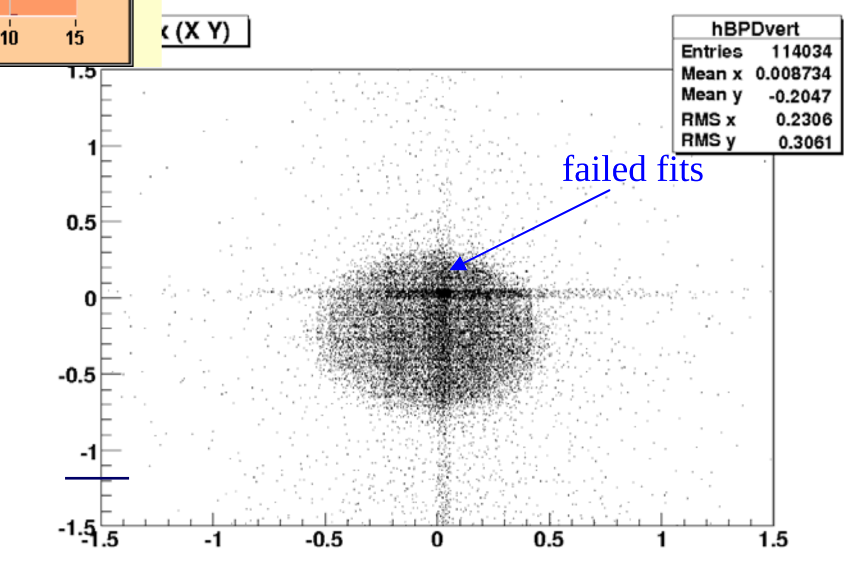


Beam Profiles – Thin Target

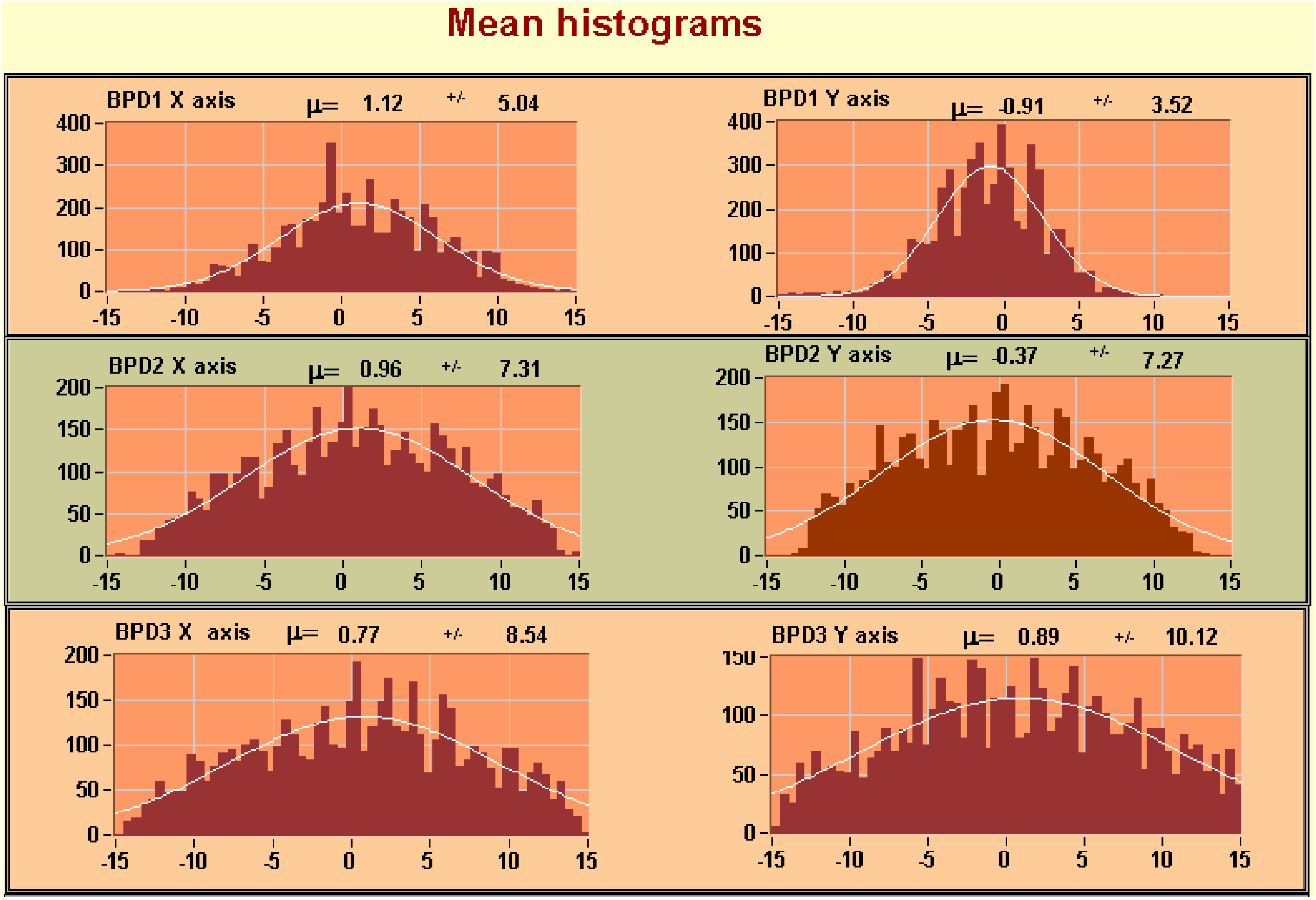


Thin target trigger target 'in' profiles

beam spot at the Z position of the target



Beam Profiles – Thick target



Trigger: B=S1·S2·C1·$\overline{C2}$, S2 28 mm diameter

new BPDs for 2008 with larger active area 48 x 48 mm^2

NA61 - p+C @ 30 GeV Data

- Target density: 1.8395 g/cm^3.
- Target thickness 2.0 cm ⇒ **effective thickness 1.948 cm.**
- “20GeV” magnetic field (Bm=1.14 Tm).
- **Note that only limited statistics has been used so far and results are preliminary.**

Target	Intaraction rate (%)
out	1.737 ± 0.021
in	7.077 ± 0.053

↓

Fake trigger = 25%

Interaction probability = 5.34% ± 0.06%

NA61 - p+C @ 30 GeV Data (2)

- Using the described procedure from the interaction probability we calculate the trigger cross section:

$$P_{int} : 5.34\% \pm 0.06\% \Rightarrow \sigma_{trigger} : 289.5 \pm 3.3 \text{ mb}$$

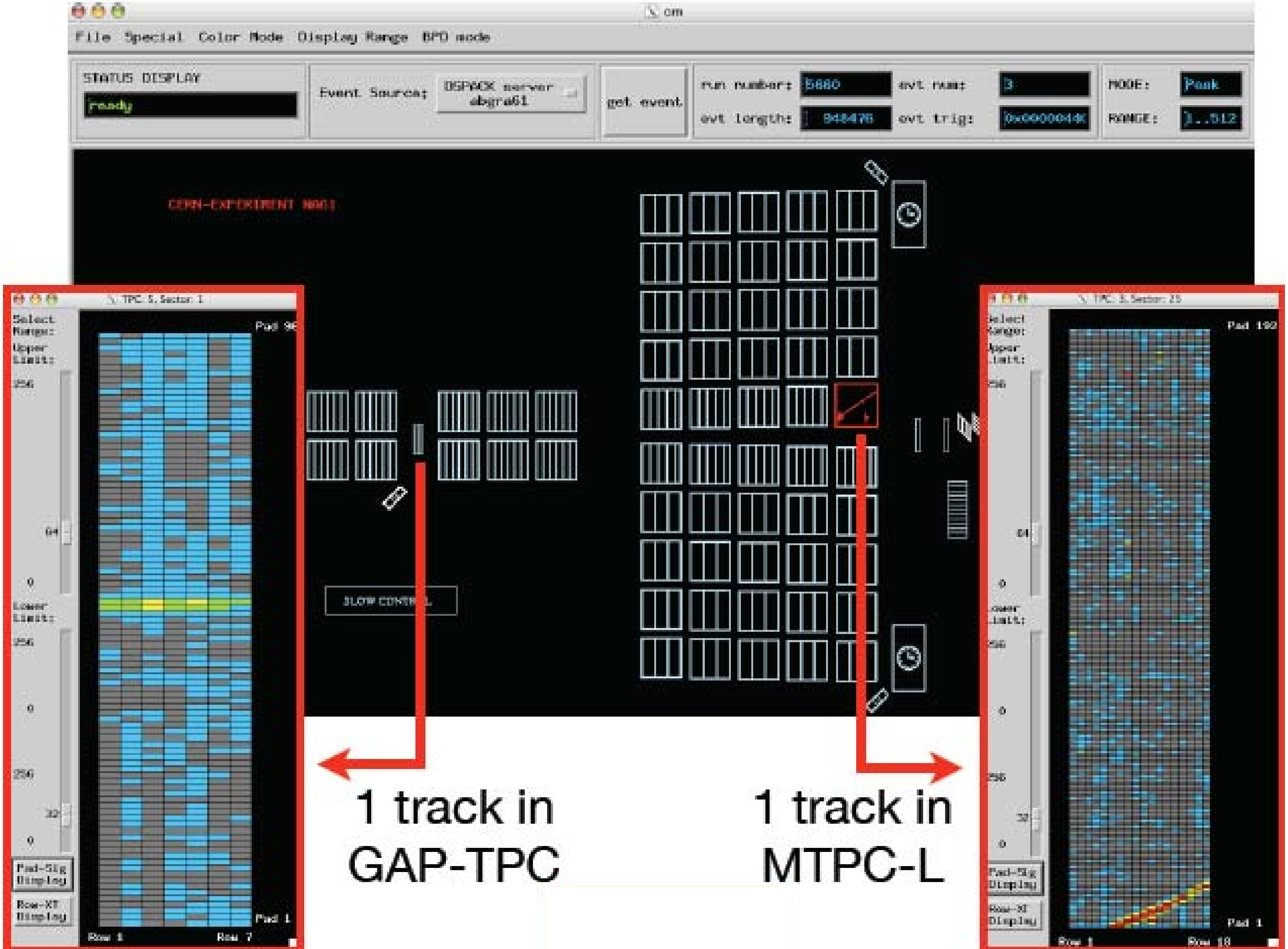
- We can therefore calculate the effective thickness of the target and correct the value of the trigger cross section:

$$L = 2 \text{ cm}, L_{eff} = 1.948 \text{ cm} \Rightarrow \sigma_{trigger} : 297.2 \pm 3.4 \text{ mb}$$

- Using the values of $\sigma_{loss-p/\pi/K}$ and $\sigma_{elastic}$ contribution, obtained from GEANT4 simulation, we can estimate the value of the interaction cross section:

σ contribution	value	comments
$\sigma_{trigger}$	297.2 ± 3.4 mb	
σ_{loss-p}	16.0 ± 0.3 mb	GEANT4 correction
$\sigma_{loss-\pi/K}$	0.45 ± 0.05 mb	GEANT4 correction
$\sigma_{elastic}$ contribution	- 48.1 ± 0.6 mb	GEANT4 correction
$\sigma_{interaction}$	265.25 ± 3.5 mb	Expected: 247 mb

Online Display



Analysis Plan / Progress

STEP 1: detector geometry and alignment, TPC drift velocity,
space points, residual distortion corrections, database, …

↓

event reconstruction (by end of Feb.)

↓

STEP 2: **B** calibration, ToF calibration, dE/dx calibration, …

↓

dst and mini-dst for physics analysis
(by end of May)

↓

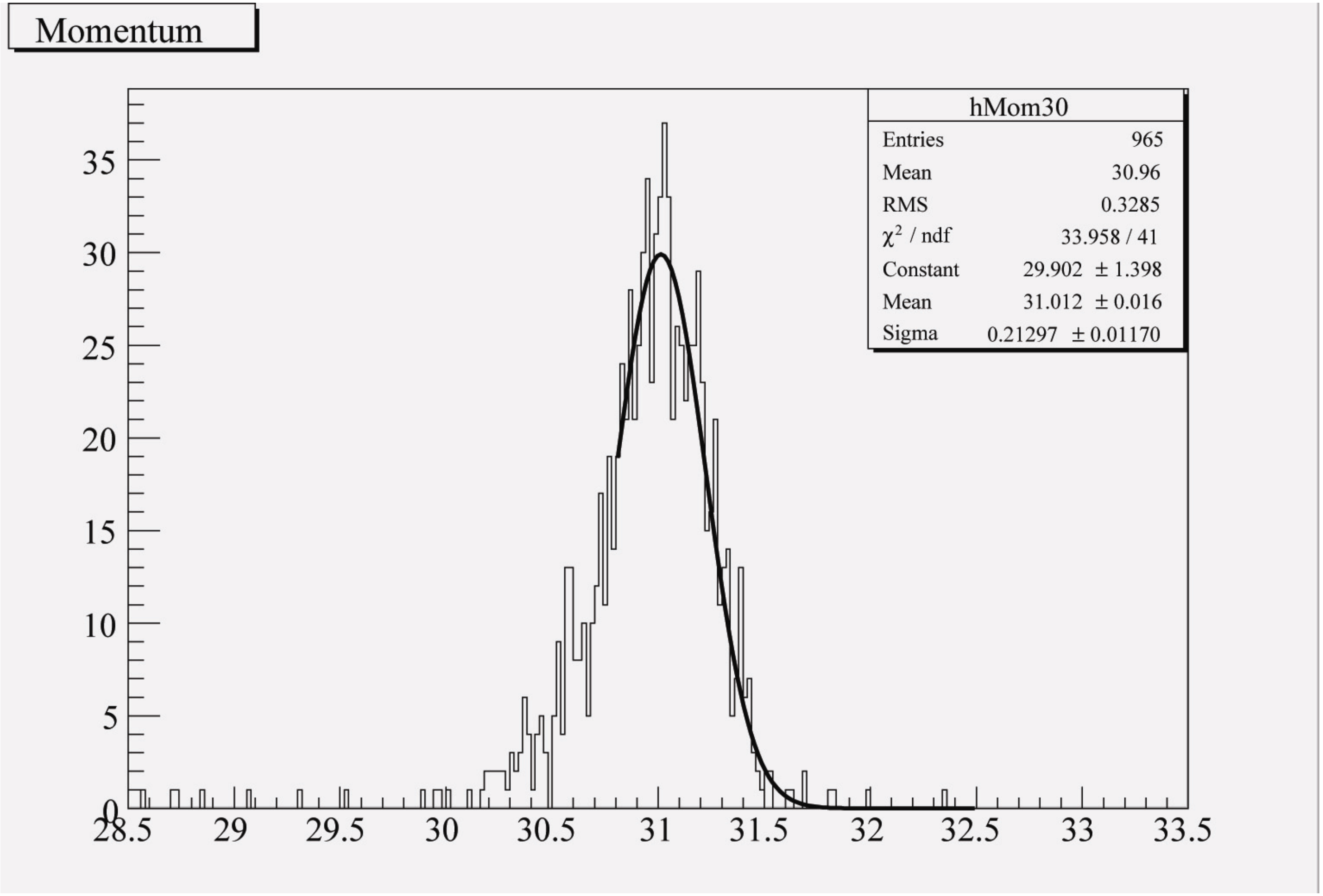
STEP 3: physics analysis
cross section normalization, acceptance and eff. corrections,
particle identification, …

↓

first results (summer 2008)

Beam Momentum

- beam steered into the TPC (max B)
- $\Delta p / p \sim 1\%$ (p spread and TPC resolution)

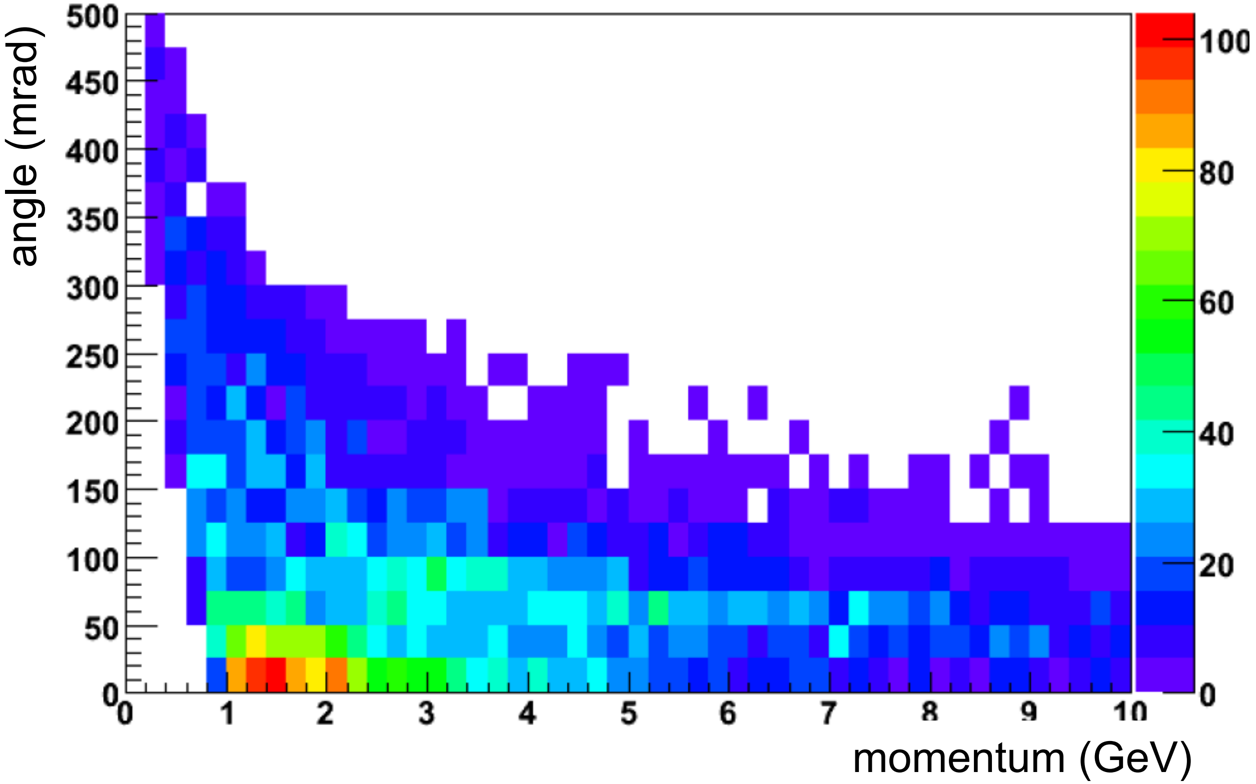


momentum vs angle distribution

p + C -> h + X - NA61 data

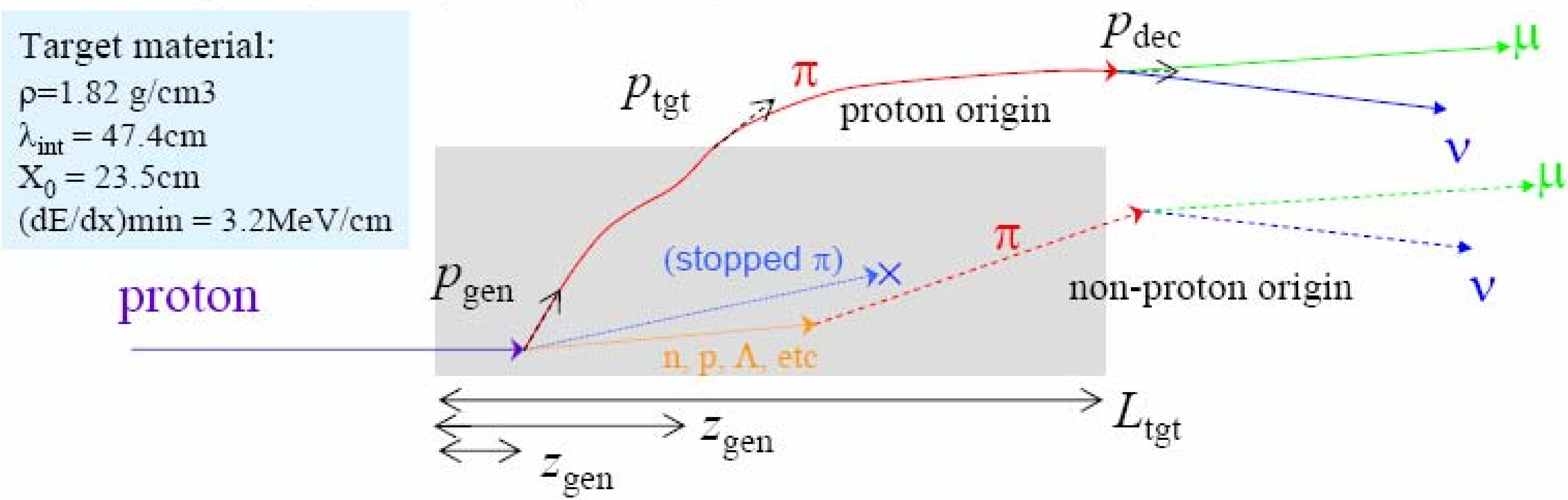
NO CORRECTIONS applied !
and not weighted for acceptance !
(raw distributions)

we have tracks over the whole T2K phase space



Secondary Interactions

- Effect of secondary Interaction vs. L_{target}
  - Is primary interaction dominant?
    - Fraction of pions from the proton to all the secondary pions.
  - Absorption
    - Fraction of pions which stops inside the target.
  - Multiple-scattering inside the target.
    - Compare (p, θ) for pions between the generation point and the target surface.
- Beam simulation (jnubeam) for several target configurations.
  - 2cm, 5cm, 10cm, 20cm, 45cm, 90cm.

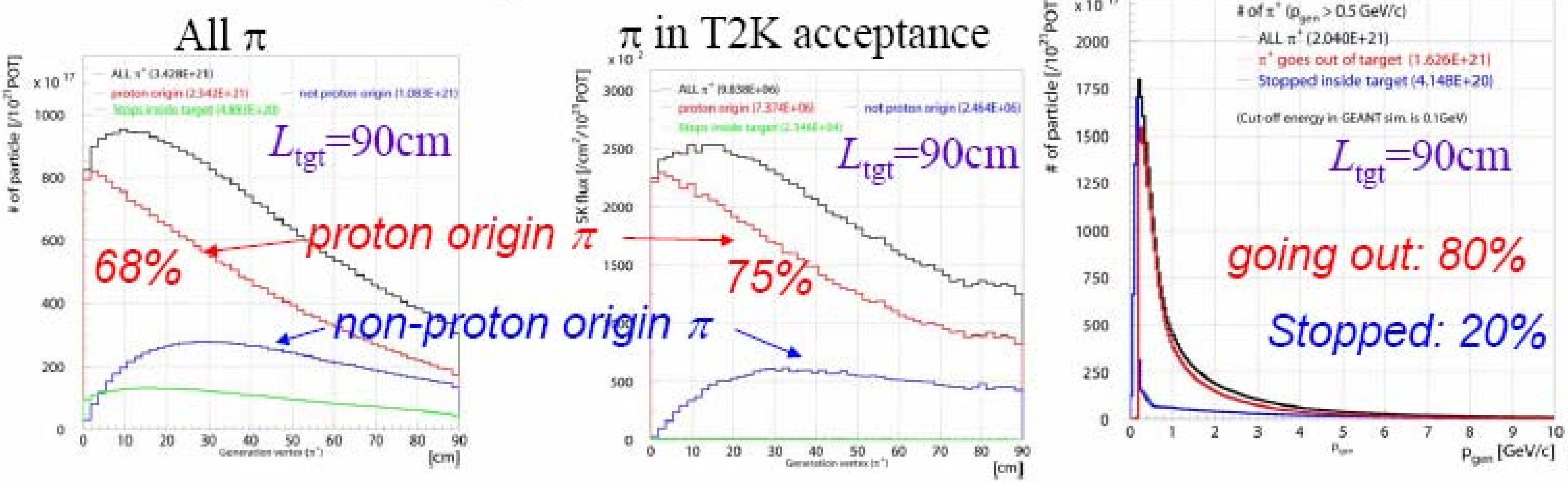


Secondary Interactions in the 90 cm Target

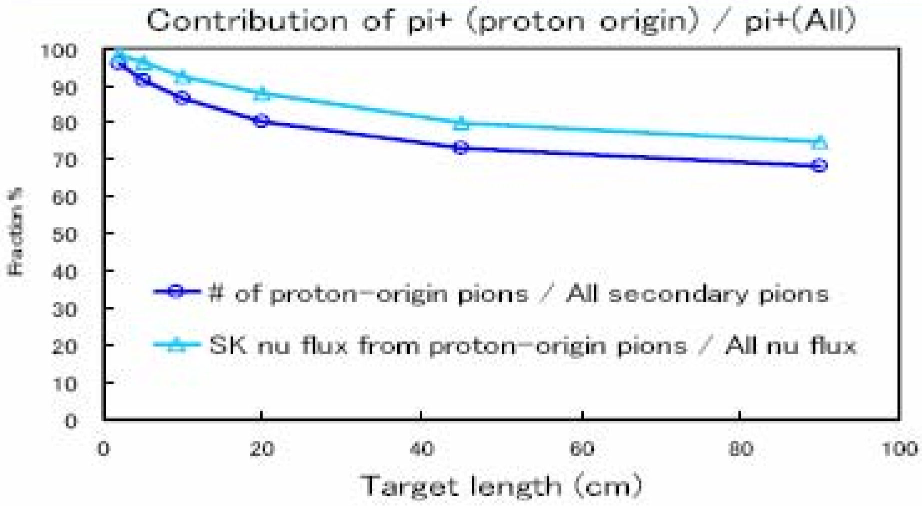
T2K beam MC (GFLUKA+GEANT3)

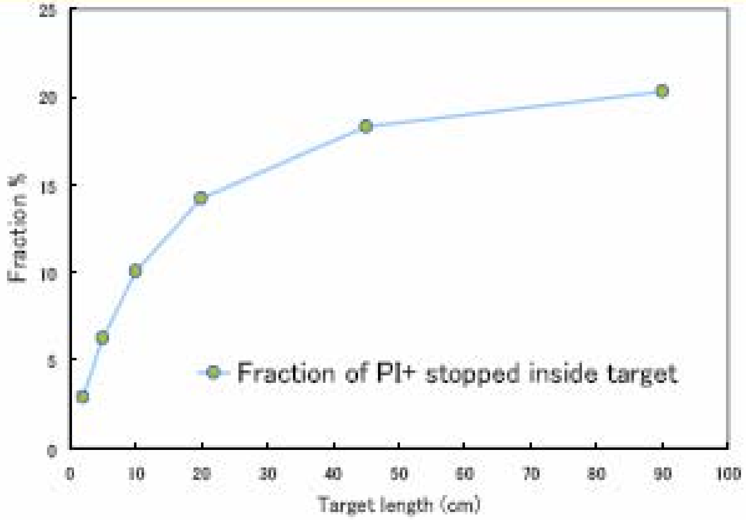
- Origin of pions:
  - All π: 68% proton ⇔ 32% non-proton
  - π in T2K acceptance: 75% proton ⇔ 25% non-proton
- Pion absorption for (Pπ > 0.5 GeV)
  - 80%: going out ⇔ 20% stopped inside target:
- Effect of secondary Interaction: 20~30% level

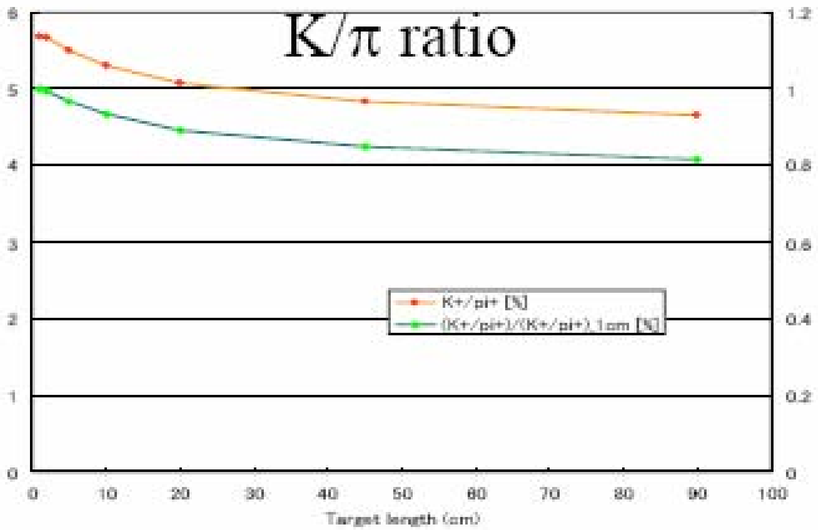
Production point of π



Secondary Interaction vs. Target Length







- 1cm target:
  - Effect is less than a few%.
- 10cm target:
  - Size of effect is ~1/2 compared to 90cm target
    → Suitable for Intermediate target.

How to Use NA61 Data in T2K Analysis ?

strategy A:

- measure $d^2\sigma/dpd\Omega$ for p + C -> π/K + X with a thin C target
- use the measured x-section as input to the beam MC (secondary interactions, absorbtion, etc. described by e.g. FLUKA)
- compare the MC predictions to the π/K yields measured off C targets of different lengths (including the T2K replica target) and adjust the MC accordingly

strategy B:

- measure π/K yields off the T2K replica target
- use the measured π/K yields as input to the beam MC (no simulation of secondary interactions required)

the difference in the predicted flux at SK with different models would be an indication of the reliability of the procedure

Summary

π+ / K+ / K0 measurements essential to achieve T2K physics goals
beam related sys. errors should be smaller than statistical ones
⇒ $R_{\mu,e} < 2 – 3$ %
⇒ π, K data samples of ~ 200 k tracks required

The NA61 2007 run quite successful:

+ we learned many things on the NA61 apparatus, beam, …
+ new ToF wall completed on time and successfully opearted
– very very slow DAQ, effective rate ~1 HZ

Collected enough data (~ 1 M triggers) for a first look at the pC cross section and secondary interactions in the target

Just started to develop a T2K focused analysis strategy

Look forward to the 2008 fall run