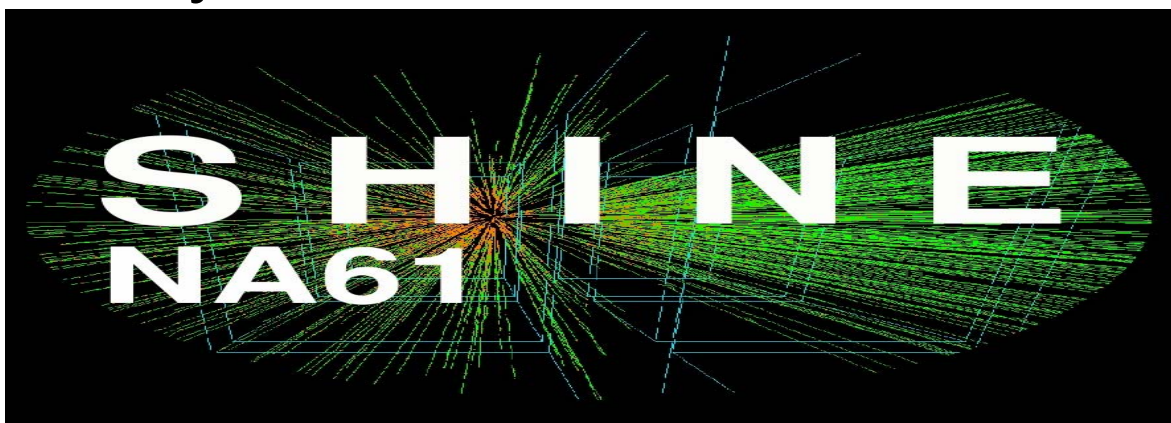
The NA61 (SHINE) experiment : hadronproduction measurements for T2K

3rd CHIPP Swiss Neutrino Workshop, 17-18 November 2008, ETH (Zurich)

Boris A. Popov (LPNHE, Paris & JINR, Dubna) for the NA61 Collaboration

- NA61: the experiment to study hadron production in hadron-nucleus and nucleus-nucleus collisions at the CERN SPS
- Experimental apparatus and 2007 run
- Status of 2007 data analysis
- 2008 run
- Plans for 2009
- Summary

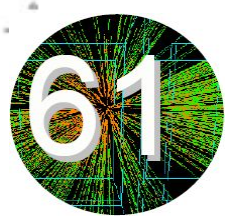


NA61 : COLLABORATION

~120 physicists from 24 institutes and 14 countries:

- University of Athens, Athens, Greece
- University of Bergen, Bergen, Norway
- ➡ University of Bern, Bern, Switzerland
- KFKI IPNP, Budapest, Hungary
- Cape Town University, Cape Town, South Africa
- Jagiellonian University, Cracow, Poland
- Joint Institute for Nuclear Research, Dubna, Russia
- Fachhochschule Frankfurt, Frankfurt, Germany
- University of Frankfurt, Frankfurt, Germany
- ➡ University of Geneva, Geneva, Switzerland
- Forschungszentrum Karlsruhe, Karlsruhe, Germany
- Swietokrzyska Academy, Kielce, Poland
- Institute for Nuclear Research, Moscow, Russia
- ➡ LPNHE, Universites de Paris VI et VII, Paris, France
- Pusan National University, Pusan, Republic of Korea
- Faculty of Physics, University of Sofia, Sofia, Bulgaria
- St. Petersburg State University, St. Petersburg, Russia
- State University of New York, Stony Brook, USA
- ➡ KEK, Tsukuba, Japan
- ➡ Soltan Institute for Nuclear Studies, Warsaw, Poland
- Warsaw University of Technology, Warsaw, Poland
- ➡ University of Warsaw, Warsaw, Poland
- Rudjer Boskovic Institute, Zagreb, Croatia
- ➡ ETH Zurich, Zurich, Switzerland

➡ Also in T2K



NA61 (SHINE): PHYSICS GOALS

SHINE = SPS Heavy Ion and Neutrino Experiment

Physics of strongly interacting matter

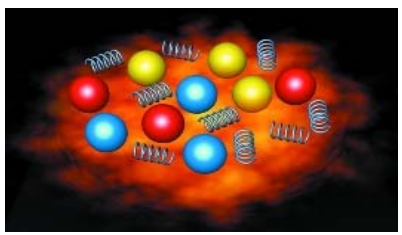
Discovery potential:

Search for the critical point of strongly interacting matter

Precision measurements:

Study the properties of the onset of deconfinement in nucleus-nucleus collisions

Measure hadron production at high transverse momenta in p+p and p+Pb collisions as reference for Pb+Pb results



Data for neutrino and cosmic ray experiments

Precision measurements:

Measure hadron production in the T2K target needed for the T2K (neutrino) physics

Measure hadron production in p+C interactions needed for T2K and cosmic-ray, Pierre Auger Observatory and KASCADE, experiments

NA61 : Physics Goals (I)

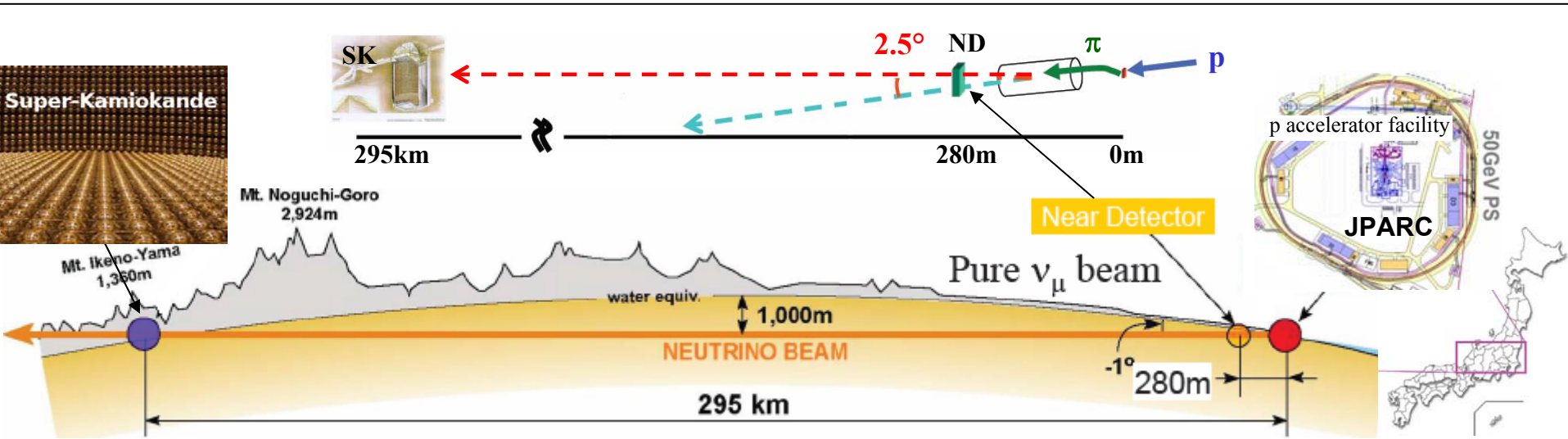
- **One of the main physics goals of NA61/SHINE:**

Precision measurements of hadron production

for prediction of ν-fluxes in the T2K experiment

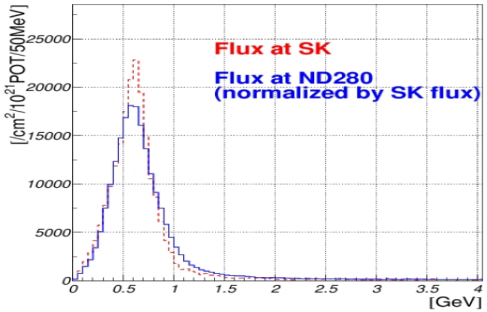
- **T2K @ JPARC (Japan):**

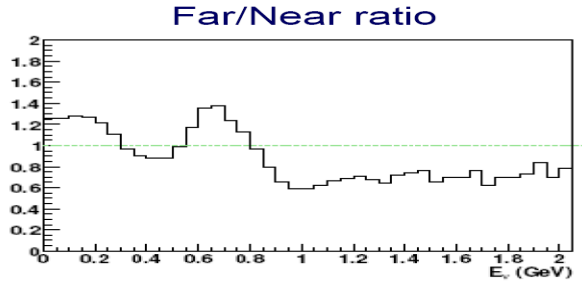
  - **Long baseline (295km) neutrino oscillation experiment**
  - **Protons (30-50GeV) + carbon target (90cm) → intense off-axis ν_μ–beam**
  - **Neutrino spectra measured at the near and far detectors: ND280 and SK**



NA61 : Physics Goals (II)

- **Main aims of T2K:**
  - o **Search for and measurement of the $\nu_\mu \rightarrow \nu_e$ appearance**
  - » **improved sensitivity to the so far unknown mixing angle θ_{13}**
  - o **Refinement of ν_μ disappearance measurements**
  - » **improved determination of θ_{23} and Δm^2_{23}**





- **Both analyses rely on the comparison of ν spectra measured at SK and the extrapolated spectra at SK from the ND measurement:**

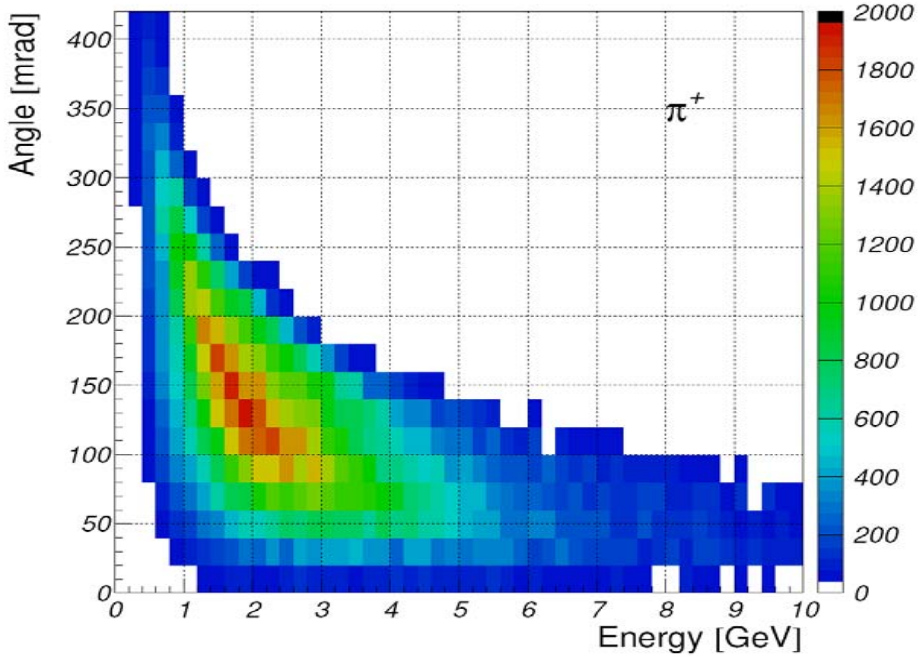
Extrapolated at SK ● $\Phi^{SK}_{\mu,e}(E_\upsilon) = R_{\mu,e}(E_\upsilon) \times \Phi^{ND}_{\mu,e}(E_\upsilon)$ ● Measured at ND

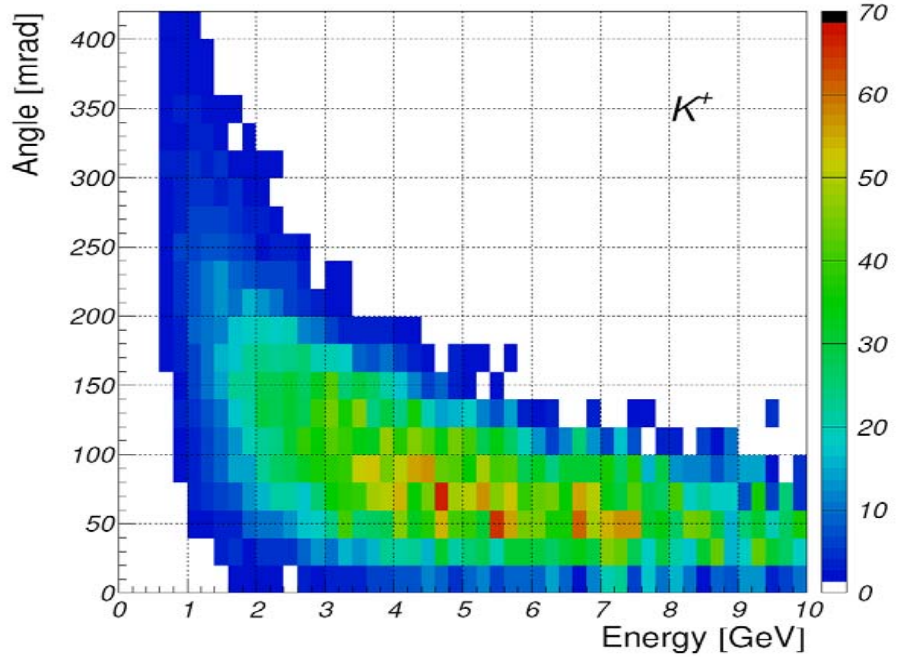
- **Far to Near (F/N) ratio R: is not constant with respect to the ν energy and therefore depends on the particle production properties**

→ To fulfill the T2K goals detailed information on the pion and kaon production off the T2K target is needed!

NA61 : Physics Goals (III)

Simulated distributions of pions and kaons whose daughter neutrinos pass through the SK



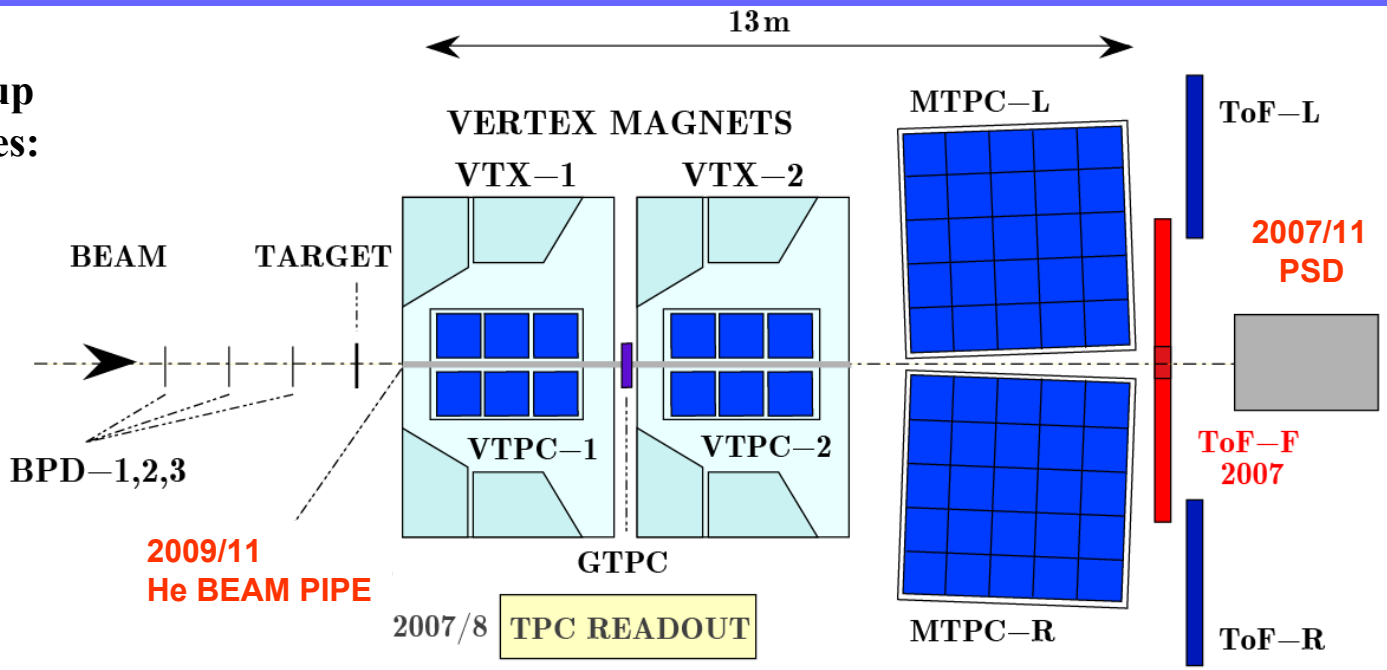


The goal is to reduce the error on the F/N ratio to a negligible level compared to other contributions to the systematics (ND280 spectrum measurements, cross-section, efficiencies, etc.), therefore we aim at: $\delta (R_{\mu,e}) < 3\%$

In order to reach this precision we need ~200k reconstructed π^+ tracks (at the same time we will collect a similar number of π^- since the NA61 acceptance is symmetric)

We also need to measure the K/π ratio with an uncertainty of: $\delta (K/\pi) < 10\%$

NA61/SHINE – Fixed Target Experiment at CERN SPS



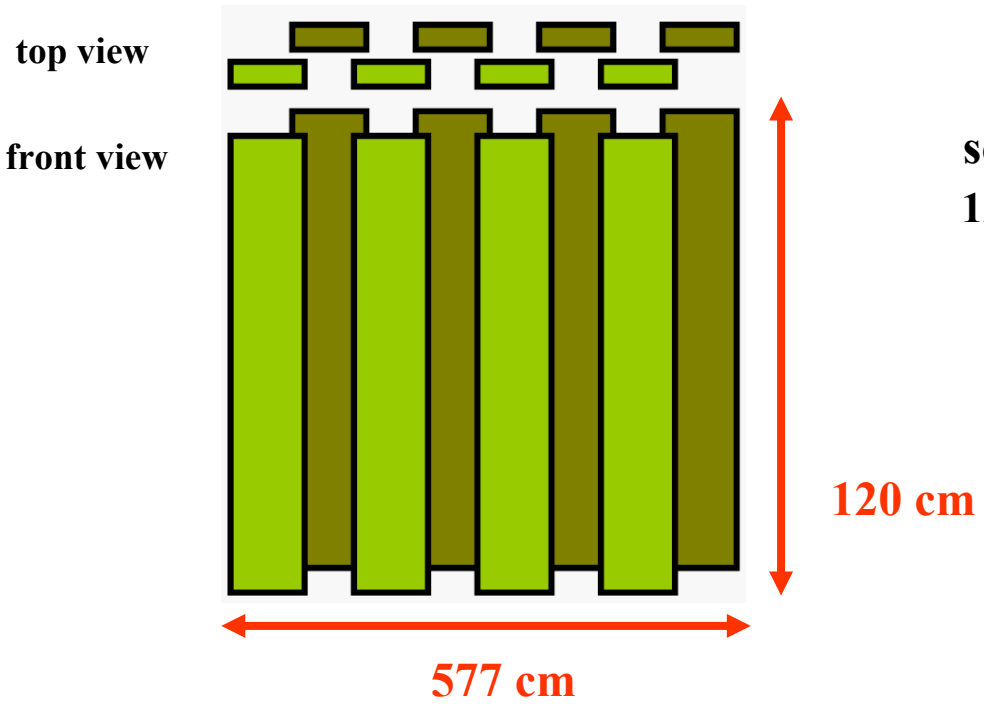
- **Large Acceptance Spectrometer for charged particles**
- **TPCs as main tracking devices**
- **2 dipole magnets with bending power of max 9 Tm over 7 m length** (2007-Run: 1.14 Tm)
- **New ToF-F to entirely cover T2K acceptance**
- **High momentum resolution**
- **Good particle identification:** σ(ToF-L/R) ≈ 60 ps, σ(ToF-F) ≤ 120 ps,
  $\sigma(dE/dx)/\langle dE/dx\rangle \approx 0.04$, $\sigma(m_{inv}) \approx 5$ MeV

CERN-SPS-2006-034

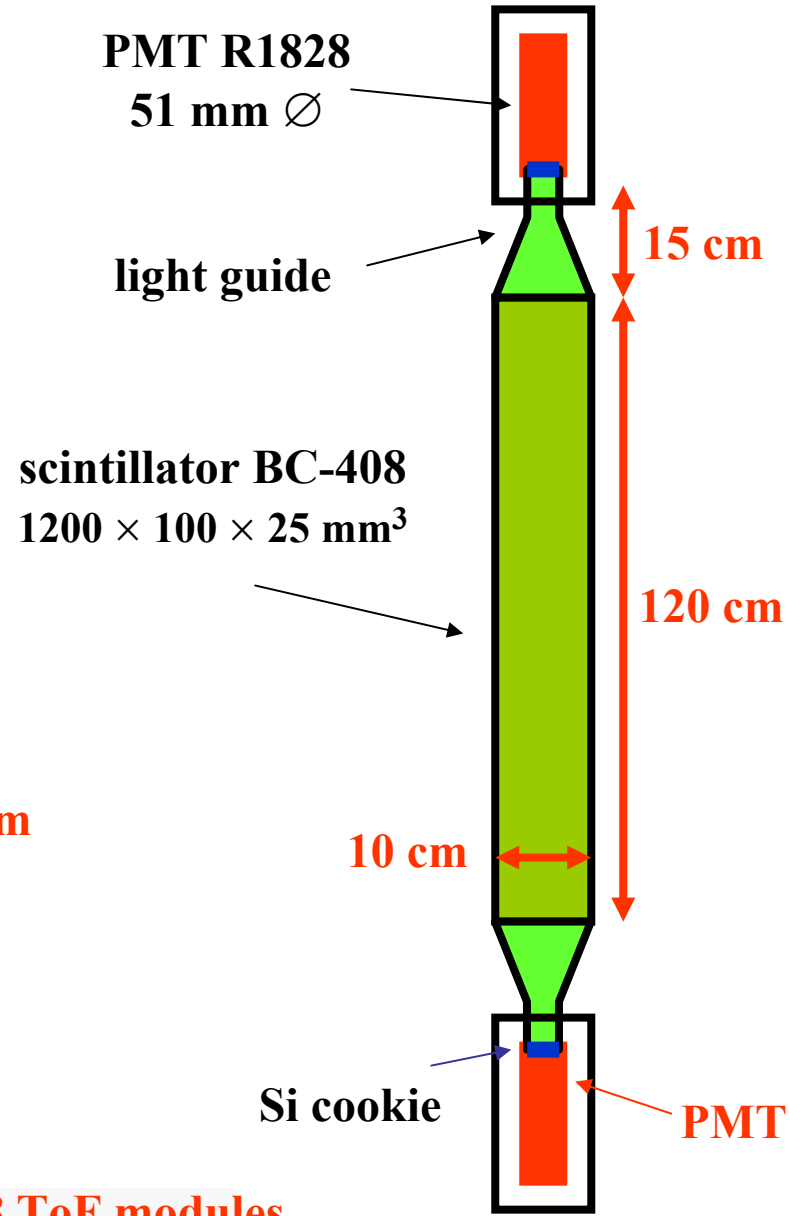
NA61 : Forward TOF (2007)

total area 577 × 120 cm²

64 scintillator bars readout on both sides
128 readout channels



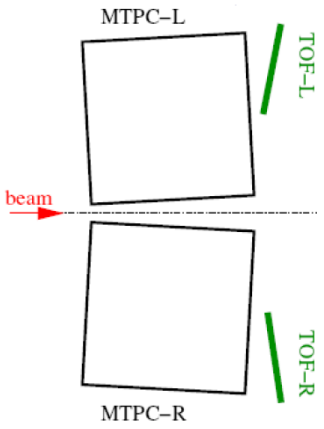
64 staggered scintillator bars
(10 mm overlap)

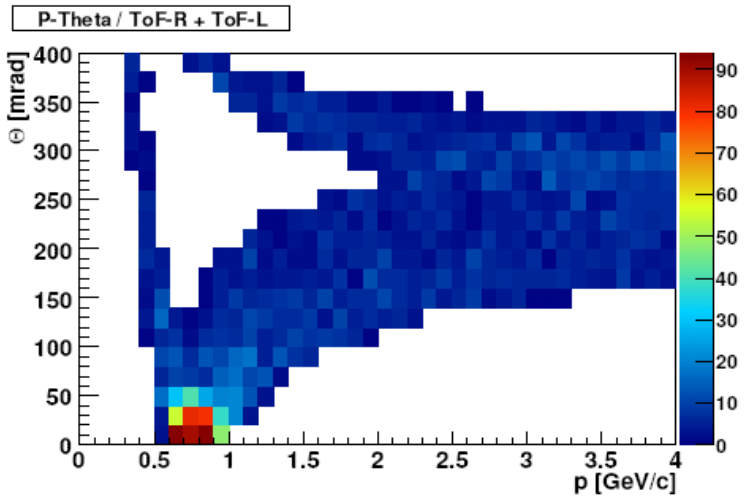


8 scintillators mounted on a single frame → 8 ToF modules

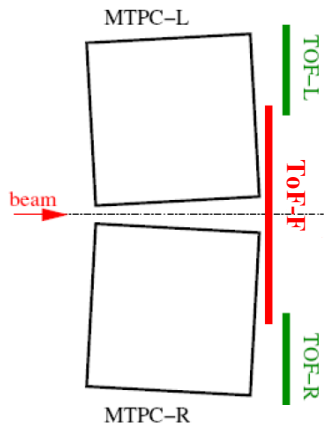
NA61 : TOF Acceptance

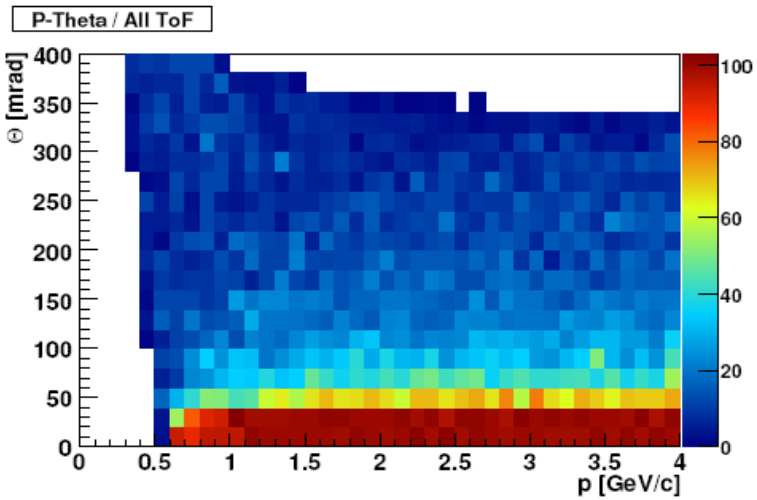
Without ToF-F



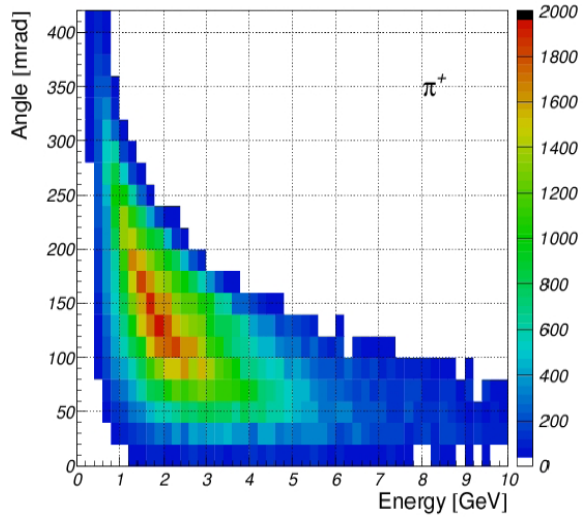


With ToF-F





π contributing to ν flux (SK)



→ Extended acceptance with new ToF wall

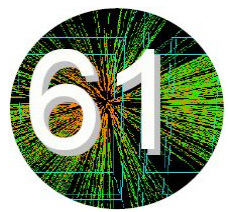
→ Full coverage of the T2K "phase space"

NA61 2007 DATA TAKING

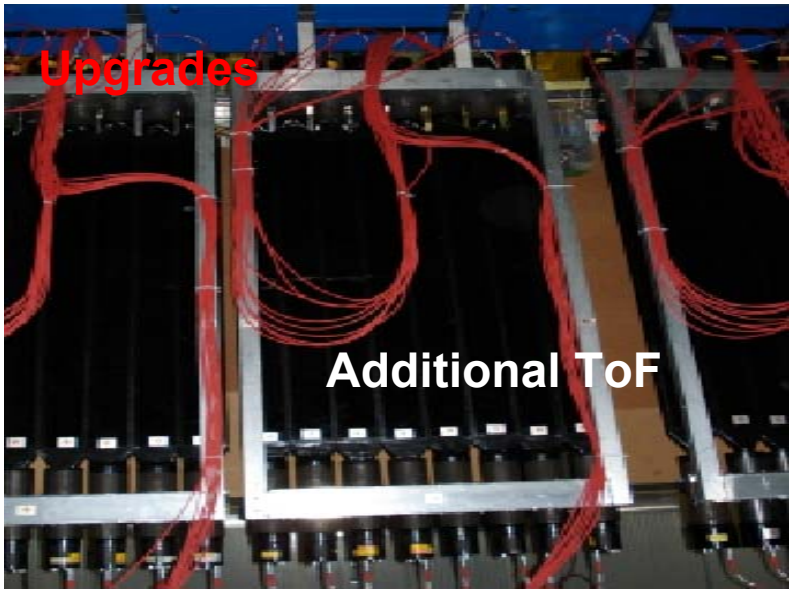
NA61 experiment was approved in June 2007

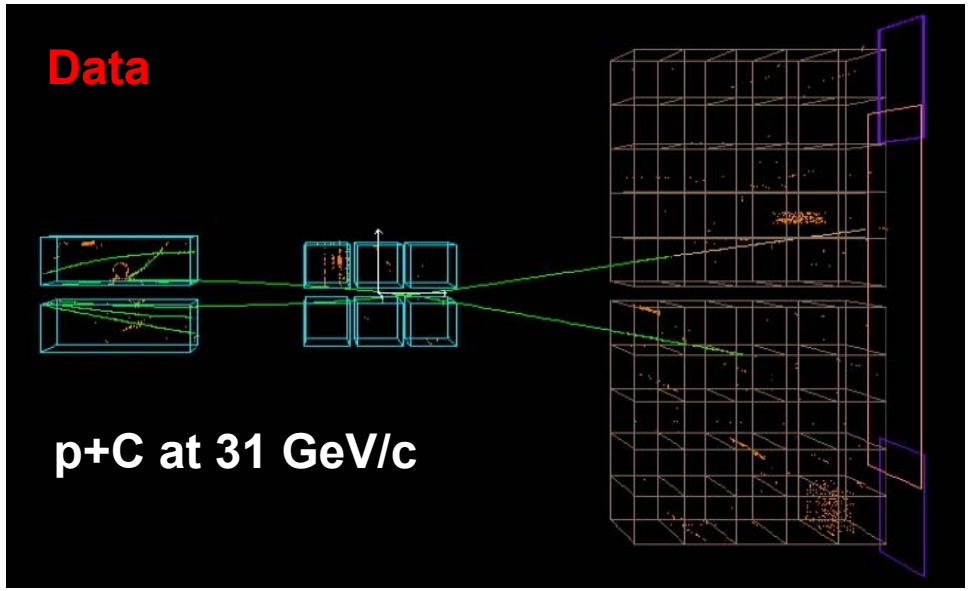
2007 run: September 27 – October 29:

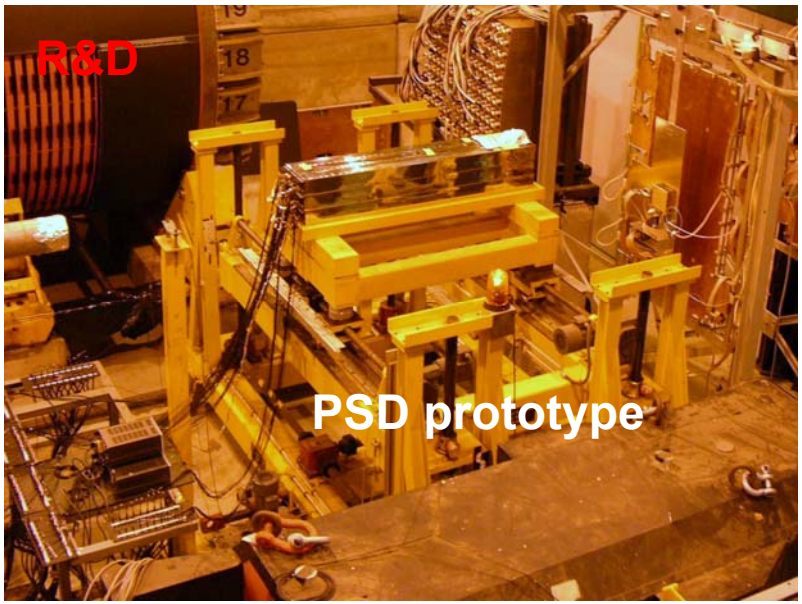
- test of the PSD super-module with beams of muons and hadrons,
- optimization of the proton beam at 31 GeV/c, detector setup,
- pilot data taking with 31 GeV/c protons on the thin (2 cm) C target,
- pilot data taking with 31 GeV/c protons on the T2K replica (90cm) C target,
- TPC read-out test with the "FE Tester"



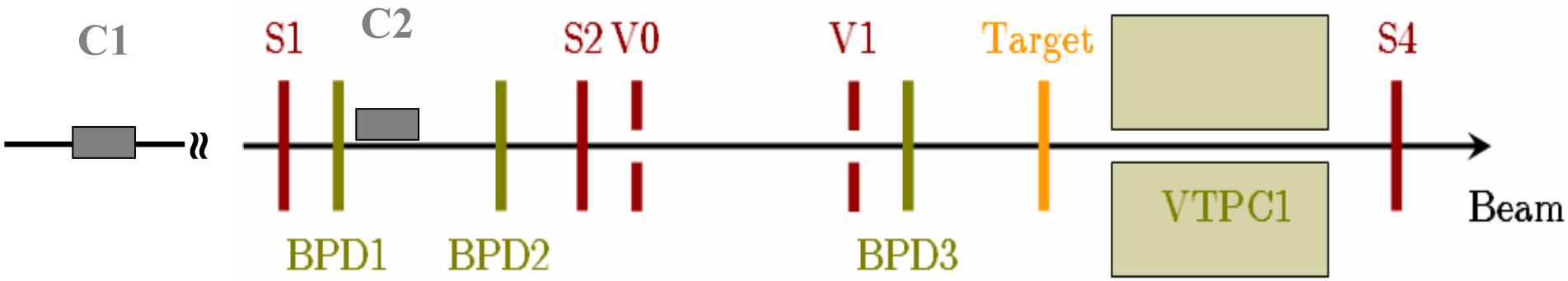
NA61 : 2007 PILOT RUN







NA61 : Beamline setup



- **30.9 GeV/c secondary hadron beam from CERN SPS**
- protons in the beam identified by a **differential Cerenkov** C1 (CEDAR) and a **threshold Cerenkov counter** C2
  - **beam composition: 83.7% π, 14.7% p** and **1.6% K**
- incoming **proton** selection
  - **$S1 \bullet S2 \bullet \overline{V} \bullet C1 \bullet \overline{C2}$**
- beam particle trajectories measured by **beam position detectors** (BPD-1/-2/-3)
- **minimum bias interaction trigger**
  - proton particle$\bullet \overline{S4}$

NA61 : Targets in 2007

- **2 different carbon targets (isotropic graphite)**

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}**

- **During October 2007 Run (~30 days):**

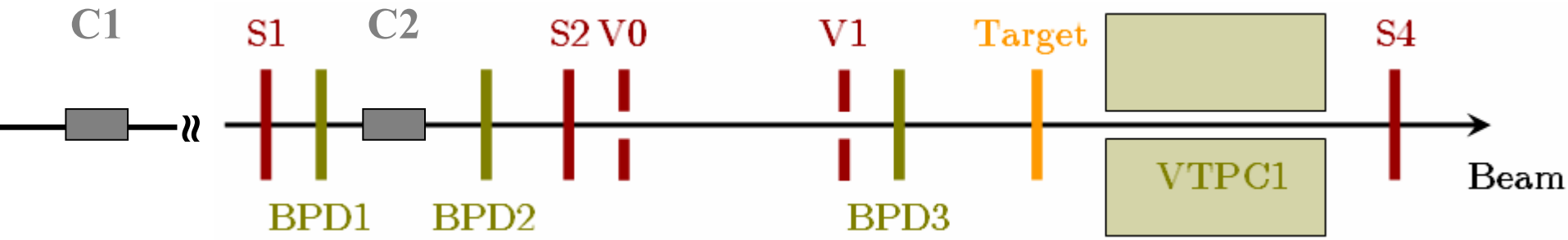
- taken pilot physics data for T2K with 30.9 GeV/c protons (~2 weeks)

Thin target: ~670k triggers

Replica target: ~230k triggers

Empty target: ~80k triggers

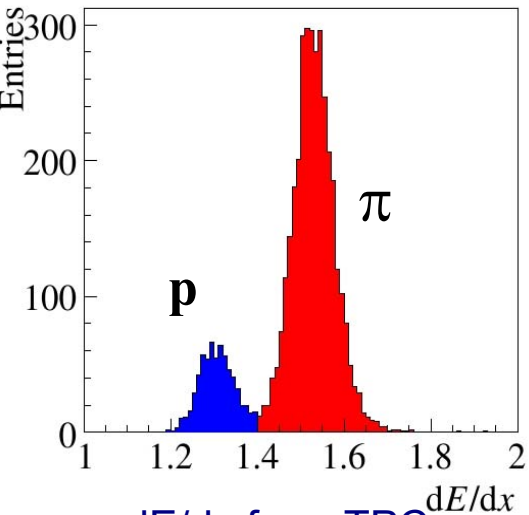
NA61 : Beam properties during 2007 run



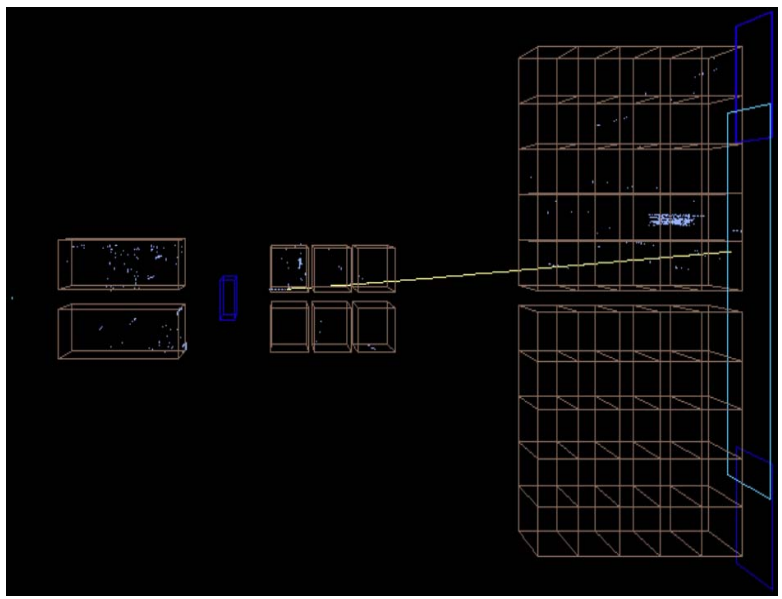
Beam Purity Check

with special empty target run with full magnetic field and trigger on Beam (S1•S2•$\overline{V}$ and S1•S2•$\overline{V}$•C1•$\overline{C2}$)

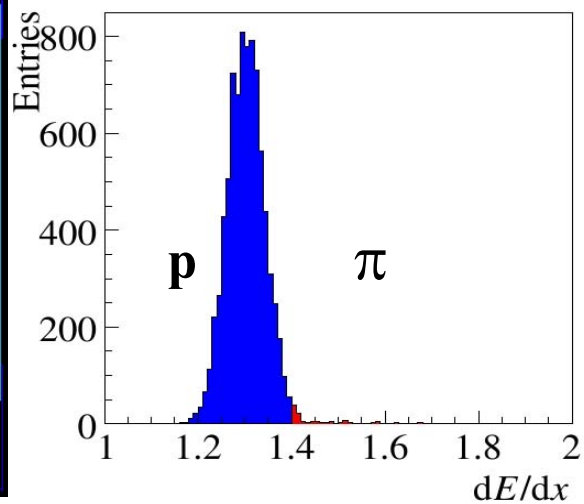
All Beam Particles



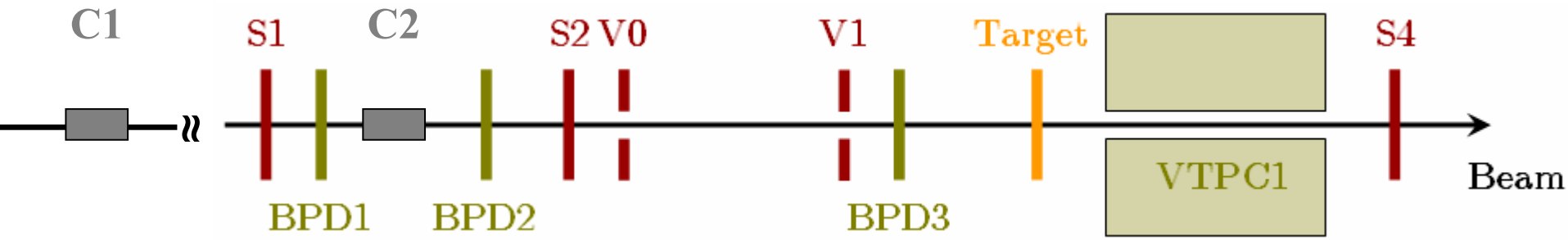
dE/dx from TPC



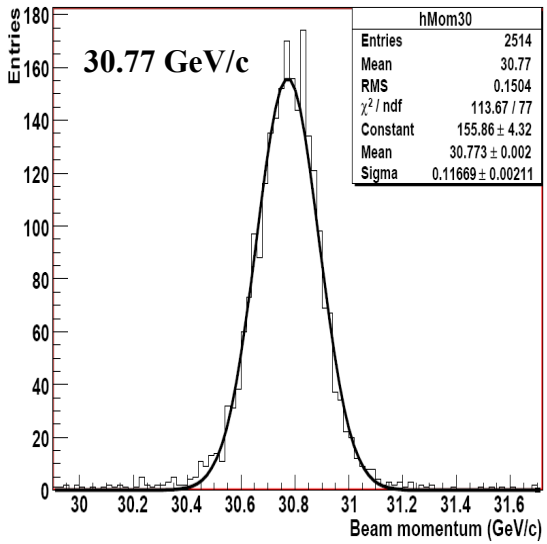
Triggered Protons (C1·$\overline{C2}$)



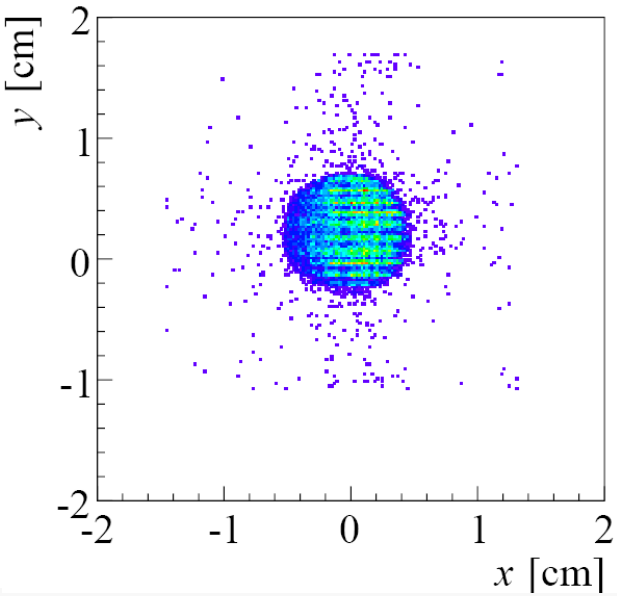
NA61 : Beam properties during 2007 run



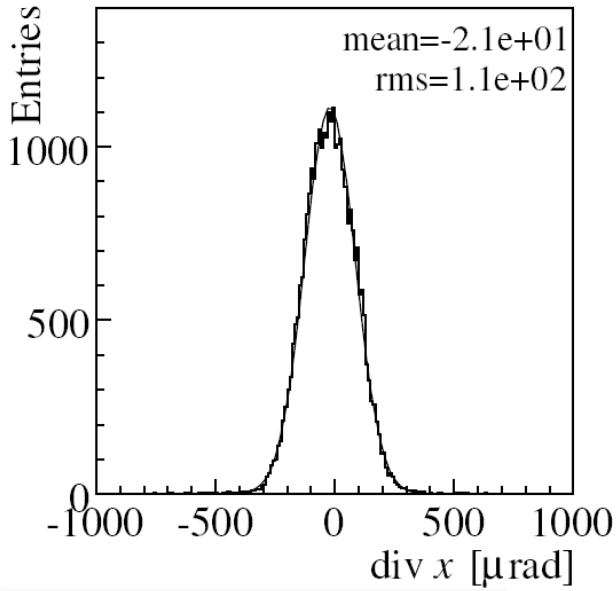
Beam Momentum measured in TPCs



Beam Spot at BPD3



Beam Divergence measured with BPDs



NA61 : Cross-section normalization – Trigger Cross-section

- **Trigger Cross Section $\sigma_{trigger}$:**

- Determined by the interaction probability:

$$\sigma_{trigger} = \frac{P_{int}}{\rho L_{eff} N_A / A}$$

with

$$L_{eff} = \lambda_{abs}(1 - e^{-L/\lambda_{abs}}),$$

$$\lambda_{abs} = \frac{A}{\rho N_A \sigma}$$

Target properties:

ρ: density

L: length

N_A: Avogadro number.

A: Atomic number

L_{eff}: effective length

λ_{abs}: abs. length

- The real interaction probability (P_{int}) is calculated as the difference of probabilities obtained with and without target:

$$P_{\text{int}} = \frac{Rate_{TargetIN} - Rate_{TargetOUT}}{Rate_{BeamTrigger}} = P_{TargetIN} - P_{TargetOUT}$$

- **Interaction rate (2007 Data):**

- Empty target : (1.72±0.01)%

- Thin target: (7.07±0.01)%

- L_{eff} = 1.95 cm:

$\sigma_{trigger}$ = 297.5±0.7 mb

NA61 : Cross-section normalization

- **For the thin target data the goal is to present data both in terms of yields and inclusive cross sections**

→ **NA49 approach is followed** (Eur. Phys. J. C45 (2006) 343)**:**

- $\sigma_{trigger}$ can then be used to determine the invariant inclusive cross section:

$$f(x_F, p_T) = E(x_F, p_T) \cdot \frac{d^3\sigma}{dp^3}(x_F, p_T)$$

which is experimentally defined by the measured quantity:

$$f_{meas}(x_F, p_T, \Delta p^3) = E(x_F, p_T, \Delta p^3) \cdot \frac{\sigma_{trigger}}{N_{ev}} \cdot \frac{\Delta n(x_F, p_T, \Delta p^3)}{\Delta p^3},$$

Δp^3: finite phase space defined by the bin width, N_{ev}: # of evts off the target,

Δn: # of identified particles in a given bin Δp^3

→ **Several steps of normalization and correction have to be applied in order to make $f_{meas}(x_F, p_T, \Delta p^3)$ approach $f(x_F, p_T)$**

- **treatment of empty target contribution, trigger bias correction, effect of finite bin width, correction for bias from event selection**

NA61 : Interaction cross-section p+C @ 31 GeV/c

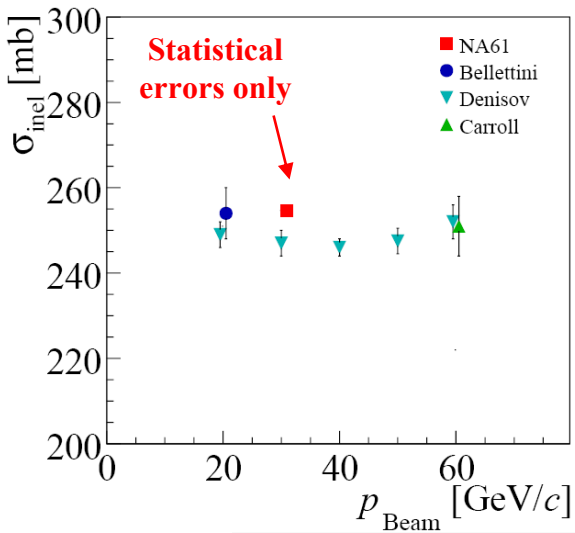
- σ_{int} can be obtained from $\sigma_{trigger}$ by applying the following corrections:

1) Subtract the $\sigma_{elastic}$ contribution, i.e. remove those events where the primary particle undergoes a large angle coherent elastic scattering on the target nuclei and does not reach S4
2) Add the $\sigma_{loss\text{-}p}$ contribution, i.e. take into account interactions where a secondary proton hits S4 and therefore prevents from triggering on the event. The major contribution comes from incoherent elastic scattering of the incident protons on the individual nucleons of the nuclei (quasi-elastic scattering)
3) Add the $\sigma_{loss\text{-}\pi/K}$ contribution, i.e. take into account interactions where a secondary pion or kaon at high x_F hits S4 and therefore prevents from triggering on the event

Statistical errors only!

σ contribution	Value
$\sigma_{trigger}$	297.5±0.7 mb
$\sigma_{loss\text{-}p}$	5.8±0.2 mb
$\sigma_{loss\text{-}p/K}$	0.6±0.1 mb
$\sigma_{elastic}$	-49.2±0.6 mb
$\sigma_{interaction}$	254.7±1.0 mb

Corrections Estimated with Geant4



→ Preliminary value for the σ_{int} is in good agreement with previous experiments

G. Bellettini et al., Nucl. Phys. 79 (1966) 609, S.P. Denisov et. al. Nucl. Phys. B61 (1973) 62, A. Carroll et al., Phys. Lett. B80 (1979) 319

NA61 : Status of 2007 data analysis

- **Step 1: Detector geometry and alignment, TPC drift velocity, space points, residual distortion correction, database, …**

√

→ event reconstruction

- **Step 2: Magnetic field calibration, ToF calibration, dE/dx calibration, …**

✓ **First round of calibrations done**

X **Some refinement still needed**

→ DST and mini-DST for physics analysis

- **Step 3: physics analysis including particle identification, acceptance and efficiency corrections, cross section normalization, …**

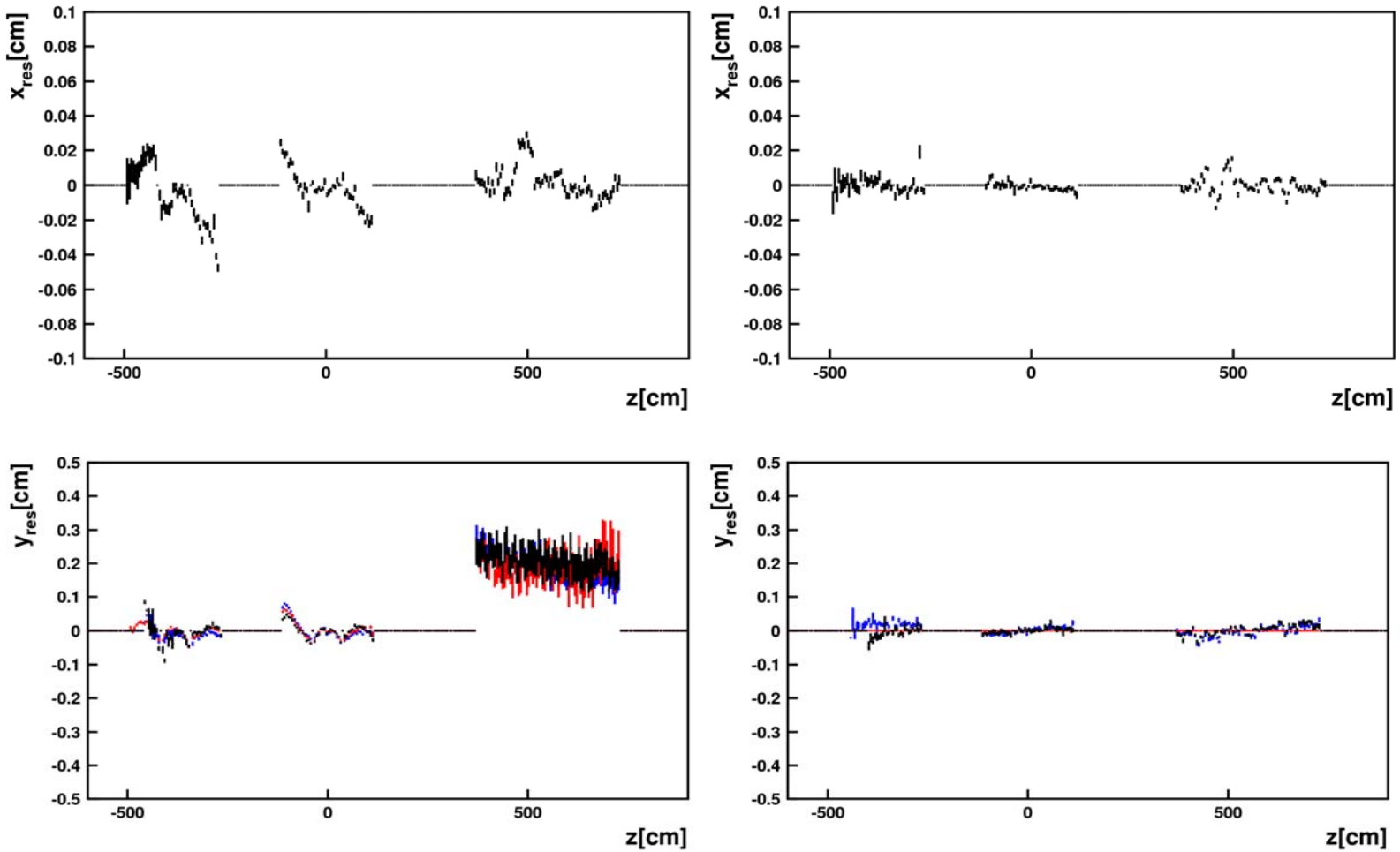
NA61 : Geometry and TPC drift velocity calibration

Residuals before and after calibration for:

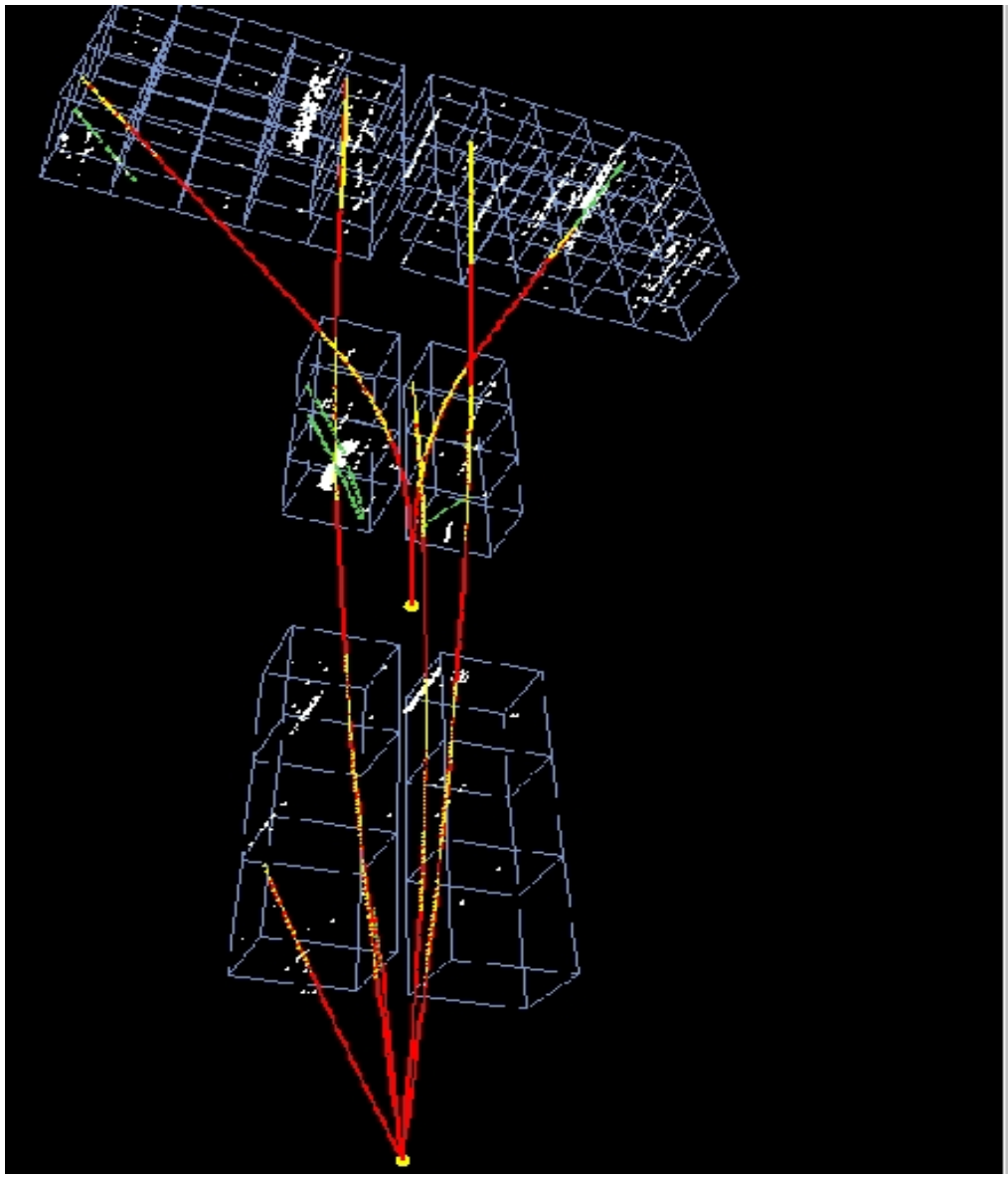
-detector geometry
-drift velocity
-residual distortions

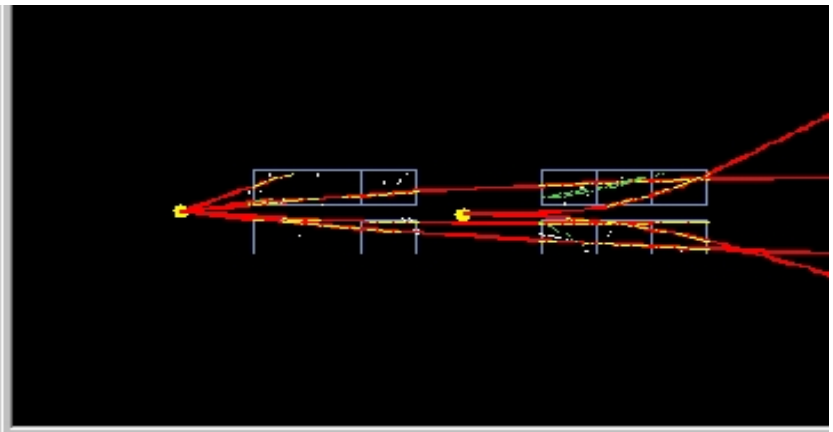
before

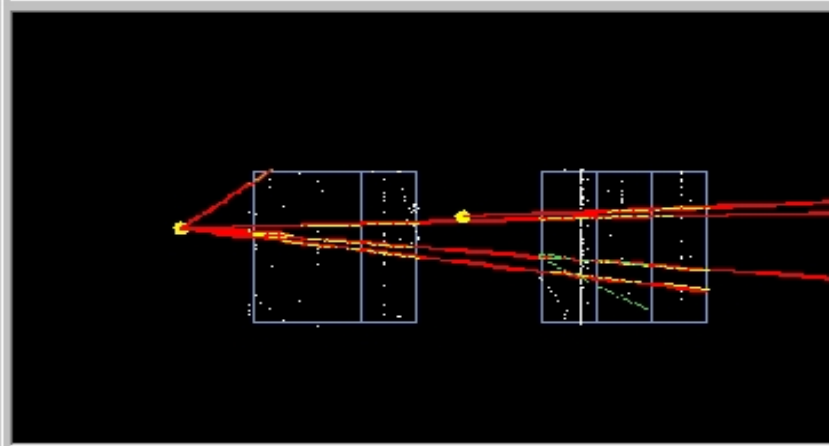
after



NA61 : Event display for 2007 data







Run: 5638

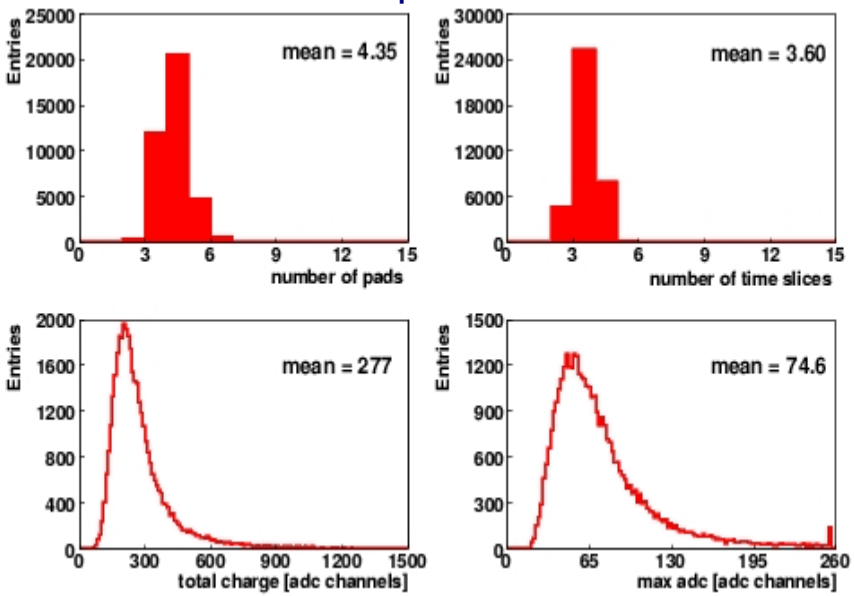
Event: 3411

Number of tracks: 6 (11)

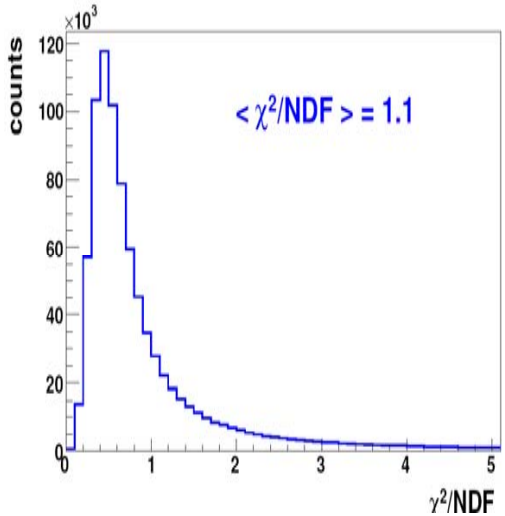
Number of vertices: 2

NA61 : TRACKING PERFORMANCE (2007 DATA)

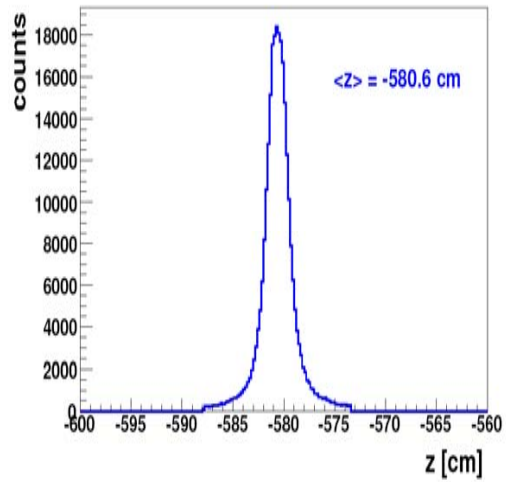
TPC cluster parameters



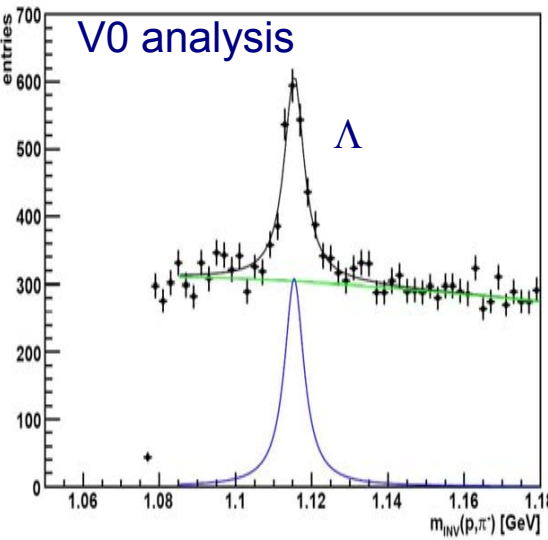
Momentum fit

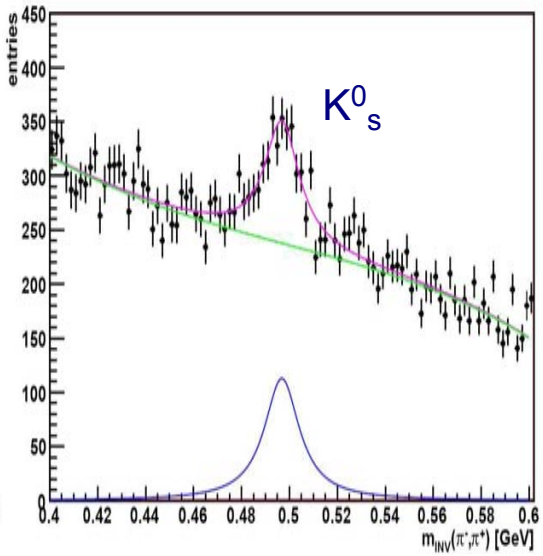


Vertex fit

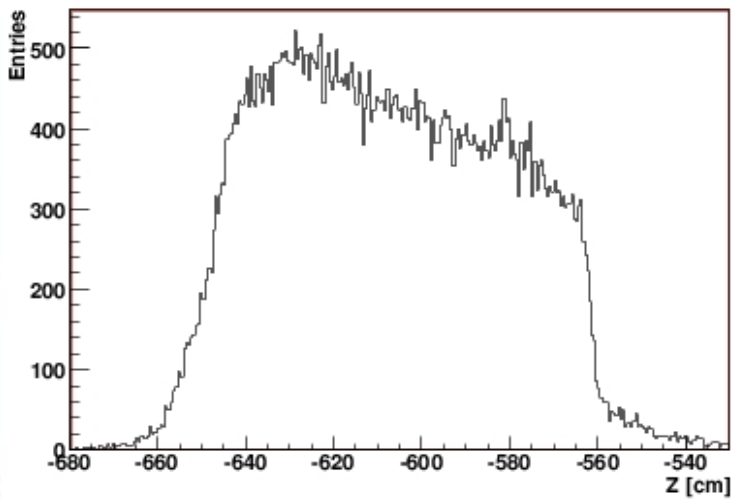


V0 analysis





T2K replica vertex fit



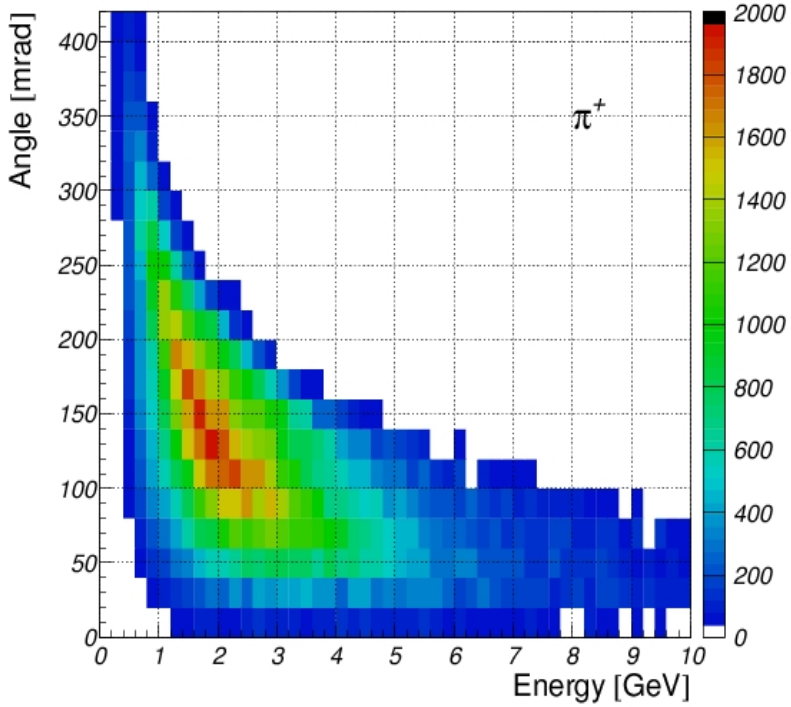
NA61 : Example of event reduction for 2007 data

Current set of event and track quality cuts for the thin Carbon target:

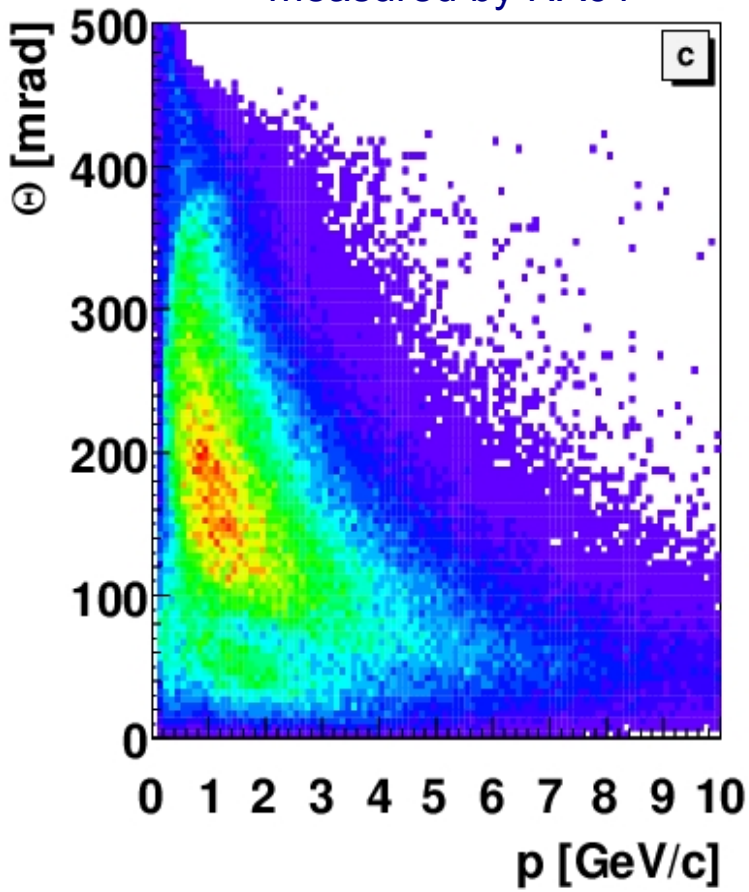
Total number of events processed:	671714
Cut on the BPD position:	522893 (77.8%)
Successful vertex fit:	403417 (60.1%)
Cut on the vertex z position:	277288 (41.3%)
Total number of primary tracks analysed:	1044560 (multiplicity 3.77)
Cut on the minimal number of points in VTPCs:	1013212 (97.0%)
Cut on the ratio of measured and potential points:	1012413 (96.9%)
Cut on the Bx impact parameter:	921265 (88.2%)
Cut on the By impact parameter:	907734 (86.9%)
Cut on the number of potential points:	894383 (85.6%)
among those positively charged:	573550 (64.1%)
among those negatively charged:	320833 (35.9%)
Primary tracks with associated FTOF hit:	
positively charged:	116491
negatively charged:	45787

NA61 : NEGATIVELY CHARGED HADRONS

Pions which produce neutrinos measured by Super-Kamiokande

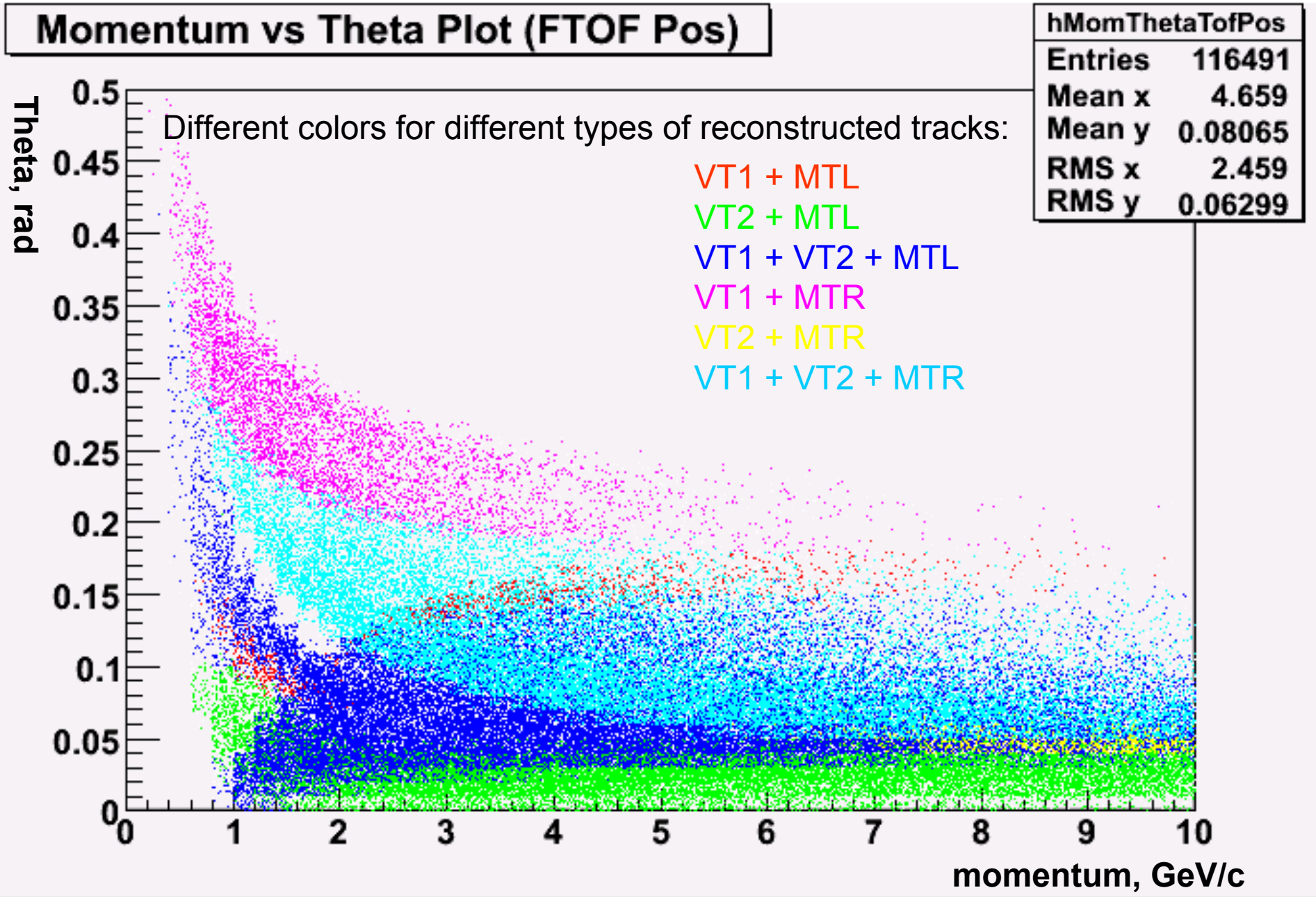


Raw distribution of negatively charged hadrons measured by NA61



π^- = h^- - small (5%) corrections

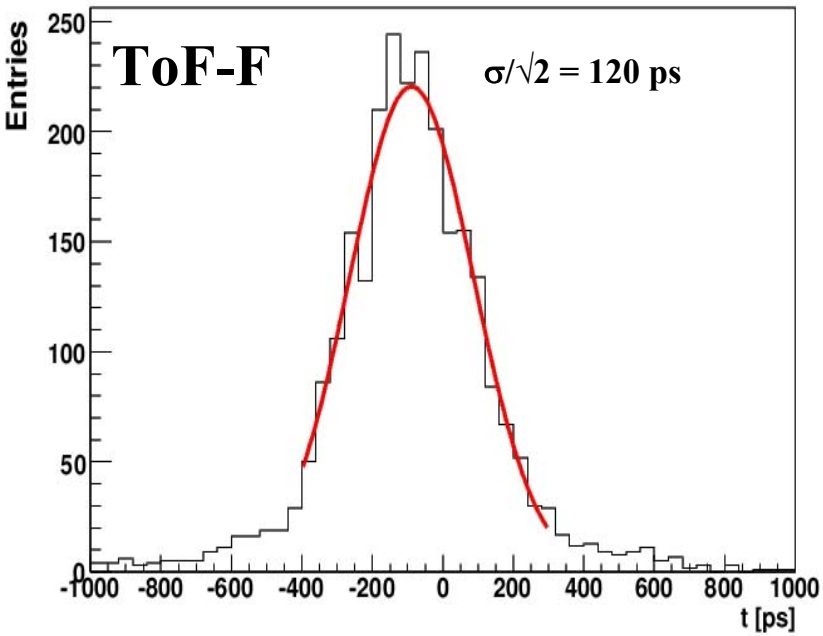
NA61 : T2K {p-θ} plot (positively charged particles with FTOF hit)



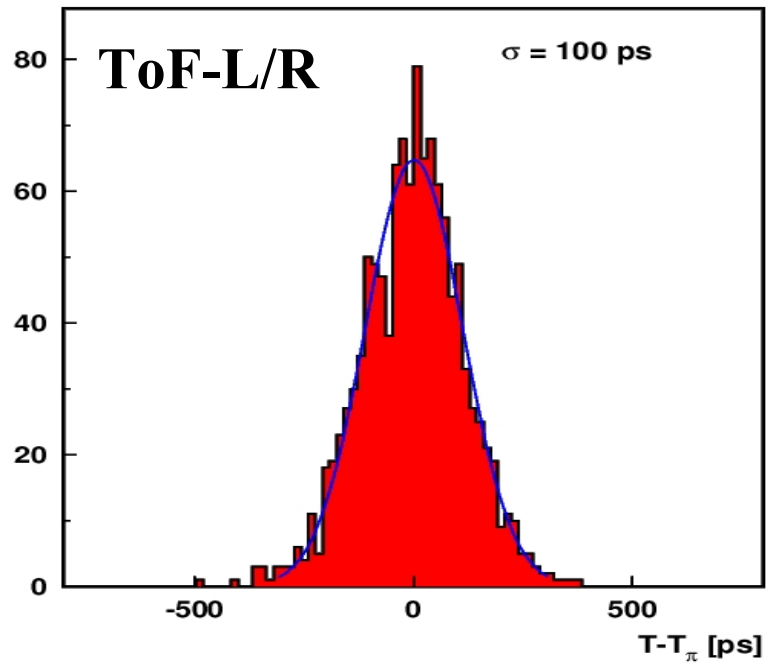
NA61 : TOF resolution

ToF-F and ToF-L/R resolution after calibration for:

-detector geometry
-time off-set



time difference between two overlapping scintillators

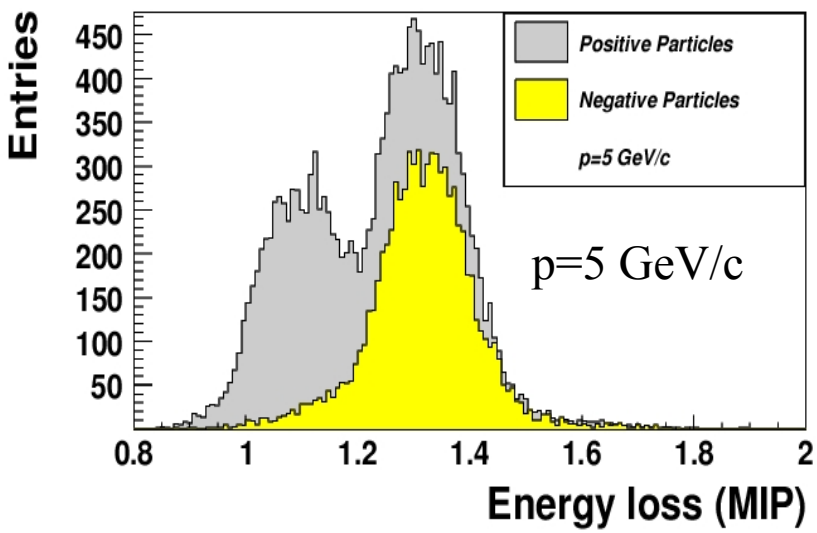


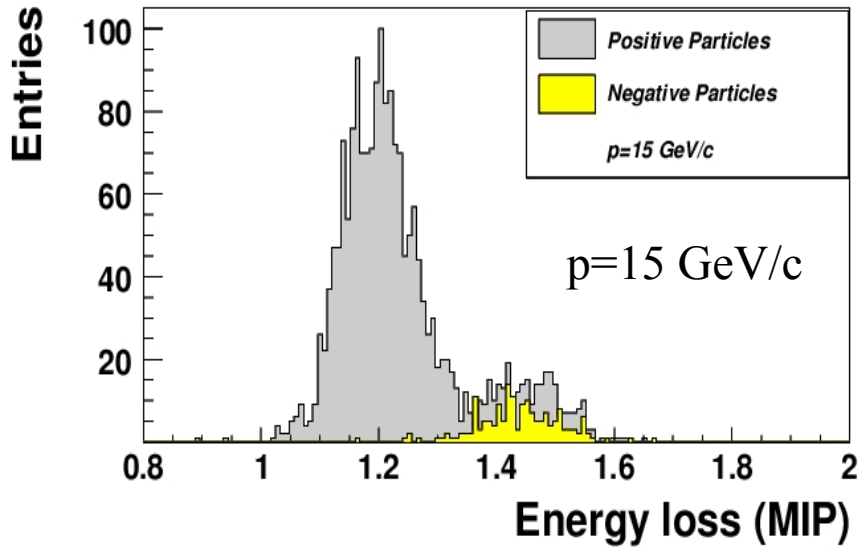
time difference between measured and calculated values

NA61 : Specific energy loss measurements in TPCs

dE/dx resolution after calibration for:

-time dependence of the gas pressure
-residual time dependence
-charge loss during the drift
-differences in the sector gains
-differences in the amplification in the preamplifiers
-edge effects at sector boundaries

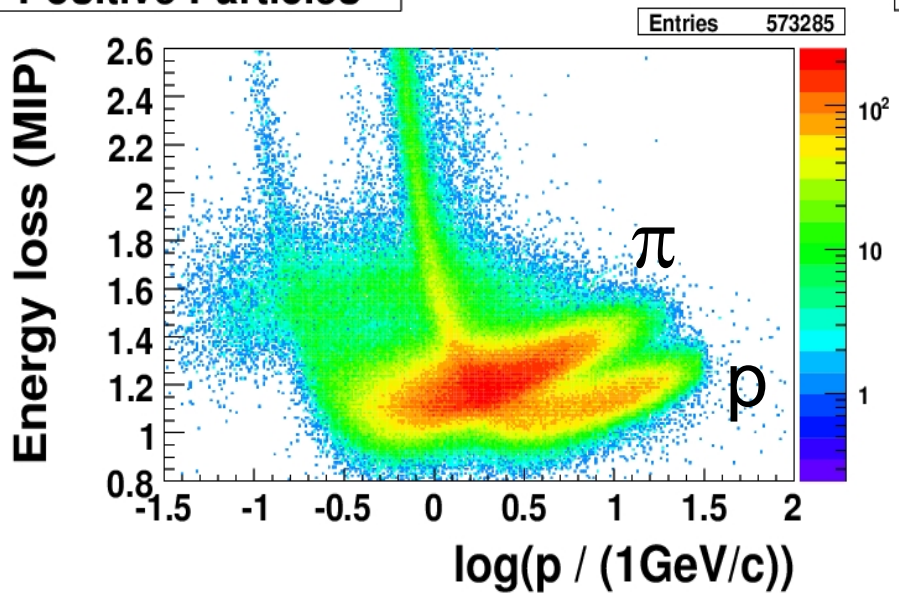




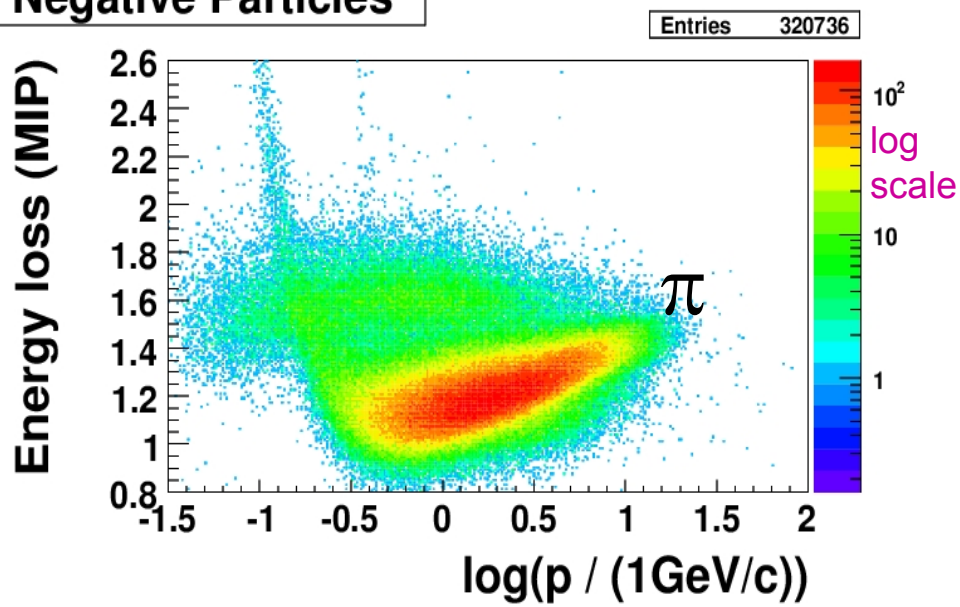
- **dE/dx resolution ~ 4-5 %**

NA61 : PID by dE/dx and TOF measurements

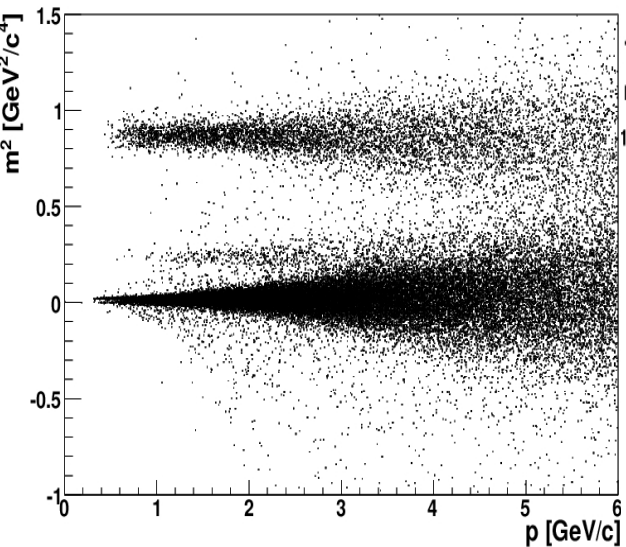
Positive Particles



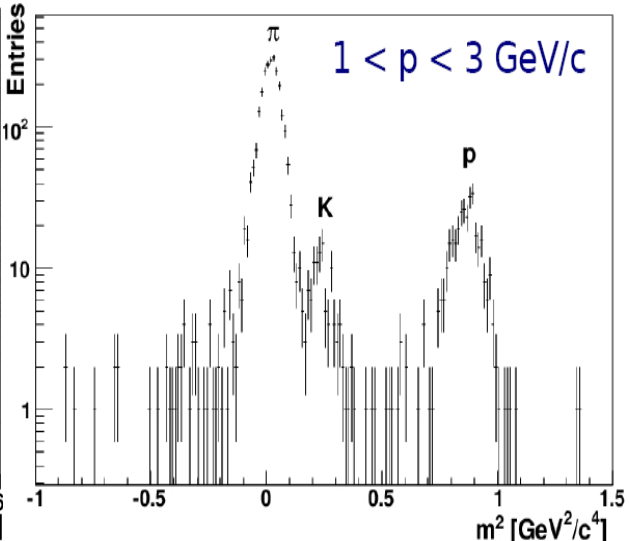
Negative Particles



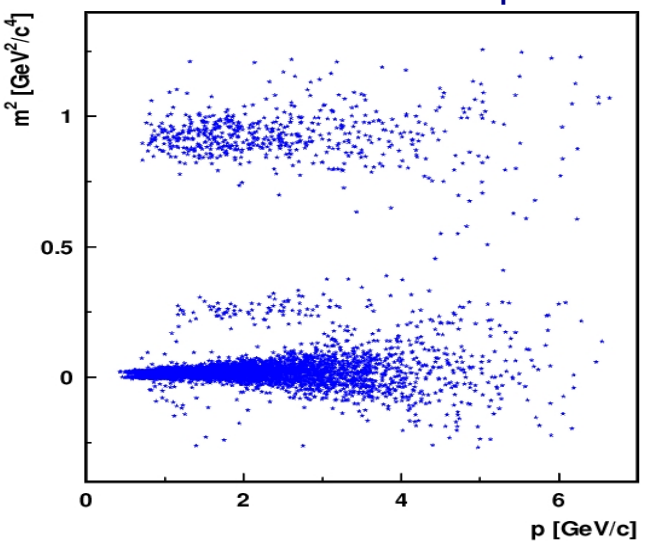
ToF-F calibrated spectrum



Mass-squared from ToF-F

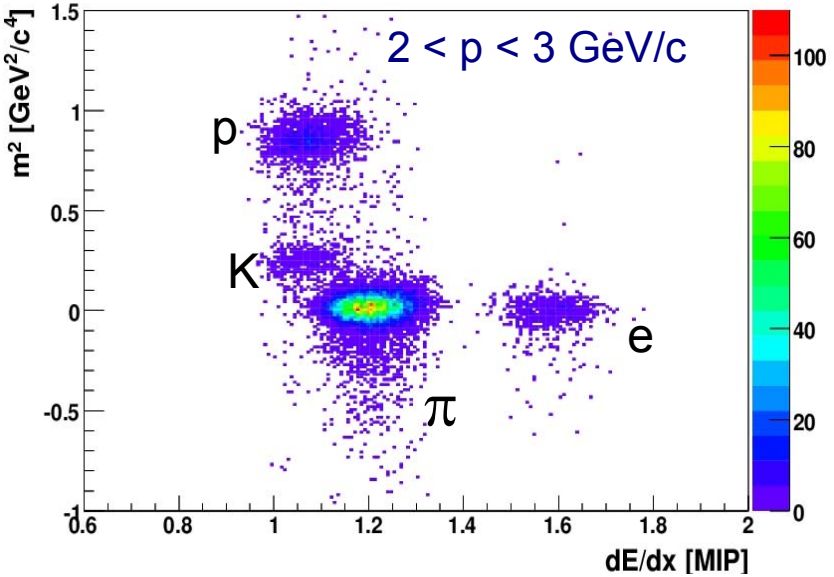


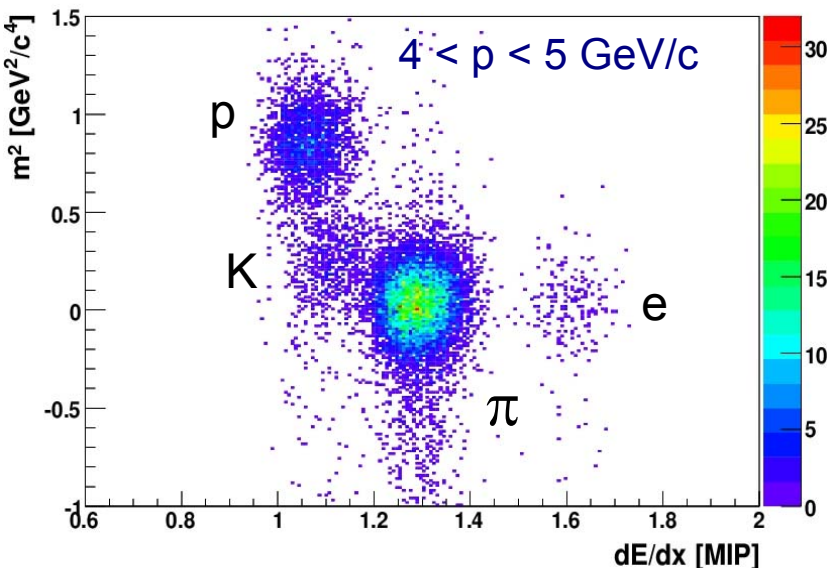
ToF-L/R calibrated spectrum

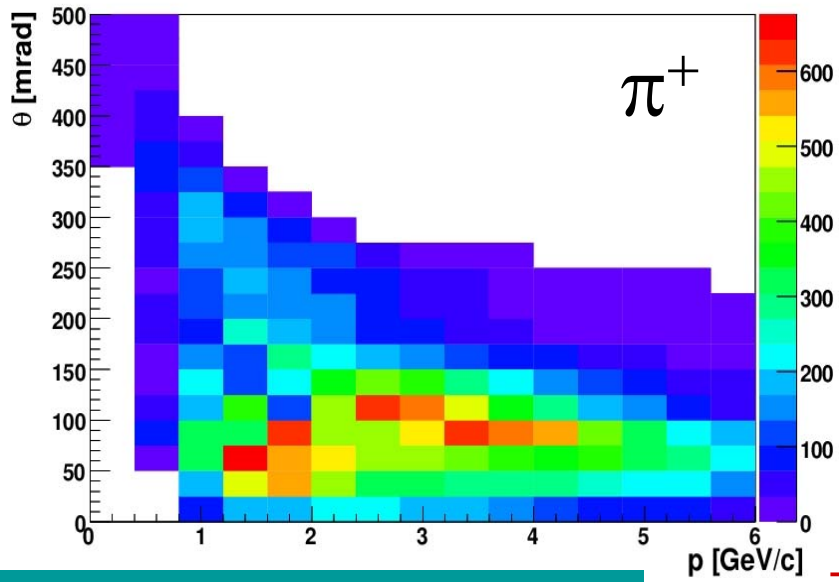


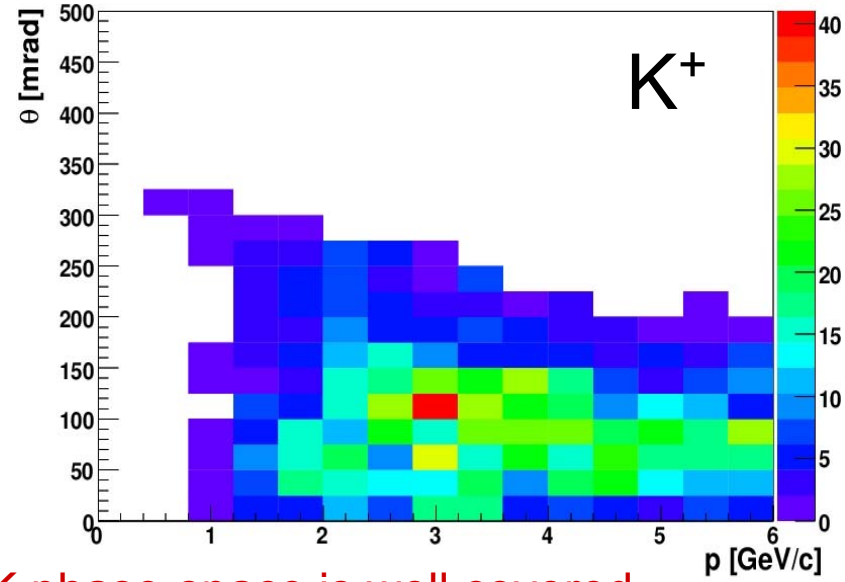
NA61 : PID by combined dE/dx and TOF measurements

ToF-F and TPCs









T2K phase-space is well covered

NA61 : Acceptance and efficiency studies

- **Corrections to the raw spectra to determine acceptances and efficiencies are calculated using the NA61 simulation chain which includes:**

- event generation: primary interaction (VENUS,…)

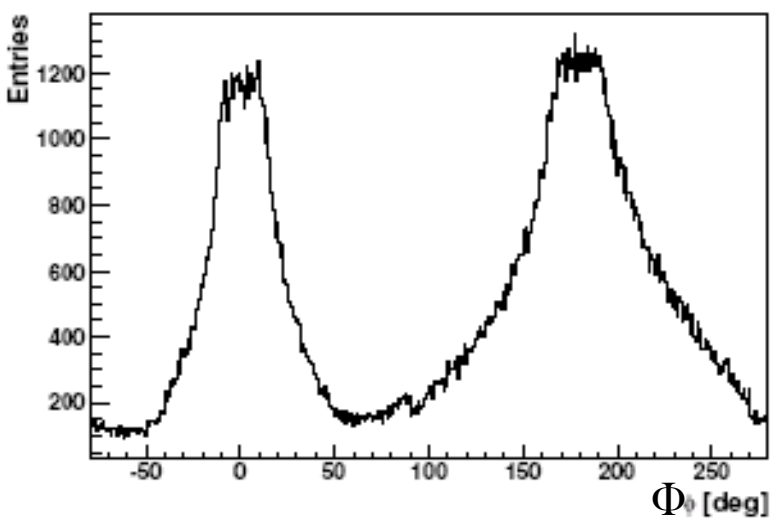
- particle propagation through the detector (GEANT 3.21)

- distortions and TPC digitization

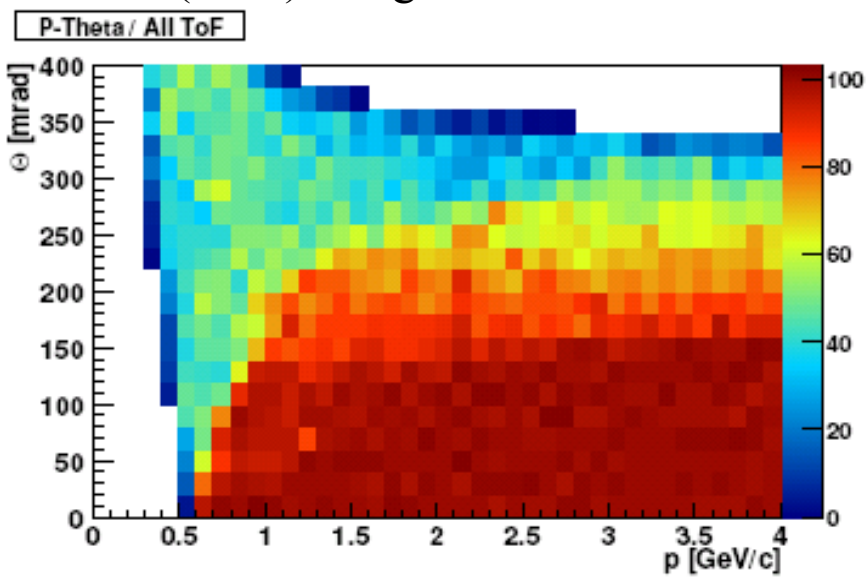
- embedding of simulated raw data into real events

- reconstruction of the simulated data

Example of acceptance studies for positive tracks that reach ToFs

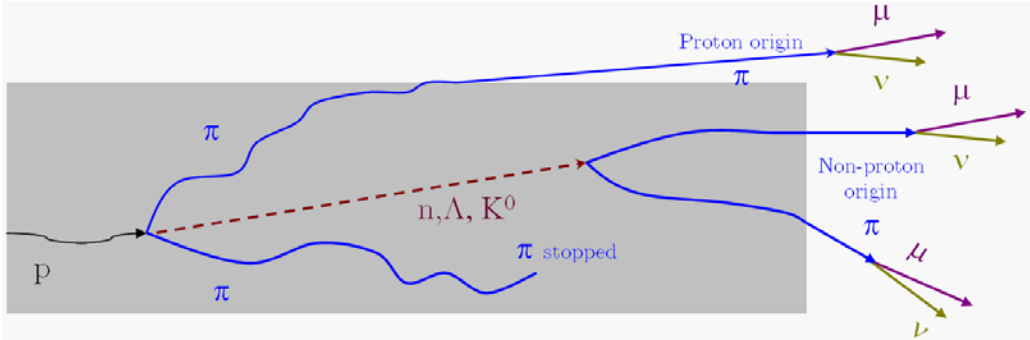


for 2 ΔΦ (=30°) wedges at Φ=0° and Φ=180°



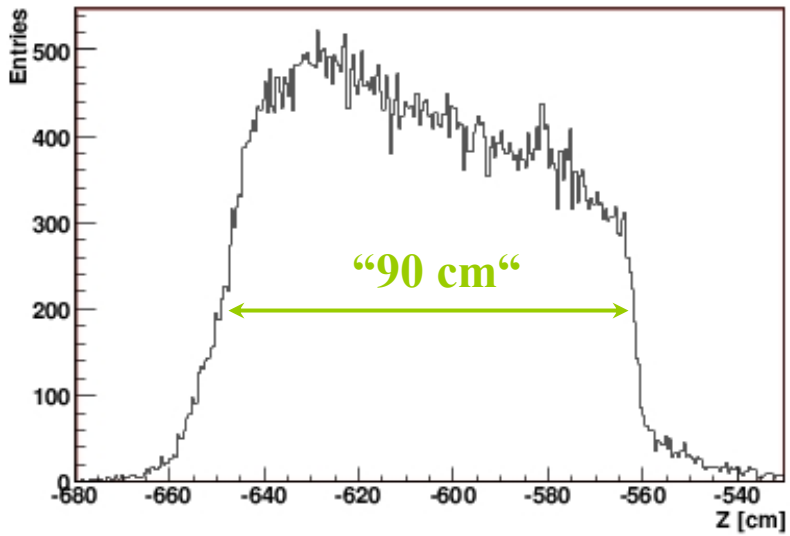
NA61 : First look at 2007 T2K replica target data

- **T2K replica target data will allow for the study of secondary interactions**



- **First look at data**

T2K Replica Target Vertex Distribution



NA61 : Analysis strategies for T2K

Strategy A:

- **Measure the invariant inclusive p+C cross section with a thin target over a broad kinematical range and different particles (π, K, p)**
- **Use the measured cross sections as input to the beam MC for generating the primary interaction. Secondary interactions, however, will be described by hadronization models (e.g. FLUKA)**
- **Compare the MC predicitions to the π/K yields measured off C-targets of different lengths (e.g. T2K replica target) and adjust the model accordingly**

Strategy B:

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

Work in progress

NA61 : Original plans for 2008 run

- ~50 days of beam time were foreseen for September – October 2008

  → T2K and cosmic ray measurements

- NA61 Coll. decided for a TPC read-out and DAQ upgrade before the physics run

- an increase of the event rate by a factor of 10 (crucial for NA61 physics program)
- new TPC read-out electronics and DAQ designed and tested in 2008
- total cost 400 k CHF
- the production and installation of the new electronics was completed by mid September
- during the commissioning phase the designed event rate of ~70Hz was reached

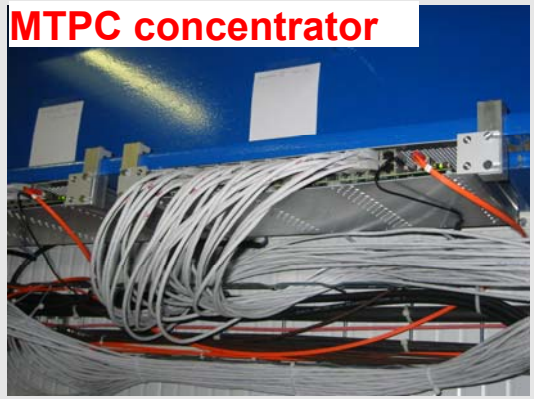
New motherboard (1 out of 250)

- In addition to the TPC upgrade
  - upgrade of Data Control System for gas, LV, HV and trigger systems to new PCs running Scientific Linux (in place of old Macintoshes)
  - commissioning of new beam position detectors of 5x5 cm^2 area (instead of 3x3 cm^2) to fully cover cross section of the T2K replica target

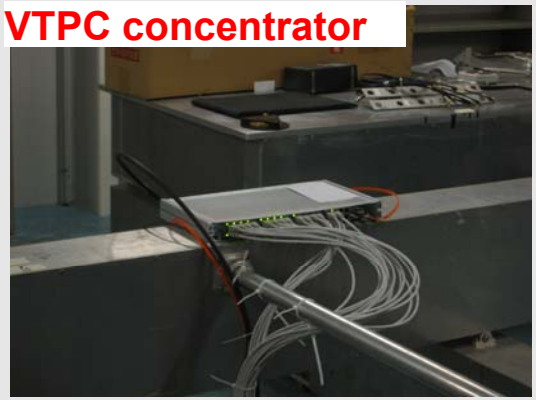
NA61 : New TPC readout electronics in 2008 run

MTPC motherboards

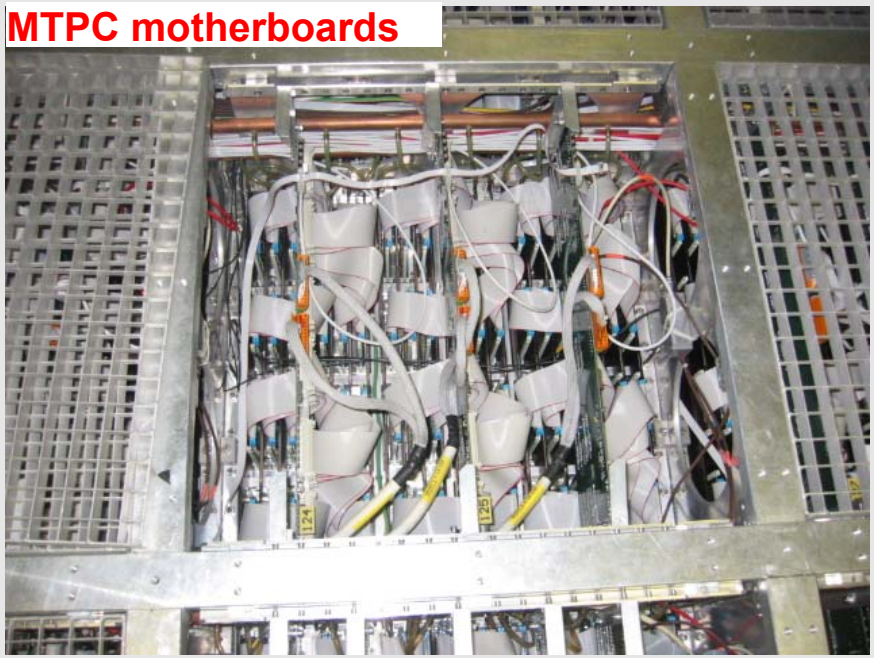
MTPC concentrator



VTPC concentrator



MTPC motherboards



VTPC motherboards

NA61 : 2008 data taking

- **Due to the LHC incident the CERN directorate decided to stop the SPS extraction to the North Area on October 6 at 06:00 am**

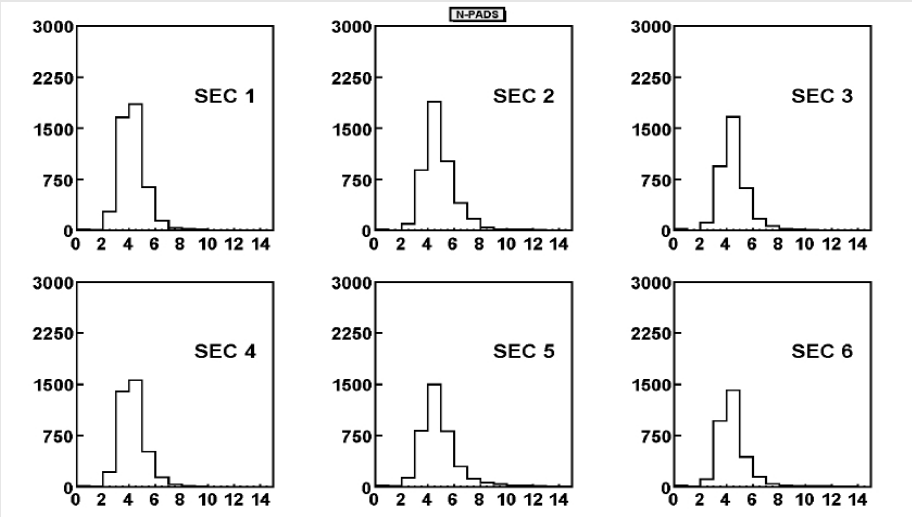
> To: the Spokespersons of the North Area fixed target experiments
>
> From: J. Engelen, CSO
>
> Following a careful analysis and aiming at an expeditious start-up of the LHC injectors after the 2008/2009 Winter shutdown and at a minimization of the beam time lost for the North Area fixed target programme it has been decided to stop SPS extraction to the North Area on October 6 at 06:00 am.
>
> A large part of the beam time lost this year will be recovered next year.
>
> I apologize for the inevitable inconvenience this decision causes to you and your collaborators but I am sure we can count on your understanding.

- **What we achieved**
  - **First try of full TPC readout with new DAQ. Stable operation at ~70 Hz, but still some futher developments needed to integrate other subdetectors in the DAQ; observed digital noise in 10% of TPC channels to be eliminated before 2009 run**
  - **Tests of the new BPDs, data to be analyzed, some instabilities observed**
  - **Setup of interaction trigger for 30.9 and 75 GeV/c beam and measurements of trigger rates for p, π and K to understand systematics for σ_{inel} determination**

TPC read-out and DAQ upgrade

-the new TPC read-out electronics was produced, installed and tested,
-the new firmware and DAQ software were written and tested,
-the event rate up to 70 Hz was achieved **(10 times more than NA49)**,

2008 pad number distributions for clusters on VTPC-1 tracks



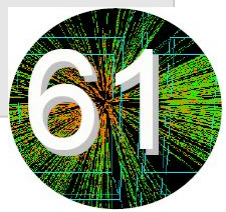
Physics data with TPCs were not recorded due to run stop on October 6, 2008

NA61 : Plans for 2009

Date: Mon, 3 Nov 2008 16:40:04 +0100
From: Marek Gazdzicki marek@mail.cern.ch
To: na61-all@cern.ch
Subject: NA61 in 2009

Dear All,
Many thanks for your contributions to and participation in the last collaboration meeting!
During this meeting as well as during the last collaboration board
we discussed and fixed our plans for 2009.

The NA61 memorandum submitted to the SPSC
and the NA61 beam request submitted to the SPS Coordinator include:
-request for the test run in the period: May 18-24, 2009 and
-request for the physics run in the period: August 12-November 16, 2009.
…
Best regards,
Marek



NA61 : SUMMARY (I)

- NA61 experiment was approved at CERN in June 2007,

- the pilot run was performed during October 2007,

- calibration of all detector components have been performed successfully

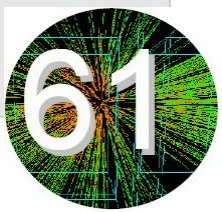
- preliminary uncorrected spectra have been obtained,

- high quality of track reconstruction and particle identification (similar to NA49) has been achieved,

- a preliminary result on the total inelastic p+C cross section at 31 GeV/c was obtained,

- the data and detailed simulations confirm that the phase-space needed for the T2K measurements is covered,

- first physics results from the 2007 run are expected soon



NA61 : SUMMARY (II)

- **Significant progress in data calibration and analysis during last months**
  - **See status report to SPSC:** http://cdsweb.cern.ch/record/1113279
- **SPSC positively evaluated the calibration and analysis of the 2007 data**
- **Good quality of 2007 data, though limited in statistics**
  - **1st round of calibrations completed (TPC, ToF, dE/dx)**
  - **Until now only thin target data analyzed. Work on replica target starting**
- **The next step is to get acceptance and efficiency corrected distributions for π and K and to extract cross-sections**
- **We will hopefully be able to recover this year's lost beam time during 2009 run**
  - **NA61 submitted beam request for 2009 → 3 months of beam time**
- **Important to have a large participation of NA61-T2K group during that run**

Thank you for your attention

Backup slides

NA61 : DOCUMENTS AND REFERENCES

Status Report: *CERN-SPSC-2008-018, SPSC-SR-033 (July 2, 2008)*

Addendum-3	*CERN-SPSC-2007-033, SPSC-P-330 (November 16, 2007)*
Addendum-2:	*CERN-SPSC-2007-019, SPSC-P-330 (June 15, 2007)*
Addendum-1:	*CERN-SPSC-2007-004, SPSC-P-330 (January 25, 2007)*
Proposal:	*CERN-SPSC-2006-034, SPSC-P-330 (November 3, 2006)*
Status Report:	*CERN-SPSC-2006-023, SPSC-SR-010 (September 5, 2006)*
LoI:	*CERN-SPSC-2006-001, SPSC-I-235 (January 6, 2006)*
EoI:	*CERN-SPSC-2003-031, SPSC-EOI-001 (November 21, 2003)*

Report from the NA61/SHINE experiment at the CERN SPS, CERN-OPEN-2008-012
Na61/Shine at the CERN SPS, CPOD 2007, arXiv:0709.1867