Hadron Production and Neutrino Oscillation experiments

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IFAE 2004

Torino, 14-16/04/2004

Outline

- Motivations
- Historical overview
- Recent and present measurements
- Possible future extensions

Outline

Experiment	Proton E	Some H.P. exp	ref
Ps169, Ps180, Ps181	~ 20GeV	Allaby et al. Eichten et al.	CERN 70-12 N.P. B44 (1972)
CDHS, CHARM, BEBC	~400GeV	NA20 (Atherton)	CERN 80-07
CHORUS, NOMAD, CNGS	~400GeV	NA56/SPY	SPSC 96-01
K2K, MiniBooNE	12.9 GeV, 8GeV	HARP	CERN- ps214
NuFact/SuperBeam designs	~2GeV	HARP	==
Atm. Neutrinos	>10GeV	HARP/NA49	CERN- ps214 SPSC 2001-017
MINOS	120GeV	HARP/NA49 FNAL E907	SPSC 2001-017
Future?			

why hadron production

- Neutrino sources from hadron interactions
  - From accelerators
  - From cosmic rays
- Energy, composition, geometry of the beam is determined by the development of the hadron interaction and cascade.
  - And by target/collection optics, but this we can know easily
- In neutrino oscillation experiments the beam is (part of) the experiment → no credible result without a reliable understanding of the beam itself.
- Design parameters of future neutrino beams influenced by target/energy choices

One example: MINOS

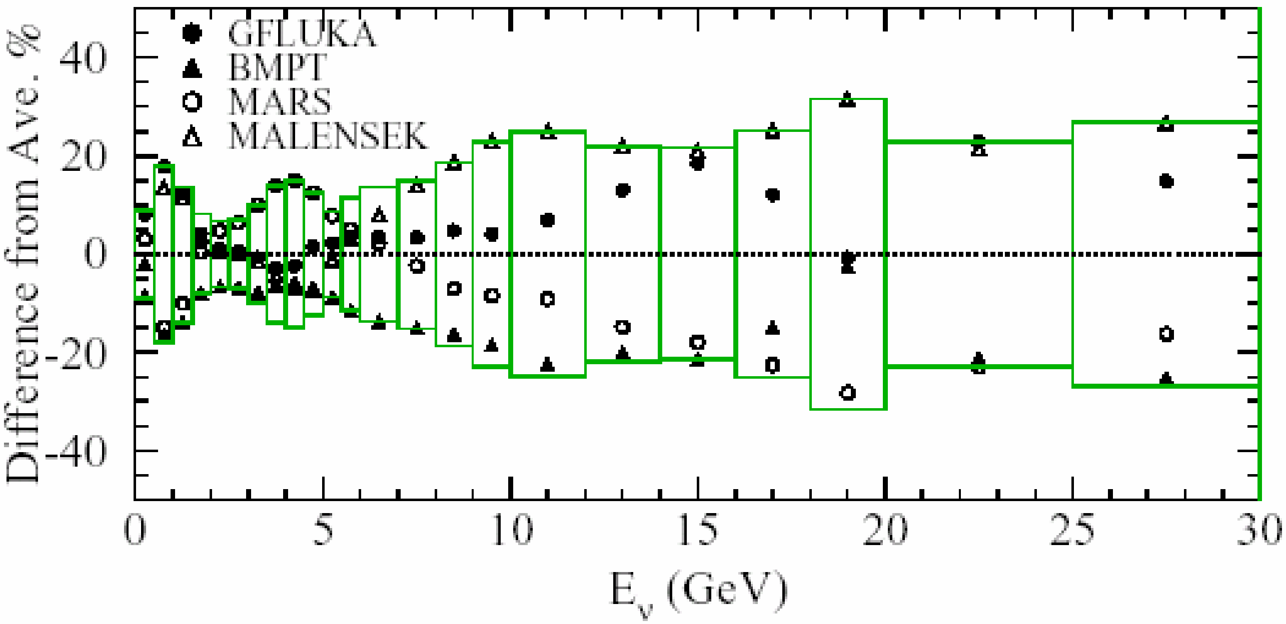


Figure 4: Predictions of the absolu
four hadron production models [7,

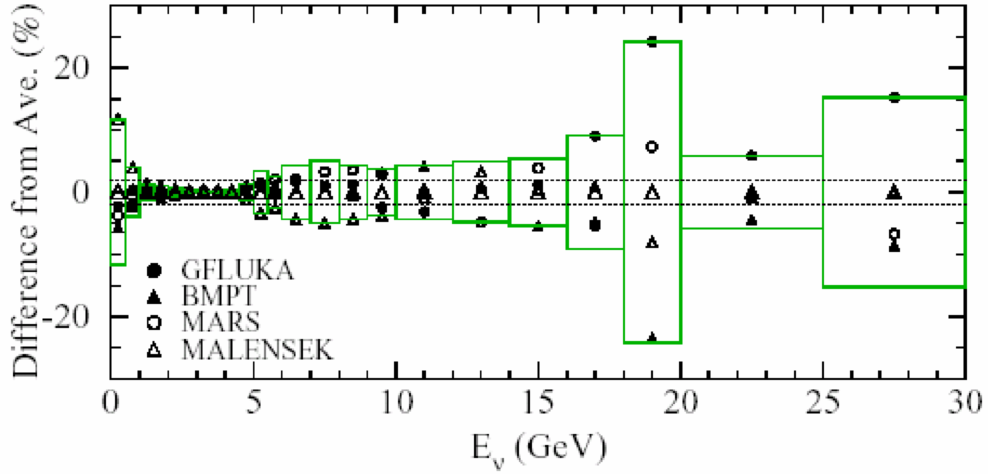
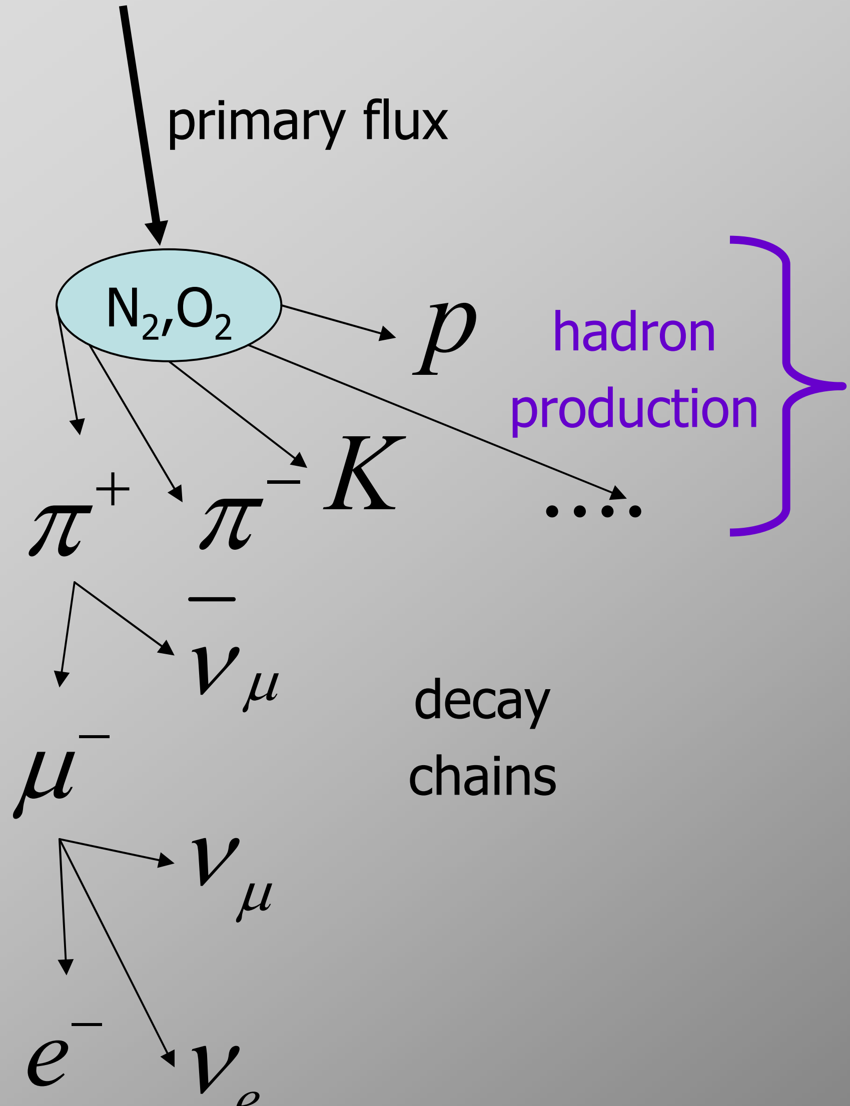


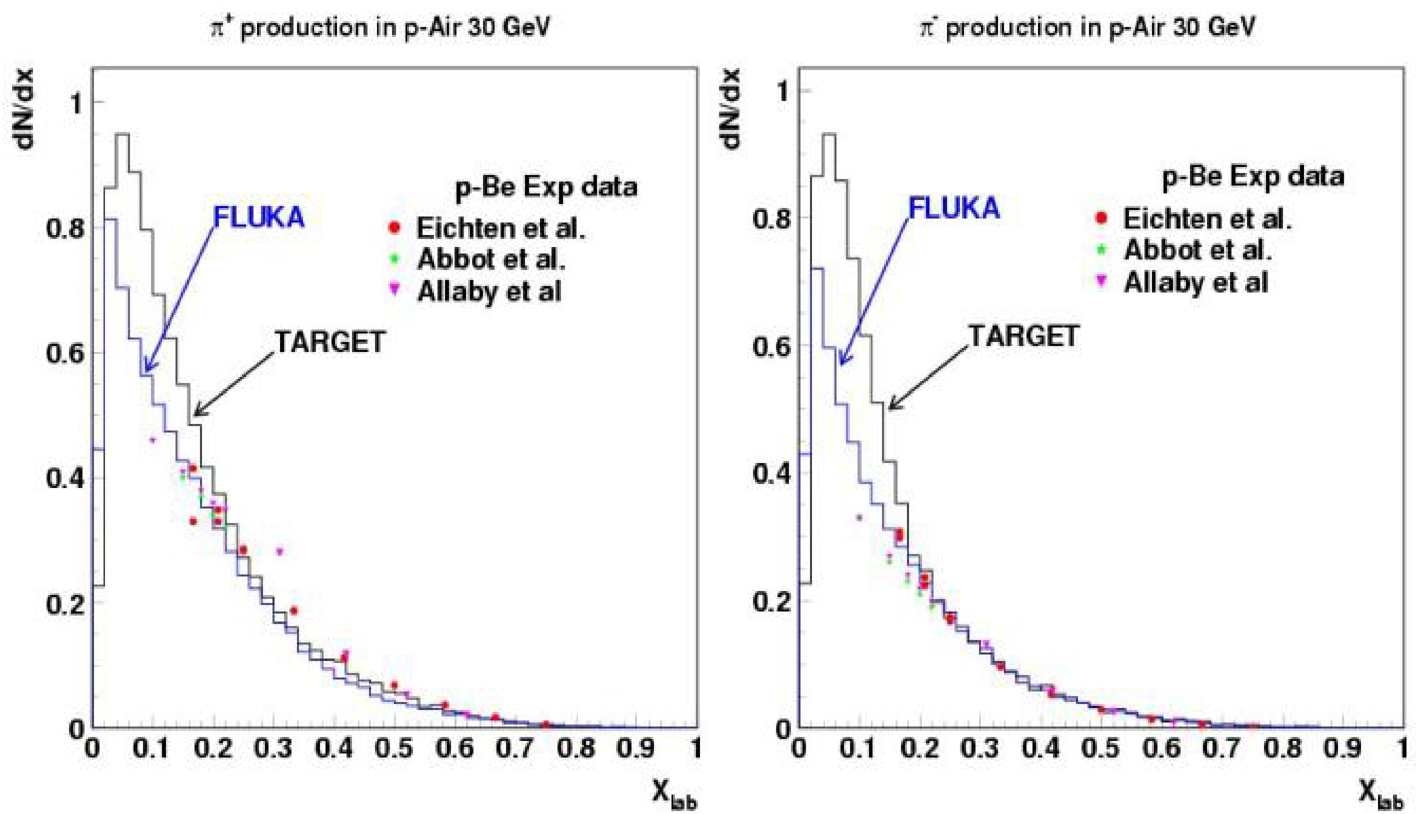
Figure 5: The predictions for the ratio of the far neutrino flux to the near neutrino flux using the same four models as Figure 4.

Atmospheric neutrino fluxes



- Primary flux is now considered to be known to better than 10%
- Most of the uncertainty comes from the lack of data to construct and calibrate a reliable hadron interaction model.
- Model-dependent extrapolations from the limited set of data leads to about 30% uncertainty in atmospheric fluxes
- → cryogenic targets

Discrepancies between hadronic generators



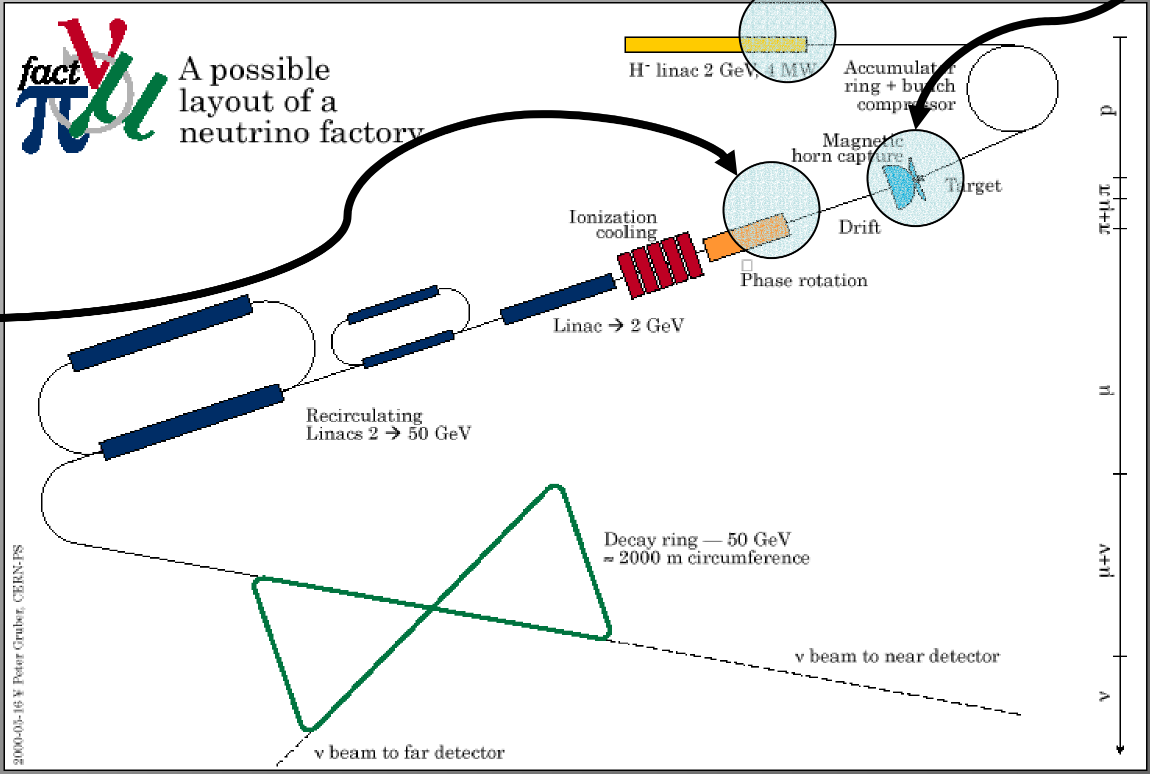
G.Battistoni, Now2000

Example of future projects

Primary energy, target material and geometry, collection scheme
- maximizing the π^+, π^- production rate /proton /GeV
- knowing with high precision (<5%) the P_T distribution

CERN scenario: 2.2 GeV/c proton linac.

Phase rotation
- *longitudinally freeze* the beam: slow down earlier particles, accelerate later ones
- need good knowledge also of P_L distribution



Historical overview

- Mostly based on measurement of particle yields along beam lines
- Experiments done making (smart) use of existing facilities
  - No experiments built on-purpose
- Low (~20GeV/c) and high (~400GeV/c) primary proton momenta, forward angular region (<150mrad)
- Low statistics and/or limited number of data points

Low-energy

- J. Allaby et al., CERN-70-12
  - p-nuclei (B4C, Be, Al, Cu, Pb) and p-p collisions at 19.2 GeV/c
  - Single arm spectrometer
- G. Eichten et al., Nucl. Phys. B44(1972) 333
  - p, K production in p-nuclei collisions (Be, B4C,Al, Cu, Pb targets) at 24 GeV/c
  - single arm magnetic CERN-Rome spectrometer
- All datasets useful, but suffer from low statistics and high systematics (15 % on cross sections)

CERN/PSCC/80-1[illegible]
PSCC/P30
August 29, 198[illegible]

PROPOSAL

SEARCH FOR NEUTRINO OSCILLATIONS

CERN-DORTMUND-HEIDELBERG-SACLAY Collaboration

H. Abramowicz[1], I. Becker[3], J. Duda[2], F. Dydak[1], F. Eisele[2], T. Flottmann[3], C. Geweniger[3], J.G.H. de Groot[1], C. Guyot[4], J.T. He[6], V. Hepp[3], R. Herden[3], H.P. Klasen[2], K. Kleinknecht[2], J. Knobloch[1], J. Królikowski[3], J. May[1], J.P. Merlo[4], P. Palazzi[1], A. Para[5], B. Peyaud[4], D. Pollmann[2], B. Pszola[2], J. Rander[4], F. Ranjard[1], B. Renk[2], J. Rothberg[1], T.Z. Ruan[6], W. von Rüden[1], J.P. Schuller[4], J. Steinberger[1], H. Taureg[1], K. Tittel[3], R. Turlay[4], H. Wahl[1], J. Wotschack[1] and W.M. Wu[6]

CERN/PSCC/80-130
PSCC/P33
30.10.1980

…to Search for Neutrino Oscillations

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A. Nanni, R. Pazzi, C. Petri, G. Pierazzini

PROPOSAL

CONTRIBUTION OF THE CHARM COLLABORATION TO THE CERN NEUTRINO OSCILLATION PROGRAM

CHARM Collaboration

Eichten et Al. based on
CERN-70-12

PARTICLE PRODUCTION IN PROTON INTERACTIONS IN NUCLEI AT 24 GeV/*c*

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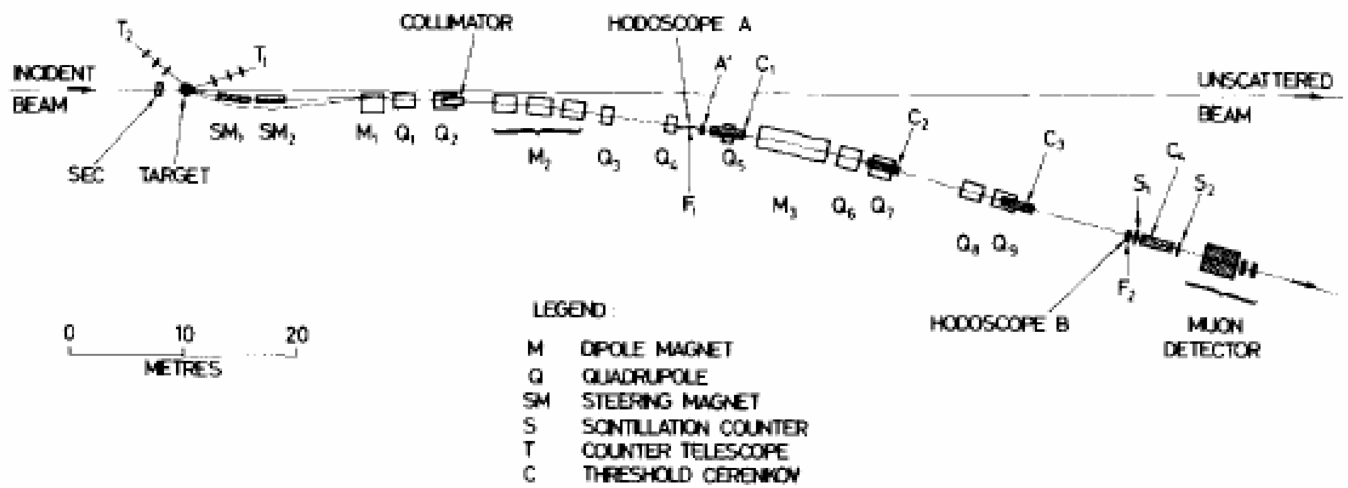
Received 15 March 1972

Abstract: Particle production by 24 GeV/*c* protons from Be, B_4C, Al, Cu and Pb has been measured. Pion, kaon, proton and antiproton production spectra measured over a range of angles from 17 to 127 mrad and momenta from 4 to 18 GeV/*c* are given in a table.



- Motivations and scope

The aim of the present experiment was to measure pion and kaon production in proton-nucleus collisions at 24 GeV/c primary proton momentum. The measurements cover the secondary momentum range 4–18 GeV/c and the angular range 17–127 mrad. These data are essential for the estimation of the neutrino spectrum for the present CERN neutrino experiment.

- Experiment's uncertainties

The statistical errors were nearly always negligible compared to the systematic errors. The overall scale error arising from the uncertainties in the spectrometer acceptance and in the absolute calibration of the primary proton beam intensity (by Al activation) is estimated to be 15% [4]. The systematic errors of individual data points are determined by the irreproducibility of a given spectrometer (setting (about 5%) and by the uncertainties in the corrections applied (2–5% depending on momentum). Ratios obtained from one and the same spectrometer setting (K/π ratios and ratios between different targets) are much more accurate (total error generally less than 4%), as most systematic errors drop out. Details of the data evaluation have been given in refs. [5, 6].

NA20 (Atherton et al.) @ CERN-SPS

List of targets

Length (in beam direction) (mm)	Width (horizontal) (mm)	Height (vertical) (mm)
500	160	2.0
300	160	2.0
300	160	1.5
100	160	2.0
40	160	

- Secondary energy scan: 60,120,200,300 GeV

- H2 beam line in the SPS north-area

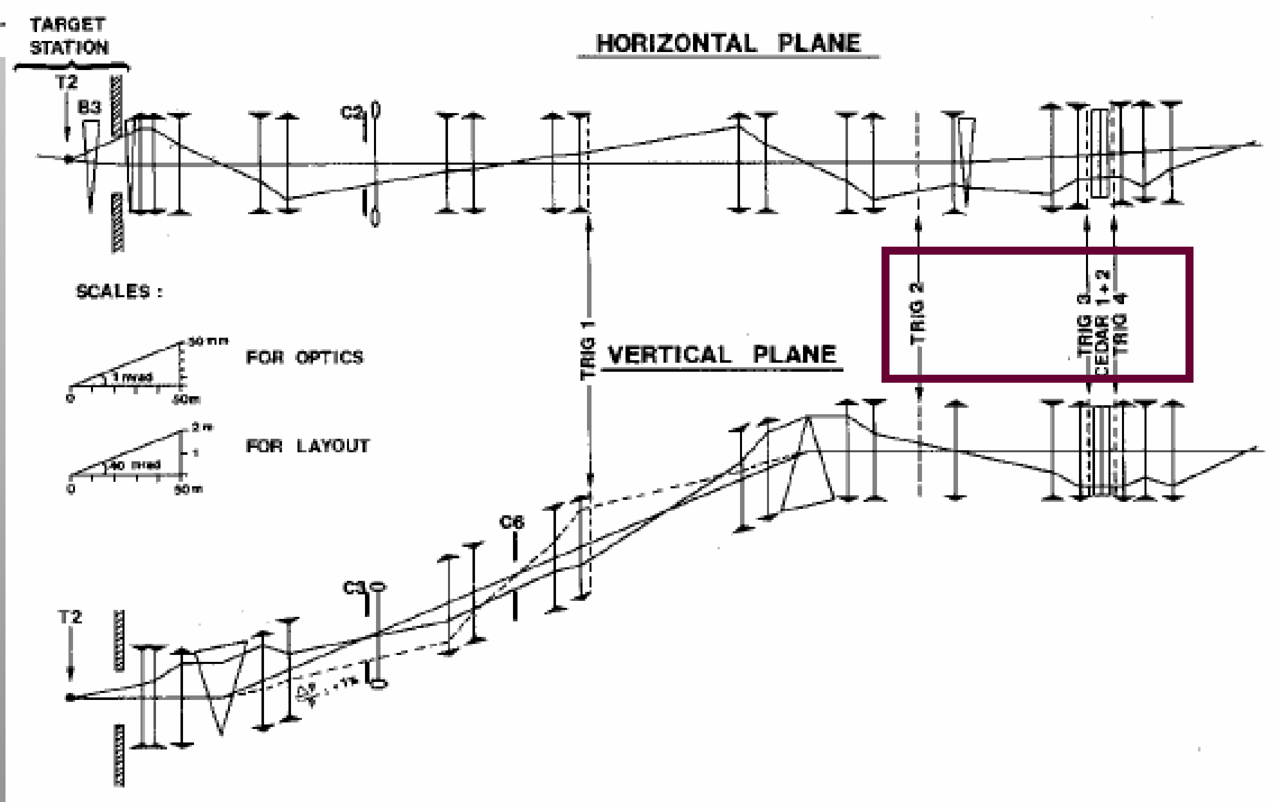


Fig. 1 Layout and optics of H2 beam

The total measurement error is dominated by the following three systematic errors:

i) SEM calibration, see Section 3.2.1 ≃ 5%

ii) errors in beam optics, see Section 3.1.4 ≃ 4%

iii) collimator opening uncertainty ≃ 1-4%.

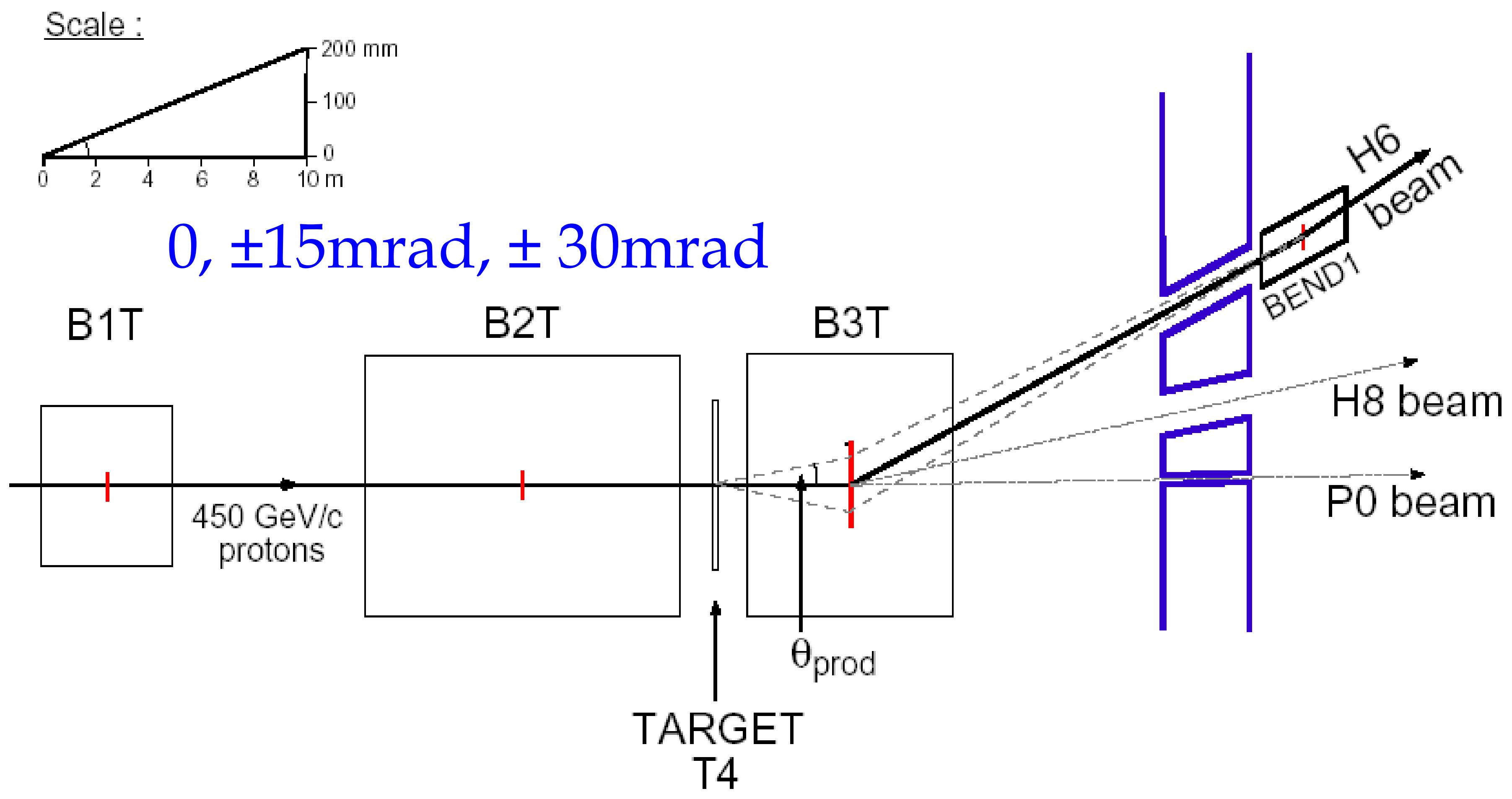
All other corrections are of the order of or less than 1%.

- Overall quoted errors
  - Absolute rates: ~15%
  - Ratios: ~5%
- These figures are typical of this kind of detector setup

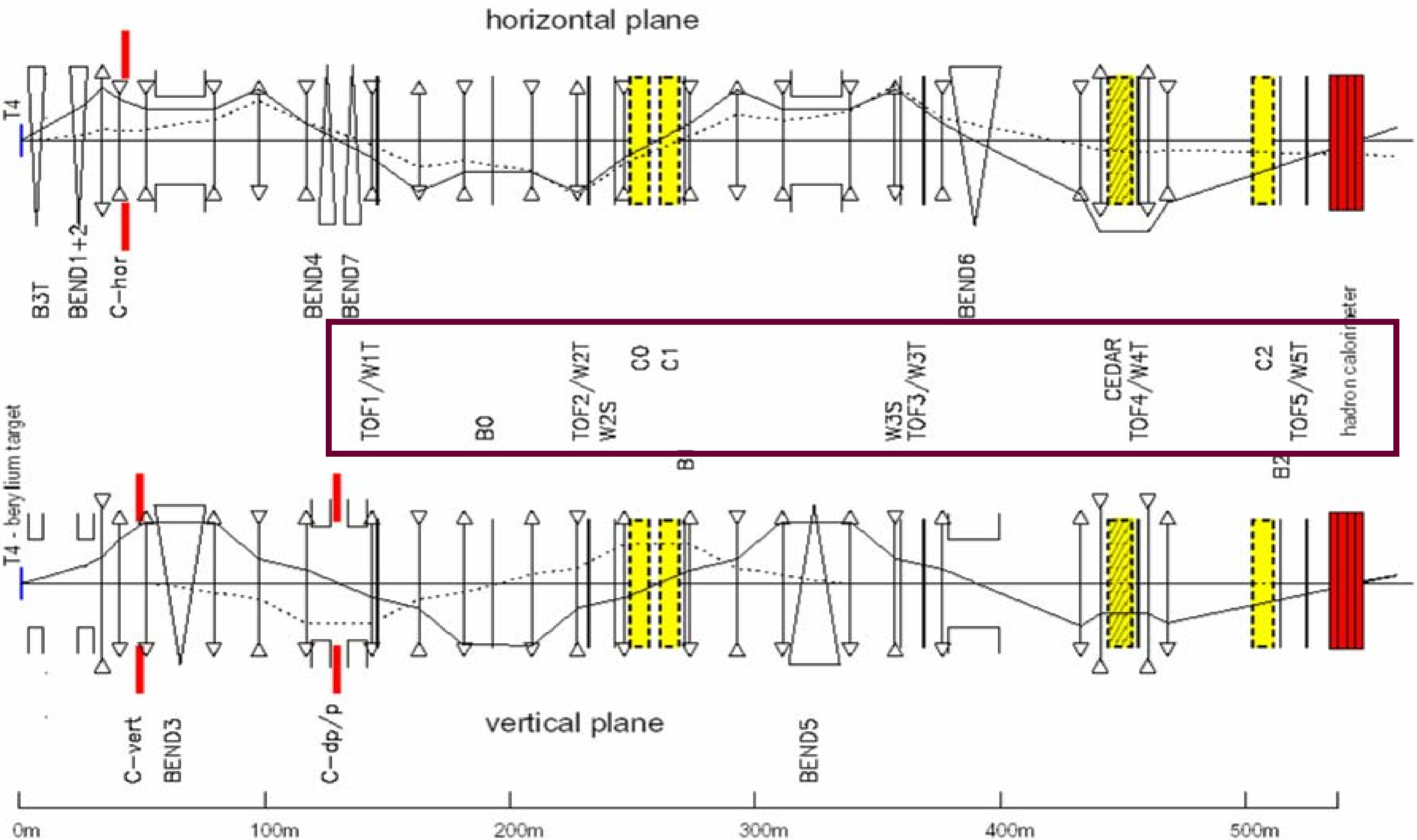
SPS: NA56/SPY

- Most likely the most advanced study done with instrumented beam line experiments
- Dedicated to WANF (CHORUS/NOMAD) (and CNGS) experiments
- To address discrepancies beam spectrum, shape and composition as measured in CHORUS/NOMAD compared to MC predictions.
- 450GeV/c incident protons, 7→135 GeV/c secondaries (overlap with Atherton)
- Exploits TOF / Cherenkov / Calorimetry

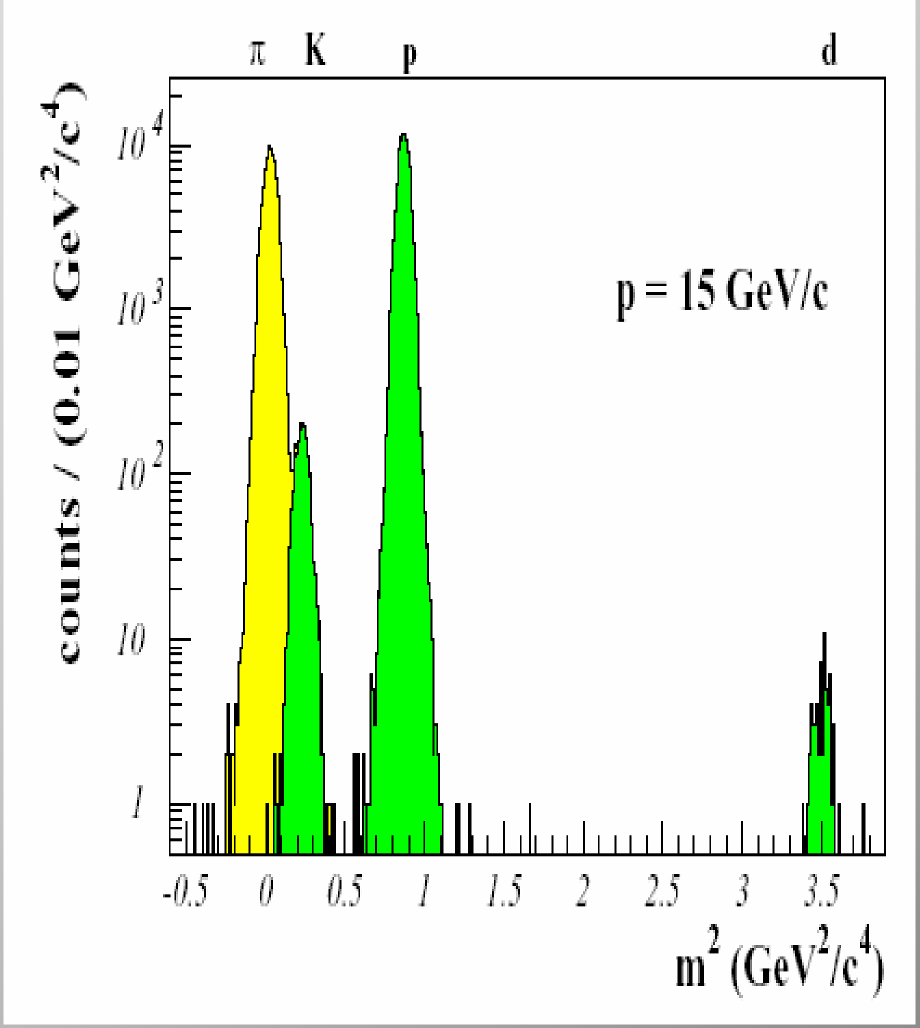
SPY target region

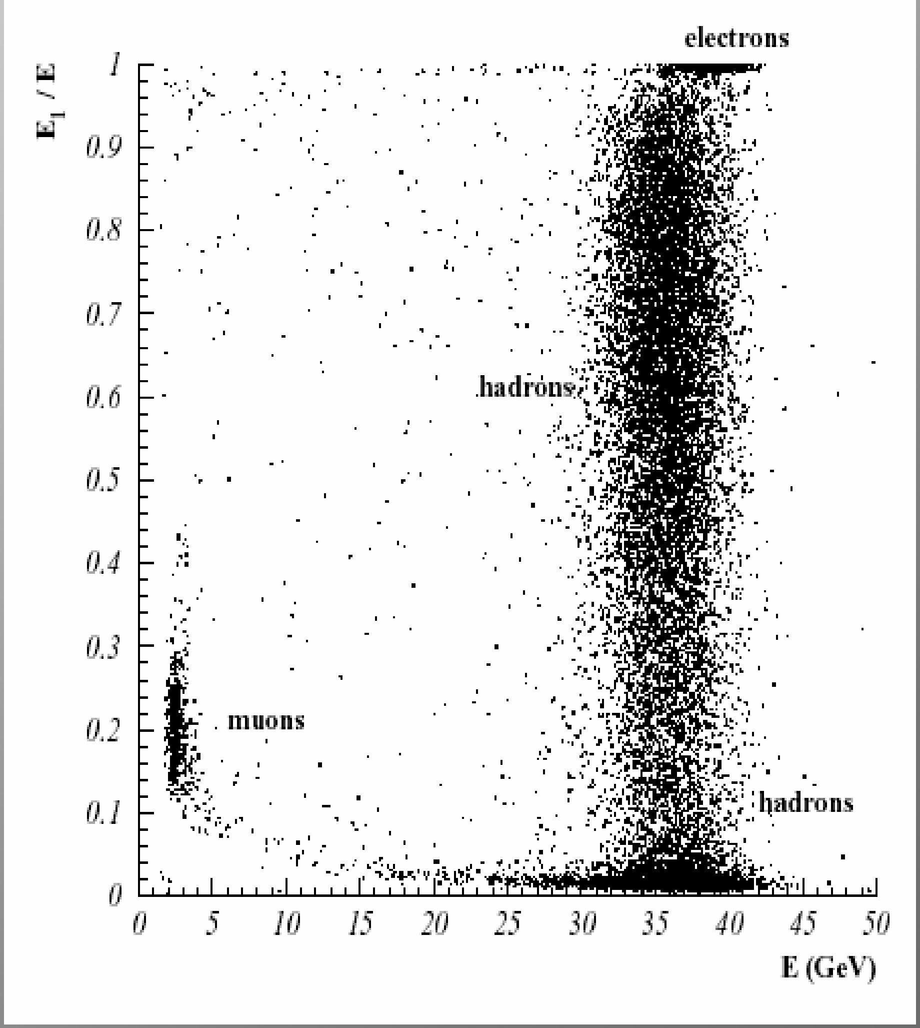


SPY spectrometer



SPY measurement principle





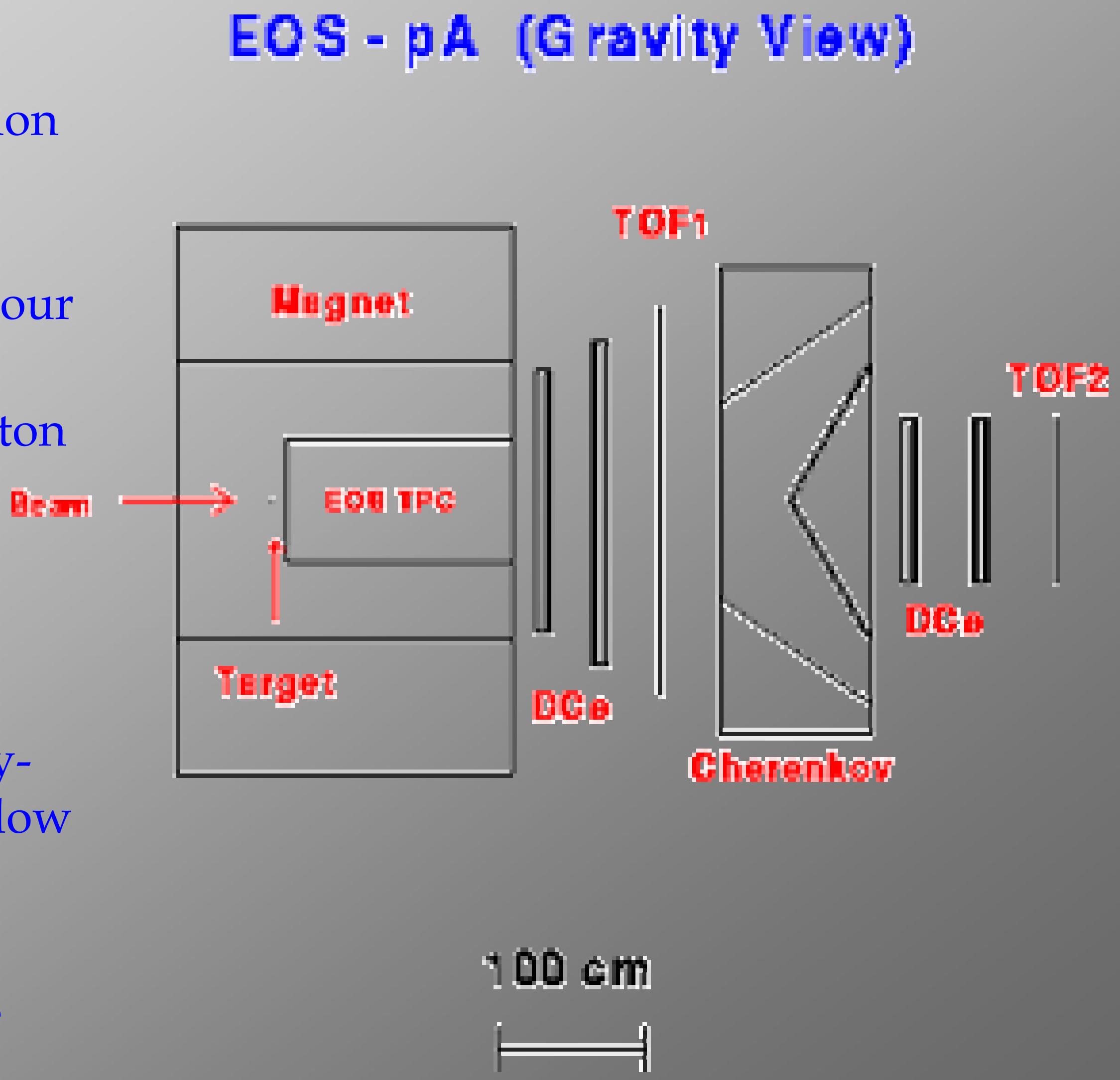
- TOF + Cherenkov, cross-check with calorimetry.

Present

- Aim at event-by-event experiments, not particle-by-particle
- Modern design
  - Open-geometry spectrometers
  - Full solid angle and P.Id.
  - Design inherited from Heavy Ions experiments (multiplicity, correlations, pion interferometry, …)
- Full momentum acceptance, scan on incident proton momenta (not only on momentum of secondaries)
- High event rate
  - Heavy ions experiments are designed for very high track density per event, not for high rate of relatively simple events

E910

- BNL E910
  - main goal: Strangeness production in p-A collision (comparison with A-A collisions)
  - Some data overlap with our needs
  - 6,12,18 GeV/c beam proton momenta
  - Be, Cu, Au targets
- however
  - low statistics in general (this is common in heavy-ions experiments), very low at 6GeV/c
  - no thick targets
  - no backward acceptance (target outside the TPC)



HARP

- Inaugurates a new era in Hadron Production for Neutrino Physics:
- Based on a design born for Heavy Ions physics studies
  - Full acceptance with P.Id.
  - High event rate capability (3KHz on TPC)
- Built on purpose
- Collaboration includes members of Neutrino Oscillation experiments
  - And makes measurements on specific targets of existing neutrino beams.

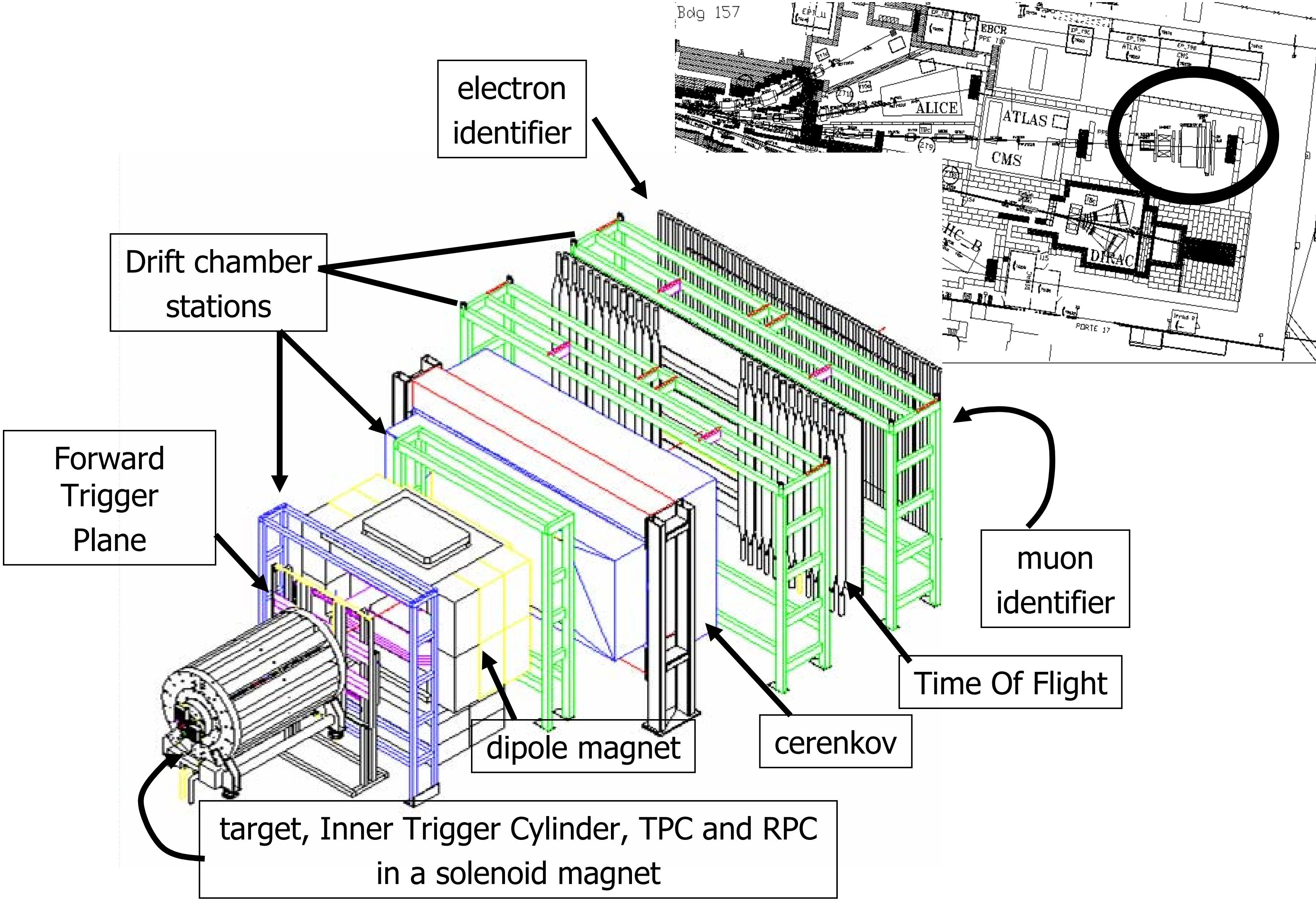
HARP motivations

- Input to neutrino factory designs
  - Low-energy beam
  - Many target samples (material and length)
- Atmospheric neutrinos
  - Cryogenic targets
- Measurement of experimental targets
  - Collaboration with K2K and MiniBooNE
- Calibration of hadron production MC generators
  - Explicit collaboration with Geant-4

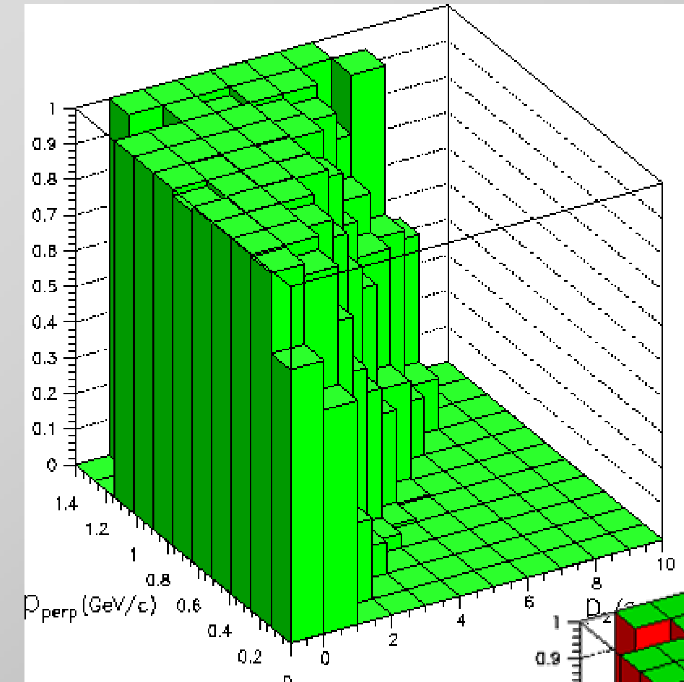
HARP's goals

- secondary hadron yields
  - for different beam momenta
  - as a function of momentum and angle of daughter particles
  - for different daughter particles
- as close as possible to full acceptance
- the aim is to provide measurements with about 2% overall precision
- → efficiencies must be kept under control, down to the level of 1%
  - primarily trough the use of redundancy from one detector to another
- thin, thick and cryogenic targets
- T9 secondary beam line on the CERN PS allows a 2→15 GeV energy range
- O(10^6) events per setting
    - a setting is defined by a combination of target type and material, beam energy and polarity
  - Fast readout
    - aim at ~10^3 events/PS spill, one spill=400ms. Event rate ~ 2.5KHz
    - corresponds to some 10^6 events/day
    - ➔ very demanding (unprecedented!) for the TPC.

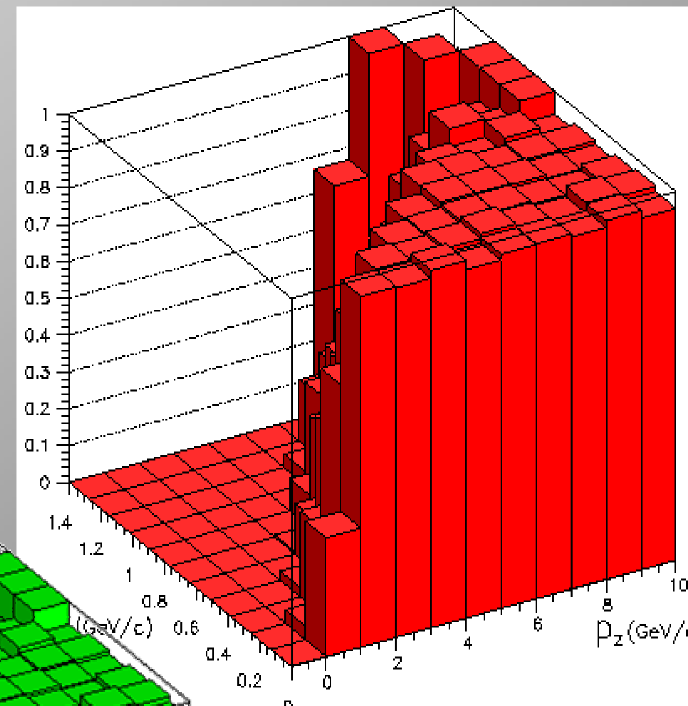
Experimental area & detector layout



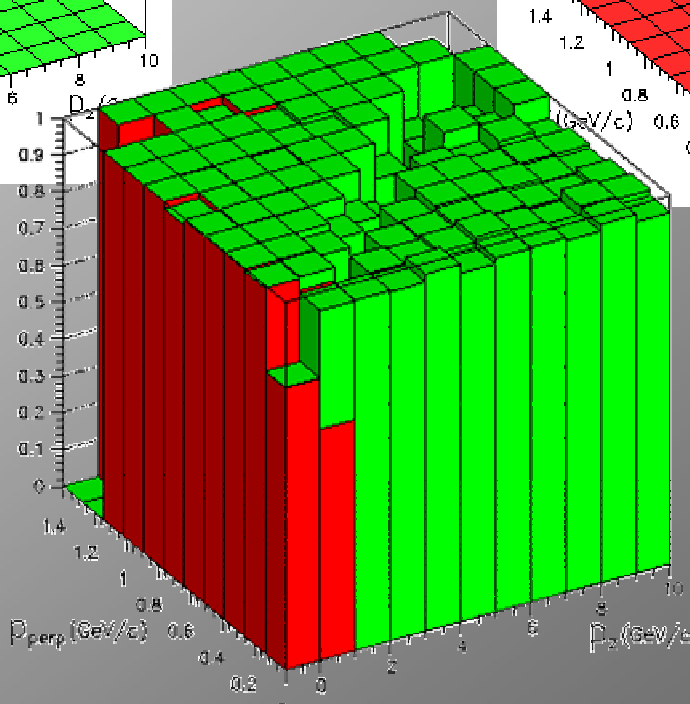
Acceptances



TPC

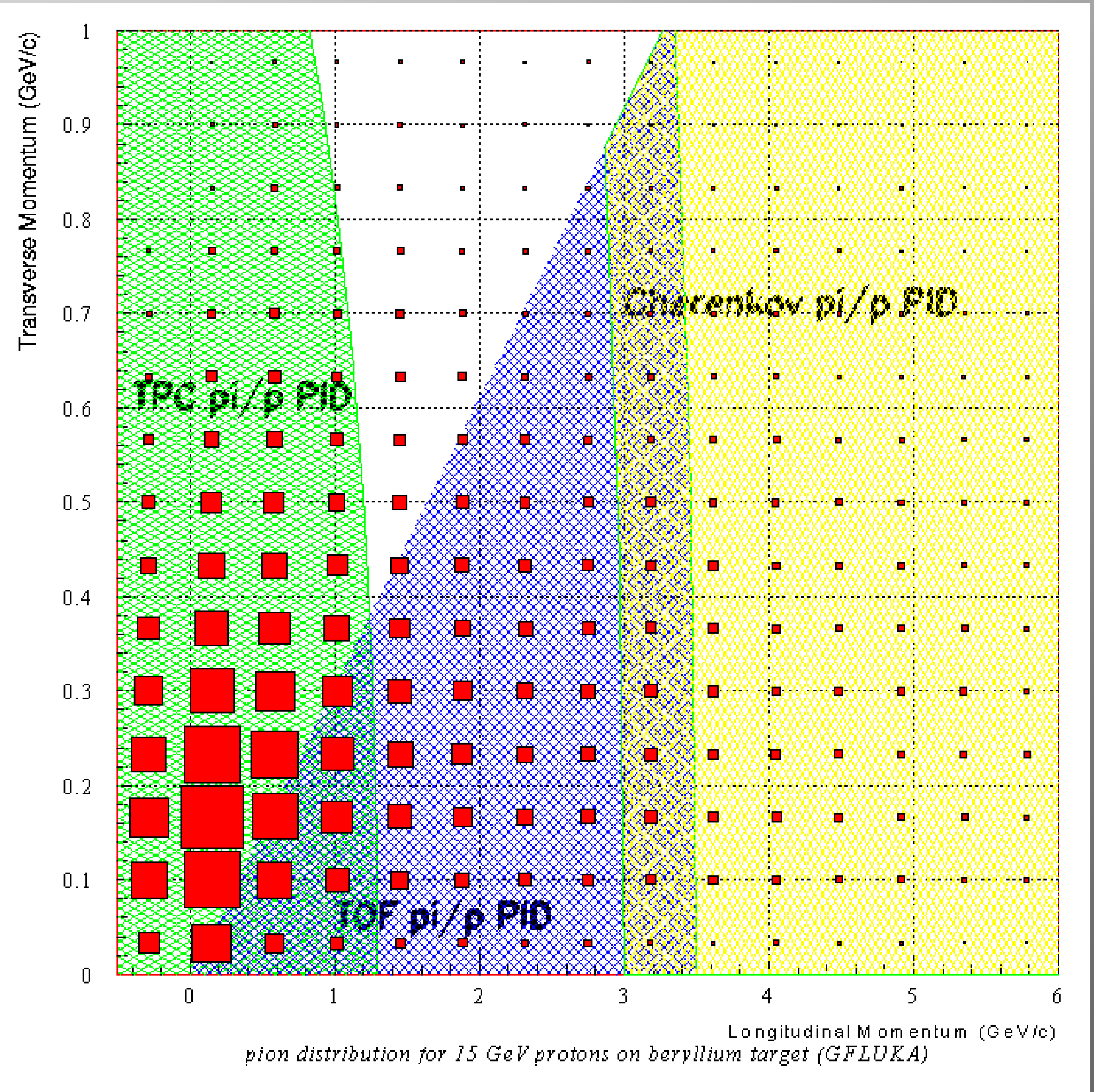


Forward spectrometer



Acceptances

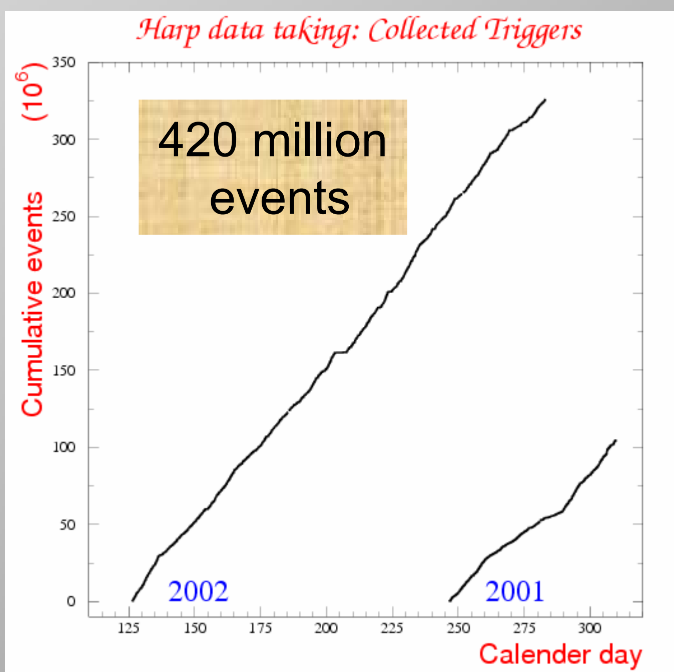
- Acceptance: P_T vs. P_L box plot for pions produced in 15GeV/c interactions of protons on thin Be target
- redundancy in overlap regions



Data taking

- Programme completed successfully
- Despite the non optimal beam conditions the DAQ system showed high performance

30 TB of data



	Target material	Target length (λ%)	Beam Momentum (GeV)	#events (millions)
Solid targets	Be	2 (2001) 5 100	±3 ± 5 ± 8 ± 12 ± 15 Negative only 2% and 5%	233.16
	C			
	Al			
	Cu			
	Sn			
	Ta			
	Pb			
K2K	Al	5, 50, 100, replica	+12.9	15.27
MiniBooNE	Be		+8.9	22.56
Cu "button"	Cu		+12.9, +15	1.71
Cu "skew"	Cu	2	+12	1.69
Cryogenic targets	N_7	6 cm	±3 ± 5 ± 8 ± 12 ± 15	58.43
	0_8			
	D_1			
	H_1			
	H_2	18 cm	±3, ±8, ±14.5	13.83
Water	H_20	10, 100	+1.5, +8(10%)	9.6

TPC

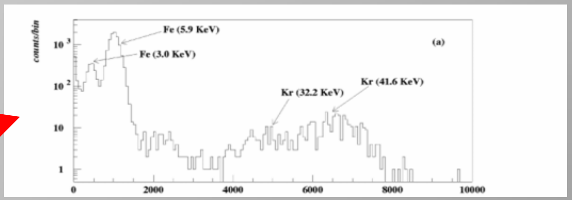
• A high-statistics calibration with cosmic rays and radioactive sources (Fe55 and Kr) has been made in 2003.

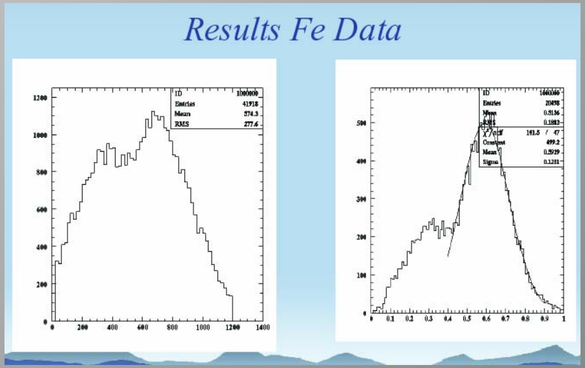
•Using these data it has been possible to

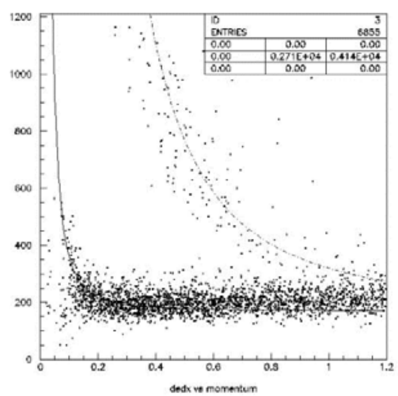
- •Make a first evaluation and correction of the X-talk
- •Compute the gain curves and map the dead regions
- •Get a 30% improvement of the momentum resolution
- •Make a first trial of a dE/dx measurement

•As a first check of the improvements, data taken with a cryogenic H_2 target and 3GeV/c pions and protons is being analyzed, looking for the elastic scattering:

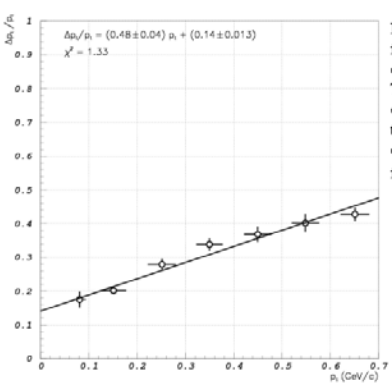
$$p,(\pi)\ p \ \rightarrow\ p,(\pi)\ p$$



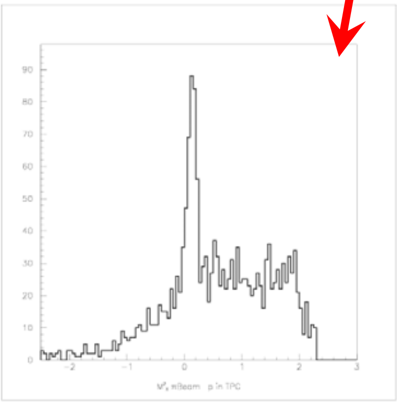




dE/dx in cosmic rays events. The energy loss is evaluated with a truncated mean discarding the three most and the three less energetic samples.

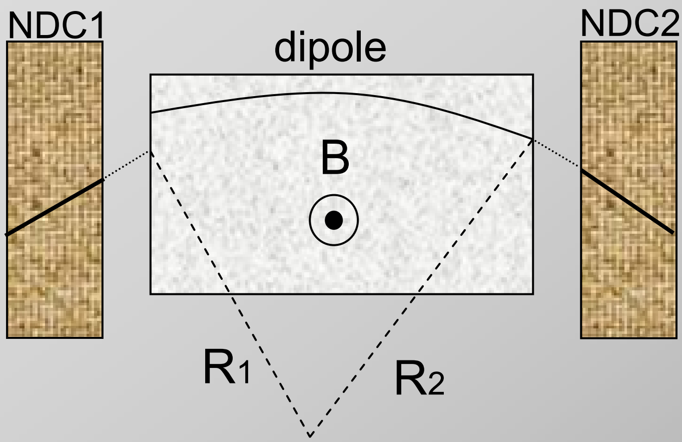


Momentum resolution as a function of momentum on cosmic rays events. The resolution is evaluated comparing the parameters of the fit of the two arms of a cosmic track with the global fit of all the points.



Missing mass in a pion-proton interaction in which only the proton of the final state particles is measured.

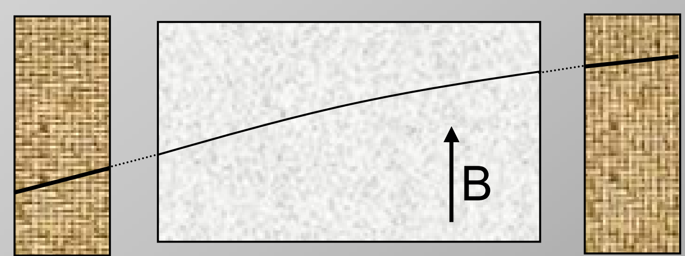
Momentum reconstruction



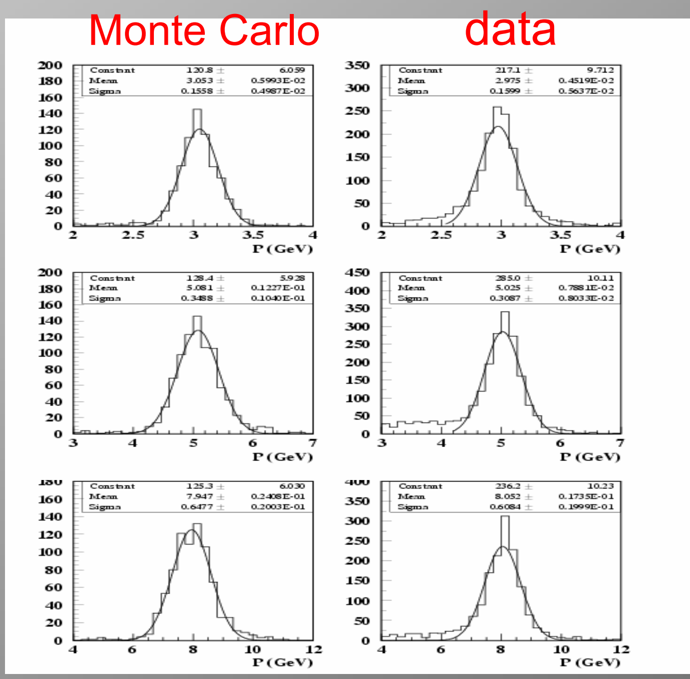
$$\chi_R^2 = \left(\frac{\Delta R}{\sigma_{\Delta R}}\right)^2$$

analytic

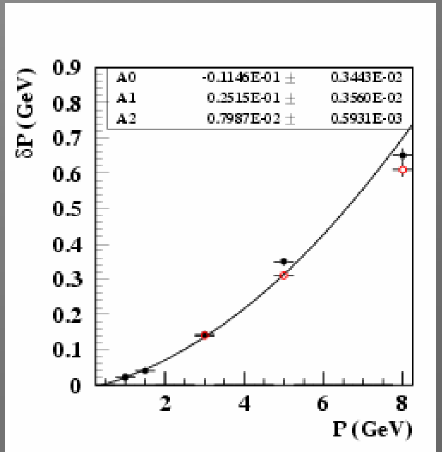
Homogeneous B



$$\chi^2_{yy'}(\Delta y \quad \Delta y')$$



momentum resolution

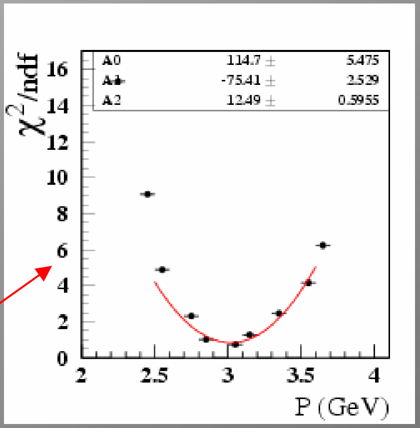


B field map

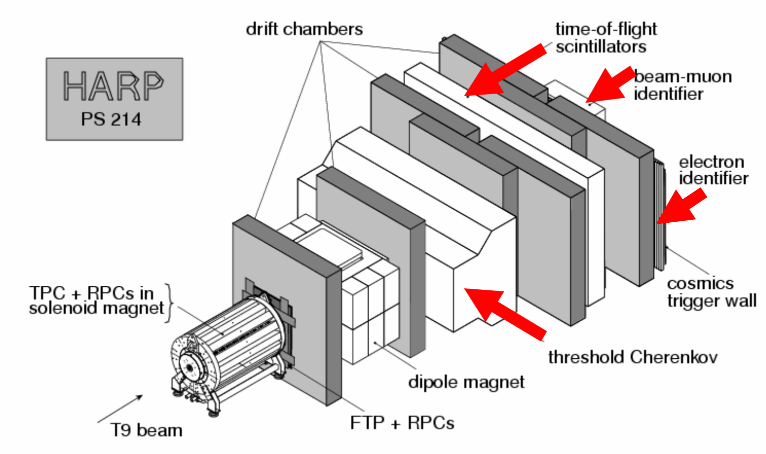
Loop over momentum around p_0

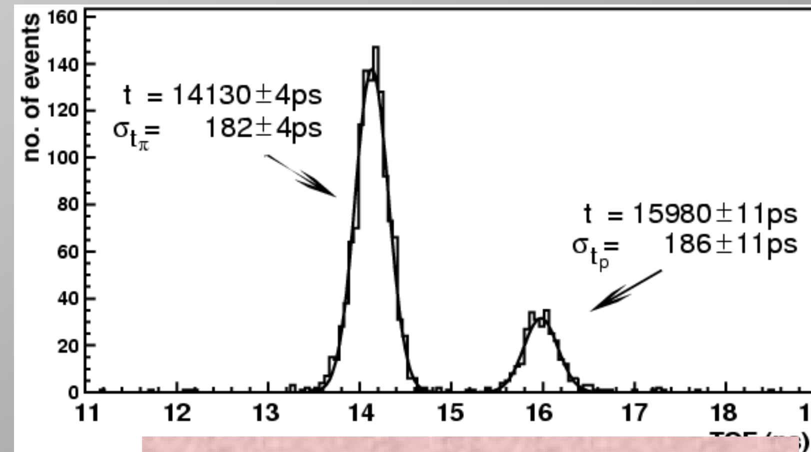
$$p_0 = \frac{0.3 \cdot |R| \cdot B_{avg}}{\sin\alpha}$$

$$\chi^2_{all}(\Delta x \quad \Delta y \quad \Delta x' \quad \Delta y')$$



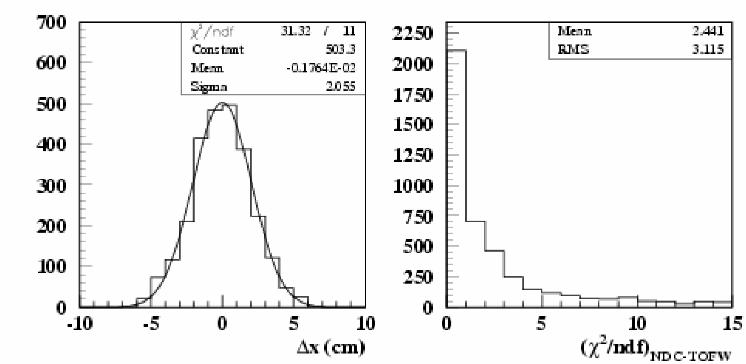
Matching to forward PID detectors



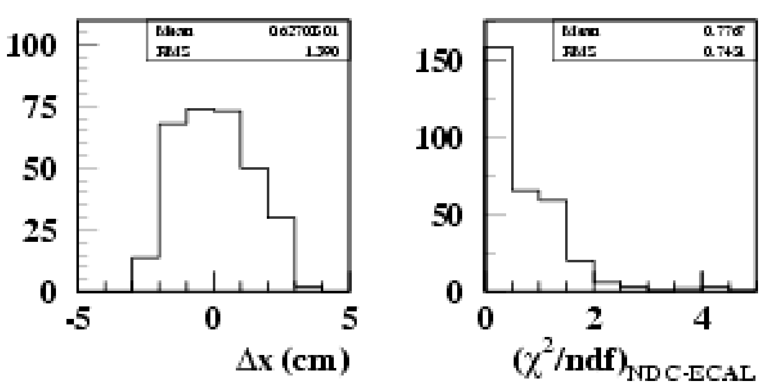


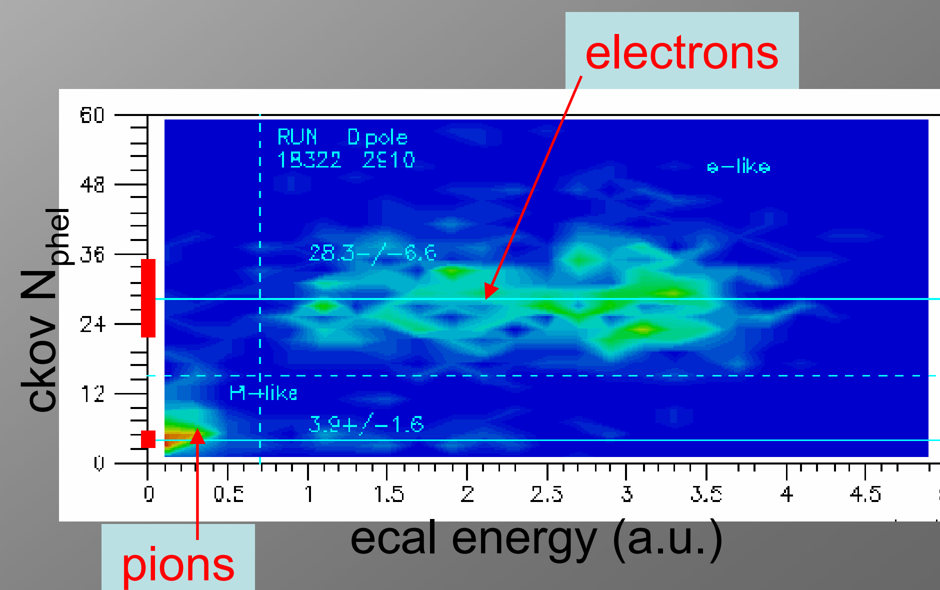
TOF 7σ separation at 3GeV

NDC-TOF Wall

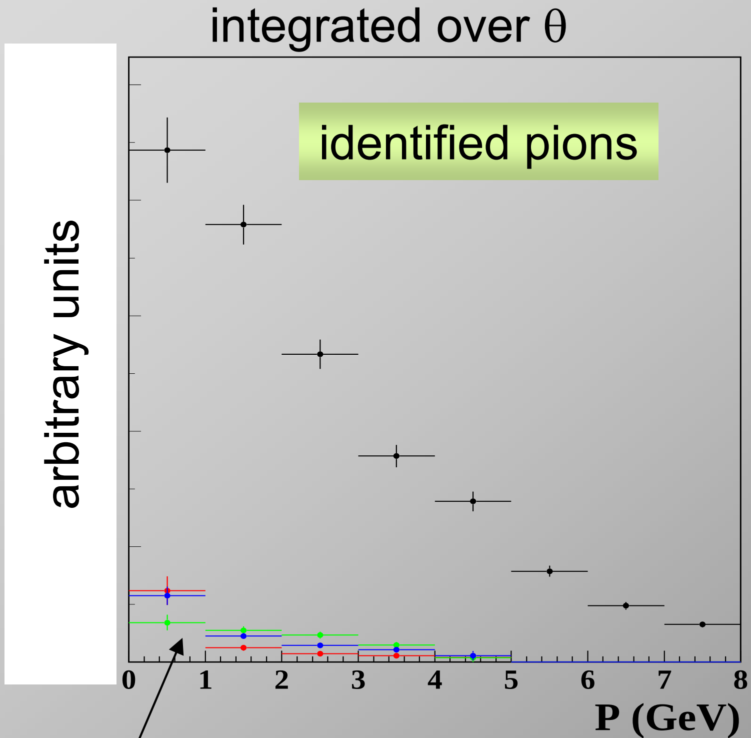


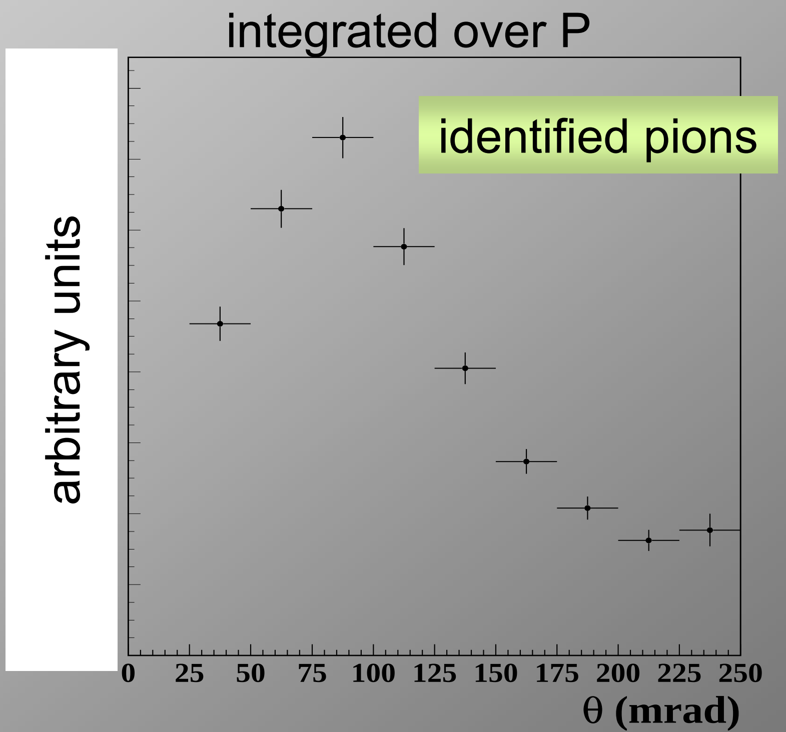
NDC-Electron id





First distributions from HARP





proton background for Tof
3 MC hadron generators

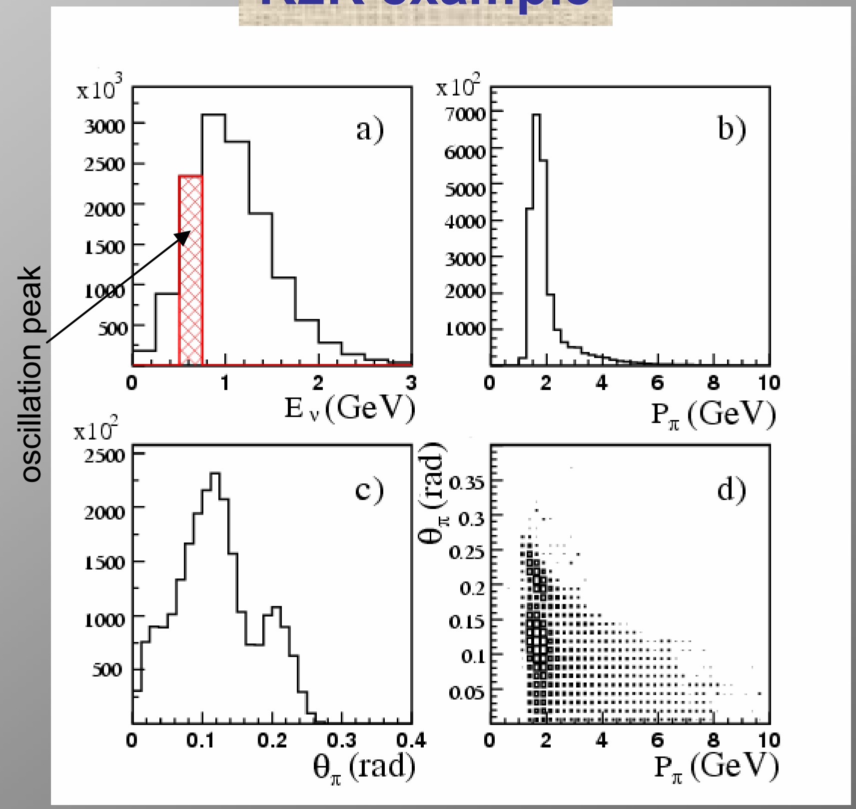
IMPORTANT
This background can be computed with the data

- *Integrated over θ and p*
- *No systematic errors included*

Prospects on physics analysis

- Forward and beam detectors are already functional for analysis:
  - Calibrated and aligned
  - High P.Id. performance
  - Efficient track reconstruction
  - Monte Carlo available
- We have selected strong physics cases within our reach and of our immediate interest
- The forward analysis is of immediate interest to the K2K and MiniBooNE experiments

K2K example

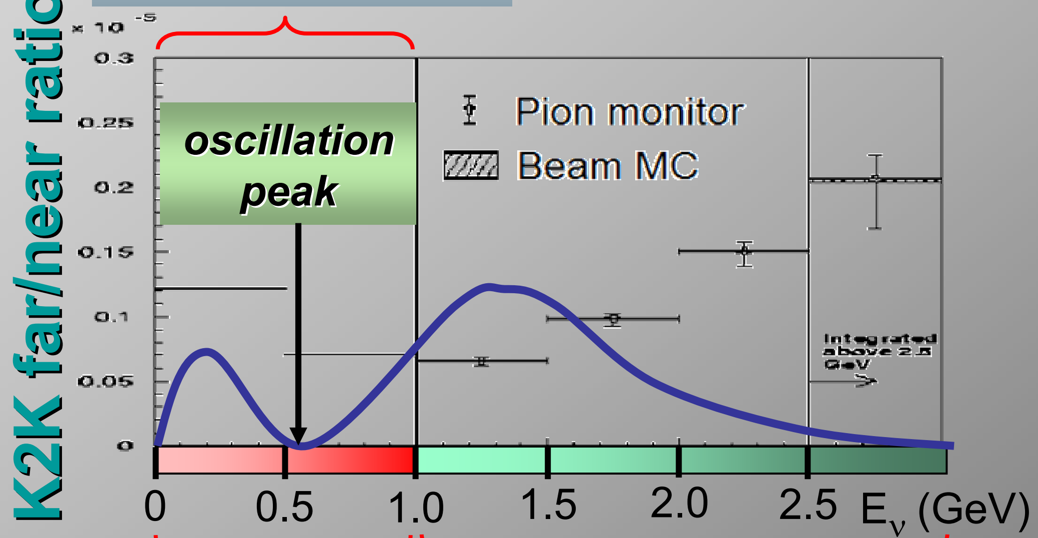


- P>1 GeV → reach forward P.Id detectors
- P<4.5 GeV → >3σ π/p separation with TOF and overlap with cherenkov
- θ<300 mrads → covered by forward spectrometer

Relevance of HARP for K2K neutrino beam

One of the largest K2K systematic errors comes from the uncertainty of the far/near ratio

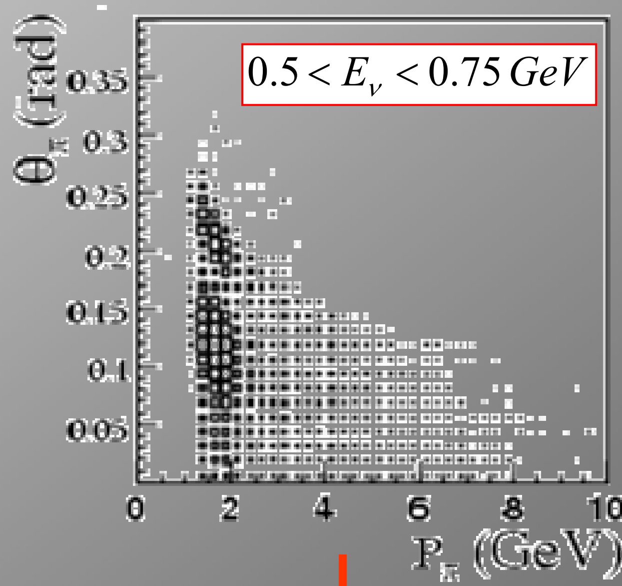
To be measured by HARP



Beam MC

Beam MC confirmed by Pion Monitor

pions producing neutrinos in the oscillation peak

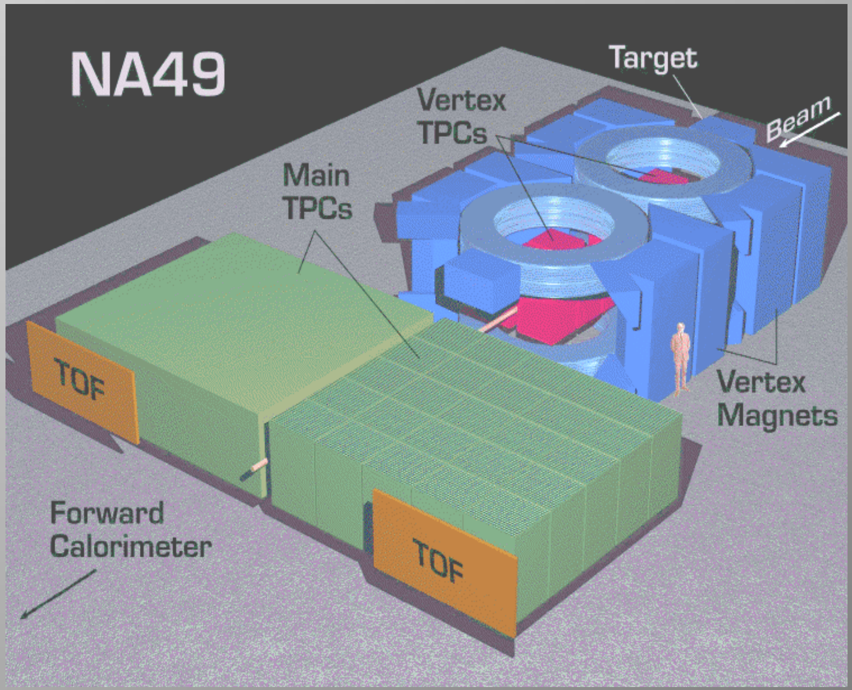


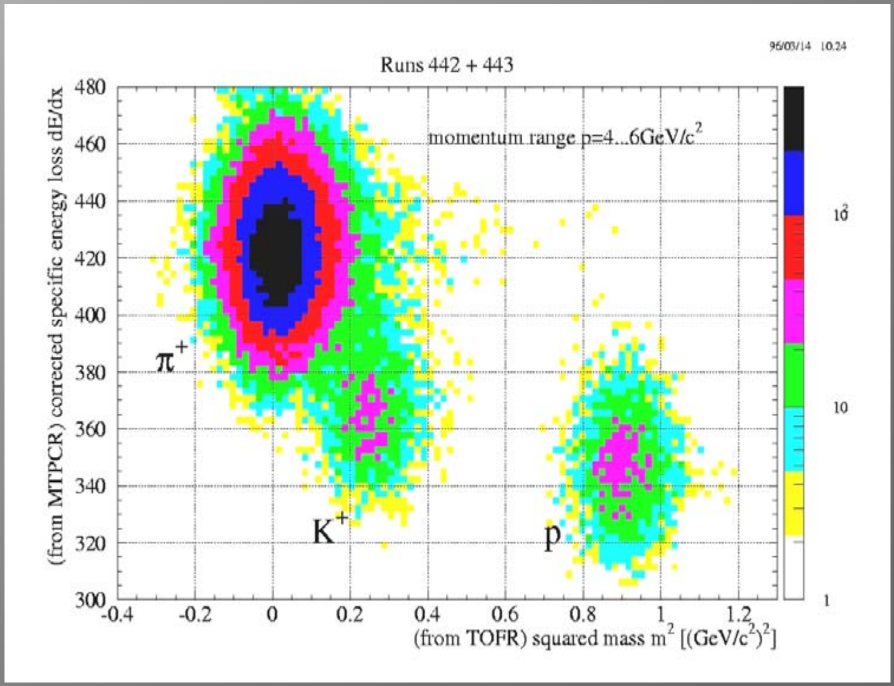
K2K interest

$$\begin{cases} P_\pi > 1\,GeV \\ \theta_\pi < 250\,mrad \end{cases}$$

HARP/NA49

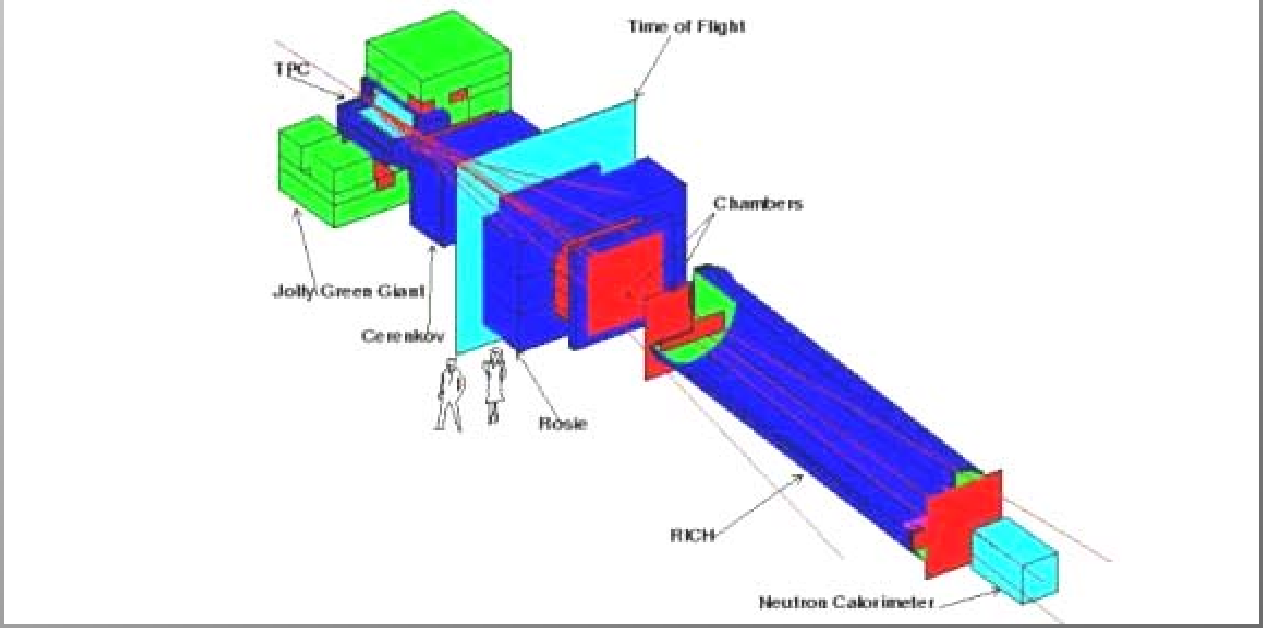
- particle ID in the TPC is augmented by TOFs
- leading particles are identified as p or n by a calorimeter in connection with tracking chambers
- rate somehow limited (optimized for VERY high multiplicity events).
  - order 10^6 event per week is achievable
- NA49 is located on the H2 fixed-target station on the CERN SPS.
  - secondary beams of identified π, K, p; 40 to 350 GeV/c momentum
- Relevant for atmospheric neutrinos and NuMI beam





E907 @ FNAL

- proposed on the FNAL main injector, secondary beams of π, K, p; 5 to 120 GeV/c
- In addition to tests of scaling lows in high-energy particle production, nuclear and heavy-ions physics, E907 is relevant for atmospheric neutrinos, NuMI beam, higher-energy proton drivers for ν-factories
- As in all modern hadron production experiments, it is an open-geometry spectrometer.
- TPC + spectrometer, complemented with TOFs and ring-imaging Čerenkov
- aiming at the same precision level as HARP: 2%
- Planning for data points with statistics of $3 \cdot 10^6$ events. One data point would take about 6 days.



Outline

Experiment	Proton E	Some H.P. exp	ref
Ps169, Ps180, Ps181	~ 20GeV	Allaby et al. Eichten et al.	CERN 70-12 N.P. B44 (1972)
CDHS, CHARM, BEBC	~400GeV	NA20 (Atherton)	CERN 80-07
CHORUS, NOMAD, CNGS	~400GeV	NA56/SPY	SPSC 96-01
K2K, MiniBooNE	12.9 GeV, 8GeV	HARP	CERN- ps214
NuFact/SuperBeam designs	~2GeV	HARP	==
Atm. Neutrinos	>10GeV	HARP/NA49	CERN- ps214 SPSC 2001-017
MINOS	120GeV	HARP/NA49	SPSC 2001-017
T2K	50GeV, off-axis	An upgraded NA49? A brand-new exp?	

Conclusions

- Hadron production for Neutrino Experiments is a well established field since the ’80s
- Present trends
  - Full-acceptance, low systematic errors
  - High statistics
  - Search for smaller and smaller effects → characterization of actual neutrino beam targets to reduce MC extrapolation to the minimum
  - Direct interest of neutrino experiments in hadron production
- If the beam is (part of) the experiment, calibration of the beam is an unavoidable step.