Hadron Production cross-sections

Emilio Radicioni
INFN-Bari

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outline

- Motivations
- Past experiment
- Present experiment
- Future projects

Why ?

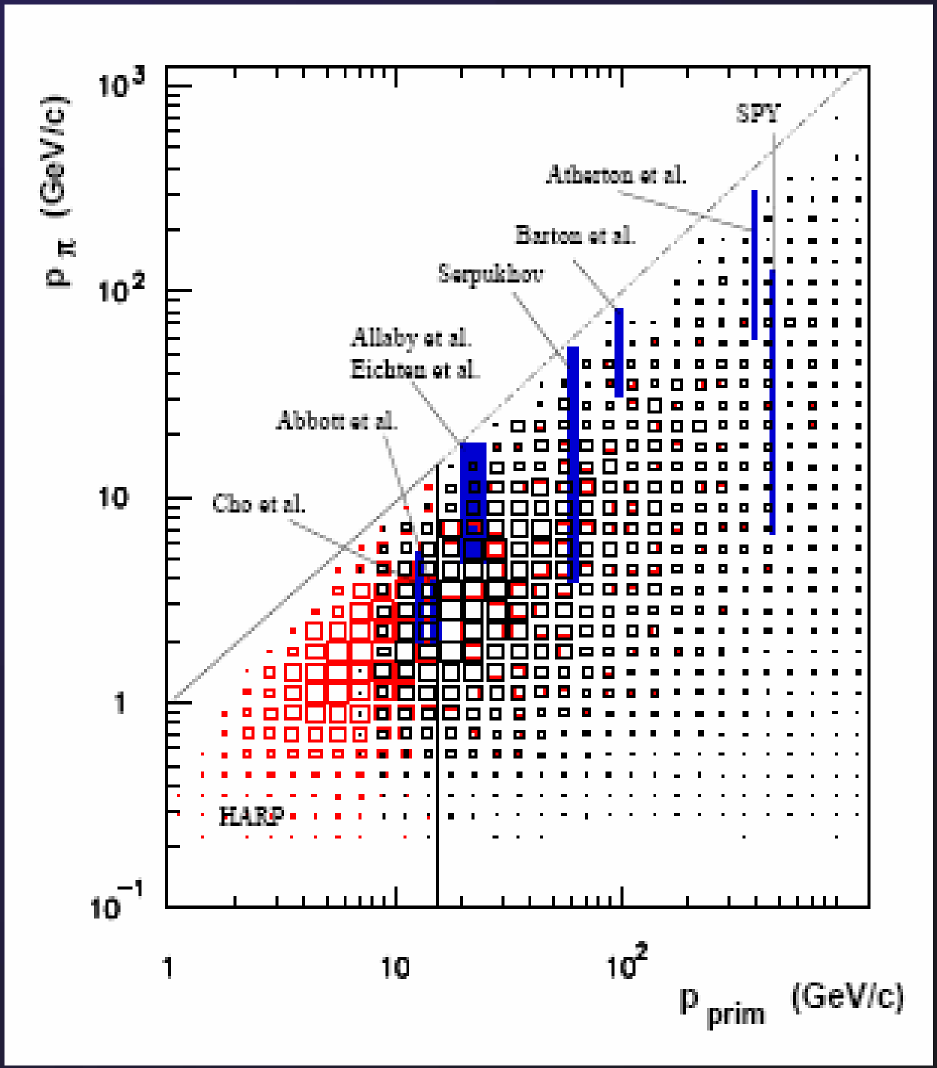
- Neutrino sources from hadronic interactions
  - From accelerators
  - From cosmic rays
- Energy, composition, geometry of the beam is determined by the development of the hadron interaction and cascade.
  - And of course by target/collection optics, but this we can know easily
- In neutrino oscillation 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.

Hadron Production

- Low energy / soft processes
  - Modeling and extrapolation difficult, MonteCarlo simulations must calibrate to data.
- Sparse measurements, low statistics
- Limited acceptance → difficult extrapolation → large uncertainties
- For the purposes of neutrino physics one needs unbiased triggers. In recent experiments (usually built for heavy-ions physics) the p-A data are reference samples taken with the same trigger conditions (i.e. centrality) as A-A data.

Existing data

- Interesting secondary hadron production phase space for atmospheric neutrino studies
- Almost the same holds for neutrino oscillation experiments and Neutrino Factories / SuperBeam proton drivers
- All measurements from single-arm spectrometers



G.Barr, astro-ph 0504356

Experiments: 2 possibilities

- Single-arm / instrumented beam lines
  - Particle-by-particle measurements
  - Overall event topology unknown
  - Sources of large uncertainties:
    - Limited acceptance
    - Overall normalization
  - Simple, reliable and (once a beam line is available) relatively inexpensive, easy to operate.
- Open geometry, full acceptance
  - Originated from Heavy-Ions physics
    - Event-by-event
    - Large acceptance, well-defined trigger systems , full tagging and counting of incoming beam particles
  - Technically challenging, expensive, needs mastering of broad range of experimental techniques

Single arm spectrometers

- High energy
  - Barton et al.
  - Atherton, SPY/NA56
- Low energy
  - Allaby, Eitcten
  - E802

- Low-energy ones more relevant for NuFact community

Eichten et Al.
CERN-70-12

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

T. EICHTEN and D. HAIDT
III. Physikalisches Institut, Aachen, Germany

J.B.M. PATTISON, W. VENUS, H.W. WACHSMUTH and O. WÖRZ
CERN, Geneva, Switzerland

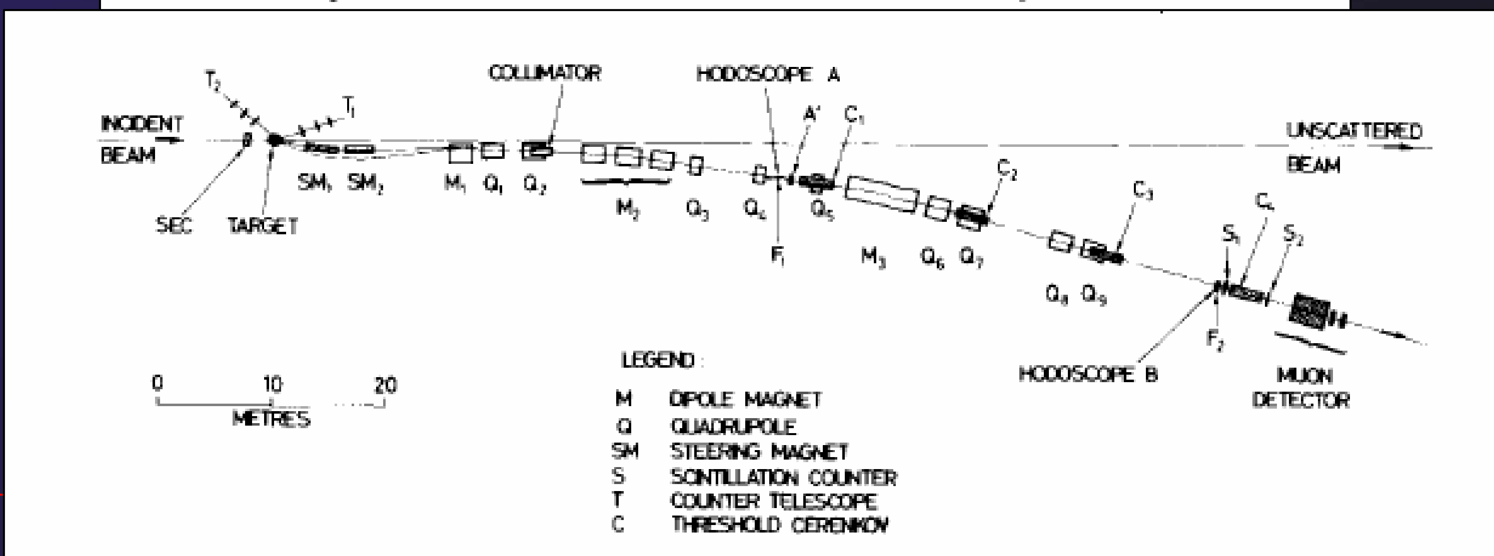
T.W. JONES
UCL, London, England

B. AUBERT, L.M. CHOUNET and P. HEUSSE
Laboratoire de l'Accélérateur Linéaire, Orsay, France

C. FRANZINETTI
University of Torino, Italy

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

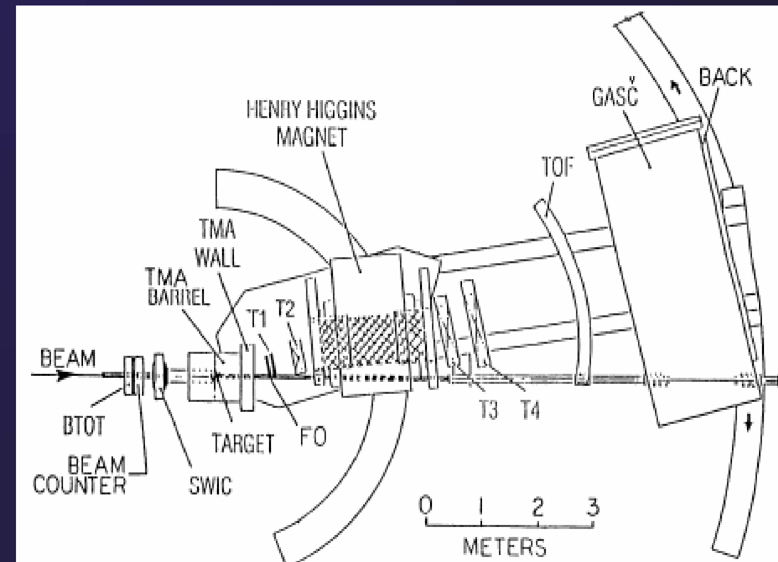
The aim of the present experiment was to measure pion and kaon production in proton-nucleus collisions at 24 GeV/c primary proton momentum. The measurements cover the secondary momentum range 4–18 GeV/c and the angular range 17–127 mrad. These data are essential for the estimation of the neutrino spectrum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

E802 (Abbot et al.)

- Rotating single arm
- Larger acceptance than beam lines …
- … but challenging evaluation challenging of acceptance/efficiency
- 7-8% normalization error on overlapping spectrometer settings
- 10-15 % normalization error on cross-section



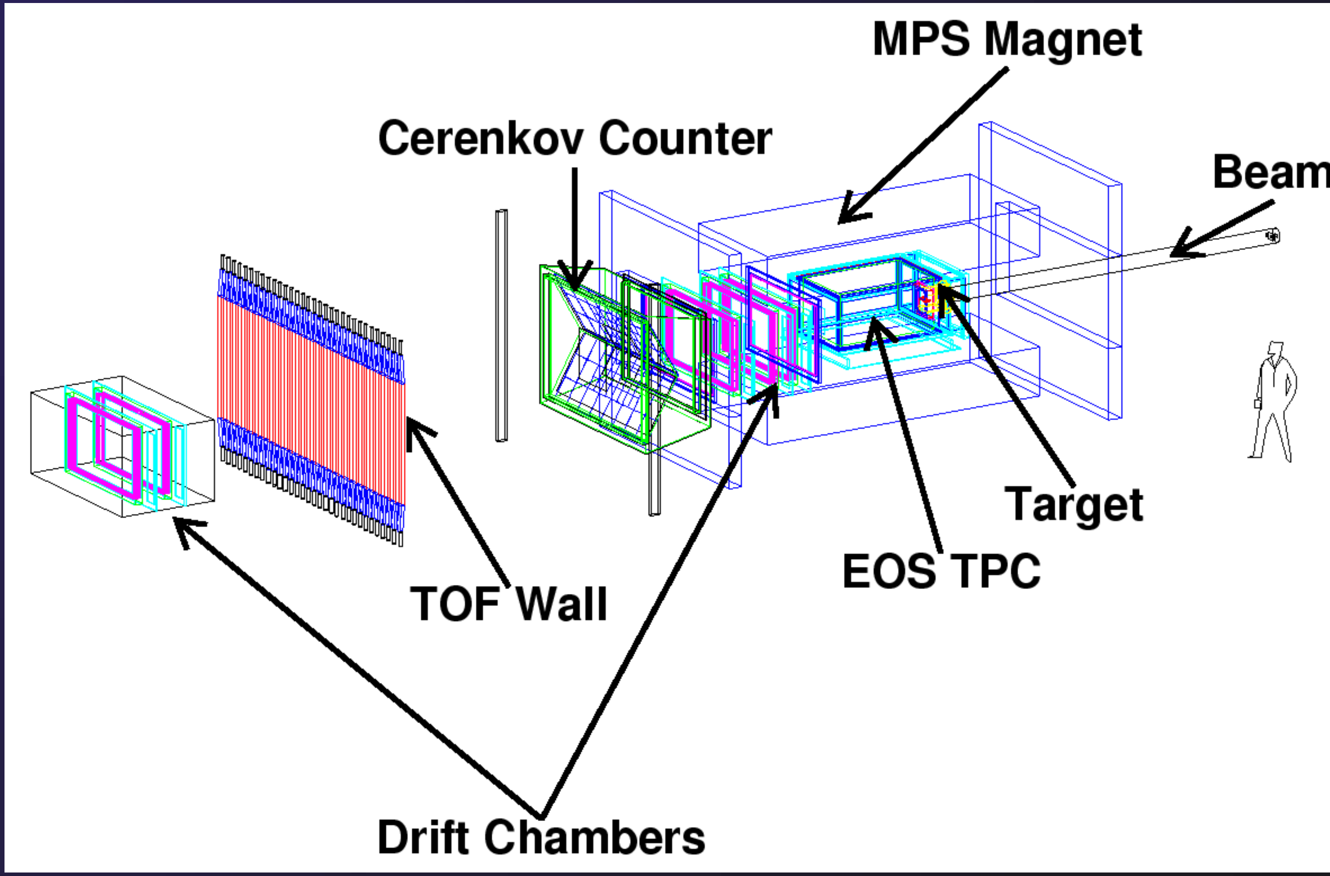
The main part of the E-802 spectrometer [12] (Fig. 1) consists of a dipole magnet ($\int B\,dl \le 1.5$ Tm) with four sets of tracking chambers (two before the magnet and two after), a 160-element time-of-flight (TOF) wall, and a 40-segment high-pressure (4-atm) gas Čerenkov counter (GASC) followed by a position-sensitive back counter (BACK). The spectrometer has a geometrical solid angle of 25 msr, and it can be rotated to cover laboratory angles from 5° to 58° in five angular settings, namely, by placing the beam side edge of the magnet at 5°, 14°, 24°, 34°, and 44°. The polar angle bite is 14°. Data are taken at each angle with both magnet polarities.

Today we aim at …

- Event-by-event experiments, not particle-by-particle
- Modern design
  - Open-geometry spectrometers, large momentum range and complete PID.
  - Design inherited from Heavy Ions experiments (multiplicity, correlations, pion interferometry, …)
- Full acceptance in angle and momentum
  - fewer acceptance/efficiency corrections -> smaller errors
- 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 → dedicated approach to electronics/daq

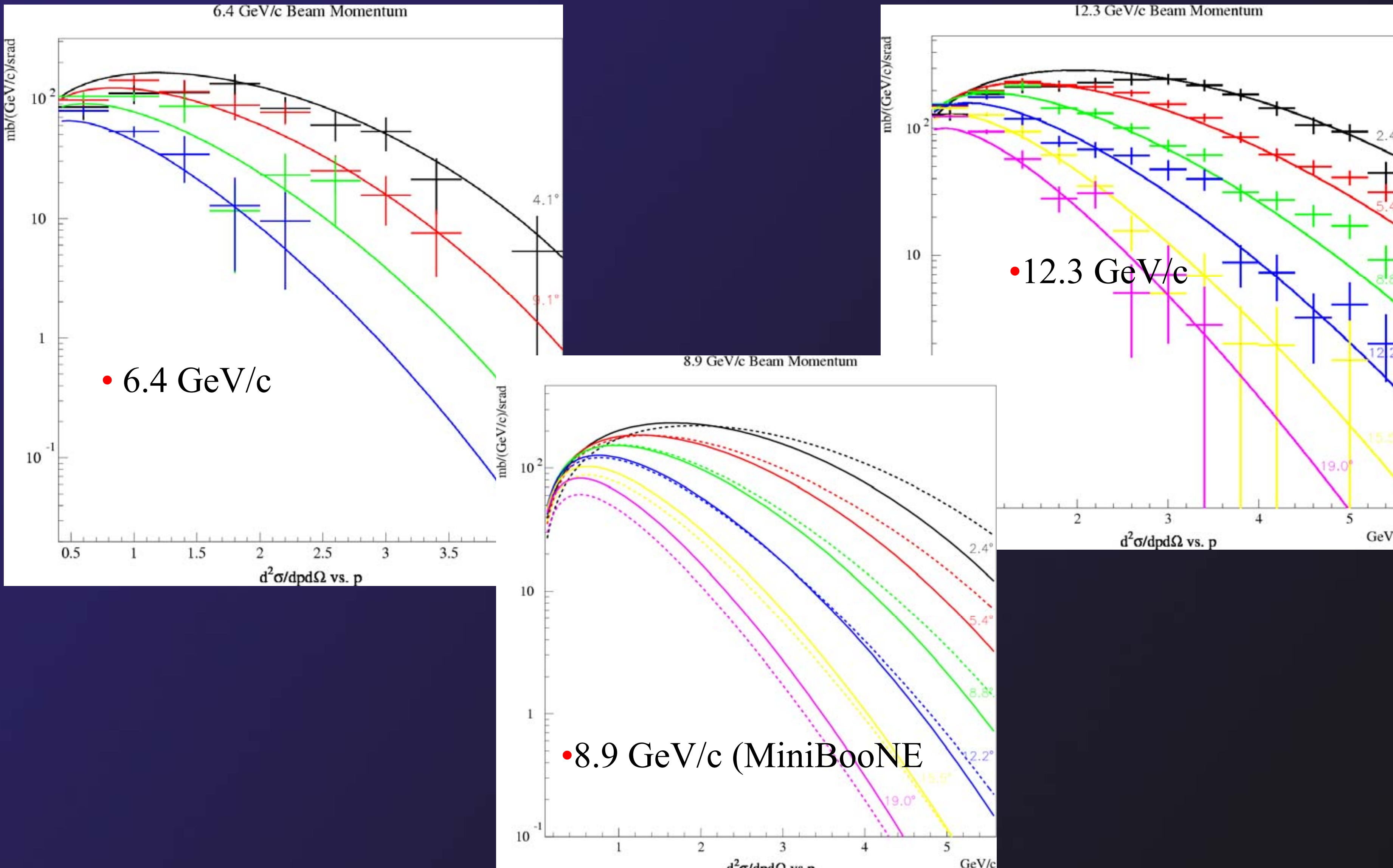
E910

- 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 (this is common in heavy-ions experiments), very low at 6GeV/c
  - no backward acceptance (target outside the TPC)

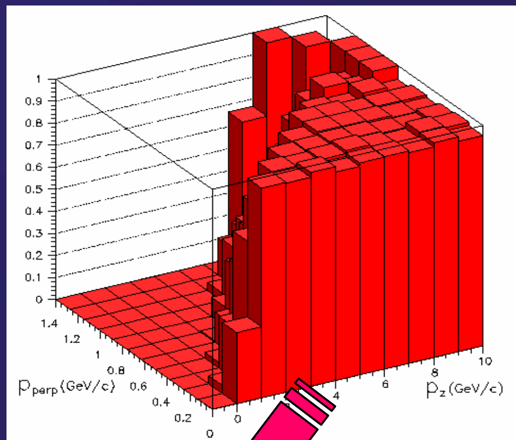
E910



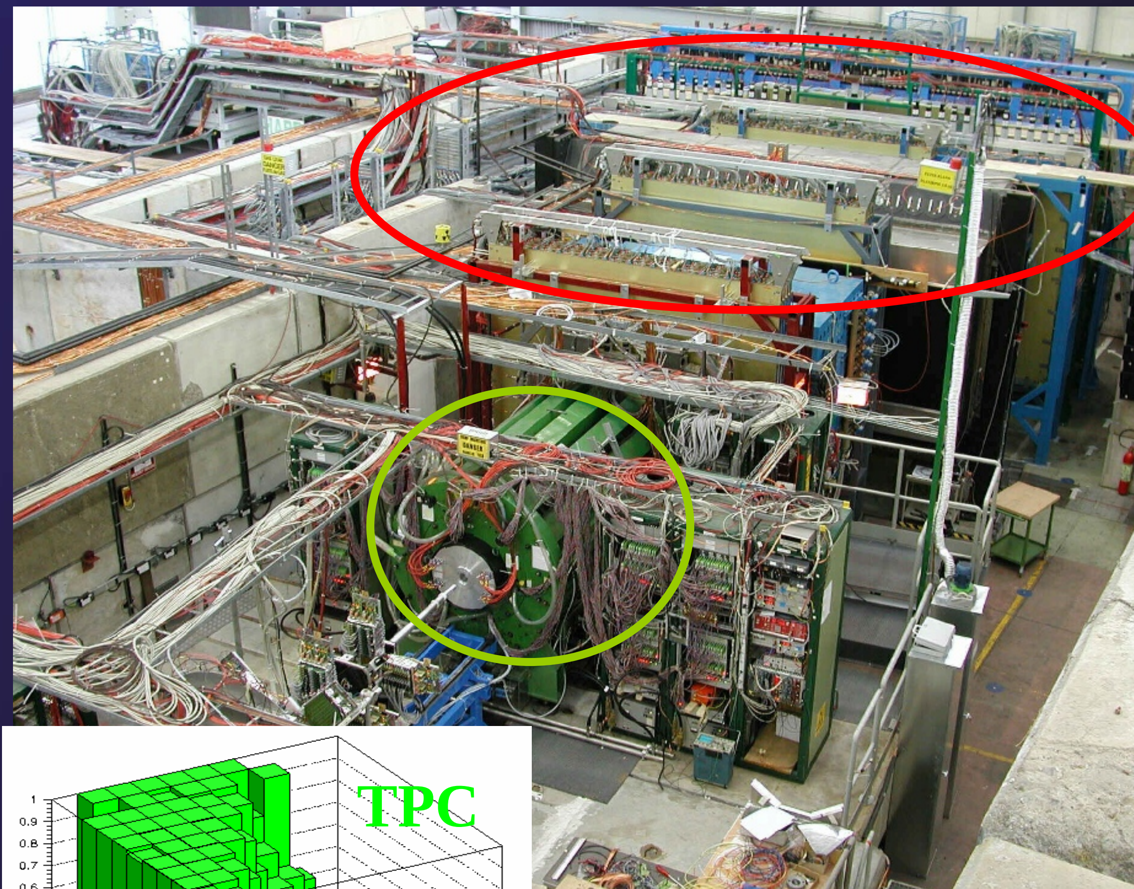
6.4 GeV/c Beam Momentum
mb/(GeV/c)/srad
4.1°
9.1°
d²σ/dpdΩ vs. p
• 6.4 GeV/c
12.3 GeV/c Beam Momentum
2.4°
5.4°
8.8°
12.2°
15.5°
19.0°
GeV/c
d²σ/dpdΩ vs. p
•12.3 GeV/c
8.9 GeV/c Beam Momentum
d²σ/dpdΩ vs p
•8.9 GeV/c (MiniBooNE

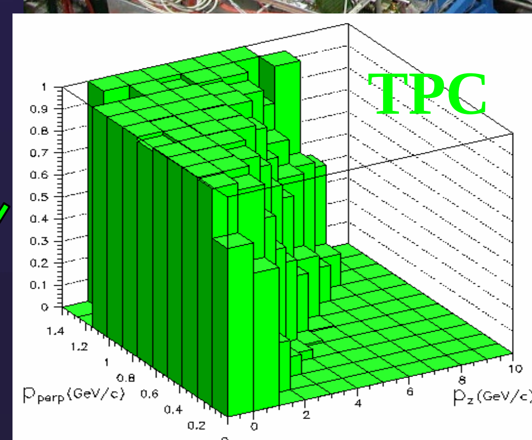
HARP

- Built on purpose
- Collaboration includes members of Neutrino Oscillation experiments
  - And makes measurements on specific targets of existing neutrino beams.
- Input to neutrino factory and low-energy SuperBeam designs
  - 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 (collaboration with Geant4)

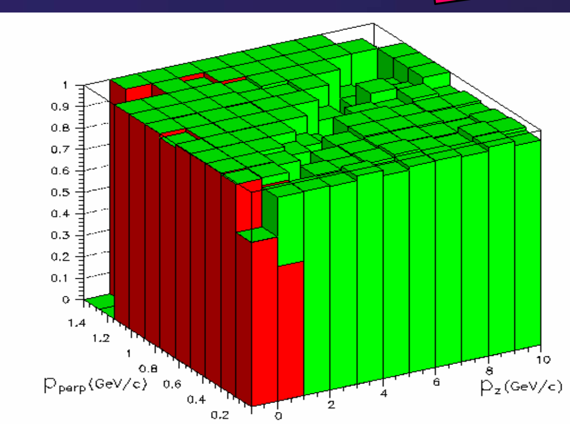


Forward Spectrometer





TPC



Total Acceptance

HARP data set

- 420 M events
- 30 TB of data
- > 100 settings

<table>
<tr><th></th><th>Target material</th><th>Target length (l%)</th><th>Beam Momentum (GeV)</th><th>#events (millions)</th></tr>
<tr><td rowspan="7">Solid targets</td><td>Be</td><td rowspan="7">2
(2001)
5
100</td><td rowspan="7">±3
± 5
± 8
± 12
± 15
Negative only
2% and 5%</td><td rowspan="7">233.16</td></tr>
<tr><td>C</td></tr>
<tr><td>Al</td></tr>
<tr><td>Cu</td></tr>
<tr><td>Sn</td></tr>
<tr><td>Ta</td></tr>
<tr><td>Pb</td></tr>
<tr><td>K2K</td><td>Al</td><td rowspan="2">5, 50, 100, replica</td><td>+12.9</td><td>15.27</td></tr>
<tr><td>MiniBooNE</td><td>Be</td><td>+8.9</td><td>22.56</td></tr>
<tr><td>Cu “button”</td><td>Cu</td><td></td><td>+12.9, +15</td><td>1.71</td></tr>
<tr><td>Cu “skew”</td><td>Cu</td><td>2</td><td>+12</td><td>1.69</td></tr>
<tr><td rowspan="4">Cryogenic targets</td><td>N_7</td><td rowspan="4">6 cm</td><td rowspan="4">±3
± 5
± 8
± 12
± 15</td><td rowspan="4">58.43</td></tr>
<tr><td>0_8</td></tr>
<tr><td>D_1</td></tr>
<tr><td>H_1</td></tr>
<tr><td></td><td>H_2</td><td>18 cm</td><td>±3, ±8, ±14.5</td><td>13.83</td></tr>
<tr><td>Water</td><td>H_20</td><td>10, 100</td><td>+1.5, +8(10%)</td><td>9.6</td></tr>
</table>

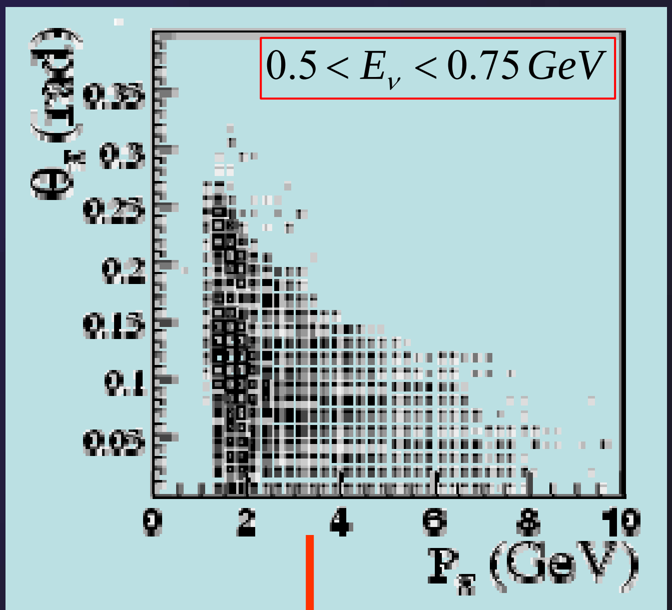
HARP status

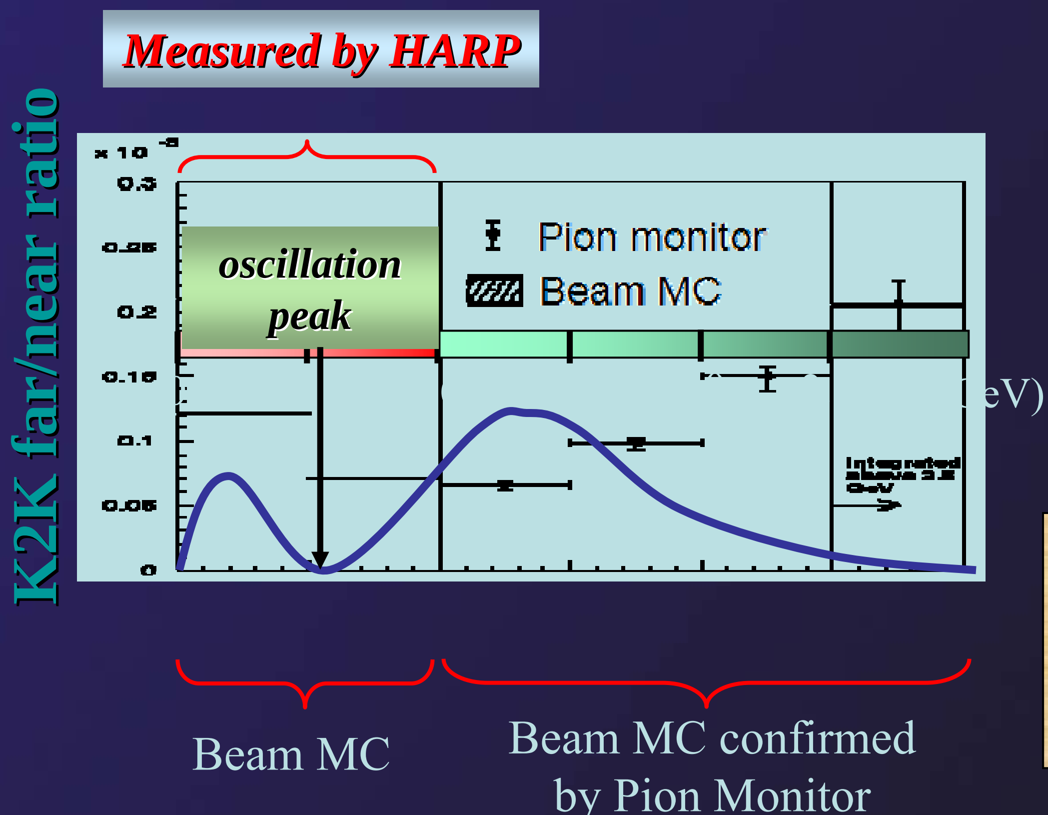
- HARP has completed the detector calibration up to readiness for data analysis
- First analysis rounds confirm that the basic ingredients for analysis are under control, namely
  - PID, resolution and momentum scale
  - Efficiency correction and normalization
- Data are being actively analyzed. 3 outstanding priorities
  - Pion production on 12.9 GeV/c protons on K2K target
  - Pion and K production on MiniBooNE target
  - Pion yields from 3, 5, 8 GeV/c protons on Ta target (NuFact proton driver conditions)

Relevance of HARP for K2K neutrino beam

- Cross-check of K2K beam simulation
- Potentially reduce the uncertainties of the experiment

pions producing neutrinos in the oscillation peak



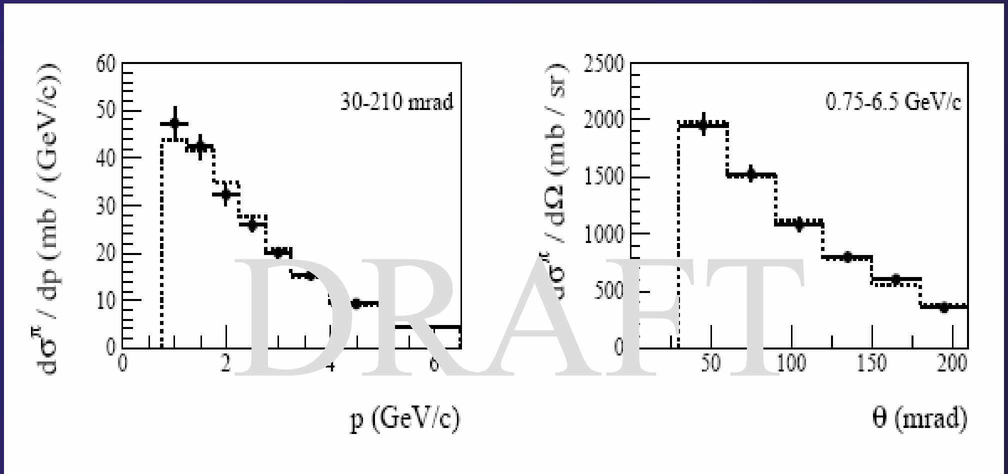


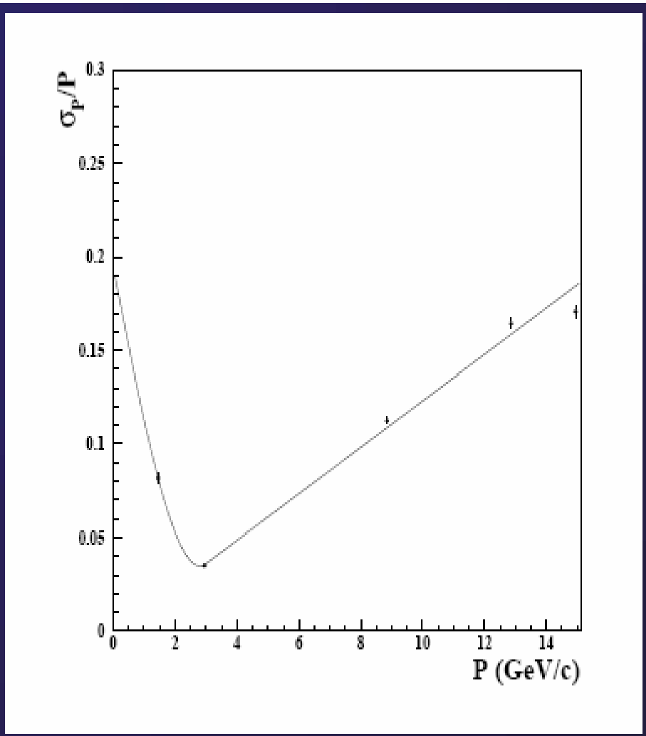
K2K interest

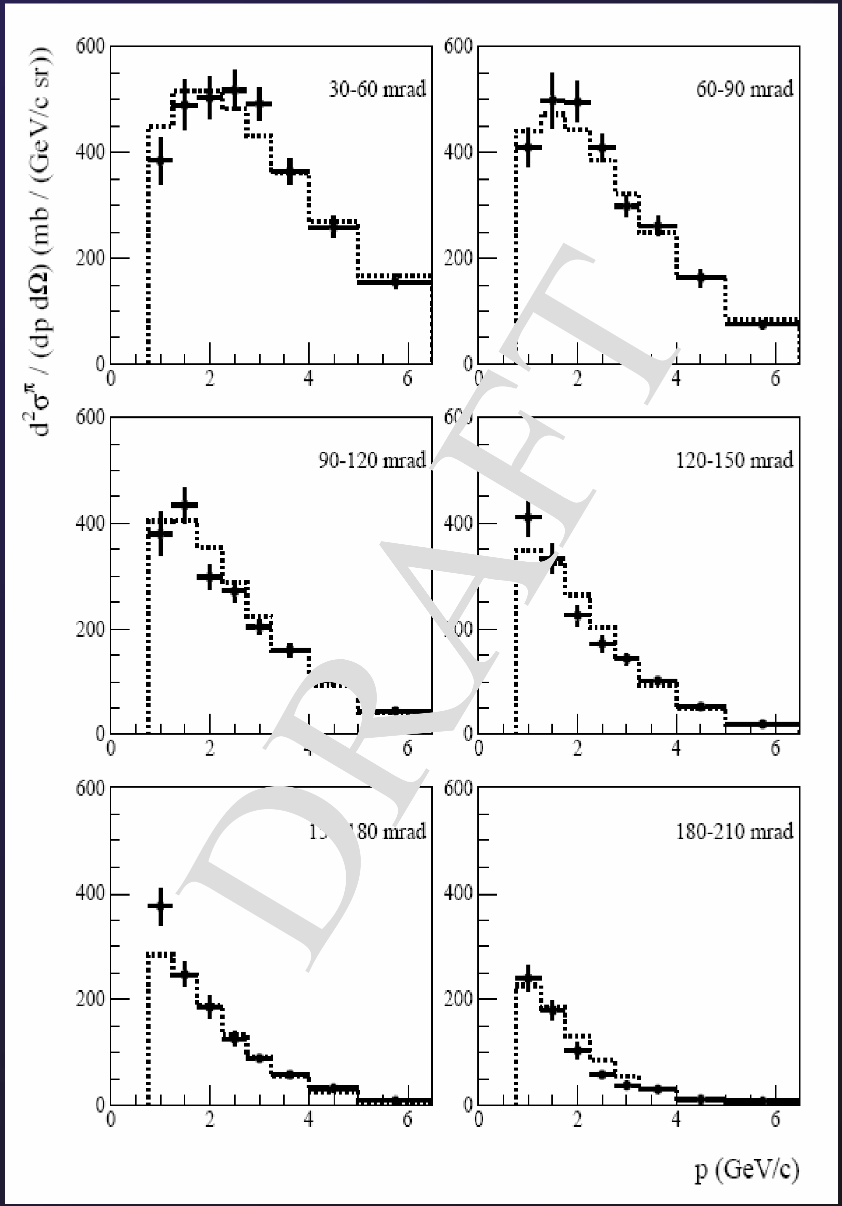
$$\begin{cases} P_\pi > 1\,GeV \\ \theta_\pi < 250\,mrad \end{cases}$$

Forward analysis

- Tracking and PID
- Data are divided in θ,|p| bins, compatible with resolutions
- Unfolding technique to correct for bin migration
- Double differential (dp,dΩ) and total cross-sections
- Sanford-Wang parametrization fit to make comparison easier with similar measurements
- Overall error ~ 5% on total cross-section
- First analysis on MiniBooNE data will be presented to the collaboration next week.
- Compared to previous measurements, agreement ranges from good to 30% lower depending on the experiment, however older measurements have larger uncertainties.


30-210 mrad
0.75-6.5 GeV/c
$d\sigma^{\pi} / dp$ (mb / (GeV/c))
$d\sigma^{\pi} / d\Omega$ (mb / sr)
p (GeV/c)
θ (mrad)
DRAFT


σ_p/P
P (GeV/c)

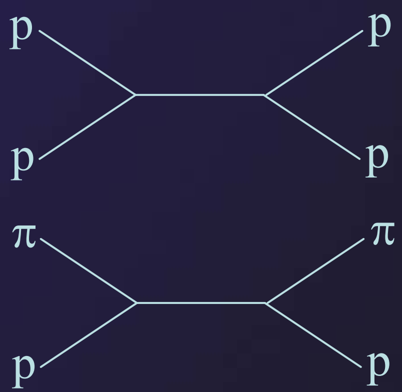

$d^2\sigma^{\pi} / (dp\, d\Omega)$ (mb / (GeV/c sr))
30-60 mrad
60-90 mrad
90-120 mrad
120-150 mrad
180-210 mrad
p (GeV/c)
DRAFT

HARP large-angle

- The large-angle region (mainly TPC) has now been calibrated.
- Strategy:
  - Checked PID capabilities, momentum scale, efficiency and normalization with well-known reference process: pp and πp elastic scattering
  - Then go through settings one by one.
- Now processing Ta data sets at 3, 5, 8 GeV/c
  - Most relevant for Neutrino Factory and SuperBeam communities
  - First distributions shown for 3 GeV/c

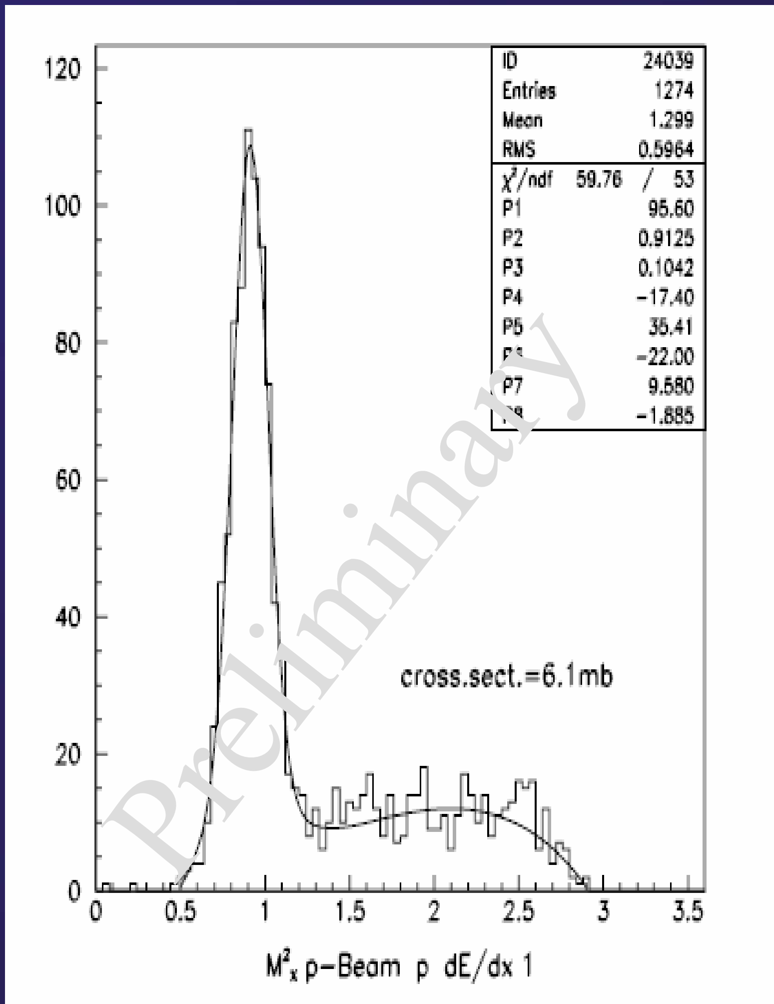
Elastic scattering in the HARP TPC

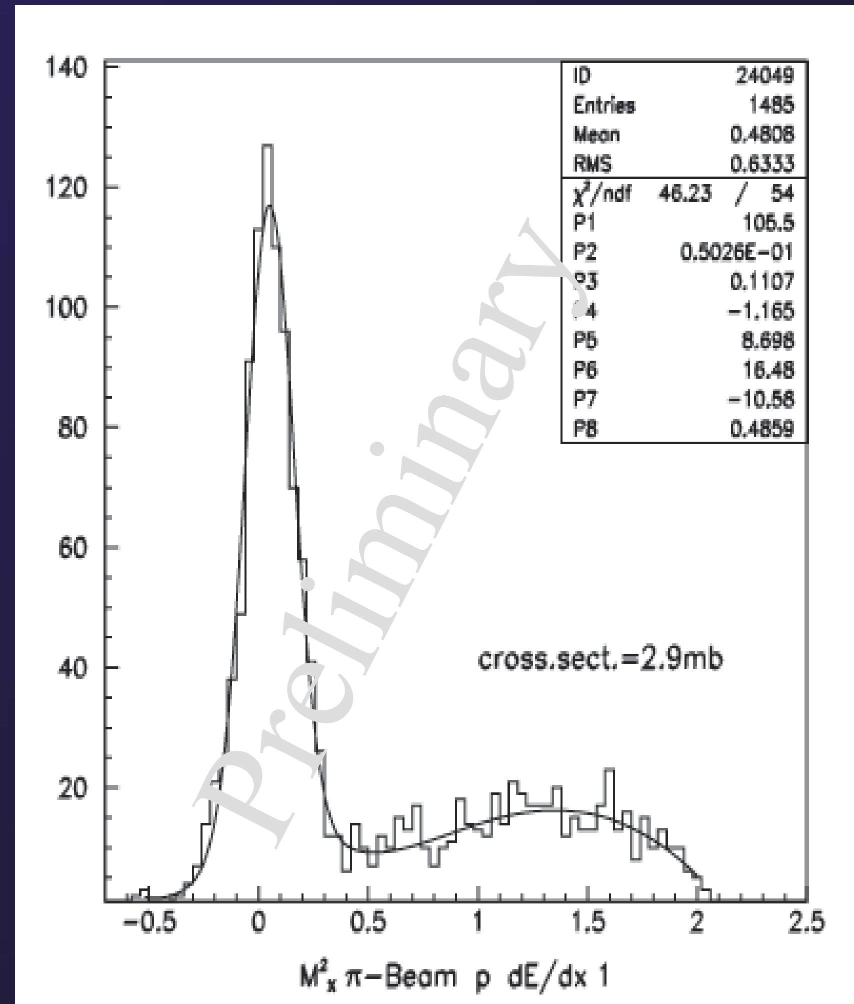
- Elastic scattering: p and π on LH_2 target → 1- or 2- prong final state
- Kinematical selection, dE/dx cuts
- Missing-mass plots shows:
  - Correct missing mass value → momentum scale is correct
  - Integrated cross-section in our acceptance compatible with PDG data → efficiencies and systematics are under control



- More cross-checks possible on energy dependence by using additional (e.g. 5 and 8 GeV/c beam) settings.
- No error treatment yet, but we'll get there soon.
- Even if not in mainstream of HARP, these results will be published if error competitive with PDG data.

HARP large-angle status





PDG data, integrated in our acceptance region:

$$\sigma_{pp\to pp} \simeq 6.6 \pm 0.27\ mb$$

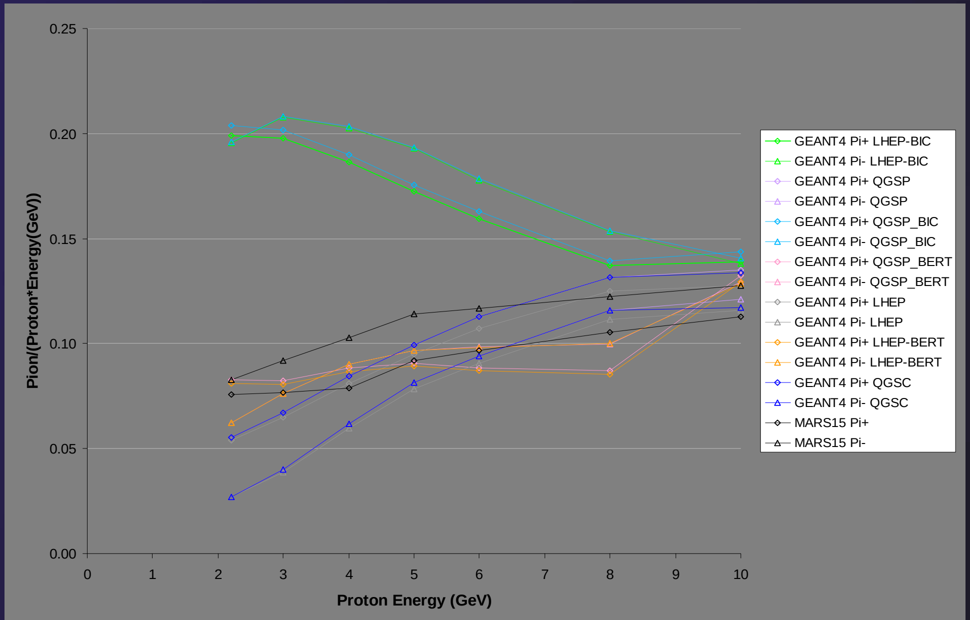
$$\sigma_{\pi p\to \pi p} \simeq 3.2 \pm\ 0.14 mb$$

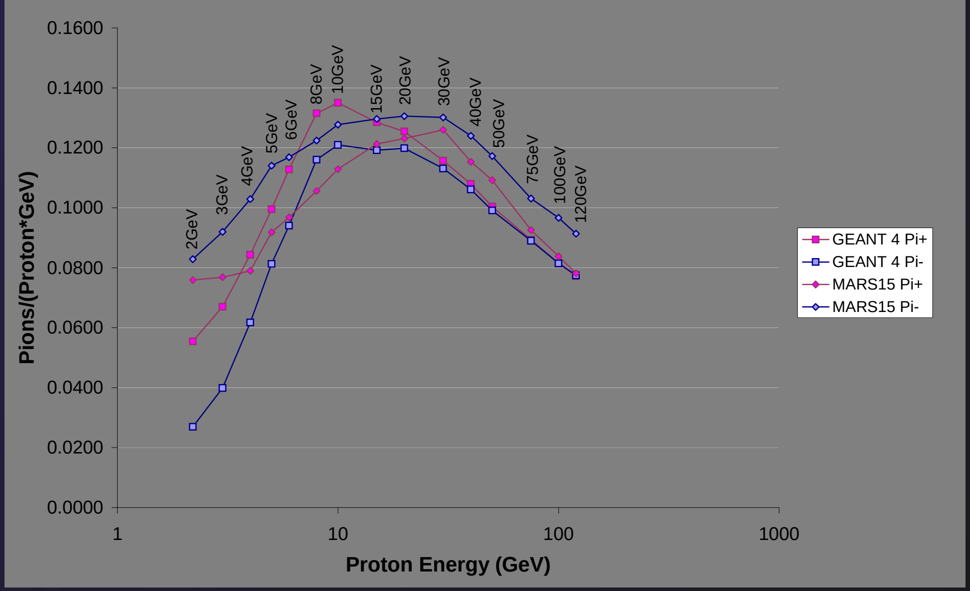
Possible proton-driver energies

Proton Driver	GeV	RAL Studies
Old SPL energy	2.2	
	3	5MW ISIS RCS 1
[New SPL energy 3.5GeV]	4	
	5	Green-field synch.
	6	5MW ISIS RCS 2
FNAL linac (driver study 2)	8	RCS 2 low rep. rate
	10	4MW FFAG
[FNAL driver study 1, 16GeV]	15	ISR tunnel synch.
[BNL/AGS upgrade, 24GeV]	20	
JPARC initial	30	PS replacement
	40	
JPARC final	50	
	75	
	100	
FNAL injector/NuMI	120	

Pion production uncertainties

- "We might be entering the precision era in neutrino physics, but for sure not in hadron production generators*".
- Geant4/Mars comparison, proton beam on long Ta target
- Obvious discrepancies in
  - Total yields
  - Relative abundance +/-
- Larger discrepancies at low proton energy

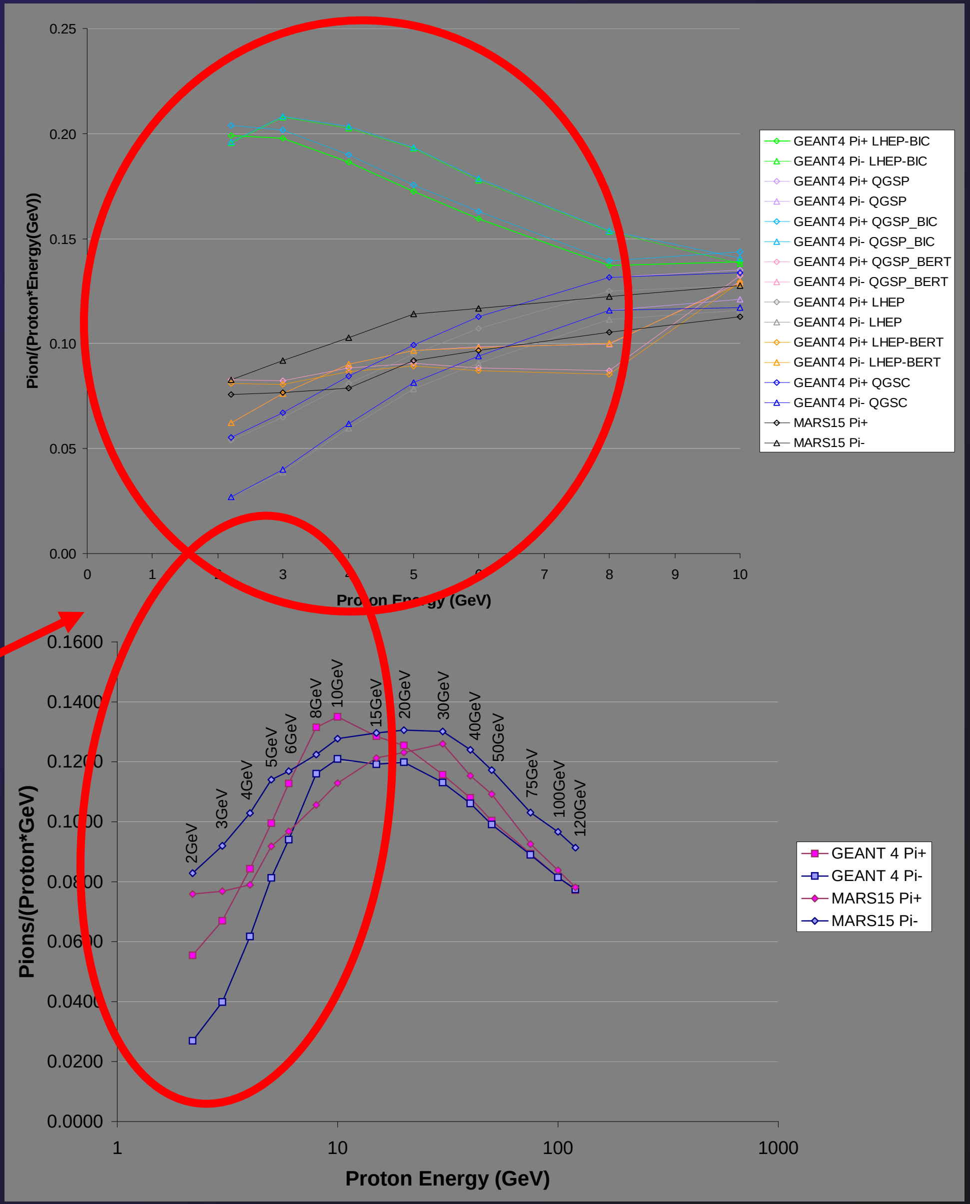




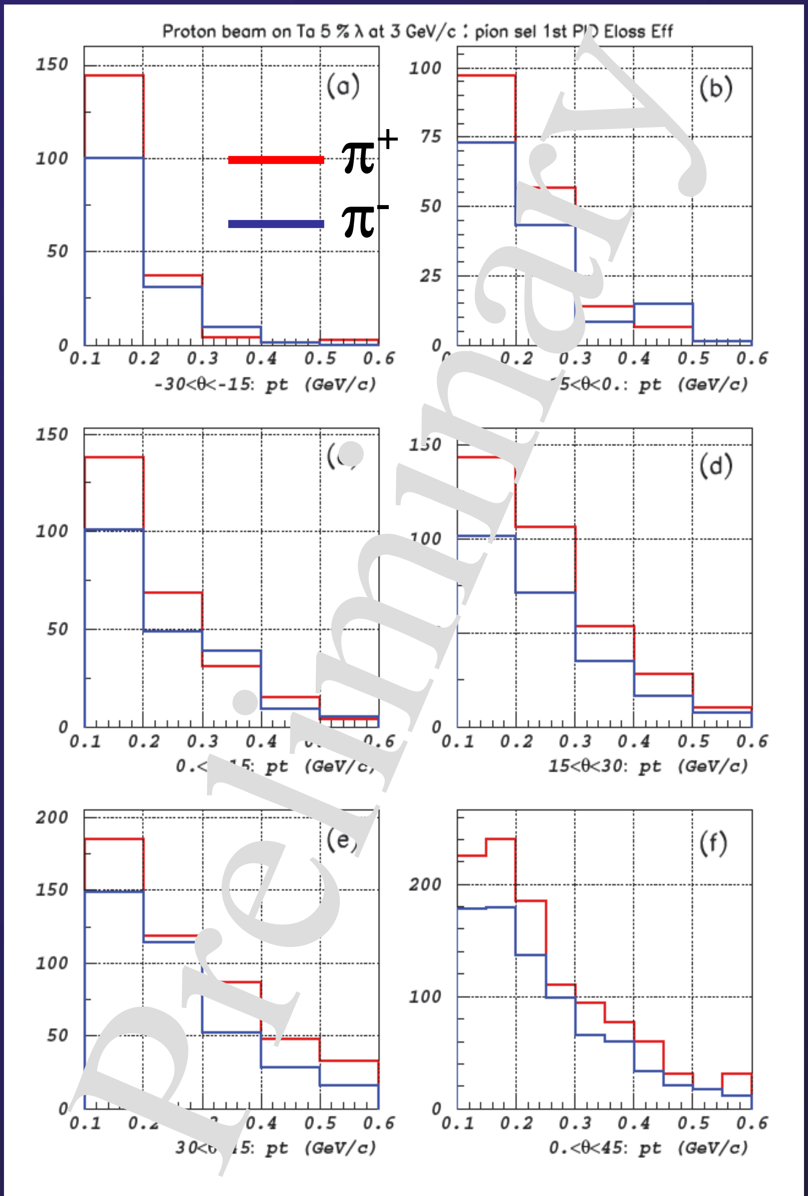
- * Plots (and sentence) courtesy Stephen Brooks, RAL.

Pion production uncertainties

HARP sits there ...

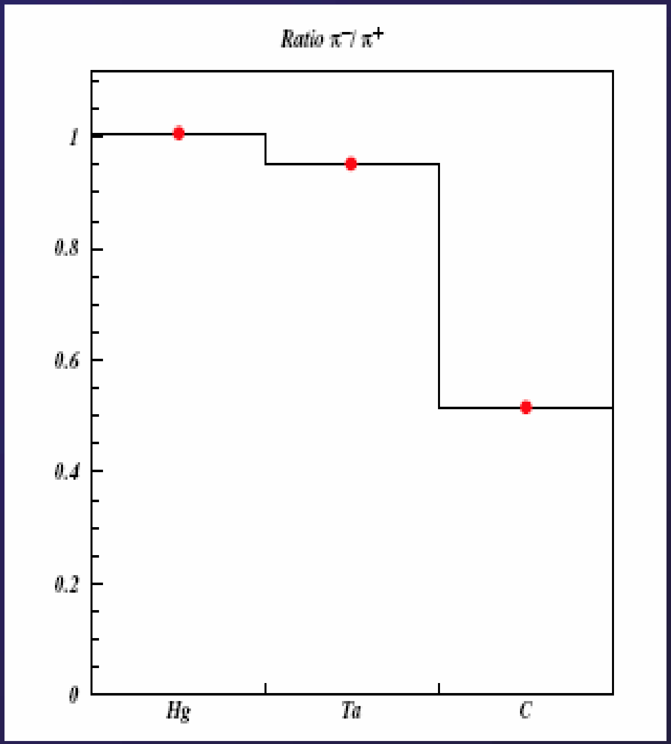


HARP large-angle



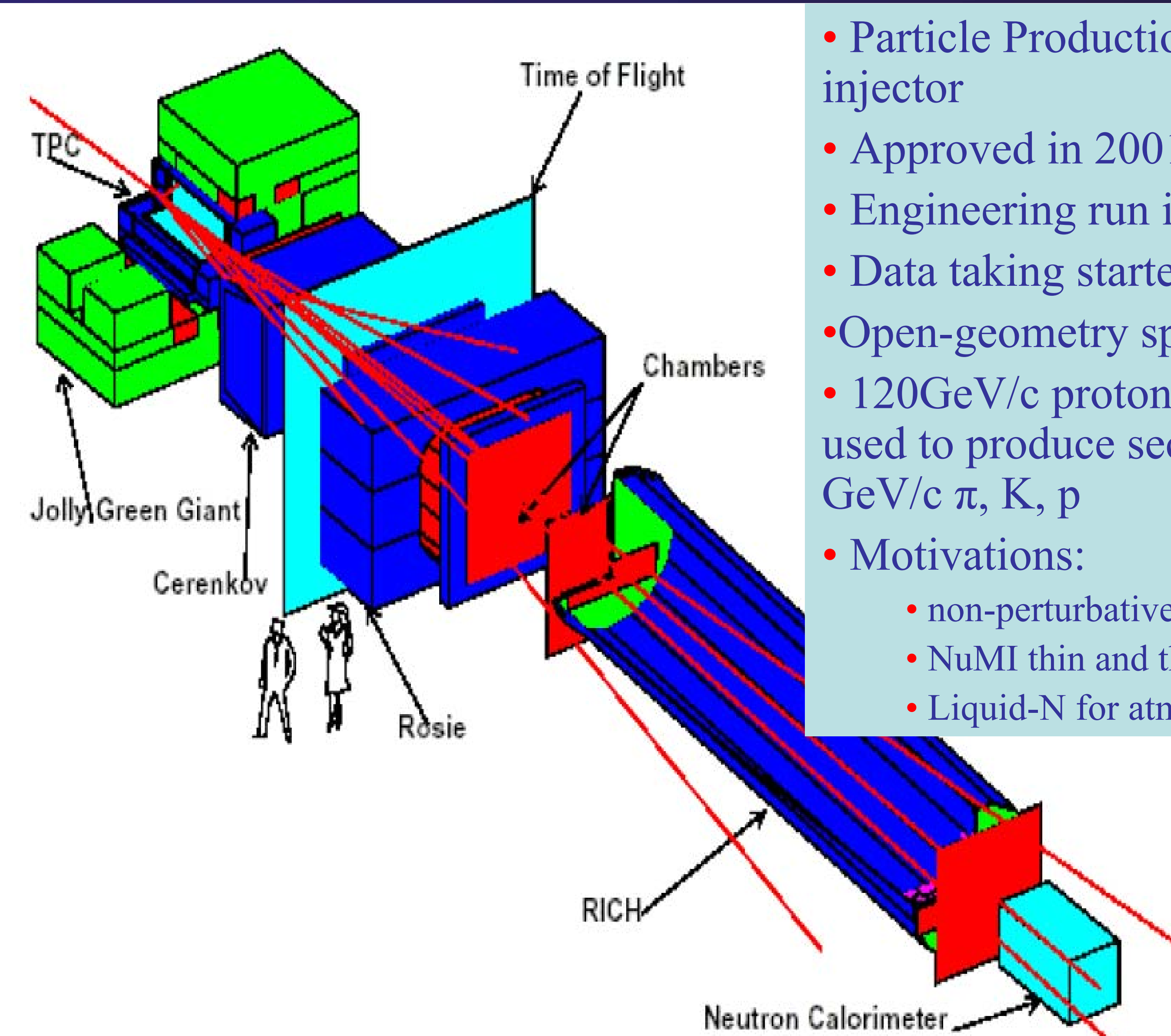
- Un-normalized pion distribution as a function of momentum in several angular bins (including backwards!)
- Number of π^+ and π^- almost the same
- Normalization being worked out

Material	π^+ per p.o.t.	π^- per p.o.t.
C	0.30	0.153
Ta	0.183	0.174
Hg	0.185	0.186



- First comparison possible: ratio $N(\pi^-) / N(\pi^+)$ can be cross-checked with MonteCarlo simulations
- Presented data is generated by MARS in same conditions as data taking (3 GeV/c momentum, Ta target)
- Data and plot: courtesy S.Gilardoni, CERN

MIPP



- Particle Production at FNAL's main injector
- Approved in 2001, now in 2001
- Engineering run in 2004
- Data taking started Jan. 2005
- Open-geometry spectrometer
- 120GeV/c protons from Main Injector used to produce secondary beams of 5-85 GeV/c π, K, p
- Motivations:
  - non-perturbative QCD
  - NuMI thin and thick targets
  - Liquid-N for atmospheric neutrinos

MIPP's data taking plan

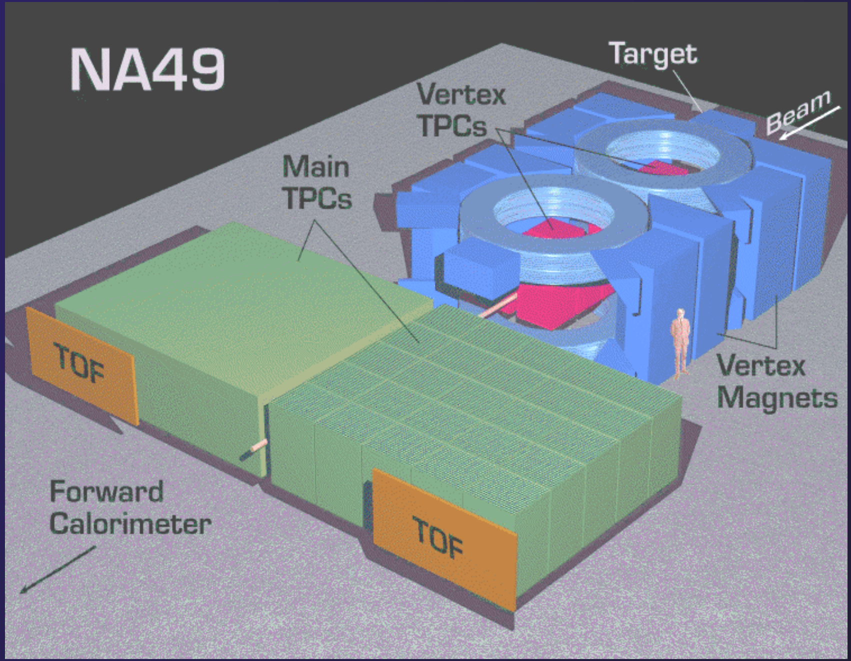
Run Plan v7		Summary by Target and Beam Energy Number of events, x 10^6										
Target		Momentum (GeV/*c*)										Totals
Z	Element	5	13.3	15	20	30	40	50	60	75	120	
1	H	4.40		4.20		4.40		4.20		4.20		21.40
1.2	D	0.60		0.60		0.60		0.60		0.60		3.00
4	Be	1.00	1.00			1.00		1.81		1.00	6.60	12.41
6	C	1.00	1.00		1.57		1.66		1.57		1.58	8.38
	NuMI										4.61	4.61
7	N	1.00	1.00			1.00						3.00
29	Cu					1.00		2.00		1.00	4.00	8.00
83	Bi	1.00	1.00			1.00		2.00		1.00	6.60	12.60
92	U							2.00				2.00
Totals		9.00	4.00	4.80	1.57	9.00	1.66	12.61	1.57	7.80	23.39	75.40

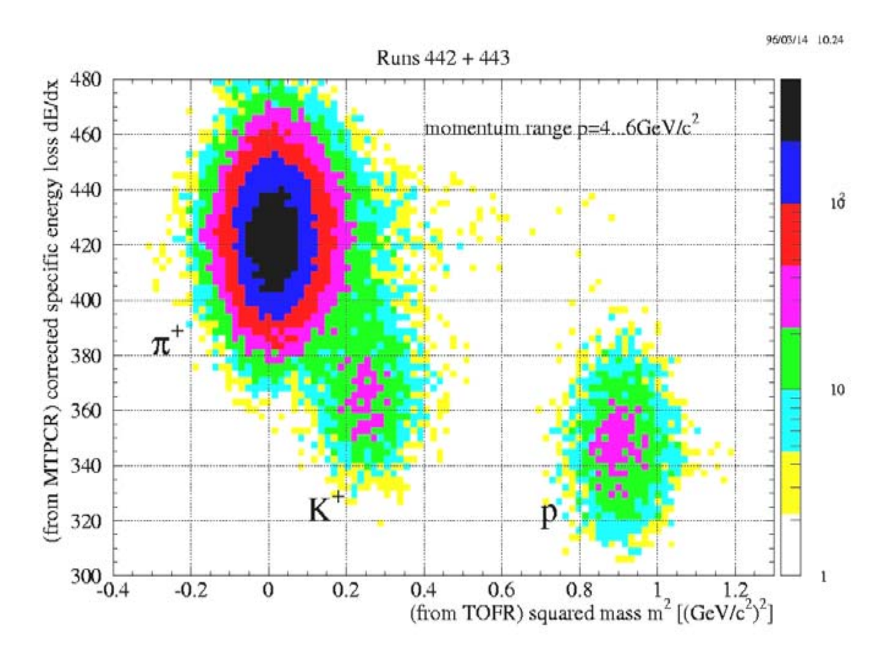
MIPP upgrade plan

- TPC inherited from E910
  - Built for Heavy-Ions physics, slow DAQ
- Detector performs beautifully, but data taking is proceeding somewhat slowly.
  - TPC cannot take data at more than 30-60 Hz in-spill
  - Beam sharing and machine downtime further limit the data collection speed
- TPC upgrade plan proposed, with new DAQ, promises far better performances and generously-sized data sets
- The neutrino community should see this as a very positive decision.

NA49 at CERN

- particle ID in the TPC complemented 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





NA49's future

- NA49 has already made measurements with C targets and 158 GeV/c p beam for atmospheric neutrino studies.
- A new collaboration is forming to re-start data taking after the SPS shutdown.
- The experiment will use the existing NA49 apparatus
  - Possibly with improved DAQ and TOF
  - Maybe revised low-bias trigger, very relevant for our purposes
- Discussions are ongoing to include high-statistics hadron production on experimental targets (i.e. T2K) and light targets for atmospheric neutrinos.

Conclusions

- Every generation of neutrino experiments has been accompanied by hadron production measurements
- Today, the claimed “high precision” era in neutrino experiments is not backed by an equivalent precision in the knowledge of the relevant hadronic cross-sections
- In recent years we have seen a boost in activity, with increasing quality, complexity (and cost …) of hadron production experiments
- New data is now being provided by HARP.
- Future harvesting looks promising, thanks to MIPP and NA49.