Hadron Production results from the HARP Experiment

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Outline

- HARP detector description
- Few highlights of calibration and performances
- Relevance for present $\nu$-oscillation experiments
- Measurements dedicated to CR shower development
- Calibration data for NuFact and new beamlines studies
- Data available for general hardron production studies and MC calibration
- Conclusions
HARP is a full solid-angle spectrometer to measure hadron production from various nuclear targets and a range of incident beam momenta.

- Nuclear target materials: $A = 1 - 200$
- Nuclear target thickness: $\lambda = 2\% - 100\%$
- Beam particles: $p, \pi^{\pm}, e^{\pm}$
- Beam momenta: $1.5 GeV/c - 15 GeV/c$
- Measured secondaries: $p, \pi^{\pm}, K^{\pm}$
- Kinematical acceptance:
  - forward:
    $p = 0.5 - 8.0 GeV/c, \theta = 20 - 250 \text{ mrad}$
  - large angle:
    $p = 0.1 - 0.7 GeV/c, \theta = 350 - 2150 \text{ mrad}$
Motivation(s)

- Oscillation experiments (K2K): near, far detectors. Far flux different from near flux (solid angle) in a way that is sensitive to primary hadron (p,θ) distribution.
- Even more so for experiments without near detector (MiniBooNE)
- Also: neutrino cross-sections are poorly known at low energies
- Near detector is/will be also a cross-section measurement device, but PROVIDED FLUX IS KNOWN ... ! (SciBooNE)

- Hadron production measurements are beneficial for Cosmic Ray studies and detector simulations
- Production of secondaries on nuclear targets is complicated to model
- difficult to measure well
- data are sparse
- Monte-Carlos are very uncertain
- absolutely mandatory for neutrino beam experiments
Neutrino Factory and new ν Beam Design: maximize $\pi^+ , \pi^-$ production rate (/proton /GeV)

Larger discrepancy at lower energy (indicently, the most interesting one for NuFact)

Need to choose

- Primary energy
- Target material
- Collection geometry and scheme

Geant4 vs Mars comparison, proton beam on long Ta target
2 matching spectrometers

Large Angle Spectrometer: Pion production and capture, Neutrino Factories
- \(0.45 \text{ rad} < \theta < 2.15 \text{ rad}\)
- \(100 \text{ MeV}/c < p < 700 \text{ MeV}/c\)

Forward Spectrometer
K2K, MiniBooNe, Cosmic rays
- \(30 \text{ mrad} < \theta < 210 \text{ mrad}\)
- \(750 \text{ MeV}/c < p < 6.5 \text{ GeV}/c\)
PID + Momentum

\[
\begin{align*}
\frac{\pi}{e} & \quad \text{CERENKOV} \quad \text{TOF} \quad \text{CALORIMETER} \\
\frac{\pi}{p} & \quad \text{TOF} \quad \text{CERENKOV} \\
\frac{\pi}{k} & \quad \text{TOF} \quad \text{CERENKOV}
\end{align*}
\]

Harp Particle Identification

\[
\begin{align*}
\text{Cerenkov Light (p.e.)} & \quad 50 \quad 45 \quad 40 \quad 35 \quad 30 \quad 25 \quad 20 \quad 15 \quad 10 \quad 5 \quad 0 \\
\text{velocity (c)} & \quad 1.05 \quad 0.95 \quad 0.9 \quad 0.85 \quad 0.8 \quad 0.7 \quad 0.6 \quad 0.5 \quad 0.4 \quad 0.3 \quad 0.2 \quad 0.1 \quad 0 \\
\text{momentum (GeV/c)} & \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10
\end{align*}
\]

\[
\begin{align*}
\text{Cher. light (p.e.)} & \quad \text{Dipole} \\
\text{TOF}
\end{align*}
\]
Example of redundancy: checks of momentum resolution

- open: data
- filled: MC

Theta-p plane:

- TOF
- BEAM
- ELASTICS
Momentum scale & PID in the TPC

- Elastic scattering of $p, \pi$ allows to check the resolution and momentum scale
- Particle ID with $dE/dx$ is cross-checked by means of the barrel RPC TOF system to evaluate efficiency
Papers on Detectors and Performance description

Relevance for K2K

One of the most relevant K2K systematic errors comes from the uncertainty in the near/far extrapolation.

Region of $\nu_\mu \rightarrow \nu_\tau$ Oscillation maximum: only Beam MC

Pions producing $\nu$ at the oscillation peak $0.5 < E_\nu < 0.75 [GeV/c]$: 
- $P_\pi > 1 GeV/c$
- $\theta_\pi < 250 mrad$
Far/Near Ratio in K2K

HARP gives ~ factor 2 error reduction across all energies

hep-ex/0510039
HARP Be 5% 8.9 GeV/c Results

Relevance for MiniBooNE:
- $0.75 < p < 5\text{[GeV/c]}$
- $30 < \theta < 210\text{[mrad]}$

- MiniBooNE $\nu$ cross-section measurement by SciBooNE
- HARP data will provide useful normalization to SciBooNE too.

HARP results (data points), parametrization of HARP results (histogram)
Comparison with older data (at different beam momenta)
Measurements relevant for air showers and atmospheric neutrino flux

Most of the uncertainty comes from lack of data to construct a reliable hadron interaction model at low energy.

One is now obliged to model-dependent extrapolations, leading to \( \approx 30\% \) uncertainty in the computed fluxes.

Several measurements:

- Carbon, Liquid \( N_2 \) and \( O_2 \)
- Positive and Negative beams: \( (p, \pi^+, \pi^-) \)
- Several beam energies

Notice, incidentally, that the same problems stand for precise (predictive) detector simulation for LHC experiments: lack of data to reliably simulate hadron showers (however in different materials)
Phase space region

- New data sets
  \((p+C, \pi^++C \text{ and } \pi^-+C \text{ at } 12 \text{ GeV}/c)\)
- Important phase space region covered
- Data available for model tuning and simulations
- \(N2\) and \(O2\) data being processed now

References:

HARP (PS)
$p+C@12\text{ GeV/c}$

- $\pi^+$: leading particle effect
- Error: stat. and syst.

Draft in preparations
Model comparison: $p+C \rightarrow \pi^+ + X$
Model comparison: $p+C \rightarrow \pi^- + X$
$\pi^+ + C @ 12$ GeV/c (lower statistics)
$\pi^- + C @ 12 \text{ GeV/c (high statistics)}$
Boxes show importance of phase space region for contained atmospheric neutrino events.

Measurements:

- 1-2 $p_T$ points
- 3-5 $p_T$ points
- $>5$ $p_T$ points
Forward-region papers


- Thick + replica targets are on the way

- In preparation: Charged pion production by 3 GeV/c–12 GeV/c protons on a carbon target (Atmospheric Flux)
Large-Angle analysis, p+Ta 3,5,8,12 GeV/c

HARP p-Ta π⁺

forward
0.35 < θ < 1.55

backward
1.55 < θ < 2.15
forward \( 0.35 < \theta < 1.55 \)

backward \( 1.55 < \theta < 2.15 \)

HARP \( p-Ta \) \( \pi^- \)
Neutrino factory study

dσ/dθ cross-sections can be fed into neutrino factory studies to find optimum design
Hadronic generators

- Little experimental data to develop/calibrate the models --> large uncertainties
- Many targets at different beam energies and full solid-angle -->
- Input calibration data for hadronic generators (collaboration with GEANT-4)
- What follows is a collection of examples of secondary particle distributions
p-C data as an example of many other available spectra
comparison of $p$-$C \pi^-/\pi^+$ and $p$-$Ta \pi^-/\pi^+$ ratios
forward production only $0.35 < \theta < 1.55$ rad
comparison of $\pi^+$ and $\pi^-$ and yields for p-A for Be, C, Cu, Sn, Ta and Pb

forward production only $0.35 < \theta < 0.95$ rad
A-dependence of $\pi^+$ and $\pi^-$ and yields for p-A for Be, C, Cu, Sn, Ta and Pb (3, 5, 8, 12 GeV/c)

forward production only $0.35 < \theta < 1.55$ rad
papers on Large Angle analysis


- In preparation: Large-angle production of charged pions by 3 GeV/c–12.9 GeV/c
Conclusions

- HARP has taken a comprehensive set of data and begin to produce hadron production cross-sections with errors in the 4-8% range over a large fraction of phase-space.
- Started with forward analysis for K2K and MiniBooNE and large-angle analysis for Tantalum (NuFact) – only pions.
- Will continue with analysis of other targets (automated procedure).
- Analysis improvements to come:
  - Forward Kaon production
  - Large angle analysis full spill analysis (better statistics – and maybe also systematics)
  - Thick targets (for tertiary production and real neutrino targets)