New Results from the HARP/PS214 experiment at CERN PS

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• results for conventional neutrino beams
  – HARP for K2K, MINIBoone
• new Harp forward $\pi^+$ production results: final p-A data, final $\pi$-A data (A=Be,C,Al,Cu,Sn,Ta,Pb)
• results for a Neutrino Factory
  – HARP Large Angle Data analysis
  – Comparison with MC simulations
• new LA results for $\pi$-A (A=Be,C,Al,Cu,Sn,Ta,Pb)
• new results for long replica targets for $\nu$ beams
• results for EAS and atmospheric neutrinos
  – HARP results with incident C, N$_2$, O$_2$
• conclusions
the HARP experiment at CERN PS

2000 – 2001 Installation
2001- 2002 Data taking

Systematic study of hadron production:
Beam momentum: 3-15 GeV/c
Target: from hydrogen to lead
• Acceptance over full solid angle
• Final state particle identification

- Input for prediction of neutrino fluxes for the MiniBooNE and K2K experiments
- Pion/Kaon yield for the design of the proton driver of neutrino factories and super-beams
- Input for precise calculation of the atmospheric neutrino flux and EAS
- Input for Monte Carlo generators (GEANT4, e.g. for LHC or space applications)
### Experimental setup

![Diagram of experimental setup](image)

**Harp detector layout and data taken**

**HARP:** barrel spectrometer (TPC) + forward spectrometer (DCs) to cover the full solid angle, complemented by PID detectors

\[
p = 0.5 - 8.0 \text{ GeV/c} \quad \theta = 25 - 250 \text{ mrad (forward)}
\]

\[
p = 0.1 - 0.8 \text{ GeV/c} \quad \theta = 350 - 2150 \text{ mrad (large angle)}
\]

<table>
<thead>
<tr>
<th>Target</th>
<th>Target length (λ%)</th>
<th>Beam Momentum (GeV)</th>
<th>#events (Mevts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>2</td>
<td>±3</td>
<td>233.16</td>
</tr>
<tr>
<td>C</td>
<td>(2001)</td>
<td>±5</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td></td>
<td>±8</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>5</td>
<td>±12</td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td></td>
<td>±15</td>
<td></td>
</tr>
<tr>
<td>Ta</td>
<td>100</td>
<td>For negative polarity, only 2% and 5%</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K2K</td>
<td>Al</td>
<td>5, 50, 100, replica</td>
<td>+12.9</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>Be</td>
<td></td>
<td>+8.9</td>
</tr>
<tr>
<td>Cu “button”</td>
<td>Cu</td>
<td></td>
<td>+12.9, +15</td>
</tr>
<tr>
<td>Cu “skew”</td>
<td>Cu</td>
<td></td>
<td>+12</td>
</tr>
<tr>
<td>Cryogenic targets</td>
<td>N(_7)</td>
<td>6 cm</td>
<td>±3</td>
</tr>
<tr>
<td></td>
<td>0(_8)</td>
<td></td>
<td>±5</td>
</tr>
<tr>
<td></td>
<td>D(_1)</td>
<td></td>
<td>±8</td>
</tr>
<tr>
<td></td>
<td>H(_1)</td>
<td></td>
<td>±12</td>
</tr>
<tr>
<td></td>
<td>H(_2)</td>
<td>18 cm</td>
<td>±3, ±8, ±14.5</td>
</tr>
<tr>
<td></td>
<td>H(_2O)</td>
<td>10, 100</td>
<td>+1.5, +8(10%)</td>
</tr>
</tbody>
</table>

For negative polarity, only 2% and 5%
1. HARP forward analysis: particle identification

For particles with momentum $p$, the following techniques are used for identification:

- $\pi/p$: Time-of-Flight (TOF) and Cerenkov
- $\pi/K$: TOF and Cerenkov
- $\pi/e$: Cerenkov and Calorimeter

For $p$ below pion threshold, use Cerenkov technique for electrons and hadrons. For $p$ above pion threshold, use Calorimeter technique.

- TOF for $p=2\pm0.25$
- $N_{\text{ch}}$ for $p$ below pion threshold
- $E/p$ and $E(1\text{st layer})/E$ for $p$ above pion threshold
Recipe for a cross-section

\[
\frac{d^2 \sigma^{\pi}}{dp \, d\Omega} = \frac{A}{N_A \rho \, t} \frac{1}{N_{pot}} \left[\text{correction factors}(p, \theta)\right] \frac{\Delta^2 N^{\pi}}{\Delta p \, \Delta \Omega}
\]

- Select events identified as primary protons interacting in the target
- For each event reconstruct tracks and their 3-momentum
- Identify pions among secondary tracks

Apply corrections for reconstructed-to-true pion yield conversion:
- Momentum resolution
- Spectrometer angular acceptance
- Track reconstruction efficiency
- Efficiency and purity of pion identification
- Other

Count protons on target corresponding to selected events
Multiply by physics constants and accurately measured target properties
Why dedicated Hadroproduction expts: conventional neutrino beams

**MiniBooNE Neutrino Beam**

**Ingredients to compute a neutrino flux:**
- \( \pi \) (and k) production cross section (use same target and proton energy than proton driver of the experiment)
- Reinteractions (take data with thin and thick target)

**Oscillation probability at 250 km from the source for atmospheric parameters: maximum effect at \( \sim 1\text{GeV} \)**

**K2K: Disappearance experiment to confirm atmospheric osc.**
HARP in black, Sanford-Wang parametrization in red

HARP p-Al data 12.9 GeV/c:

HARP data on inclusive pion production fitted to Sanford-Wang parametrization:

\[
\frac{d^2 \sigma (p+Al \rightarrow \pi^+ + X)}{dpd\Omega}(p,\theta) = c_1 p^{c_2} (1 - \frac{p}{p_{beam}}) \exp[-c_3 \frac{p^{c_4}}{p_{beam}^{c_5}} - c_6 \theta (p - c_7 p_{beam} \cos^2 \theta)]
\]

where:
X: any other final state particle
\[p_{beam} = 12.9\]: proton beam momentum (GeV/c)
p, \theta: \pi^+ momentum (GeV/c), angle (rad)
\[d^2 \sigma/(dpd\Omega)\] units: mb/(GeV/c sr), where \[d\Omega = 2\pi d(\cos \theta)\]
c_1, ..., c_7: empirical fit parameters

- Good coverage of phase space of relevance to K2K flux predictions:
Reconstructed « single ring » Quasi-elastics in SuperKamiokande $\rightarrow$ spectral shape + normalization show oscillation (no oscillation curve for demonstration only)

M. H. Ahn et al. [K2K Collaboration]
HARP Be 5% 8.9 GeV/c Results

Error Analysis: Overall error ~ 5%

$\delta_{\text{diff}} = \sqrt{\sum_{i,j} (\delta\sigma_i/(\Delta p\Delta\Omega)_i)^2}$

$\delta_{\text{int}} = \sqrt{\sum_{i,j} (\Delta^2\sigma_j/(\Delta p\Delta\Omega)_j)}$

Error Category | Error Source | $\delta_{\text{diff}}$ (%) | $\delta_{\text{int}}$ (%) |
--- | --- | --- | --- |
Statistical | Be target statistics | 4.2 | 0.6 |
Empty target subtraction (stat.) | 4.6 | 0.6 |
Sub-total | 6.3 | 0.8 |
Track yield corrections | Reconstruction efficiency | 1.3 | 0.8 |
Pion, proton absorption | 3.6 | 3.7 |
Tertiary subtraction | 1.8 | 1.8 |
Empty target subtraction (syst.) | 1.3 | 1.2 |
Sub-total | 4.6 | 4.3 |
Particle Identification | Electron veto | 0.2 | <0.1 |
Pion, proton ID correction | 0.4 | 0.1 |
Sub-total | 0.5 | 0.1 |
Momentum reconstruction | Momentum scale | 3.6 | 0.1 |
Momentum resolution | 3.4 | 1.0 |
Sub-total | 5.2 | 1.0 |
Overall normalization | Sub-total | 2.0 | 2.0 |
All | Total | 9.8 | 4.9 |

HARP results (data points), Sanford-Wang parametrization of HARP results (histogram)
MiniBoone $\nu$ flux predictions

$0.75 < p < 5$ GeV/c, $30 < \theta < 210$ mrad relevance for MiniBooNE

HARP $p$-Be-$\pi$ data 8.9 GeV/c:

MiniBooNE with Harp input,
Comparison with older p+Be data

albeit, different beam momenta
New HARP results: FW data with incident $\pi^+/\pi^-$

- All FW data taken in pion beams have been published on NP A 801 (2009) 118
- Bad agreement data montecarlo (GEANT4/MARS)
- Interesting to tune models for re-interactions (and shower calculations in calorimeters etc.)
- Final FW results on p-A (A = Be, C, Al, Sn, Cu, Ta, Pb)
- SW parametrization of all data, comparison with MC
- submitted to PRC
Comparison of FW $p\rightarrow{}^{\pi}X$ with MC

$\chi^2$ assuming a 20% error on MC

Just one example
Neutrino factory design

- maximize $\pi^+(\pi^-)$ production yield as a function of:
  - proton energy
  - target material
  - geometry
  - collection efficiency ($p_L, p_T$)
- but different simulations show large discrepancies for $\pi$ production distributions, both in shape and normalization. Experimental knowledge is rather poor

⇒ **Aim:** measure $p_T$ distribution with high precision for high Z targets
2. HARP Large Angle Analysis

Beam momenta:
3, 5, 8, 12 GeV/c

Data:
5% $\lambda_1$ targets Be, C, Al, Cu, Sn, Ta, Pb

TPC tracks:
>11 points and momentum measured
and track originating in target

PID selection

Corrections:
Efficiency, absorption, PID, momentum and angle smearing by unfolding
method

Backgrounds:
secondary interactions (simulated)
low energy electrons and positrons (all from $\pi^0$)
predicted from $\pi^+$ and $\pi^-$ spectra (iterative) and normalized to identified $e^+$-

Full statistics analysed (“full spill data” with dynamic distortion
corrections) although no significant difference is observed with the
first analysis of the partial data (first 100-150 events in the spill).
9 angular bins: p-Ta $\pi^+/\pi^-$

Pion production yields

forward
$0.35 < \theta < 1.55$

backward
$1.55 < \theta < 2.15$
Neutrino factory study

Cross-sections to be fed into neutrino factory studies to find optimum design: Ta and Pb x-sections at large angle (see Eur. J. Phys C51 (2007) 787)
Comparisons with available data...

BNL E910 at 12.3 GeV/c: data points; HARP: shaded region

squares: Shibata et al. (KEK), 12 GeV/c at 90°; circles: HARP data
Comparisons with MC

Many comparisons with models from GEANT4 and MARS to the GiBUU model have been done.

Only some examples will be shown here for C and Ta for the GEANT4 and MARS packages:
- Binary cascade
- Bertini cascade
- Quark-Gluon string models (QGSP)
- Frittiof (FTFP)
- LHEP
- MARS

Some models (inside MARS/GEANT4) do a good job in some regions, but there is no model that describes all aspects of the data. GiBUU seems a little better in the region covered by HARP.
8 GeV/c $p$-C $\pi^{+/−}$

5% $\lambda$ target

MODELS
3 GeV/c p-Ta π⁺⁻
3 GeV/c $\pi^+$ HARP LA data vs GiBUU

$\frac{d^2\sigma}{dp\,d\theta}$ [mb/(GeV rad)]

$p$ [GeV]

GiBUU (arXiv:0901.1770 [hep-ex])
12 GeV/c $\pi^+$ HARP LA data vs GiBUU
Comparison with MC at Large Angle

1. Data available on many thin (5%) targets from light nuclei (Be) to heavy ones (Ta)

2. Comparisons with GEANT4 and MARS15 MonteCarlo show large discrepancies both in normalization and shape
   - Backward or central region production seems described better than more forward production
   - In general $\pi^+$ production is better described than $\pi^-$ production
   - At higher energies FTP models (from GEANT4) and MARS look better, at lower energies this is true for Bertini and binary cascade models (from GEANT4)
   - Parametrized models (such as LHEP) have big discrepancies

3. Comparison with GiBUU seems better
New LA data with incident $\pi^+$
- $\pi^- A \rightarrow \pi^- X$ data published for $A=$Be,C,Al,Sn,Cu,Ta,Pb
- comparisons with GEANT4/MARS MC
- for more details see HARP Collaboration, arXiv 0907.1428
Houston we have a problem (from WEB: originally reporting of a life threatening fault. Now humorously used to report ANY problem

We conclude that claims and results published by OH [5–8, 25, 32–34, 36–38] suffer from systematic biases and shortcomings that are absent in our analyses presented in this and forthcoming papers.

The systematic precision of our inclusive cross-sections is at the few-per-cent level, from errors in the normalization, in the momentum measurement, in particle identification, and in the corrections applied to the data.
Well ... let's have a look, take p-Be data

Why only that one bin? and at the one at high energy? Other dozens of similar plots ...

Just remind: quark's counting rules

In addition "a few % systematic error", may be largely underestimated (for a TPC with many problems) …. (we are at \( \sim 10\% \))
And what about raw data?

- Simple cross-check in the region 300-400 MeV/c (where background are negligible) for thin Be at 8.9 GeV/c
- $\pi/p$ separation is large (difficult to make errors)
- Momentum resolution $\sim 10$-$15\%$
- other corrections (efficiencies, backgrounds …) similar
- $R_{\text{raw}} = N_{\pi^+}/N_{\pi^-} = 1.52^{+0.10}_{-0.10}$
  published HARP results $1.55^{+0.10}_{-0.10}$

Conclusions are left to the reader …
3. Realistic production targets

In practice neutrino beams production targets are not thin: *Cascade calculations or dedicated measurements with “replica targets” are needed.*

HARP has taken, albeit with somewhat lower statistics, and analysed $p+A$, $\pi^+ A$ and $\pi^- A$ data at different beam momenta with 100% $\lambda_{int}$ targets (for K2K and MiniBOONE experiments).

They can be used for complete parametrizations or tuning of models.

Preliminary spectra available
$p + Al$ versus GEANT4

$p + Al \rightarrow \pi^+ + X$ at 12.9 GeV/c

$\frac{d^2\sigma}{dp d\Omega}$ (mb/GeV*sr) for different angles:
- 30 - 60 mrad
- 60 - 90 mrad
- 90 - 120 mrad
- 120 - 150 mrad
- 150 - 180 mrad
- 180 - 210 mrad

Data comparison with FTFP, QGSP, QGSC models.
$p + \text{Be} \rightarrow \pi^+ + X$ at 8.9 GeV/c

30 - 60 mrad

90 - 120 mrad

150 - 180 mrad

60 - 90 mrad

120 - 150 mrad

180 - 210 mrad

$\frac{d^2\sigma}{dp d\Omega}$ (mb/(GeV sr))

$\frac{d^2\sigma}{dp d\Omega}$ (mb/(GeV sr))

$\frac{d^2\sigma}{dp d\Omega}$ (mb/(GeV sr))

$\frac{d^2\sigma}{dp d\Omega}$ (mb/(GeV sr))

FTFP

QGSP

QGSC

Data
4. Atmospheric $\nu$ flux

- Primary flux (70% p, 20% He, 10% heavier nuclei) is now considered to be known to better than 15% (AMS, Bess p spectra agree at 5% up to 100 GeV, worse for He)

- 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

- $\rightarrow$ cryogenic targets (or at least nearby C target data)

- 78% nitrogen
- 21% oxygen
Hadron production experiments

Population of hadron-production phase-space for pA → πX interactions.

νμ flux (represented by boxes) as a function of the parent and daughter energies.

Measurements.

- 1-2 p_T points
- 3-5 p_T points
- >5 p_T points

But with different targets (mainly Be)
Harp: $p, \pi^{\pm} + C$ at 12 GeV/c data

SW parametrization superimposed
Model comparison
Measurements with N$_2$,O$_2$ cryogenic targets

HARP results confirm that p-C data can be used to predict p-N$_2$ and p-O$_2$ pion production
Comparison with GEANT4

$p + O_2 \rightarrow \pi^+ + X$ at 12 GeV/c
• New data sets
  \((p-C, \pi^+–C \text{ and } \pi^––C, p-O_2, p-N_2 \text{ at } 12 \text{ GeV/c})\)

• Important phase space region covered

• Data available for model tuning and simulations

[\text{Barton83}] \quad \text{Phys. Rev. D 27 (1983) 2580} \quad \text{(Fermilab)}

[\text{NA49_06}] \quad \text{Eur. J. Phys., hep-ex/0606028} \quad \text{(SPS)}

\text{HARP} \quad \text{(PS)}
Harp Published physics results


*Large-angle production of charged pions by 3 GeV/c-12.9 GeV/c protons on beryllium, aluminium and lead targets*, EPJ **C54** (2008) 37, [arXiv: 0709.3458]


Conclusions

• HARP has provided results useful for conventional ν beams study, ν factory design, EAS, atmospheric ν studies and in addition for general MC tuning (Geant4, FLUKA …) with full solid angle coverage, good PID identification on targets from Be to Pb at low energies (< 15 GeV) with small (but not negligible) total errors (syst+stat < 15 %).

Nine physics paper published plus another two submitted

• More HARP results coming: forward production with incident pions; production with long targets, …

• Comparison with available MC show some problems
Backup material
Harp physics goals

Input for prediction of neutrino fluxes for the K2K and MiniBooNE / SciBooNE accelerator experiments

Pion/Kaon yield for the design of the proton driver and target system of Neutrino Factories and Super-Beams

Input for precise calculation of the atmospheric neutrino flux (from yields of secondary $\pi$, $K$)

Input for Monte Carlo generators (GEANT4 and others)
Momentum Resolution

- theta-p plane:
  - 0.5 to 1.5

- TOF
  - open: data
  - filled: MC

- ELASTICS
  - RMS(p)/p vs p (GeV/c)

- BEAM
  - RMS(p)/p vs p (GeV/c)

- 100-150

- empty target beam

- TOF

- elastics
Spectrometer performance

momentum resolution

elastic scattering: absolute calibration of efficiency
momentum angle
(two spectrometers!)

PID: dE/dx used for analysis
TOF used to determine efficiency

π-p PID with dE/dx

π-e PID with dE/dx

momentum calibration: cosmic rays elastic scattering
The two spectrometers match each other
Harp TPC: corrections for dynamic distortions

Analyses of full data sample