Review of Hadron Production Experiments

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• Motivations
• The Experiments
• HARP
• NA61/SHINE
• Future Prospects
• Summary

PITT PAC Workshop, Pittsburgh, December 6, 2012
Motivations

- Input for precise prediction of neutrino fluxes in modern accelerator neutrino experiments

- Hadron production uncertainties have big impact on the energy, composition, geometry of the neutrino beam

- Various models of Monte Carlo generators are used and show large differences in $\nu$ rate predictions, hadron production data can be used as input for validation/tuning of Monte Carlo generators (GEANT4 and others)

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

- Dedicated experiments such as HARP, MIPP, NA61/SHINE...
The Experiments
The HARP detector

• Forward Spectrometer
  $0.5 \leq p \leq 8.0$ GeV/c
  $25 \leq \theta \leq 250$ mrad
  
  - track reconstruction with drift chambers + dipole magnet
  
  - PID with threshold Cherenkov + time-of-flight wall + electromagnetic calorimeter

• Large-Angle Spectrometer
  $0.1 \leq p \leq 0.8$ GeV/c
  $350 \leq \theta \leq 2150$ mrad
  
  - track reconstruction & PID with solenoid magnet + TPC + RPCs
NA61 Detector

- Track reconstruction:
  - TPC as main tracking devices
  - 2 dipole magnets
- Particle Identification:
  - Time-of-flight wall L/R, speed for high momentum particles produced at small angle
  - New ToF-F, speed for low momentum particles produced at large angle
- TPC, dE/dx

Updated detector covers entirely the T2K acceptance!

Combined ToF-F & TPCs PID

4 < p < 5 GeV/c
The MIPP detector

• Track Reconstruction:
  • Two dipole magnets deflecting in opposite direction
  • TPC + drift chambers + MWPCs

• Particle Identification

\[ p \text{ (GeV/c)} \]
\[ \text{dE/dx} \]
\[ \text{velocity} \]
\[ \text{light yield} \]
\[ \text{ring radius} \]

\[ \log(\text{dE/dx}) \]

\[ \text{Velocity (cm/ns)} \]

\[ \text{TPC} \]
\[ \text{TOF} \]

\[ \text{Threshold Cherenkov} \]

\[ \text{RICH} \]
## The Experiments

<table>
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<tr>
<th>Accelerator-based Neutrino Beams</th>
<th>K2K, MiniBooNE</th>
<th>MINOS</th>
<th>T2K off-axis</th>
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<td>H, Be, C, Bi, U</td>
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HARP
Studies for Accelerator-based Neutrino Beams
• F/N contribution to uncertainty in number of unoscillated muon neutrinos expected at Super-K reduced from 5.1% to 2.9% with HARP.
HARP/MiniBooNE

\[ p(8.9 \text{ GeV/c}) + \text{Be} \rightarrow \pi^+ + \chi \]

- 5% \( \lambda \), same (beam, target material) as FNAL Booster Neutrino Beam
- typical error on point = 9.8%
- error on integral = 4.9%
- analysis includes significant improvements relative to Al measurement in PID and momentum resolution description
• Combining HARP and E910 data gives maximal coverage of the relevant pion phase space for MiniBooNE

• Use the parameterization of Sanford and Wang and fit to both data sets combined

\[ p(8.9 \text{ GeV/c}) + \text{Be} \rightarrow \pi^+ + X \]

Black boxes are the distribution of \( \pi^+ \) which decay to a \( \nu_\mu \) that passes through the MiniBooNE detector

[Graphs and plots showing data distributions and kinematic boundary]
HARP/NuFact

- Pion yield normalized to beam proton kinetic energy
- Restricted phase space most representative for NuFact design
- Optimum yield in HARP kinematic coverage for 5-8 GeV/c beam momenta
- Confirms Ta target results
- Quantitative optimization possible using full spectra range available for 4 beam momentum settings (3-12 GeV/c)

\[ p + Pb \rightarrow \pi^\pm + X \]

Full forward acceptance:
- \[ 350 < \theta < 950 \text{ mrad} \]
- \[ 0.25 < p < 0.50 \text{ GeV/c} \]

Filled: \( \pi^+ \)
Empty: \( \pi^- \)

EPJC 54, 37 (2008)

EPJC 51, 787 (2007)
HARP
Atmospheric Neutrinos
Atmospheric Neutrinos

- Challenge for accurate neutrino flux prediction: primary cosmic ray spectrum & hadronic interactions (primary with nuclei)
- Carbon is isoscalar as nitrogen and oxygen
- Simulations predict that collisions of protons with a carbon target are very similar to proton interactions with the air


78% nitrogen
21% oxygen
Incoming charged pion HARP data were the first precision measurements in this kinematic region.

Data relevant to the prediction of atmospheric neutrino fluxes and extensive air shower (EAS) simulations

First precision measurement for N$_2$ and O$_2$ in this energy range

HARP data confirmed that p+C data can be used to predict p+N$_2$ and p+O$_2$ pion production
HARP
Systematic Target Studies
Dependence on the atomic number $A$ of the pion yields in $\pi$-$A$ interactions averaged over two FW angular regions ([50,150], [150,250] rad) and four momentum regions ([0.5-1.5], [1.5,2.5], [2.5,3.5], [3.5,4.5] GeV/c) for incoming beam momenta 3,5,8,12 GeV/c
Dependence on the atomic number $A$ of the pion yields in p-A interactions averaged over two FW angular regions ($[50,150]$, $[150,250]$ rad) and four momentum regions ($[0.5-1.5]$, $[1.5,2.5]$, $[2.5,3.5]$, $[3.5,4.5]$ GeV/c) for incoming beam momenta 3,5,8,12 GeV/c
A-dependence of the $\pi^+$ and $\pi^-$ yields in $\pi^{\pm}$-A interactions for Be, C, Al, Cu, Sn, Ta, Pb as a function of beam momentum (full spill data)
• Comparison of $\pi^+$ and $\pi^-$ yields in p-A for Be, C, Al, Cu, Sn, Ta, Pb as a function of beam momentum (full spill data)

$0.1 < p < 0.7$ (GeV/c)  
$0.35 < \theta < 1.55$ (rad)

• A-dependence of the $\pi^+$ and $\pi^-$ yields in p-A interactions for Be, C, Al, Cu, Sn, Ta and Pb (full spill data)

$0.35 < \theta < 1.55$ (rad)
HARP Data-MC Comparison

- Many comparisons with models from GEANT4 and MARS
- Only some examples shown here
  - Binary Cascade
  - Bertini Cascade
  - Quark-Gluon string (QGS)
  - Fritiof (FTFP)
  - LHEP
  - MARS
  - GiBUU
  - FLUKA
- GiBUU transport model covers the full energy range of HARP data
- Models do a good job in some regions, but no model that describes all aspects of the data
HARP Data-MC Comparison

A lot more comparison plots can be found in the technical notes https://edms.cern.ch/file/1184197/2/fluka2011_harp_updated.pdf https://edms.cern.ch/file/1218221/1/fluka2011_harp_ta.pdf for charged pion and proton production in proton- and charged pion- Interactions at 3, 5, 8 and 12 GeV/c on C, Al and Ta targets.
• Ratio of pion yields in 100% λ over 5% λ Carbon target
• Dotted line – ratio of pions produced by “first generation” beam proton to all pions produced by the beam in MARS
HARP Publications

- 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]
- Measurement of the production cross-sections of $\pi^\pm$ in p-C and $\pi^\pm$-C interactions at 12 GeV/c, Astr. Phys. 29 (2008) 257, [arXiv: 0802.0657]
- Large-angle production of charged pions with incident protons on nuclear targets as measured in the Harp experiment, Phys. ReV.C77 (2008) 055207, [arXiv: 0805.2871]
- Forward production of charged pions with incident $\pi^\pm$ on nuclear targets as measured at CERN PS, Nucl. Phys. A821 (2009) 118 [arXiv: 0902.2105]

Tables with HARP results are available e.g. from the DURHAM database
NA61/SHINE
Two different carbon (isotropic graphite) targets were used:

- **Thin Carbon Target**
  - length = 2 cm, cross section 2.5x 2.5 cm²
  - ρ = 1.84 g/cm³
  - ~0.04 λ_int

- **T2K replica Target**
  - length = 90 cm, Ø=2.6 cm
  - ρ = 1.83 g/cm³
  - ~1.9 λ_int

Data for T2K with incoming 31 GeV/c protons collected:

- 2007 run (~670k triggers on thin target and ~230k triggers on replica target). Analysis finalized and corresponding results published.

- 2009 run (~6M triggers on thin target and ~2M triggers on replica target). These data are now fully calibrated and analysis is well advanced.

- 2010 run (~10M triggers on replica target). Data being calibrated now. Ultimate data set for most precise neutrino flux predictions.

Three complementary analysis techniques which differ by PID method.
T2K beam simulation: the $(p, \theta)$ distribution for $\pi^+$ weighted by the probability that their decay produces a $\nu_\mu$ passing through SK

Very well covered by NA61/SHINE
NA61/SHINE

$p(31 \text{ GeV/c}) + C \rightarrow K^+$

Relevant for high energy tail of $\nu_\mu$ spectrum and intrinsic $\nu_e$ component in T2K
• Special reconstruction and analysis techniques developed for the replica target
• Pilot analysis on $\pi^+$ emission from the replica target surface performed on 2007 data
• Replica target hadron production measurements allow to constrain up to 90% of neutrino flux in T2K
• Proof-of-principal neutrino flux re-weighting performed with NA61/SHINE replica target data
• Results consistent with the thin target tuning
- Replica target data are used for the first time for neutrino flux predictions.
- Combination of thin and replica target measurements to better understand effects of re-interactions in the long target.
- Ultimate precision on T2K neutrino flux will be achieved with replica target re-weighting, once 2010 NA61/SHINE data are analyzed.

Re-weighted $\nu_\mu$ flux at the far detector based on the NA61/SHINE thin target and replica target measurements.
NA61/SHINE

- Additional preliminary results using the 2007 data:
  - $p(31 \text{ GeV/c}) + C \rightarrow p$
  - $p(31 \text{ GeV/c}) + C \rightarrow K_0S$

- In 2007 data analysis statistical errors dominate.

- Further analysis of data collected for T2K in 2009 and 2010 with both thin and replica targets as well as for Cosmic Ray experiments ($\pi-C @158$ and @$350 \text{ GeV/c}$) is on-going

- With 2009 data, hope to reduce statistical errors by a factor of 3.

- Systematic errors will become more important

- NA61/SHINE 2009 & 2010 $pC@31\text{GeV/c}$ and $pRT@31\text{GeV/c}$ data provide even a better coverage of phase space of interest for T2K

- Will allow to reach T2K requirements on neutrino flux predictions: 5% error on absolute neutrino fluxes in the near and far detectors (as well as 3% error on the far-to-near ratio)

- Both thin target and replica target with improved statistics expected in early 2013

- US groups involved in Fermilab neutrino experiments plan to join NA61 in order to perform required hadron production measurements

- See Alexis Hasler’s talk on Friday
NA61/SHINE Publications


Future Prospects
• Preliminary results cover high $E_\nu$
• NuMI beam momentum: 120 GeV/c
• Both NuMI replica and thin C targets
• Preliminary: fully corrected $\pi^\pm$, $K^\pm$ particle yields ratios only ($p_t < 0.2$ GeV/c)

Phase space at production of $\pi^+$'s producing $\nu_\mu$ CC interactions in MINOS far detector

$p(120\text{ GeV/c}) + C \rightarrow \pi^\pm, K^\pm$
MIPP

• Current status:
  • Event selection has been finalized
  • MC has been mostly tuned (some further fine-tuning is required)
  • Acceptance corrections and efficiencies are understood
  • Reconstructed -> true unfolding and PID algorithm almost done
  • 4-6 months (full-time) to wrap current analysis

• Future plan:
  • Kaon production at low momenta relevant for the NOvA ND on surface prototype analysis
  • See Jon Paley’s talk on Friday
Interpolating Existing NA49/NA61 Data

- Precise hadron production measurements in p + C collision at energy E=120 GeV are needed for improving calculation of the NuMI neutrino flux

- Charged pion spectra in p + C interactions were measured in NA61 and NA49 experiments at proton energies 31 and 158 GeV, respectively

- These data cover kinematic region of interest for charged pion $0.02 \leq x_F \leq 0.3$ and $0.1 \leq p_T \leq 0.5$(GeV/c) whose daughter muon neutrino gives the main contribution to NuMI neutrino flux

- Study energy dependence of the measured spectra to estimate the pion invariant cross section at proton energy 120 GeV

- Published NA49 and NA61(low statistic 2007 run) data used

MINERvA collaboration, FNAL

A. Butkevich, INR Moscow
Interpolating Existing NA49/NA61 Data

- The measured NA61 differential cross section $d\sigma/dp$ was transformed into invariant cross section $f(x_F, p_T)$.

- This cross section is interpolated using the effective variance recursive method and compared with interpolated NA49 data at the same values of [$x_F (p_{61}, \theta), p_T (p_{61}, \theta)$].

- The invariant cross section at proton energy 120 GeV is evaluated and a "scaling violation" effect in the energy range $E = 120$ to $158$ GeV is estimated.

- In the first calculation an effect of $\leq 10\%$ is seen and depends on ($x_F, p_T$) and is of the same order as the statistical errors of the NA61 2007 data.

http://nova-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=7674&version=1
• Measuring hadron production at the CERN NA61/SHINE experiment with 120GeV protons on NuMI replica target
• The data would be relevant for MINERvA, MINOS, MINOS+, NOvA and LBNE
• The program would take about four years to complete
• Pilot run in June 2012: primary goal to evaluate the capabilities of NA61/SHINE in a 120 GeV/c proton beam and the US-NA61 collaborators to get familiar with NA61/SHINE
• See Elena Guardincerri’s talk later today

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<th>Target</th>
<th>Incident proton/pion beam momentum</th>
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<tr>
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<tr>
<td>NuMI (spare) replica</td>
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<tr>
<td>BNB replica</td>
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<tr>
<td>LBNE replica</td>
<td>201X</td>
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<tr>
<td>thin graphite (&lt; 0.05λf)</td>
<td>2012</td>
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<tr>
<td>thick graphite (~ 1λf)</td>
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Summary

- Hadron production for neutrino experiments is a well established field
- Hadron production knowledge is limiting factor in understanding and optimization of a variety of neutrino sources (accelerator-based neutrino beams, atmospheric neutrinos)
- Search for smaller effects: characterization of actual neutrino beam targets to reduce MC extrapolation to the minimum
- Not mentioned in this talk but important:
- US-NA61 collaboration formed, pilot run in June 2012
Backup Slides
SW parameterization

\[
\frac{d^2 \sigma(p + A \rightarrow \pi^+ + X)(p, \theta)}{dpd\Omega} = c_1 p^{c_2} \left(1 - \frac{p}{p_{\text{beam}}}\right) \exp \left[ -c_3 \frac{p^{c_4}}{p_{\text{beam}}^{c_5}} - c_6 \theta(p - c_7 p_{\text{beam}} \cos^{c_8} \theta) \right]
\]

- $X$ : any other final state particle
- $p_{\text{beam}}$ : proton beam momentum (GeV/c)
- $p, \theta$ : pion lab-frame momentum (GeV/c) and angle (rad)
- $c_1, ..., c_8$ : empirical fit parameters

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<th>Value</th>
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<td>$(6.47 \pm 1.62)$</td>
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<td>$(9.06 \pm 2.03) \cdot 10^1$</td>
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<td>$c_6$</td>
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<td>-0.776</td>
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HARP measurements for p+Be at 8.9 GeV/c

HARP PID

- TPC for $p < 0.8$ GeV/c
- TOF for $0.5 < p < 5$ GeV/c ($p/\pi$)
- CHE for $p > 2.6$ GeV/c
HARP TPC dynamic distortion corrections

Full statistics now analysed (“full spill data” with dynamic distortion corrections). No significant difference is observed with respect to first analyses of the partial data (first 100-150 events in spill).

arXiv:0903.4762 [physics.ins-det]
MIPP Upgrade

- MIPP was limited by DAQ rate, dominated by the TPC readout time (~30 Hz). This is ~1/5 of desired statistics for NuMI target run.

- In addition, the Jolly Green Giant magnet failed at end of run (repair is now complete)

- Upgrade of the TPC electronics is expecting to increase the readout speed by a factor of 50

- Other improvements would result in:
  - more stable TPC performance
  - greatly reduced ExB effects in the TPC
  - an improved beamline for low (down to ~1 GeV/c) momentum running

- An upgraded MIPP would allow for the measurement of hadron production for any target in a matter of just a few days

- FNAL has purchased ALTRO chips for the TPC upgrade and repair of the JGG dipole magnet has begun
HARP TPC calibration

- Elastic scattering benchmark
- Missing mass peak from large angle proton track (position of peak verifies momentum scale: +15% completely excluded)
- Comparison of predicted vs. measured tracks allows LA tracking benchmark

Full statistics now analysed (“full spill data” with dynamic distortion corrections). No significant difference is observed with respect to first analyses of the partial data (first 100-150 events in spill)
NA61 2008-9 upgrade

- New DAQ
  - 70Hz, but ToF not yet in DAQ stream
- new trigger logic (FPGA based) with trigger mixing
  - successfully tested during test run
  - adds multihit TDC to monitor pileup
- Increased ToF-F acceptance ($p_{\text{min}} \sim 1 \text{ GeV/c} \rightarrow 0.6 \text{ GeV/c}$)
  - two new ToF modules under construction, hopefully on time
- New beam detectors (> acc. for wide beam)
  - tested during test run, some more work required
- 2 forward tracking chambers (bigger acc. at small $\theta$), not tested during test run