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Status and latest results from MIPP

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Abstract

We briefly review the need for high quality hadron production data. The Main Injector Particle Production experiment (MIPP) at Fermilab collected data in 2005/2006 and published final results on forward neutron production and the charged kaon mass. Preliminary results on other topice, including particle production on the NuMI target, have also been presented. We provide a summary of past results and an outlook.

Keywords: particle production, MIPP

1. Motivation

The theory of strong interactions, quantum chromodynamics (QCD), is limited in its ability to answer very simple questions. Although perturbative methods are used successfully in a limited phase space where the strong coupling constant α_s is small, QCD does not allow in general to calculate particle production cross sections. This is quite unlike the situation in quantu electrodynamics (QED), which of course has been applied to make extremely precise calculations that agree with measurements, for example in the anomalous magnetic dipole moment of the electron.

This situation – having a theory that is believed to be correct, yet can not be applied to make predictions for many simple processes – should be discomforting to theorists, but it also has profound implications to experimentalists. Hadronic particle production information is needed throughout the field of particle physics as illustrated by the examples below. Since QCD does not allow us to calculate the cross sections, they have to be measured by particle production experiments.

1.1. Need for particle production data in calorimetry

The detectors at the LHC are operating in an environment different from that at other colliders. The beam energy and the number of events per bunch crossing result in a density and energy of particles hitting the calorimeters that is different from other calorimeters.

The energy resolution in calorimeters can be improved using the particle flow algorithm (PFA). The energy of charged particles is deduced from their bending in the magnetic field of the tracking system and the calorimeter is used to measure the neutral particles only. How well the PFA works depends on the size of each calorimeter cell. In designing the calorimeter one important parameter is the transverse size of the hadronic shower that develops in the calorimeter for a given type of primary particle. With insufficient data on the angular differential cross sections, the cell size may be chosen too large, resulting in inferior performance, or too small, resulting in an increased cost for little or no improvement in performance. Thus detailed and accurate data on particle production on the materials used in the calorimeter is needed during design of the calorimeter. Particle production data is also important while operating the calorimeter to model and understand it properly during data analysis. The Monte Carlo simulation of showers in the calorimeter should agree with the data.

1.2. Need for particle production data in cosmic ray experiments

Ultra high energy cosmic rays (UHECR) pose interesting questions that are studied using the Pierre Auger

Observatory [1] and similar detectors. The number of UHECRs (with energies at or above the Greisen-Zatsepin-Kuzmin (GZK) cutoff [2, 3]) hitting earth is low, so the observatory needs to cover a large area to record events at a sufficient rate. UHECRs interact in the upper atmosphere and create cosmic ray air showers. The air showers are detected in the Pierre Auger Observatory in two ways. Fluorescence detectors (FD) record the fluorescence light emitted from nitrogen atoms excited by the particles in the air shower and the surface detector (SD) samples the air shower as it reaches the ground using an array of water Cherenkov tanks spaced 1 km apart. The FDs look at the entire air shower rather than just a sample of the shower at ground level, but they are active only during moonless nights. This low FD duty cycle implies that the FDs are used mainly to calibrate the surface detector and the data for a large fraction of the cosmic rays is recorded solely from the surface detector consisting of stations that sample only a tiny fraction of the particles in the shower. Also each station of the SD has limited capability due to solar panel provided power, low bandwidth radio communication for the data acquisition, and the need for high reliability due to the high cost of accessing the tanks for maintenance.

Given all these constraints and limitations one might expect that knowledge of particle production is not the limiting factor in extracting physics from the data. However, even in cosmic ray experiments better knowledge of the shower development, i.e. particle production data, would improve the science reach. The questions under investigation include the composition of the cosmic rays: Are they mainly protons, iron nuclei, other elements, or a combination of several of these? The variables used to investigate the composition are the mean depth along the air shower of the maximum transverse size of the shower $< X_{\max} >$ and the width of the $X_{\max}$ distribution. These variables depend on the primary particle species and their modeling is sensitive to the particle production cross sections at energies of the primary UHECR interaction down to the energy of particles a the shower maximum.

While particle production data at the energy of the primary interaction obviously cannot be obtained at accelerators, the energy at the shower maximum is of the order of a few hundred GeV, almost independent of the primary energy. Precise data at lower energies may constrain particle production at higher energy through extrapolation and scaling methods.

1.3. More examples for particle production data needs

Particle production cross section data is needed in many other experiments. Neutrino oscillations and other properties of neutrinos are studied using neutrinos produced in the decay of pions and kaons that in turn are the products of the interaction of an accelerator beam on a neutrino production target. The number, energy spectrum, and angular spectrum of neutrinos depends on the spectra of the pions and kaons. Thus a detailed understanding of the neutrino beam relies on particle production data of protons (beam) on carbon, beryllium, or other material used in the target. In accelerator neutrino experiments with near and far detectors, the ratio of rates obtained in the two detectors cancels much of the beam uncertainties. However, the near detector sees a line source of neutrinos generated throughout the beam decay volume whereas the far detector sees a point source of neutrinos. Thus the cancellation of beam spectrum dependence is incomplete in the near-to-far ratio and a detailed beam model is necessary.

Other experiments are interested in studying charged kaons. The ORKA experiment discussed by E. Worcester at this conference [4] is a proposed experiment to measure the $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio. The kaons are to be produced using proton interactions on a kaon production target. The charged kaon production cross section on the production target in the relevant kinematic regime has a large uncertainty of approximately a factor of 2. This directly corresponds to an uncertainty in running time of the ORKA experiment to reach a given sensitivity. Better constraints on the kaon production can at the least improve cost estimates associated with running time and perhaps guide design choices to maximize the physics potential.

The particle production cross sections are directly relevant in the two examples in the preceeding paragraphs. The final example shows an indirect impact of particle production data. As reported by J. Albert at this conference [5], BaBar measured CP violation in several τ decays with K_s^0 in the final states. Differences in the nuclear interaction cross sections of K^0 and $\bar{K}^0$ with detector materials cause the observed asymmetry to differ from the CP asymmetry in τ decays. Ko et al. [6] estimated the correction using total cross section data on five different elements at momenta from 5 to 200 GeV/c. They also rely on isospin symmetry, and approximations where particle production data is not available. Just as in the other examples, more precise particle production data could improve the precision of the calculated asymmetry correction, although the CP measurement precision is currently limited by other factors.

The availability of particle production cross section data (or the lack of it) directly or indirectly impact particle physics experiments at the intensity, cosmic, and energy frontiers as shown in the examples above. There is also good physics behind the frontiers. The Main Injector Particle Production experiment can look for missing baryon resonances, examine scaling laws of particle fragmentation and look for patterns in the detailed cross section data, and address various topics in nuclear physics such as nuclear y-scaling [7].

The MIPP experiment also found a novel technique to measure the charged kaon mass [8]. This measurement was reported at BEACH2010 [9].

2. MIPP detector and beam

The MIPP experiment [10, 11] uses protons from the Fermilab Main Injector to generate secondary beams of charged pions, charged kaons, protons, and antiprotons at momenta from five to 85 GeV/c. The beam particles are identified using two beam Cherenkov detectors. The secondary beams or primary protons at 120 GeV/c interact in the experimental targets of liquid hydrogen, solid discs of elements spanning the periodic table up to uranium, and the composite Neutrinos at the Main Injector (NuMI) neutrino production target. All charged particles are tracked in a double spectrometer through a TPC and 24 planes of wire chambers and identified using dE/dx in the TPC, time-of-flight to a TOF-wall scintillator hodoscope, multi-cell Cherenkov detector, RICH, and calorimeters. The detector is shown in Fig. 1.

MIPP collected data in a physics run in 2005/2006 after construction, installation, and commissioning since 2001. Approximately 17 million particle interactions have been recorded.

Tracking in the highly redundant system of TPC and wire chambers with two large bending magnets, Jolly Green Giant (JGG) and Rosie, resulted in very good momentum resolution of $dp/p < 5\%$ up to 100 GeV/c, although a refined method of correcting for large $\vec{E} \times \vec{B}$ drift distortions had to be developed to achieve this.

The particle identification in the time of flight system suffered from cross talk in the electronics and large variations in the measured delay with temperature due to the use of twist'n'flat delay cables. These temperature depended delay changes of up to 4000 ps could be corrected to achieve a $\sim$ 200 ps resolution, twice the design value. The C_4F_8O radiator gas in the Cherenkov detector included trace contaminations that resulted in significantly fewer photoelectrons than expected. This could not be recovered offline and particle identification in the momentum range of $\sim$ 3 GeV/c to $\sim$ 20 GeV/c is degraded. Despite these challenges the MIPP experiment recorded a unique data set that has only been partially analyzed to date.

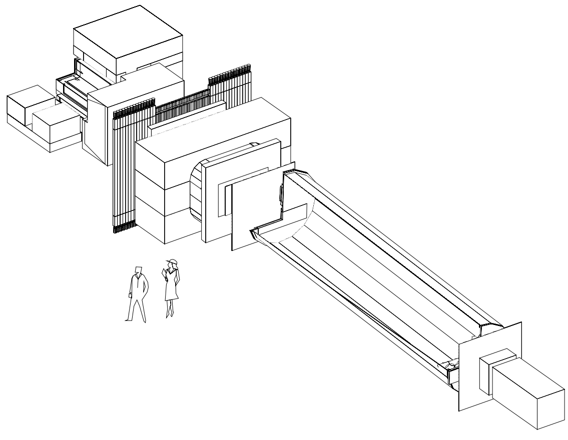

Figure 1: The MIPP detector shown from a downstream perspective. Beam enters from the left. Detectors shown from left to right are TPC inside the JGG magnet (cut view), multi-cell Cherenkov, time-of-flight wall, Rosie magnet, wire chambers, RICH (cut view), wire chamber, EM- and hadron calorimeters. Wire chambers between JGG and Rosie are not shown.

3. NuMI target data analysis

Approximately 1.78 million interactions of 120 GeV/c protons on the NuMI neutrino target were recorded during the MIPP run in order to determine the production of pions and kaons off the NuMI target from direct measurement to reduce the uncertainty in the MINOS experiment near detector to far detector neutrino spectra ratio.

The detector Monte Carlo simulation reproduces the momentum spectrum from data well and momentum and track angle resolutions are well understood. The particle identification uses an iterative global log likelihood algorithm. It is important to take prior particle fractions into account. The GlobalPID algorithm developed in the MIPP collaboration does this. For example a particular track's dE/dx measurement may be most close to the dE/dx expected for a kaon at the track's momentum. Here the distance from the Bethe-Bloch dE/dx predictions for each particle hypothesis may be expressed in units of the width of the distribution of each particle type's dE/dx around the central value to take into account the possibility of the resolution varying as a function of dE/dx. A cut-based analysis or other analysis technique which does not take particle fractions into account would assign a kaon particle identification to this particle. However, the much larger number of pions and finite resolution of the dE/dx measurement may result in the likelihood of the particle actually being a pion being higher than that of being a kaon. It becomes apparent that neither identification should actually be assigned to the particle. Instead each particle enters the momentum spectra for all particle hypotheses with the appropriate hypothesis dependent weights. Of course this applies not just to dE/dx measurements, but also to any other particle identification variable like time-of-flight, RICH ring radius, etc. and any analysis must take particle fractions into account. Of course these particle fractions are what we are interested in determining from the data. An iterative approach is needed. It can be seeded with equal fractions of all particles and iteration terminates when the output of a given iteration is equal to the input particle fractions to within the desired precision. The GlobalPID algorithm also combines likelihoods from different PID detectors used in MIPP.

We now present the important features of the GlobalPID algorithm in a more formal way. The joint probability $P(H, x)$ for a particle with observed particle id variable x (where x is dE/dx, ToF, RICH ring radius, ...) to be of type H (where H =e,π,K,p) is given by the product of the probabilities of the particle being of type H, $P(H)$, which we try to determine in the experiment, and the conditional probability $P(x|H)$ that a particle of type H produces a signal x:

$$P(H, x) = P(x|H)P(H). \tag{1}$$

These probabilities all depend on particle momentum. The momentum dependence is not shown in the equations for clarity.

By Bayes' theorem we also have:

$$P(H, x) = P(H|x)P(x). \tag{2}$$

Combining both equations leads to

$$P(H|x) = \frac{P(x|H)P(H)}{\sum_H P(x|H)P(H)}. \tag{3}$$

The $P(x|H)$ are given by detector resolutions. The $P(H)$ are initially unknown and may be assumed to be equal as a starting point. The posterior probabilities $P(H|x)$ are then used as a weight for the track for each hypothesis. The resulting $P(H)$ are used for the next iteration. Of course the posterior probabilities must preserve unity:

$$\sum_H P(H|x) = 1. \tag{4}$$

The NuMI data analysis is near final. The GlobalPID algorithm has been applied to Monte Carlo (MC) to verify that the particle fractions obtained from GlobalPID agree with the input to the MC. MC is treated separately from data and the algorithm is applied to data independently. What remains to be done is fine tuning to add the minority particle species (kaons and anti-protons) to the analysis and verify their yields agree with the MC input when the algorithm is run on MC. It should be noted that the separate treatment of data and MC reduces the potential effect of differences between MC and data particle fractions on the data analysis.

4. Forward neutron production cross sections

The MIPP calorimeters [12] have been used to measure inclusive forward neutron production cross sections [13] on hydrogen, beryllium, carbon, bismuth, and uranium using proton beam at 20, 58, 84, and 120 GeV/c. The neutrons were required to have momenta larger than a low, beam proton depended threshold. Well understood data and reconstruction quality cuts with high efficiencies were applied and empty target contributions subtracted. The beam flux determination, event reconstruction, and detector simulation were validated using known p-p cross sections and multiplicities.

The largest background were secondary neutrons generated in the TOF wall and RICH detector. These were fully simulated in the Monte Carlo simulation. The largest uncertainty to the neutron cross sections arises from the acceptance correction. The acceptance has been modeled using different event generators (DPMJET [14] or FLUKA [15] and LAQGSM [16]). The acceptances differ significantly mainly due to the different transverse momentum distributions from the generators.

The Lorentz invariant cross sections $\frac{E}{p^2\Omega}\frac{d\sigma}{dp}$ plotted against Feynman x are observed to scale from 58 GeV/c to 84 GeV/c for $p + p \rightarrow n + X$, but do not scale for $p + A \rightarrow n + X$ for A being carbon or bismuth.

Data at the various nuclear masses A has also been fit to exponentials in A for beam momenta of 58 GeV/c and 120 GeV/c as shown in Fig. 2. For elements other than hydrogen a dependence of $\sigma \propto A^{0.5}$ is observed.

5. Hadronic shower simulation and MIPP upgrade

The forward neutron production measurement in MIPP was limited by the acceptance simulation. The input to MC generators needs to improve. All event generators and detector simulation packages are tested against the available data and agree where data is available. In reactions or regions of phase space where data is not available, the differences between different

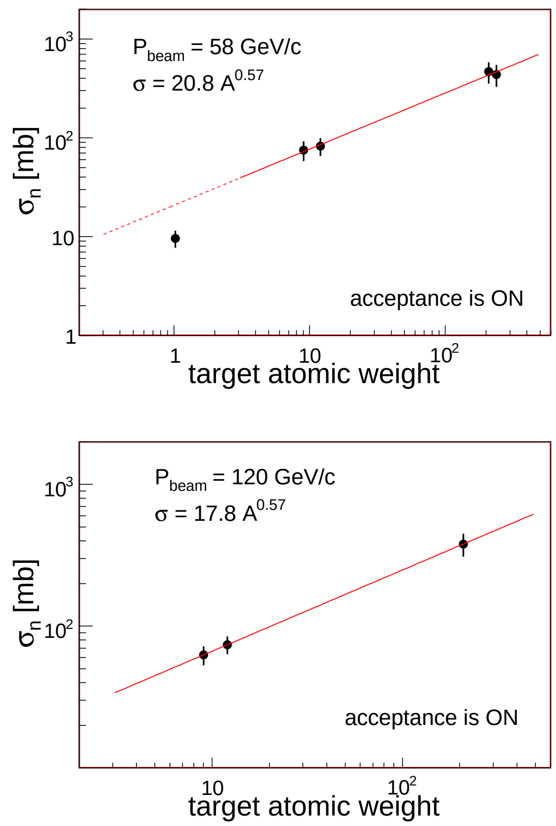

Figure 2: Forward neutron production cross section dependence on target atomic number [13].

packages can be large. The resulting MIPP neutron cross sections have been compared to FLUKA [15], LAQGSM [16], and MARS [17, 18]. Large discrepancies have been observed from one model to another and between models and data. New versions of the various packages will likely agree with the now available forward neutron measurements. However, there is no fit, model, or extrapolation that can be trusted over the entire phase space. This situation could be remedied with a large library of particle interaction events obtained by an upgraded MIPP experiment and sampled in packages like GEANT4 [19].

Upgrades to MIPP have been proposed [20] to increase the rate at which events can be recorded from 20–50 Hz to ~ 3kHz. This would allow the experiment to record 5 million interactions per day with minimal impact (5% or less) on the beams delivered to other experiments. The upgrades are actually well developed and prototype boards of all important components exist. New coils have been installed in the Jolly Green Giant magnet after the coil failure at the end of the last run. The new coils provide a more uniform magnetic field, significantly reducing $\vec{E} \times \vec{B}$ drift distortions in the TPC which had to be carefully corrected in the first run. This represents a large fraction of the proposed upgrades in cost and effort. However, the upgrade proposal has been rejected and a future MIPP run is currently not scheduled.

Several other upgrades can enhance the MIPP physics potential. Adding a detector in the backward hemisphere upstream of the target will allow detection of photons and nuclear fragments moving backward in the lab. The plastic ball detector [21] is being considered for this purpose. Low current power supplies and Hall probes in the beam line magnets would allow the secondary beams to reach momenta as low as 1 GeV/c [22]. With the higher data rate tagged neutral beams will also be feasible. The charged kaon mass measurement could be repeated with better statistics and systematics.

References

[1] K.-H. Kampert, Highlights from the Pierre Auger Observatory, arXiv:1207.4823 astro-ph (2012).

[2] K. Greisen, End to the Cosmic Ray Spectrum?, Phys. Rev. Lett. 16 (1966) 748.

[3] G. T. Zatsepin, V. Kuzmin, Upper Limit of the Spectrum of Cosmic Rays, JETP Letters 4 (1966) 78.

[4] E. T. Worcester, ORKA: The Golden Kaon Experiment, these proceedings.

[5] J. Albert, Searches for New Sources of CP and T Violation at BaBar, these proceedings.

[6] B. Ko, et al., Effect of nuclear interactions of neutral kaons on CP asymmetry measurements, Phys. Rev. D 84 (2011) 111501.

[7] H. Meyer, Physics of the MIPP Experiment, Nucl. Phys. B (Proc. Suppl.) 142 (2005) 453–458.

[8] N. Graf, et al., Charged Kaon Mass Measurement using the Cherenkov Effect, Nucl. Inst. Meth. 615 (2010) 27–32.

[9] N. Solomey, Measurement of the Charged Kaon Mass, Nucl. Phys. B (Proc. Suppl.) 210 (2011) 185–188.

[10] H. Meyer, The Main Injector Particle Production experiment, Nucl. Phys. B (Proc. Suppl.) 187 (2009) 194–199.

[11] R. Raja, Nucl. Instr. Meth. A 553 (2005) 225.

[12] T. Nigmanov, et al., Electromagnetic and Hadron Calorimeters in the MIPP experiment, Nucl. Inst. Meth. A 598 (2009) 394–399.

[13] T. Nigmanov, et al., Forward neutron production at the Fermilab Main Injector, Phys. Rev. D 83 (2011) 012002.

[14] S. Roesler, R. Engel, J. Ranft, in: Proceedings of the 27th ICRC, Hamburg, 2001 (Report No. SLAC-PUB-11093).

[15] A. Ferrari, P. Sala, A. Fasso', J. Ranft, FLUKA: a multi-particle transport code, CERN 2005-10, INFN/TC_05/11, SLAC-R-773 (2005).

[16] K. K. Gudima, et al., User Manual for the Code LAQGSM, LANL Report No. LA-UR-01-6804 (2001).

[17] N. Mokhov, Report No. Fermilab-FN-628 (1995).

[18] N. Mokhov, S. I. Striganov, in: Proceedings of the Hadronic Shower Simulation Workshop, Fermilab, 2006, AIP Conf. Proc., Vol. 896, 2007, pp. 50–60.

[19] S. Agostinelli, et al., GEANT4 – a simulation toolkit, Nucl. Inst. Meth. A 506 (2003) 250–303.

[20] MIPP Upgrade collaboration, MIPP Upgrade Proposal, http://ppd.fnal.gov/experiments/e907/Upgrade/.

[21] A. Baden, et al., The plastic ball spectrometer: An electronic 4π detector with particle identification, Nucl. Inst. Meth. 203 (1982) 189–211.

[22] H. Meyer, MIPP Low Momentum Beam, MIPP-Doc-367, mipp-docdb.fnal.gov/cgi-bin/ShowDocument?docid=367 (2006).