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A Very Forward Hadron Spectrometer for the LHC and Cosmic Ray Physics

Michael Albrow[*†]
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA.
E-mail: albrow@fnal.gov

Charged hadron production in hadron-hadron collisions with longitudinal momentum fraction Feynman-x, x_F, between 0.1 and 0.9 has not been measured above $\sqrt{s}$ = 63 GeV at the CERN Intersecting Storage Rings. I discuss a way to measure this at the Large Hadron Collider at $\sqrt{s}$ = 13 TeV, which is 40,000 times higher in equivalent fixed target energy, and important for understanding cosmic ray showers.

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[*]Speaker.
[†]Scientist emeritus

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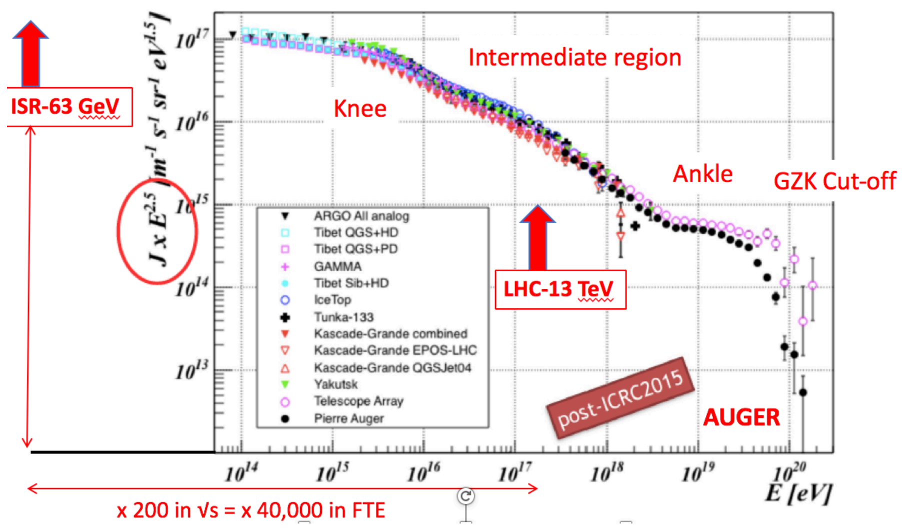

Figure 1: The flux of cosmic rays multiplied by $E^{2.5}$, showing the "knee" and the "ankle" vs. primary energy E. All this data is based on measuring showers in the atmosphere. The maximum energy of the CERN ISR and LHC are indicated.

1. Introduction

When the first hadron collider, the CERN Intersecting Storage Rings, ISR, came into operation in 1971 it was known that most produced particles in inelastic collisions have small transverse momenta, $p_T = \sqrt{p_x^2 + p_y^2}$ less than about 1 GeV/c. Feynman had proposed, based on the idea of parton constituents of protons, that their longitudinal momenta, p_z, should scale with the beam momentum, so the spectra at high energies should be a function only of x_F and p_T where Feynman-x, $x_F = p_z/p_{BEAM} = 2 \times p_z/\sqrt{s}$. With p_{BEAM} ranging from 11.5 GeV/c to 31.4 GeV/c at the ISR most produced particles would be at very small angles. The Small Angle Spectrometer, Experiment R201, was designed to measure the spectra of identified $\pi^+, \pi^-, K^+, K^-, p$,and $\bar{p}$ in this region, with $p_T < 2.5$ GeV/c [1, 2]. There are no measurements at higher $\sqrt{s}$, which is 200 times higher at the LHC than at the ISR, with the exception of Roman pot devices measuring diffractively scattered protons with $x_F > 0.9$, and neutral particles, mainly neutrons and $\pi^0 \to \gamma\gamma$, in calorimeters at $\theta = 0°$. The π^+ and π^- spectra are bound to be very different from each other (with two u-quarks and only one d-quark in the proton) with π^0 in-between. Similarly, we expect $K^+ > K^-$ and $p > n > \bar{p}$, etc. We should measure all of these charged particles at the LHC, and can do so with high precision with new detectors. Decaying particles such as $K_s^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^+$ may be accepted, but especially interesting would be $D^0 \to K^{\pm}\pi^{\mp}$ and $J/\psi \to \mu^+\mu^-$.

The flux of hadrons or nuclei in cosmic rays at such high energies is $< 1\ m^{-2}$ per year, so direct detection, which would have to be from space, is impractical. Therefore, all our knowledge of cosmic ray spectra, see Fig. 1, from below the "knee" at 10^{15} - 10^{16} eV to the highest energies at the GZK cut-off around 10^{20} eV, comes from showers in the atmosphere. The measurements are calorimetric, e.g. detecting the scintillation light (fluorescence) in the atmosphere (a homogeneous calorimeter) or sampling the shower with a ground array of scintillation counters or water tanks (which is a sampling calorimeter with a single sparsely-covered layer). Figure 1 shows the flux of cosmic ray showers, multiplied by $E^{2.5}$ from the top ISR energy, far below the "knee", and well beyond the LHC energy. There have been speculations that the knee is caused by a change in the nature of the interactions, even perhaps in the forward direction, the subject of this note.

Understanding the calibration of these "calorimetric" detectors, i.e. the relation between measured signal and the energy of the incident cosmic ray, is crucial. The shower process is complicated, from the first interaction on a nucleus of nitrogen or oxygen, at energies up to a thousand times higher than those accessible at the LHC, with secondaries, tertiaries, etc. down to low energies in a cascade. There are many Monte Carlo programs modelling these inelastic interactions, such as KASKADE, DPMJET, EPOS, QGSJET, PYTHIA and SYBIL. When these are used to predict the spectra of high x_F neutrons and π^0 at LHC energies they differ by more than an order of magnitude. Those are measured [3] with small calorimeters and are not very precise, but they serve to show that very forward hadron production is poorly understood. Of course, these simulations assume nothing unexpected occurs in small angle hadron production over many orders-of-magnitude in energy. Precise measurements, of order 2% in both momentum and cross-section, of charged hadron spectra are possible, and will enable these various models to be rejected, modified or tuned, or they may reveal unexpected phenomena. Importantly, there are some puzzles in cosmic ray showers such as an anomalous high content of muons [4]. Muons can come from decays of charm and beauty hadrons which have never been measured at high x_F, as well as Drell-Yan annihilation of very low-$x_{Bjorken}$ antiquarks with quarks.

Figure 2 shows the region of small p_T and the full range of x_F, most of which is *"Terra Incognita"*, not measured above $\sqrt{s} = 63$ GeV, except for nearly elastic protons $x_F > 0.9$ and neutral hadrons in calorimeters.

The most conventional mechanism for producing a high-x_F low-p_T hadron at the LHC is as a product of diffractive excitation. The simplest, lowest-mass examples are $p^* \to n\pi^+$ or $p^* \to p\pi^+\pi^-$, where p^* is a diffractively excited proton. Such processes were measured at the ISR in the Split Field Magnet and, at lower $\sqrt{s}$, in the Omega Spectrometer at the SPS (fixed target). At the LHC the diffractively scattered proton will have $x_F = 1 - M^2(p^*)/s \approx 1.0$ and could be measured in a Roman pot, only possible with special high-β^* running. There will be a very large rapidity gap, with no hadrons, between that scattered proton and the lowest-rapidity hadron from the p^* fragmentation.

There are many reasons, apart from measurements of diffraction fragments, to add a Very Forward Hadron Spectrometer, VFHS, to an (existing) collision region at the LHC. It can cover a large region of parameter space $(p_T, x_F, \sqrt{s})$ which is completely unexplored. These are "legacy measurements" and it would be a serious omission to close the LHC without having measured them, not only in pp but in pA and AA collisions. They probe non-perturbative QCD, in a region not yet well understood, in novel ways. They will greatly improve our understanding of cosmic rays (and hence of the high-energy cosmos) in terms of their spectra and composition, including muon content, e.g. from heavy flavours.. And novel and unexpected phenomena may be revealed.

2. A possible spectrometer design

At $\sqrt{s}$ = 13 TeV a hadron with $x_F > 0.1$ and p_T = 1 GeV/c has polar angle θ < 1/650 = 1.5

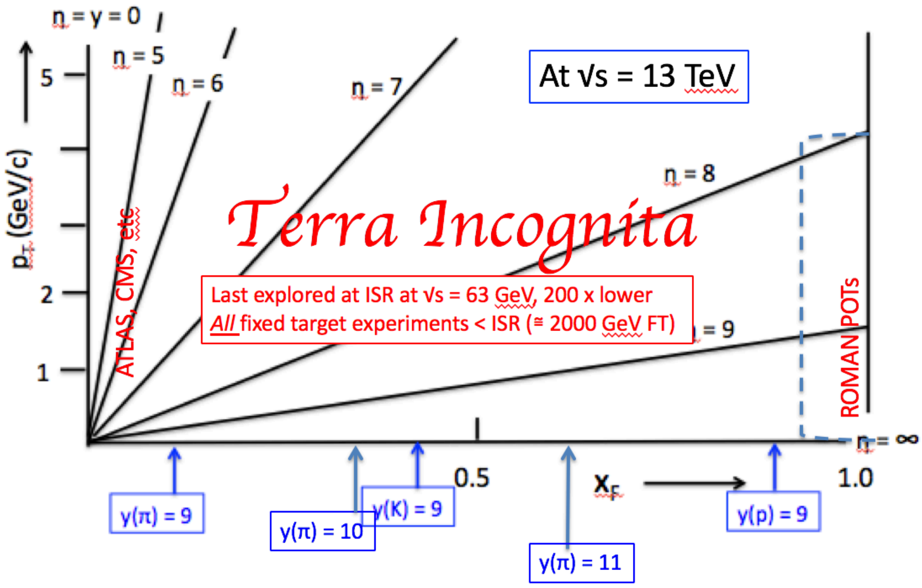

Figure 2: For pp collisions at $\sqrt{s}$ = 13 TeV, regions of low transverse momentum p_T and all Feynman-x, x_F, showing lines of constant pseudorapidity η. Protons with $x_F > 0.9$ are measured in Roman pots, and neutral particles in calorimeters around 0°. Identified charged hadrons have not been measured except at $\eta < 4$ at LHCb, so most of this phase space is Terra Incognita.

mrad. It passes down the vacuum pipe, through quadrupole fields and then the (MBX) "beam separation dipoles", spectrometer magnets with an integral field of $B.dL$ = 30 Tesla-meters. Charged hadrons are bent out of the beam. Behind these dipoles is a field-free region from about 80 to 140 m, where the TAN absorber, which protects the superconducting LHC magnets, is located. At Point 5 (where CMS is located) this is a simple cylindrical pipe, which transitions to two separate pipes for the incoming and outgoing beams at 140 m. (Zero-degree calorimeters for neutral particle measurement are located between these pipes.) This pipe can be redesigned to allow the deflected hadrons to emerge from the vacuum through little material. The pipe for the outgoing protons may start at a z-position about 12-15m in front of the TAN, making that much space available for the detectors. The pipe cross section should be as small as allowable by the machine operations to maximize the acceptance, with positive hadrons emerging on one side and negative on the other.

I present the concept with approximate numbers, to show that such a spectrometer is feasible. Cross sections are relatively high and running with modest luminosity (pile-up of a few interactions per bunch crossing) is preferred. The size of the detectors is small, only tens of cm^2 per layer. Immediately outside the vacuum chamber window, precision tracking with silicon strips or pixels measures the straight tracks, to a precision in x, y, θ_x, θ_y of about 10 μm and a few μr. With the assumption that the track originated in a beam-beam collision, the particle's charge is known and its momentum with a resolution of about 2%. Non-primary tracks coming from interactions in the beam pipes and other material will generally have forbidden values of x, y, θ_x, θ_y, and also can mostly be removed by comparing momentum with the energy measured in a calorimeter at the back of the spectrometer.

Between the tracker and the calorimeter one can budget about 8 m of longitudinal space for hadron identification, which is the main technical challenge of the detectors, discussed later. The calorimeter, about 2.5 m long and of order 1 m^2 in area, should fill the transverse area as closely as possible around the outgoing beam pipe. Since it is small compared to most LHC calorimeters it can be of high performance, with longitudinal segmentation (e.g. 2 EM segments plus 3 HADronic segments) and fine transverse granularity, as in an "imaging" calorimeter. This should allow a good measurement of more than one particle, correction for lateral leakage of showers close to the edge of the fiducial region, and distinction between photons, electrons, hadrons and muons.

Behind the calorimeter, tracking chambers identify muons and signal any hadron shower leakage. Note that muons in this 1 - 6 TeV range have radiative energy losses several times higher than minimum-ionizing particles; they are on the "relativistic rise". Good muon measurement is very important, since they can come from heavy flavours c and b; the branching fraction of $D^0 \rightarrow \mu + X$ is 6.7%, and leptons also come from J/ψ and Υ decays. Background muons from π- and K-decay will be well known since their spectra will be measured, and $\gamma c\tau(\pi)$ = 340 km at 2.5 TeV (18.55 km for $K^{\pm}$)!

Between the upstream tracking and the calorimeter about 8 m of space can be dedicated to charged hadron identification. Cherenkov counters cannot separate such high momentum π and K, but transition radiation detectors which measure $\gamma = E/m$ are the most likely (perhaps the only) techniques. Their use in high energy experiments is usually to aid in e/π separation at low momenta, in a limited space and difficult environment. Motivated by this VFHS initiative, R & D is being carried out at CERN [5] to identify these multi-TeV hadrons. X-radiation from the interface between two materials with different dielectric properties has a γ-dependent probability of order 1/137, and an emission angle θ_X of order $1/\gamma$. A typical detector has hundreds of radiator foils separated by gaps, and design parameters (foil material and thickness, spacing and the gas in the gaps) can be tuned for different γ-ranges. We need to cover the range from the slowest particles accepted (1 TeV protons, $\gamma = E/m = 10^3$) to the fastest (5 TeV π, $\gamma = 3.6 \times 10^4$). A 10 - 20% γ measurement should give adequate $\pi/K/p$ separation. The "angle-TRD" concept has many short stacks followed by pixel X-ray detectors, whose superimposed signals form a ring with radius θ_X. (Unlike Cherenkov radiation, the emission angle *decreases* as the particle speed increases.) Together with the X-ray energy measurement, such a detector can minimize the material budget for optimum particle identification, and provide the tracking information in addition, alleviating the need for a separate tracker.

The detector elements of the VFHS are accessible in the LHC tunnel and modular, so detectors can be replaced as techniques improve. We do not have multi-TeV test beams, so electrons and pions are used for tests, which have been done at the CERN SPS [5, 6] and compares well with simulations.

Without having a detailed technical design for the spectrometer it appears feasible, with well-understood state-of-the-art detectors together with an innovative TRD system that is being developed with very encouraging results. Beam-line and detector (GEANT) simulations, and a realistic vacuum chamber design, are needed for a technical proposal, including acceptances for physics processes.

Where could such a spectrometer be located? Of the four existing collision regions, the strongest cases can be made to add the VFHS to ALICE or LHCb (or even both!). Relatively low luminosity running is an advantage, as the cross sections are not small. This would give ALICE, whose focus is on heavy-ion collisions, a programme of $p+p$ physics orthogonal (in more than one sense!) to the high-p_T central physics done well by ATLAS and CMS. The LHC is capable of making both p-N and N-N collisions (after a short machine study), and the VLHC can then measure the spectra of very forward showers produced in the atmosphere by cosmic rays. The physics focus of LHCb is heavy flavors. Potentially the VLHC can measure very forward charm and beauty, from "direct" leptons or possibly $D^0 \rightarrow K^{\pm}\pi^{\mp}$, but acceptance calculations need to be done for a realistic detector design. Studies of the central event correlated with leading hadrons may also be interesting.

I apologise for the very incomplete list of citations. I would like to thank Pierre Petroff and the organisers of "Exploring the Dark Side of the Universe" for the invitation.

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