PHYSICS WITH JETS AT THE LHC*

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Prospects for jet physics at the CERN large hadron collider are examined. Jets will play an important role in planned searches for Higgs and supersymmetry as well as the search for other new phenomena.

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1. Introduction

The CERN Large Hadron Collider (LHC) is designed to study *pp* collisions at a center-of-mass energy of 14 TeV and luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The GHz collision rate with 20 interactions per 25 ns bunch crossing places unprecedented demands on detector performance. This report will concentrate on jet physics anticipated from the two big general purpose detectors, a toroidal large hadron collider apparatus (ATLAS) and the compact muon solenoid (CMS). Two additional detectors, a large ion collider experiment at CERN (ALICE), and LHC-*b*, are designed to explore heavy ion and *b*-quark physics, respectively.

Both ATLAS and CMS have charged particle tracking a magnetic field, electromagnetic and hadronic calorimetry, and outer muon chambers. Gone are the days when major collider detectors were designed without magnets! The 7-kiloton ATLAS detector has approximate dimensions 25 m $\times$ 46 m featuring huge 0.5-T toroids, while the 14-kiloton CMS is 15 m $\times$ 22 m with a 4-T solenoid. The zeroth-order difference between the detectors is that ATLAS has a high fractional magnet cost (40%) providing good stand alone muon measurement, while the lower CMS magnet cost (25%) allows more resources to be spent on a high-resolution silicon tracker and high-performance crystal calorimetry (Fig. 1).

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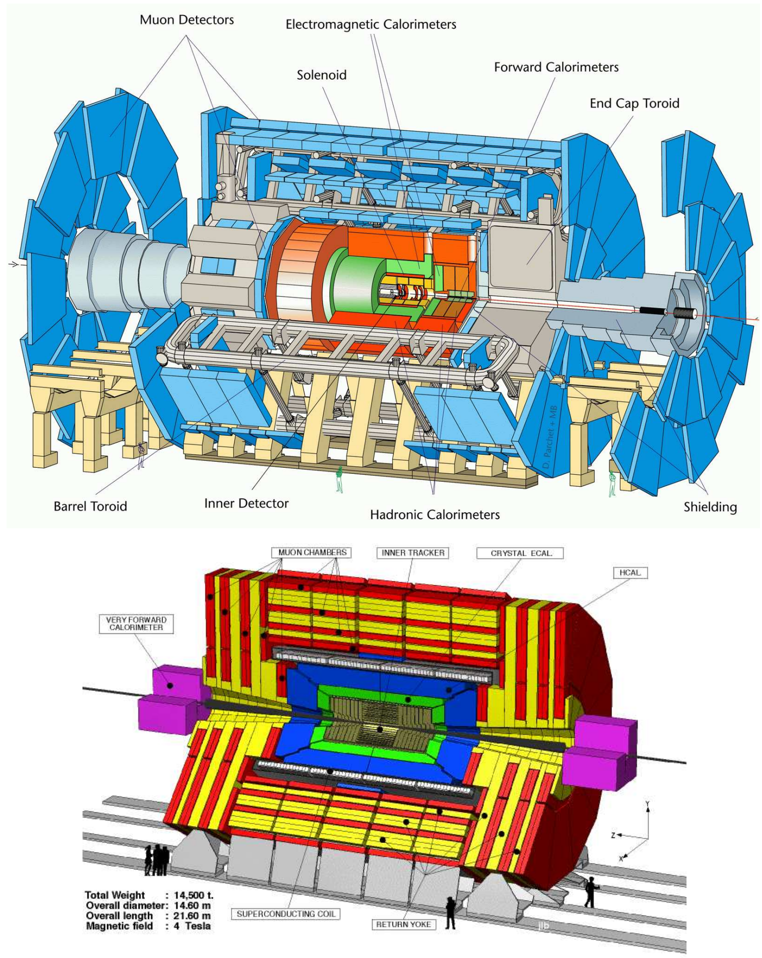

Fig. 1. ATLAS (top) and CMS (bottom) shown approximately to scale.

Jet physics is impacted by the design of the hadron calorimetry. ATLAS has slightly better energy resolution, while CMS has slightly better segmentation, resulting in comparable jet–jet mass resolution for the two detectors.

2. Event rates and triggering

The cross section for jets expected at the LHC, together with Tevatron comparison, is shown in Fig. 2. Near the Tevatron kinematic endpoint (800 GeV), the cross section is more than 7 orders of magnitude greater at the LHC. Since the LHC collision rate will also be much greater, one sees clearly that a brand new window to jet physics is opened up at the LHC.

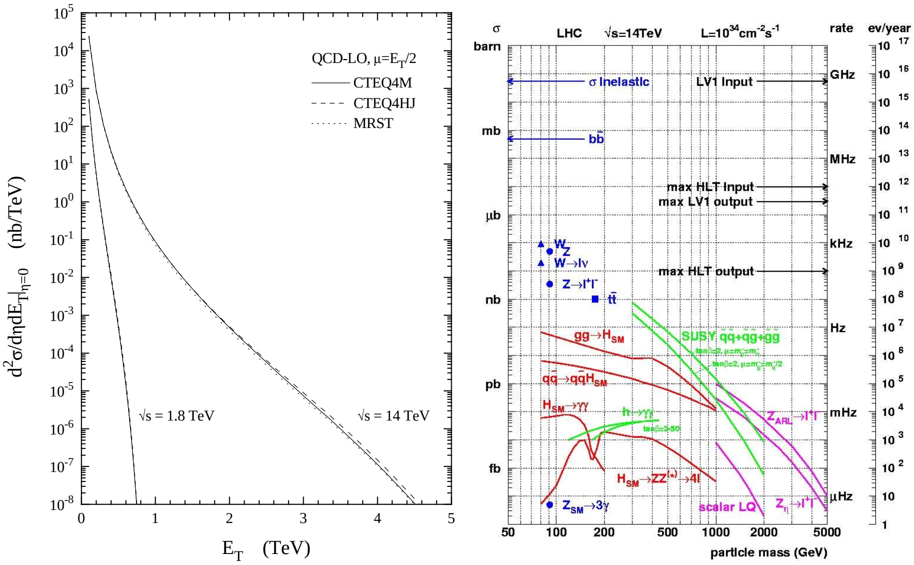

Fig. 2. Left: Inclusive jet cross section at the LHC compared to Tevatron (1.8 TeV) [1]. Right: Event rates at the LHC [2].

Both ATLAS and CMS will trigger on electrons, muons, photons, and jets individually and in various combinations, including missing transverse energy ($\not{E}_{\mathrm{T}}$) [2–3]. Figure 2 indicates the demands placed on the trigger systems. Intermediate vector bosons will be produced at kHz rates and the top quark, which presents a formidable background to almost all physics, will be produced at 10 Hz. New TeV-scale objects, on the other hand, may have rates of mHz.

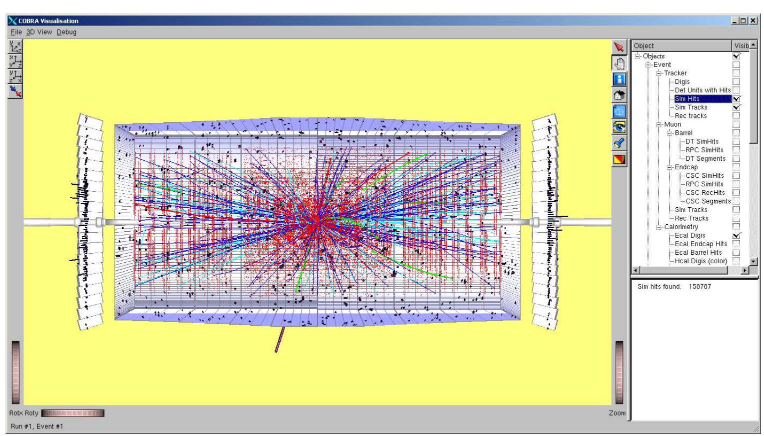

Fig. 3. Simulated CMS event with pile-up at a luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The occurrence of multiple events (pile-up) in the same 25 ns proton bunch crossing, an average of 20 at design luminosity, further complicates the events. Figure 3 shows a simulated CMS event. Figure 2 illustrates the effect of pile-up on jet–jet mass resolution using hadronic decays of W from top.

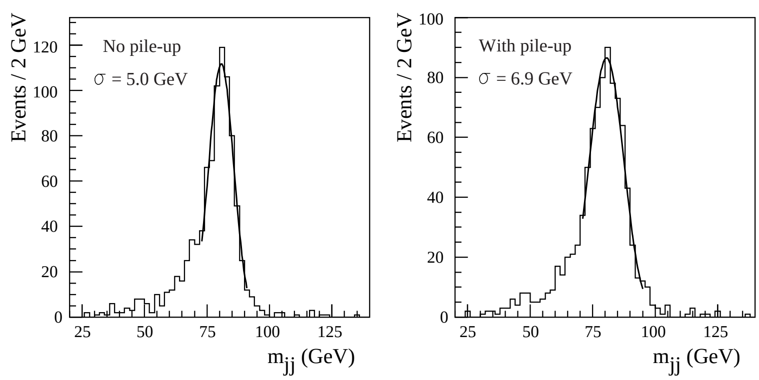

Fig. 4. Contribution of event pile-up to jet–jet mass resolution. The jets are from hadronic W decays originating from top quarks simulated in the ATLAS detector [3].

3. Targeted physics

Much work has been done to prepare for a variety of scenarios which may be responsible for the mechanism of electroweak symmetry breaking [4–5]. Jets play a major role many aspects of this physics.

3.1. Higgs

The standard model Higgs has been studied extensively theoretically [6]. The cross section (Fig. 5) is dominated by gluon fusion. Over much of the interesting mass region, the Higgs branching ratio is dominated by $b\bar{b}$. QCD backgrounds, however, make it difficult to make an inclusive measurement. An interesting possibility is Higgs production by W/Z fusion, the signature of which is two forward jets (Fig. 6).

Another interesting possibility is $t\bar{t}$ production (Fig. 7). Such events are tagged by the presence of 4 b jets.

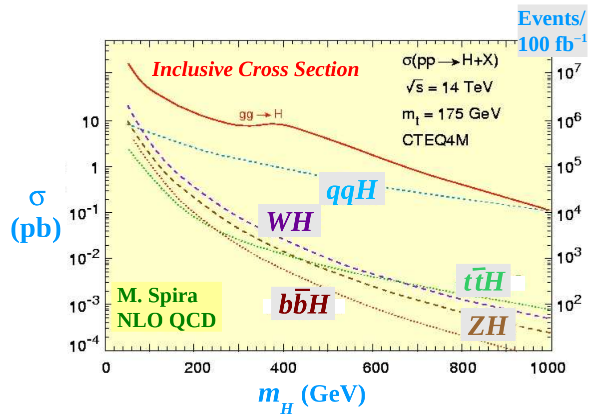

Fig. 5. Standard model Higgs boson production cross sections at the LHC calculated in next to leading order QCD [7].

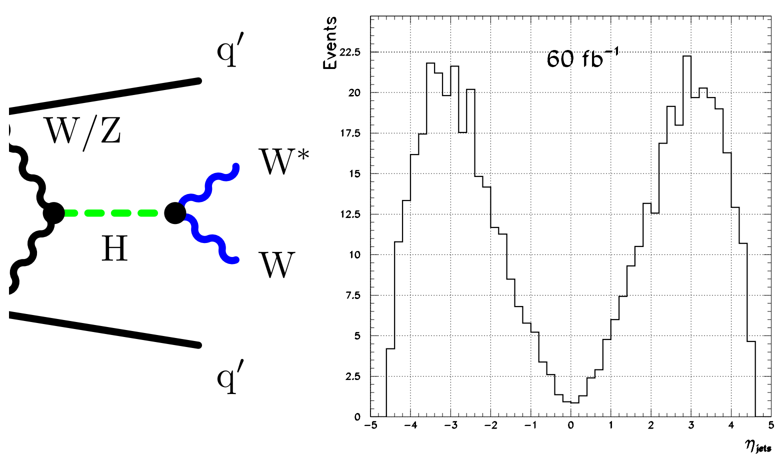

Fig. 6. Left: Diagram for Higgs boson production by vector–boson fusion. Right: Rapidity distribution of quark jets from the vector–boson fusion process [8]. Forward calorimetry is important for tagging these jets.

Supersymmetry would greatly enhance the Higgs sector, requiring the presence of at least two doublets leading to five physical states: two scalars (h and H), one pseudoscalar (A), and two charged (H^+ and H^-). The large values of $\tan\beta$, the standard coupling that specifies the ratio of vacuum expectation values of the two Higgs doublets [6], implied by LEP data, would lead to a large branching ratio into taus (Fig. 8).

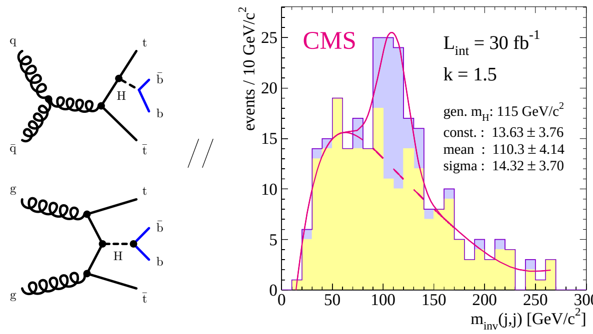

Fig. 7. Left: Representative diagrams for SM Higgs boson production via radiation from a top quark and decay into b-quarks. Right: Reconstructed jet–jet mass for a 115 GeV/c^2 SM Higgs boson produced in association with a top quark pair and decaying into $b\bar{b}$ for 30 fb $^{-1}$ [9]. The study was done with fast simulation.

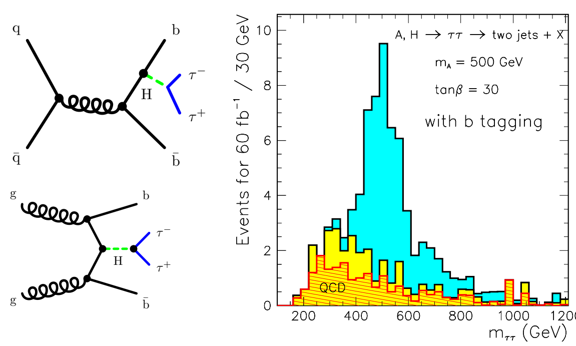

Fig. 8. Left: Representative diagrams for Higgs decays giving taus. Right: Dijet mass distribution for decay of H and A into $\tau^+\tau^-$ with both taus decaying into hadrons together with misidentification backgrounds from QCD and processes producing real taus. The plot is for m_{A}=500 GeV/c^2, tanβ=30 and 60 fb^{-1} [10].

3.2. Supersymmetry

If supersymmetry (SUSY) exists, the spectroscopy will be rich and complicated, providing material in this conference series for decades to come. Events from SUSY will be distinguished from standard model processes by having multiple jets with large missing E_{T} cause by stable neutralinos. In minimal supergravity (mSUGRA), the lightest supersymmetric particle is the stable neutralino χ_1^0. The decay chain $\chi_2^1 \to \ell^+\ell^- \to \ell^-\chi_1^0\ell^+$ (Fig. 9) may provide an early signature. Combining a tagged b-quark jet with the dilepton would allow reconstruction of the b-squark, while adding a second tagged b-quark jet would yield the gluino. Mass reach is indicated in Fig. 10.

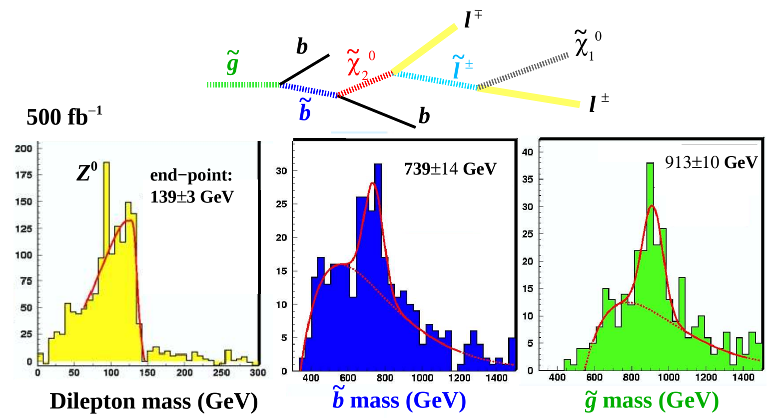

Fig. 9. Top: Gluino decay chain producing b-quarks and charged leptons. Left: Reconstructed di-lepton mass. Center: Reconstructed b-squark mass. Right: Reconstructed gluino mass. The event reconstruction is done with fast simulation and corresponds to an integrated luminosity of 500 fb^{-1} [11].

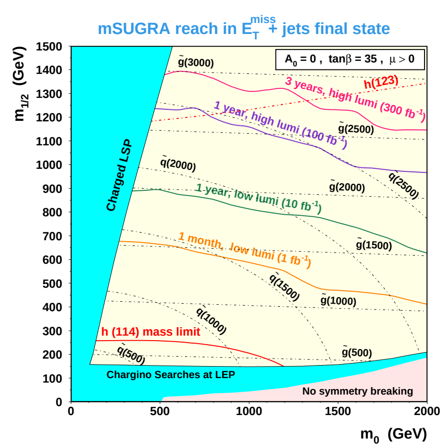

Fig. 10. Physics reach in CMS for mSUGRA Jets + missing E_{T} final state [12].

3.3. Z'

Detection of a Z' below 1.2 TeV decaying into jets is hampered by huge QCD backgrounds; it is a well-known difficult problem of triggering on an exponentially falling spectrum with a relatively poor resolution device. One can greatly reduce the time needed for discovery by prescaling the events to allow more lower E_{T} jets to be recorded (Fig. 11).

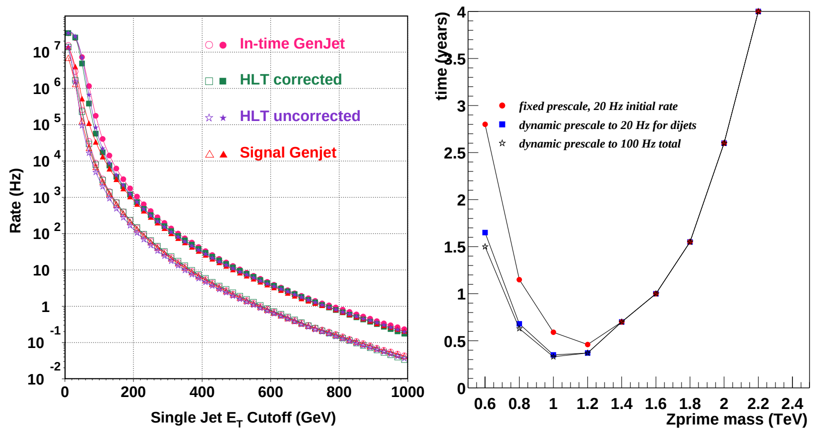

Fig. 11. Left: Corrected jet rate at startup luminosity, $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Right: Time to discover a Z' in CMS as a function of mass. Below about 1.2 TeV a potential discovery is limited by data acquisition where the events must be prescaled, while at higher masses it is rate limited [2].

3.4. Compositeness

The flavor problem has prevented the existence of any credible model of compositeness. From the experimental point of view, this provides some incentive to look to shorter distance scales, especially considering that probes with 10^4 times the energy used to discover proton structure will be available at the LHC!

Compositeness gives rise to a contact interaction (strength proportional to $s/\alpha\lambda^2$) which would effect the jet E_{T} distribution (Fig. 12). A more sensitive measurement, but one requiring a more sophisticated understanding of detector acceptance and efficiencies, comes from measuring the jet angular distribution (Fig. 12).

3.5. The unknown

While the "planned" physics is useful for understanding hardware performance and tuning the software, the true excitement from the LHC is from the possibility of new and unanticipated physics. At the LHC we must be prepared for the unexpected. This involves understanding, in as much detail as possible, QCD backgrounds from the standard model.

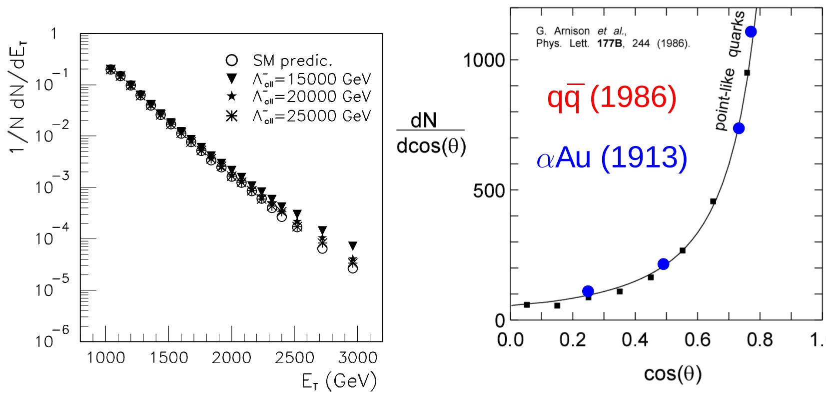

Fig. 12. Left: Deviations from the ATLAS jet spectra at high-E_{T} expected from compositeness [3]. Right: Angular distribution of jets as a search for quark compositeness with UA1, and comparison to Rutherford's famous α-gold scattering experiment which discovered the atomic nucleus [13, 14].

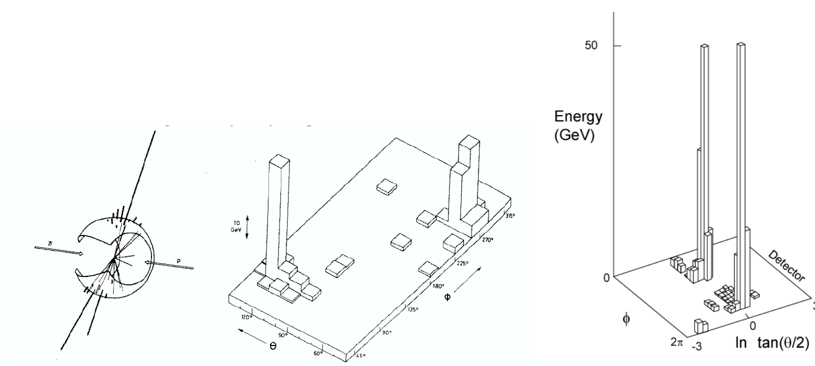

Fig. 13. First high-p_{T} jet events observed in the calorimeters of UA2 (left and center) and UA1 (right).

4. Summary and outlook

Jets are an important part of LHC physics. The "planned" discoveries of Higgs and SUSY depend crucially on good jet measurement. Any unexpected discovery such as compositeness depends on measurement and understanding of the QCD jet rates. Detector calibration, synchronization and triggering will be challenging.

My first contribution to the multiparticle dynamics conference series, was 27 years ago [15]. I was a graduate student at the time and we had just made the first calorimeter jet trigger and measurement of the jet cross section [16], hot on the heels of the high-p_T single particle measurements at the CERN Intersecting Storage Rings. A central issue that has been with us since the discovery of jets, is how to best relate a measured jet to a parton 4-vector [17]. If we are lucky, we may have an opportunity to do high-mass jet spectroscopy with high statistics at the LHC.

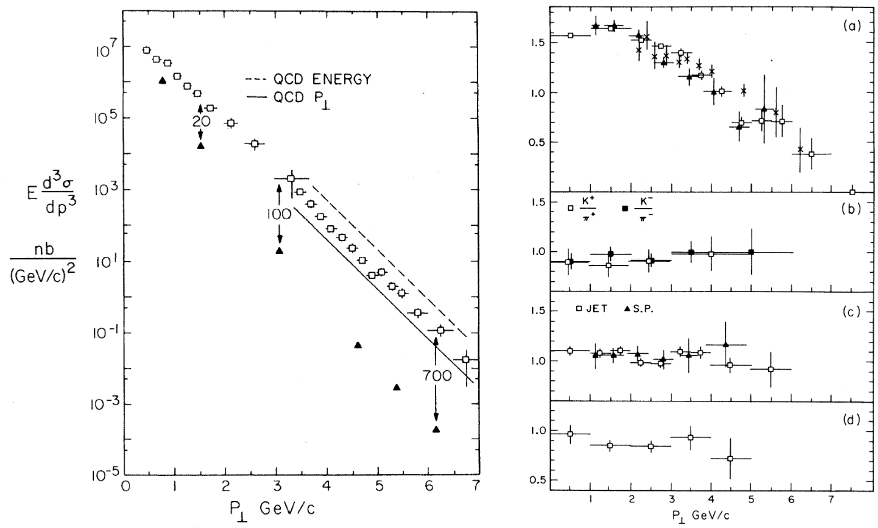

Fig. 14. Left: Inclusive jet cross measured in Fermilab E260 using the first calorimeter jet trigger, and comparison with single particles. Right: Ratio of jet cross sections induced by pions, kaons, and protons on a proton target. (a) p/π, (b)K/π, (c) π^+/π^-, $d)$ $p/\bar{p}$. Pion and kaon beams make high-p_T jets more easily than protons due to having only two valence quarks providing evidence that quarks are the source of the jets [17].

It is a pleasure to thank Matt Dobbs for providing material on ATLAS.

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