ASPECTS OF JETS AND CALORIMETRY
AT FUTURE HADRON COLLIDERS

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Invited talk given at the
ECFA Study Week on Instrumentation for
High Luminosity Hadron Colliders
Barcelona, September 14-21, 1989
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1. INTRODUCTION

Calorimetry plays an important role at existing hadron collider experiments to measure electrons, jets, and non-interacting particles from the transverse momentum imbalance. There is no doubt that this will be even more the case in the future. The physics goals require colliders with very high luminosity and energy. Fast calorimetric information will be needed for triggering and precise energy measurements to extract the physics signals.

Jets and calorimetry at future hadron colliders have been studied at several workshops on experimentation at LHC [1-3] or SSC [4,5], and it is certainly not possible to summarize the conclusions in this brief introduction. The purpose is rather to raise some of the questions which most likely will affect the design of the calorimetry for a LHC experiment.

Section 2 recalls very briefly some of the physics signals and the importance of the calorimetric measurements to detect them. Two-jet mass resolutions are discussed in Section 3. The role of triggering is touched upon in Section 4. Finally, Section 5 addresses some of the instrumental issues.

2. PHYSICS SIGNALS

The calorimetry is a major tool to measure energies and directions for electrons (and photons), jets in order to infer the 4-vectors of final state quarks and gluons, and neutrinos or other non-detected particles by the missing transverse energy ($E_T^m$) signature. These measurements are among the key elements (together with muon detection) to search for New Physics at future pp colliders which will offer the possibility to explore a very large mass
range extending into the TeV mass region. The most prominent examples are the searches for the Higgs, for new heavy W' or Z', for SUSY particles, and for quark compositeness.

The Higgs search is the central topic of many physics studies for future hadron colliders. The different production mechanisms and the experimental signatures have been analysed in detail [1-6]. A heavy Higgs ($m_H > 2 m_{\text{VBF}}$) could be searched for in the decays $H \to WW$ or $ZZ \to 4$ jets (BR ~ 56%), $H \to WW \to l\nu + 2$ jets (BR ~ 16%) or $H \to ZZ \to 2l + 2$ jets (BR ~ 3%), $H \to ZZ \to 2l\nu\nu$ (BR ~ 0.7%) or $llll$ (BR ~ 0.1%) with $l$ standing for $e$ or $\mu$. The branching ratios BR are indicative only. The 4-jet decay is experimentally not accessible because of the very large QCD multi-jet background (see Sect. 4). The mixed case with one IVB decaying leptonically and the other one into $\bar{q}q \to 2$ jets has become even much more difficult [7] as anticipated in earlier studies [2,3] which at that time assumed a top quark mass $m_t < m_W$ for the QCD background considerations (for the $H \to WW$ case). However it remains a typical test case. Its demands on the calorimetry are particularly stringent: electron and $E_T^{\text{miss}}$ capability for one IVB, 2-jet mass resolution for the other IVB, and also calorimetry at very small angles with respect to the beam line to "tag" the forward jets from the out-going quarks of the H production (IVB fusion) process [8]. Figure 1, taken from Ref. [9], illustrates the importance of the 2-jet mass resolution for retaining signal events within a given mass interval around $m_W$. The case considered is $H \to WW \to l\nu jj$ at $\sqrt{s} = 20$ TeV with $m_H = 600$ GeV. The W 2-jet mass reconstructed with a high resolution detector ($\sigma_E = 0.35 \sqrt{E} + 0.02 \ E$ and no error on the jet directions, giving $\sigma_m = 4.0$ GeV) or a detector with more modest resolution ($\sigma_E = 0.5 \sqrt{E} + 0.05E$ and direction errors of 10 mrad, giving $\sigma_m = 5.7$ GeV) are compared with the generated W line shape with $\Gamma_W = 3$ GeV. The pseudorapidity ($\eta$) distributions for the jet pair from the IVB decay and from the forward "tagging" jets are shown in Figs. 2(a) and (b) respectively, reproduced from Ref. [8]. These distributions are valid for $H \to WW \to l\nu jj$ at $\sqrt{s} = 17$ TeV and $m_H = 500$ GeV. The forward jets emerge at large $\eta$ corresponding to angles of very few degrees with respect to the beam line. It has been shown [8,9] that their measurement is important to suppress backgrounds and to constrain the transverse momentum ($p_T$) of the H. The 4 lepton decays of the $H \to ZZ$ events give the cleanest final states [9], albeit at the price of low rates. In particular the $llll$ case has been considered [10] for a very high luminosity ($5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$) LHC. It is obvious that calorimetry capable to select and measure electron pairs in such conditions would enhance the observable H rate by a factor four over a pure $\mu\mu\mu\mu$ experiment.
Reconstructed $W \rightarrow 2$-jet mass from $H \rightarrow WW$ decays ($m_H = 600$ GeV). From Ref. [9].

The second example, the search for a new heavy $Z'$, is expected [11,12] to be relatively easy compared to the Higgs search. In particular the decay $Z' \rightarrow e^+e^-$ would be clearly visible above the background (from heavy flavours, $WW \rightarrow evv$, Drell-Yan ...), as would be $Z' \rightarrow \mu^+\mu^-$. Figure 3 shows the simulation of Ref. [12] for $m_{Z'} = 1$ TeV produced at $\sqrt{s} = 17$ TeV and the detected signal after a calorimetric detection with $\sigma_E = 0.10 \sqrt{E} + 0.01 E$, 10 mrad angular error and polar angle coverage of 25° to 155° with respect to the beam line. It has been concluded by Refs. [11,12] that any attempt to detect $Z' \rightarrow q\bar{q}$ to 2 jets will require excellent resolution and good control over systematic errors for the jet measurements. However, it will be very difficult to see such a signal over the QCD 2-jet background. A further possible signature is $Z' \rightarrow WW$ in spite of the large WW continuum background.

The search for SUSY particles, and in particular for $\tilde{q}$ and $\tilde{g}$, is one of the most exciting prospects at future hadron colliders. It has been studied abundantly [1-5]. As an illustration Fig. 4 shows the calculation of Ref. [13] for the inclusive $E_T$ distribution from $q\bar{q}$ pair production ($m_q = 1$ TeV) at $\sqrt{s} = 17$ TeV and for Standard Model backgrounds (heavy flavours with $m_t = 40$ GeV and IVB single and pair production followed by decays...
Fig. 3 \( Z' \rightarrow e^+e^- \) signal before (solid curve) and after (dashed curve) detector simulation. From Ref. [12].

Fig. 4 Missing transverse energy \( E_T \) distributions for Standard Model backgrounds (curves and dots) and for a \( q\bar{q} \) signal (histogramme) with \( m_{q\bar{q}} = 1 \) TeV. From Ref. [13].

with neutrinos). The signal over background ratio can be largely improved by topological cuts on calorimetric information alone [13], even in the presence of a large (\( \sim 25 \)) number of pile-up events in the case of a very high luminosity LHC as studied in Ref. [14]. It is interesting to note [3] that a \( \eta \)-coverage of about \( |\eta| \leq 3 \) is sufficient to have only negligible instrumental contributions to \( E_T^m > 200 \) GeV at \( \sqrt{s} = 16 \) TeV, contrary to the situation at much higher \( \sqrt{s} \).

QCD 2-jet events with very large \( p_T \) jets will be the dominant feature of hard scatterings at the LHC. A rate of 1 Hz \( p_T = 0.5 \) TeV jets is expected [15,16] from the inclusive jet cross-section at central \( \eta \) for \( \Delta p_T = 100 \) GeV and \( \Delta \eta = 1 \) at a luminosity of \( 10^{33} \) cm\(^{-2}\) s\(^{-1}\). Jets with \( p_T \) of several TeV will be observed. It will be interesting to compare the measured cross-sections at high \( p_T \) with the expectations of QCD calculations. Deviations could be due to a possible manifestation of quark compositeness [17], visible only at extremely large momentum transfers. The calorimeter response to TeV jets will play a crucial role for such measurements as studied in Ref. [18]. The systematic uncertainties in the knowledge of the calorimeter linearity and in the resolution behaviour (non-Gaussian tails) have to be minimized in order to achieve a reliable measurement of very high \( p_T \) jet cross-sections.
3. **TWO-JET MASS RESOLUTION**

The two-jet mass resolution $\sigma_m$ depends on the calorimeter performance but also, among other effects, on the jet algorithm, the additional energy due to pile-up events, and errors on the jet directions. The main effects have been studied for example in Ref. [16]. Figure 5 from this study illustrates $\sigma_m/m$ as a function of $m$ for different jet definitions and for the case without event vertex information (centre of detector used as origin for the jets). The calorimeter was simulated with a lateral granularity of $\Delta \phi \times \Delta \eta = 5^\circ \times 0.05$, an electromagnetic (em) resolution $\sigma_{\text{em}} = 0.08 \sqrt{E_{\text{em}}}$, a hadronic resolution $\sigma_{\text{had}} = 0.35 \sqrt{E_{\text{had}}}$, and an em over hadronic response ratio of one (e/h = 1). The best resolution, approaching the one for an "ideal calorimeter" measuring the 4-vectors of all showering particles, would be obtained by considering all the cell energies in large cones with half-opening angles $\theta \lesssim 60^\circ$ around the jet directions. However, such an algorithm is not realistic at a hadron collider with several minimum bias pile-up events as expected at very high luminosity. Their effect is shown in Fig. 6 as a function of $\theta$. A more selective jet algorithm will have to be applied, for example a cluster algorithm as described in Ref. [16] which joins adjacent cells and then applies a total energy threshold of 10 GeV. The effect on $\sigma_m$ is shown in Figs. 5 and 6.

![Diagram](image_url)

**Fig. 5** Two-jet mass resolution for different jet algorithms (see text). From Ref. [16].

**Fig. 6** Two-jet mass reconstruction for $m = 1$ TeV as a function of the jet cone half-opening angle. The effect of minimum bias pile-up events is shown. From Ref. [16].
An interesting conclusion of Ref. [16] is also that $\sigma_m$ is not very strongly dependent on the lateral granularity, $\sigma_{m/m}$ would degrade for $\Delta\phi \times \Delta\eta = 10^\circ \times 0.1$ from 1 to 1.5% at the cell level (for $m \geq 1$ TeV) whereas the change at the cluster level would be completely negligible.

The jet energy resolution depends strongly on the $e/h$ ratio as shown in Fig. 7 from the studies of Ref. [16]. This effect, related to compensation, will be further discussed in Sect. 5.

Only sparse experimental data exist for jet spectroscopy (finding mass bumps in two-jet mass distributions) at hadron colliders. A search for IVB decays into two-jets giving a first indication of a signal has been reported by UA2 [19], and confirmed by the upgraded UA2 experiment at the recent CERN $\bar{p}p$ Collider runs. Their preliminary data [20] are shown in Fig. 8. The fitted two-jet resolution is $9 \pm 2\%$, as expected for the non-compensating UA2 calorimeter, which is not sufficient to separate the $W$ and $Z$ peaks.

![Jet energy resolution](image1)

**Fig. 7** Jet energy resolution for various values of $e/h$ response ratios. Studies done by Ref. [16].

![Preliminary two-jet mass distribution](image2)

**Fig. 8** Preliminary two-jet mass distribution from UA2 [20] at the CERN $\bar{p}p$ Collider in the mass region of the IVBs.
4. TRIGGERING

At hadron colliders the calorimeter must also provide a very fast selection of interesting events (together with a muon trigger). The main calorimetric trigger signatures consist of electrons, jets, $E_{T}^{\text{jet}}$, and combinations of them. It is well known that the cross-sections of interesting events are expected to be up to $10^{10}$ times smaller than the total pp cross-section as documented for example in Refs. [21, 22]. Soft interactions give the bulk of the pile-up events. More directly relevant for the rejection needed at the trigger level may be the jet cross-section at relatively low $p_T$. Expected 2- and multi-jet cross-sections for the LHC have been studied in Ref. [21] from which Fig. 9 is reproduced. Recalling that 1 nb cross-section means 1 Hz event rate at $10^{33}$ cm$^{-2}$ s$^{-1}$ it is obvious from Fig. 9 that a very large jet rejection (compared to typically < $10^{5}$ of present experiments) is needed in case one is aiming at a single electron trigger at low $p_T$ (order 30 GeV) from IVBs. However, the large inclusive lepton rates from heavy flavour decays [23] may anyhow preclude such a trigger. On the other hand it seems possible to trigger on low $p_T$ $e^+e^-$ pairs, enabling one to use the large rate of $Z$ production [21] for calibration purposes.

It seems important for trigger studies that reliable Monte Carlo tools become available for relatively low $p_T$ QCD jet production. They will be needed to optimize trigger schemes. Such studies will have to take into account also the detailed trigger signal response behaviour of the calorimeter in question which may be different, due to clipping etc., from the full information available at the analysis level.

5. INSTRUENTAL CONSIDERATIONS

There is a very large variety of detector aspects for calorimetry, and only a few considerations can be brought up for discussion here. A much broader coverage of the field can be found for example in the recent review of Ref. [24] which contains also an extensive bibliography.

The resolution of calorimeters for hadrons (and for hadronic jets) is strongly affected by the response ratio $e/h$ as already mentioned in Sect. 3 and Fig. 7. It is experimentally established [24] that $e/h \approx 1$ is a necessary condition to achieve a good resolution which scales as $E^{-1/2}$ without leveling off at a constant value of several percent at high energy. This condition also enables one to obtain Gaussian signal distributions without large tails as well as a linear response as a function of the energy. The best hadronic resolution has been observed for compensating calorimeters with absorber and read-out media chosen such as to
obtain directly the same response on average to em and hadronic showers and to include a measurement of the fluctuations due to the nuclear physics processes (by detecting the neutrons for example). Another approach, which has been pioneered in an explicit way by CDHS [25], is to exploit measurements of several shower samples, in particular along the shower. These samples are then given different weights as a function of their energy in order to minimize the effects of response differences and fluctuations. The resolution and the linearity obtained with this so-called weighting method are ultimately not as good as the ones for a compensating calorimeter. However they may well be adequate for the requirements of a hadron collider experiment. As shown in the case of the HERA H1 Pb and Fe/LAr calorimeter [26] such an approach may feature other desirable calorimeter qualities (like for example good em resolution and very high segmentation).

There are several parameters to tune e/h and to achieve compensating sampling calorimeters [26-30]. They act either on the response to the em shower part (choice of the absorber and detector material Z) and/or "boost" the hadronic response by detecting neutrons or γ's released in the nuclear processes, the prime example being the signal from slow recoil protons. Figure 10, adapted from Ref. [29], shows as an example the predicted e/h ratio for

Fig. 9  Integrated two- and multi-jet cross-sections. From Ref. [21].

Fig. 10  Predicted e/h response ratios for calorimeters with Pb absorbers by Ref. [29]. The data is from Ref. [31].
various calorimeters with Pb as absorber material as a function of the thickness ratio $R_d$ of absorber over active layers. Also indicated is the experimental point from a ZEUS [31] Pb-scintillator (SCSN-38) test calorimeter which has shown compensating behaviour.

It is worth noting that the jet energy response and resolution depend also on the behaviour of the calorimeter to very low energy hadrons which carry a non-negligible fraction of the jet energy [16]. This is illustrated by Fig. 11 which shows the effect of ignoring in a Monte Carlo study all particles with $E < 1$ GeV in $W \rightarrow 2$-jet decays (without the Lorentz boost expected in heavy H decays). The e/h ratio as a function of the available (kinetic) energy is shown in Fig. 12 from Ref. [24]. Non-linearities at low energy result from an enhanced hadron response due to an increased fraction of energy deposited directly in ionization.

Fig. 11 $W \rightarrow 2$-jet simulations (UA2 calorimeter) including (solid histogram) and excluding (dashed histogram) particles with $E < 1$ GeV.

Fig. 12 e/h response ratios as a function of available energy. From Ref. [24].
The jet energy resolution depends also on the depth of the calorimeter. It is expected [16] that at least 10 $\lambda_{\text{int}}$ (interaction lengths) are needed to contain TeV jets and to minimize effects on $E_{\text{T}}^m$ due to fluctuations in the starting point of the showers. Data from WA78 [32] on the containment of showers from single hadrons up to 210 GeV lend support to such conclusions. It will be an interesting question of design (and cost) optimization to share eventually the calorimetry between a high quality front part and a backing calorimeter.

There is little doubt that the rapidity coverage has to include for LHC at least $|\eta| \leq 3$ (about $5^o$ with respect to the beam axis) for $E_{\text{T}}^m$ measurements (see Sect. 2). Care in the design will have to be taken if the coverage is to be extended beyond these $\eta$, given for example the presence of supports, magnet flux return yoke, low-$B$ quadrupoles and other machine elements.

The main arguments for the segmentation are usually guided, at least for the very front part of the calorimeter, by electron identification criteria (hadron rejection, minimal isolation). Natural limits are given by the em and hadronic shower sizes [24]. Good longitudinal segmentation throughout the full calorimeter is needed for non-compensating devices in order to use the weighting method. A typical segmentation often assumed [1,5] is $\Delta\phi \times \Delta\eta = 1^o \times 0.02$ for the em part and $5^o \times 0.1$ for the hadronic part, each with about 3 longitudinal compartments. However the optimum choice of the segmentation (cell structure and geometry) will also depend also on the calorimeter type, the tolerated occupancy at high luminosity, and the overall integration into a collider detector. In this context it would be interesting to investigate for example the role of the addition of a pre-sampler detector (of a few radiation lengths) with high spatial resolution for the very early part of the em shower.

Obviously major attention has to be paid to the signal speed and the rate capability of a calorimeter at a high luminosity hadron collider. This is not only a question of charge (or light) collection time and read-out electronics, but also of the hadron shower physics. Compensation based on detection of the slow neutrons (via recoil protons) requires typical gate times of up to 100 ns, and even longer times of up to 1 $\mu$s are needed for the $\gamma$ signal from $n$-capture processes [30, 24]. Calorimeters with fast intrinsic read-out media (like scintillator or potentially silicon) may have some advantages in the LHC environement of high rates and short time intervals between bunch crossings. Typical charge collection times in liquid ionization chamber read-outs are shown in Fig. 13 from Ref. [33]. Ways of handling high rates in ionization chambers (bipolar pulse shaping) have been extensively discussed in Ref. [33], considering also additional effects like charge transfer time, detector capacitance, and minimal cable lengths. Estimates for electronic noise and pile-up effects for
Fig. 13

Induced currents (relative to LAr) as a function of collection time (gap 2 mm) for liquid ionization read-out. From Ref. [33].

LHC operation conditions have been given by Ref. [34]. Further studies and operational experiences seem particularly necessary in this important field.

Another crucial aspect of calorimetry will be the calibration. In order to exploit resolutions reaching the 1% level one needs to know the energy scale calibration of each cell at a level < 1%, and one needs to maintain this knowledge over long running periods. The method of initially calibrating all cells in a test beam is likely not to be practical for future calorimeters. Calibration methods have to be developed further which are based on strict material controls (tight tolerances on absorber and active media) and on measurements in situ (charge or light injection, radioactive sources, physics signals like $Z \rightarrow e^+e^-$, use of precise momentum measurements for isolated particles ...).

The last and by far not simplest aspect in this certainly in no way complete list of instrumental considerations is the question of radiation hardness. Expected radiation doses for an LHC experiment have been computed by Ref. [35]. Needless to say that much effort will have to be spent in order to understand which calorimeter designs will be able to cope with these conditions.

In conclusion one may observe that there remain a lot of questions to be answered. But the great physics potential of a LHC makes it very worthwhile to accept the great challenge to design an excellent calorimeter.
References


[26] H1 Collaboration, Technical Proposal for the H1 Detector, DESY, March 1986; H1 Collaboration, G. Flügge et al., these proceedings.