VI. SIGNATURES FOR GEOMETRICAL FLAVOUR INTERACTIONS AND B+L VIOLATION AT THE LHC

Contributors: J. Ellis, V.A. Khoze, A. Ringwald, F. Schrempp, C. Wetterich

VI.1. Introduction

It has recently been suggested that there may be a large non-perturbative cross-section for electroweak interactions at high energies [1 − 4]. This suggestion originated from the observation that the s-wave cross-section for electroweak baryon (B) and lepton (L) number violating interactions [5] rises rapidly with energy [1, 2], and could become large at energies comparable to the sphaleron [6] energy $M_{sp} \simeq 10$ TeV. Instanton calculations suggest [1 − 3] a sharp threshold for strong flavour interactions at $E \sim M_{sp}$, with a high mean multiplicity of weakly-interacting particles $\overline{n}_w \simeq \pi/\alpha_w = \mathcal{O}(100)$, which would be produced quasi-isotropically close to threshold. At higher energies, the s-wave amplitude would then be bounded by unitarity and other partial waves as well as (B+L)-conserving amplitudes would become strong, inducing large forward-peaked cross-sections at asymptotic energies $E \gg M_{sp}$ [3].

There remain considerable theoretical uncertainties in these non-perturbative estimates, notably whether the rapidly-rising (B+L)-violating cross-section flattens out at some energy below M_{sp}, and whether it ever reaches a sizeable fraction of the unitarity limit. Nevertheless, there is by now a consensus that analogous (B+L)-violating effects are important in a hot plasma [7], and the consequences of large non-perturbative electroweak interactions are so far-reaching and dramatic[5], that we believe our experimental colleagues should include this contingency in their planning for the LHC.

There may even be deeper analogies between the electroweak interactions and QCD at very high energies, as both are non-Abelian gauge theories with similar infrared divergences [4] and topological features. These analogies refer not only to the scattering of a few particles at large angles, which is well described by (parton model) perturbation theory, but also to the large, logarithmically-rising, total inelastic cross-section, where perturbation theory presumably fails. In this note we adopt the following working hypotheses, motivated by the above considerations [3, 4, 8]:

1) At high parton cm energies $\sqrt{\hat{s}}$ the total weak inelastic cross-section becomes approximately energy-independent
$$\sigma_w = 4\pi c_w m_w^{-2} \approx 0.1 \text{ nb} \; - \; 10 \; \mu\text{b}, \tag{1}$$
where c_w is a logarithmically-varying coefficient;

2) the asymptotic behaviour sets in abruptly above a certain threshold energy of the order of a few TeV to about 20 TeV;

3) the mean constituent multiplicity is high, typically of order $1/\alpha_w \sim 30$;

4) there is a substantial contribution of (B+L)-violating events to the total weak cross-section;

[5]For a detailed discussion of the expected phenomenology see ref. [8].

5) the inclusive differential cross-sections decrease rapidly for transverse momenta exceeding a characteristic value of order m_w.

We call processes with these characteristics Geometric Flavour Interactions (GFI) [8].

VI.2. Cross-Sections and Production Rates

We start from the working hypothesis that the parton cross-section $\sigma_w(\hat{s})$ becomes almost constant above the threshold $E_w^{\rm crit}$, with a size of order $\sigma_w^0 \simeq 0.1$ nb $-$ 10 μb [4,8]. In particular, let us assume in this paper a relatively sudden onset of geometrical QFD cross-sections for $\sqrt{\hat{s}} \geq E_w^{\rm crit}$ and approximate $\sigma_w(\sqrt{\hat{s}}) = \sigma_w^0 \theta(\sqrt{\hat{s}} - E_w^{\rm crit})$. After folding σ_w with the parton distributions (no gluons) we obtain the event rate for the production of many weakly interacting particles in proton-proton collisions, see fig. 1. The limit of detectability should be around 100 events per year. We conclude that GFI events can be seen for $E_w^{\rm crit} < 11$ TeV for the LHC if σ_w^0 is around 1 nb.

VI.3. Critical Energy and Multiplicity

Weakly-interacting particles produced by geometrical flavour interactions at high energies comprise W and Z bosons, photons, Higgs bosons, leptons, and quarks. Quarks will appear as jets and we count jets as particles.

We explore the notion that GFI events set in abruptly once the energy is high enough to produce a critical number $n_w^{\rm crit}$ of weakly interacting particles. These phenomena are presumably related to the breakdown of perturbation theory for large particle numbers, namely when $n_w \alpha_w$ becomes large. We therefore, assume $n_w^{\rm crit} \alpha_w = \nu_w$ with ν_w some constant of order one. The threshold energy can then be roughly guessed by requiring that $\sqrt{\hat{s}}$ must be large enough to produce $n_w^{\rm crit}$ particles with mass m_w without a strong phase space suppression. We therefore parametrize

$$E_w^{\rm crit} = f_w n_w^{\rm crit} m_w = f_w \nu_w m_w / \alpha_w. \tag{2}$$

Both, instanton estimates $[1-3]$ as well as a comparison with QCD [4,8] suggest values of $n_w^{\rm crit}$ and $E_w^{\rm crit}$ in the range $n_w^{\rm crit} \simeq 30$ $-$ 100, $E_w^{\rm crit} \simeq (3.5 - 20)$ TeV. We use a conservative value $n_w = 30$ for the remainder of this paper: all results can be rescaled easily for the experimentally even more advantageous case of higher multiplicity.

VI.4. Transverse Momentum and Energy

At very high parton energies the characteristic transverse momentum of the weakly interacting particles produced in GFI events presumably corresponds to the geometrical size R_w of the cloud of gauge bosons and scalars around the quarks [3,8]. Exploiting the analogy to hadronic cross-sections, we take the (inclusive) distribution $d\sigma_w/dp_t \sim p_t \exp(-R_w \sqrt{m^2 + p_t^2})$, $R_w \simeq \sqrt{2} \cdot \pi / m_w$, for the transverse momentum of a "geometrically" produced particle with mass m [8]. This gives an average transverse momentum for a produced W, $\overline{p}_t \simeq 48$ GeV [6].

[6] Throughout this paper we denote by $\overline{A}$ the average of a quantity A for events with given parton kinematics, whereas $\langle A \rangle$ denotes averages in pp scattering with the (anti) quark distributions in the proton folded in. In particular one has $\langle p_t \rangle = \overline{p}_t$.

The W, Z bosons, Higgs scalars and top quarks will not be directly observable in the detectors of future pp colliders. They decay into jets and leptons. Let l_w denote the number of *light* quarks and leptons produced in GFI events, i.e. those particles with mass much smaller than $\langle p_t \rangle$, including the bottom quark. We expect $l_w/n_w \simeq 1.5 - 2$. Due to the decay of the heavy particles the average transverse momentum per light fermion will be somewhat smaller than the average transverse momentum of a produced W, namely $\overline{p}_t{}^l \simeq 36$ GeV [8]. The average total transverse energy per GFI event (for l_w between 45 and 60) is $\overline{E}_t^{\text{tot}} = l_w \cdot \overline{p}_t^l \simeq (1.6 - 2.2)$ TeV.

VI.5. Event Topology

We estimate in fig. 2 the fraction $\langle l_{\text{centr.}}/l_w \rangle$ of the number of light particles in a central range of pseudo-rapidities, $|\ \eta\ | < \eta_0 \simeq 2.5$, corresponding to $10^\circ < \vartheta < 170^\circ$, as a function of the dimensionless quantity $\sqrt{s}/\overline{E}_t^{\text{tot}}$ for three values of $E_w^{\text{crit}}/\sqrt{s}$. We assume for an individual light fermion an essentially constant rapidity distribution in the parton cms (for more details see ref. [8]). In order to provide an impression of the angular distribution of the light fermions in a GFI event, we plot in fig. 3 the relative number of particles in the angular region $\vartheta_0 < \vartheta < 180^\circ - \vartheta_0$ as a function of ϑ_0 for a fixed value $\overline{E}_t^{\text{tot}} = 2$ TeV. We find that the average "centrality" of the events depends strongly on the parton threshold energy E_w^{crit}. This effect arises since the average gets a large contribution from partons with "threshold kinematics" for which the "centrality" of the events essentially depends on f_w [8]. If f_w is near one, very little longitudinal momentum is available. In this case we expect important activity at scattering angles around or even above 35°.

VI.6. Charged Lepton Multiplicity

The cleanest signature of these events is probably the expected high number of isolated charged leptons in each event. We expect [8] $R_L \equiv \langle \#\text{ charged leptons}/n_w \rangle \simeq 1/8 - 1/3$, leading to a mean lepton multiplicity larger than $4 - 10$ for $n_w \geq 30$. Assuming that at least one third of the produced particles are gauge bosons and at most one fifth are scalars one finds (for $n_w = 30$) $R_L > 0.16$, $\langle \#\text{ charged leptons} \rangle > 5$. Similarly, one finds [8] $\langle N_{e,\mu}/l_w \rangle \simeq 1/20 - 1/25$, giving an average of 2.4 - 3 electrons and 2.4 - 3 muons for $l_w = 60$.

VI.7. Missing Transverse Momentum and Energy

The mean number of neutrinos is comparable to that of charged leptons. For $n_w = 30$ we thus expect around 5-9 neutrinos, each with an average transverse momentum $\sim 30 - 40$ GeV. We expect that the total missing transverse momentum and the total missing energy are given by $\langle \not{p}_t^{\text{tot}} \rangle \simeq \sqrt{\langle N_\nu \rangle} \overline{p}_t^l \simeq 100$ GeV and $\langle \not{E}^{\text{tot}} \rangle \simeq 1$ TeV, respectively.

VI.8. Jet Activity

We expect [8] $\langle \#jets/l_w \rangle \approx 3/4 - 5/6$. For $l_w = 60$, a typical event contains the enormous number of $45 - 50$ jets with a total charged hadron multiplicity ~ 500. These numbers are so high that it becomes hard to resolve all the jets individually if much of the activity is in the forward direction.

Within the range of the central detector ($\eta < 2.5$), however, there should be a good chance to resolve almost all jets. The number of jets in this region can be found from fig. 2, using # central jets = # jets $\langle l_{\mathrm{centr.}}/l_w \rangle$. We see that more than 20 central jets are expected, yielding more than $\sim$ 200 charged hadrons in the central detector. If there are too many jets in the central region one may simply watch out for an impressive "jet-fireball topology" in the central region.

VI.9. Signal and Background

The main background [8] comes from the tails of strong interaction processes where leptons are produced from semi-leptonic decays of heavy quarks. Near the threshold of detectability, the effective cross section is only of order 10^{-2} pb. At the LHC, the QCD cross section for 6 widely separated jets ($\theta_{jj} > 50^\circ$) with $p_t > 20$ GeV exceeds this value by seven orders of magnitude [9].

In order to reduce this huge QCD background we propose [8] to use criteria based on total transverse energy deposition and on the expected characteristics of GFI events in the central and forward/backward regions.

Typical cuts are in the total transverse energy ($E_t^{\mathrm{tot}} > 700$ GeV) and the total missing transverse momentum ($\not{p}_t^{\mathrm{tot}} > 50$ GeV). Another possible cut would select events containing more than two clearly isolated charged leptons with $p_t > 25$ GeV in the central region. One would also require 200 charged hadrons or more in the range $5^\circ < \vartheta < 175^\circ$.

These selection criteria reduce the background from strong interaction events considerably without affecting much the GFI event rate. Subsequently, the detailed leptonic and hadronic structure of the events has to be analyzed in the central region. This strategy should result in a clean distinction from QCD events, and we conclude that GFI events stand a very good chance to be seen, even if the rate is near the threshold of detectability.

VI.10. Violation of Baryon and Lepton Number

If B+L violation becomes strong in the TeV range [1 – 3], the topology of the (B+L)-violating events will, presumably, resemble roughly the one corresponding to generic GFI events described above (for f_w not much bigger than one). It will be rather central close to the threshold energy and increasingly forward-oriented as the parton energy increases beyond the threshold. A search for B+L violation should therefore directly concentrate on quantum numbers [8] (see also ref. [10]). A (B+L)-violating interaction [5, 1] $q + q \Longrightarrow 7\overline{q} + 3\overline{l} + X$ produces on average more positrons and μ^+ than electrons and μ^-. Thus one should measure the average lepton charge asymmetries, $\langle N_{e^+(\mu^+)} - N_{e^-(\mu^-)} \rangle / \langle N_{e^+(\mu^+)} + N_{e^-(\mu^-)} \rangle$, for isolated electrons and muons (with $p_t > 20$ GeV) in the central region. The asymmetry vanishes, in principle, for L-conserving GFI events and gives, therefore, a direct measure of the relative strength of (B+L)-violating interactions. In addition, one expects the primary e^+'s and μ^+'s from a (B+L)-violating interaction to be more energetic than the decay products of the associated gauge bosons. This leads to an asymmetry in the mean energy of the fastest anti-lepton as compared to that of the fastest lepton. However, only L violation that is large compared to the (B+L)-conserving GFI background can be detected by a measurement of these asymmetries.

VI.11. Conclusions

We have discussed strategies to detect possible signals of geometrical flavour production (see points 1)-5) in the introduction) in the TeV regime. The corresponding events are characterized by the production of many $\mathcal{O}(\alpha_w^{-1}) \approx 30$ weakly-interacting particles. We have concentrated on light fermions of mass smaller than the transverse momentum, which may be produced both promptly and as decay products of W, Z bosons, etc. The associated jets and charged leptons are directly accessible experimentally.

We find the following characteristic features of "geometrical flavour interaction" (GFI) events (for $n_w = 30$):

1) For parton kinematics near the threshold ($\sqrt{\hat{s}} \approx E_w^{\rm crit}$), the events look rather central, i.e. jets and charged leptons are distributed over the whole angular range. Only partons with energies much above $E_w^{\rm crit}$ produce more forward-oriented events. At the LHC most of the activity will be in the central detector ($10° < \vartheta < 170°$).

2) The average transverse momentum per light particle is estimated to be $\overline{p}_t^l \approx 35$ GeV, and the total transverse energy is large: $\langle E_t^{\rm tot}\rangle \approx 1.6 - 2.2$ TeV.

3) We expect on average at least 3.5 "isolated" electrons or muons per event.

4) A similar number of neutrinos is responsible for an average missing transverse momentum $\langle \not{p}_t^{\rm tot}\rangle \approx 100$ GeV.

5) More than 20 jets/event, corresponding to ~ 200 charged hadrons, should be seen in the central detector.

6) In addition, we expect many events with a high charged hadron multiplicity ($n_h > 100$) in the forward and/or backward detectors ($|\,\eta\,| > 2.5$).

7) If B+L violation is relatively strong in comparison to the (B+L)-conserving GFI processes, it may be possible to observe the L violation by measuring average lepton charge asymmetries and/or $\langle E_{e^+,\mu^+}\rangle > \langle E_{e^-,\mu^-}\rangle$.

We conclude that there is essentially no background for these events. Even with a parton cross-section $\sigma_w^0 \approx 1$ nb they should be detected at the LHC if the threshold energy $E_w^{\rm crit}$ is below 11 GeV.

Acknowledgement: We thank W. Bartel, G. Schuler and J. Vermaseren for useful discussions.

Figure Captions

Fig. 1: Number of GFI events per second as a function of the (parton) threshold energy $E_w^{\rm crit}$ (taken from ref. [8]). We assume a constant cross section $\sigma_w^0 = 1$ nb for weakly interacting partons with energies above $E_w^{\rm crit}$ and a pp luminosity of $\mathcal{L} = 10^{33}$ cm^{-2}sec^{-1}.

Fig. 2: Fraction of the number of light particles in the angular region, $10° < \vartheta < 170°$, of a typical central detector, displayed versus $\sqrt{s}/\overline{E}_t^{\rm tot}$ for three representative values of $E_w^{\rm crit}/\sqrt{s}$ [8]. The values for a fixed number of light fermions, $l_w = 60$, are marked by solid circles ($\sqrt{s} = 16$ TeV) and square ($\sqrt{s} = 40$ TeV).

Fig. 3: Relative number of light particles in the angular region $\theta_0 < \vartheta < 180° - \theta_0$ versus θ_0 for fixed total transverse energy $\overline{E}_t^{\text{tot}} = 2$ TeV and the same values of E_w^{crit} and $\sqrt{s}$ as in fig. 2 [8].

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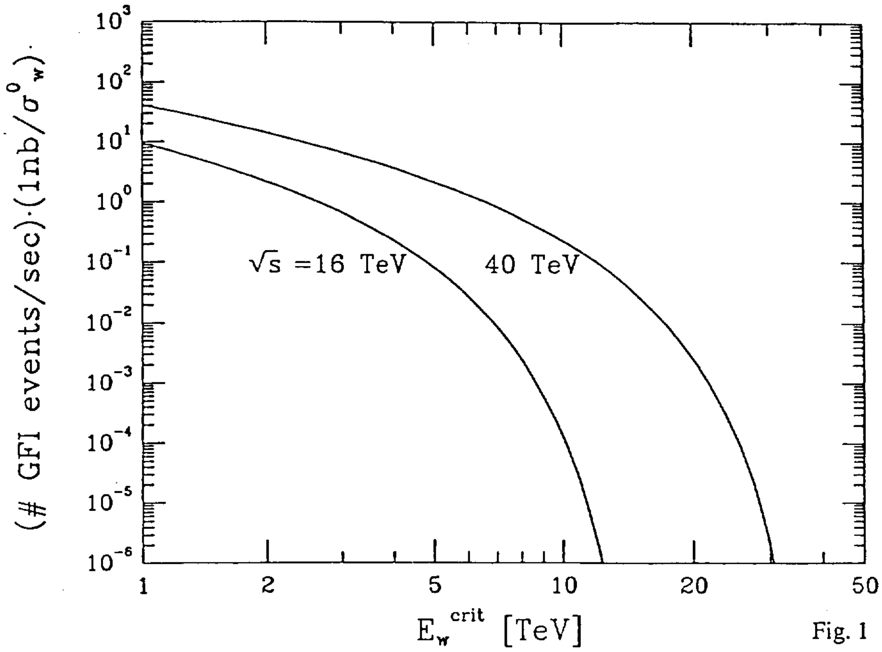

Fig. 1

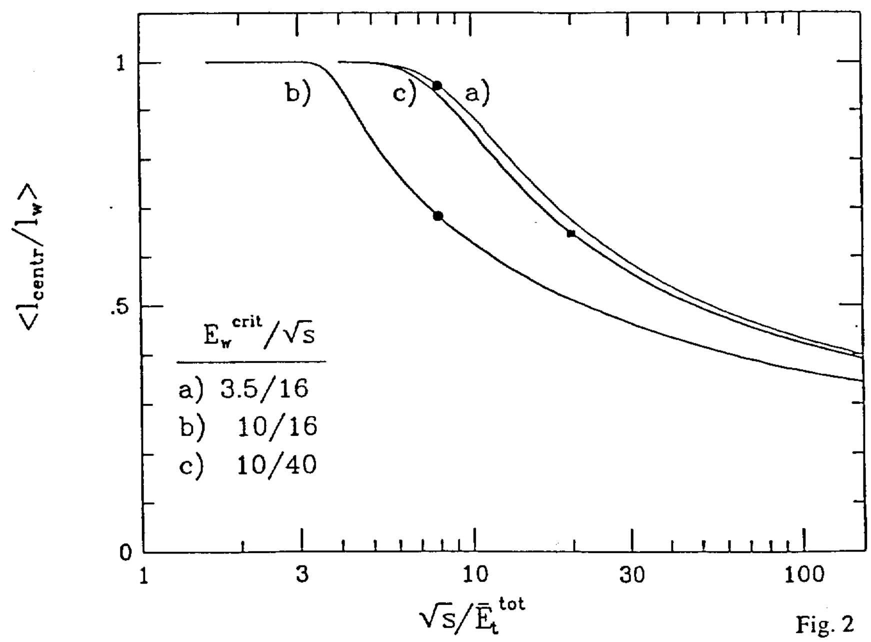

Fig. 2

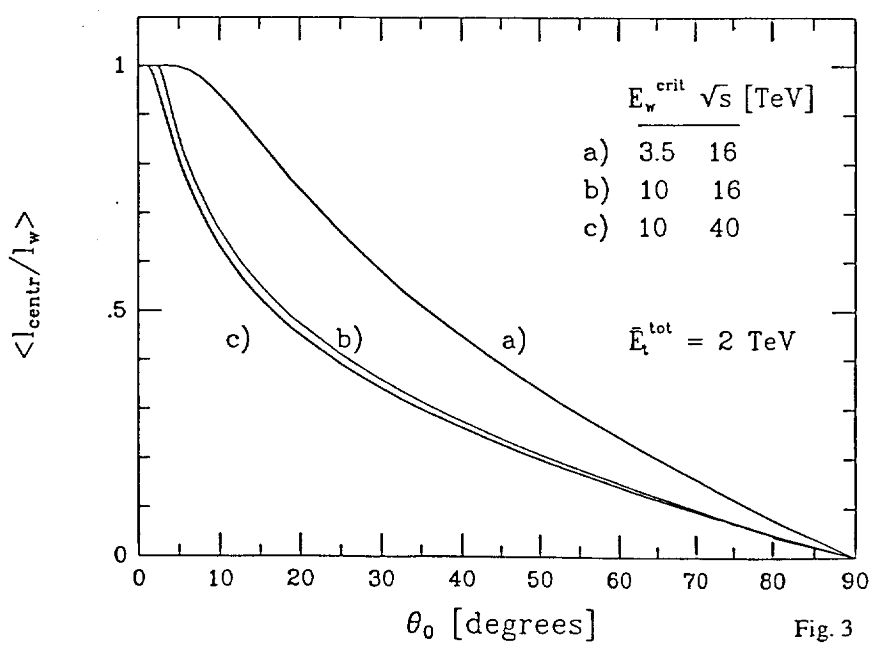

Fig. 3