Cosmic ray air showers from sphalerons

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The discovery of the Higgs boson marks a key ingredient to establish the electroweak structure of the Standard Model. Its non-abelian gauge structure gives rise to, yet unobserved, non-perturbative baryon and lepton number violating processes. We propose to use cosmic ray air showers, as measured at the Pierre Auger Observatory, to set a limit on the hadronic production cross section of sphalerons. We identify several observables to discriminate between sphaleron and QCD induced air showers.

INTRODUCTION

The recent discovery of the Higgs boson [1, 2] was the last missing piece to establish the Standard Model of particle physics as effective theory describing interactions at $\mathcal{O}(1)$ TeV. The Standard Model is predicted to give rise to non-perturbative solutions at energies of $\mathcal{O}(\alpha_W^{-1} m_W)$ TeV $\simeq \mathcal{O}(10)$ TeV which can result in the production of many quarks, leptons and electroweak gauge bosons. This production of multiple electroweak gauge bosons can occur with [3–5] or without [6–8] baryon and lepton number violating (BLNV) processes. The latter can be indicative for the existence of electroweak sphalerons [9], unstable solutions of the classical action of motion for the Standard Model's $SU(2)_L$ that are interpolating between topologically distinct vacua. Their discovery would yield direct implications for the observed matter-anti-matter asymmetry of the universe [10–12]. However, whether these processes can be observed at the LHC or a future collider remains an open question as their production cross section is largely theoretically unknown [13–18].

Phenomenologically lepton-number violating processes with many gauge bosons would give striking signatures at hadron colliders, easily distinguishable from Standard Model backgrounds generated in perturbatively describable interactions: events with many leptons, missing energy and large H_T are expected [19, 20]. Thus, the limiting factor to study non-perturbative solutions of the Standard Model gauge group is the center-of-mass energy of the initial state particles and the sphaleron production cross section. While the LHC with up to $\sqrt{s} = 14$ TeV is unlikely to be able to induce these processes, a future proton-proton collider with $\sqrt{s} \simeq 100$ TeV might be able to [21].

Intriguingly, ultra high energy cosmic rays (UHECRs) provide us with a natural source for proton-nucleon collisions, where the most energetic ones, $E = 10^{11}$ GeV, reach collision energies with nucleons in the atmosphere of $\sqrt{s} \simeq \sqrt{2m_N E} \simeq 500$ TeV. In this paper we study whether the striking signatures of BLNV processes induced by sphalerons can be observed at ground-based detection experiments, e.g. the Pierre Auger Observatories.

Previous work aimed at setting limits on new physics using cosmic ray interactions has either predominantly focused on exploiting primary and secondary neutrinos [22–25] or hadronic shower particles [26]. We instead propose to study the longitudinal shower profile of electro-magnetic particles with the fluorescens detectors at Auger. Furthermore, we show the intense imprint the hard process leaves in the shower distributions of muons at ground level.

In the following section we first discuss our analysis framework and the potential final states induced. We then compare these signatures with existing data as measured by the Auger Observatory and derive actual limits on the production cross section of sphaleron processes in the second section of this paper. In the last section we extend the analysis assuming more detailed shower data was accessible. Finally we provide a summary of our findings.

ELEMENTS OF THE ANALYSIS

Calculating processes involving multi-vector boson final states accompanied by several quarks and leptons is a very difficult task in proton-proton collisions. Not only because the phase space is very complex, but also because in our case the final state is induced by a non-perturbative hard process.

For the signal events we use HERBVI [15, 27] as implemented in HERWIG [28], specifically designed to generate BLNV processes. The BLNV process we study induces a change in baryon and lepton number $\Delta B = \Delta L = -3$ and is assumed to be

$$qq \rightarrow 7\bar{q} + 3\bar{l} + n_V W/Z + n_H H, \qquad (1)$$

where the incoming quarks and one outgoing antiquark are of first generation, and three outgoing antiquarks are of each of the second and third generations.

While it is for sphaleron-induced processes not necessary to involve electroweak bosons, it was suggested

that production cross sections are enhanced if many electroweak bosons $\mathcal{O}(1/\alpha_W)$ are produced in association with the fermions [3–5, 29, 30]. Hence we select $n_V = 24$ and $n_H = 0$ in our simulation.

To compute observables for Auger we further process the events with CORSIKA [31] version 4.7. As default interaction models we chose QGSJET [32] and GHEISHA [33]. The QCD background we compute with HERWIG as well. To make sure that HERWIG handles the signal and background collisions correctly we let CORSIKA also simulate primary collisions on its own and compare to our Herwig results. We find very good agreement, for example in the spacial number distribution of secondaries over all energies.

OBSERVABLES AND LIMITS FROM AUGER

The probability to produce a sphaleron in proton-proton collisions from high-energetic proton-cosmic rays is readily parametrised by

$$\mathcal{P}_{\text{sphal}} = A\,\sigma_{\text{sphal}}/\sigma_T, \qquad (2)$$

where $A = 14.6$ is the average atomic mass of a nucleus of air [26] and σ_T is the total cross section of a proton with the air. The numerical value for σ_T for center-of-mass collision energies $\sqrt{s}$ corresponding to EeV primaries we quote from [34] to be $505 \pm 22\,(\text{stat})\,^{+28}_{-36}\,(\text{sys})$ mb.

The Auger Observatory is a ground-based cosmic ray detector. It uses a surface detector array (SD) consisting of 1600 water Cherenkov detectors covering an area of 3000 km^2 and a fluorescence detector (FD) to study detailed properties of cosmic ray showers in the atmosphere. The combination of SD and FD allows the sampling of electrons, photons and muons at ground level and the measurement of the longitudinal development of air showers [35, 36].

The number distribution of particles in longitudonal direction can be measured by the FD system. It follows the Gaisser-Hillas function [37]. X_{max} denotes the atmospheric depth, where the number of electro-magnetic particles reaches its maximum. It can be used to measure the nature of cosmic rays [38]. In Fig. 1 we show the distribution of X_{max} for QCD and sphalerons at $E = 1$ EeV. Both distributions approximate gaussians of the same width, however, with clearly distinguishable mean values. This is important information as the width can be used to differ between protons and heavy nuclei [39]. Furthermore, we note that the mean value depends not only on the short scale physics but also on the collision energy, angle and interaction height. In Tab. I we show the expected X_{max} for different inclinations and heights for both QCD and sphaleron induced events. While the dependence on the angle is rather strong this does not pose a problem as the incident angle can be measured well by

Auger[*]. The dependence on the collision height only becomes significant when the uncertainty on the primary interaction exceeds several kilometres. The third column in each box indicates the background survival probability ϵ_B, after fixing the signal efficiency for a cut on X_{max} to $\epsilon_S = 50\%$, see the dashed line in Fig. 1. The structure of $\langle X_{\text{max}} \rangle$ encourages us to set a limit using a simple cut and count analysis. Asking for $S/\sqrt{B} > 2$ to set a 95 % confidence limit we can compute an upper limit on the
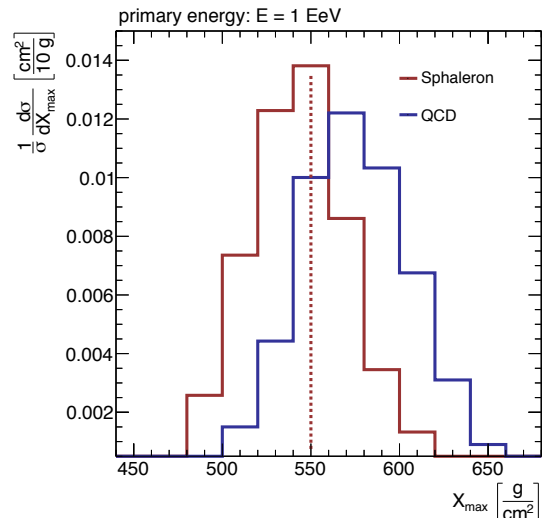

FIG. 1: Distribution of X_{max} for QCD and sphaleron induced events at 1 EeV. We showered 2000 primary events for each sample.

$\log E[eV]$	17	18	19	20
	629 ± 36	696 ± 38	757 ± 41	815 ± 42
20° at 18.3 km	679 ± 40	739 ± 42	796 ± 45	849 ± 47
	0.10	0.12	0.22	0.21
	542 ± 28	594 ± 29	641 ± 30	682 ± 33
45° at 15.0 km	580 ± 31	624 ± 31	672 ± 34	710 ± 35
	0.08	0.15	0.19	0.23
	491 ± 28	544 ± 28	590 ± 31	633 ± 32
45° at 18.3 km	529 ± 29	576 ± 32	618 ± 35	660 ± 35
	0.07	0.12	0.20	0.22
	474 ± 29	525 ± 28	572 ± 30	616 ± 33
45° at 20.0 km	513 ± 31	557 ± 32	600 ± 35	640 ± 37
	0.07	0.12	0.20	0.21

TABLE I: $\langle X_{\text{max}} \rangle$ for sphalerons (first number) and QCD (second number) as well as ϵ_B at 50% signal efficiency ϵ_S for different primary energies, inclinations and interaction heights.

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[*]We use the vertical optical depth here and not the SLANT depth.

fraction of the total proton air cross section

$$f_{\sigma_T} \leq \sqrt{\frac{4\epsilon_B}{\epsilon_S^2 A^2 N}}, \tag{3}$$

where N is the number of recorded air showers. To estimate the sensitivity of Auger we study its hybrid measurement mode. For the EeV energy range [40] found 4329 events recorded between December 2004 and April 2007, while [38] found 3754 until 2009. Another analysis [41] extracted 6744 events until 2011. We estimate that Auger has $10000 - 15000$ suitable events by now. Cutting at 50% signal efficiency yields approximately a 10–20% background efficiency. This yields a limit of $(0.0008 - 0.0011) \times \sigma_T$, e.g. $\sigma_{\mathrm{sphaleron}} \leq 500\,\mu\mathrm{b}$. Furthermore, a dedicated sphaleron analysis could also take lower energy data ($E \approx 10^{17}$ eV) into account, where the difference between sphalerons and QCD is more pronounced. Additionally Auger may design less stringent shower quality cuts streamlined for a dedicated sphaleron analysis. Auger could therefore be in a position to limit the sphaleron cross section to the level of few micro barn.

SHOWER OBSERVABLES FOR IMPROVED LIMITS

So far we have shown that Auger is able to set an upper limit on the sphaleron cross section using a simple cut and count approach for the longitudinal shower profile. However, we expect a structural imprint in each cosmic ray shower itself, which we can possibly connect to the short distance physics during the collision. It is therefore our aim in this section to identify additionally discriminating observables in air showers. These will not be simply reconstructible from the Auger detectors, but rather show the great power of cosmic ray showers as window to new physics. We hope to trigger discussion in the experimental community concerning the practical feasibility of such measurements. In the following we only use showers with zero inclination and fix the height of the primary collision to 18.3 km.

In Fig. 2 we plot the expected average energy a muon carries when reaching the Cherenkov chambers. We observe a huge difference between the sphaleron induced events and QCD. To trace back this difference we first exploit the expected energy distribution per event, see Fig. 3. QCD and sphalerons look exactly the same except for the high energy region, where the sphaleron distributions are enhanced. Indeed, as we show in Fig. 4, it is almost exclusively the highest energy muon which induces this difference. To learn more we also plot the radial energy distribution in Fig. 5. Again QCD and sphaleron events almost agree completely except for the shower core. We can therefore conclude that a sphaleron event will most likely be accompanied by a very highly

energetic muon within its shower core. Tagging this one muon constitutes a powerful method to observe sphaleron induced air showers. In addition we note that sphaleron events are significantly bigger than QCD events, see Fig. 5. While all energy of QCD events is confined in a radius of less than 10 km around the primary collision point, sphaleron events can induce air showers with radii of 100 km and more. Some of the quarks and gauge bosons in the sphaleron decay can have large transverse momenta. Although the flux of muons is small in the
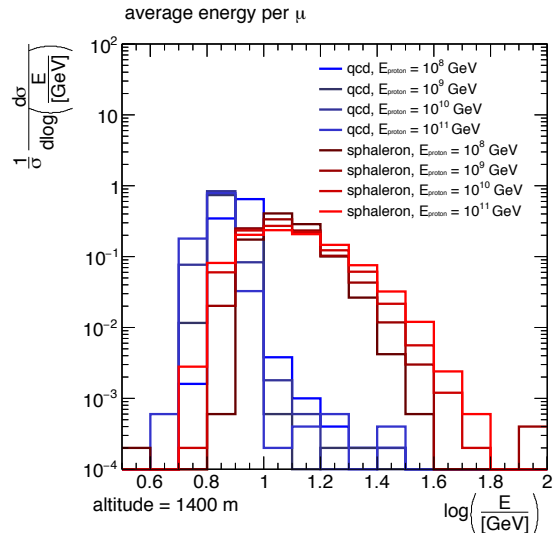

FIG. 2: Expected average energy of a muon at the altitude of Auger for different primary energies. Sphalerons in red and QCD blue.
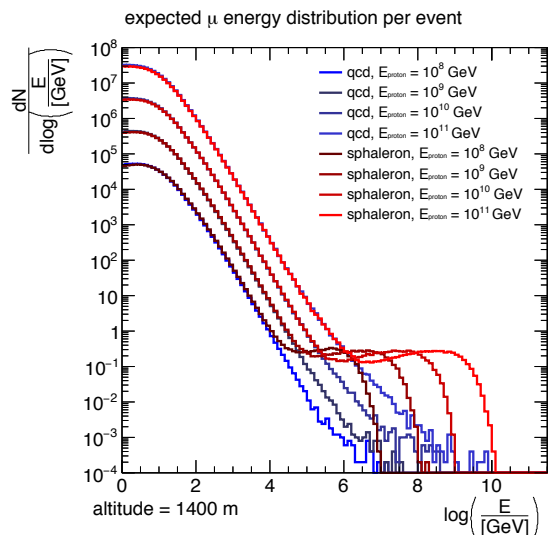

FIG. 3: Expected energy distribution per event for muons.

most outer part of the air shower, it can be used as a smoking gun signature for sphalerons.

While the former observables are difficult to measure, as they are relying on the experiment's ability to measure the muons' energy, their structure is rather simple. Let us now assume that we have a perfect detector layer on the ground, able to measure the spatial and energetic distribution of all muons of the air shower. To search for structural differences we can cluster the muons with a jet algorithm, a very promising strategy at the LHC [42]. We use an anti-k_T algorithm in spherical coo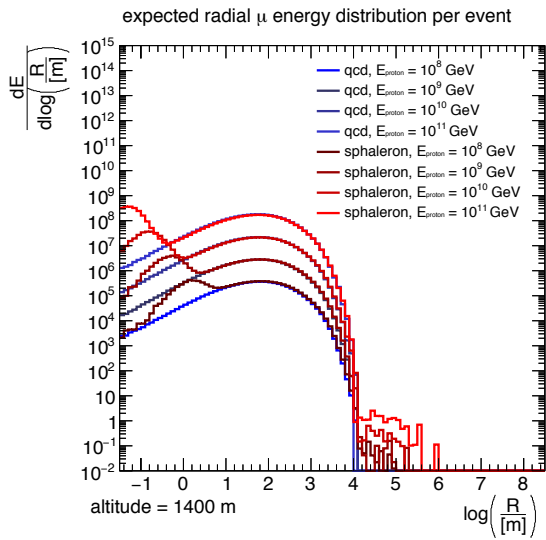rdinates as implemented in FastJet [43] with radius parameter $R = 0.2$. This choice guarantees good performance in the forward region as well as circular jet shapes when projected onto a sphere. However, due to the practical necessity of including a thinning procedure during air shower evolution[†], we are confronted with a structural problem: the thinning algorithm (over)simplifies the kinematics of soft muons.
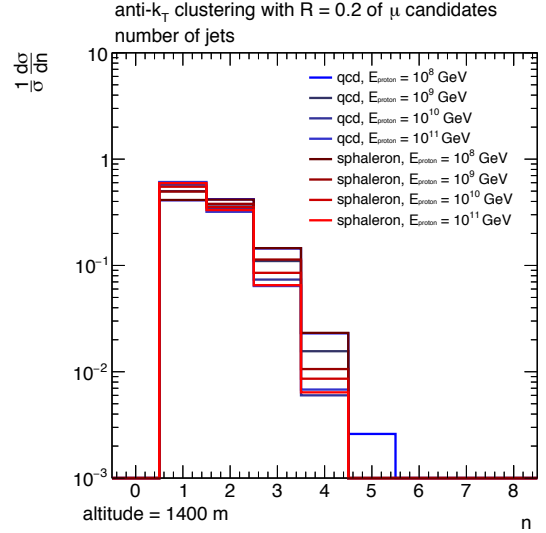

FIG. 4: Distribution of the most energetic muon in sphaleron (red) and QCD (blue) events.

FIG. 5: Radial energy distribution.

FIG. 6: Number of jets from anti-k_T $R = 0.2$ jet clustering algorithm.
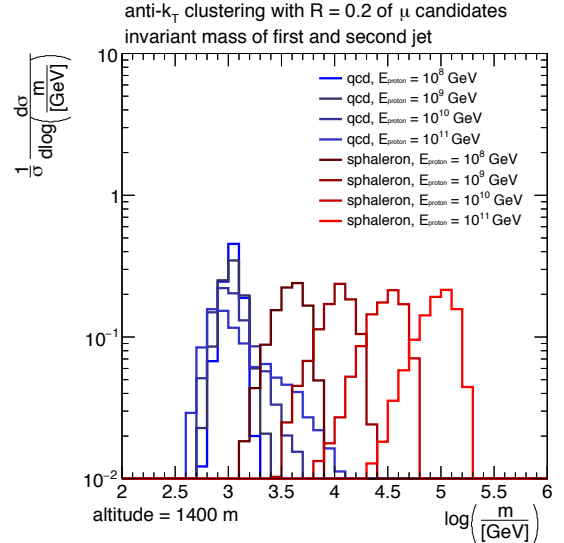

FIG. 7: Invariant mass of the sum of the first and second leading jet in energy.

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[†]We process several thousand events per run.

To avoid a strong sensitivity of our observables to badly modelled soft particles, we only allow muon clusters with $E > 10$ GeV to be recombined into jets.

In Fig 6 we show the number of muon-jets, an observable with sensitivity to decay structure. However, we can observe no difference between both hypothesis. The situation changes once we sum over the two[‡] leading jets in energy and compute the invariant mass, see Fig 7. Obviously, there is a strong correlation between this observable and energy distribution of the hardest muon in Fig. 4.

CONCLUSIONS AND OUTLOOK

Using $X_{\max}$, a well known air shower observable, we are able to set an upper limit on the sphaleron cross section $\sigma_{\mathrm{sphaleron}} \leq 500\,\mu$b assuming an amount of $10000 - 15000$ events by now. We encourage the experimentalists to perform a dedicated sphaleron analysis which might set even more stringent limits of the order of several μb.

We introduce new air shower observables connected to the energy distribution of the muons and show that sphaleron events most like have one very hard muon in their shower core. Any experiment to measure these hard muons could help to identify sphaleron events in air showers. A second observable we identified to provide a strong discrimination between sphaleron and QCD events is the radial size of the air shower.

In the last part of the paper we use jet clustering, a technique well developed in collider physics, on air shower muons. We demonstrate that we can recover the powerfull discriminating behaviour observed for the energy distribution before. However, from a technical point of view the thinning algorithm poses an obstacle. Because the algorithm is computer wise neccessary we propose an enhancemnt, where, for example, the particles are not just dropped but clusterd to ghost particles to have directional information available as well. This, however, is clearly a field of further study.

We hope to initiate discussion in the community about the technological feasibility of such measurements. Even if one eventually concludes that the Auger Observatory will not be able to exploit these observable, it might be intriguing to use the wide and densely packed coverage of smart phones [44] to search for non-perturbative solutions of the Standard Model.

[‡]Summing over more jets does not change the result any further.

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