Search for Sphalerons in Proton-Proton Collisions

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Abstract

In view of new possibilities becoming more realistic with FCC design and of recent promising results regarding $(B + L)$-violating processes detection we concentrated our research on generation and analysis of sphaleron transitions. The existence of instanton and sphaleron solutions which are associated with transitions between different vacuum states is well known since 1980s. However first calculations of instanton rate killed any hope to detect them even at very high energies while the calculation of sphaleron transitions rate is a tricky problem which continue being widely discussed. In our research we used HERBVI package to generate baryon- and lepton-number violating processes in proton-proton collisions at typical energies 14, 33, 40 and 100 TeV in order to estimate the upper limit on the sphaleron cross-section. We considered the background processes and determined the zero background regions.

1 Introduction

The non-Abelian nature of a Yang-Mills theory leads to a topologically nontrivial vacuum structure with an infinite number of ground states, which can be enumerated by Chern-Simons numbers N_{CS}. The transition between different vacuum states [1] leads to the baryon and lepton number violation in electroweak Standard model. One can easily find the relation between lepton and baryon numbers variation $\Delta(B + L) = 6N_{CS},\ \Delta(B - L) = 0$.
The gauge-Higgs system is similar to a particle in the periodic potential (see Fig.1). An **instanton** is a localized, finite-action solution of the Euclidean field equations, which describes the tunneling event between vacua with different Chern-Simons numbers. There is also the second - static, unstable, finite-energy solution, known as **sphaleron** - which describes the transitions in a classical way possible only at high energies. The height of the barrier between different vacua at zero temperature is equal to the static energy of the sphaleron solution:

$$E_{sph} = \frac{2m_W}{\alpha_W} B \left(\frac{m_H}{m_W} \right) \approx 9 \text{ TeV} \tag{1}$$

where m_W, m_H are W- and Higgs boson masses, $\alpha_W = \frac{g^2}{4\pi} = \frac{1}{29}$ - electroweak constant, B - a tabulated function.
Sphaleron can be also considered as an unstable configuration of fields, which decays to the vacuum by emission of many particles (see Fig.2).

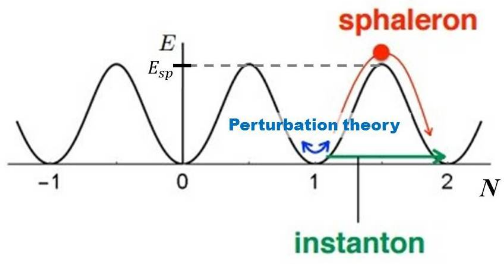

Figure 1: Energy density of the gauge field as a function of Chern-Simons numbers

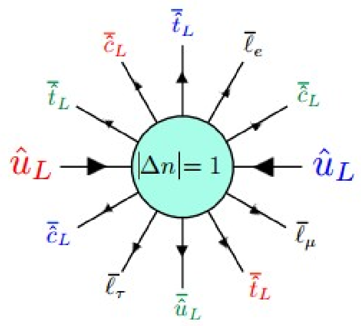

Figure 2: Graphical representation of the Stadard Model electroweak process, referred to as a sphaleron. The simplest type of sphaleron, pictured, changes baryon number by 3 units

2 Sphaleron at colliders

In analogy to the quantum-mechanical results for a particle tunneling under the potential barrier between different states, one can estimate the instanton tunneling probability $\sigma_{inst} \propto \exp\left(-\frac{4\pi}{\alpha_W} \sim 10^{-170}\right)$, which is unobservably small. The amplitude is expected to be enhanced when the energies approach E_{sph}, since at energies above sphaleron the system can in principle evolve from one vacuum state to another in a classical way. We can treat a sphaleron at collider in the following way:

$$q + q \rightarrow 7\overline{q} + 3\overline{l} + n_B W(Z) + n_H H \tag{2}$$

The amplitude of Baryon and Lepton number violating (BLNV) process increases when it involves a large number of gauge and Higgs bosons. The BLNV process (2) can not be described in terms of Feynman diagrams (is non-perturbative), but still it is possible to estimate its rate within the instanton "perturbation theory" [3], which leads to the following expression for the BLNV cross section:

$$\sigma_{sph} \propto \exp\left[\frac{4\pi}{\alpha_W} S\left(\frac{E}{E_{sph}}\right)\right] \tag{3}$$

The function S is called the suppression factor, whereas its expansion is known only for low energies ($E << E_{sph}$) [4]. The estimation of boson multiplicity in the same region of energies leads to the following results:

$$\overline{n}_B \sim \frac{3}{2}\frac{\pi}{\alpha_W}\left(\frac{E}{E_{sph}}\right)^{4/3}, \quad \frac{n_H}{n_B} \sim \frac{1}{16} \tag{4}$$

The instanton approach breaks down at energies close or higher than the spahleron, because of the suppresion factor expansion incorrectness, when E/E_{sph} is no longer small, and the unitarity violation due to the exponential growth.
Another method to calculate sphaleron cross section (Tye and Wong (TW) approach [2]) is to consider the sphaleron transitions modelled by a one-dimensional Schrödinger equation. It was shown that there is no any further exponential suppression since the energies become higher than E_{sph}, the obtained cross section result still allows to calculate the value scaled by unknown constant. The main prediction of the research based on this approach [5] is the real possibility of sphaleron detection at FCC energies (maybe even at HL-LHC). Such a powerful statement renewed the interest toward the sphaleron study and stimulated our research, since we want to have a look at these processes within numerical methods based on instanton approach.

3 Simulation of sphaleron process

In order to simulate a sphaleron process we used HERBVI [6] - hard-process Monte Carlo event generator interfacing to HERWIG, which is a general-purpose Monte Carlo event generator (version 6.5). The BLNV process generated by HERBVI corresponds to the transition between closest vacuum states: $\Delta B = \Delta L = -3$ and it is considered in terms of reaction (2) for valence quarks only (u or d quark) with a flat parton level cross section. We should emphasize the fact that HERBVI does not allow us to calculate the magnitude of sphaleron cross section, but still it provides us possibility to investigate the properties of events. In order to continue with the qualitative and statistical analysis of generation results we changed the HERBVI output to the HepMC format. The advantage of using HERBVI+HERWIG is that one can control:

– parton distributions. Initially there were three internal HERWIG sets [7] of PDFs, but we also managed to interface it to LHAPDF library (the latest version - 6.1)

– boson multiplicity n_B. The default distribution is a fixed value, but it is also possible to apply a normal distribution modelled on the leading order BLNV matrix elements.

– process type - BLNV (sphaleron) process or multi-W (B+L conserved) process (consider only qq interaction, since the $\bar{q}\bar{q}$, $q\bar{q}$ are much smaller in magnitude):

$$q_1 + q_2 \to q_3 + q_4 + n_B W(Z) + n_H H \tag{5}$$

4 Simulation results

It was important to check the correctness of HERBVI generation as well as distinction of the results one can get applying different conditions. Hence we would like to discuss in this section basic HERBVI running modes. As it was mentioned earlier, we can control in HERBVI parton and boson distributions. One can see on the Fig.3 that there is an evident difference between modern (LHAPDF) parton distributions and the old one (MSTW1998), when the difference between modern PDFs themselves is small enough to choose any of them without expecting any noticeable influence.

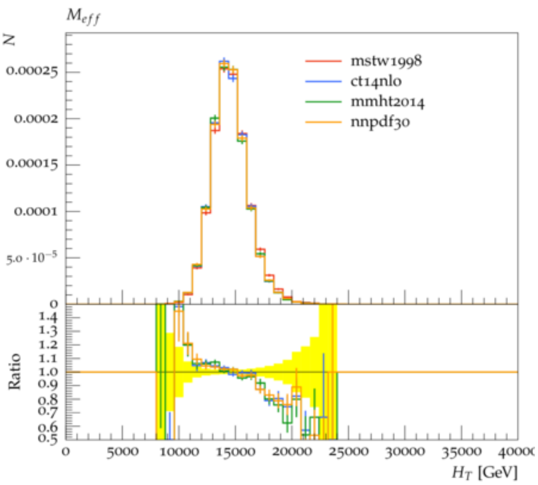

Figure 3: Distribution of the total energy of the events for different PDFs

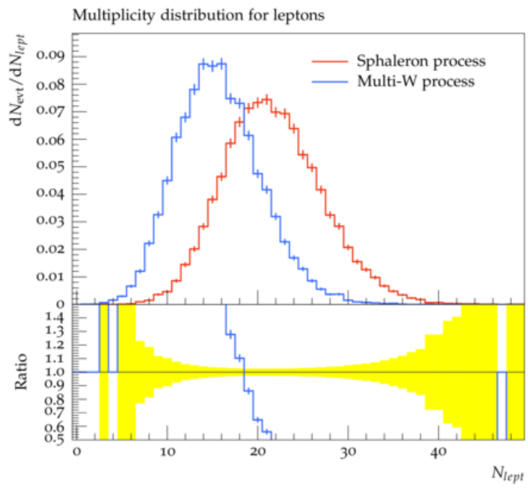

Figure 4: Distribution of lepton multiplicity in events for two different HERBVI running modes

Another important question is how the boson multiplicity influences the generation, because two modes are possible in HERBVI. First one is for fixed number of bosons, since we don't have any theoretical prediction for sphaleron cross section, it's quite natural to use the simplest model we can. We expect a process with a huge number of produced bosons and we know the estimation of $n_B \sim 1/\alpha_W \approx 30$ (see results on Fig.(6)). On the other hand the instanton approach leads to the energy dependence of boson multiplicity (4). The main idea of instanton approach is to use the perturbation theory for BLNV process (2) and to calculate the cross section and other parameters in leading order in the electroweak coupling α_W, that's why the resulting model is called LOME (leadig order matrix element) (Fig. (5)). Since the boson multiplicity increases with the collision energy, it becomes easier to distinguish signal for higher energies, because there are not any other observable processes with such a big number of leptons in the end.

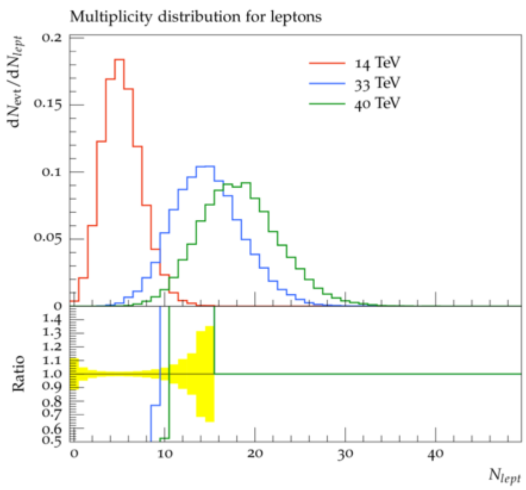

Figure 5: Distribution of lepton multiplicity in events for differen energies in case of LOME number of bosons

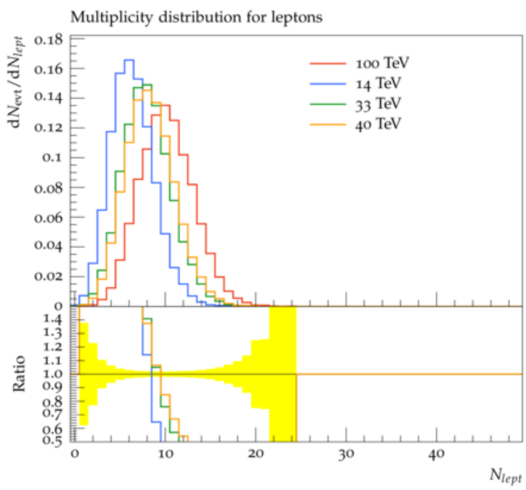

Figure 6: Distribution of lepton multiplicity in events for differen energies in case of fixed number of bosons ($n_B = 30$)

5 Cross section limits

The distributions we got allow us to carry out a qualitative analysis and put the limits on the sphaleron rate. We expect it to be possible to detect sphalerons at high energy proton-proton colliders, therefore we should know how the background looks like. The main sphaleron characteristic is the huge number of bosons resulting in huge number of leptons. The possible backgrounds are multi-W(Z) production and multiple top quark production processes. HERBVI can generate SM multi-W processes (5) and as we see (Fig. 4) the distributions of final particles (leptons) are similar for sphaleron and multi-W processes with a small shift to the region of higher lepton numbers for sphalerons, but the difference is so small, that it should be very difficult to separate signal and background. On the other hand it is possible to calculate multi-W production and multiple top quark production in terms of perturbation theory for numbers ≤ 6 and then extrapolate the data. We see (Fig. (7, 8)) that the cross section is decreasing with the growth of W-boson and top quarks number, that allows us to expect negligibly small cross section for such kind of processes at $n_B \sim 10$ (more detailed explanation can be found in [8,9]).

In table 1 we indicate the cutting points for lepton numbers at different energies and the corresponding acceptance (we plot the lepton distribution provided that $p_T > 25$ TeV, $|\eta| < 2.5$), the integrated luminosity is supposed to be $L = 3000 fb^{-1}$. We assume zero background, thus the 95% confidence level upper limit for number of events gives us $s_{upl} \sim 3$ evt (note: the estimation is made by frequentist approach without systematic uncertainties for simplicity). The last two columns of the table 1 include the cross section upper limit for sphalerons and

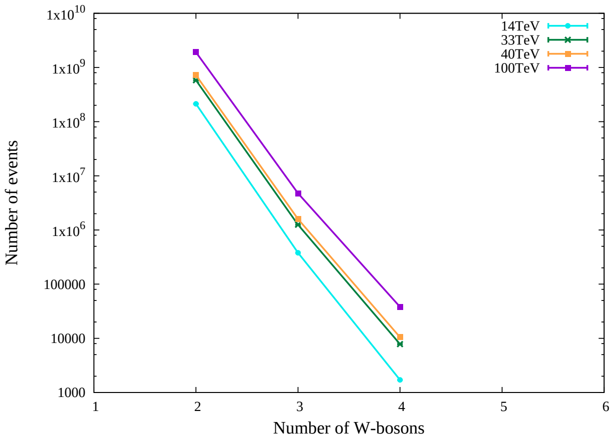

Figure 7: Dependence of multi-W process number of events on number of Ws for different energies. Integrated luminosity is assumed $3000 fb^{-1}$.

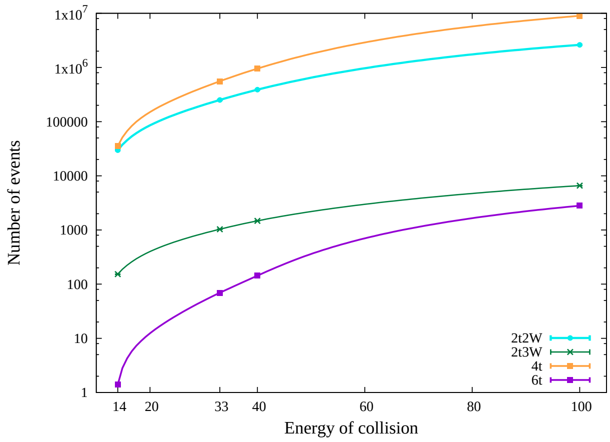

Figure 8: Dependence of different multiple top and multi-W process number of events on energy. Integrated luminosity is assumed $3000 fb^{-1}$.

the values calculated in [5], which are obviously excluded within our assumptions. In fact the magnitudes for sphaleron cross section in the last column can be substantially reduced, because they contain an unknown factor p, which was fixed by authors equal to 1, but nobody forbids it to be $\ll 1$.

Table 1: Upper limit for sphaleron cross section at different energies

E [TeV]	cuts	Acceptance	σ_{upl}, pb	σ_{sph}, pb [5]
14	6	0.439	$2.27 \cdot 10^{-6}$	$41 \cdot 10^{-3}$
33	10	0.979	$1.08 \cdot 10^{-6}$	300
40	10	0.998	$1.013 \cdot 10^{-6}$	-
100	12	1	$1.00 \cdot 10^{-6}$	$141 \cdot 10^{3}$

6 Conclusions

Sphaleron transitions provide the $(B + L)$-violation in Standard model and are of a great interest for future collider physics, since they can only be observed in high energy proton-proton collisions. The sphaleron process rate is unknown, but it is still possible to study their properties. We used HERBVI for the sphaleron simulation, its output was modified to the format common for collider physics (HepMC) to continue detector simulation and further statistical analysis of the HERBVI results. The background simulation was performed and it was shown that one can confidently consider zero background for the region where the produced lepton number is higher than 6 at 14 TeV, 10 at 33-40 TeV and 12 at 100 TeV. A qualitative analysis of sphaleron process was carried out, the influence of parton and boson distribution was considered, the upper limits for the cross section were set.

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