Search for Sphalerons in Proton-Proton Collisions

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Abstract

The electroweak sector of the Standard Model accepts solutions which violate baryon- and lepton-number. These sphalerons are associated with transitions between topologically different vacuum states. Sphaleron transitions can occur at hadron colliders, and while the magnitude of their cross-section is unknown, it is expected to be enhanced with energy and multiplicity of additional gauge bosons. In this work we used the HERBVI generator to study the properties of sphaleron processes at the energies of interest for FCC-hh colliders (14, 33, 40 and 100 TeV). After estimating the dominant backgrounds from multi-top and W-boson production with Madgraph5_aMC@NLO, a background free signal region is defined. Upper limits at 95 % confidence level on the cross-section of sphaleron transitions ranging from $2.27 \cdot 10^{-6}$ pb at 14 TeV and $1.00 \cdot 10^{-6}$ pb at 100 TeV are obtained.

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 leads to the baryon and lepton number violation in electroweak Standard Model [1]. One can 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 between vacua with different Chern-Simons numbers. There is also a 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 considered as an unstable configuration of fields, which decays to the vacuum by emission of many particles (see Fig.2).

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

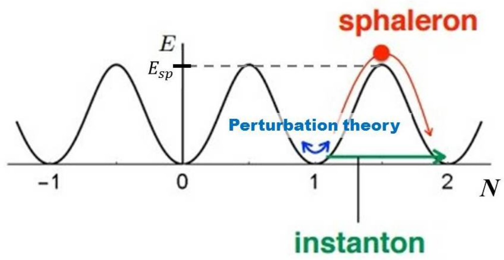

Figure 1: Energy density of the gauge field as a function of Chern-Simons numbers

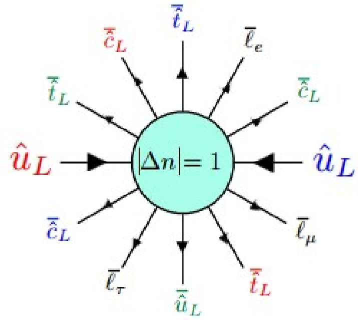

Figure 2: Graphical representation of an electroweak sphaleron transition

evolve from one vacuum state to another in a classical way. At colliders we expect a sphaleron transition to give us the following Baryon and Lepton number violating (BLNV) process:

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

The amplitude of it increases when it involves a large number of gauge and Higgs bosons. This process can not be described in terms of Feynman diagrams (is non-perturbative), but attempts to estimate its rate have been made 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, and its expansion is known only for low energies ($E << E_{sph}$) [4]. The estimation of the boson multiplicity 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 to or higher than the sphaleron, eventually violating unitarity.

Another method to approximate sphaleron cross section [2] considers the sphaleron transitions modelled by a one-dimensional Schrödinger equation. It was shown that there is no further exponential suppression at energies 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.

3 Simulation of sphaleron process

In our study 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). HERBVI generates the BLNV process (2) corresponding to the transition between closest vacuum states: $\Delta B = \Delta L = -3$ initiated by 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 provides us with the 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

As it was mentioned in the previous section, 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.

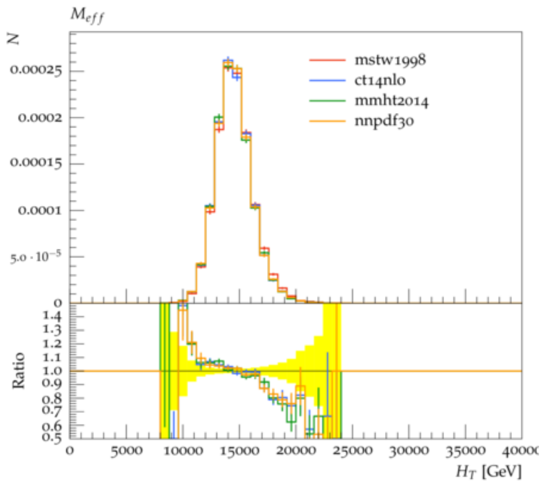

Figure 3: Distribution of the total energy of the events for different PDFs

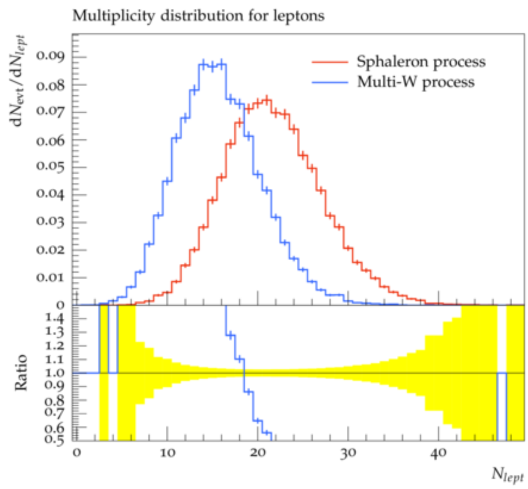

Figure 4: Distribution of the lepton multiplicity for two different HERBVI running modes

Another important question is how the boson multiplicity influences the generation, since there are two possible modes for it in HERBVI. In the first mode the average number of bosons per event is fixed. We expect 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)). The second mode is based on the instanton approach, calculating the cross-section and other parameters at leading order in the electroweak coupling α_W. The resulting model is called LOME (leadig order matrix element) (Fig. (5)). It leads to an energy dependence of the boson multiplicity. 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.

5 Cross section limits

We expect it to be possible to detect sphalerons at high energy proton-proton colliders, therefore we should know how the background looks like. A striking feature of sphaleron events is the large number of bosons they are accompanied by, resulting in a large number of leptons. The possible backgrounds are multi-W(Z) production (which can be generated with HERBVI (5)) and multiple top quark production processes.

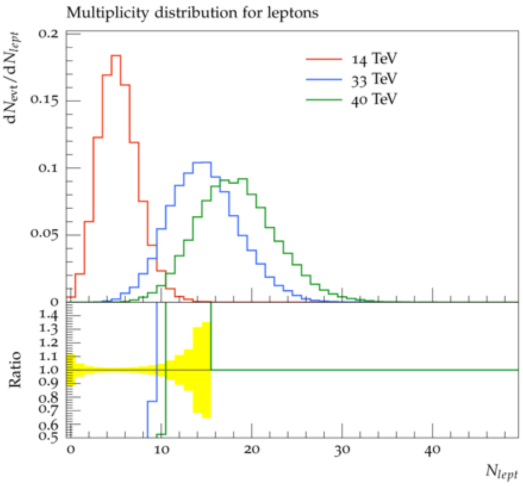

Figure 5: Distribution of the lepton multiplicity at different collision energies within LOME model for n_B

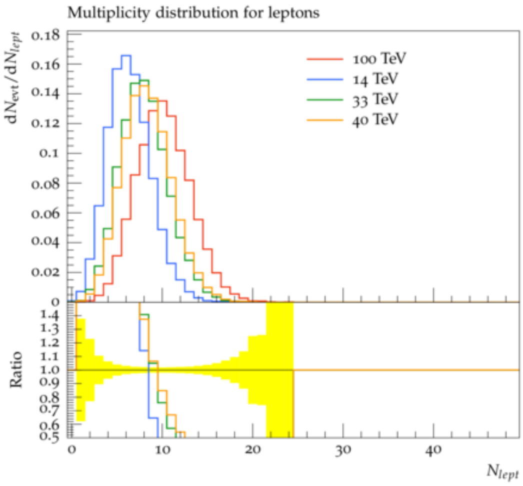

Figure 6: Distribution of the lepton multiplicity at different energies in case of fixed number of bosons ($n_B = 30$)

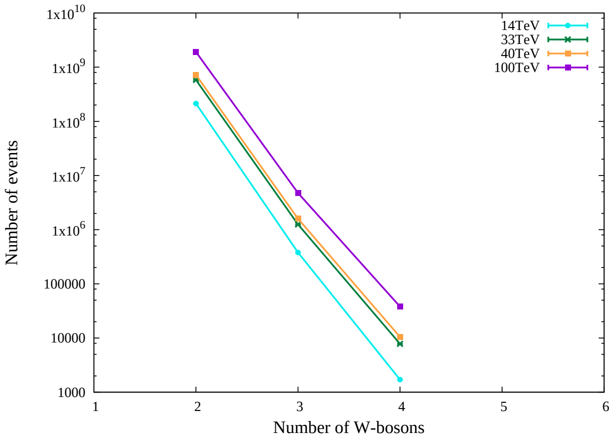

Figure 7: Dependence of multi-W process number of events on number of Ws for different energies. Integrated luminosity is assumed $3000 fb^{-1}$.

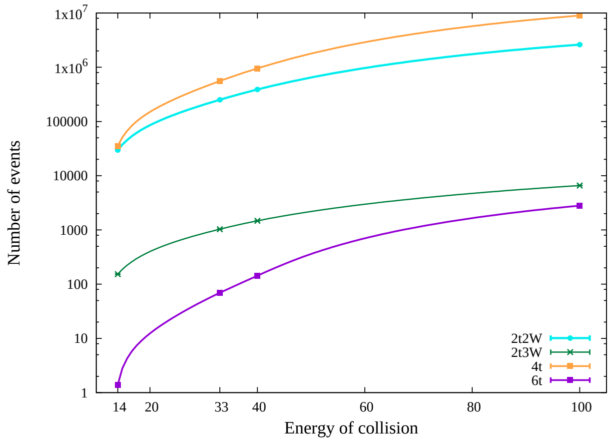

Figure 8: Dependence of different multiple top and multi-W process number of events on energy. Integrated luminosity is assumed $3000 fb^{-1}$.

As we see (Fig. 4) the lepton distribution is similar for sphaleron and multi-W processes with a small shift to the region of higher lepton numbers for sphalerons. Being this difference small, it should be difficult to separate signal and background. It however is possible to calculate multi-W and multiple top quark cross-sections in ordinary perturbation theory. With the help of MadGraph we calculated in the leading order the multi-W cross section for up to 4 W-bosons and multi-top cross sections for up to 6 top quarks as well as 2t2W and 2t3W processes and then extrapolated the data. To continue calculations with a larger number of W-bosons and top quarks in proton-proton collisions we require much more computing resources than we have or the development of non-perturbative approach which faces with the same problems as one for sphalerons. 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 lepton requirements applied at different energies to reach a background expectation of zero events and their corresponding acceptance (where the leptons satisfy $p_T > 25$ TeV, $|\eta| < 2.5$). The integrated luminosity at all energies considered is assumed to be $L = 3000 fb^{-1}$. With zero expected events, the 95% confidence level upper limit for the number of signal events in the signal region is of $s_{upl} \sim 3$ events (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 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]	N_{lep} cut	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 a source of $(B + L)$-violation in the Standard Model and are of a great interest for future high energy proton colliders, such as FCC-hh. While the cross-section for sphaleron production is unknown, it is still possible to study its properties. We used HERBVI for the sphaleron simulation, while the background was studied with MadGraph. It was shown that one can consider zero background for the region where the produced lepton number is higher than 6 at 14 TeV, 12 at 100 TeV. The upper limit obtained for sphaleron cross section is $2.27 \cdot 10^{-6}$ pb at 14 TeV and $1.00 \cdot 10^{-6}$ pb at 100 TeV, which excludes the cross section predictions made in [5].

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