Search for Sphalerons in Proton-Proton Collisions

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Theoretical overview

**Electroweak lagrangian:**

\[ \mathcal{L} = -\frac{1}{2} \text{Tr}[F_{\mu\nu}F^{\mu\nu}] + \frac{1}{2} (D\Phi)^\dagger D\Phi - \frac{\lambda}{4} (\Phi^\dagger \Phi - v^2)^2 + i\bar{\Psi}_L \gamma^\mu D_\mu \Psi_L^{(i)}, \]

Non-abelian theories have a nontrivial vacuum structure with an infinite number of ground states ("topological charges")

**Two non-perturbative solutions of the ewk sector in the SM**

- **an instanton** is a localized, finite-action solution of the classical field equations
- **a sphaleron** is a static, unstable, finite-energy solutions of the classical field equations

Perturbation theory → Baryon and Lepton number **CONSERVATION**

Non-perturbative theory → Baryon and Lepton number **VIOLATION**

\[ N = \frac{g^2}{16\pi^2} \int d^4x \text{Tr} \left[ F_{\mu\nu} F^{\mu\nu} \right], \]
Sphaleron corresponds to an unstable configuration of fields, which, after a small perturbation, decays to the vacuum by emission of many particles.

The sphaleron solution is known explicitly and its energy is

\[ E \sim \frac{m_W}{\alpha_W} \sim 9 \, TeV \]
Sakharov conditions for cosmological baryogenesis:
1. C and CP violation (CKM)
2. Thermal nonequilibrium (inflation)
3. Baryon number (B) violation (sphaleron)

PROBLEM:
Thermal nonequilibrium $\rightarrow$ 1$^{\text{st}}$ order phase transition $\rightarrow$ Higgs mass < 73 GeV

Higgs mass ~ 125 GeV $\rightarrow$ 2$^{\text{nd}}$ order phase transition $\rightarrow$ 2$^{\text{nd}}$ Sakharov condition is broken

We need Standard Model extensions
• Electroweak sector of the SM is always seen as perturbative. **If these sphaleron processes can be detected** → a truly remarkable breakthrough in realising & understanding non-perturbative EW dynamics!

• The rate of the B+L violating processes is still not known theoretically. There are optimistic phenomenological models with ~pb or ~fb cross sections, and there are pessimistic models with unobservable rates even at infinite energy.

• B+L violating processes provide the physics programme which is completely unique to the very high energy pp machine (FCC). This cannot be done anywhere else!
Baryon- and lepton-number violation in SM (electroweak interaction):

\[ \Delta(B + L) = 3 \, N_{CS} \]

\[ \Delta(B - L) = 0 \]

\(N_{CS}\) - Chern–Simons number

Instantons \(\rightarrow\) quantum tunneling - exponentially suppressed!!

Low energies (\(E < E_{sp}\)):

\[ \sigma_{inst} \sim e^{-4\pi/\alpha_W} \sim 10^{-150} \]

Higher energies (\(m_W < E < E_{sp}\)) \(\rightarrow\) Consider spahleron as instanton perturbation \(\rightarrow\) \(\sigma_{inst}\) grows exponentially with collision energy and number of bosons

\[ q + q \rightarrow 7\bar{q} + 3\bar{l} + n_B W(Z) + n_H H \]

Sphaleron process

Large boson multiplicity, \(n_B\), typical value:

\(n_B = 30 \sim \frac{1}{\alpha_W}\) and \(\frac{n_B}{n_H} \sim \frac{1}{16}\)
The cross section for sphaleron events is absolutely unknown (since energies are close to 10 TeV).

**Sphaleron (instanton approximation)**

\[ \sigma(\Delta n = \pm 1) \propto \exp \left[ \frac{4\pi}{\alpha_W} S(E) \right] \]

**Suppression factor**

\[ S(E) = -1 + \frac{9}{8} \left( \frac{E}{E_0} \right)^{\frac{4}{3}} - \frac{9}{16} \left( \frac{E}{E_0} \right)^2 + \cdots \]

1\(^{st}\) ord  
2\(^{nd}\) ord

**BUT:** Instanton perturbation theory breaks down as the energy approaches \( E_0 \)

**Unitarity constraints**
Sphalerons (Tye and Wong)

Tye and Wong approach (TW) [1505.03690]

They evaluated the sphaleron rate by constructing a 1D quantum mechanical system

\[
\left( -\frac{1}{2m} \frac{\partial^2}{\partial Q^2} + V(Q) \right) \Psi(Q) = E \Psi(Q)
\]

V(Q) – periodic potential

There is no tunneling suppression near the sphaleron energy

LHC at 14 TeV has good chances to observe this process

According to TW theory the cross section is NOT negligible even at small energies

\[
\sigma(\Delta n = \pm 1) = \frac{p}{m_W^2} \sum_{ab} \int dE \frac{d\mathcal{L}_{ab}}{dE} \exp \left( \frac{4\pi}{\alpha_W} S(E) \right)
\]

\[
S(E)
\]

- \( S(E) \) - suppression factor
Sphalerons (TW)

In 2016 John Ellis, Kazuki Sakurai performed the calculations of sphaleron transition rate within the Tye-Wong model (1601.03654)

The energy dependence of the total cross section for sphaleron transitions

\[ p=1, \ E_{sp} = 9 \ TeV \]

The rate is not infinitely small even at HL-LHC energies!!!

!!! TW calculation is debated and uncertainties admittedly remain large !!!

[1603.08749 ]
[1612.05431]
Sphaleron process simulation
**HERWIG** is a general-purpose Monte Carlo event generator, which includes the simulation of hard lepton-lepton, lepton-hadron and hadron-hadron scattering and soft hadron-hadron collisions in one package.


**JIMMY (JM)** Generator is a library of routines, which allows you to generate multiple parton scattering events in hadron-hadron collisions (we use jimmy-4.31)

**Main principles of HERBVI generation**

1. Flat parton level cross section (constant matrix elements)
2. Gauge boson multiplicity $n_B$ : fixed OR normal distribution (modelled on the leading-order BLNV matrix elements)
3. In addition to BLNV processes generates the main background process – B- and L-conserving multi-W production:
   $$ q_1 + q_2 \rightarrow q_3 + q_4 + n_B W(Z) + n_H H $$
Main steps of HERBVI generation

**STEP 1**
- HB: generates the hard process

**STEP 2**
- HW: generates parton showers
- JM: generates multiple parton scattering

**STEP 3**
- HW: hadronisation, decay

**STEP 4**
- RIVET: analyzes the BLNV events

Uses LHAPDF (vers. 6.1) for parton distributions

**INPUT**
- HERWIG
- HEPEVT
driver.cc
HepMC

**OUTPUT**
- RIVET
Simulation of electroweak BLNV process with HERBVI

\[ u + d \rightarrow 7\bar{q} + 3\bar{l} + n_B W(Z) + n_H H \]

- \( \Delta B = \Delta L = -3 \)
- 2 incoming quarks + one outgoing quark – 1\textsuperscript{st} generation
- 3 outgoing quarks of 2\textsuperscript{nd} and 3\textsuperscript{rd} generations

- A steeply rising cross section \( \leftrightarrow \) cut off at \( \sigma_{\text{unit}} \)
- Boson multiplicity, \( n_B \), typical value: \( n_B = 30 \sim \frac{1}{\alpha_W} \) and \( \frac{n_B}{n_H} \sim \frac{1}{16} \)
- Step-function parton level cross section model:
  \[
  \sigma(\sqrt{s}) = \sigma_0 \theta(\sqrt{s} - \sqrt{s_0}), \quad \sqrt{s_0} \sim M_{sp} \sim 18 \text{ TeV},
  \]
  \( \sigma_0 \leftrightarrow \) rate of interactions (still not known)
HERBVI RESULTS: BLNV events analysis

- Multiplicity distribution for leptons
  - $H_T$ vs. $N_{\text{lep}}$
  - $dN_{\text{lep}}/dN_{\text{lep}}$

- Vector missing $E_T$
  - Ratio
  - $H_T$ vs. $E_T$

- Multiplicity distribution for jets
  - $N_{\text{jet}}$ vs. $N_{\text{jet}}$
  - $dN_{\text{jet}}/dN_{\text{jet}}$
HERBVI RESULTS: BLNV events analysis

Multiplicity distribution for Z bosons

Multiplicity distribution for W bosons

Multiplicity distribution for top quarks

Multiplicity distribution for bottom quarks
PDF’s comparison

Sum of the jets transverse momentum distribution

Missing transverse energy distribution

**HERBVI**

- uses the internal sets of distribution: *on the plot* – **mstw1998** (very old one)
- We add interface to LHAPDF to be able to use the most recent global fits: *on the plot* – **ct14nlo, mmht2014, nnpdf30**
Try different simulation modes of HERBVI

NOTE:
HERBVI allows us to simulate B- and L-conserving multi-W processes that will constitute the main background to sphaleron production

\[ q_1 + q_2 \rightarrow q_3 + q_4 + n_B W(Z) + n_H H \]

The simulation principle is the same as for sphaleron processes:

- Flat parton level cross section
- Typical boson number - 30

Sum of the jets transverse momentum distribution
Next step – using FCC software

- We have HERBVI generation results in HepMC format
- Modified the standard JobOption configuration in order to link Delphes directly with our HepMC file

Use FCC-EDM format and write an analysis with heppy

Delphes is a C++ framework, performing a fast multipurpose detector response simulation.

Delphes

E = 40 TeV
Sphaleron processes only
To do …

• Further validation of the HERBVI output
  o Still having some issues with JIMMY, the current results don’t include multiple parton interaction

• Look at the perspective for sphaleron production at FCC-hh energies
  o Generate sphaleron and (multi-boson) background samples with HERBVI
  o Develop an analysis selection for sphaleron in heppy
  o Try to obtain an estimate for the multi-boson cross-section from Madgraph
  o Estimate the upper limit on the sphaleron cross-section for different energies and integrated luminosities