Non-perturbative phenomena in the Standard Model

Non-Abelian gauge theories have non-trivial vacuum structures with an infinite number of ground states differing by topological charges (Chern-Simons number)

Tunnelling transitions between these classically degenerate vacua (instantons) cannot be described by ordinary perturbation theory

- In the electroweak sector, sphaleron transitions violate Baryon plus Lepton number (B+L) with important connections to Baryogenesis
- QCD instantons are a source of chirality violation forbidden in pQCD and are thought to be responsible of several long-distance aspects of the theory

*Can we directly observe these processes in high energy collisions?*

Electroweak Sphalerons

The rate of sphaleron processes is unknown. Optimistic phenomenological models predict cross-sections of order pb or even fb, making it accessible at either LHC or future collider energies, but in other models it remains unobservable even at infinite energy

The simplest $\Delta N=1$ transition involves one member from each electroweak doublet

In addition the amplitude is expected to be enhanced when the process involves a large number of electroweak bosons

$$ q_1 + q_2 \to 7\bar{q} + 3\bar{l} + n_B W(Z) + n_H H $$

We have studied sphaleron production using HERBVI, a MC generator for B+L number violating processes

- Written as plugin of HERWIG6, which provides showering multiple parton interactions and hadronisation
- Implements $\Delta N=1$ sphaleron transitions as well as its main background of B- and L-conserving multi-boson production
- Both processes are assumed to be valence-quark initiated and are generated with a flat matrix element
- The multiplicity of additional gauge boson and its energy dependence is modelled to leading order in instanton approximation

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

A potential search strategy has been defined:

- Given the huge number of gauge bosons produced, the number of leptons (electrons, muons) provides an excellent discriminant to define a background free signal region
- In addition the difference in the number of leptons and anti-leptons can directly prove the lepton number violation
- We have computed 95% CL upper limits on the allowed sphaleron cross-sections at different pp collision energies
- The expected cross-sections for the most optimistic estimates are excluded even at 14 TeV, but need higher energies to go above the sphaleron barrier of ~9 TeV

$$ M_{sp} \sim \frac{\pi}{\alpha_s} \rho \sim \begin{cases} 10 \text{ TeV} & \text{in QFD} \\ 10 \text{ GeV} & \text{in QCD} \end{cases} $$

QCD Instantons

The cross-section for QCD instanton production can instead be approximated for quantities with a well defined hard scale where large distance instantons do not contribute

This can be obtained if a final state parton radiates a vector boson. Unique possibility to search for additional hard scattering processes, either in deep-inelastic lepton-hadron scattering or in virtual $\gamma W/Z$ production at hadron colliders

- An event generator for instanton production, QCDINS, is available, but only for ep scattering events

In DIS

$$ \gamma^* \to g \to \sum (q_R + \bar{q}_R) + n_g $$

In pp

$$ g + g \to V + (2n_f - 1)\bar{q}_R + n_f q_R + n_g $$

Searches for QCD instantons have been successfully performed at the HERA collider

- The decay products of the instanton are isotropically distributed in the instanton rest-frame. One then expects a pseudo rapidityband densely populated by high transverse momentum particles
- Limits reach the range of predicted cross-sections, but no excess is observed

The instanton cross-section should increase exponentially with energy, interesting opportunity for LHC and HE-LHC

- In particular, no phenomenological study for instanton production at hadronic collider currently exists
- Likely hard to disentangle the instanton “fireball” events from extremes in the underlying event