Sphaleron and Instanton processes at high energy colliders

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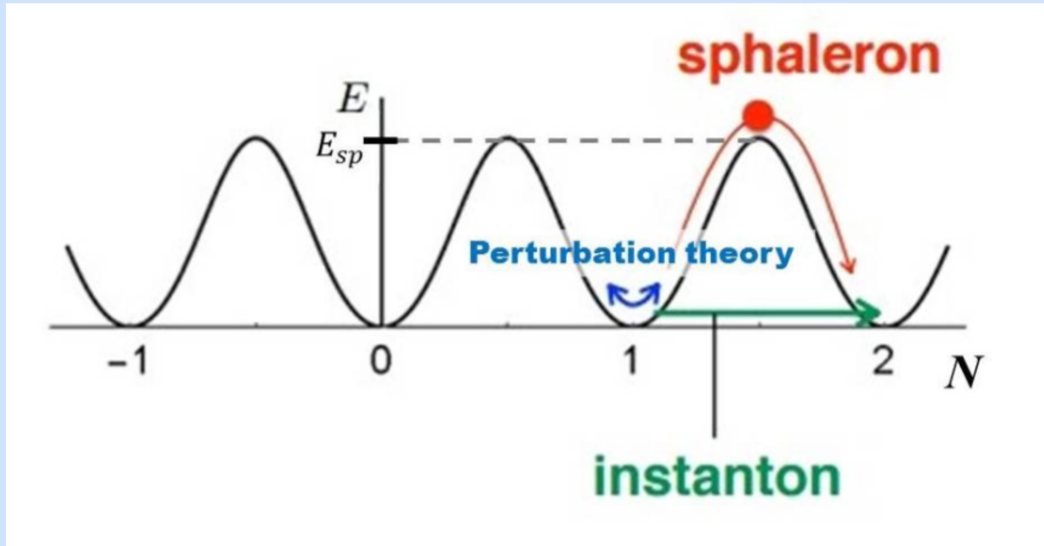
Non perturbative phenomena in the Standard Model

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 Baryogenesys
- 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?



Natural scale of the process:

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

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 ΔN=1 transition involves one member from each electroweak doublet

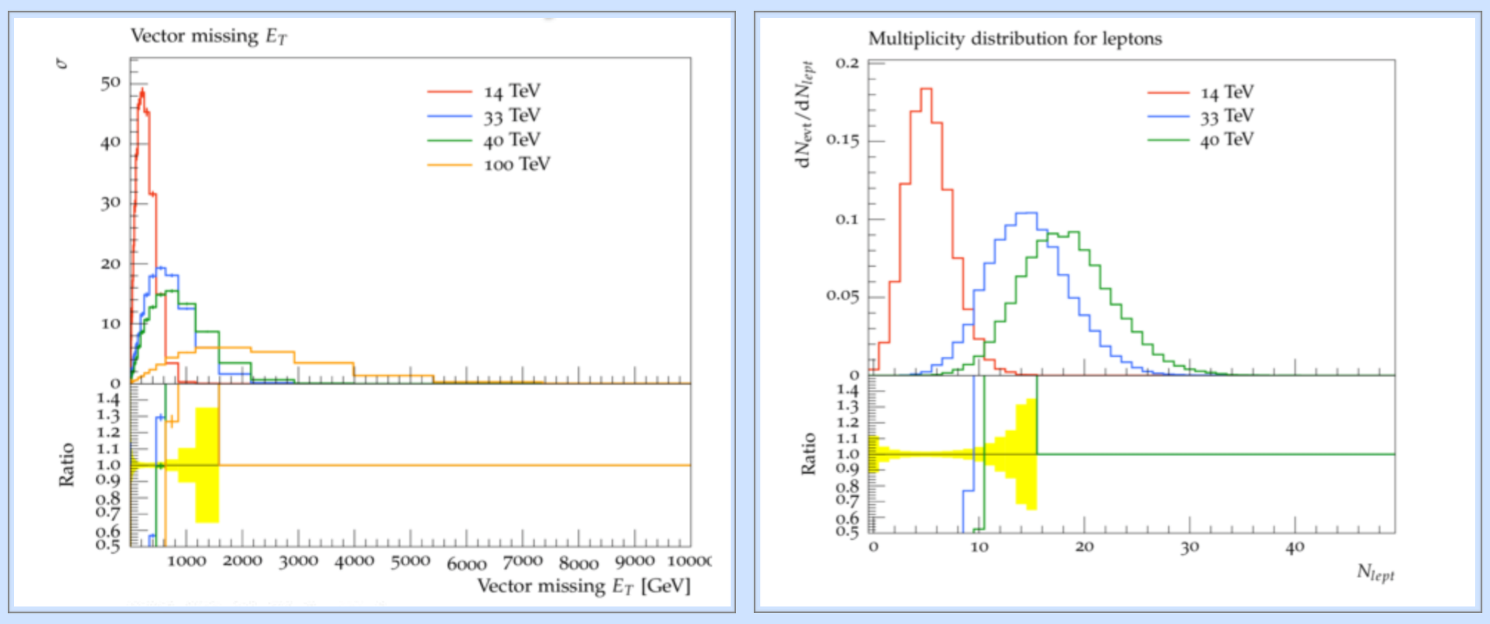
In addition the amplitude is expected to be enhanced when the process involves a large number of electroweak bosons

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

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 ΔN=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

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



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

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

E [TeV]	$N_{\rm lep}$ 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	$1.00 \cdot 10^{-6}$	$141 \cdot 10^{3}$

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 anomalous hard scattering processes, either in deep-inelastic lepton-hadron scattering or in virtual γ/W/Z production at hadron colliders

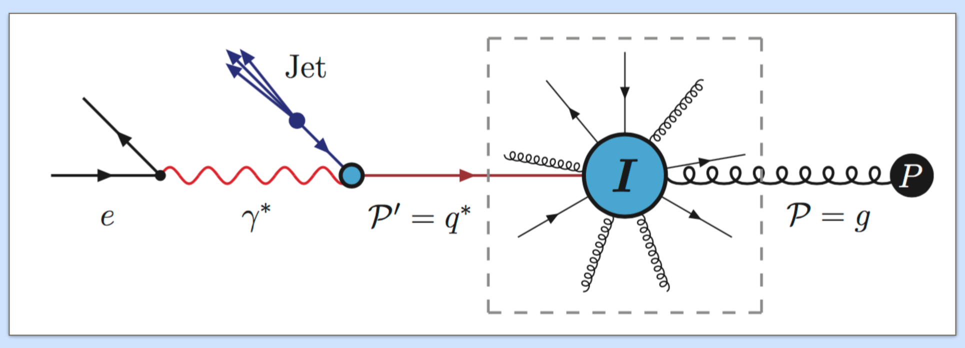
- An event generator for instanton production, QCDINS, is available, but only for ep scattering events

In DIS $\quad \gamma^* + g \rightarrow \sum(q_R + \bar{q}_R) + n_g g$

In pp: $\quad g + g \rightarrow V + (2n_f - 1)\bar{q}_R + n_f q_R + n_g g$

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