Sphaleron induced transitions at the HE- and HL-LHC

HL/HE-LHC Workshop

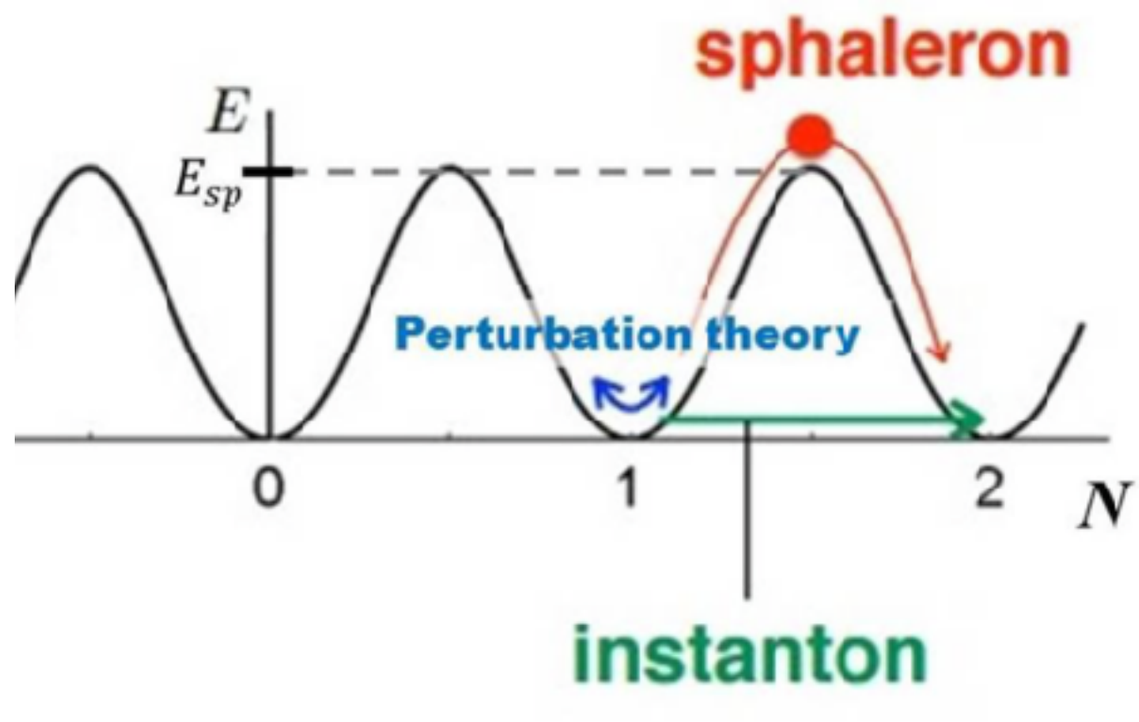
June, 18th, 2018

Simone Amoroso
Dasha Shatco

Sphalerons

- Non-Abelian gauge theories have non trivial vacuum structures with an infinite number of ground states differing by topological charges (Chern-Simons number)
  - These solutions *are not* described in ordinary perturbation theory
- In the EWK sector of the Standard Model transitions between different vacua, "*Sphalerons*", violate Baryon and Lepton number
  - The energy of the sphaleron barrier height in the SM is known explicitly:

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



- Being a source of B+L violation Sphalerons they can originate baryogenesys
  - However with a Higgs mass of 125 GeV SM sphalerons cannot explain the matter-antimatter asymmetry in the universe (2nd order phase transition)

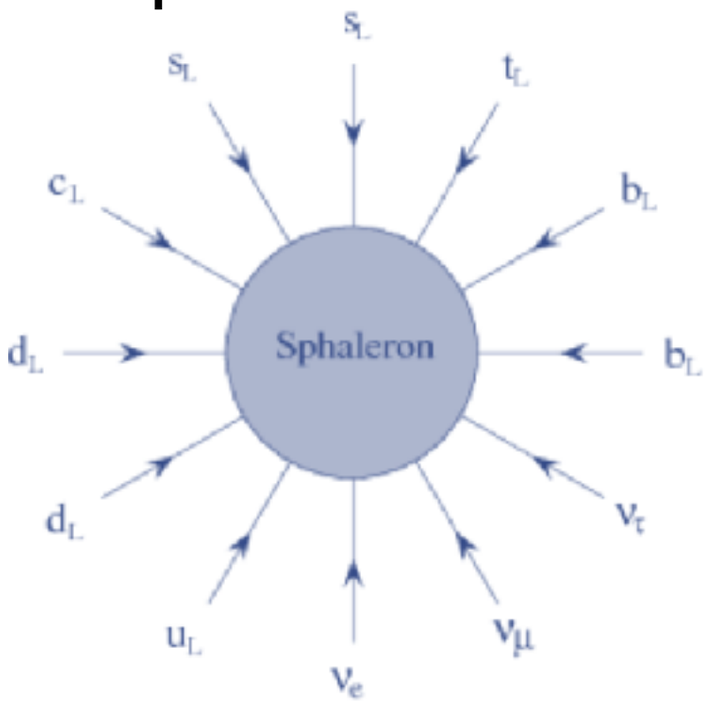
Sphalerons transitions

- At low energy tunnelling processes are exponentially suppressed

$$\sigma_{\rm Inst} \sim e^{-\frac{4\pi}{\alpha W}} \sim 10^{-150}$$

- But it has been argued that at high enough energies, the system can pass over the energy barrier avoiding the suppression (*0307034*)
- This opens the unique possibility of studying such processes at high energy hadron colliders
  - An ΔN=-1 qq scattering would look like:

$$u_L + u_L \to e^+\mu^+\tau^+\bar{b}\bar{b}\bar{b}\bar{c}\bar{c}\bar{c}\bar{u} + X$$



- The sphaleron rate is expected to grow exponentially with the number of additional accompanying gauge bosons
- Typical expected multiplicities from approximate results are:

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

Phenomenology

- Studies for sphaleron production in pp collisions where first done at the beginning of the 90ies, in view of the SSC (*0212099*)
  - Cross-section estimated in the "instanton approximation", valid for $E << E_{sph}$ predicted to increase with energy up to the unitarity limit
  - Produced in association with $O(4\pi/\alpha_W)$ gauge bosons
  - Unknown wether this growth will actually continue close to the barrier (*0307034*)

- More recently Tye and Wong (*1505.03690*, *1710.07223*) claimed, using semiclassical methods, that due to the periodic nature of the potential, multi-sphaleron transitions at high energy would travel as plane-waves not being affected by the exponential suppression
  - This would potentially make them observable at LHC energies!!
  - Triggered several phenomenological papers (*1601.03654*) and a couple of refusals of this claim (*1612.05431*, *1603.08749*)

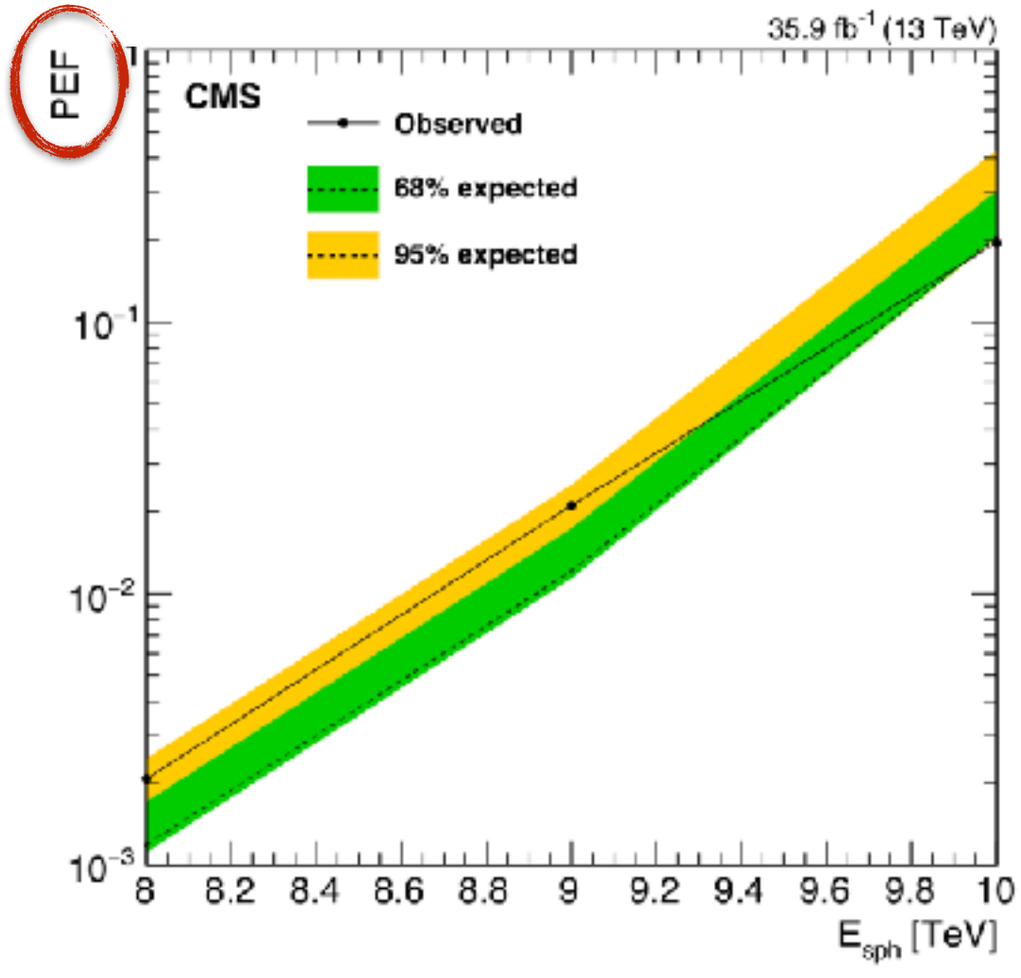
The CMS result

- Inspired by these papers CMS recently interpreted a 13 TeV search for QBH in high jet multiplicity events (1805.06013) for the production of sphaleron transitions
  - Using a newly written generator, BaryoGen (1805.02786), which simply decays a given set of particles through phase-space

Tye-Wong cross-section:

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

Unknown prefactor



- Unfortunately this result is completely neglecting the predicted large boson multiplicities in sphaleron transitions
- Or assuming that the EW boson multiplicity decrease at scales above the sphaleron
- Not an obvious connection to sphaleron induced processes

Aim of this study

- it is not obvious wether sphaleron induced processes can be observed (be it at 7, 27 or 100 TeV)
- But sphaleron transitions are a non trivial prediction of the SM
  - And they would provide insight into baryogenesis
  - A real breakthrough if they could be observed experimentally
- In addition, they provide an interesting new class of signatures that traditional searches are not explicitly looking for

- Aim of this study was to evaluate the sensitivity to sphaleron induced transitions at HL/HE-LHC (and FCC-hh)
  - Stuydying the phenomenology and potential search strategies being agnostic on the production cross-section

HERBVI

- HERBVI (9504232) a MC generator for B+L number violating processes
  - Written in 1993 as a plugin of HERWIG, which provides routines for showering and hadronisation
  - Implements N=1 sphaleron transitions as well as its main background process of B- and L- conserving multi boson production
  - Both processes are assumed to be valence quark initiated and are implemented with a flat matrix element (kinematic only through phase-space)

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

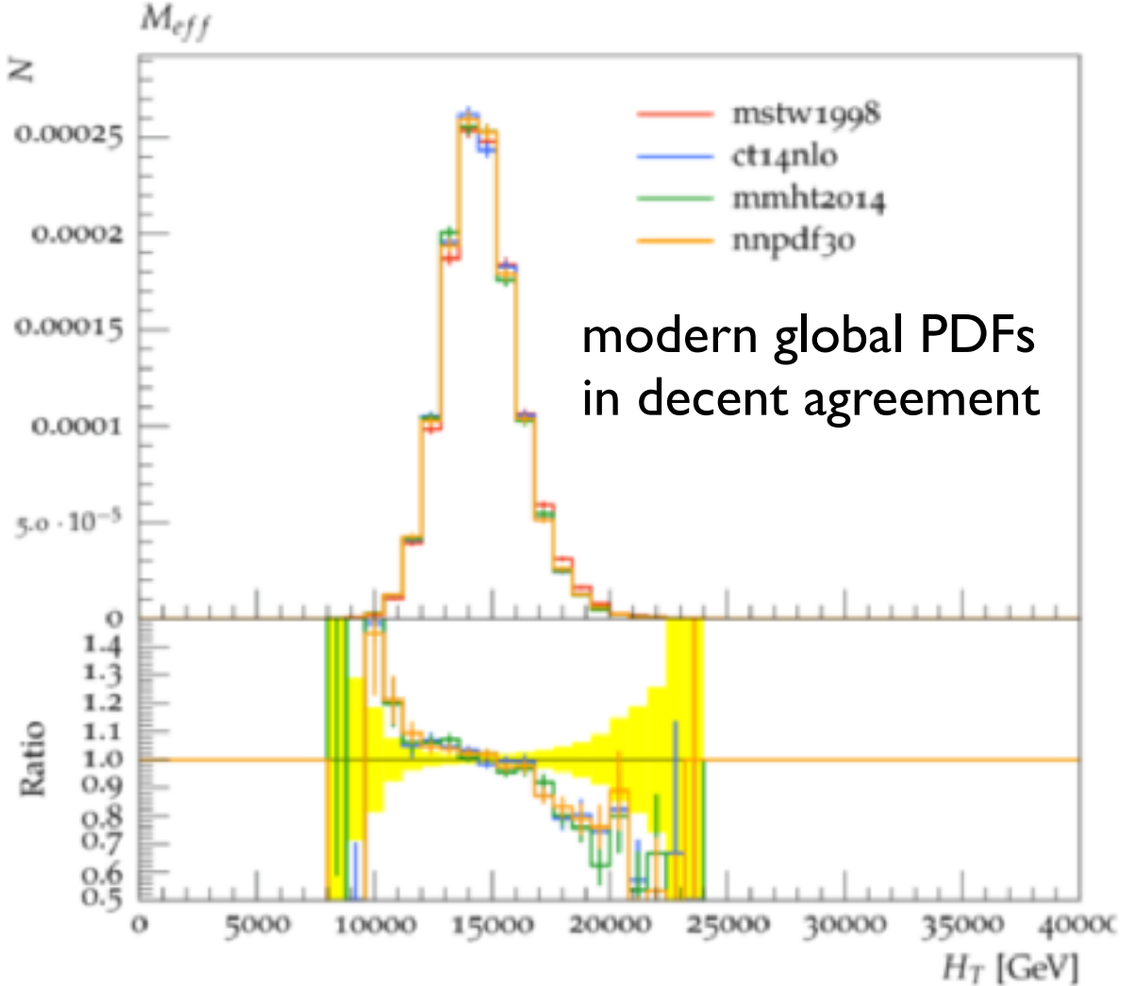
multi-boson: $q_1 + q_2 \to q_3 + q_4 + n_B W(Z) + n_H H$

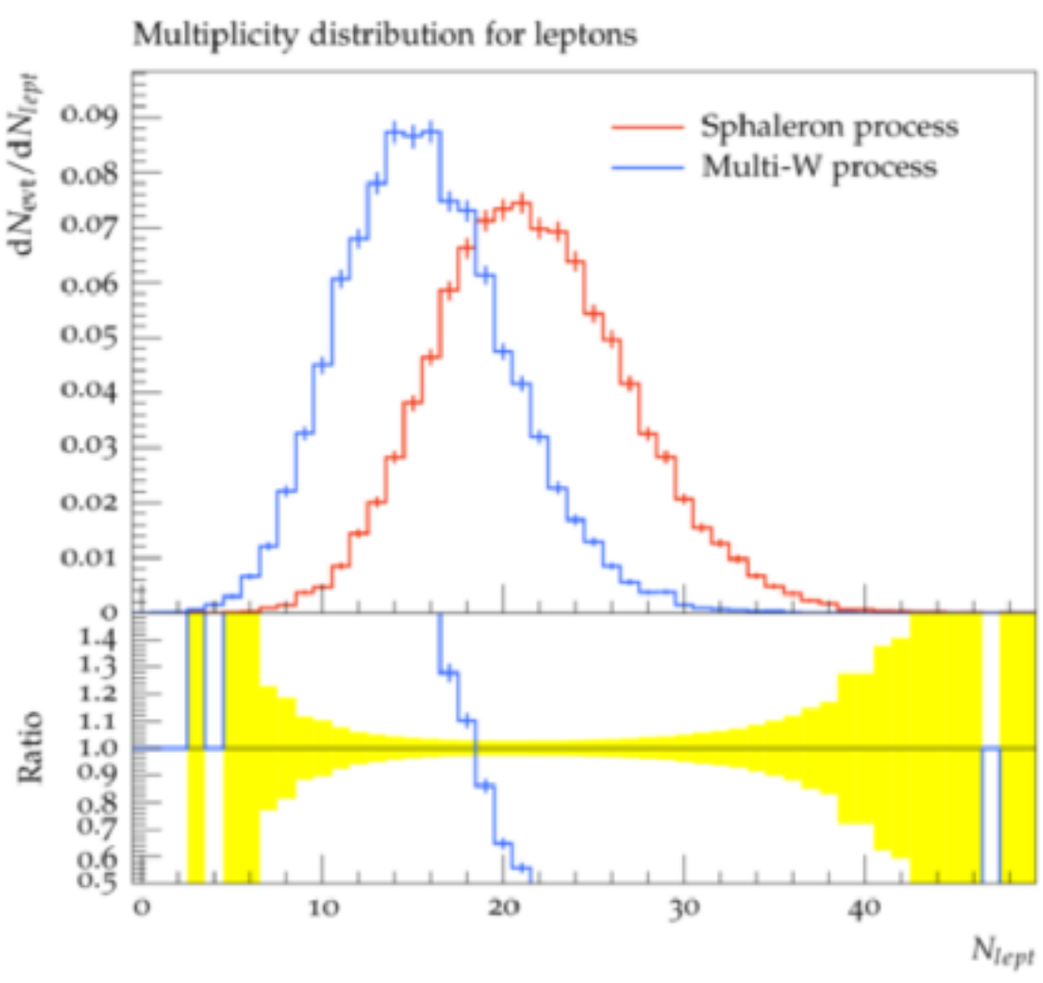
  - For the sphaleron it allows for either an arbitrary fixed multiplicity of additional gauge bosons or for an energy dependent distribution based on leading order estimates in the instanton perturbation theory

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

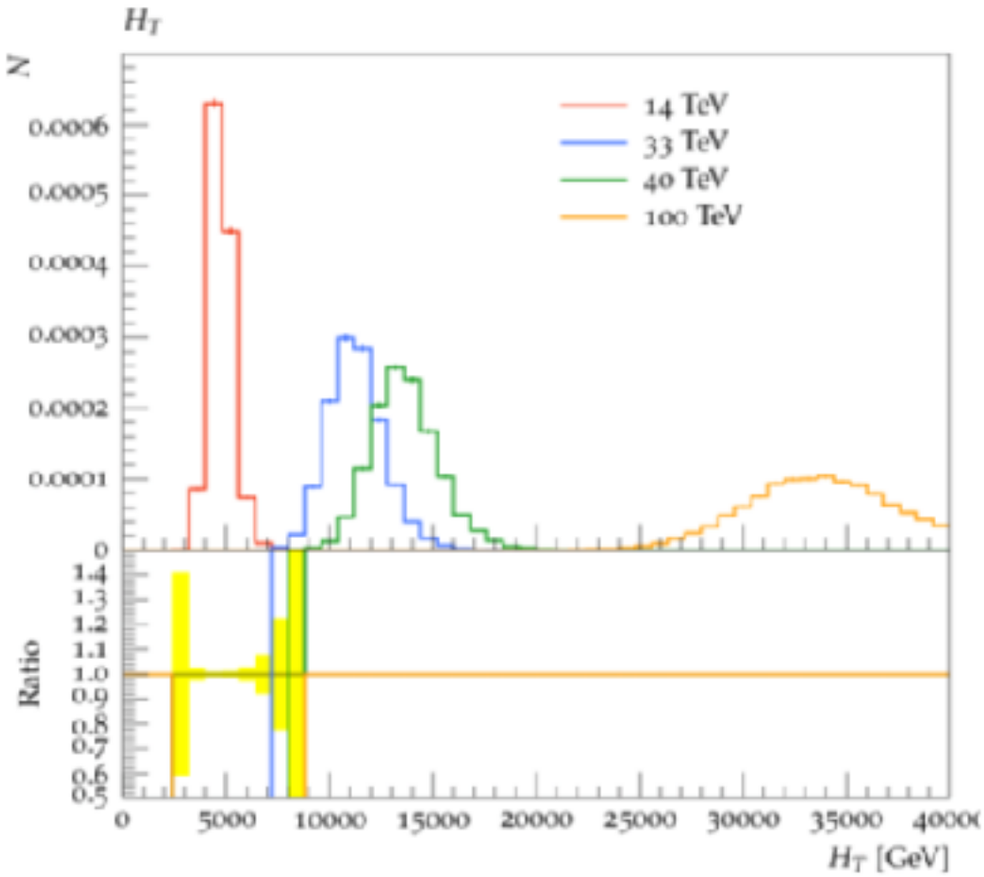
HERBVI

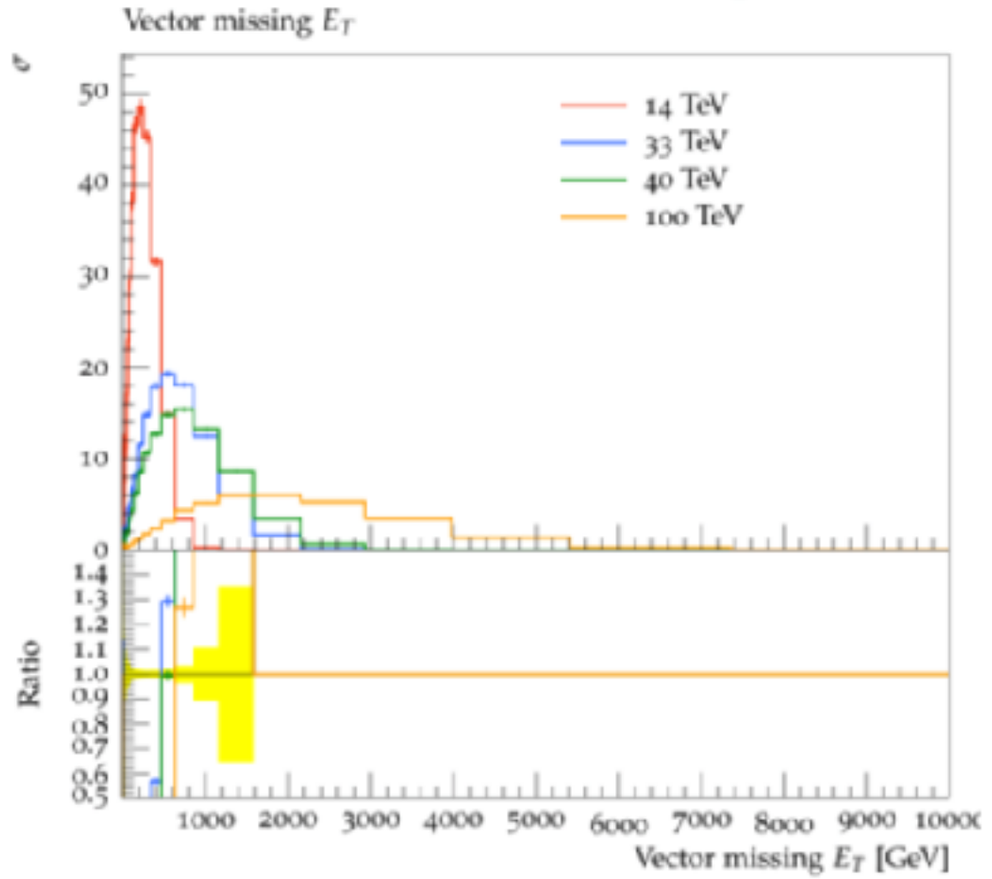
- For our study we have resurrected HERBVI and interfaced it to HERWIG6.521
  - Including Jimmy-4.31 for multiparton interactions and adding an LHAPDF interface to have access to more modern PDF sets
- The HERWIG HEPEVT output is then converted to HepMC which allows us to make a particle-level analysis in RIVET-2.5.4

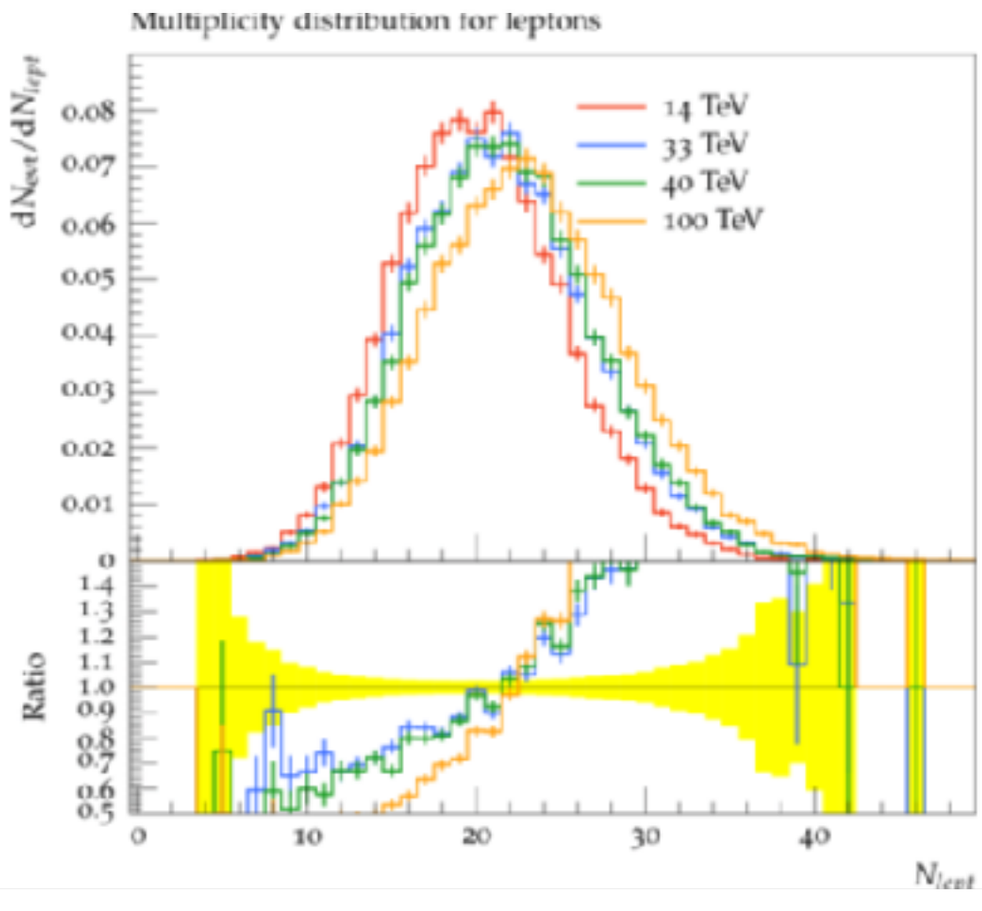


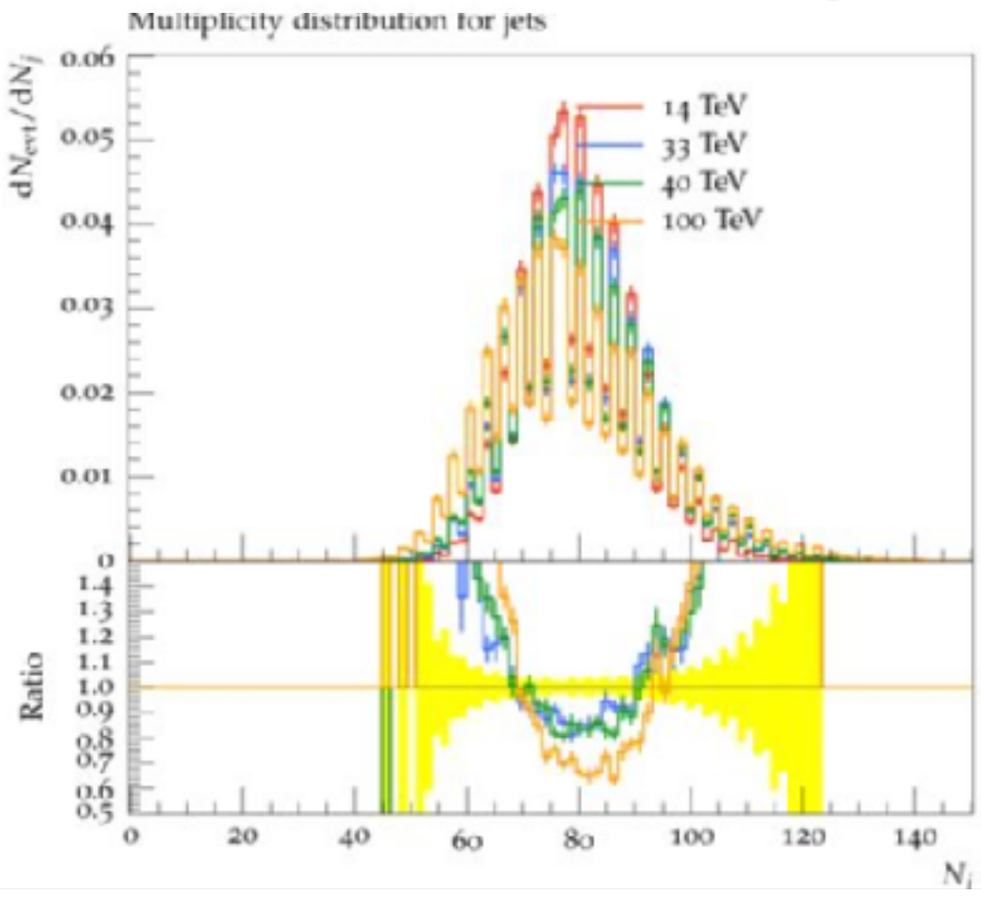


SOME DISTRIBUTIONS









Search Strategy

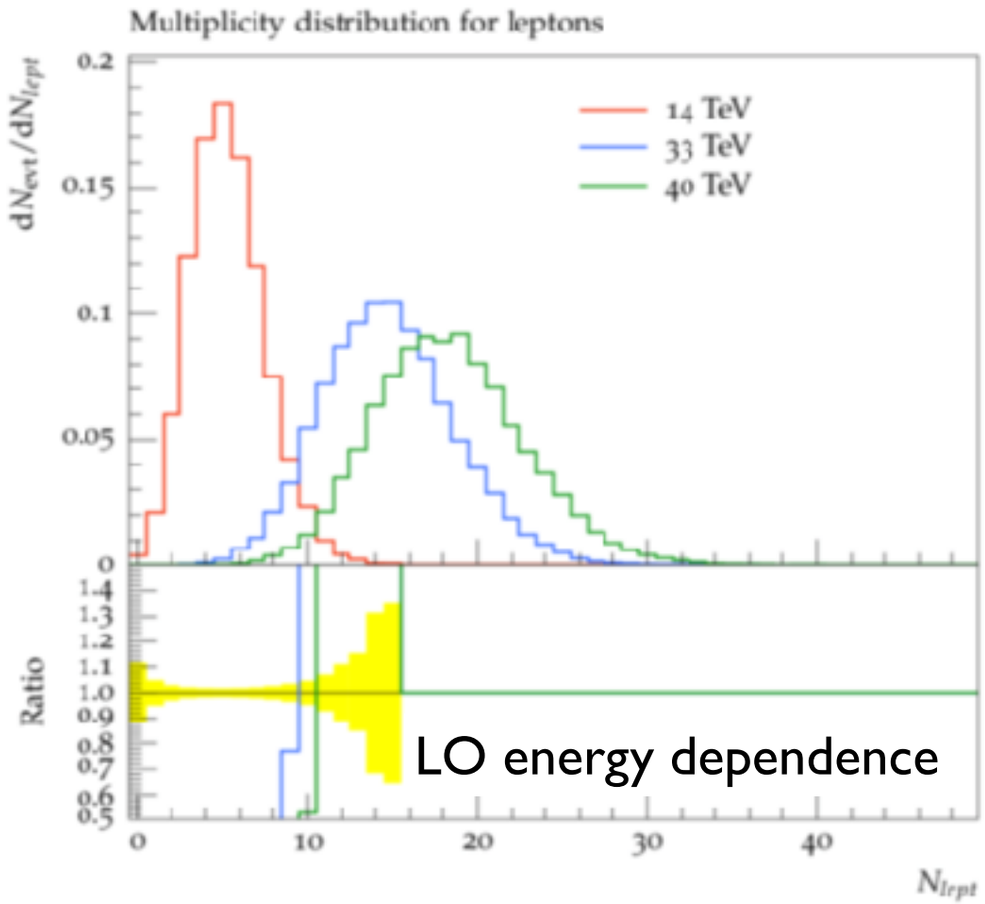
- The sphaleron gives a distinct final state with a very high object multiplicity

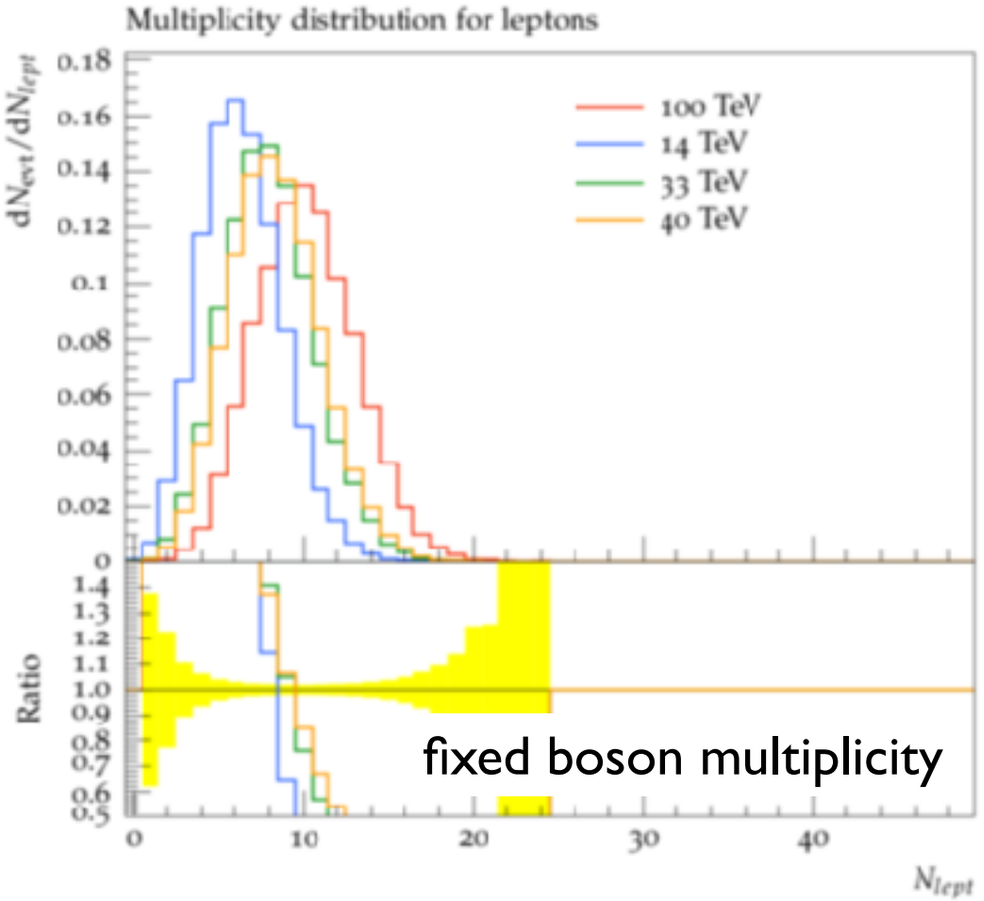
- A unique and easy signature of such a large gauge boson multiplicity is the total number of leptons (e,μ) in the event
  - Using "standard" requirements of p_T>25 GeV and |η|<2.5 and without detector simulation (should have a negligible impact)
  - Background dominated by multiboson production, direct or through decay of top-quarks

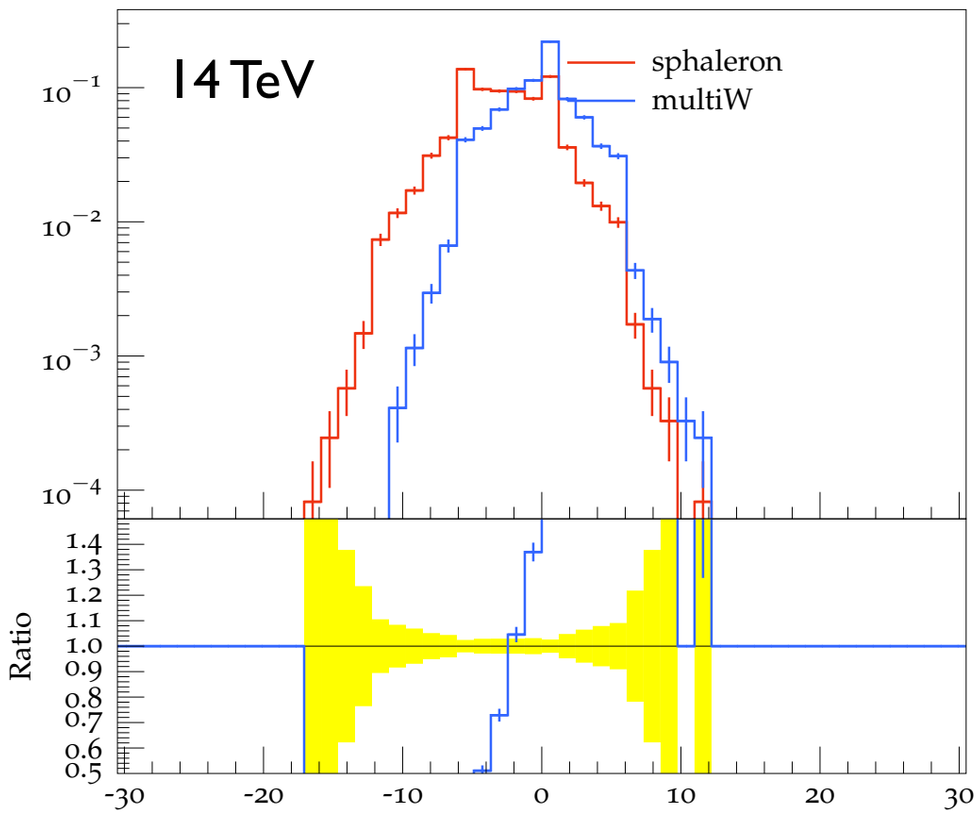
- Define a background free signal-region requiring a high-multiplicity lepton final state

- And given we have no realistic estimate of the sphaleron rate we will only derive upper limits on the allowed cross-section

Lepton Number



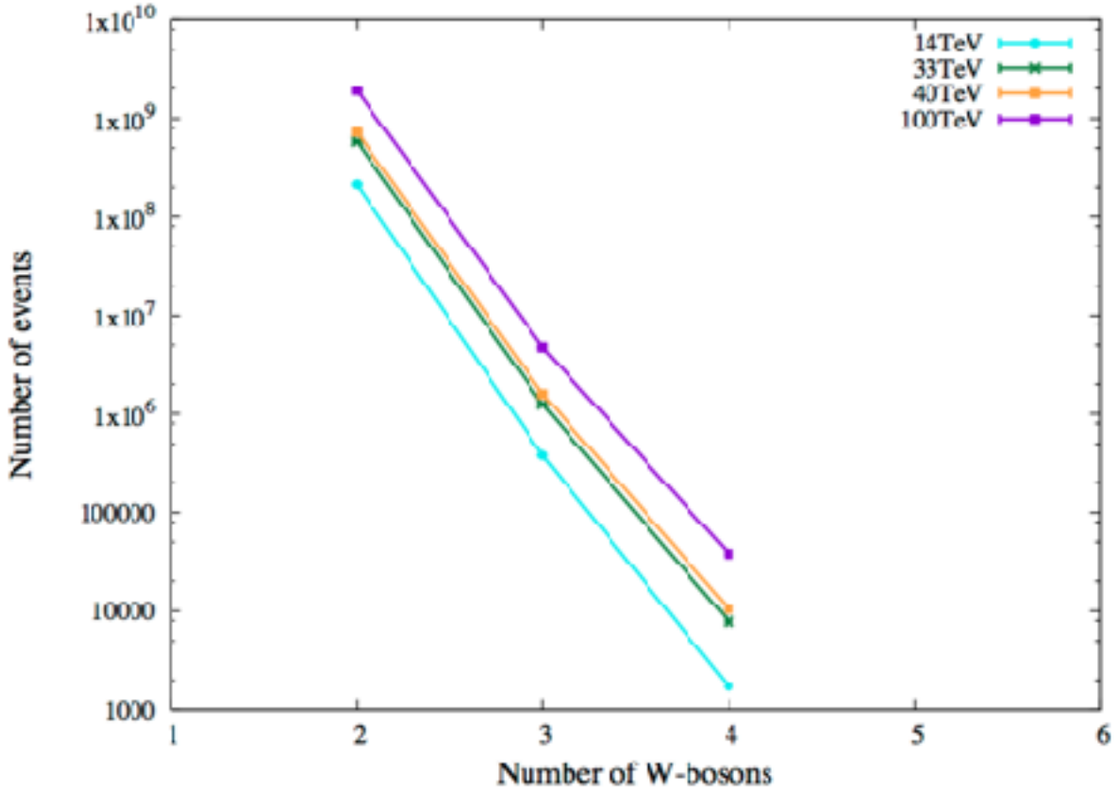


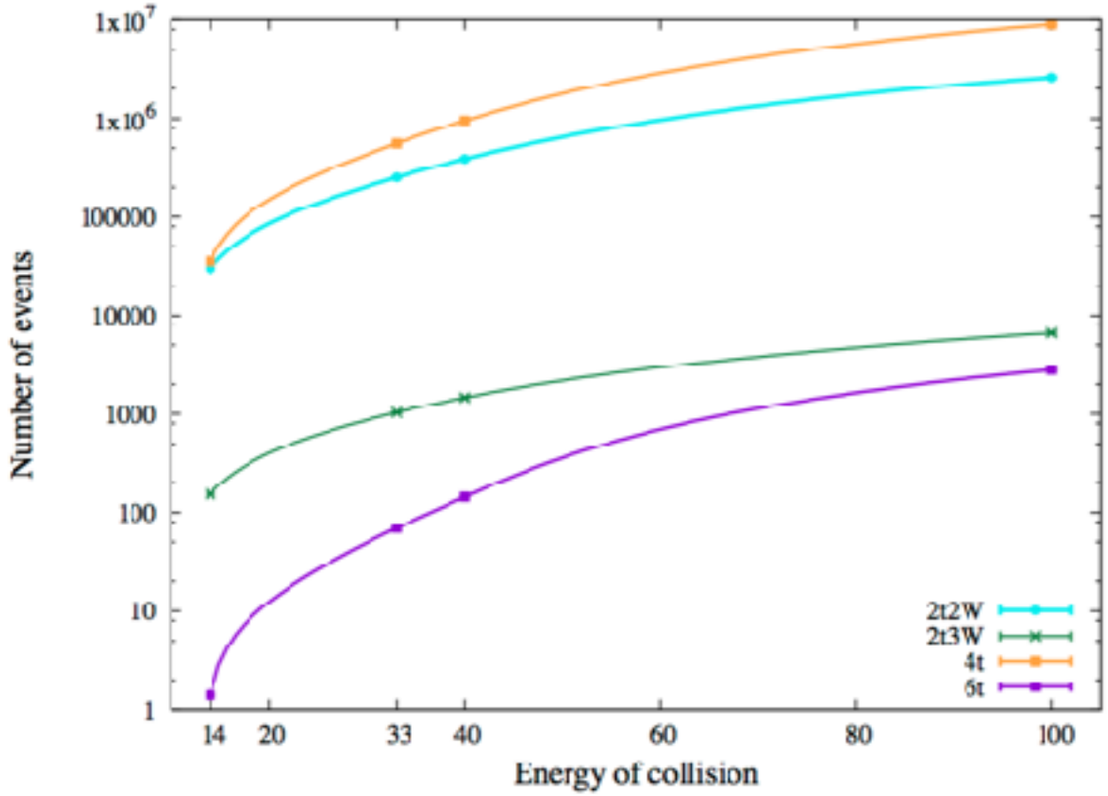


- The lepton number in the event is a useful discriminant
  - Centered at zero for SM multiboson production
  - Shifted for sphalerons
- Helpful to characterise a signal

Background cross-sections

- HERBVI doesn't calculate cross-sections for multi boson processes which will make up the main background
- We used MG5_aMC@NLO to compute inclusive cross-sections of multi-W and multi-top production at different energies
  - To determine the minimum number of bosons giving us a non-negligible background expectation
- Limited by CPU to production of up to 4 W-bosons or 6 tops; would still give us ~100/1000 expected events at 100 TeV





Results

- From the cross-sections in the previous slide we extrapolate the minimum number of leptons guaranteeing us to be in a background free region at each energy
  - Signal acceptances are very close to one for all energies but 14 TeV

- Assuming 3000 fb^{-1} of integrated luminosity we then compute the 95% upper limit on the allowed sphaleron cross-section

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

Tye-Wong estimate

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	$1.00 \cdot 10^{-6}$	$141 \cdot 10^{3}$

Summary

- Sphaleron transitions are a important prediction of the SM vacuum structure
  - These processes involve B+L violation and hence Baryogenesis
- Presented a search strategy and sensitivity estimates for the production of Sphaleron transitions in pp collisions
  - Using HERBVI+HERWIG6 to model the sphaleron transitions
  - Considering a search strategy based only on lepton multiplicity and defining a background free signal region
  - The range of predicted cross-sections from the most optimistic (and likely wrong) models would be fully explored even at 14 TeV
- A draft of the YR contribution on the overleaf documenting these studies (and moving 33 TeV to 27 TeV) will be uploaded shortly
  - Ongoing work on implementing these processes into Herwig7 and extend the studies to QCD instantons, but likely on a longer timescale

Backup