Search for Sphalerons at FCC-hh

FCC-hh analysis meeting

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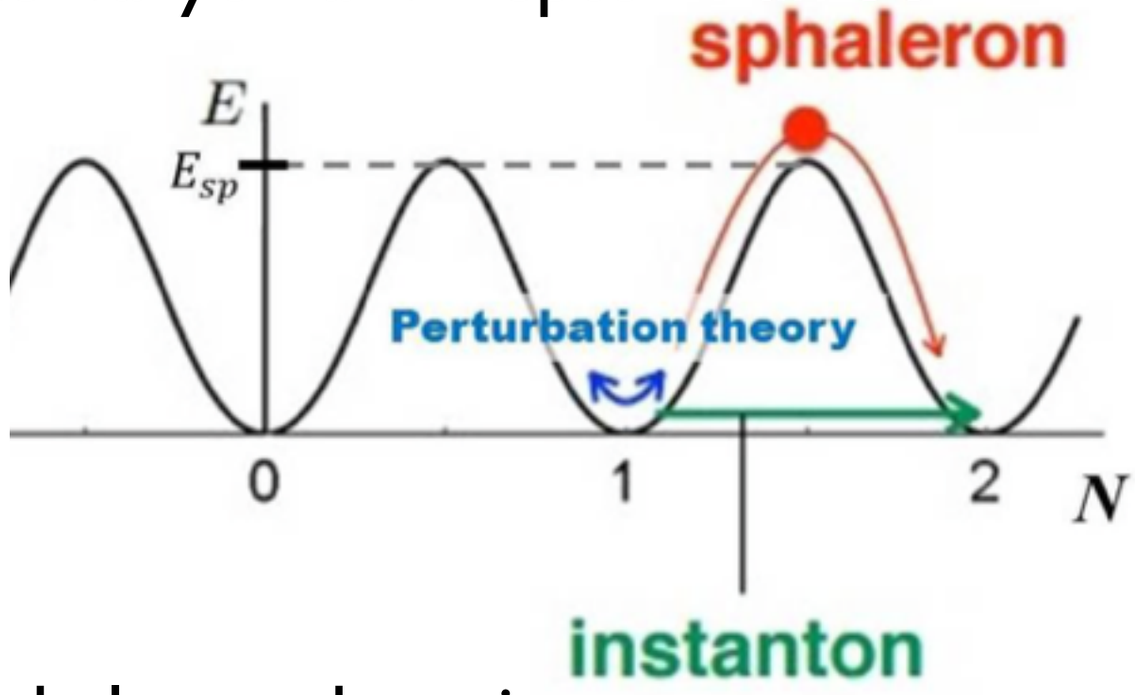
Sphalerons

- 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 have important connections to baryogenesys
  - However with a Higgs mass of 125 GeV SM sphalerons cannot explain the matter-antimatter asymmetry in the universe (2nd order phase transition)

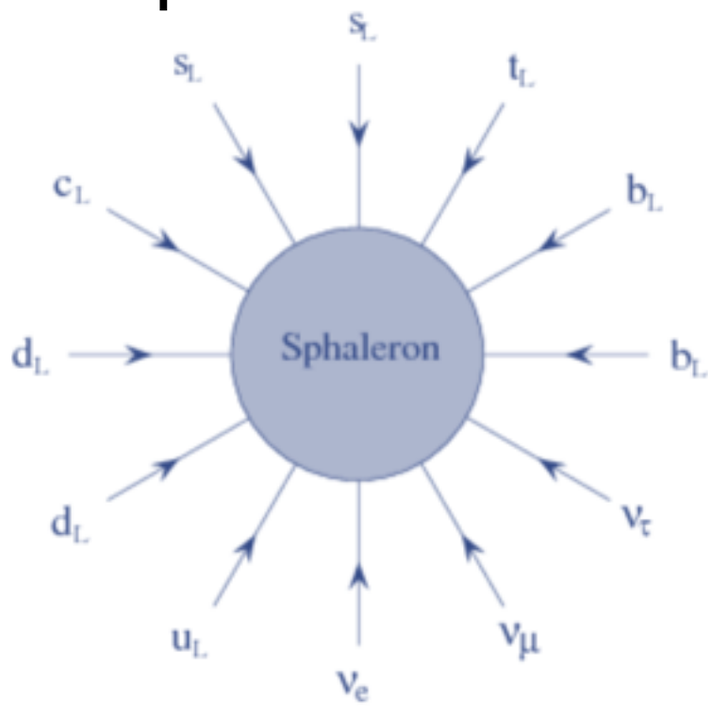
Sphalerons at colliders

- 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:

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

Sphalerons at colliders

- Studies for sphaleron production in pp collisions where first done at the beginning of the 90ies, in view of the SSC
  - Cross-section estimated from an "instanton approximation", valid for $E << E_{sph}$ predicted to increase with energy up to the unitarity limit
  - Unclear wether the growth will actually continue close to the barrier

- 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 thigh energy would travel as plane-waves not being affected by the exponential suppression
  - Triggered several phenomenological papers (*1601.03654*) and a couple of refusals of their claim (*1612.05431*, *1603.08749*)

While the actual observability of sphaleron processes at future colliders is still unclear, they offer

HERBVI

- HERBVI is 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

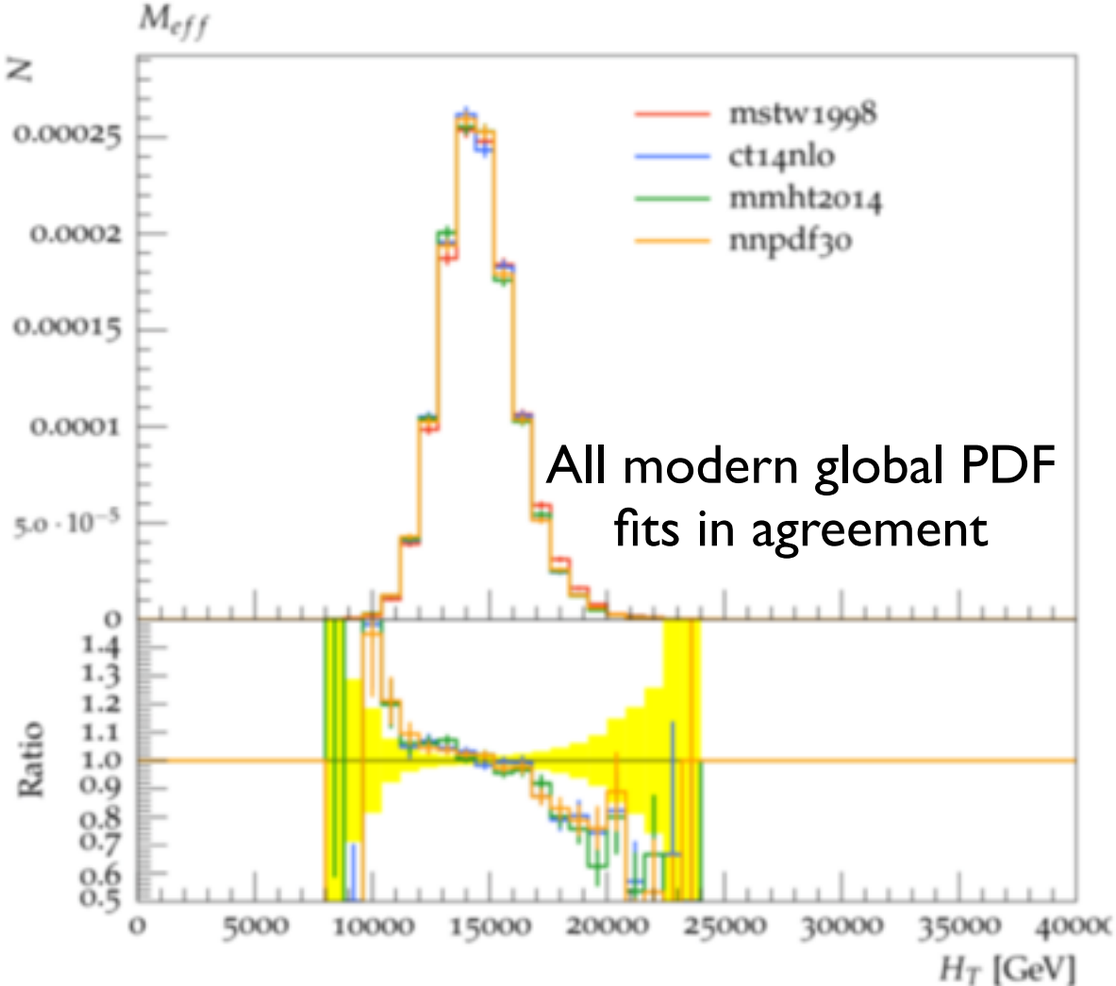
sphaleron: $q_1 + q_2 \to 7\bar{q} + 3\bar{l} + n_B W(Z) + n_H H$

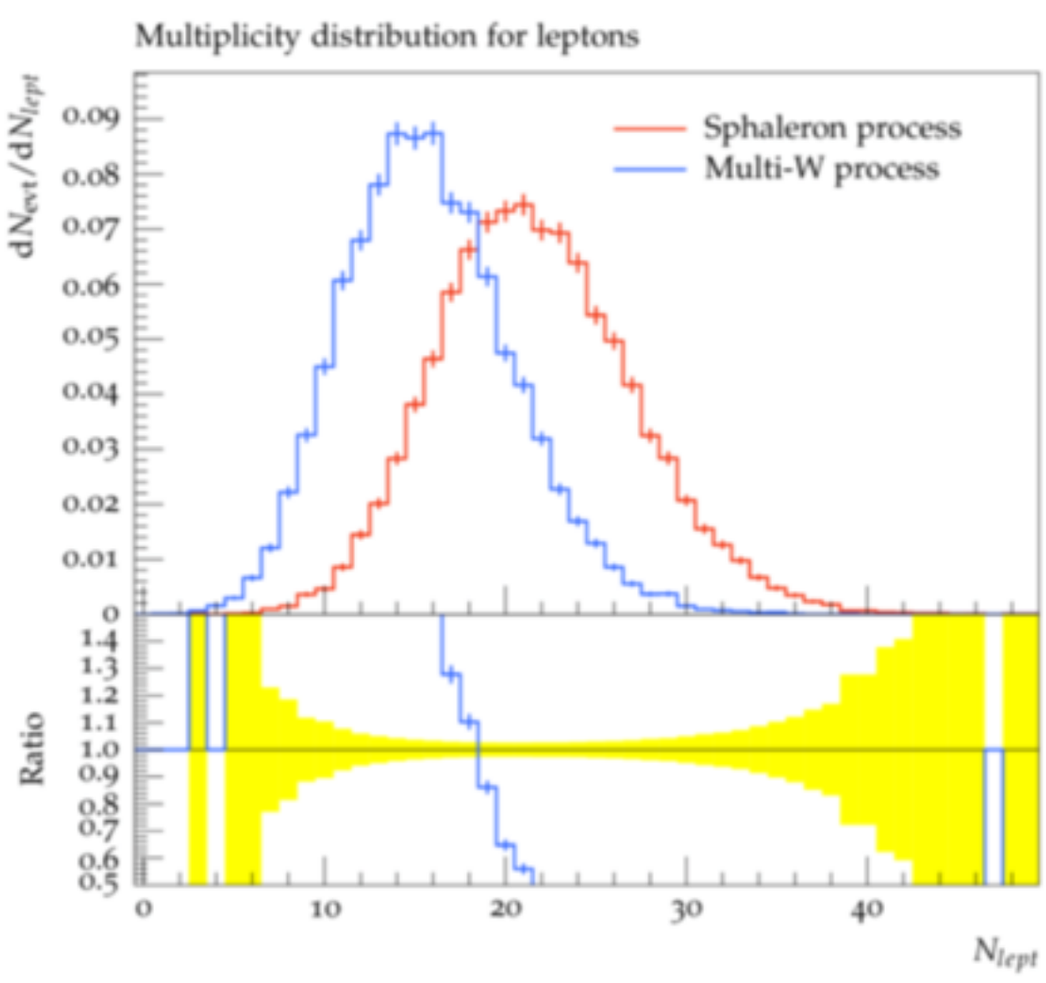
multi-boson: $q_1 + q_2 \to q_3 + q_4 + n_B W(Z) + n_H H$

  - 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
  - Both processes are assumed to be valence quark initiated and are implemented with a flat matrix element (kinematic only through phase-space)

HERBVI

- For our study we have used HERBVI interfaced to HERWIG6.5
  - Including Jimmy-4.31 for multiparton interactions and LHAPDF-6.1 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
  - We have also been able to interface our events to HEPPY, although we didn't use it as detector effects should not play a big role





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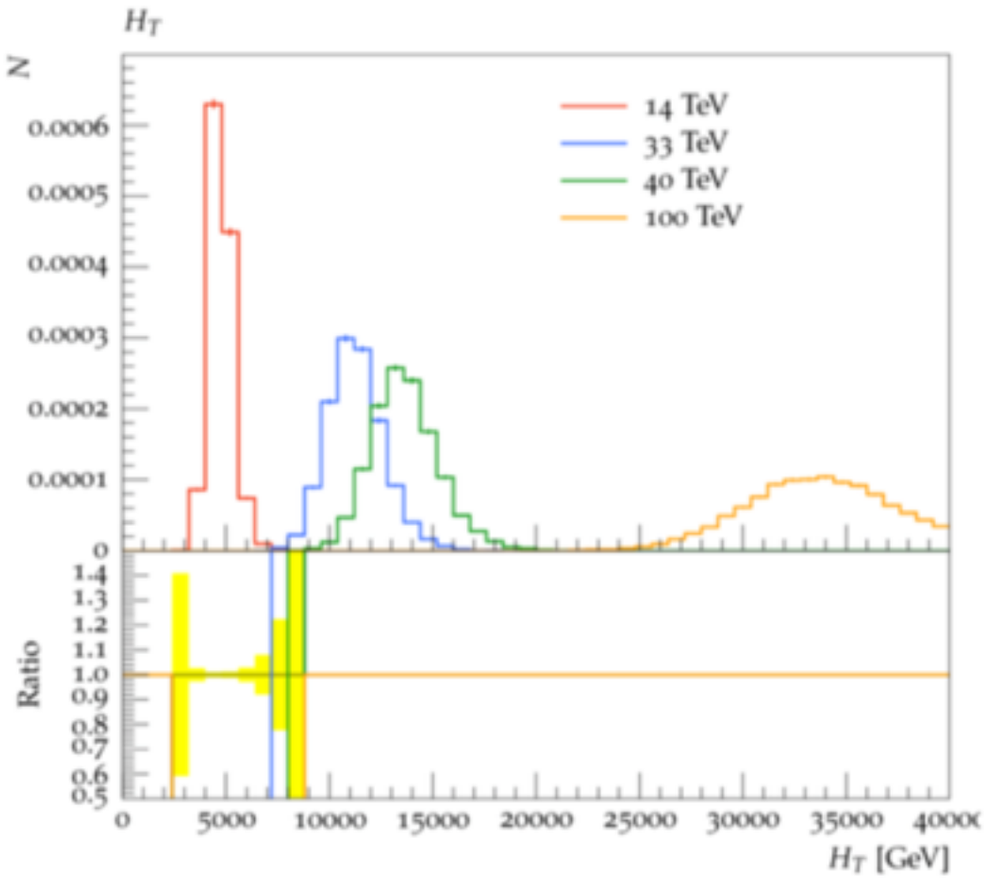
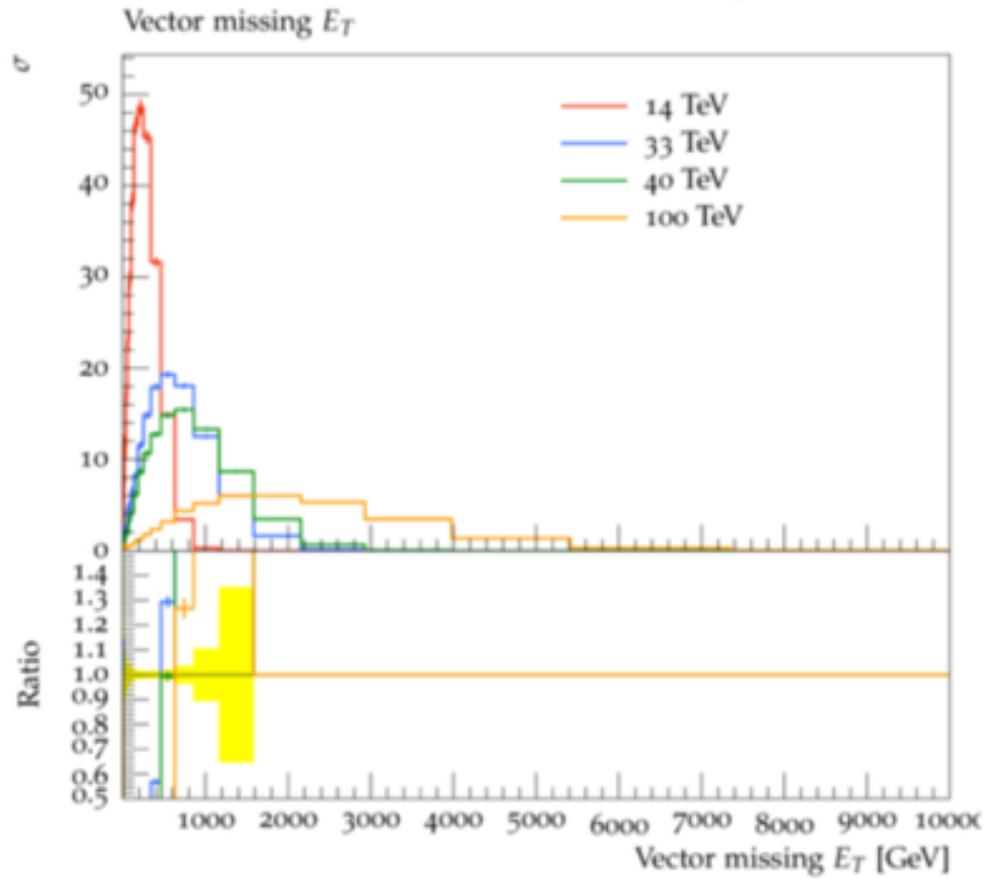
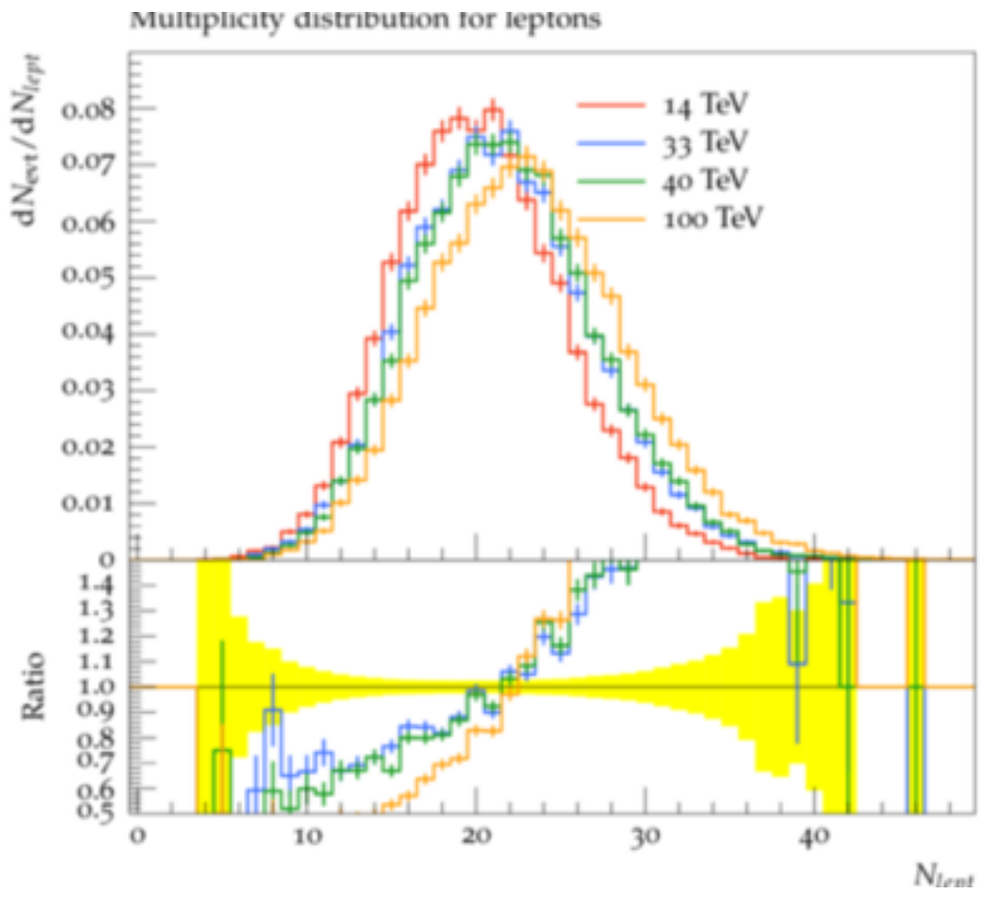
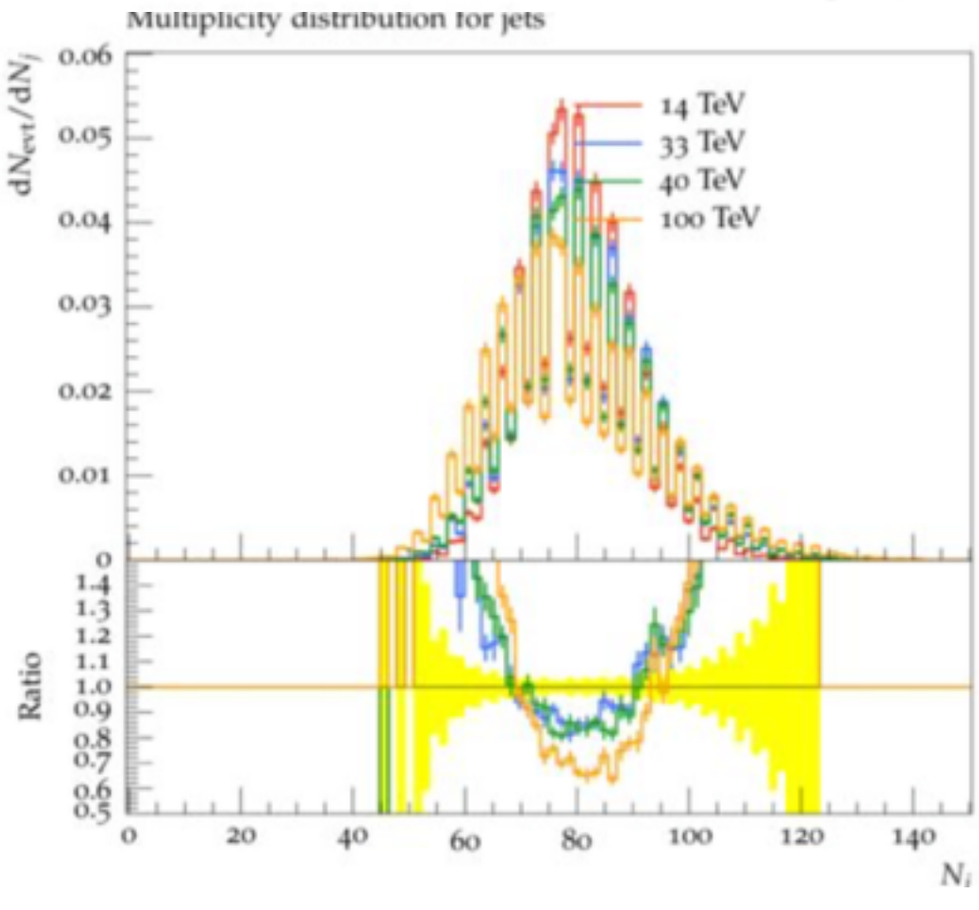


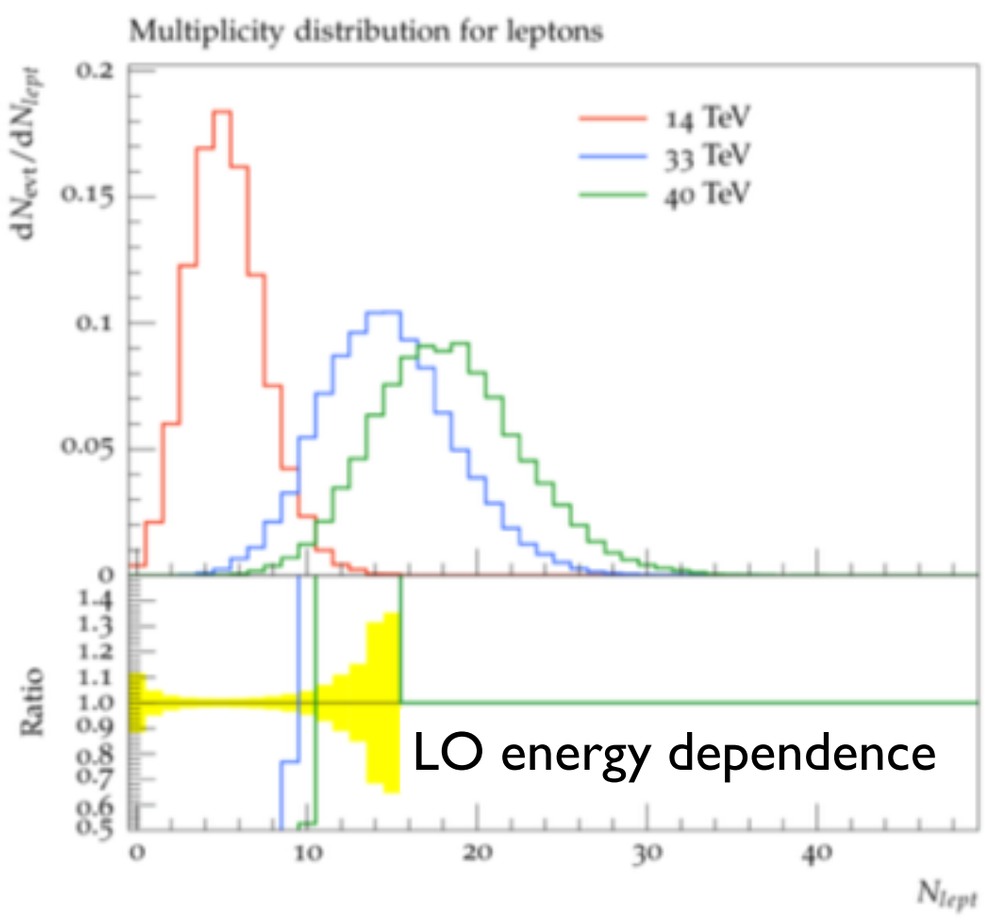


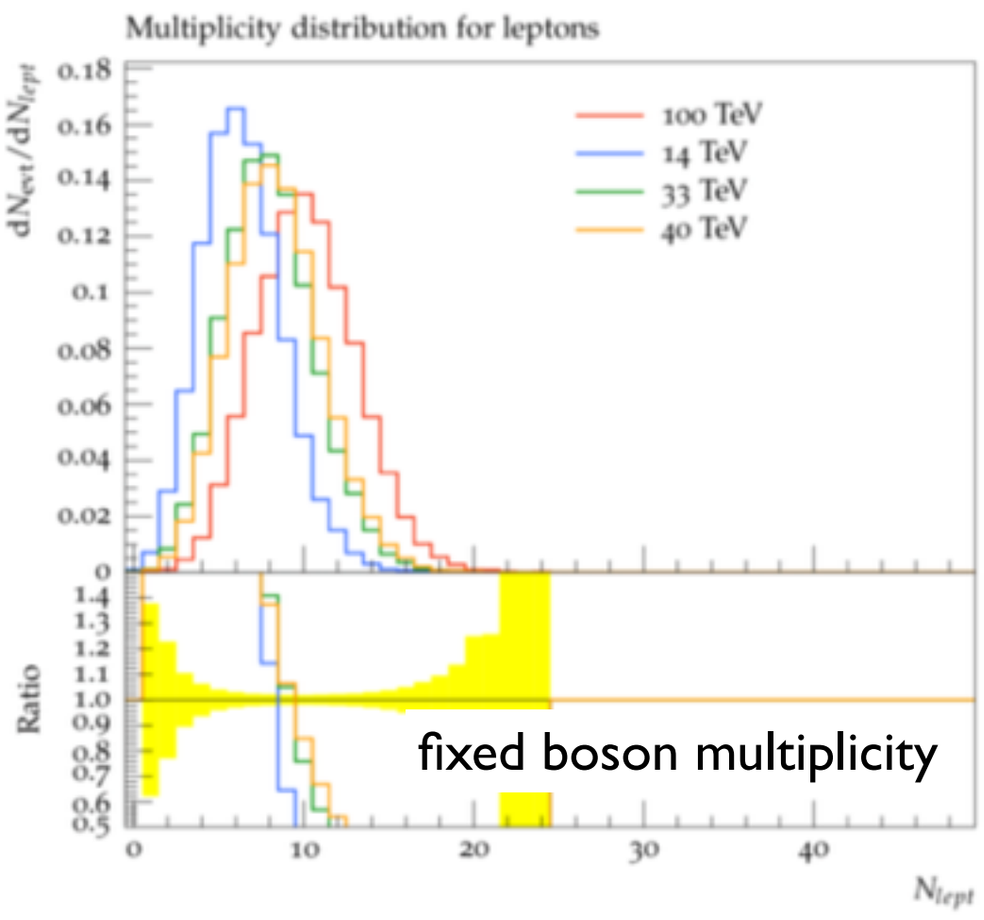




Search Strategy

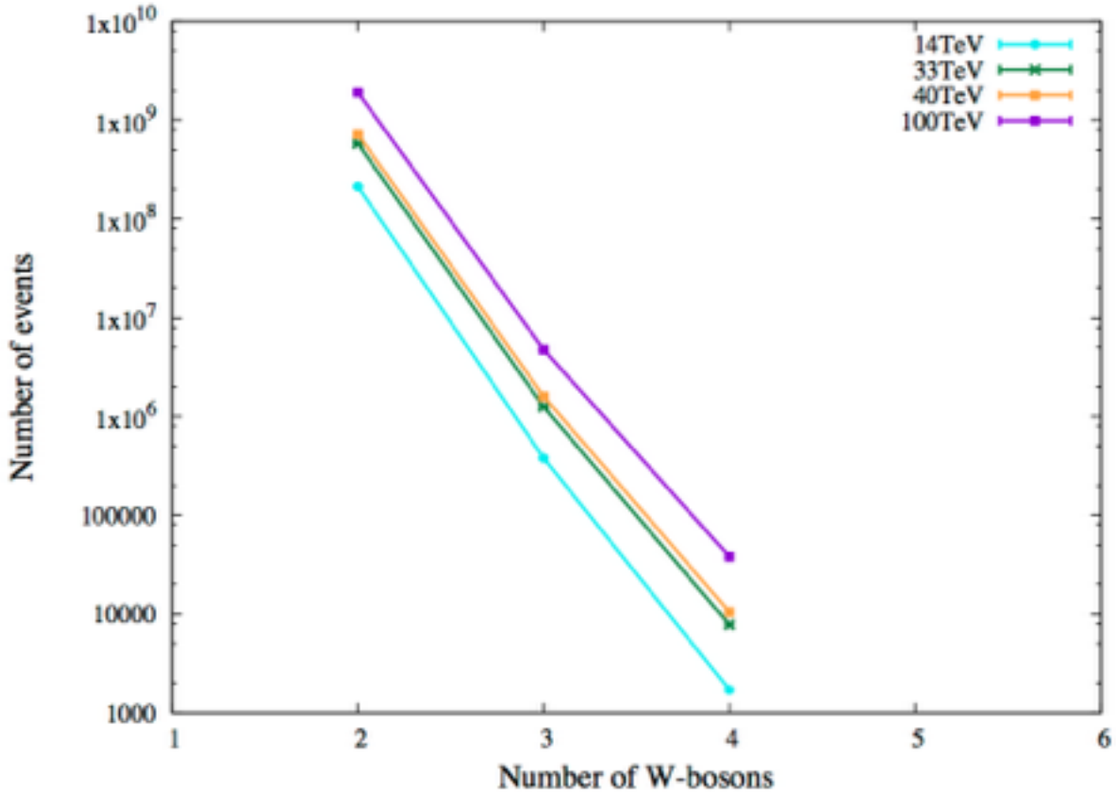
- The sphaleron gives a distinct final state with a very high object multiplicity
- A unique and simple signature of such a large gauge boson multiplicity is the total number of leptons (e,mu) in the event
- If we go in a background-free regime
- Given we have no realistic estimate of the sphaleron rate we will only derive upper limits on the allowed cross-section

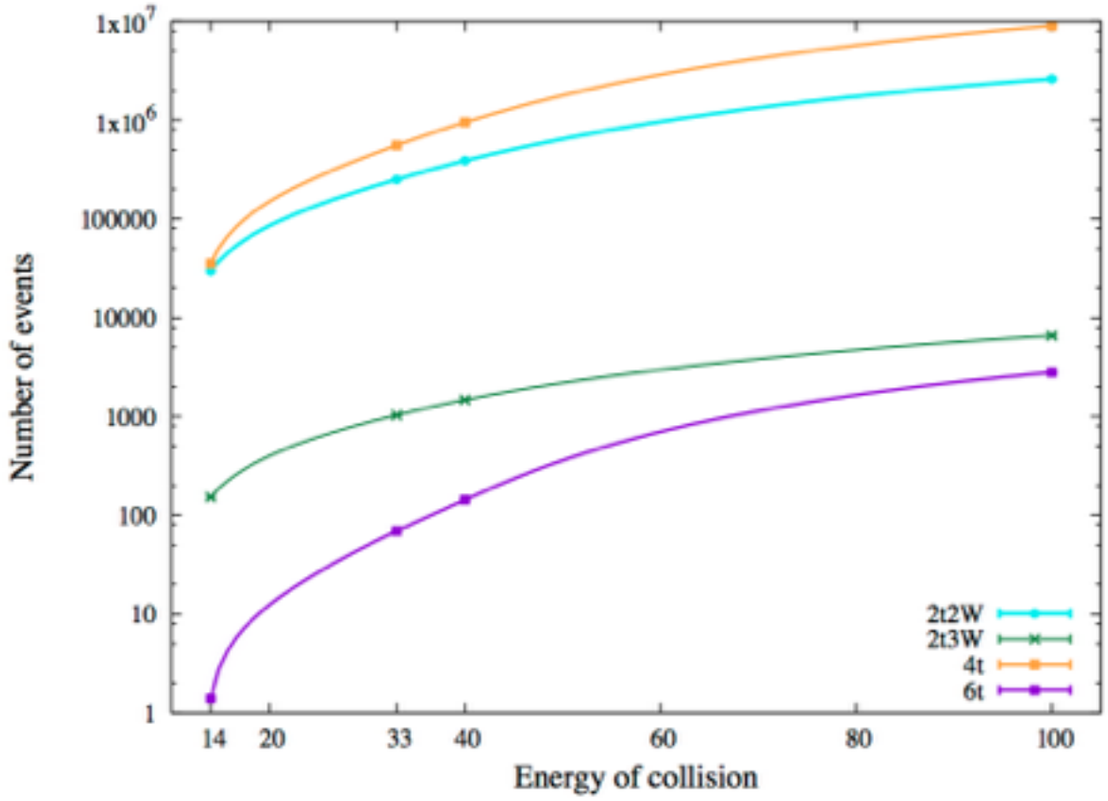




Background cross-sections

- While HERBVI doesn't calculate any cross-section we can use MG5_aMC@NLO to calculate cross-sections of multi-W and multi-top production at different energies
  - Aim of determining the minimum number of bosons giving us a non-negligible background expectation
- Unfortunately with the current code we only compute production of up to four W-bosons or six tops, which 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

- 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

- Presented a search strategy and sensitivity estimates for the production of Sphaleron transitions in pp collisions at high energy
  - Looking at lepton multiplicities to define a search strategy
  - The range of predicted cross-sections from the most optimistic (and debated) models would be fully explored even at 14 TeV
  - The less optimistic (but still very optimistic) cross-section estimates from Ringwald et al should be accessible at 100 TeV

- Still few things that might be worth including
  - It would be nice to get cross-section estimated for at least 8-tops and 6-bosons; I am sure those would constitute a background to many other searches (e.g. SUSY) and are also interesting processes per-se
  - We have so far neglected the possible impact of weak-showers, although with our conservative selections I would expect it not to be extremely relevant

Backup