

Motivation

- The Standard Model (SM) is successful in describing most of experimental results but it cannot explain such problems as the baryon asymmetry or the existence of dark matter.
- They could be potentially solved by introducing to the SM **heavy neutrinos** which would be produced at **future linear e^+e^- colliders**.

Future linear e^+e^- colliders

- An **electron-positron Higgs factory** is foreseen as the highest-priority next large-scale collider facility.
- Two **linear** colliders are being considered: the **CLIC** and the **ILC**.
- In the presented analysis, 3 different collider options are studied:

scenario	collision energy [GeV]	int. luminosity [ab^{-1}]	e^-/e^+ beam pol.
ILC500	500	1.6	-80% / +30%
ILC1000	1000	3.2	-80% / +20%
CLIC3000	3000	4.0	-80% / unpol.

Heavy neutrinos

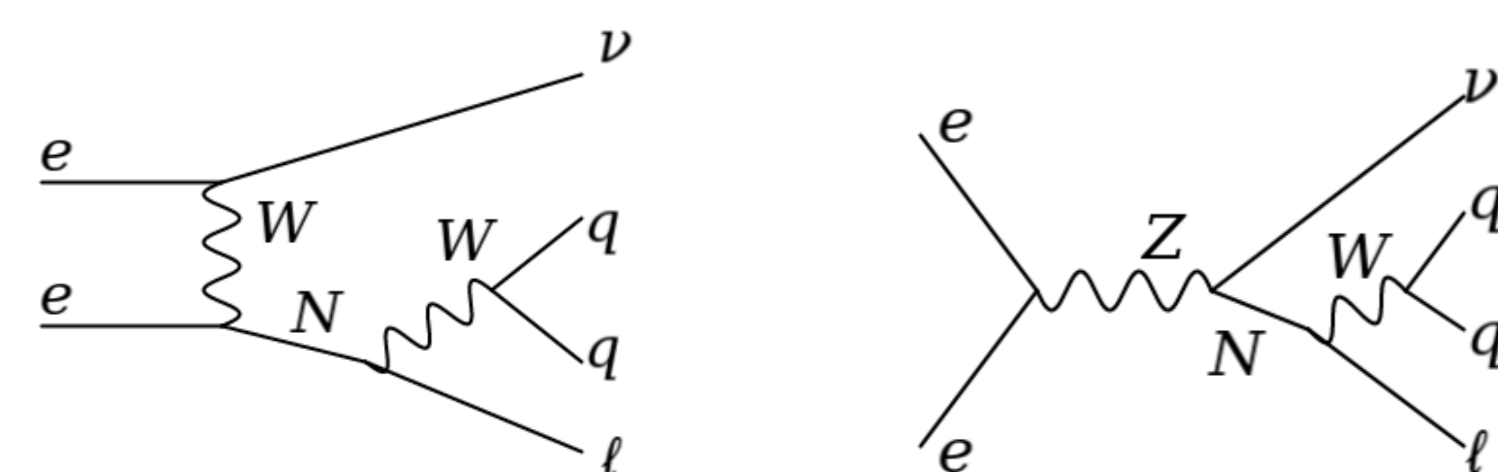
- A **right-handed heavy neutrino**, which is a singlet under the SM gauge symmetry, can be introduced by adding new terms to the SM Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{WNl} + \mathcal{L}_{ZN\nu} + \mathcal{L}_{HN\nu},$$

where \mathcal{L}_N – heavy neutrino propagator and the others introduce new vertices:

$$-\frac{g}{\sqrt{2}}W_{\mu}^{+}\bar{N}_kV_{lk}^{*}\gamma^{\mu}P_Ll^{-} \quad -\frac{g}{2\cos\theta_W}Z_{\mu}\bar{N}_kV_{lk}^{*}\gamma^{\mu}P_L\nu_l \quad -\frac{gm_N}{2M_W}h\bar{N}_kV_{lk}^{*}P_L\nu_l$$

- Such neutrinos could be observed at linear colliders in a **light-heavy neutrino pair production** process with a subsequent heavy neutrino decay into a lepton and two quarks:



Event generation and detector simulation

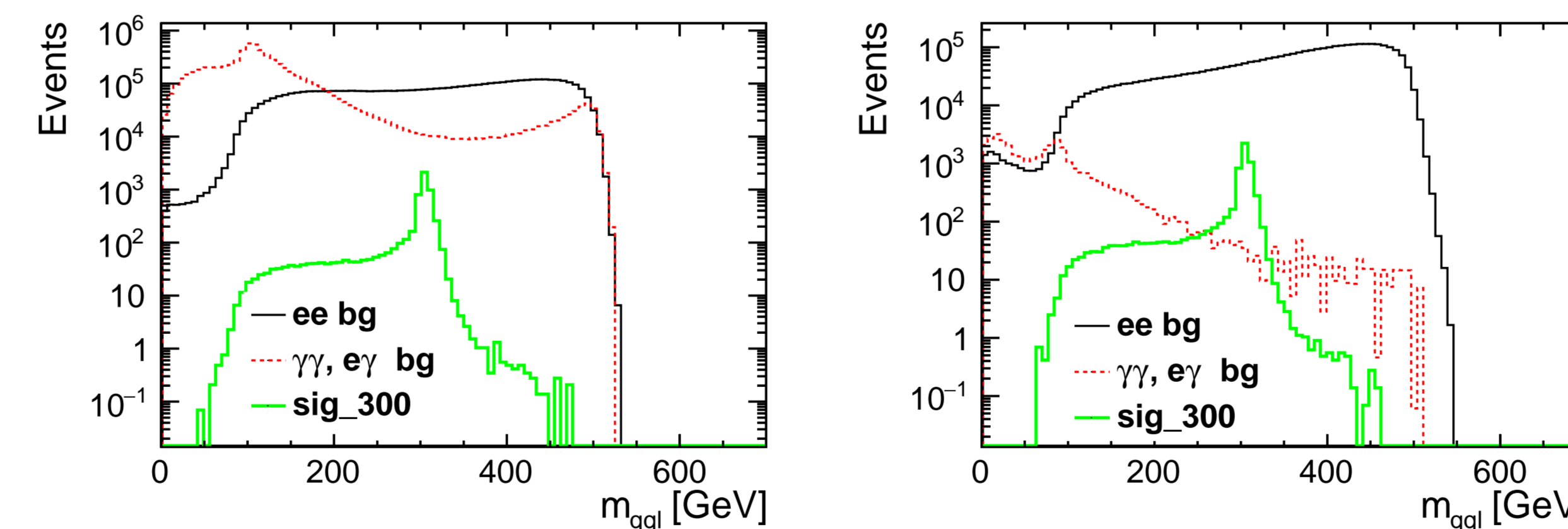
- Events were generated with Whizard 2.8.5 (v. 3.0.0 for the Majorana) [1].
- Both **ISR** and **beam energy spectra** were taken into account.
- The **HeavyN** model [2] with one heavy neutrino coupled to the SM was used in the study.
- Both **Dirac** and **Majorana** neutrinos with masses in the range **200-3200 GeV** were considered and all the couplings were set to the same value:

$$|V_{eN}|^2 = |V_{\mu N}|^2 = |V_{\tau N}|^2 \equiv V_{lN}^2.$$

- Beamstrahlung** (BS) and **Equivalent Photon Approximation** (EPA) photon interactions were also taken into account.
- The following processes were studied:
 - $\star e^+e^- \rightarrow qq\nu, qql, lll, qq\nu\nu, qqql\nu, qqqll,$
 - $\star e^{\pm}\gamma \rightarrow qql,$
 - $\star \gamma\gamma \rightarrow qql\nu, qql$ (γ from BS or EPA).
- To test many different points in the parameter space, Delphes [3] with built-in cards for ILC and CLIC detectors was employed.

Data analysis

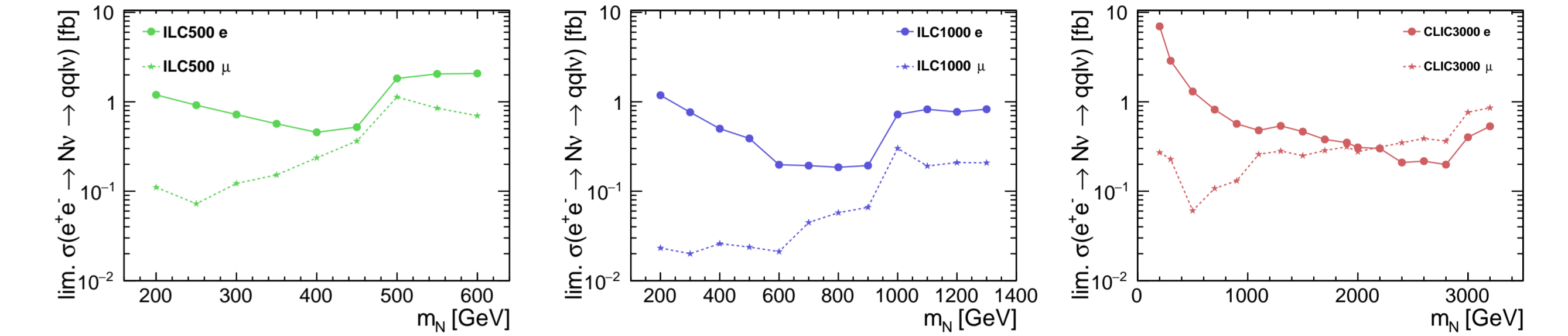
- Only events consisting of **two jets and one lepton** (electron or muon) were accepted for the analysis.
- In the figure below, the qq invariant mass distributions (reference scenario: Dirac neutrino with mass of 300 GeV) are shown for ILC500 for electrons (left) and muons (right) in the final state.



- The **Boosted Decision Trees** (BDT) method with 8 input variables describing lepton and dijet kinematics was used.
- To get final results, the **CLs method** basing on the BDT response was employed with:
 - \star electron and muon channels combined,
 - \star normalisation uncertainty applied.

Cross section limits

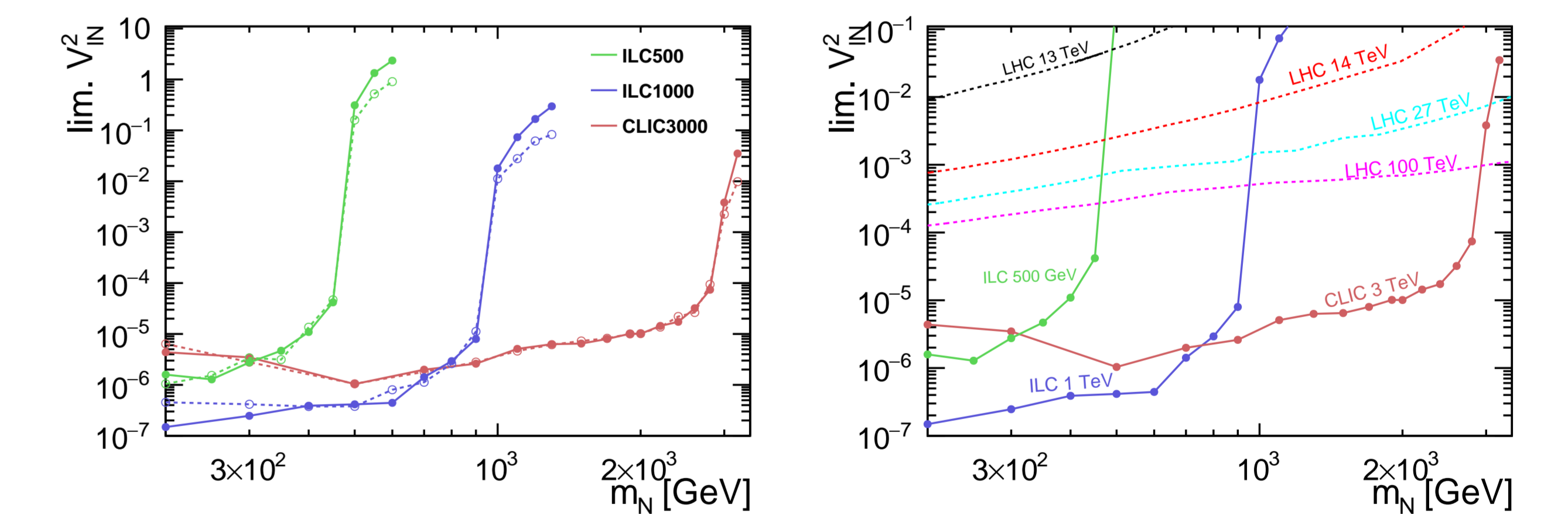
- By scaling results for the reference scenario, one can extract exclusion limits on the cross section for the considered process:



- In the most cases, results for the **muon channel** are more stringent than those for electrons.

Coupling limits

- The above limits can be translated into limits on the V_{lN}^2 coupling parameter.
- Left:** limits for **Dirac** (solid lines) and **Majorana** (dashed lines) neutrinos are very similar up to the energy thresholds; above the threshold, the splitting due to width-related effects is visible.
- Right:** the results are compared with the **current limits** from the CMS (black line) and possible successors of the LHC (red, cyan, magenta lines) [4].



- Sensitivity of future e^+e^- machines to heavy neutrino production is **orders of magnitude higher** than that of the hadron machines.

References

- [1] W. Kilian, T. Ohl, and J. Reuter, "WHIZARD: Simulating Multi-Particle Processes at LHC and ILC," *Eur. Phys. J.*, vol. C71, p. 1742, 2011.
- [2] <https://feynrules.irmp.ucl.ac.be/wiki/HeavyN>.
- [3] J. de Favereau *et al.*, "DELPHES 3, A modular framework for fast simulation of a generic collider experiment," *JHEP*, vol. 02, p. 057, 2014.
- [4] S. Pascoli, R. Ruiz, and C. Weiland, "Heavy neutrinos with dynamic jet vetoes: multilepton searches at $\sqrt{s} = 14, 27,$ and 100 TeV," *JHEP*, vol. 06, p. 049, 2019.