ENP: Exploring New Physics

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The research activity of the INFN LNF unit of the ENP (Exploring New Physics) project (Iniziativa Specifica) addresses the phenomenology of particle physics at present and future high-energy colliders, both within and beyond the Standard Model (BSM). In particular, we worked on Higgs physics, Dark Matter, top-quark phenomenology, heavy-ion collisions, heavy neutrinos, Effective Field Theories, supersymmetry and 331 models. We actively contributed to the input for the 2026 update of the European Strategy for Particle physics as well as to the LHC forum for reinterpretation and preservation of data and analyses. Hereafter we highlight the main results achieved in 2025 by the ENP team.

- We contributed to the whitepaper of the LHC Dark Matter Working Group [1] addressing the phenomenology of t-channel dark matter models. We explored both minimal setups with a single dark matter candidate and mediator, as well as more complex scenarios close to UV-complete models. Within each model, the implications on collider, cosmological and astrophysical observations were studied. Furthermore, possible signals due to promptly-decaying or long-lived particles were investigated. From the cosmological viewpoint, we tackled possible dark matter production processes in the early universe. As a whole, computing tools and guidelines were provided for the sake of t-channel dark matter studies in collider phenomenology and cosmology.

- Beyond the Standard Model, we investiged signals of bileptons, i.e. heavy vectors with charge ± 2 and lepton number $L = \pm 2$, also labelled Y^{++} (Y^{--}), whose mass is predicted about 1.3 TeV, according to renormalization group arguments [2]. They are among the main predictions of the 331 model, which is based on a $SU(3)_L \times SU(3)_C \times U(1)_X$ symmetry and manages to explain the number of quark and lepton families and why the third one is asymmetric with respect to the other two. Besides bileptons, the 331 model also features the existence of heavy quarks charged either 5/3 or 4/3 and mass in the TeV range. We considered a scenario where such heavy quarks T, with charge 5/3, are produced in pp collisions, i.e. $pp \to T\bar{T}$, and decay according to $T \to Y^{++}b$, followed by $Y^{++} \to \mu^+\mu^+$. Our decay chain then yields a final state with two same-charge muon pairs and two b-jets. We chose a benchmark of the parameter space, not yet excluded by the LHC searches, and found that the 331 signal can be visible at a future 100 TeV hadron collider, namely FCC-hh, while the LHC statistics are not sufficient, even in the high-luminosity phase.

- We tackled supersymmetry scenarios at LHC featuring electroweakinos with masses of a few hundreds GeV [3, 4]. In fact, the searches for the so-called 'golden channel' $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm \to (\tilde{\chi}_1^0 Z)(\tilde{\chi}_1^0 W^\pm)$ exhibited some excess at ATLAS and CMS for events with 2 or 3 soft leptons plus missing energy, assuming $m_{\tilde{\chi}_2^0} \simeq m_{\tilde{\chi}_1^+} > 200$ GeV and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq 20$ GeV. Such excesses were explored in the framework of the NMSSM, with the lightest neutralino being a singlino and a dark matter candidate, and the second and third lightest ones being higgsino-like. Moreover, in the considered scenario the mixing parameter μ is smaller than the parameters M_1 and M_2, the GUT-inspired relation $M_1 \sim M_2 \sim M_3/6$ is satisfied, while all scalars are too heavy to play any role. It was hence found that, in this framework, one is capable of explaining the observed excesses, which leads to the hope of a possibile discovery of physics beyond the Standard Model. One is therefore looking forward to the LHC Run 3 analyses, which are expected to give conclusive results, either confuting or confirming such an excess.

- We tackled top-quark physics at a future electron-positron collider, such as FCC-*ee*, which will ultimately allow to study the top properties with an accuracy which cannot be achieved at hadron colliders, such as the LHC. In Ref. [5] we focused on the possibility to bound exotic top decays at the FCC-*ee*, by making use of the recoil mass in $t\bar{t}$ events, assuming that one tags only one of the two tops. We considered a centre-of-mass energy $\sqrt{s} = 365$ GeV and, in order to avoid complications due to neutrino missing energy, we investigated the all-hadron channel. We set up a simple strategy to reconstruct $t\bar{t}$ pairs, based on the k_T jet-clustering algorithm and the use of the recoil mass, and obtained an efficiency about 99.5%. The complementary 0.5% can hence be interpreted as the sensitivity of FCC-*ee* to exotic top decays.

- Work was carried out for the purpose of Higgs decays. In particular, the grids used by the code HDECAY were improved by including finite mass effects in $H \to gg$ at NLO and the explicit branching ratios of the Yukawa part of $H \to s\bar{s}$ decay [6]. Furthermore, strong and weak Dalitz decays $H \to s\bar{s} + g(\gamma)$ were calculated, where Dalitz decays separate the Yukawa-induced part from the continuum one, not due to Yukawa-like couplings. By using the improved code, one will be able to set bounds on the strange-Yukawa coupling at LHC and ultimately at the future FCC-*ee*.

- We contributed to the ECFA Higgs, electroweak and top factory study [7], which was carried out between 2021 and 2025, as a common effort of both theoretical and experimental communities working on the different projects of future colliders. The report [7] updates the current knowledge of the potentials of future e^+e^- accelerators as Higgs, electroweak and top factories.

- We actively contributed to European Strategy for Particle Physics (ESPP), namely the plans of the European particle physics community to improve the human knowledge in fundamental physics. The Briefing Book [8] presents a summary of all submissions by the community. In particular, nine working groups of the PPG (Physics Preparatory Group) were made, leading to corresponding chapters in the report: electroweak, strong interactions, flavour, BSM physics, neutrinos and cosmic messengers, dark matter and dark sectors, accelerator science and technology, detector instrumentation, computing. The briefing book evaluates the performance of the proposed colliders and experiments in terms of benchmark processes and measurements, as defined by the PPG working groups. The differences in the potential of the various options were thoroughly discussed, in such a way to provide an essential input for the final recommendations of future accelerators.

- We contributed to the debate on the preservation and possible reinterpretation of data and analyses in high-energy physics [9]. In fact, it is mandatory that the experimental collaborations publish and store sufficient information on data and analyes, in such a way that their impact can be achieved even in future. It was then recommended that one should preserve algorithms, statistical information, simulations and, of course, recorded data.

- We studied ultrafaint dwarf galaxies (UFD), which are an ideal environment to explore dark matter, thanks to the minimal baryonic effects. In particular, it was found [10] that the so-called fuzzy dark matter cannot explain DM core profiles, as suggested by UFDs.

- First-order phase transitions in the early Universe can lead to the emission of both relativistic and heavy particles, due to the collision of ultra-relativistic bubble shells, which can yield CP violation. Among the CP-violating processes, one has production and decay of heavy particles, as well as production of light and relavistic SM ones. Such mechanisms can explain dark matter and baryon number asymmetry [11], while an inverse-seesaw mechanism can yield tiny neutrino masses. A typical signal of such first-order phase transitions is an irreducible gravitational-wave background, possibly testable at the Einstein telescope [11].
- We investigated multi-phase critical scenarios, with two connected phases, differing by the vacuum choice. Furthermore, the model [12] predicts an extra light scalar, named dilaton, weakly coupled with the Higgs boson, and a heavy state, playing the role of dark matter. We studied the phenomenology of this model by means of Effective Field Theory methods, taking particular care about the running of the scalar couplings and quantum corrections due to the dark matter candidate.

References

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