Theory aspects: contributions to ESG

(GT1, GT2, GT3 and GT4)

S. Lavignac, C. Marquet, C. Smith and A.M. Teixeira

Role of Theory

Standard Model - incredibly successful description of particle physics

(although many aspects remain to be explored: collective phenomena, finite temperature, phase transitions, topological effects,…)

Going beyond the SM - the case for **New Physics**

Observational problems (**neutrino masses**, BAU, dark matter candidate)

Theoretical inconsistencies & challenges:

understanding EWSB (and stability of EW vacuum), hierarchy problem, flavour puzzle, strong CP problem, unification, ...

So far, no new physics has been discovered...

⇒ **Direct searches** for new states at the different frontiers

⇒ Precision and consistency **tests of the SM,** including searches for forbidden processes

Theory: **crucial** part of the general effort of particle physics to ***understand the fundamental laws of nature*** and to ***identify the NP*** at work

Theoretical approaches are essential for **advances** in the field of **Particle Physics**

Precise theoretical predictions

Confirming SM and/or identifying **deviations** (**hints** of underlying **New Physics**)

⇒ ***Bring down theory errors*** to match experimental precision!

⇒ Advances in multi-loop **corrections**, control **precision of SM input** parameters

- Precise predictions of **Higgs** **production** cross sections and various **decays** (ideally full 2-loop)
- Efforts for each **EW threshold** at future collider (possibly 3 to 4-loop level in EW and QCD...)

- **Precise predictions for flavour** physics observables
- Crucial role of **Lattice QCD** (hadron form factors and decay constants, PDFs, GPD, ...)

- **Precise computations** of **neutrino** **cross-sections**
- Improvements in **accuracy of nuclear matrix elements**
  (neutrinoless double beta decays, dinucleon transitions, ...)

- Even if in **perturbative** (high-energy) **QCD regimes**, ensure expansion in conjunction with **all-order resummation** of large logarithms: **new developments** required
- **Lattice QCD:** critical for key insights on **QCD phase structure** & **hadron spectroscopy**

Precise theoretical predictions

Confirming SM and/or identifying **deviations** (**hints** of underling **New Physics**)

⇒ ***Bring down theory errors*** to match experimental precision!

⇒ Advances in multi-loop **corrections**, control **precision of SM input** parameters

- Precise predictions of **Higgs production** cross sections and various **decays** (ideally full 2-loop)
- Efforts for each **EW threshold** at future collider (possibly 3 to 4-loop level)

Massive developments in **integration techniques** & state-of-the-art **event generators**
(incorporating higher-order QCD and EW corrections, factorisation theorems, parton evolution,
and resummation of QCD and QED effects...) and in **LQCD methods**

⇒ **Significant increase in computational needs**

- **Precise predictions** for **nuclear matrix elements**
(neutrinoless double beta decays, dinucleon transitions, ...)

- Even if in **perturbative** (high-energy) **QCD regimes**, ensure expansion in conjunction with **all-order resummation** of large logarithms: **new developments** required
- **Lattice QCD:** critical for key insights on **QCD phase structure** & **hadron spectroscopy**

Searching for new phenomena

Theoretical approaches in close dialog with **experimental searches:**

learning from experimental advances, **fuelling** experimental searches

Model building: the quest for the *ultimate **BSM** construction!*

Addressing observational problems & providing a full understanding of theoretical issues

(naturalness, hierarchy problem, unification, flavour puzzle, strong CP problem, ...)

⇒ **sourcing** new **experimental ideas & approaches** to probe such constructions!

Interpreting experimental results & phenomenological studies:

- strive to **understand SM emergent phenomena** (e.g. in QCD high-energy/density/temperature regimes) which *may cloud interpretation of results*
- confrontation with **detailed phenomenological studies** of given (class of) **NP models**
- **"model-independent" characterisation of NP** via Effective Field Theory approach
- development of **automated searches** (proto model builders, ...)
- ...

All experimental frontiers are crucial for **reconstruction and tests of underlying BSM:**

high-energy, flavour and precision, QCD, neutrino physics, dark matter and cosmology!

Transverse theory contribution

The role of theoretical approaches - the community's message to the ESG

Theory is a crucial part of the general effort of the particle physics community to understand the fundamental laws of nature and to identify the NP required to address the shortcomings of the SM. In the quest for NP, precision tests of the SM play a crucial role, especially in view of the preparation of future leptonic Higgs factories (also offering the Tera-Z run): theory uncertainties must be strongly reduced to be on par with the expected experimental accuracy. Likewise, precision calculations of flavour observables and of neutrino cross sections are also very important. A realistic assessment of the theory errors requires massive developments of both analytical and numerical integration techniques: this includes EW and QCD higher order contributions (2 to 4-loops), as well as innovation of multi-purpose event generators; such developments can strongly benefit from ML methods. LQCD is also critical to access new observables.

At the crossroads of theoretical and experimental particle physics ultimately lies the interpretation of data, which includes model-independent characterisations of NP (effective approach), as well as dedicated studies of specific NP models, complemented by proto-model builders. Model building approaches offer complete high-energy constructions; tests of the latter can then inspire dedicated experimental searches. The reconstruction of the NP model will call upon input from all experimental frontiers: high-energy, flavour and EW precision, neutrino physics, QCD, dark matter searches and cosmology.

Therefore, any strategy on the future of experimental particle physics must be accompanied by a vision concerning the support that must be provided to particle theory, and to further foster European initiatives promoting theory-experiment collaborations.