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Discussione su European Strategy per INFN

Tor Vergata 06-11-2024

open questions in particle physics

inputs from roberto frezzotti and alberto salvio

caveat: please don't expect a well-thought presentation

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- on the other hand, we are discussing here the **update** of the European Strategy, and ...

- **the starting point is already excellent!**

CERN-ESU-004
10 January 2020

Physics Briefing Book

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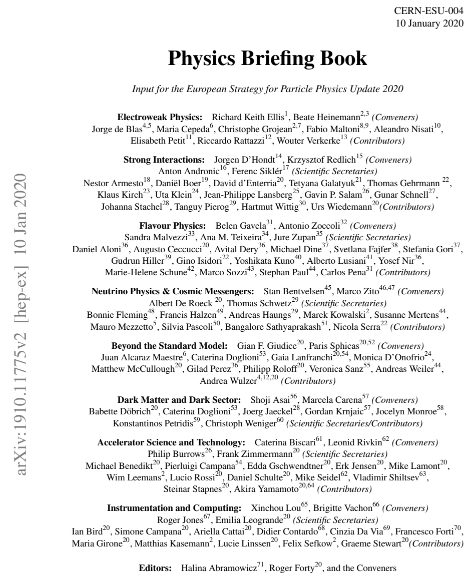
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arXiv:1910.11775v2 [hep-ex] 10 Jan 2020

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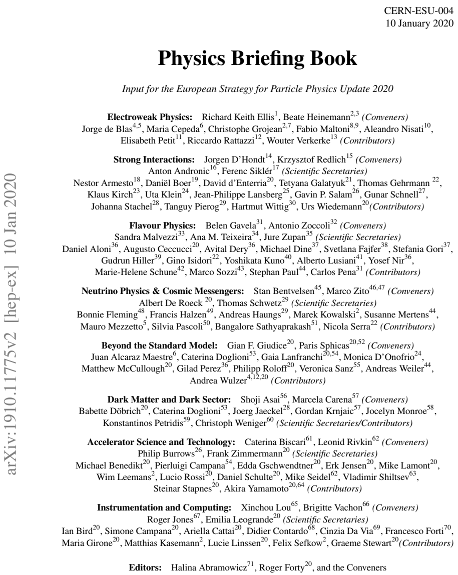

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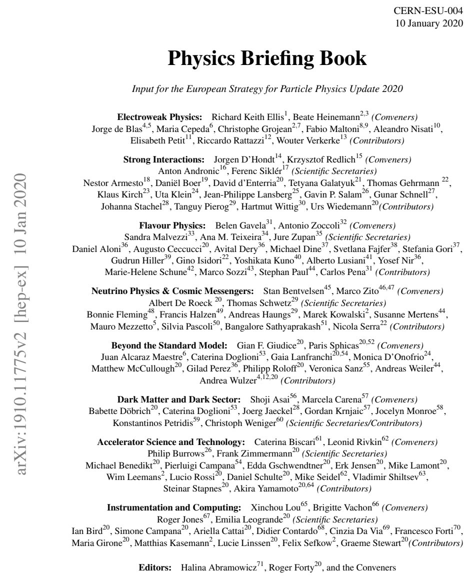
- let's quickly go through the questions . . .



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2 Higgs Naturalness

- we have discovered the Higgs and now we have to understand it
- more than a matter particle, the Higgs is the mediator of the flavour-structured SM Yukawa interaction
- on the countrary of the sector of the spin-1 gauge-mediators, the Higgs sector is essentially unconstrained by symmetry
- by looking at the SM as an Effective Quantum Field Theory (EQFT), one is tempted to say that the experimentally measured value of the Higgs mass is unnatural ...
- we must take at face-value **the fact** that, unlike most of the phenomenologically-useful EQFTs, **the SM** is renormalizable and therefore consistent at all energies: it **doesn't predict its destruction!**
- in other words: **new physics exists** (gravity, dark matter, dark energy, neutrino masses, etc.) **but has to be found somewhere between 10^{-22} eV** (fuzzy DM) **and 10^{19} GeV** (quantum gravity, unification, etc.)!

1 Electroweak Symmetry Breaking

2 Higgs Naturalness

- immensely-difficult experimental challenges: **HL-LHC, HE-LHC, FCC-ee, FCC-hh, CLIC, ILC, etc.** will allow to explore smaller distances and to continue the long-lasting exciting adventure of the **direct search for new physics**

- the FCC-ee precision-goal on the Higgs couplings is $O(5\%)$: this is a theoretical challenge but not a big one

- extremely challenging is to provide non-perturbative predictions for hadronic matrix elements to use **the pletora of results** that will be provided at future (and have already been collected at the past) colliders for **indirect searches**

- immensely challenging is to find the new theory of fundamental interactions, but certainly doable is the task of continuing to devise well motivated extensions of the SM

3 Strong Interactions

- the QCD sector fo the SM is a fully-satisfactory first-principles theory of the strong interactions
- from the theoretical perspective, QCD is a single theory
- from the technical perspective, the fact that QCD is asymptotically free requires **radically different approaches to study** strong interacting particles at **high ($E \gg m_p$) or at low ($E = O(m_p)$) energies**
- high-energy QCD challenge: developing automated NNLO Monte Carlo tools is mandatory to do physics with HL-LHC, FCC-hh, etc. but keep in mind the irreducible uncertainty of $O(m_p)$
- high-low-energy QCD challenge: getting the required PDFs is, again, mandatory to do physics at the future hadron colliders

3 Strong Interactions

- low-energy QCD challenge: take properly into account EW radiative corrections on precision ($O(1\%)$) observables both on the theoretical (lattice QCD) and experimental (Monte Carlo) sides

- lattice QCD has demonstrated that it is possible to compute low-energy hadronic quantities, including inclusive cross sections and decay rates (R-ratio and $g_\mu - 2$, hadronic τ decays, etc.) with full control of the theoretical errors at the sub-percent level of accuracy . . .

  recently we gave an important contribution to this endeavour, e.g., arXiv:2403.05404, arXiv:2212.08467

- these theoretical results started to rise serious doubts on the reliability of the experimental systematic uncertainties associated with QED radiative corrections that have been estimated with the present available Monte Carlo generators

  see e.g., g.abbiendi et al. arXiv:2201.12102, CMD-3 collaboration arXiv:2302.08834, BaBar collaboration arXiv:2308.05233, m.davier et al. arXiv:2312.02053

- the theoretical methods needed to compute with the required non-perturbative accuracy generic hadronic matrix elements have now been developed

- **an important investment** (nevertheless a small fraction of that needed to build FCC-xx) **in HPC is needed in order to unlock the immense amount of information that (has already been) will be collected on hadronic processes**

- i'm sure that experiments such as LHCb, but also ATLAS, CMS and the future ones, would open a big champagne bottle!

4 Strong CP

- there is one parameter in the SM that has not been measured yet: the strong θ angle
- no accidental symmetry can justify the present upper bound $\theta < 10^{-9}$
- the axion-like solutions to the so-called strong CP problem remain the all-time favourite by theory
- **the search for the axion is therefore a central task of particle physics and requires dedicated experiments**

5 Flavour Physics

- understanding the origin of Flavour means understanding the Higgs and the way new physics works

- in fact we have already mentioned the main challenges . . .

- controlling precision at the sub-percent level of accuracy requires huge HPC resources and improved experimental methods to take into account EW radiative corrections

- a big challenge but possibly a very high gain: **the study of flavour observables can reveal deviations from the SM and/or put constraints on the scale of new physics at much higher energies (up to 10^5 TeV) w.r.t. direct searches**

see the PBB and, e.g., b.grzadkowski et al. arXiv:1008.4884, r.alonso et al. arXiv:1312.2014, j.ellis et al. arXiv:2012.02779

- dedicated experiments are not mandatory, but extremely welcome!

6 Neutrino Physics

7 Dark Matter

8 Dark Sectors and Feebly Interacting Particles

- understanding the origin of neutrino masses and firmly establishing CP violation in the leptonic sector . . .
- understanding the origin of Dark Matter . . .
- means understanding the origin and nature of new physics and **might lead to the discovery of hidden sectors with tiny interactions with SM particles**
- this is the physics observation that **motivates the study of precision observables, theoretically and experimentally, at all energies!**
- **dedicated experiments**, complementary to and independent from collider ones (SHiP at CERN SPS, Borexino, Super-Kamiokande, T2K, NOvA, DUNE, nEXO, SuperNEMO, etc.) **are needed**

9 The Cosmos

10 Gravity

- at the classical level gravity is the gauge theory of space-time
- unlike the SM **quantum gravity predicts its destruction**: unfortunately at the huge energy scale of about 10^{19} GeV
- early-cosmology and black-hole physics are the play-grounds to test ideas about quantum gravity
- according to the SM, the Higgs mechanism took place as a smooth cross-over when the Universe cooled down to temperatures of about 160 GeV but in presence of new physics the phase-transition could have been very different
- **theoretical modelling, the study of gravitational waves and the precision study of the Higgs sector** can shed light on the new physics, on the quantum formulation of gravity and its embedding in the quantum theory of fundamental interactions and **must be supported**
- a key-point: **the cosmos is the most powerful accelerator!**

summarizing

- the **Physics Briefing Book** opens the theoretical section with the question: **Can we predict new discoveries?**
- the answer is no: **The value of an exploratory project should not be measured by the number of promised new discoveries, but by the importance of the questions addressed and by the amount of fundamental knowledge that can be extracted from its results.**
- the amount of fundamental knowledge that can be extracted from future experimental searches **crucially depends on the theoretical inputs and on the ability of taking under control experimental systematics at the (sub) percent level**
- **dedicated investments in HPC resources will allow to exploit the full power of next-generation experiments**
- indeed, even in if devised to do **direct search for new physics**, particle physics **experiments produce a huge amount of (hadronic) information that must profitably be used to do indirect search!**