LHCP2021

The Ninth Annual Conference on Large Hadron Collider Physics

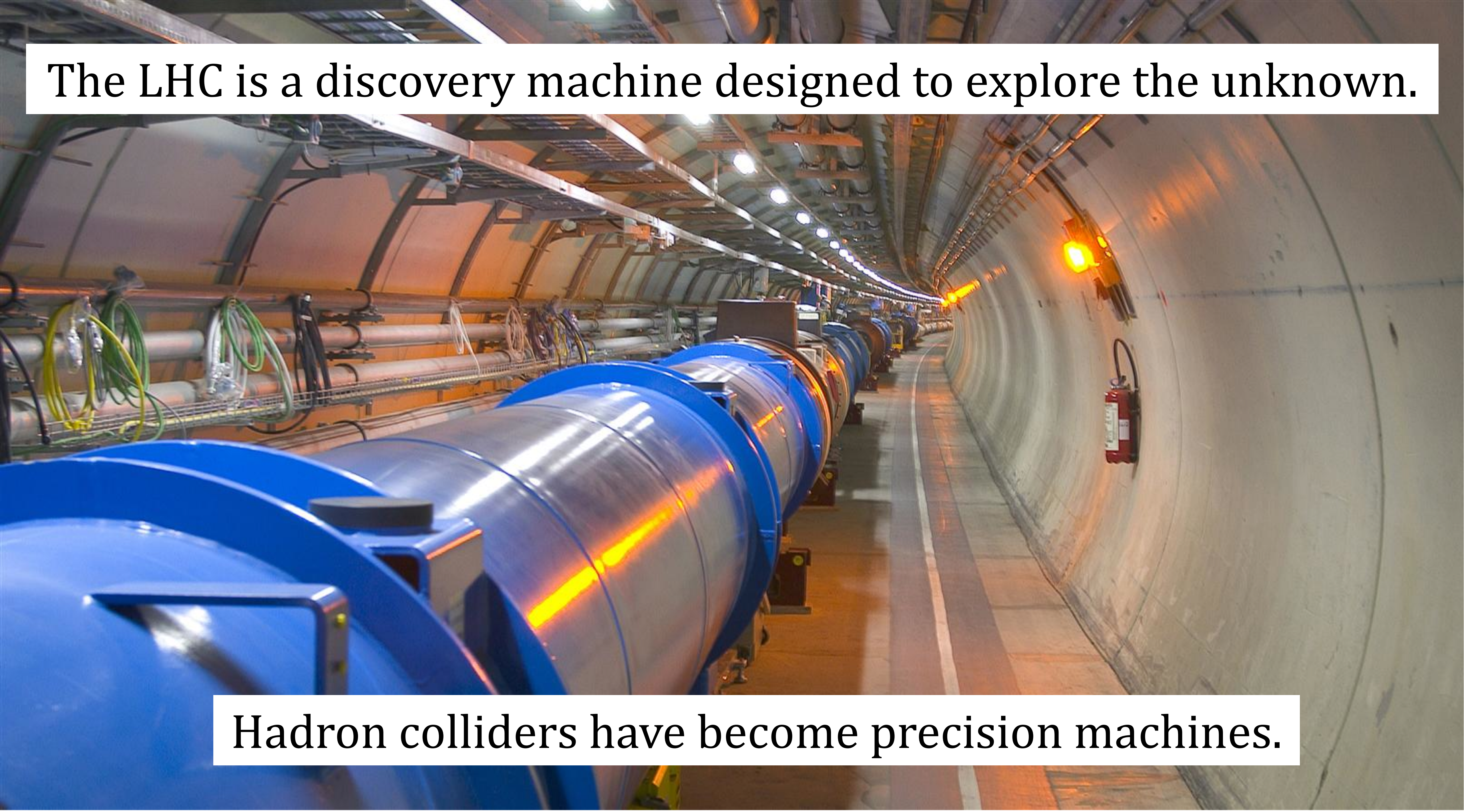
7-12 June 2021 ~~Paris (France), Sorbonne Université (IN2P3/CNRS,IRFU/CEA)~~

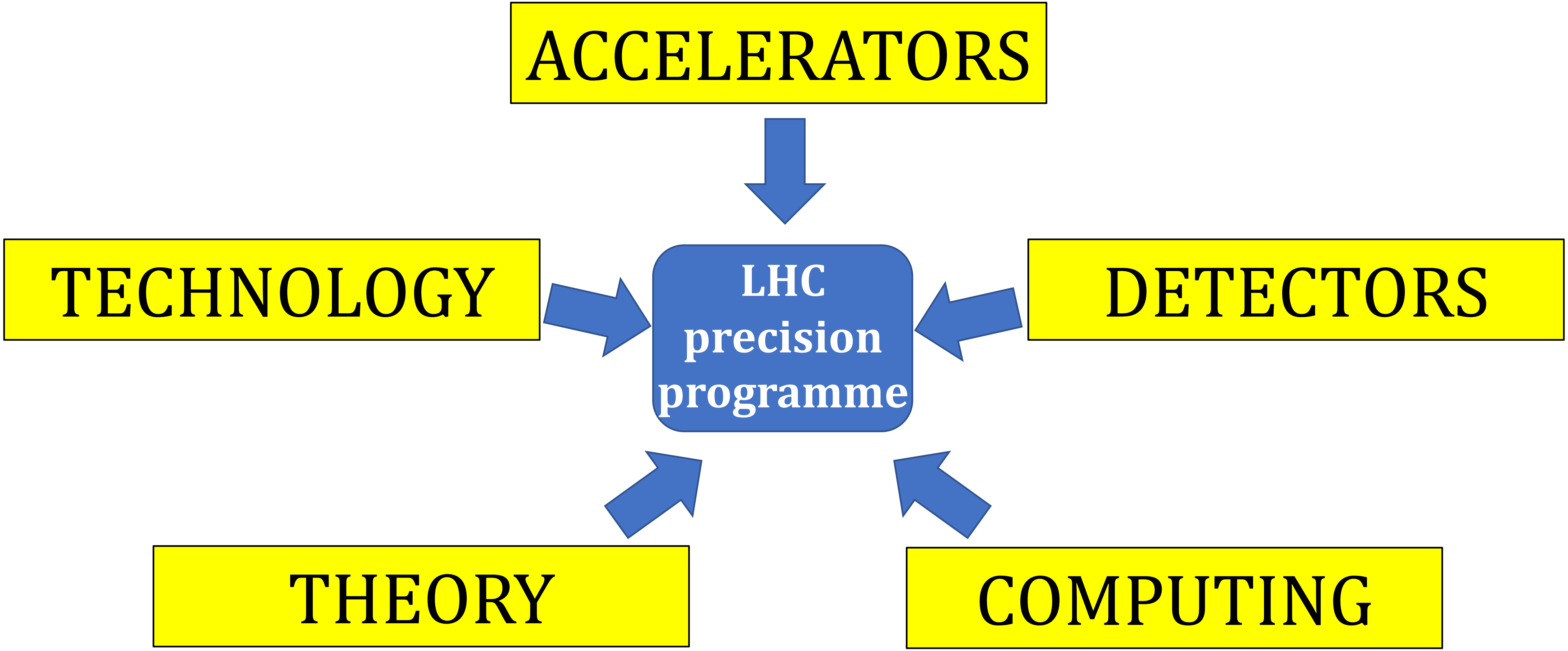
Online

# Closing Talk (Theory)

G. F. Giudice

CERN


The LHC is a discovery machine designed to explore the unknown.
Hadron colliders have become precision machines.




Precision in strong interactions, EW interactions, top and Higgs physics, flavour physics, hadron spectroscopy, heavy-ion physics, ..., compressed spectra, FIPs, LLPs, ...

Precision has become key for present and future exploration.

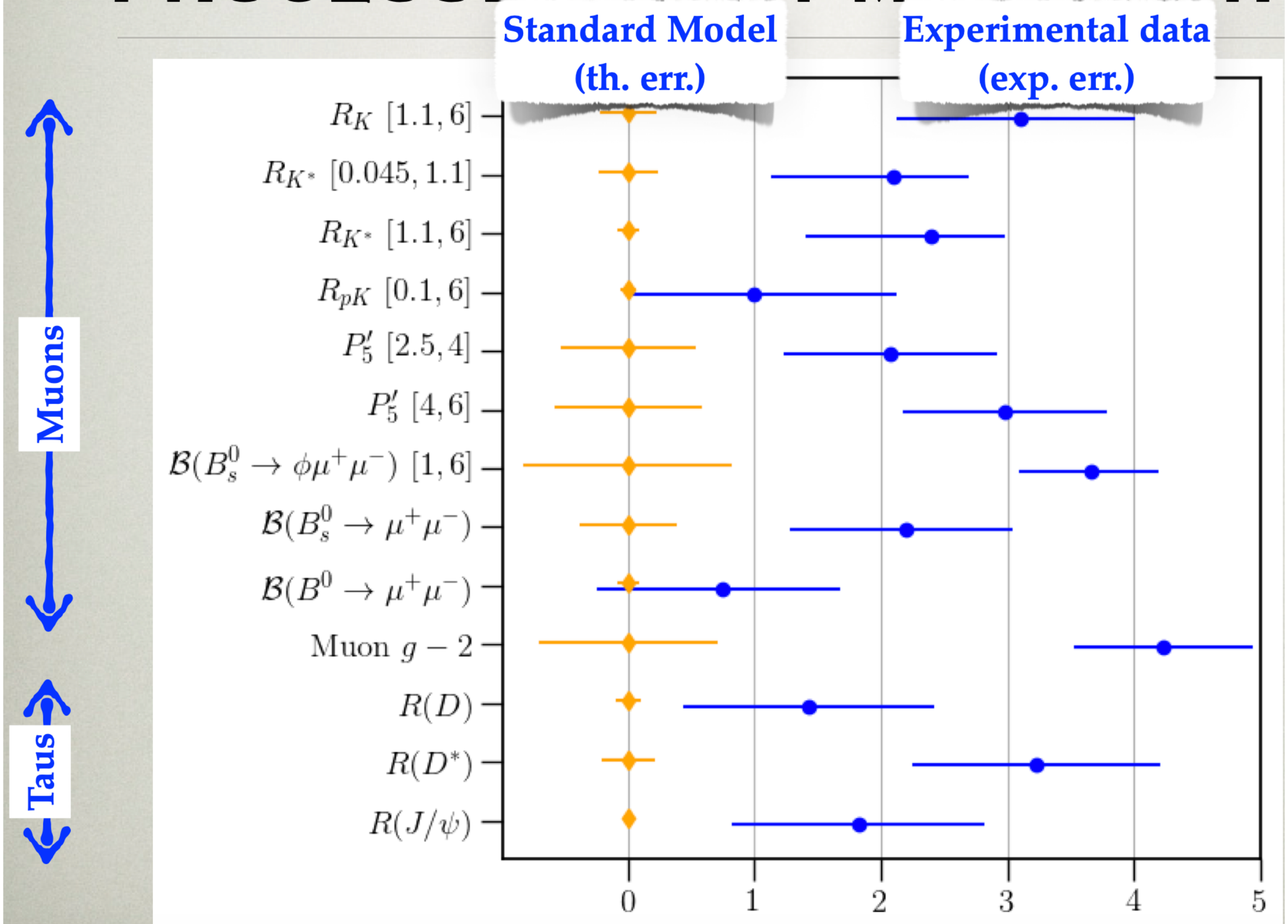



figure credit: Patrick Koppenburg

## If true, this result...

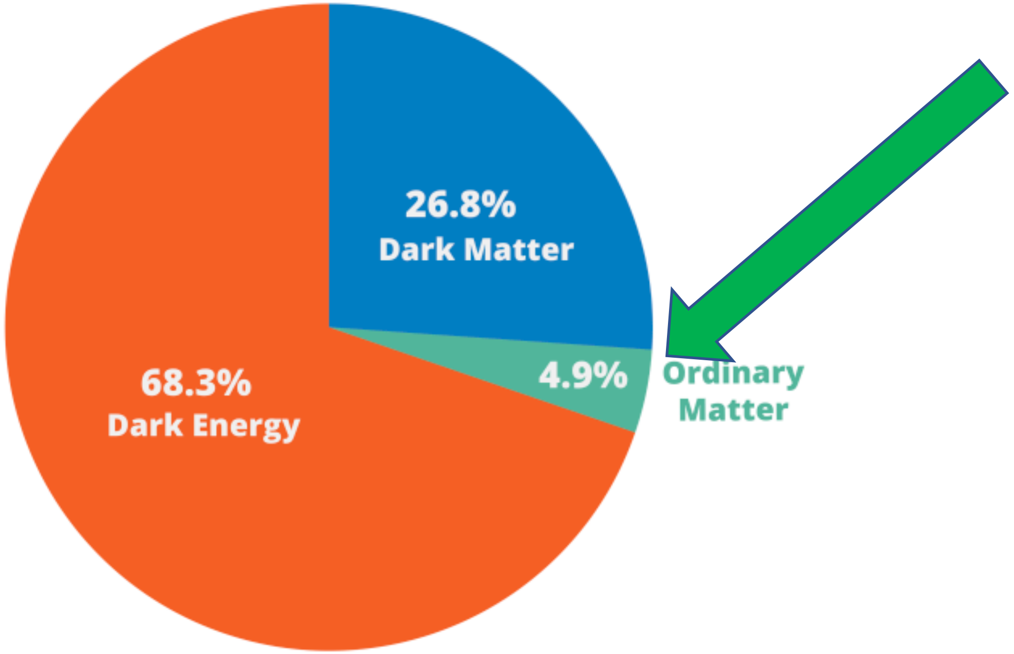
- would be the most revolutionary surprise in fundamental physics since the discovery that the Universe is expanding at an accelerating rate.

- would break apart the flavour structure of the Standard Model and the symmetries on which it rests.

- would radically change our future perspective: a boost for the flavour, precision, and high-energy programmes.

$$\mathcal{L} = y_{ij}^{(u)} \bar{q}_L^i \tilde{H} u_R^j + y_{ij}^{(d)} \bar{q}_L^i H d_R^j + y_{ij}^{(e)} \bar{\ell}_L^i H e_R^j + \text{h.c.}$$

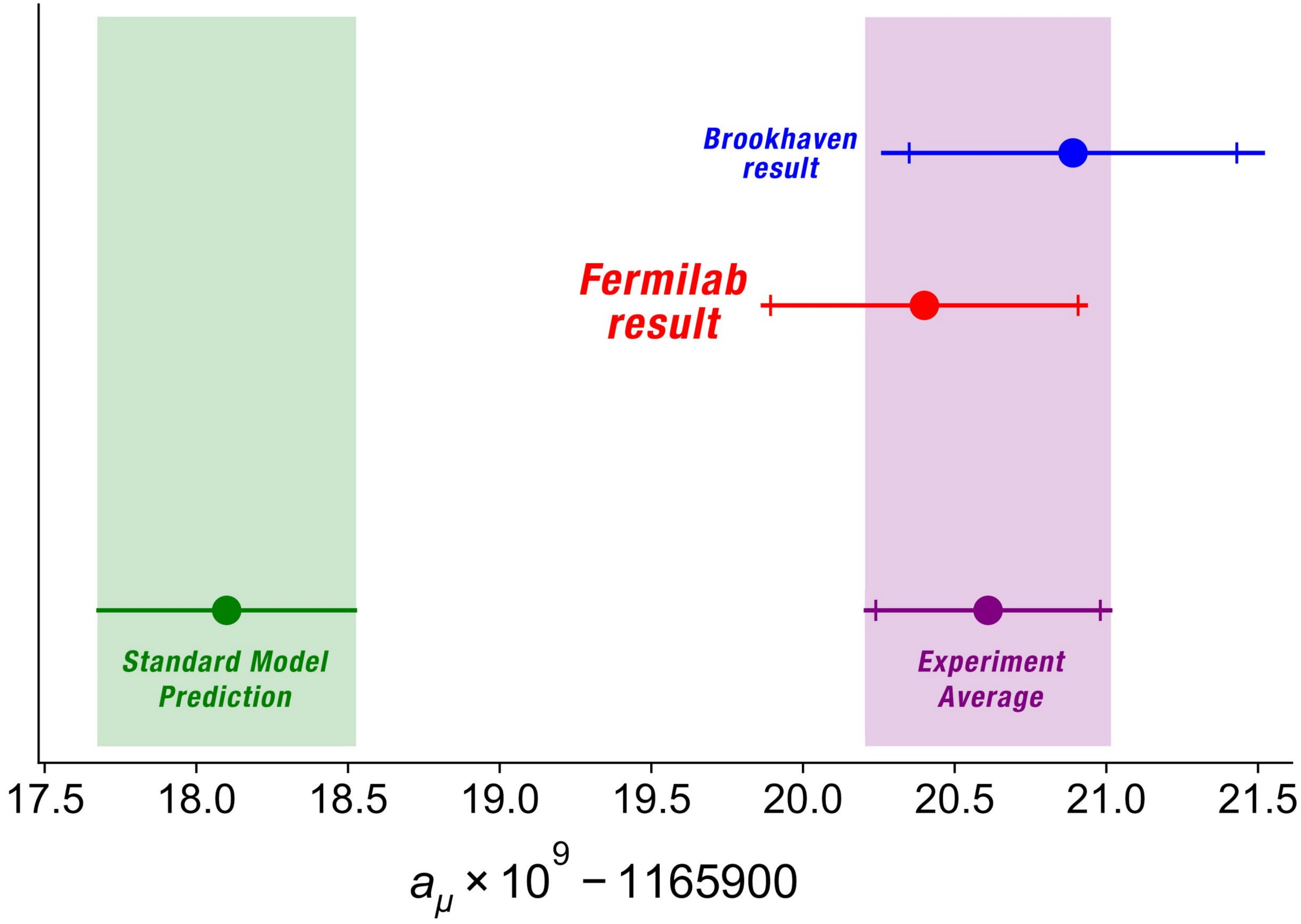
???

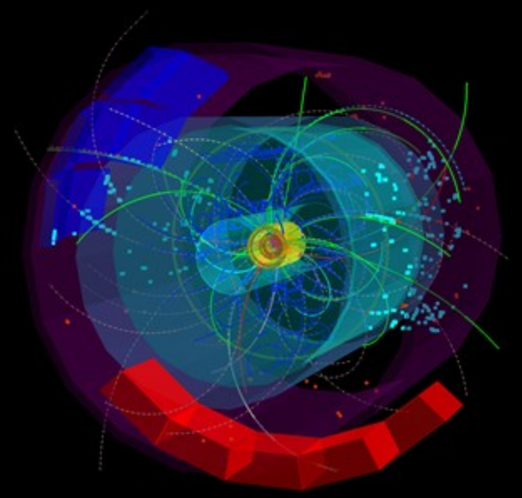


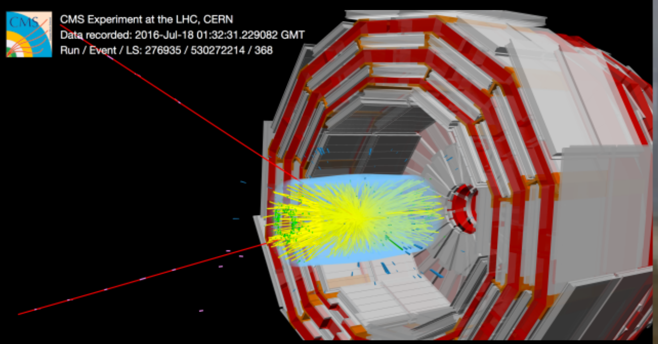

Do we understand this?

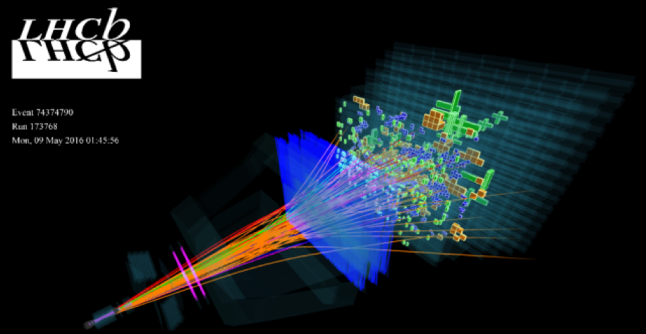
How do we compute $m_H$ ? (The Higgs was discovered 9 yrs ago)

How do we compute $m_e$ ???? (The electron was discovered 124 yrs ago)


Brookhaven
result
Fermilab
result
Standard Model
Prediction
Experiment
Average
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
$a_\mu \times 10^9 - 1165900$




CMS Experiment at the LHC, CERN
Data recorded: 2016-Jul-18 01:32:31.229082 GMT
Run / Event / LS: 276935 / 530272214 / 368


Event 74374790
Run 173768
Mon, 09 May 2016 01:45:56


Symmetry paradigm

Gauge symmetry

↓

Standard Model + General Relativity

↓

Higgs naturalness problem

↓

Technicolor, supersymmetry, Higgs compositeness, ...

↓

???

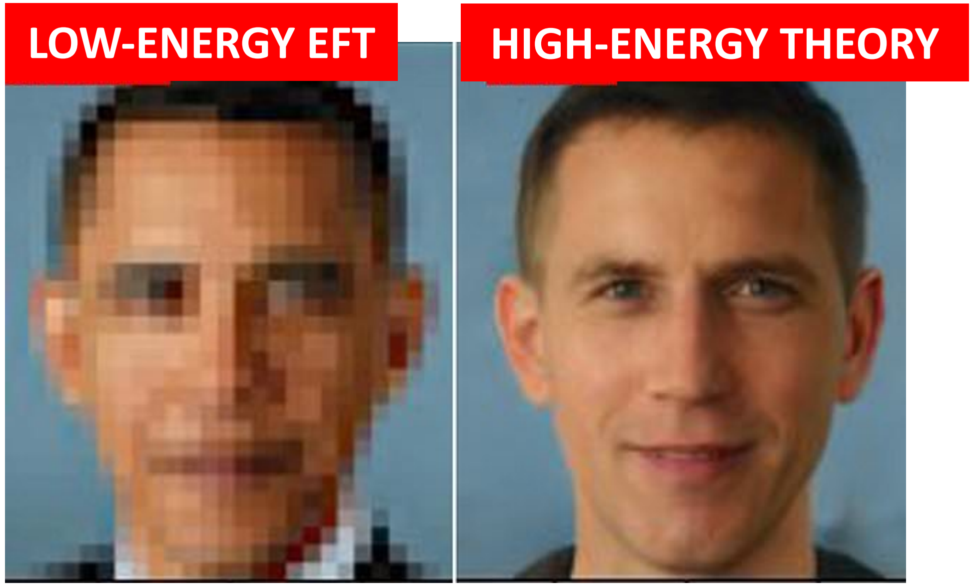
# Symmetry ?? (Experimental clues)

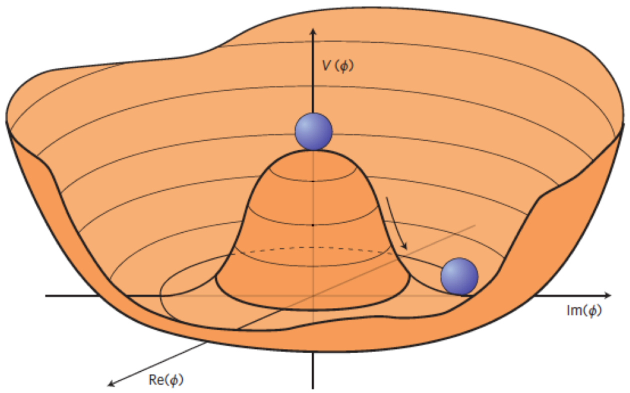
- No new particles at the LHC
- Smallness of the cosmological constant

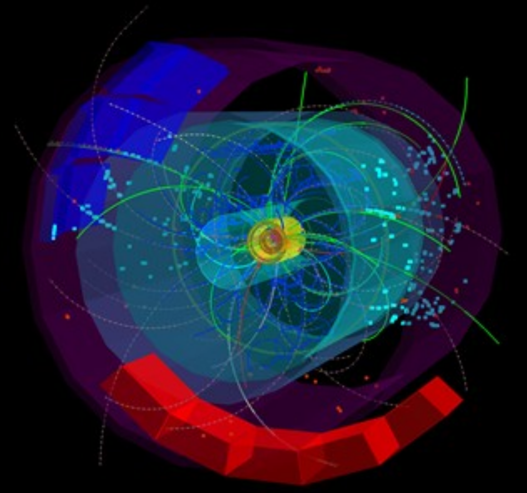
$$V_{\text{eff}}(H) = \Lambda_{\text{CC}}^4 + m_H^2|H|^2 + \lambda|H|^4 + \dots$$

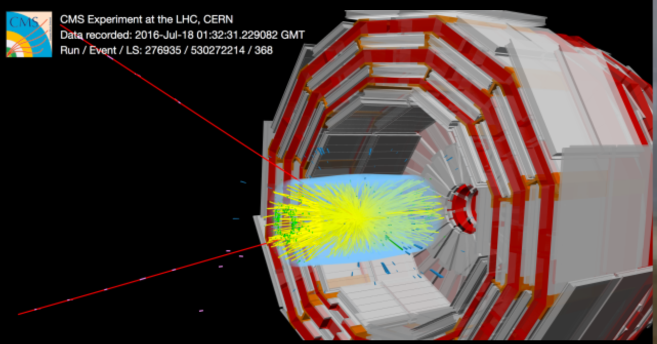
# Symmetry ?? (Theoretical clues)

- Global symmetries are (probably) violated by quantum gravity.
- Global symmetries are an accidental effect of looking at a system at long distances, without sufficient short-distance resolution.
- Gauge symmetries and not physical symmetries, but only a redundancy in the parametrization.
- Gauge symmetries may be emergent.



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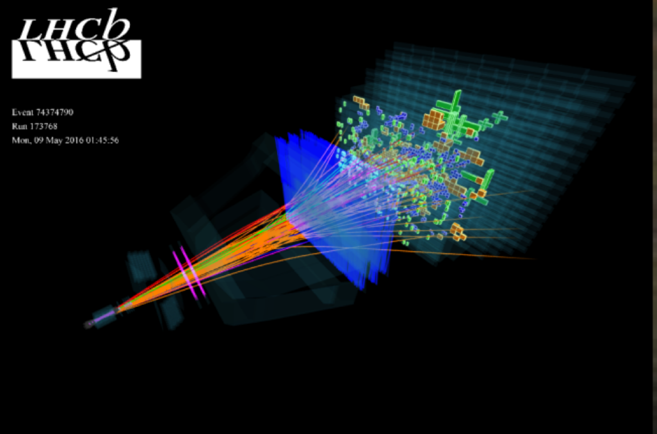
LHCb
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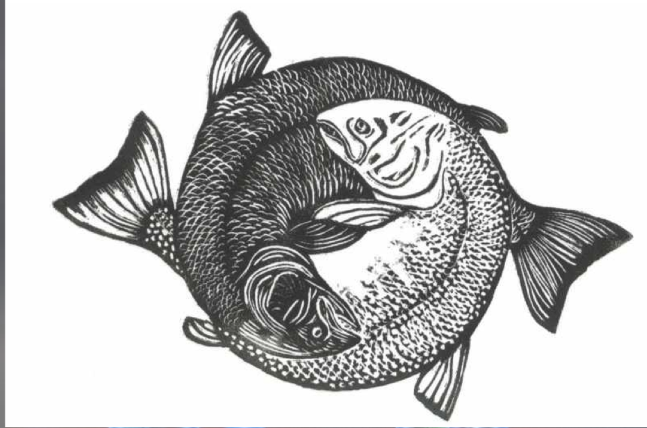
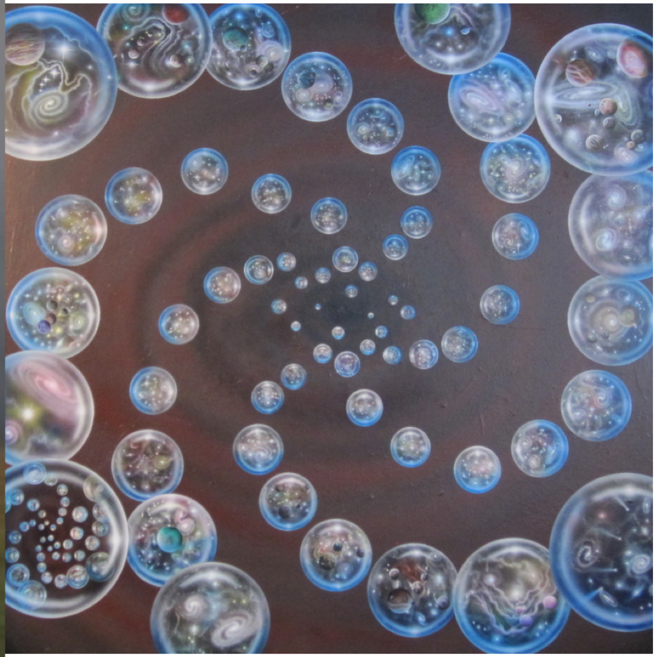
Symmetry paradigm
A new paradigm?





?

The scientific method:

Hypothesis $\Rightarrow$ Thesis $\Rightarrow$ Experiment

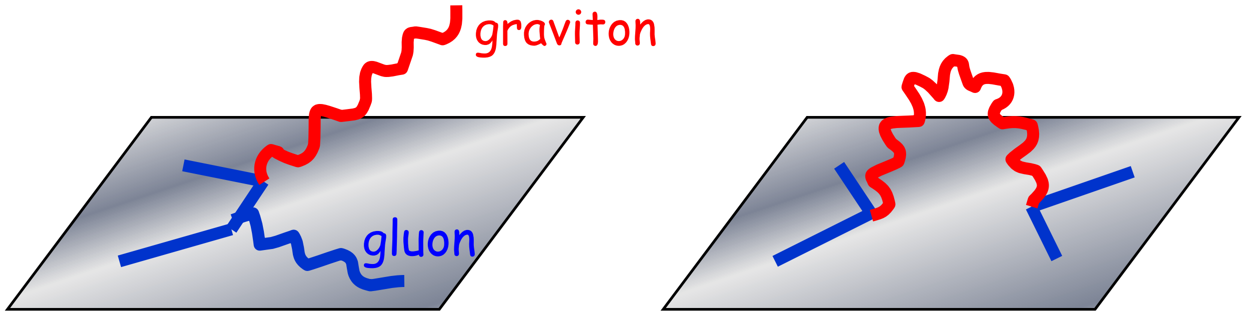
What are the hypotheses on which naturalness rests?

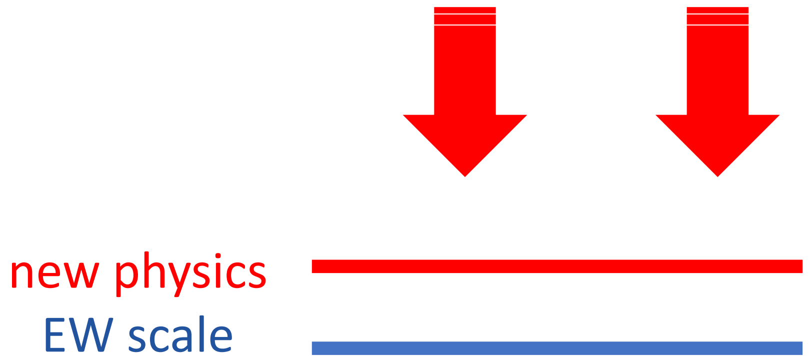
# Scale separation

Are there any new energy scales above the weak scale?

Quantum gravity, neutrino masses, the strong CP problem, inflation, gauge coupling unification, flavour,…?

Large Extra Dimensions

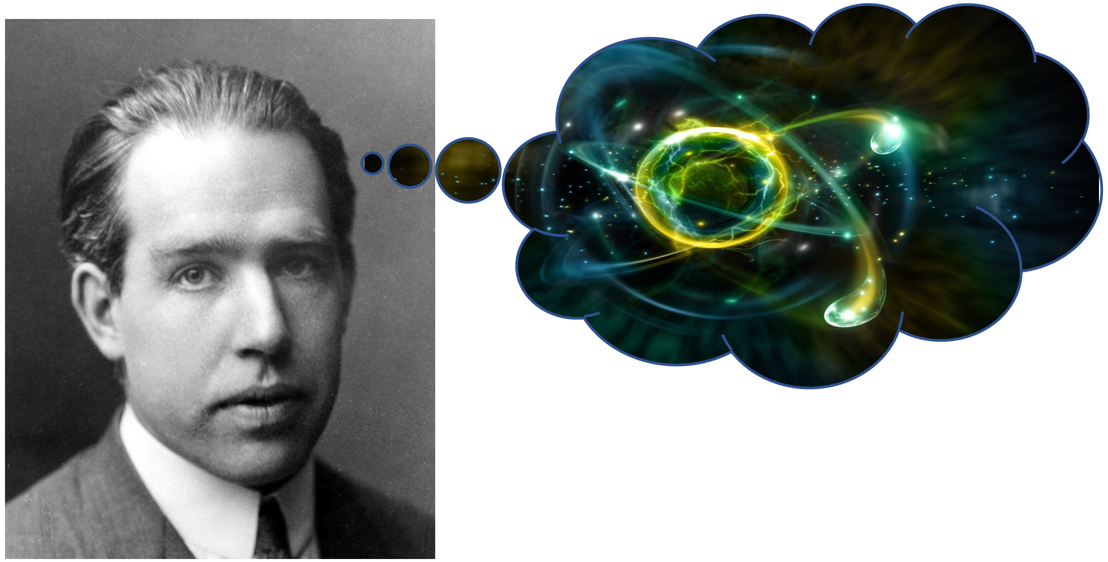



Asymptotic safety in quantum gravity?

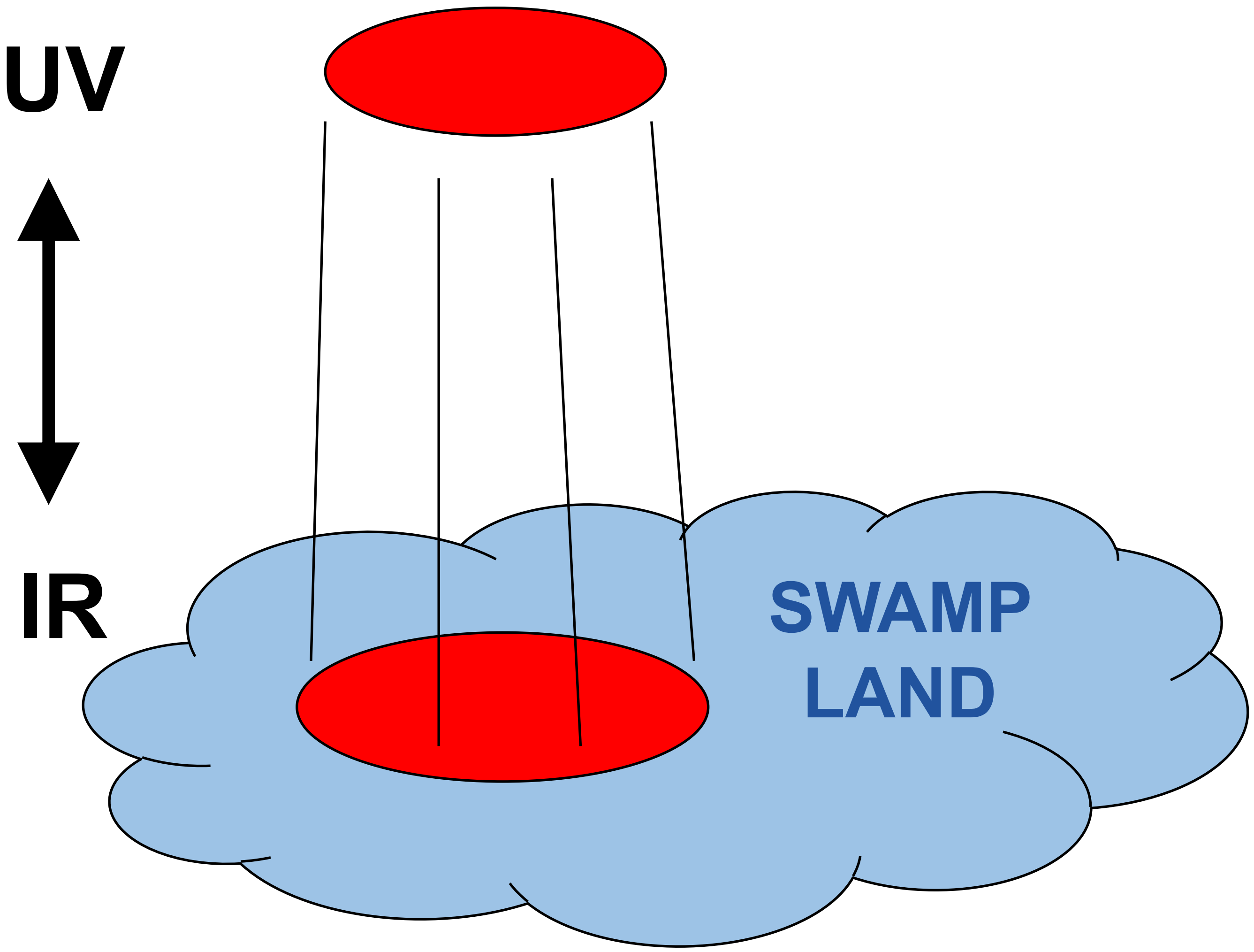
# EFT hypothesis

Physical phenomena can be consistently described by an effective theory valid in a limited energy range.



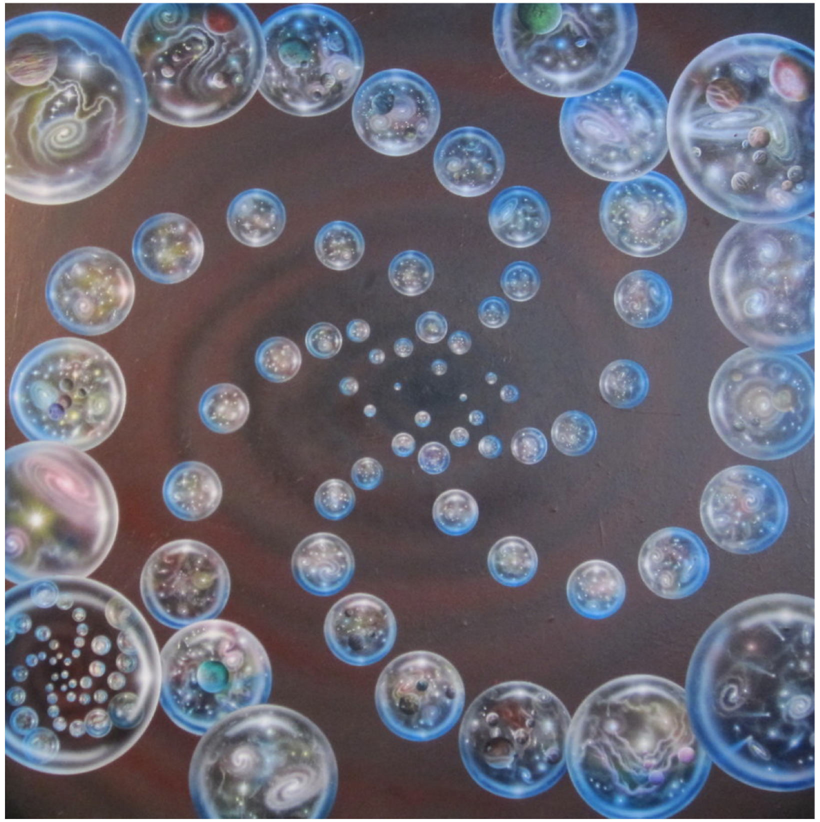
- This hypothesis has been the very reason for progress in physics.
- Progress can proceed step by step, without requiring simultaneous knowledge of physics at all scales.

Some theories allowed by low-energy symmetries live in the swampland



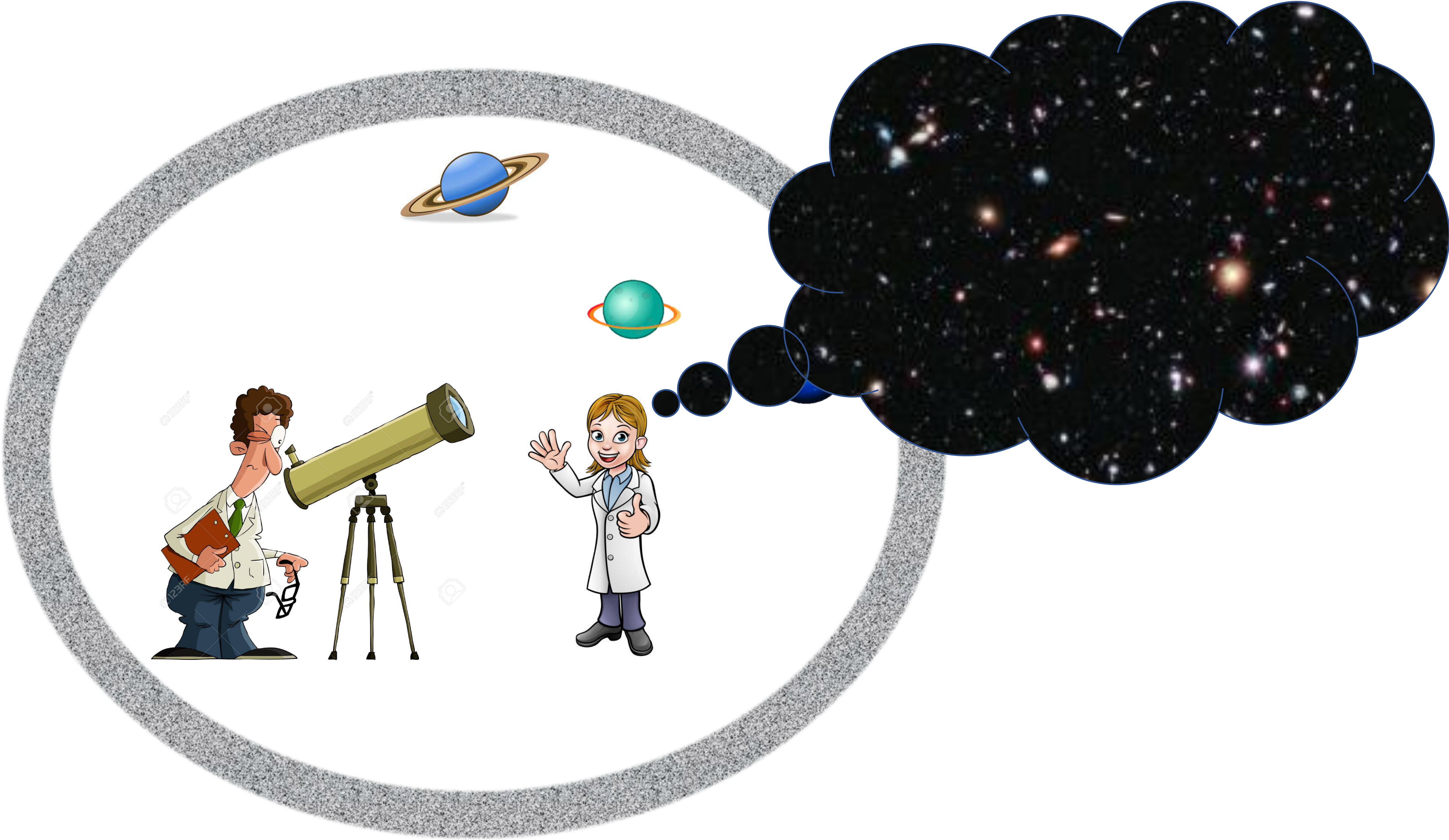

It challenges the EFT intuition on which naturalness is based

# Low-energy free parameters are calculable quantities in a fundamental high-energy theory



SM parameters do not correspond to a unique expression in the fundamental theory, but are functions of some fields whose values vary during the cosmological history or throughout a complex vacuum structure.

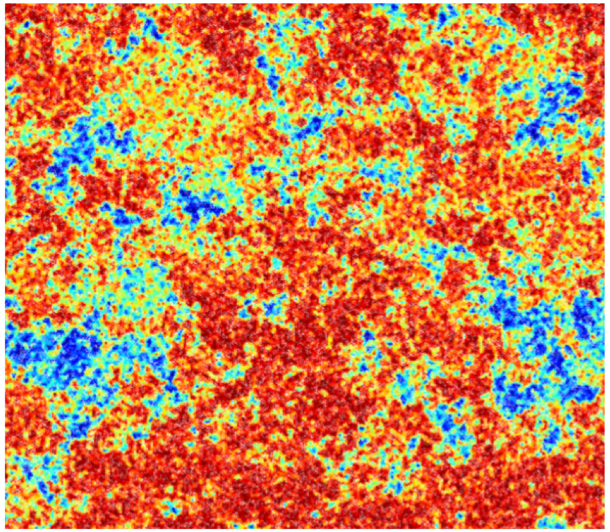
The Multiverse

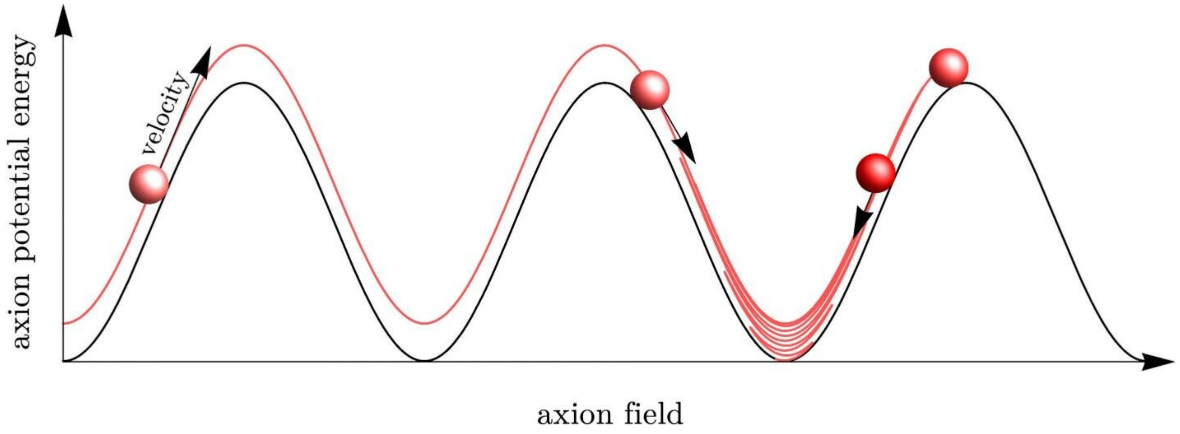


# Axion

$$\mathcal{L}_{\dim=4} = \frac{g_s^2}{32\pi^2}\,\bar{\theta} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a} \qquad d_n \sim e\,\frac{\bar{\theta} m_*}{\Lambda^2_{\rm had}} \sim \bar{\theta}\cdot(6\times 10^{-17})\,e\,{\rm cm} \qquad |\bar{\theta}| < 10^{-10}$$

$$\bar{\theta} \Longrightarrow a$$



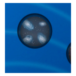



$\Longrightarrow$ multiverse explanation of a low-energy parameter

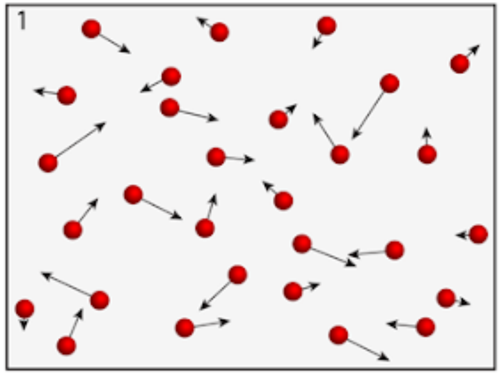
# Critical points of quantum phase transitions can become dynamical attractors during inflation and determine low-energy parameters.

GFG, M. McCullough, T. You, 2105.08617

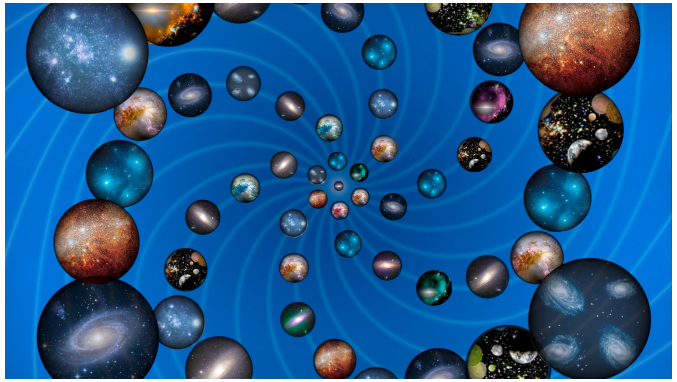
Single atom: energy?



Single Universe: SM parameters?

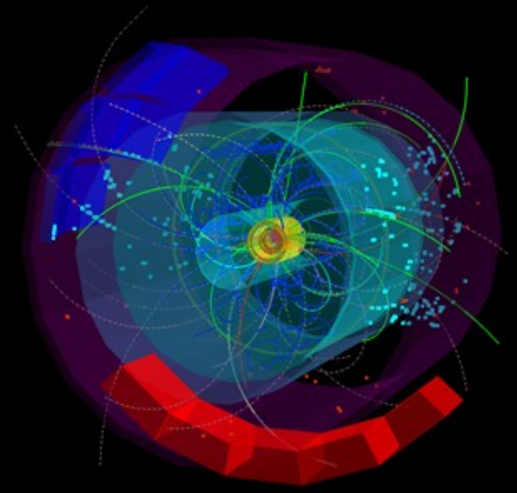


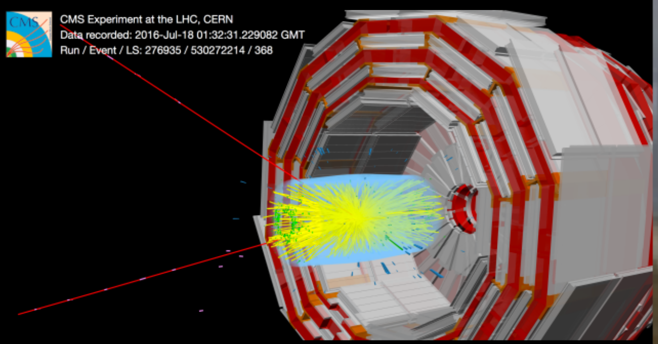
Gas in statistical equilibrium:
probabilistic prediction.

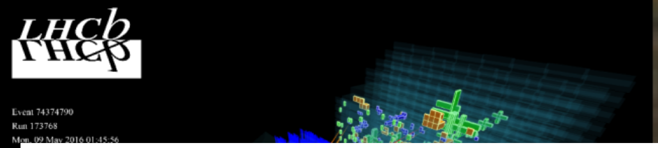


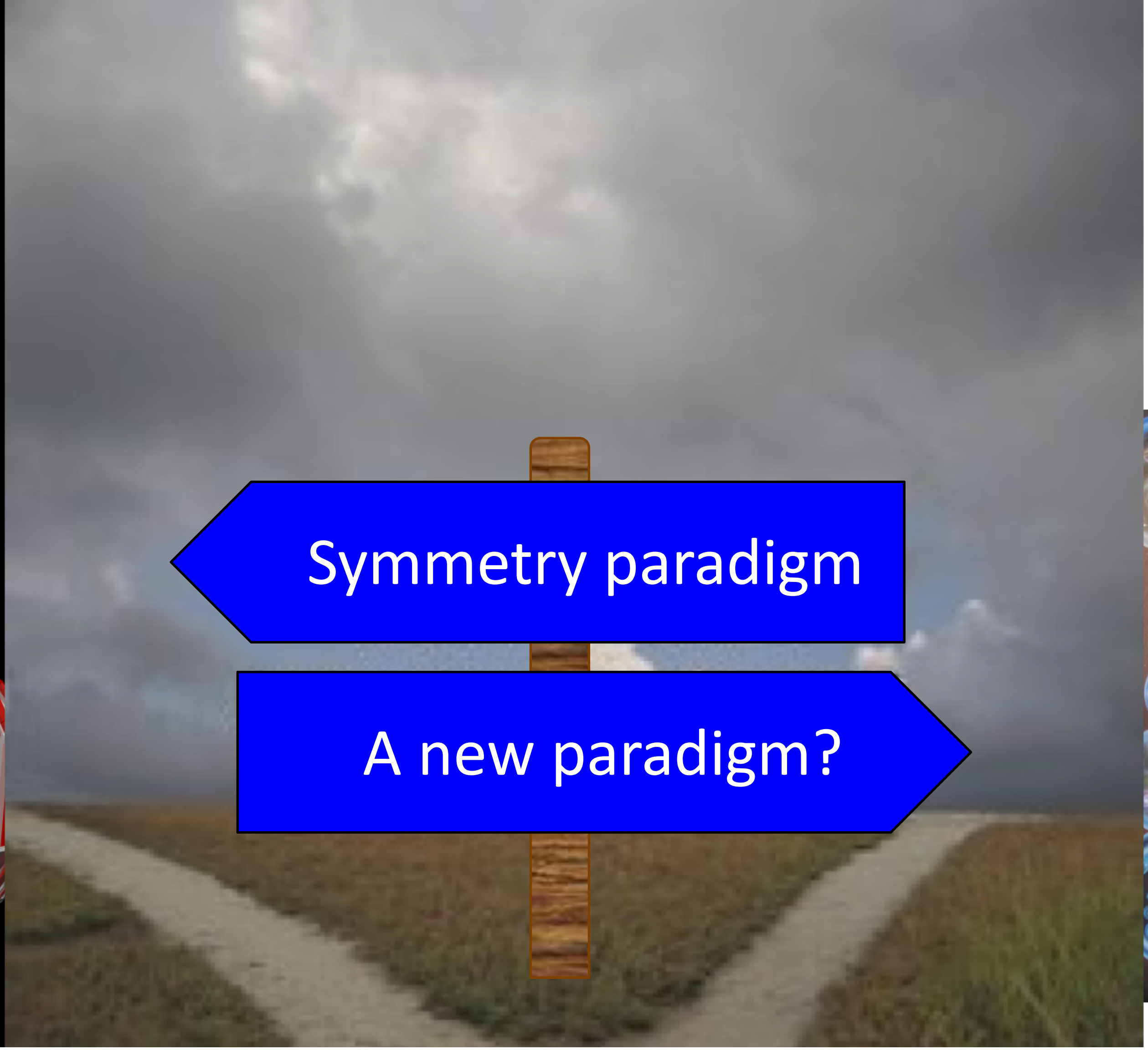
Multiverse in steady-state:
probabilistic prediction.

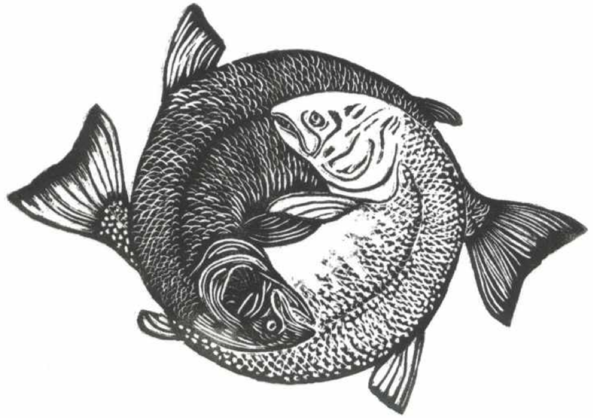
The multiverse as a quantum statistical system.

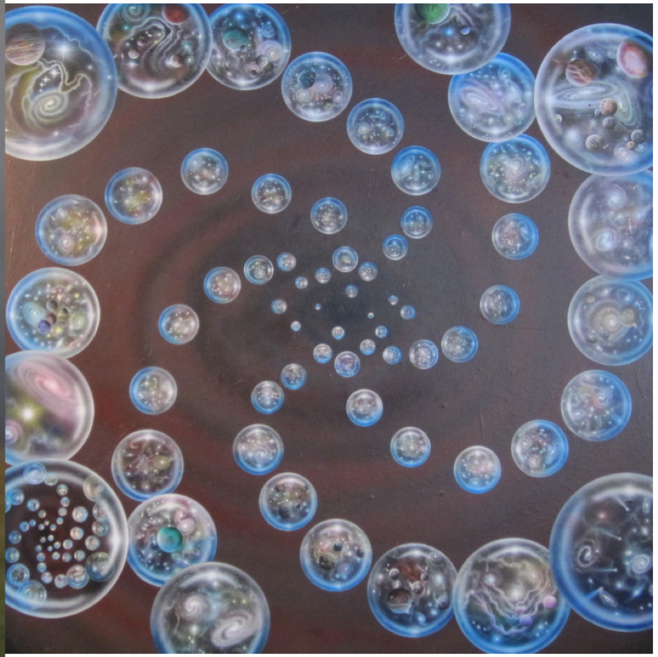




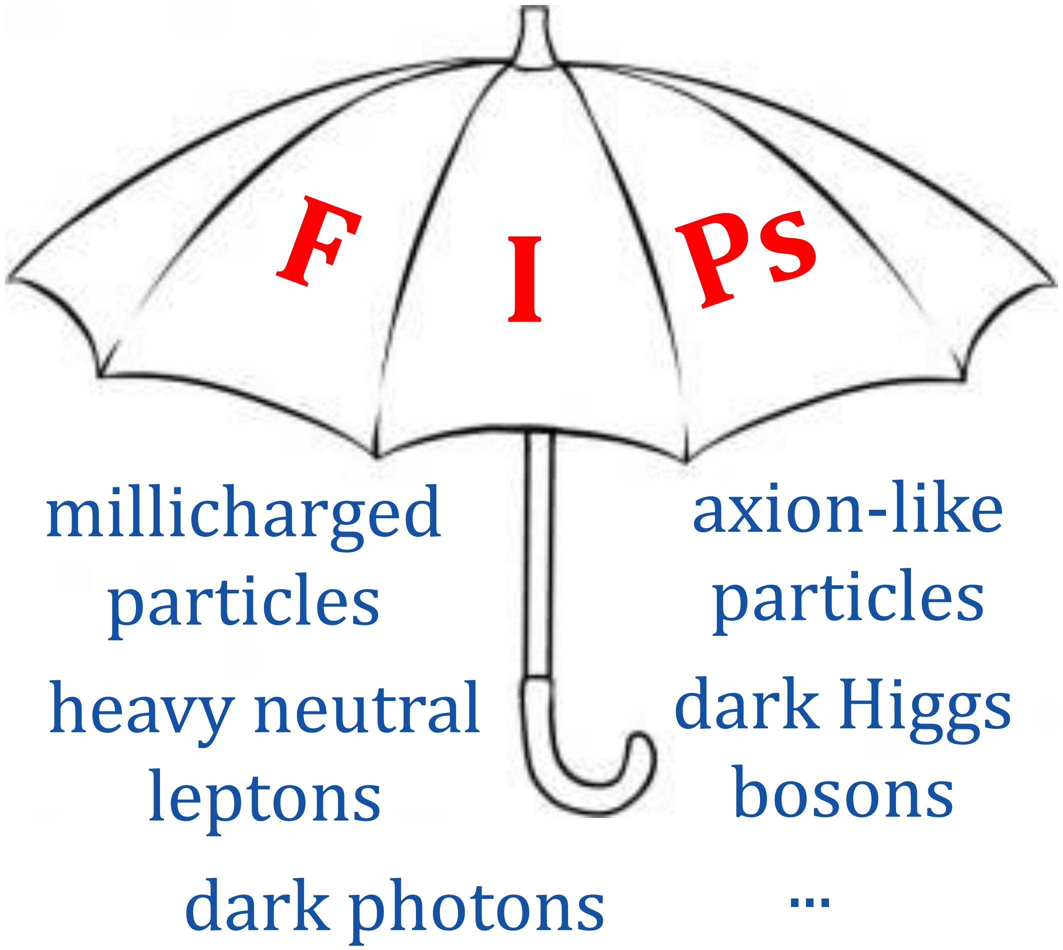





Giving up naturalness by relaxing one of its hypotheses often leads to consequences that are even more radical than those of naturalness itself.




Collaboration between theorists and experimentalists in designing out-of-the-box experiments, searching for new kinds of phenomena and often using experimental techniques borrowed from other fields.

The LHC results have changed our perspective on the particle world.

We have fewer convictions
and more untraveled paths.

We shouldn't be ashamed to admit that we don't know how to answer many fundamental questions.
However, we should be ashamed if our theoretical research and experimental projects don't address these fundamental questions.

- We need theoretical research that addresses fundamental conceptual problems and has ambitious, wide-ranging goals.
- We need a bold experimental programme that explores nature at the smallest possible scale. The spirit of particle physics has always been to break new ground and explore new knowledge.
- We need a diversified experimental approach. New ideas for smaller-scale experiments are emerging and should be pursued, together with the traditional low-energy precision frontier (EDM, g-2, DM, axion, flavour, ...). New experimental techniques are opening bridges with other fields (atomic & nuclear physics, condensed matter, astrophysics and observational cosmology, ...).
- High-energy colliders remain the most powerful microscope at our disposal to explore nature at small distances and discover the fundamental laws that govern the Universe. Colliders are not single-purpose projects but are, in themselves, a diversified physics programme (Higgs, top, EW, QCD, heavy-particles, strongly-interacting phenomena, compositeness of SM particles, DM, FIPs, LLPs, precision tests, flavour, hadron spectroscopy, heavy-ions, ...).

- The world of particle physics is changing, but the world is changing as well. Our responsibility is to provide fundamental knowledge, but to do it responsibly.
- Particle physics should not simply adapt to societal changes, but lead them.
- Technologies developed by particle physics are valuable resources for society and must be developed with applications in mind.
- The Covid emergency has taught society the value of science. Particle physics cannot create vaccines, but we have created the web, which was instrumental for society to survive during the crisis.
- Environmental sustainability is the biggest challenge that our society has to face. We cannot remain indifferent and our way of operating has to change accordingly.
- Energy consumption, sustainability and efficiency are critical issues for the accelerator complex and computing.
- Containment of greenhouse gas emissions from detectors.
- Reconsider our travel practices.