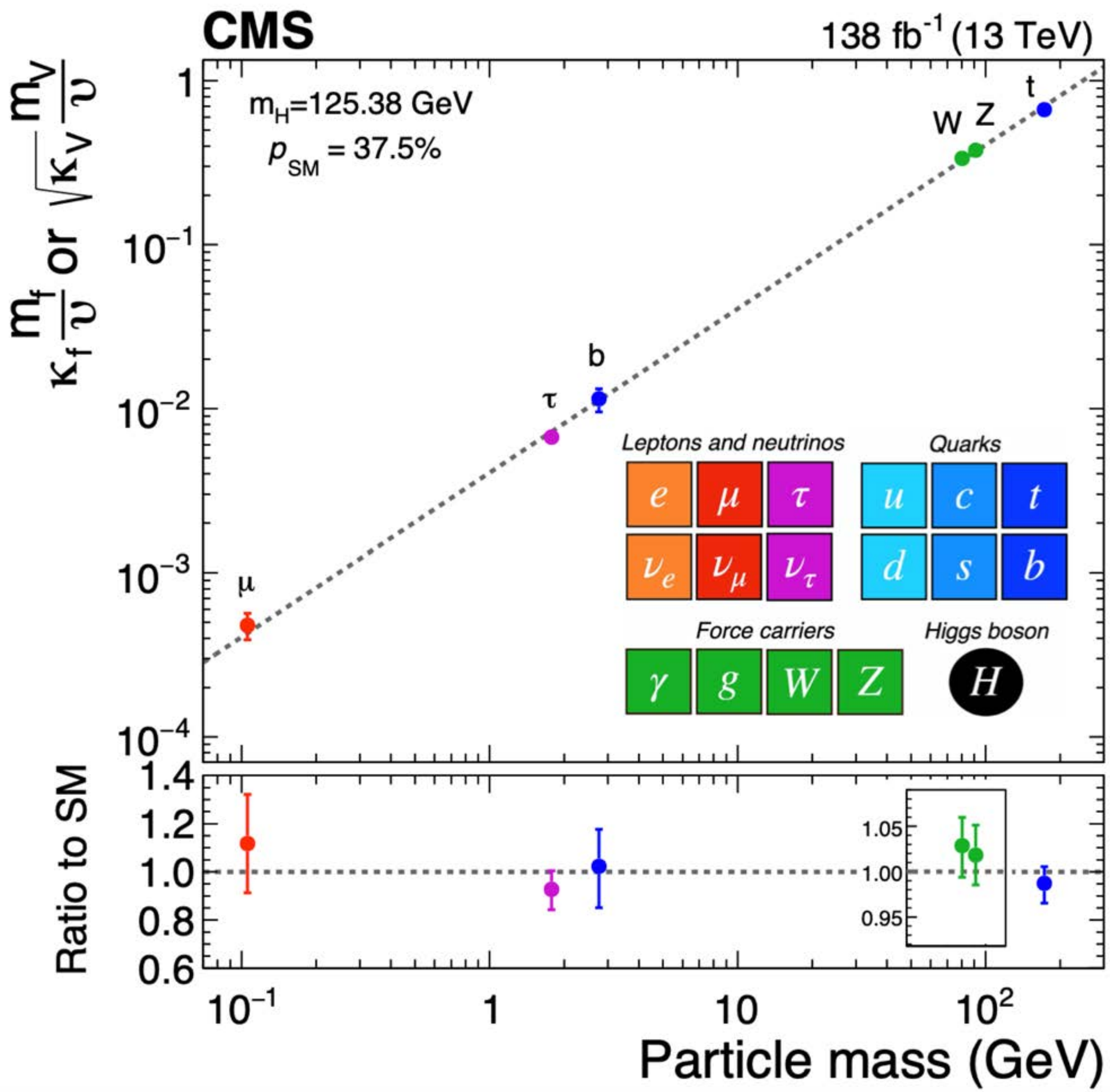
The status of naturalness

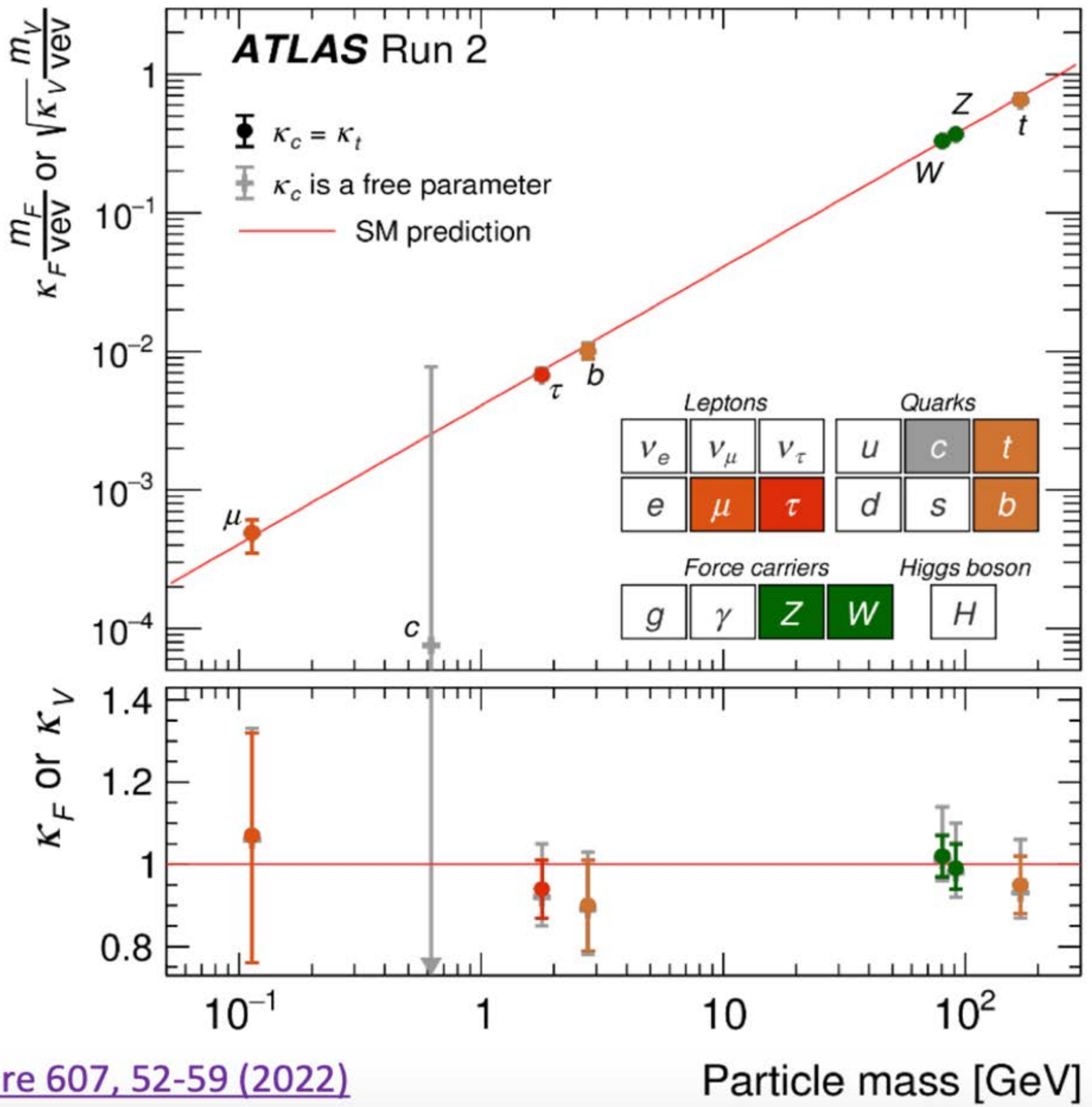
G. F. Giudice

Erwin Schrödinger Guest Professor Lectures, October 2023

The LHC has revolutionised our views on the particle world.

$$m_H = 125.22 \pm 0.14 \text{ GeV}$$

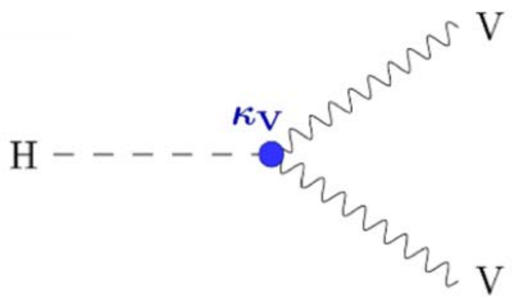


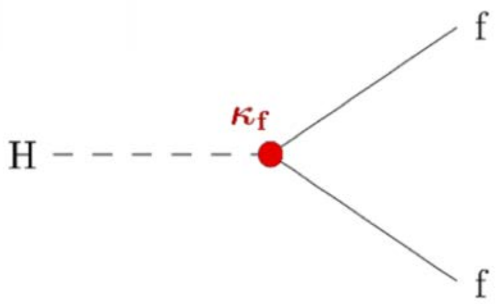


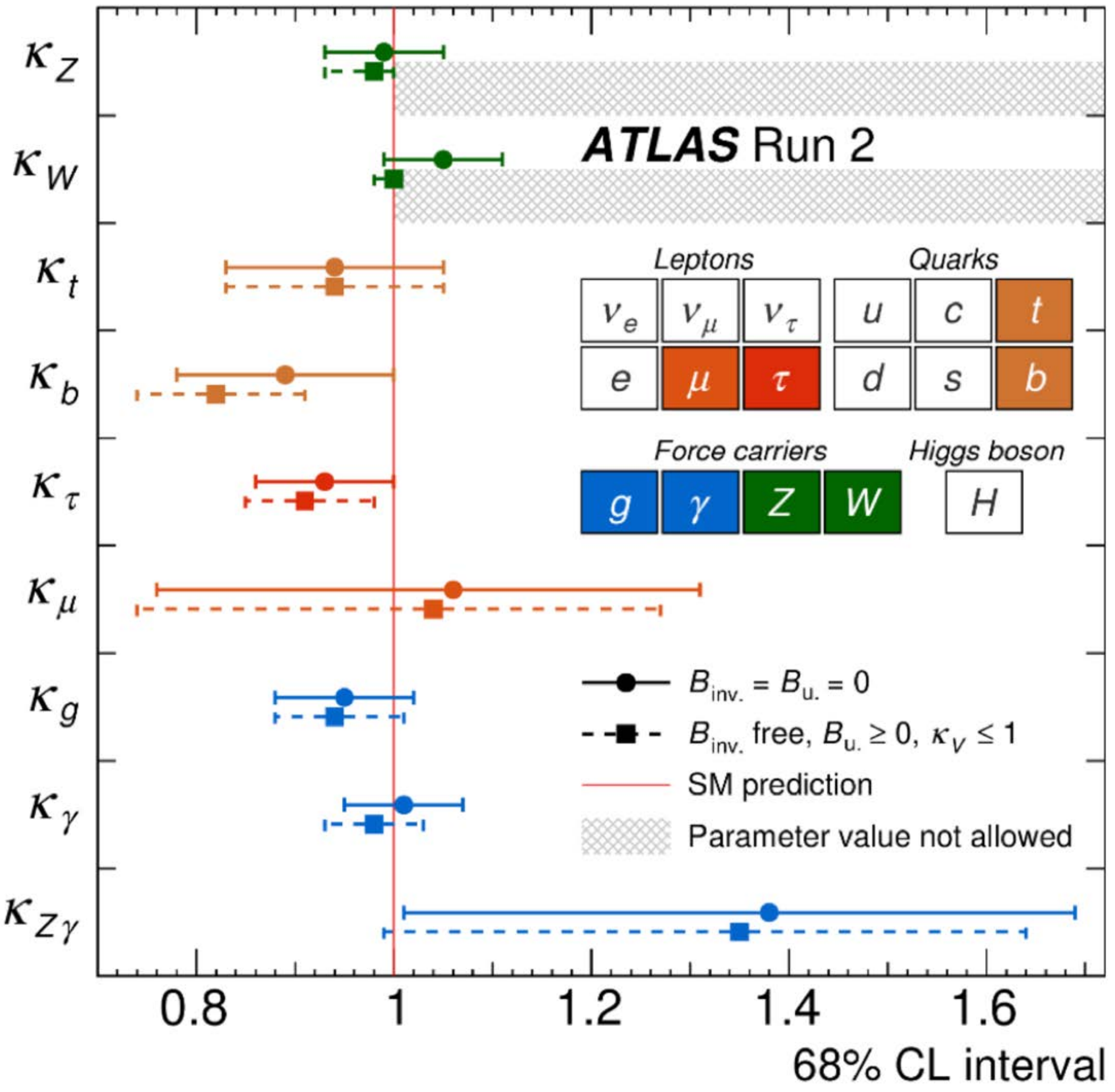
Nature 607, 52-59 (2022)

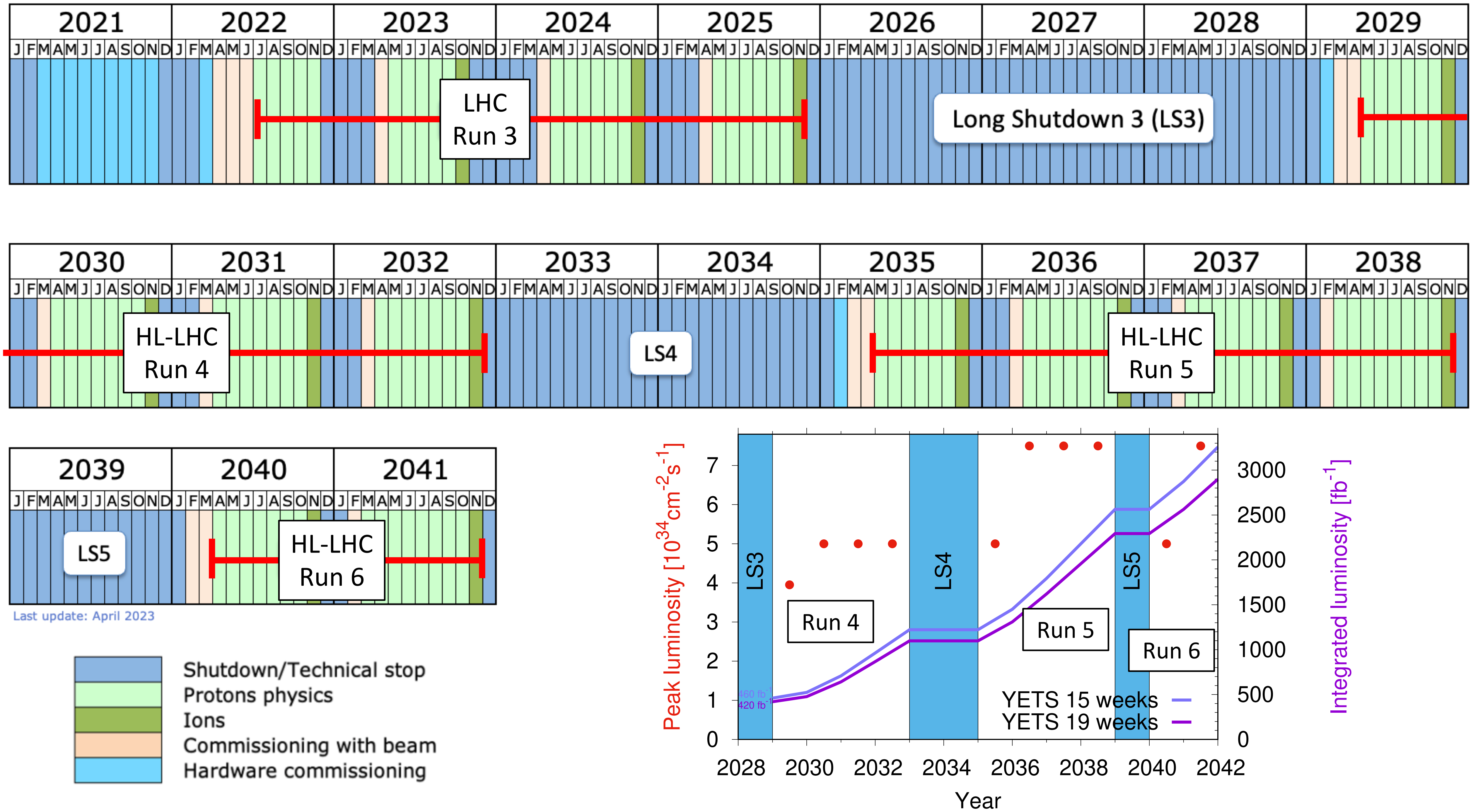
Precision in the measurements of Higgs couplings:

- Gauge bosons (below 10%)
- 3rd gen. fermions (below 20%)

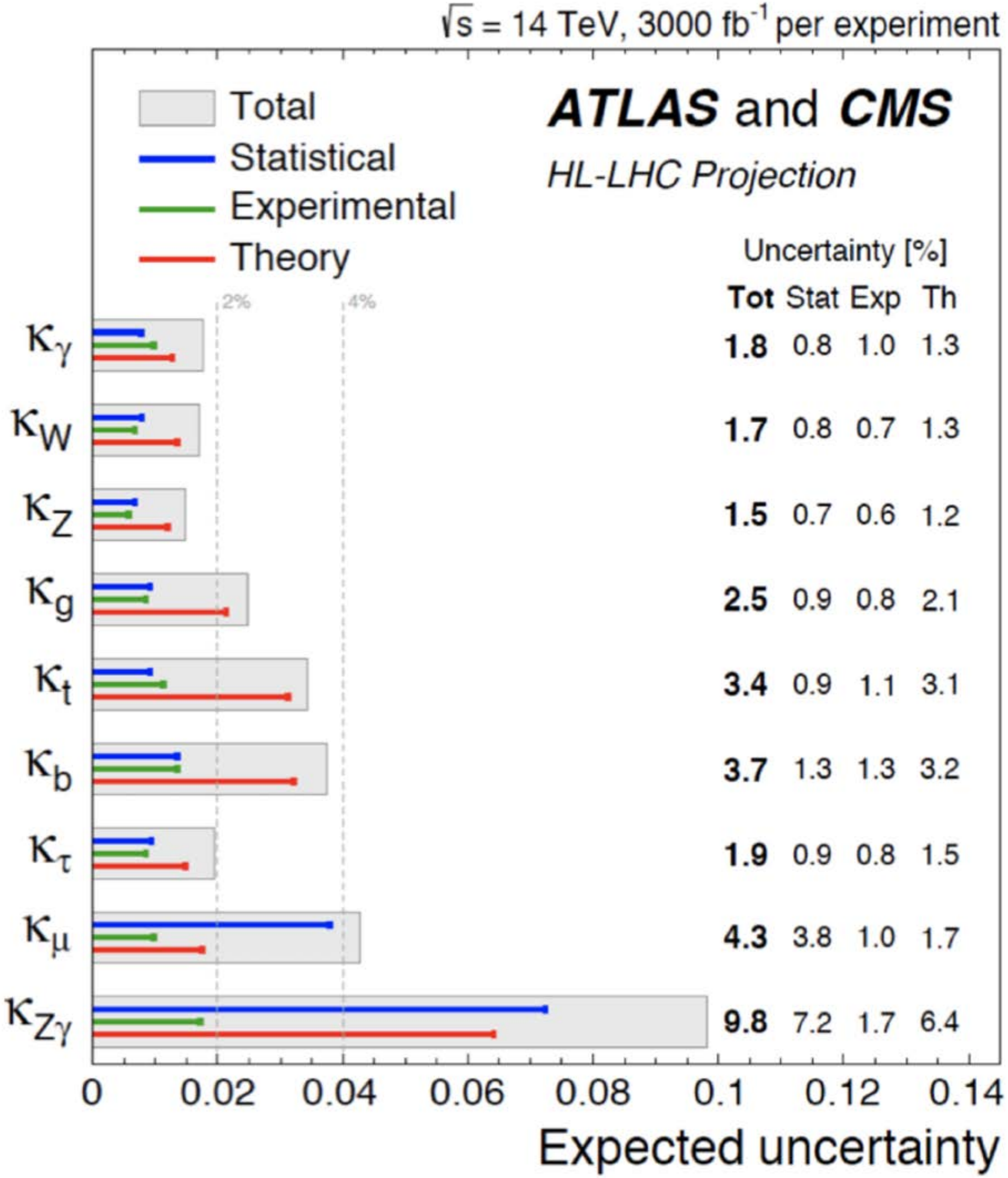








2021
2022
2023
2024
2025
2026
2027
2028
2029
LHC Run 3
Long Shutdown 3 (LS3)
2030
2031
2032
2033
2034
2035
2036
2037
2038
HL-LHC Run 4
LS4
HL-LHC Run 5
2039
2040
2041
LS5
HL-LHC Run 6
Last update: April 2023
Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning
Peak luminosity [10^34 cm^-2 s^-1]
Integrated luminosity [fb^-1]
LS3
LS4
LS5
Run 4
Run 5
Run 6
460 fb^-1
420 fb^-1
YETS 15 weeks
YETS 19 weeks
Year



HL-LHC will reach % accuracy

Why do we care about measuring precisely the properties of the Higgs boson?

Gauge sector

$$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$$

Higgs sector

$$L = \left(h_{ij}\bar{\psi}_i\psi_j H + \text{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda_{CC}^4$$

Non-gauge fundamental forces!

Flavor puzzle

Stability of the potential

Naturalness problem

Cosmological constant problem

All of the SM puzzles are associated with the Higgs structure!

Higgs boson

Unprecedented phenomenon in particle physics:

- New types of fundamental forces?
- Fundamental or composite particle?
- Flavor problem?
- Naturalness problem?
- Portal to new sectors? (Only Lorentz and gauge invariant term with $d<4$)

Deeply related to the history of our universe:

- Spacetime vacuum structure
- Metastability and ultimate fate of the universe
- Prototype for inflation
- Prototype for early-universe phase transitions (GW)

Higgs precision study is a not-to-be-missed experimental program

What do you learn from Higgs precision measurements?

In composite Higgs:

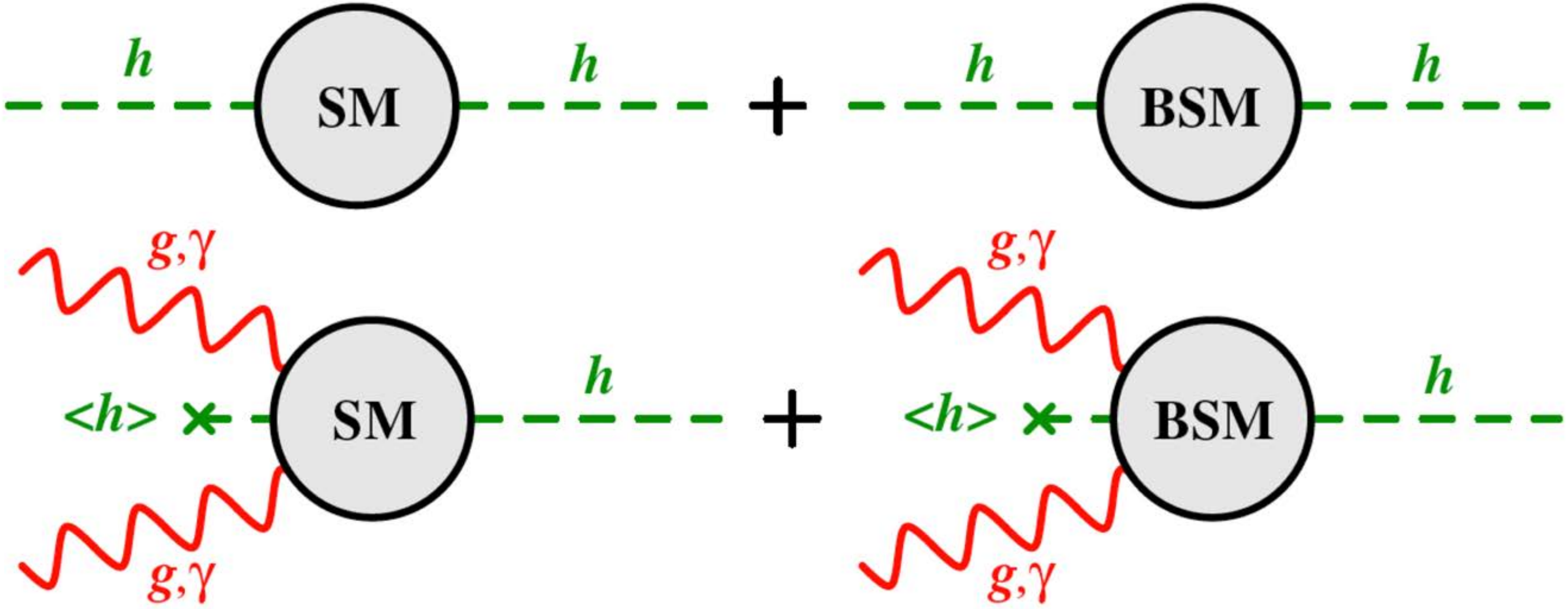
$$\Delta = \frac{v^2}{f^2} \quad \Rightarrow \quad \text{compositeness scale} \;\; 4\pi f > \sqrt{\frac{0.1\%}{\Delta}} \;\; 100 \text{ TeV}$$

particle	degree of compositeness (effective size / Compton wavelength)	
proton	$\frac{m_p}{2\pi\Lambda_{\rm QCD}} \approx 1$	fully composite
pion	$\frac{m_\pi}{2\pi m_\rho} \approx 3 \times 10^{-2}$	composite but approximate Goldstone
Higgs	$\frac{m_H \ell_H}{2\pi} \approx \begin{cases} 10^{-2} \\ 10^{-3} \end{cases}$	$\begin{cases} \text{today} \\ \text{at future colliders} \end{cases}$

$$\text{Compton wavelength} = \frac{h}{mc}$$

What do you learn from Higgs precision measurements?

In general, testing Higgs couplings is testing naturalness:



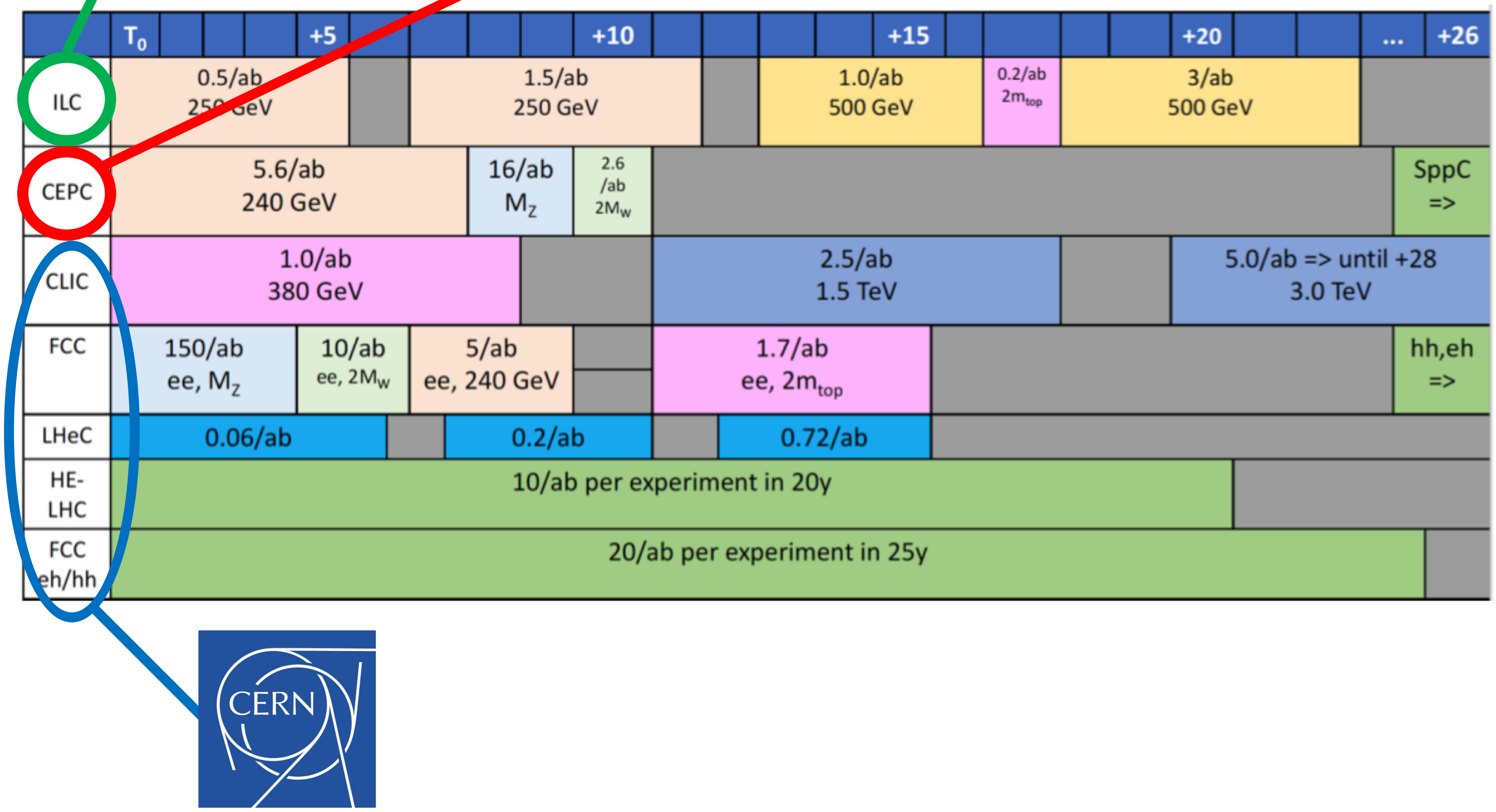
The more natural the Higgs is,
the more its properties deviate from the SM

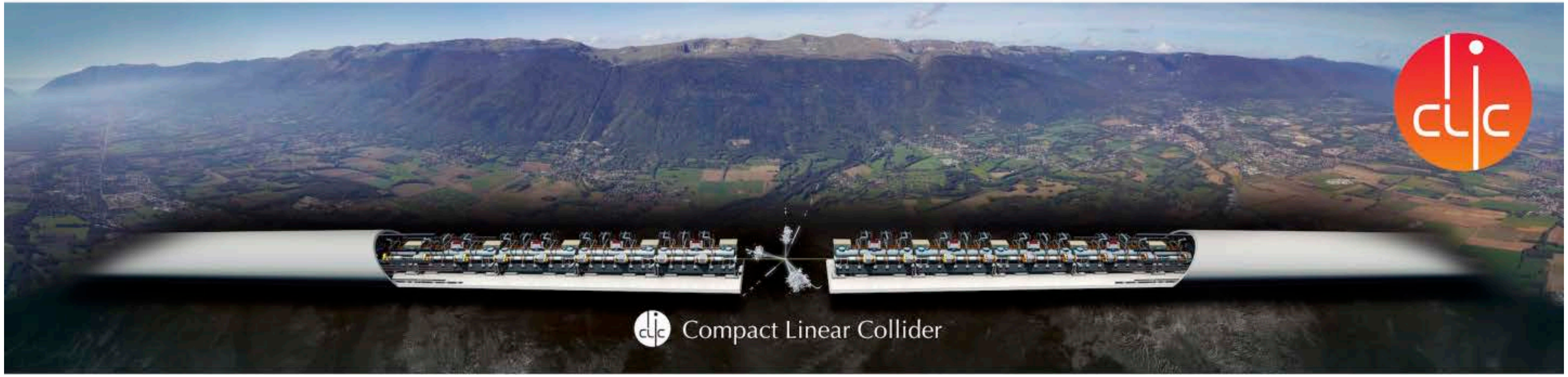
Higgs: the new frontier

- Precision in H-couplings below the percent (probing Higgs substructure at $10^{-5}\, r_p$; probing naturalness)
- Test H-couplings to 2nd and 1st generation (probing flavor)
- Test invisible H-decays (probing DM)
- Test H-self-coupling (probing EW phase transition)
- Test of rare decays: $h \to Z\gamma$, $h \to \mu e/\tau\mu/\tau e$, CP violation (probing BSM)

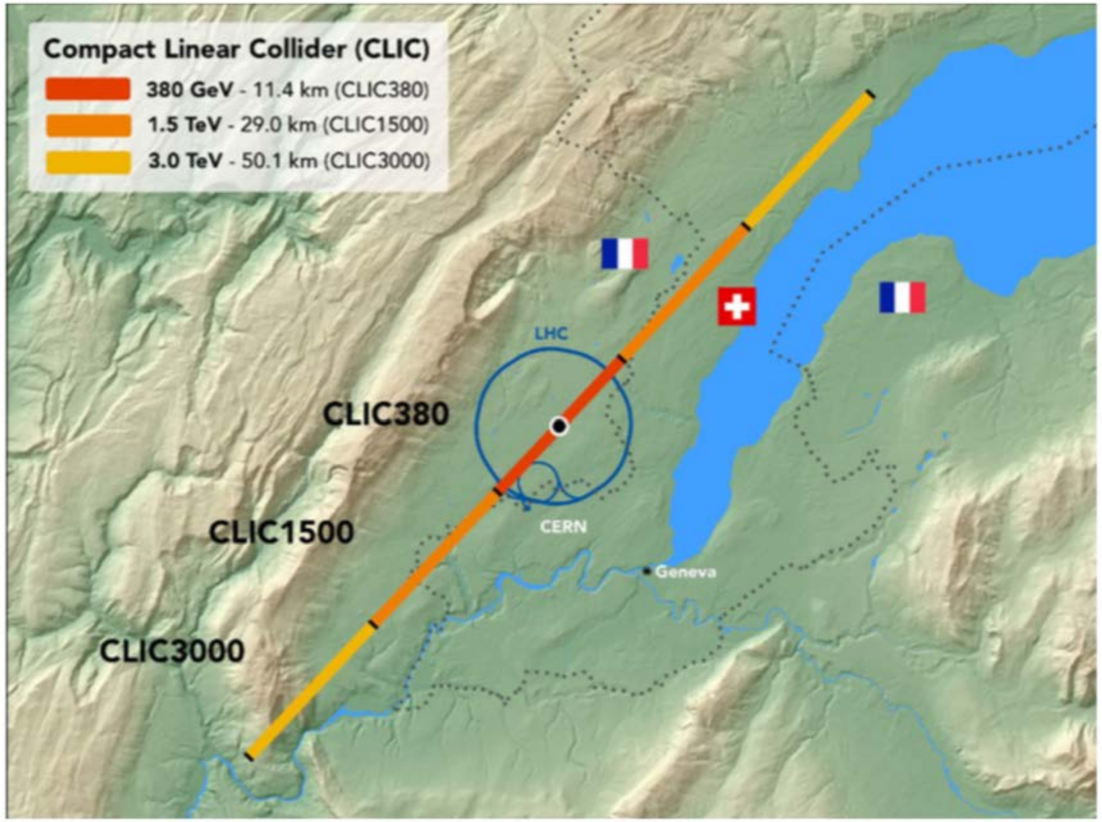
A broad physics program at the heart of all puzzles related to EW breaking

How can we reach these goals?





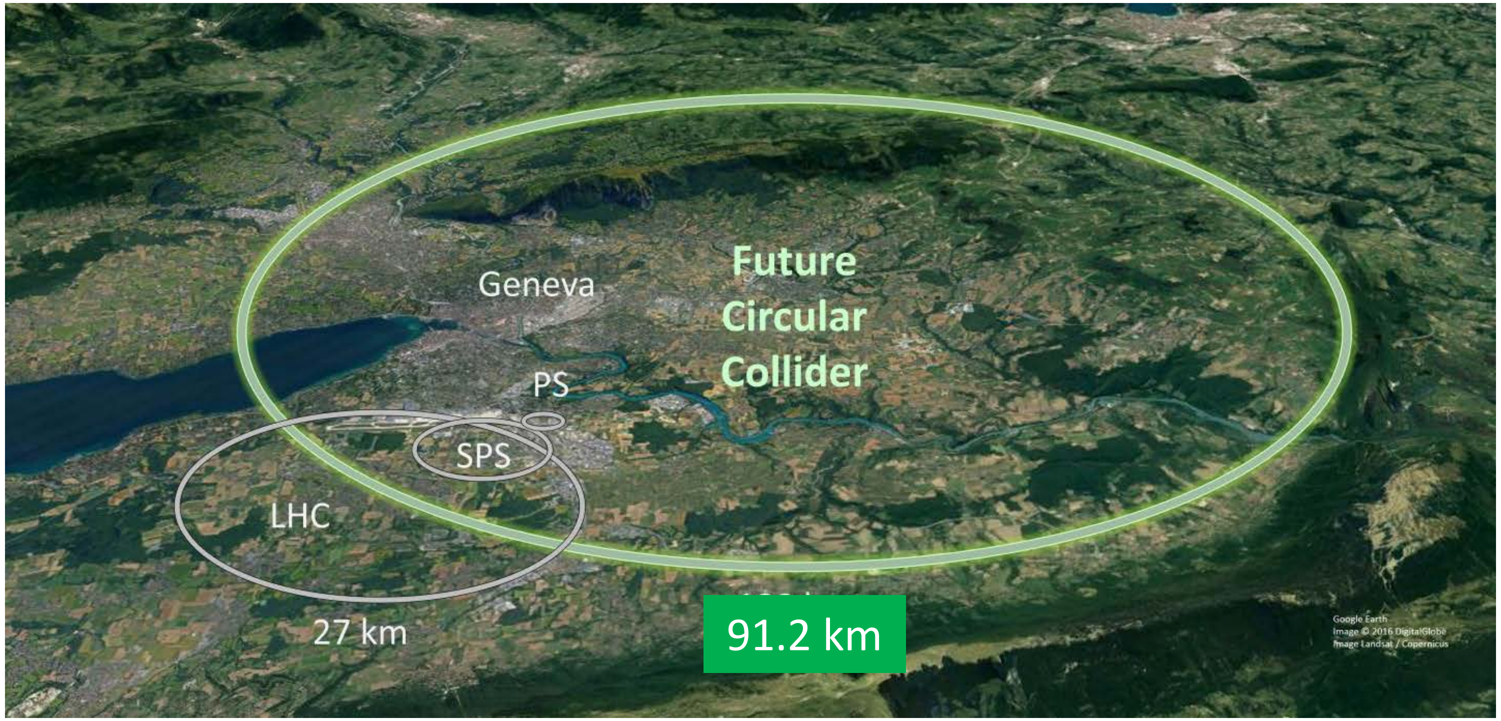
Parameter	Unit	Stage 1	Stage 2	Stage 3
√s	GeV	380	1500	3000
Tunnel length	km	11	29	50
Gradient	MV/m	72	72/100	72/100
Pulse length	ns	244	244	244
Luminosity (above 99% of √s)	10^{34} $cm^{-2}s^{-1}$	1.5 0.9	3.7 1.4	5.9 2
Repetition frequency	Hz	50	50	50
Bunches per train		352	312	312
Bunch spacing	ns	0.5	0.5	0.5
Particles/bunch	10^9	5.2	3.7	3.7
Beam size at IP (σ_y/σ_x)	nm	2.9/149	1.5/60	1/40
Annual energy consumption	TWh	0.8	1.7	2.8
Construction cost	BCH	5.9	+5.1	+7.3



FCC-ee:

5×10^{12} Z ($10^{5}\times$ LEP), 10^{8} WW ($10^{3}\times$ LEP), 10^{6} h, 10^{6} tt

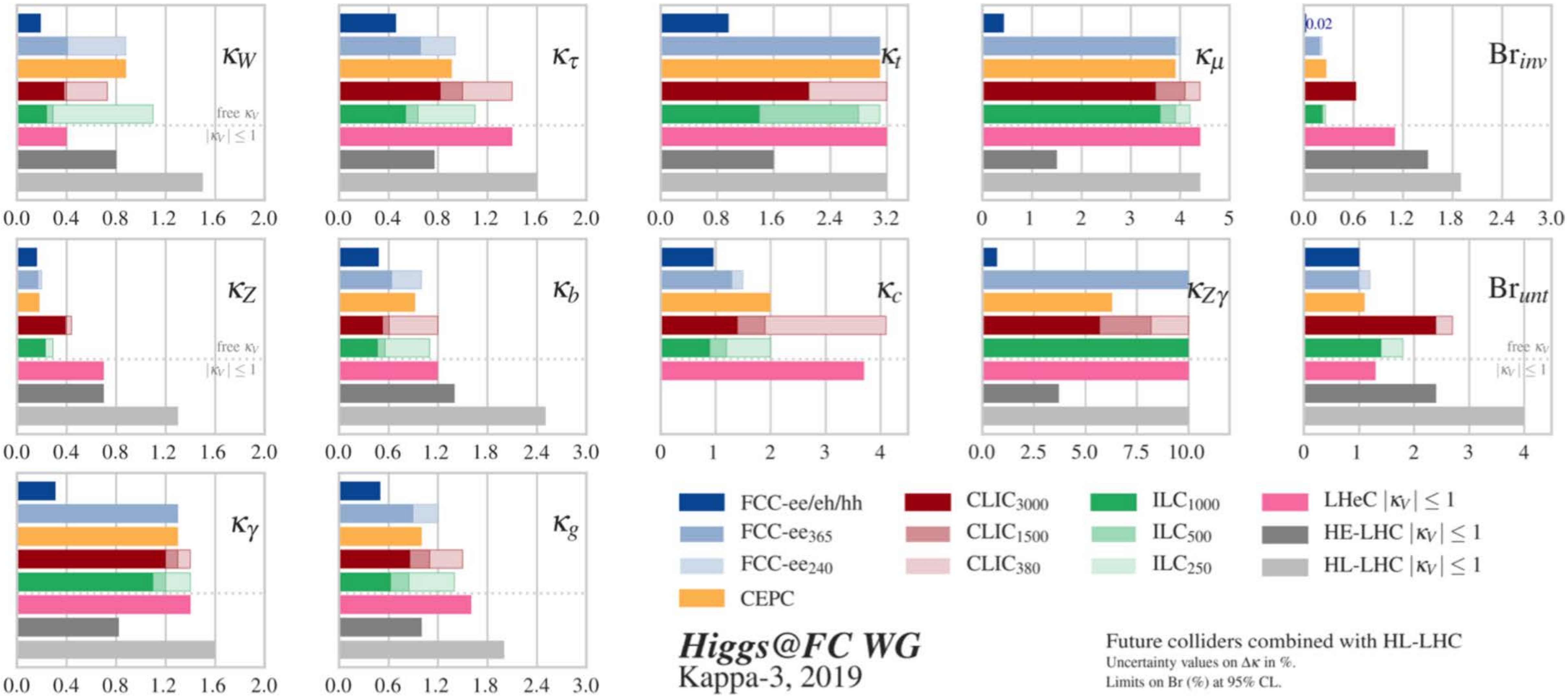
Estimated cost: ~ **11.6** BCHF: 5.4 B (tunnel), 5.1 B (injectors + collider up to √s=240 GeV), 1.1 B (additional RF for operation at √s ~365 GeV)



FCC-hh:

100 TeV with Nb_3Sn 16T magnets
~ **150 TeV** with HTS magnets?
~ **40 TeV** with NbTi 6T magnets?

Estimated cost: ~ **17** BCHF (13.6 B collider [magnets!] + injectors) if built after FCC-ee (tunnel and part of infrastructure exists); 24 BCHF if standalone.



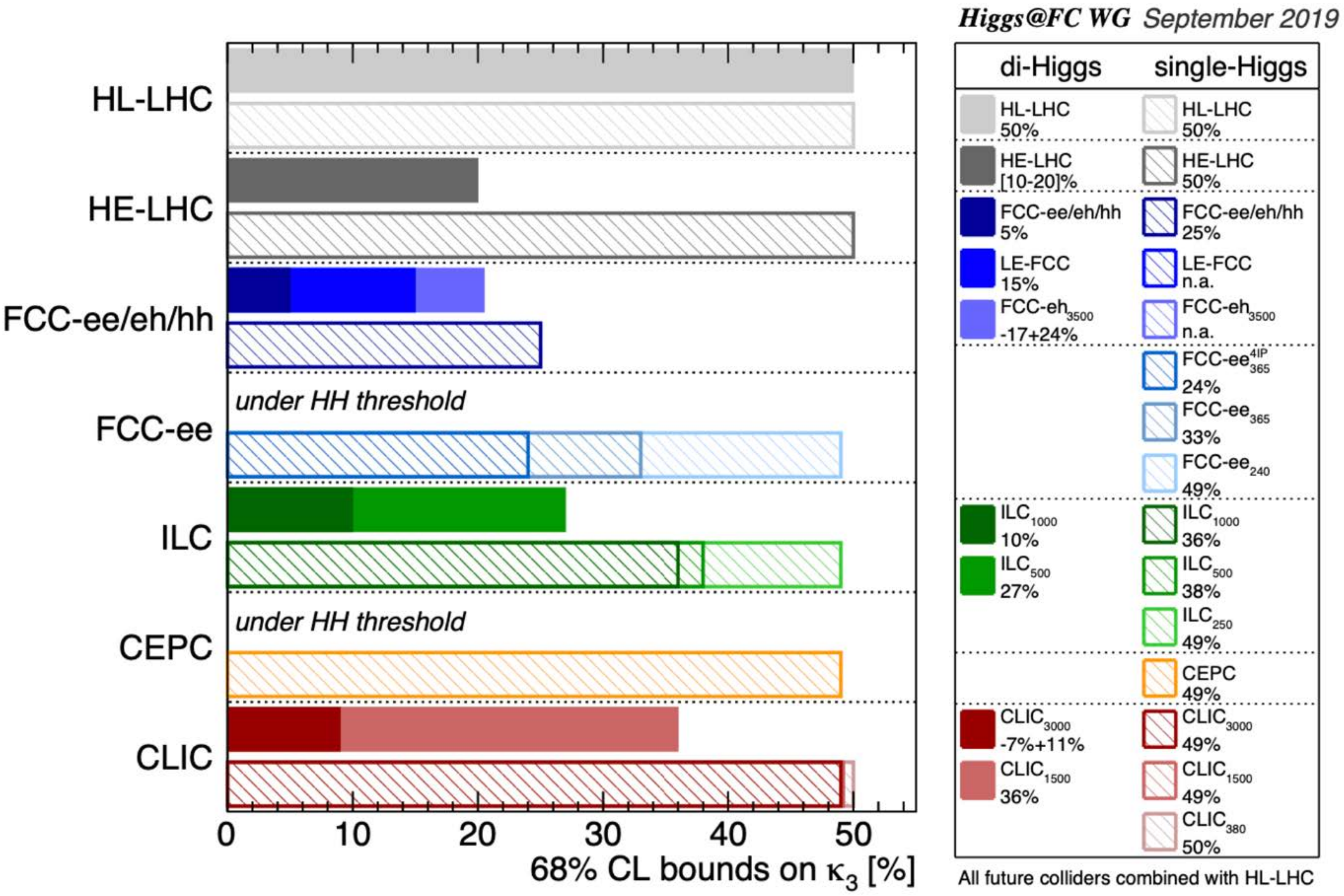
κ_W
κ_τ
κ_t
κ_μ
Br_{inv}
0.02
κ_Z
κ_b
κ_c
$\kappa_{Z\gamma}$
Br_{unt}
κ_γ
κ_g
free κ_V
$|\kappa_V| \leq 1$
FCC-ee/eh/hh
$FCC\text{-}ee_{365}$
$FCC\text{-}ee_{240}$
CEPC
$CLIC_{3000}$
$CLIC_{1500}$
$CLIC_{380}$
ILC_{1000}
ILC_{500}
ILC_{250}
LHeC $|\kappa_V| \leq 1$
HE-LHC $|\kappa_V| \leq 1$
HL-LHC $|\kappa_V| \leq 1$
Higgs@FC WG
Kappa-3, 2019
Future colliders combined with HL-LHC
Uncertainty values on $\Delta\kappa$ in %.
Limits on Br (%) at 95% CL.

The SM Higgs potential is today one of the best measured quantities in particle physics:

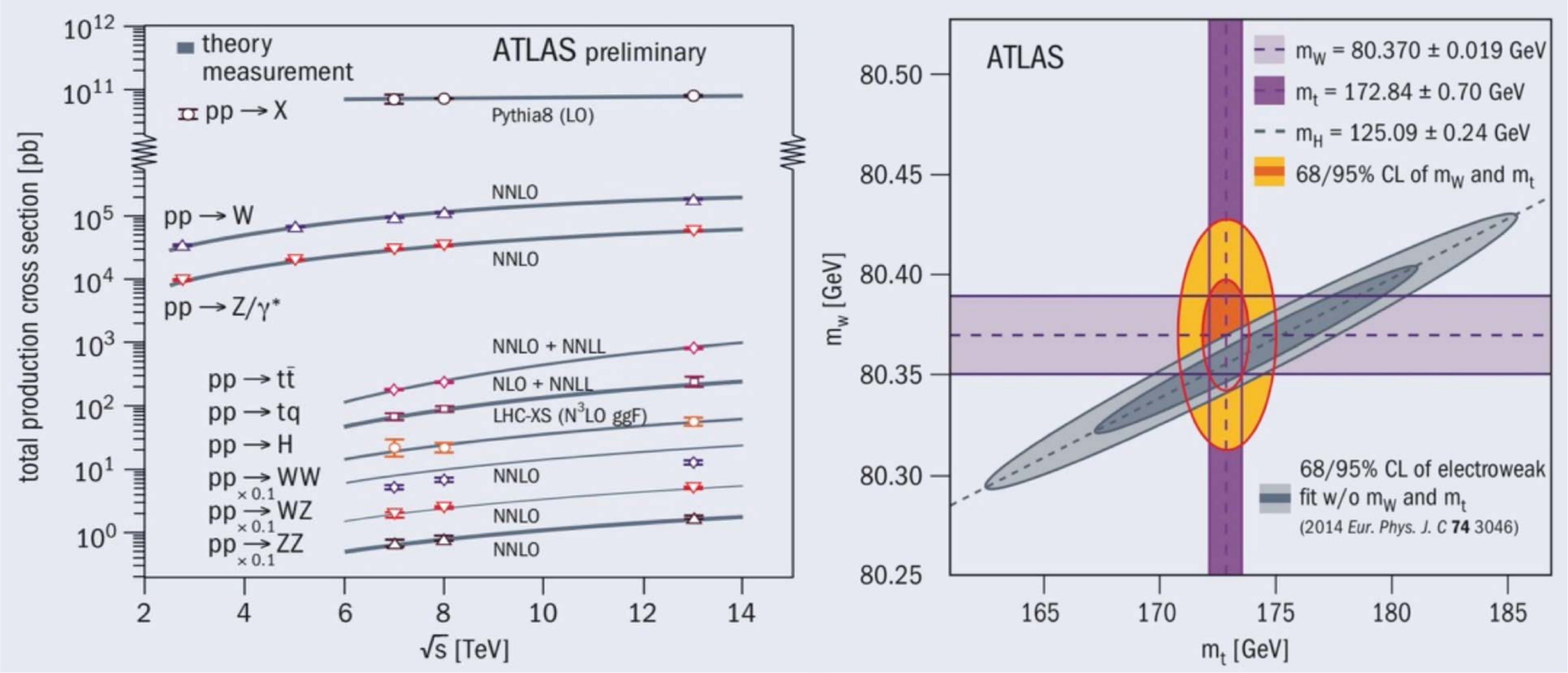
$$V_{\rm SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4 = M_h^2 \left(\sqrt{2} G_F |H|^2 - 1\right) \frac{|H|^2}{2}$$

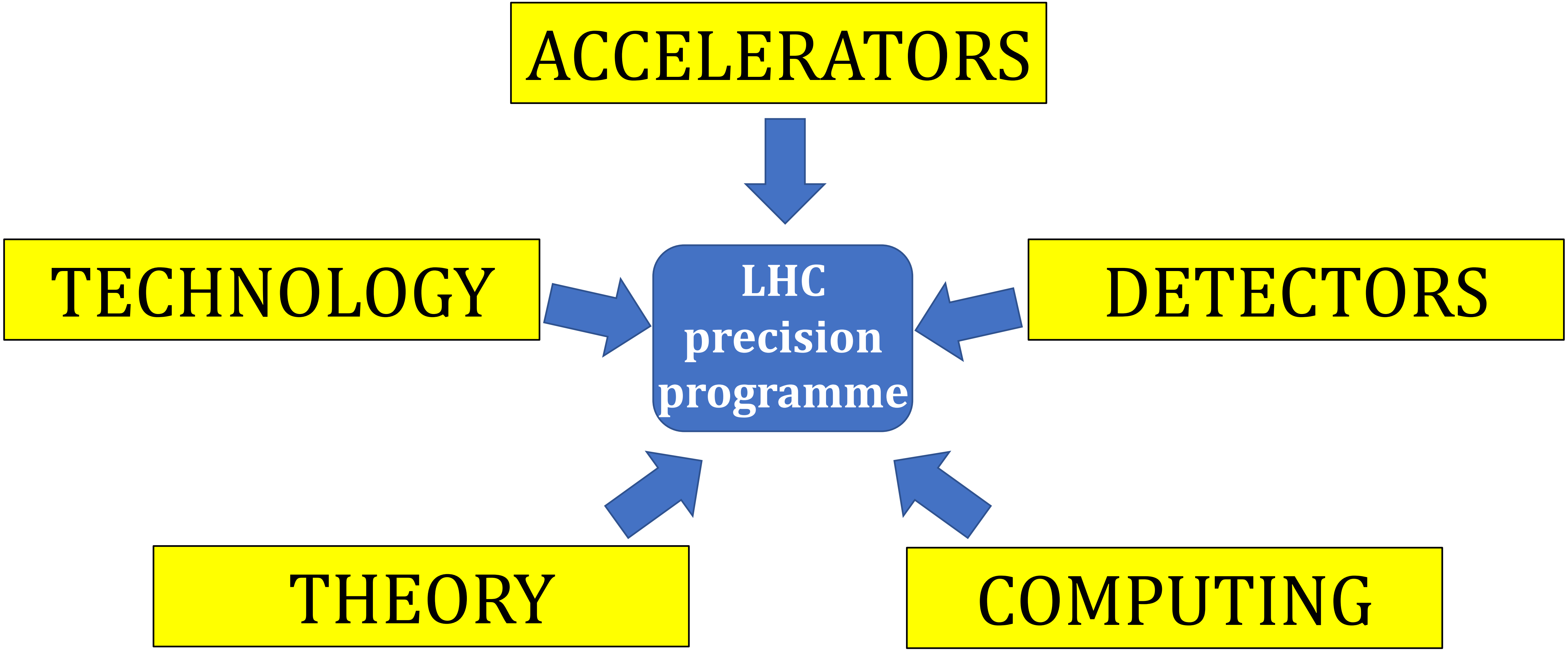
0.1% 0.001%

Now we want to measure the effect of BSM higher-dim operators


Higgs@FC WG September 2019
HL-LHC
HE-LHC
FCC-ee/eh/hh
FCC-ee
under HH threshold
ILC
CEPC
under HH threshold
CLIC
0 10 20 30 40 50
68% CL bounds on κ_3 [%]
di-Higgs
single-Higgs
HL-LHC 50%
HL-LHC 50%
HE-LHC [10-20]%
HE-LHC 50%
FCC-ee/eh/hh 5%
FCC-ee/eh/hh 25%
LE-FCC 15%
LE-FCC n.a.
FCC-eh$_{3500}$ -17+24%
FCC-eh$_{3500}$ n.a.
FCC-ee$^{4IP}_{365}$ 24%
FCC-ee$_{365}$ 33%
FCC-ee$_{240}$ 49%
ILC$_{1000}$ 10%
ILC$_{1000}$ 36%
ILC$_{500}$ 27%
ILC$_{500}$ 38%
ILC$_{250}$ 49%
CEPC 49%
CLIC$_{3000}$ -7%+11%
CLIC$_{3000}$ 49%
CLIC$_{1500}$ 36%
CLIC$_{1500}$ 49%
CLIC$_{380}$ 50%
All future colliders combined with HL-LHC

LHC precision in EW/QCD

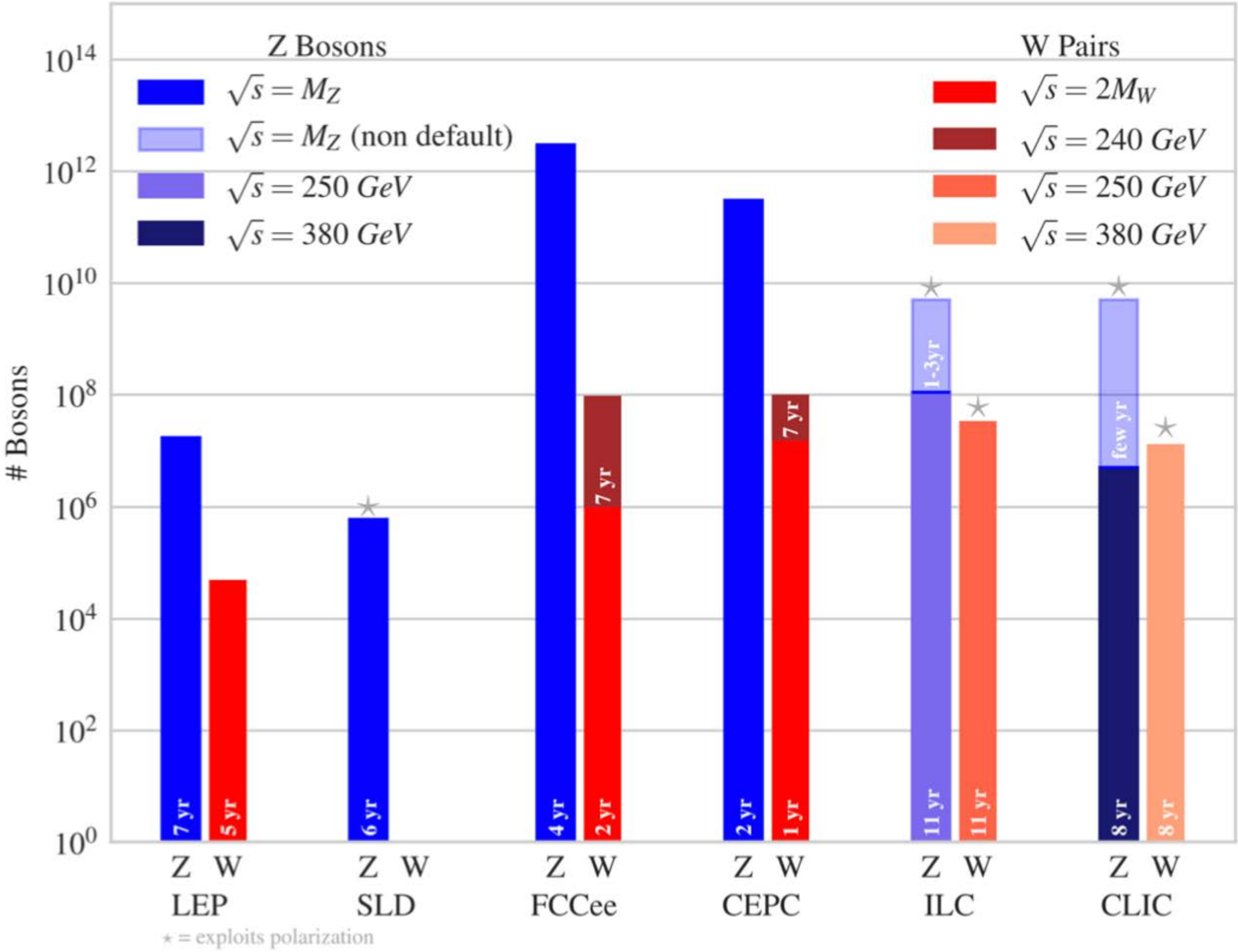


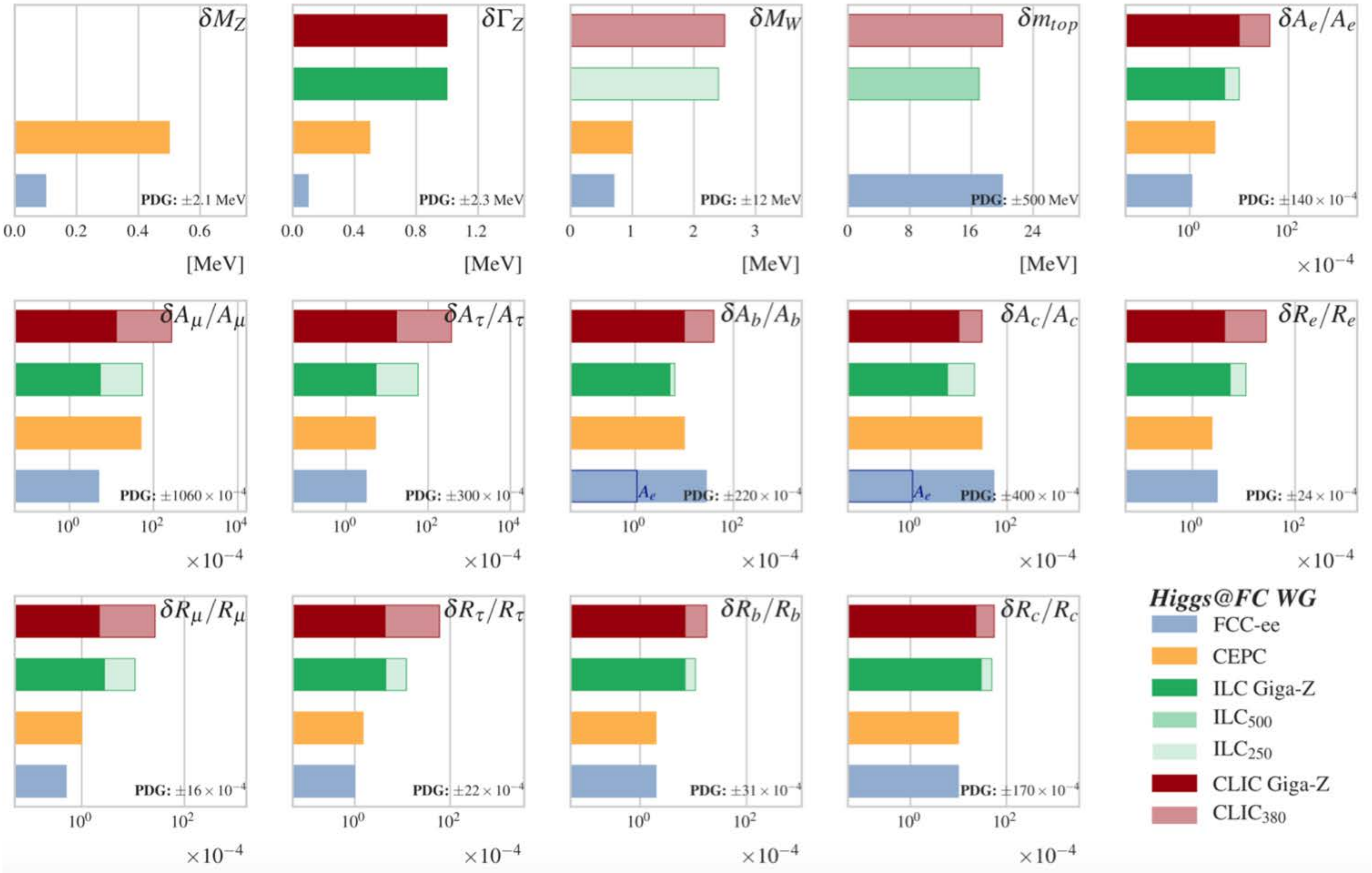


Precision in strong interactions, EW interactions, top and Higgs physics, flavour physics, hadron spectroscopy, heavy-ion physics, ..., compressed spectra, FIPs, LLPs, ...

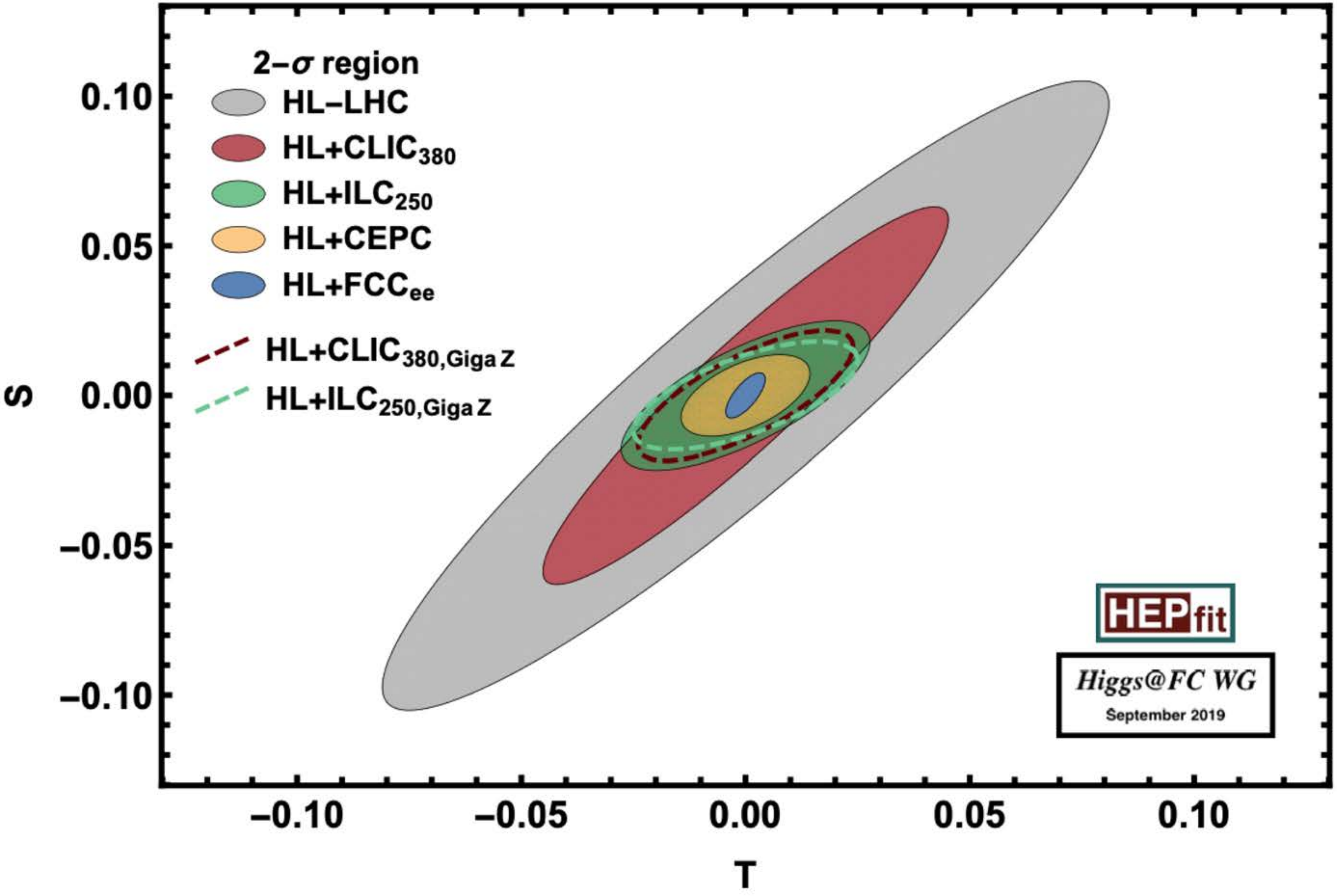
Precision has become key for present and future exploration.

The future of the precision program





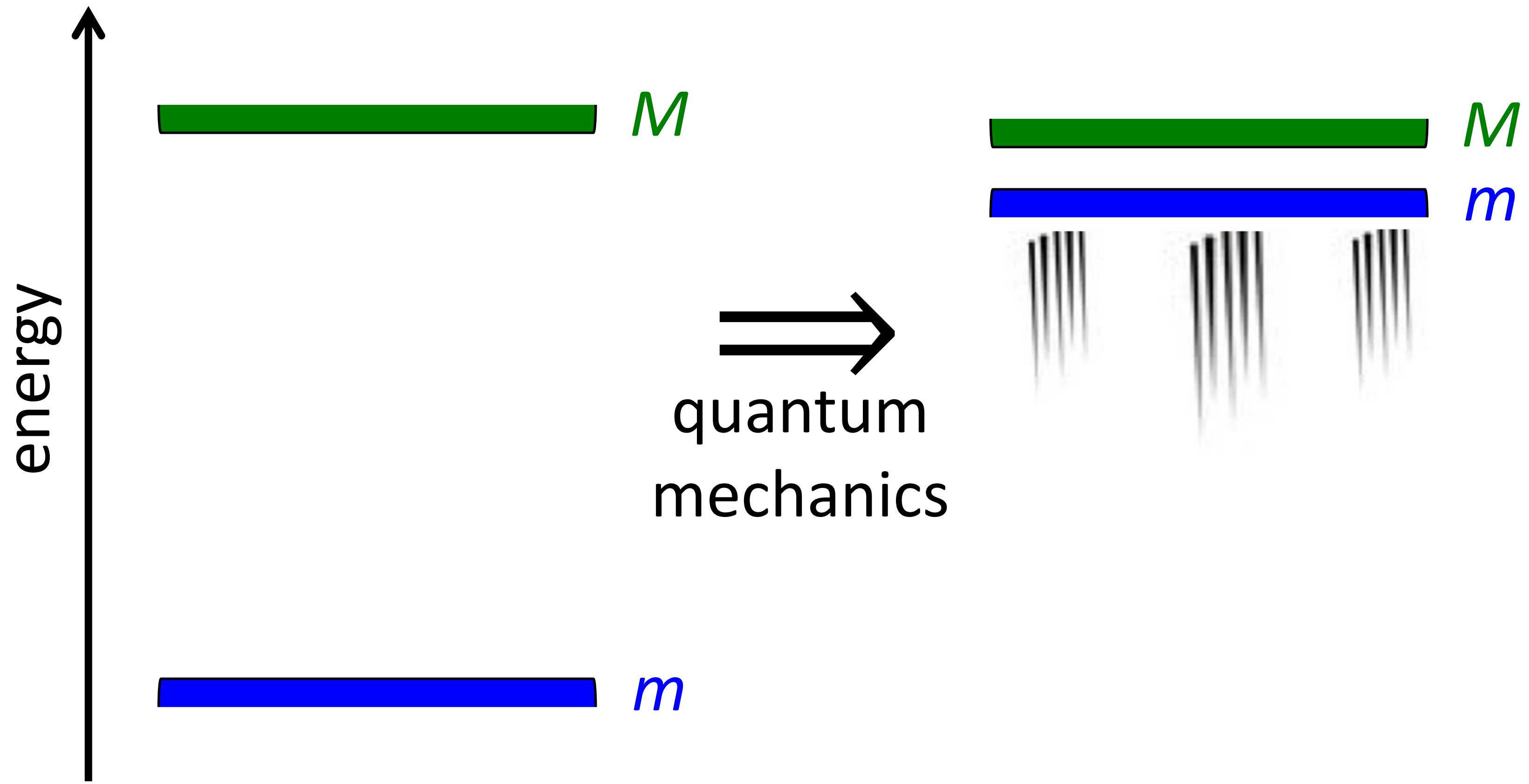
δM_Z
PDG: ±2.1 MeV
[MeV]
δΓ_Z
PDG: ±2.3 MeV
[MeV]
δM_W
PDG: ±12 MeV
[MeV]
δm_top
PDG: ±500 MeV
[MeV]
δA_e/A_e
PDG: ±140 × 10^-4
×10^-4
δA_μ/A_μ
PDG: ±1060 × 10^-4
×10^-4
δA_τ/A_τ
PDG: ±300 × 10^-4
×10^-4
δA_b/A_b
A_e
PDG: ±220 × 10^-4
×10^-4
δA_c/A_c
A_e
PDG: ±400 × 10^-4
×10^-4
δR_e/R_e
PDG: ±24 × 10^-4
×10^-4
δR_μ/R_μ
PDG: ±16 × 10^-4
×10^-4
δR_τ/R_τ
PDG: ±22 × 10^-4
×10^-4
δR_b/R_b
PDG: ±31 × 10^-4
×10^-4
δR_c/R_c
PDG: ±170 × 10^-4
×10^-4
Higgs@FC WG
FCC-ee
CEPC
ILC Giga-Z
ILC500
ILC250
CLIC Giga-Z
CLIC380



2−σ region
HL−LHC
HL+CLIC380
HL+ILC250
HL+CEPC
HL+FCCee
HL+CLIC380,Giga Z
HL+ILC250,Giga Z
0.10
0.05
0.00
−0.05
−0.10
S
T
HEPfit
Higgs@FC WG
September 2019

Revolutionary impact of the LHC in reshaping our vision about the search for the fundamental principles of nature.

Higgs naturalness



Wrong statements

- Naturalness depends on the regularization procedure.
- Naturalness depends on probability measures in theory space.
- Naturalness depends on arbitrary aesthetic criteria.
- Naturalness is a statement that parameters cannot be small or large.
- Naturalness is no longer a problem because LHC hasn’t discovered any new particles.
- Naturalness is no longer a motivation for future colliders.

- Naturalness is a powerful tool provided by QFT to explore the properties of a theory beyond the boundaries of what has been tested experimentally.
- It gives information about the maximum energy up to which you can extrapolate your low-energy description.

1. Classical electron self-energy

New physics (positron) at $m_e < \Lambda$ ($m_e = 0.5$ MeV)

$$\text{electrostatic energy}: \; E \approx \frac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha} \approx 70 \text{ MeV}$$

$$\text{magnetic energy}: \; E \approx \frac{\mu^2}{r^3}, \mu = \frac{e\hbar}{2m_e c} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha^{1/3}} \approx 3 \text{ MeV}$$

$$\text{quantum mechanics}: \; \Delta m_e \approx \frac{\alpha \Lambda^2}{m_e} \Rightarrow \Lambda < \frac{m_e}{\sqrt{\alpha}} = 6 \text{ MeV}$$

1. Classical electron self-energy

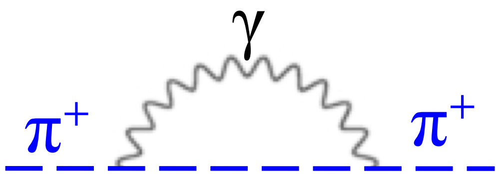
electrostatic energy : $E \approx \frac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha} \approx 70 \text{ MeV}$

magnetic energy : $E \approx \frac{\mu^2}{r^3}, \mu = \frac{e\hbar}{2m_e c} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha^{1/3}} \approx 3 \text{ MeV}$

quantum mechanics : $\Delta m_e \approx \frac{\alpha \Lambda^2}{m_e} \Rightarrow \Lambda < \frac{m_e}{\sqrt{\alpha}} = 6 \text{ MeV}$

New physics (positron) at $m_e < \Lambda$ ($m_e = 0.5$ MeV)

2. QED contribution to pion mass difference



$$\frac{3\alpha}{4\pi}\Lambda^2 < M^2_{\pi^+} - M^2_{\pi^0} \Rightarrow \Lambda < 850 \text{ MeV}$$

New physics (hadrons) at $M_\rho < \Lambda$ ($M_\rho = 770$ MeV)

1. Classical electron self-energy

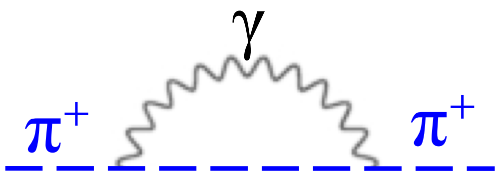
electrostatic energy: $E \approx \frac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha} \approx 70\ \text{MeV}$

magnetic energy: $E \approx \frac{\mu^2}{r^3}, \mu = \frac{e\hbar}{2m_e c} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha^{1/3}} \approx 3\ \text{MeV}$

quantum mechanics: $\Delta m_e \approx \frac{\alpha \Lambda^2}{m_e} \Rightarrow \Lambda < \frac{m_e}{\sqrt{\alpha}} = 6\ \text{MeV}$

New physics (positron) at $m_e < \Lambda$ ($m_e = 0.5$ MeV)

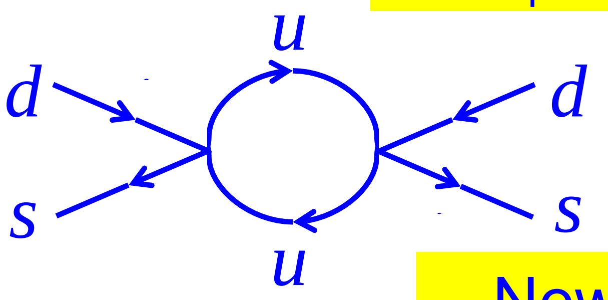
2. QED contribution to pion mass difference



$$\frac{3\alpha}{4\pi}\Lambda^2 < M^2_{\pi^+} - M^2_{\pi^0} \Rightarrow \Lambda < 850\ \text{MeV}$$

New physics (hadrons) at $M_\rho < \Lambda$ ($M_\rho = 770$ MeV)

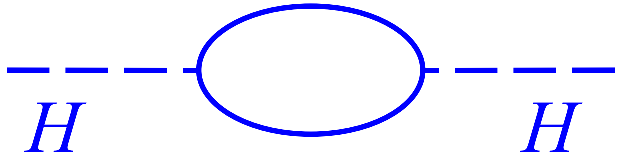
3. Neutral kaon mass difference



$$\frac{G_F^2 f_K^2}{6\pi^2}\sin^2\theta_c \Lambda^2 < \frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} \Rightarrow \Lambda < 2\ \text{GeV}$$

New physics (charm) at $m_c < \Lambda$ ($m_c = 1.2$ GeV)

Higgs mass



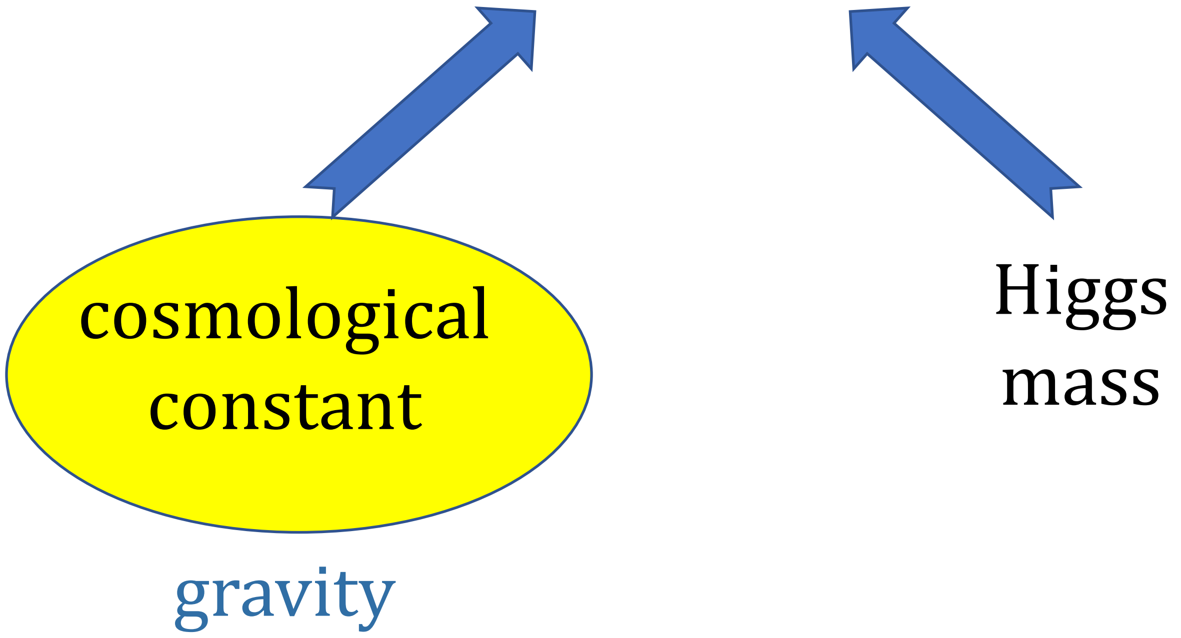
$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 < m_h^2 \Rightarrow \Lambda < 500 \text{ GeV}$$

Cosmological constant

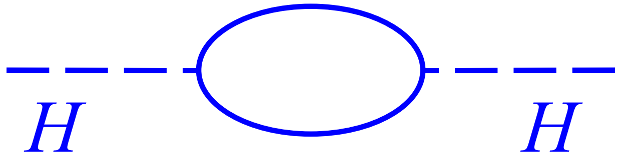
$$\Lambda_{\rm CC} = \frac{\Lambda^4}{16\pi^2} < (10^{-3} \text{ eV})^4$$

Another clue: the cosmological constant

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



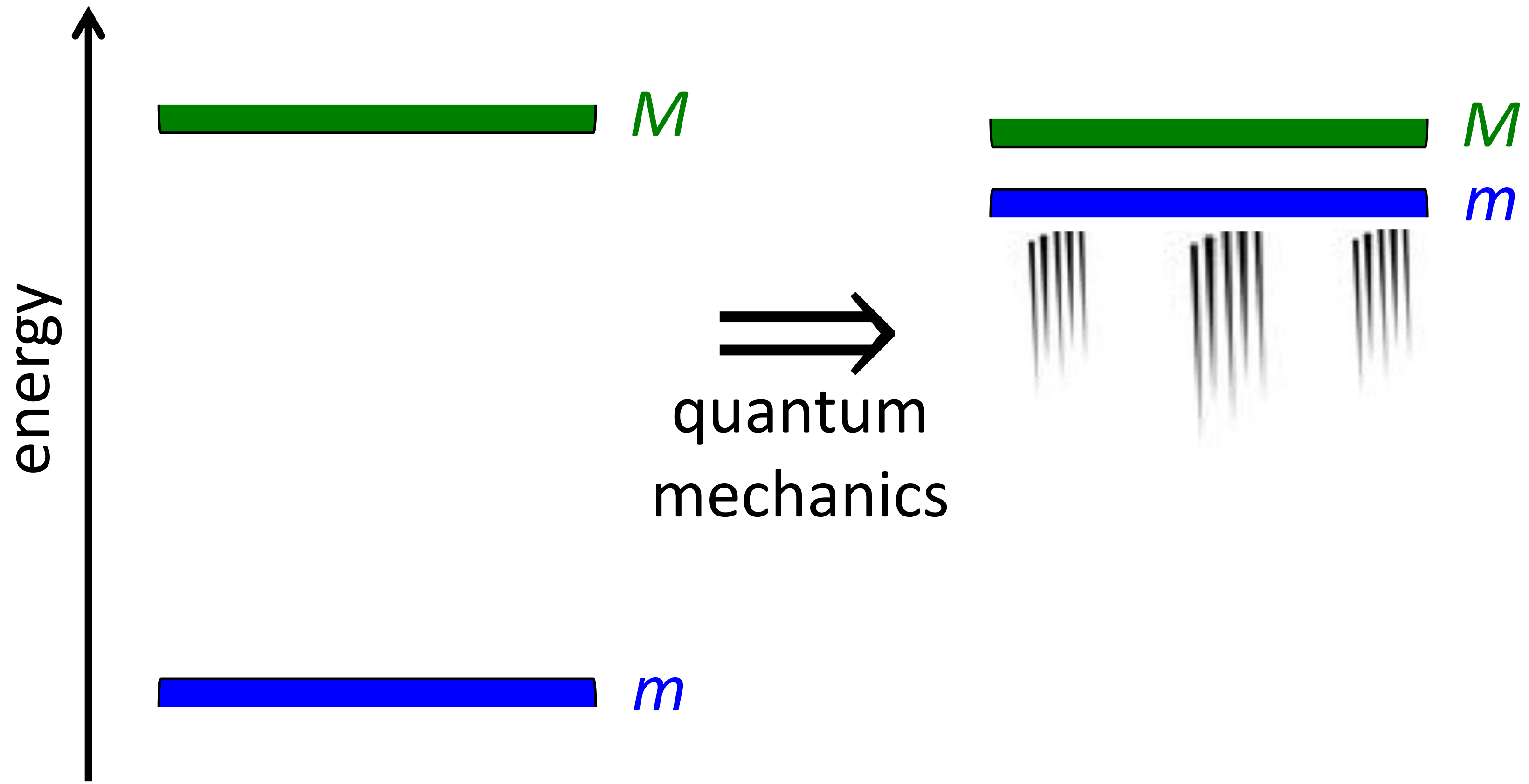
Higgs mass



$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 < m_h^2 \Rightarrow \Lambda < 500 \text{ GeV}$$

- What happens when you don't find the missing pieces?
- One must question the hypotheses on which the naturalness principle rests.

1) Scale separation



1) Scale separation

Are there any new energy scales above the weak scale?

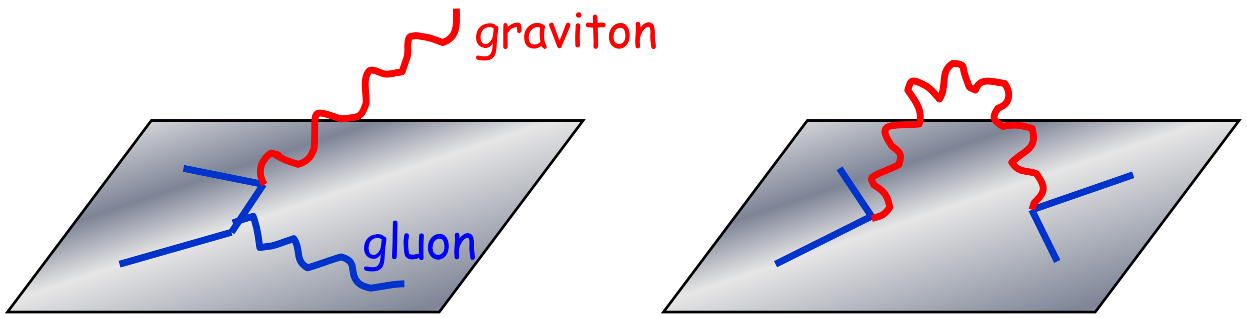
Quantum gravity?

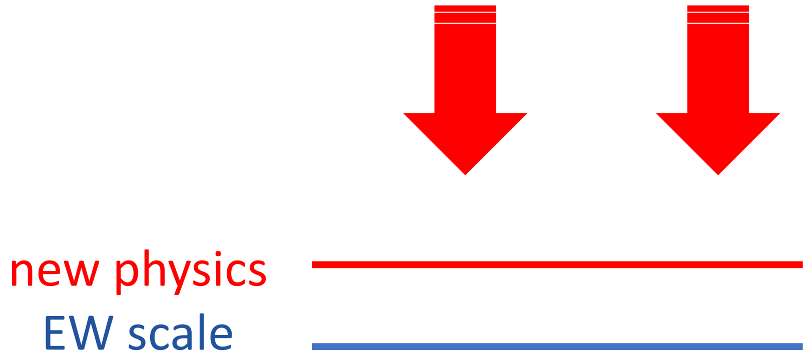
Neutrino masses, the strong CP problem, inflation,

gauge coupling unification, …?

Flavour?

Large Extra Dimensions



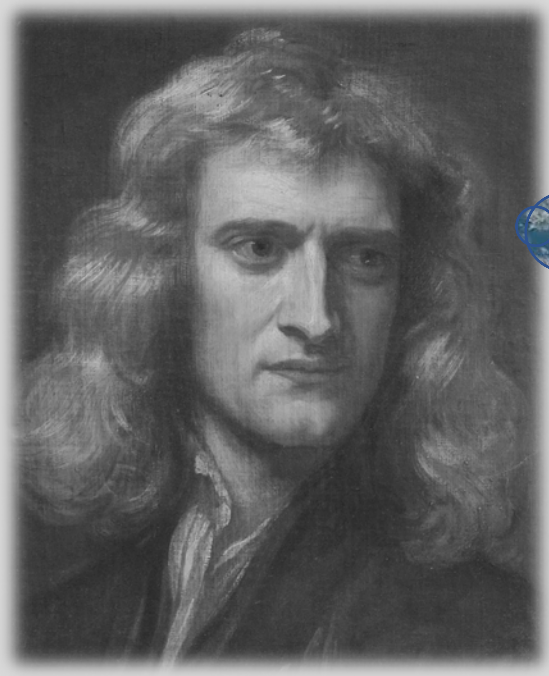


Asymptotic safety in quantum gravity?

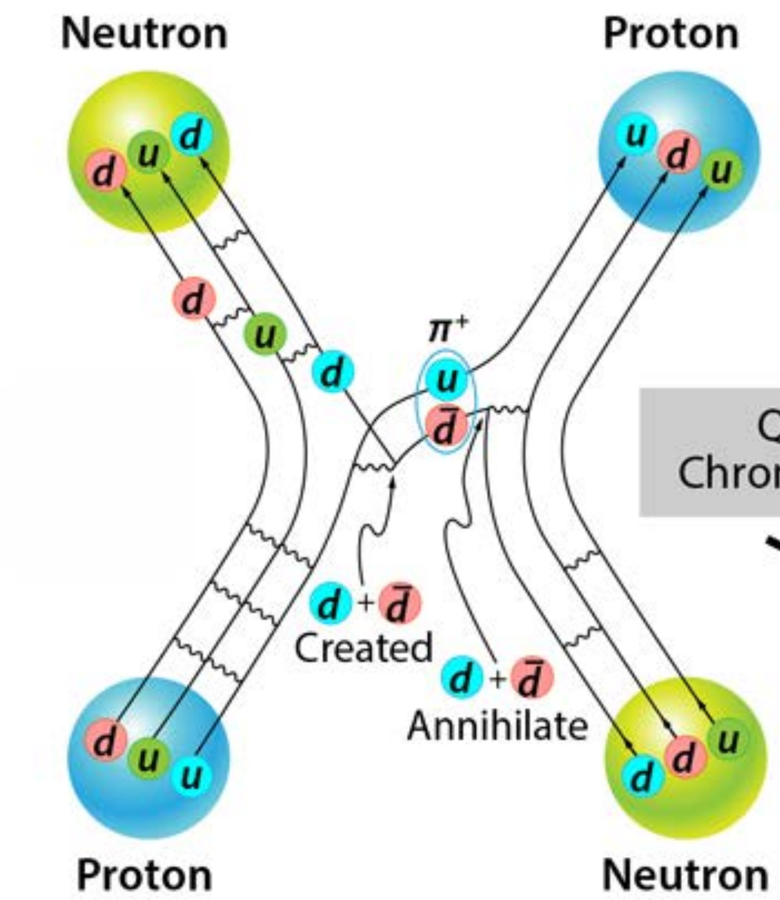
2) EFT validity

Naturalness: parameters being sensitive to heavy modes integrated out from the low-energy theory.

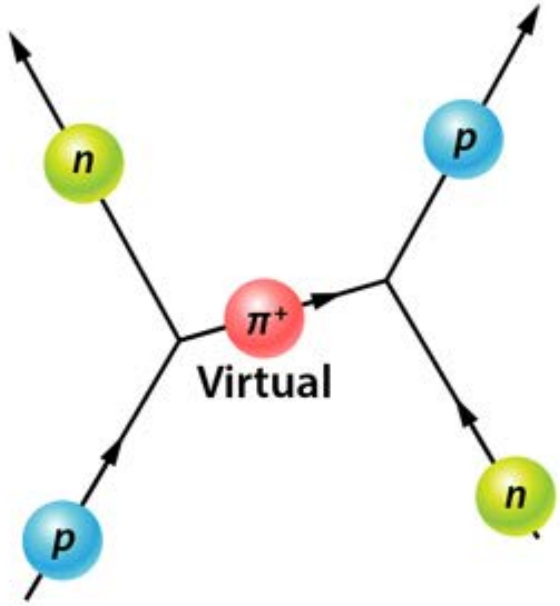
Could it be that the rules of EFT break down?




Physics is only dimensional analysis and Taylor expansions



Quantum Chromodynamics

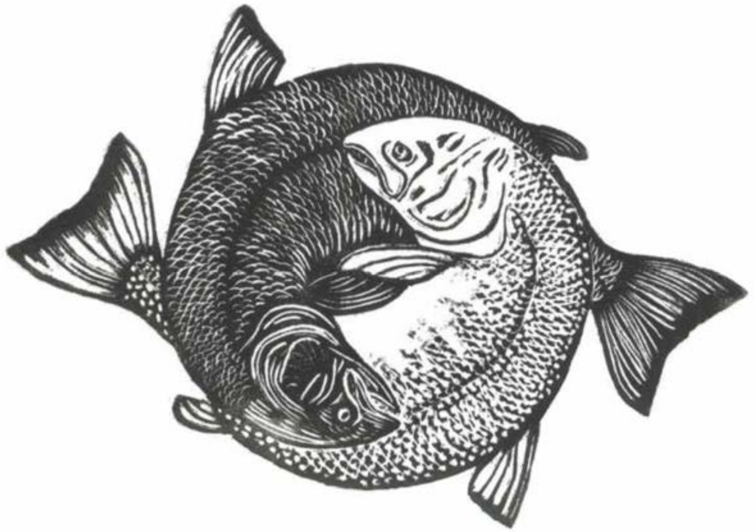


Chiral Effective-Field Theory

Nuclear Few- and Many-Body Problems

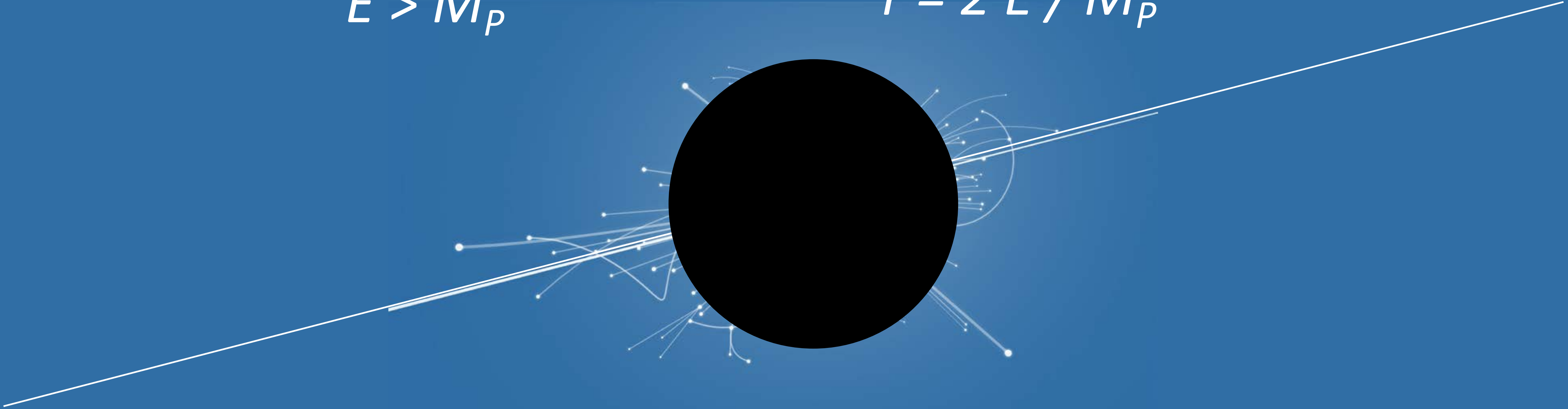
Could it be that the rules of EFT break down?

IR/UV correlation



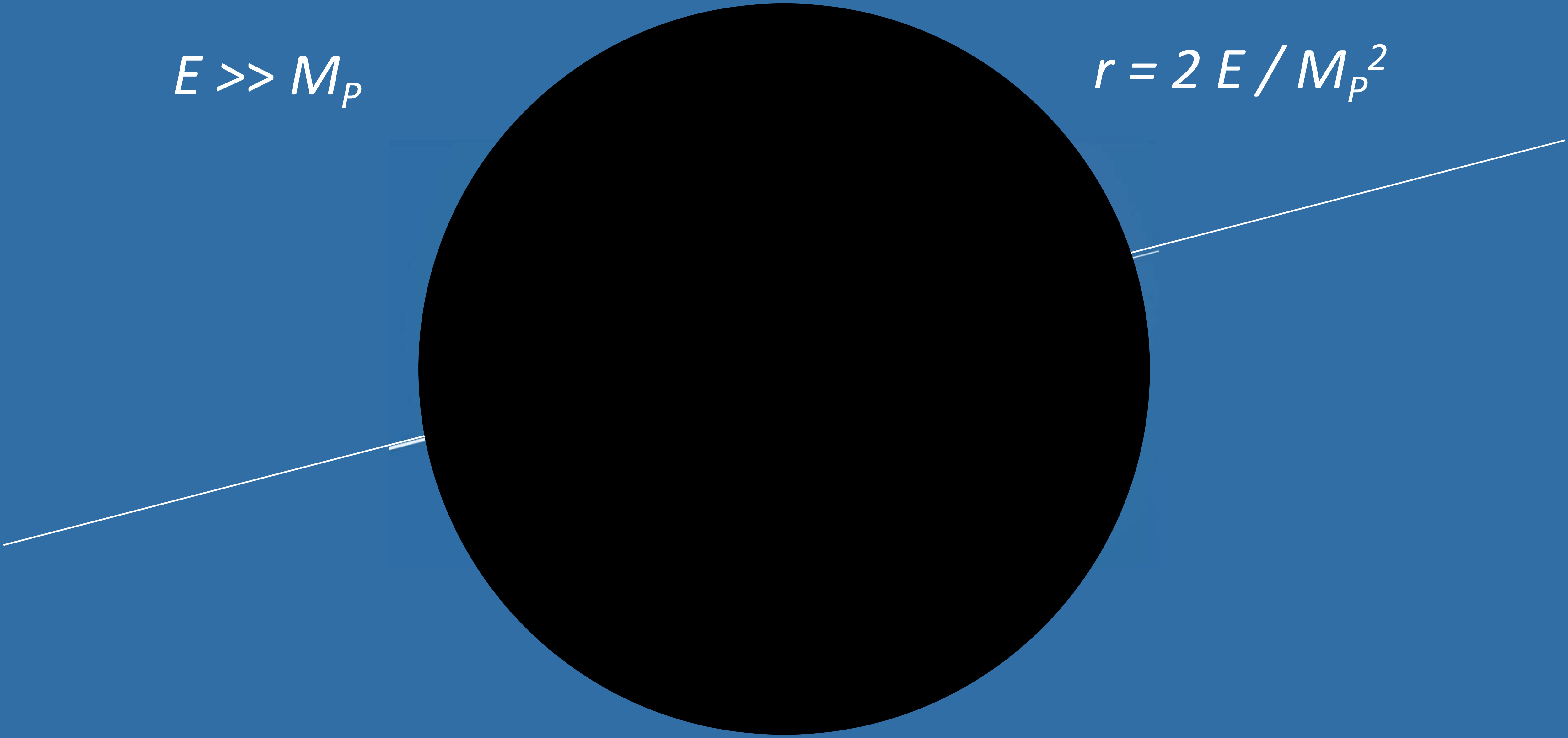
$E > M_P$

$r = 2\,E / M_P^{\,2}$

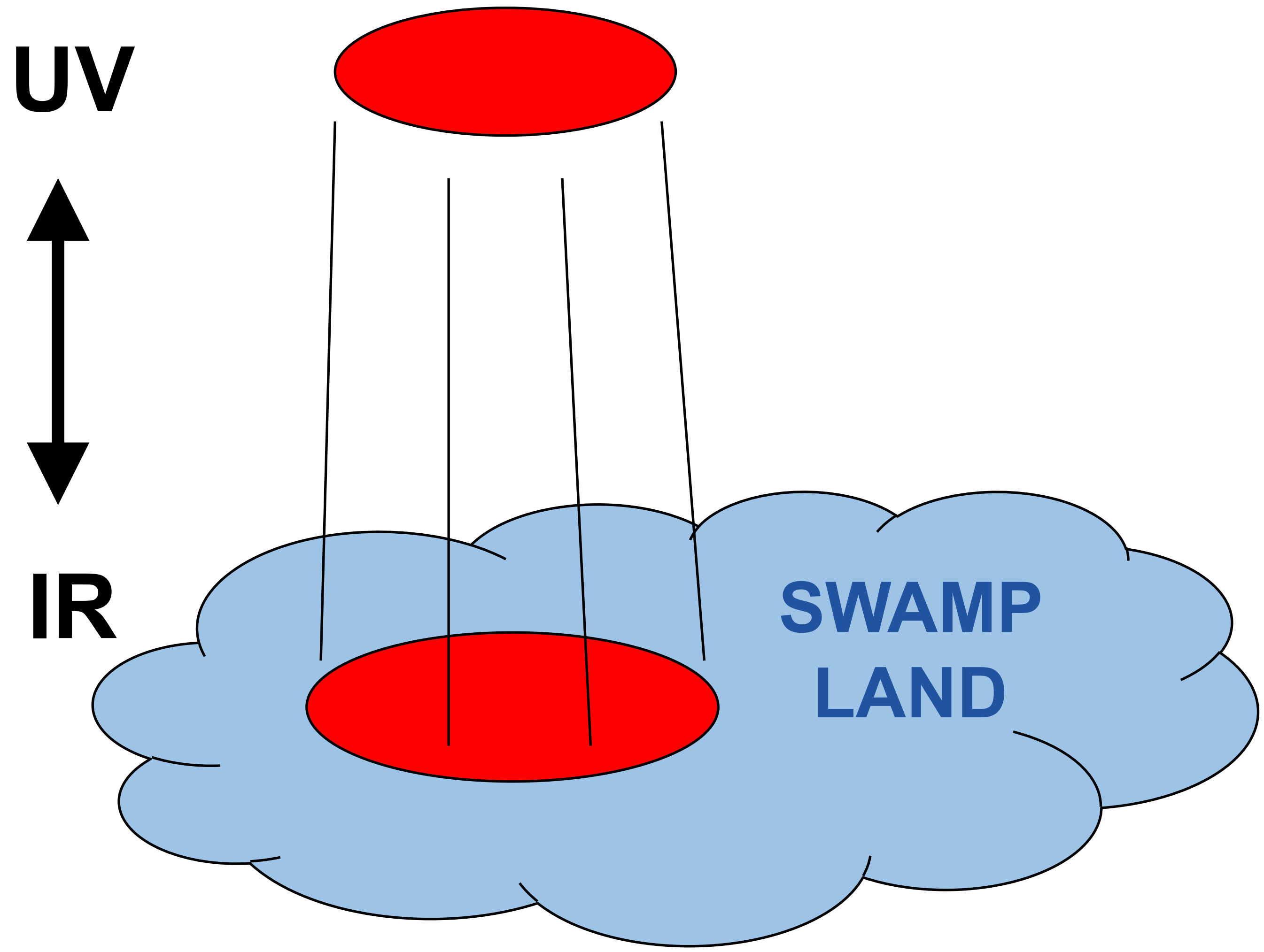


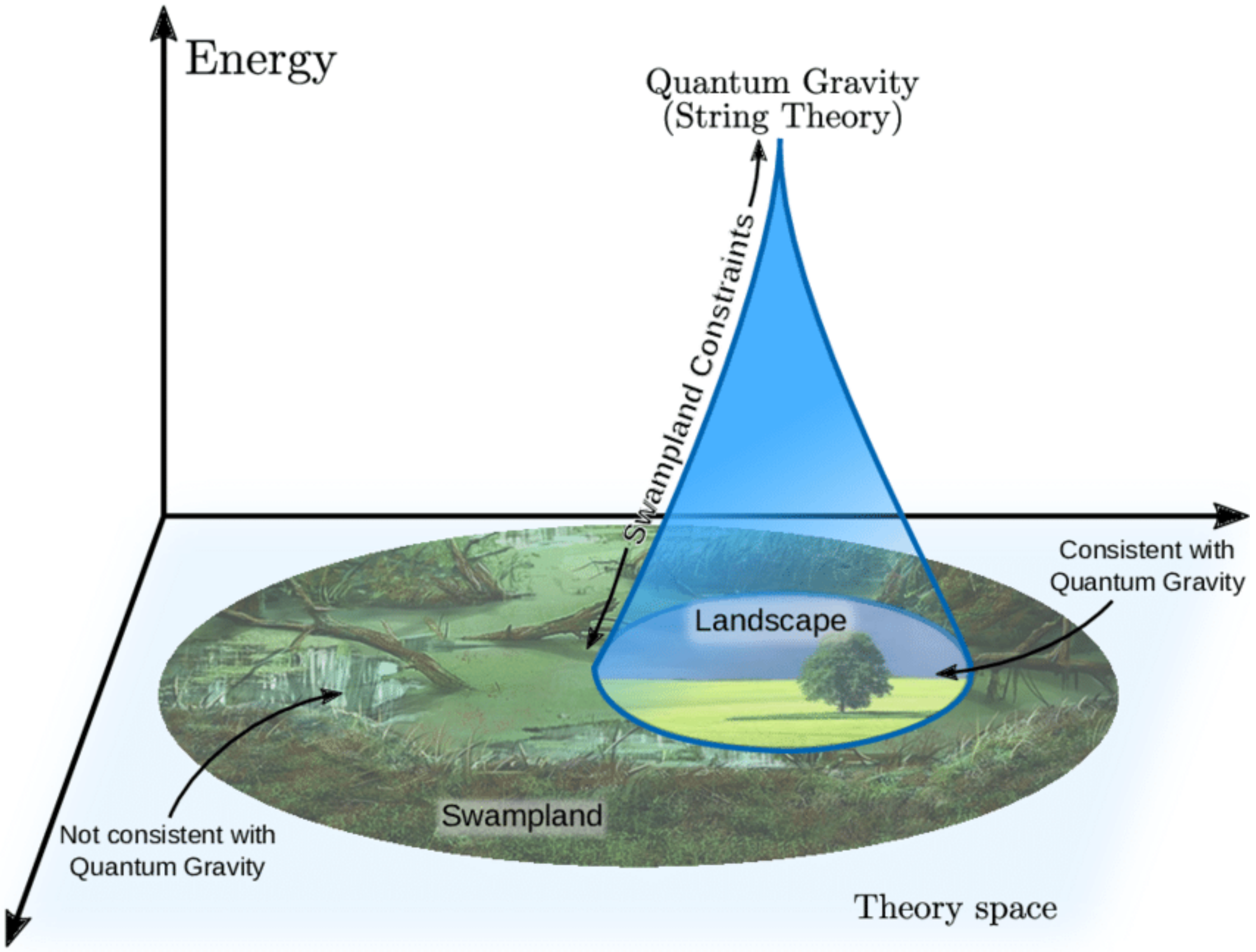
$E >> M_P$

$r = 2E / M_P^2$

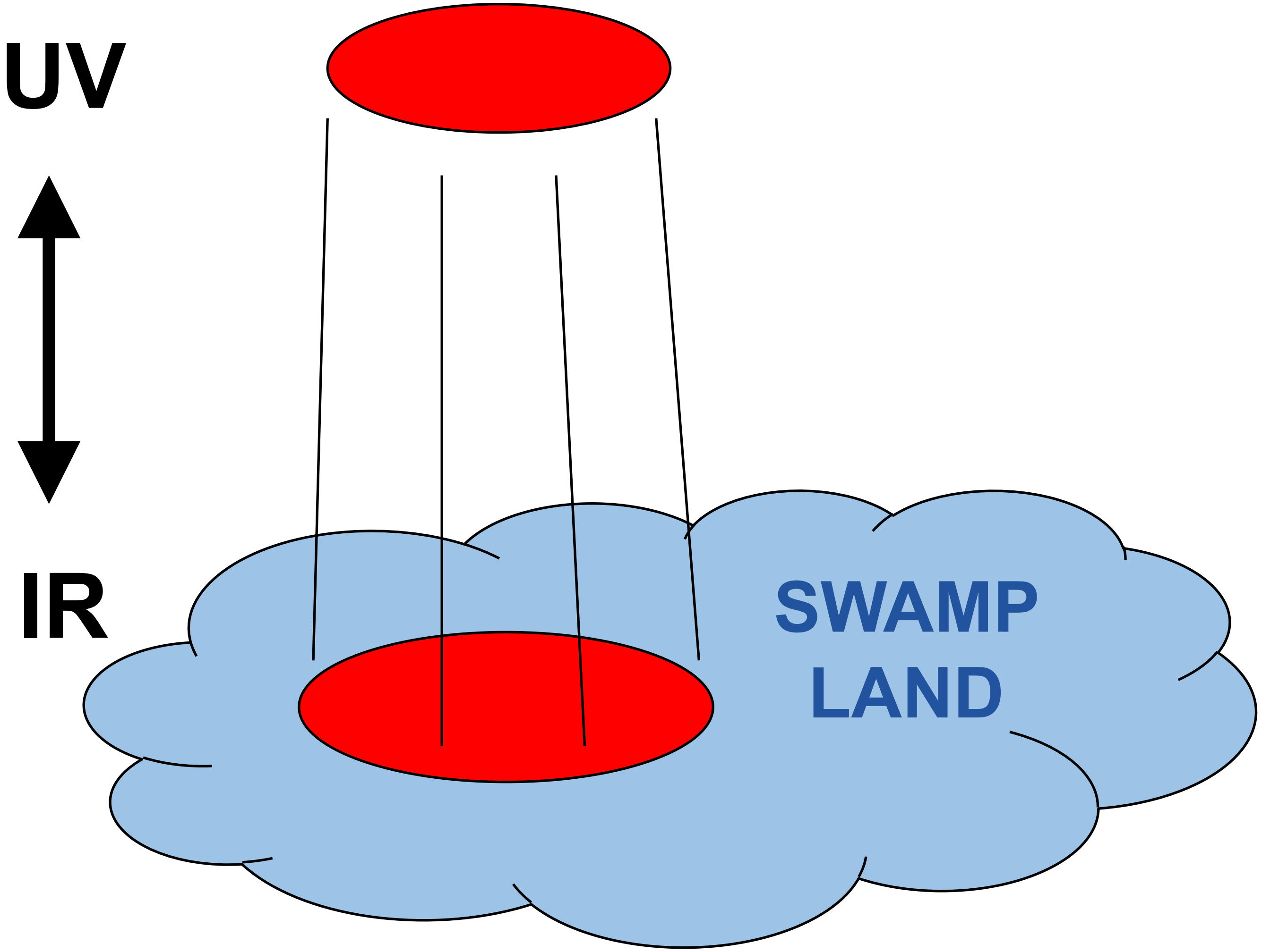


Some theories allowed by EFT symmetries live in the swampland



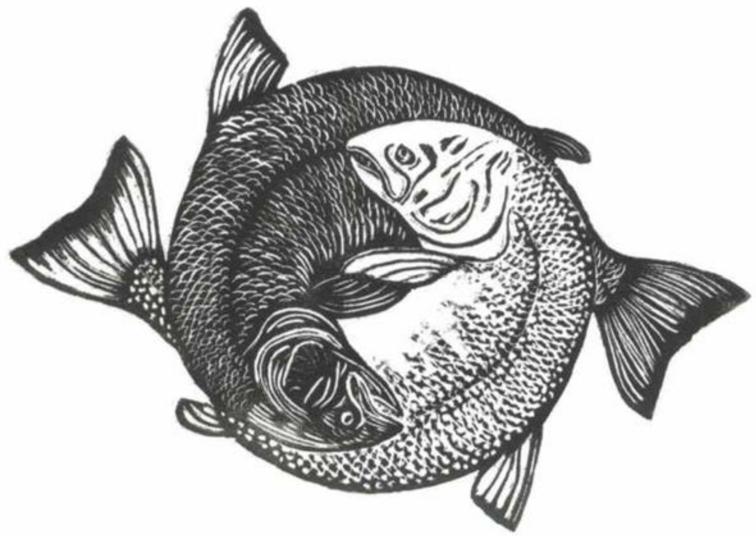

Energy
Quantum Gravity
(String Theory)
Swampland Constraints
Consistent with
Quantum Gravity
Landscape
Swampland
Not consistent with
Quantum Gravity
Theory space

Some theories allowed by EFT symmetries live in the swampland



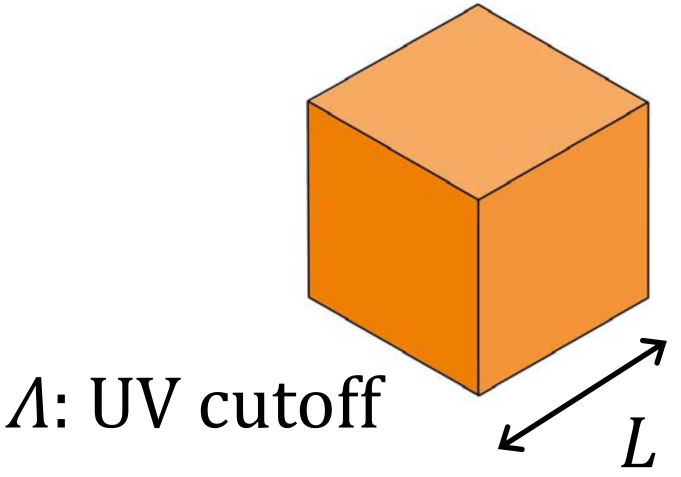
It challenges EFT intuition
and naturalness is based on EFT intuition

IR/UV correlation



Breakdown of locality in QFT

IR/UV correlation (Cohen-Kaplan-Nelson bound)



QFT:

dof $\sim L^3$

entropy $S \sim L^3 \Lambda^3$

Bekenstein max entropy:

$S_B = \pi L^2 M_P^2$

$S < S_B \Rightarrow L < M_P^2 / \Lambda^3$

Maximum energy states must have a Schwarzschild radius smaller than the size of the box.

energy density of max-energy states $\sim \Lambda^4$

total energy $\sim L^3 \Lambda^4$

Schwarzschild radius $R_S \sim L^3 \Lambda^4 / M_P^2$

$R_S < L \Rightarrow L < M_P / \Lambda^2$

$L = H_0 \Rightarrow \Lambda < 10^{-3}$ eV

Symmetry paradigm

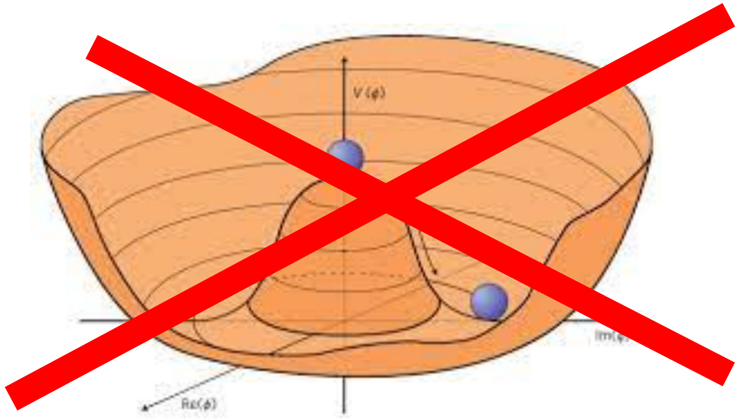
Is the “symmetry paradigm” crumbling down?

Are gauge symmetries a fundamental principle or an emergent phenomenon?

Is the LHC telling us that it is time to look for radically different paradigms?

The decline of symmetry?

- Global symmetries are violated in Quantum Gravity
- Local symmetries are not symmetries
  (act trivially on Hilbert space)



- Gauge symmetries can be emergent
- Symmetries may not be sufficient to determine the low-energy theory

There is more in a low-energy theory than simply the rules of symmetry.

Constraints from swampland conjectures.

Constraints from analyticity, unitarity, crossing, and Lorentz invariance give non-trivial limitations on UV completions.

Duality: new faces of reality

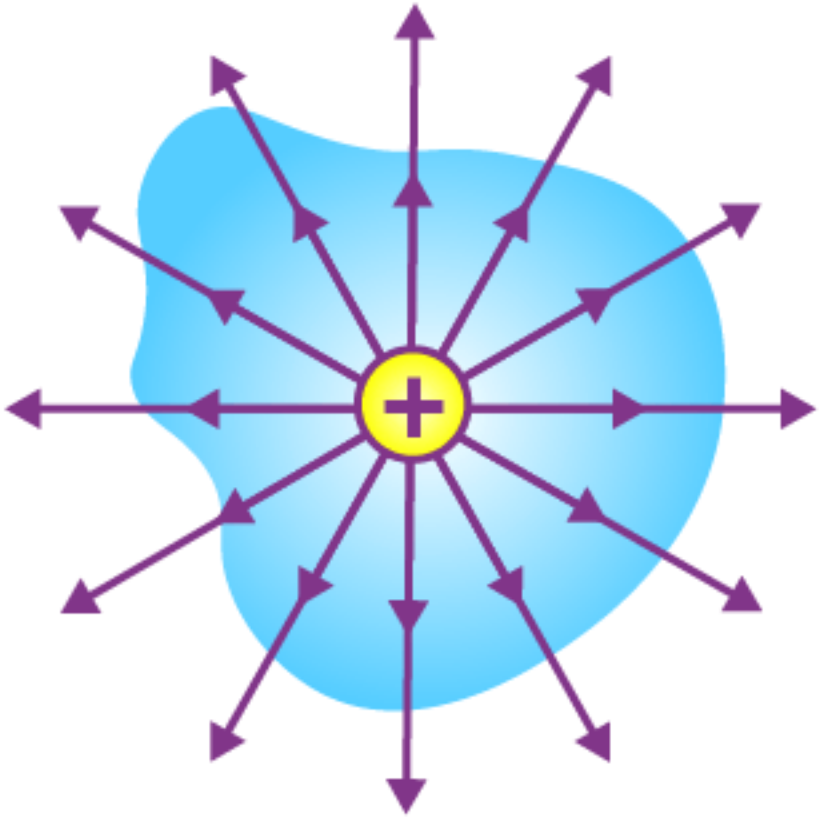
(neither language of dual theory captures reality)

- AdS/CFT: gravity/gauge duality
- Beyond a Lagrangian description?
- Tensor networks (description of complex many-body systems based on their entanglement structure) reproduce properties of AdS/CFT
- Quantum gravity as a quantum information theory?

Generalised symmetries

Noether: invariance ⇒ conserved charge

$$Q = \int_V d^3x \, J_0$$



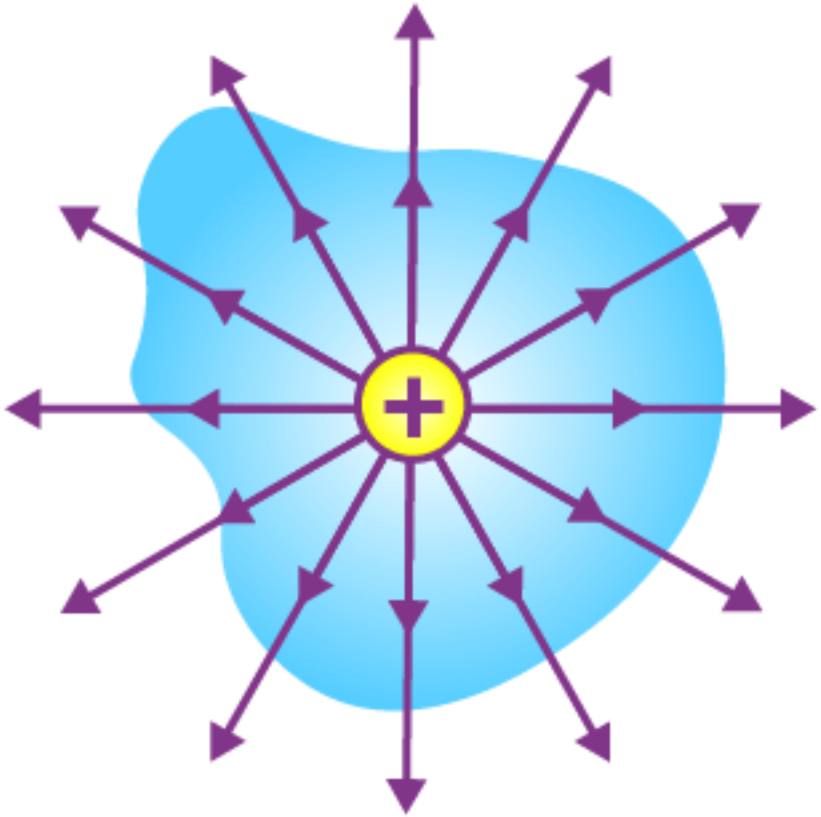
Symmetry ⇒ topological defect

Is the converse true?

Generalised symmetries

Noether: invariance ⇒ conserved charge

$$Q = \int_V d^3x \, J_0$$



Topological quantities from integrals in different numbers of co-dimensions.

Supersymmetry

Coleman-Mandula

Symmetries in QFT

Higher-form symmetry

Non-invertible symmetry

Symmetries in QFT

2) EFT validity

Could it be that the rules of EFT break down?

3) IR free parameters are calculable quantities in the UV completion

Example: supersymmetry

breaks chiral symmetry

$$m_H^2 = |\mu|^2 - \frac{3h_t^2}{8\pi^2} m_{\tilde{q}}^2 \ln \frac{\Lambda^2}{m_{\tilde{q}}^2}$$

breaks supersymmetry

Example: composite Higgs

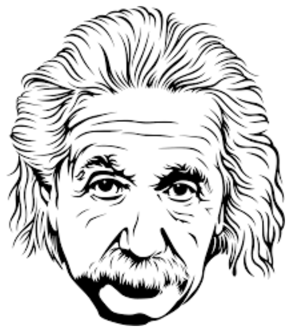
$$m_H^2 = \frac{3h_t^2}{4\pi^2} m_*^2 \xi$$

breaks shift symmetry

Can we give up hypothesis 3)?

The Higgs mass is not a calculable quantity

Nature is comprehensible



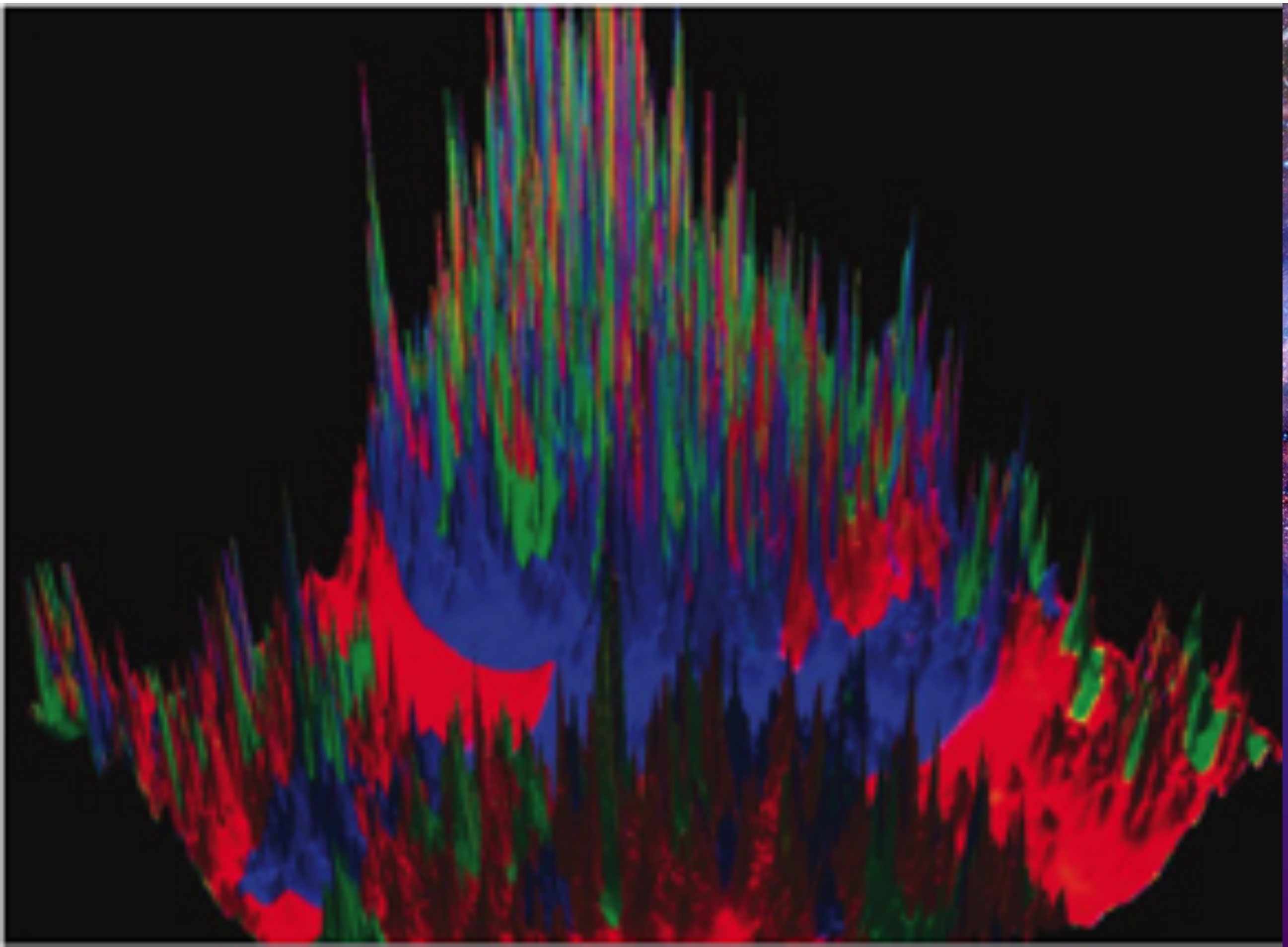
A more scientific approach:

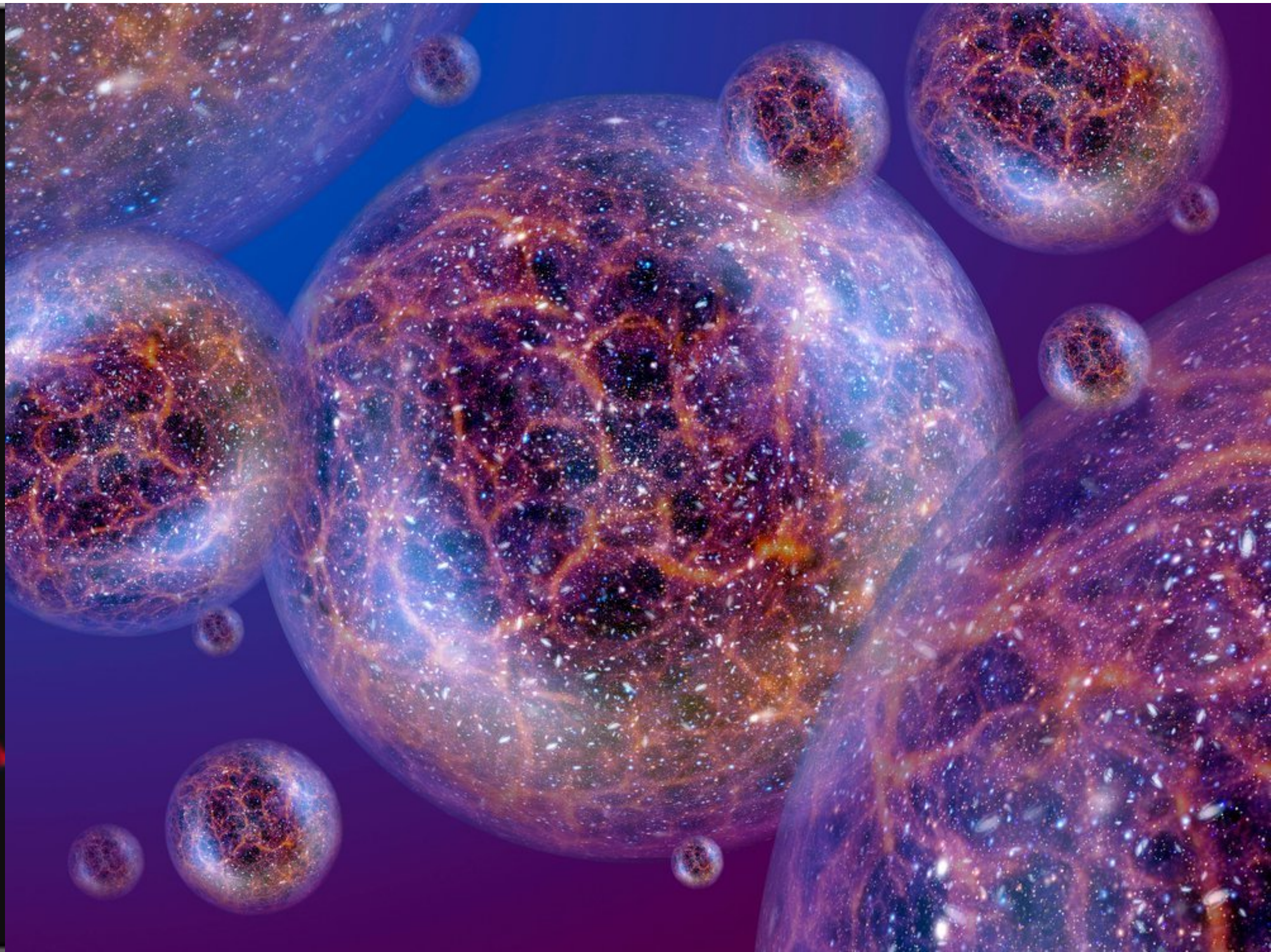
IR parameters are functions of some fields whose value vary during the cosmological history or throughout a complex vacuum structure

A radical change in perspective, a description of physical reality that can lead to precise predictions.

Relaxion, NNaturalness, crunching, sliding, selfish Higgs, self-organization, …

Multiverse: low-energy parameters are functions of fields with a non-trivial vacuum structure which is explored during the history of the universe.

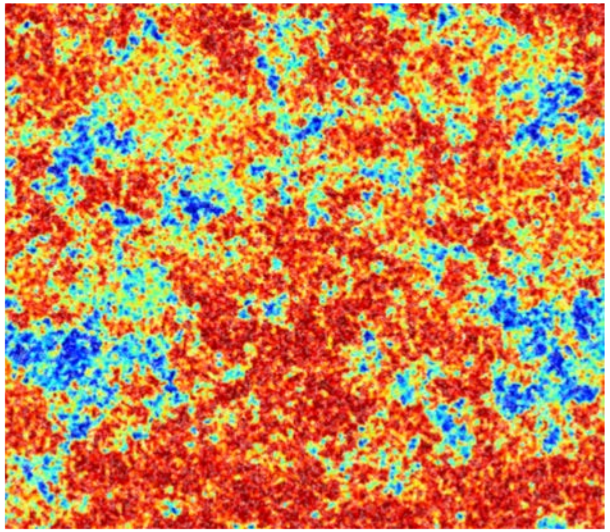


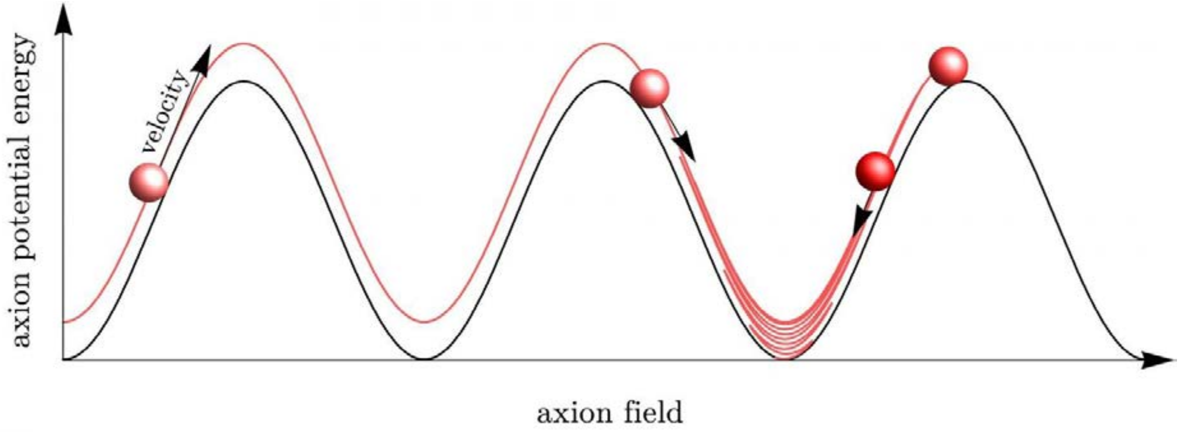


Axion

$$\mathcal{L}_{\text{dim}=4} = \frac{g_s^2}{32\pi^2}\,\bar{\theta} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a} \qquad d_n \sim e\,\frac{\bar{\theta} m_*}{\Lambda^2_{\text{had}}} \sim \bar{\theta}\cdot(6\times10^{-17})\;e\,\text{cm} \qquad |\bar{\theta}| < 10^{-10}$$

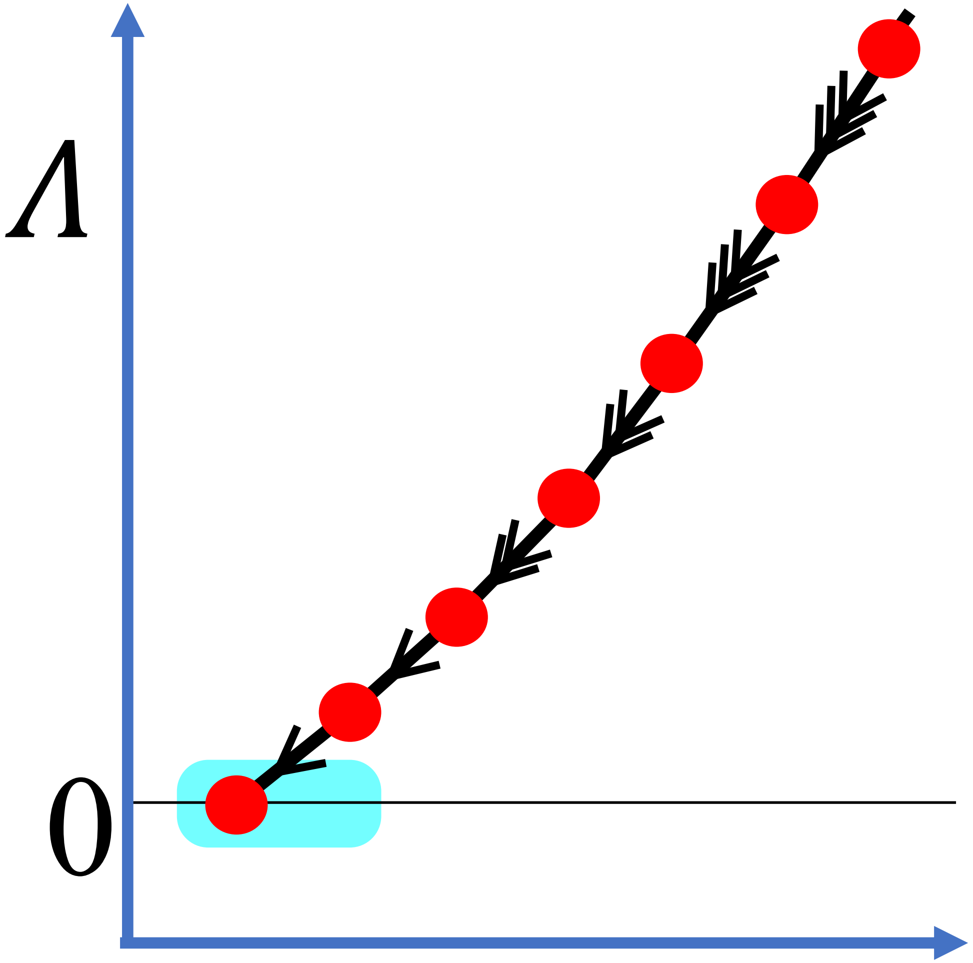
$$\bar{\theta} \implies a$$

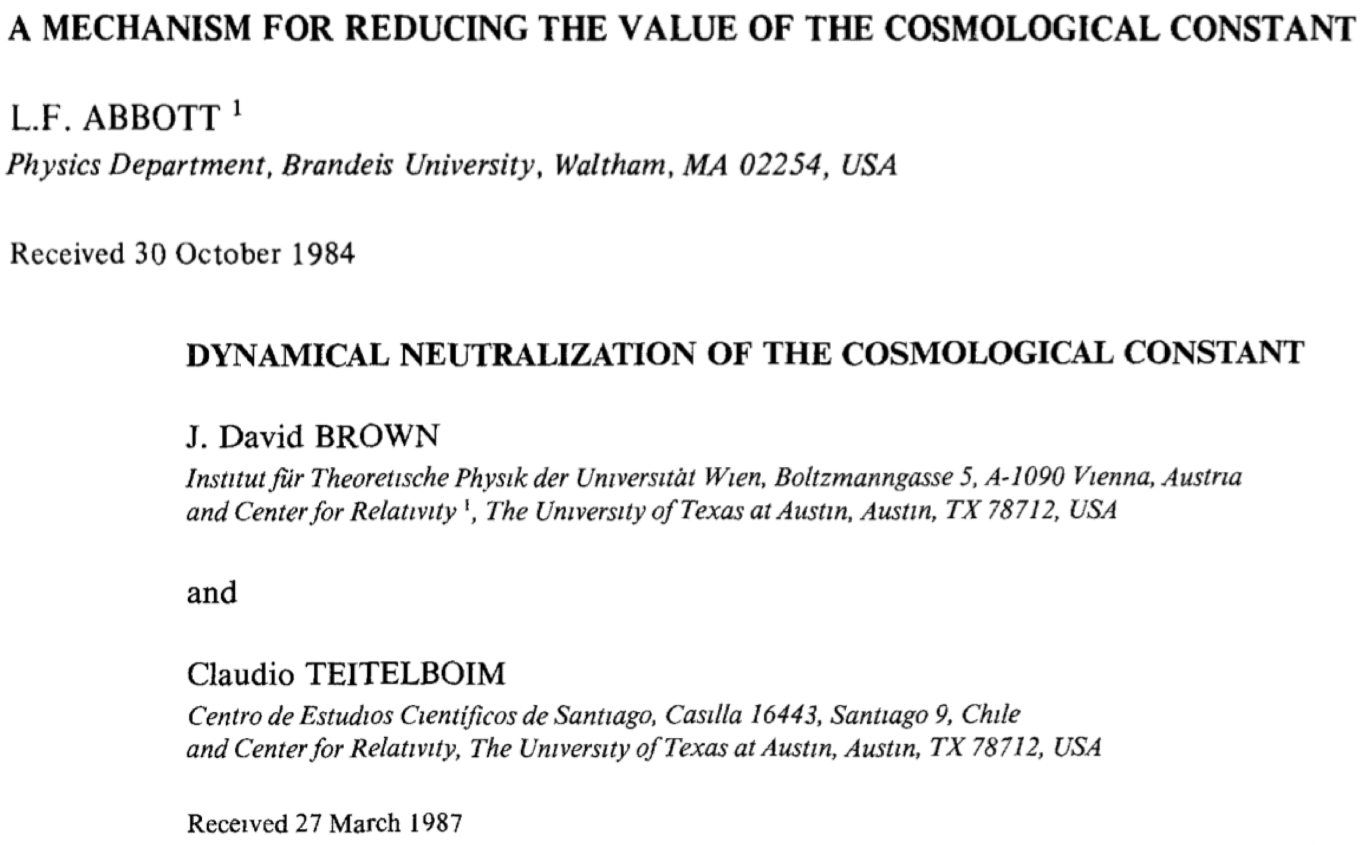




$\implies$ multiverse explanation of a low-energy parameter

DYNAMICAL RELAXATION MODELS





A MECHANISM FOR REDUCING THE VALUE OF THE COSMOLOGICAL CONSTANT

L.F. ABBOTT [1]
Physics Department, Brandeis University, Waltham, MA 02254, USA

Received 30 October 1984

DYNAMICAL NEUTRALIZATION OF THE COSMOLOGICAL CONSTANT

J. David BROWN
Institut für Theoretische Physik der Universität Wien, Boltzmanngasse 5, A-1090 Vienna, Austria and Center for Relativity [1], The University of Texas at Austin, Austin, TX 78712, USA

and

Claudio TEITELBOIM
Centro de Estudios Científicos de Santiago, Casilla 16443, Santiago 9, Chile and Center for Relativity, The University of Texas at Austin, Austin, TX 78712, USA

Received 27 March 1987

Two problems

- Smallness of scanning steps
- Empty Universe

Quantization of four-form fluxes and dynamical neutralization of the cosmological constant

Raphael Bousso

Department of Physics, Stanford University
Stanford, California 94305-4060
E-mail: bousso@hbar.stanford.edu

Joseph Polchinski

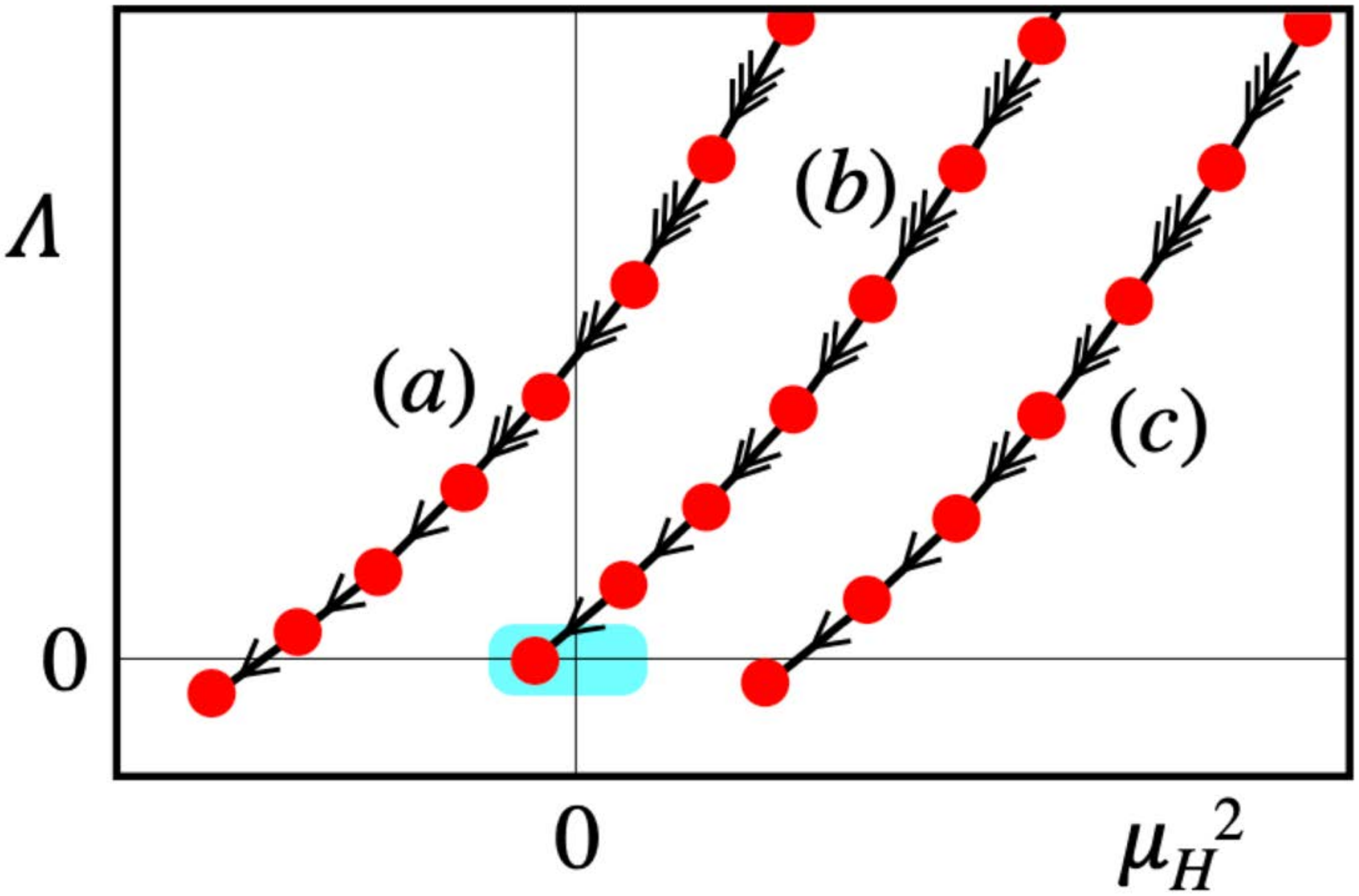
The Selfish Higgs

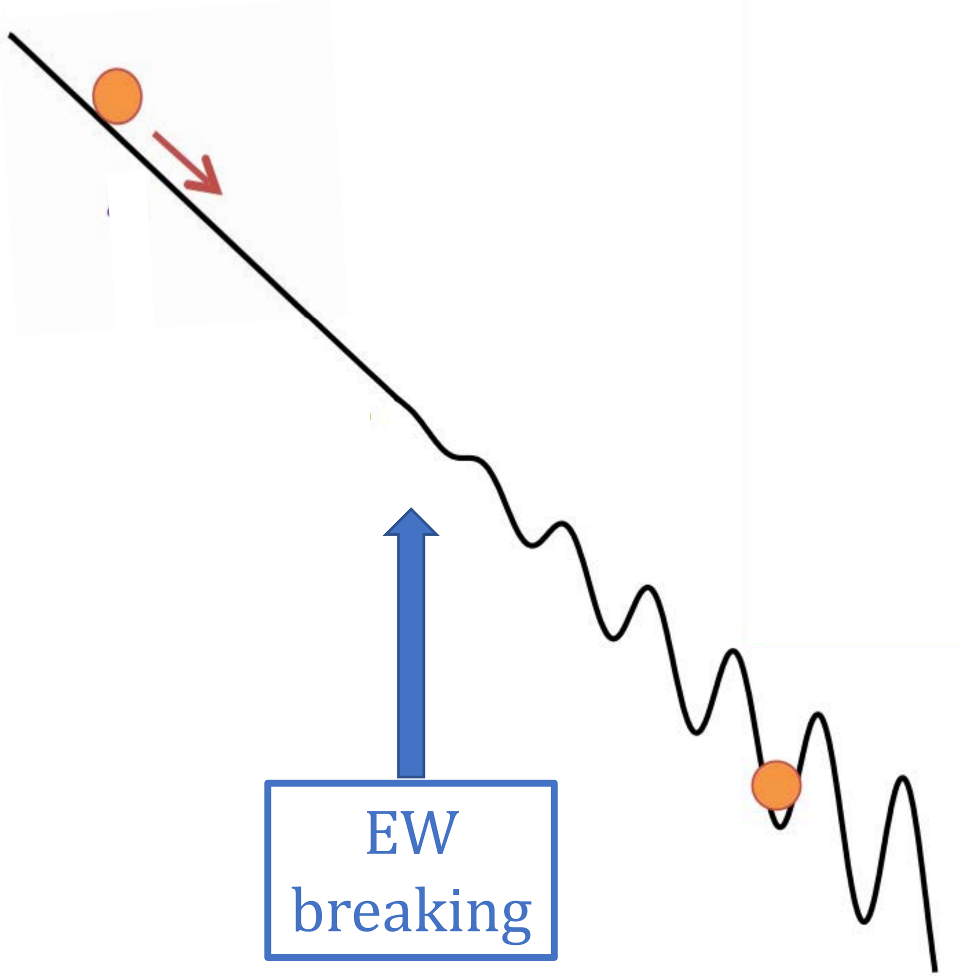
G.F. Giudice,[a] A. Kehagias[b] and A. Riotto[a,c]

PHYSICAL REVIEW D, VOLUME 70, 063501

Cosmic attractors and gauge hierarchy

Gia Dvali[1] and Alexander Vilenkin[2]





Cosmological Relaxation of the Electroweak Scale

Peter W. Graham,[1] David E. Kaplan,[1,2,3,4] and Surjeet Rajendran[3]

$$V_{\mathrm{QCD}} = f_\pi^3 m_q \cos(\phi/f_{\mathrm{PQ}})$$

f_{PQ} >> EW scale

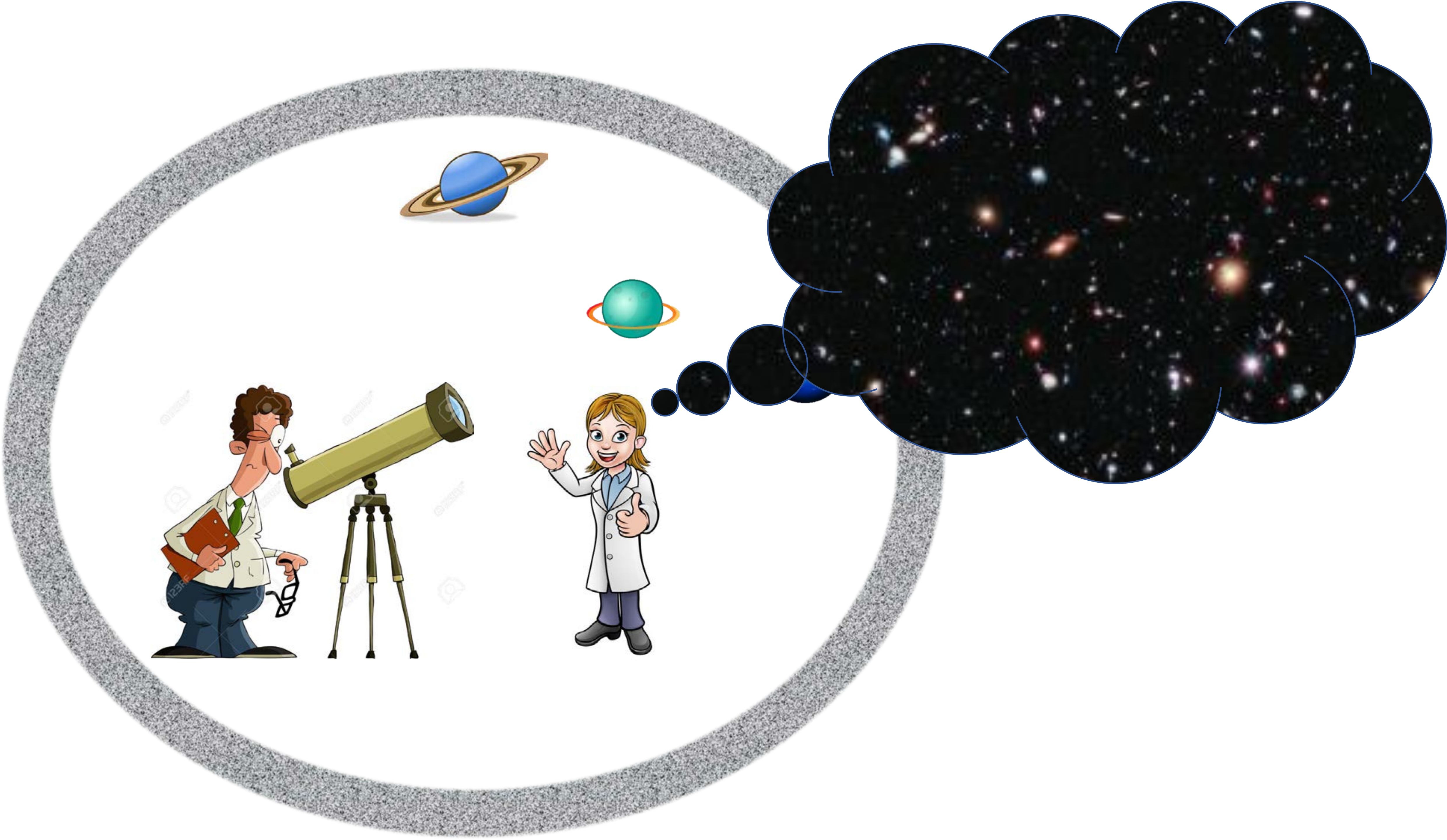

©2012

Gravitational coupling ⇧ ⇒ stars burn too fast
Gravitational coupling ⇩ ⇒ no stable galaxies
Electromagnetic coupling ⇧ ⇒ no nuclear fusion in stars
Weak coupling ⇧ ⇒ only hydrogen

The majority of universes are unable
to host complex structures.

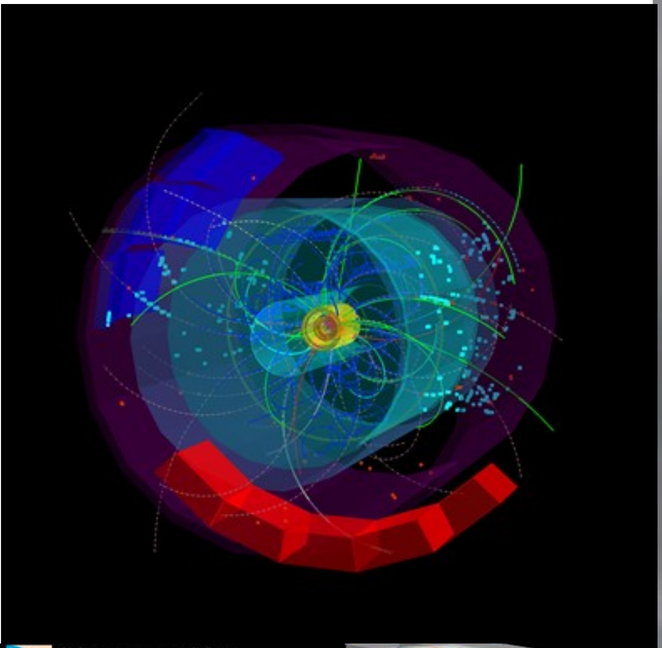
Complexity is a rare property that requires a
delicate balance between physical parameters.

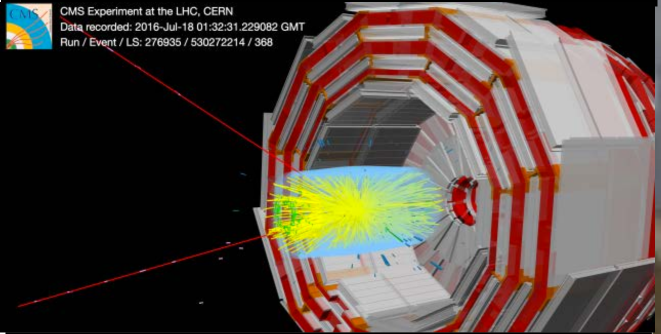
The anthropic principle

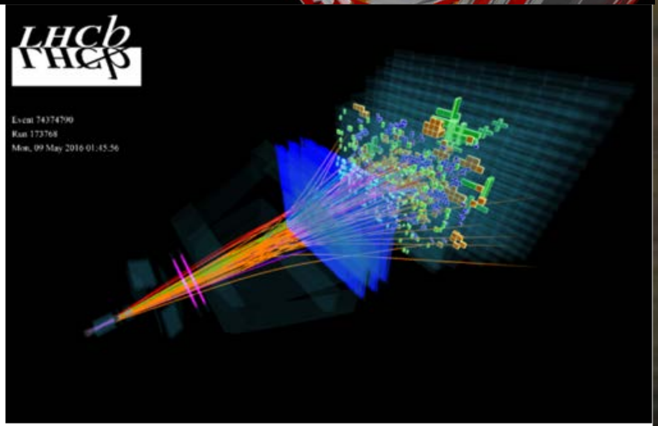


CONCLUSIONS

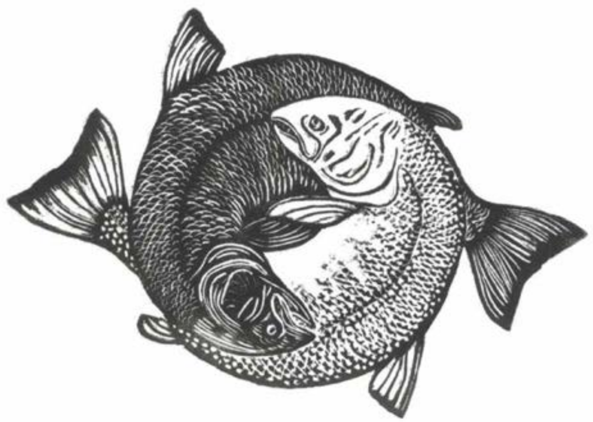
- Naturalness is a powerful tool for extrapolating our knowledge and infer the scale where a certain EFT breaks down.
- Relaxing the hypotheses on which naturalness is based has consequences that are even more radical than naturalness itself.
- This may lead to a paradigm change and this is the revolutionary legacy of the LHC.

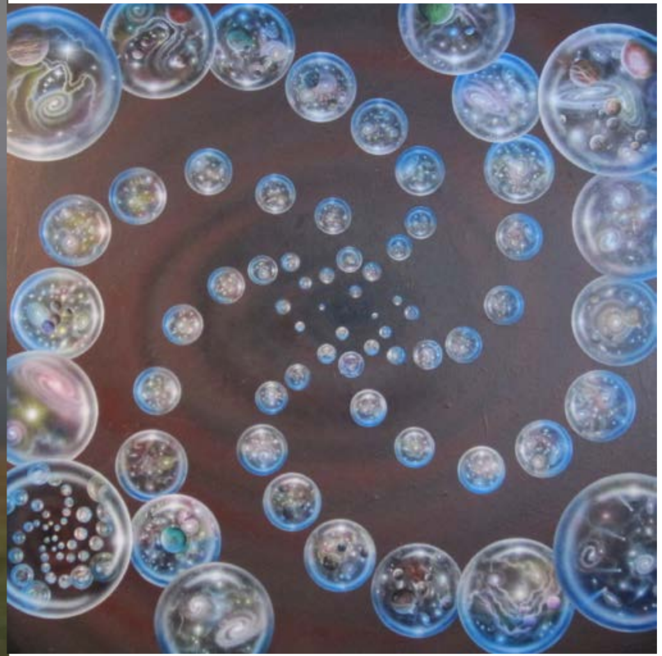



CMS Experiment at the LHC, CERN
Data recorded: 2016-Jul-18 01:32:31.229082 GMT
Run / Event / LS: 276935 / 530272214 / 368


LHCb


Symmetry paradigm
A new paradigm?





?

New paradigms?

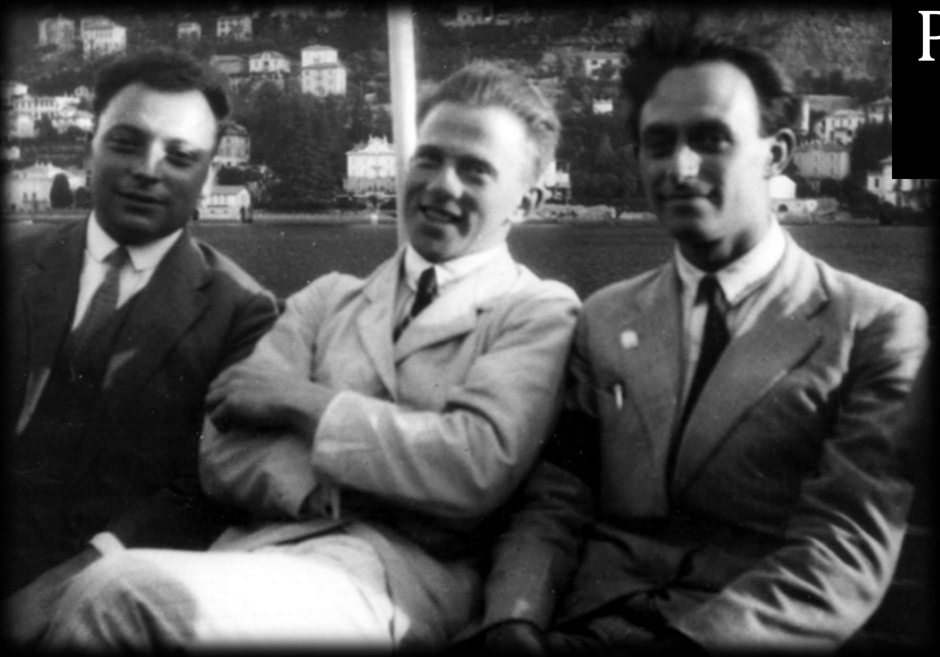
Modifications of QFT?

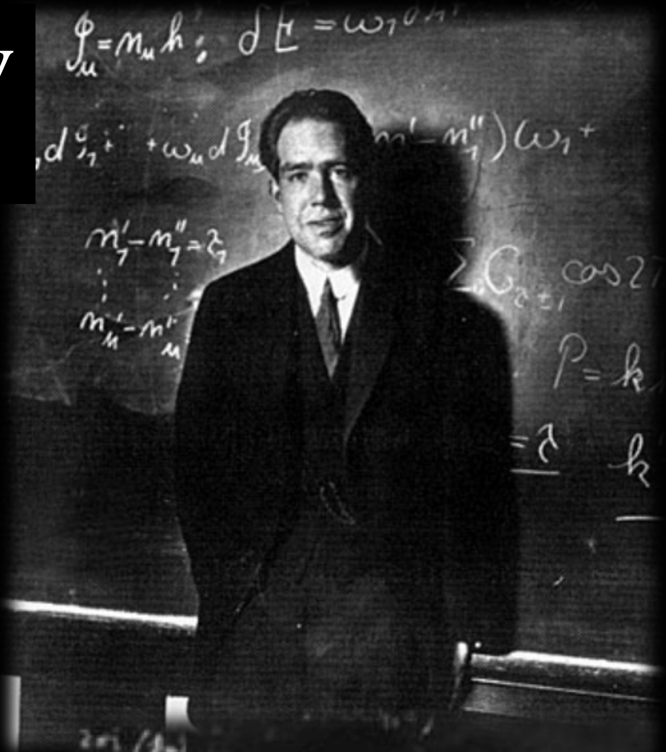
Modifications of the vacuum structure of the universe?

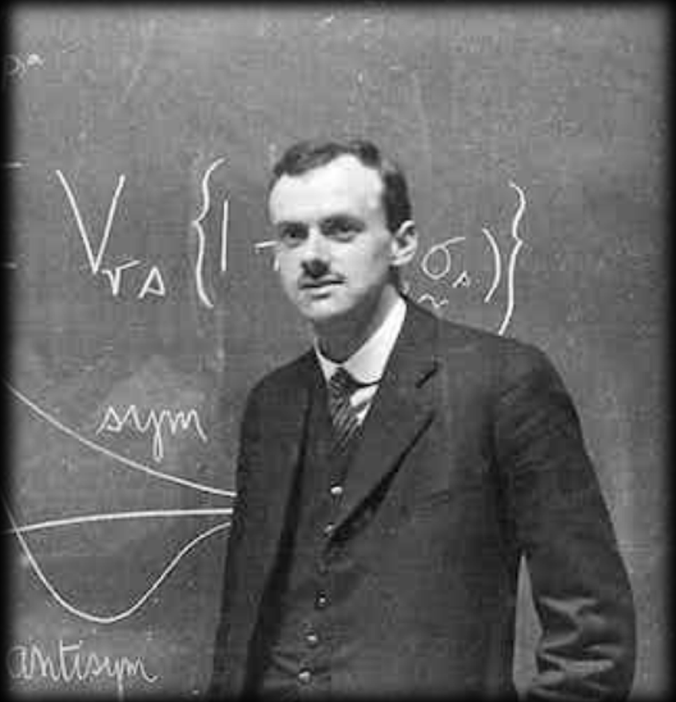
CONCLUSIONS

- Naturalness is a powerful tool for extrapolating our knowledge and infer the scale where a certain EFT breaks down.
- Relaxing the hypotheses on which naturalness is based has consequences that are even more radical than naturalness itself.
- This may lead to a paradigm change and this is the revolutionary legacy of the LHC.
- We are confronted with a conceptual crossroads.
- Experimentally, we should pursue both directions.
- Research in high-energy physics is in a state of great uncertainty.

Periods of great uncertainty are the best in research







The status of naturalness

G. F. Giudice

Erwin Schrödinger Guest Professor Lectures, October 2023