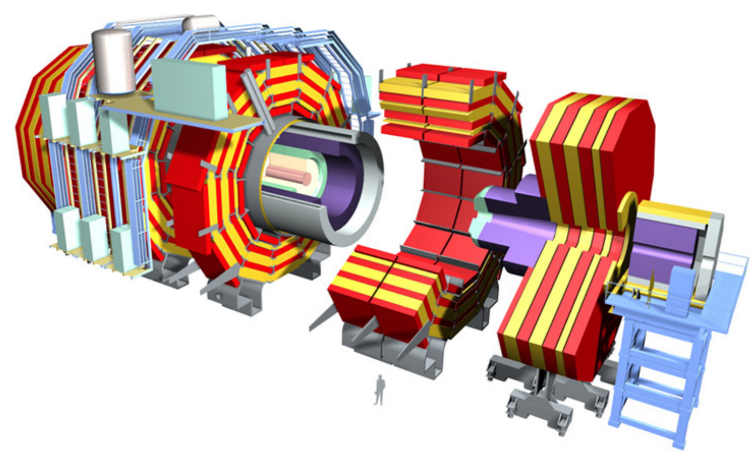
Understanding the emptiness: the Higgs field and beyond

Andrei Gritsan
Johns Hopkins University



July 27, 2021

Johns Hopkins University

Johns Hopkins University QuarkNet Physics Workshop

FCC (CERN) vision of the next 70 years

LHC program (funded)

Future Circular Collider pp 100 TeV (in R&D now)

2021 present LHC

2026 High Luminosity - LHC

2038 FCC-e^+e^-

10 years

2063 FCC-hh

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

LHC run 3 | LS 3 | LHC run 4 | LS4 | LHC run 5 | LS5 | LHC run 6

15 years operation

34 35 36 37 38 39 40 41 42 43

~ 25 years operation

70

Project preparation & administrative processes Funding & governance strategy

Permis-sions

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee accelerator R&D and technical design

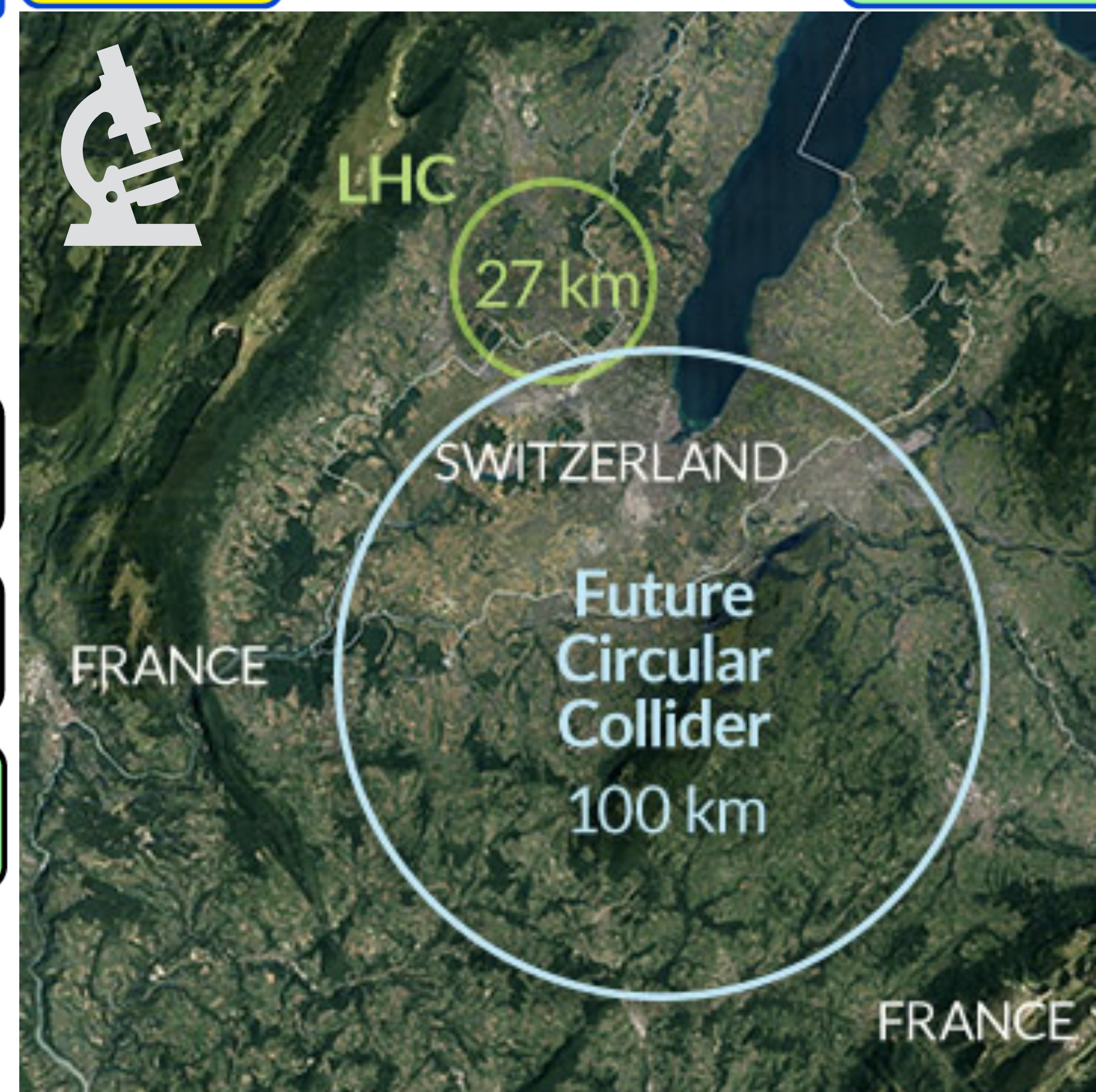
FCC-ee accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

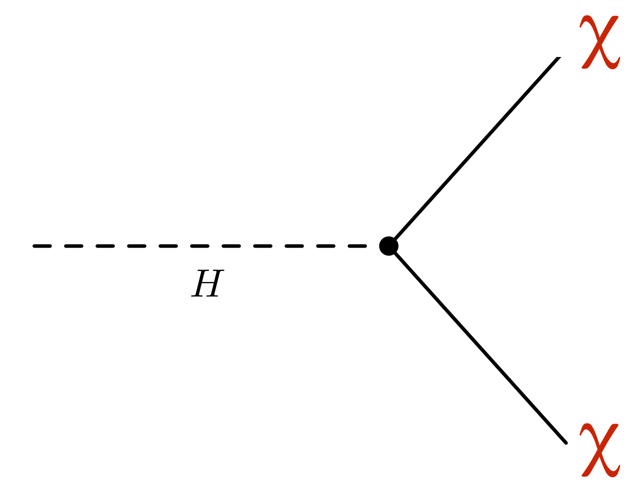


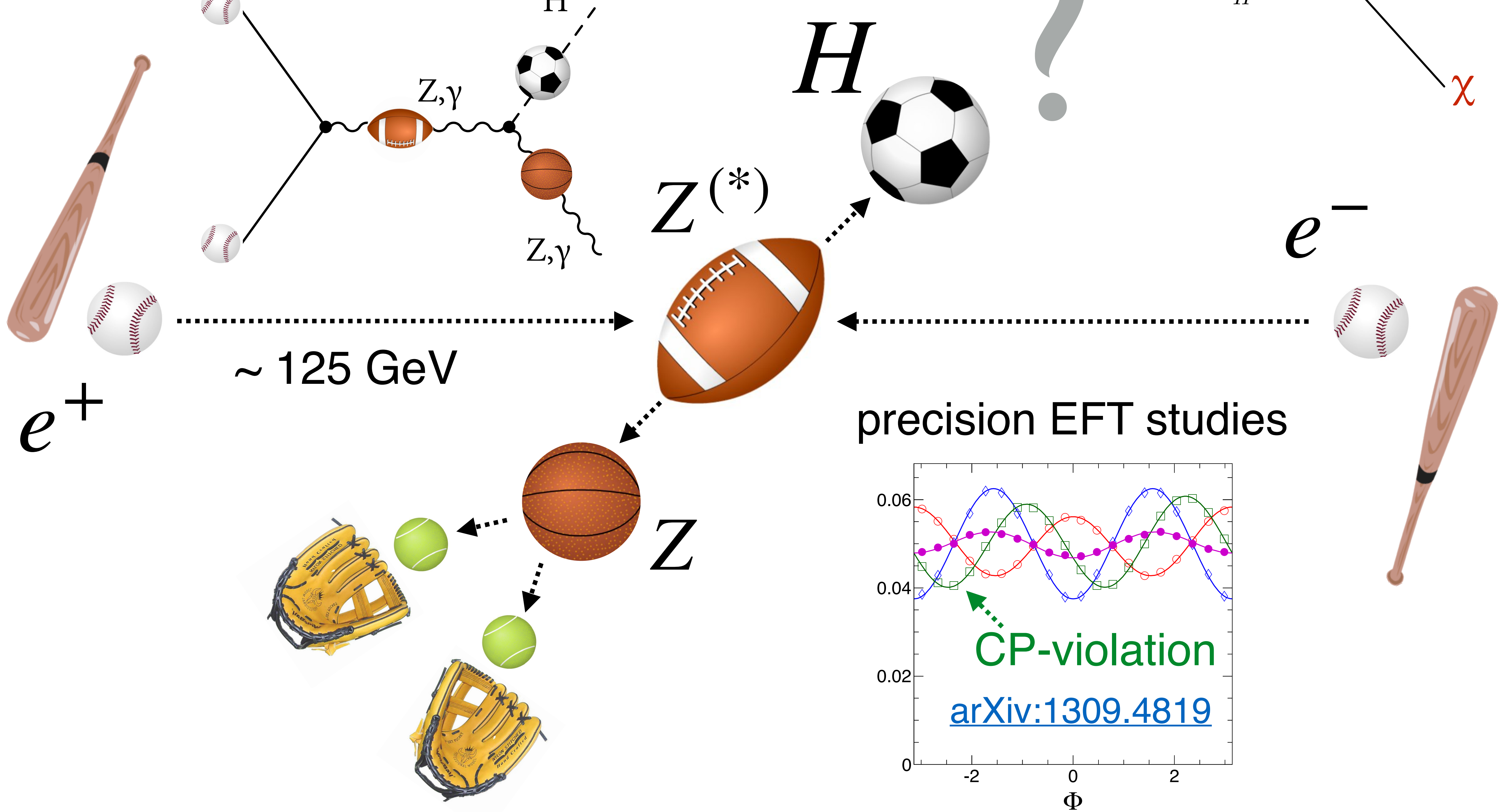
"backup:" High Energy - LHC (27 TeV)

The Next Microscope (Collider Proposals)

Future e^+e^- Higgs Factory

linear or circular, in Europe or Asia…





The Future of Particle Physics: “Snowmass” planning

Decadal community planning process

1982 — concept of SSC…
…
2001 — flavor physics and future facilities (LHC)
2013 — Higgs discovery and the next steps (see P5 below)
2022 — starting now…

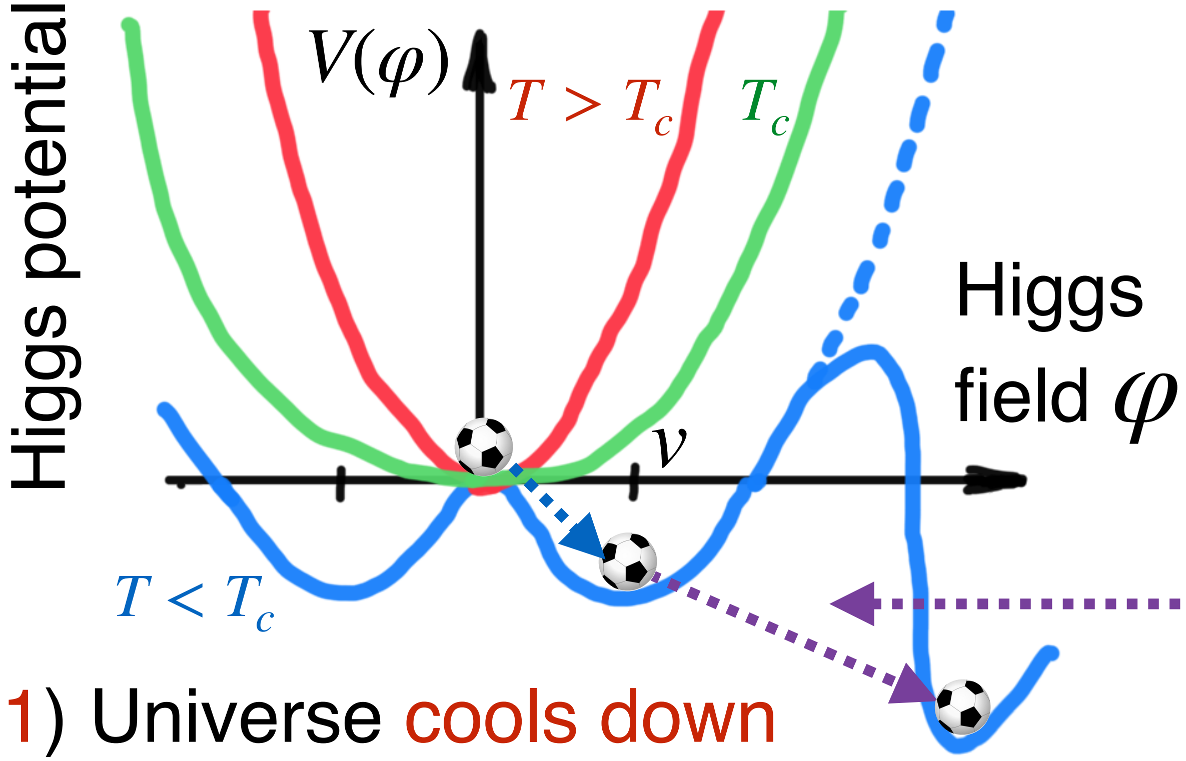
US strategic planning (P5), advise NSF and DOE through HEPAP
(P5 = Particle Physics Project Prioritization Panel)

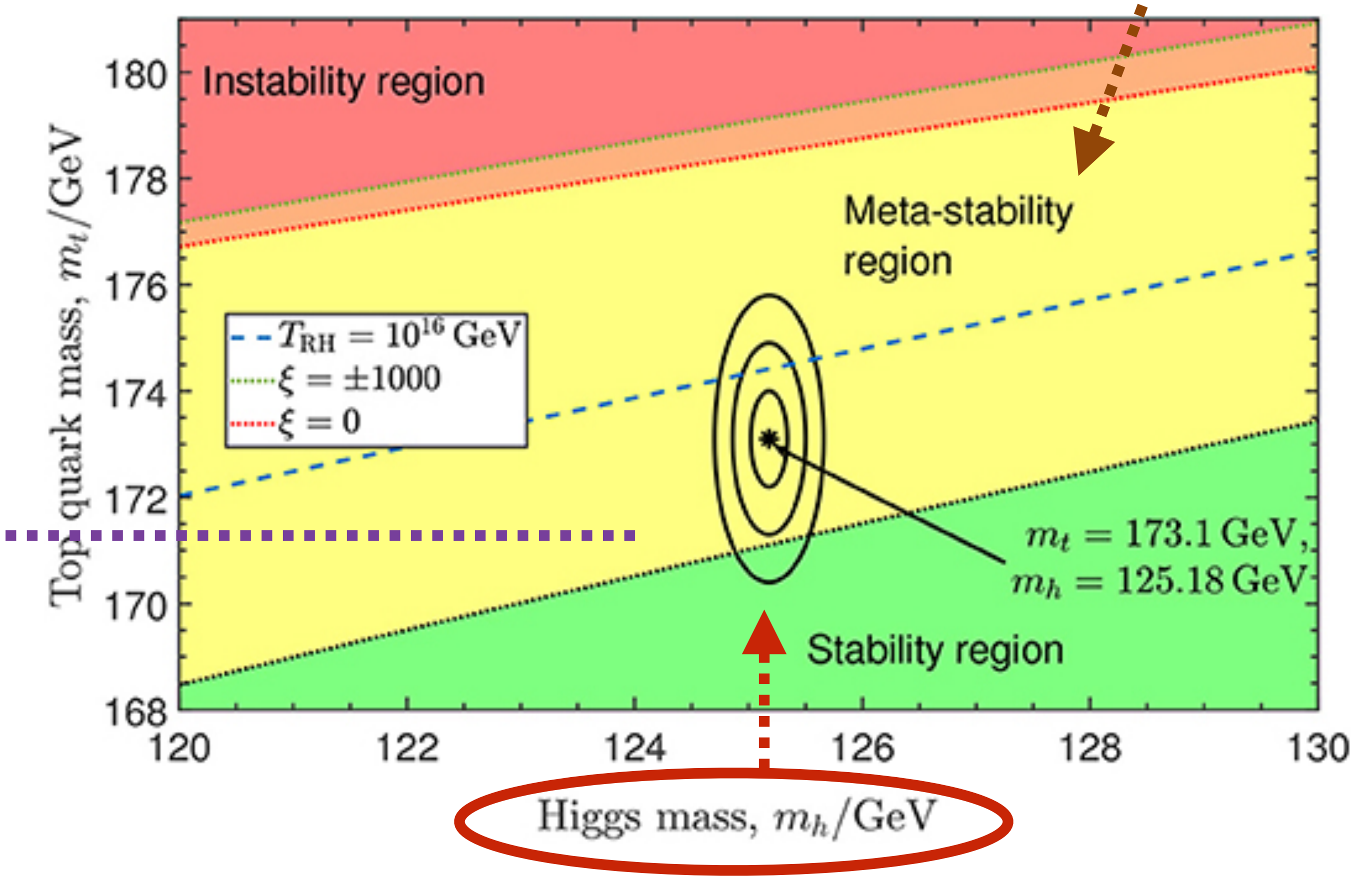
- Use the Higgs boson as a new tool for discovery ⇐ focus today
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

Higgs Potential and Stability of the Vacuum

$$V(\varphi) = \mu^2 \varphi^\dagger \varphi + \lambda^2 (\varphi^\dagger \varphi)^2$$

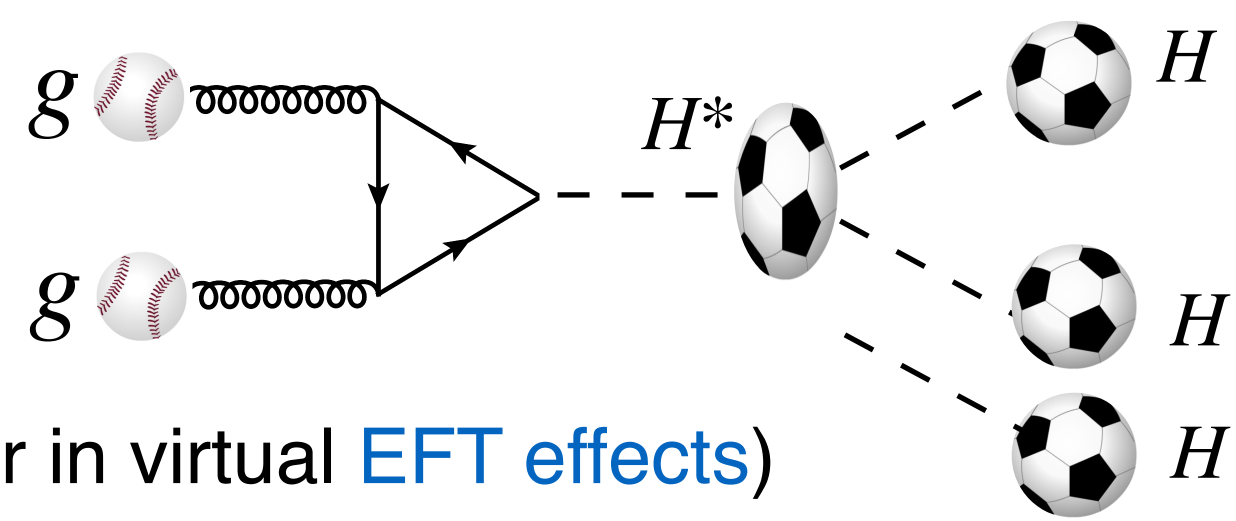
- Quantum corrections ⇒ metastable vacuum
  — assume SM up to very large M





(1) Universe cools down
(2) symmetry spontaneously breaks
(3) tunnel away?

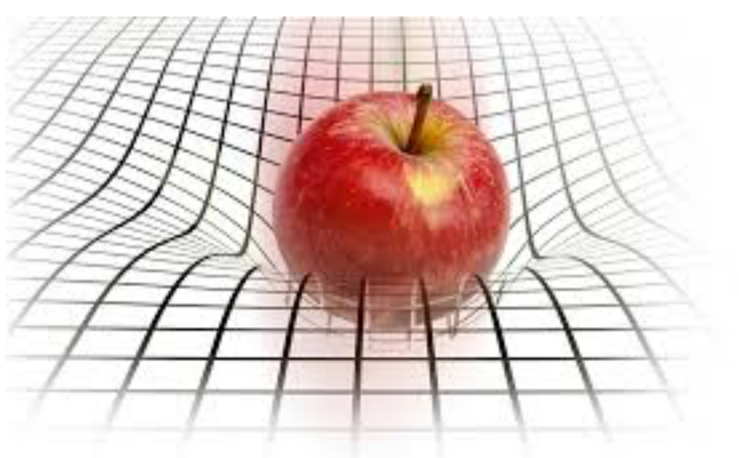
- First steps to test Higgs potential $V(\varphi)$
  $+(\varphi^\dagger\varphi)^3 \ldots ?$
  — test $HHH(H)$ interaction
  — need more data, new facilities…



(or in virtual EFT effects)

Vision of the World by a Physicist

We learn that there are fields…



Gravity

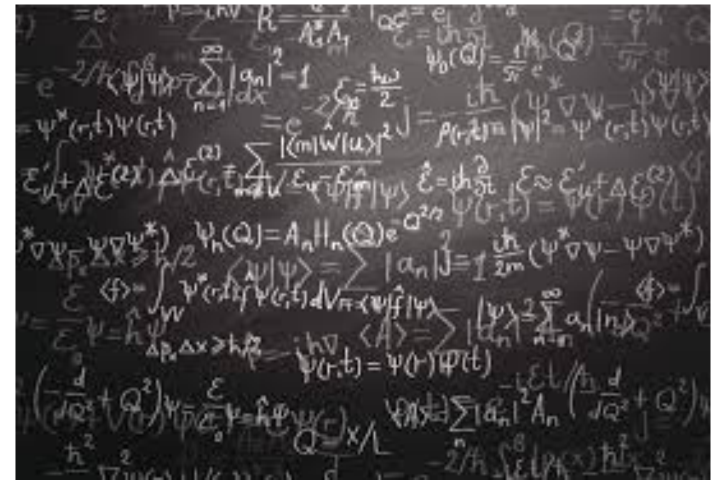
Electricity

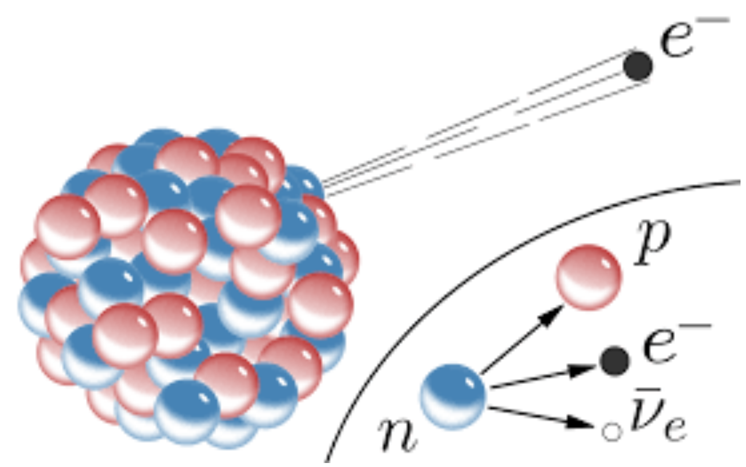
Magnetism

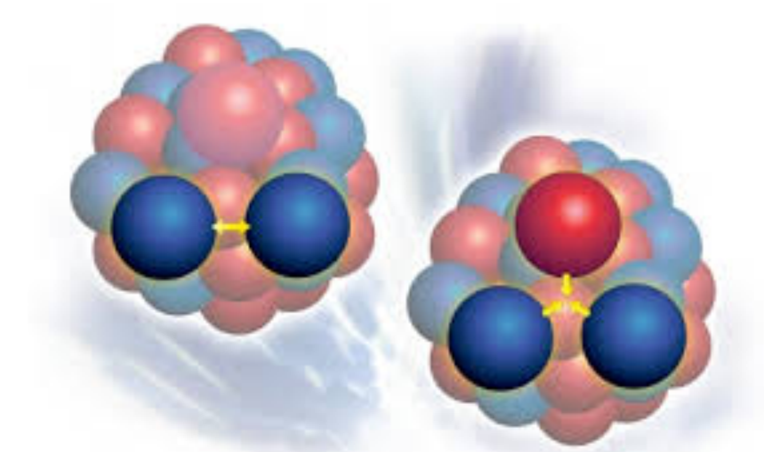
Vision by a Particle Physicist

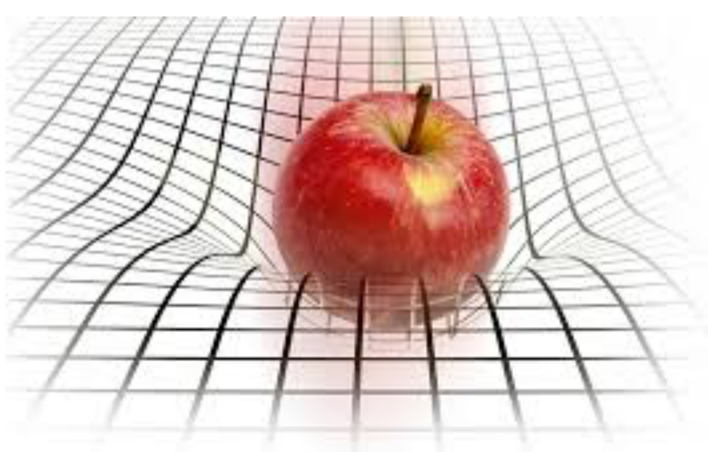
Quantum Field Theory =

Quantum Mechanics (very small)
+ Special Relativity (very fast)









Weak

E&M

Strong

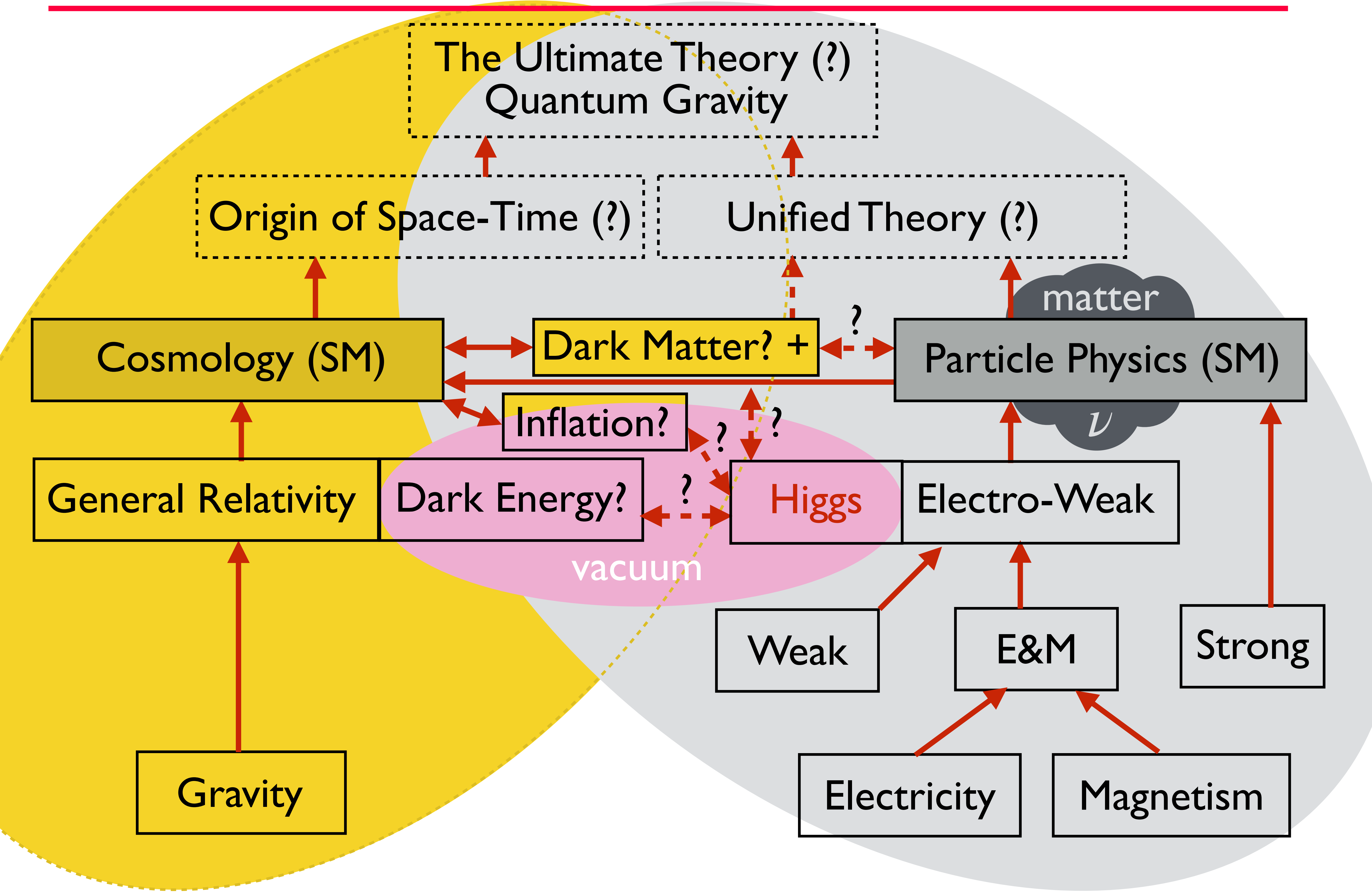
4 forces

Gravity

Electricity

Magnetism

The Unified Vision: the Standard Model (SM)



The Unified Vision: the Standard Model (SM)

The Ultimate Theory (?)
Quantum Gravity

Origin of Space-Time (?)

Unified Theory (?)

Cosmology (SM)

Particle Physics (SM)

Problems:

understanding the matter

— Dark matter?

— Baryogenesis? (matter over antimatter)

baryon number violation (p decay?)

CP violation? non-equilibrium?

— Are neurinos special? …

understanding the vacuum

— Higgs field and masses (hierarchy problems)

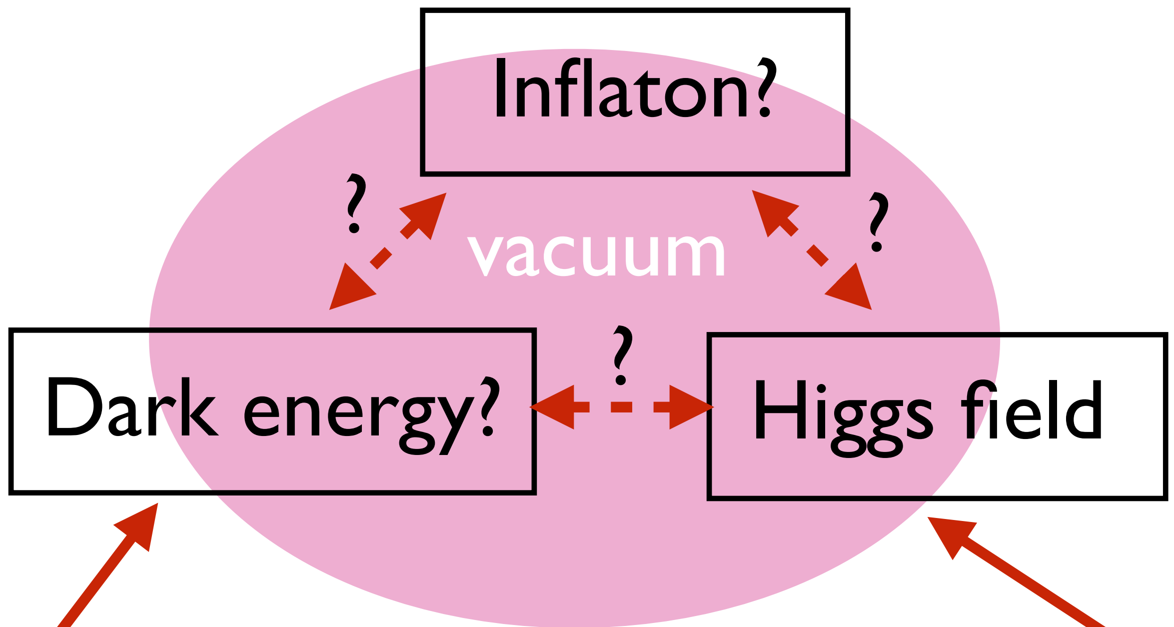
(vacuum stability)

— Dark energy?

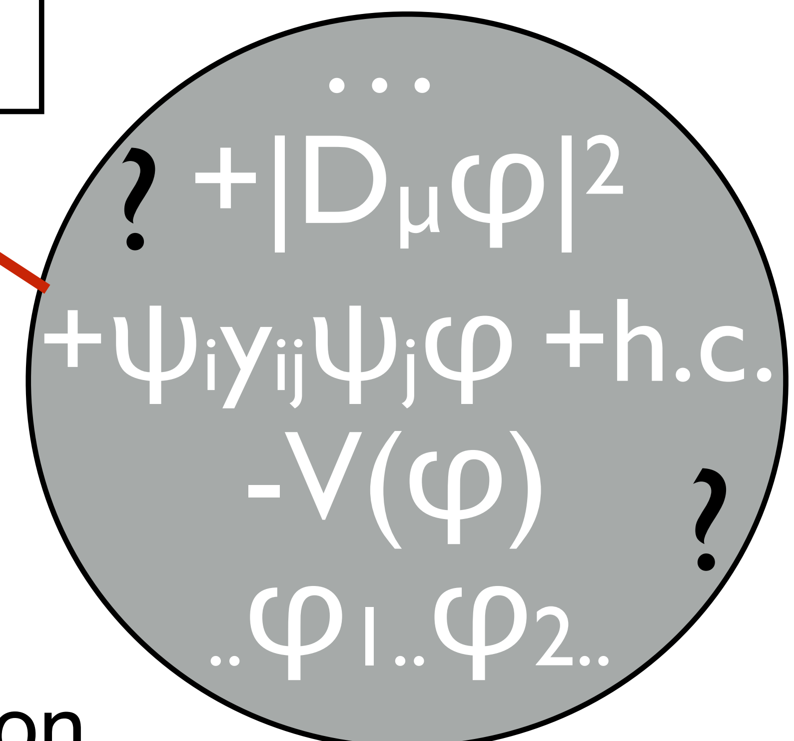
— Inflation?

- Crisis of Standard Models of Particles Physics & Cosmology

Understanding the Vacuum



$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu}R - \Lambda g_{\mu\nu} = -8\pi G T_{\mu\nu}$$



energy density of the vacuum = $\Lambda/8\pi G$

many orders away from the Higgs field expectation

$H^0(125)$ has quantum numbers of the vacuum $J^{PC} = 0^{++}$

scalar field(s) may be at the core of solutions, Higgs field is the first “studied”

- $H^0(125)$ boson is an excitation of the Higgs field

  completely new state of matter-energy

Approach the Problems: Astrophysics

Origin of Space-Time (?)

Cosmology (SM)

Dark Matter? +

Particle Physics (SM)

General Relativity

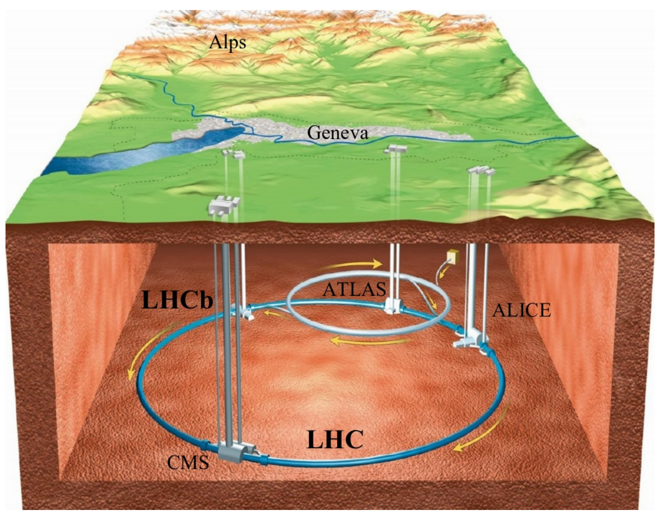
Dark Energy?

Gravity

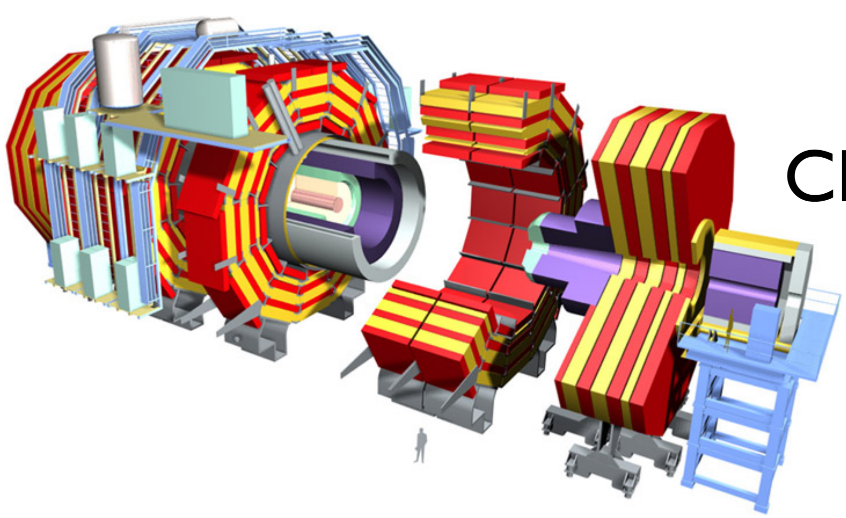
Telescope

Approach the Problems: Particle Physics

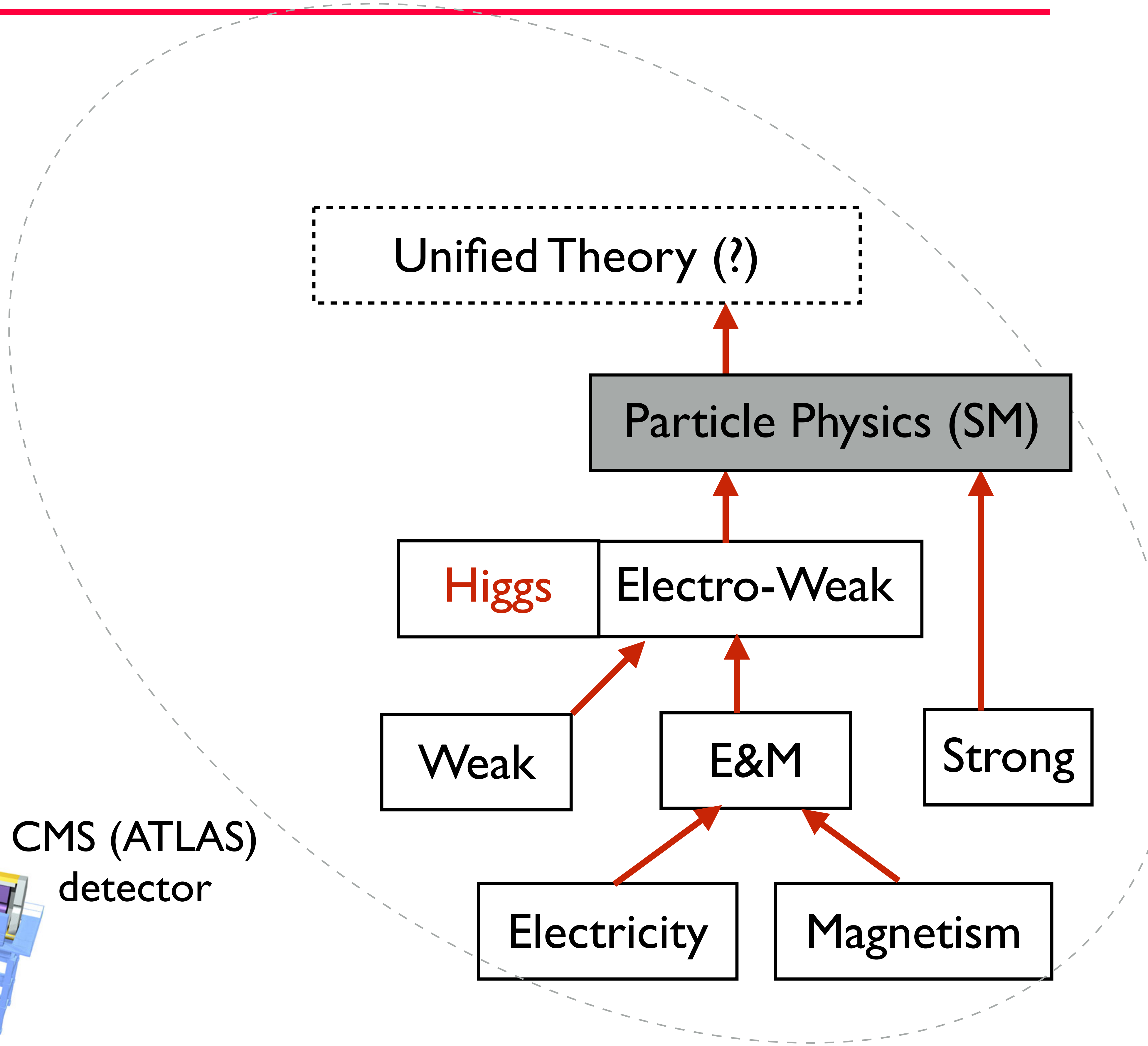
Microscope



Large Hadron Collider



CMS (ATLAS) detector



Scales in Particle Physics

$$\text{Energy} = \frac{hc}{\text{Distance}}$$

Energy

⇒ High-Energy Physics

"new physics" $M = ?$

Unified Theory (?)

unknown gap

v $\sim 246\,\mathrm{GeV}$

$\sim 5 \times 10^{-15}\,\mathrm{m}$

Higgs	Electro-Weak	top quark

$\sim 1\,\mathrm{GeV}$

$\sim 10^{-12}\,\mathrm{m}$

Strong

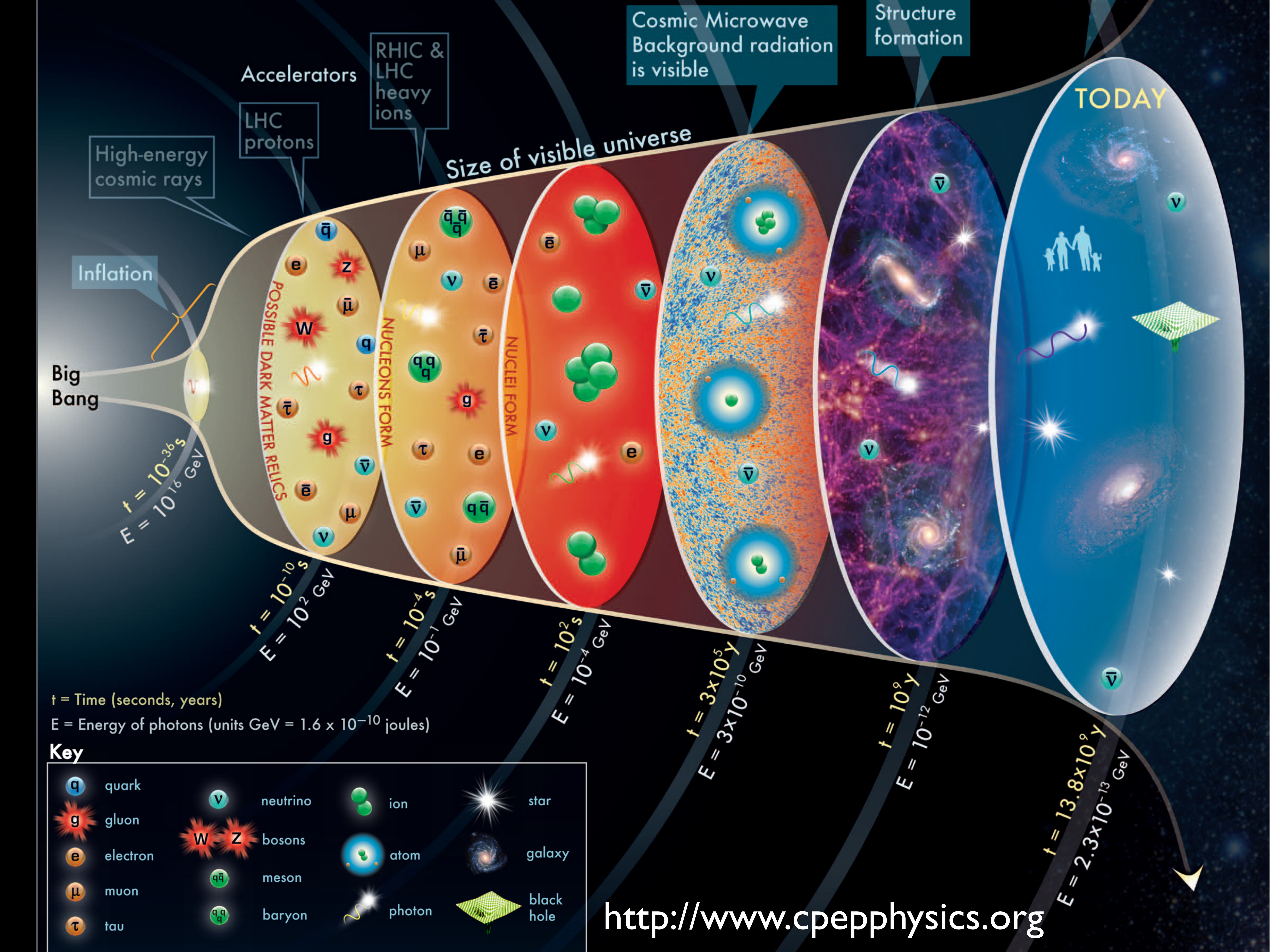
visible light $\sim \mathrm{eV}$

$\sim \mu\mathrm{m}$

Distance

Electricity

Magnetism

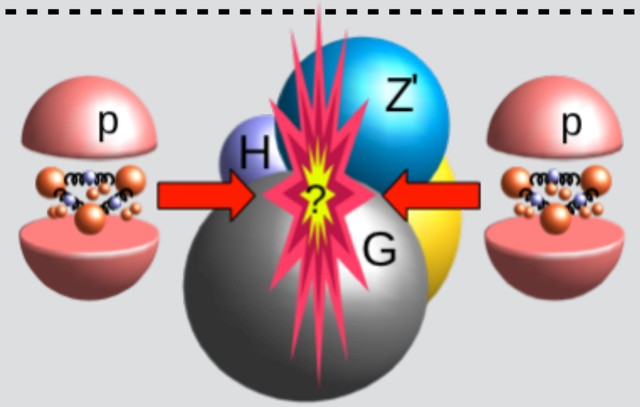


Accelerators
RHIC & LHC heavy ions
Cosmic Microwave Background radiation is visible
Structure formation
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8x10^{9}$ y
$E = 2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
http://www.cpepphysics.org

"Optimistic" Scale in Particle Physics

Energy

Unified Theory (?)



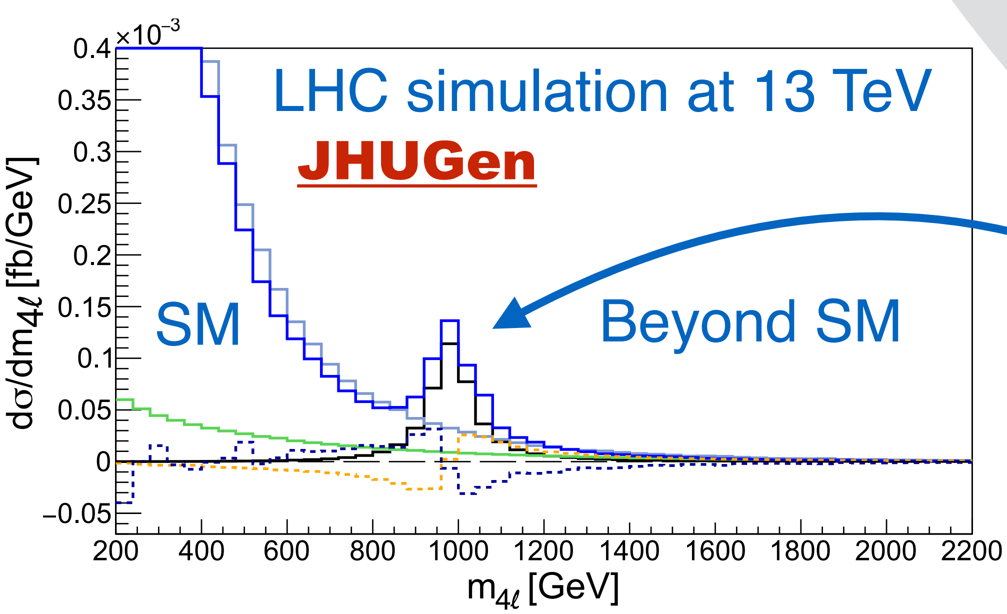
"new physics"

$M = ?$ — $\sim$ TeV

v $\sim$ 246 GeV

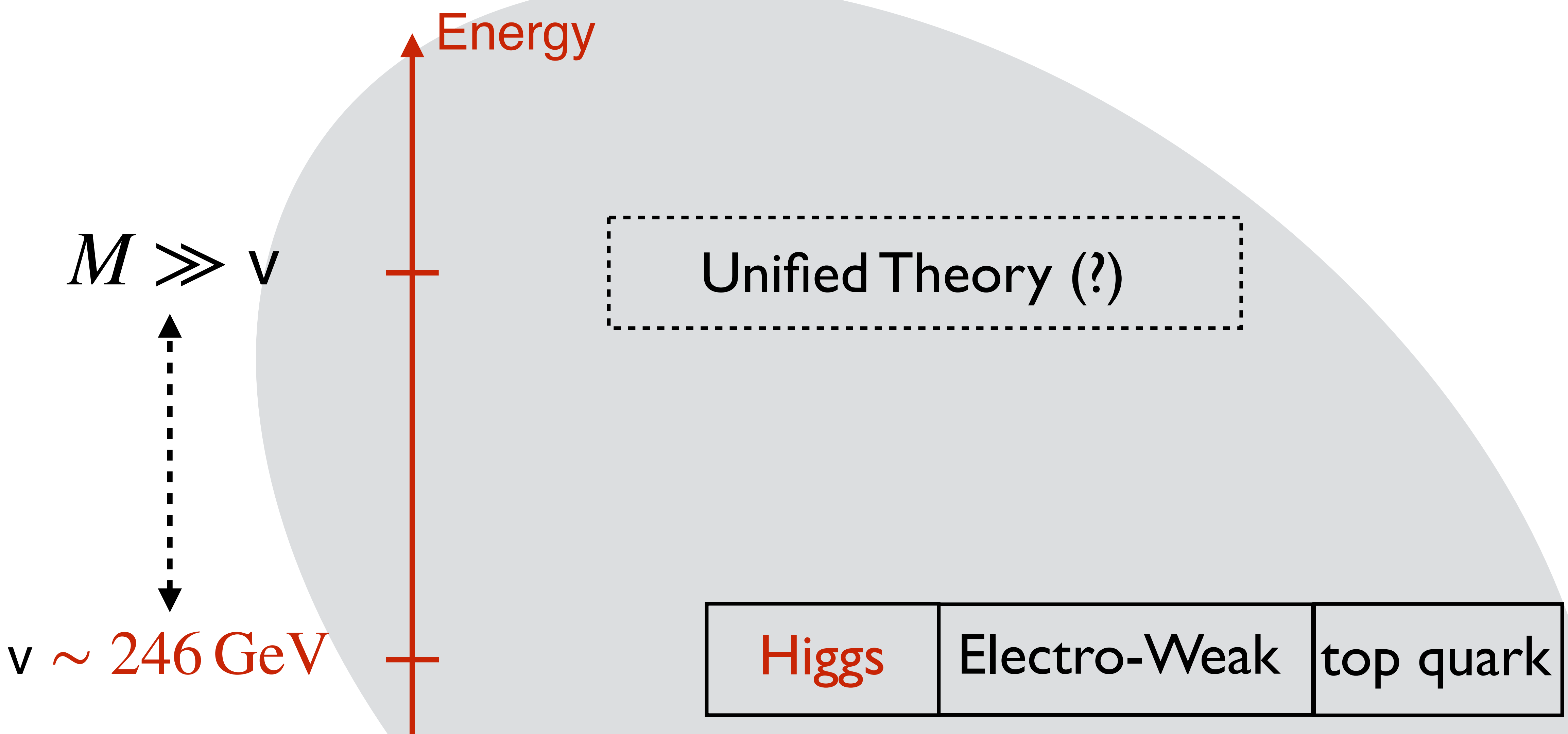
Higgs	Electro-Weak	top quark

We did find this "bump"



Find new physics "bump"
but none appeared so far…

“Pessimistic” Scale in Particle Physics

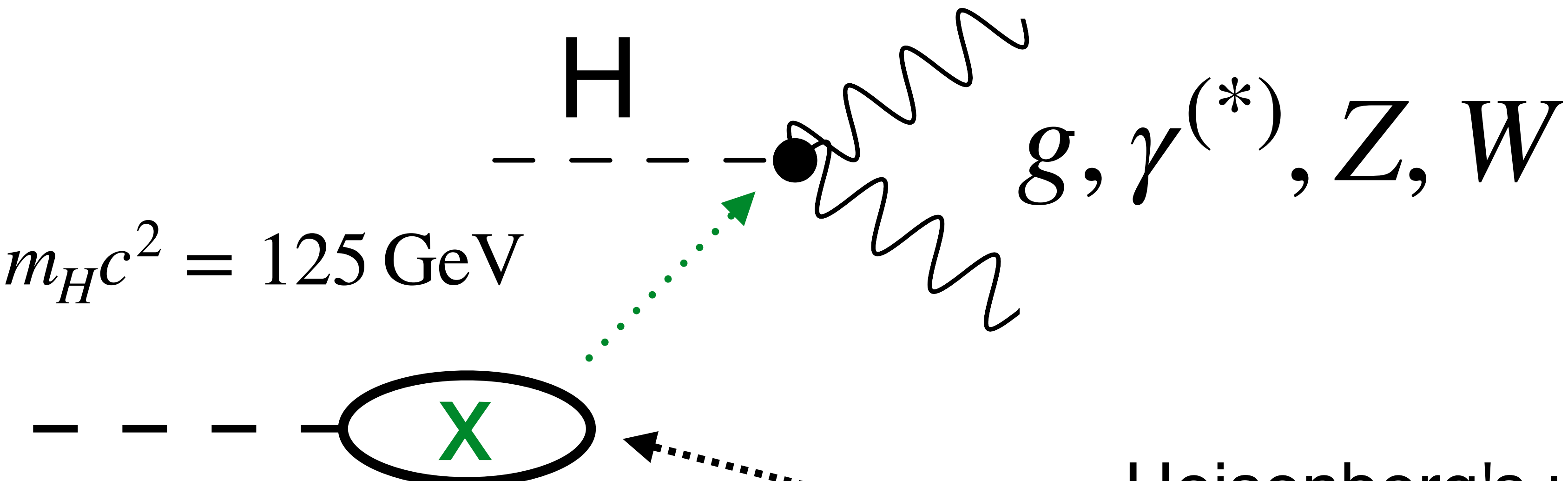


Particle Physics (SM) is an Effective Field Theory (EFT)

precise up to $\sim \left(\frac{\mathrm{v}}{M}\right)^2$

Effective Field Theory

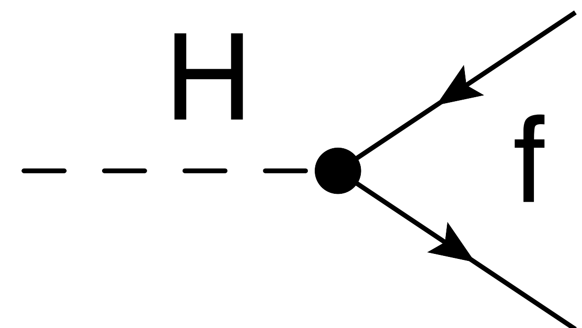
- Effective Field Theory (EFT)
  - — describes energies (of interest) below M (underlying dynamics)
  - — no "new physics" up to M $\gg m_H$



$m_H c^2 = 125\,\mathrm{GeV}$

$\Delta E = m_x c^2 \gg m_H c^2$

point-like interaction



Heisenberg's uncertainty principle

$$\Delta E\, \Delta t \sim \hbar$$

- Look for deviations $\sim \left(\frac{\mathrm{v}}{M}\right)^2$ parameterized in EFT

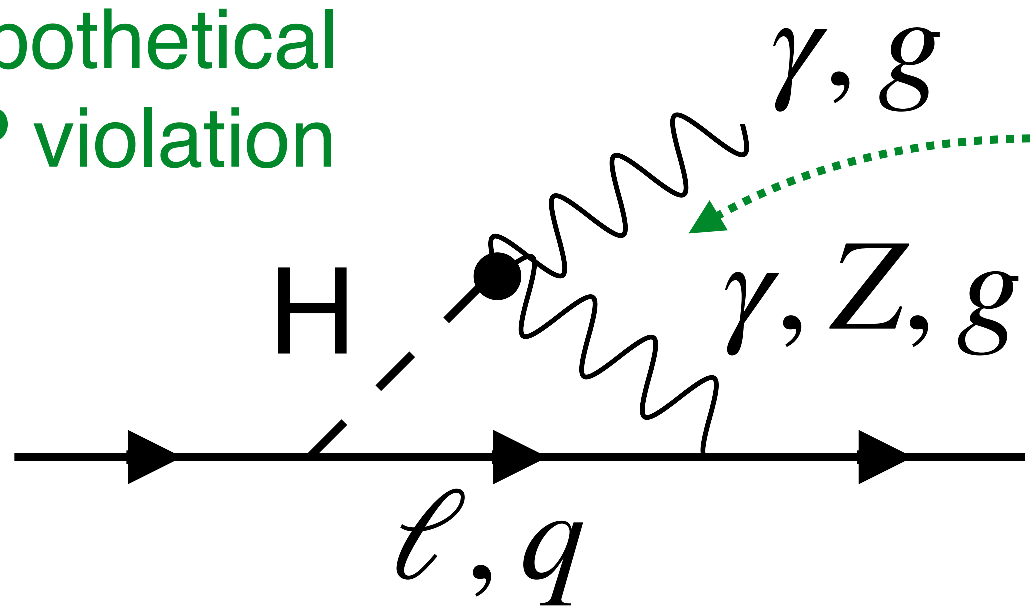
Table-Top, “Low-Energy,” LHC experiments

- Electric Dipole Moment (EDM) of electron $d_e < 1.1 \times 10^{-29}\ e\,\mathrm{cm}$

$d_e^{\mathrm{SM}} \sim 10^{-38}\ e\,\mathrm{cm}$

$d_n < 3.0 \times 10^{-26}\ e\,\mathrm{cm}$

hypothetical
CP violation

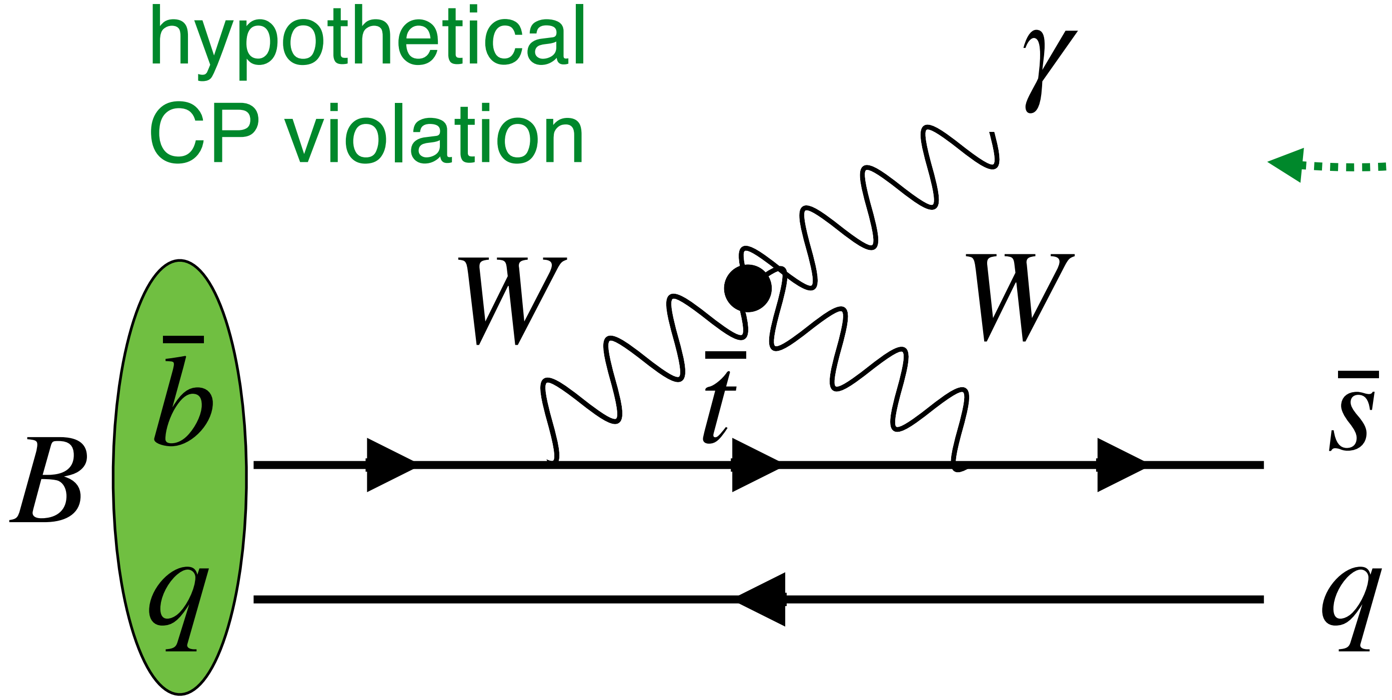


complementary to LHC in EFT

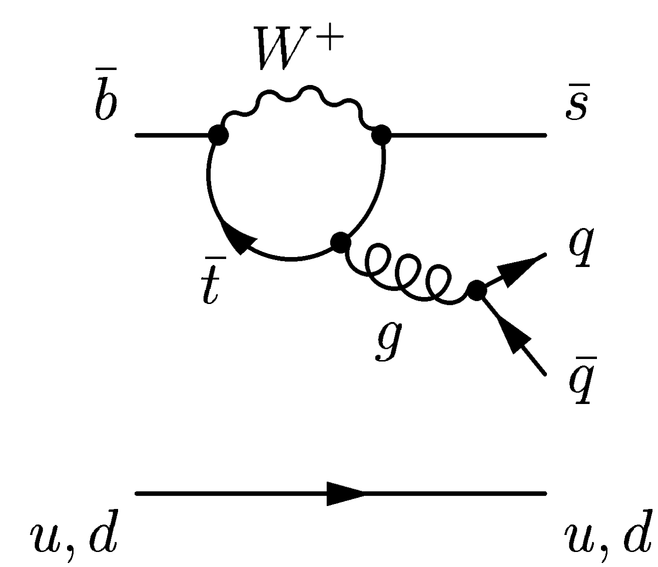
SU(2)xU(1)

- Heavy-Quark meson decays:

hypothetical
CP violation



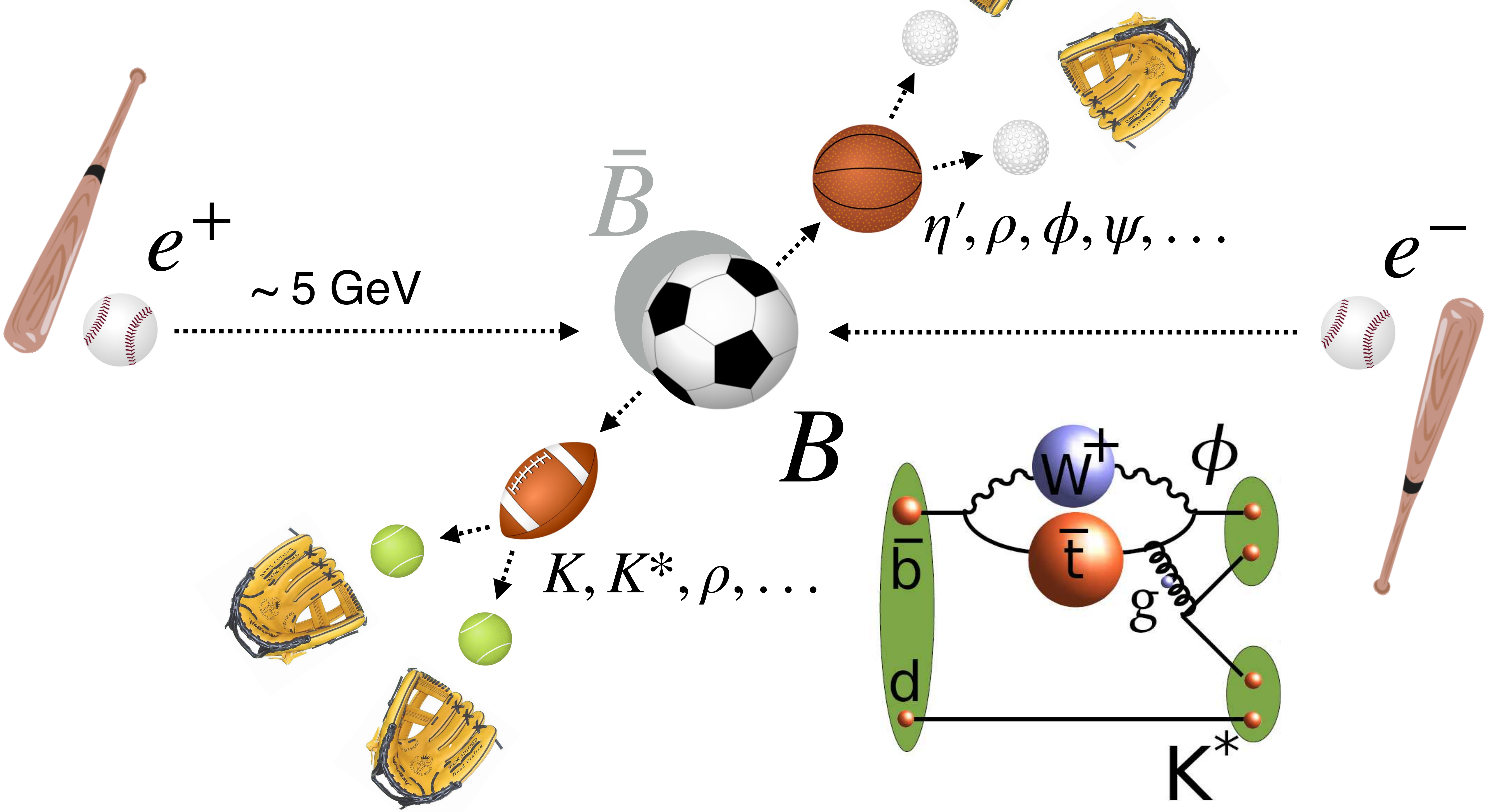
25 year old…



Colloquium 2007

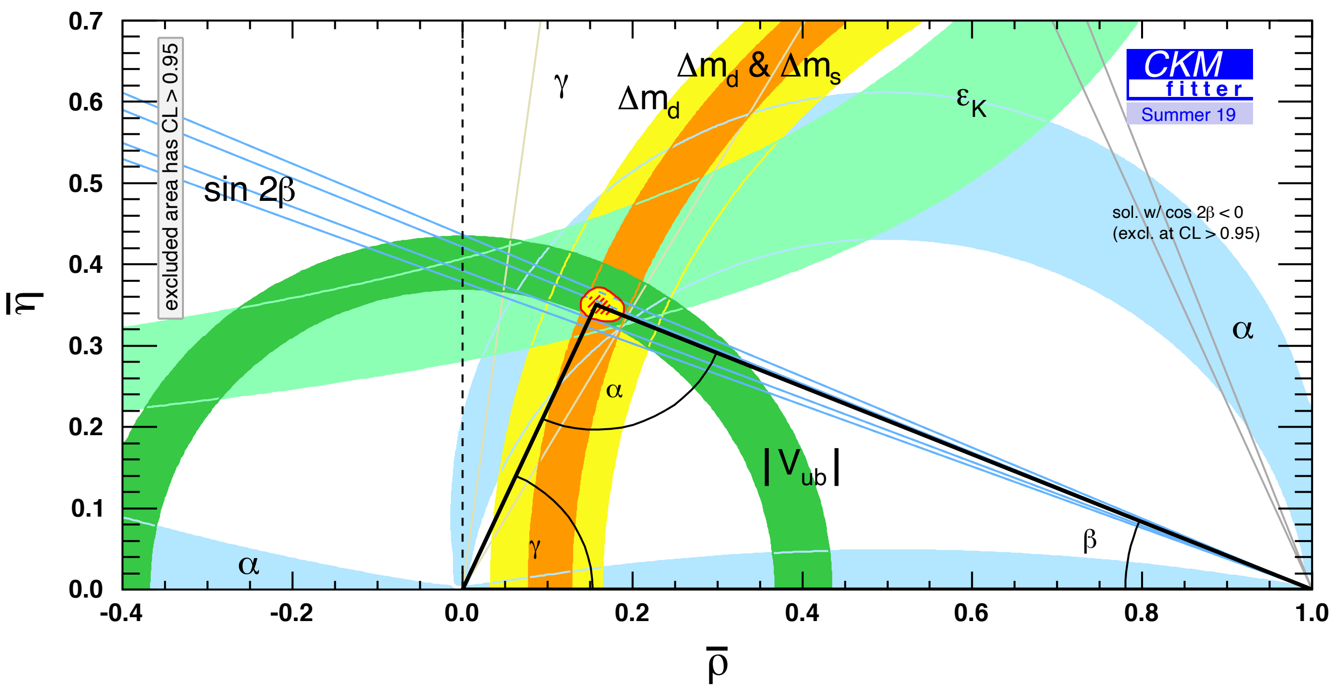
Heavy-Quark ("Low-Energy") Experiments

(e^+e^-) CLEO, BABAR, BELLE(II),
$(p\bar{p}, pp)$ CDF/D0, LHCb,…



Quark and Neutrino "Flavor" Physics: CP Violation

- The only known source of CP violation (difference matter-antimatter)
  - in the Quark sector (completion of the Standard Model in this sector)
  - the Lepton (neutrino ν) sector in active development (Nobel Prize 2015: ν mass)



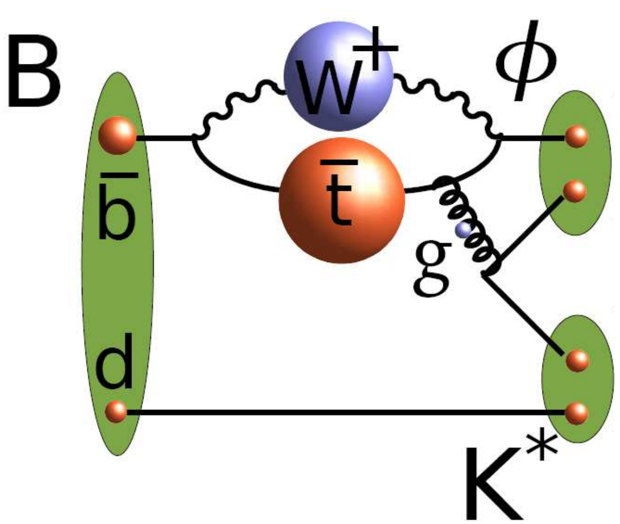
The Nobel Prize in Physics 2008

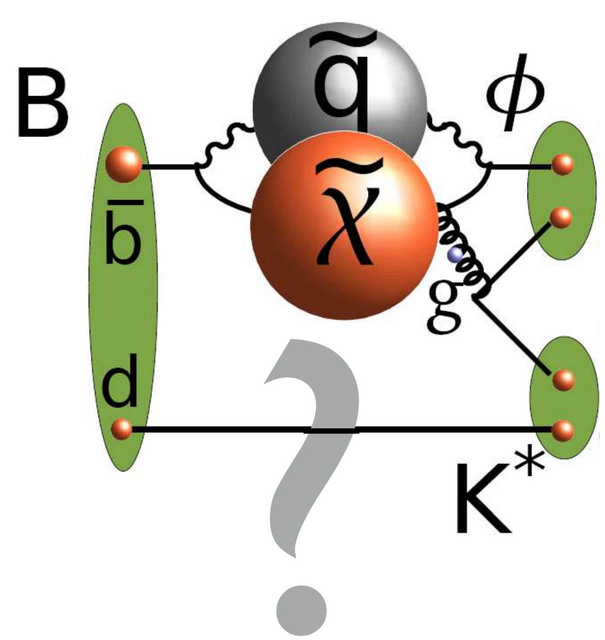
Photo: University of Chicago
Yoichiro Nambu
Prize share: 1/2

© The Nobel Foundation
Photo: U. Montan
Makoto Kobayashi
Prize share: 1/4

© The Nobel Foundation
Photo: U. Montan
Toshihide Maskawa
Prize share: 1/4

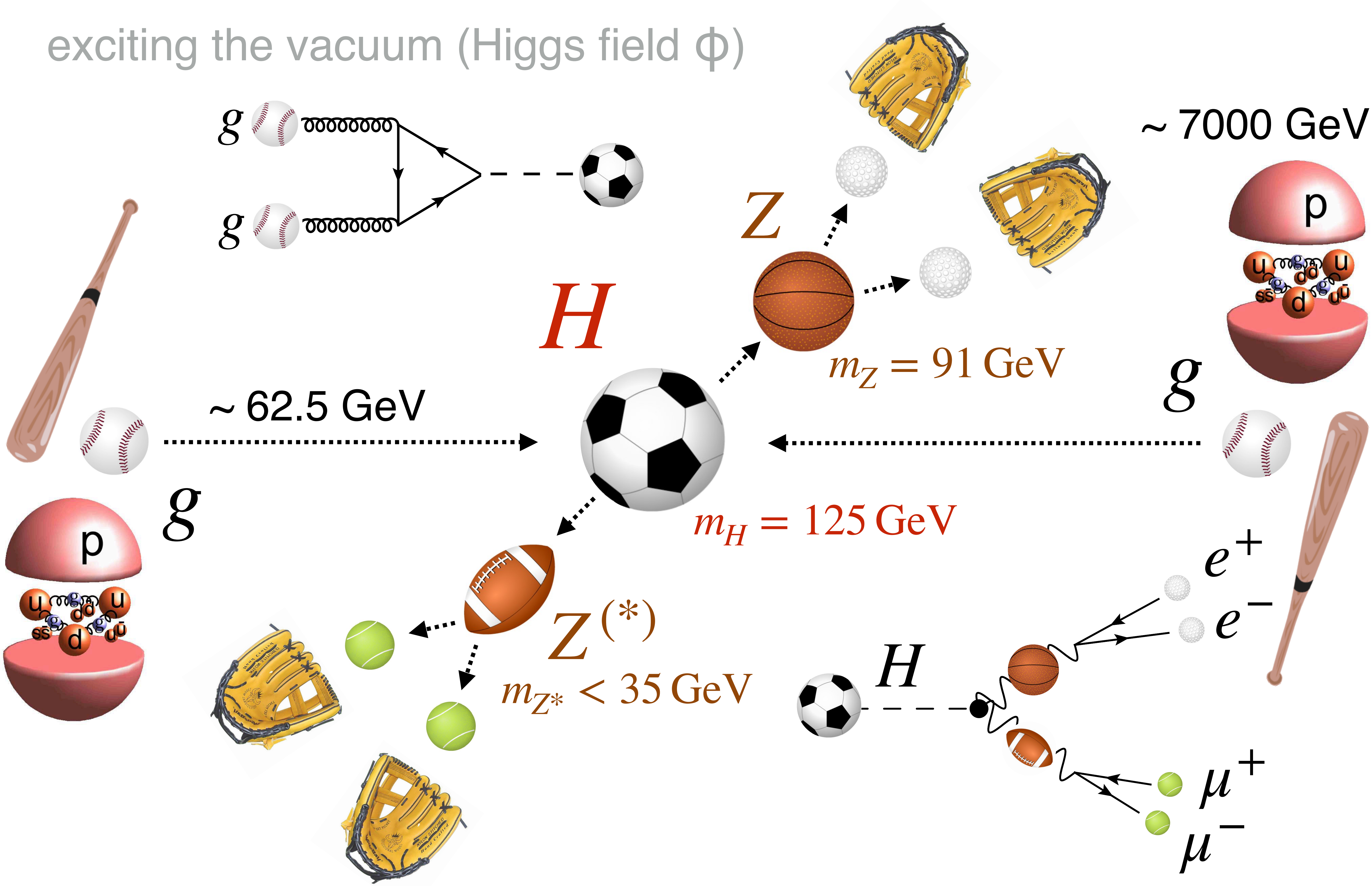
The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

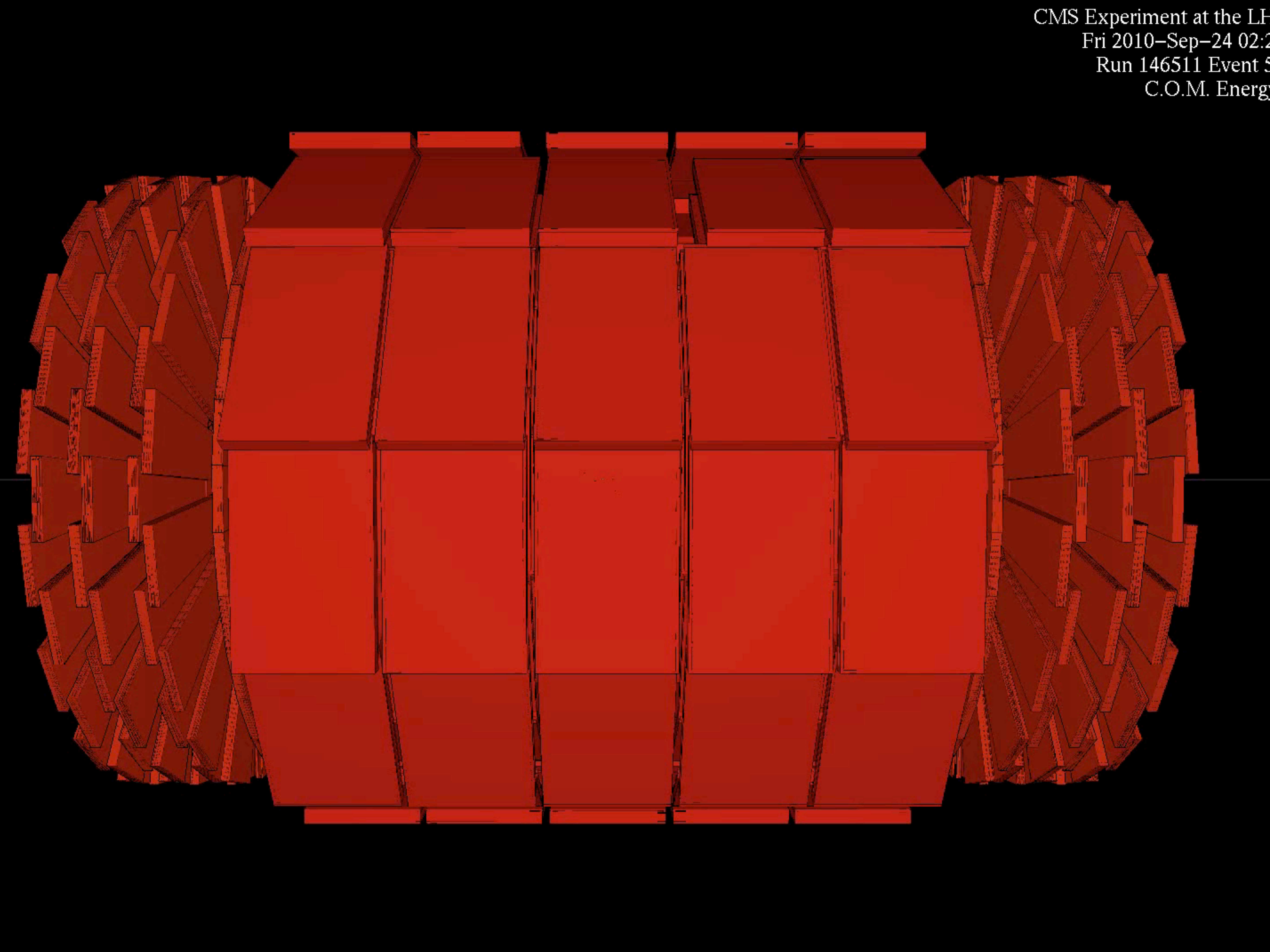




Large Hadron Collider

exciting the vacuum (Higgs field ϕ)




CMS Experiment at the
Fri 2010−Sep−24
Run 146511 Event
C.O.M.

The Higgs boson: 2012-2013

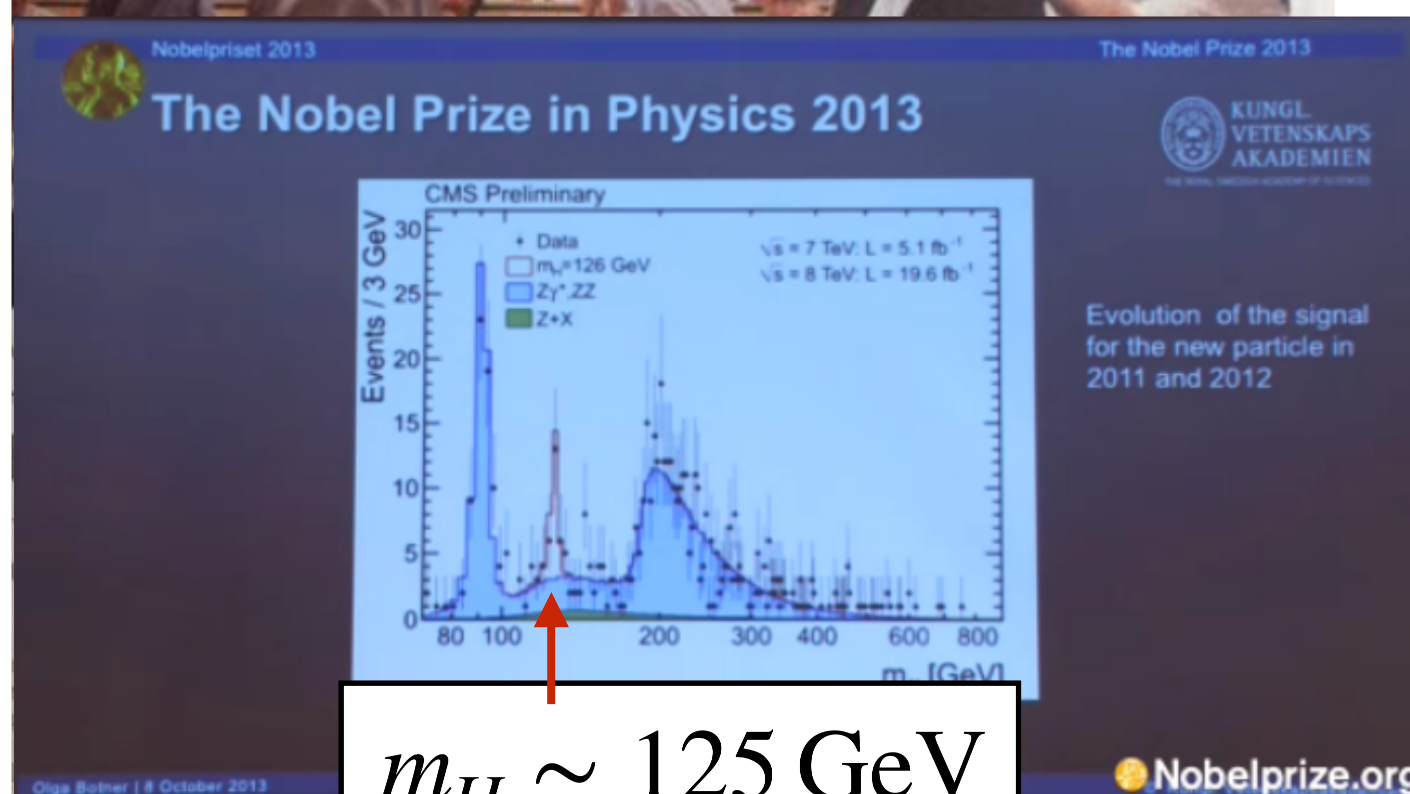

"All the News That's Fit to Print"
The New York Times
Late Edition
Today, sunny to partly cloudy, rather hot, high 92. Tonight, mostly clear, low 72. Tomorrow, mostly sunny, hot and humid, high 90. Weather map appears on Page B16.
VOL. CLXI . . No. 55,823 ©2012 The New York Times NEW YORK, THURSDAY, JULY 5, 2012 $2.50
Oil Backed Up, Iranians Put It
ROMNEY NOW SAYS HEALTH MANDATE
Physicists Find Elusive Particle Seen as Key to Universe

The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

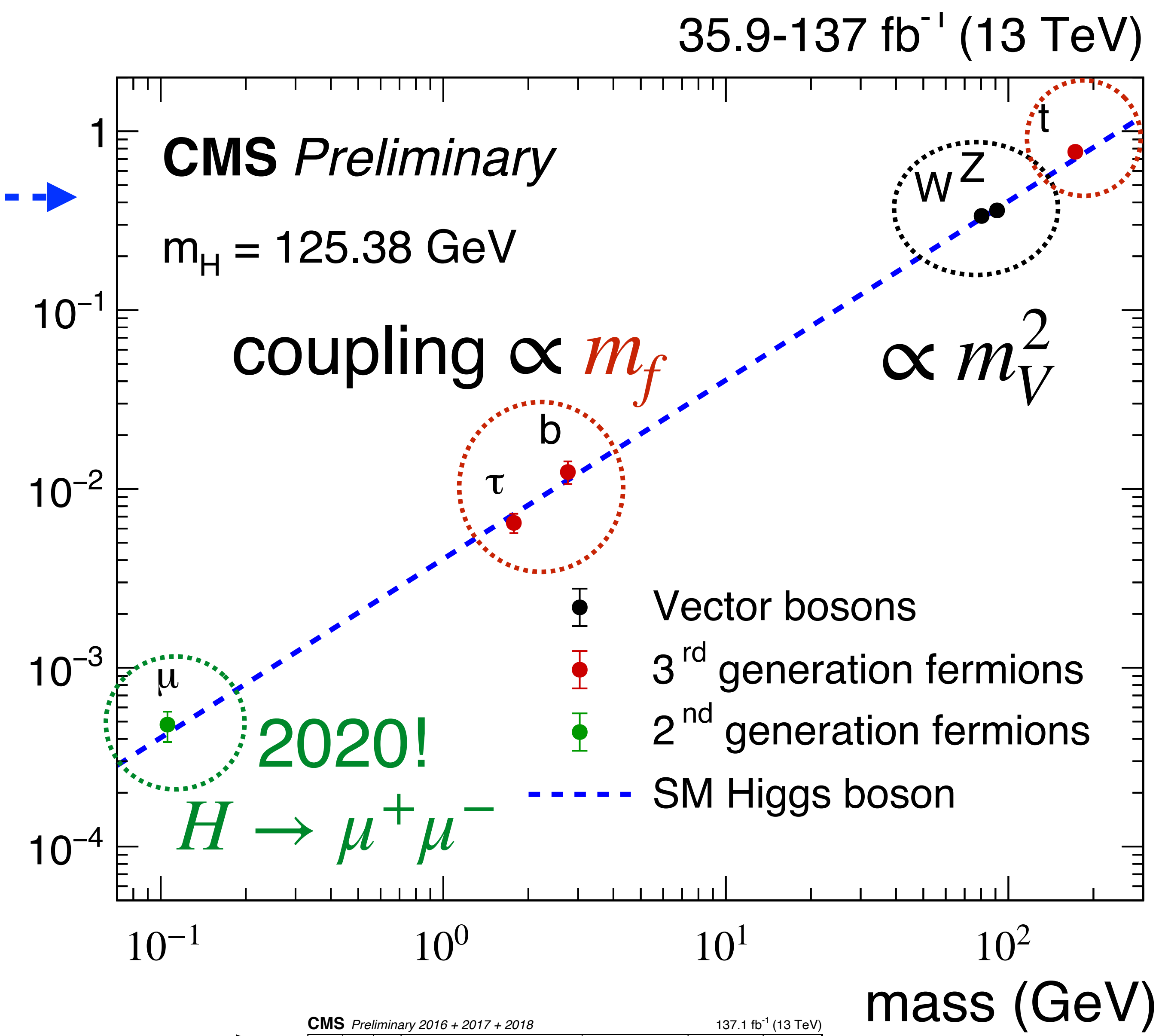


$m_H \sim 125$ GeV

The Higgs boson eight years later…

- Couples to matter-energy

  rates as ~ expected



- Mass: quantum corrections

- Lifetime:

  faster decay to new states?

  to dark matter?…

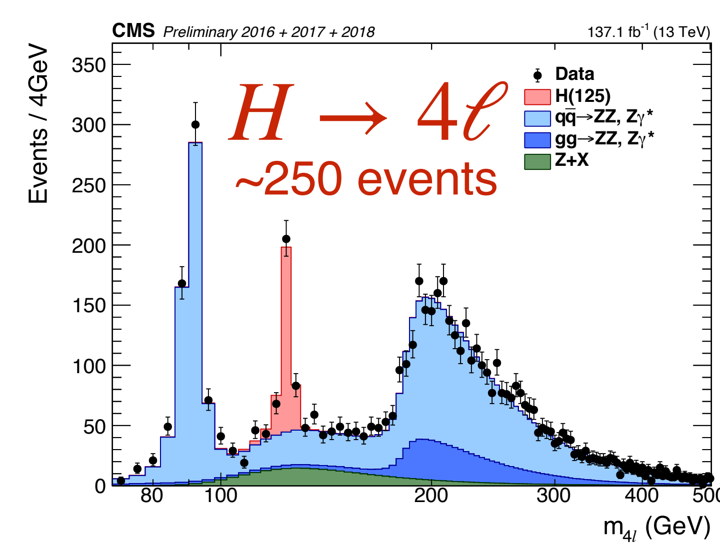
- Quantum numbers?

  expect $J^{PC} = 0^{++}$ as vacuum

- New source of CP violation?

- Any hints of EFT effects $\sim \left(\frac{\mathrm{v}}{M}\right)^2$?…

- Higgs field(s) and potential?



The Higgs boson eight years later…

- Couples to matter-energy

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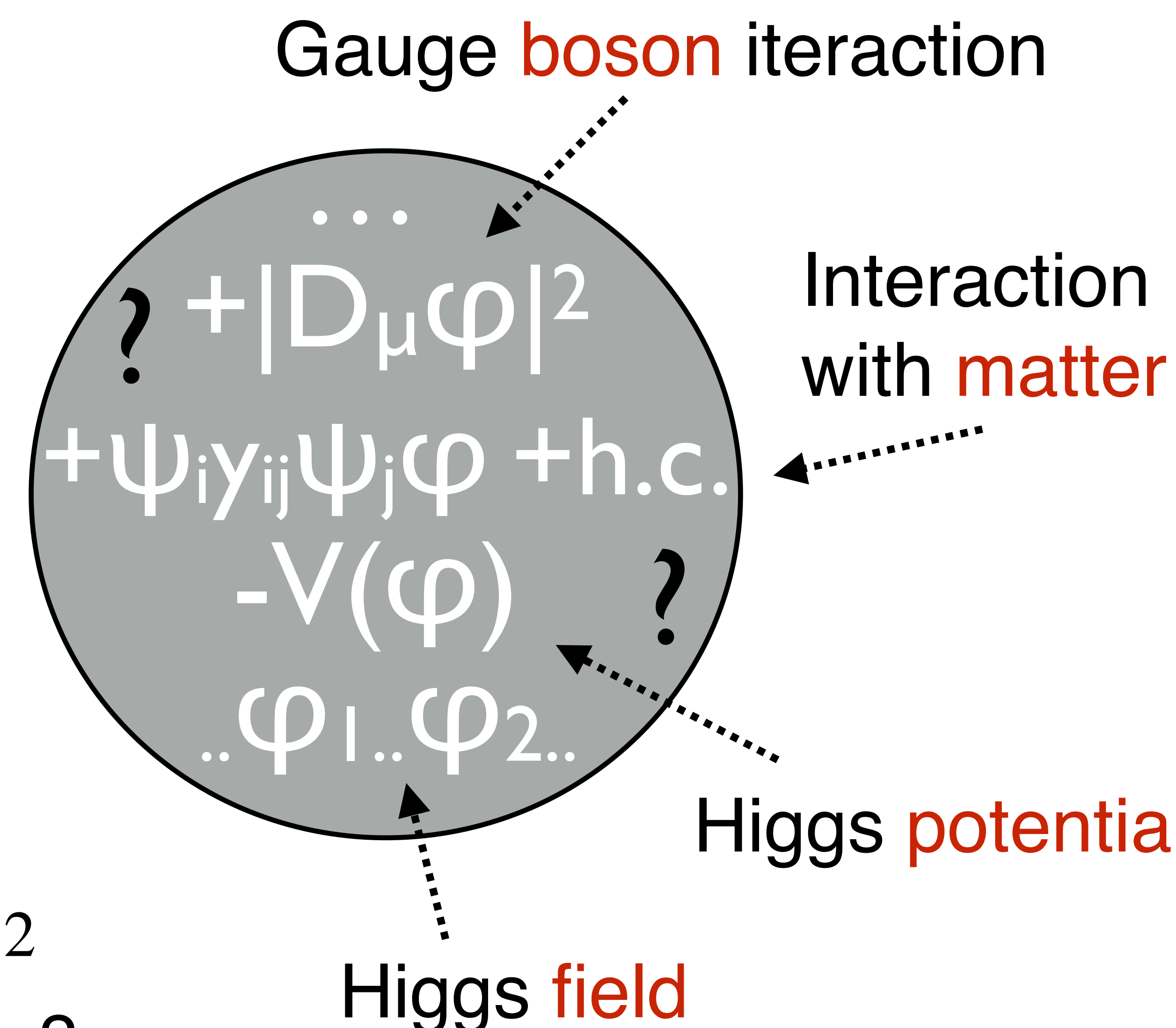
- Higgs field(s) and potential?

$\mathscr{L}$agrangian involving the Higgs field



Summary

- Crisis of Standard Models of Particles Physics & Cosmology
- Use the Higgs boson as a new tool for discovery
  - — may reach to new particles, interactions (EFT)
  - — may be our window to dark matter
  - — may relate to baryogenesis (CP)
  - — Higgs field responsible for stability of the vacuum
  - — interplay with inflation and dark energy: scalar fields in vacuum

- Active research program of Higgs physics
  - — from discovery to detailed properties
  - — Run-3 of LHC, to High-Luminosity LHC
  - — Higgs Factory on the horizon…
  - — synergy with table-top, dark-matter, low-energy experiments