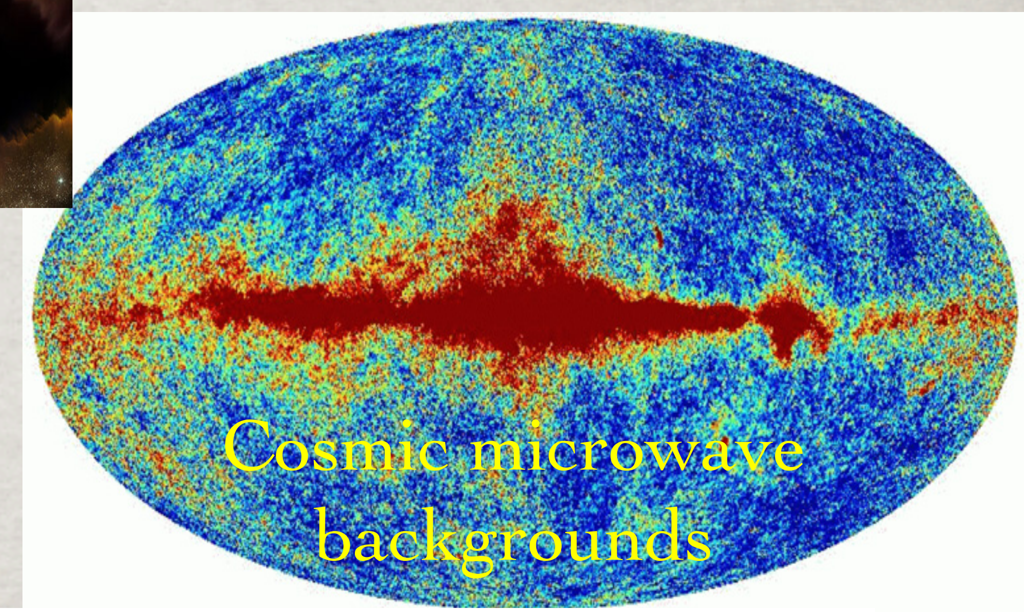
Fifty Years of Discoveries in High-Energy Physics

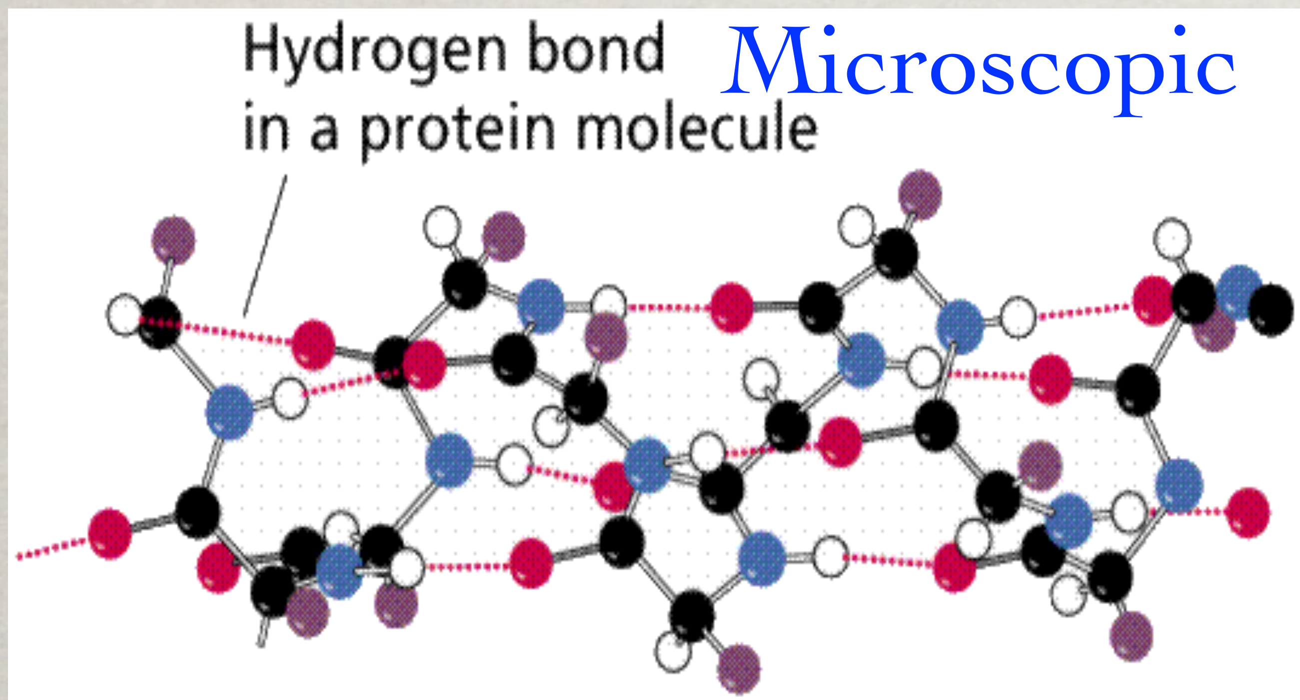
-- From quarks to the Higgs boson

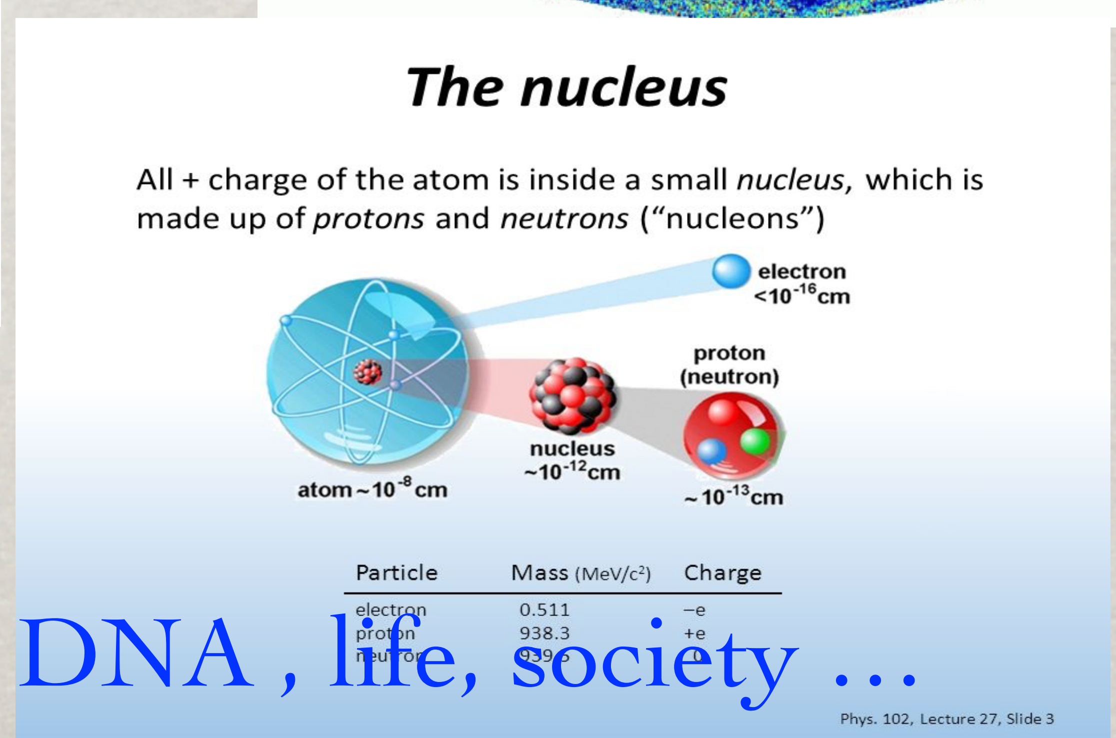
Tao Han
University of Pittsburgh

第六届中国LHC物理会议, **Nov. 6, 2020**

Our Fascinating World ...



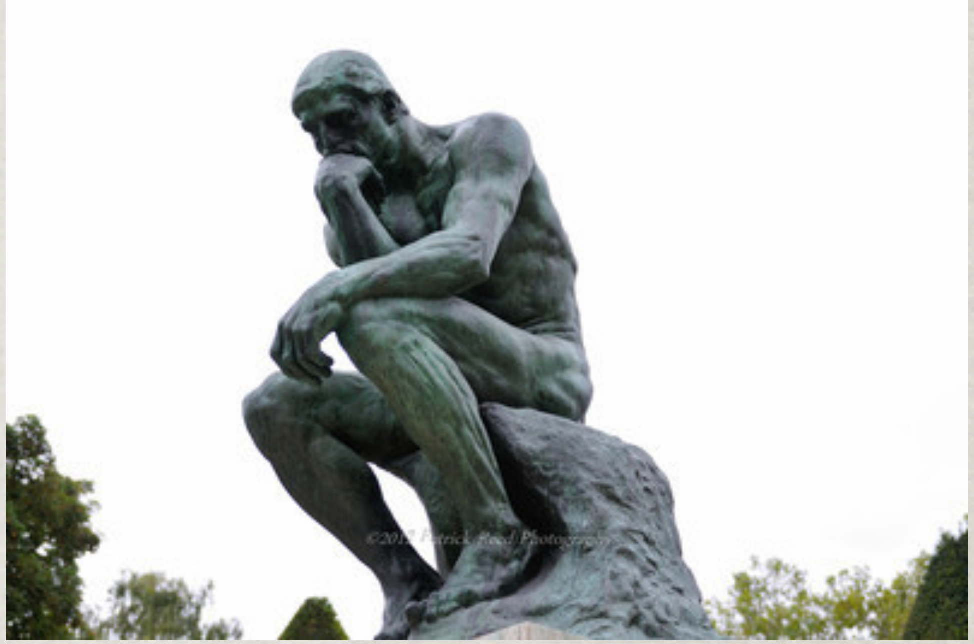




The complexity: DNA , life, society …

Quest for Nature ...

Human being's curiosity about Nature drives the development of physics & basic science!



Science is to

- Ask fundamental questions, quest for the nature
- Seek for answers
- Advance human knowledge

Physics is to

- Understand Laws of Nature
- Matter, space, time of the Universe

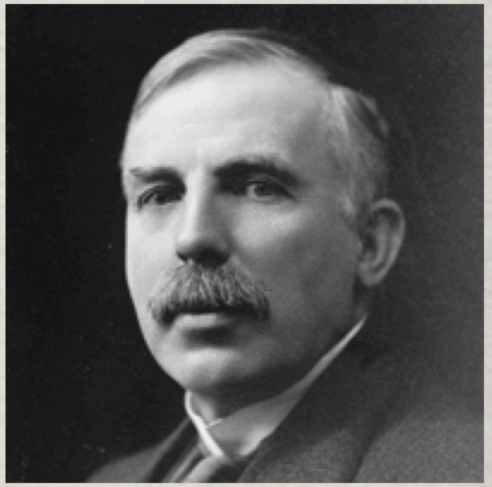
100 years back: Sub-atomic Particles

Rontgen's X-ray (1895)

Bequerel & Curie's radioactivity: α,β-particles

Thomson's cathode rays: the "electrons" (1897)

Rutherford's experiments (1908-1913)



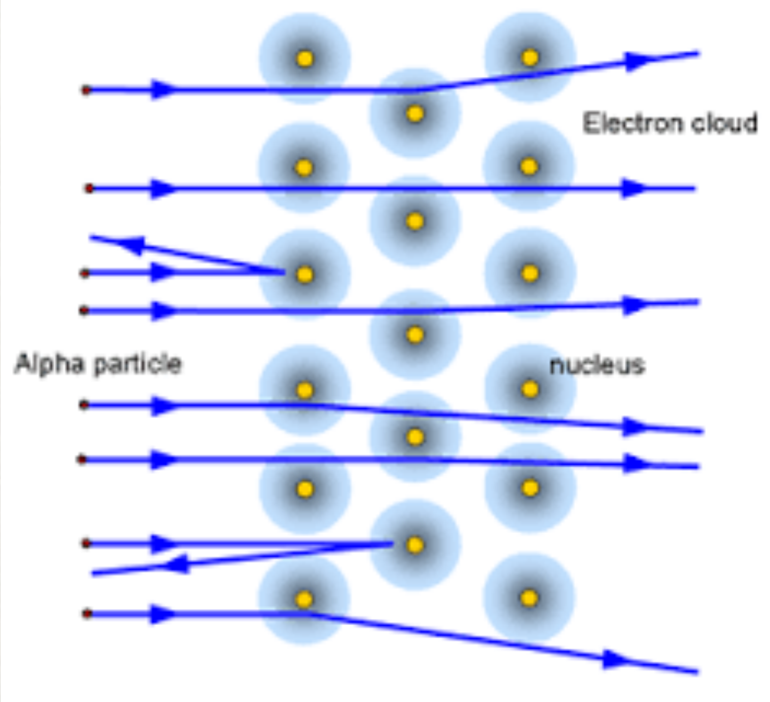
Accelerated **α**-particles bombard a Gold foil target

Coulomb scattering for two point-like charges:

$$V = -\alpha / r$$

$$d\sigma \propto \frac{(\alpha Z_1 Z_2)^2}{(q^2)^2} \approx \frac{(\alpha Z_1 Z_2)^2}{4E^2 \sin^4 \theta/2}$$

(q^2 the momentum-transfer)



Rutherford discovered the planetary atom, the nucleus < 10^{-8} m

What Is the "Proton" ?

Rutherford named the hydrogen nucleus the "Proton"
(Greek for the "first") the building block for all nuclei.

- Its magnetic moment (2.79μ) deviates from point-like fermion
- Panofsky (1953, SLAC): spatial distribution ~ 10^{-15} m

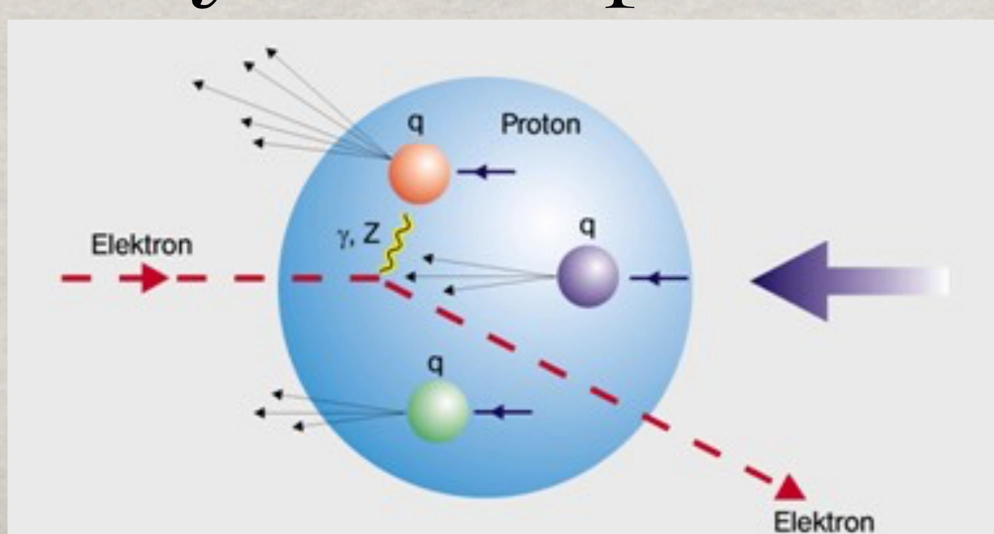
$$d\sigma \propto \frac{(\alpha Z_1 Z_2)^2}{(q^2)^2} \frac{4M_p^2}{q^2 + 4M_p^2}$$

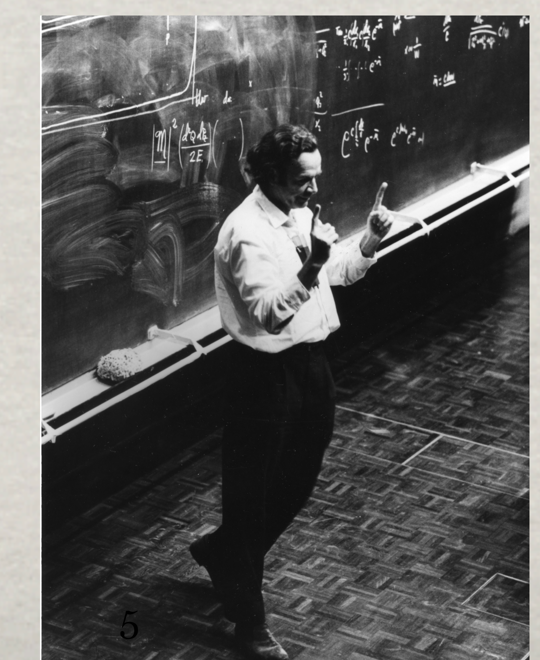
- Deeply In-elastic Scattering (1968-'70, SLAC): "scaling behavior" at higher energies

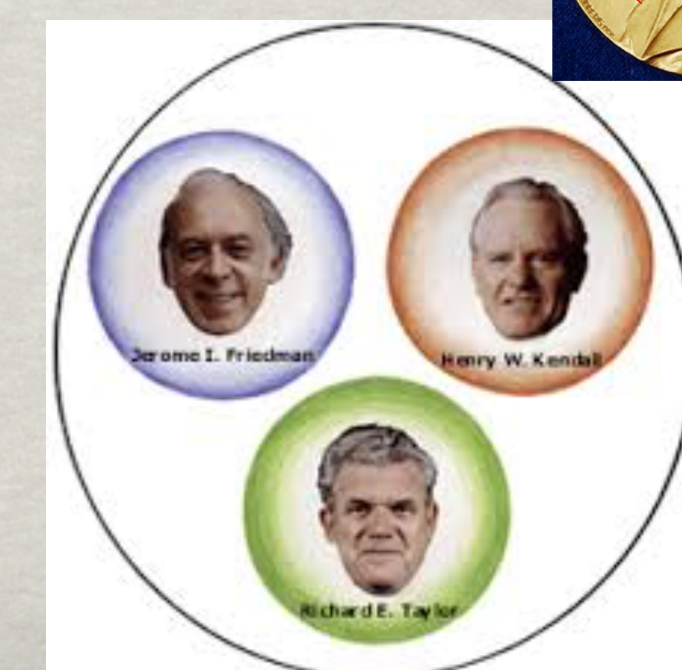
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \left(\frac{F_1(x,Q^2)}{m_p} \sin^2 \frac{\theta}{2} + \frac{F_2(x,Q^2)}{E - E'} \cos^2 \frac{\theta}{2} \right)$$

→ structureless / point-like constituents!

Feynman's "partons"







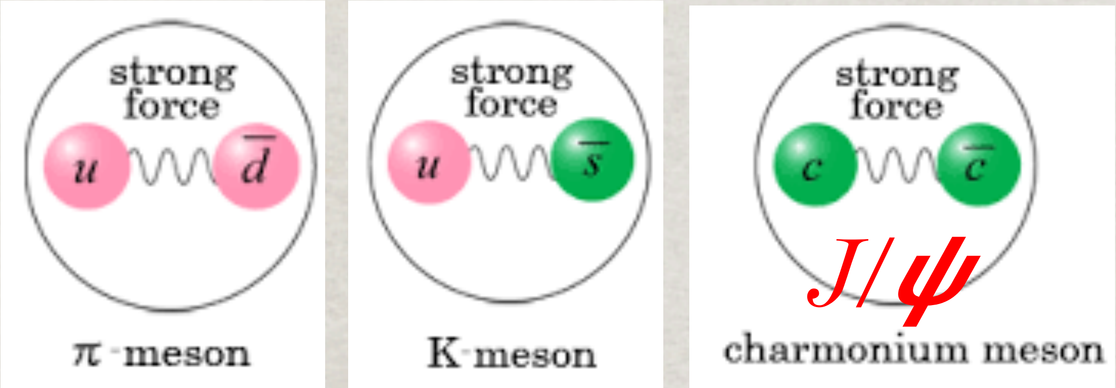
“Quarks” as the constituents

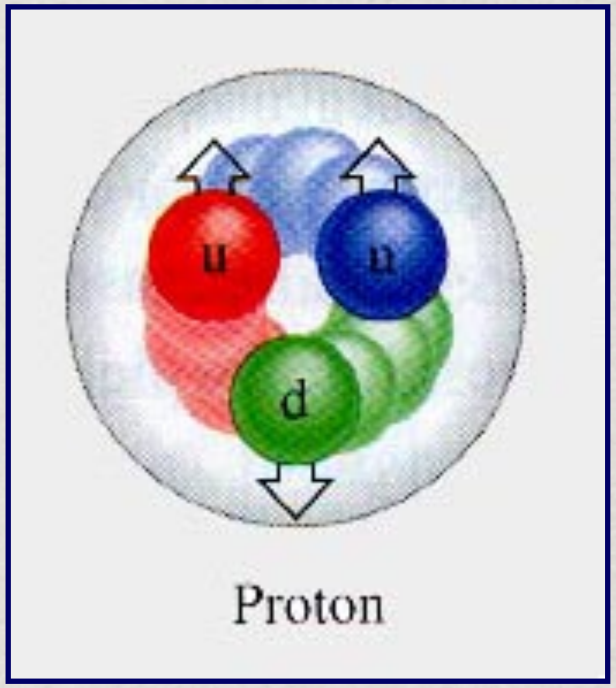
M. Gell-Mann et al (1963):

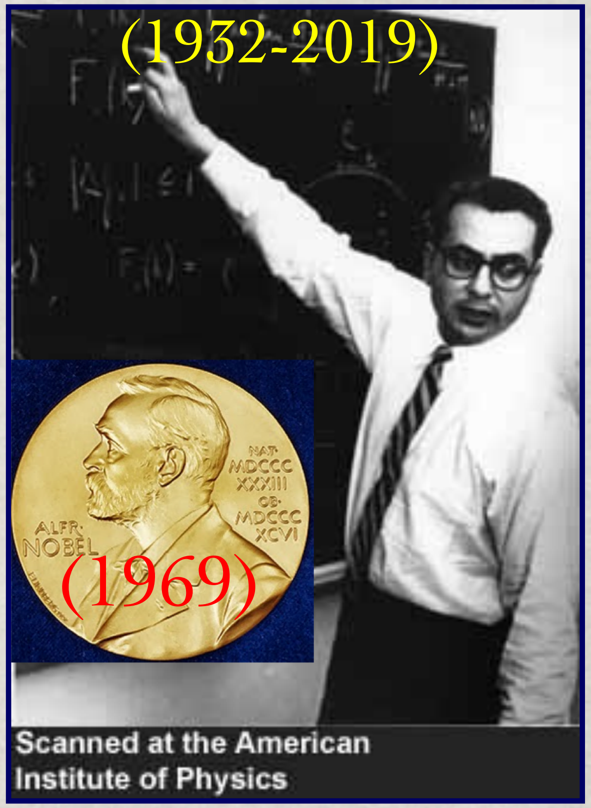
Nucleons (p, n) ≈ 3 quarks:

2 “up” + 1 “down” quarks

Strong force binds them to “hadrons”

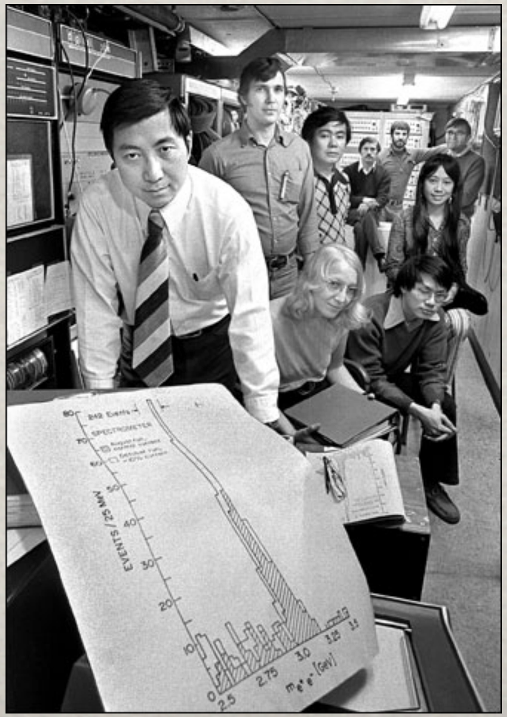






November revolution: Heavy quark “charm” ***mass ~ 1.5 m_p***

Opened up a new window to understand strong/weak forces.



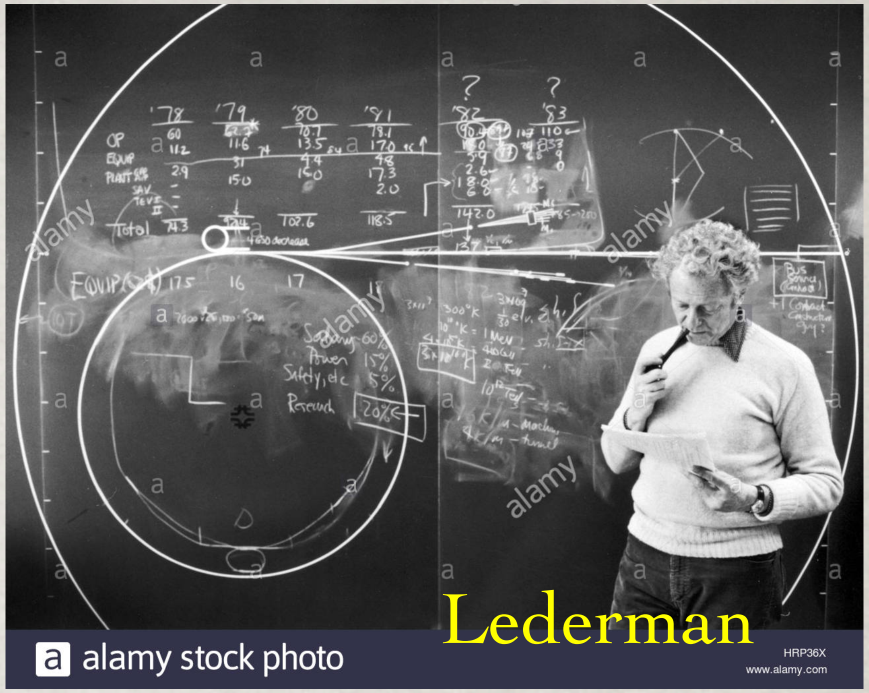
(1976)

Even more:
3rd generation quarks

Heavy quark "bottom/beauty"

1977 @ Fermilab

mass ~ 5 m_p



And last, 1995@Fermilab

(1988)
(for muon neutrino)


SPECIAL EDITION

FermiNews

The Newsletter of the Fermi National Accelerator Laboratory

IS IT THE TOP QUARK? YES!!!

Physicists at Fermilab today announced the discovery of a subatomic particle known as the top quark, the last undiscovered quark of the six predicted to exist by current scientific theory. Scientists worldwide had sought the top quark since the discovery of the bottom quark at Fermilab in 1977.

Two research papers, submitted simultaneously on Friday, February 24, to *Physical Review Letters* by the CDF and DZero experiment collaborations respectively, describe the observation of top quarks produced in high-energy collisions between protons and antiprotons, their antimatter counterparts, at Fermilab's Tevatron, the world's highest energy particle accelerator. The collaborations, each with about 450 members, will present their results at seminars held at Fermilab today.

"Last April, CDF announced the first direct experimental evidence for the top quark," said WILLIAM CARITHERS, JR., cospokesman for the CDF experiment, "but at that time

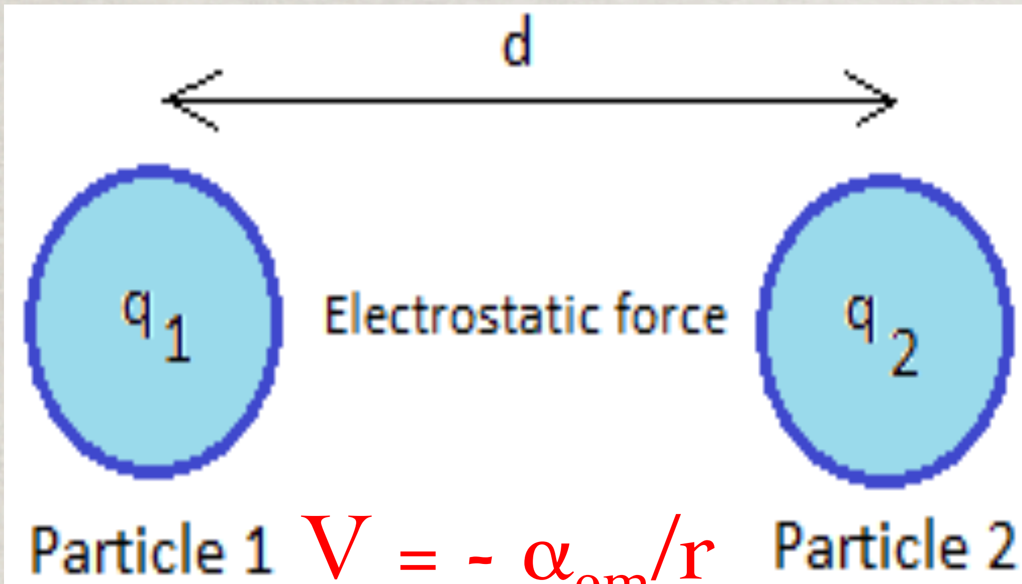
Collision!

In this artist's representation of a particle collision, a proton and antiproton collide at nearly the speed of light.

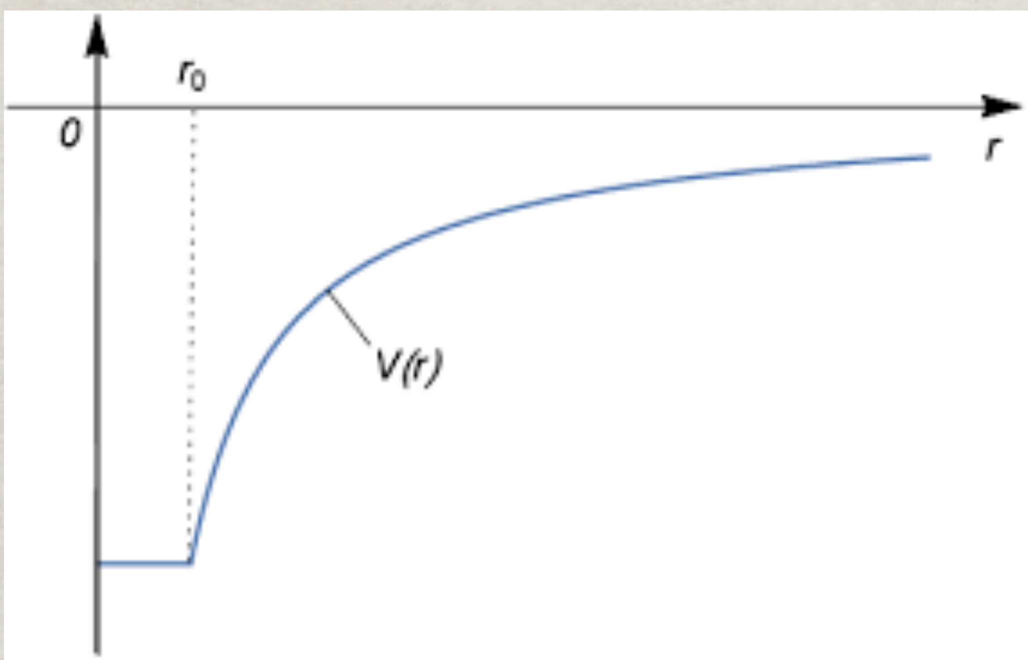
Still a mystery: top quark mass ~ 175 m_p
as heavy as a gold atom!

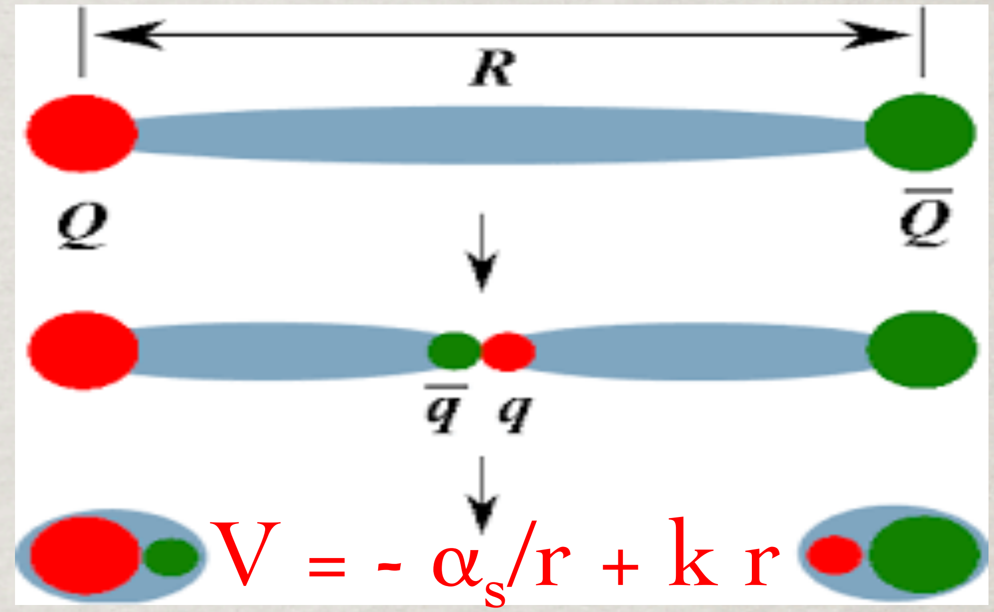
Why no free quarks seen?!

Electromagnetism vs. Strong force

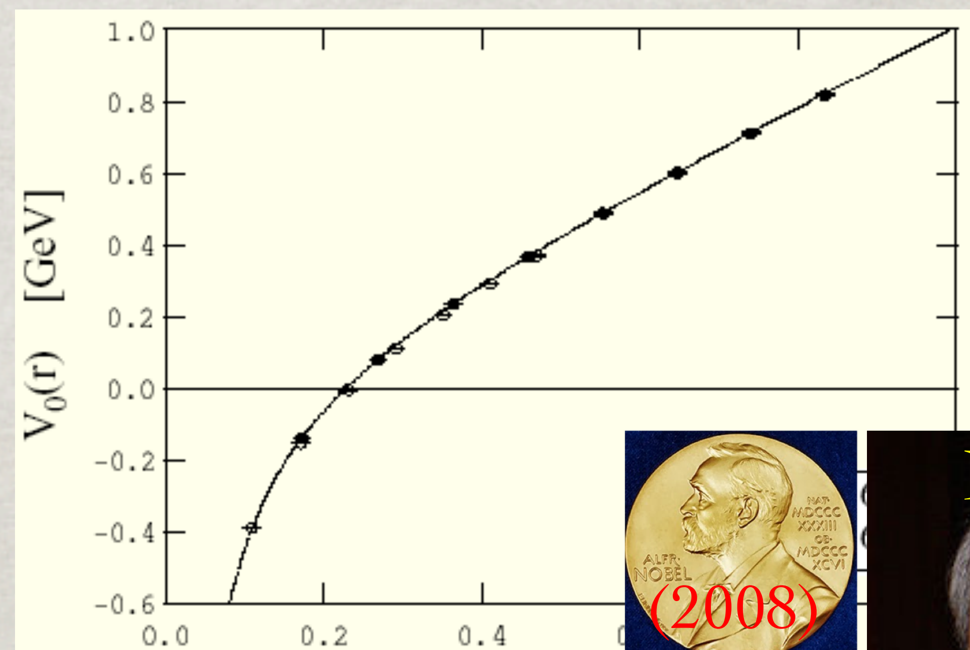


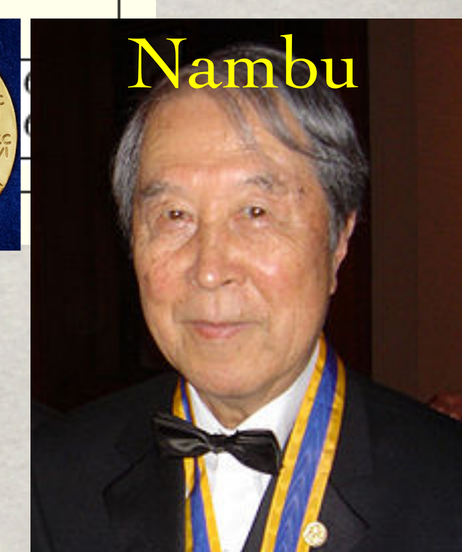
$V = -\alpha_{em}/r$





$V = -\alpha_s/r + k\, r$





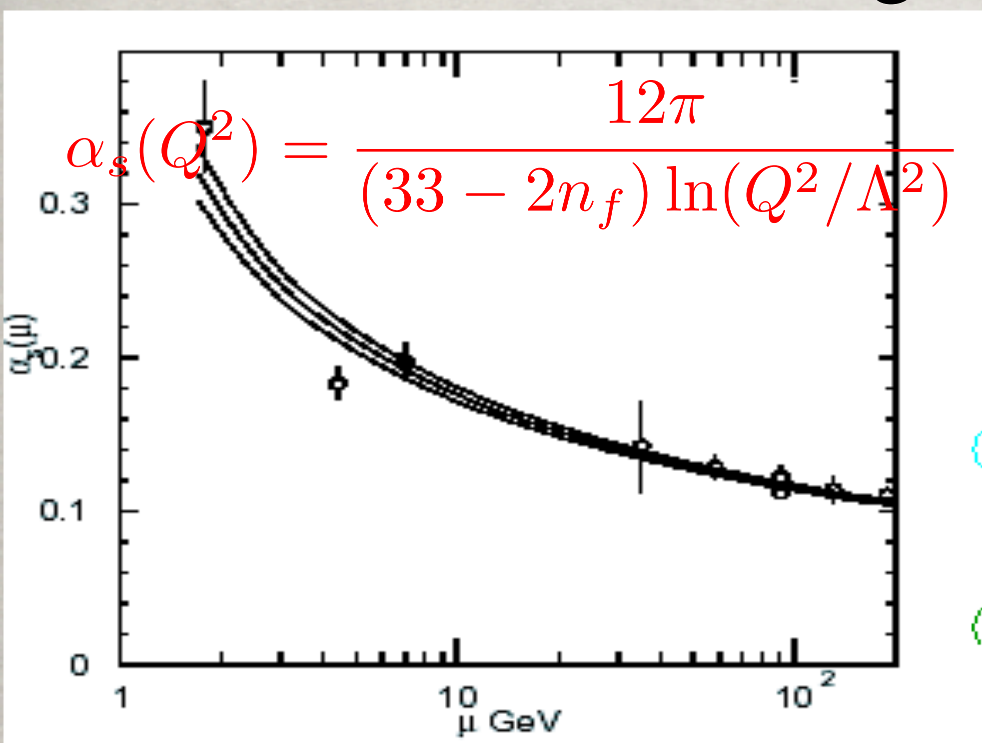
$E = mc^2$: Energy input on $Q\bar{Q}$

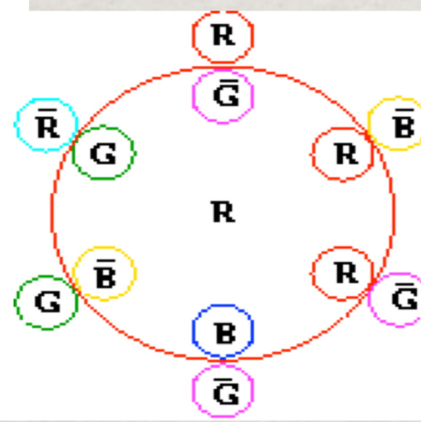
→ more hadrons π^0, $\pi^{\pm}$, p^+, n…

The strong force can be "weak": Quantum Chromo-Dynamics

- At short distances/high energies asymptotically free (anti-screening effects)

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln(Q^2/\Lambda^2)}$$



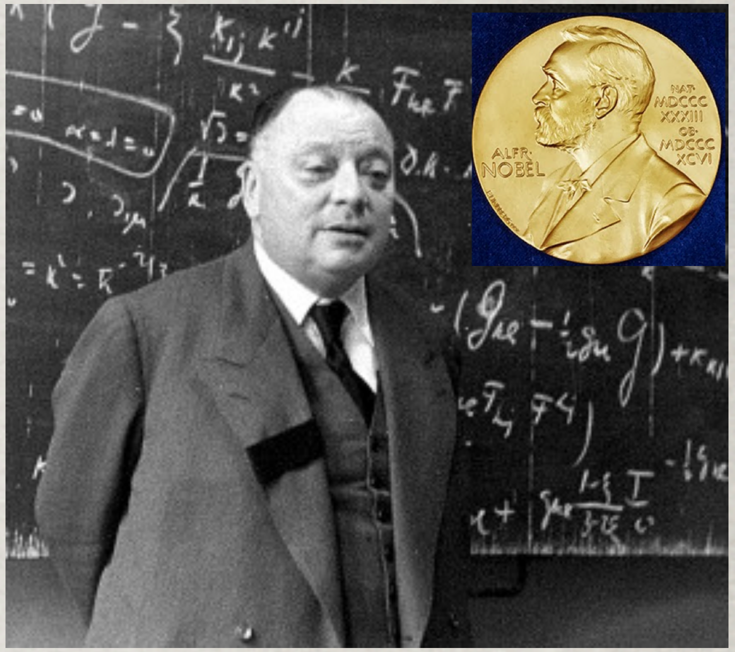


Asymptotic freedom

- **Quantum field theory at work!**
- **Perturbative, predictable at high energies:**
  - Crucial for HEP
  - early Universe cosmology …

What about the "weak force" ?

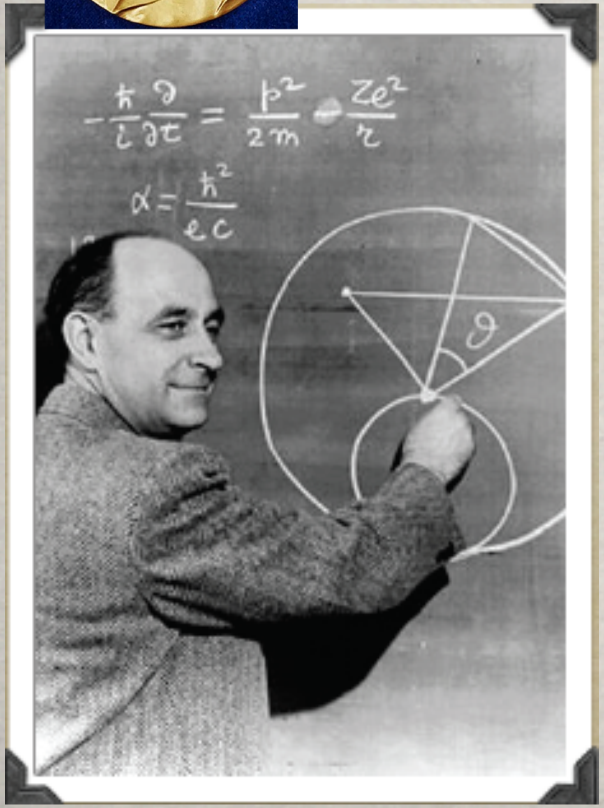
Beta decay $n \rightarrow p^{+} e^{-} \nu$

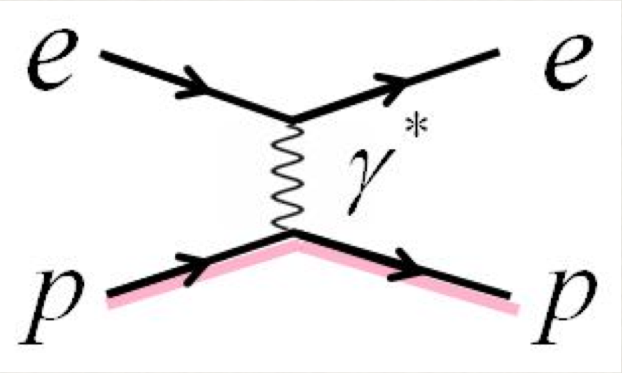


- Pauli's "neutron" (1930): a little neutral particle escaping from detection.
- Chadwick discovered the neutron (1932)

- Fermi's "neutrino" (1934):

Inspired by EM current-current interactions, 4-fermion interaction was proposed:





$$\rightarrow \quad \mathcal{L}_{weak} = -\frac{G_F}{\sqrt{2}} J^{\mu}(p^{+}n) J_{\mu}(e^{-}\nu)$$

"weak" coupling $G_F \sim 1.15 \times 10^{-5}\ \mathrm{GeV}^{-2}$

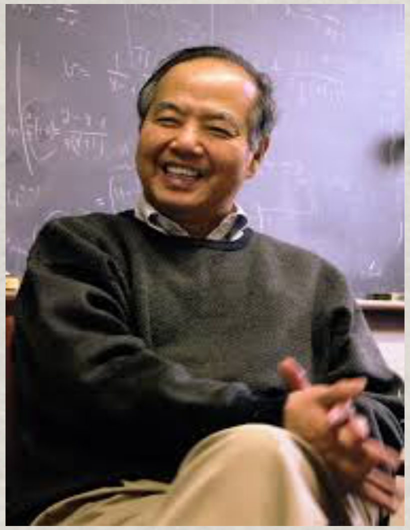
Remains to be a good description.

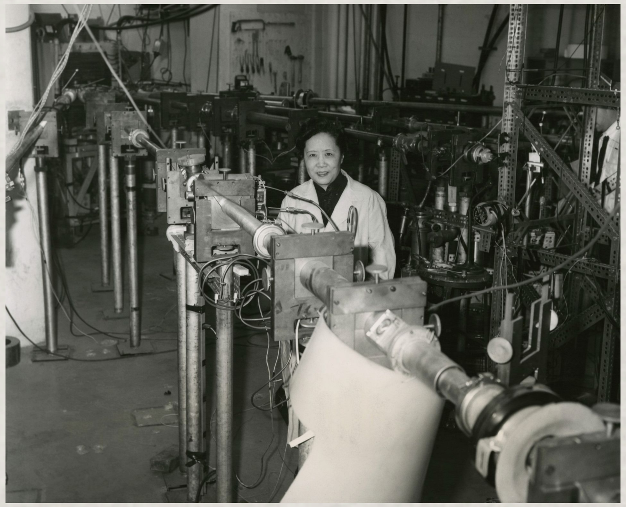
Three discrete transformations in QFT:

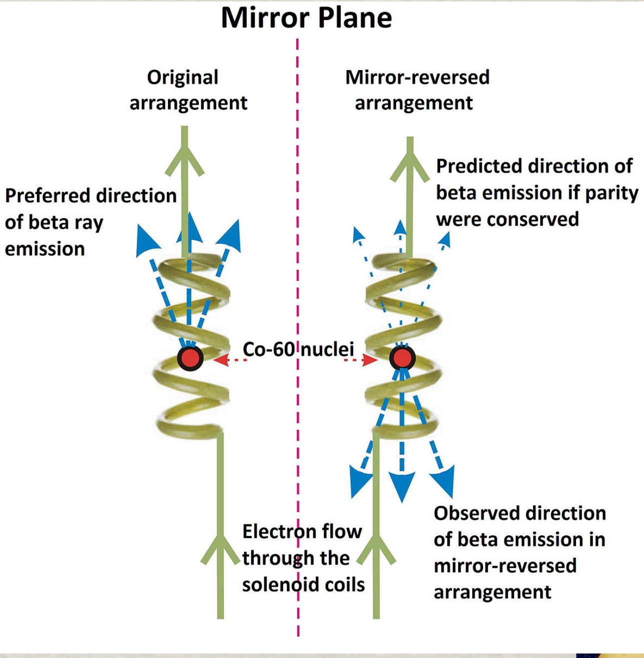
Space reflection (P); Time reversal (T); particle→anti-particle (C)

Electromagnetic & gravitational forces respect these,
but parity is violated in weak interaction

The Wu expt. (1956)

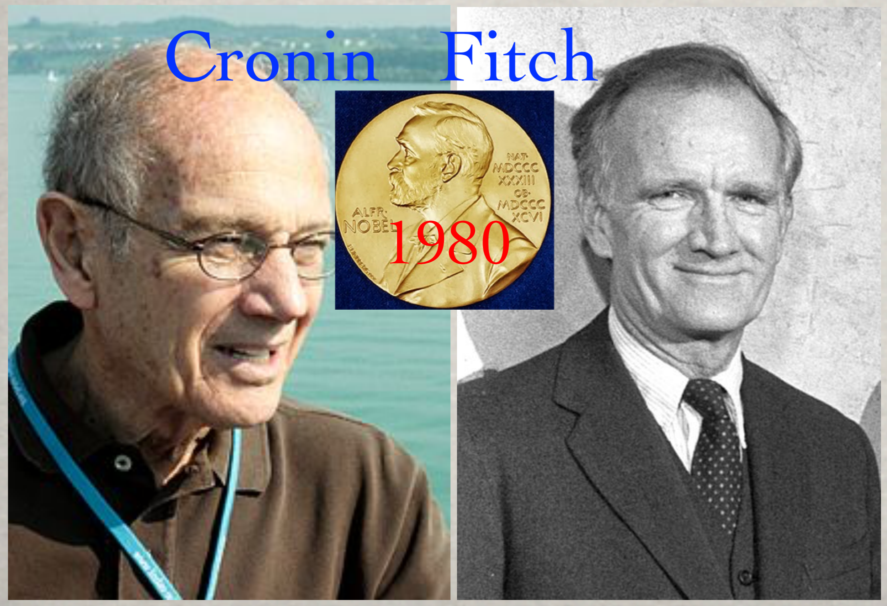






More surprise! CP Violation

Charge-Parity symmetry violation was discovered

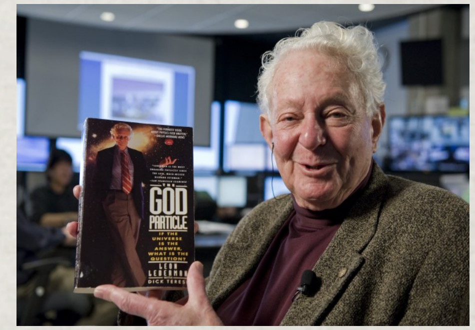


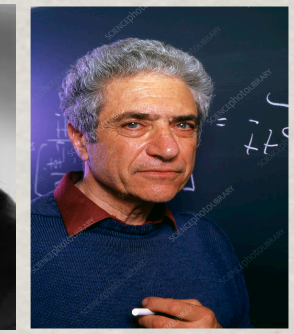
- In K^0 system
- B-Factories @ SLAC/KEK;
- LHCb **Congratulations!**
- Flavor mixing established: Cabibbo-Kobayashi-Maskawa
- Matter-antimatter asymm.

Most elusive particles: Neutrinos

"The most tiny quantity of reality ever imagined by a human being"

ν_e: 1956 Cowen-Reines






ν_μ: 1962 Lederman-Schwartz-Steinberger

ν_τ: 2000, "DONUT" collaboration, FNAL

Neutrinos have tiny masses & they oscillate

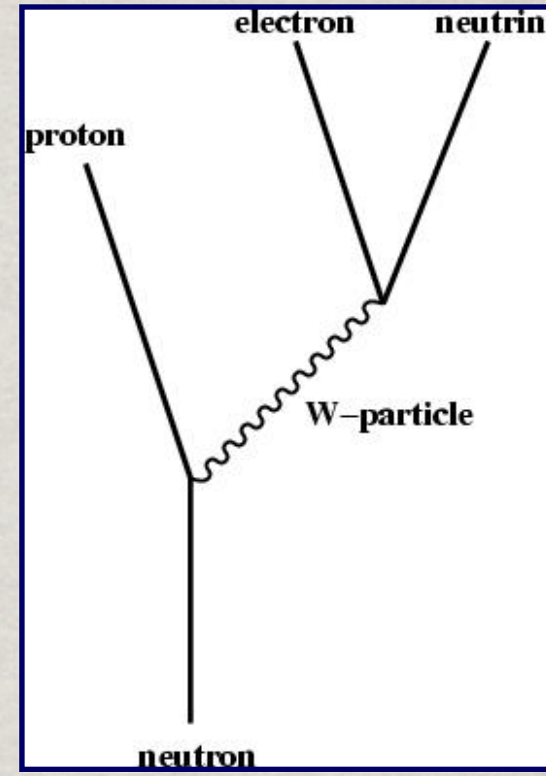
- From the sun
- From the atmosphere
- From reactors
- From accelerators

Why the weak force so "weak"? (or neutrinos so elusive?)

$$\mathcal{L}_{weak} = -\frac{G_F}{\sqrt{2}} J^{\mu}(p^+ n) J_{\mu}(e^- \nu)$$

$$\text{force range} \sim \sqrt{G_F} \sim M_W^{-1} \sim 10^{-18}\text{m}$$

suppression owing to a heavy particle?



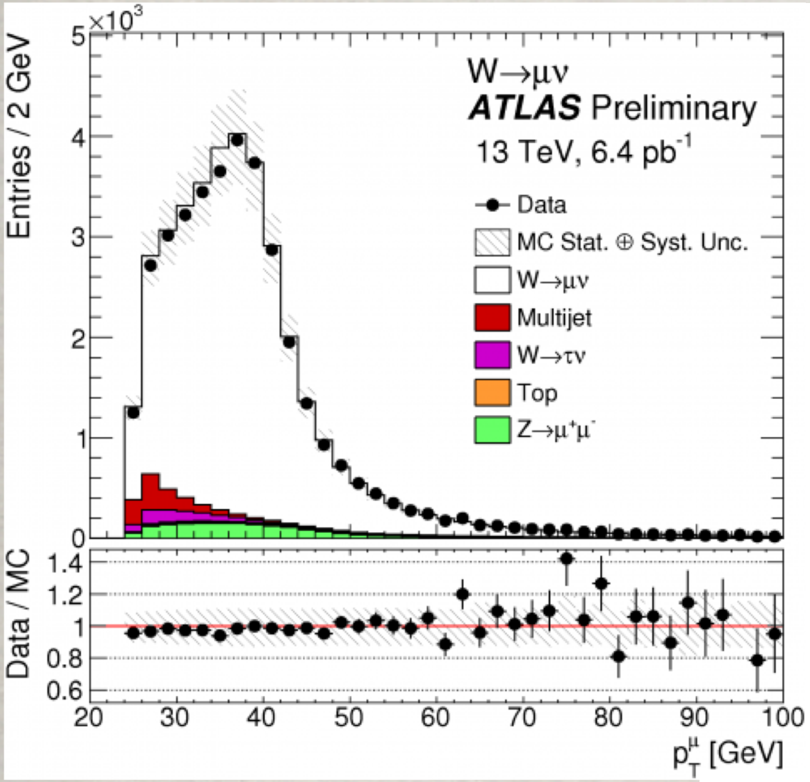
A MODEL OF LEPTONS*

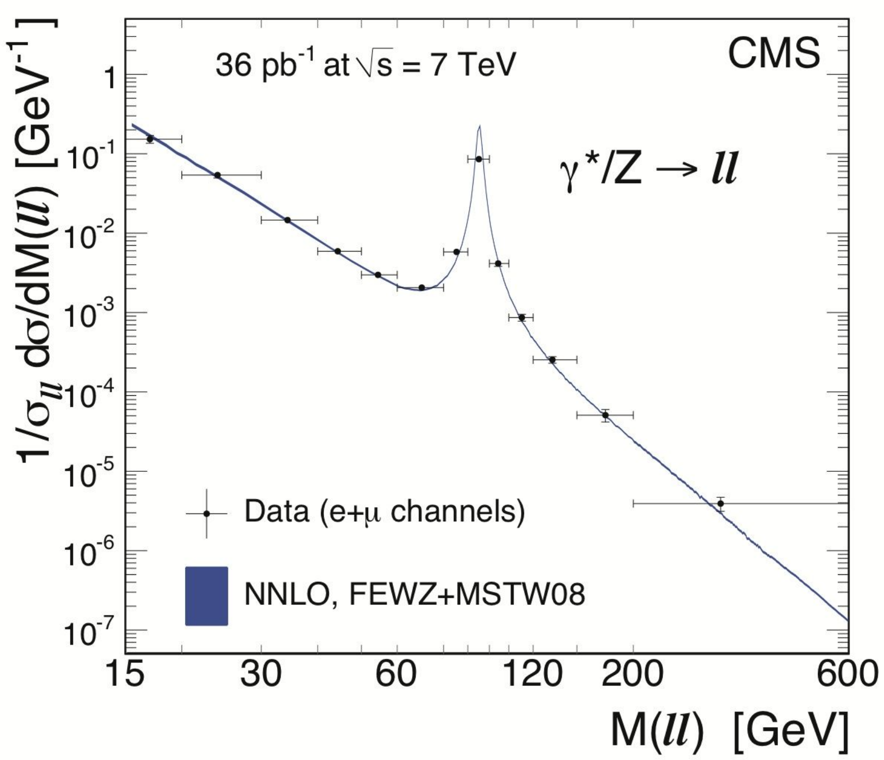
Steven Weinberg†

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences

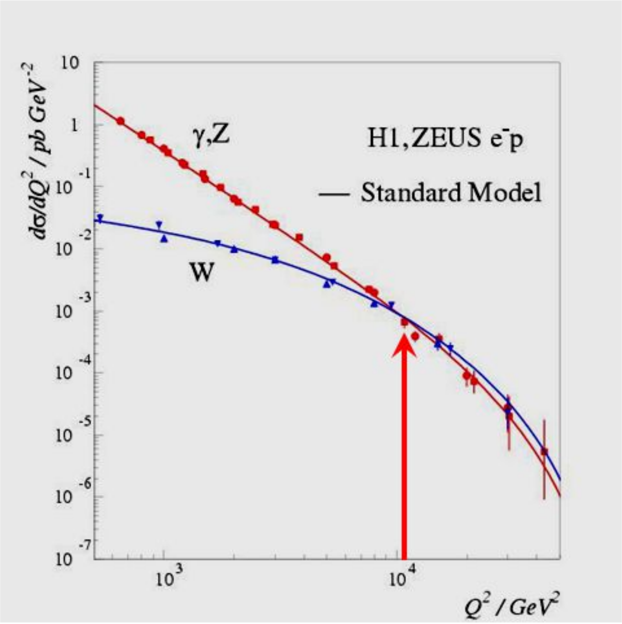
(1979)

Weak bosons W^{+-}, Z^0 discovered @ CERN, as estimated M < 100 GeV





Electroweak unification shows up very nicely in experimental results



Deep inelastic scattering data from the HERA collider at DESY, Hamburg

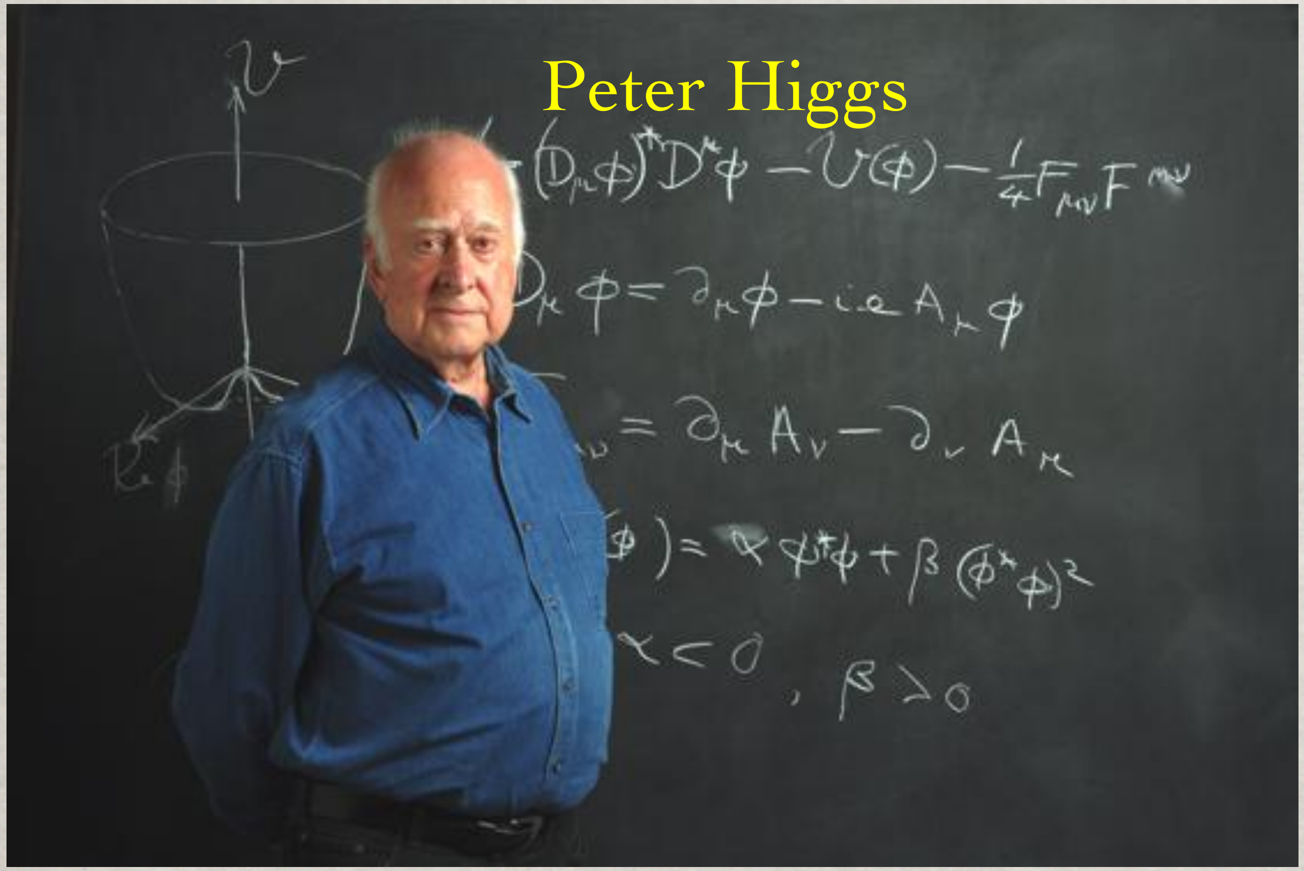
Gauge symmetries prevent the mass terms: All elementary particle masses are forbidden!

The Higgs Magic (1964) !

"If a LOCAL gauge symmetry is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode."

Gauge bosons massless? A Goldstone scalar?

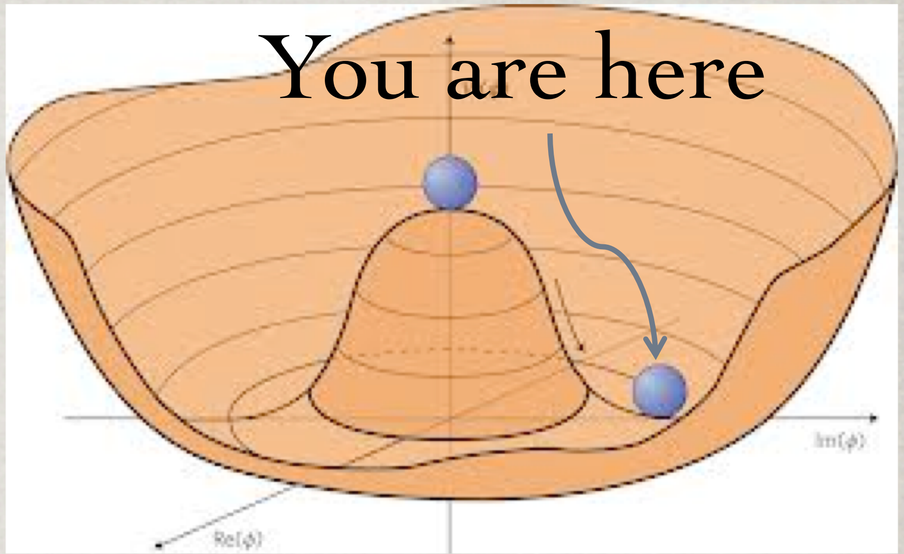
No No! → Two diseases cured each other!



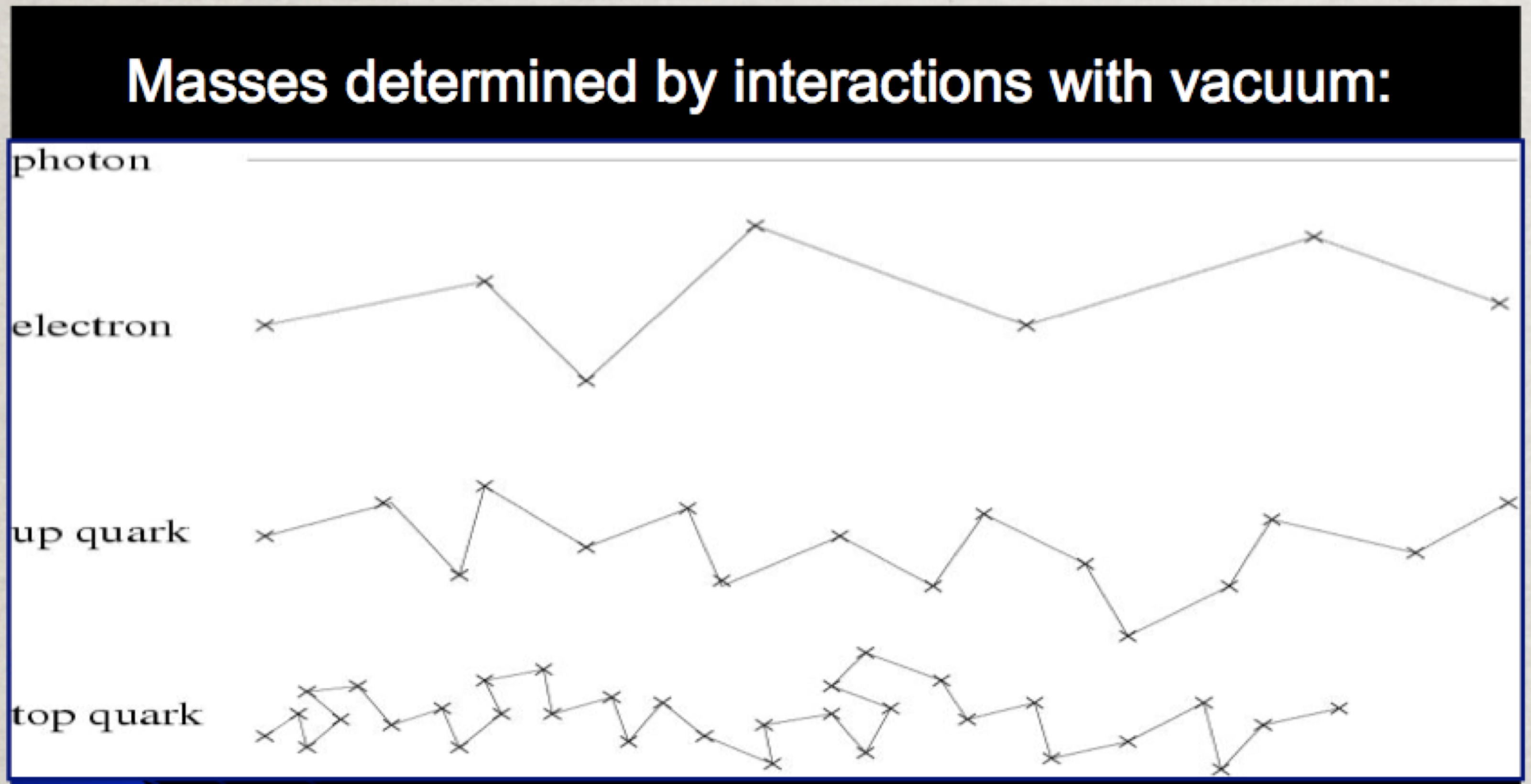
The vacuum (ground state) we live

$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

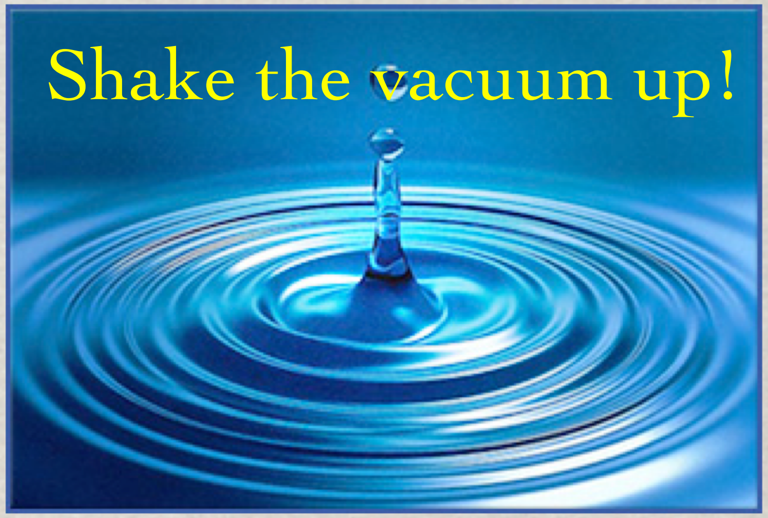
$$<|\Phi|> = v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}$$



A new vacuum state,
with H as the excitation.



$$M_{W,Z} = \frac{1}{2} g_V v, \quad m_f = \frac{g_f}{\sqrt{2}} v, \quad v^{-2} = \sqrt{2}\, G_F.$$



Thus, where ever is mass, there will be *H!*

The couplings to SM particles: $m \to m(1 + \frac{H}{v})$

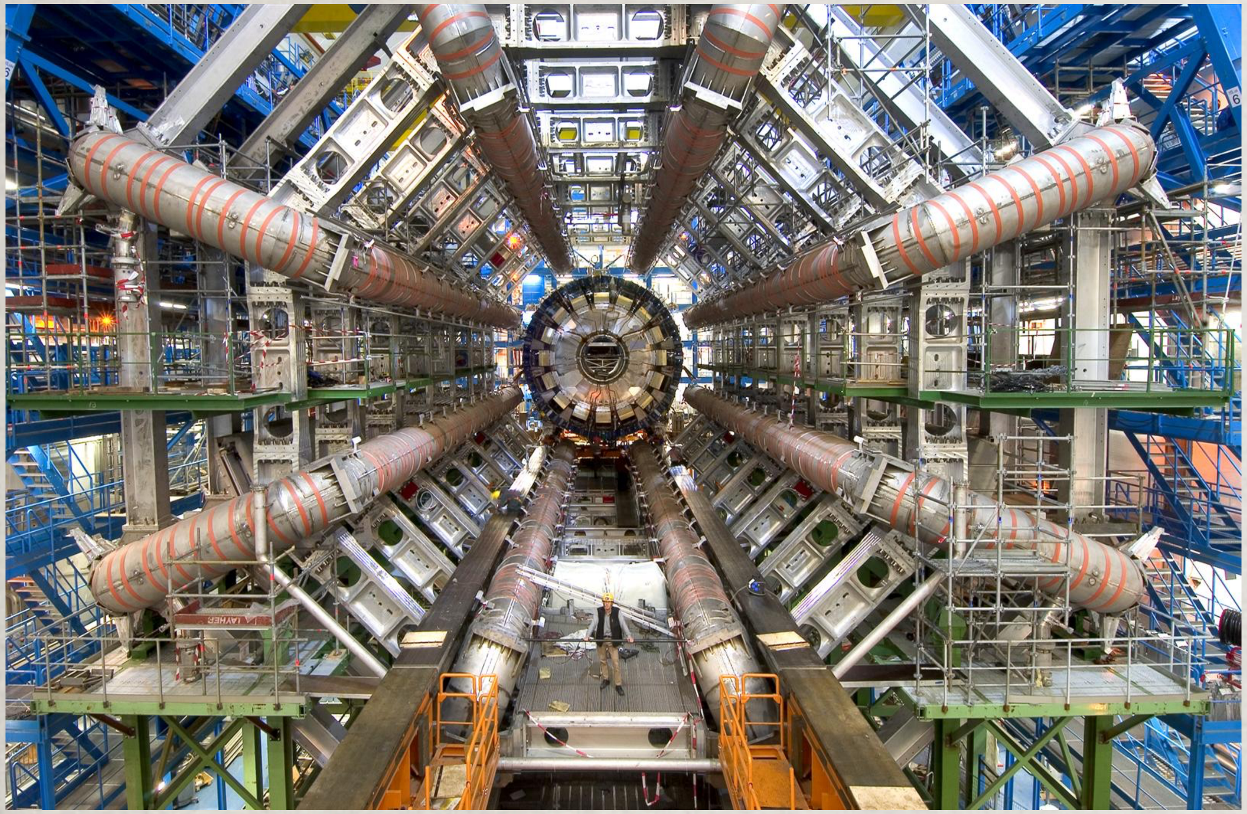
And its own mass and self-couplings (vacuum quantum #):

$$V(|\Phi|) \sim \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

Large Hadron Collider (LHC)

- proton-proton collider at CERN, Geneva
- 14 TeV energy by design
- Protons move slower than the speed of light by 3.1 m/s
- Beam kinetic energy: aircraft carrier at 15 knot = 30 km/h!

Requires detectors of unprecedented scales



- Two large multi-purpose detectors
- ATLAS has 8 times the volume of CMS

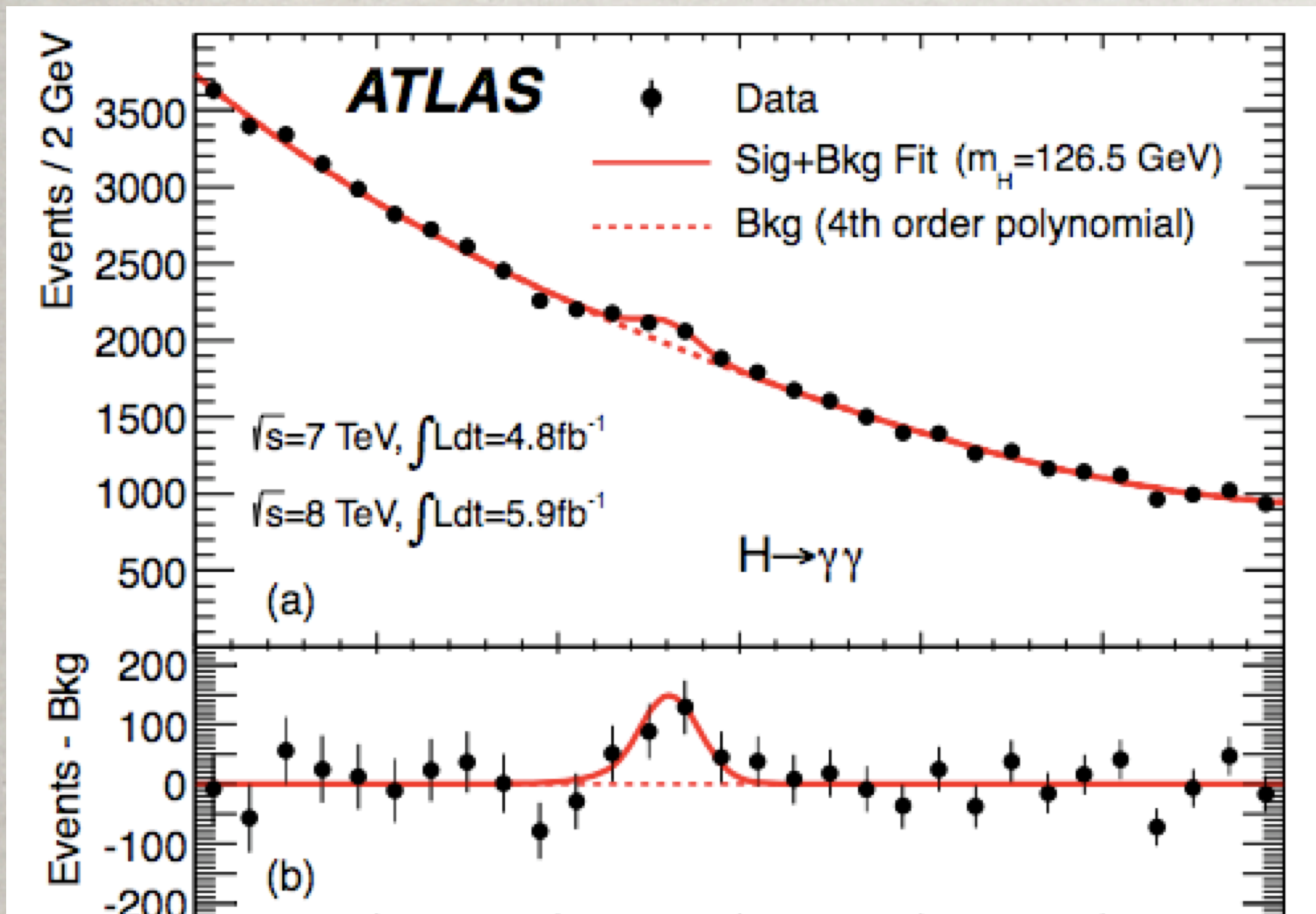
  (IHEP, Tsinghua, SJTU …)
- CMS is 12,000 tons

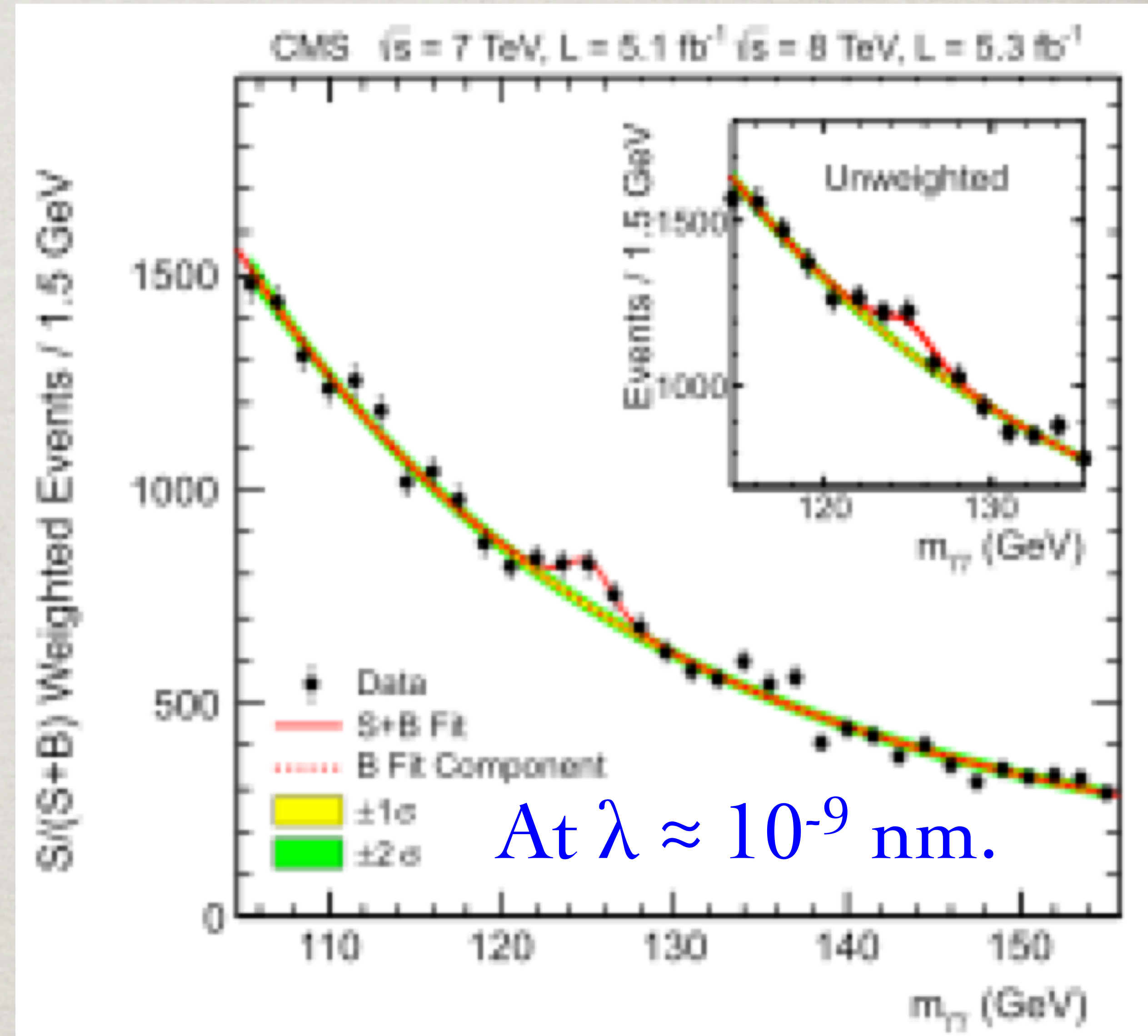
  (2 x's ATLAS)

  (IHEP, PKU …)

The discovery: July 4th, 2012

A neutral boson decay to two photons





At $\lambda \approx 10^{-9}$ nm.

The combined signal significance:

ATLAS: 5.9σ

CMS: 5.0σ

Phys. Lett. B716, 1 (2012)

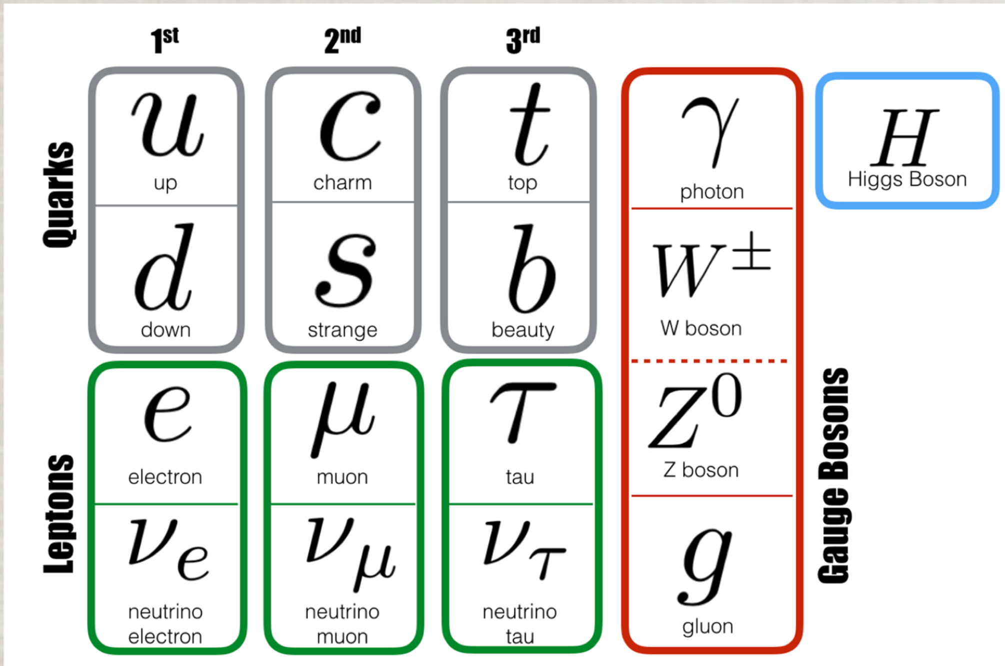
Phys. Lett. B716, 30 (2012)

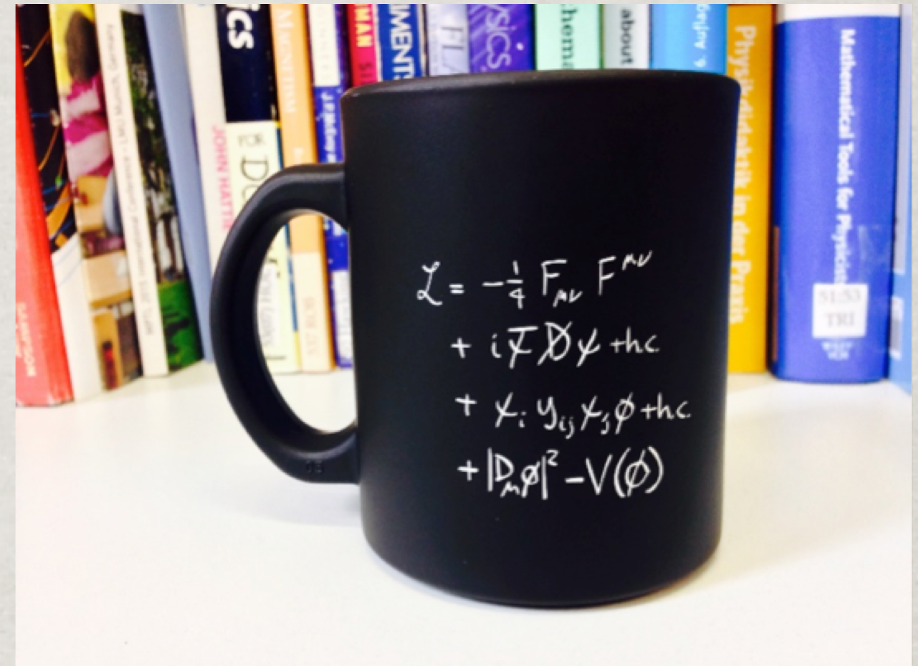
François Englert and Peter W. Higgs (2013)

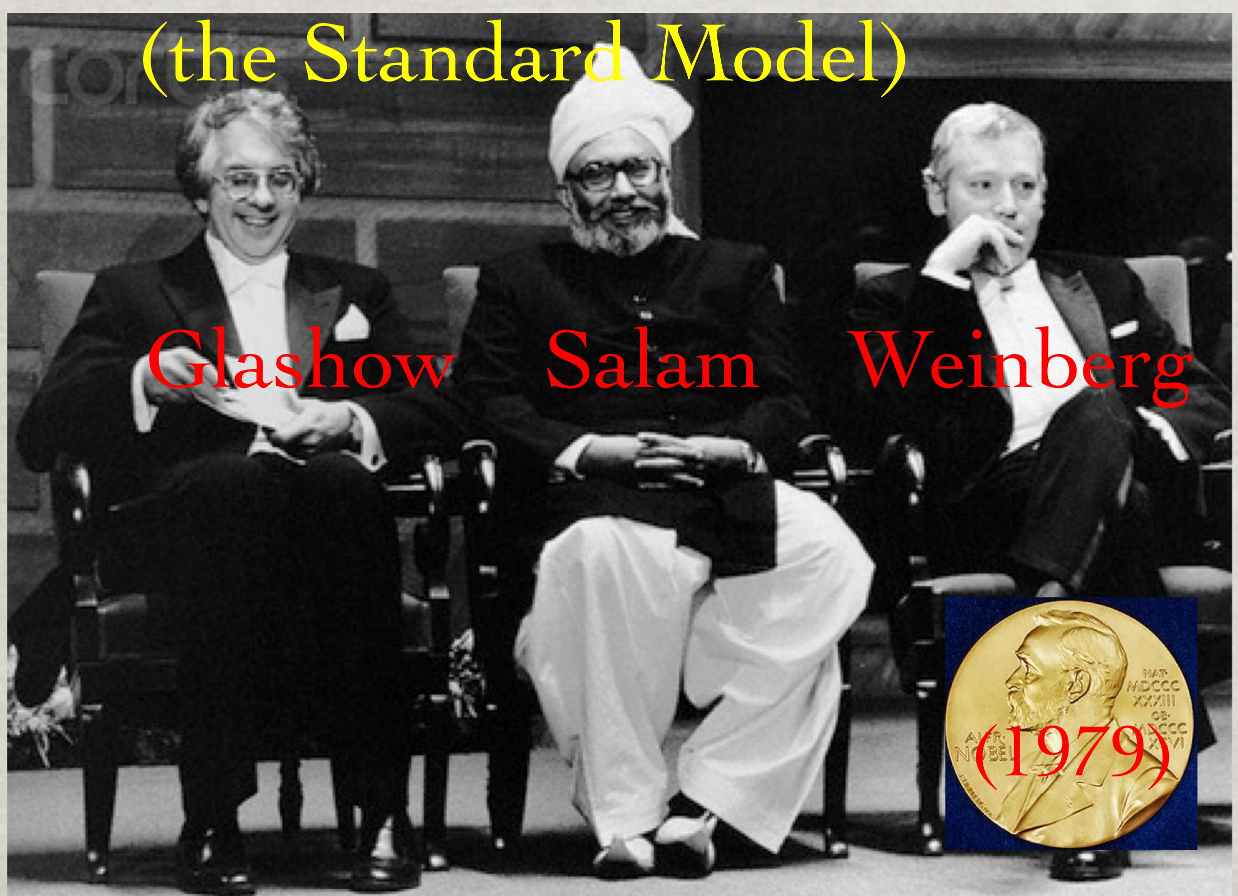
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

The EW Unification: *The "Standard Model"*

~ 50 years from quarks to the Higgs boson!







With the Higgs discovery, completion of the SM:

A relativistic, QM, renormalizable, self-consistent theory, valid up to an exponentially high scale! … M_{Pl} **?**

"… most of the grand underlying principles have been firmly established … The future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

Michelson–Morley experiments (1887):
"the moving-off point for the theoretical aspects of the second scientific revolution"

Will History repeat itself (soon)?

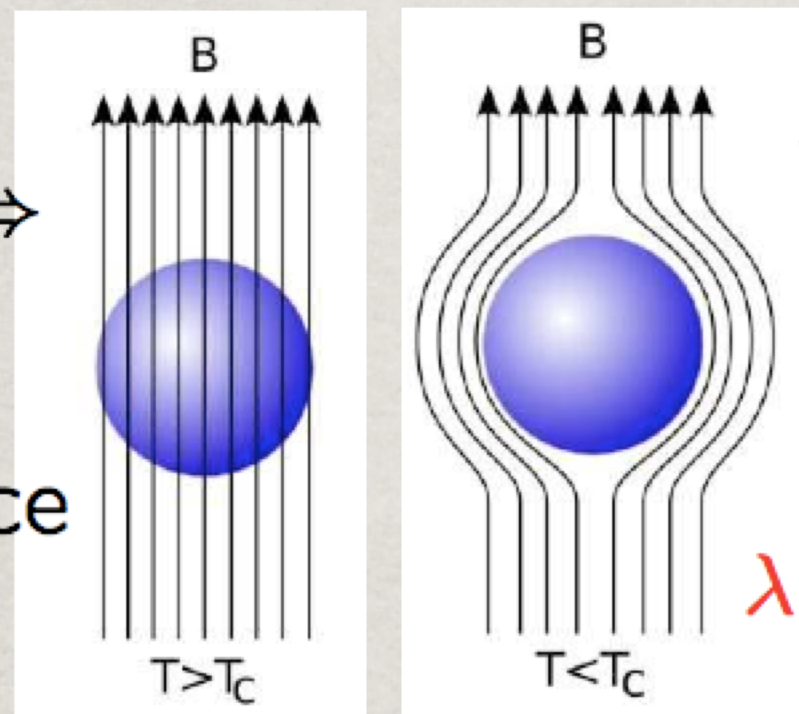
More puzzles ...

1. Electroweak Super-Conductivity

Normal phase⇒

$E^2 = p^2c^2$

Long-range force



⇐Superconducting phase

$E^2 = p^2c^2 + m^2c^4$

gap leads to $\sim exp(-r/\lambda)$

$\lambda \sim m^{-1}$ penetration depth

In "conventional" electro-magnetic superconductivity:

$m_\gamma \sim m_e/1000$, $T_c^{em} \sim \mathcal{O}(\text{few } K)$. BCS theory.

In "electro-weak superconductivity":

$m_w \sim G_F^{-\frac{1}{2}} \sim 100$ GeV, $T_c^w \sim 10^{15} K!$

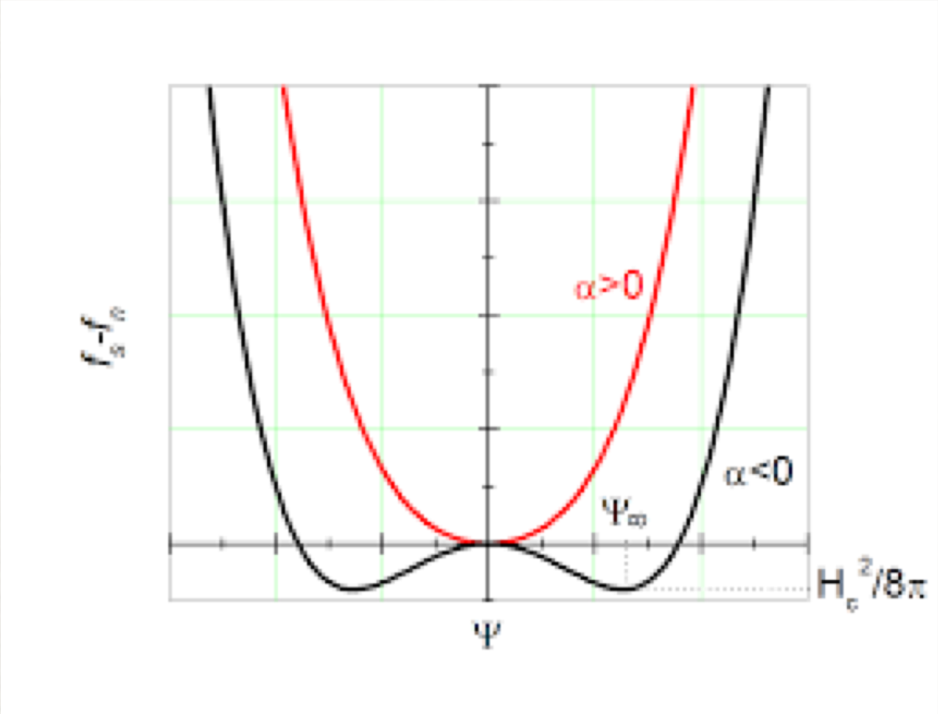
We are living in an EW superconducting phase!

It's like Landau-Ginzburg Theory:

A mean-field phenomenological theory to describe Type-I superconductivity for a second order phase transition, by an "order parameter"

$$F = \alpha(T)|\psi|^2 + \frac{\beta(T)}{2}|\psi|^4$$

$$|\psi|^2 = -\frac{\alpha(T)}{\beta(T)}$$



It is --

- an effective phenomenological theory near the phase transition; an "order parameter" description.
- **BCS (Bardeen-Cooper-Schrieffer) theory,**

to understand the underlying mechanisms.

It's NOT Landau-Ginzburg Theory

In the SM, with a scalar field theory,

$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$<|\Phi|> = v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV} \qquad m_H = \sqrt{2\lambda}v = 125 \text{ GeV}$$

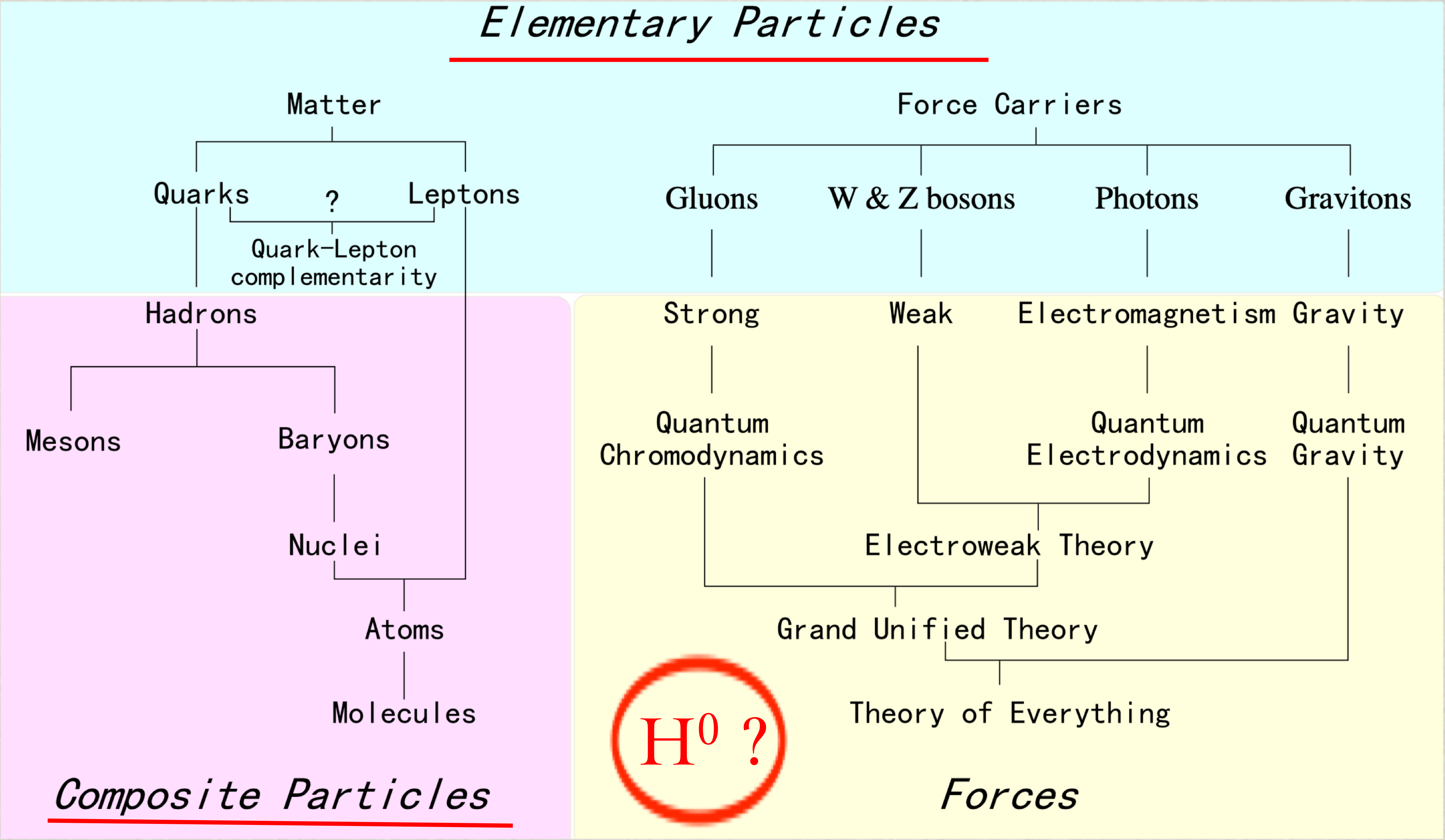
$$\kappa \equiv \frac{\text{penetration depth}}{\text{coherence length}} = \frac{m_H}{M_W} \approx 1.5$$

The Universe underwent a cross-over phase change;
The vacuum is a Type II EW superconductor.

- A scalar field, a consistent relativistic quantum mechanical field theory, valid to high scales.
- The Higgs boson weakly coupled,
  a very narrow resonance: width/$m_h \approx 10^{-5}$.
- Elementary up to a scale >1000 GeV!

What is the underlying theory, a new BCS theory?

2. The Higgs boson IS new physics!



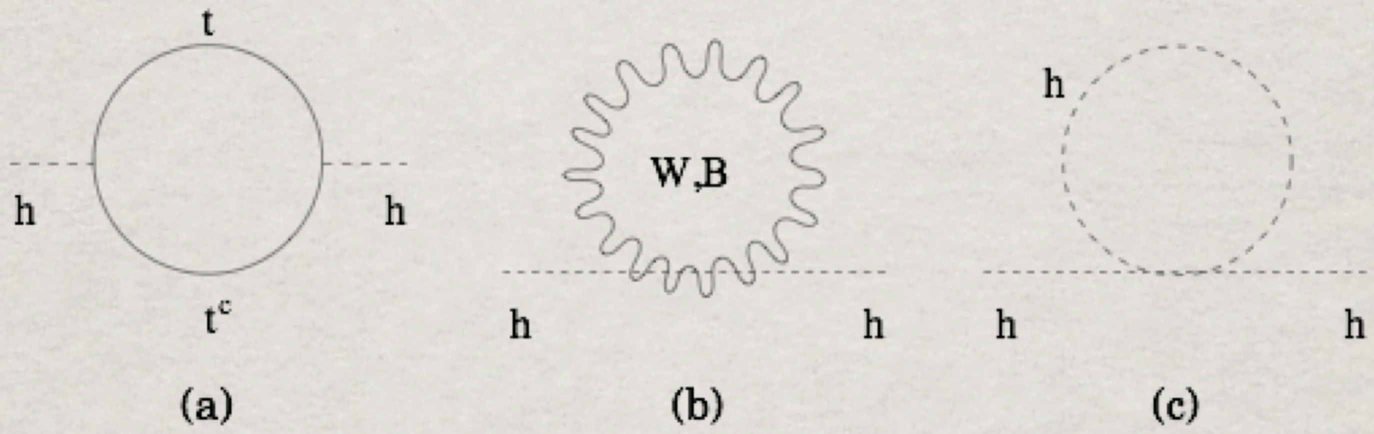
→ New strong force: "Technicolor"

→ New week force: "Super Symmetry"

→ We need to probe the next scale !

a. The Higgs Mass Puzzle:

The Higgs potential: $V = -\mu^2|\phi|^2 + \lambda|\phi|^4$



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

If $\Lambda^2 \gg m_H^2$, then unnaturally large cancellations must occur.

Cancelation in perspective:

m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023

–36,127,890,984,789,307,394,520,932,878,928,917,398

= $(125\ \mathrm{GeV})^2$! ?

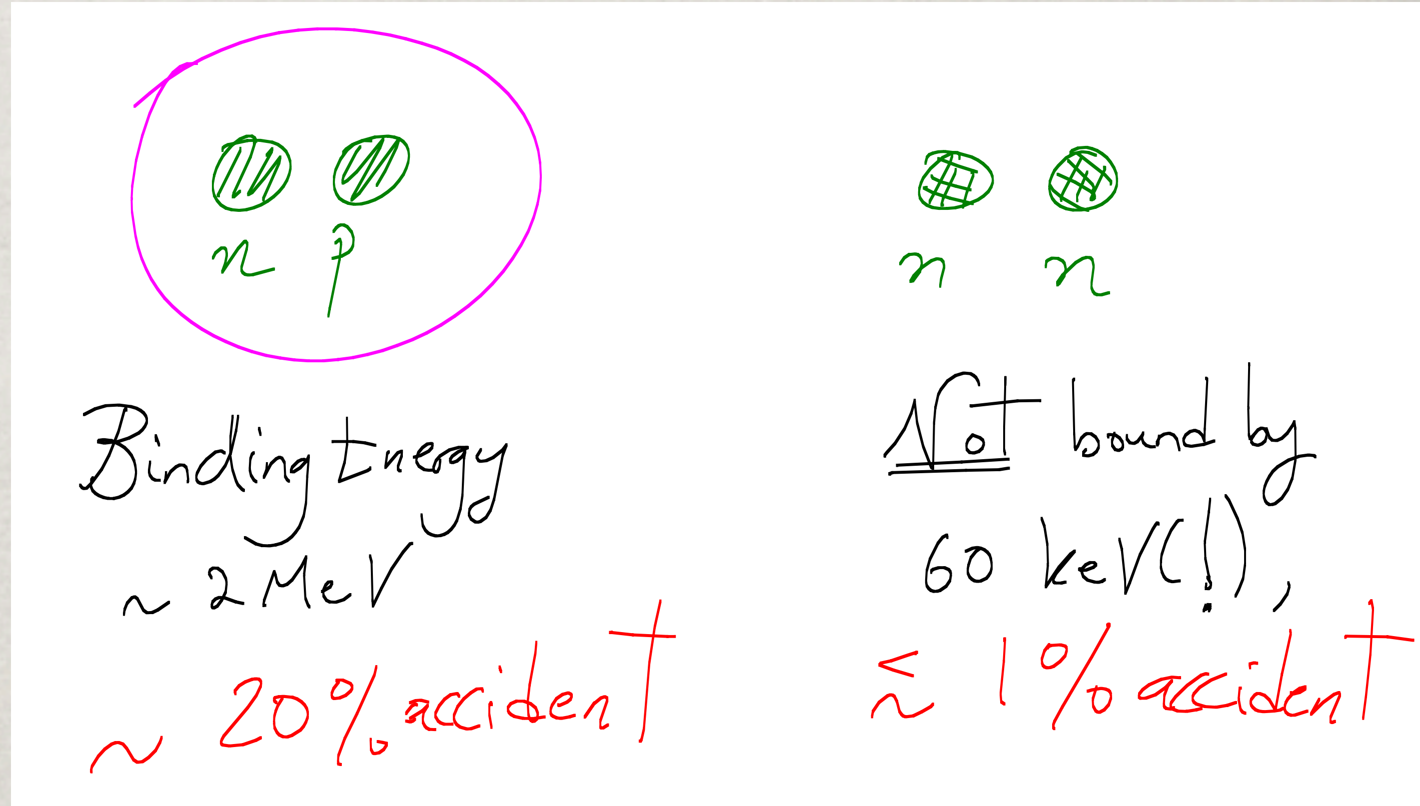
How much "tune" is fine-tuned?

Atomic physics:

Rydberg const. $E_0 \sim \alpha^2 m_e \rightarrow O(25\ \mathrm{eV})$, very natural!

Nuclear physics?

	Mass (amu)	Binding Energy (J)	
		Total	Per Nucleon
$^{2}_{1}\mathrm{H}$	2.01410	3.57×10^{-13}	1.78×10^{-13}
$^{3}_{2}\mathrm{He}$	3.01603	1.24×10^{-12}	4.13×10^{-13}
$^{4}_{2}\mathrm{He}$	4.00260	4.52×10^{-12}	1.13×10^{-12}
$^{16}_{8}\mathrm{O}$	15.99491	2.04×10^{-11}	1.28×10^{-12}
$^{17}_{8}\mathrm{O}$	16.999131	2.10×10^{-11}	1.24×10^{-12}
$^{56}_{26}\mathrm{Fe}$	55.934939	7.90×10^{-11}	1.41×10^{-12}
$^{238}_{92}\mathrm{U}$	238.0508	2.89×10^{-10}	1.22×10^{-12}

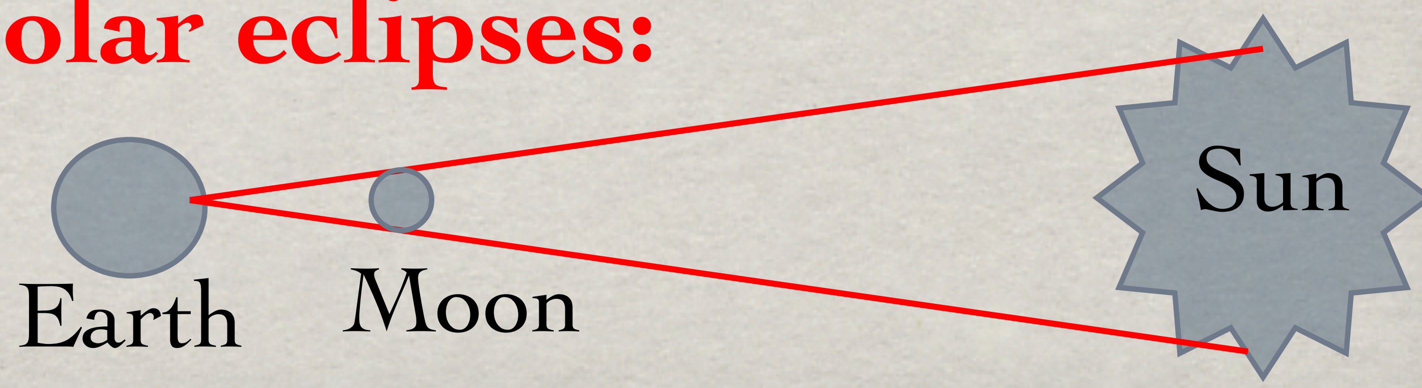


$r_m/d_m = 0.5583$; $r_s/d_s = 0.5450$ at perigee

$\rightarrow \delta\theta/\theta \sim 2.10^{-2}$

rather unnatural!

Solar eclipses:



b. λ: a "New Force"?

The Higgs potential: $V = -\mu^2 |\phi|^2 + \lambda|\phi|^4$

It represents a weakly coupled new force (a 5th force):

- **In the SM, λ is a free parameter, now measured:**

  $\lambda = m_H^2 / 2v^2 \approx 0.13$

  Is it fundamental? Or induced?

  Landau-Ginzburg<->BCS? Van der Waals<->Coulomb?

- **In Supersymmetry, it is related to the gauge couplings tree-level:** $\lambda = (g_L^2 + g_Y^2)/8 \approx 0.3/4 \leftarrow$ **a bit too small**

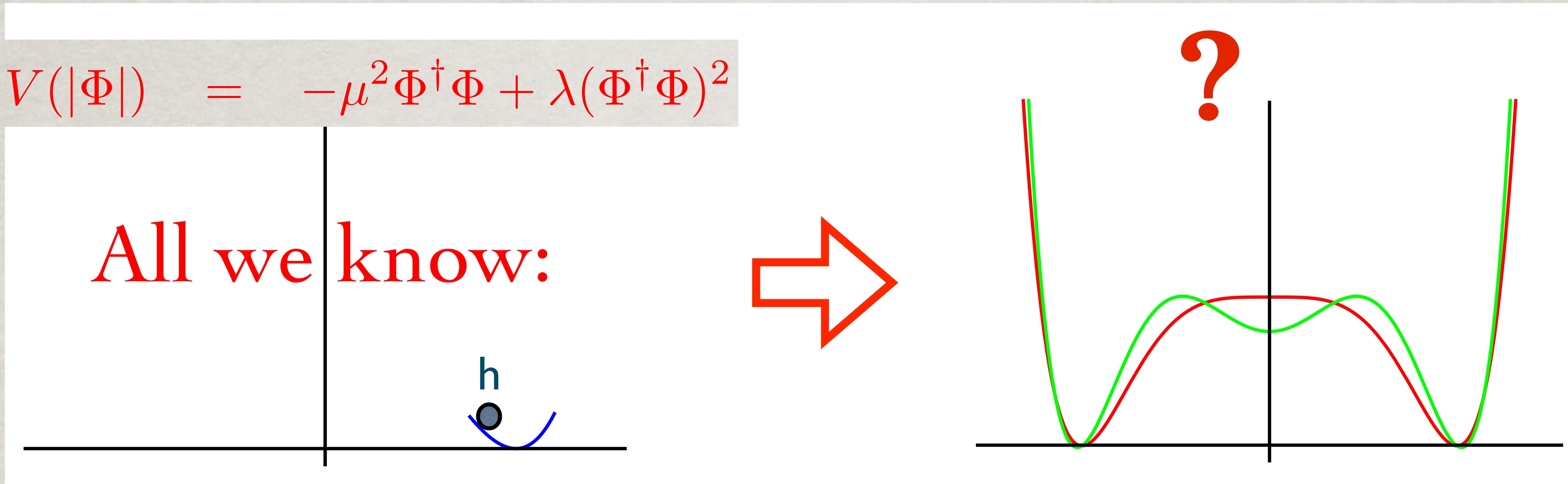
- **In composite/strong dynamics, harder to make λ big enough. (due to the loop suppression by design)**

Measured m_H already put constraints on theory:

too light to be heavy (new dynamics);

too heavy to be light (SUSY)

3. Nature of the EW Phase Transition



With new physics near the EW scale could modify the Higgs potential:

$$V(h) \to m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3,$$

$$\to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$ (Coleman-Weinberg potential)

→ Could lead to order 1 modification on λ_{hhh}, leading to strong 1^{st} order EW phase transition! Significant impact on early universe cosmology!

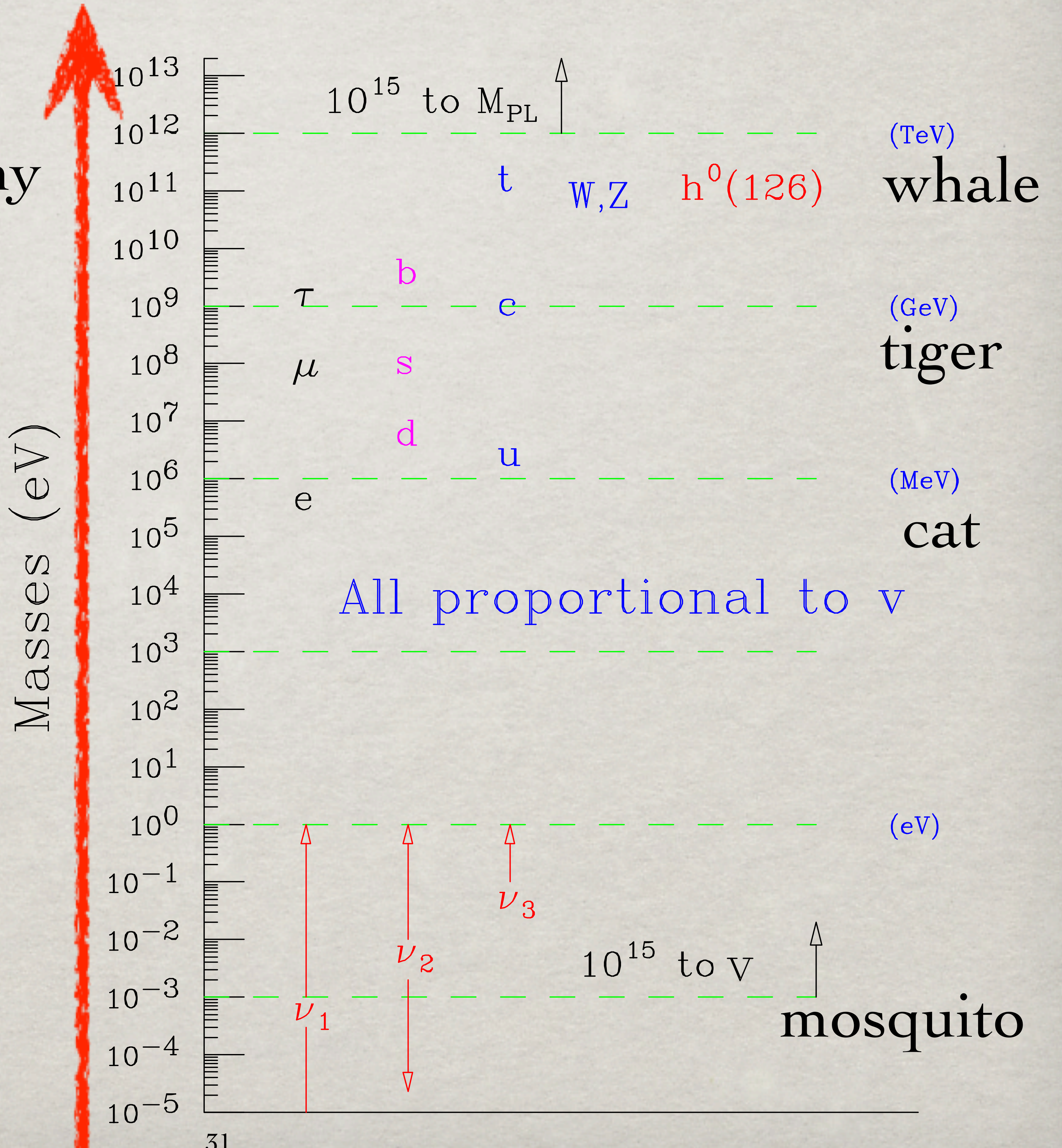
→ **We need an answer !**

4. The "Flavor Puzzle": much^n harder problem

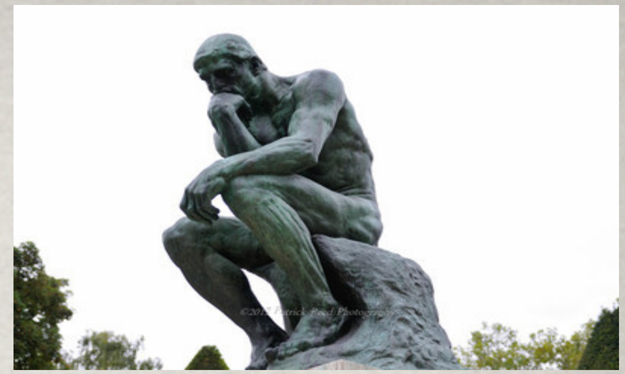
- Particle mass hierarchy
- New CP-violation sources?

Non-Higgs mass: The "seesaw" mechanism

$$m_\nu \sim \kappa \frac{\langle H^0 \rangle^2}{M}$$



The list of puzzles continues …



5. Dark Matter: 25% of mass?

what is the nature of particle dark matter?

6. Matter–Antimatter asymmetry

Where is the anti-matter?

7. E&M + Weak + Strong → single force?

Grand Unification? proton instability?

8. Larger space-time symmetry?

Super-symmetry at EW scale?

9. Cosmology: inflation, dark energy …

Does the Higgs play a role?

10. Quantum gravity?

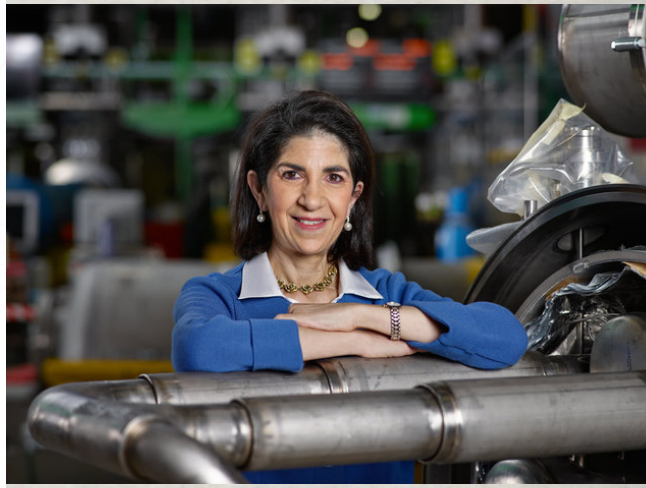
… … We need answers !

Future Energy Frontier

"No doubt that future high energy colliders are extremely challenging projects.

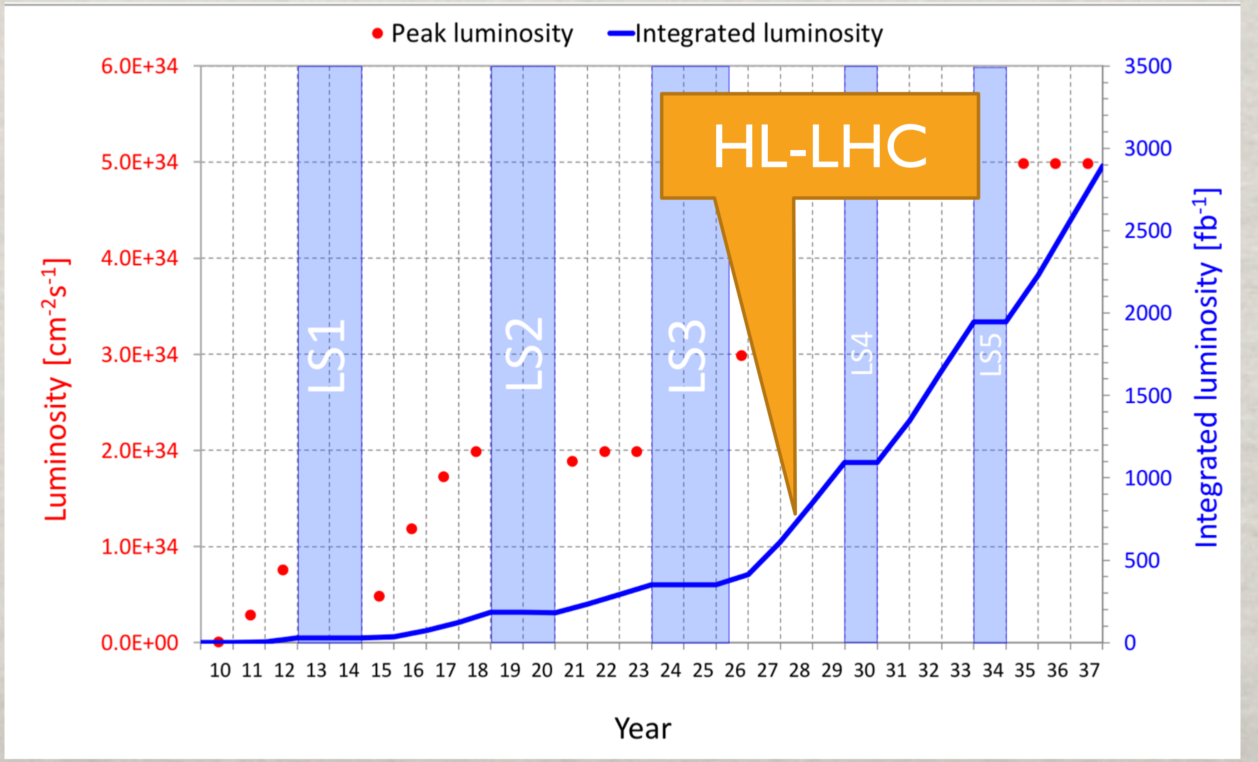
However, the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable."

Fabiola Gianotti, DG CERN

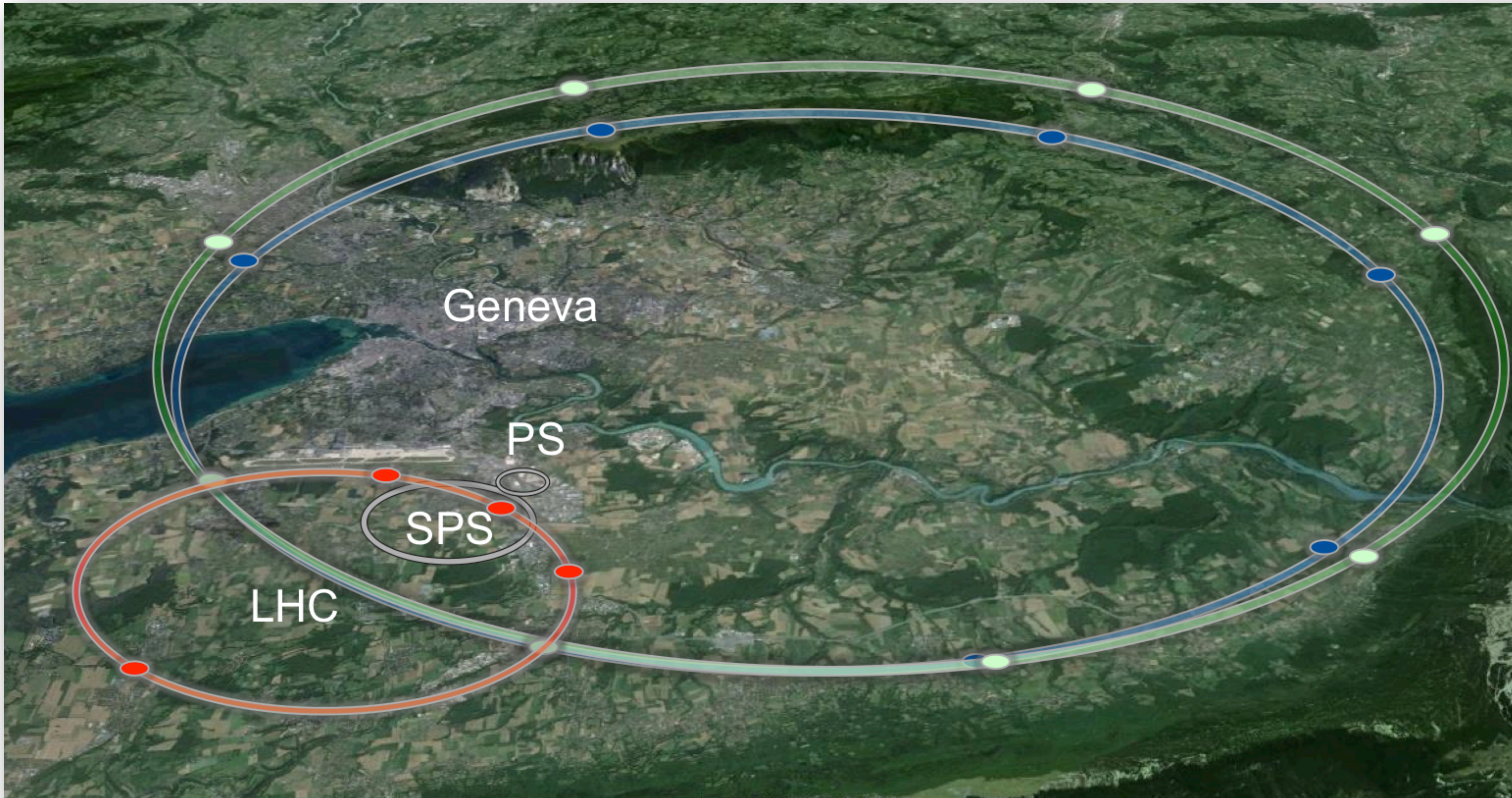


The High Luminosity LHC Project: (operation 2026-2037)

HL-LHC is the top priority of the European Strategy for Particle Physics in its 2013 update. It is formally approved by CERN Council in June 2016.

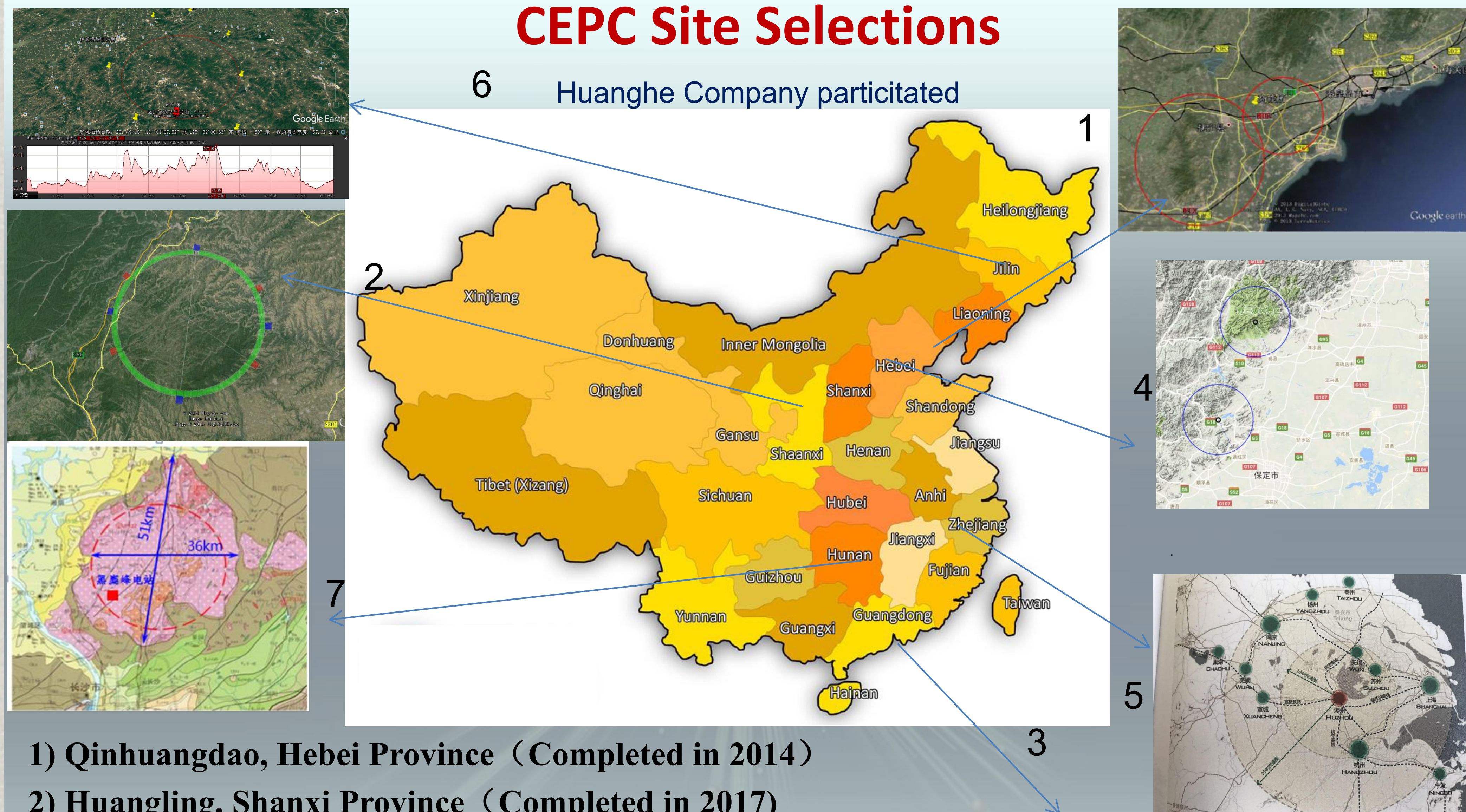


“European Strategy for Particle Physics”
FCC (future circular collider): CERN



HE-LHC	FCC-ee	FCC-hh
27 km, 20T	80/100 km	80 /100 km, 16/20T
33 TeV	90 - 400 GeV	100 TeV

CEPC (circular e^-e^+)/SppC: China



1) Qinhuangdao, Hebei Province（Completed in 2014）
2) Huangling, Shanxi Province（Completed in 2017)
3) Shenshan, Guangdong Province(Completed in 2016)
4) Baoding (Xiong an), Hebei Province (Started in August 2017)
5) Huzhou, Zhejiang Province (Started in March 2018)
6) Chuangchun, Jilin Province (Started in May 2018)
7) Changsha, Hunan Province (Started in Dec. 2018)

Please join the exciting journey ahead!

HEP & Society

Human being's curiosity about Nature drives the development of physics & basic science!

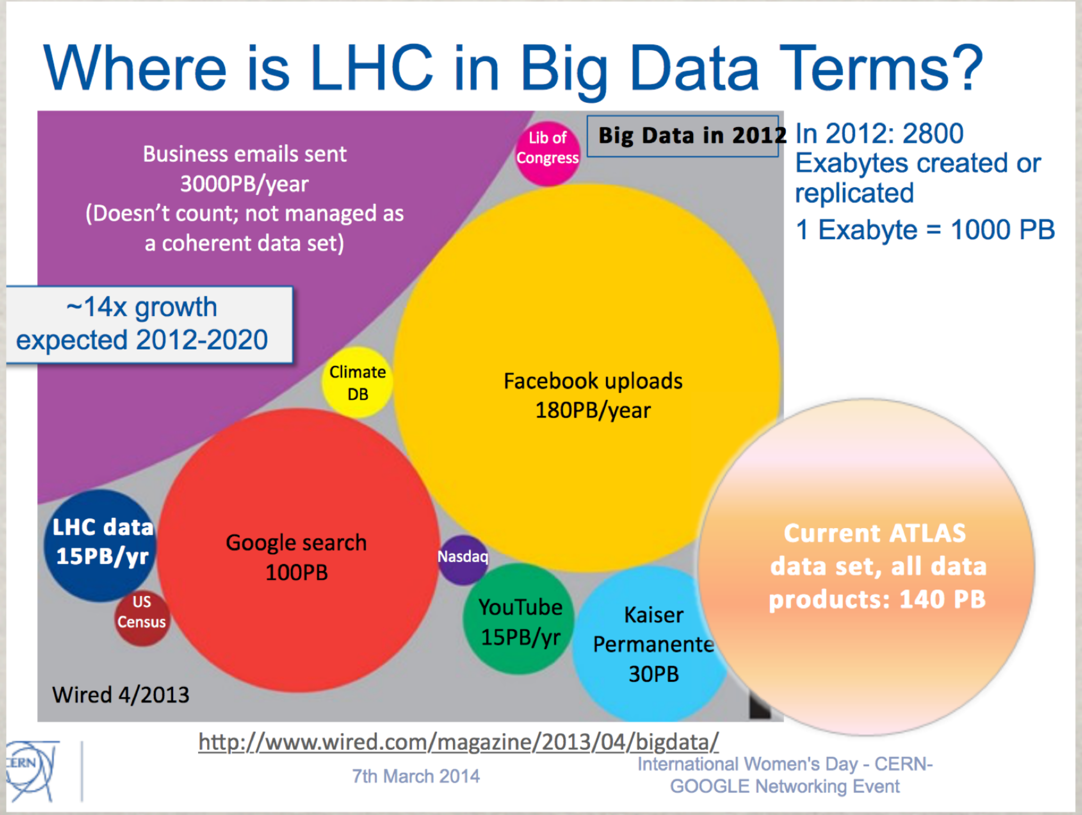
The outcome may have huge impacts on society.

Technology:

- Quantum mechanics → MRI, electronics in your hands
- General Relativity → GPS/Google Map
- Accelerators → 30,000 in operation (other than HEP)!
- Big data → WWW (Tim Berners-Lee, 1990, CERN)

& IT Neural Network,

Machine Learning …



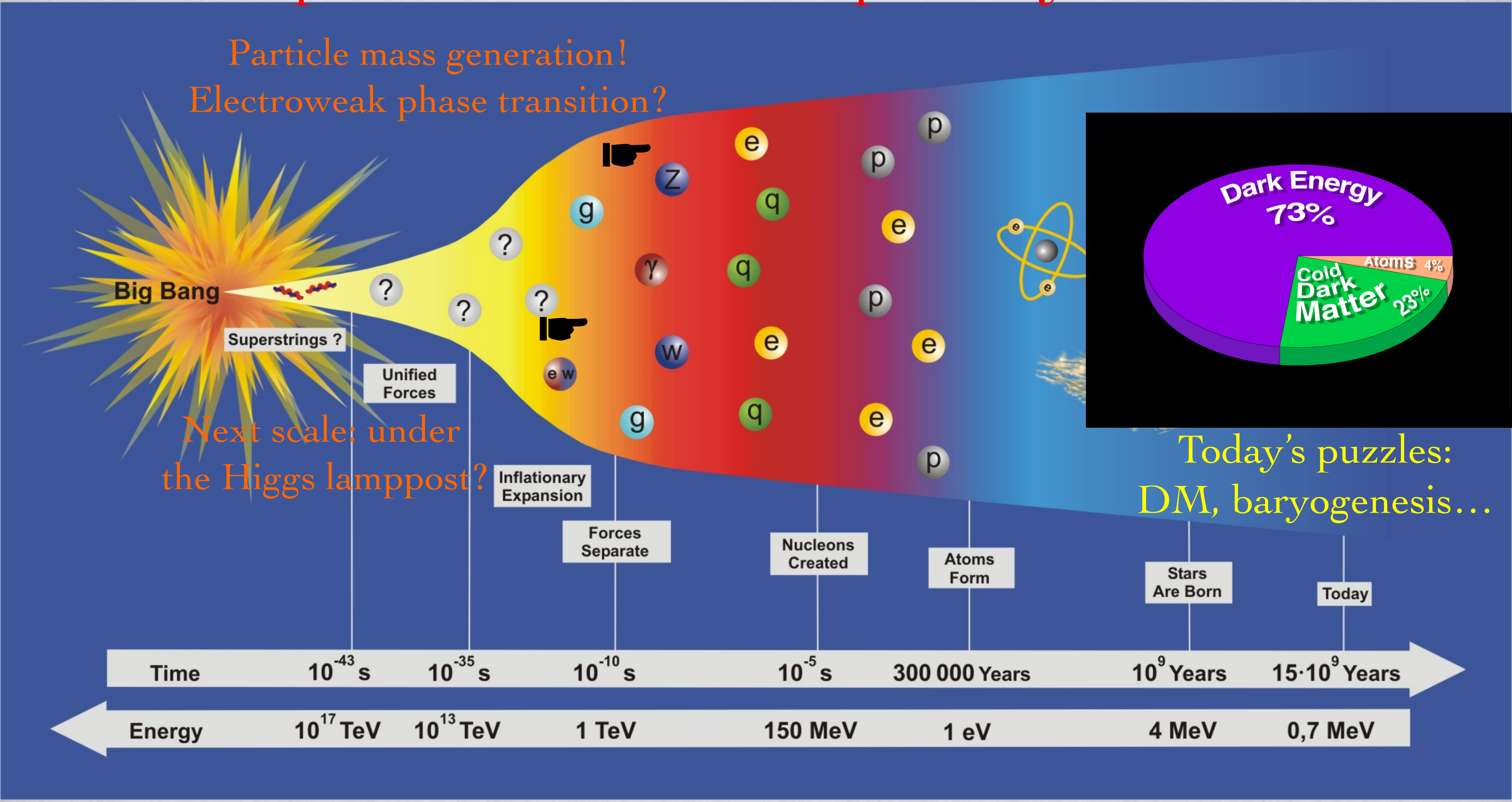
HEP & Society

- Workforce training → a PhD investment 10x in return.
- The CERN model → established after WWII for international collaboration: cultural, financial, scientific.

Fermilab's founding director, Robert Wilson, responded to the question of how the laboratory would help defend the United States:
"… It has nothing to do directly with defending our country except to make it worth defending."

Concluding Remarks

Uninterrupted discoveries in the past 50 years led us to …



Future of High Energy Physics Is Bright.
Future of Basic Science Is Bright.