Quest For Nature
Fifty Years of Discoveries in HEP

Tao Han
University of Pittsburgh / Tsinghua University

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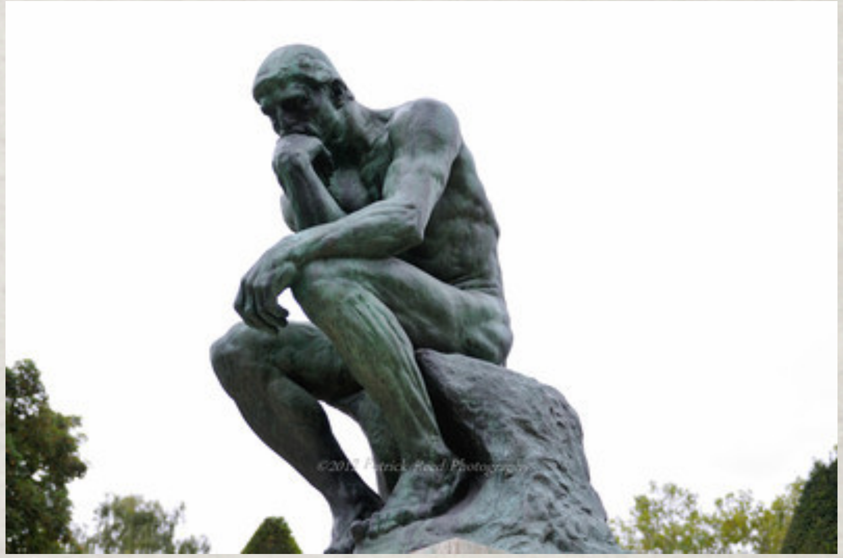
Quest for Nature ...

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

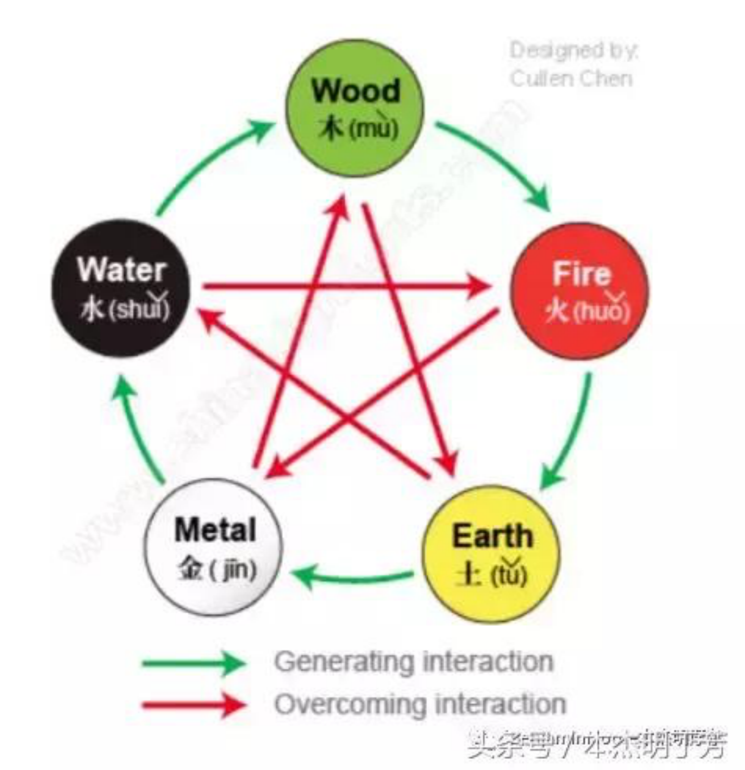
Doing science is to

- Ask fundamental questions
- Seek for answers
- Advance human knowledge



Antient Quest: What is the world made of?

Ancient Chinese philosophers: Five phases "metal, wood, water, fire, earth".

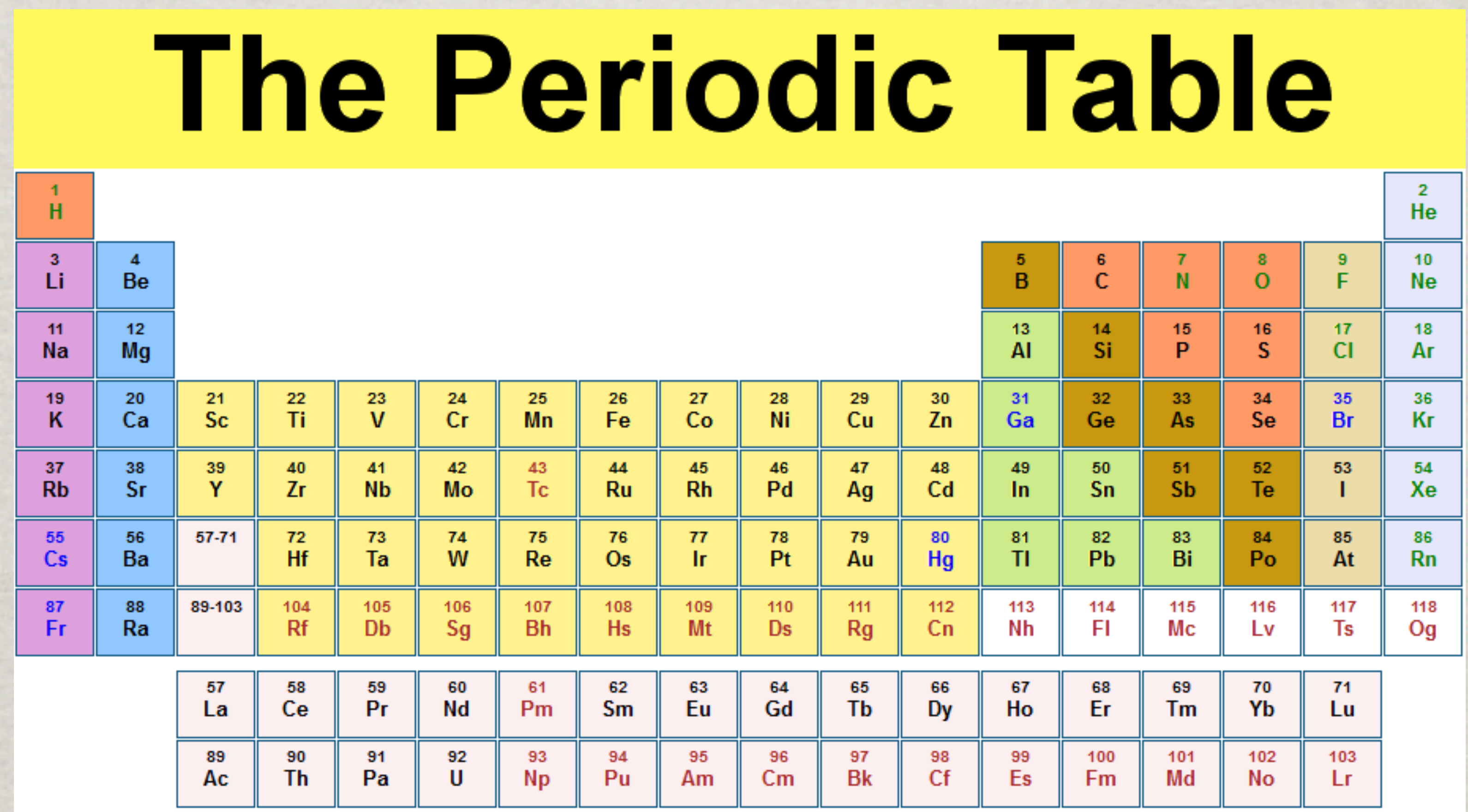


Ancient Greek philosophers: Four elements "earth, water, air, fire".

The concept of "atoms": indivisible.

What are the “Elements” ?

Lavoisier: chemical elements (1773,1789)
Lomonosov: chemical reaction (1774)
Dalton: Law of definite proportion (1808)
Avogadro’s law (1811)
Mendeleev’s periodic table (1869)

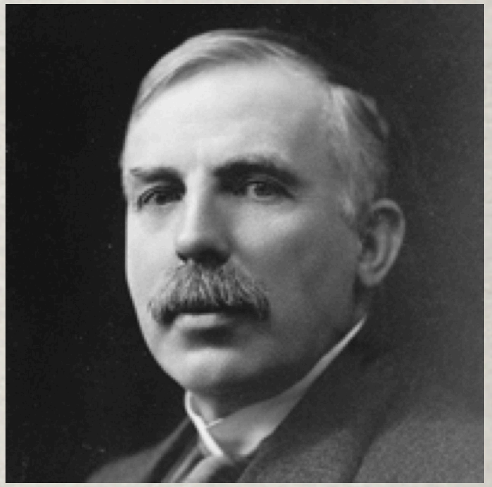


- Then, chemical elements/molecules: ~10^{-10} m (1860)
- Now, spin-½ electrons in Quantum mechanics/QFT

Particles & Nucleus

Rontgen's X-ray (1895)
Bequerel & Curie's radioactivity: α,β-particles
Thomson's cathode rays: the "electrons" (1897)

Rutherford's experiments (1991)



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

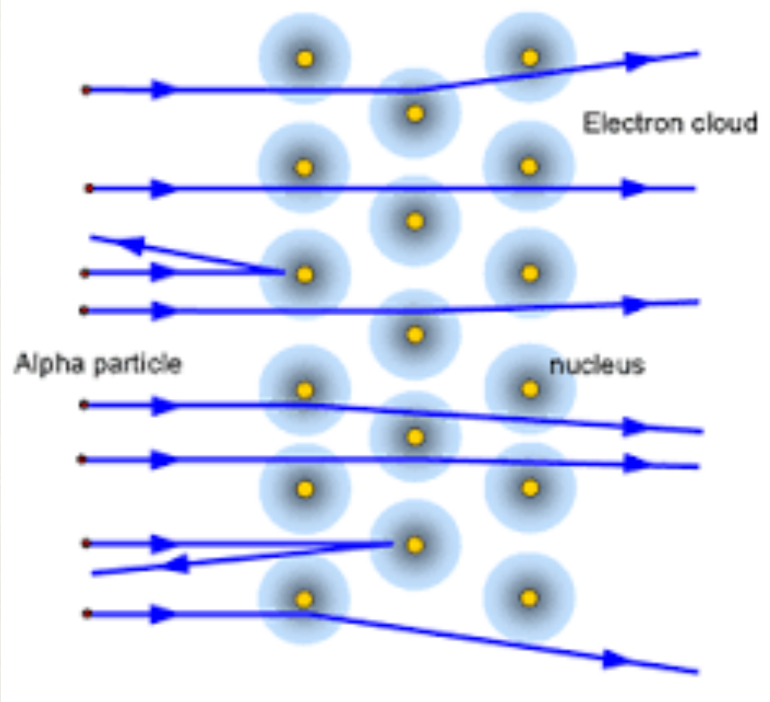
Coulomb scattering for two point-like charges:

$$V = -\alpha / r$$

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

$$\approx \quad \frac{(\alpha Z_1 Z_2)^2}{4E^2 \sin^4 \theta/2}$$

(q^2 the momentum-transfer)



Rutherford discovered the planetary atom, the nucleus $< 10^{-9}$ m

Rutherford's legendary experiment still leads the way for high energy physics

With a high energy/momentum probe p

→ Reach short distances: $\Delta l \sim \hbar / p$

→ Explore the laws of Nature at a deeper level

PARTICLE PHYSICS = HIGH ENERGY PHYSICS

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
- Hofstadter et al. (1953, SLAC): spatial distribution ~ 10^{-15} m

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

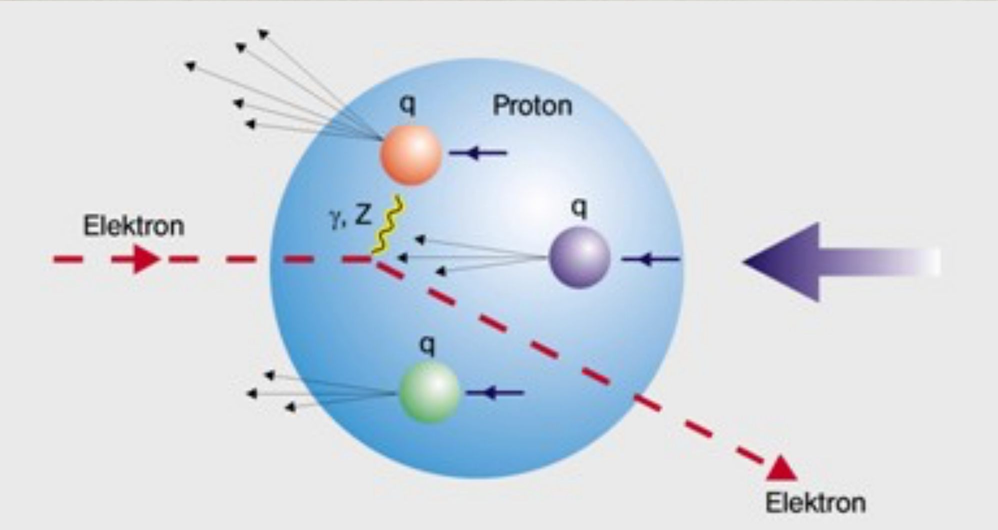
- Deeply In-elastic Scattering (1968-'70, SLAC): "scaling behavior" at higher energies

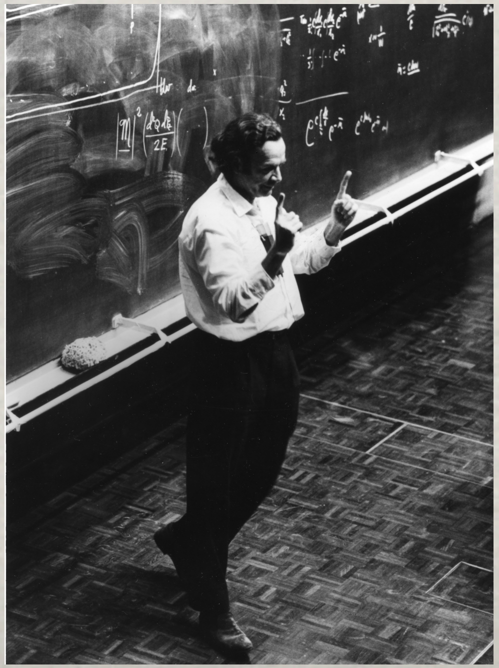
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \left(\frac{F_1(x, Q^2)}{m_p} \sin^2 \frac{\theta}{2} + \frac{F_2(x, Q^2)}{E - E'} \cos^2 \frac{\theta}{2} \right)$$

→ structureless / point-like constituents!

(1990)

Feynman's "partons"





“Quarks” as the constituents

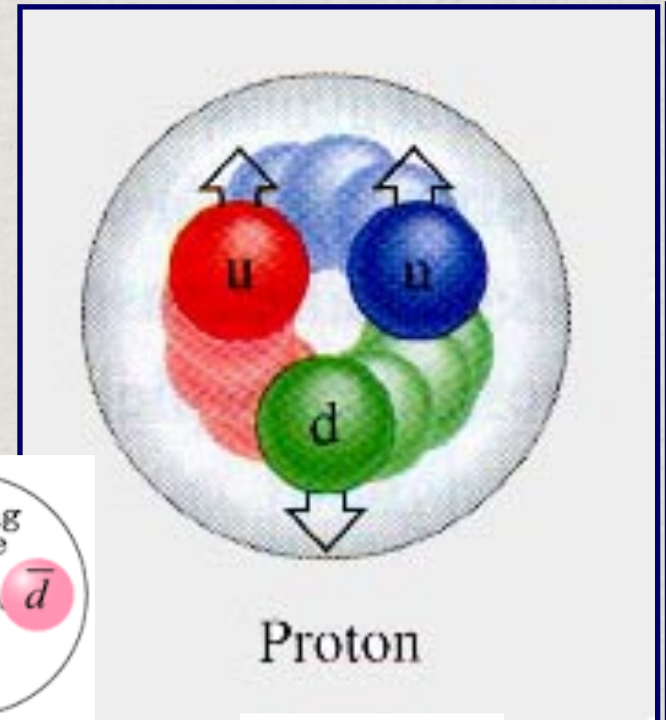
M. Gell-Mann et al (1963):

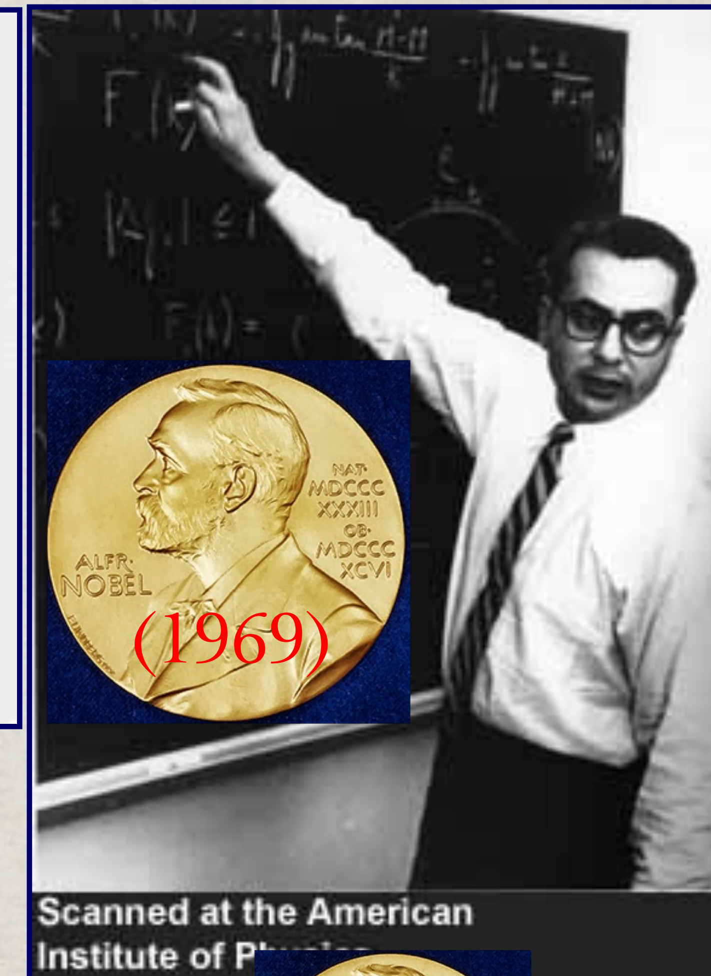
Nucleons (p, n) ≈ 3 quarks:

“up” quark (Q=+2/3),

“down” quark (-1/3)

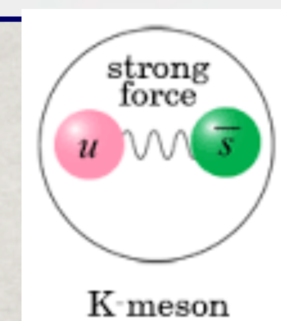
And many “hadrons”





Plus some new unstable mesons

→ there is the “strange quark”



Surprise! A heavy quark

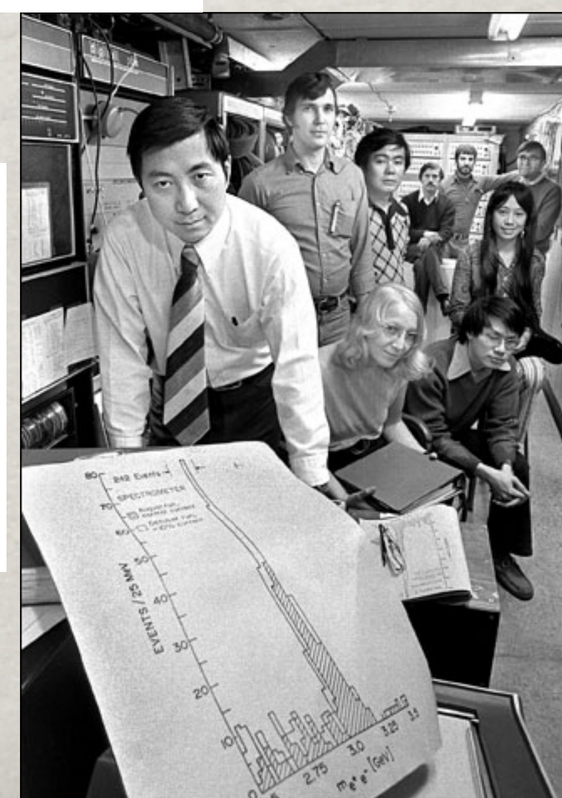
Heavy quark “charm”:

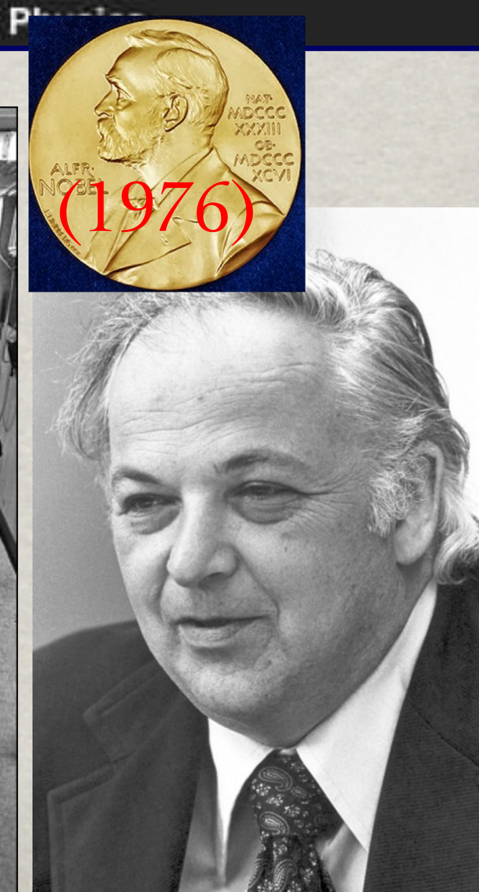
November revolution!

mass ~ 1.5 m_p

Opened up a new window

to study strong/weak forces.





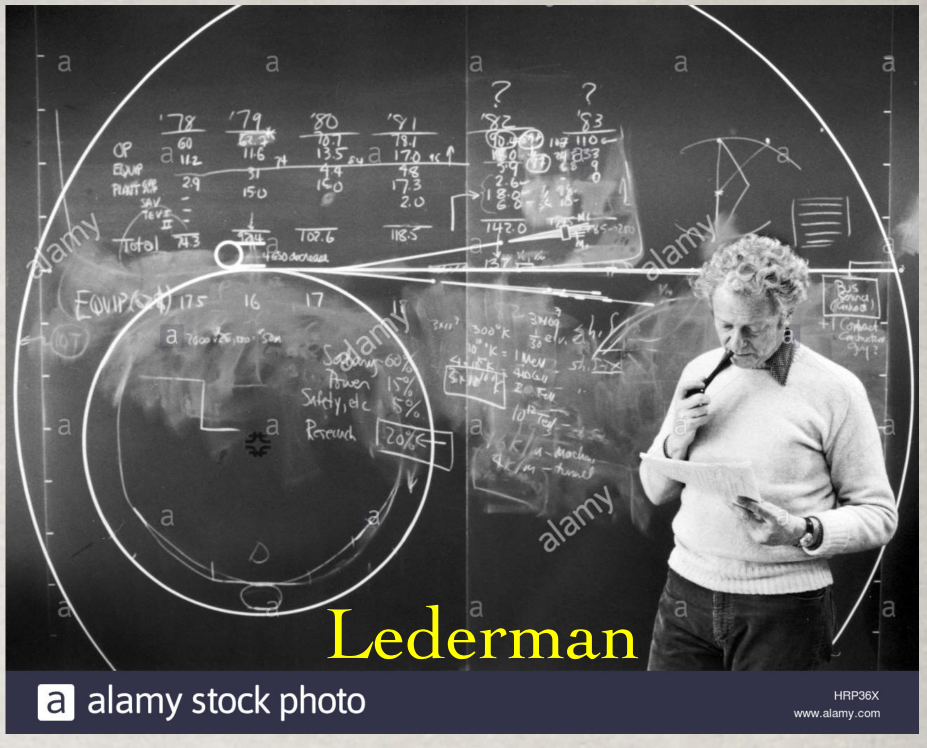
3^{rd} generation quarks

Heavy quark “bottom/beauty”

1977 @ FNAL

mass ~ 5 m_p

And last, 1995@FNAL



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!

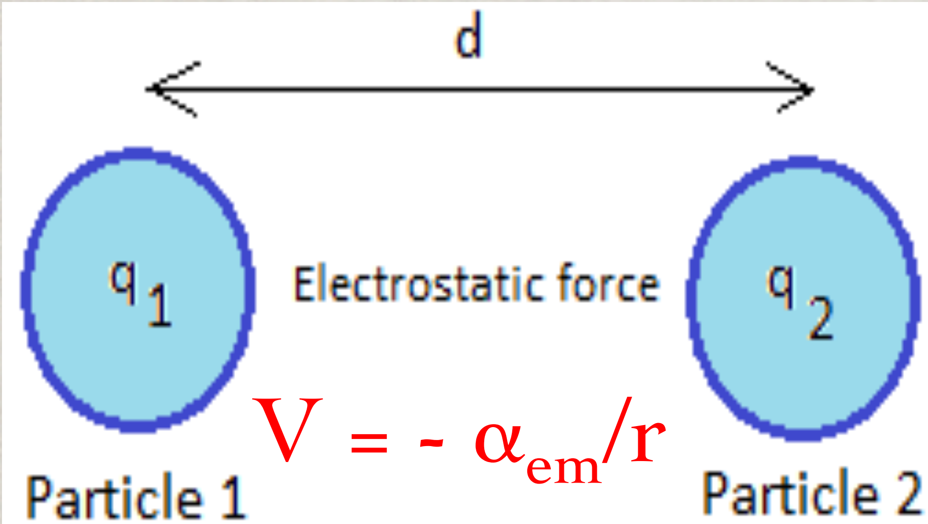
In this artist's representation of a particle collision, a proton and antiproton collide at nearly the speed of light.

Still a mystery: top quark mass ~ 175 m_p

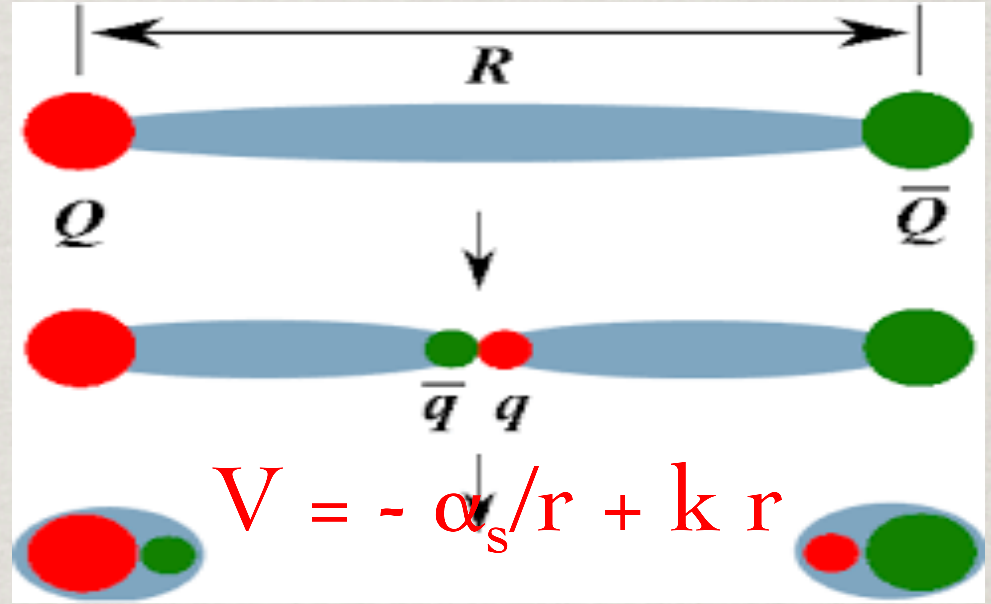
as heavy as a gold atom!

Why no free quarks seen?!

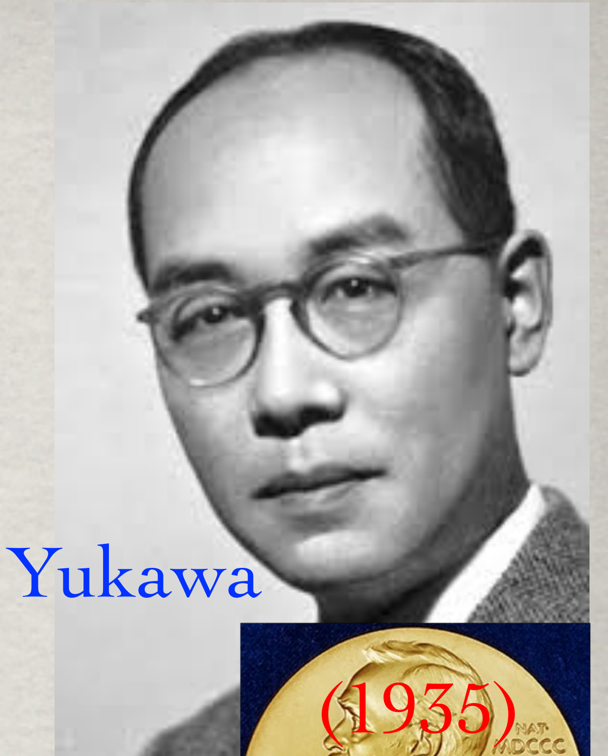
Electromagnetism vs. Strong force



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



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

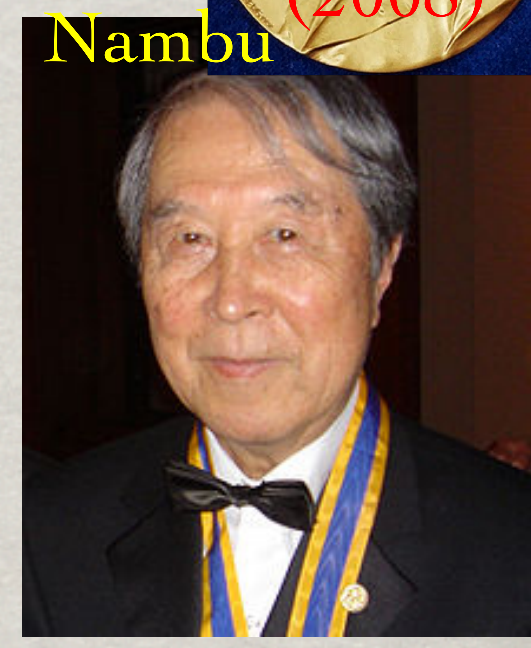


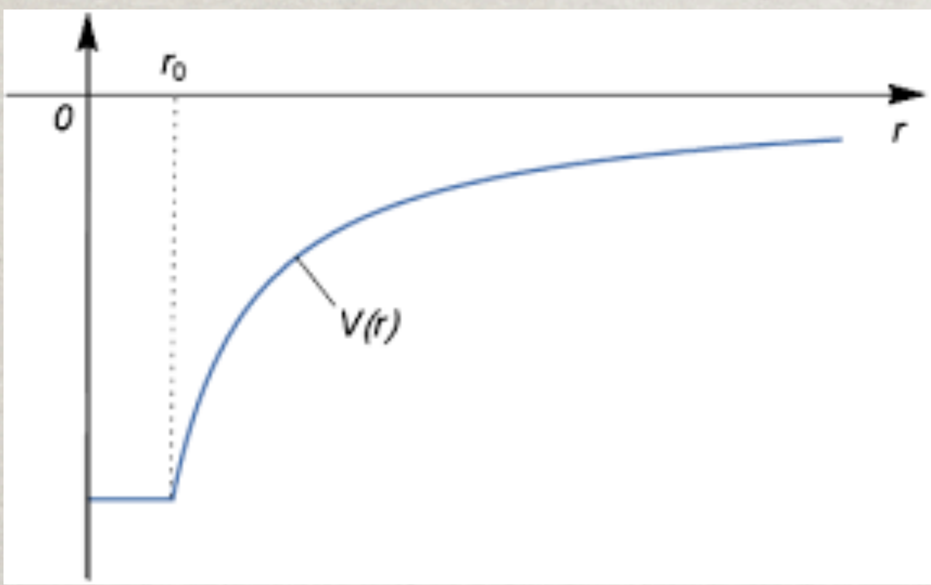
Yukawa

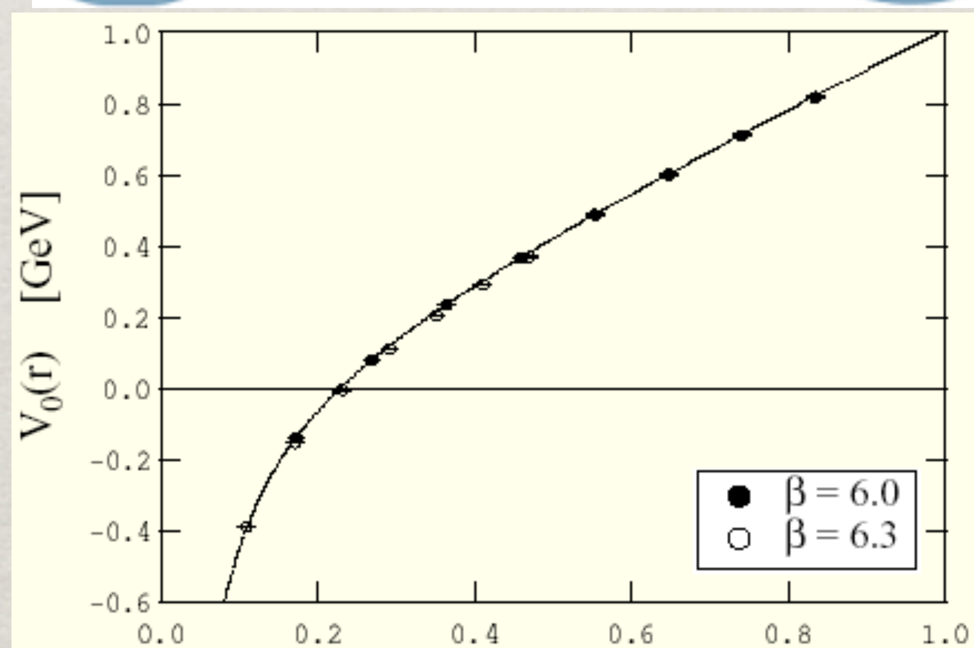
(1935)

(2008)

Nambu







At long distances > 10^{-15} m

- Strong force results in a confinement phase: $e^{-m_\pi r}/r^2$
- Quarks condensate (color-neutral): π^0, $\pi^\pm$…

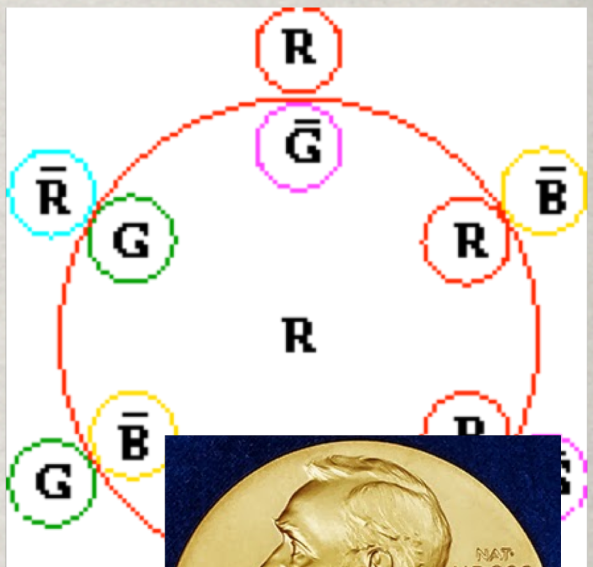
Hadrons p^+, n… formed: Most of the (luminous) mass!

The strong force: Quantum Chromo-Dynamics

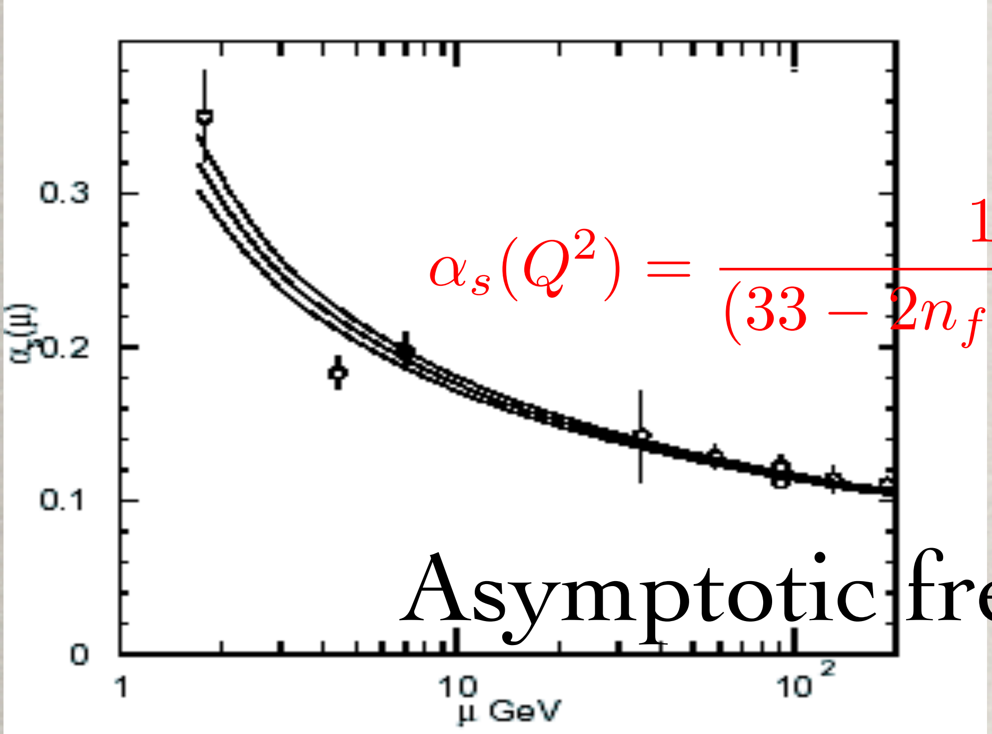
$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \sum_f^{n_f} \bar{q}_f (i\gamma^\mu \partial_\mu - g_s \gamma^\mu A_\mu - m_f) q_f$$

$$F_{\mu\nu} = \partial\mu A_\nu - \partial\mu A_\nu + i g_s [A_\mu, A_\nu]$$

$$A^\mu(x) = \sum_1^8 A(x)^\mu_a \, T^a, \qquad [T^a, T^b] = i f_{abc} T^c.$$

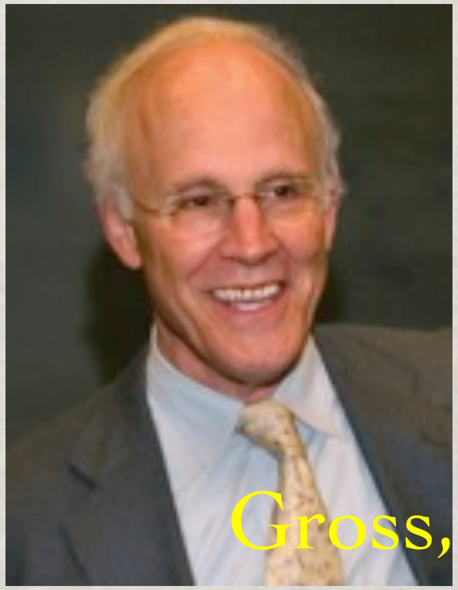
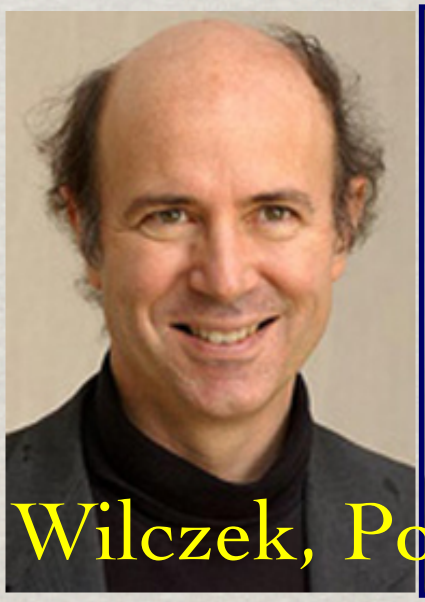


- At short distances/high energies asymptotically free (anti-screening effects)



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

Asymptotic freedom

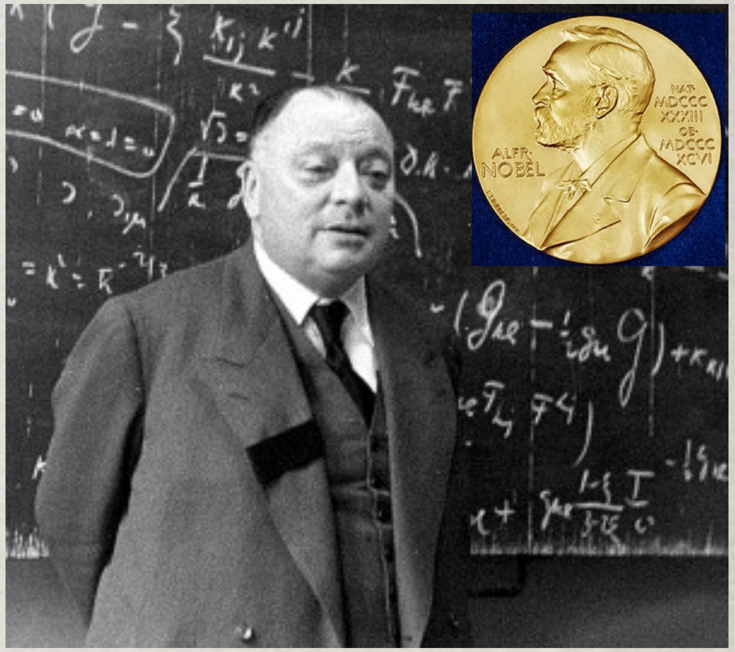




Gross, Wilczek, Politzer

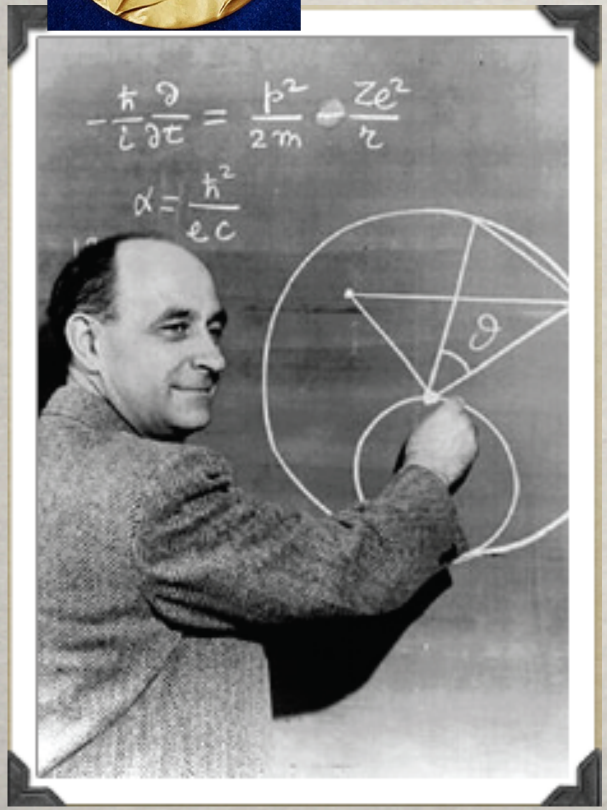
Perturbative, predictable at high energies: Crucial for HEP, early Universe cosmology …

What about the "weak force" ?

Beta decay n → $p^+ e^- \nu$

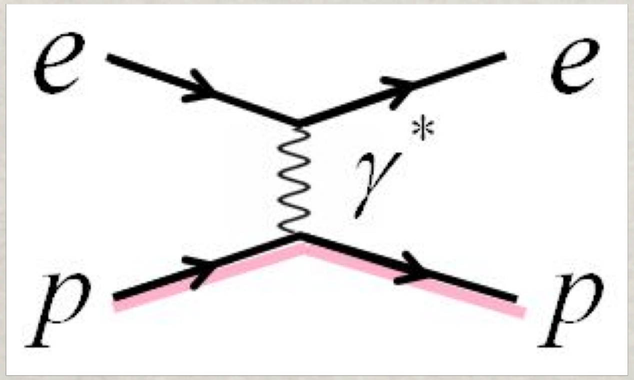


- Pauli's "neutron" (1930): a little neutral particle escaping from detection.
- Chadwick discovered the neutron (1932)



- Fermi's "neutrino" (1934):

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



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

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

Remains to be a good description.

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

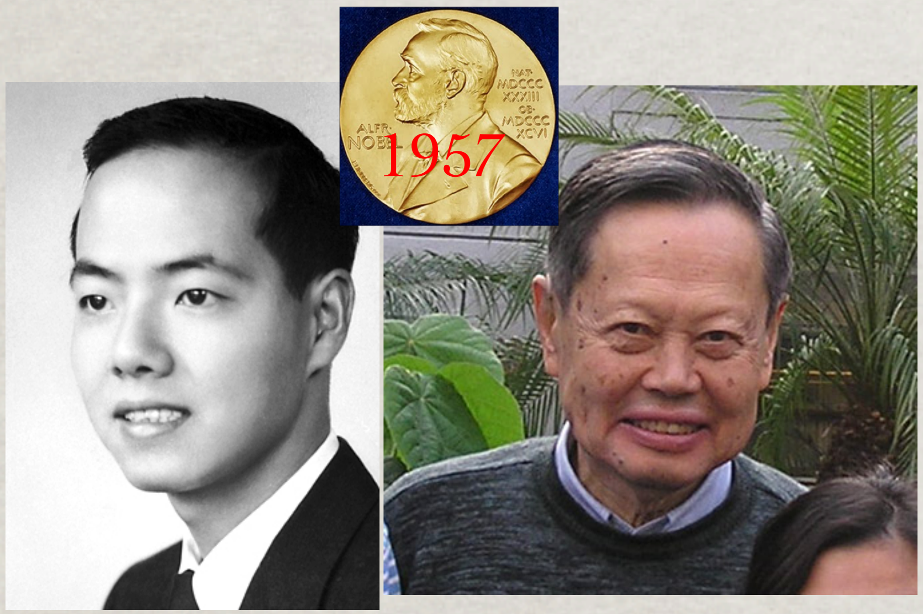
- From the sun
- From the atmosphere
- From reactors
- From accelerators

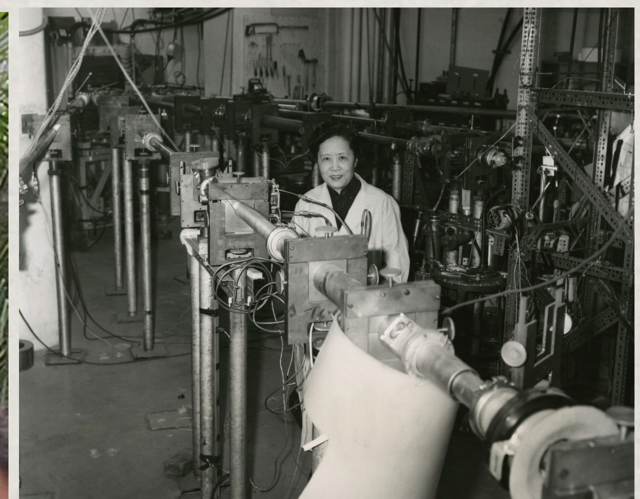
Three discrete transformations:

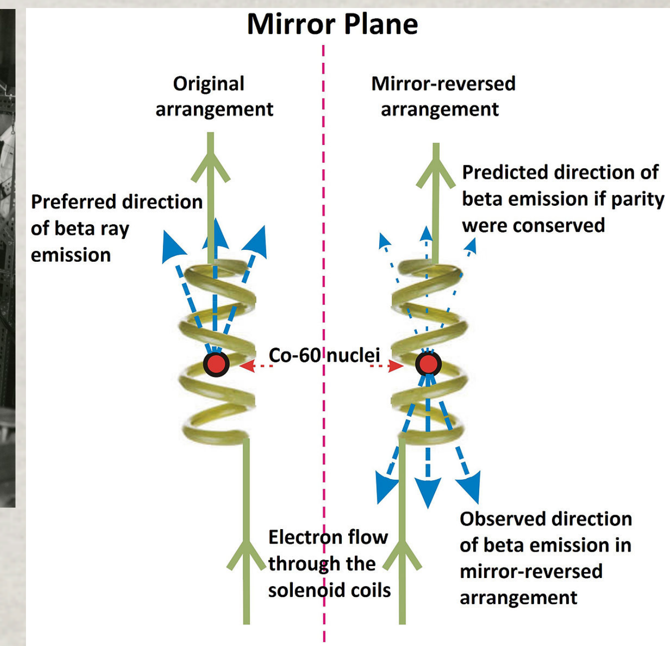
Space reflection (P); particle→anti-particle (C); Time reversal (T)

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

The Wu expt. (1956)

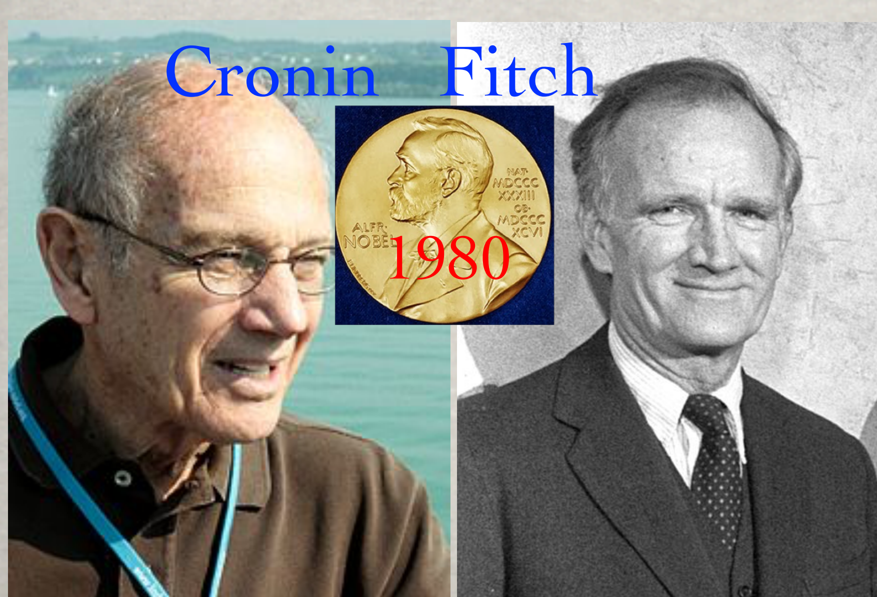






More surprise! CP Violation

Charge-Parity symmetry violation was discovered



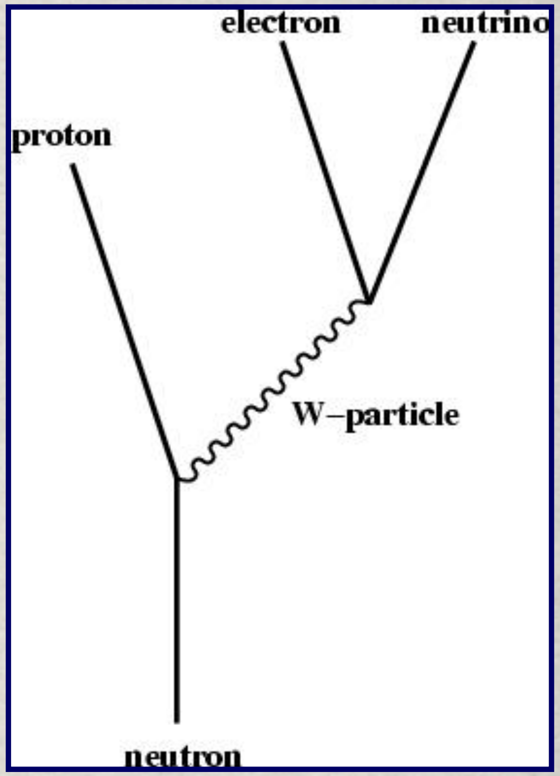
- In K^0 system
- B-Factories @ SLAC/KEK;
- LHCb
- Flavor mixing established: Cabibbo-Kobayashi-Maskawa
- Matter-antimatter asymm.

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

LETTERS 20 November 1967

slightly larger than that (0.23%) obtained from
dominance model of Ref. 2. This seems to be
ther case of the ratio $\Gamma(\eta \to \pi^{+}\pi^{-}\gamma)/$
in Refs. 12 and 14.
nd P. Singer, Phys. Rev. Letters 8,

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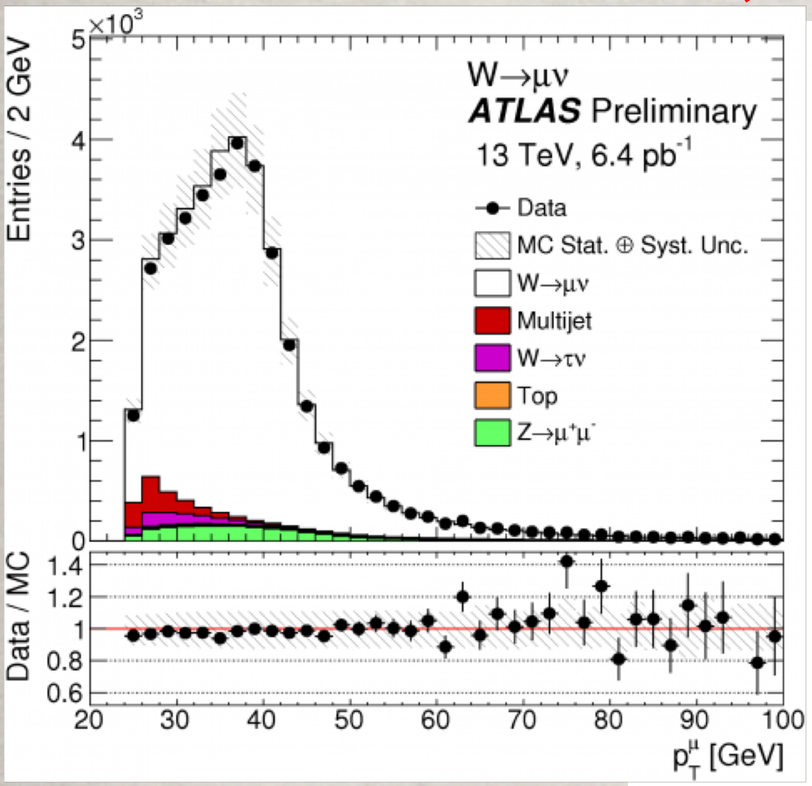
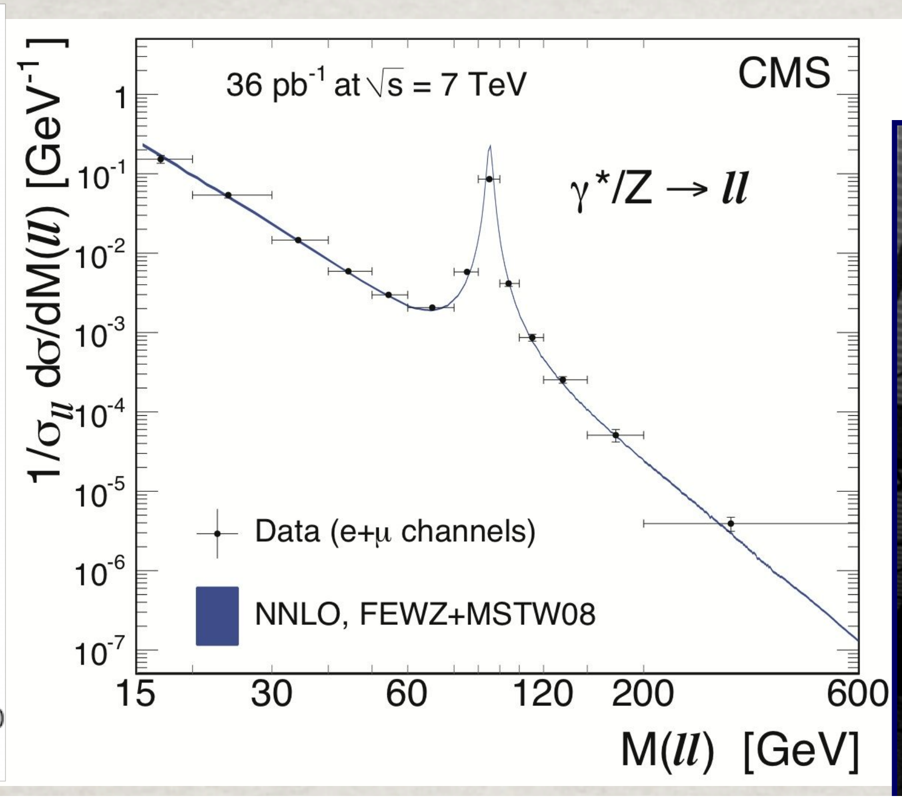
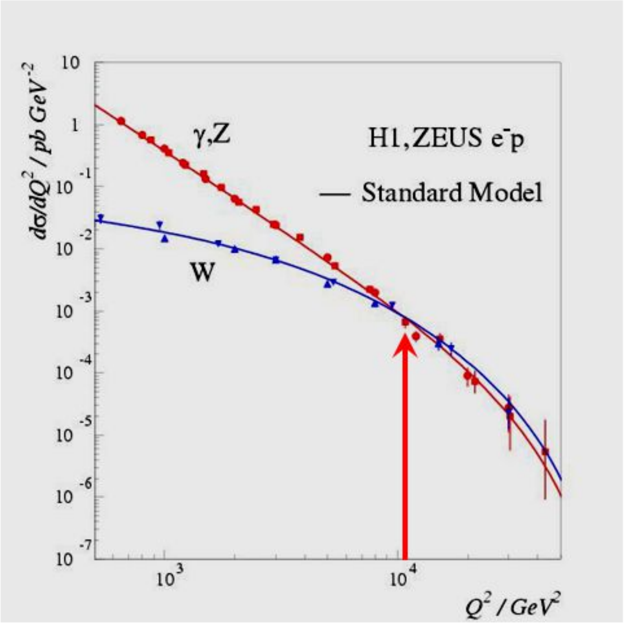
$R = [\frac{1}{2}(1-\gamma_5)]e.$

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





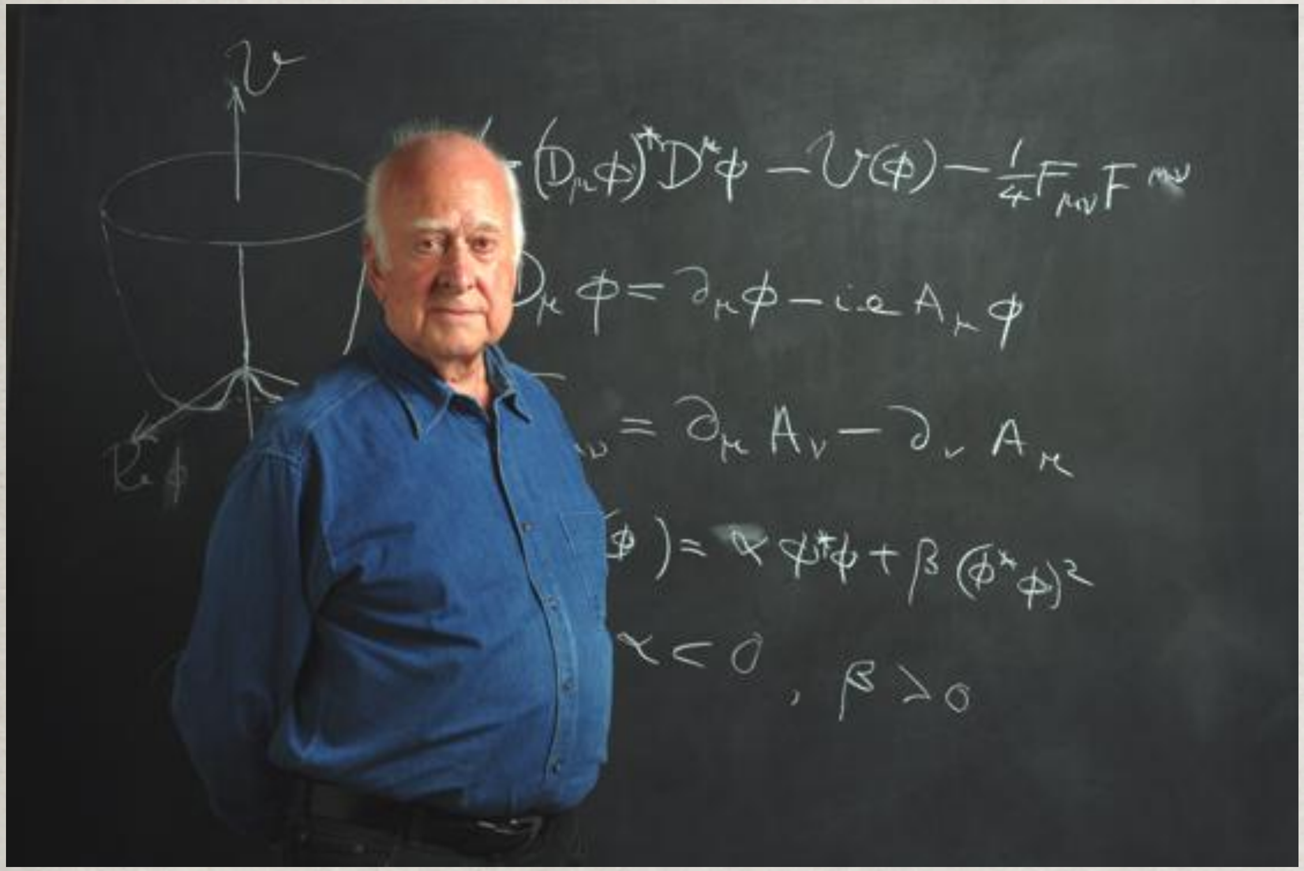
Electroweak unification shows up very nicely in experimental results



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

Gauge symmetries prevent the mass terms?

The Higgs mechanism (1964)



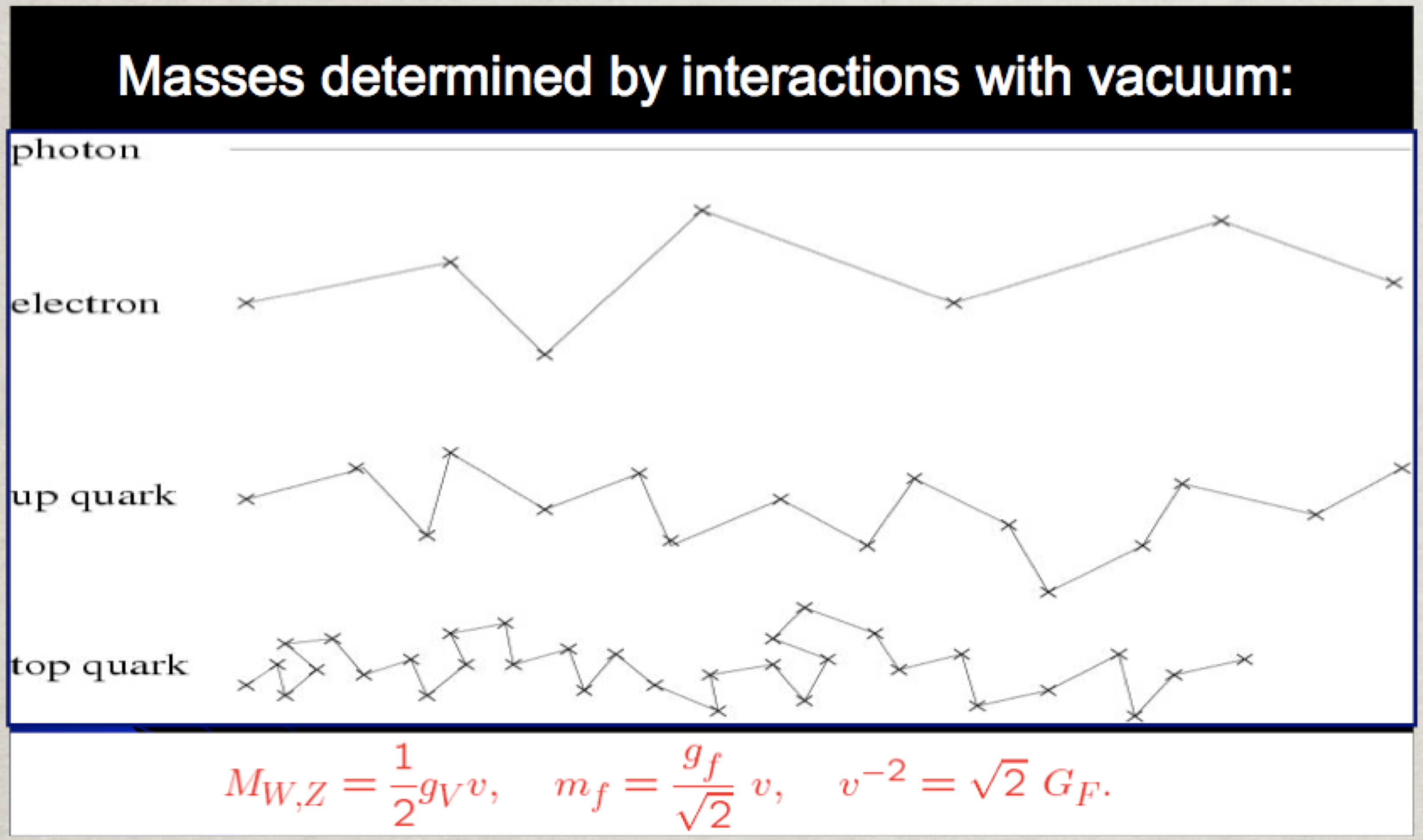
"If a LOCAL gauge symmetry is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode."

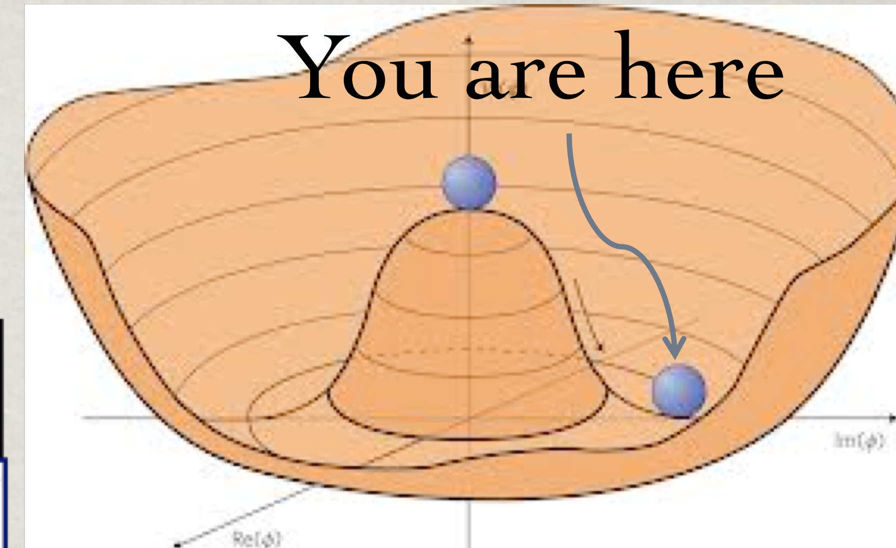
The Higgs Magic!

The vacuum we live

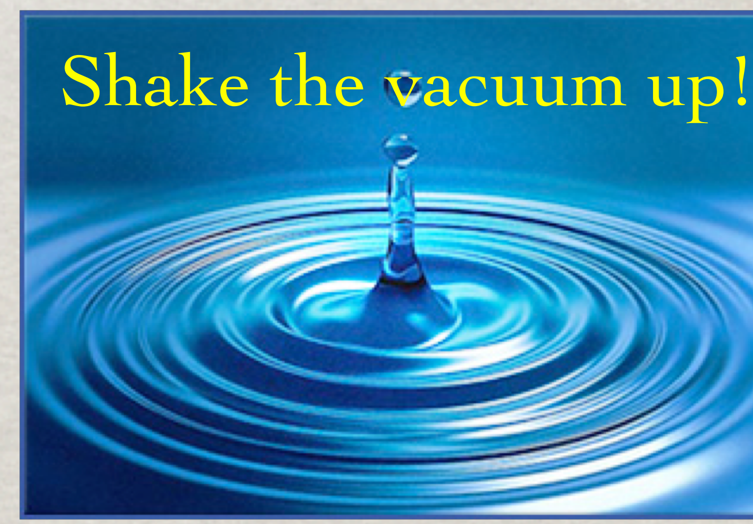
$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

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





A new vacuum state,
with H as the excitation.



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

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

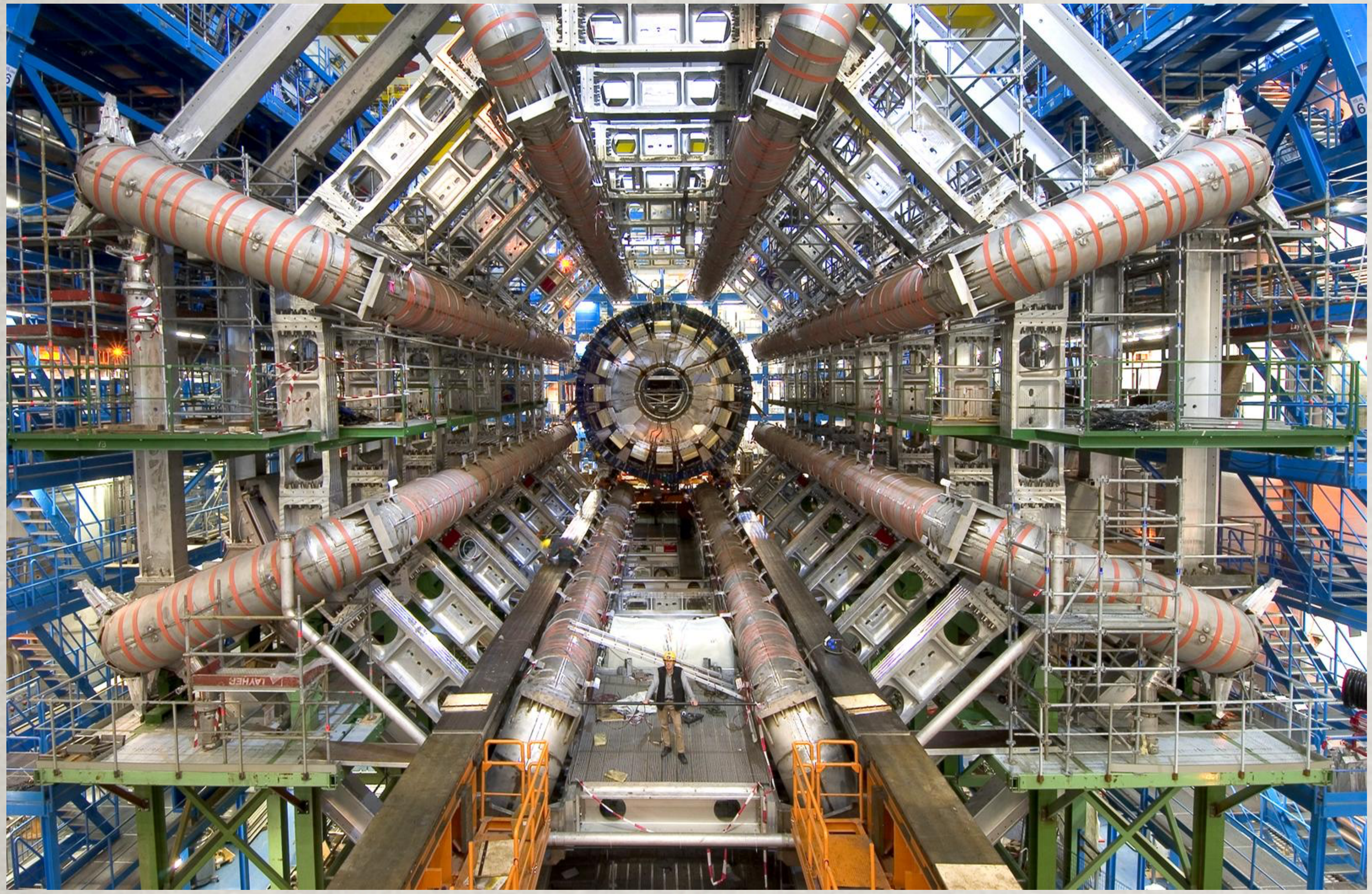
And its own mass and self-couplings:

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

Large Hadron Collider (LHC)

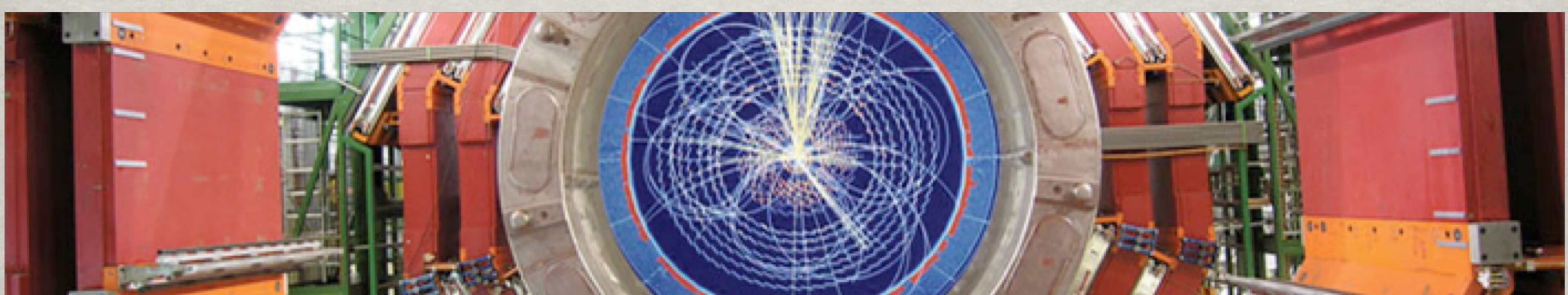
- proton-proton collider at CERN, Geneva
- 14 TeV energy by design
- Protons move 7 mph slower than the speed of light
- Beam kinetic energy: aircraft carrier at 15 knot = 30 km/h!

Requires detectors of unprecedented scales



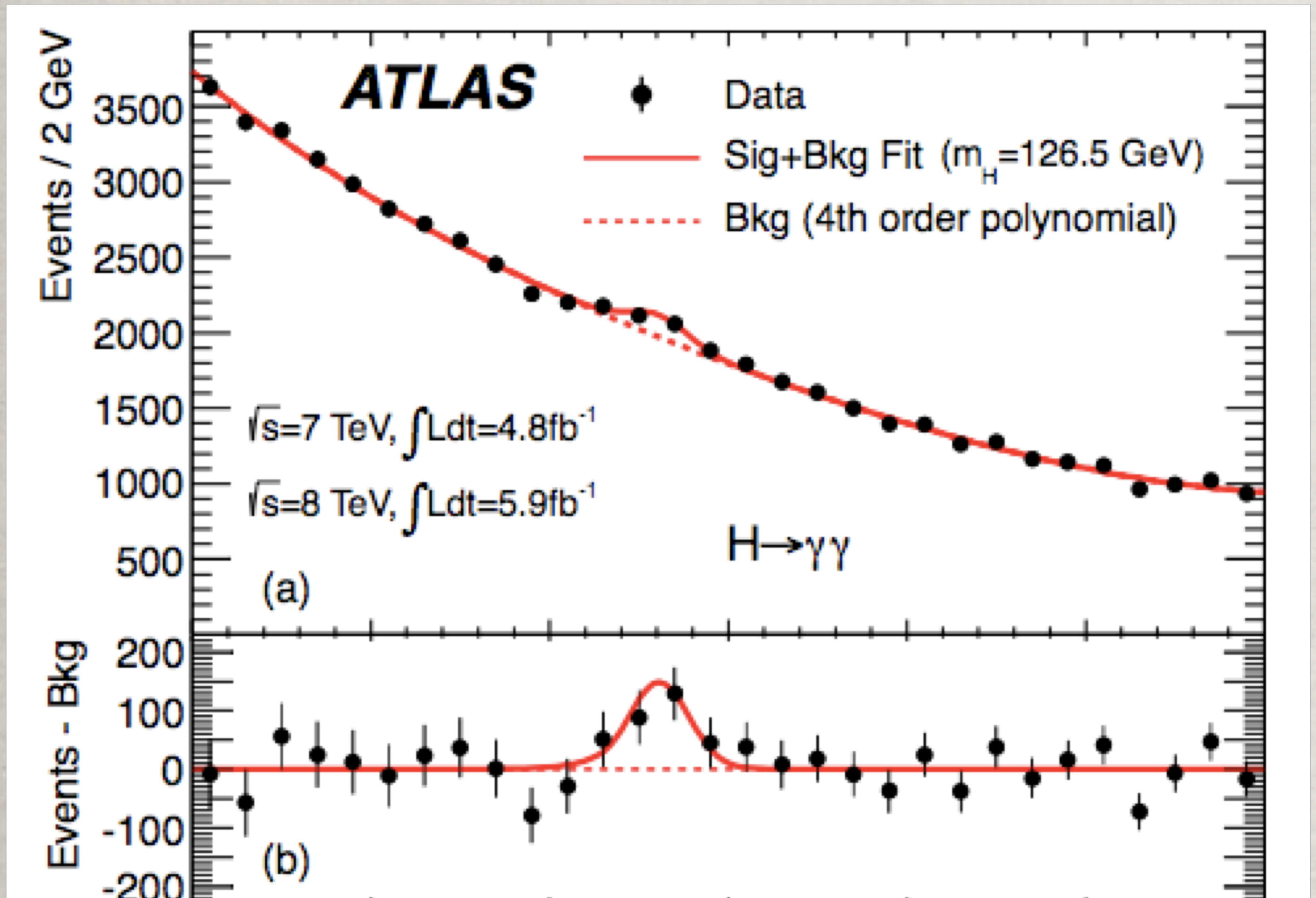
- Two large multi-purpose detectors
- ATLAS has 8 times the volume of CMS

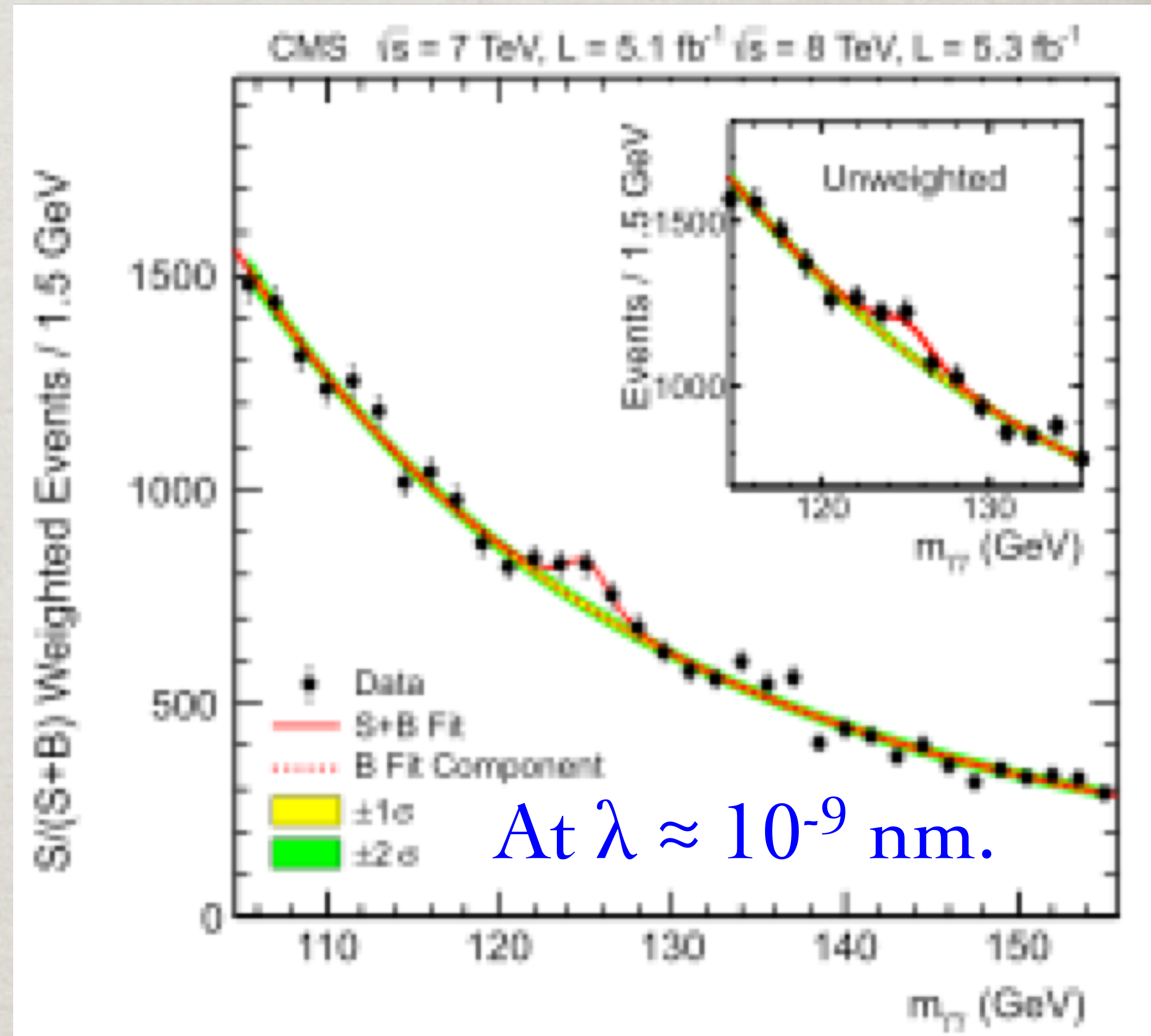
  (HK involvement)
- CMS is 12,000 tons (2 x's ATLAS)



The discovery: July 4th, 2012

A neutral boson decay to two photons





The combined signal significance:

ATLAS: 5.9σ

CMS: 5.0σ

Phys. Lett. B716, 1 (2012)

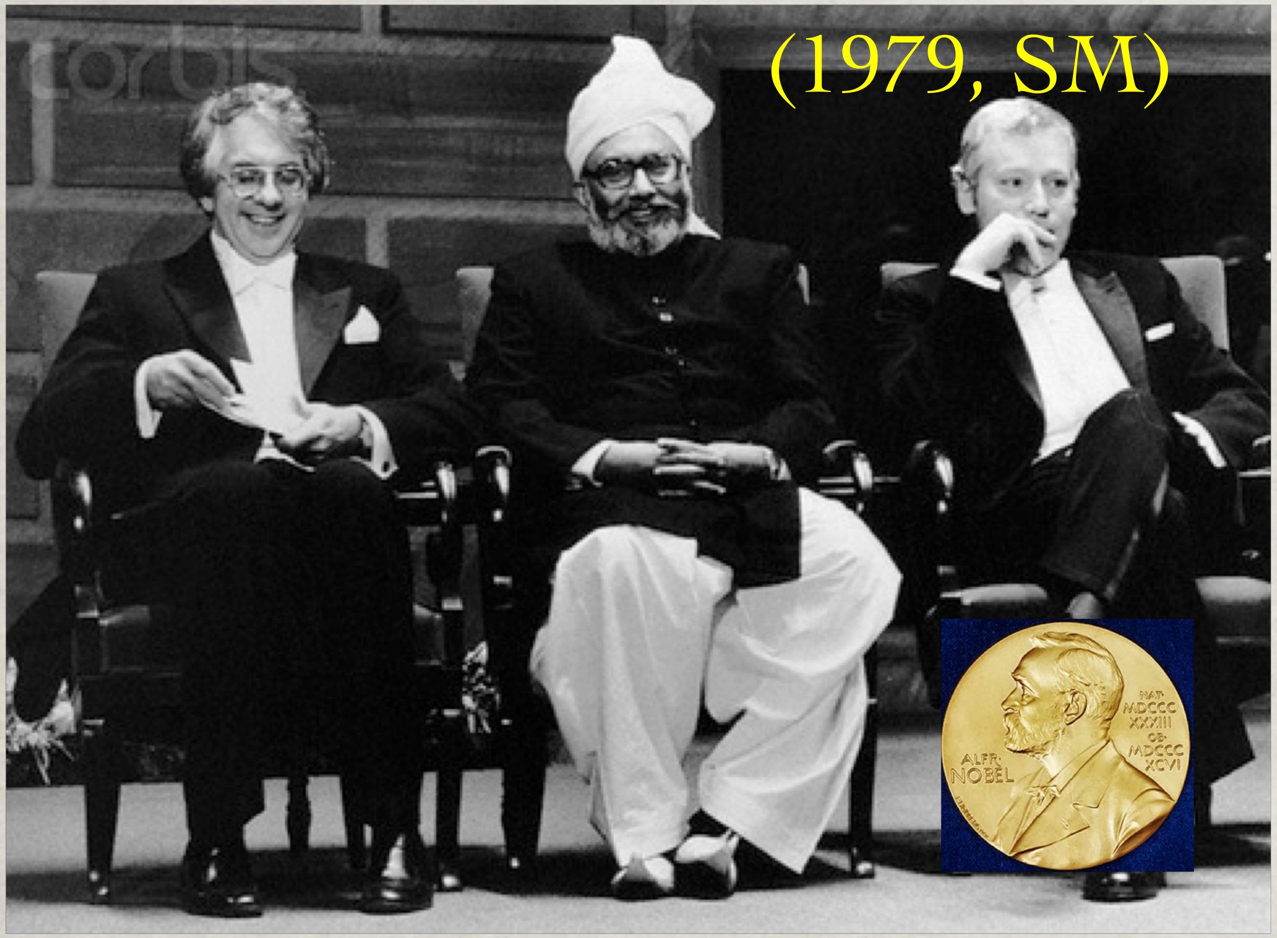
Phys. Lett. B716, 30 (2012)

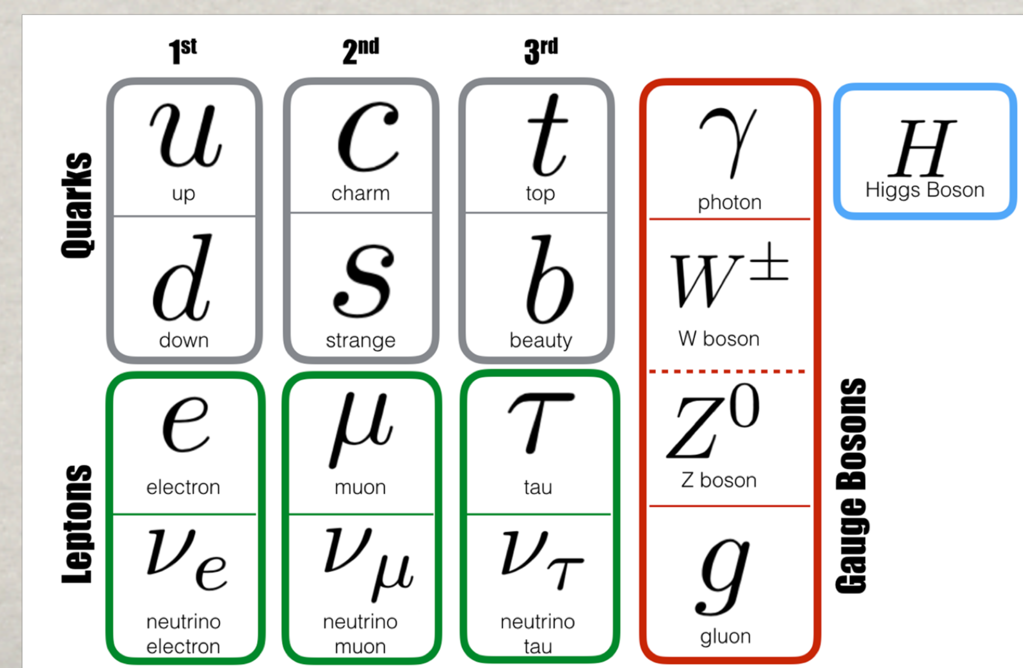
François Englert and Peter W. Higgs (2013)

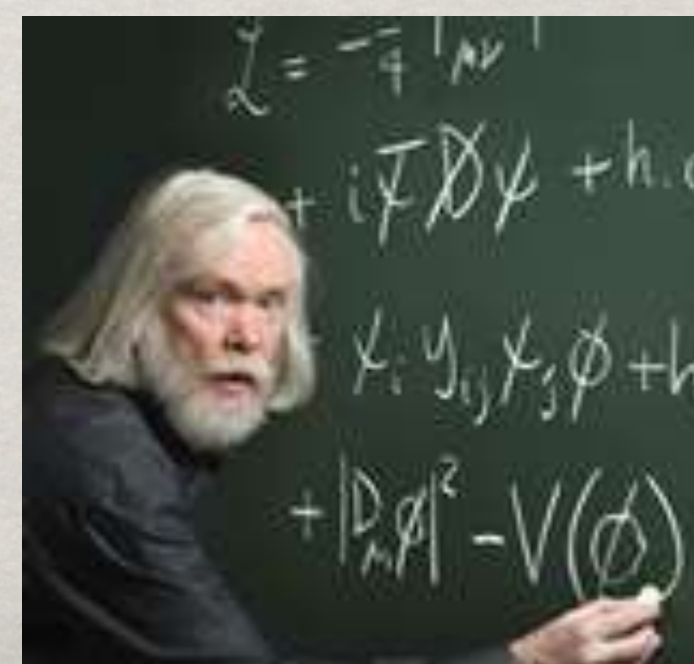
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

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. (An eminent physicist remarked that) 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)?

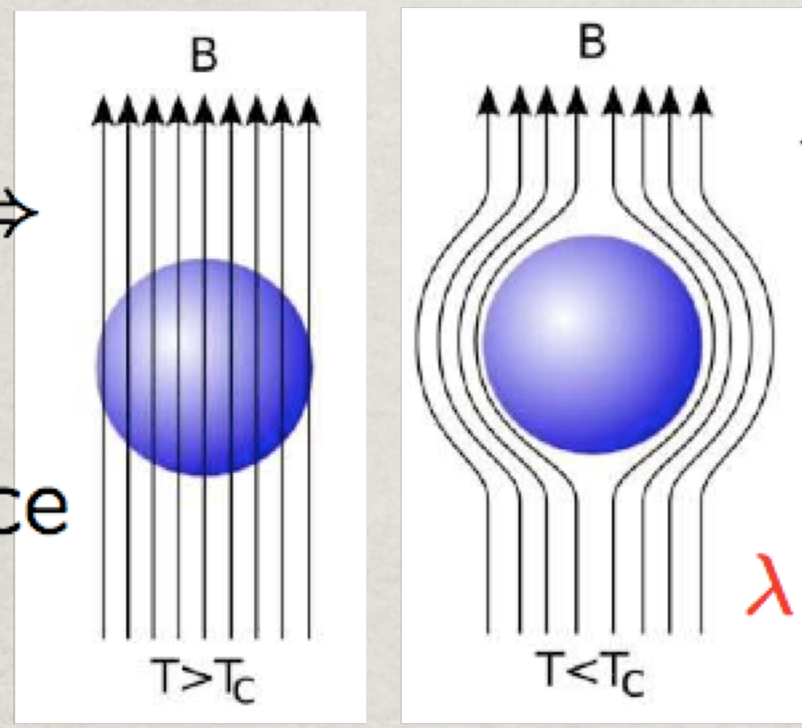
More puzzles ...

1. Electroweak Super-Conductivity

Normal phase$\Rightarrow$

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

Long-range force



$\Leftarrow$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, $T_c^w \sim 10^{15} K!$

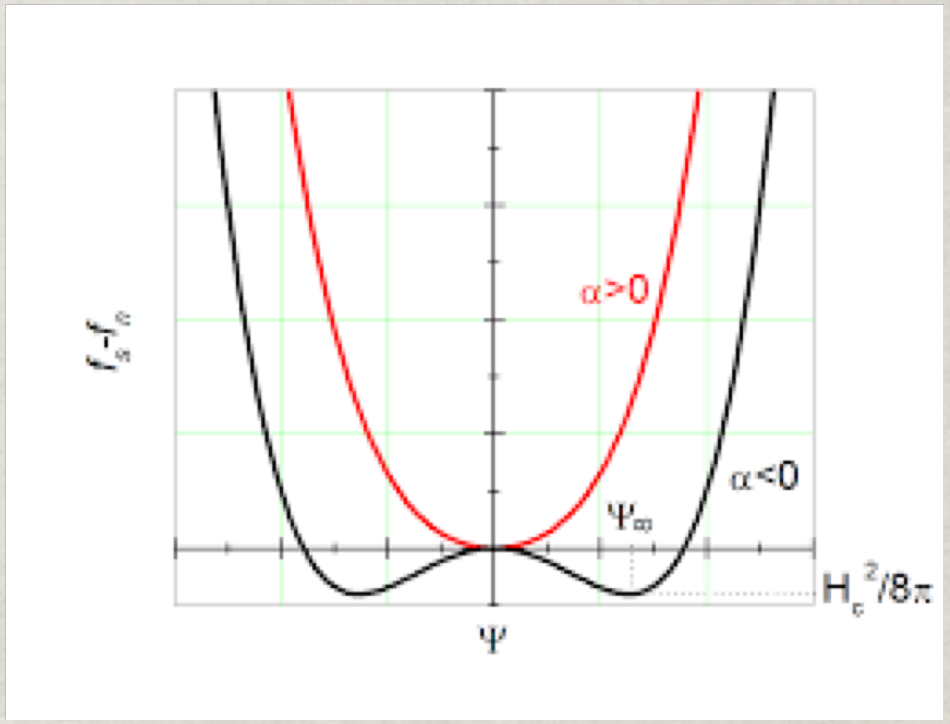
We are living in an EW superconducting phase!

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"

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

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



BCS as the underlying theory to understand the dynamical mechanisms, Cooper pairs, and Bose-Einstein condensation.

In a 2014 report, a "Higgs mode" of Tera Hertz (10^{12} Hz, 10^{-3} eV) vibration observed!

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REPORT

Light-induced collective pseudospin precession resonating with Higgs mode in a superconductor

Ryusuke Matsunaga[1,*], Naoto Tsuji[1], Hiroyuki Fujita[1], Arata Sugioka[1], Kazumasa Makise[2], Yoshinori Uzawa[3,†], Hirotaka Terai[2], Zhen Wang[2,‡], Hideo Aoki[1,4], Ryo Shimano[1,5,*]

+ Author Affiliations

↵*Corresponding author. E-mail: matsunaga@thz.phys.s.u-tokyo.ac.jp (R.M.); shimano@phys.s.u-tokyo.ac.jp (R.S.)

↵† Present address: Terahertz Technology Research Center, National Institute of Information and Communications Technology, Tokyo 184-8795, Japan.

↵‡ Present address: Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China.

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It's NOT Landau-Ginzburg Theory

In the SM, with a scalar field,

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

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

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

The Universe underwent a second order phase transition;

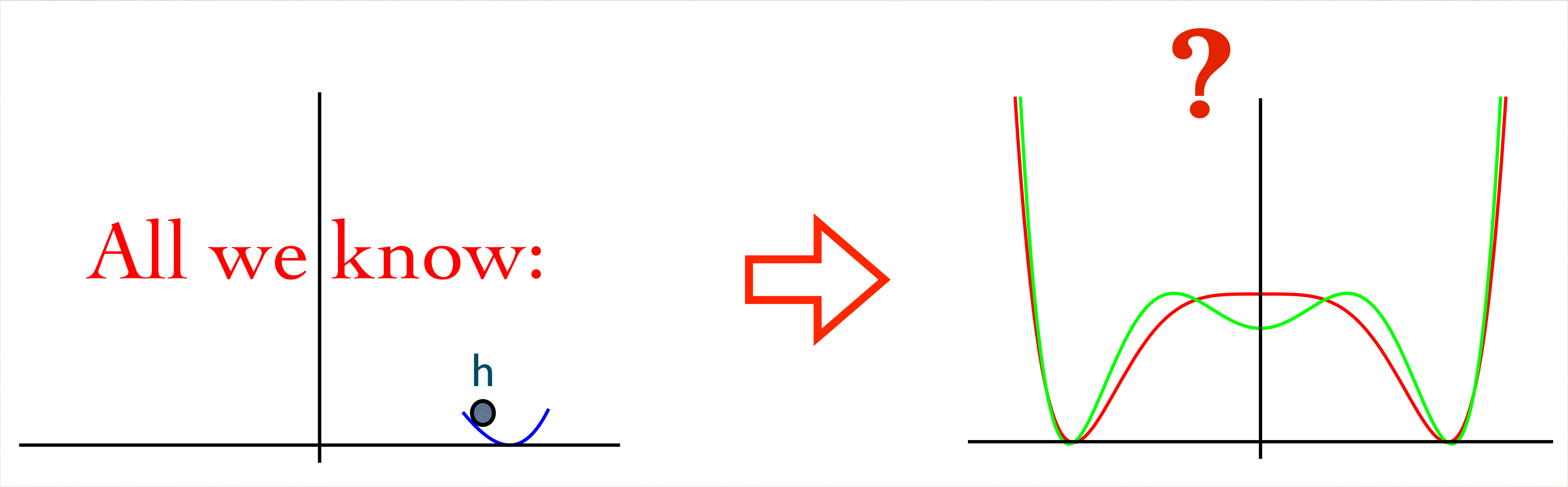
The vacuum is a Type II EW superconductor.

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

- BCS dynamical theory: Higgs composite at M?
- Elementary particle protected by symmetry: SUSY?

→ We need an answer !

2. Nature of the EW Phase Transition



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

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

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

→ 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 !

3. 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:** $\lambda = (g_L^2 + g_Y^2)/8 \approx 0.3/4$ **← a bit too small**

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

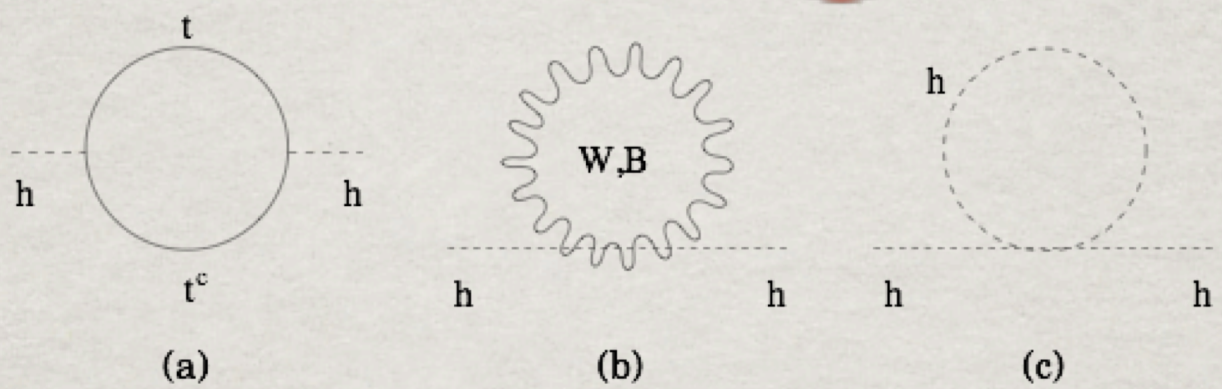
Measured m_H already put constraints on theory:

too light to be heavy (SUSY);

too heavy to be light (new dynamics)

4. μ^2: Higgs Mass Puzzle:

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



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

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

Natural: O(1 TeV) new physics, associated with ttH.
Unknown: Deep UV-IR correlations: gravity at UV?
Agnostic: Multiverse/anthropic?

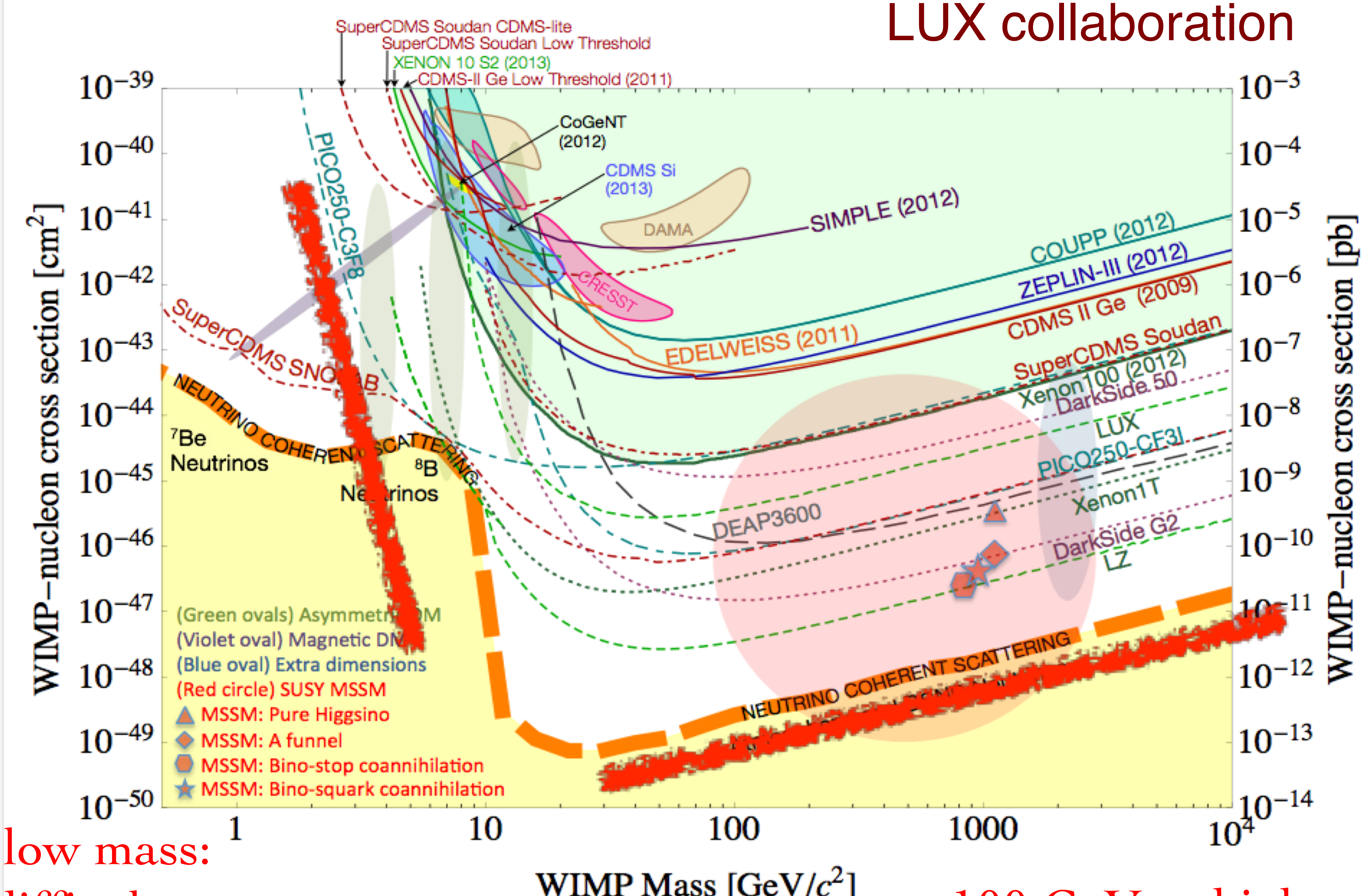
→ **We need an answer !**

5. The Dark Sector

The un-protected operator may reveal secret

Higgs portal: $k_s H^\dagger H\ S^* S, \quad \frac{k_\chi}{\Lambda} H^\dagger H\ \bar{\chi}\chi.$

LUX collaboration



GeV low mass:
DD difficult;
Collider complementary

100 GeV or higher mass:
DD + ID + HE Collider

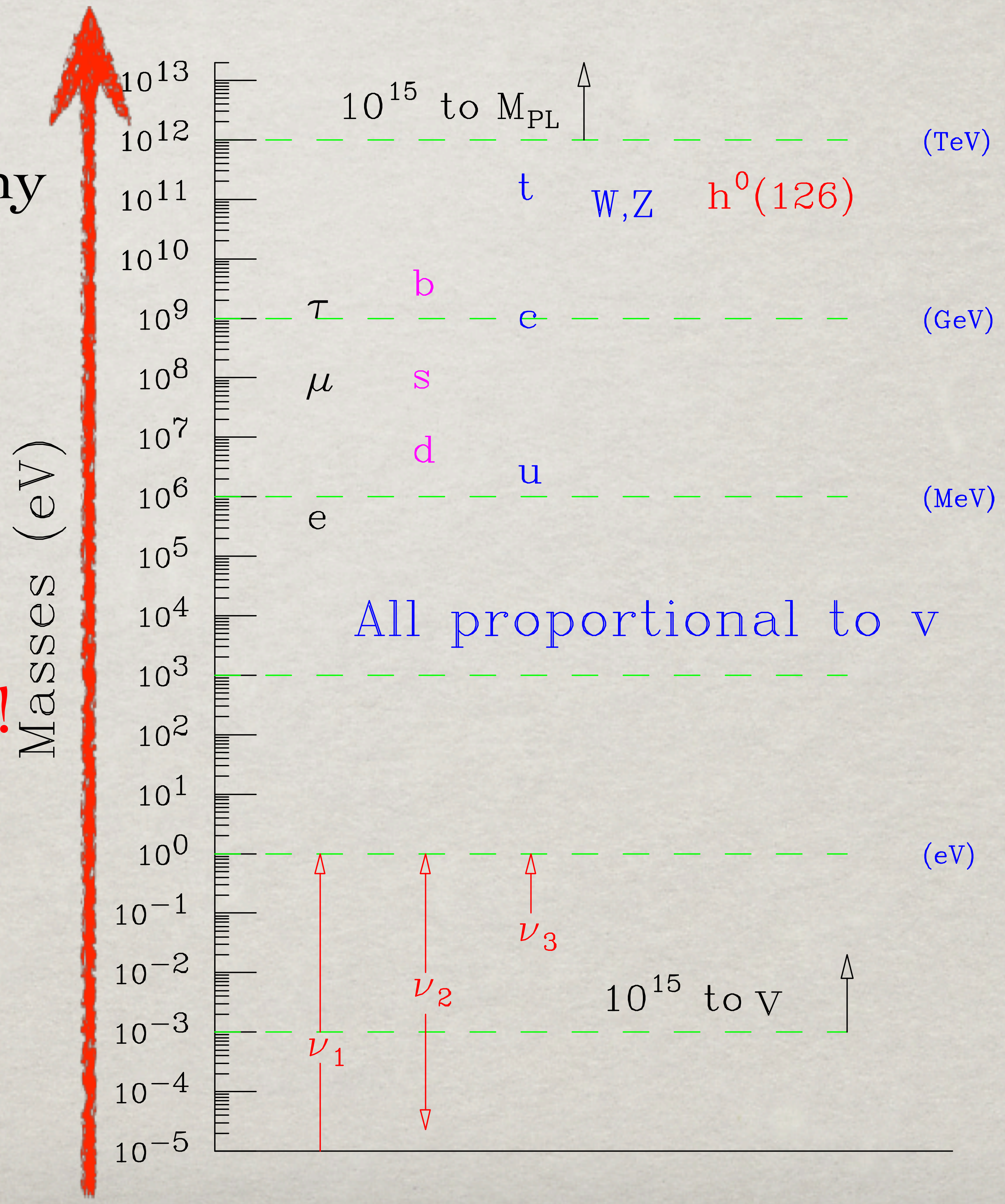
6. The "Flavor Puzzle"

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- New CP-violation sources?

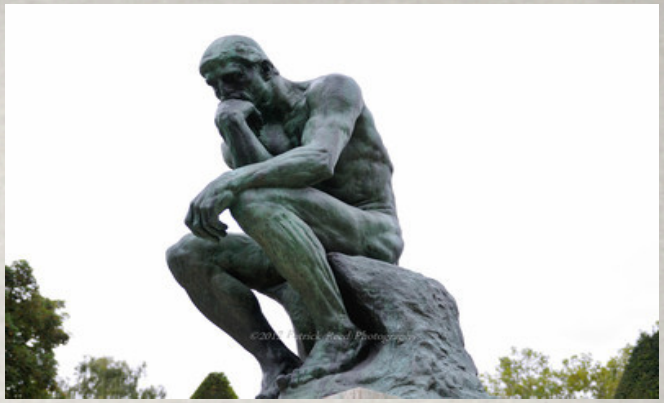
Higgs Yukawa couplings as the pivot!

The "seesaw" mechanism:

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



The list of puzzles continues …



7. Matter–Antimatter asymmetry

We hold these truths to be self-evident, that **all matter & antimatter were created equal.** Then where is the anti-matter?

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

Grand Unification? proton instability?

9. Larger space-time symmetry?

Super-symmetry at EW scale?

10. Cosmology: inflation, dark energy …

Does the Higgs play a role?

11. Quantum gravity?

… … We need answers !

Particle Physics Project Prioritization Panel (P5, 2014)

Five intertwined scientific Drivers

- Use the Higgs boson as a new tool for discovery
- 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.

Vibrant program for the next two decades!

- Large projects, in time order, include the Muon g-2 and Muon-to-electron Conversion (Mu2e) experiments at Fermilab, strong collaboration in the high-luminosity upgrades to the Large Hadron Collider (HL-LHC), and a U.S.-hosted Long Baseline Neutrino Facility (LBNF) that receives the world's highest intensity neutrino beam from an improved accelerator complex (PIP-II) at Fermilab.
- U.S. involvement in a Japanese-hosted International Linear Collider (ILC), should it proceed, with stronger participation in more favorable budget scenarios.
- Areas with clear U.S. leadership in which investments in medium- and small-scale experiments have great promise for near-term discovery include dark matter direct detection, the Large Synoptic Survey Telescope (LSST), the Dark Energy Spectroscopic Instrument (DESI), cosmic microwave background (CMB) experiments, short-baseline neutrino experiments, and a portfolio of small projects.
- Specific investments in particle accelerator, instrumentation, and computing research and development are required to support the program and to ensure the long-term productivity of the field.

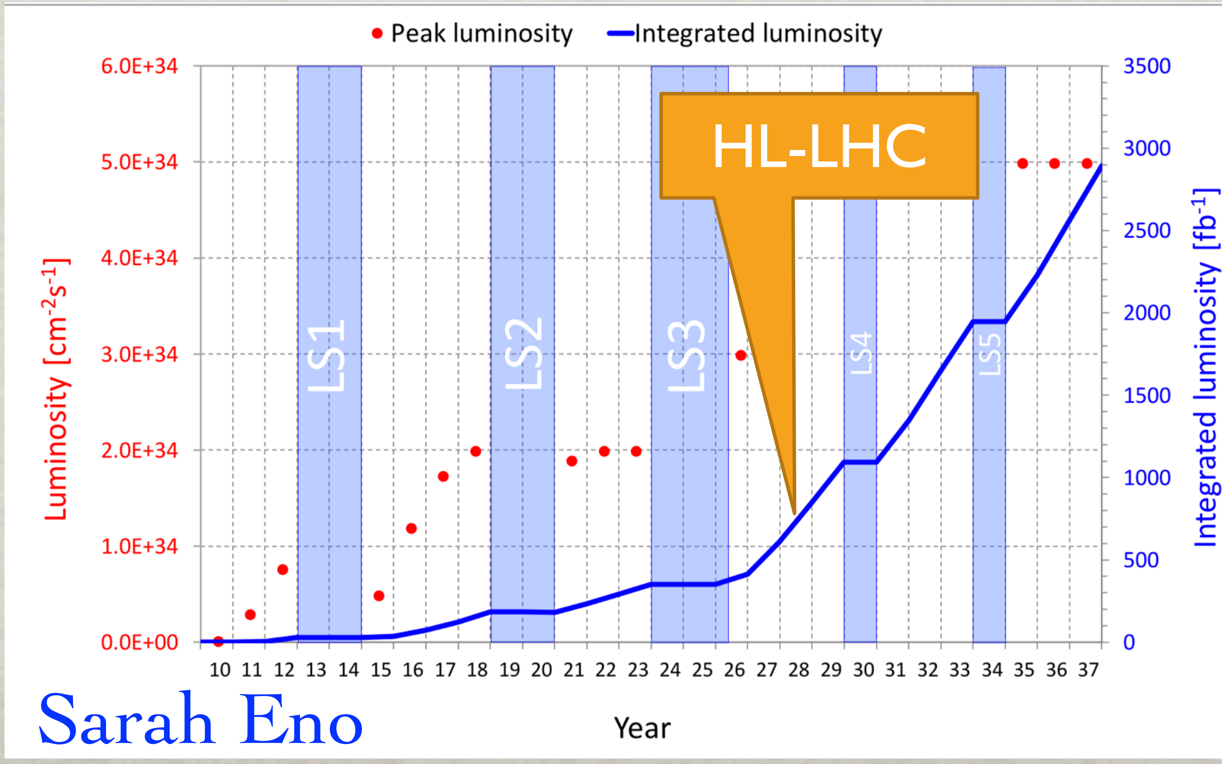
"No doubt that future high energy colliders are extremely challenging projects.

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

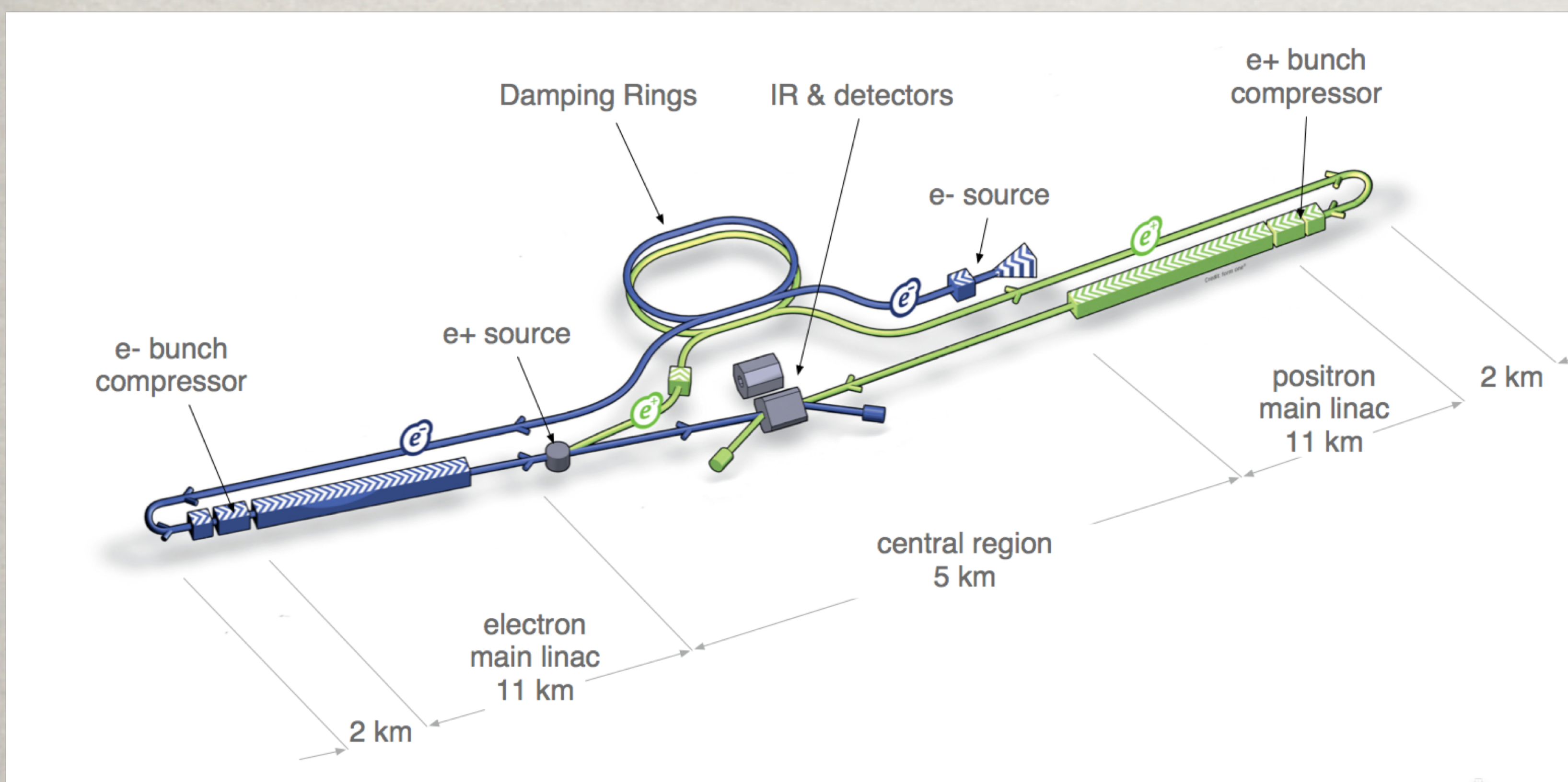
The High Luminosity LHC Project: (operation 2026-2037)

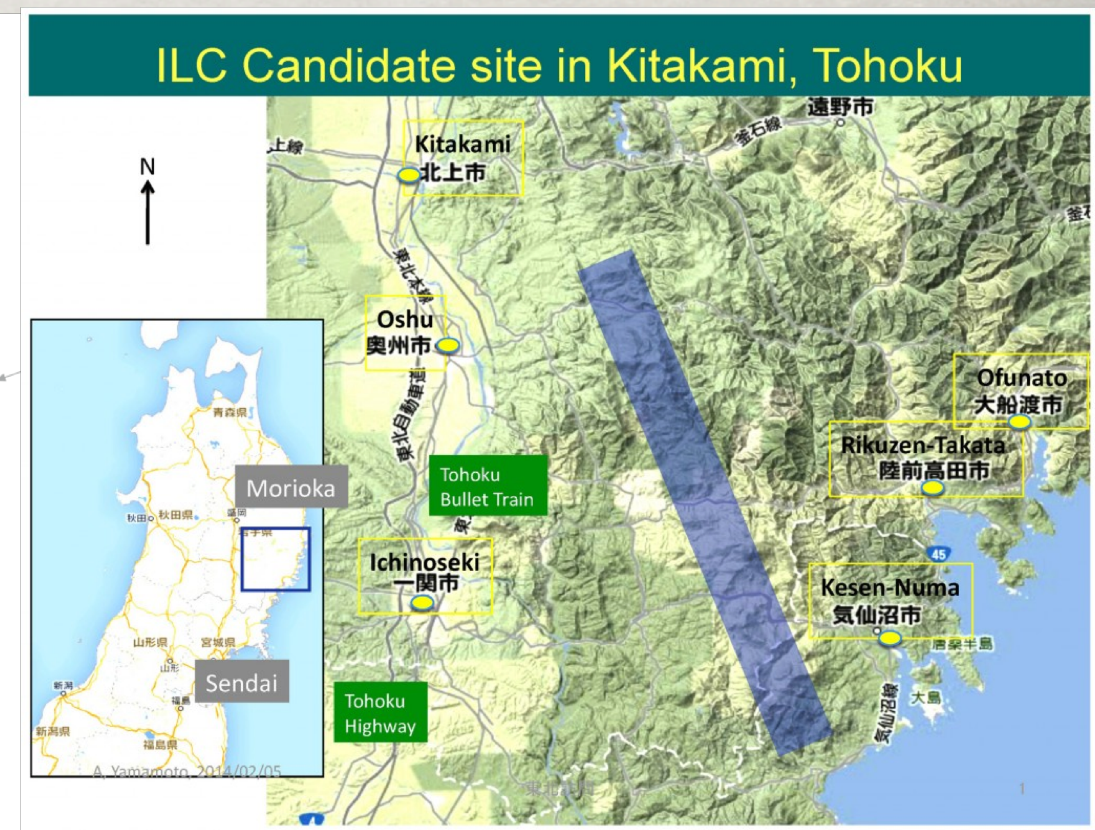
HL-LHC is the top priority of the European Strategy for Particle Physics in its 2013 update. It is formally approved by CERN Council in June 2016.



International Linear Collider
as a Higgs Factory & beyond

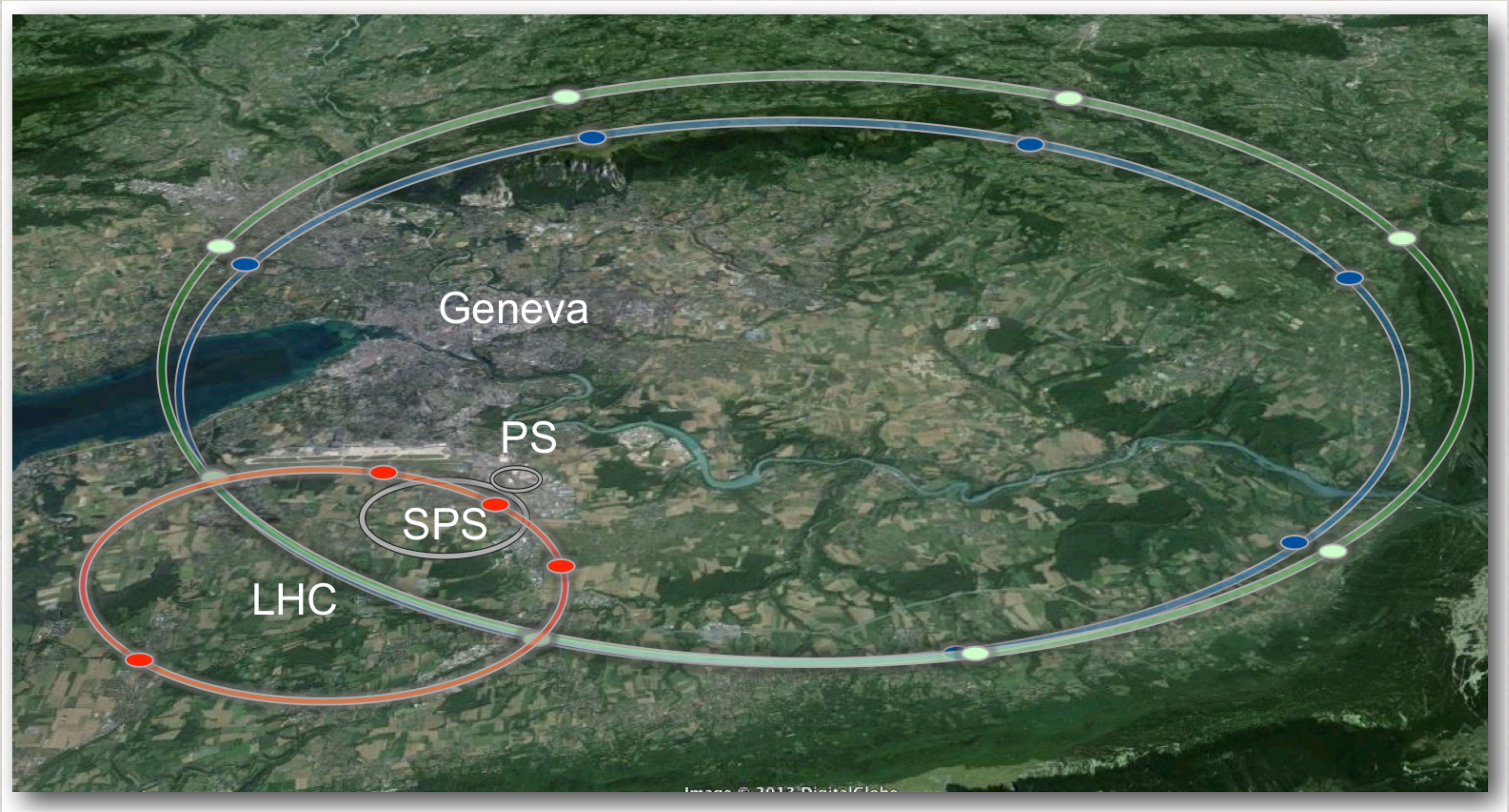
Under serious consideration in Japan:
(likely decision this year)





Ecm (GeV) = 250 (Higgs), 500 (top), 1000 (new particles)
Lumi (ab^{-1}) = 0.25 - 2

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

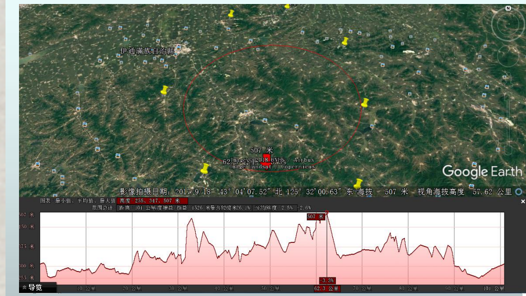


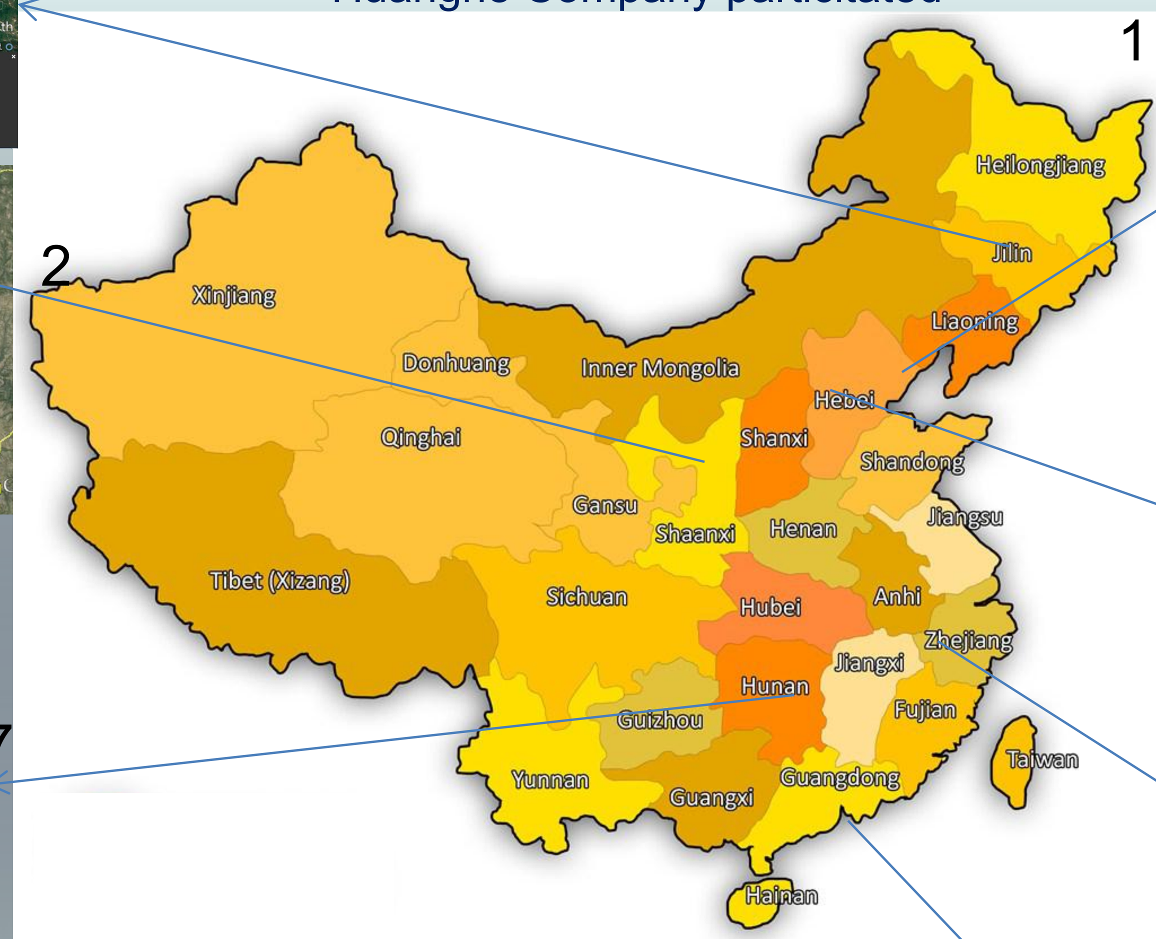
HE-LHC	FCC-ee	FCC-hh
27 km, 20T	80/100 km	80 /100 km, 16/20T
33 TeV	90 - 400 GeV	100 TeV

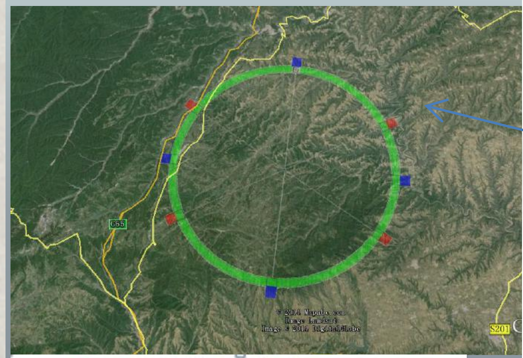
CEPC (circular e^-e^+)/SppC: China

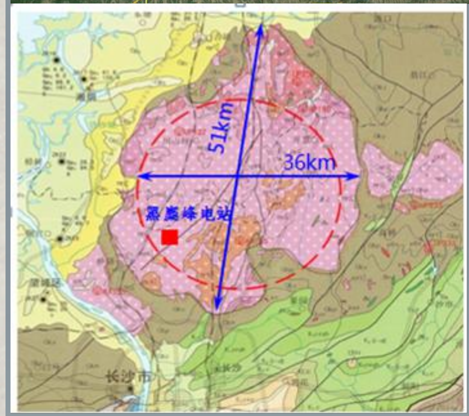
CEPC Site Selections

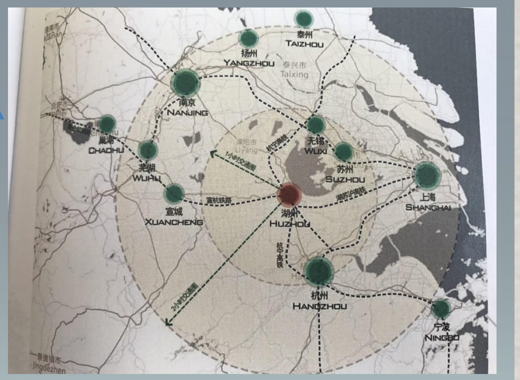
Huanghe Company particitated







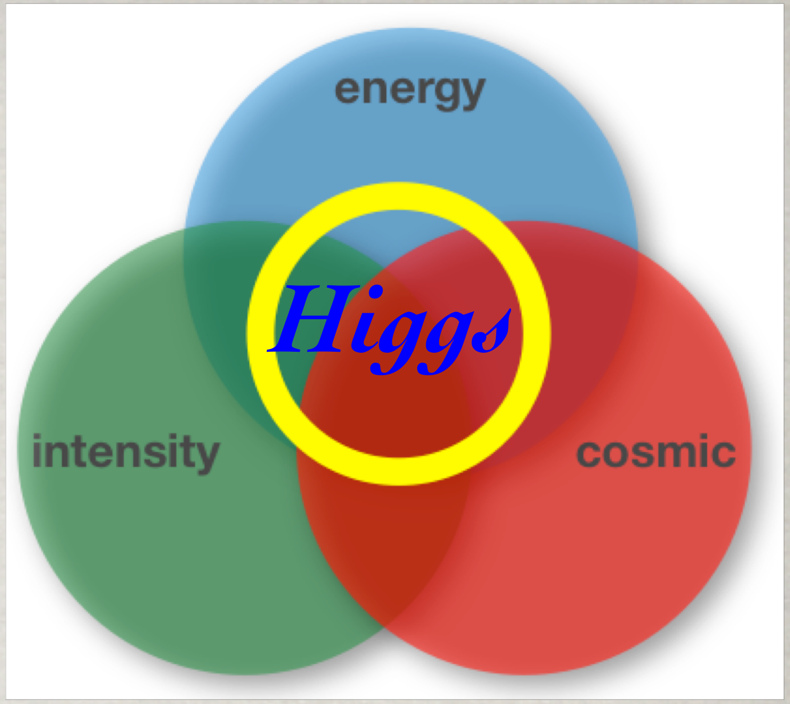




1) Qinhuangdao, Hebei Province（Completed in 2014）
2) Huangling, Shanxi Province（Completed in 2017)
3) Shenshan, Guangdong Province(Completed in 2016)
4) Baoding (Xiong an), Hebei Province (Started in August 2017)
5) Huzhou, Zhejiang Province (Started in March 2018)
6) Chuangchun, Jilin Province (Started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

Jie Gao

Under the Higgs lamppost:



- Precision Higgs physics:
  LHC lights the way: couplings~10%; λ_{HHH} ~ (20-50)%
  Future Higgs factory/SppC:
  Couplings~1%; $\lambda_{HHH} < 10\%$ Study the EW phase transition
  Dark matter coupling ~ 2% Search for the dark sector
- FCC_{hh} / SppC New physics reach:
  New heavy particles~10 – 30 TeV → fine-tune < 10^{-4}
  (WIMP) DM mass reach ~ 1 – 5 TeV
- Neutrino, flavor physics / Dark matter searches complementary.

An exciting journey ahead!

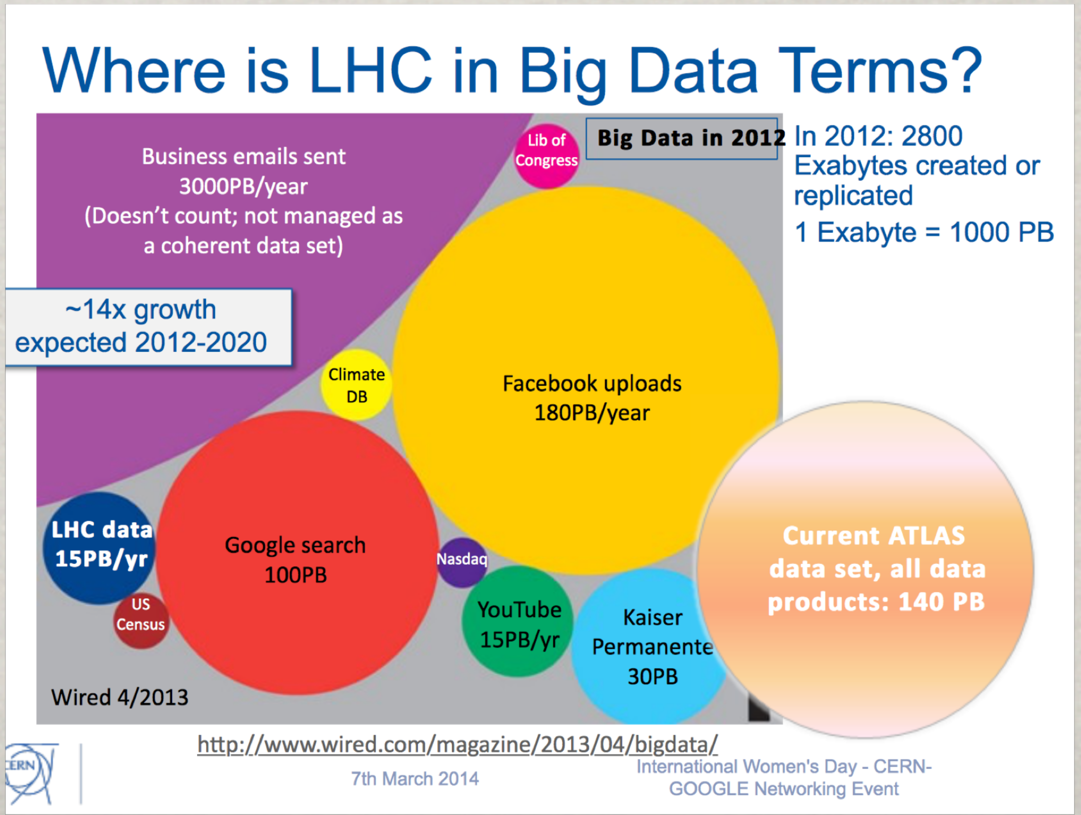
HEP & Society

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 …



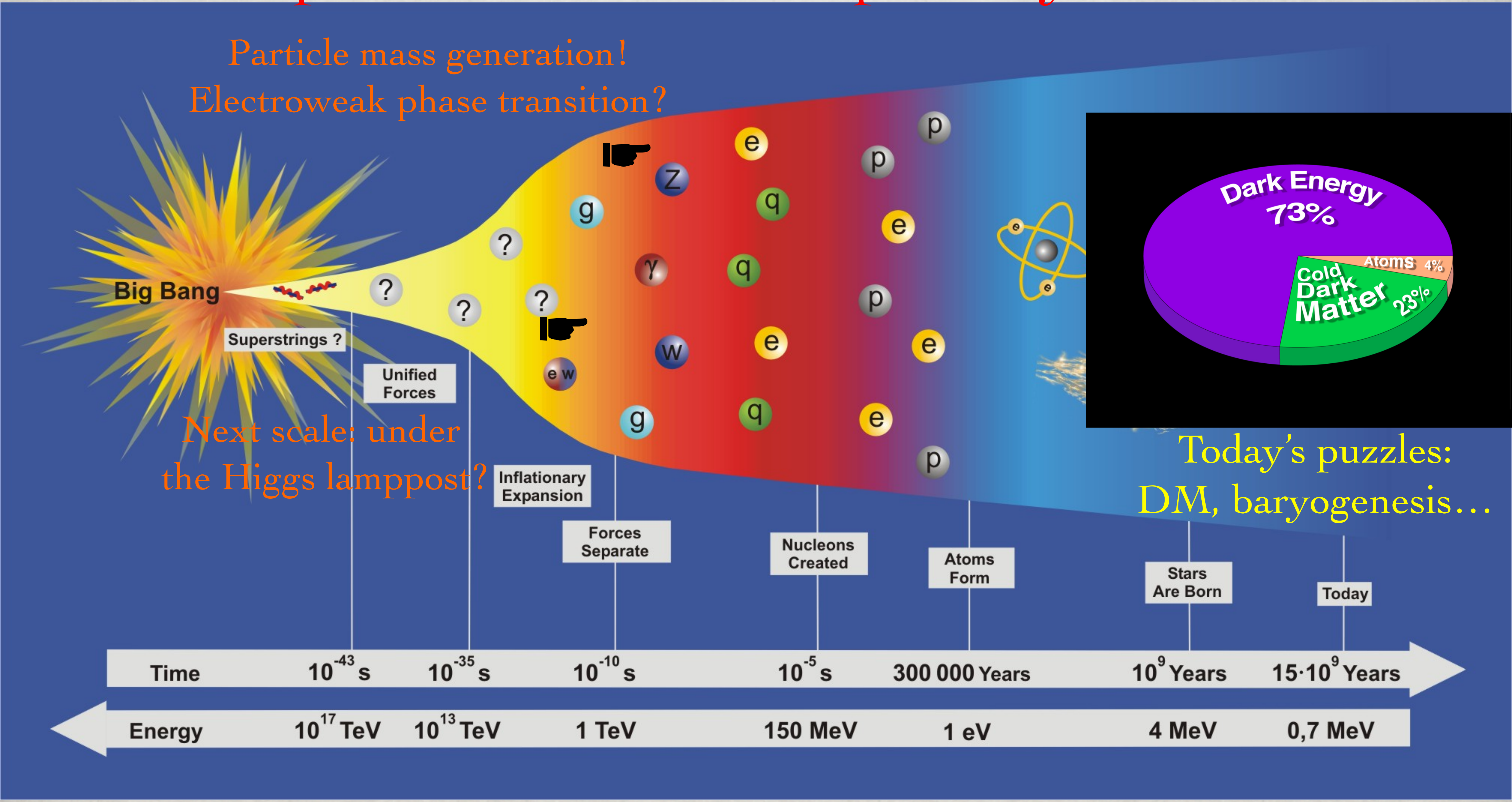
HEP & Society

- 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.

Backup slides …

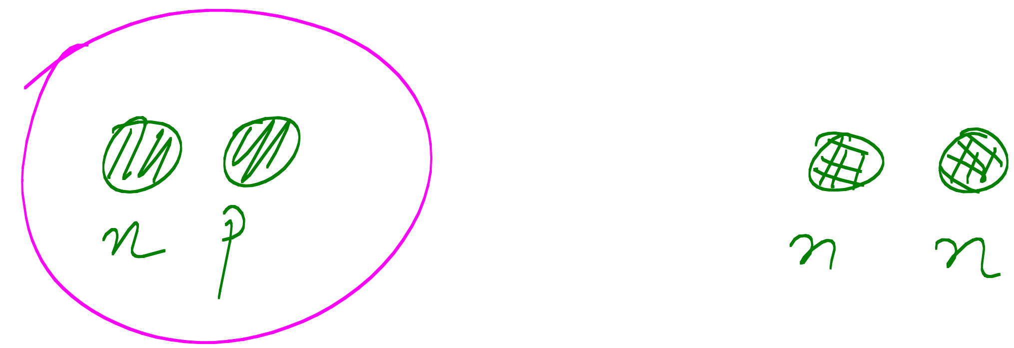
How much “tune” is fine-tuned?

Atomic physics:

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

Nuclear physics?

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



Binding Energy $\sim$ 2 MeV

$\sim$ 20% accident

Not bound by 60 keV(!),

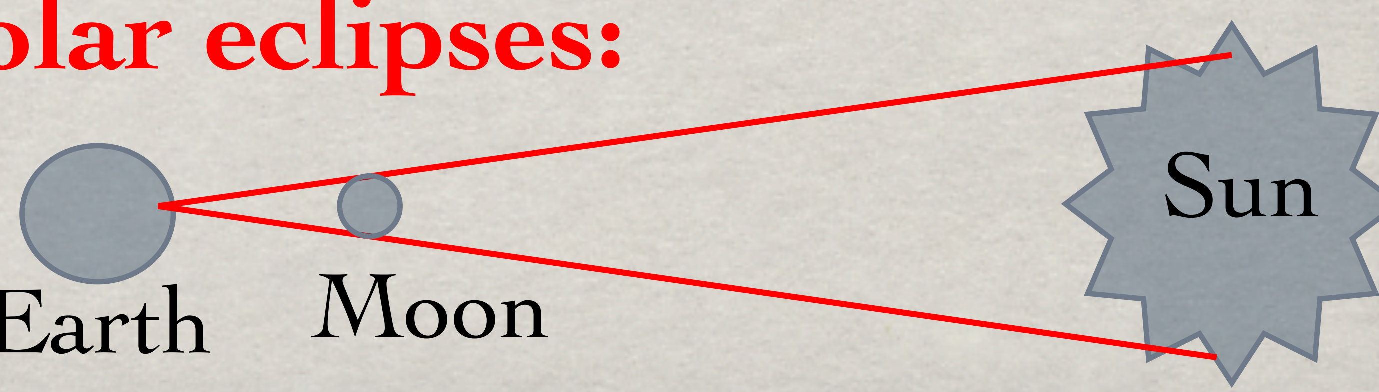
$\lesssim$ 1% accident

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

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

rather unnatural!

Solar eclipses:



"Naturalness" in perspective:

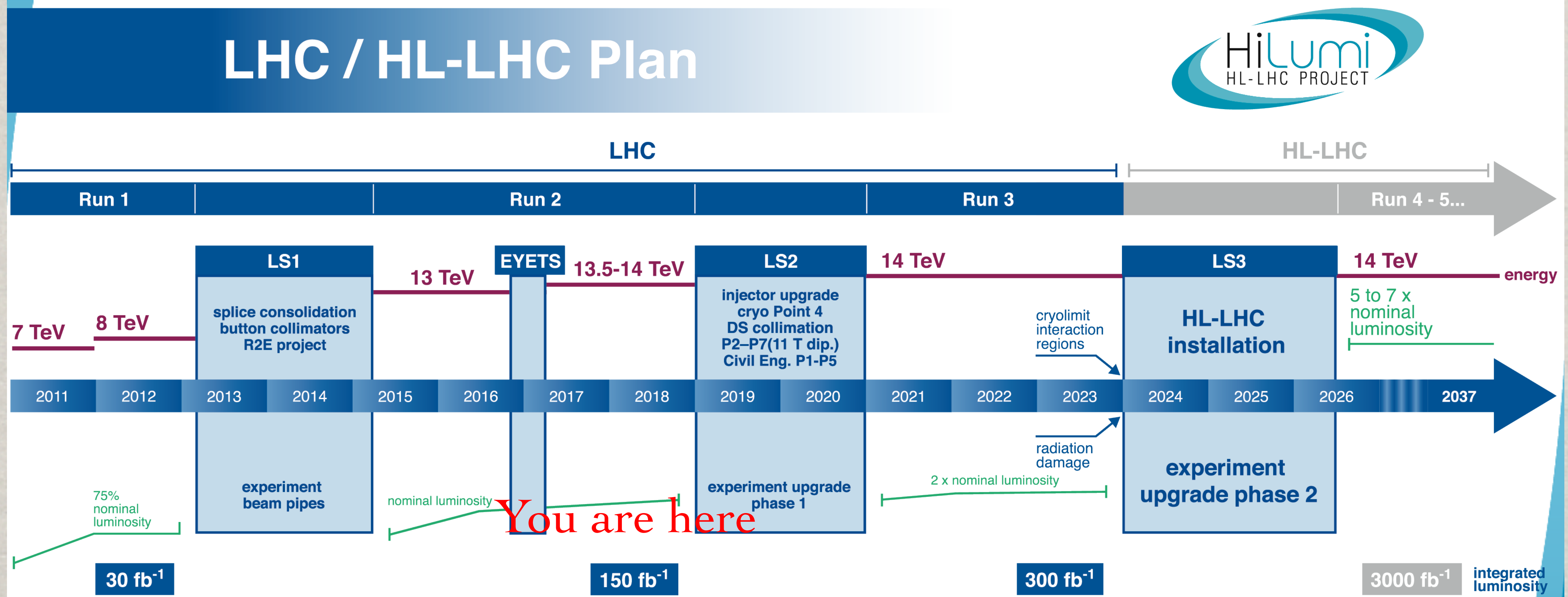
Unbelievable! 4 mm^2 / 20 cm^2 ~ 10^{-3} fine-tune.

"Naturalness" → TeV scale new physics.

→ We need an answer !

HL-LHC:
The Energy & Precision Frontier

Timeline & Goal:
Commissioning 2026; 3 ab^{-1} by 2037 (250 fb^{-1}/y)



Levelled Luminosity $L = 5{\times}10^{34} cm^{-2} s^{-1}$

HE-LHC: The New Energy Frontier

HE-LHC design goals and basic choices

physics goals:

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
- target luminosity ≥ 4 x HL-LHC (cross section $\propto 1/E^2$)

key technologies:

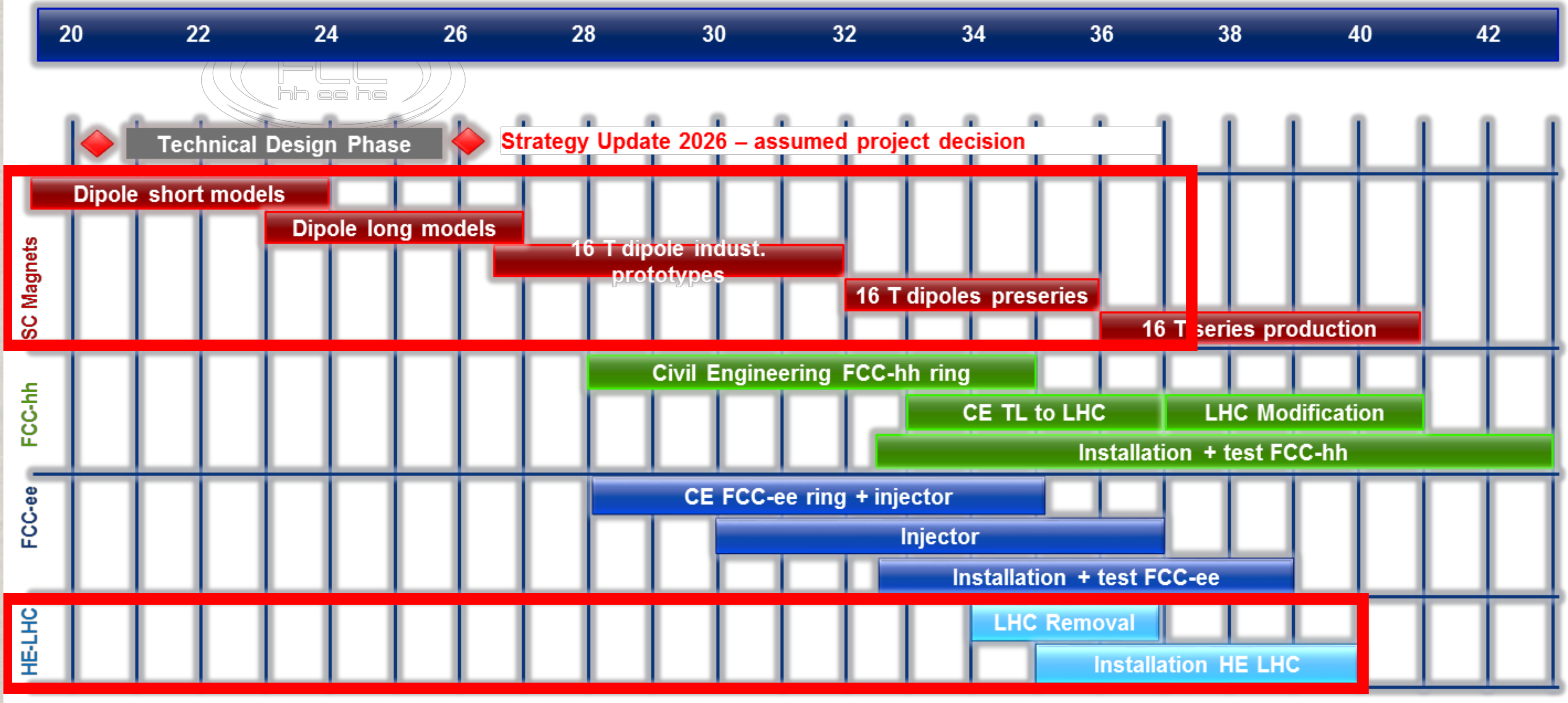
- FCC-hh magnets (curved!) & FCC-hh vacuum system
- HL-LHC crab cavities & electron lenses

beam:

- HL-LHC/LIU parameters (25 ns baseline, also 5 ns option)

Fastest Possible Technical Schedules

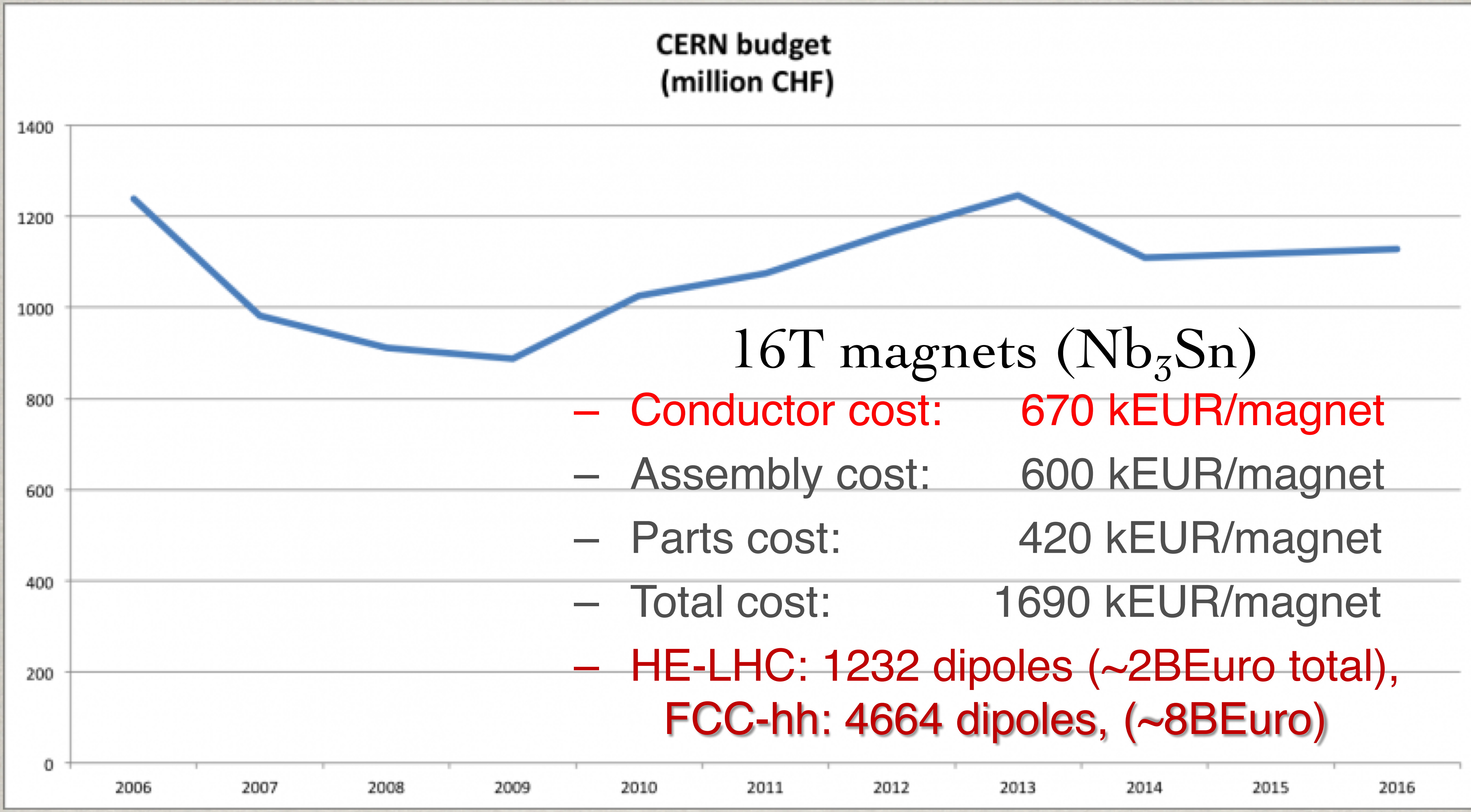
M. Benedikt, F. Zimmermann '17



HE-LHC design & construction

technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)
- Options: FCC-ee @ 2039; FCC-hh @ 2043.



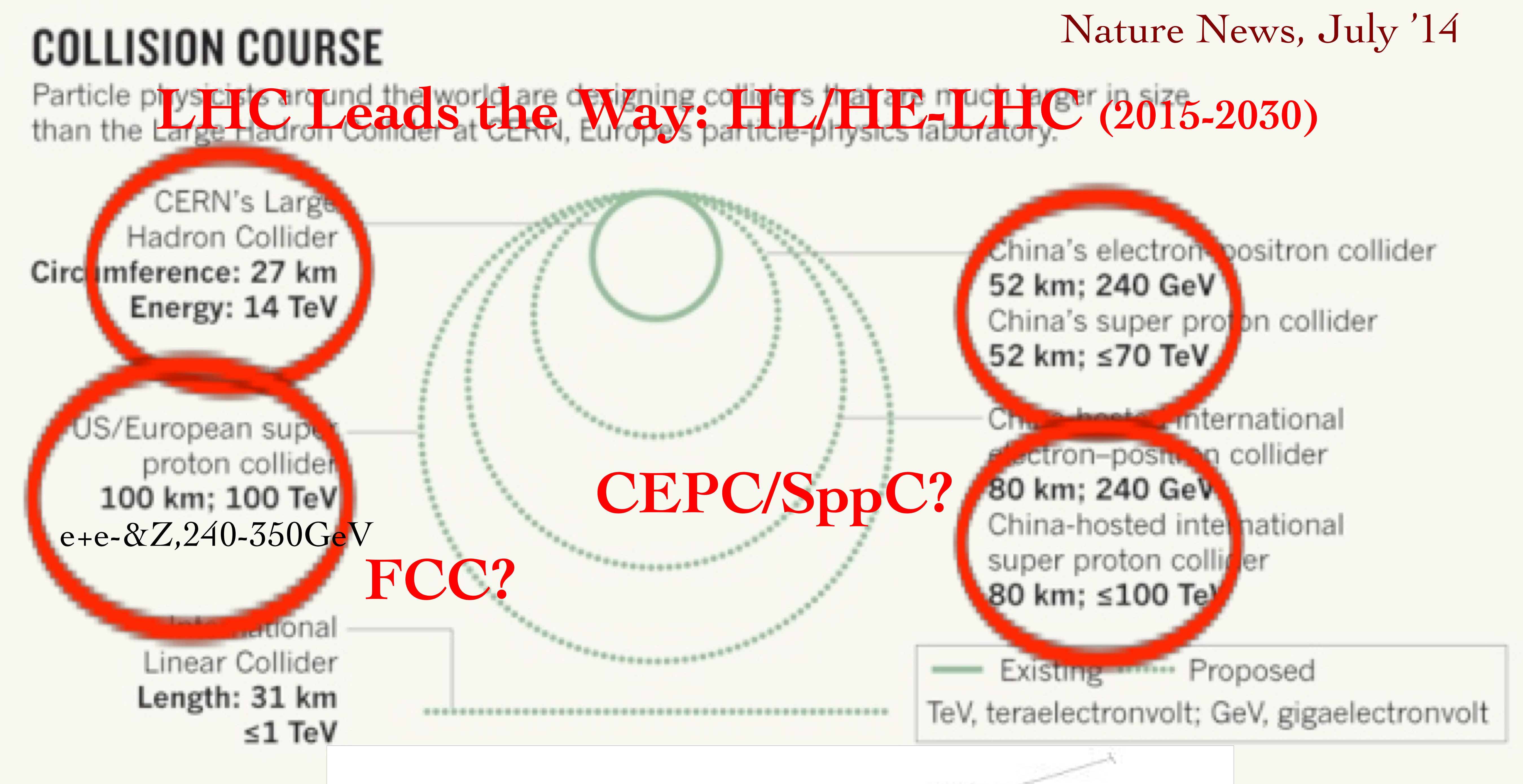
16T magnets (Nb_3Sn)

- Conductor cost: 670 kEUR/magnet
- Assembly cost: 600 kEUR/magnet
- Parts cost: 420 kEUR/magnet
- Total cost: 1690 kEUR/magnet
- HE-LHC: 1232 dipoles (~2BEuro total), FCC-hh: 4664 dipoles, (~8BEuro)

Vladimir Shiltsev, this workshop

Nature News, July '14

LHC Leads the Way: HL/HE-LHC (2015-2030)



e+e-&Z,240-350GeV

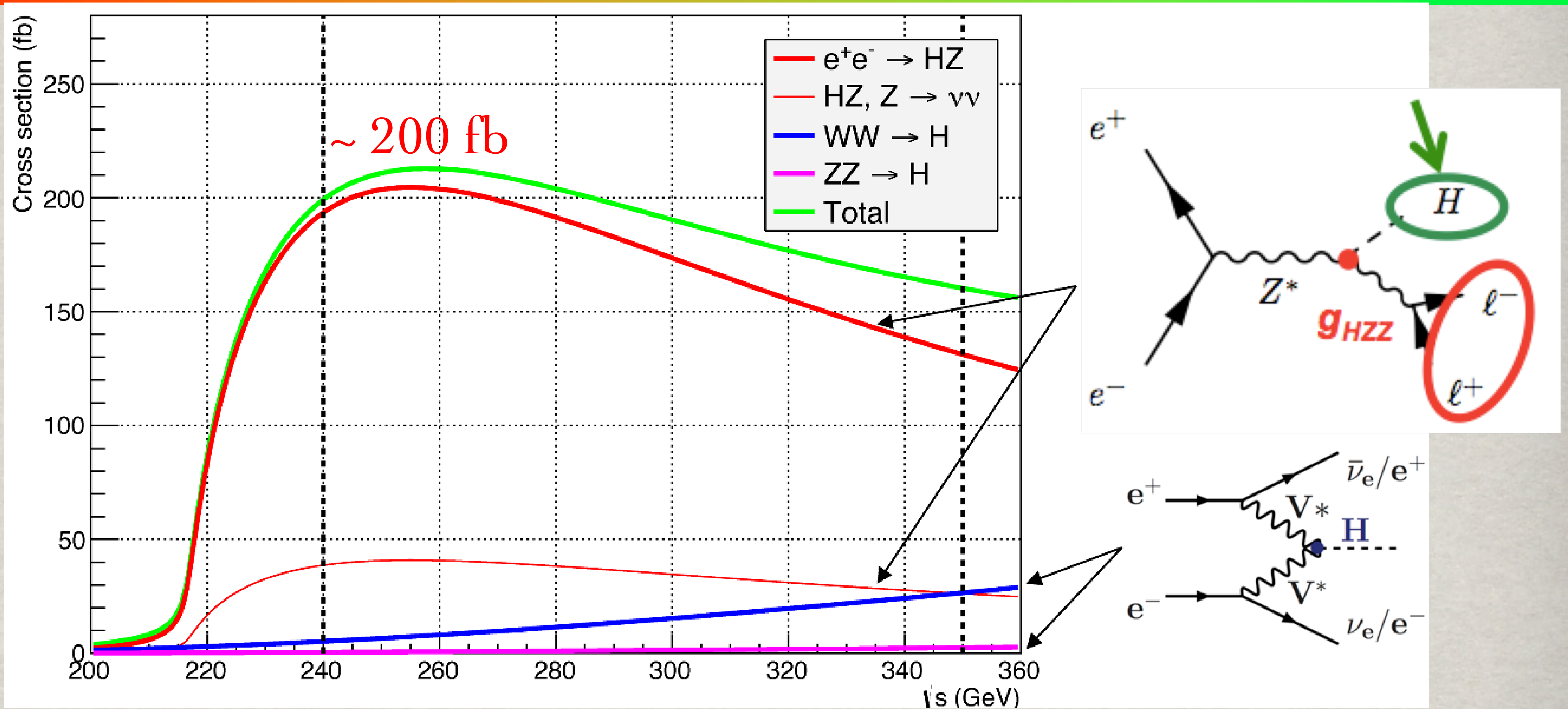
FCC?

CEPC/SppC?

ILC as Higgs Factory & beyond

Ecm = 250 (Higgs), 500 (top), 1000 GeV

Higgs-Factory: Mega (10^6) Higgs Physics



ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1}

- Model-independent measurement: ILC Report: 1308.6176

  $\Gamma_H \sim 6\%$, $\Delta m_H \sim 30$ MeV

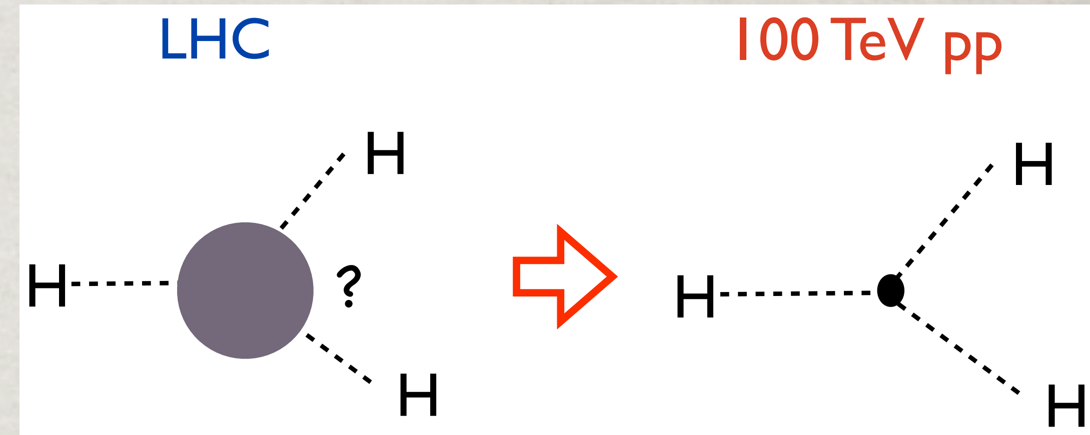
  (HL-LHC: assume SM, $\Gamma_H \sim 5\text{-}8\%$, $\Delta m_H \sim 50$ MeV)

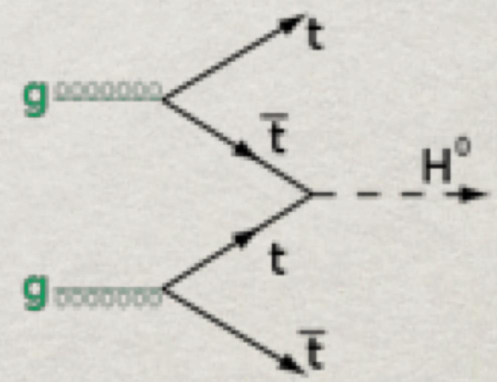
- TLEP 10^6 Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

  TLEP Report: 1308.6176

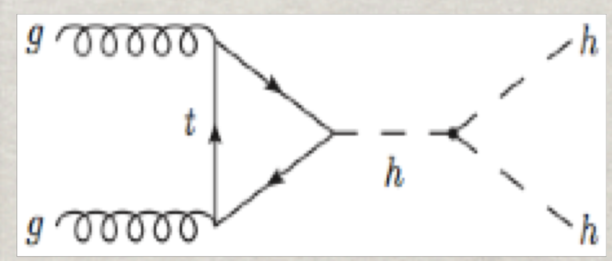
The Next Energy Frontier:
100 TeV Hadron Collider

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
$t\bar{t}$	~30
H	~15 ($t\bar{t}$H ~60)
HH	~40
stop (m=1 TeV)	~10^3





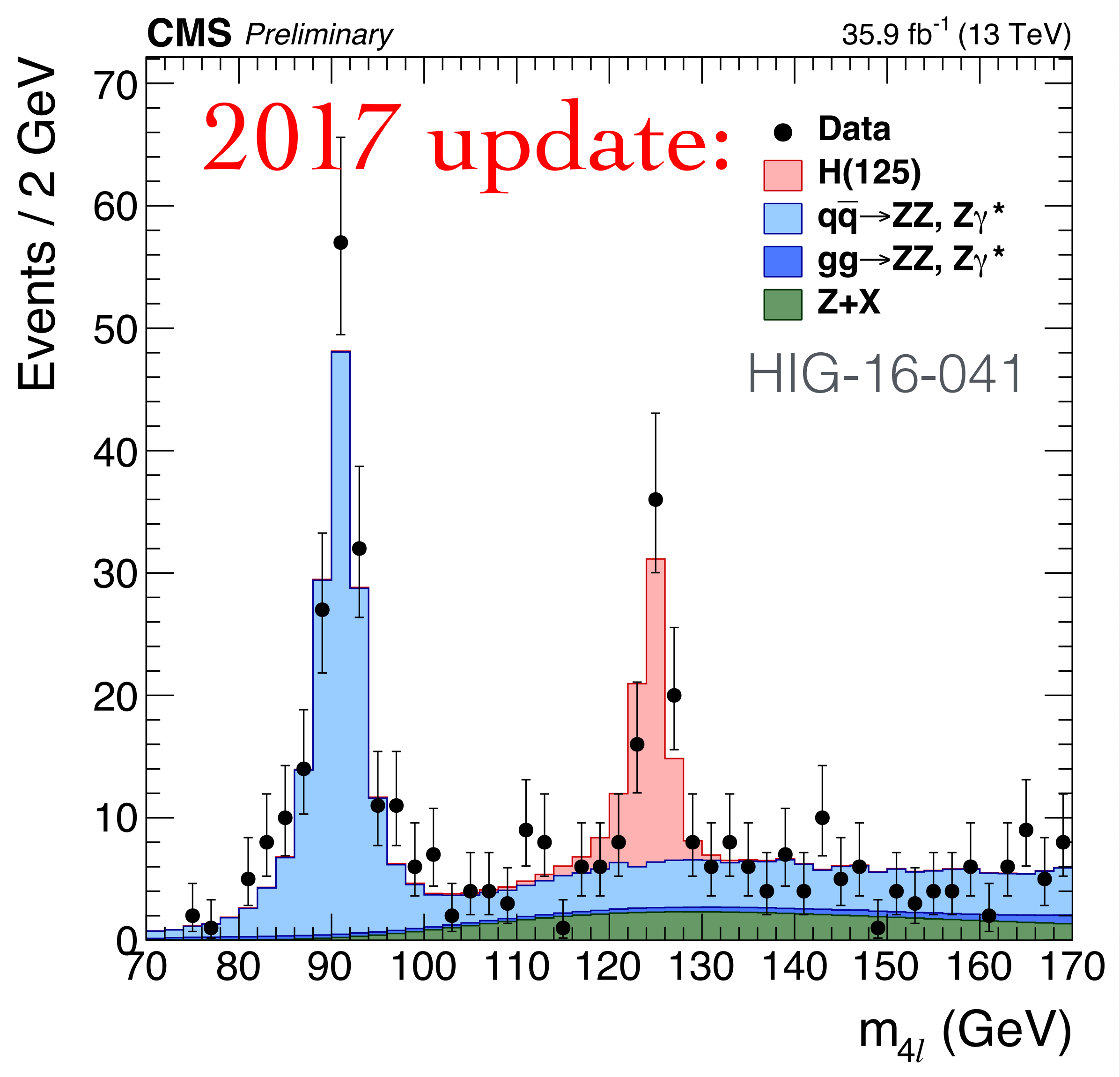
λ_t : 1%



λ : 8%

EW phase transition strong 1^{st} order:
→ O(1) deviation on λ_{hhh}

Snowmass QCD Working Group: 1310.5189
Arkani-Hamed, TH, Mangano, LT Wang, 1511.06495, to appear in Phys Report



Measured mass accuracy < 0.2% :

$$m_H = 125.26 \pm 0.20(\mathrm{stat}) \pm 0.08(\mathrm{syst})\ \mathrm{GeV}$$

50 years theoretical work …

25 years experimental work …

We Made It !

QED: Most Successful in Theory & Practice!

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m_e)\psi$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu,\ D_\mu = \partial_\mu + ieA_\mu$$

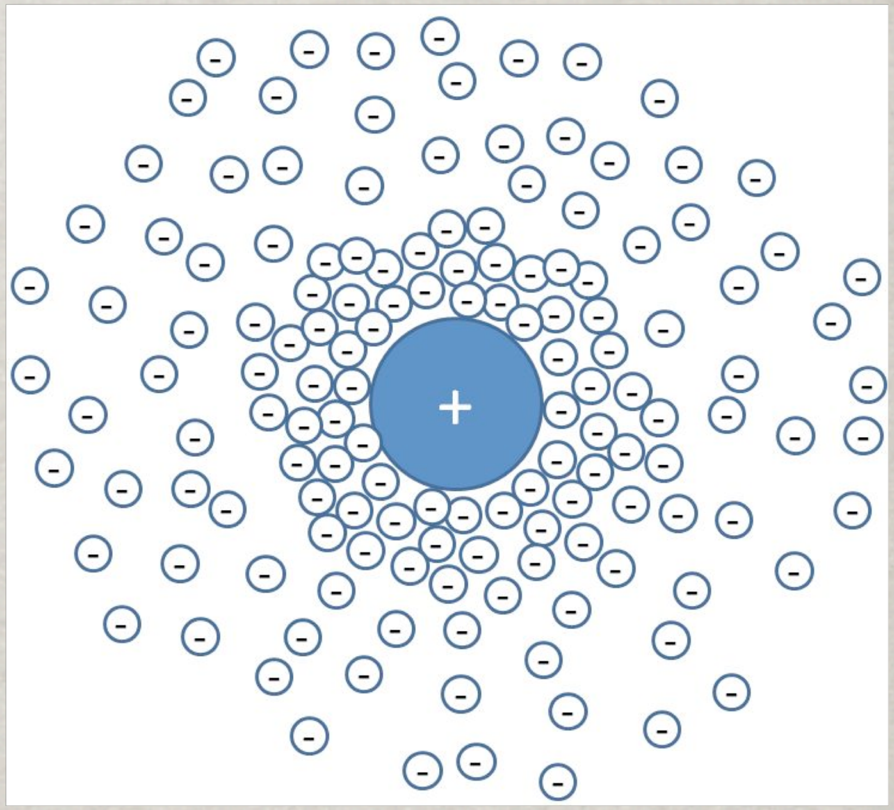
- At low energies → Maxwell's theory; vector-like coupling by a $U_{em}(1)$ gauge symmetry
- At high energies → Quantum-mechanical, renormalizable, most accurate (in science!): a part of trillion

$$a_e^{theo} = 0.001159652181643(763)$$
$$a_e^{exp} = 0.00115965218073(28)$$

- QED becomes strongly interacting asymptotically (screening effects):

Fine structure constant:

$$\alpha(Q^2) = \frac{\alpha(Q_0^2)}{1 - \frac{\alpha(Q_0^2)}{3\pi}\ln(Q^2/Q_0^2)}$$



At ultra-violet (UV) → theory is invalid: the "Landau pole".

Completion of the SM:

First time ever, we have a quantum-mechanical, relativistic, perturbative, renormalizable, unitary theory, valid up to an exponentially high scale, possible M_{Pl} (!?)

"... most of the grand underlying principles have been firmly established..."

An eminent physicist remarked:

"the future truths of physical science are to be looked for in the sixth place of decimals."

--- Albert Michelson (1894)

More Questions Than Answers:
(a). All about $\mu^2 |\phi|^2$

the only "relevant operator" not protected by any symmetry.

--- Ken Wilson, 1970

Question 1

Is there a symmetry, new principle to protect m_h?
(SUSY? Extra-dim? New gauge symmetry? …)

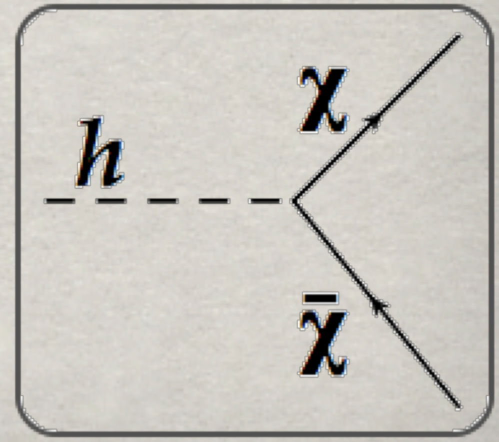
Question 2

Is there an underlying mechanism, BCS-like, responsible for the Higgs mechanism?
(composite Higgs? a form-factor at a scale **Λ ?**)

Question 3

Unprotected term serves as the "Higgs portal"?

$$k_s H^\dagger H \; S^* S, \qquad \frac{k_\chi}{\Lambda} H^\dagger H \; \bar{\chi}\chi.$$

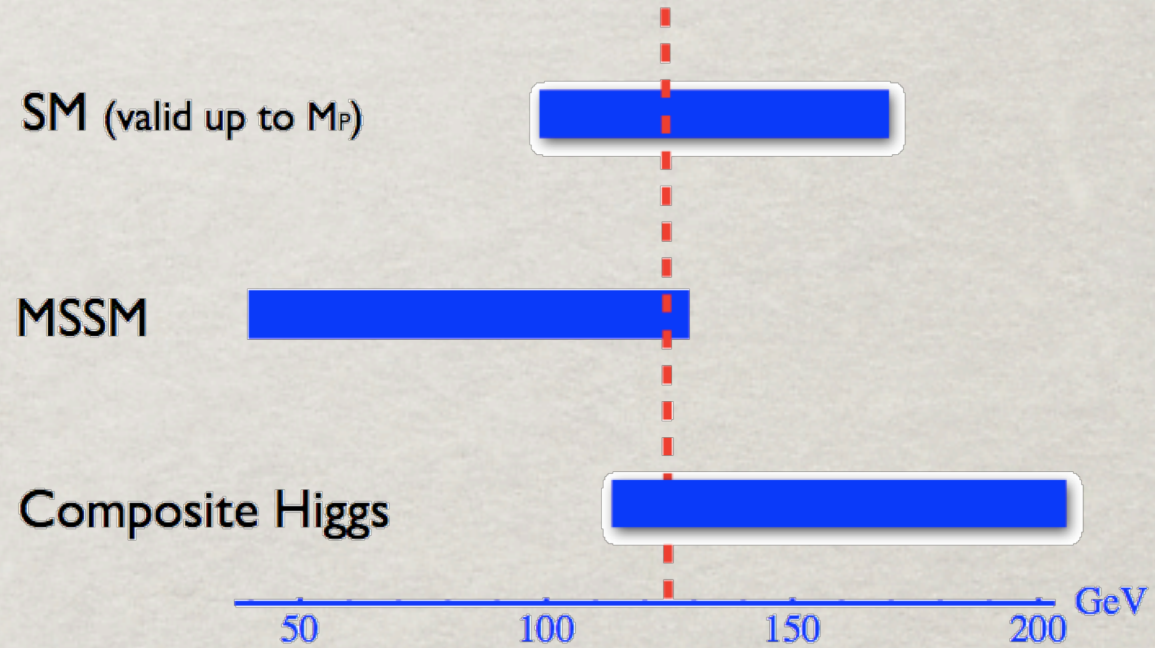


More Questions Than Answers:
(b). All about $\lambda|\phi|^4$

A weakly coupled new force: $\lambda \approx 0.13$

Question 4

Is it "induced" by more fundamental interactions:



Like in SUSY: (tree-level)

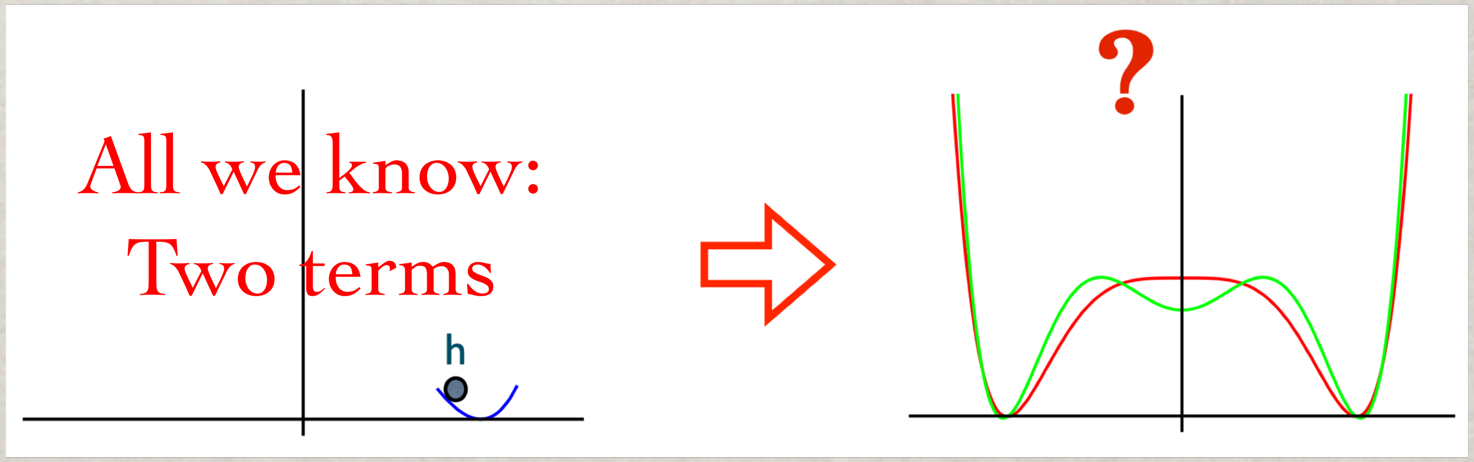
$\lambda = (g_L^2 + g_Y^2)/8 \approx 0.3/4$

Or like in strong dynamics:

$$m_H^2 \sim \frac{f^2}{(4\pi)^2} \sim \frac{m_t^2 M_T^2}{f^2}.$$

Question 5

Nature of EW phase transition: 2nd order?



If O(1) deviation on λ_{hhh} → strong 1st order!

Many more Questions

- Higgs is in a pivotal position for fermion masses & flavor mixing.
- Neutrino mass connection?
- EW baryogenesis?
- Vacuum stability?
- Inflation?
- Relationship with dark energy?
- … …

We need the answers to understand Nature to a deeper level $<10^{-18}$m!

Potentially rich program ahead:

- HL-LHC / HE-LHC lead the way:

  3 ab^{-1} @ 14 TeV; 15 ab^{-1} @ 27 TeV

  LHeC

  e(60 GeV) + p(7 TeV)@1 ab^{-1}; e(60 GeV) + p(14 TeV)@2 ab^{-1}
- ILC e^+e^-

  250 (500) GeV @ 2 (4) ab^{-1}, 80% / 30% polarization
- FCC(ee) / CEPC

  250 / 240 GeV @ 5 / 20 ab^{-1}; 350 GeV @ 1 ab^{-1}
- CLIC

  380 GeV@0.5 ab^{-1}, 80% / 0% pol; 1.5 TeV@1.5 ab^{-1}; 3 TeV@3 ab^{-1}
- FCC(hh)

  100 TeV @ 30 ab^{-1}

  FCC(eh) e(60 GeV) + p(50 TeV) @ 2 ab^{-1}
- Muon Collider

  mh @ 1 fb^{-1} ; 20 TeV @ 5 ab^{-1}

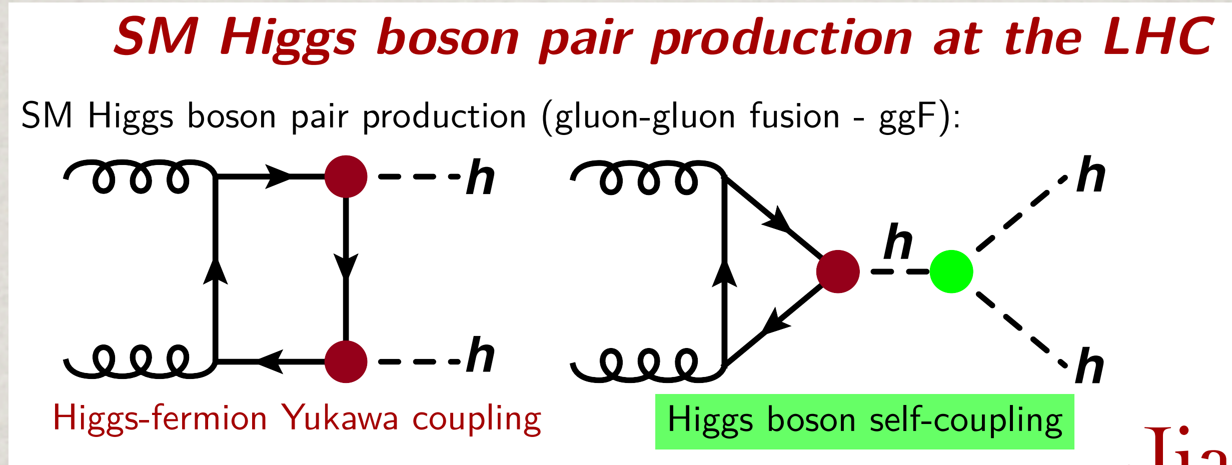
The Nambu-Goldstone Theorem

"If a continuous symmetry of the system is spontaneously broken, then there will appear a massless degree of freedom, called the Nambu-Goldstone boson."

Except the photon, no massless boson (a long-range force carrier) has been seen in Nature!

The Spontaneous Symmetry Breaking:
Brilliant idea & common phenomena, confronts the Nambu-Goldstone theorem!
-- A show stopper ?

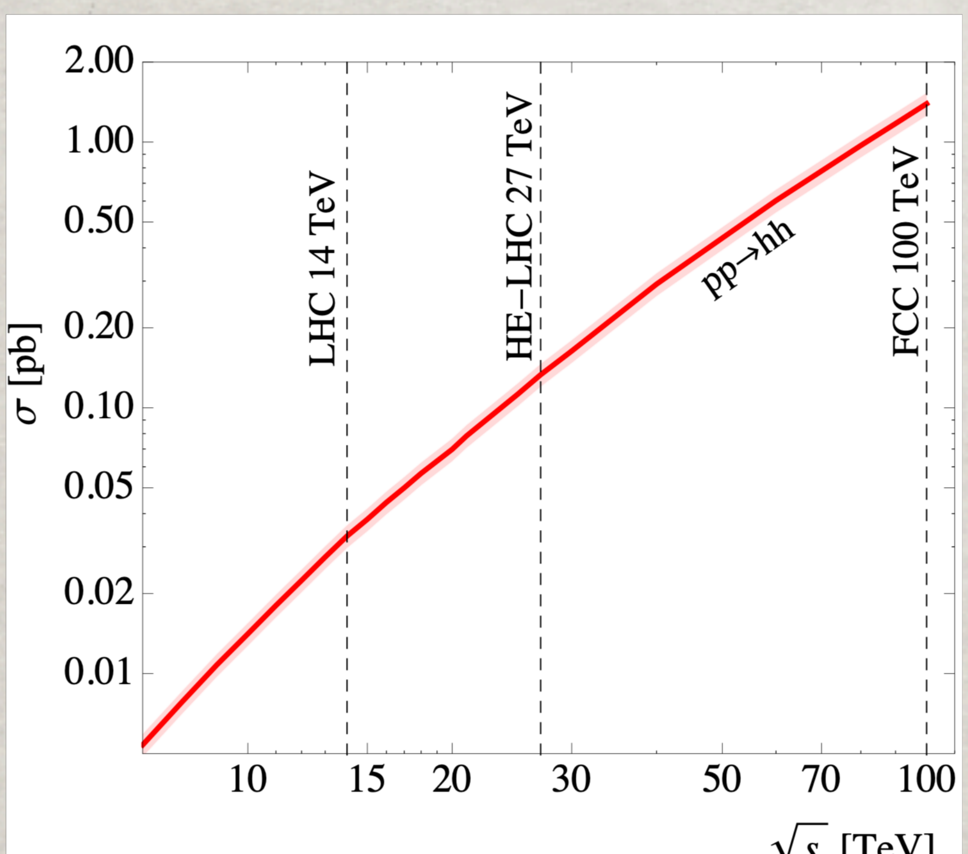
HE-LHC: Higgs self-coupling

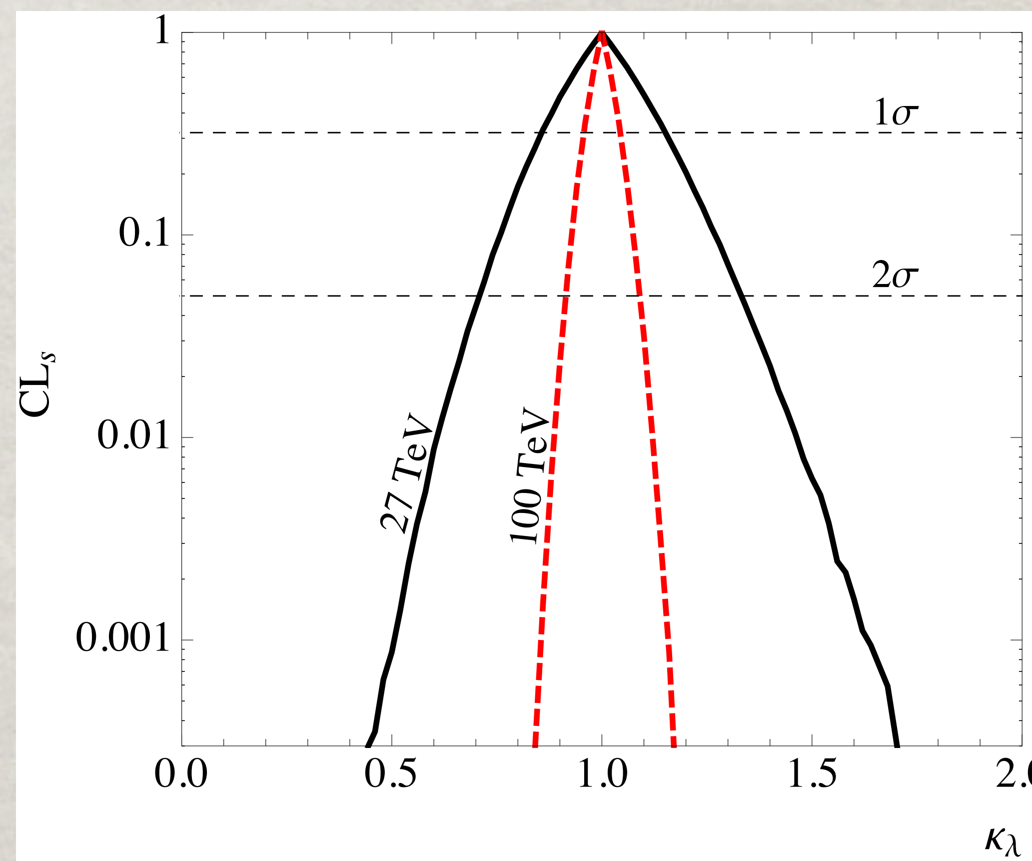


Jianming Qian's talk;
E. Vryonidou's talk

At HL-LHC: self-coupling **δλ ~ 50%**

At HE-LHC: cross section increases ~3x. **δλ ~ 30%@2σ**

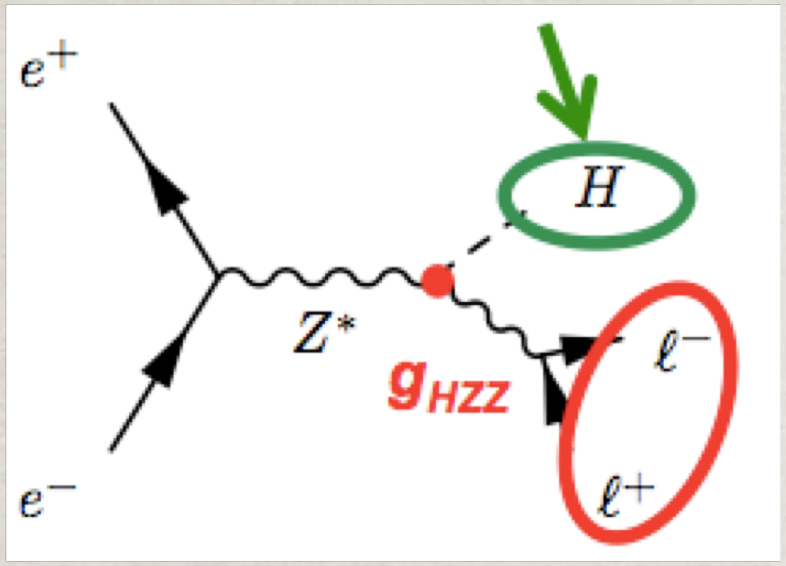


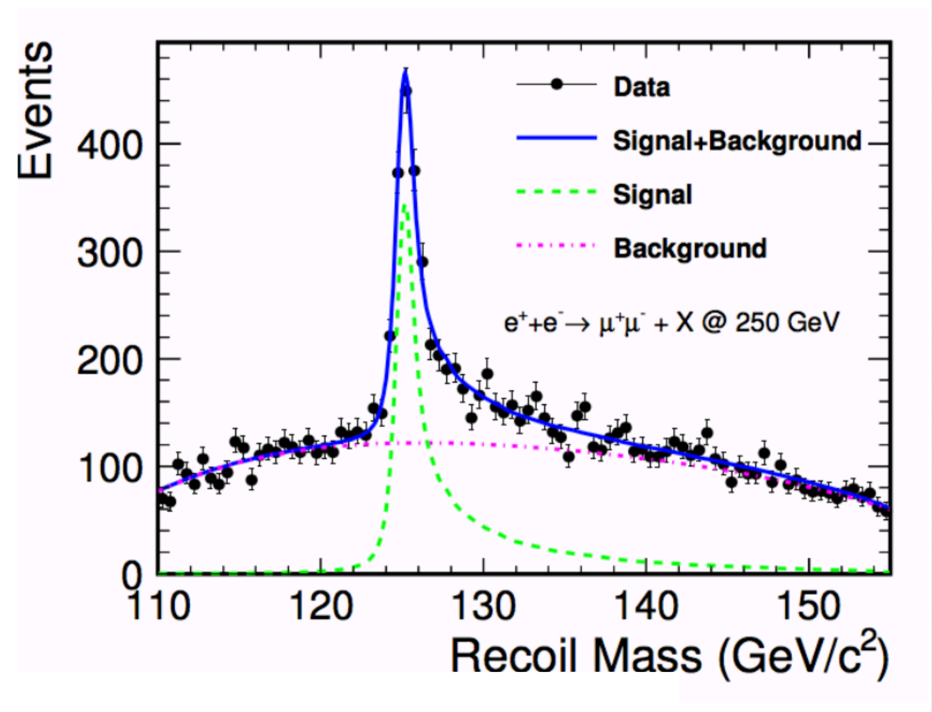


D. Goncalves, TH, F. Kling, T. Plehen, M. Takeuchi, arXiv:1802.04319.

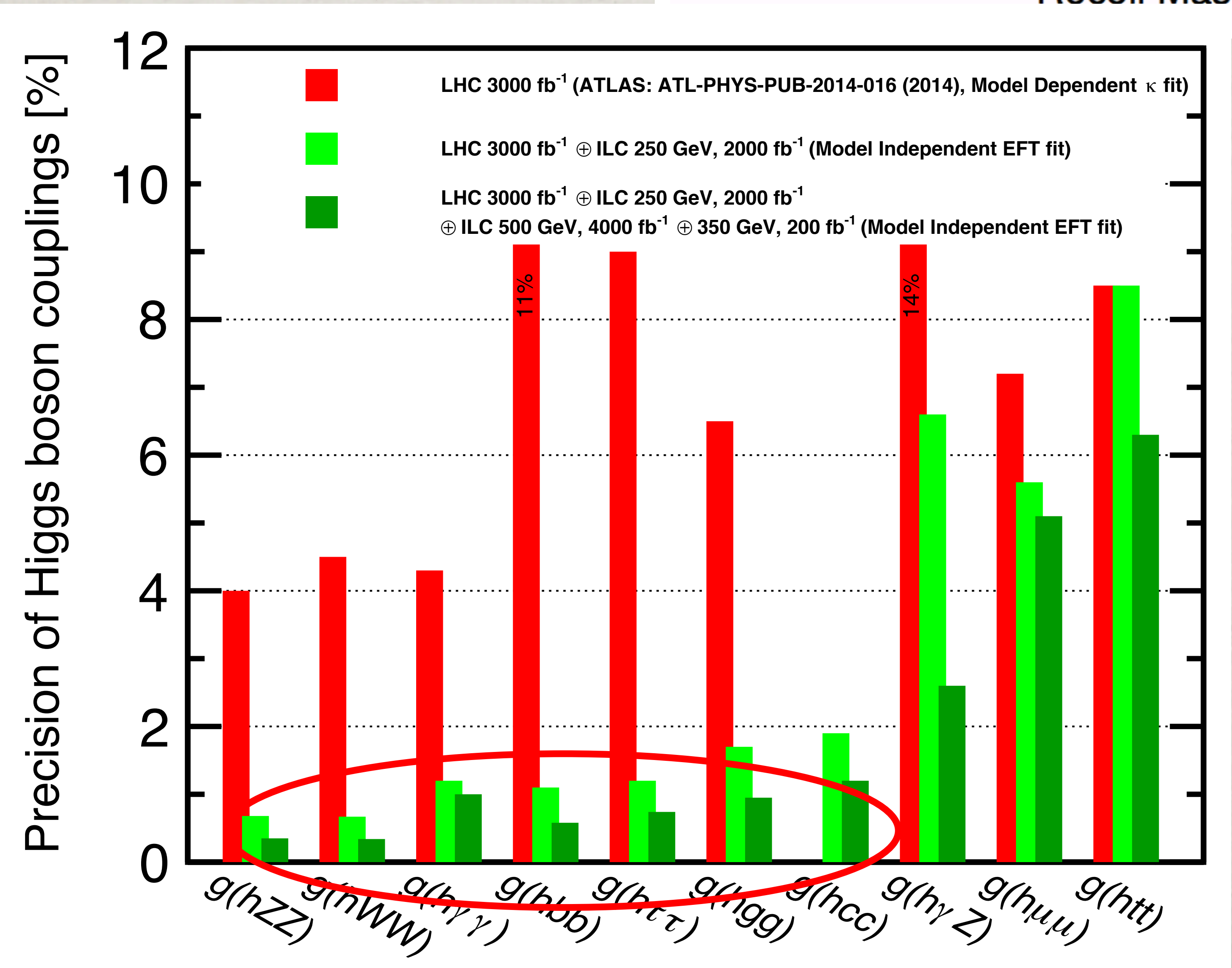
Recoil mass: Model-independent measurement

$$m_h^2 = (p_{e+}^2 + p_{e-}^2 - p_{\ell+}^2 - p_{\ell-}^2)^2$$



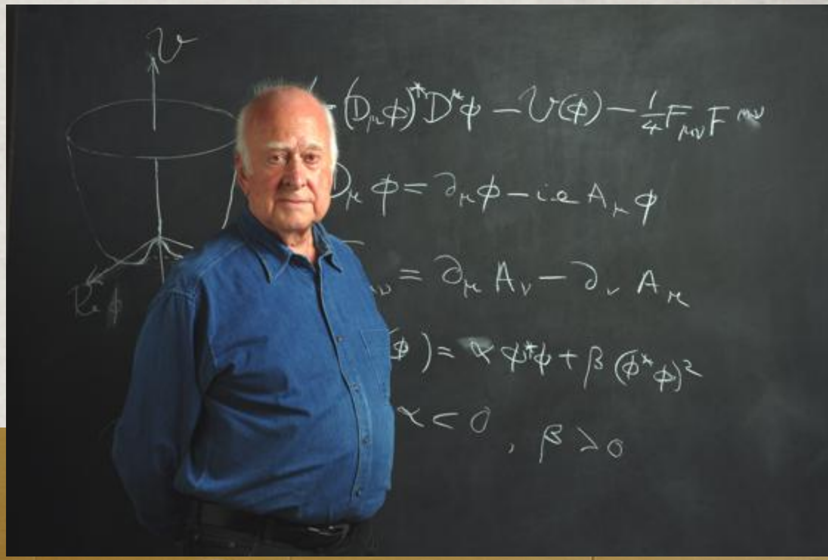


arXiv:1710.07621, LCC, Fujii et al.



Gauge symmetries prevent the mass terms?

The Higgs mechanism (1964)



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

Kibble, Guralnik, Hagen, Englert, Brout

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

PRL

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

PLB

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

PRL

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

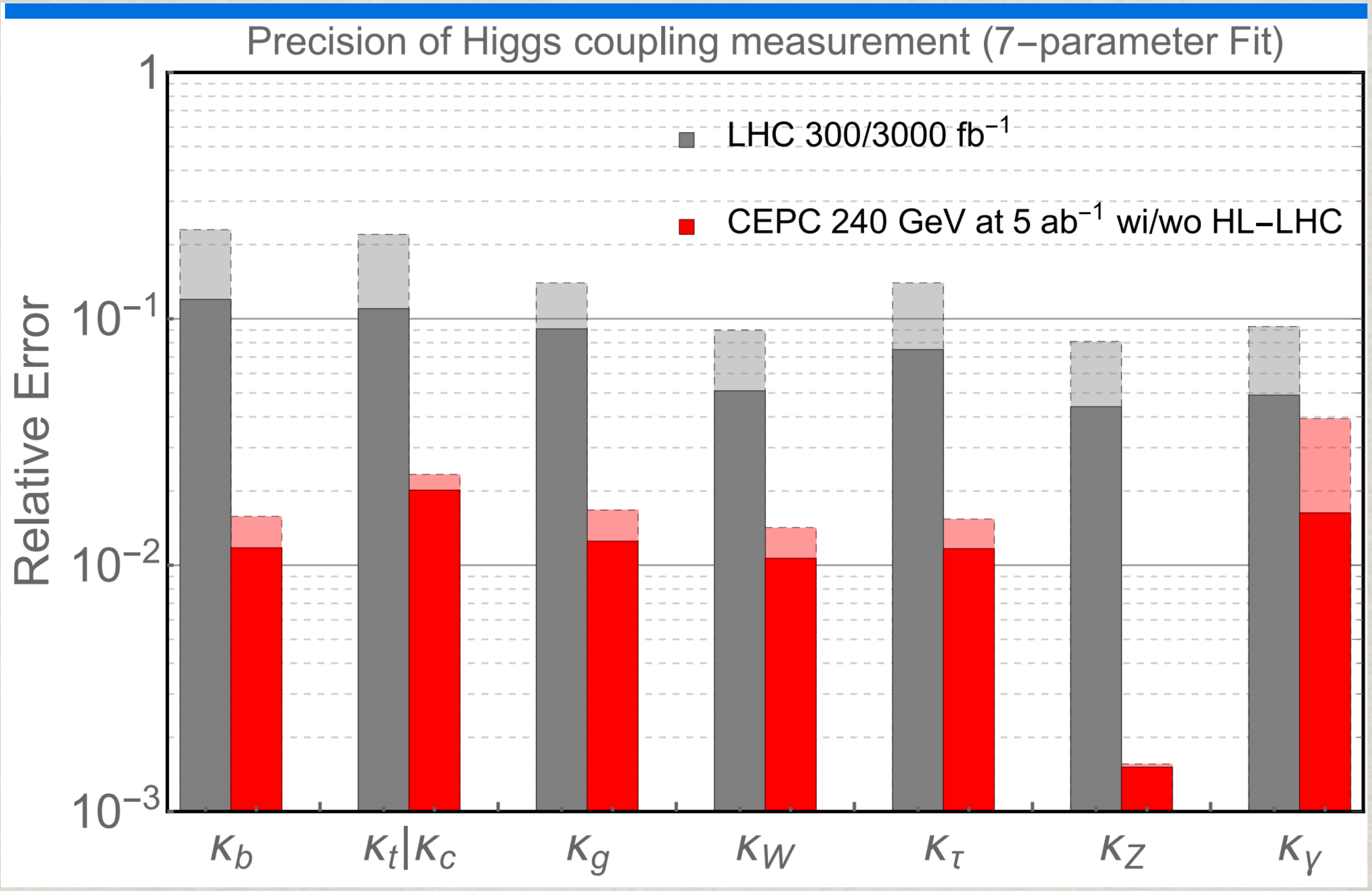
The Higgs Magic!

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

PRL

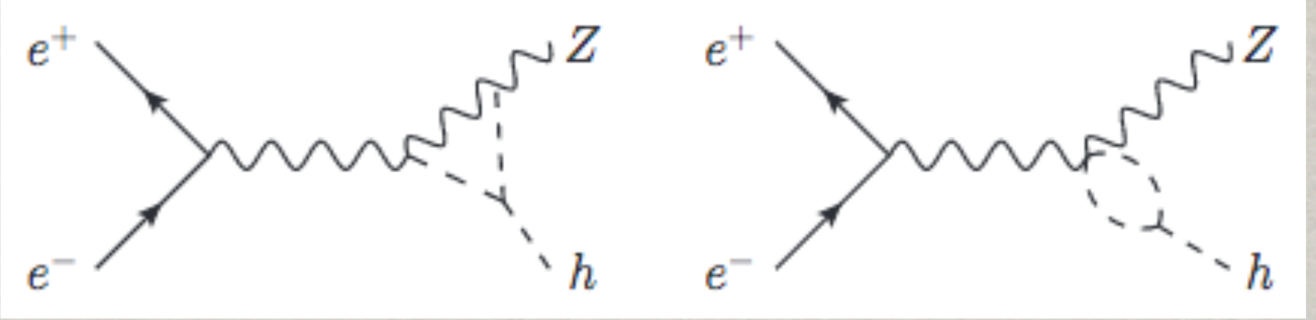
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

CEPC: 240 GeV, 5 ab^{-1}



Z. Liu et al., CEPC White paper/CDR (2018).

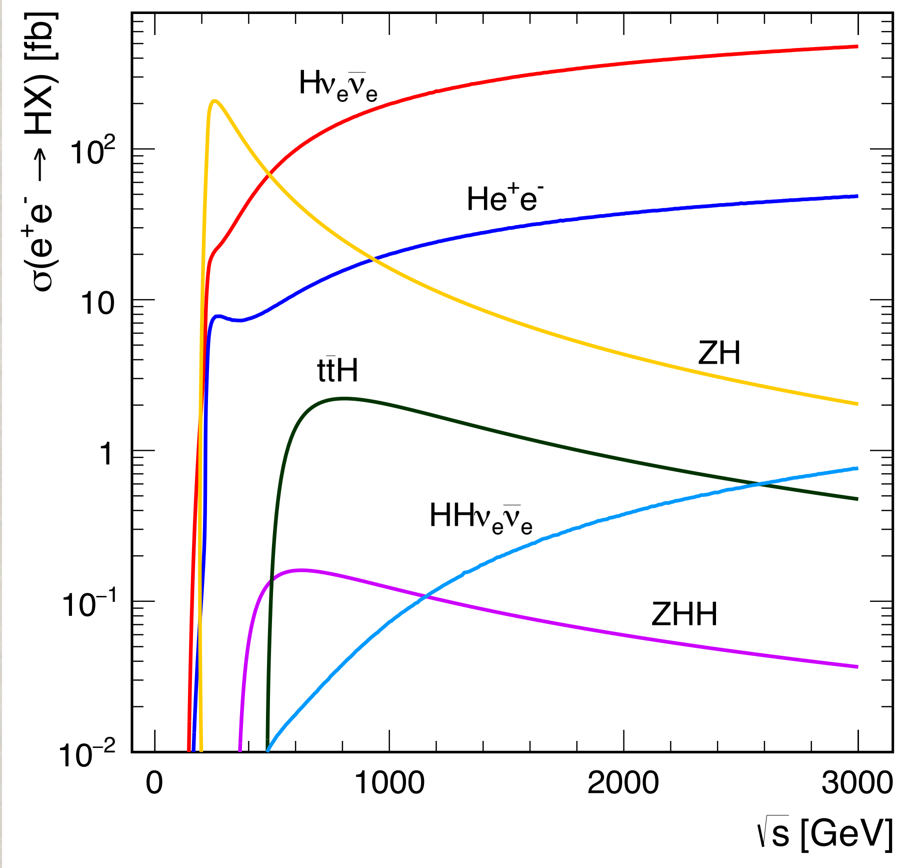
Higgs self-coupling involved at 1-loop level: ~40% accuracy.



M. McCullough'14; X. Zhao's talk.

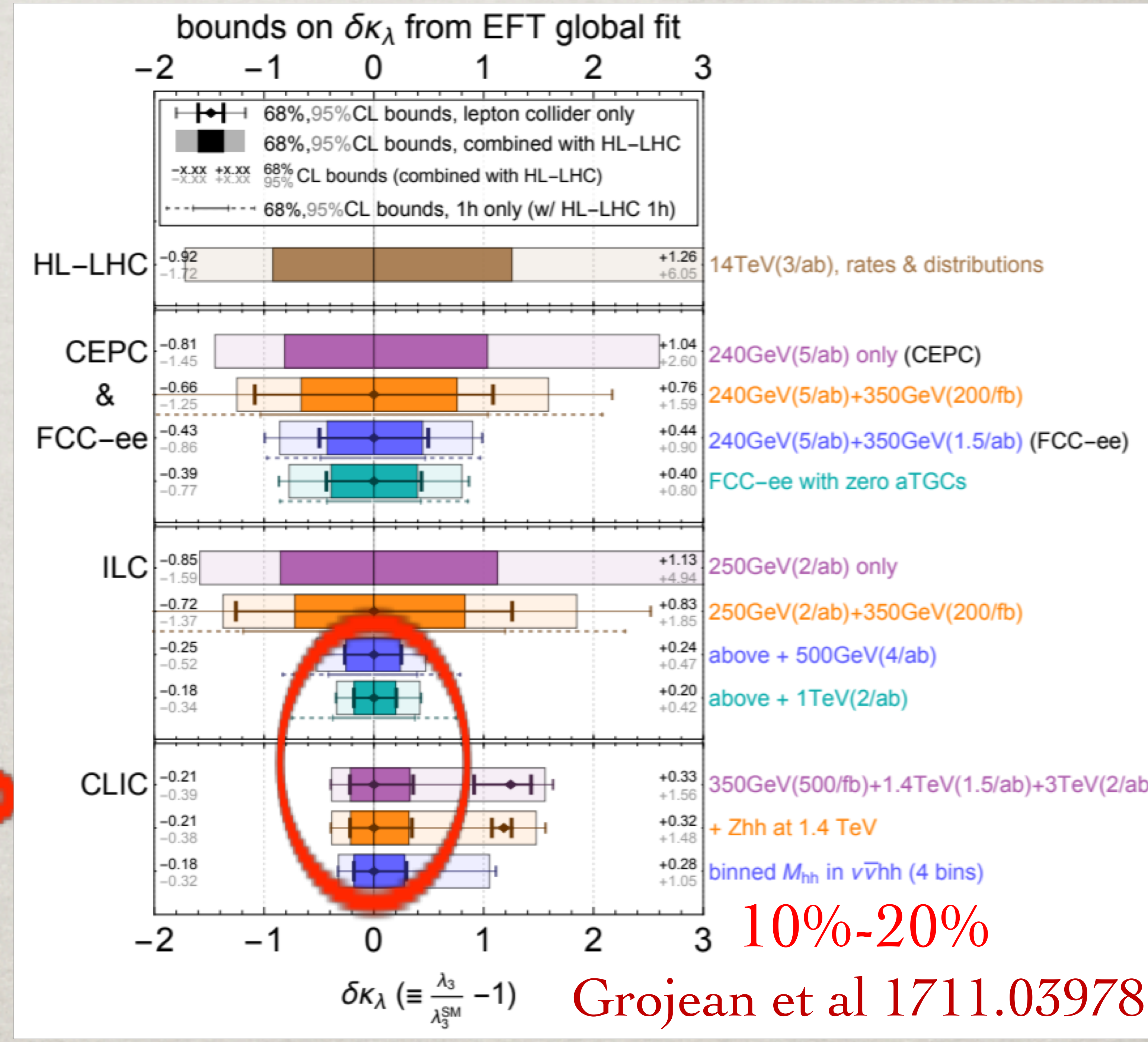
CLIC Improvements:

WW/ZZ fusion dominates



Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV + 1.5 ab^{-1}	+ 3 TeV + 2 ab^{-1}
κ_{HZZ}	0.6 %	0.4 %	0.3 %
κ_{HWW}	1.1 %	0.2 %	0.1 %
κ_{Hbb}	1.8 %	0.4 %	0.2 %
κ_{Hcc}	5.8 %	2.1 %	1.7 %
$\kappa_{H\tau\tau}$	3.9 %	1.5 %	1.1 %
$\kappa_{H\mu\mu}$	–	14.1 %	7.8 %
κ_{Htt}	–	4.1 %	4.1 %
κ_{Hgg}	3.0 %	1.5 %	1.1 %
$\kappa_{H\gamma\gamma}$	–	5.6 %	3.1 %
$\kappa_{HZ\gamma}$	–	15.6 %	9.1 %
$\Gamma_{H,\text{md, derived}}$	1.4 %	0.4 %	0.3 %

Self-coupling summary:



10%-20%

Grojean et al 1711.03978

arXiv:1608.07538, H. Abramowicz et al.

FCC_{hh} / SPPC: New energy frontier

Arkani-Hamed, TH et al. Phys Rep. 2016; Mangano et al, CERN Yellow Repts

FCC-hh contributions to Higgs physics

- Huge Higgs production rates:
  - access (very) rare decay modes
  - push to %-level Higgs self-coupling measurement
  - new opportunities to reduce syst uncertainties (TH & EXP) and push precision

- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$

- High energy reach
  - direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)
    - …

Michelangelo Mangano, June 2018 CERN talk.

100 TeV @ 30 ab^{-1}

	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24 x 10^9	2.1 x 10^9	4.6 x 10^8	3.3 x 10^8	9.6 x 10^8	3.6 x 10^7
N_{100}/N_{14}	180	170	100	110	530	390

process	precision on σ_{SM}	precision on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	2%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$\sim 25\%$	$\lambda_3 \in [\sim 0.6, \sim 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$\sim 15\%$	$\lambda_3 \in [\sim 0.8, \sim 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$\sim 100\%$	$\lambda_4 \in [\sim -4, \sim +16]$

~3%@1$\boldsymbol{\sigma}$

Table 26: Expected precision (at 68% CL) on the SM cross section and on the Higgs trilinear coupling. All the numbers are obtained for an integrated luminosity of 30 ab^{-1} and do not take into account possible systematic errors.

arXiv:1606.09408, arXiv:1607.01831, CERN Yellow Repts

Overall:

- With ~ 50 year's un-interrupted success of HEP program world-wide, the field remains vibrant, with a rich collider program ahead.
- While searches for Higgs' "relatives & siblings" will continue, the precision SM Higgs measurements will be crucial to answer fundamental questions.
- Anticipated precisions for Higgs physics, sensitive to BSM physics

LHC leads the way: g_i ~10%; λ_{HHH} ~ 50%; $Br_{inv.}$ ~ 5%

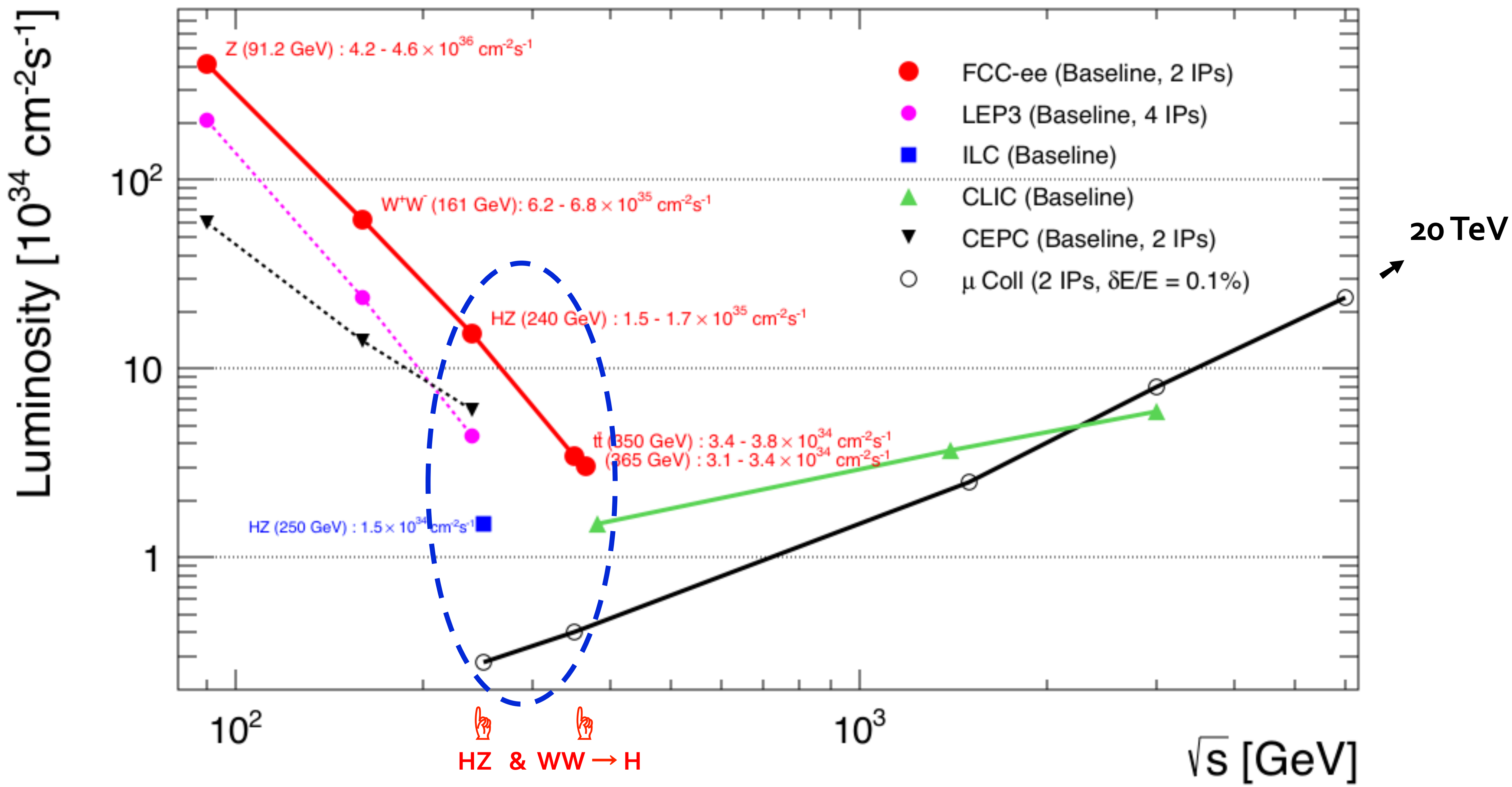
FCC/CEPC: g_i < 1%; Br_{inv} ~0.3%; Γ_{tot} < 6%

FCC/SppC: λ_{HHH} ~ 5%; Br_{inv} ~5%; reaching multi-TeV!

An exciting journey ahead!

Lepton collider overview

- Six different lepton colliders cover the 240-380 GeV range (some partially)



- Significant differences in luminosity, access to the energy frontier, infrastructure, …

Towards FCC-μμ ? (1)

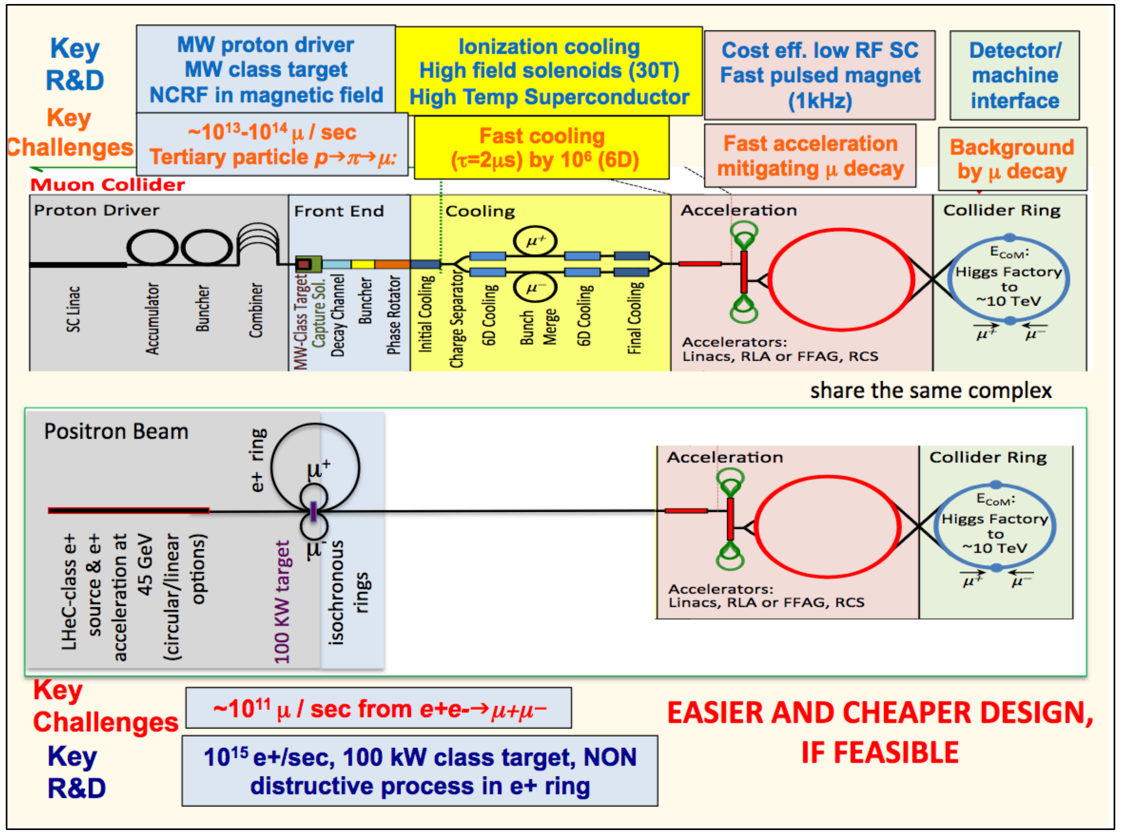
- Recently revived approach to muon collider : LEMMA

D. Kaplan, T. Hart, P. Allport
arXiV:0707.1546

- MAP
- LEMMA

M. Antonelli et al.
arXiV:1509.04454

Mario Antonelli
FCC Week 2016



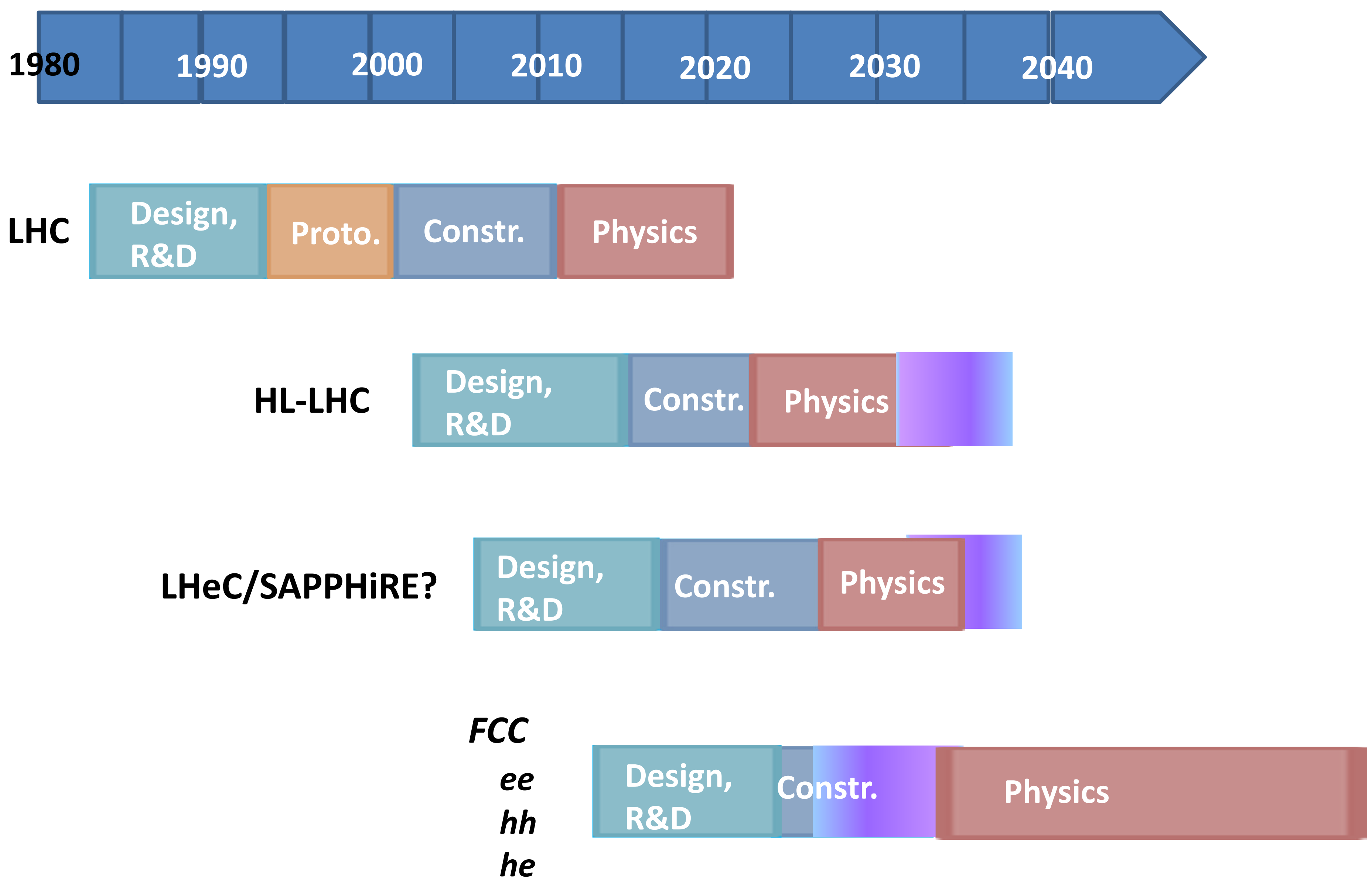
10^{33} cm^2 s^{-1}

Towards FCC-μμ ? (2)

- Recently revived approach to muon collider : LEMMA
  - Produce low emittance muon beams with $e^+e^- \to \mu^+\mu^-$ at production threshold
  - The threshold e^+ energy for $\mu^+\mu^-$ production on a thin target (e^-) is ... 43.7 GeV !
    - Can use the FCC-ee/LEP3 e^+ ring / booster as internal accumulation and target ring
      - ➨ Requires an e^+ source at least 20 times more intense than FCC-ee / CLIC
        Intense e^+ source and polarized e^- target feasibility to be demonstrated
    - All muons are produced with ~ the same energy, in the same direction
      - ➨ No longitudinal muon cooling needed at high √s (ΔE/E ~ 0.07% at √s = 6 TeV)
      - ➨ Unfortunately not better suited for a 125 GeV Higgs factory (ΔE/E ~ 3%)
        Would still require a three-order of magnitude longitudinal cooling
    - Transverse emittance 500 × smaller than with protons on target + cooling (MAP)
      - ➨ Two orders of magnitude less muons needed for same luminosity as MAP
        Lower background from $e^\pm$ in the detector (from muon decays)
        Lower radiation hazard from neutrino interactions at the surface
      - ➨ MAP was limited to √s = 4 TeV to cope with regulations on CERN site

LEMMA could go to √s > 20 TeV (in the FCC or LEP tunnel) within the same regulations

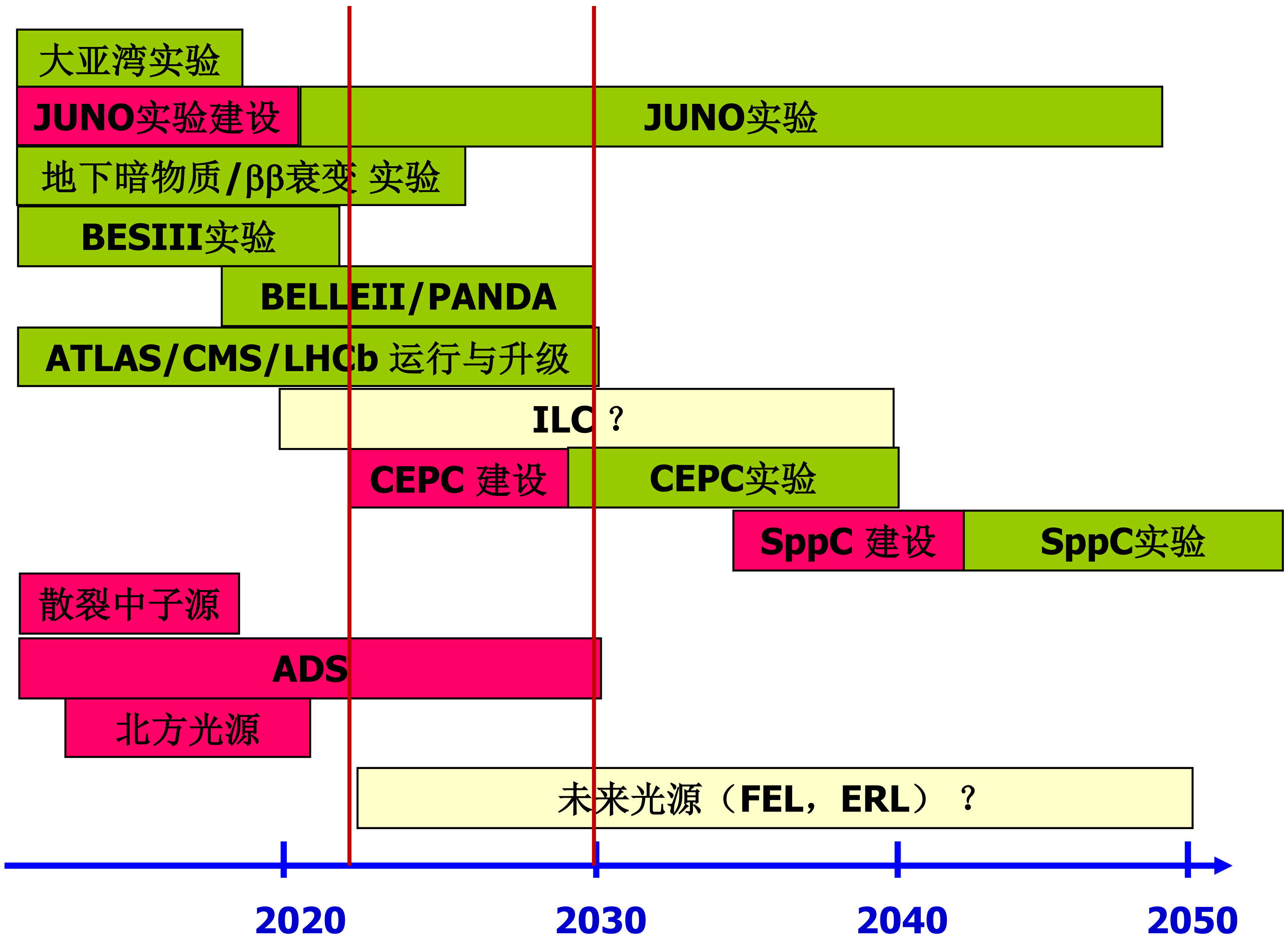
FCC Timeline



M. Benedikt

CERN Reports on "a 100 TeV pp Collider" to appear soon: Vol. 1. SM; 2. Higgs; 3. BSM; 4. Accelerator

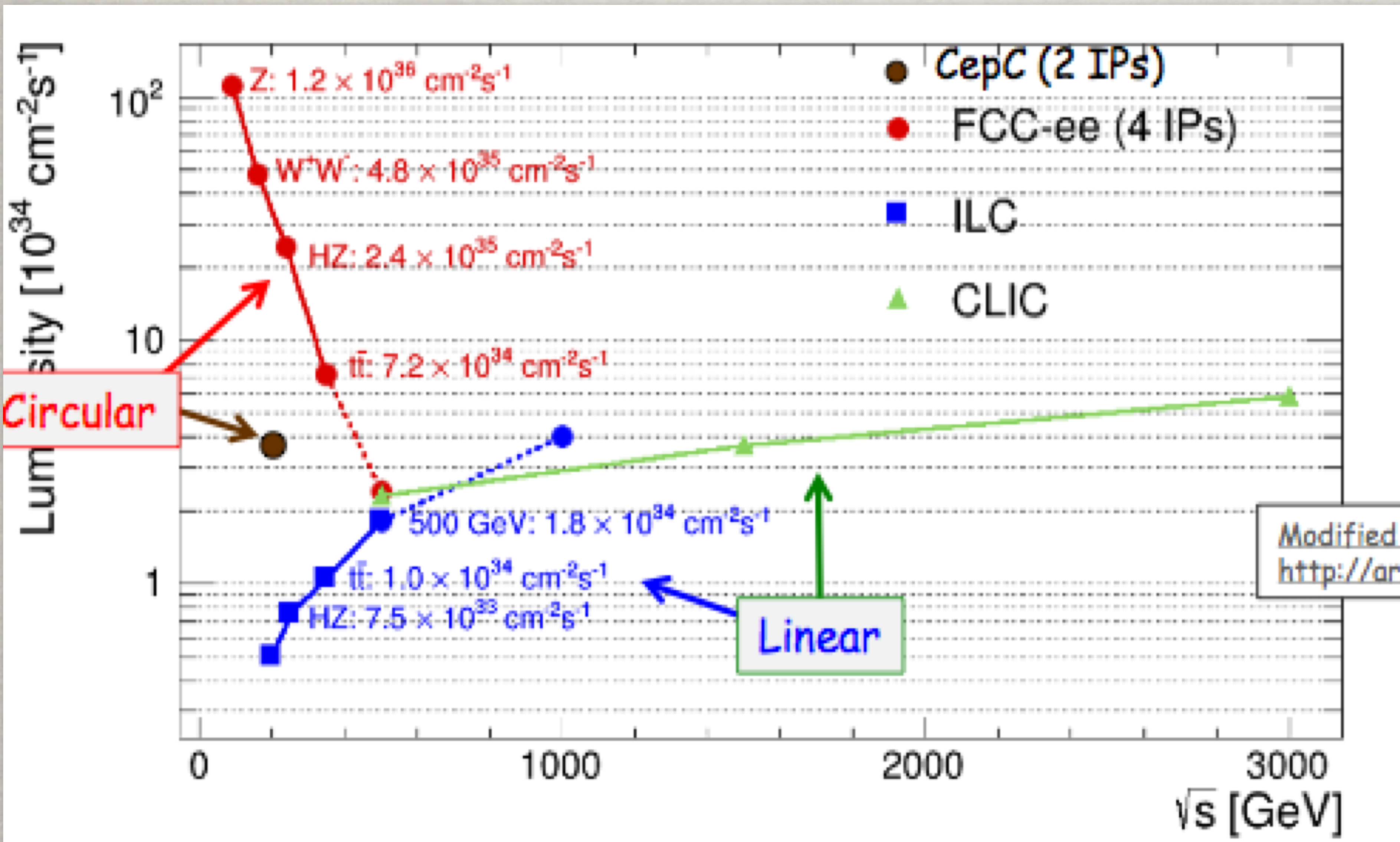
CEPC-SPPC Timeline



Y. Wang

CEPC/SppC Preliminary Conceptual Design Reports:
Vol. 1: Physics & Detector; Vol. 2: Accelerator
http://cepc.ihep.ac.cn/preCDR/volume.html

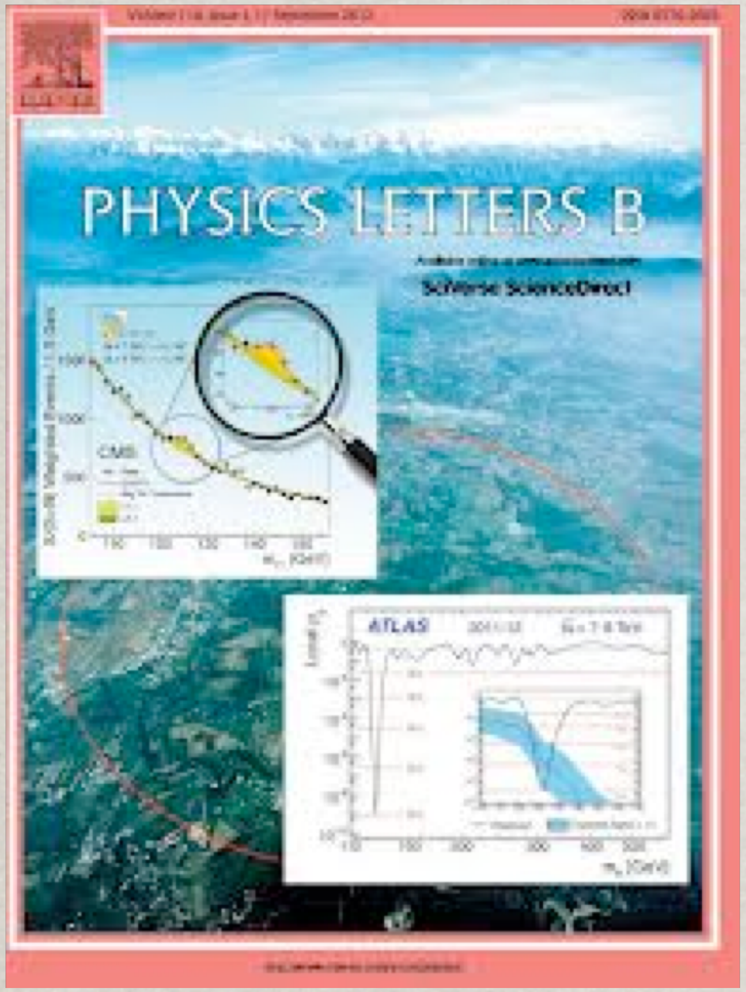
e^+e^- colliders: Energy/Lumi projection

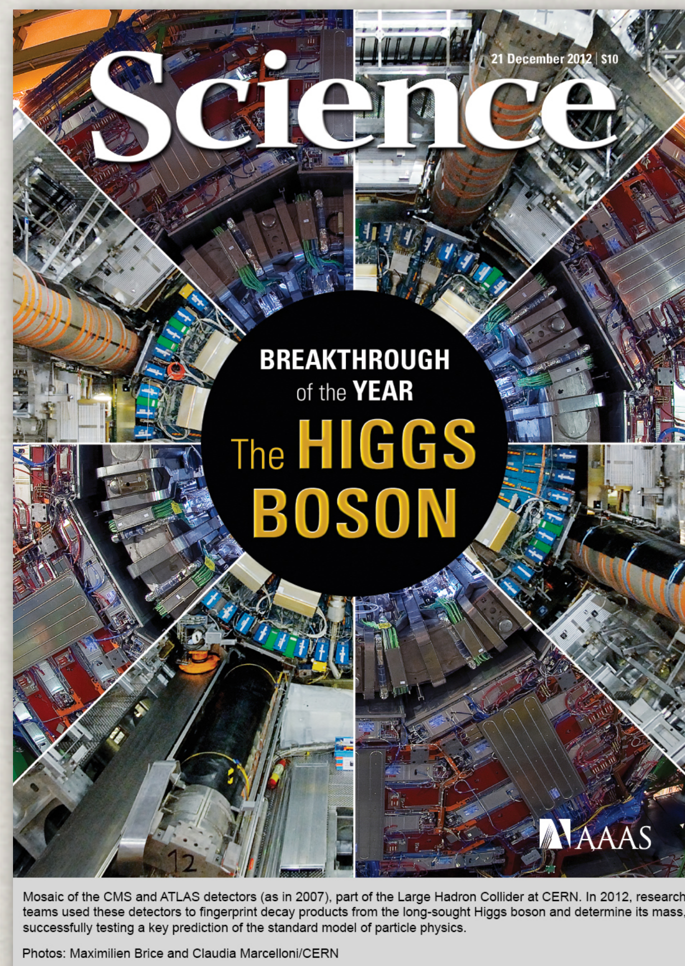


TLEP Report: 1308.6176

E_{cm}	running time	statistics (FCC-ee)
	b,c,τ	10^{11} b,c,τ
90 GeV	1-2 yrs	10^{12} Z (Tera Z)
160 GeV	1-2 yrs	10^8- 10^9 WW(Oku W)
240 GeV	4-5 yrs	$2x10^6$ ZH (Mega H)
350 GeV	4-5 yrs	10^6 tt (Mega top)

A milestone discovery:
It is a brand new class!





50 years theoretical work …

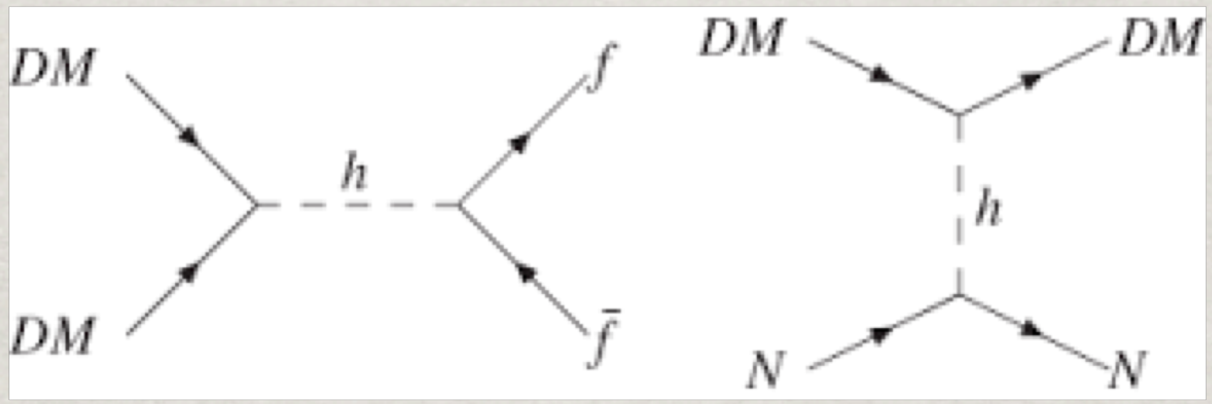
25 years experimental work …

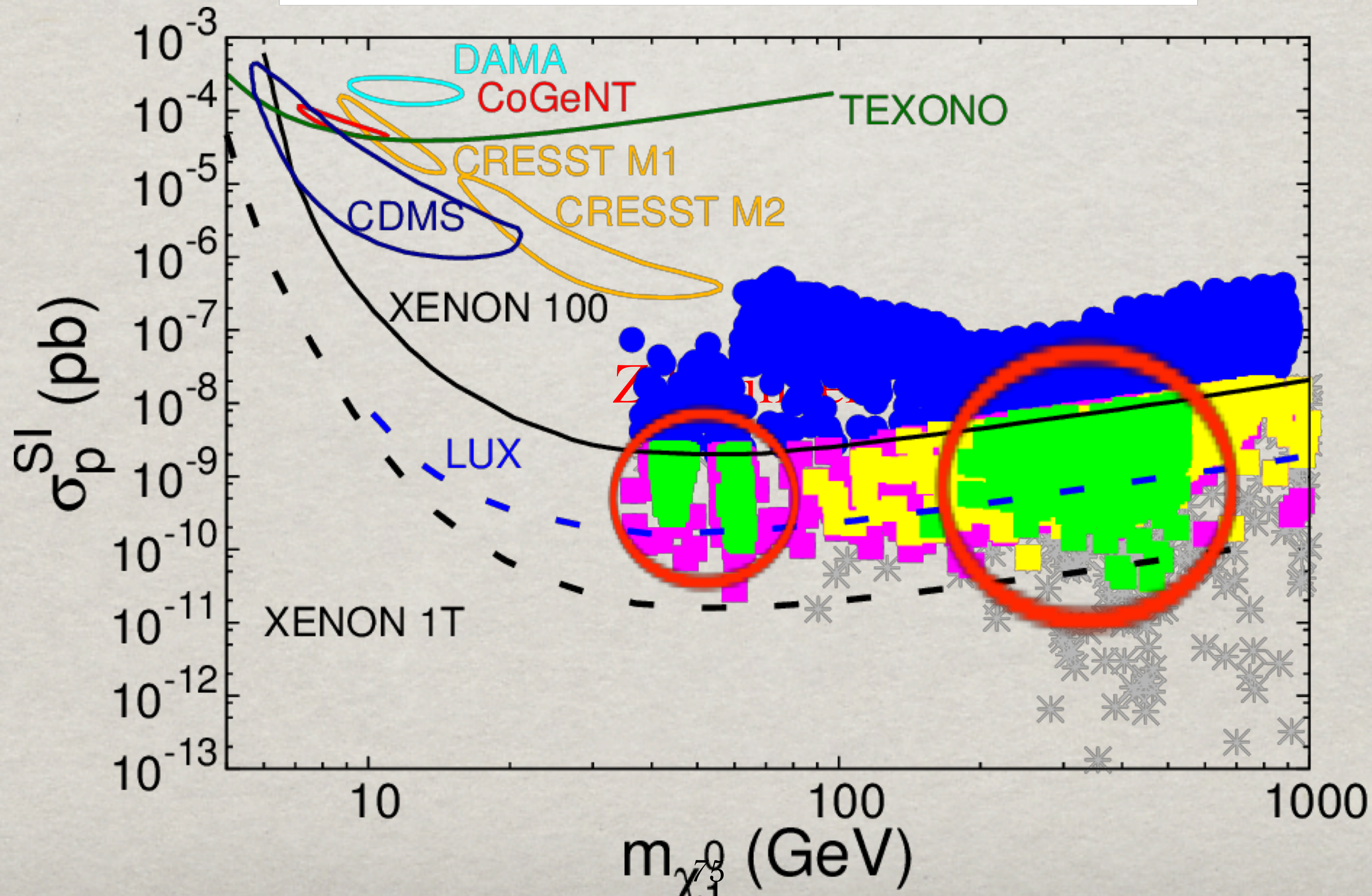
We Made It !

5. The Dark Sector

The un-protected operator may reveal secret

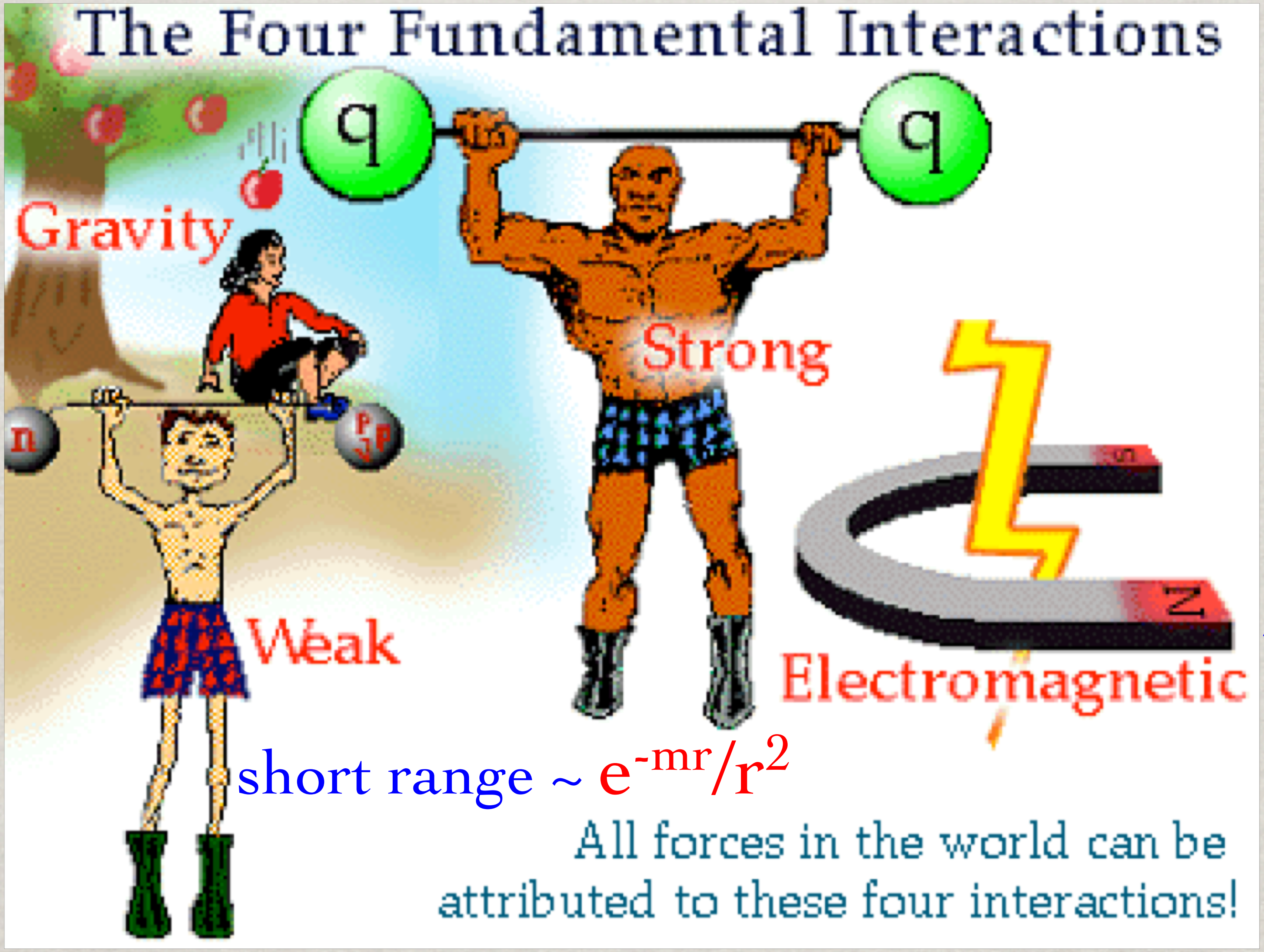
Higgs portal: $k_s H^\dagger H \; S^* S, \quad \frac{k_\chi}{\Lambda} H^\dagger H \; \bar{\chi}\chi.$





The Nature of Forces:

long range
$\sim (G_N\, m_1 m_2)/r^2$



short range $\sim e^{-mr}/r^2$

long range
$\sim (\alpha\, e_1 e_2)/r^2$

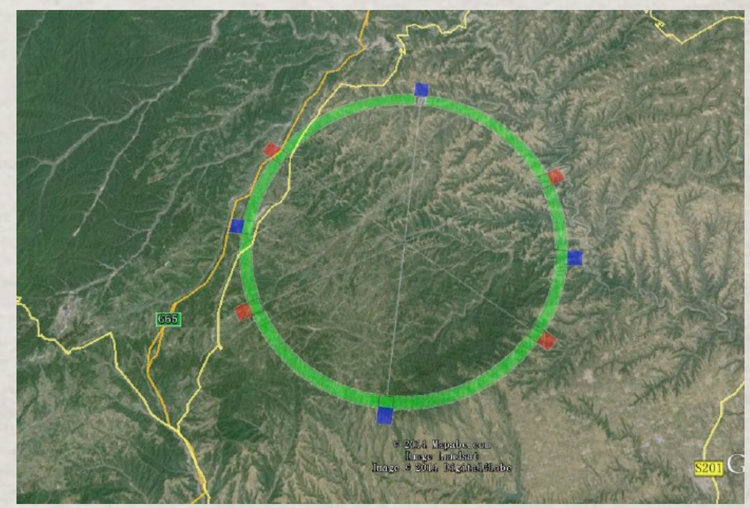
All known physics

$$W = \int_{k<\Lambda} [\mathcal{D}g \ldots] \; \exp\left\{ \frac{i}{\hbar} \int d^4x \sqrt{-g} \left[\frac{1}{16\pi G} R - \frac{1}{4} F^2 + \bar{\psi} i \not{D} \psi - \lambda \phi \bar{\psi} \psi + |D\phi|^2 - V(\phi) \right] \right\}$$

amplitude — current understanding — quantum mechanics — spacetime — gravity — strong & electroweak — matter — Higgs

Site selections (a few main candidates)

1)



2)

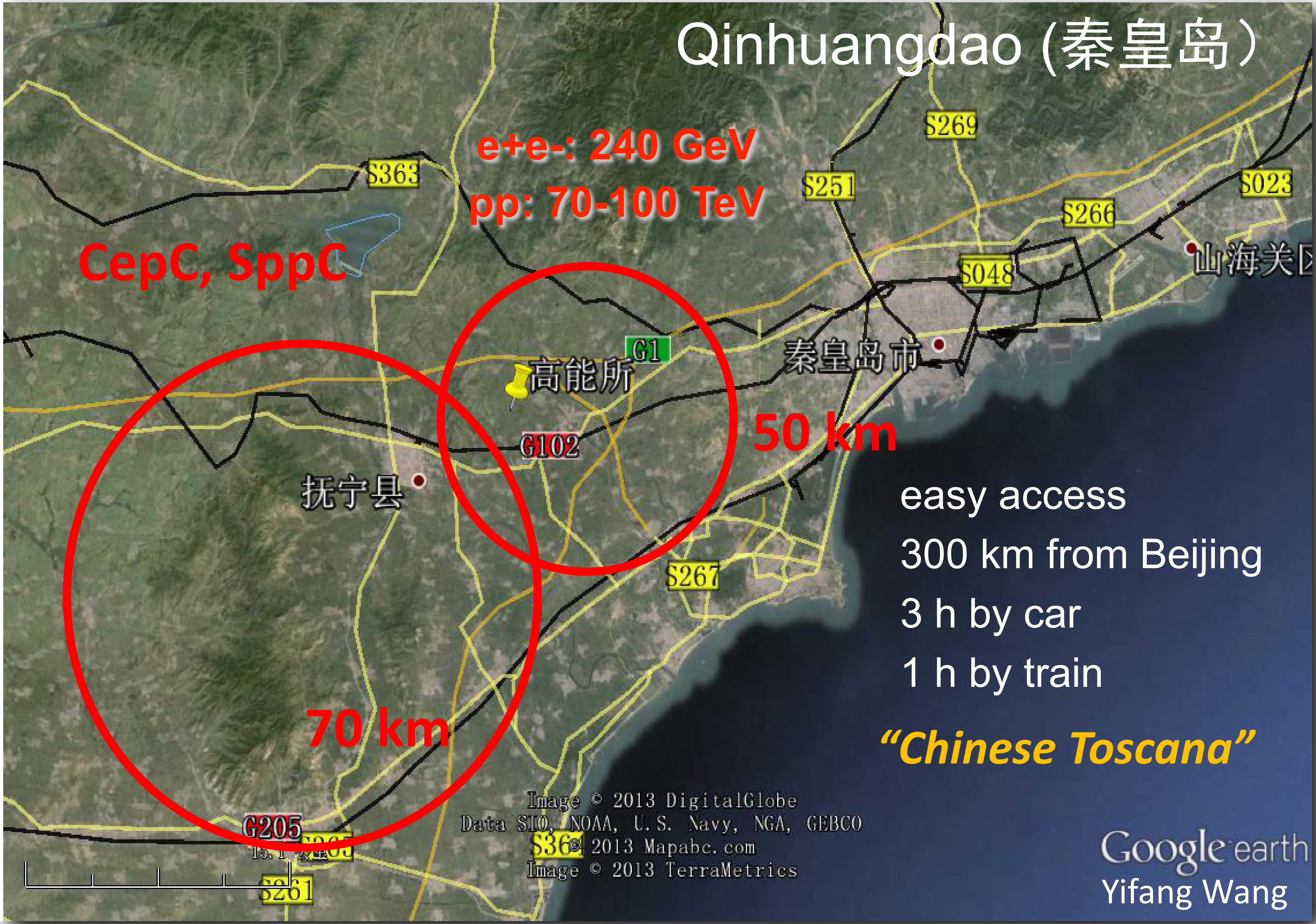
3)

1) Qinhuangdao

2) Shaanxi Province

3) Near Shenzhen and Hong Kong

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



Future of High Energy Physics

is too ambitious a topic, because

- **its scope:** accelerator-based, non-accelerator, astro-particle & cosmic connections …
- **its depth:** deep into unknowns, with theoretical concepts, experimental techniques …
- **its scale:** international, interdisciplinary, tens of thousand researchers, multi-$B annual investment
- **its connectivity:** philosophy, society, politics

Would have to be (personally) selective:

Under the Higgs Lamppost

The plan:

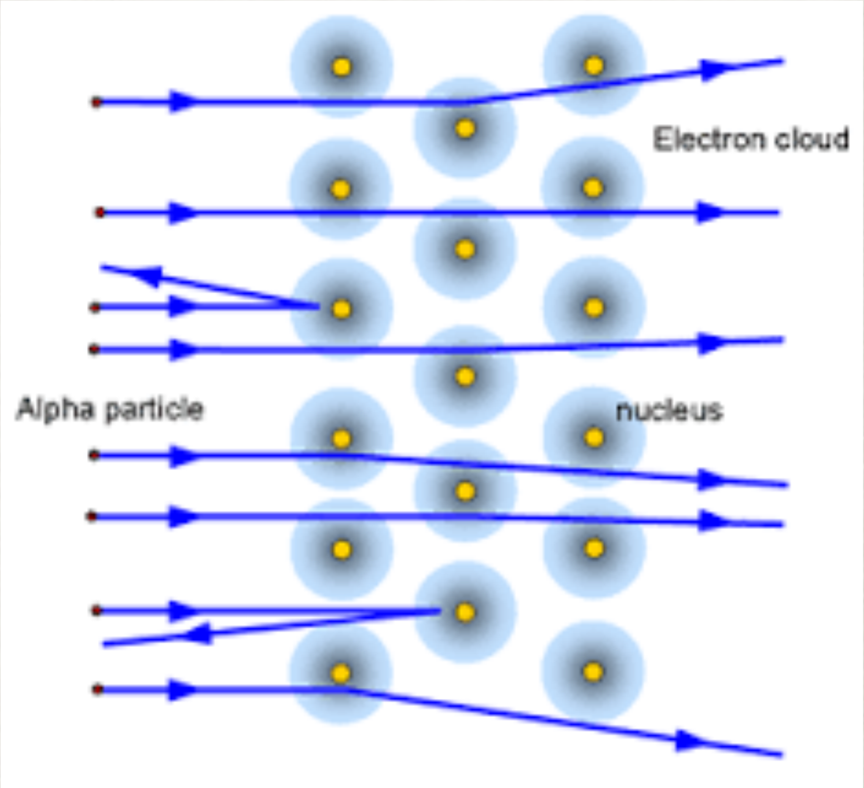
- Past: Uninterrupted discoveries in the past 50 years.
- Current status: The completion of the “Standard Model” leaves many fundamental questions.
- Future: Pathways to seek for answers.
- High energy physics & Society

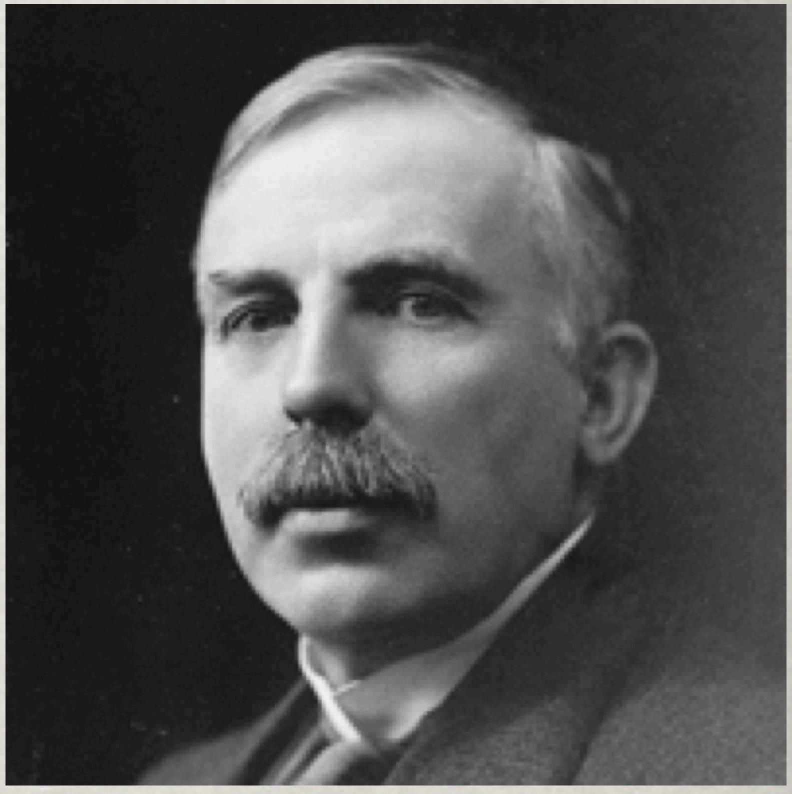
A planetary atom, the nucleus (1911)

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

Coulomb scattering
between two charges:

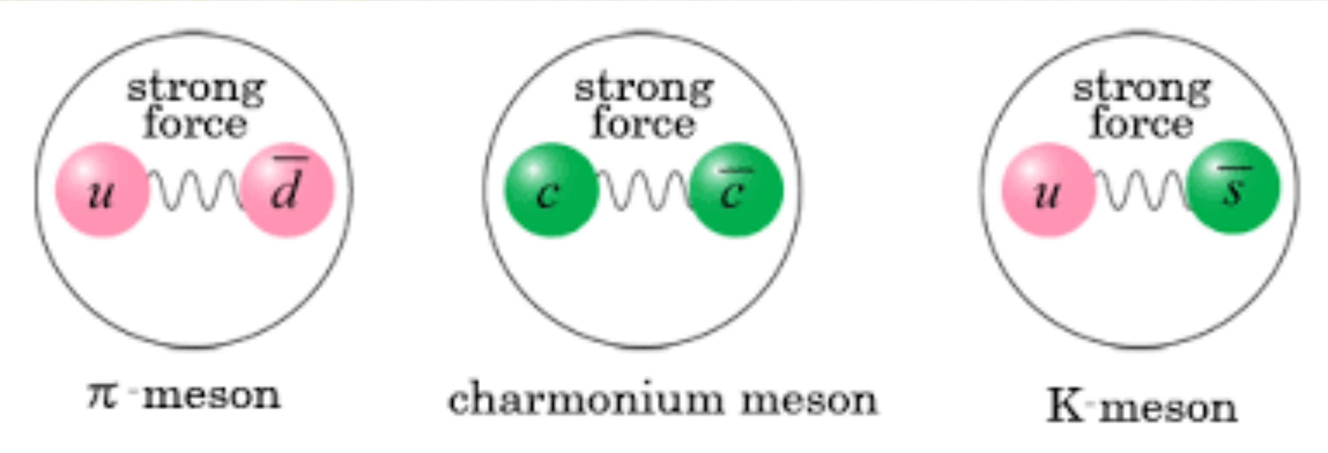
$$d\sigma \propto \frac{(\alpha Z_1 Z_2)^2}{(q^2)^2} \approx \frac{(\alpha Z_1 Z_2)^2}{4E^2 \sin^4 \theta/2}$$





- The hydrogen nucleus, named as "Proton" (Greek for "first") as a fundamental particle, a building block for other nuclei.

Heavy quark "charm":
1974 November revolution



Tau-lepton was discovered in the same SLAC experiment:
The 1^{st} 3^{rd} generation fermion!

In the 30's – 50's: